Phenomenology of TMDs

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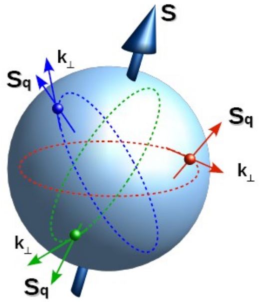
Scuola di Scienze della Natura

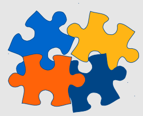
3D Structure of the Nucleon

The exploration of the ***3-dimensional structure of the nucleon***, both in momentum and in configuration space, is one of the major issues in high energy hadron physics.

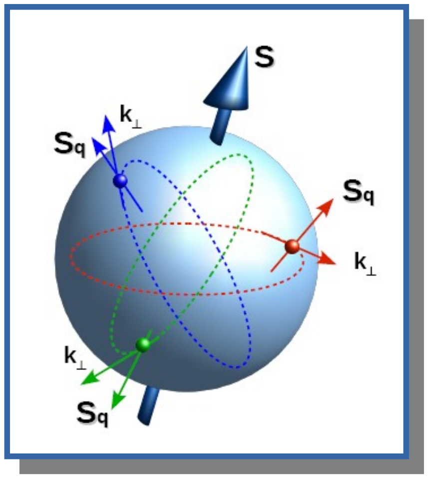


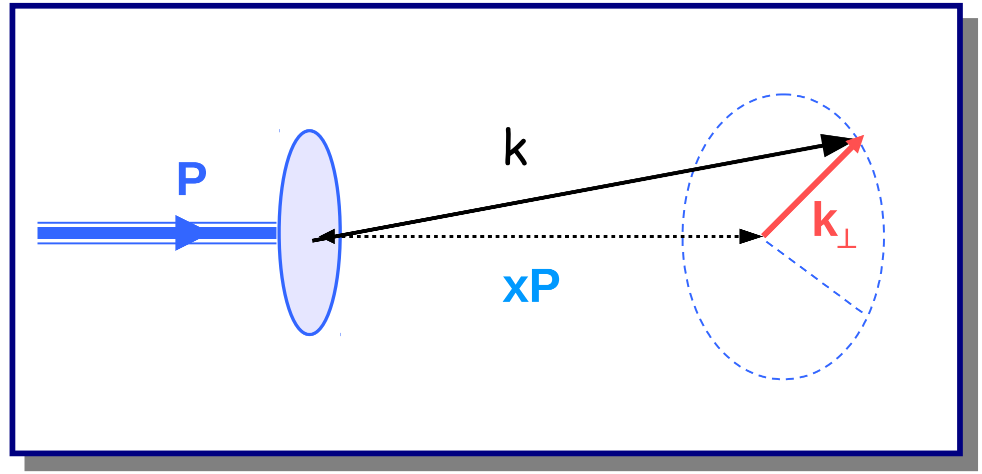
Information on the 3-dimensional structure of the nucleon is embedded in the ***Transverse Momentum Dependent*** distribution and fragmentation functions (***TMDs***).

In a very simple **phenomenological** approach, hadronic cross sections and spin asymmetries are generated, within a ***QCD* factorization** framework, as convolutions of **distribution** and (or) **fragmentation** functions with elementary cross sections.

	***This simple approach can successfully describe a wide range of experimental data.***

Intrinsic Transverse Momentum





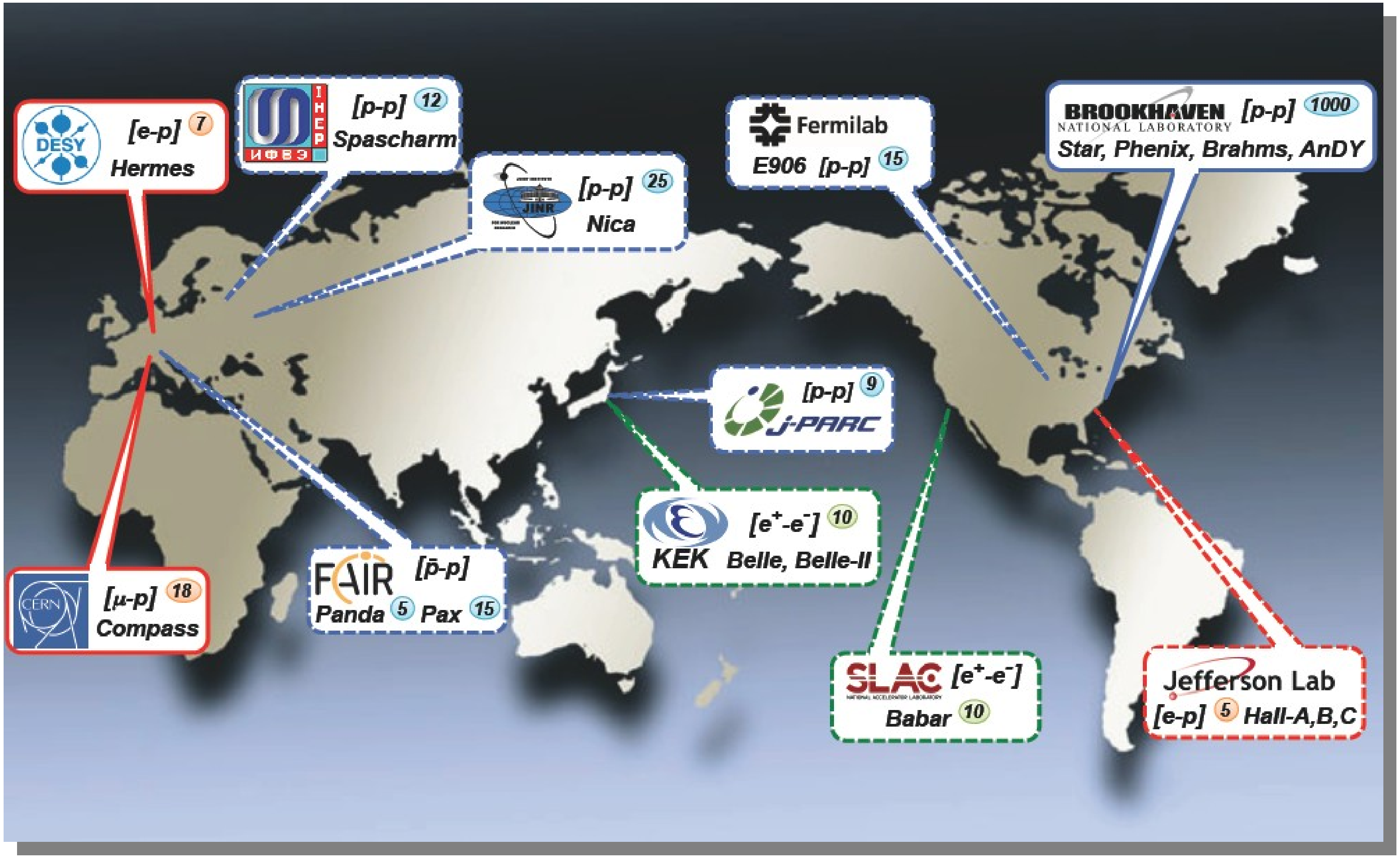
We cannot learn about the spin structure of the nucleon without taking into account the **transverse motion** of the partons inside it

