Inclusive Spectra in Hadronic Events at SLD and BaBar

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Workshop on Fragmentation Functions and QCD
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- **Introduction**
- **Detectors and physics programs**
- **Stable charged hadrons:** $\pi^{\pm}$, $K^{\pm}$, **and** $p/\bar{p}$
- **Neutral reconstructed hadrons:** η, K^0, K^{*0}, ϕ, $\Lambda/\bar{\Lambda}$
- **Results:** **all (4 or 5) flavors**
  light, $c\bar{c}$ and $b\bar{b}$ flavors
  light q (vs $\bar{q}$) jets
  $q/\bar{q}$ vs gluon jets

  } Comparison with LEP, ARGUS

- **Conclusion and outlook**

Introduction: what is a Fragmentation Function?

- Ideally, given a (hard) parton $k=u,d,s,c,b,\bar{u},\bar{d},\bar{s},\bar{c},\bar{b},g$ with energy E_k, momentum $p_k\hat{z}$, and polarization $j_k\hat{s}_k$

  we want to know the probability density

$$F_k^h(m_h, f_h, j_h, p_h, \theta_h, \phi_h, \hat{s}_h ; E_k, p_k, j_k, \hat{s}_k)$$

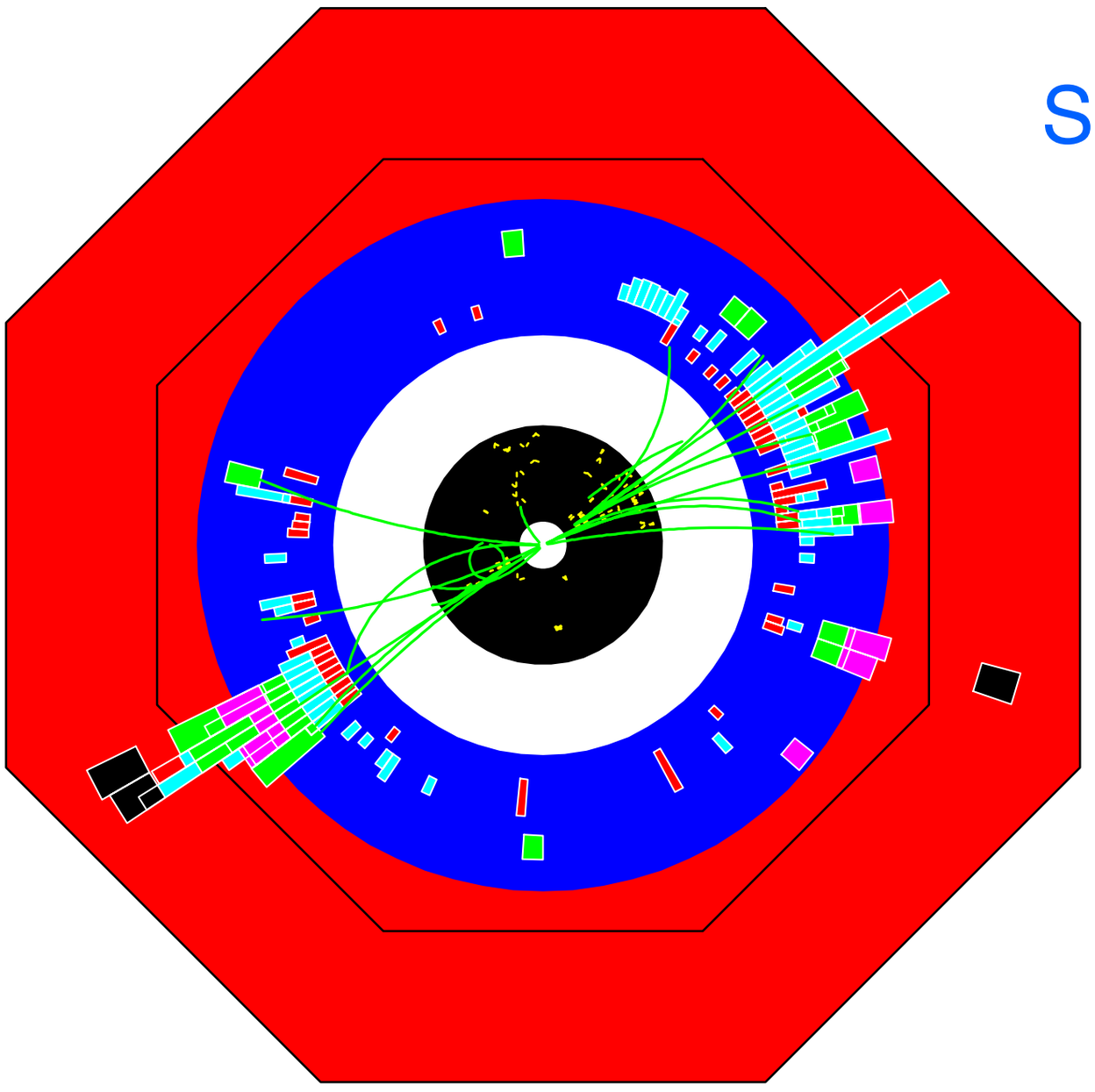
  to find a hadron h in its jet with: mass m_h, flavor f_h, spin j_h, polarization $\hat{s}_h$, momentum $(p_h\sin\theta_h\cos\phi_h, p_h\sin\theta_h\sin\phi_h, p_h\cos\theta_h)$

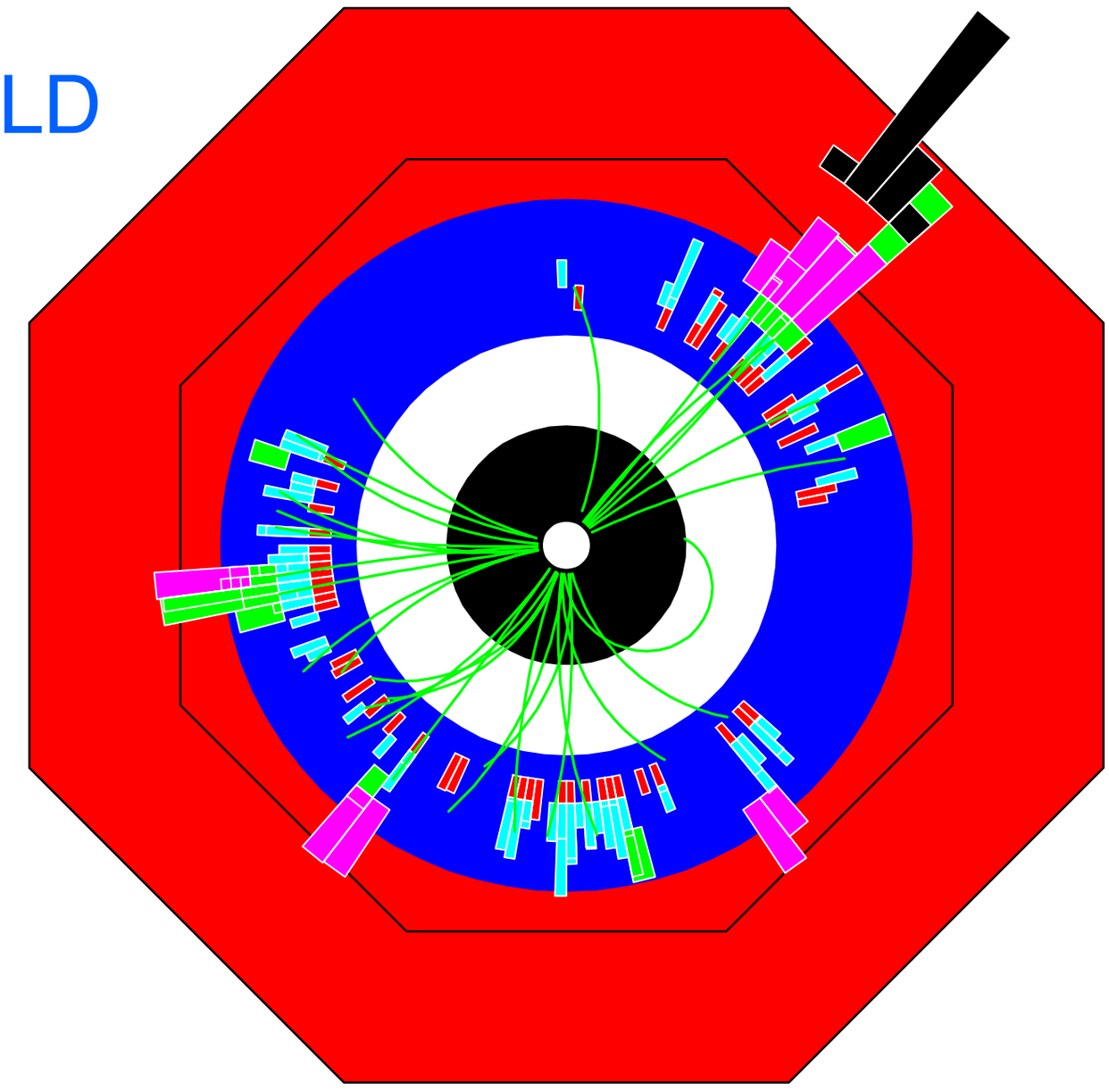
- We can integrate out/sum over many of these
- Today, consider: $F_k^h(x_h)$, where $x_h = f(p_h, E_k)$
  for several specific $h = \pi^\pm, K^\pm, p/\bar{p}$, ...
  and $k=u/\bar{u}/d/\bar{d}/s/\bar{s}/c/\bar{c}/b/\bar{b}$, $u/\bar{u}/d/\bar{d}/s/\bar{s}$
  $u/\bar{u}/d/\bar{d}/s/\bar{s}/c/\bar{c}$, $c/\bar{c}$, $b/\bar{b}$, $u/d/s$, g

but partons do not appear alone

- rather, in colorless sets, e.g. $q\bar{q}$, $q\bar{q}g$, $q\bar{q}gg$, ...
- how many jets are in these $e^+e^- \rightarrow Z^0 \rightarrow$ hadrons events?

SLD

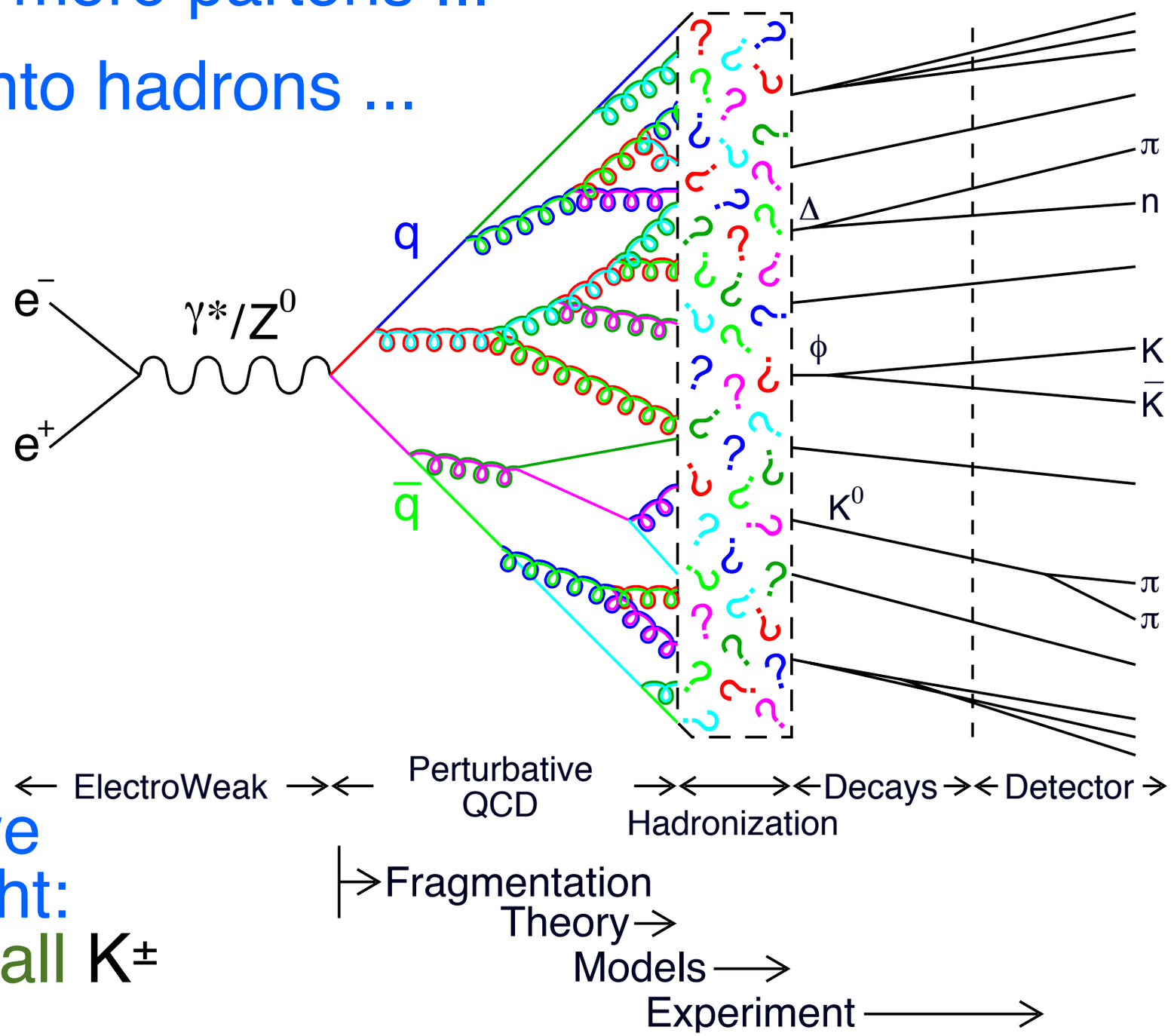




- at BaBar, jets are much wider....

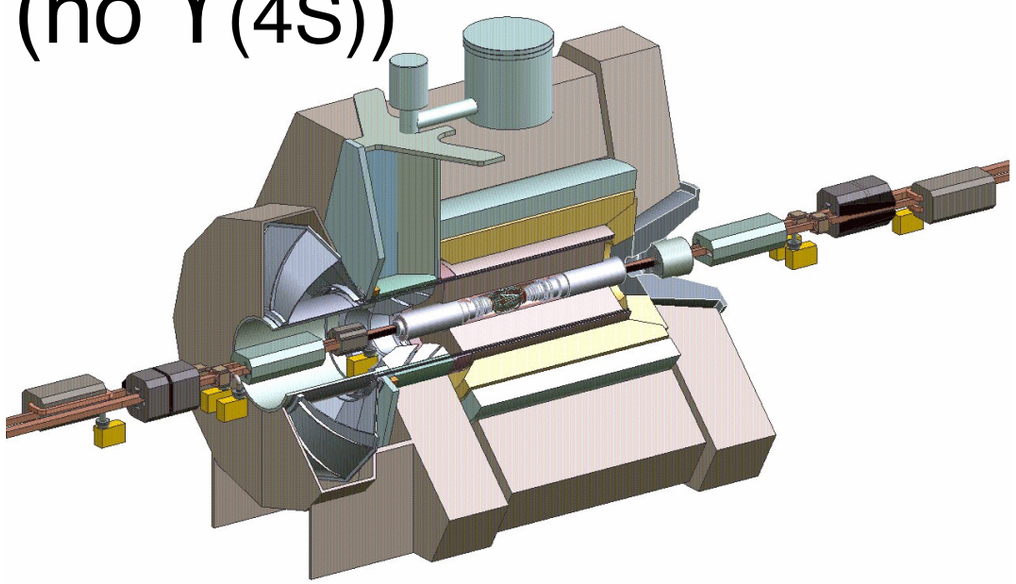
What do we mean by fragmentation?

- 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
- or some subset of these
- experimentally, we push from the right:
  - measure e.g. all $K^{\pm}$
  - then ϕ
  - subtracting ϕ daughters gets closer to primary $K^{\pm}$

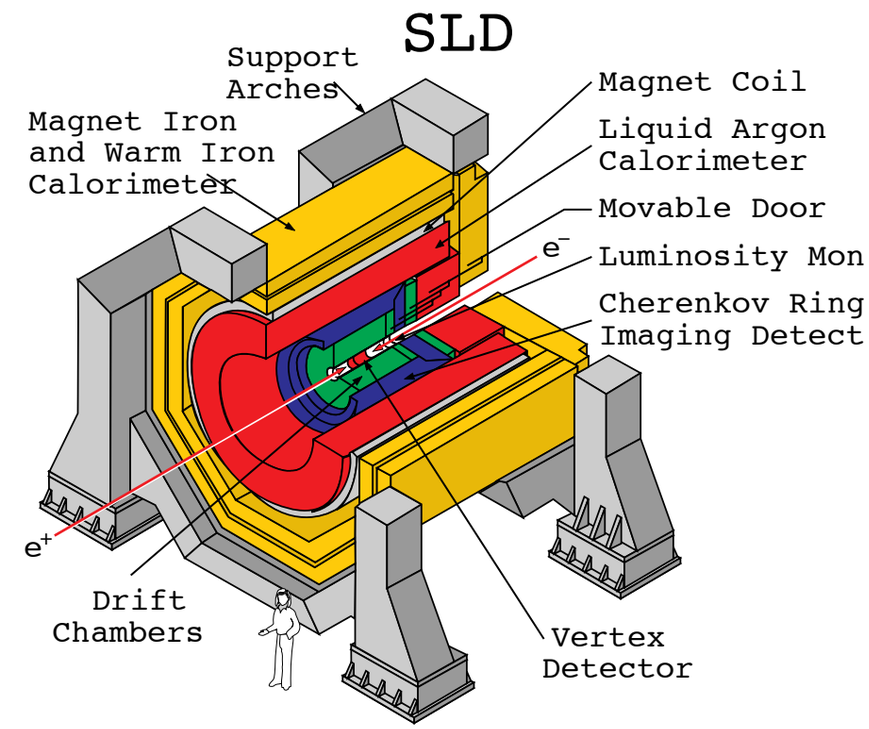


The BaBar and SLD Experiments

- $e^+e^- \rightarrow \gamma^* \rightarrow u\bar{u}:d\bar{d}:s\bar{s}:c\bar{c}$
  10.54 GeV 4 : 1 : 1 : 4
  (no $\Upsilon(4S)$)



- $e^+e^- \rightarrow Z^0 \rightarrow u\bar{u}:d\bar{d}:s\bar{s}:c\bar{c}:b\bar{b}$
  91.2 GeV 17:22:22:17:22



→ cm frame boosted in the lab, $\beta\gamma$=0.55

→ excellent tracking, particle ID, γ/π^0 recon

→ very high luminosity: ~200M hadronic events here use only 3 million

→ cm, lab frames the same

→ excellent tracking particle ID

→ decent luminosity: ~0.5 million hadronic events

Track Finding

- both detectors have very good tracking
  - → efficiency >90% within acceptance
  - → momentum, angular resolution more than adequate
- we must understand the efficiency as well as possible
  - → varies rapidly with momentum p below ~1 GeV/c
  - → calibrate using data and simulated Bhabha, $\tau^+\tau^-$, exclusive hadronic final states (BaBar)
  - → uncertainties are strongly correlated across the full p range

    SLD: 1% norm.⊕(0.3→4.2)% (p=0→45.6 GeV/c)

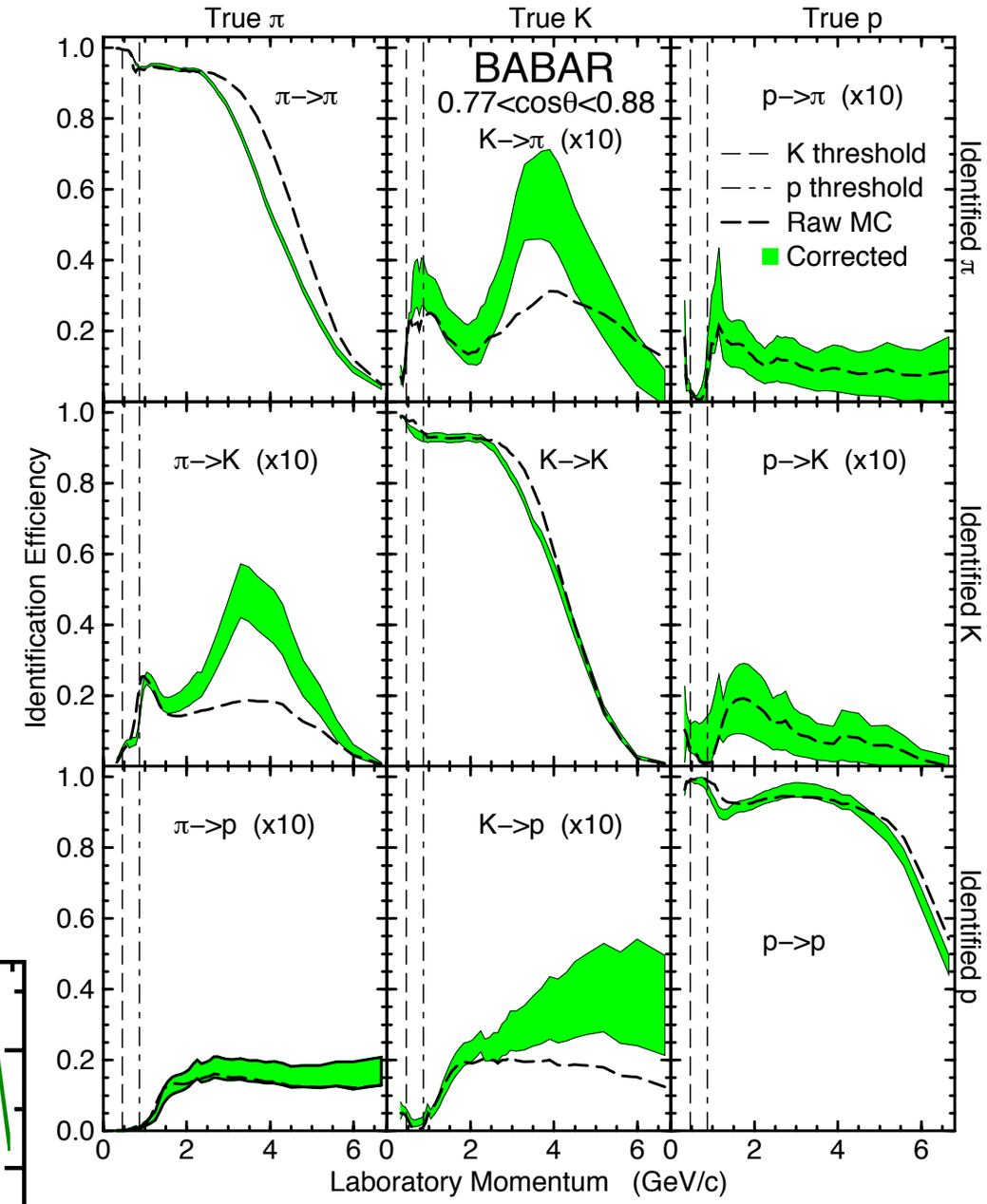
    BaBar: ~2.4→0.8% (p=0.2→1); 0.8% p>1 GeV/c
- we must understand the resolution well enough
  - → varies rapidly with (1/p) below ~1/(35 GeV/c)
  - → calibrated using known masses, K_S, ...

