TMD extractions from COMPASS SIDIS data

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TMD extractions from COMPASS SIDIS data

outlook

- **a leading order extraction of the intrinsic transverse momentum**
  - **transverse momentum distributions in SIDIS**
  - **the COMPASS and the Belle measurements**
  - **results for the intrinsic transverse momentum**

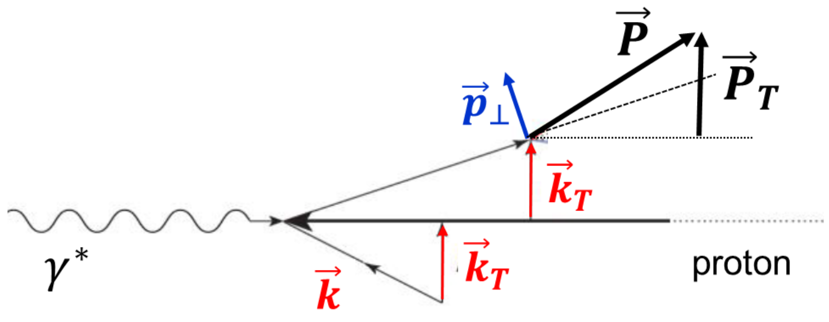
ongoing work - COMPASS Transversity group

- **extraction of Transversity and Sivers function from SIDIS Transverse Spin Asymmetries** (reminder)

transverse momentum distributions in SIDIS

the measurement of the transverse-momentum distributions / cross-sections of hadrons produced in DIS allows to access
the transverse momentum of quarks in the nucleon

- $\vec{k}_T$ transverse momentum of the initial quark in the GNS
- $\vec{p}_\perp$ transverse momentum acquired by the hadron in the fragmentation process with respect to the quark direction
- $\vec{P}_T$ transverse momentum of the final state hadron in the GNS



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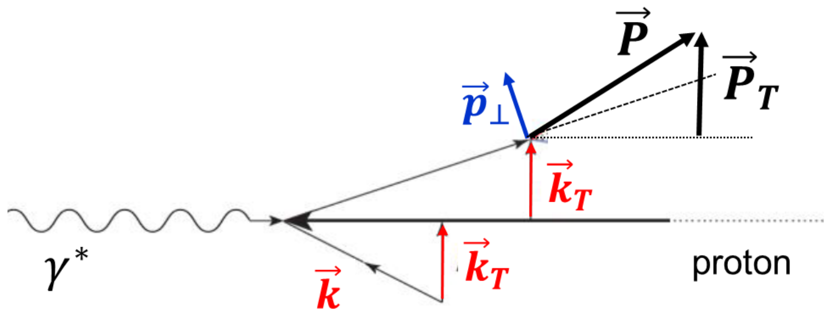

at leading order $\vec{P}_T \simeq z\vec{k}_T + \vec{p}_\perp$ ⇨ $\langle P_T^2 \rangle \simeq z^2 \langle k_T^2 \rangle + \langle p_\perp^2 \rangle$

⇨ the mean value of k_T^2 can be obtained from the P_T^2 distributions

LO approach: on the theory side, a huge effort is ongoing

factorisation, TMD formalism applicability, Next-to-Next-to-Next-to Leading Order, separation of phase space regions …

transverse momentum distributions in SIDIS

measured since a long time

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

and, more recently

- HERMES, Jlab
- **COMPASS –** charged hadrons in DIS of 160 GeV muons

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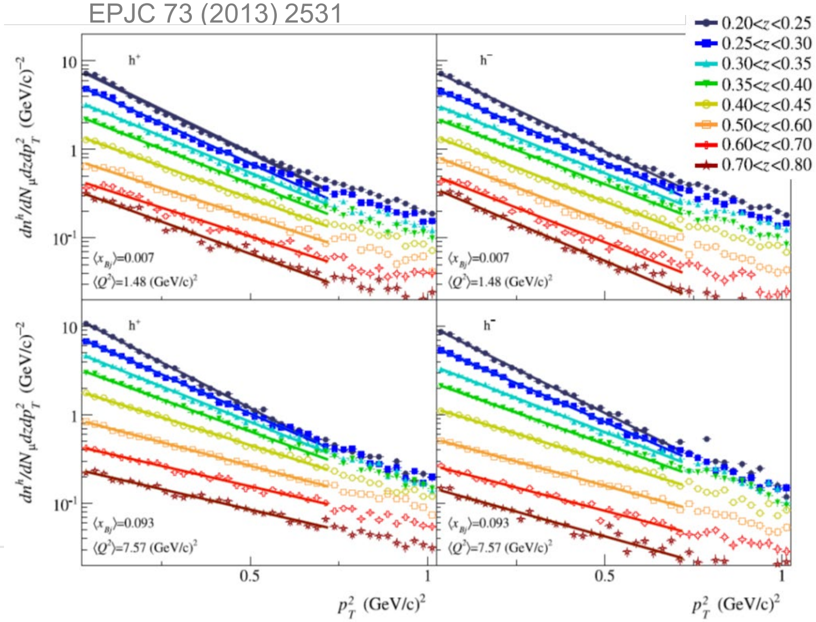
EPJC 73 (2013) 2531



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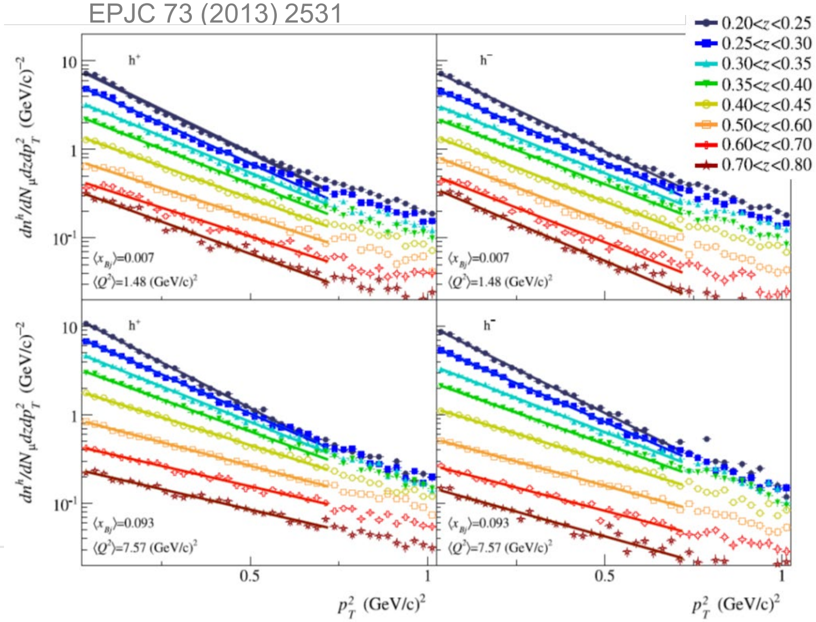

