Charm Production at 91 GeV

J.M. Steuerer

OPAL / DESY

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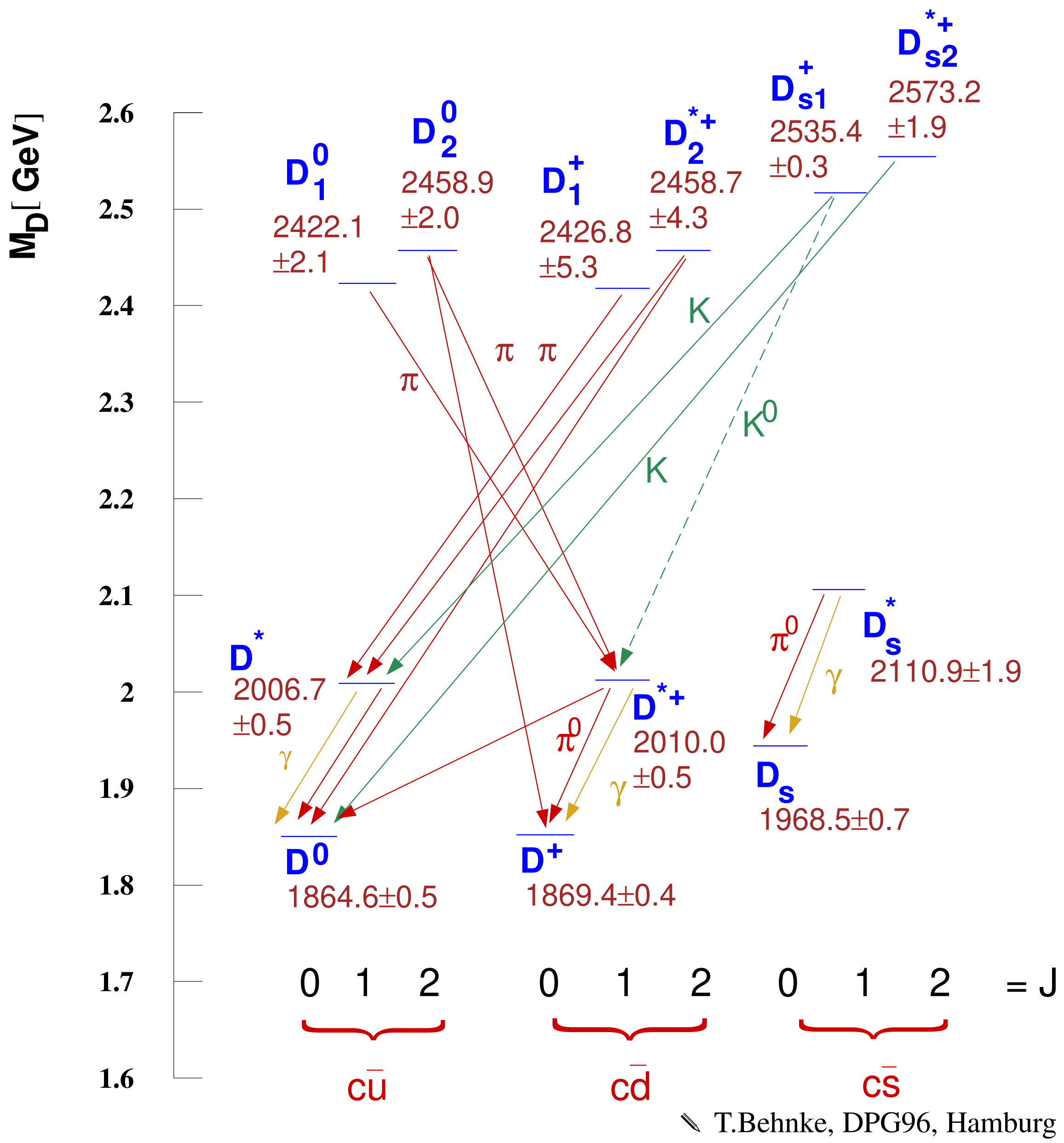
- Charm Spectroscopy
- R_c Measurements
- Measurements of Gluon Splitting

Introduction

Why are we interested in charm:

- LEP is a charm factory, each experiment recorded about 700 k $Z^0 \rightarrow c\bar{c}$ events and 800 k $Z^0 \rightarrow b\bar{b}$ events.
- Test of electro-week theory, Z^0 couplings: $R_c = \Gamma_{c\bar{c}}/\Gamma_{\mathrm{had}}$, Asymmetry
- Study of perturbative QCD, $g \rightarrow c\bar{c}$
- Study of fragmentation: Production rates of excited D-meson
- c-Hadrons are heavy enough to be approximated by HQET
- and light enough to be affected by non spectator processes

Charm Spectroscopy



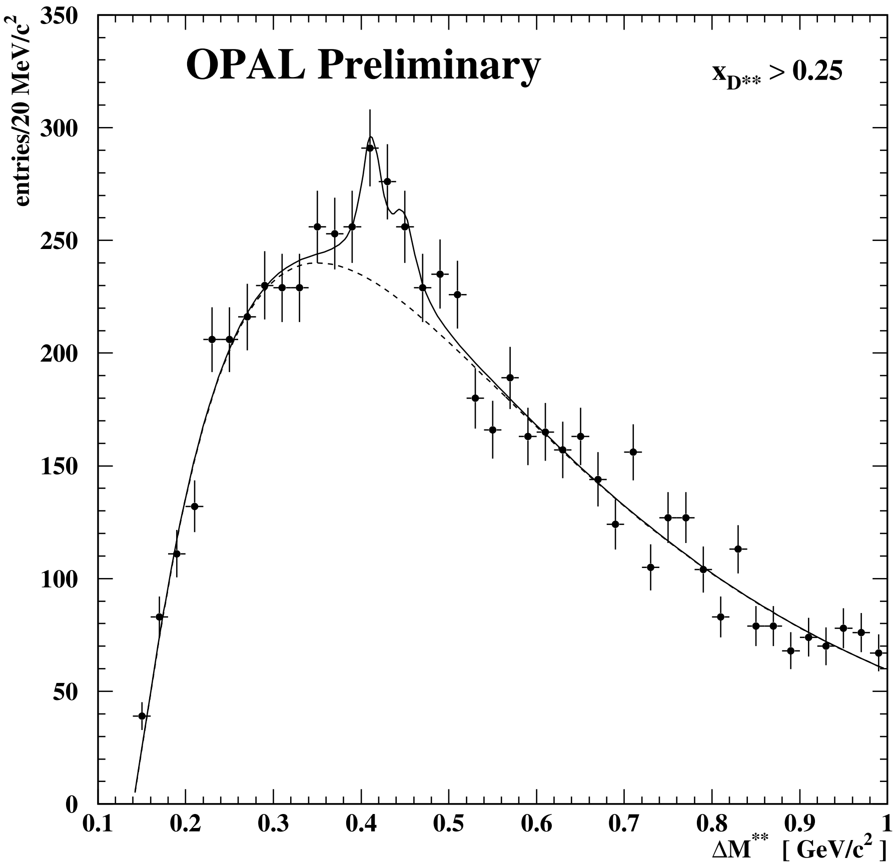
Plus: J/ψ, Λ_c^+, ...

