Heavy Quark Fragmentation Functions in e^+e^- annihilation

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Heavy Flavor Productions &
Hot/Dense Quark Matter '05, BNL

-Introduction

-Charm Fragmentation Functions @ 10.6 GeV

c →D^0,D^+,D_s^+,Λ_C^+,D^{*+} and D^{*0}

-Beauty Fragmentation Function @ 91.2 GeV

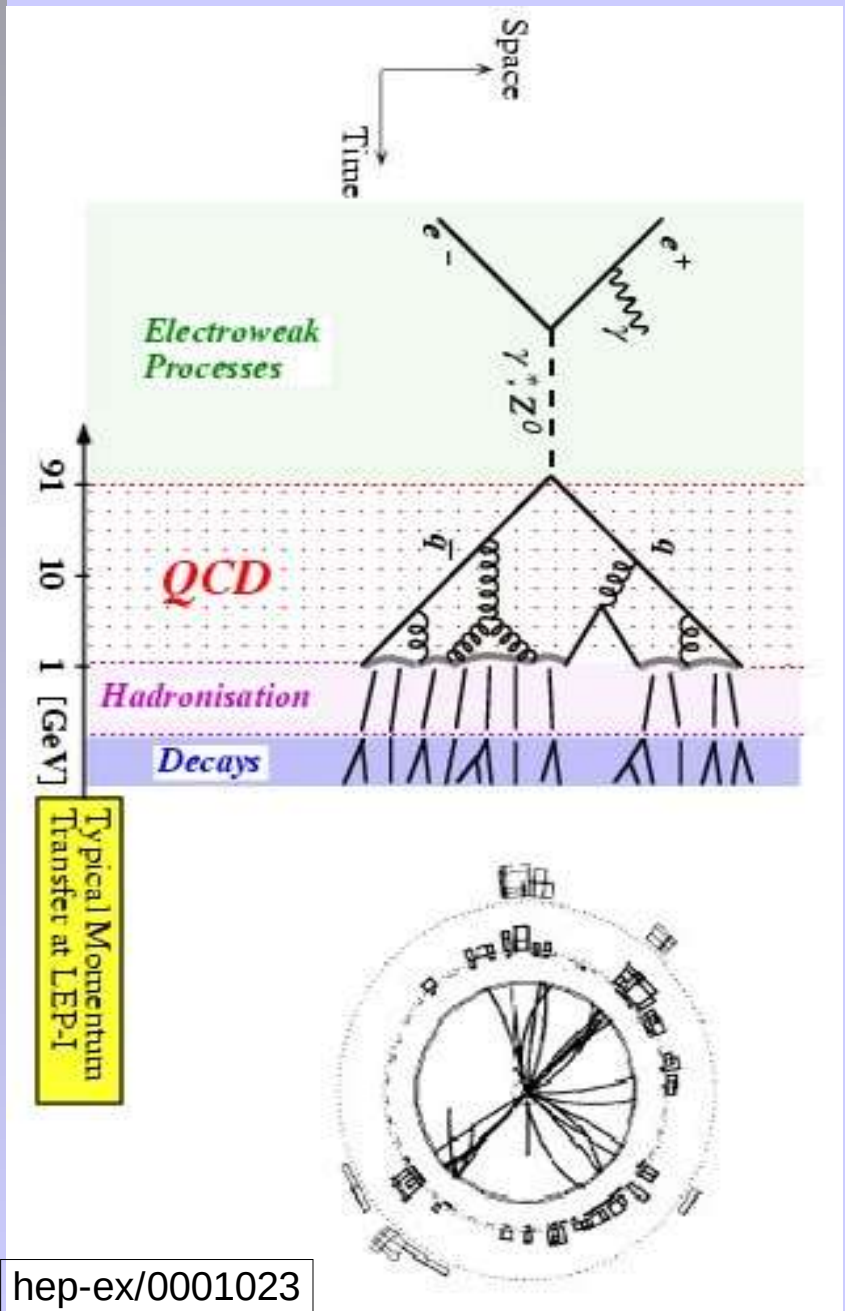
b → weakly decaying B's

D^{*+} from Z_0→cc decays

-Discussion

-Summary

Introduction: typical e^+e^- event

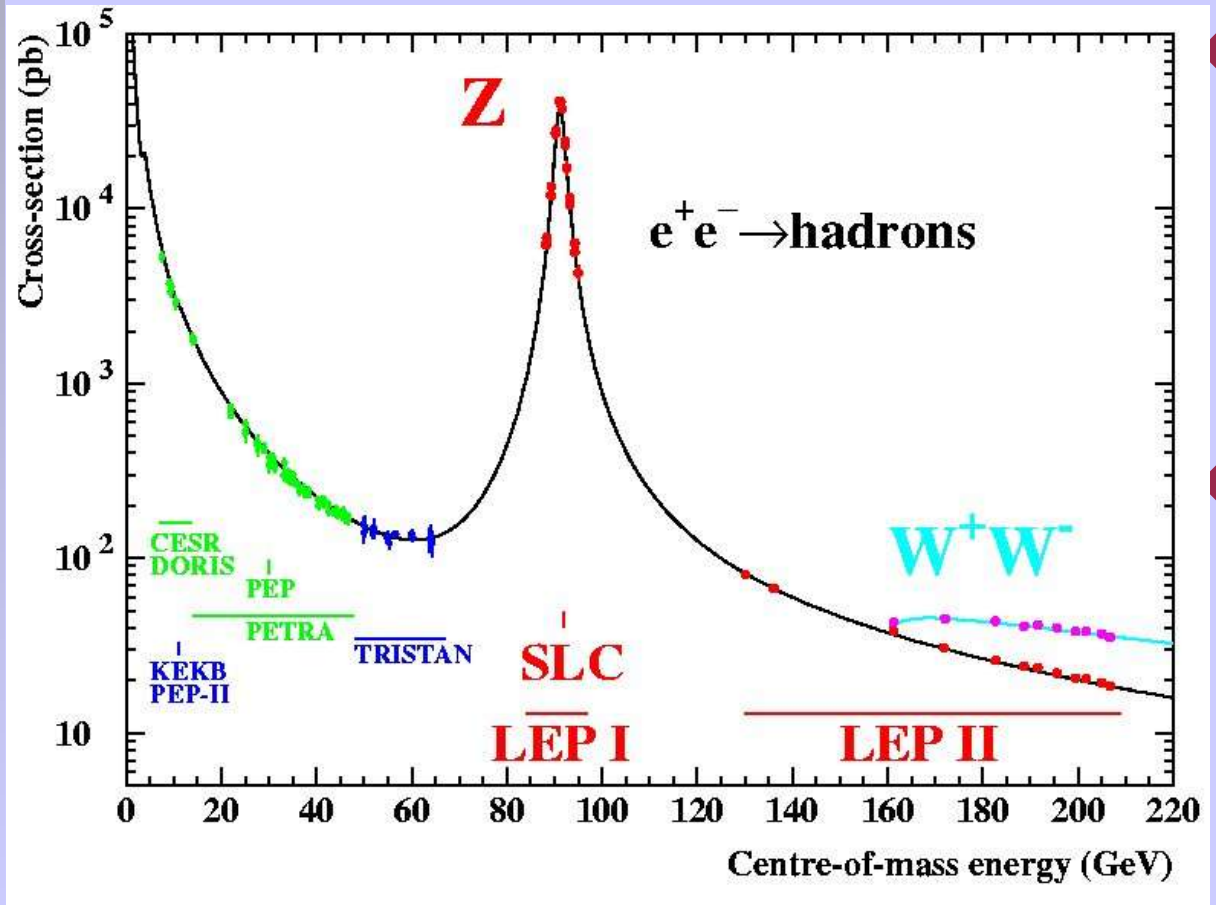


- different states of a typical e^+e^- annihilation event
- QCD:
  parton shower, gluon splitting, hadronization
  "fragmentation function"
- electroweak phase:
  decay of most resonances

hep-ex/0001023

Introduction: Experiments

- implication:
  heavy quark must be produced far above production threshold



- Belle/KEKB @10.6 GeV only charm frag.fcn
- expm. at LEP and SLD @ 91.2 GeV, charm and beauty frag.fcn

Introduction: Fragmentation Function

- Fragmentation Functions F describe transition amplitude of quark Q to hadron H

- parameters to $F(z,m_{\perp})$ are:

$$z \equiv \frac{(E+p_z)_H}{(E+p_z)_Q}$$ "longitudinal momentum fraction"

$$m_{\perp}^2 \equiv m^2 + p_x^2 + p_y^2$$ "transverse mass"

Fragmentation Functions

- Peterson et al.: $N_{\mathrm{P}}\frac{1}{z}\left(1-\frac{1}{z}-\frac{\epsilon_{\mathrm{C}}}{1-z}\right)^{-2}$
- Lund: $N_{\mathrm{L}}\frac{1}{z}(1-z)^{\mathrm{a}}\exp\left(\frac{-bm_{\perp}^{2}}{z}\right)$
- Bowler: $N_{\mathrm{B}}\frac{1}{z^{1+bm^{2}}}(1-z)^{\mathrm{a}}\exp\left(\frac{-bm_{\perp}^{2}}{z}\right)$
- Kartvelishvili et al.: $N_{\mathrm{K}}z^{\alpha_{\mathrm{C}}}(1-z)$
- Collins & Spiller: $N_{\mathrm{C}}\left(\frac{1-z}{z}+\frac{(2-z)\epsilon'_{\mathrm{C}}}{1-z}\right)(1+z^{2})\left(1-\frac{1}{z}-\frac{\epsilon'_{\mathrm{C}}}{1-z}\right)^{-2}$

Note: at most 2 variables! (z and $m_{\perp}$) ⇒ Reweighting

Introduction: Variables

- 2 variables commonly used:

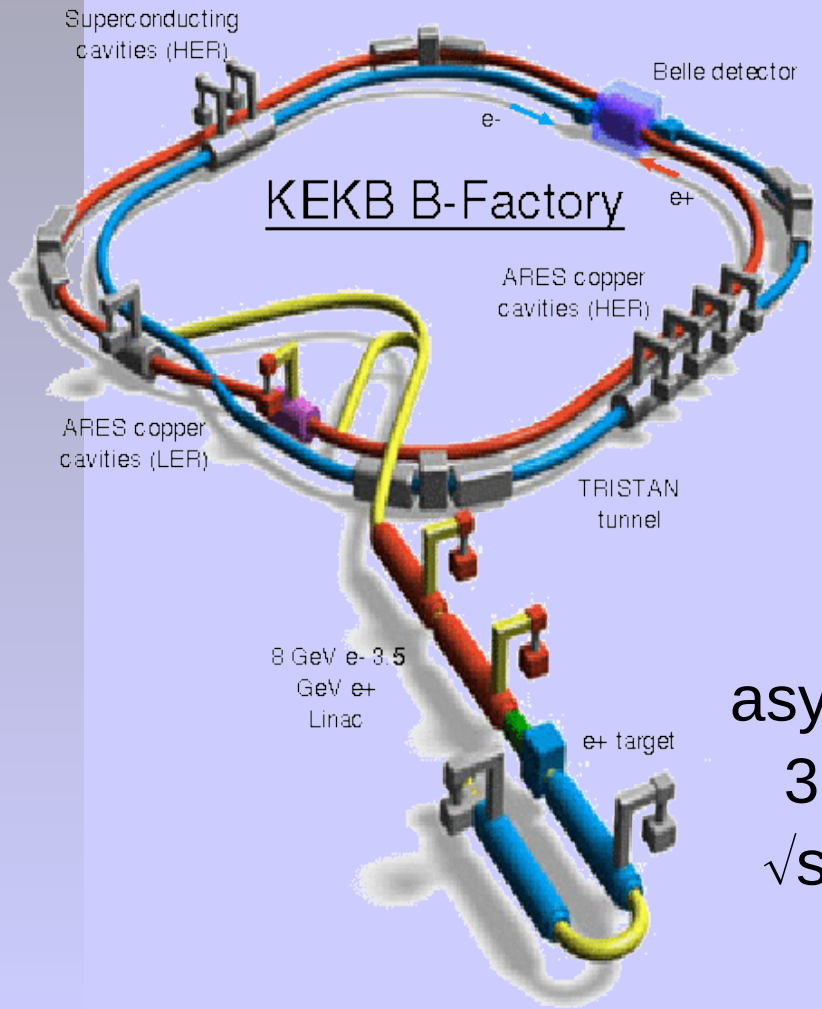
$$x_P \equiv \frac{|\vec{p}_{Candidate}|}{|\vec{p}_{MAX}|}$$