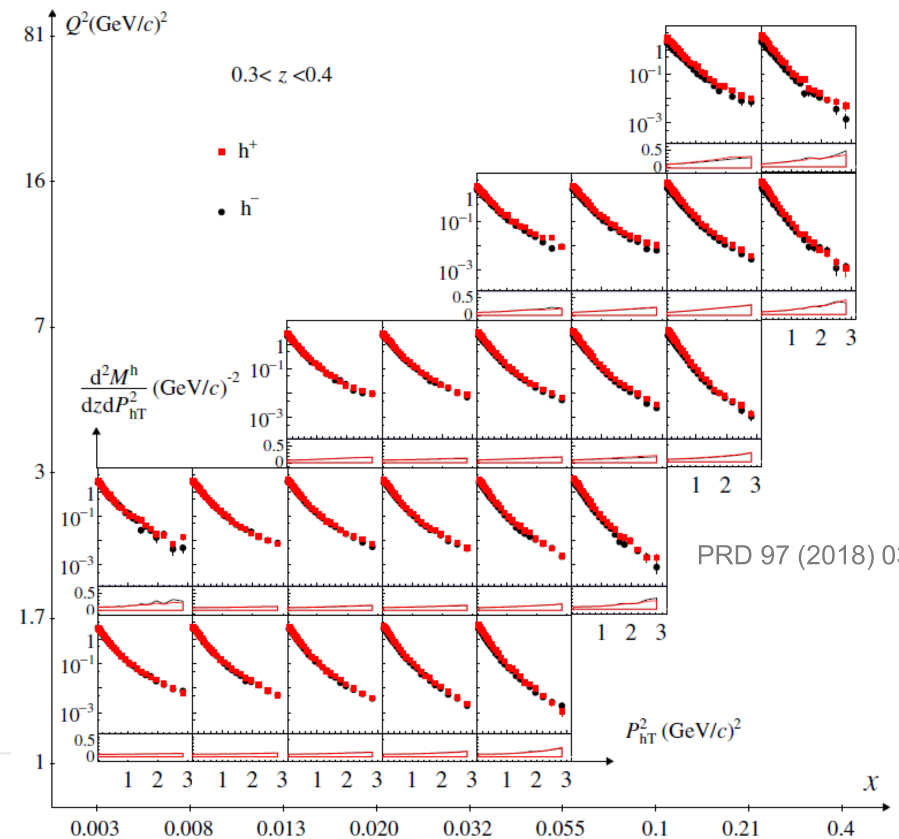

PRD 97 (2018) 032006

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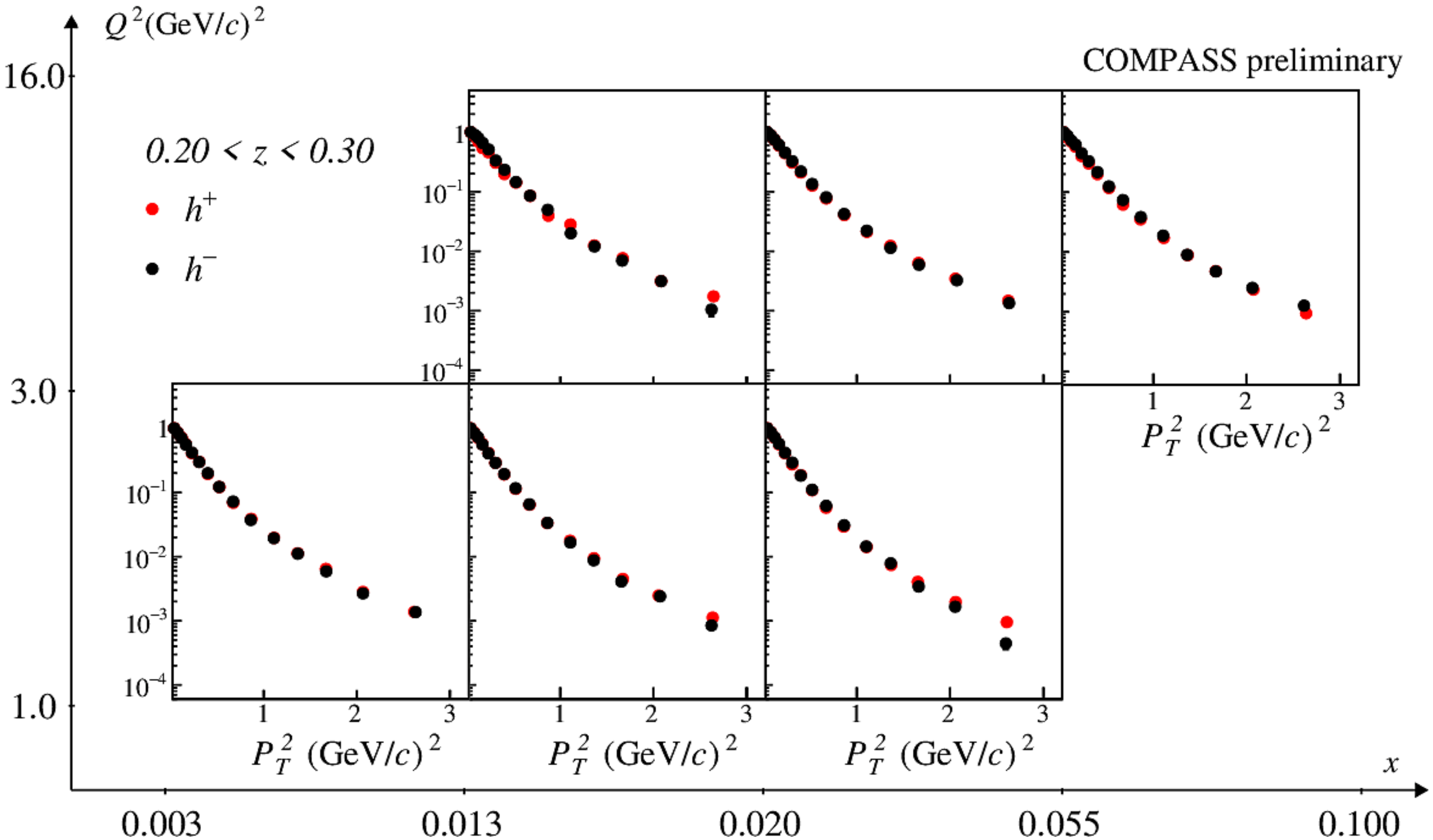
  - $^{6}\mathrm{LiD}$ – 2006 data $0.003 < x < 0.40$ $1 < Q^2 < 81\ \mathrm{GeV}^2$
  - **$\mathbf{LH_2}$ – 2016 data $\boldsymbol{0.003 < x < 0.10}$ $\boldsymbol{1 < Q^2 < 16\ \mathrm{Ge}V^2}$ NEW** → *A. Moretti*
    - **$\boldsymbol{4x \times 2\ Q^2 \times 4z}$ ← used in this work**
    - $4x \times 2\ Q^2 \times 7z$
    - $4x \times 4\ Q^2 \times 4z$
    - $4x \times 2\ Q^2 \times 2W \times 4z$
    - $4x \times 4\ Q^2 \times 2W \times 4z$

transverse momentum distributions in SIDIS

COMPASS – charged hadrons, DIS with 160 GeV muons and LH_2 target
2016 data



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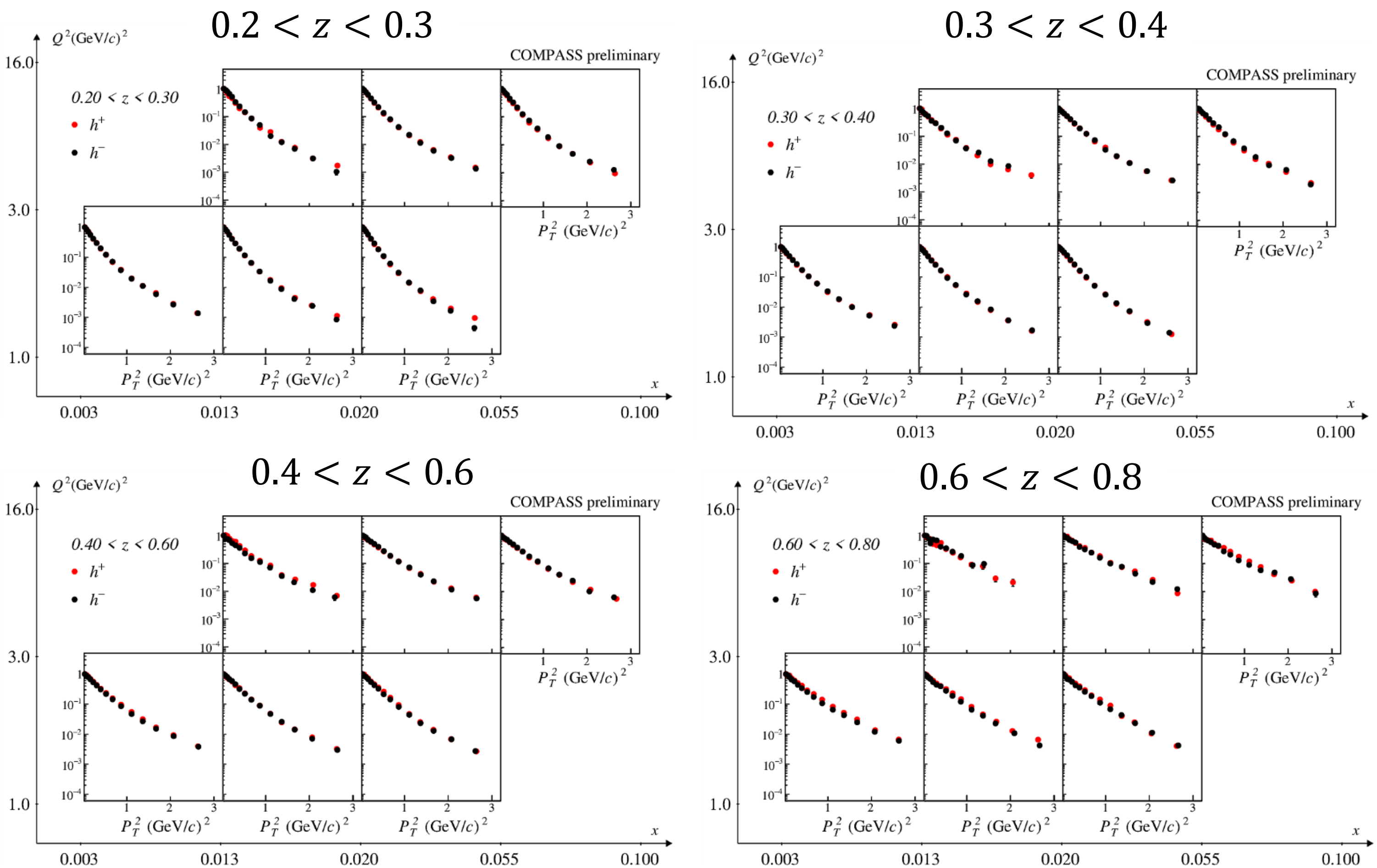


strong z dependence

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

clear Q^2 dependence

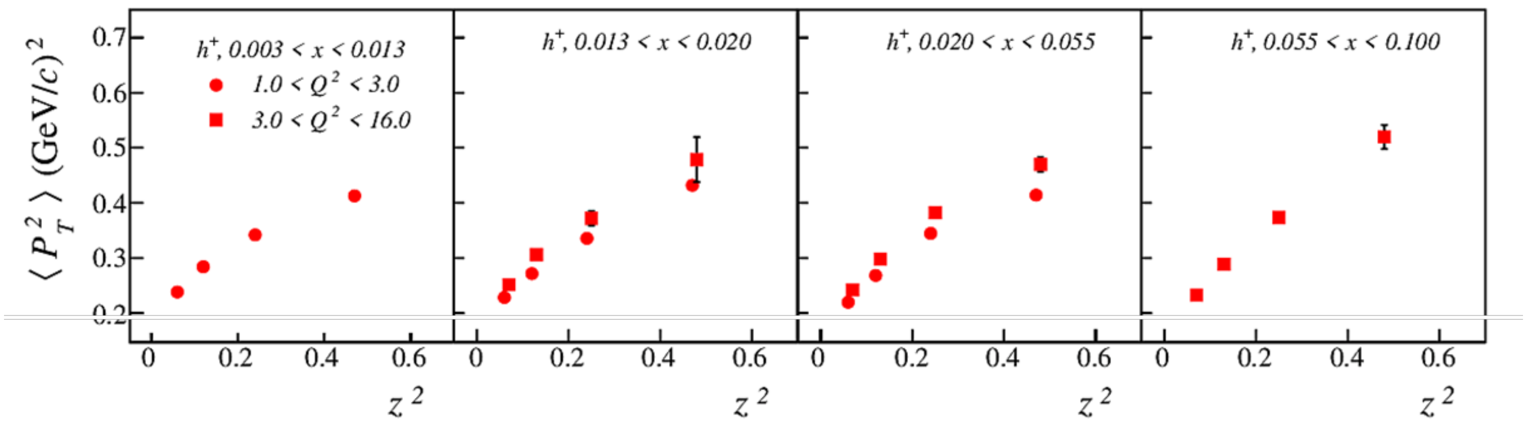
- good quality fits with the sum of two exponentials up to $3\ (\mathrm{GeV/c})^2$
- reasonable fits with one exponential up to $1\ (\mathrm{GeV/c})^2$ - bad χ^2 at low z → $\langle P_T^2 \rangle$

transverse momentum distributions in SIDIS

COMPASS – charged hadrons, DIS with 160 GeV muons and $\mathrm{LH_2}$ target
2016 data

$\langle P_T^2 \rangle$ from fits with an exponential function up to $1\ (\mathrm{GeV}/c)^2$