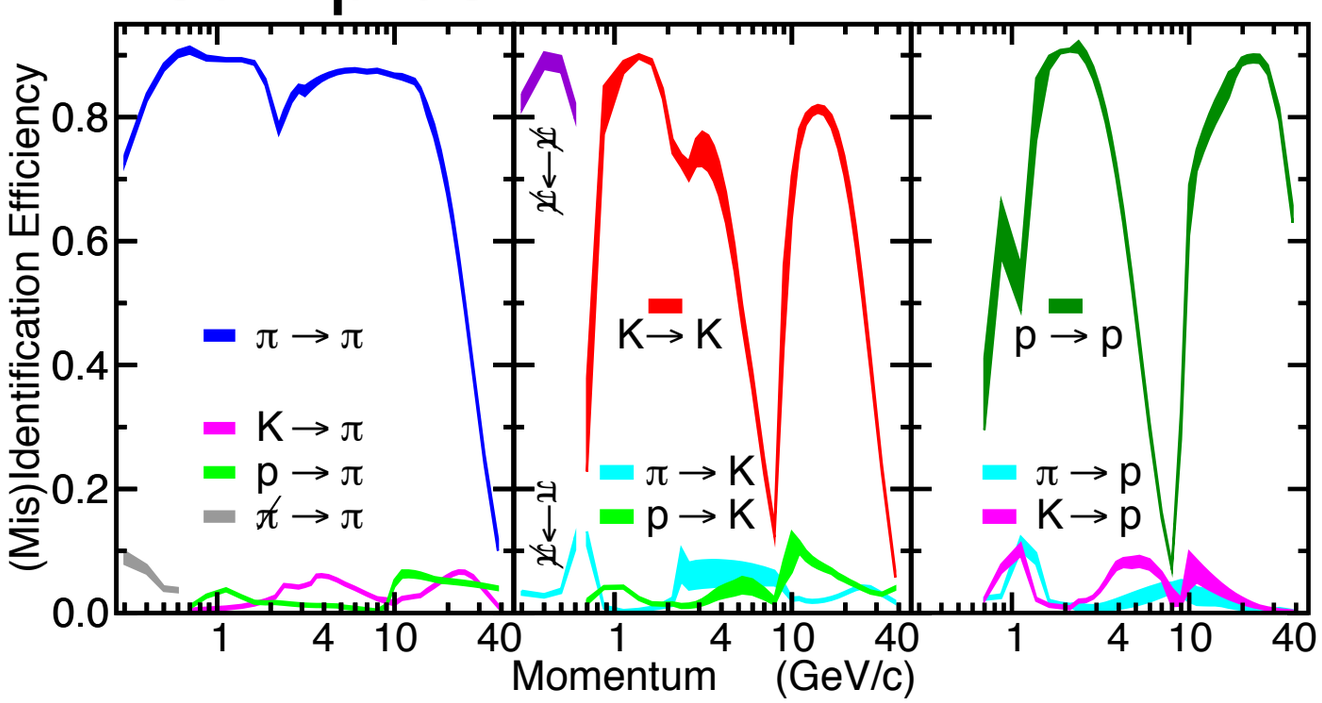
    SLD: 4% in highest p bin

    BaBar: not an issue due to low E_{CM}, high B-field

Charged Hadron Identification

- both detectors have excellent identification of (high quality) tracks as $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$ (or $e^{\pm}$, $\mu^{\pm}$)
  - → Ring Imaging Cherenkov detectors, plus dE/dx (BaBar)
  - → >90% efficiency over much of the p range
  - → few-% misidentification
  - → calibrated with data control samples





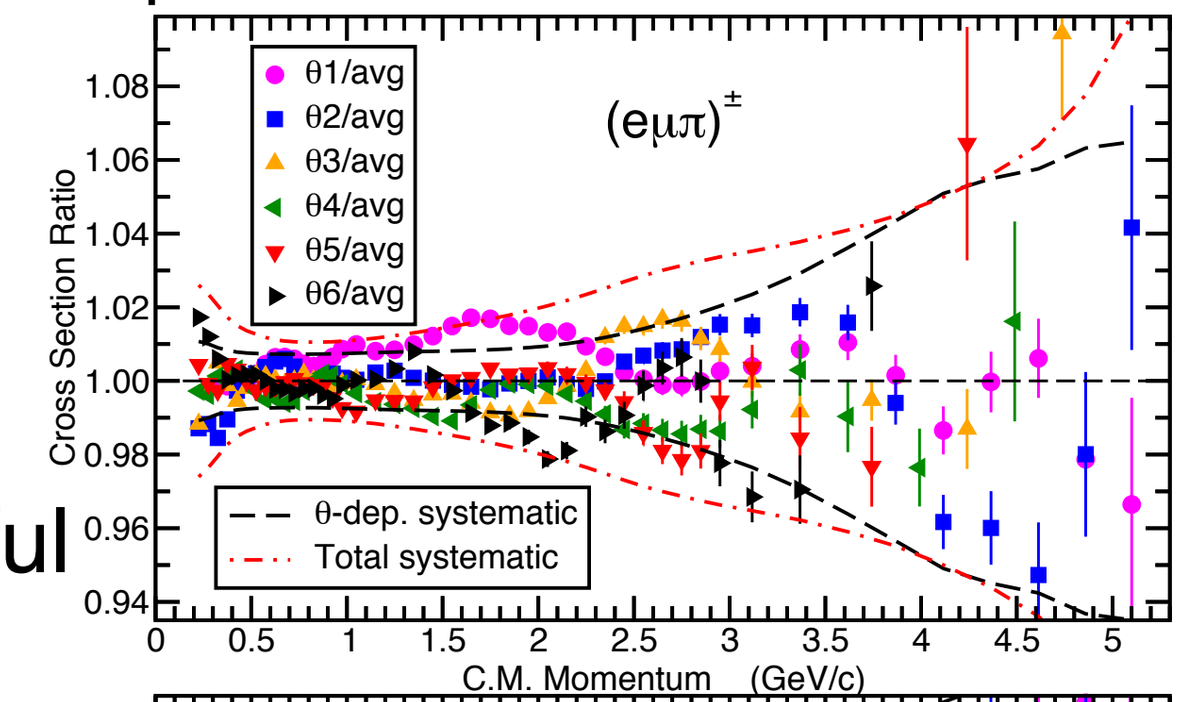
- → few-% uncertainties, up to very high p
- → strongly correlated over ±2-5 bins

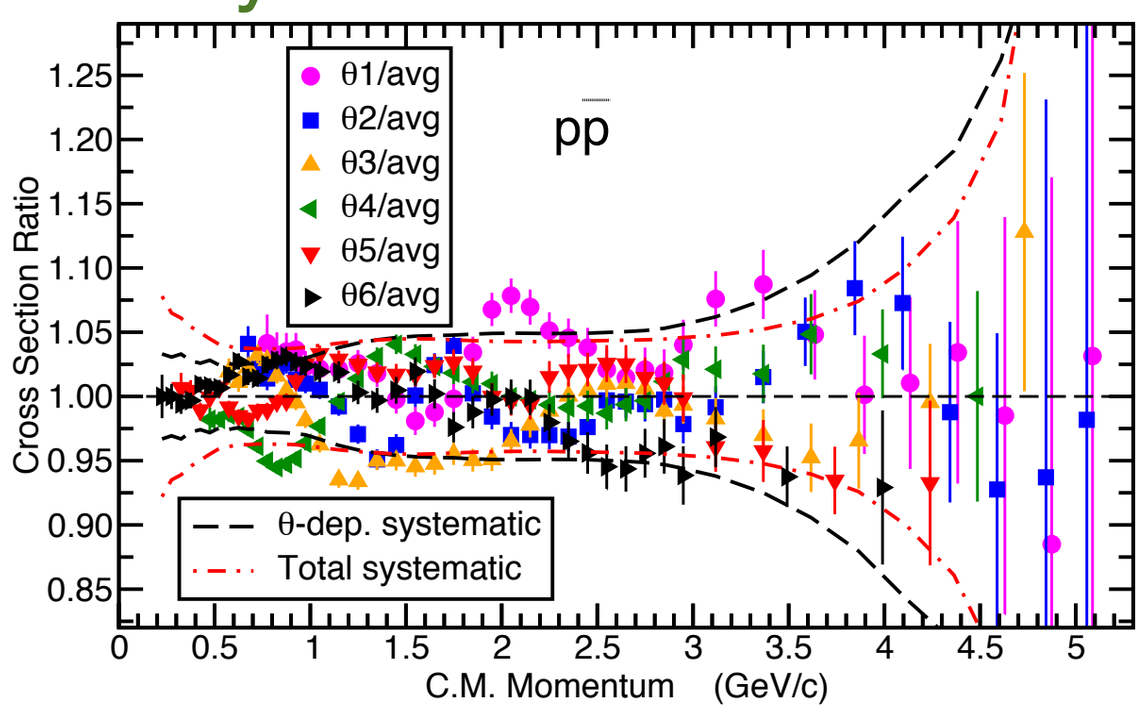
$\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$ Analysis

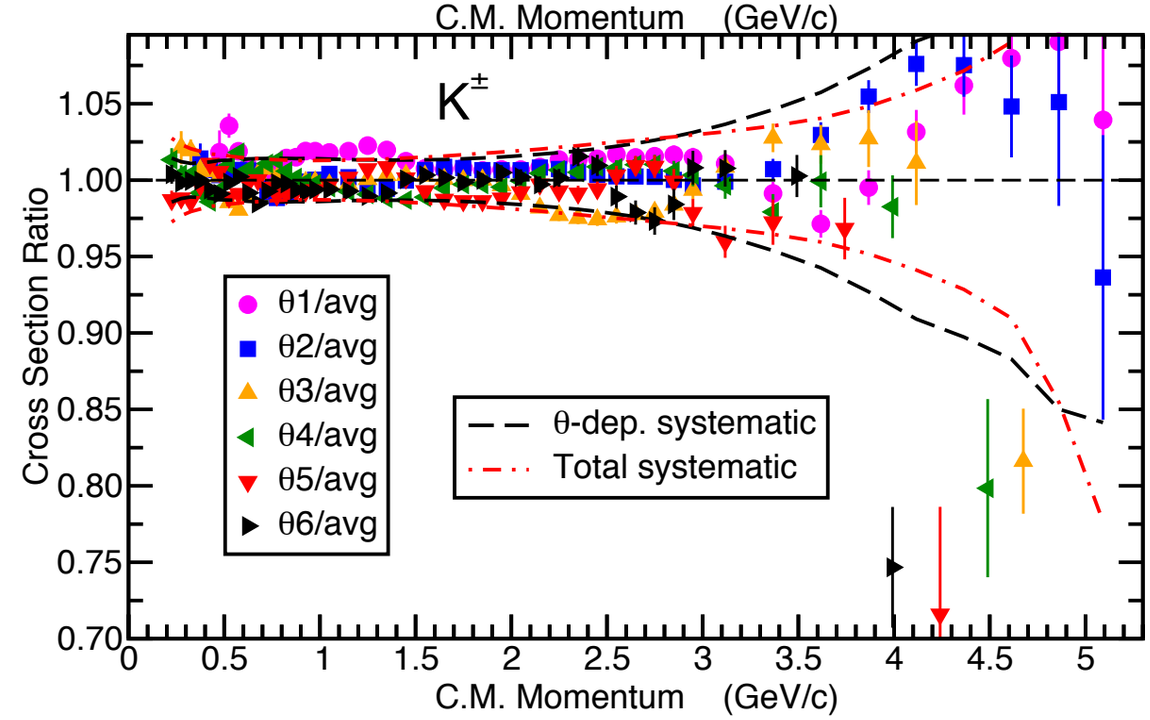
- select hadronic events
  - → nontrivial to get unbiased samples
  - → require 3-5 charged tracks, T-axis well within acceptance, high visible energy
- select good tracks
  - → many measured coordinates, extrapolation near the primary interaction point (IP)

  convention: include tracks from K_S, s-baryon decays
- identify the particles
  - → count ID'd tracks, apply inverse of efficiency matrix
  - → check that they sum to the total number of tracks
- correct these spectra for
  - → physics backgrounds: few %, mostly $\tau^+\tau^-$
  - → interactions in detector material: up to 4% at low p, SLD uses only $\bar{p}$ below 2 GeV/c
  - → efficiency, resolution, transform to c.m. frame (BaBar)

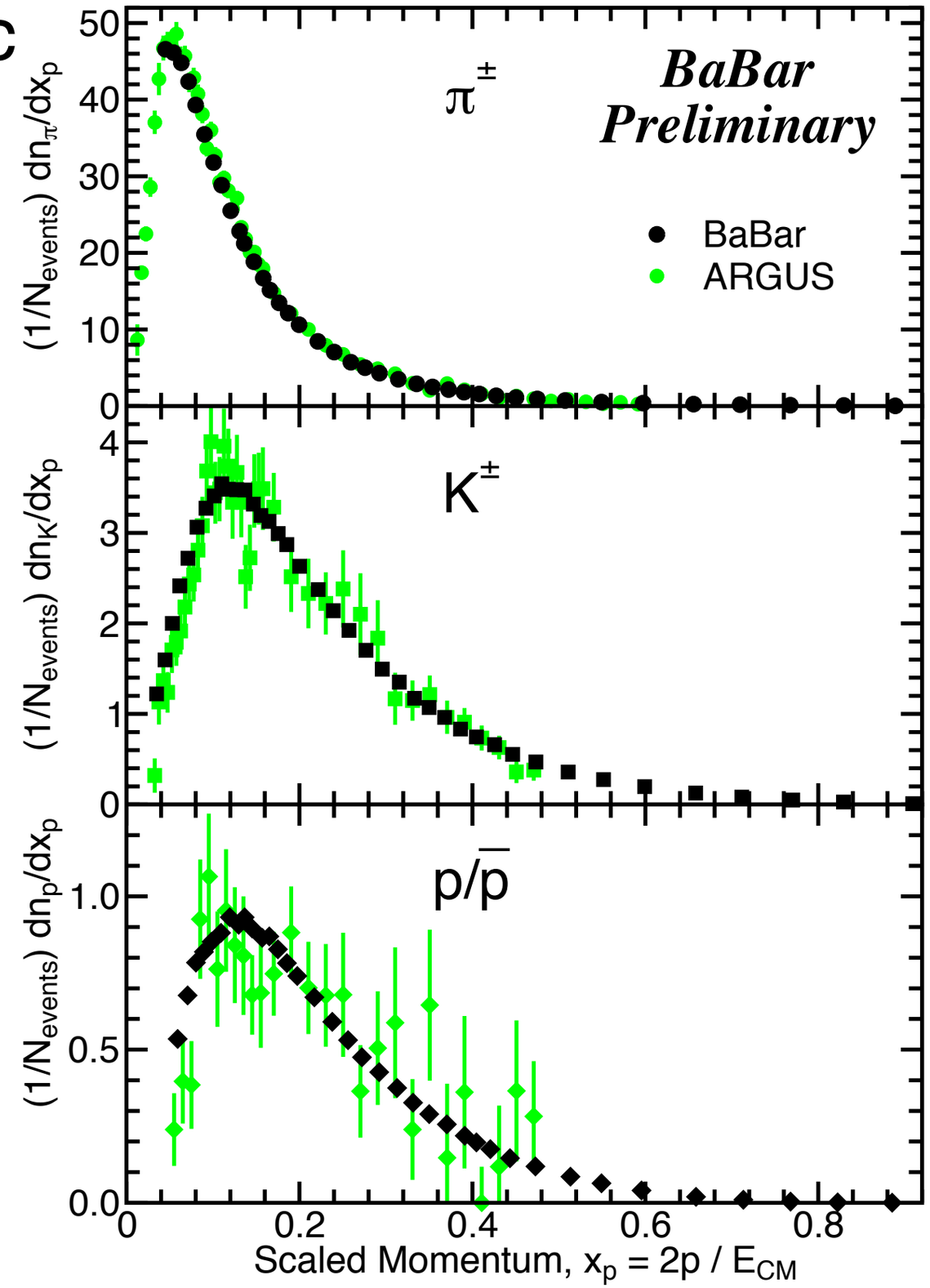
- extensive systematic cross checks
  - → compare data with MC in every variable
  - → compare positively and negatively charged tracks
  - → check for dependence on θ, ϕ ....
- BaBar makes ~independent msmts. in six θ regions
  - → different backgrounds, amounts of material, transforms to CM frame
  - → comparison gives powerful systematic checks





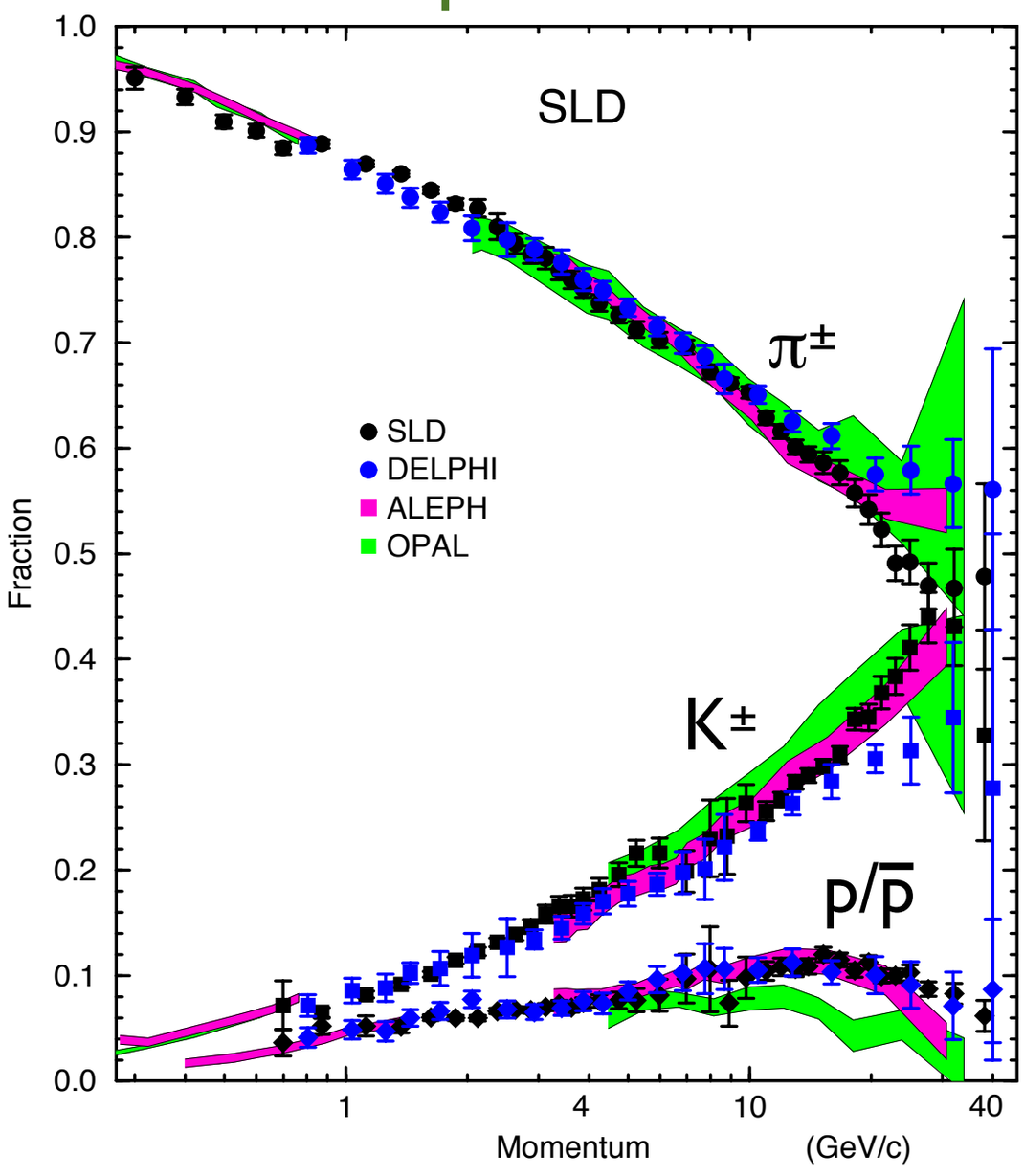


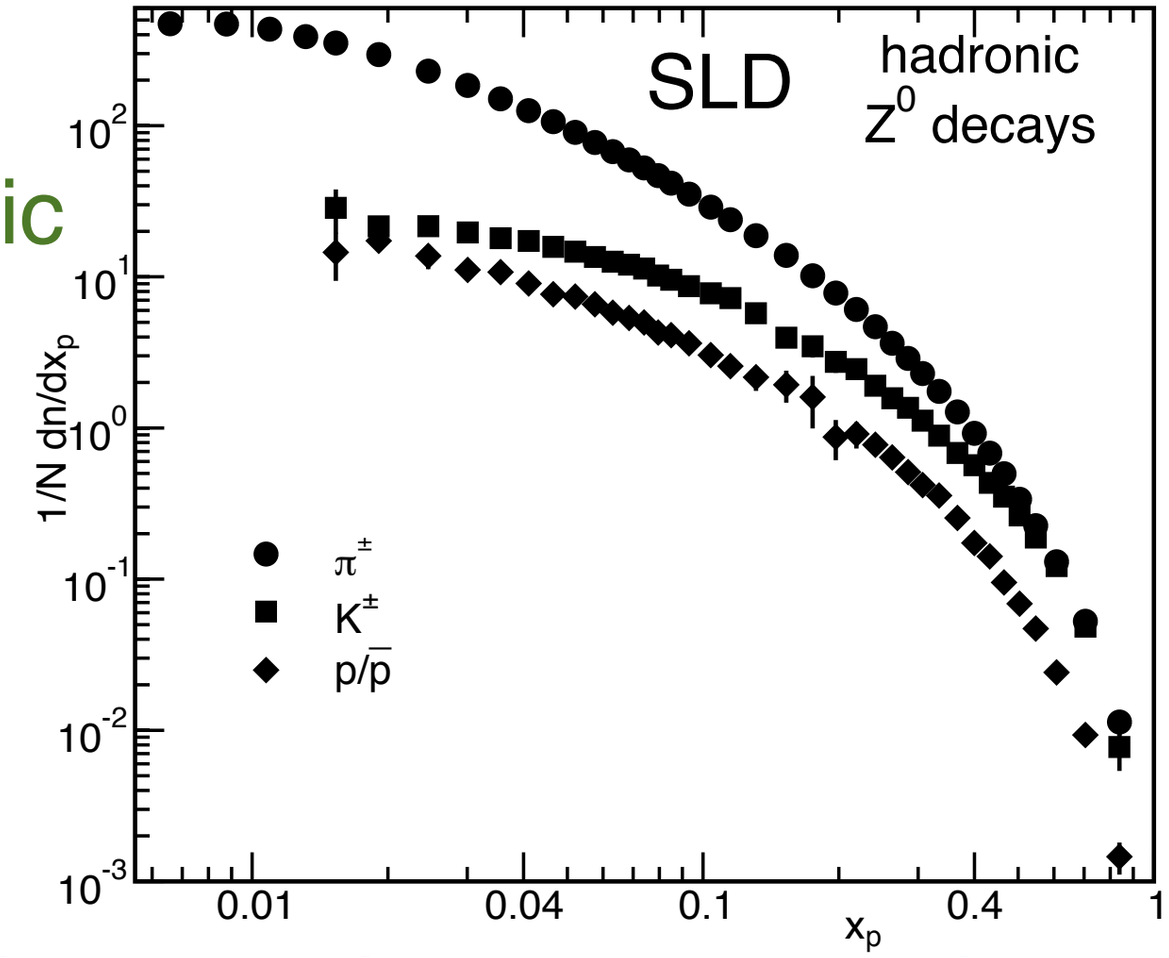
- BaBar results, averaged over θ, in terms of $x_p = 2p/E_{CM}$
  - → coverage from 0.2 GeV/c to the kinematic limit, 5.27 GeV/c
  - → captures the bulk of the $K^{\pm}$ and $p/\bar{p}$ spectra
  - → ...but just gets the peak of the $\pi^{\pm}$ spectrum



- compares nicely with previous data from ARGUS
  - → consistent everywhere
  - → generally more precise
  - → better high-x_p coverage
  - → ARGUS extends to lower x_p for $\pi^{\pm}$, nice complementarity

- SLD results
  - → coverage from 0.2 ($\pi^{\pm}$) or 0.65 GeV/c to the kinematic limit, 91.2 GeV/c
  - → just gets the peaks of all three spectra

