Inclusive Production of Light Charged Hadrons at BaBar

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- **Introduction**
- **Analysis**
  - **production rates for $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$**
- **Results**
  - **model and scaling tests**
  - **tests of MLLA QCD**
  - **fractions, ratios, totals**
- **Summary**

arXiv:1306.2895
to appear in PRD

} including preliminary η results

Introduction

- partons (quarks and gluons) from hard interactions appear as hadronic jets in a detector

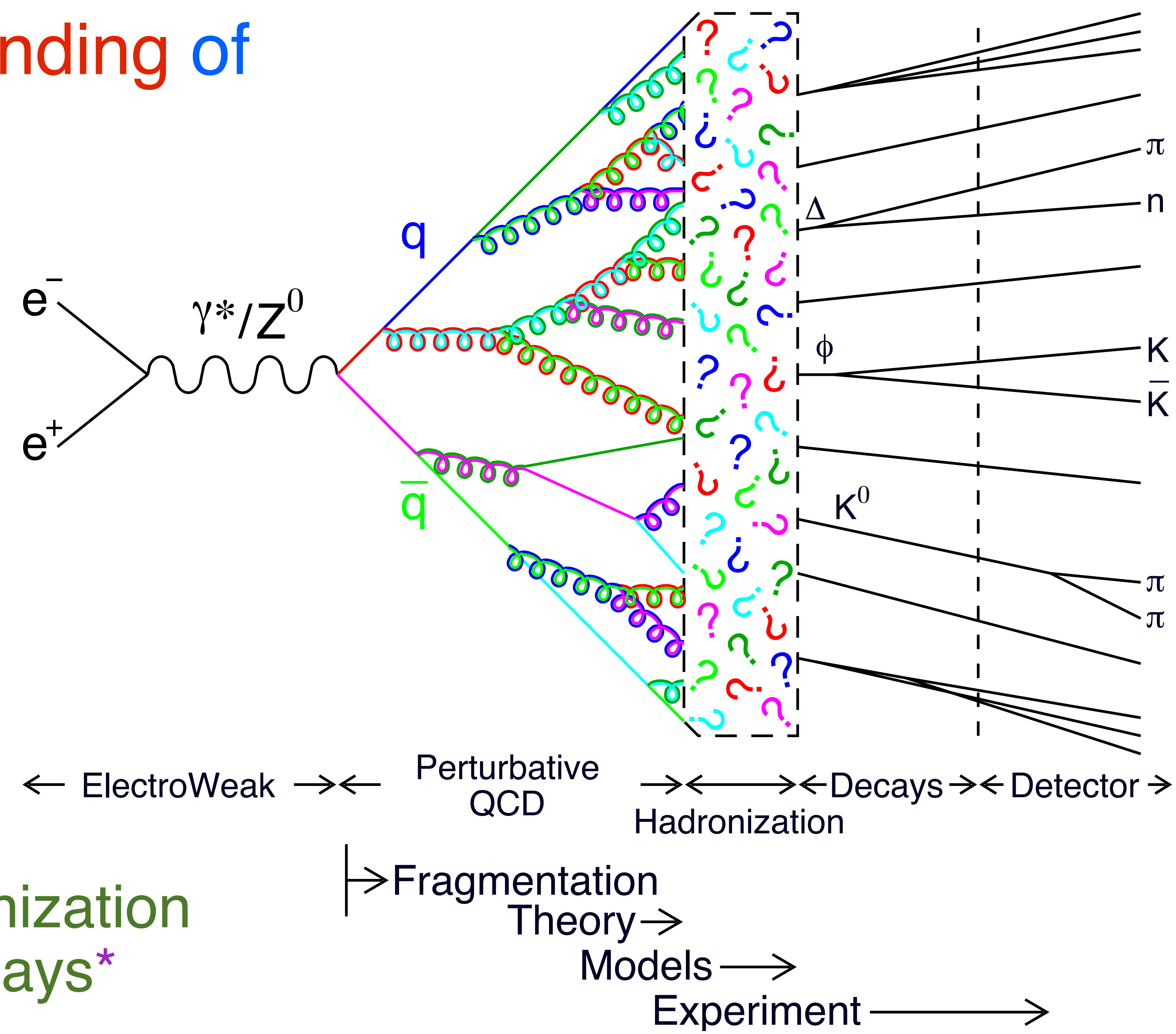
- need to understand hadronization / structure of jets
  → fundamental strong interaction physics
  → jets are signals and backgrounds at high E, e.g. LHC
  → jet substructure becoming important

- best studied in e^+e^- annihilations
  → initial state is known (E_{CM}, $\vec{p}_{CM}$), non-hadronic
  → fine-grained detectors with precise tracking and particle identification

- identified hadrons provide
  → effect of flavor, baryon #, spin, etc. on hadronization
  → dependence on mass, scaling issues
  → information on the parton flavor, spin, ...

- our current understanding of $e^+e^- \to$ hadrons

- theory:
  - → EW physics known
  - → inclusive features of the parton shower are calculated in MLLA QCD*
  - → E_{CM} dependence calculated in pQCD*



- phenomenology:
  - → parton shower, hadronization modelled in various ways*

- experiment:
  - → measurements at several E_{CM}*
  - → and for many particles
  - → the only measurements with good precision and coverage are at 91.2 GeV (the Z^0 peak)

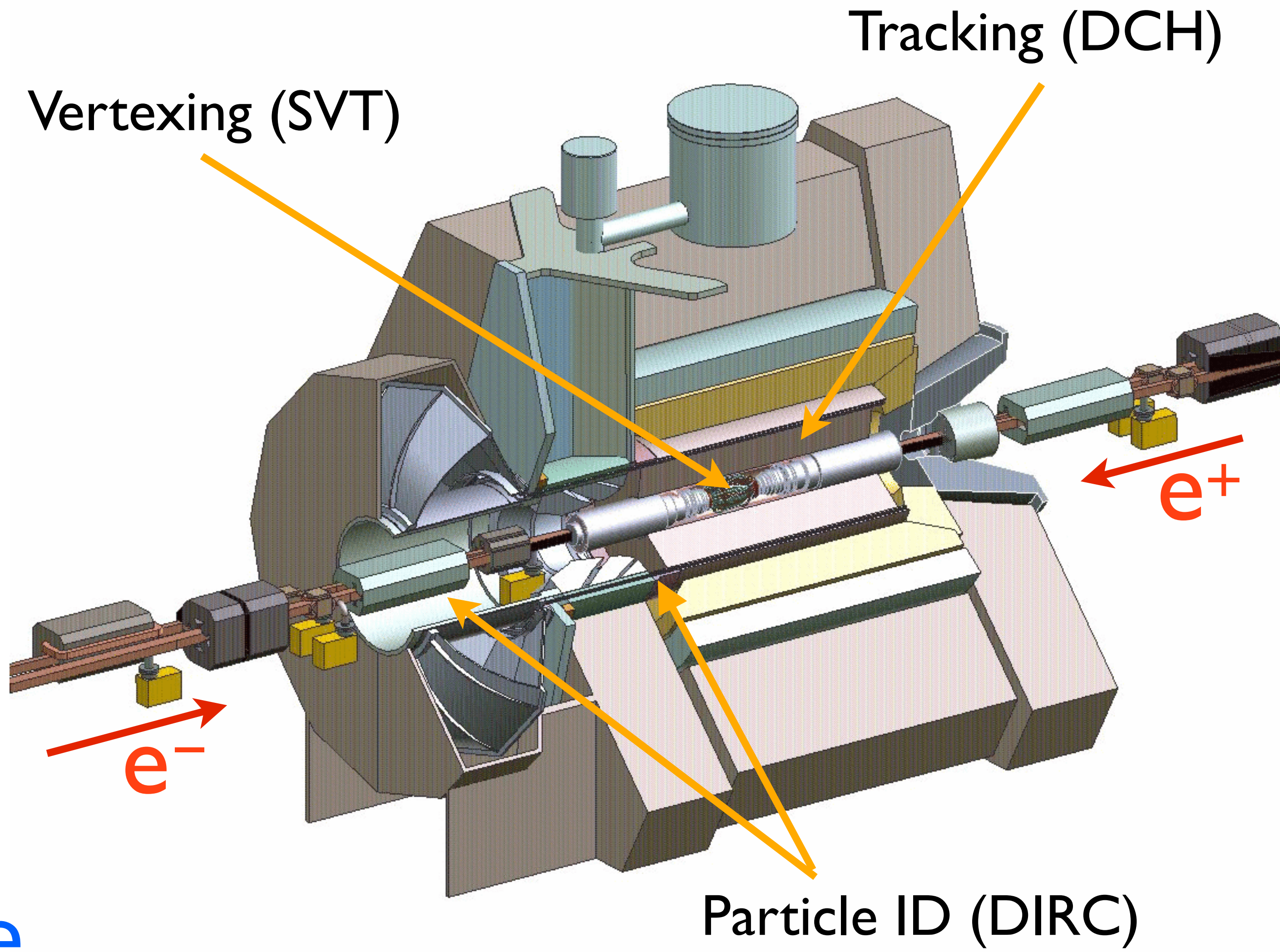
*see references in backup

The BaBar Experiment

- e^+e^- collisions at E_{CM} near 10.6 GeV, designed for CP violation in B decays

- different beam energies
  - → E_{e-} = 9.0 GeV
  - → E_{e+} = 3.1 GeV
  - → CM-lab boost, $\beta\gamma$=0.55

- asymmetric detector
  - → CM frame acceptance $-0.9 \sim \cos\theta^* \sim 0.85$ wrt e^- beam



- with excellent performance
  - → good tracking, mass resolution
  - → good γ, π^0 recon.
  - → full e,μ,π,K,p ID

- High luminosity
  - → ~520 fb^{-1} accumulated
  - ↔ 1.7 billion $e^+e^- \to q\bar{q}$ events

Hadronic Event and Track Selection

- use data from a very good running period
  - → "only" 1 fb^{-1} at 10.54 GeV   +4 fb^{-1} on the Υ(4S) for calibration
  - → dominated by systematics
- select a clean sample of $e^+e^- \to u\bar{u}$, $d\bar{d}$, $s\bar{s}$ and $c\bar{c}$ events with low bias in track multiplicity, momentum, ...
  - → requirements on event vertex, topology, visible energy, $|\cos\theta^*_{thrust}|$, $e^\pm$ content   (details in backup)
  - → 70% efficiency, 2.2 million events
  - → critical to understand backgrounds:

