Fragmentation and Hadronization in e^+e^- Annihilations: The Z^0 Era

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Precise Measurements

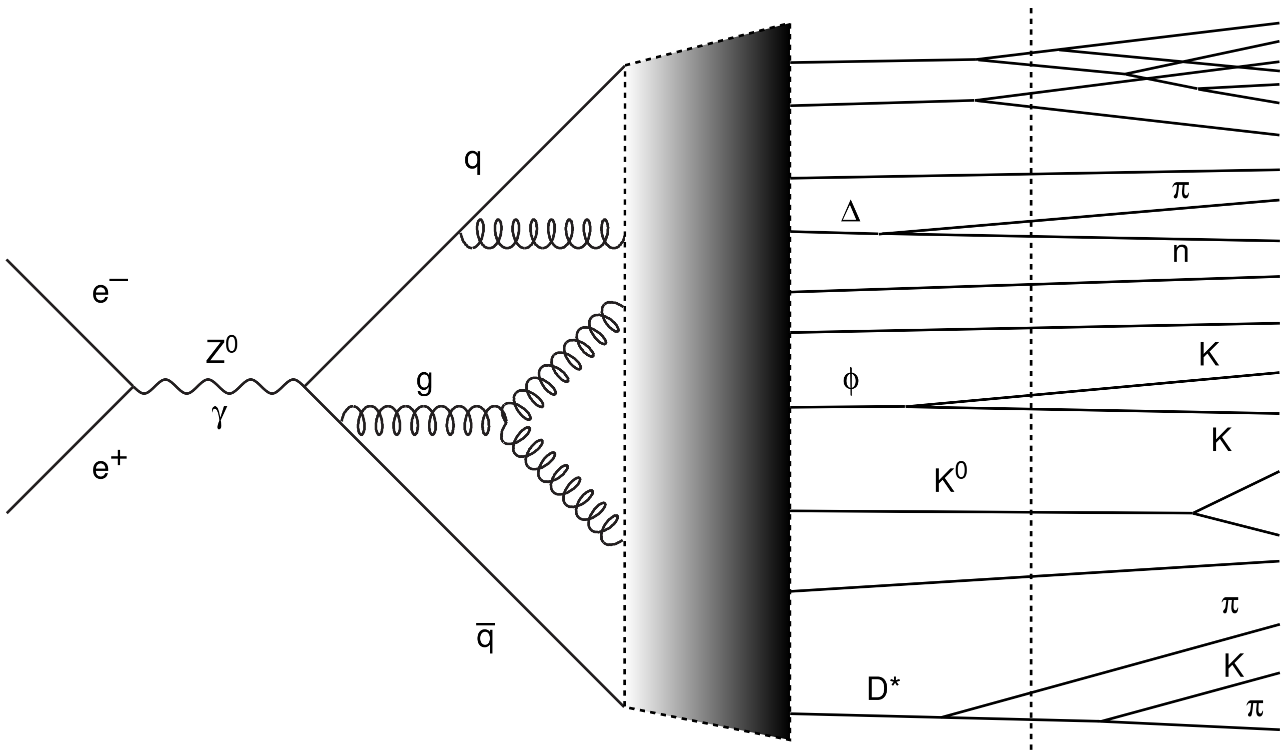
- Multiplicities and moments 512
- Rapidity Gaps 511
- Identified Particles 211,670

Flavor Dependence and
Leading Particles

- Heavy vs. Light Quarks 512, 670
- Leading Particles 217,673,670
- Individual Light Quarks 21
- Gluons 670

Summary & Future Prospects

Fragmentation/hadronization remains a (last?) frontier in elementary particle physics



Fragmentation (~left of black box)

- calculable (XLLA, parton showers)
- observable (particle/energy flow, multiplicities)

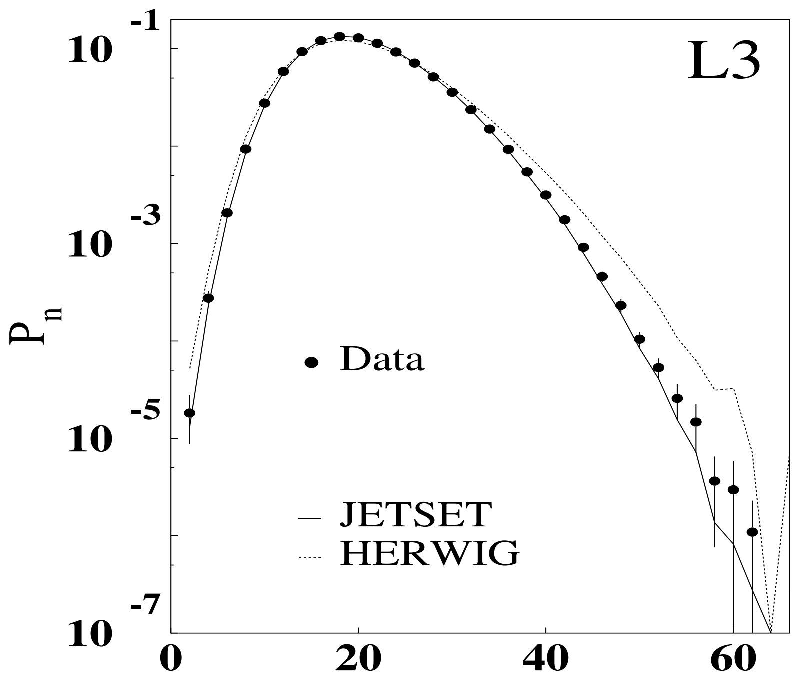
Hadronization (~black box)

- intrinsically non-perturbative
- may look like XLLA (LPHD)
- many phenomenological models
- study using
  - → precise inclusive measurements
  - → identified/rec'd particles (push from right)
  - → flavor-tagged jets
  - → correlations (see talk by T. Aziz) ....

Precise Inclusive Measurements

Many studies of inclusive distributions have become quite precise indeed

- New study of charged track multiplicity and scaled momentum distributions from L3

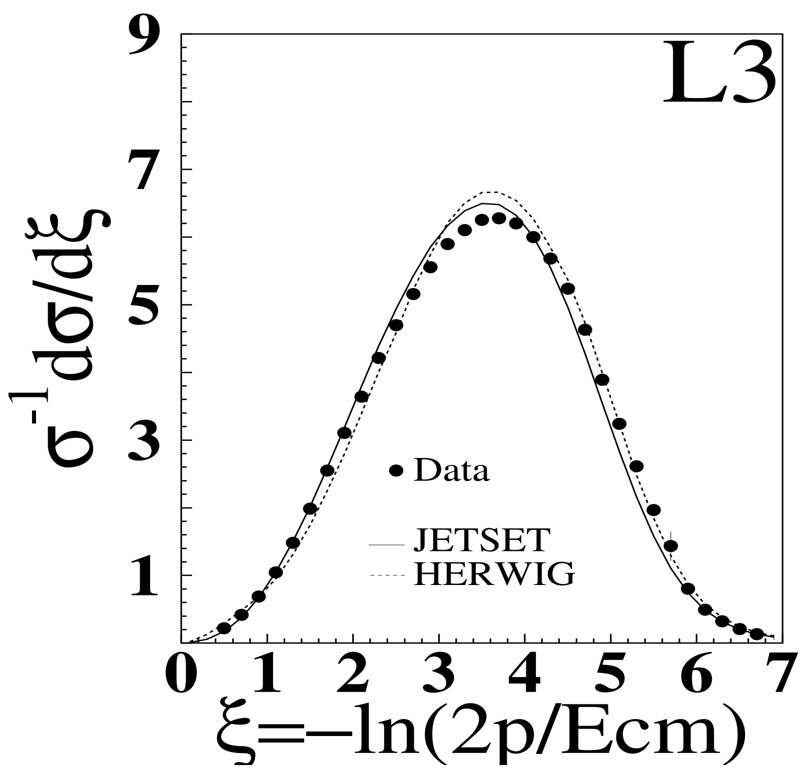


→ these are very difficult msmts!

