R_c Measurements at LEP

DESY

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$$R_c = \frac{\Gamma(Z^0 \longrightarrow c\bar{c})}{\Gamma(Z^0 \longrightarrow \mathbf{hadrons})}$$

Overview

Outline:

Heavy Flavor Physics at the Z^0

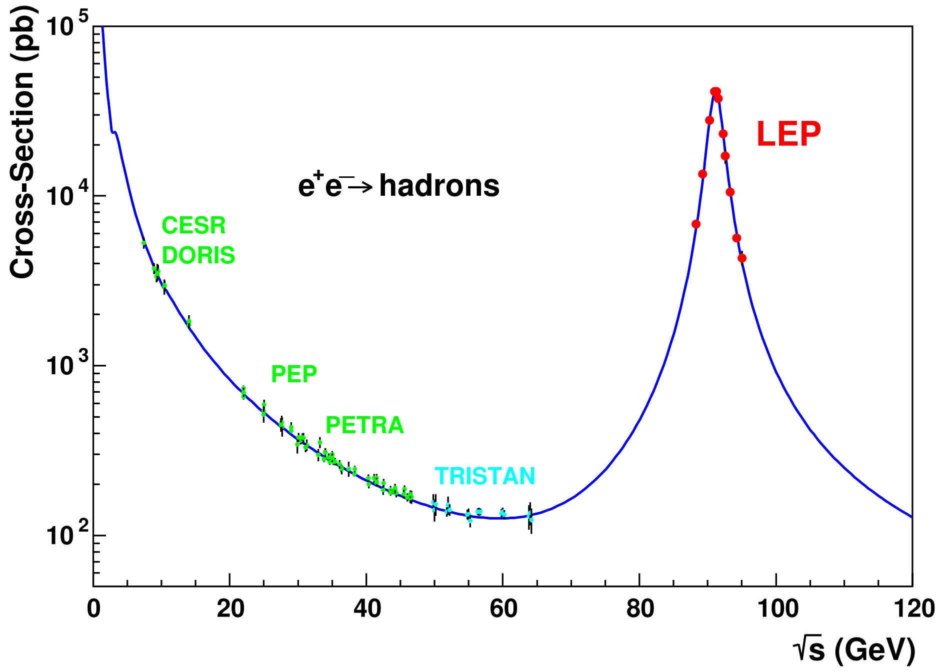
- Introduction to EW parameters
- Heavy Flavor Tagging
- Strategies for measuring R_c

Measurements of R_c at LEP

Future Prospects for $R_c(Z^0)$ and R_c at LEP II

Many thanks to: LEP electroweak working group
LEP heavy flavour group
LEP Collaborations

Introduction: Physics at the Z^0



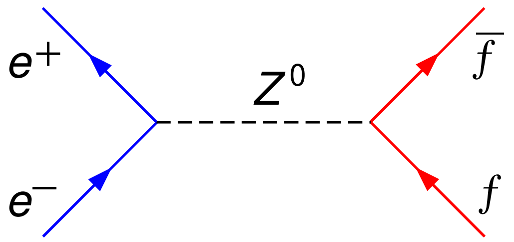
The tree level cross section for fermion-pair production:

$$\sigma_f(s) = \sigma_f^0 \frac{s\Gamma_Z^2}{(s - M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} + [\gamma] + [\gamma/Z]$$

where the peak cross-section is

$$\sigma_f^0 = \frac{12\pi\Gamma_e\Gamma_f}{M_Z^2\Gamma_Z^2}$$

and the partial widths are given by



$$\Gamma_f = \frac{G_\mu M_Z^3}{6\pi\sqrt{2}} \left(v_f^2 + a_f^2\right) N_{col}$$

Introduction: What is R_c?

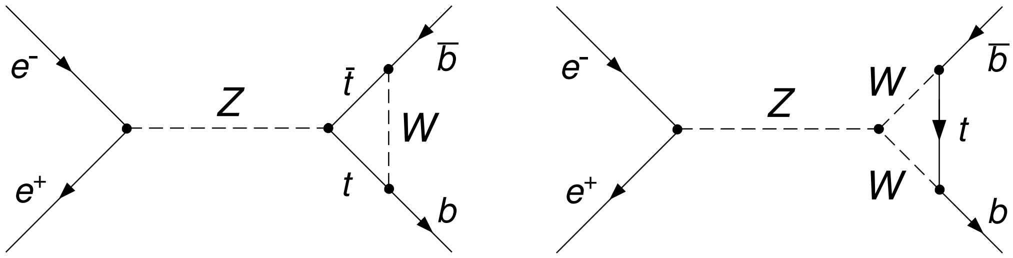
The measured $\Gamma_{f\bar{f}}$ is modified by oblique, initial-state, and QCD radiative corrections.

Experimentally, the quantity

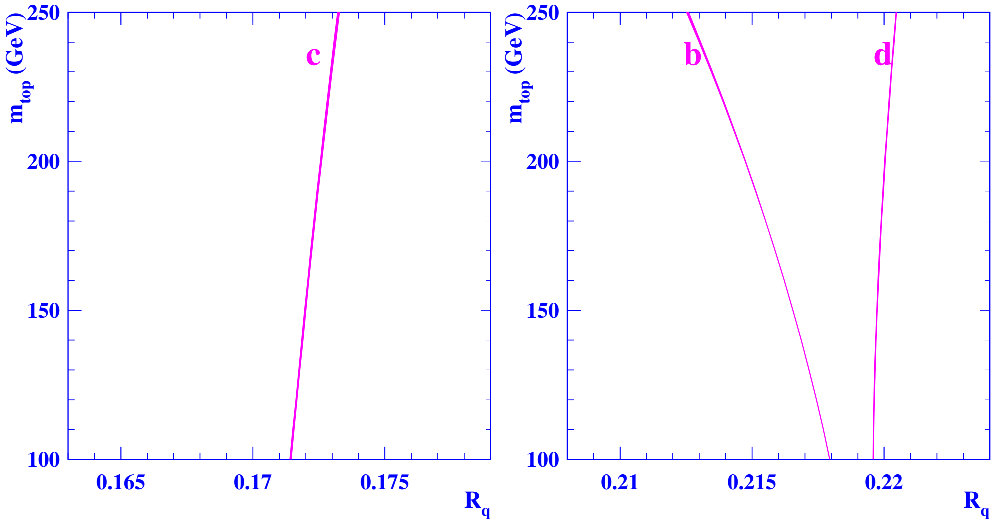
$$R_{\mathrm{Q}} \equiv \frac{\Gamma(\mathrm{Z}^0 \to \mathrm{Q\overline{Q}})}{\Gamma(\mathrm{Z}^0 \to \mathrm{hadrons})}$$

is more readily accessible, and has the added advantage that these radiative corrections essentially cancel, leaving final-state vertex corrections as a possible window on new physics.

This is particularly important in the case of R_{b}:



where the vertex loops induce a large dependence on the top quark mass (and possibly other heavy particles which can modify the coupling)



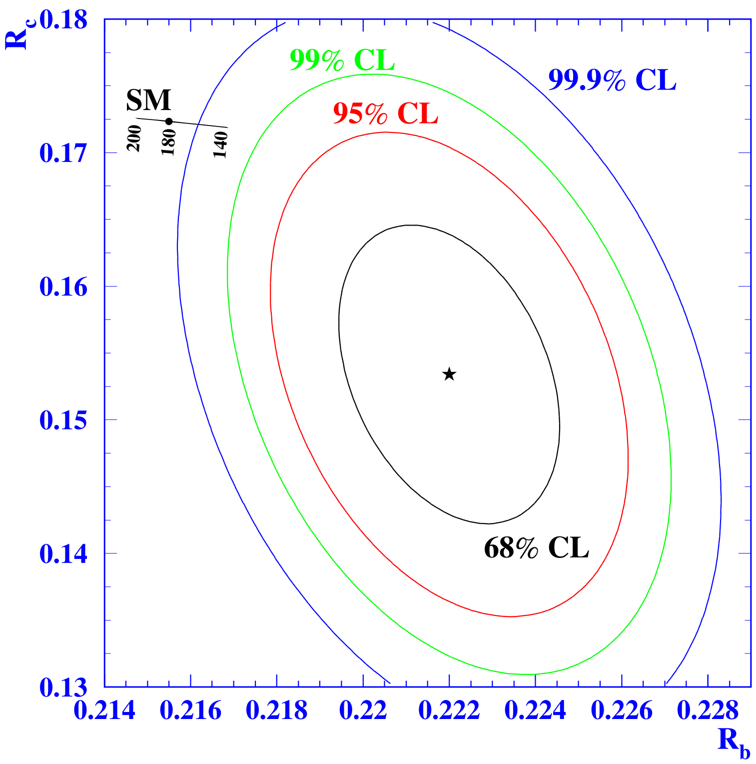
Some History

The Situation as of Summer 1995:

$$R_b = 0.2219 \pm 0.0017 \qquad R_b(\mathrm{SM},\ m_t = 180) = 0.2155$$

$$R_c = 0.1540 \pm 0.0074 \qquad R_c(\mathrm{SM},\ m_t = 180) = 0.1720$$

Together, the values of R_b (3σ high) and R_c (2.5σ low) were only consistent with the Standard Model at the 0.1% level



Since then:

Experimentalists have tried to improve the measurements (all new)

Theorists have been furiously writing papers

Why Measure R_c?

Practical Reasons:

- One of the measurements necessary to extract v_c and a_c
- Uncertainty in R_c is one of the largest systematic errors for R_b

$\longrightarrow$ Solid Electroweak Physics, test the Standard Model

More Interesting Reasons:

⋆ No deviation from (standard) new physics expected

$\longrightarrow$IF you see something, it's weird new physics

⋆ It's hard

So, you want to measure R_c:

Step 1: obtain a pure sample of primary charm quarks

Not so easy, since we have three important sources of charm:

• $Z^0 \rightarrow c\bar{c}$	$\sim 1/2$
• $Z^0 \rightarrow b\bar{b},\ \bar{b} \rightarrow \bar{c}$	$\sim 1/2$
• $Z^0 \rightarrow q\bar{q}g,\ g \rightarrow c\bar{c}$	small

We need some techniques...

Heavy Flavor Tagging at the Z^0

Any measurement that tries to isolate a particular quark flavor relies on characteristics of heavy quark production and decay to separate b and c from uds as well as to separate b from c:

- large masses
- hard fragmentation functions
- weakly decaying $\longrightarrow$ long lifetimes

These result in several properties of heavy quark events that are useful for flavor separation:

- HQ mesons and decay products have high momentum
- decay products have large $p_\perp$ w.r.t. HQ direction
- long decay lengths (e.g.: $\langle L_{D+} \rangle \sim 2\,\mathrm{mm}$)
  - $\longrightarrow$ discernible secondary vertices
  - $\longrightarrow$ many tracks which don't originate at the collision point
- Event/Jet shapes are different

Also, the smaller mass of charmed mesons results in lower multiplicity (simpler) final states

$\longrightarrow$ Exclusive reconstruction of specific decays is useful

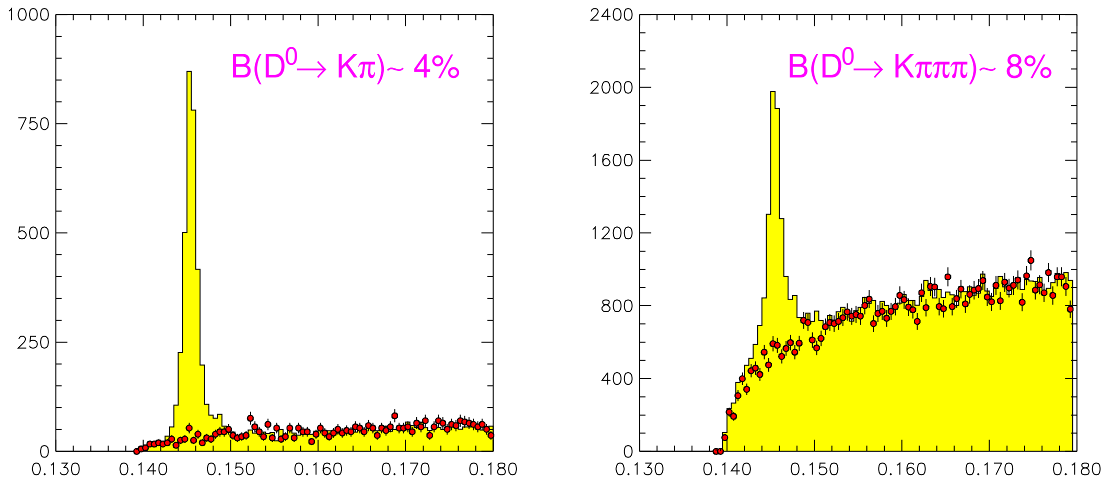
. . . A quick review of experimental techniques. . .

