A Measurement of $\overline{n}_{\mathrm{g}\rightarrow\mathrm{c\bar{c}}}$ using D* Mesons

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Abstract

An analysis is presented that aims to measure the average multiplicity $\overline{n}_{\mathrm{g}\rightarrow\mathrm{c\bar{c}}}$ of gluons splitting to a $\mathrm{c\bar{c}}$ pair in hadronic events. $\mathrm{D}^{*\pm}$ mesons are reconstructed via their decay $\mathrm{D}^{*+}\rightarrow\mathrm{D}^0\pi_s^+\rightarrow\mathrm{K}^-\pi^+\pi_s^+$ down to $X_E = 0.04$. D*'s originating from gluon splitting are found more likely in a hemisphere with rather large invariant mass compared to those produced from primary quarks. The characteristic distributions of hemisphere masses are exploited to fit the corresponding distribution of reconstructed D*'s. The data collected from 1991 to 1995 yield

$$\overline{n}_{\mathrm{g}\rightarrow\mathrm{c\bar{c}}} = (2.65 \pm 0.74(stat.) \pm 0.51(syst.))\% \, .$$

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1 Introduction

At LEP I heavy quark pairs (c,b) are produced by two processes: The decay of the Z and the perturbative splitting of a gluon as in

$$\mathrm{Z} \rightarrow \mathrm{q\overline{q}} + \mathrm{g} \rightarrow \mathrm{q\overline{q}} + \mathrm{Q\overline{Q}}$$

where here and in the following 'q' will stand for any flavour and 'Q' for c and b. Quarks originating directly from the Z will be called primary quarks, those from the gluon splitting secondary quarks.
Defining $\overline{n}_{\mathrm{g}\rightarrow\mathrm{Q\overline{Q}}}$ as the probability to have a gluon splitting to a $\mathrm{Q\overline{Q}}$ pair in a hadronic Z decay the respective quantities for charm and bottom quarks are calculated [1] to be $\overline{n}_{\mathrm{g}\rightarrow\mathrm{c\overline{c}}} \approx 1.35\%$ and $\overline{n}_{\mathrm{g}\rightarrow\mathrm{b\overline{b}}} \approx 0.18\%$.
Hadronic Z decays with a gluon splitting to heavy quarks show characteristic differences in the event topology compared to "ordinary" hadronic events: In order to produce a pair of heavy quarks the gluon has to have a correspondingly high virtuality which usually results in 3 – or 4 – jet events. The kinematics of the process is such that in most cases the primary quark radiating the gluon and both secondary quarks all lie in the hemisphere opposing the other primary quark. This hemisphere has therefore a larger invariant mass than the one containing only the primary quark. The analysis makes use of the *difference* of the two hemisphere masses. The Monte Carlo distributions for events with and without $\mathrm{g} \rightarrow \mathrm{Q\overline{Q}}$ are shown in Fig.1.
In order to tag the presence of charm quarks, $\mathrm{D}^{*\pm}$ mesons are reconstructed. These are counted as a function of the hemisphere mass difference ΔM_H. Then two Monte Carlo ΔM_H distributions containing D^{*}'s from primary and secondary quarks, respectively, are fitted to the distribution of reconstructed D^{*}'s, yielding the fraction of D^{*}'s originating from gluon splitting.

2 Reconstruction of $\mathrm{D}^{*\pm}$ mesons

$\mathrm{D}^{*\pm}$ mesons are reconstructed in the decay chain $\mathrm{D}^{*+} \rightarrow \mathrm{D}^0\pi_s^+ \rightarrow \mathrm{K}^-\pi^+\pi_s^+$. As can be seen in Fig.2 for D^{*}'s from $\mathrm{g} \rightarrow \mathrm{c\overline{c}}$ $\langle X_E \rangle$ is about 0.2 with a most probable value of ≈ 0.1. Consequently, it has been tried to reconstruct $\mathrm{D}^{*\pm}$ down to the kinematic threshold $X_{E\,min} = 2 \cdot M_{\mathrm{D}^{*\pm}}/E_{CM} \approx 0.04$. For the reconstruction different cuts are applied in three X_E–bins from 0.04 to 0.1, 0.1 to 0.2, and 0.2 to 1.0.
Firstly, all pairs of oppositely charged tracks are combined, one of them being assigned the kaon mass, the other one the pion mass. If their invariant mass falls within a $\pm 30\,\mathrm{MeV}/c^2$ window of the nominal D^0 mass and both tracks can be fitted to a common vertex these are kept as a D^0 candidate. Then tracks with charge opposite to the kaon candidate are added to build D^* candidates. For all tracks for which the ionisation loss is available it is required that their dE/dx is consistent with the respective particle hypothesis, i.e.

