COMPASS Semi-inclusive measurement of hadron multiplicities

in muon-deuteron deep inelastic scattering

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On behalf of the COMPASS Collaboration

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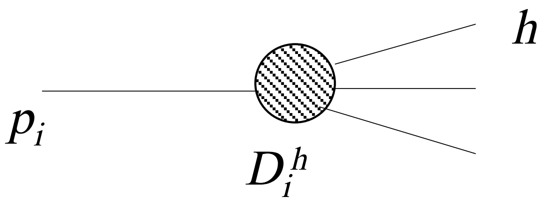
Motivation: Fragmentation Functions

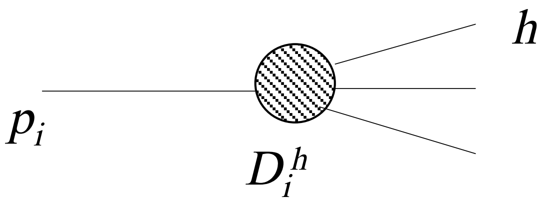
- Fragmentation functions (FF) describe parton fragmentation into hadron



- Relevant any time a final-state hadron is produced in high energy collisions
- Key ingredient in the flavor-separation of polarised parton distributions Δq
- Fundamental role in understanding single spin asymmetries, transversity (h_1)…
- Accessible in different processes

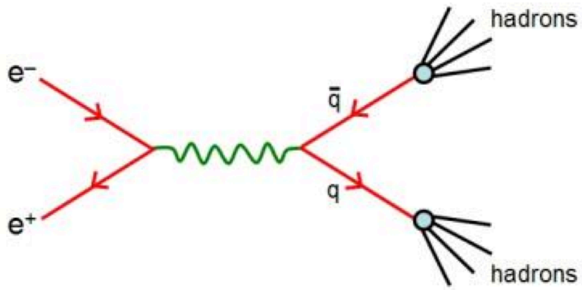
Fragmentation Functions

✧ Fragmentation functions (FF) describe parton fragmentation into hadron



✧ Accessible in different processes:

e^+e^- annihilation



✧ Clean process (only FFs enter)

✧ Very precise data (LEP/ SLD, BELLE, BABAR,…)

✧ only sensitive to $q + \bar{q}$ FF

Fragmentation Functions

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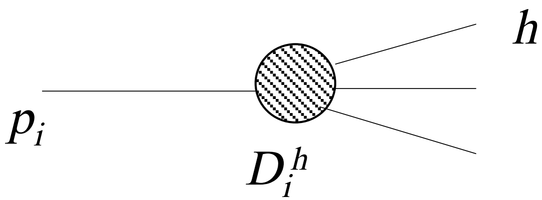

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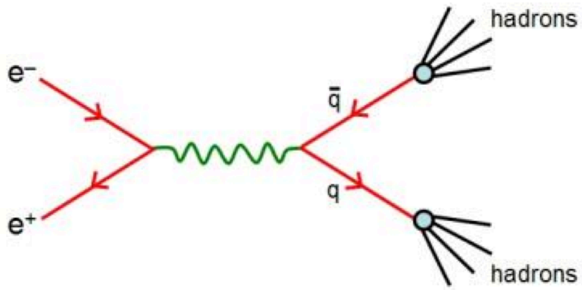

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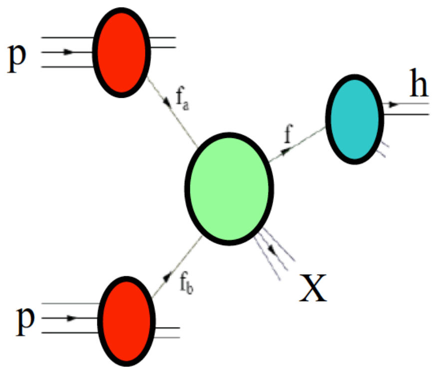
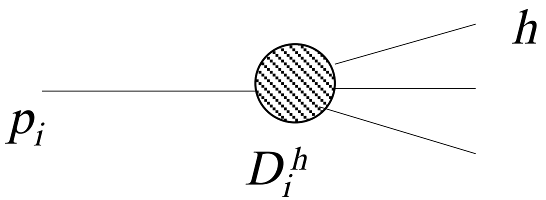


- ✧ Highly sensitive to gluon FF (high p_T hadron production)
- ✧ Large dependence on PDFs

Fragmentation Functions

- Fragmentation functions (FF) describe parton fragmentation into hadron



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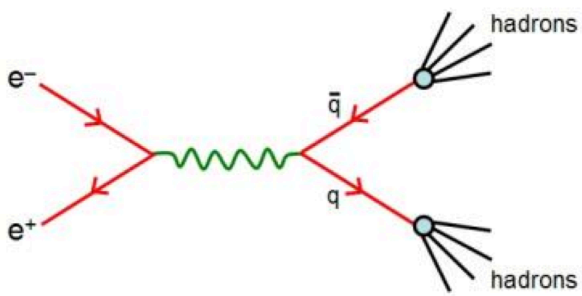

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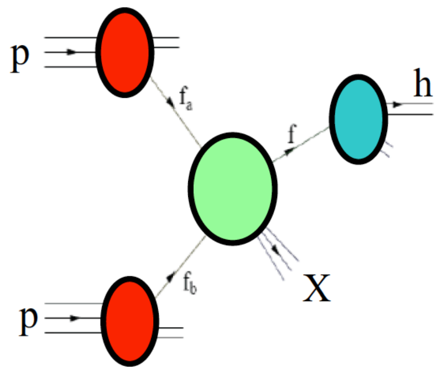

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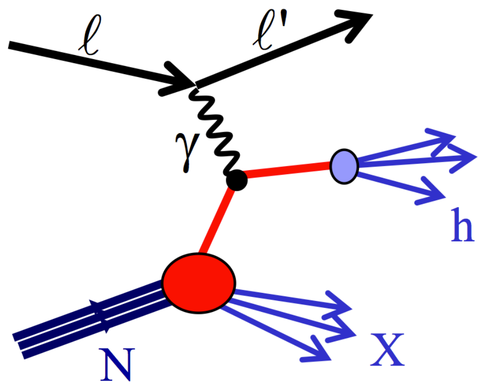
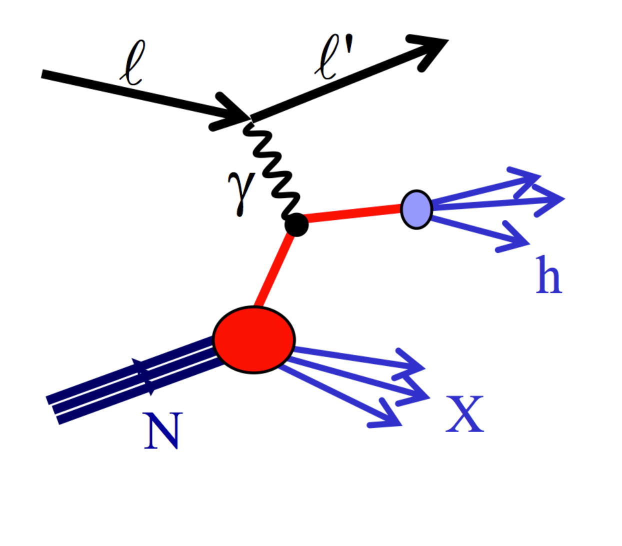
SIDIS



SIDIS data are crucial to understand quark fragmentation mechanism

Semi-Inclusive DIS

SIDIS: a powerful tool to study $q \rightarrow h$ fragmentation



- Assess PDFs/FFs
- Flavor/charge separation
- wide scale coverage
- Nuclear target provide laboratory for fragmentation in nuclear medium
- Relevant for spin physics kinematic

PDFs

FFs

$$d\sigma^{\ell p \rightarrow \ell h X} \sim \sum_q e_q^2 f_q(x, Q^2) \cdot d\sigma^{\ell q \rightarrow \ell q} \cdot D_q^h(z, Q^2)$$

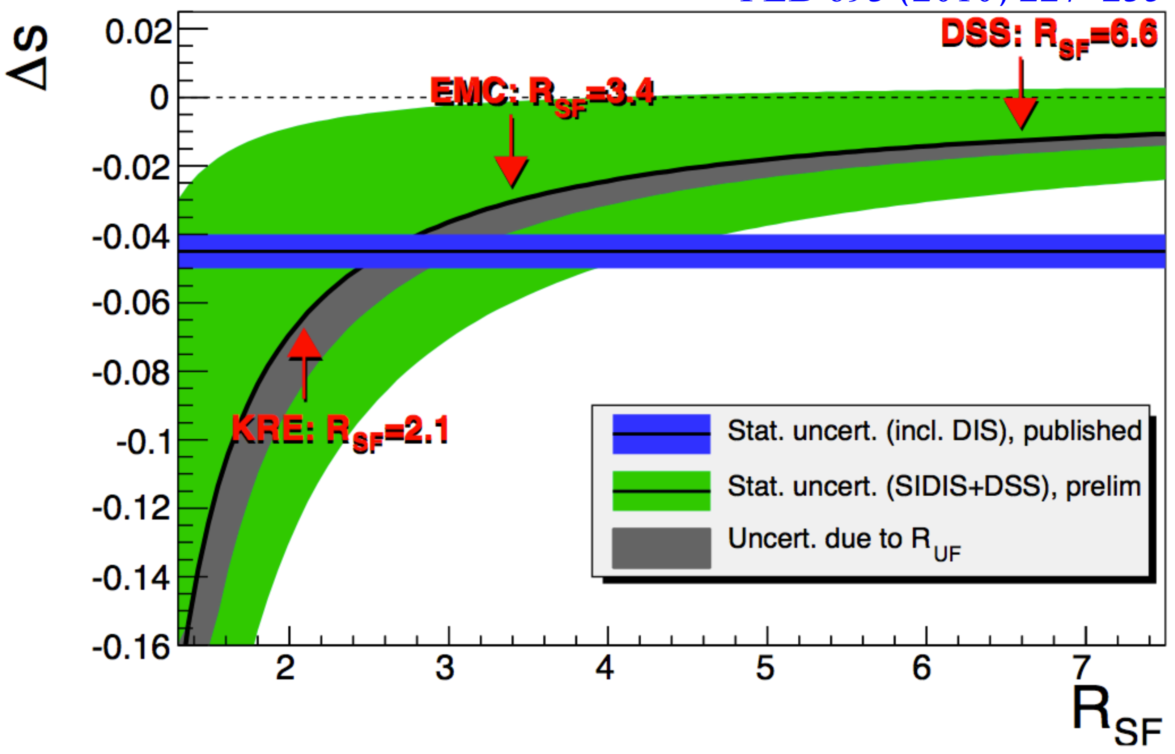
Polarised parton distributions

Strange sea quark polarisation

- ΔS obtained from fits to g_1 data (SU(3) symmetry) is negative
- SIDIS *K* data prefer zero or positive value at middle x values
- However SIDIS *K* data strongly depends upon the choice of strange quark FF – D_S^K

Different FFs ➔ different results for ΔS

PLB 693 (2010) 227–235



$$= \frac{D_s^{K+}}{D_u^{K+}}$$

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Different FFs ➔ different results for ΔS

Transversity

Single hadron production: $$A_{Coll} \approx \frac{\sum_q e_q^2 h_1^q \otimes H_{1q}^{\perp}}{\sum_q e_q^2 f_1^q \otimes D_q}$$

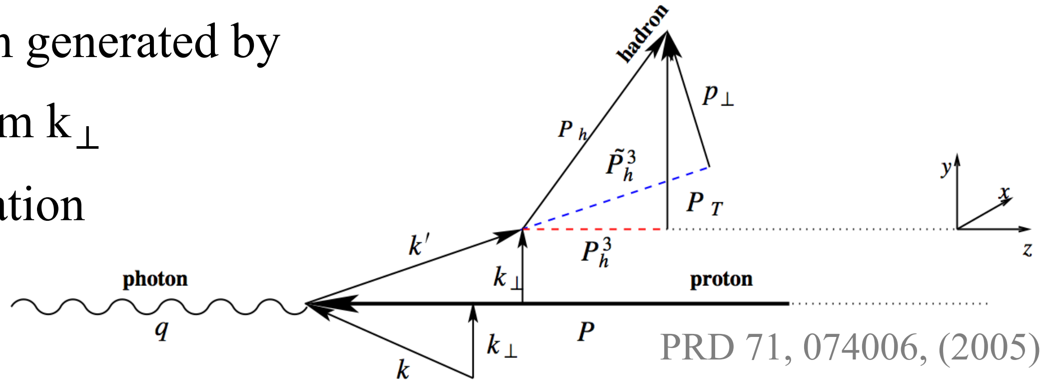
hadron pair production: $$A_{2h} \approx \frac{\sum_q e_q^2 h_1^q \otimes H_{1q}^{\angle}}{\sum_q e_q^2 f_1^q \otimes D_q^{2h}}$$

