Charmed-hadron production and charm fragmentation at ZEUS

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on behalf of the ZEUS collaboration

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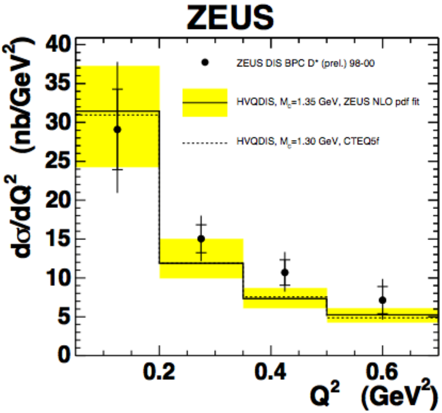
Previous inclusive D^* DIS measurement



- Inclusive c cross-sections have been measured previously at ZEUS
- ZEUS-prel-04-032
  - 82 pb^{-1}
  - $p_T(D^*) < 9$ GeV, $|\eta(D^*)| < 1.6$
  - $0.05 < Q^2 < 0.7$
  - probe transition region
- Differential $\sigma(D^*)$
- Shape well described by NLO

Aims and Motivations

- Follow Eur. Phys. J. C. **44**, 351-366 (2005)
- Reconstruct the charm mesons D^0, $D^{\pm}$, $D^{*\pm}$, $D_s^{\pm}$ and the charm baryon $\Lambda_c^{\pm}$. Hereafter D^+, Λ^+ is taken to mean $D^{\pm}, \Lambda^{\pm}$
- Use measurements of the cross sections of those hadrons to obtain
  - Fragmentation fractions
    →*Are fragmentation fractions independent of experiment?*
  - Strange suppression
    →*How frequently are s quarks picked up by c quarks in D mesons?*
  - Ratio of u/d production
    →*Are u and d quark picked up equally by c quarks in D mesons?*
- Integrated luminosity of 79 pb^{-1} in photoproduction regime

Charm fragmentation fractions

The fraction of c quarks hadronising as a particular charm hadron is given by

$$f(c \to D, \Lambda_c) = \frac{\sigma_{D,\Lambda c}}{\mathrm{Total}\ \sigma_{gs}}$$

- $\sigma_{D,\Lambda c}$ - production cross section (σ) for the hadron
- $\mathrm{Total}\ \sigma_{gs}$ - sum of production σ for all c **ground states** (ie not D^{*+}) that decay weakly
  - Dominated by: D^+, D^0, D_s^+ and Λ_c^+
  - Charm-strange baryons Ξ_c^+, Ξ_c^0 and Ω_c^0 included by estimating they contribute 14% of Λ_c^+

The σ_{D^+} and σ_{D^0} contributions to $\mathrm{Total}\ \sigma_{gs}$ are the sums of their direct cross section and D^* decay contribution

By definition $\Sigma_{gs} f(c \to D, \Lambda_c) = 1$

Reconstruction of charmed hadrons

- D^{*+}, D^{+}, D^{0}, D_s^{+}, and Λ_c^{+} are *all* measured in PHP in the *same* kinematic range $p_T(D, \Lambda_c) > 3.8$ GeV OR $|\eta(D, \Lambda_c)| < 1.6$
- Background reduction gained by cutting on p_T and decay angles of the decay products
- Problem: Some D^{*+} decay into D^0's which fall outside of the kinematic range
  - We must keep track of those D^0's which arise from D^{*+} decay to avoid double counting in $\sigma(D^{*+})$
- Solution: We divide up the D^0 sample into those that originate from a D^{*+} decay and those that do not

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Separation of D^0 sample

- For D^0 candidates a search is made for a soft pion in a $D^{*+} \to D^0\pi^+$ decay and tagged if this is the case
- $D^{*+} \to D^0 + \pi_s$ events are considered a sum of two subsamples
  - 'Tagged' events with $p_T(D^0) > 3.8$ GeV and $|\eta(D^0)| < 1.6$
  - 'Additional' events with $p_T(D^0) < 3.8$ GeV and $|\eta(D^0)| > 1.6$
- The 1st sample is represented by labeling these D^0 events with a special 'tag'.
- The 2nd sample is a set of separately measured 'additional' D^* events
- $\sigma^{\mathrm{kin}}(D^{*+}) = \sigma^{\mathrm{add}}(D^{*+}) + \sigma^{\mathrm{tag}}(D^0)/B_{D^* \to D^0\pi^+}$