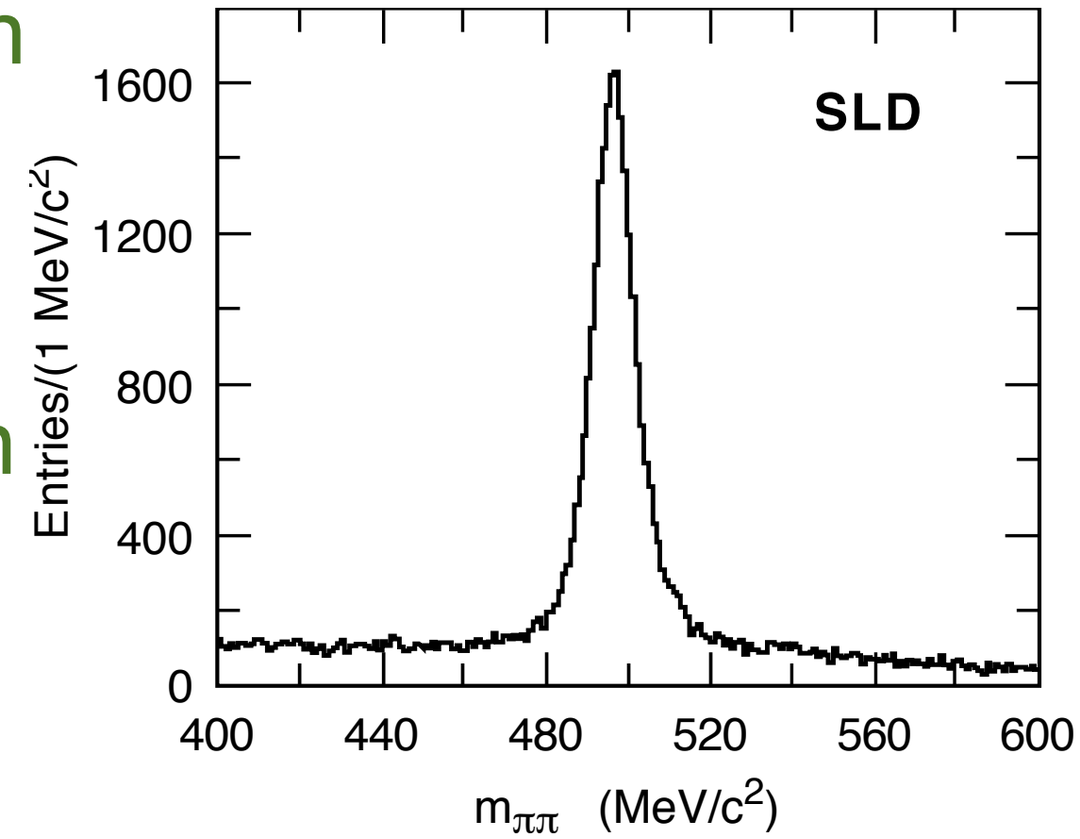


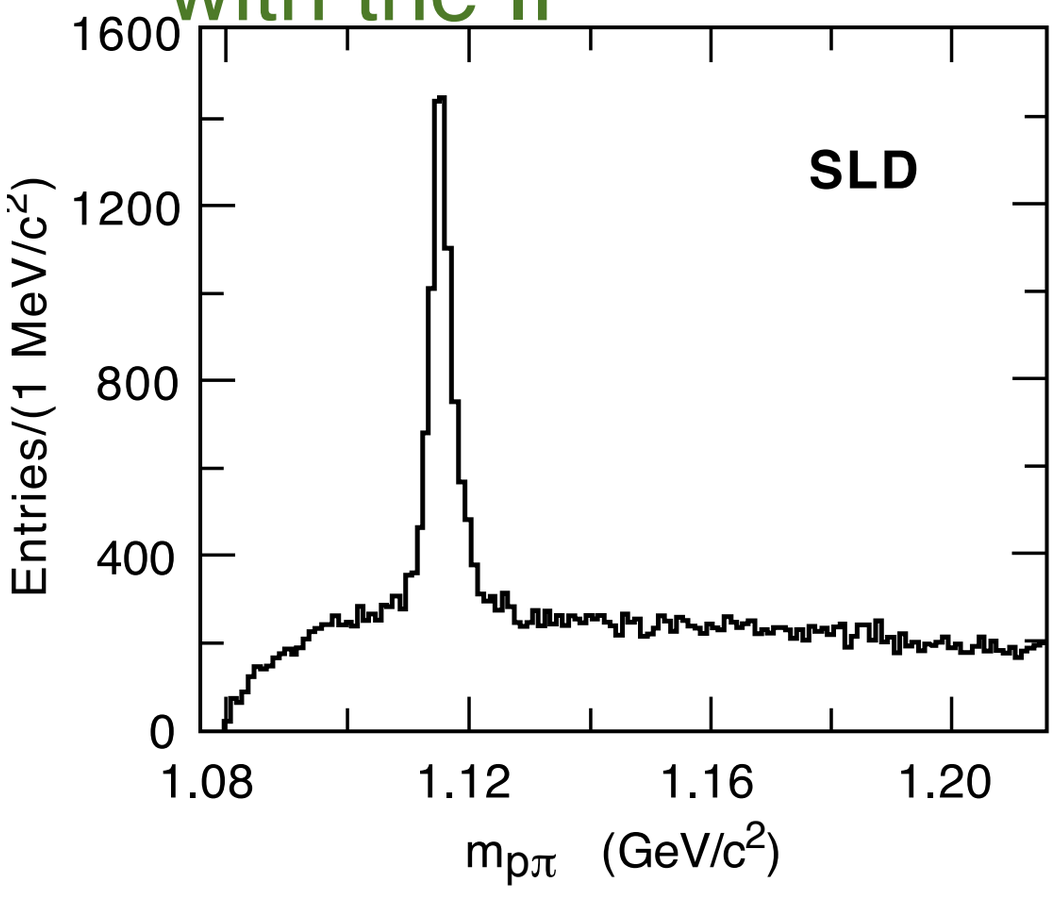


- nice complementary results from LEP
  - → DELPHI also uses RICH hadron ID
  - → ALEPH, OPAL use dE/dx in their tracking chambers
  - → all results strongly correlated

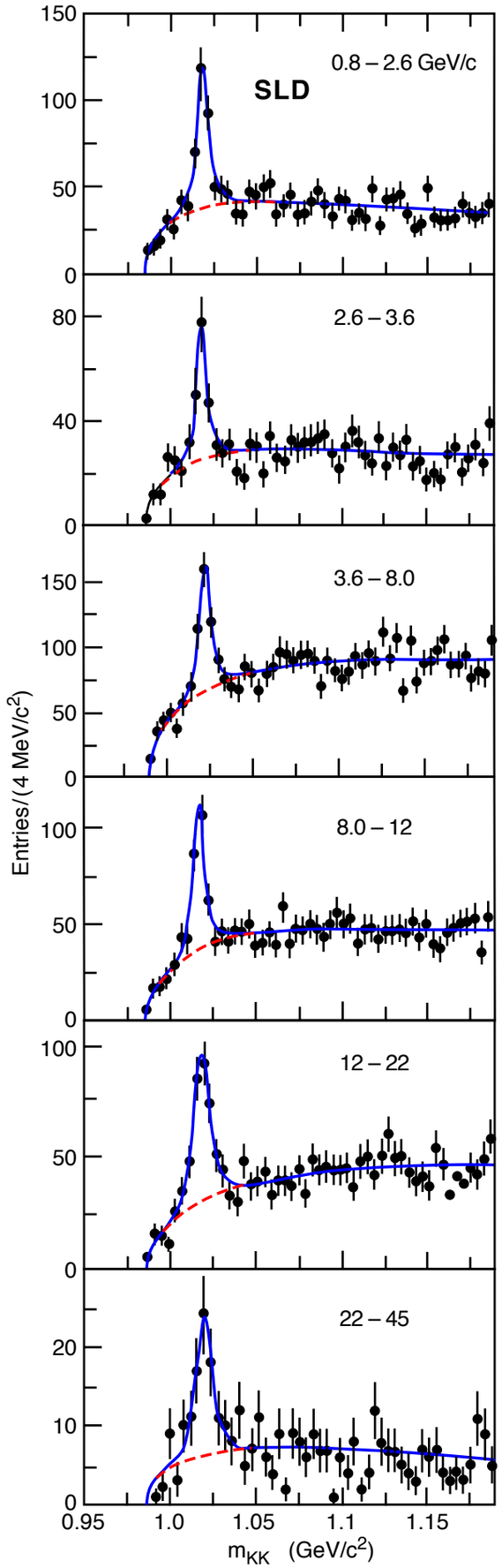
Neutral Hadron Analyses

- reconstruct unstable particles by combining tracks
  - → same/similar event selection
- SLD $K_S \rightarrow \pi^+\pi^-$:
  - → pairs of oppositely charged tracks
  - → with loose pion identification
  - → good vertex, inconsistent with the IP

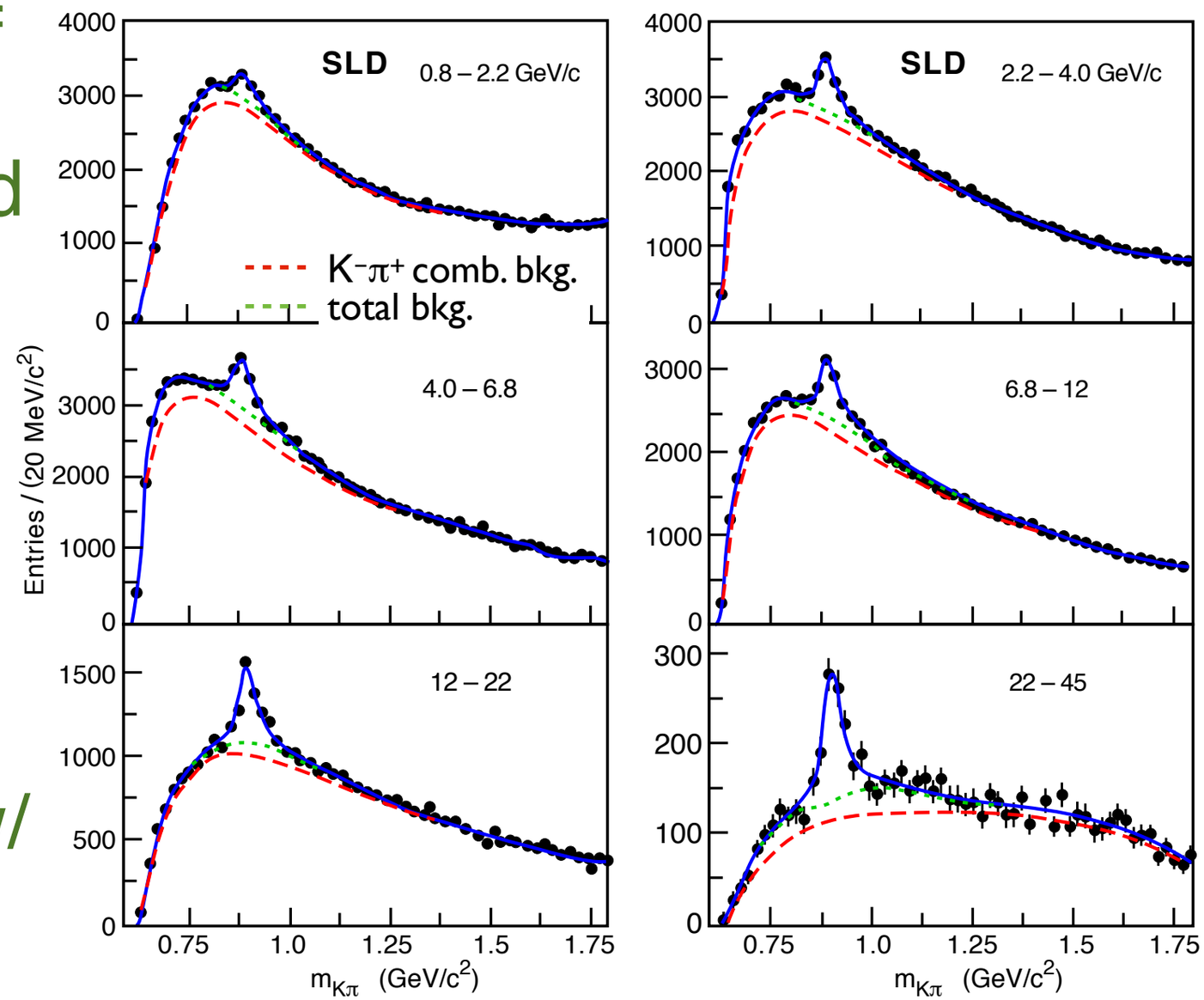




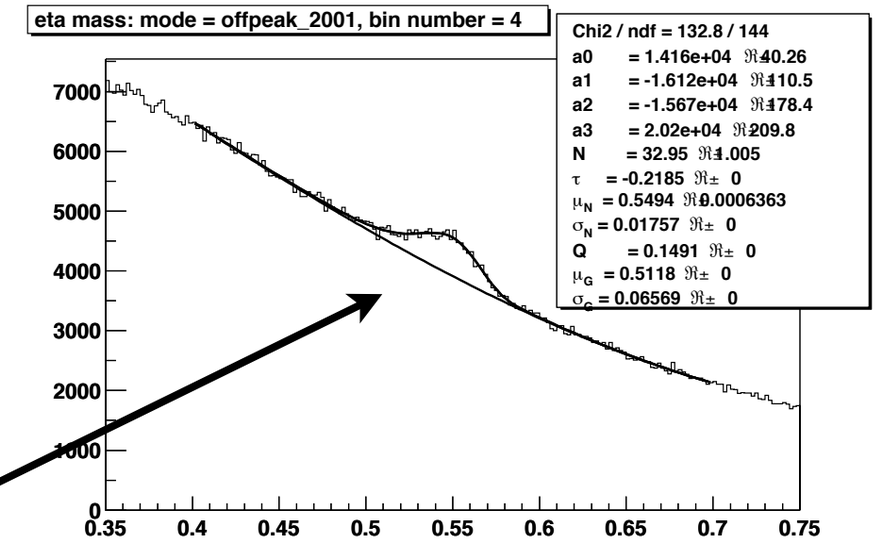
- SLD $\Lambda^0 \rightarrow p\pi^-$ (& c.c.):
  - → pairs of oppositely charged tracks
  - → tight proton, loose pion identification
  - → good vertex inconsistent with the IP

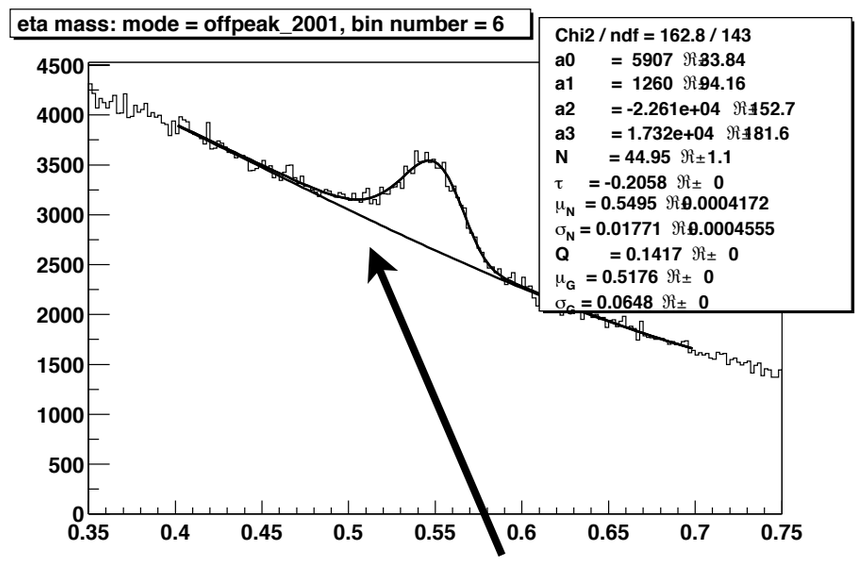


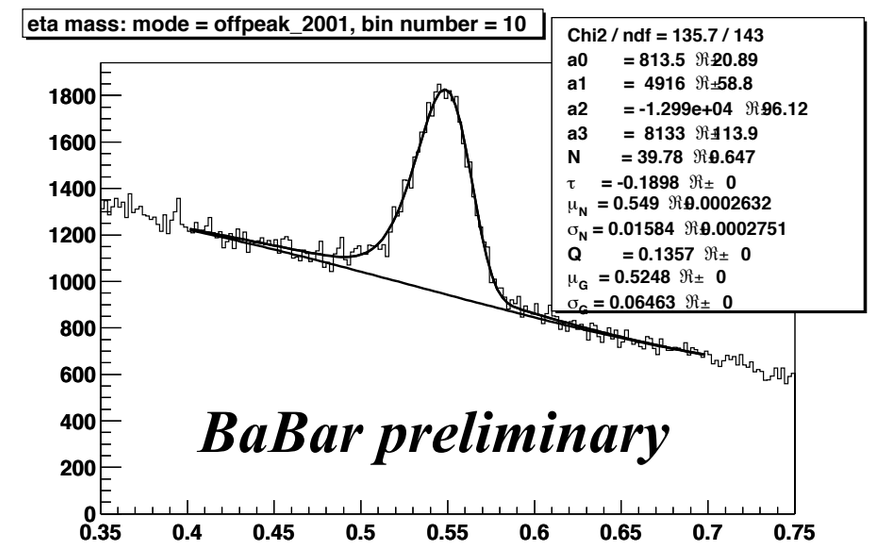
- SLD $\phi \rightarrow K^+K^-$:
  - → pairs of oppositely charged tracks
  - → both tightly identified as kaons
  - → good vertex consistent with the IP
- SLD $K^{*0} \rightarrow K^-\pi^+$ (& c.c.):
  - → pairs of opp. charged tracks
  - → tight kaon, loose pion
  - → good vertex cons. w/ the IP

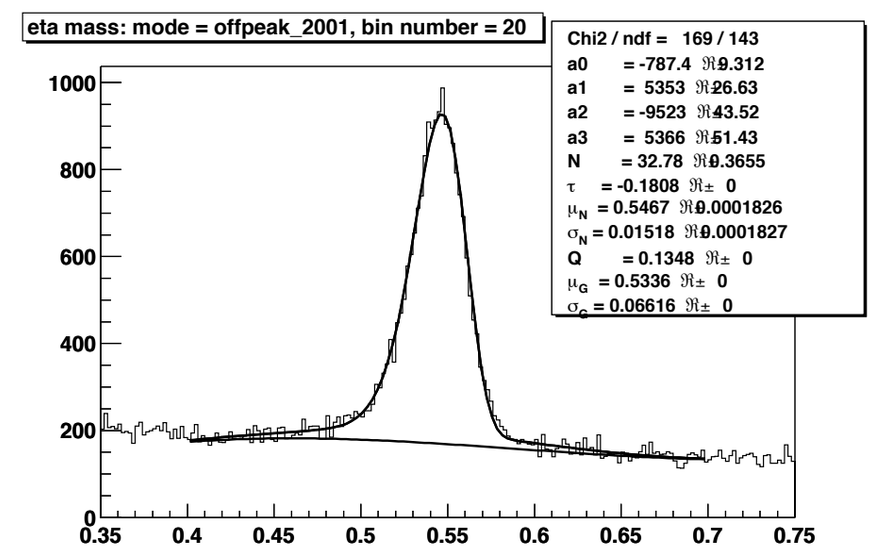


- BaBar $\eta \rightarrow \gamma\gamma$:
  - → pairs of energy deposits in the EM calorimeter
  - → not part of any π^0 candidate
  - → still, high background at low p



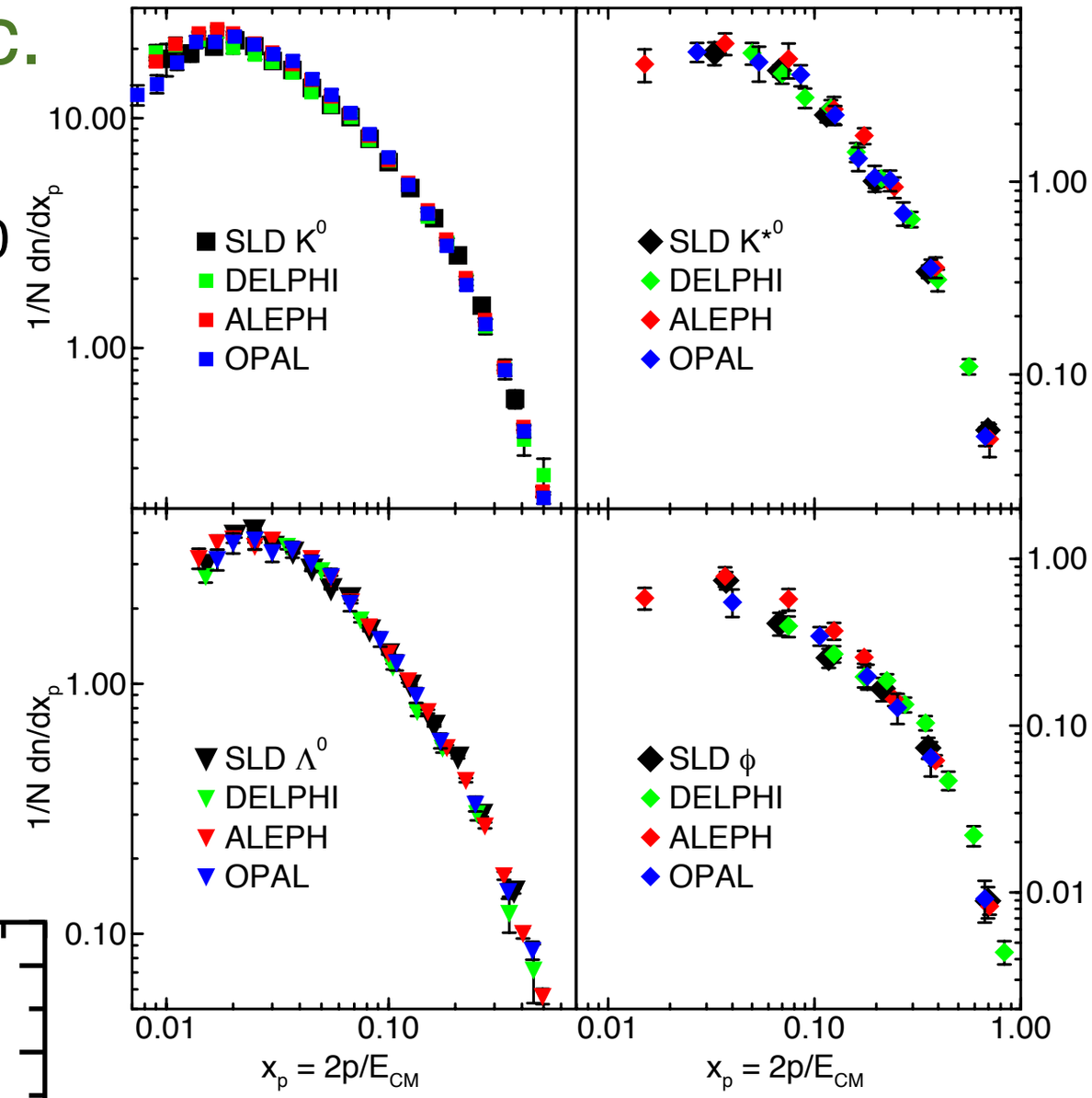




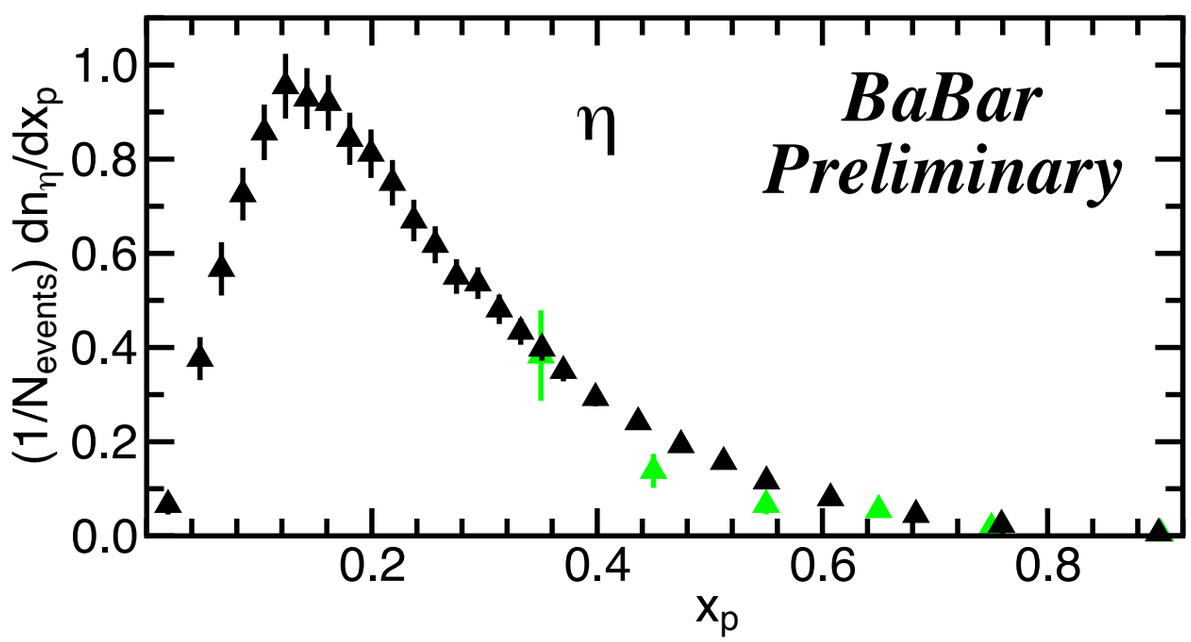


  - → must be careful with signal shape
  - → 3-6% systematics associated with fitting functions

