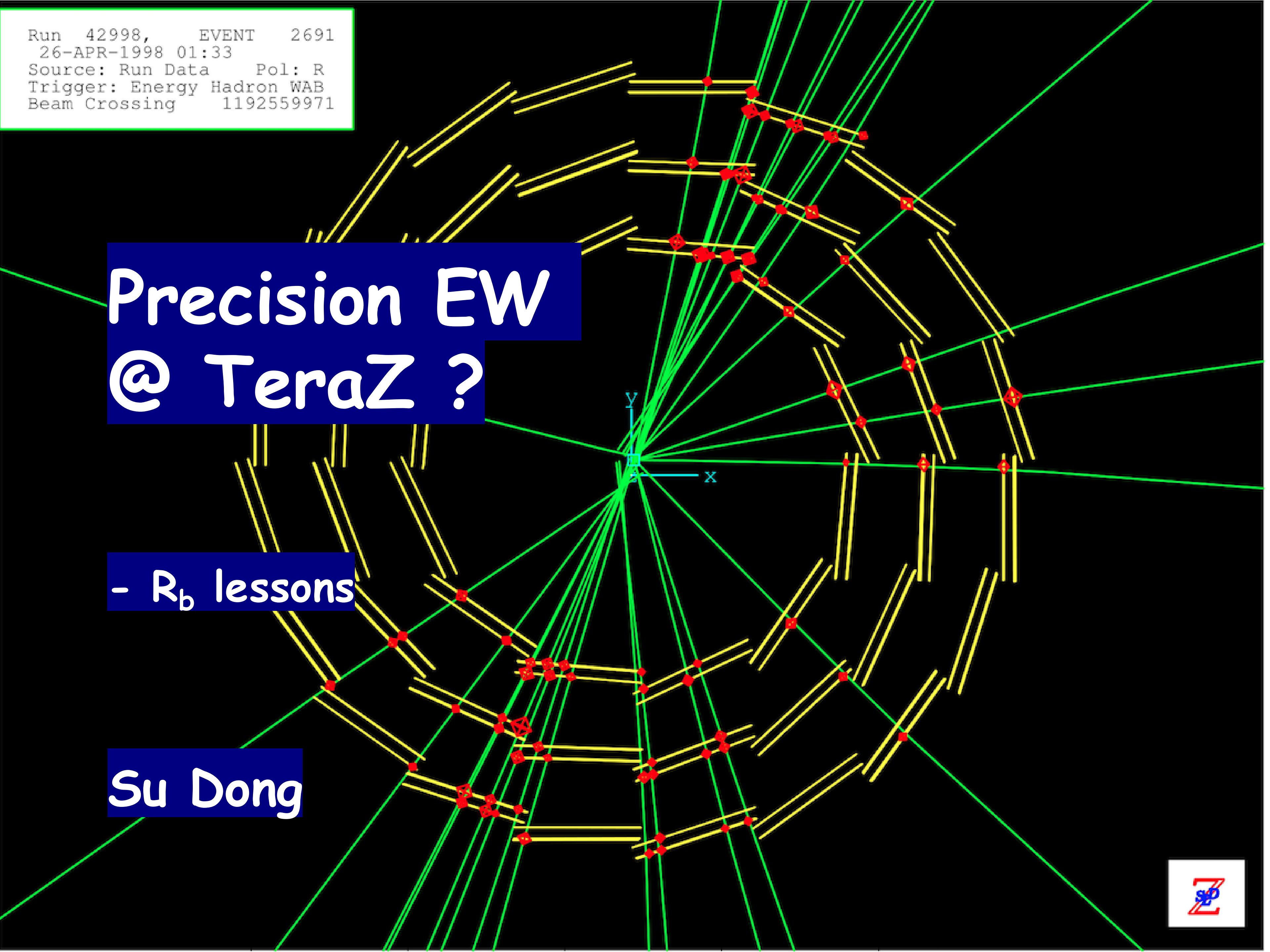
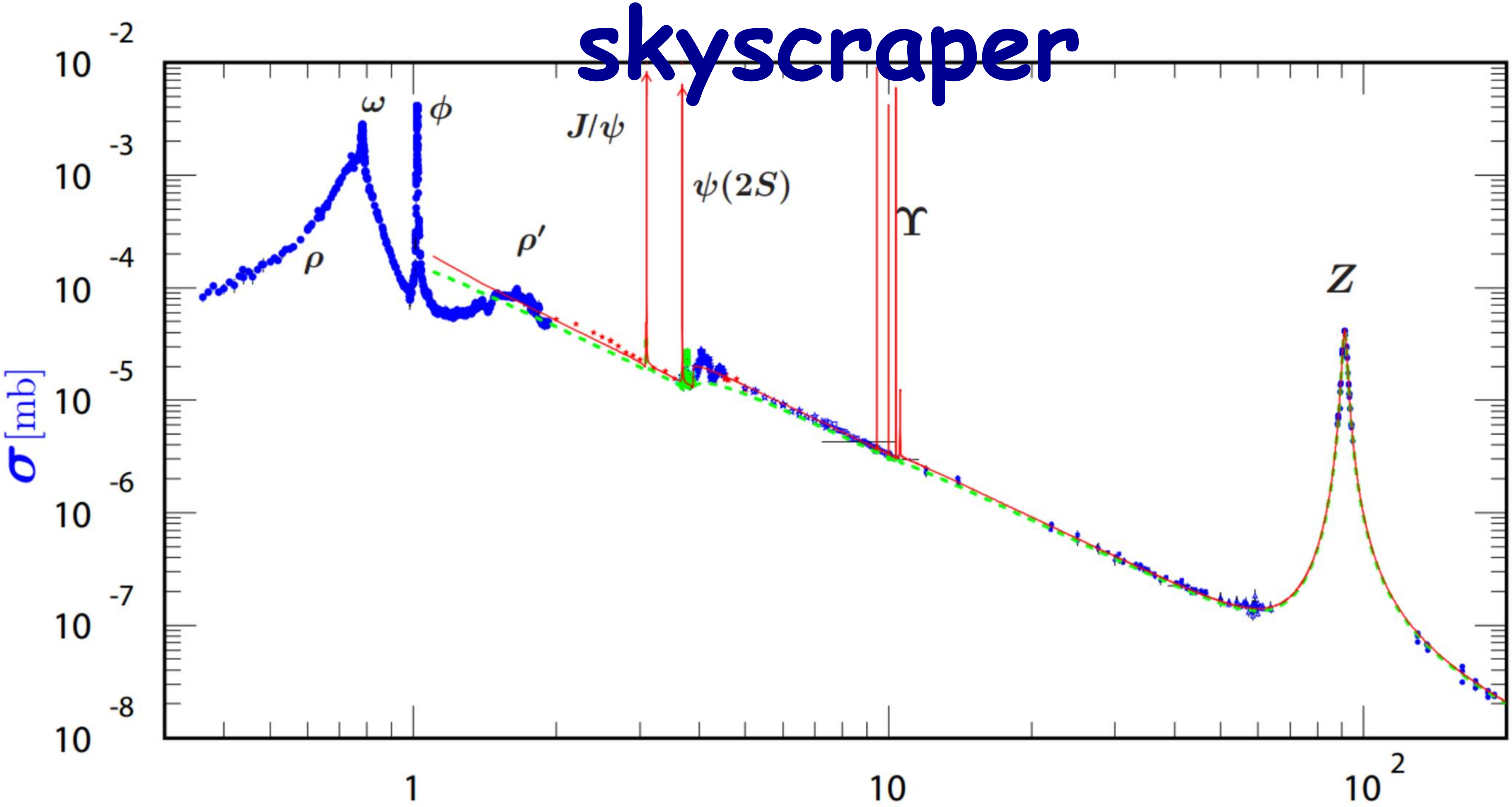


Precision EW @ TeraZ ?

- R_b lessons

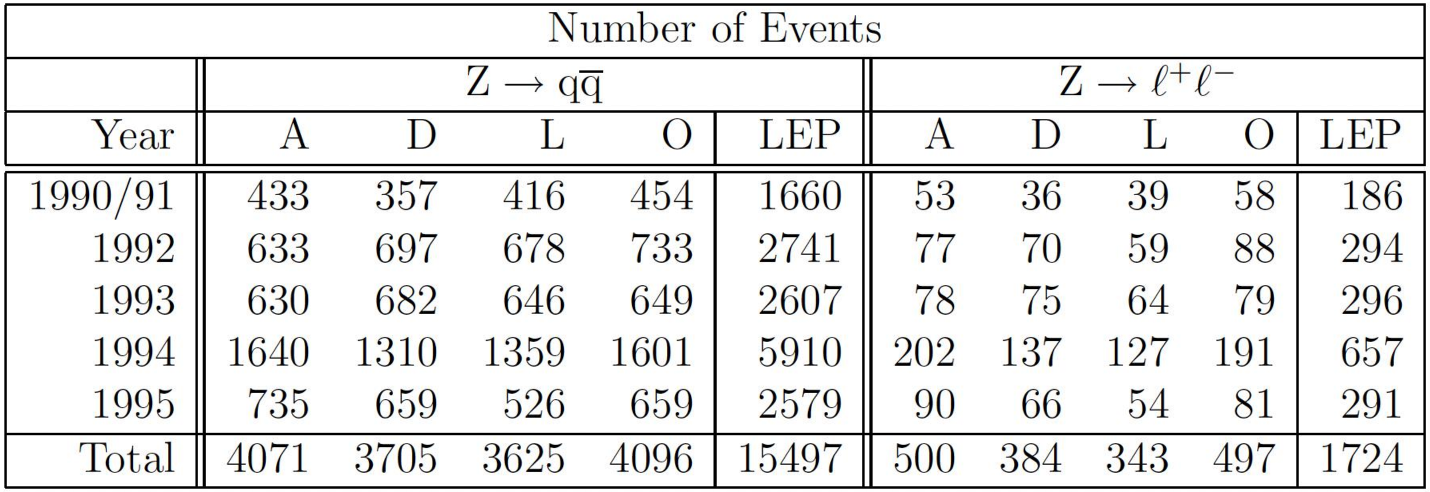
Su Dong

$e^+e^- \to Z^0$ Peak is a skyscraper



- ☐ Υ(4s)->bb peak is only 1.1nb at the B factories
- Z^0 pole Z^0->bb = σ_{had}*R_b ~30*0.216 ~6.5nb

Existing e^+e^- ->Z Pole Data



Number of Events										
	$Z \to q\bar{q}$					$Z \to \ell^+\ell^-$				
Year	A	D	L	O	LEP	A	D	L	O	LEP
1990/91	433	357	416	454	1660	53	36	39	58	186
1992	633	697	678	733	2741	77	70	59	88	294
1993	630	682	646	649	2607	78	75	64	79	296
1994	1640	1310	1359	1601	5910	202	137	127	191	657
1995	735	659	526	659	2579	90	66	54	81	291
Total	4071	3705	3625	4096	15497	500	384	343	497	1724

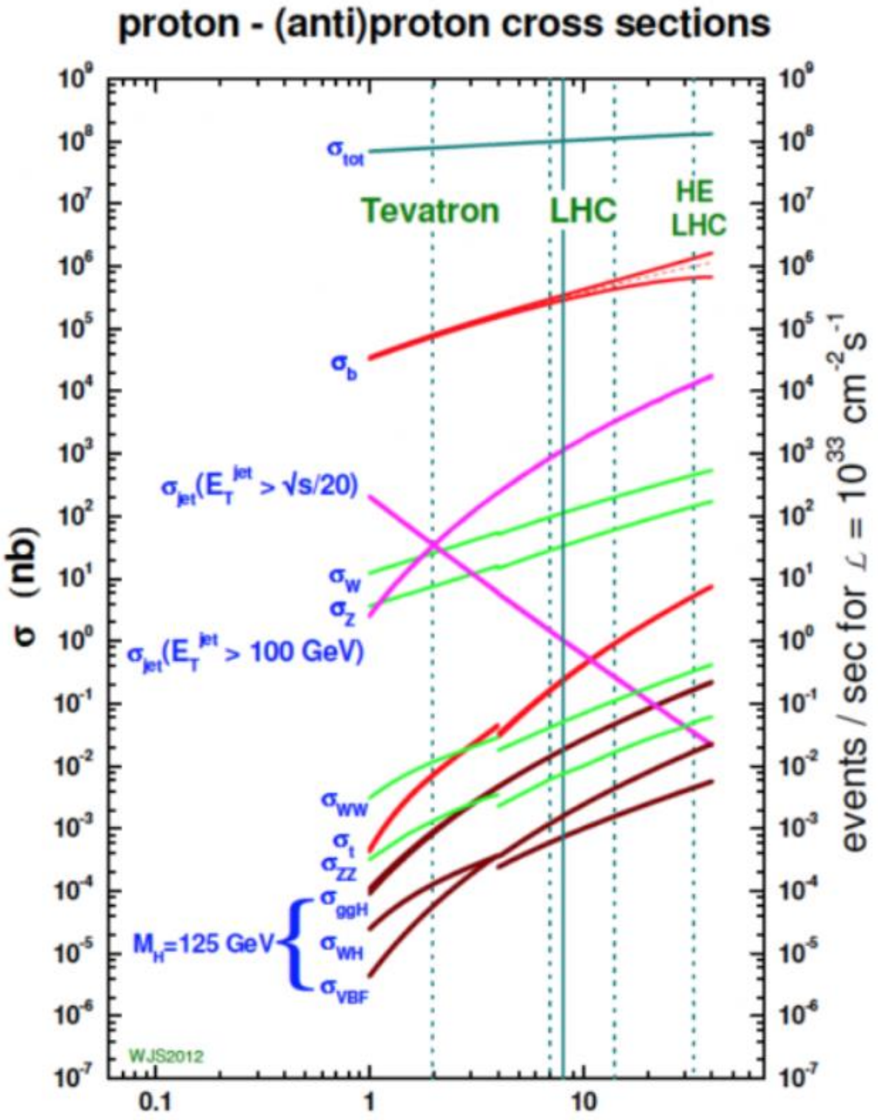
Table 1.2: The $q\bar{q}$ and $\ell^+\ell^-$ event statistics, in units of 10^3, used for Z analyses by the experiments ALEPH (A), DELPHI (D), L3 (L) and OPAL (O).