Orbital Excited D-Mesons, D^{**}, $L = 1$

- Several D^{**} states are observed at LEP
- In general, the resolution is not good enough to be competitive with measurements of mass and width at the Υ_{4s} resonance
- Production rate measurements are constrains to fragmentation models

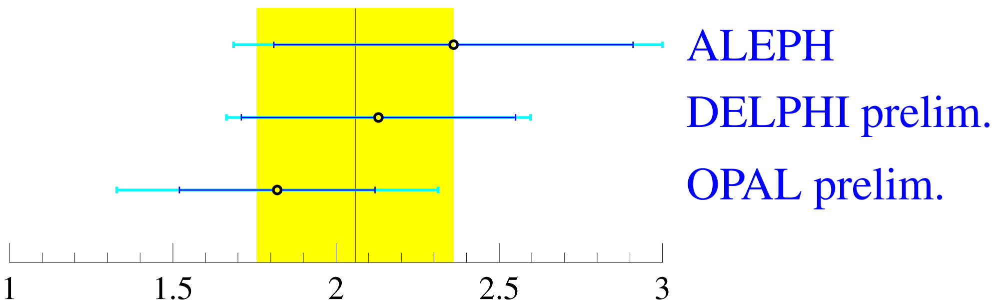
D^{**0}

4 States:			
Name	$^{2s+1}L_J$	Width / MeV	Decay
not observed	$^1P_1$	≈ 100	S-wave
not observed	$^3P_0$	≈ 100	
D_1^0	$^3P_2$	≈ 19	D-wave
D_2^{*0}	$^3P_1$	≈ 23	



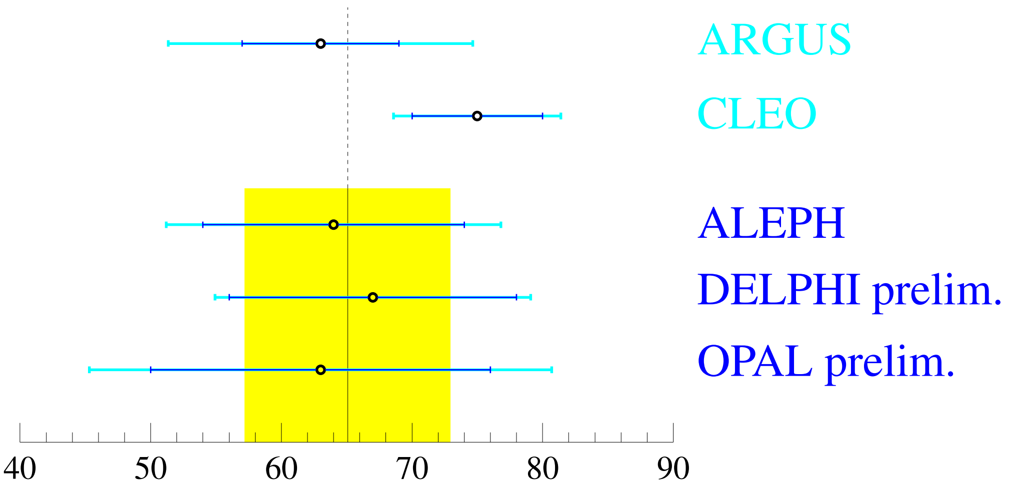
Average D^{**} Multiplicity * Branching $D^{**0} \to D^{*+}\pi^-$

$$\boxed{\frac{\#D^{**0} \to D^{*+}\pi^- \ \text{candidates}}{N_{\text{had}}}}$$



$$\overline{n}_{Z^0 \to D^{**0}X} \cdot Br(D^{**0} \to D^{*+}\pi^-)\ /10^{-2}$$

Relative Production Rate, $D_1^0/(D_1^0 + D_2^{*+})$

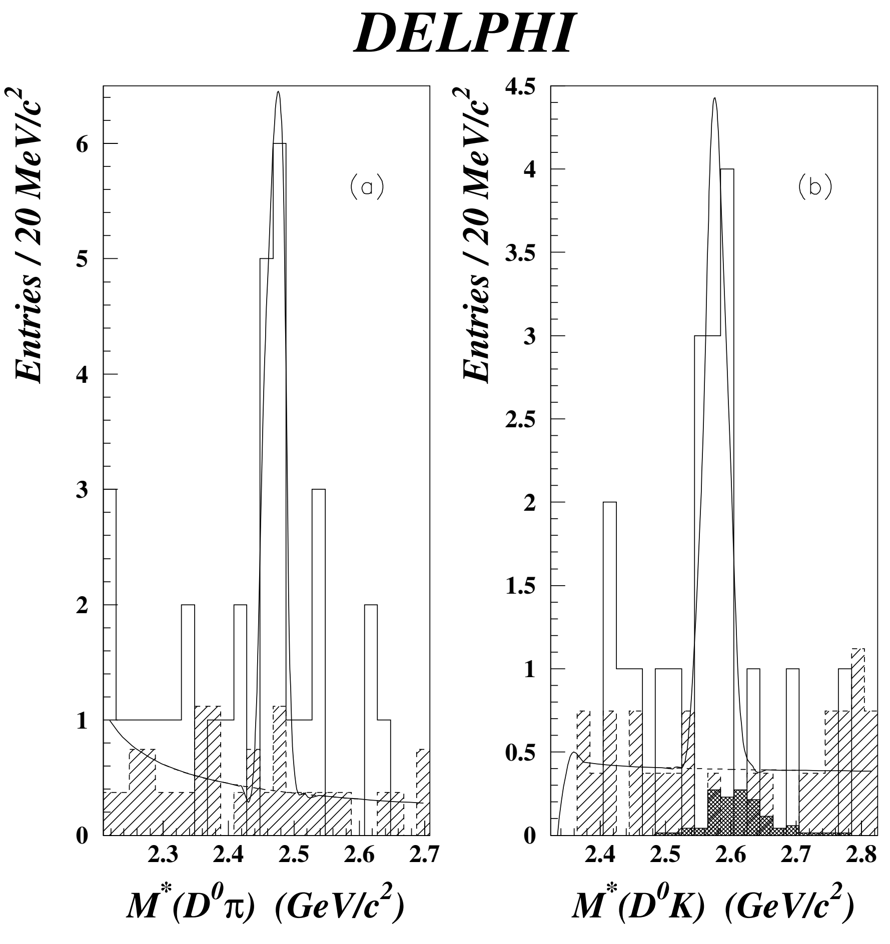


$$R_{D_1^0} = \frac{N_{D_1^0 \to D^{*+}\pi^-}}{N_{D_1^0 \to D^{*+}\pi^-} + N_{D_2^{*0} \to D^{*+}\pi^-}} \text{ in } \%$$

$D_{(s)}^{**+}$

- The observation of the D_1^+ in semileptonic B decays was reported by ALEPH
  $Br(b \to \overline{B}) \cdot Br(\overline{B} \to D_1^+ \ell^- \overline{\nu} X) \cdot Br(D_1^+ \to D^0 \pi^+)$
  $= (2.1 \pm 0.7) \times 10^{-3}$