$$|\chi_{dE/dx}| = \left|\frac{I_{meas} - I_{exp}}{\sigma_I}\right| < 2.5$$

where I_{meas} and I_{exp} are the measured ionisation and the one expected for a given particle hypothesis, respectively, and σ_I the dE/dx resolution.
X_E dependent cuts are shown in table 1. Θ_K^* is the decay angle of the kaon with respect to the D^0 flight direction, measured in the D^0 rest frame. The second cut requires the D^0 flight direction to be close to the direction of the D^0 decay vertex with respect to the primary vertex. In the $\Delta M = M_{K\pi\pi} - M_{K\pi}$ distribution D^* candidates are considered in a $\pm 2\,\mathrm{MeV}/c^2$ wide window around the nominal value. For $X_E > 0.2$ the background is determined from side–band events. $K\pi$ combinations with $2.0\,\mathrm{GeV}/c^2 < M_{K\pi} < 2.4\,\mathrm{GeV}/c^2$ are retained and their $M_{K\pi\pi} - M_{K\pi}$ distribution normalized to

X_E	$\lvert cos\Theta^*_K \rvert$	$\frac{\vec{p}_{D^0} \cdot \vec{x}_{K\pi-Vertex}}{\lvert\vec{p}\rvert \cdot \lvert\vec{x}\rvert}$
$0.04 < X_E < 0.1$	< 0.8	> 0.5
$0.1 < X_E < 0.2$	< 0.8	> 0.9
$0.2 < X_E < 1.0$	< 0.9	–

Table 1: X_E dependent cuts

the signal distribution in the window $0.16\,\mathrm{GeV}/c^2 < \Delta M < 0.18\,\mathrm{GeV}/c^2$. This is no longer possible for the lower X_E bins where kinematic effects distort the shape of the side–band background. Here the background is determined using wrong–sign combinations, i.e. two like–sign particles are combined to form the "D^0" candidate and an opposite–sign track is added. The same cuts are applied to these events and the normalization is done as for the high–X_E bin.
Fig.3 shows the signal and background obtained in four X_E bins from $3.7 \cdot 10^6$ selected events taken in 1991 to 1995. $10\,527 \pm 130$ D$^{*\pm}$ candidates are observed. The reconstruction efficiency is poor for $X_E < 0.1$, this region will therefore be excluded from the fit. Likewise, D*'s with $X_E > 0.5$ will be dropped since there the contribution from gluon splitting is negligible.

3 Fit procedure and calculation of $\overline{n}_{\mathrm{g}\to\mathrm{c\bar{c}}}$

The hemispheres are defined by calculating the thrust axis using charged tracks and neutral calorimeter objects with an energy above 1 GeV. From these the invariant mass of each hemisphere is calculated assuming the pion mass for charged tracks. The hemisphere mass difference distribution ΔM_H is divided into 16 bins in the range $0.0 - 45.0\,\mathrm{GeV}/c^2$. For each bin the background subtracted X_E distribution is built and efficiency corrected. The resulting distribution of D*'s as a function of ΔM_H is then normalized to one. The same procedure is applied to the Monte Carlo, separating hemispheres containing D*'s from gluon splitting, and hemispheres containing only D*'s from primary quarks. The ΔM_H distributions for general hadronic Z decays are in good agreement between data and Monte Carlo as can be seen in Fig.4. Let $f(\Delta M_H)$ be the distribution of reconstructed D*'s, and $f_g(\Delta M_H)$ and $f_q(\Delta M_H)$ the Monte Carlo distributions for events with and without gluon splitting. Then

$$f(\Delta M_H) = P_g \cdot f_g(\Delta M_H) + (1 - P_g) \cdot f_q(\Delta M_H)\,. \tag{1}$$

P_g is the fraction of D*'s originating from gluon splitting in the considered sample. A χ^2 fit is performed leaving P_g as a free parameter. The average number of D$^{*\pm}$ from gluon splitting in hadronic Z decays is then

$$\overline{n}_{\mathrm{g}\to\mathrm{D}^*} = a \cdot \frac{P_g \cdot N^{meas}_{\mathrm{D}^*}}{B_{\mathrm{D}^*} \cdot N^{sel}_{had}}\,. \tag{2}$$

