Recent Heavy-Flavor Measurements from OPAL

Tom Junk
Carleton University
Ottawa, Canada

for the
OPAL Collaboration

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- Average Polarization of b Baryons
- Search for the Radial Excitation $D^{*'}$
- Measurement of the product B.R.

$$f(b \to \Lambda_b) \cdot BR(\Lambda_b \to \Lambda X)$$

Studying the Longitudinal Polarization of b Baryons in Z^0 Decays

Z^0 coupling to b quarks almost maximally parity-violating

$$P_b = \frac{2v_b a_b \beta(1+\cos^2\theta)+2r_e(v_b^2+a_b^2\beta)\cos\theta}{(v_b^2+a_b^2)\beta^2(1+\cos^2\theta)+v_b^2(1-\beta^2)+4r_e v_b a_b \beta^2\cos\theta}$$

where

$$r_e = (4\sin^2\theta_W - 1)(8\sin^4\theta_W - 4\sin^2\theta_W + 1)$$

$$\langle P_b \rangle = -0.94$$

With only a 2% variation over cosθ

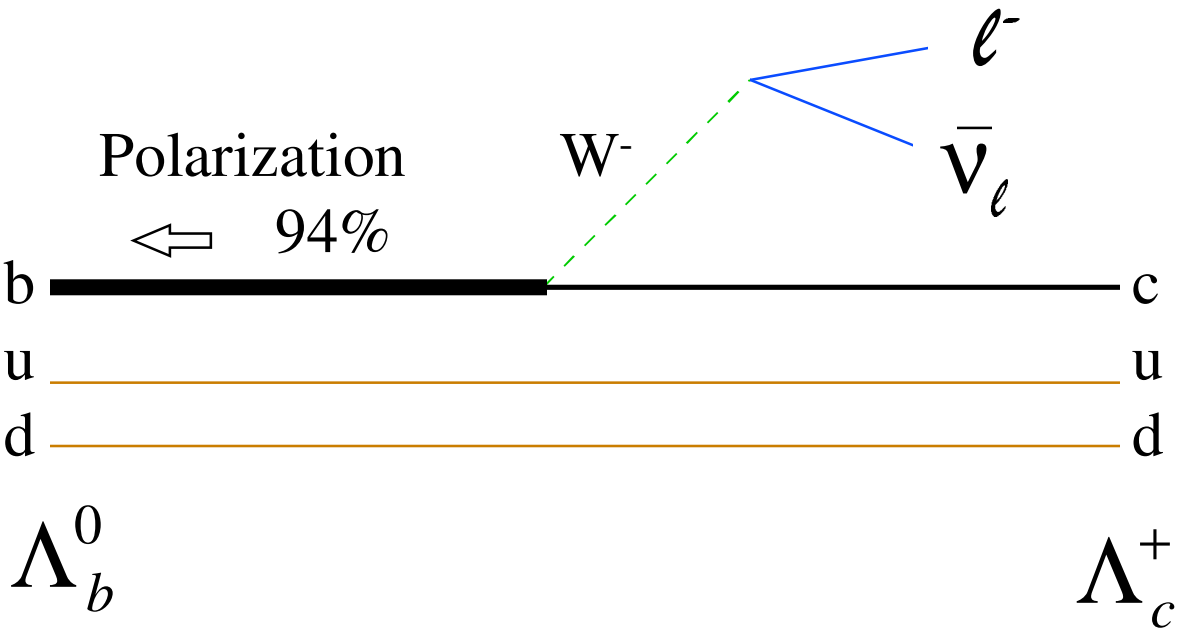
c.f. A_b and A_{FB} forward-backward asymmetries

Some of this polarization survives fragmentation and hadronization, but how much?

B^0, $B^{\pm}$ are pseudoscalars -- no polarization possible
B^* decays with an isotropic γ -- polarization not measurable. Look to b Baryons

b Baryon Polarization

Polarization-analyzing leptons



Directly (non cascade) produced Λ_b's expected to retain close to full polarization

Non Weakly-Decaying b Baryons:

$\Sigma_b^+ = [(uu)_1 b]_{1/2}$

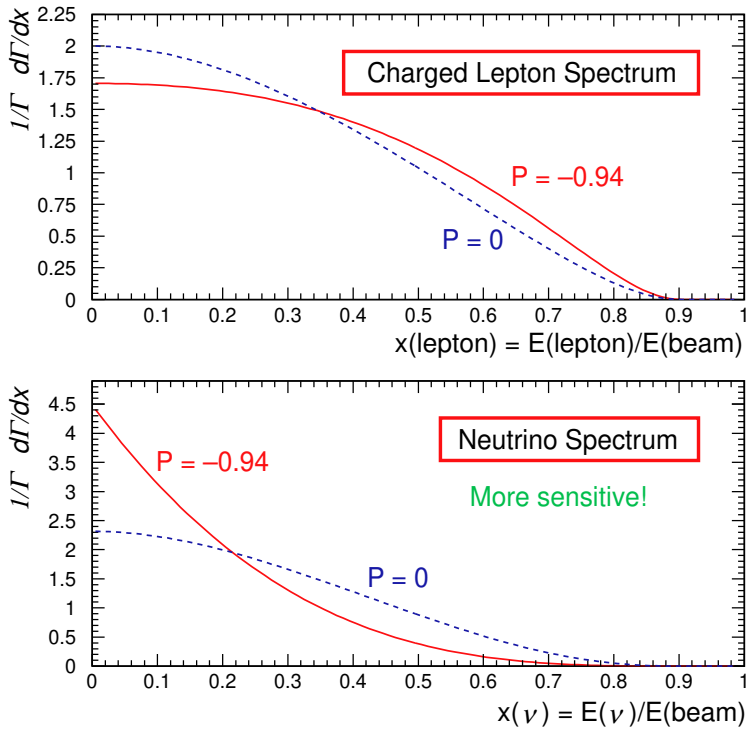
$\Sigma_b^{+*} = [(uu)_1 b]_{3/2}$ (strong decays)

➡ *Dilution of polarization*

Falk and Peskin, PRD**49** (1994) 3320.

Polarization-Dependent Lepton Momenta

Semileptonic decay conserves angular momentum, violates parity. Lepton forwards, neutrino backwards, in Λ_b frame.



Modeling uncertainties in spectrum

- B fragmentation function
- form factors
- quark masses
- ISGW**/ACCMM spectra

Ratio of P_ℓ/P_ν is more *(Bonvicini & Randall)*

- statistically sensitive (x4)
- insensitive to modeling

Λ_b *Event Selection*

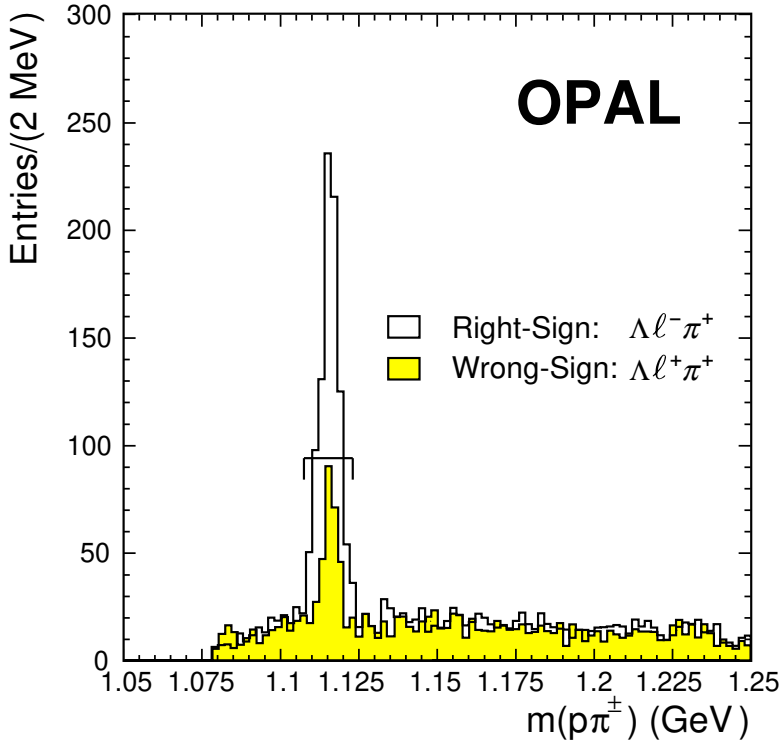
Seek Λ-lepton correlations: (high p, p_t lepton)

