Momentum structure of the nucleon and hadron production in unpolarised SIDIS at COMPASS:

Transverse Momentum Dependent Hadron Multiplicities

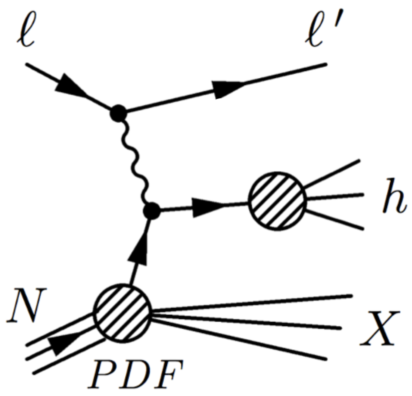
N. Makke[1,2] for the COMPASS Collaboration

[1] *INFN/University of Trieste*
[2] *International Center for Theoretical Physics, Trieste*

The 21st International Symposium on Spin Physics
October 20-24, 2014,
Beijing, China

Semi-inclusive DIS

$$\boxed{\ell N \to \ell' h(X)}$$



DIS with a hadron detected in its final state

Powerful tool

- PDF and FF dependent cross section
- Allows flavor & charge separation of FFs
- Covers wide scale (Q^2) range
- Relevant for spin physics kinematics

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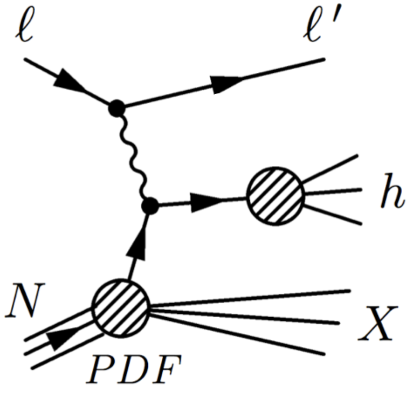

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At Leading twist:

quark pol.

nucleon pol.	U	L	T	
U	f_1		$h_1^\perp$	
L		g_1	$h_{1L}^\perp$	
T	$f_{1T}^\perp$	g_{1T}	h_1	$h_{1T}^\perp$

- 8 intrinsic-transverse-momentum dependent PDFs
- Azimuthal asymmetries with different angular modulations in the hadron and spin azimuthal angles, Φ_h and Φ_s
- Vanish upon integration over k_T except f_1, g_1, and h_1

Semi-inclusive DIS

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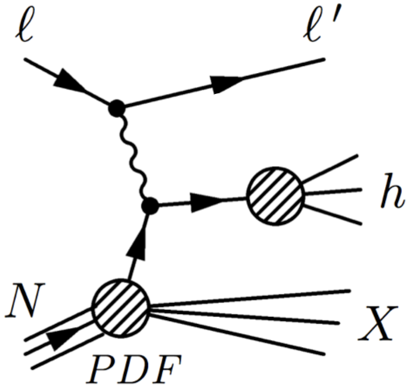

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At Leading twist:

8 TMD PDFs

2 TMD FFs

Unpolarized PDFs & FFs

quark pol.

nucleon pol.	U	L	T	
U	f_1		$h_1^\perp$	
L		g_1	$h_{1L}^\perp$	
T	$f_{1T}^\perp$	g_{1T}	h_1	$h_{1T}^\perp$

quark pol.

	U	L	T
U	D_1		$H_1^\perp$

Relevance of unpolarized SIDIS

Very good knowledge of PDFs and FFs is a key element for a reasonably precise determination of polarized quantities, e.g. polarization of quarks in

- Longitudinally polarized nucleon
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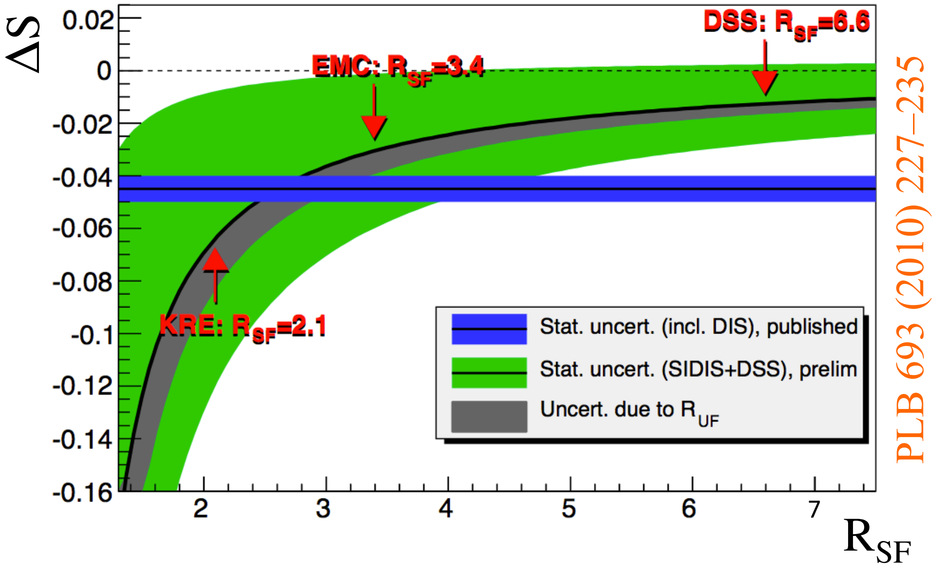
- Strange quark polarization (ΔS) and its strong dependence on FFs parameterizations



PLB 693 (2010) 227–235

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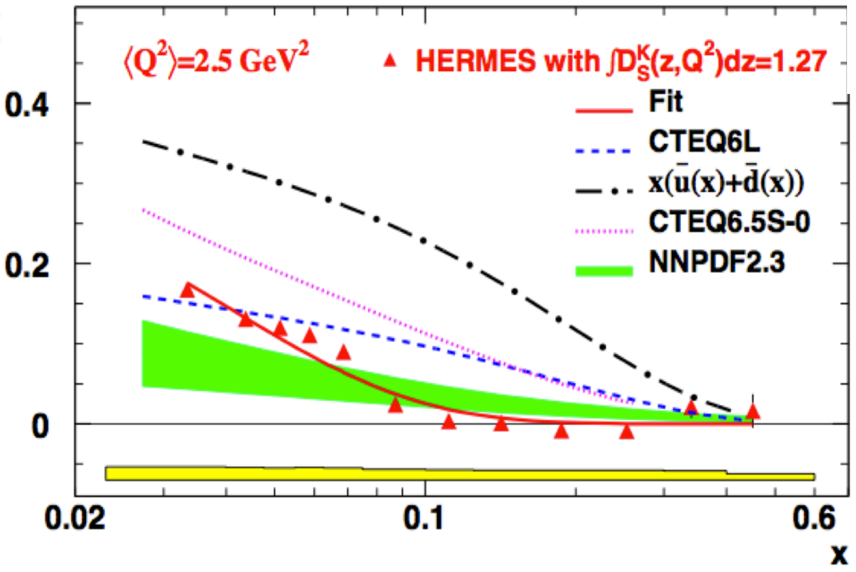
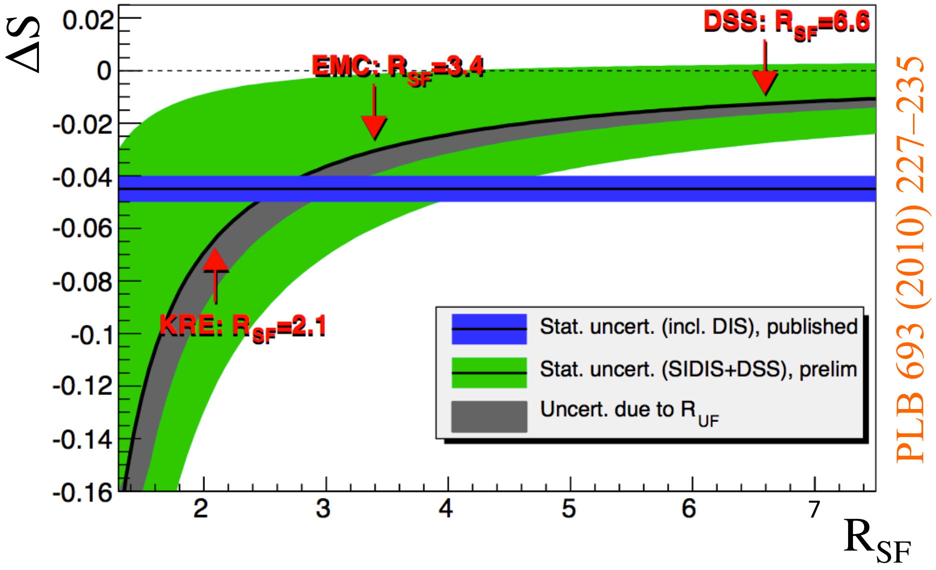
- Poor knowledge of S(x)



[arXiv:1312.7028]



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Collins mechanism

$$A_{\mathrm{Coll}} = \frac{\sum_q e_q^2 \cdot \boxed{\Delta_T q(x)} \cdot \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, p_T^h)}$$

Hadron production mechanism

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

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Hadron pair production

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Unknown !!!

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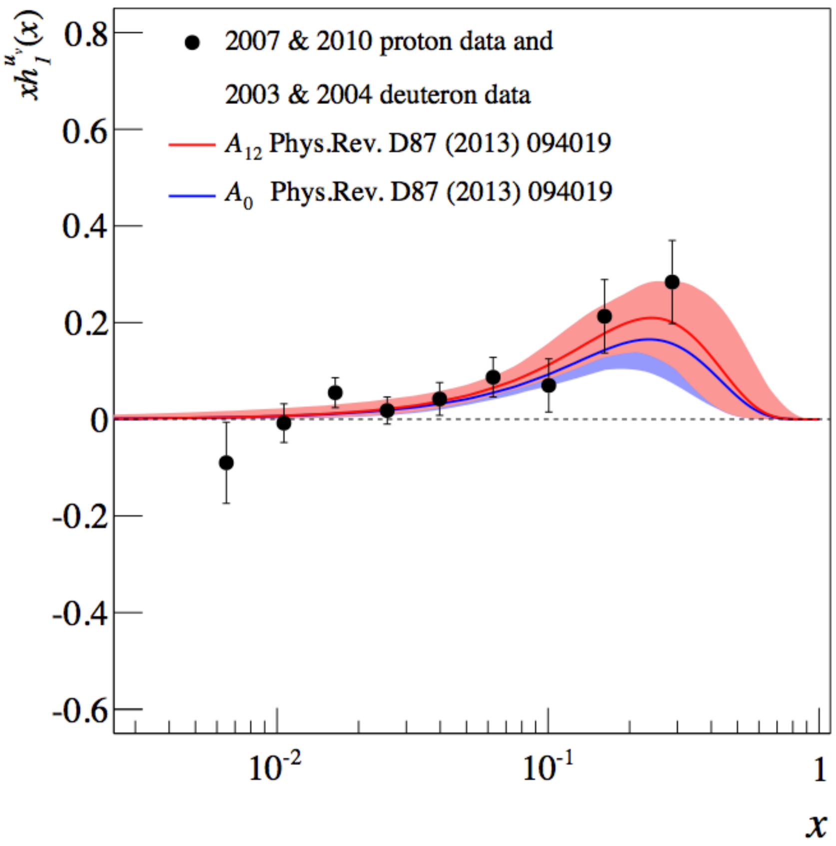
- Longitudinally polarized nucleon
- Transversely polarized nucleon
  - Extraction of transversity function (Δq_T) using h^+h^- asymmetries



Input unpolarised hadron pair fragmentation functions (D_q^{h+h-}) extracted from MC simulation !!!

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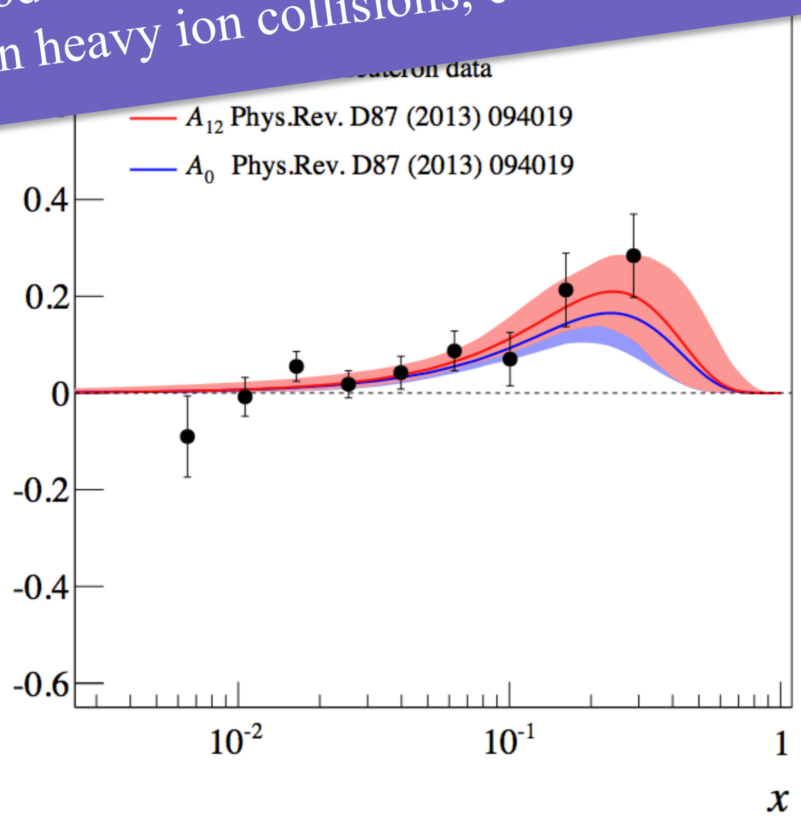
Not only needed in spin physics studies but in any reaction where hadrons are produced in its final-state, exp @ LHC (in-medium effect in heavy ion collisions, e^+e^- anihilation, …



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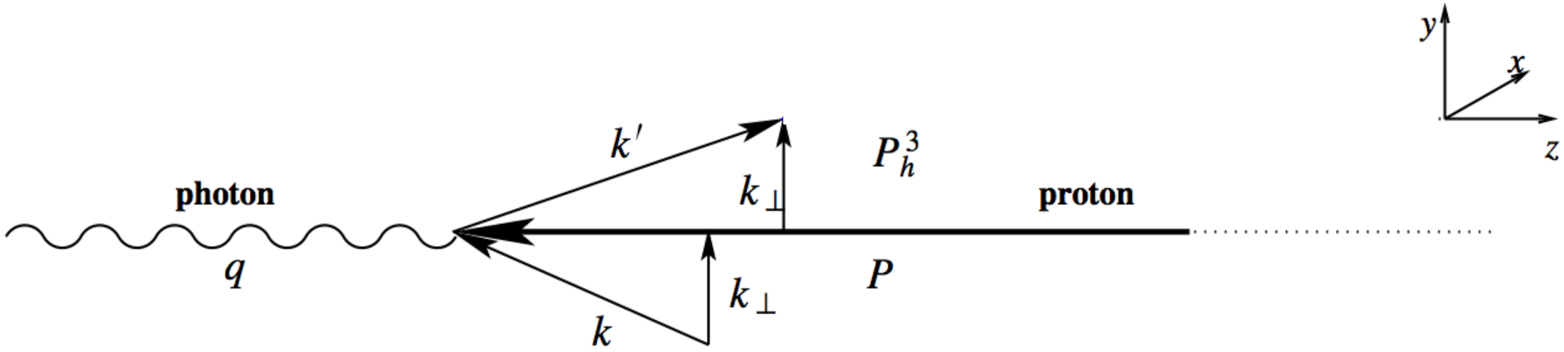
Transverse Momentum Dependence