B_{D^*} is the branching ratio $B_{\mathrm{D}^*} = B(D^{*\pm} \to D^0\pi_s) \cdot B(D^0 \to K\pi) = (2.62 \pm 0.10)\%$ [3], N^{sel}_{had} the total number of selected hadronic events and $a = 0.971 \pm 0.002$ takes into account that the acceptance for gluon splitting events is higher than the average one. $\overline{n}_{\mathrm{g}\to\mathrm{D}^*}$ still contains a contribution from $\mathrm{g} \to \mathrm{b\bar{b}}$ processes. This cannot be measured independently and has to be subtracted making assumptions about the relative branchings of $\mathrm{g} \to \mathrm{c\bar{c}} \to D^{*\pm}$ and $\mathrm{g} \to \mathrm{b\bar{b}} \to D^{*\pm}$. The average number of gluon splittings to charm quarks in hadronic Z decays is calculated to be

$$\overline{n}_{\mathrm{g}\to\mathrm{c\bar{c}}} = \frac{\overline{n}_{\mathrm{g}\to\mathrm{D}^*}}{2 \cdot f(c \to D^{*\pm})} \left[\epsilon_c + \epsilon_b \cdot \delta \cdot \frac{f(b \to D^{*\pm})}{f(c \to D^{*\pm})}\right]^{-1}\,. \tag{3}$$

Here ϵ_Q is the efficiency to find a D* within given cuts such as a specified X_E range or the requirement to be found in the heavy hemisphere and $\delta = \frac{\overline{n}_{g \to b\overline{b}}}{\overline{n}_{g \to c\overline{c}}}$. The parameters have been chosen as $\delta = 0.13 \pm 0.04$ [1], $f(c \to D^{*\pm}) = (25.65 \pm 1.41)\%$ ([5] and [6]), $\frac{f(b \to D^{*\pm})}{f(c \to D^{*\pm})} = 0.92 \pm 0.14$ ([2] and [6]).

4 Result and systematic errors

In order to enrich the D* sample with gluon splitting events the fit has been performed demanding that the X_E of a D* lie between 0.1 and 0.5 and that it is found in the heavy hemisphere. The efficiency for $g \to c\overline{c} \to D^*$ is $\approx 54\%$ (72% for the cut on X_E and 75% for the hemisphere requirement). The data sample from 1991 to 1995 yields $3.7 \cdot 10^6$ selected hadronic events and the result of the fit is

$$P_g = 0.111 \pm 0.031 \qquad , \qquad N_{D^{*\pm}} = 7398 \pm 183$$

with a χ^2/d.o.f $= 9.5/15$ which results in

$$\overline{n}_{g \to c\overline{c}} = (2.65 \pm 0.74)\% \; .$$

The fit is shown in Fig.5. Systematic errors have been investigated for the construction of the Monte Carlo hemisphere distributions, branching ratios entering equation 3, fragmentation parameters and Λ_{QCD}, and the reconstruction of D$^{*\pm}$ mesons. The resulting errors on $\overline{n}_{g \to c\overline{c}}$ are listed in table 2.

Source	Variation	$\Delta\overline{n}_{g\to c\overline{c}}$
Mass effect	$\pm 50\%$	± 0.01
δ	± 0.04	± 0.11
R_b, R_c	0.222, 0.154	-0.04
B_{D^*}	± 0.001	± 0.10
$f(c \to D^*)$	± 0.014	± 0.15
$\frac{f(b\to D^*)}{f(c\to D^*)}$	± 0.14	± 0.04
ϵ_c	± 0.013	$^{+0.11}_{-0.18}$
ϵ_b	± 0.0015	$^{+0.24}_{-0.07}$
Λ_{QCD}	$^{+71}_{-64}$ MeV	$^{+0.27}_{-0.34}$
Background	see text	± 0.04
dE/dx cuts	see text	± 0.10
D^0 flight direction	$-1.0...0.999$	± 0.09
Efficiency	$\pm 5\%$	± 0.14
Efficiency	$\pm 5\%$ for $X_E < 0.2$	± 0.15
Total		± 0.51