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Subtraction of Reflections

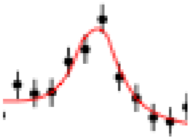
- We must ensure in the mass region about the signal there is no contribution from any other decay modes
  - This would provide a false signal and must be corrected for
- List decays with same number of daughter particles in this mass region
- Obtain reflections by assigning masses to tracks which correspond to these daughter particles
- These *reflection* shapes taken from MC and normalised by signals in nominal decay modes
- Reflections are much wider than signal and provide complex background shapes
- Signal fits are more stable after reflection subtraction

The Modified Gaussian

- Mass distributions were fitted with a 'modified' Gaussian function + background

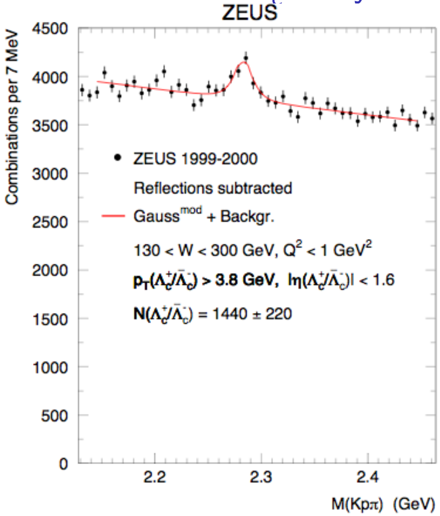
$$Gauss^{mod} \propto exp\left[-0.5x^{1+1/(1+0.5x)}\right]$$

- $x = ([M - M_D]/\sigma)$
- Background function is:
  - linear for Λ_c^+ and D^+
  - exponential for D_s^+ and D^0
  - polynomial for D^{*+}



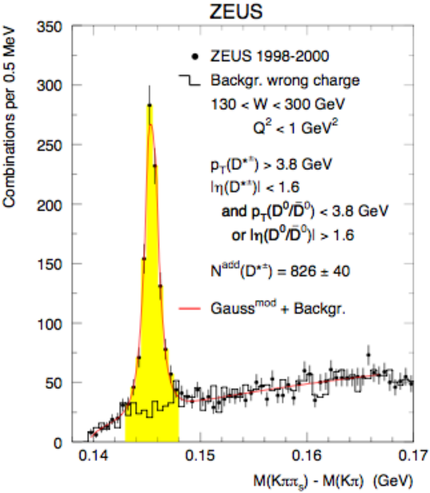
- Modified Gaussian has 3 free parameters like the regular Gaussian $\rightarrow$ far superior fit to data and MC signals $\rightarrow$ especially useful for high statistics MC signals

Reconstruction of Λ_c^+ baryons



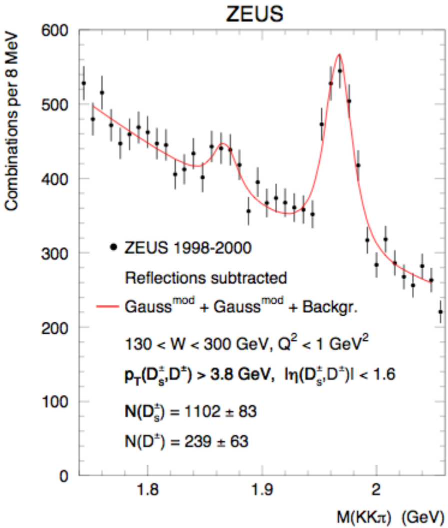
- $M(Kp\pi)$ spectrum after all cuts
- dE/dx cuts applied to suppress background
- Reflections from D^+ D_s^+ to 3 charged particles subtracted using the simulated reflection shapes.