Transverse motion is usually integrated over, but there are important **spin-$k_\perp$** correlations which should not be neglected

	Several theoretical and experimental evidences for transverse motion of partons within nucleons, and of hadrons within fragmentation jets.

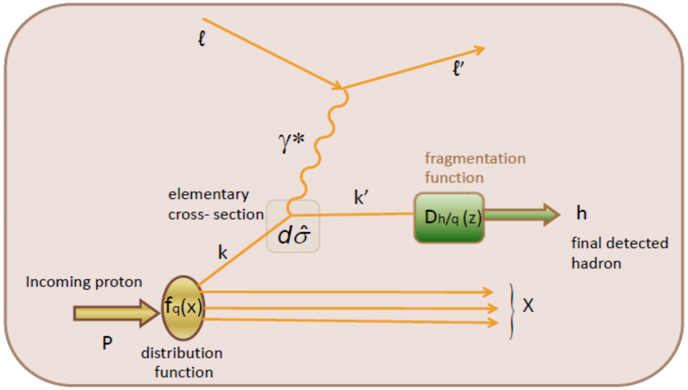
Where can we learn about the 3D structure of matter ?

Where can we learn about the 3D structure of matter ?



Experimental data for TMS studies

Unpolarized and Polarized SIDIS scattering

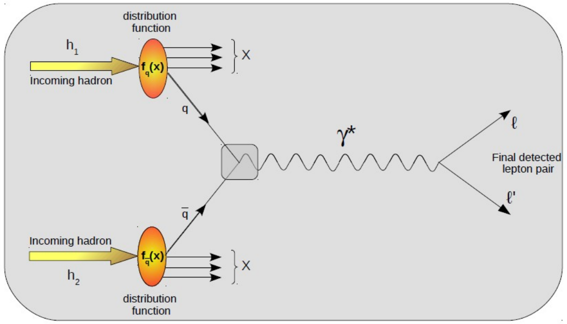


$$\sigma_{SIDIS} = f_q(x) \otimes \hat{\sigma} \otimes D_{h/q}(z)$$

Allows the extraction of TMD distribution and fragmentation functions

Experimental data for TMS studies

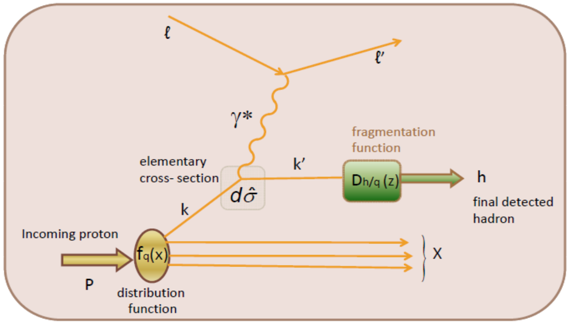
Unpolarized and Polarized Drell-Yan scattering



$$\sigma_{Drell-Yan} = f_q(x,k_\perp) \otimes f_{\bar{q}}(x,k_\perp) \otimes \hat{\sigma}^{q\bar{q}\to\ell\ell'}$$

Allows extraction of distribution functions

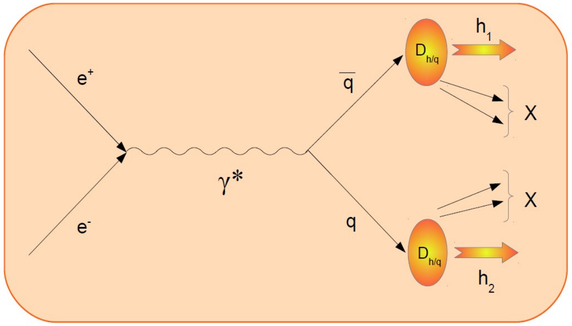
Unpolarized and Polarized SIDIS scattering



$$\sigma_{SIDIS} = f_q(x) \otimes \hat{\sigma} \otimes D_{h/q}(z)$$

Allows extraction of distribution and fragmentation functions

$e^+ e^- \to h_1 h_2 X$



$$\sigma_{h1\,h2} \propto D(z_1) \otimes D(z_2) \otimes \hat{\sigma}$$

Allows extraction of fragmentation functions

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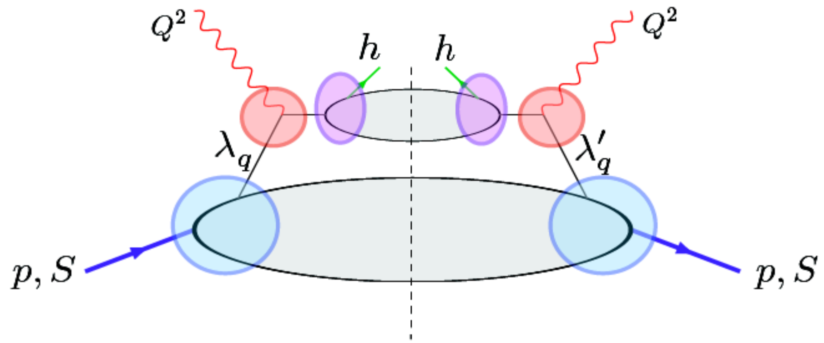
From the theory point of view ...

