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Determination of pion fragmentation functions from a QCD analysis of the HERMES and COMPASS data on multiplicities

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OUTLINE

- **Why the Fragmentation Functions (FFs) are so important for the determination of the *polarized* PDFs ?**

- **The present status of fragmentation funcrtions (FFs)**

→ **The strange quark polarization puzzle**

- **NLO QCD analysis of the *COMPASS'06/d* and *HERMES/(p,d)* data on pion multiplicities**

→ **new *pion FFs***

- **Consistency between COMPASS and HERMES data ?**

- **Summary**

LSS: arXiv 1312.5200 [hep-ph]

Due to the lack of the charged current neutrino data *only* the sums of pol. *PDFs* can be determined from the polarized inclusive DIS

$$(\Delta q + \Delta\bar{q})(\mathrm{x},\, \mathrm{Q}^2)$$

$$g_1(x,Q^2)_{LT} = \frac{1}{2}\sum_q^{N_f} e_q^2 [(\Delta q + \Delta\bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q) + \frac{\alpha_s(Q^2)}{2\pi}\Delta G \otimes \frac{\delta C_G}{N_f}]$$

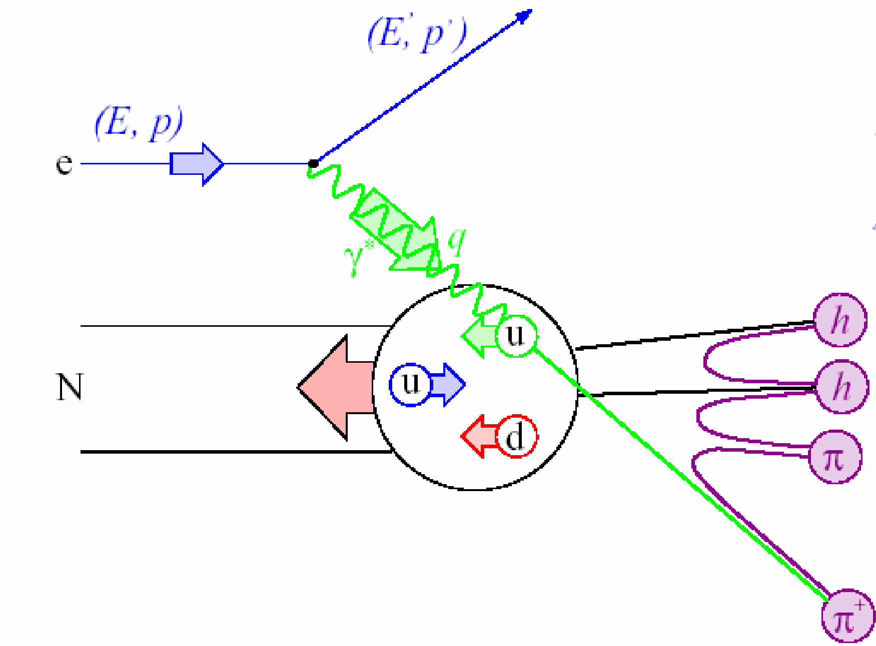
LT – leading twist QCD contribution

$\delta C_q, \delta C_G - Wilson$ coefficient functions

In order to extract separately Δq and $\Delta\bar{q}$ another reactions are needed. One possibility is to use the polarized semi-inclusive lepton-hadron processes.

Semi-inclusive processes

→ allow to separate Δq and $\Delta \overline{q}$



Fragmentation functions

D_q^h from quark q into hadron h

$z = \frac{E_h}{\nu}$ energy fraction carried by h

$$A_1^h(x,z,Q^2) = \frac{g_1^h - \gamma^2 g_2^h}{F_1^h}$$

In LO QCD: $$A_1^h(x,z,Q^2) \sim \frac{g_1^h}{F_1^h} = \frac{\sum_{q,\bar{q}} e_q^2\, \Delta q(x,Q^2)\, D_q^h(z,Q^2)}{\sum_{q,\bar{q}} e_q^2\, q(x,Q^2)\, D_q^h(z,Q^2)}$$

New physical quantities appear – fragmentation functions $D^h_{q,\bar{q}}(z,Q^2)$**. Due to a different fragmentation of** q and $\bar{q}$, Δq and $\Delta\bar{q}$ **can be fixed separately.**

To determine correctly the *polarized* parton densities from a combined analysis of *polarized* DIS and SIDIS data good knowledge of FFs is very important !

There are 3 modern versions of FFs based on an analysis of different data sets:

- **Hirai et al. (HKNS), from SI e+e- annihilation data,** ***PR D75 (2007) 094009***
- **Albino et al. (AKK), from $e^+e^- \oplus$ SI pp (RHIC) data,** ***Nucl. Phys. B803 (2008) 42***
- **De Florian et al. (DSS), from $e^+e^- \oplus$ SI pp $\oplus$ SIDIS unpolarized data (*PR D75, 114010; D76, 074033 (2007)*)**

Unpublished HERMES'05 which differ from the final HERMES'13 data (*Phys.Rev. D87 (2013) 074029*)

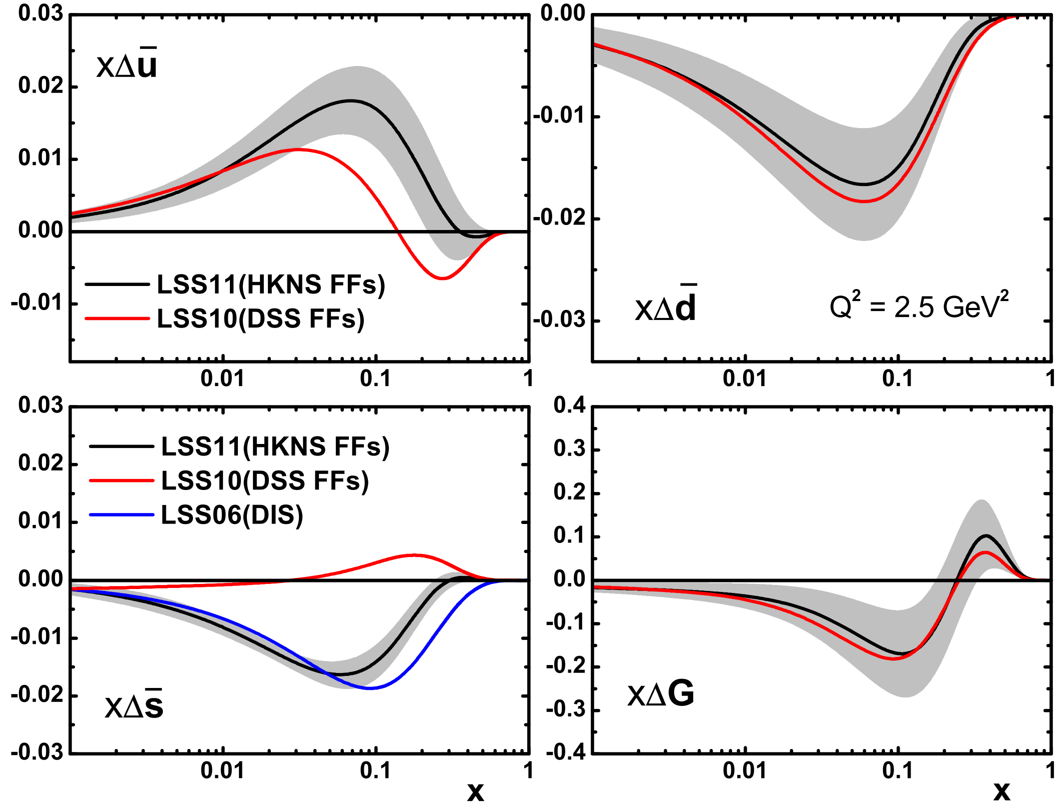
The unpolarized SIDIS processes are crucial for a reliable determination of FFs $\Longrightarrow$ one can separate $D_q^h(z,Q^2)$ from $D_{\bar{q}}^h(z,Q^2)$

Sensitivity of polarized sea quark densities on FFs

Sea quark densities obtained from NLO QCD analyses of DIS+SIDIS data using DSS and HKNS FFs are compared

- $\Delta\bar{d}(x)_{DSS}$ and $\Delta\bar{d}(x)_{HKNS}$ **are almost the same**
- **At x > 0.03** $\Delta\bar{u}(x)_{DSS}$ **and** $\Delta\bar{u}(x)_{HKNS}$ **are different**
- **Significant difference between** $\Delta\bar{s}(x)_{DSS}$ (positive) and $\Delta\bar{s}(x)_{HKNS}$ (*negative*)
- **Inconsistency between** $\Delta\bar{s}(x)_{DSS}$ and $\Delta\bar{s}(x)_{DIS}$ **a puzzle which has to be solved**

Error bands → $\Delta\chi^2 = 1$



$err^2 = stat^2 + sys^2$

LSS'10, PR D82 (2010); LSS'11, PR D84 (2011)

The present sets of pion and kaon FFs are NOT in agreement with the recent HERMES and COMPASS data on multiplicities !!!