Reconstruction of additional D^{*+} mesons



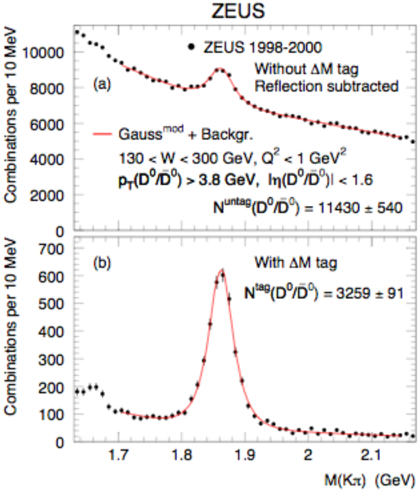
- ΔM spectrum
- $N(D^{*+})$ counted by subtracting wrong charge background in yellow region
- D^*'s counted in range: $0.143 < \Delta M < 0.148$ GeV

Reconstruction of D_s^+ mesons



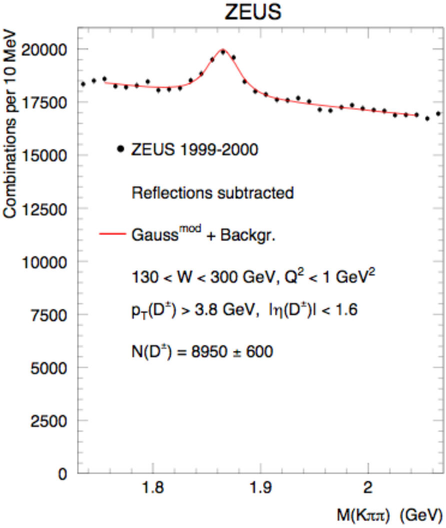
- $M(KK\pi)$ spectrum after all cuts
- Reflections from $D^+, \Lambda_c \to 3$ charged particles subtracted
- Clear signal at $M_{\text{nom}}(D_s^+)$
- 2nd signal at $M(D^+)$
  - $D^+ \to \phi\pi^+$
  - $\phi \to K^+K^-$

Reconstruction of D^0 mesons



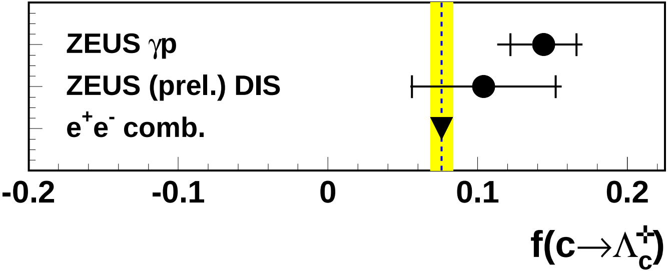
- D^0's are tagged if they originate from a D^{*+} decay
  - Later necessary to remove the D^{*+} contribution to D^0
- Tagged D^0 signal is more pronounced
- Fit performed simultaneously

Reconstruction of D^+ mesons



- Reflections from $D_s^+, \Lambda_c \rightarrow 3$ charged particles subtracted
- All signals are resolved cleanly at ZEUS

Fragmentation fractions for Λ_c^+



- Decay channel: $\Lambda_c^+ \to K^- p \pi^+$
- Larger than but consistent with world average

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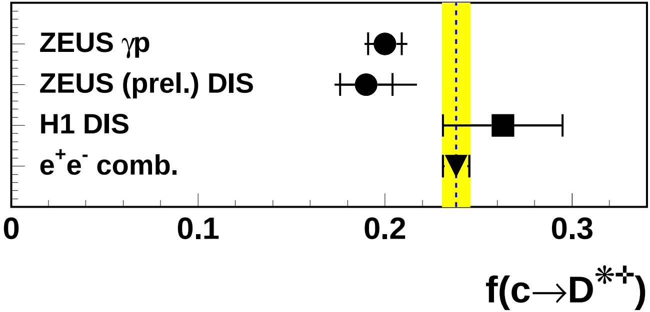
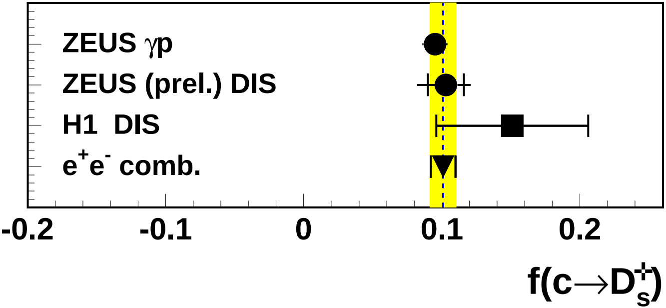
Fragmentation fractions for D^*



- Decay channel: $D^{*+} \rightarrow D^0\pi_s^+$
- Smaller than but consistent with previous measurements
- About half of the difference due to low f($c \rightarrow \Lambda_c^+$)