→ years of work on systematics

→ note log scales

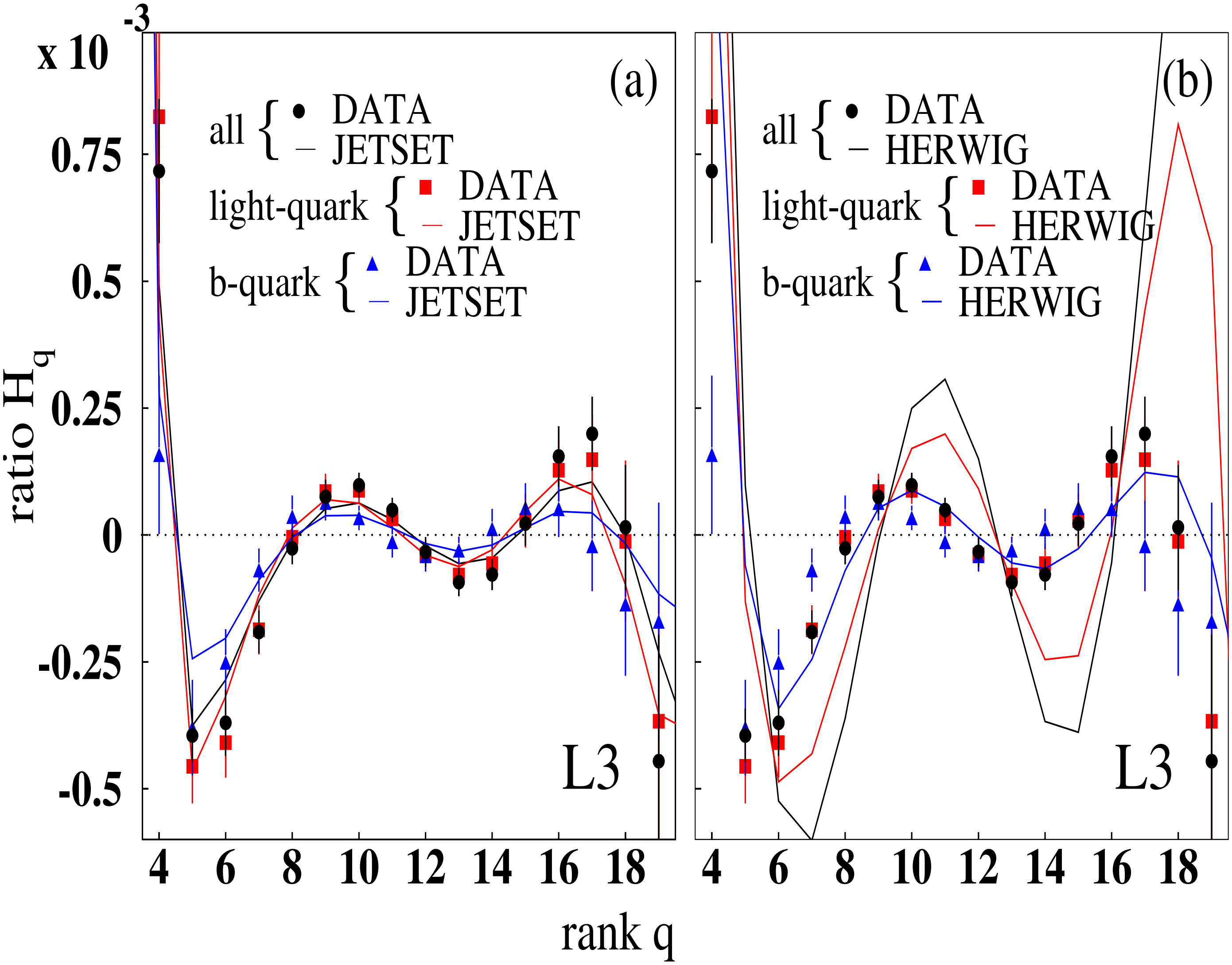
→ coverage over very wide ranges



→ stringent tests of fragmentation models:

→ all OK to few % ...but imperfect

- Now measure the q^th cumulant and factorial moments of the mult. distn. and the ratio H_q



→ minimum at q≈5 and subsequent oscillations predicted by NNLLA QCD

→ observed in nuclear, lepton-nuclear, e^+e^-

→ ...but also seen in models with ~NLLA

→ ...and by L3 in different flavor, n-jet events

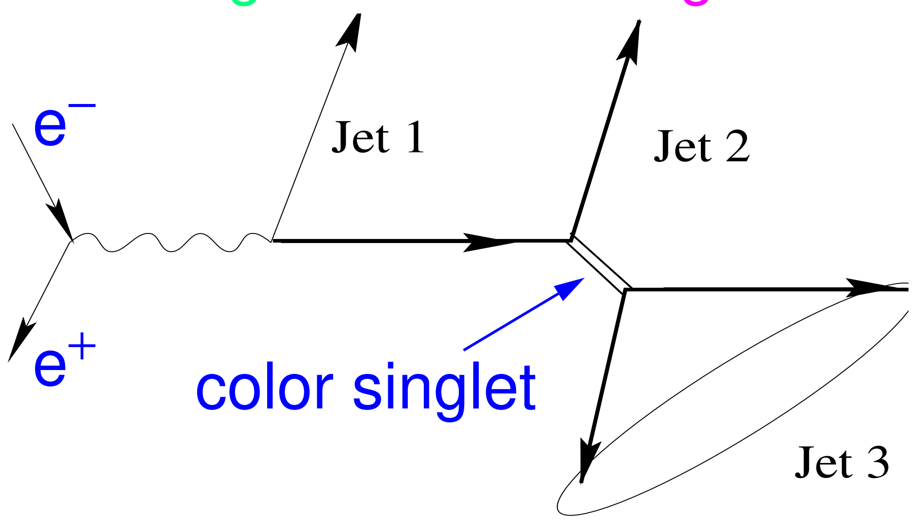
→ nice search for origin of effects in MC

