Measurements of b and c fragmentation functions and of orbitally excited B states

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Content

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   - Hadronisation terminology
   - Fragmentation models
   - Results in the c and b sector
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   - Fragmentation at hadron colliders
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   - General ideas of HQET
   - HQET predictions
   - Measurements in the b sector
3. Conclusions

Hadronisation of quarks

Strong coupling α_s too large
$\rightarrow$ rely on pQCD + Model

<u>common variables:</u>

physical variables:

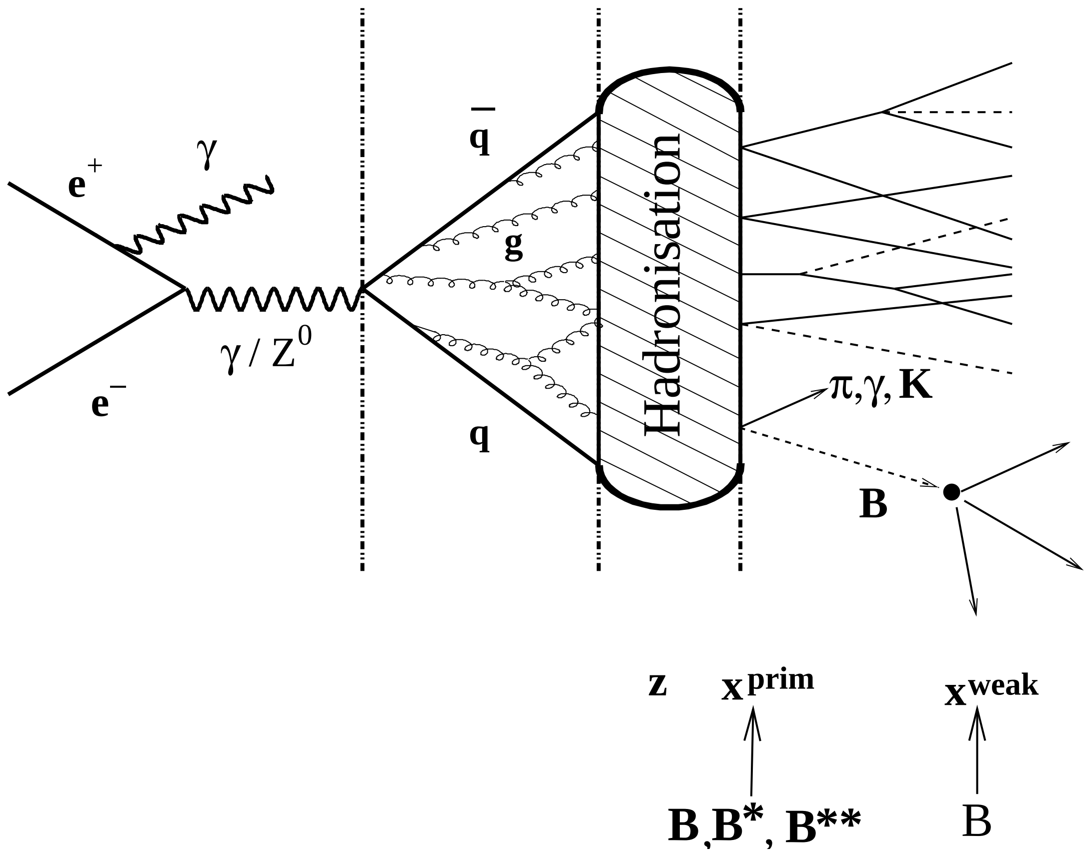
- $x^{prim} = \frac{E^{prim.B}}{E^{beam}}$:
  primary (excited) state

- $x^{weak} = \frac{E^{weak}}{E^{beam}}$:
  weakly decaying state

String fragmentation variable:

- $z = \frac{(E+p_{\|})_{hadron}}{(E+p)_{q0}}$

where $(E+p)_{q0}$ is the energy/momemtum of the quark <u>after</u> gluon emisson



Fragmentation models (in chronological order)

- Kartvelishvili et al. (1978): $f(z) \propto z^{\alpha}(1-z)$

  from heavy meson structure functions, developed for c physics

- Bowler (1981) $f(z) \propto \frac{1}{z^{1+r_b m_\perp^2}} z\,(1-z)^a \exp\left(\frac{-bm_\perp^2}{z}\right)$

  constant probability for $q\bar{q}$ creation per space-time interval

- Peterson et al. (1982): $f(z) \propto z^{-1}\left(1-\frac{1}{z}-\frac{\epsilon}{1-z}\right)^{-2}$

  from kinematical considerations: Energy transfer in process $Q \to H + q$

- Lund (1983) $f(z) \propto z^{-1}(1-z)^a \exp\left(\frac{-bm_\perp^2}{z}\right)$

  starting on left/right end of string gives symmetric result

- Collins-Spiller (1984) $f(z) \propto (\frac{1-z}{z}+\frac{2-z}{1-z}\epsilon)(1+z^2)(1-\frac{1}{z}-\frac{\epsilon}{1-z})^{-2}$

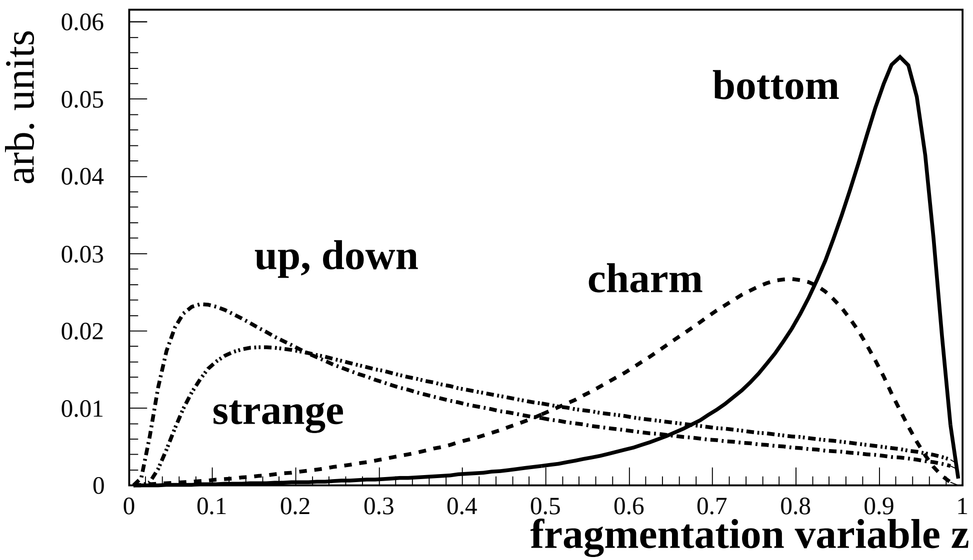
  calculation based on a scheme also used for hadron structure functions