Spin-independent dihadron FF
Only existing values yet are evaluated in MC

Beyond collinear case

Transverse Momentum Dependence

- ✧ Transverse momenta of final-state hadron generated by
  - ⇒ Quark intrinsic transverse momentum $k_\perp$
  - ⇒ $p_\perp$ generated in the quark fragmentation



PRD 71, 074006, (2005)

TMD PDFs TMD FFs

$$d\sigma^{\ell p \to \ell h X} \sim \sum_q e_q^2 f_q(x, Q^2, \boldsymbol{k}_\perp) \otimes d\sigma^{\ell q \to \ell q} \otimes D_q^h(z, Q^2, \boldsymbol{p}_\perp)$$

- ✧ A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to

$$\langle p_T^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$$

Final-state hadron transverse momentum

Hadron Multiplicity

Hadron Multiplicities are defined as observed number of hadrons in a number of DIS events

$$\frac{d^2 M^h(x, Q^2, z, p_T^2)}{dz\, dp_T^2} = \frac{d^4\sigma^h(x, Q^2, z, p_T^2)/\, dx\, dQ^2\, dz\, dp_T^2}{d^2\sigma(x, Q^2)/\, dx\, dQ^2}$$

quark FFs

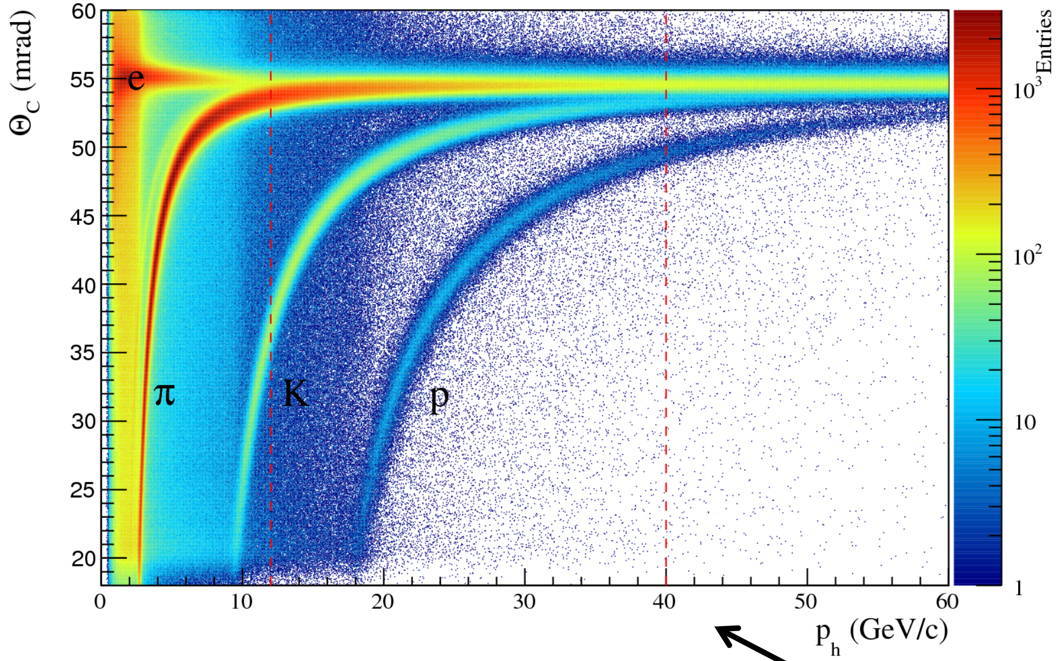
$$= \frac{\sum_q e_q^2 f_q(x, Q^2, k_\perp) D_q^h(z, Q^2, p_\perp)}{\sum_q e_q^2 f_q(x, Q^2, k_\perp)}$$

quark PDFs

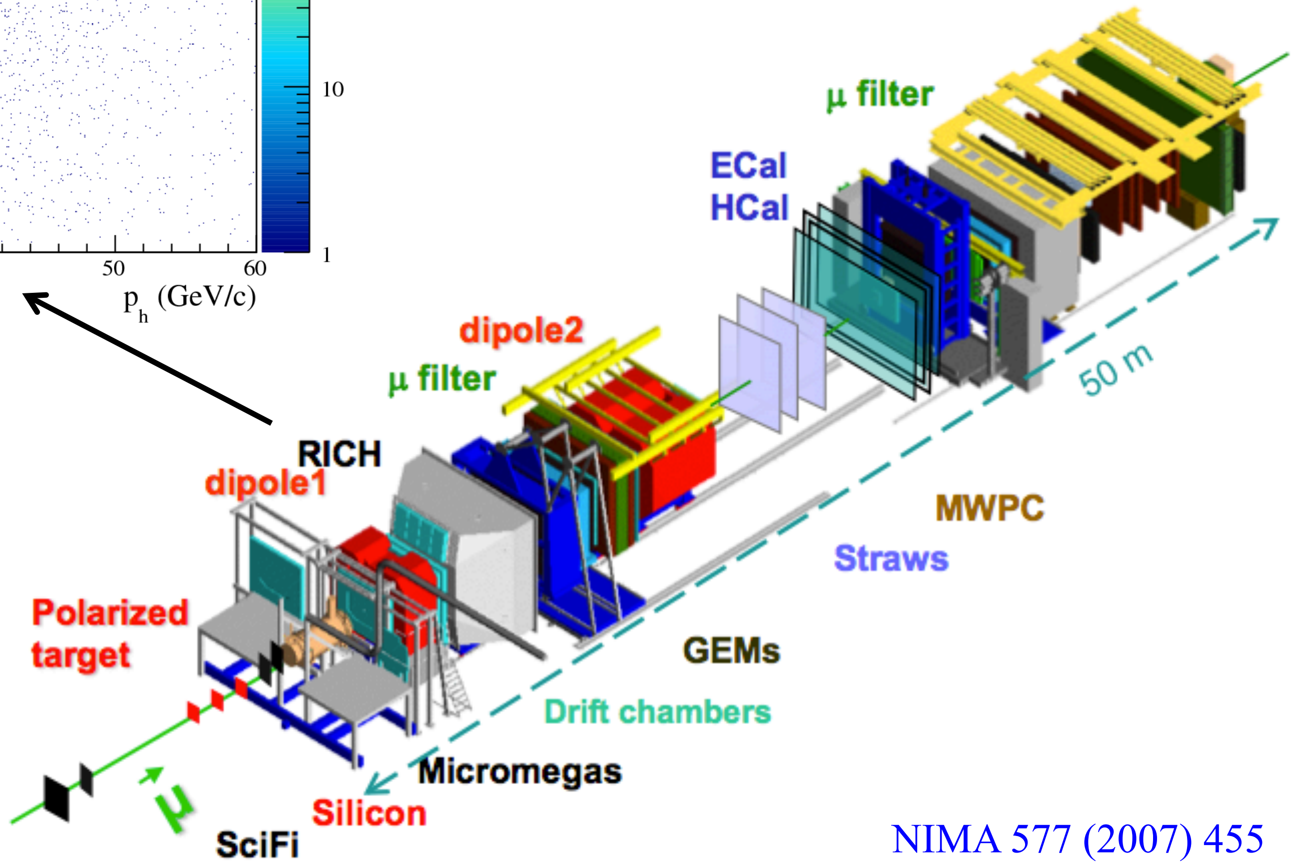
Experimentally measured multiplicity must be corrected for many effects as

- Spectrometer acceptance
- RICH efficiency and purity
- Radiative effects
- Diffractive vector meson production

COMPASS Spectrometer



- Fixed-target
- Polarised muon beam & polarised targets p&d



Excellent discrimination between π, K, p using RICH

This analysis:
160 GeV μ^+ beam
1.2 m long polarised ^{6}LiD isoscalar target (2006)

NIMA 577 (2007) 455

Quark fragmentation into single hadron

Multi-dimensional p_T-integrated multiplicities

Charged pion multiplicity results

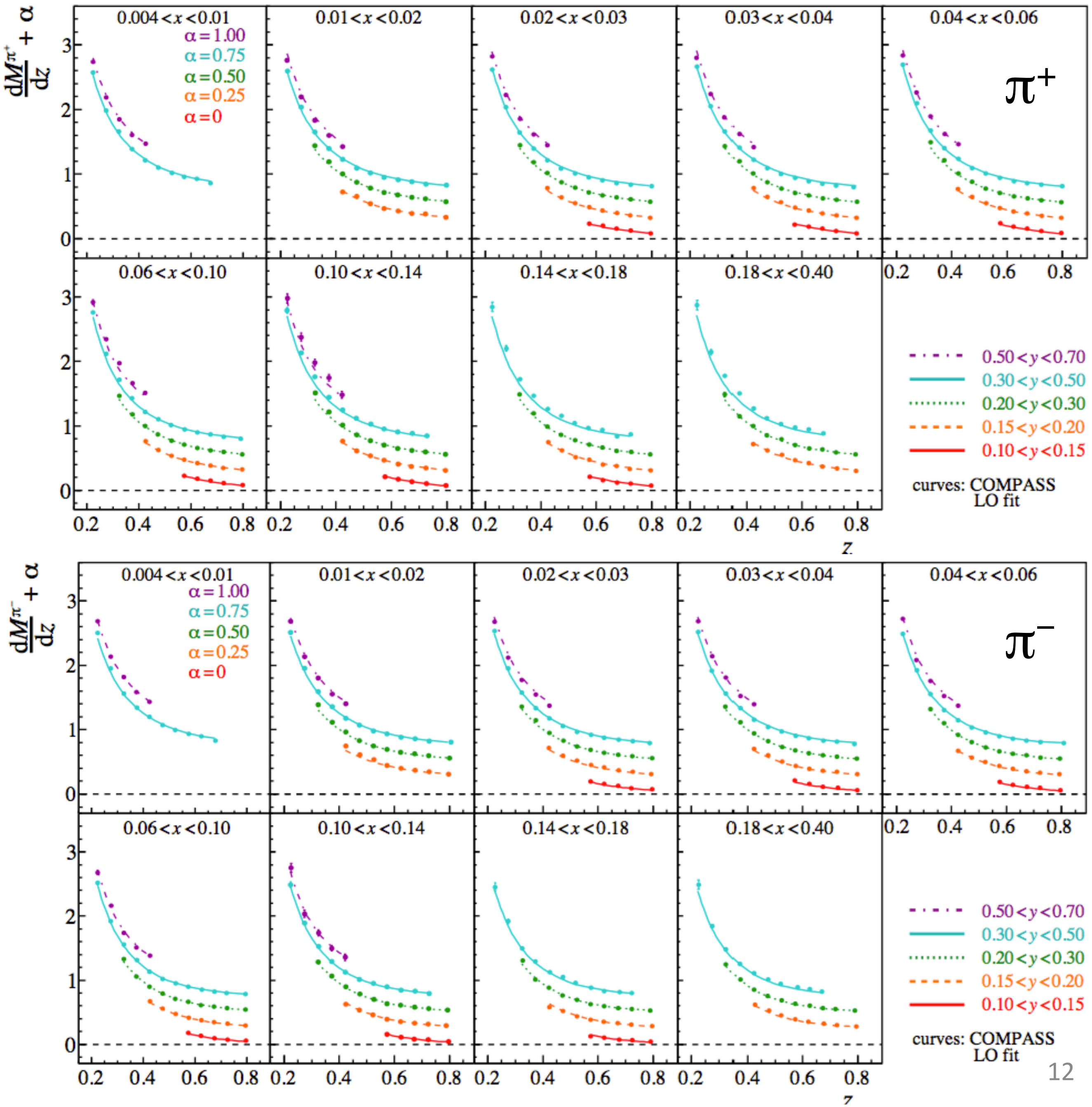
3-D kinematic binning
in *x*, *y*, and *z*

- ✧ 317 kinematic bins
- ✧ Strong z dependence
- ✧ Preliminary data (only 189 kinematic bins) were used in DSS++ fit of FFs
- ✧ LO fit to COMPASS data only: Results agree with world FFs

