Single hadron and hadron pair multiplicities measurement at COMPASS and NLO extraction of quark fragmentation functions

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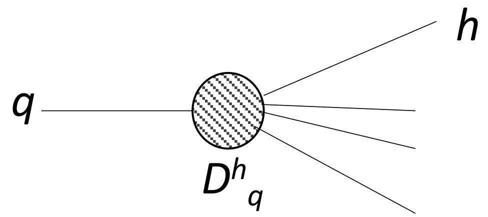
Outline

- Single-hadron fragmentation functions
- Di-hadron fragmentation functions
- Semi-inclusive DIS & Hadron multiplicities
- Results
- NLO QCD fit of fragmentation functions by LSS
- Summary and outlook

Single-hadron Fragmentation Functions (FFs)

- Describe the collinear transition of a quark *q* into a final-state hadron *h* carrying momentum fraction *z* (*q -> h X*)

- *D^h_q gives the mean number of hadrons produced in the quark hadronization*



- Relevant in every reaction where a hadron is produced in the final state
- Play a key role in flavour separation of polarised PDFs
- Universal and non-perturbative quantities
- Depend on energy fraction of the photon transferred to the hadron:

$$z = \frac{E_h}{E_\gamma}$$

- Depend on Q^2, evolution described by DGLAP equations
- Energy conservation sum rule (used their determination):

$$\sum_h \int_0^1 z D_i^h(z, Q^2) dz = 1$$

The ΔS puzzle

- Strange quark contribution to nucleon spin:

$$\Delta S = \int dx[\Delta s(x) + \Delta\bar{s}(x)]$$

Inclusive DIS measurement

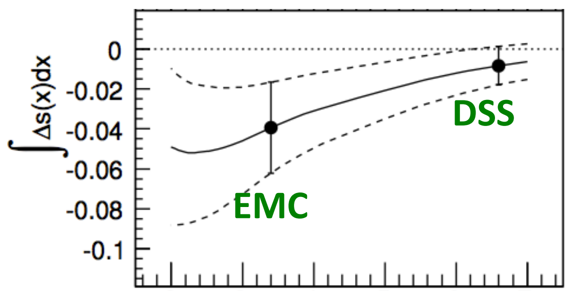
- $\Gamma_1 = g_1(x)$
- SU(3) flavor symmetry & axial charges of baryons

$\Delta S = -0.08 \pm 0.01_{stat.} \pm 0.02_{syst.}$

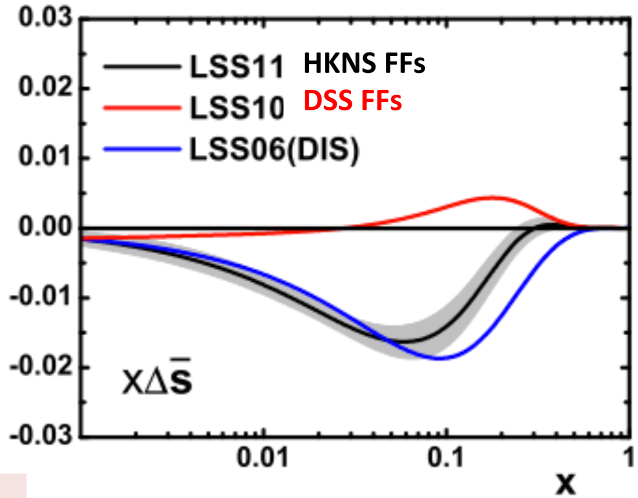
Semi-Inclusive DIS measurement

- Depending on fragmentation functions
- Strongly dependent on the ratio R_{SF}

$\Delta S = -0.02 \pm 0.02_{stat.} \pm 0.02_{syst.}$



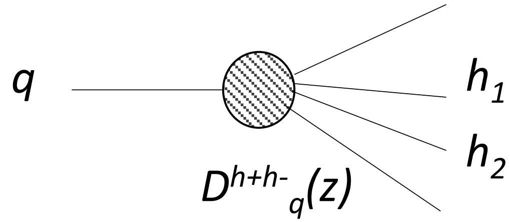
$$R_{SF} = \frac{D_{\bar{s}}^{K^+}}{D_u^{K^+}}$$



Single-hadron FFs remain a key element in the ΔS puzzle

Dihadron Fragmentation Functions (DiFFs)

- Describe the probability that a quark of given flavour (q_f) fragments into a final-state hadron pair ($q_f \to h_1^+ h_2^- X$):



- First introduced in the late 1970's to study the hadron structure of jets
  *Konishi, Ukawa and Veneziano, Phys. Lett. B **78**, 243 (1978)*

- Needed in NLO calculations in α_S for hadron pair production in e^+e^- annihilation
  *Phys. Lett. B **578**, 139 (2004)*

- Useful to investigate the in-medium effects in heavy ion collisions
  *Phys. Rett. L **99**, 152301 (2007)*

- Key element to access transversity distribution of the nucleon (h_1) in SIDIS

DiFFs are needed in several high energy processes with final state hadrons

Current knowledge of unpolarized FFs & DiFFs

Single-hadron FFs

- Experimental information available in several hard scattering reactions
- Most experimental data measured in e^+e^- colliders
  - Clean process ⇔ depends only on FFs (no dependence on PDFs)
  - Fixed energy scales (far from fixed target scales)
  - Mostly sensitive to singlet combinations
  - No separation of quark and anti-quark fragmentation
- Accessible in hadron-hadron collisions:
  - Most sensitive to gluon FFs
  - Useful for medium modifications of FFs
- Accessible in semi-inclusive DIS using hadron yields produced in DIS events
- Several global NLO QCD analyses exist (KRE, KKP, DSS, AKK, …)
  - Use different data sets and assumptions
  - Significantly disagree

Hadron pair FFs

- No global QCD analyses exist.
- Available experimental information consists of only invariant mass spectra of hadron pairs, no information on simultaneous (z, Q^2, M_{inv}) dependence
- An extraction of DiFFs done using Monte Carlo simulation of e+e- annihilations

  (by A. Courtoy, A. Bacchetta, M. Radici and A. Bianconi)

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Poorly known fragmentation functions, especially kaon's FFs

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Hadron pair FFs

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Unknown DiFFs

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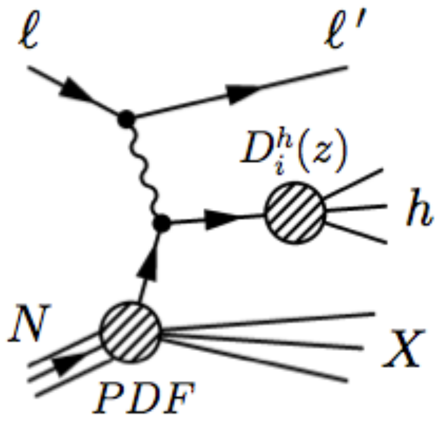
Semi-Inclusive DIS (SIDIS)



- *l N -> l' h X : at least one hadron is detected in coincidence with the scattered lepton in the final state*
- Allows flavor/charge separation of FFs
- Covers a wide Q^2 coverage in contrary to e^+e^- colliders