Hadron multiplicities – theory and experiment

$$M^h(x,Q^2,z)_{\mathrm{exp}} = \frac{d^3N^h(x,Q^2,z)/dxdQ^2dz}{d^2N^{DIS}(x,Q^2)/dxdQ^2} = \frac{\text{Nr of hadrons yelds}}{\text{DIS events yelds}}$$

$$M^h(x,Q^2,z)_{\mathrm{th}} = \frac{d^3\sigma^h(x,Q^2,z)/dxdQ^2dz}{d^2\sigma^{DIS}(x,Q^2)/dxdQ^2}$$

$$= \frac{(1+(1-y)^2)2xF_1^h(x,Q^2,z)+2(1-y)xF_L^h(x,Q^2,z)}{(1+(1-y)^2)2xF_1(x,Q^2)+2(1-y)F_L(x,Q^2)}$$

F_1^h, F_L^h - SIDIS str. functions, F_1, F_L - nucleon str. functions, $y = Q^2/2MxE$

In LO QCD: $\mathbf{F_L^h}$, $\mathbf{F_L = 0}$

$$M^h(x,Q^2,z) = \frac{F_1^h(x,Q^2,z)_{LO}}{F_1(x,Q^2)_{LO}} = \frac{\sum_{q,\bar{q}} e_q^2 q(x,Q^2) D_q^h(x,Q^2,z)}{\sum_{q,\bar{q}} e_q^2 q(x,Q^2)}$$

NLO QCD fit to the pion data

Input FFs at $Q^2_0 = 1$ GeV^2

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

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

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

→ $N_{\{u,\bar{u},g\}},\ \alpha_{\{u,\bar{u},g\}}\ \beta_{\{u,\bar{u},g\}},\ \gamma_{\{u,\bar{u}\}},\ \delta_{\{u,\bar{u}\}}$ – free parameters

Additional assumptions for pion FFs:

- $D_{\bar{d}}^{\pi+}(z,Q_0^2) = D_u^{\pi+}(z,Q_0^2),\ D_d^{\pi+}(z,Q_0^2) = D_{\bar{u}}^{\pi+}(z,Q_0^2)$ ← **from SU(2) symmetry**
- $D_d^{\pi+}(z,Q_0^2) = D_s^{\pi+}(z,Q_0^2) = D_{\bar{s}}^{\pi+}(z,Q_0^2) = D_{\bar{u}}^{\pi+}(z,Q_0^2)$ **for unfavored FFs**

NLO QCD analysis of COMPASS'06/d data on pion multiplicities

(N. Makke, DIS'2013, Marseille, April, 22-26)

398 exp. points for π^+ and π^- in $[y, x(Q^2), z]$ presentation

(still preliminary)

Statistical and systematic errors are taken in quadrature

12 *free* parameters for the input FFs

Excellent description of the data

$$\chi^2/\mathrm{DOF} = 283.12/(398-12) = 0.73$$

Remark: A fit to the data using only the statistical errors does not practically change the pion fragmentation functions

$$\chi^2/\mathrm{DOF} = 625.02/(398-12) = 1.62$$

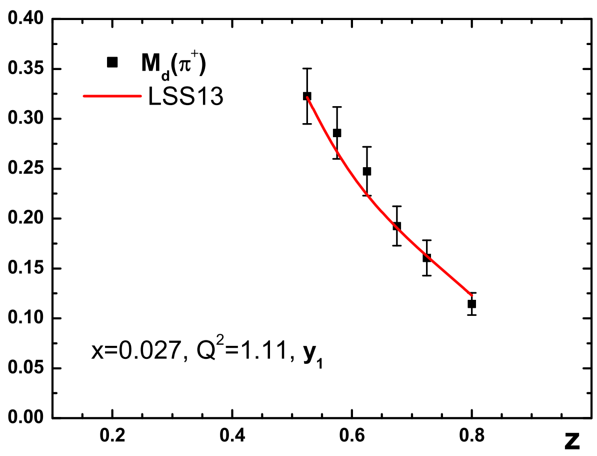
COMPASS data on pion multiplicities $M_d(\pi^+)$ vs NLO QCD fit curves

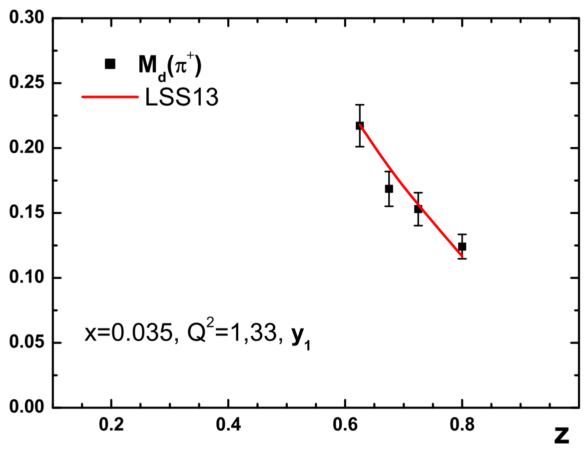
199 exp. points in $(y, x(Q^2), z)$ presentation

