Experimental review of b & c Hadronization in High Energy e^+e^-

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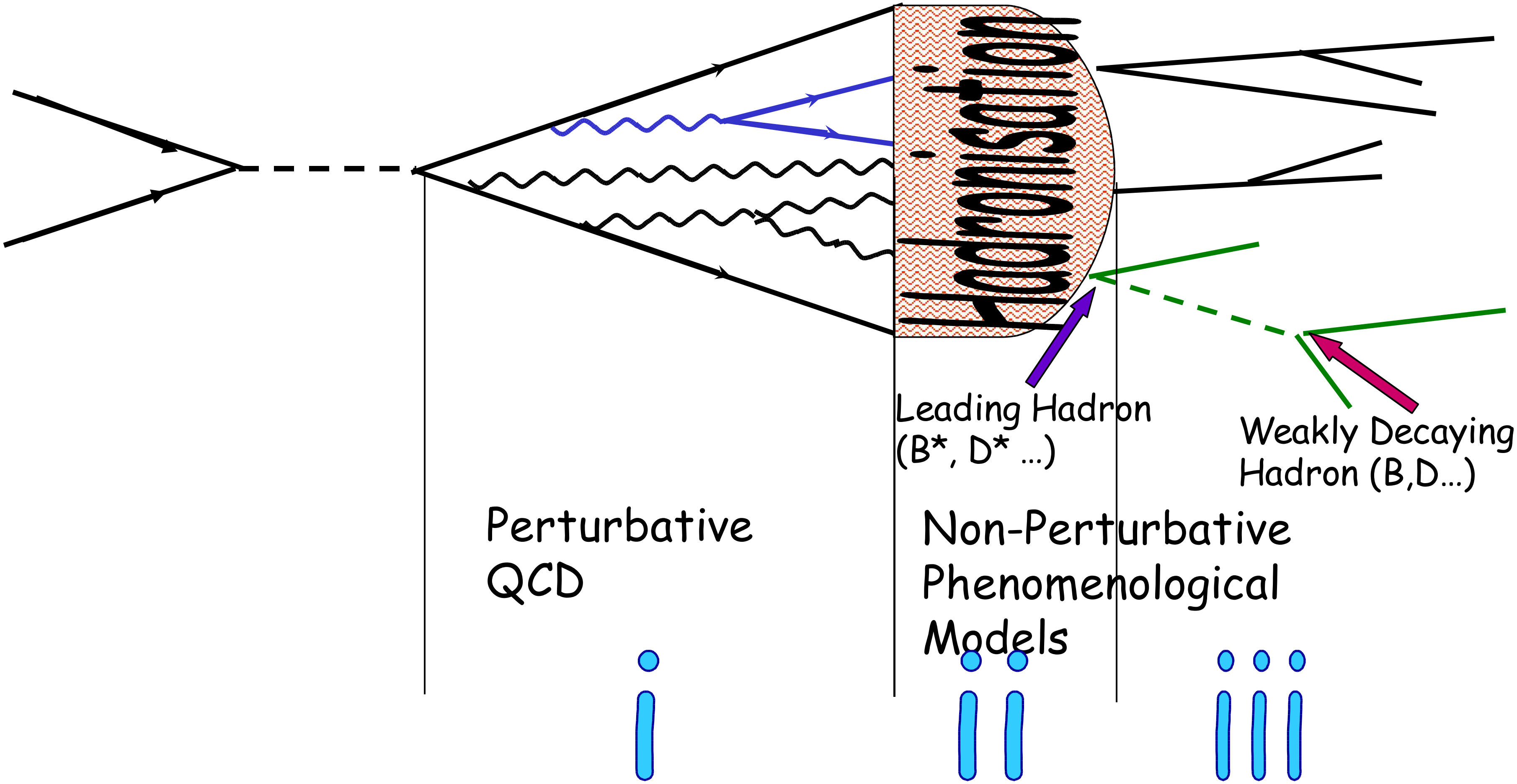
Hadronisation



Leading Hadron
(B*, D* ...)

Weakly Decaying
Hadron (B,D...)

Perturbative
QCD

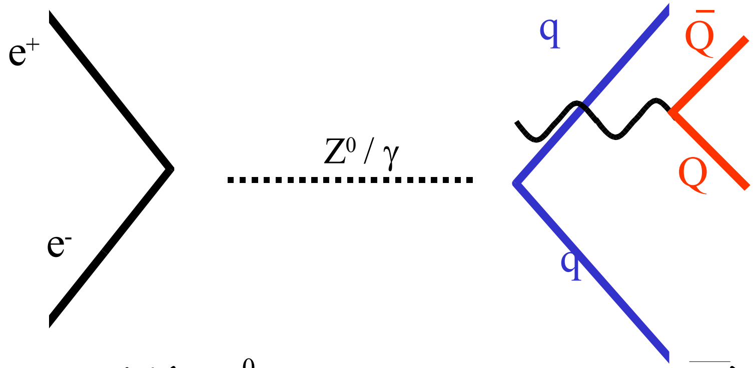
Non-Perturbative
Phenomenological
Models

- Gluon splitting to ccbar, bbbar

- Fragmentation function b,c
- c fragmentation fraction

Gluon splitting to $b\bar{b}$ ($c\bar{c}$)

AKA gbb (gcc)



Q= b or c

$$g_{Q\bar{Q}} = \frac{N(Z^0 \rightarrow q\bar{q}g \quad , \quad g \rightarrow Q\bar{Q})}{N(Z^0 \rightarrow \text{hadrons})}$$

- Sensitive to quark mass and strong coupling constant (α_s)
- Uncertainty source in EW measurements (especially R_b,R_c)
- Increases with energy

interference with diagrams where Q is a primary quark is negligible

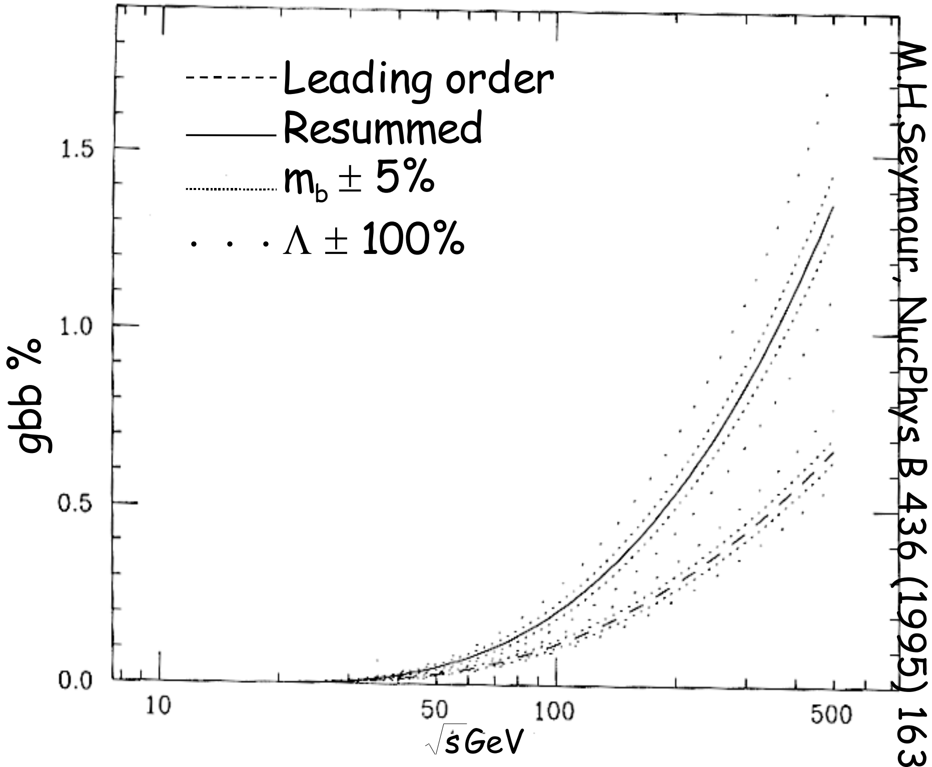
Theoretical predictions (gQQ)

gbb @ 90 GeV	*** 10^{-2}**
Resummed + Leading Order Leading Order	0.18 0.1
Herwig Jetset Ariadne	0.227 ± 0.001 0.160 ± 0.004 0.326 ± 0.006

gcc @ 90 GeV	*** 10^{-2}**
Resummed + Leading Order Leading Order	2.007 0.607
Herwig Jetset Ariadne	0.923 ± 0.013 1.301 ± 0.013 2.177 ± 0.015