LEP-1

~4M Z/expt

- **SLD @ SLC has ~380K Z_{had} with VXD3 and ~75% electron beam polarization.**
- **FCC-ee is proposing 4 year run at 88-95 GeV for 150 ab^{-1} with 3T visible Z decays.**

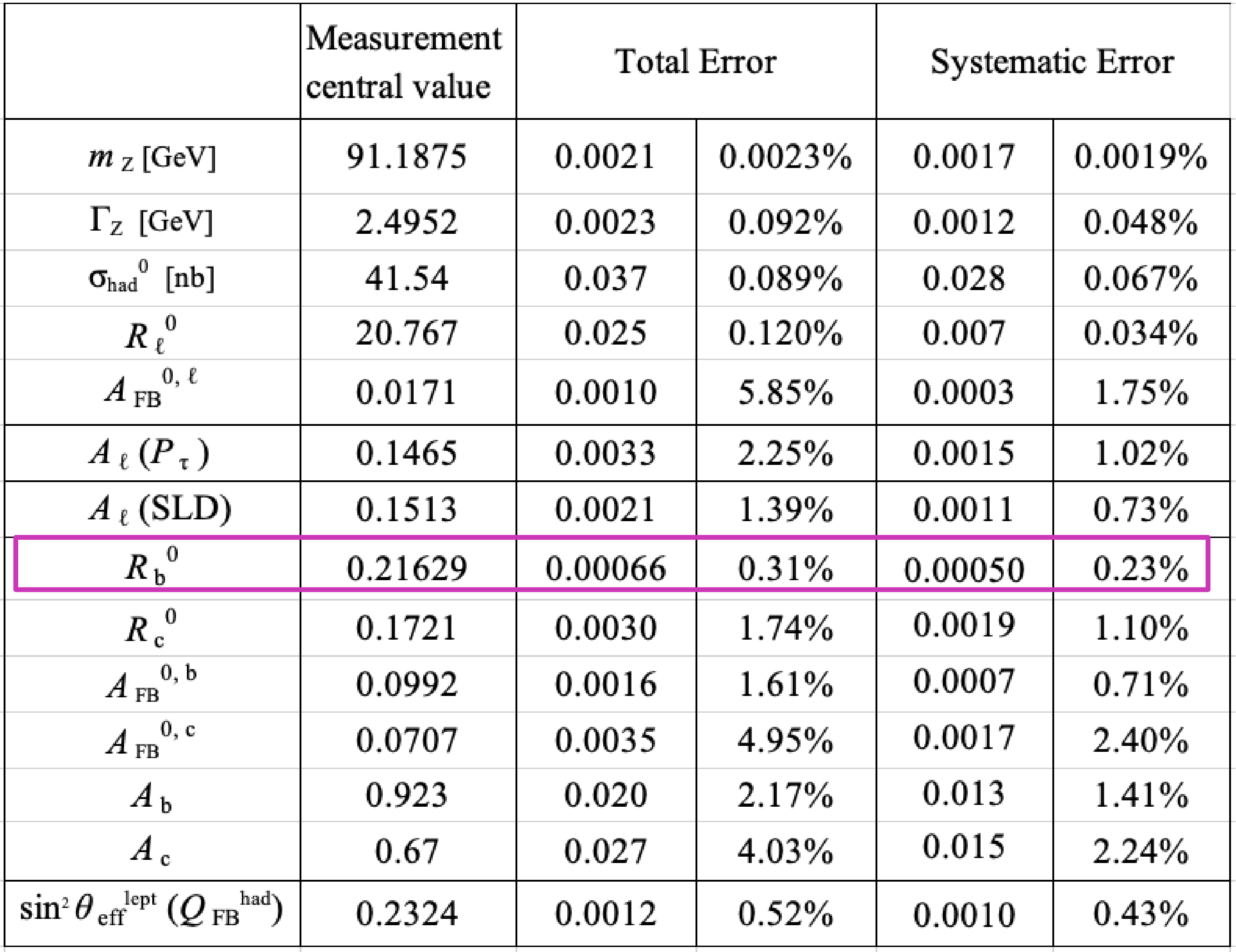
Z^0 @ LHC



- Z production @13TeV has **~58nb** cross section
- ATLAS already integrated >500 fb^{-1} luminosity with **29T Z** produced by LHC.
- How much precision EW physics came from that ?

=> Impressive statistics is only meaningful when systematics is also considered.

Z-Pole EW Summary



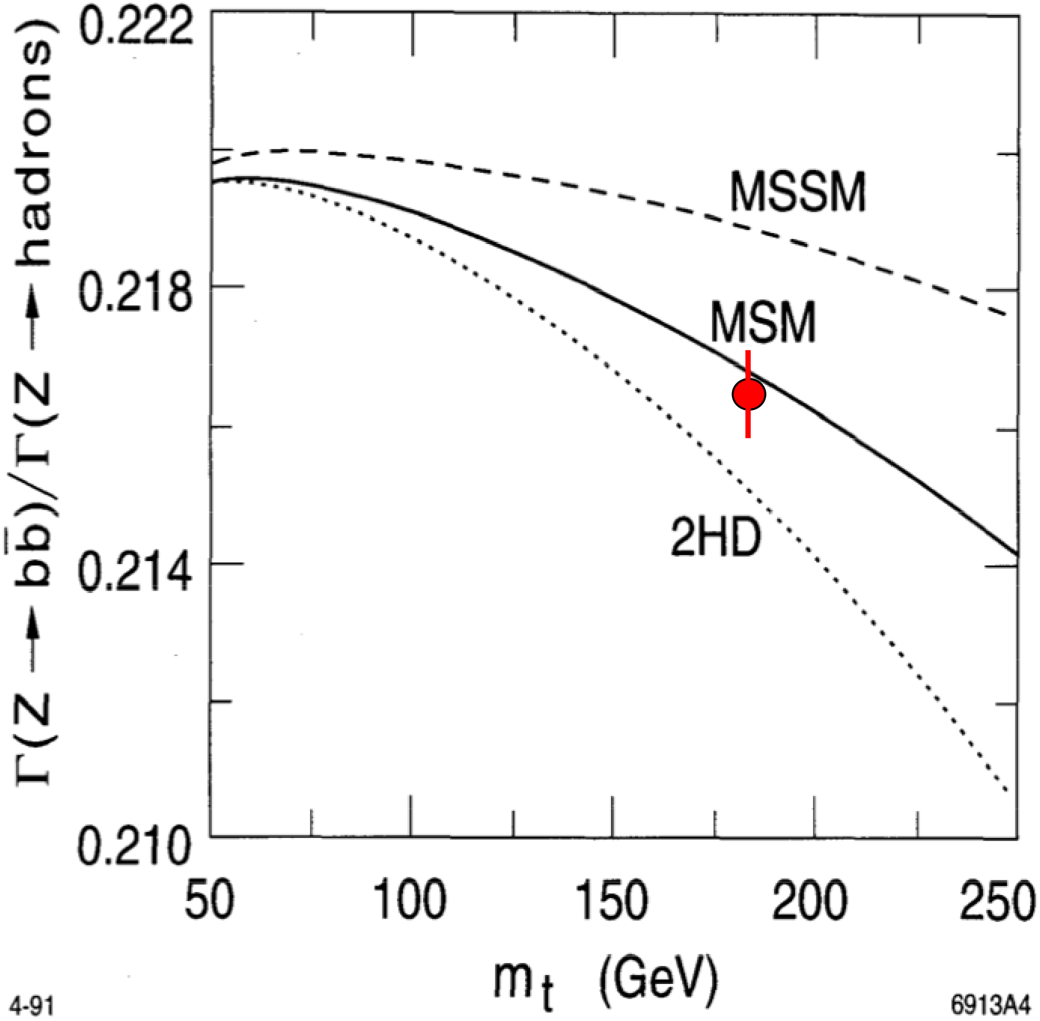
	Measurement central value	Total Error		Systematic Error	
m_Z [GeV]	91.1875	0.0021	0.0023%	0.0017	0.0019%
Γ_Z [GeV]	2.4952	0.0023	0.092%	0.0012	0.048%
σ_{had}^0 [nb]	41.54	0.037	0.089%	0.028	0.067%
R_ℓ^0	20.767	0.025	0.120%	0.007	0.034%
$A_{FB}^{0,\ell}$	0.0171	0.0010	5.85%	0.0003	1.75%
$A_\ell(P_\tau)$	0.1465	0.0033	2.25%	0.0015	1.02%
A_ℓ (SLD)	0.1513	0.0021	1.39%	0.0011	0.73%
R_b^0	0.21629	0.00066	0.31%	0.00050	0.23%
R_c^0	0.1721	0.0030	1.74%	0.0019	1.10%
$A_{FB}^{0,b}$	0.0992	0.0016	1.61%	0.0007	0.71%
$A_{FB}^{0,c}$	0.0707	0.0035	4.95%	0.0017	2.40%
A_b	0.923	0.020	2.17%	0.013	1.41%
A_c	0.67	0.027	4.03%	0.015	2.24%
$\sin^2\theta_{eff}^{lept}(Q_{FB}^{had})$	0.2324	0.0012	0.52%	0.0010	0.43%

Z^0 line shape defines SM

Precision EW observables test the SM

Systematic errors significant in most cases already

Why Interests in R_b ?



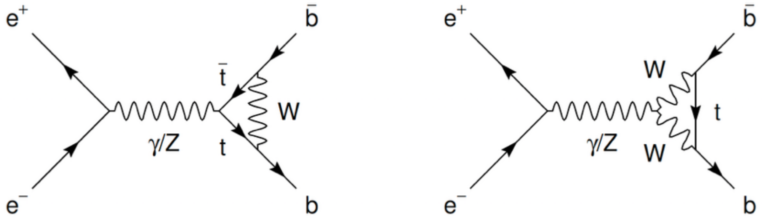


Figure 1.10: Vertex corrections to the process $e^+e^- \to b\bar{b}$.

Combined LEP+SLD

R_b=0.21629 ± 0.00066

is sensitive to m_t through top correction and BSM effects

Precision EW Observables

$$R^0_{\mathrm{q}} \equiv \Gamma_{\mathrm{q\bar{q}}}/\Gamma_{\mathrm{had}}, \; e.g. \; R^0_{\mathrm{b}} = \Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{had}}.$$

$$\mathcal{A}_{\mathrm{f}} = \frac{g^2_{\mathrm{Lf}} - g^2_{\mathrm{Rf}}}{g^2_{\mathrm{Lf}} + g^2_{\mathrm{Rf}}} = \frac{2 g_{\mathrm{Vf}} g_{\mathrm{Af}}}{g^2_{\mathrm{Vf}} + g^2_{\mathrm{Af}}}$$

$$\frac{\mathrm{d}\sigma_{\mathrm{f\bar{f}}}}{\mathrm{d}\cos\theta} = \frac{3}{8}\sigma^{\mathrm{tot}}_{\mathrm{ff}}\left[(1 - \mathcal{P}_{\mathrm{e}}\mathcal{A}_{\mathrm{e}})(1+\cos^2\theta) + 2(\mathcal{A}_{\mathrm{e}} - \mathcal{P}_{\mathrm{e}})\mathcal{A}_{\mathrm{f}}\cos\theta\right]$$

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

$$A_{\mathrm{LR}} = \frac{\sigma_{\mathrm{L}} - \sigma_{\mathrm{R}}}{\sigma_{\mathrm{L}} + \sigma_{\mathrm{R}}} \frac{1}{\langle|\mathcal{P}_{\mathrm{e}}|\rangle}$$

$$A_{\mathrm{LRFB}} = \frac{(\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}})_{\mathrm{L}} - (\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}})_{\mathrm{R}}}{(\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}})_{\mathrm{L}} + (\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}})_{\mathrm{R}}} \frac{1}{\langle|\mathcal{P}_{\mathrm{e}}|\rangle}$$

$$\begin{aligned}
A^{0,\mathrm{f}}_{\mathrm{FB}} &= \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{\mathrm{f}} \\
A^{0}_{\mathrm{LR}} &= \mathcal{A}_{\mathrm{e}} \\
A^{0}_{\mathrm{LRFB}} &= \frac{3}{4}\mathcal{A}_{\mathrm{f}} \\
\langle\mathcal{P}^0_{\tau}\rangle &= -\mathcal{A}_{\tau} \\
A^{\mathrm{pol},0}_{\mathrm{FB}} &= -\frac{3}{4}\mathcal{A}_{\mathrm{e}}.
\end{aligned}$$

Observable Sensitivities

	g_L^f	g_R^f	$R_f = \frac{\Gamma(Z^0 \to f\bar{f})}{\Gamma(Z^0 \to \text{hadrons})}$	A_f	$\frac{\delta A_f}{\delta \sin^2\theta_w}$
e, μ, τ	−0.27	−0.23	0.05	0.15	−7.9
u, c	0.35	0.15	0.17	0.67	−3.5
d, s, b	−0.42	−0.08	0.22	0.94	−0.6

- Leptons has low Xsec, small asymmetry but large sensitivity to $\sin^2\theta_w$
- q=1/3 down quarks have large asymmetry bot insensitivity to $\sin^2\theta_w$

$$\delta R_b / R_b \sim -3.57\, \delta g_L^b - 0.65\, \delta g_R^b$$

$$\delta A_b / A_b \sim -0.31\, \delta g_L^b + 1.72\, \delta g_R^b .$$

R_b more sensitive to g_L

A_b more sensitive to g_R

How is R_b Measured ?