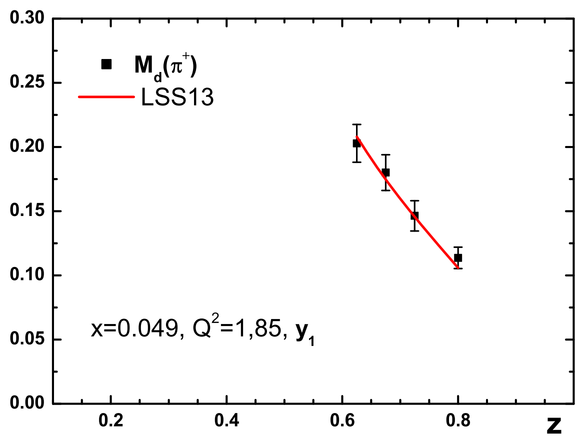
$$\chi^2/\text{point} = 0.61$$

$y = Q^2/2MEx$ E = 160 GeV

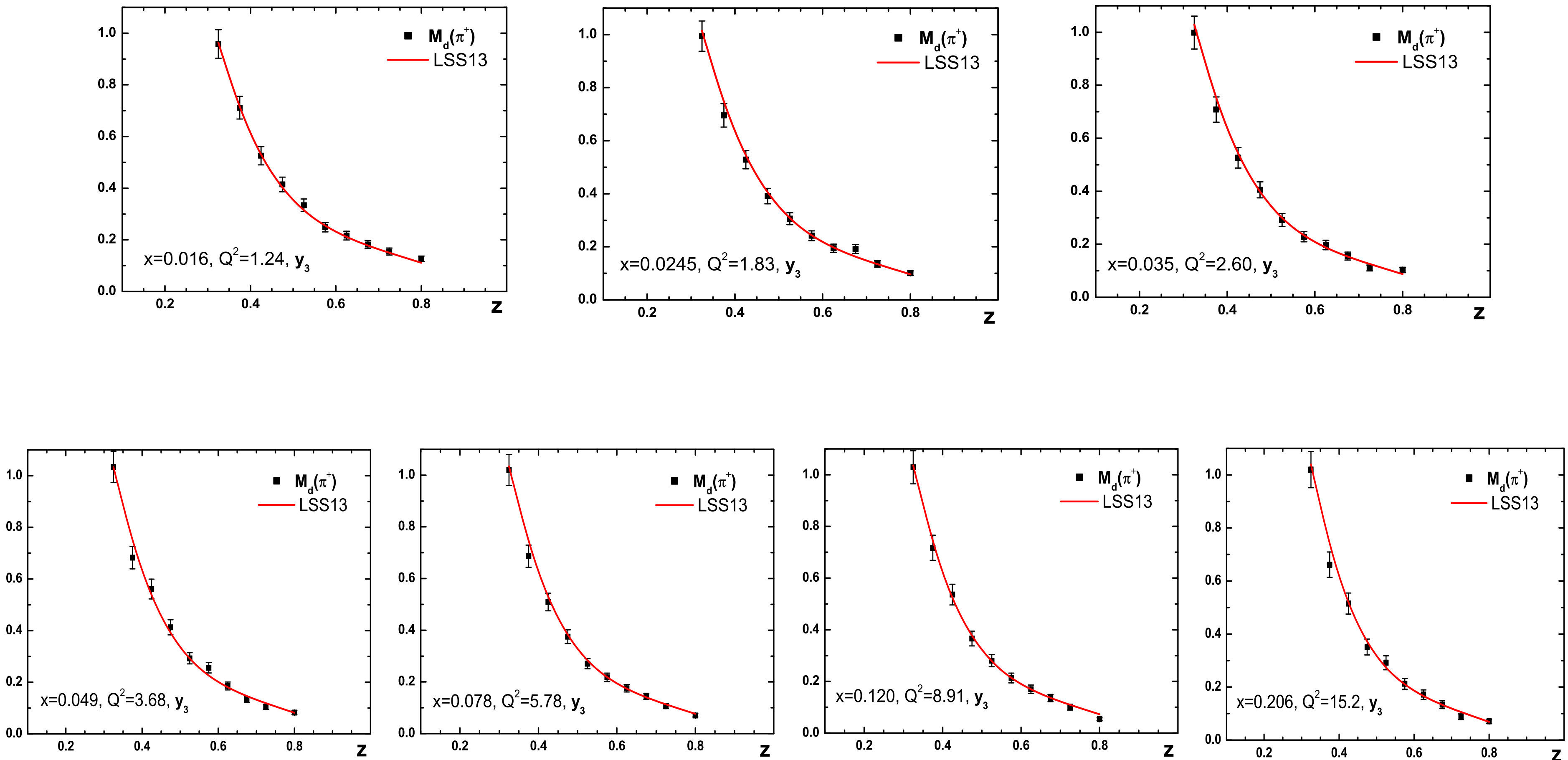
$y_1 = 0.10 - 0.15$





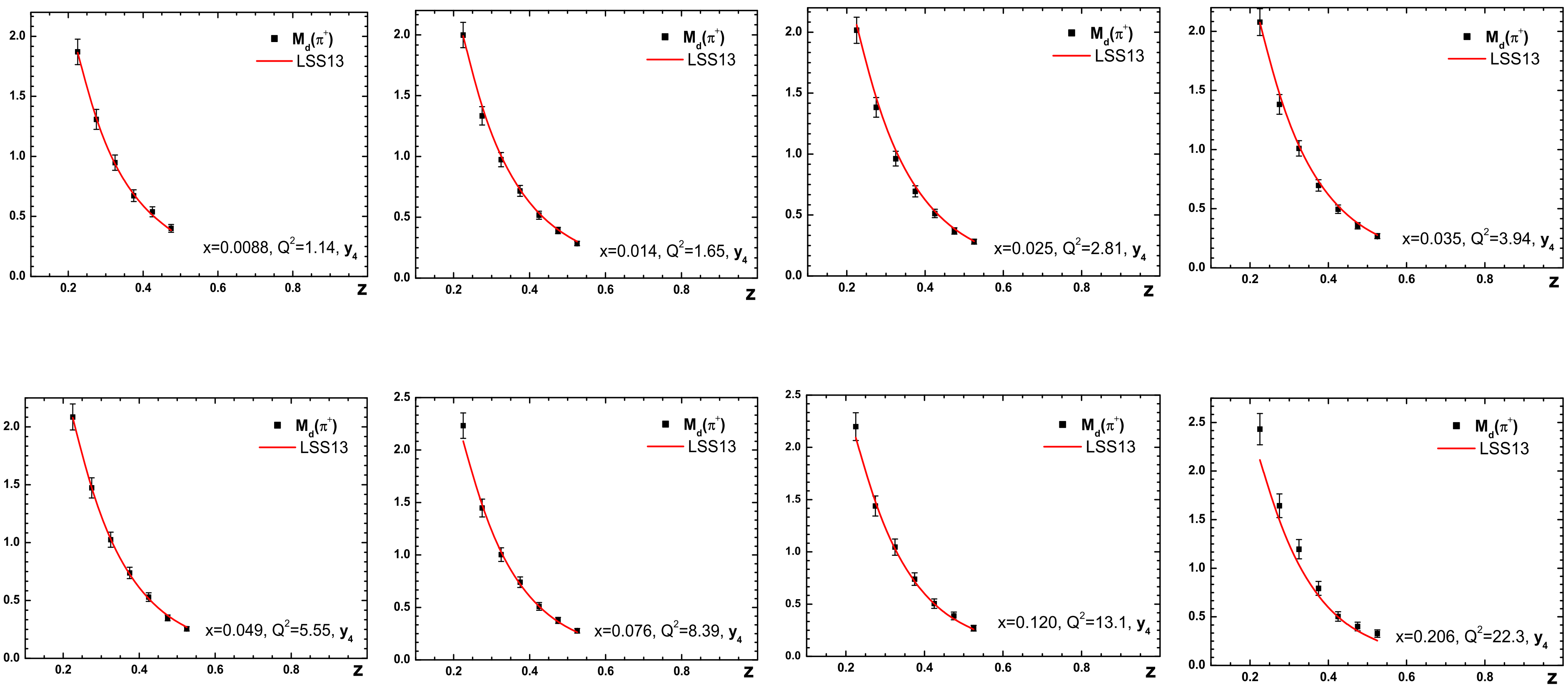


$y_3 = 0.20 – 0.30$



$M_d(\pi^+)$
LSS13
x=0.016, Q^2=1.24, y_3
x=0.0245, Q^2=1.83, y_3
x=0.035, Q^2=2.60, y_3
x=0.049, Q^2=3.68, y_3
x=0.078, Q^2=5.78, y_3
x=0.120, Q^2=8.91, y_3
x=0.206, Q^2=15.2, y_3
z

$y_4 = 0.30 – 0.50$



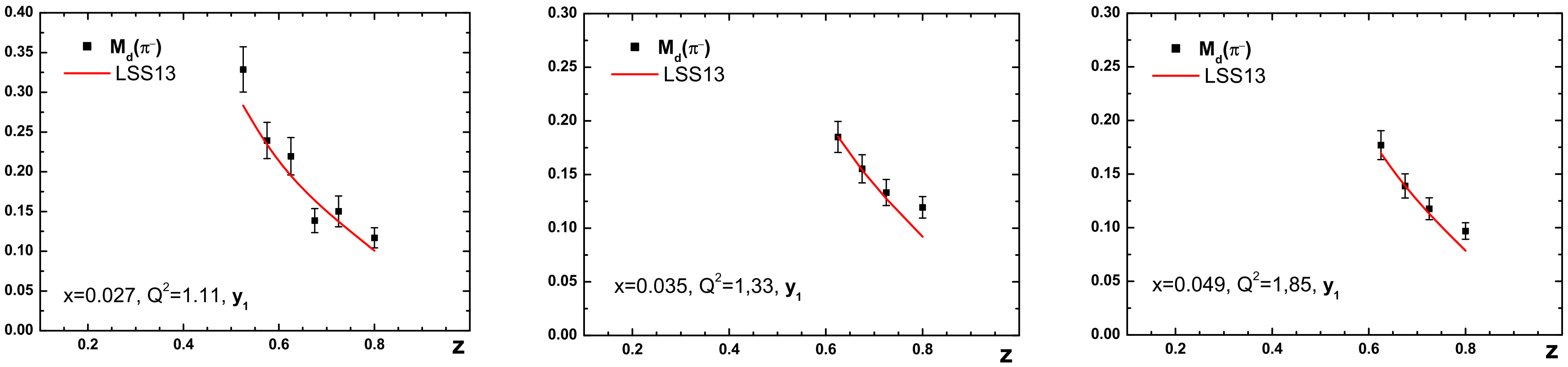
$M_d(\pi^+)$
LSS13
x=0.0088, Q^2=1.14, y_4
x=0.014, Q^2=1.65, y_4
x=0.025, Q^2=2.81, y_4
x=0.035, Q^2=3.94, y_4
x=0.049, Q^2=5.55, y_4
x=0.076, Q^2=8.39, y_4
x=0.120, Q^2=13.1, y_4
x=0.206, Q^2=22.3, y_4
z

COMPASS data on pion multiplicities $M_d(\pi^-)$ vs NLO QCD fit curves

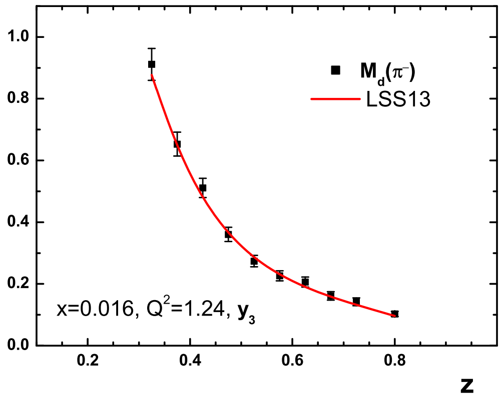
199 exp. points in (y, $x(Q^2)$, z) presentation