historically: fit for energy of weakly decaying state x

modern analyses: hadronisation has to be evaluated in <u>fragmentation variable</u> z

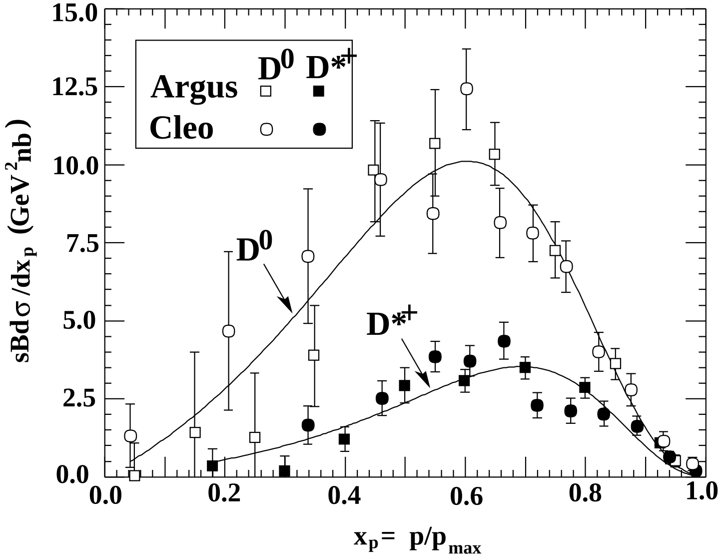
Expectations for different quark species

e.g. Peterson: $f(z) \propto \frac{1}{z\left(1-\frac{1}{z}-\frac{\epsilon}{1-z}\right)^2}$



- $\epsilon \approx \frac{m_q^2}{m_Q^2}$, treated as free parameter
- harder spectrum for heavier quarks
- common to all models, exact shape depends on parametrisation

Results from charm sector



Cleo: Phys.Rev D37, 1719 (1988),

Argus: Z. Phys. C52, 353 (1991)

Variable: $x = \frac{p(D)}{p_{max}(D)}$

Fit Peterson function to x

open questions:

- Same spectrum for
  - weakly decaying mesons created directly at the end of the fragmentation process
  - weakly decaying mesons originating from decay of excited states?
- Same spectrum for all mesons within a family, i.e. same spectrum for $D^0, D^{\pm}, D_s$, etc?

Results from the b sector (1)

- Aleph (Phys. Lett. B 512): exclusive
  reconstruct $B \to D^{(*)} l\nu$ in 5 channels

- Opal (hep-ex/0210031): inclusive
  reconstruction of B hadrons from weak B decay vertices, lepton from B decay vertex, charged and neutral decay products, reconstruct based on likelihood.

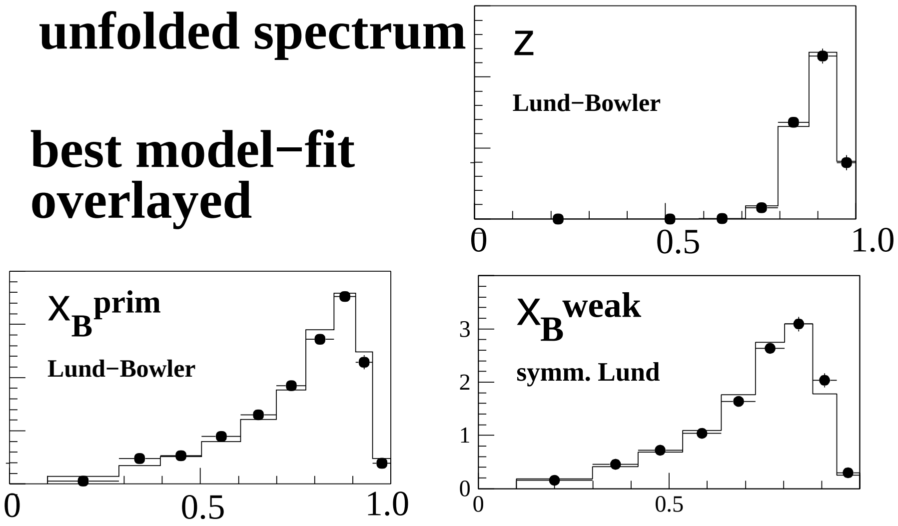
- SLD (Phys. Rev. D 65): inclusive
  reconstruct B energy from vertex flight directions and charged B decay products

- Delphi (prelim.): inclusive
  see next transparency

Results from the b sector (2)

