Study of the $B^0 \rightarrow D^{*-} \ell^+ \nu$ with the Partial Reconstruction Technique

University of Ferrara / INFN Ferrara
Dottorato di Ricerca in Fisica Ciclo XVII
Mirco Andreotti

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✗ Measurement of $\mathcal{B}(B^0 \rightarrow D^* \ell \nu)$ from *BABAR* data

✗ $\mathcal{B}(B^0 \rightarrow D^* \ell \nu)$ as first step for the evaluation of $|V_{cb}|$

<u>Outline</u>

- ✔ The *BABAR* Experiment
- ✔ $|V_{cb}|$ CKM matrix element and its extraction
- ✔ Existing measurements of $\mathcal{B}(B^0 \rightarrow D^* \ell \nu)$
- ✔ Extraction of $\mathcal{B}(B^0 \rightarrow D^* \ell \nu)$
- ✔ Semileptonic selection
- ✔ Partial reconstruction of $B^0 \rightarrow D^* \ell \nu$
- ✔ Results for $\mathcal{B}(B^0 \rightarrow D^* \ell \nu)$

The *BABAR* Experiment - PEP II

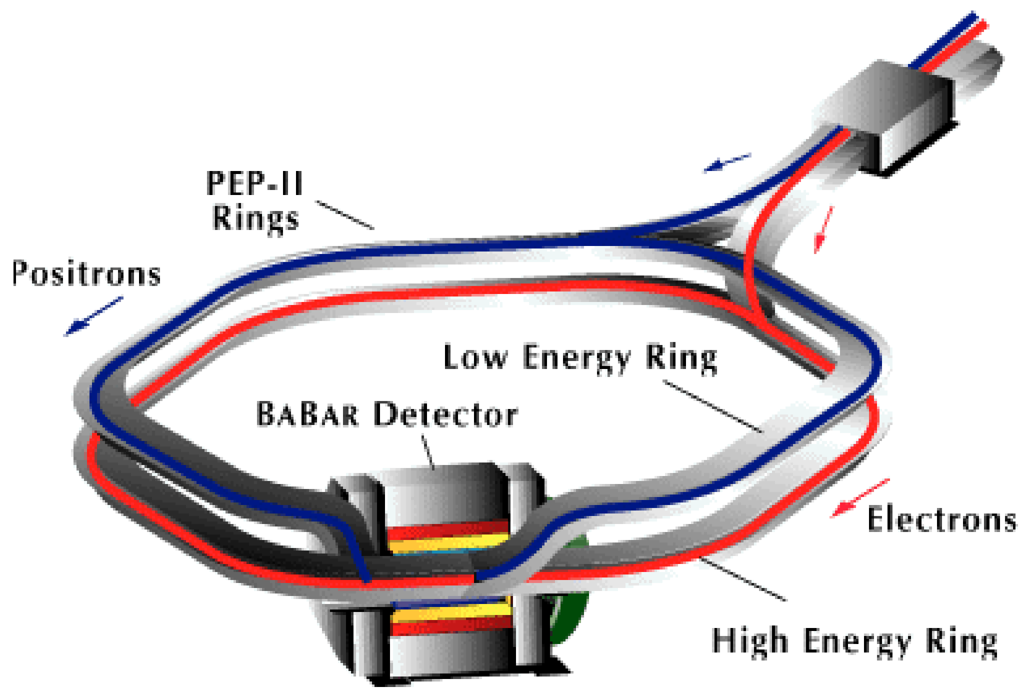
✔ 9 GeV e^- head-on 3.1 GeV e^+

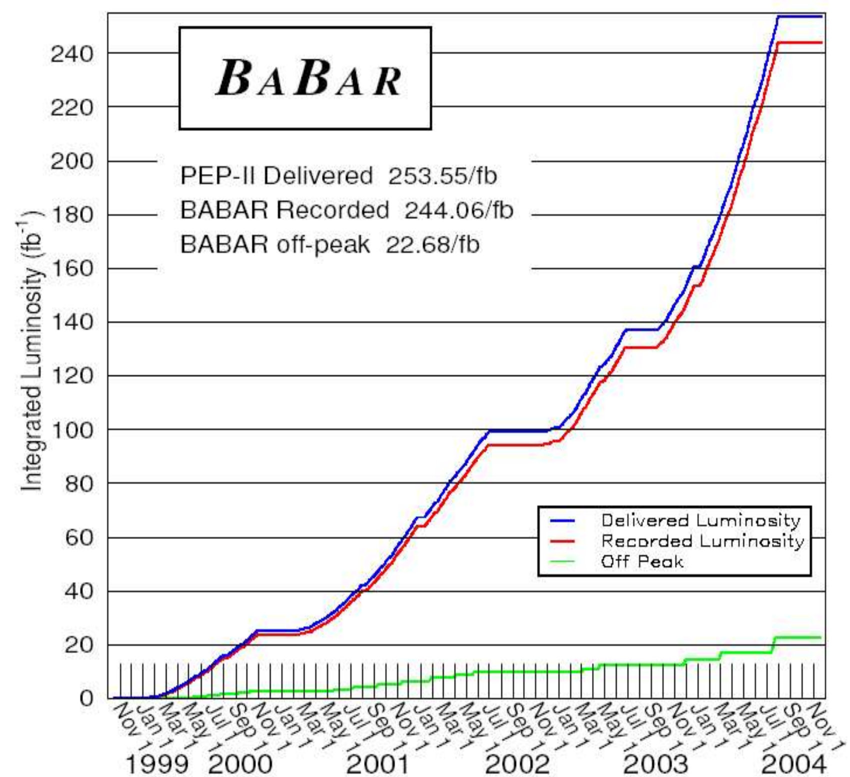
$\Rightarrow E_{CM} = 10.58$ GeV = Υ(4*S*) mass

- Υ(4S) → $\bar{B}B$ ¼ of all Υ(4S) decays
- $e^+e^- \to \bar{q}q$ ¾ continuum background

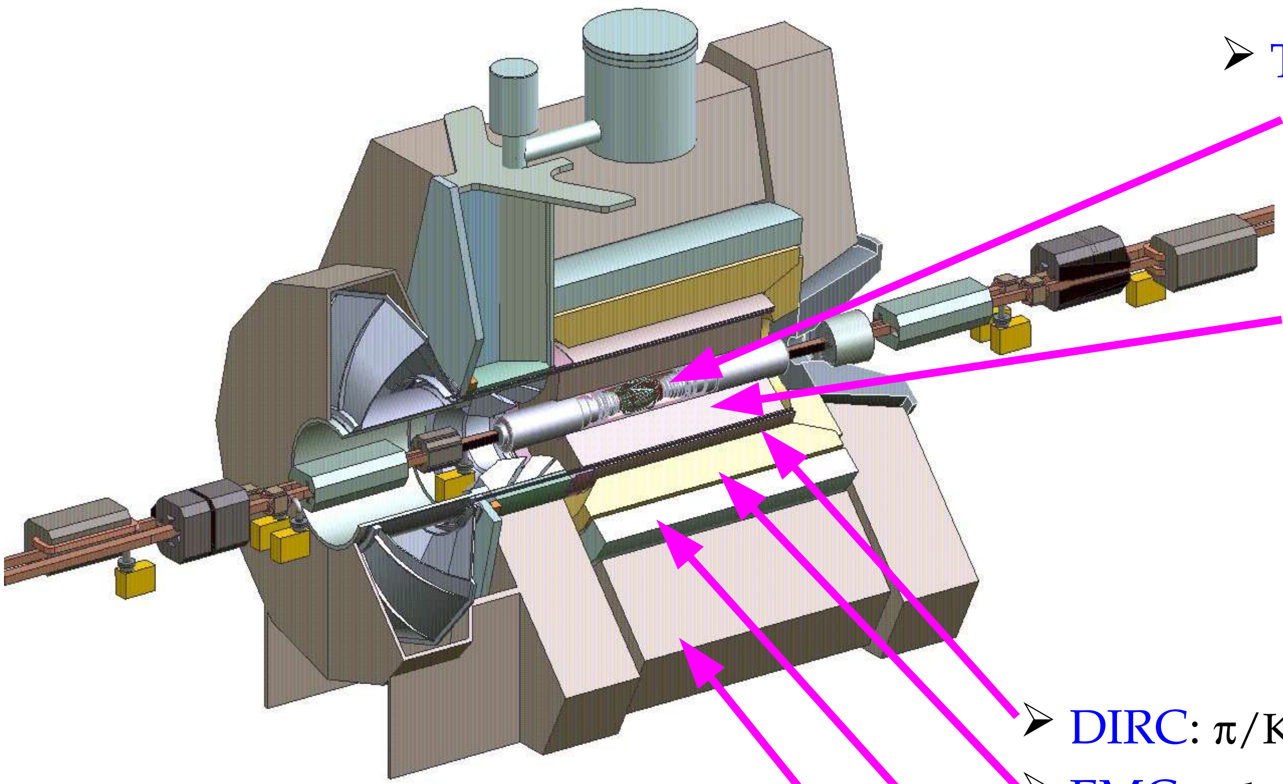
✔ βγ=*0.56* allows to measure B decay time

✔ Peak lumi = $9.2\times10^{33}/cm^2/s$ gives a $\bar{B}B$ production rate of 10 Hz





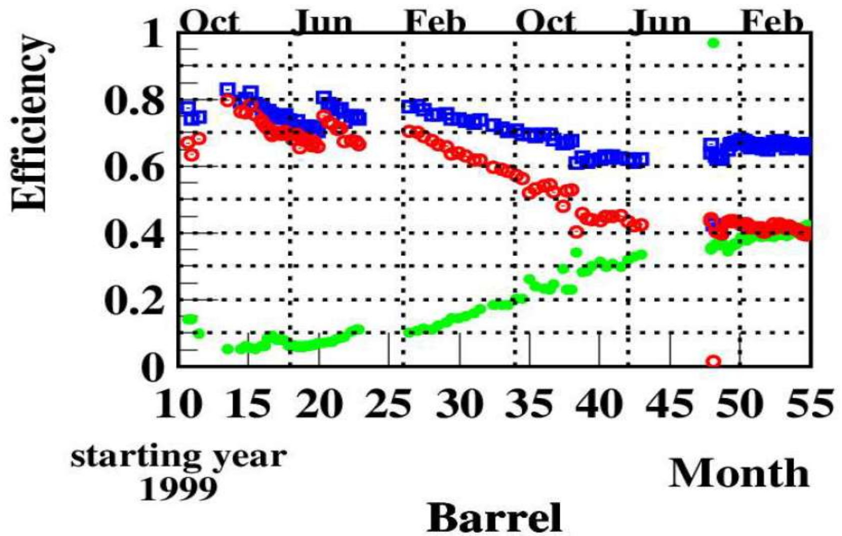
The *BABAR* Detector

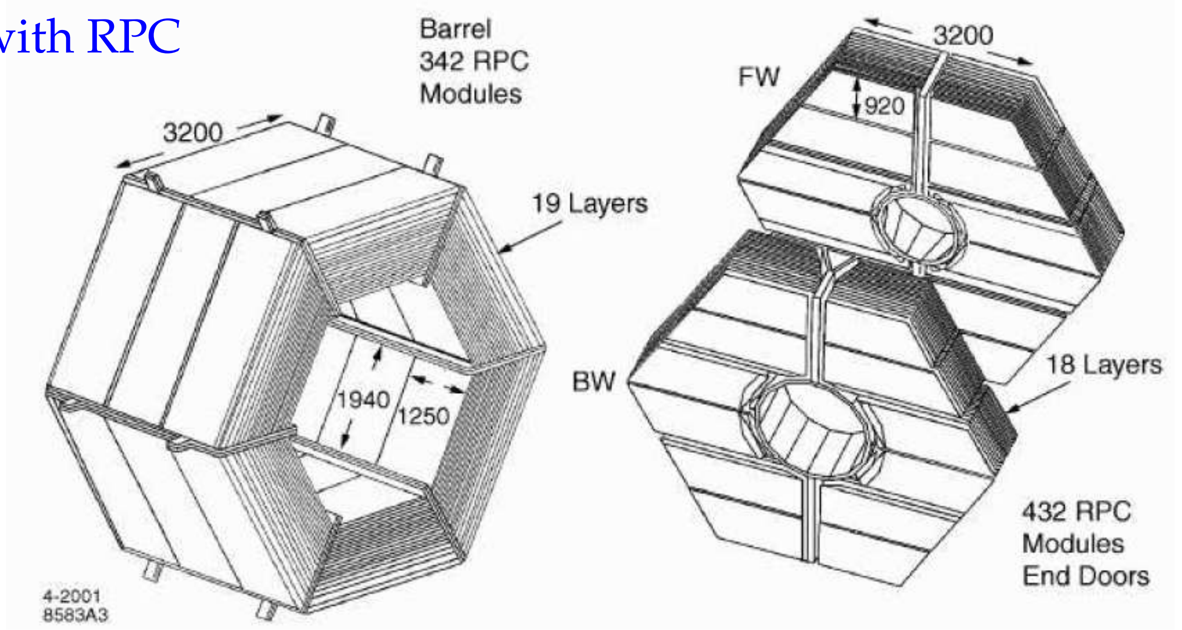


- Tracking system:
  - SVT: - measurement of B decay vertices
    - p_T < 120 MeV (charged)
  - DCH: - measurement of p_T from curvature of charged particle in 1.5 T magnetic field for p_T > 120 MeV
    - PID for low p by *dE/dx*
- DIRC: π/K discrimination
- EMC: - detection of γ and $e^{\pm}$ with 20 MeV < E < 4 GeV
  - electron/hadron separation
- Magnet: superconducting solenoid provides an axial magnetic field of 1.5 T
- IFR: - muon and neutral hadron ID (K_L^0)
  - instrumented iron yoke for the magnetic flux return