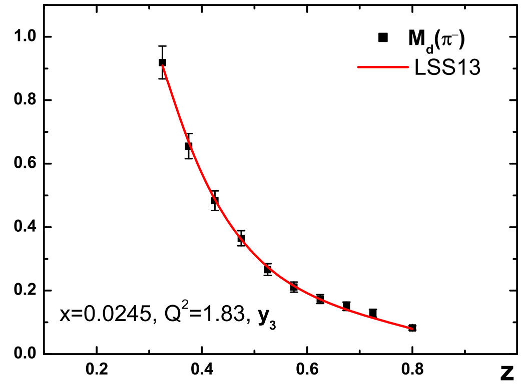
χ^2/point = 0.81

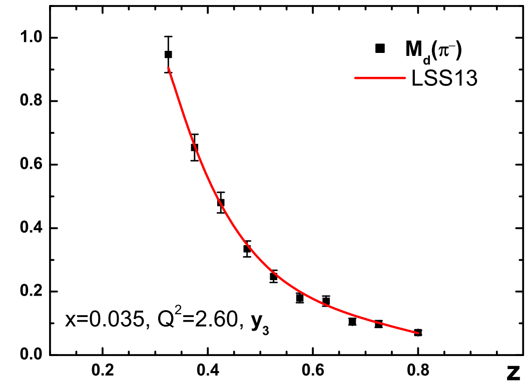
$y_1 = 0.10 - 0.15$

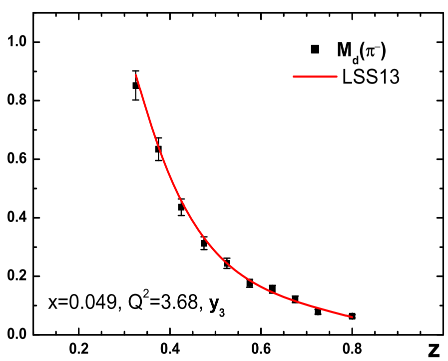


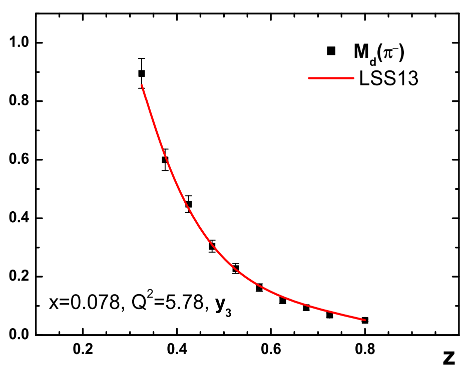
$y_3 = 0.20 - 0.30$

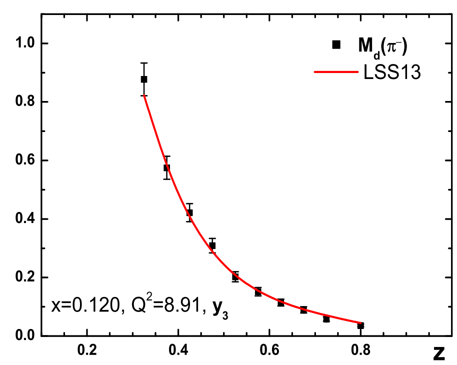

$M_d(\pi^-)$
LSS13
x=0.016, Q^2=1.24, y_3
z

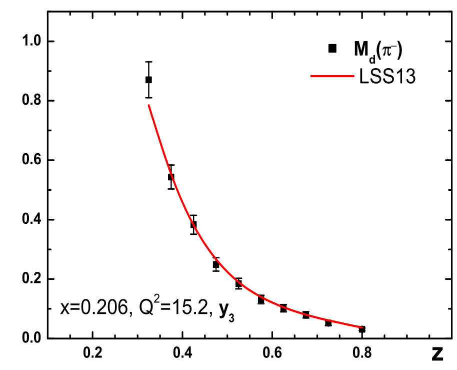

$M_d(\pi^-)$
LSS13
x=0.0245, Q^2=1.83, y_3
z


$M_d(\pi^-)$
LSS13
x=0.035, Q^2=2.60, y_3
z

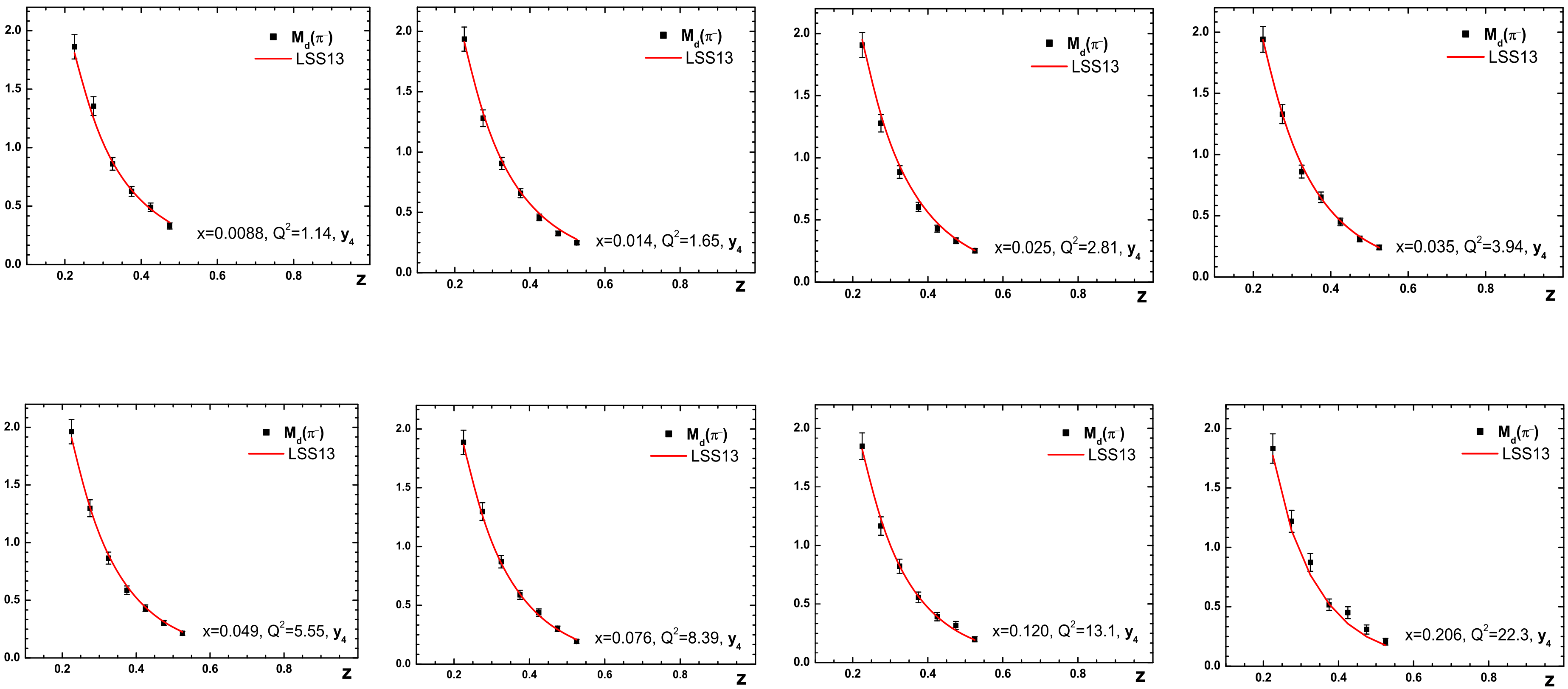

$M_d(\pi^-)$
LSS13
x=0.049, Q^2=3.68, y_3
z


$M_d(\pi^-)$
LSS13
x=0.078, Q^2=5.78, y_3
z


$M_d(\pi^-)$
LSS13
x=0.120, Q^2=8.91, y_3
z

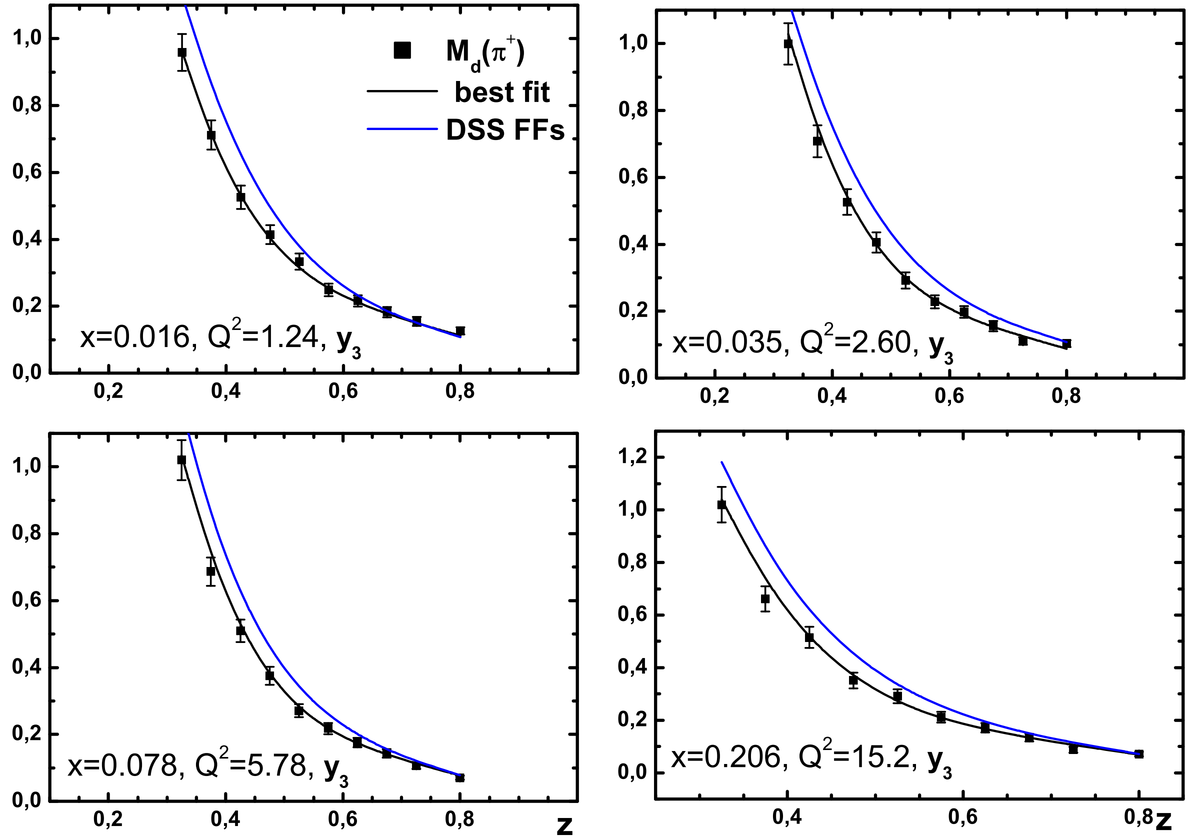

$M_d(\pi^-)$
LSS13
x=0.206, Q^2=15.2, y_3
z

$y_4 = 0.30 – 0.50$

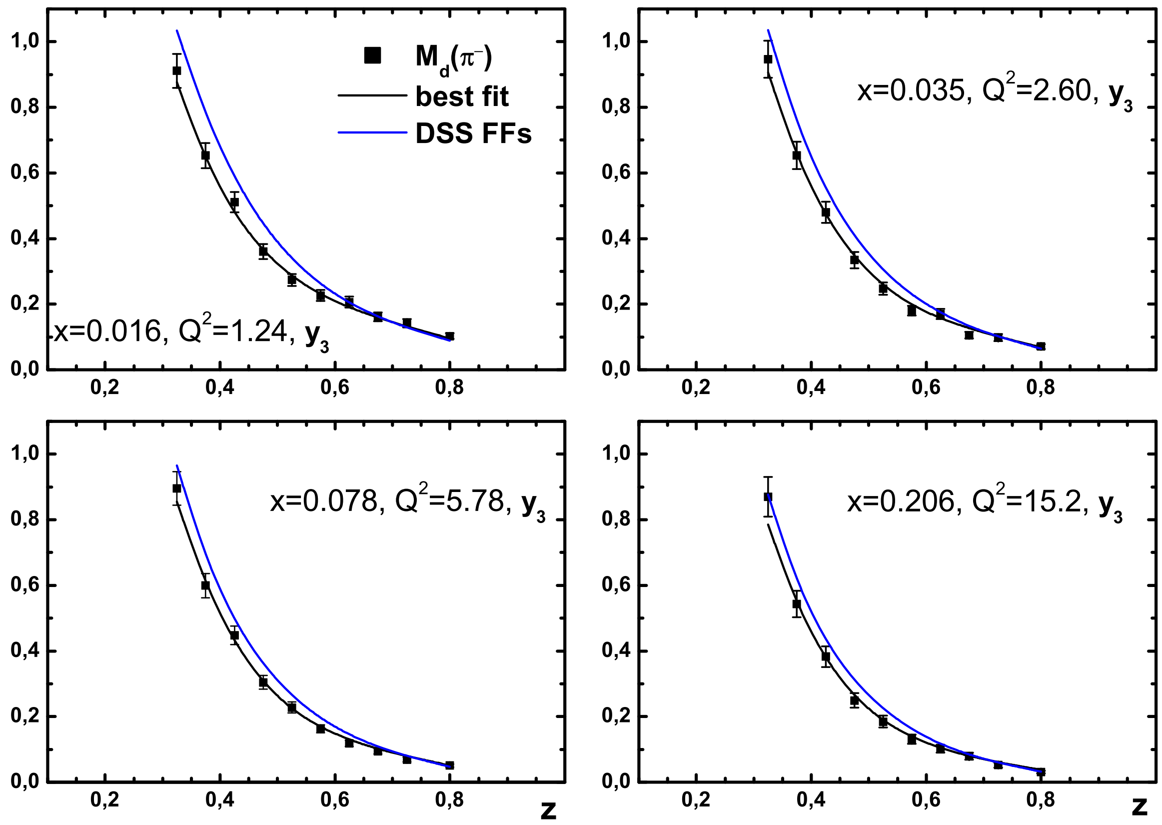


M_d(π⁻)
LSS13
x=0.0088, Q²=1.14, y₄
x=0.014, Q²=1.65, y₄
x=0.025, Q²=2.81, y₄
x=0.035, Q²=3.94, y₄
x=0.049, Q²=5.55, y₄
x=0.076, Q²=8.39, y₄
x=0.120, Q²=13.1, y₄
x=0.206, Q²=22.3, y₄
z

Comparison of our NLO QCD results for COMPASS π^+ multiplicities (black curves) with the data. Blue curves correspond to the multiplicities at COMPASS kinematics computed with the DSS FFs.