Perturbative QCD
Parton model
Factorization
...



TMD factorization holds at large Q^2 and $P_T \approx k_\perp \approx \lambda_{QCD}$

Two scales: $P_T << Q^2$

(Collins, Soper, Ji, Ma, Yuan, Qiu, Vogelsang,Collins, Metz)

$$\frac{d\sigma^{\ell(S_\ell)+p(S)\to\ell'+h+X}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{P}_T\, d\phi_S} = \rho^{\ell,S_\ell}_{\lambda_\ell,\lambda'_\ell} \otimes \rho^{q/p,S}_{\lambda_q,\lambda'_q} \hat{f}_{q/p,S}(x,\boldsymbol{k}_\perp) \otimes \hat{M}_{\lambda_\ell,\lambda_q;\lambda_\ell,\lambda_q} \hat{M}^*_{\lambda'_\ell,\lambda'_q;\lambda'_\ell,\lambda'_q} \otimes \hat{D}^h_{\lambda_q,\lambda'_q}(z,\boldsymbol{p}_\perp)$$

TMD-PDF **hard scattering** **TMD-FF**

Phenomenology

THEORY
- Perturbative QCD
- Factorization theorem
- ...

PHENOMENOLOGY
Mission: devise simple flexible and efficient models to link THEORY with EXPERIMENTS

EXPERIMENTS
- Drell-Yan scattering
- Di-hadron production from e+e- scattering
- DIS and SIDIS processes
- Inclusive single particle production from hadronic scattering

Phenomenology

The blind men and the elephant
from H. Avakian

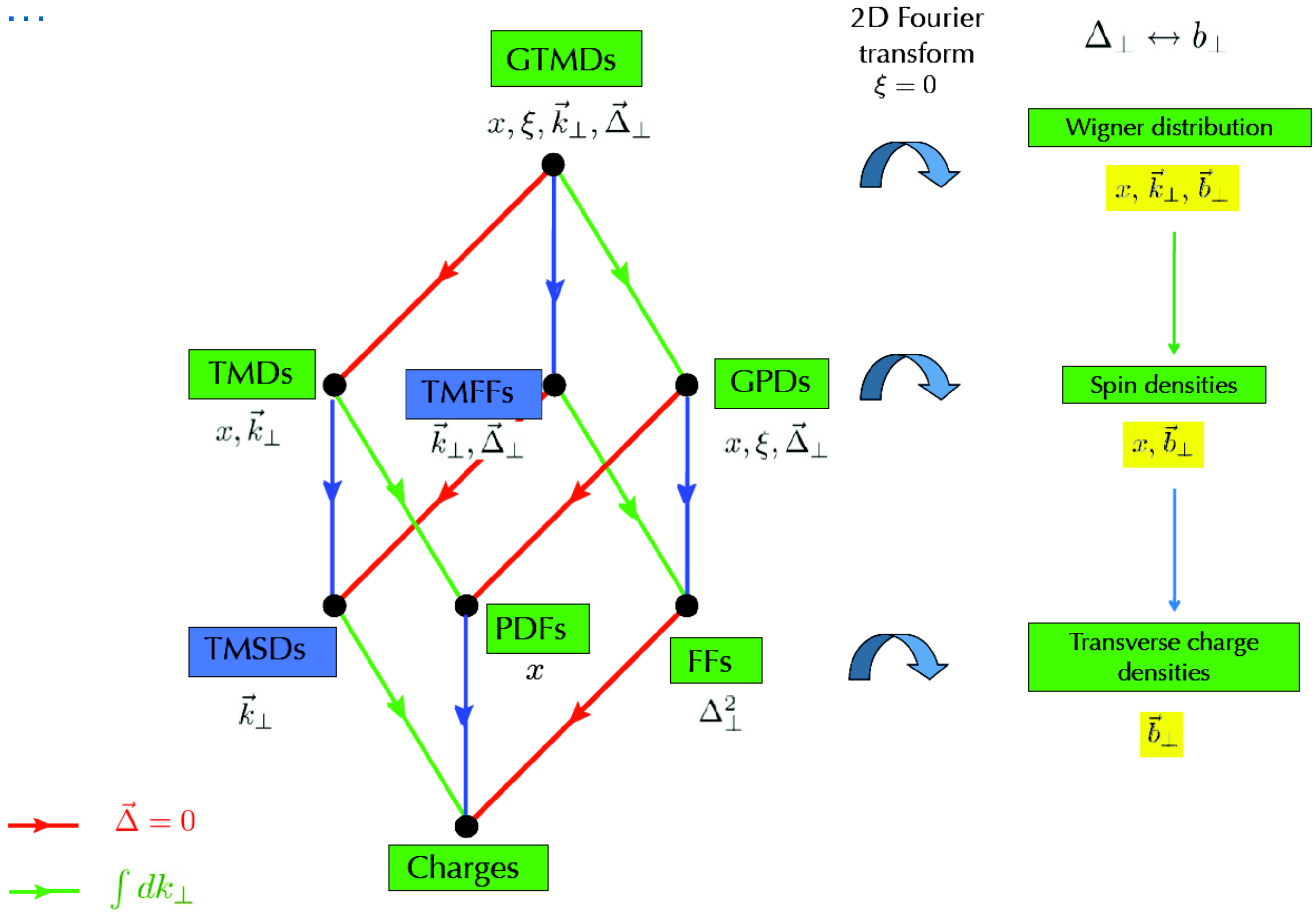
Experiments → Blind Men
Several different experiments
Measuring the same observable,
with limited coverage

Phenomenology → "where everything comes together nicely"
Combine different sources of information to get the whole picture

How can we learn about the 3D structure of matter ?