→ ...but no clear source...or interpretation of the data

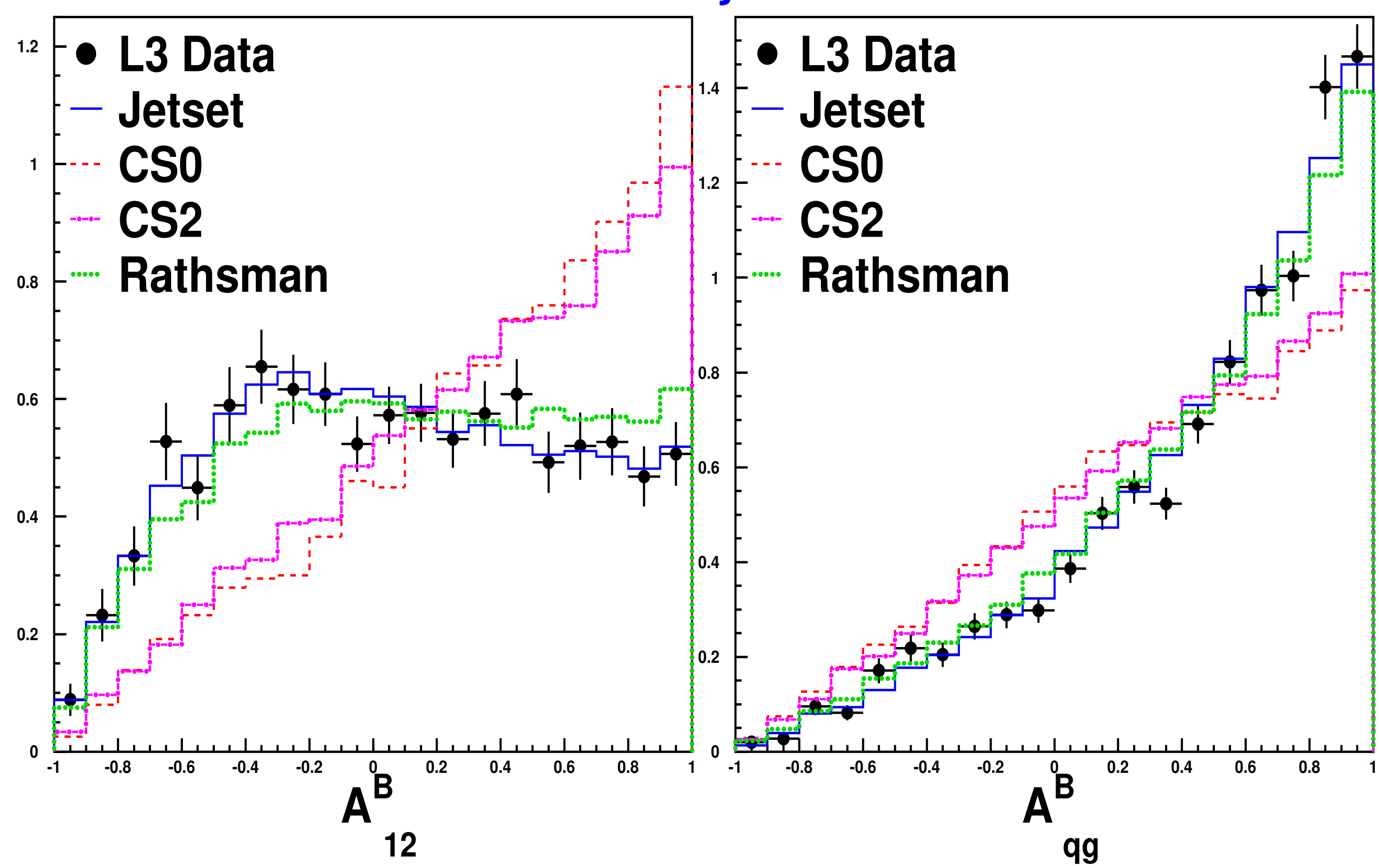
Rapidity Gaps in 3-jet Events

Rapidity gap events at ~1% level in ep, $p\bar{p}$
interpreted as exchange of a color singlet

Might expect in
up to 10%
of $e^+e^- \rightarrow$3-jets



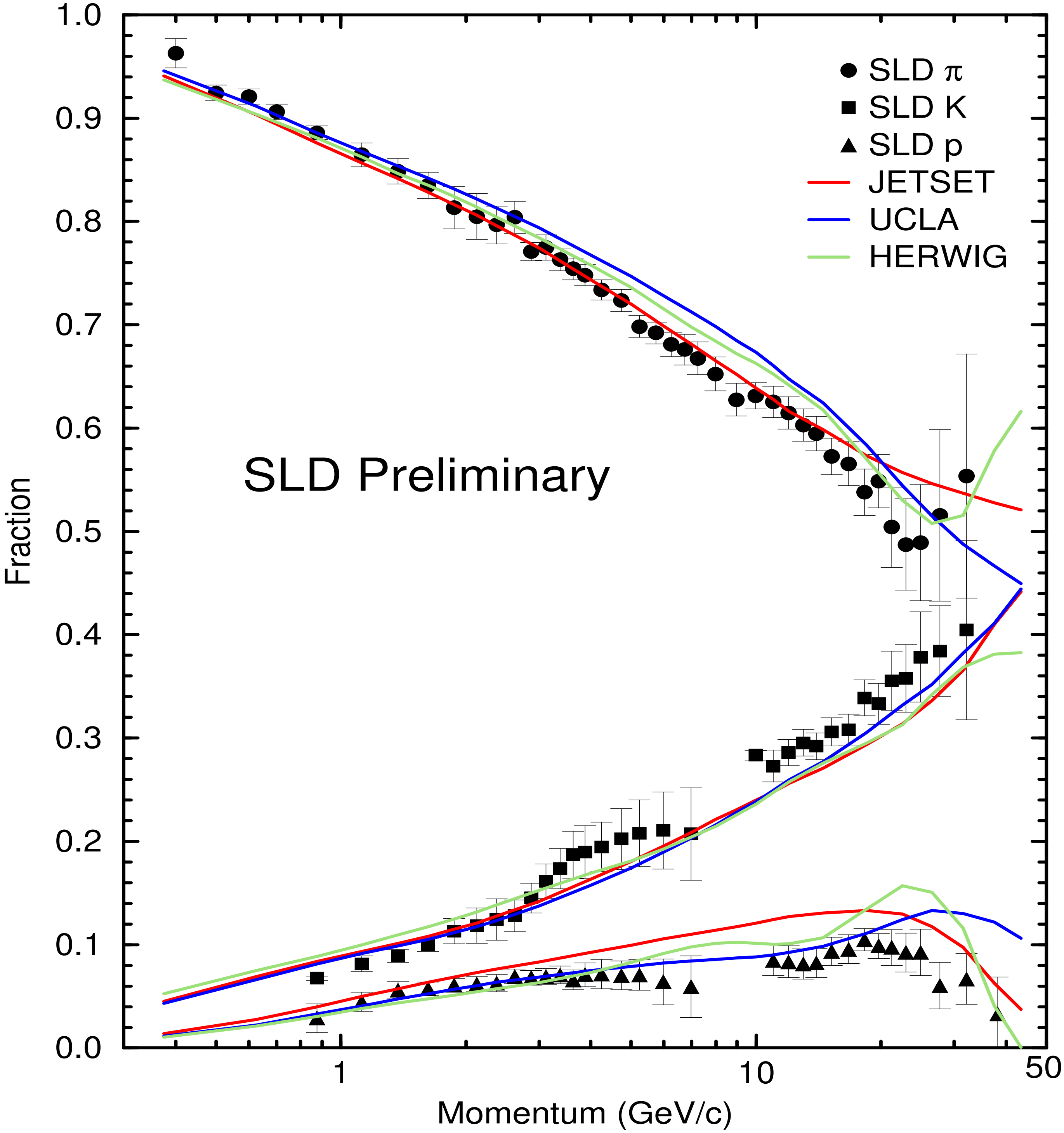
• New L3 study using e.g. asymmetry in angles between tracks in ea. jet to their bisector