- Evidence for D_2^{*+} and D_{s2}^{*+} was shown by DELPHI



$D_2^{*+} \to D^0 \pi^+$ $\qquad$ $D_{s2}^{*+} \to D^0 K^+$

$D^0 \to K^- \pi^+$

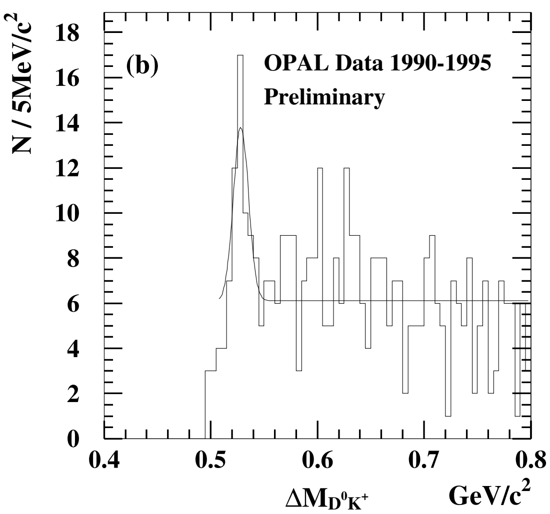
➪ Evidence for D_{s1}^{+} is reported by OPAL

$$\overline{n}_{Z^0 \to \mathrm{D}_{s1}^{+}} \cdot Br(\mathrm{D}_{s1}^{+} \to \mathrm{D}^0\mathrm{K}^+) = (1.8 \pm 0.6) \times 10^{-3}$$

$$\overline{n}_{Z^0 \to \mathrm{D}_{s1}^{+}} \cdot Br(\mathrm{D}_{s1}^{+} \to \mathrm{D}^+\mathrm{K}^0) = (1.0 \pm 0.6) \times 10^{-3}$$

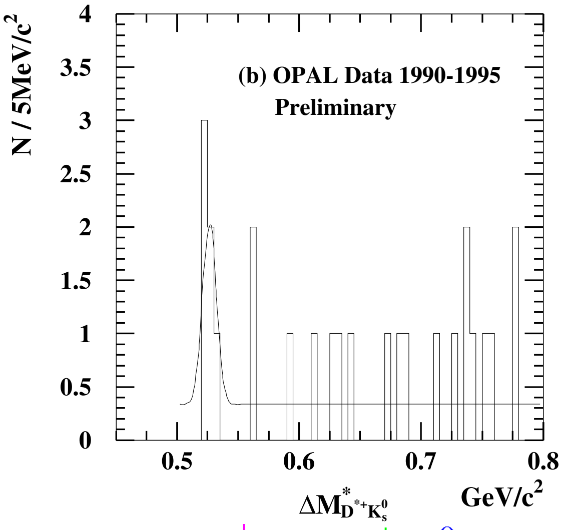
Assuming these are the only possible D_{s1}^{+} decay channels

