Transverse momentum distributions in SIDIS at COMPASS

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Trieste University and INFN

SPIN2021
Matsue, Japan
24th International Spin Symposium
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COMPASS

***Co**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy*

fixed target experiment at the CERN SPS

proposed in 1997

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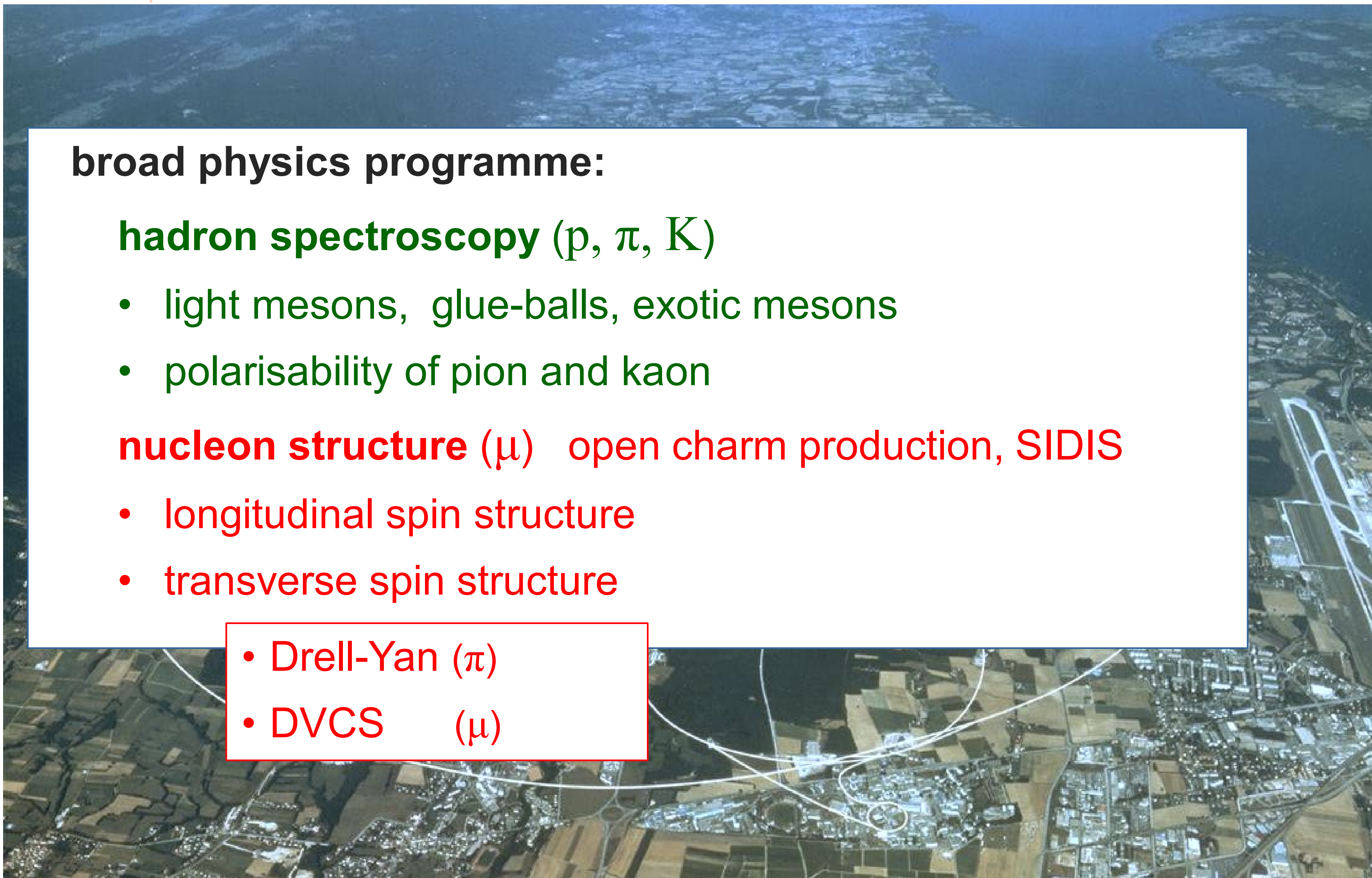


broad physics programme:

hadron spectroscopy (p, π, K)

- light mesons, glue-balls, exotic mesons
- polarisability of pion and kaon

nucleon structure (μ) open charm production, SIDIS

- longitudinal spin structure
- transverse spin structure

- Drell-Yan (π)
- DVCS (μ)

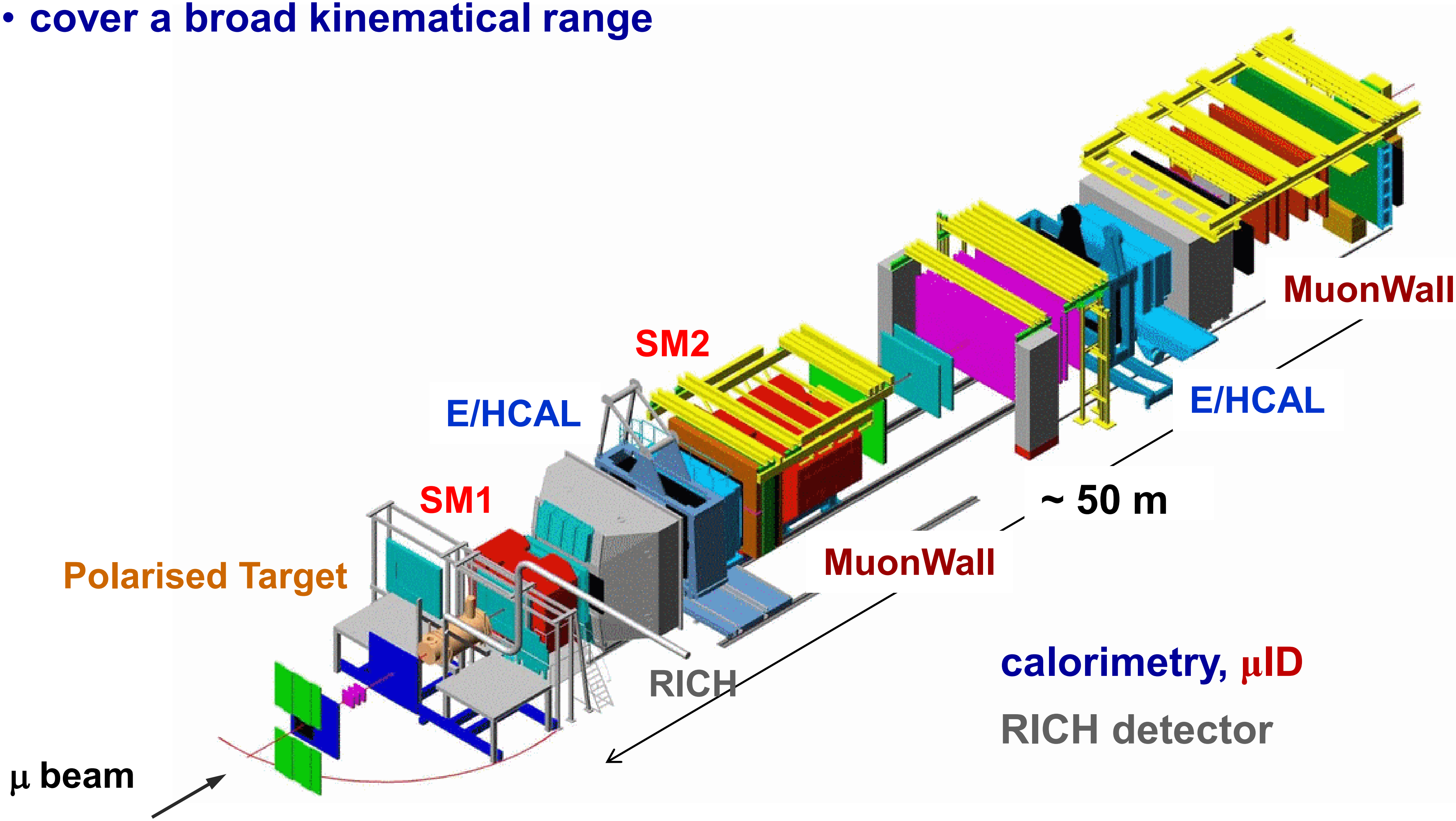
COMPASS spectrometer

designed to

- use high energy beams
- have large angular acceptance
- cover a broad kinematical range

two stages spectrometer

- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)



COMPASS data taking

muon beam 160 GeV	deuteron (^{6}LiD) **PT**	2002 2003 2004	80% L target polarisation 20% T
		2006	100% L PGF SIDIS
	proton (NH_3) **PT**	2007	50% L 50% T SIDIS
hadron beam	LH target	2008 2009	spectroscopy, Primakoff
muon beam 160,200 GeV	proton (NH_3) **PT**	2010	100% T SIDIS
		2011	100% L

hadron beam	Ni target	2012	Primakoff
muon beam	LH_2 target	2012	Pilot DVCS
pion beam	proton (NH_3) UT proton (NH_3) **PT**	2014 2015	Pilot Drell-Yan 100% T, Drell-Yan
muon beam 160 GeV	LH_2 target	2016 2017	DVCS, unpol. SIDIS
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muon beam 160 GeV	*deuteron (^{6}LiD)* ***PT***	*(2021) 2022*	*100% T SIDIS*

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A. Moretti

J. Giarra
M. Peskova
K. Augsten

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A. Chumakov

muon beam 160 GeV	*deuteron (^{6}LiD)* ***PT***	*(2021) 2022*	*100% T*	*SIDIS*

COMPASS SIDIS results

COMPASS has produced a lot of interesting results in SIDIS off polarized targets

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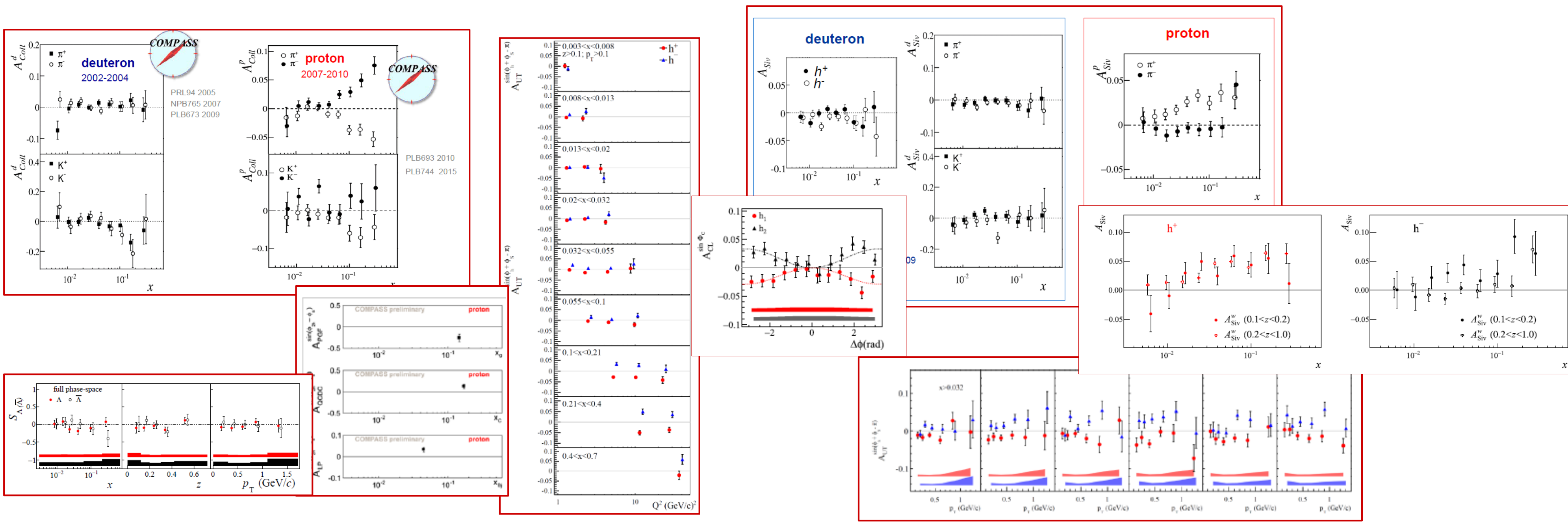
SIDIS off polarized targets

in particular, with transversely polarized p and d targets
very well known results
Collins asymmetry, di-hadron asymmetry, Sivers asymmetry, and many others



