Charged pion, kaon, and unidentified hadron multiplicities

in semi-inclusive deep-inelastic scattering from COMPASS

Erin SEDER

Strange sea quark polarisation

Strange quark polarisation in the nucleon:

$$\int_0^1 \Delta s(x) + \Delta\bar{s}(x)\, dx = 2\Delta S$$

From NLO QCD fits of g_1 along with a_8 from hyperon β decay, assuming $SU(3)_f$

$$2\Delta S = -0.08 \pm 0.01 \pm 0.02$$ (PLB 647(2007) 8-17)

From LO QCD fits of longitudinal SIDIS $A_1^{K\pm}$, $A_1^{\pi\pm}$ and $A_1^{p,d}$

$$2\Delta S = -0.01 \pm 0.01 \pm 0.01$$ (PLB 693 (2010) 227-235)

➔ ΔS from Semi-Inclusive Asymmetries strongly depends upon the choice of poorly known quark fragmentation functions

FFs

$$2\Delta S = f(R_{SF}),\quad R_{SF} \equiv \frac{\int D_{\bar{s}}^{K^+}(z)\mathrm{d}z}{\int D_{u}^{K^+}(z)\mathrm{d}z}$$

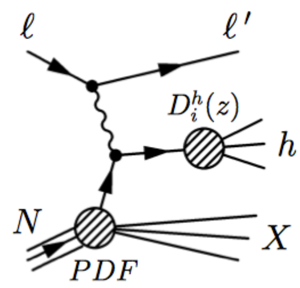
the R_{SF} used in the publication above is taken from DSS parameterisations (PRD 75 (2007) 114010)

➔ One goal of this analysis: Extract R_{SF} (& FFs) from COMPASS kaon data

Hadron multiplicities from SIDIS

What is a SIDIS hadron multiplicity measurement?
The differential cross section for hadron production normalised to the differential inclusive DIS cross section:

$$\frac{dM^h(x,z,Q^2)}{dz} = \frac{d^3\sigma^h(x,z,Q^2)/dxdQ^2dz}{d^2\sigma\ (x,Q^2)/dxdQ^2}$$



$$x = \frac{Q^2}{2M_N(E_l - E_{l'})}$$

$$z = \frac{E_h}{(E_l - E_{l'})}$$

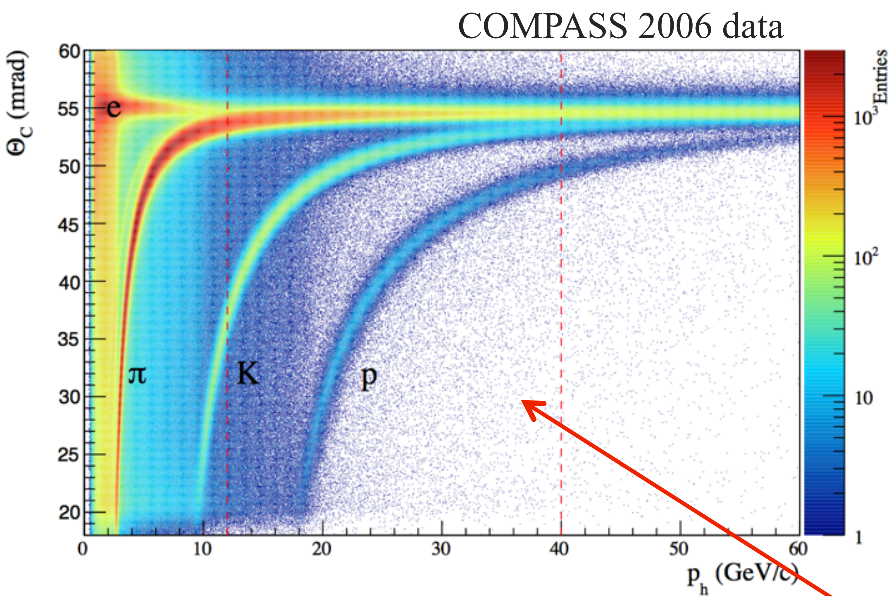
$$Q^2 = -(\mathbf{p}_l - \mathbf{p}_{l'})^2$$

Hadron multiplicities can be expressed in terms of parton distribution functions (pdfs) and fragmentation functions (FFs), in **LO pQCD** this reads:

quark pdfs → quark to hadron FFs

$$\frac{dM^h(x,z,Q^2)}{dz} = \frac{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

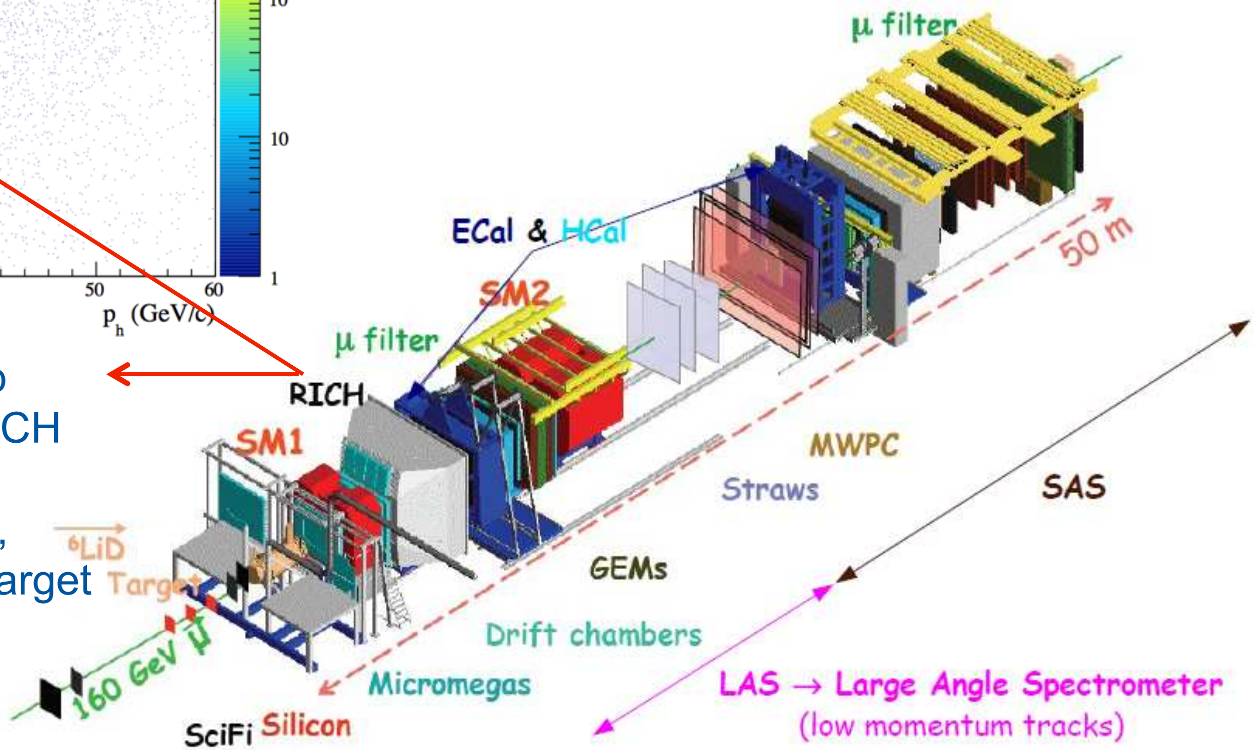
COMPASS spectrometer



- ✧ Designed for fixed-target experiments at CERN SPS
- ✧ Can operate with muon or hadron beams
- ✧ This analysis: 160 GeV μ^+ beam (2006)