$R_b = 0.21680 \pm 0.00073$

$R_c = 0.1694 \pm 0.0038$



M.H.Seymour, NucPhys B 436 (1995) 163

Experimental considerations

	gcc	gbb
Experimental Signature	Three jets. One of the jets (low-energy, broad, infrastructure) with c decay products	Four jets. Two of the jets (low-energy, close in phase space) with b decay products
Background:	• gbb • Primary b quarks • Other events (qqxx) Triple gluon vertex, Double bremsstrahlung	• gcc • Primary c quarks • Other events (qqxx) Triple gluon vertex, Double bremsstrahlung
Strategy:	1. Select hadronic decays 2. Look for 3 jet events 3. Choose the gluon jet 4. c-tagging	1. Select hadronic decays 2. Look for 4 jet events 3. Choose the gluon jets 4. b-tagging

gcc

Gluon jet candidate is chosen by:

- Lowest energy jet (opal, Aleph, L3)
- Jet sub-structure (opal, L3)

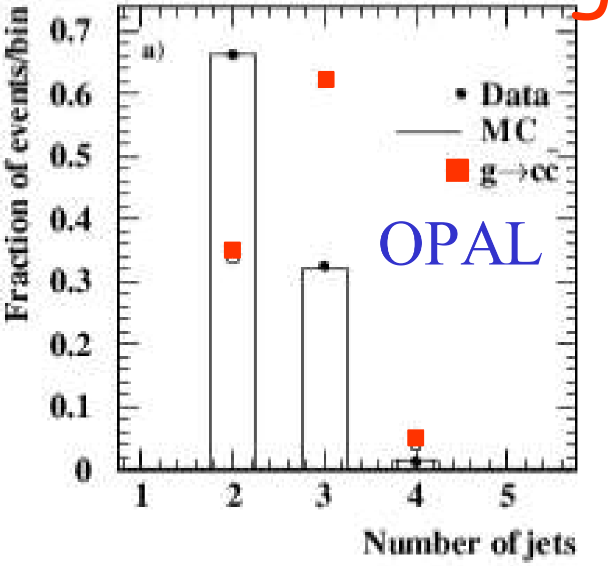
c-tagging is done using:

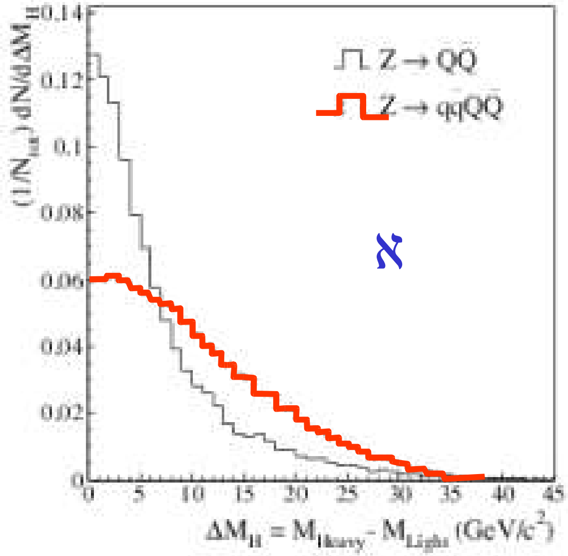
- $D^{*\pm} \rightarrow D^0\pi^\pm$, $D^0 \rightarrow \pi^\pm K^\pm$ (opal, Aleph)
- Lepton tag (opal, Aleph, L3)
- Event shape variables (L3)

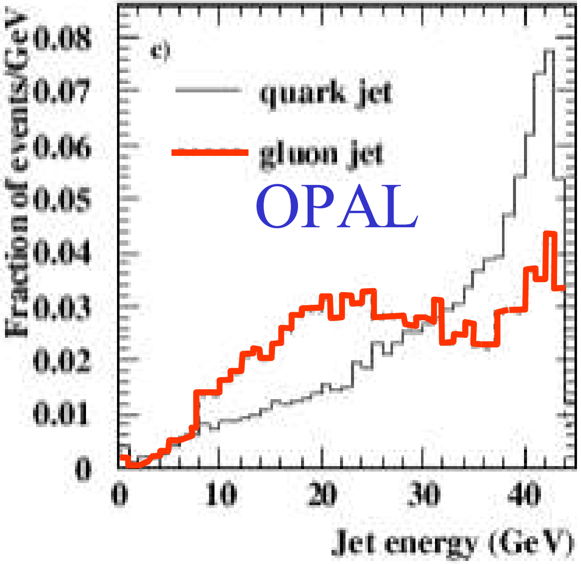
Additional selection criteria like:

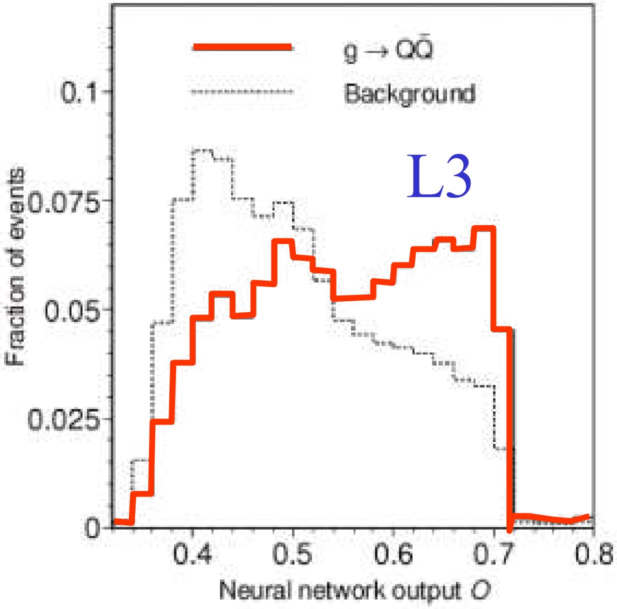
- Jet masses
- Hemisphere masses
- Thrust
- Secondary vertices
- D* energy spectra (w.r.t jet / beam)
- …