Relevant observable for FF access: **Hadron Multiplicities**

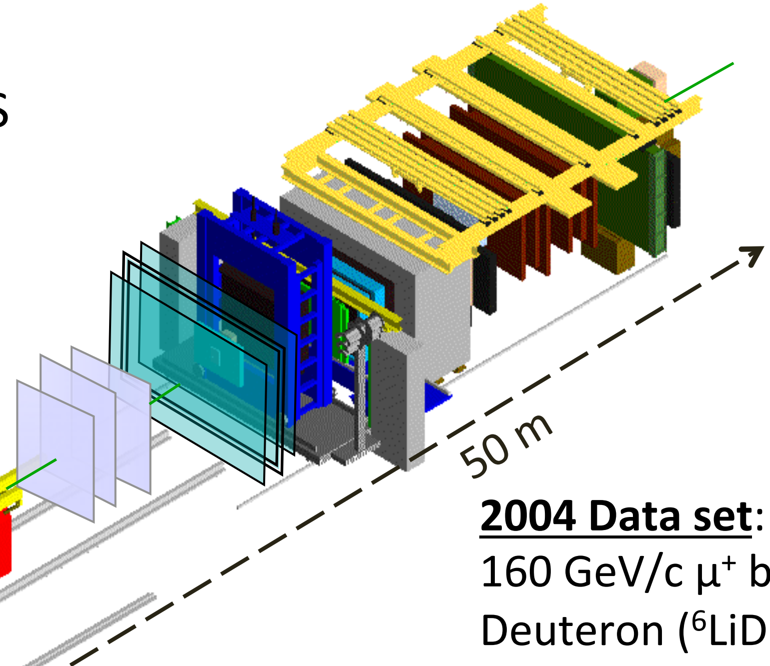
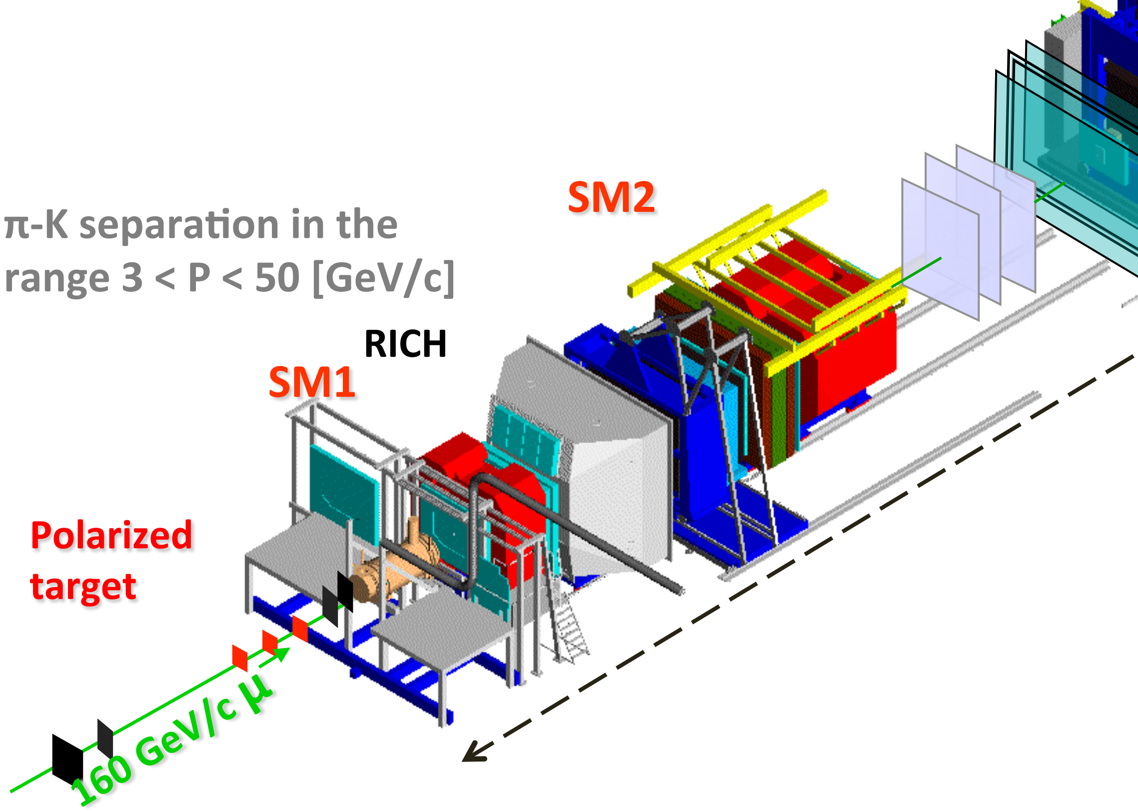
$$M^h(x,z) = \frac{d\sigma_{SIDIS}/dxdz}{\sigma_{DIS}} = \frac{\sum_q e_q^2 (q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z))}{\sum_q e_q^2 (q(x) + \bar{q}(x))}$$

- ***Disadvantage***: Dependence on unpolarised PDFs:
  - Up, down unpolarised PDFs well known
  - ***Strange PDF s(x) poorly known*** => More information from hadron multiplicities
- Useful to study the hadronisation process in nuclear medium (using different targets)

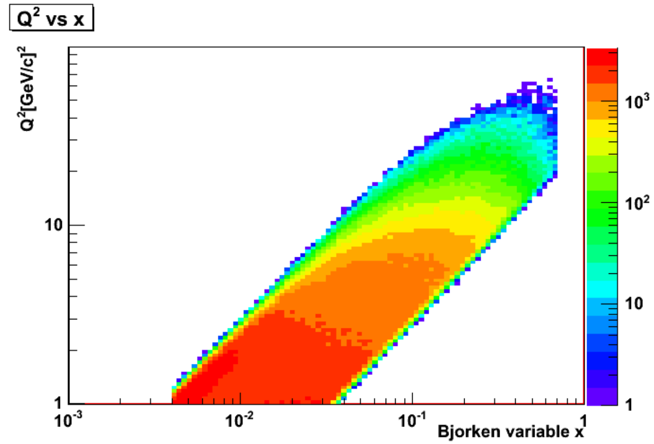
The COMPASS Experiment

Common Muon and Proton Apparatus for Structure and Spectroscopy

- Fixed target experiment @ CERN
- Secondary polarized μ beam from SPS
- Tracking, PID

2004 Data set:
160 GeV/c μ^+ beam
Deuteron (^{6}LiD) target



Multiplicity definition and method of extraction

Definition: averaged number of hadron produced per DIS event.

