Heavy Quark Fragmentation

David Muller
SLAC
representing the BaBar collaboration

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- **Introduction**
- **c, b fragmentation at 29-35 GeV**
- **b fragmentation at the Z^0**
- **c fragmentation at the Z^0**
- **c fragmentation at ~10 GeV**
- **B, D production near threshold**
- **Conclusion and outlook**

DELCO, HRS, MAC, MARKII, TPC; JADE, MARK-J, TASSO

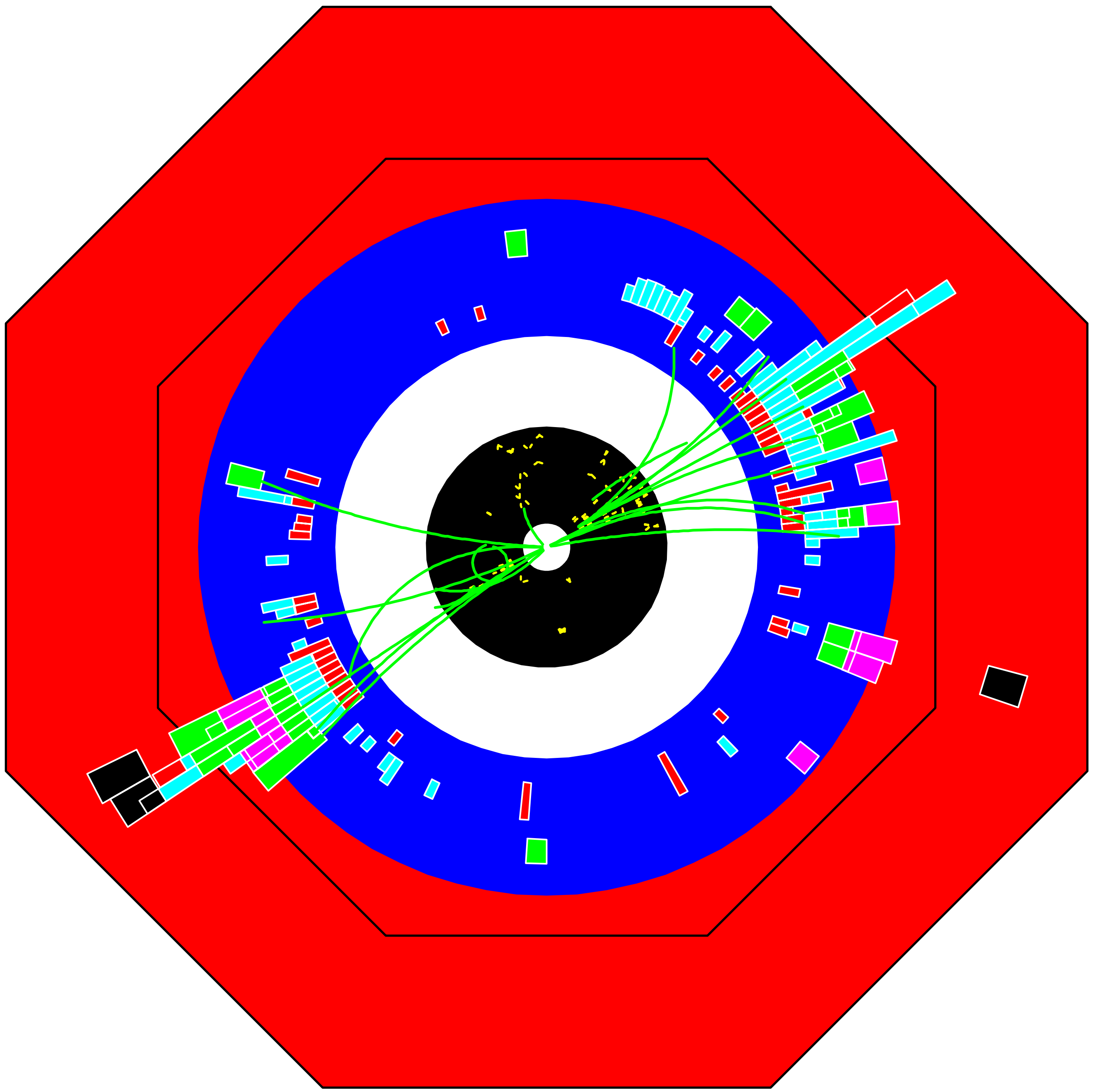
ALEPH, DELPHI, L3, OPAL, SLD

CLEO, ARGUS Belle, BaBar

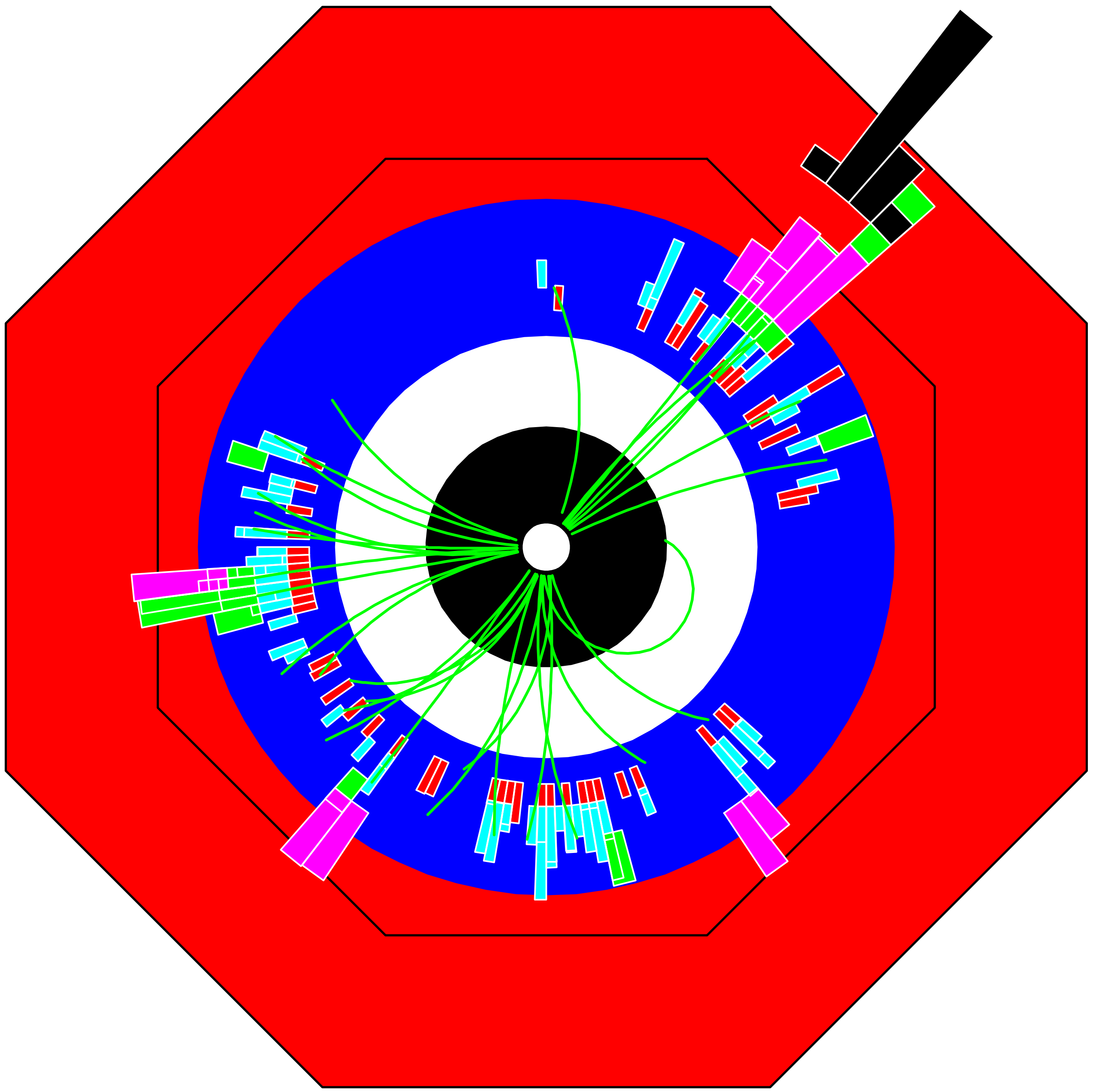
also H1, ZEUS, CDF, D0 (see backup)

Introduction

- high-energy quarks and gluons appear as hadronic jets
- for example: $e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}(g) \rightarrow$ jets

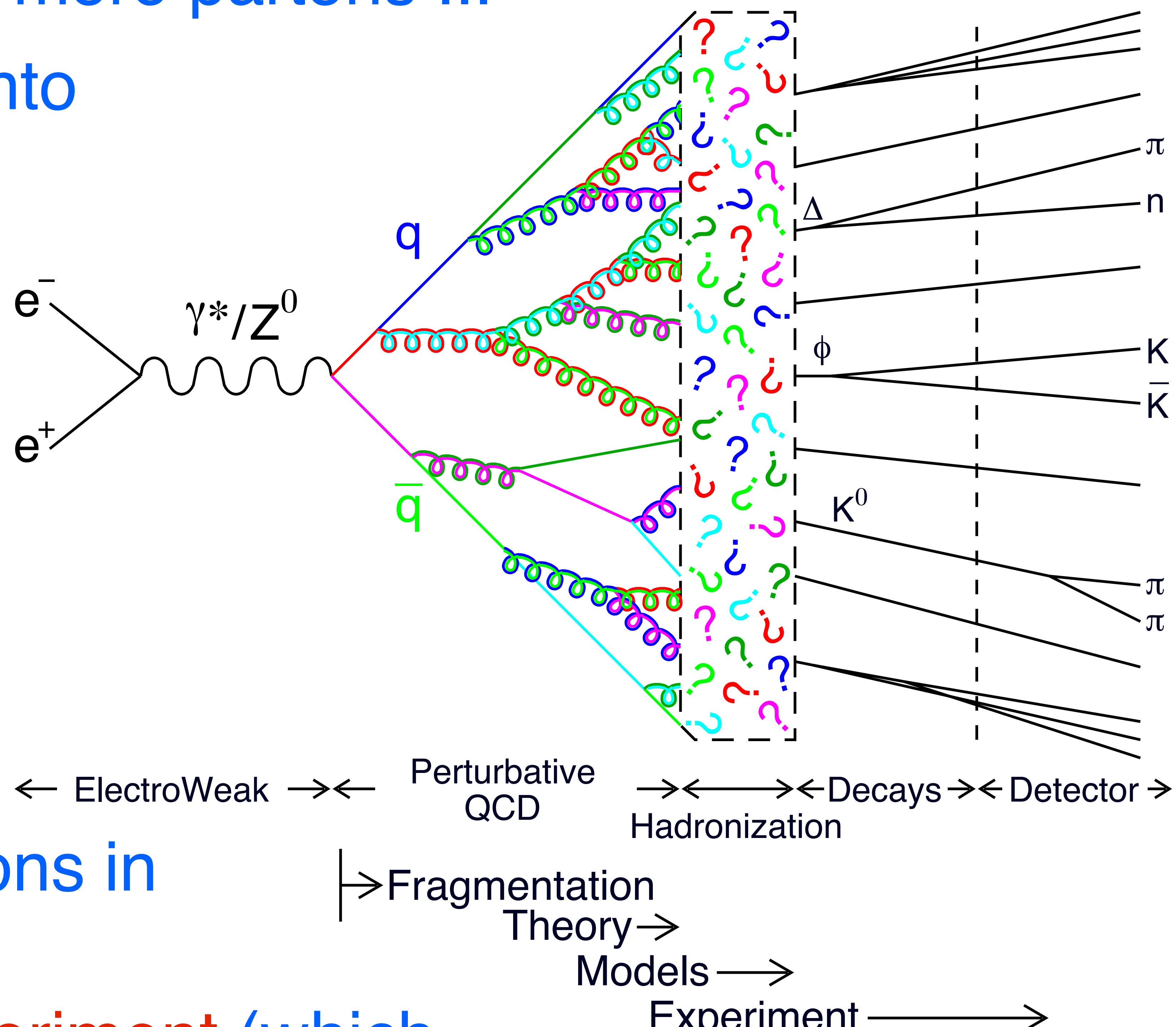


SLD



What do we mean by fragmentation?

- the process by which a (system of) hard quark(s) and/or gluon(s) radiates more partons ...
- ... that combine into hadrons ...
- ... that decay into “stable” particles ...
- ... that can be observed in a detector



- at least 3 definitions in common use
- I will discuss experiment (which tries to push toward the primary level)

Four questions:

- What types of particles are produced? In what ratios?
  - → charged vs. neutral?
  - → ordinary vs. strange/charmed/beautiful?
  - → mesons vs. baryons
  - → relative population of spin states?

- What is their energy/momentum spectrum?
  - → transverse to the jet axis? (~Gaussian, σ = 350 MeV/c)
  - → parallel to the jet axis? (see next slide)

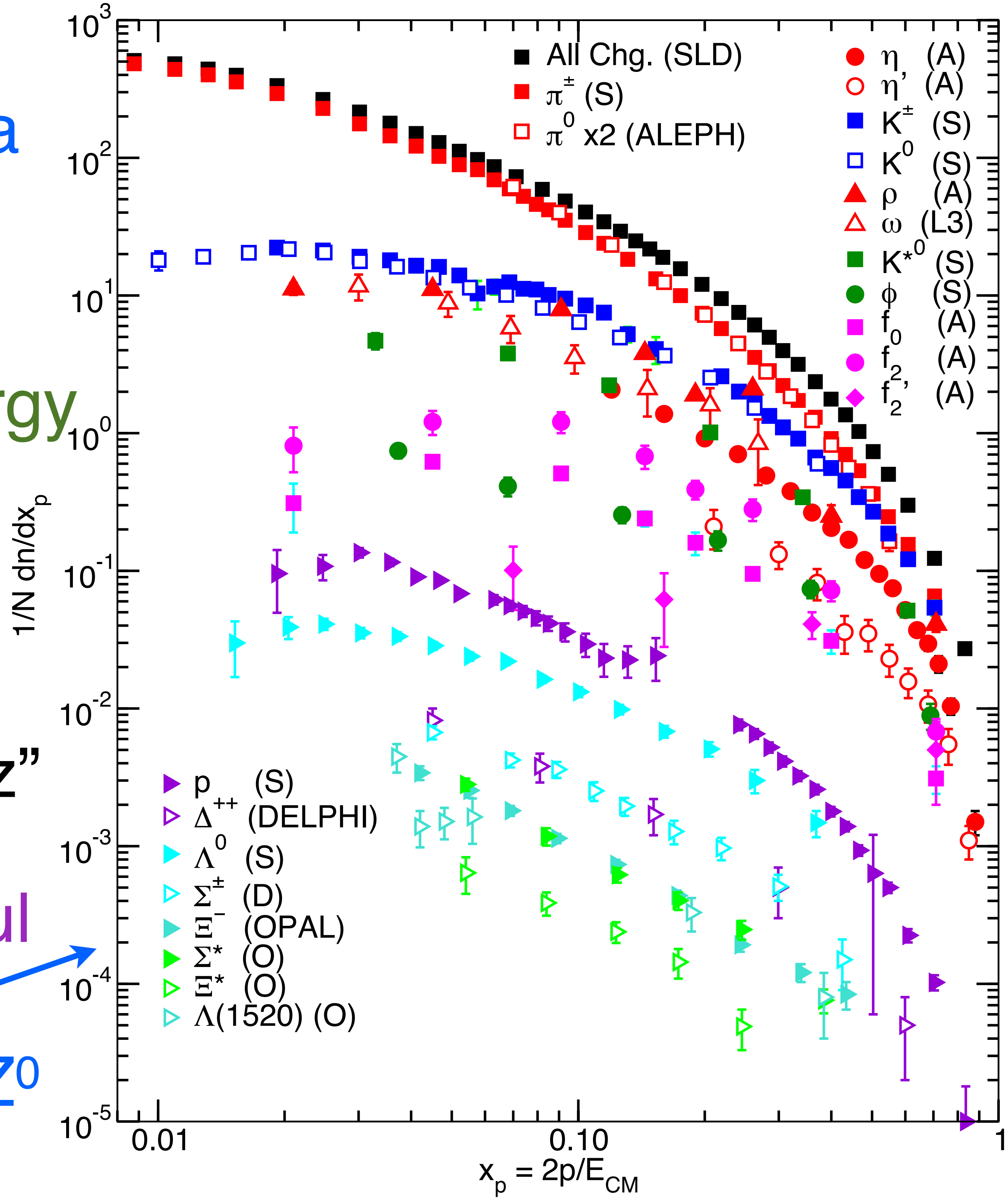
- Are they polarized?

- Are they correlated?

The Fragmentation Function (FF)

- describes the longitudinal or total momentum distribution
- expressed in terms of a scaled variable, e.g.
  - → $x_E = 2E_{hadron} / E_{CM}$, where $E_{CM}/2$ is also the initial quark energy
  - → $x_p = p_{hadron} / p_{max}$, where p_{max} is the kinematic limit for pair production
  - → and several more! "z" has many meanings

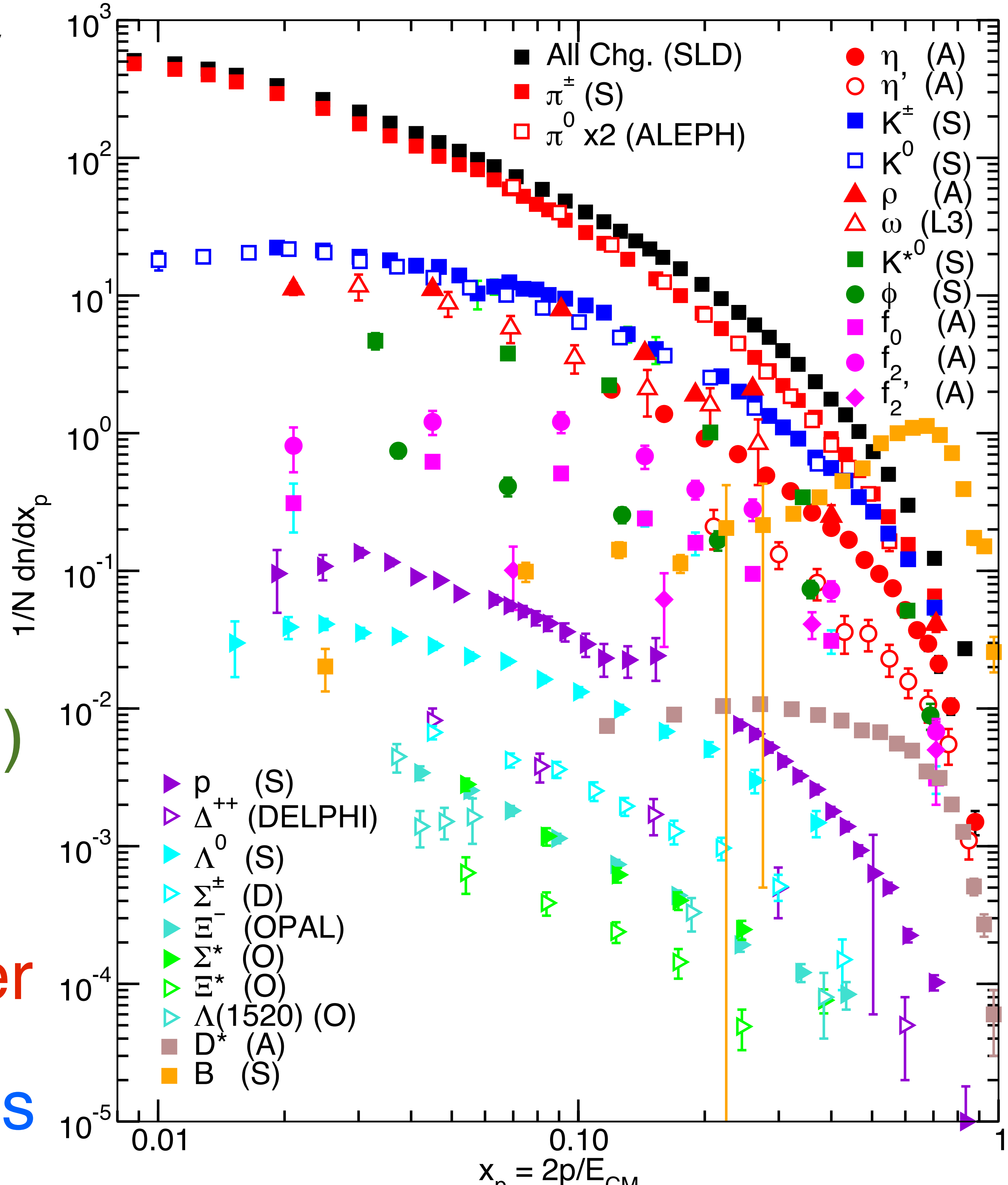
  ⇒ be careful



- some of the measurements at the Z^0
  - → vs. $x_p = 2p_{had} / E_{CM}$

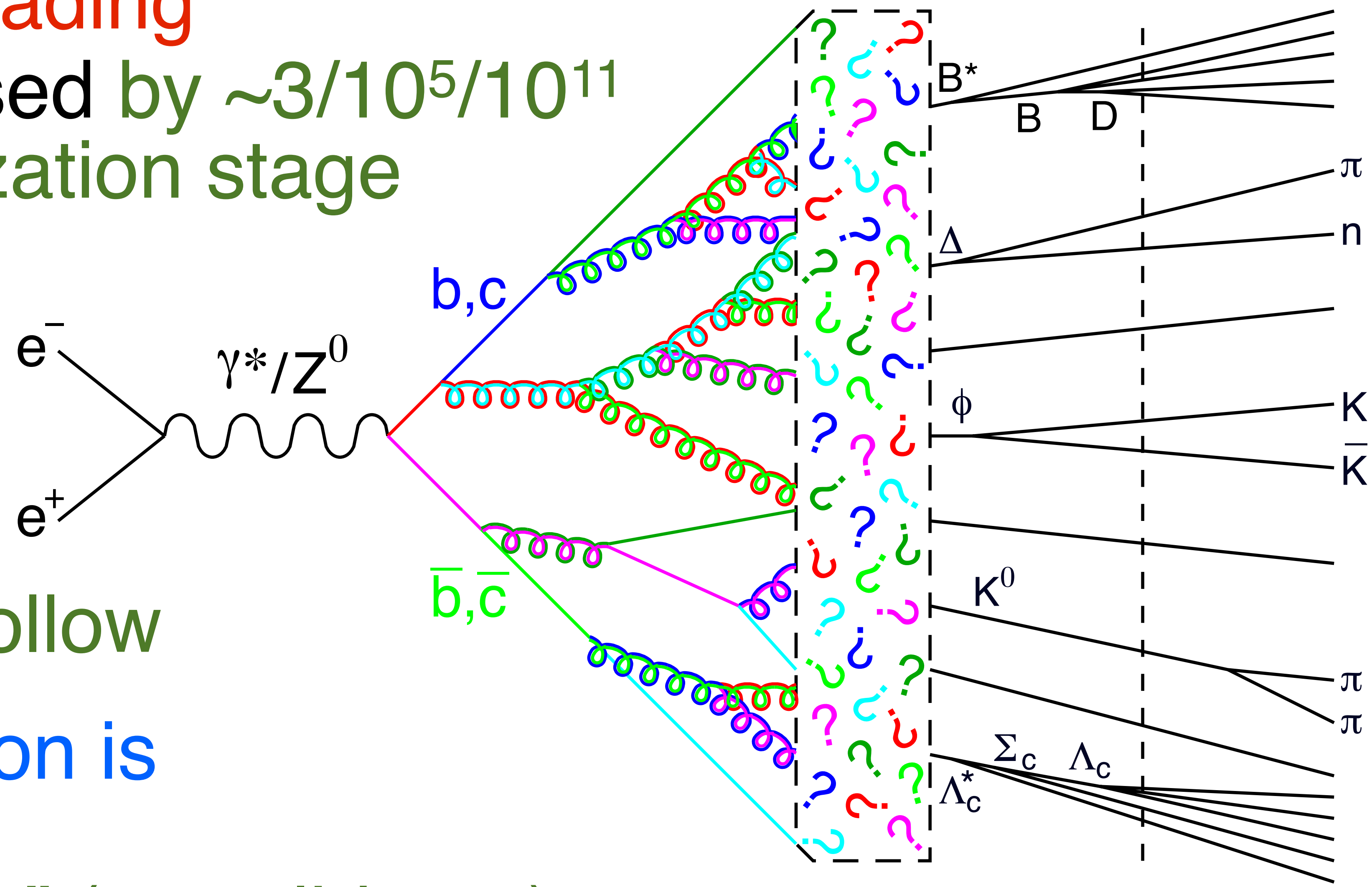
The Fragmentation Function (FF)

- in e^+e^- annihilations, these variables are well defined
  - → clear experimentally
  - → all (final state) radiative corrections included naturally
- modellers use iterative definitions
  - → often using inaccessible variables
  - → ... which don't (quite) work for heavy quarks
- heavy hadron FFs differ in several ways from those of lighter particles



Features of heavy quark fragmentation

- almost entirely leading
  - ➞ s/c/b suppressed by ~3/10^5/10^{11} in the hadronization stage
  - ➞ and produced occasionally in the PQCD stage
  - ➞ see slides to follow

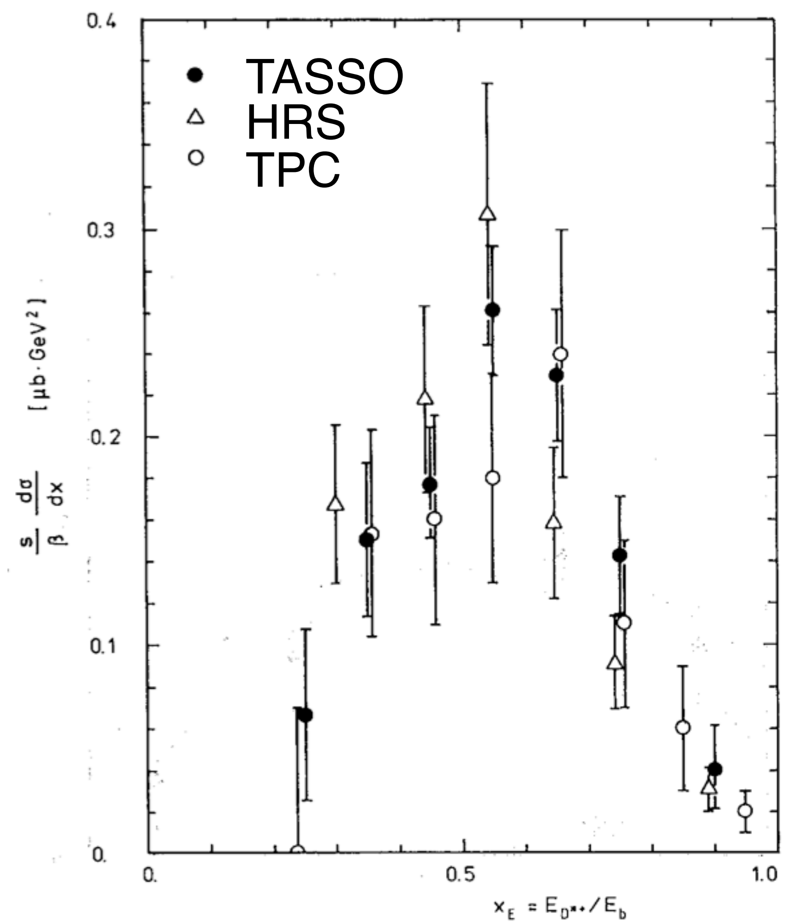


- soft gluon radiation is suppressed
  - ➞ the “dead cone” (see slide 10)
- the leading heavy hadrons are hard, carrying a large fraction of the jet energy
  - ➞ ~50% for charm, 70% for bottom
- the heavy hadrons can be polarized