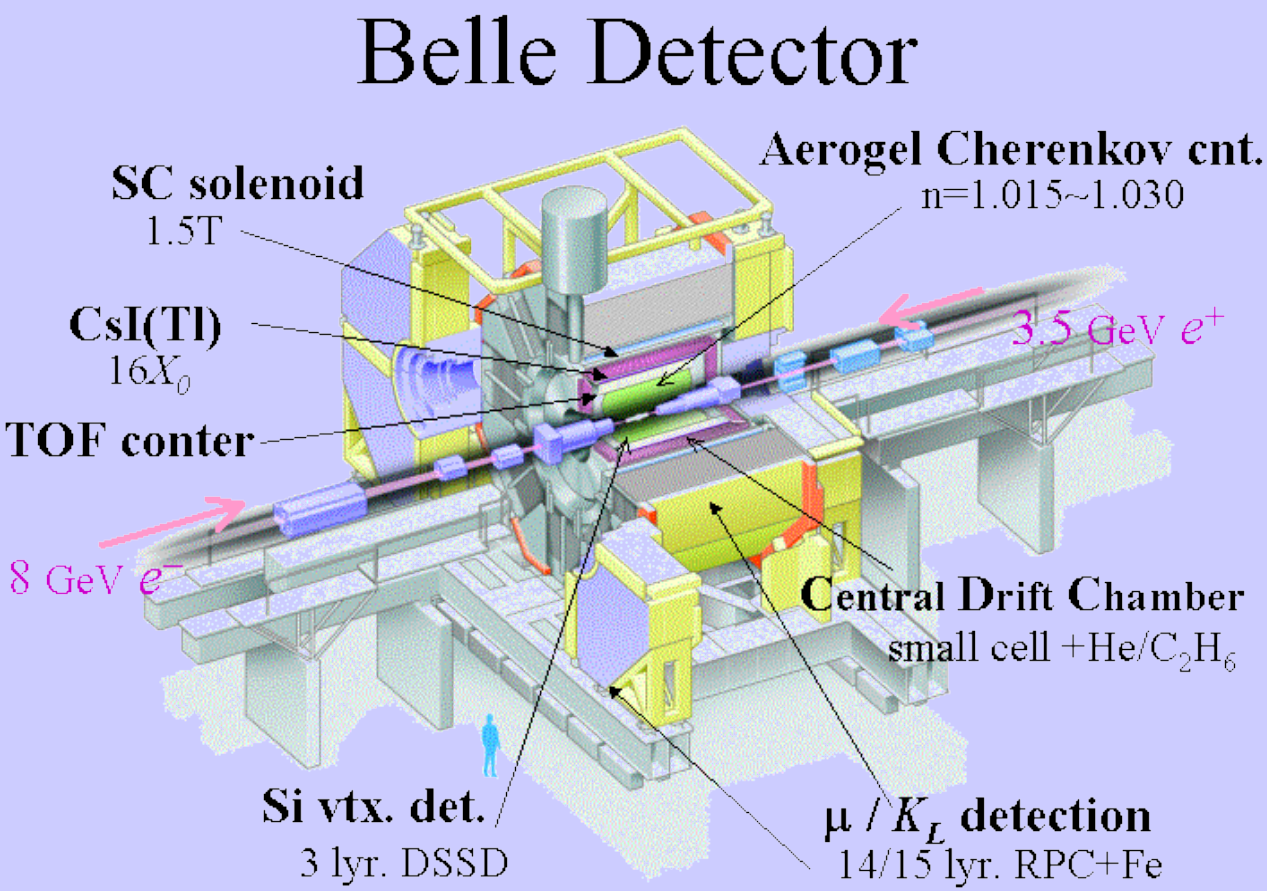
scaled momentum

$$x_E \equiv \frac{E_{Candidate}}{E_{MAX}}$$

scaled energy

Experimental Apparatus @ 10.6 GeV





asymmetric beam energies:

3.5 GeV e^+ on 8 GeV e^-

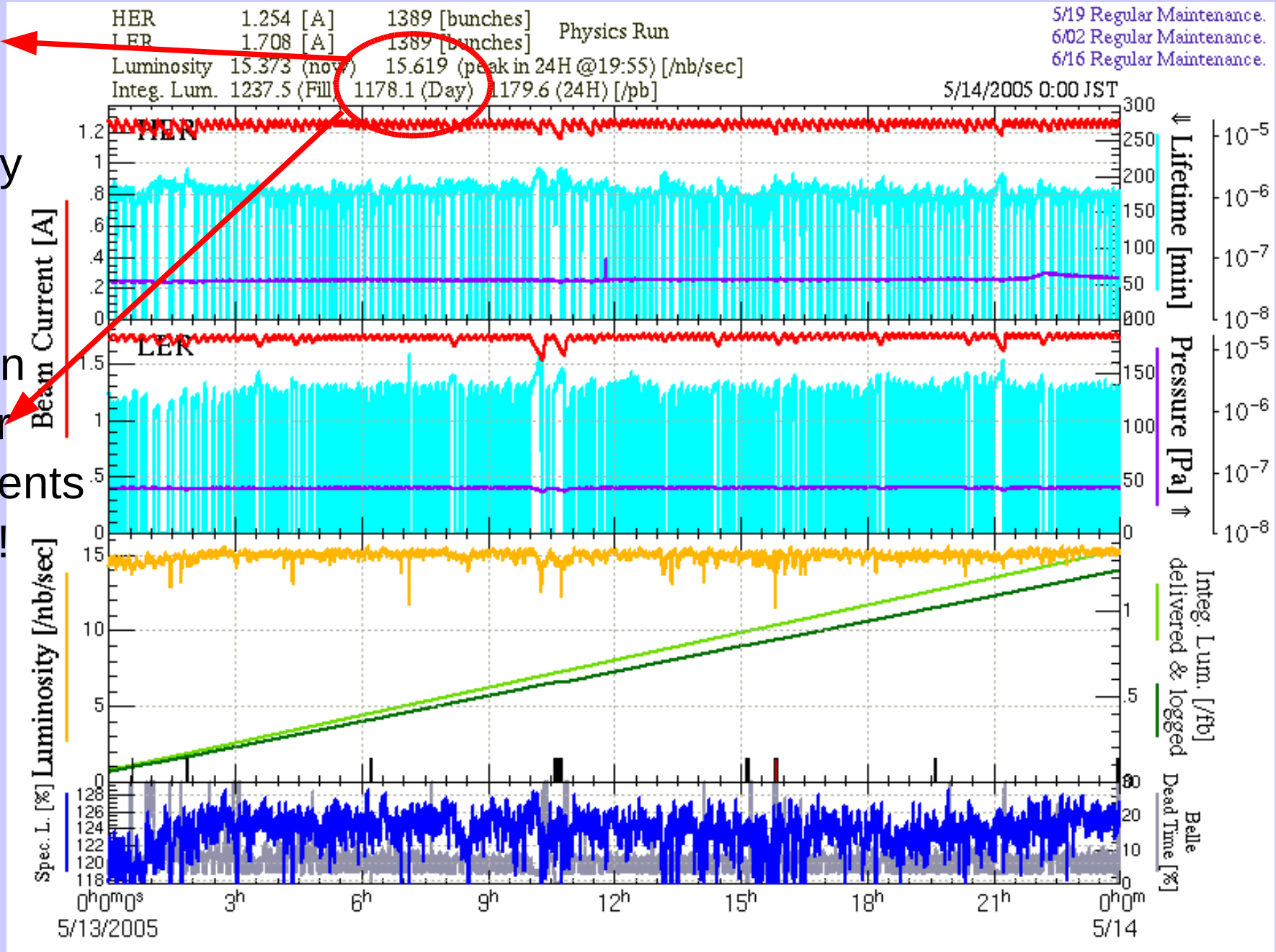
$\sqrt{s}$=10.58 GeV, moving in lab-frame

Accelerator Performance

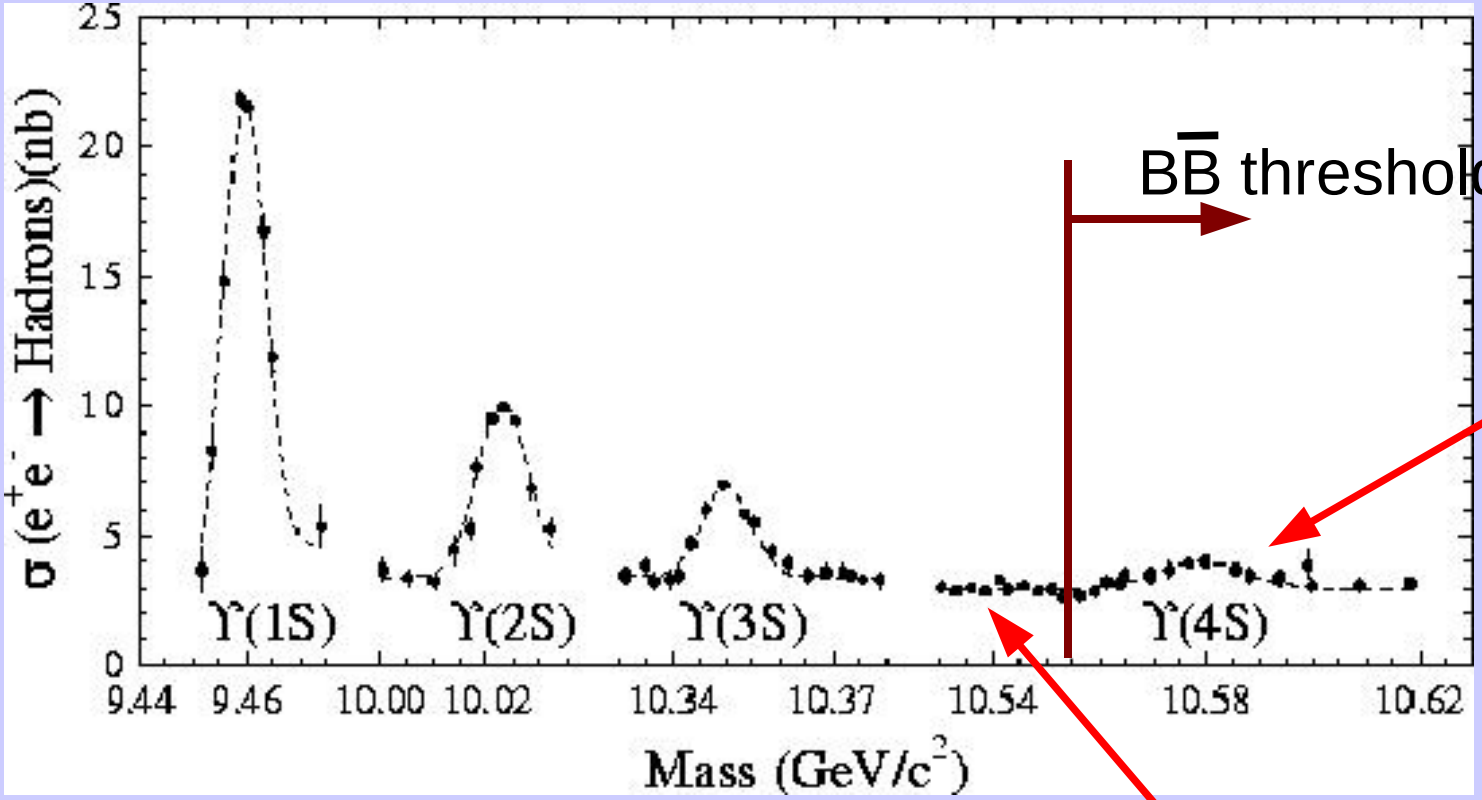
Highest instant. luminosity ever!!

more than 10^6 BB or $4 \cdot 10^6$ events per day !!

in total >500 fb^{-1} collected



Continuum and On-Resonance



~90% of data taken above $B\bar{B}$ threshold labelled as "on-resonance"

~10% of data taken below $B\bar{B}$ threshold
-to study dominant background to B decays
-to do QCD studies with $e^+e^- \rightarrow q\bar{q}$ (q=d,u,s,c) labelled as "continuum"

Charm Fragmentation Functions

hep-ex/0506068

- $c \rightarrow D^0$, D^+, D_s^+, Λ_c^+, D^{*+} and D^{*0}

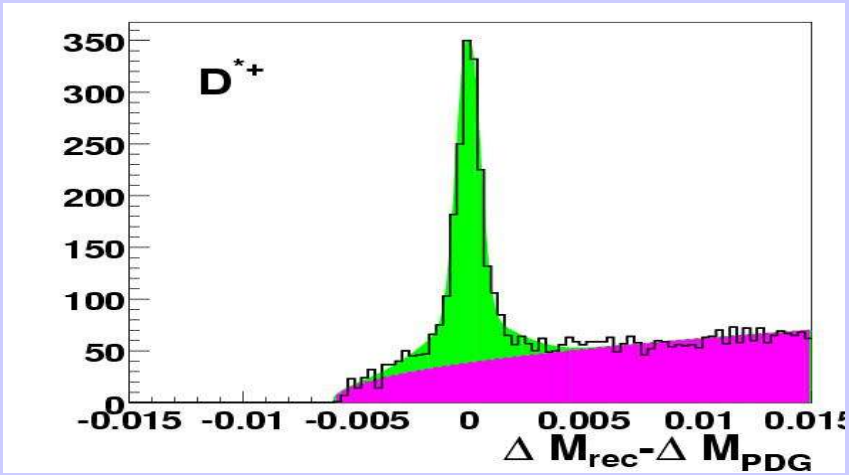
- 'standard' decay modes:

  $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D_s^+ \rightarrow \phi(K^+K^-)\pi^+$, $\Lambda_c^+ \rightarrow pK^-\pi^+$,

  $D^{*+} \rightarrow (K^-\pi^+)\pi^+_{Slow}$, $D^{*+} \rightarrow (K^-\pi^+\pi^+)\pi^0_{Slow}$ and $D^{*0} \rightarrow (K^-\pi^+)\pi^0_{Slow}$

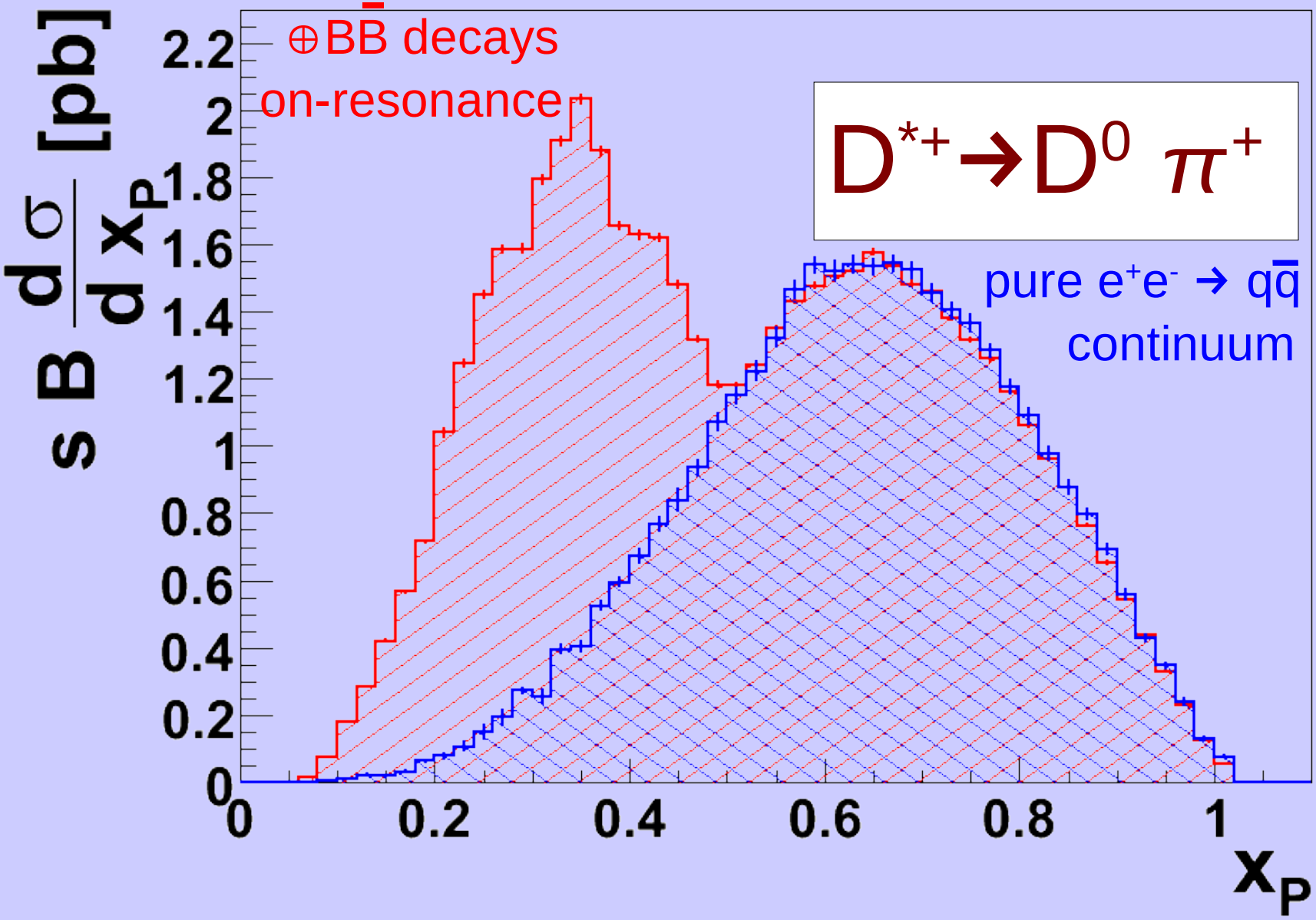
- fit signal yield in bins of

$$x_P \equiv |\vec{P}_{Cand}| / |\vec{P}_{MAX}|$$

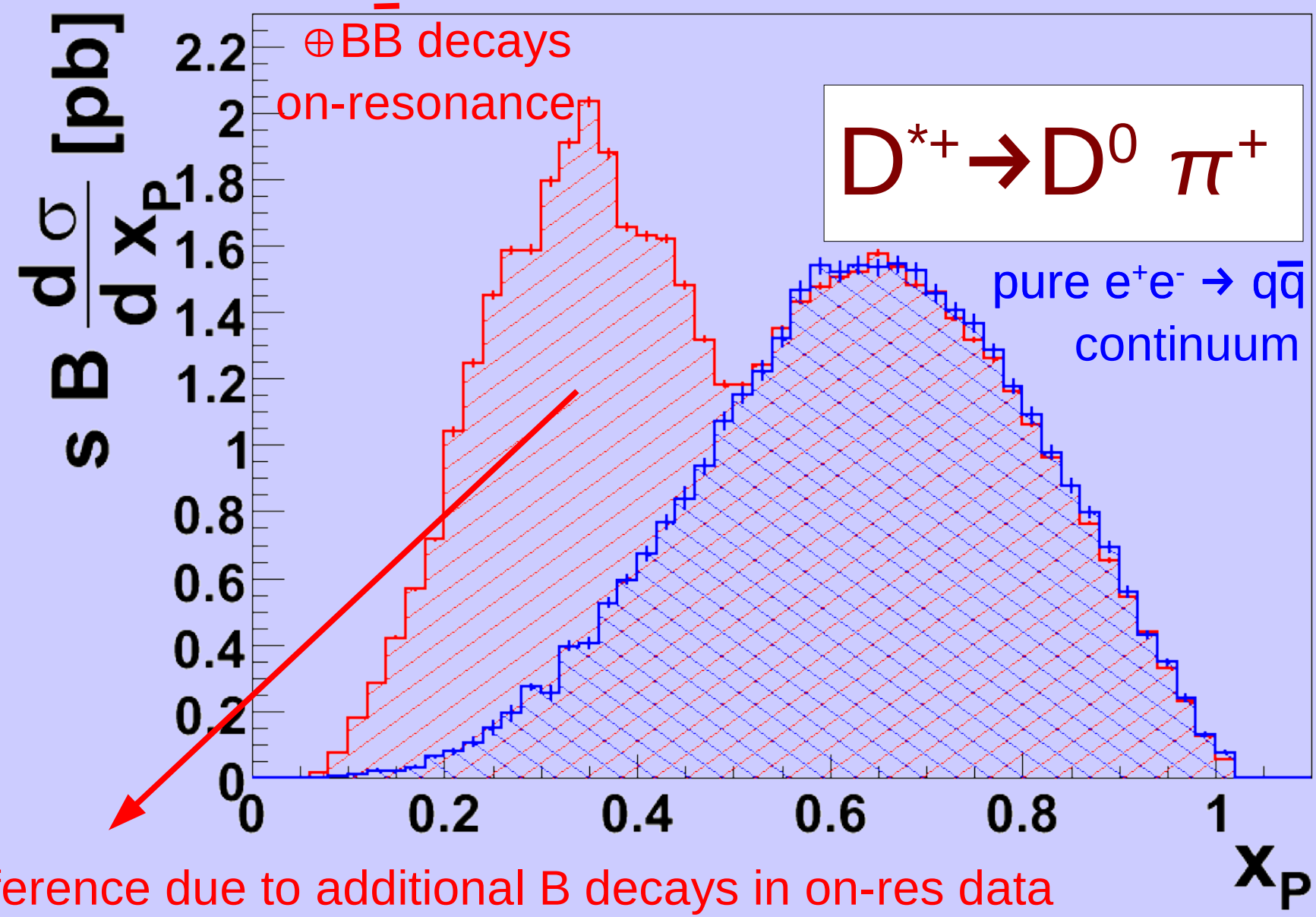


- data set: 15 fb^{-1} continuum, or $45 \cdot 10^6$ events
  88 fb^{-1} on-resonance, $264 \cdot 10^6$ events