$e^+e^- \to \tau^+\tau^-$	4.5%
$e^+e^- \to e^+e^-\gamma$	0.1%
$e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-$+hadrons	< 1%
beam-gas, others,	very small

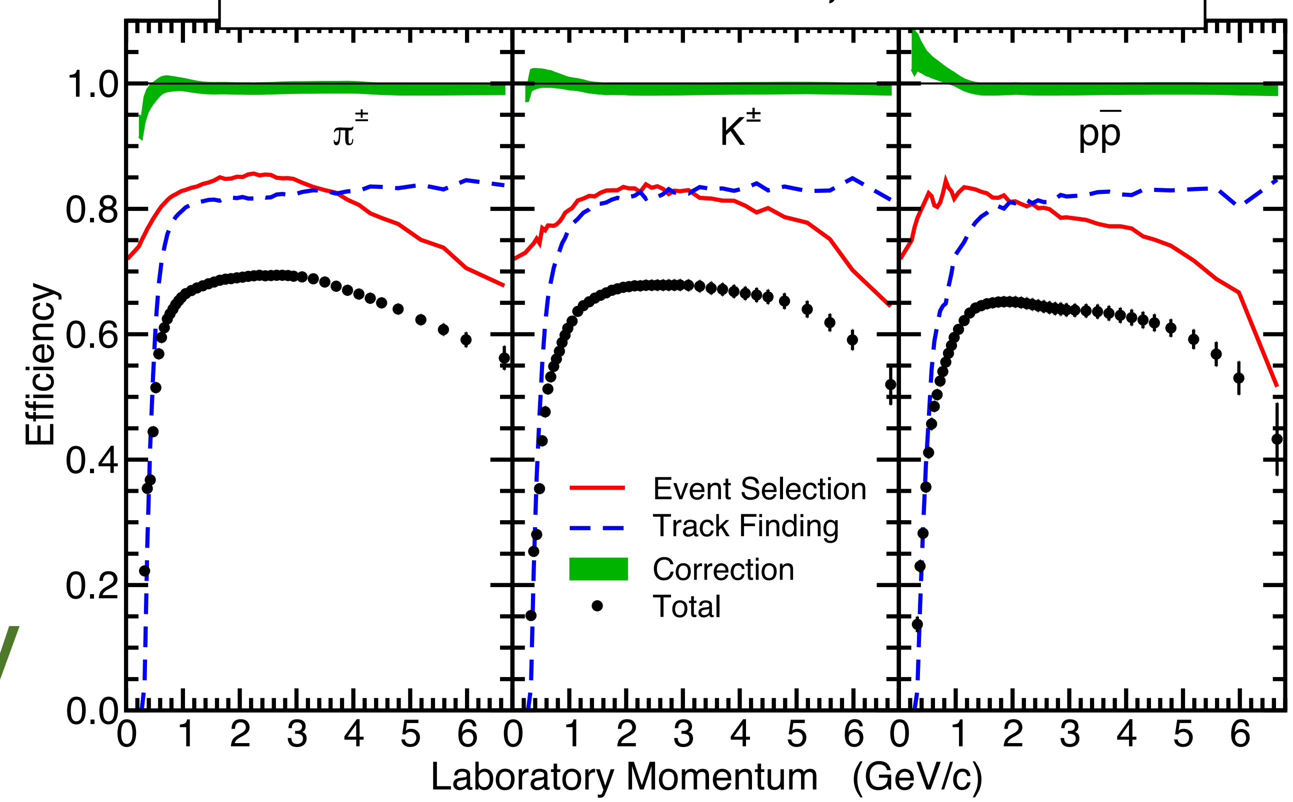
- track sample unbiased, good DCH, DIRC information
  - → reqmts. on hits, extrapolation to event vertex, DIRC
  - → $p_t > 0.2$ GeV; $-0.77 < \cos\theta < 0.88$ (details in backup)

Event and track selection, II

- charged hadron definition
  - → no decay products of "stable" $\mu^\pm$, $\pi^\pm$, $K^\pm$, K^0_L, $n/\bar{n}$
  - → ...or of K^0_S, Λ, Σ, Ξ, Ω measure "prompt" production

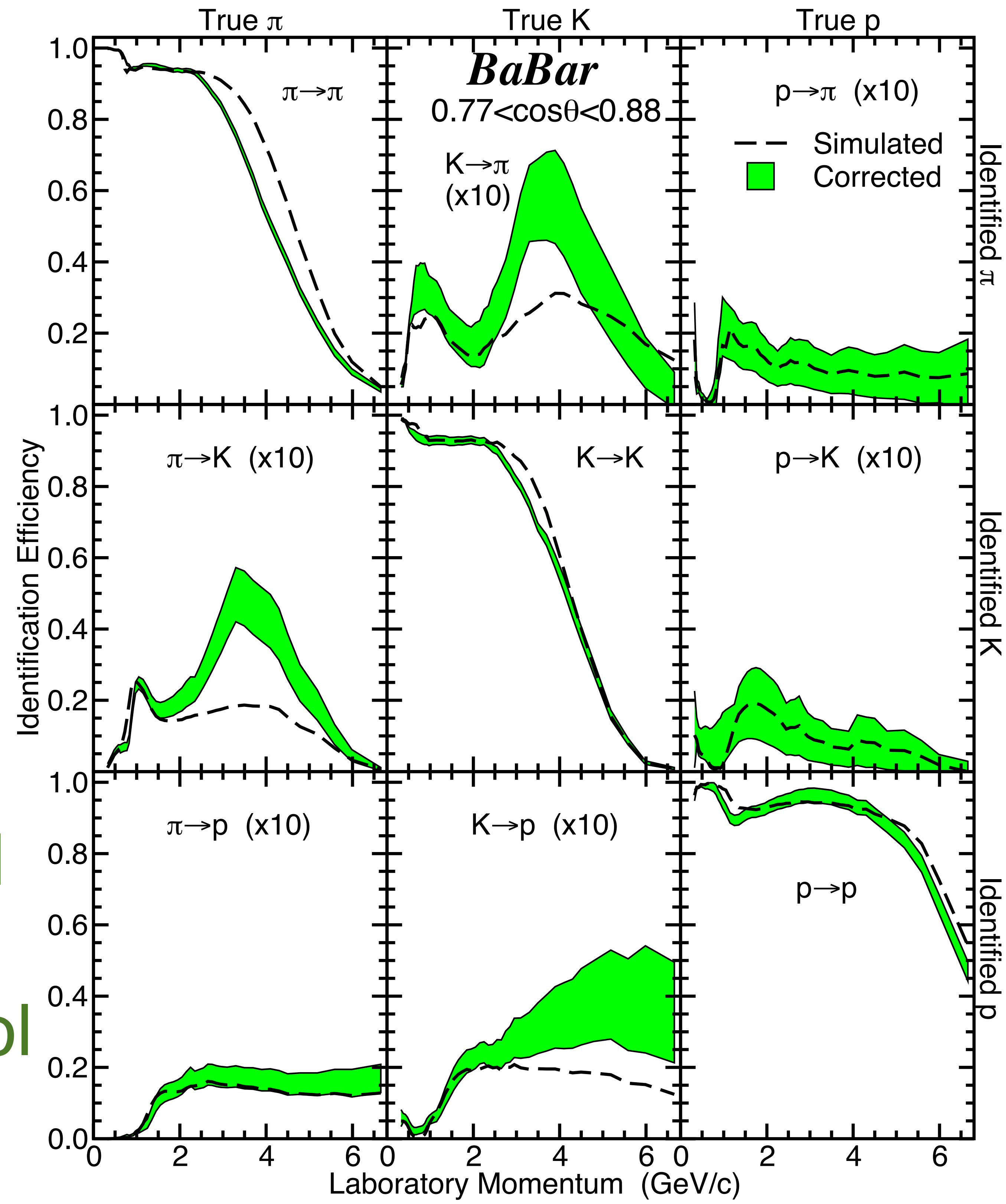
    also add back the latter for "conventional"
- divide into 6 subsamples of polar angle: $\theta1$, $\theta2$ … $\theta6$
  - → perform analysis ~independently in each
  - → tremendous set of systematic cross checks
- extensive studies, corrections to the simulation
  - → hit effs., dE/dx, material interactions (Δ's)
- performance:
  - → bias understood
  - → π,K,p tracking similar
  - → small corrections
  - → ~1% error for p > 1 GeV; few% <

$\theta6$: $0.77<\cos\theta<0.88$; worst case



Particle Identification

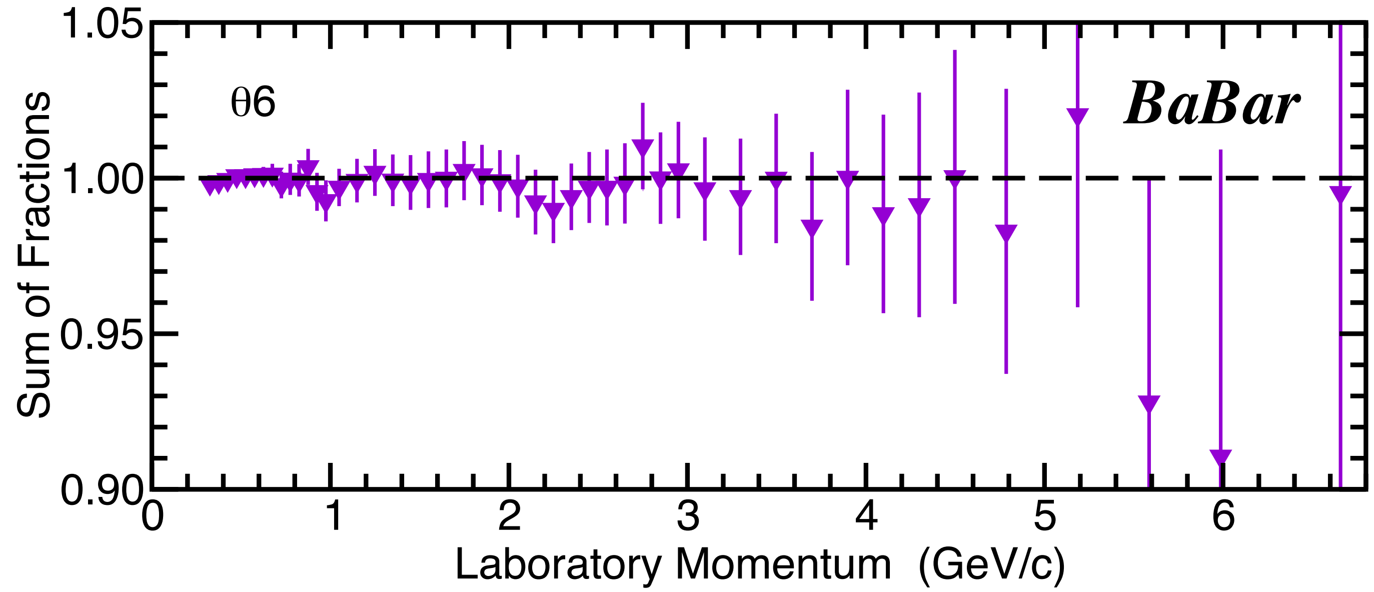
- want high efficiency, low misidentification, smooth variation with p, θ
  - → optimized linear comb. of DCH and DIRC likelihood ratios



