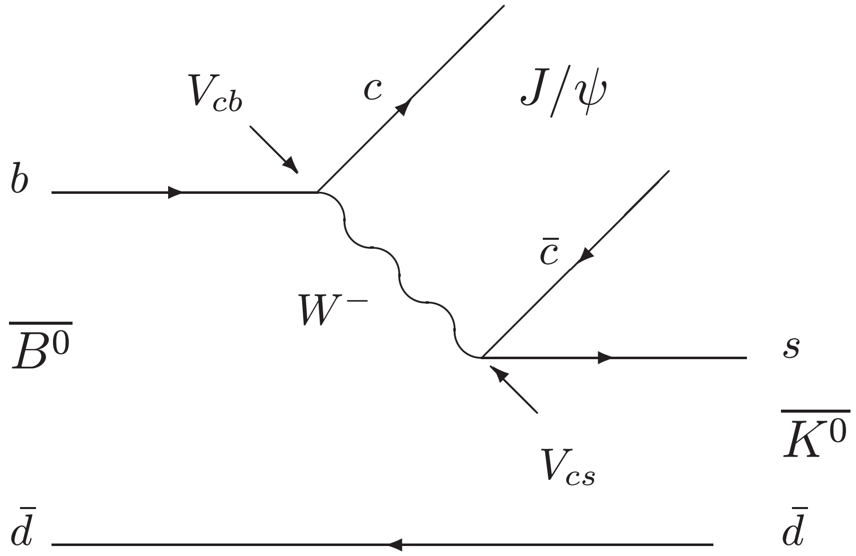
J/ψ Production at DELPHI

Tim Adye
Rutherford Appleton Laboratory
26th May 1998

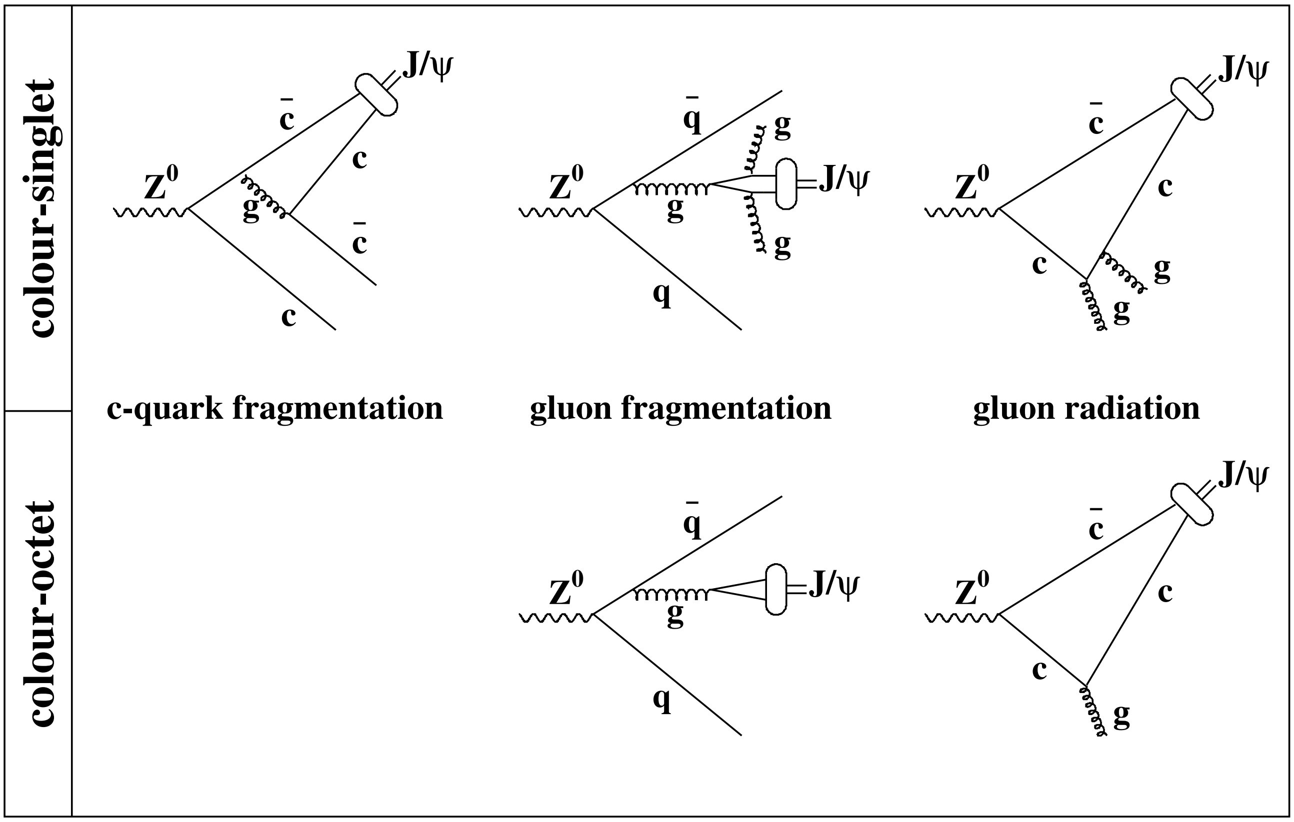
1. J/ψ Production from the Z^0
2. Candidate Selection
3. Fit Method
4. Fit Result Representation
5. B Decay Times
6. Sample Composition
7. Lifetime fit
8. Systematic Errors
9. Results
10. B Lifetime Measurements

Two classes of production mechanism:–

via B, eg.