Raw Yield in Continuum and On-Resonance



Raw Yield in Continuum and On-Resonance

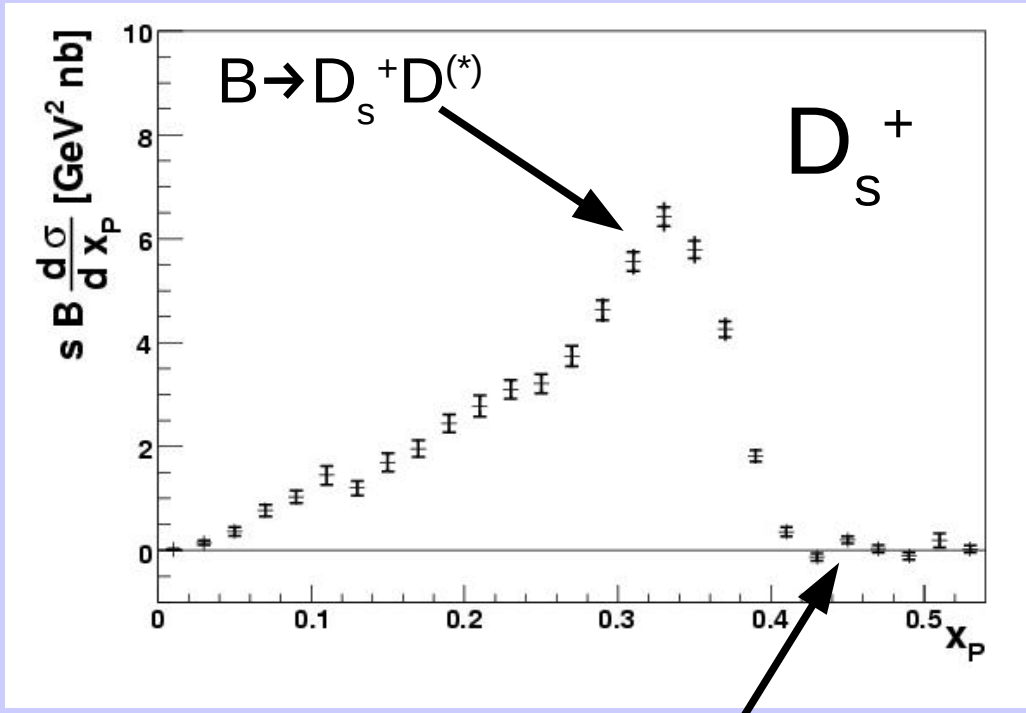


difference due to additional B decays in on-res data

Average Charmed Meson per B Decay

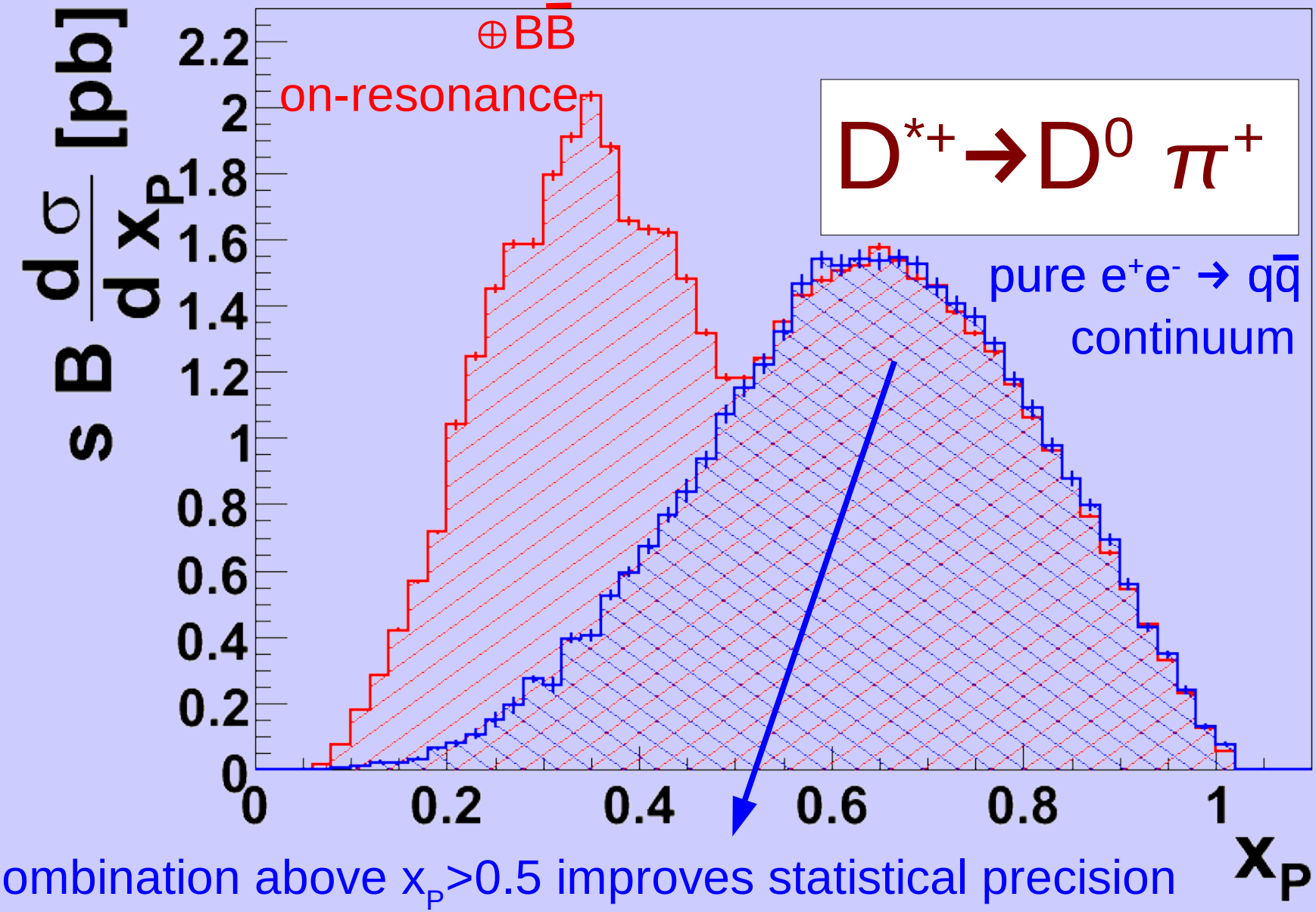
Subtract continuum from On-Resonance data:

	$N_{B\to c}[\%]$			$\pm stat \pm syst \pm B$
D^0	64.4	± 0.3	± 2.4	± 2.1
D^+	24.8	± 0.4	± 3.3	± 2.0
D_s^+	12.2	± 1.5	± 3.3	± 3.0
Λ_C^+	4.2	± 1.1	± 3.3	± 1.8
D^{*0}	21.7	± 1.4	± 2.0	± 1.8
D^{*+}	21.5	± 0.6	± 2.2	± 1.6



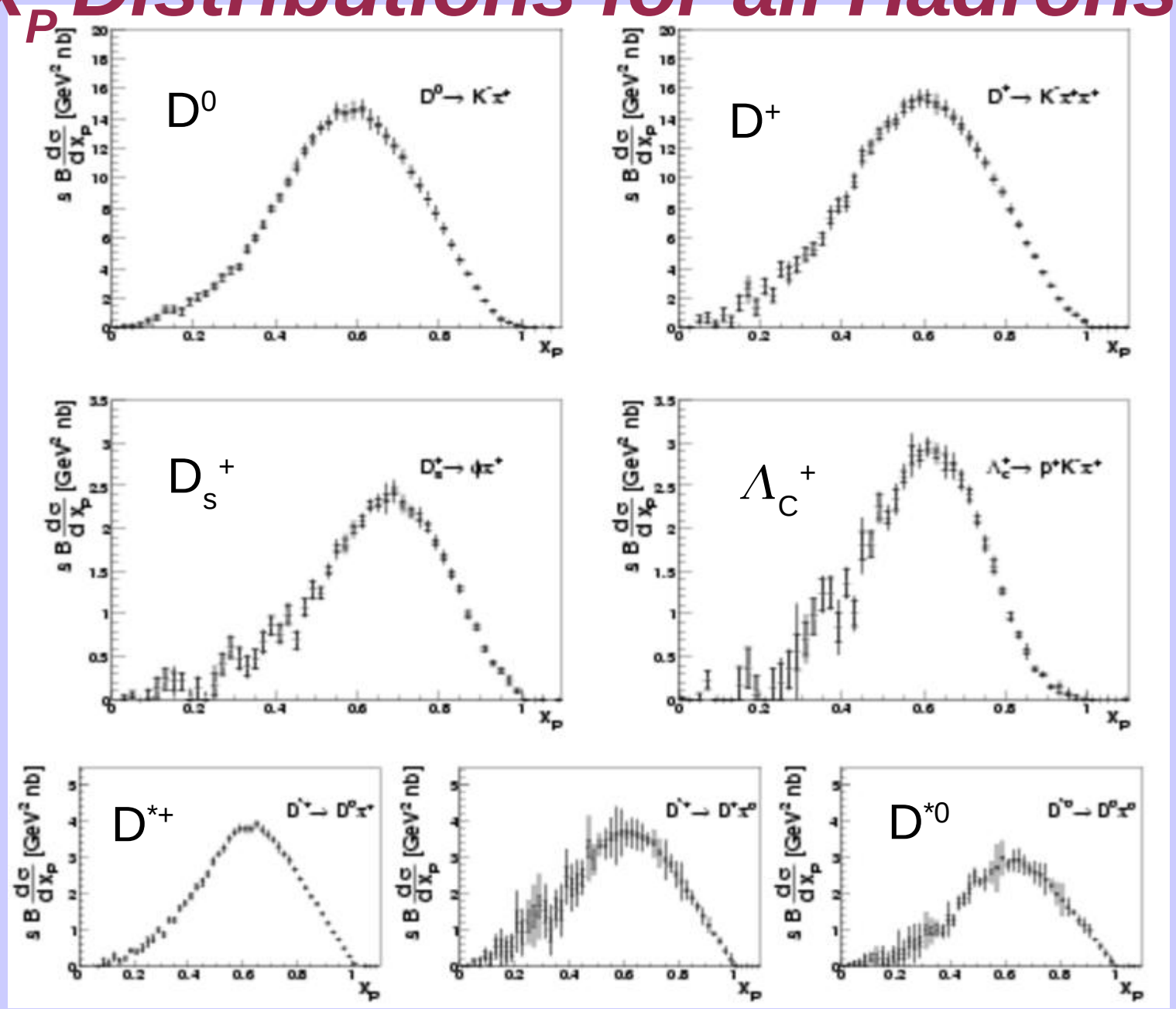
b → u transition

Raw Yield in Continuum and On-Resonance



Combination above x_p>0.5 improves statistical precision

x_P Distributions for all Hadrons



⇒ precise and detailed spectrum !

Total Cross Section

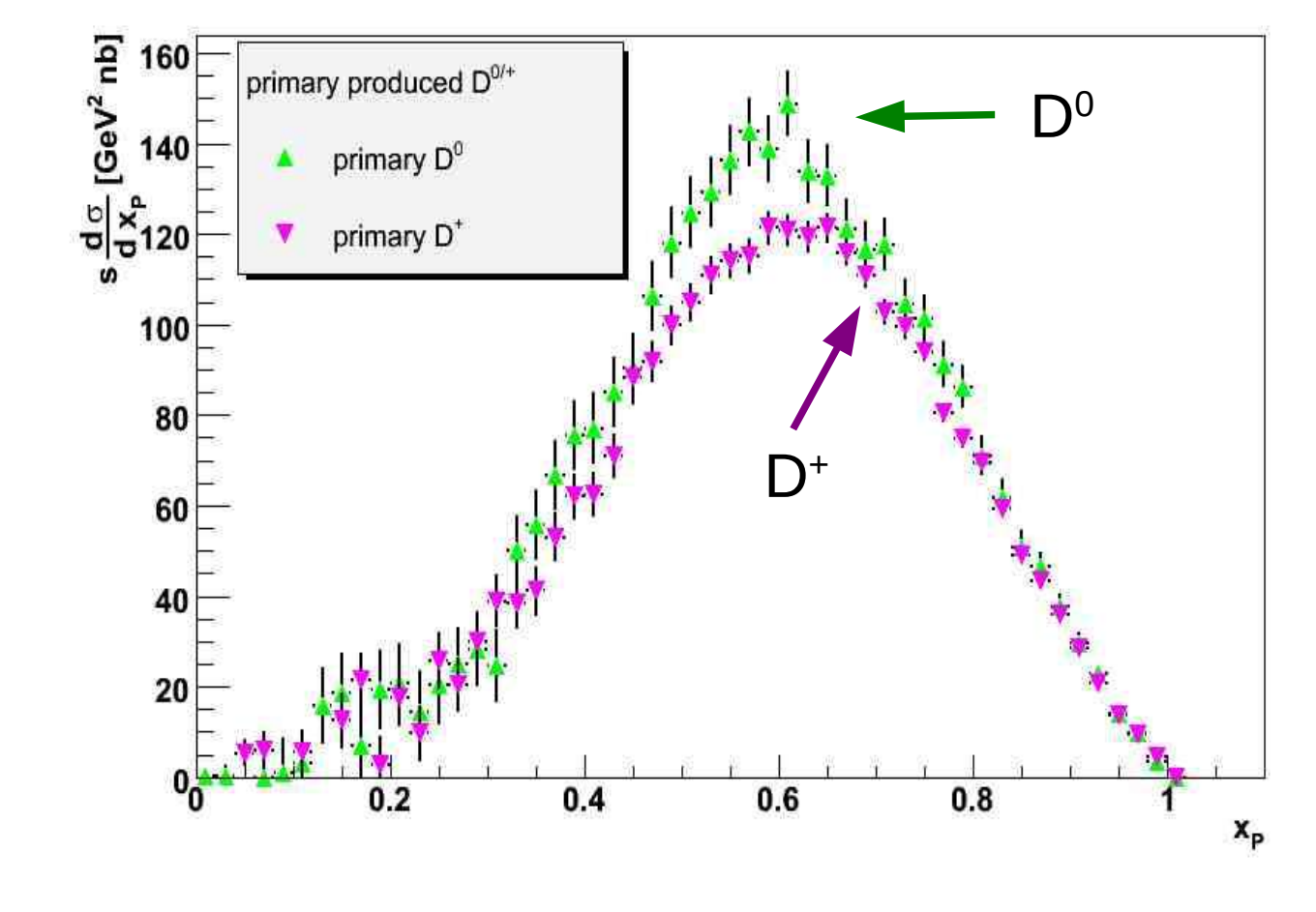
	production cross section			
D^0	1448	± 2	± 64	$\pm 38\ pb$
D^+	654	± 1	± 36	$\pm 46\ pb$
D_s^+	231	± 2	± 92	$\pm 77\ pb$
Λ_C^+	189	± 1	± 66	$\pm 66\ pb$
D^{*0}	510	± 3	± 84	$\pm 39\ pb$
D^{*+}	597	± 2	± 78	$\pm 25\ pb$