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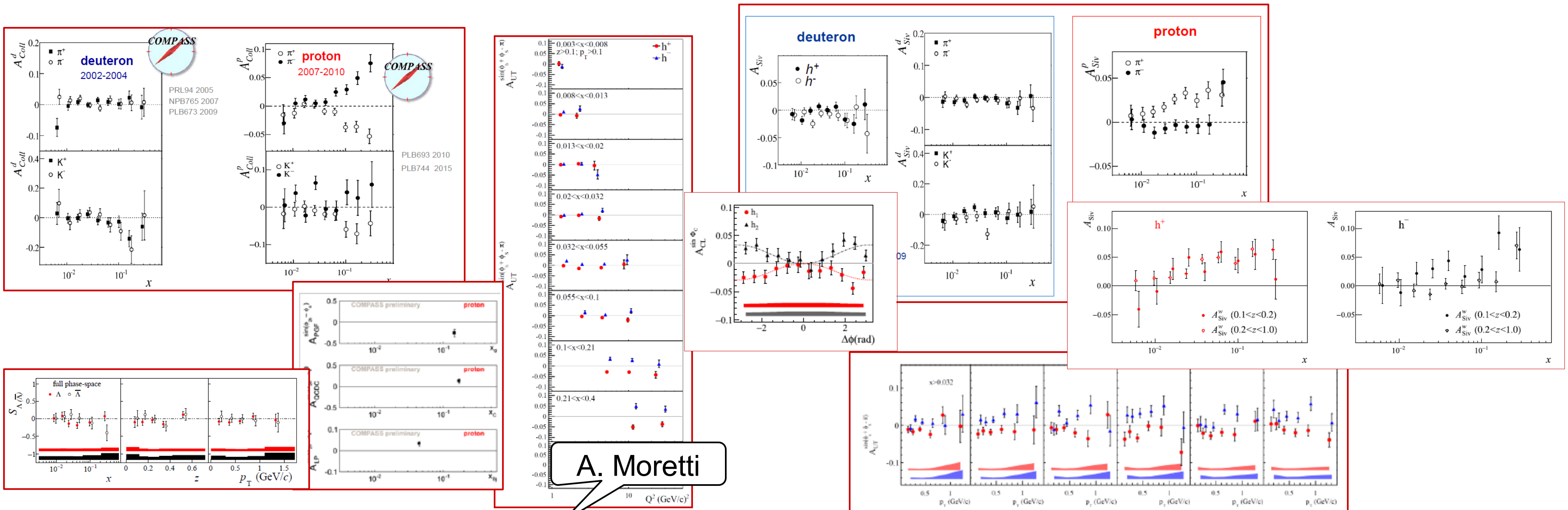
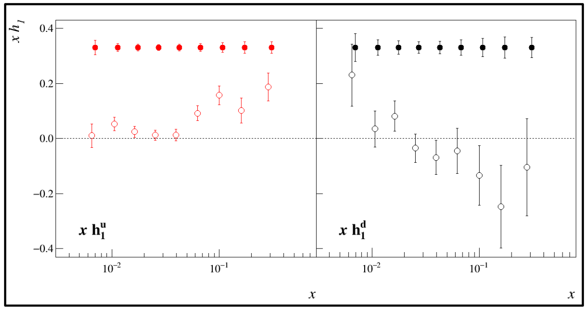


and other results are coming,

and hopefully will come from the d↑ run,
next year



COMPASS SIDIS results

in this talk the focus is on TMD observables in unpolarised SIDIS

COMPASS has measured and is measuring

- **azimuthal asymmetries**

- **transverse-momentum distributions of final state hadrons**

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J. Matousek

- **azimuthal asymmetries**
  - give access to intrinsic transverse momentum via Cahn effect and to the Boer Mulders TMD PDF

- **transverse-momentum distributions of final state hadrons**

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COMPASS has measured and is measuring

J. Matousek

- **azimuthal asymmetries**
  - give access to intrinsic transverse momentum via Cahn effect and to the Boer Mulders TMD PDF

this talk

- **transverse-momentum distributions of final state hadrons**
  - in spin asymmetries many effects cancel
  - still, understanding unpolarised SIDIS is a must to "validate" the theoretical framework
  - the transverse-momentum distributions of final state hadrons depend on the parton transverse momentum and give independent and unique information
  - a big theoretical effort is ongoing to describe them in different processes

measured since a long time

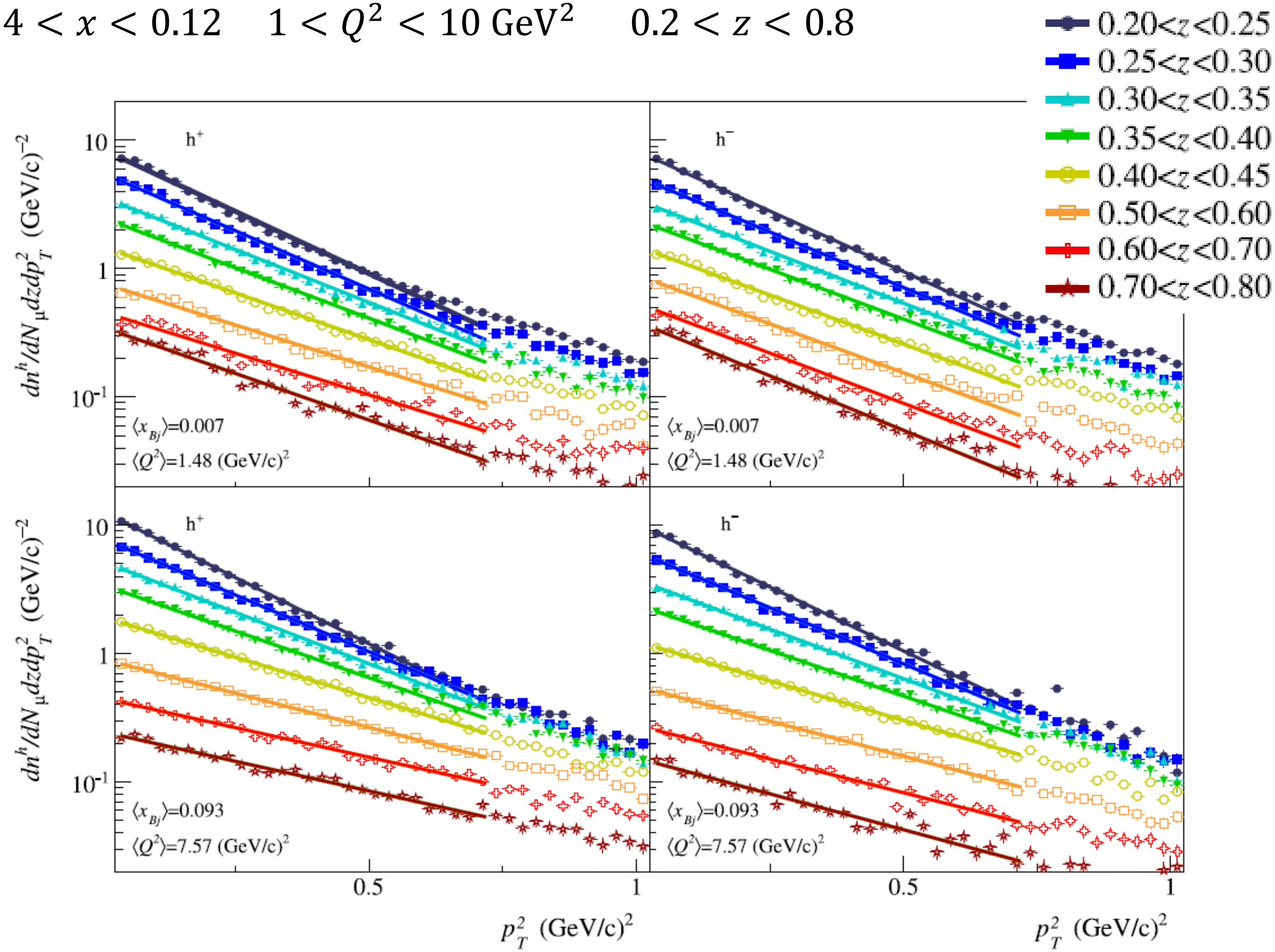
- EMC (1991), ZEUS (1996), H1 (1997, 2008)

and more recently

- HERMES, JLab, COMPASS

the COMPASS contribution

- first results published in 2013: *Eur. Phys. J. C 73 (2013) 2531*
  transverse momentum distributions of charged hadrons in DIS of 160 GeV muons on ^6LiD
  in bins of x, Q^2, z (2004 data)
  $0.004 < x < 0.12 \quad 1 < Q^2 < 10\ \mathrm{GeV}^2 \quad 0.2 < z < 0.8$



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  in bins of x, Q^2, z (2006 data)
  larger acceptance / kinematic range
  $0.003 < x < 0.40 \quad 1 < Q^2 < 81\ \mathrm{GeV}^2 \quad 0.2 < z < 0.8$

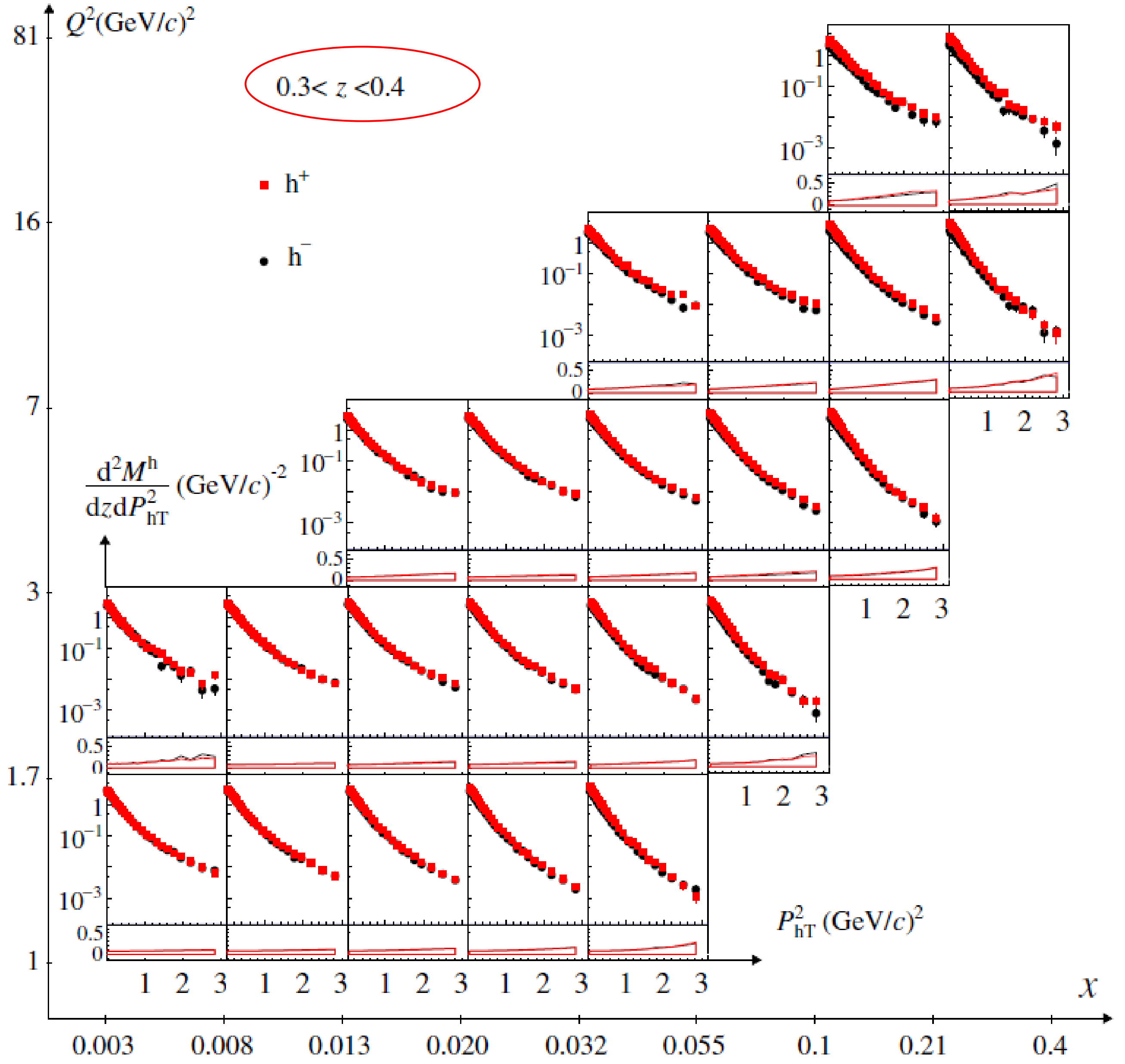
the COMPASS contribution

multiplicities of charged hadrons in DIS of 160 GeV muons on ^6LiD

2006 data

Phys. Rev. D 97 (2018) 032006

- similar shapes for h^+ and h^- (not normalization)
- strong x, Q^2 (W) dependence , not easy to disentangle