➥ $f(c \to \mathrm{D}_{s1}^{+}) = (1.6 \pm 0.6)\%$



$\mathrm{D}_{s1}^{+} \to \mathrm{D}^0\mathrm{K}^+$

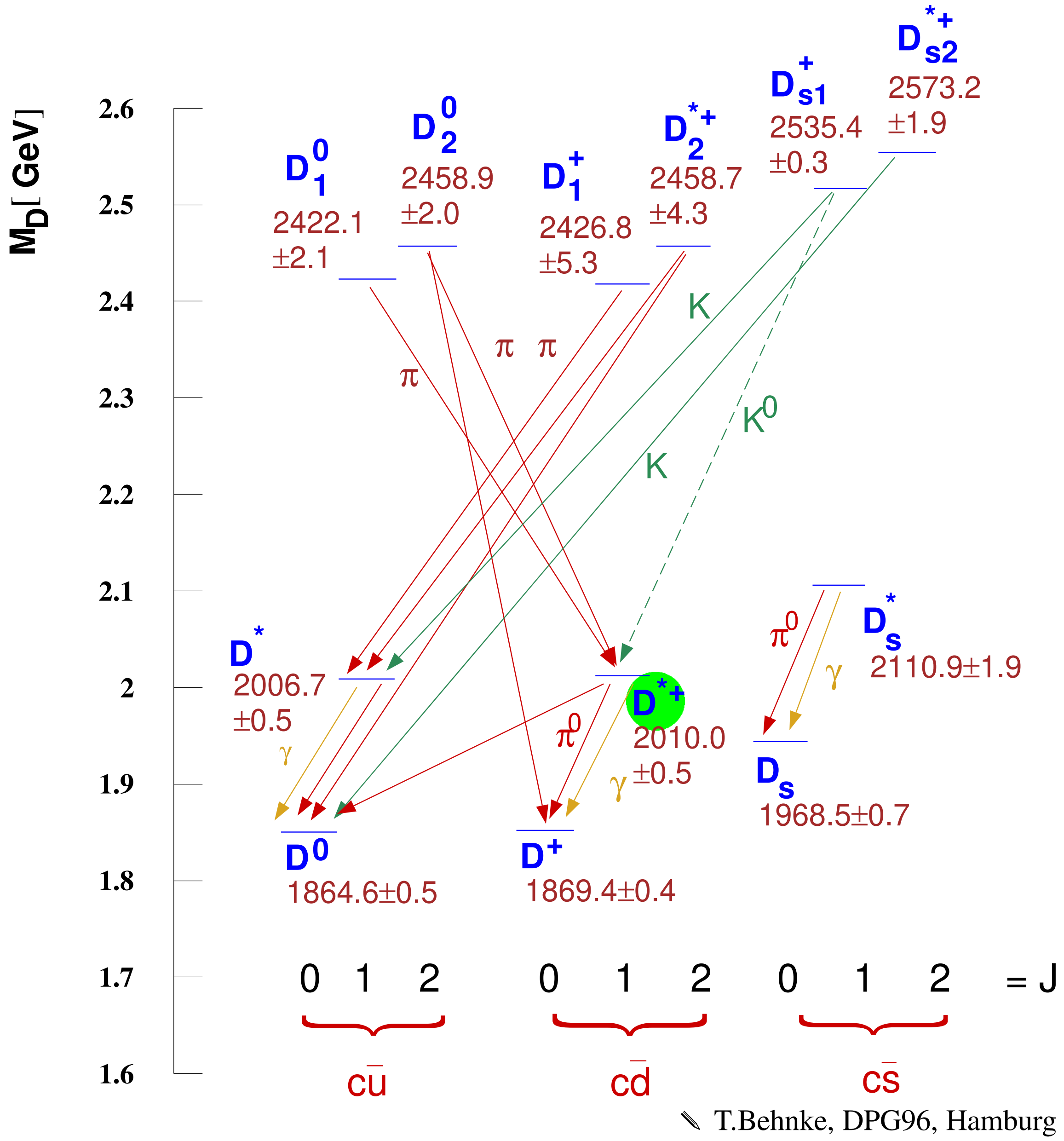
$\mathrm{D}^0 \to \mathrm{K}^-\pi^+$



$\mathrm{D}_{s1}^{+} \to \mathrm{D}^+\mathrm{K}^0$

$\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$

D* and R_c

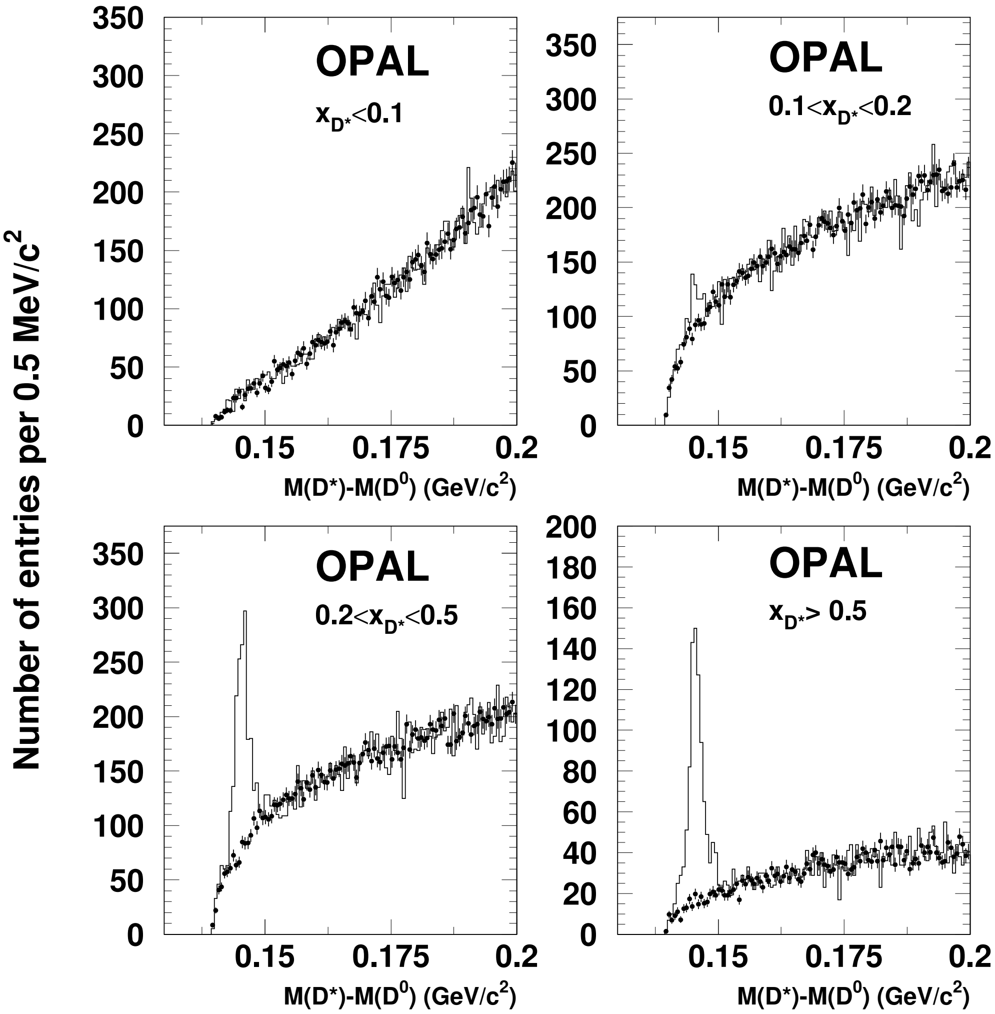


M_D [GeV]
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
D_1^0
2422.1
±2.1
D_2^0
2458.9
±2.0
D_1^+
2426.8
±5.3
D_2^*+
2458.7
±4.3
D_s1^+
2535.4
±0.3
D_s2^*+
2573.2
±1.9
π
π π
K
K^0
K
D^*
2006.7
±0.5
γ
D^*+
2010.0
±0.5
π^0
γ
D_s^*
2110.9±1.9
π^0
γ
D_s
1968.5±0.7
D^0
1864.6±0.5
D^+
1869.4±0.4
0 1 2
0 1 2
0 1 2
= J
cū
cd̄
cs̄
T.Behnke, DPG96, Hamburg

Excited D-Mesons, $J^P = 1^-$

- No reports from LEP about D^{*0} or D_s^{*0} since dominant decay modes are: $\mathrm{D}^{*0} \to \mathrm{D}^0\gamma$ and $\mathrm{D}_s^{*0} \to \mathrm{D}_s^0\pi^0/\gamma$ and π^0/γ are hard to reconstruct in dense jet environment

- $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$ well established, due to small Q-value. For Example: $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$ with $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$



D^{*+}

- The low Q-value of the $D^{*+} \to D^0\pi^+$ decay
  - ⋗ clean and/or high statistic samples
- High Statistics ⋗ b/c separation on life-time base

Number of selected $D^{*\pm}$ in hadronic-Events:

$$
\begin{aligned}
n_{D^{*\pm}} \quad = \quad & 2\, N_{\mathrm{had}}\, Br(D^{*+} \to D^0\pi^+) \\
& [\qquad R_c\, P(c \to D^{*+})\, \varepsilon_c \\
& \quad + \; R_b\, P(b \to D^{*\pm})\, \varepsilon_b \\
& \quad + \; h.c.\ gluon\ splitting \quad]
\end{aligned}
$$

Known scaled energy: $\langle x_{D^{*\pm}} \rangle_c > \langle x_{D^{*\pm}} \rangle_b$

⋗ selection can be optimised to enhance c: $\varepsilon_c > \varepsilon_b$

✌ remaining b-fraction can be estimated on life time base

c-enriched sample used for measuring:

- ➪ charm asymmetry
- ➪ $R_c = \Gamma_{c\bar{c}}/\Gamma_{\mathrm{had}}$

R_c from D^{*+}

3 Attempts:

❶ OPAL: simply count D^{*+}
decay channel: $D^{*+} \rightarrow D^0\pi^+$ with $D^0 \rightarrow K^-\pi^+$

$$\boxed{R_c \approx \frac{n_{D^{*\pm}}}{2\ N_{had}\ P(c \to D^{*+})\ Br(D^{*+} \to D^0\pi^+)\ \varepsilon_c}}$$

$P(c \to D^{*+})\ Br(D^{*+} \to D^0\pi^+)$ value measured at Υ_{4s}

❷ OPAL & DELPHI: Mixed Double Tag

same as ❶, but $P(\mathrm{c}\to\mathrm{D}^{*+})\ Br(\mathrm{D}^{*+}\to\mathrm{D}^0\pi^+)$ is determined by mixed double tag.

Procedure:

- Look for an exclusively reconstructed $\mathrm{D}^{*+} \to n_{\mathrm{sing}}$

  $n_{\mathrm{sing}} \approx N_{\mathrm{had}}\ R_{\mathrm{c}}\ P(\mathrm{c}\to\mathrm{D}^{*+})\ Br(\mathrm{D}^{*+}\to\mathrm{D}^0\pi^+)\ \varepsilon_{\mathrm{recon.}}$

- Look also in opposite hemisphere for an $\mathrm{D}^{*+} \to n_{\mathrm{doub}}$, but look more inclusively to gain statistics

  $n_{\mathrm{doub}} \approx n_{\mathrm{sing}}\ P(\mathrm{c}\to\mathrm{D}^{*+})\ Br(\mathrm{D}^{*+}\to\mathrm{D}^0\pi^+)\ \varepsilon_{\pi^+}$

- The double tag rate

  $f = \frac{n_{\mathrm{doub}}}{n_{\mathrm{sing}}} = P(\mathrm{c}\to\mathrm{D}^{*+})\ Br(\mathrm{D}^{*+}\to\mathrm{D}^0\pi^+)\ \varepsilon_{\pi^+}$

  is independent of exclusive reconstruction efficiency

And Therefore:

$$\boxed{P(\mathrm{c}\to\mathrm{D}^{*+})\ Br(\mathrm{D}^{*+}\to\mathrm{D}^0\pi^+) \approx \frac{f}{\varepsilon_{\pi^+}}}$$