- ✧ Paper submitted to PLB

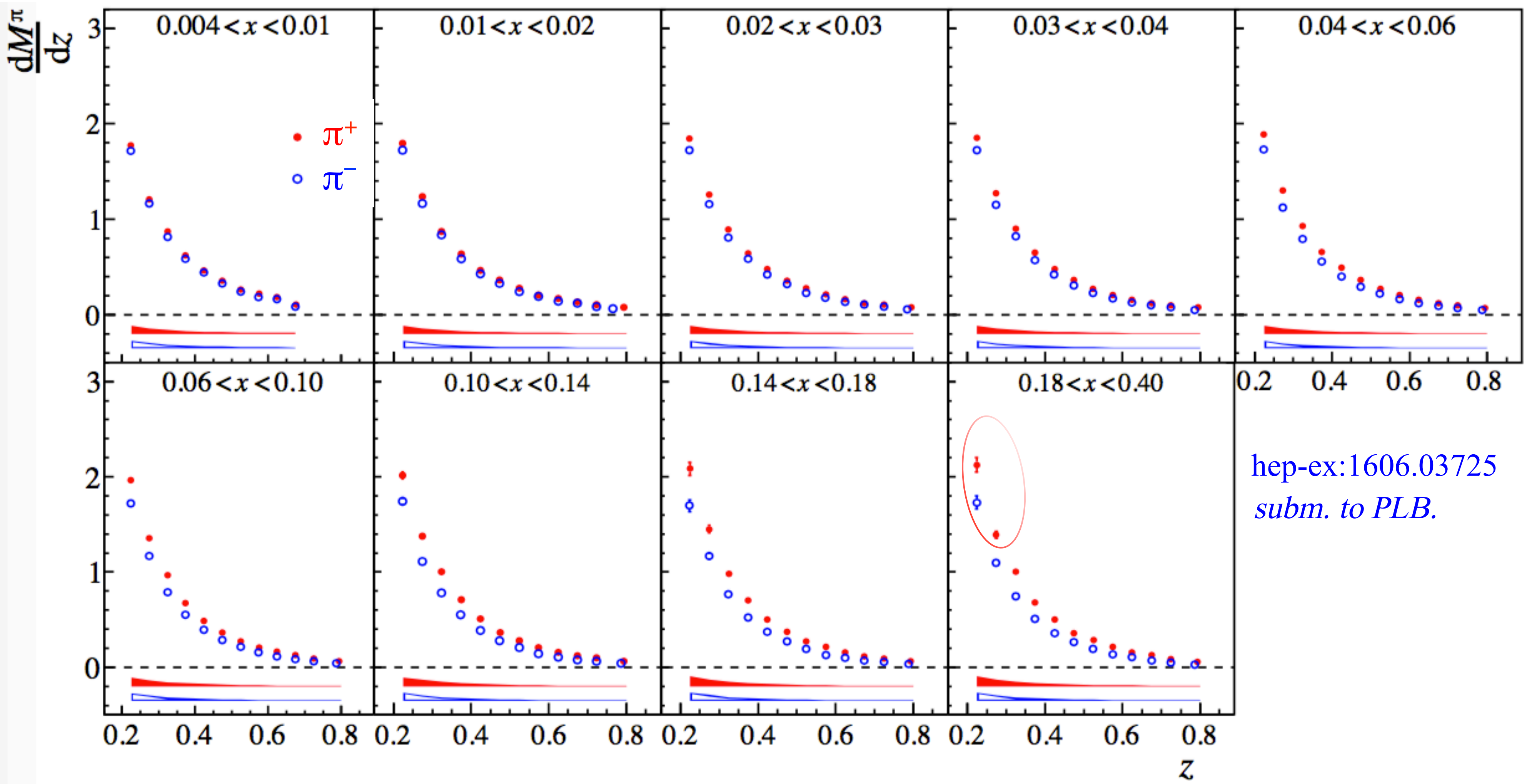
  hep-ex:1606.03725

- ✧ Serve as inputs for future NLO QCD analyses of FFs



Charged pion multiplicity results

2-D projection in *x*,*z*



hep-ex:1606.03725
subm. to PLB.

⇒ reflects valence structure of produced mesons

Pion multiplicity sum

For the isoscalar target, when expressed at LO the sum is:

$$M^{\pi^+ + \pi^-} = \underbrace{D_{fav} + D_{unf}}_{\text{z-dep.}} - \underbrace{\frac{2(s+\bar{s})}{5(u+\bar{u}+d+\bar{d})+2(s+\bar{s})}}_{\text{x-dep.}} \underbrace{(D_{fav} - D_{unf})}_{\text{z-dep.}}$$

D_q is favoured if the quark flavour is a valence quark in the hadron

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z-dependent term

very small ➔ neglected

➔ $\int_{0.2}^{0.85} M^{\pi^+ + \pi^-} dz$ is expected to be almost flat vs. x

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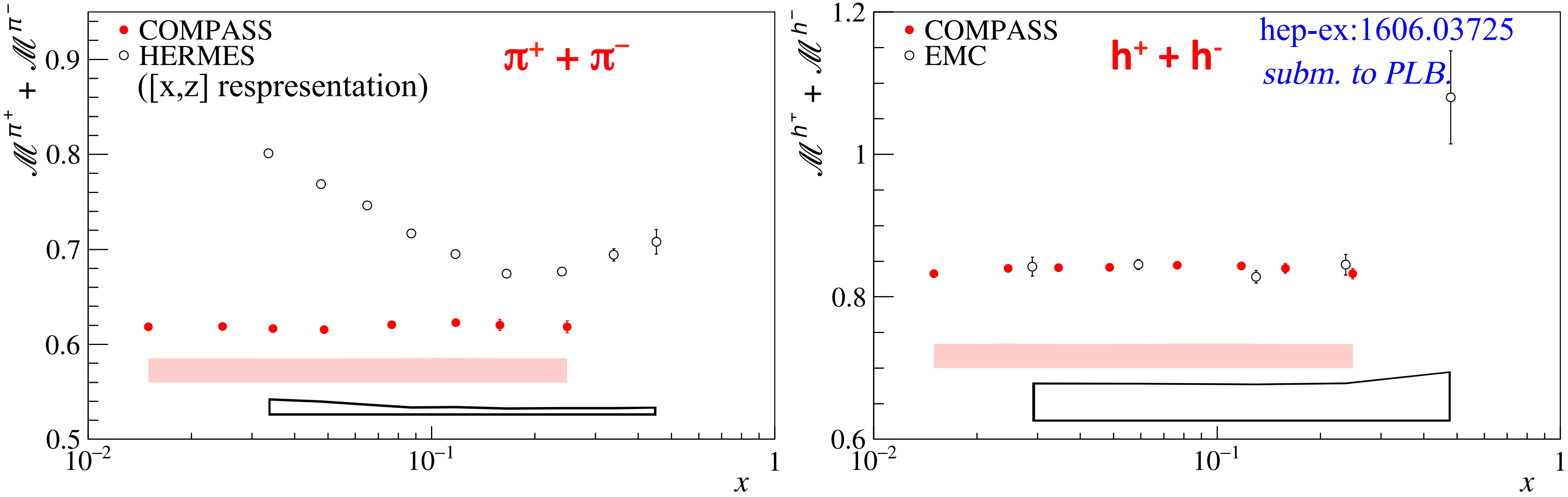
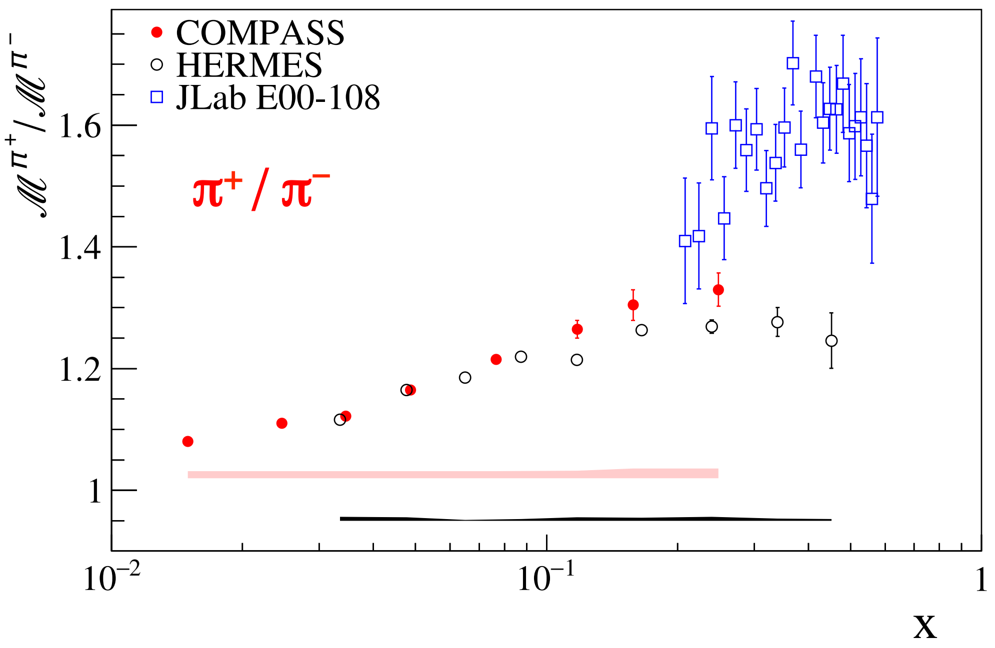
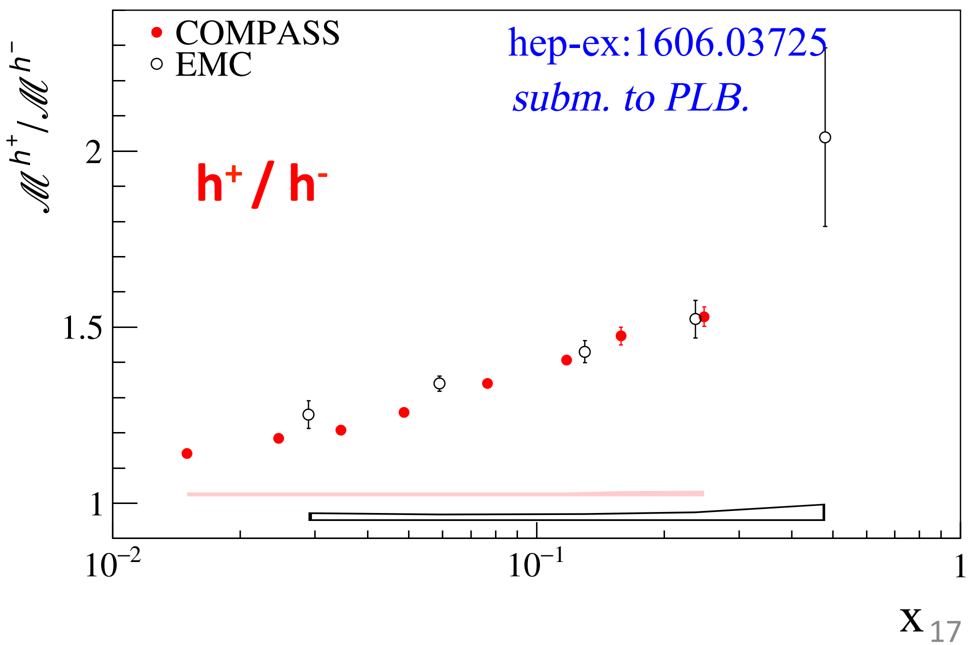


no x-dependence observed neither in COMPASS nor in EMC data as expected from LO predictions, at variance with HERMES data

π^+/π^- multiplicity ratio

- ✧ Interesting observable (π^+/π^- , h^+/h^-) because of cancellation of most of experimental systematic uncertainties
- ✧ Excellent agreement between COMPASS and EMC for charged hadrons, similar kinematic ranges covered by both experiments
- ✧ Reasonable agreement between COMPASS and HERMES results despite the discrepancy observed in the sum
- ✧ Tension between HERMES and JLab observed at high x