Charm tagging: D^{*+} Mesons

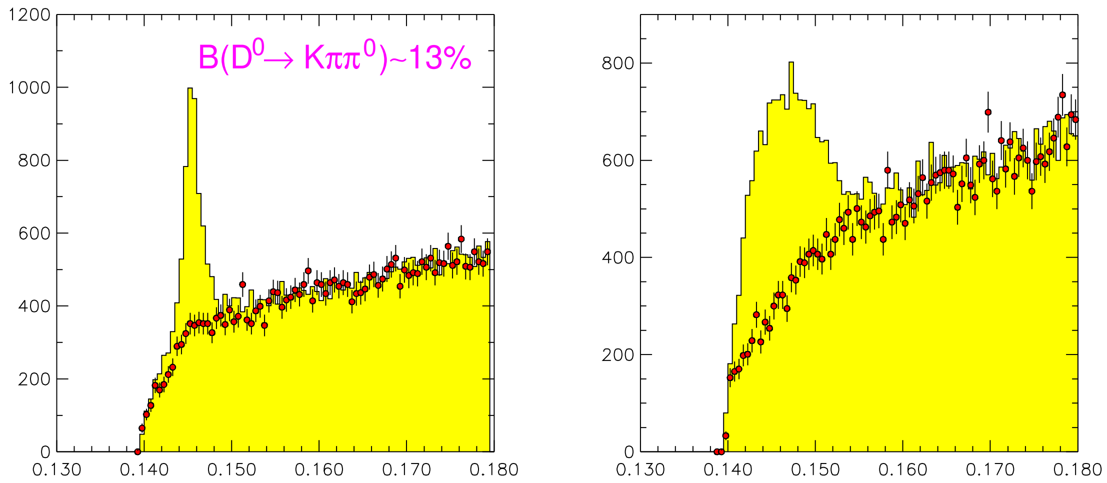
Due to the small available Q in the decay $D^{*+} \rightarrow \pi D^0$, the pion has a very small ($< 40\ \mathrm{MeV}/c$) momentum in the D^{*+} rest frame.

Using this distinctive kinematic signature, a pure sample of D^{*+} decays can be isolated by looking at the mass difference $\Delta M = M_{D^*} - M_{D^0}$

ALEPH



$D^* \rightarrow \pi_s K\pi$ **and** $D^* \rightarrow \pi_s K\pi\pi\pi$

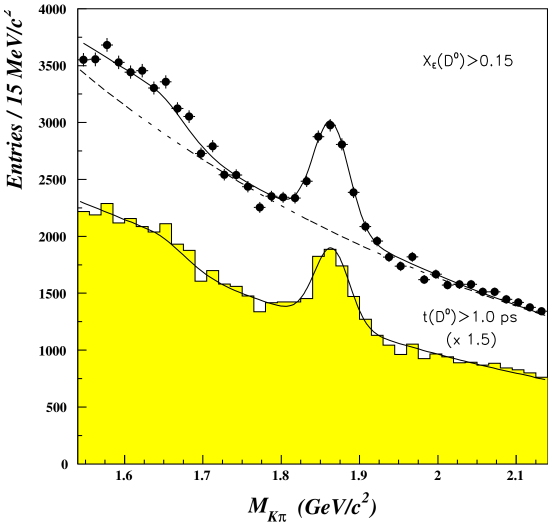


$D^* \rightarrow \pi_s K\pi\pi^0$ **and** $D^* \rightarrow \pi_s K\pi(\pi^0)$

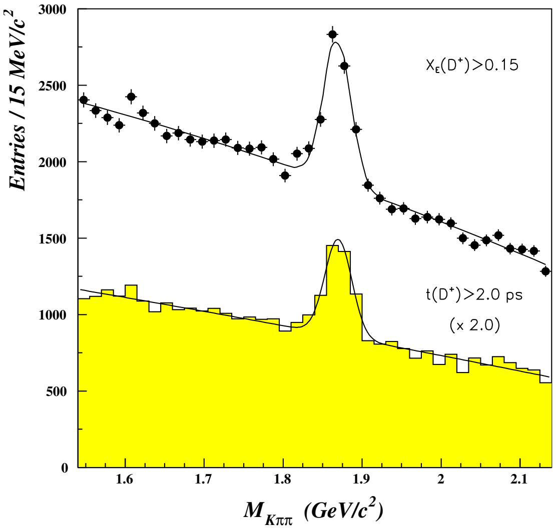
Charm tagging: Exclusive Final States

To increase the available statistics, other exclusive final states are often used:

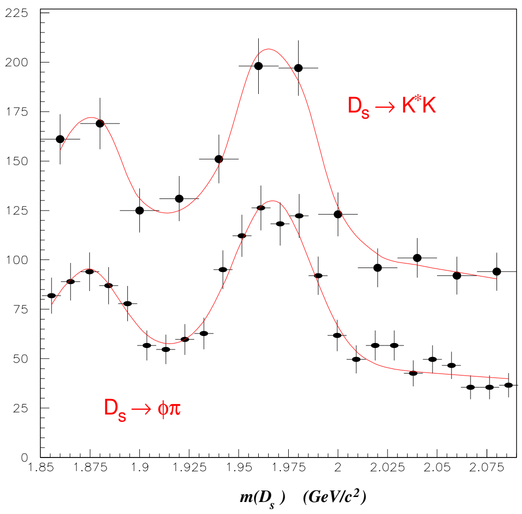
$D^0 \rightarrow K\pi$



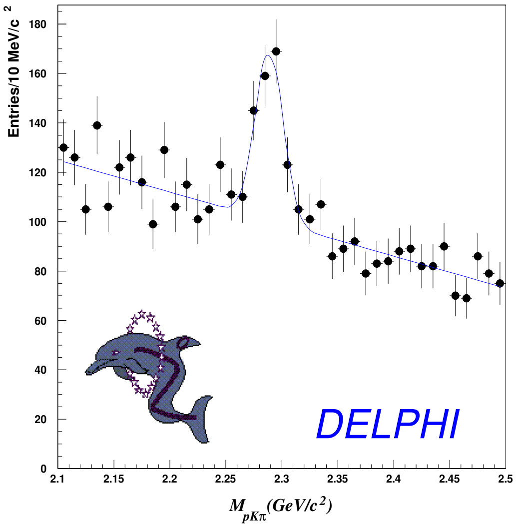
$D^+ \rightarrow K\pi\pi$



$D_s \rightarrow \phi\pi$ or $K^\star K$



$\Lambda_c \rightarrow pK\pi$



Cleaner samples of these exclusive modes can be used in inclusive tags

or

the production rates of charm hadrons can be used to obtain R_c

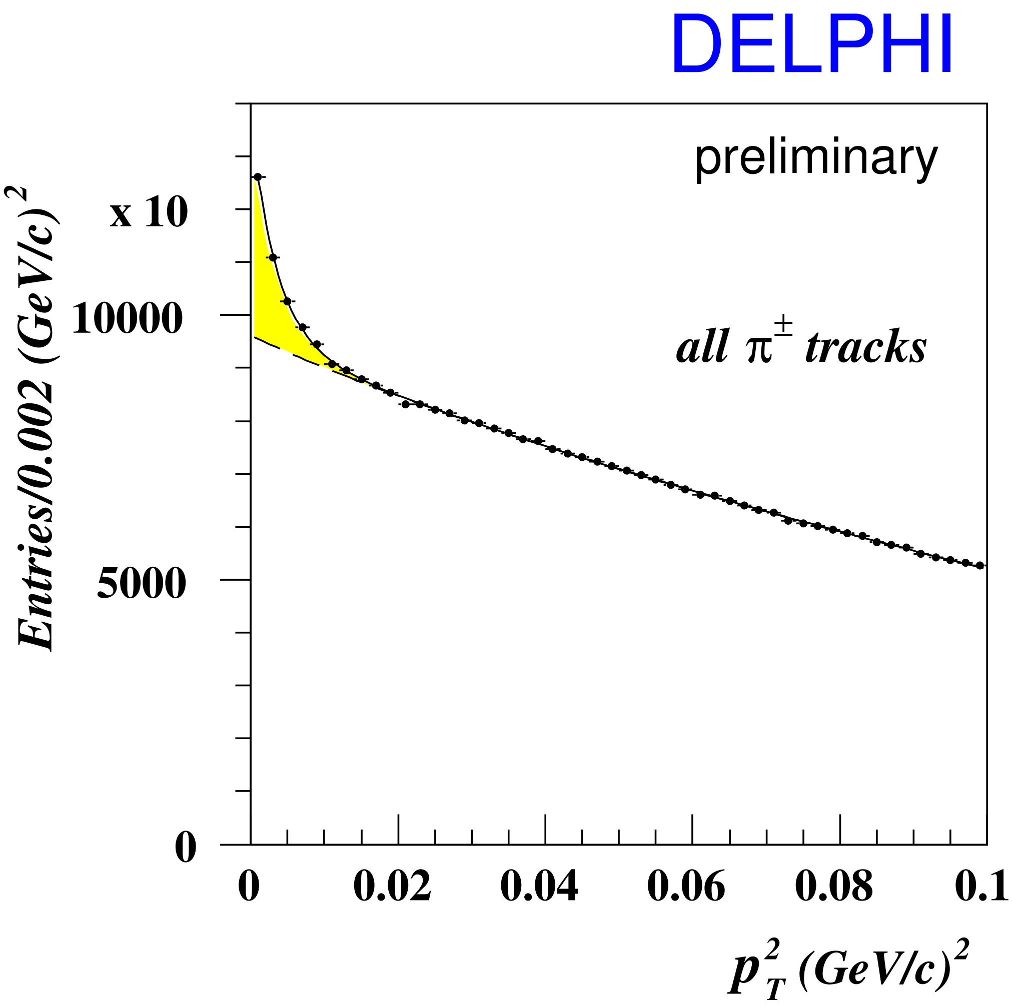
Charm tagging: Inclusive π_s

If the D^{*+} direction is approximated by the jet axis direction, the $p_\perp$ of the π_s with respect to the jet direction will be ≈ 0. (old technique!)

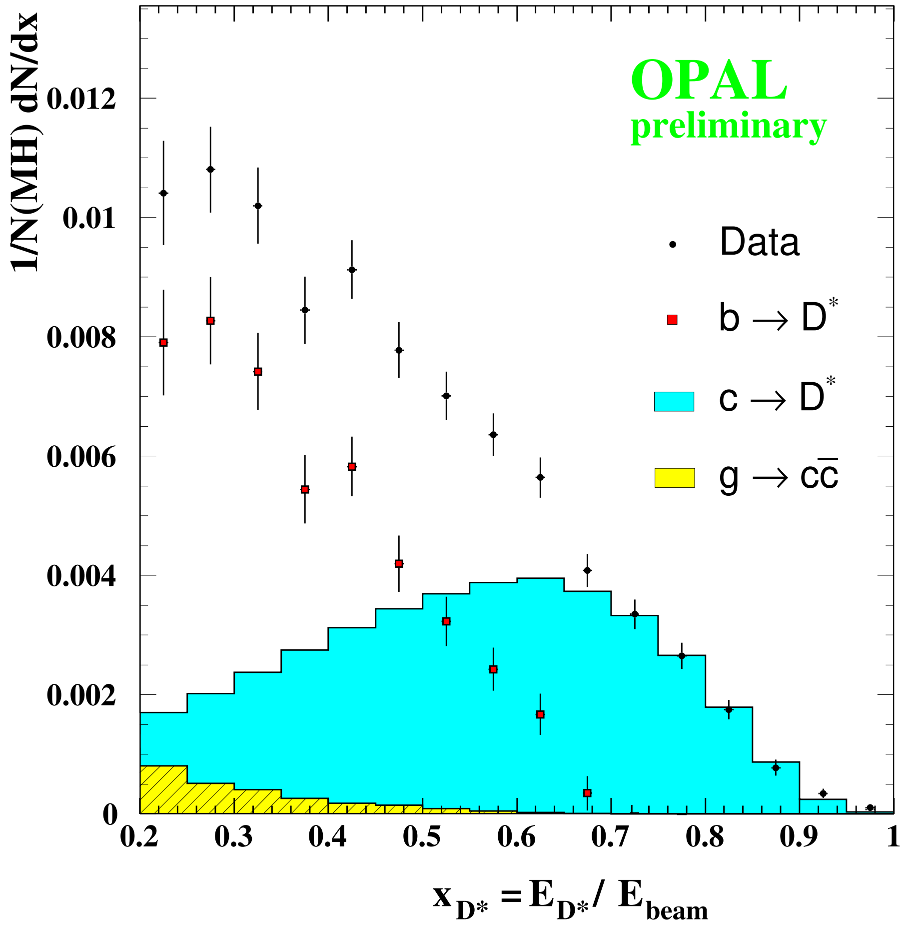
This can be used as a signal for D^{*+} production without needing to reconstruct the final state D^0 meson.