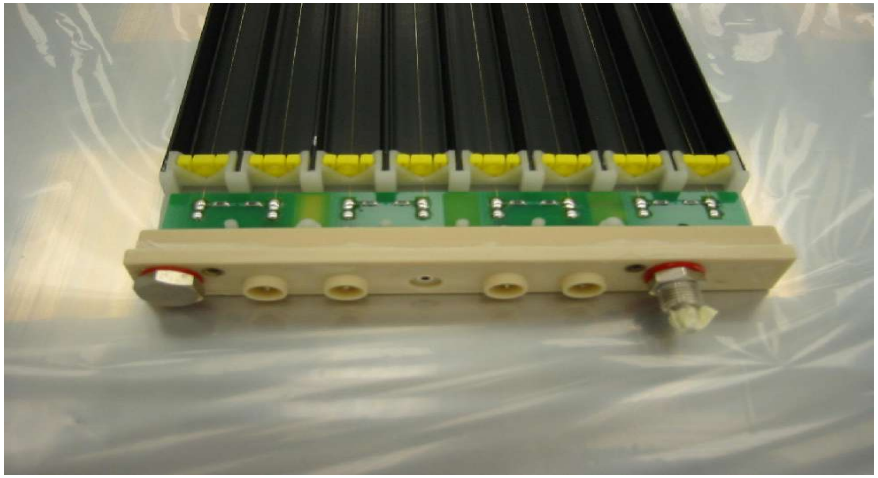
The *BABAR* Detector – Upgrade of muon detector

- Initial design: IFR was instrumented with RPC
- Decreasing of efficiency:



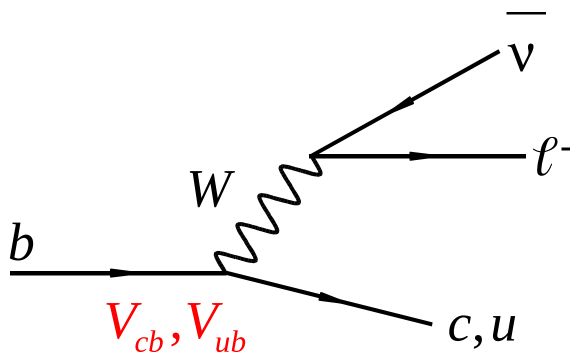


- Upgrade of muon detector:
  - ✗ Forward endcap: replacements with new RPCs in 2002
  - ✗ Barrel: replacement of RPCs with LSTs (two sextants in 2004, the other 4 sextants in 2006)



➔ Muon ID is fundamental for this analysis, then data with new muon detector will be used for a future update of this analysis.

$|V_{cb}|$ CKM matrix element

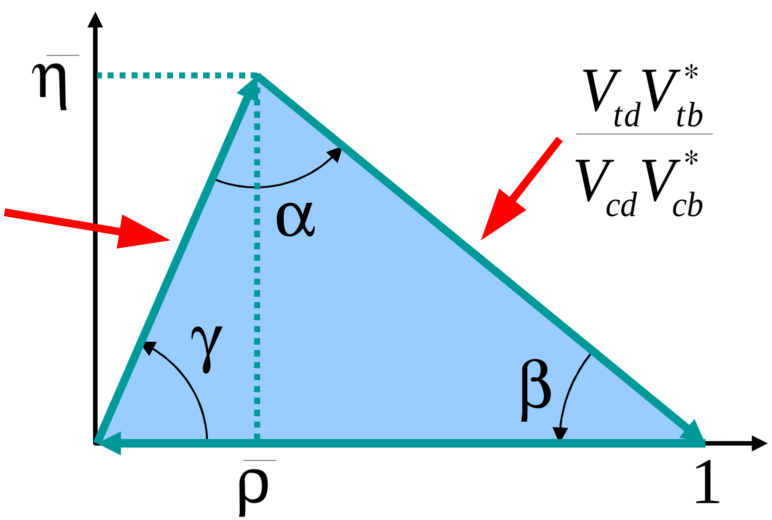


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- V_{ub} and V_{cb} are fundamental in order to confirm the unitary relation:

$$V^{\dagger}_{CKM} V_{CKM} = 1 \Rightarrow V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

- The unitary relation can be expressed in complex plane by the known triangle:



$$\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}} \qquad \frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}}$$

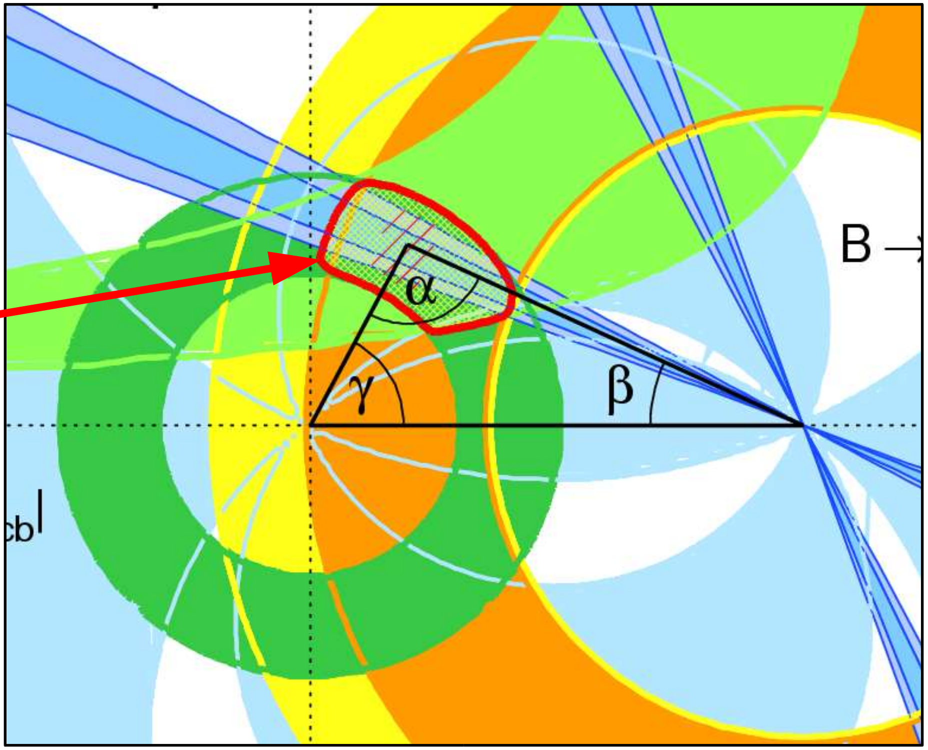
$$\alpha = \arg\left(-\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right)$$

$$\beta = \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right)$$

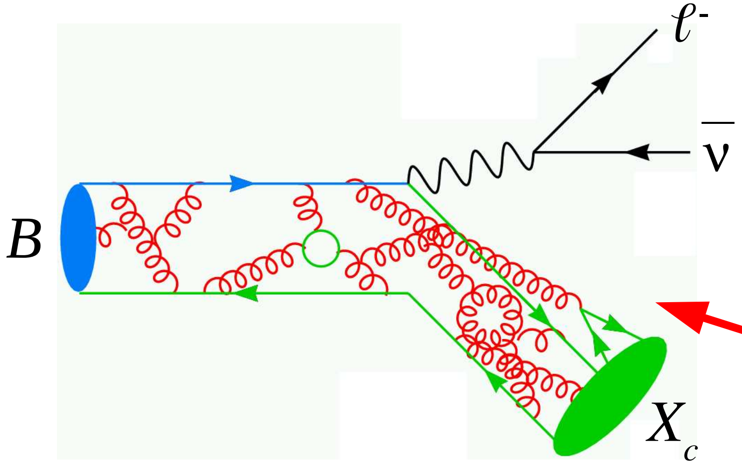
$|V_{cb}|$ CKM matrix element

- ✗ If the Standard Model is true the triangle has to be closed.
- ✗ More precise measurements of V_{ub} and V_{cb} are needed for the evaluation of their ratio in order to reduce the current uncertainties



- ✗ V_{cb} can be evaluated from semileptonic B decays

  ➡ decoupling strong and weak interaction



Hadronic current is parametrized in terms of form factors

$|V_{cb}|$ extraction from differential BR

✗ Heavy Quark Effective Theory (HQET) gives a "simple" relation for differential branching ratio of $B^0 \to D^*\ell\nu$

Phase space factor

$$\frac{d\mathcal{B}\left(B^0 \to D^{*-}\ell^+\nu_\ell\right)}{dw} = \frac{G_F^2}{48\pi^3}\tau_B \; |V_{cb}|^2 \; \Phi(w) \; \mathcal{F}^2(w)$$

Form factor

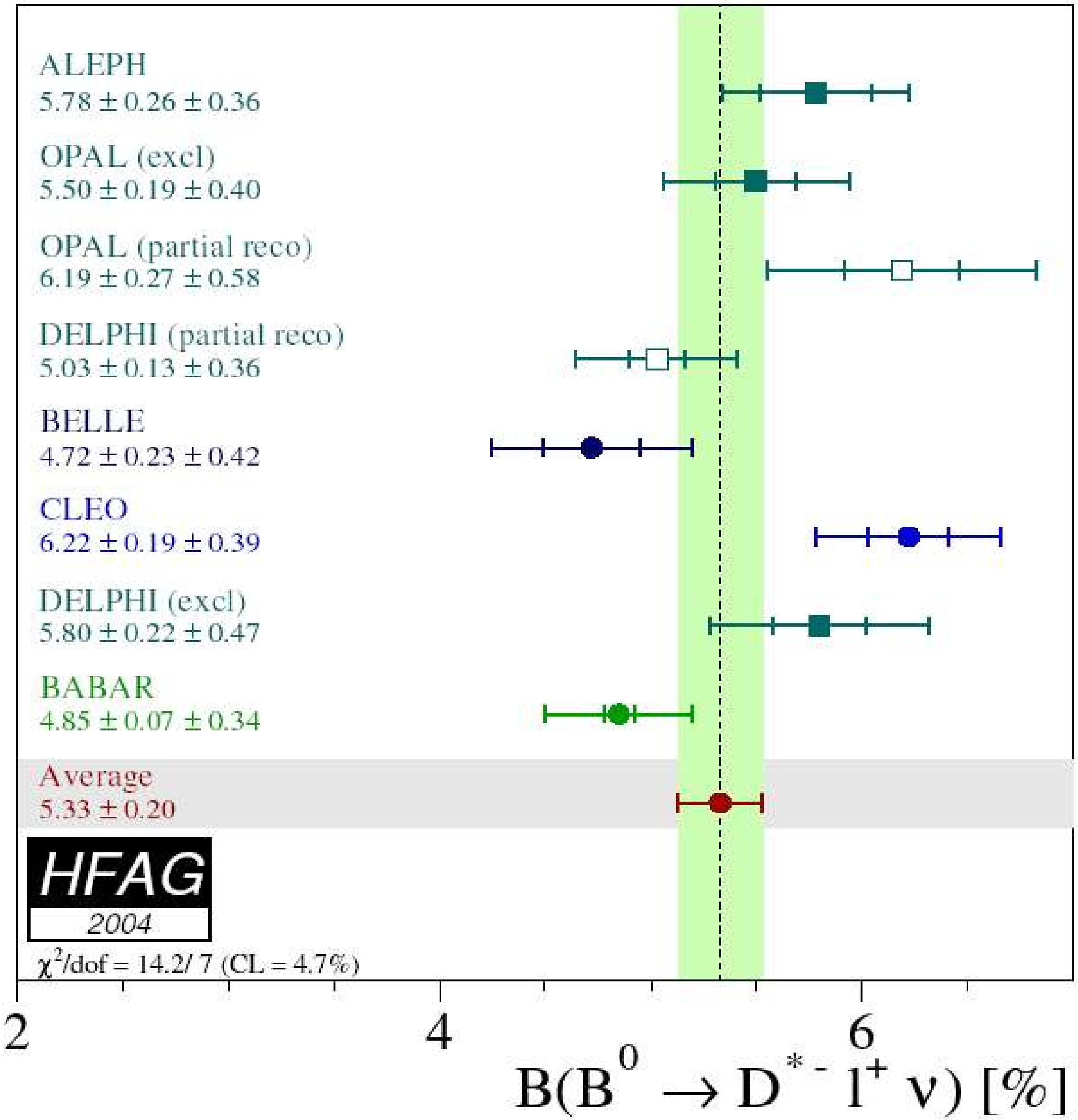
$w=\gamma_{D^*}$ in B^0 rest frame

✗ The form factor can be evaluated at $w=1$, and in the limit $m_b, m_c \to \infty$ $\mathcal{F}(1) \approx 1$

✗ $|V_{cb}|$ can be evaluated extrapolating the product $|V_{cb}|\,\mathcal{F}(w)$ as a function of w

➢ A first step in order to measure $|V_{cb}|$ is the measurements of $\mathcal{B}(B^0 \to D^*\ell\nu)$

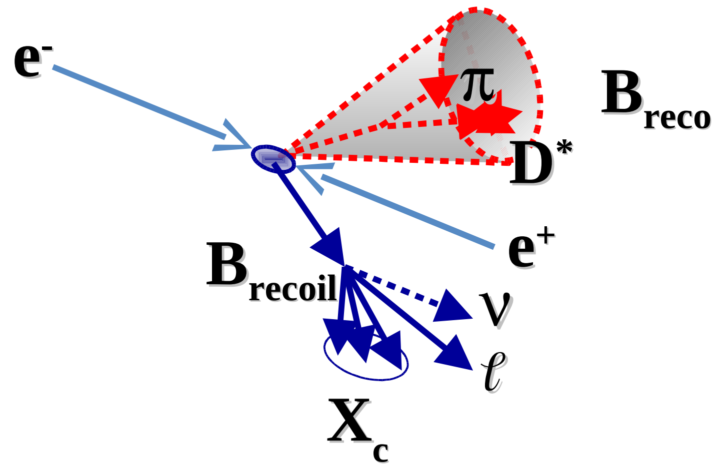
Existing measurements of $\mathcal{B}(B^0 \rightarrow D^* \ell \nu)$



- χ/dof (~2) of the 8 existing measurements of $\mathcal{B}(B^0 \rightarrow D^* \ell \nu)$ is marginal.
- A new measurement of the branching ratio by using a different approach is an important cross-check of the existing measurements.
- BaBar measured $\mathcal{B}(B^0 \rightarrow D^* \ell \nu)$ from an exclusive selection.
- The uncertainty on BaBar measurement is dominated by systematic effects, mainly due to the exclusive reconstruction of the final state.