*Method of extraction: In a given kinematic bin **i***

1. Experimental hadron multiplicity:

$$M_{raw}(i) = N^h(i) / N^{DIS}(i)$$

2. Acceptance estimation using Monte Carlo simulation, acceptance defined as

$$a_i = M_{rec}(i_R) / M_{gen}(i_G)$$

3. Final multiplicities:

$$M_{cor}(i) = M_{raw}(i) / a_i$$

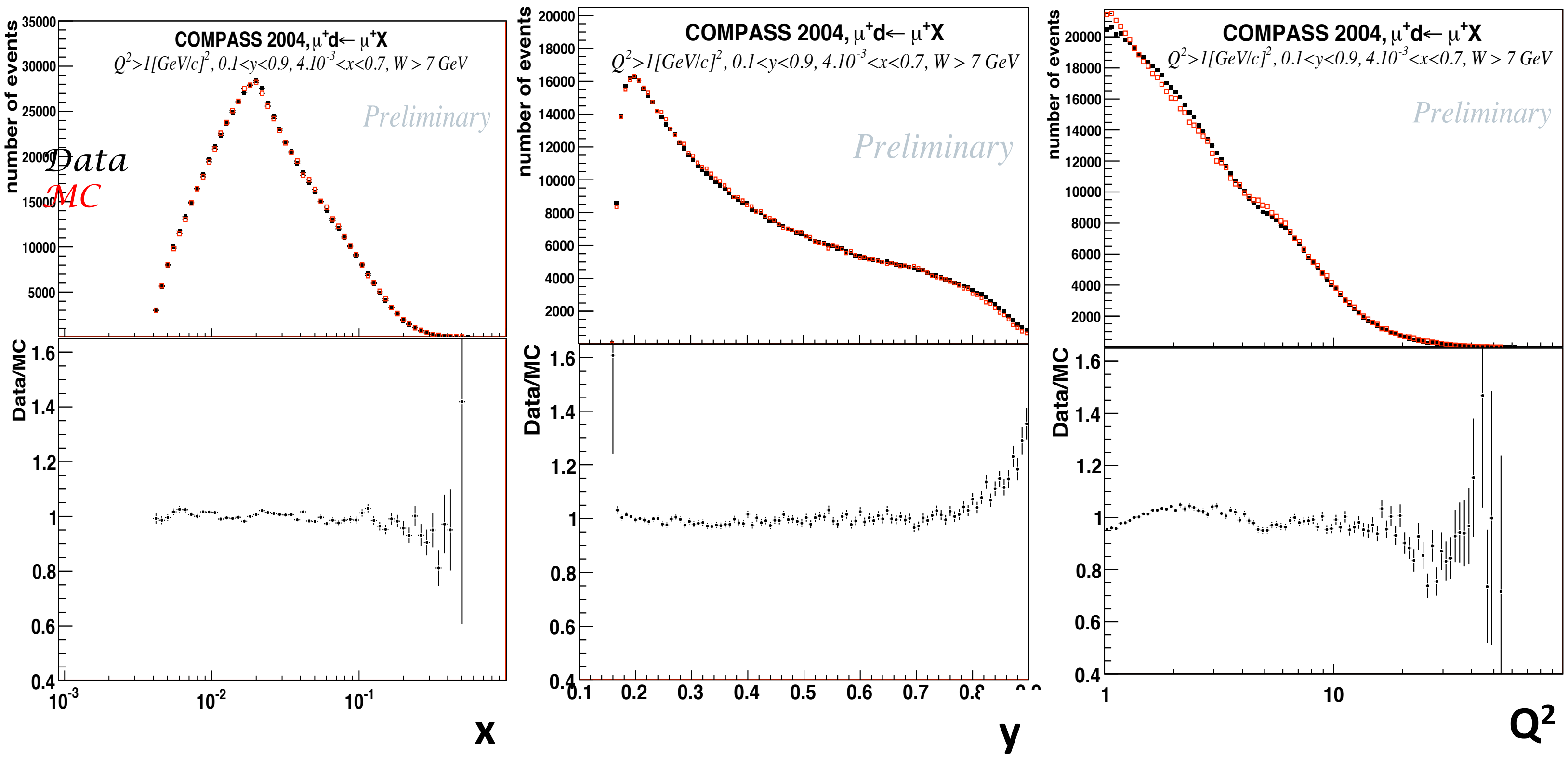
Kinematic domain

$Q^2 > 1$ (GeV/c)^2, $0.1 < y < 0.9$, W . 7 (GeV), $0.003 < x < 0.7$

$0.2 < z < 0.85$

N(DIS)	N(π^+)	N(π^-)	N(K^+)	N(K^-)
5.3 10^6	10^6	9.5 10^5	~ 2.10^5	~ 1.3 10^5

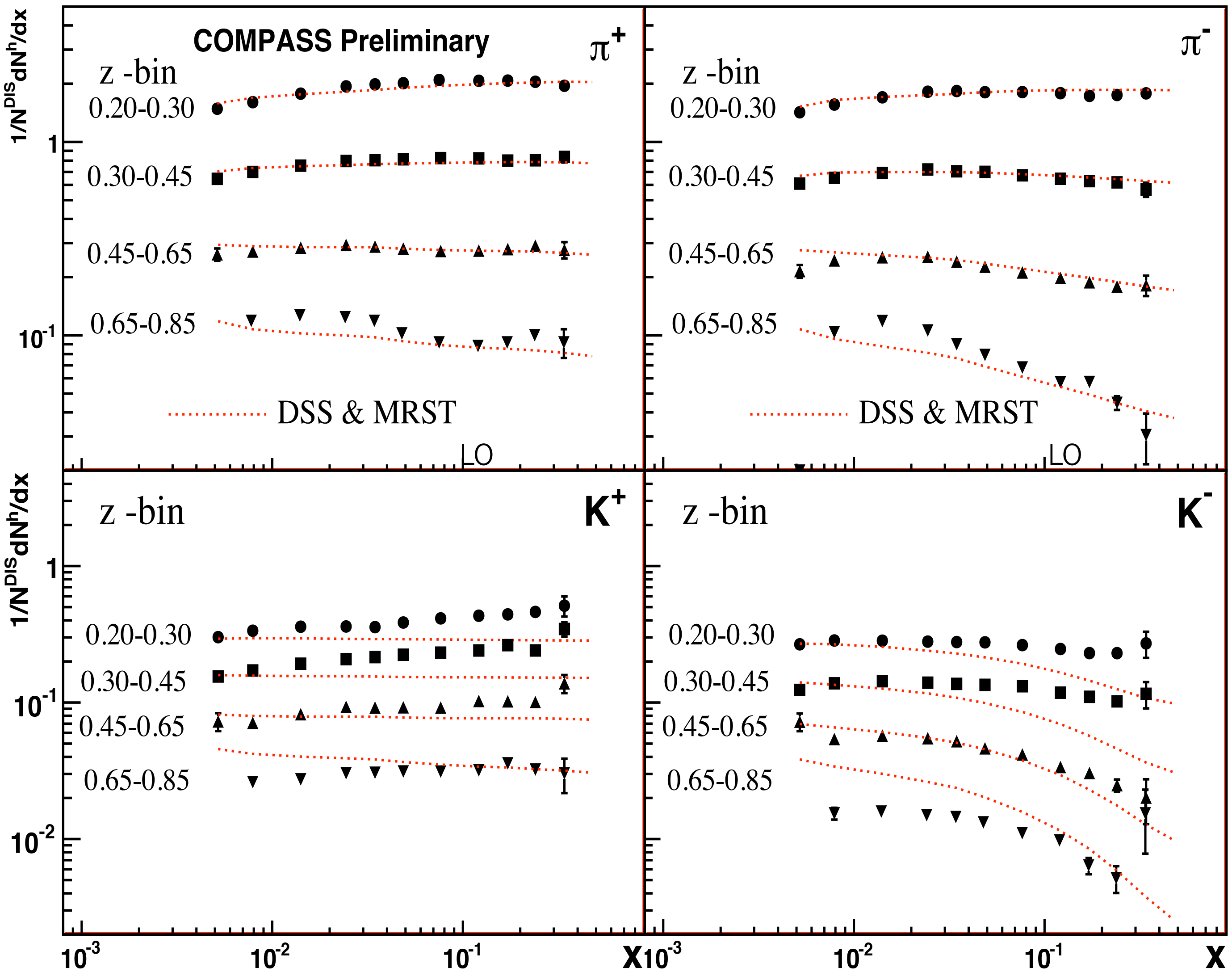
Monte Carlo description of COMPASS data for DIS variables



Good decscription of data by Monte Carlo for inclusive variables

Results on single hadron multiplicities

Results: 2D (x,z) multiplicities



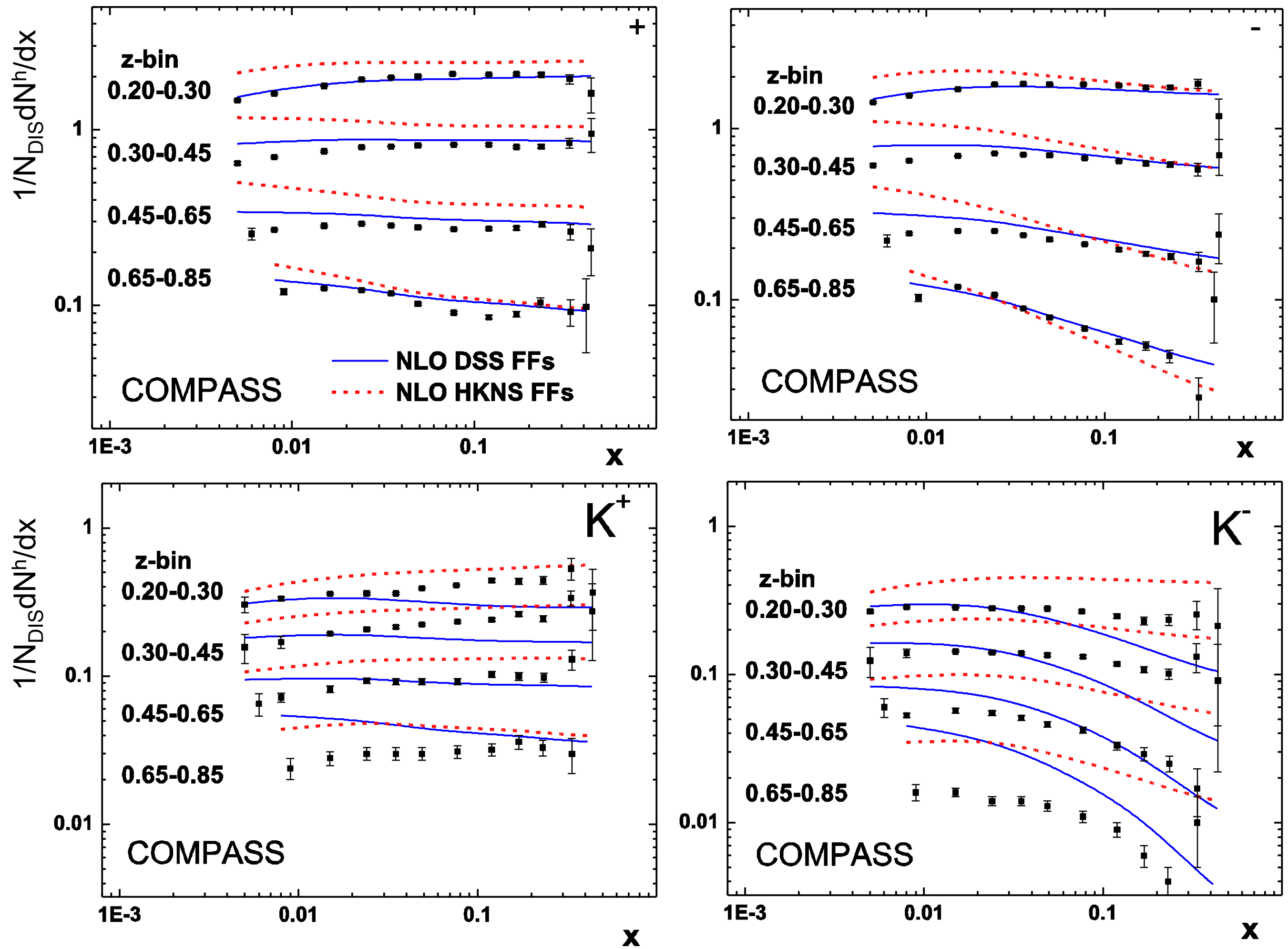
- $\pi^{\pm}$: fair agreement up to z=0.65
- $K^{\pm}$: Significant disagreement in all z bins
  - Unknown s(x) ?
  - Missing higher orders ?
  - COMPASS data favors different FFs than DSS