Jet finding algorithms have been optimized by only using tracks with high rapidity

$\longrightarrow$ better estimate of D^* direction



Heavy Flavor Tagging: x_D



Every charm tagging analysis used the scaled momentum

$$x_D = E_D/E_{beam}$$

to statistically separate Ds produced in c decays from those produced in b decays or in $g \longrightarrow c\bar{c}$

- *primary* heavy quark hadrons have high energy

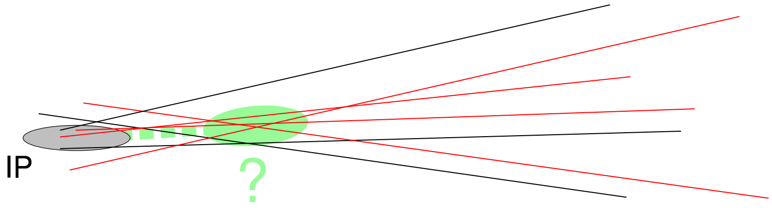
  BUT

- charm hadrons produced in $b \longrightarrow c$ are softer

- charm hadrons from $g \longrightarrow c\bar{c}$ are softer still

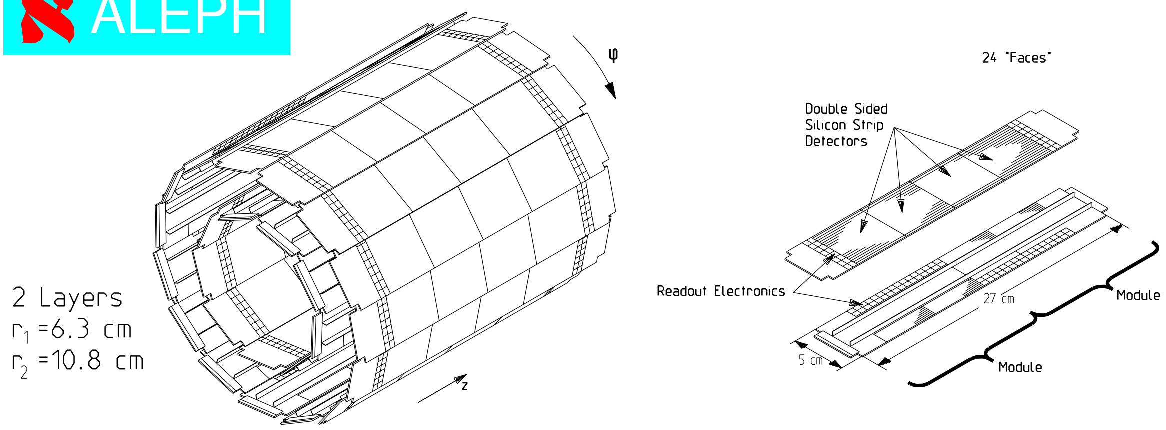
Lifetime measurements at the Z^0

To determine if a heavy, long-lived particle was produced and decayed after travelling a short (< 1mm) distance, precise measurements of track parameters are critical

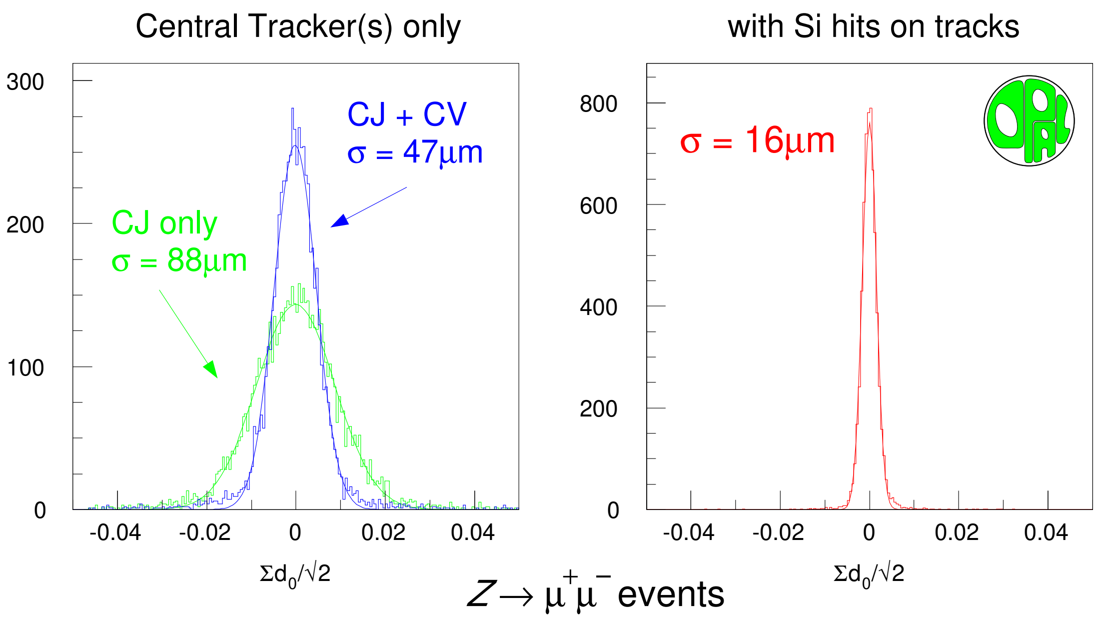


All LEP experiments have Si-strip detectors with $r - \phi$ and $r - z$ readout

ALEPH

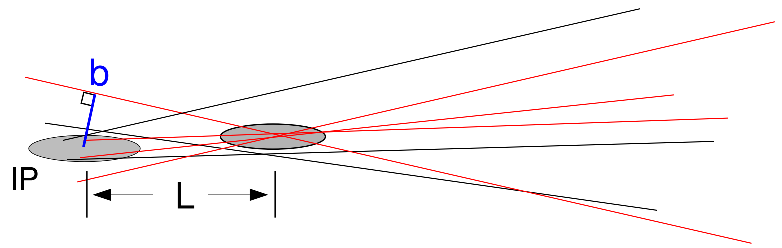


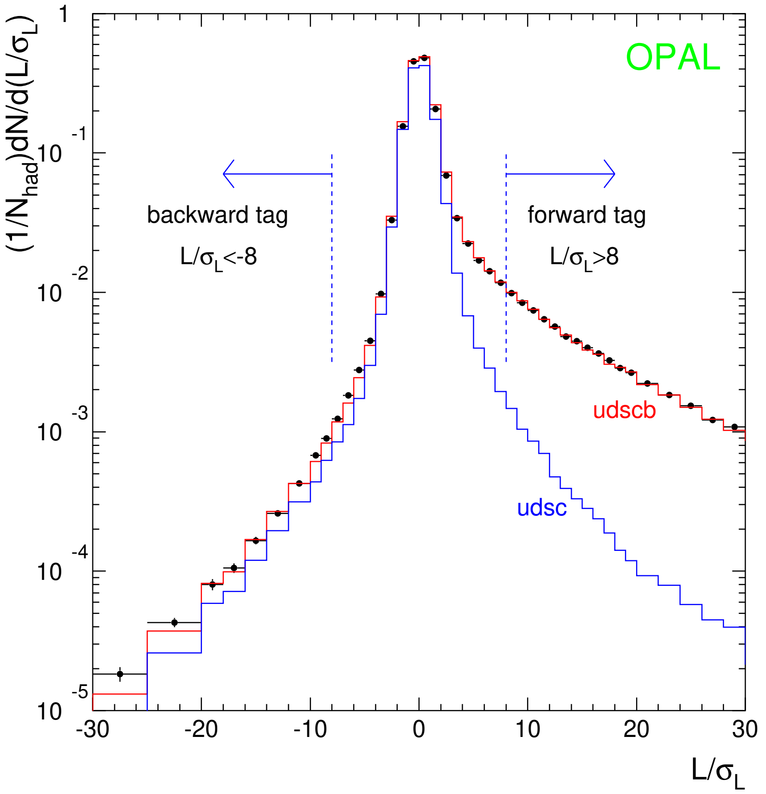
An example $\longrightarrow$ Improvements in resolution:



b Tagging: Secondary Vertices

- Reconstruct high-multiplicity secondary vertices from tracks in each jet
- Construct physics-signed decay length significance





- vertices with significant long decay lengths are from b hadrons
- backward "lifetime" tail mostly from detector resolution

Typical resolution on secondary vertex position is $\sigma \sim 300\mu\mathrm{m}$

b Tagging: Lifetime Probability

One can form a "no-lifetime" probability for tracks with physics signed impact parameter $b > 0$:

$$\mathcal{P}_T = \int_b^\infty \mathcal{R}(x)\mathrm{dx}$$

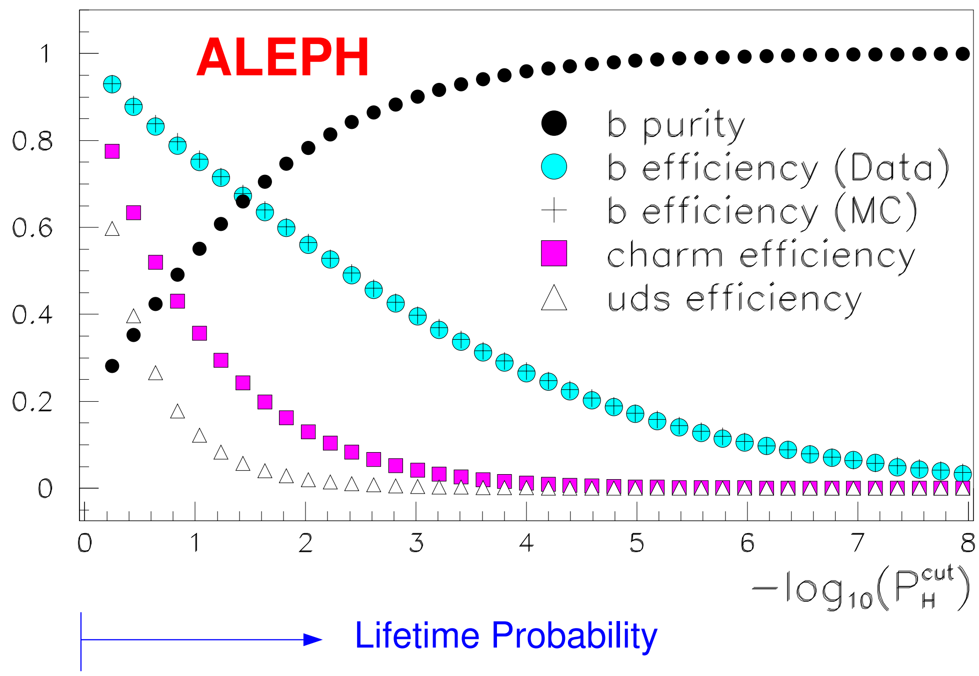
resolution function $\mathcal{R}$ measured from $b < 0$ distribution

The joint probability for "no-lifetime" in the hemisphere is then:

$$\mathcal{P}_N \equiv \Pi \sum_{j=0}^{N-1} \frac{(-\ln \Pi)^j}{j!}$$

where

$$\Pi \equiv \prod_{i=1}^{N} (\mathcal{P}_T)_i$$



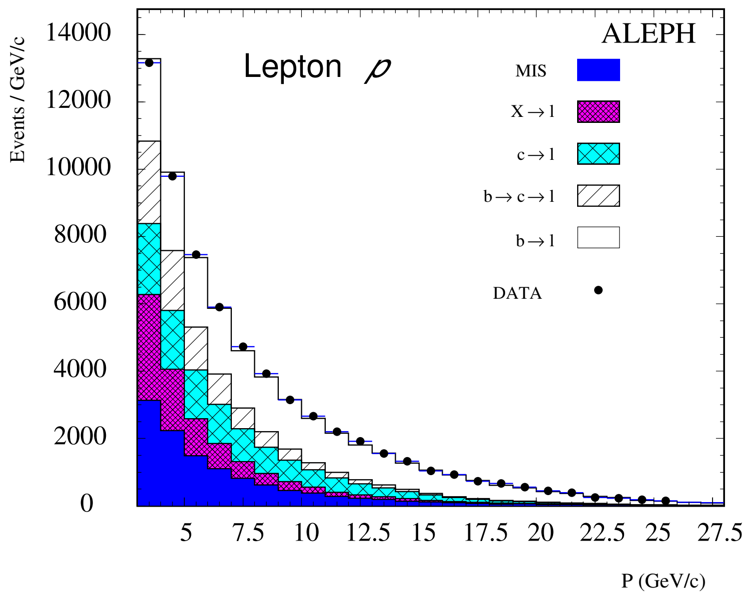
Lifetime Probability or Secondary Vertices used as ANTI-tag for charm

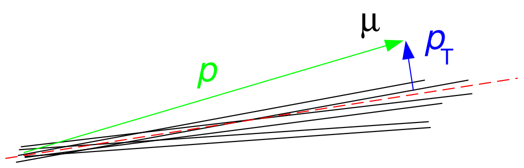
Heavy Quark identification with leptons

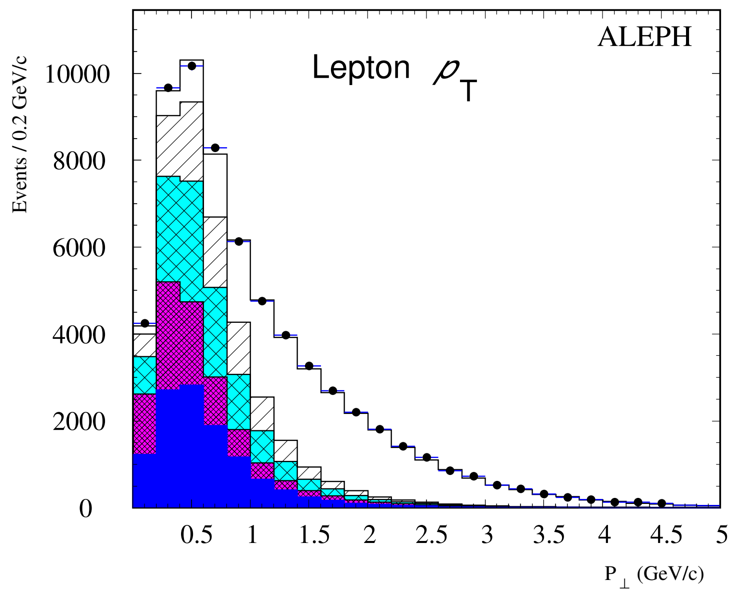
- Muons can be identified by standard absorption/penetration techniques