→ No evidence for singlets, limits of 6-8%

Identified Particles

- $\pi^{\pm}K^{\pm}p$ data now quite precise, wide coverage

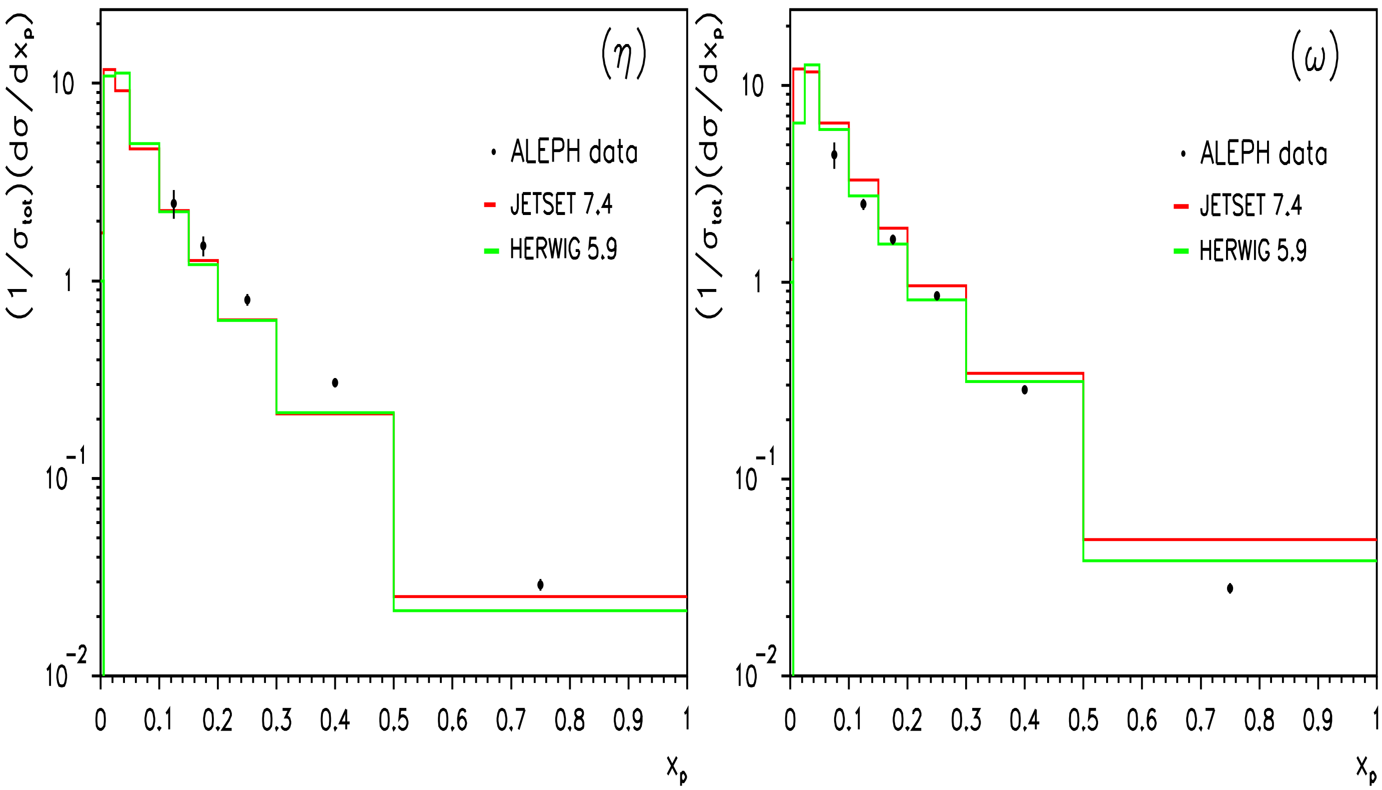


→ again, not easy to measure well

→ need to combine all LEP/SLC msmts.

→ nice range for fragmentation model tests

- Improved results from ALEPH on ω,η



$\rightarrow$ another challenging analysis

$\rightarrow$ nice coverage and precision

$\rightarrow$ ...though would like to go to lower x_p

$\rightarrow$ continuing to push the models

Have observed

pseudoscalar, vector, scalar, tensor mesons,
octet, decuplet, orbitally excited baryons

Are still more type of particles produced?

How many (few!) primaries are in a typical event?

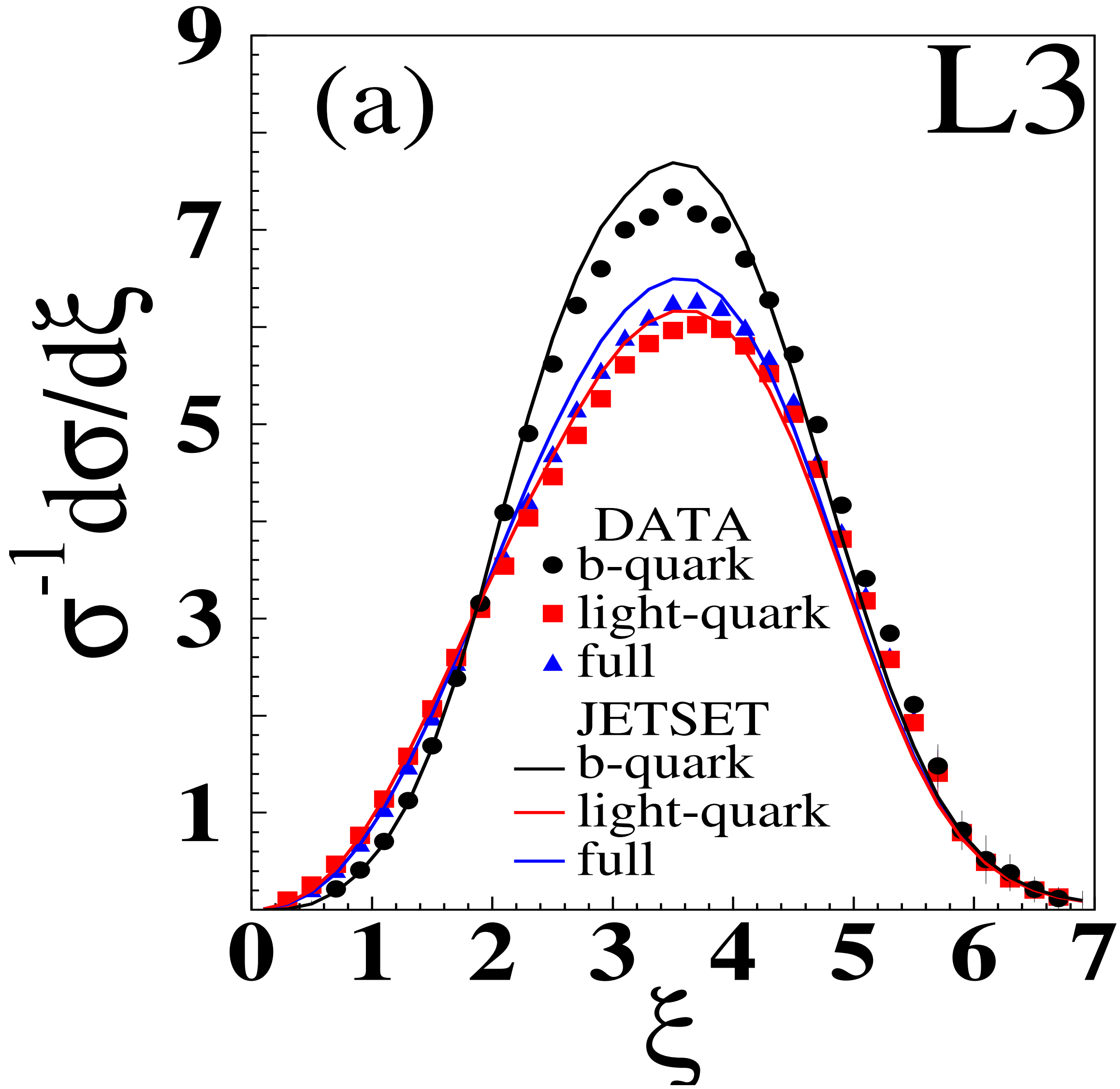
Heavy and Light Flavors

Effect of the b-quark mass seen in

- Hard Gluon radiation (see talk by P.Bambade)
- Soft Gluon radiation (dead cone)