includes decays of D^{*+} and D^{*0}

same, within systematic uncertainties

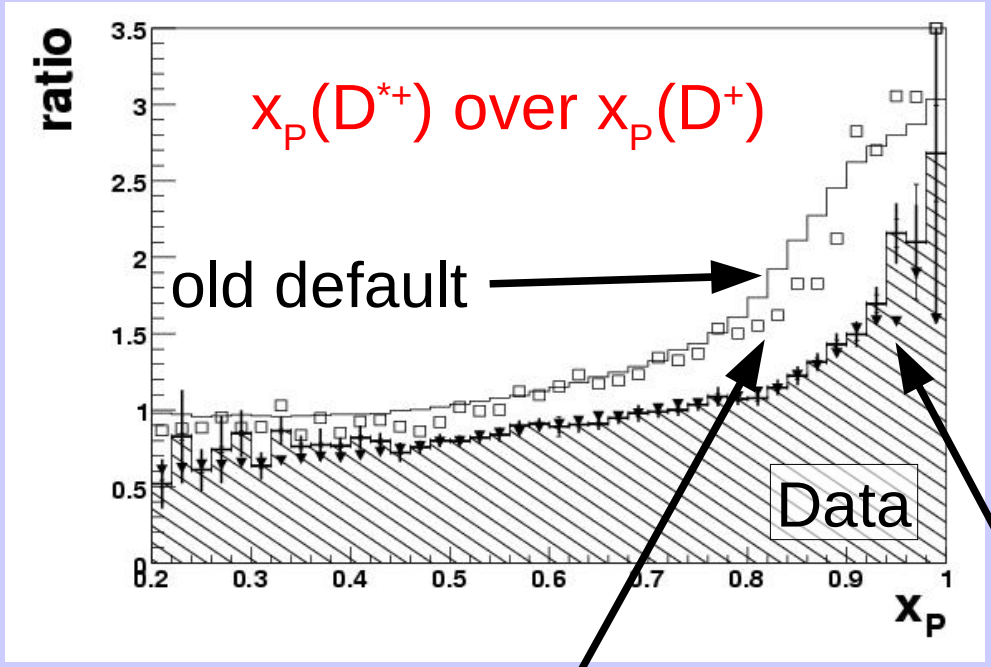
Primary D^0 and D^+

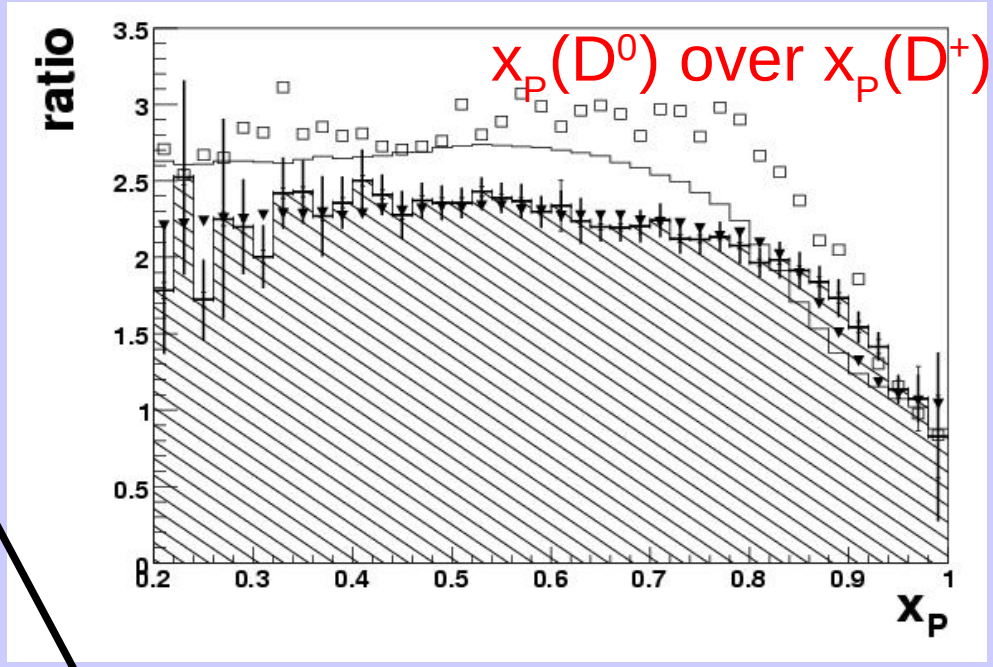
Subtract yield from $D^{*0} \rightarrow D^0$ and $D^{*+} \rightarrow D^0/D^+$ from D^0 and D^+ spectra



Primary produced D^0 and D^+ agree reasonably,
remaining difference due to neglected higher resonances ?

Ratios I



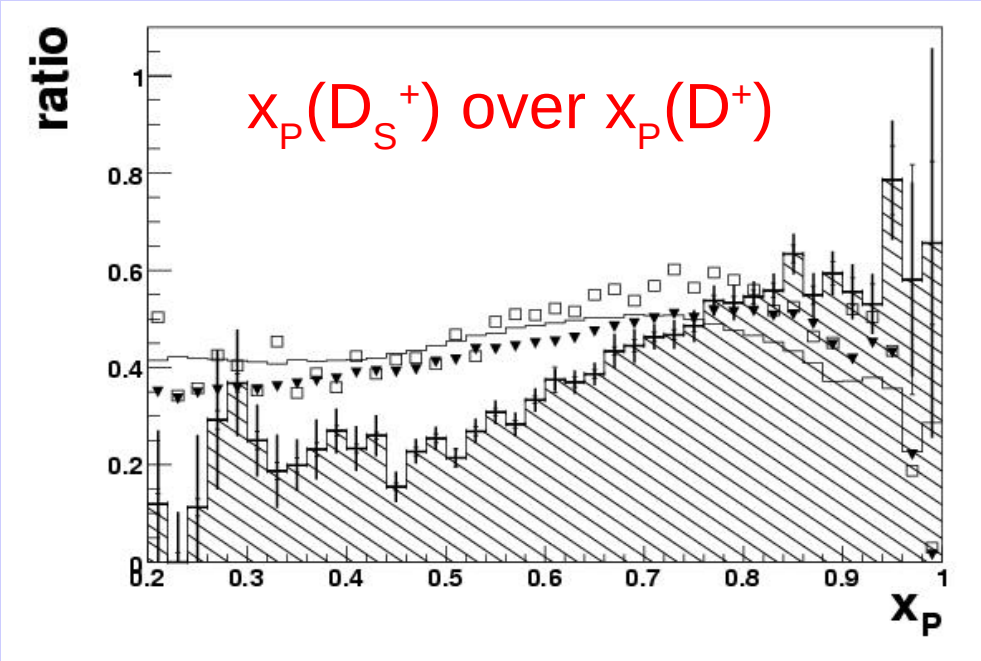


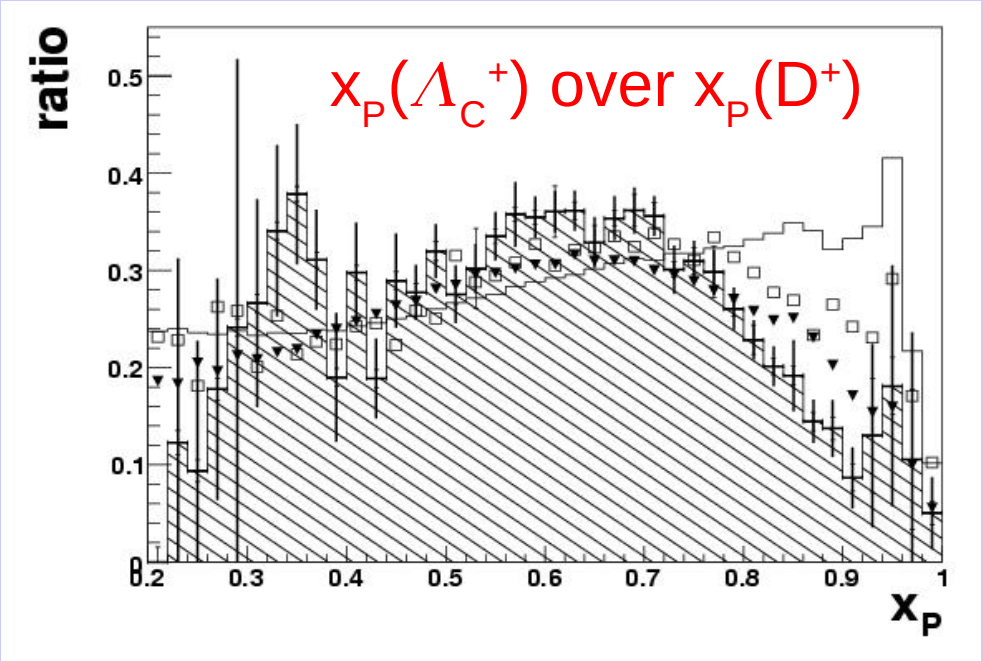
old tune, Bowler

new Tune, PARJ(13)=0.59

With new tune (“probability of producing a charmed meson with spin=1”) excellent agreement btw. data and MC

Ratios II





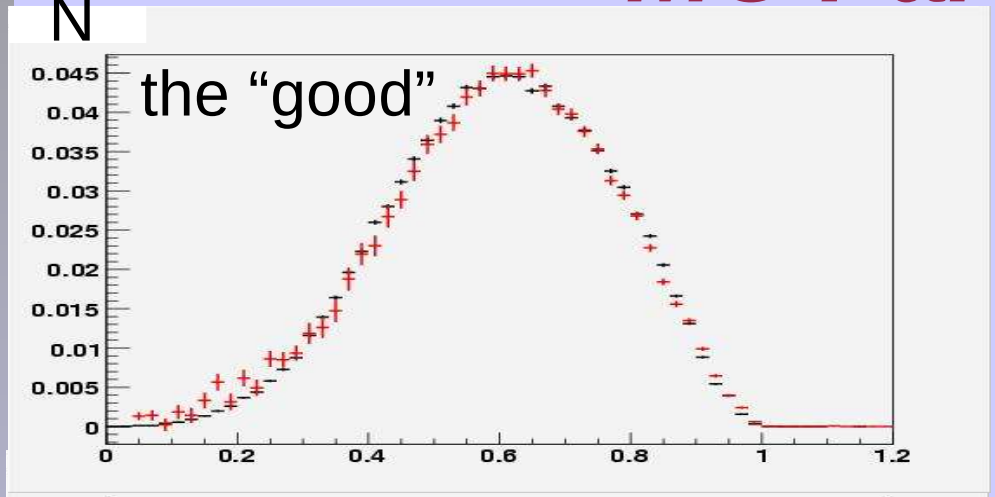
no parameter in MC to tune these ratios

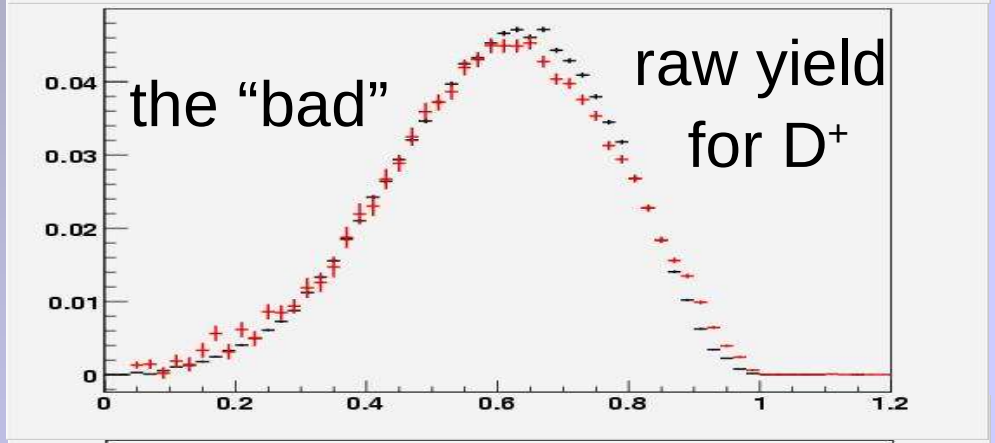
- changing to Bowler improved slightly, but still large differences
- something more fundamental not modelled ??

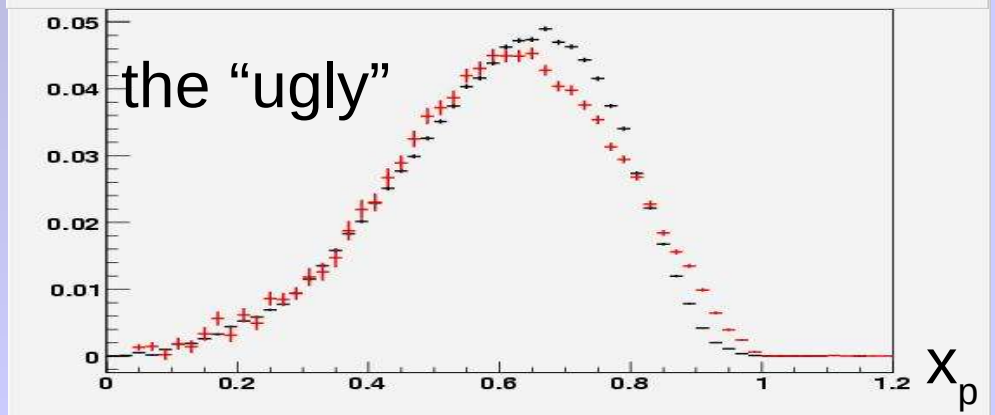
MC Comparison

- reweighting technique: mimic different fragmentation function/parameters than used during generation of events
- allows comparison with functions not included in MC
- 5 functions:
  Peterson et al., Lund, Bowler,
  Kartvelishvili et al. and Collins and Spiller