$\Lambda_b^0 \to X_c \ell^- \nu_\ell$ "Right-sign:" *signal*

$\hookrightarrow \Lambda X$ "Wrong-sign:" *background*

$\hookrightarrow p\pi^-$

Signal/noise improved using Λ–π^+ correlations in $\Lambda_b^0 \to \Lambda_c^+ X \to \Lambda \pi^+ X$



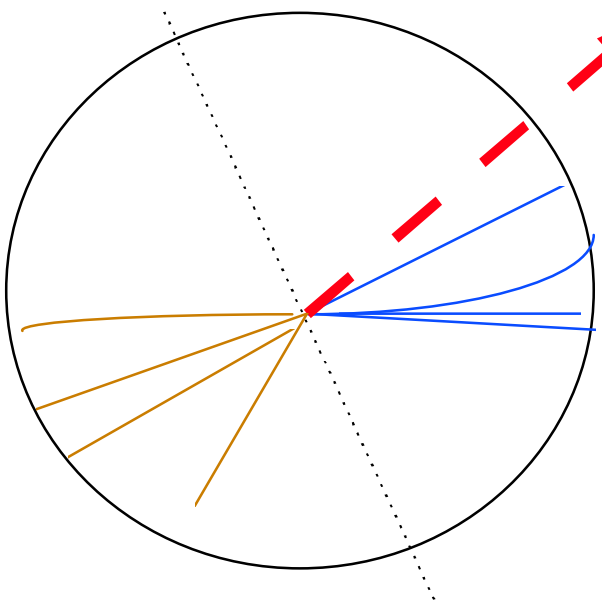
In 4.3 million hadronic Z^0's, have

912 Right-Sign

316 Wrong-Sign

difference: 596

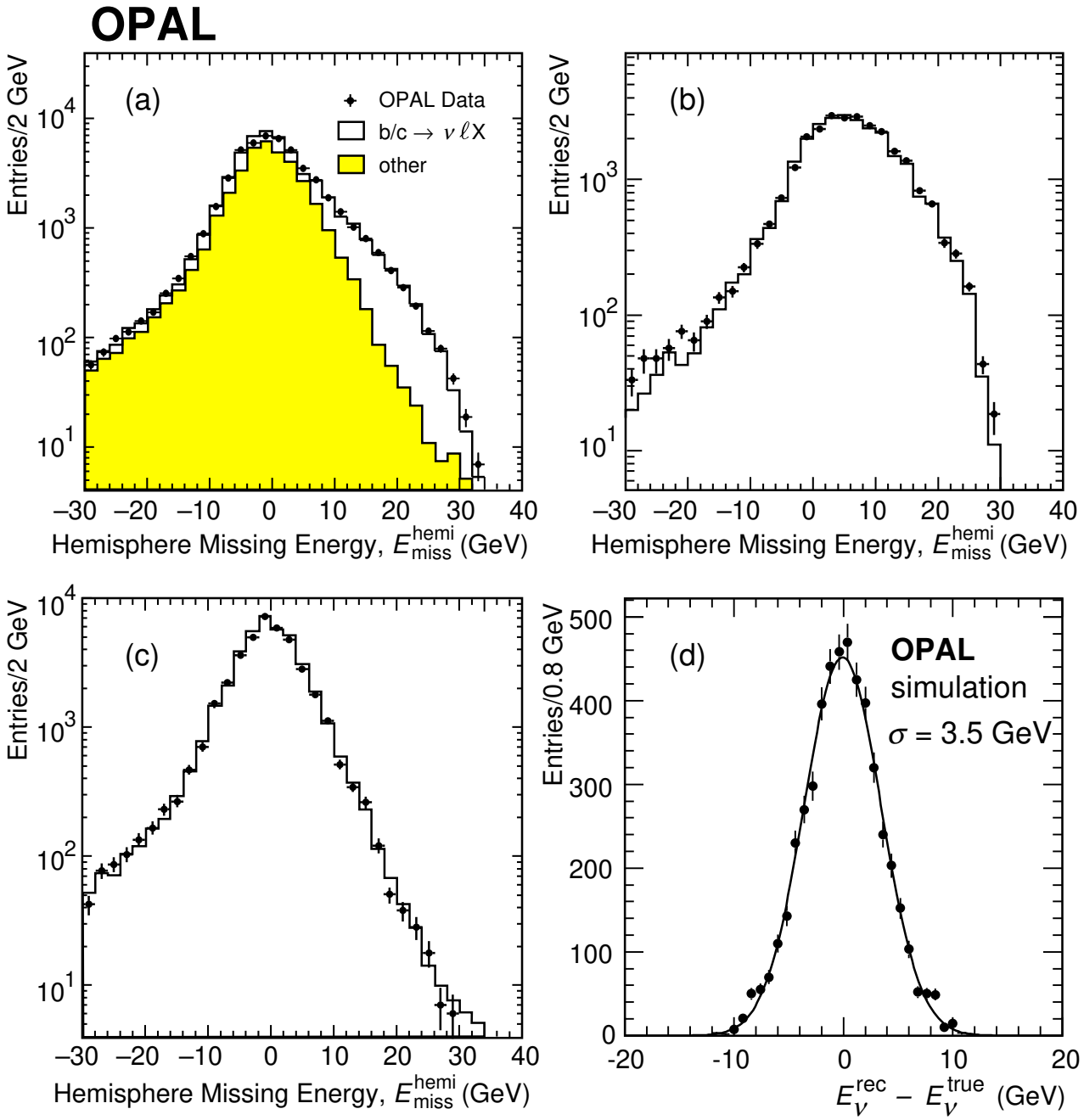
Neutrino Energy Estimation



$$E_\nu = \left[E_{beam} + \frac{M_{hemi}^2 - M_{recoil}^2}{4E_{beam}} \right] - E_{hemi}^{visible}$$