Direct production



Start with 1992–5 shortDST.

- Standard ('open') hadronic track and event cuts
- Two tracks with muon tags (L, S, or T)
- opening angle, $\omega \leq 90^\circ$
- reconstructed parent (putative J/ψ) mass, $M_{\mu\mu} \geq 1.5\ \mathrm{GeV}/c^2$
- reconstructed momentum, $p_{\mu\mu} \geq 10\ \mathrm{GeV}/c$ →
- measured decay time, $-4 \leq t < 10$ ps (described later)

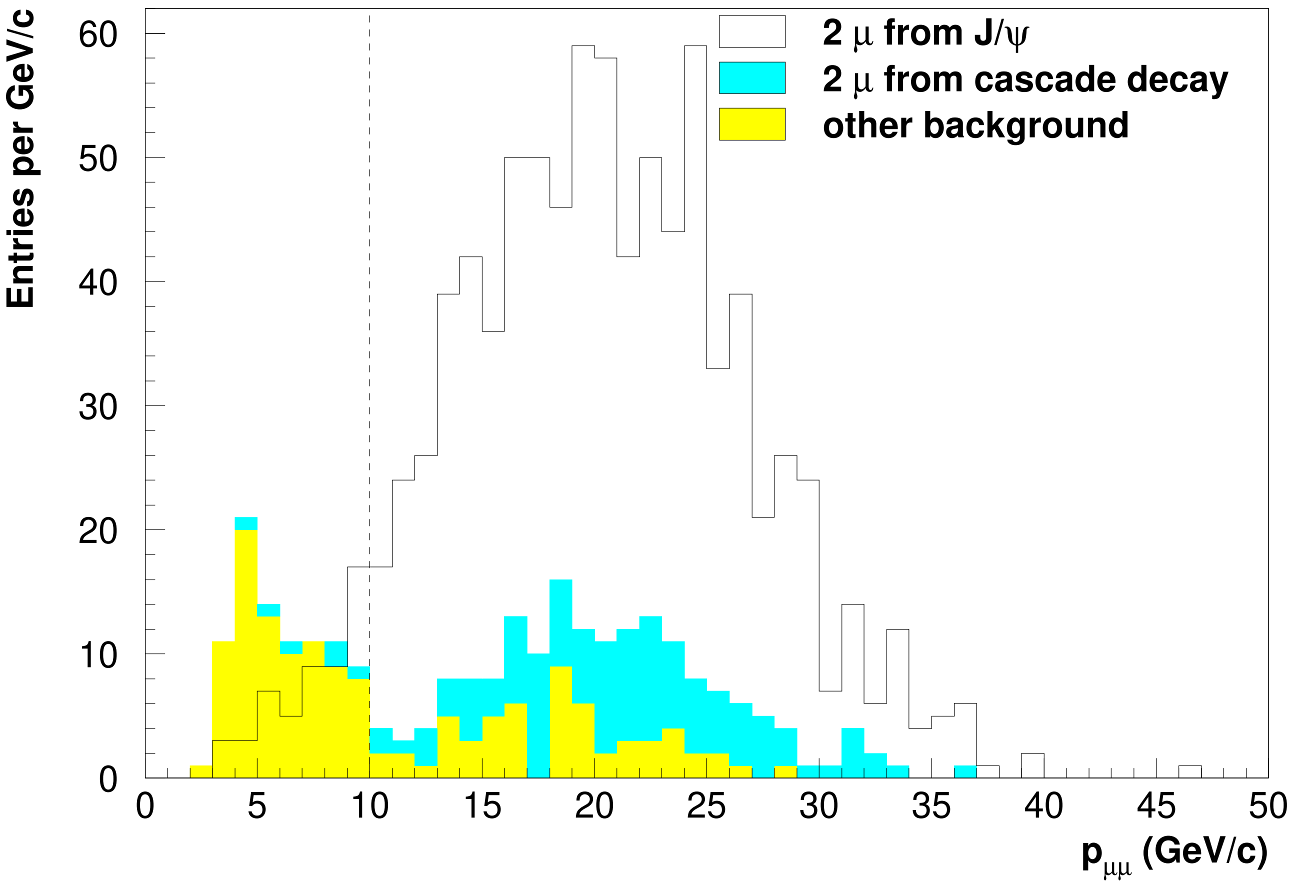
These candidates include the signal sample