- Transverse momenta of unpolarised final-state hadron generated by
  ⇒ Transverse momentum of the quark (k_{perp}) in the target proton



TMD-PDFs

PRD 71, 074006, (2005)

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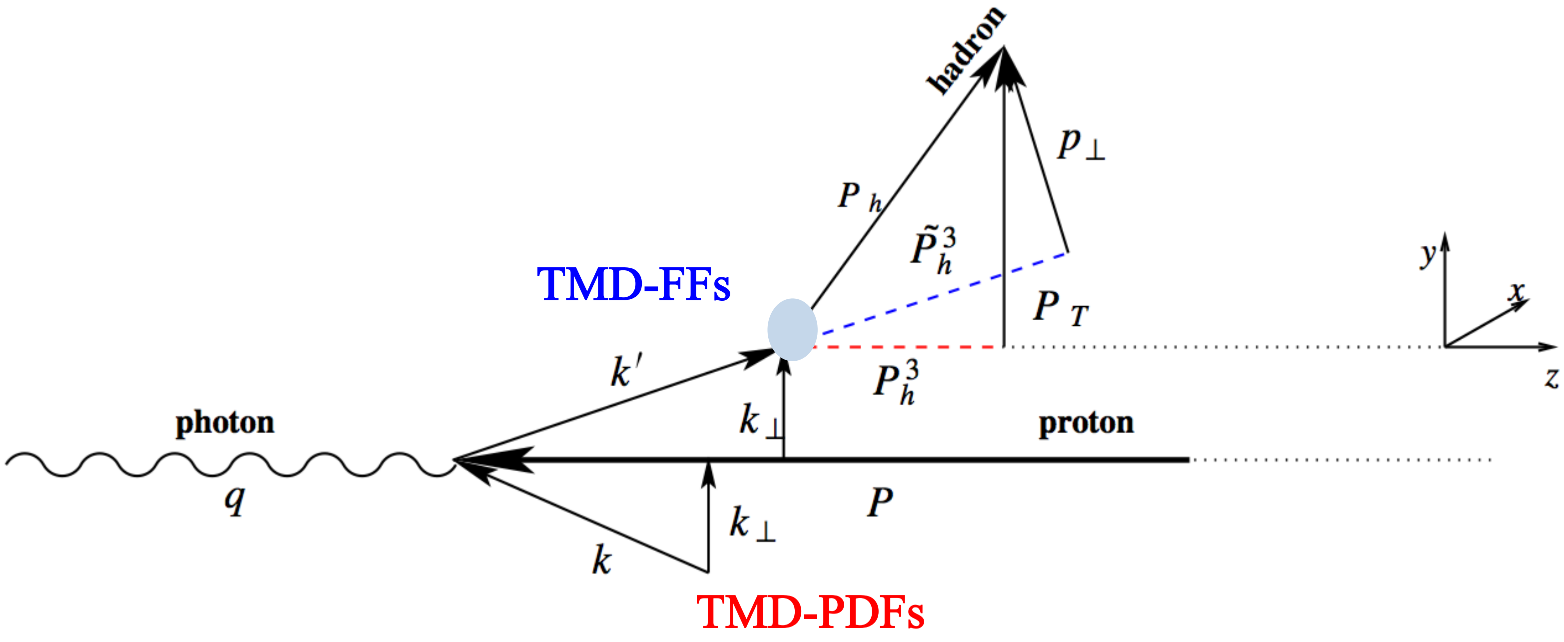

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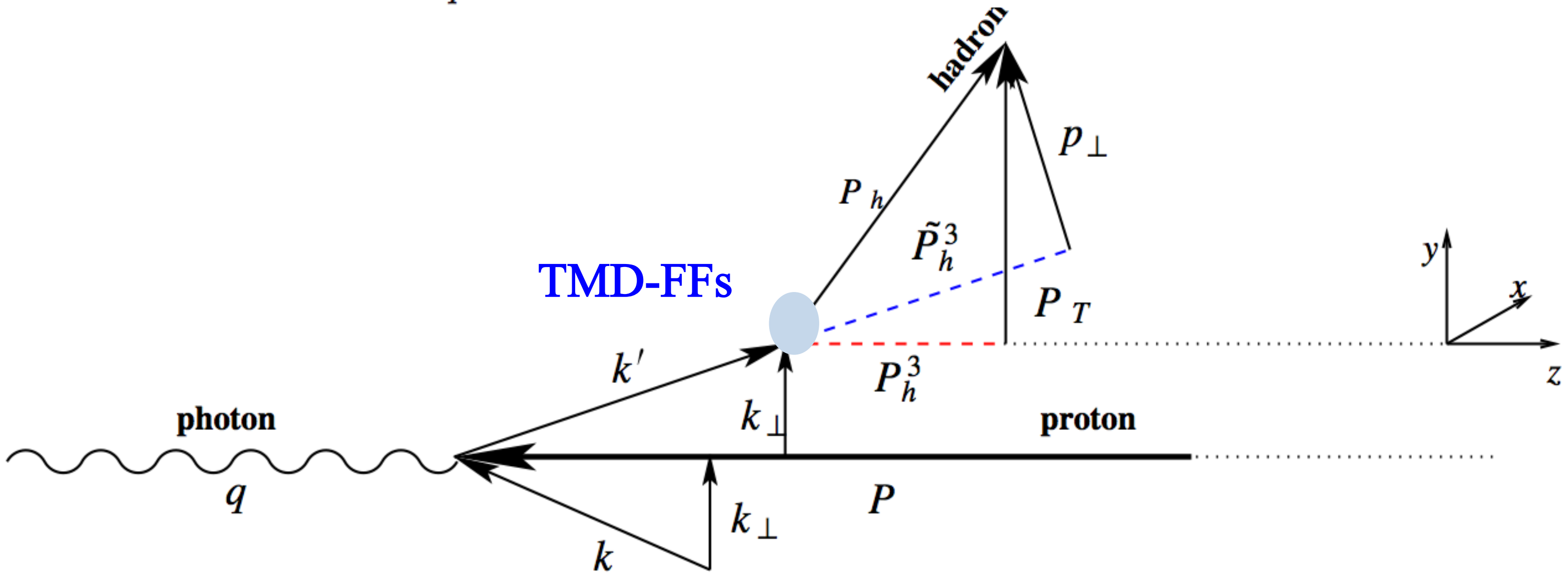
Parton model

$$F_{UU}(x,z,p_T^2;Q^2)=\sum_q e_q^2 x\int dk_\perp dp_\perp \delta(zk_\perp+p_\perp-p_T)f_1^q(x,k_\perp^2,Q^2)D_1^{q\to h}(z,p_\perp^2,Q^2)$$

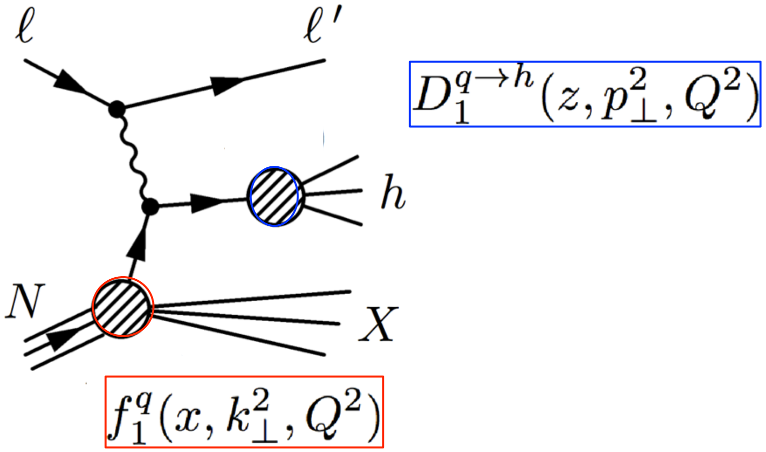


TMD-PDFs

PRD 71, 074006, (2005)

Hadron Multiplicities

Defined as average number of hadrons produced per DIS event



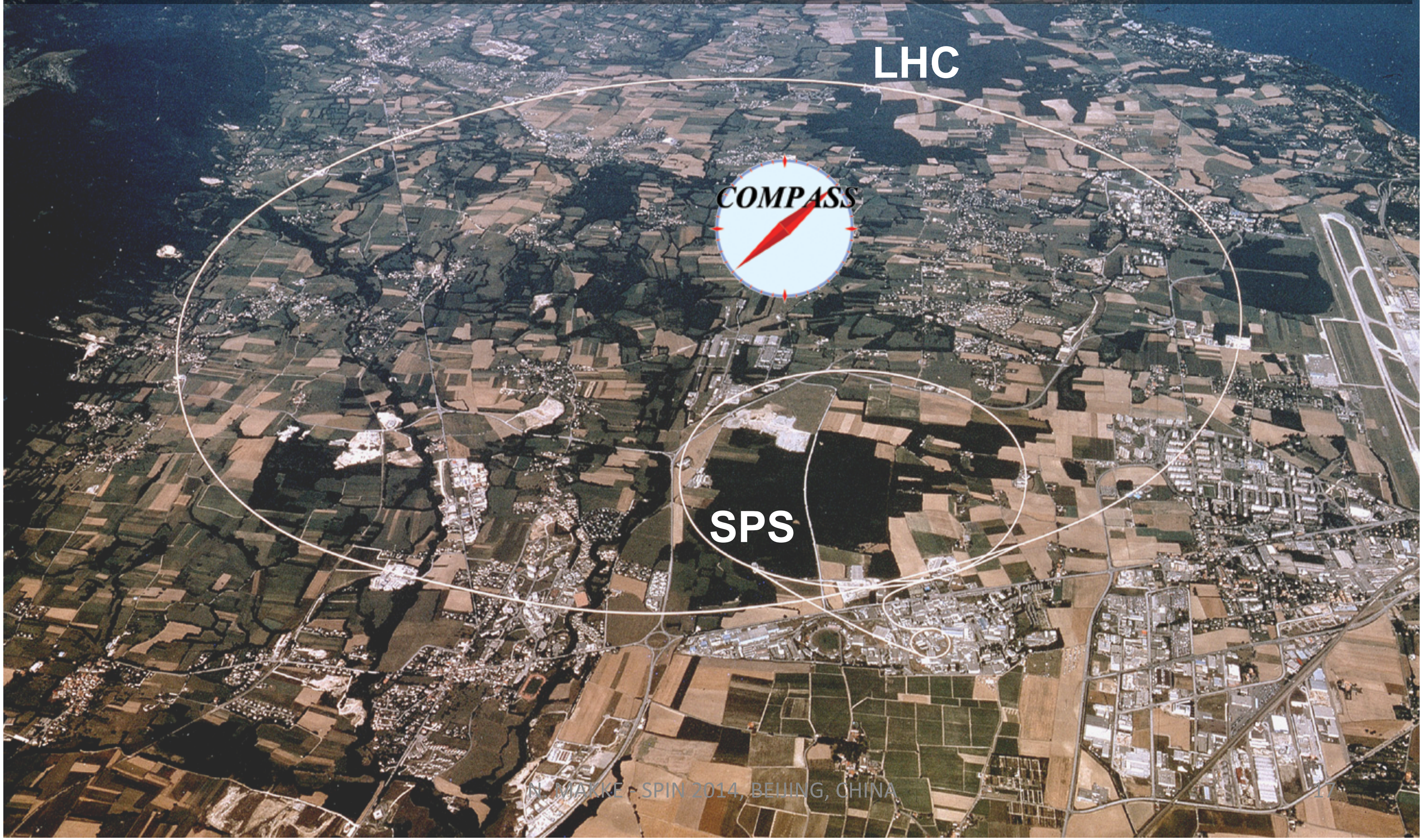
$$M_N^h(x, z, p_T^2, Q^2) = \frac{d^4\sigma_N^h/(dx dz dp_T^2 dQ^2)}{d^2\sigma_{DIS}/(dx dQ^2)} \sim \frac{F_{UU}(x, z, p_T^2; Q^2)}{F_T(x, Q^2)}$$

$$\sim f_1^q(x, k_\perp^2, Q^2) \times D_1^{q\to h}(z, p_\perp^2, Q^2)$$

TMD-PDFs x TMD-FFs

COMPASS:

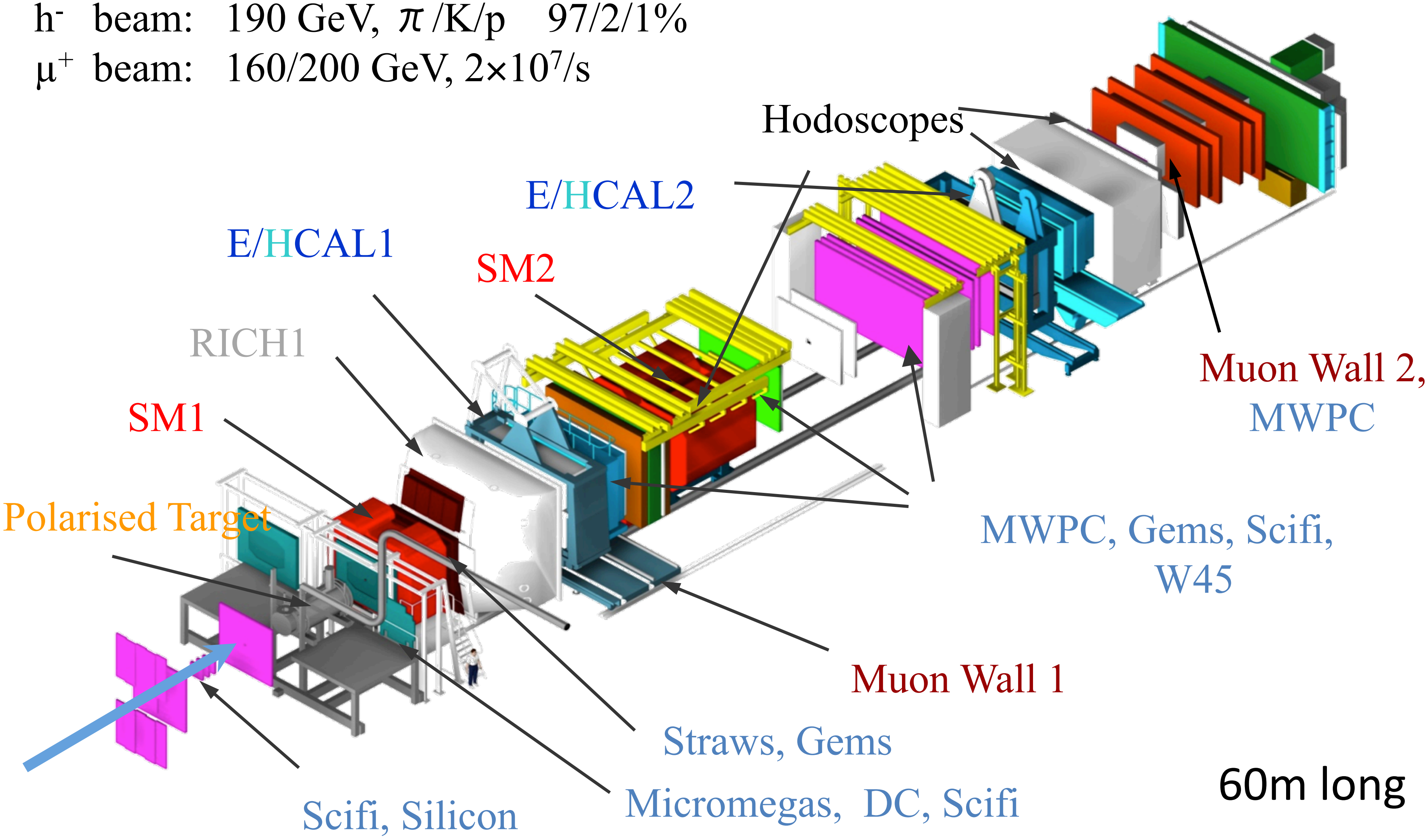
COmmon Muon and Proton Apparatus for Structure and Spectroscopy”