gcc

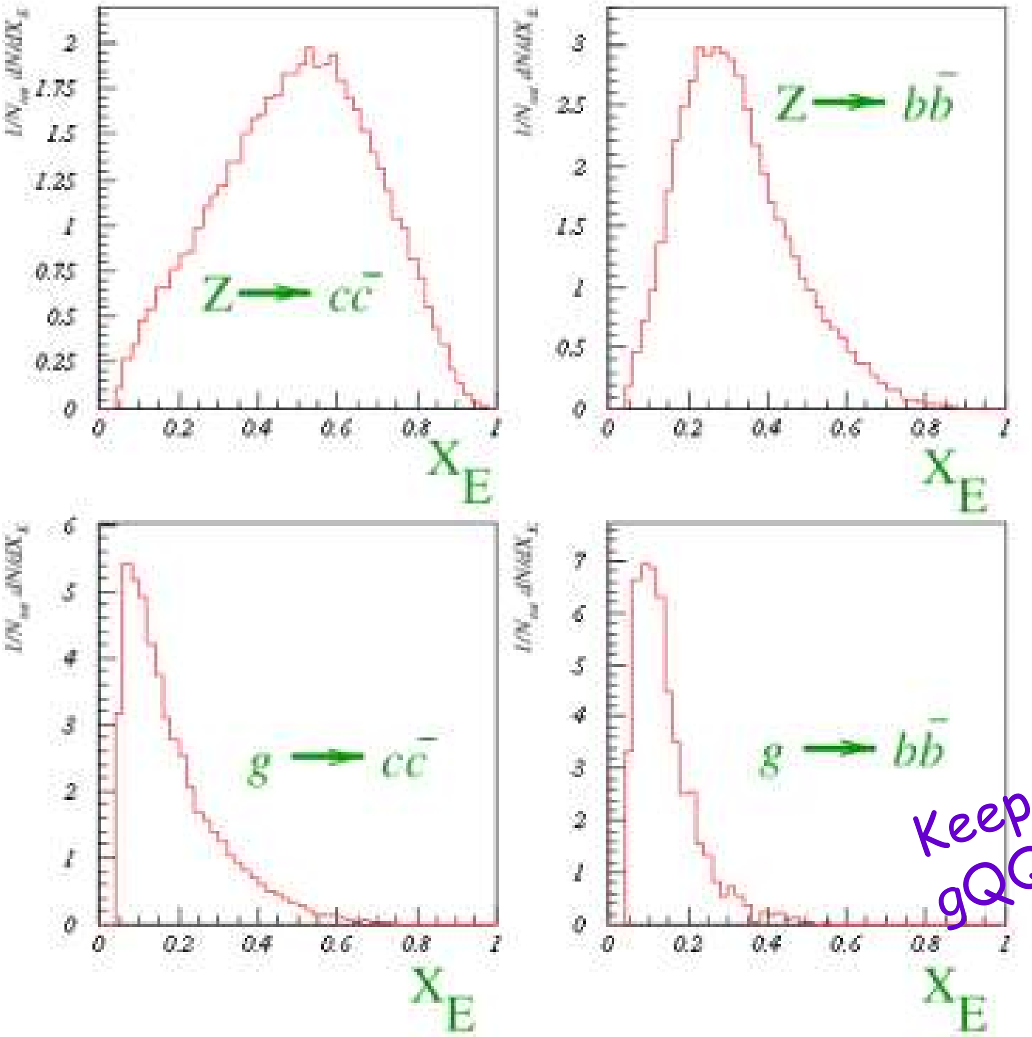

a)
Fraction of events/bin
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
Number of jets
• Data
MC
■ g→cc
OPAL


(1/N_tot) dN/dΔM_H
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
40
45
ΔM_H = M_Heavy - M_Light (GeV/c²)
Z → QQ̄
Z → qq̄QQ̄
א


c)
Fraction of events/GeV
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
10
20
30
40
Jet energy (GeV)
quark jet
gluon jet
OPAL


g → QQ̄
Background
L3
Fraction of events
0.1
0.075
0.05
0.025
0
0.4
0.5
0.6
0.7
0.8
Neural network output O

gcc: D* Reconstruction



$X_E = E_{D^*}/E_{beam}$

Keep in mind for frag:
gQQ is in low X

gcc

Main systematic uncertainties:

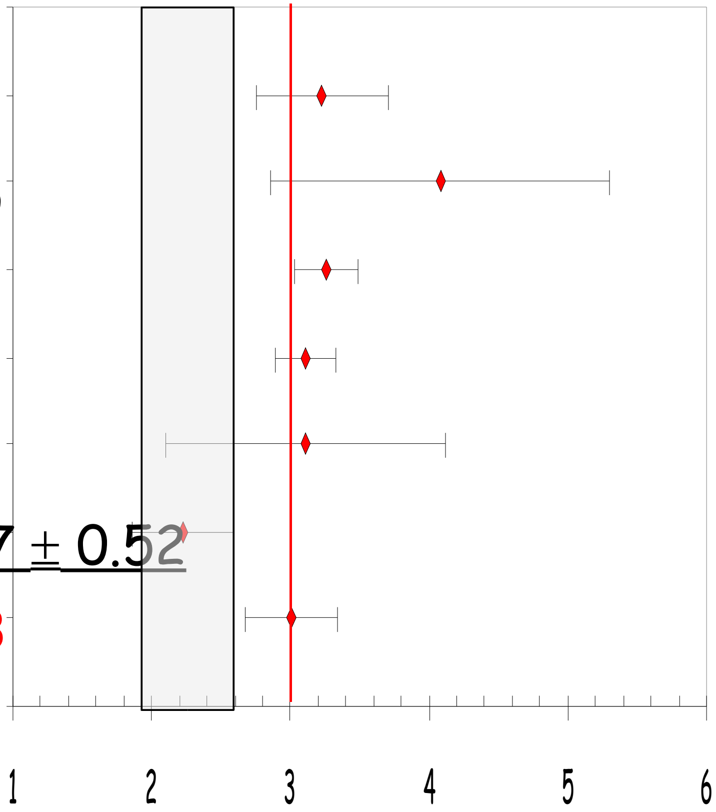
MC statistics.

gbb Semileptonic branching ratios: BR (c→l), BR (b→l)

Heavy quarks fragmentation models

Results	(gcc in %) :
ALEPH D*	3.23 ± 0.48 ± 0.53
OPAL D*	4.08 ± 1.22 ± 0.69
ALEPH lepton	3.26 ± 0.23 ± 0.42
OPAL lepton	3.11 ± 0.22 ± 0.41
L3 lepton	3.11 ± 1.01 ± 0.69
L3 event-shape	2.227± 0.37 ± 0.52
World average:	3.01 ± 0.33

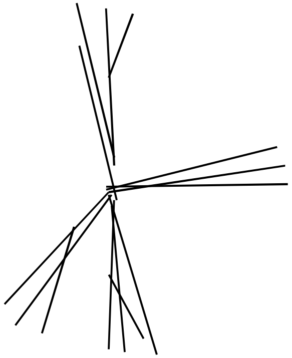
(by Andrea Giammanco and Tomasso Boccali)



gbb

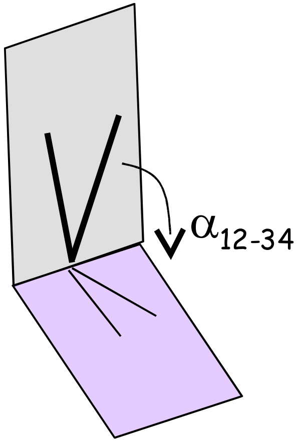
Gluon jets candidate are chosen by:

- Likelihood to have originated from the primary vertex
- Two jets with the smallest angle between them
- Lowest energy jets.



b-tagging is done using:

- Decay Length
- Jet mass



Other selection criteria like:

- $\alpha_{12\text{-}34}$
- jet mass, energy
- rapidity

g_{4b}

Opal: four-jet events with two b-jets closest in phase space, and four jet events with 3 b-jets.

Simultaneous fit to gbb and g_{4b}.