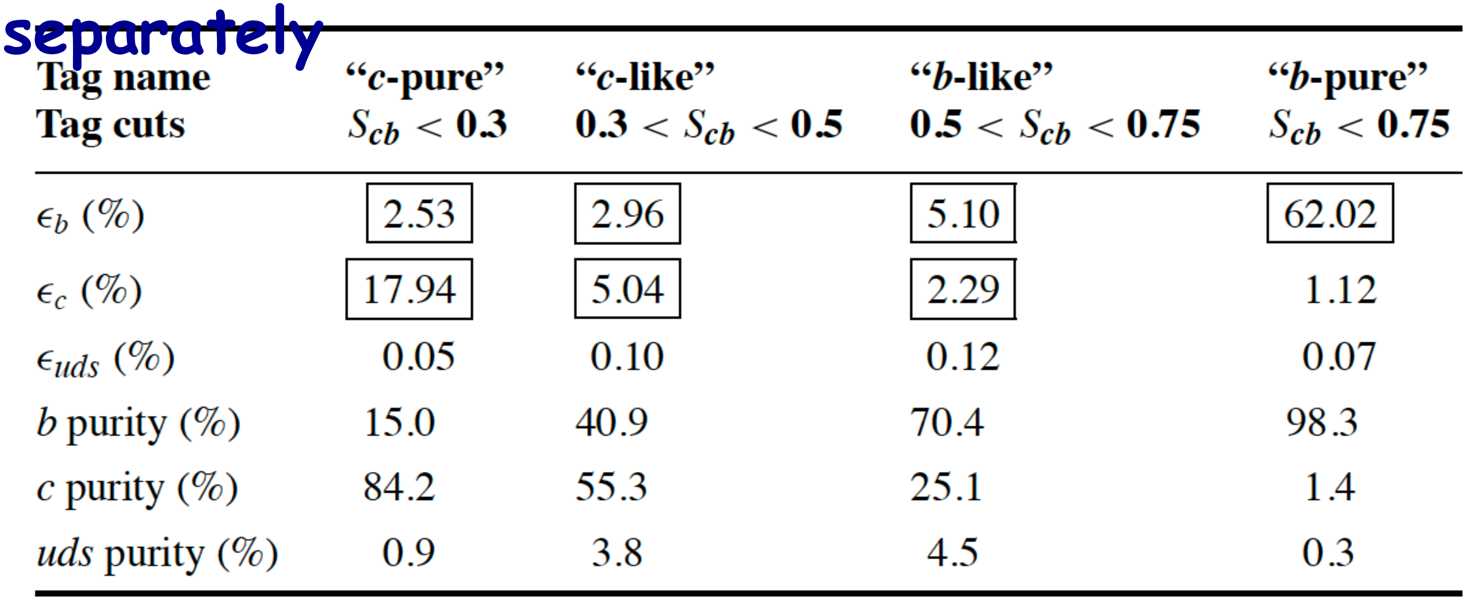
Measure single and double hemisphere tag rates F_s & F_d

$$F_s = \epsilon_b R_b + \epsilon_c R_c + \epsilon_{uds}(1 - R_b - R_c),$$

$$F_d = C_b \epsilon_b^2 R_b + C_c \epsilon_c^2 R_c + \epsilon_{uds}^2 (1 - R_b - R_c).$$

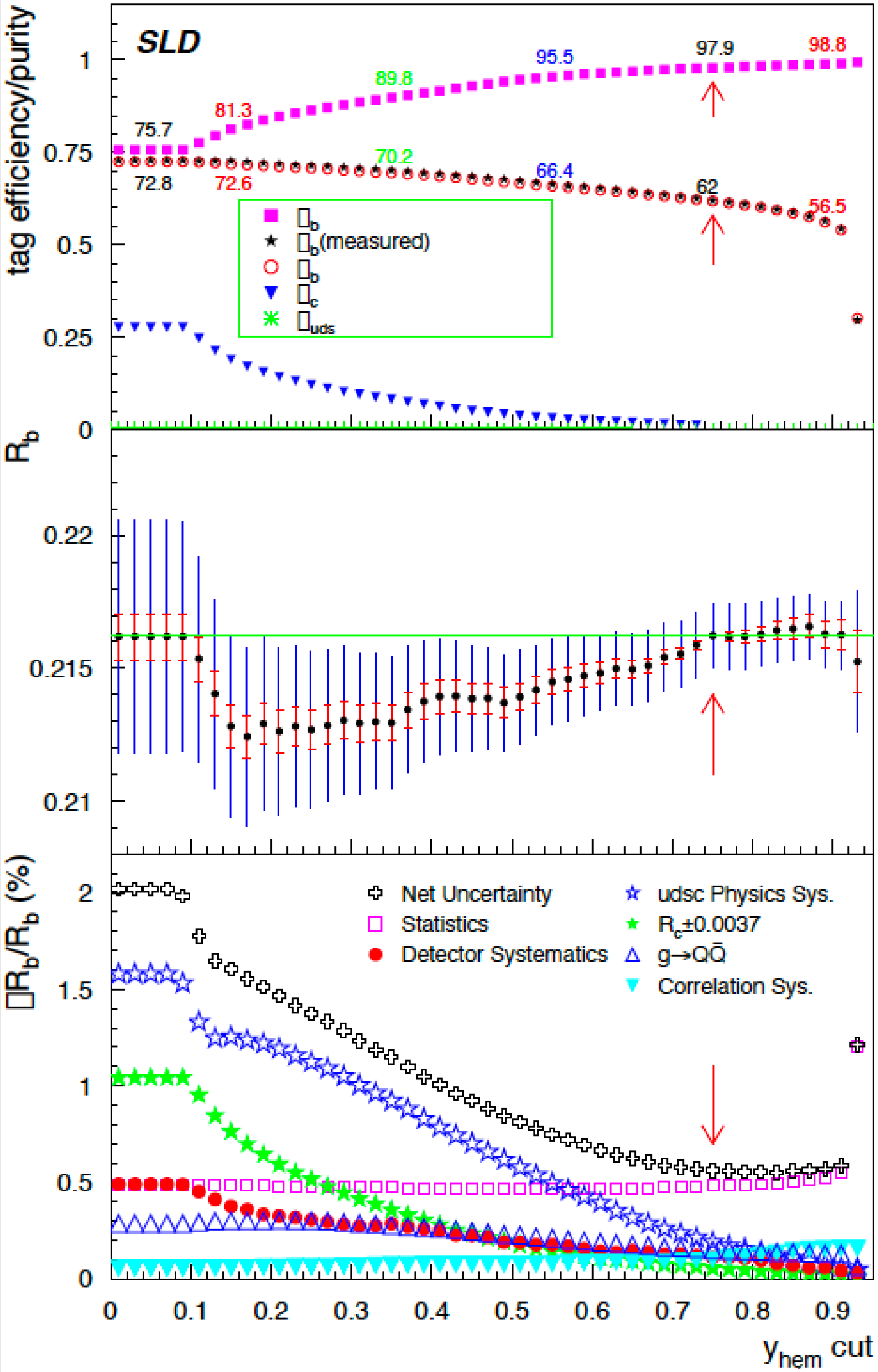
Hemisphere tag correlations $C_b = \frac{\epsilon_b^{\text{double}}}{\epsilon_b^2}$ and $C_c = \frac{\epsilon_c^{\text{double}}}{\epsilon_c^2}$

4 tag regions measured separately



Tag name	"*c*-pure"	"*c*-like"	"*b*-like"	"*b*-pure"
Tag cuts	$S_{cb} < 0.3$	$0.3 < S_{cb} < 0.5$	$0.5 < S_{cb} < 0.75$	$S_{cb} < 0.75$
ϵ_b (%)	$\boxed{2.53}$	$\boxed{2.96}$	$\boxed{5.10}$	$\boxed{62.02}$
ϵ_c (%)	$\boxed{17.94}$	$\boxed{5.04}$	$\boxed{2.29}$	1.12
ϵ_{uds} (%)	0.05	0.10	0.12	0.07
b purity (%)	15.0	40.9	70.4	98.3
c purity (%)	84.2	55.3	25.1	1.4
uds purity (%)	0.9	3.8	4.5	0.3

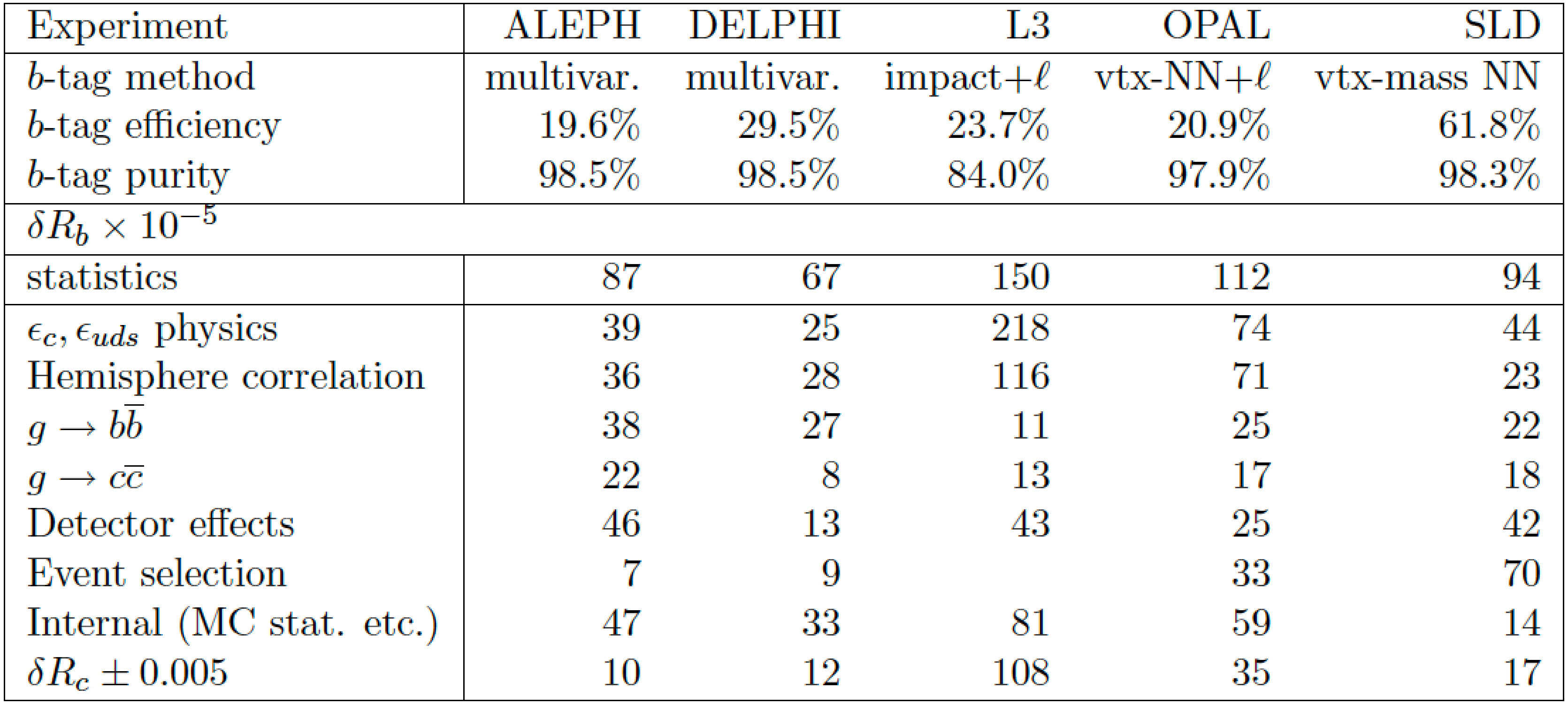
Extract R_b,R_c and ε in boxes from data



Systematic Behavior vs Cuts

- For tighter tags, light,c background drop while stat and correction systematic grow.
- For measurements with larger statistics, can gain overall precision with tighter tag. *Main concern is tag correlation behavior.*

Systematic Category Summary



Experiment	ALEPH	DELPHI	L3	OPAL	SLD	
b-tag method	multivar.	multivar.	impact+ℓ	vtx-NN+ℓ	vtx-mass NN	
b-tag efficiency	19.6%	29.5%	23.7%	20.9%	61.8%	
b-tag purity	98.5%	98.5%	84.0%	97.9%	98.3%	
$\delta R_b \times 10^{-5}$						
statistics	87	67	150	112	94	
$\epsilon_c, \epsilon_{uds}$ physics	39	25	218	74	44	
Hemisphere correlation	36	28	116	71	23	⬅
$g \to b\bar{b}$	38	27	11	25	22	
$g \to c\bar{c}$	22	8	13	17	18	
Detector effects	46	13	43	25	42	?
Event selection	7	9		33	70	
Internal (MC stat. etc.)	47	33	81	59	14	
$\delta R_c \pm 0.005$	10	12	108	35	17	

Most systematics have good prospect to reduce by ~ /3 but correlation sysmatic is unclear can be significantly lower.

g->bb,g->cc

Expt.	$g \rightarrow c\bar{c}$ $(\times 10^{-2})$	$g \rightarrow b\bar{b}$ $(\times 10^{-3})$
ALEPH	$3.23 \pm 0.48 \pm 0.53$	$2.77 \pm 0.42 \pm 0.57$
DELPHI		$2.1 \pm 1.1 \pm 0.9$ $3.3 \pm 1.0 \pm 0.8$
L3	$2.45 \pm 0.29 \pm 0.53$	
OPAL	$3.20 \pm 0.21 \pm 0.38$	$3.07 \pm 0.53 \pm 0.97$
SLD		$2.84 \pm 0.61 \pm 0.59$
LEP Std	3.19 ± 0.46	2.51 ± 0.63

- Observed rate ~2x JETSET (PYTHIA) MC
- GZ would allow much better measurements but uncertainty cannot legitimately go <10% of correction. Hopefully theory/generator can improve significantly.