B-hadron properties seen in many ways

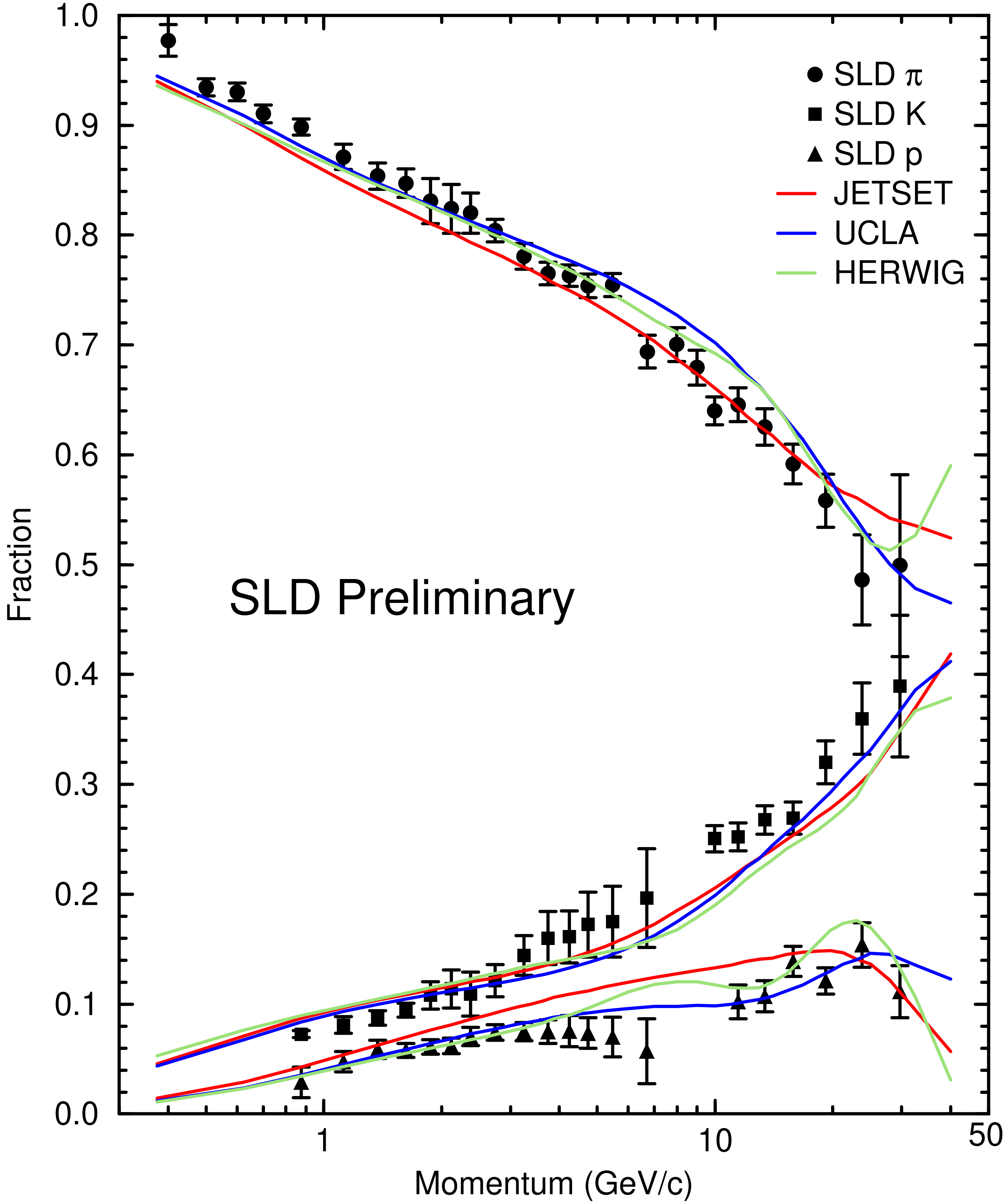
- Inclusive distributions from L3



→ coverage same as for full data sample

→ precision still very good

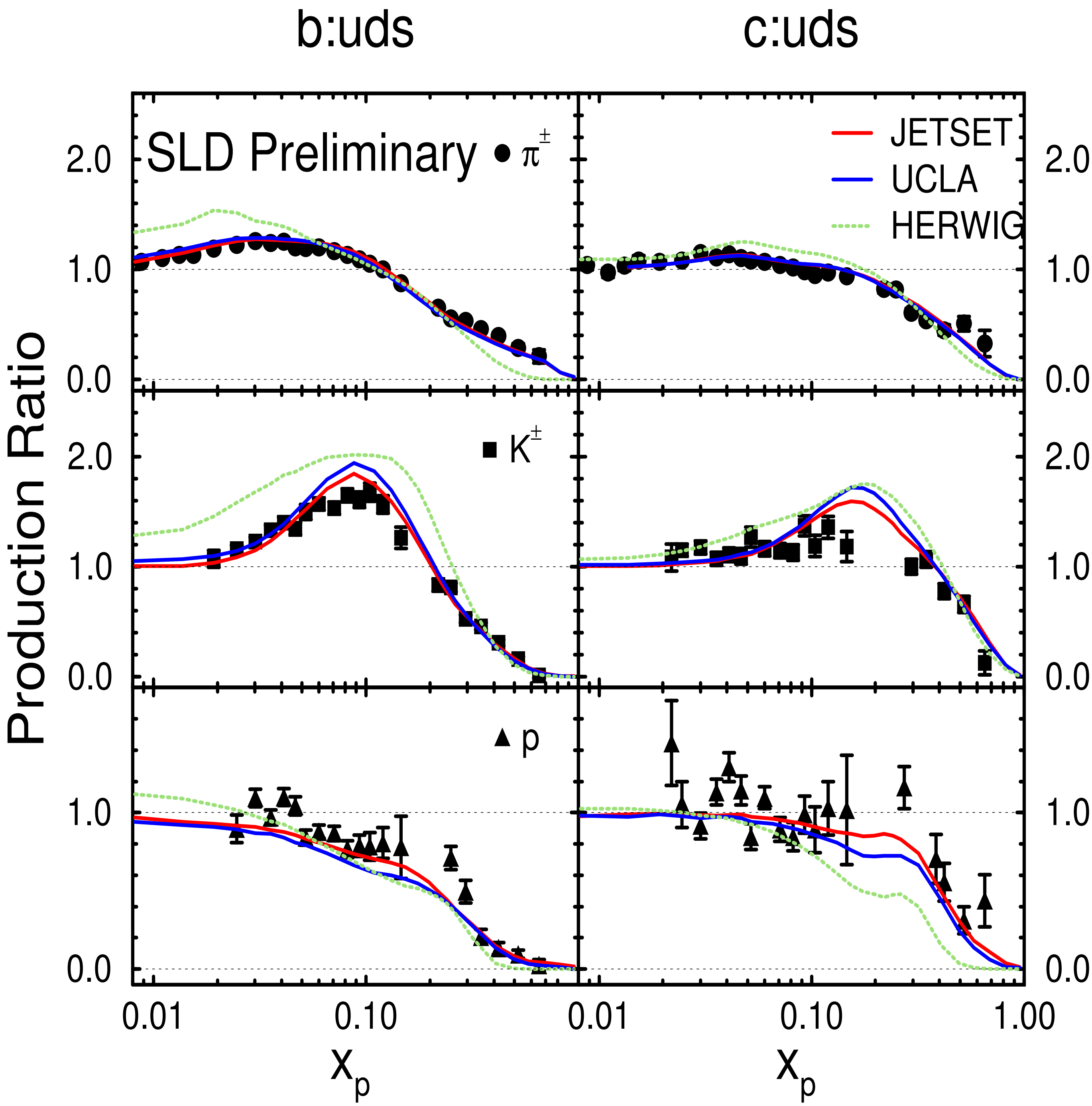
• Identified particles from SLD, in light-flavors