- In all cases, fit the invariant mass distn. in each p bin
  - → correct for efficiency, etc.
- SLD results:
  - → nice coverage for K_S, Λ^0
  - → useful for K^{*0}, ϕ
  - → several LEP results
  - → all consistent, some complementarity



- BaBar results:

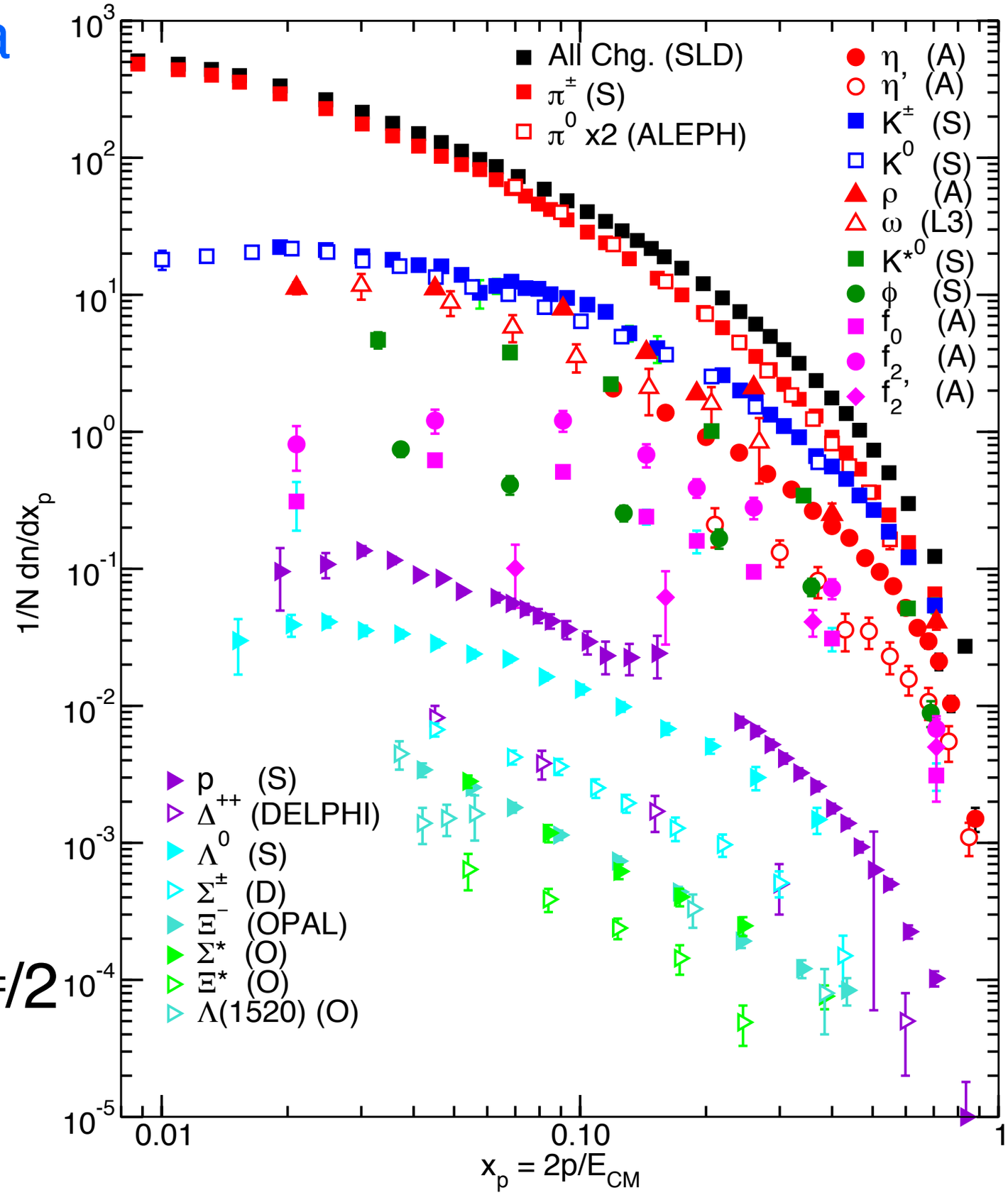


→ full coverage for η

→ big improvement over ARGUS

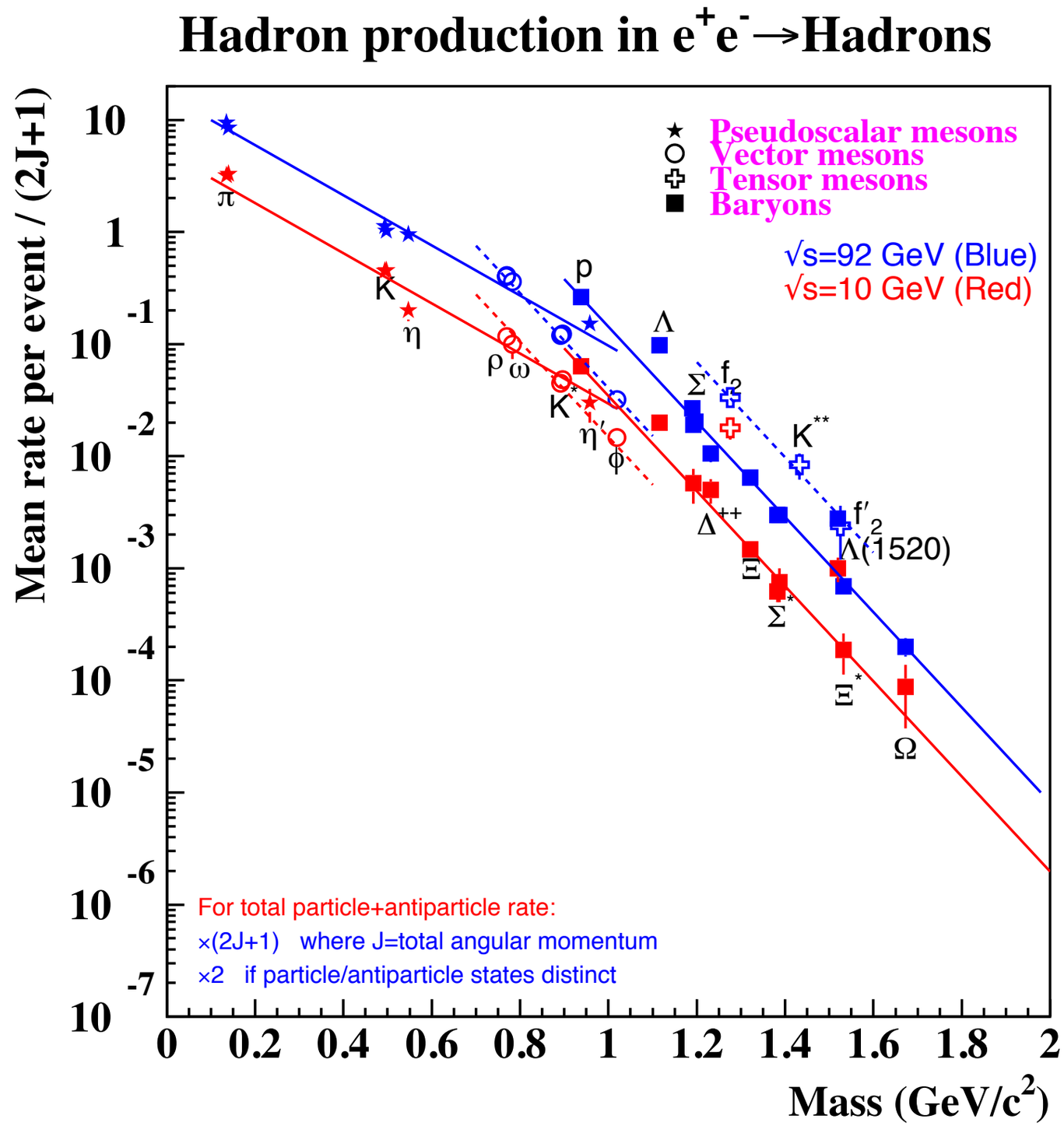
...and there's plenty more from LEP

- a sampling of spectra measured at the Z^0
- one representative measurement shown for each particle
- several interesting features:
  - → pseudoscalar, scalar, vector, tensor mesons seen
  - → octet, decuplet, orbitally excited baryons
  - → π^0 consistent w/ $\pi^{\pm}/2$
  - → K^0 below $K^{\pm}$
  - → ...



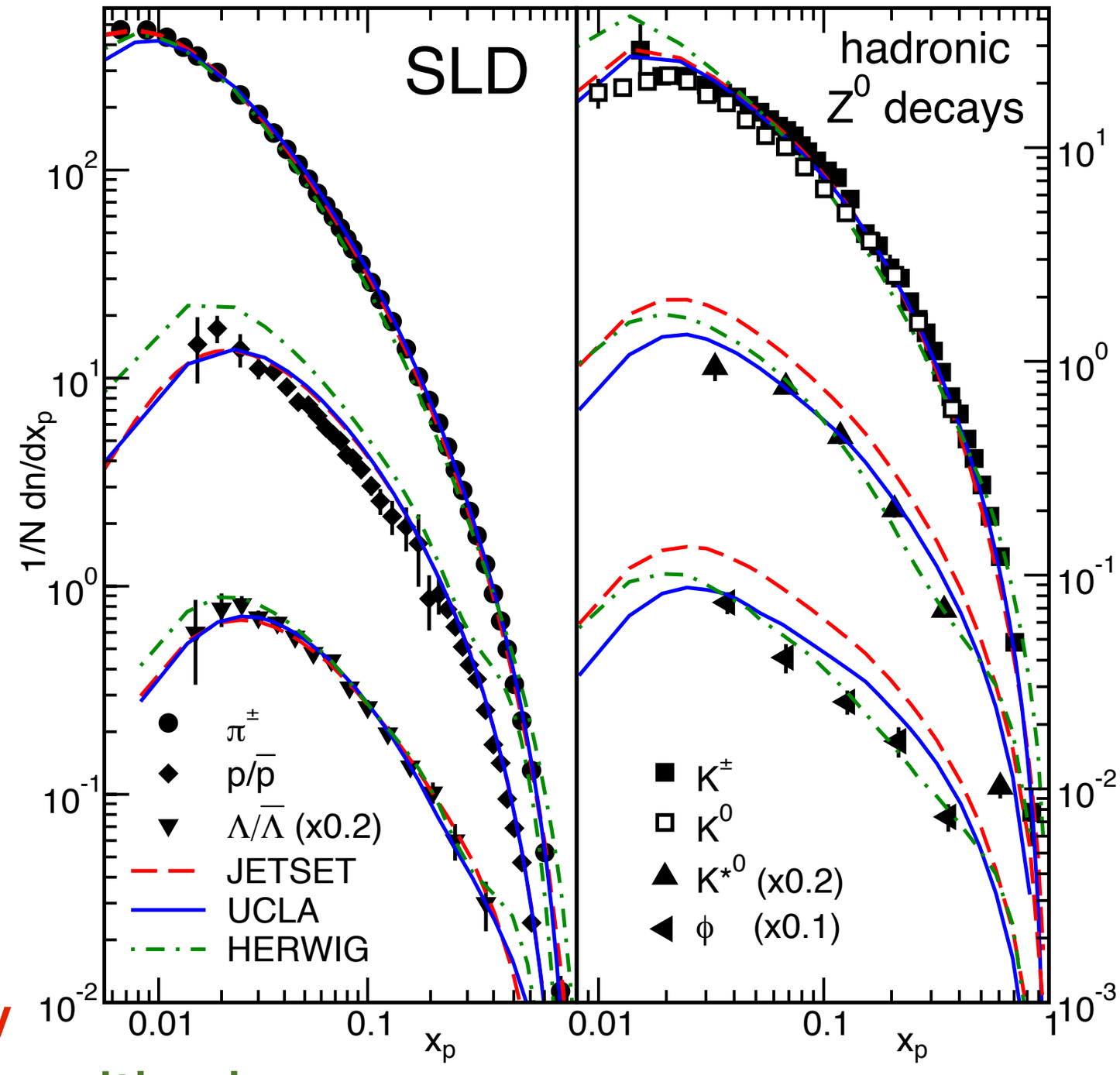
...and also CLEO and ARGUS...

- have observed a large number of light-flavor particles
  → including most of those seen at the Z^0
- but very few spectra are measured
  → statistics, momentum coverage limited
  → measurements of total rates are model dependent
- still, total rates are consistent with a simple scale factor relative to those at the Z^0



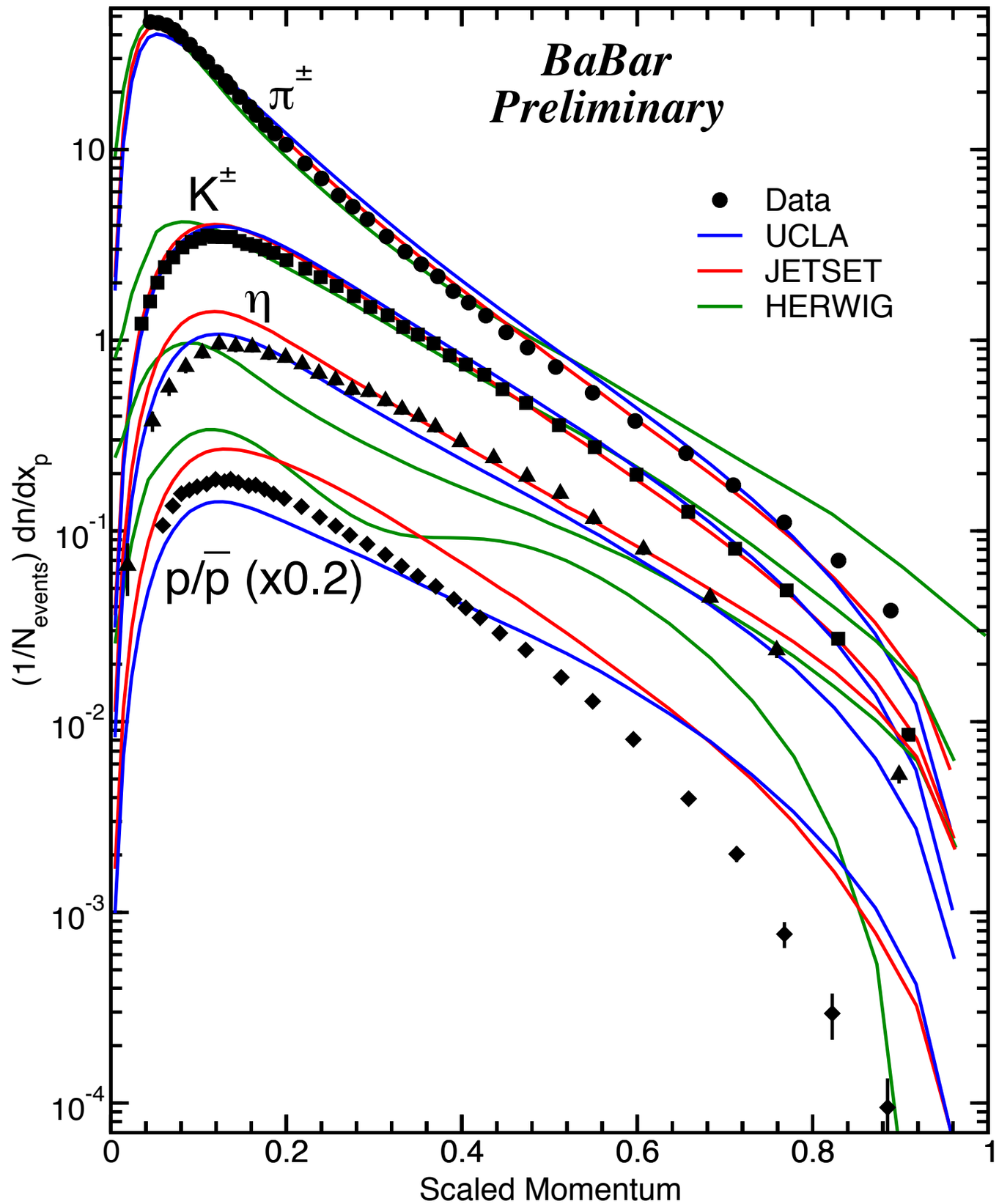
Tests of Hadronization Models

- ~~not relevant to~~ this workshop? motivation for
- consider three models representing 3 types of particle production models
  - → JETSET: string, many free parameters
  - → UCLA: area law, ~1 free param
  - → HERWIG: clusters, few free params



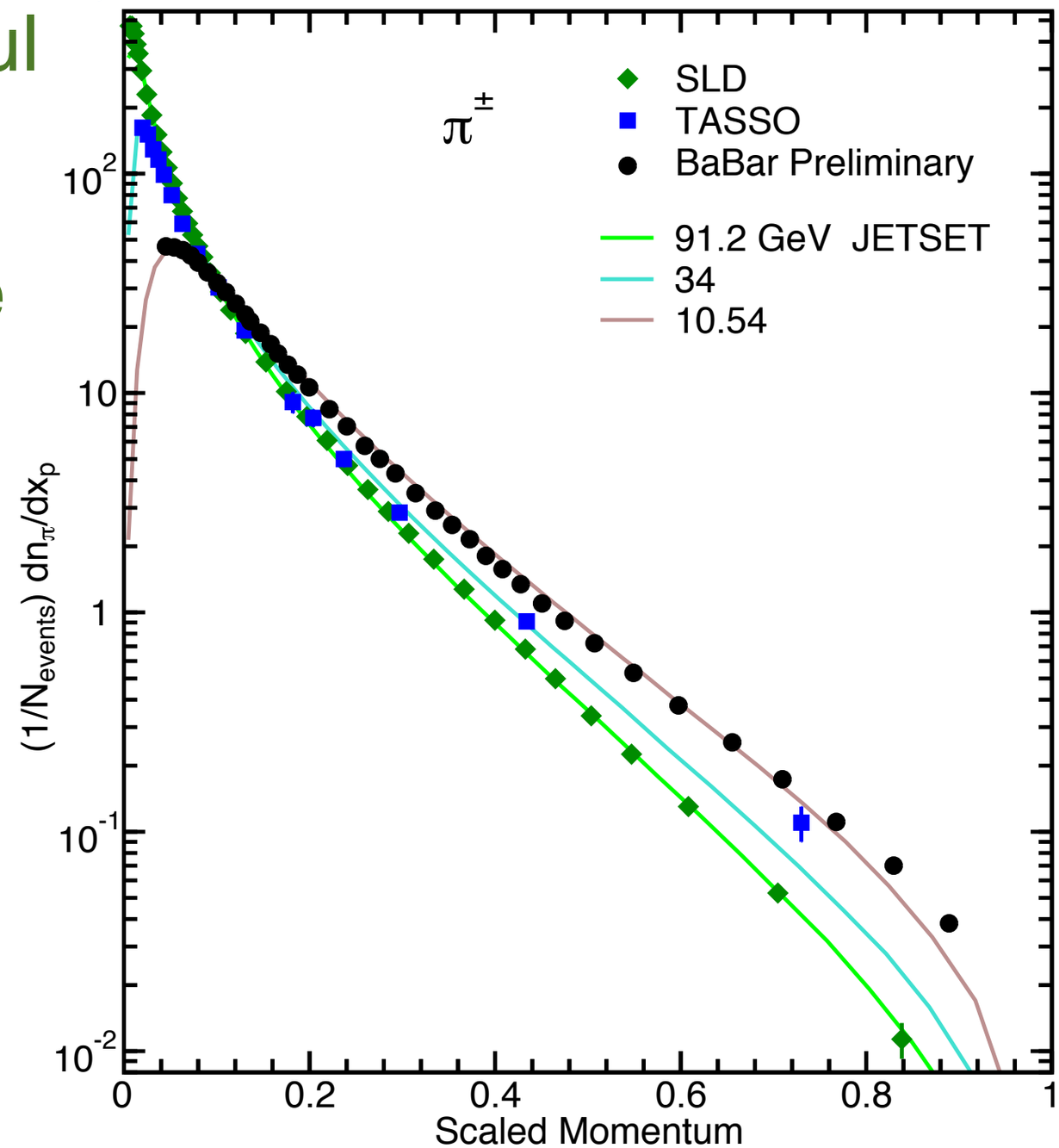
- they work qualitatively
  - → mostly minor issues with shapes
  - → some large problems with overall rates

- similar results for BaBar at lower E_{CM}
  - → discrepancies are larger in general
  - → but often of the same sign ...
  - → and similar structure
  - → perhaps the models do a reasonable job of describing the scaling properties?