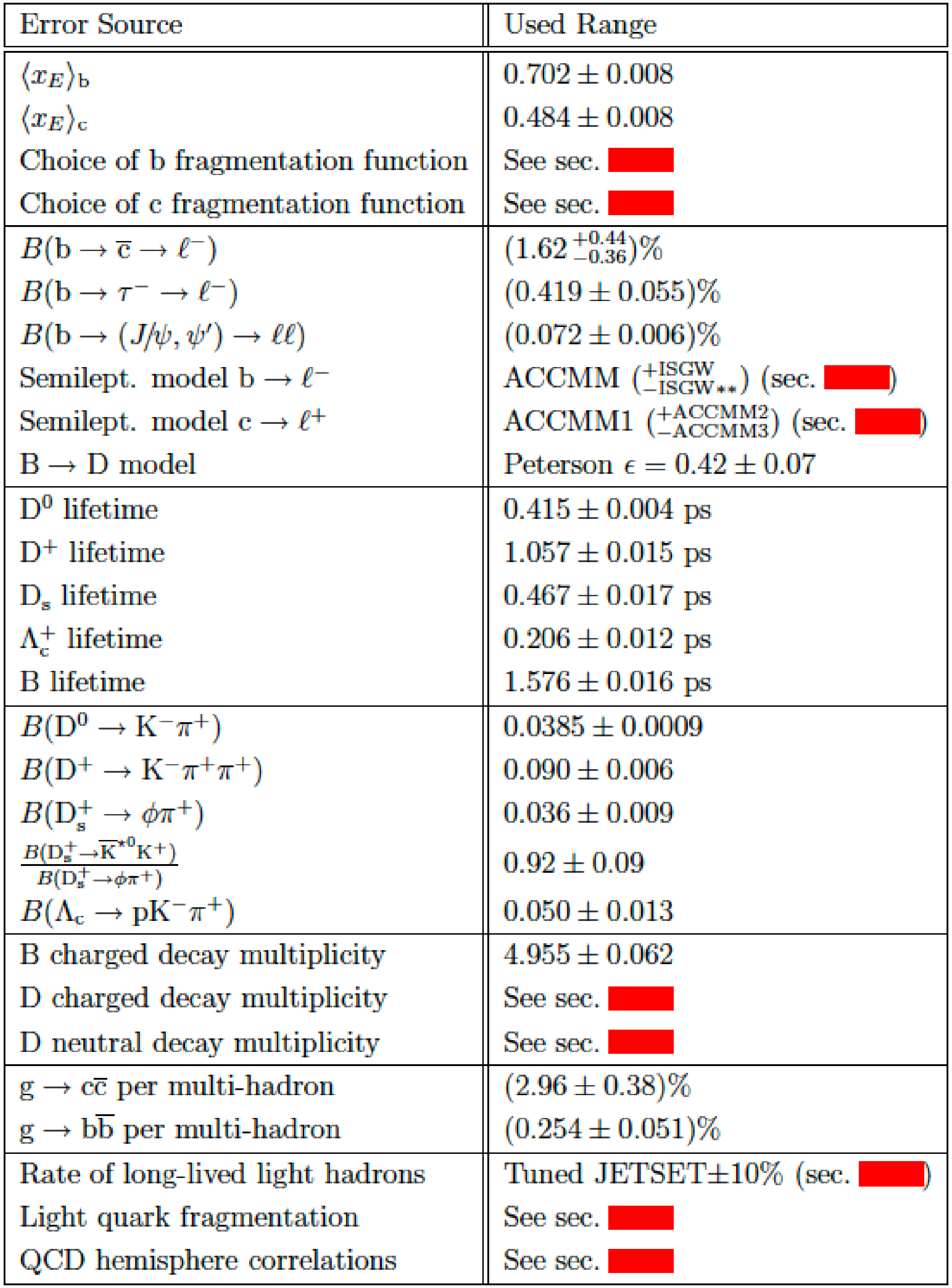
Correlation Systematic

- MC measures a combined net effect as a sum of many components:
  - Efficiency angular (mostly cosθ) dependence (+ve)
  - IP/PV bias effect: longitudinal (-ve), transverse (+ve)
  - Gluon emission: soft rad (+ve), hard rad (-ve)
  - Probably many other effects not recognized
- Net effect and component sum always discrepant.

R_b Overall Impression

- Even GigaZ can turn stat error to be ~netligible.
- Many systematics sources can lower to /3, but less clear can easily go further.
- Correlation systematic most difficulty. Not clear can even /2.
- Overall systematic 0.00066 -> 0.00020 might be possible which can be achieved with GigaZ.
- Not clear how to improve with Giga Z->Tera Z…

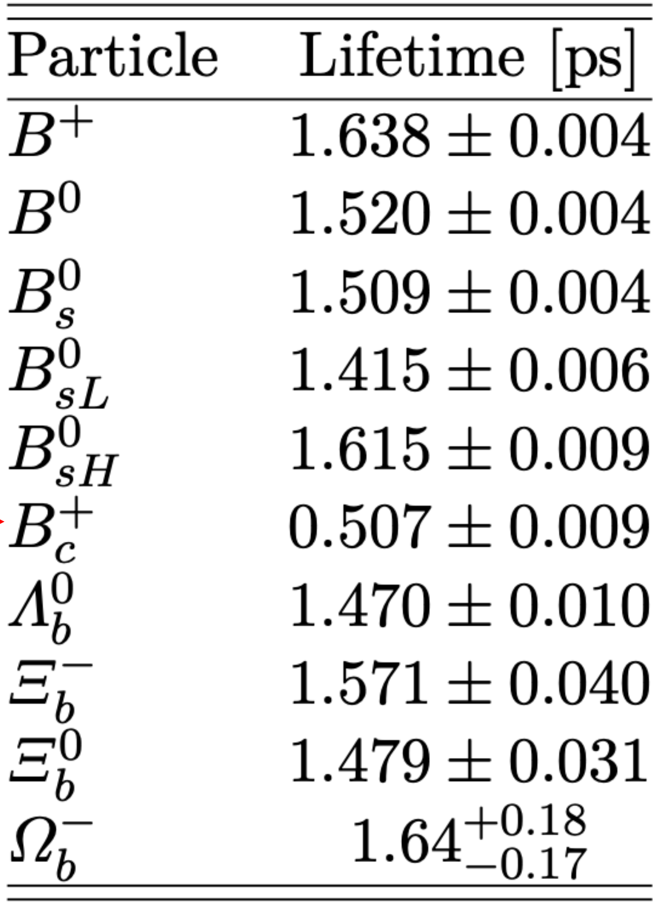
BACKUP



Error Source	Used Range
$\langle x_E \rangle_{\mathrm{b}}$	0.702 ± 0.008
$\langle x_E \rangle_{\mathrm{c}}$	0.484 ± 0.008
Choice of b fragmentation function	See sec. [redacted]
Choice of c fragmentation function	See sec. [redacted]
$B(\mathrm{b} \to \overline{\mathrm{c}} \to \ell^-)$	$(1.62\,^{+0.44}_{-0.36})\%$
$B(\mathrm{b} \to \tau^- \to \ell^-)$	$(0.419 \pm 0.055)\%$
$B(\mathrm{b} \to (J/\psi, \psi') \to \ell\ell)$	$(0.072 \pm 0.006)\%$
Semilept. model $\mathrm{b} \to \ell^-$	ACCMM $(^{+\mathrm{ISGW}}_{-\mathrm{ISGW**}})$ (sec. [redacted])
Semilept. model $\mathrm{c} \to \ell^+$	ACCMM1 $(^{+\mathrm{ACCMM2}}_{-\mathrm{ACCMM3}})$ (sec. [redacted])
B → D model	Peterson $\epsilon = 0.42 \pm 0.07$
$\mathrm{D^0}$ lifetime	0.415 ± 0.004 ps
$\mathrm{D^+}$ lifetime	1.057 ± 0.015 ps
$\mathrm{D_s}$ lifetime	0.467 ± 0.017 ps
Λ_{c}^+ lifetime	0.206 ± 0.012 ps
B lifetime	1.576 ± 0.016 ps
$B(\mathrm{D^0} \to \mathrm{K^-}\pi^+)$	0.0385 ± 0.0009
$B(\mathrm{D^+} \to \mathrm{K^-}\pi^+\pi^+)$	0.090 ± 0.006
$B(\mathrm{D_s^+} \to \phi\pi^+)$	0.036 ± 0.009
$\frac{B(\mathrm{D_s^+} \to \overline{\mathrm{K}}^{*0}\mathrm{K}^+)}{B(\mathrm{D_s^+} \to \phi\pi^+)}$	0.92 ± 0.09
$B(\Lambda_{\mathrm{c}} \to \mathrm{pK^-}\pi^+)$	0.050 ± 0.013
B charged decay multiplicity	4.955 ± 0.062
D charged decay multiplicity	See sec. [redacted]
D neutral decay multiplicity	See sec. [redacted]
$\mathrm{g} \to \mathrm{c\overline{c}}$ per multi-hadron	$(2.96 \pm 0.38)\%$
$\mathrm{g} \to \mathrm{b\overline{b}}$ per multi-hadron	$(0.254 \pm 0.051)\%$
Rate of long-lived light hadrons	Tuned JETSET±10% (sec. [redacted])
Light quark fragmentation	See sec. [redacted]
QCD hemisphere correlations	See sec. [redacted]

b and c Hadron Lifetimes

PDG b prod + decay review



Particle	Lifetime [ps]
B^+	1.638 ± 0.004
B^0	1.520 ± 0.004
B^0_s	1.509 ± 0.004
B^0_{sL}	1.415 ± 0.006
B^0_{sH}	1.615 ± 0.009
B^+_c	0.507 ± 0.009
Λ^0_b	1.470 ± 0.010
Ξ^-_b	1.571 ± 0.040
Ξ^0_b	1.479 ± 0.031
Ω^-_b	$1.64^{+0.18}_{-0.17}$

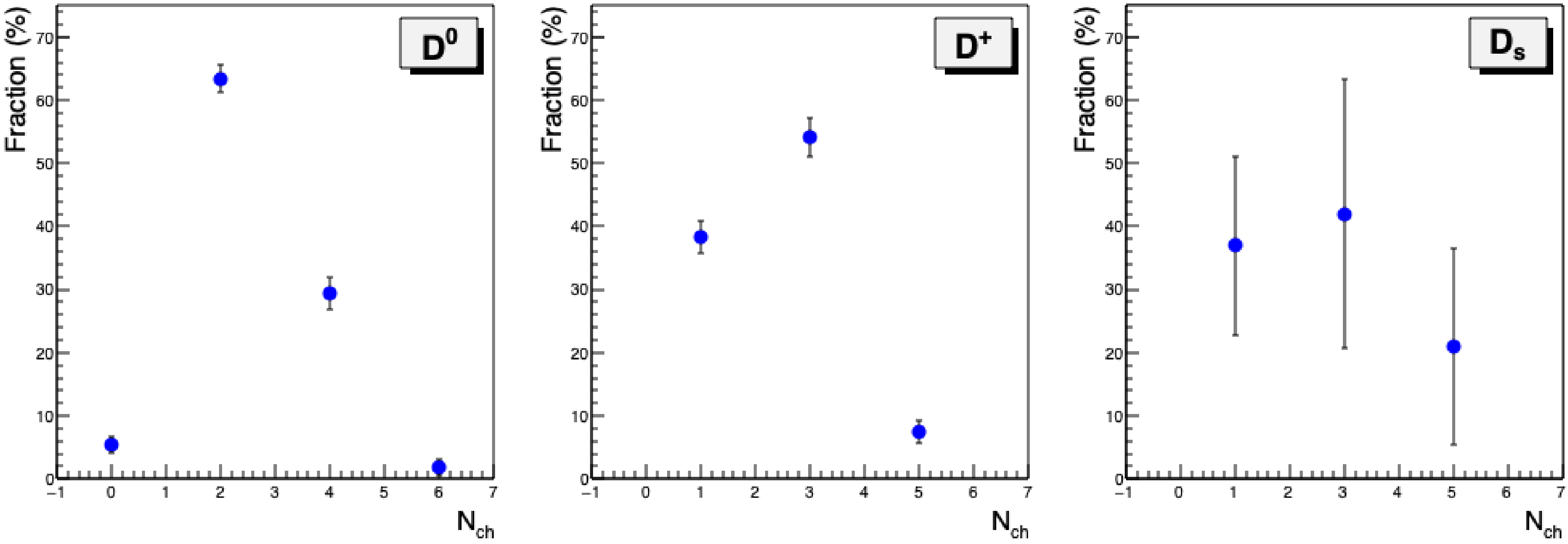
Charm decays first more often for B_c

Particle	Lifetime (ps)	Br(x+lν)
D^+	1.040+-0.007	16.1+-0.3%
D^0	0.410+-0.002	6.5+-0.1%
D_s^+	0.504+-0.004	6.5+-0.4%
Λ_c^+	0.200+-0.006	3.95+-0.35%
Ξ_c^+	0.442+-0.026	
Ξ_c^0	0.112+-0.013	
Ω_c^0	0.268+-0.026	

Large variations of lifetime among charm hadrons, correlated with semi-leptonic Br.

Other b,c hadrons decay strongly or electromagnetically to these weakly decaying states