COMPASS spectrometer

h^+ beam: 190 GeV, p/π/K 75/24/1%
h^- beam: 190 GeV, π/K/p 97/2/1%
μ^+ beam: 160/200 GeV, 2×10^7/s

Data taking since 2002



60m long

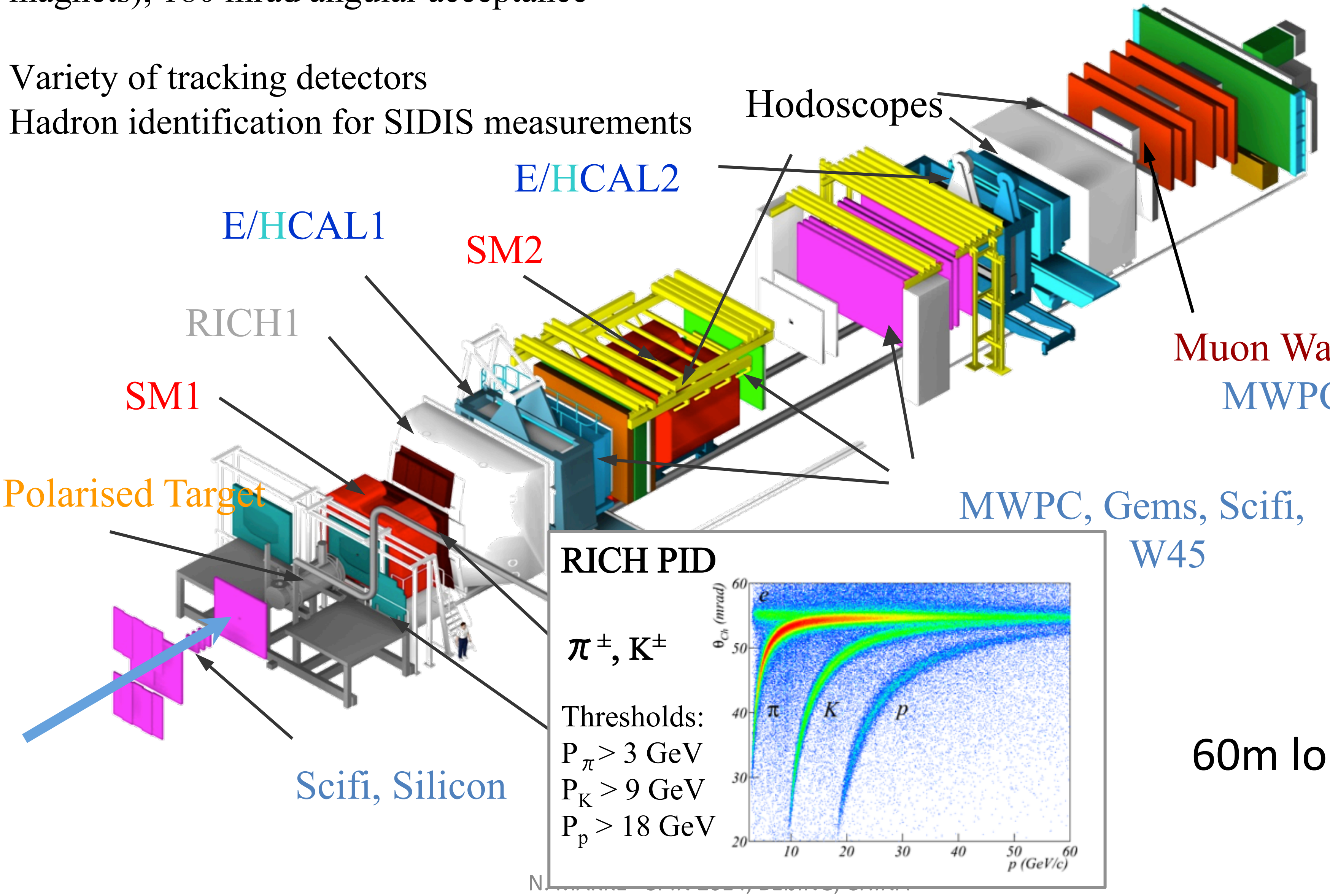
COMPASS spectrometer

Two stages spectrometer (with SM1/2 magnets), 180 mrad angular acceptance

Data taking since 2002

Variety of tracking detectors

Hadron identification for SIDIS measurements



Hodoscopes

E/HCAL2

E/HCAL1

SM2

RICH1

SM1

Muon Wall 2, MWPC

Polarised Target

MWPC, Gems, Scifi, W45

Scifi, Silicon

RICH PID

$\pi^{\pm}$, $K^{\pm}$

Thresholds:

$P_{\pi} > 3$ GeV

$P_K > 9$ GeV

$P_p > 18$ GeV

60m long

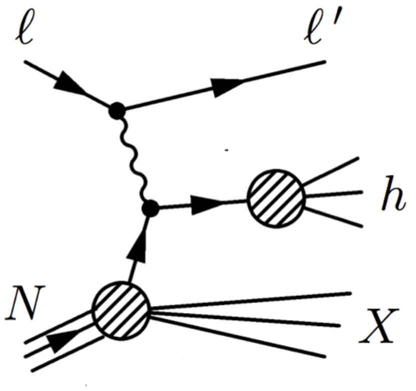
Results on unpolarized SIDIS data ($Q^2 > 1$ $(GeV/c)^2$)

160 GeV/c μ-d (data taken in 2004 & in 2006)

- Single-hadron multiplicities (2006)
  - vs. (x,y,z) ➠ F. Kunne's talk
  - vs. (x,Q^2,z,p_T^2) ✔
- Hadron-pair multiplicities (2004) ✔
- Unpolarized azimuthal asymmetries ➠ A. Martin's talk

Hadron Multiplicities – Experimental extraction

Defined as average number of hadrons produced per DIS interaction



Experimentally measured number of DIS and hadrons binned in (x,Q^2,z,p_T^2)

$$M_N^h(x,z,p_T^2,Q^2) = \frac{N^h(x,Q^2,z,p_T^2)}{N^{DIS}(x,Q^2)} \times \eta^{qed} \times \frac{1}{\epsilon^h(x,z,p_T^2,Q^2)}$$

QED radiative effects

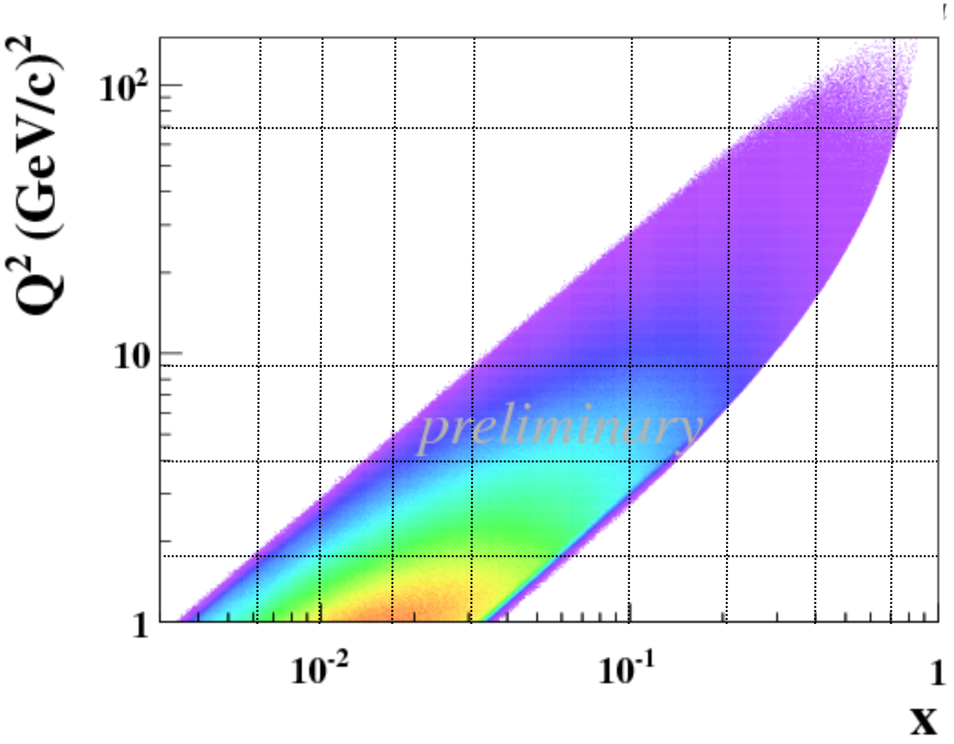
Acceptance and smearing effects evaluated and applied in each (x,Q^2,z,p_T^2) bin

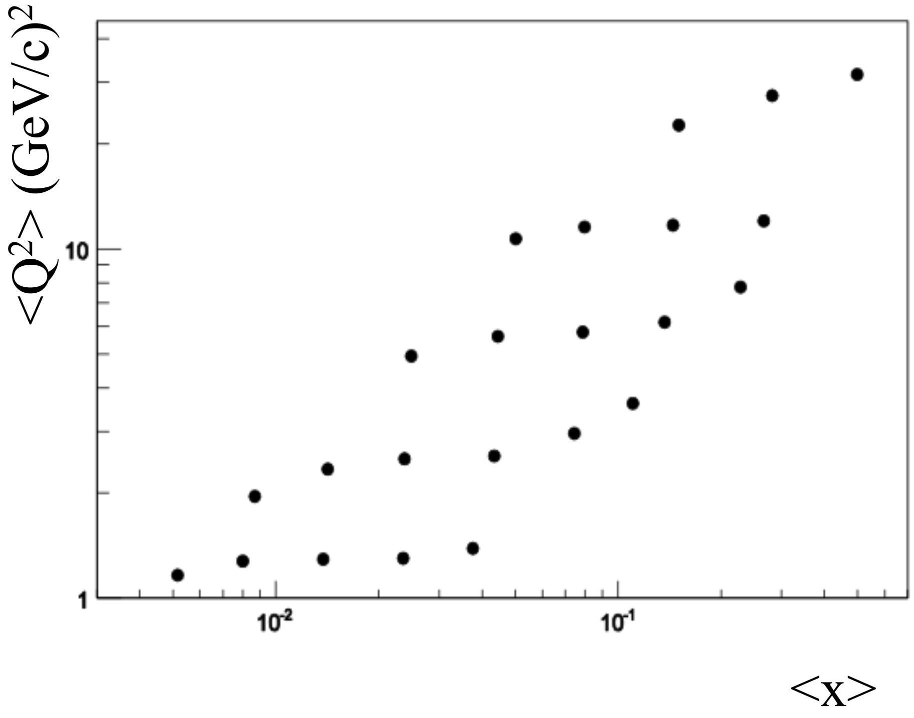
Hadrons from diffractive vector meson production evaluated vs. (z,Q^2) & (z,p_T) without applying any correction

Data set & Multi-dimensional analysis

SIDIS data sample collected in 2006

- ○ Large angular acceptance
- ○ Very good π /K PID efficiency
- ○ Large statistics sample