$\Rightarrow$ <u>The partial reco of D* on the recoil of fully reconstructed B</u>

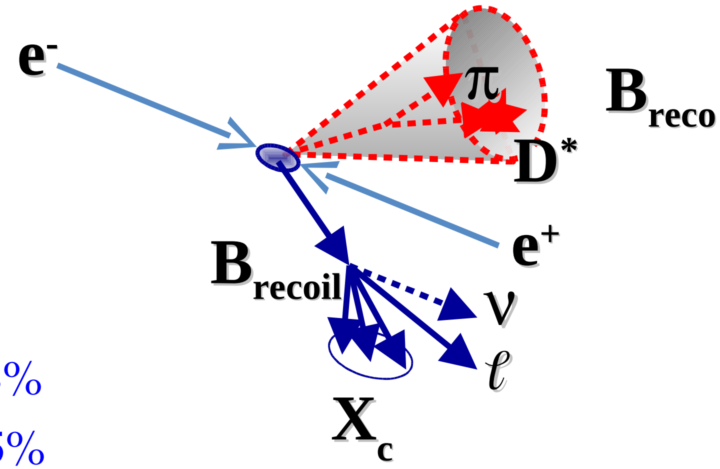
Analysis on the recoil of fully reconstructed B



- Full reconstuction of one B:
  - ✔ Low efficiency ⇒ low available statistics ⇒ available data increase
  - ✔ Clean samples with one B
  - ✔ Clean separation between decay products of the two B mesons
  - ✔ Low background contamination on the recoil
- Partial reconstruction on the recoil of the fully reconstructed B:
  - ✔ Less systematic effects
  - ✔ More efficient than full D^0 reconstruction

One fully reconstructed B

- ✗ One *B* is reconstructed by looking at its hadronic decays (about 1000 decay modes) and its flavor is determined.
- ✗ The kinematic consistency checked with two variables:

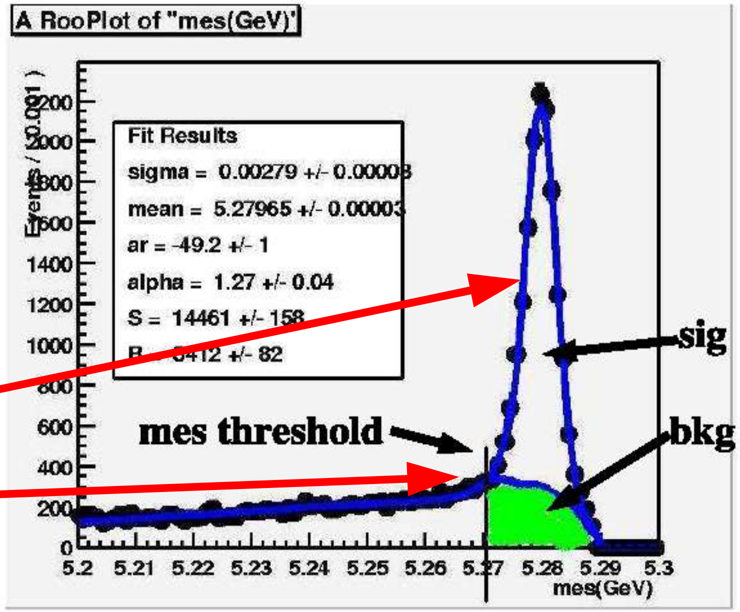


$$m_{ES} = \sqrt{\frac{s}{4} - \vec{p}_B^{\,2}} = m_B$$

$$\Delta E = E_B - \frac{\sqrt{s}}{2} = 0$$

- ✗ Efficiency for B^0 is 0.3%
- ✗ Efficiency for B^+ is 0.5%

- ✗ Fit on m_{ES} variables is used for subtraction of background:
  - ✔ Continuum background ($c\bar{c}$ and *uds*)
  - ✔ Combinatorial background in *B* decays
  - ✗ Crystal-Ball function for signal events
  - ✗ Argus function for background events



Measurement of $\mathcal{B}(B^0 \to D^*\ell\nu)$ with the partially reconstructed D^*

- Partial reconstruction technique is useful to reconstruct $B^0 \to D^*\ell\nu$ with $D^* \to D^0\pi^+$

From PDG — Efficencies of selections

$$\mathcal{B}\left(B^0 \to D^{*-}\ell^+\nu_\ell\right) = \frac{\mathcal{B}\left(B^0 \to X l\nu\right)}{\mathcal{B}\left(D^{*+} \to D^0\pi^+\right)} \times \frac{N_{sel}^{D^* l\nu}}{N_{sel}^{SL,B^0}} \times \frac{1}{\epsilon^{cut}} \times \frac{\epsilon_{SL}^{Breco,SL}}{\epsilon_{sig}^{Breco,SL}}$$

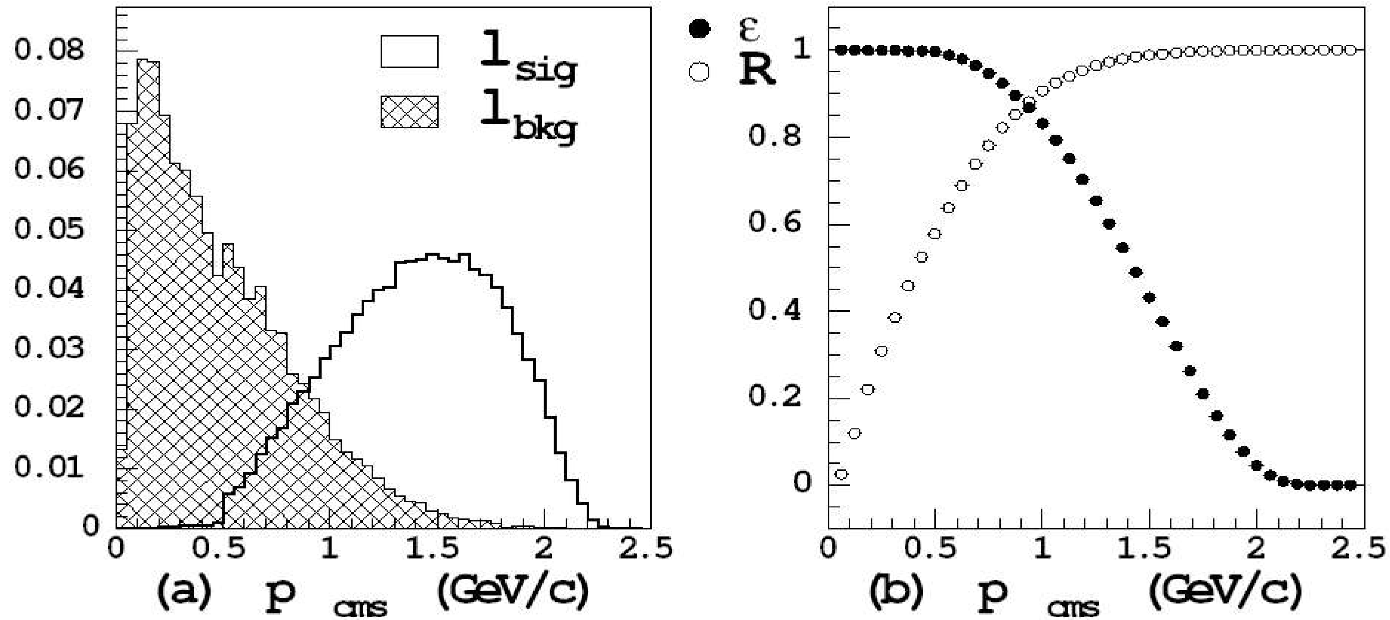
$$\frac{N_{sel}^{D^* l\nu}}{N_{sel}^{SL,B^0}}$$

- ✗ Number of signal events : $B^0 \to D^{*+}\ell^-\nu$, $\hookrightarrow D^0\pi^+$ — ✗ Partial reconstruction of D^*
- ✗ Number of semileptonic events : $B^0 \to X\ell\nu$ — ✗ Semileptonic selection

Semileptonic selection - Lepton reconstruction

✗ The lepton from a semileptonic *B* decay has to be discriminated from other leptons:

➔ $p_{cms} > 1\ GeV$



✗ The lepton identification use information from all detectors:

- ✔ Efficiency electrons ID ≈ 95%
- ✔ Efficiency muons ID ≈ 60-70%

Semileptonic selection

✗ Semileptonic B^0 decays are selected with these cuts:

1. $P^{\ell}_{cms} > 1$ GeV.
2. $B^{reco}_{charge} = 0$.
3. correlation between B flavor and lepton charge ($B^0 - \ell^+$ or $\overline{B}^0 - \ell^-$).

✗ Selected SL sample compositions:

- ✔ B^0 semileptonic decays → ✗ B^0 semileptonic events
- ✔ Continuum background ($c\overline{c}$ and uds)
- ✔ Combinatorial background in B decays

  } ✗ subtracted perfoming m_{ES} fit.
- ✔ B^+ reconstructed as B^0
- ✔ Wrong lepton
- ✔ Fake lepton

  } ✗ Taken into account in a Monte Carlo factor:

$$K^{SL} = 1.100 \pm 0.004(stat_{mc})$$

$$\Rightarrow N^{SL,B^0}_{sel} = \frac{N^{SL}_{sel}}{K^{SL}}$$

Semileptonic selection

- ✔ On 210.5 fb^{-1} of real data:

$$N_{sel}^{SL,B^0} = 21504 \pm 202(stat_{dat}) \pm 80(stat_{mc})$$

- ✔ Semileptonic selection eff on signal events calculated from Monte Carlo :

$$\epsilon_{sig}^{Breco,SL} = (2.668 \pm 0.017(stat_{mc})) \times 10^{-3}$$

- ✔ Semileptonic selection eff on SL events calculated from Monte Carlo :

$$\epsilon_{SL}^{Breco,SL} = (2.470 \pm 0.010(stat_{mc})) \times 10^{-3}$$

$\epsilon_{sig}^{Breco,SL} / \epsilon_{SL}^{Breco,SL} = 1.08 \pm 0.001(stat_{mc})$ near 1 as expected.