COMPASS preliminary



LO expectation: $\langle P_T^2 \rangle \simeq z^2 \langle k_T^2 \rangle + \langle p_\perp^2 \rangle$ ⇨ $\langle p_\perp^2 \rangle$ depends on z

information from the recently published Belle data

transverse momentum distributions in SIDIS

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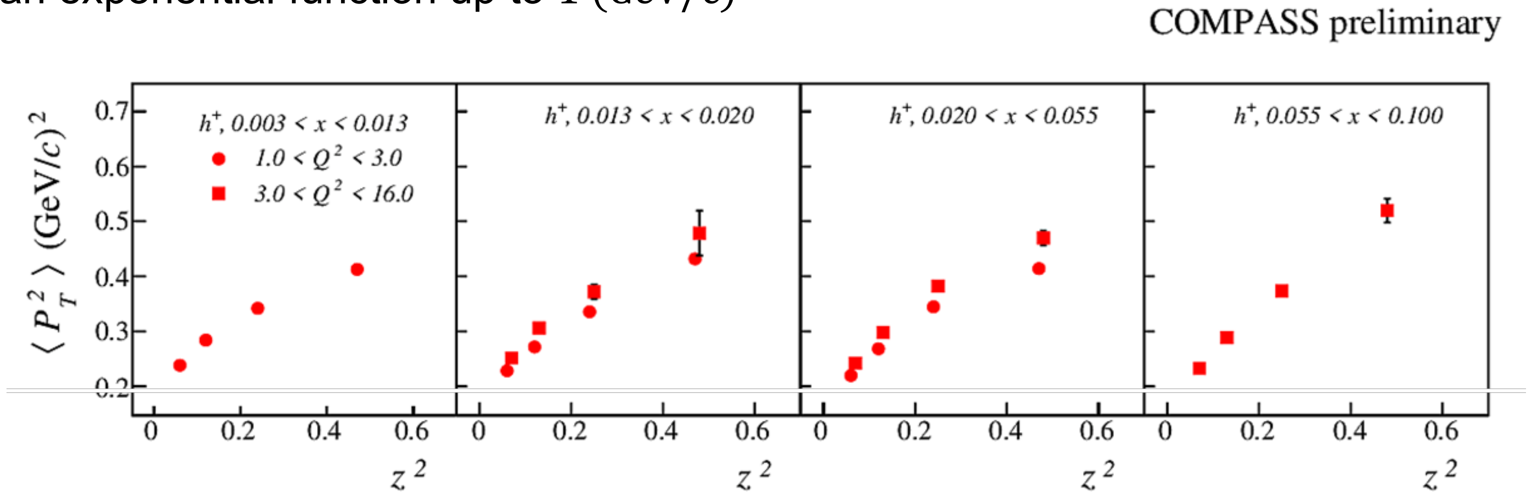

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this work:
same analysis of the COMPASS and Belle data to extract $\langle P_T^2 \rangle$ and $\langle p_\perp^2 \rangle$ respectively, and then evaluate $\langle k_T^2 \rangle$ using the LO expression

transverse momentum distributions in SIDIS

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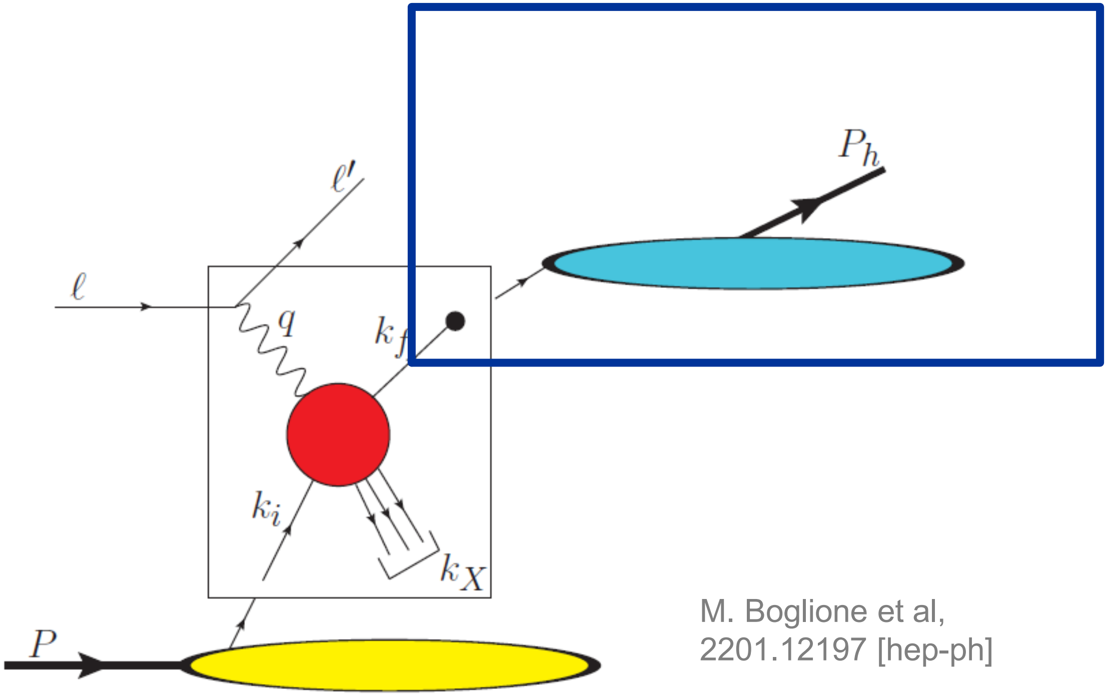

same in SIDIS and e^+e^-annihilation

M. Boglione et al,
2201.12197 [hep-ph]

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same analysis of 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

the Belle P_{hT}^2 cross-sections

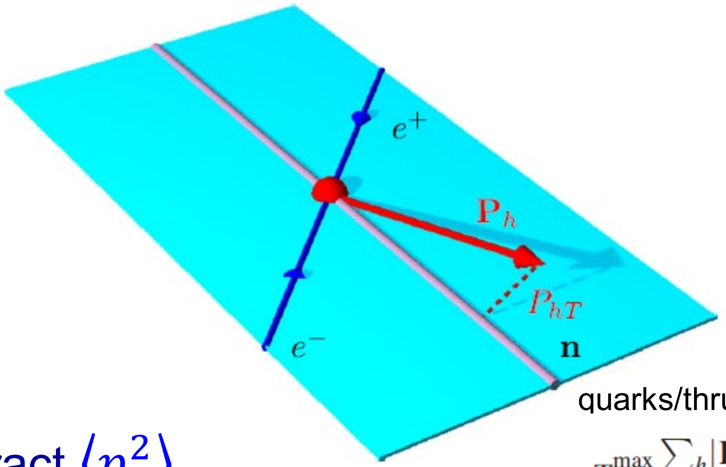
PRD 99, 112006 (2019)

"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 thrust axis ~ quark direction

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



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

the Belle data can be used to extract $\langle p_\perp^2 \rangle$

and then $\langle k_T^2 \rangle$ from the COMPASS $\langle P_T^2 \rangle$

all fragmentation properties in !

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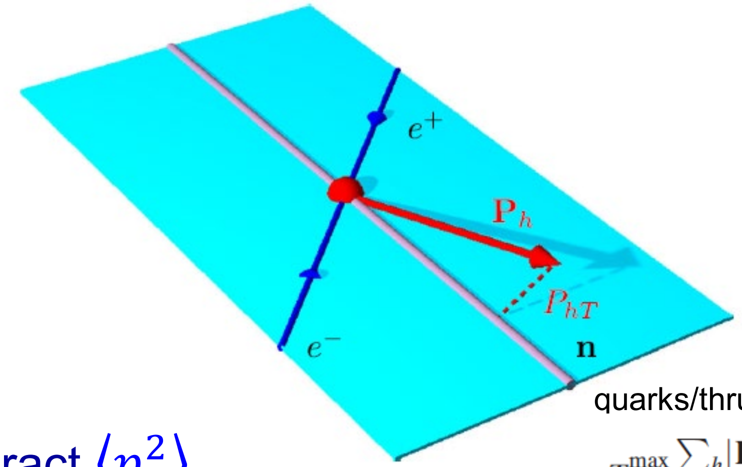

quarks/thrust axis

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all fragmentation properties in !

main problem when comparing SIDIS and e^+e^- data: the scale s (or Q^2) in e^+e^-, Q^2 and W is SIDIS

$Q^2_{COMPASS} \ll Q^2_{Belle}$ but $W_{COMPASS} \simeq W_{Belle}$ …

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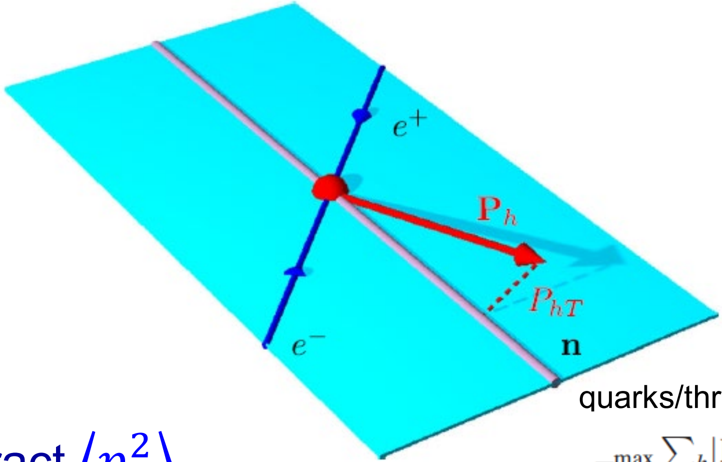

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and then $\langle k_T^2 \rangle$ from the COMPASS $\langle P_T^2 \rangle$