OPAL & DELPHI use as exclusive channels $D^{*+} \to D^0\pi^+$

with: D^0 ➡ $K^-\pi^+$

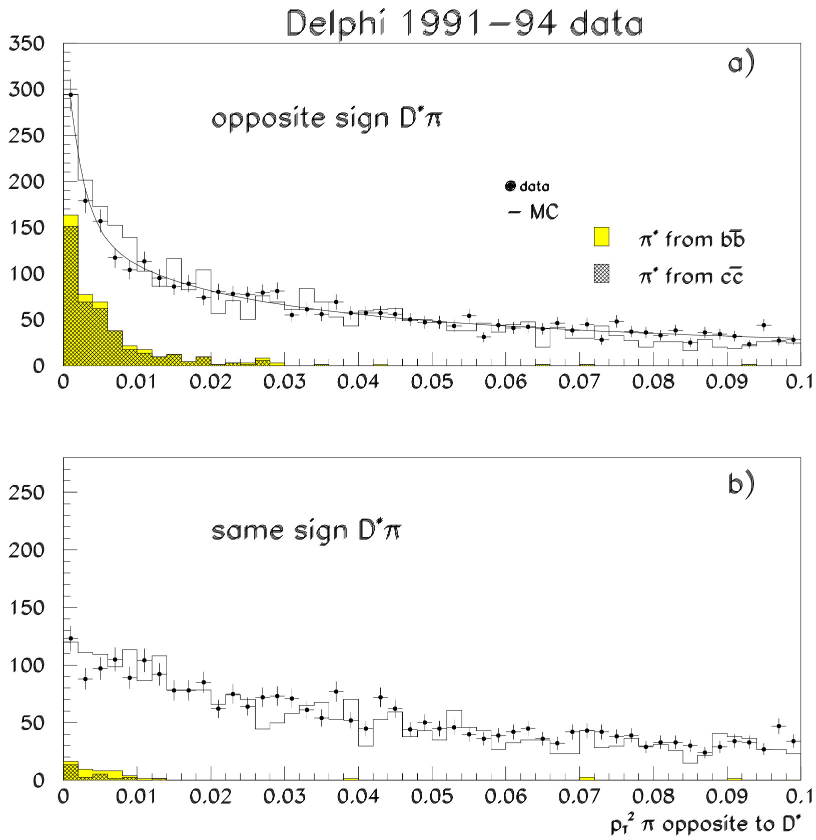
➥ $K^-\pi^+(\pi^0)$

➥ $K^-\ell^+(\nu X)$

➥ $K^-\pi^+\pi^-\pi^+$

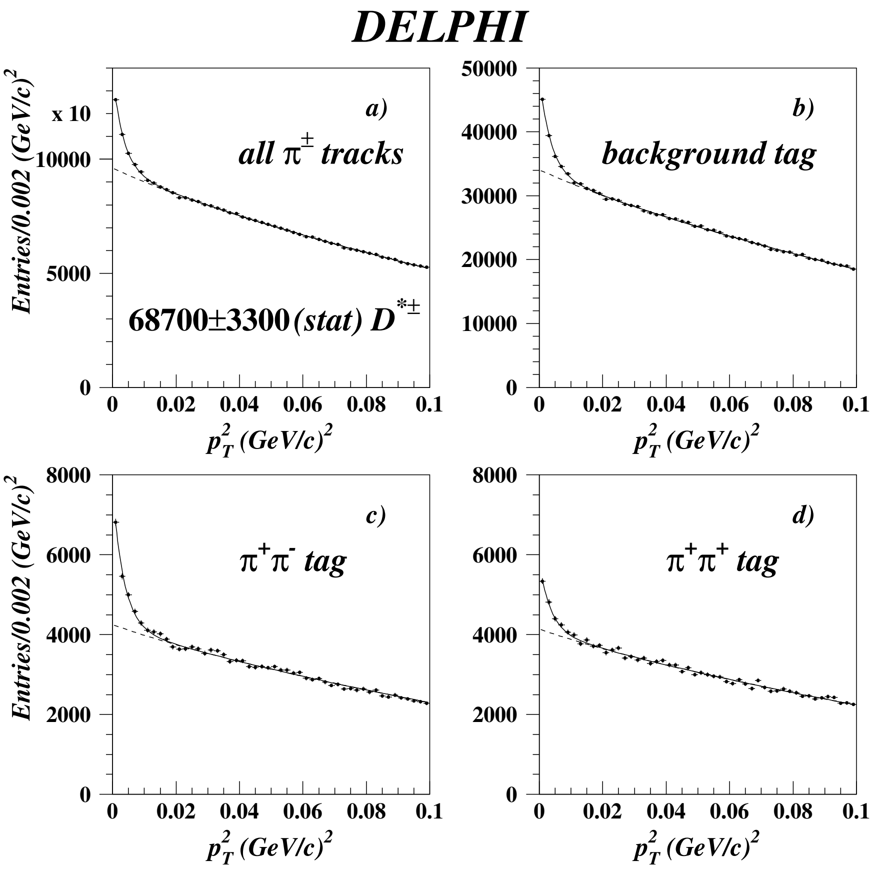
➥ $K^0\pi^+\pi^-$ (DELPHI only)

In the opposite hemisphere the D^0 direction is approximate with jet or a fraction of jet. The small Q value of the $D^{*+} \to D^0\pi^+$ decay lead to a small transverse momentum of soft π



Third method to measure R_c using D^{*+}, DELPHI:

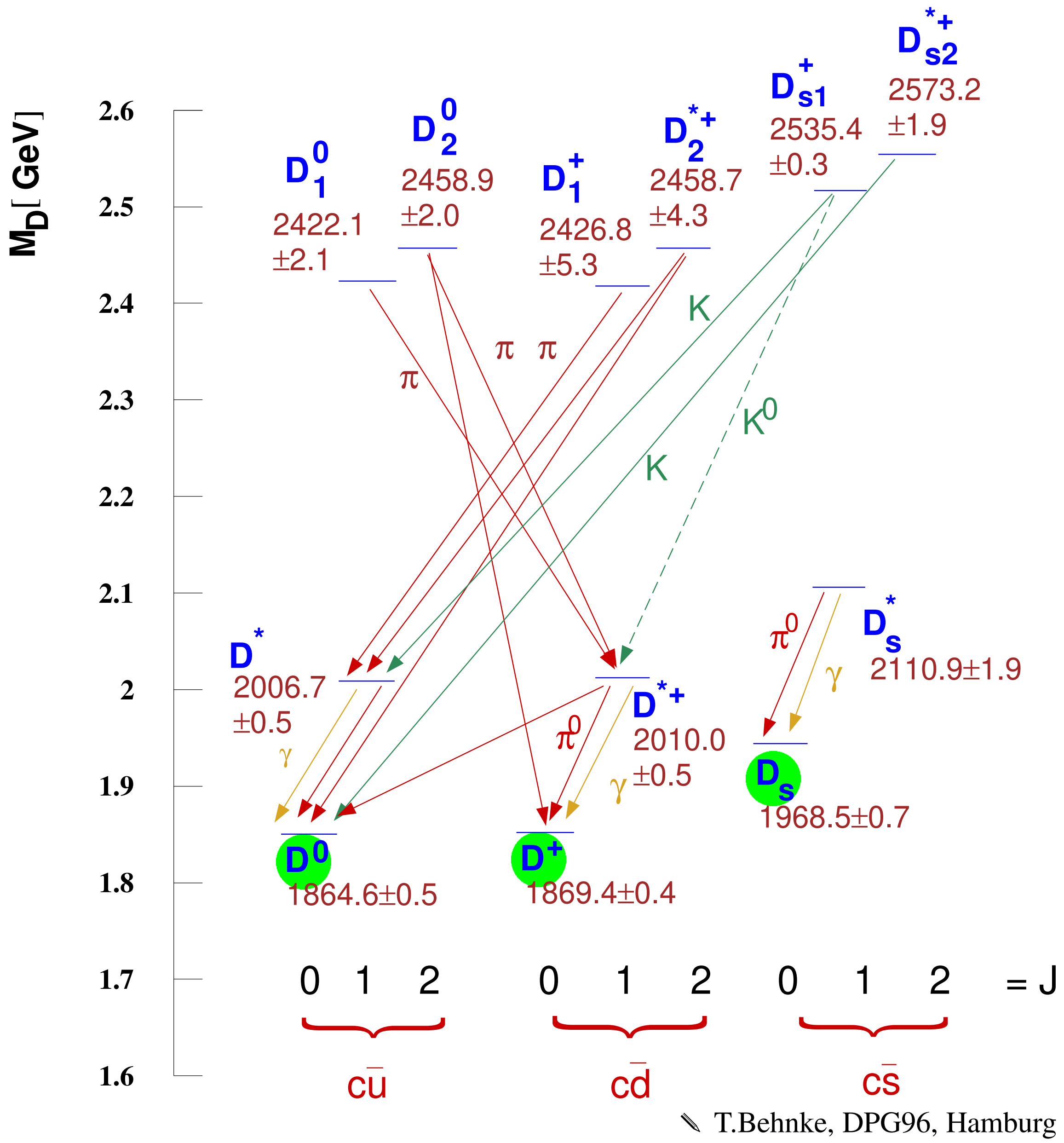
- inclusive soft π double tag



- Simultaneous fit to distribution a to d
- Free parameter among others:
  - $\Gamma_{c\bar{c}}/\Gamma_{\mathrm{had}}$
  - $P(c \rightarrow D^{*+})\,\mathrm{Br}(D^{*+} \rightarrow D^0\pi^+)$

Direct measurement of both!

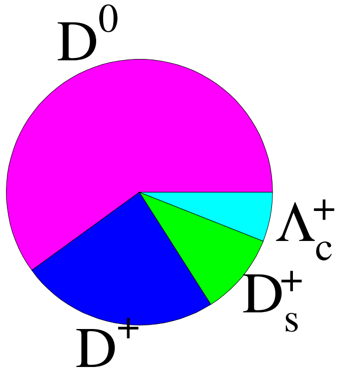
R_c from Charm Counting



All D mesons decay into one of the D ground states

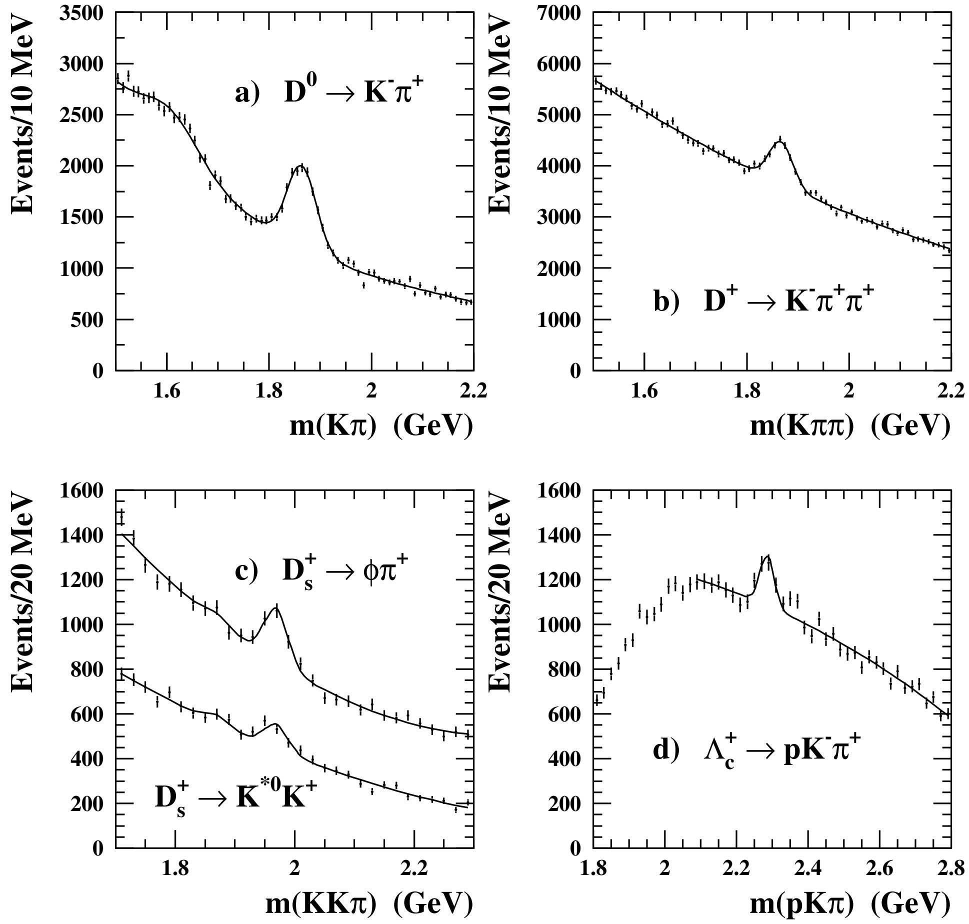
other ground states: Λ_c^+, J/ψ, Σ_c....

Fraction in cc



Decay Channels Used			
state	decay mode	Br	$\Delta Br/Br$
D^0	$K^-\pi^+$	4.0%	3.0%
D^+	$K^-\pi^+\pi^+$	9.1%	6.5%
D_s^+	$\phi\pi^+,\ K^{*0}K^+$	6.8%	9.4%
Λ_c^+	$pK^-\pi^+$	4.4%	14%