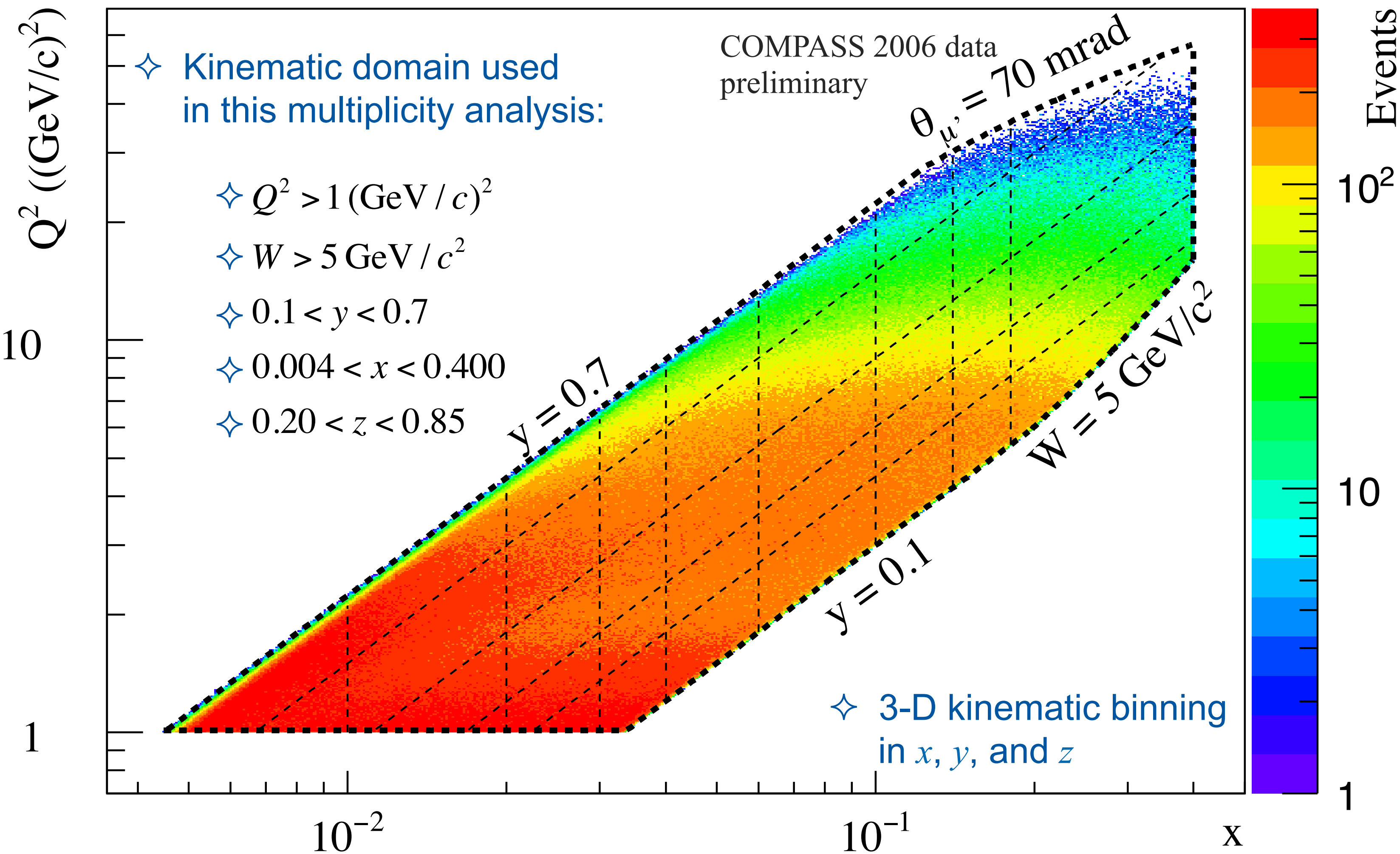
- ✧ Excellent charged π, K, p discrimination with the RICH

- ✧ This analysis: 1.2 m long, polarized ^{6}LiD isoscalar target (2006)



COMPASS kinematics

The COMPASS kinematic range:



Multiplicity analysis

$$\frac{dM^h(x,y,z)}{dz} = \frac{N^{\boldsymbol{h}}(x,y,z)/\Delta z}{N^{DIS}(x,y)}$$

COMPASS Raw Data

- ✧ Event and particle reconstruction
- ✧ Event and particle selection
- ✧ RICH PID and unfolding

Corrections

- ✧ Radiative correction
- ✧ Diffractive VM correction
- ✧ Electron contamination*
- ✧ Kinematic bin smearing
- ✧ Detector acceptance

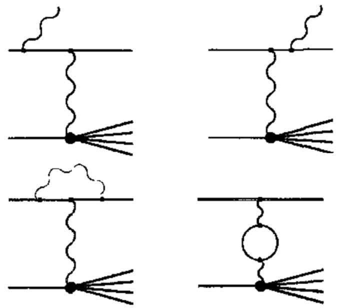
Final Multiplicities

*because of poor RICH electron/pion discrimination, necessary for pion and unidentified hadron multiplicities

Corrections to data:

radiative

emission of an additional real photon, vertex correction, and vacuum polarization



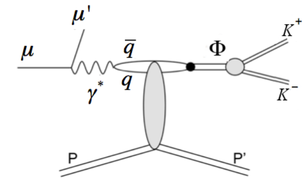
$$\eta(x,y) = \frac{d^2\sigma_{1\gamma} / dxdy}{d^2\sigma_{measured} / dxdy}$$

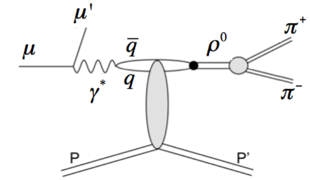
correction factors for both the numerator (N_h) and denominator (N_{DIS}) of the multiplicity:

N_{DIS} correction: Dubna scheme (TERAD)
N_h correction: “TERAD − el tail − qel tail”

The total radiative correction applied to the multiplicity ranges from ~5% at low x - high y, down to <1% at high x - low y.

diffractive vector meson





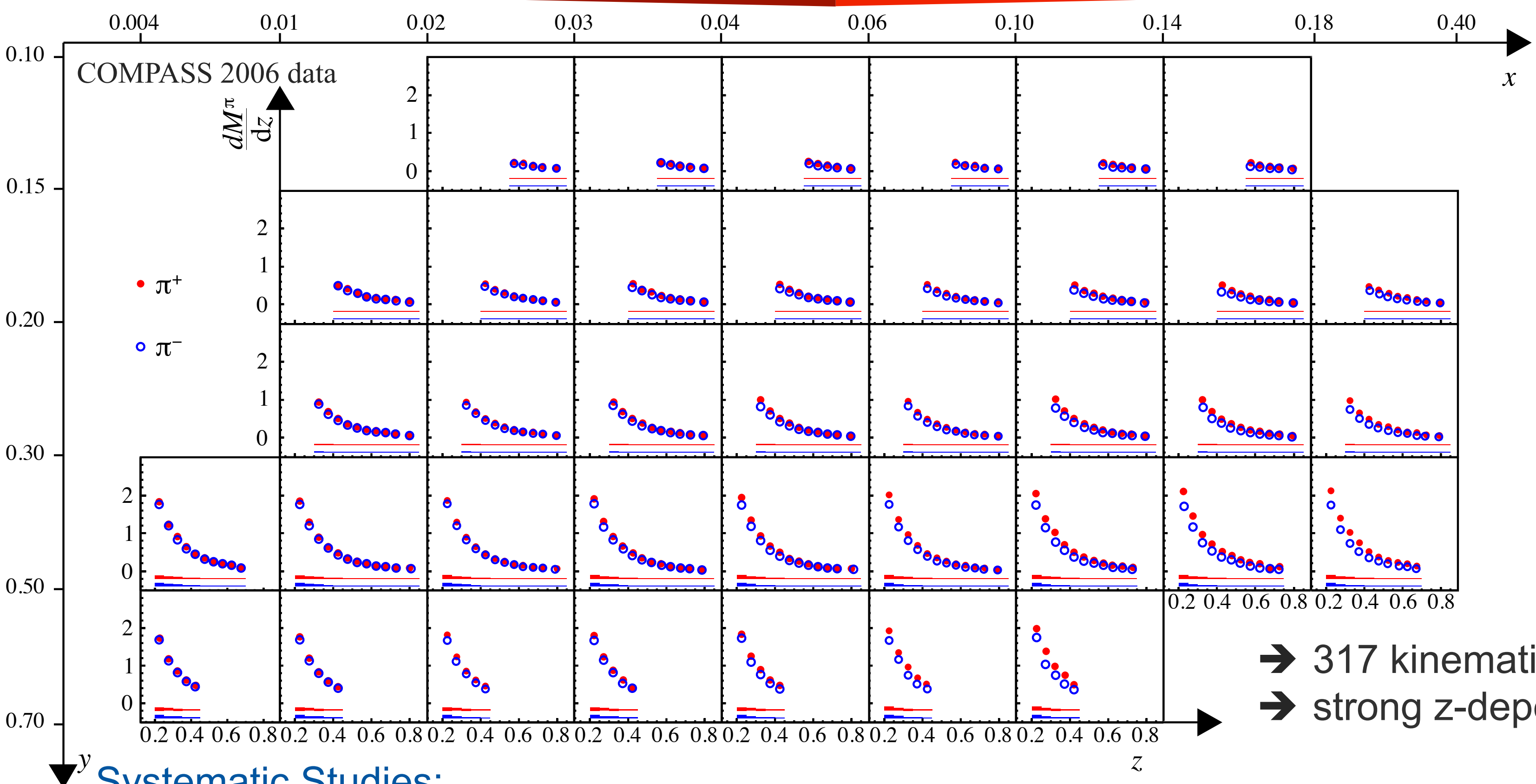
correction factor to the hadron yields determined using LEPTO(SIDIS) and HEPGEN(Diffractive) Monte Carlo, with each sample normalized using the respective luminosities

$$f^h_{\rho^0,\Phi}(x,y,z) = \frac{N^h_{HEPGEN}(x,y,z)}{N^h_{LEPTO}(x,y,z) + N^h_{HEPGEN}(x,y,z)}$$

similar correction for the diffractive events in the DIS sample

overall correction is <10% in most bins except:
kaons: low x, mid z where it can reach ~25%
pions: low x, high z where it can reach ~55%

Pion multiplicity results



- ➔ 317 kinematic bins
- ➔ strong z-dependence

Systematic Studies:

Acceptance: 5%
RICH PID/efficiency for pions : 0.1 %(low y) - 2 %(high y)
Diff. Vector Meson correction: 12 % maximum (low x, high z)
Electron correction: 50 % conservative systematic error

Extraction of quark FF into Pions

Charge and isospin symmetry gives:

$$D_{fav}^{\pi} = D_{u}^{\pi+} = D_{\bar{d}}^{\pi+} = D_{d}^{\pi-} = D_{\bar{u}}^{\pi-}$$

$$D_{unf}^{\pi} = D_{d}^{\pi+} = D_{\bar{u}}^{\pi+} = D_{u}^{\pi-} = D_{\bar{d}}^{\pi-}$$