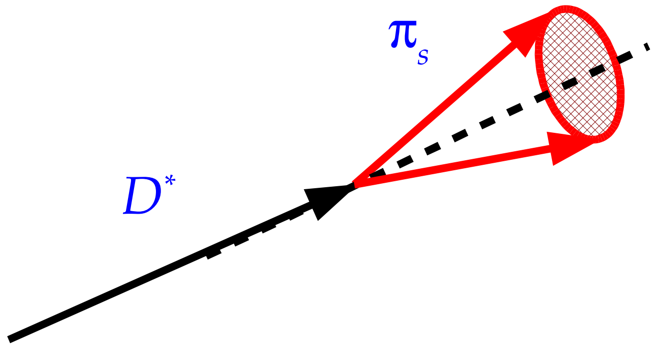
Partial reconstruction of the $B^0 \to D^* \ell \nu$ decay

$$B^0 \to D^{*+} \ell^- \nu$$
$$\hookrightarrow D^0 \pi^+$$

➔ $B^0 \to D^* \ell \nu$ decay is reconstructed using only the lepton and the soft pion from D^*

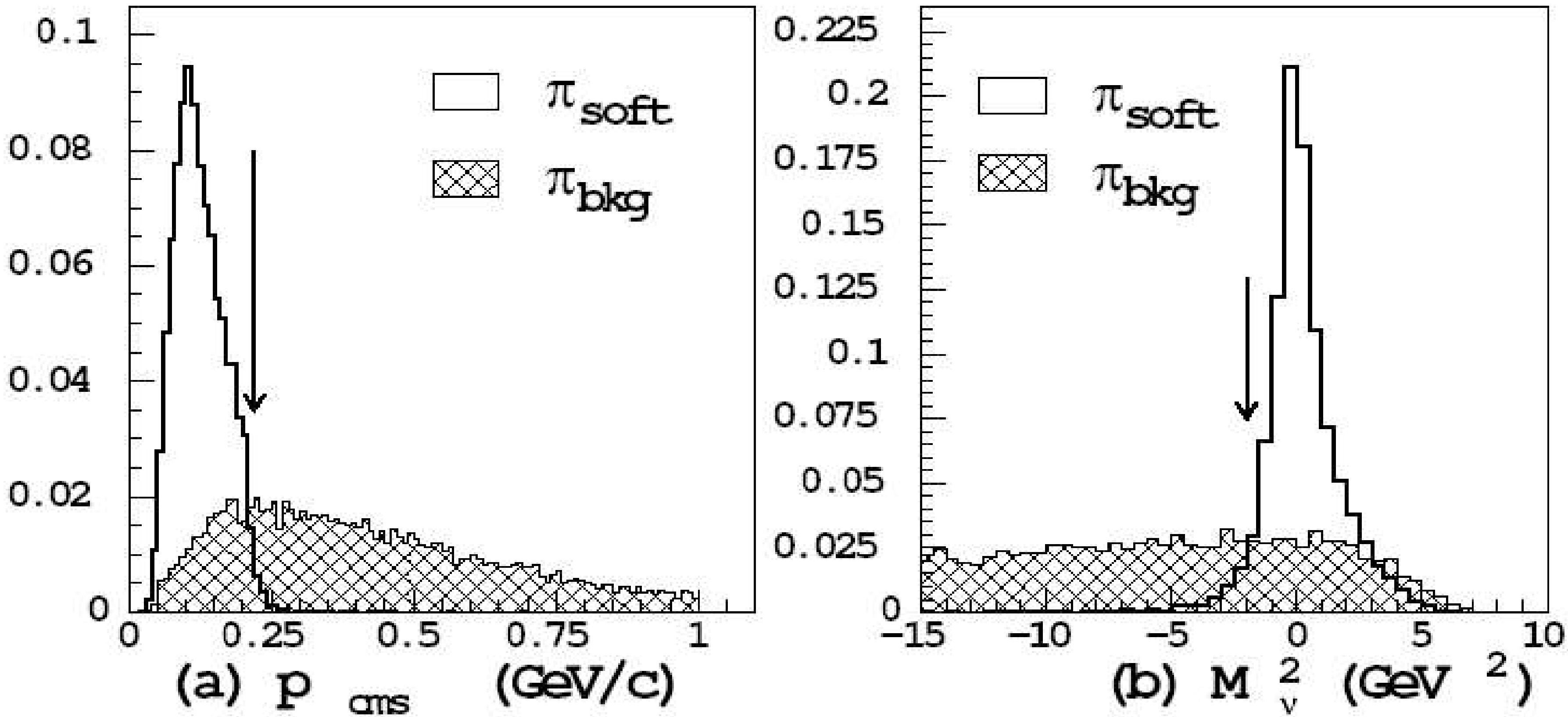
✔ The special kinematics of the decay $D^* \to D^0 \pi^+$ allows to reconstruct D^* using only π information. $p_\pi \Rightarrow p_{D^*}$

$$M_{D^*} = M_{D^0} + M_\pi + \underline{5\text{ MeV}} \quad \Rightarrow \beta_\pi \approx \beta_{D^*}$$



Discriminating variables for $B^0 \to D^*\ell\nu$ selection

✗ Soft pion p_{cms} ✗ Squared mass of neutrino: M_ν^2



➢ Best cuts are those values corresponding to the max of the ratio:

$$SB = \frac{N_{sel}^{Sig}}{\sqrt{N_{sel}^{Sig} + N_{sel}^{bkg}}} \Rightarrow \begin{array}{r} 50 \text{ MeV} \le p_{cms} \le 220 \text{ MeV} \\ M_\nu^2 \ge -2.0 \text{ GeV}^2 \end{array}$$

Selection of $B^0 \to D^{*+} \ell^- \nu$ events
$\hookrightarrow D^0 \pi^+$

1. $B^{reco}_{charge} = 0$.
2. Correlation between B flavor and charge of lepton ($B^0 - \ell^+$ or $\overline{B}^0 - \ell^-$).
3. $P^{\ell}_{cms} > 1$ GeV.
4. Correct charge correlation between lepton and soft pion ($\ell^+ - \pi^-$ or $\ell^- - \pi^+$).
5. If more than one pion is found, choose the one with minimum p^{π}_{cms}.
6. 50 MeV $\leq p^{\pi}_{cms} \leq$ 220 MeV.
7. $M^2_{\nu} \geq -2.0$ GeV^2.

✗ Requests 4 and 7 are also used "reversed" for background estimation:

➔ $N^{\alpha,\beta}$ where $\alpha =$ RS (right sign correlation) / WS (wrong sign correlation)

$\beta =$ 2 for $M_{\nu}^2 \geq -2$ / 5 for $M_{\nu}^2 \leq -5$

Selection of $B^0 \to D^{*+} \ell^- \nu$ events
$\hookrightarrow D^0 \pi^+$

✗ Composition of the selected sample $N_{sel}^{RS,2}$:

1. $D^{*-}\ell^+\nu_\ell$ events with $D^{*+} \to D^0\pi^+$ and $\pi_{sel} = \pi_s$ (~87%) } Signal ➔ ~48%
2. $D^{*-}\ell^+\nu_\ell$ events with $D^{*+} \to D^0\pi^+$ and $\pi_{sel} = \pi_{wrong}$ (~13%) } Signal
3. $D^{*-}\ell^+\nu_\ell$ with $D^{*+} \to D^+\pi^0$ with a charged pion reconstructed as soft pion ➔ ~4%
4. Physical background: all semileptonic and non-semileptonic B events ➔ ~20%
5. Continuum background ($c\bar{c}$ and uds) } ➔ ~28%
6. Combinatorial background in B decays }

⟹ Background subtraction has to be performed

Background subtraction

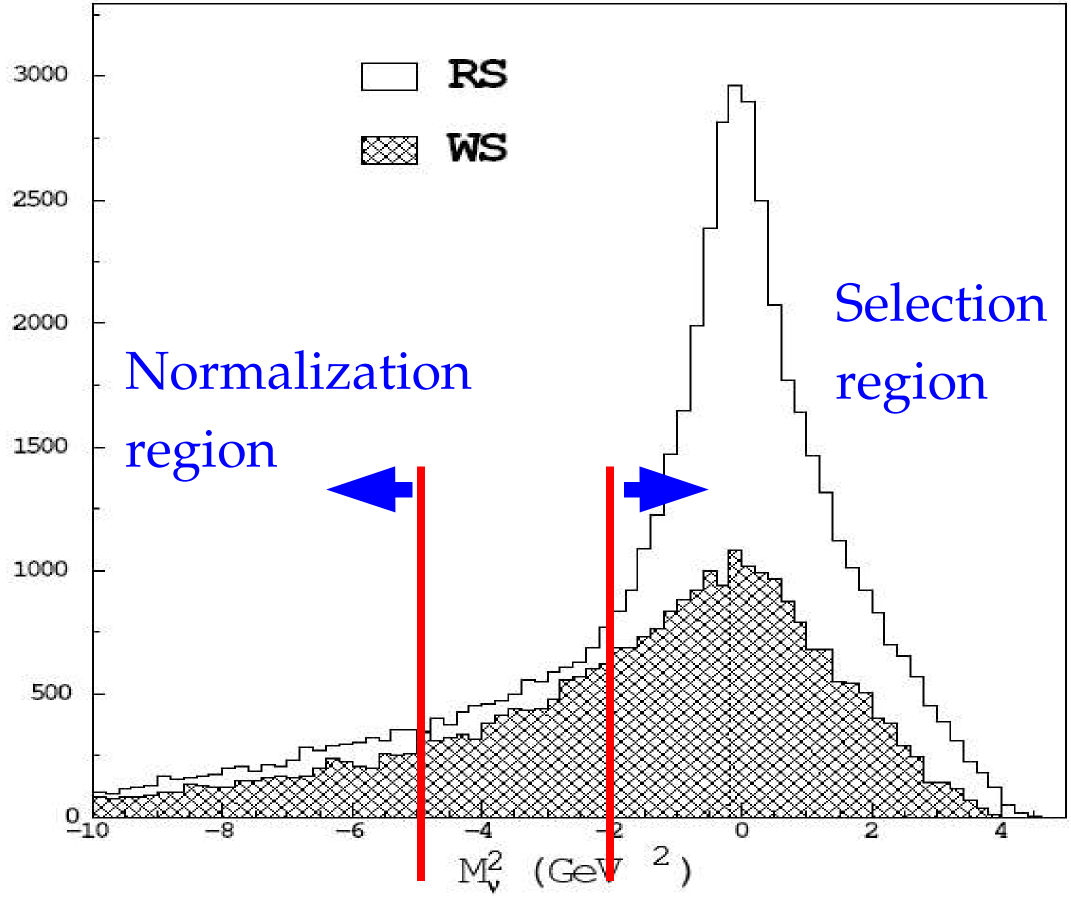
✗ (5,6) continuum and combinatorial backgrounds are subtracted performing an m_{ES} fit as done for the semileptonic selection.

✗ (4) Physical backgrounds are evaluated assuming:

➔ The number of physical background events RS events at M_ν^2>-2 are extrapolated from the events WS at M_ν^2>-2 normalized to the ratio RS/WS at M_ν^2<-5:

$$NF^5 = \frac{N^{RS,5}}{N^{WS,5}}$$

$$N^{RS,2}_{bkg,calc} = NF^5 \times N^{WS,2}_{sel} + MC_{corr}$$



✔ Monte Carlo corrections take into account deviations from the extrapolation.

Background subtraction - MC_{corr}

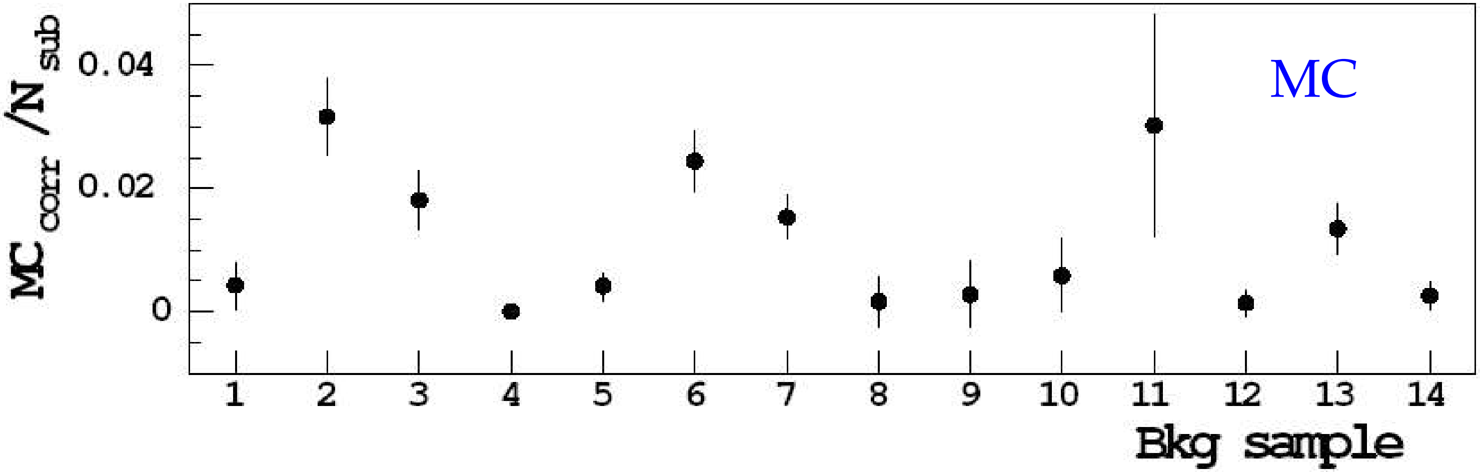
✗ MC_{corr} are studied in Monte Carlo looking at 14 background samples:

- 7 backgrounds from B^0
- 7 backgrounds from B^+

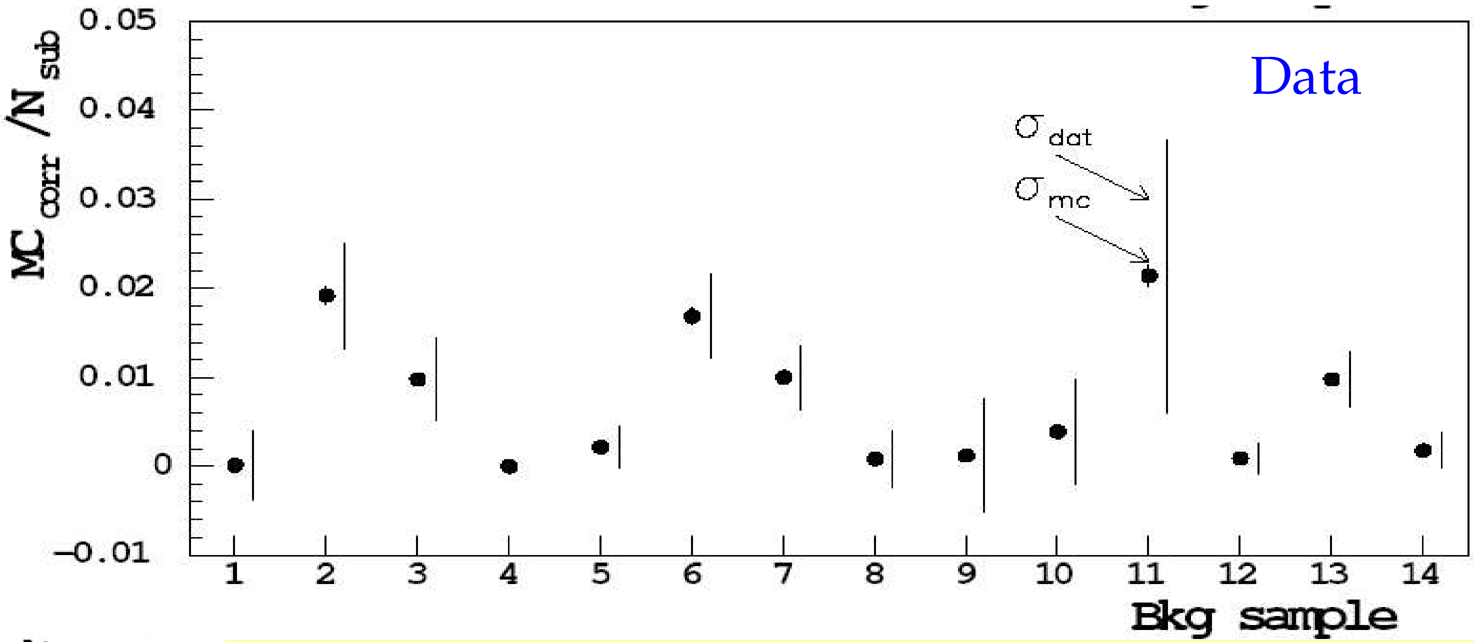
Type of decay	Index for decays from B^0	Index for decays from B^+
Non-SL	1	8
Other SL	2	9
$D^0, D^+ l\nu$	3	10
$D^{*0} l\nu$	4	11
$D_2^* l\nu$	5	12
$D_1 l\nu$	6	13
other $Dl\nu$	7	14

Background subtraction – MC_{corr} on Monte Carlo

- MC_{corr} relative contribution at $N_{sel}^{RS,2} - NF^5 \times N_{sel}^{WS,2}$



- Tot on MC 16%



- Tot on data 14%

Signal selection - Background subtraction corrections

✗ The background subtraction cuts also a few on signal events

⇒ a Monte Carlo correction factor is applied on final calculation:

$$K_{MC}^{dat} = 0.835 \pm 0.019(stat_{data}) \pm 0.006(stat_{mc})$$

Signal calculation

✗ In summary the number of signal events is calculated with:

$$N_{sel}^{D^* l\nu} = \frac{1}{K_{MC}} \times \left(N_{sel}^{RS,2} - NF^5 \times N_{sel}^{WS,2} - MC_{corr} \right)$$

$$N_{sel,data}^{RS,2} = 4748 \pm 301(stat_{dat}) \pm 117(stat_{mc})$$

✗ Selection efficiency from Monte Carlo :

$$\epsilon^{cut} = \frac{N_{sig}^{RS,2}}{N_{sig}^{Breco,SL}} = \frac{20877 \pm 174}{36529 \pm 236} = 0.572 \pm 0.006(stat_{mc})$$

Systematic uncertainties

1. Uncertainties on used branching ratio (from PDG2004): $\mathcal{B}(B^0 \to X \ell \nu) = (10.5 \pm 0.8)\%$
$\mathcal{B}(D^{*+} \to D^0 \pi^+) = (67.7 \pm 0.5)\%$

2. Limited Monte Carlo statistics $\Rightarrow$ statistical errors from MC

3. Uncertainties from MC_{corr}: Monte Carlo does not reproduce exactly the real data

3a. Limited knowledge of semileptonic B decays in D** states: $\mathcal{B}(B \to D_2^* \ell \nu)$
$\mathcal{B}(B \to D_1 \ell \nu)$
$\mathcal{B}(\text{other } B \to D^{**} \ell \nu)$

singles BR is not known, only their sum is known $\mathcal{B}_{tot}=0.027$, then systematic is obtained with a random variation of each single BR between 0 and the total mantaining constants the sum.

3b. Limited knowledge of other B decays: $\mathcal{B}(B \to \text{other})$

a random variation of 100% is used to evaluate the systematic

Systematic uncertainties

4. systematic effects on ratio between efficiencies of the full reconstruction of one B
   $\Rightarrow$ taken from V_{ub} analysis

5. lepton tracking $\Rightarrow$ wrong reconstruction probability of 1.3%

6. lepton identification $\Rightarrow$ wrong identification probability of 3%

7. lepton misidentification $\Rightarrow$ wrong misidentification probability of 15%

8. soft pion detection $\Rightarrow$ wrong soft pion reconstruction probability of 2.6%

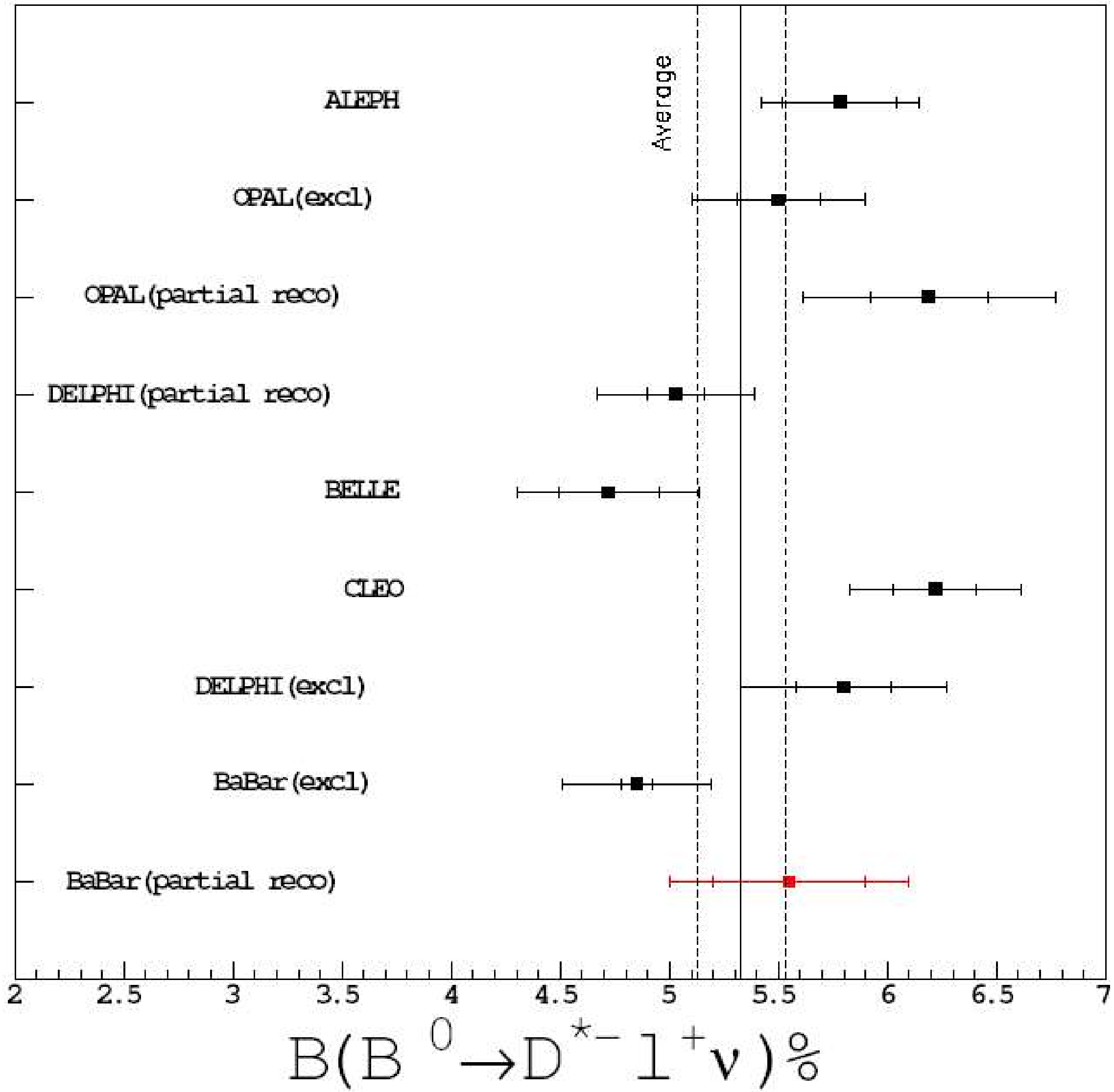
9. systematic effects from m_{ES} fit $\Rightarrow$ fit with Gaussian instead of a Crystal-Ball function

Uncertainties

Error contribution	$\sigma_{\mathcal{B}} \times 10^{-2}$	$\frac{\sigma_{\mathcal{B}}}{\mathcal{B}}\%$
data statistics	0.35	6.3
1. uncertainties on $\mathcal{B}(B^0 \to Xl\nu)$ and $\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.42	7.7
2. Monte Carlo statistics	0.16	2.8
3a. unknown $\mathcal{B}(B \to D_2^* l\nu)$, $\mathcal{B}(B \to D_1 l\nu)$ and $\mathcal{B}(\text{other}B \to D^{**}l\nu)$	0.18	3.3
3b. unknown $\mathcal{B}(B \to \text{hadrons})$	0.0033	0.06
4. Fully reconstructed B	0.17	3.0
5. Lepton tracking	0.043	0.8
6. Lepton ID	0.11	2.1
7. Lepton misID	0.047	0.8
8. soft pion reconstruction	0.13	2.3
9. m_{ES} fit	0.0062	0.11
total systematics	0.55	9.9
total error	0.65	11.7

Measured value of $\mathcal{B}(B^0 \to D^* \ell \nu)$

$$\mathcal{B}\left(B^0 \to D^{*-} \ell^+ \nu_\ell\right) = (5.55 \pm 0.35(stat_{dat}) \pm 0.55(syst)) \times 10^{-2}$$



$$\mathcal{B}_{ave} = 5.33 \pm 0.20$$

Conclusions

- ✗ The measured value of the branching ratio results to be comparable with the world average.
- ✗ As preliminary measurement the signal events have been extracted from semileptonic B^0 decays, then the branching ratio is calculated normalizing with $\mathcal{B}(B^0 \to X \ell \nu)$.
- ✗ The systematic uncertainties have been evaluated in a simple and conservative way.

Outlook

- ✔ Extract signal events from all semileptonic decays $B \to X \ell \nu$ and not only from B^0 : the branching ratio will be calculated normalizing with $\mathcal{B}(B \to X \ell \nu)$, which is known better than $\mathcal{B}(B^0 \to X \ell \nu)$, this change will reduce the associated systematic from 7.7% to 3%.
- ✔ More Monte Carlo events are now available, allowing a reduction of the statistical errors from the simulation.
- ✔ The others systematic uncertainties have to be evaluated in more detail.

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Backup slides

Partial reconstruction of the $B^0 \to D^* \ell \nu$ decay

$B^0 \to D^{*+} \ell^- \nu$
$\hookrightarrow D^0 \pi^+$

➔ $B^0 \to D^* \ell \nu$ decay is reconstructed using only the lepton and the soft pion from D^*

✔ Squared mass of the neutrino is one of the useful variables for signal reconstruction:

$$M_\nu^2 = p_\nu^2 \qquad p_\nu = p_B - p_{D^*} - p_l$$

✔ where $p_B = p_\Upsilon - p_{\overline{B}}$

✔ p_l is known from lepton reconstruction.