Table 2: List of systematic errors

For the Monte Carlo distributions we have used $R_b = 0.2156$ and $R_c = 0.171$. These have been varied to the measured values presented at the Brussels conference. The suppression of hard gluon emission from heavy quarks has been changed by $\pm 50\%$. We have used the JETSET [4] Monte Carlo to produce simulated events with parameters tuned to optimize observables measured by the ALEPH collaboration. Three parameters have been changed for systematic studies: the fragmentation parameters $\epsilon_b = 0.0045 \pm 0.0015$, $\epsilon_c = 0.030 \pm 0.013$, and $\Lambda_{QCD} = 314^{+71}_{-64}$ MeV. Uncertainties on the fragmentation

parameters have been derived from measurements of $\langle X_E \rangle_{D^*}$ [6] and $\langle X_E \rangle_{\text{B-hadrons}}$ [7],[8]. The error on Λ_{QCD} corresponds to a 4% variation in $\alpha_s(M_Z^2)$.
A further source of errors refers to the D* reconstruction. The efficiencies of the dE/dx cuts have been studied by comparing the number of signal events in Monte Carlo and data with and without the requirement $|\chi_{dE/dx}| < 2.5$. For the data the efficiency is lower by a factor 0.976 ± 0.009 for $X_E < 0.2$ and 0.991 ± 0.003 for $X_E > 0.2$ compared to the Monte Carlo. This has been corrected for in the D* counting procedure. A systematic error is derived by not applying the correction. Furthermore, the dE/dx cut has been dropped and varied to $|\chi_{dE/dx}| < 1.5$ and 3.5, respectively. The maximum change in the number of D* mesons has been taken as a systematic error.
The cut on the direction of flight of the D^0 has been treated in a similar manner. No discrepancies between Monte Carlo and data have been found regarding the efficiency. The cut has been changed from -1.0 (i.e. applying no cut) to 0.999, and the variation in the number of D*'s again taken as a systematic error.
Errors due to background subtraction have been evaluated by changing its normalization within the statistical errors. Also, the wrong–sign background has been used vor $X_E > 0.2$ instead of the side–band background. Finally, the efficiency has been varied by $\pm 5\%$ over the whole X_E range (which does not change the shape of the distribution), and by $\pm 5\%$ for $X_E < 0.2$ only.
Adding all systematic errors in quadrature results in

$$\overline{n}_{g \to c\bar{c}} = (2.65 \pm 0.74(stat.) \pm 0.51(syst.))\% .$$

5 Conclusions

The rate of gluon splitting to charm quarks has been measured by reconstructing D$^{*\pm}$ mesons in the decay channel $D^{*+} \to D^0 \pi_s^+ \to K^- \pi^+ \pi_s^+$ and counting them as a function of the difference of the hemisphere masses. Fitting this distribution yields the fraction of D*'s originating from gluons. From this the average number of gluons splitting to a $c\bar{c}$ pair has been calculated.

References

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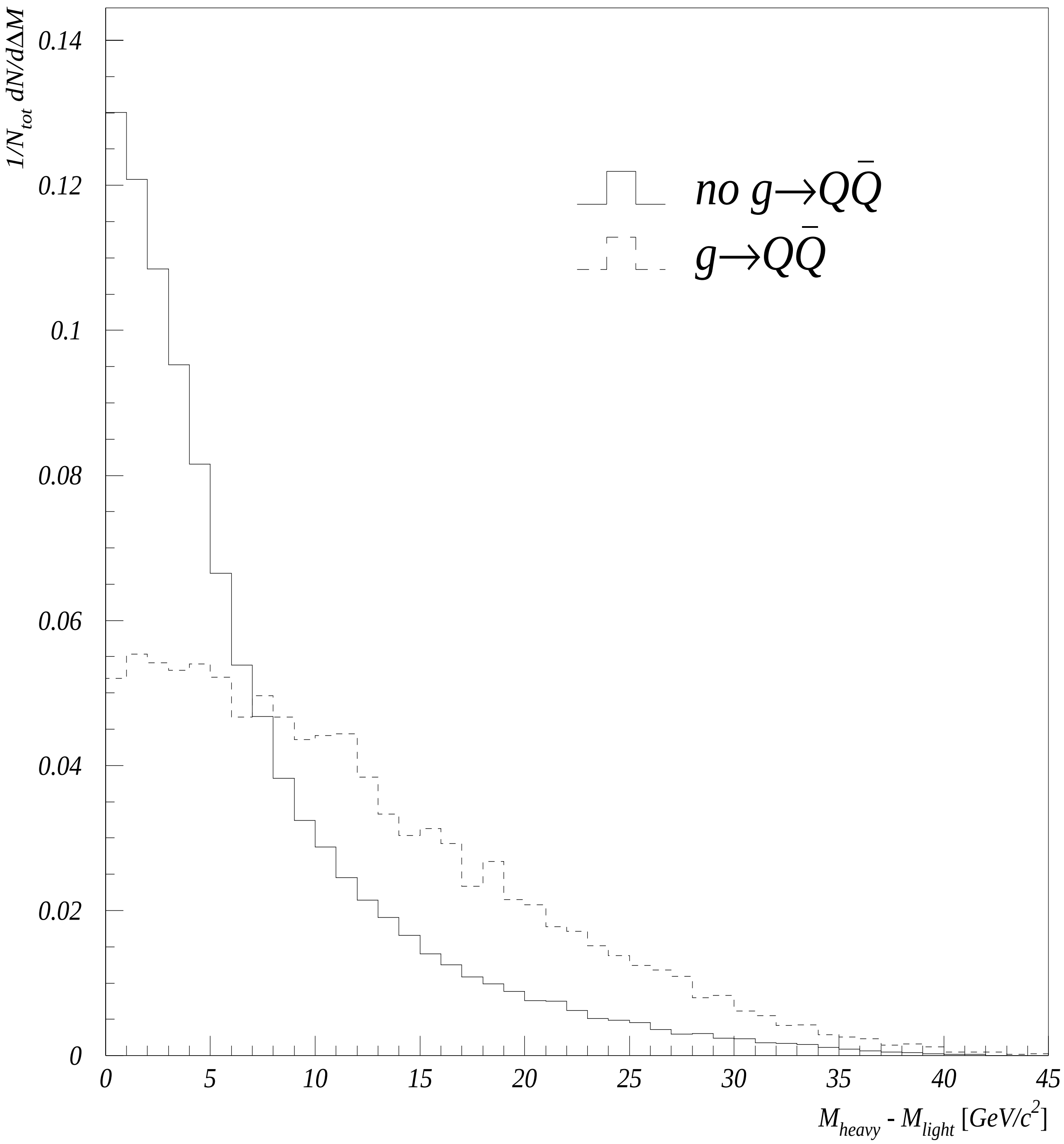