- muons with opposite charges
- reconstructed mass window, $2.95 \leq M_{\mu\mu} < 3.25\ \mathrm{GeV}/c^2$

and samples used for background estimation. →

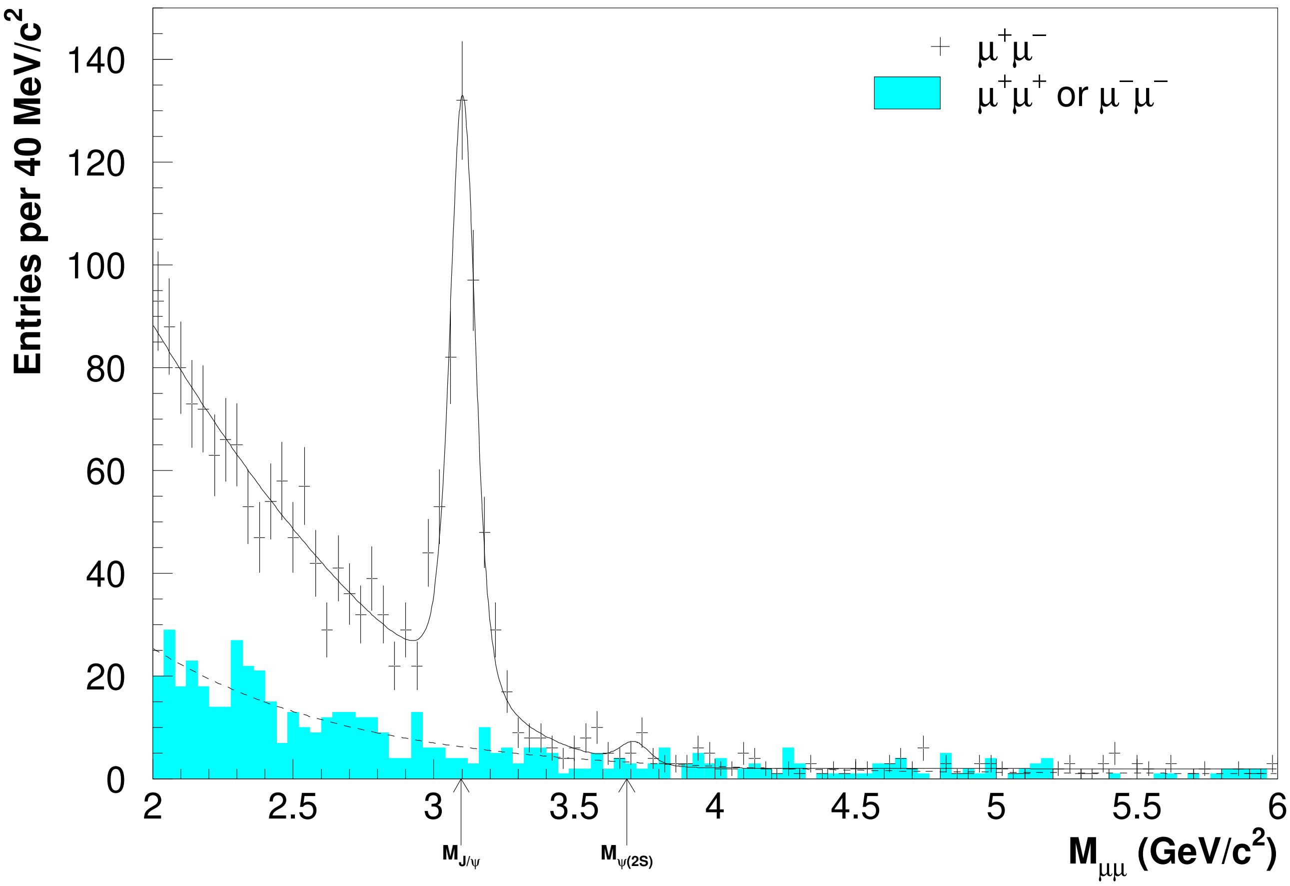
J/ψ Momentum Distribution (MC)

Momenta of selected candidates (within mass window).



The dashed line shows the limit of the $p_{\mu\mu} \geq 10$ GeV$/c$ cut.

Candidate Mass Distribution



Opposite-sign fit (1941 cands.; 495 in $2.95 \leq M_{\mu\mu} < 3.25$ GeV/c^2)

J/ψ fraction in window	$f_{J/\psi} =$	(73.3 ± 2.1) %	
total ψ(2S)s	$N_{\psi(2S)} =$	16.7 ± 6.6	
J/ψ mass	$M_{J/\psi} =$	(3102.3 ± 3.4) MeV/c^2	
ψ(2S) mass	$M_{\psi(2S)} =$	(3713 ± 24) MeV/c^2	
error scale factor	$\alpha_\sigma =$	1.34 ± 0.09	
function vs. histogram	$\chi^2 =$	52.5	(55 d.f.)
χ^2 in window	$\chi^2_w =$	8.9	(5 d.f.)

Like-sign fit (532 candidates; 41 in $2.95 \leq M_{\mu\mu} < 3.25$ GeV/c^2)

total in window	$N_w =$	47.0 ± 2.4	
function vs. histogram	$\chi^2 =$	58.6	(51 d.f.)
χ^2 in window	$\chi^2_w =$	6.9	(5 d.f.)