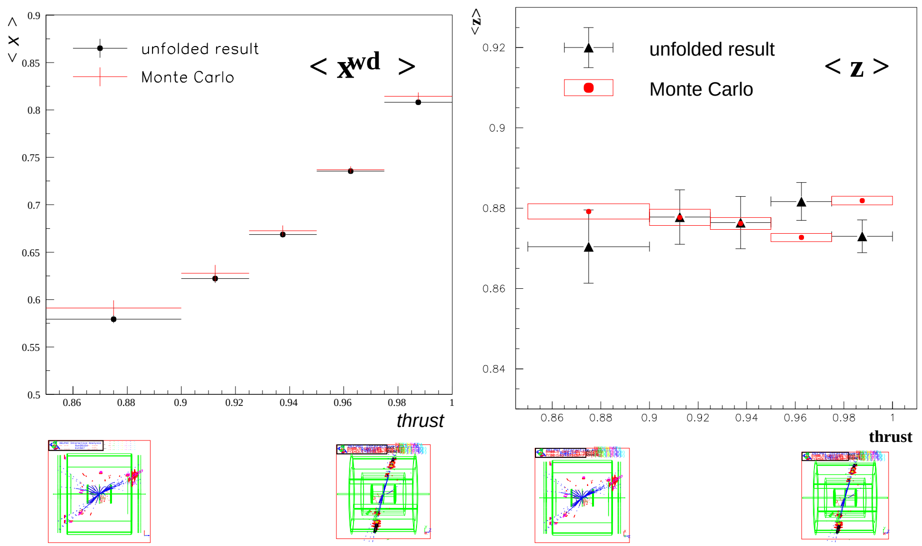
Delphi (prelim):

inclusively reconstruct z, x_B^{prim}, x_B^{weak} with NN, regularised unfolding ($\mathcal{RUN}$, V.Blobel, Hamburg)



- hard b-quark fragmentation
- Lund, Bowler fit data best

Effect of hard gluon radiation:

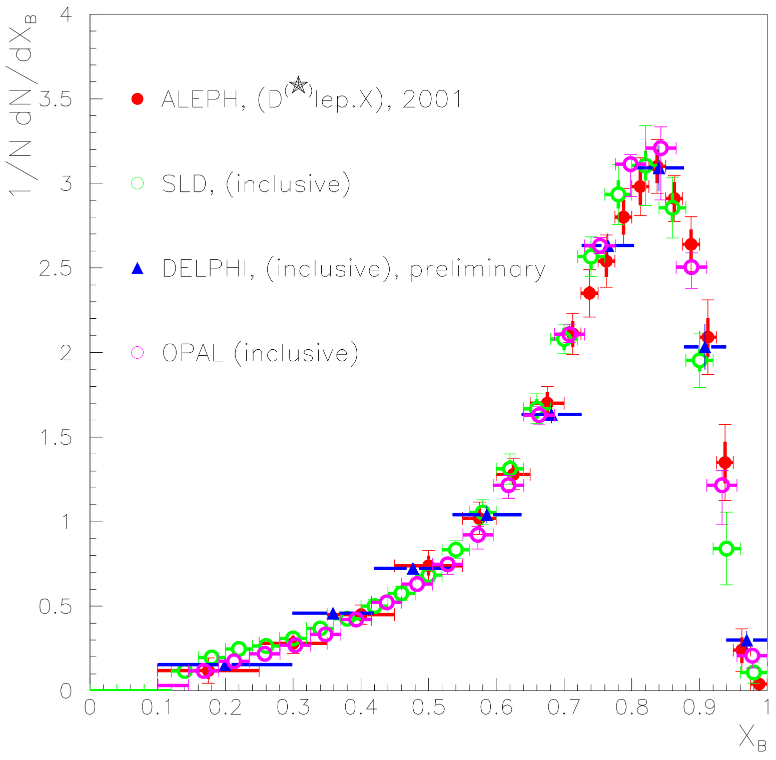


thrust $T \approx 1$: 2-jet event

thrust $T \approx 0.5$: isotropic topology

x_B^{weak} varies with gluon emission,
z (describes hadronisation) does not

Unfolded x^{wd} spectrum



- high precision measurements
- good agreement between experiments

experiment	$< x^{wd} >$
Aleph	$0.7163 \pm 0.0061 \pm 0.0056$
Delphi (prelim)	$0.7131 \pm 0.0007 \pm 0.0070$
Opal	$0.7193 \pm 0.0016^{+0.0036}_{-0.0031}$
SLD	$0.709 \pm 0.003 \pm 0.003 \pm 0.002$

Tests of fragmentation models (1)

Aleph, Opal, SLD:

reweight default Monte Carlo:

- different fragmentation models
- Model parameters

$\rightarrow$ determine best choice via χ^2 fit.

Delphi:

unfold detector effects,

χ^2 fit at generator level to determine best hadronisation model.

Test of fragmentation models (2)

χ^2/ndf from fit of weakly decaying B hadron:

model	Aleph	Delphi (prelim)	Opal	SLD
Bowler	—	31/7	67/44	17/15
Lund	—	12/7	75/44	17/15
Kartvelishvili et al.	107/84	—	99/45	32/16
Peterson et al.	117/94	336/8	159/45	70/16
Collins-Spiller	181/94	—	407/45	142/16

- Lund, Bowler favoured over Peterson, Kartv., CS
- same ranking seen by all experiments
- SLD, Opal: Also Herwig, but disfavoured
- Delphi (prelim.): consistent picture for x^{prim}, z (also Kartv., CS disfavoured)

New approach: Moment analysis

Motivation: Be independent of fragmentation model

Idea: (Cacciari et al.) exploit factorisation ansatz (hep-ph/0301047)

1. in x space: convolution: $D^{meas}(x) = \int D^{pert}(x') \otimes D^{non-pert}(x')\, dx'$
2. Mellin-Transform $\tilde{D}(N) = \int dx\, x^{N-1} D(x) \rightarrow$ moment space.
3. now: product instead of convolution: $\tilde{D}^{meas}(N) = \tilde{D}^{np}(N) * \tilde{D}^{pert}(N)$
4. take perturbative part from calculation to extract non-pert. part from measurement: $\tilde{D}^{np}(N) = \frac{\tilde{D}^{meas}(N)}{\tilde{D}^{pert}(N)}$
5. inverse Mellin-Transform: non-pert. part in x space

keep in mind:

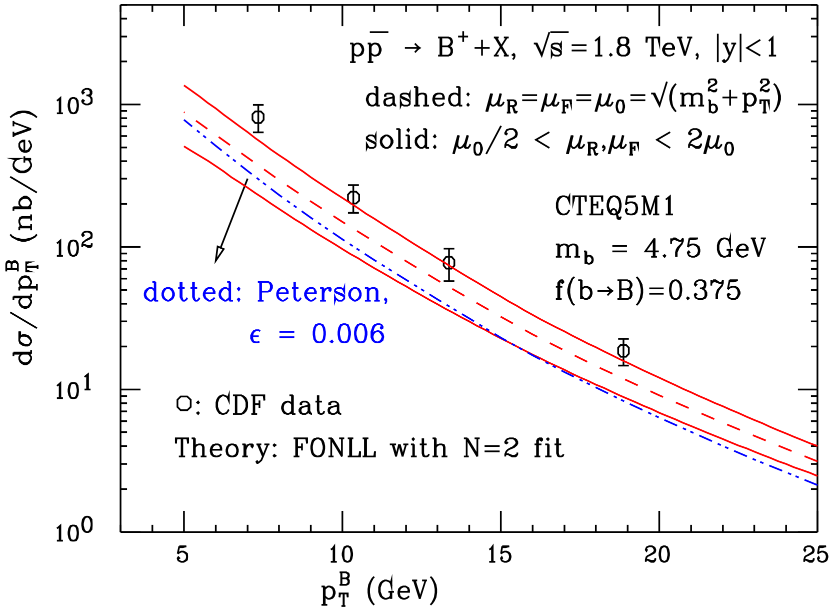
- Experiments measure binned x spectrum
  $\rightarrow$ very high correlation between extracted moments

Applications

Tevatron data:

improved agreement of $\sigma_{b\bar{b}}$ measurement and prediction by:

- using perturbative calculation by Cacciari et al.
- using other hadronisation models than Peterson (ad-hoc model similar to Kartvelishvili used here)



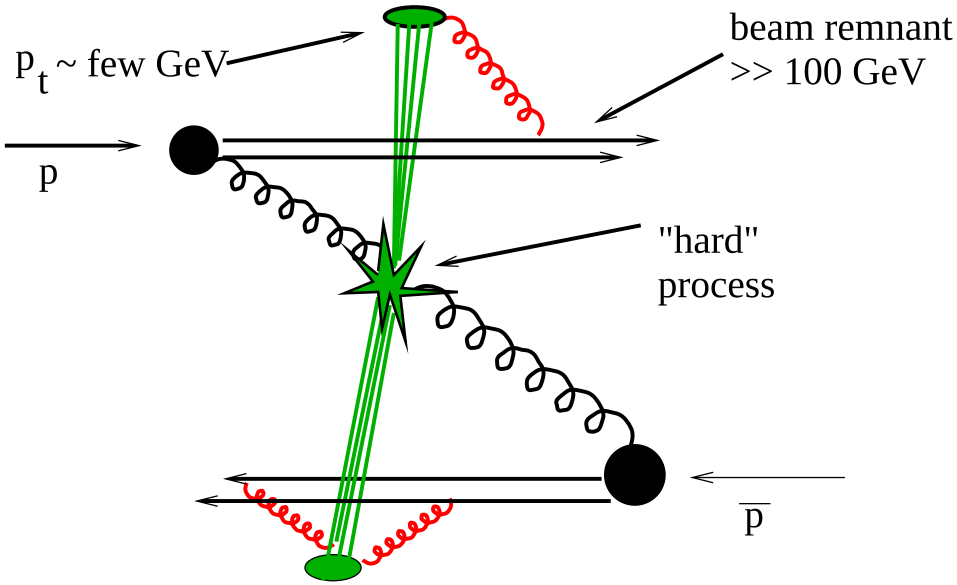
e^+e^- data: E. Ben-Haim et al. (hep-ph/0302157)

- b-fragmentation function peaked in high z regime.
- Lund, Bowler model describe data best, other models disfavoured.

Fragmentation at hadron colliders

Fragmentation is more complex at hadron machines:

- no colour-singlet initial state
- many gluons from other particles
- colour connections not necessarily between $Q\bar{Q}$
- large $\sigma_{b\bar{b}}$ $(\mathcal{O}(\mu b))$ but $\sigma_{inel} \approx 1000\sigma_{b\bar{b}}$
- $\sigma_{b\bar{b}}$ dropping quickly with p_t
  $\rightarrow \sigma_{b\bar{b}}^{FNAL} \approx \sigma_{b\bar{b}}^{LEP}$ at $p_t \approx 35$ GeV

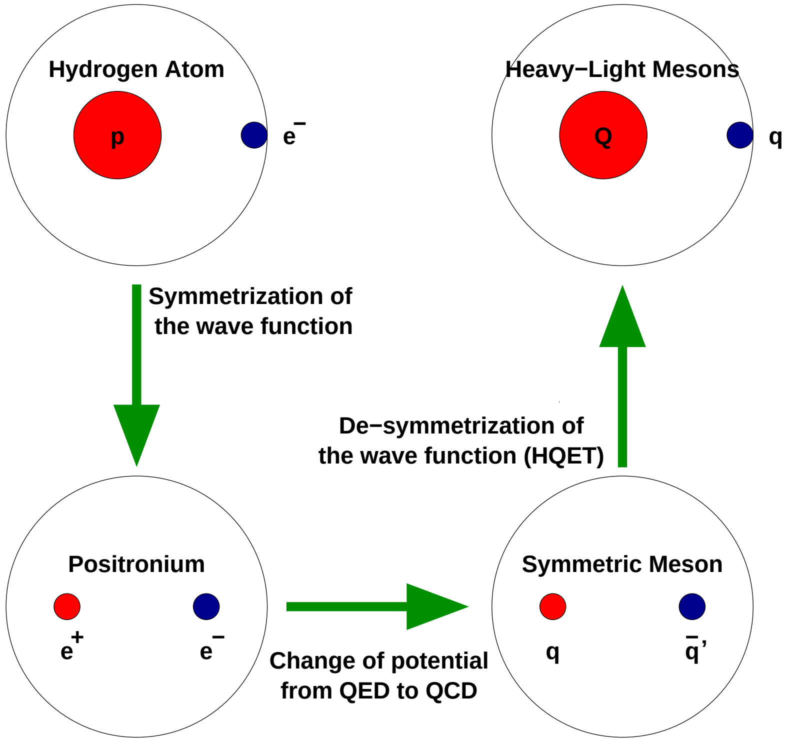


Part 2:

Excited Mesons

and
spectroscopy

General Idea of HQET

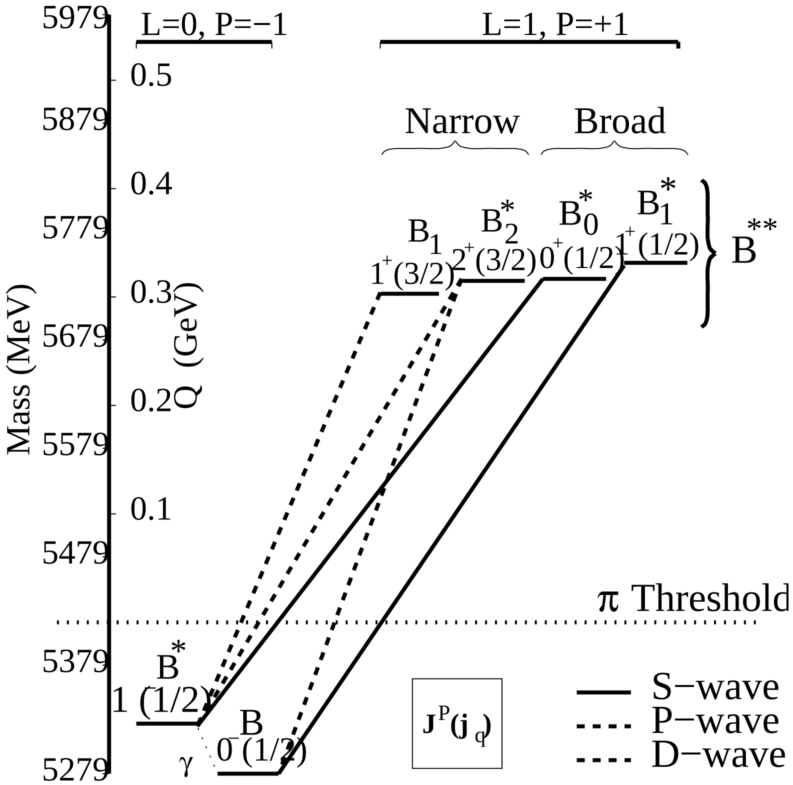


- Analogy to hydrogen atom: heavy quark as static colour source in $Q\bar{q}$ system
- $\mathcal{L}_{eff}$ symmetric under $b \leftrightarrow c$
- spin of light and heavy quarks decouple:

$$\begin{aligned} s_q \oplus L &\longrightarrow j_q \\ s_Q \oplus j_q &\longrightarrow J \end{aligned}$$

HQET predictions

4 predicted orbitally excited ($L = 1$) Mesons:



Production fraction:

$70\% : L = 0,\ 30\% : L = 1$,

e.g. from spin-counting:

$B_0^* : B_1^* : B_1 : B_2^* = 1 : 3 : 3 : 5$

(other definitions possible)

decay modes

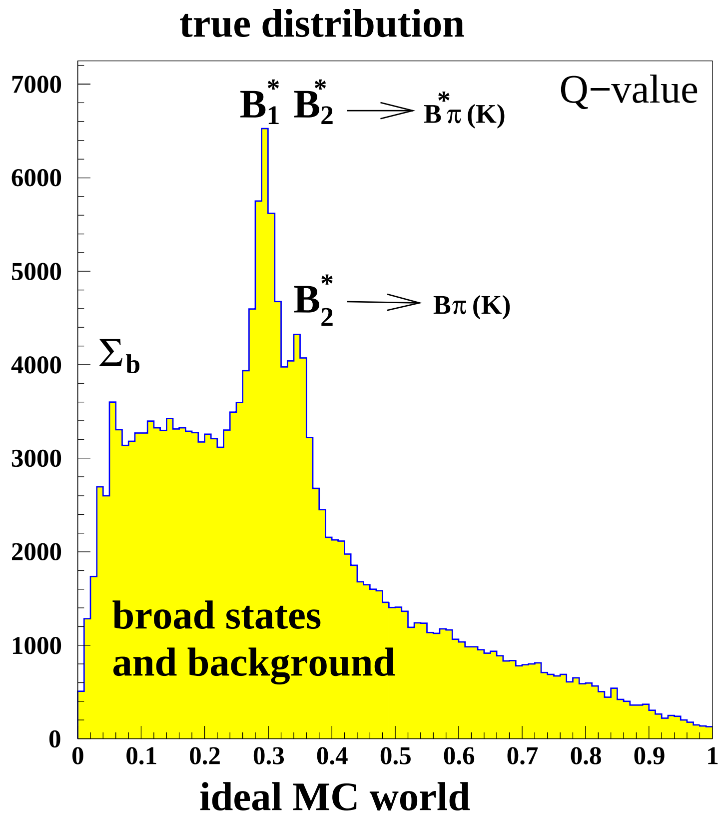
(2 narrow, 2 broad states):

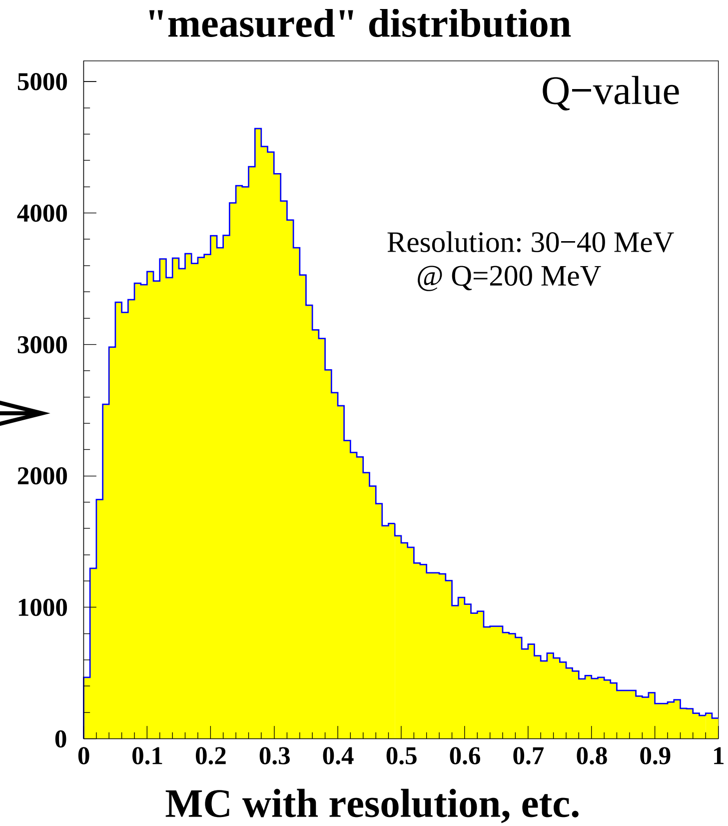
obtained from quantum numbers.