Fragmentation fractions for D_s^+



- Decay channel: $D_s^+ \rightarrow \phi^0(\rightarrow K^+K^-)\pi^+$
- Excellent agreement

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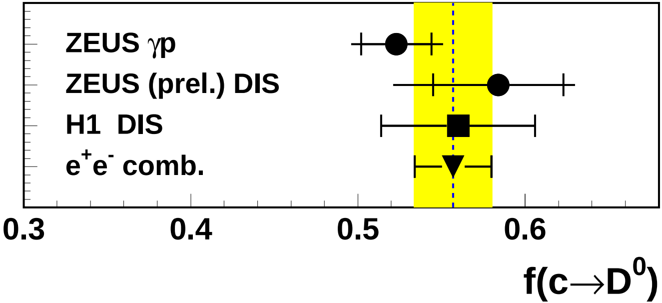
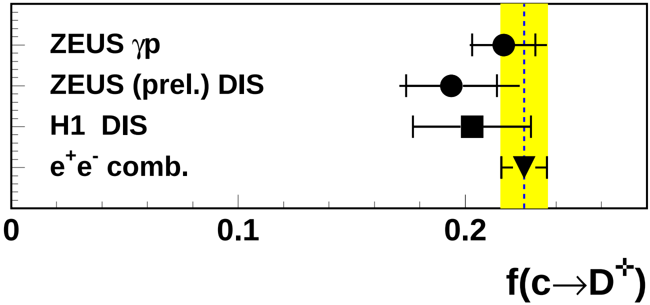
Fragmentation fractions for D^0



- Decay channel: $D^0 \rightarrow K^- \pi^+$
- Good agreement

Fragmentation fractions for D^+



- Decay channel: $D^+ \to K^-\pi^+\pi^+$
- Excellent agreement

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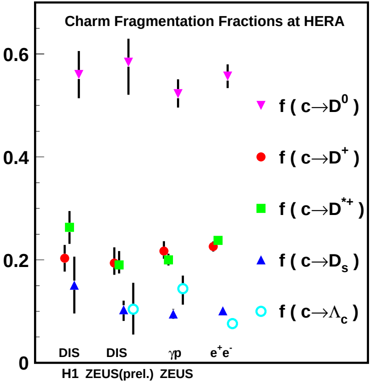
Overview: Charm fragmentation fractions



Consistent with universality assumption of charm fragmentation

Disentangling D^*'s

"In the measurement of $f(c \to X)$ it is sometimes necessary to disentangle which of the decay modes have a contribution from a D decay and which do not. Often it is necessary to subtract this contribution before making a measurement."*

- Recall D^0's are tagged if they are a result of a D^{*+} decay
- Any D^{*+} which give rise to a D^0 outwith the kinematic cuts are called *additional* D^{*+}
- The measured quantities in this analysis are
  - $\sigma^{\rm untag}(D^0)$: The production cross section for D^0 mesons not originating from the $D^{*+} \to D^0\pi_s^+$ decay
  - $\sigma^{\rm tag}(D^0)$: The production cross section for D^0 mesons originating from the $D^{*+} \to D^0\pi_s^+$ decay
  - $\sigma^{\rm add}(D^{*+})$: The production cross section for additional D^{*+} mesons ($p_T(D^0) < 3.8$ GeV OR $\eta(D^0) > 1.6$)
- give list of equations? like sigma kin relationships etc

$R_{u/d}$: Relative number of u and d quarks

The ratio of neutral to charged D meson production rates

$$R_{u/d} = \frac{\sigma^{\mathrm{dir}}(D^0) + \sigma(D^{*0})}{\sigma^{\mathrm{dir}}(D^+) + \sigma(D^{*+})}$$

- We are now dealing with both excited and ground state mesons. Care must be taken to treat D^* contribution correctly
- $\sigma^{\mathrm{dir}}(D^0)$ and $\sigma^{\mathrm{dir}}(D^+)$ are those parts of $\sigma(D^0)$ and $\sigma(D^+)$ not originating from D^* decays
- Problem: $\sigma^{\mathrm{dir}}(D^0)$ and $\sigma^{\mathrm{dir}}(D^+)$ are not measured

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$R_{u/d}$: Relative number of u and d quarks