- the efficiency matrix is calibrated from the data
  - → $\pi^{\pm}$ from K^0_S, Λ, D^0, τ
    $K^{\pm}$ from D^0, ϕ
    $p/\bar{p}$ from Λ decays
  - → most corrections small
  - → and show the expected correlations
  - → error bands from control sample statistics:
    sub-% to few-%

Analysis

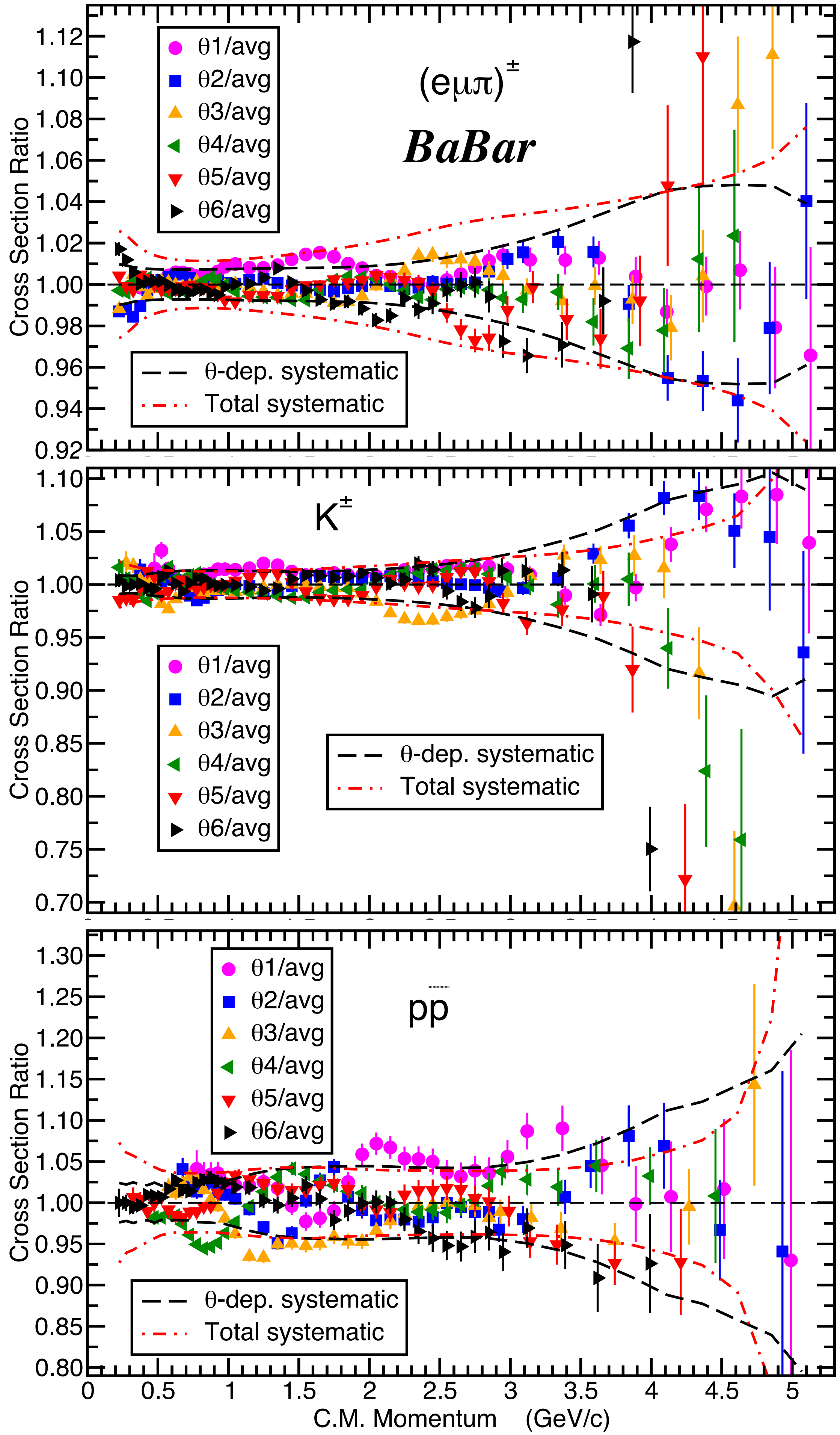
- count identified tracks $n_{\pi,K,p}$ in p, θ bins
  - → check that the sum $\Sigma_{ij}\,\varepsilon^{-1}_{ij}\,n_j / n_{tot} = 1$
    efficiency matrix ↗



  - → get raw production rates $\left(\frac{1}{N^{sel}_{evt}}\right)\left(\frac{dn_j}{dp}\right)$
- subtract backgrounds, correct for efficiencies
  - → see previous slides
- transform to the e^+e^- CM frame ⟶ $\left(\frac{1}{N^{had}_{evt}}\right)\left(\frac{dn_j}{dp^*}\right)$
  - → includes corrections for resolution in p, θ
  - → uses a transfer matrix sensitive to the true p* distn.
    iterative procedure to estimate, remove bias
  - → ...and an acceptance factor sensitive to the true θ* distribution
    the simulation must be verified ...

Analysis, II

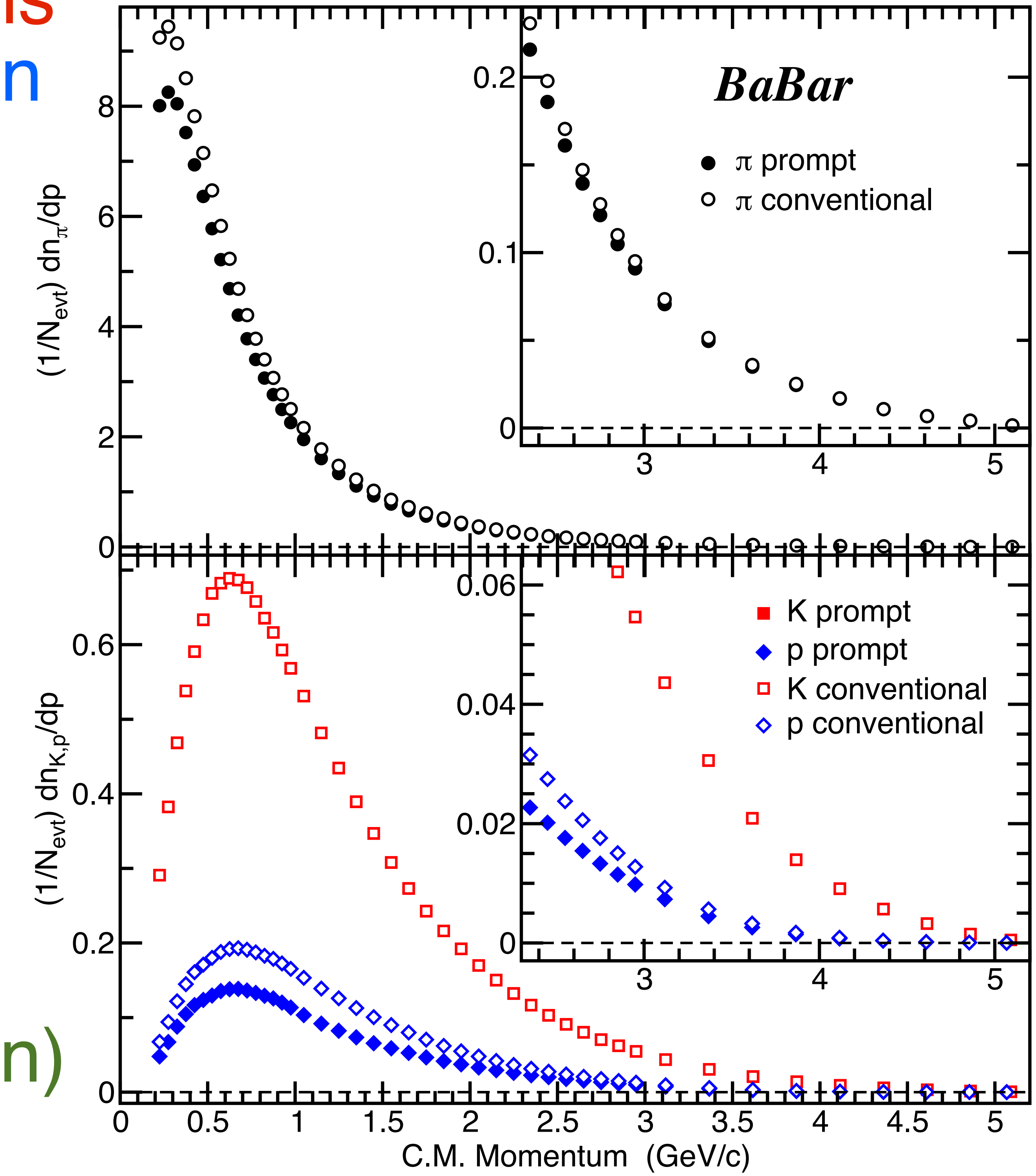
- extensive cross checks
  - → many data-MC comparisons
  - → compare positively and negatively charged tracks
  - → check for dependence on θ, φ ....
- ~independent measurements in the six θ regions
  - → different: backgrounds
    amounts of material
    lab.→CM transforms
  - → comparison limits many systematic effects:
    angular distribution
    CM system boost
    p* distribution
    ...