Hemisphere energy estimated from 2-body Z^0 decay kinematics

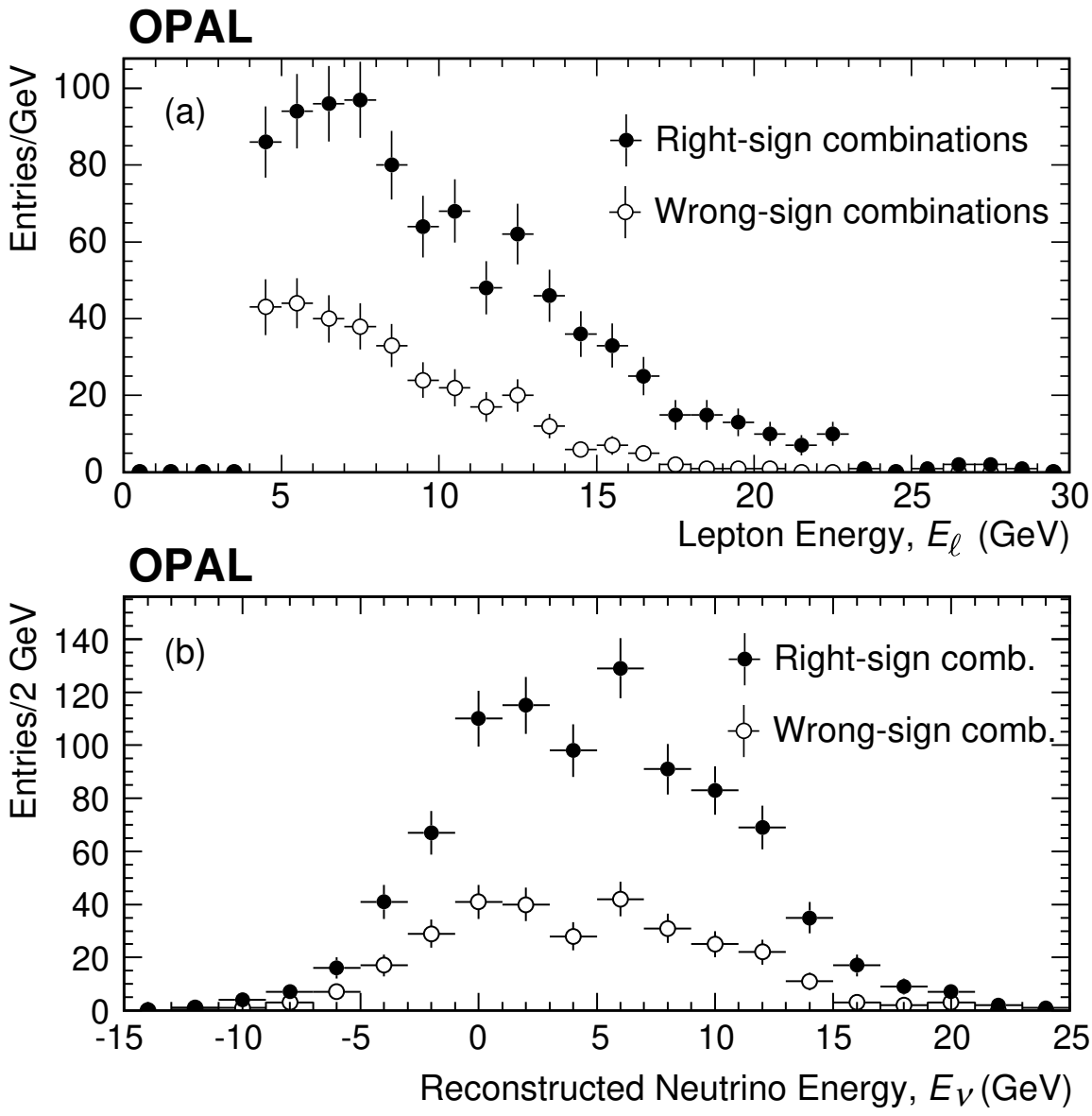
Checking Neutrino Energy Spectrum in Tagged b events



Corrections to MC estimations and syst. errors estimated.

Measured Lepton and Neutrino Spectra

Special to this measurement: take the ratio of E_ν/E_ℓ for each candidate and fit the distribution