How can we learn about the 3D structure of matter ?

As Barbara Pasquini nicely explained yesterday …



Lorcé, BP, Vanderhaeghen, JHEP05 (2011) 041

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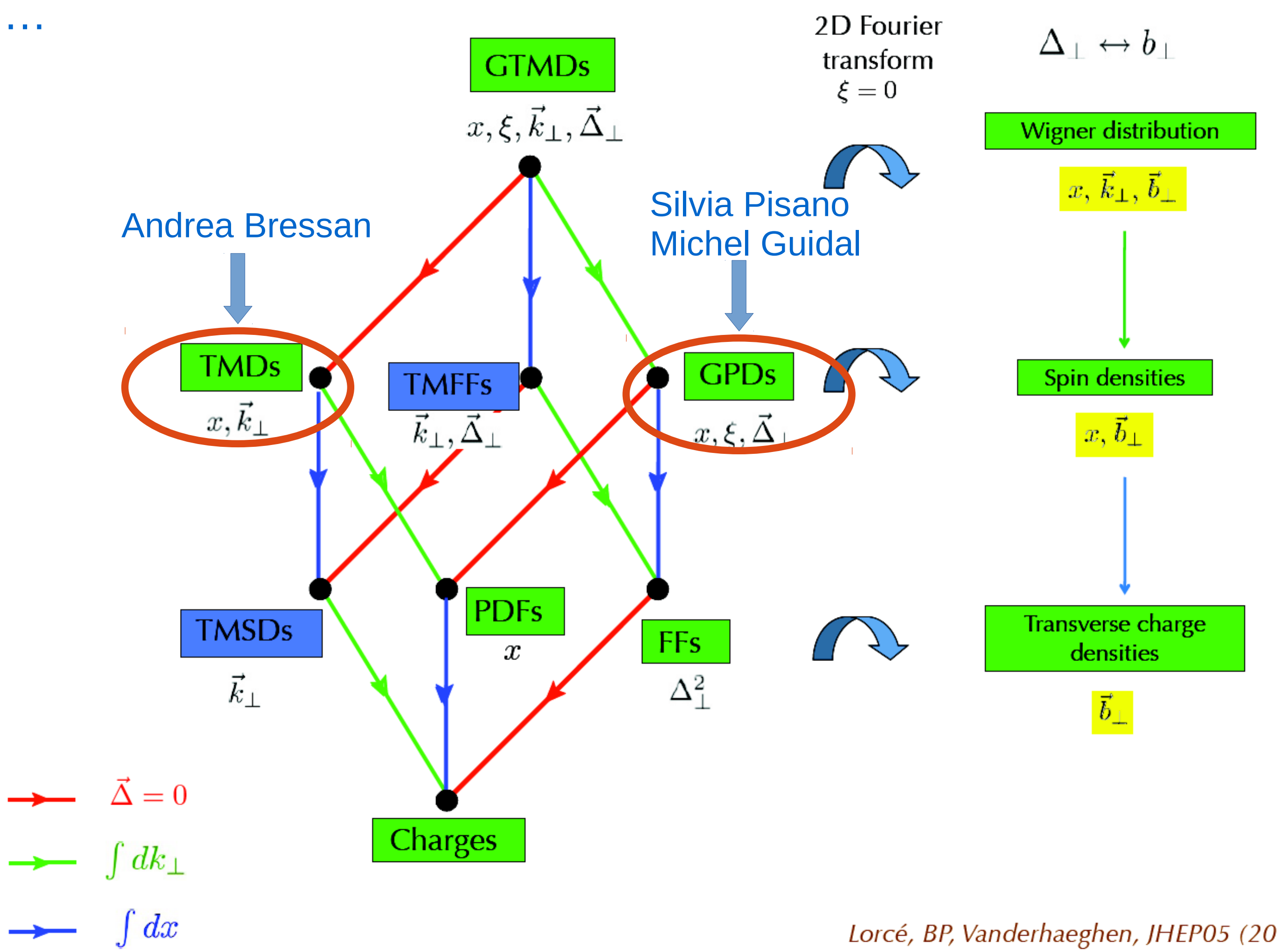
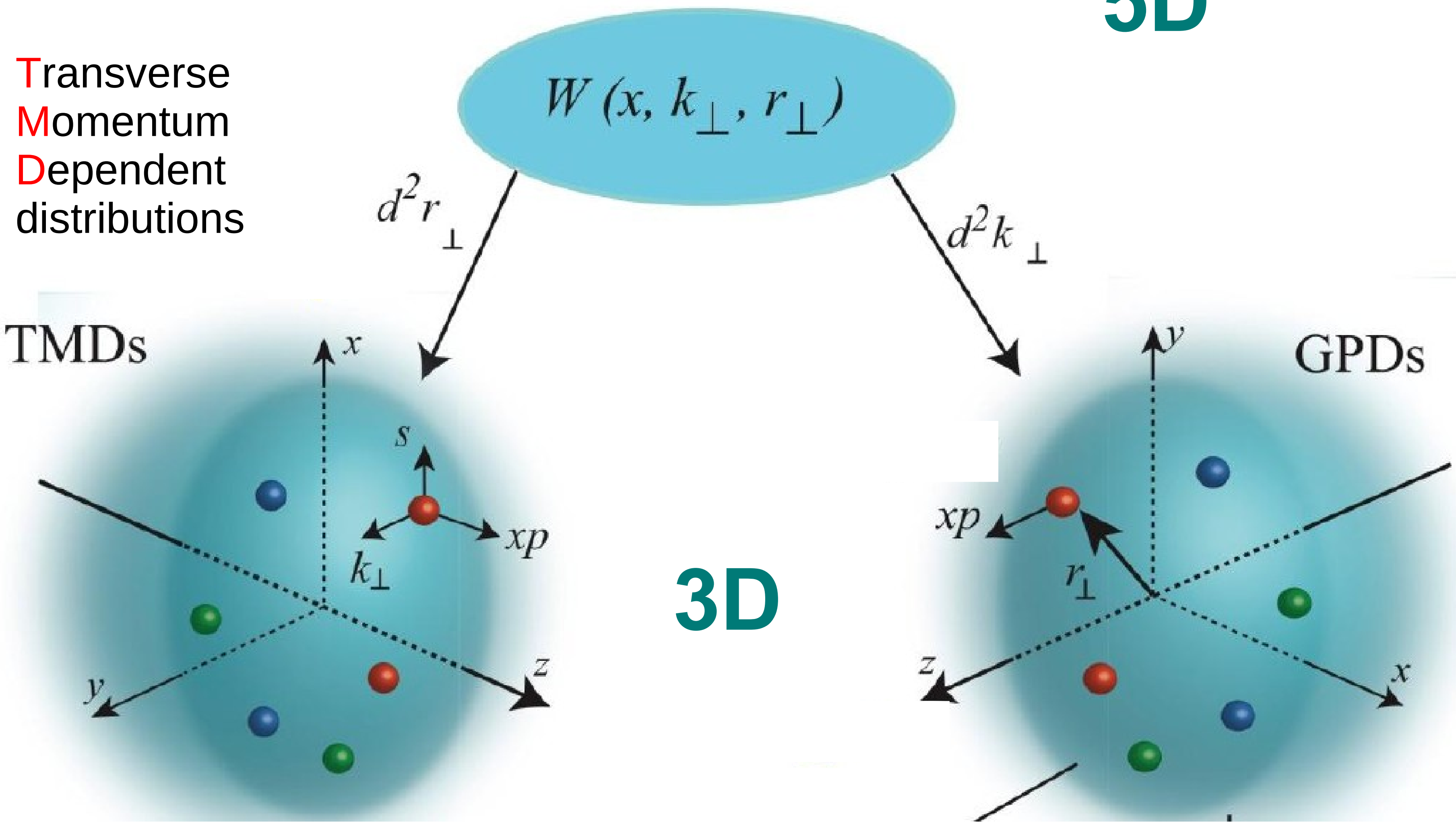