- To express this formula in terms of quantities measured at ZEUS we make use of a number of relationships
- *Since* $D^{*0} \rightarrow D^0 + X$ *always*
    - $\sigma^{\mathrm{dir}}(D^0) + \sigma(D^{*0}) = \sigma^{\mathrm{untag}}(D^0)$ (i.e. not from D^{*+})
- $\sigma^{\mathrm{dir}}(D^+) = \sigma(D^+) -$ the contribution from D^{*+}
    - $\sigma^{\mathrm{dir}}(D^+) = \sigma(D^+) - \sigma(D^{*+})(1 - B_{D^{*+} \rightarrow D^0_{\pi^+}})$
- By substitution we arrive at the usable expression

$$R_{u/d} = \frac{\sigma^{\mathrm{untag}}(D^0)}{\sigma^{\mathrm{tag}}(D^0) + \sigma(D^+)}$$

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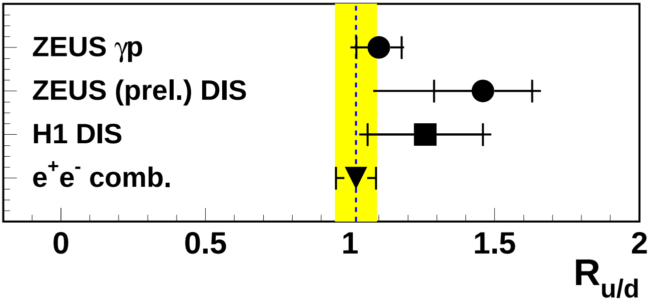
$R_{u/d}$: Relative number of u and d quarks



$$R_{u/d} = \frac{\sigma^{\text{dir}}(D^0)+\sigma(D^{*0})}{\sigma^{\text{dir}}(D^+)+\sigma(D^{*+})} = \frac{c\bar{u}}{c\bar{d}}$$

- u and d quarks are produced equally in charm fragmentation
  $\longrightarrow$ *Strong Isospin Invariance Holds*

Fraction of Vector Meson Production

3 VM spin states	1 PS spin state
$\|\uparrow\uparrow>$	.
$\|\uparrow\downarrow> + \|\downarrow\uparrow>$	$\|\uparrow\downarrow> - \|\downarrow\uparrow>$
$\|\downarrow\downarrow>$	.

- The number of permitted spin states:
  - Vector mesons (D^{*+}) have a total of 3
  - Pseudoscalar mesons (D^0, D^+) have only 1.
- By naive spin counting we expect D mesons to be produced in a VM state 3× more often than in a PS state
  - $\frac{V}{V+PS} = 0.75$
- Can be verified by measurements of D^{*+} and D^+

Fraction of Vector Meson Production

The fraction of D mesons produced in a vector state

$$P_V^d = \frac{V}{V + PS} = \frac{\sigma^{\mathrm{kin}}(D^{*+})}{\sigma^{\mathrm{kin}}(D^{*+}) + \sigma^{\mathrm{dir}}(D^+)}$$

- $\sigma^{\mathrm{kin}}(D^{*+})$ = the production $\sigma(D^{*+})$ in an equivalent kinematic range to $\sigma^{\mathrm{dir}}(D^+)$

  $p_T(D^*) > 3.8$ GeV, $|\eta(D^*)| < 1.6$

- $\sigma^{\mathrm{dir}}(D^+)$ = the part of $\sigma(D^+)$ not from D^{*+} decays

$$P_V^d = \frac{\sigma^{\mathrm{tag}}(D^0)/B_{D^{*+}\to D^0\pi^+} + \sigma^{\mathrm{add}}(D^{*+})}{\sigma(D^+) + \sigma^{\mathrm{tag}}(D^0) + \sigma^{\mathrm{add}}(D^{*+})}$$

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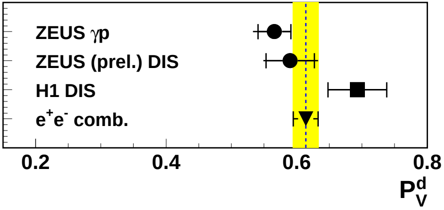
P_V^d: Fraction of VM in f($c \rightarrow D$) fragmentation