Figure 1: *Difference of heavy and light hemisphere masses in events with and without gluon splitting to heavy quarks.*

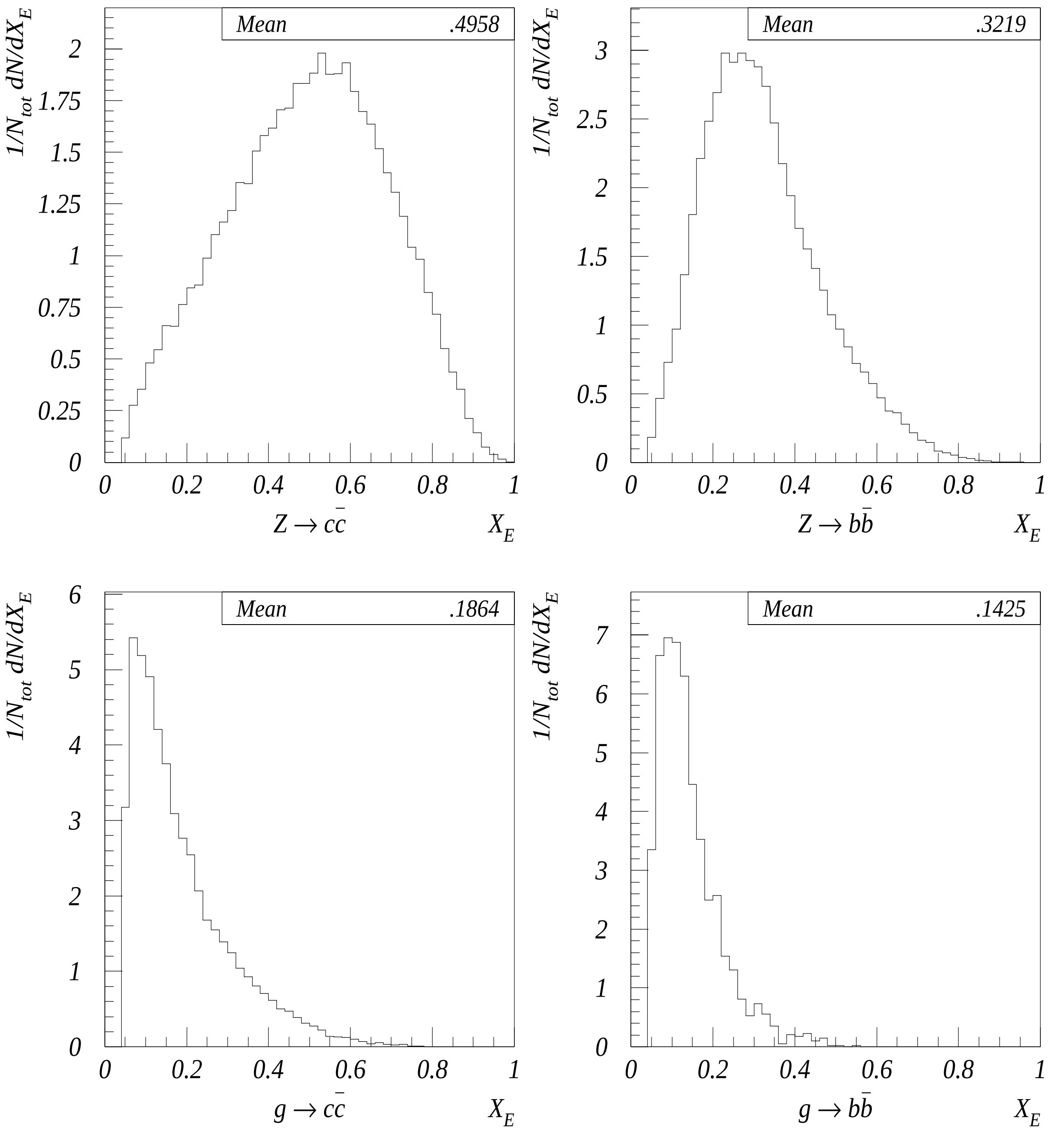