Fit Method

Both mass and lifetime fits use

- unbinned maximum likelihood fit
- includes each event's reconstruction errors

$$
\begin{aligned}
f(x;\sigma) &= f_{\text{true}}(x) \otimes G(x;\sigma) \\
&= \int f_{\text{true}}(u) \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-u)^2/2\sigma^2} \mathrm{d}u
\end{aligned}
$$

For mass fit

- $f_{\text{true}}(x)$ is the sum of delta function, exponential, hemiparabola (one side of $(x_0 - x)^2$), and/or constant
- proportions of each term included in fit, but sometimes a combination of the actual fit parameters (eg. J/ψ fraction within the signal window) — allows errors to account for correlations

Representation of the fit result is problematic, because each event's error (and hence fit function) is different.

The fit representation is important, not only to check the quality of the fit, but also to determine the area within the signal window (to determine background fractions).

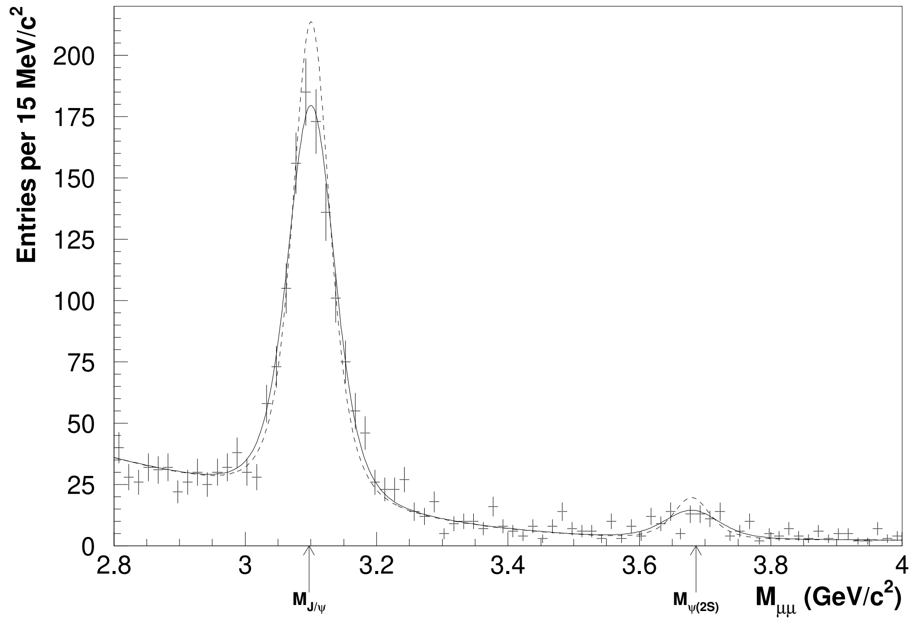
Conventionally

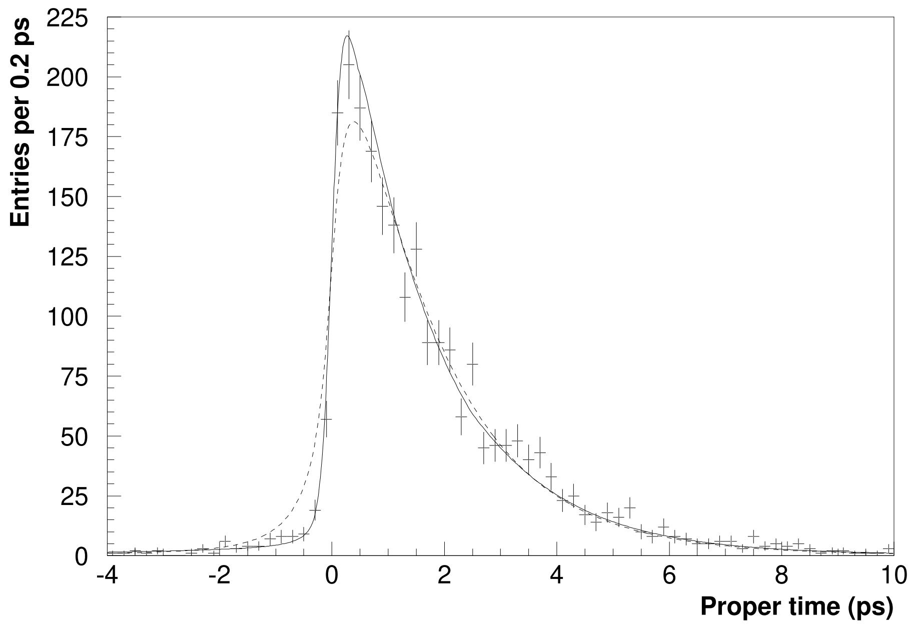
$$F(x) = \sum_i f(x; \sigma_i)$$

is used. This assumes that the 'true' distribution of errors, $S(x;\sigma)$, may be approximated by the distribution of errors seen in the data, $\sum_i \delta(\sigma - \sigma_i)$. This is only reasonable if if the dependence of $S(x;\sigma)$ upon x is weak — not the case for either the mass or lifetime distributions.

This is taken into account by using $f(x; \sigma_i x/x_i)$ in the above sum for the mass fit representation. The lifetime fit is more difficult, but a reasonable approximation involves summing over different events for different abscissa ranges.