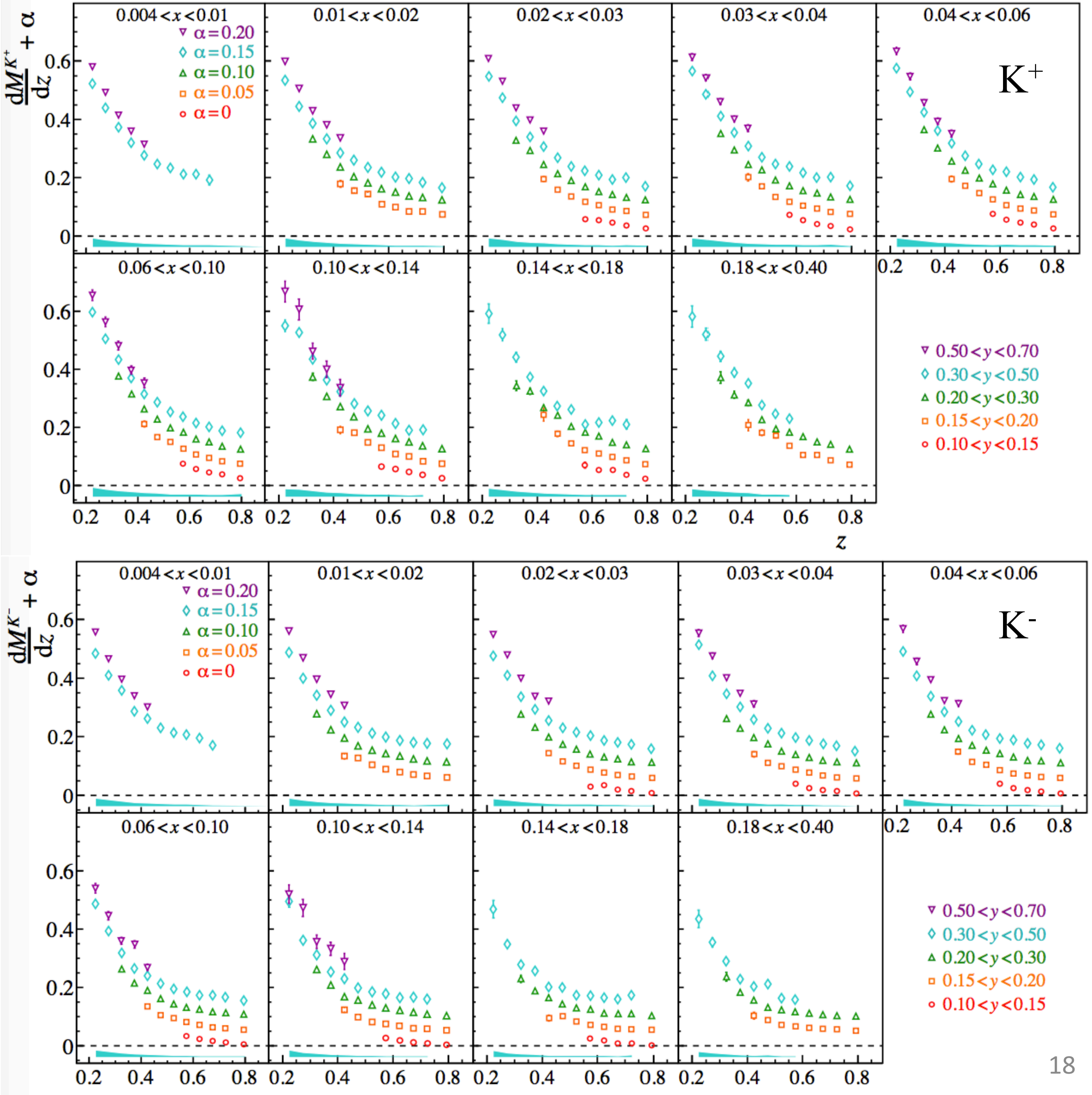




Charged Kaon multiplicity results

3-D kinematic binning
in x, y, and z

- 317 kinematic bins
- Strong z dependence as expected
- Paper submitted to PLB.
  hep-ex:1608.06760
- Valuable inputs for NLO QCD analyses foreseen in the near future



Kaon multiplicity sum

For the isoscalar target, when expressed at LO the sum is:

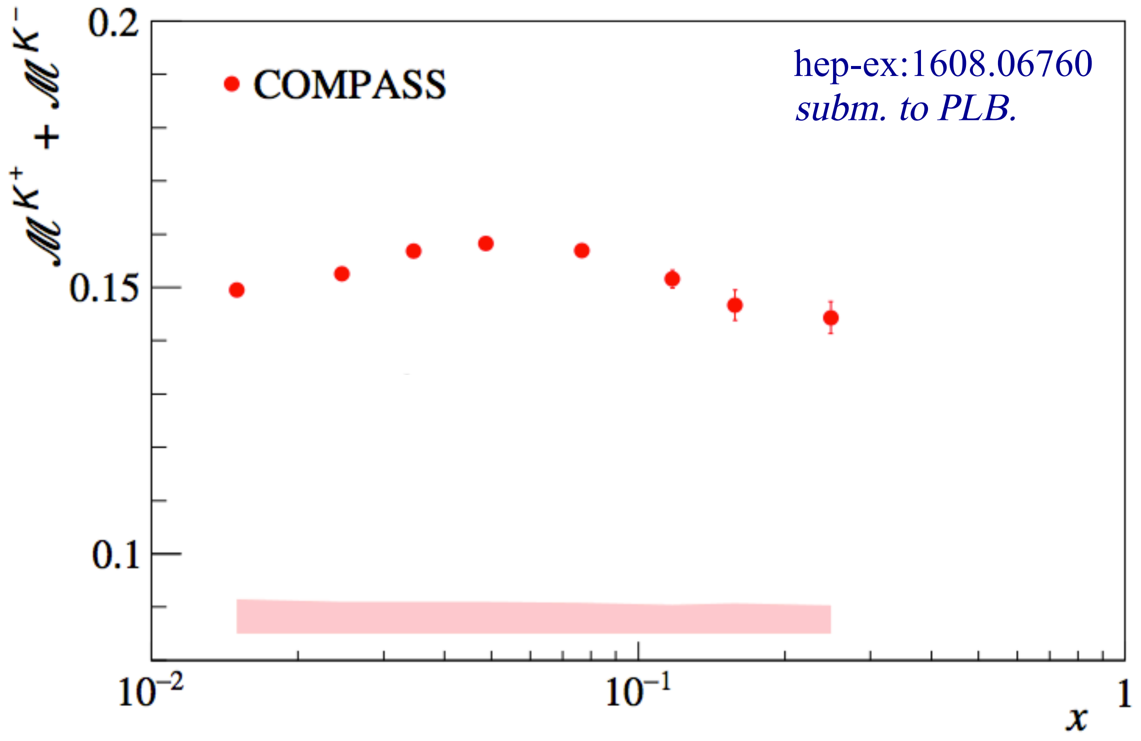
$$M^{K^{+}+K^{-}} \approx \frac{QD_Q^K + SD_S^K}{5Q + 2S}$$

non-strange: $Q = u + d + \bar{u} + \bar{d}$

$D_Q^K = 4D_{fav}^K + 6D_{unf}^K$

strange: $S = s + \bar{s}$, D_S^K

→ Separate strange and non-strange contributions



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→ Separate strange and non-strange contributions

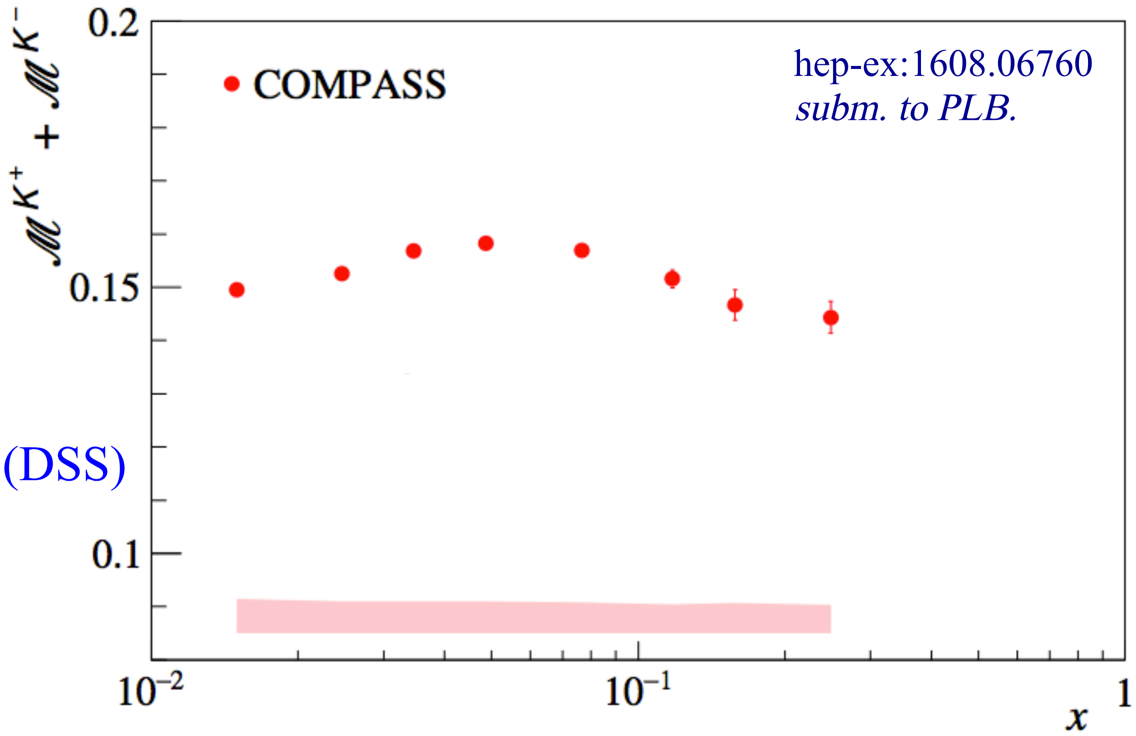
At high x

S ≈ 0 → access D_Q^K

$$M^{K^+ + K^-} = \frac{4D_{fav}^K + 6D_{unf}^K}{5} = \frac{D_Q^K}{5}$$

D_Q^K = 0.65-0.7 compared to 0.43±0.04 (DSS)

Kaon results suggest larger non-strange than in DSS (PRD 75 114010)



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At high x

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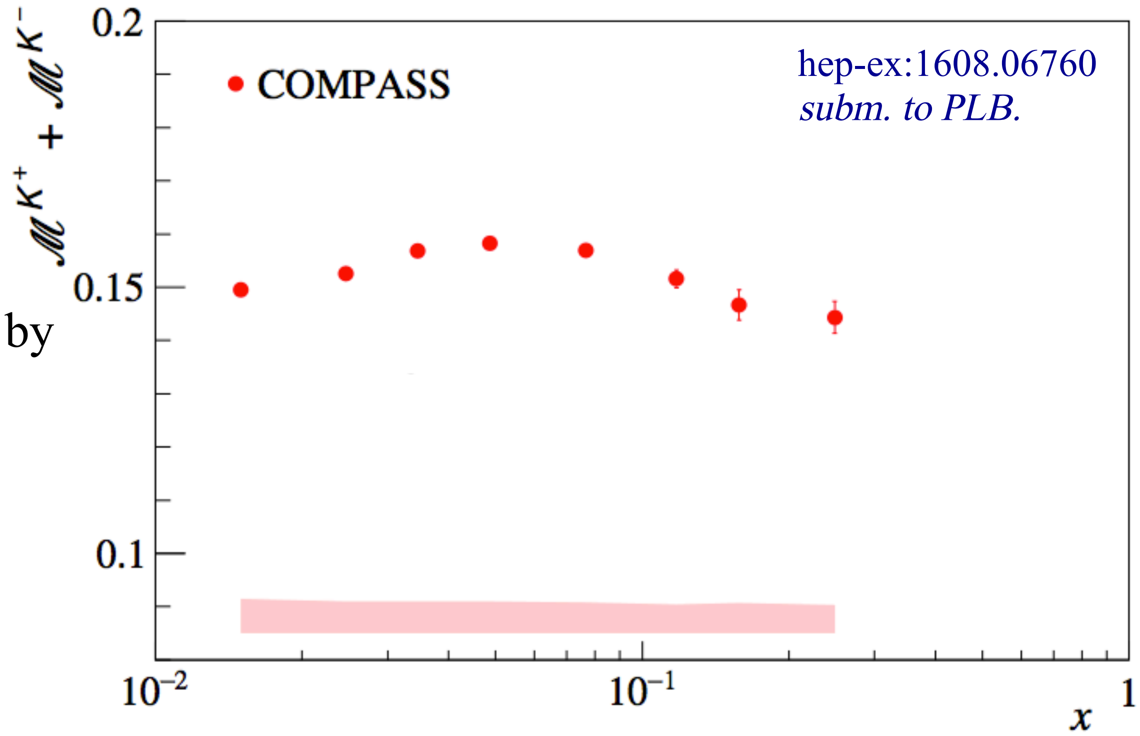
At low x

A rise in the kaon multiplicity sum towards low x where S≠0 is expected (DSS ~ 50% increase)



Strong increase of $M^{K+ +K-}$ towards low x is not observed

Results point to rather lower FF ratio, D_{str}/D_{fav}, than in the DSS parameterisation