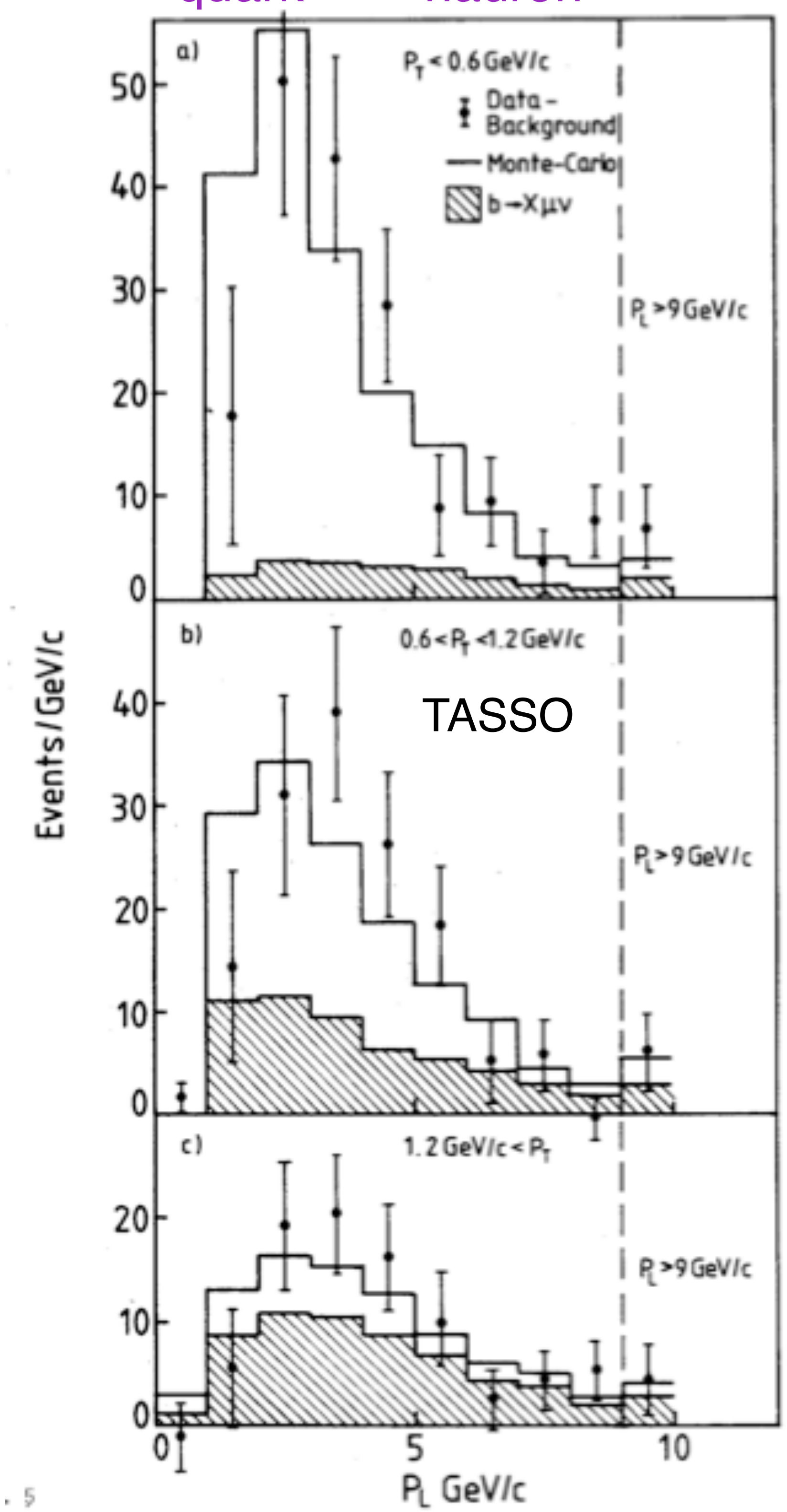
b and c fragmentation at E_{CM}=29-35 GeV

- measurements are difficult
  - → D(B) hadrons decay to ~3(8) particles on average
  - → PEP/PETRA expts. had ~10^4-10^5 events, combinatorics challenging
  - → some D* spectra

E_{quark} / M_{hadron} = 3-9



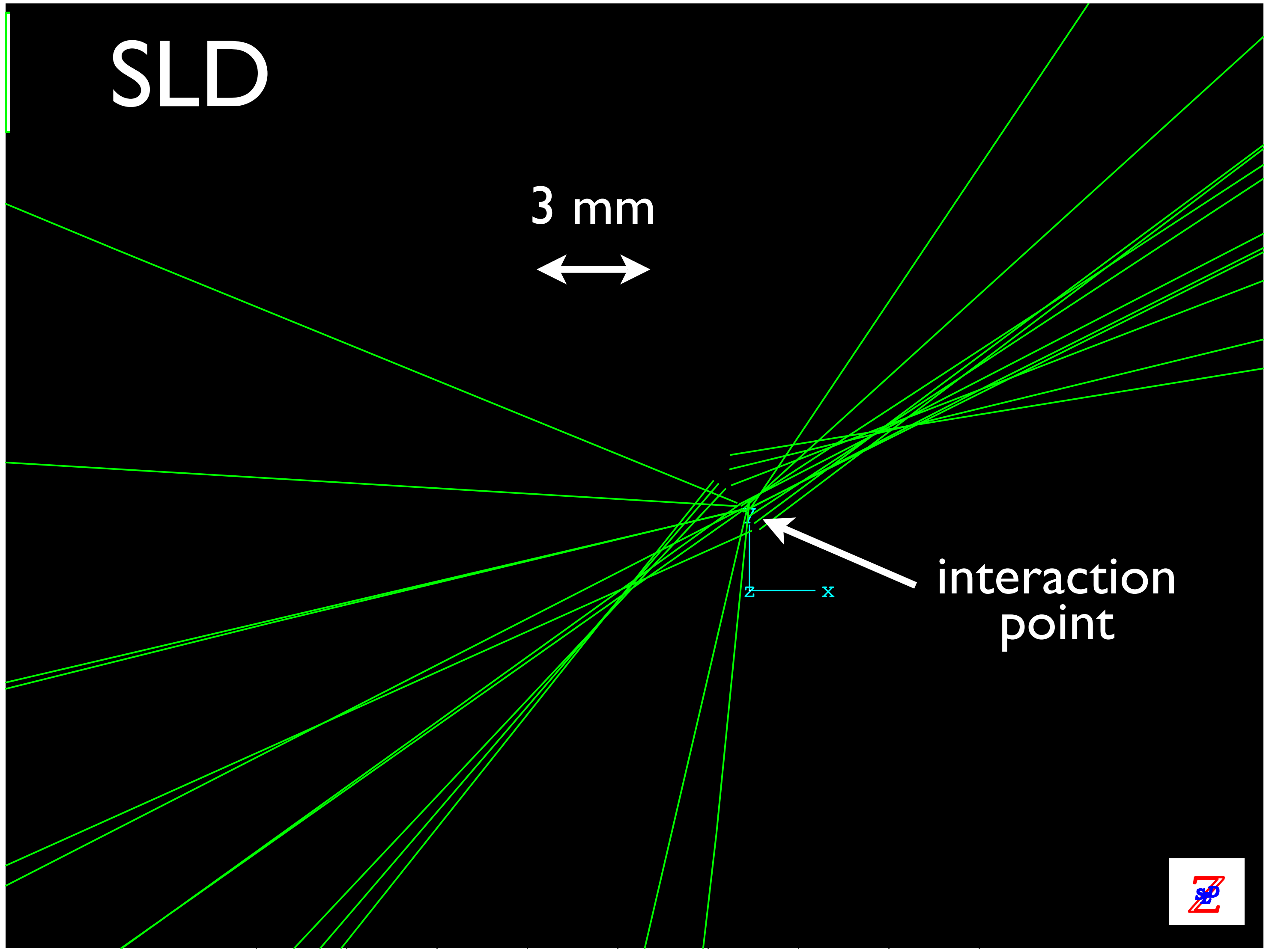
- best information is from leptons
  - → $p_{transverse}$ to jet axis tags B, D decays
  - → p_{total} gives info on the FFs
- results qualitative, model dependent
  - → hard FFs: $<x>_c$ ~ 0.52; $<x>_b$ ~ 0.73
  - → consistent with no nonleading production



b fragmentation at 91.2 GeV

$E_q / M_{had} = 8.6$

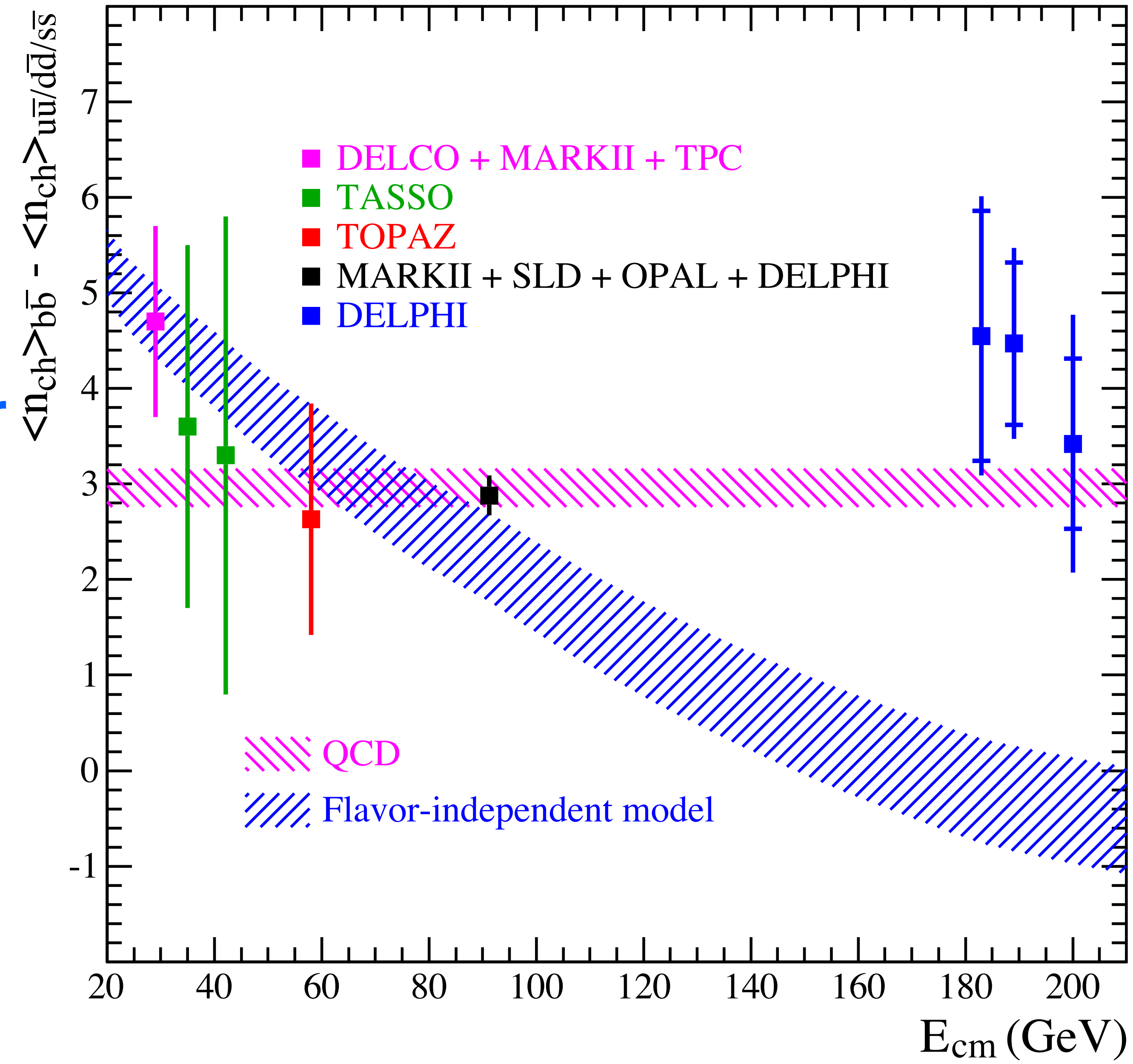
- inclusive tagging of (weakly decaying) B and D hadrons
  - → pioneered at PEP/PETRA experiments
  - → tremendous progress at the Z^0
  - → exploit long b, c lifetimes, plus leptons, ...



- example: inclusive vertex seeds
  - → find displaced vertices using the charged tracks in a jet
  - → use mass, particle content, kinematic constraints, etc. to form discriminating variables
  - → then ...

The dead cone

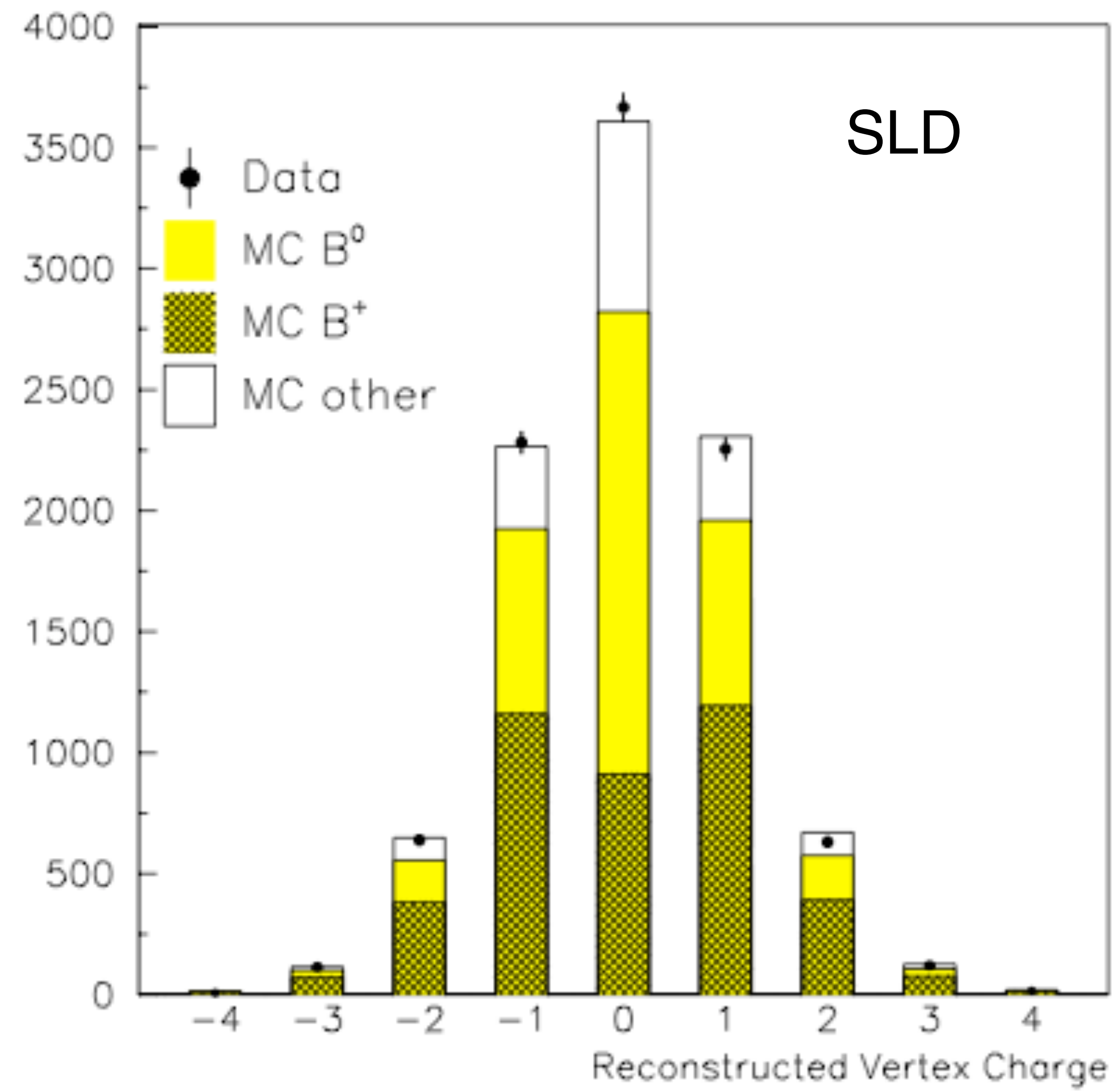
- apply such techniques to tag $b\bar{b}$ and $c\bar{c}$ events
  → measure their average (charged) particle multiplicities
- PQCD: the difference in multiplicity between cc or bb and $u\bar{u}/d\bar{d}/s\bar{s}$ events is independent of E_{CM}
  → this is consistent with the data
  → a model in which the residual jet has the same multiplicity as a light-flavor jet of the same energy is not consistent



- also measured for charm; consistent results
- this can be used to measure the b quark mass (backup)

Relative prod. of weakly decaying B states

- tag the flavor of the B hadron seed
  - ➞ use multiplicity (odd vs. even), total charge
  - ➞ identified $K^{\pm}$, $p/\bar{p}$, $e^{\pm}$, $\mu^{\pm}$
  - ➞ reconstructed $D^{(*)\pm,0}$

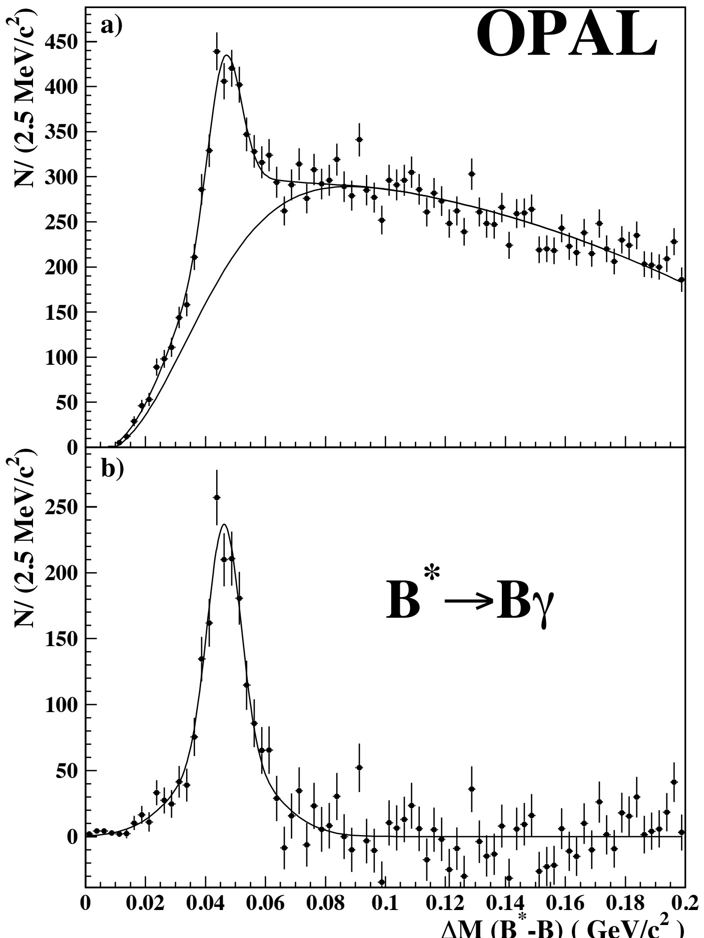


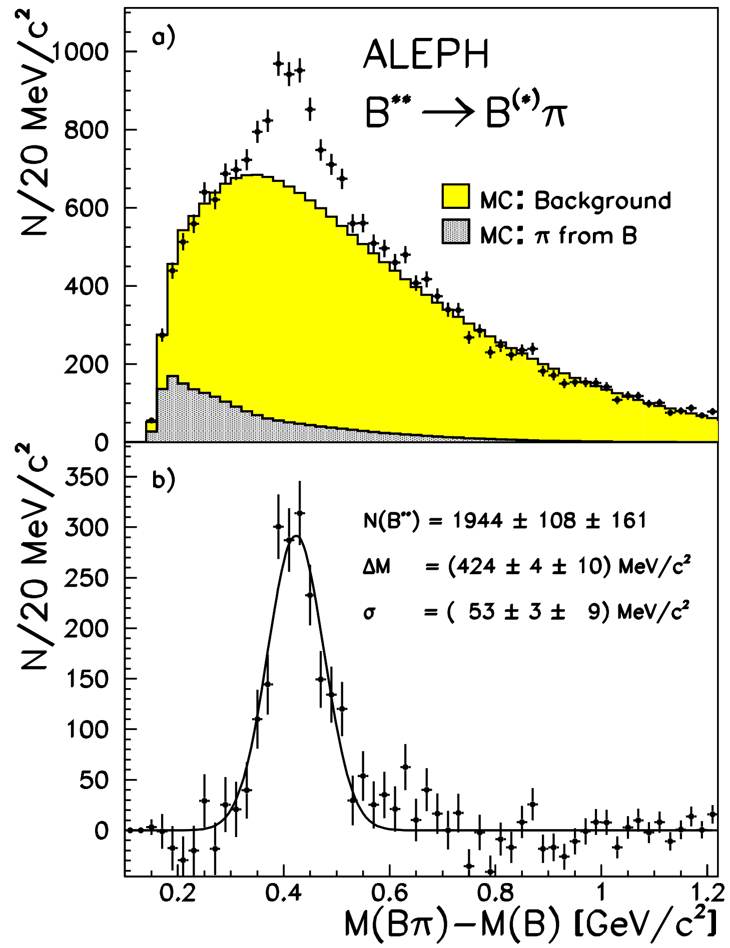
- fractions of weakly decaying B hadrons in Z^0 decays
  - ➞ 0.103±0.018 b-baryons
  - ➞ 0.098±0.012 B_s
  - ➞ 0.399±0.011 B_u and B_d, equal within ~1%
  - ➞ f_{Bs} is less than the expected ~13%
    $\Rightarrow$ will affect s-suppression msmt. in HI collisions
  - ➞ but this is a LEP avg; PDG has different values....

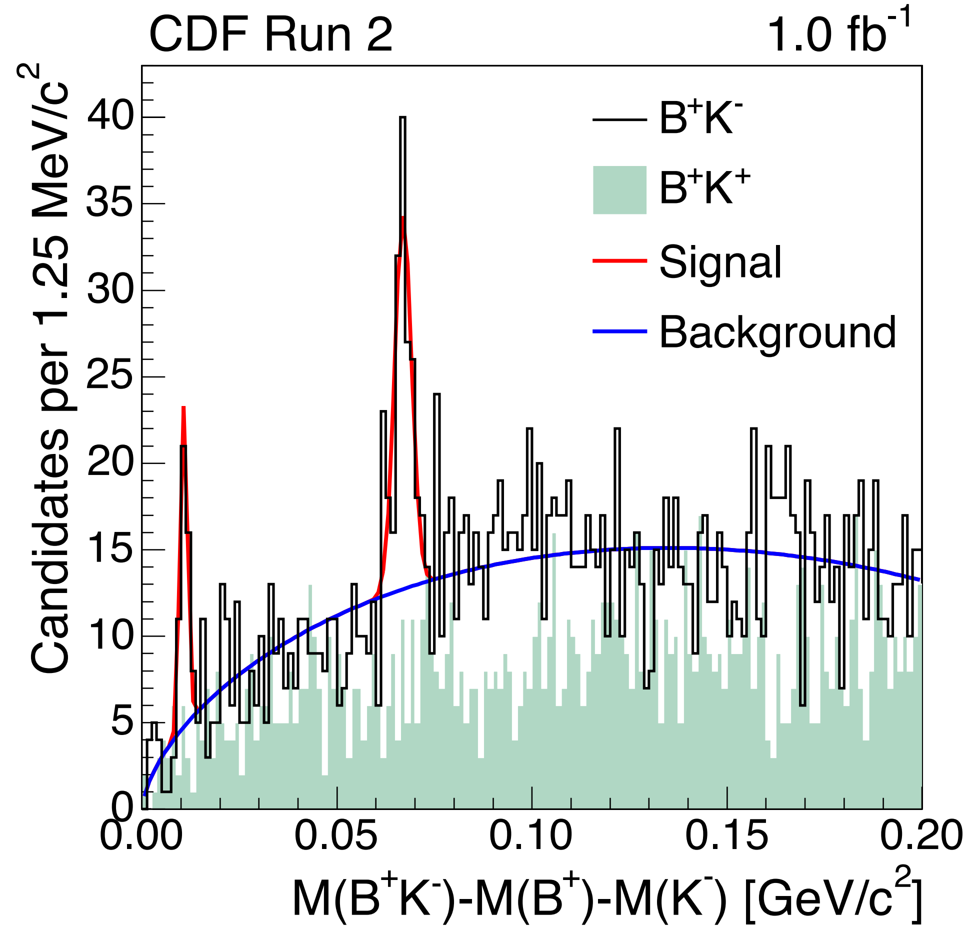
Non-weakly decaying B states

- combine vertex/seed w/ particles from the interaction pt.