- ZEUS: $P_V^d = 0.566 \pm 0.025(\text{stat})^{+0.007}_{-0.022}(\text{syst.})^{+0.022}_{-0.023}(\text{br})$
- Smaller than but consistent with previous measurements
- Considerably smaller than simple spin counting prediction.
- Thermodynamical & String Fragm. models: $P_V^d \approx 0.666$
  - closer to but still above the measured value
- $P_V^D \neq 0.75$. Simple spin counting does NOT work with charm

Strangeness suppression factor

"Strangeness suppression is a parameter which determines the ratio of probabilities to create a s to u, d quark in the fragmentation process."

$$\gamma_s = \frac{2\sigma(D_s^+)}{\sigma^{\rm eq}(D^+) + \sigma^{\rm eq}(D^0)}$$

- Using relationships for the equivalent cross sections $\sigma^{\rm eq}(D)$

$$\sigma^{\rm eq}(D^0) = \sigma^{\rm untag}(D^0) + \sigma^{\rm tag}(D^0) + \sigma^{\rm add}(D^{*+})(R_{u/d} + B_{D^{*+}\to D^0\pi^+})$$

$$\sigma^{\rm eq}(D^+) = \sigma(D^+) + \sigma^{\rm add}(D^{*+})(1 - B_{D^{*+}\to D^0\pi^+})$$

$$\gamma_s = \frac{2\sigma(D_s^+)}{\sigma(D^+) + \sigma^{\rm untag}(D^0) + \sigma^{\rm tag}(D^0) + \sigma^{\rm add}(D^{*+})(1 + R_{u/d})}$$

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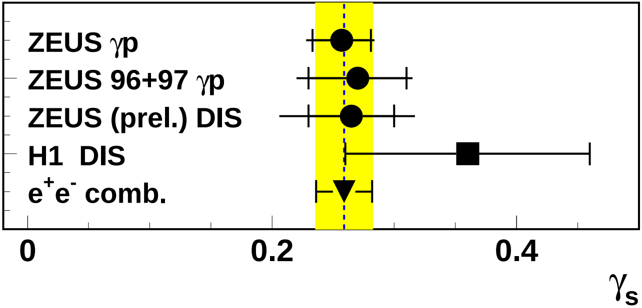
Strangeness suppression factor



- The strangeness suppression factor in c fragmentation $\approx \frac{1}{3.9}$

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Summary & Outlook

- Summary
  - Fragmentation fractions are consistent with universality
  - Ratio of u to d is consistent with Isospin invariance
  - Vector to Pseudoscalar ratio has been measured is inconsistent with naive spin counting
- HERA II outlook
  - More luminosity
  - MVD will reconstruct secondary vertices and measure lower P_t

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BONUS SLIDES

There now follows a selection of additional slides for the interested reader

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Λ_c^+

Reconstruction Λ_c^+ baryons

- Decay channel: $\Lambda_c^+ \rightarrow K^- p \pi^+$
- Λ_c^+ constructed from tracks of $++-$ charge configuration
- Given that $M(p) >> M(\pi)$
  - $M(p)$ is assigned to the $+$ track with highest p
  - Remaining $+$ track is assigned $M(\pi)$
  - $M(K)$ assigned to remaining track and $M(Kp\pi)$ is calculated
- To reduce background:
  - $p_T(K) > 0.75$, $p_T(p) > 1.3$, $p_T(\pi) > 0.5$ GeV
  - $\cos\theta^*(K) < -0.9$.
  - $\cos\theta^*(p) > 0.25$.
  - $p^*(\pi) > 90$ MeV. $p^*(\pi)$ is $p(\pi)$ in the Λ_c^+ rest frame
  - Cuts on dE/dx values of decay tracks

$\theta^*(X)$ is θ between X in Λ_c^+ rest frame and Λ_c^+ line of flight in lab

D^{*+}

Reconstruction of additional D^{*+} mesons

- Decay channel: $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi_s^+$
- D^{*+} constructed from tracks of $-++$ configuration
- $+-$ tracks with $p_T > 0.4$ GeV combined in pairs to form D^0 candidates
- K and π masses assumed in turn and $M(K\pi)$ calculated
- D^0 candidate kept provided
  - $1.81 < M(K\pi) < 1.92$ GeV
  - and either $p_T(D^0) < 3.8$ GeV or $|\eta| > 1.6$
- Remaining $+$ track assigned $M(\pi)$ if $p_T > 0.2$ GeV
- $\Delta M = M(D^{*+}) - M(D^0)$ histogrammed