Assume strangeness equals unfavoured :

$$D_{unf}^{\pi} = D_{s}^{\pi\pm} = D_{\bar{s}}^{\pi\pm}$$

$$M^{\pi+}(x,Q^2,z) = \frac{(4(u+d)+\bar{u}+\bar{d})D_{fav}^{\pi} + (u+d+4(\bar{u}+\bar{d})+2(s+\bar{s}))D_{unf}^{\pi}}{5(u+d+\bar{u}+\bar{d})+2(s+\bar{s})}$$

$$M^{\pi-}(x,Q^2,z) = \frac{(u+d+4(\bar{u}+\bar{d}))D_{fav}^{\pi} + (4(u+d)+\bar{u}+\bar{d}+2(s+\bar{s}))D_{unf}^{\pi}}{5(u+d+\bar{u}+\bar{d})+2(s+\bar{s})}$$

$u, d, \bar{u}, \bar{d}, s, \bar{s}$ = parton distribution functions(MSTW08)

Two methods of LO extraction

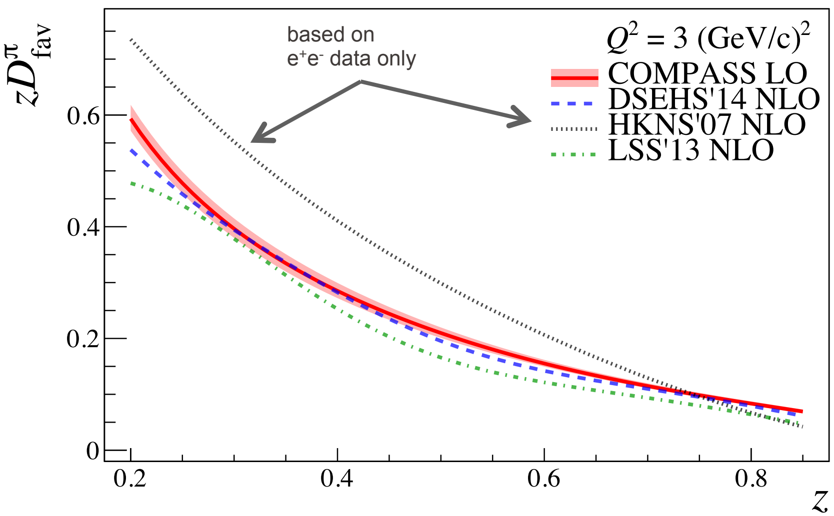
1) Fits of experimental multiplicities:

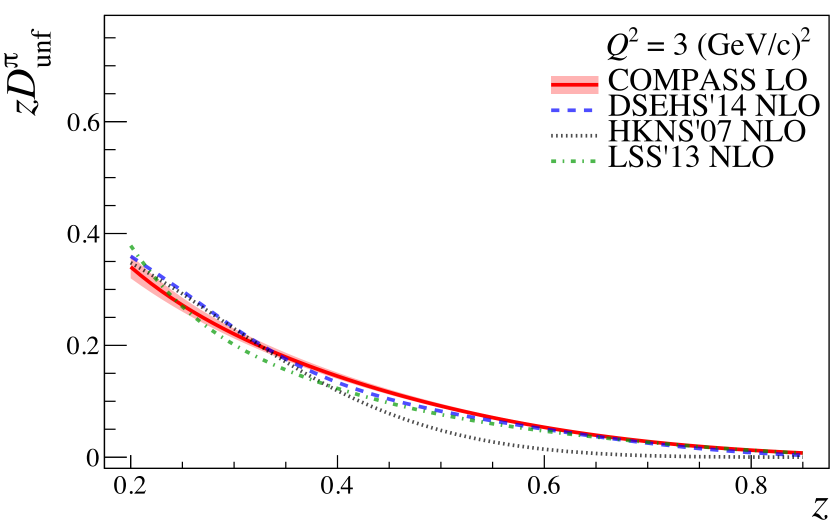
Functional form: $$z D_i(z, Q_0^2) = N_i \frac{z^{\alpha_i}(1-z)^{\beta_i}}{\int_{0.2}^{0.85} z^{\alpha_i}(1-z)^{\beta_i}\, dz}$$

Evolution from Q^2_0 = 1 (GeV/c)^2 to Q^2 of data points with DGLAP

2) Direct extraction in each kinematic bin

$M^{\pi^\pm}$ Fits Results

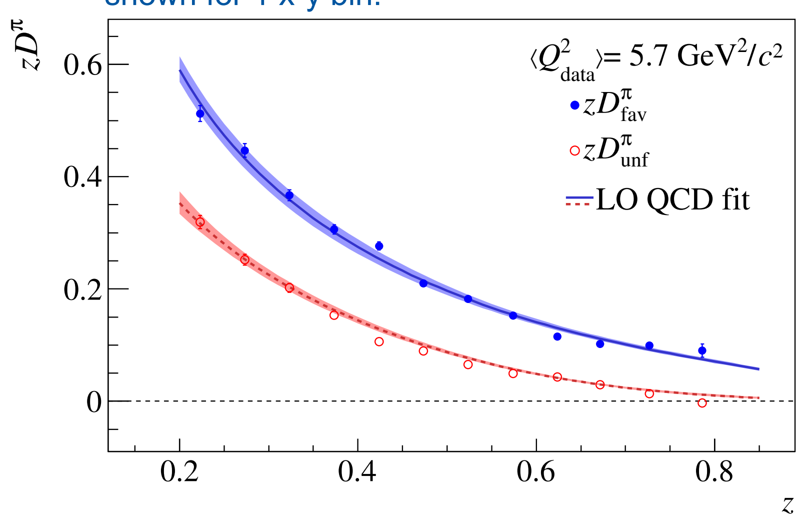




1) LO fit of experimental multiplicities: Results for D^{π}_{fav} and D^{π}_{unf} agree with results from world data fits

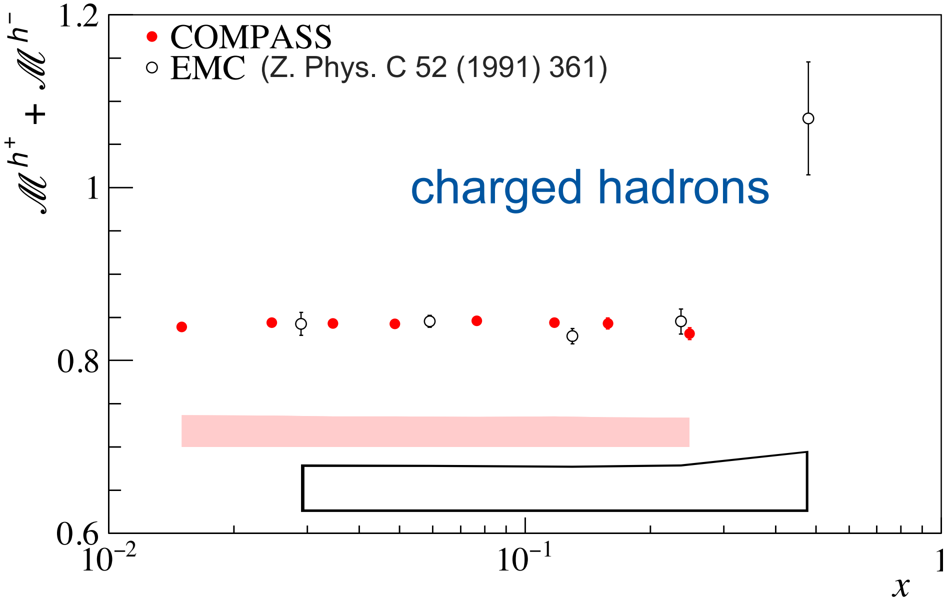
2) The fit results agree very well with D^{π}_{fav} and D^{π}_{unf} extracted in each kinematic bin using the average Q^2 and x of each bin (no functional form assumptions and no Q^2 evolution needed):

shown for 1 x-y bin:

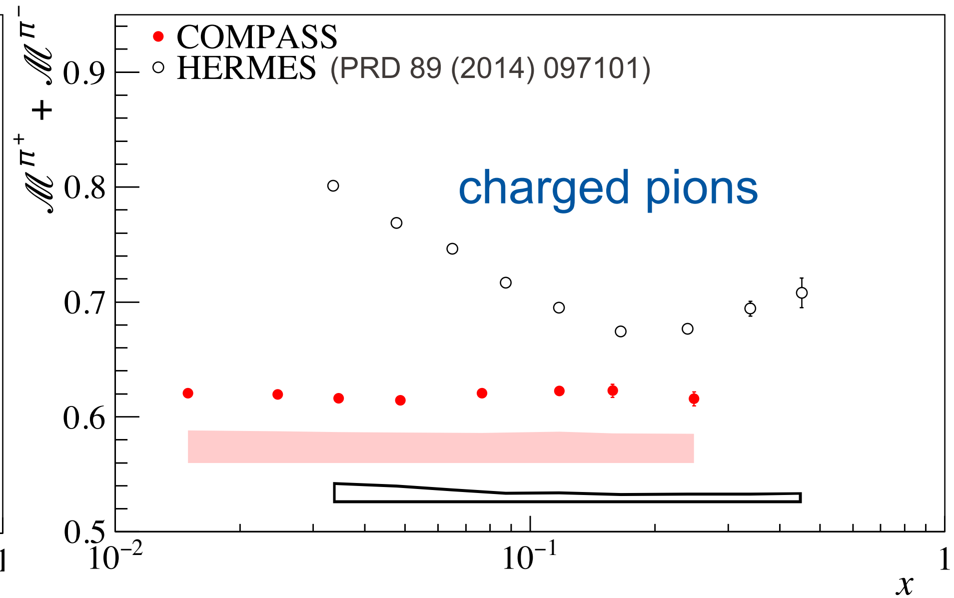


Multiplicity sum

Data are averaged over y and integrated over z



Data are averaged over y and integrated over z



Results on charged hadrons are in good agreement with those of EMC (similar kinematic range)