→ coverage comparable to full data sample

→ same problems with models

- ...and b-, c-flavors



→ qualitative features expected from hard frag., high decay multiplicity of B,D hadrons

→ precise model tests for B,D prod. & decay

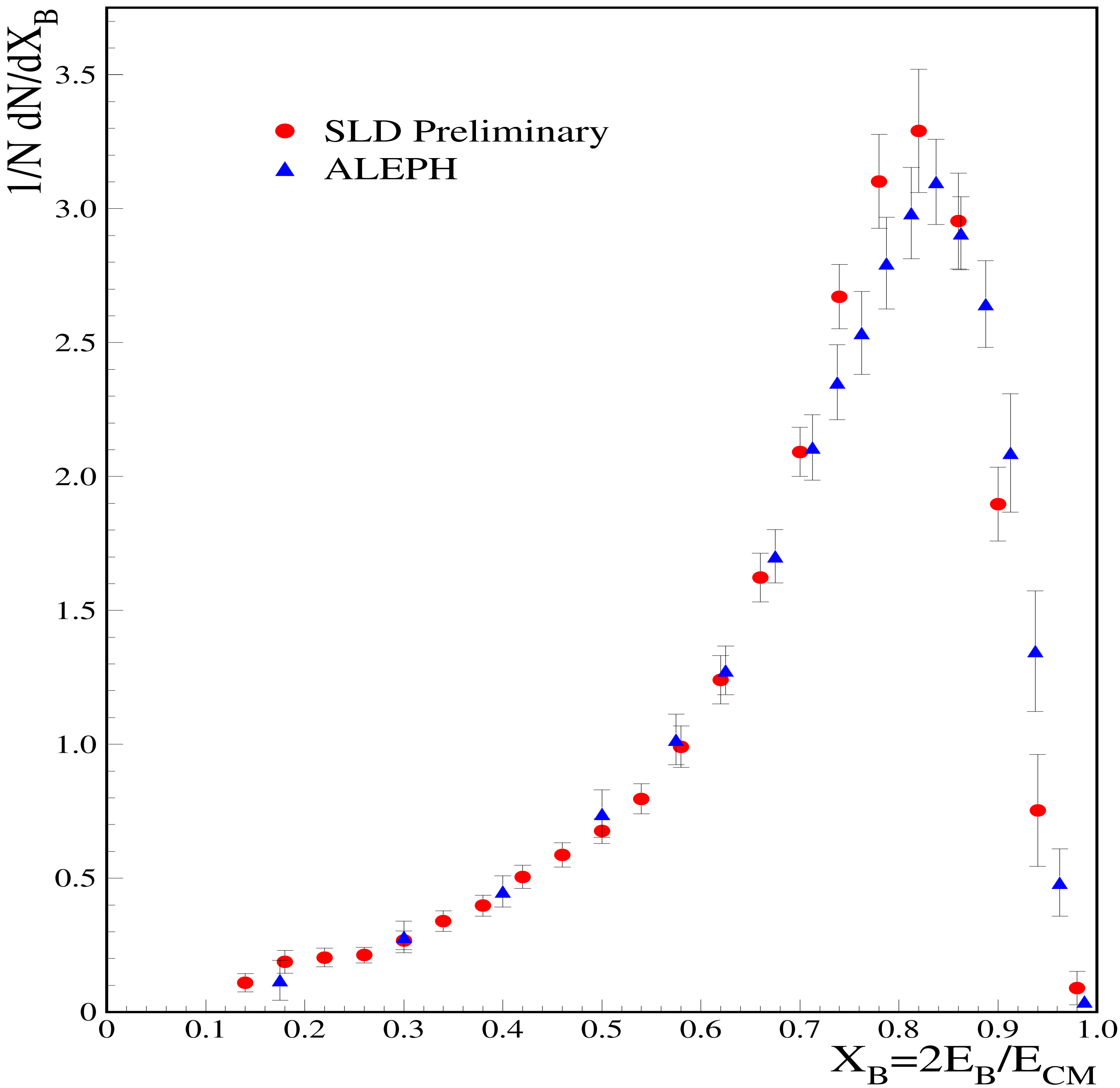
problems with HERWIG π, K

all models suspect for high-x $p/\bar{p}$

Leading Particles

Leading B hadrons

- Spectrum ~calculable in pQCD!
- Partial reconstruction of large samples done