Lorcé, BP, Vanderhaeghen, JHEP05 (2011) 041

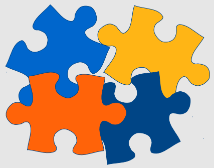
Wigner function

5D

Transverse
Momentum
Dependent
distributions



3D

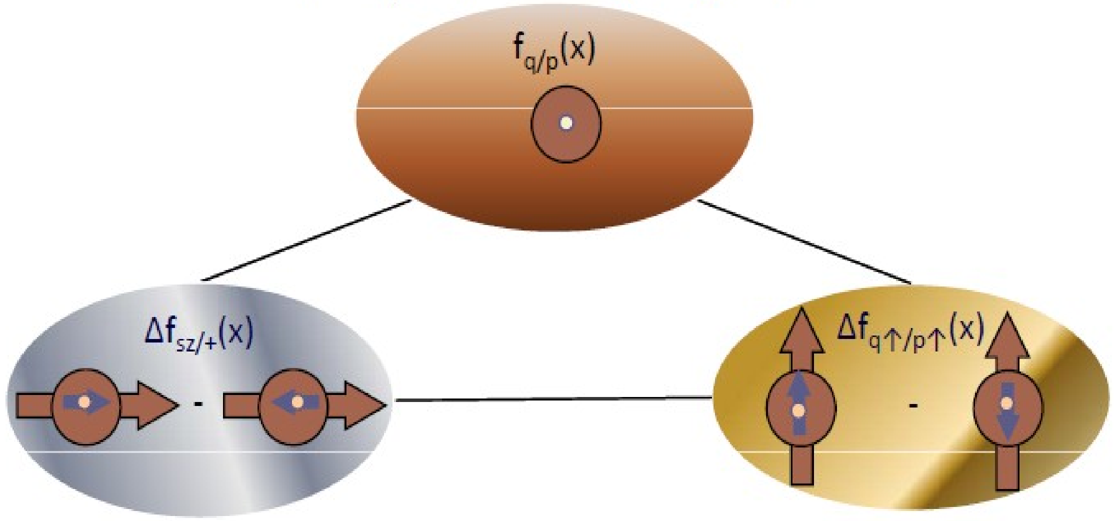
	***The mechanism which describes how quarks and gluons are bound into hadrons is embedded in the parton distribution and fragmentation functions (PDFs and FFs), the so-called "soft parts" of hadronic scattering processes. These are non-perturbative objects which connect the ideal world of pointlike and massless particles (pQCD) to our much more complex real world, made of nucleons, nuclei and atoms.***

PDFs versus TMDs

Collinear parton distribution functions

Unpolarized distribution functions

$q = q_+^+ + q_-^+ \qquad g = g_+^+ + g_-^+$



Helicity distribution functions

$\Delta q = q_+^+ - q_-^+ \qquad \Delta g = g_+^+ - g_-^+$

Transversity distribution functions

$\Delta_T q = q_\uparrow^\uparrow - q_\downarrow^\uparrow$

Collinear parton distribution functions

Transversity

- The **transversity distribution function** contains basic information on the spin structure of the nucleons.