✔ While the special kinematics of the decay $D^* \to D^0 \pi^+$ allows to reconstruct D^* using only π informations.

$$p_\pi \Rightarrow p_{D^*}$$

Partial reconstruction of the $B^0 \to D^* \ell \nu$ decay

$B^0 \to D^{*+} \ell^- \nu$
$\hookrightarrow D^0 \pi^+$

- ✔ $M_{D^*} = 2010$ MeV
- ✔ $M_{D^0} = 1865$ MeV

$$\Rightarrow E^*_{\pi_s} = \frac{m^2_{D^*} - m^2_{D^0} + m^2_{\pi}}{2 m_{D^*}} = 145 \text{ MeV}$$

✔ From D^* rest frame to Lab frame:

✔ D^*

$$\underbrace{\begin{pmatrix} E^{lab}_{D^*} \\ \vec{p}^{\,lab}_{D^*} \end{pmatrix}}_{\text{to be calculated}} = \begin{pmatrix} \gamma_{D^*} & \gamma_{D^*}\beta_{D^*} \\ \gamma_{D^*}\beta_{D^*} & \gamma_{D^*} \end{pmatrix} \underbrace{\begin{pmatrix} m_{D^*} \\ \vec{0} \end{pmatrix}}_{\approx \text{ known}}$$

Boost of D^* can be evaluated from soft pion

✔ π_s

$$\underbrace{\begin{pmatrix} E^{lab}_{\pi_s} \\ \vec{p}^{\,lab}_{\pi_s} \end{pmatrix}}_{\text{detected}} = \begin{pmatrix} \gamma_{D^*} & \gamma_{D^*}\beta_{D^*} \\ \gamma_{D^*}\beta_{D^*} & \gamma_{D^*} \end{pmatrix} \underbrace{\begin{pmatrix} E^*_{\pi_s} \\ \vec{p}^{\,*}_{\pi_s} \end{pmatrix}}_{\approx \text{ known}}$$

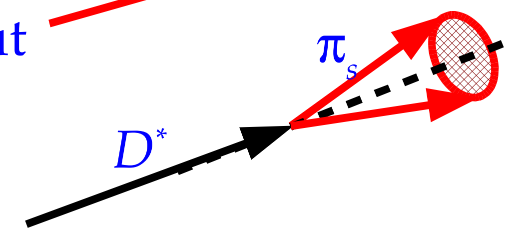
Partial reconstruction of the $B^0 \to D^* \ell \nu$ decay

✔ Boost of D^* can be evaluated solving

$$E_{\pi_s}^{lab} = \gamma_{D^*} E_{\pi_s}^* + \gamma_{D^*} \beta_{D^*} \vec{p}_{\pi_s}^{\,*}$$

✔ Relative direction between π_s and D^* is not known, but

✔ in Lab (also CMS) frame the soft pion will be emitted in a restriced cone around D^* direction



⟹ Two approximation can be used for boost calculation

➢ First approx: D^* // π

$$\beta_{D^*}^{\pm} = \frac{E_{\pi_s}^{lab} \left|\vec{p}_{\pi_s}^{\,lab}\right| \pm E_{\pi_s}^* \left|\vec{p}_{\pi_s}^{\,*}\right|}{E_{\pi_s}^{*2} + \left|\vec{p}_{\pi_s}^{\,lab}\right|^2}$$

➢ Second approx: D^* // π and p_π=0

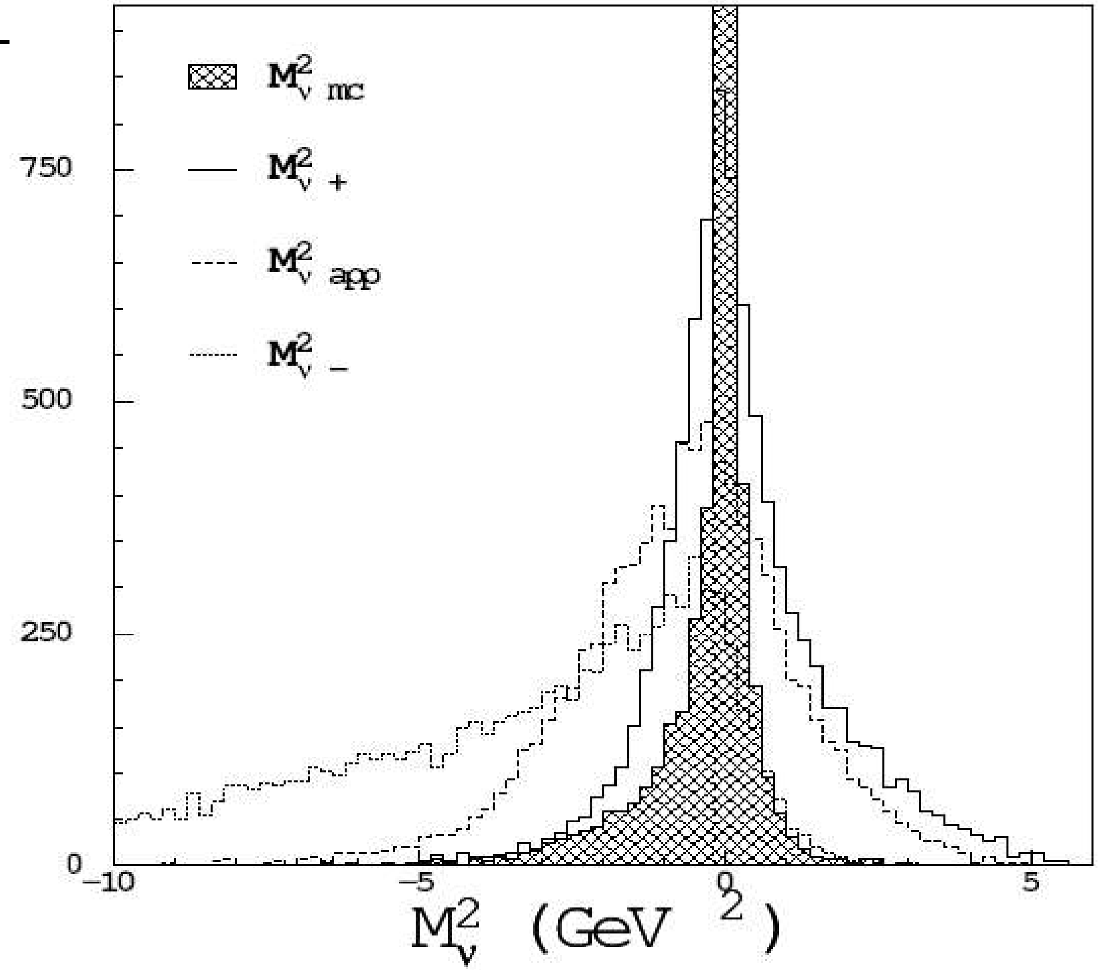
$$\gamma_{D^*}^{app} = \frac{E_{\pi_s}^{lab}}{E_{\pi_s}^*}$$

} M_ν^{2+}, M_ν^{2-}, M_ν^{2app}

Partial reconstruction of the $B^0 \rightarrow D^* \ell \nu$ decay

Solution type	Fraction (%) with best $M^2_{\nu reco}$ between three solutions	Fraction (%) with best $M^2_{\nu reco}$ between two solutions $\pm$
$M^{2+}_{\nu det}$	53.1 ± 0.8	74.7 ± 0.9
$M^{2-}_{\nu det}$	18.8 ± 0.5	25.3 ± 0.5
$M^{2App}_{\nu det}$	28.1 ± 0.6	

$\Rightarrow$ The best solution is the positive one: M_ν^{2+}



Ratio SB for the two signal definitions.

1. $D^{*-}\ell^+\nu_\ell$ events with $D^{*+} \to D^0\pi^+$ and $\pi_{sel} = \pi_s$ ➔ N_1
2. $D^{*-}\ell^+\nu_\ell$ events with $D^{*+} \to D^0\pi^+$ and $\pi_{sel} = \pi_{wrong}$ ➔ N_2

➔ 2 definitions for the number of signal events:

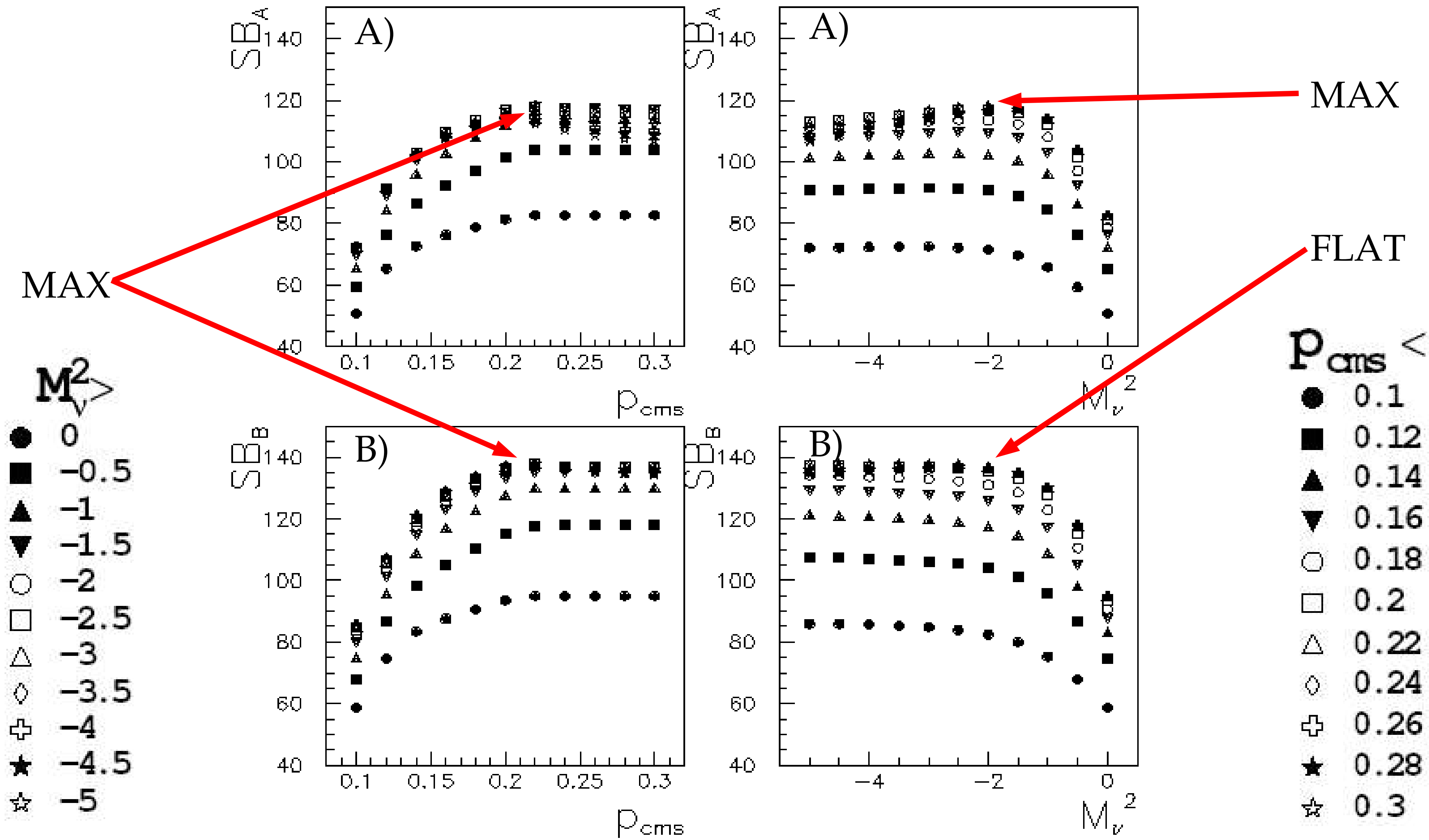
A) $N_A = N_1$

B) $N_B = N_1 + N_2$

A) The ratio SB has maximum value for p_{cms}=220 MeV and for M_ν^2=-2.0

B) The ratio SB has maximum value for p_{cms}=220 MeV, while for M_ν^2 the ratio is approximately constant from -2.0 to -5.0. At low values of M_ν^2 the background contamination becomes high, then the lower value -2.0 is better concerning background contamination and it also corresponds to the maximum of the first definition.

Ratio SB for the two signal definitions.



Comparison of ratio N/ε between the two signal definitions.

✗ Efficiencies

$N_A \Rightarrow$ $$\epsilon^{cut} = \frac{N_{sig}^{RS,2}}{N_{sig}^{Breco,SL}} = \frac{20877 \pm 174}{36529 \pm 236} = 0.572 \pm 0.006(stat_{mc})$$

$N_B \Rightarrow$ $$\epsilon^{cut,\pi_s} = \frac{N_{sig(\pi_s)}^{RS,2}}{N_{sig}^{Breco,SL}} = \frac{18122 \pm 149}{36529 \pm 236} = 0.496 \pm 0.005(stat_{mc})$$

✗ Numbers of selected events

$N_A \Rightarrow$ $$N_{sel,data}^{RS,2} = 4748 \pm 301(stat_{dat}) \pm 117(stat_{mc})$$

$N_B \Rightarrow$ $$N_{sel(\pi_s),data}^{RS,2} = 4118 \pm 241(stat_{dat}) \pm 135(stat_{mc})$$