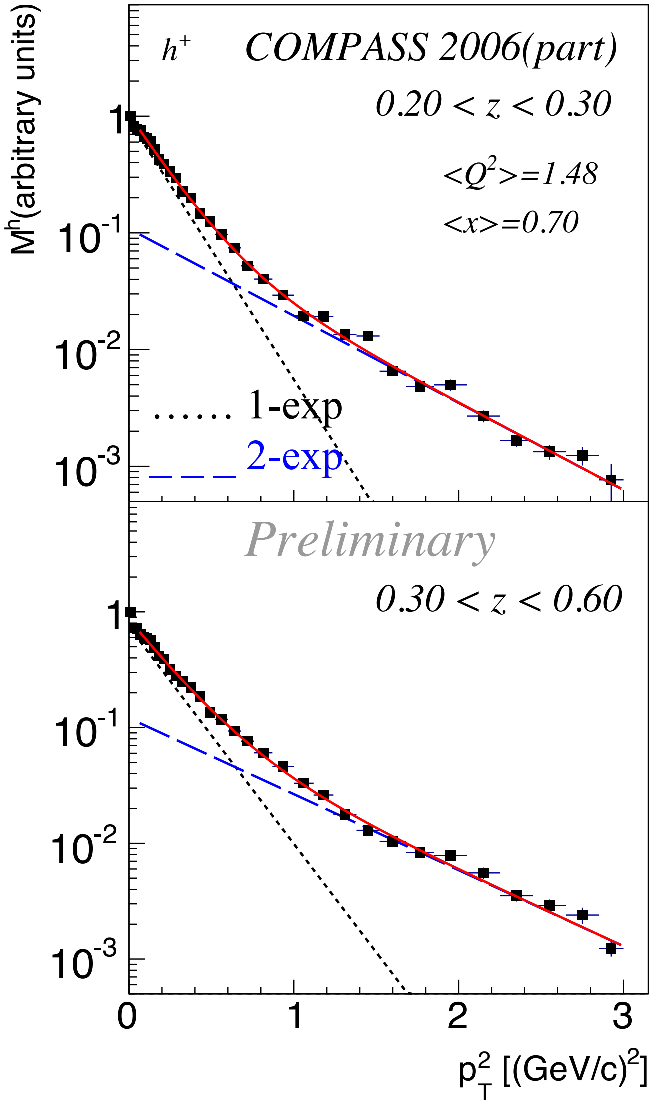


Multi dimensional analysis in x, Q^2, z, $p_T{}^2$ bins

Common binning for SSAs and unpolarized measurements

p_T^2 – dependent distributions vs. (x,z,p_T^2,Q^2) for h^+

Transversity, June 2014

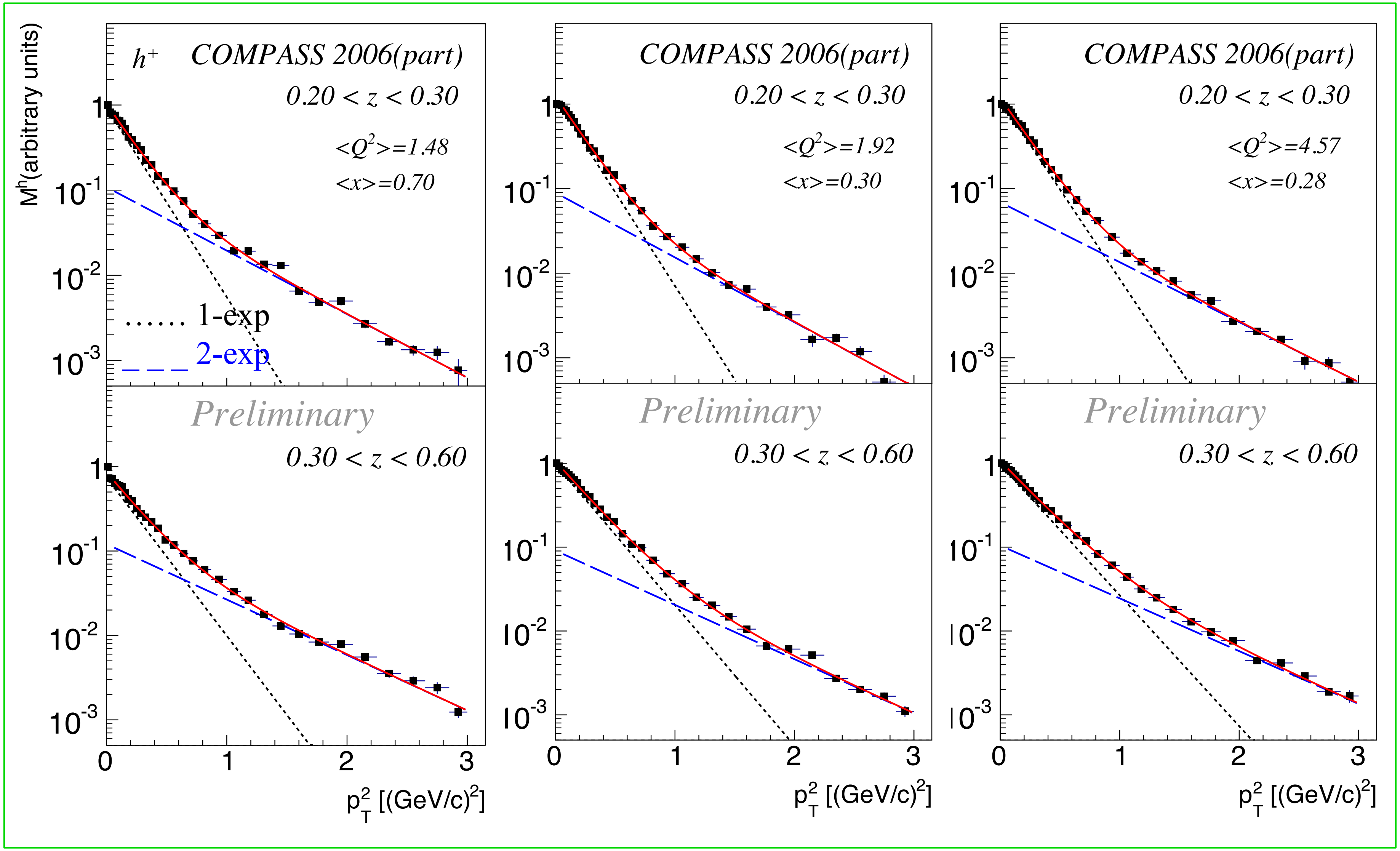


- Precise measurement using 2006 data with larger angular acceptance
- p_T^2 range extended to 3 $(\mathrm{GeV}/c)^2$
- Very promising to extract physics on transverse momentum dependent PDFs and FFs
- Fit multiplicities with
  - 1-exponential for $p_T^2 \in [0.05, 0.68]$
  - 2-exponentials for $p_T^2 \in [0.05, 3]$
  - ⇒ Need 2-exponentials to describe p_T^2 shape of COMPASS data
- Ongoing analysis to extract complete set of multiplicities in full kinematic domain

p_T^2 – dependent distributions vs. (x,z,p_T^2,Q^2) for h^+

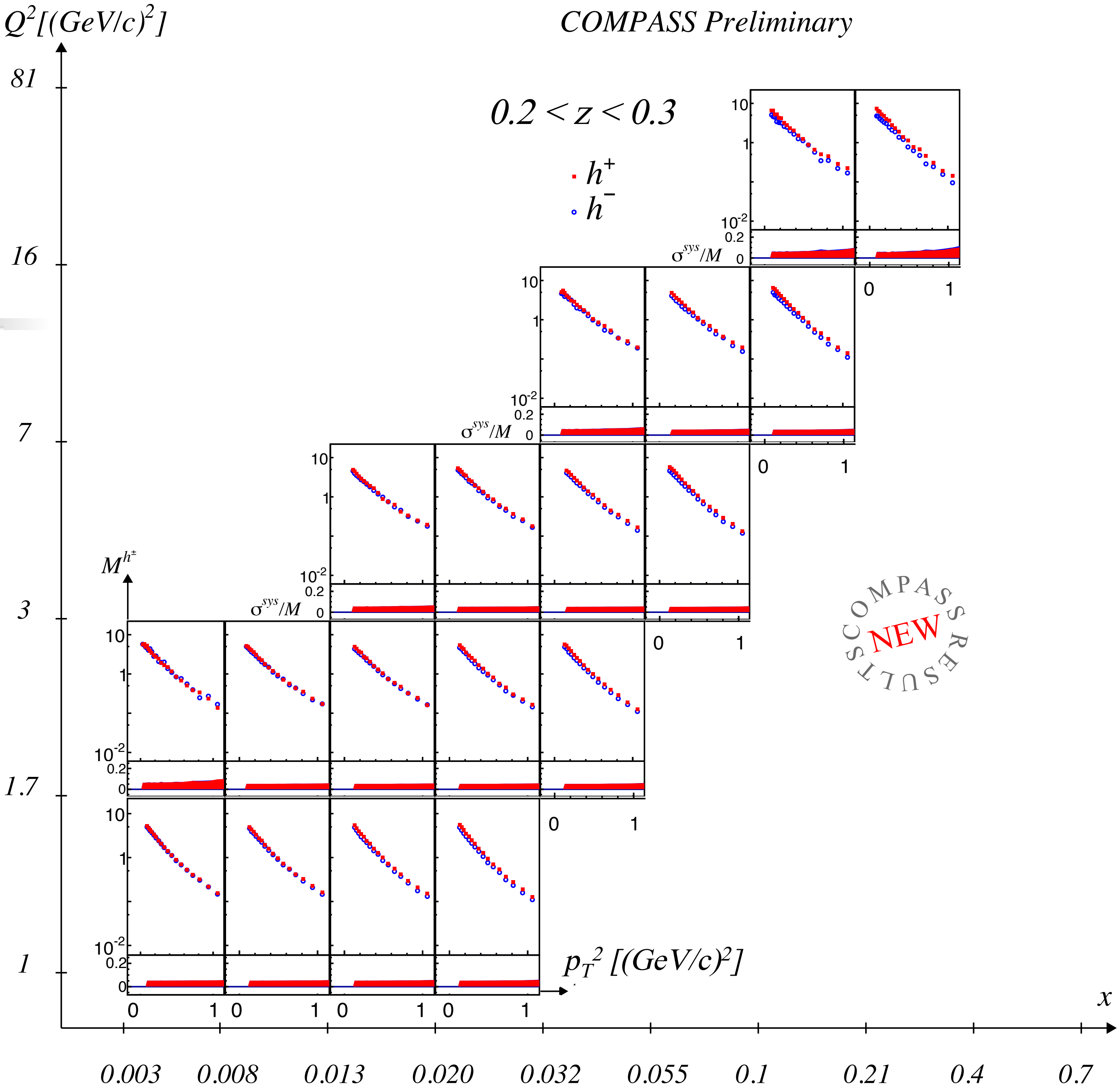
Transversity, June 2014

… Only 3 (x,Q^2) bins released



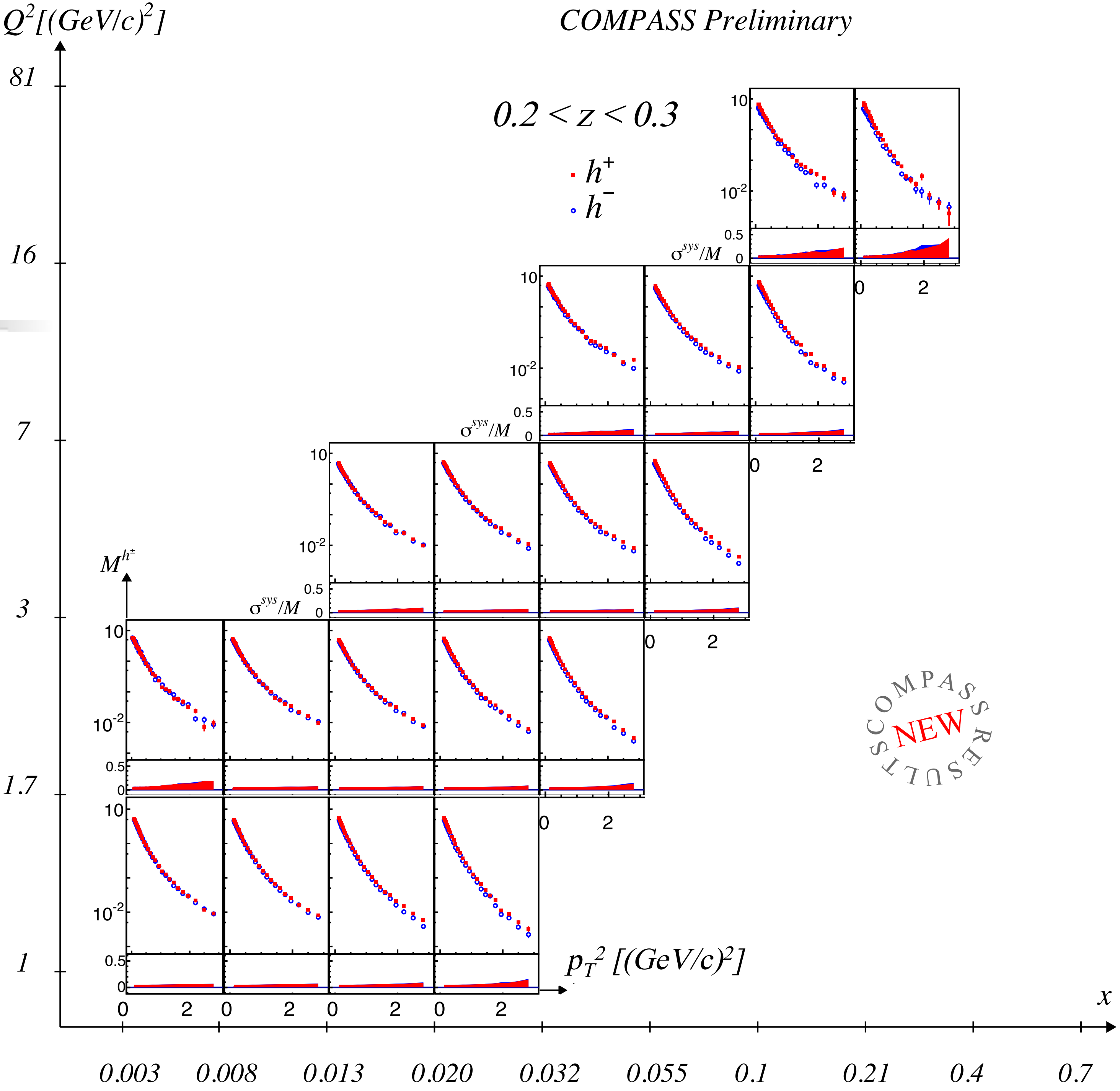
$p_T{}^2$ – dependent multiplicities vs. (x,Q^2,z) for $h^\pm$

$p_T{}^2 \leq 1$



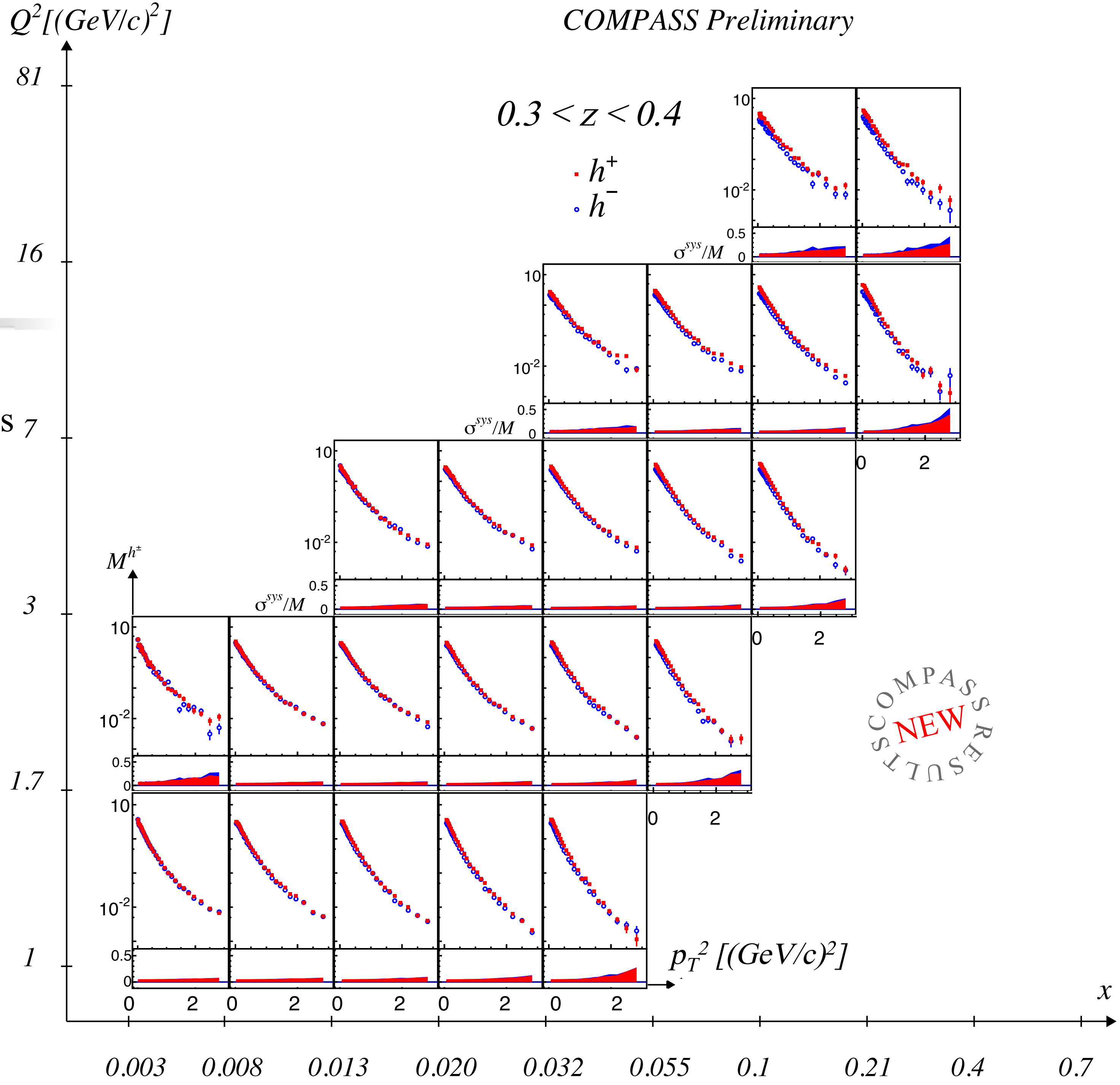
p_T^2 – dependent multiplicities vs. (x,Q^2,z) for $h^\pm$