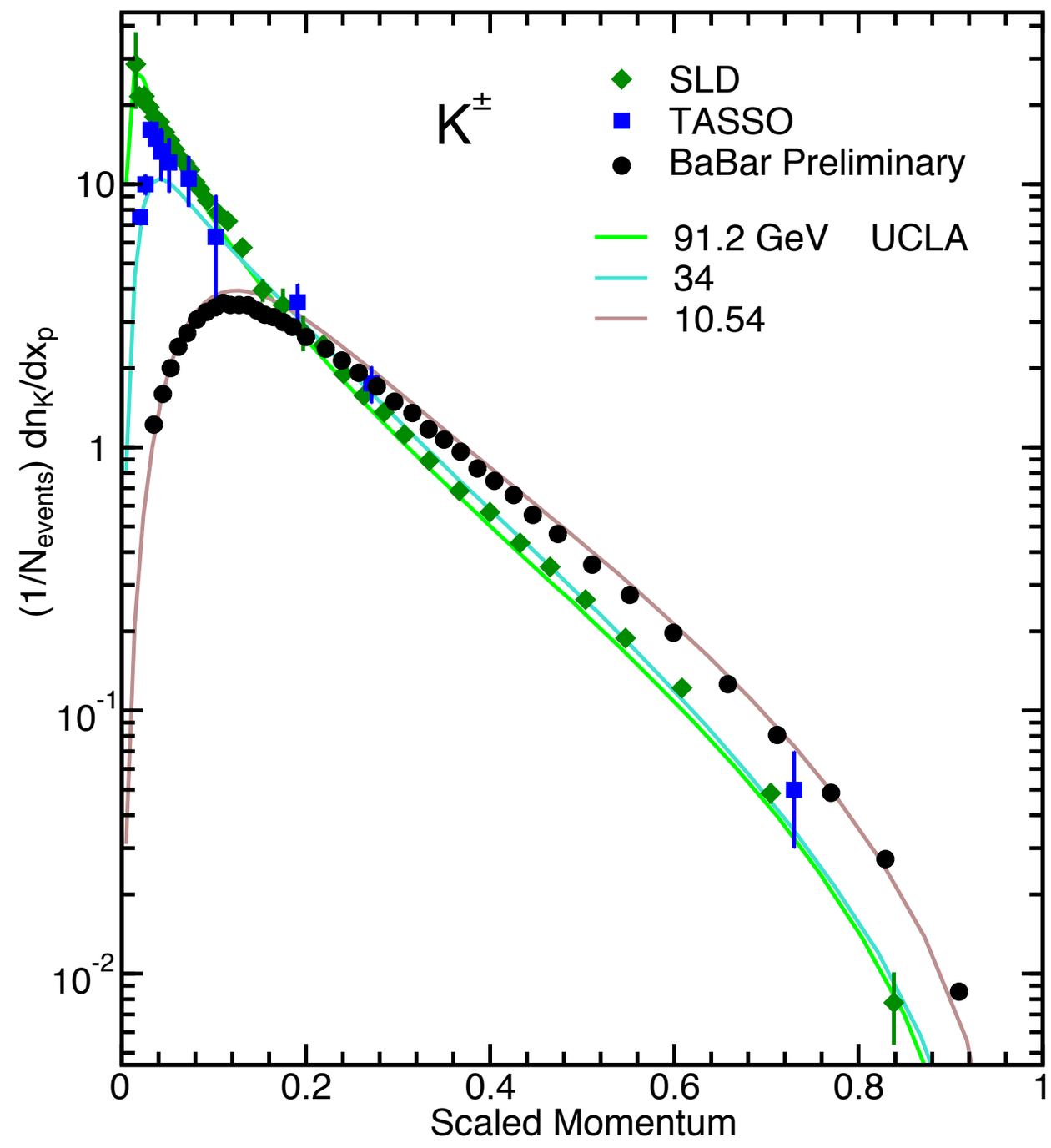


Scaling properties at high x_p

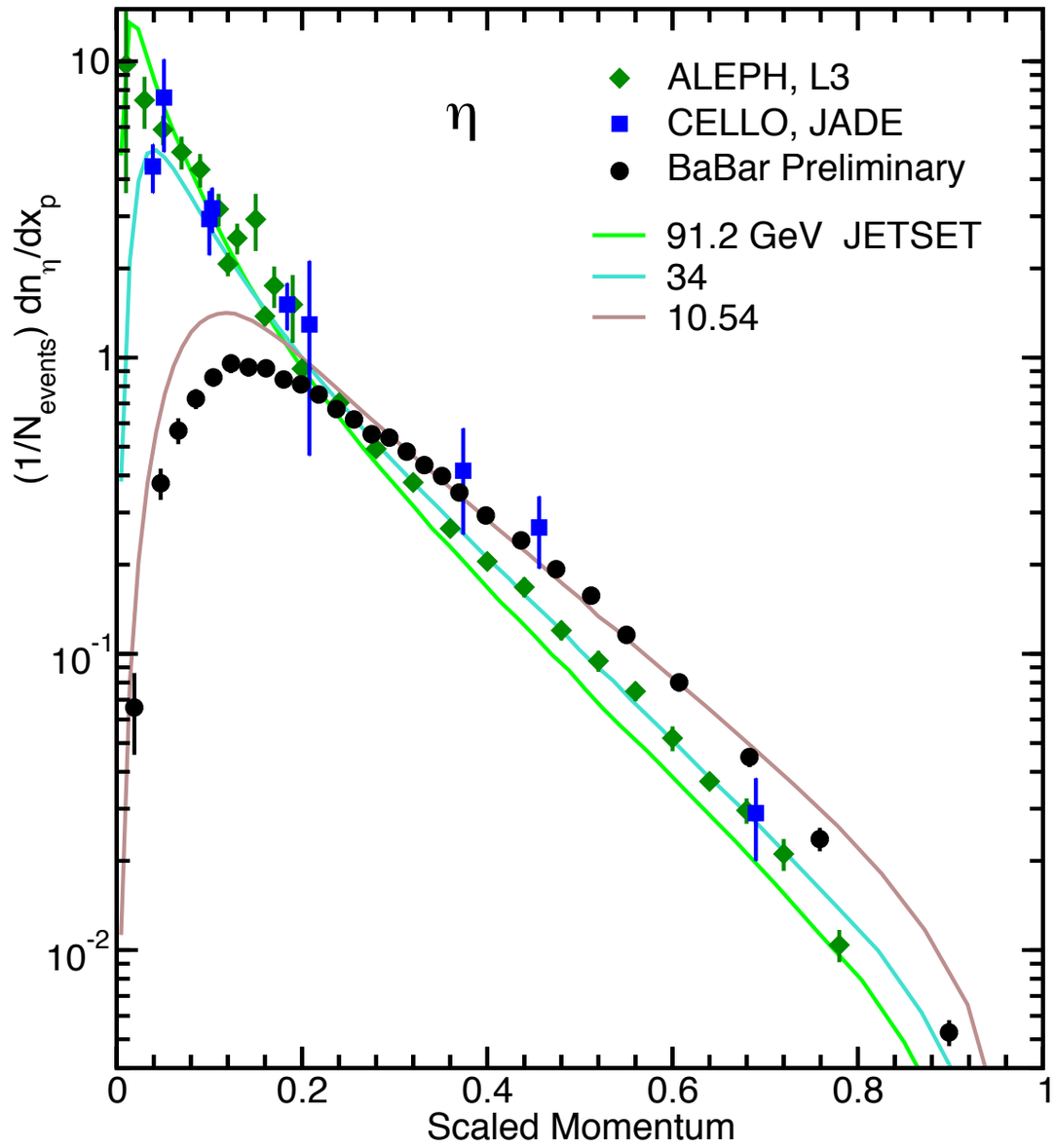
- very relevant to this workshop
  → but I'll just compare with models
- consider $\pi^{\pm}$ data from BaBar, SLD and TASSO
  → TASSO has most useful high-x_p data at an intermediate E_{CM}
  → LEP, ARGUS data give the same conclusions
- strong scaling violation at high-x_p
  → also at low x_p
- modeled well, at most few-% changes in data:MC ratios with E_{CM}
  → JETSET shown
  → UCLA, HERWIG show similar scaling



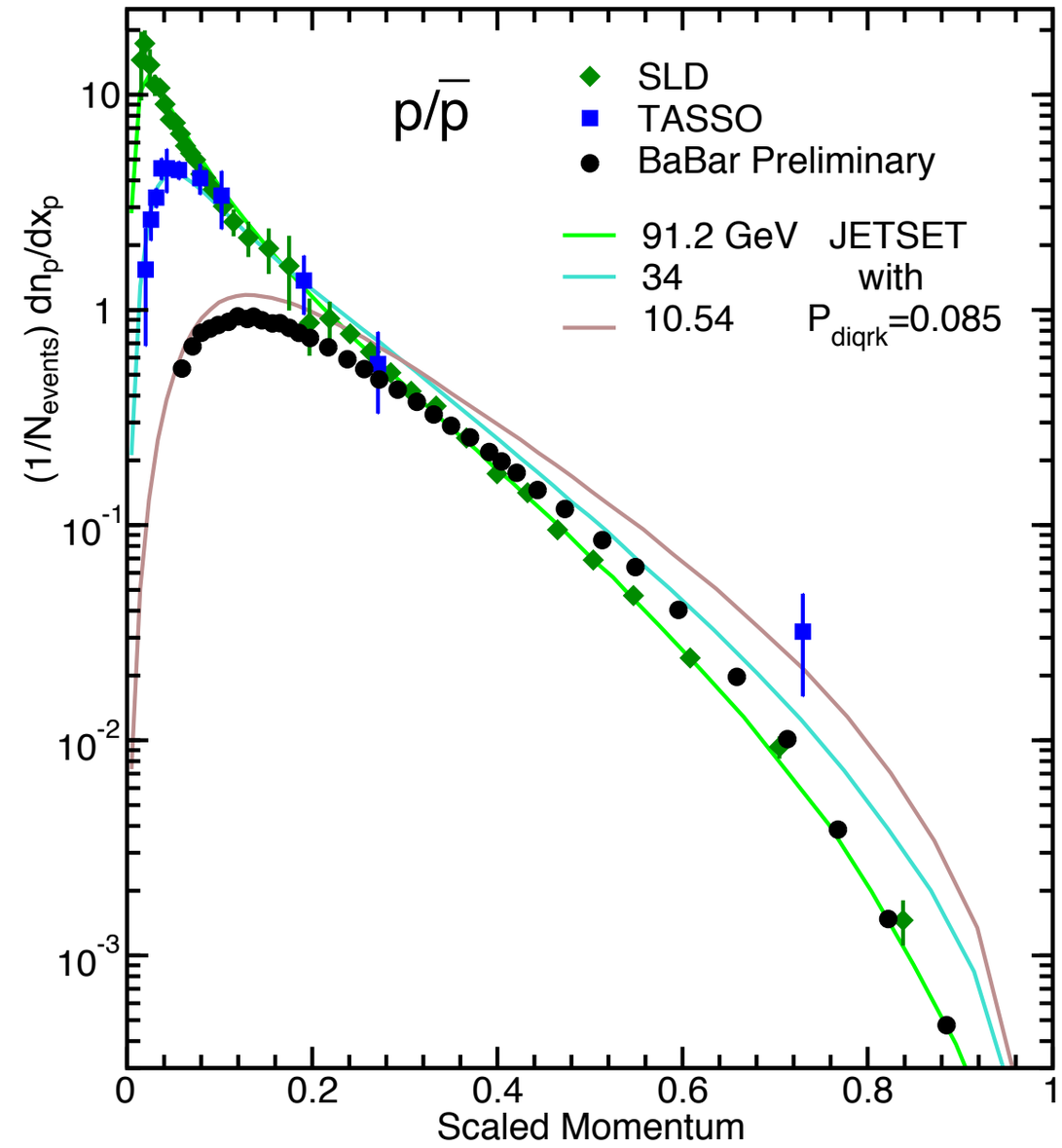
- now consider $K^{\pm}$ data from BaBar, SLD and TASSO
- again, strong scaling violation at high (and low) x_p
  - → well, between at 10.54 and 91.2 GeV...
  - → 34 GeV data not precise enough
- only ~10% change in models from 34-91 GeV
  - → due to changing flavor composition
  - → UCLA shown, other models similar
- change from 10-91 GeV is ~15% larger than in the data
  - → .. ±~6% experimental
  - → ...how uncertain are flavor composition effects?



- now BaBar η data vs. ALEPH/L3 and CELLO/JADE



$p/\bar{p}$ vs. SLD and TASSO



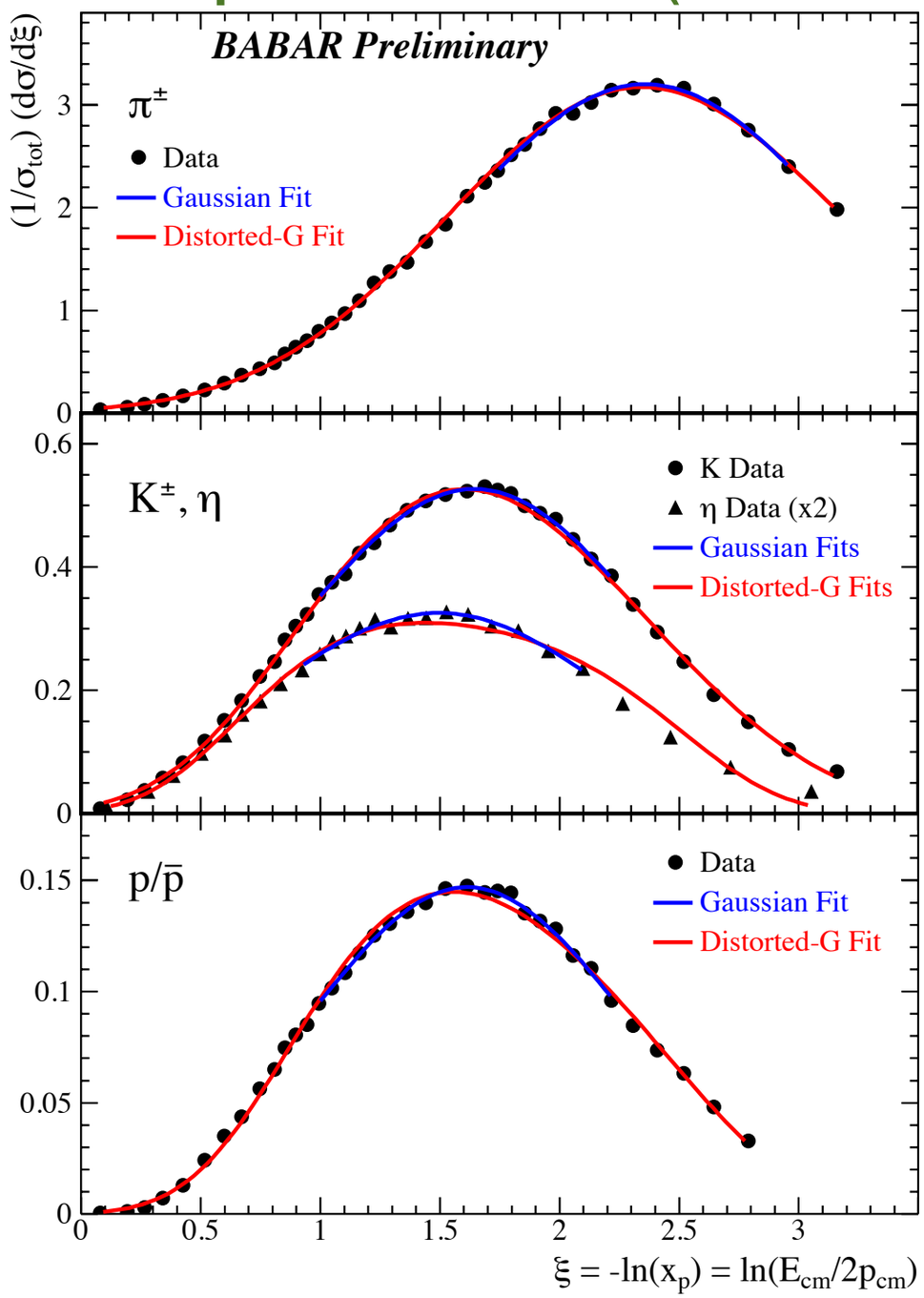
- the MC η and p scaling violations are ~25% and 50% larger than the data at high x_p

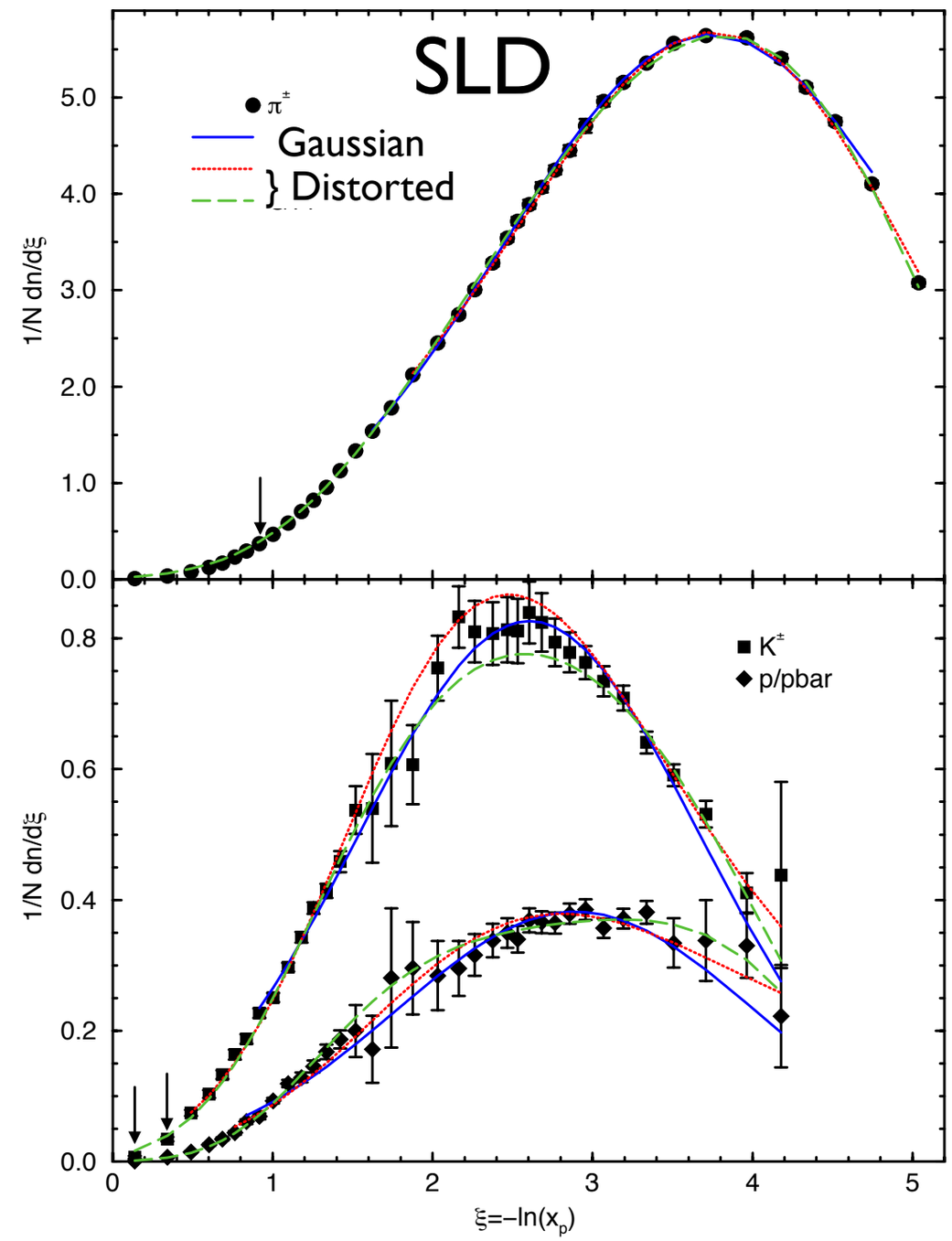
  → is there something we don't understand about heavy particles, strange particles, baryons, ...?

Tests of Modified-Leading-Log QCD

- Transform to xi = $-\ln(x_p)$, study low-p scaling

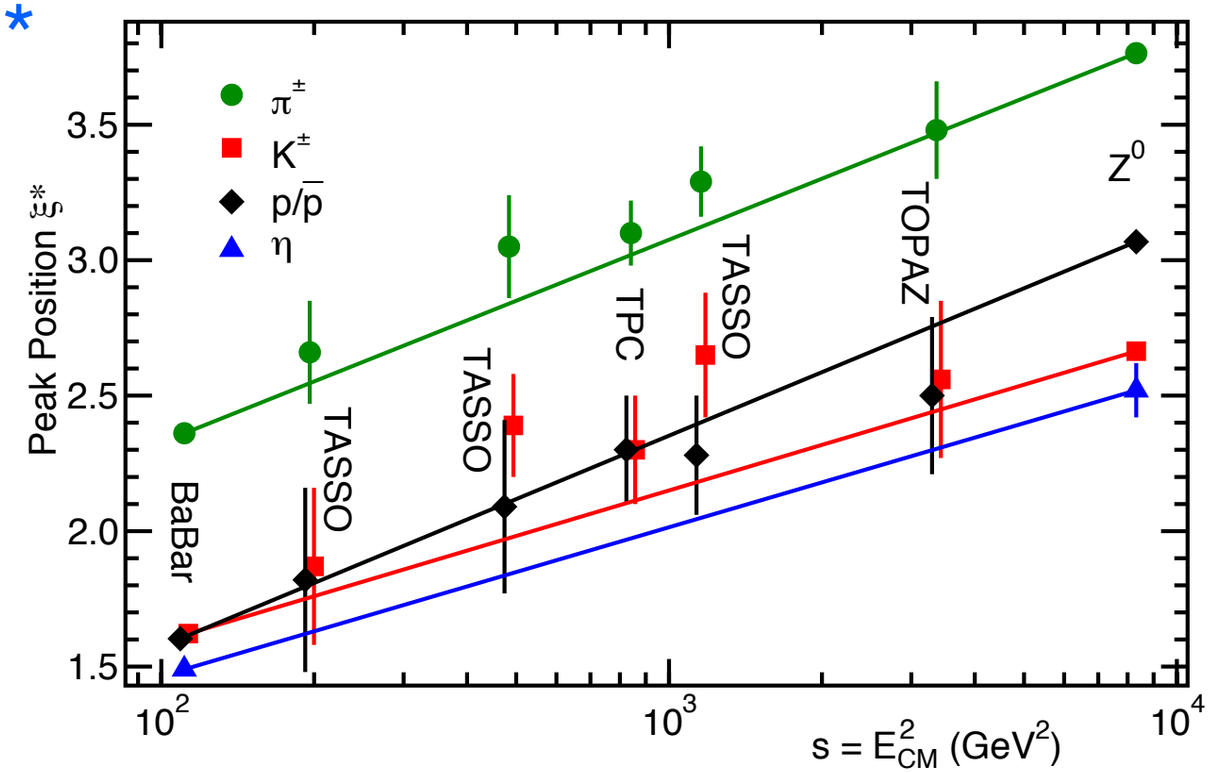
→ fit spectra with (distorted) Gaussian function



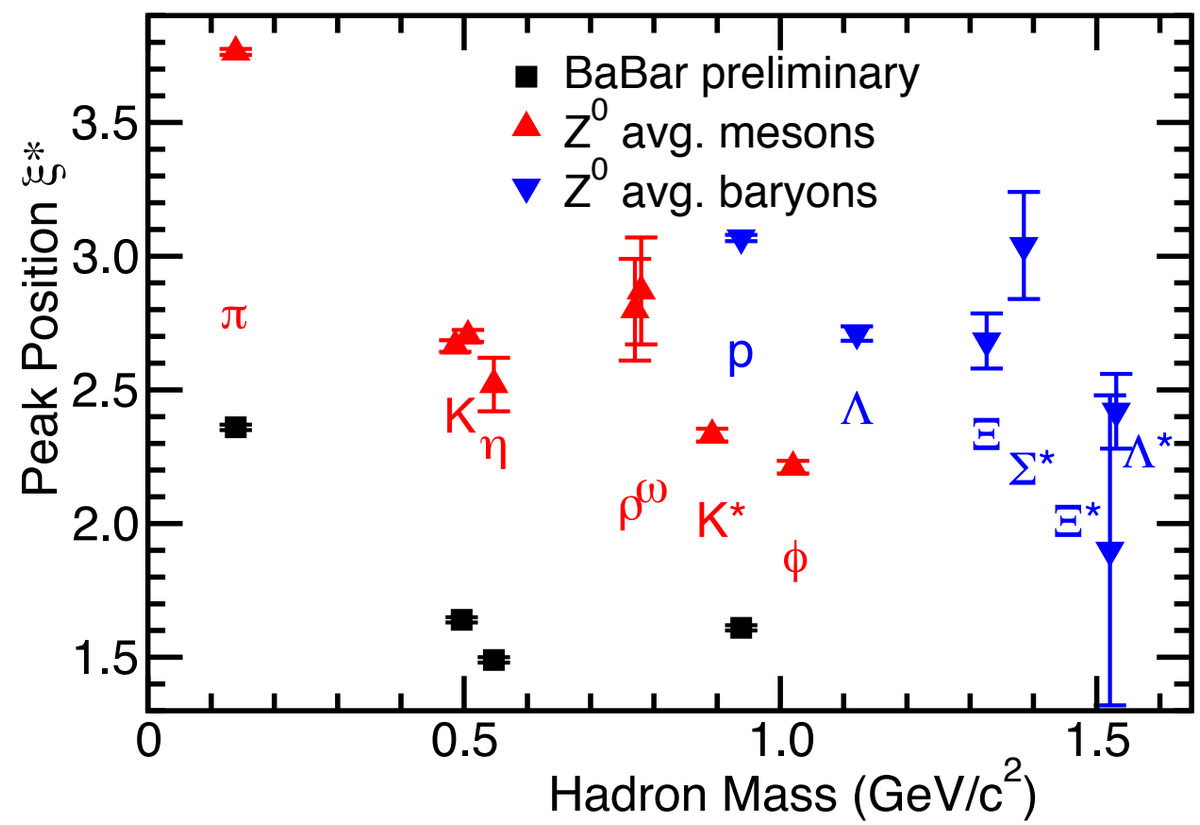


→ provides reasonable descriptions of the data

- measure peak positions, xi*
  - → MLLA QCD predicts a logarithmic increase with E_{CM} for a given particle
  - → data are consistent
  - → BaBar and Z^0 data provide precise slope



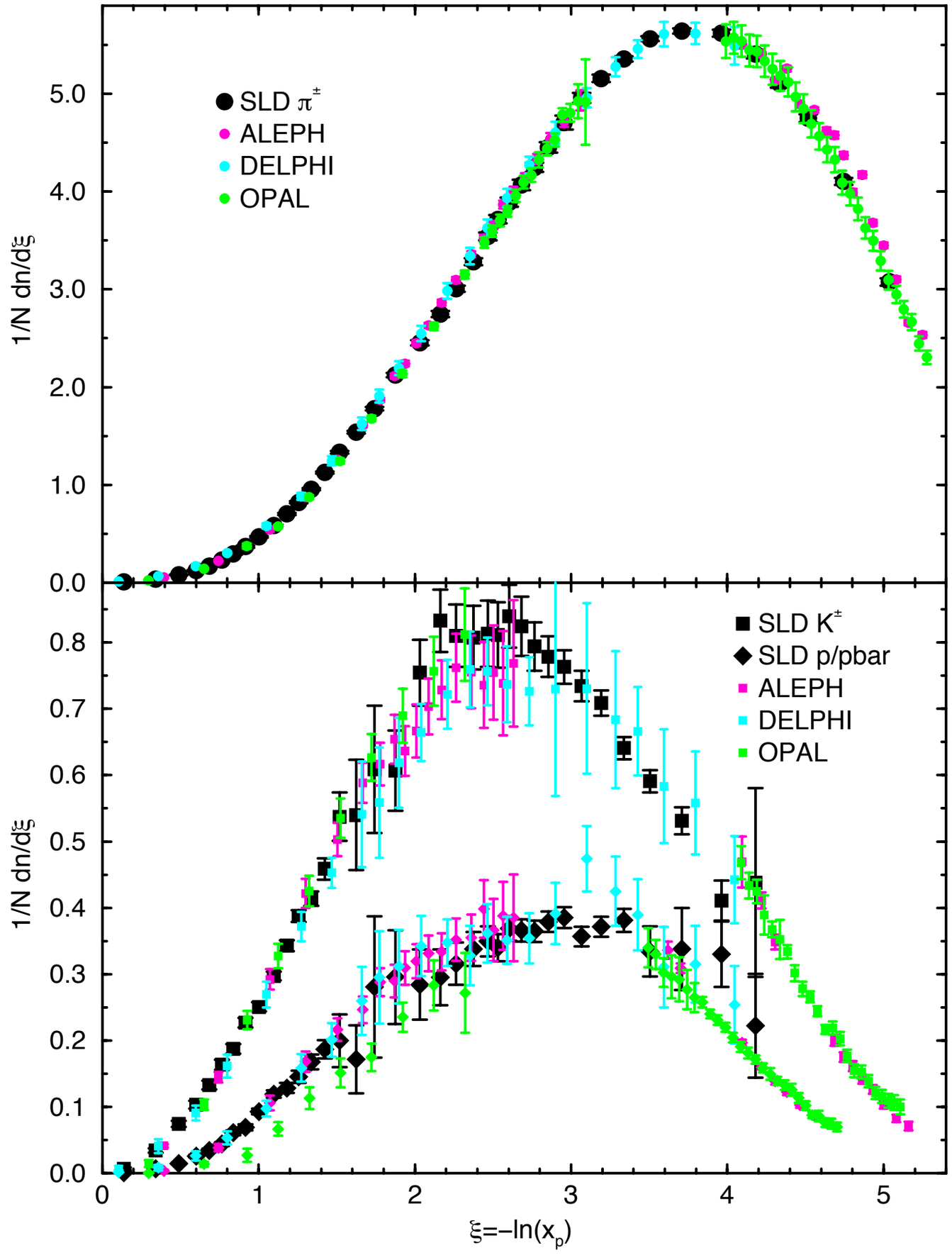
  - → MLLA QCD predicts an exponential decrease with mass for a given E_{CM}
  - → meson data are consistent
  - → baryons seem to follow a different trajectory



- a comparison of data from different Z^0 experiments shows their complementarity
  - → all are consistent
  - → two RICH and two dE/dx
  - → good coverage by combining all four

but we must take all the correlations into account!!

between momenta
particles
RICH msmts
dE/dx msmts
...