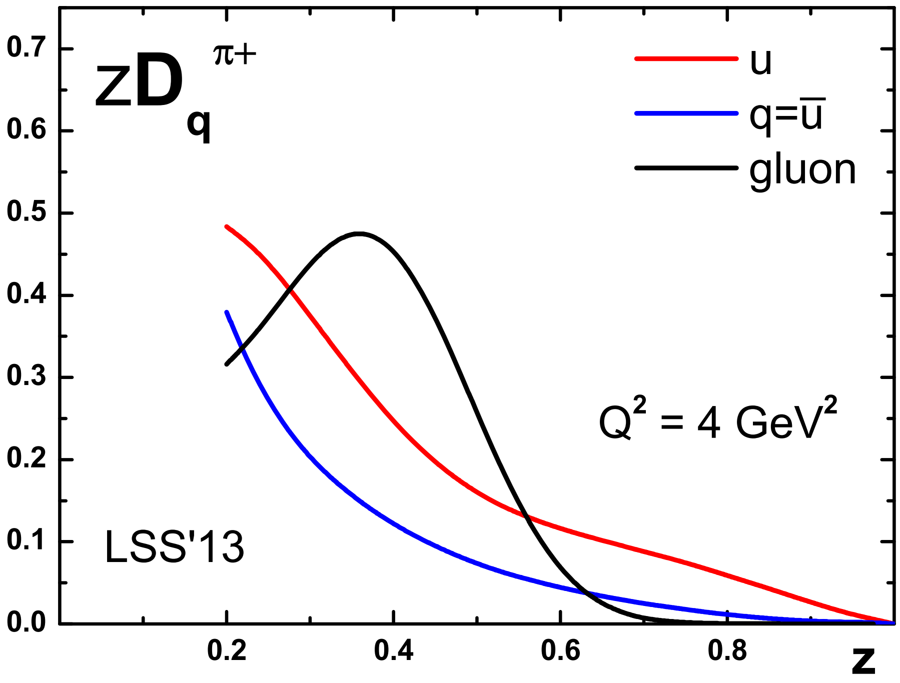


Comparison of our NLO QCD results for COMPASS π^- multiplicities (black curves) with the data. Blue curves correspond to the multiplicities at COMPASS kinematics computed with the DSS FFs.



The DSS FFs are in disagreement with the COMPASS data !

NLO LSS’2013 pion FFs extracted from the *COMPASS* data



HERMES/(p,d) data on pion multiplicities (*Phys.Rev. D87 (2013) 074029*)

72 π^+ and π^- data points for a proton as well as for a deuteron target

Total: 144 exp. points in 4 z-bins: [0.2 - 0.3; 0.3 - 0.4; 0.4 - 0.6; 0.6 - 0.8]

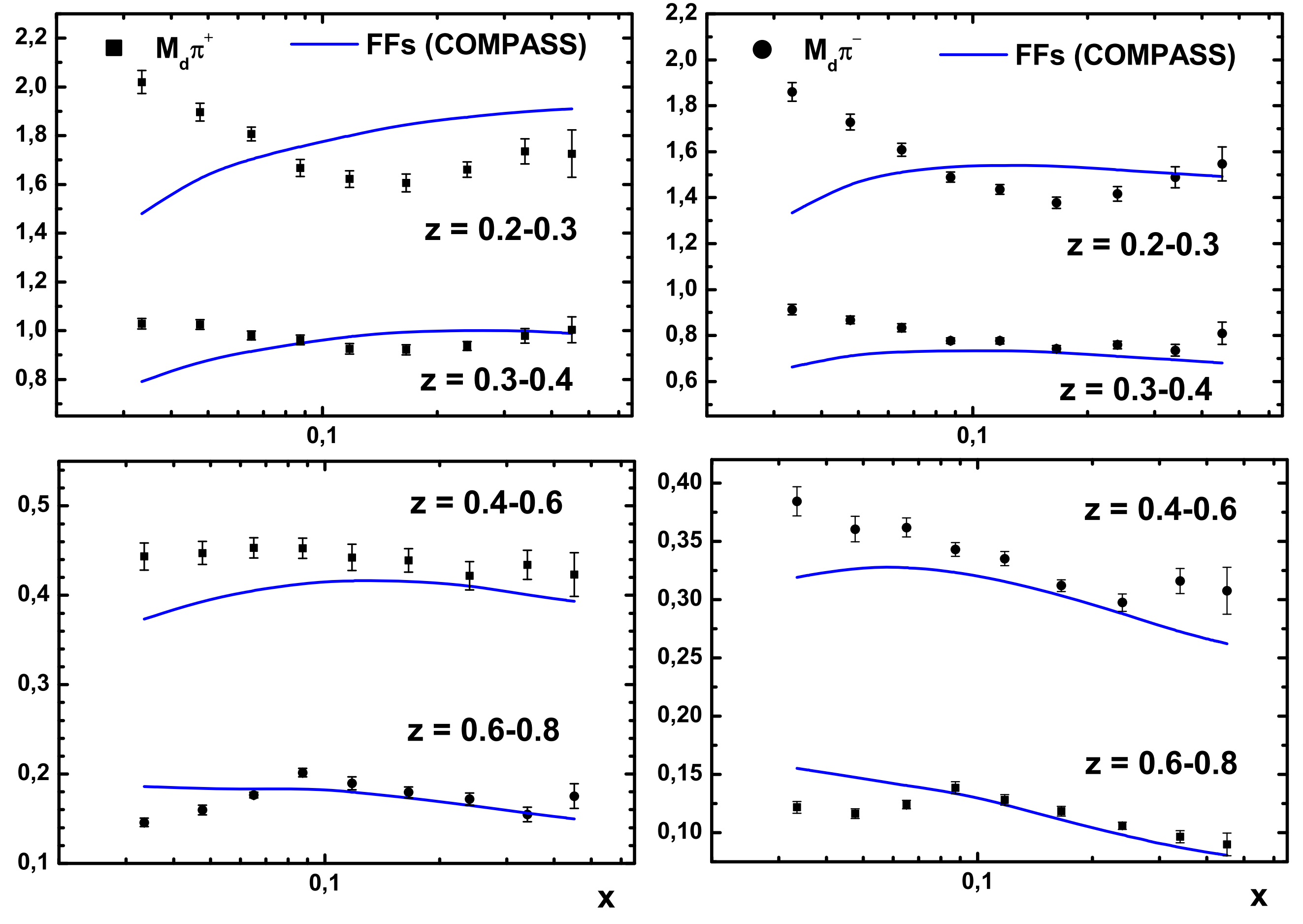
submitted in $[x(Q^2), z]$ as well as in $[Q^2(x), z]$ presentation

! We can not find a reasonable fit to the HERMES $[x(Q^2), z]$ pion data !

There are also indications that the HERMES $[x(Q^2), z]$ and COMPASS data are not consistent

Pion multiplicities at HERMES *[x(Q²), z]* kinematics computed with the FFs determined from the analysis of COMPASS data (LSS'13)

χ^2/point $(M_d^{\pi+}) = 21.1$ χ^2/point $(M_d^{\pi-}) = 23.0$



The situation is essentially changed if

the HERMES [$Q^2(x), z$] data on pion multiplicities

are used in the QCD analysis ??!!