These methods have the desired properties: the function representations better agree with the data histogram, the χ^2 variation at the minimum is correct, and the background fractions from the MC mass plot agree with the true values, within errors.

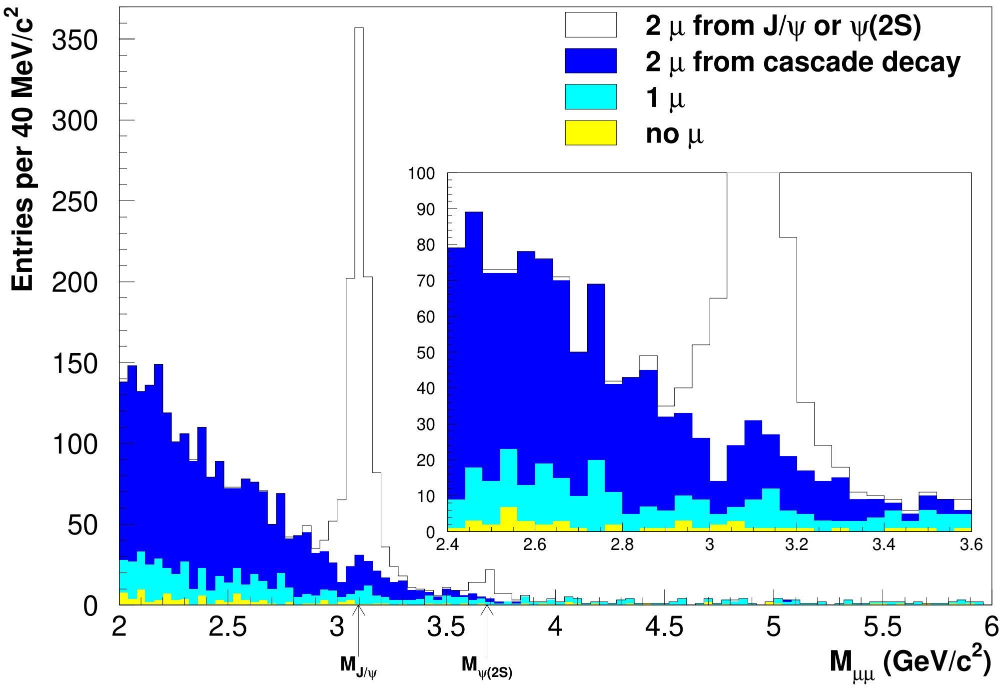




MC mass and backgroundless lifetime distributions. The solid curve shows the representation of the fit result after correction.

- measure xy decay distance WRT beamspot (l_{xy})
- project along J/ψ direction ($\phi_{\mathrm{J}/\psi}$)
- use J/ψ direction as estimate of B direction ($\theta_{\mathrm{J}/\psi}$)
- use J/ψ velocity ($\beta\gamma = p_{\mathrm{J}/\psi}/M_{\mathrm{J}/\psi}$) as estimate of B velocity (J/ψ boost in B rest frame is small WRT boost of B)
- apply $\alpha = 1.094$ correction factor to account for these approximations from MC (also introduces additional statistical uncertainty on each decay time)

$$t = \alpha \frac{l_{xy} M_{\mathrm{J}/\psi} \cos(\phi_{\mathrm{J}/\psi} - \phi_{\mathrm{V}})}{p_{\mathrm{J}/\psi} \sin\theta_{\mathrm{J}/\psi}}$$



The background can be divided into

- hadrons misidentified as muons, and
- cascade decays: $b \to c\mu^-\bar{\nu}_\mu$, $c \to s/d\mu^+\nu_\mu$ (+CC)

They have very different lifetime distributions and relative proportions (under the peak vs. sidebands), so must consider them separately

- use like-sign data to model misidentified muons
- use opposite-sign data to model the combined background

Cascade decays produce muons of opposite charges, while there is no such constraint on misidentified muon background.

A single fit is performed on three samples of events:

1. like-sign candidates in the sideband ($2 \leq M_{\mu\mu} < 2.8$ GeV$/c^2$)

2. opposite-sign candidates in the sideband

3. opposite-sign candidates in the window ($2.95 \leq M_{\mu\mu} < 3.25$ GeV$/c^2$)

Each component within these samples (misidentified muons, cascade decays, and J/ψ) is fitted with a smeared exponential + Gaussian + constant (no constant term for the J/ψ component).