  → look at the mass difference distributions; examples:







- the PDG now lists: $B^*(5325)$, $B_1(5721)$, $B_2^*(5747)$; $B_s^*(5415)$, $B_{s1}(5830)$, $B_{s2}^*(5840)$; $\Sigma_b(5812)$, $\Sigma_b^*(5833)$, $\Xi_b(5790)$, $\Omega_b(6071)$

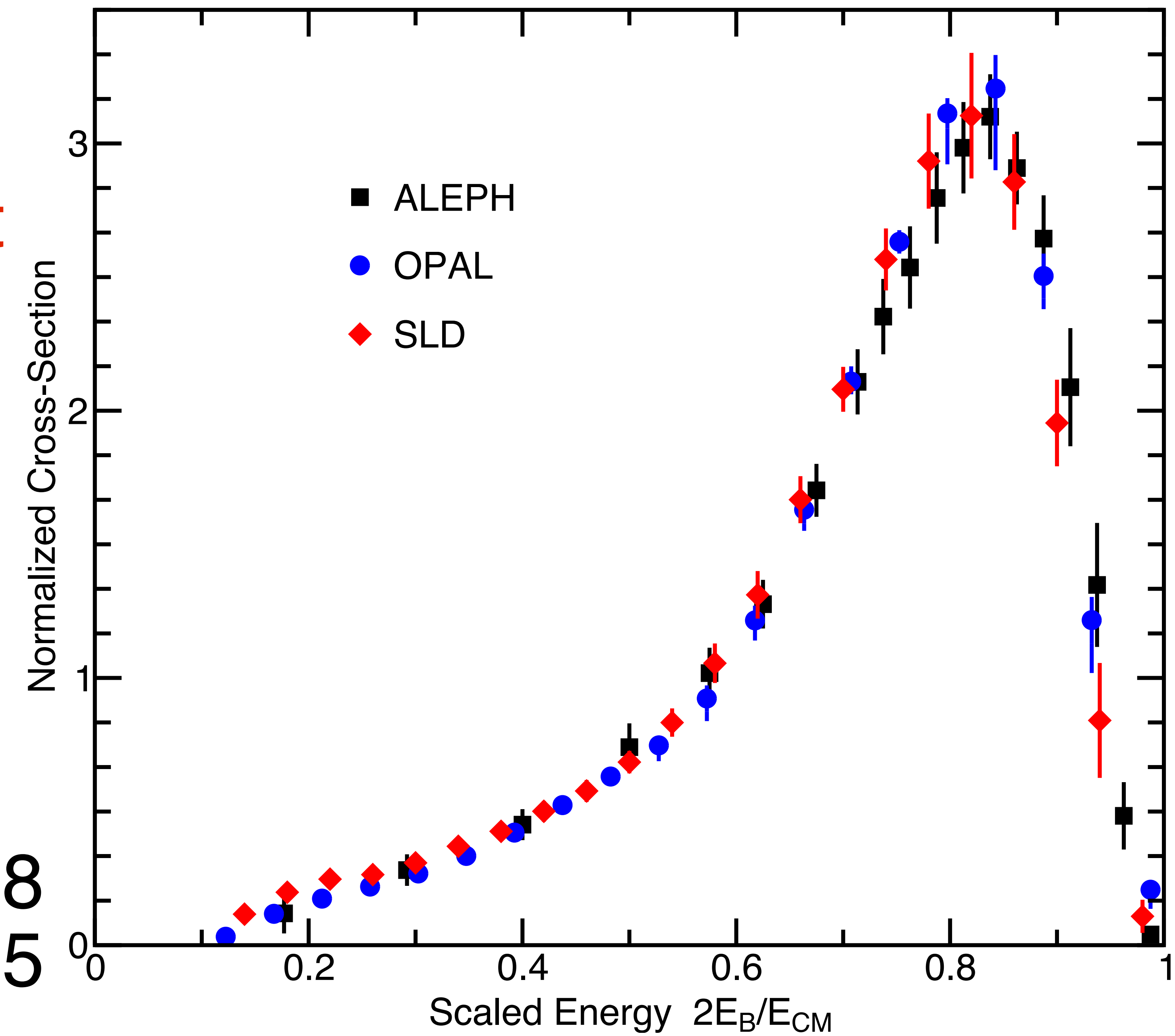
  → evidence for others; presumably many more exist

  → branching fractions, hence production fractions poorly known, B^*:B~0.75 $B_{s1,2}$ → BK explains f_{Bs}

Inclusive (weakly decaying) B hadron FF

- estimate the energy of the B hadron
  - → use measured E/p, kinematic constraints
  - → achieve 10-20% resolution
- this is one of the best measured FFs
  - → covers the full kinematic range
  - → errors must be considered a shape envelope
  - → good precision on

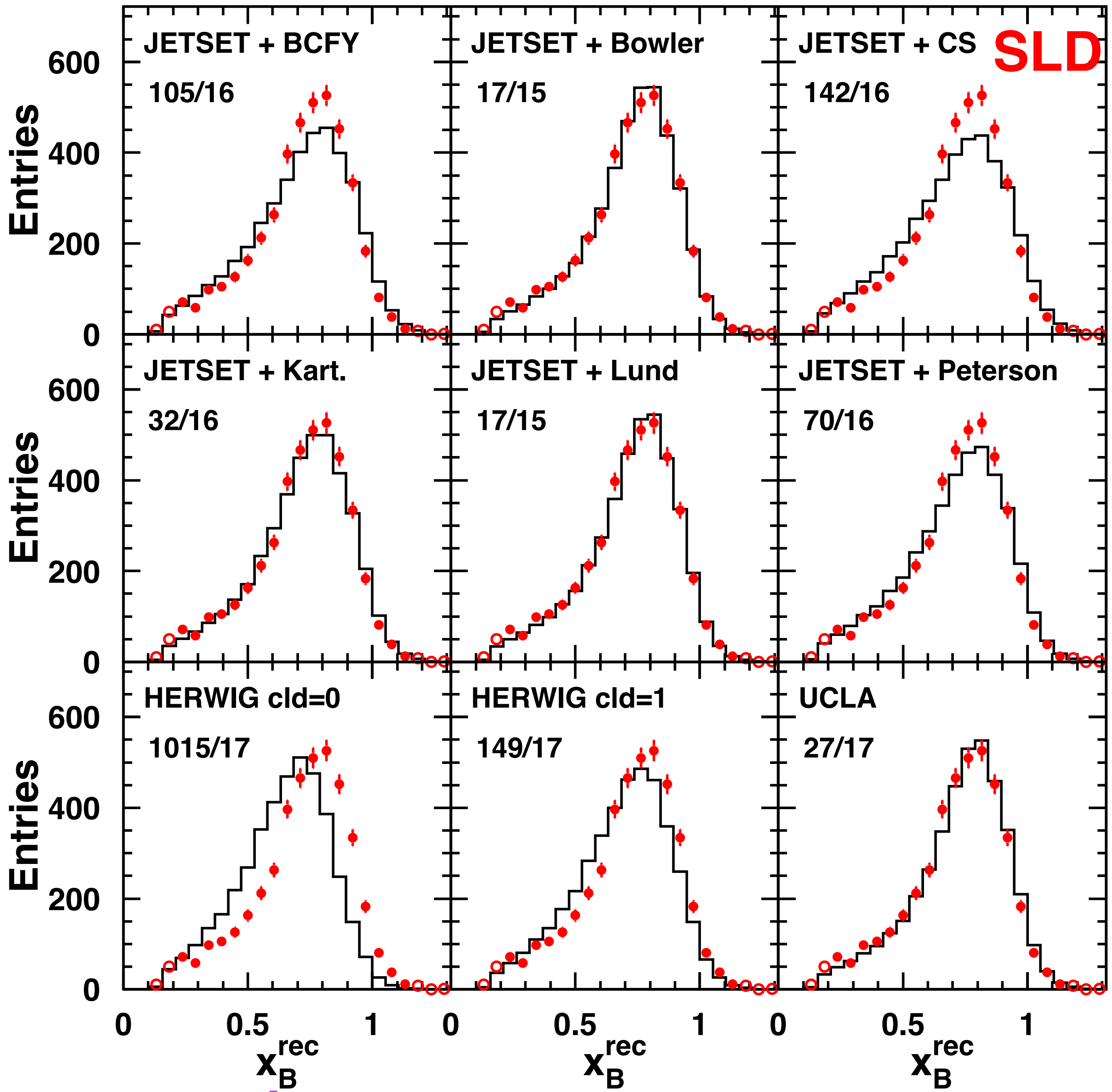
$$\langle x_E \rangle_b = 0.702 \pm 0.008$$
$$(x_E)_{max} = 0.835 \pm 0.005$$



- FFs for a few excited states measured imprecisely
  - → estimate that primary spectrum has $\langle x_E \rangle \sim 0.722$

Tests of heavy quark fragmentation models

- can test models of the shape of the heavy quark FF
  - → some must/should be embedded in a MC generator
  - → best done before data correction
  - → examples from SLD:



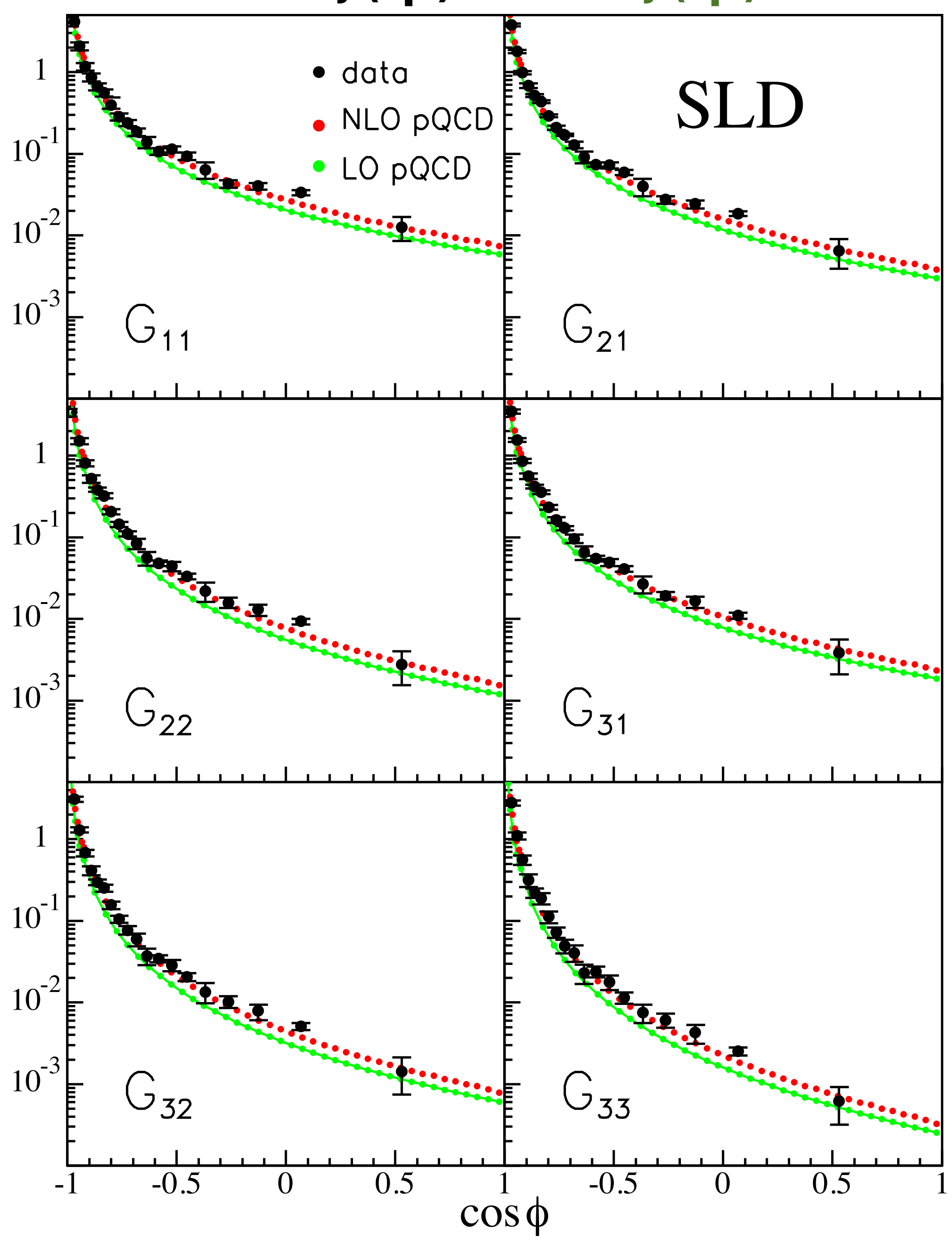
- most models excluded
  - → Bowler, Lund "good"; Kartvelishvili, UCLA may be adequate
  - → similar results from other expts; more examples in backup
  - → these are not default (available) in (m)any generators

⇒ beware if this matters to you!

Two-dimensional B fragmentation

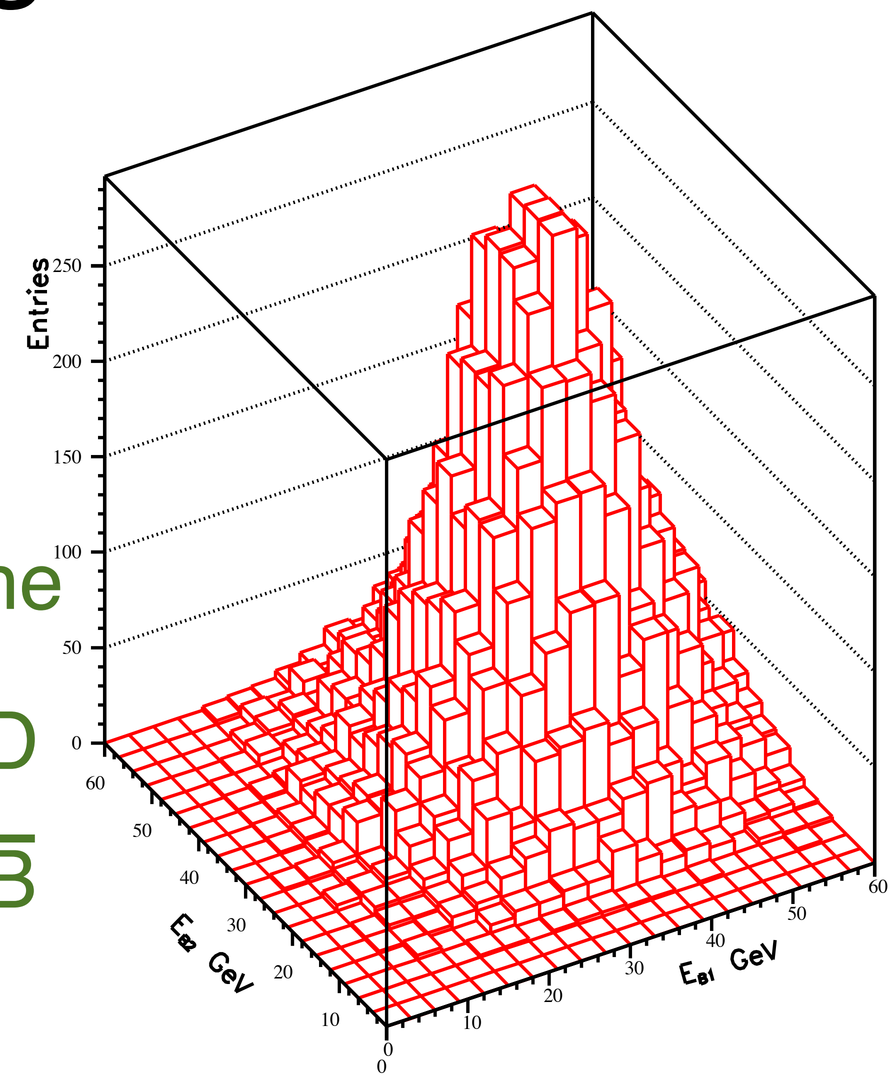
- find two tags in an event
  - → look at 2D FF of the B and $\bar{B}$
  - → use the normalized moments:

$$G_{ij}(\phi) = D_{ij}(\phi) \,/\, D_i D_j\text{, where}$$



D_k is the k^{th} moment of the 1-D FF

$D_{ij}(\phi)$ is the 2-D moment in a bin of the B-$\bar{B}$ opening angle ϕ

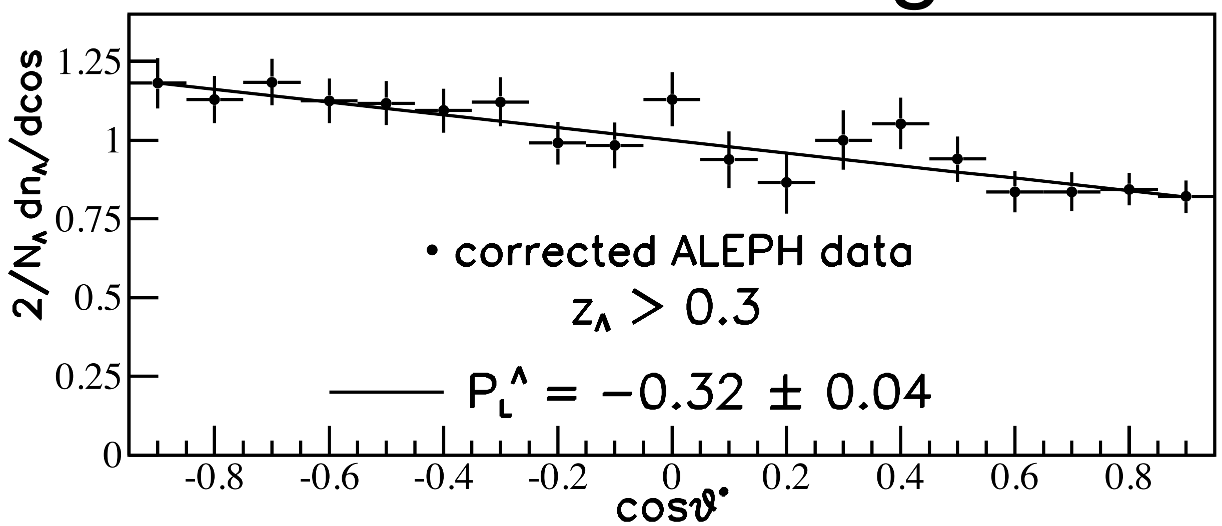


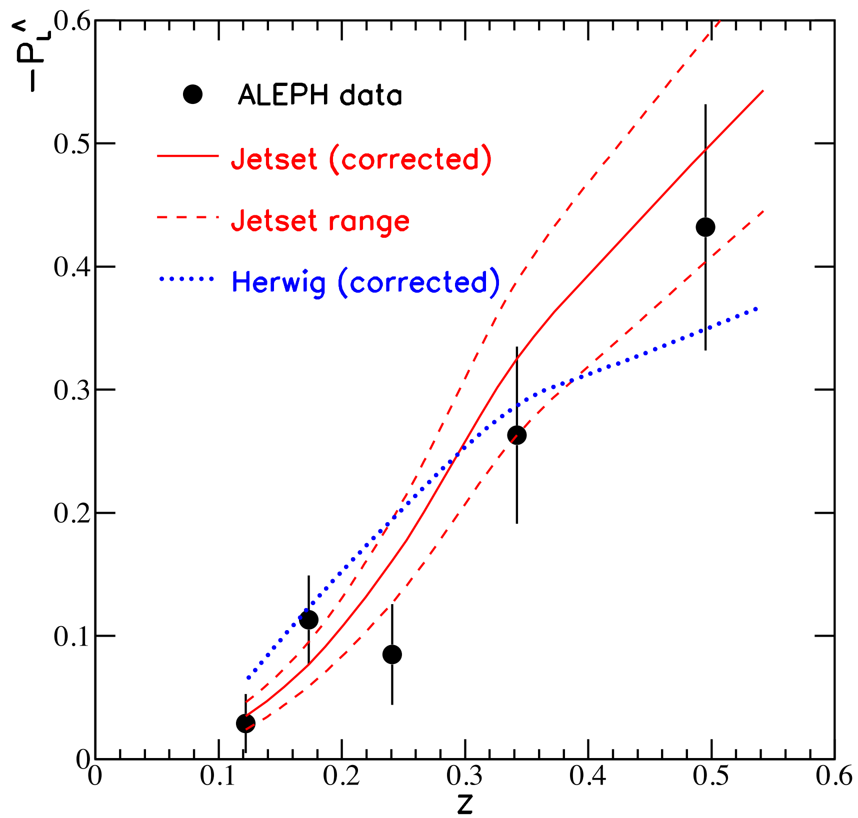
- PQCD explains the data well
  - → next-to-leading order corrections needed
  - → test of factorization, implies the only correlation is due to (hard) gluon radiation

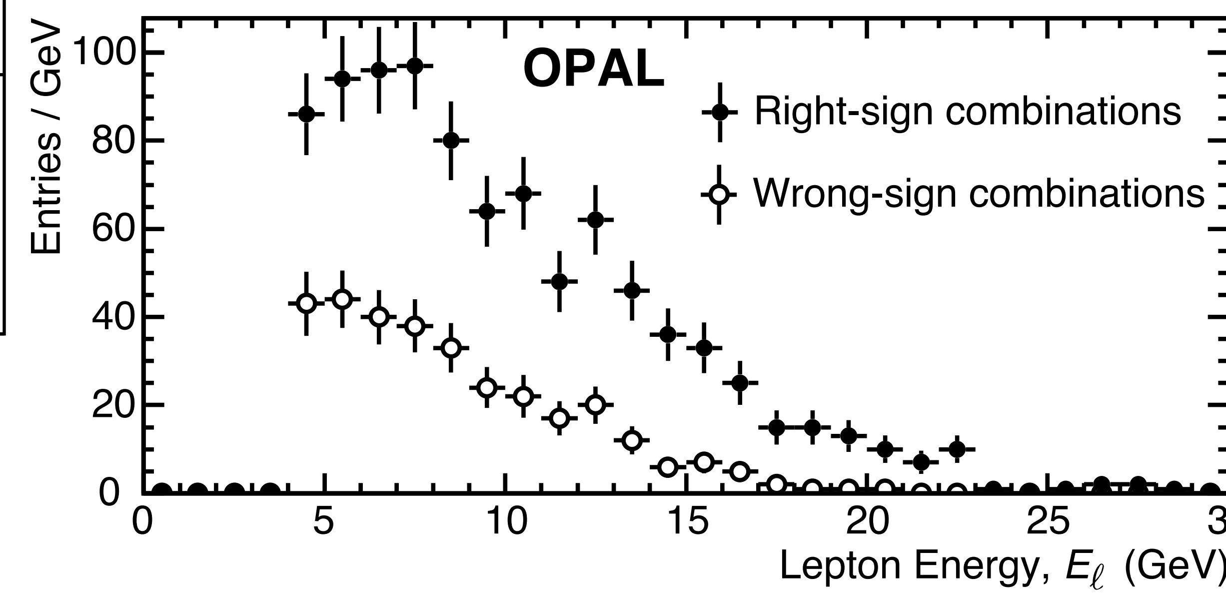
Polarization of B hadrons

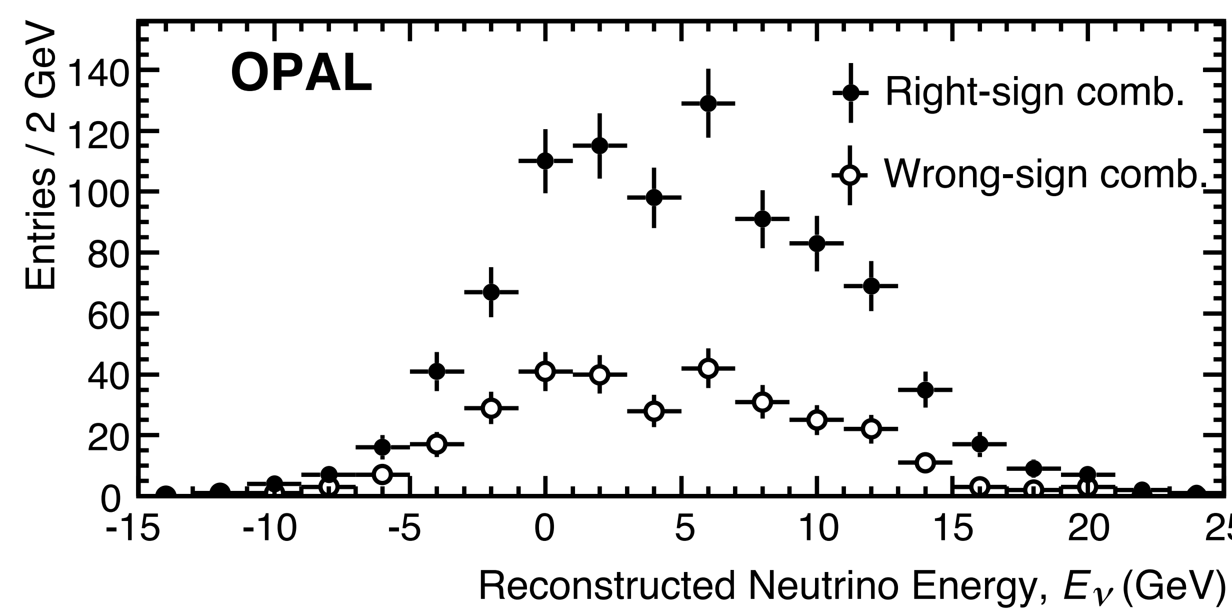
- measure decay angle distributions

  → reconstructed high-x Λ^0 baryons show high longitudinal polarization









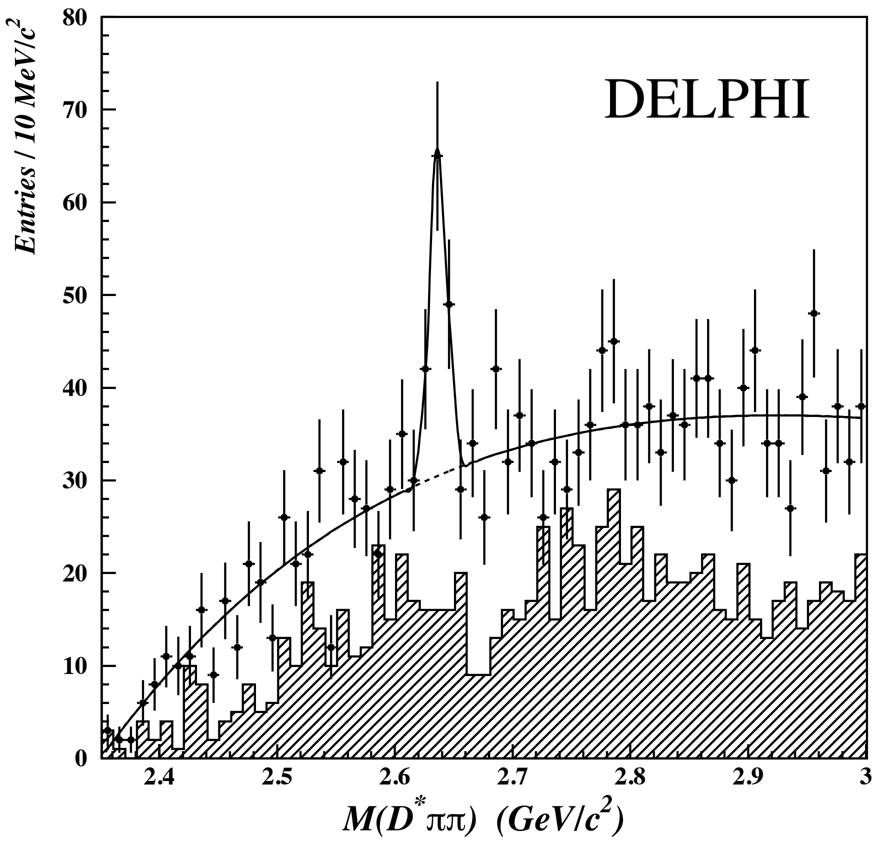
→ evidence that Λ_b are polarized: $-0.45\pm0.16\pm0.08$