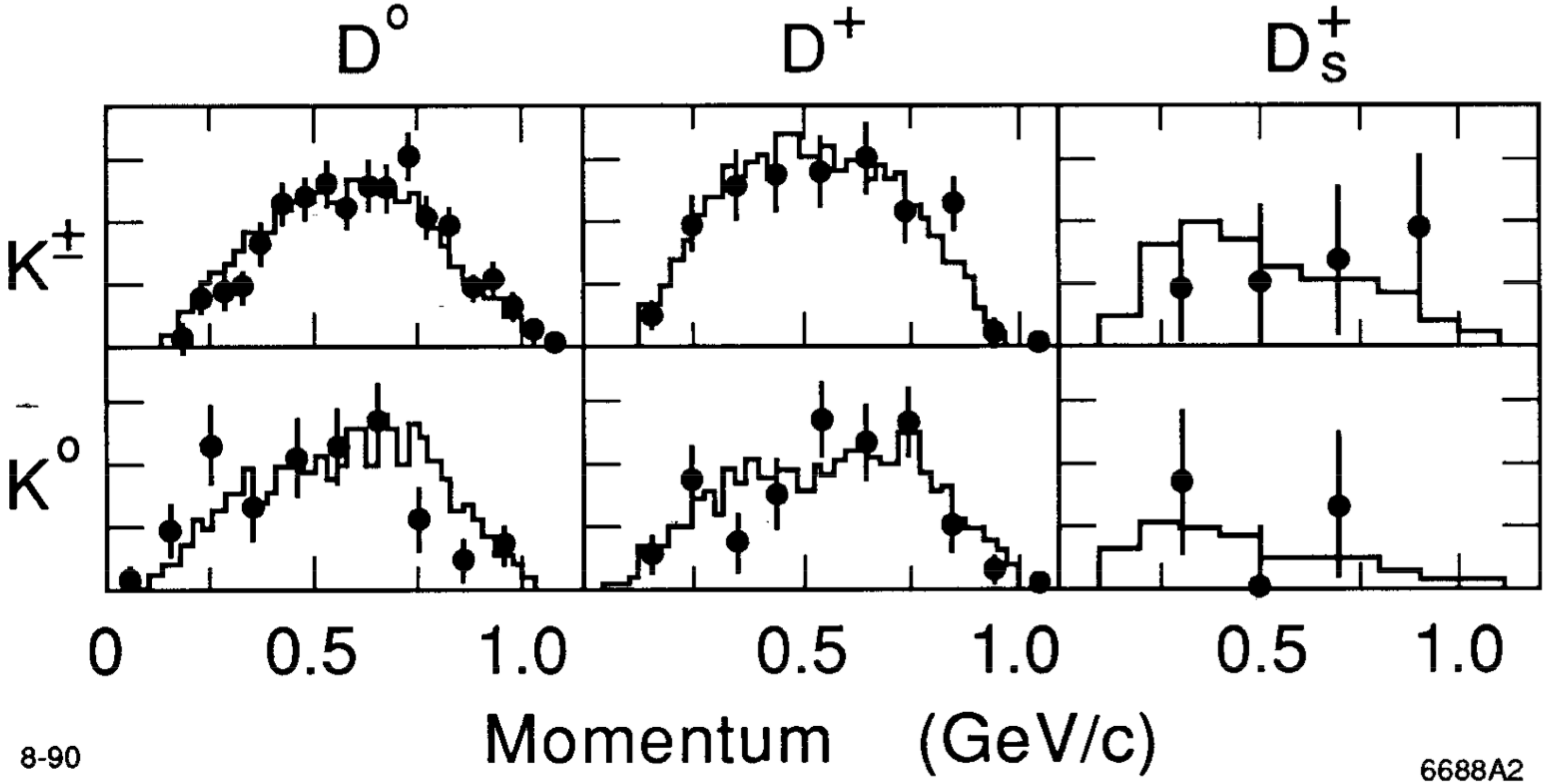
D Decay Charged Multiplicity



Mark-III D.Coffman *et al.* Phys. Lett. **B263** (1991) 135

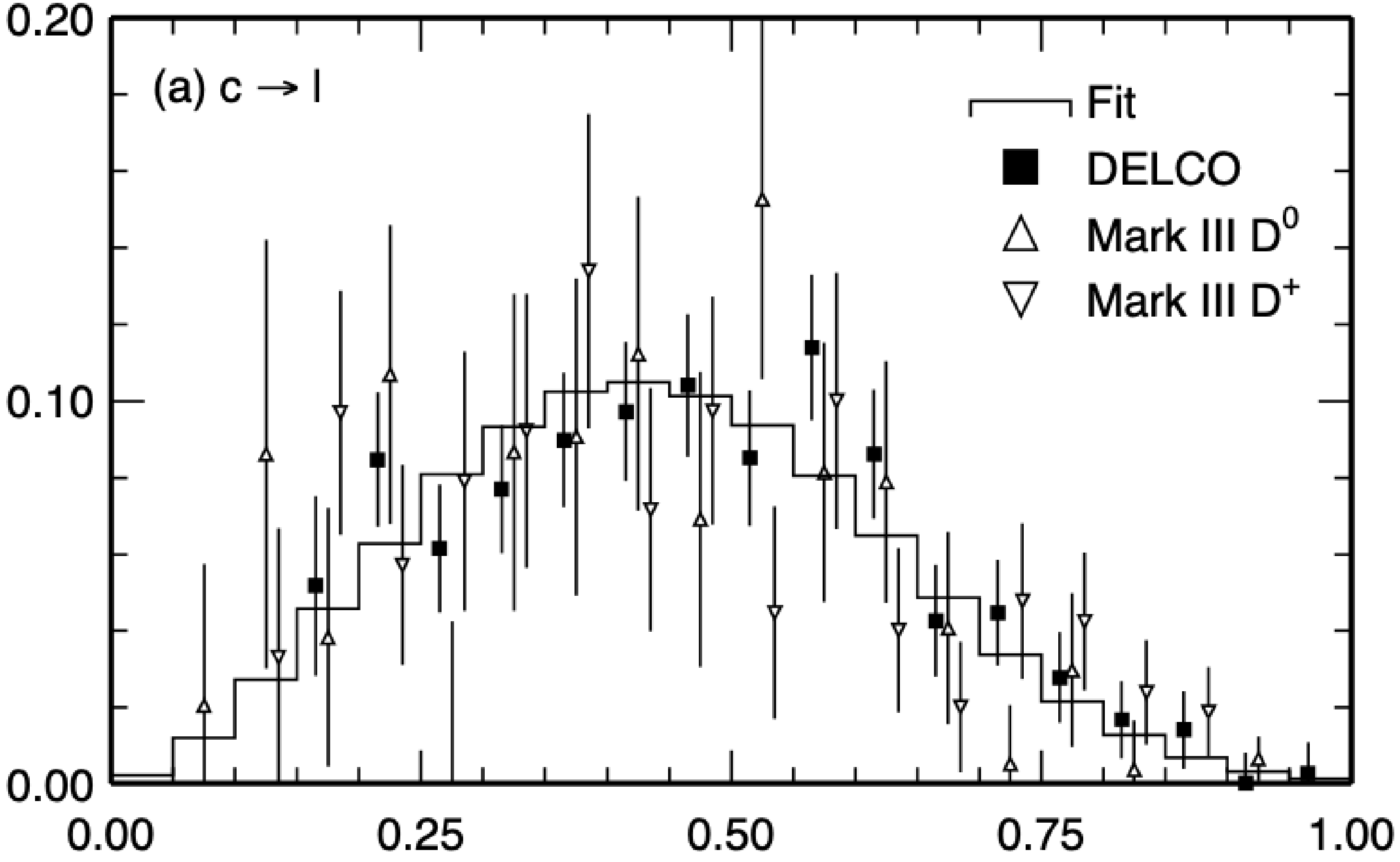
- **Charged multiplicity include decays from parent with lifetime < K^0_L**
- **D^+ N_{ch}=1 quite difficult to reconcile in D decay simulation**

D Decay Kaon Momentum



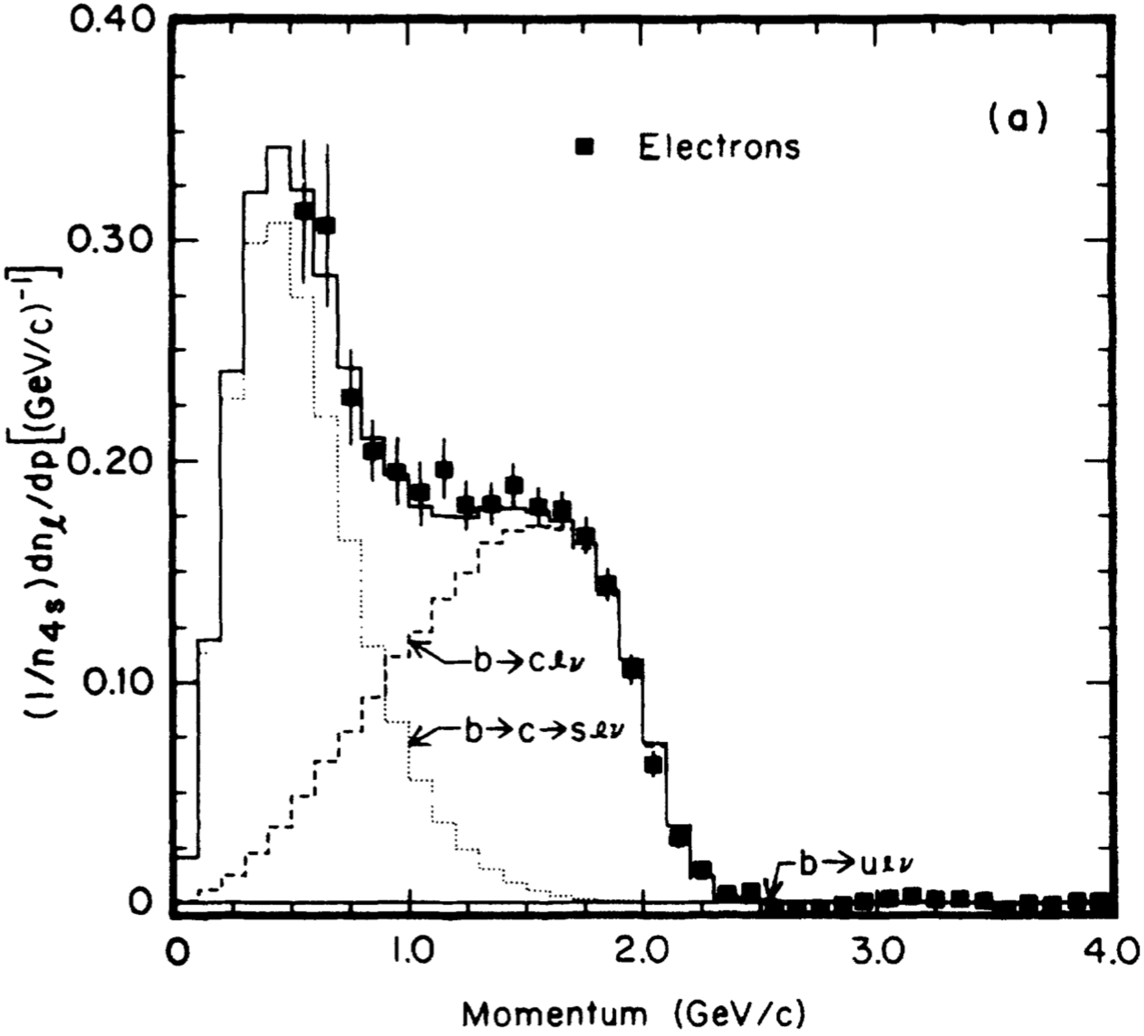
Mark-III D.Coffman *et al.* Phys. Lett. **B263** (1991) 135

D semileptonic Decays



CERN PPE/96-017

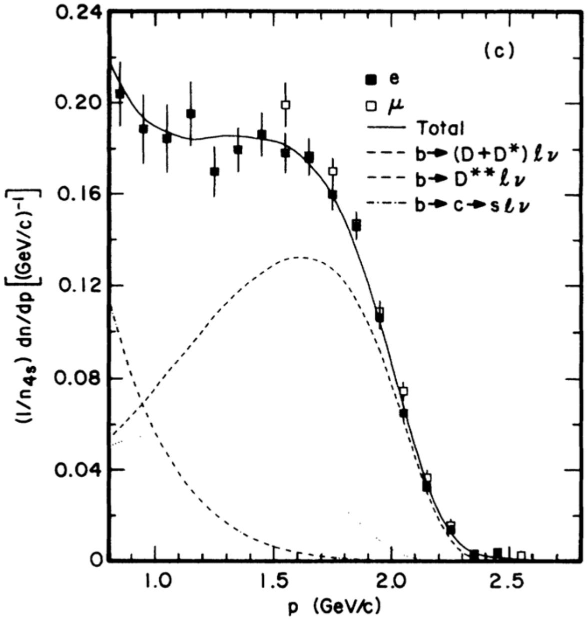
B Semileptonic Decays



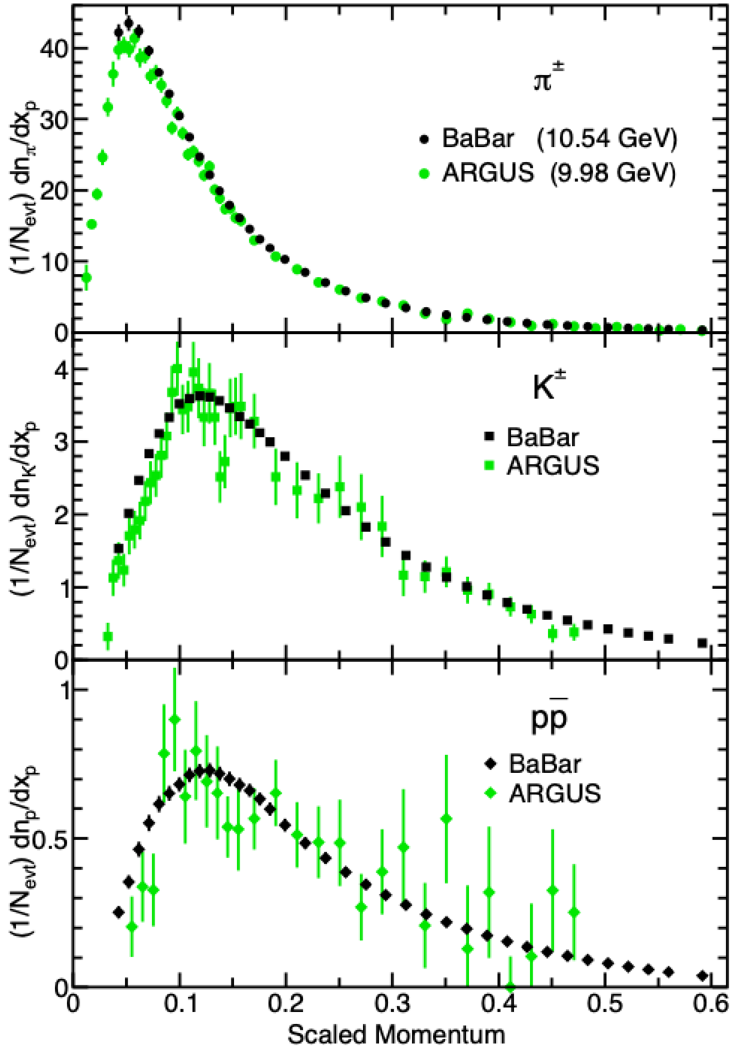
CLEO

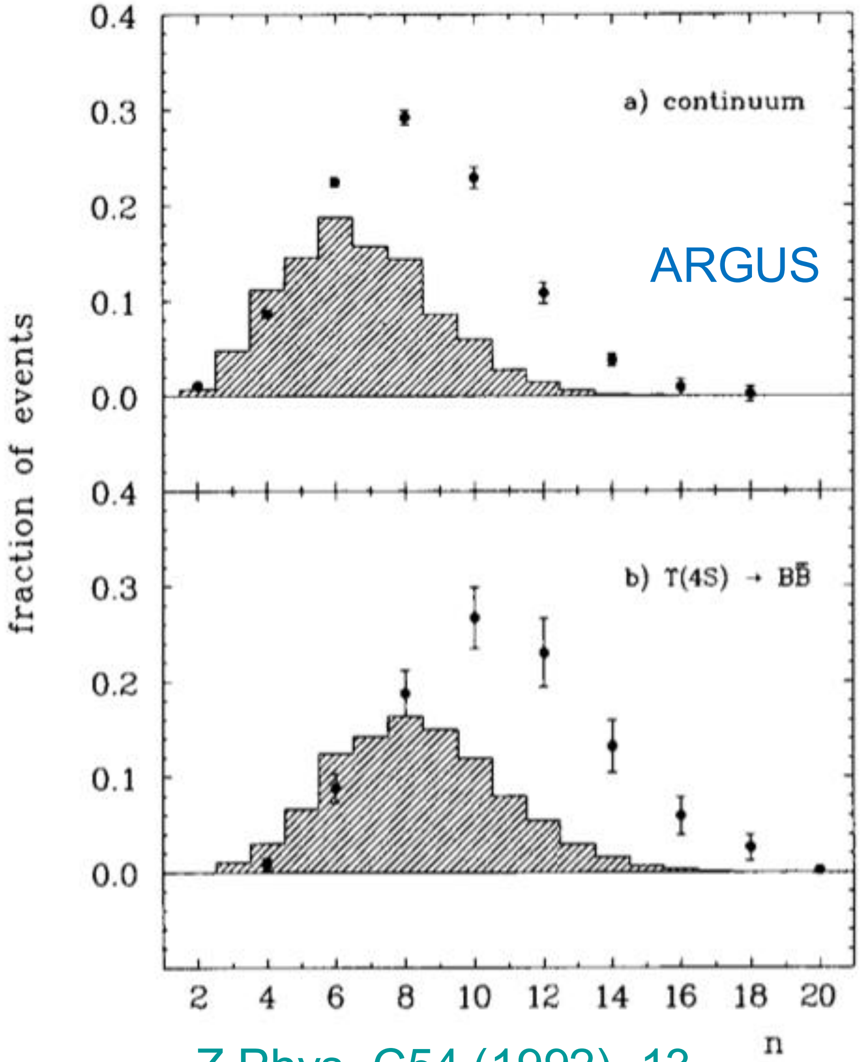
S. Henderson et al.