- 968 experimental data points, valuable input for phenomenology TMDs extraction
- Wide (x,Q^2; 9x5 bins) experimental coverage
- p_T^2 range up to 3 $(GeV/c)^2$



p_T^2 – dependent multiplicities vs. (x,Q^2,z) for $h^\pm$

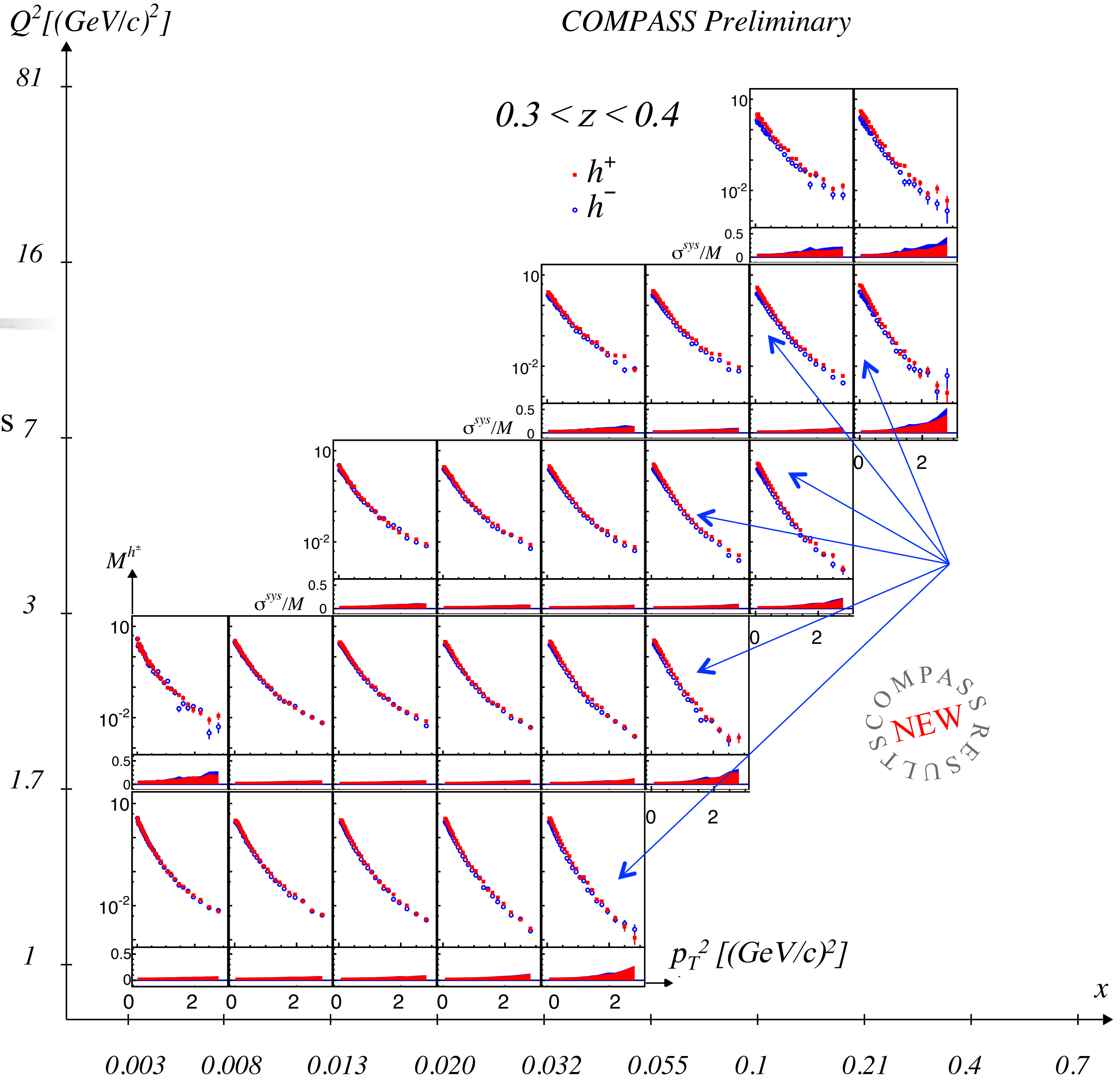
- 968 + 1326 experimental points



p_T^2 – dependent multiplicities vs. (x,Q^2,z) for $h^\pm$

- 968 + 1326 experimental points
- At large x, h^+/h^- difference more pronounced

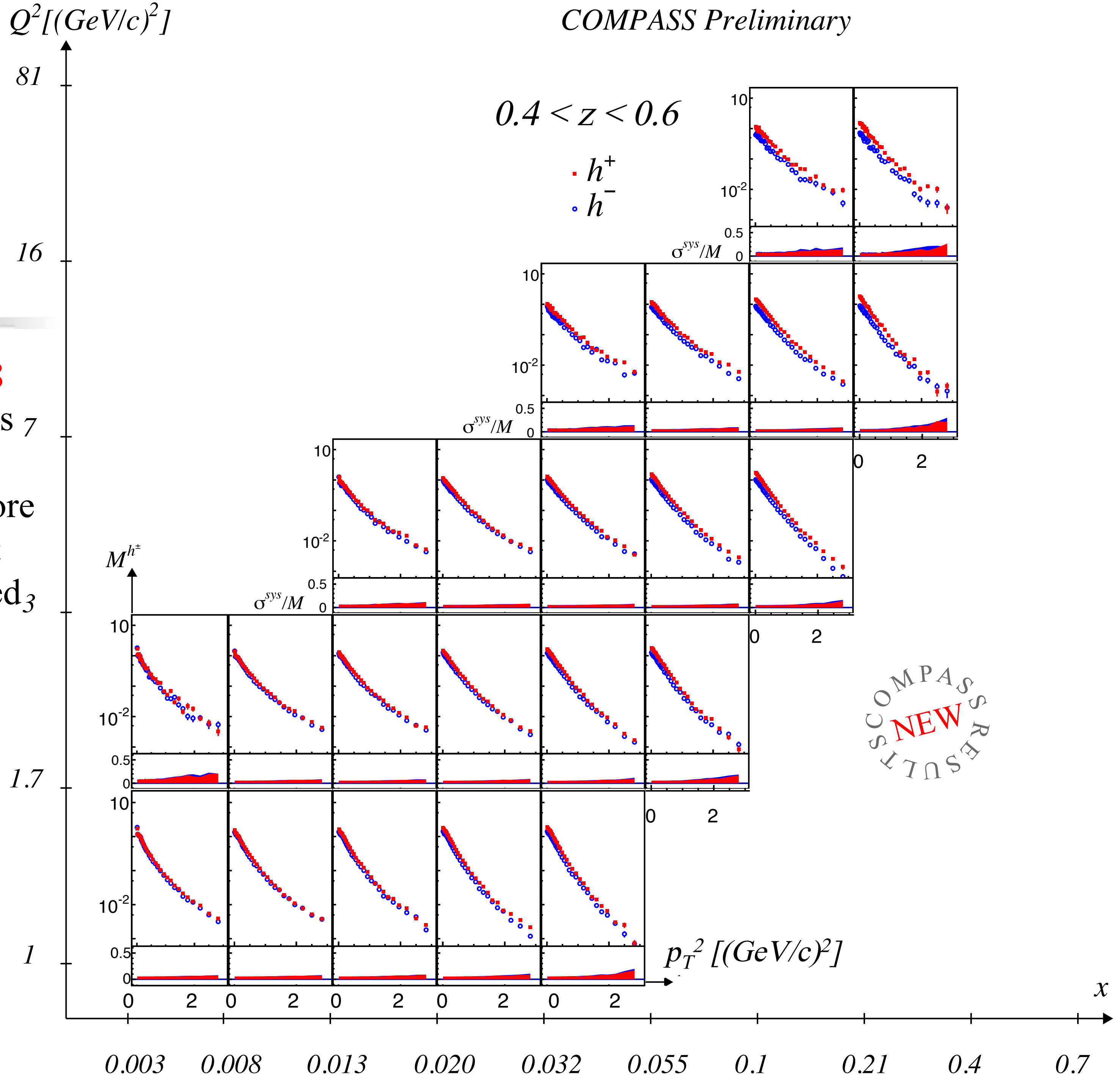
→ Expected as h^+ composition at large x is dominated by valence quark, in contrary to h^-



p_T^2 – dependent multiplicities vs. (x,Q^2,z) for $h^\pm$

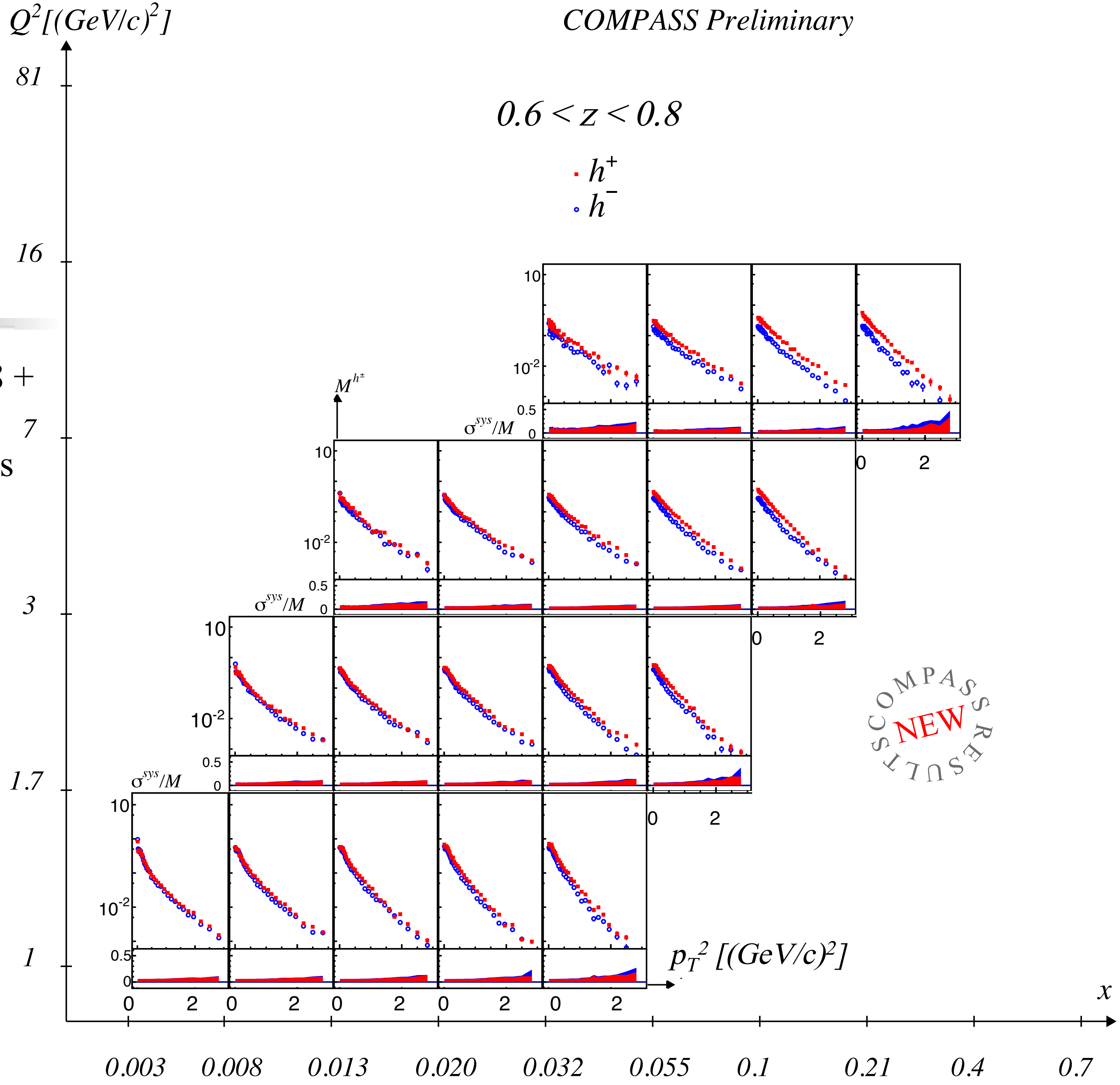
- 968 + 1326 + 1408 experimental points
- h^+/h^- difference more pronounced also at large z ⇔ generated by FFs

$D_u^{\pi+} >>> D_u^{\pi-}$



p_T^2 – dependent multiplicities vs. (x,Q^2,z) for $h^\pm$

- 968 + 1326 + 1408 + 1216 ➔ 4918 experimental points



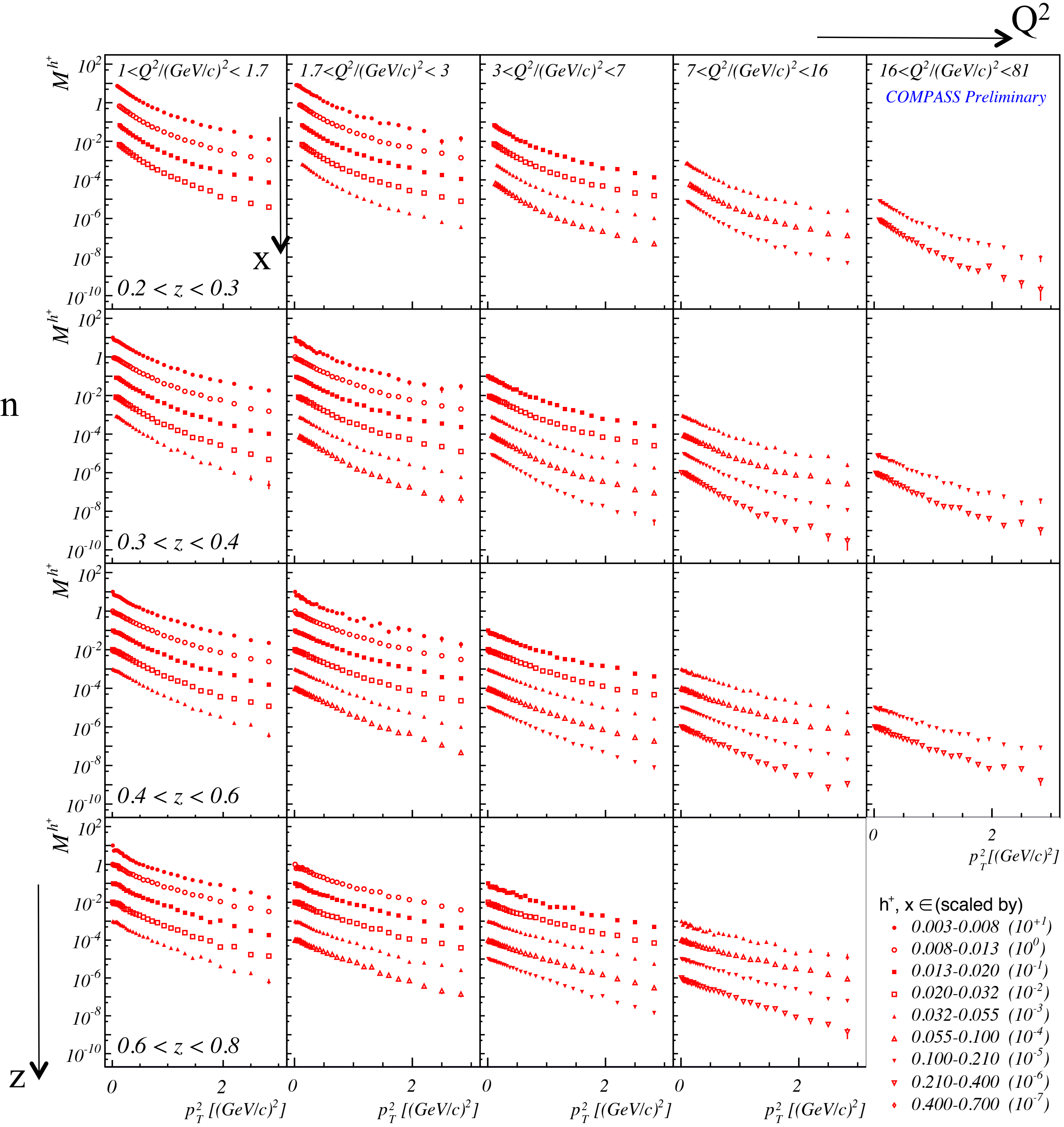
p_T^2 – dependent multiplicities vs. (x,Q^2,z) for h^+