- Electrons typically leave all of their energy in the EM calorimeter, so $E_{EM}/p_{\mathrm{track}} \approx 1$; also, dE/dx and shower shape can be used

Once you have identified leptons, the large p and $p_\perp$ characteristic of heavy quark decays can be used for flavor separation



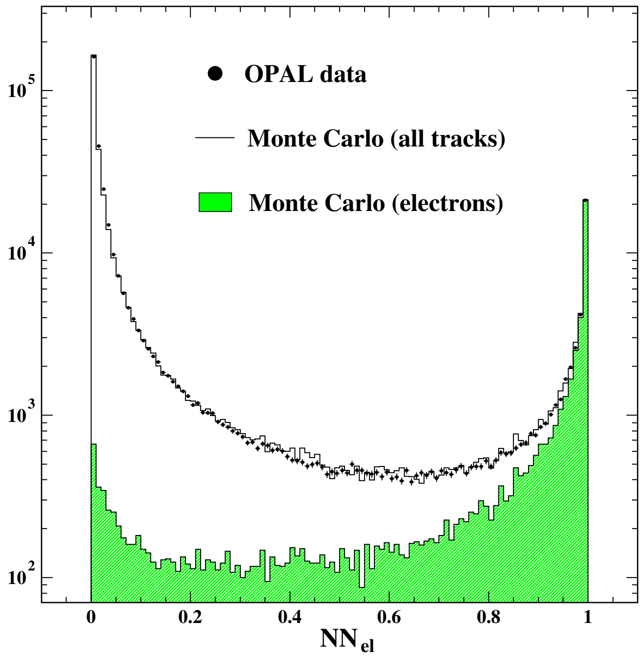




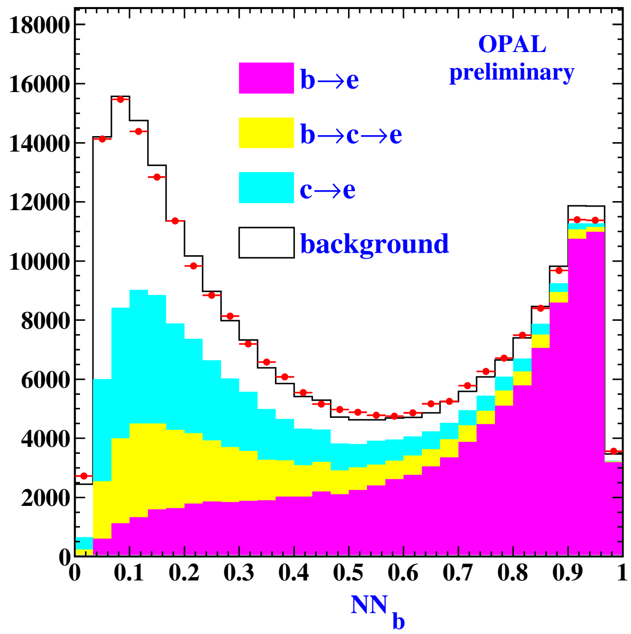
. . .and Today's techniques

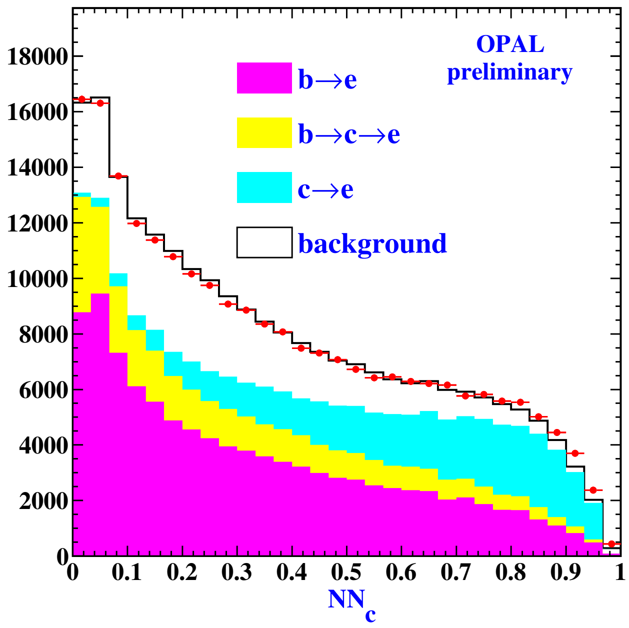
Naturally, these inputs are used more efficiently in a multivariate technique like a Neural Net (NN):

electron ID:



b/c separation:





Heavy Flavor Tagging Performance

A summary of tag performance – Some typical values

Charm Tags

tag method	hemisphere efficiency	purity
inclusive π_s	13%	12%
exclusive $D^{\star +}$	2%	85%
exclusive D^0	2%	75%
electrons	1%	30%

B Tags

tag method	hemisphere efficiency	purity
OPAL (vertexing)	21%	94%
DELPHI (lifetime prob.)	25%	95%
ALEPH (lifetime prob.)	24%	98%
electrons	1%	90%

$\Rightarrow$ A high-purity, high-efficiency charm tag does not exist yet

$\Rightarrow$ Measurements more complicated...

R_c: Measurement Strategy

High Purity and High Efficiency tags are optimal.

Since these don't exist,

- choose a tag with high enough efficiency to minimize the statistical error
- use as many techniques as possible to minimize the systematic errors

  High Purity helps

  Some systematics cancel in "Double Tags"

Well-understood b/c separation is crucial

- any and all methods used in most powerful combination

  ⋆ reject b contamination

  or

  ⋆ measure b component of signal

- usually a dominant source of systematic error

Methods of Background Subtraction must be carefully considered

- Usually the other dominant source of systematic error...

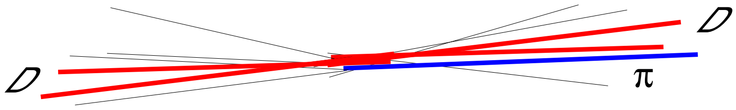
R_c: Types of Measurements

The current R_c measurements fall into several categories:

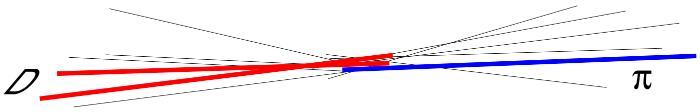
Charm Counting:

- Rates of production for weakly-decaying charm hadrons are measured
- If all charm quarks are accounted for, total rate $= R_c$

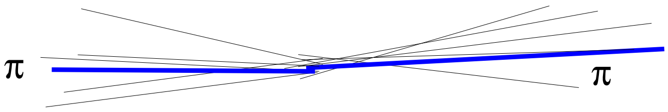
Double Tags:



exclusive-exclusive

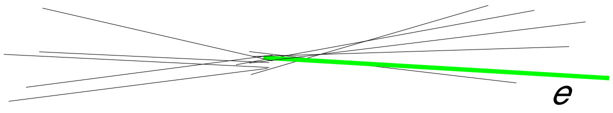


exclusive-inclusive



inclusive-inclusive

Single Tag:



inclusive lepton-tag

Describe each in turn...

R_c: Charm Counting

Simple Premise: All charm quarks end up in weakly decaying hadrons, or

$$P_{c\to \mathrm{D}^0} + P_{c\to \mathrm{D}^+} + P_{c\to \mathrm{D_s}^+} + P_{c\to \Lambda_\mathrm{c}} \times (1 + S_{\mathrm{c\ baryon}}) = 1$$

Method: R_c can be measured from the total production rates of

$$\mathrm{D}^0,\ \mathrm{D}^+,\ \mathrm{D}_\mathrm{s}^+,\ \mathrm{and}\ \Lambda_\mathrm{c}$$

This is used by OPAL and DELPHI

The decay modes of the charm hadrons used are:

Mode	Assumed $B(X_c \to ?) \equiv \mathcal{B}_X$ (%)
• $D^0 \to K\pi$	3.84 ± 0.13
• $D^+ \to K\pi\pi$	9.1 ± 0.6
• $D_s \to \phi\pi$ or $K^{*0}K$	$3.5 \pm 0.4^\star$
• $\Lambda_c \to pK\pi$	4.4 ± 0.6

* The relative rate $B(D_s \to K^{*0}K)/B(D_s \to \phi\pi) = 0.95 \pm 0.10$ is used to fix the contributions of the two D_s decay modes

All of these decays are reconstructed using “standard” techniques $\longrightarrow$

After b/c separation, one measures:

$$R_c \cdot P_{c\to X_c} \cdot \mathcal{B}_X$$

$\Rightarrow$ Using the input $\mathcal{B}_X$, R_c can be extracted

"Standard" Charm Reconstruction

D^0 à la DELPHI:

Event Selection:

- $\geq$ 4 charged tracks with $p > 0.4\ \mathrm{GeV}/c$
- Visible energy $E_{vis} > 0.12 \times E_{CM}$

Hadronic event samples:

1991-1993: $\sim$ 1.7 MZ 1994: $\sim$ 1.4 MZ 1995: $\sim$ 0.8 MZ

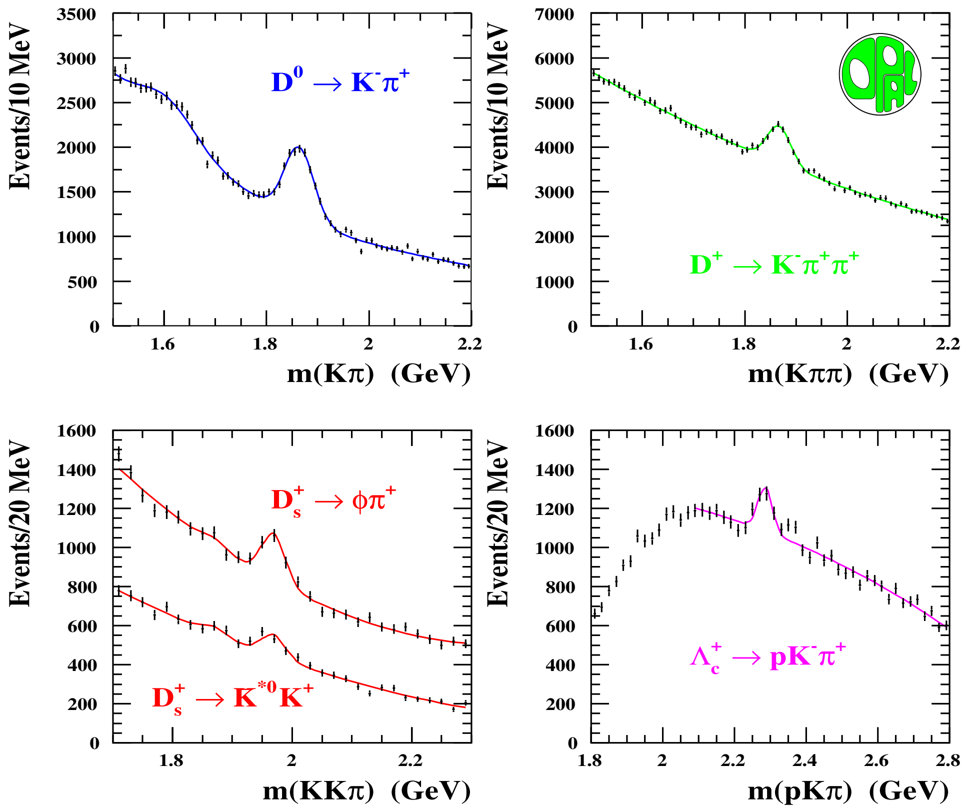
Selection of $D^0 \rightarrow K^-\pi^+$ candidates:

- all oppositely-charged pairs of tracks with $p >$ 1 GeV/c are considered
- $x_{D^0} > 0.15$
- $\cos\theta^*_K >\sim -0.8$ (cut varies with x_{D^0})
- $(dE/dx)_K < (dE/dx)_\pi - 1\sigma$ for K candidate
- $L_{vtx}/\sigma_L > 1.0$ for D^0 vertex

In this case, the number of signal events is obtained by *fitting* the mass peak rather than cutting on a mass window

R_c: Charm Counting

Clear signals for the various decays are seen:



Background subtraction necessary!