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COMPASS

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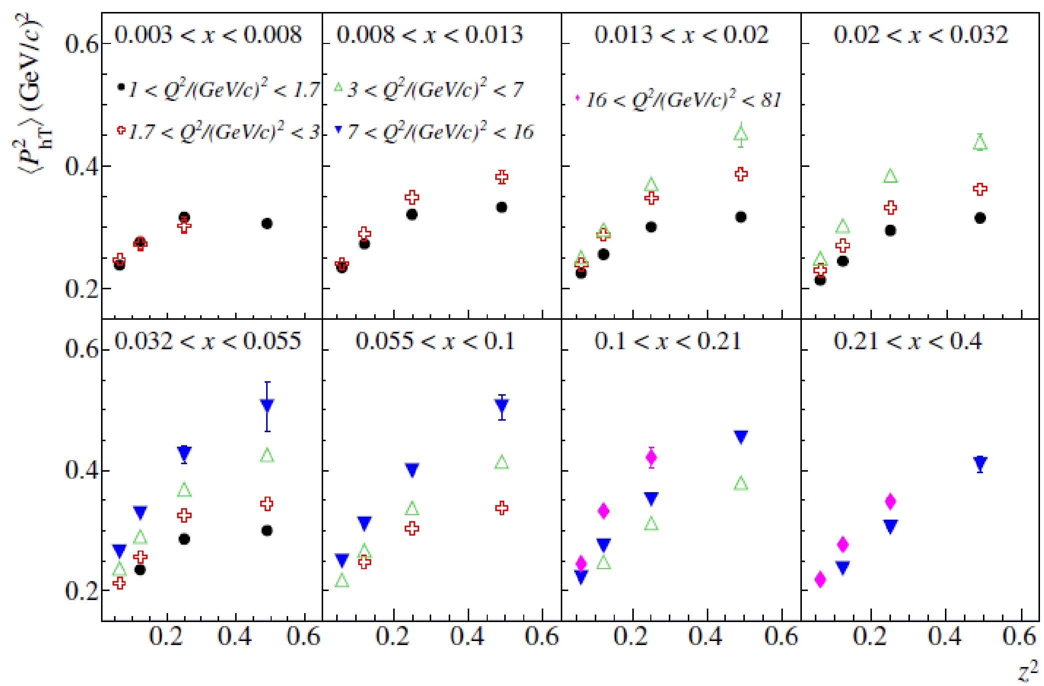
$\langle P_T^2 \rangle$ from 1 exp fit up to 0.85 GeV/c



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- strong z dependence

the COMPASS contribution

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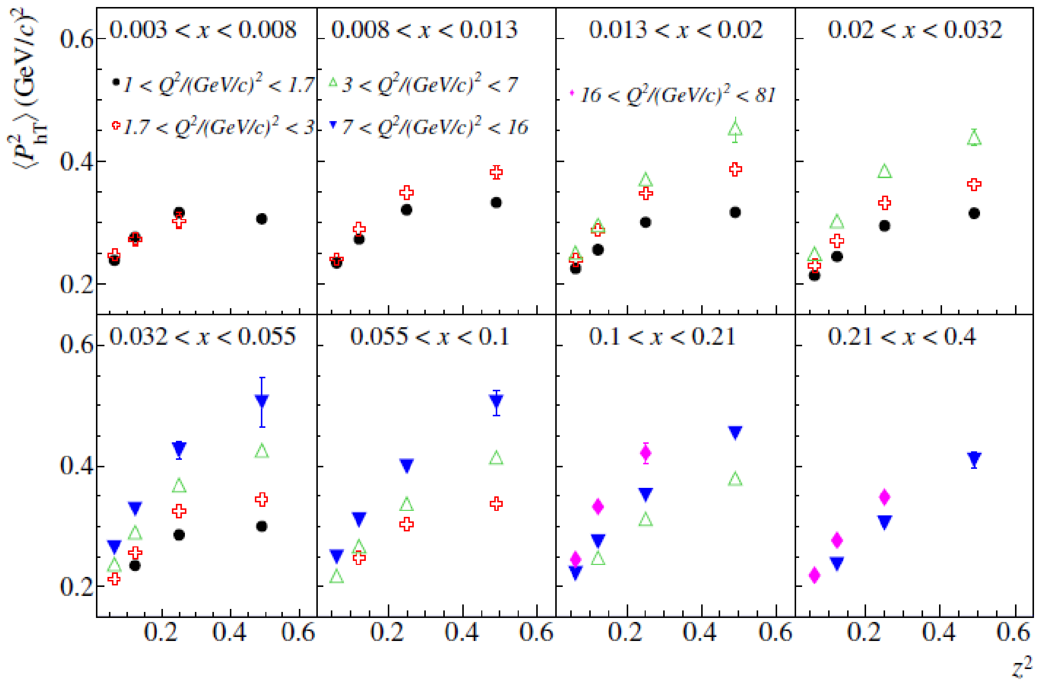

- similar shapes for h^+ and h^- (not normalization)
- strong x, Q^2 (W) dependence , not easy to disentangle
- strong z dependence expected at LO

$$\vec{P}_T \simeq z\vec{k}_T + \vec{p}_\perp \quad \Rightarrow \quad \langle P_T^2 \rangle \simeq z^2 \langle k_T^2 \rangle + \langle p_\perp^2 \rangle$$

SIDIS intrinsic fragmentation

clear evidence that, if the LO approximation holds, $\langle p_\perp^2 \rangle$ must depend on z

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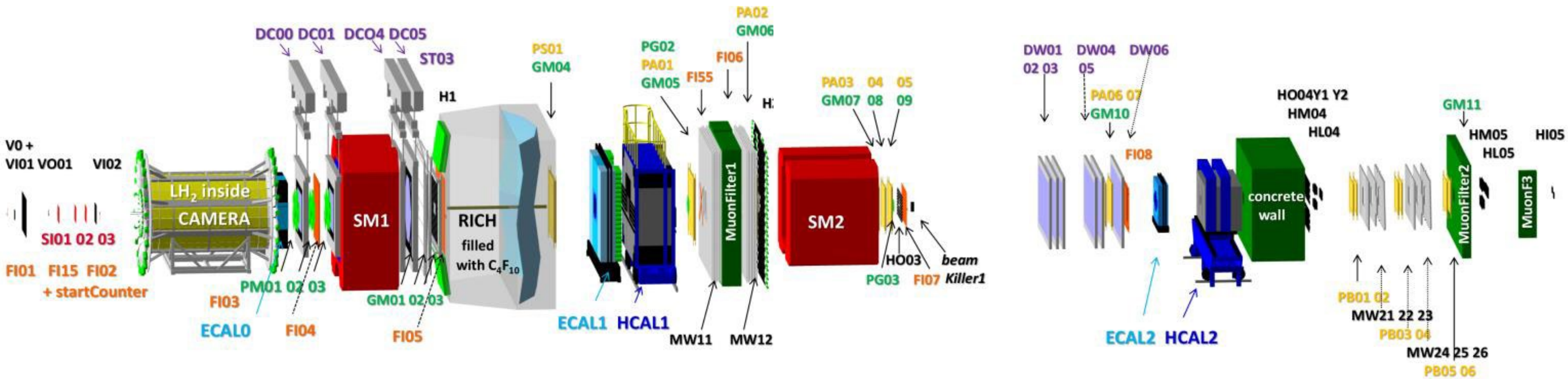
- now:
  transverse momentum distributions of charged hadrons in DIS of 160 GeV muons on LH_2 (2016 data)

  paper in preparation

  cross-section will come later

the 2016 COMPASS SIDIS data

- data collected in during DVCS run (2016/17) with 160 GeV μ^+/μ^- beams and a LH_2 target



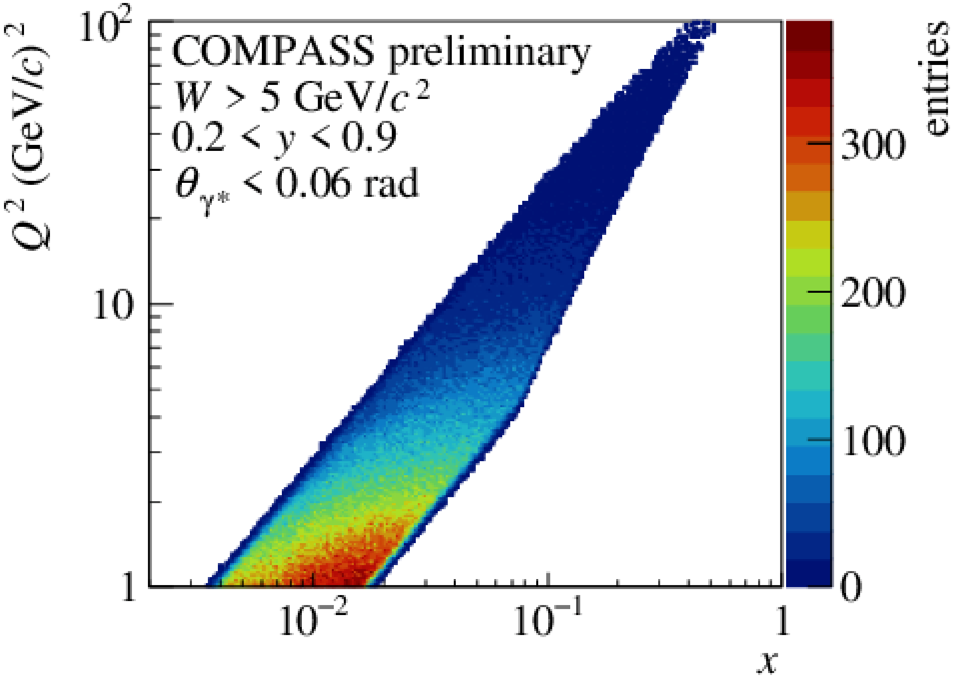
- photon acceptance maximized → reduced charged hadron acceptance restricted kinematic range (to avoid too large acceptance corrections)

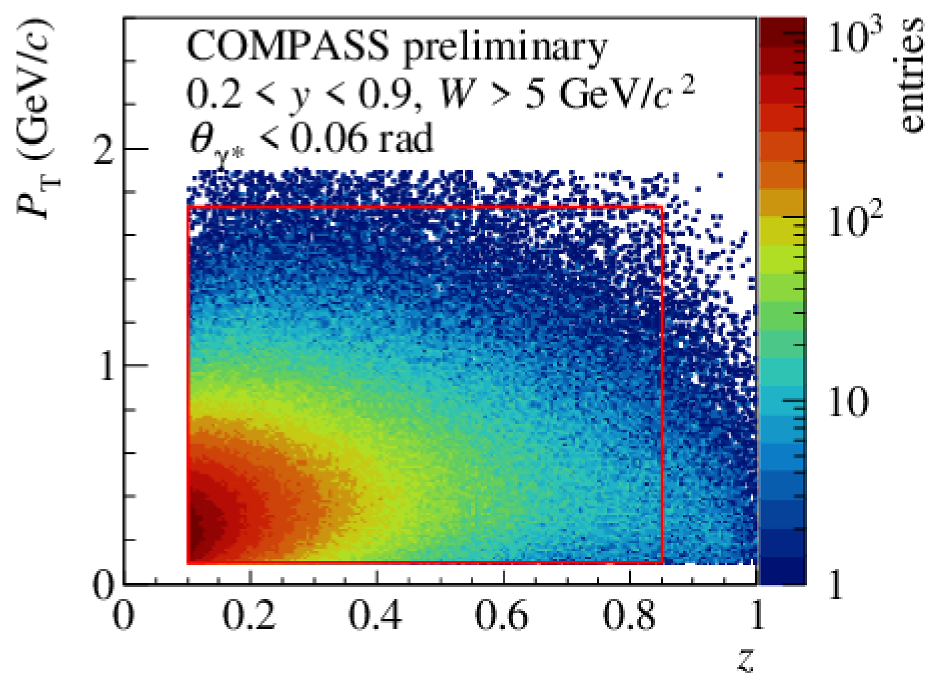
$$0.004 < x < 0.11 \qquad 1 < Q^2 < 16\ \mathrm{GeV}^2 \qquad 0.1 < z < 0.8 \qquad y > 2$$

- a complete set of results for azimuthal asymmetries and P_T^2 distributions from ~20% of the data collected in 2016 has been produced and shown at DIS2021