- Being related to the expectation value of a chiral odd operator, it appears in physical processes which require a quark helicity flip; therefore it cannot be measured in usual DIS.

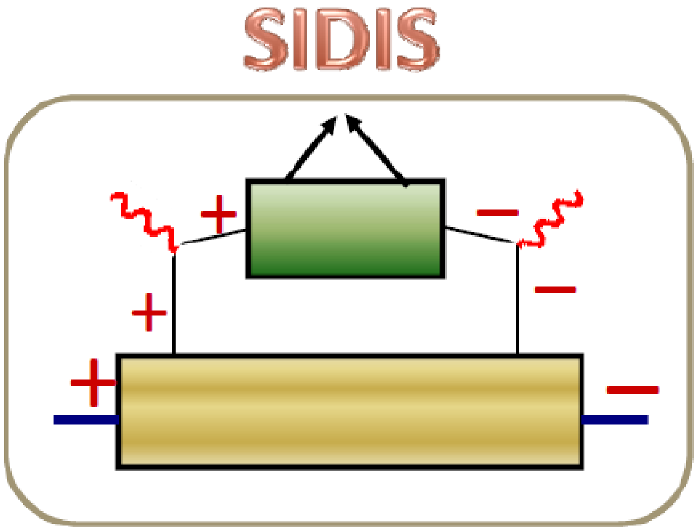
- Drell-Yan → planned experiments in polarized pp at PAX.

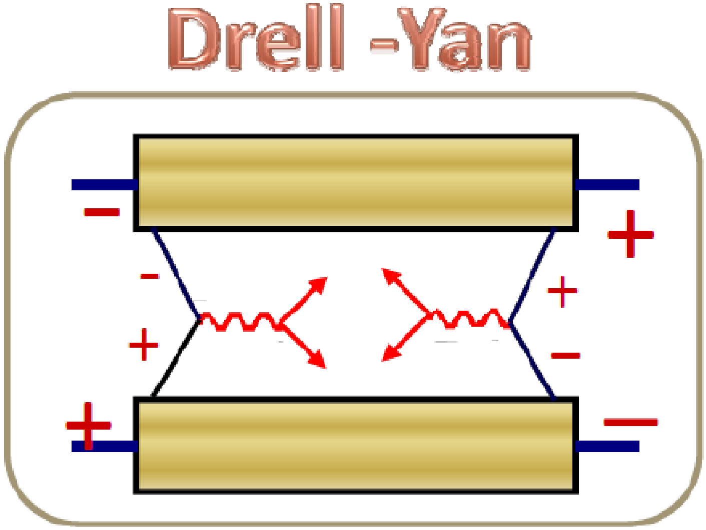
- At present, the only chance of gathering information on transversity is **SIDIS**, where it appears associated to the Collins fragmentation function.

- **DOUBLE PUZZLE**: we cannot determine transversity if we do not know the Collins fragmentation function.

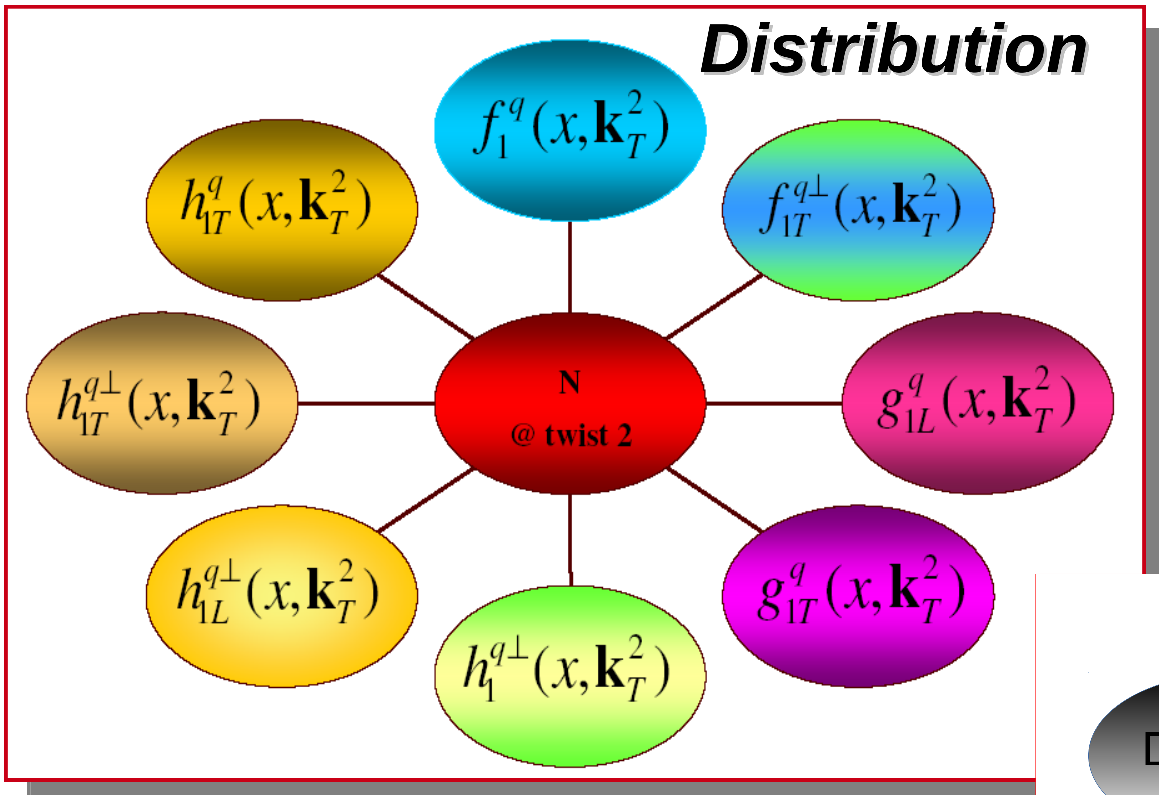
Transversity

- There is no gluon transversity distribution function
- Transversity cannot be studied in deep inelastic scattering because it is chirally odd
- Transversity can only appear in a cross-section convoluted to another chirally odd function