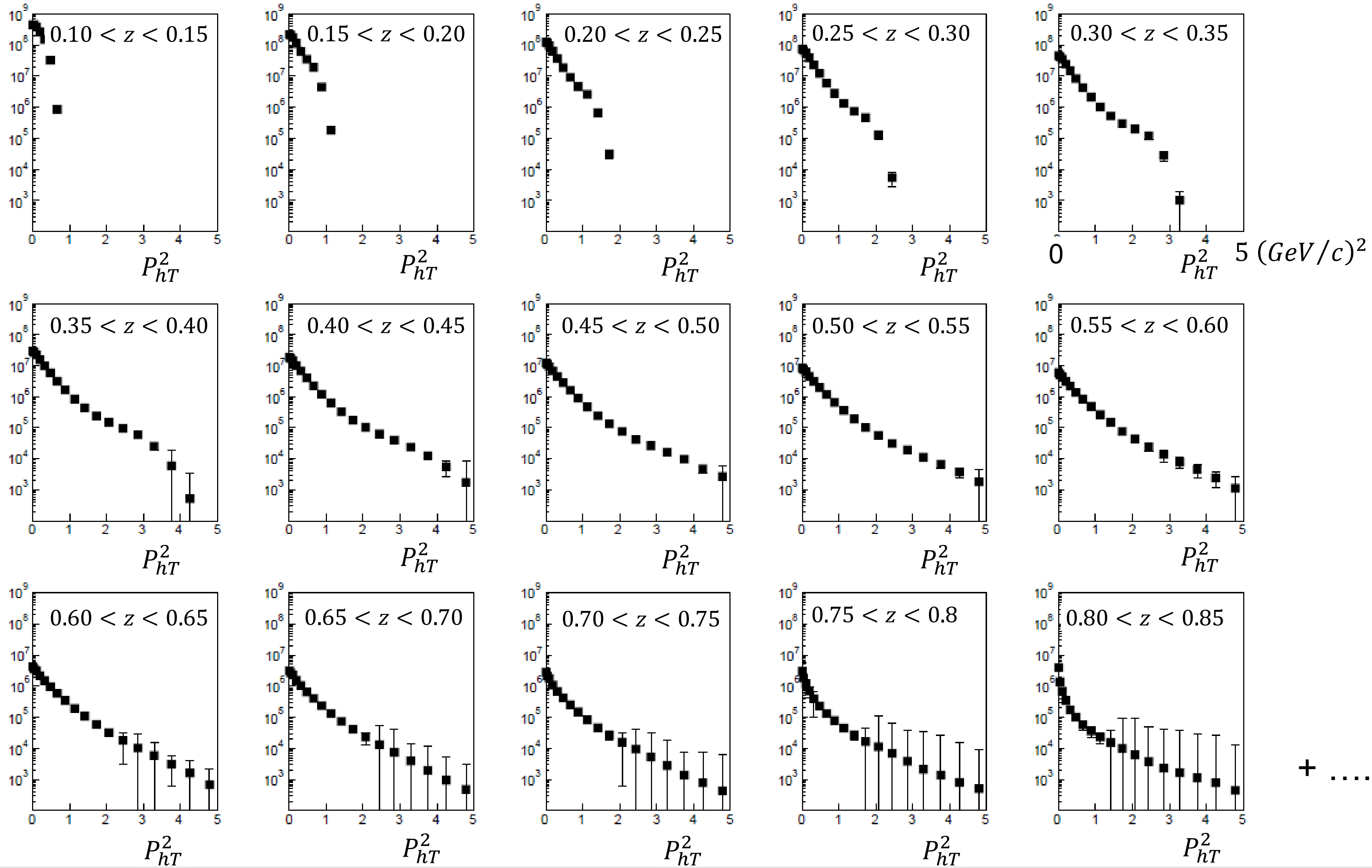
all fragmentation properties in !

we added up the cross-sections in all the *T* bins excluding only 0.95<*T*<1.00

small cross-section and large uncertainties

the Belle P^2_{hT} cross-sections

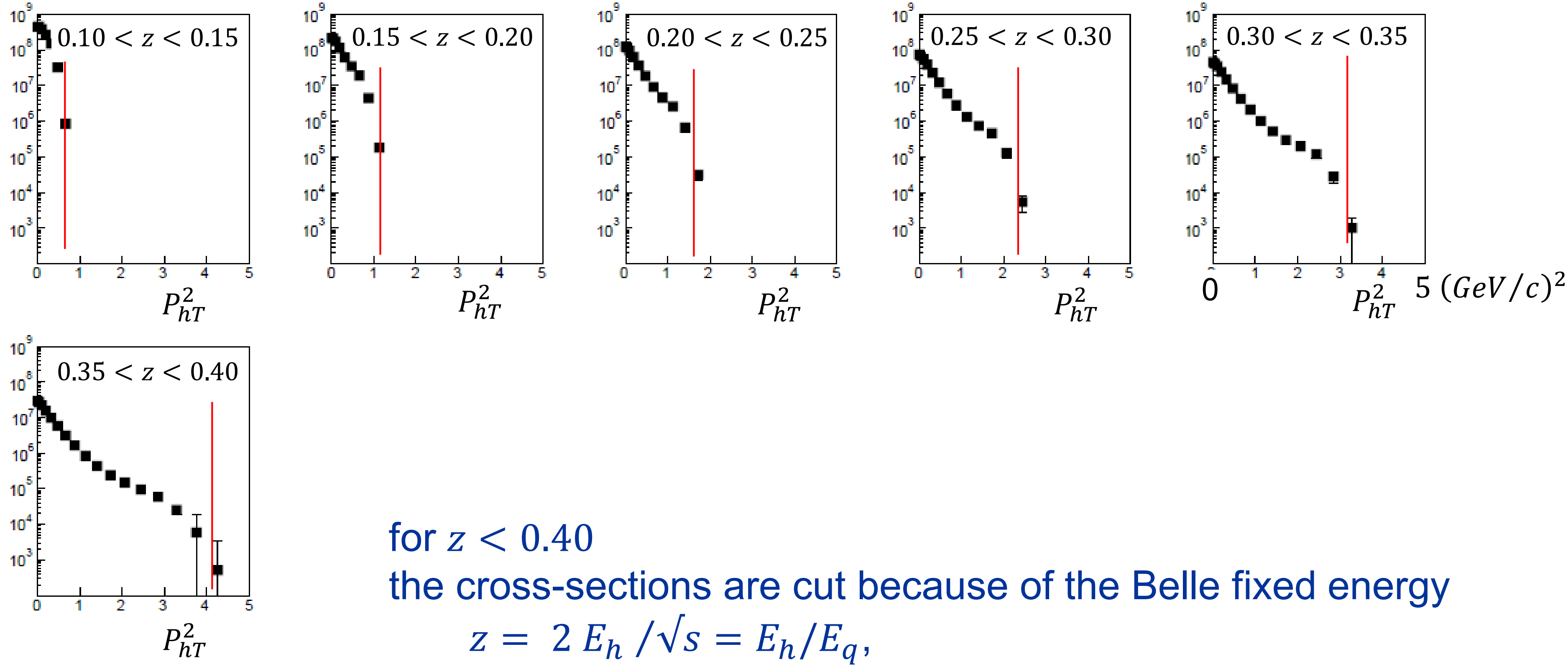
$\pi^{\pm}$ integrated over *T*



+ .....

the Belle P_{hT}^2 cross-sections

$\pi^{\pm}$ integrated over T



for $z < 0.40$

the cross-sections are cut because of the Belle fixed energy

$$z = 2E_h/\sqrt{s} = E_h/E_q,$$

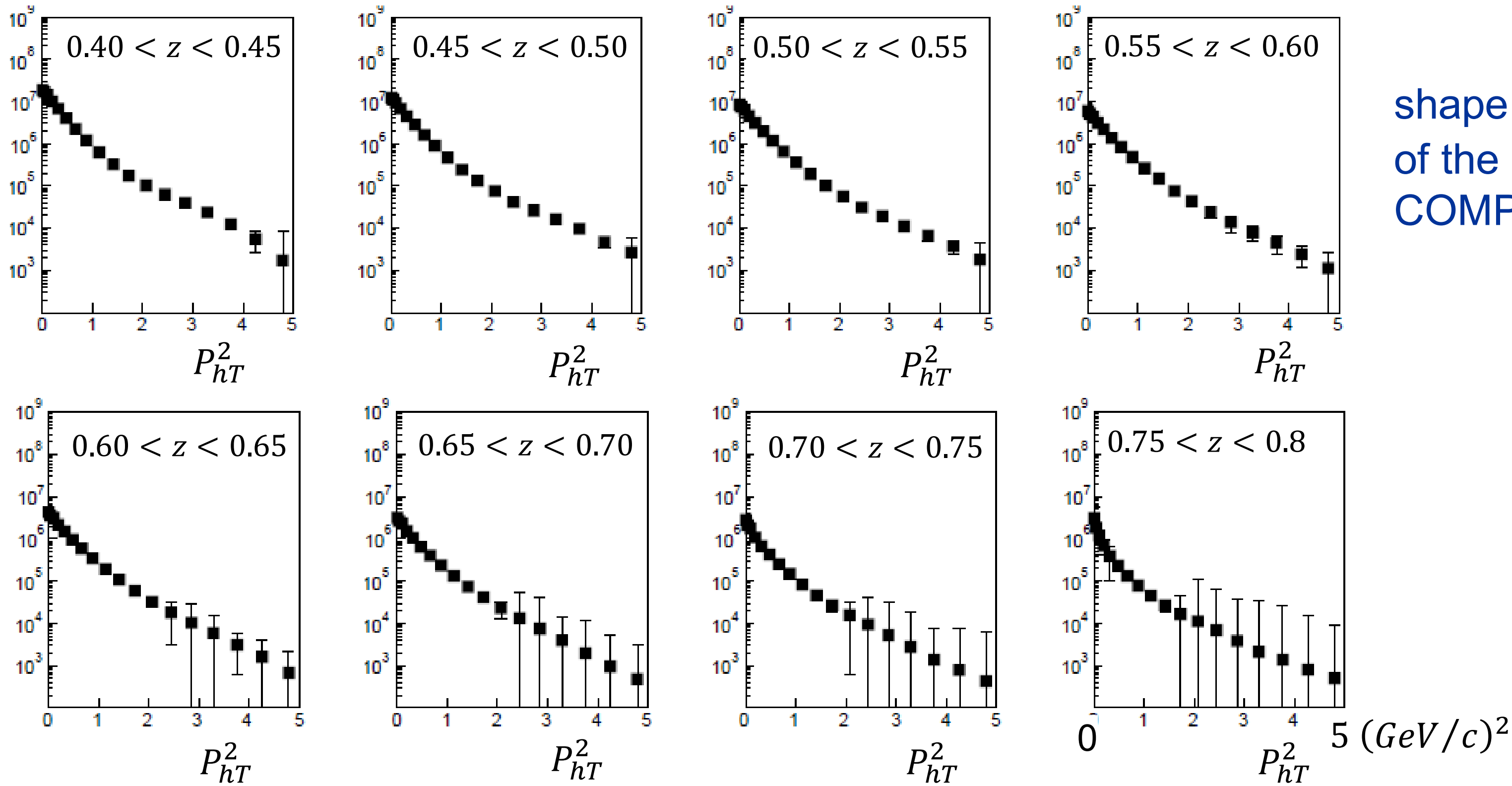
$$z < z^* \rightarrow P_{hT} < z^*\sqrt{s}/2$$