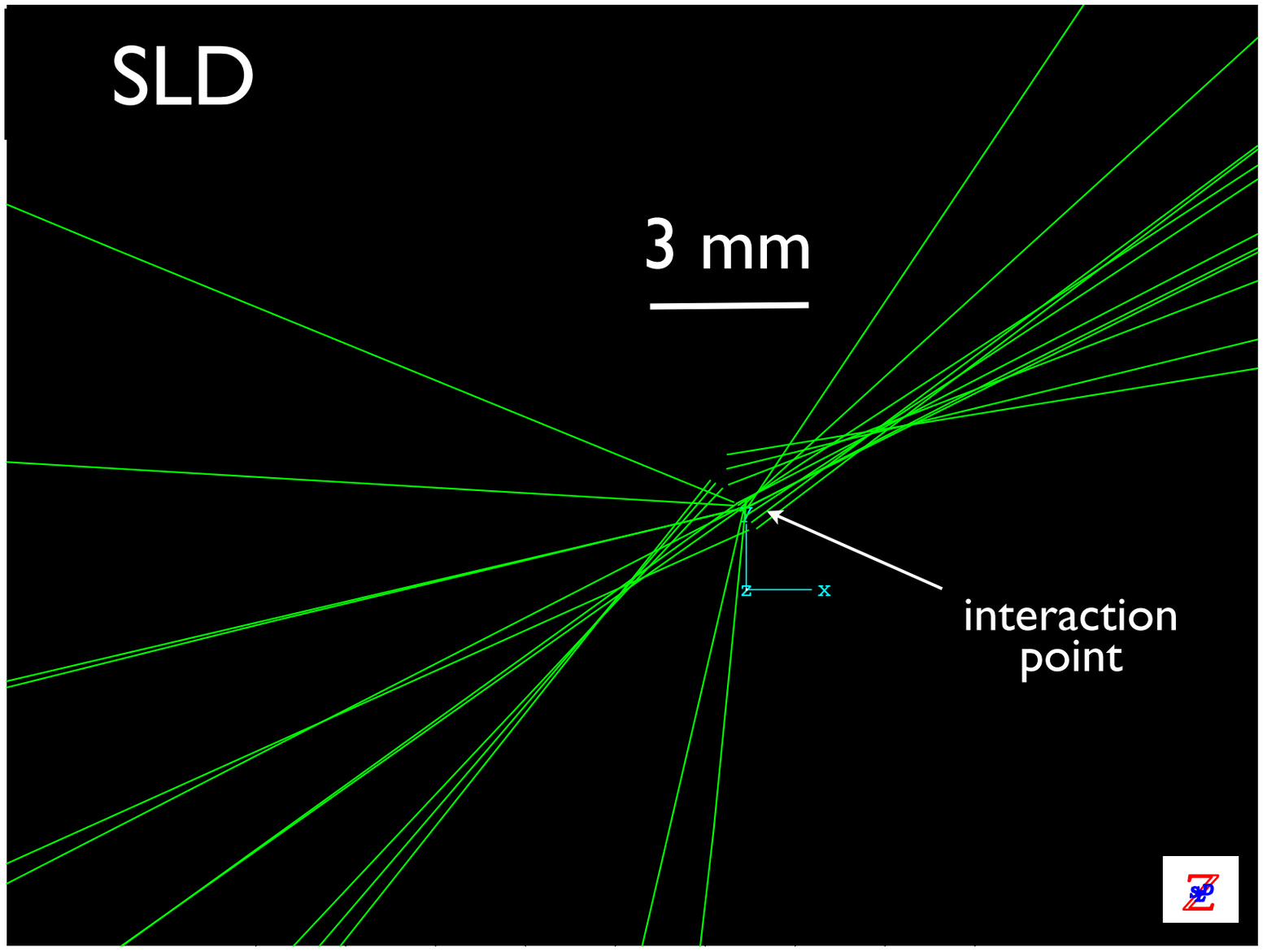
Flavor Dependence

- heavy and light flavor events can be separated using the flight distance of the leading heavy hadrons
  → zoom of an $e^+e^- \to b\bar{b}$ candidate event

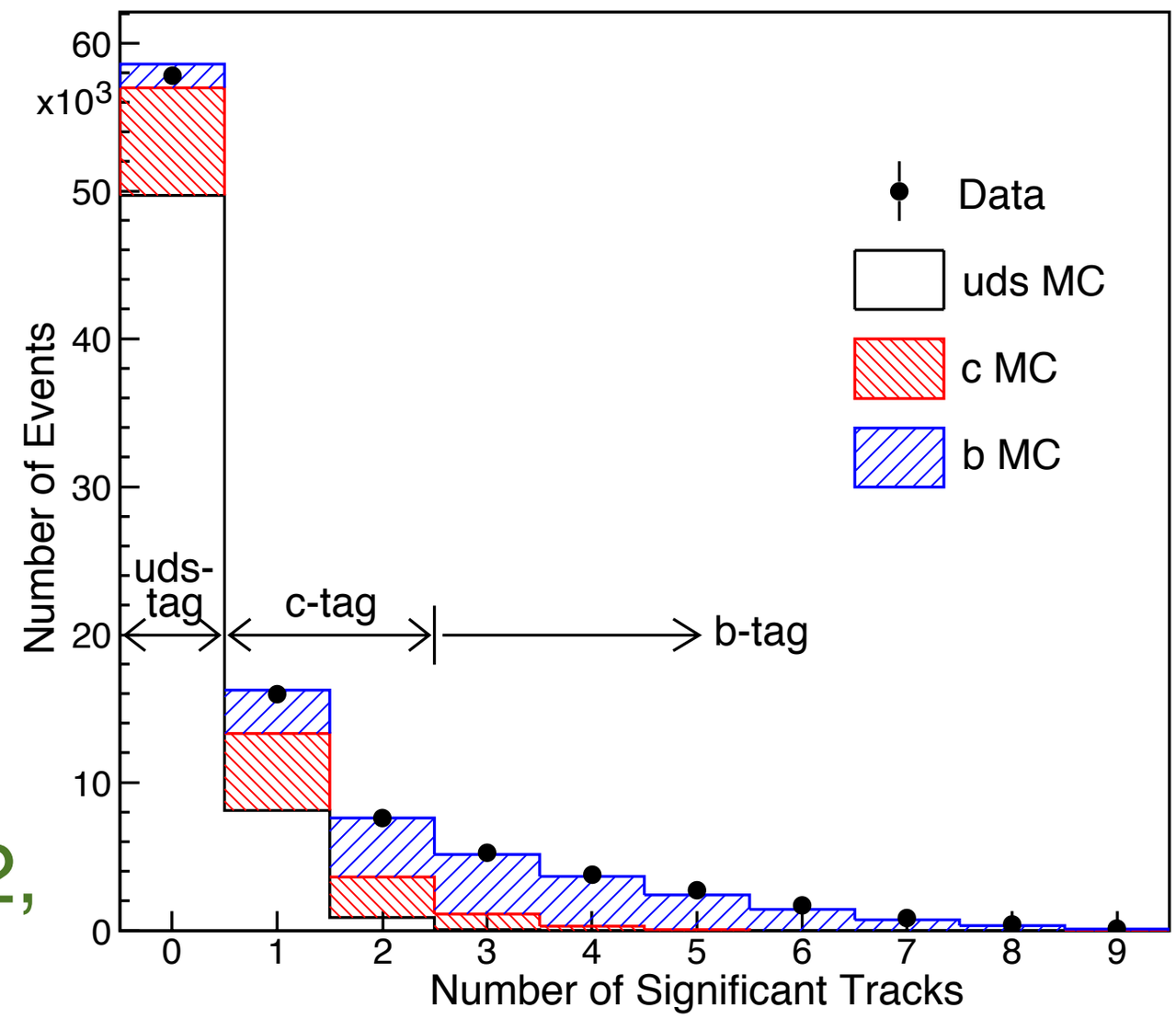
- B hadrons travel 3 mm on average before decaying

- Charmed hadrons travel 1.3 mm on average before decaying

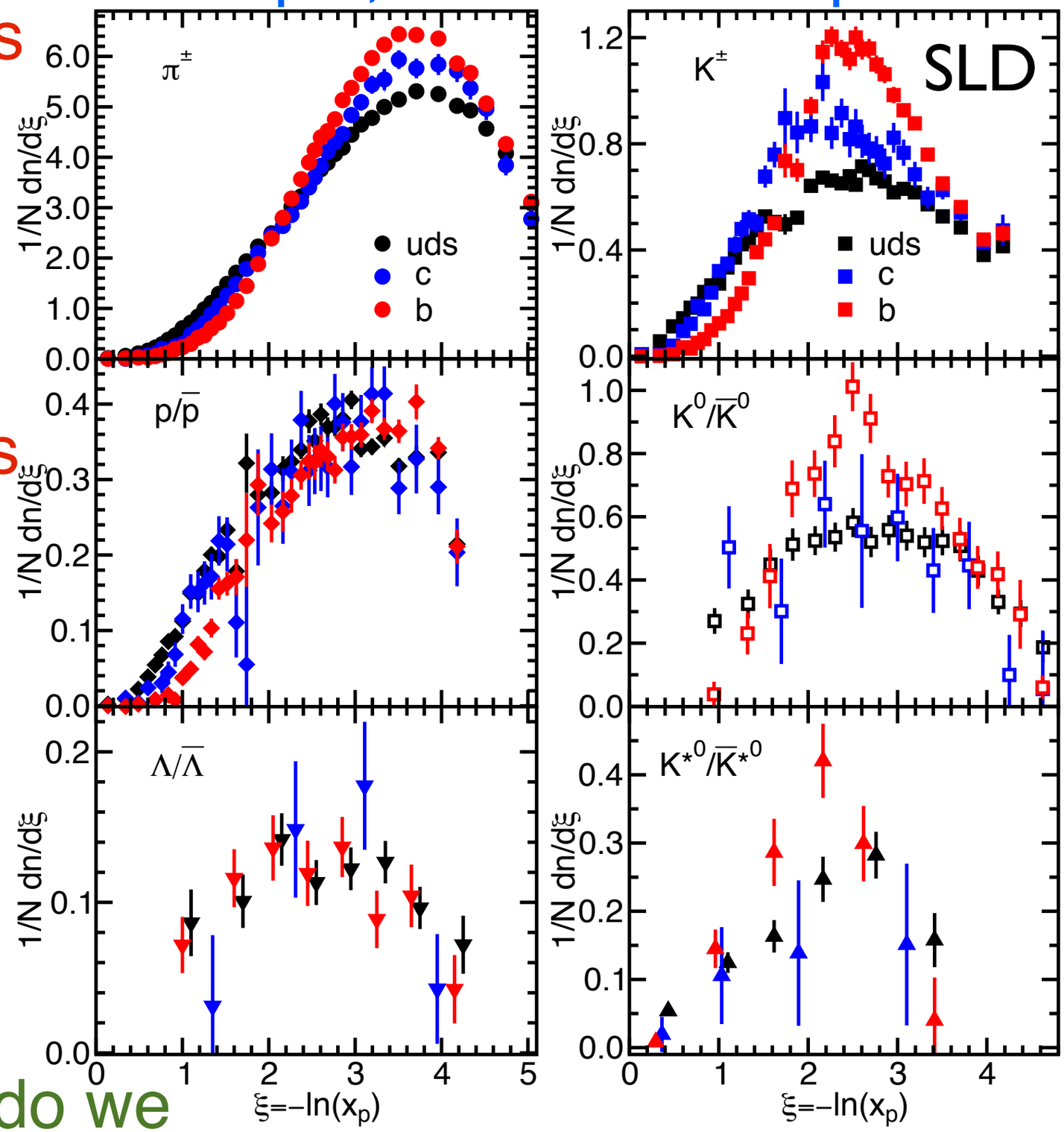
- Many techniques developed to tag c and b jets and events
  → e.g., search for good, secondary vertices, select on flight distance, mass , ...



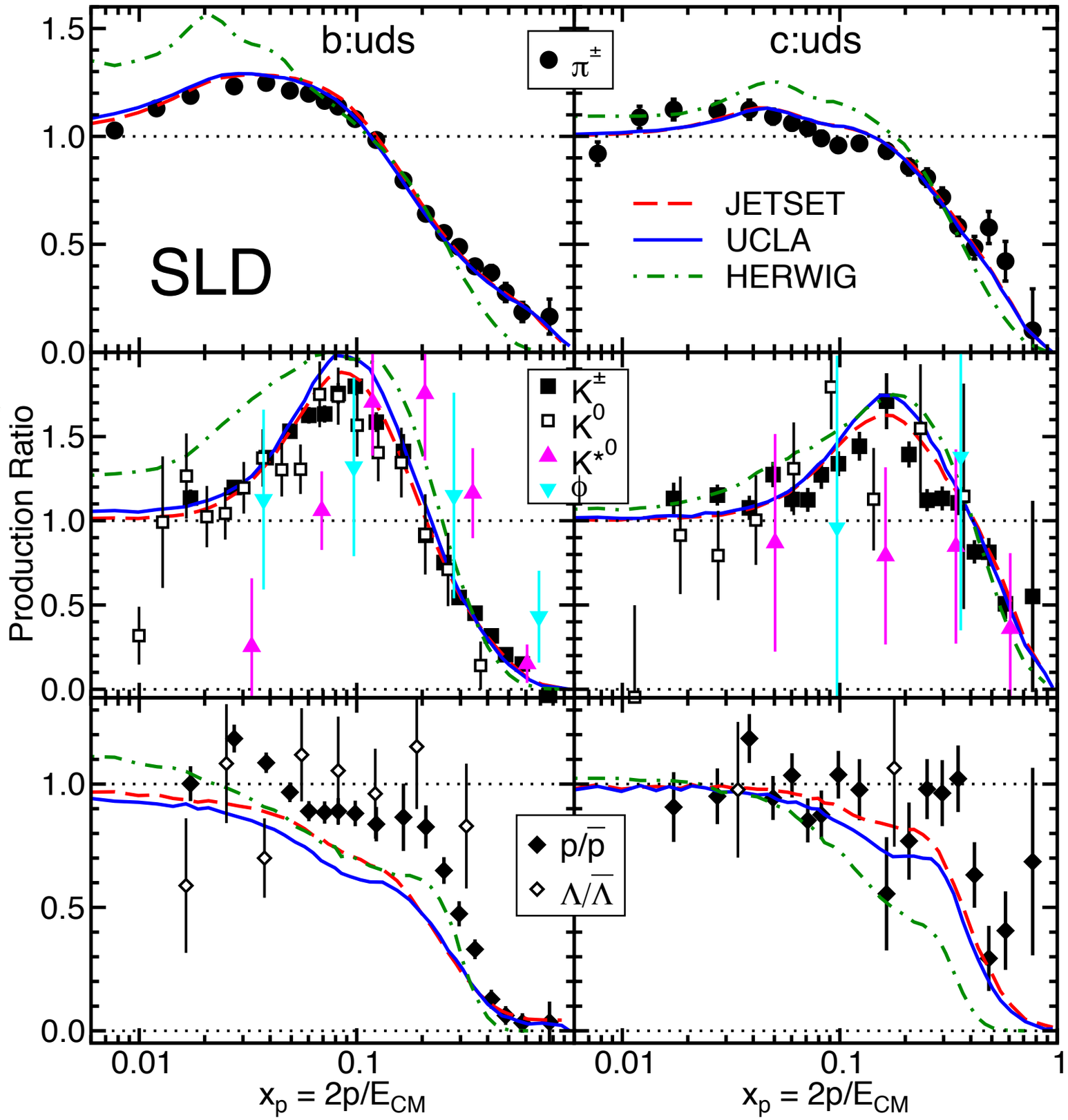
- For inclusive spectra analyses, optimize low bias and statistics by combining vertex info with the number of tracks inconsistent with the interaction point
  - → define a track as significant if its extrapolation misses the IP by at least 3σ
  - → B hadrons tend to have several such tracks
  - → D hadrons have 1 or two
- define four independent samples
  - → no vertex & $n_{sig}=0$, uds tag, 93% pure
  - → high-mass vtx I $n_{sig}>2$, b tag, 97% pure
  - → low-mass vtx I $n_{sig}=1,2$, c tag, 64% pure
  - → the rest



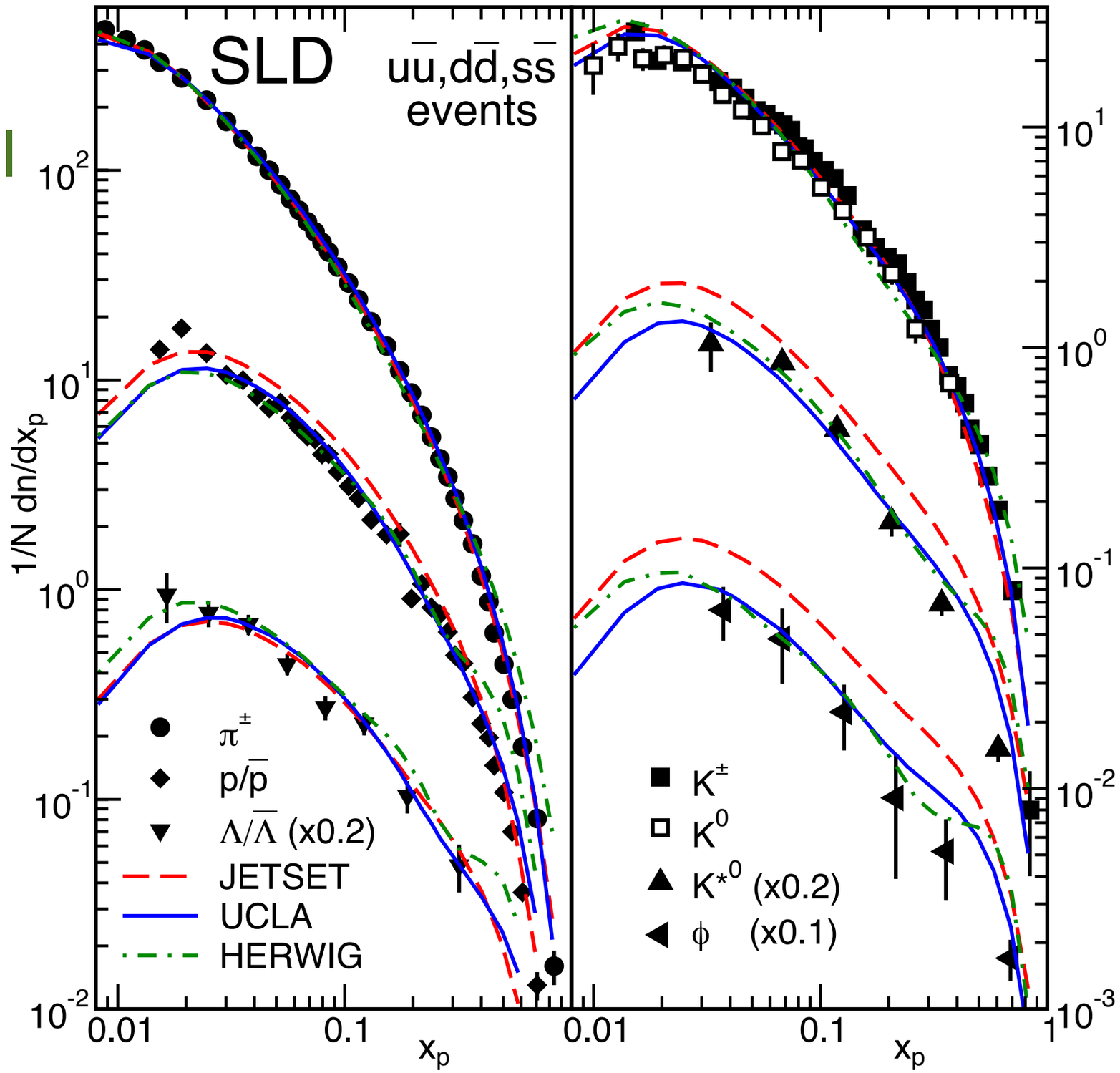
- measure spectra in each sample, unfold for sample composition and bias
  - → nice $\pi^{\pm}$ statistics in all three flavors
  - → $K^{\pm}$, K^0, $p/\bar{p}$ also interesting
- the three flavor types are quite different
  - → heavy-flavor events have very few tracks at high x_p/low xi
  - → ...but quite a few medium-x_p kaons from B, D decays
  - → all expected, but do we understand the details???