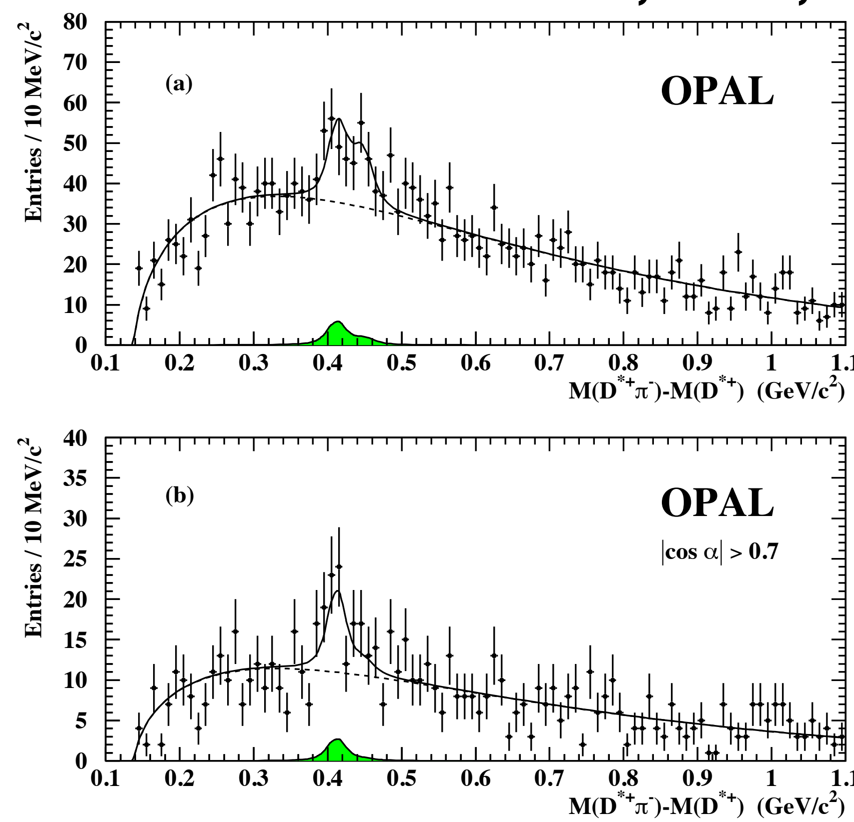
→ no evidence for B* polarization (slide 19)

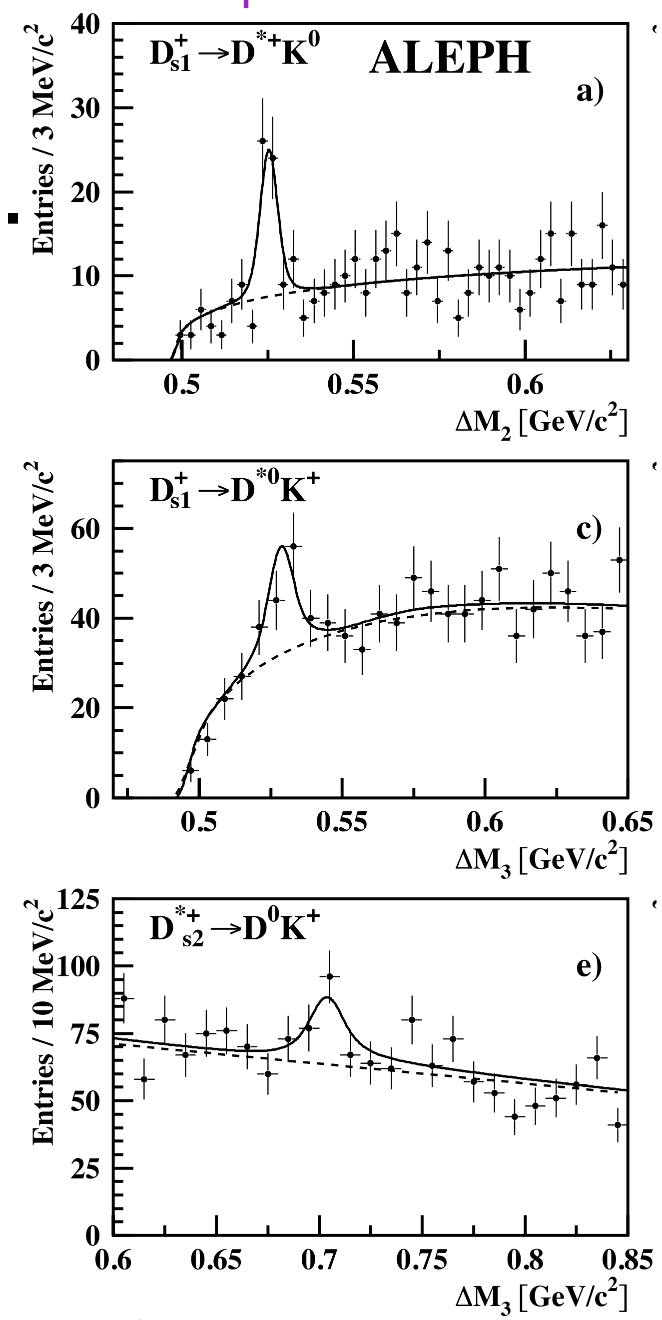
c Fragmentation at 92 GeV

$E_q / M_{had} = 24$

- inclusive tagging not so useful for masses, FFs
  → resort to full reconstruction of D, D*, ...





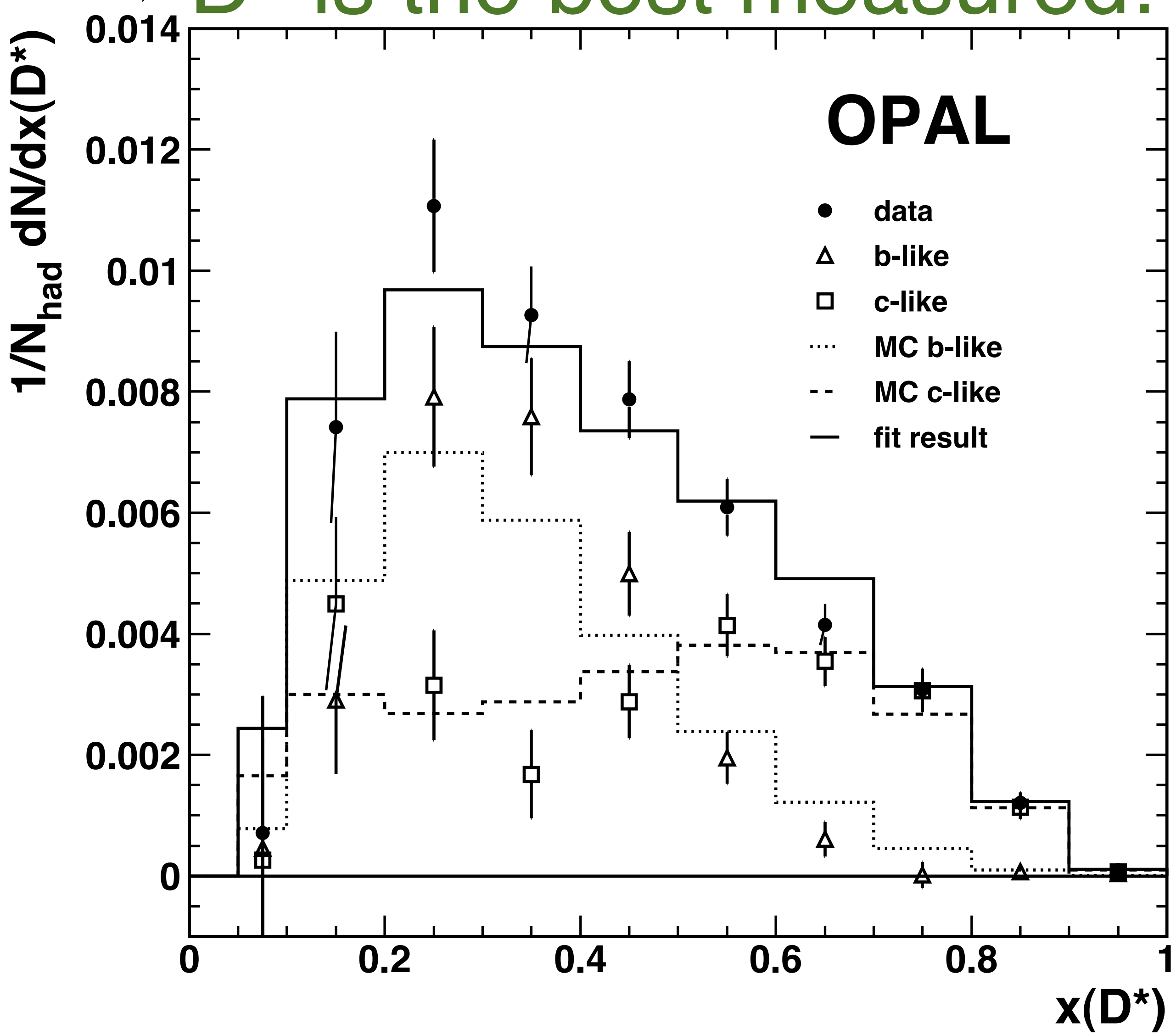


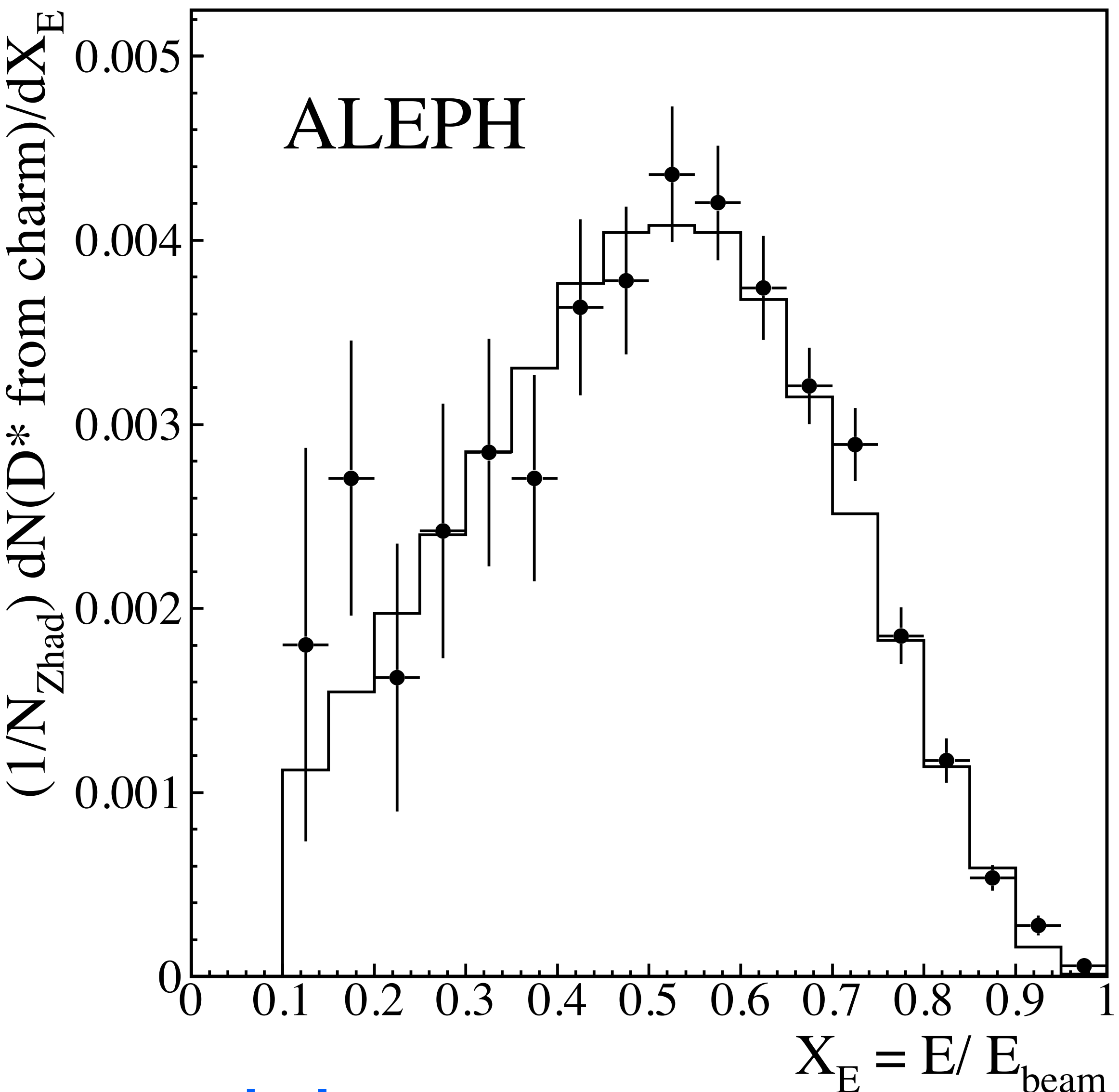
- have observed: $D^*(2010)$, $D_1(2420)$, $D_2^*(2460)$; $D_s^*(2112)$, $D_{s1}(2536)$, $D_{s2}^*(2573)$

- fractions of weakly decaying c-hadrons in Z^0 decays
  → $0.093\pm0.022\ \Lambda_c^+$
  → $0.125\pm0.026\ D_s^+$ $\quad\therefore D_d^0 = 0.547$, which is $> D_d^+$
  → $0.235\pm0.016\ D_d^+$ $\quad$ due to $D^{*+} \to D_d^0\,\pi$ decays

The D* fragmentation function

- E, p measured well, but huge B decay backgrounds
  → FF measurements are severely statistics limited
  → reconstruct D mesons, use $c\bar{c}$ and $b\bar{b}$ event tags
  → D* is the best measured:

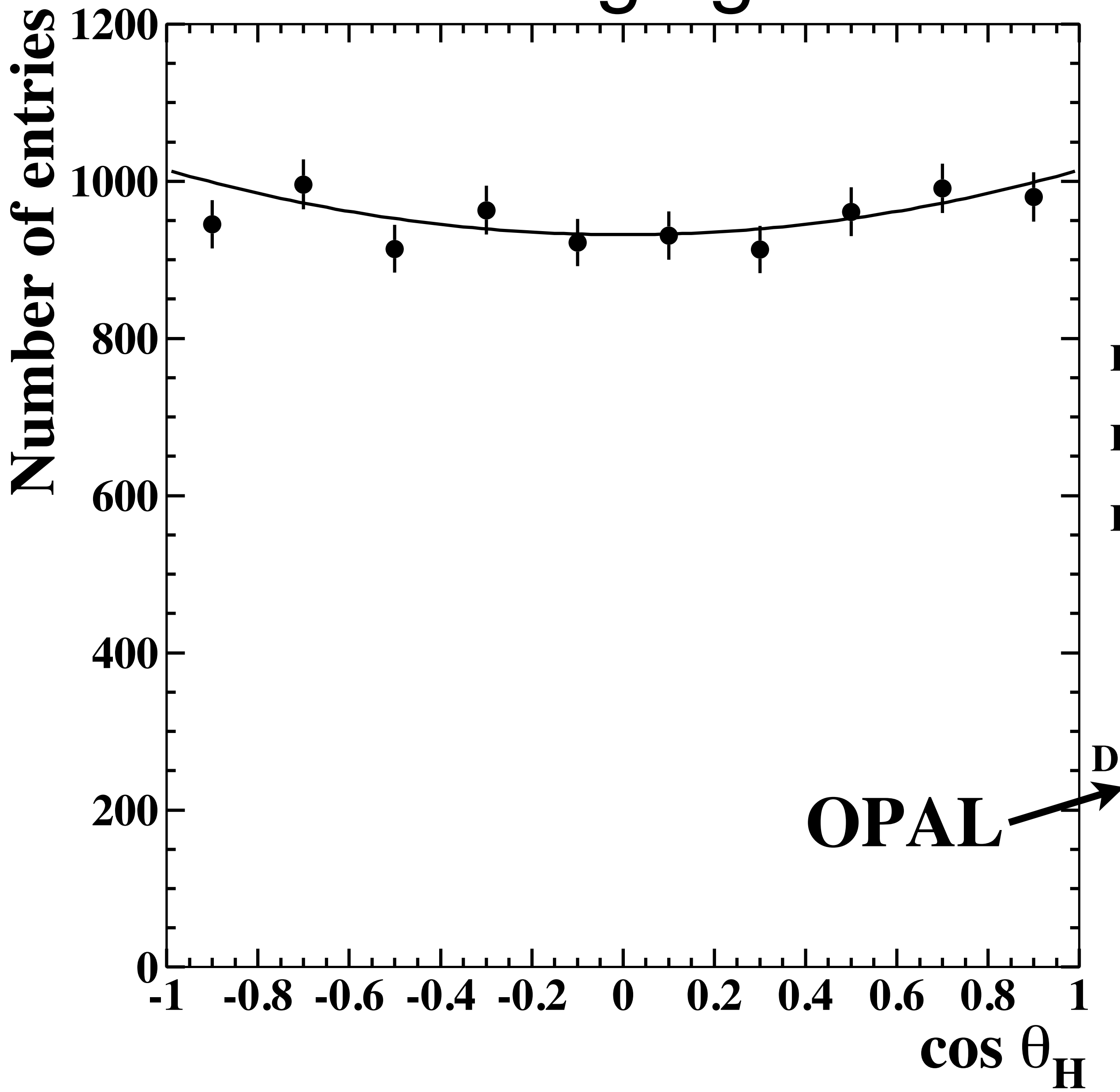


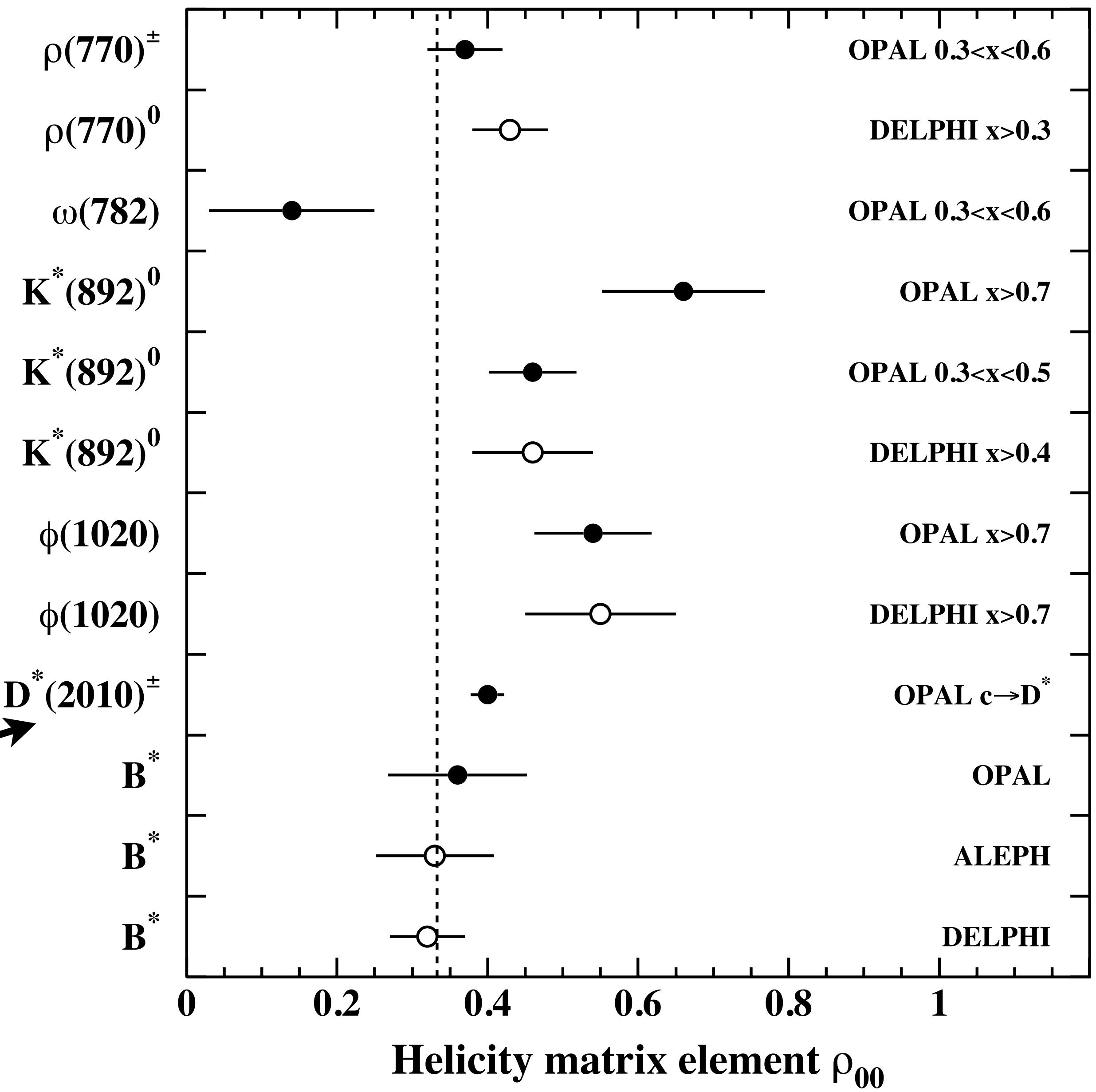


- not possible to make rigorous model tests
  → $\langle x_E \rangle_{D^*} = 0.484 \pm 0.008$ ... plus model/shape dep.

Spin-alignment of vector mesons

- can also measure angular distributions very well
  → still challenging statistically at high momentum

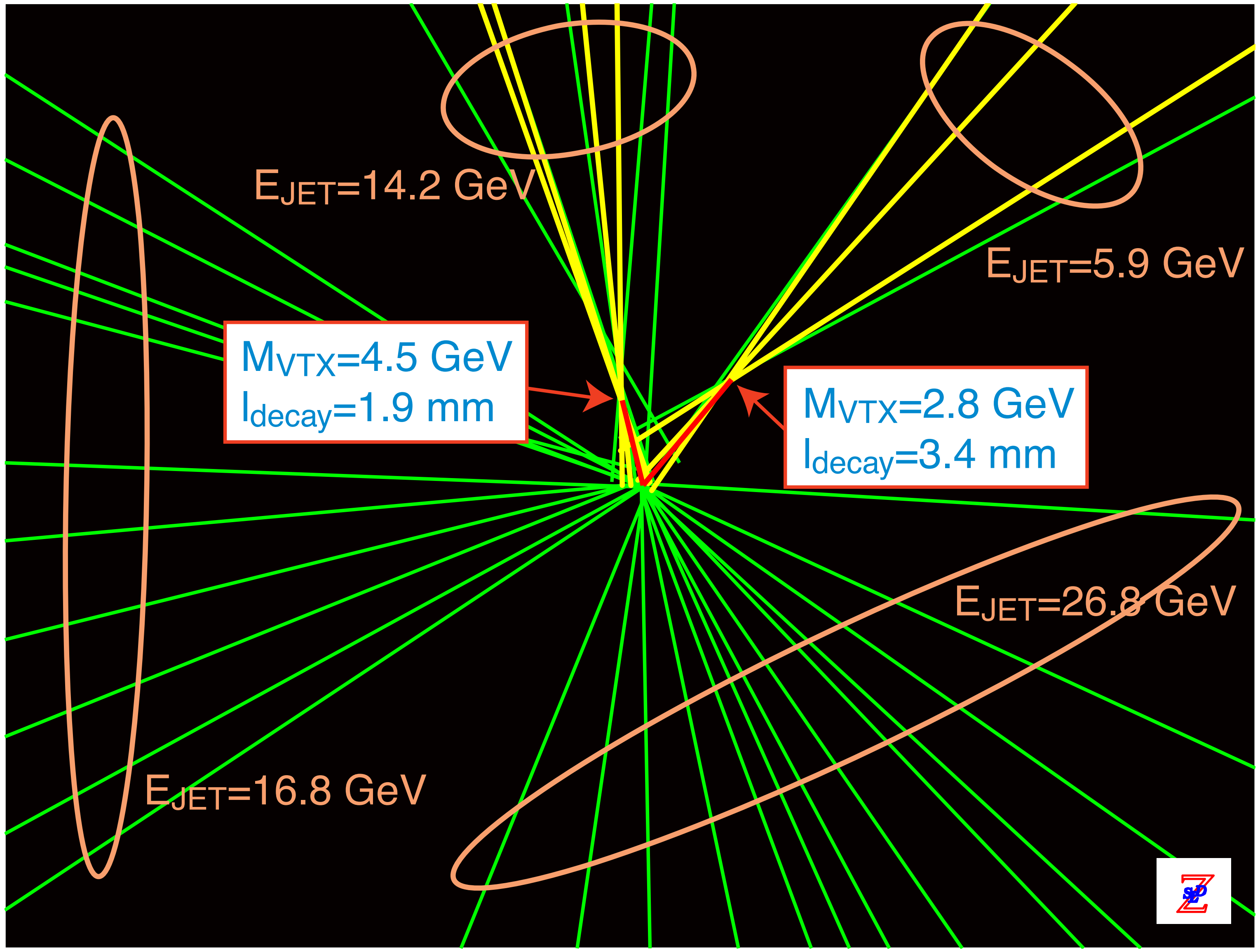




- D* spin alignment is small
  → B* consistent with zero
  → but several lighter mesons show higher values

Gluon splitting into $c\bar{c}$, $b\bar{b}$ pairs

- look for pairs of low-E $D^{(*)}$ or B tags in 3- or 4-jet events
  → some clean evts; a candidate from SLD:

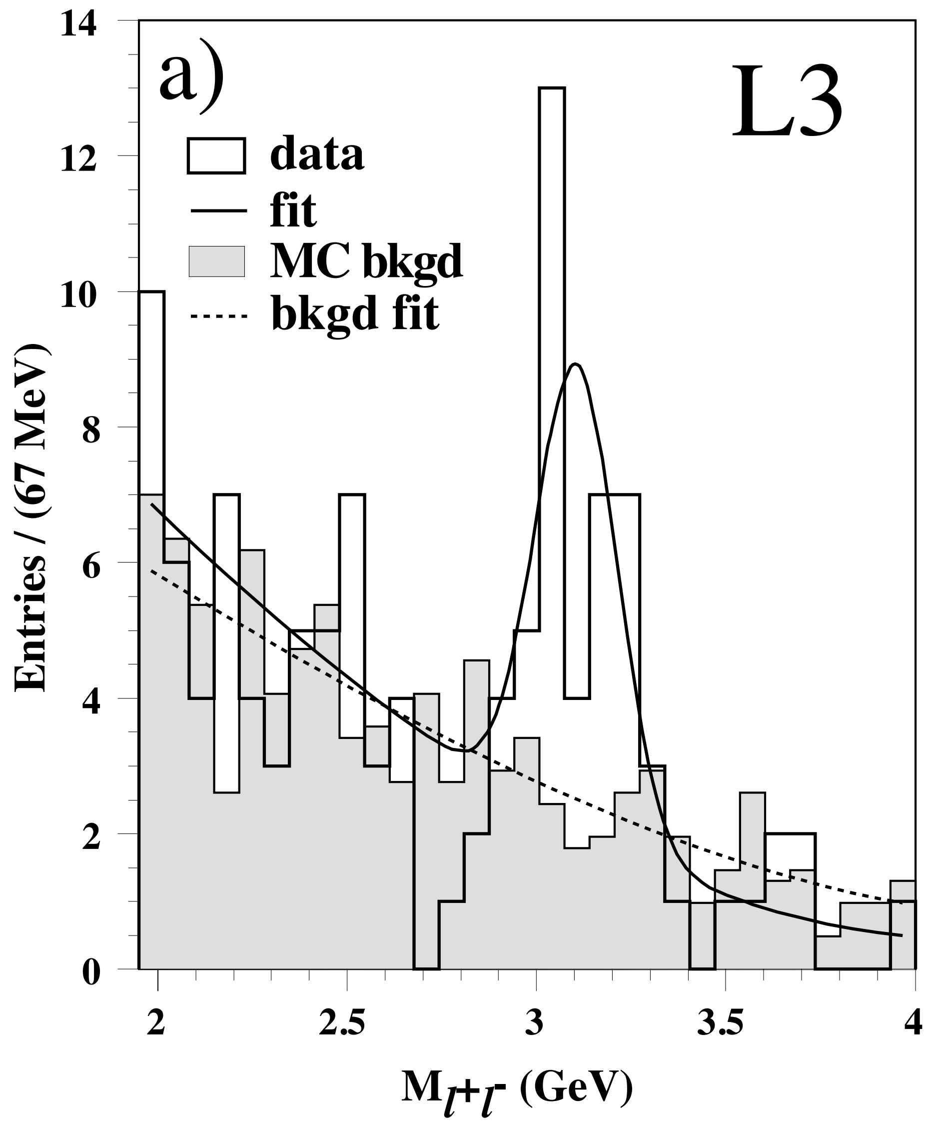


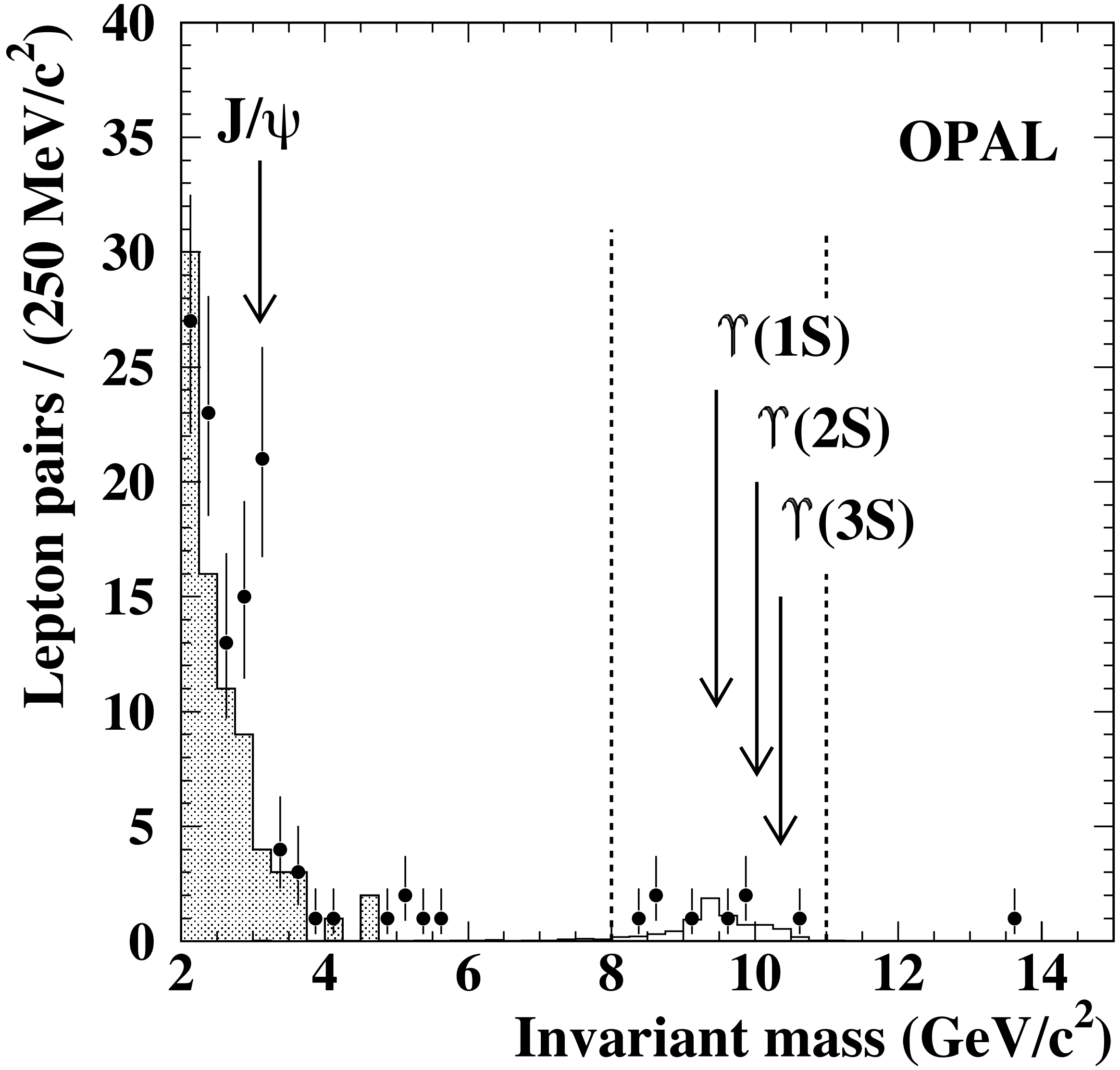
- jet energies and angles consistent with PQCD predictions
  → "secondary" $c\bar{c}$ in 2.96±0.38% $b\bar{b}$ in 0.25±0.05% of events

- but rates are ~2x higher than initial predictions
  → implications for $c\bar{c}/b\bar{b}$ production in $p\bar{p}$ collisions
  ⇒ and heavy ion collisions?
  → $c\bar{c}/b\bar{b}$ production in hadronization <~ 0.5/0.3%

Charmonium and Bottomonium

- reconstruct J/ψ, ψ′ and ϒ candidates
  → could be from gluon splitting or hadronization





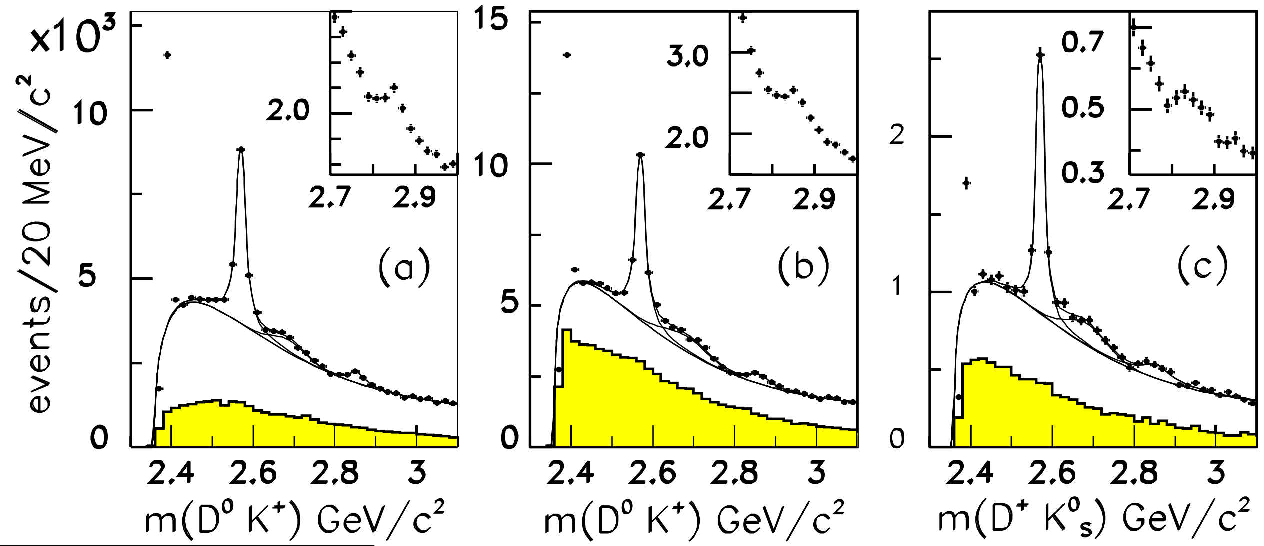
- rates are very low, spectra are very soft
  → consistent with gluon splitting
  → $c\bar{c}/b\bar{b}$ production in hadronization <~ 0.1/0.03%

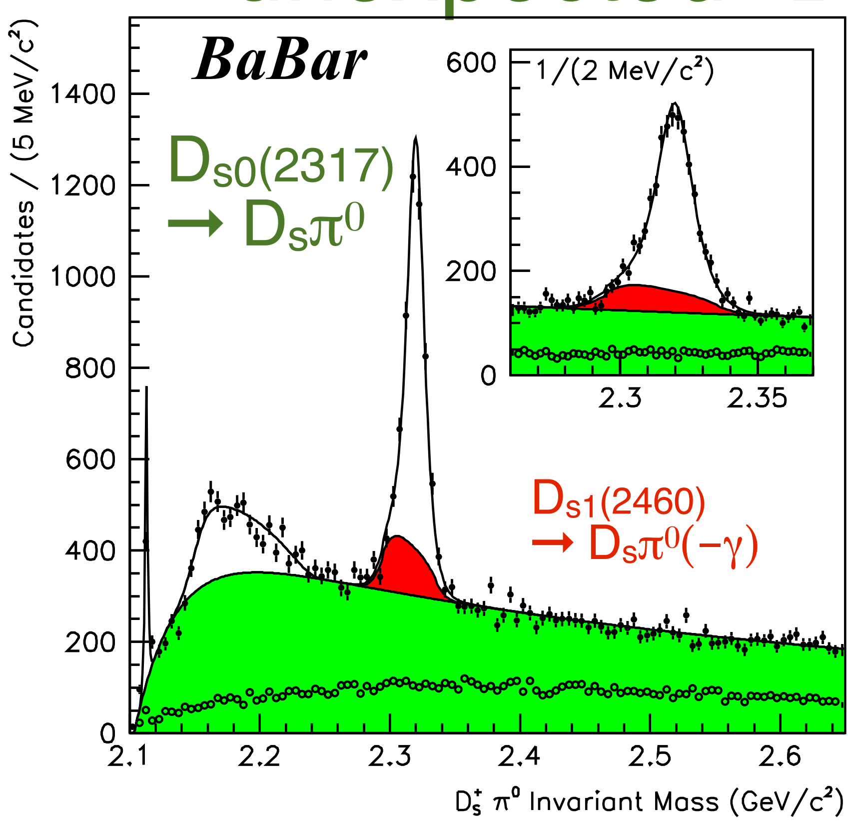
c Fragmentation at 10.6 GeV

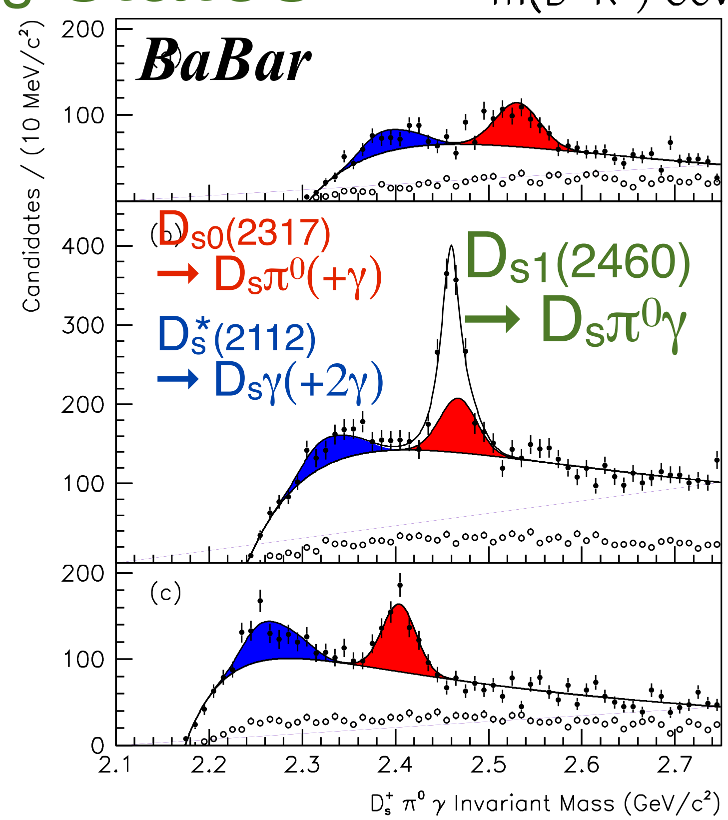
$E_q / M_{had} = 2.8$

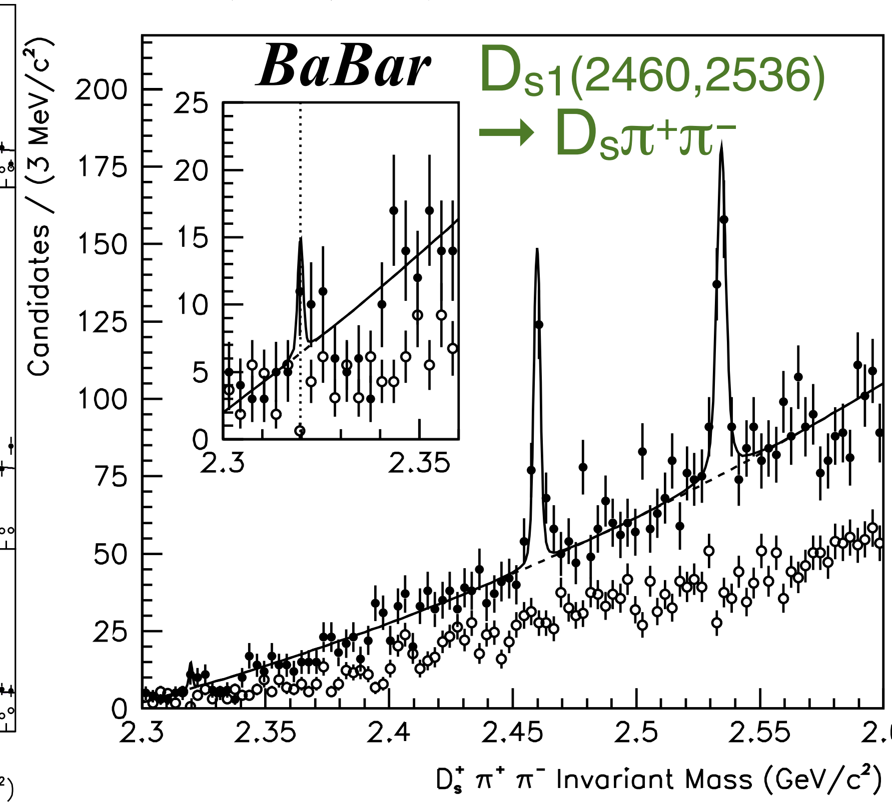
- experiments here have very high statistics
  - → ARGUS, CLEO 10^7, 10^8 events
  - → Belle, BaBar 10^9 evts
- can therefore reconstruct many higher states
  - → including some "unexpected" D_s states

$D_{s2,J}(2573,2860) \rightarrow D^0K^+$



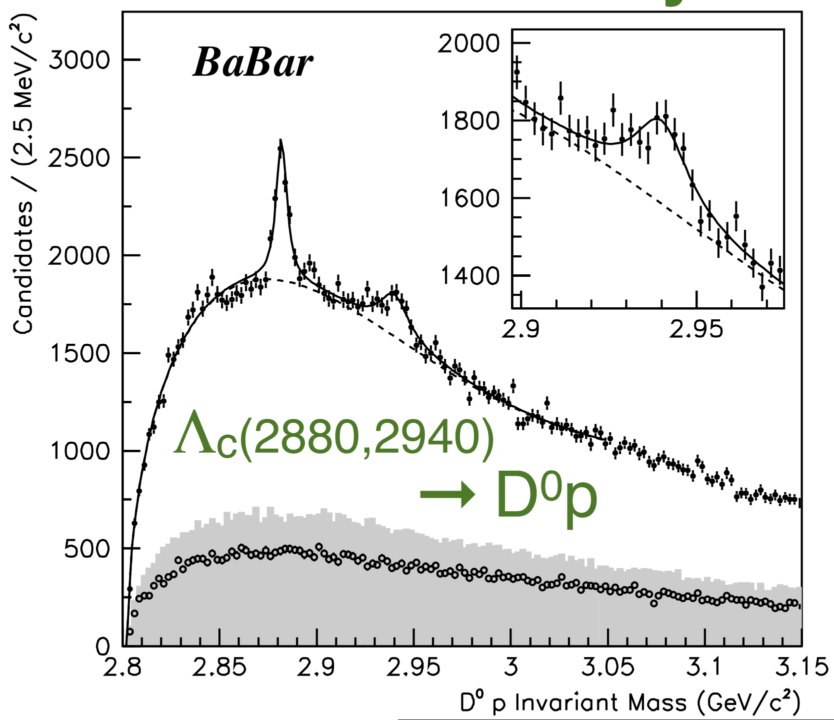


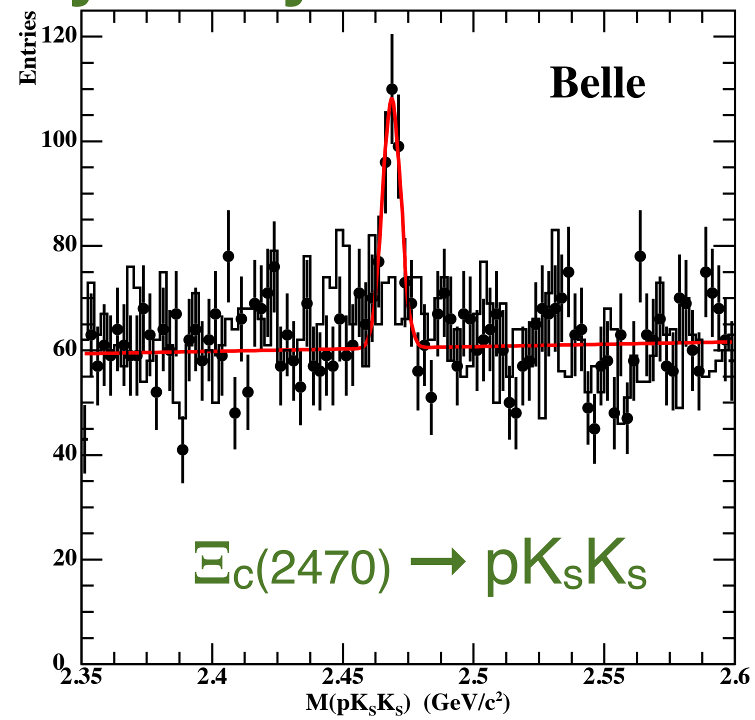


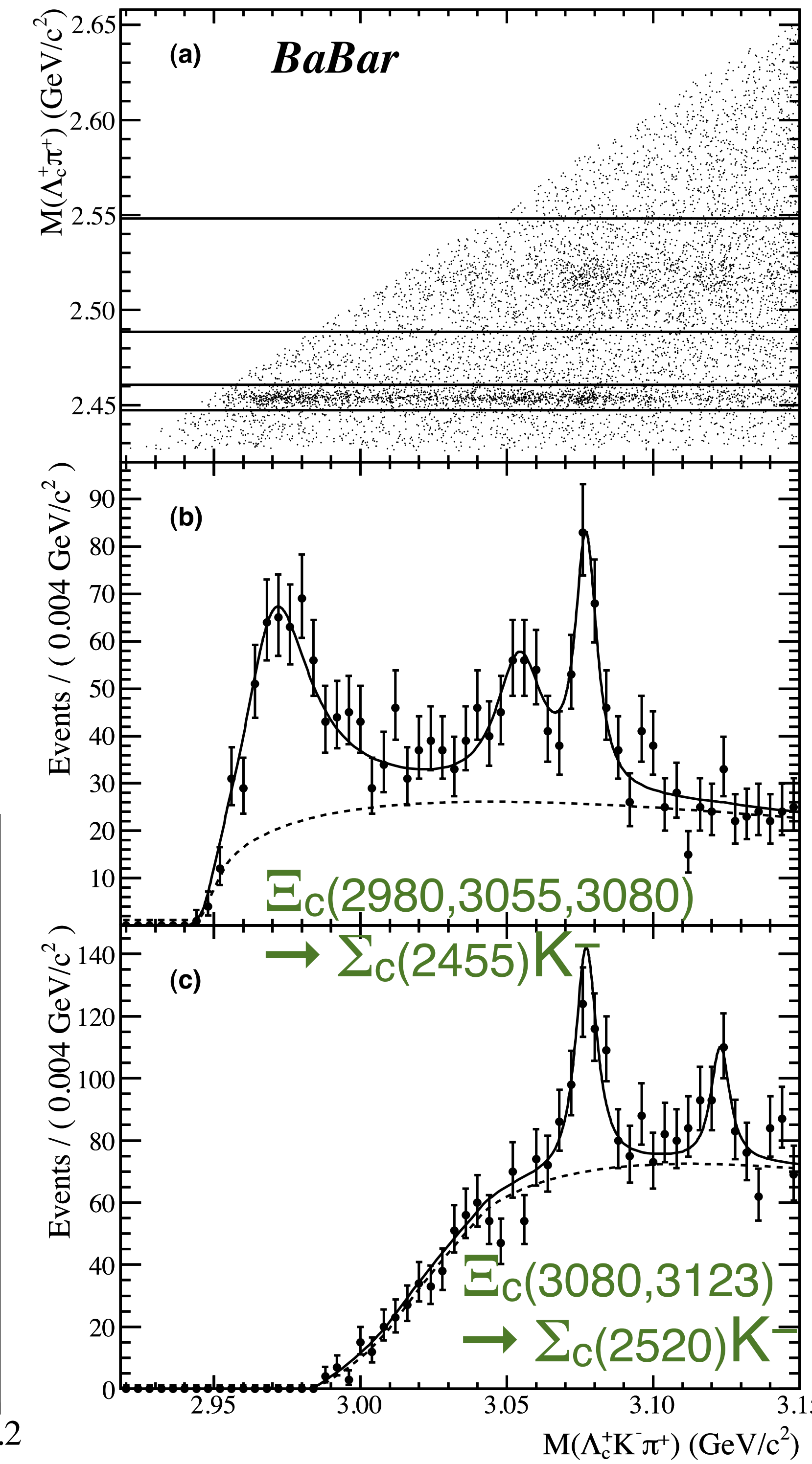


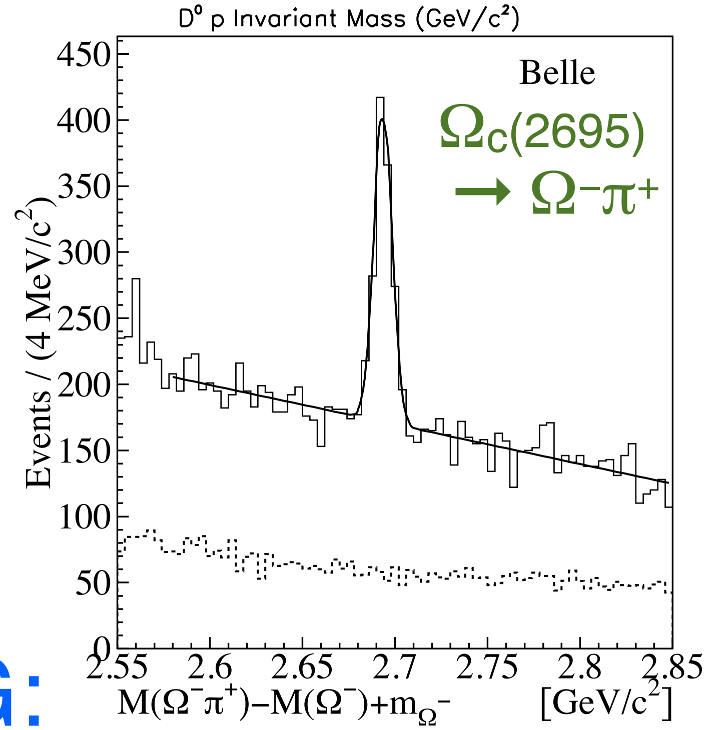
- PDG lists: $D_s(1969)$, $D_s^*(2112)$, $D_{s0}^*(2317)$, $D_{s1}(2460)$, $D_{s1}(2536)$, $D_{s2}(2573)$, $D_{s1}^*(2700)$, $D_{sJ}^*(2860)$, $D_{s2}^*(3040)$