- Misreconstructed charm must be taken into account:

  e.g.: $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, $\overline{D^0} \to K^+\pi^-$ all look like $D^0 \to K^-\pi^+$

- backgrounds different as x_D increases

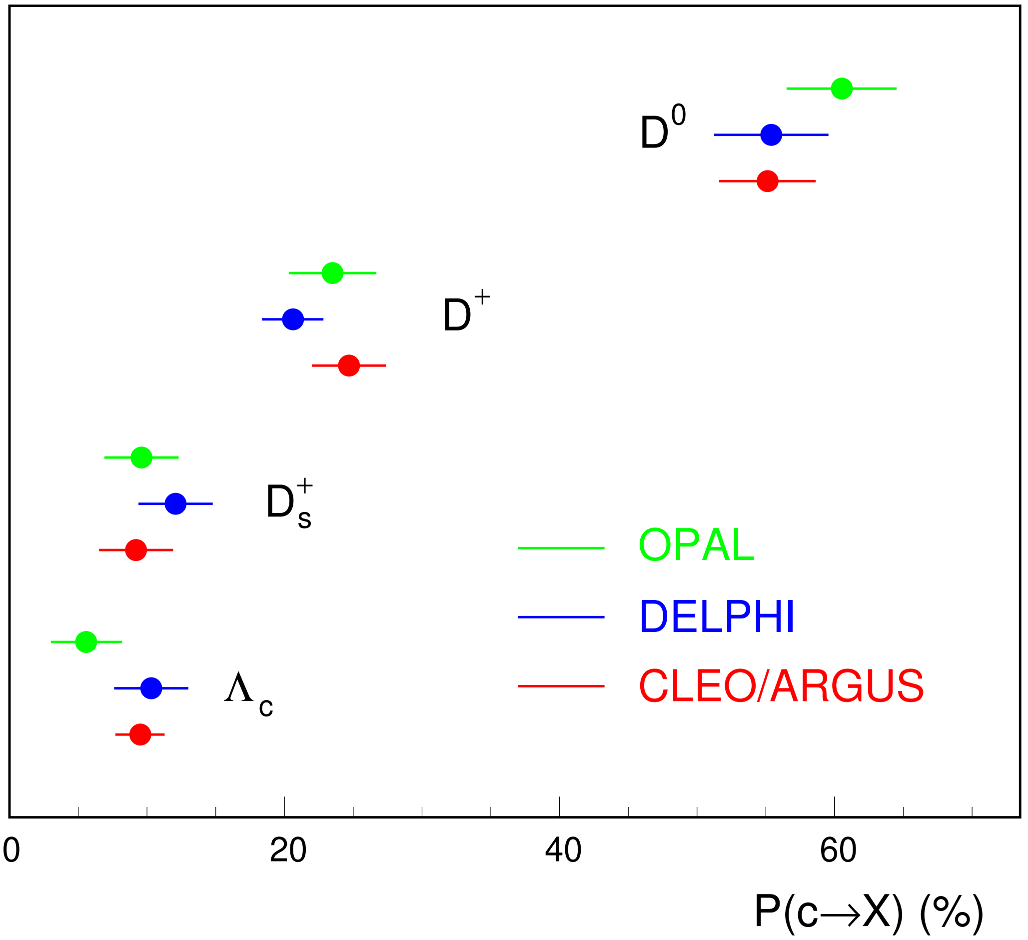
b/c separation

- done in bins of x_D, vertex decay length — OPAL
- done in bins of x_D; lifetime probability used for $b \to X$ — DELPHI

R_c: Charm Counting

Results:

Charm production fractions, comparison with low-energy ($\Upsilon(4S)$) data



*CLEO/ARGUS values were used for all previous LEP measurements

R_c:

OPAL ('91-'93) $\quad R_c = 0.167 \pm 0.011(stat) \pm 0.011(syst)$

DELPHI ('91-'94) $\quad R_c = 0.168 \pm 0.011(stat) \pm 0.013(syst)$

R_c: Charm Counting

Dominant Systematic Errors: Total 0.011

- dE/dx resolution/understanding 0.006
- tracking efficiency and resolution 0.004
- c fragmentation model 0.007
- X_c branching fractions 0.005

Comments and Prospects:

- LEP only analysis; only small dependence on external $\mathcal{B}_X$
- standard, well-understood techniques
- some systematics do scale with statistical error...
- but still a "single tag" measurement $\longrightarrow$ hard to push too far
- adding ALEPH could help

R_c: Double Tag Methods

A double-tag measurement of R_c proceeds as follows:

the presence in one hemisphere of a charm meson ("D") from $Z^0 \to c\bar{c}$ is established, somehow. The number of "single tags", N_D, is given by

$$N_D \propto 2N_{had} \cdot R_c \cdot P(c \to D \to X) \times \epsilon_D$$

The number of "double tags", $N_{DD'}$, where another "D'" is found opposite a single-tag "D", is then

$$N_{DD'} \propto N_D \cdot P(c \to D' \to X') \times \epsilon_{D'}$$

where

- N_{had} is the number of observed $Z^0 \to q\bar{q}$ decays
- ϵ_D is the efficiency for reconstructing a "D"
- $P(c \to D \to X)$ is the probability that a primary charm quark fragments into a "D" which subsequently decays into X

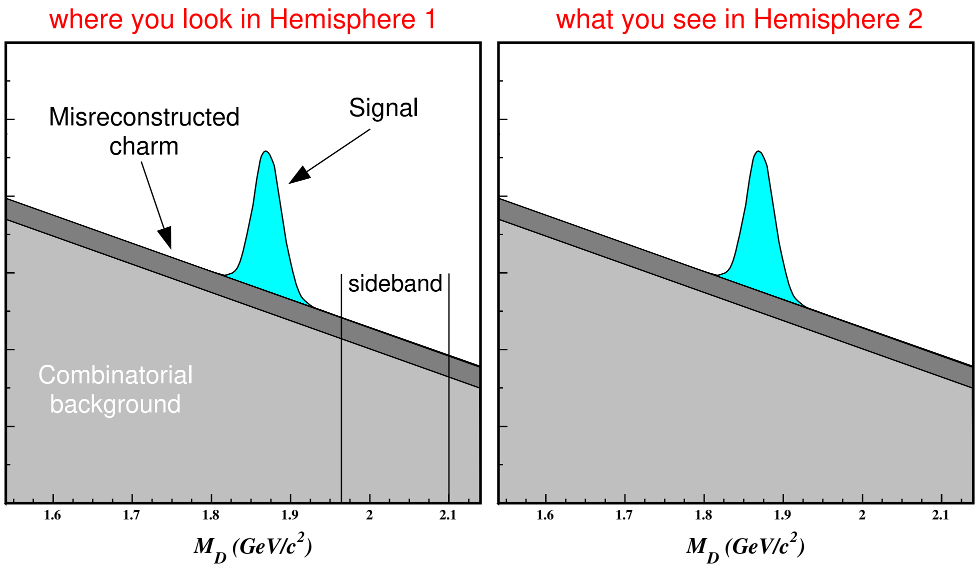
> If D and D' are the same, then R_c and $P(c \to D)$ can be measured simultaneously.
>
> $\longrightarrow$ Cancellation of several systematic errors

There are several modifications to the above equations in "real life"

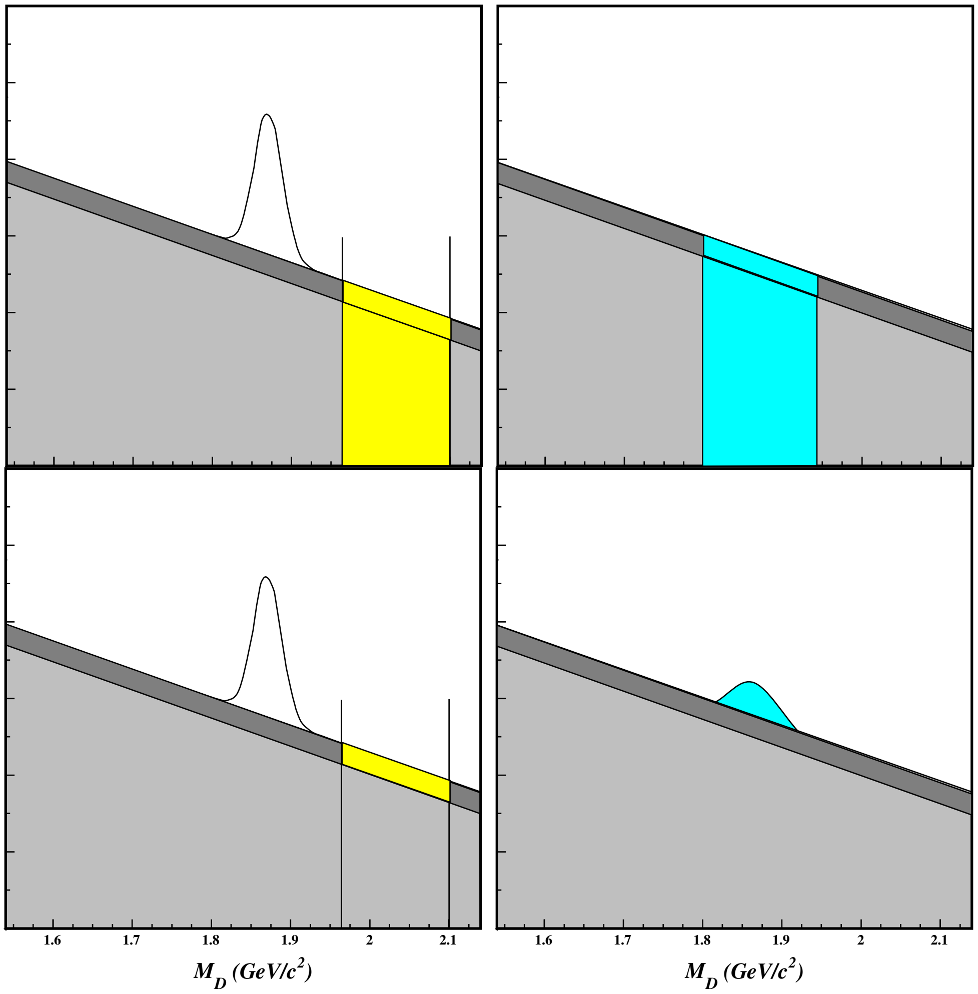
- combinatoric background and b decays must be removed
- $B^0 - \overline{B^0}$ mixing can produce *same sign* pairs D and D'
  - $\longrightarrow$ observable "signal" in b events is reduced
  - $\longrightarrow$ can't be ignored in b/c separation
- even if $D = D'$, ϵ_D may not equal $\epsilon_{D'}$ due to correlations in tagging efficiency between the two event hemispheres

Double Tags: Signal and Background

True Double Tag Signal:

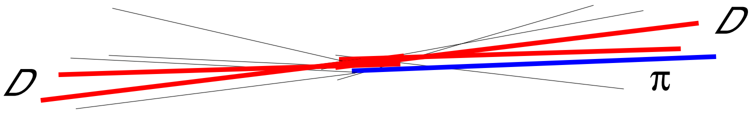


Backgrounds to Subtract:



R_c: Exclusive-Exclusive Double Tag

Method: Search for a fully reconstructed D in each event hemisphere



Results from ALEPH

Modes used:

- $D^{\star +} \rightarrow \pi D^0$, where $D^0 \rightarrow K\pi$, $D^0 \rightarrow K\pi\pi^0$, or $D^0 \rightarrow K\pi\pi$
- $D^0 \rightarrow K\pi$, D^0 not from $D^{\star +}$
- $D^+ \rightarrow K\pi\pi$

b/c separation:

- ALEPH uses lifetime probability of those tracks *not* associated with the D candidate to distinguish b from c decays

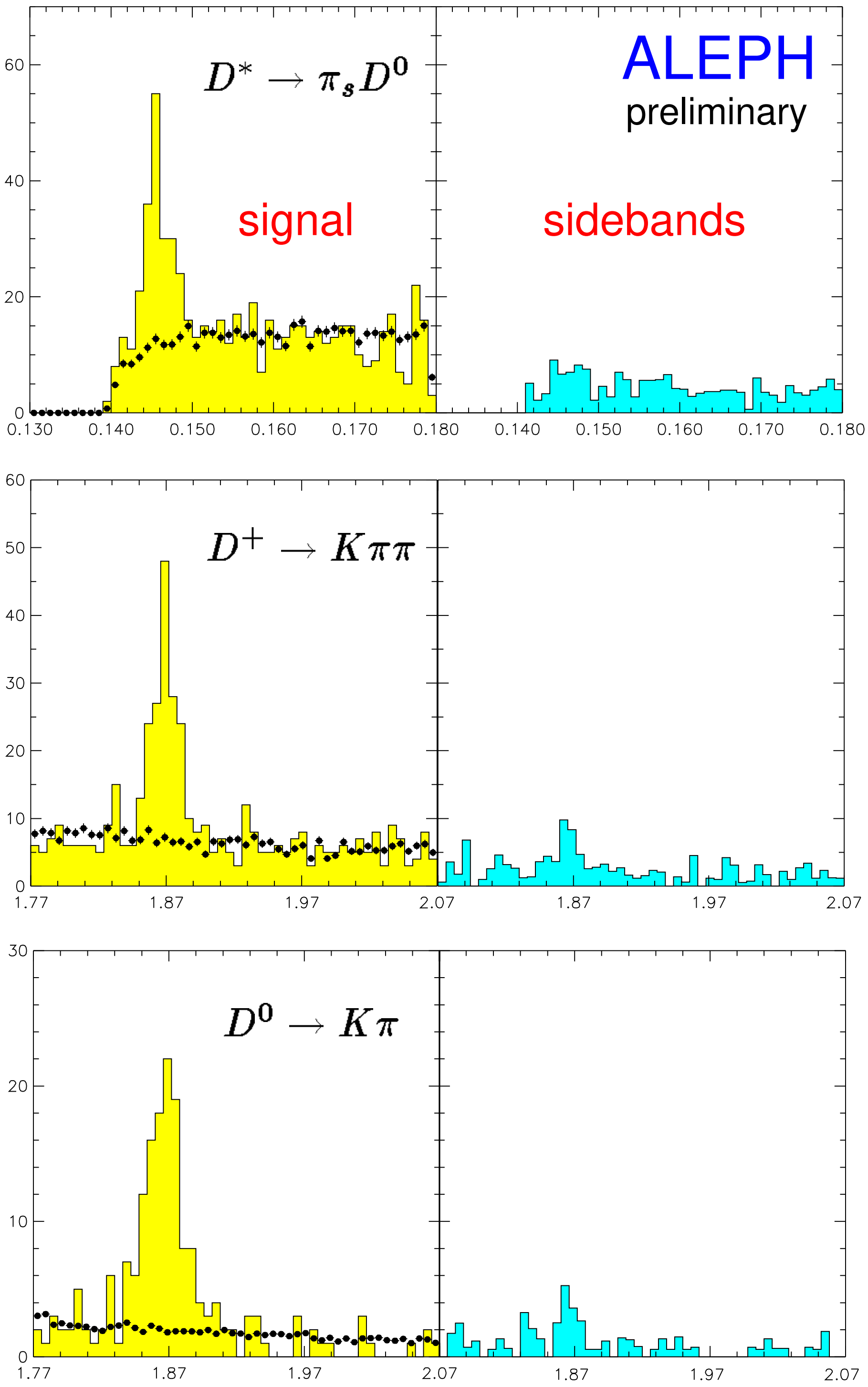
$\Rightarrow$ For $x_{D^\star} > 0.5$, a charm purity of 87% is obtained