P_T^2 distributions from 2016 LH_2 SIDIS data

- standard analysis, usual hadron and muon reconstruction



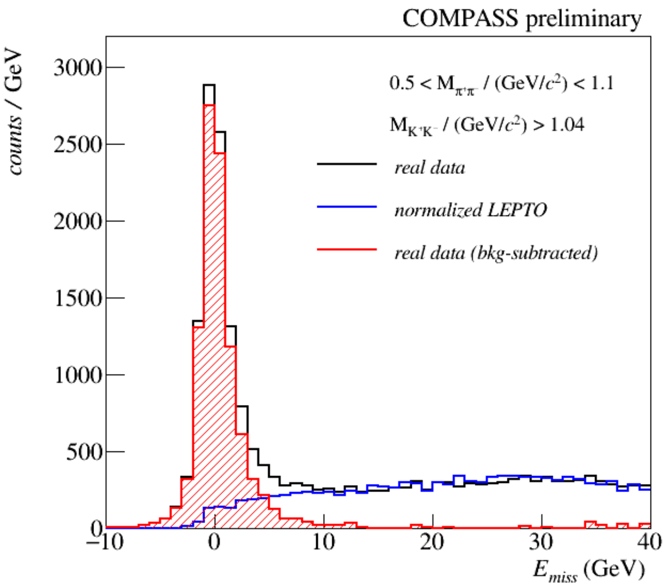


P_T^2 distributions from 2016 LH_2 SIDIS data

- standard analysis, usual hadron and muon reconstruction

- new: rejection/subtraction of hadrons from diffractive vector meson production

$$\rho^0 \rightarrow \pi^+\pi^- \; and \; \phi \rightarrow K^+K^-$$



events with only a h^+h^- pair reconstructed in the final state

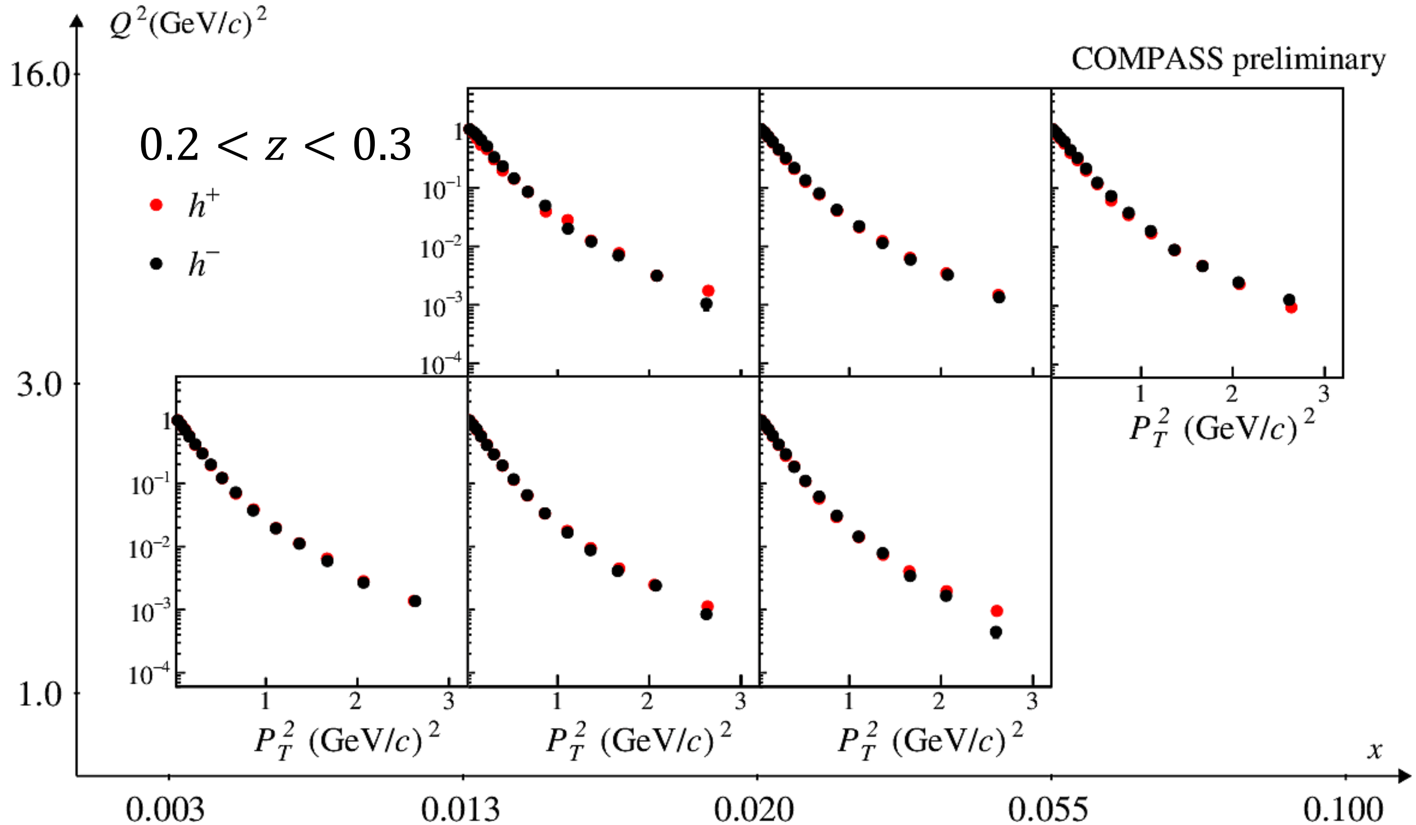
- removed asking $z_1 + z_2 < 0.95$
- used to normalized the simulated (HEPGEN) events with only one reconstructed h from diffractive VM decay

the residual contamination (~1/5 of the initial one) is evaluated with MC

no need to know the cross-sections
less model dependent

P_T^2 distributions from 2016 LH_2 SIDIS data

- results for P_T^2 distributions in "standard" bins: $4x \times 2\ Q^2 \times 4z$
  in the range $0.003 < x < 0.40$ $1 < Q^2 < 16\ \mathrm{GeV}^2$ $0.2 < z < 0.8$



almost the same for h^+ and h^-

strong x, Q^2, W dependence

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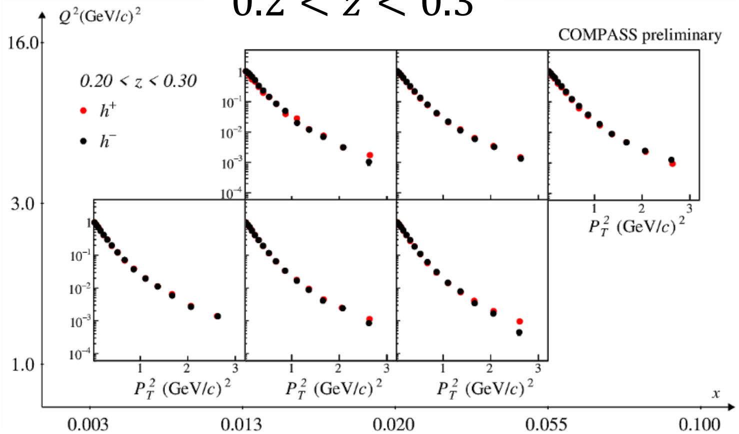
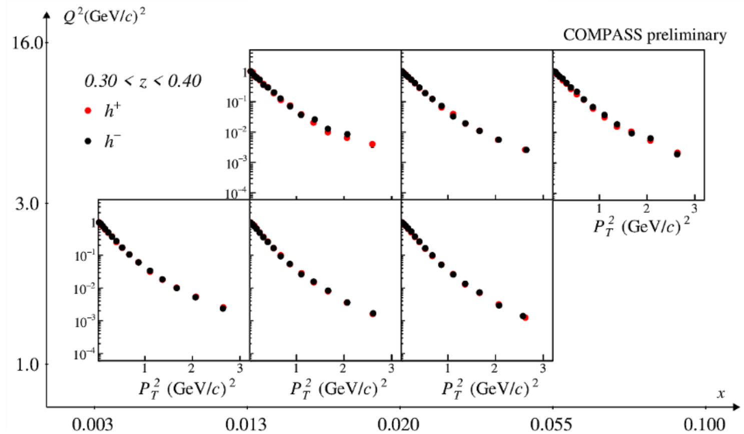
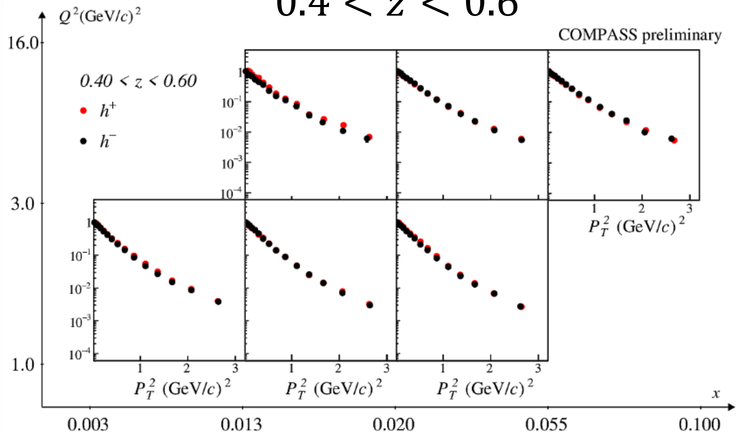
$0.2 < z < 0.3$



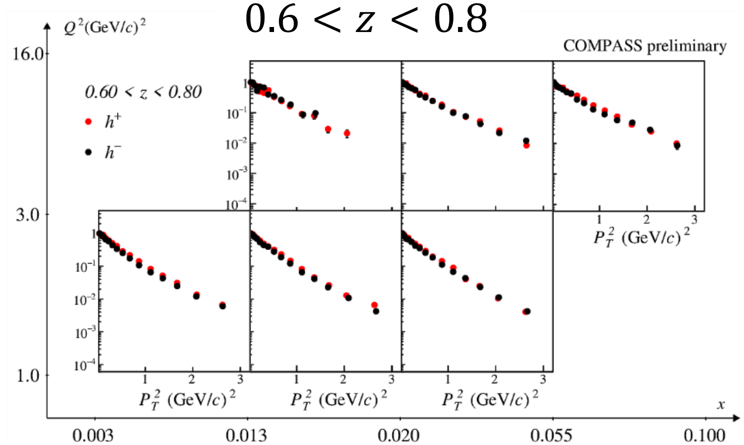
$0.3 < z < 0.4$



$0.4 < z < 0.6$



$0.6 < z < 0.8$



strong z dependence

almost the same shapes for h^+ and h^-

strong x, Q^2 (W) dependence

P_T^2 distributions from 2016 LH_2 SIDIS data

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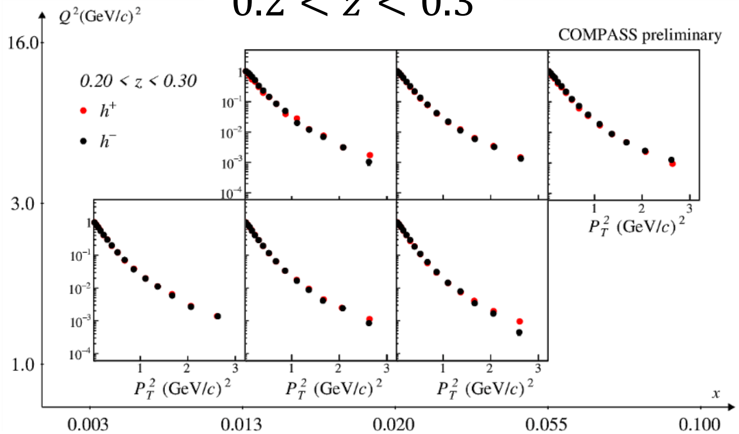

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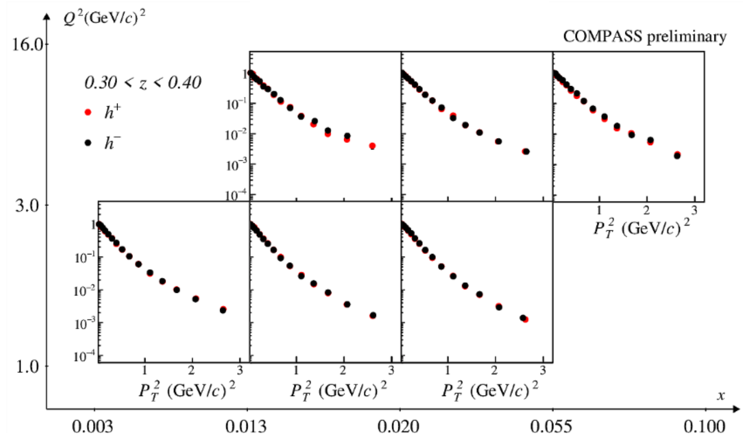

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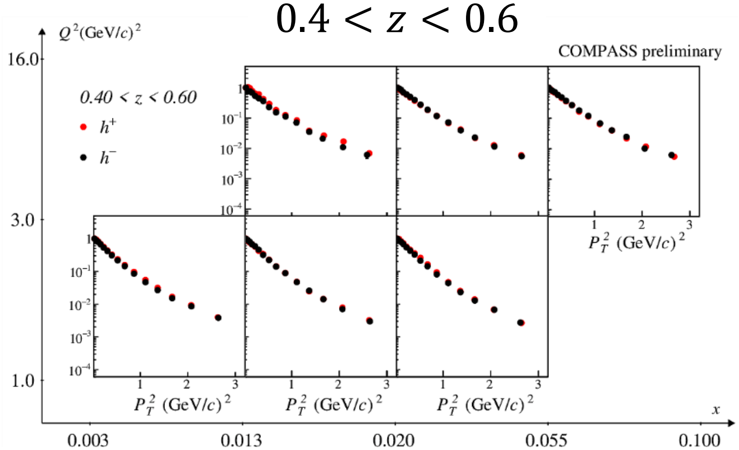

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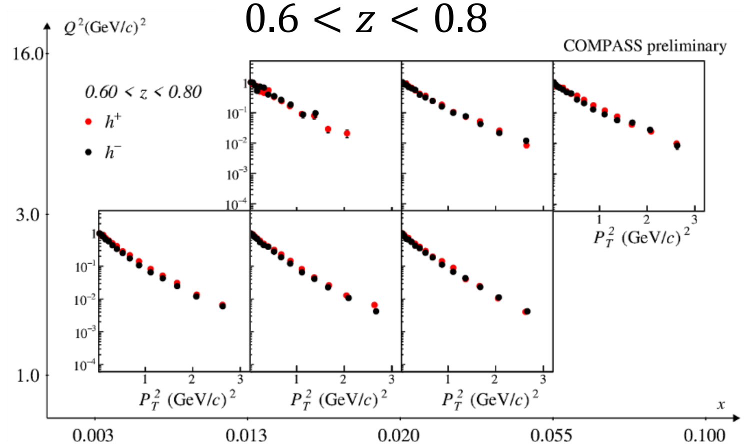

strong x, Q^2 (W) dependence

- in agreement with the deuteron results
- reasonable fits with one exponential up to $1\ (\mathrm{GeV}/c)^2$
- good quality fits withT-Sallis functions and sum of two exponentials up to $3\ (\mathrm{GeV}/c)^2$