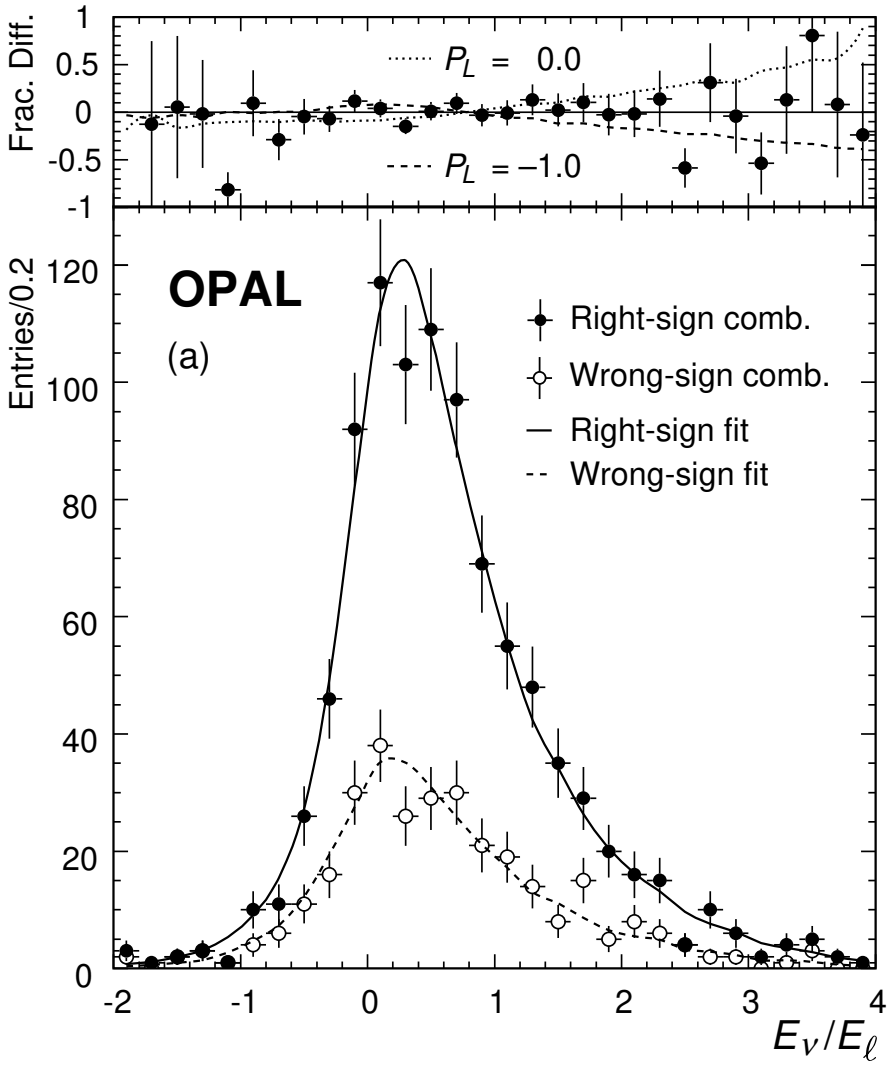


Likelihood Fit to E_ν / E_ℓ Distribution

Depends on $P_{\Lambda b}$

$$PDF_{right-sign} = (1 - f_{bkg})PDF_{signal} + f_{bkg}PDF_{bkg}$$

Estimated with wrong-sign distribution



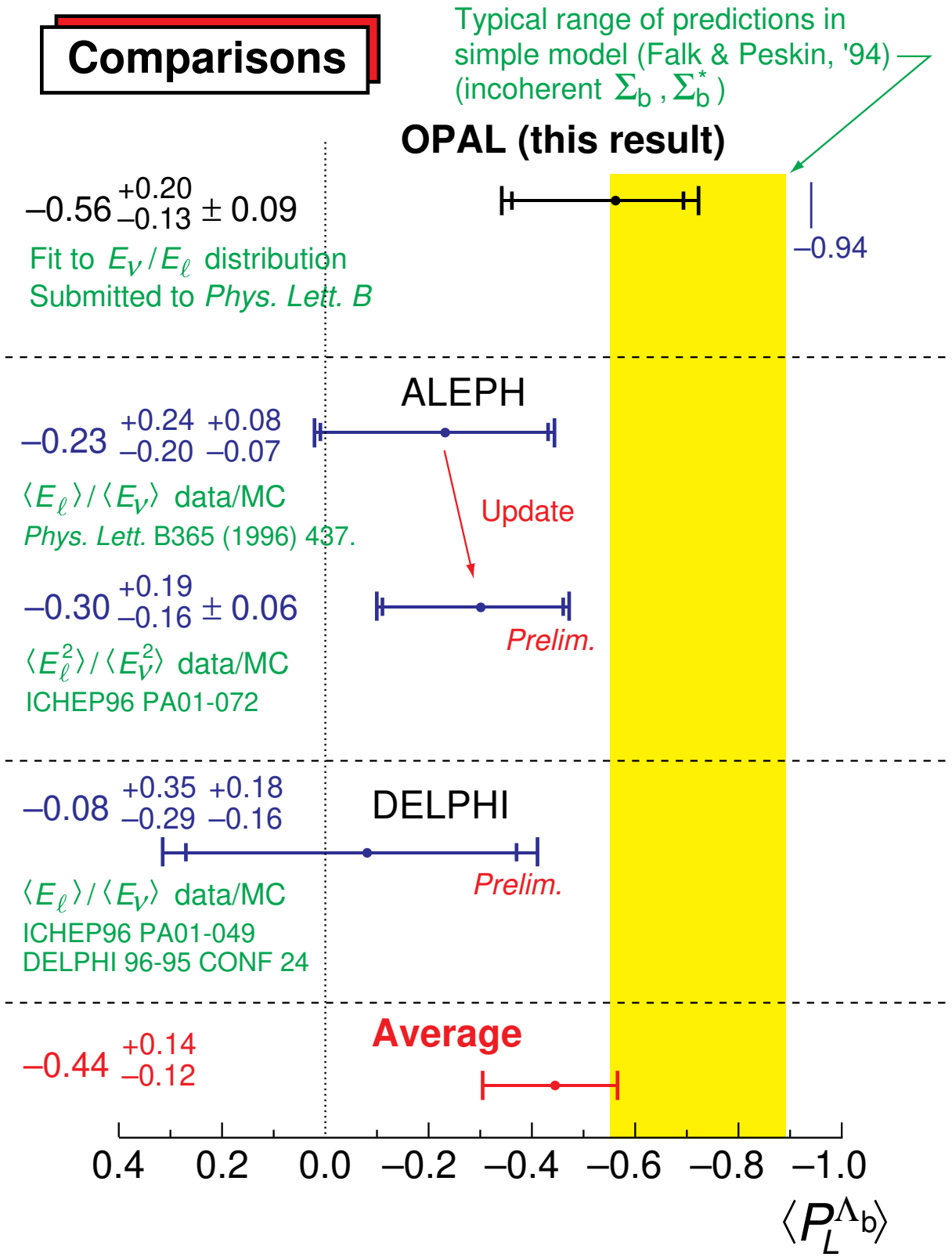
$$\left\langle P_{\Lambda_b} \right\rangle = -0.56^{+0.20}_{-0.13}(stat.)$$

Systematic Uncertainties

Source	$\Delta\left\langle P_{\Lambda_b}\right\rangle$
E_ν reconstruction, shape	± 0.05
E_ν resolution	± 0.02
E_ℓ scale and shape	± 0.03
Bkg fraction and shape	± 0.04
Fitting Method	± 0.03
Selection Criteria	± 0.02
b Fragmentation (x_E weights)	± 0.03
Λ_c Polarization (0:1)	± 0.02
b → τ Decays	± 0.01
Theory (form factors, QCD corr'n, m_c/m_b)	± 0.03
Total	**± 0.09**

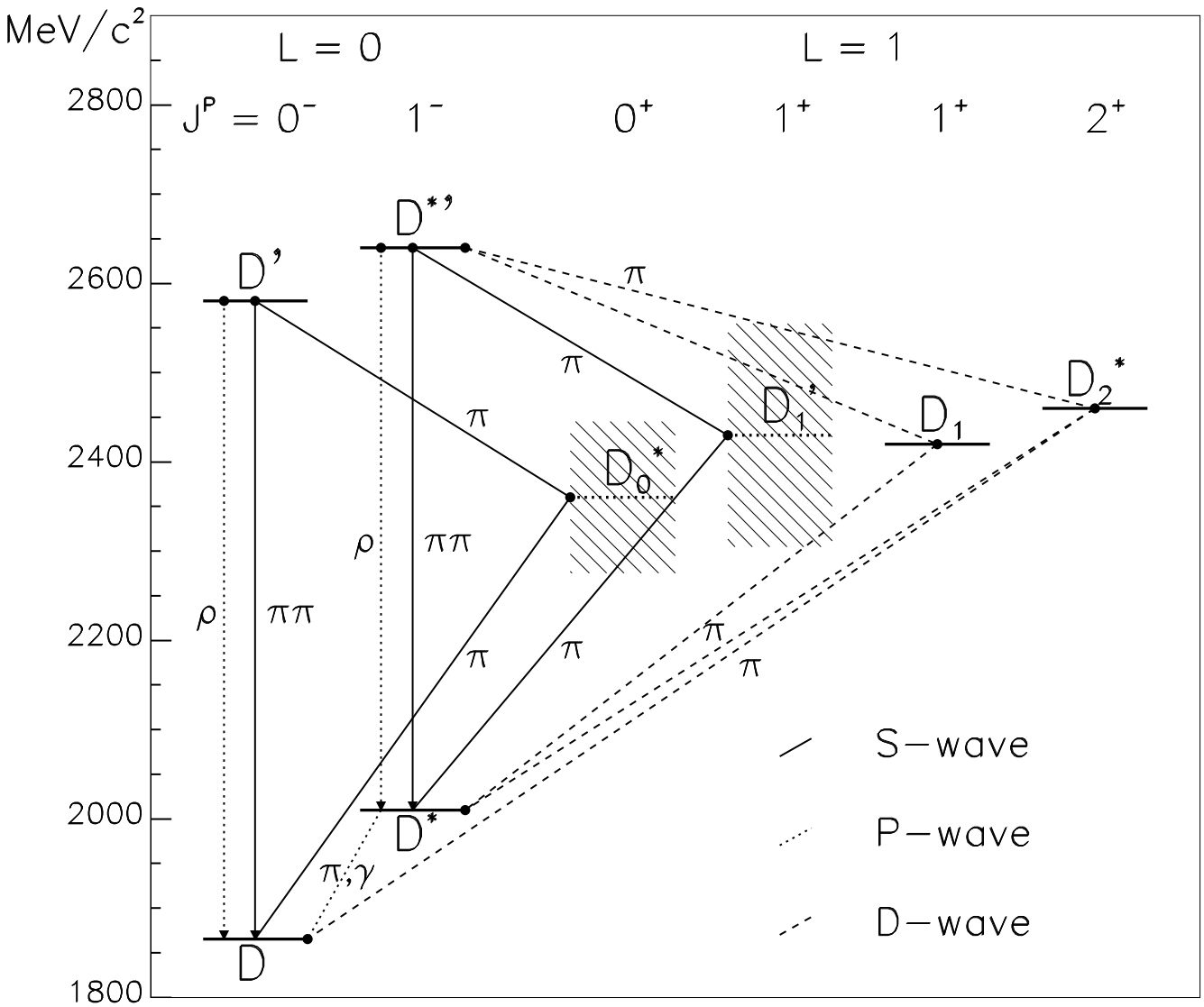
$$\left\langle P_{\Lambda_b}\right\rangle = -0.56^{+0.20}_{-0.13} \pm 0.09$$

World Measurements of b Baryon Polarization



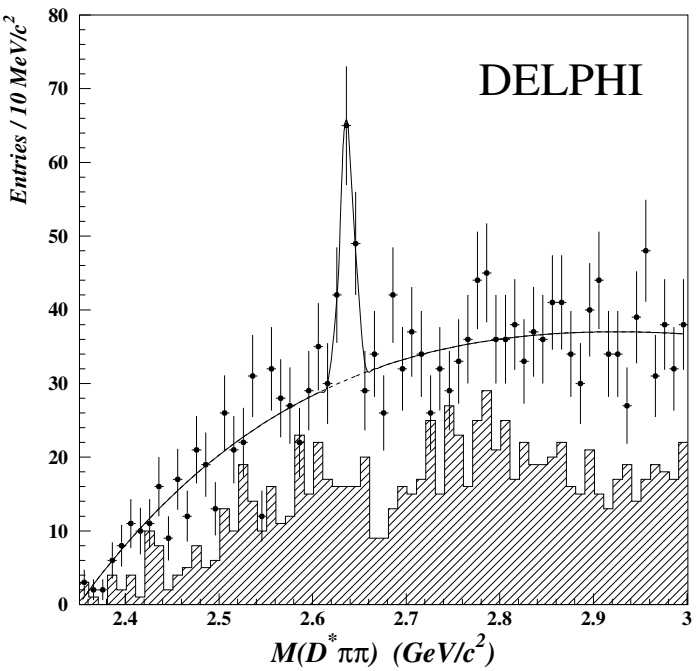
Search for the Radially Excited $D^{*\prime +}$