Number of double-tagged events is:

$$N_D = 313.0 \pm 21.4(stat) \pm 12.9(syst)$$

R_c: Exclusive-Exclusive Double Tag

Invariant mass of D candidates opposite first D or sidebands:



ALEPH('91 –'95) $R_c = 0.169 \pm 0.013(stat) \pm 0.011(syst)$

R_c: Exclusive-Exclusive Double Tag

Dominant Systematic Errors: Total 0.011

- background subtraction, charm properties 0.010
- b modelling (fragmentation, charged multiplicity) 0.004
- hemisphere efficiency correlations 0.003

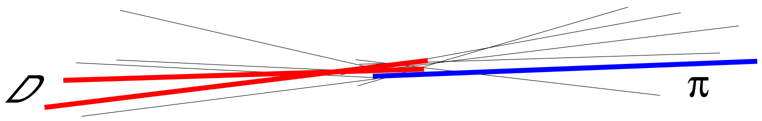
Comments and Prospects:

- measurement best suited to ALEPH due to their superior mass resolution
- LEP-wide analysis could double number of double-tagged D's
- Preliminary result $\longrightarrow$ systematic errors can be improved

  $\longrightarrow$ could have smallest systematic errors of all R_c measurements

R_c: Exclusive-Inclusive Double Tag

Method: Search for a fully reconstructed D in one hemisphere, use low $p_\perp$ slow pion π_s in the other



Results from OPAL, DELPHI, and ALEPH

Modes used:

$D^{\star +} \to \pi D^0$

- $D^0 \to K\pi,\ K\pi\pi^0,\ K\pi\pi\pi$ — OPAL, DELPHI, ALEPH
- $D^0 \to K^*\ell\nu$ — OPAL, DELPHI
- $D^0 \to K^0\pi\pi$ — DELPHI

b/c separation:

- x_{D^*} and $p(\pi_s)$
- vertex decay length — OPAL, ALEPH
- NN based on event shapes — OPAL
- lifetime probability — DELPHI, ALEPH

R_c: Exclusive-Inclusive Double Tag

Once a D is found, a π_s can be selected...

In principle:

- $D^{\star+} + \pi_s^- \longrightarrow$ Correct Combination
- $D^{\star+} + \pi_s^+ \longrightarrow$ background

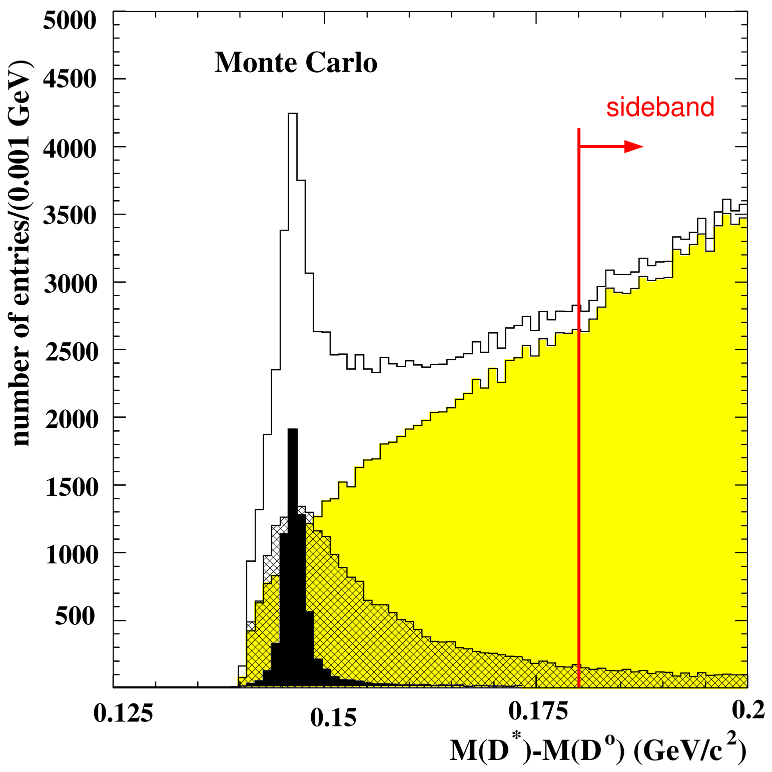
$\longrightarrow$ Subtract these to get number of double-tags

Some subtleties:

$D^{\star+} + \pi_s^-$ can be background if

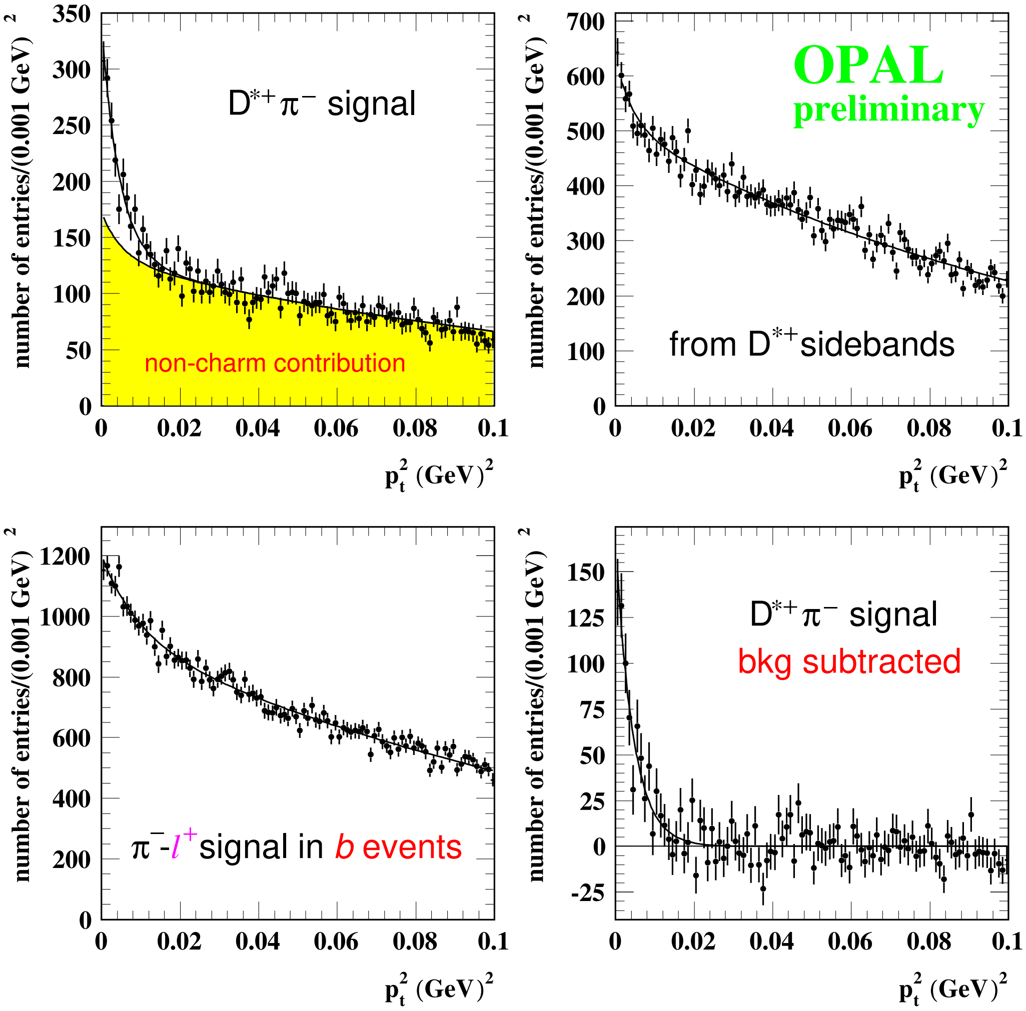
- $D^{\star+}$ is a fake with the wrong sign, π_s^- is correct
- b-mixing: $\overline{B^0} \rightarrow B^0 \rightarrow D^{\star+}$

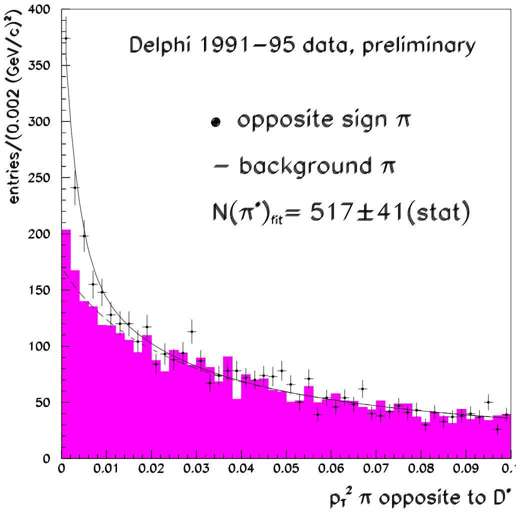
Sidebands aren't signal-free

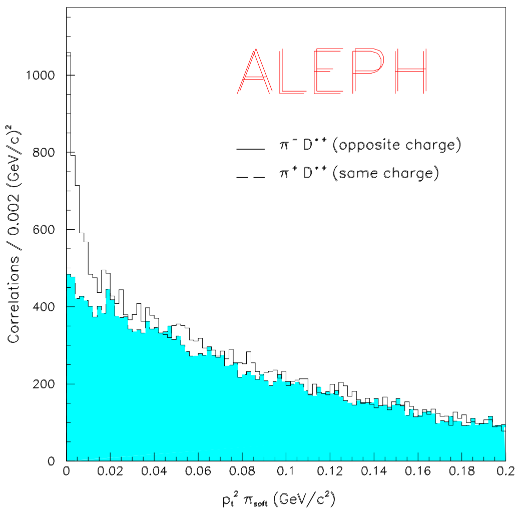


- misreconstructed Ds must be treated with care...

R_c: Exclusive-Inclusive Double Tag







R_c: Exclusive-Inclusive Double Tag

The number of double tag events is evaluated from a simultaneous fit of the opposite charge, same charge, and background distributions, including the effects of b mixing

$P(c \to D^{\star +}) \times B(D^{\star +} \to \pi D^0)$:

OPAL ('91-'95)

$$P(c \to D^{\star +}) \cdot \mathcal{B}_* = 0.151 \pm 0.011(stat) \pm 0.011(syst)$$

DELPHI ('91-'94)

$$P(c \to D^{\star +}) \cdot \mathcal{B}_* = 0.169 \pm 0.014(stat) \pm 0.012(syst)$$

R_c:

OPAL ('91-'95)	$R_c = 0.182 \pm 0.011(stat) \pm 0.015(syst)$
DELPHI ('91-'94)	$R_c = 0.167 \pm 0.015(stat) \pm 0.015(syst)$
ALEPH ('91-'95)	$R_c = 0.176 \pm 0.013(stat) \pm 0.011(syst)$

Dominant Systematic Errors (on R_c): Total ~0.015

- background subtraction 0.010
- detector/resolution effects 0.006
- $g \to c\bar{c}$ rate 0.003
- $b \to c$ rates 0.003

R_c: Exclusive-Inclusive Double Tag

Comments and Prospects:

What Changed!?!