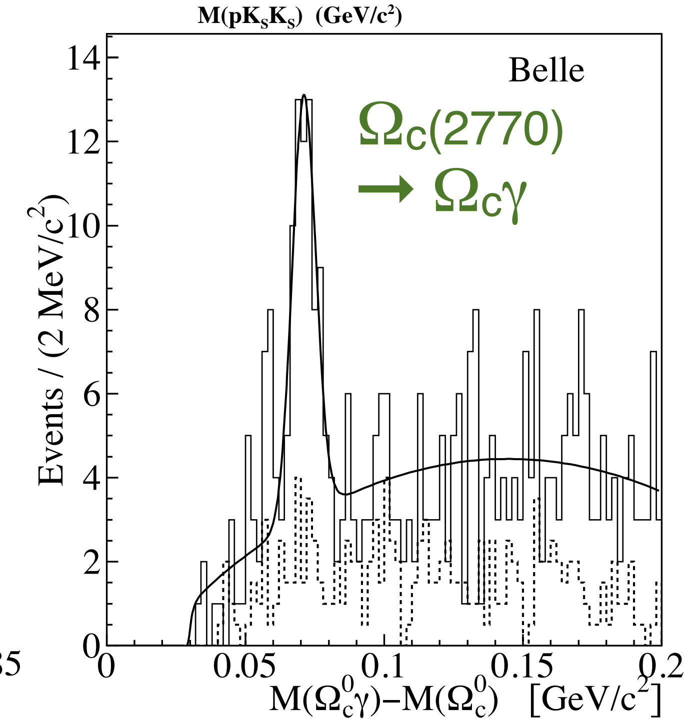
→ ...and many many baryons





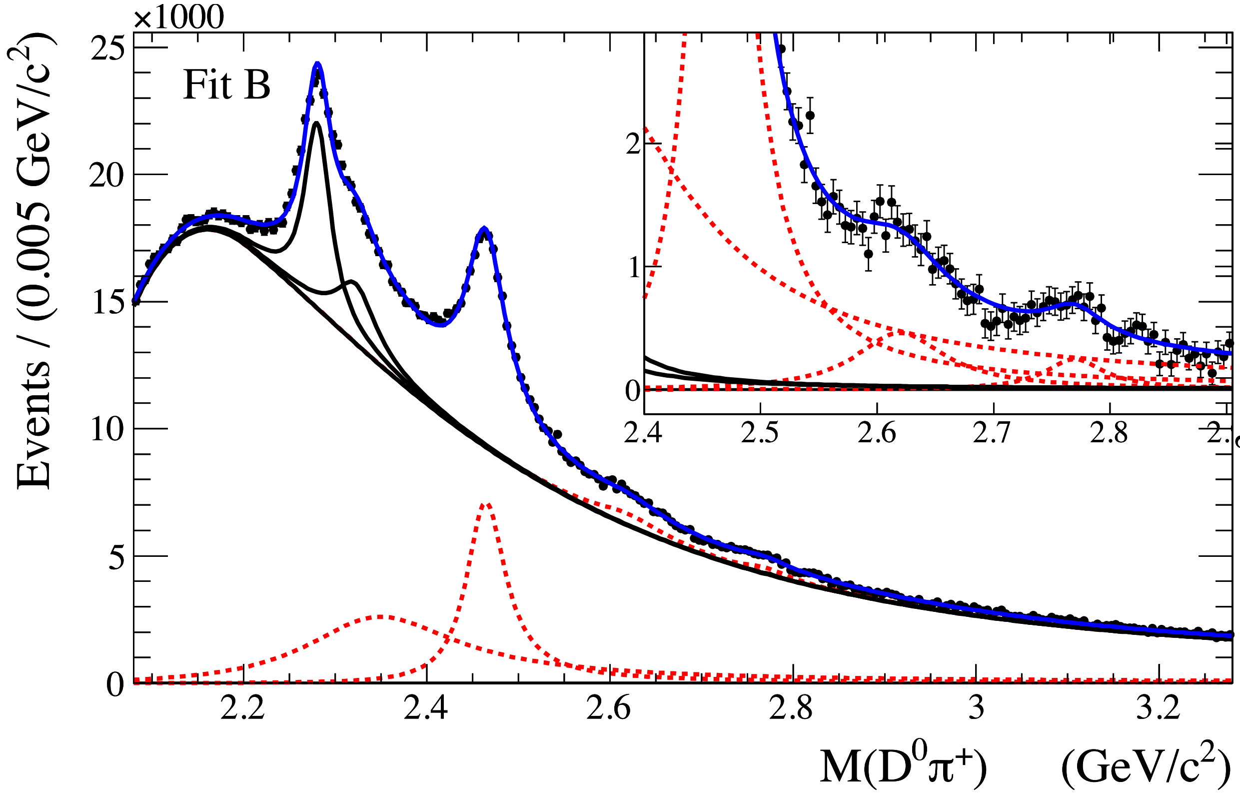


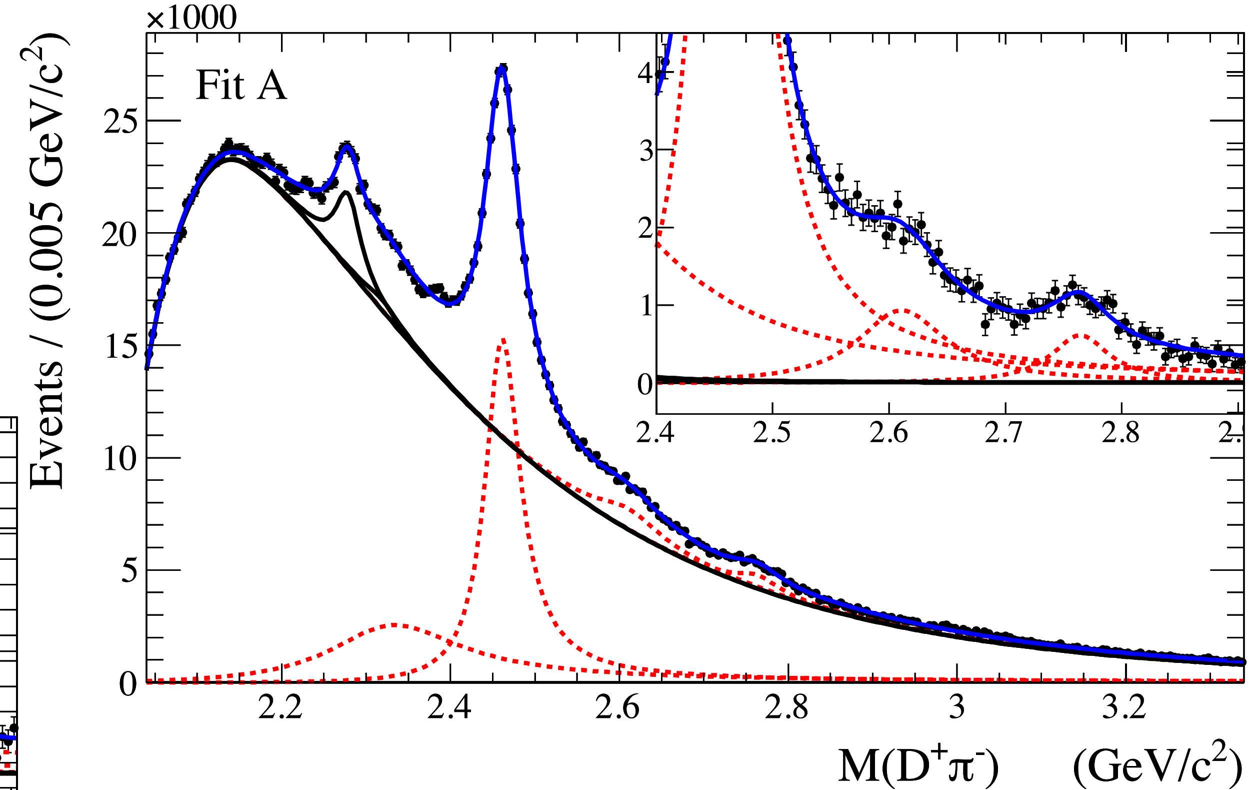


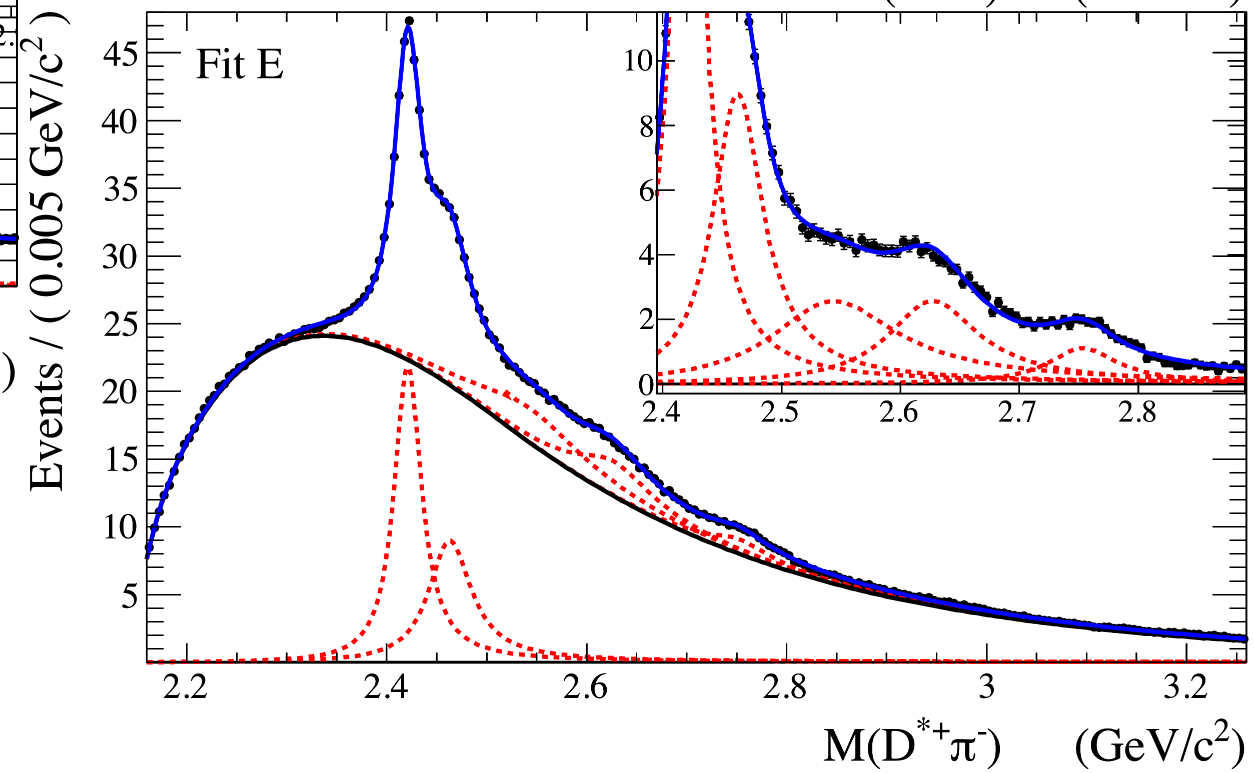


- PDG:
  Λ_c(2285, 2595, 2625, 2765, 2880, 2940); Σ_c(2455, 2520, 2800), Ξ_c(2470, 2577, 2645, 2790, 2815, 2930, 2980, 3055, 3080,3123), Ω_c(2695, 2770)

→ ...and recently six new orbitally excited D’s







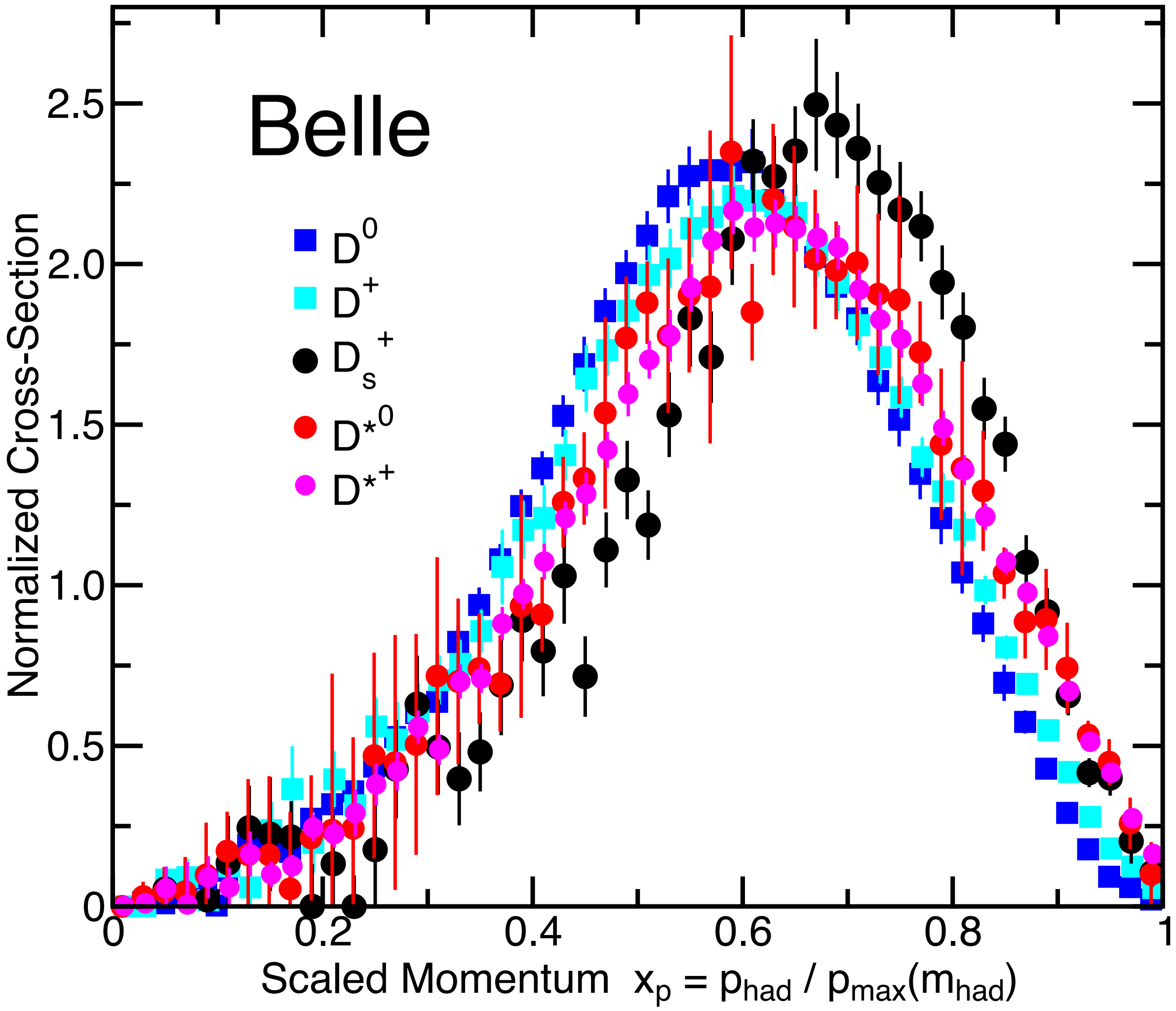
- PDG: D(1868), D^*(2010), D_0^*(2400), D_1^*(2425), D_2^*(2460), D^*(2640)

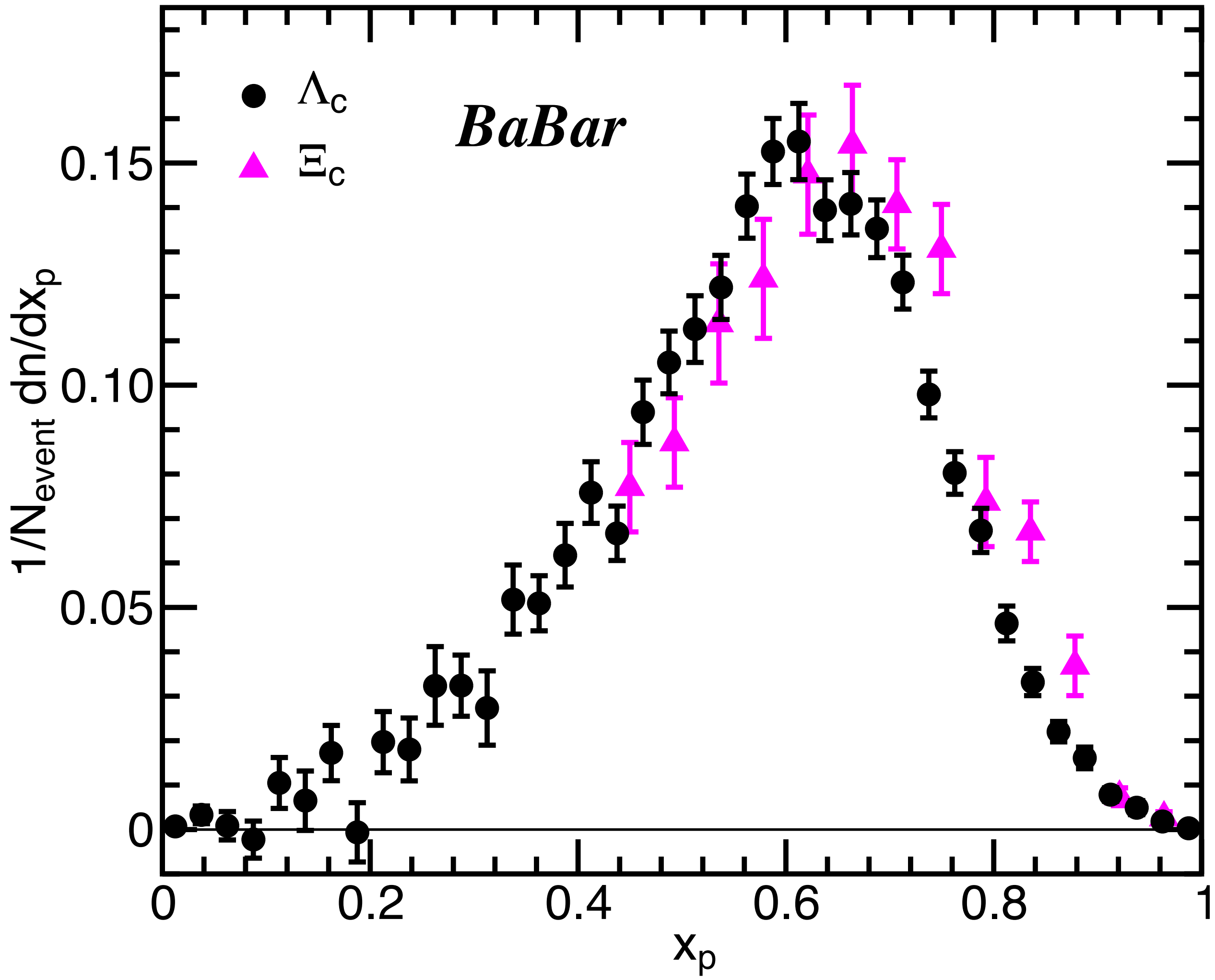
→ most of what we know about charm spectroscopy is from these experiments

→ just starting to measure branching fractions, and hence relative production rates

D meson, baryon fragmentation functions

- can measure some of the FFs precisely
  - → no B background when running at E_{CM}<10.57 GeV
  - → ...or for x>0.48, the kinematic limit for B decays





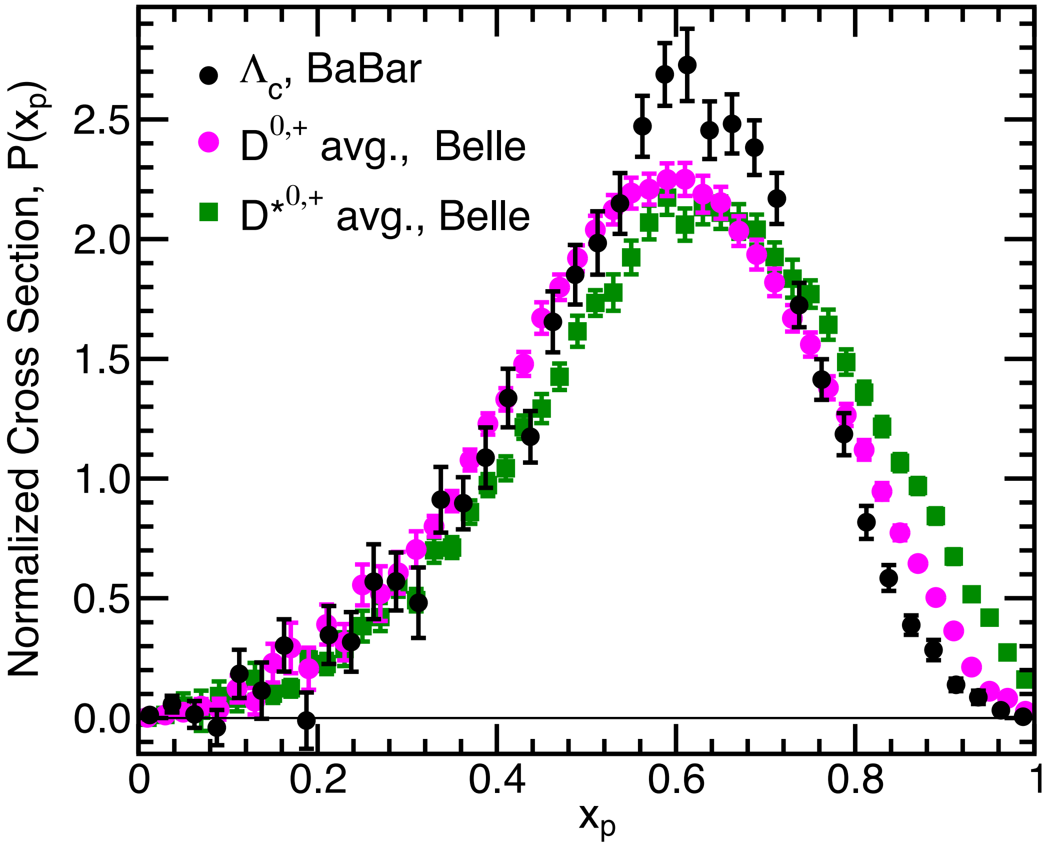
- the heavier particles have harder FFs
  - → shapes are similar for all mesons, also all baryons
  - → mesons have entries near x=1; heavier/excited mesons have more of them

Results on the FF shapes

- these are some of the best measured FFs
  - → full kinematic range
  - → Belle:

	$<x_p>$	x_{max}
D^0	0.5703±0.0022	0.587±0.002
D^+	0.5780±0.0015	0.600±0.002
D_s	0.6353±0.0042	0.681±0.003
D^{*0}	0.6076±0.0061	0.612±0.004
D^{*+}	0.6122±0.0014	0.631±0.002
Λ_b	0.5825±0.0025	0.618±0.023

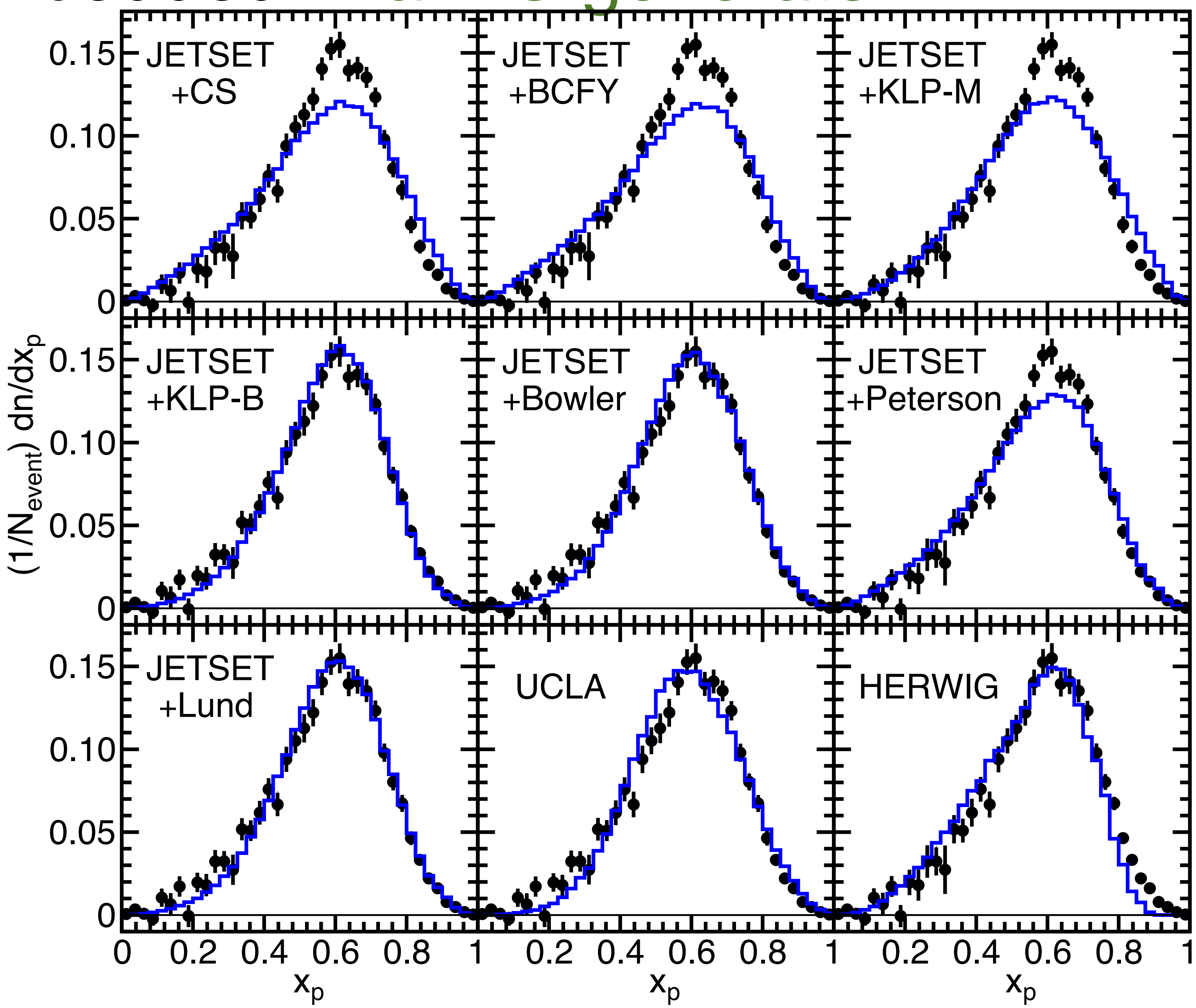
- the shapes of the baryon and meson spectra differ
  - → baryon FFs are narrower and more strongly peaked
- model/shape tests are generally consistent with those for the inclusive B FF at the Z^0



Model tests for Λ_c baryons

$E_q / M_{had} = 2.3$

- models have been tested extensively for the Λ_c FF
  - → some must be embedded in a MC generator
- most models can be excluded
  - → no model has a good χ^2
  - → Bowler, Lund ok
  - → Kartvelishvili, UCLA not too bad; predict meson-baryon difference
  - → these are not default, or even available, in any generator

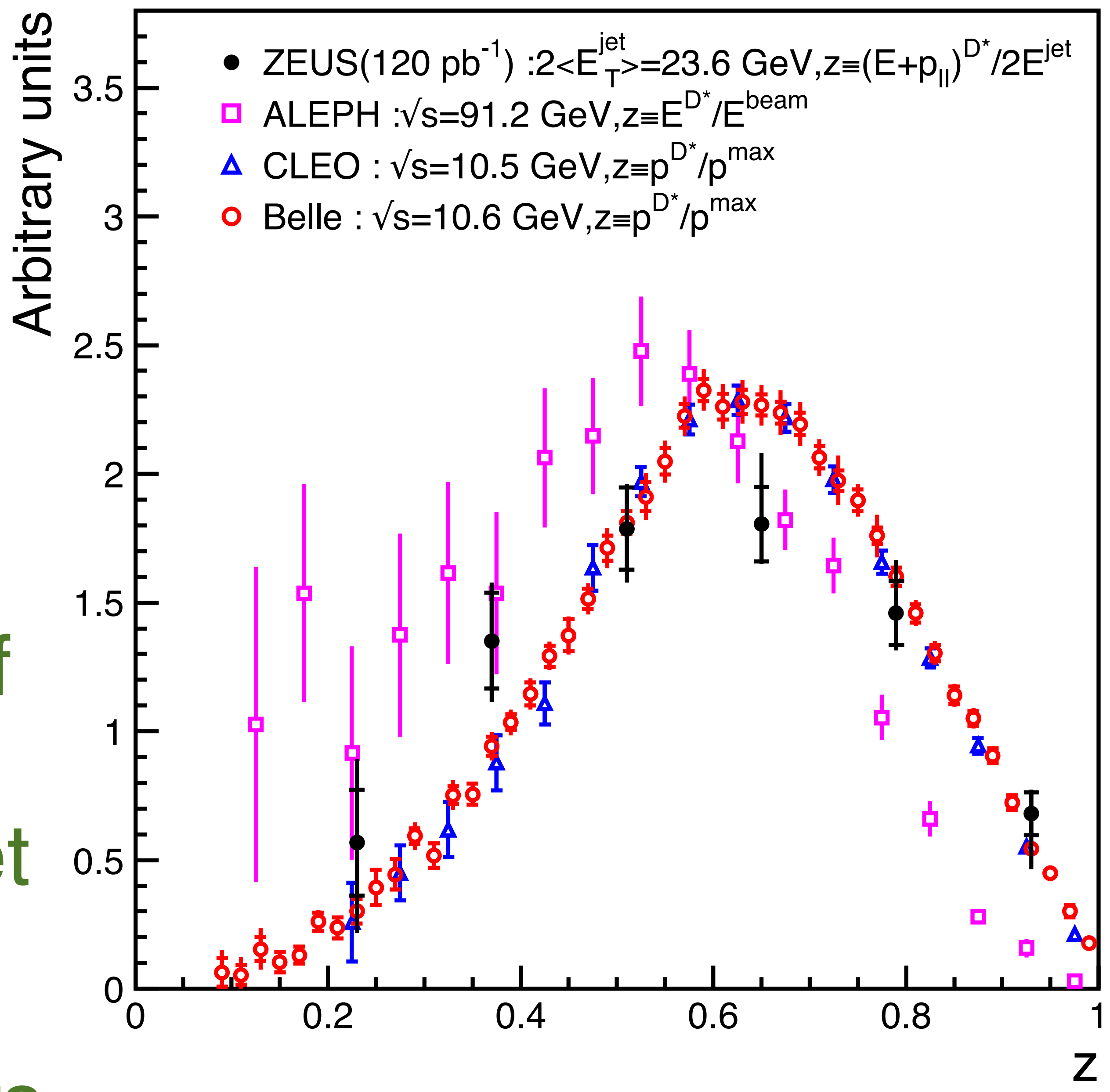


$\Rightarrow$ beware if this matters to you!

