DELPHI Open Data at the Z Pole

Direct R_b^0, R_c^0, and R_s^0 with holistic event tagging

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LEP1 open data
1994–1995 nominal period

↓

5-flavor ParticleNet
event-level classification

↓

Joint 8-bin fit
3 POIs + 15 NPs

LEP legacy and the direct R_s^0 gap

Z-pole ratios

$$R_q^0 = \frac{\Gamma(Z \to q\bar{q})}{\Gamma_{\text{had}}}$$

SM R_b^0	0.216
SM R_c^0	0.172
SM R_s^0	0.220

Z-pole precision

flavor universality

Published LEP measurements

Observable	Experiment / method	Result	Limitation
R_b^0	DELPHI, lifetime double tag	$0.21634 \pm 0.00065 \pm 0.00060$	heavy flavor
R_c^0	DELPHI, charm tags	$0.1665 \pm 0.0051 \pm 0.0081$	charm response
$R_d = R_s$	OPAL, light-quark tags	0.219 ± 0.007	$d = s$ imposed

Historical coverage

R_b^0: per-mille precision · R_c^0: percent precision
R_s^0: no DELPHI direct result · OPAL comparison under $d = s$

Open-data opportunity

2024 DELPHI release · modern five-flavor event classifier
direct R_s^0 · combined u/d response · no $d = s$ constraint

Data periods, simulation samples, and event-quality handling

Selected events
2,064,411
1994–1995 hadronic-Z candidates

Barrel
1,344,913
$|\cos\theta_{\mathrm{thrust}}| < 0.70$

Endcap
719,498
$|\cos\theta_{\mathrm{thrust}}| \geq 0.70$

Analysis-note sample names

Type	Year	Official sample	Score product
Data	1994	`short94_c2/nanoaod_job_*.root`	`pred_data_1994_data.root`
Data	1995	`short95_d2/nanoaod_job_*.root`	`pred_data_1995_data.root`
KK2F MC	1994	`sh_kk2f4146qqpy_e91.25_l94_2l_c2/`	`pred_mc_1994_<flav>_<flav>.root`
KK2F MC	1995	`..._e91.25_c95_1l_d2/` + `..._e91.25_l95_1l_d2/`	`pred_mc_1995_<flav>_<flav>.root`

`<flav>` = `bb, cc, ss, uu, dd`   year-matched DELPHI full simulation

$d0$ sentinel
data peak: $|d0| \simeq 999$ mm → remove tracks with $|d0| \geq 100$ mm
feature extraction before ParticleNet inference

`Beam_errorCode`
data: require $= 0$ → $-13,348$ bad-run / ghost events
MC: branch fixed to zero · no-op selection

ParticleNet as a holistic five-flavor event classifier

Whole-event representation

up to 80 particles per event
↓
dynamic particle graph
local EdgeConv
↓
global aggregation
event embedding
↓
5-way softmax
s_b, s_c, s_s, s_u, s_d

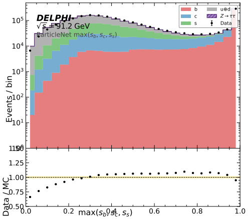
Inputs

- $\Delta\eta, \Delta\phi, \Delta R, \log p_T, \log E$
- charge and particle type
- dE/dx and RICH response
- $\tanh(d0)$, $\tanh(z0)$

Training configuration

1994 official MC · 5 balanced flavors
100k/flavor · 500k events
30 epochs · batch 512
Ranger · learning rate 0.01
Weaver · five-class cross entropy

Score-shape diagnostic

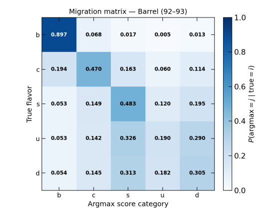


Data/MC overlay; continuous score shape not fitted

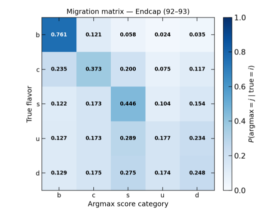
Fit interface

event scores → argmax + thresholds
→ four exclusive bins / detector region

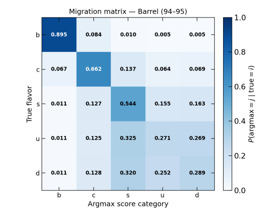
Detector era drives the 1992–1995 tagging hierarchy