Only statistical errors shown

h^+, $x \in$ (scaled by)

- ● *0.003-0.008* (10^{+1})
- ○ *0.008-0.013* (10^{0})
- ■ *0.013-0.020* (10^{-1})
- □ *0.020-0.032* (10^{-2})
- ▲ *0.032-0.055* (10^{-3})
- △ *0.055-0.100* (10^{-4})
- ▼ *0.100-0.210* (10^{-5})
- ▽ *0.210-0.400* (10^{-6})
- ♦ *0.400-0.700* (10^{-7})

COMPASS NEW RESULTS

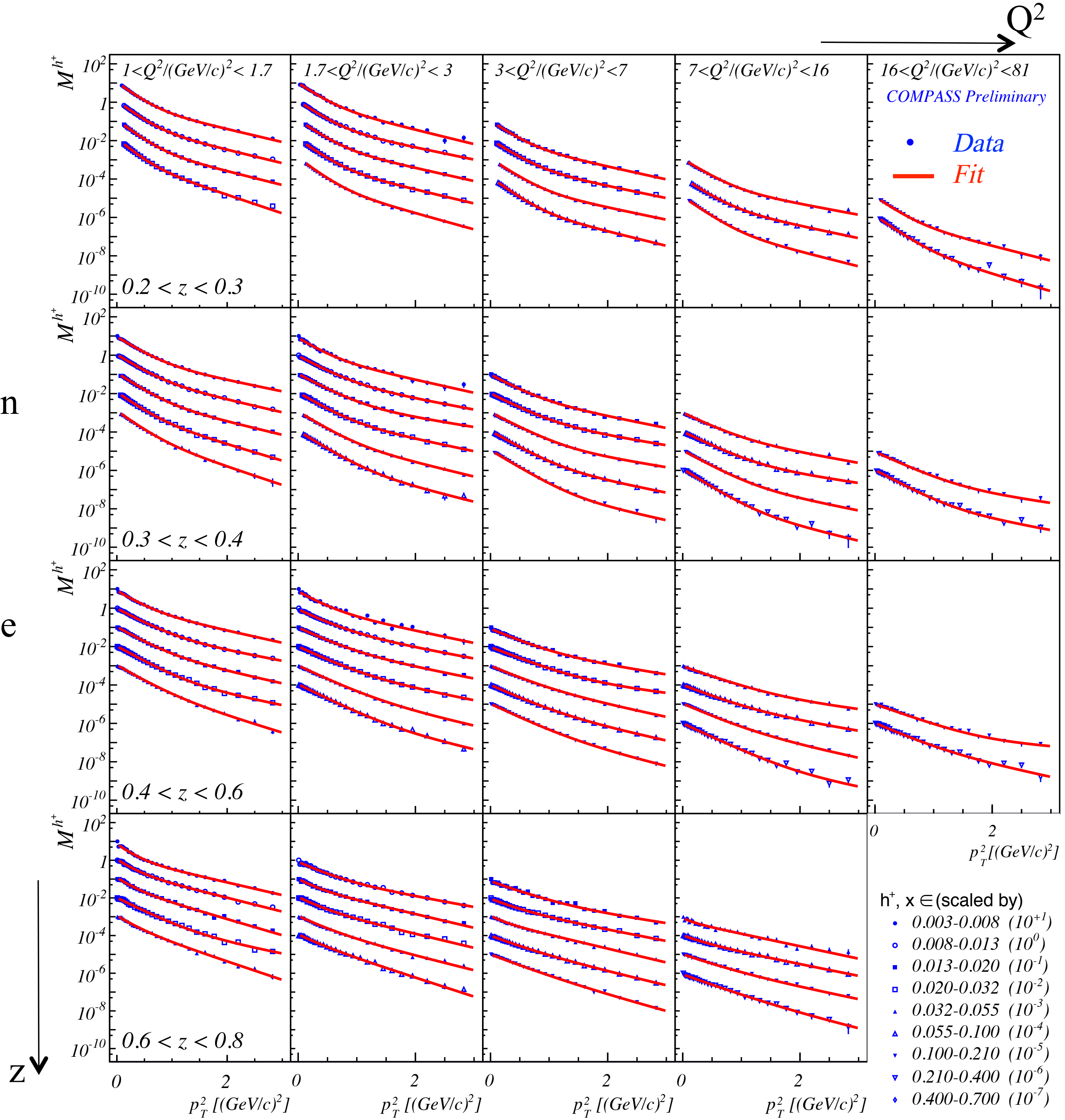


p_T^2 – dependent multiplicities vs. (x,Q^2,z) for h^+

Only statistical errors shown

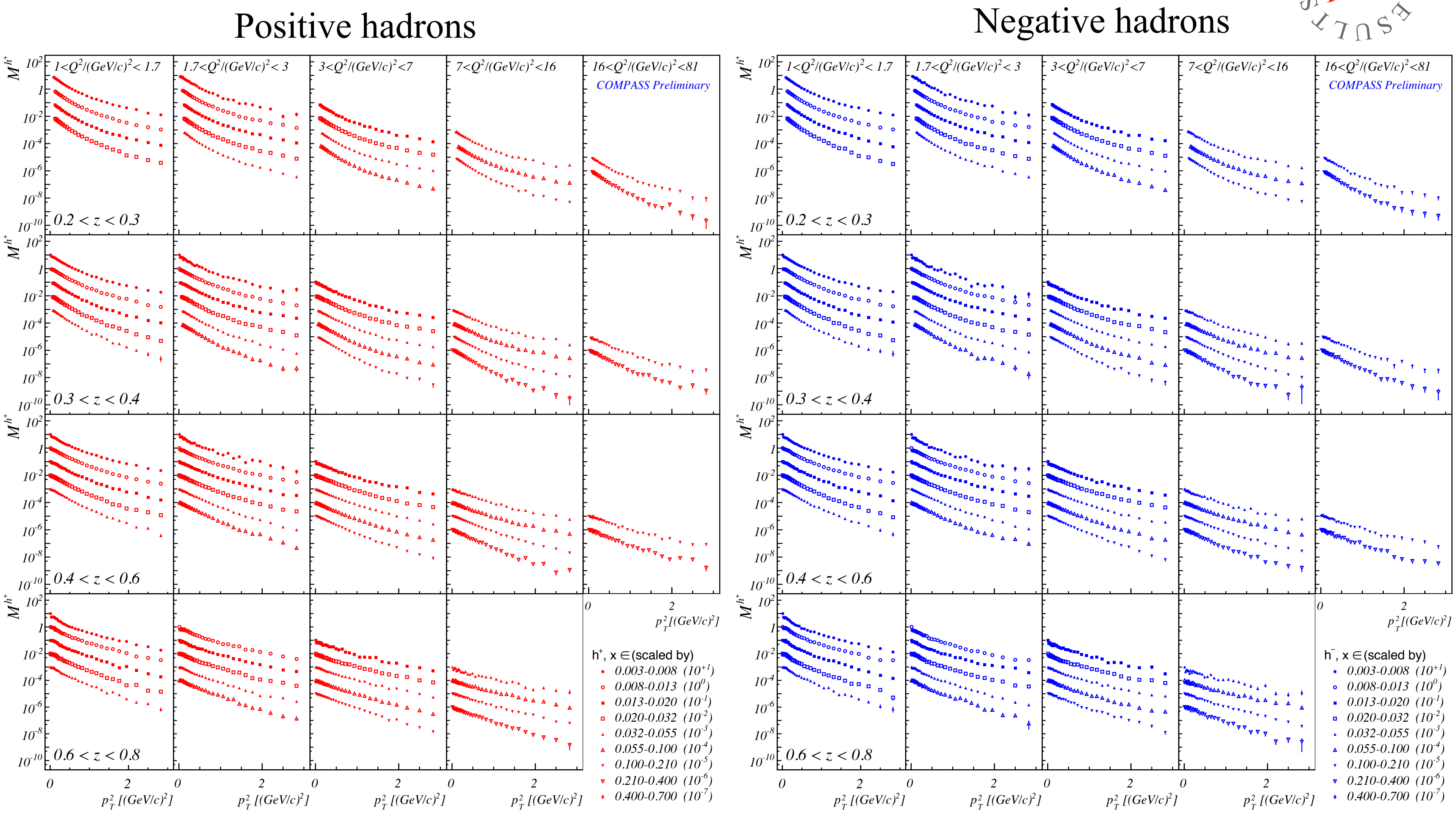
Fitted with 2-exponentials function $a.e^{-\alpha pt2} + b.e^{-\beta pt2}$

- ➢ Describes well the shape (and magnitude) of data points



p_T^2 – dependent multiplicities vs. (x,Q^2,z,p_T^2) for $h^\pm$

COMPASS NEW RESULTS

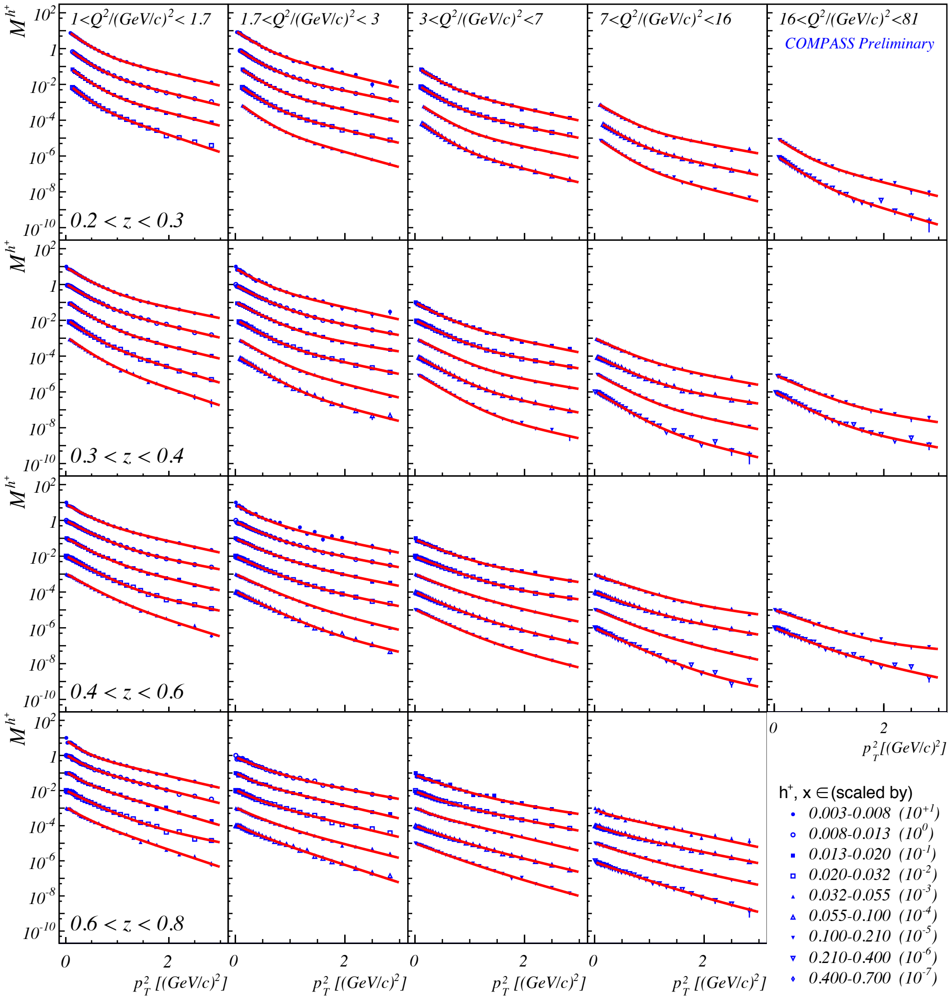

Positive hadrons

Negative hadrons

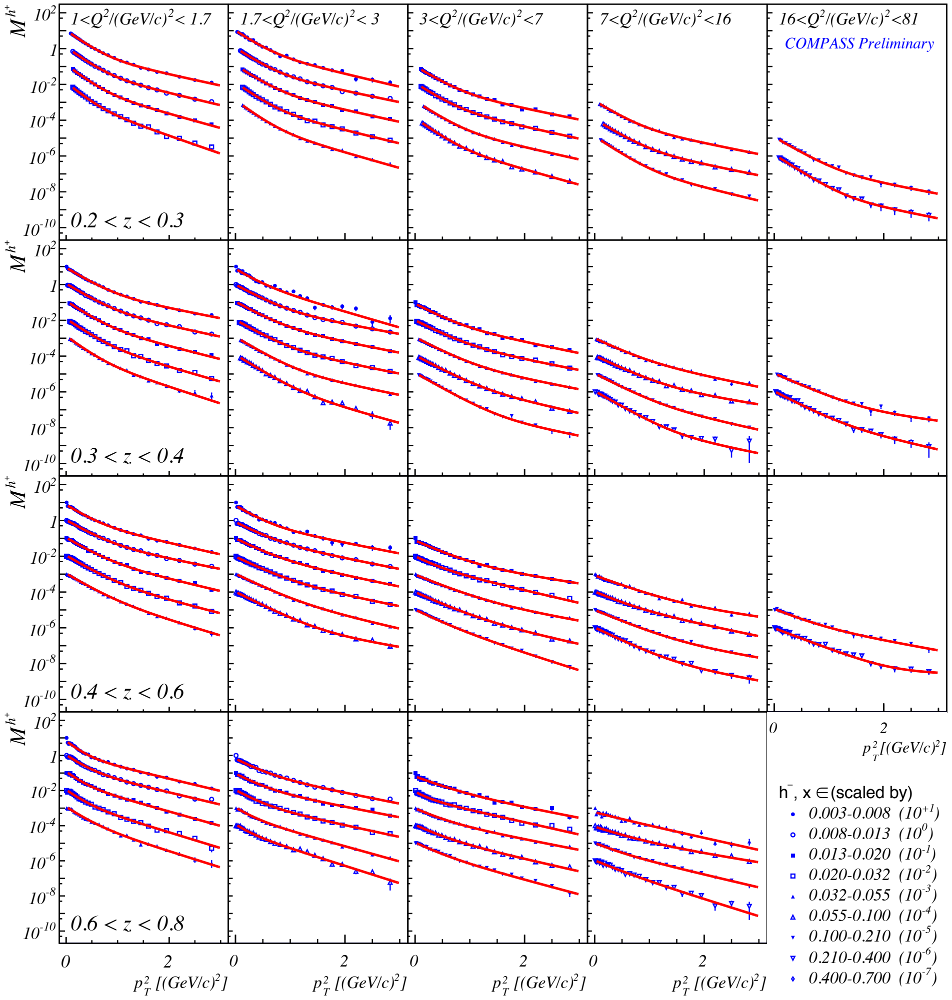
p_T^2 – dependent multiplicities vs. (x,Q^2,z,p_T^2) for $h^\pm$