syst. Uncertainties due to: MC: ~ 1% (2%) for π (K) for x < 0.15

Particle identification < 8%(5%) for π (K)

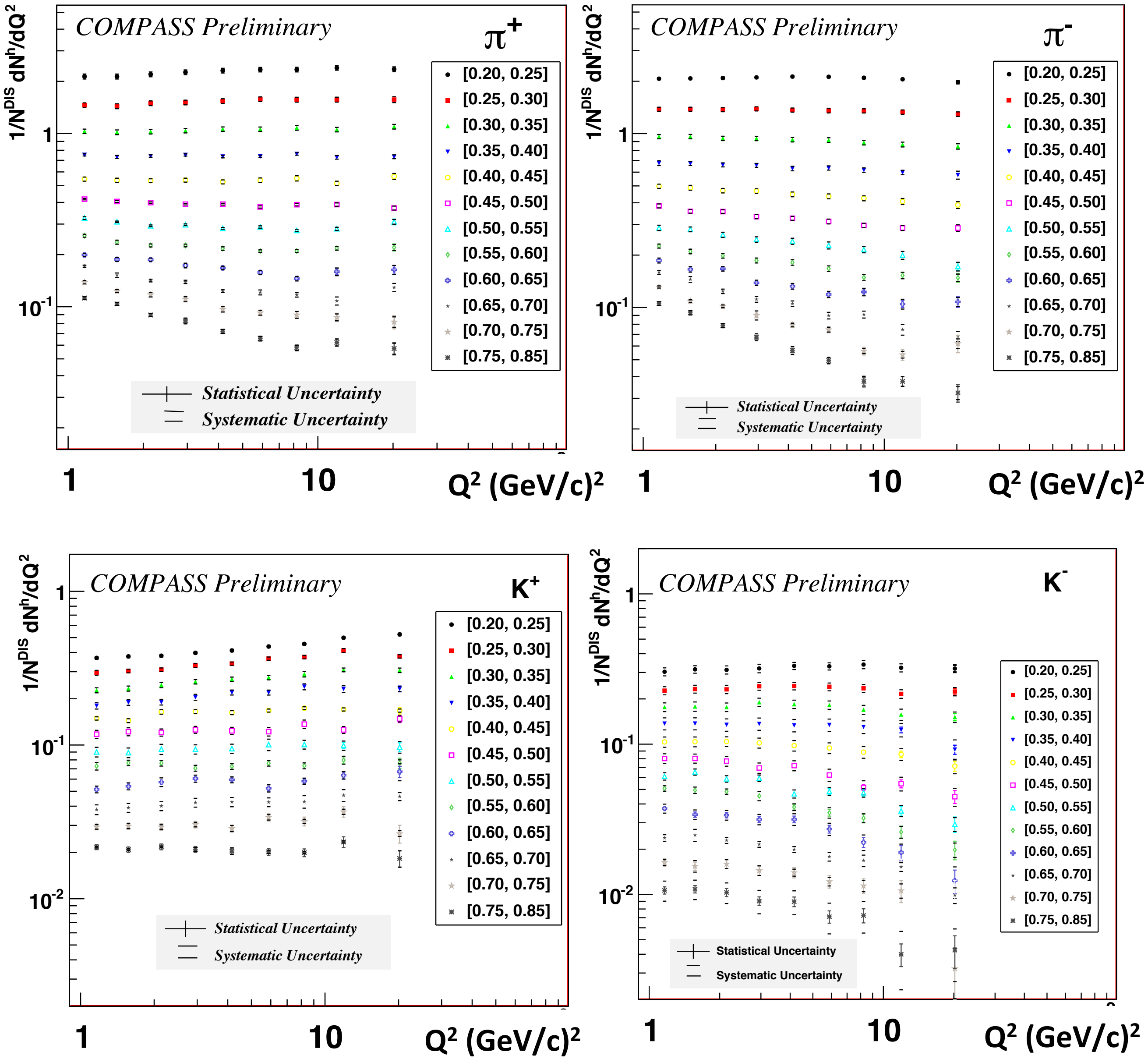
Comparison between COMPASS data on pion and kaon multiplicities and the NLO QCD predictions based on DSS and HKNS FFs

(*see A. Sidorov talk at SPIN 2012*)



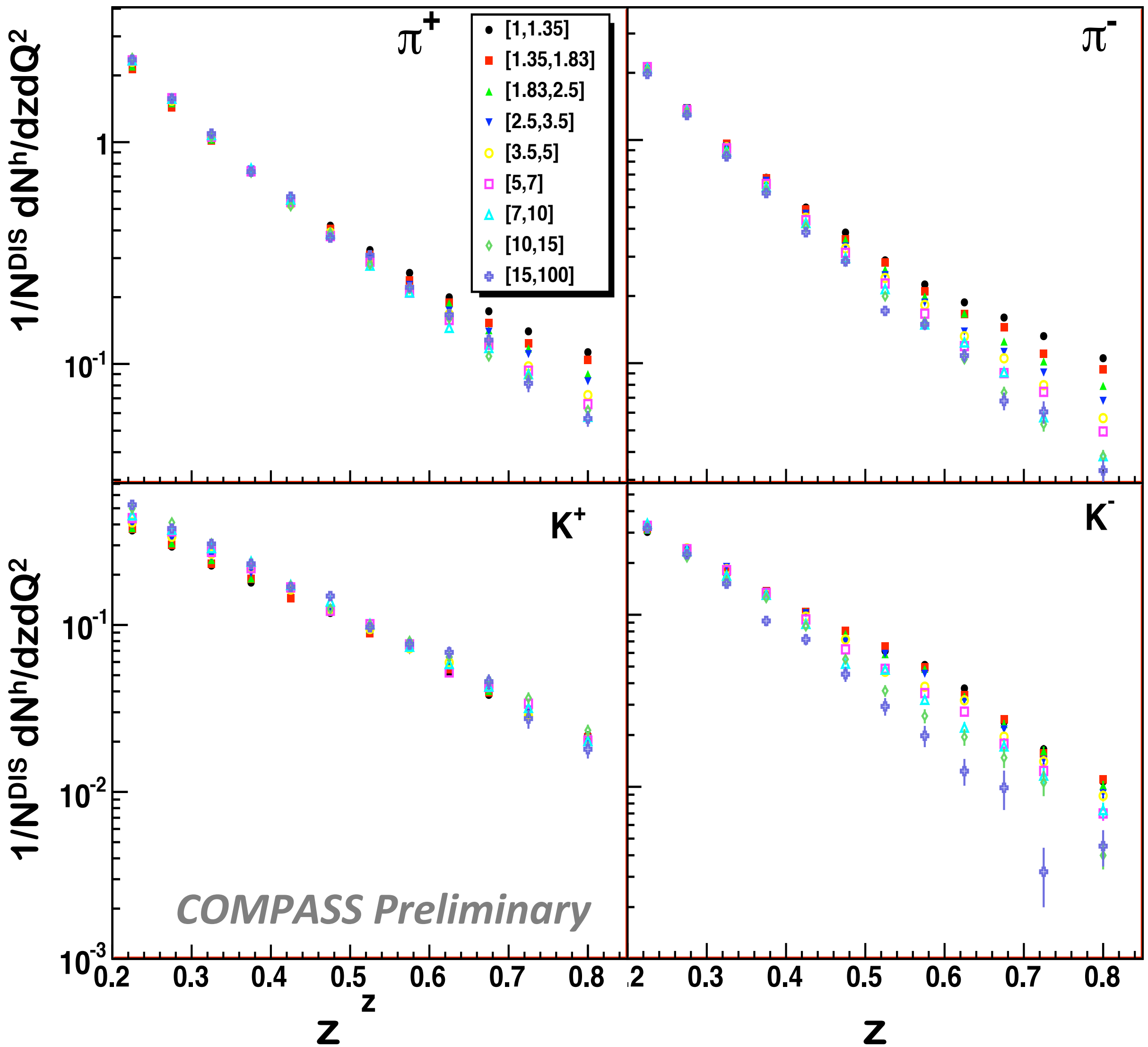
Fair agreement with the data for DSS and disagreement with HKNS FFs