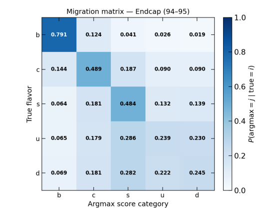
1992–1993 barrel



1992–1993 endcap



1994–1995 barrel



1994–1995 endcap

Heavy flavor

$b \to b$: stable · barrel > endcap

1994 VD upgrade

$c \to c$: $0.42–0.44 \to 0.59–0.61$

Analysis period

1994–1995 nominal · 1992–1993 performance cross-check

Rows: true flavor; columns: maximum-score category

Exclusive bins, nominal thresholds, and an MC-only reference

One event → one bin

b-enr	$s_b = \max(s_b, s_c, s_s, s_u, s_d)$, $s_b \geq \theta_b$
c-enr	not b-enr, $s_c \geq s_s$, $s_c \geq \theta_c$
s-enr	not b/c-enr, $s_s \geq \max(s_u, s_d)$, $s_s \geq \theta_s$
rest	all remaining events

Threshold comparison

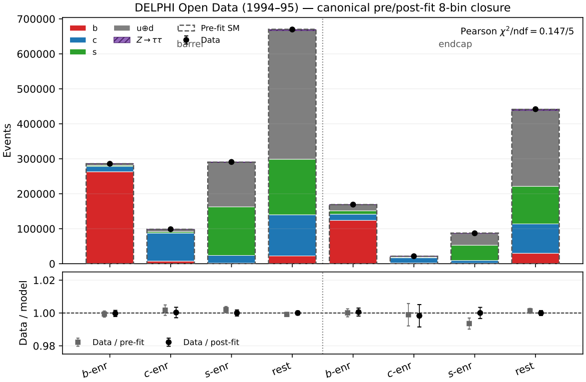
Choice	Barrel (b, c, s)	Endcap (b, c, s)
Nominal	$0.35, 0.75, 0.35$	$0.25, 0.70, 0.40$
MC-only proxy	$0.45, 0.65, 0.40$	$0.45, 0.80, 0.40$

proxy purities: $P_b \gtrsim 80\%$, $P_c \gtrsim 75\%$, $P_s \gtrsim 50\%$

$80/80/60\%$ target: no stable scanned point

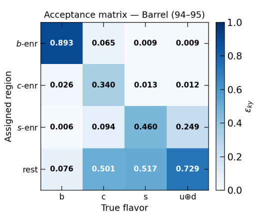
nominal: Data/MC closure · proxy: MC-only cross-check

Eight observed counts

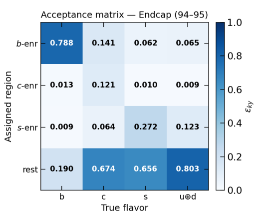


Dashed: pre-fit SM · solid: profiled 18-parameter fit

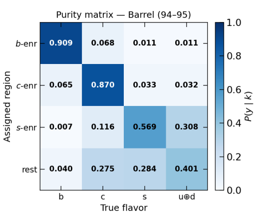
Acceptance and purity define the eight-bin response



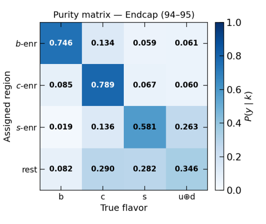
Acceptance barrel



Acceptance endcap



Purity barrel



Purity endcap

Acceptance $A_{r,t,f}$
truth flavor $f \rightarrow$ assigned bin t · direct likelihood input

Purity $P(f \mid r, t)$
SM-weighted composition · barrel/endcap contrast · working-point interpretation