Figure 2: X_E *distributions of* D^* *mesons from different sources in Monte Carlo events.*

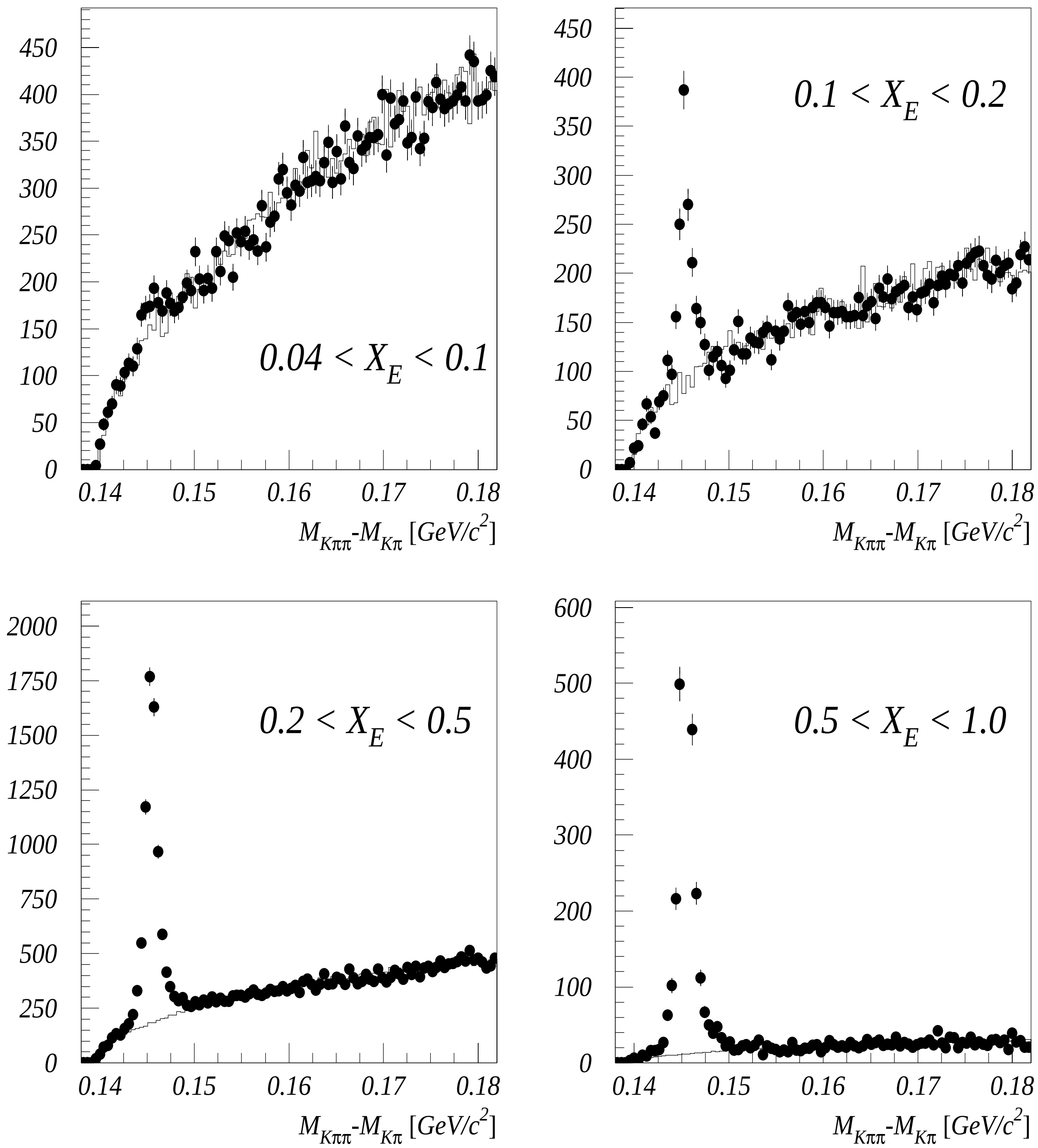
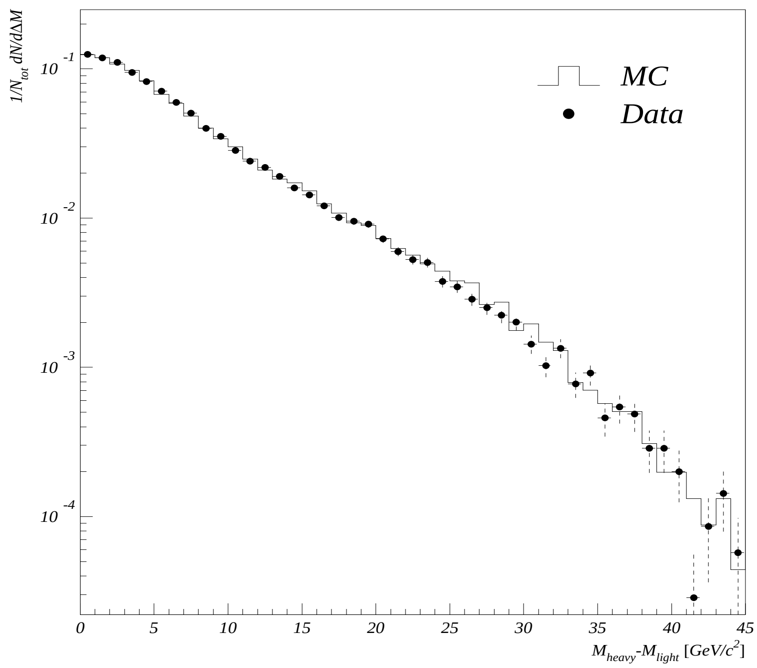