D_s^+

Reconstruction of D_s^+ mesons

- Decay channel: $D_s^+ \rightarrow \phi(\rightarrow K^+K^-)\pi^+$
- Oppositely charged tracks with $p_T > 0.7$ GeV assigned $M(K)$ to form ϕ candidates
  - ϕ candidate kept if $M(\phi) - 8\text{MeV} < M(KK) < M(\phi) + 8\text{MeV}$
- Any additional $p_T > 0.5$ GeV track combined with ϕ to form D_s^+ candidate
- to reduce background:
  - $\cos\theta^* < 0.85$. θ^* is angle between π in D^{*+} rest frame and D^{*+} line of flight in lab frame
  - $|cos^3\theta^{'}(K)| > 0.1$. $theta^{'}(K)$ is angle between K and π in ϕ rest frame. Motivated by spin alignments.

D^0

Reconstruction of D^0 mesons

- Decay channel: $D^0 \to K^-\pi^+$
  - Oppositely charged tracks with $p_T > 0.8$ GeV from D^0 candidates
  - K and π masses are assigned to each track $\to M(K\pi)$ calculated
  - Rest frame angle between K,π $\theta^*(K)$ is cut $|\cos\theta^*(K)| < 0.88$
- Ambiguity in K,π assignment to tracks is corrected for by 'tagging' D^0's arising from $D^{*+} \to D^0\pi_s$
  - In this decay K,π are correctly assigned to D^0 decay tracks
  - This D^0 spectrum using incorrect assignment is normalised by $N^{\mathrm{untag}}(D^0)/N^{\mathrm{tagged}}(D^0)$ and subtracted from the untagged D^0 spectrum.

D^+

Reconstruction of D^+ mesons

- Decay channel: $D^+ \rightarrow K^- \pi^+ \pi^+$
  - Like charged tracks with $p_T > 0.5$ GeV combine with third opposite charge track to from D^+ candidates
  - π masses are assigned to both like charged tracks, K mass to third and $M(K\pi\pi)$ calculated
  - Angle between K in D^+ rest frame and D^+ line of flight in lab frame is cut at $|\cos\theta^*(K)| < 0.88$
- Background reduced by removing $M(K\pi\pi) - M(K\pi) < 0.15$ GeV candidates
- Background from $D_s^+ \rightarrow \phi(\rightarrow K^+K^-)\pi^+$ suppressed by demanding
  - $|M(1,2) - M(\phi)| > 8$ MeV where 1,2 are any two opposite charge D^+ candidate tracks.

Systematics

Systematics

Systematics are determined by changing the analysis procedure and repeating all calculations.

The following groups or systematic uncertainty were considered:

- The model dependence of the acceptance corrections
  - Using the HERWIG MC sample
  - Varying the $p_T(D, \Lambda_c)$ and $\eta(D, \Lambda_c)$
  - Changing the MC fraction of charged D mesons produced in a vector state from 0.6 to 0.5 or 0.7
- The uncertainty of the beauty subtraction
  - The b-quark σ was varied by a factor of 2
  - The branching ratios of b-quarks to charm hadrons were varied by their uncertainties

Systematics II

Systematics II

- The uncertainty of the tracking simulation
  - All momenta varied by $\pm 0.3\%$ (magnetic field uncertainty)
  - Track loss probability varied by $\pm 20\%$
  - Track momentum and angular resolutions varied by $^{+20\%}_{-10\%}$ (asymmetric resolution variation arise because MC signals had narrower widths than data)
- The uncertainty of the CAL simulation
  - CAL energy scale varied by $\pm 2\%$
  - CAL resolution varied by $\pm 20\%$
  - Efficiencies of CAL first-level trigger varied

Systematics III

Systematics III

- Uncertainties related to signal extraction
  - For the D^0 signals the background parameterisation and fitted range varied
  - for the additional D^{*+} signal the area used in background normalisation was varied and the fit was used instead of the subtraction procedure.
  - for the D^+ D_s^+ and Λ_c^+ signals the background parameterisation, fitted region and amounts of mutual reflections were varied
- The uncertainties of the luminosities of the $e^-p(\pm1.8\%)$ and $e^+p(\pm2.25\%)$ were included
- The uncertainty in the rate of charm-strange barons