Results

- average over the θ regions contributing to each p* bin
  - → gives prompt results
  - → add in K^0_S, s-baryon decay products to get conventional results

- nice coverage, precision
  - → see most of the $K^\pm$ and p/$\bar{p}$ spectra
  - → and peak, high-p* side of the $\pi^\pm$ spectrum

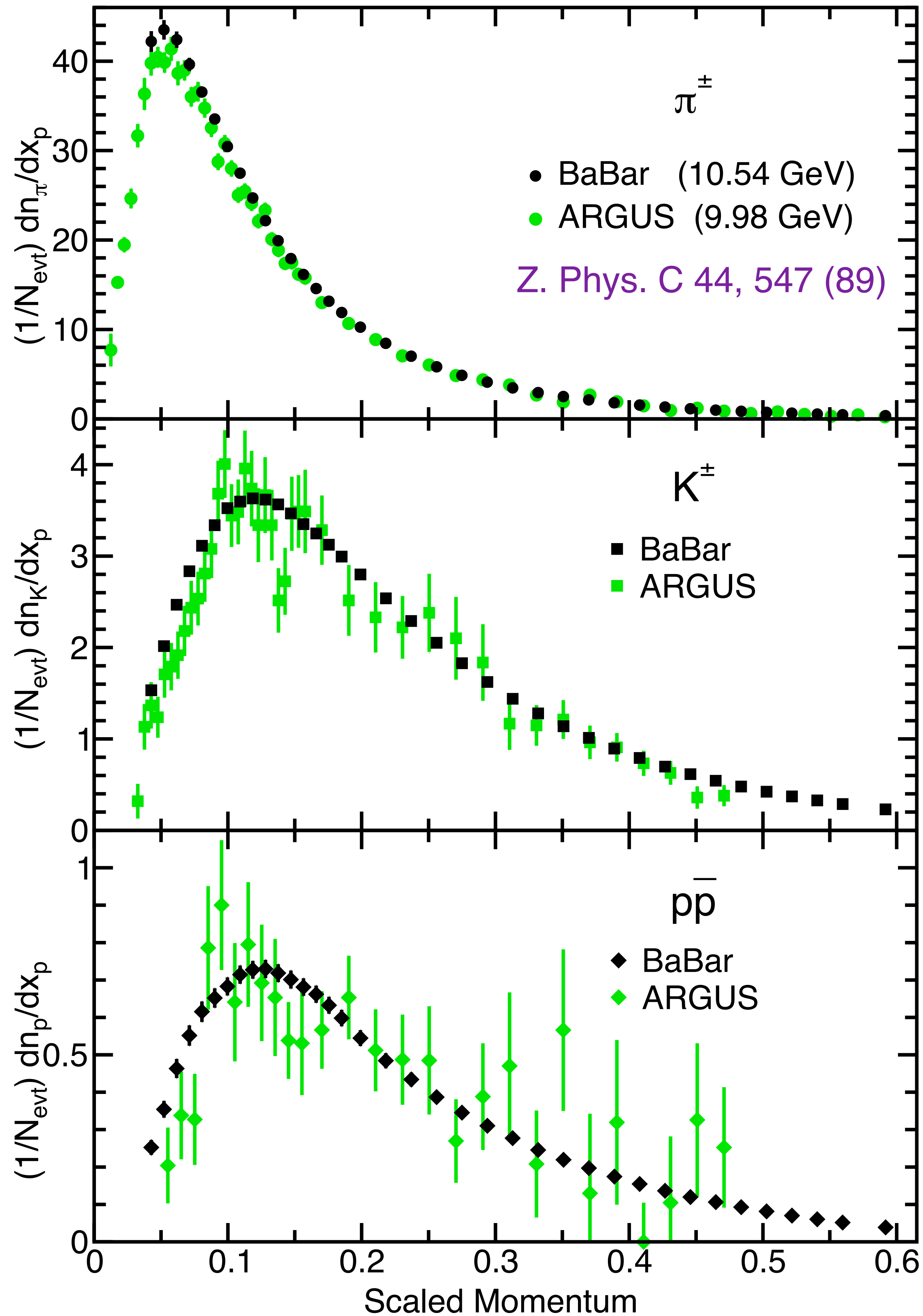


→ uncertainties:
statistics small (shown)
1% normalization
1.3-50% other systematics, correlated over short and long momentum ranges

Comparison with ARGUS

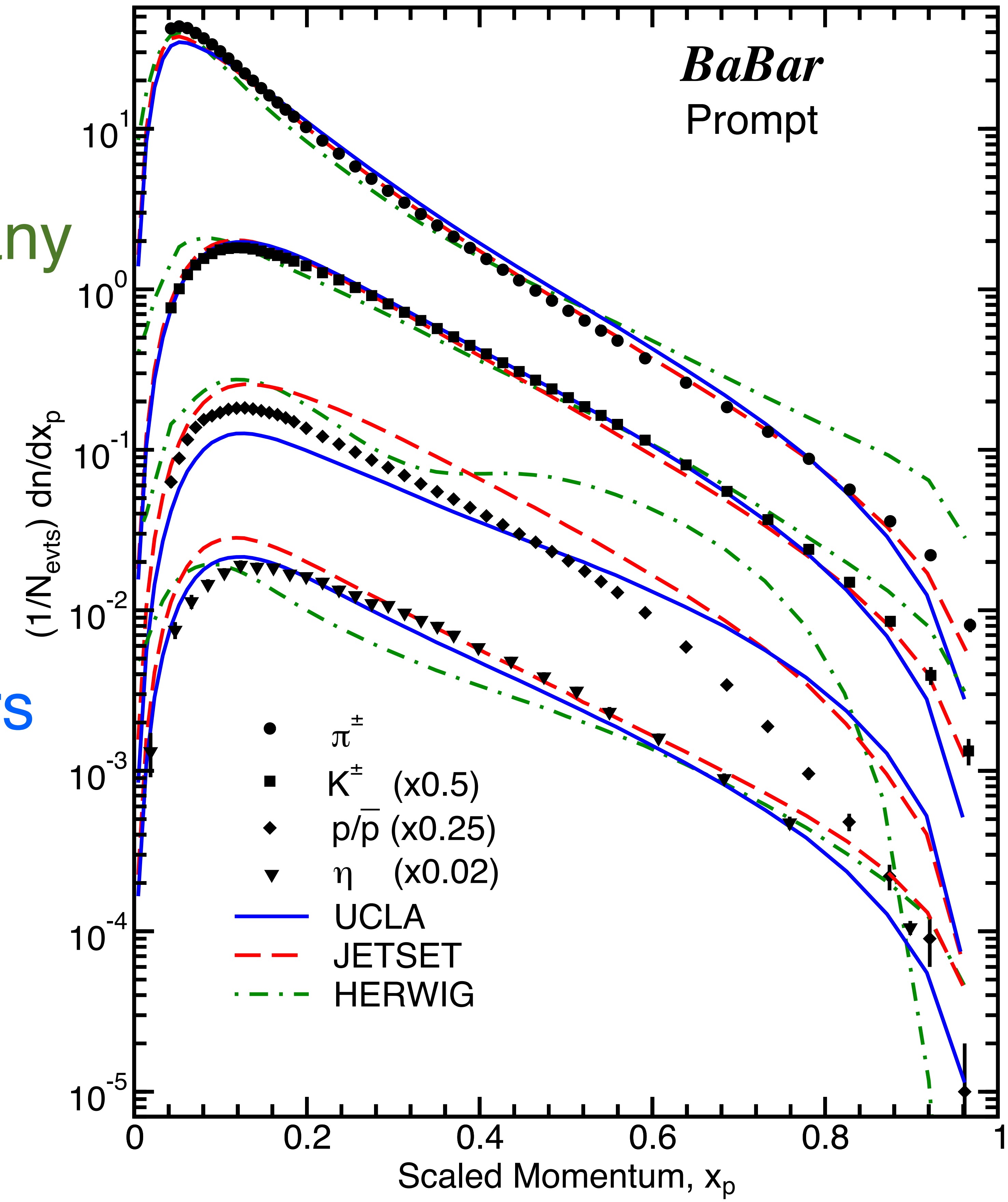
- compare with other experiments using scaled quantities
  - → e.g., scaled momentum
    $x_p = 2p^*/E_{CM}$

- ARGUS has results* at a nearby E_{CM}=9.98 GeV
  - → consistent above 1 GeV
  - → ~expected scaling violation below
  - → big improvement in precision (mostly stat.)
  - → we (they) have better high-(low-)x_p coverage
  - → nicely complementary