Figure 3: *$D^{*\pm}$ signal from the decay $D^{*+} \rightarrow D^0\pi_s^+ \rightarrow K^-\pi^+\pi_s^+$ in four X_E bins. The histogram shows the background from wrong sign candidates ($X_E < 0.2$) and sideband candidates ($X_E > 0.2$) normalized to the signal distribution in the range $0.16\ GeV/c^2 < M_{K\pi\pi} - M_{K\pi} < 0.18\ GeV/c^2$.*



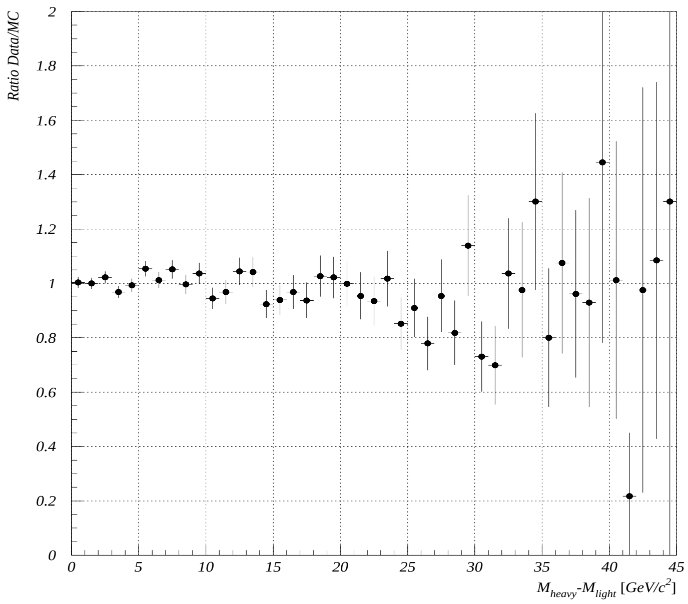


Figure 4: *Distribution of hemisphere mass differences for hadronic events. The upper plot shows Monte Carlo and real data distributions, the lower one the ratio of these two.*