COMPASS NEW RESULTS

Positive hadrons

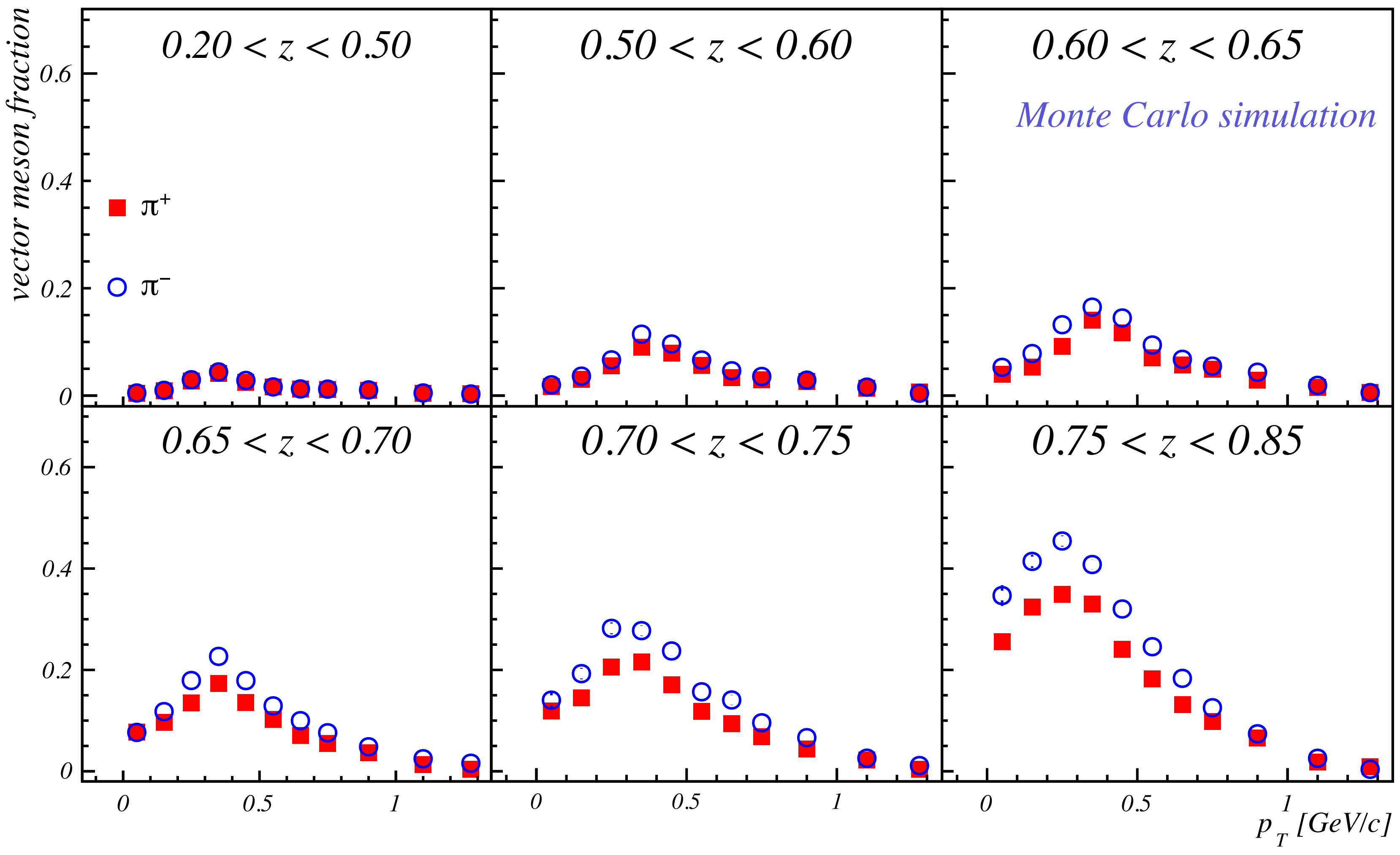


Negative hadrons



Very good description of shape of experimental data fitting with $a.e^{-\alpha pt2} + b.e^{-\beta pt2}$

2006 – DVMP Contribution to SIDIS hadrons



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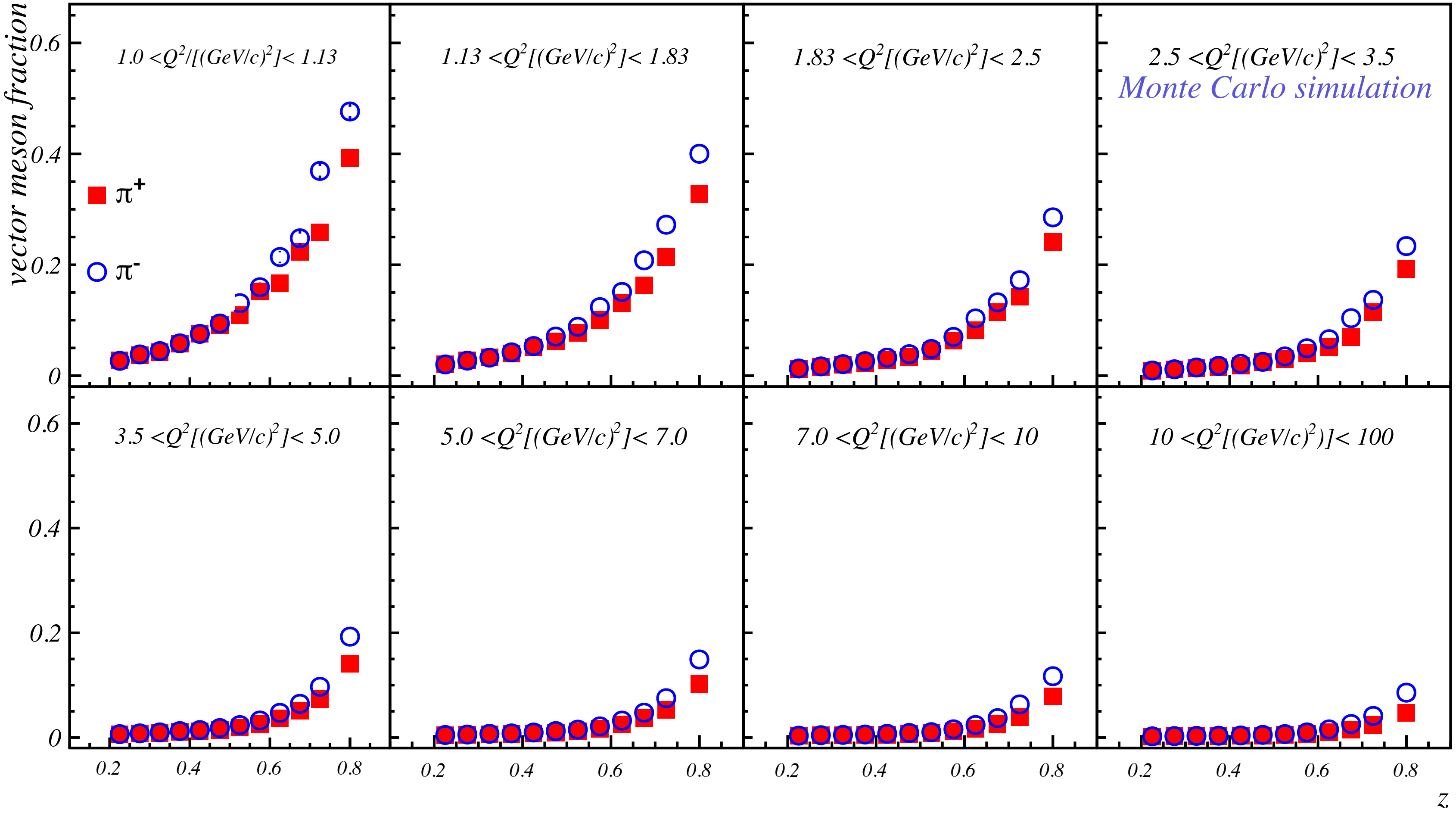

Results on unpolarized SIDIS data ($Q^2 > 1$ $(GeV/c)^2$)

160 GeV/c μ-d (data taken in 2004 & in 2006)

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  - vs. (x,Q^2,z,p_T^2) ✔
- Hadron-pair multiplicities (2004) ✔
- Unpolarized azimuthal asymmetries ➟ A. Martin's talk

Hadron pair multiplicities

motivation:

Transversity from hadron pair transverse spin asymmetry

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

But Di-hadron fragmentation functions unknown

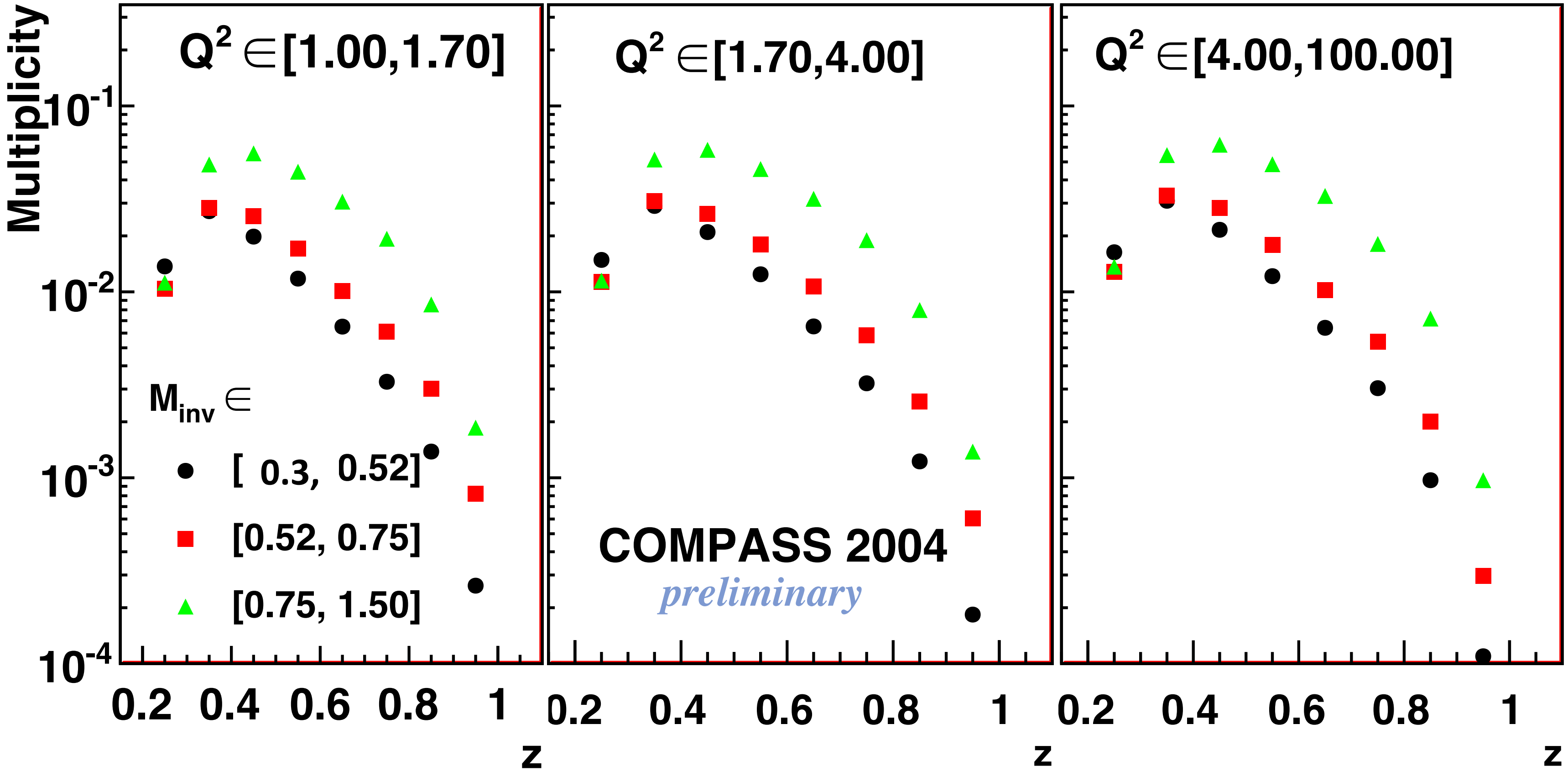
➠ Extract them via hadron pair multiplicities