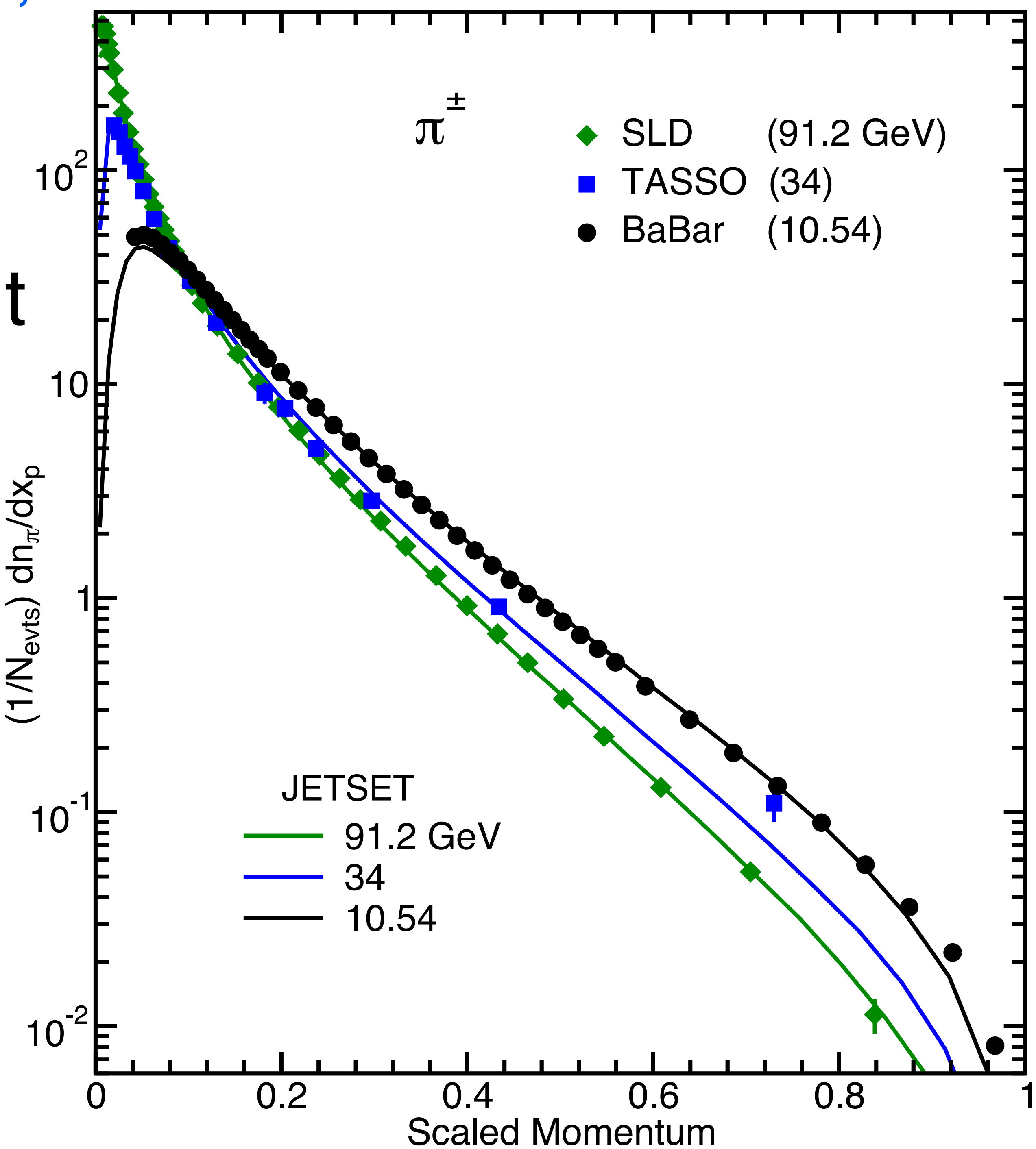
Tests of Hadronization Models

- consider 3 models representing three types of particle prod.
  - → JETSET*: string, many free parameters
  - → UCLA*: area law, ~1 free parameter
  - → HERWIG*: clusters, few free params
- use default parameters
  - → the models all fail
  - → better tunes exist...
  - → but none get the shapes right
  - → our data provide valuable input



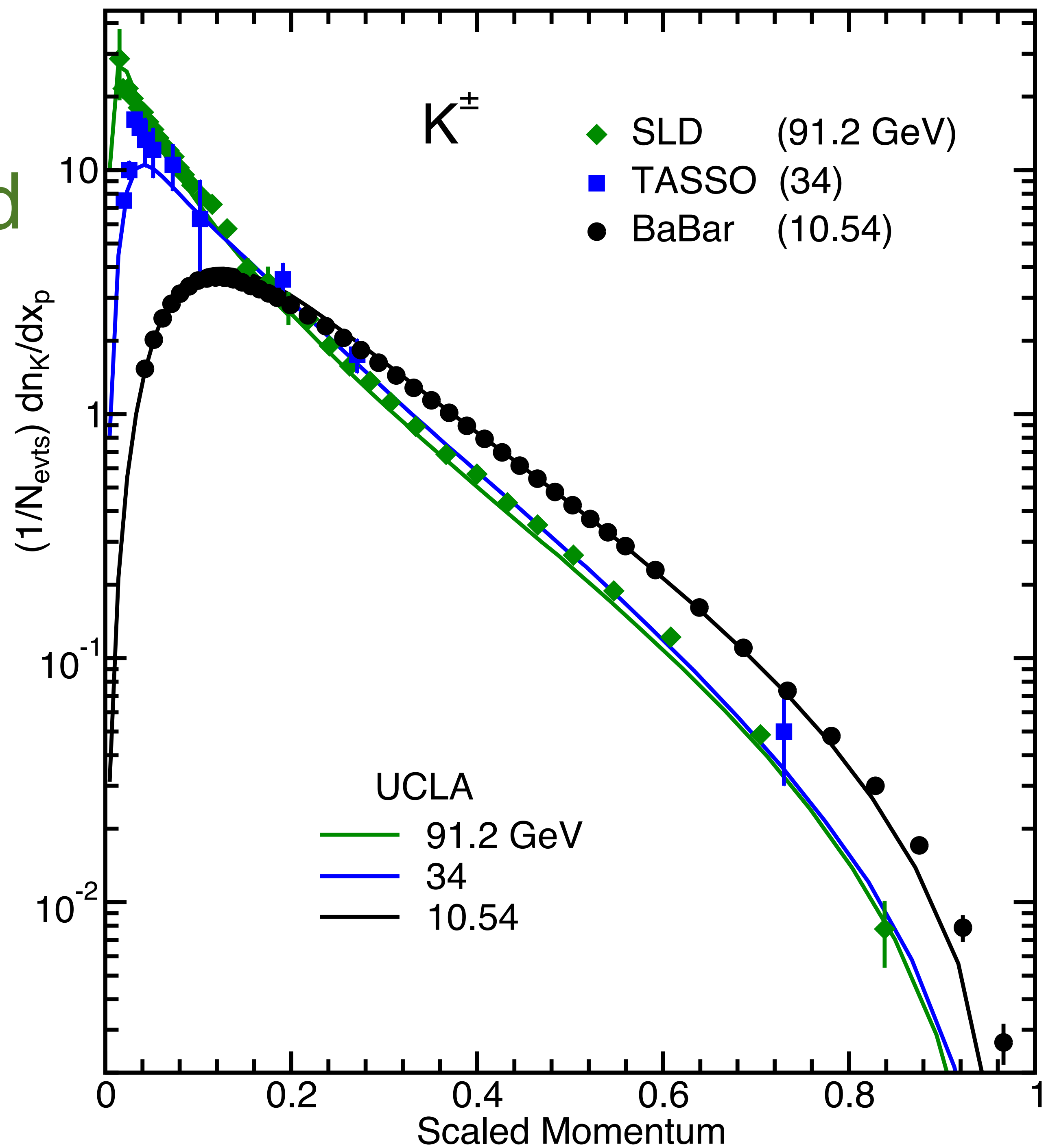
Scaling Properties: high x_p

- the evolution of jets with energy is calculable
  - → ...by theorists, but we can test models
- consider $\pi^{\pm}$ data from BaBar, TASSO* and SLD*
  - → the most useful high-x_p data sets near 34 GeV and at the Z^0
  - → other data are consistent
- strong scaling violation at high-x_p
  - → and at low x_p
- modelled well – only few-% changes in data:MC ratios with E_{CM}
  - → JETSET shown
  - → UCLA, HERWIG show similar scaling



High-x_p scaling, II

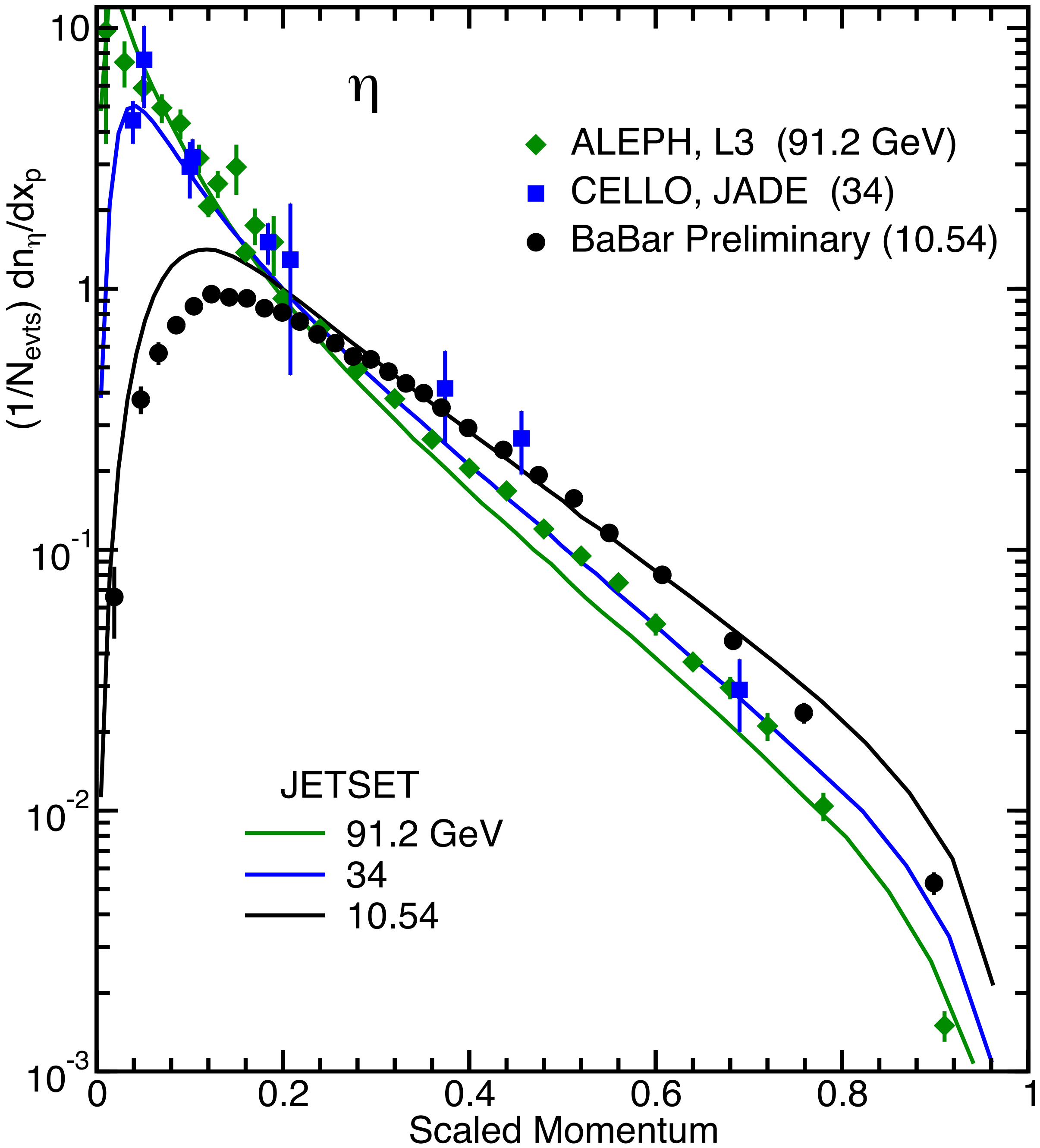
- now consider the corresponding $K^{\pm}$ data
- again, strong scaling violation at high (and low) x_p
  - → ...at least from 10.5 to 91.2 GeV...
  - → 34 GeV precision limited