Results: 2D (Q^2,z) Multiplicities for $\pi^\pm$



- Significant Q^2 dependence observed

Results: 2D (Q^2,z) Multiplicities for π and K



Input for global QCD analyses of FFs using SIDIS, e^+e^- and pp collisions

NLO QCD fit of pion multiplicities by E. Leader, A. Sidorov, D. Stamenov

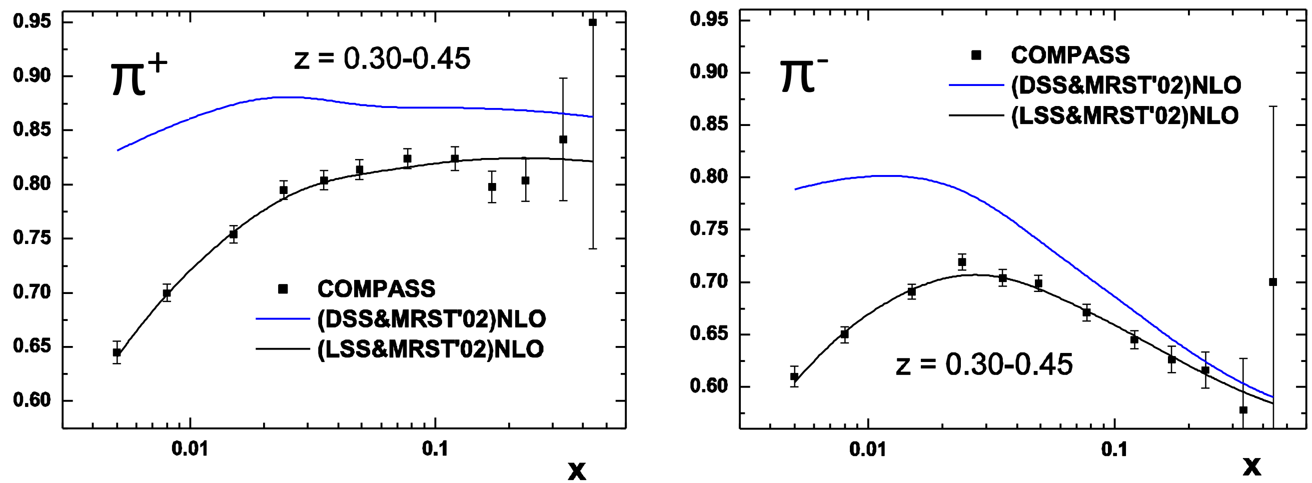
- Using SU(2) symmetry: $D_u^{\pi^+} = D_{\bar{d}}^{\pi^+}, D_{\bar{u}}^{\pi^+} = D_d^{\pi^+}$
- Assuming equal unfavored FFs : $D_d^{\pi^+} = D_s^{\pi^+} = D_{\bar{s}}^{\pi^+} = D_{\bar{u}}^{\pi^+}$
- 3 fragmentation functions to fit:

$$zD_u^{\pi^+}(z, Q_0^2) = N_u z^{\alpha_u}(1-z)^{\beta_u}(1+\gamma_u(1-z)^{\delta_u}) \quad \text{favored}$$

$$zD_{\bar{u}}^{\pi^+}(z, Q_0^2) = N_{\bar{u}} z^{\alpha_{\bar{u}}}(1-z)^{\beta_{\bar{u}}}(1+\gamma_{\bar{u}}(1-z)^{\delta_{\bar{u}}}) \quad \text{unfavored}$$

$$zD_g^{\pi^+}(z, Q_0^2) = N_g z^{\alpha_g}(1-z)^{\beta_g}$$

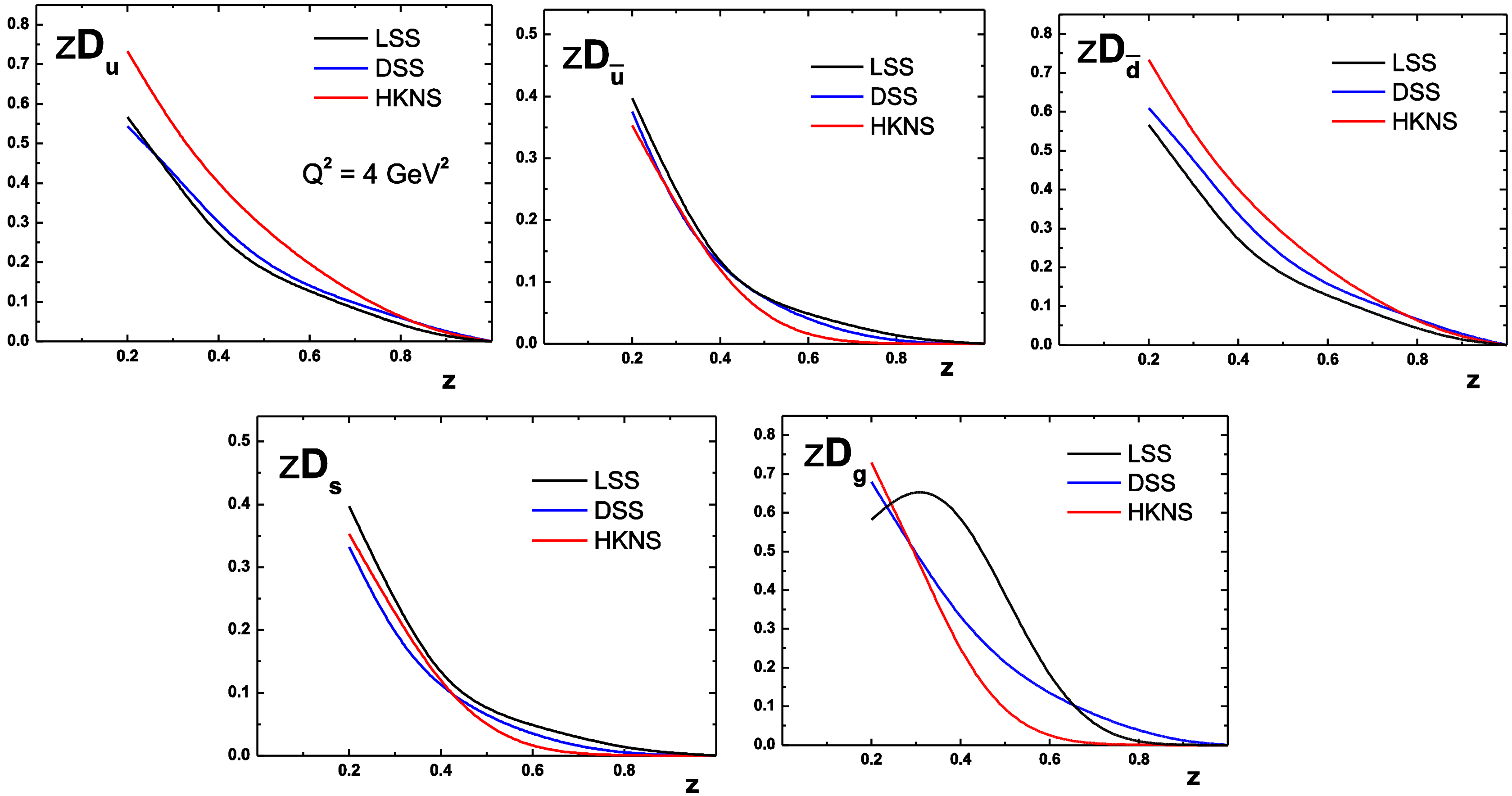
A good description of pion multiplicities is achieved for the z range 0.2-0.65