Expected spectrum of Excitations in the D system:



DELPHI's Observation

Narrow peak in the $D^{*+}\pi^+\pi^-$ mass distribution:



$N_{obs} = 66 \pm 14$ $\quad M = 2637 \pm 2 \pm 6$ MeV

$\Gamma < 15$ MeV @95% CL

D*' Predicted mass: 2629 ± 20 MeV

(Ebert, Galkin, Faustov, 1997)

Predicted width: 40 to 200 MeV

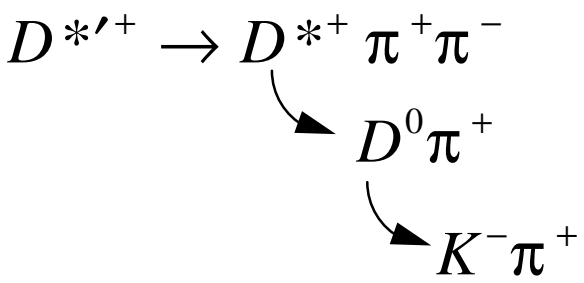
(Melikhov and Péne, 1998)

$$R' \equiv \frac{\bar{n}_{Z^0 \to D^{*\prime\pm}} BR(D^{*\prime +} \to D^{*+}\pi^+\pi^-)}{\sum_{J=1,2} \bar{n}_{Z^0 \to D_J^{(*)0}} BR(D_J^{(*)0} \to D^{*+}\pi^-)}$$

$$= 0.49 \pm 0.18 \pm 0.10$$

OPAL Selection for D′*

Use the same decay chain as DELPHI



No D^0 to $K\pi\pi\pi$ though. Cannot use the $K\pi^{+-}\pi^0$ channel either (need mass resolution)

D* selection uses the usual tricks:

- cut on $m(D^0)$, $\Delta m(D^*,D^0)$
- Helicity angle of Kaon
- dE/dx requirement for Kaon (also loose requirements on dE/dx for $\pi^+\pi^-$ pair

Suppress *uds* background: *Two analysis branches*

b-Enriched:

- Vertex requirements: L/σ_L of $D^0 > 4.0$ (mostly from B hadron lifetime)
- Requirement on D^0, $\pi^+\pi^-$ vertex separation

c-Enriched:

- $x_{D^*} > 0.4$
- $p_{\pi+\pi-} > 3.6$ GeV

D' Search Sensitivity*

OPAL Data sample size: 4.23 million hadronic Z^0 decays (1990 to 1995)

OPAL reconstruction efficiency

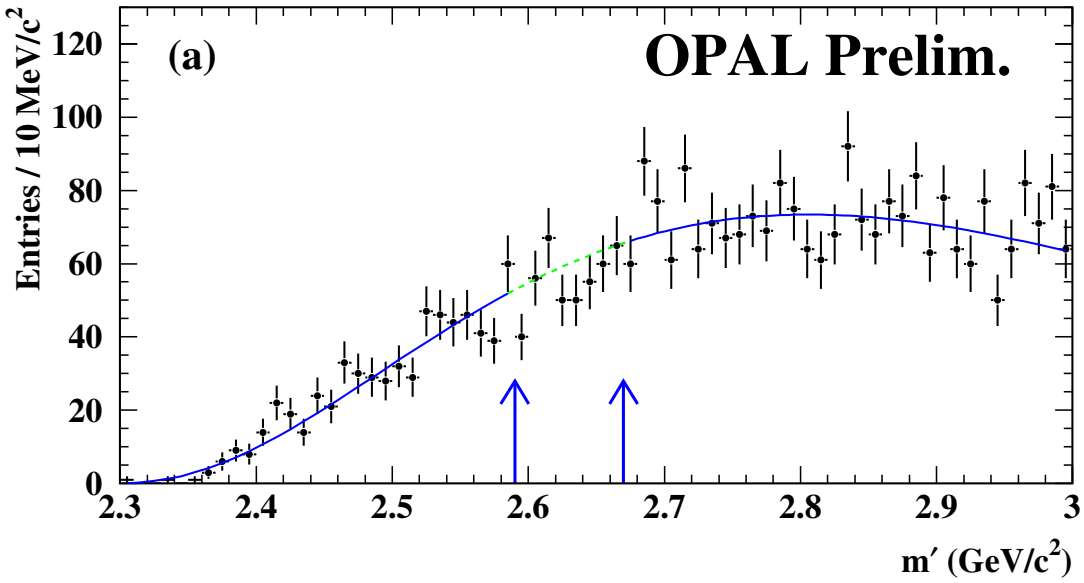
b events: (6.9 ± 0.6)% (error: MC statistics)
c events: (7.1 ± 0.6)%

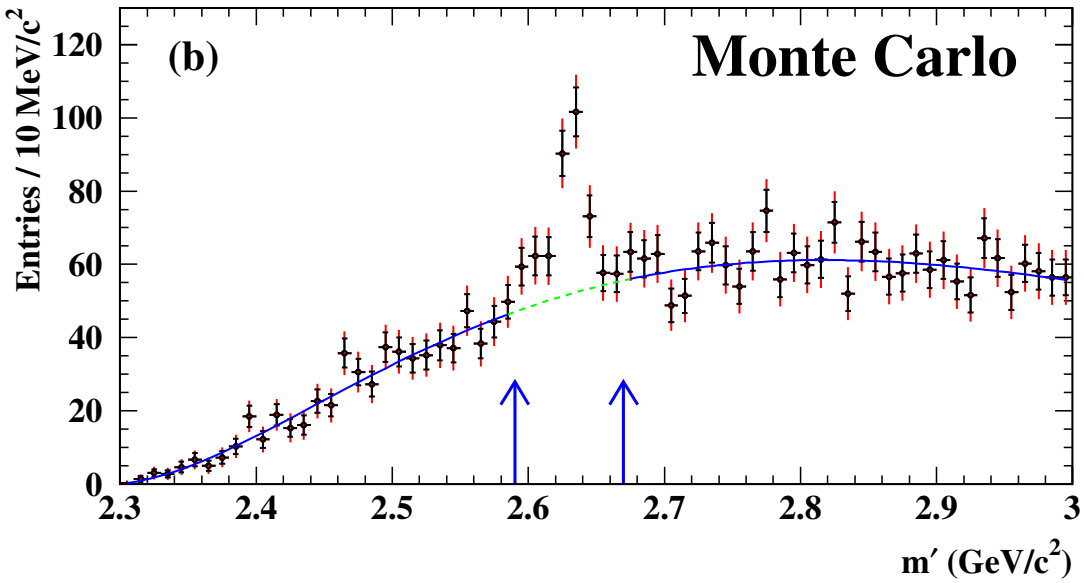
Signal efficiency very similar to that of DELPHI:

$$\frac{\varepsilon \times BR \times N_{hadr.Z^0}(OPAL)}{\sum_{i=1,2} \varepsilon_i \times BR_i \times N_{hadr.Z^0}(DELPHI)} \cong 1.1 \pm 0.1$$

Mass Resolution ~15 MeV (OPAL)
Background rate: 50% higher (combined b and c analyses)