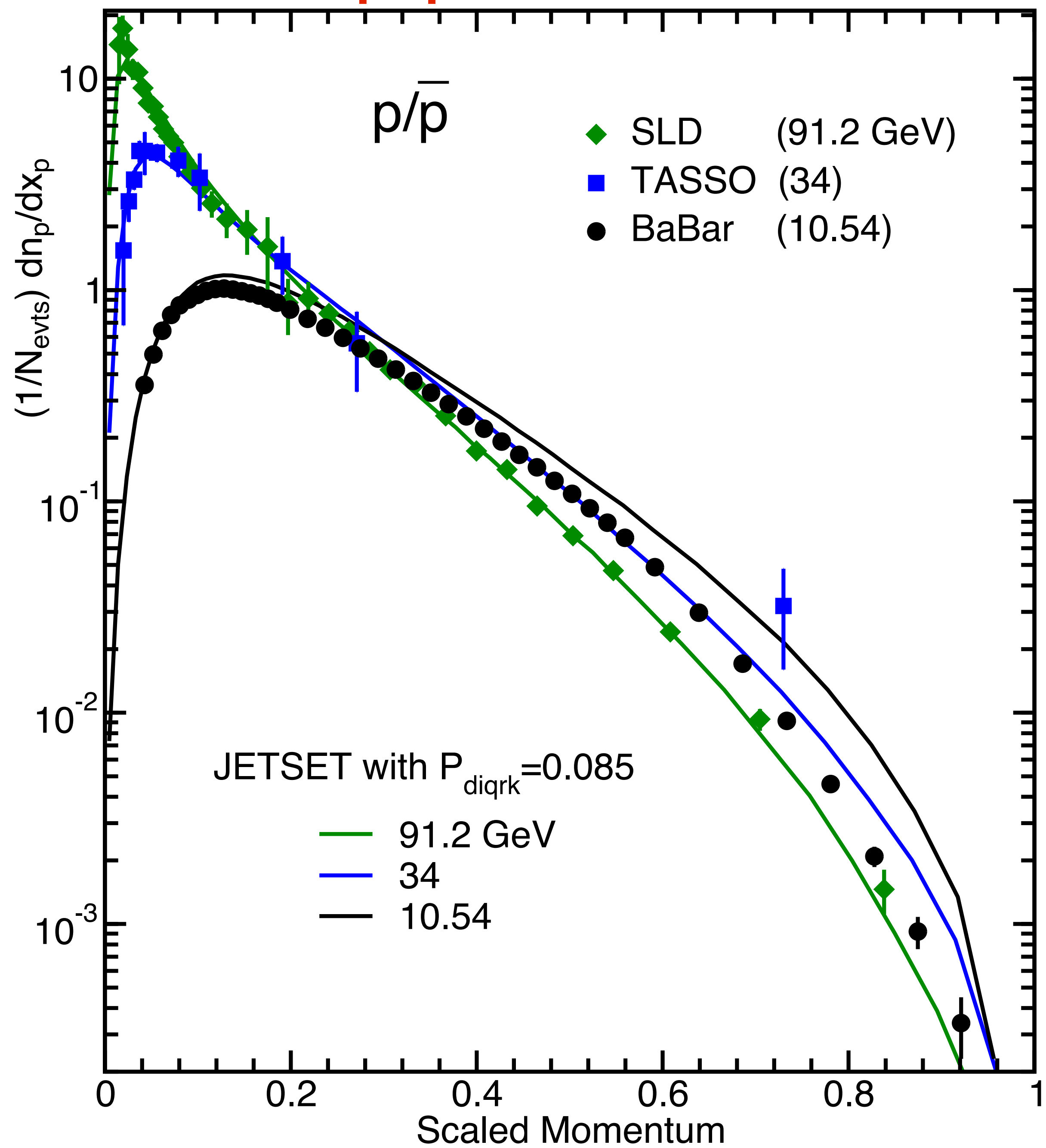


- only ~10% change in models from 34-91 GeV
  - → due to changing flavor composition
  - → UCLA shown, other models similar
- the change from 10.5→91.2 GeV is ~15% larger than in the data
  - → … ±~6% experimental
  - → …how uncertain are flavor composition effects?

High-x_p scaling, III

- and η vs. CELLO/JADE, ALEPH/L3; $p/\bar{p}$ vs. TASSO, SLD



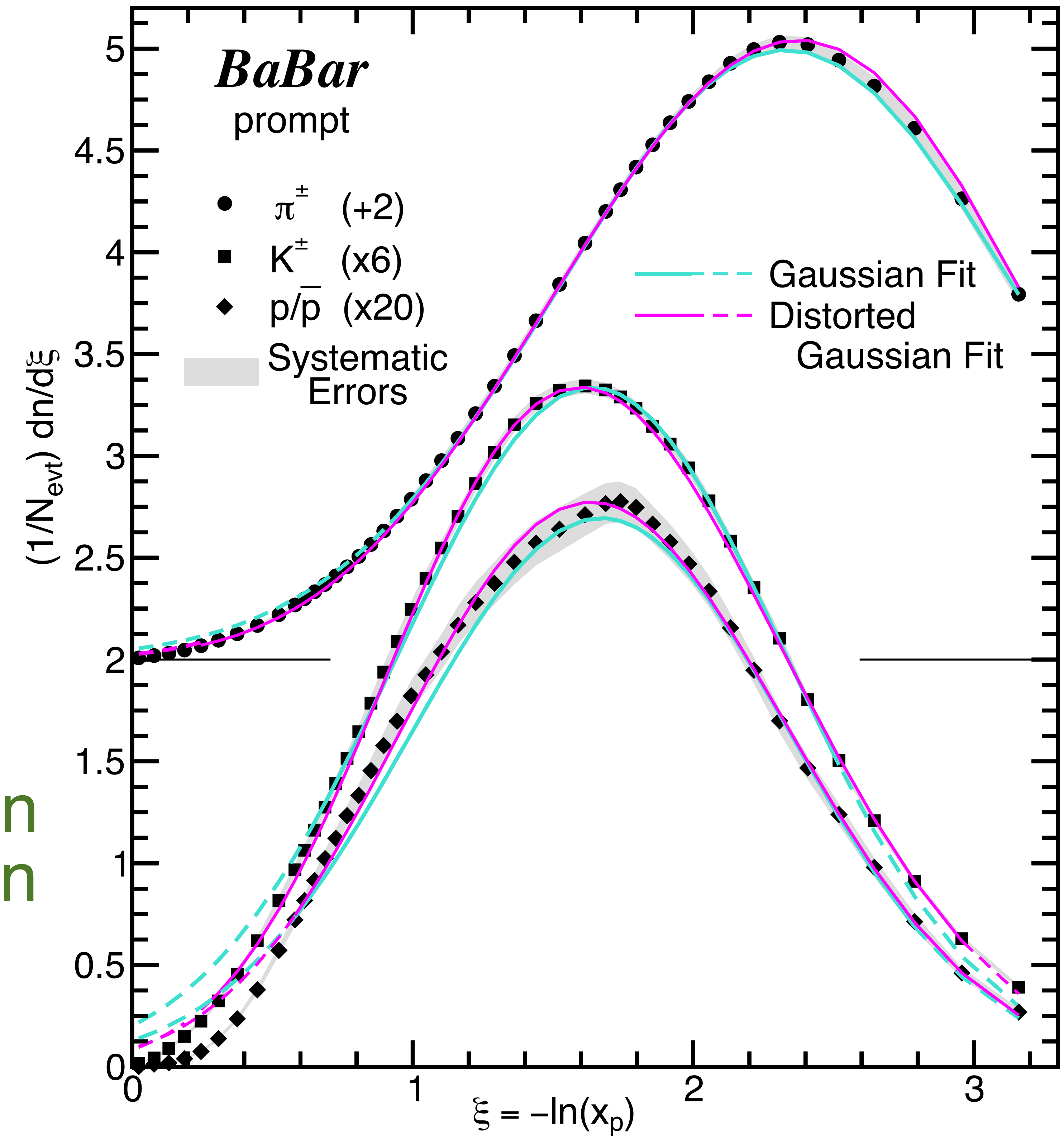


- high x_p η and $p/\bar{p}$ scaling violations are ~40% and 80% larger in MC than data

we don't understand scaling for baryons …
or perhaps heavier / stranger particles