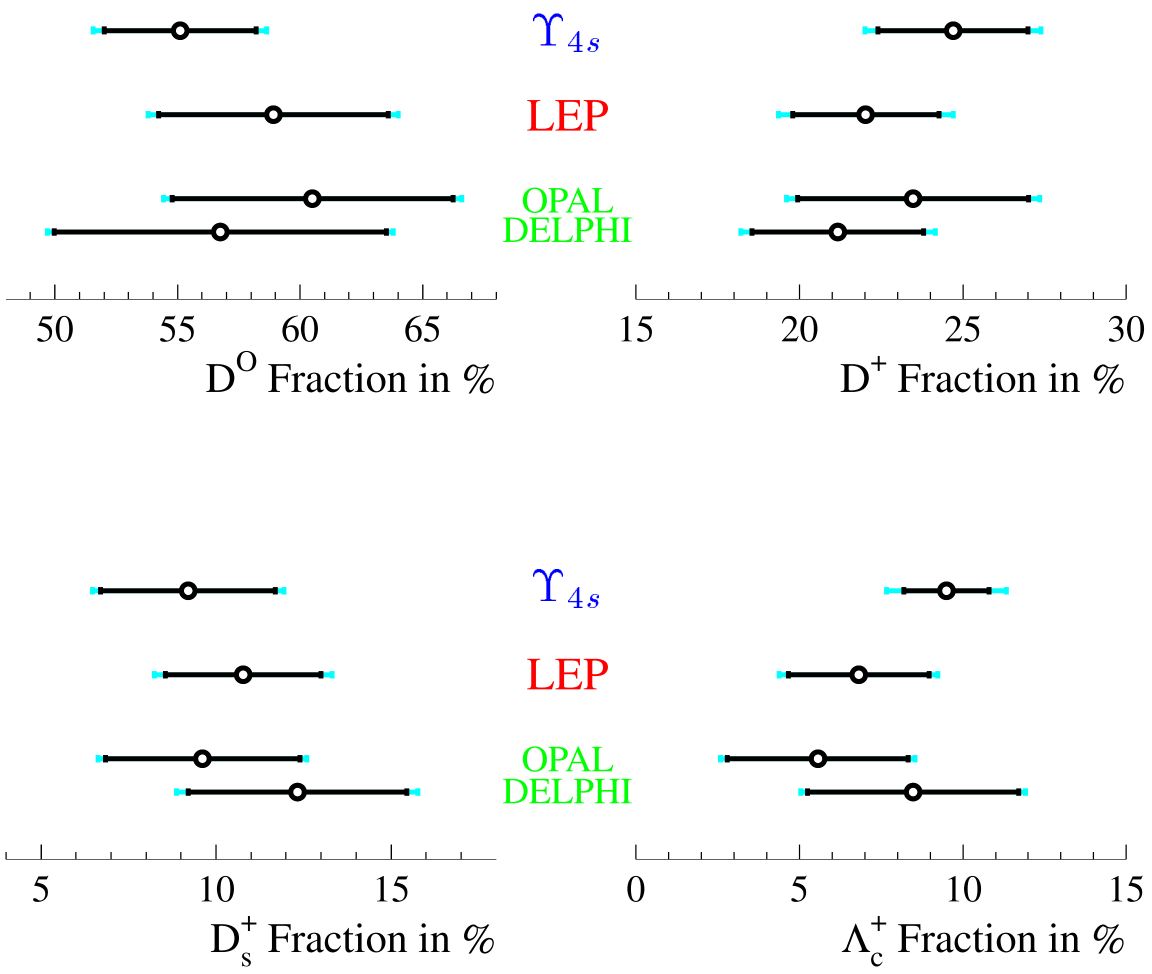
OPAL



☞ b/c separation using lifetime and momentum information

Method used by OPAL and DELPHI

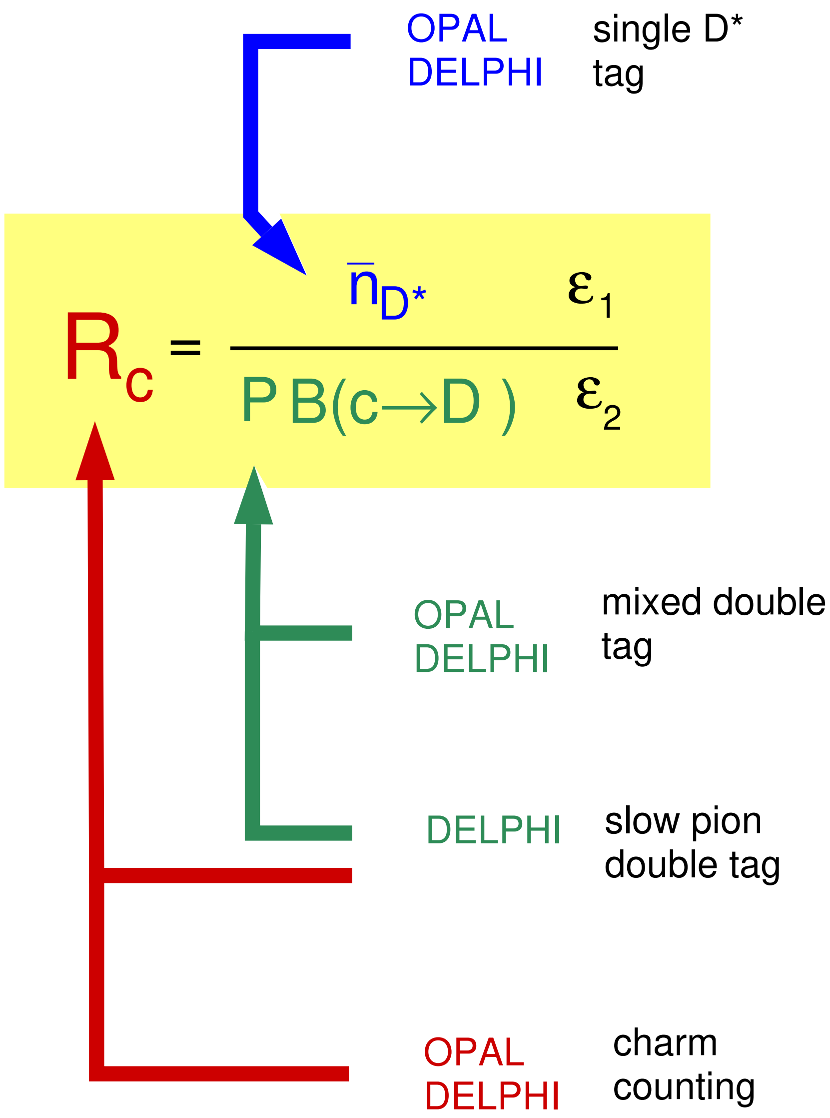
The relative production rates in c-events can be compared to those measured by ARGUS and CLEO at the Υ_{4s}