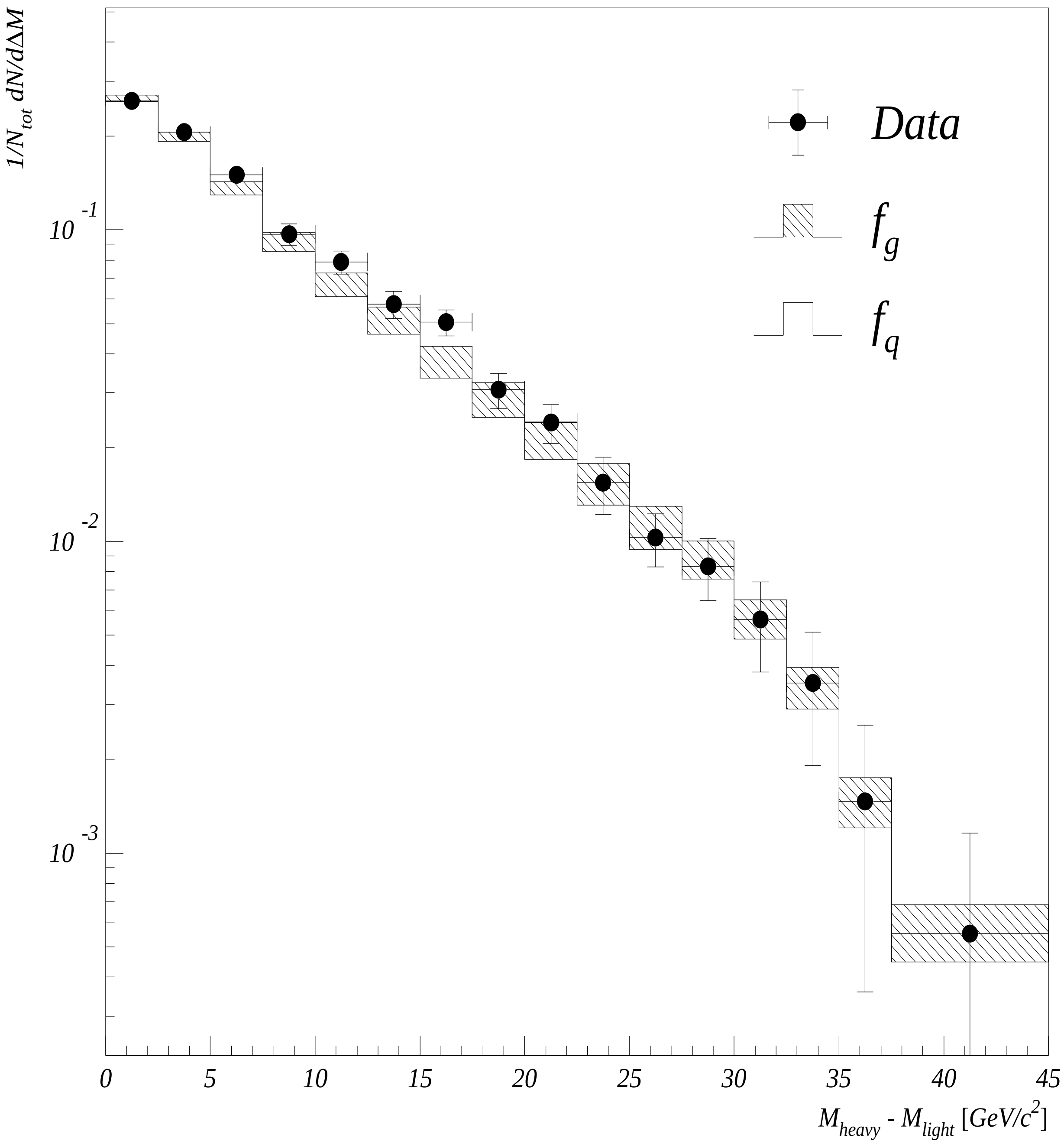


Figure 5: *Result of the fit requiring the $D^{*\pm}$ to be in the heavy hemisphere and having $0.1 < X_E < 0.5$. The empty histogram shows the Monte Carlo distribution of D^* mesons from primary quarks and the dashed one the one from gluon splitting, respectively. The errors on the data points are statistical only.*