LSS pion FFs in comparison with DSS & HKNS

LSS, HKNS, 3 FFs: $D_u^{\pi^+} = D_{\bar{d}}^{\pi^+}, \quad D_d^{\pi^+} = D_s^{\pi^+} = D_{\bar{s}}^{\pi^+} = D_{\bar{u}}^{\pi^+}$

DSS, 4 FFs: $D_u^{\pi^+} \neq D_{\bar{d}}^{\pi^+}, \quad D_{\bar{u}}^{\pi^+} = D_d^{\pi^+}, \quad D_{\bar{u}}^{\pi^+} \neq D_{\bar{s}}^{\pi^+}, \quad D_{\bar{s}}^{\pi^+} = D_s^{\pi^+}$



LSS pion FFs compatible with DSS and HLNS FFs

NLO QCD fit of kaon multiplicities by E. Leader, A. Sidorov, D. Stamenov

Assuming that unfavored FFs are equal: $D_d^{K^+} = D_s^{K^+} = D_{\bar{d}}^{K^+} = D_{\bar{u}}^{K^+}$

4 fragmentation functions:

favored

$$zD_u^{K^+}(z,Q_0^2) = N_u z^{\alpha_u}(1-z)^{\beta_u}(1+\gamma_u(1-z)^{\delta_u})$$

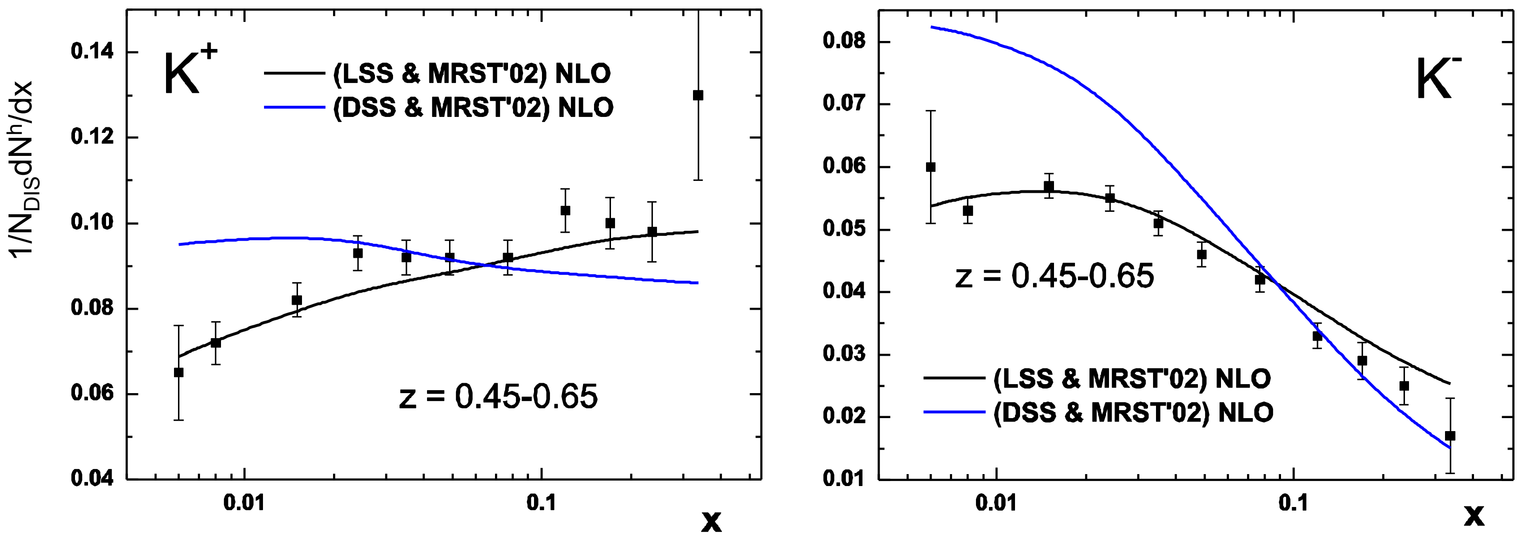
$$zD_{\bar{s}}^{K^+}(z,Q_0^2) = N_{\bar{s}} z^{\alpha_{\bar{s}}}(1-z)^{\beta_{\bar{s}}}(1+\gamma_{\bar{s}}(1-z)^{\delta_{\bar{s}}})$$

unfavored

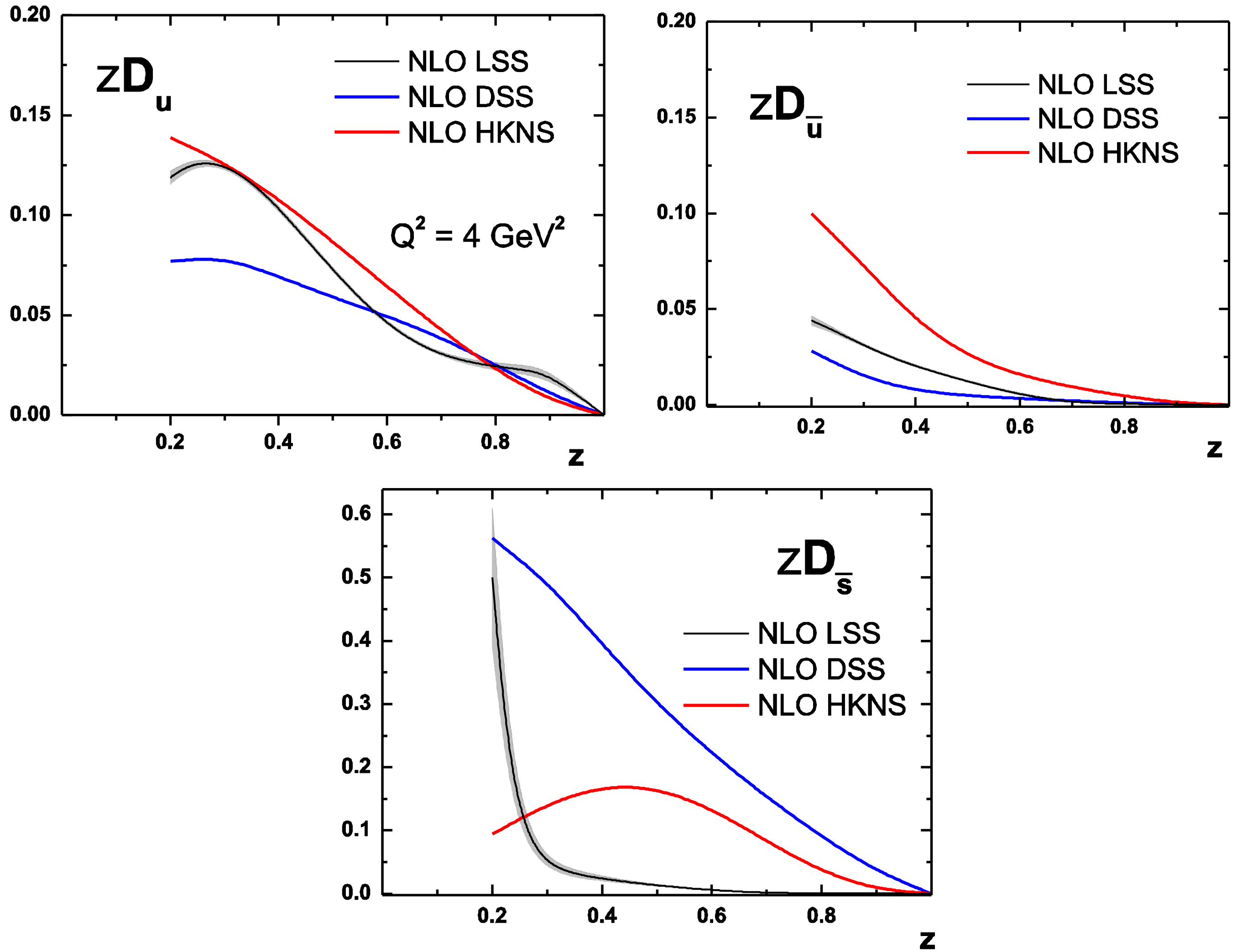
$$zD_{\bar{u}}^{K^+}(z,Q_0^2) = N_{\bar{u}} z^{\alpha_{\bar{u}}}(1-z)^{\beta_{\bar{u}}}$$