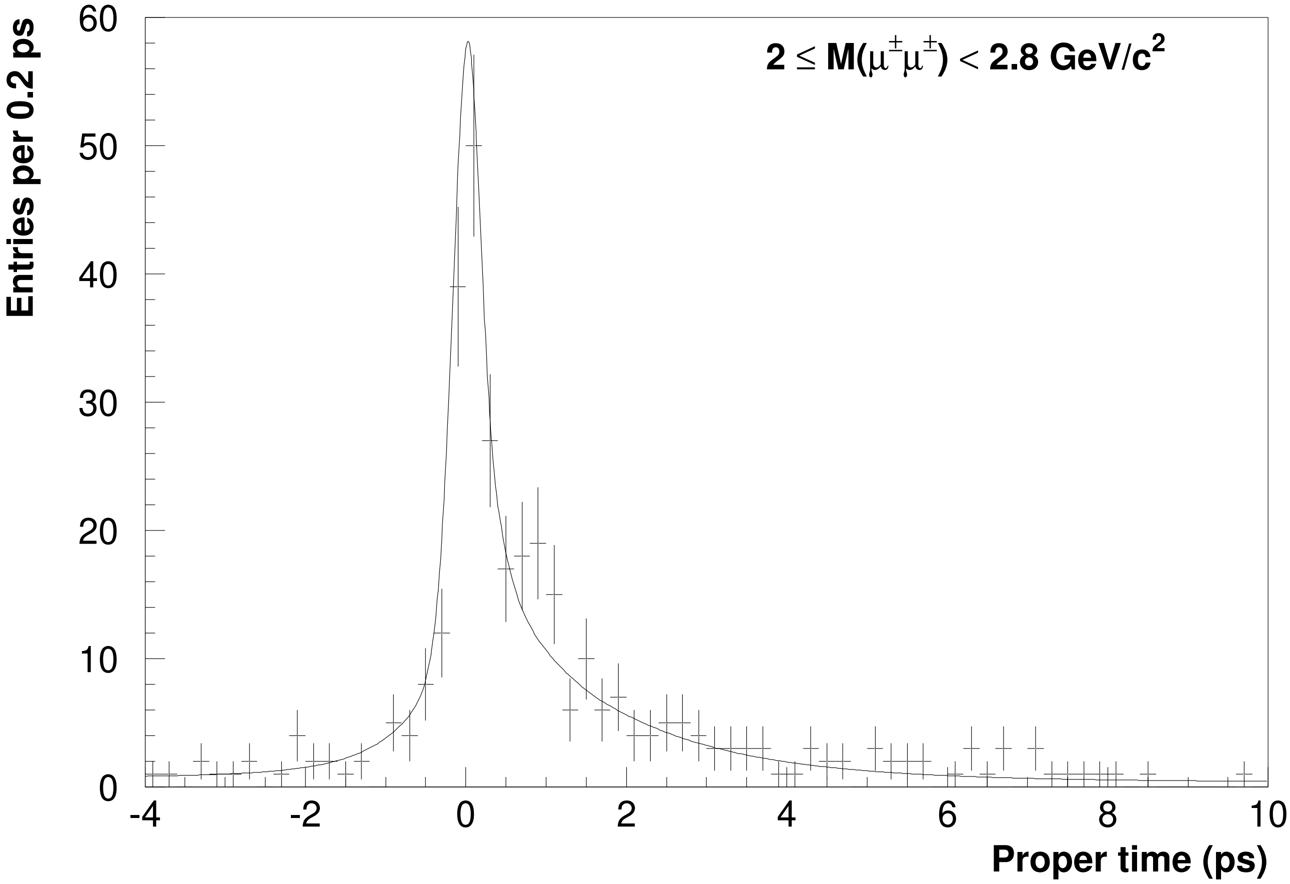
For each component

- component fractions are fixed from the mass plot ($f_{\mathrm{J}/\psi}$ and N_w)

- mean lifetimes are fit parameters (τ_m, τ_c, and τ_{B})

- relative proportions of each term are fit parameters (G_m, E_m, G_c, E_c, and G_ψ; other fractions are constrained by unitarity)