Eight counts constrain three POIs and fifteen nuisance parameters

Poisson counting model

$$n_{r,t} \sim \mathrm{Pois}\left[(N_r - B_r) \sum_{f=b,c,s,ud} R_f A_{r,t,f}(\boldsymbol{\theta}, \alpha_{\mathrm{frag}}) + B_{r,t} \right]$$

$$R_{ud} = 1 - R_b^0 - R_c^0 - R_s^0$$

$$-2 \ln L = -2 \sum_{r,t} \ln \mathrm{Pois}(n_{r,t} \mid \lambda_{r,t}) + \sum_i \frac{(\theta_i - \mu_i)^2}{\sigma_i^2}$$

Parameter inventory

$$3 + 15 = 18$$

3 POIs: R_b^0, R_c^0, R_s^0
8 flavor-column response NPs
4 detector / bin-response NPs
2 $ud \to s$ mistag NPs
1 fragmentation NP

$Z \to \tau\tau$ background

KoralZ template · $f_\tau = 0.489\%$ · $10,104$ events per-bin 0.04%–1.34% · fixed additive term · $\pm 2\%$ normalization negligible

Uncertainty propagation

15 Gaussian-constrained NPs profiled · threshold choice as external discrete envelope

Fifteen constrained nuisance parameters: priors and definitions

How each flavor-column prior is set

Data–MC gap + statistics $\Longrightarrow$ **Core response width** $\oplus$ **Hadronization allowance** $\Longrightarrow$ **Gaussian response prior**

$|\delta_{\mathrm{data-MC}}| + \sigma_{\mathrm{stat}}$ | σ_{core} | $\sigma_{\mathrm{had,f}}$ | $\delta_f \sim N(0, \sigma_f)$

current: signal-region residual $\rightarrow$ circularity risk $\Longrightarrow$ replace with: source-specific MC variations / independent CR calibration

Flavor response · 8 NPs

Parameter	Prior	Target
δ_b^{brl}	$N(0, 0.00384)$	barrel b
δ_b^{ec}	$N(0, 0.00496)$	endcap b
δ_c^{brl}	$N(0, 0.00928)$	barrel c
δ_c^{ec}	$N(0, 0.01604)$	endcap c
δ_s^{brl}	$N(0, 0.02214)$	barrel s
δ_s^{ec}	$N(0, 0.03433)$	endcap s
$\delta_{ud}^{\mathrm{brl}}$	$N(0, 0.01811)$	barrel ud
$\delta_{ud}^{\mathrm{ec}}$	$N(0, 0.03417)$	endcap ud

core + hadronization in each width

Detector, bin, physics · 7 NPs

Parameter	Prior	Target / source
$\delta_{\mathrm{det,l}}^{\mathrm{brl}}$	$N(0, 0.010)$	barrel IP
$\delta_{\mathrm{det,l}}^{\mathrm{ec}}$	$N(0, 0.00880)$	endcap common
$\delta_{\mathrm{pid}}^{\mathrm{brl}}$	$N(0, 0.015)$	PID envelope
$\delta_{\mathrm{ec,res}}$	$N(0, 0.021)$	endcap s-enr.
$\delta_{ud\to s}^{\mathrm{brl}}$	$N(0, 0.15)$	barrel mistag
$\delta_{ud\to s}^{\mathrm{ec}}$	$N(0, 0.15)$	endcap mistag
α_{frag}	$\mathcal{N}(+.031, .029)$	kaon yield

α_{frag} best fit $+0.0134$ · pull -0.63σ

Hadronization + threshold

$\sigma_{\mathrm{had}}^{b/c/s/ud} = (.0024, .0058, .0125, .0121)$ in flavor priors · external WP $\Delta(R_b^0, R_c^0, R_s^0) = (.00016, .00010, .00151)$