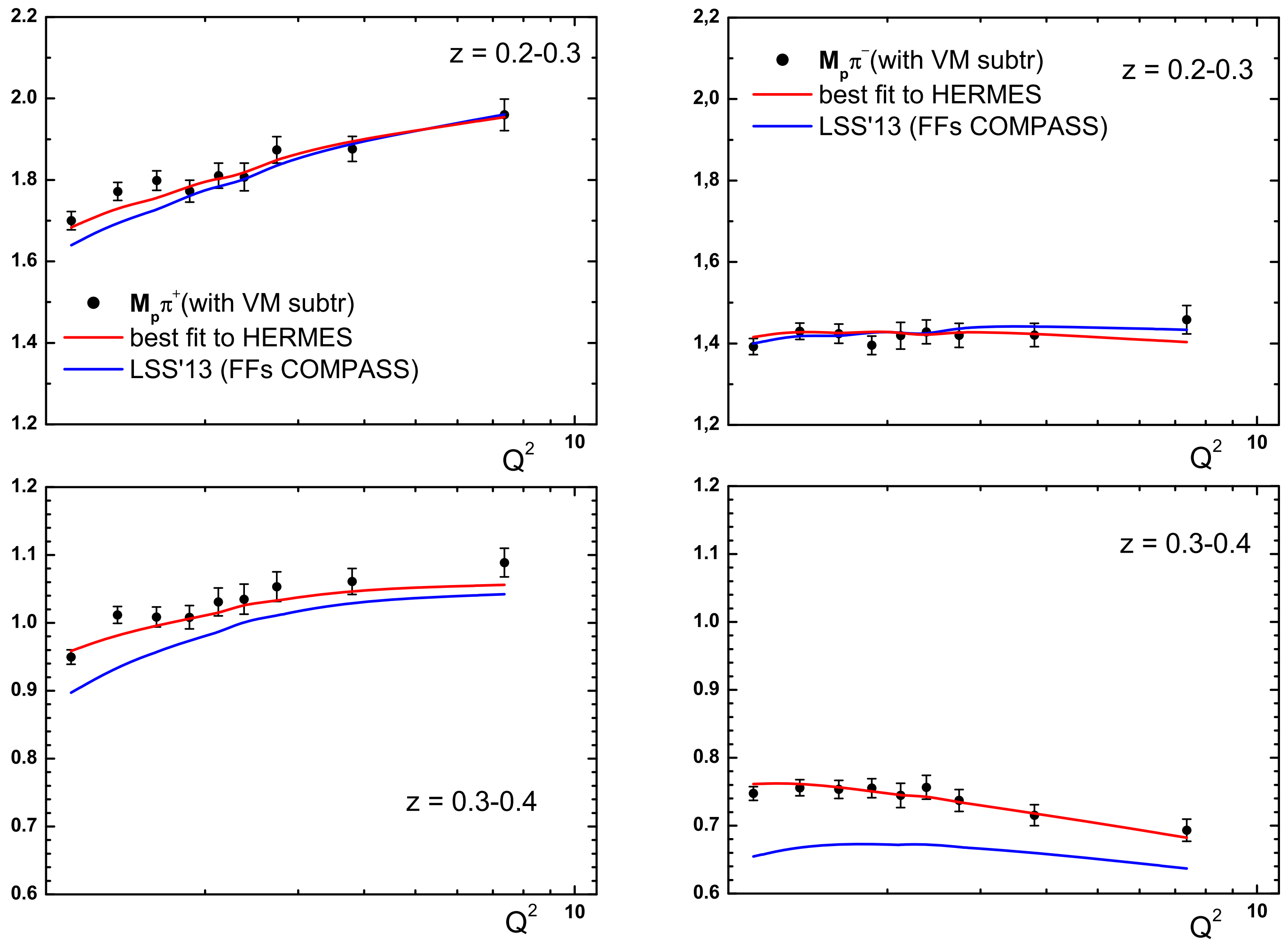
NLO QCD fit to HERMES/p,d data on multiplicities [(Q^2, z) presentation]

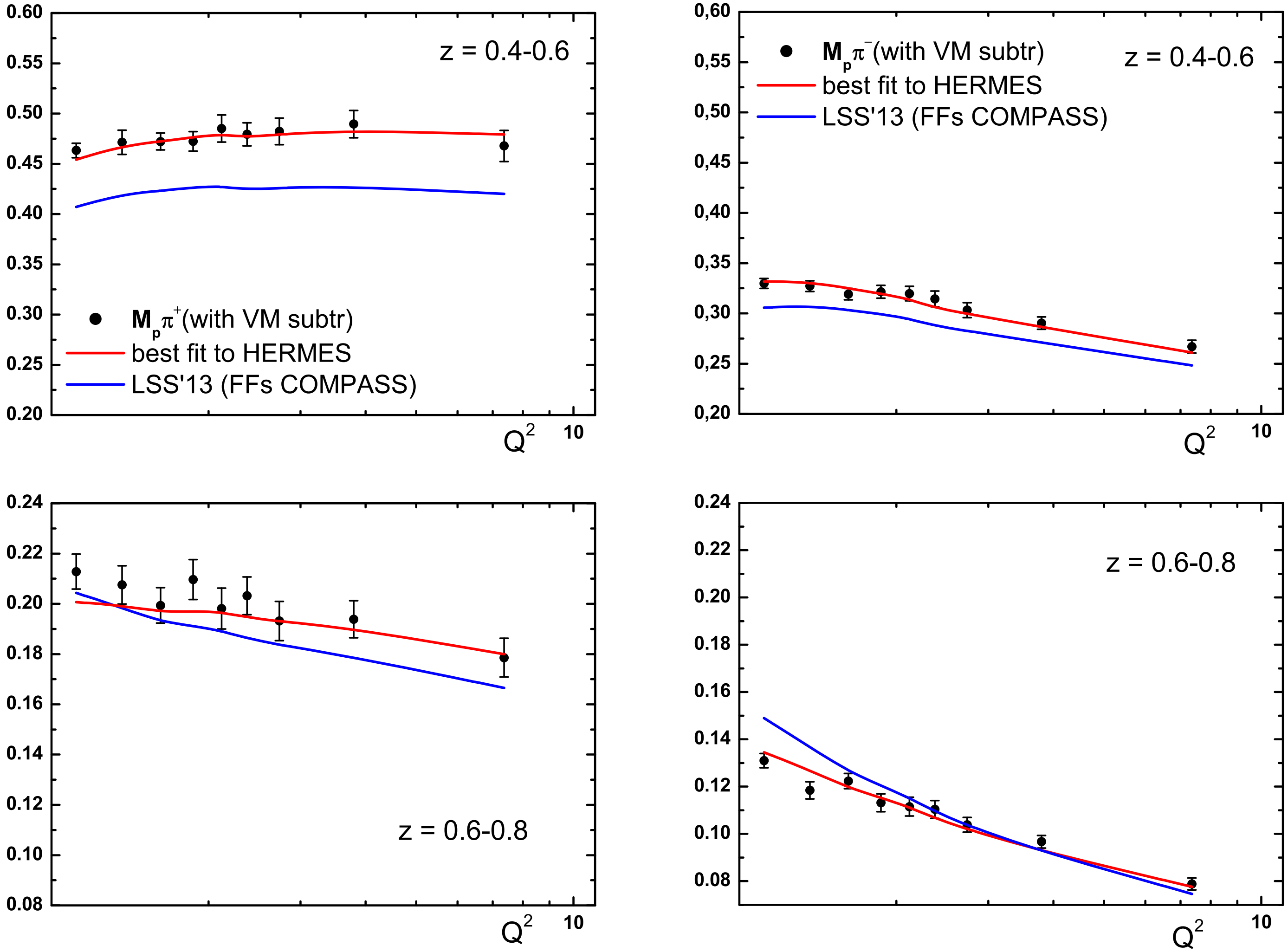
A good description of the data is achieved !

Proton target

χ^2/point ($M_p^{\pi+}$) = 0.87

χ^2/point ($M_p^{\pi-}$) = 0.75

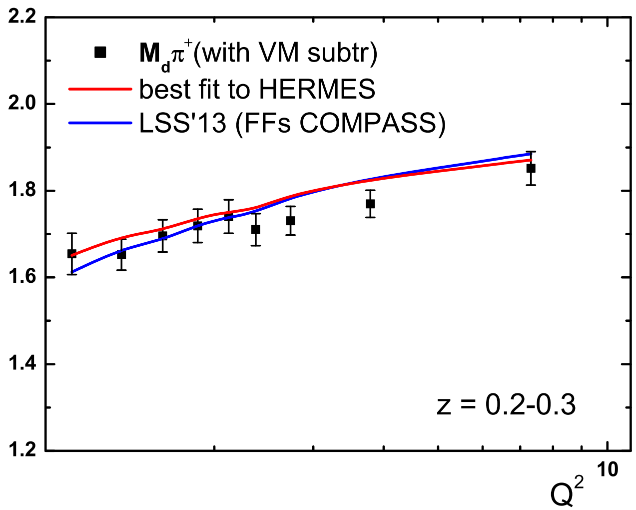


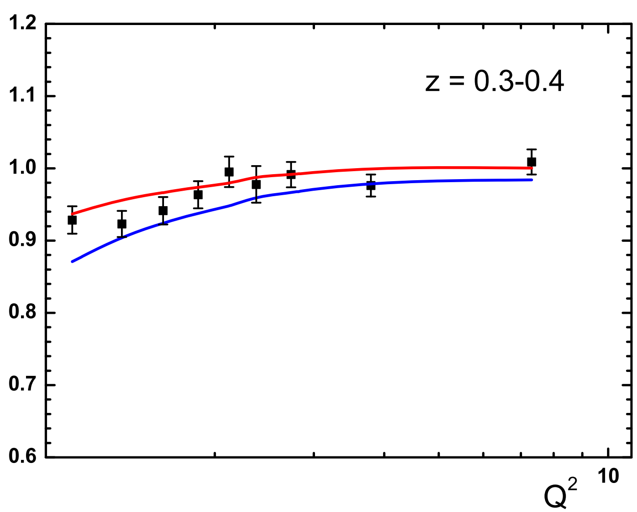


0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
z = 0.4-0.6
Mpπ+(with VM subtr)
best fit to HERMES
LSS'13 (FFs COMPASS)
Q2
10
0,60
0,55
0,50
0,45
0,40
0,35
0,30
0,25
0,20
Mpπ−(with VM subtr)
best fit to HERMES
LSS'13 (FFs COMPASS)
z = 0.4-0.6
Q2
10
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
z = 0.6-0.8
Q2
10
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
z = 0.6-0.8
Q2
10