MC Parameter





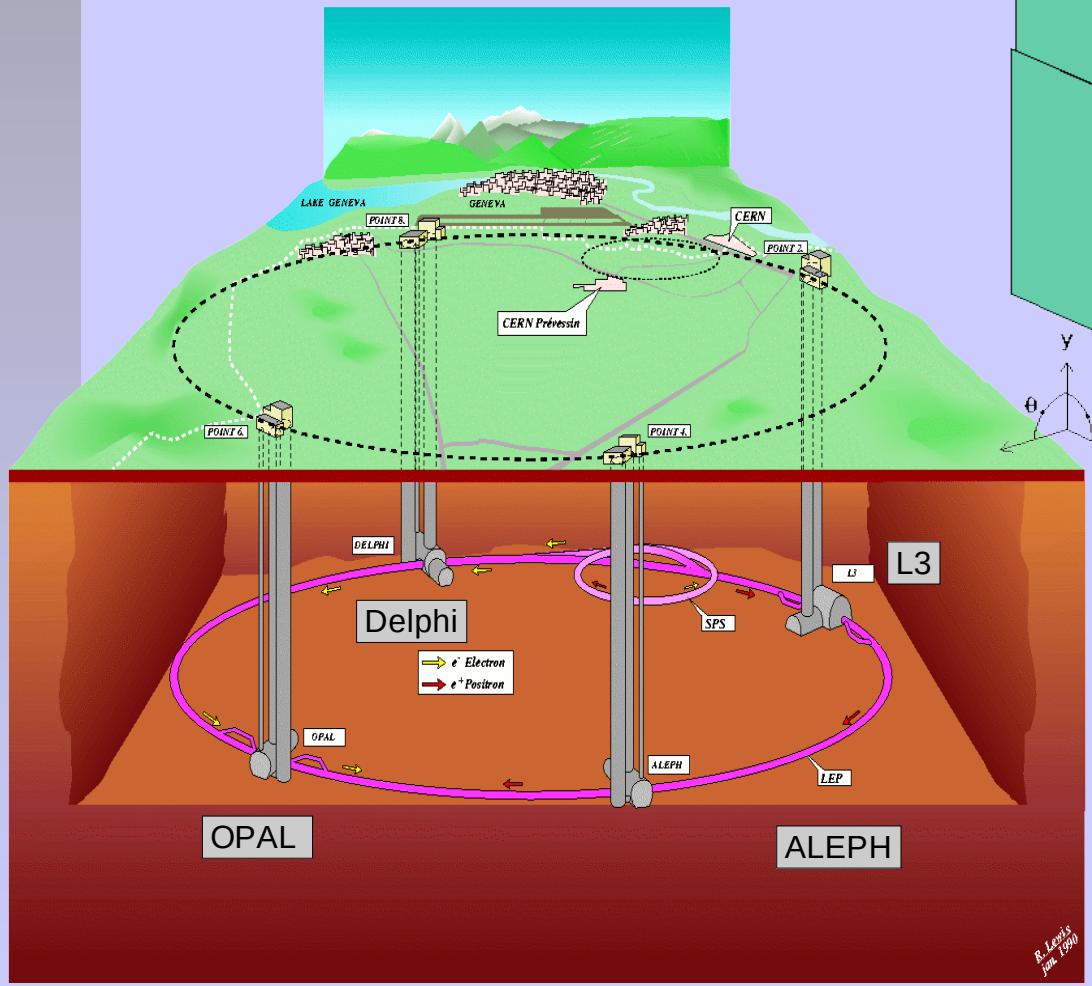


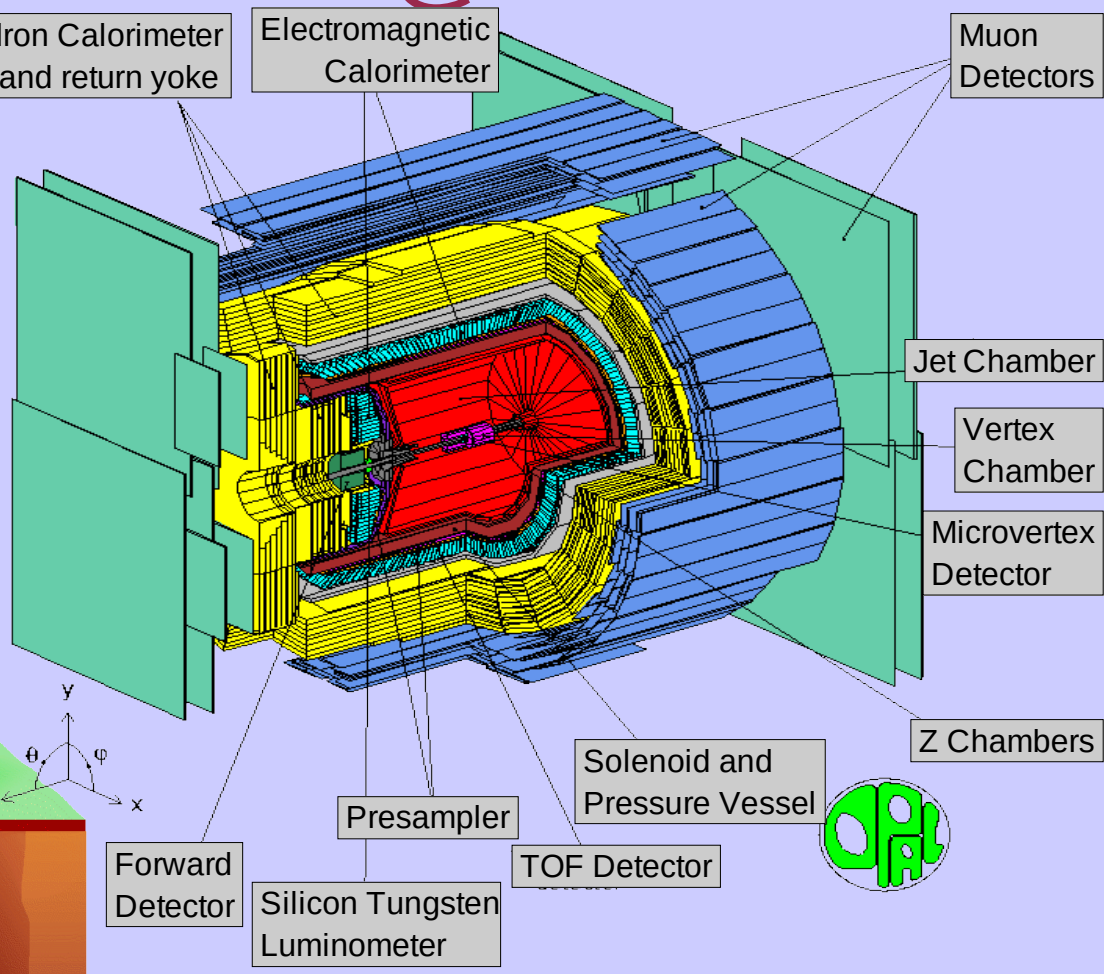
Function	Parameter in Minimum
Bowler	(a|b)=(0.12|0.58) χ^2/d.o.f.=188/60
Kartvelishvili	α_c=4.0 χ^2/d.o.f.=861/60
Peterson	ϵ_c=0.039 χ^2/d.o.f.=2230/60

other two btw. Bowler and Kartvel.

Experimental Apparatus @ 91.2 GeV

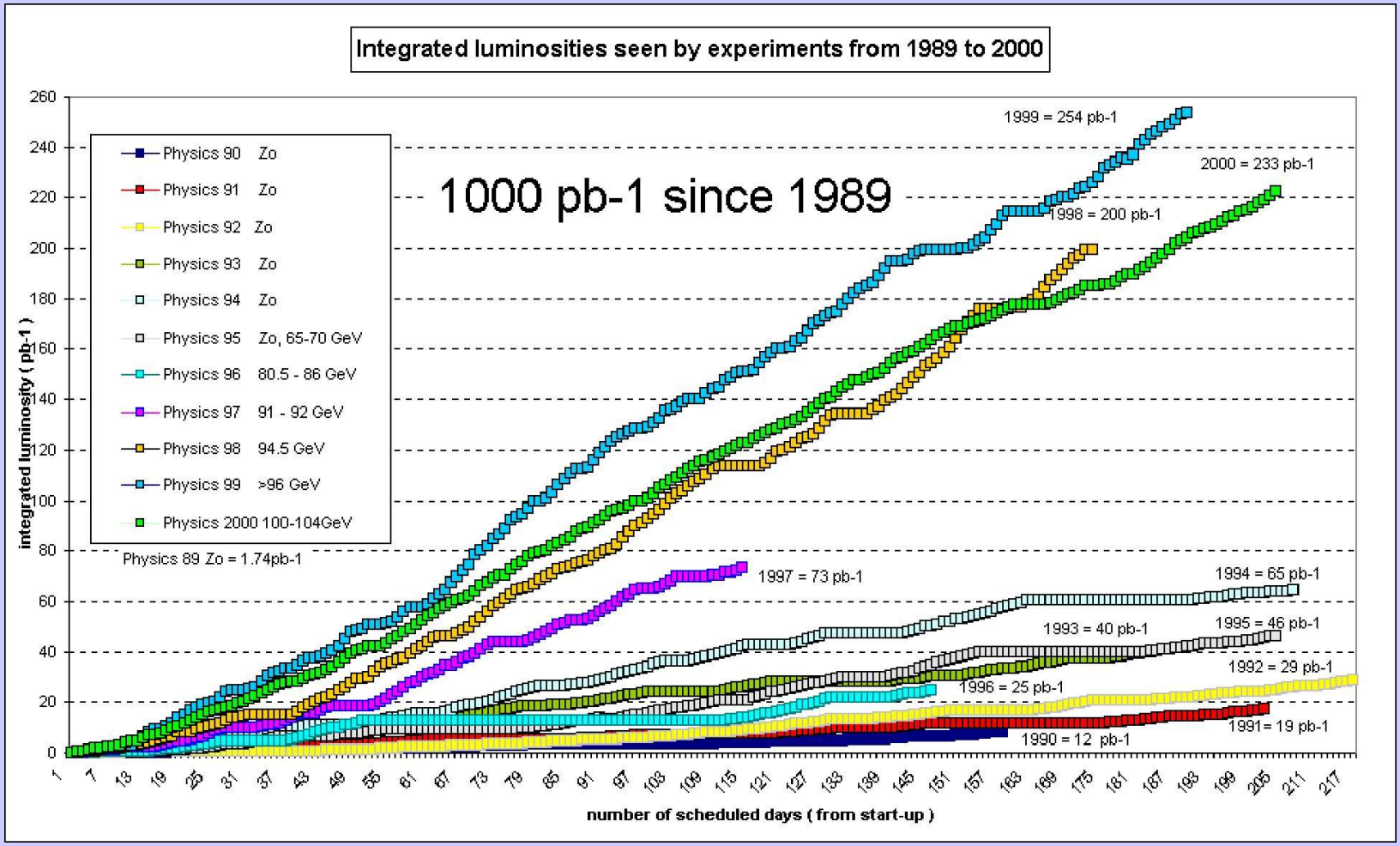
PL B512 (2001) 30
EPJ C29 (2003) 463
PR D65 (2002) 092006





I am (still) member of OPAL, many examples will show OPAL

LEP Accelerator Performance



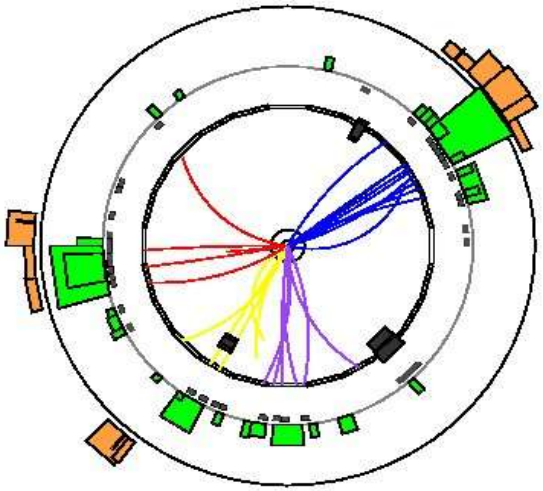
integrated luminosity over 11 years, one good day @ b-factories !

~ $4 \cdot 10^6$ events @ 91.2 GeV per experiment

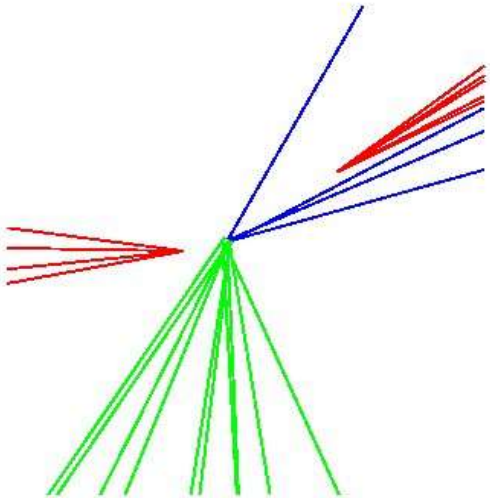
Selection of B Hadrons @ 91.2 GeV

- B hadrons have many decay modes, more than charmed hadrons, many multibody
- exclusive reconstruction not practical
- B hadrons have long lifetime compared to light quarks
  →production and decay vertices separated
  mixture of all B hadrons in tagged sample
  still contamination by charmed hadrons