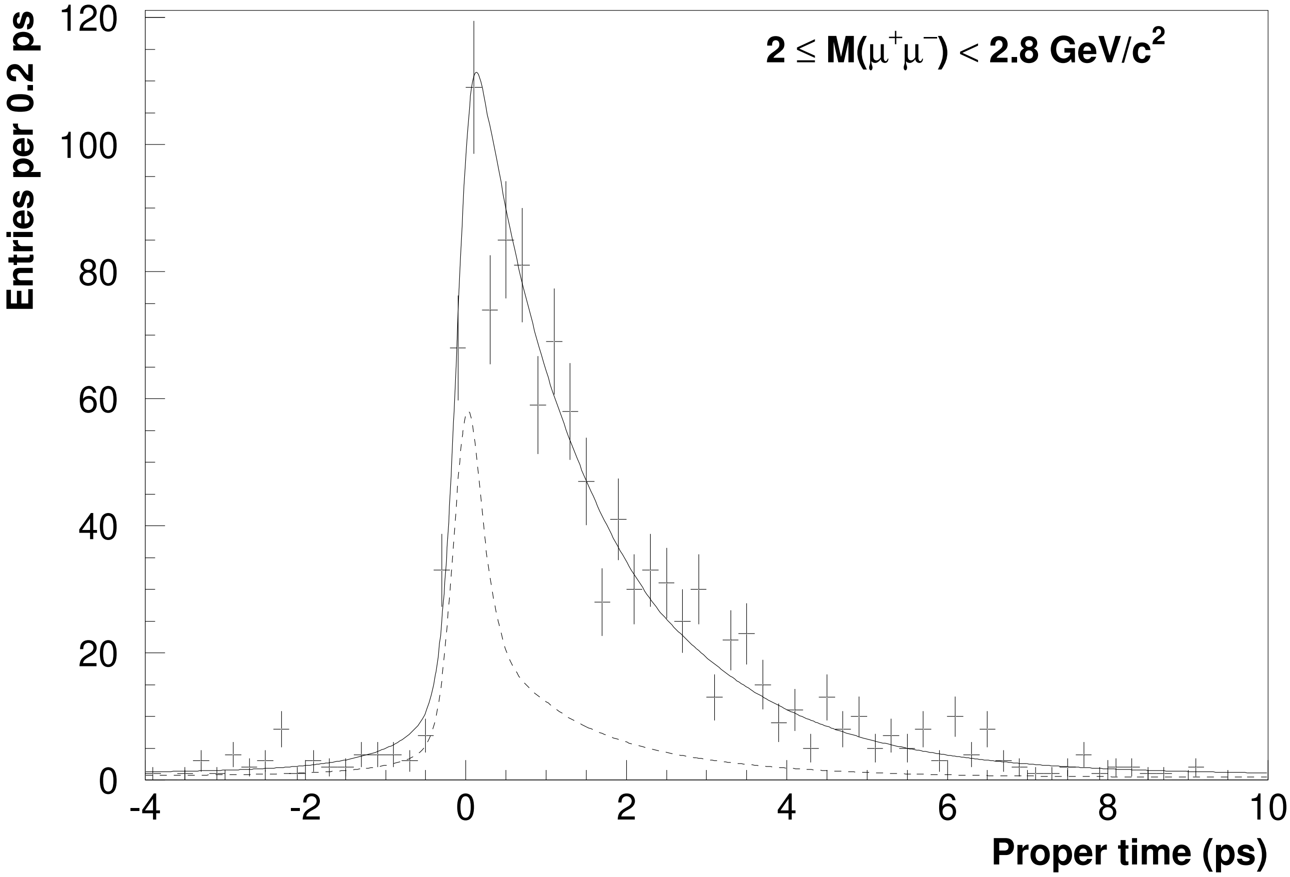
The following plots show the three samples and the relevant part of the fit function. $\rightarrow$



Like-sign function (333 candidates)

prompt fraction	$G_m = (35.5 \pm 4.0)$ %
decay fraction	$E_m = (53.2 \pm 4.4)$ %
lifetime	$\tau_m = (1.35 \pm 0.15)$ ps
function vs. histogram	$\chi^2 = 30.4$ (22 d.f.)

This sample contains only misidentified muons.