Kaon multiplicity sum

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$D_Q^K = 4D_{fav}^K + 6D_{unf}^K$

strange: $S = s + \bar{s}$, D_S^K

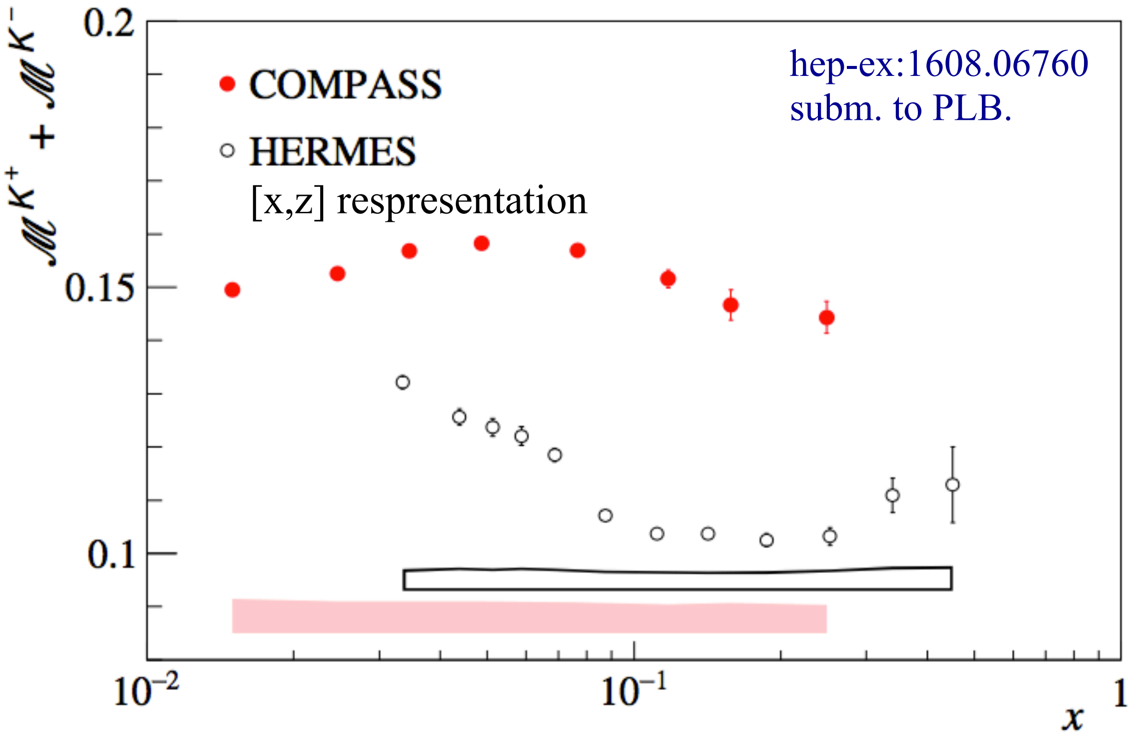
COMPASS vs. HERMES

Significant discrepancies observed:

- shape of the sum at low x
- value of the sum at high x

Being investigated by Accardi *et al.* (JHEP 1509 (2015)), using hadron mass corrections

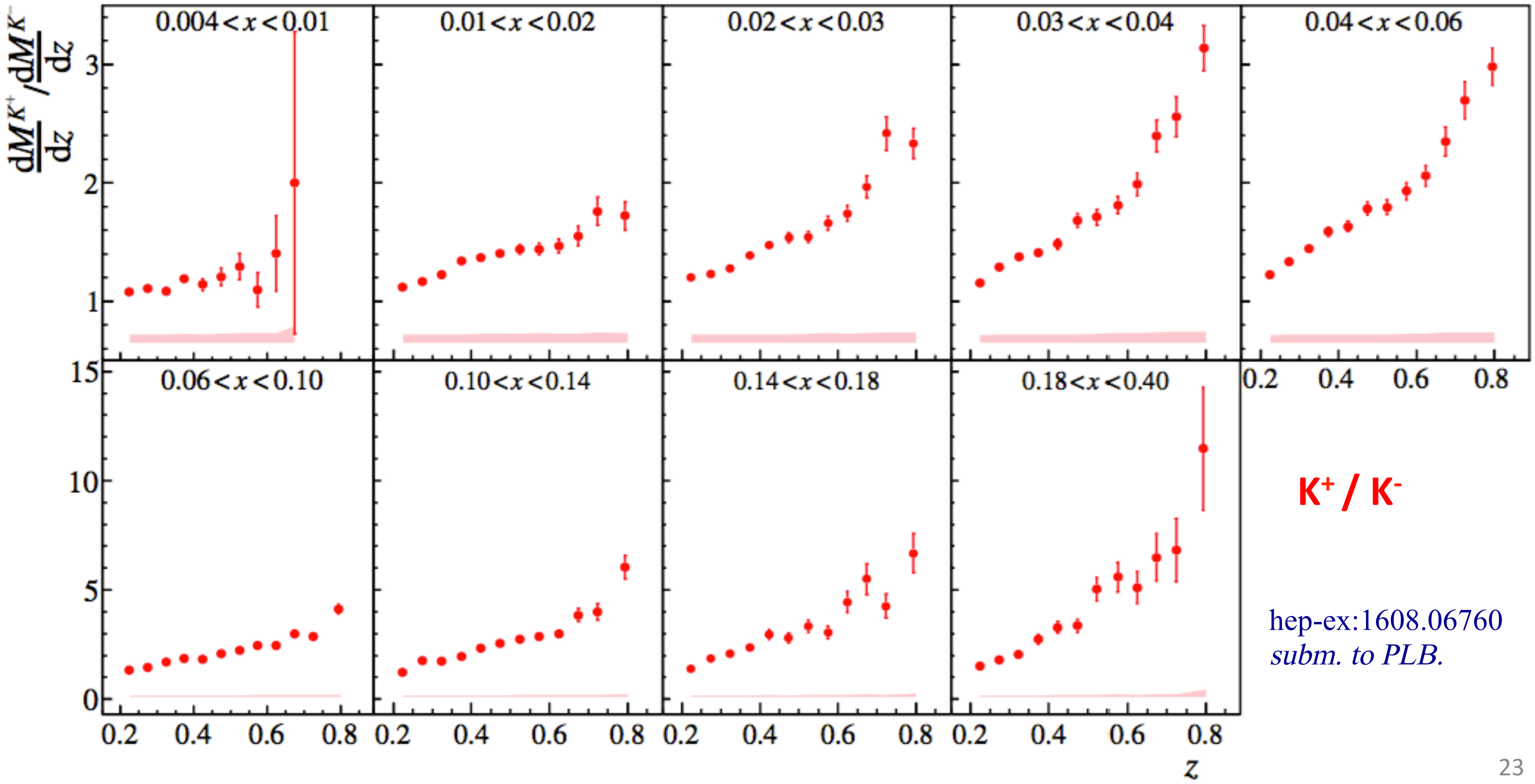
NLO QCD analysis of FF may explain this observation.



Kaon multiplicity ratio

2-D projection in x, and z

- ✧ K^+/K^- is interesting to study due to significant cancellation of systematic uncertainties
- ✧ Larger ratio at large z reflects favoured fragmentation dominance in K^+

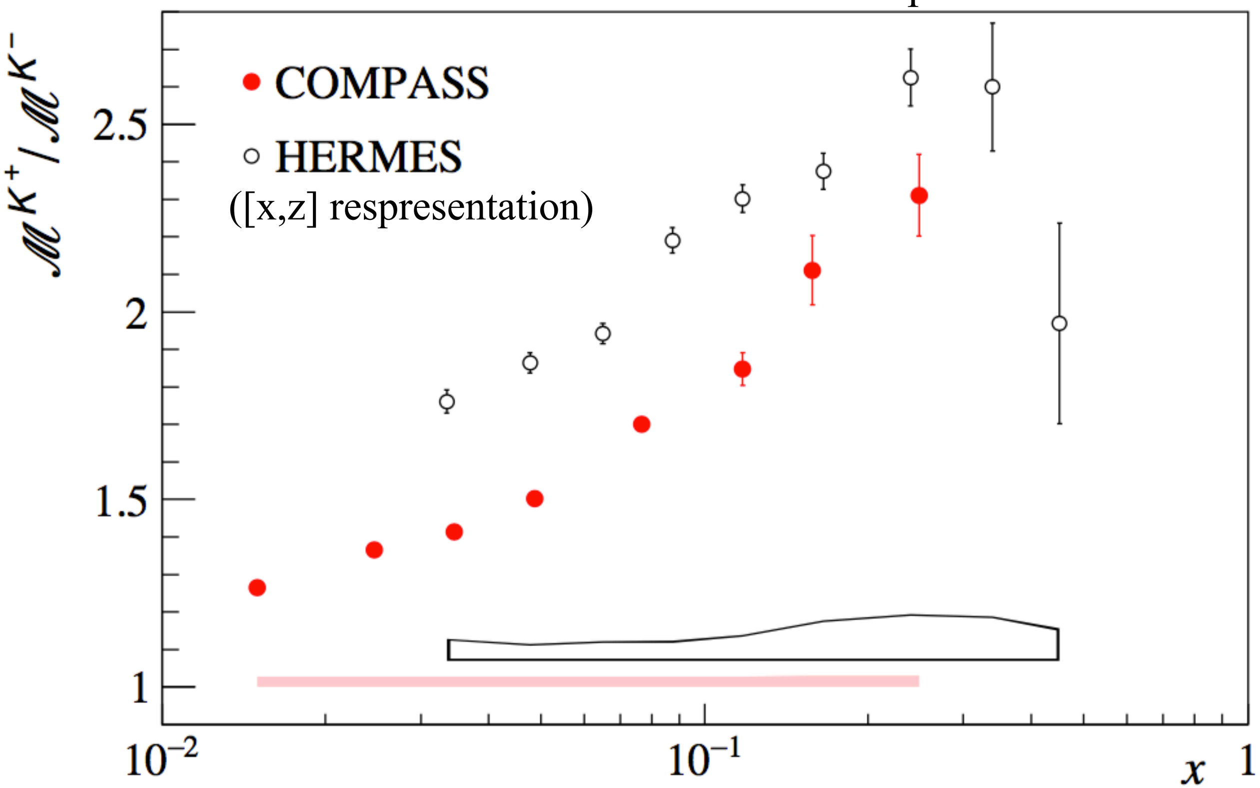


hep-ex:1608.06760
subm. to PLB.

Kaon multiplicity ratio, COMPASS vs. HERMES

- The ratio K^+/K^- is interesting to study due to significant cancellation of systematic uncertainties
- Significant discrepancy between COMPASS and HERMES is observed in contrast with the pion case (π^+/π^-) where a good agreement was found
- Theoretical effort is taking place (A. Accardi's *talk at QCD-N'2016,* JHEP 1509 (2015) 169) to investigate this discrepancy using hadron mass corrections.

hep-ex:1608.06760



Beyond collinear case

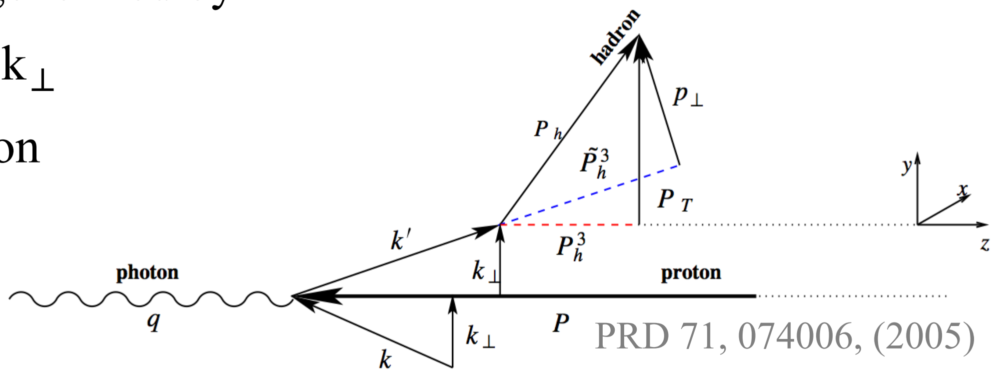
Transverse Momentum Dependent (TMD) hadron multiplicities

Relevance of Unpolarised SIDIS for TMDs

✧ Transverse momenta of final-state hadron generated by

⇒ Quark intrinsic transverse momentum $k_\perp$

⇒ $p_\perp$ generated in the quark fragmentation



PRD 71, 074006, (2005)