not used

the Belle P_{hT}^2 cross-sections

$\pi^{\pm}$ integrated over *T*

for $0.4 < z < 0.80$
the cross-sections look fine, at least up to $P_{hT}^2 = 3\ (GeV/c)^2$



shape similar to that of the low-z COMPASS distributions

we summed the cross-sections to obtain the distributions in the bins

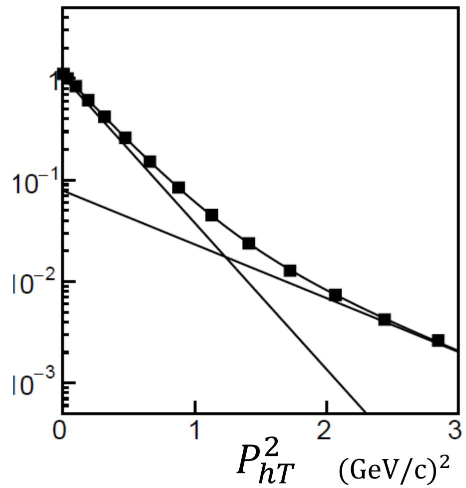
$0.40 < z < 0.60$ and $0.60 < z < 0.80$,

the same z bins as in COMPASS

$\langle P_{hT}^2 \rangle$ from Belle distributions

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

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

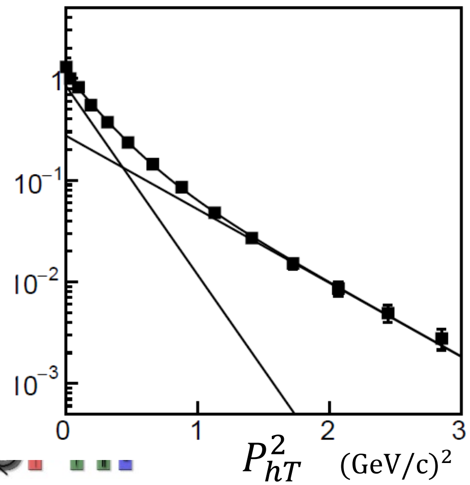


$\mathbf{0.40 < z < 0.60}$ $\langle \boldsymbol{P_{hT}^2} \rangle = \mathbf{0.389}$ $(\mathrm{GeV}/c)^2$

↑

$\langle p_\perp^2 \rangle$

↓



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

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

$\langle P_T^2 \rangle$ from COMPASS distributions

for consistency with Belle

- we have produced the $\boldsymbol{h^+ + h^-}$ **distributions** (almost no difference between h^+ and h^-) 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 have used

- the x bin $\mathbf{0.020 < x < 0.055}$ (statistics) $\langle x \rangle = 0.037$
- the Q^2 bin $\mathbf{3 < Q^2 < 16\ GeV^2}$

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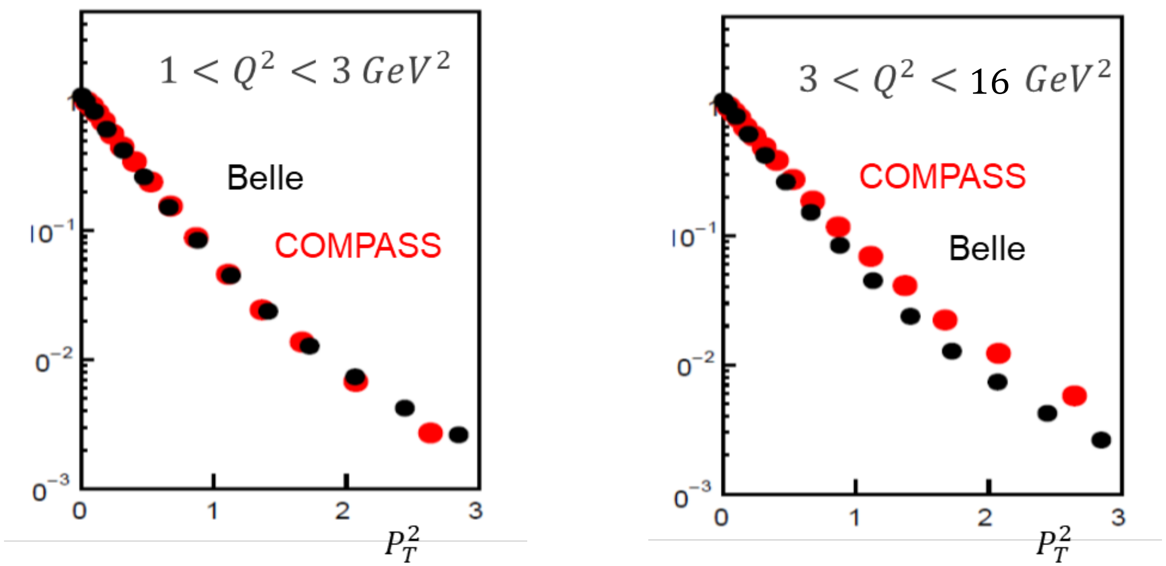
$0.40 < z < 0.60$



too low Q^2
from SIDIS measurements there is evidence that the Q^2 dependence is stronger at low Q^2 values

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fit up to $\mathbf{3\ (GeV/c)^2}$ with the same function used for the Belle data

very good χ^2

$$p_0 \cdot exp\left(-\frac{P_T^2}{p_1}\right) + p_2 \cdot exp\left(-\frac{P_T^2}{p_3}\right)$$

and calculated $\langle P_T^2 \rangle$ in the same way $\langle P_T^2 \rangle = \dfrac{p_0 p_1^2 + p_2 p_3^2}{p_0 p_1 + p_2 p_3}$

results:

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

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

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

to summarise

$\langle z \rangle$	$\langle P_T^2 \rangle$ $(\mathrm{GeV/c})^2$	$\langle p_\perp^2 \rangle$ $(\mathrm{GeV/c})^2$
0.48	0.456	0.389
0.68	0.545	0.398

using $\langle P_T^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_\perp^2 \rangle$ one gets, from the two z bins,

$\langle k_T^2 \rangle = 0.29\ (\mathrm{GeV/c})^2$ and $\langle k_T^2 \rangle = 0.32\ (\mathrm{GeV/c})^2$

final results: $\boldsymbol{\langle k_T^2 \rangle = 0.31\ (\mathrm{GeV/c})^2}$

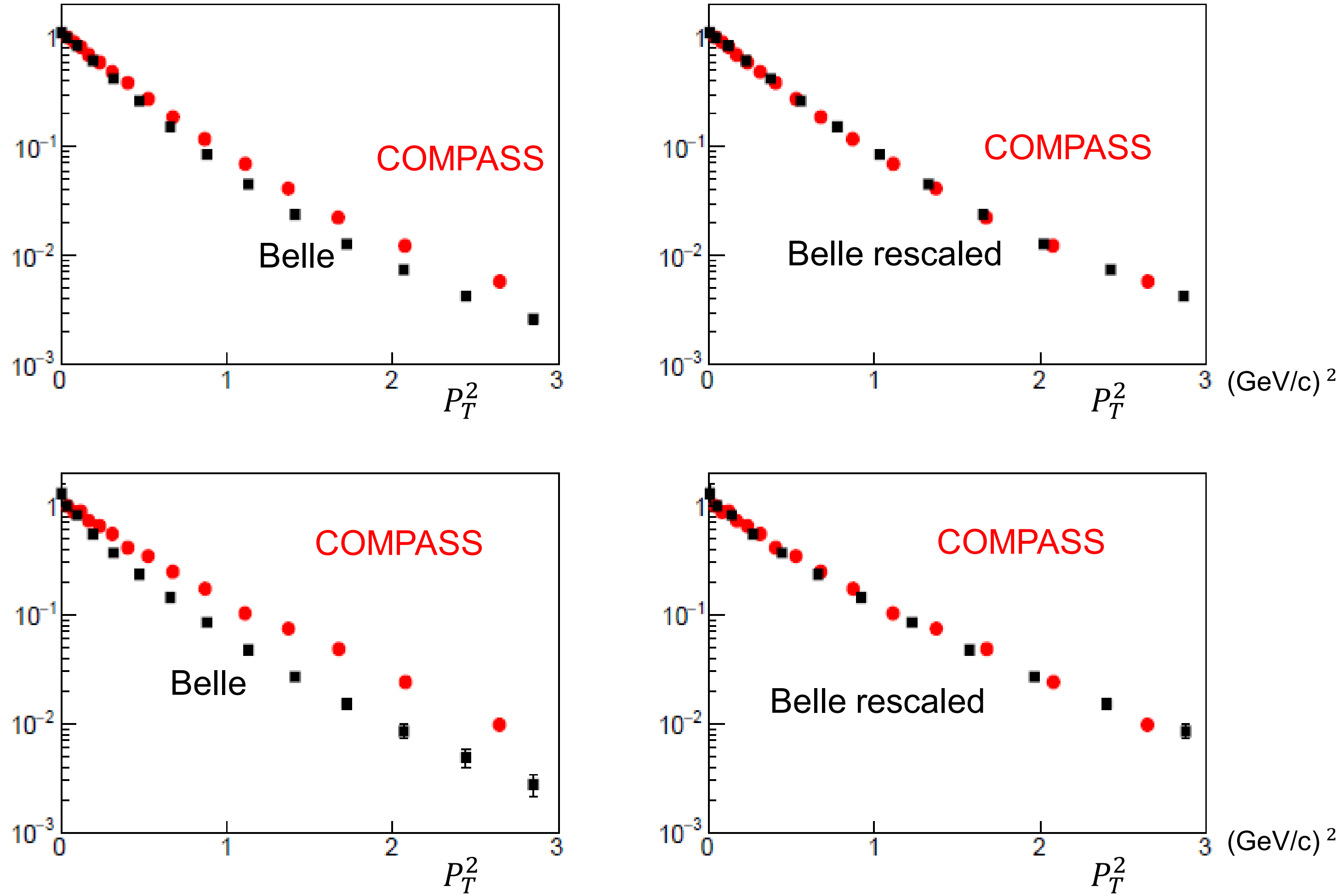
at $\langle x \rangle = 0.037$, $\langle Q^2 \rangle = 4.7\ \mathrm{GeV}^2$, $\langle W \rangle = 11\ \mathrm{GeV/c}^2$

$\langle k_T^2 \rangle$ 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 $p_{\perp i}^2$ is scaled by $(z^2\langle k_T^2 \rangle + \langle p_\perp^2 \rangle)/\langle p_\perp^2 \rangle$

$0.40 < z < 0.60$

$0.60 < z < 0.80$



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this simple, LO extraction of the mean intrinsic transverse momentum looks promising