PRD 45 (1992) 2212



B->charged particles



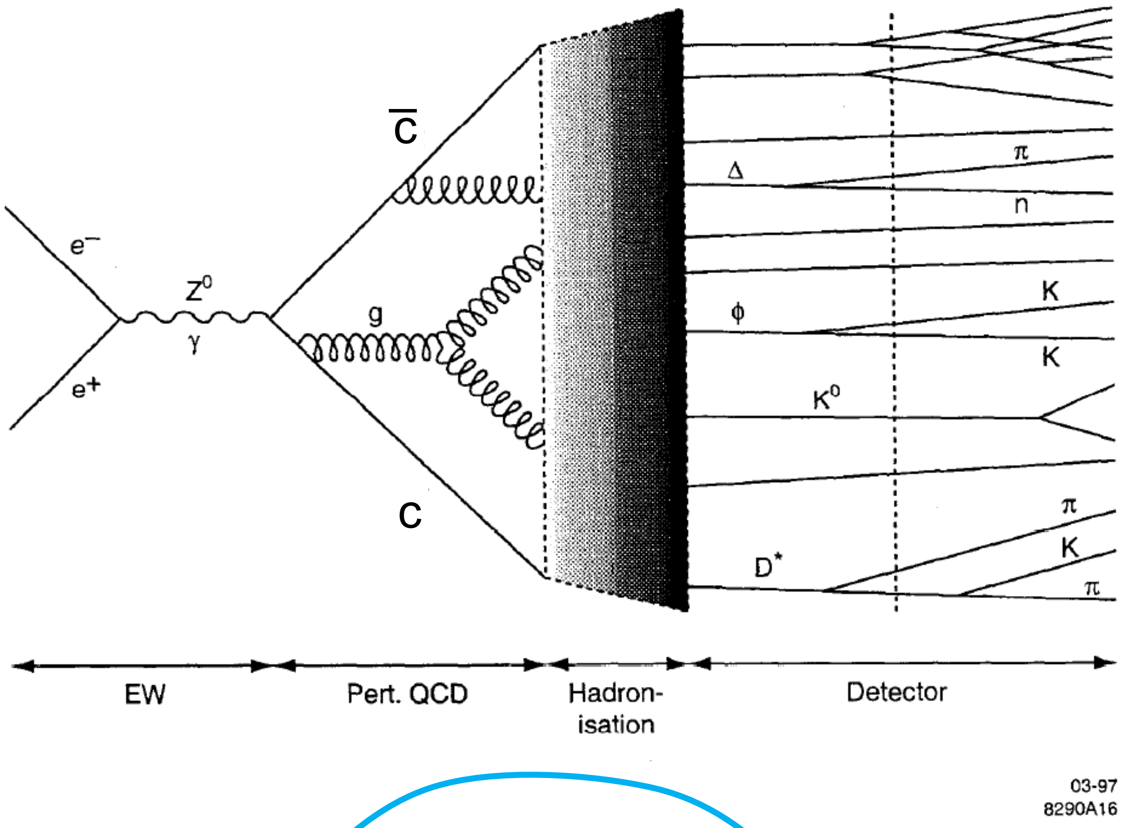


ARGUS

Z Phys. C54 (1992), 13

BaBar arXiv:1310.0520
ARGUS Z phys C58 (1993), 191

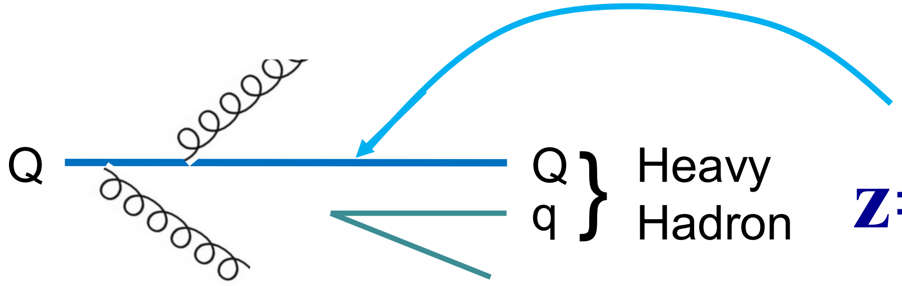
b/c Jet Fragmentation



$$x_E = \frac{E_{had}}{E_{beam}}$$

is a proper observable

but still needs care with excited hadrons decayed to weakly decaying hadron

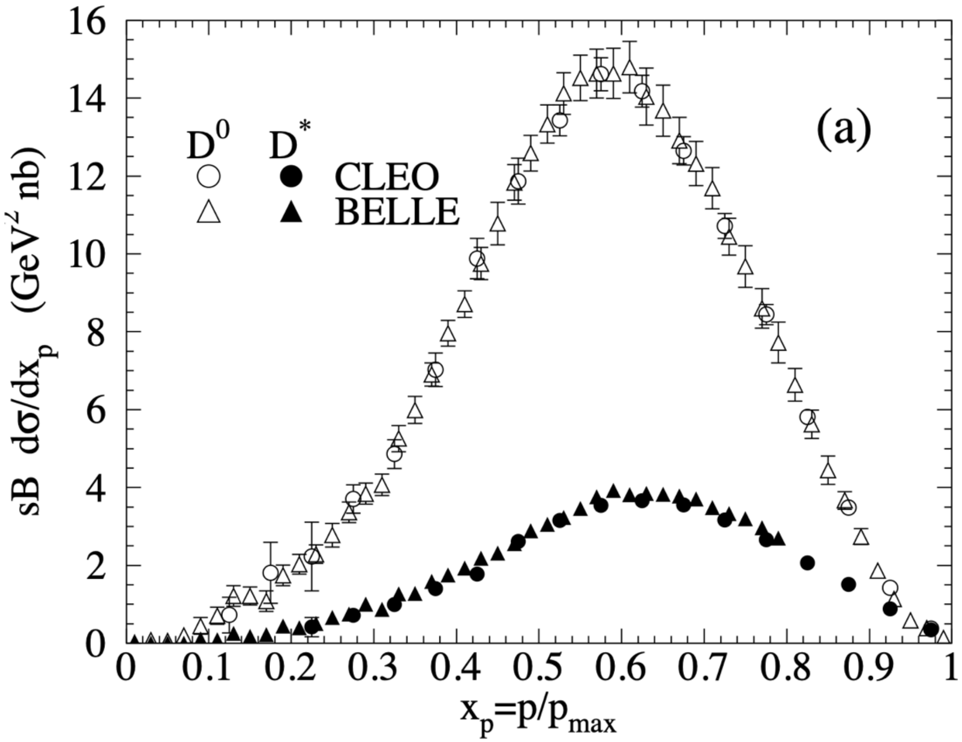


$$z = \frac{E_{had}}{E_Q}$$

Fragmentation functions formulate on local z for simulation but E_Q is not observable at hadron

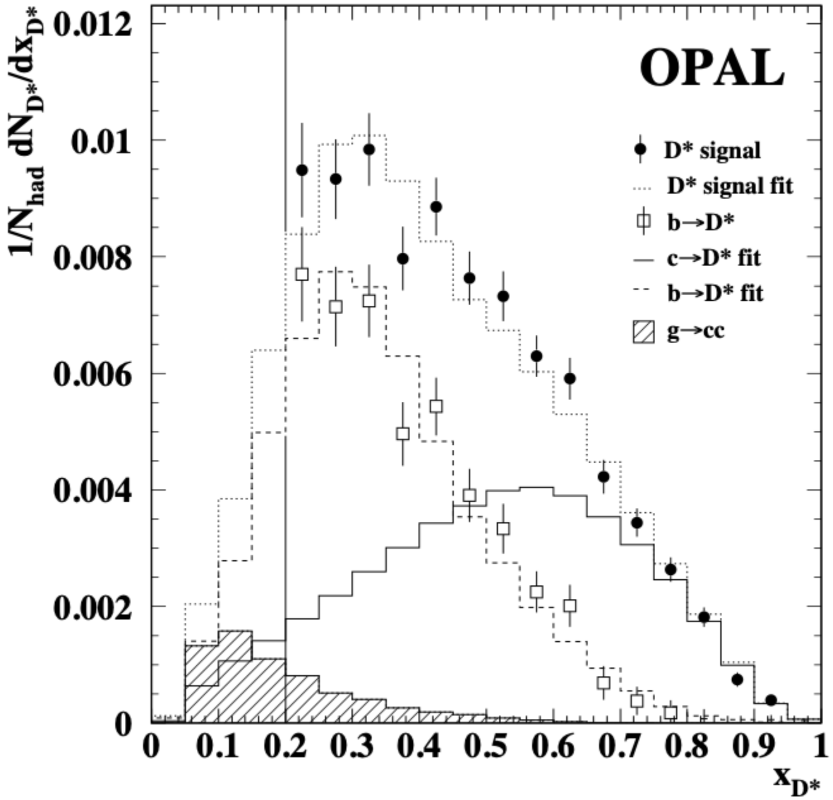
Charm Fragmentation

Fully reconstructed D^0, D^{*+}
e^+e^- $\sqrt{s}$ ~ 10.8 GeV



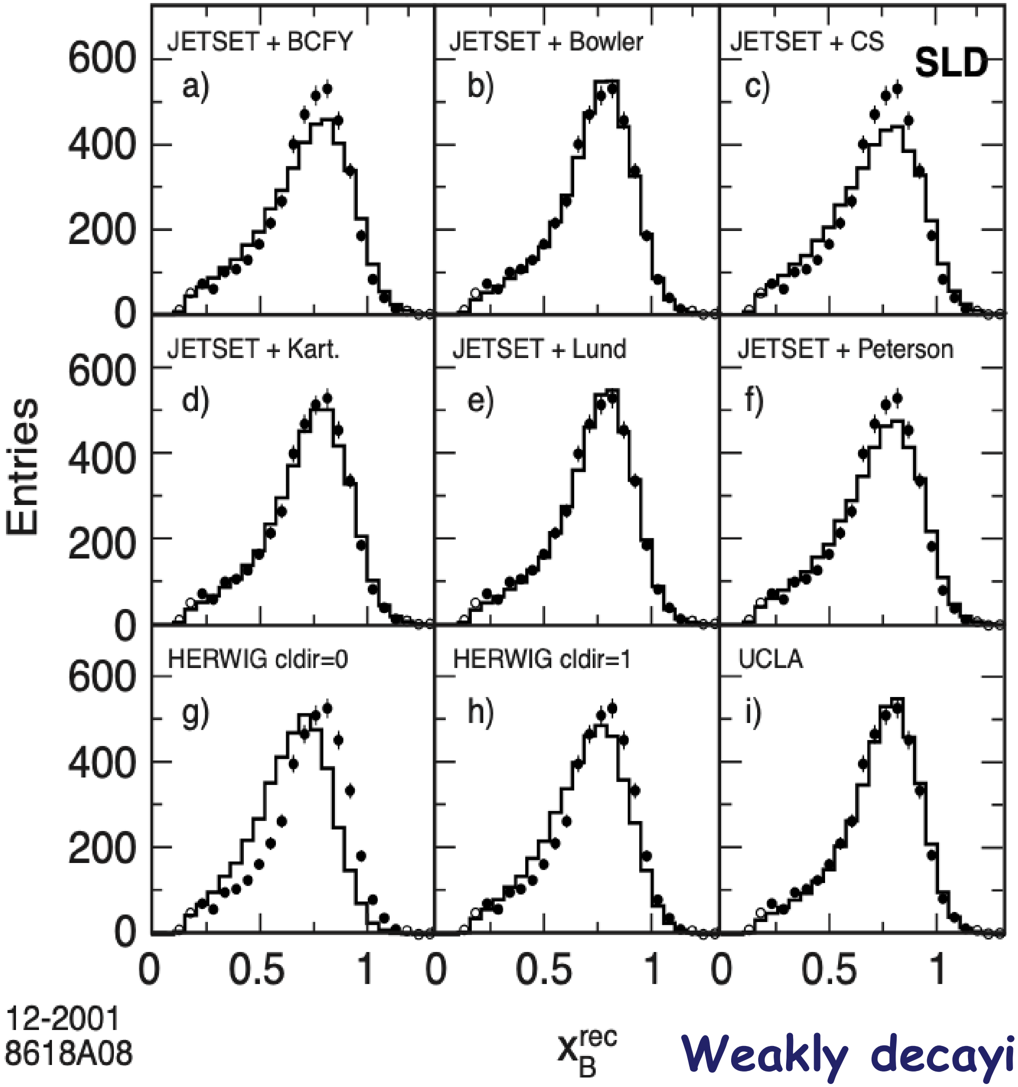
(PDG review fragmentation functions)