$$zD_g^{K^+}(z,Q_0^2) = N_g z^{\alpha_g}(1-z)^{\beta_g}$$

A good description of kaon multiplicities is also achieved

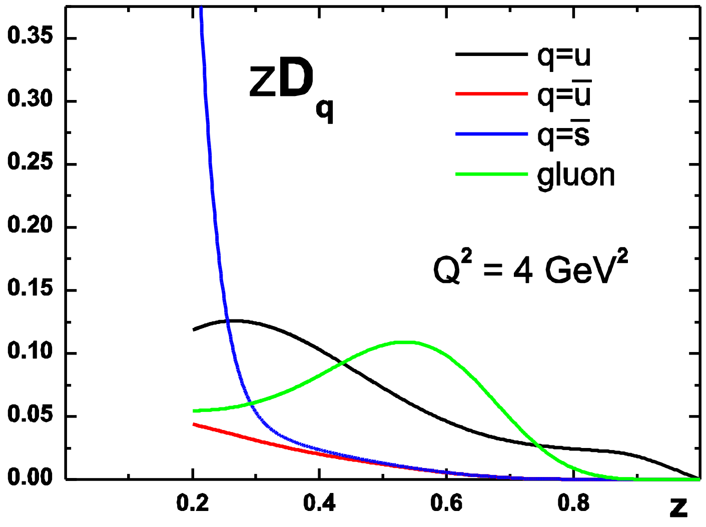


LSS kaon FFs in comparison with DSS & HKNS



New kaon FFs disagree with DSS and HKNS FFs

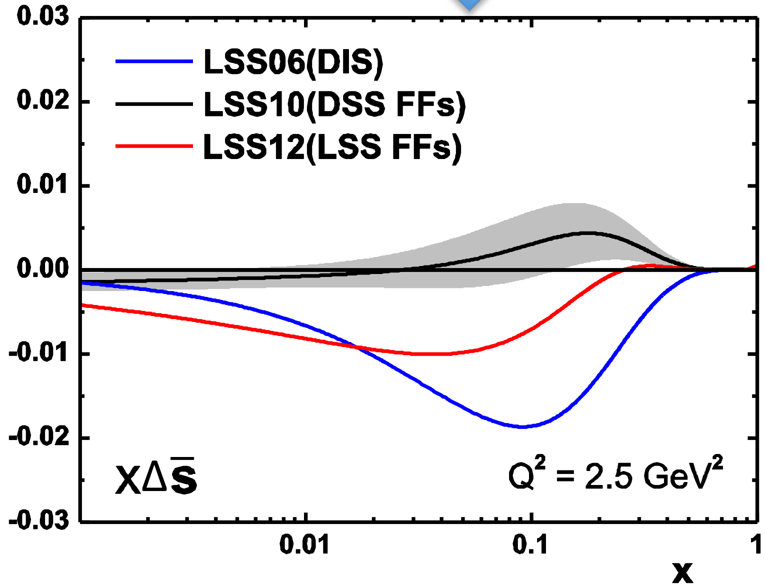
LSS kaon FFs and impact on ΔS



- D_s^K decreases very rapidly from 0.2 to 0.3
- At Q^2 = 3 GeV^2:

$$I_u = \int_{0.2}^{0.85} dz D_u^{K+}(z,Q^2) = 0.126, \quad I_{\bar{s}} = \int_{0.2}^{0.85} dz D_{\bar{s}}^{K+}(z,Q^2) = 0.116,$$