Matsue, Japan

P_T^2 distributions from 2016 LH_2 SIDIS data

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  in the same bins
  - $q_T = P_T/z$ distributions

- deep investigation of the kinematic dependences
  - binning $4x \times 2\,Q^2 \times \boldsymbol{7z}$
  - binning $4x \times \boldsymbol{4\,Q^2} \times 4z$
  - binning $4x \times 2\,Q^2 \times \boldsymbol{2W} \times 4z$
  - binning $4x \times \boldsymbol{4\,Q^2} \times \boldsymbol{2W} \times 4z$

  same binning used in the measurement of the azimuthal asymmetries, in view of a combined analysis

  interesting results, not all expected

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  same binning used in the measurement of the azimuthal asymmetries, in view of a combined analysis

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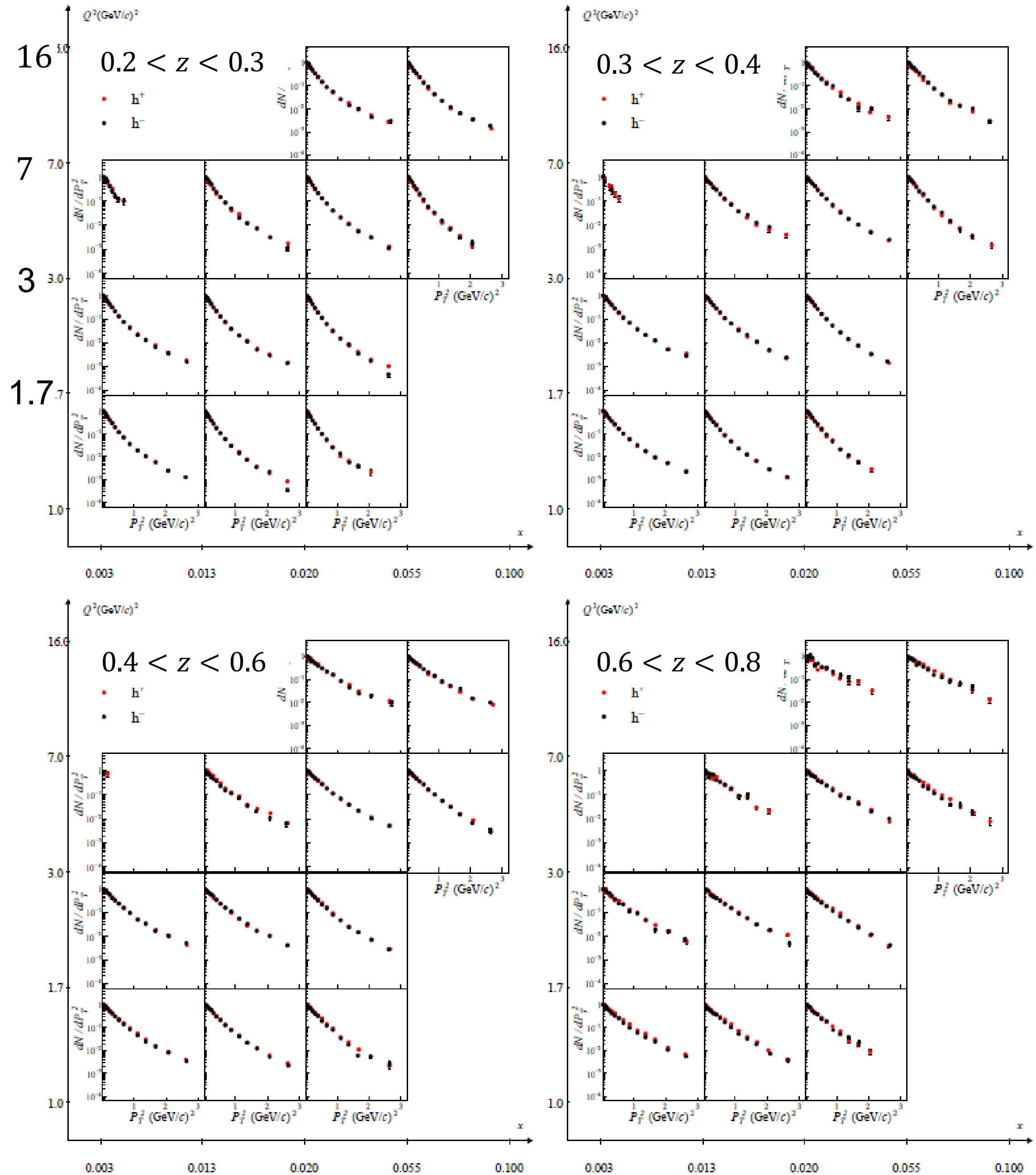
here only a few of them are shown

P_T^2 distributions from 2016 LH_2 SIDIS data

COMPASS

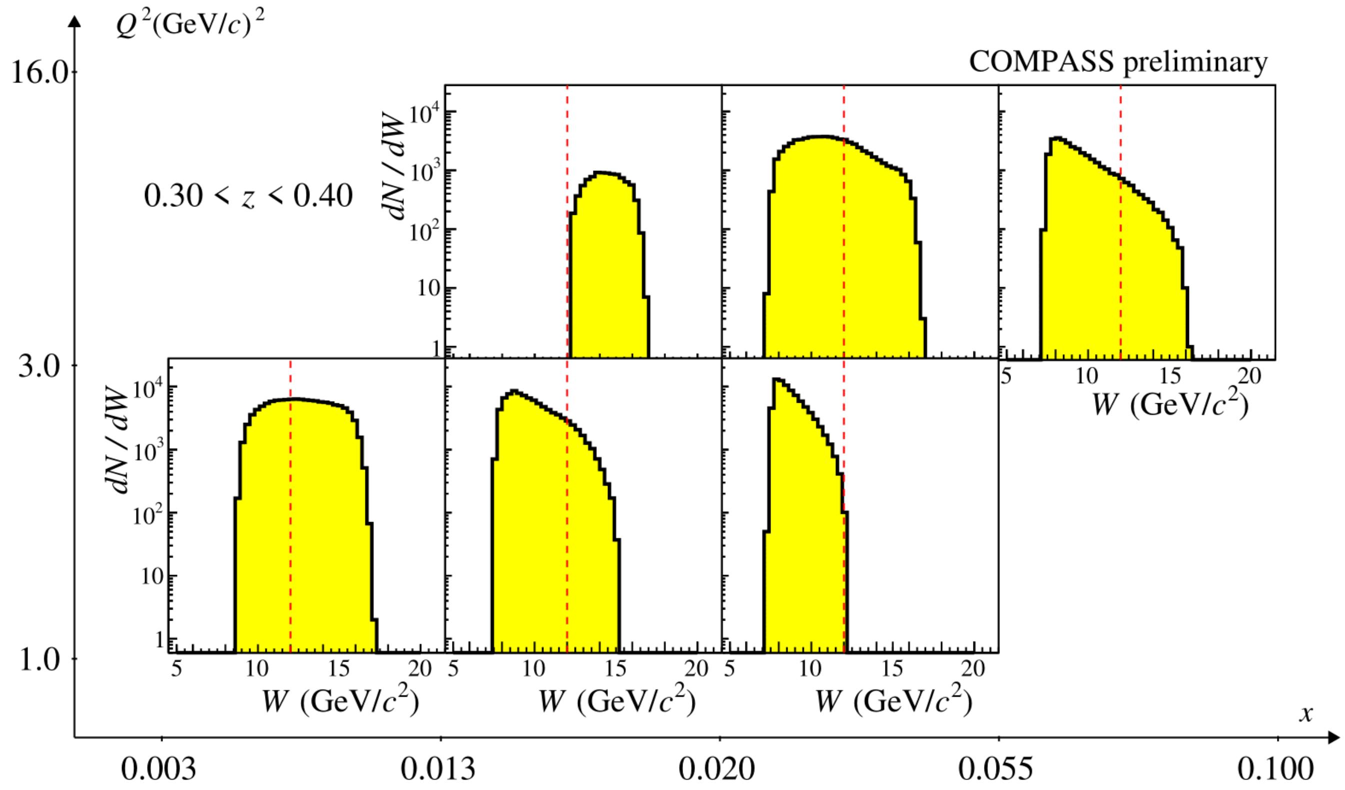
binning $4x \times 4\,Q^2 \times 4z$



to investigate the
x, Q^2 dependence
and the possible W
dependence
(EMC, 1997)

P_T^2 distributions from 2016 LH_2 SIDIS data

binning $4x \times 2\,Q^2 \times 4z \times 2W$



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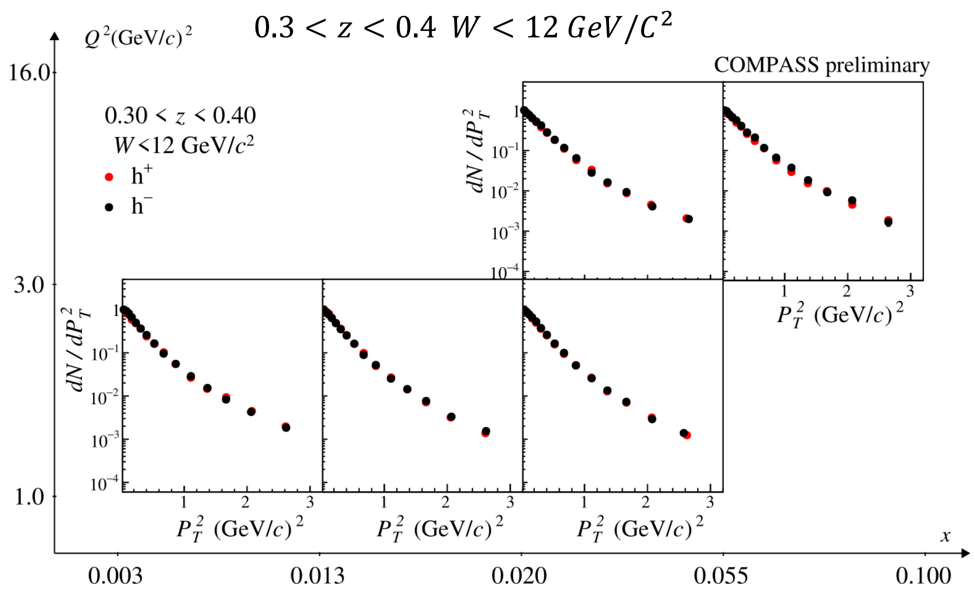
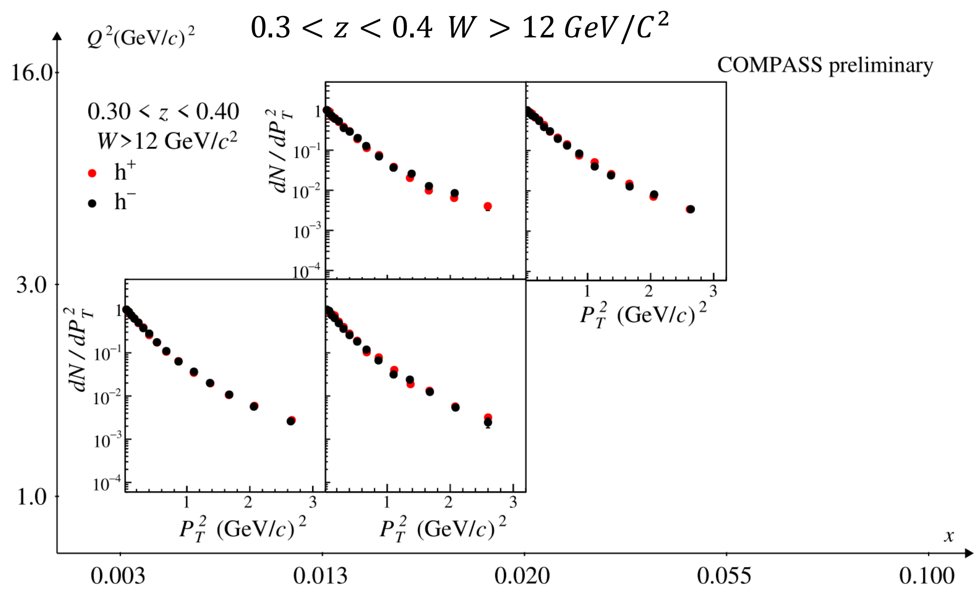