Energy dependence of the D* FF

- would like to compare FFs at different E_{CM}
  - → such comparisons are dangerous ...
  - → different experimental methods
  - → different definitions of x/z

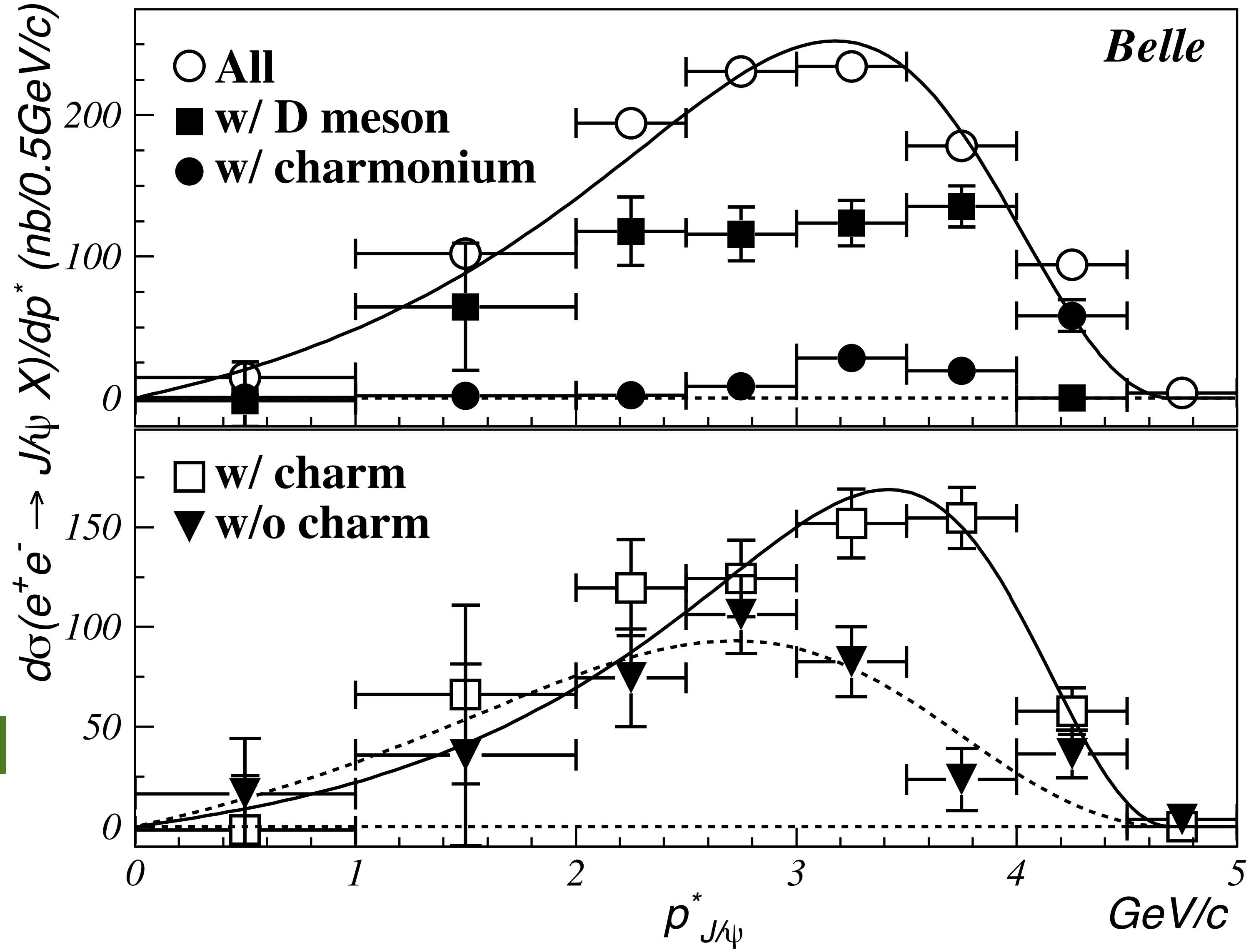
- but try it anyway
  - → CLEO and Belle are consistent
  - → difference from ALEPH at low z within syst. errors, ...
  - → at high z due to defn. of z, few-body events, ...?
  - → ZEUS has a range of jet energies, another z defn.; is probably consistent with all others



Charmonium production

$E_q / M_{had} = 1.7$

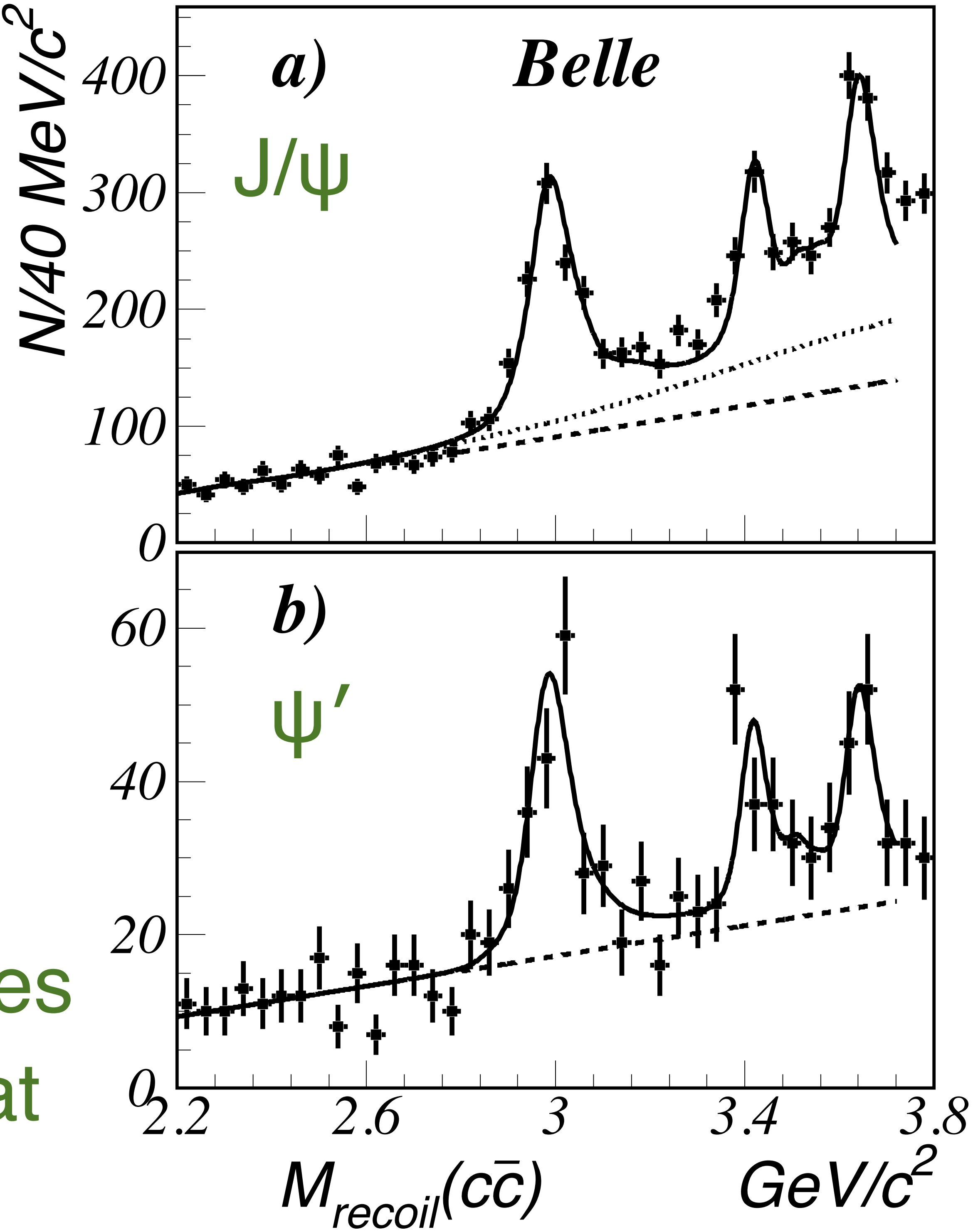
- inclusive J/ψ and $\psi(2S)$ spectra measured
  - → one of the earliest Belle results
  - → very nice recent follow-up, in-depth study
- the inclusive FF is very hard!
  - → expected for $c\bar{c}$ pairs from the hadronization stage
- look for additional $c\bar{c}$
  - → many rec'd $D/\bar{D}$ mesons: expected
  - → and charmonium (see next slide)
  - → but ~30% have none: gluon splitting, or ...?



⇒ relative $c\bar{c}$ production in hadronization >~ $2\text{x}10^{-4}$

Exclusive charmed final states

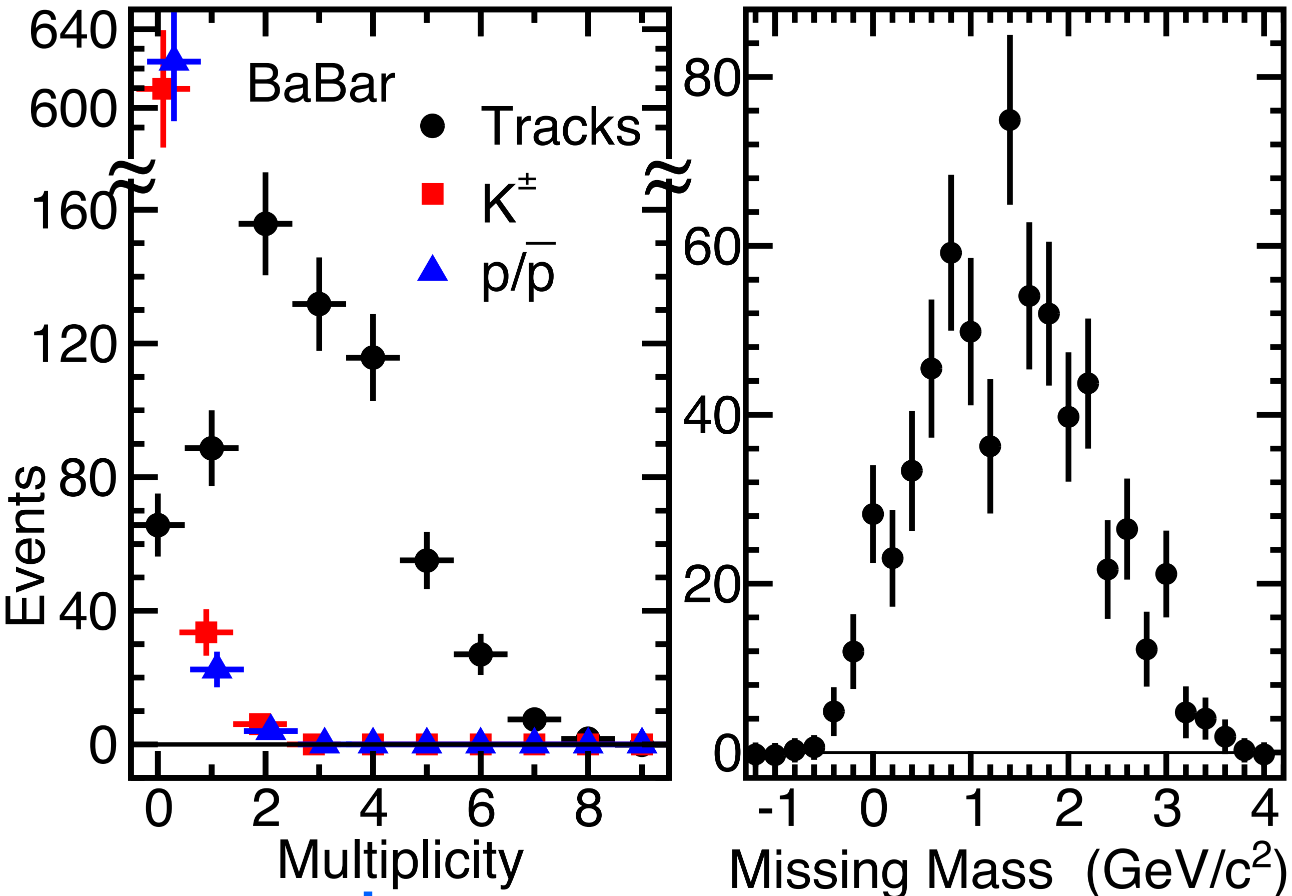
- CLEO, Belle have seen $e^+e^- \rightarrow D\bar{D}$ at a rate of one in $\sim 10^4$ $c\bar{c}$ events
  - → "pair" production of several combinations
- Belle, BaBar have seen $e^+e^- \rightarrow J/\psi^{(\prime)}\eta_c$, $J/\psi^{(\prime)}\chi_{c0}$, $J/\psi^{(\prime)}\chi_{c2}$ as one in 10^4
  - → rates are ~2x higher than predicted
  - → production mechanism not understood
- not really considered fragmentation,
  - → but presumably becomes larger as E_q/M_{had} decreases
  - → must also happen for $b\bar{b}$ at similar scale



Correlated Λ_c-$\overline{\Lambda}_c$ production

$E_q / (M_{\Lambda c}+M_p) = 1.6$

- CLEO saw ~4x too many events with both a Λ_c and a $\overline{\Lambda}_c$
  - → explained via long-range baryon # correlation
  - → could also be (pair) production of heavier states, e.g. pentaquarks, or ....
- BaBar studied these events in detail
  - → most have no other baryons
  - → but several pions
  - → structure consistent w/ “normal” fragmentation
  - → but not with decays



- this is a new feature of fragmentation
  - → affects ~4% of $c\bar{c}$ events at 10.6 GeV
  - → how does it vary with E_{CM}?
  - → must also affect $b\bar{b}$ at corresponding E_{CM} ⇒ beware!

What other issues are there at low scales?

- Could there be other long-range correlations?
  - → between flavor, spin, etc. of leading heavy hadrons
  - → between their momenta

- At what scale do we move from few-body processes to jets?
  - → at $E_{quark}=M_{hadron}$, can have only pair production
  - → few pion masses higher could give 3-, 4-body, decays of heavier 2-body, are they jet like?
  - → again, not really fragmentation, but important

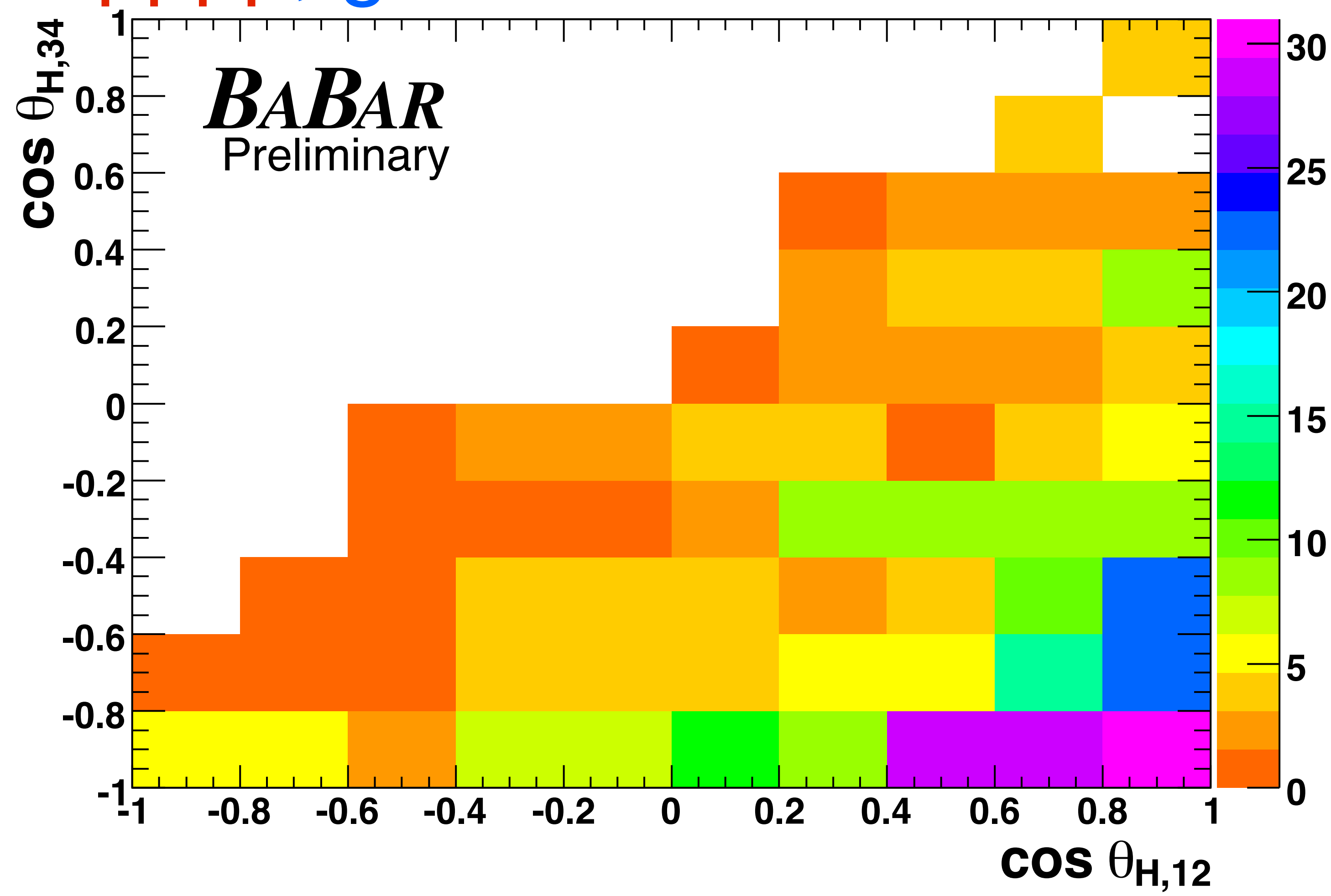
- There are a few relevant measurements
  - → studies of few-body non-heavy systems at 10.6 GeV
  - → near $c\bar{c}$ threshold via initial state radiation
  - → studies just above bb threshold

$\Rightarrow$ see slides to follow

Exclusive states at 10.6 GeV

- BaBar, Belle have studied exclusive processes w/ σ~fb
  - → $e^+e^- \to \rho^0\rho^0, \rho\phi$: discovery of 2-$\gamma^*$ annihilations into hadrons
  - → $e^+e^- \to \phi\eta, \rho^+\rho^-$: nice new tests of QCD
  - → also some non-resonant component, could be jets

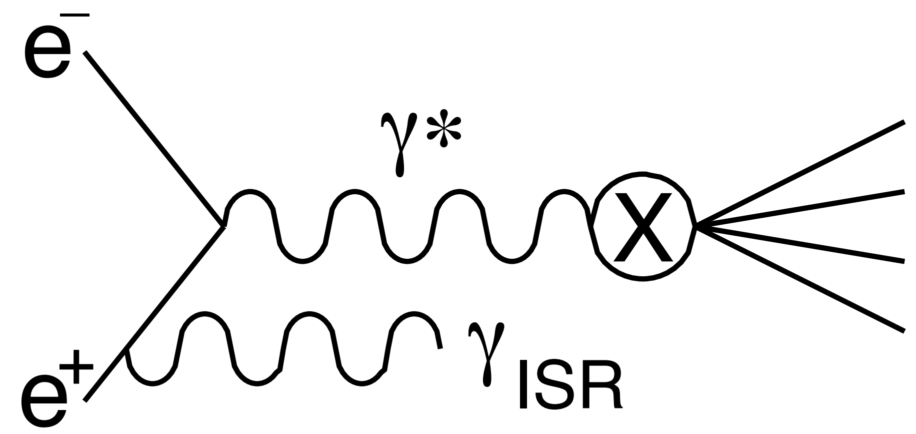
- one such study, $e^+e^- \to p\bar{p}p\bar{p}$, gave no such "interesting" results
  - → concentration in lower right, as expected in normal fragmentation ...
  - → but it's a rather extreme case, with $M_q / 2M_p = 2.9$



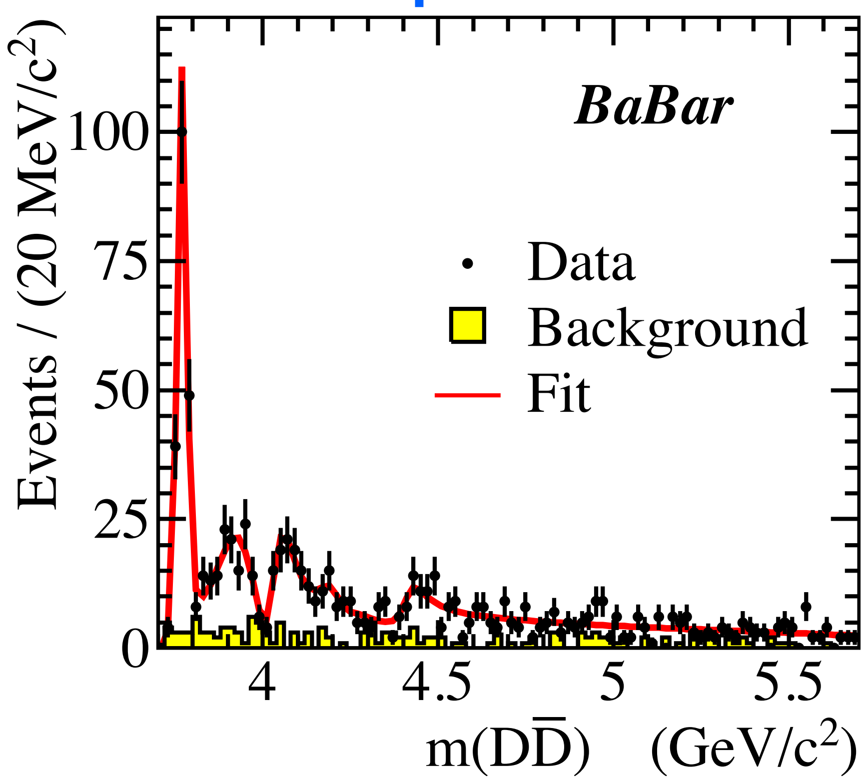
⇒ open question as to when/how jets start forming

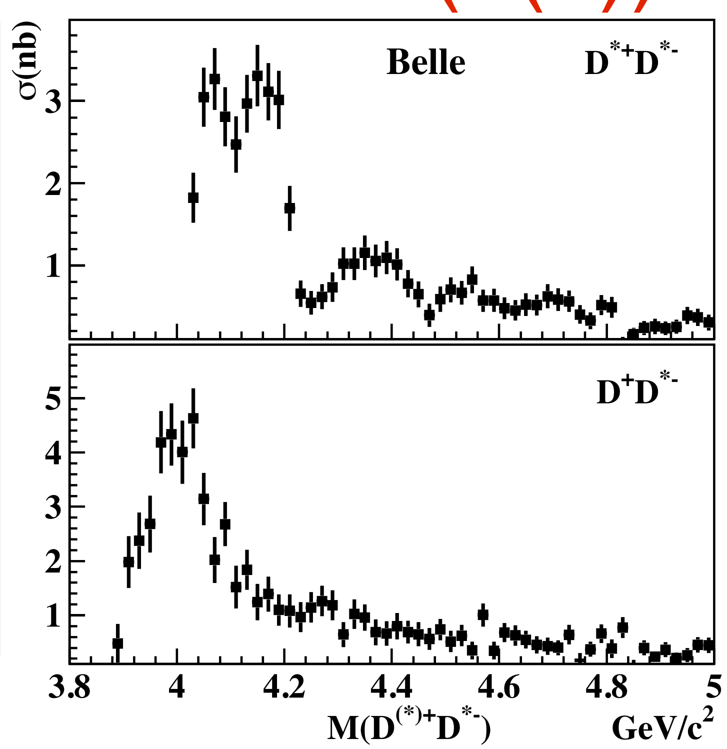
ISR/radiative return to near $c\bar{c}$ threshold

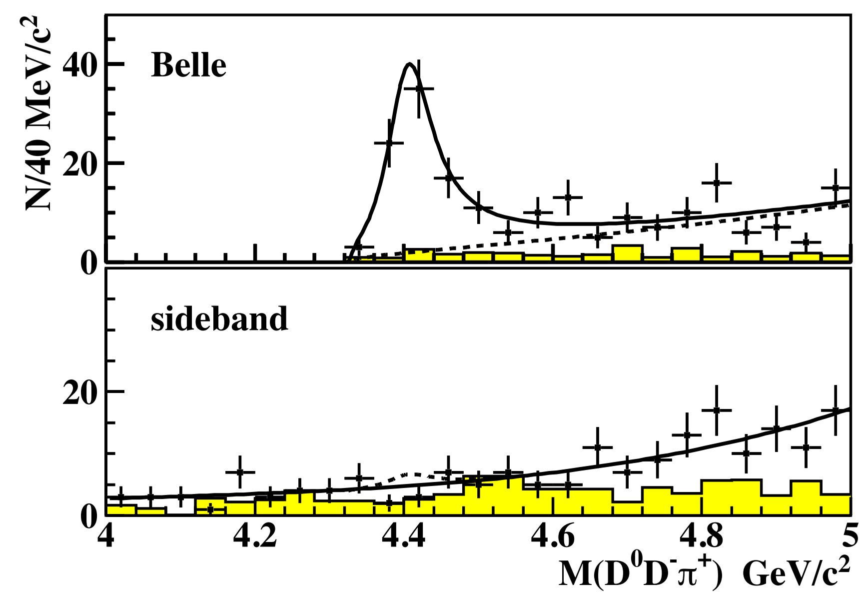
- can access lower E_{CM} given sufficient statistics
- discovery of new charmonium states (see backup)



- which spurred studies of $D\bar{D}(\pi(\pi))$ and $\Lambda_c\bar{\Lambda}_c$ final states



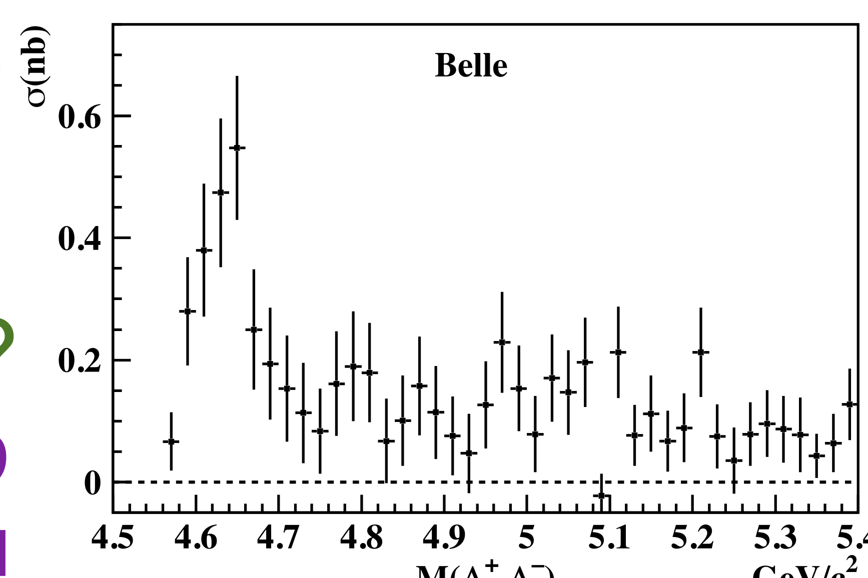




→ much interesting structure;

→ useful for fragmentation studies?