Combined Search Results





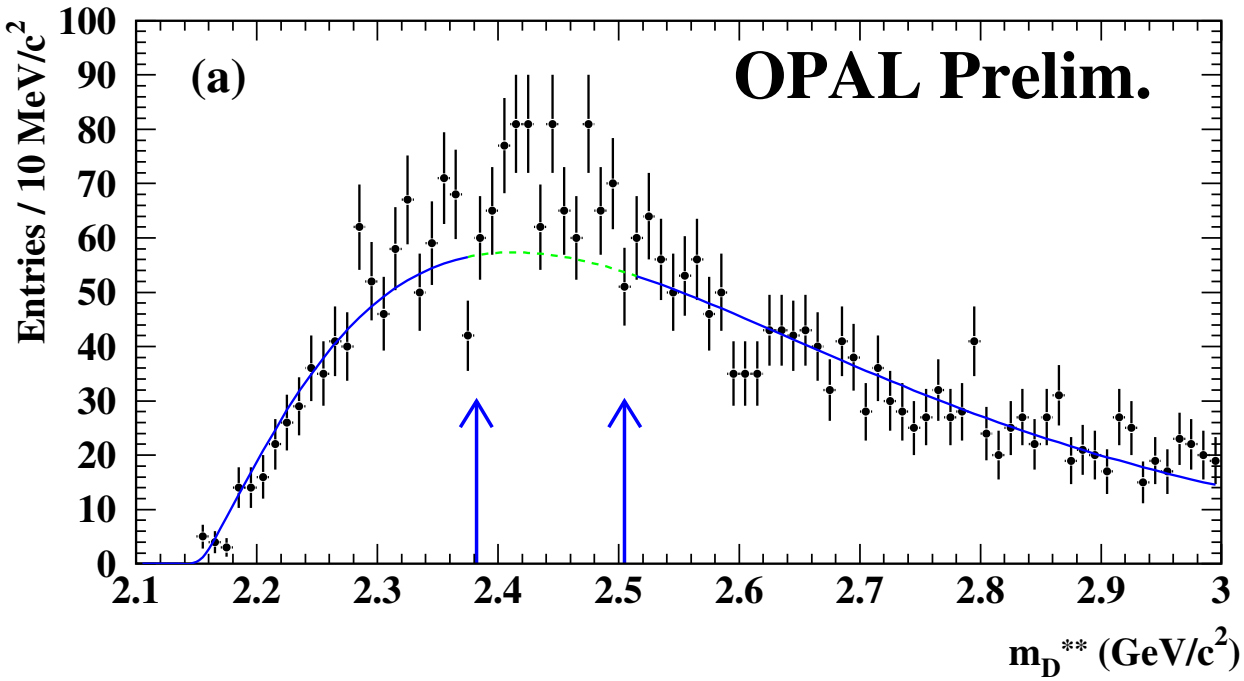
In the signal region, $N(D^{*\prime\pm})=-32\pm24$
(< 32.8 at 95% CL)

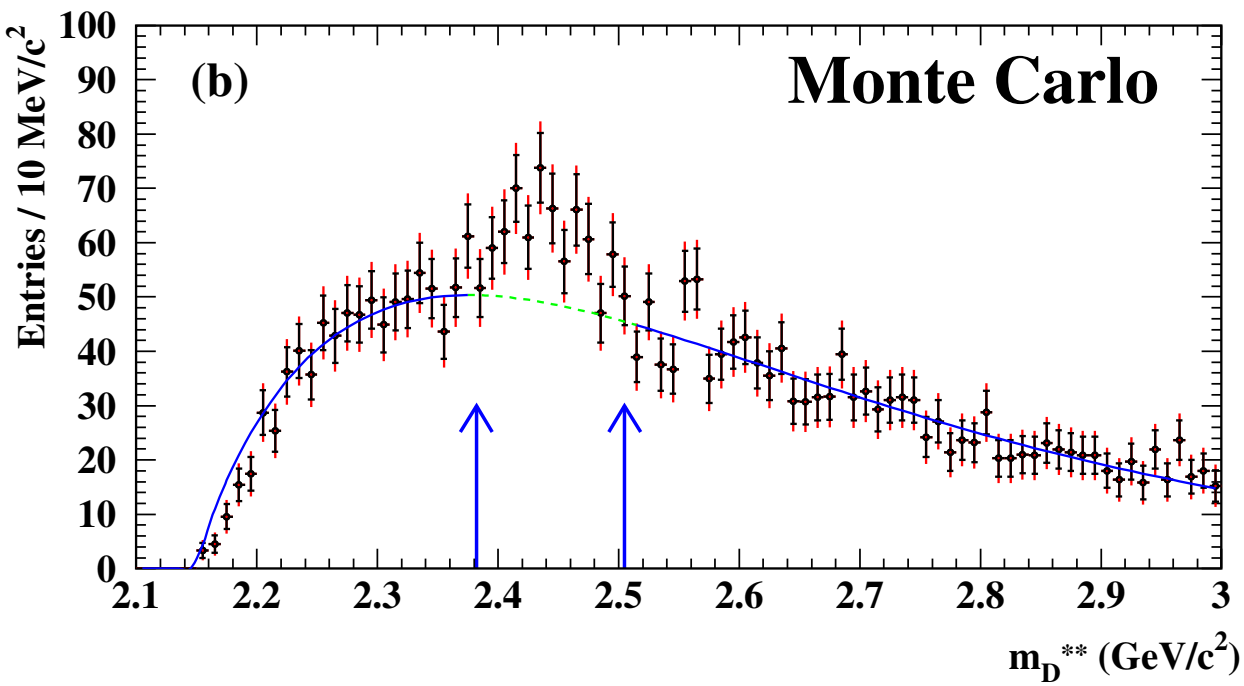
Monte Carlo Signal is normalized to R', the ratio of D*'/D**. Zero width assumed.

~10% b,c sample overlap accounted properly

Cross-Check: Reconstructing Orbitally-Excited D_1^0 and D_2^{*0} States

Same D* reconstruction, similar requirements on the D** decay pion.





Systematic Uncertainties on the Efficiency

Source	*Relative Error on Efficiency*		
	c sample	b sample	combined sample
Monte Carlo Statistics	9.3%	9.1%	6.2%
Detector Resolution	8.9%	0.7%	5.1%
Kaon dE/dx	0.5%	0.9%	0.7%
Pion dE/dx	0.8%	0.8%	0.8%
$D^{*'+}$ Width	1.2%	16.7%	3.6%
Fragmentation Model	2.7%	2.8%	1.9%
Production rate b/c	------	------	0.3%
External Branching ratio uncertainties			
BR($D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$)	3.1%	3.1%	3.1%
Error on Γ_{qq}/Γ_{had}	4.5%	0.6%	------
Total	***14.3%***	***19.5%***	***9.6%***

Systematic uncertainties are incorporated into the limit calculations

Limits on D' Production*

The evidence for D*'±(2629) is not confirmed by OPAL. Poisson Upper Limits on production:

Inclusively in hadronic Z^0 decays:

$$f(Z^0 \to D^{*\prime\pm}(2629)) \times BR(D^{*\prime\pm} \to D^{*+}\pi^+\pi^-) < 2.1 \times 10^{-3}$$

at 95% CL

Separate search limits in b and c events:

For D'± produced in $Z^0 \to c\bar{c}$*

$$f(c \to D^{*\prime\pm}(2629)) \times BR(D^{*\prime\pm} \to D^{*+}\pi^+\pi^-) < 1.2 \times 10^{-2}$$

at 95% CL

For D'± produced in $Z^0 \to b\bar{b}$*

$$f(b \to D^{*\prime\pm}(2629)) \times BR(D^{*\prime\pm} \to D^{*+}\pi^+\pi^-) < 1.0 \times 10^{-2}$$

at 95% CL

The D*'/D** ratio $R < 0.21$ at 95% CL

c.f. DELPHI $R = 0.49 \pm 0.18\ (\text{stat}) \pm 0.10\ (\text{syst})$

Measurement of $f(b \to \Lambda_b) \cdot BR(\Lambda_b \to \Lambda X)$

Important measurement to combine with the OPAL measurement of

$$f(b \to \Lambda_b) \cdot BR(\Lambda_b \to \Lambda \ell X)$$

Z. Phys. **C74** (1997) 423.

to obtain

$$\Gamma(\Lambda_b \to \Lambda \ell X) / \Gamma(\Lambda_b \to \Lambda X)$$

and provide more information about the Λ_b lifetime and semileptonic BR.