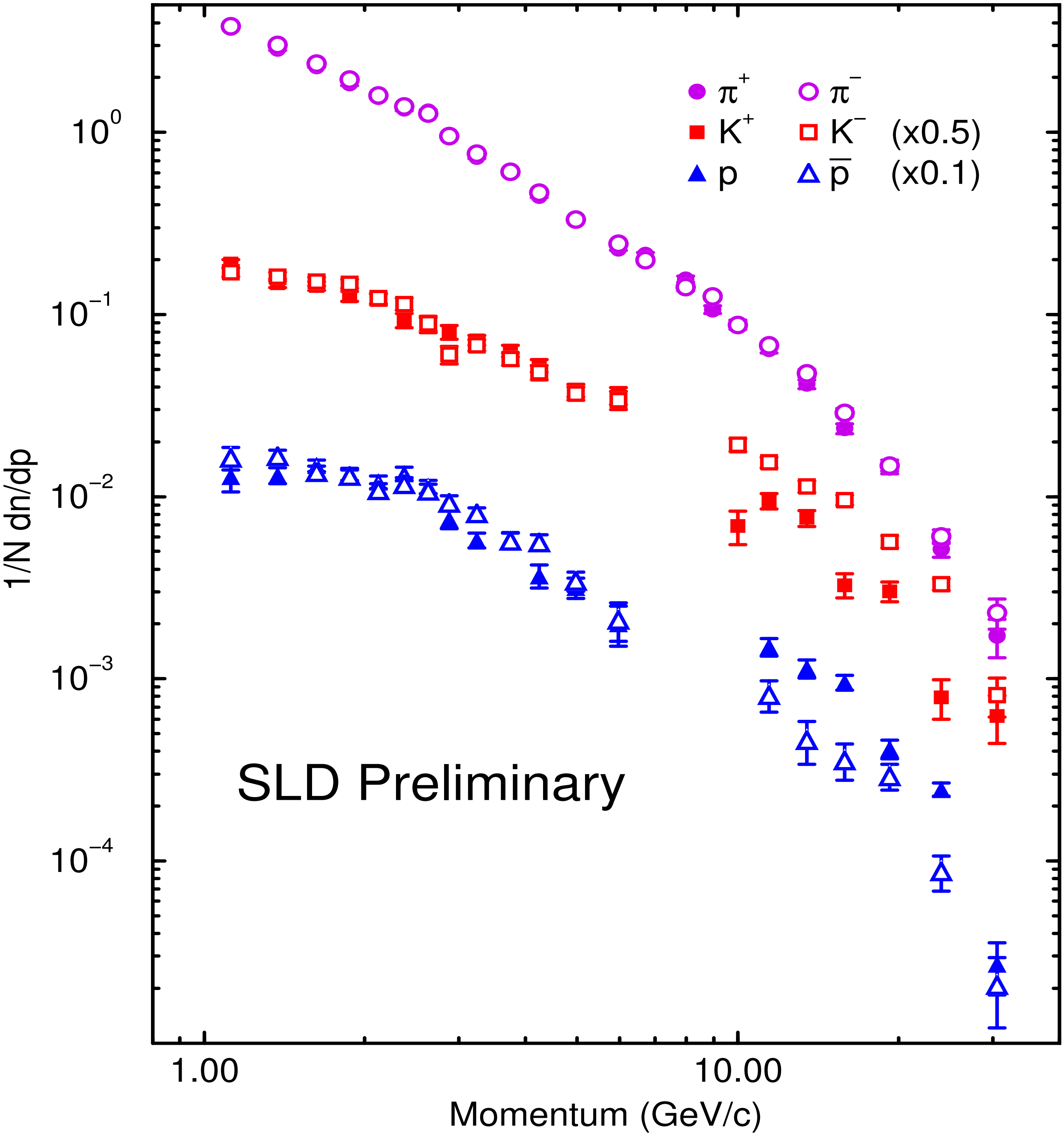


→ wonderful coverage, precision

→ experimental disagreement!

Leading light hadrons

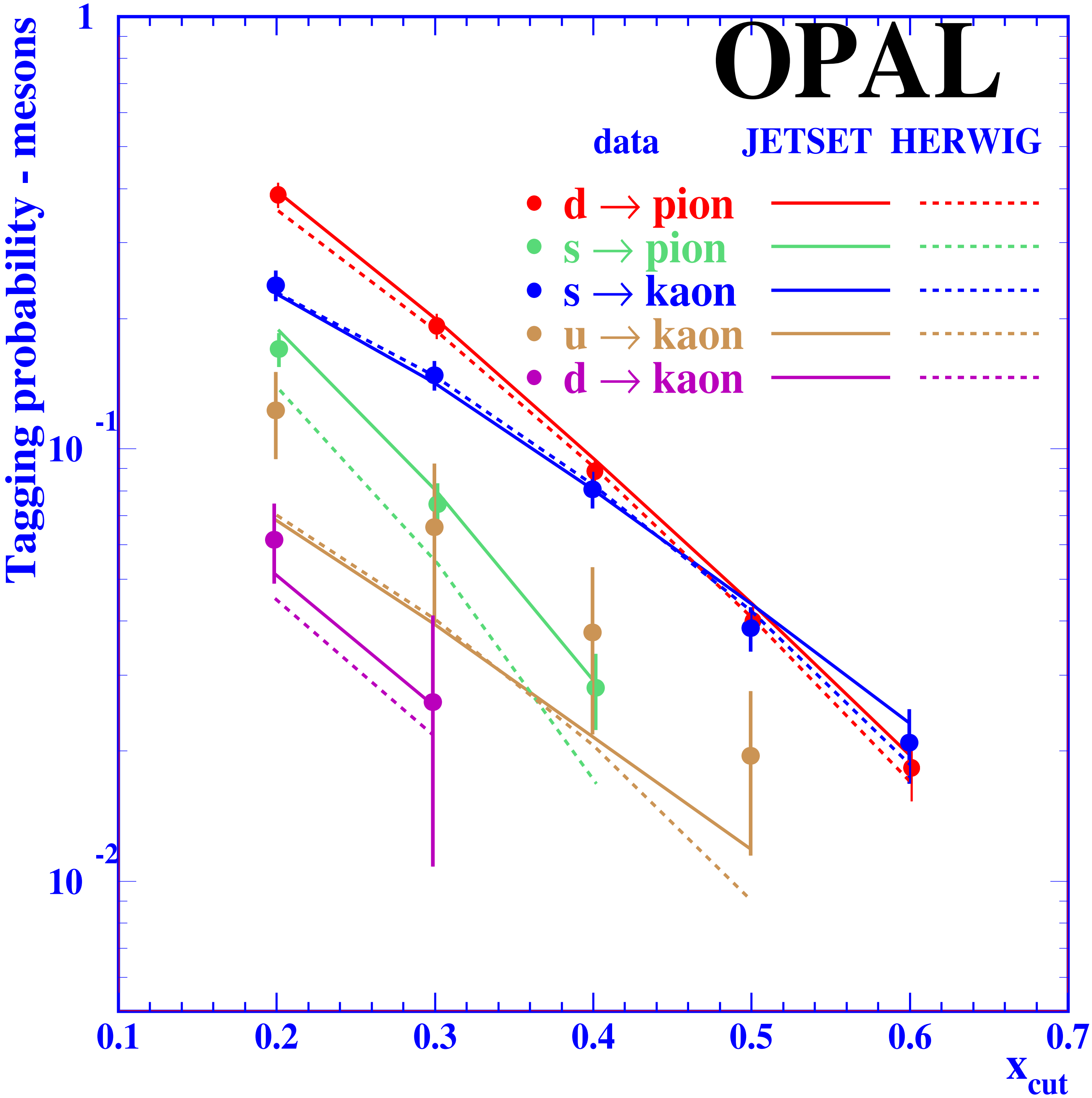
- updated u+d+s result from SLD



→ nice qualitative results, clear signals

→ ...but no quantitative information on the individual light flavors

- Can extract using very high statistics and double tagging of jets with high-p particles
- Published result from OPAL