A Gaussian ansatz *for* $k_\perp$ *and* $p_\perp$ leads to

$<p_T^2> = <p_\perp^2> + z^2<k_\perp^2>$

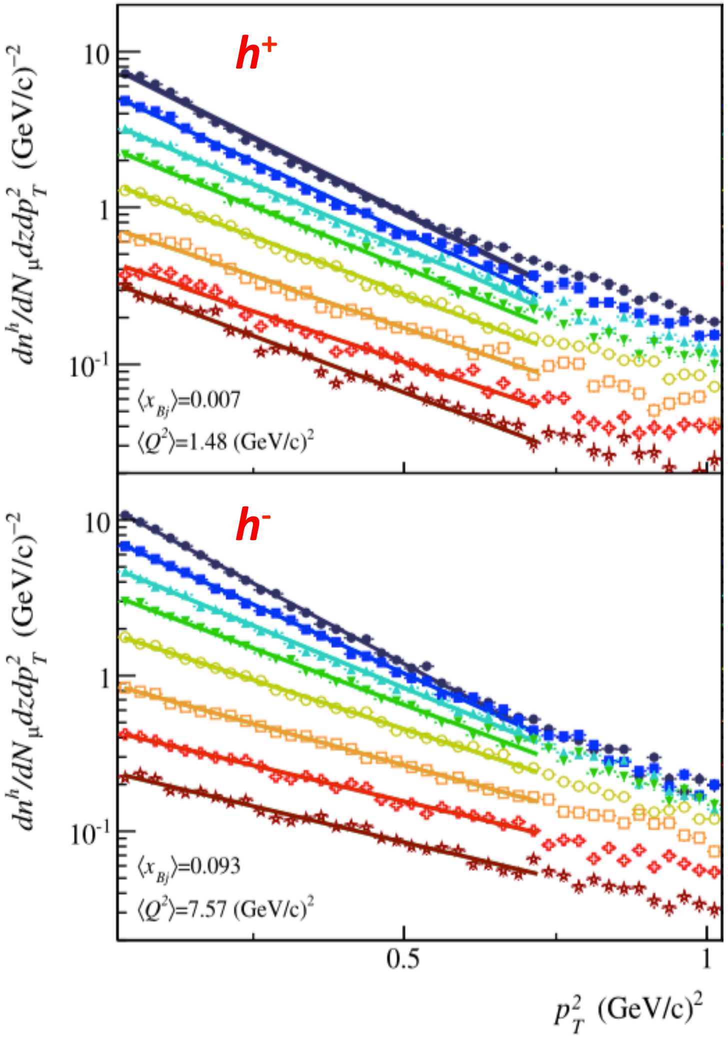
The azimuthal modulations in the unpolarised cross-section result from

- intrinsic $k_\perp$ of the quarks -> **hadron multiplicities**, azimuthal asymmetries
- The Boer-Mulders PDF -> azimuthal asymmetries
- …

Combined analysis allows to disentangle the different effects

p_T distributions of charged hadrons

EPJC 73 (2013) 2531

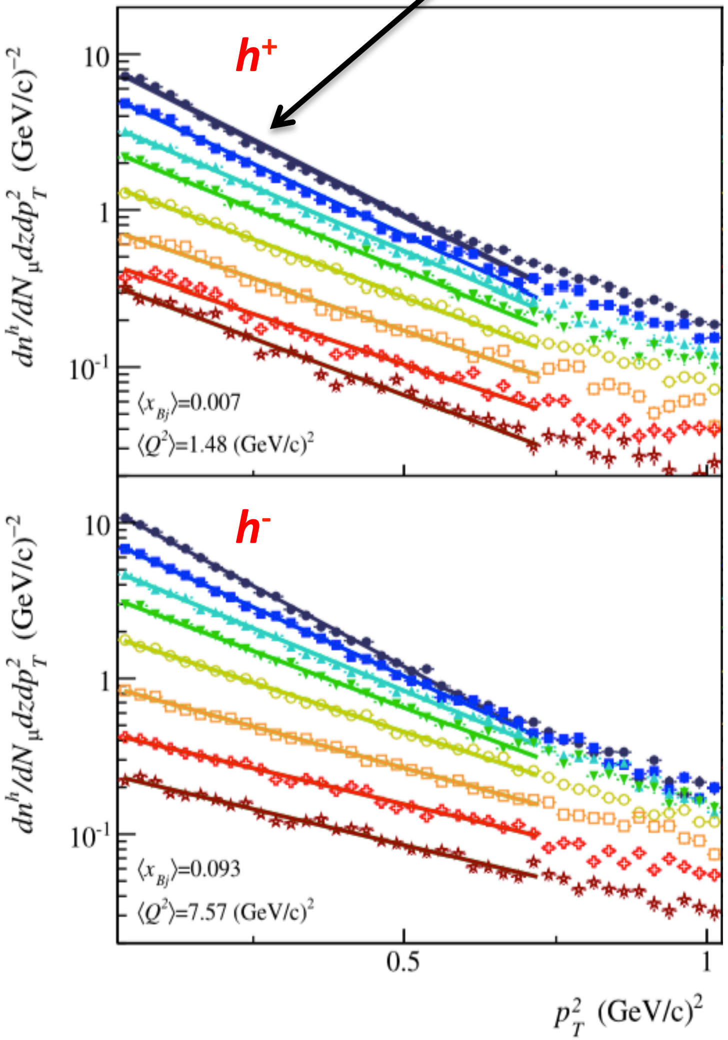


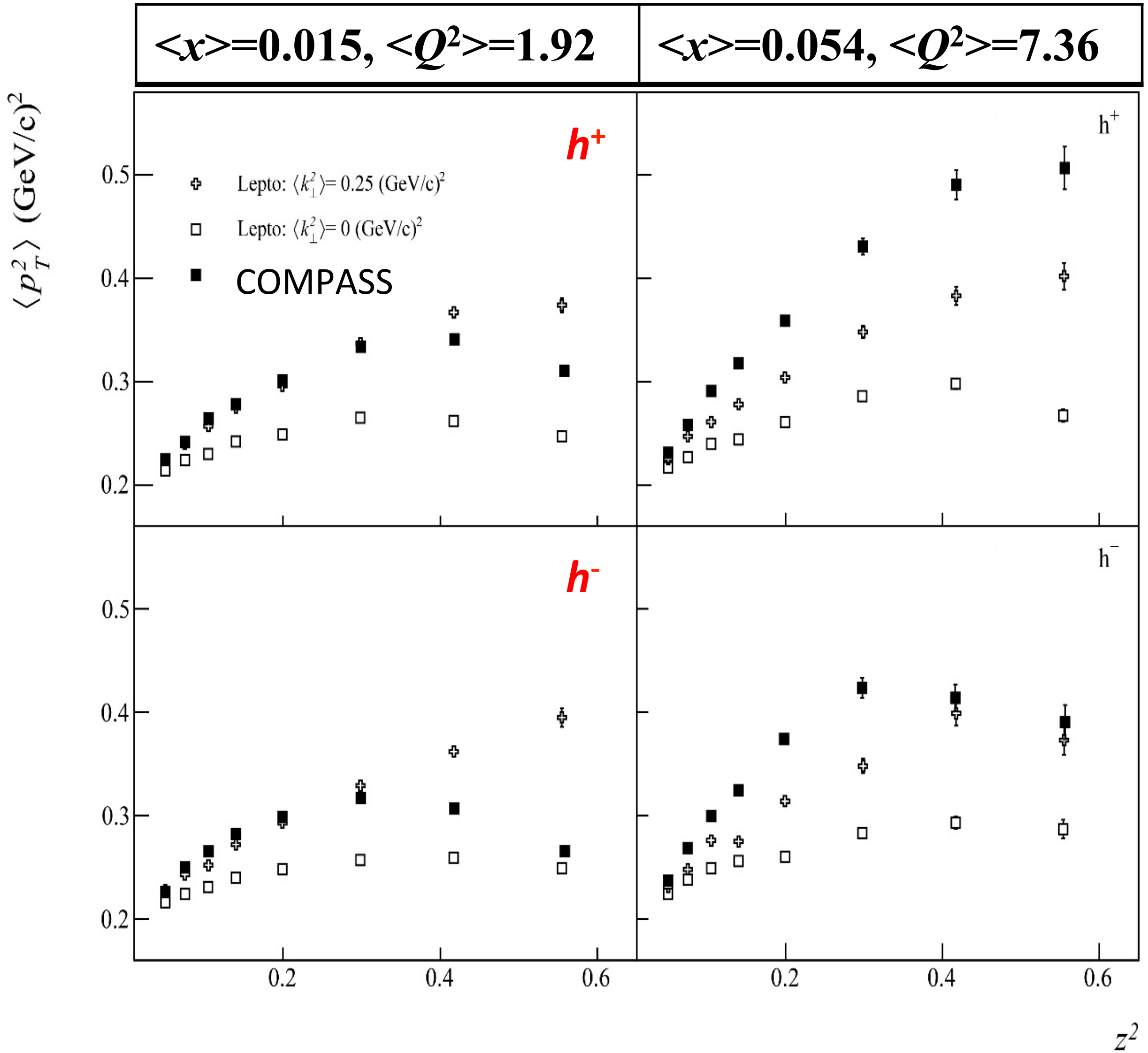
+ 22 (x,Q^2) kinematic bins

- First analysis to extract $h^\pm$ **distributions** vs. p_T^2 used:
  - **2004 data**
  - kinematic domain:
    - $1 < Q^2\ (GeV/c)^2 < 10$
    - $W > 5\ GeV/c^2$
    - $0.1 < y < 0.9$
    - $0.004 < x < 0.12$
    - $0.2 < z < 0.8$
    - $0.01 < p_T^2 < 1.2$
  - 4-D binning in x, Q^2, z, p_T^2
- aimed to study the x, Q^2 and *z* kinematic dependences of $<p_T^2>$ using Gaussian functional form

p_T^2 averaged values

$$Ae^{-p_T^2/\langle p_T^2\rangle}$$





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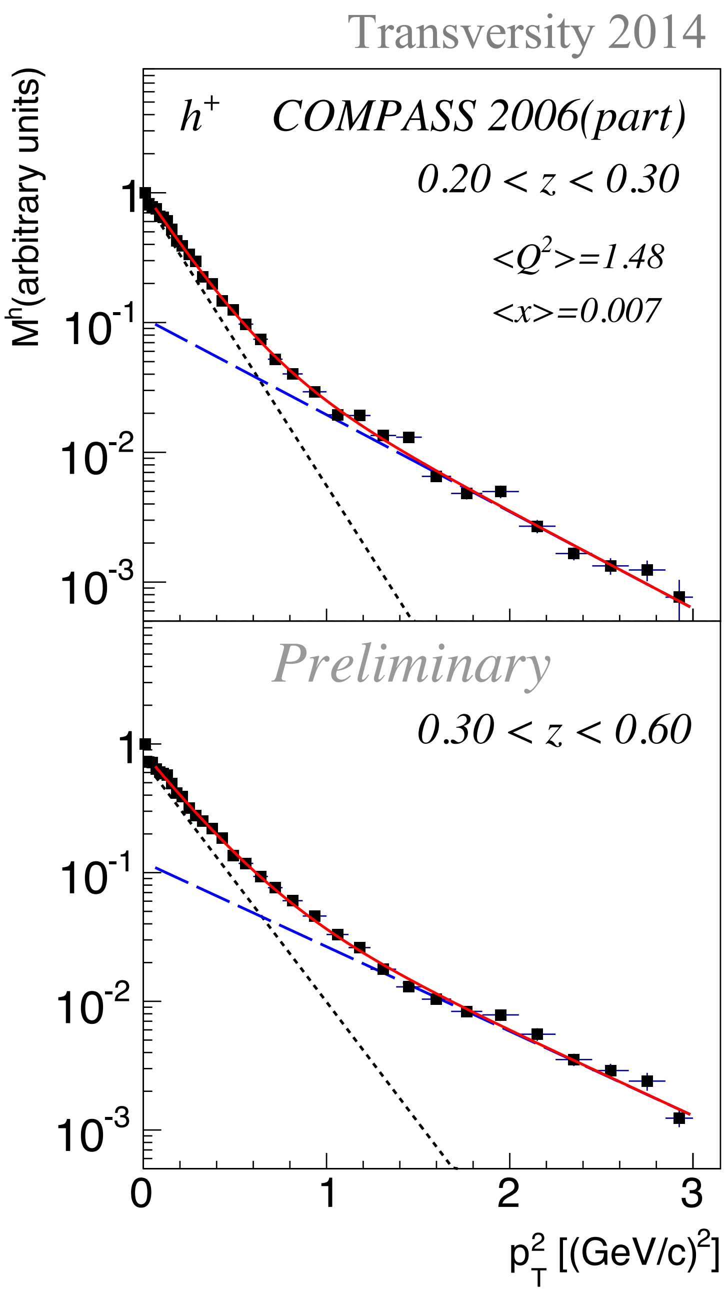
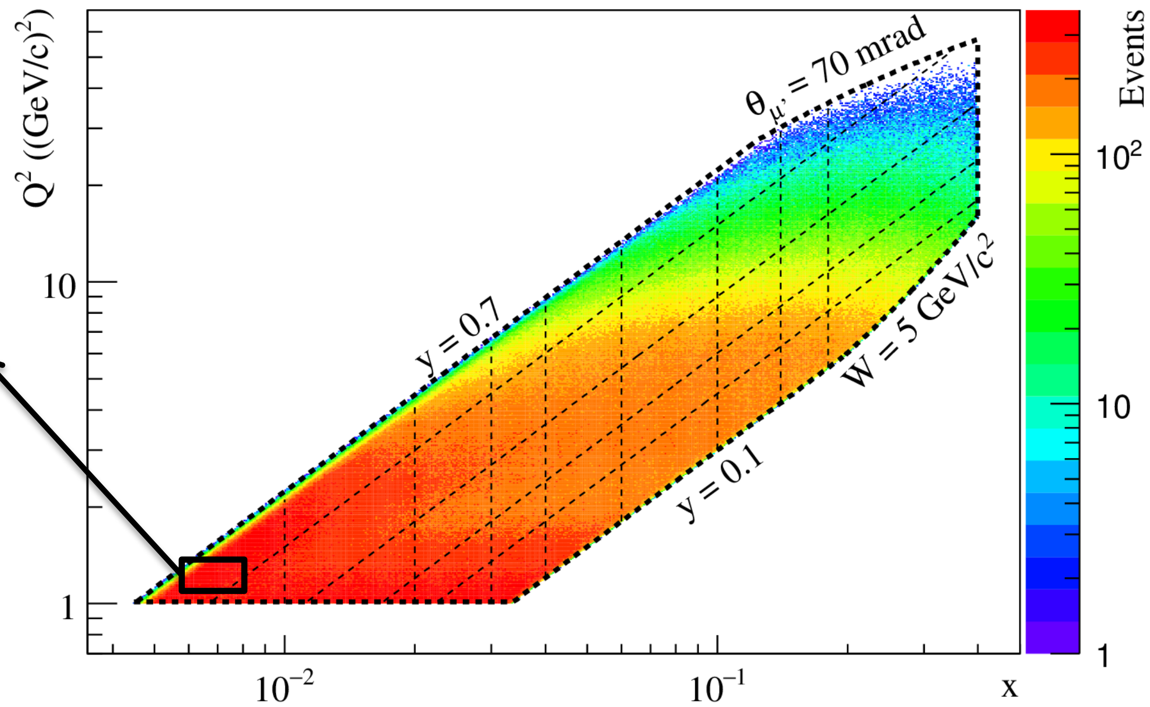
p_T distributions of charged hadrons