Updated measurement, submitted to Eur. Phys. Journal C. Combined with previous measurement.

Λ *Selection*

Requirements:

- Event must have a jet tagged as b

  $\varepsilon=(21.2 \pm 0.9)\%$, $\Pi=(95.5 \pm 0.5)\%$

Requirements on Λ candidates:

- $|\, M(\Lambda)-M(p\pi) \,| < 8$ MeV
- $|\, M(K^0)-M(\pi\pi) \,| > 6$ MeV
- Significant $r\phi$ impact parameter for both p and π
- dE/dx requirement on proton
- 8 cm decay flight distance in $r\phi$
- Momentum pointing: 14 mrad
- No hits in silicon microvertex det.
- $P(\Lambda) > 5$ GeV
- P within 0.2 radians of jet axis

Fake Λ rate: 2% (sidebands of $M(p\pi)$)
same in data and MC
mostly a real Λ and a random track

1582 Events pass selection

Backgrounds to $\Lambda_b \rightarrow \Lambda X$

Fragmentation Λ's in b events

- Associated with Λ_b production, or
- Associated with a light baryon

Similar p and p_t distributions -- both softer than the signal.

Λ's from B Meson Decay

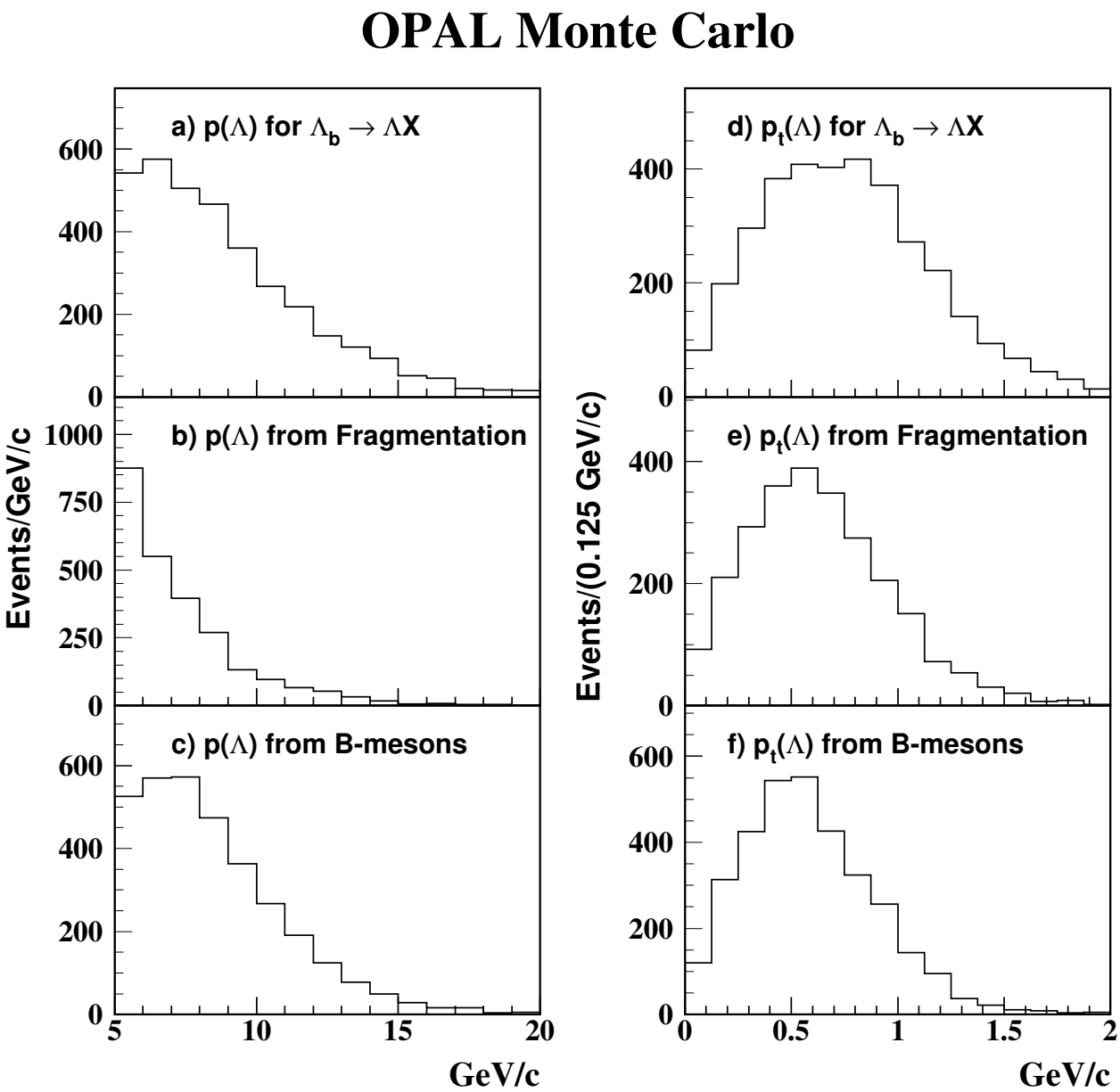
- Small BR, but most b hadrons are B mesons
- Softer p and p_t than the signal.

Other Sources of Λ Baryons

- 3% total. Mostly from D^+ passing the b-tag, associated with fragmentation Λ's
- D^+ decay to Λ and another baryon kinematically impossible
- *uds* events < 1% of sample

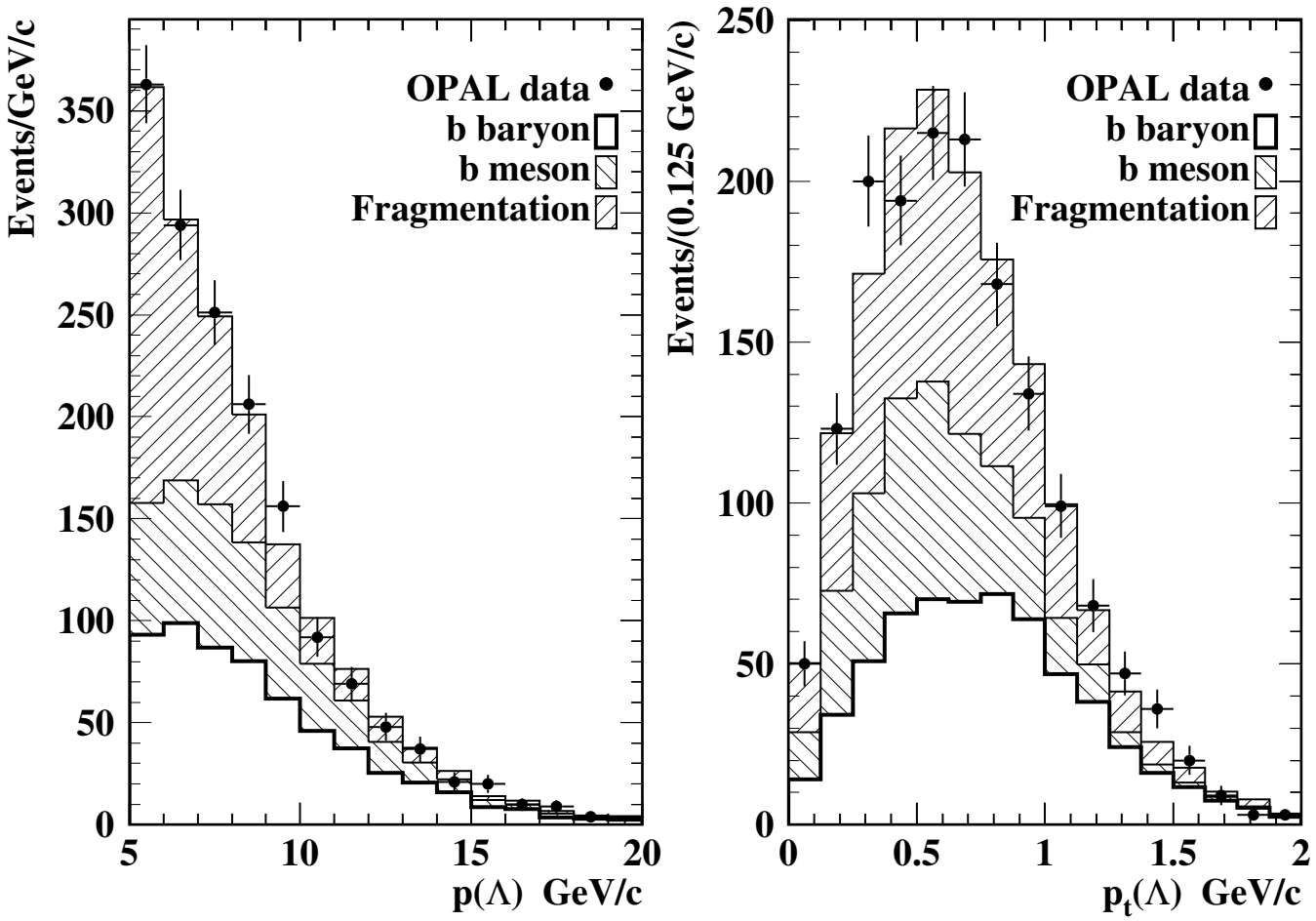
Separate these backgrounds from signal using p and p_t (wrt the nearest jet. Λ is included in the jet)