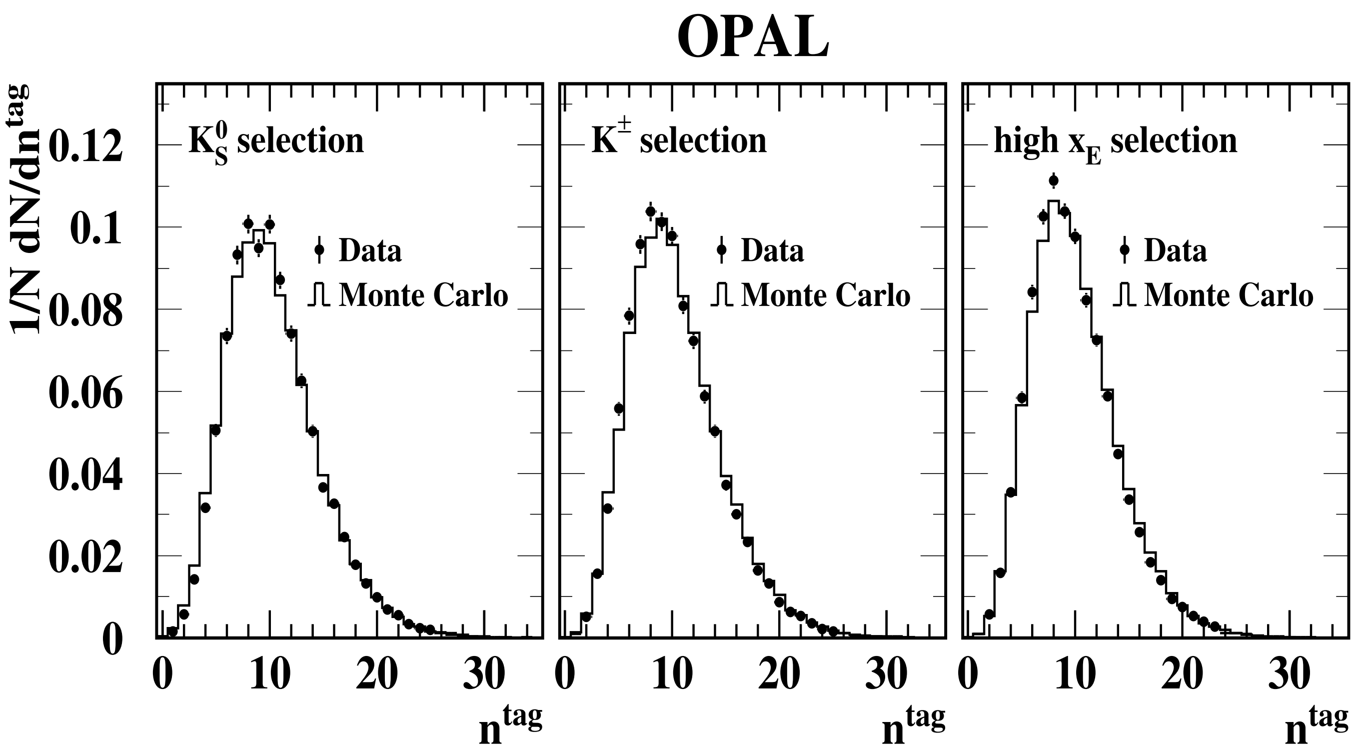
→ experimental tour de force

→ ...but limited by double-tag statistics

Individual Light Flavors

Applying leading particle tags

- New result from OPAL



→ distributions for tagged samples consistent with good precision

→ ...but universality test limited by knowledge of the tagged sample compositions

$$\bar{n}_u = 17.77 \pm 0.51\ \text{(stat)}\ {}^{+0.86}_{-1.20}\ \text{(syst.)}$$

$$\bar{n}_d = 21.44 \pm 0.63\ {}^{+1.46}_{-1.17}$$

$$\bar{n}_s = 20.02 \pm 0.13\ {}^{+0.39}_{-0.37}$$

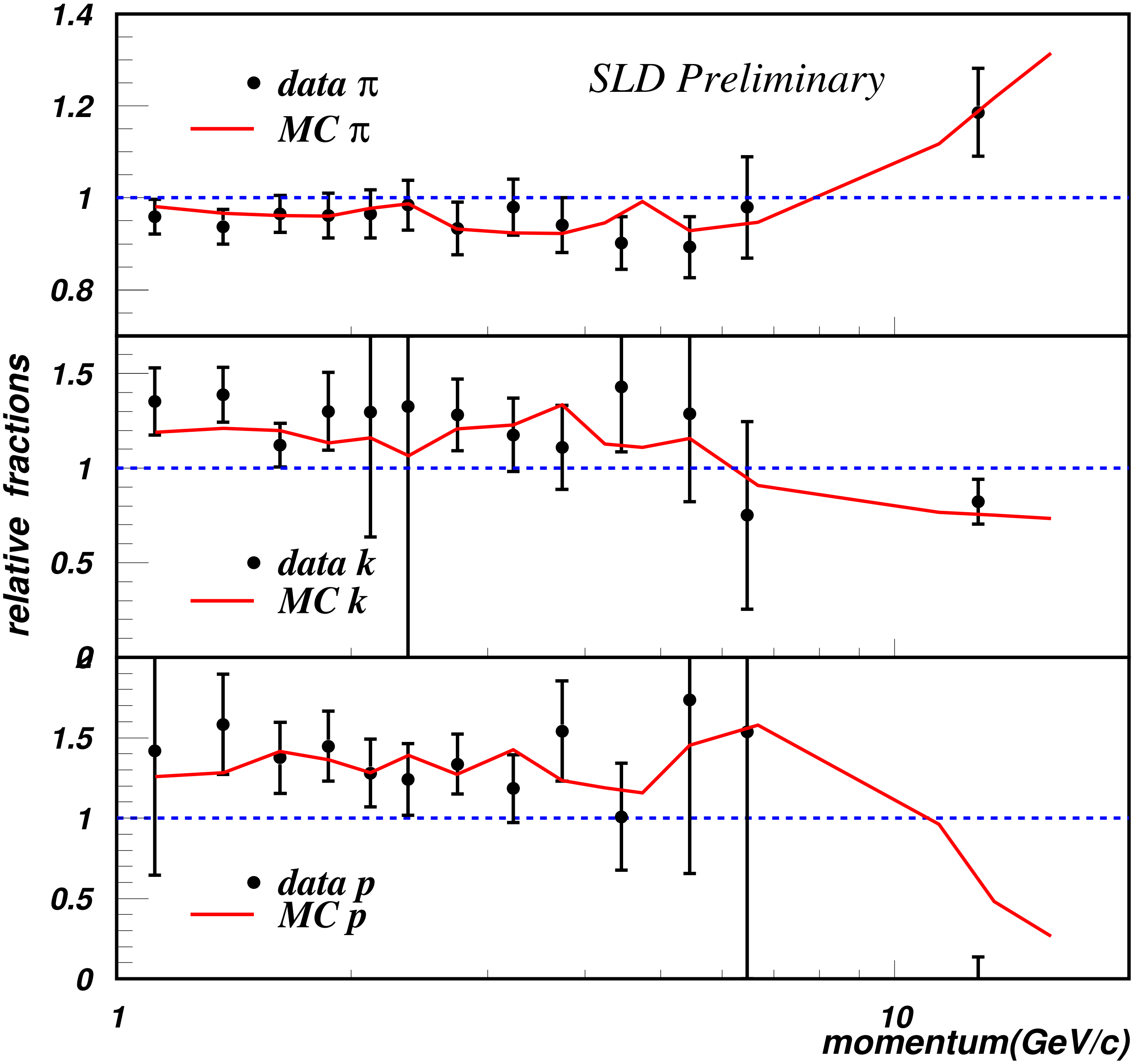
→ $\bar{n}_u$, $\bar{n}_d$ anticorrelated; results consistent

Gluon Jets

Well known that gluon jets fragment differently from quark jets: more, softer gluons/particles

Is there any difference in hadronization?

- New study from SLD: $f_{\pi}^{g\text{-}tag}/f_{\pi}^{uds\text{-}tag}$, etc.



→ uncorrected data deviate from unit ratio

→ ...but MC consistent; diffs. <~few % level

What have we Learned?

- Fragmentation is ~understood; LL calculations work too well
  - $\rightarrow$ but still plenty of new ways to test
- Hadronization is still exciting experimentally
  - $\rightarrow$ observation of tensor, scalar mesons excited baryons
  - $\rightarrow$ effects of large quark masses
  - $\rightarrow$ energy dependence
  - $\rightarrow$ quarks vs. gluons
  - $\rightarrow$ leading particles
- Models are quite useful; need more!
  - $\rightarrow$ JETSET: can do it all...but with an ever increasing number of parameters
  - $\rightarrow$ HERWIG: now the fragmentation standard; less succesful for hadronization
  - $\rightarrow$ UCLA: does a remarkable job for so few parameters – needs further testing

What's Next?

- Many more studies could be done with Z^0 data
  - → but already pushing experimental limits from
    - statistics of double-tags
    - detector calibration with data
- Higher energy lepton colliders:
  - → not clear how useful without a huge increase in statistics....
  - → jet flavor tagging has many potential applications at higher E
  - → run these machines at the Z^0 to calibrate detector and physics!
- B Factories
  - → plenty of statistics
  - → low energy is good!
    - clean observation of resonances
    - handful of primary particles?!?
    - clean charm below $b\bar{b}$ threshold
  - → asymmetric machines have no gaps in tracking, PID in the c.m. frame