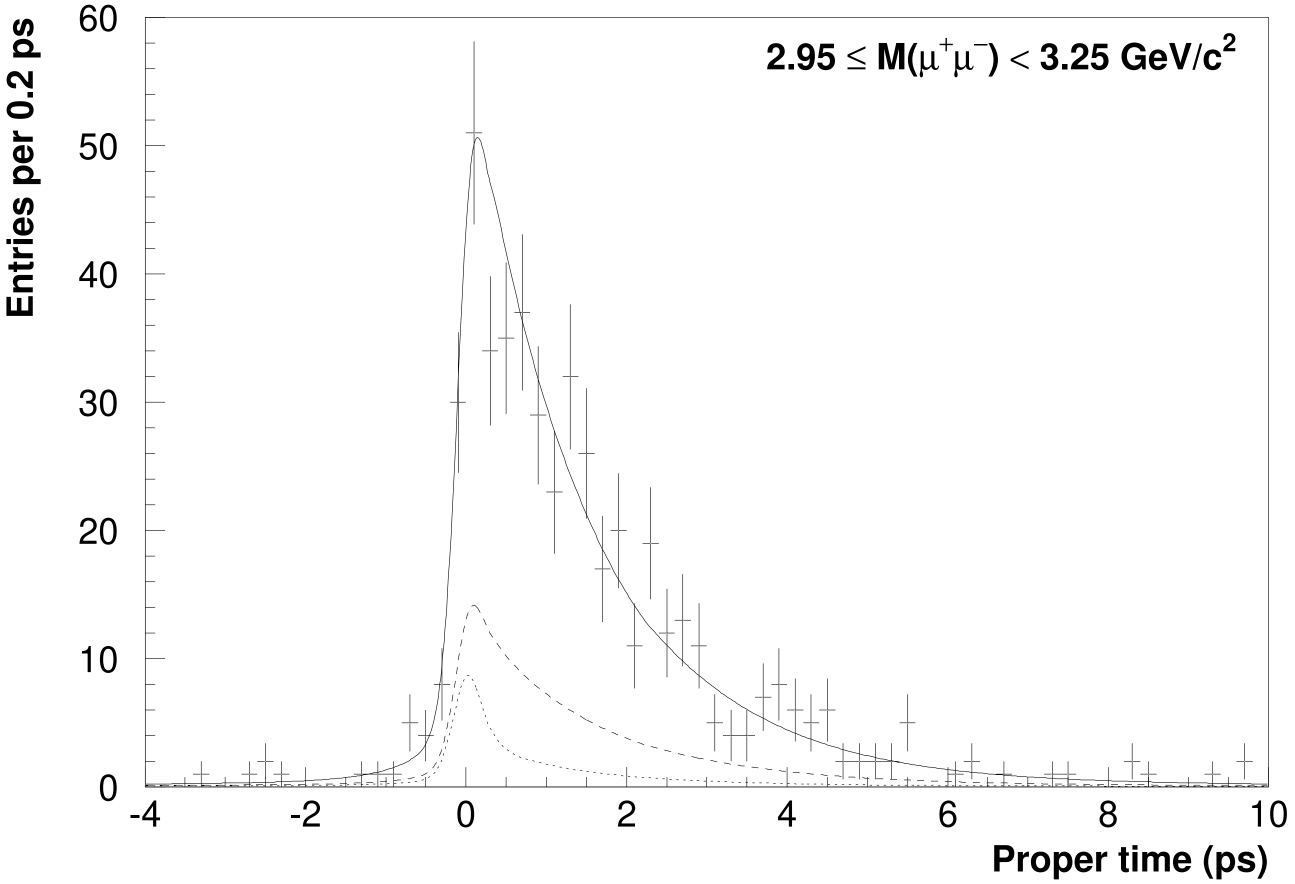


Sideband function (1155 candidates)

prompt fraction	$G_c =$(-0.5 $\pm$2.9)	%
decay fraction	$E_c =$(98.1 $\pm$3.3)	%
lifetime	$\tau_c =$ (1.52 $\pm$0.08)	ps
function vs. histogram	$\chi^2 =$ 65.1	(40 d.f.)

The dashed curve shows the misidentified muon component (from the previous plot); the remainder is due to cascade decays.

Opposite-sign Window



Window function (495 candidates)

prompt fraction	$G_\psi = (8.1 \pm 3.5)\ \%$
lifetime	$\tau_B = (1.41 \pm 0.11)$ ps
error correction	$\Delta_\sigma = (0.14 \pm 0.02)$ ps
function vs. histogram	$\chi^2 = 29.9$ (24 d.f.)

The dotted curve shows the misidentified muon component; the dashed curve shows the cascade component; the remainder is the J/ψ component.

Systematic Errors

- statistical error on the component fractions from mass plot (included in the statistical errors)
- fixing $M_{\mathrm{J}/\psi}$, $M_{\psi(2\mathrm{S})}$, α_σ to their ideal values
- comparing fitted and actual number of like-sign events in the window
- changing mass plot background parameterization
- changing cascade lifetime parameterization (double exponential)
- using a different B-momentum smearing function (double Gaussian)

An additional contribution to the systematic errors (mainly on τ_{B}) is due to the uncertainty in the only significant MC inputs to this analysis, the B-momentum correction factor (α) and B-momentum estimation spread (σ_α).

- compare for pure samples of $\mathrm{B}^{0\pm}$, $\mathrm{B_s}$, and Λ_{B} (the main contribution to α is from the boost of the J/ψ in the B frame)
- check the effect of the J/ψ selection cuts

- number of selected J/ψs, $N_{J/\psi} = 363 \pm 19$
- B lifetime,
  $\tau_B = (1.41 \pm 0.11\ (\text{stat.}) \pm 0.03\ (\text{syst.}))$ ps
  cf. previous LEP average $B \to J/\psi$
  $\tau_B = (1.40 \pm 0.13)$ ps
- fraction of prompt J/ψ,
  $$\frac{N(Z^0 \to \text{prompt } J/\psi X)}{N(Z^0 \to J/\psi X)} = (8.1 \pm 3.7\ (\text{stat.}) \pm 1.6\ (\text{syst.}))\%$$
  cf. previous DELPHI measurement: $(7.7^{+6.3}_{-5.4})$ and OPAL: $(4.8 \pm 1.7\ (\text{stat.}) \pm 1.1\ (\text{syst.}) \pm 1.3\ (\text{theo.}))\%$

But for the **serious objection** that we have not considered the different momentum distributions of $B \to J/\psi$ and prompt J/ψ (NB. $p_{J/\psi} \geq 10$ GeV$/c$ cut), we could use PDG's $\text{Br}(Z^0 \to J/\psi X) = (0.380 \pm 0.027)\%$ to obtain

- $\text{Br}(Z^0 \to \text{prompt } J/\psi X) = (0.031 \pm 0.015)\%$
  cf. ALEPH: $(0.0300 \pm 0.0078\ (\text{stat.}) \pm 0.0030\ (\text{syst.}) \pm 0.0015\ (\text{theo.}))\%$ and theoretical prediction: 0.027% (P. Cho, 1996 with update)

Compare with LEP B lifetimes working group

Sample	τ_{B} (ps)
Mean $\mathrm{B} \rightarrow \mathrm{J}/\psi$ at LEP	1.40 ± 0.09
Mean Inclusive B decay at LEP	1.576 ± 0.016
Mean Semileptonic B decay at LEP	1.537 ± 0.020
Mean $\mathrm{B} \rightarrow \mathrm{J}/\psi$ at the Tevatron ($\mathrm{p\bar{p}}$)	1.533 ± 0.036
B^0	1.56 ± 0.04
$\mathrm{B}^{\pm}$	1.65 ± 0.04
$\mathrm{B_s}$	1.54 ± 0.07
Λ_{B}	1.22 ± 0.05