$L = 0$ (s-wave, broad),

$L = 2$ (d-wave, narrow)

experimentally accessible variable





observable: Q-value: (remaining kinetic energy)

$Q = m(B\pi) - m(B) - m(\pi)$ for $B^0, B^\pm$,

$Q = m(BK) - m(B) - m(K)$ for B_s

Excited B states analyses

- Delphi (Phys. Lett B345, 1995): inclusive
- Opal (Z. Phys. C66, 1995): inclusive
- Aleph (Z. Phys. C69, 1996): inclusive
- Aleph (Phys. Lett. B425, 1998): exclusive
  $B \to D^{(*)}X$ where $X = \pi, \rho, a_1$, $B \to J/\Psi(\Psi')X$ where $X = K^{(*)}$
- L3 (Phys. Lett. B465, 1999): inclusive
- CDF (Phys. Rev. D64, 2001): semi-exclusive
  primary $\pi^{\pm} \oplus$ part. rec. B in semi-lep. decay to charm
- new Delphi analysis (prelim.): inclusive
  dedicated neural networks for Q-value reconstruction, B^{**} enrichment, etc.

B^{**} results (1)

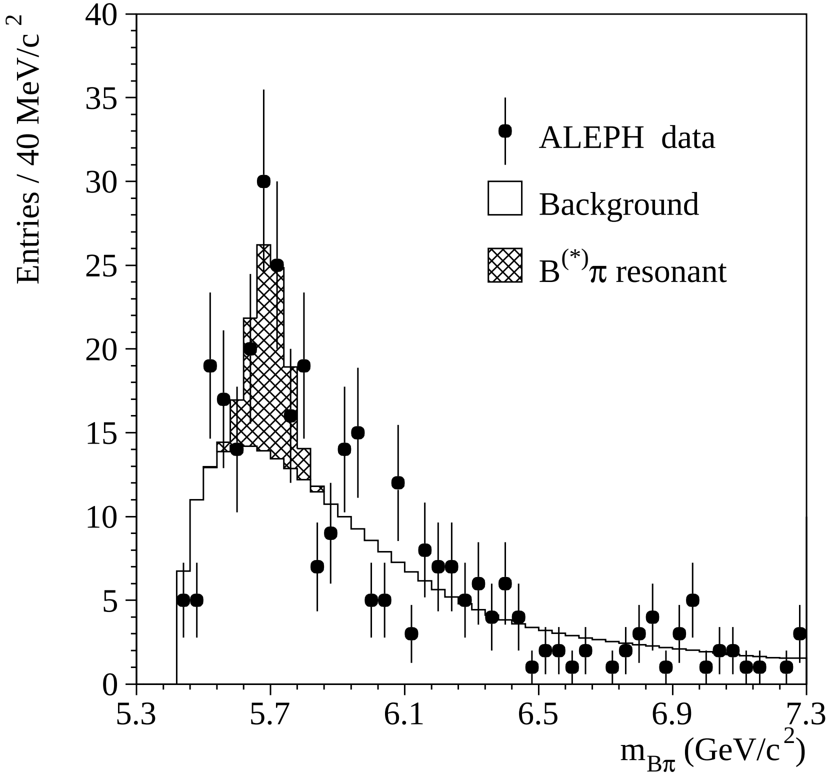
Production fractions for excited B $(L = 1)$ states:

experiment	$f_{B^{**}_{u,d}}$ in % (narrow and broad states)
Delphi	27 ± 2 (stat) ± 6 (sys)
Opal	27 ± 5.6
Aleph (inclusive)	27.9 ± 1.6 (stat) ± 5.9 (sys) $^{+3.9}_{-5.6}$ (model)
Aleph (exclusive)	31 ± 9 (stat) $^{+6}_{-5}$ (sys)
L3	32 ± 3 (stat) ± 6 (sys)
CDF	28 ± 6 (stat) ± 3 (sys)
	$f_{B^{**}_{u,d}}$ in % (narrow states only)
Delphi (prelim.)	9.8 ± 7 (stat) ± 1.2 (sys)

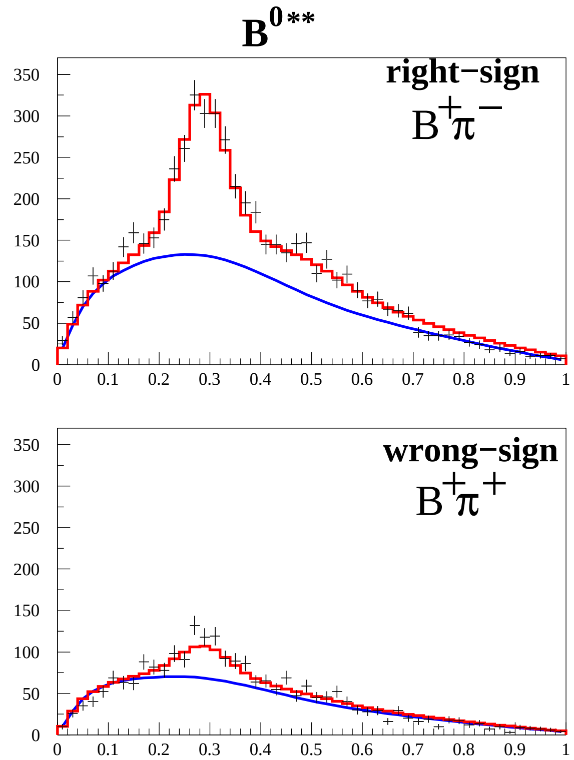
B_s^{**} :