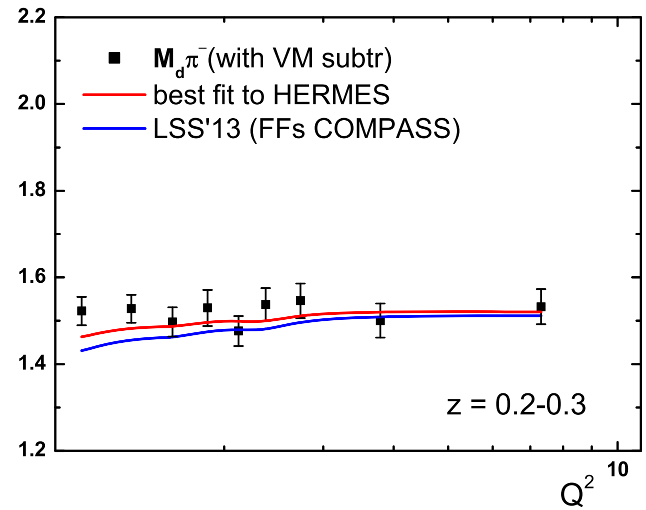
Deuteron target

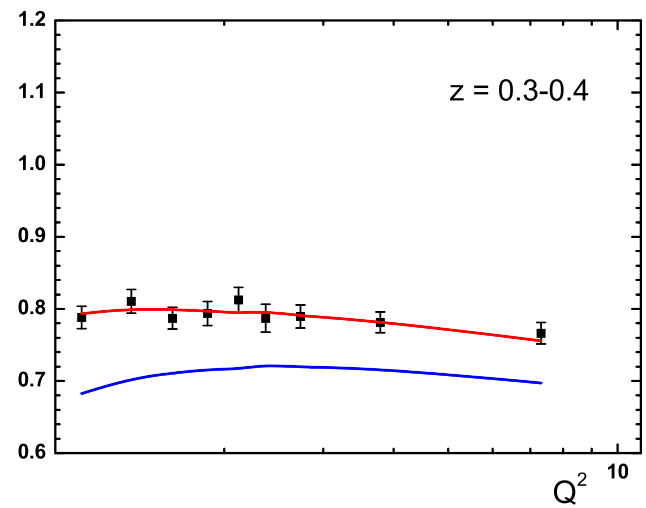
χ^2/point ($M_d^{\pi+}$) = 1.02

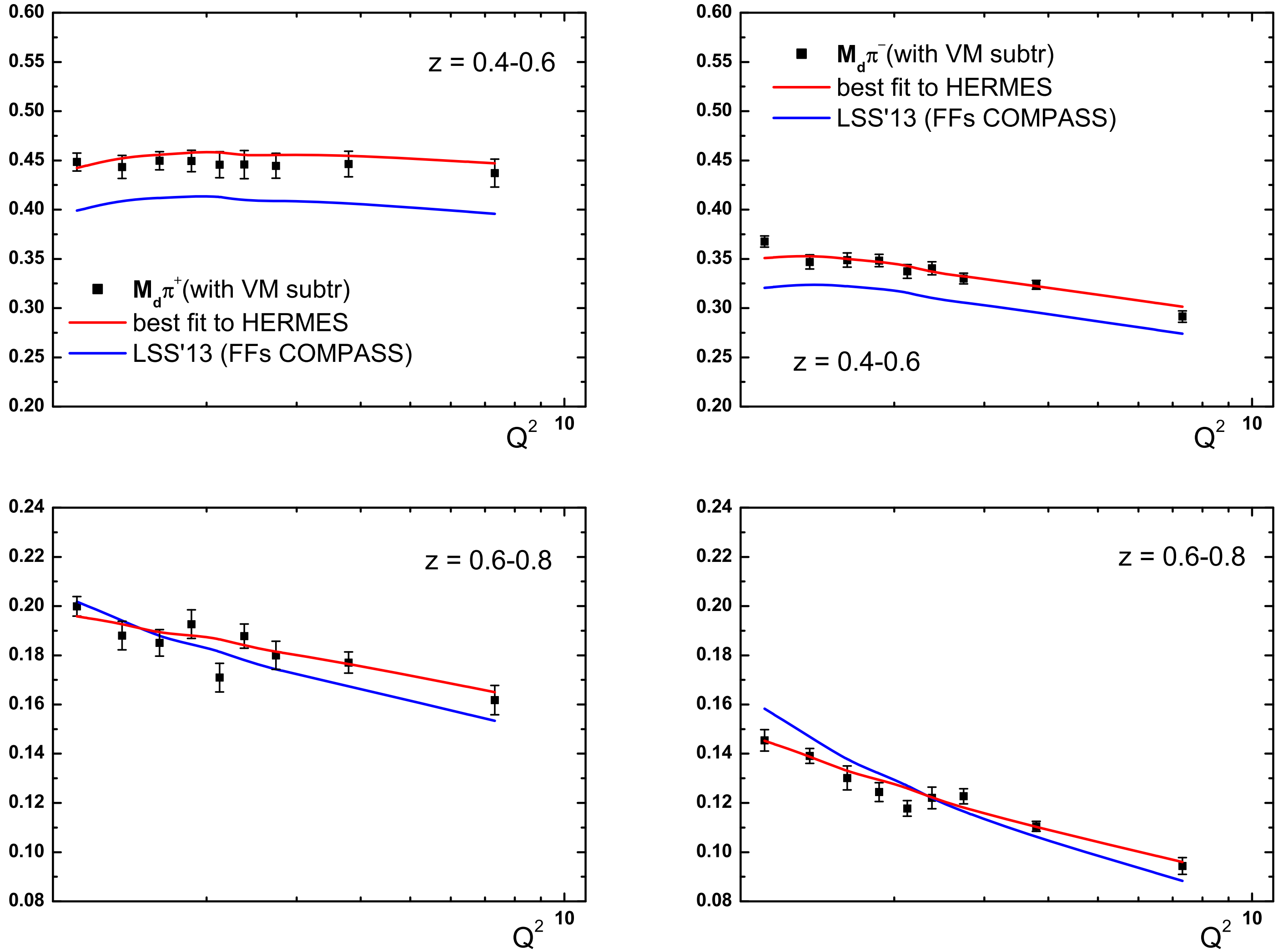




χ^2/point ($M_d^{\pi-}$) = 1.04



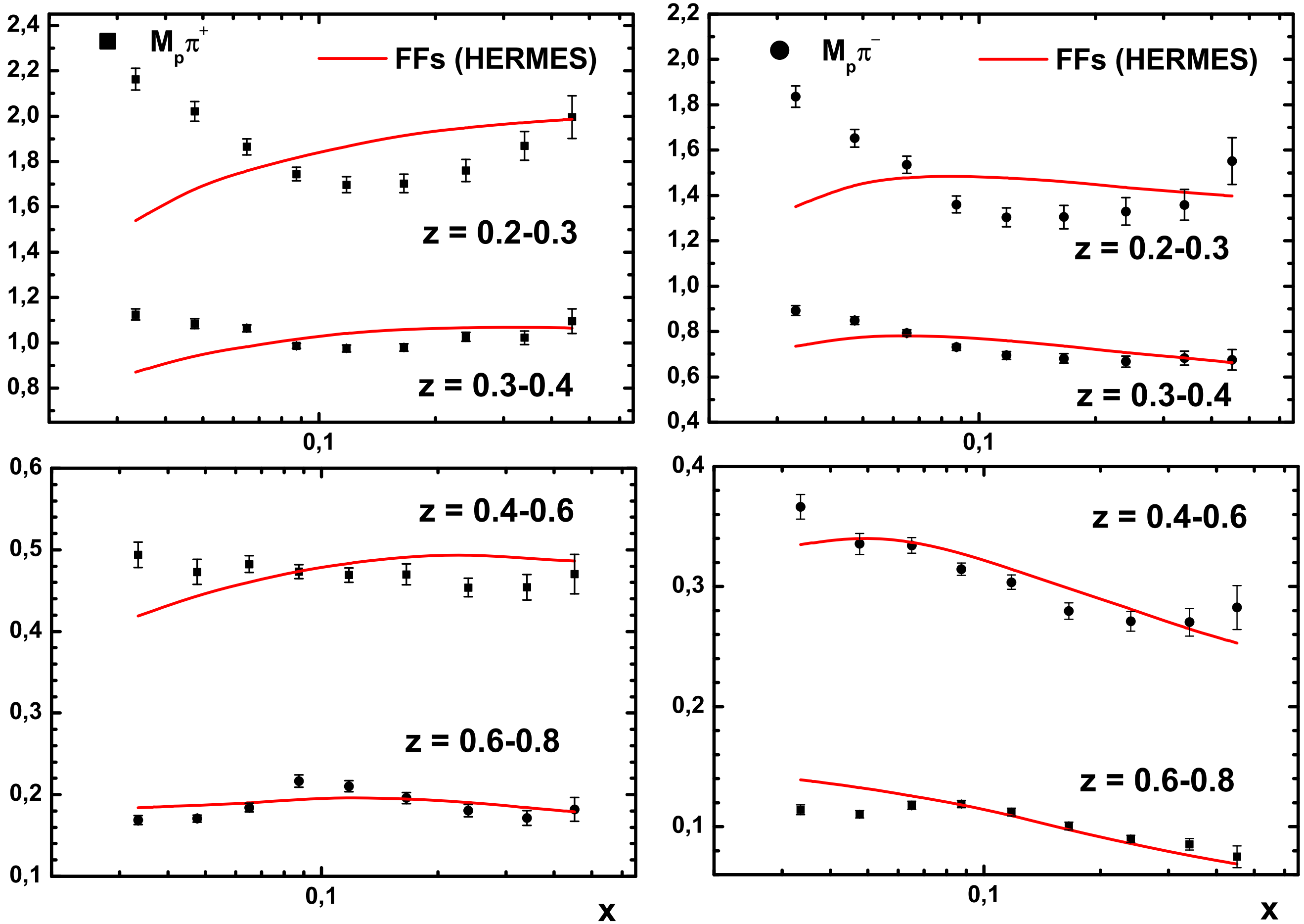




z = 0.4-0.6
$M_d\pi^+$(with VM subtr)
best fit to HERMES
LSS'13 (FFs COMPASS)
$M_d\pi^-$(with VM subtr)
best fit to HERMES
LSS'13 (FFs COMPASS)
z = 0.4-0.6
z = 0.6-0.8
z = 0.6-0.8
Q^2
10