Discriminating Power of P and P_t



Shapes important in fit; MC rates play no role.
P and P_t have a 25% correlation.

Fitting for the Λ_b, Fragmentation, and B Meson Fractions



Source	*Fit Fract (%)*	*Correlations*		
		$\Lambda_b \to \Lambda X$	$frag \to \Lambda X$	$B \to \Lambda X$
$\Lambda_b \to \Lambda X$	37.4 ± 5.3	1.0	-0.15	-0.64
$frag \to \Lambda X$	37.1 ± 5.1	-0.15	1.0	-0.61
$B \to \Lambda X$	25.5 ± 6.6	-0.64	-0.61	1.0

Systematic Uncertainties on Fit Fractions

Source	Relative Uncertainty on f_{Λ_b} Negative Error	Positive Error
p(Λ), p_t(Λ) in B→ΛX	-3.5%	3.5%
p(Λ) of Frag Λ's	-1.3%	0.8%
p_t(Λ) of Frag Λ's	-12.5%	12.7%
p(Λ) of Λ_b→ΛX	-2.9%	4.8%
p_t(Λ) of Λ_b→ΛX	-16.6%	19.8%
Tracking Modeling	-2.7%	2.7%
Total	***-21.5%***	***24.4%***

- p, p_t in B meson decays from CLEO
- p, p_t of Frag. Λ's from wrong-sign Λ-lepton correlations with a high-p,p_t lepton with m(Λ,lepton) > 2 GeV
- p, p_t of Λ's from Λ_b decay from right-wrong sign Λ–lepton combinations.
- Checked with leptons in opposite hemi to Λ to reduce bias. Less sensitive due to mixing.

B-tag Efficiency and Purity from the Data

Fix R_b, compute eff'y for b and non-b using double-tags (R_b measurement in reverse)

$$R_b \varepsilon_b + (1 - R_b)\varepsilon_{udsc} = f_{1v}$$

$$R_b \varepsilon_b^2 + (1 - R_b)\varepsilon_{udsc}^2 = f_{2v}$$

$$\varepsilon_b = (21.2 \pm 0.9)\%$$

But ε_b is lower for events with a Λ_b and/or Λ

- shorter lifetime of the Λ_b
- Λ's not included in vertex tag and reduce mometa of the tracks that are
- Even fragmentation Λ's reduce ε

Address these biases:

- Count Λ's in hemispheres containing and opposite b-tags.
- Adjust MC ε for Λ_b, frag, B meson classes to match the same/opposite rate (50% change in efficiency!)

$$\varepsilon_b^{sig} = \varepsilon^b_{\Lambda_b \to \Lambda X} + \varepsilon_b (1 - \varepsilon^b_{\Lambda_b \to \Lambda X}) = (29.4 \pm 1.5)\%$$

Systematic Uncertainties on $f(b \to \Lambda_b) \times BR(\Lambda_b \to \Lambda X)$

Impacts of model inputs and measurements via

$$f(b \to \Lambda_b) \times BR(\Lambda_b \to \Lambda X) = \frac{N_\Lambda f_{\Lambda_b}}{2 R_b N_{hadrZ^0} \varepsilon_\Lambda \varepsilon^b_{sig} BR(\Lambda \to p\pi)}$$

Quantity	***Value***	***Uncertainty on*** $f(b \to \Lambda_b) \times BR(\Lambda_b \to \Lambda X)$
N_Λ	1582 ± 40 (stat)	± 0.07 (stat)
f_{Λ_b}	$0.374 \pm 0.053(stat)^{+0.091}_{-0.080}(sys)$	$0.38(stat)^{+0.65}_{-0.57}(sys)$
R_b	0.2169 ± 0.0012 (sys)	± 0.01 (sys)
$N_{hadr.Z}$	2,323,302	-----
ε_Λ	0.117 ± 0.006 (sys)	± 0.14 (sys)
ε^b_{sig}	0.294 ± 0.015 (sys)	± 0.14 (sys)
$BR(\Lambda \to p\pi)$	0.639 ± 0.005 (sys)	± 0.02 (sys)

Result and Interpretation

This measurement:

$$f(b \to \Lambda_b) \times BR(\Lambda_b \to \Lambda X) = (2.67 \pm 0.38(stat)^{+0.67}_{-0.60}(sys))\%$$

Combined with previous OPAL "companion baryon" analysis (Z. Phys. **C74** (1997) 423):

$$f(b \to \Lambda_b) \times BR(\Lambda_b \to \Lambda X) = (3.50 \pm 0.32(stat) \pm 0.35(sys))\%$$

Using $f(b \to \Lambda_b) = (10.1^{+3.9}_{-3.1})\%$

C. Caso *et al.*, Eur. Phys. J. **C3** (1998) 17.

$$BR(\Lambda_b \to \Lambda X) = (35^{+14}_{-12})\%$$

An updated $R_{\Lambda\ell}$ (related to the semileptonic BR)

$$R_{\Lambda\ell} = BR(\Lambda_b \to \Lambda\ell X) \,/\, BR(\Lambda_b \to \Lambda X) = (8.0 \pm 1.2 \pm 0.9)\%$$

Consistent with the short Λ_b lifetime coming from the hadronic width.

Summary

- Lots of new heavy-flavor physics results from OPAL this year.
- Much more summarized in reviews on R_b, lifetimes, semileptonic BR's, CP violation studies, etc.

Average Longitudinal Polarization of b Baryons

$$\left\langle P_{\Lambda_b} \right\rangle = -0.56^{+0.20}_{-0.13} \pm 0.09$$

Search for the Radially Excited $D^{*\prime +}$

$$f(Z^0 \to D^{*\prime\pm}(2629)) \times BR(D^{*\prime\pm} \to D^{*+}\pi^+\pi^-) < 2.1 \times 10^{-3}$$

At 95% CL

Measurement of $f(b \to \Lambda_b) \cdot BR(\Lambda_b \to \Lambda X)$

$$f(b \to \Lambda_b) \times BR(\Lambda_b \to \Lambda X) =$$

$$(2.67 \pm 0.38(stat)^{+0.67}_{-0.60}(sys))\%$$