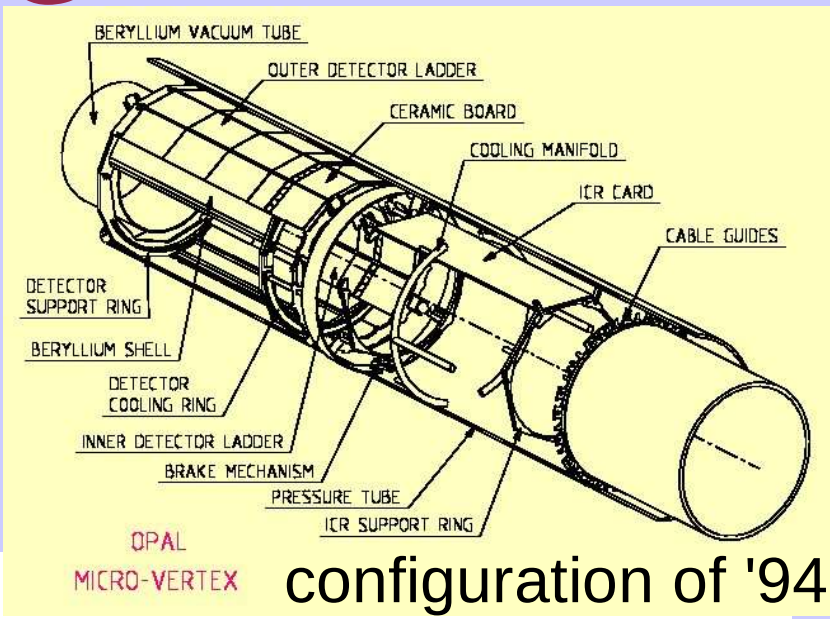
tagging B Hadrons @ 91.2 GeV



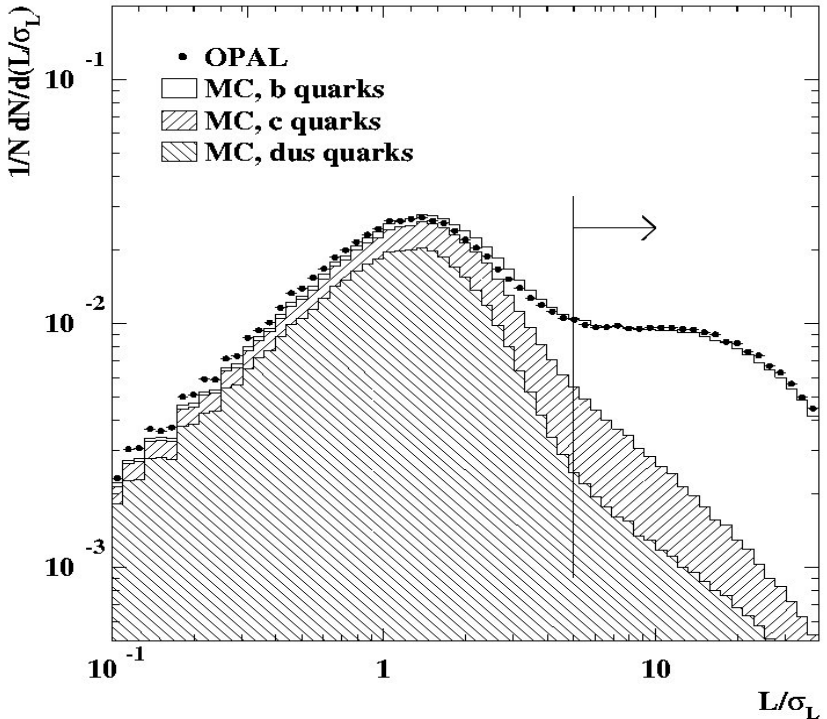
1m



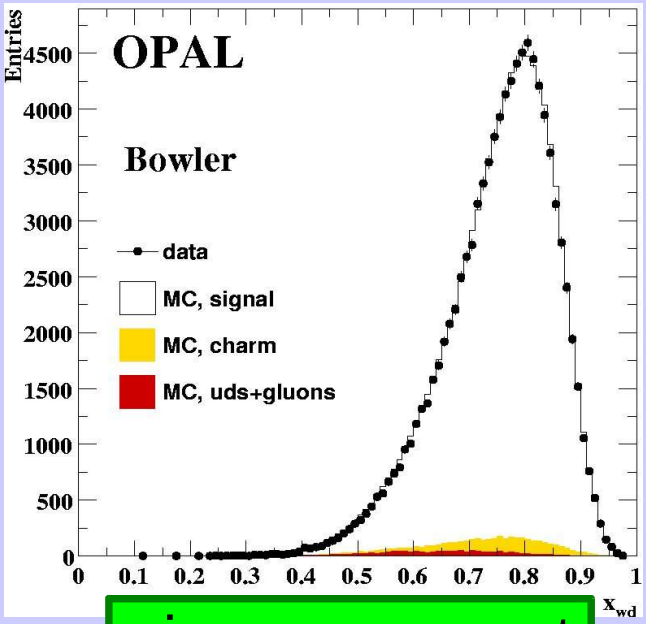
2 mm

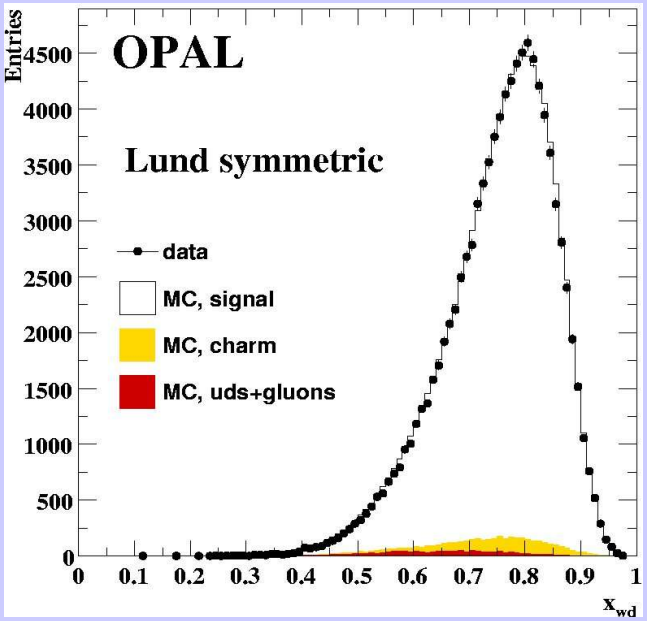


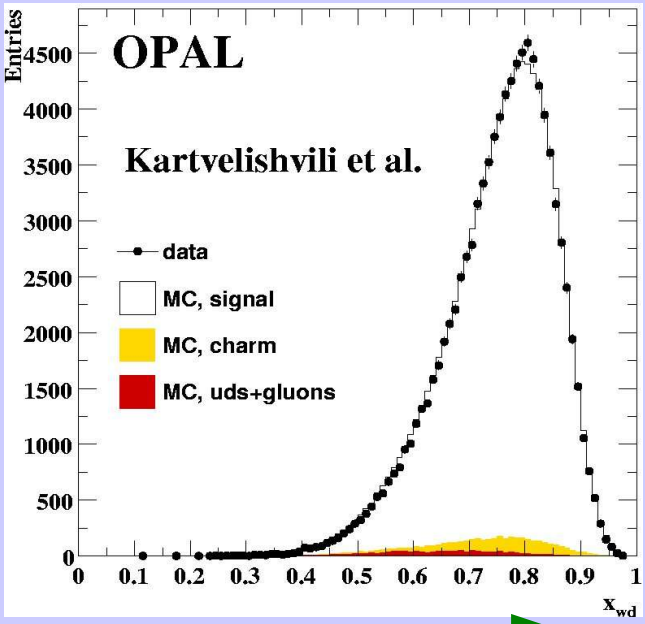
configuration of '94



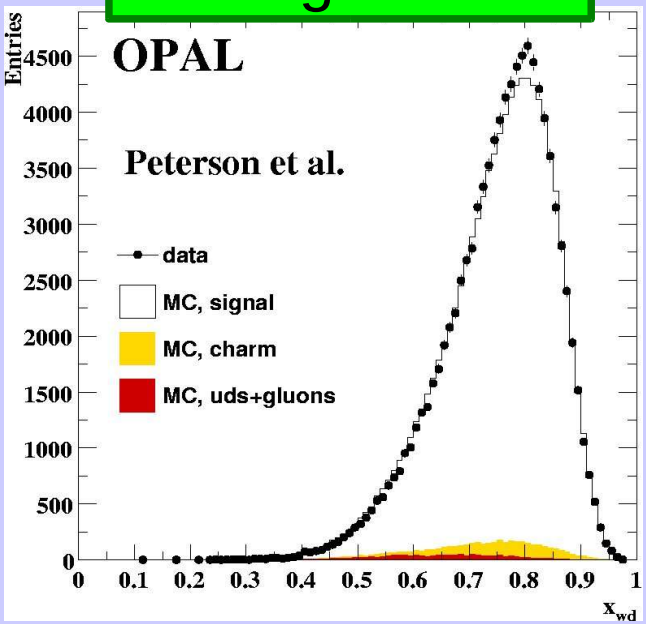
Results for $Z_0 \rightarrow bb$ (OPAL)

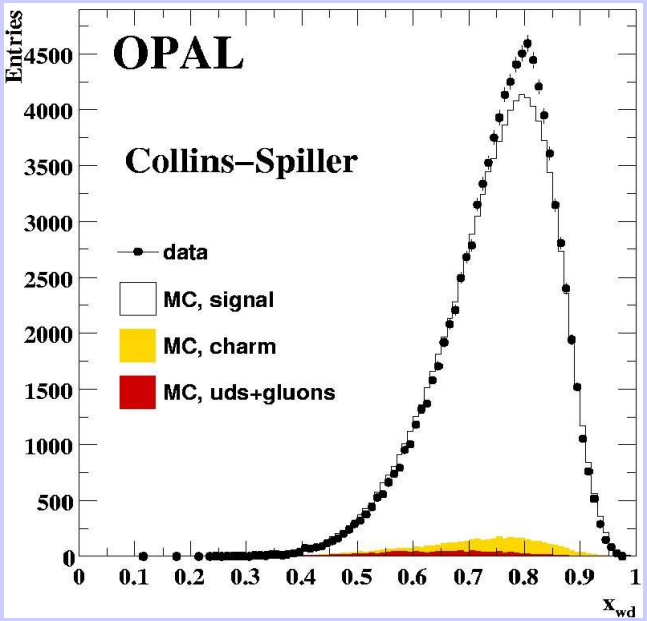


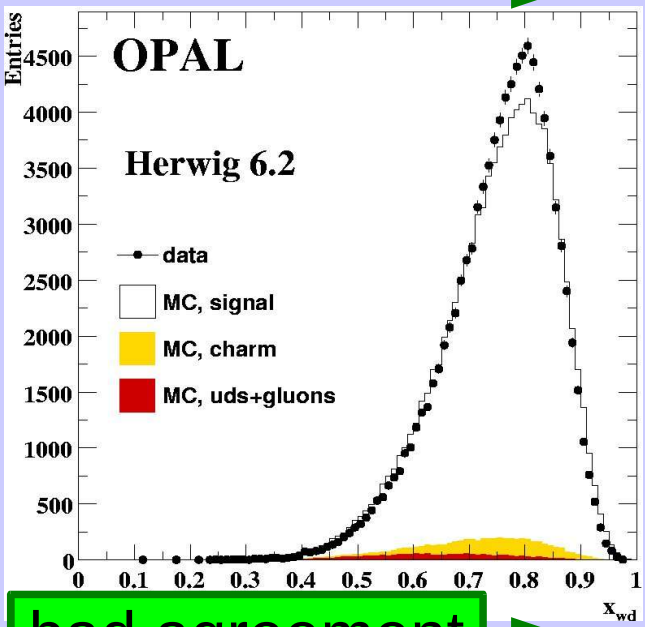




nice agreement







bad agreement

Status @ ICHEP '02

... but not much changed since

Overview: model test χ^2/d.o.f.

	ALEPH	DELPHI (prelim.)			OPAL	SLD
		x_{wd}	x_L	z		
Bowler	—	35/8	43/8	1/2	67/44	17/15
Lund	—	42/8	53/8	2/2	75/44	17/15
UCLA	—	—	—	—	—	27/17
Kartvelishvili et al.	107/94	—	—	36/3	99/45	32/16
Peterson et al.	117/94	287/9	245/9	187/3	159/45	70/16
BCFY	—	—	—	—	—	105/16
Collins/Spiller	181/94	—	—	536/3	407/45	142/16
Herwig 6 cldir=1	—	—	—	—	540/46	—
Herwig 5 cldir=1	—	—	—	—	4279/46	149/17
Herwig 5 cldir=0	—	—	—	—	—	1015/17

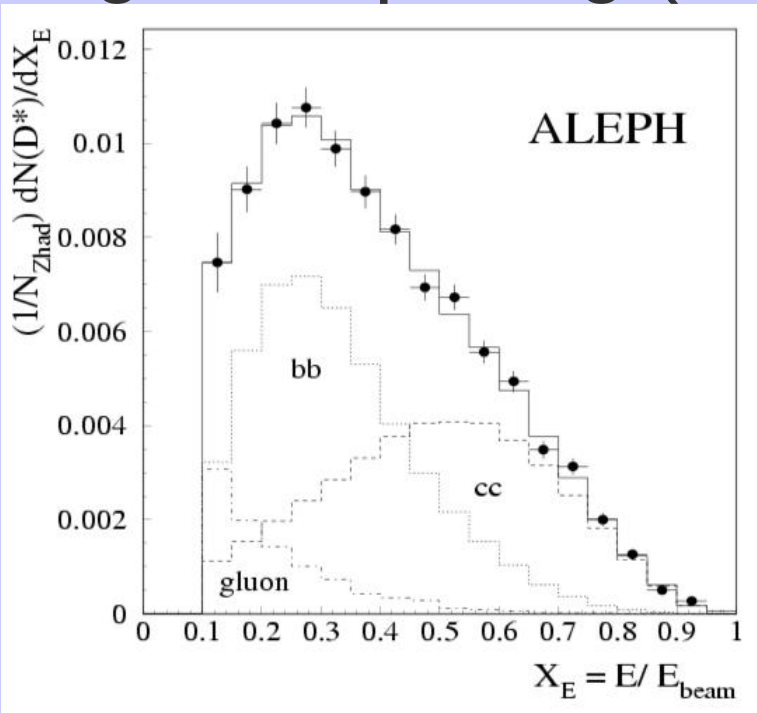
same ranking observed by all experiments!