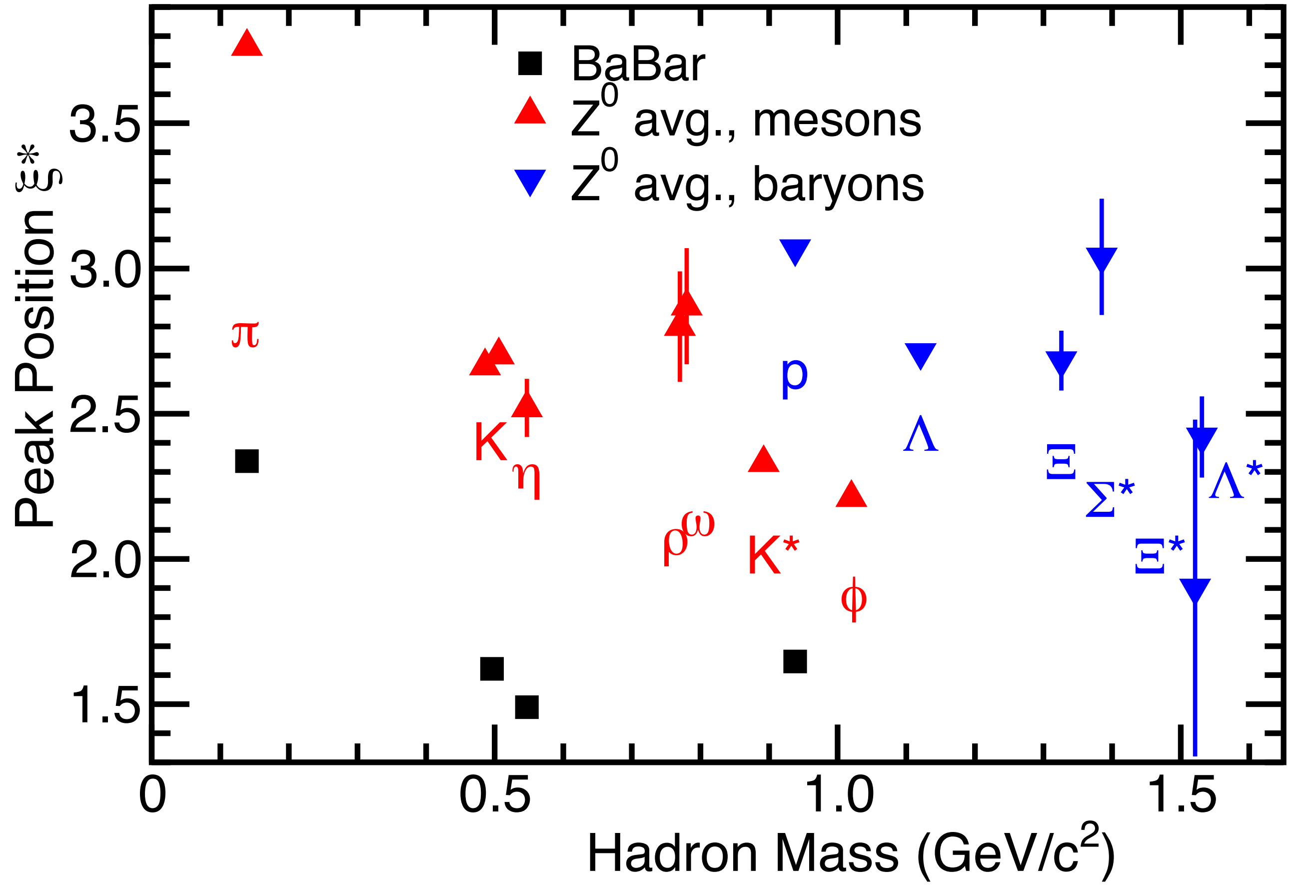
Tests of QCD, modified-leading-log approx.

- MLLA(+local parton-hadron duality)* predicts:
  - → shapes of spectra
  - → low-x_p scaling behavior
- transform to $\xi = -\ln(x_p)$
  - → emphasizes low-x_p region
  - → ... on a linear scale
  - → measure peak position, ξ^*
- test shape prediction
  - → (distorted) Gaussian should fit data within (more than) ±1 unit of ξ^*
  - → looks good

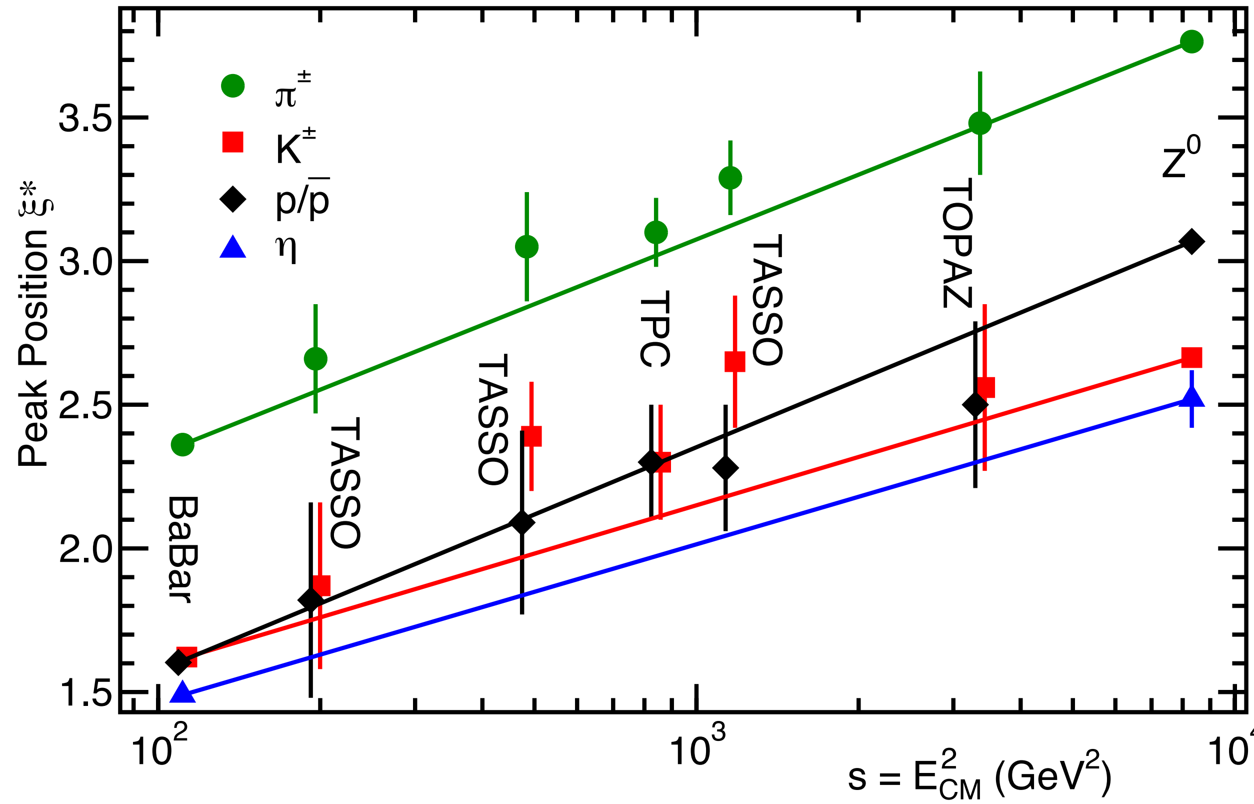


MLLA QCD, II

- test scaling prediction 1
  - → ξ* should decrease exponentially with mass for a given E_{CM}
  - → meson data are consistent
  - → baryons seem to follow a different trajectory