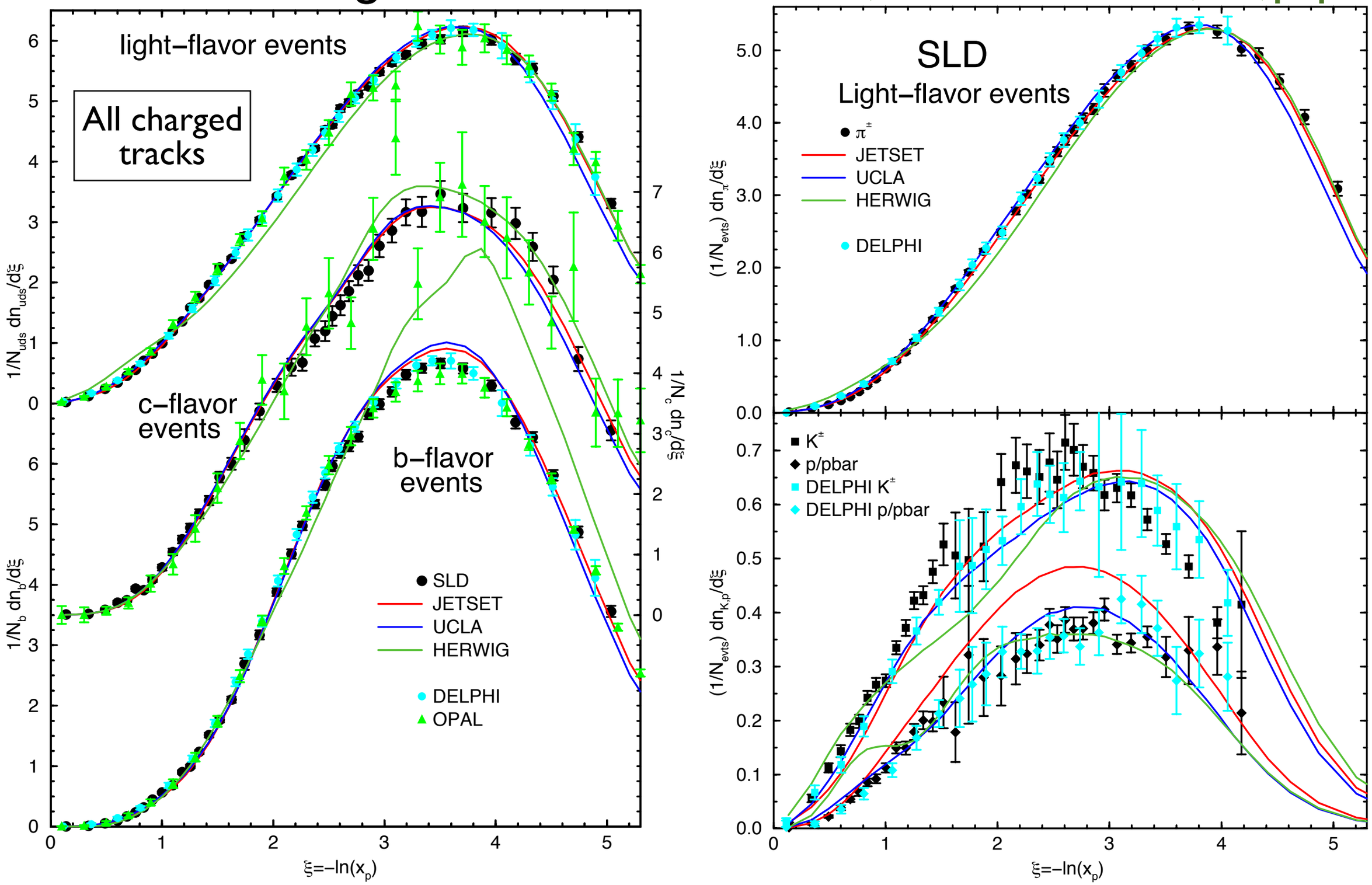
- can test models in terms of ratios
  - → reasonable description of $\pi^{\pm}$ ratios, except for HERWIG
  - → peaks in kaon ratios wrong by ~10-30%
  - → shape of $p/\bar{p}$ ratios ok, but too much suppression overall



- purists want to test the model predictions for light flavors only
  - → same general issues as for all flavors
  - → several small differences in scale factors
  - → slightly more pronounced shape differences

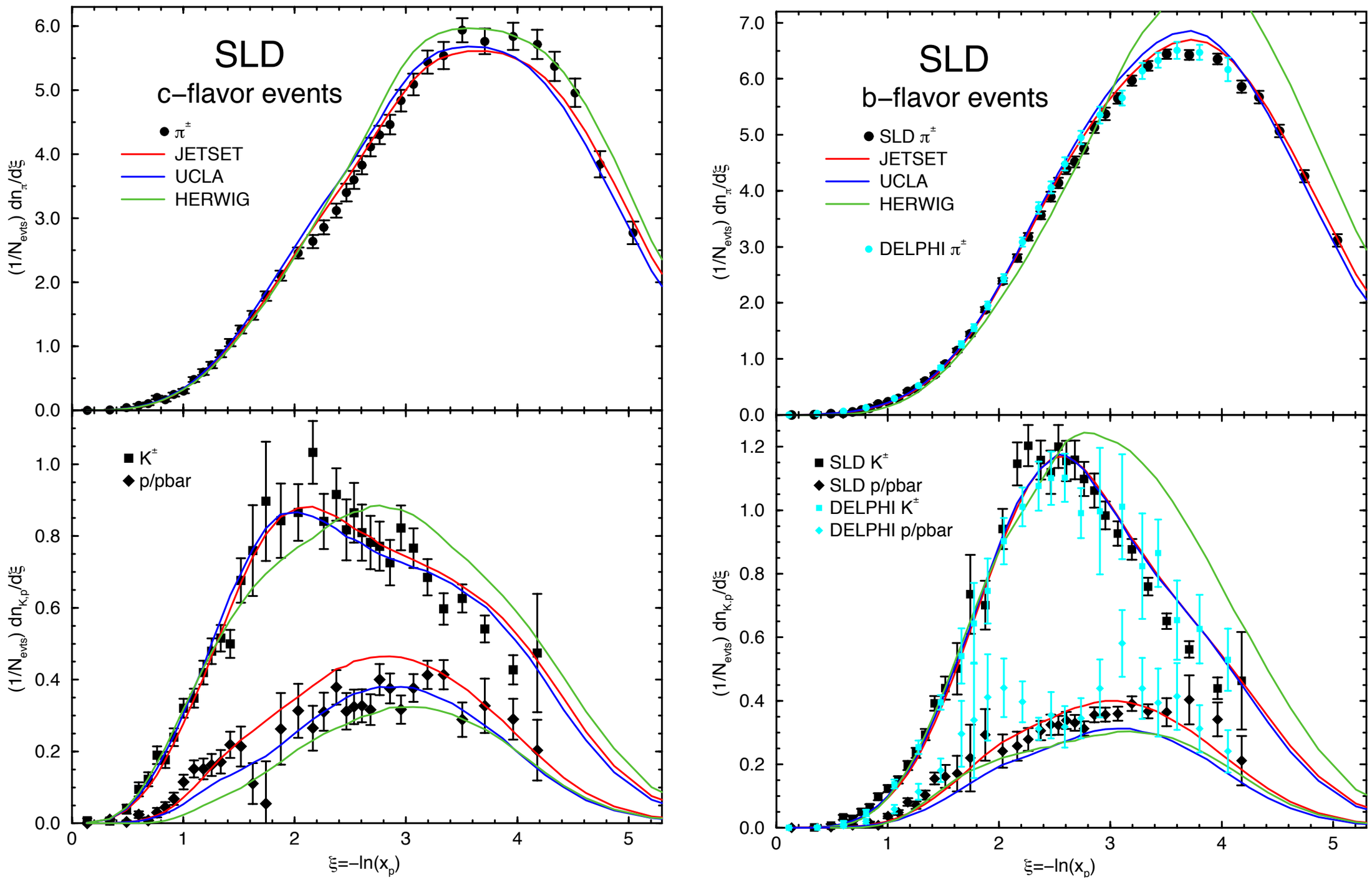


- several similar LEP measurements
  → all all-charged msmts consistent; also uds→$\pi^{\pm}$,$K^{\pm}$,p/$\bar{p}$



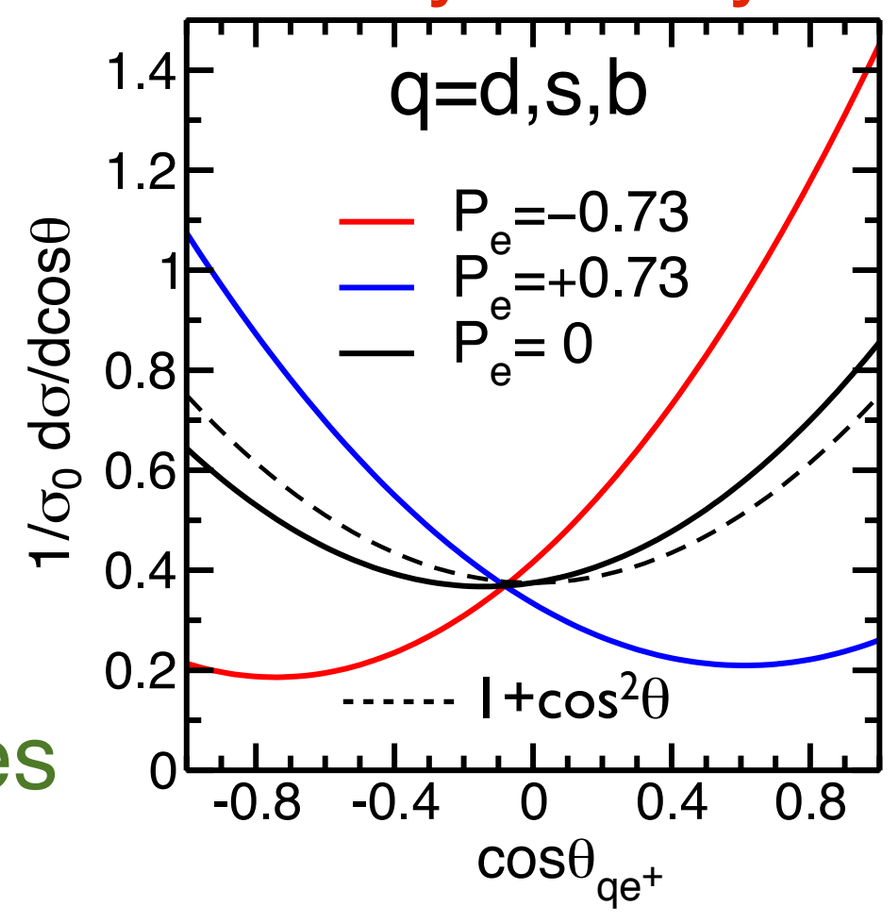
→ and DELPHI and SLD on $b\bar{b}$ events

→ also a different perspective in model tests



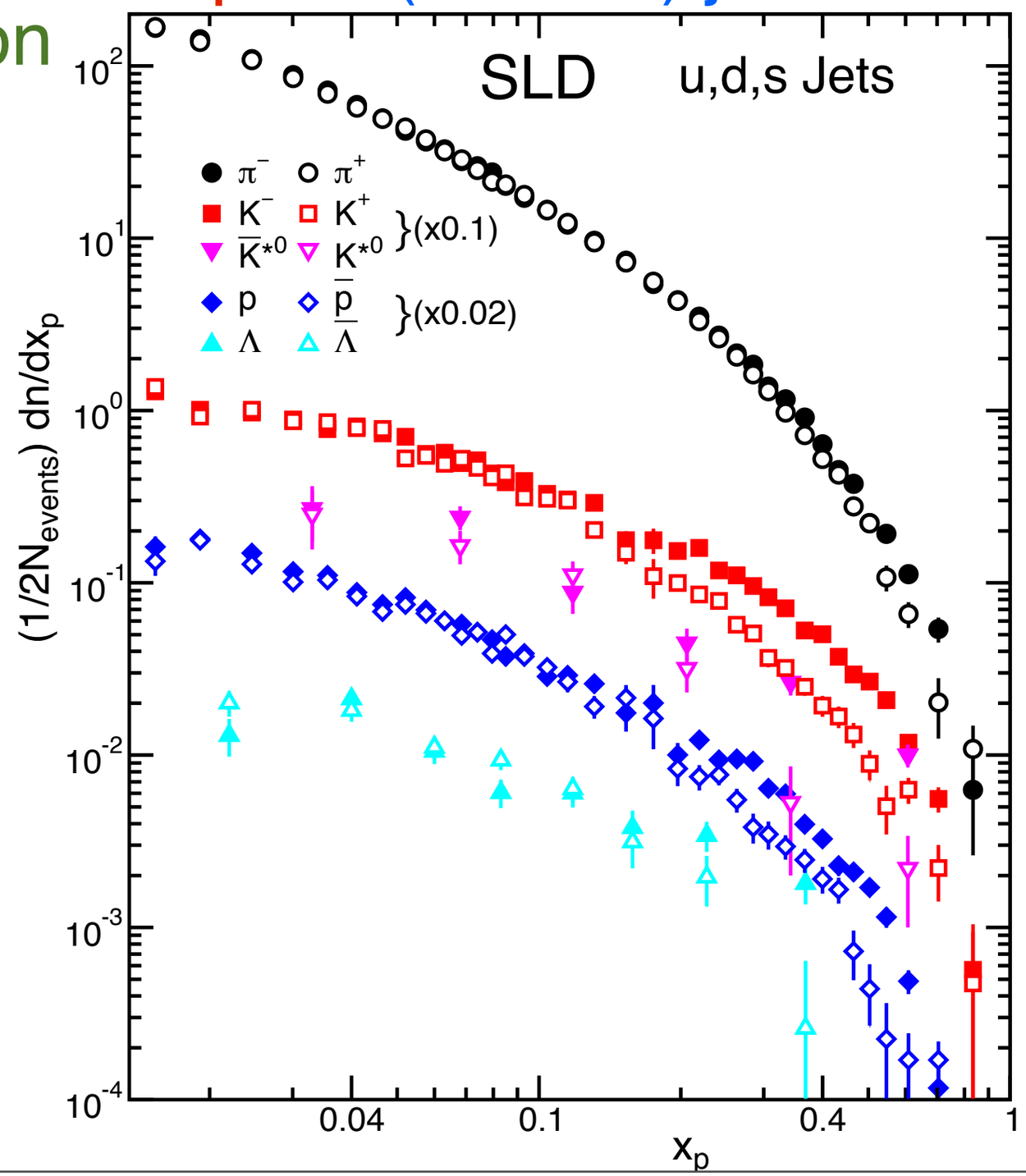
Quark Jets vs. Antiquark Jets

- The SLC ran with a polarized e^- beam
  - → switched randomly between left- and right-handed polarization
- results in a large quark forward-backward asymmetry
  - → Z^0 decays prefer left-handed q and right-handed $\bar{q}$
  - → left-(right)handed e^- pushes the q forward (backward)



- consider uds-tagged events with left-handed beam and $|\cos\theta_{thrust}| > 0.15$
  - → 73% of the forward hemispheres contain a quark (rather than $\bar{q}$)
  - → analyze particle, antiparticle separately in these jets
  - → assume CP symmetry: combine π^+ from the q-tag sample with π^- from $\bar{q}$-tag sample, etc.

- subtract small heavy flavor background
  → models checked against heavy-tagged data
- unfold to obtain spectra in uds quark (not $\bar{u}\bar{d}\bar{s}$) jets
  → clear hadron-antihadron differences develop at high x_p
  → large excesses of p,Λ over $\bar{p},\bar{\Lambda}$ above ~0.2
  → even larger effects for K^- over K^+, and $\bar{K}^{*0}$ over K^{*0} develop earlier, ~0.1
  → a small excess of π^+ over π^- develops later, ~0.3



- convenient to take the normalized differences

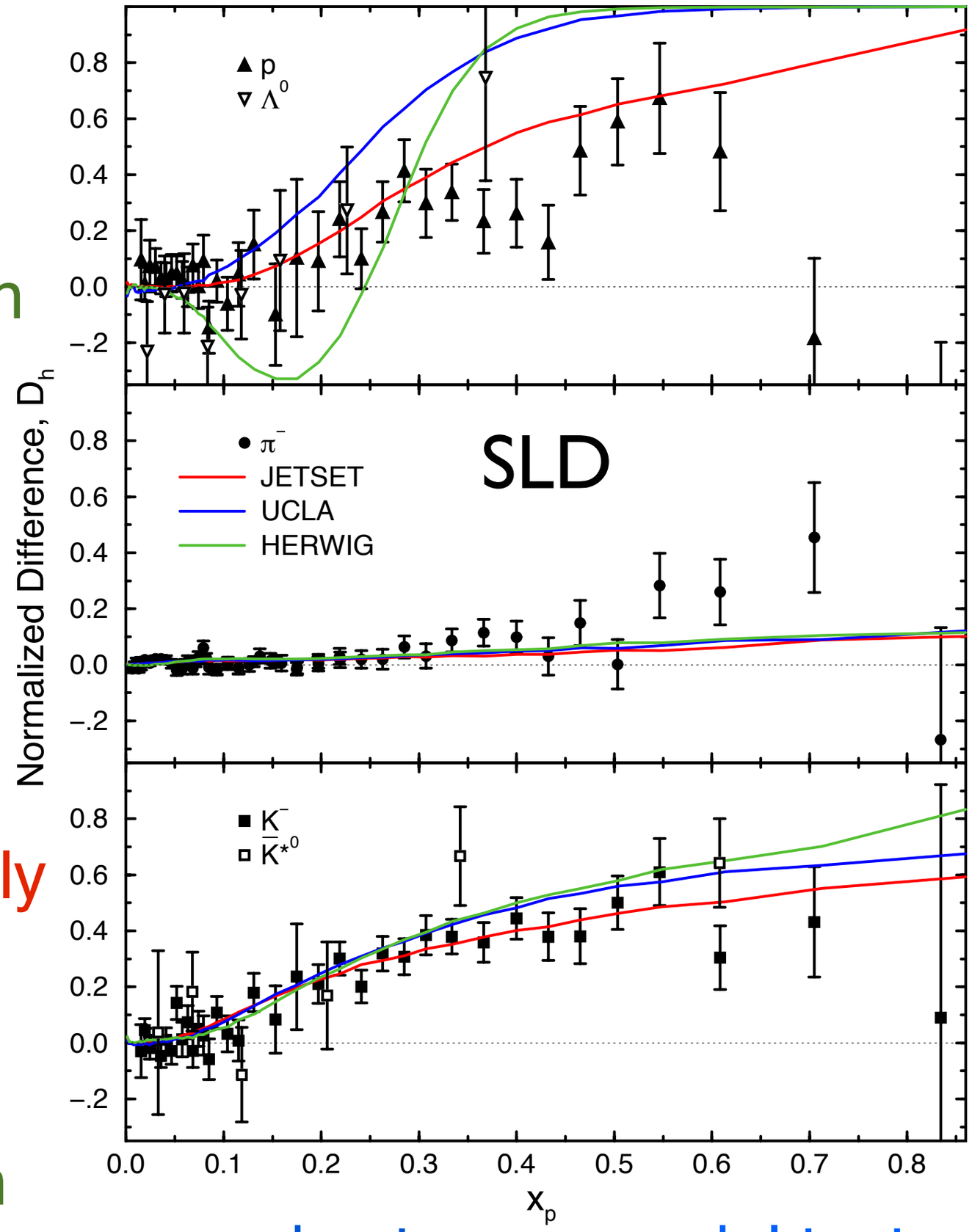
$$D_h = \frac{\sigma_{q\to h} - \sigma_{\bar{q}\to\bar{h}}}{\sigma_{q\to h} + \sigma_{\bar{q}\to\bar{h}}}$$

→ 0 ↔ equal production
±1 ↔ total dominance of one or the other

- D_p rises slowly, 0.1-0.3
  → p contains valence q only
  →...but there's always a subleading $\bar{p}$ or $\bar{n}$

- D_{K^-,K^*} rise more smoothly
  → s jets, need no compensating K+

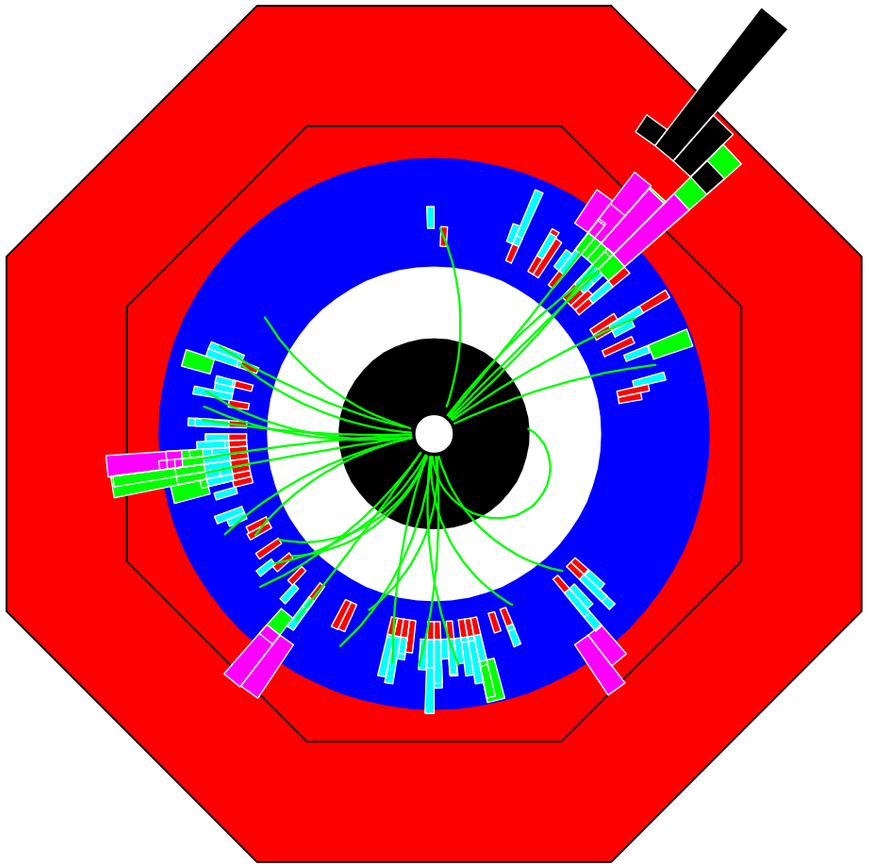
- D_{π^-} rises very slowly
  → competition between $u\to\pi^+$ and $d\to\pi^-$