- Opal: $f^{**}_{B_s} = 2.6 \pm 0.5$ (stat) ± 0.6 (sys) %
- Delphi (prelim.): $f^{**}_{B_s} < 1.5\%$ @95 % CL

B^{**} results (2)



Aleph exclusive: clear B^{**} signal, background from ws combinations in data



Delphi (prelim.):

Q-value reconstructed by neural net, highly enriched sample background from MC

Conclusions

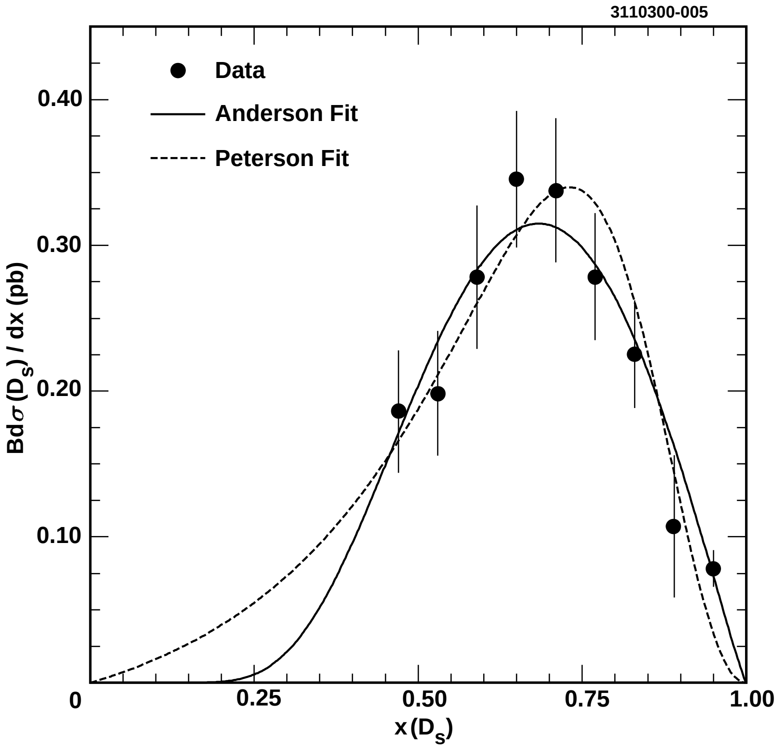
- All recent fragmentation analyses give consistent picture.
- Lund / Bowler model favoured over Peterson, etc. for heavy quarks (c, b) as well (in terms of frag. variable z).
- Moment approach promising
- Narrow $(L = 1)$ $B^{**}_{u,d}$ states well established
- Ongoing efforts to separate narrow and broad states.
- B^{**}_s and $\Sigma_b^{(*)}$ still not yet unambiguously identified, work in progress.

backup transparencies

Hadronisation in MC Generators

- Herwig: Employ cluster hadronisation model:
  - split outgoing gluons into light quarks $\rightarrow$ colour singlet clusters
  - low mass clusters: consider as hadron and shift mass to appropriate value
  - high mass clusters: decay isotropically into pairs of hadrons
- Pythia/Jetset:
  - perturbative part: Parton Shower (LL, Pythia) or Colour Dipole (Ariadne)
  - non-perturbative part: Lund string model
    gluon self interaction force colour connections between quarks into a small string,
    create hadrons by iteratively breaking the string according to fragmentation model

CLEO analysis: D_s^{*+}



CLEO (Phys. Rev. D62 (2000)) :

Charm fragmentation into D_s^{*+} and D_s^+

exclusive reconstruction:

$D_s^{*+} \rightarrow D_s^+ \gamma,\ D_s^+ \rightarrow \Phi\pi^+,\ \Phi \rightarrow K^+K^-$

Variable: $x = \frac{p(D_s^+)}{p_{max}(D_s^+)}$

(to approximate z)

$\rightarrow$ Lund model ("Andersson") favoured over Peterson

SLD b-fragmentation measurement (1)

Part I: Test of frag. model

- Use Jetset, Herwig, UCLA MC-Generator $\rightarrow D^{true}_{model}\ \ x_B^{true}, \beta$
- Get reconstructed distribution by weighting:

  $$D^{rec}_{model}\ \ x_B^{rec}, \beta\ \ = D^{rec}_{def}\ \ x_B^{rec}\ \ \times \frac{D^{true}_{model}(x_B^{true}, \beta)}{D^{true}_{def}(x_B^{true})}$$

- χ^2-fit based on x_B-distribution to get optimal parameter(s) β for each model (ignore bins with low statistics)

Part II: Test of functional forms

- Consider fragmentation models in terms of x_B^{true}
- Get $D^{rec}_{model}\ \ x_B^{rec}, \lambda$ in a similar way
- Obtain optimal parameter(s) λ for each model

$\rightsquigarrow$ 8 models (with parameters β, λ) found to be consistent with the data

SLD b-fragmentation measurement (2)

Correction of B-energy distribution

use 25×25 bin matrix approach:

$$D^{true}\left(x_B^{true}\right) = \epsilon^{-1}\left(x_B^{true}\right) E\left(x_B^{true}, x_B^{rec}\right) D^{rec}\left(x_B^{rec}\right)$$

where:

- ϵ: effciency correction (from MC)
- E: detector $\otimes$ input model
  $E(i,j)$: number of vertices with x_B^{true} in bin i and x_B^{rec} in bin j normalised to total number of vertices x_B^{rec} in bin j
- obtain E from MC (no iteration):
  $D_{model}^{true}\ \ x_B^{true}, \beta/\lambda\ \ = \epsilon^{-1}\ \ x_B^{true}\ \ E\ \ x_B^{true}, x_B^{rec}\ \ D_{model}^{rec}\ \ x_B^{rec}, \beta/\lambda\ )$
  and apply to data for each model with parameters β, λ from part I and II