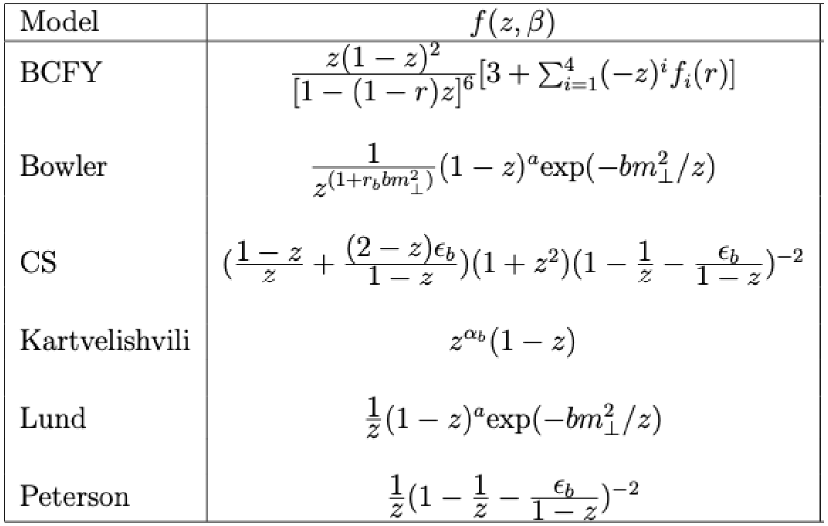
e^+e^- at Z^0 pole with fully recon D^{*+} and b-tag subtraction of b->D*



EPJ C1 439 (1998)

b Fragmentation (SLD)





Model	$f(z,\beta)$
BCFY	$\frac{z(1-z)^2}{[1-(1-r)z]^6}[3+\sum_{i=1}^{4}(-z)^i f_i(r)]$
Bowler	$\frac{1}{z^{(1+r_b b m_\perp^2)}}(1-z)^a \exp(-b m_\perp^2/z)$
CS	$(\frac{1-z}{z}+\frac{(2-z)\epsilon_b}{1-z})(1+z^2)(1-\frac{1}{z}-\frac{\epsilon_b}{1-z})^{-2}$
Kartvelishvili	$z^{\alpha_b}(1-z)$
Lund	$\frac{1}{z}(1-z)^a \exp(-b m_\perp^2/z)$
Peterson	$\frac{1}{z}(1-\frac{1}{z}-\frac{\epsilon_b}{1-z})^{-2}$

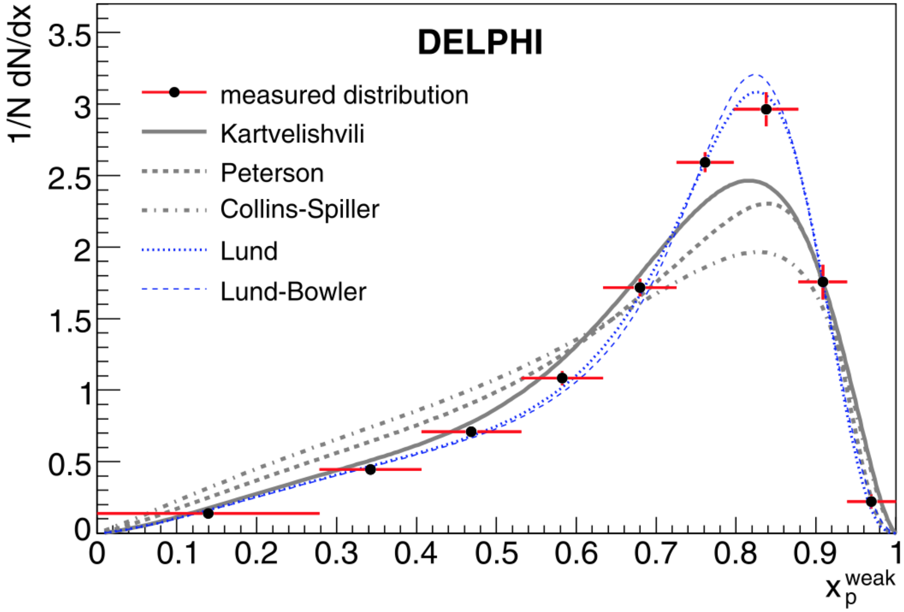
SLD Koya Abe et al.
Phys Rev D 65 (2002) 092006
Phys Rev D 66 (2002) 079905

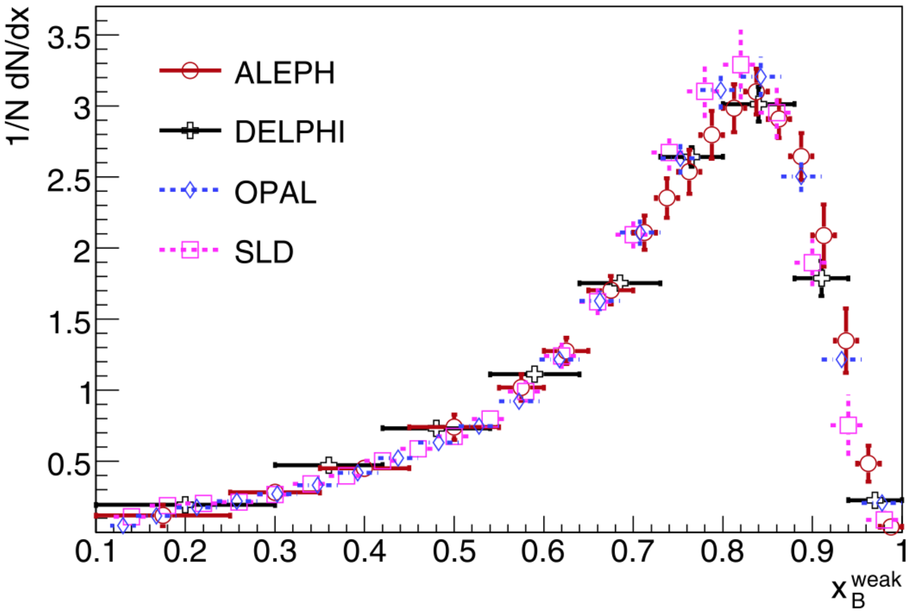
Danning Dong, MIT thesis (1999)
SLAC-R-550

Weakly decaying b hadron

b Fragmentation (DELPHI)

Euro Phys J. C71 (2011) 1557





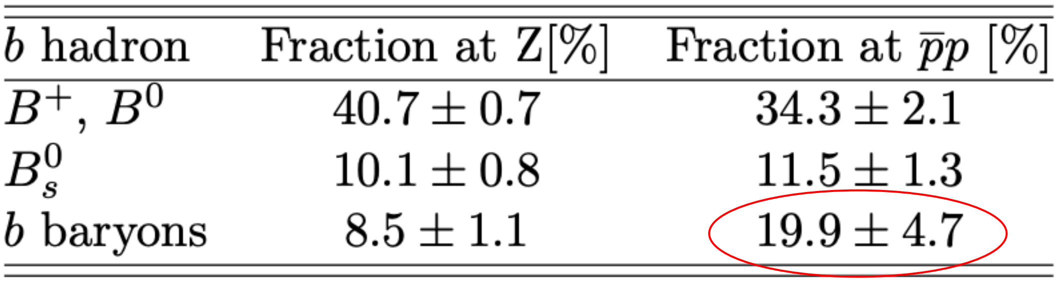
- Slight disagreement with SLD in shape
- LUND-Bowler seems to fit best for all measurements (Bowler also favored by c fragmentation measurements)
- LUND-Bowler became default since PYTHIA 6

Heavy Hadron Production

- What heavy hadron mix can we expect from a heavy quark jet hadronization ?
- c jet: PDG compilation for e^+e^- near ϒ(4s) (10.9 GeV) (in good agreement with LEP/SLD at Z pole)

Particle	Rate	Particle	Rate
D^0	0.565+-0.032	D^{*0}	0.213+-0.024
D^+	0.246+-0.020	D^{*+}	0.224+-0.028
D_s	0.080+-0.017	D^*_s	0.061+-0.018
Λ_c	0.094+-0.035		

- b jet:



b hadron	Fraction at Z[%]	Fraction at $\bar{p}p$ [%]
B^+, B^0	40.7 ± 0.7	34.3 ± 2.1
B^0_s	10.1 ± 0.8	11.5 ± 1.3
b baryons	8.5 ± 1.1	19.9 ± 4.7

Low P_t b production

PDG compilation

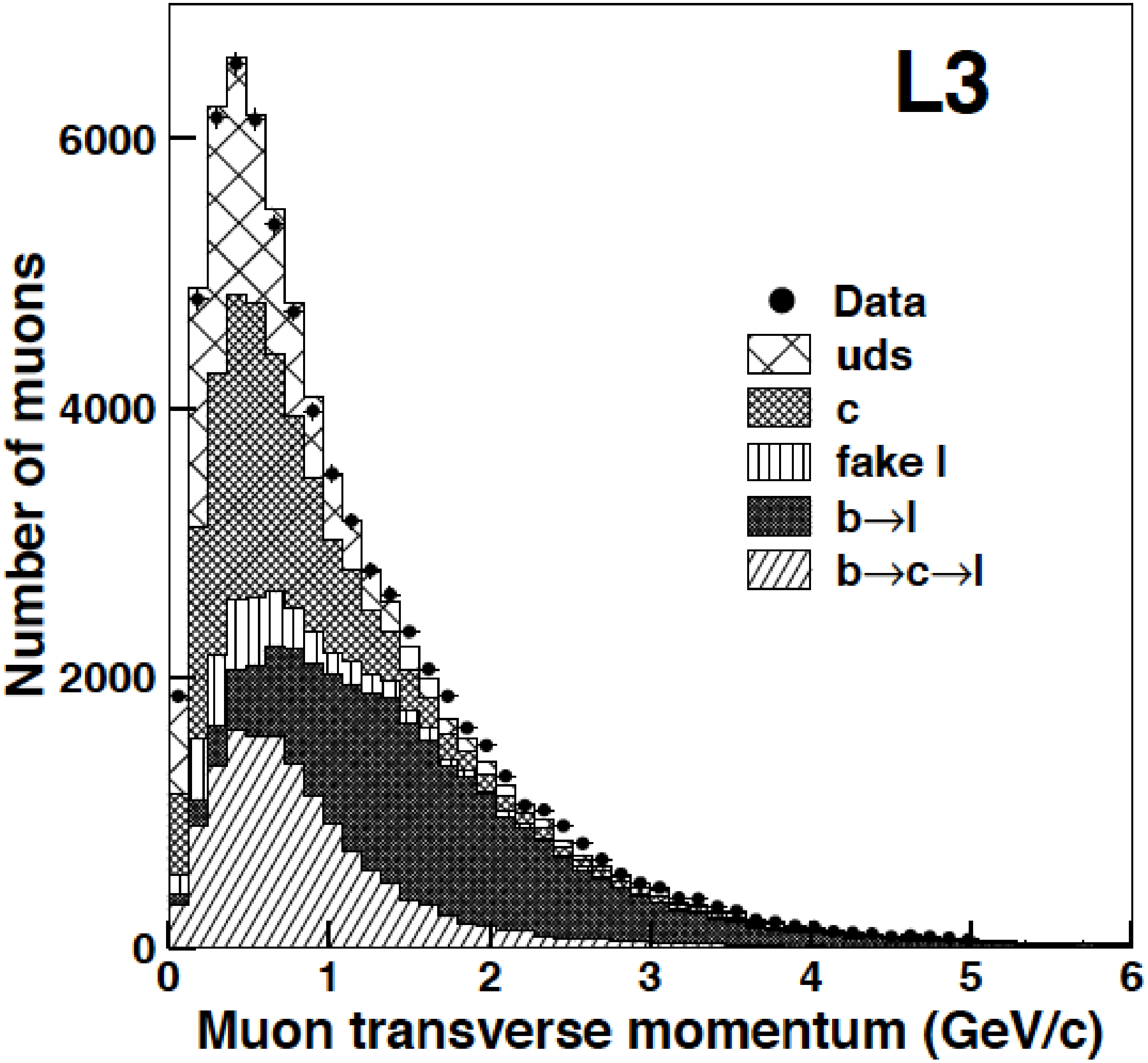
e^+e^- Z pole & Tevatron

HFLAV-2018 discussion

Heavy quark tagging signatures

- b quark
  - High P_t lepton was the oldest technique
  - Lifetime based b tag took over in the 90s everywhere
  - Room for improvements ? How good is charm background control ?
- Charm quark:
  - Traditional exclusive D*,D,Λ_c reconstruction are clean signals but suffer from low efficiency
  - Inclusive vertex+mass tag worked well for SLD in late 90s
  - Can inclusive vertexing performance improve to the level to qualify as a distinctive tag in ATLAS also ?
- Strange quark tag ?
  - Was done with leading kaons in SLD.