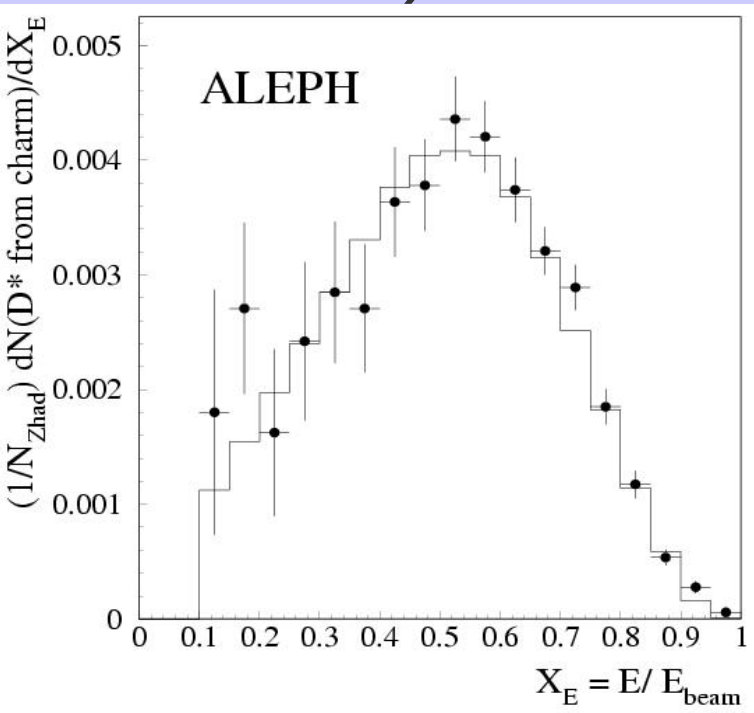
(fragm. function parameters: rough agreement)

D^{*+} @ 91.2 GeV *(ALEPH)*

EPJ C16(2000) 597

- $D^{*+} \rightarrow D^0 \pi^+$ (same decay chain as @ 10.6 GeV)
- most D^{*+} at 91.2 GeV are from B decays
- gluon splitting (negl. at 10.6 GeV)





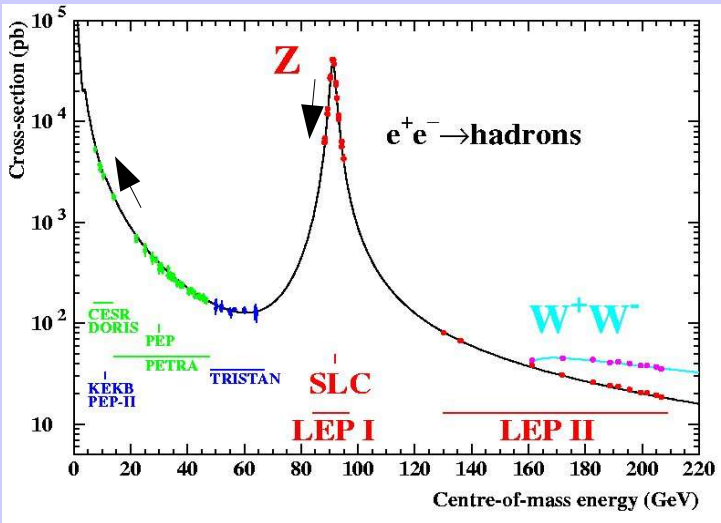
3 parameter fit: relative contributions from bb and gluon and ϵ_c parameter of Peterson frag.fcn. $\epsilon_c = (33.9 \pm 3.7) \cdot 10^{-3}$

for comparison: Belle @ 10.6 GeV $\epsilon_c = 54 \cdot 10^{-3}$

Comparisons between different Energies

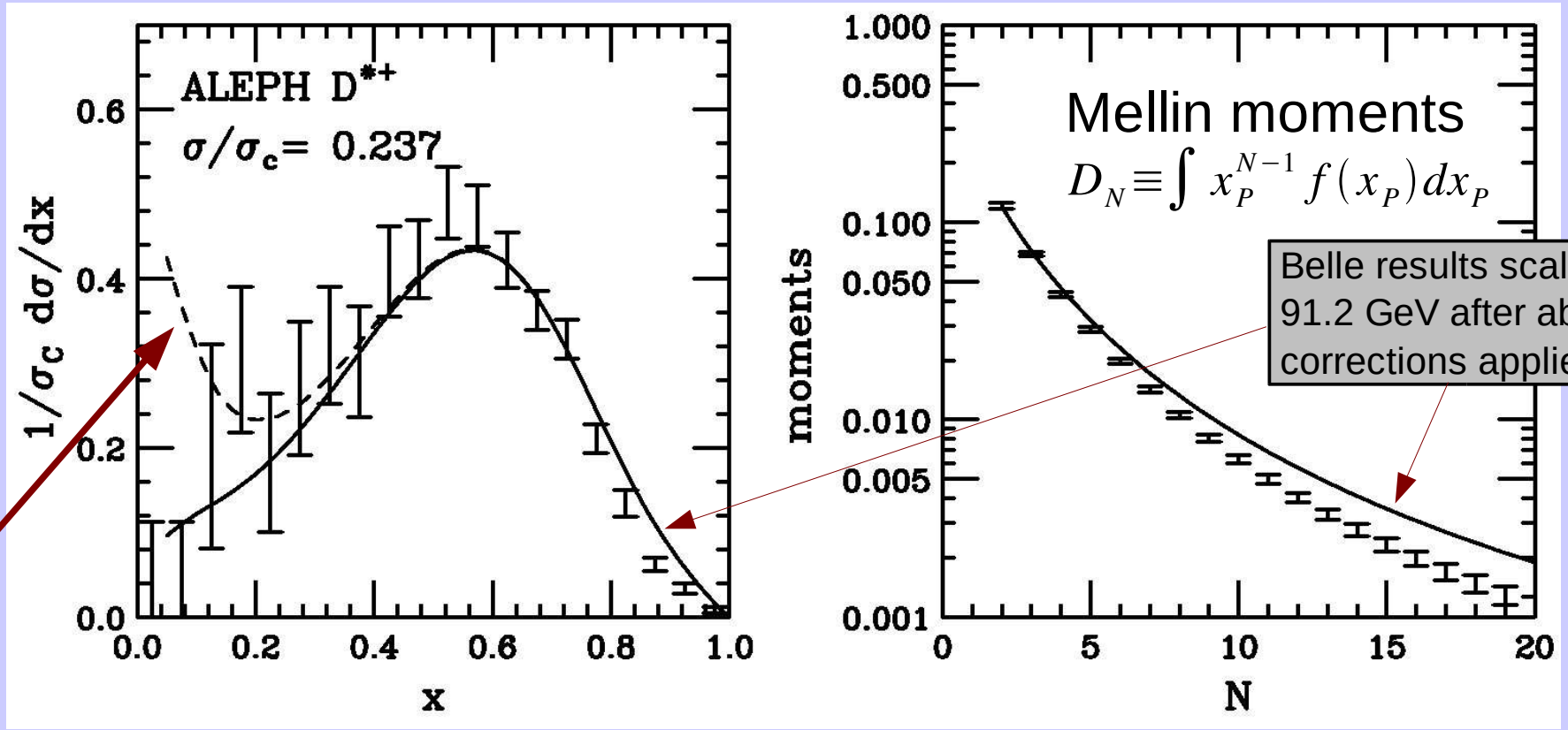
hep-ph/0510032

- direct comparison of spectra at different energies not possible:
  -different phase space
  -different scales (CME)
  → evolution via DGLAP
  -ISR corrections substantially different



Comparisons between different Energies, cont'd

- previous corrections applied:



after all → remaining difference !

Mellin Moments

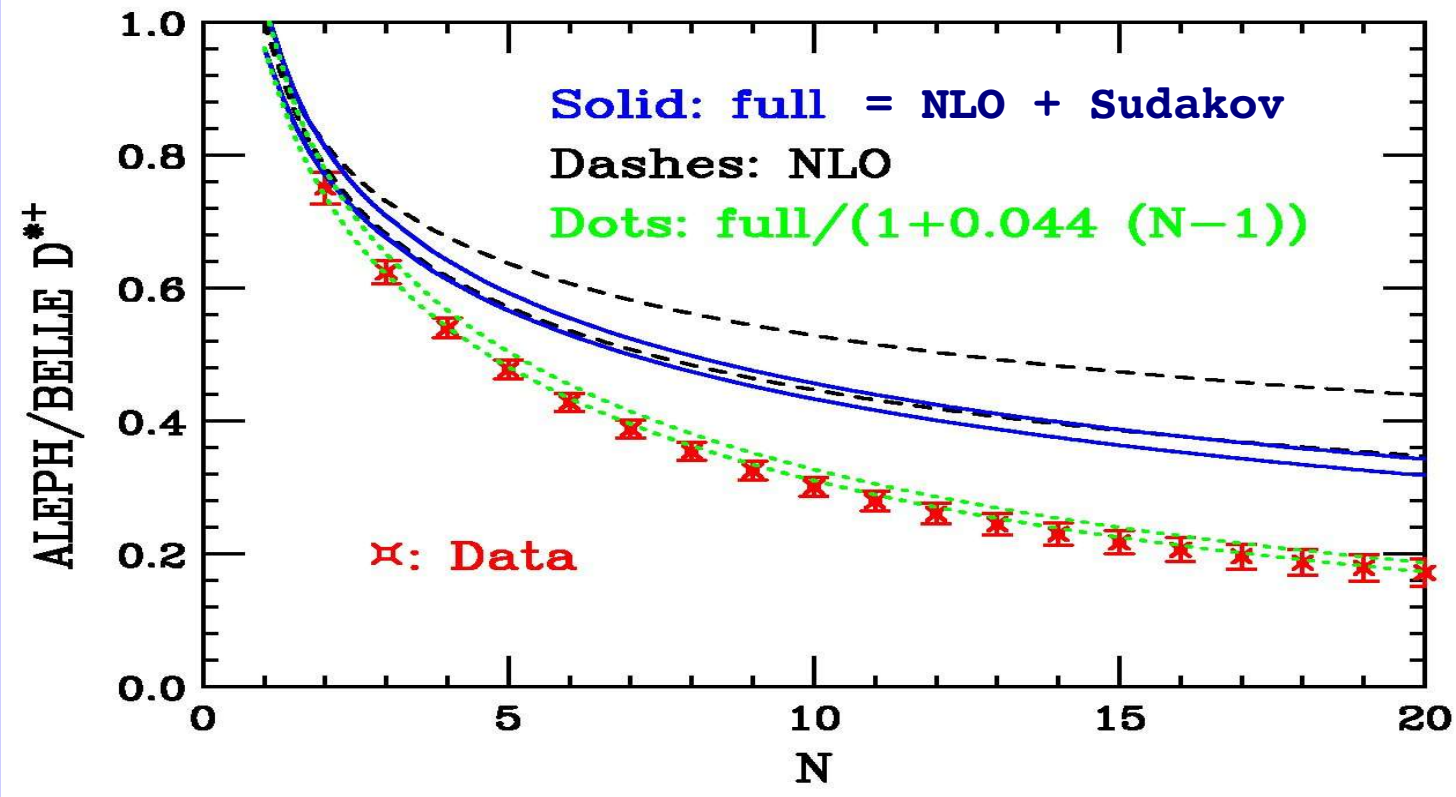
- defines as

$$D_N \equiv \int x_P^{N-1} f(x_P) dx_P$$

- pert. and non-pert. effects factorize
- high moments stress high x region
- non-perturbative parts of fragmentation function (e.g. transition of quark->meson)
- Note: perturbative part different in e^+e^-, ep and pp, non-perturbative part same !

Difference between 91.2 GeV and 10.6 GeV

- empirical fit: 1/(1+0.044(N-1)) dependence



source unclear, data inbetween 10.6 and 91.2 needed to resolve 1/E or $1/E^2$ corrections

Summary

- new, precise measurement of charm fragmentation function at $\sqrt{s}$ = 10.6 GeV
- conclusions for charm @ 10.6 GeV and beauty @ 91.2 GeV in good agreement:
  -Bowler or Lund frag.fcns. prefered
  -Peterson disfavoured

- differences between charm @ 10.6 GeV and charm @ 91.2, yet unresolved