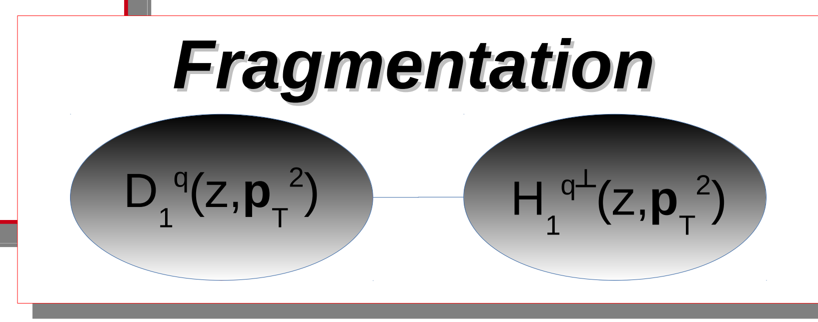




TMD distribution and fragmentation functions



Correlations between spin and transverse momentum



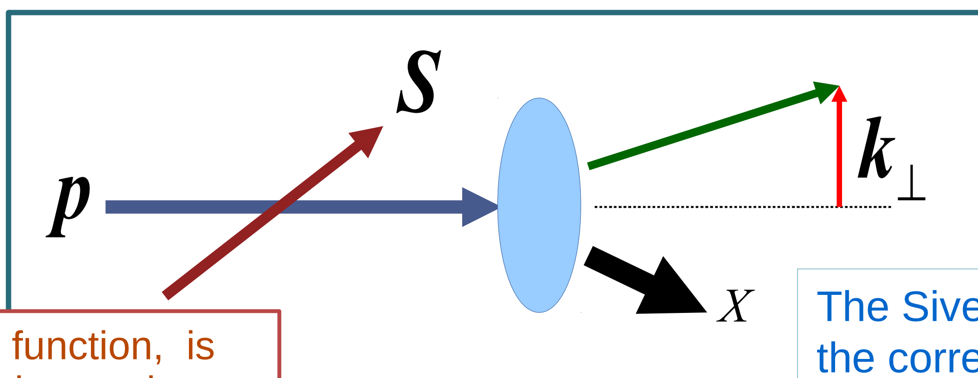
The Sivers function

$$f_{q/p,S}(x,k_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

The Sivers function is related to the probability of finding an unpolarized quark inside a transversely polarized proton

The Sivers function is T-odd



The Sivers function, is particularly interesting, as it provides information on the partonic orbital angular momentum

The Sivers function embeds the correlation between the proton spin and the quark transverse momentum

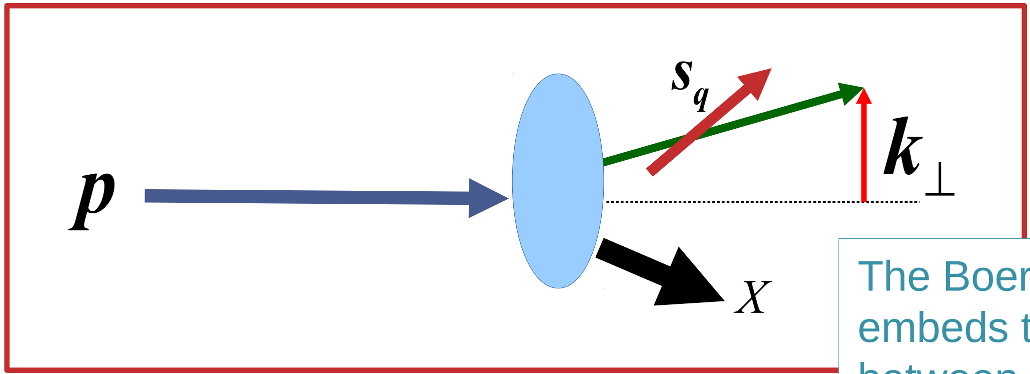
The Boer-Mulders function

$$f_{q,s_q/p}(x,\boldsymbol{k}_\perp) = \frac{1}{2} f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta f_{q^\uparrow/p}(x,k_\perp)\, \boldsymbol{s}_q \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)$$

$$= \frac{1}{2} f_{q/p}(x,k_\perp) - \frac{1}{2}\frac{k_\perp}{M} h_1^{\perp q}(x,k_\perp)\, \boldsymbol{s}_q \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{k}}_\perp)$$

The Boer-Mulders function is related to the probability of finding a polarized quark inside an unpolarized proton

The Boer Mulders function is chirally odd



The Boer-Mulders function embeds the correlation between the quark spin and its transverse momentum

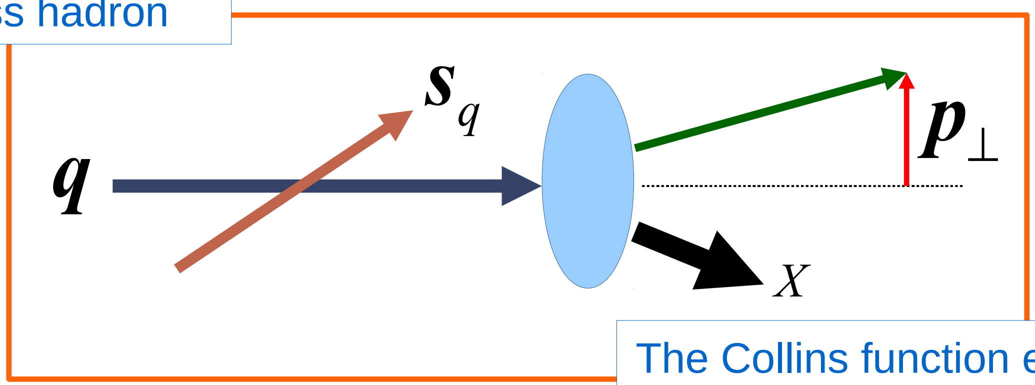
The Collins function

$$D_{h/q,\boldsymbol{s}_q}(z,\boldsymbol{p}_\perp) = D_{h/q}(z,p_\perp) + \frac{1}{2}\Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

$$= D_{h/q}(z,p_\perp) + \frac{p_\perp}{z\,M_h}H_1^{\perp q}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