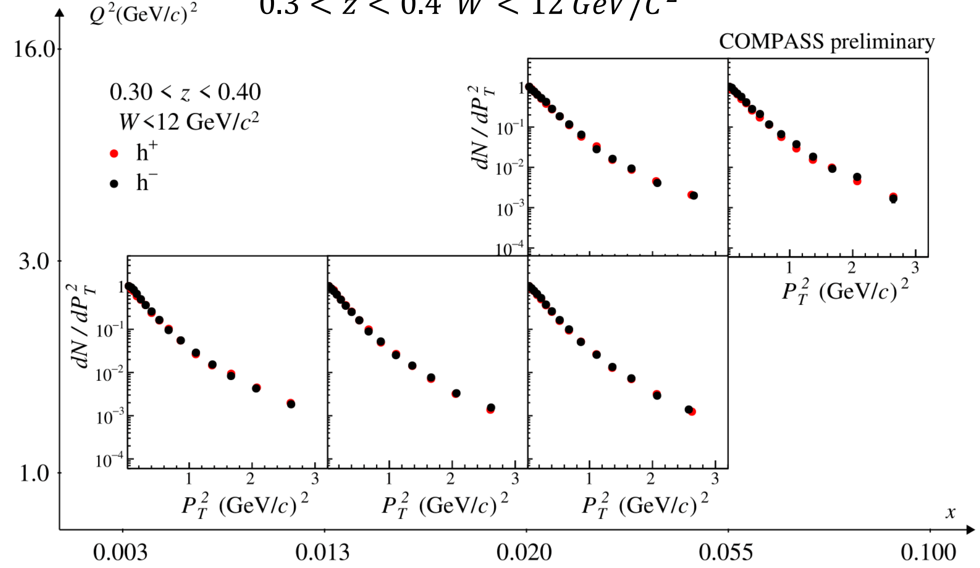


P_T^2 distributions from 2016 LH_2 SIDIS data

COMPASS

binning $4x \times 2\,Q^2 \times 4z \times 2W$

$0.3 < z < 0.4 \;\; W < 12\; GeV/C^2$



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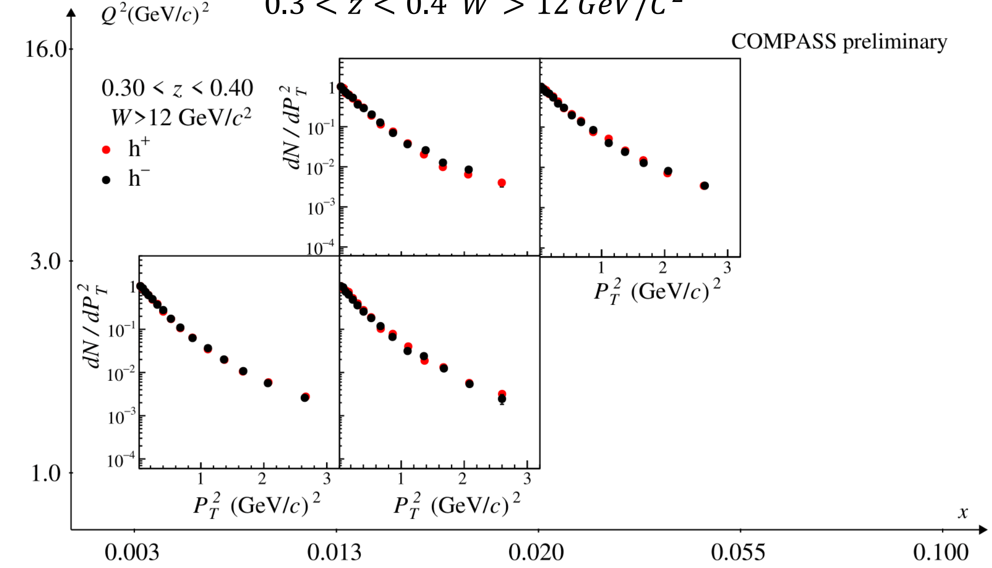
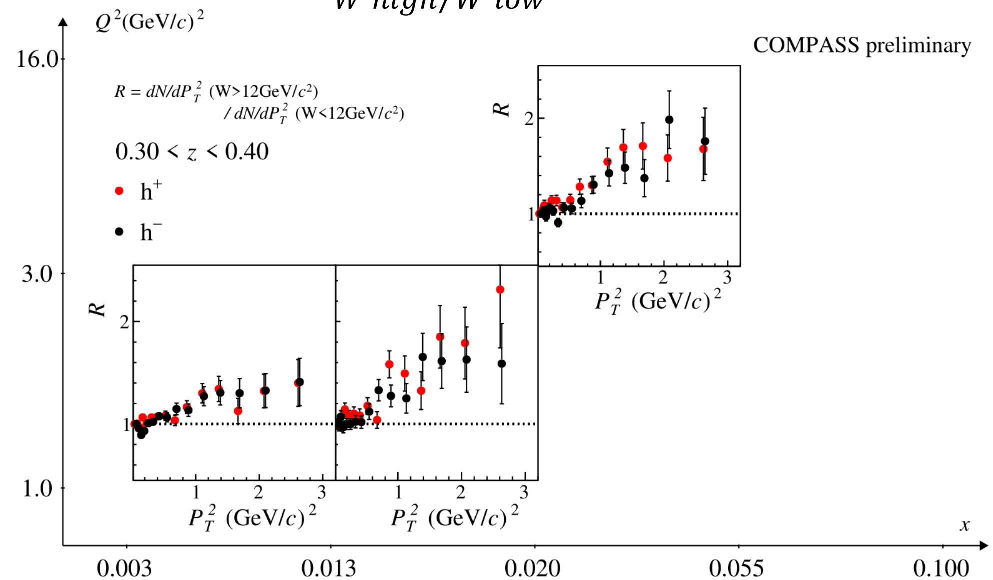


$W\ high/W\ low$



strong dependence on W
but x, Q^2 and W are not independent

also, the Q^2 dependence is weaker at high W

difficult to disentangle …

extraction of $\langle k_T^2 \rangle$ from the SIDIS P_T^2 distributions

ongoing discussions within the
COMPASS Transversity group

$\langle k_T^2 \rangle$ from the P_T^2 distributions

P_T^2 distributions measured in SIDIS:

allow to extract information on $\langle k_T^2 \rangle$ from the shape of the distributions
however it is difficult to disentangle the contributions of the intrinsic momentum and that of fragmentation using SIDIS data only

at LO $\vec{P}_T \simeq z\vec{k}_T + \vec{p}_\perp$ ⇨ $\langle P_T^2 \rangle \simeq z^2 \langle k_T^2 \rangle + \langle p_\perp^2 \rangle$

($\vec{P}_T$: SIDIS; $\vec{k}_T$: intrinsic; $\vec{p}_\perp$: fragmentation)

clear evidence that,
if the LO approximation holds,
$\langle p_\perp^2 \rangle$ must depend on z

main idea:
analyse consistently the COMPASS and Belle data to extract $\langle P_T^2 \rangle$ and $\langle p_\perp^2 \rangle$ respectively, and then evaluate $\langle k_T^2 \rangle$ using the LO expression

$\langle k_T^2 \rangle$ from the P_T^2 distributions

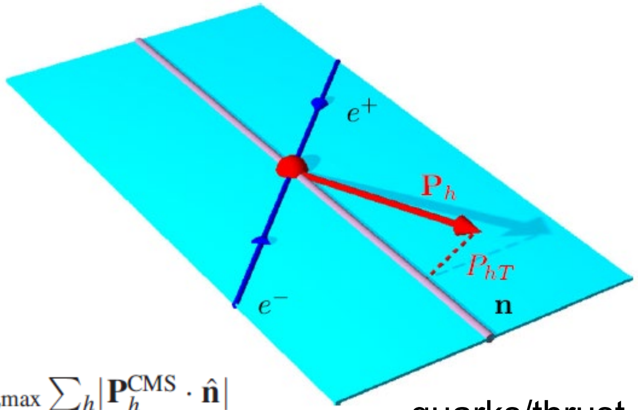
Belle PHYSICAL REVIEW D 99, 112006 (2019)

"Transverse momentum dependent production cross sections of charged pions, kaons and protons produced in inclusive e^+e^- annihilation at $\sqrt{s}$ =10.58 GeV"

in 18 z bins from 0.10 to 1.00 and in 5 bins of the event shape variable T

transverse momentum measured with respect to the trust axis ~ quark direction

$$P_{hT}^2 \rightarrow p_\perp^2$$



$$T^{\max}_{=} \frac{\sum_h |\mathbf{P}_h^{\mathrm{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\mathrm{CMS}}|}.$$

quarks/thrust axis

we assume that
- the hadrons in Belle come mainly from u(ds) as in our case;
- the fact that Belle can not distinguish between $q/\bar{q}$ (h^+/h^-) is not a problem (no difference and we can use at $h^+ + h^-$ distributions)

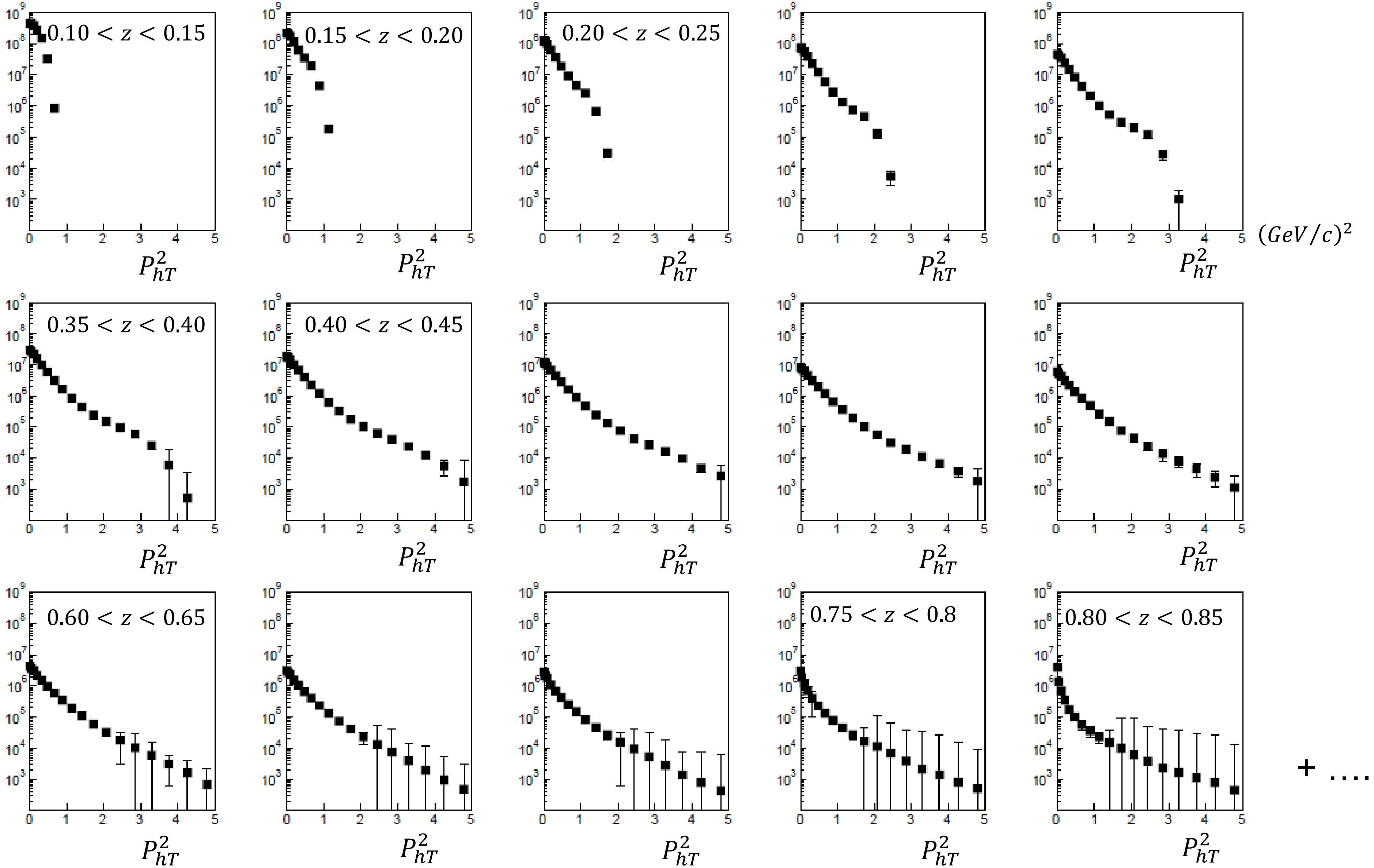
open point: different scales in Belle and COMPASS $(Q^@, W)$

we added up the cross-sections in all the *T* bins but not 0.95<*T*<1.00
low cross-section and large uncertainties