Results on charged pions are in good agreement with LO predictions:

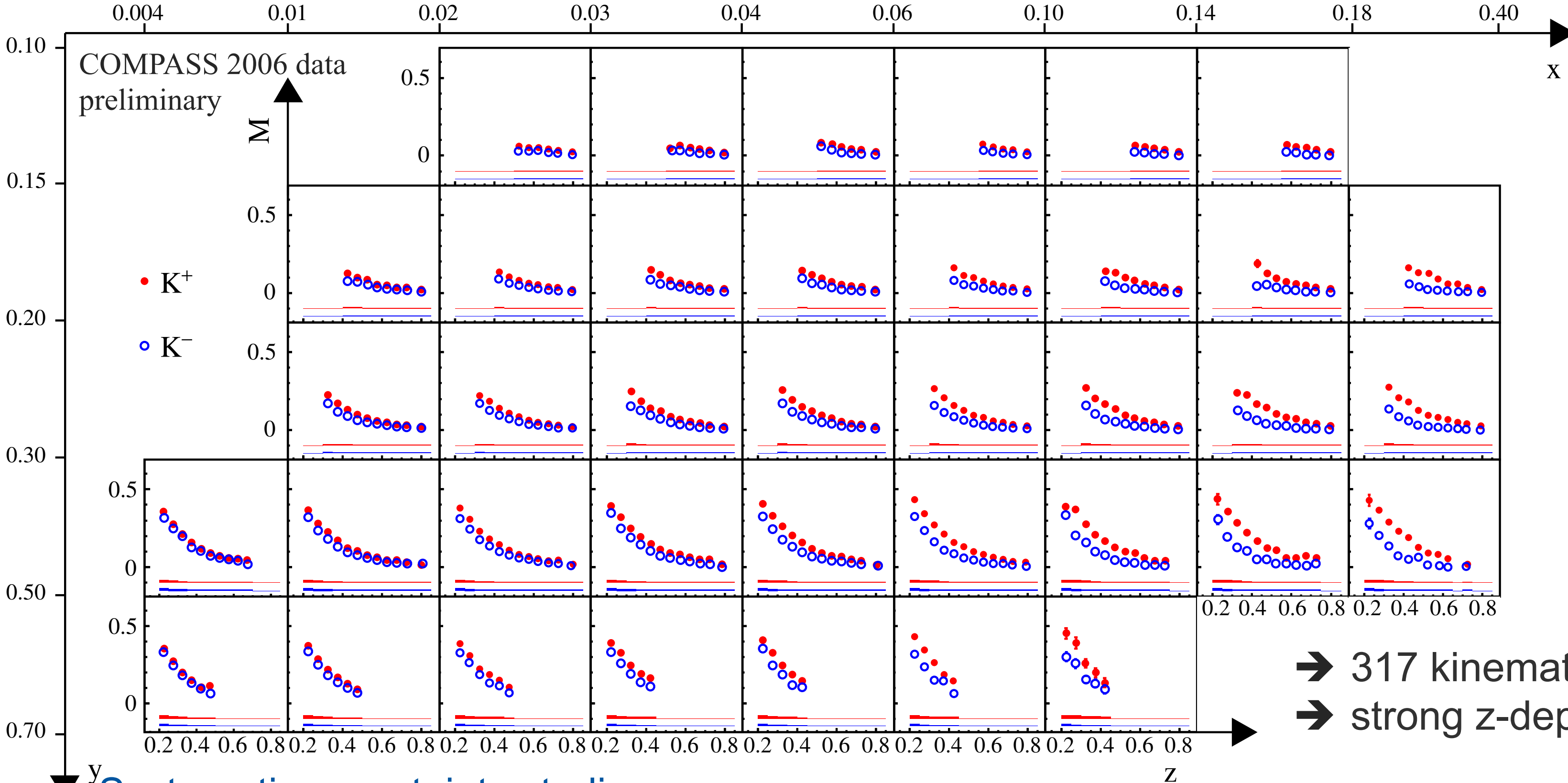
$$D^{\pi}_{fav} = D^{\pi+}_{u} = D^{\pi+}_{\bar{d}} = D^{\pi-}_{d} = D^{\pi-}_{\bar{u}}$$

$$D^{\pi}_{unf} = D^{\pi+}_{d} = D^{\pi+}_{\bar{u}} = D^{\pi-}_{u} = D^{\pi-}_{\bar{d}} = D^{\pi\pm}_{s} = D^{\pi\pm}_{\bar{s}}$$

$$\mathcal{M}^{\pi+} + \mathcal{M}^{\pi-} = D^{\pi}_{fav} + D^{\pi}_{unf} - \underbrace{\frac{2(s(x)+\bar{s}(x))(D^{\pi}_{fav} - D^{\pi}_{unf})}{5(u(x)+d(x)+\bar{u}(x)+\bar{d}(x))+2(s(x)+\bar{s}(x))}}_{\text{very small x-dependent term}}$$

however there is a disagreement with HERMES (lower energy)

Kaon multiplicity results



➔ 317 kinematic bins
➔ strong z-dependence

Systematic uncertainty studies :

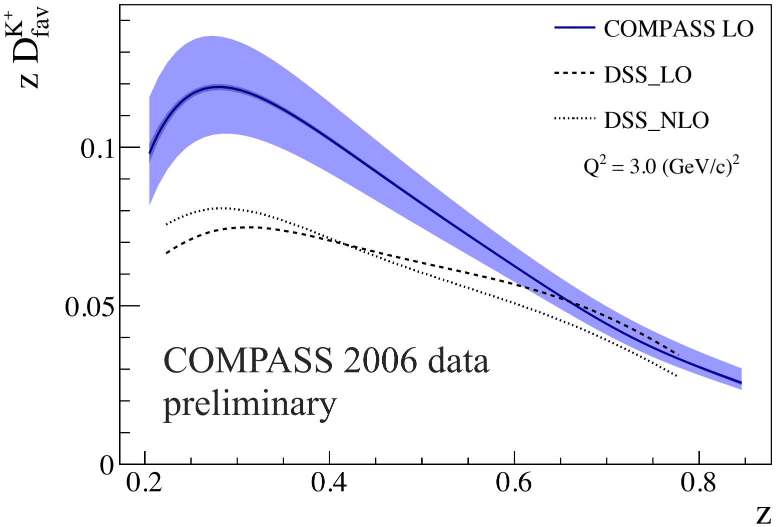
Acceptance: 5%

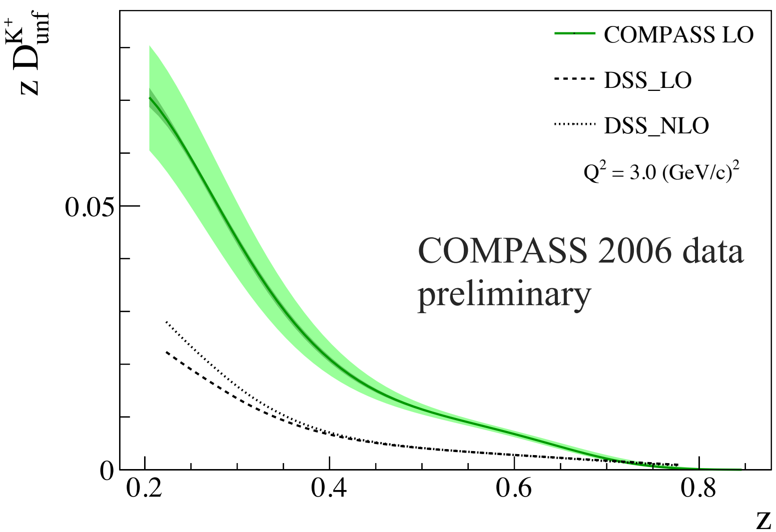
RICH PID/efficiency for kaons : 0.2 %(low y) - 15 %(high y, high z)

Diff. Vector Meson correction: < 6 % maximum (low x, mid z)

Not shown: asymmetric systematic error of the radiative corrections (later slide)

$M^{K^\pm}$ Fits Results





COMPASS performed LO fits to kaon Multiplicities:

$$M^{K+}(x,z,Q^2) = \frac{2\bar{s}D^K_{str} + 4(u+d)D^K_{fav} + (u+d+5(\bar{u}+\bar{d})+2s)D^K_{unf}}{5(u+d+\bar{u}+\bar{d})+2(s+\bar{s})}$$

$$M^{K-}(x,z,Q^2) = \frac{2sD^K_{str} + 4(\bar{u}+\bar{d})D^K_{fav} + (5(u+d)+\bar{u}+\bar{d}+2\bar{s})D^K_{unf}}{5(u+d+\bar{u}+\bar{d})+2(s+\bar{s})}$$