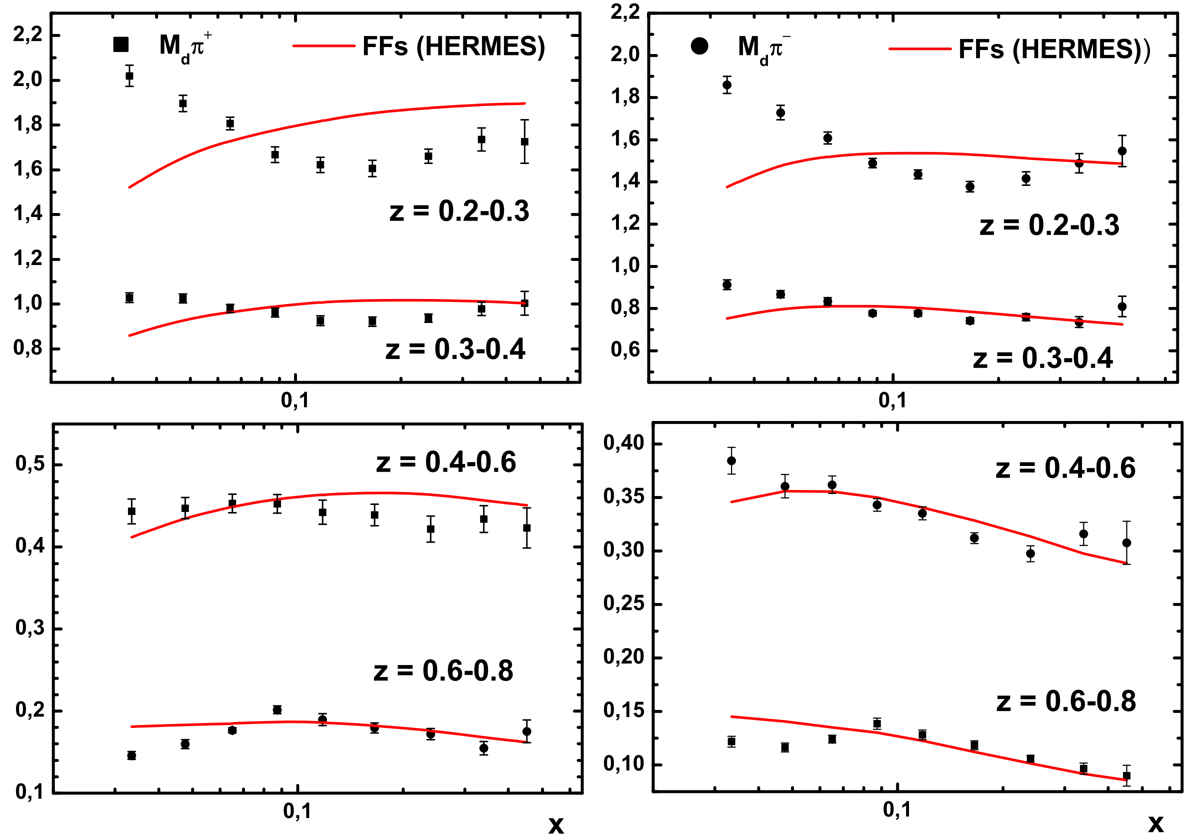
Pion multiplicities at HERMES *[x(Q^2), z]* kinematics computed with the FFs determined from the analysis of HERMES *[Q^2(x), z]* data

Proton data



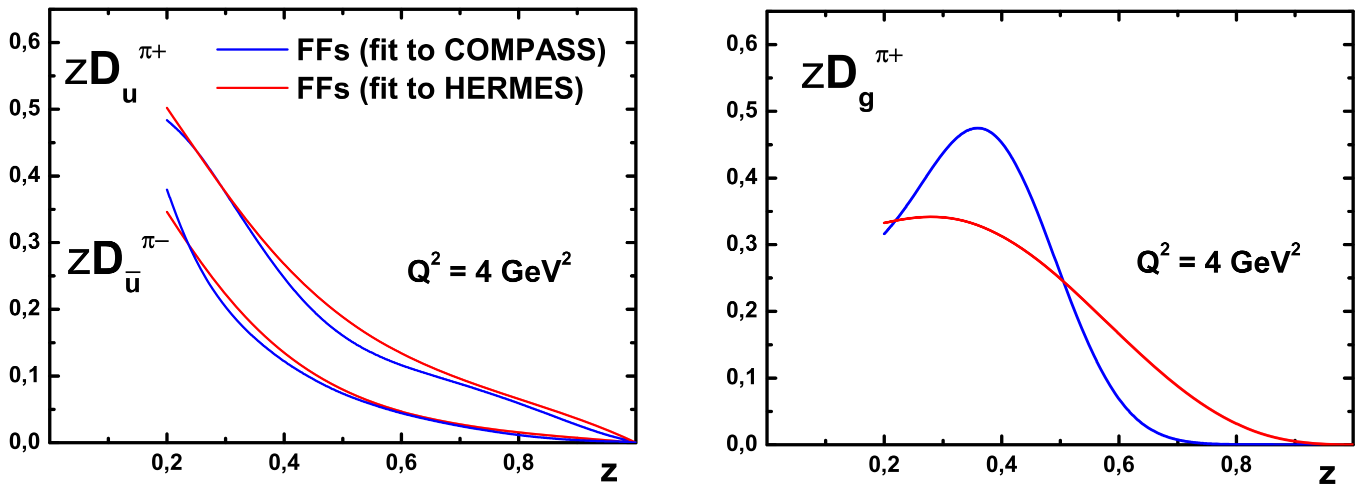
Pion multiplicities at HERMES *[x(Q²), z]* kinematics computed with the FFs determined from the analysis of HERMES *[Q²(x), z]* data

Deuteron data



There is a strong indication that the *[x, z]* and *[Q2, z]* presentations of the HERMES data on the pion multiplicities are not equivalent and lead to different physical results ?!

Comparison between FFs (COMPASS) and FFs (HERMES)

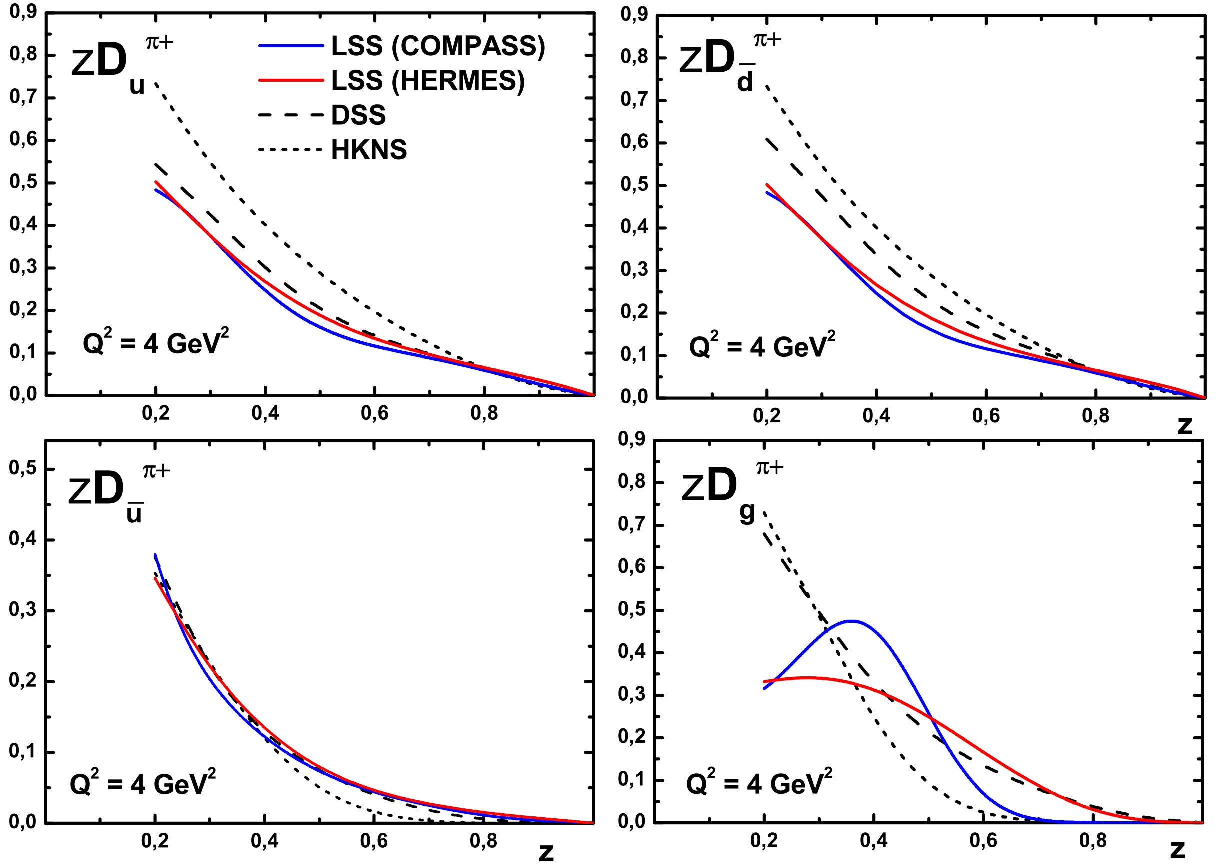


- A **visible** difference in the z region [0.4-0.6] between the **favored** FFs
- A **large** difference between the **gluon** FFs

Comparison between the new pion FFs and those of DSS and HKNS

DSS: SU(2) is broken for favored FFs $(D_u^{\pi+} \neq D_{\bar{d}}^{\pi+})$

LSS, HKNS: SU(2) is assumed



The new pion FFs differ from those of DSS and HKNS obtained before these data were available

SUMMARY

- A good NLO QCD fit to COMPASS pion data is achieved

- A good NLO QCD fit to HERMES $[Q^2(x), z]$ pion data is also achieved

  → a new sets of pion FFs

- There is a strong indication that the $[x(Q^2), z]$ and $[Q^2(x), z]$ presentations of the HERMES data on the pion multiplicities are not equivalent → answer to this question is required !!!

Combined fits to the COMPASS and HERMES $[Q^2, z]$ data on pion multiplicities are under way. The results will answer the important question if the two data sets are or not consistent.