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

Hadron pair multiplicities

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

First measurement in M_{inv}, $z=z_1+z_2$, Q^2 bins

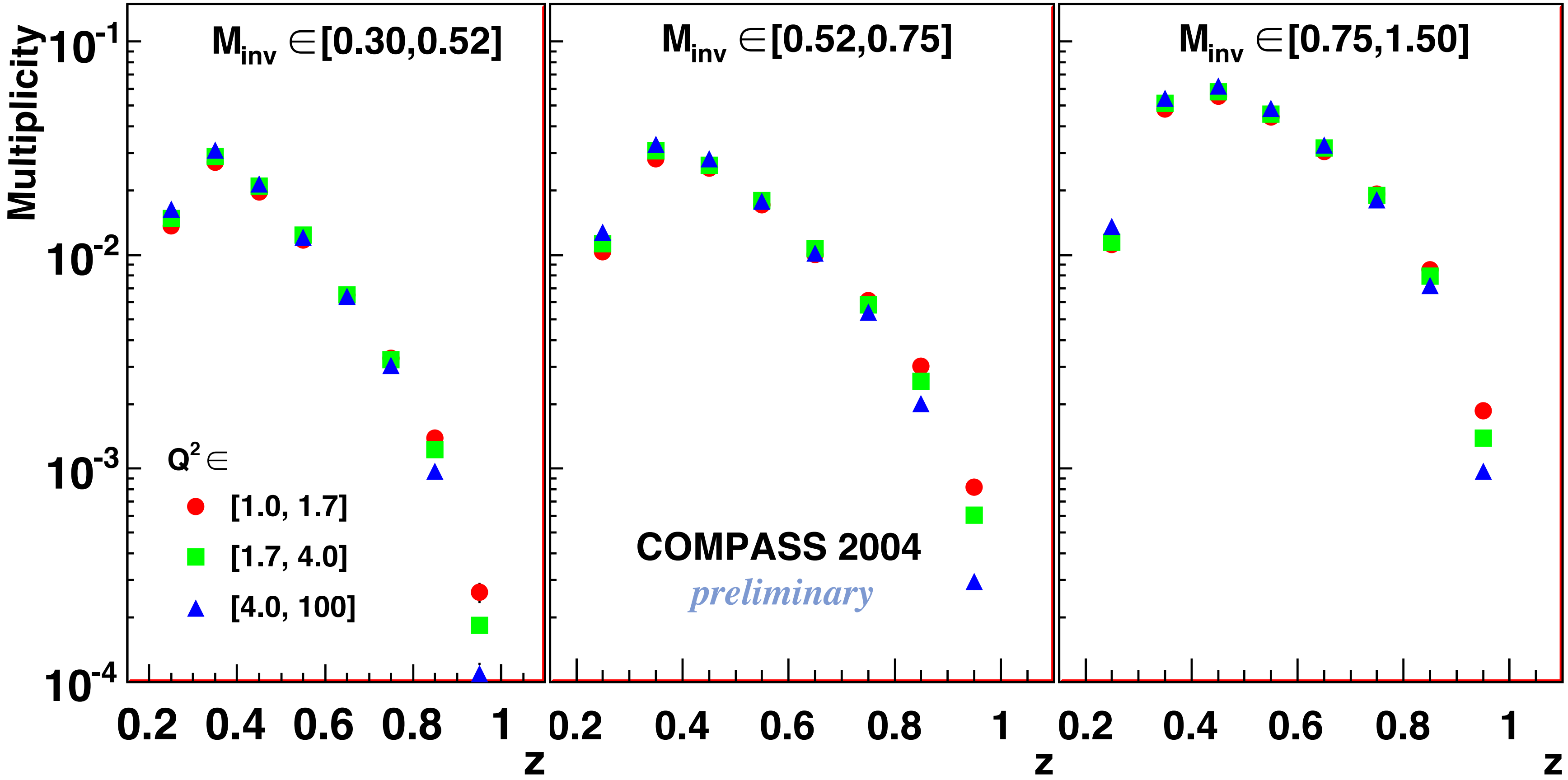


Significant z,M_{inv} dependence compatible with LEPTO's expectation

Hadron pair multiplicities

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

First measurement in M_{inv}, $z=z_1+z_2$, Q^2 bins



Weak Q^2 dependence

Summary & conclusions

New Extraction of transverse-momentum dependent multiplicities

- versus (x,Q^2,z) ⇔ 81 kinematic bins
- 4918 experimental data points
- Input to phenomenology analyses for TMDs extraction
- h^+/h^- difference clearly visible at large x and large z as expected

… and more to come from 2006 deuteron data

- p_T^2-dependent multiplicities for pions
- Hadron pair multiplicities

Future:

Measurements with proton target, in parallel to DVCS planned for 2016-2017

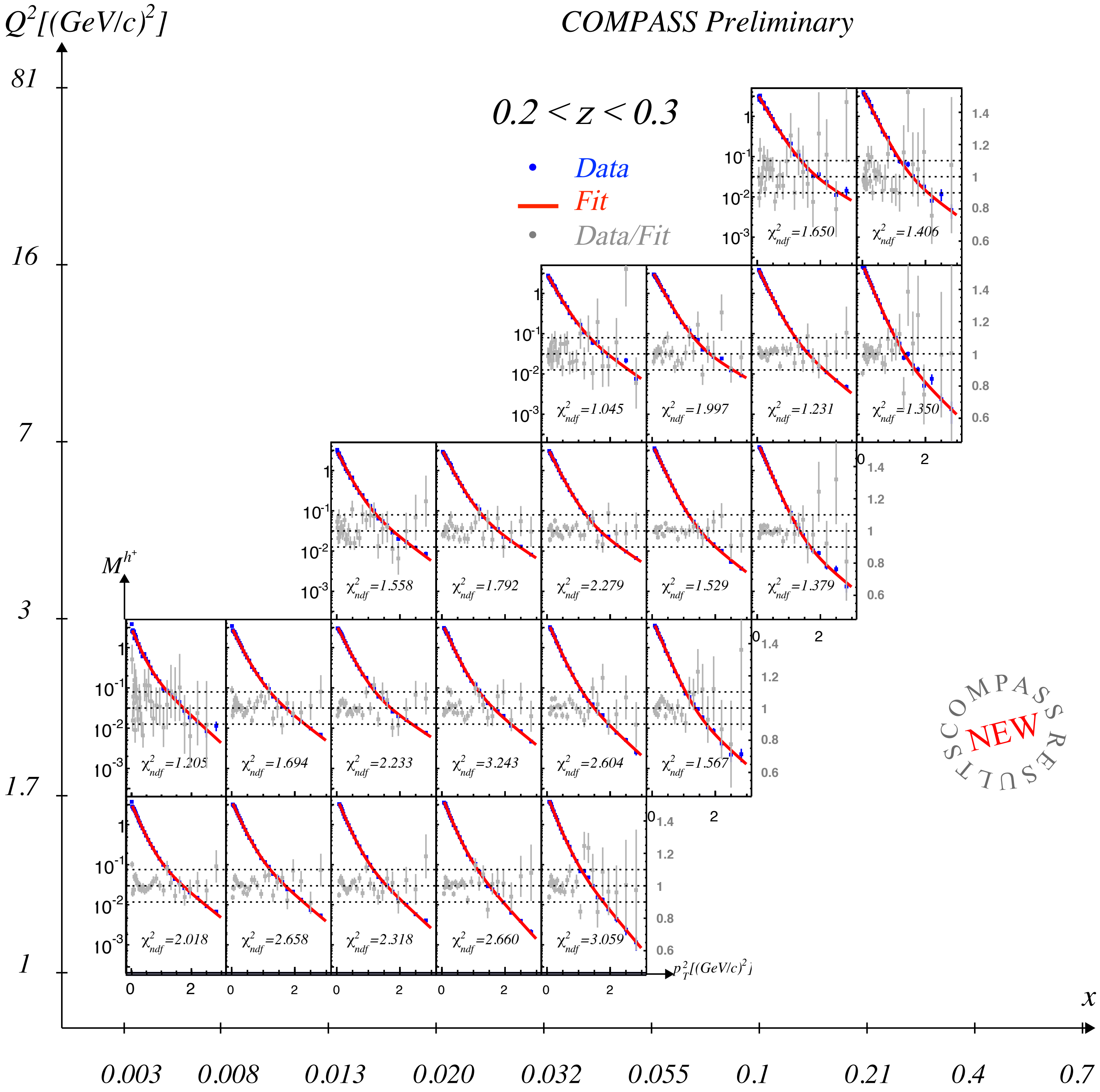
Thank you !

Additional Slides

$$M^{h+}(x,Q^2,z,p_T^2)$$

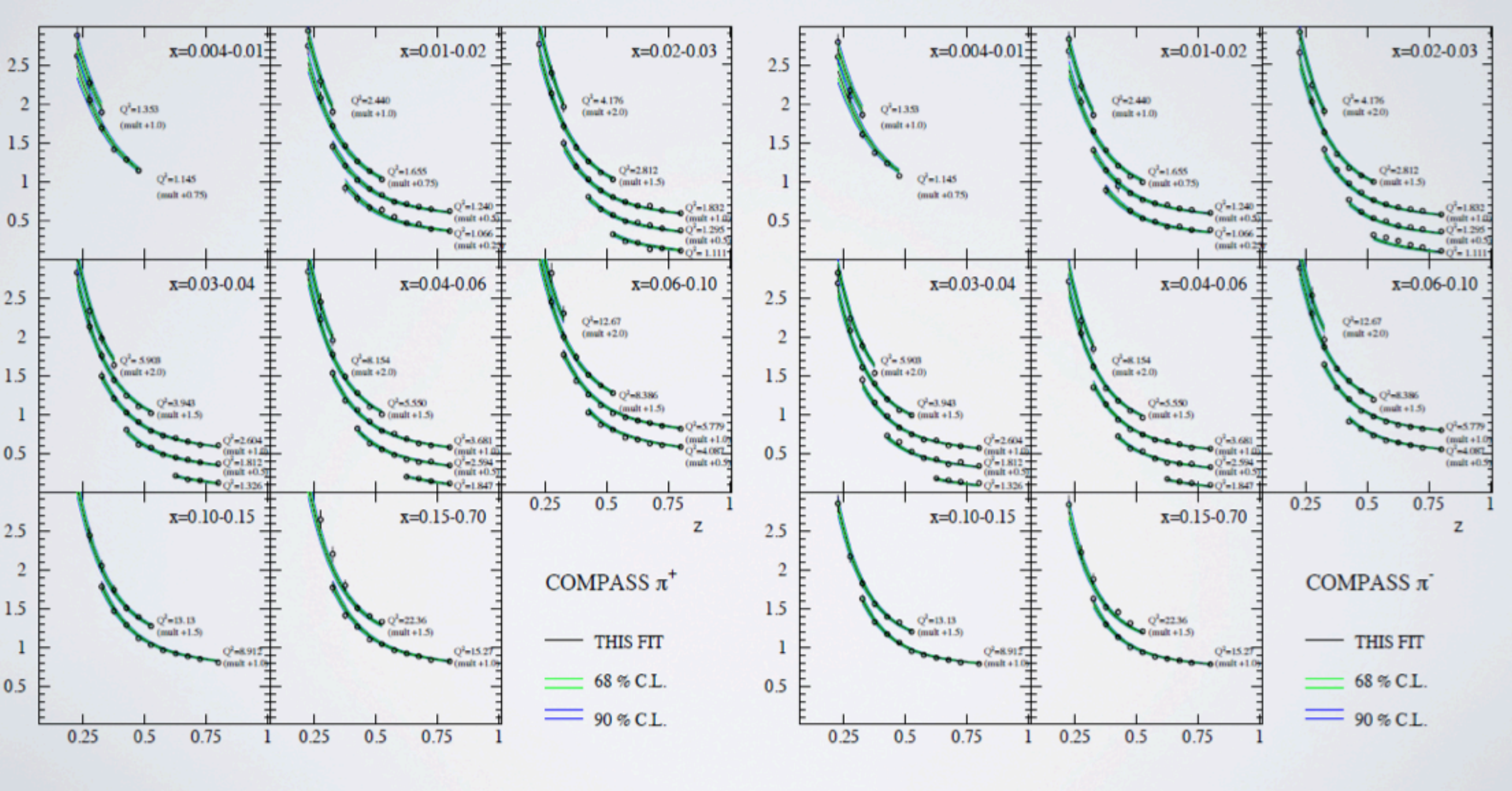
vs.

$$a.e^{-\alpha pt2} + b.e^{-\beta pt2}$$



COMPASS NEW RESULTS

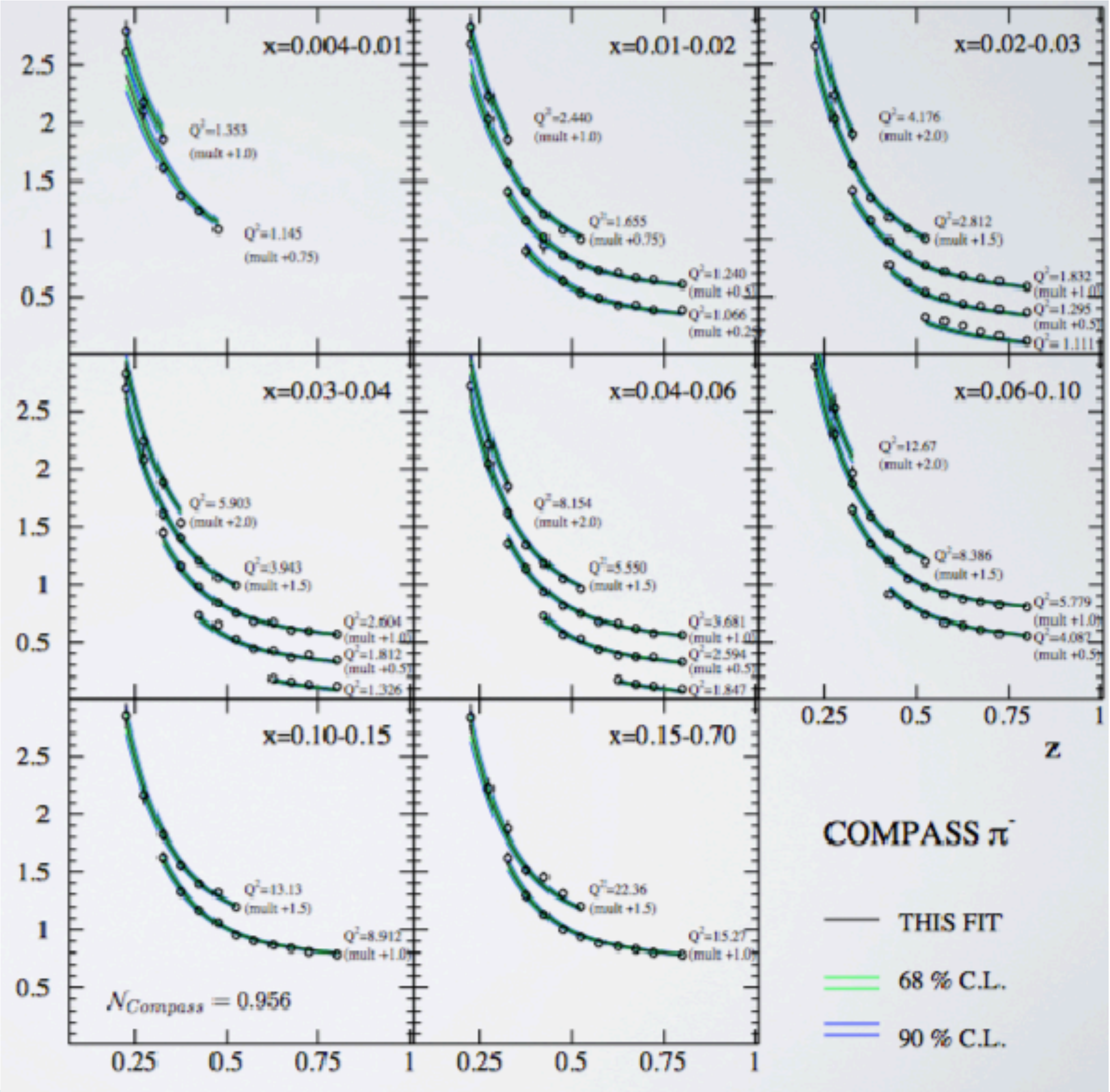
COMPASS p_T-integrated multiplicities



R. Sassot,
Indiana-Illinois workshop on Fragmentation Functions,
Bloomington, IN, December 2013

COMPASS p_T integrated multiplicities

COMPASS results
DIS 2013



R. Sassot,
Indiana-Illinois workshop
on FFs, Bloomington, IN,
December 2013