3.6±1.7 ±2

Delphi: Force events to 3 jets, btag in all 3 jets, calculate g4b , Extract gbb : gbb= R4b x Rth

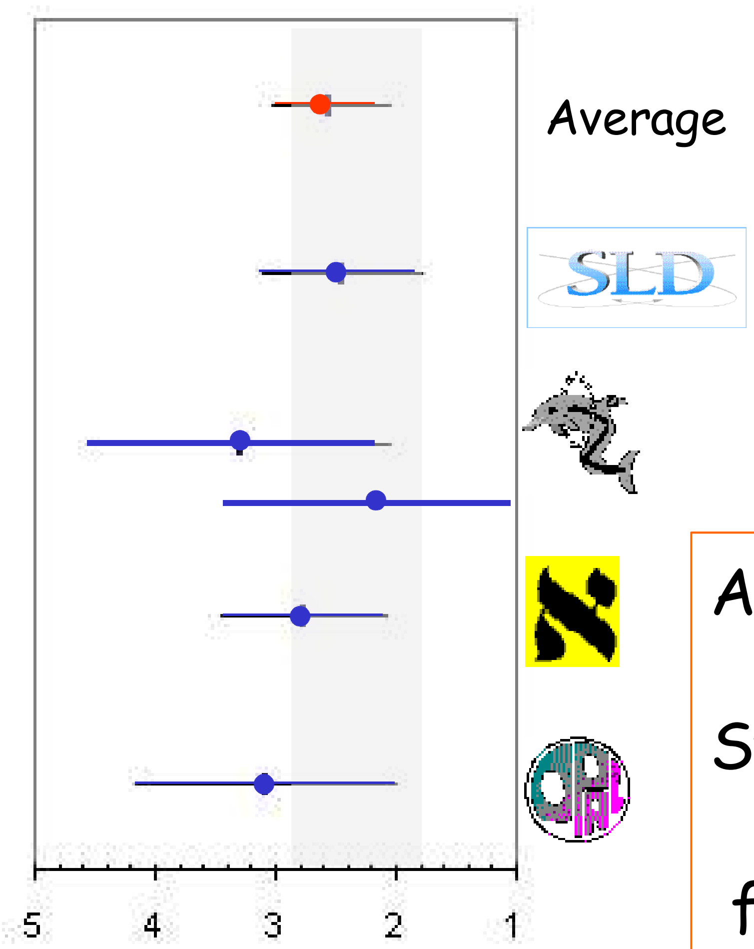
6 ±1.9 ±1.4

Delphi : $\frac{g_{4b}}{g_{bb}} = 0.1833 \pm 0.0003$ (calculated)

OPAL : $\frac{g_{4b}}{g_{bb}} = 0.116 \pm 0.088$ (measured)

Rb : 0.21680 ± 0.00073

Results gbb



SLD	2.44 ±0.59 ±0.34
Delphi i	2.10 ±1.10 ±0.9
ii	3.30 ±1.00 ±0.8
Aleph	2.77 ±0.42 ±0.57
OPAL	3.07±0.53 ±0.97
W.Average	2.54 ± 0.51

x10^{-3}

Aleph, OPAL – largest data sample

Systematics – g_{bb} Modeling.
MC statistics
for delphi 4b –g_{cc}
MC statistics

Fragmentation function:

$D_q^H(V)$ is the probability that a hadron H is produced from quark q with a kinetic variable V.

Variables:

$Z=(E+P_{||})_H/(E+P)_Q$

E = energy of hadron

$P_{||}$= momentum of hadron in direction of Q.

E_Q,P_Q = after g emission…just before fragmentation

- Used in some phenomenological models
- Un-measurable

$X_L=E_{lead}/E_{beam}$ (or using momentum)

•~17% b → B ~83% b → B*,B** → B

$X_{wd}=E_{wd}/E_{beam}$ (or using momentum)

- measurable!

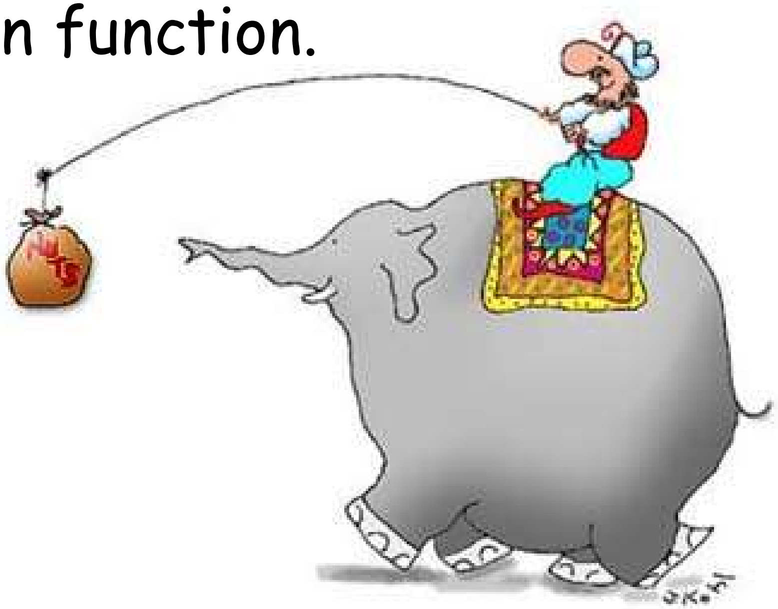
Why heavy fragmentation?

➔ The heavy flavored hadron contains the primary heavy quark.

➔ Heavy flavored hadron retains a large fraction of the momentum of the primordial heavy quark.

➔ Their differential cross section is proportional to the relevant fragmentation function.

➔ … Easy to tag c or b.



Fragmentation Function Measurement

How to tag hadrons ?

Inclusive :
Tag b/c content in jet/hemisphere
+High Efficiency
- Energy reconstruction

Exclusive:
Exclusively reconstruct hadron
+ Energy reconstruction
- Low Efficiency

How to present results ?

"Which model describes data best?"

Model dependent:
Compare result to a model
-The model and the measurement depends on different parameters
Solution: Unfold detector effects to compare data to model or do detector simulation on MC to compare model to data
Solution: Fit model directly to measured spectrum.

"How does the spectrum look like?"

Model independent:

- Present X_{wd} distribution

and/or

- Present Unfolded distribution.
  $X_{wd} \rightarrow X_{wd\text{-true}}$

and/or

- Estimate X_L
  $X \rightarrow X$

b Fragmentation Function Measuremnt

hep-ex/0106051 :
reconstruct B→D*lv exclusively using 5 channels.