Recall, $u, d, \bar{u}, \bar{d}, s, \bar{s}$ = parton distribution functions and charge and isospin symmetry gives:

$$D^K_{fav} = D^{K\pm}_{fav} = D^{K+}_{u} = D^{K-}_{\bar{u}}$$

$$D^K_{unf} = D^{K\pm}_{unf} = D^{K+}_{\bar{u}} = D^{K+}_{s} = D^{K-}_{u} = D^{K-}_{\bar{s}} = D^{K\pm}_{d} = D^{K\pm}_{\bar{d}}$$

$$D^K_{str} = D^{K\pm}_{str} = D^{K+}_{\bar{s}} = D^{K-}_{s}$$

Results of D^K_{fav} and D^K_{unf} (shown) are very stable, it is not the case with D^K_{str}

Extracted D^K_{fav} and D^K_{unf} are significantly larger than in the DSS parametrisation

Kaon multiplicity sum

For the isoscalar target, when expressed at LO the sum has a simple form:

$$\frac{dN^{K^+ + K^-}}{dN^{DIS}} = \frac{(u+d+\bar{u}+\bar{d})(4D^K_{fav}+6D^K_{unf})+2(s+\bar{s})(D^K_{str}+D^K_{unf})}{5(u+d+\bar{u}+\bar{d})+2(s+\bar{s})} = \frac{QD^K_Q + SD^K_S}{5Q+2S}$$

Recall, $u, d, \bar{u}, \bar{d}, s, \bar{s}$ = parton distribution functions and charge and isospin symmetry gives:

$$D^K_{fav} = D^{K\pm}_{fav} = D^{K+}_u = D^{K-}_{\bar{u}}$$

$$D^K_{unf} = D^{K\pm}_{unf} = D^{K+}_{\bar{u}} = D^{K+}_s = D^{K-}_u = D^{K-}_{\bar{s}} = D^{K\pm}_d = D^{K\pm}_{\bar{d}}$$

$$D^K_{str} = D^{K\pm}_{str} = D^{K+}_{\bar{s}} = D^{K-}_s$$

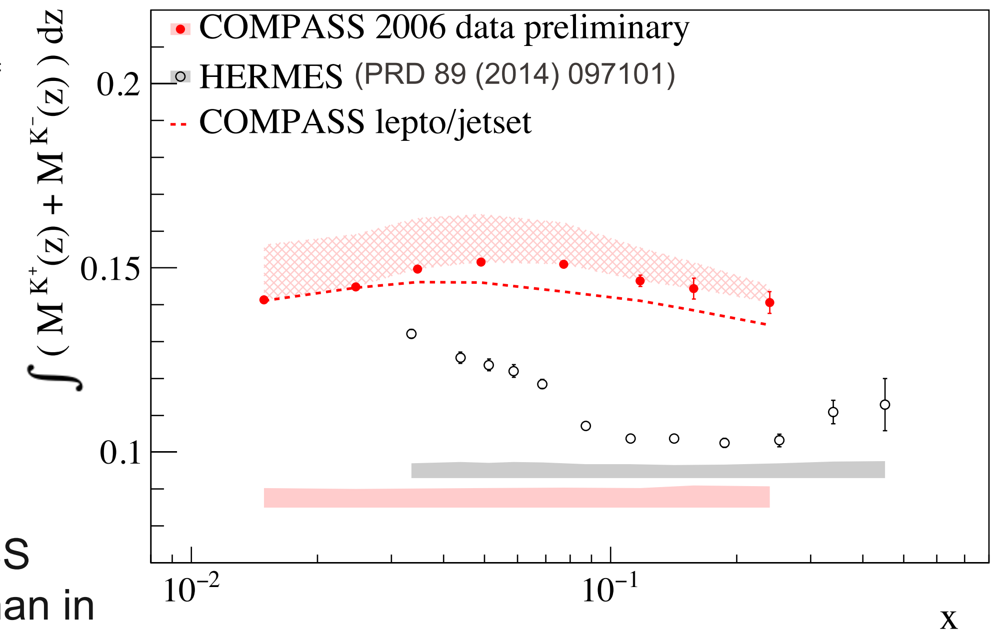
At **high x,** the S term can be neglected:

$$\frac{dN^{K^+ + K^-}}{dN^{DIS}} \approx \frac{(4D^K_{fav}+6D^K_{unf})}{5} = \frac{D^K_Q}{5}$$

This analysis: $D^K_Q \approx 0.7$

DSS: $D^K_Q \approx 0.43 \pm 0.04$

Data are averaged over y and integrated over z



Again, as with the LO fits results the COMPASS kaon results point to larger non-strange FFs than in the DSS parametrisation

Kaon multiplicity sum

For the isoscalar target, when expressed at LO the sum has a simple form:

$$\frac{dN^{K^+ + K^-}}{dN^{DIS}} = \frac{(u+d+\bar{u}+\bar{d})(4D^K_{fav}+6D^K_{unf}) + 2(s+\bar{s})(D^K_{str}+D^K_{unf})}{5(u+d+\bar{u}+\bar{d})+2(s+\bar{s})} = \frac{QD^K_Q + SD^K_S}{5Q+2S}$$

Recall, $u, d, \bar{u}, \bar{d}, s, \bar{s}$ = parton distribution functions
and charge and isospin symmetry gives:

$$D^K_{fav} = D^{K\pm}_{fav} = D^{K+}_u = D^{K-}_{\bar{u}}$$

$$D^K_{unf} = D^{K\pm}_{unf} = D^{K+}_{\bar{u}} = D^{K+}_s = D^{K-}_u = D^{K-}_{\bar{s}} = D^{K\pm}_d = D^{K\pm}_{\bar{d}}$$

$$D^K_{str} = D^{K\pm}_{str} = D^{K+}_{\bar{s}} = D^{K-}_s$$

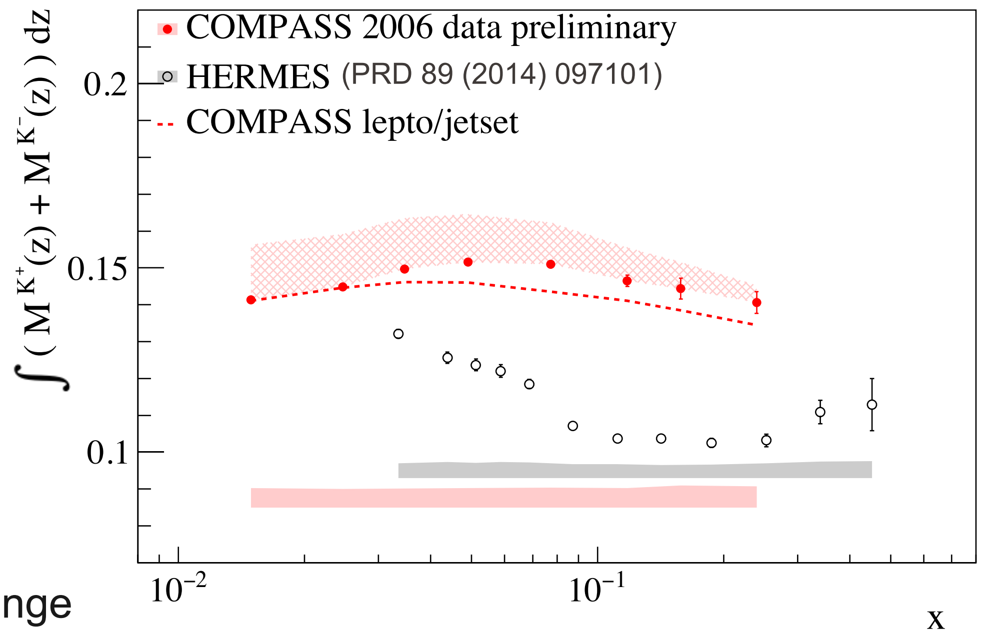
At **high x,** the S term can be neglected:

$$\frac{dN^{K^+ + K^-}}{dN^{DIS}} \approx \frac{(4D^K_{fav}+6D^K_{unf})}{5} = \frac{D^K_Q}{5}$$

This analysis: $D^K_Q \approx 0.7$

DSS: $D^K_Q \approx 0.43 \pm 0.04$

Data are averaged over y and integrated over z



At **low x**, with $D^K_{str} > D^K_{fav}$

D^K_Q has weak Q^2 dependence (3%) in our range
so one would expect a rise in the kaon multiplicity sum going to low x (DSS ~50% increase) which is not what we observe