- OPAL had $R_c = 0.155 \pm 0.022$ for Brussels (EPS '95)

  $\star$ $g \rightarrow c\bar{c}$ rate fixed to $2.38 \pm 0.48\%$

  (was fitted as $\bar{n}_{g\rightarrow c\bar{c}} = 4.4 \pm 2.1\%$ previously)

  $\star$ $B(D^0 \rightarrow K\pi) = 3.83 \pm 0.12\%$, rather than $4.01 \pm 0.13\%$

  $\longrightarrow$ These two effects move old central value to 0.169

  $\star$ improved treatment of background, fake rates

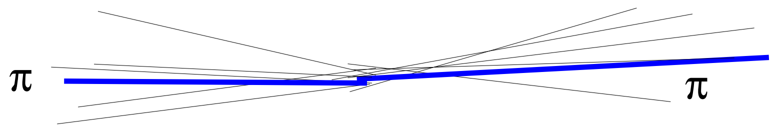
- New Measurements from DELPHI and ALEPH

- More inclusive tags coming $\longrightarrow$ smaller statistical errors

- work on systematic errors also progressing

R_c: Inclusive-Inclusive Double Tag

Method: Use low $p_\perp$ slow pion π_s in each hemisphere to tag the $D^\star$

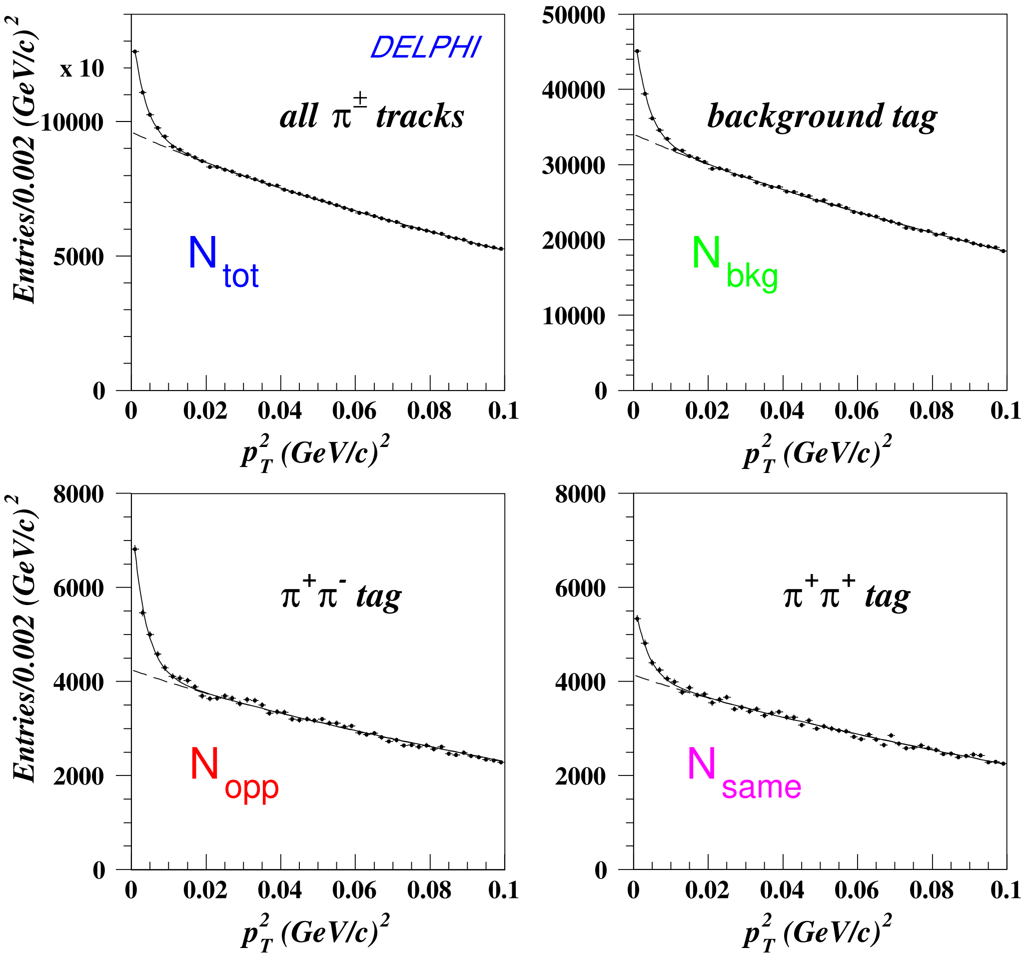


Results from DELPHI

Some cuts to clean up pions, enrich in c decays:

- $1.4\ \mathrm{GeV}/c < p_\pi < 4.0\ \mathrm{GeV}/c \longrightarrow$ removes bs
- $|d_0| < 3$mm
- dE/dx consistent with pion id

Different combinations of pions used to extract the “signal”:



R_c: Inclusive-Inclusive Double Tag

All of the plots will be fit with an exponential signal and polynomial background shape to obtain the Ns

Then, the analysis proceeds as follows:

$$N_{tot} = 2N_{had}R_c P(c \to D^{*+})\mathcal{B}_* \epsilon_*^c \left[1 + r\frac{\epsilon_*^b}{\epsilon_*^c}\right](1+\delta)$$

where $r = \frac{R_b P(b \to D^{*+})}{R_c P(c \to D^{*+})}$ ($\Rightarrow$ can also be measured in this analysis)
ϵ_*^q is the efficiency for slow pion reconstruction,
and δ is a "fudge factor"

The total number of double-tagged signal events is

$$N_{opp} + N_{same} - \alpha N_{bkg} =$$
$$2N_{had}R_c \left(P(c \to D^{*+})\mathcal{B}_*\right)^2 \epsilon_{**}^c \left[1 + r^2 \frac{R_c}{R_b}\frac{\epsilon_{**}^b}{\epsilon_{**}^c}\right](1+\delta)^2$$

One can then extract

$$R_c \propto \frac{N_{tot}^2}{N_{opp} + N_{same} - \alpha N_{bkg}}$$

Different combinations of the Ns allow fitting for $(1+\delta)$ as well

Results:

DELPHI ('91-'94)

$$P(c \to D^{\star+}) \cdot \mathcal{B}_* = 0.170 \pm 0.009(stat) \pm 0.013(syst)$$

DELPHI ('91-'94) $\quad R_c = 0.171 \pm 0.013(stat) \pm 0.015(syst)$

R_c: Inclusive-Inclusive Double Tag

What changed?!?

DELPHI quoted $R_c = 0.150 \pm 0.010(stat) \pm 0.012(syst)$ for Brussels

- new (lower) value of $\bar{n}_{g \to c\bar{c}} = (1.6 \pm 0.8)\%$
- reevaluation of π_s reconstruction efficiency
- new background fitting shape
- new measurement of r 25% lower

Dominant Systematic Errors (on R_c): Total 0.015

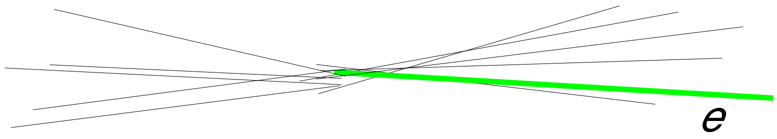
- Monte Carlo statistics (reconstruction bias) 0.009
- b fragmentation 0.005
- background subtraction (α) 0.007
- b/c separation in r 0.005
- detector effects (ϵ_{**}) 0.004

Comments and Prospects:

- Complicated analysis, many subtleties
- large background subtraction is difficult
- Results still preliminary $\longrightarrow$ more refinement possible (necessary?)
- Only one experiment has dared to use this method so far $\longrightarrow$ more coming...

R_c: Lepton Tag

Method: tag charm events with high p, $p_\perp$ electrons



Results from ALEPH

The probability $\mathcal{P}(p, p_\perp)$ to observe a lepton of a given p, $p_\perp$ is given by

$$\mathcal{P}(p, p_\perp) = R_b \mathcal{P}^{b \to \ell} + R_c \mathcal{P}^{c \to \ell} + (1 - R_b - R_c) \mathcal{P}^{uds \to \ell}$$

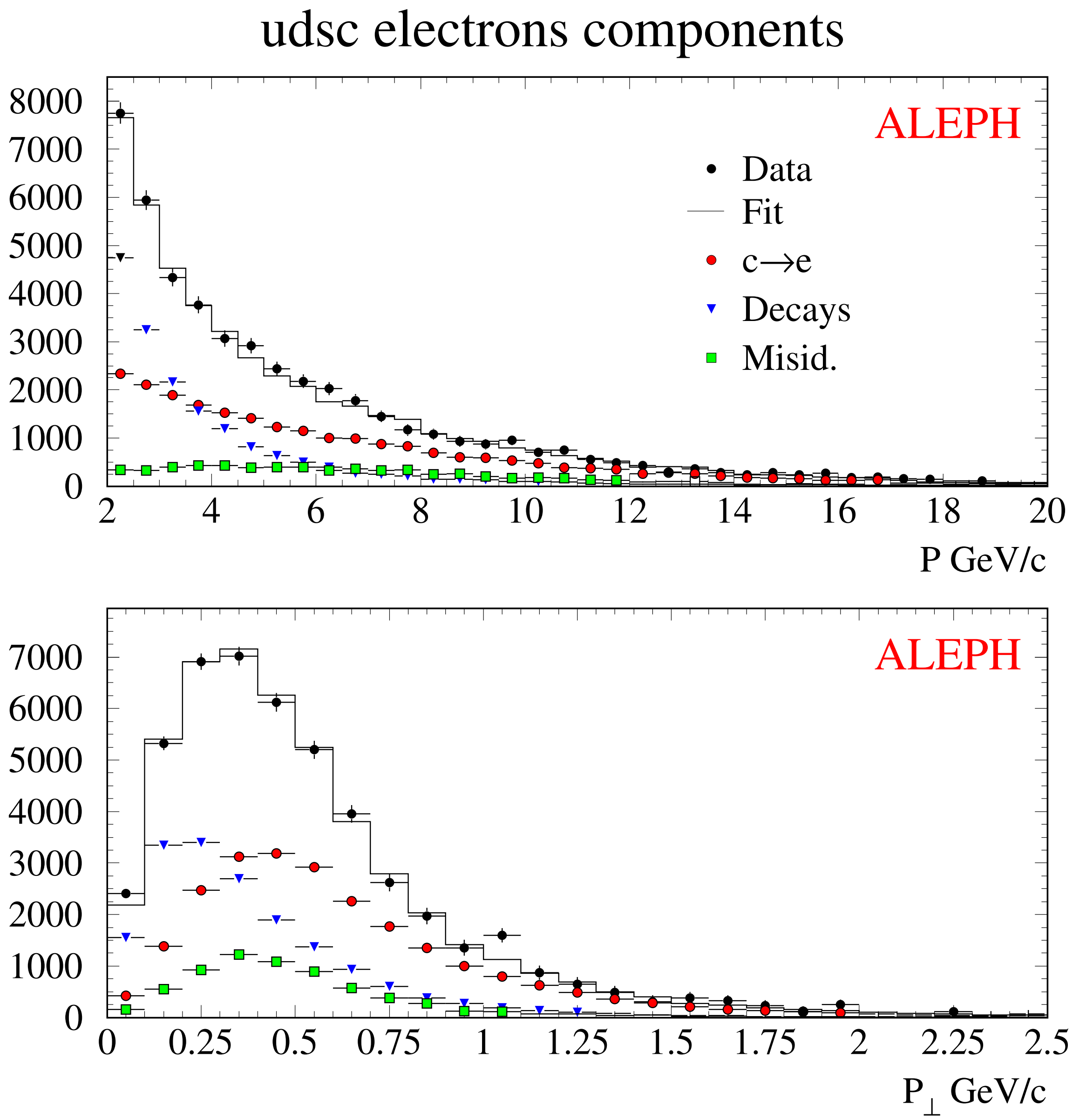
where $\mathcal{P}^{c \to \ell} = B(c \to \ell) \epsilon^{c \to \ell}(p, p_\perp)$

- $\mathcal{P}^{b \to \ell}$ is measured by applying a high-purity ($> 98\%$) b tag to the hemisphere opposite the lepton
- $\mathcal{P}^{uds \to \ell}$ is measured from conversions and K^0s in the data
- The shape of $\mathcal{P}^{c \to \ell}$ is taken from Monte Carlo, detection efficiency for electrons from data
- $B(c \to \ell) = 0.098 \pm 0.005$ is taken from low-energy data

Simultaneous fit for b, c, and uds (conversions) content, including ε_c, the Peterson fragmentation parameter for c

R_c: Lepton Tag

electron p, and $p_\perp$ spectra with electrons from b decays subtracted:



Results:

ALEPH('91-'94)

$$R_c = 0.165 \pm 0.007(stat) \pm 0.007(syst) \pm 0.008(br)$$

R_c: Lepton Tag

Dominant Systematic Errors: Total 0.011

- modelling of $c \rightarrow \ell$ 0.004
- electron background subtraction 0.005
- $B(c \rightarrow \ell)$ from low energy 0.008

Comments and Prospects:

- smallest error of any single measurement
- complementary in technique
- Large reliance on MC for charm properties
- LEP can measure $B(c \rightarrow \ell)$ (cf. DELPHI)

LEP HQEW Averaging Procedure

Heavy flavour electroweak analyses often:

- measure several parameters simultaneously (A^b_{FB}, χ, etc.)
- depend on other widths, branching ratios, etc., as external inputs

The LEP Heavy Flavour group combination procedure handles all correlations and dependences on external inputs (and their errors) consistently.