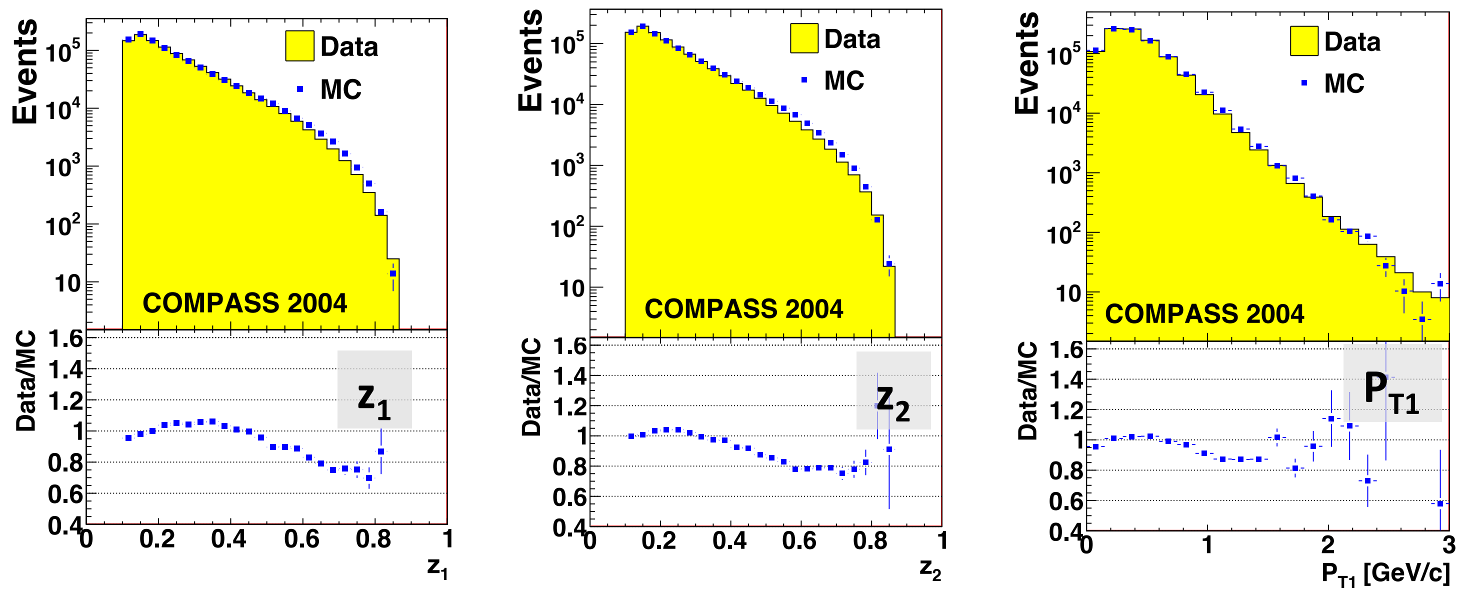
$$R_{SF} = I_{\bar{s}} / I_u = 0.921$$



Negative ΔS obtained in all measured x range using LSS kaon FFs

Results on hadron pair multiplicities

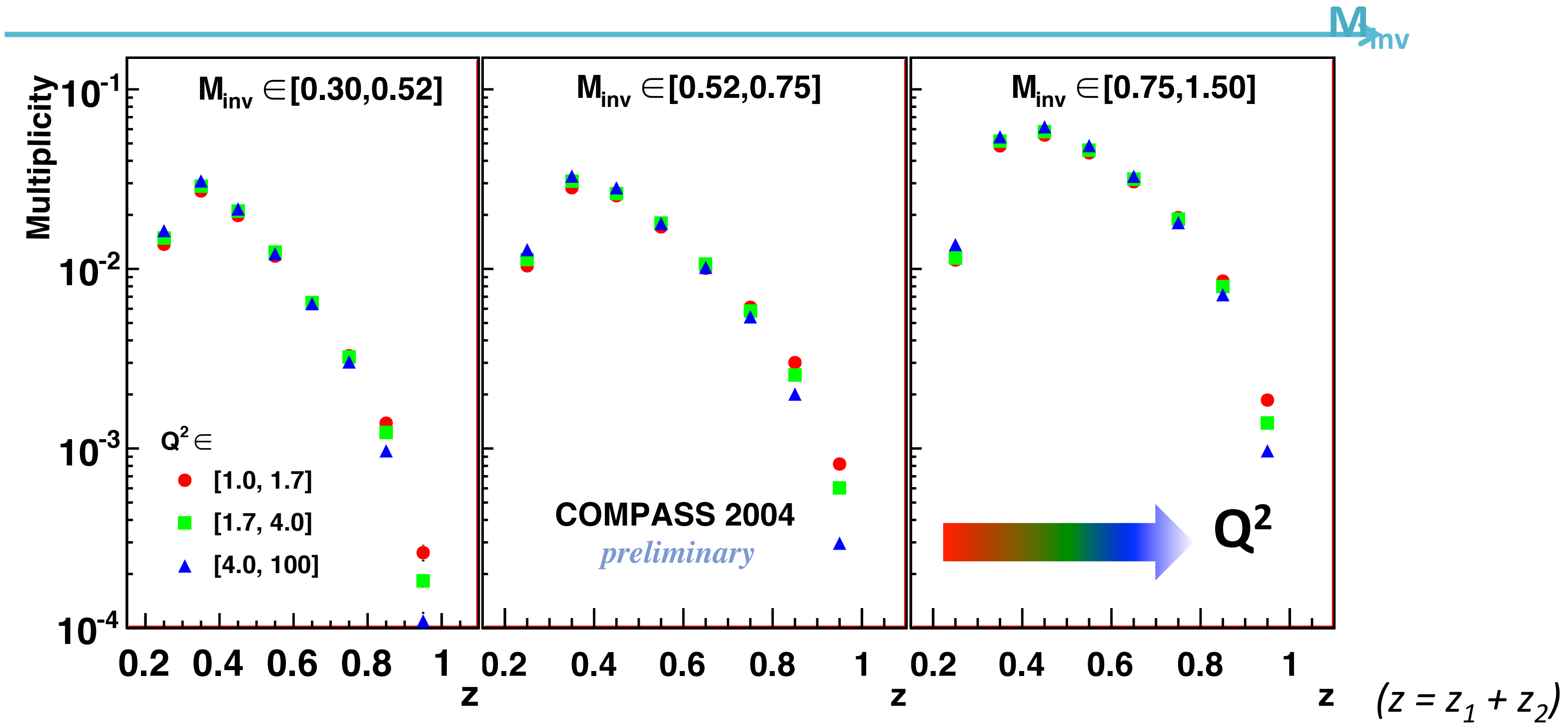
Monte Carlo description of COMPASS data for hadron pairs (I)



Reasonable description of COMPASS data by MC simulation

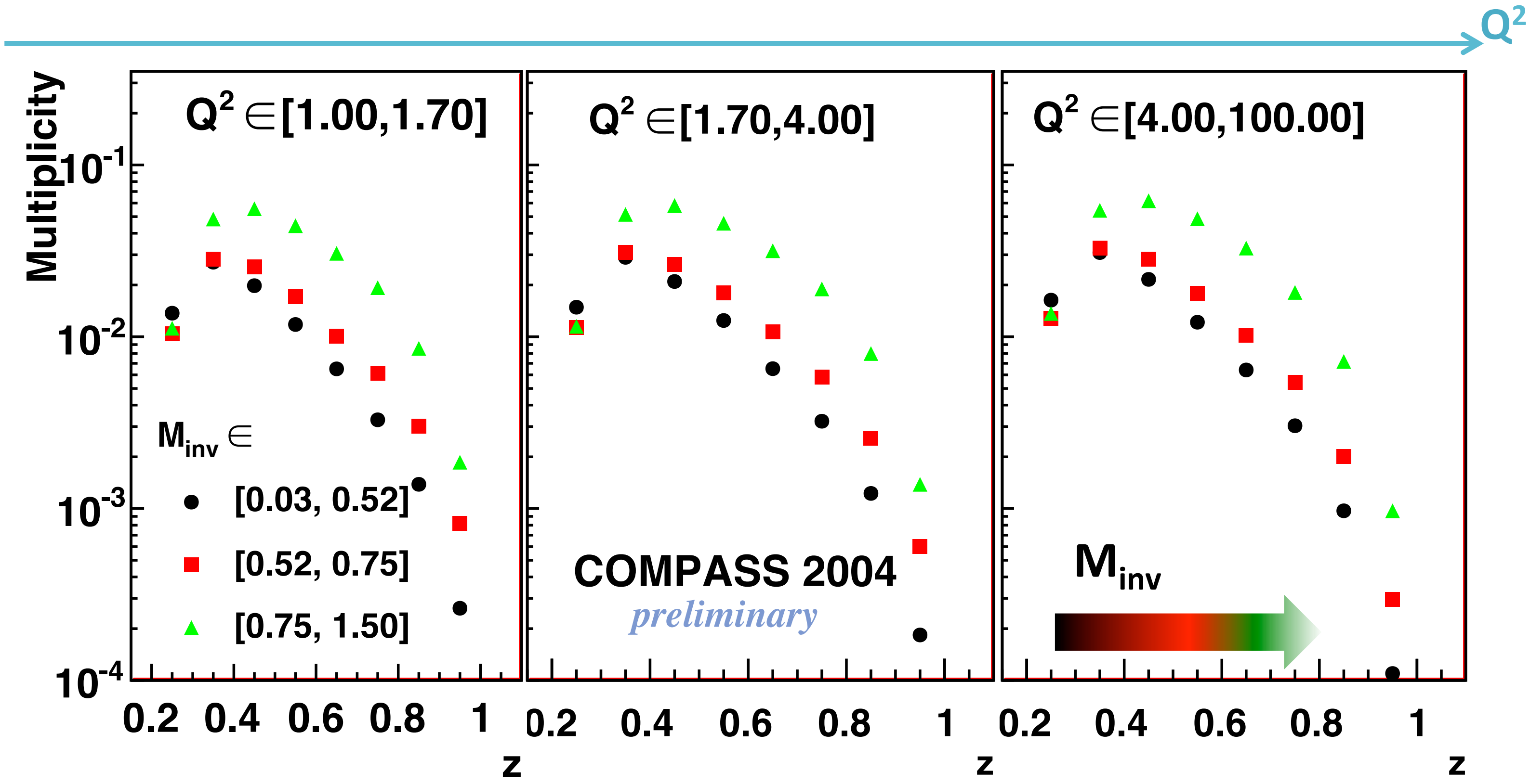
New: 2004 Hadron pair multiplicities versus (z, Q^2, M_{inv})

- Goal: measurement of $D_q^{h+,h-}(z, M_{inv}, Q^2)$
- Key ingredient to access transversity function



Weak Q^2 dependence as predicted by LEPTO generator

New: 2004 Hadron pair multiplicities versus (z, Q^2, M_{inv})



- Non negligible dependence upon M_{inv} and z
- (z, M_{inv}) dependence in agreement with LEPTO prediction

First determination of hadron pair multiplicities from SIDIS

Summary & Outlook

- π/K charged multiplicities versus (x,z) and (Q2,z) from μ-d DIS measured at COMPASS
- **π**: fair agreement with LO predictions, **K**: significant disagreement
- Input for global QCD analyses for FFs
- Useful for the determination of strange quark distribution s(x)
- First measurement of unidentified hadron pair multiplicities aiming to determine Dihadron fragmentation functions

- New pion and kaon FFs are determined from a NLO QCD analysis of the *COMPASS* 2004 deuteron data on hadron multiplicities

Outlook

- Single hadron multiplcities from μ-p DIS
- Measurement of Identified hadron pair multiplicities
- Determination of s(x)