➔ **points to a smaller FF ratio, R_{SF}, than in the DSS parametrisation**

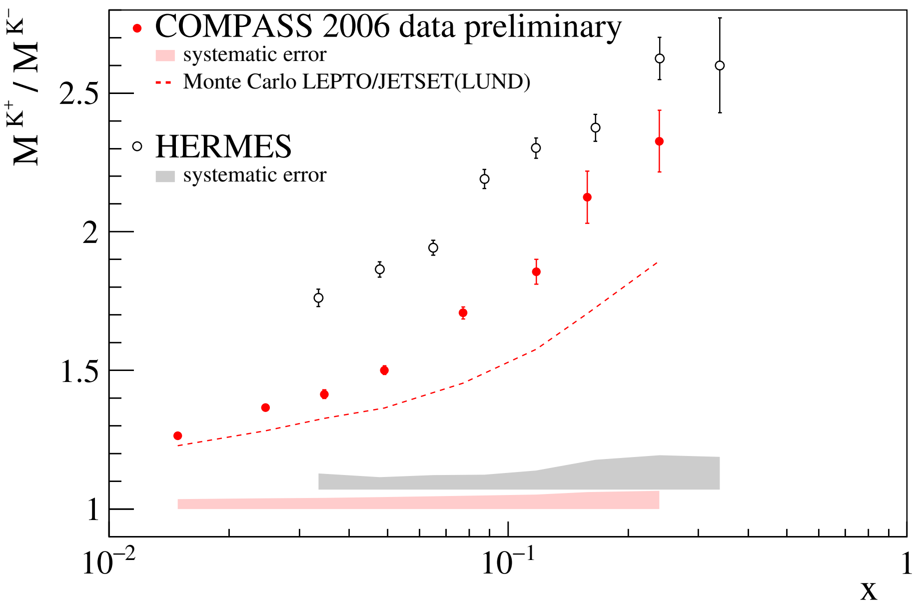
Summary

- Charged **pion, kaon, and unidentified hadron multiplicities** were measured from COMPASS 2006 data taken with an isoscalar ^{6}LiD target and a 160 GeV μ+ beam
  - 317 3-D kinematic bins of x, y, and z covering a large kinematic domain
  - to be used in future global NLO fits for fragmentation functions
  - pion and unidentified hadron multiplicities paper submitted to PLB
    - as of Tue, 12 Apr 2016 00:00:00 GMT: **arXiv:1604.02695, CERN-EP-2016-095**
- good agreement with EMC results (similar kinematics) and a discrepancy with respect to HERMES results (taken at lower energy);
- **pions**: D_{fav}^{π} and D_{unf}^{π} fragmentation functions extracted from LO fits to COMPASS multiplicities are in good agreement with results from fits on world data;
- **kaons**: extracted D_{fav}^{K} and D_{unf}^{K} are significantly larger than in the DSS parametrisation;
- fits using COMPASS charged and neutral kaon multiplicities are in progress to better constrain D_{str}^{K}.