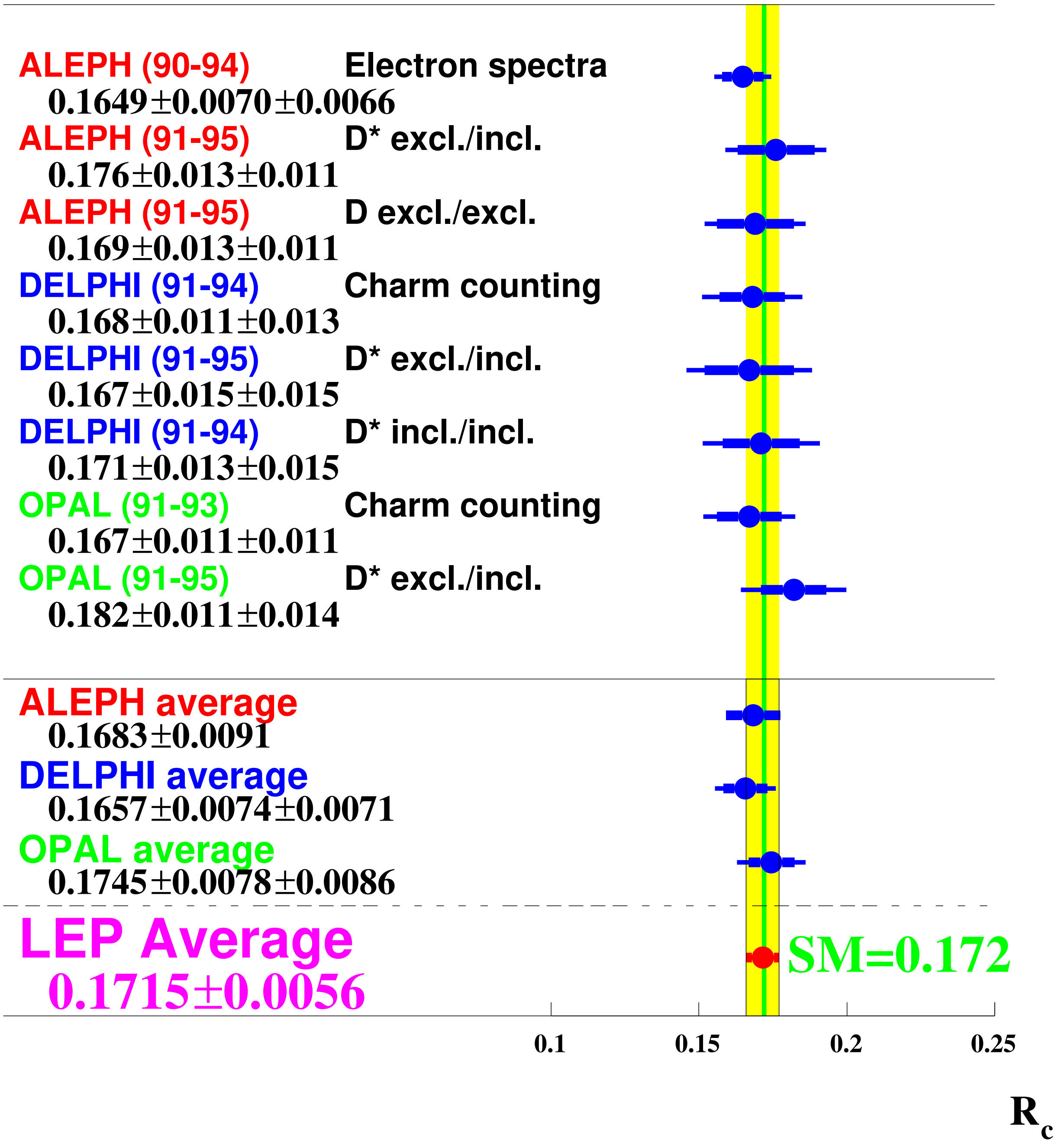
The results are derived from a 17-parameter overall χ^2 minimization fit using the full covariance matrix between measurements

Parameters include R_c, $P(c \to D^*) \cdot \mathcal{B}_*$, and R_b, as well as $P(c \to D^+)$, $P(c \to D_s^+)$, and $P(c \to \Lambda_c)$

Checks include:

- Internal consistency with simple one-parameter averages
- Varying the details of correlation assumptions only has a small effect

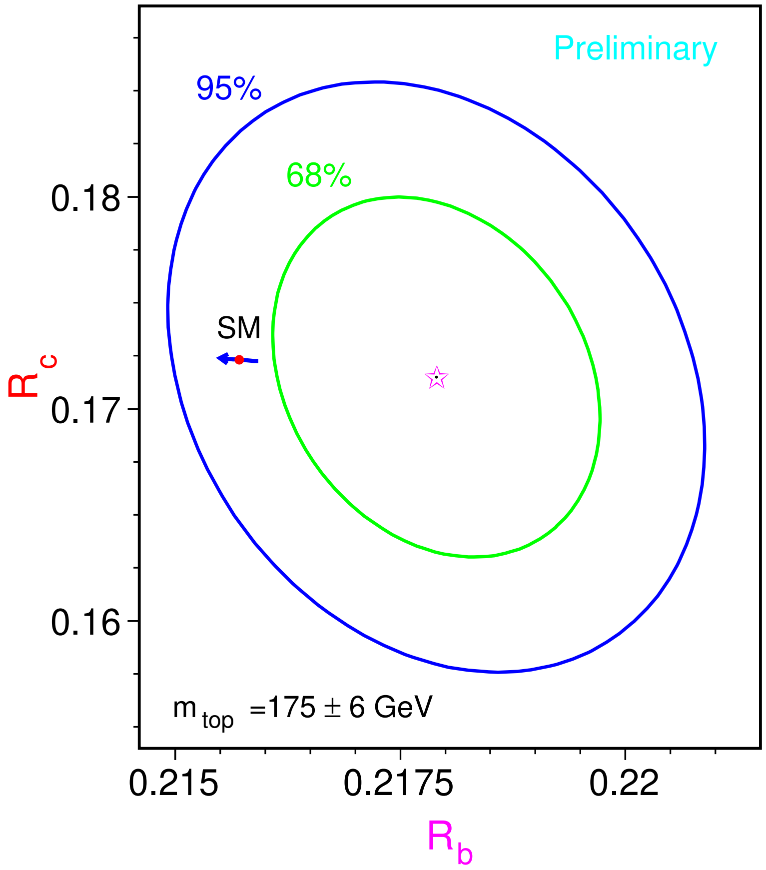
R_c: Summary



$\gamma - Z$ interference correction (-0.0003) applied to average

R_b vs R_c

Results of the combined Heavy Flavor Electroweak fit:



$$\begin{aligned} \boldsymbol{R}_{\mathbf{b}} &= \mathbf{0.2175 \pm 0.0011} \\ \boldsymbol{R}_{\mathbf{c}} &= \mathbf{0.1715 \pm 0.0056} \\ P(c \to D^{+*} \to \pi D^0) &= 0.1626 \pm 0.0066 \end{aligned}$$

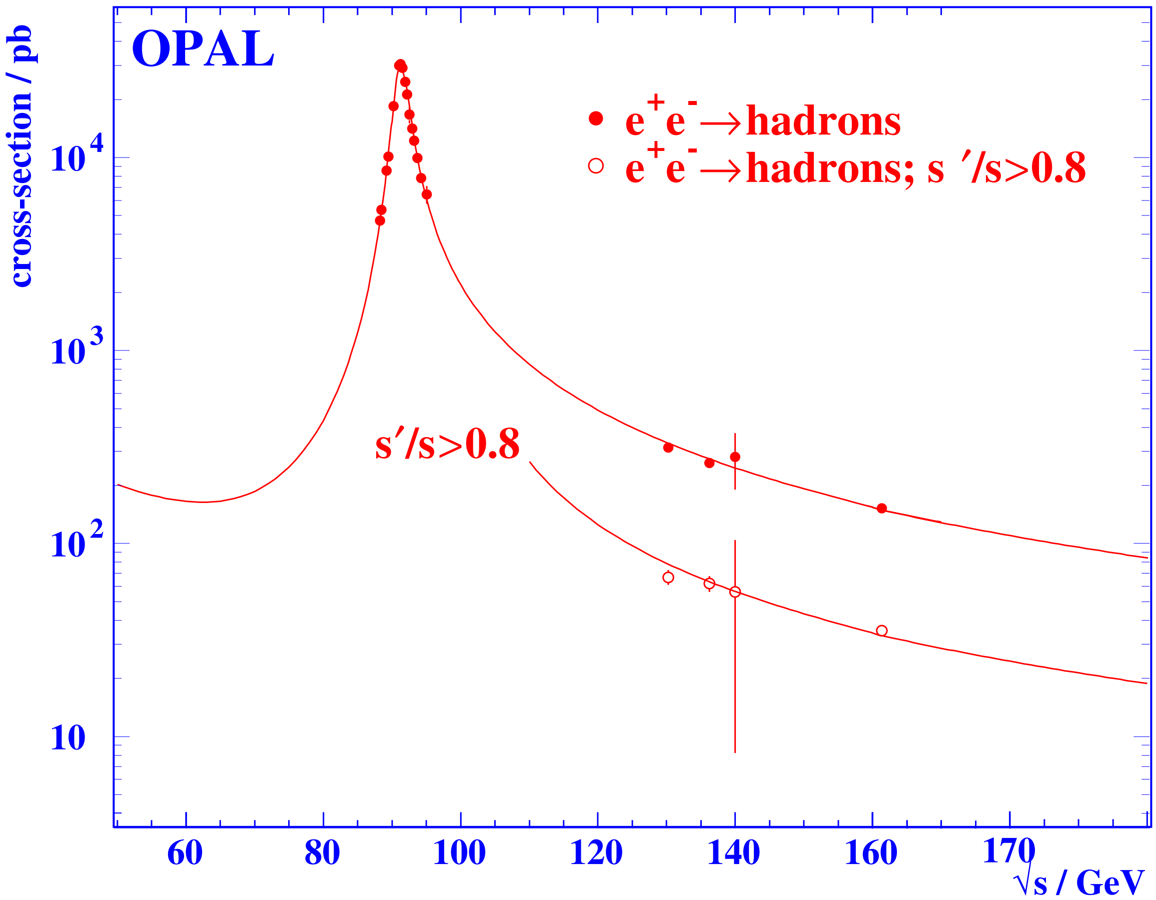
Prospects:

- New techniques from ALEPH most precise for R_b and R_c

$\longrightarrow$ Other experiments preparing new, more inclusive methods as well

- Still far away from a 1% measurement of R_c, still hoping...

Looking Forward to LEP2



R_c at High Energy:

Cross-section for non-radiative multihadrons is $\sim 20\ pb$ at higher energies
plus γ contribution to annihilation dominant
$\Rightarrow$ R_c is larger than at the Z^0 (~ 0.22)

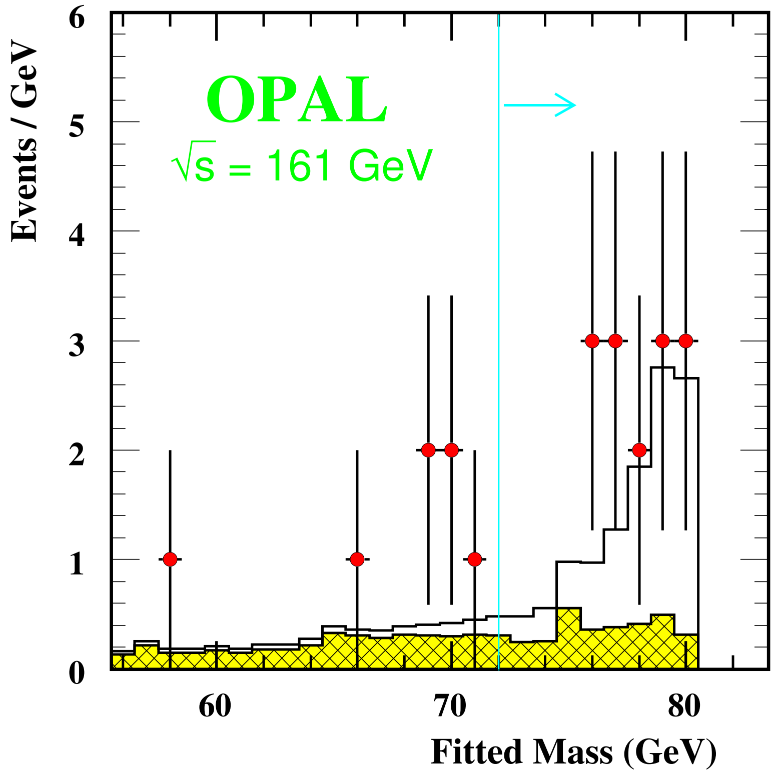
LEP2 should deliver about $\int \mathcal{L}dt = 500\ pb^{-1}$: $\rightarrow\sim 1500\ c\bar{c}$ events.

With a tagging efficiency of 15% per hemisphere at 50% purity
(not unreasonable)

$$\Delta R_c^{\sqrt{s}>M_Z} / R_c^{\sqrt{s}>M_Z} \sim 15\%$$

Looking Forward to LEP2

Also, new bosons to look at!



$\Rightarrow \Gamma(W \rightarrow c\bar{s})$ can be measured

$\Gamma(W \rightarrow c\bar{s})/\Gamma(W \rightarrow had) \sim 50\% \Rightarrow \sim 3/4$ of all $W \rightarrow qqqq$ decays have a c quark.

Using a similar tag, one could get $\Delta R_c^W / R_c^W \sim 5 - 10\%$

The Bottom Line:

Improved techniques from the Z^0 using well-understood detectors will make charm physics at LEP2 easier

Conclusions

- EW Charm physics at the Z^0 still interesting
- Large effort being put into new tags for higher precision measurements

  $\longrightarrow$ charm tagging is *hard*

  Reduction in statistical and systematic errors possible
- R_b and R_c now in agreement with the Standard Model

  BUT

  OPAL and DELPHI have yet to put out new R_b measurements

  Don't forget SLD...

  $\Rightarrow$ The story is far from over on HF EW physics at the Z^0
- There will be HF EW physics at LEP2, especially for charm
- LOTS to do...