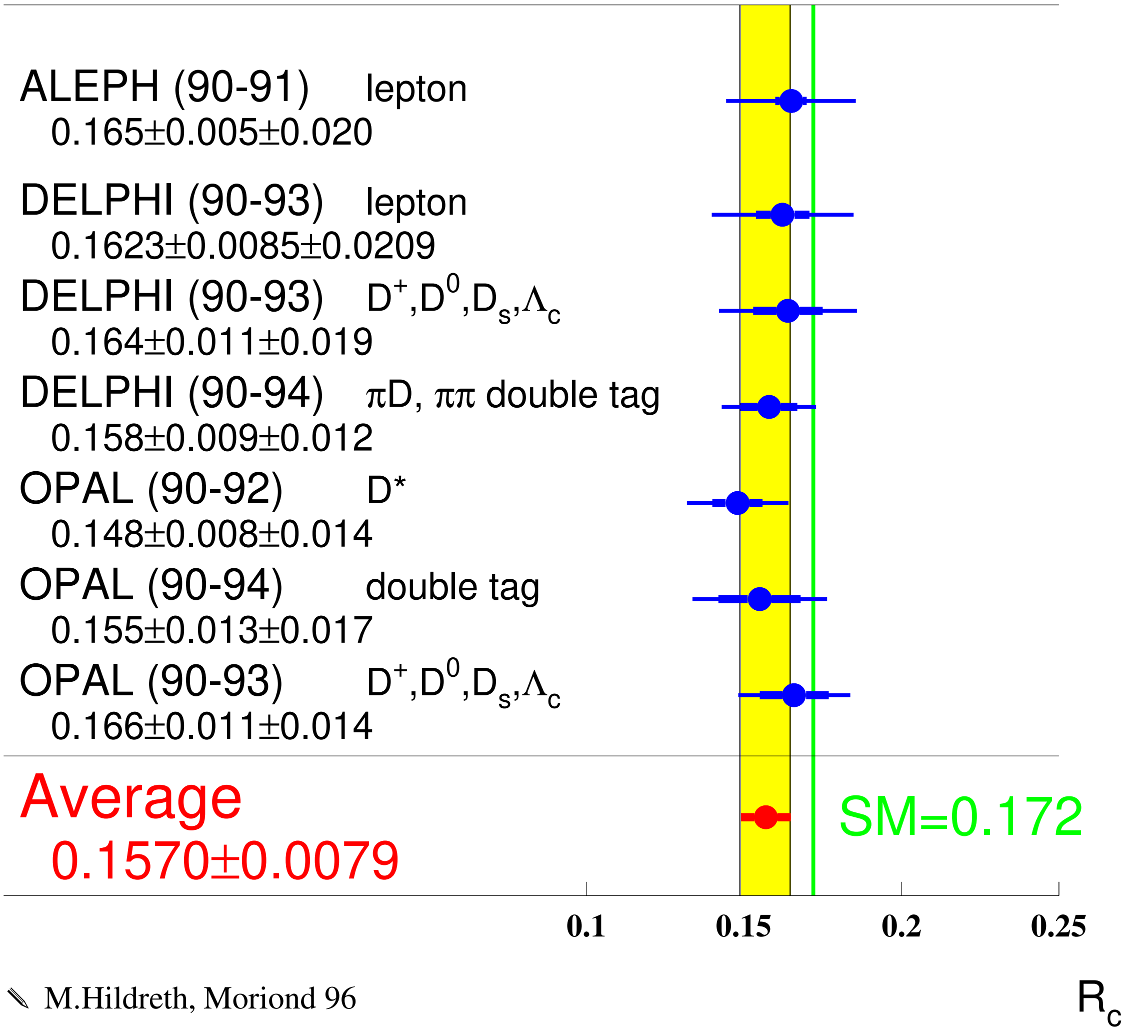
No Surprises ❣

Determining $R_c = \Gamma_{c\bar{c}}/\Gamma_{had}$

The LEP value of R_c is obtained under consideration of the correlations of the single measurements:



R_c Measurements



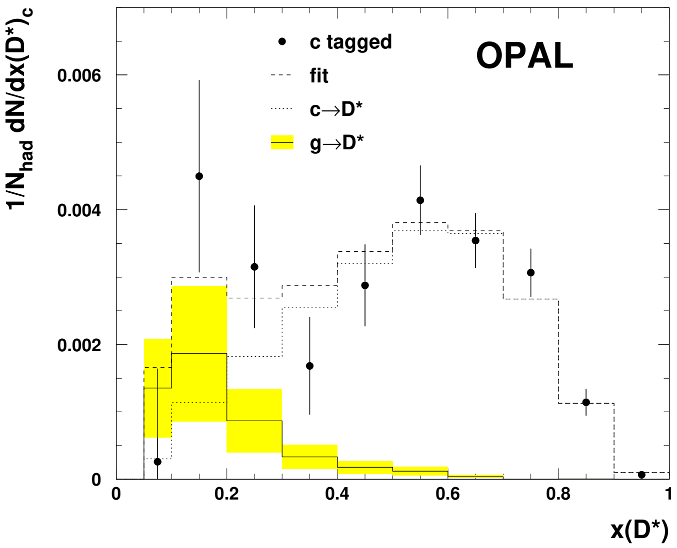
- They are all low
- Average 1.8 σ below SM
- Results are corrected for PDG 95 $Br(\mathrm{D}^0 \to \mathrm{K}\pi)$

$g \longrightarrow c\bar{c}$ Measurement

- OPAL: ℓ - tag in g-jet
  - ➪ looking for 3 - jet topology
  - ➪ lowest E jet = g-jet
  - ➪ heavy flavour ℓ tag
  - ♥ high statistic
  - ♠ theoretical uncertainties

  Result: $n_{g\rightarrow c\bar{c}} = (2.27 \pm 0.28 \pm 0.41) \cdot 10^{-2}$

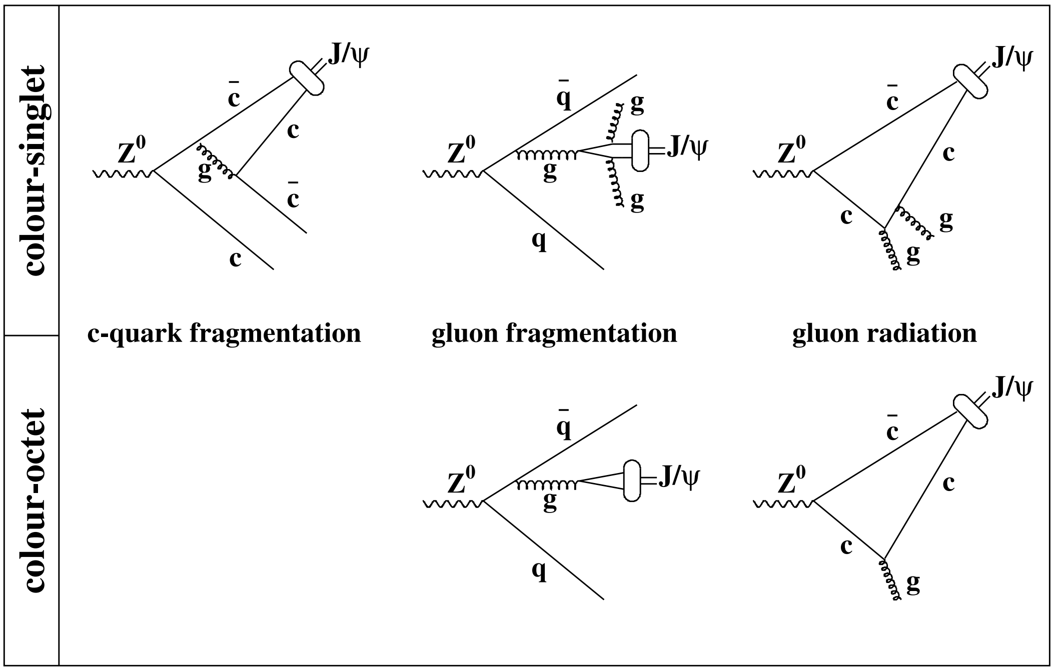
- OPAL: Scaled energy of $D^{*\pm}$ distribution



  Result: $n_{g\rightarrow c\bar{c}} = (4.4 \pm 1.4 \pm 1.5) \cdot 10^{-2}$

Average: $n_{g\rightarrow c\bar{c}} = (2.38 \pm 0.48) \cdot 10^{-2}$

❑ OPAL: Prompt J/ψ production



➪ look for $\mathrm{J}/\psi \to \ell^+\ell^-$

➪ which come from primary vertex

⋗ 24 events, background estimate 10.2 ± 2.0

$$Br(\mathrm{Z}^0 \to \text{ prompt } \mathrm{J}/\psi + \mathrm{X}) = (1.9 \pm 0.7 \pm 0.7) \cdot 10^{-4}$$

Summary

- Many charm states are observed at LEP and their production rates are measured.
- Some results are competitive to results from the Υ_{4s}.
- R_c has been determined with a 5% uncertainty. A deviation of 1.8σ from the Standard Model value has been observed, which corresponds to a 8.7% probability of being a fluctuation.
- The gluon splitting rate into charm has been determined to be $(2.4 \pm 0.5)\%$.
- Evidence for prompt J/ψ has been found.