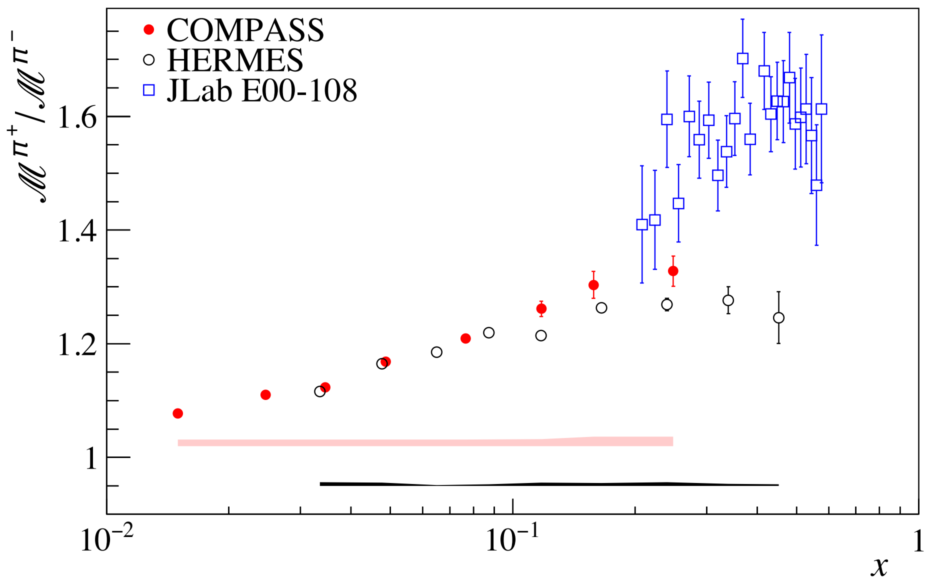
Backup

Multiplicity ratio

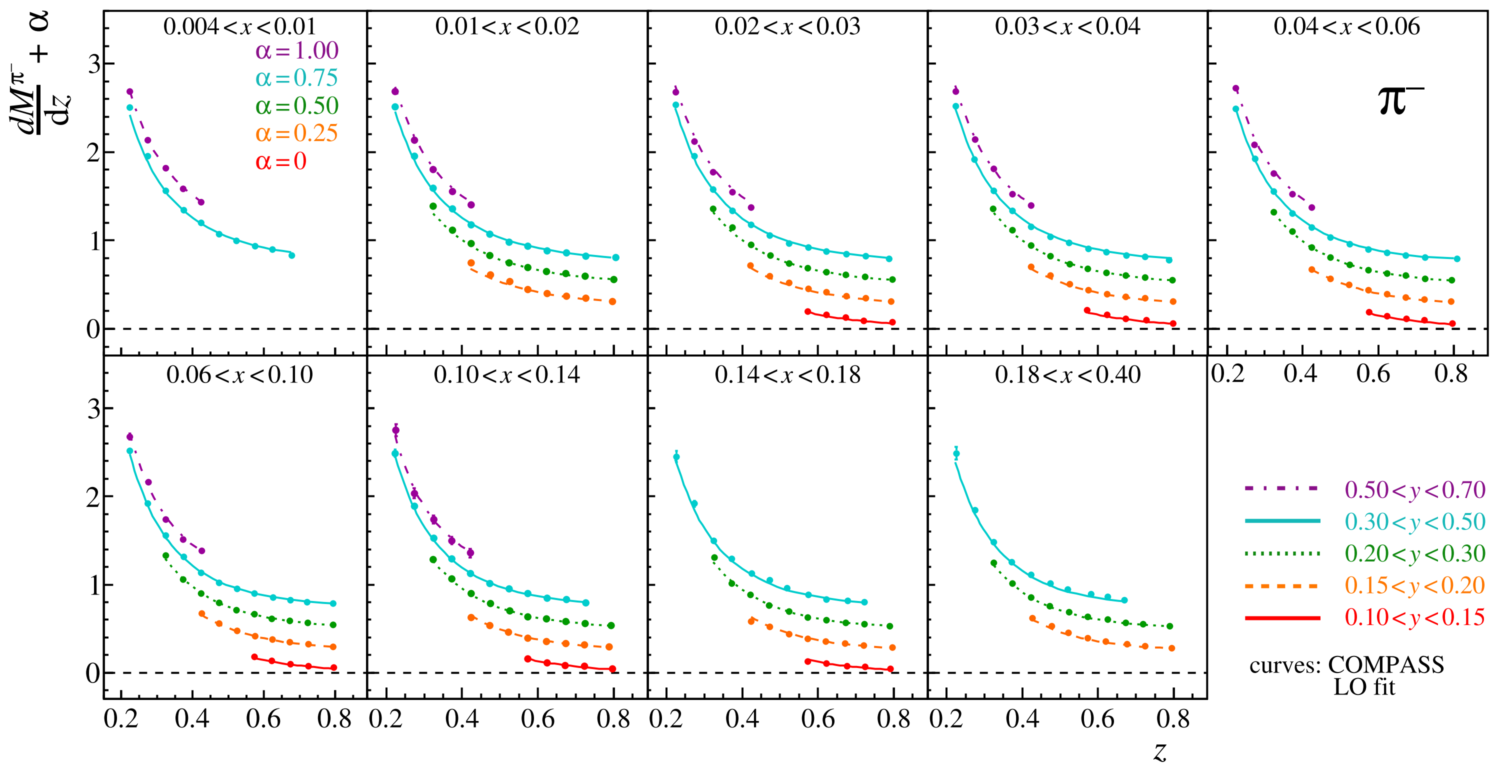
Kaon



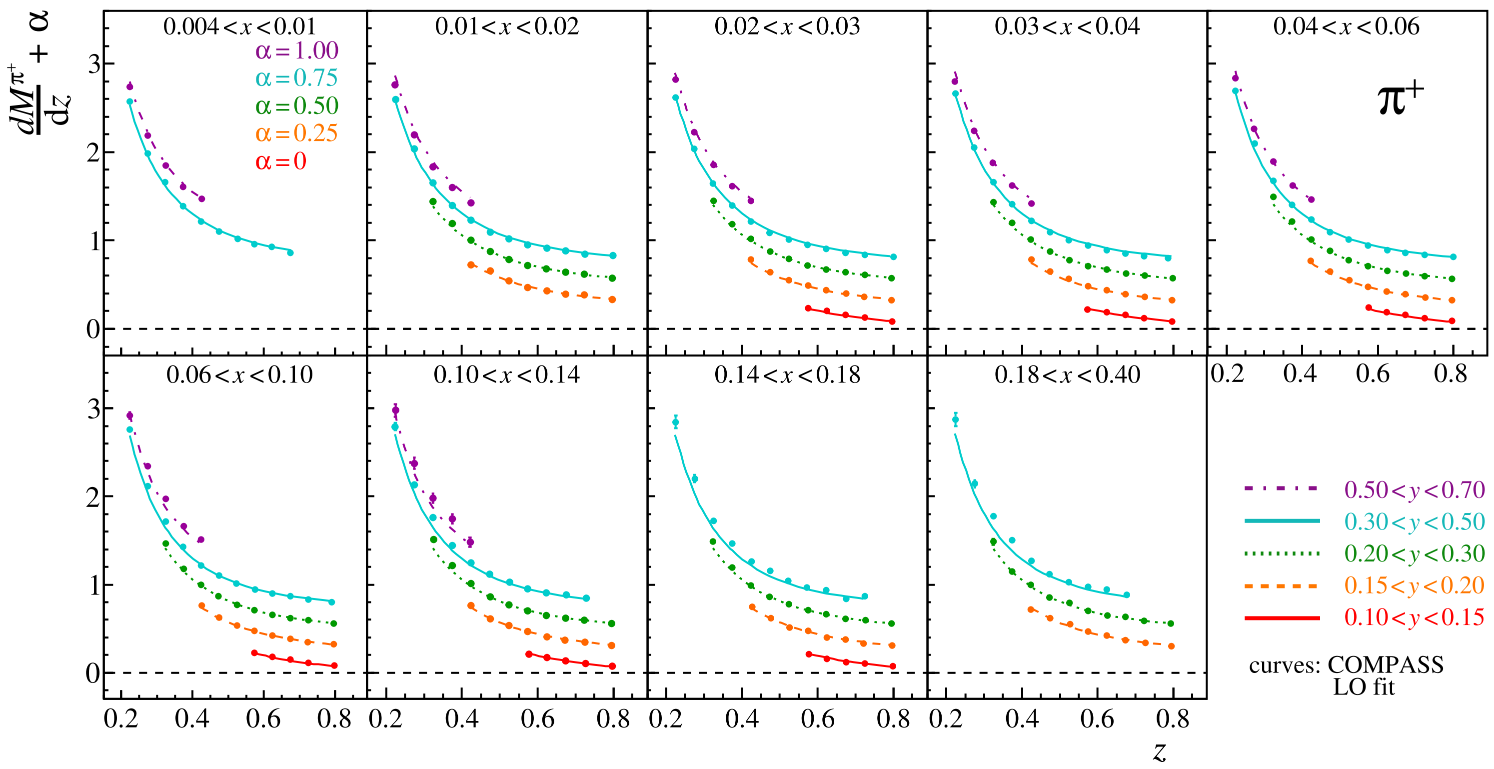
Pion



Multiplicity fits



Multiplicity fits



Leading order extraction of fragmentation functions into kaons

Charge and isospin symmetry gives:
$$D^{K}_{fav} = D^{K\pm}_{fav} = D^{K+}_{u} = D^{K-}_{\bar{u}}$$
$$D^{K}_{unf} = D^{K\pm}_{unf} = D^{K+}_{\bar{u}} = D^{K+}_{s} = D^{K-}_{u} = D^{K-}_{\bar{s}} = D^{K\pm}_{d} = D^{K\pm}_{\bar{d}}$$
$$D^{K}_{str} = D^{K\pm}_{str} = D^{K+}_{\bar{s}} = D^{K-}_{s}$$

For an isoscalar target, in LO:

$$M^{K+}(x,z,Q^2) = \frac{2\bar{s}D_{str} + 4(u+d)D_{fav} + (u+d+5(\bar{u}+\bar{d})+2s)D_{unf}}{5(u+d+\bar{u}+\bar{d})+2(s+\bar{s})}$$

$$M^{K-}(x,z,Q^2) = \frac{2sD_{str} + 4(\bar{u}+\bar{d})D_{fav} + (5(u+d)+\bar{u}+\bar{d}+2\bar{s})D_{unf}}{5(u+d+\bar{u}+\bar{d})+2(s+\bar{s})}$$

$u, d, \bar{u}, \bar{d}, s, \bar{s}$ = parton distribution functions(MSTW08)

Fits of experimental multiplicities:

Functional form: $zD_i(z, Q_0^2) = N_i z^{\alpha_i}(1-z)^{\beta_i}(1+\gamma_i(1-z)^{\delta_i})$ $\quad i = fav$

$zD_i(z, Q_0^2) = N_i z^{\alpha_i}(1-z)^{\beta_i}$ $\quad i = str, unf, glu$

Evolution from Q^2_0 to Q^2 of data points with DGLAP

RICH PID and unfolding

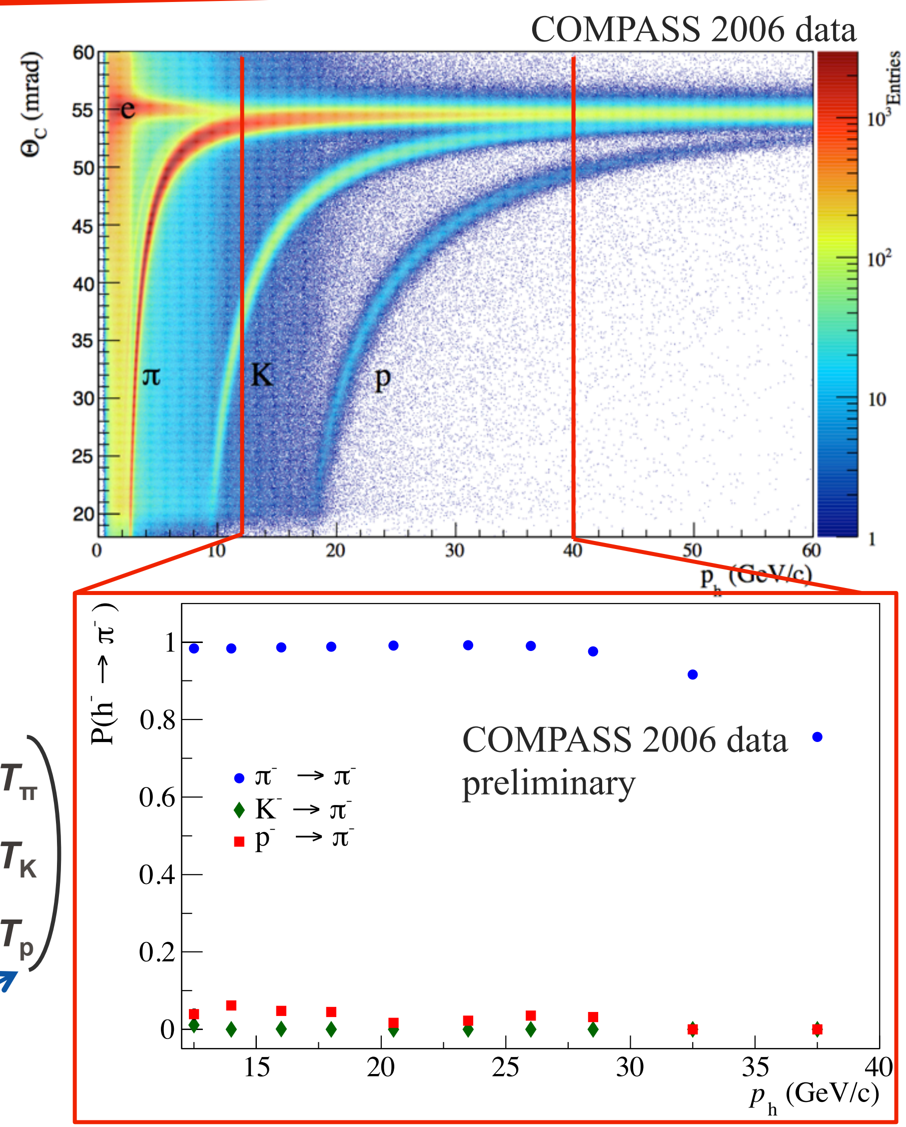
- Particle identification uses likelihoods based on the number and distribution of detected photons in RICH associated to a charged particle
- Purity of the pion and kaon sample depends on the probabilities, P, of correct identification and misidentification, determined through analysis of known decay channels in data
- The pion and kaon yields are corrected using these probabilities by unfolding:

RICH probabilities

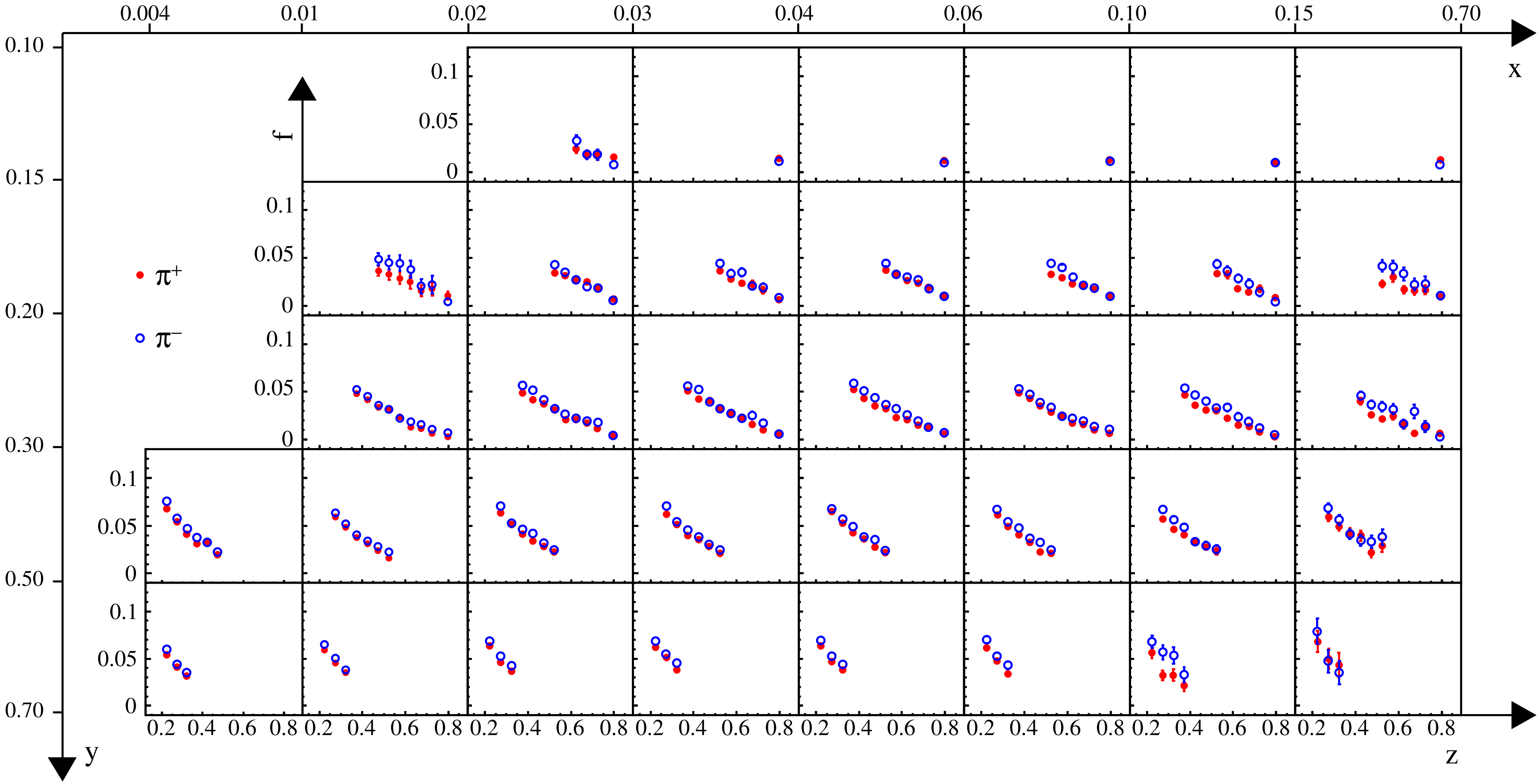
$$\begin{pmatrix} I_\pi \\ I_K \\ I_p \end{pmatrix} = \begin{pmatrix} P(\pi^\pm \Rightarrow \pi^\pm) & P(\pi^\pm \Rightarrow K^\pm) & P(\pi^\pm \Rightarrow p^\pm) \\ P(K^\pm \Rightarrow \pi^\pm) & P(K^\pm \Rightarrow K^\pm) & P(K^\pm \Rightarrow p^\pm) \\ P(p^\pm \Rightarrow \pi^\pm) & P(p^\pm \Rightarrow K^\pm) & P(p^\pm \Rightarrow p^\pm) \end{pmatrix} \begin{pmatrix} T_\pi \\ T_K \\ T_p \end{pmatrix}$$

Identified

"True"



Electron contamination



Corrections to data:

acceptance and smearing

Correction for the limited geometrical acceptance, reconstruction and detector inefficiencies as well as resolutions and electron contamination in the reconstructed sample

reconstructed multiplicity

kinematic bin determined using reconstructed values

$$A(x,y,z) = \frac{Mrec}{Mgen} = \frac{N^h_{rec}(x',y',z') / N^{DIS}_{rec}(x',y')}{N^h_{gen}(x'',y'',z'') / N^{DIS}_{gen}(x'',y'')}$$

generated multiplicity

kinematic bin determined using generated values

MC technical features:

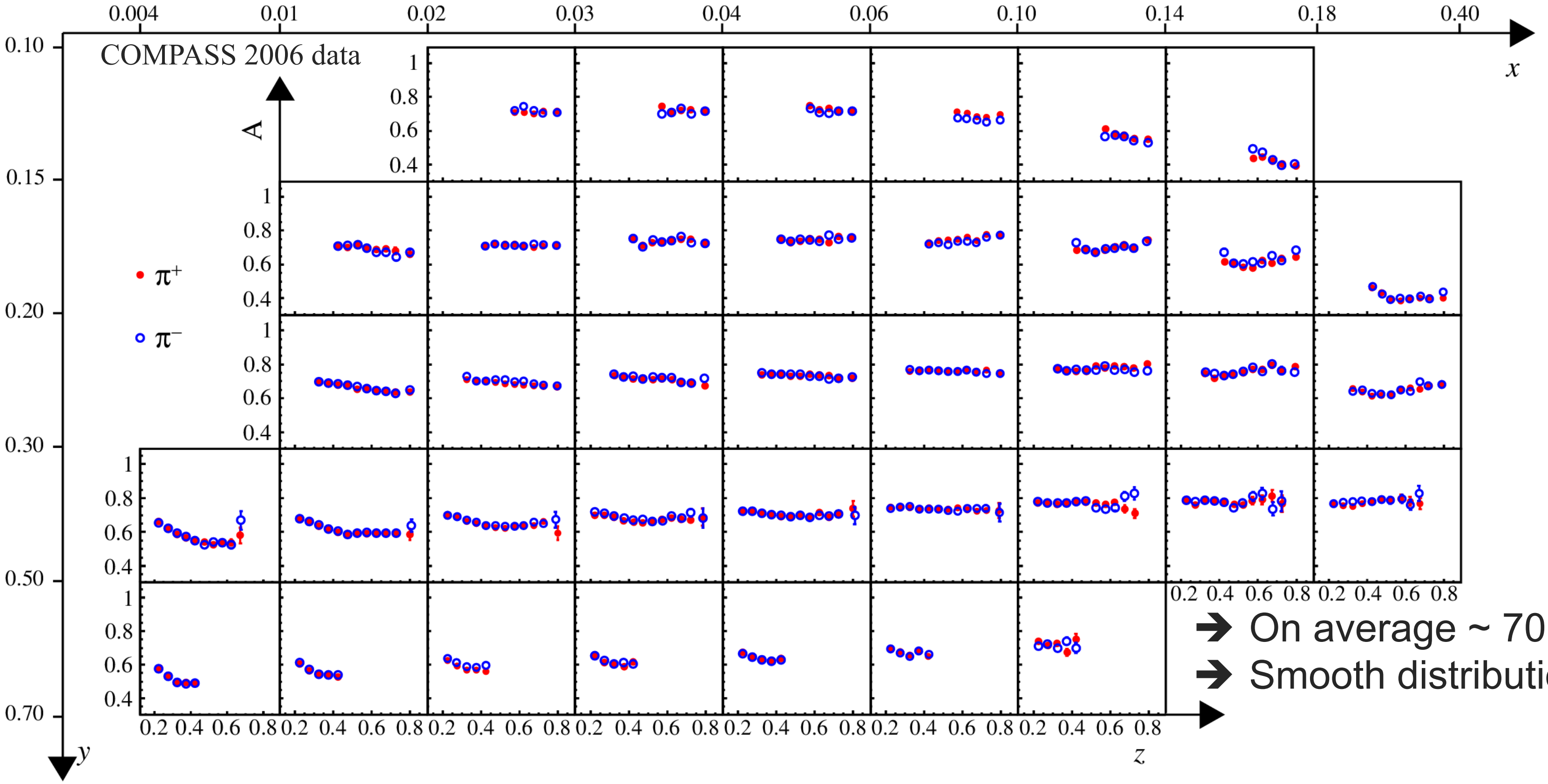
- Events are generated with the LEPTO generator (LUND model)
- JETSET package for parton hadronisation with COMPASS high p_T tuning
- FLUKA used to simulate secondary interactions in the target
- Spectrometer simulated using GEANT3

Corrections to data: Acceptance

Correction for apparatus geometric acceptance and detector efficiencies

$$A = \frac{Mrec}{Mgen} = \frac{N^h_{rec} / N^{DIS}_{rec}}{N^h_{gen} / N^{DIS}_{gen}}$$

MC: LEPTO+JETSET(high p_T tuning)

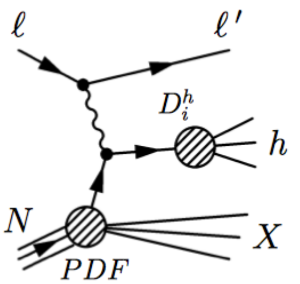


➔ On average ~ 70%

➔ Smooth distributions

Correction applied to final measurement: $M = M_{measured} / A$

Fragmentation functions from SIDIS



- ➔Fragmentation functions (FF, D_q^h) describe parton fragmentation into hadrons
- ➔FFs are needed for many types of analyses which deal with a hadron(s) in the final state
- ➔FFs are universal quantities
- ➔The cleanest way to access FFs is through the e^+e^- annihilation process

Why use SIDIS to access fragmentation functions?

Unlike e^+e^- annihilation, data from SIDIS provide charge and full flavor decomposition of FFs, and SIDIS from fixed target experiments like COMPASS explore kinematic energy scales down to 1 GeV