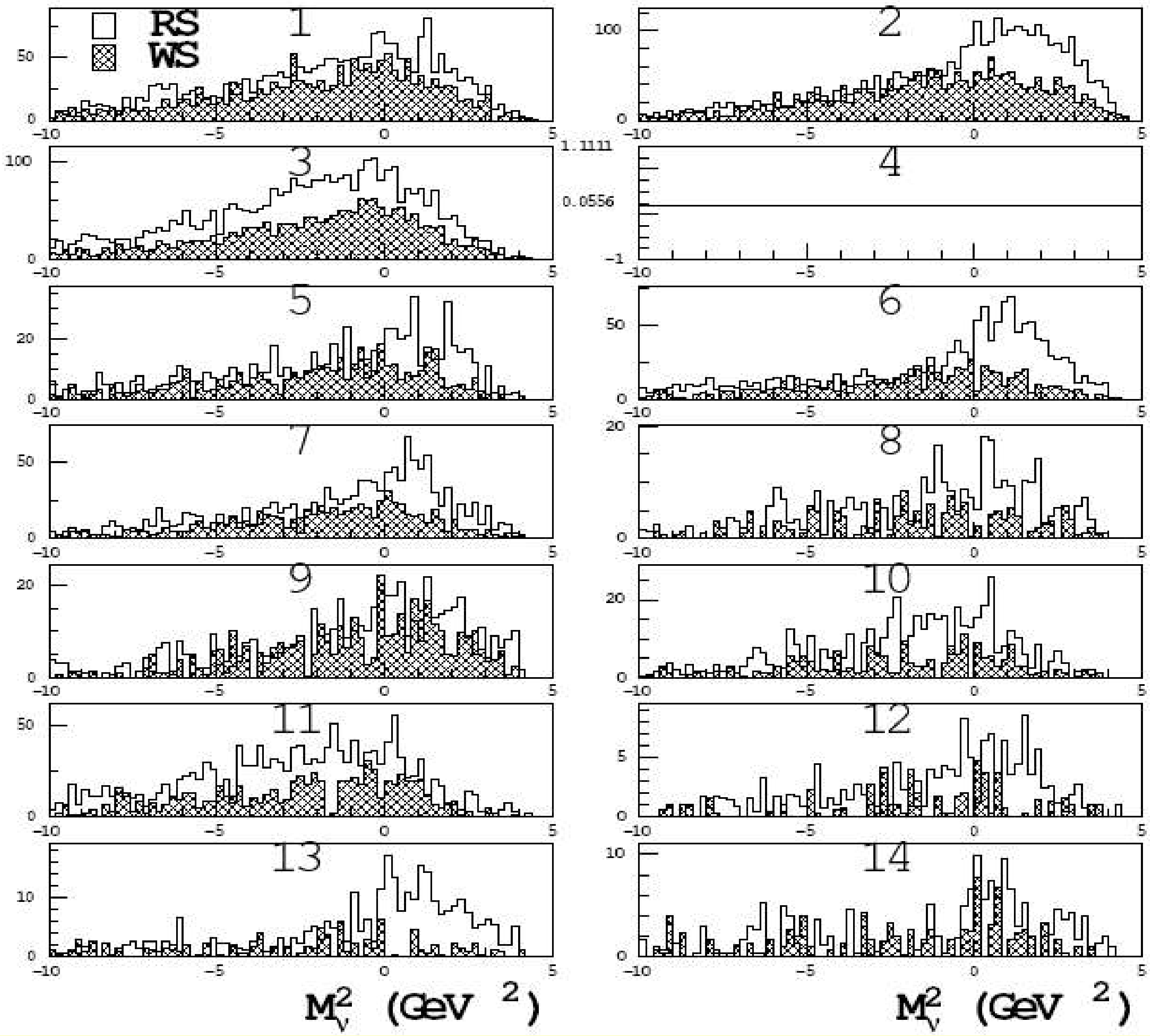
✗ Ratio between numbers of events corrected by efficiencies

$N_A \Rightarrow$

$N_B \Rightarrow$

$$\frac{N_{sig}^{RS,2} / \epsilon^{cut}}{N_{sig(\pi_s)}^{RS,2} / \epsilon^{cut,\pi_s}} = 1$$

M_ν^2 distribution of background samples



M_ν^2 distribution of background samples

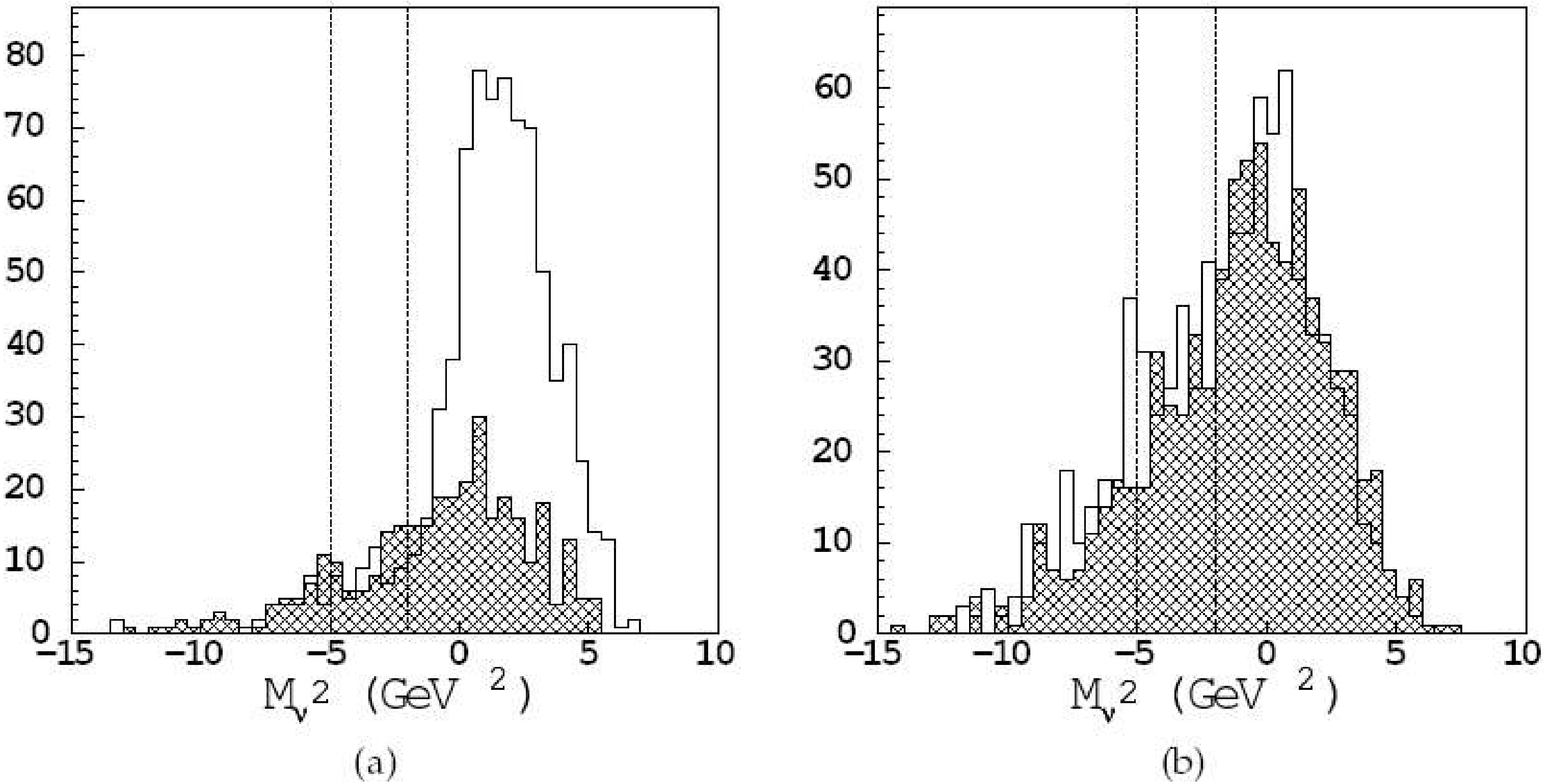


Figure A.1: M_ν^2 distribution for RS (white area) and WS (cross-hatched are) for a peaking background sample in (a) and for a non-peaking background sample in (b).

Background subtraction

✗ (5,6) continuum and combinatorial backgrounds are subtracted performing an m_{ES} fit as done for the semileptonic selection.

✗ (4) Physical backgrounds are evaluated assuming:

$$NF^5 \equiv \frac{N^{RS,5}}{N^{WS,5}} = \frac{N^{RS,2}}{N^{WS,2}} = NF^2$$

➔ the number of background events are calculated normalizing the selected WS events at $M_\nu^2 > -2$ with the ratio between RS and WS at $M_\nu^2 < -5$ and appling some corrections:

$$N^{RS,2}_{bkg,calc} = NF^5 \times N^{WS,2}_{sel} + MC_{corr}$$

$$MC_{corr} = \sum_{i, i \neq sig, D^+} (NF_i^2 - NF^5) N_i^{WS,2}$$

$$NF_i^2 = N_i^{RS,2} / N_i^{WS,2}$$

Monte Carlo corrections take into account deviation from initial RS/WS assumption.

Background subtraction - MC_{corr}

✗ MC_{corr} are studied in Monte Carlo looking at 14 background samples:
- 7 backgrounds from B^0
- 7 backgrounds from B^+

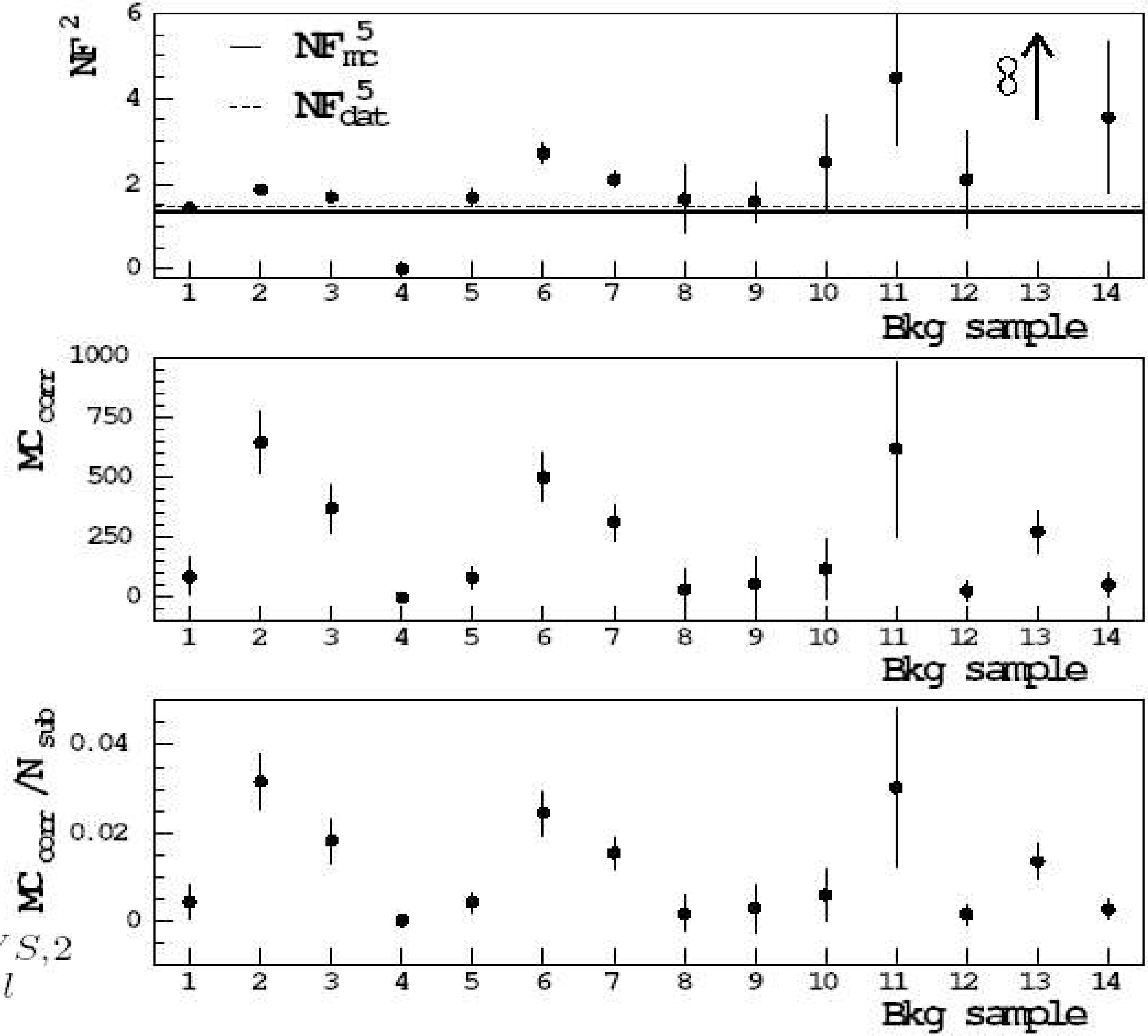
Type of decay	Index for decays from B^0	Index for decays from B^+
Non-SL	1	8
Other SL	2	9
$D^0, D^+ l\nu$	3	10
$D^{*0} l\nu$	4	11
$D_2^* l\nu$	5	12
$D_1 l\nu$	6	13
other $Dl\nu$	7	14

✗ On real data MC_{corr} has to be rescaled with luminosity as follow:

$$MC_{corr}^{data} = \frac{\mathcal{L}_{data}}{\mathcal{L}_{MC}^{B^0}} \sum_{B^0 bkg} (NF_i^2 - NF^5) N_i^{WS,2} + \frac{\mathcal{L}_{data}}{\mathcal{L}_{MC}^{B^+}} \sum_{B^+ bkg} (NF_i^2 - NF^5) N_i^{WS,2}$$