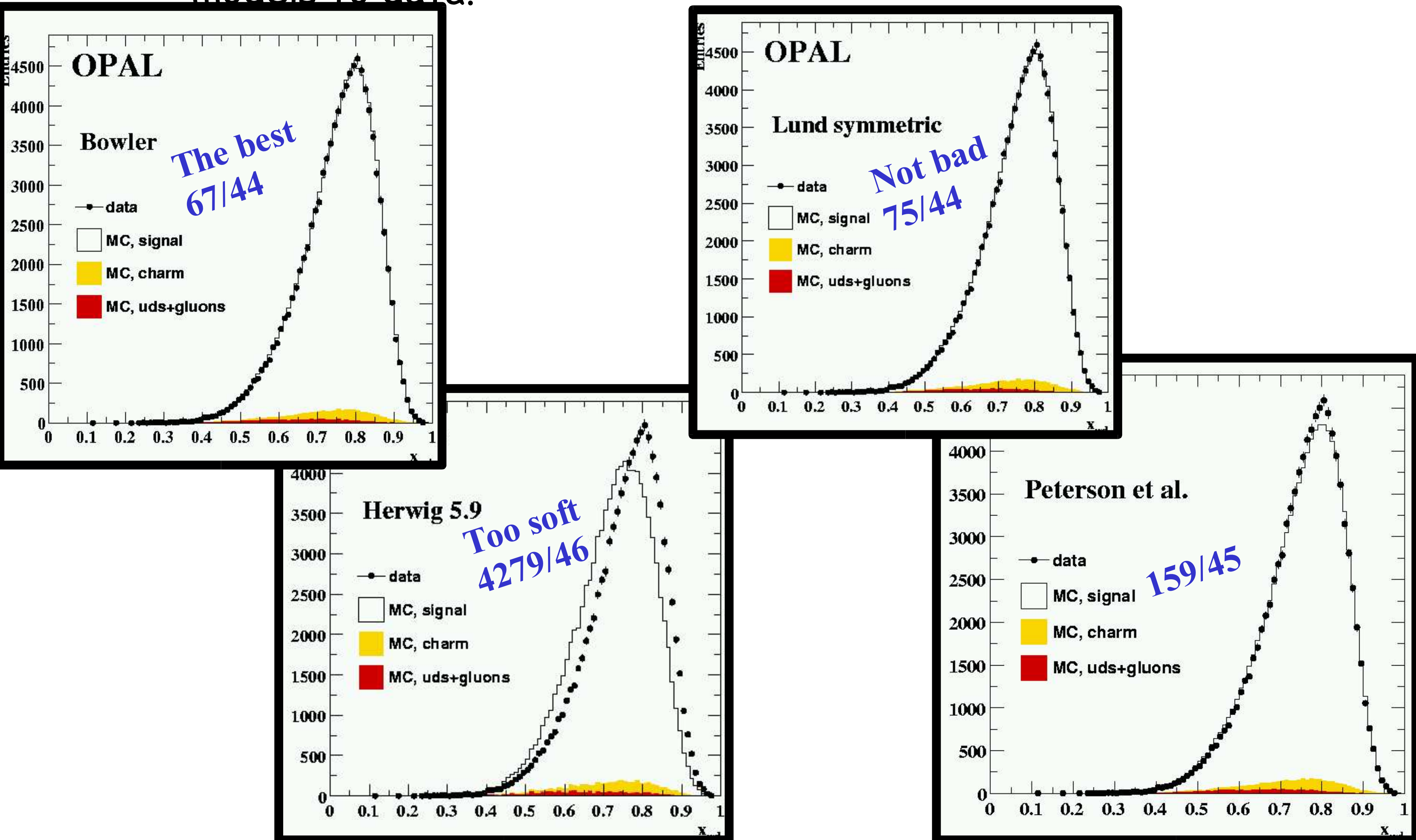
Prelimenary:
Use ANN to extract E_{wd}, E_{lead} and Z

hep-ex/021003
Btag in hemisphere using life time and leptons.
Assume decay products in a narrow cone. Reconstruct based on track likelihood.

Hep-ex/0202031
Reconstruct B energy from vertex flight direction and charged B decay product.

Fragmentation function: Model tests

Comparing the reconstructed scaled energy of weakly decaying B hadron distributions predicted by different models to data.