TMD extractions from COMPASS SIDIS data

direct extraction of Transversity and Sivers function from SIDIS Transverse Spin Asymmetries

important results have been measuring SIDIS with

- high energy muons (160, 190 obtainedGeV/c - unique facility, at CERN)
- transversely polarised d (6LiD) and p (NH3) targets

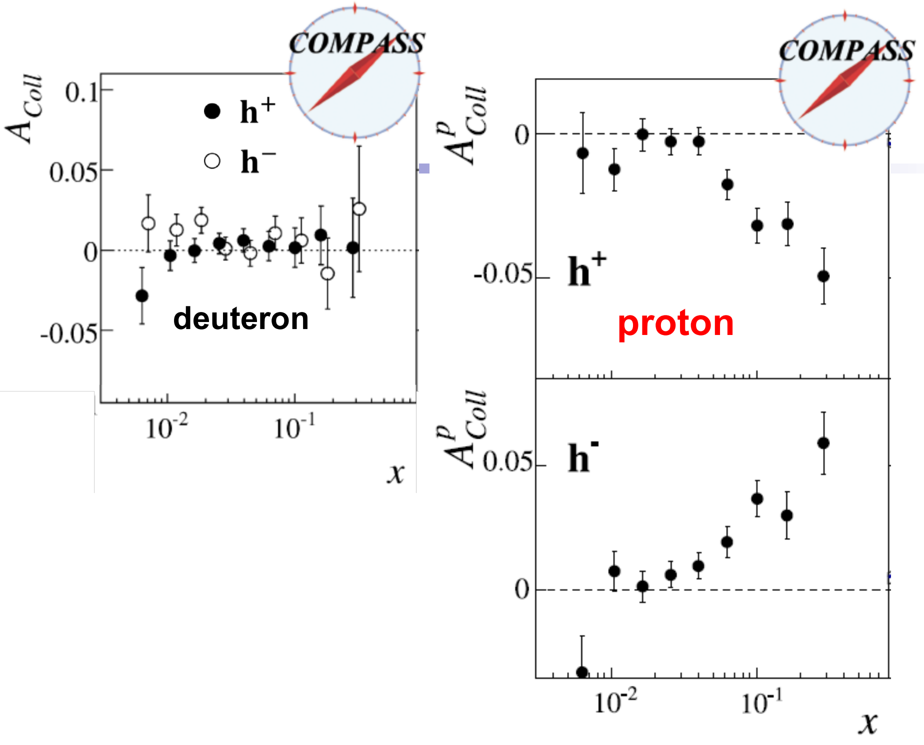
in particular, COMPASS is the only experiment that could measure TSA with p and d targets at the same energy, in the same kinematic region, with the same binning

this gave the opportunity to
directly extract the transversity and Sivers functions

Transversity extraction

using

- the h^+ and h^- Collins asymmetry in SIDIS off deuteron and protons measured by COMPASS



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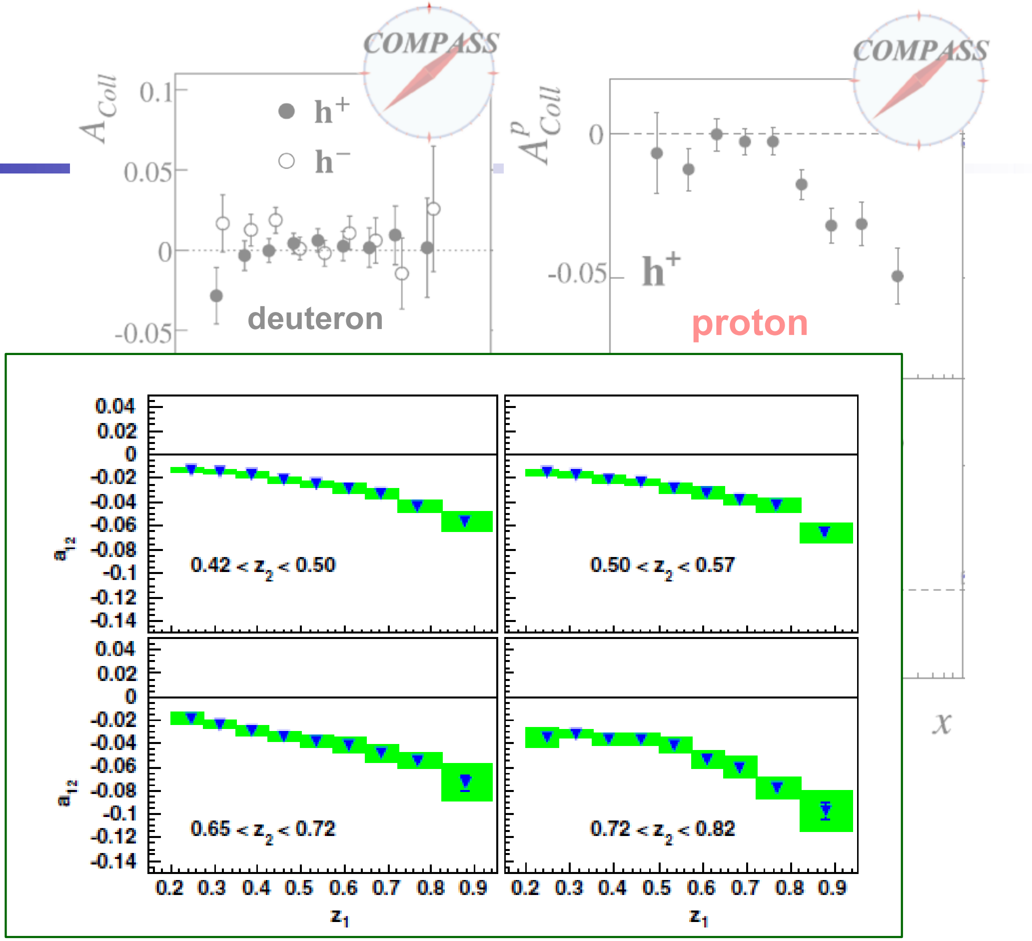
- the corresponding Belle asymmetries



Transversity extraction

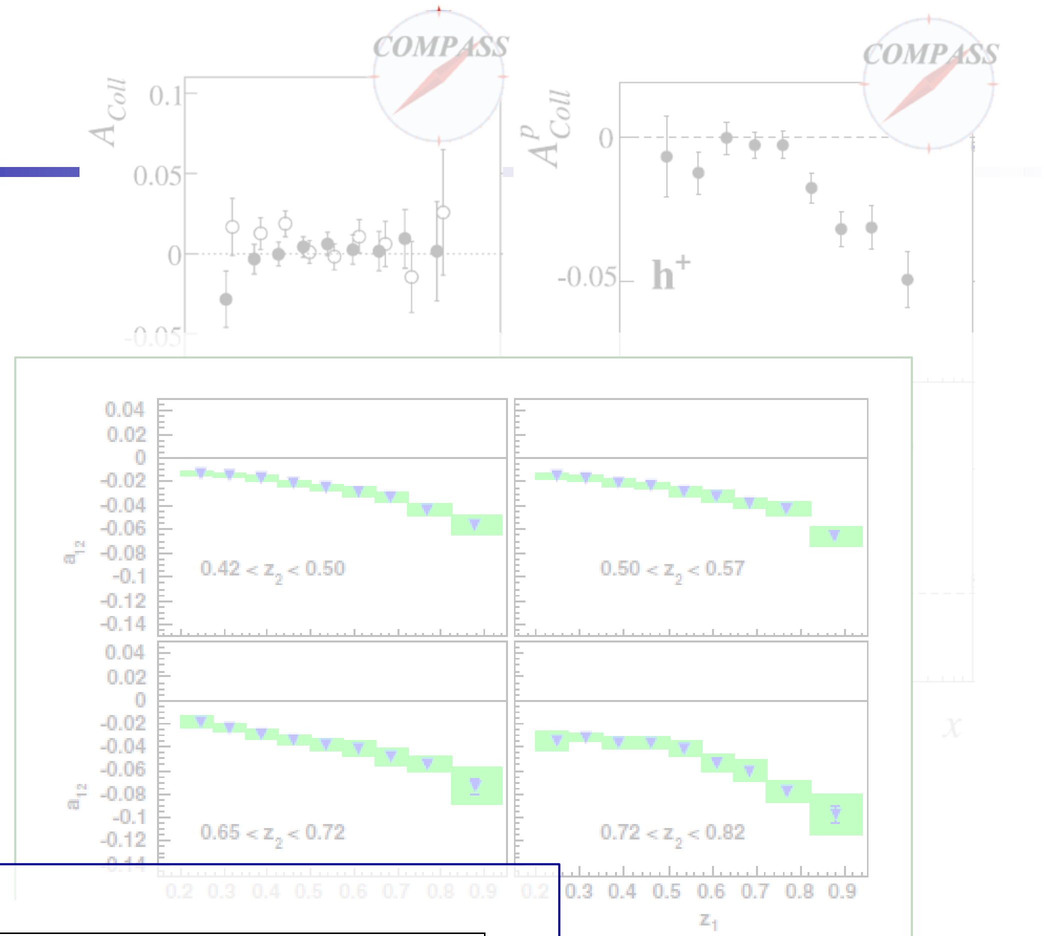
using

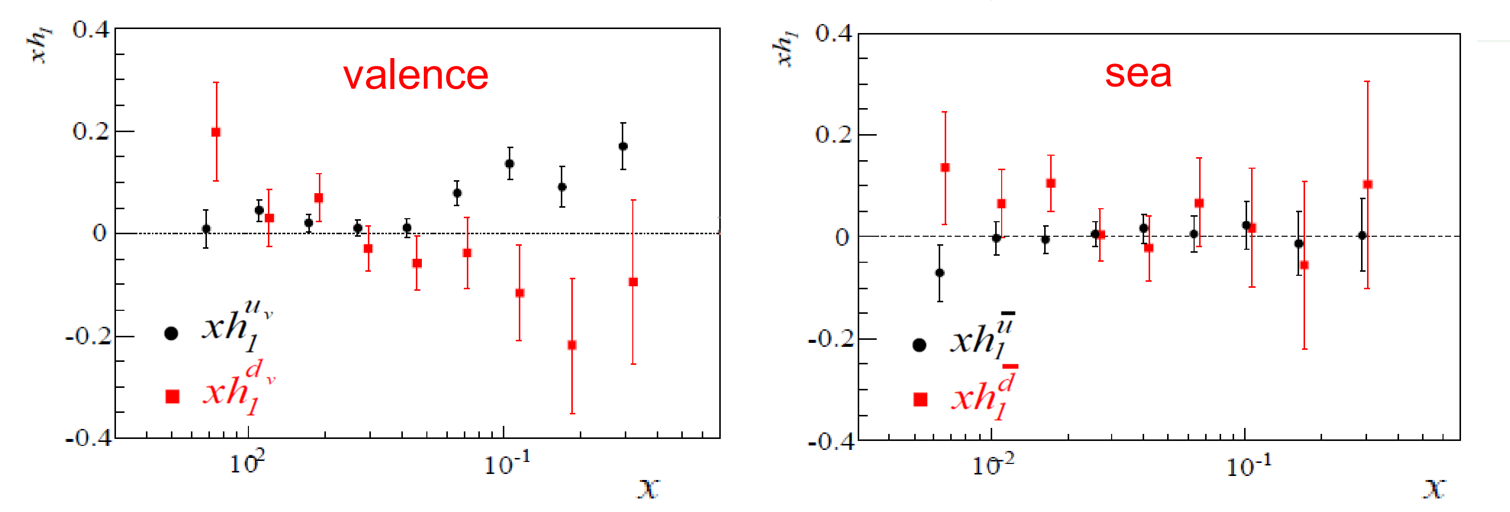
- the h^+ and h^- Collins asymmetry in SIDIS off deuteron and protons measured by COMPASS