ALEPH b-fragmentation measurement (1)

$\rightsquigarrow$ semi-exclusive approach: use $B \to l\nu D^{(*)}$ to reconstruct B energy

Part I: model-dependent analysis

- Reweight MC with $w = \frac{f(z,\epsilon)}{f_{def}(z)}$ (Peterson, CS, Kartv.)
- use χ^2 based on x_B-distribution to find optimal parameter ϵ for each function

Part II: model-independent analysis

- use iterative approach with 20 bins:

$$f_i\left(x_B\right) = \frac{1}{T}\sum_{c=1}^{5}\frac{1}{\epsilon_i(c)}\sum_{j=1}^{20} G_{ij} n_j^{data}(c)$$

T: normalisation $\epsilon_i(c)$ efficiency per bin and channel
G_{ij}: Resolution matrix:
probability of B with observed energy in bin j has true energy in bin i

ALEPH b-fragmentation measurement (2)

⇝ Get matrix G_{ij} from MC:

- Start off with G_{ij} from standard MC
- reweight MC with result from previous iteration

$$w_i^N = \frac{f_{i,data}^{N-1}(x_B)}{f_{i,MC}^{default}(x_B)}$$

- use 5th order polynomial for smoothing weights w_i^N
- repeat iterations until difference between successive iterations small compared to statistical error

OPAL b-fragmentation measurement

Part I: Test of fragmentation models:

- compare reconstructed x^{weak} to MC sample (Herwig, Jetset)
- reweight Jetset sample for:
  - different fragmentation Models
  - model parameters
    (take $bm_\perp^2$ as free parameter in Lund and Bower model,
    assume $m_B \approx m_b$ for Bowler)
- determine best model and parameters via χ^2 fit

Part II: model-independent analysis

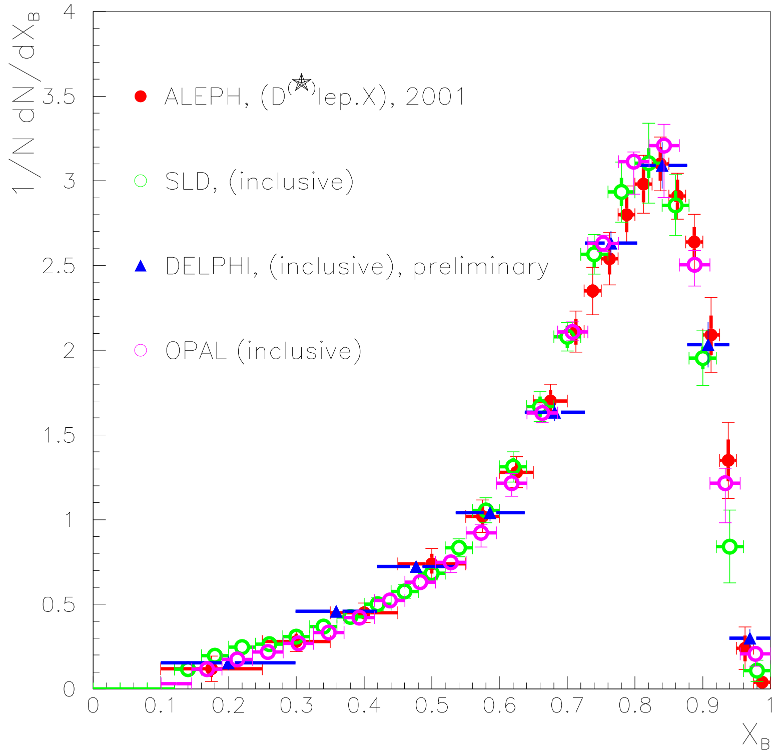
- unfold x^{weak} using $\mathcal{RUN}$ (regularised unfolding)
- use 20×20 matrix unfolding approach (SVD-GURU) as cross-check

Summary Slide

Fragmentation and excited B states

Fragmentation:

- High precision analyses from e^+e^- machines
- Unfolded spectrum of weakly decaying state consistent between experiments
- Lund, Bowler model reproduce data best.
- Moment approach promising
- Fragmentation at hadron machines much more complex.



Fragmentation and excited B states

Excited B states:

- Narrow $(L = 1)$ $B^{**}_{u,d}$ states well established
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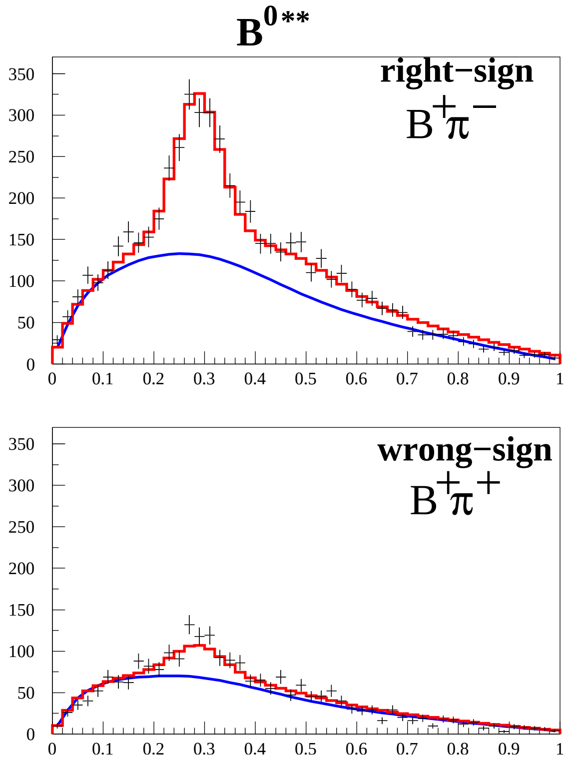
- B^{**}_s and $\Sigma^{(*)}_b$ still not yet unambiguously identified, work in progress.



Delphi (prelim.):

reconstructed Q-value