The best 67/44

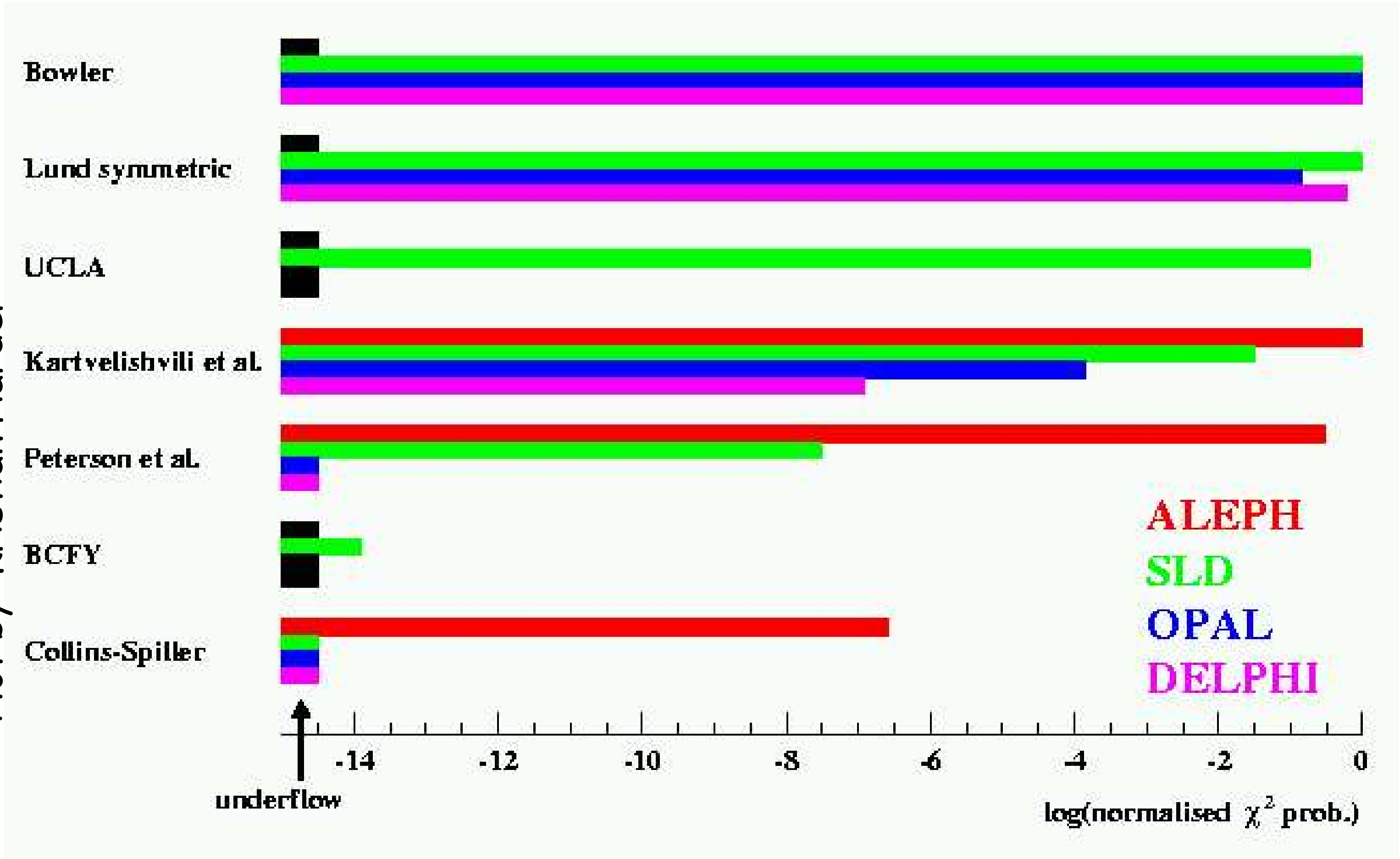
Not bad 75/44

Too soft 4279/46

159/45

Model tests: normalized $\chi 2$/d.o.f probabilities

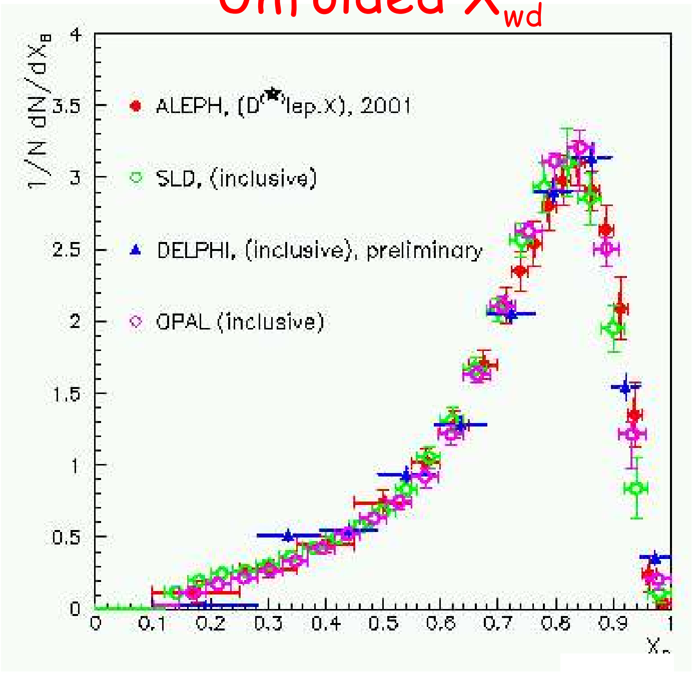
Plot by: Kristian Harder



b Fragmentation function
Model independent measurement

Unfolding the observed energy distribution:
Reweighting true and observed MC till observed distribution agrees in data and MC.

Unfolded X_{wd}



X_B

G. Barker, E. Ben-Haim et al.

SLD: $\langle X_{wd}\rangle = 0.709 \pm 0.003 \pm 0.003 \pm 0.002$

Opal: $\langle X_{wd}\rangle = 0.7193 \pm 0.0016^{+0.0038}_{-0.0033}$

Aleph:
$\langle x_{wd}\rangle = 0.7163 \pm 0.0061 \pm 0.0056$
$\langle x_{L}\rangle = 0.7361 \pm 0.0063 \pm 0.0063$

Delphi: prelimenary
$\langle X_{wd}\rangle = 0.7131 \pm 0.0007 \pm 0.007$
$\langle X_{L}\rangle = 0.7326 \pm 0.0009 \pm 0.0055$

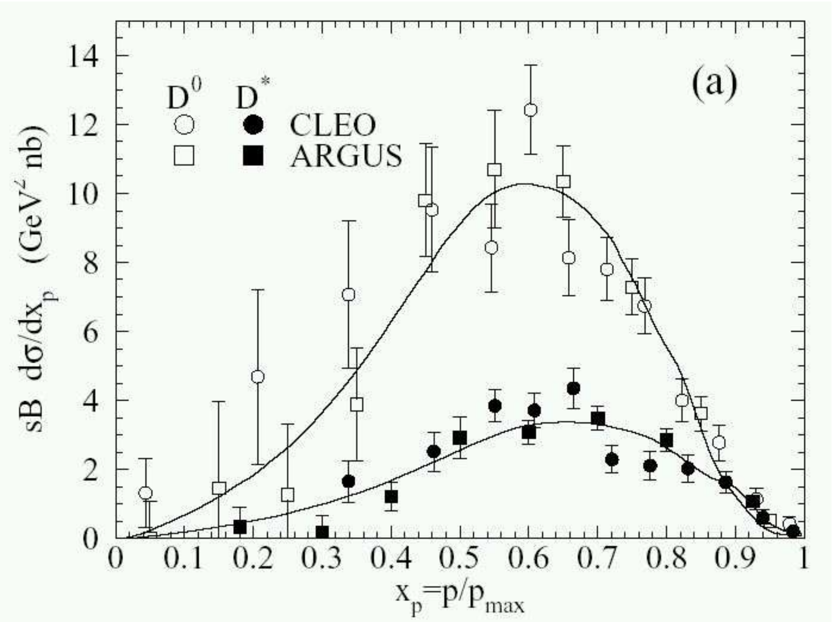
c Fragmentation function measurements

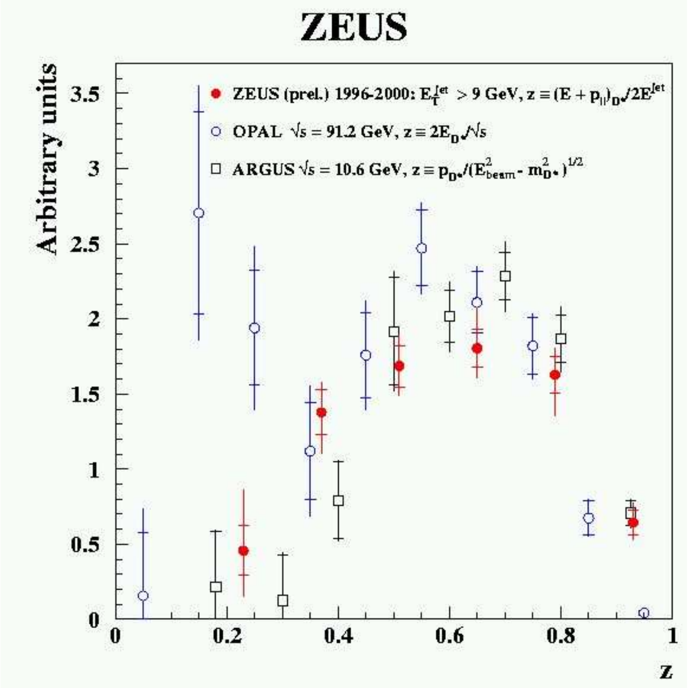
A wide selection of Measurements by CLEO, ARGUS, ALEPH, L3, OPAL and more…

Exclusive : combine tracks and reconstruct D meson

$D^{*+}\rightarrow D^0\pi^+\rightarrow\kappa^-\pi^+\pi^+$ $D_s^{*+}\rightarrow D_s^+\gamma\rightarrow\phi\pi^+\gamma\rightarrow\kappa^+\kappa^-\pi^+\gamma$ etc.

using: $X=p_D/p_{\max D}$ or $X=E_D/E_{beam}$ in LEP.





Problem 1: b→c:

solution 1: run below Υ threshold

solution 2: if @ 10.6 GeV use a lower limit cut on P_D>2.5 GeV

solution 3: Do a b/c tag (vertex, lepton, jet shape…)
in opposite hemisphere

Problem 2: D is a cascade from a higher mass state:

solution 1: Assume what you measure is softer than models

solution 2: Use D* (relatively small D**→D*)

solution 3: Use L=1 mesons; make use of forbidden decays (D_s)

Problem 3: Gluon, γ radiation *

Solution 1: Assume what you measure is softer than models

Solution 2: Use MC that "properly" handles ISR

* Increases with ECM. Need special treatment when comparing different CEM results.

c Fragmentation function measurements

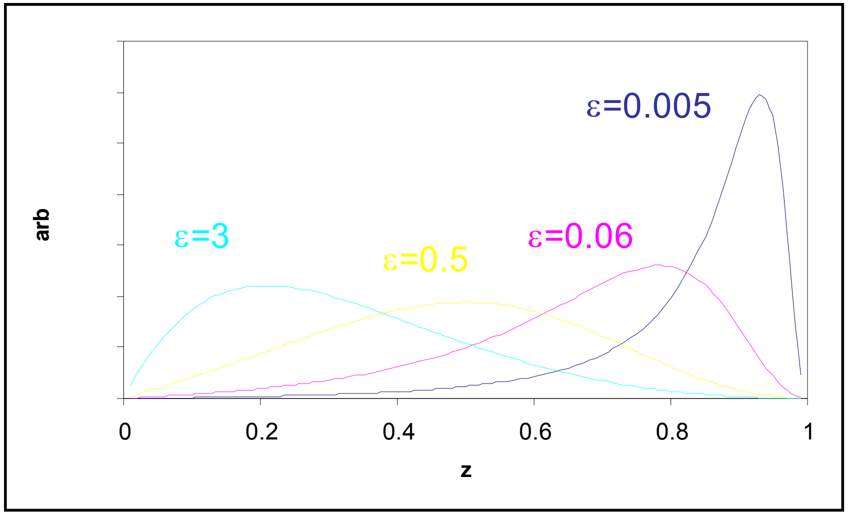
A fit of measured cross section to Peterson model:

(hep-ph/0109282)

$$f(z) \propto \frac{1}{z\left(1-\frac{1}{z}-\frac{\varepsilon}{1-z}\right)^2}$$

	ε	
D^0	0.26 ±0.024	
D^+	0.156 ±0.022	L=0
D^{*+}	0.198 ±0.022	
D_s	0.1 ±0.02	
D_s^*	0.057 ±0.008	L=1
$D_1(2420)^0$	0.015 ±0.004	
$D_2^*(2460)^0$	0.039 ±0.013	L=0
Λ_c^+	0.267 ±0.038	L=1
$\Sigma_c(2455)$	0.28 ±0.05	
$\Lambda_c(2593)^+$	0.058 ±0.022	

- ! Harder spectra for L=1
- ~ Harder spectra as mass increases



Charm Fragmentation Fractions

- Exclusively reconstruct D^{doe} hadron

$D^{*0} \rightarrow D^0\gamma$; $D^{*0} \rightarrow D^0\pi$; $D^{*}{}_s^{+} \rightarrow D_s^{+}\gamma$;

´ $D_s^{+} \rightarrow \phi\pi^{+} \rightarrow k^{-}k^{+}\pi^{+}$; $D^0 \rightarrow K^{-}\pi^{+}$

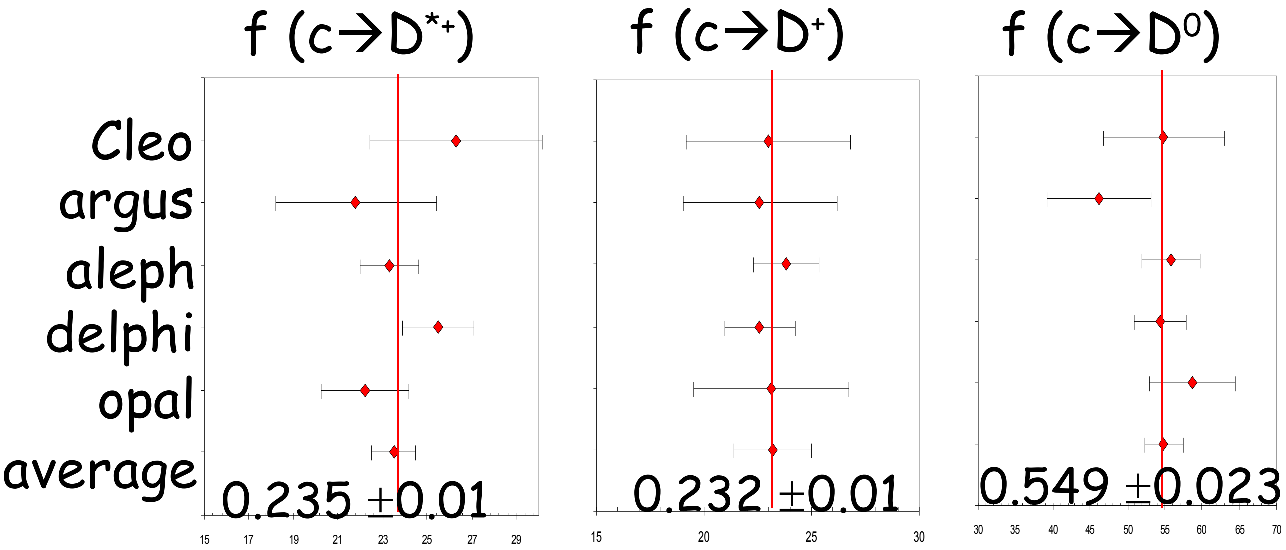
- Count (per hadronic event)
- Subtract b→c background
- Estimate efficiency
- Extract $f(c \rightarrow D^{doe})$ using : $R_c \times B.r.(D^{doe} \rightarrow \ldots) \times f(c \rightarrow D^{doe})$

@90GeV:: Rc ~ 0.17

@10GeV:: "Rc" ~ 0.37

- R_c and branching ratio – major uncertainty source

Charm Fragmentation Fractions



etc…

Average charm hadron production rates are within 1σ :

➔ Isospin Invariance $R_{u/d} \sim 1$ √

also by $R_{u/d} = \dfrac{f(c \to D^{*0})}{f(c \to D^{*+})}$

Need correction for D** decays

Pv results:

$$P_V^{eff} = \frac{V}{V+P} = \frac{\#D^*}{\#D^* + \#D_{direct}} = \frac{f(c \to D^{*+}, D^{*0})}{f(c \to D^+, D^0)}$$

Need correction for D** decays

CLEO	$(X(D_S)>0.44)$	$P_V(D_S)=0.44\pm0.04$	?
Aleph		$P_V(D_S)=0.60\pm0.19$	
Aleph		$P_V(D)=0.60\pm0.0$	√
OPAL		$P_V(D)=0.57\pm0.05$	
SLD		$P_V(D)=0.57\pm0.07$	
L3		$P_V(B)=0.76\pm0.10$	√
OPAL		$P_V(B)=0.76\pm0.09$	

Close to spin counting expectation 0.75

Conclusions:

➔ gcc is 2σaway from theoretical predictions.
All gcc measurements are consistent.

➔ gbb is in agreement with theoretical predictions.

➔ b fragmentations measurements favors Peterson and Lund models.

➔Peterson model is less favorite in c fragmentation measurements than Lund, Bowler, Collins -Spiller and Kartvelishvili.

➔b frag. Measurements are all inclusive. C frag are all exclusive…

➔ Comparison of fragmentation functions results is tricky:

Backup Slides

Recent analyses: gbb

ALEPH	CERN-EP-98-103
DELPHI	CERN-EP-99-081 CERN-PPE-97-39
OPAL	CERN-EP-2000-123
SLD	SLAC-PUB-8737 / hep-ex/0102002

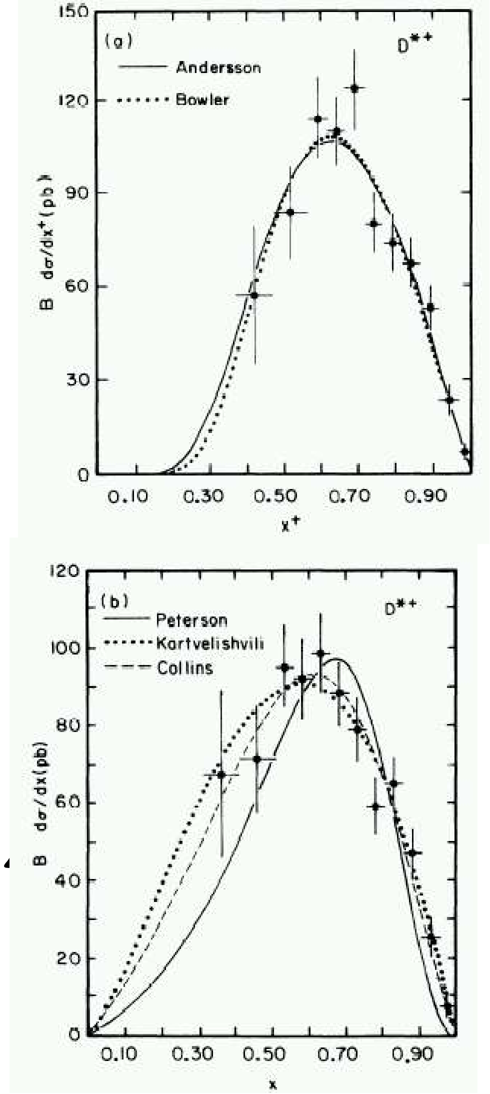
String Fragmentation Models

	$F(z) \propto$	parameters
Bowler	$\frac{1}{z^{1+r_b m_t^2}}(1-z)^\alpha \exp\left(-\frac{bm_t^2}{z}\right)$	
Lund symmetric	$\frac{1}{z}(1-z)^\alpha \exp\left(-\frac{bm_t^2}{z}\right)$	
Kartvelishvili et al.	$z^\alpha(1-z)$	
Peterson et al.	$\frac{1}{z}\left(1-\frac{1}{z}-\frac{\varepsilon}{1-z}\right)^{-2}$	
BCFY	$\frac{Z(1-z)^2}{(1-(1-r)z)^6}(3+\sum_{i=1}^{4}(-z)^i f_i(r))$	
Collins-Spiller	$\left(\frac{1-z}{z}+\frac{2-z}{1-z}\varepsilon\right)(1+z^2)\left(1-\frac{1}{z}-\frac{\varepsilon}{1-z}\right)^{-2}$	

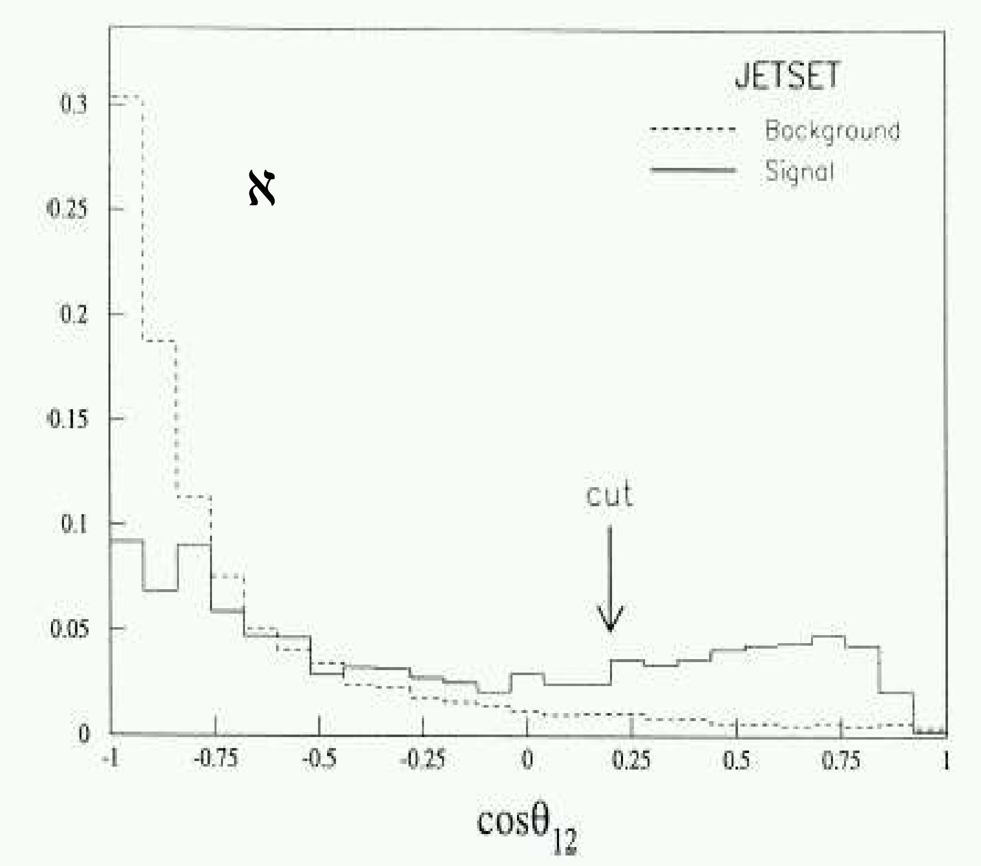
c Fragmentation function measurements
Different models

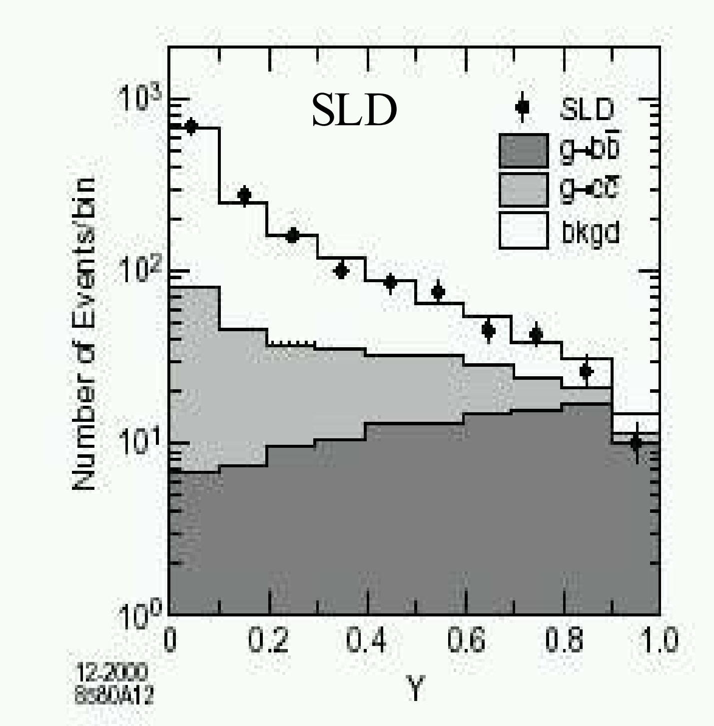
		parameters	$\chi^{2/}$/d.o.f.
$D^{*\pm}$ Cleo	Lund	1.02 ± 0.12	
		0.43 ± 0.07Gev^{-2}	7.5/8
	Bowler	0.95 ± 0.11	
		0.63 ± 0.22GeV^{-2}	7.1/8
	Peter.	0.156 ± 0.015	40/10
	Collins	0.64 ± 0.14	6.3/10
	Kart.	1.4 ± 0.18	6/10
D^*_s Cleo	Lund	0.9 ± 0.2, 1.7 ± 0.1	1.9/5
	Peter.	0.056 ± 0.008	20.5/6
D_s Cleo	Lund	1.1 ± 0.2, 1.5 ± 0.1	3.2/6
	Peter.	0.1 ± 0.02	17.4/7
D* Argus	Peter.	0.19 ± 0.03	19.2/6
	Kart.	1.5 ± 0.2	

7.



gbb


JETSET
Background
Signal
א
cut
0.3
0.25
0.2
0.15
0.1
0.05
0
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
$\cos\theta_{12}$


SLD
SLD
$g \to b\bar{b}$
$g \to c\bar{c}$
bkgd
Number of Events/bin
10^3
10^2
10^1
10^0
0
0.2
0.4
0.6
0.8
1.0
Y
12-2000
8580A12