- the corresponding Belle asymmetries

with the Gaussian ansatz

point by point extraction of h_1





A.M., F. Bradamante, V. Barone PRD91, 014034 (2015)

Transversity extraction

using

- the h^+ and h^- Collins asymmetry in SIDIS off deuteron and protons measured by COMPASS
- the corresponding Belle asymmetries

with the Gaussian ansatz

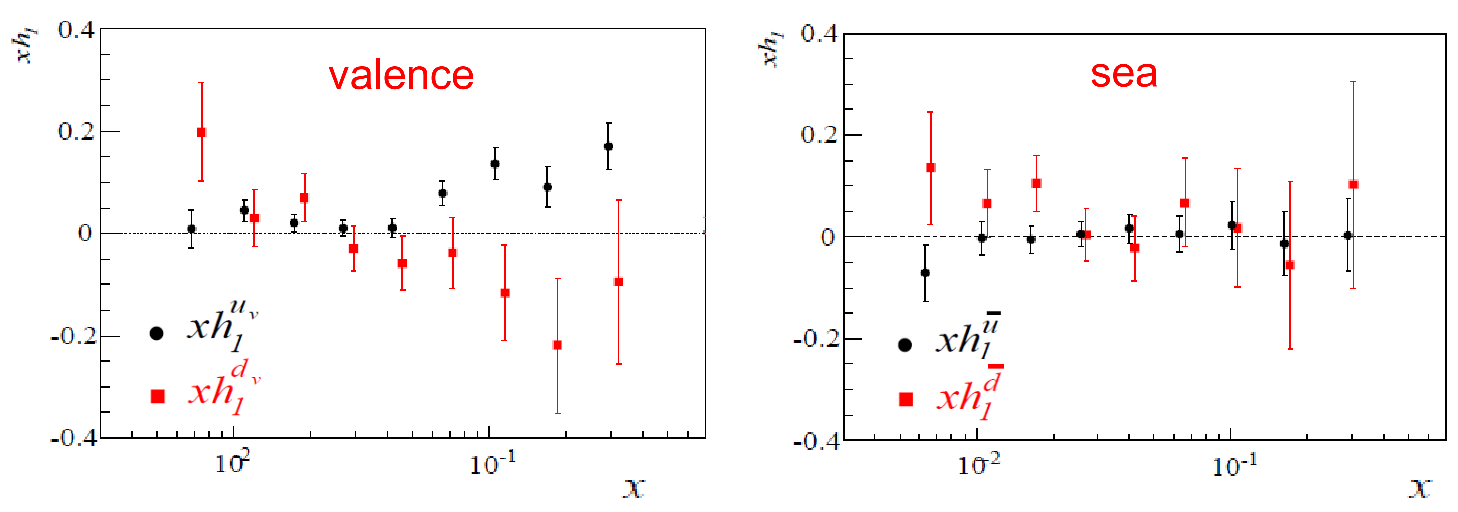
point by point extraction of h_1

main advantage: no Monte Carlo nor parametrisation of PDFs and FFs is needed

done also with 2h asymmetries – similar results

it is possible to include the HERMES results (COMPASS addendum, …)

large statistical uncertainty on d-quark transversity due to missing deuteron data (2022 run!)



A.M., F. Bradamante, V. Barone PRD91, 014034 (2015)

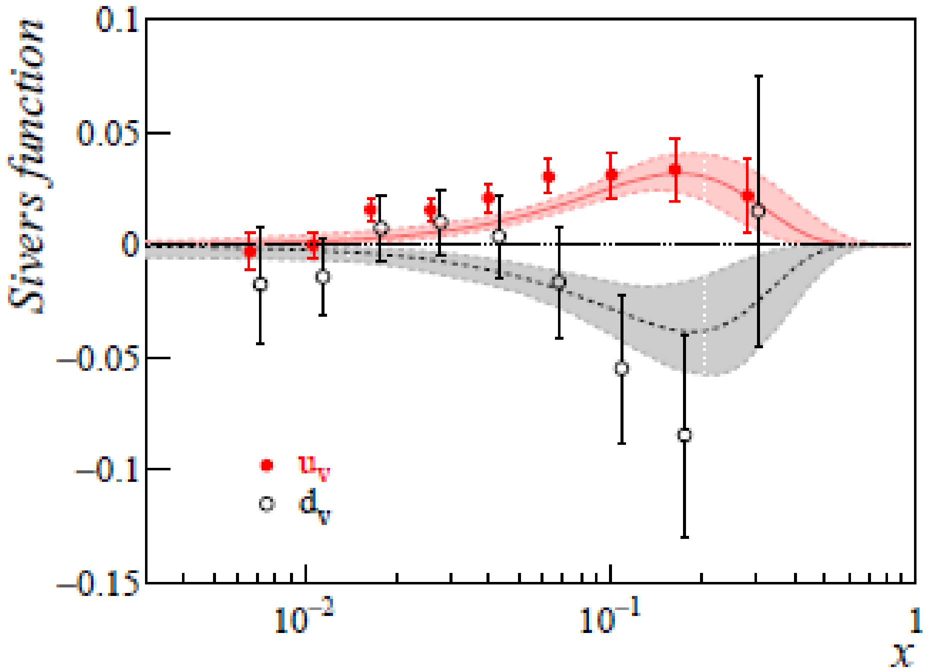
Sivers function extraction / 1

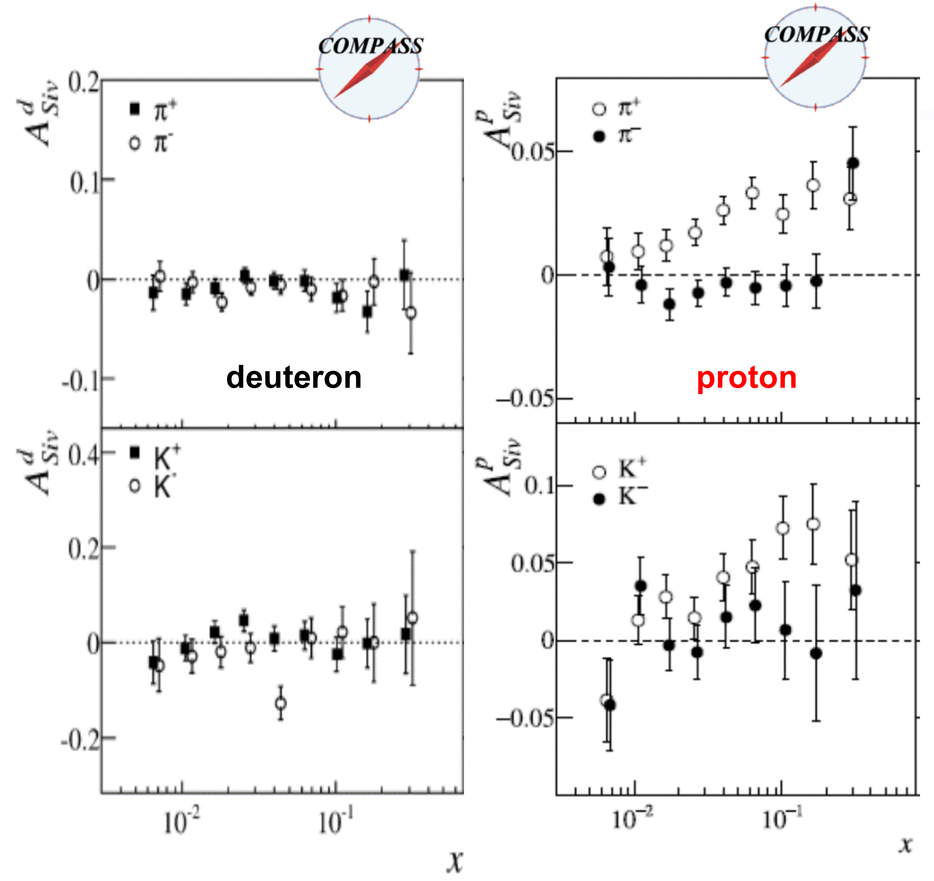
using

- the charged pion and kaon Sivers asymmetry in SIDIS off proton and deuteron measured by COMPASS