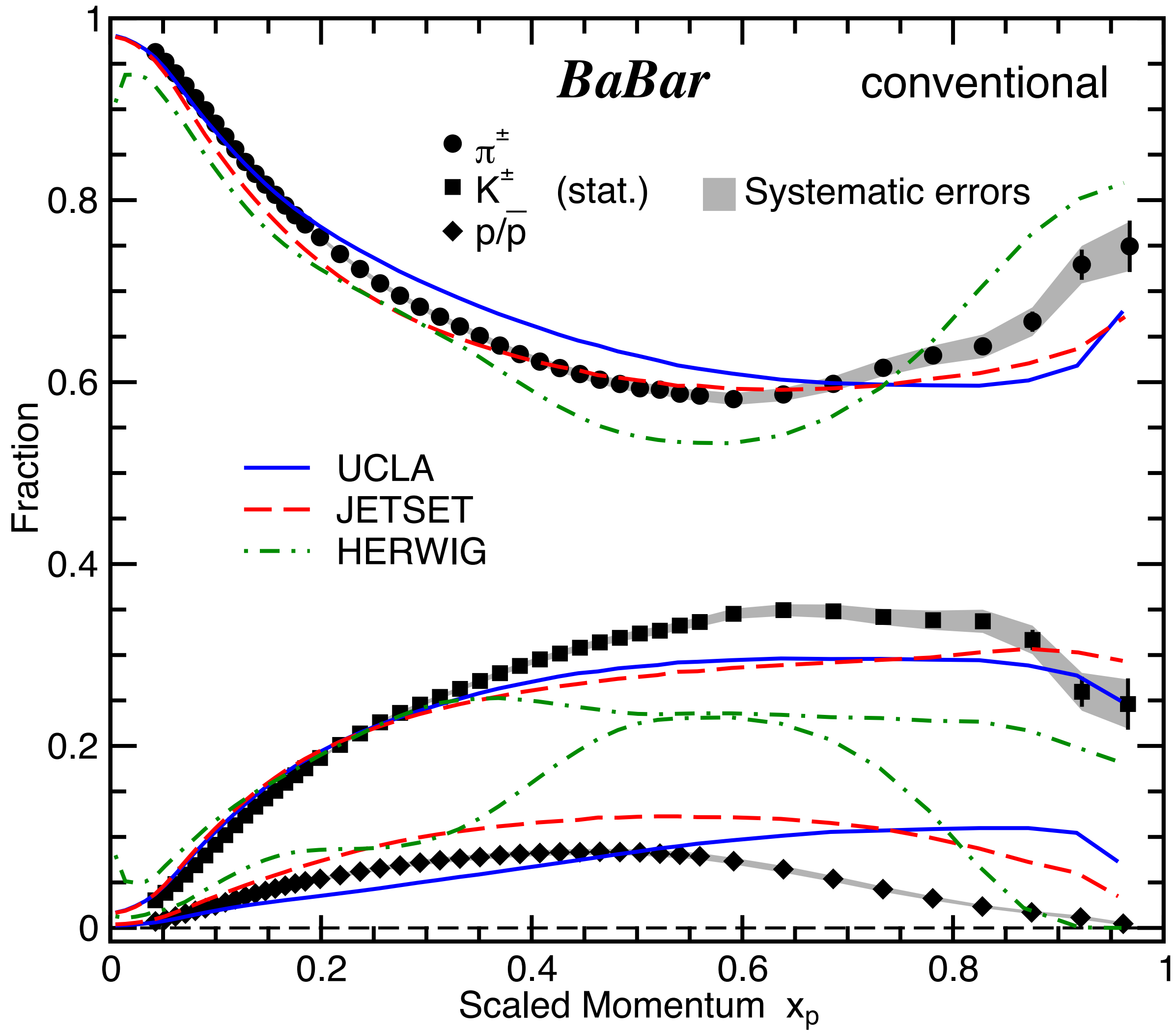


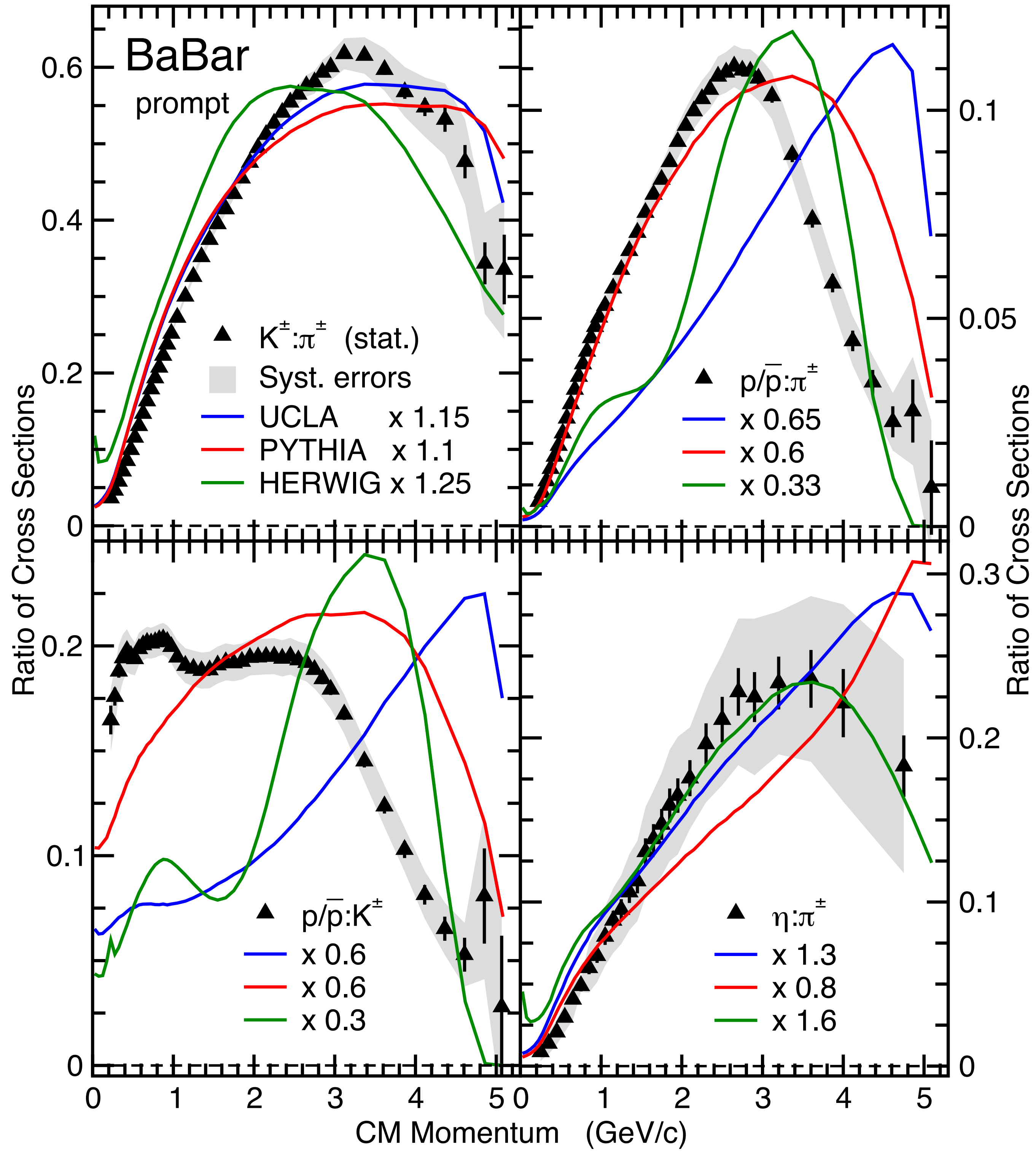
- test scaling prediction 2
  - → ξ* should increase logarithmically with E_{CM} for a given particle
  - → data are consistent
  - → BaBar and Z^0 data provide precise slopes



Production Ratios and Fractions

- calculate ratios of differential production rates
  - → and charged hadron fractions for $\pi^\pm$, $K^\pm$, $p/\bar{p}$
  - → some systematic uncertainties cancel
  - → gives complementary model tests





Total Production Rates

- integrate the differential rates over measured range
  → taking correlations in uncertainties into account
- extrapolate into unmeasured regions
  → non-trivial
  → use models, fits to estimate correction, error

Particle		Average Multiplicity in $q\bar{q}$ Events					
		BaBar	**CLEO**	ARGUS	JETSET	UCLA	HERWIG
prompt	$\pi^\pm$	6.07 ±0.09 ±0.13		5.694±0.108	5.59	5.62	5.49
	$K^\pm$	0.972±0.012±0.016		0.888±0.030	1.01	1.02	1.01
	$p/\bar{p}$	0.185±0.006±0.001		0.212±0.017	0.28	0.14	0.31
conventional	$\pi^\pm$	6.87 ±0.11 ±0.16	8.3 ±0.4	8.38 ±0.12	6.33	6.34	6.31
	$K^\pm$	0.972±0.012±0.001	1.3 ±0.2	0.888±0.030	1.01	1.02	1.01
	$p/\bar{p}$	0.265±0.008±0.002	0.40±0.06	0.271±0.018	0.37	0.20	0.46

Summary

- we have measured the inclusive production of $\pi^\pm$, $K^\pm$, and $p/\bar{p}$ in hadronic e^+e^- annihilations at 10.54 GeV
  - → for both prompt and conventional particles
  - → wide coverage, 0.2 GeV/c to the kinematic limit
  - → consistent with ARGUS results
  - → (much) more precise for $\pi^\pm$ ($K^\pm$, $p/\bar{p}$)
- they provide stringent tests of hadronization models
  - → which fail in many ways
- and, combined with higher-E_{CM} data, precise tests of scaling at high x_p
  - → models good for $\pi^\pm$, ok for $K^\pm$, poor for $p/\bar{p}$, η
  - → theory awaited eagerly
- and tests of MLLA QCD
  - → consistent with shapes, E_{CM} dependence in the data
  - → and mass dependence, except for $p/\bar{p}$

Backup Slides

References

MLLA QCD

Z. Phys. C 27, 65 (1985)
Int. J. Mod. Phys. A7, 1875 (1992)

QCD Evolution

AKK: Nucl. Phys. B 803, 42 (2008)
DSS: Phys. Rev. D 75, 114010 (2007)
HKNS: Phys. Rev. D 75, 094009 (2007)

Hadronization Models

JETSET 7.4: Comput. Phys. Commun. 82, 74 (1994)
HERWIG 5.8: JHEP 0101, 010 (2001), Comput. Phys. Commun. 67, 465 (1992)
UCLA 4.1: Phys. Rep. 292, 239 (1998)

Inclusive π,K,p measurements

CLEO: Phys. Rev. D 31, 2161 (1985)
ARGUS: Z. Phys. C 44, 547 (1989)
TPC-2γ: Phys. Rev. Lett. 61, 1263 (1988)
TASSO: Z. Phys. C 42, 189 (1989)
TOPAZ: Phys. Lett. B 345, 335 (1995)
DELPHI: Eur. Phys. J. C 5, 585 (1998); 18, 203 (2000)
OPAL: Z. Phys. C 63, 181 (1994)
ALEPH: Z. Phys. C 66, 355 (1995)
SLD: Phys. Rev. D 69, 072003 (2004)

Hadronic Event Selection

- want: clean sample of $e^+e^- \to u\bar{u}$, $d\bar{d}$, $s\bar{s}$ and $c\bar{c}$ events; low bias in track multiplicity, momentum, etc.

  → require:

  a) at least 3 charged tracks

  b) forming a good vertex within the interaction region

  c) $R_2 < 0.9$

  d) visible energy 5-14 GeV

  e) $|\cos\theta^*_{thrust}| < 0.8$

  f) $e^\pm$ veto on (2) highest-p track(s) if < 6 (4) tracks

  → efficiency: 68% for $u\bar{u}$, $d\bar{d}$, $s\bar{s}$; 73% for $c\bar{c}$

  → bias reasonable (d,e)

- backgrounds:

$e^+e^- \to \tau^+\tau^-$	4.5%	(a,c,d,f)	understood
$e^+e^- \to e^+e^-\gamma \to e^+e^-e^+e^-$	0.1%	(a,b,c,e,f)	measured
$e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-$+hadrons	< 1%	(a,d)	limited in data
beam-gas, others	very small		meas'd/lim'd

Track Selection

- want: an unbiased sample of charged particles with good DCH and DIRC information

→ require:

a) at least 4 SVT hits, including 2 in z

b) at least 19 DCH hits

c) extrapolation within 1 mm of the event vertex

d) ...and through a DIRC bar

e) includes $p_t > 0.2$ GeV, $-0.77 < \cos\theta < 0.88$

→ ~80% efficiency

→ small dependence on p, θ, particle type

- backgrounds are small except:

$\tau^+\tau^-$ events	up to 25(2)% of high-p* $\pi^\pm(K^\pm)$
radiative Bhabhas	up to 8% of high-p* $\pi^\pm$
two photon events	up to 20% of tau pair bkg
material interactions	up to 15% of low-p p/p
K^0_S, s-baryon decay prods	few % of most $\pi^\pm$, p/p