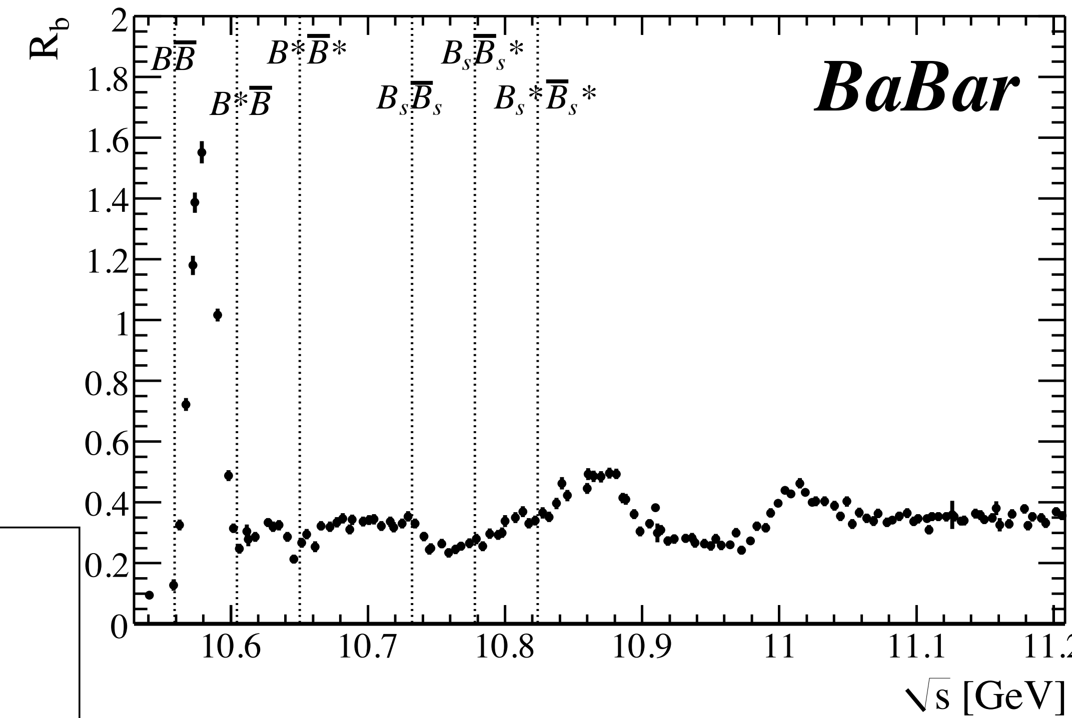
$\Rightarrow$ would be great to extend to more states, higher E_{CM}



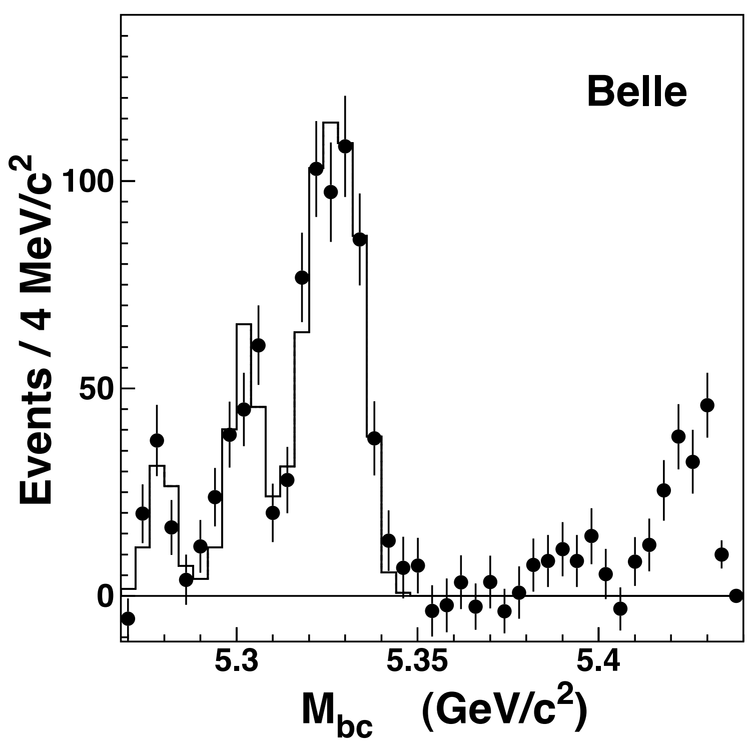
$B\bar{B}$ production just above threshold

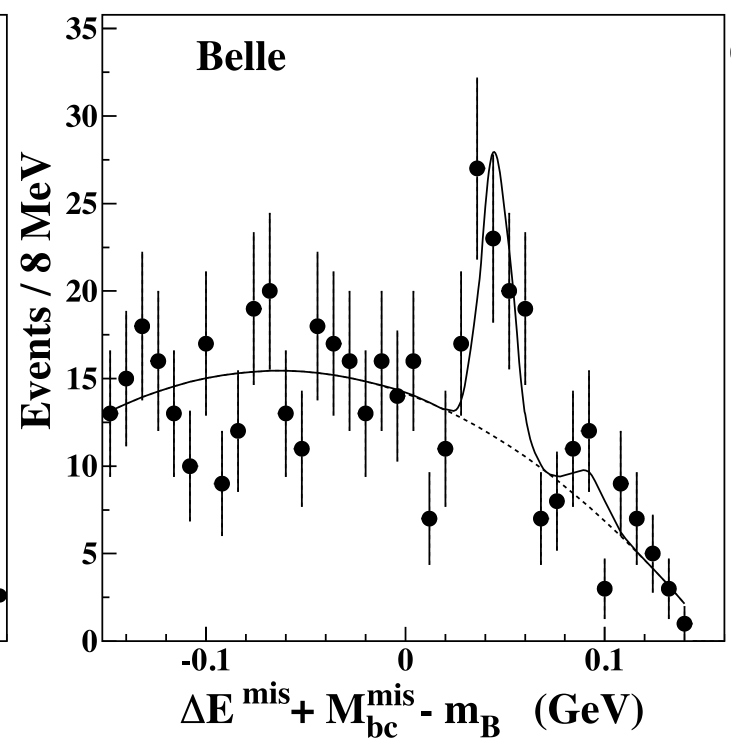
$E_q/M_{had} < 1.06$

- Belle, BaBar have run up to E_{CM}=11.2 GeV
  → stats too low for useful fragmentation studies...



- except for a Belle study at 10.86 GeV near a maximum in the $B\bar{B}$ cross section





→ information useful, if not really quite fragmentation

→ "complete" study of $B\bar{B}$ final states:

$B_s\bar{B}_s$	$B\bar{B}$	$B\bar{B}^*$	$B^*\bar{B}^*$	$B\bar{B}\pi$	$B\bar{B}^*\pi$	$B^*\bar{B}^*\pi$
= 33.0	5.5	13.7	37.5	0.0	7.3	1.0
± 9.0	1.1	1.6	4.5	1.2	2.4	1.5

can we extend to higher energy?

Summary

- Heavy quark fragmentation is understood reasonably well empirically at high energy, i.e. large E_{quark} / M_{hadron}
  - → almost all leading, very hard
  - → many primary states
  - → some FF shapes measured well
  - → some particles carry the initial quark polarization
- at lower E_q, 2-5 times the hadron mass, things evolve
  - → pair production
  - → long-range correlations
  - → we've really just scratched the surface here
- some advice and caveats
  - → be careful with models - may need to modify/tune
  - → must consider few-body processes evolving into jets

Backup Slides

References and further information

Reviews:

Particle Data Group:
JPG 37, 075021 (2010)
Z^0 ElectroWeak Working Groups:
hep-ex/0312023 (2003)
Z^0 Heavy Flavor Working Groups:
hep-ex/0112028 (2001)

HERA:

A recent review: arXiv:1012.1198

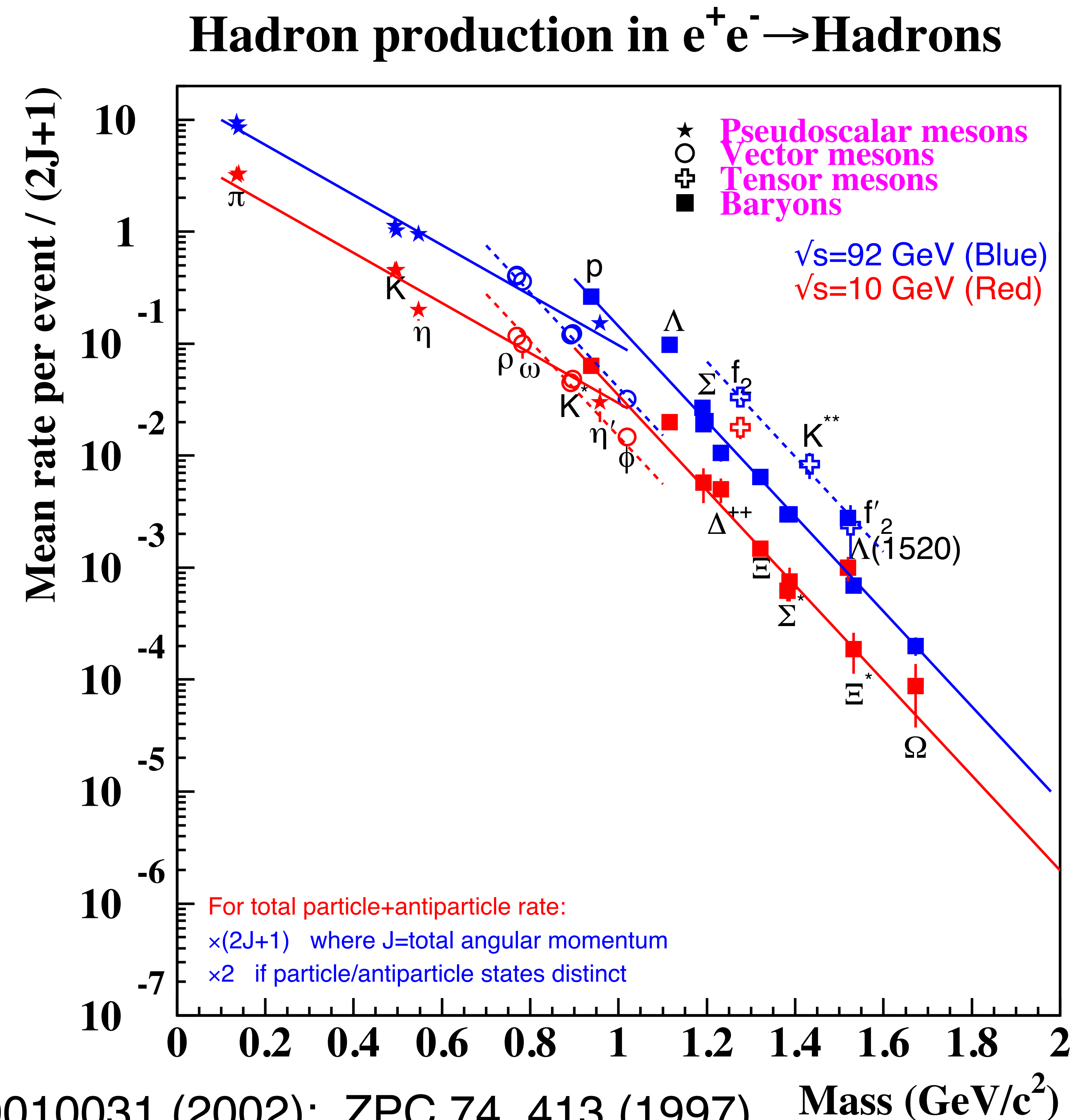
ZEUS: JHEP 0904, 82
& arXiv/0901.1210 (2009)

H1: EPJC 59, 589
& arXiv/0808.1003 (2009)

B production:

ALEPH: PLB 425, 215 (1998);
ZPC 69, 373 (1996)

DELPHI: ZPC 68, 353 (1995);
PLB 345, 598 (1995)



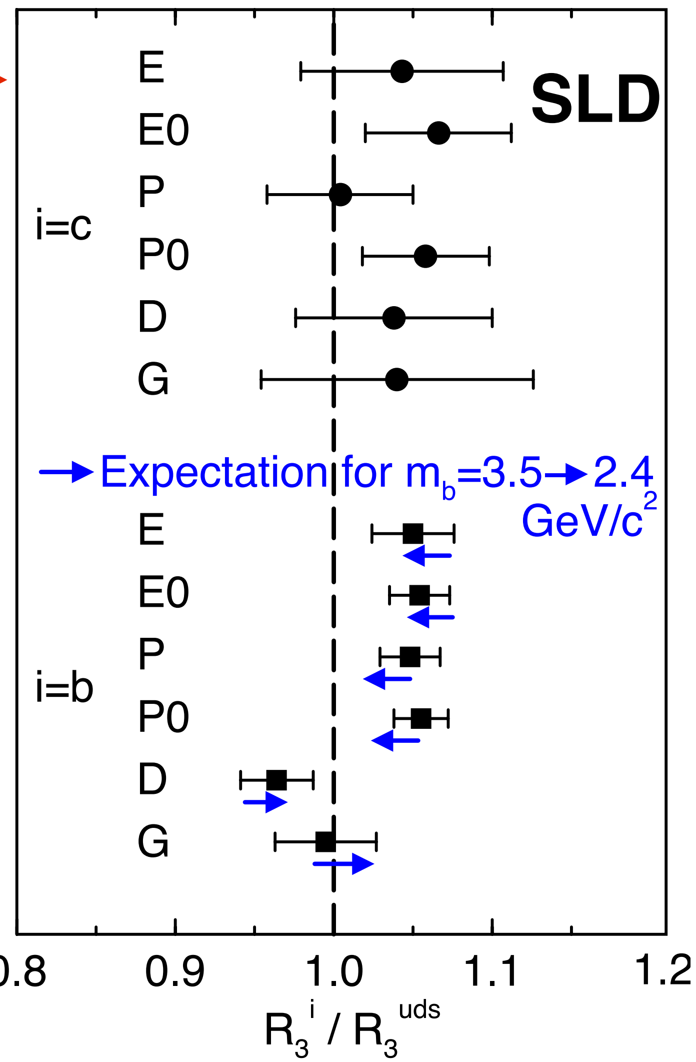
OPAL: EPJC 23, 437 & hep-ex/0010031 (2002); ZPC 74, 413 (1997)

L3: PLB 465, 323 (1999)

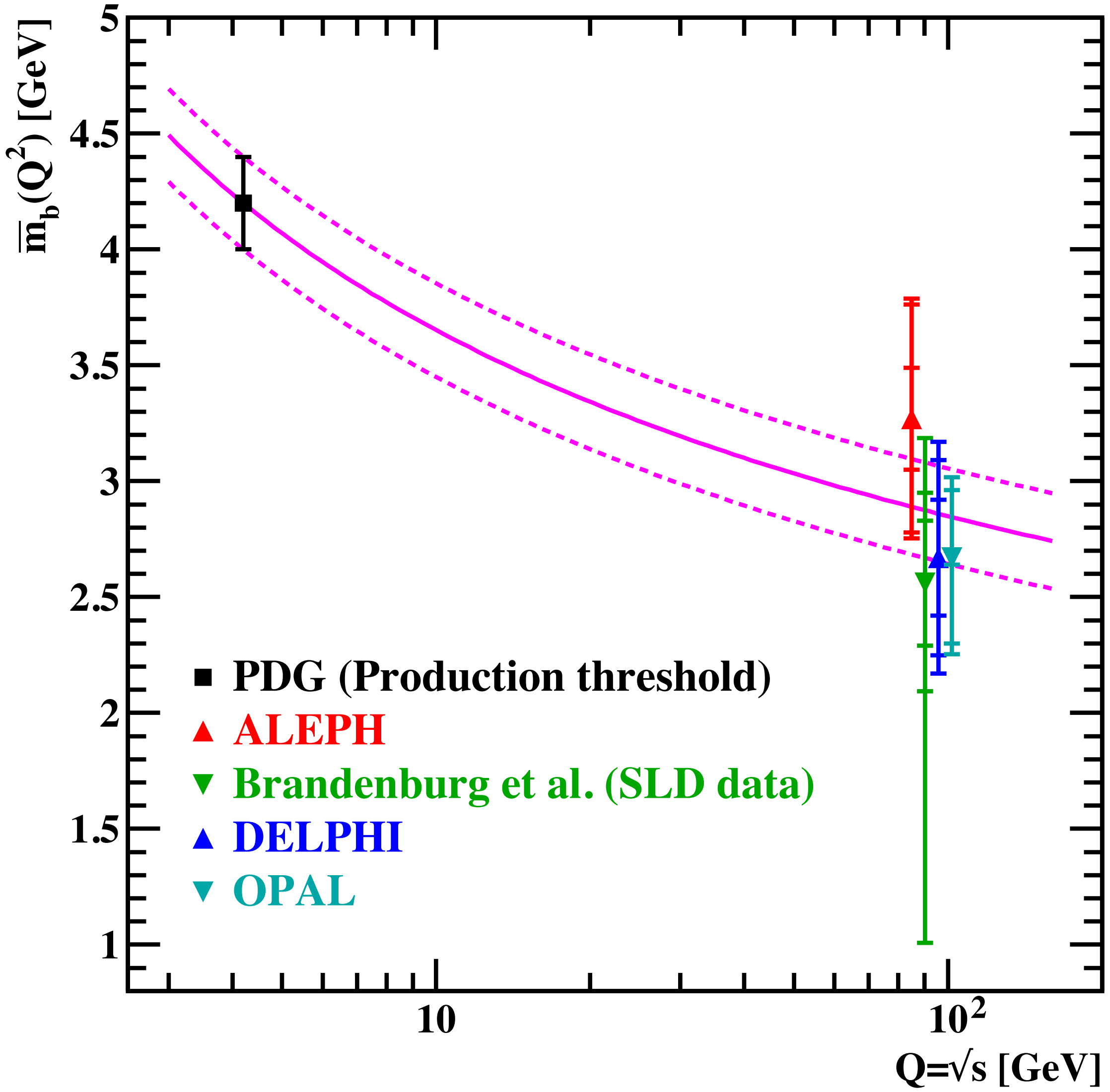
CDF: PRL 102,102003 (2009); D0: PRL 101,232002 (2008)

The (running) b quark mass

- the dead cone also affects 3-jet rates → and other event shape variables
  → few percent effects clearly visible in $Z^0 \to b\bar{b}$ events, maybe also $c\bar{c}$



- can measure the b quark mass using a set of such variables



→ some model dependence in the value

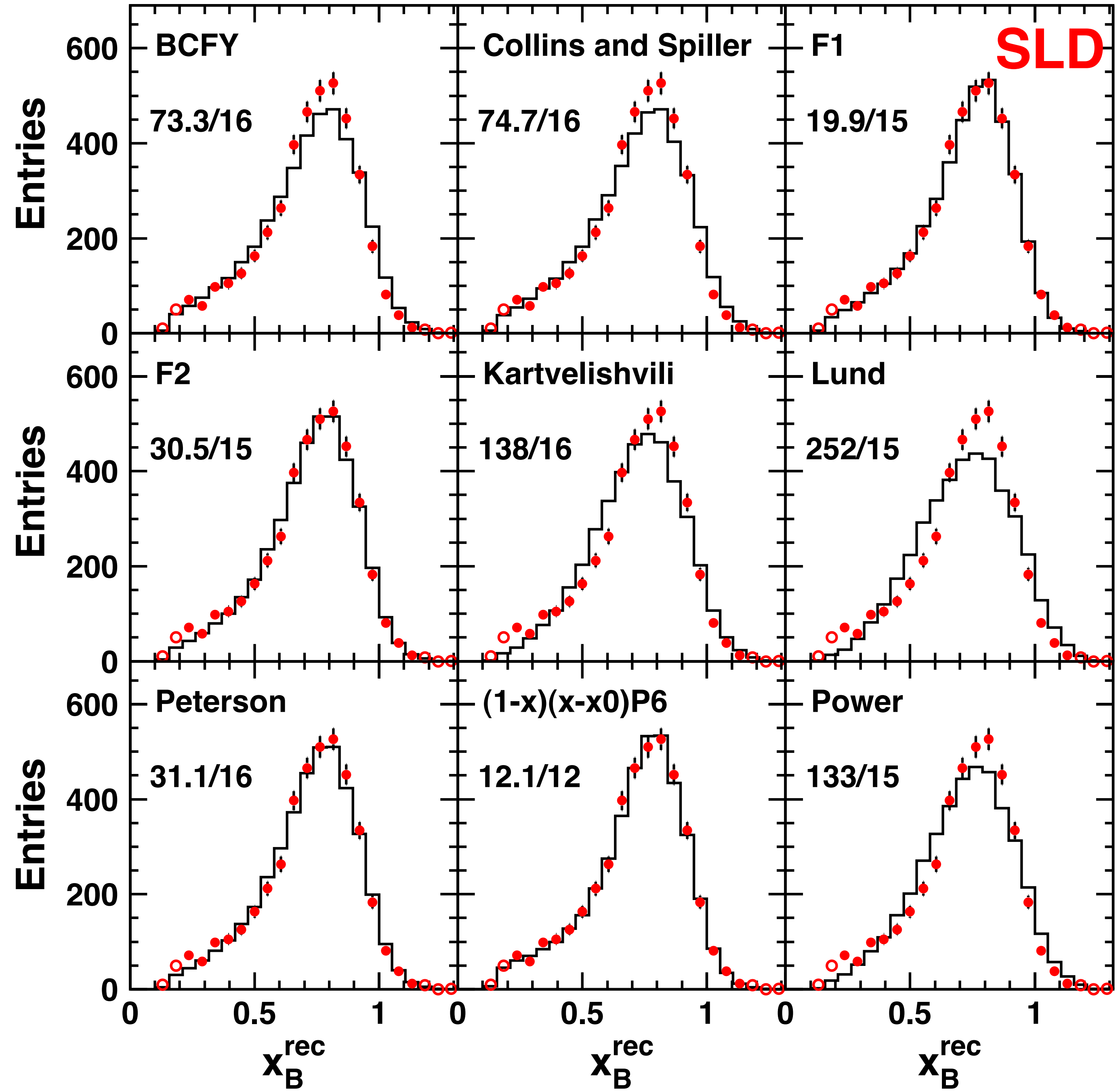
→ clear that $M_b(M_Z)$ is nonzero and lower than the pole mass

ALEPH: EPJC 18, 1 & hep-ex/0008013 (00)
Brandenburg, et al. (SLD data): PLB 468, 168 & hep-ex/9905495 (99)
DELPHI: EPJC 55, 525 (08)
OPAL: EPJC 21, 411 & hep-ex/0105046 (01)

More tests of b fragmentation models

- can also look for functions that describe the distribution
  - → and put through a detector simulation
- some model functions are better outside the MC, some are not
  - → a polynomial must be 6th order, plus cutoff factors
  - → not dft./available in many generators

⇒ beware if this matters to you!



refs:
TASSO: ZPC 22, 219 (1984)
JADE: ZPC 33, 339 (1987)
MARK-J: PRL 51, 443 (1983)
HRS: PRL 51, 1147 (1983)
ALEPH: PLB 512, 30 & hep-ex/0106051 (01); PLB 367, 699 (1995)
OPAL: EPJC 29, 463 & hep-ex/0210031 (03)
SLD: PLB 578, 44 & hep-ex/0309058 (04); PRD 65, 092006 & hep-ex/0202031 (02)

Dead cone:

DELPHI: PLB 479, 118 (2000)
SLD: PLB 386, 475 & hep-ex/9608008 (1996)

Λ_b polarization:

ALEPH: PLB 365, 437 (1996)
DELPHI - PLB 474, 205 (2000)
OPAL: PLB 444, 539 & hep-ex/9808006 (1998)

Gluon splitting to bbbar:

ALEPH: PLB 434, 437 (1998); DELPHI - PLB 462, 425 (1999)
OPAL: EPJC 18, 447 & hep-ex/0010029 (2001)
SLD: PLB 507, 61 & hep-ex/0102002 (2001)

D production:

ALEPH: PLB 526, 34 & hep-ex/0112010 (2002)
DELPHI - EPJC 12, 209 (2000); PLB 426, 231 (1998)
OPAL: EPJC 5, 1 & hep-ex/9802008 (1998); ZPC 76, 425 (1997)

BaBar: PRD-RC 82, 111101 & hep-ex/1009.2076 (2010); PRL 98, 012001 & hep-ex/0603052 (2007); PRL 97, 222001 & hep-ex/0607082 (2006); PRL 95, 142003 & hep-ex/0504014 (2005); PRD 74, 032007 & hep-ex/0604030 (2010)

Belle: PLB 672, 1 & hep-ex/0808.3677 (2009); PRL 101, 172001 & hep-ex/0807.4458 (2008); PRD 77, 032001 & hep-ex/0709.4184 (2008); PRL 100, 092001 & hep-ex/0707.3491 (2008); PRL 94, 221805 & hep-ex/0410091 (2005); PLB 605, 237 & hep-ex/0409065 (2004); PRL 92, 012002 & hep-ex/0307052 (2004)

D fragmentation:

ALEPH: hep-ex/9909032 (2000)
DELPHI: ZPC 59, 533 (1993)
OPAL: ZPC 67, 27 (1995)

TASSO: ZPC 44, 365 (1989)
JADE: PLB 146, 121 (1984)
TPC/2g: PRD 34, 1945 (1986)

BaBar: PRD 75, 012003 & hep-ex/0609004 (2006); hep-ex/1006.2216, to appear in PRD-RC
Belle: PRD 73, 032002 & hep-ex/0506068 (2006)

Gluon splitting to ccbar:

ALEPH: PLB 561, 213 & hep-ex/0305071 (2003)
OPAL: EPJC 13, 1 & hep-ex/9908001 (2000)
L3: PLB 476, 243 (2000)

Spin alignment:

OPAL: ZPC 74, 437 (1997);
DELPHI - PLB 406, 271 (1997)

onium:

DELPHI - ZPC 69, 575 (1995)
L3: PLB 453, 94 (1999)

ISR:

BaBar: PRD 82, 052004 & hep-ex/10080338 (2010)
Belle: arXiv:1011.4397, subm. to PRD-RC; PRL 98, 092001 & hep-ex/0608018 (2007)

double charmonium:

BaBar: PRD-RC 72, 131101 & hep-ex/0506062 (2010);
Belle: PRD-RC 79, 071101 & hep-ex/0901.2775 (2009)

higher-E:

BaBar: PRL 102, 012001 & hep-ex/0809.4120 (2009)
Belle: PRD-RC 81, 112003 & hep-ex/1003.5885 (2010)