and looked at the cross sections as function of P_{hT}^2 in the z bins

$\langle k_T^2 \rangle$ from the P_T^2 distributions

Belle P_{hT}^2 cross-sections



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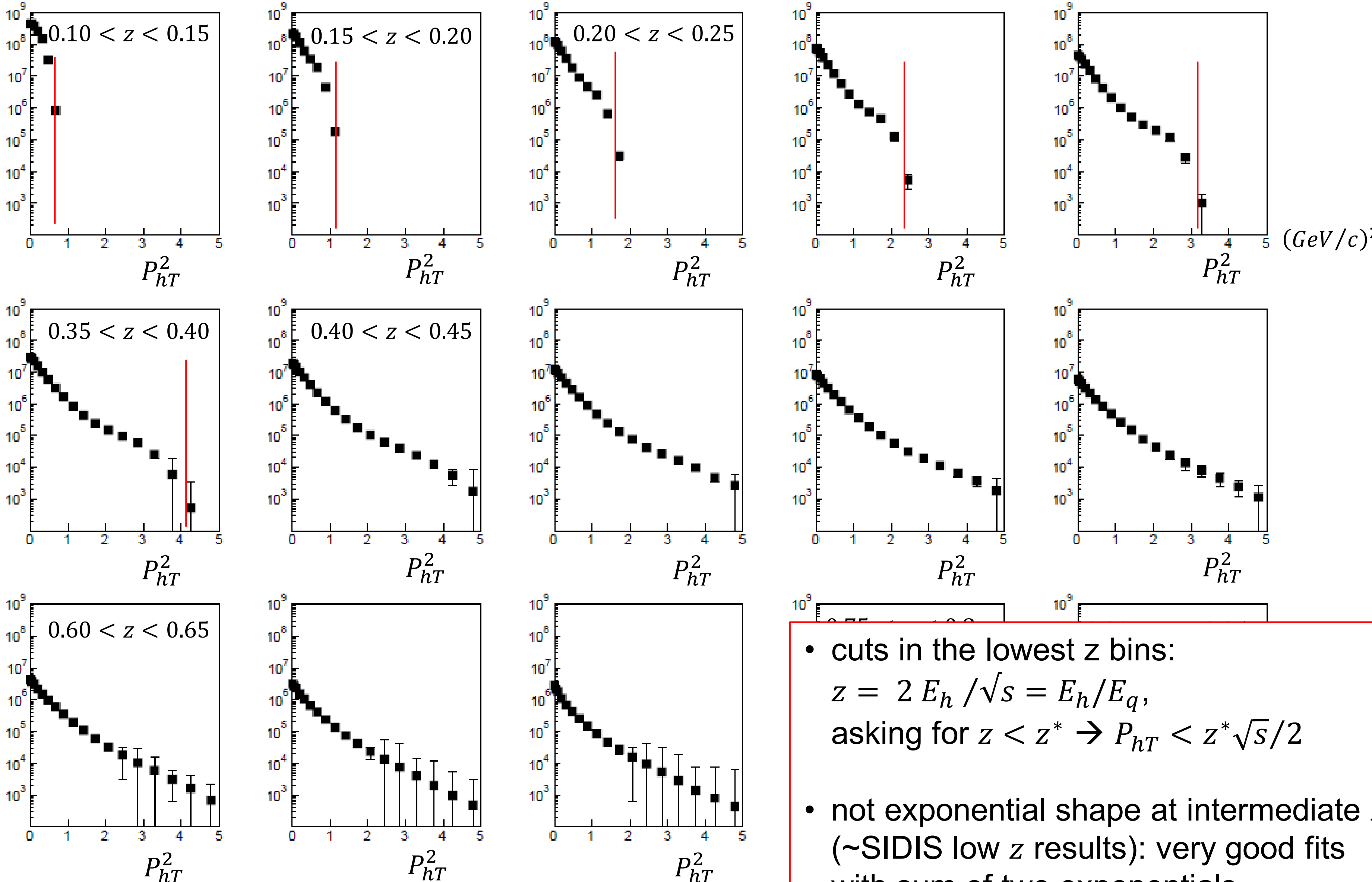
$\langle k_T^2 \rangle$ from the P_T^2 distributions

Belle P_{hT}^2 cross-sections



- cuts in the lowest z bins:
  $z = 2\, E_h / \sqrt{s} = E_h / E_q$,
  asking for $z < z^* \rightarrow P_{hT} < z^* \sqrt{s}/2$

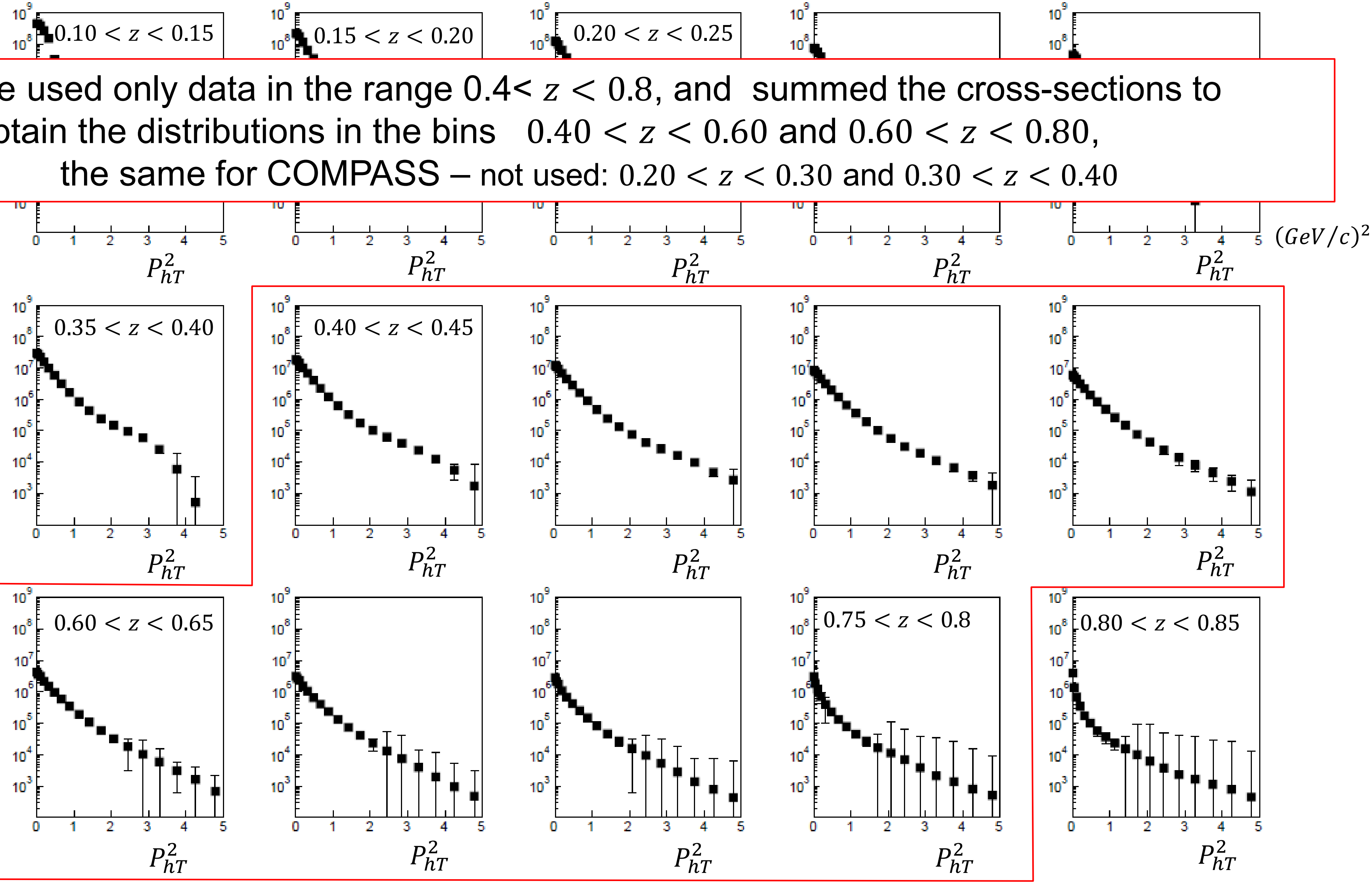
- not exponential shape at intermediate z (~SIDIS low z results): very good fits with sum of two exponentials

$\langle k_T^2 \rangle$ from the P_T^2 distributions

Belle P_{hT}^2 cross-sections

- we used only data in the range 0.4< $z < 0.8$, and summed the cross-sections to obtain the distributions in the bins $0.40 < z < 0.60$ and $0.60 < z < 0.80$,

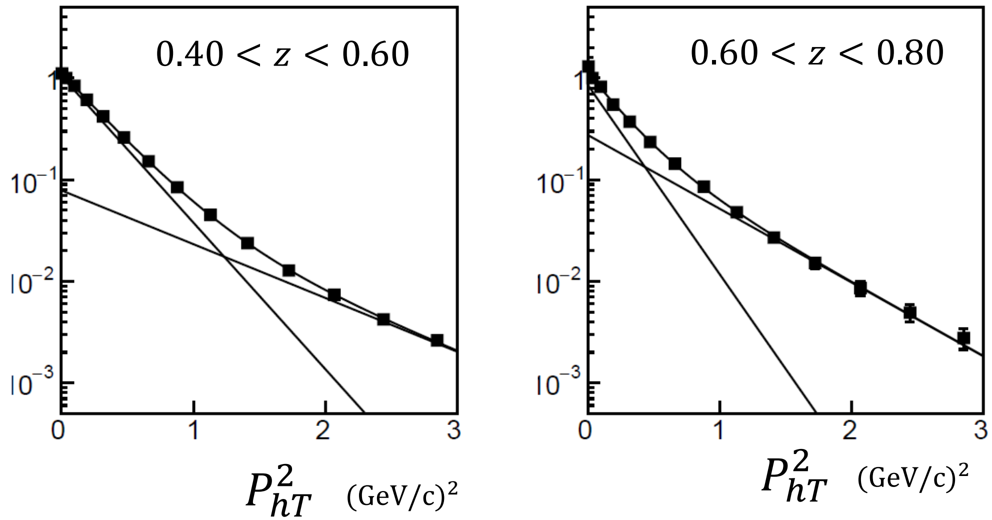
  the same for COMPASS – not used: $0.20 < z < 0.30$ and $0.30 < z < 0.40$



$\langle k_T^2 \rangle$ from the P_T^2 distributions

Belle P_{hT}^2 distributions

fits up to 3 $(\mathrm{GeV/c})^2$ with $\quad p_0 \cdot exp\left(-\frac{P_{hT}^2}{p_1}\right) + p_2 \cdot exp\left(-\frac{P_{hT}^2}{p_3}\right)$



good agreement up to 5 $(\mathrm{GeV/c})^2$

$$\langle P_{hT}^2 \rangle = \frac{p_0 p_1^2 + p_2 p_3^2}{p_0 p_1 + p_2 p_3}$$

$0.40 < z < 0.60 \quad \langle P_{hT}^2 \rangle = 0.389 \quad (\mathrm{GeV/c})^2$

$0.60 < z < 0.80 \quad \langle P_{hT}^2 \rangle = 0.398 \quad (\mathrm{GeV/c})^2$

↑ $\langle p_\perp^2 \rangle$

$\langle k_T^2 \rangle$ from the P_T^2 distributions

COMPASS P_T^2 distributions $\mathbf{4x \times 2\ Q^2 \times 4z}$ binning

for consistency with Belle

- $\boldsymbol{h^+ + h^-}$ distributions (almost no difference between h^+ and h^-)
- **fit up to** $\mathbf{3\ (GeV/c)^2}$ with $p_0 \cdot exp\left(-\frac{P_T^2}{p_1}\right) + p_2 \cdot exp\left(-\frac{P_T^2}{p_3}\right)$

  very good χ^2

in the bins $\mathbf{0.40 < z < 0.60}$ ($\langle z \rangle = 0.48$) and $\mathbf{0.60 < z < 0.80}$ ($\langle z \rangle = 0.68$)

and we used the bin $\mathbf{0.02 < x < 0.055}$ (statistics) $\langle x \rangle = 0.037$

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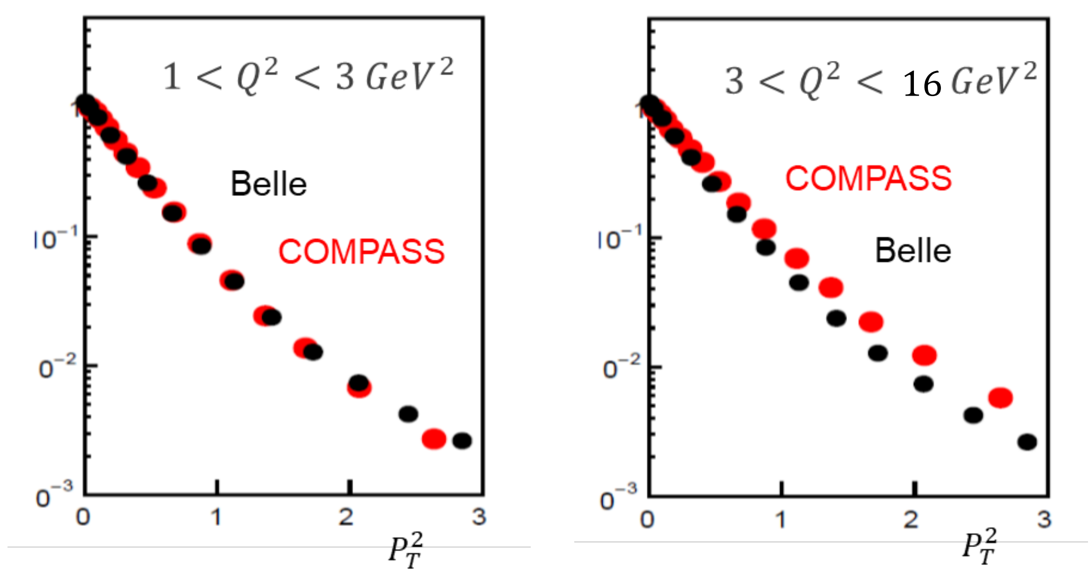
also, the lowest Q^2 bin is not used:

$0.40 < z < 0.60$



$\langle k_T^2 \rangle$ from the P_T^2 distributions

COMPASS P_T^2 distributions $\quad \mathbf{4x \times 2\ Q^2 \times 4z}$ binning

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and we used the bin $\mathbf{0.02 < x < 0.055}$ (statistics) $\quad \langle x \rangle = 0.037$

also, the lowest Q^2 bin is not used: $\quad \mathbf{3 < Q^2 < 16\ GeV^2} \quad \langle Q^2 \rangle = 11\ \ \mathrm{GeV/c^2}$

$$\langle P_T^2 \rangle = \frac{p_0 p_1^2 + p_2 p_3^2}{p_0 p_1 + p_2 p_3}$$

results:

$0.40 < z < 0.60 \qquad \langle \boldsymbol{P_T^2} \rangle = \mathbf{0.456\ \ (GeV/c)^2}$

$0.60 < z < 0.80 \qquad \langle \boldsymbol{P_T^2} \rangle = \mathbf{0.545\ \ (GeV/c)^2}$

$\langle k_T^2 \rangle$ from the P_T^2 distributions

using $\langle P_T^2 \rangle \simeq z^2 \langle k_T^2 \rangle + \langle p_\perp^2 \rangle$

at $\langle x \rangle = 0.037$, $\langle Q^2 \rangle = 4.7\ \mathrm{GeV}^2$, $\langle W \rangle = 11\ \mathrm{GeV/c}^2$

$\langle z \rangle = 0.48 \quad \langle \boldsymbol{k_T^2} \rangle = \mathbf{0.29}\ (\mathrm{GeV/c})^2$

$\langle z \rangle = 0.68 \quad \langle \boldsymbol{k_T^2} \rangle = \mathbf{0.32}\ (\mathrm{GeV/c})^2$

finally $\langle \boldsymbol{k_T^2} \rangle = \mathbf{0.31\ (GeV/c)^2}$

with an estimated statistical uncertainty of ~ 25%
(very preliminary)

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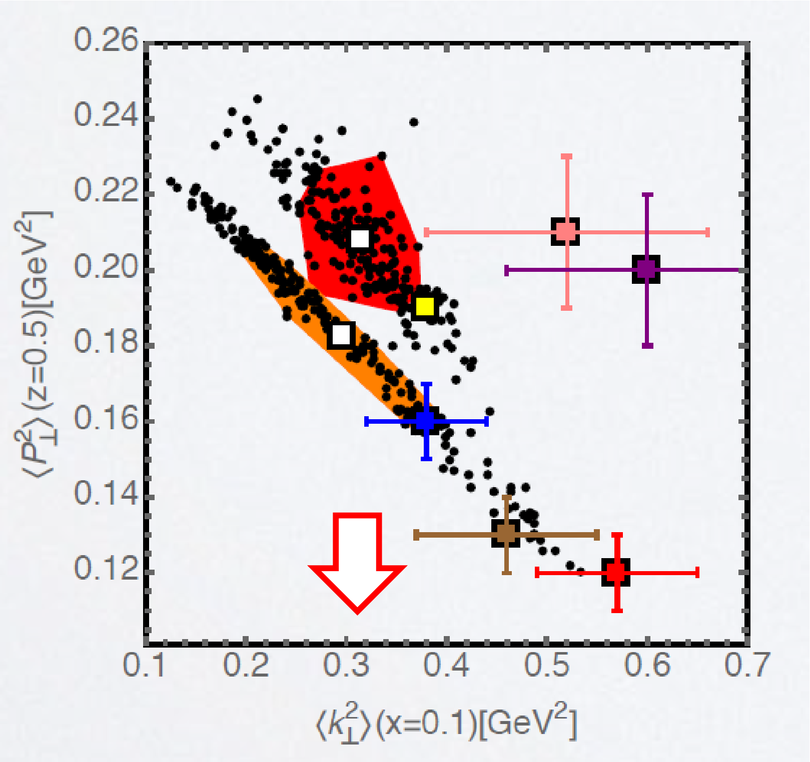
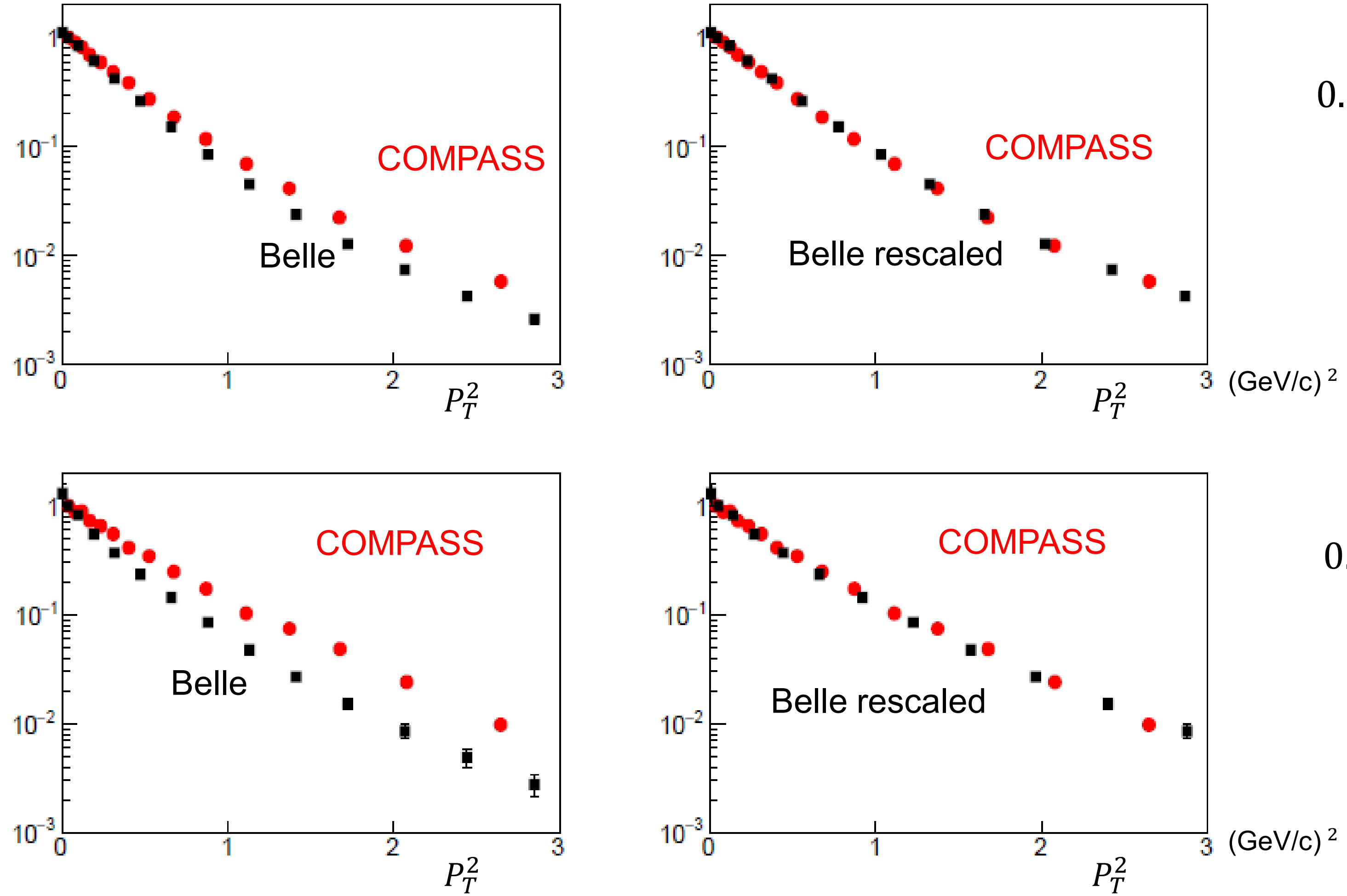
M. Radici,
QCD-N2021



$\langle k_T^2 \rangle$ from the P_T^2 distributions

check: if the intrinsic transverse momentum has a Gaussian distribution, and $\vec{P}_T \simeq z\vec{k}_T + \vec{p}_\perp$, the Belle distributions should be in agreement with the COMPASS distributions when $p_{\perp i}^2$ scaled by $(z^2\langle k_T^2\rangle + \langle p_\perp^2\rangle)/\langle p_\perp^2\rangle$



SPIN2021 Matsue, Japan

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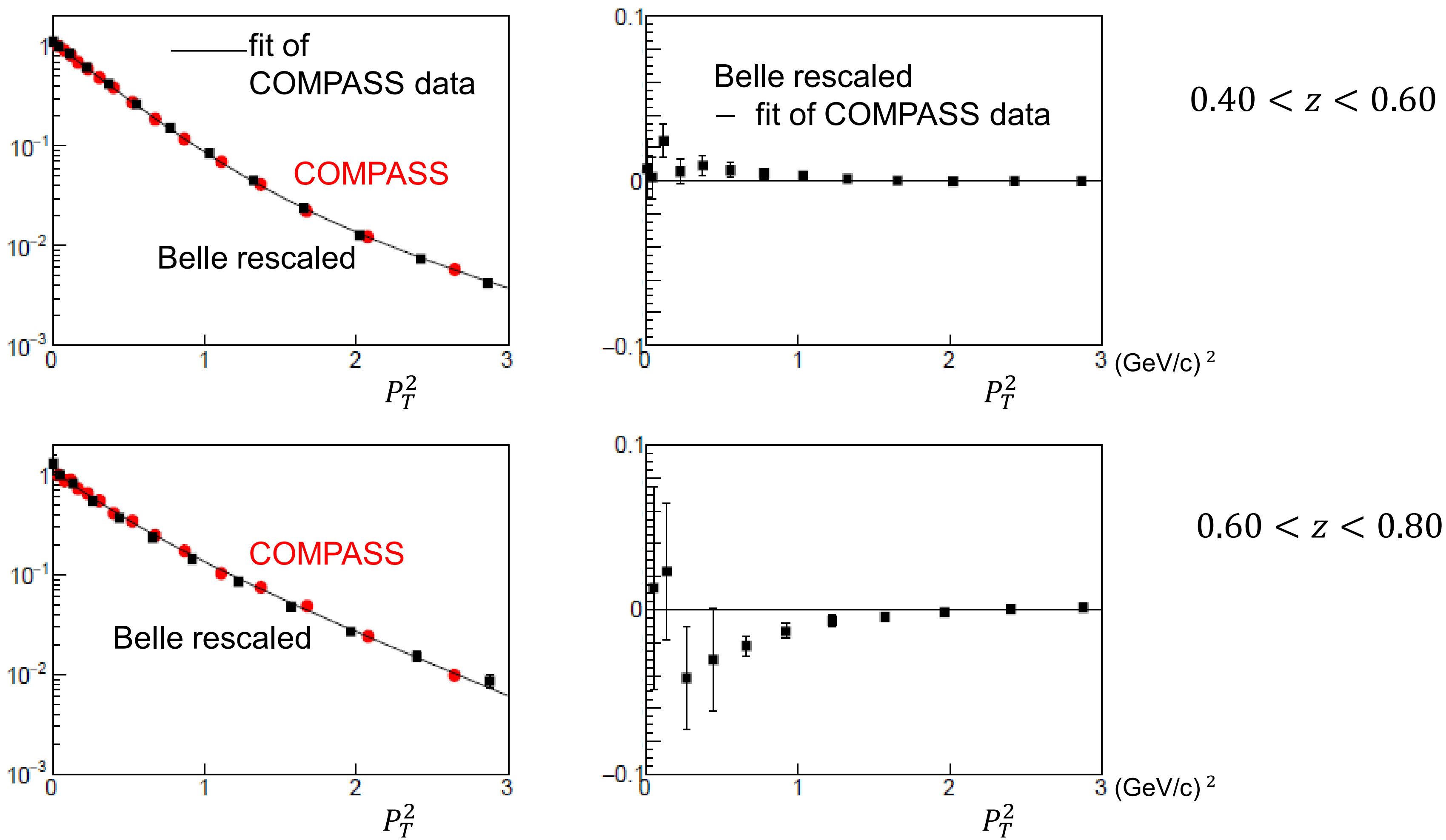

conclusions

- after the measurements with the deuteron target,
  COMPASS has done a complete set of measurements of the transverse momentum distributions using part of the proton data collected in 2016
- a deep investigation of the kinematic dependence has been performed, finding interesting results
- the analysis is still ongoing, and new results, with more statistics, as well as cross-section measurements, will come in the future

- a new and simple LO extraction of the mean intrinsic transverse momentum squared from the direct comparison of the Belle and COMPASS measurements of the transverse momentum distributions has been presented

  the results look promising

thank you!