Systematic uncertainty coverage and remaining estimates

Total systematic inventory

Source	Status	Prior / variation	ΔR_b^0	ΔR_c^0	ΔR_s^0
Included in the quoted uncertainty					
flavor-column response (8 NPs)	covered	0.00384–0.03433	0.00075	0.00144	0.01132
$ud \to s$ mistag (2 NPs)	covered	$N(0, 0.15)$ / region	0.00011	0.00033	0.02418
detector / PID / bin response	covered	0.00880–0.021	0.00008	0.00007	0.01012
fragmentation response	covered	$\mathcal{N}(+.031, .029)$	0.00044	0.00034	0.00583
hadronization proxy	covered	$\sigma_{\text{had}}^{b/c/s/ud}$	0.00053	0.00106	0.00995
threshold choice	covered	discrete WP envelope	0.00016	0.00010	0.00151
$Z \to \tau\tau$	covered	$f = 0.489\%$, norm. $\pm 2\%$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$
quoted total	covered	NP covariance $\oplus$ threshold	**0.00084**	**0.00148**	**0.02541**
Not yet represented by independent nuisance parameters					
independent tag calibration	partial	no independent prior	$\lesssim 0.00075$	$\lesssim 0.00144$	$\lesssim 0.02418$
hard radiation / topology	open	DELPHI gluon-rad. scale	~ 0.00022	–	–
1995 beam / ISR composition	open	peak-only joint stress	0.00024	0.00026	0.00440
year-specific detector response	partial	raw 1994/95 diagnostic	0.00055	0.00538	0.0429

covered rows enter the quoted total and report the largest marginal impact per POI · open estimates overlap and must not be added as independent 1σ terms

POI correlations remain below 0.27

Largest magnitude

$$\max|\rho_{ij}| = 0.262$$

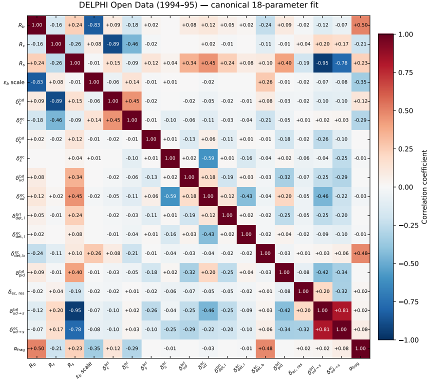
POI correlation coefficients

$\rho(R_b^0, R_c^0)$	-0.161
$\rho(R_b^0, R_s^0)$	$+0.240$
$\rho(R_c^0, R_s^0)$	-0.262

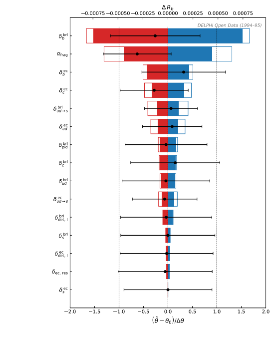
Interpretation

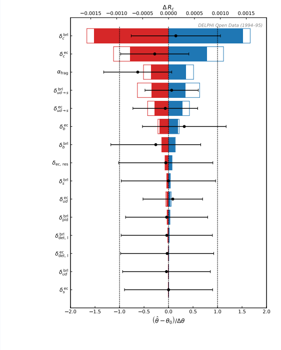
weak-to-moderate POI coupling ·
larger NP–POI / NP–NP structure