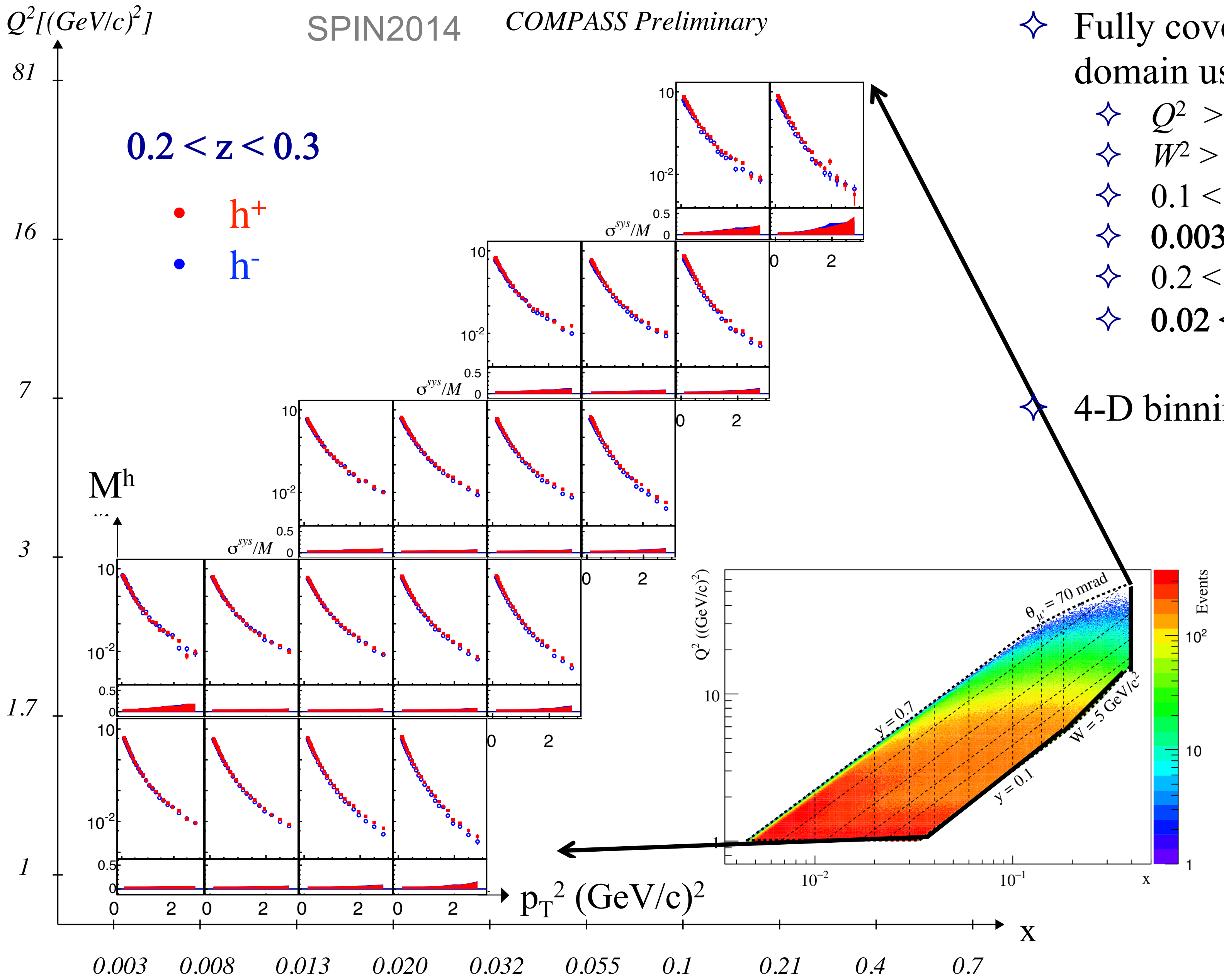
2006 data

First look in a restricted kinematic range: only 3 (x,Q^2) bins, 2 z bins, extending the p_T^2 range

$h^{\pm}$ distributions vs. p_T^2

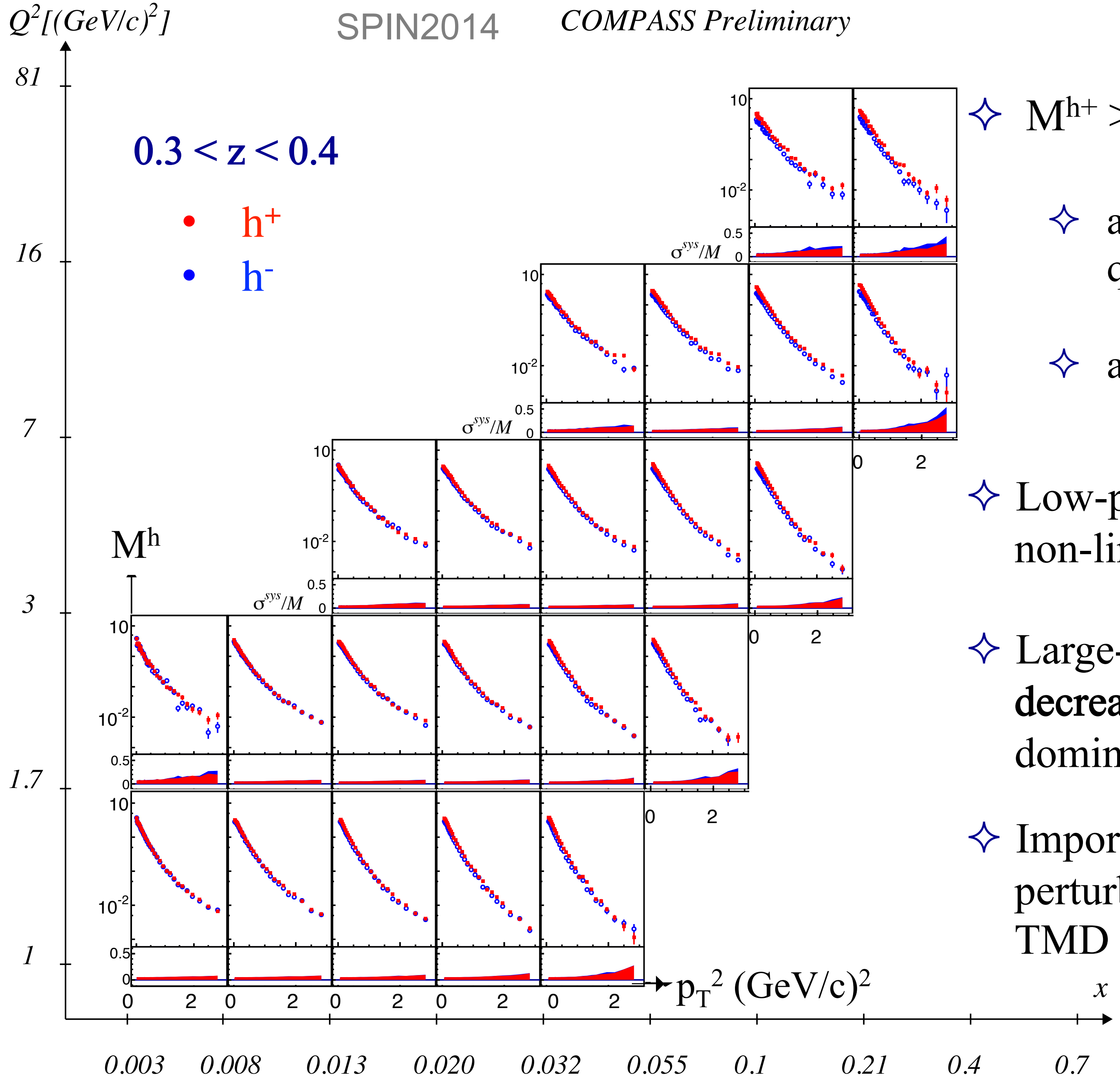


Multiplicities of charged hadron vs. p_T^2



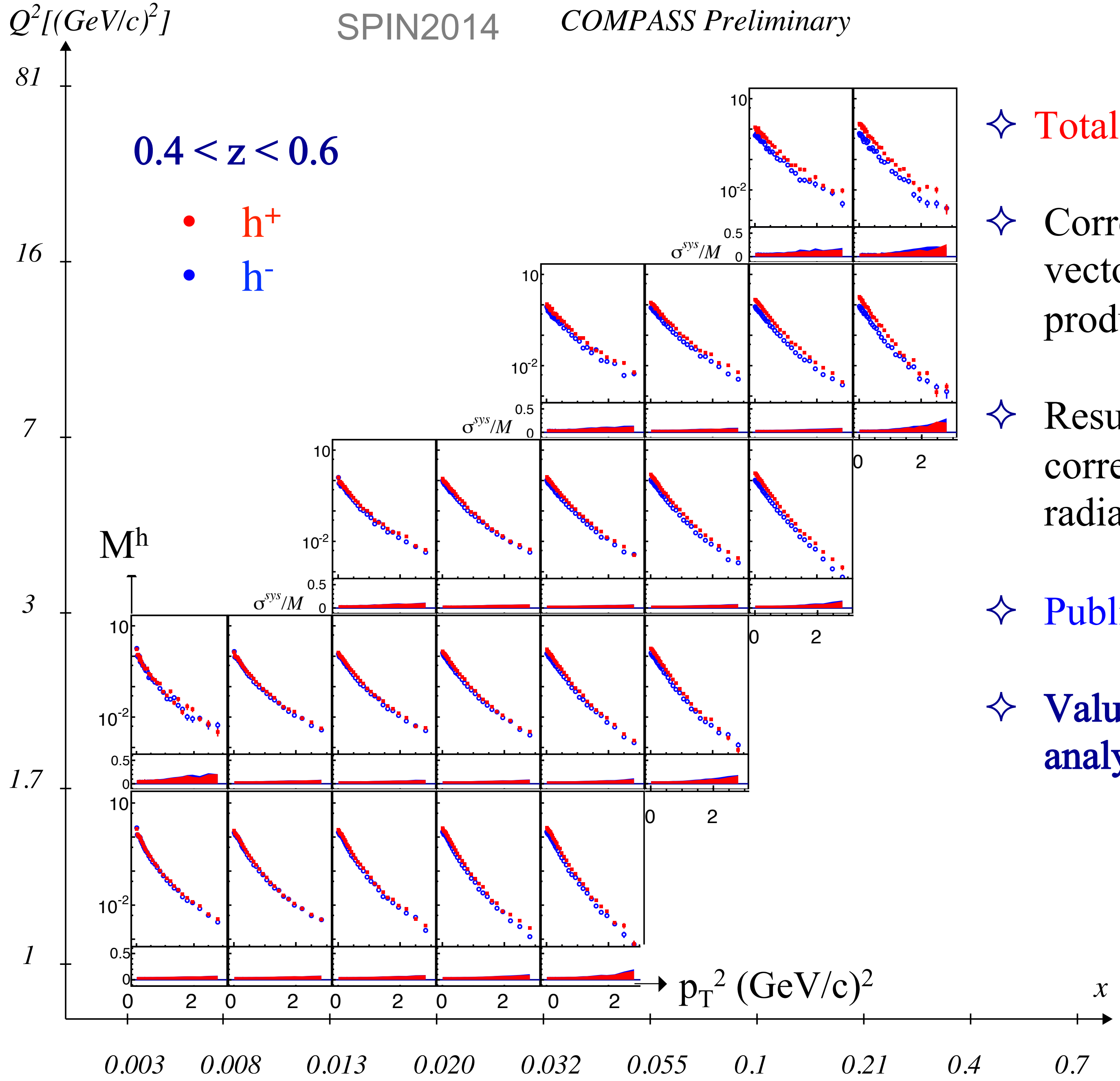
- ✧ Fully covered kinematic domain used in this analysis
  - ✧ $Q^2 > 1$ (GeV/c)^2
  - ✧ $W^2 > 5$ (GeV/c)^2
  - ✧ $0.1 < y < 0.9$
  - ✧ **$0.003 < x < 0.4$**
  - ✧ $0.2 < z < 0.8$
  - ✧ **$0.02 < p_T^2 < 3$**
- ✧ 4-D binning in x, Q^2, z, p_T^2