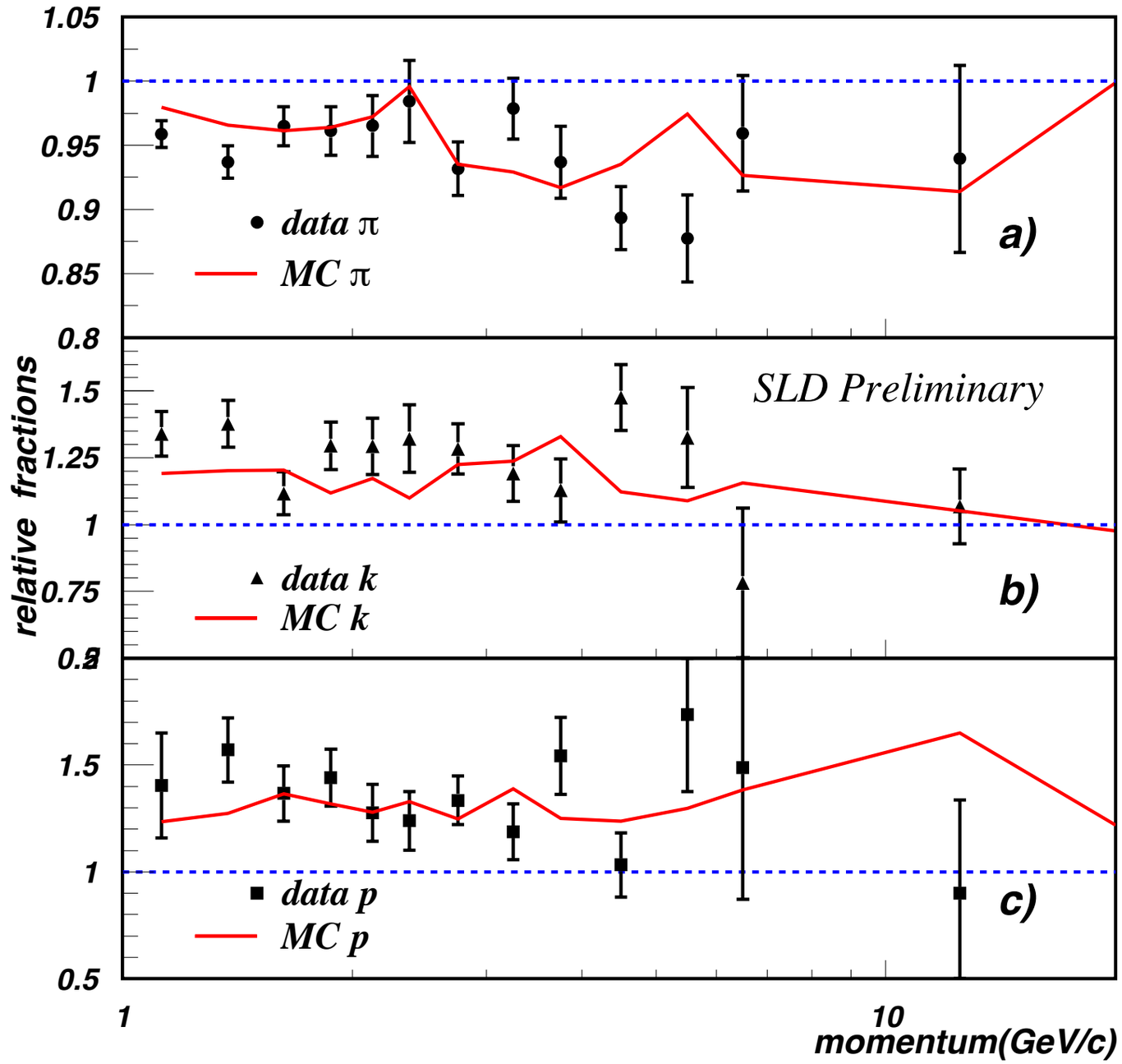
- and yet more model tests

Light quark vs. gluon jets

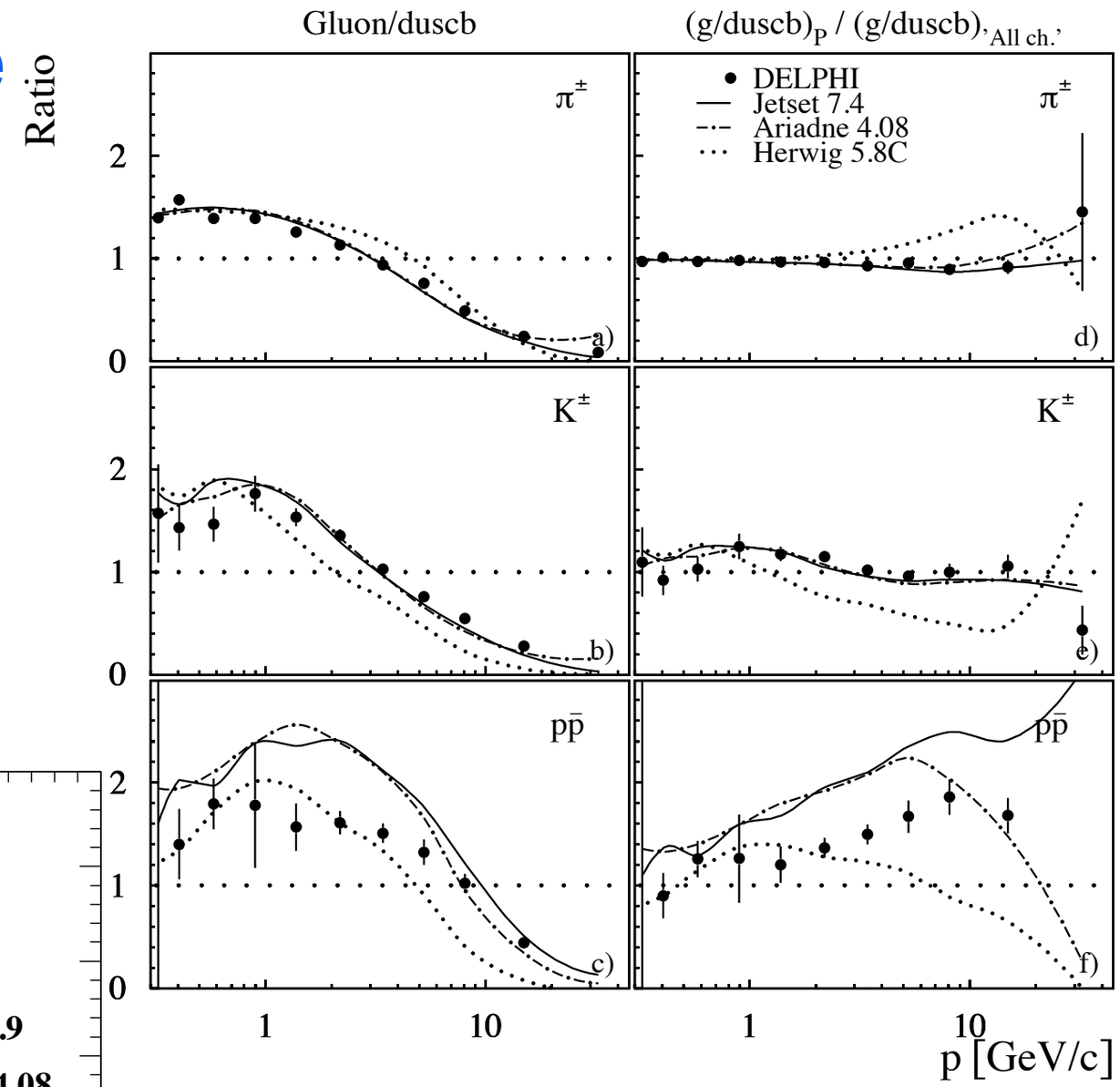
- consider 3-jet events
  - → JADE algorithm, y_{cut}=0.35
- "identify" the jets
  - → assume the highest-energy jet is a q or $\bar{q}$ (93% correct)
  - → tag one of the others as b or c
  - → then the third is a gluon jet
  - → ...or if neither is tagged, they're uds and g
  - → sometimes also tag the high-E jet as b or c
- perform analysis on these uds- g- b- and c-tagged samples
- unfold to compare g and uds jets

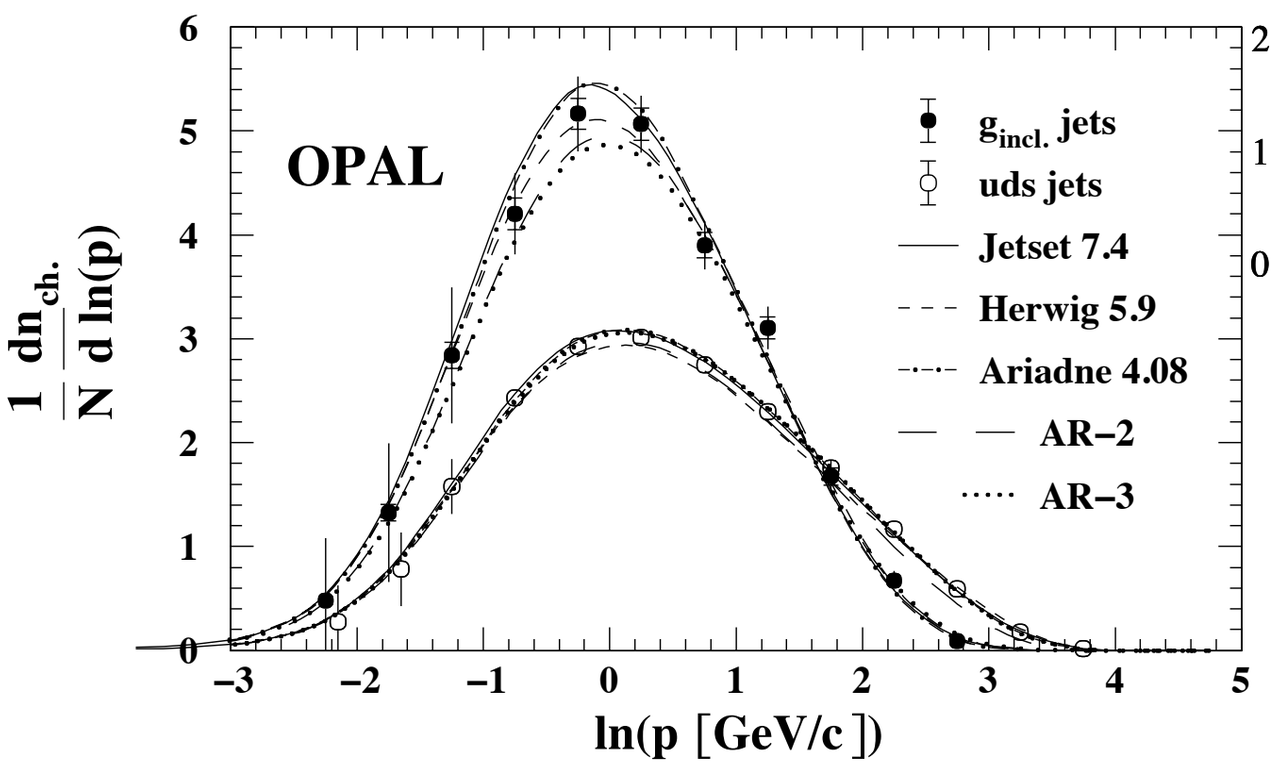


- quantify in terms of ratios of hadron fractions in gluon:uds jets
  - → gluon jets are richer in p/p̄ and K±
  - → ...with lower π± fraction, though more tracks overall
  - → consistent with results from Υ(1S) decays



- the LEP experiments have done quite a few more studies
  - → for example, a similar study from DELPHI
  - → and a complementary study from OPAL





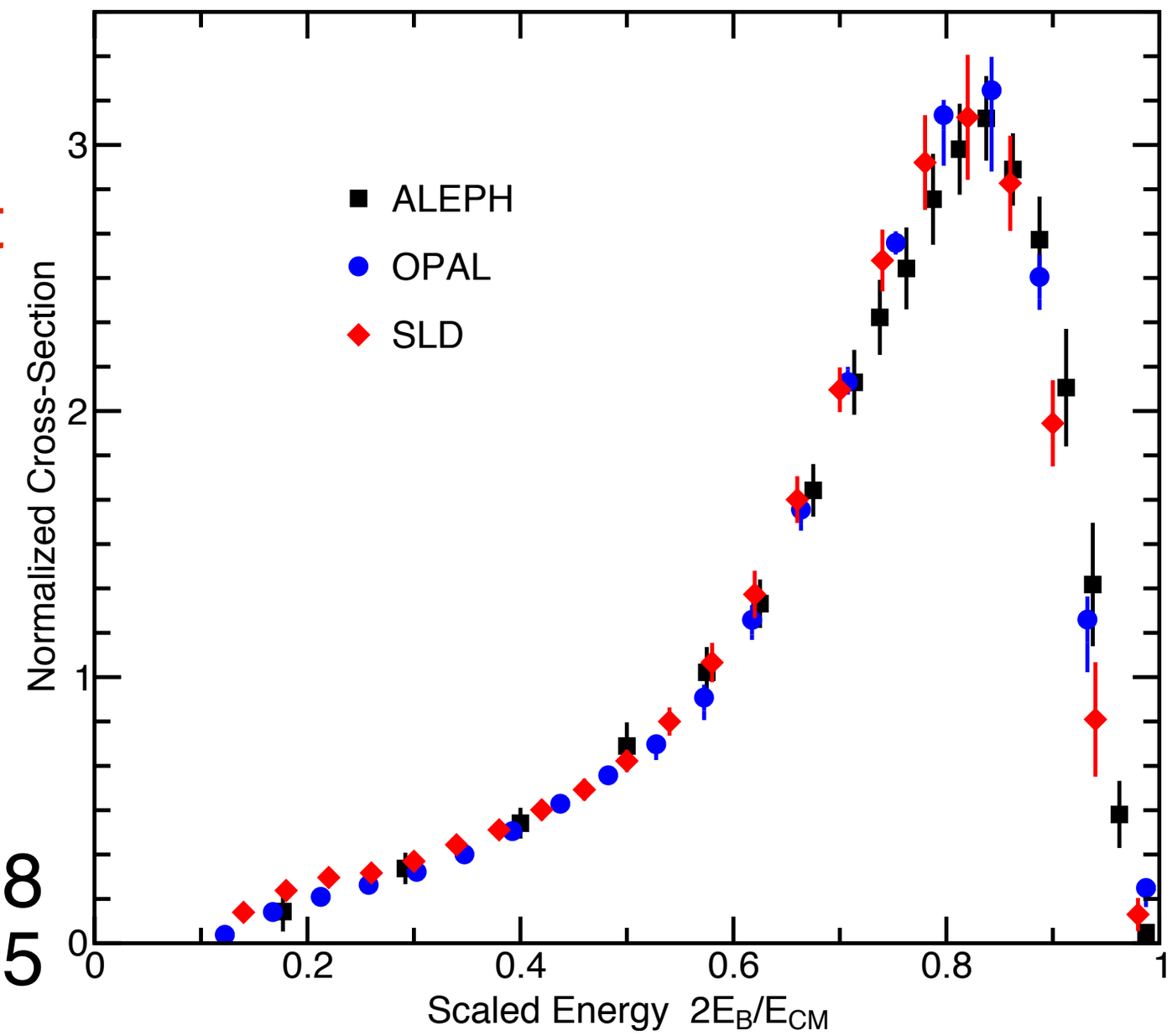
Summary

- Inclusive spectra of several identified/reconstructed hadrons measured precisely at SLD and BaBar
  - → SLD: $\pi^{\pm}$, $K^{\pm}$, $K^0/\bar{K}^0$, $K^{*0}/\bar{K}^{*0}$, ϕ, $p/\bar{p}$ and $\Lambda^0/\bar{\Lambda}^0$
    part of a large body of measurements at the Z^0
  - → Babar: $\pi^{\pm}$, η, $K^{\pm}$, $p/\bar{p}$
    consistent with, improvement upon, measurements from ARGUS
- Scaling properties measured precisely
  - → models tested – issues for η, $p/\bar{p}$
  - → MLLA QCD predictions consistent with data
- SLD has isolated $u\bar{u}$,$d\bar{d}$,$s\bar{s}$ events, uds jets, and gluon jets
  - → much additional information
  - → let's put it all together !!

Backup Slides

Inclusive (weakly decaying) B hadron FF

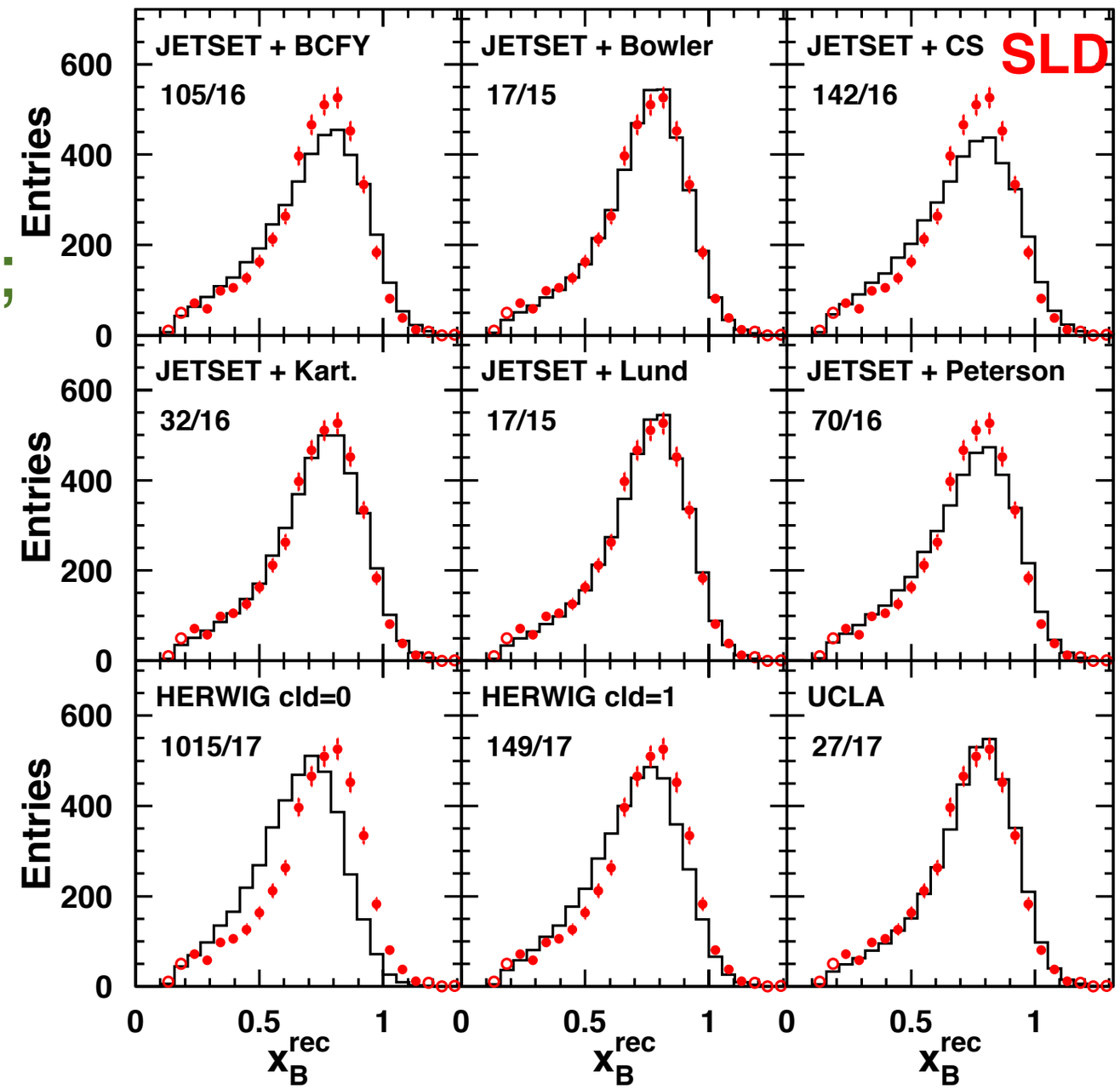
- estimate the energy of the B hadron
  - → use measured E/p, kinematic constraints
  - → achieve 10-20% resolution
- this is one of the best measured FFs
  - → covers the full kinematic range
  - → errors must be considered a shape envelope
  - → good precision on
    $\langle x_E \rangle_b = 0.702 \pm 0.008$
    $(x_E)_{max} = 0.835 \pm 0.005$



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

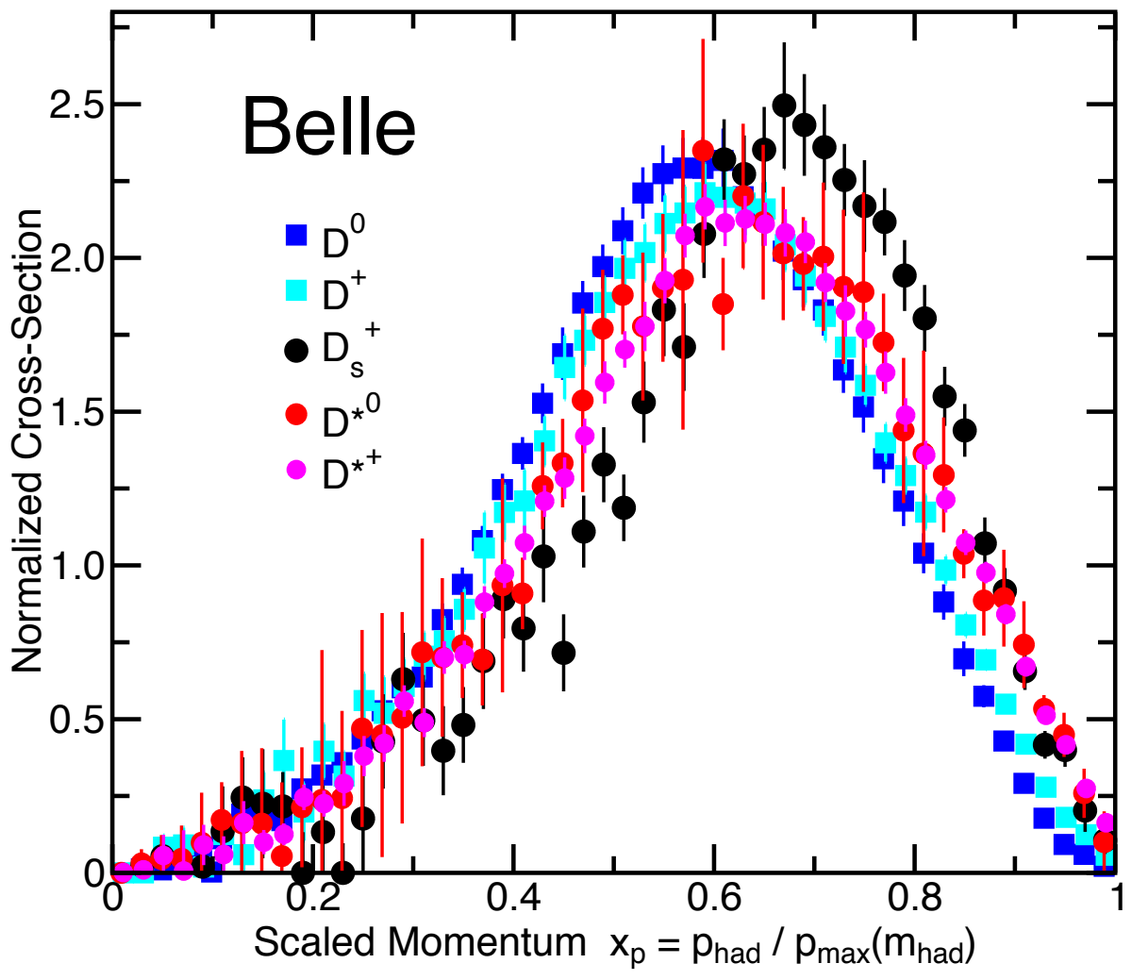
Tests of heavy quark fragmentation models

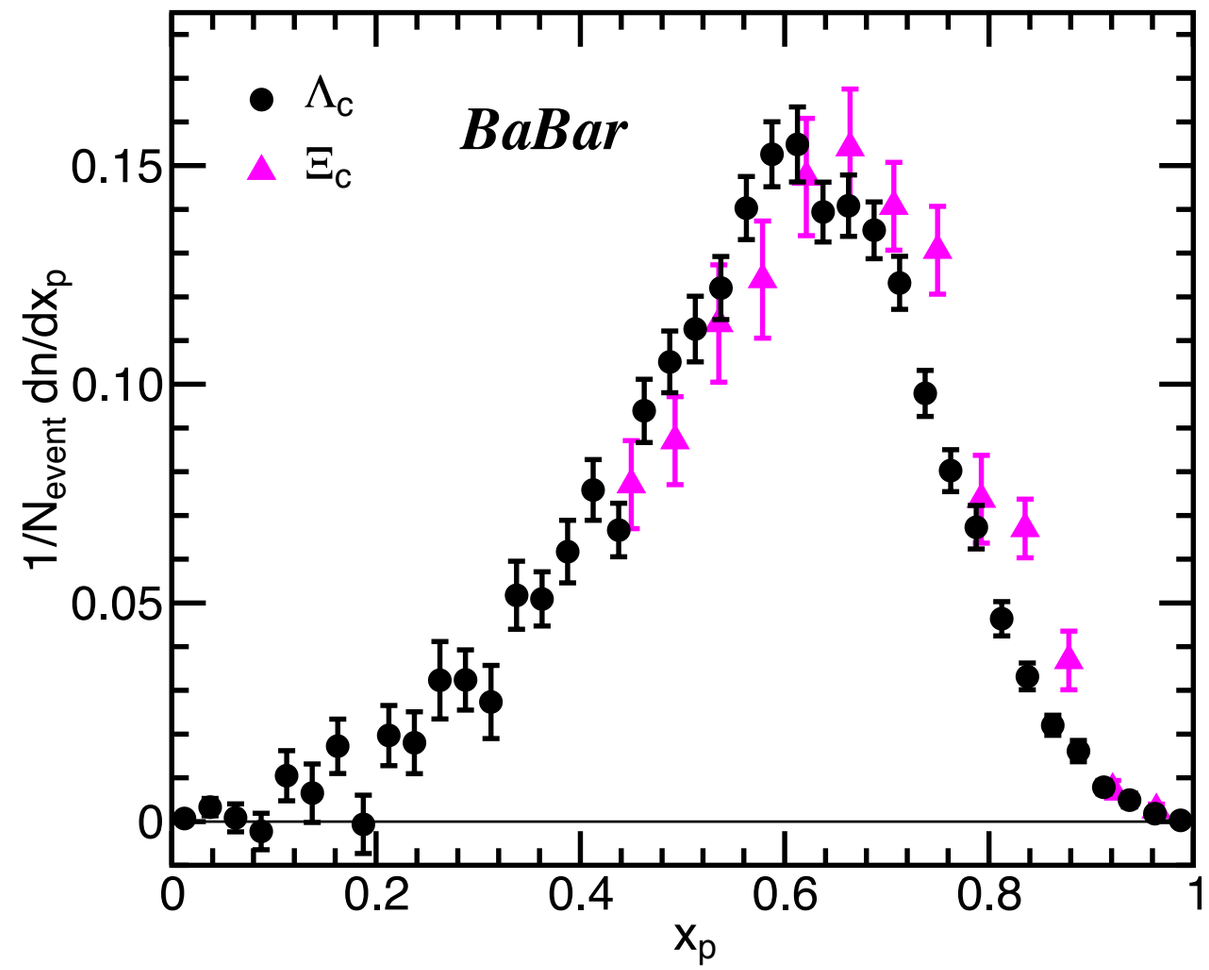
- can test models of the shape of the heavy quark FF
  - → some must/should be embedded in a MC generator
  - → best done before data correction
  - → examples from SLD:
- most models excluded
  - → Bowler, Lund "good"; Kartvelishvili, UCLA may be adequate
  - → similar results from other experiments
  - → these are not default in any, and unavailable in many generators



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

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