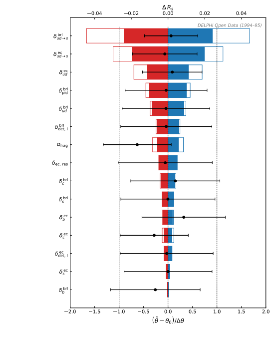
Full 18-parameter correlation matrix



Marginal impacts identify the limiting response directions







R_b^0 leading term

δ_b^{brl}: $\Delta R_b^0 = 0.00075$

R_c^0 leading term

δ_c^{brl}: $\Delta R_c^0 = 0.00144$

R_s^0 leading term

$\delta_{ud\to s}^{\mathrm{brl}}$: $\Delta R_s^0 = 0.02418$

Marginal post-fit impacts; correlated projections, not additive rows

Joint result and barrel/endcap cross-checks

R_b^0
0.21618
$\pm 0.00035_{\text{stat}} \pm 0.00084_{\text{syst}}$

R_c^0
0.17204
$\pm 0.00064_{\text{stat}} \pm 0.00148_{\text{syst}}$

R_s^0
0.22357
$\pm 0.00138_{\text{stat}} \pm 0.02541_{\text{syst}}$

Detector-region fits

Region	R_b^0	R_c^0	R_s^0
Barrel	$0.21600 \pm 0.00040 \pm 0.00106$	$0.17227 \pm 0.00069 \pm 0.00313$	$0.23227 \pm 0.00166 \pm 0.04418$
Endcap	$0.21780 \pm 0.00073 \pm 0.00361$	$0.16958 \pm 0.00179 \pm 0.00621$	$0.22820 \pm 0.00269 \pm 0.04722$

External comparison

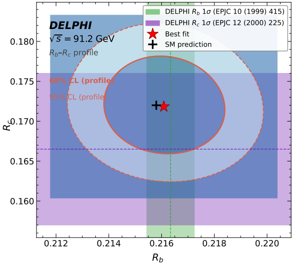
R_b^0: DELPHI compatible · R_c^0: SM compatible
R_s^0: OPAL $d = s$ comparison within uncertainty

Precision regime

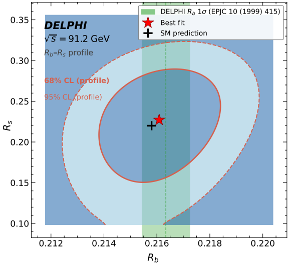
R_b^0, R_c^0: response-prior limited · R_s^0: $ud \to s$ mistag and light-flavor response limited

Two-dimensional profile-likelihood contours

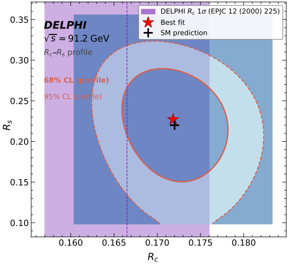
R_b^0–R_c^0



R_b^0–R_s^0



R_c^0–R_s^0



Fit geometry

68% and 95% profile contours · all remaining parameters profiled · legacy contour set retained

Year combination: which uncertainties must decorrelate

1995 off-peak share

31.85%

selected data

Peak-only residual split

$4.17\sigma_{R_c^0}$, $10.49\sigma_{R_s^0}$

beam mix not sufficient

ISR score response

0.84%

maximum argmax TVD

Cross-year covariance model

Source	1994–1995 treatment	Fit representation
R_b^0, R_c^0, R_s^0	correlated	common POIs
fragmentation / hadronization physics	correlated	common physics-response terms
$Z \to \tau\tau$ width normalization	correlated	common normalization
beam-energy mix / ISR exposure	decorrelated	year-specific composition / variation
RICH, TPC, VD calibration and validity	decorrelated or period blocks	year-specific detector-response NPs
MC acceptance statistics	decorrelated	independent year/flavor covariance
run quality / `Beam_errorCode` residuals	decorrelated	year-specific data-quality term

Combination principle

shared physics $+$ year-specific detector / beam / MC terms $\neq$ raw 1994–1995 spread as one extra nuisance

Summary: direct R_s^0, compact counting fit, remaining response work

Physics result

$R_b^0 = 0.21618 \pm 0.00091$ $R_c^0 = 0.17204 \pm 0.00161$

$R_s^0 = 0.22357 \pm 0.02544$

direct R_s^0 · no $d = s$ constraint · LEP / SM compatible

Analysis design

2.064M events · holistic five-flavor ParticleNet
8 exclusive counts · barrel + endcap
3 POIs · 15 constrained NPs · fixed $\tau\tau$

Uncertainty picture

R_b^0: δ_b^{brl} · R_c^0: δ_c^{brl}
R_s^0: $ud \to s$ mistag + light-flavor response
threshold envelope external · $\max|\rho_{\mathrm{POI}}| = 0.262$

Next uncertainty model

independent tag-response calibration
alternative-generator acceptance variations
year-specific RICH / TPC / beam composition
1992–1993: dedicated retraining or score calibration

Main message

modern event classification recovers LEP flavor information; final precision now follows the response model