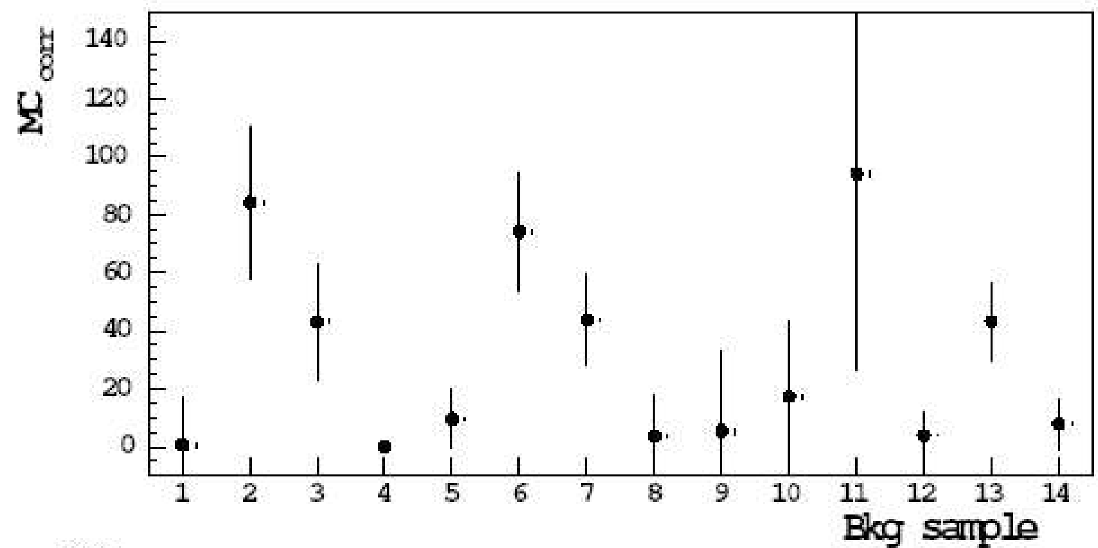
Background subtraction – MC_{corr} on Monte Carlo

- NF^2 on Monte Carlo
- MC_{corr} on Monte Carlo
- MC_{corr} relative contribution at $N_{sel}^{RS,2} - NF^5 \times N_{sel}^{WS,2}$

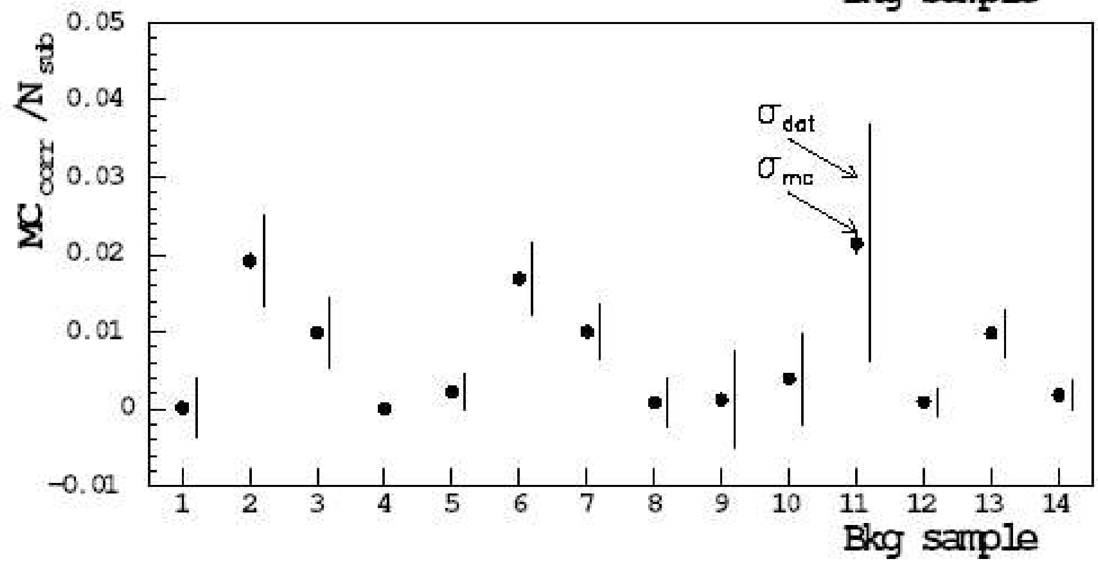


Background subtraction – MC_{corr} on Data

- MC_{corr} on Data



- MC_{corr} relative contribution at $N_{sel}^{RS,2} - NF^5 \times N_{sel}^{WS,2}$



Signal selection - Background subtraction

$$NF^5_{mc} = 1.33 \pm 0.04$$

$$NF^5_{dat} = 1.43 \pm 0.11$$

$$MC^{mc}_{corr} = 3176 \pm 478$$ ➢16%

$$MC^{dat}_{corr} = 431 \pm 46(stat_{dat}) \pm 93(stat_{mc})$$ ➢14%

on $N^{RS,2}_{sel} - NF^5 \times N^{WS,2}_{sel}$

Signal selection - Background subtraction corrections

✗ The background subtraction also operates on signal events:

1) Subtracts a fraction of signal events $= NF^5 \times N_{sig}^{WS,2}$ (the selected soft pion is from bkg)

2) Subtracts a fraction of signal events with $D^{*+} \to D^+ \pi^0 = NF^5 \times N_{sig(D+)}^{WS,2}$

3) Does not subtract a fraction of signal events (RS,2) with $D^{*+} \to D^+ \pi^0$

➔ Signal events obtained by $\left(N_{sel}^{RS,2} - NF^5 \times N_{sel}^{WS,2} - MC_{corr}\right)$ has to be divided by a Monte Carlo correction factor:

$$K_{MC} = \left(1 - NF^5 \times \left(K_{sig}^{WS/RS,2} + K_{sig(D-)}^{WS/RS,2}\right) + K_{sig(D-)}^{RS/RS,2}\right)$$

1) $$K_{sig}^{WS/RS,2} = \frac{N_{sig}^{WS,2}}{N_{sig}^{RS,2}} = 0.123 \pm 0.003$$

2) $$K_{D-/sig}^{WS/RS,2} = \frac{N_{D-}^{WS,2}}{N_{sig}^{RS,2}} = 0.051 \pm 0.002$$

3) $$K_{D-/sig}^{RS/RS,2} = \frac{N_{D-}^{RS,2}}{N_{sig}^{RS,2}} = 0.084 \pm 0.003$$

$$K_{MC}^{MC} = 0.852 \pm 0.009(stat_{mc})$$

$$K_{MC}^{dat} = 0.835 \pm 0.019(stat_{data}) \pm 0.006(stat_{mc})$$

Systematic uncertainties

- uncertainties coming from MC_{corr}:
  - σ_{3a}: limited knowledge of semileptonic B decays in higher D states $\mathcal{B}(B \to D_2^* l\nu)$, $\mathcal{B}(B \to D_1 l\nu)$ and $\mathcal{B}(\text{other} B \to D^{**} l\nu)$.

Gen value on MC

$$\mathcal{B}(B \to D_2^* l\nu) = 0.0037$$

$$\mathcal{B}(B \to D_1 l\nu) = 0.0056$$

$$\mathcal{B}(\text{other} B \to D^{**} l\nu) = 0.0177$$

Variation for syst determination:

each branching ratio has been variated randomly between 0 and the total $\mathcal{B}(B \to D^{**} l\nu) = 0.027$ mantaining the sum equal the total.

Semileptonic selection

✗ Other backgrounds are taken into account with a Monte Carlo correction factor:

$$N_{sel}^{SL,B^0} = \frac{N_{sel}^{SL}}{K^{SL}} = \frac{N_{sel}^{SL}}{1 + K_{B^+} + K_{lw} + K_{lfake}}$$

- B^+ reco as B^0: $$K_{B^+} = \frac{N_{sel}^{SL,B+}}{N_{sel}^{SL,B^0}} = (3.6 \pm 0.4)\%$$
- Wrong lep: $$K_{lw} = \frac{N_{sel}^{SL,l_w}}{N_{sel}^{SL,B^0}} = (0.16 \pm 0.02)\%$$
- Fake lep: $$K_{lfake} = \frac{N_{sel}^{SL,l_{fake}}}{N_{sel}^{SL,B^0}} = (6.21 \pm 0.12)\%$$

$$K^{SL} = 1.100 \pm 0.004(stat_{mc})$$

Crystal-Ball function

$$m_{ES} > m - \sigma \cdot a \;:\; \frac{1}{N}\frac{dN}{dm_{ES}} = \frac{1}{\sqrt{2\pi}\sigma} \cdot e^{-\frac{(m/ES-m)^2}{2\sigma^2}}$$

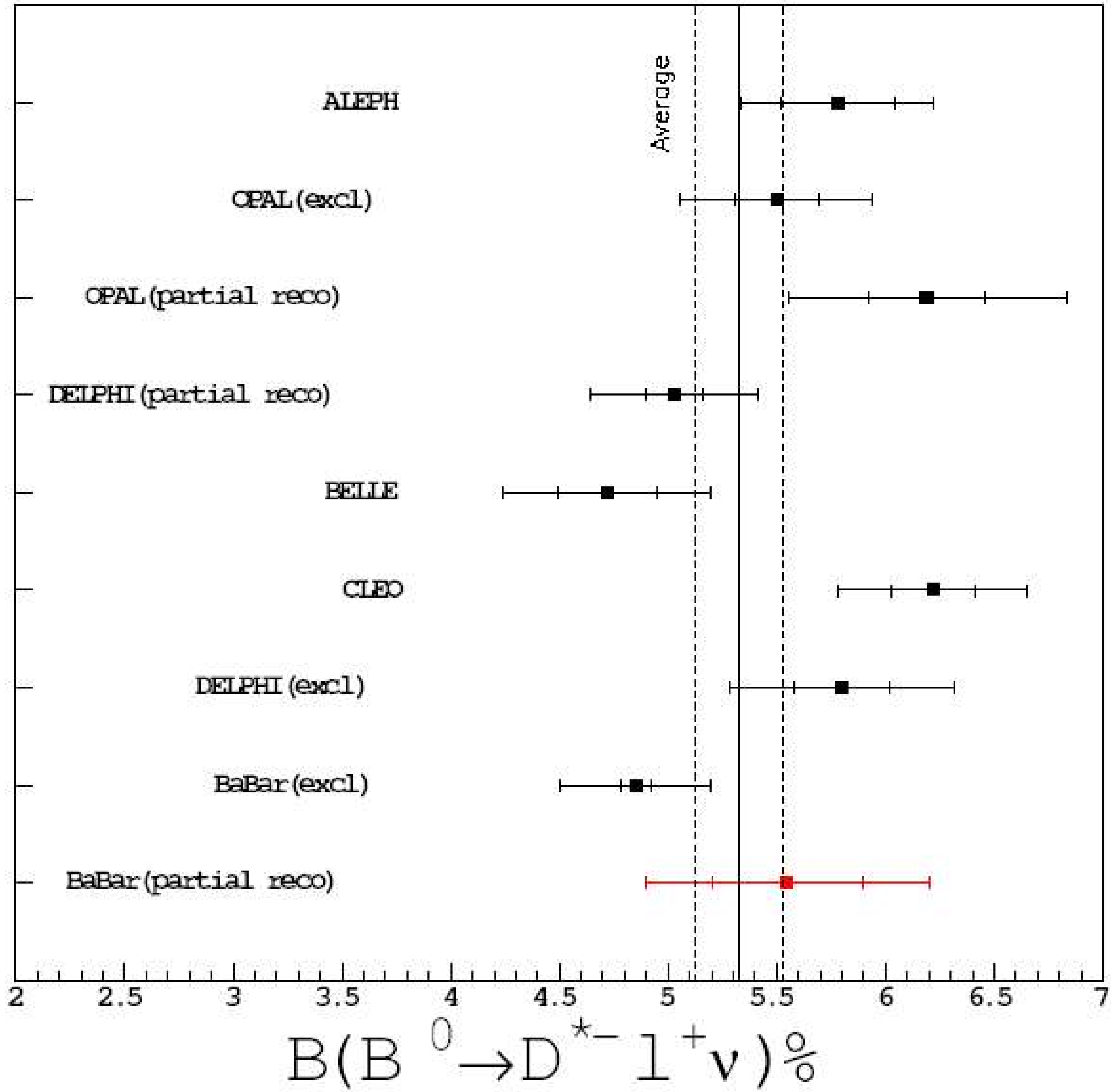
$$m_{ES} < m - \sigma \cdot a \;:\; \frac{1}{N}\frac{dN}{dm_{ES}} = \frac{1}{\sqrt{2\pi}\sigma} \cdot \left(\frac{n}{a}\right)^n \cdot e^{-\frac{a^2}{2}} \cdot \frac{1}{\left(\frac{(m_{ES}-m)}{\sigma} + \frac{n}{a} - a\right)^n}$$

where m is the peak position, σ is the width of the Gaussian distribution, a determines the crossover point from the Gaussian distribution to the power law tail distribution and n is a parameter describing the tail: smaller values generate a longer tail. The tail of this function accounts for energy losses in the shower of reconstructed π^0 mesons, thus the tail of the distribution depends on the reconstructed B decay mode and in particular on the number of π^0 present in it. The maximum total number of floating parameters in the $m_{\rm ES}$ fit is seven: two terms are for the Argus function, while the remaining five (N, m, σ, n and a) refer to the Crystal Ball function.

Argus function

$$\frac{1}{N}\frac{dN}{dm_{ES}} = x \times \sqrt{1-x^2} \times e^{-\xi(1-x^2)}$$

where $x = m_{ES}/m_{max}$ and the shape parameter ξ is determined from a fit. The endpoint of the Argus curve, m_{max}(=5.29 GeV), is fixed in the fit, since it depends only on the beam energy. The Argus function provides a good parametrization of both continuum ($c\bar{c}$ and uds) and combinatoric background from $b\bar{b}$ events.



Statistical and total errors of the measured branching ratio