with the Gaussian ansatz

point by point extraction of $f_{1T}^{\perp(1)}$





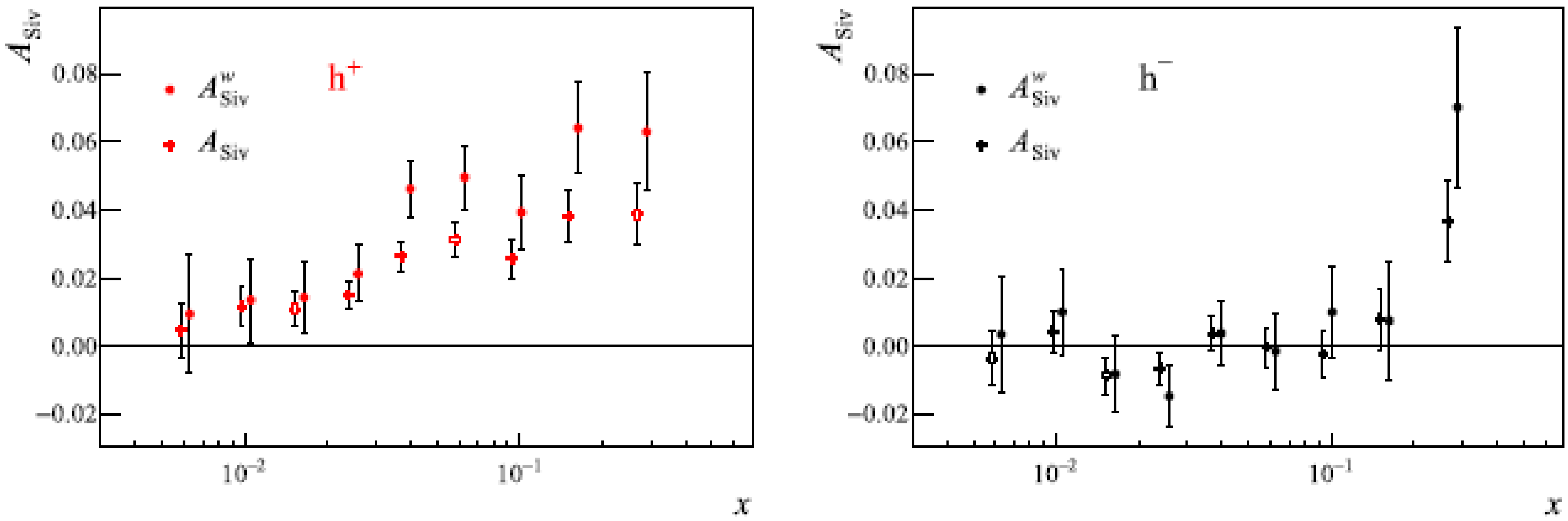
AM, Bradamante, Barone
PRD 95 (2017) 9, 094024

curves:
Anselmino, Boglione, Melis,
Phys. Rev. D 86, 014028 (2012).

Sivers function extraction / 2

COMPASS has also measured the P_T**-weighted Sivers asymmetries** for charged hadrons produced in SIDIS off protons

NPB 940 (2019) 34



Sivers function extraction / 2

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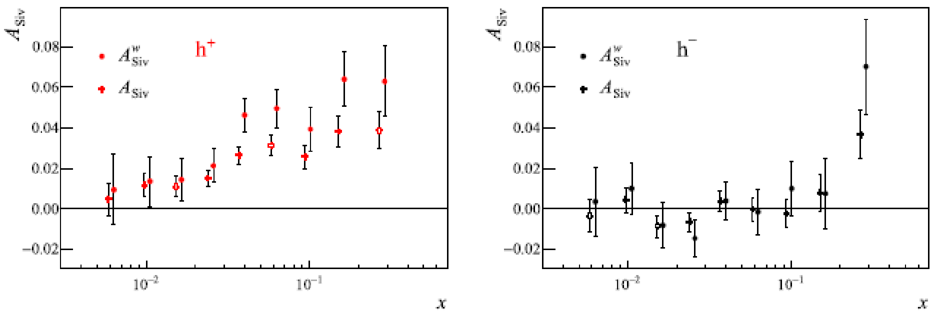
using these asymmetries the convolution over transverse momenta can be solved
→ no need for the Gaussian ansatz
to extract $f_{1T}^{\perp(1)}$



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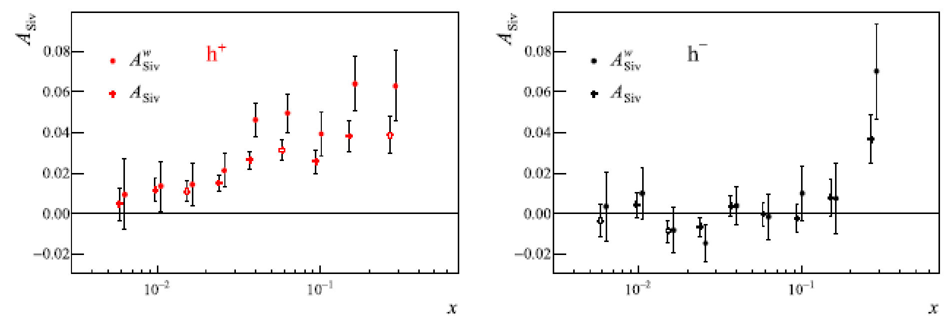

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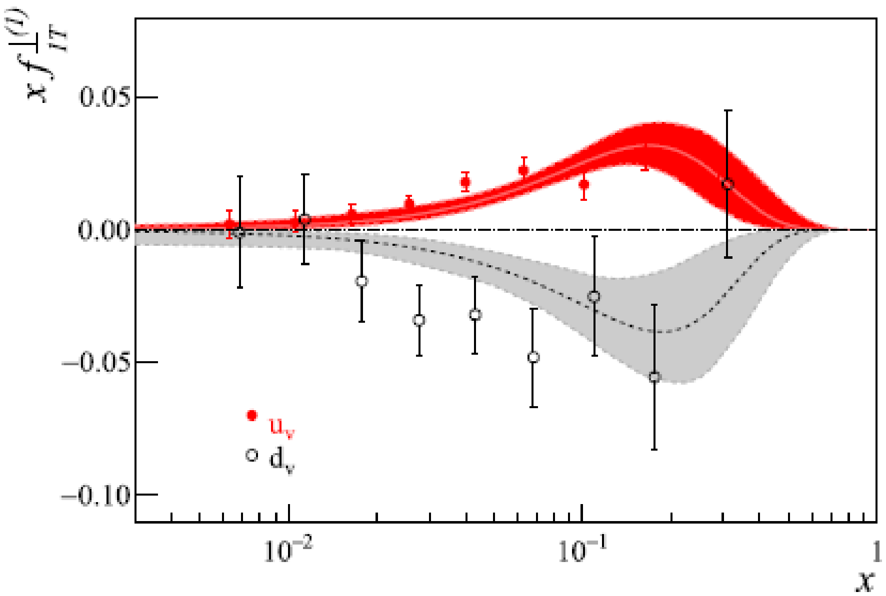

assuming the Sivers function to be zero for sea quark
(lack of the corresponding deuteron data)

conclusions

direct extractions of the transversity PDF and of the Sivers function have been performed using the COMPASS data on TSA, and the Belle data

a different approach with respect to the global fits including also HERMES, JLab and RHIC data

NEW WORK: the direct comparison of the COMPASS and the Belle measurements of transverse momentum distributions allows for a simple, LO extraction of the mean value of the intrinsic transverse momentum squared

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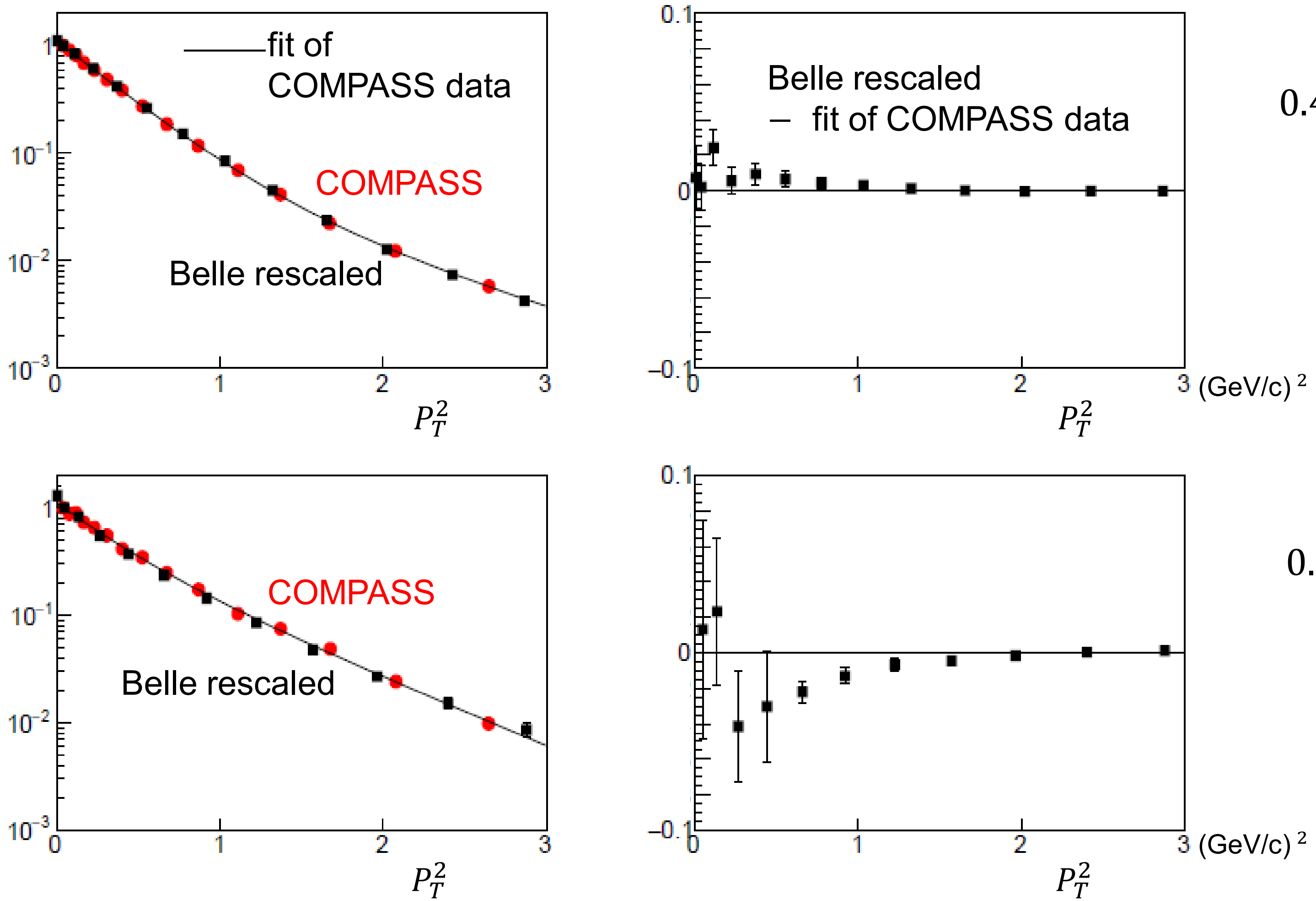
thank you !

$\langle k_T^2 \rangle$ 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 $(z^2\langle k_T^2 \rangle + \langle p_\perp^2 \rangle)/\langle p_\perp^2 \rangle$



$0.40 < z < 0.60$

$0.60 < z < 0.80$