Multiplicities of charged hadron vs. p_T^2



- $M^{h+} > M^{h-}$ significantly
  - at **high x** due to valence u-quark dominance
  - at **large z**, where $D_u^{\pi+} > D_u^{\pi-}$
- Low-p_T range fitted using 1-exp: non-linear z-dependence of $\langle p_T^2 \rangle$
- Large-p_T shape flattens as **x decreases** and **Q^2 increases**, dominated by PGF,…
- Important to constraint non-perturbative contributions in TMD factorisation studies

Multiplicities of charged hadron vs. p_T^2



- Total: **4918 kinematic bins**
- Correction for diffractive vector meson (DVM) production evaluated
- Results available with/without correction for DVM and radiative effects
- Publication expected soon
- **Valuable input for TMD analyses and evolution studies**

From single hadron to hadron pair production

Hadron pair multiplicity

Transversity from hadron pair transverse spin asymmetry

$$A_{UT}^{sin\phi_{RS}} \propto \frac{\sum_q e_q \cdot \boxed{\Delta_T q(x)} \cdot H_{1,sp}^{2h}(z, M^{2h})}{\sum_q e_q \cdot q(x) \cdot \boxed{D_q^{2h}(z, M^{2h})}}$$

Spin-averaged Dihadron fragmentation functions evaluated using MC simulation

➠ Need of experimental data

$$M^{2h}(Q^2, z, M_{inv}) \propto q(Q^2) \cdot D_q^{2h}(Q^2, z, M_{inv})$$

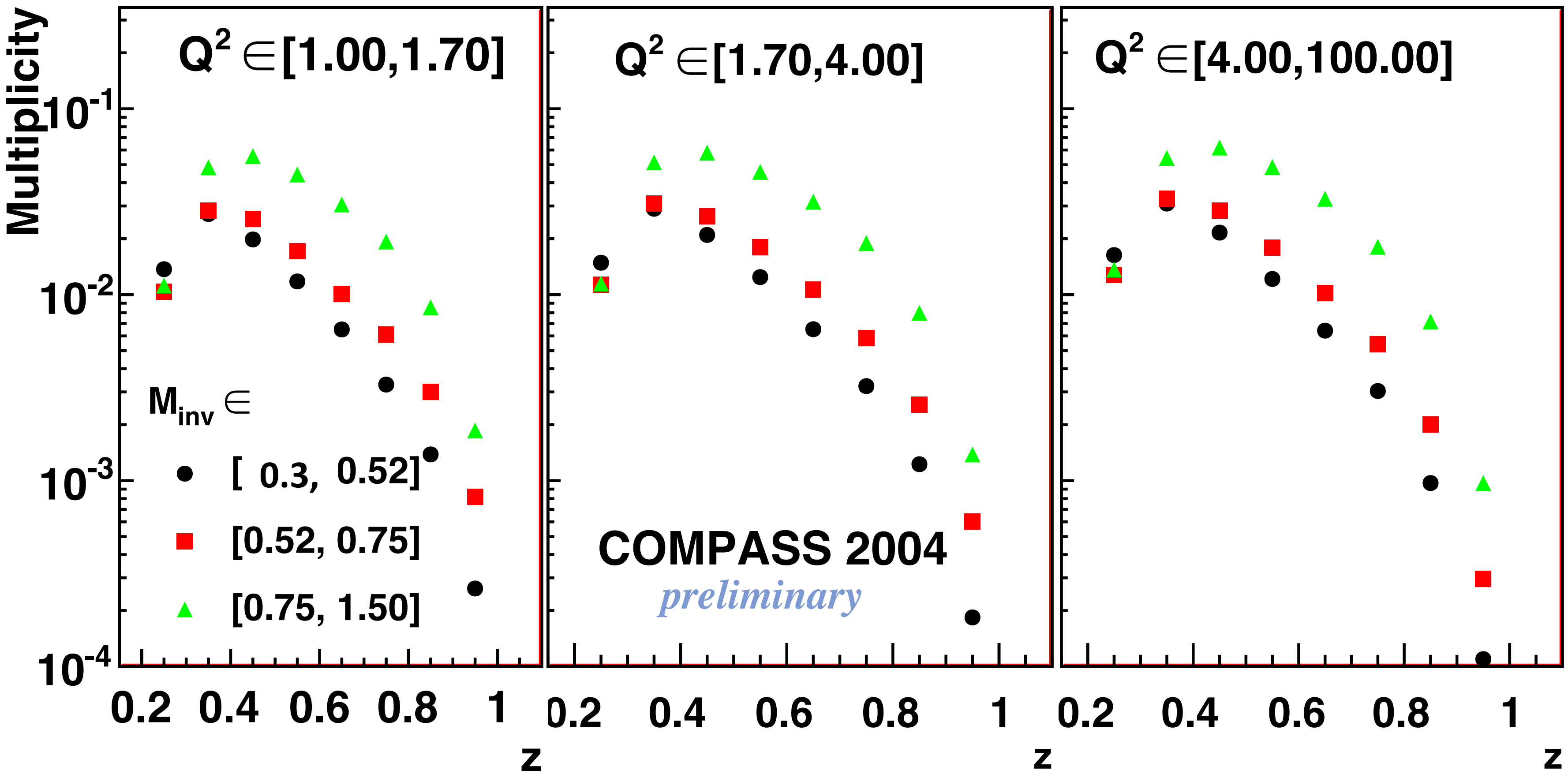
➡ First extraction in simultaneous bins in M_{inv}, z and Q^2 bins by COMPASS

➡ First attempt using data collected in 2004 for a next measurement on a larger data set

Hadron pair multiplicity results

$$M^{2h}(Q^2, z, M_{inv}) \propto q(Q^2) \cdot \boxed{D_q^{2h}(Q^2, z, M_{inv})}$$

First extraction in simultaneous bins in M_{inv}, z and Q^2 bins

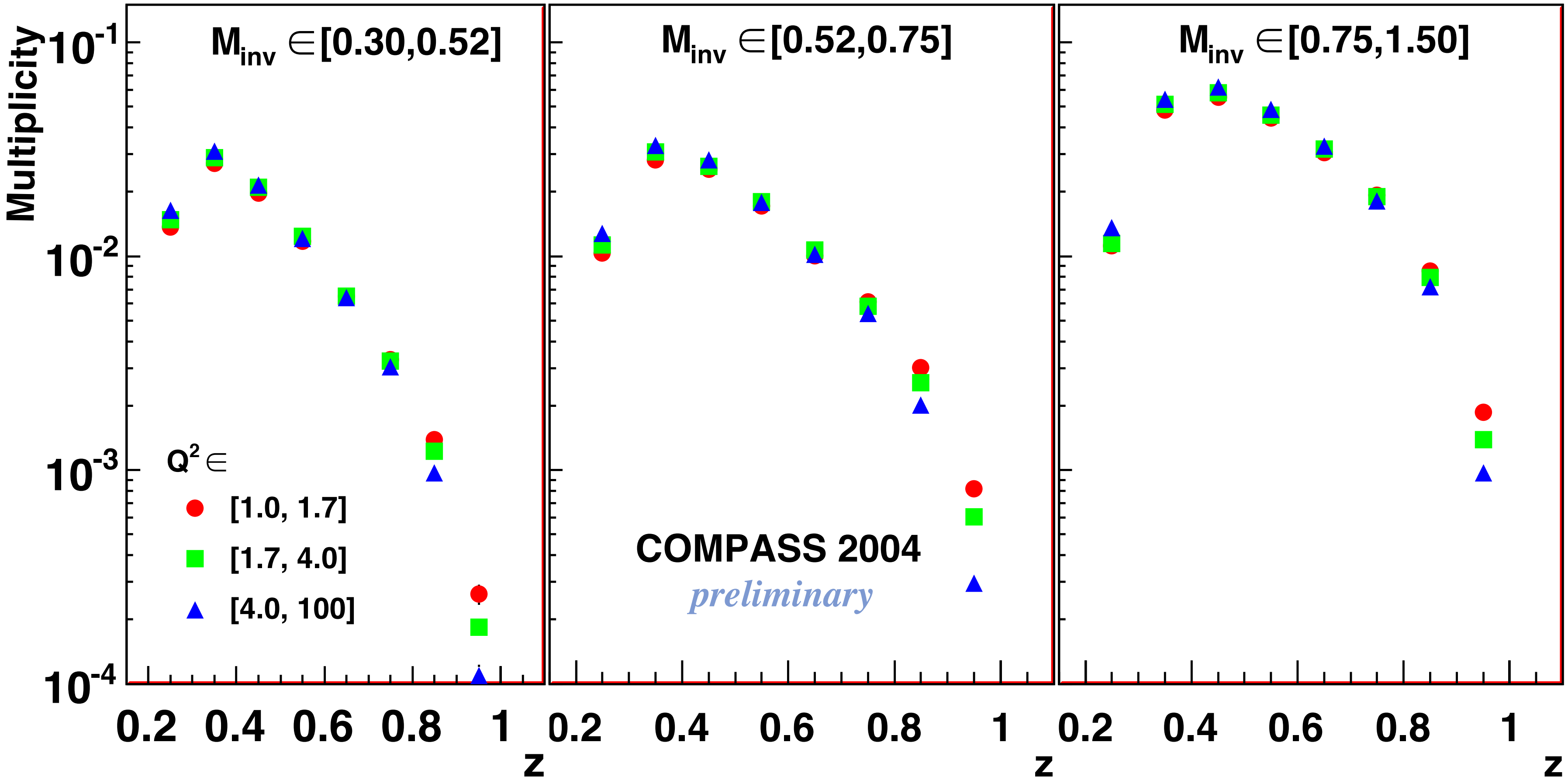


➡ Significant z,M_{inv} dependence compatible with LEPTO's expectation

Hadron pair multiplicity results

$$M^{2h}(Q^2, z, M_{inv}) \propto q(Q^2) \cdot \boxed{D_q^{2h}(Q^2, z, M_{inv})}$$

First extraction in simultaneous bins in M_{inv}, z and Q^2 bins



➡ Weak dependence upon Q^2

Summary I

- Charged pion, kaon and hadron multiplicities were measured at COMPASS using data collected with an isoscalar ^{6}LiD target and 160 GeV μ^{+} beam in 2006
  - in a wide kinematic domain
  - in 3-D kinematic binning in *x*,*y* and *z*
  - Charged pion and hadron multiplicities paper submitted to PLB
    hep-ex:1606.03725, CERN-EP-2016-095
  - Charged kaon multiplicities paper submitted to PLB
    hep-ex:1608.06760, CERN-EP-2016-206
- Visible tensions between COMPASS and HERMES (lower energy) results
- Favored and unflavored FF extracted from LO fits to COMPASS $\pi^{\pm}$ multiplicities only are in good agreement with results from global fits

Summary II

- Transverse momentum dependent multiplicities of charged hadron were measured using 2006 data collected with an isoscalar ^{6}LiD target and 160 GeV μ^+
  - in a wide kinematic domain
  - in 4-D kinematic binning in x, Q^2, z and p_T^2
- Observations for the low-p_T^2 shape confirms 2004 results
- Flattening distributions at large-p_T^2, at low x (fixed Q^2) and at high Q^2 (fixed x)
- Paper expected soon
- Both collinear multiplicities and the p_T-dependent multiplicities are in excellent agreement

- COMPASS results on hadron multiplicities represent valuable inputs to global QCD analyses of FFs and TMD analyses and TMD evolution studies
- Future measurements of hadron multiplicities on proton (LH_2) target from 2016-2017 data