High $P_\perp$ Lepton b-tag



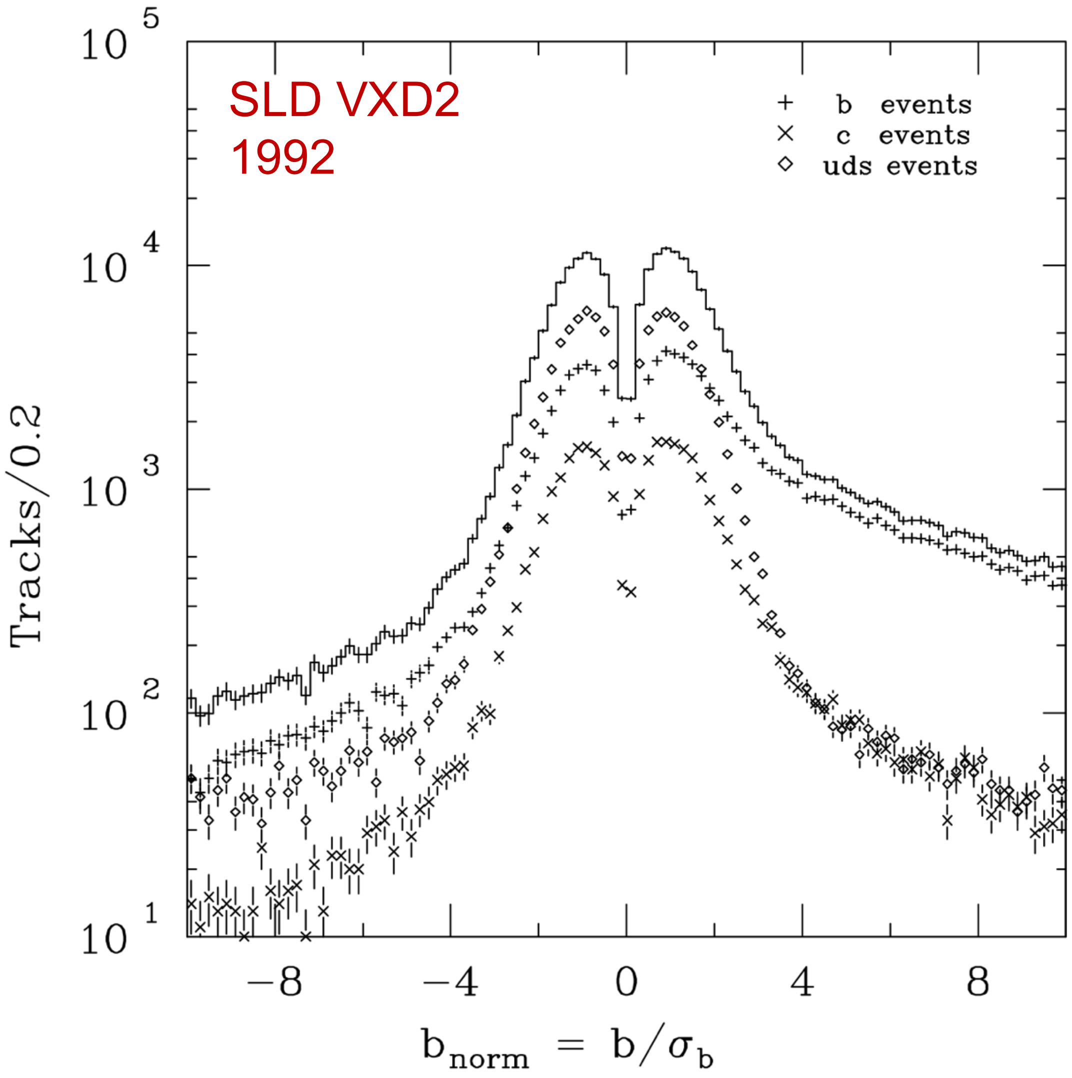
Examining lepton $P_\perp$ wrt jet

High P *b->l* in B decay rest frame largely preserved by Lorentz invariance for

$P_\perp$ to boost

Limited eff but indep to lifetime

3D impact parameter

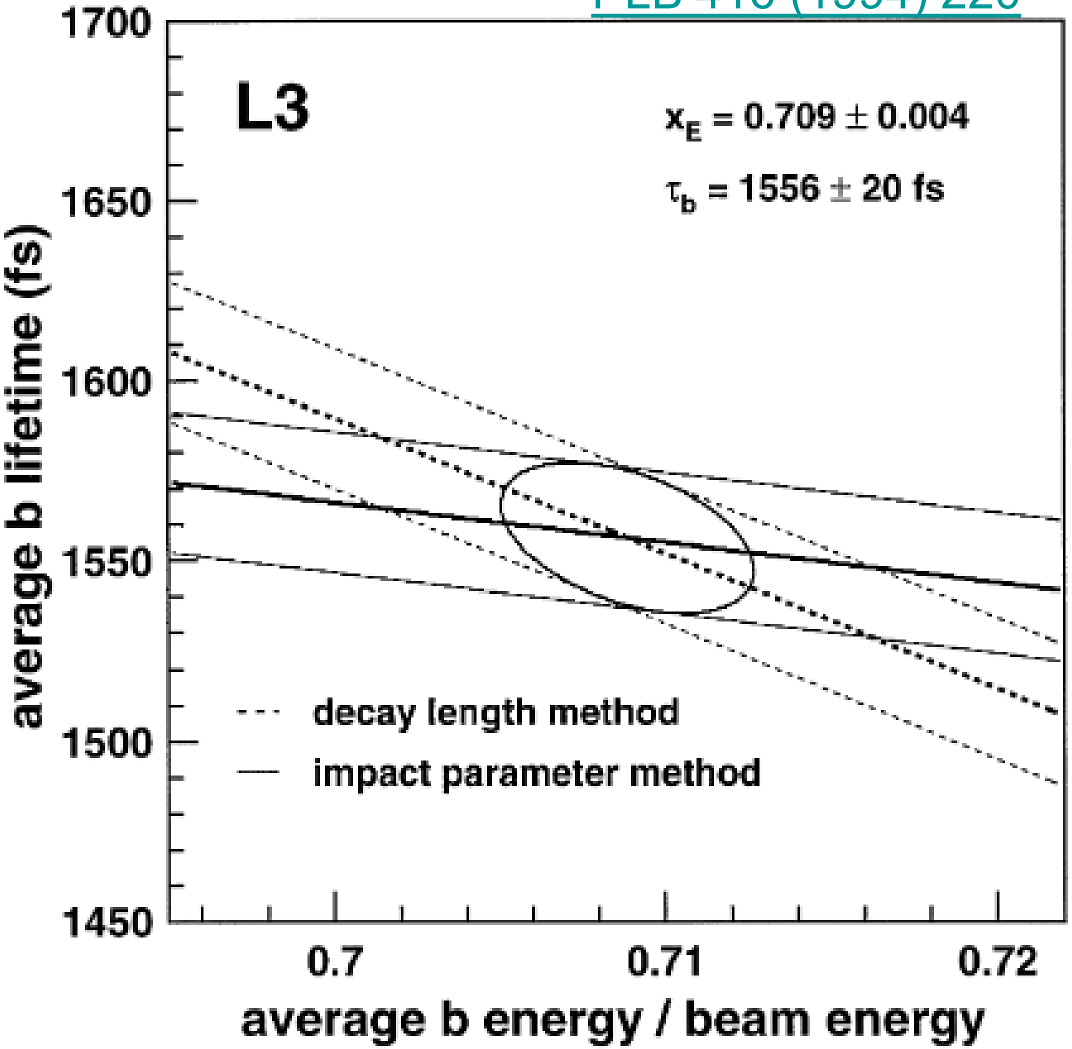


- ***ATLAS usage of combining Rϕ + RZ is not quite 3D***
- ***Real 3D impact parameter more effective if spatial resolution uniform in all dir.***
- ***More stable against signing error as phase space for (0,0,0) is zero in 3D.***

Jeff Snyder SLAC-R-669 1994), Ph.D thesis (Yale)

Impact Parameter vs Vertexing

PLB 416 (1994) 220

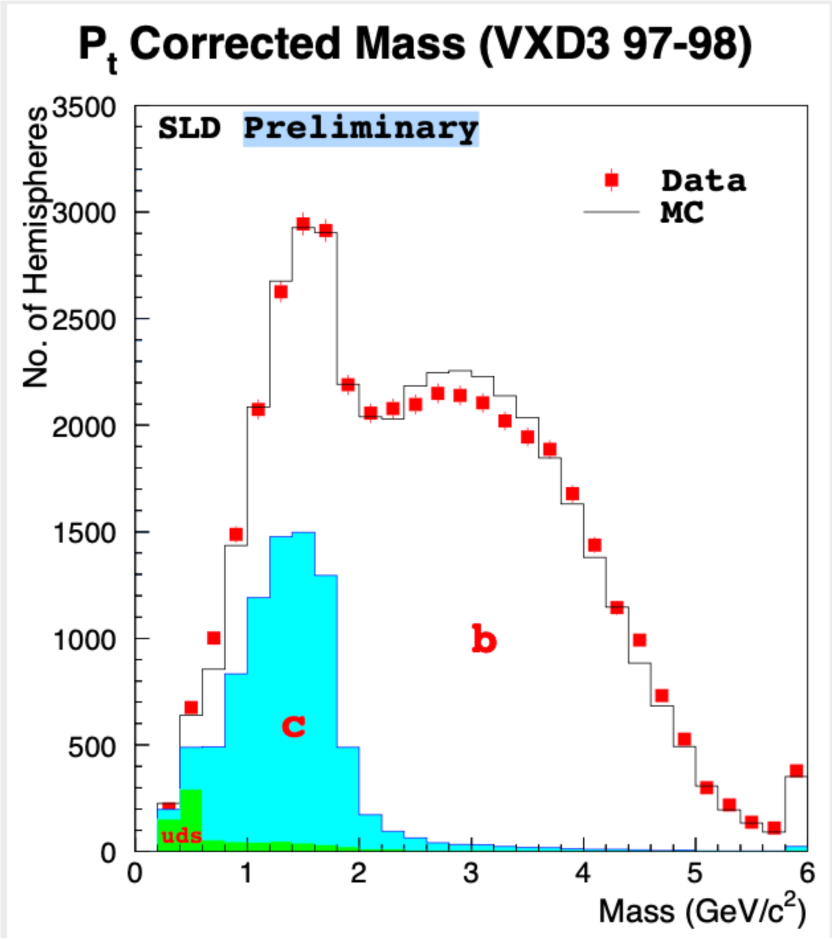


Impact parameter is a modular and independent observable, almost boost invariant

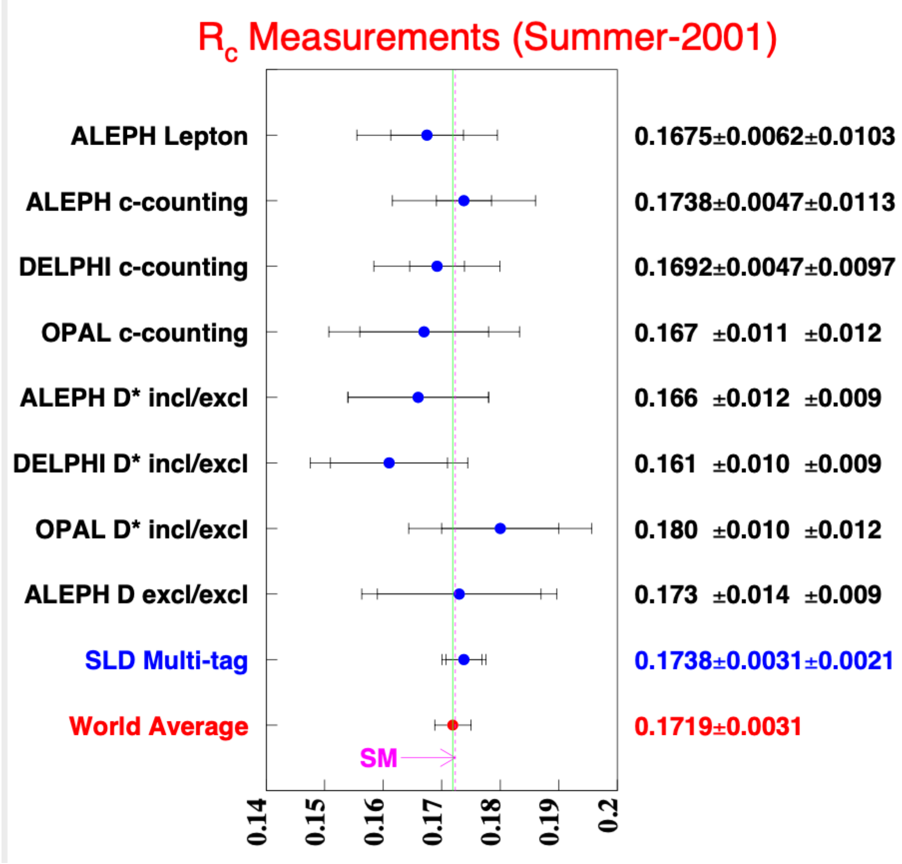
Vertexing less sensitive to PV, signing and bad tracks.

L3 simultaneously measured B lifetime and b-fragmentation $\langle x_E \rangle$

Charm tagging ?



$Z^0 \rightarrow c\bar{c}$ branching ratio



b/c separation with vertex mass tag

b contamination in c-tag also calibrated

Precision from double tag ε^2

LEP:4x4MZ vs SLD 0.5MZ

SLD R_b,R_c PRD 71 112004 (2005)

Strange quark tagging ?

SLD s-tag with fast leading K,Λ to measure polarized Z->$s\bar{s}$ asymmetry

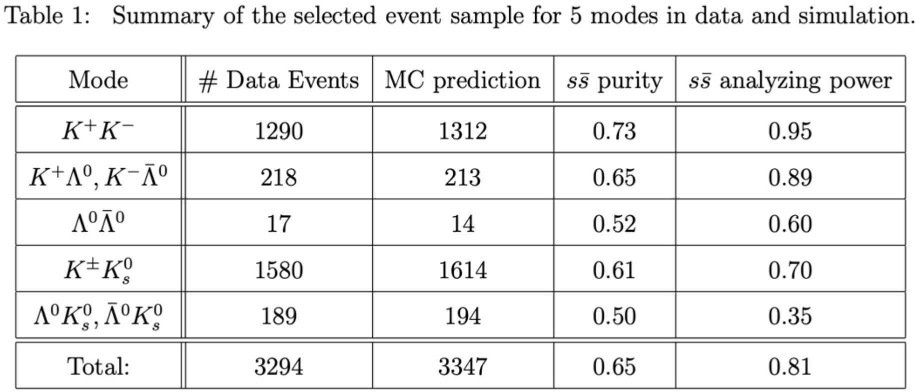


Table 1: Summary of the selected event sample for 5 modes in data and simulation.

Mode	# Data Events	MC prediction	$s\bar{s}$ purity	$s\bar{s}$ analyzing power
K^+K^-	1290	1312	0.73	0.95
$K^+\Lambda^0, K^-\bar{\Lambda}^0$	218	213	0.65	0.89
$\Lambda^0\bar{\Lambda}^0$	17	14	0.52	0.60
$K^\pm K_s^0$	1580	1614	0.61	0.70
$\Lambda^0 K_s^0, \bar{\Lambda}^0 K_s^0$	189	194	0.50	0.35
Total:	3294	3347	0.65	0.81

SLD A_s PRL 85 (2000), 5059