The Collins function is related to the probability that a transversely polarized struck quark will fragment into a spinless hadron

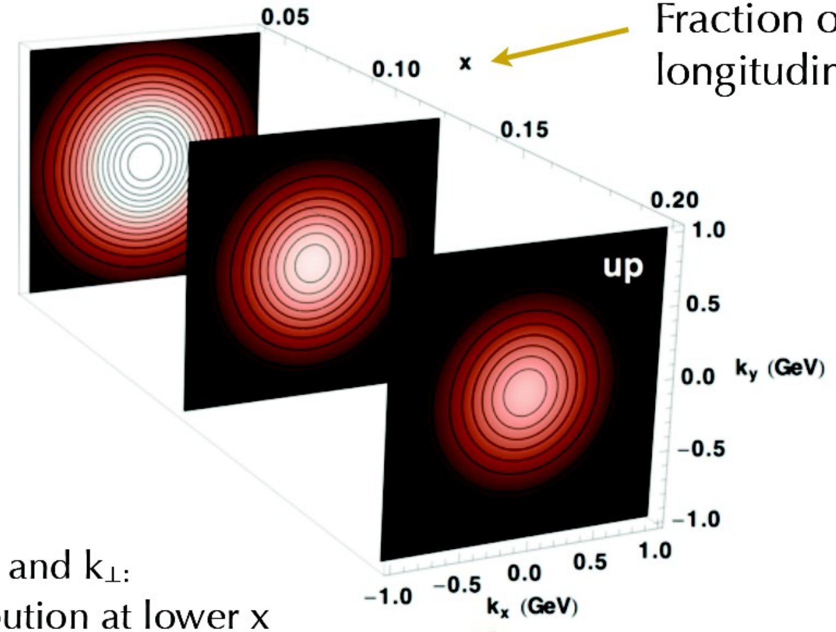
The Collins function is chirally odd



The Collins function embeds the correlation between the fragmenting quark spin and the transverse momentum of the produced hadron

An example: unpolarized TMD

From B. Pasquini talk …



Fraction of longitudinal momentum

Transverse momentum

Correlation between x and $k_\perp$:
widening of the distribution at lower x

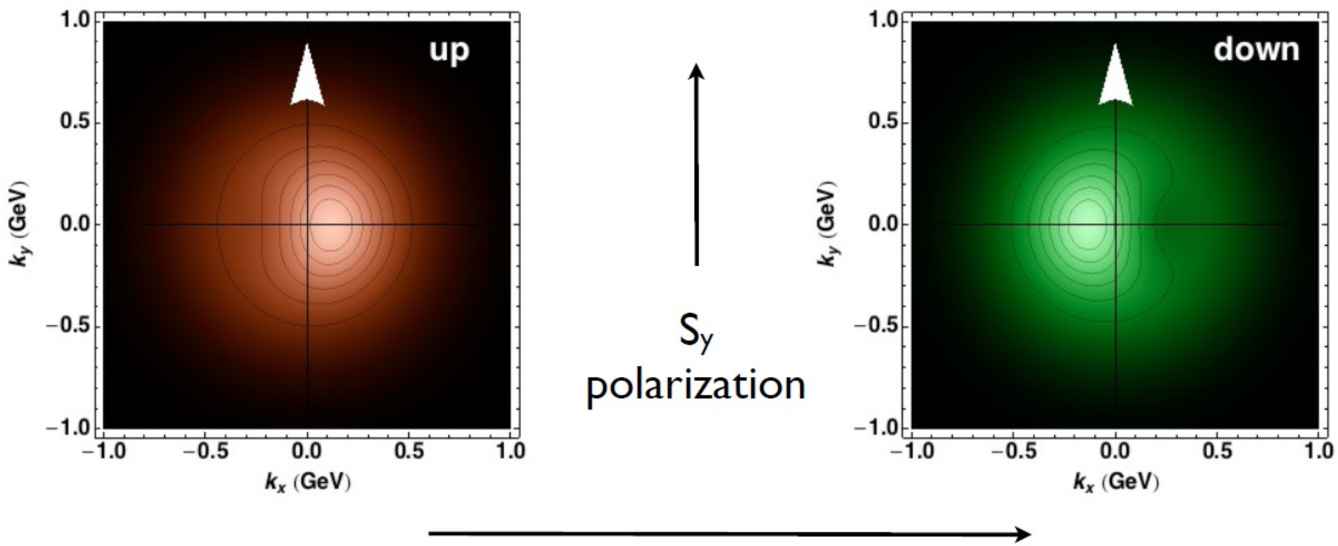
We know the integrated PDF very well.
We know the TMD still poorly.

An example: the Sivers function

From B. Pasquini talk …

distribution of unpolarized q in $\perp$ polarized $p^{\uparrow}$

$$f_{q/p^{\uparrow}}(x, \mathbf{k}_\perp) = f_1^q(x, \mathbf{k}_\perp^2) - f_{1T}^{\perp q}(x, \mathbf{k}_\perp^2)\,\frac{(\hat{\mathbf{P}} \times \mathbf{k}_\perp)\cdot \mathbf{S}}{M}$$



deformation induced by Sivers function

Bacchetta & Contalbrigo, The proton in 3D
Il Nuovo Saggiatore **28** (12) n.1,2

Spin and angular momentum

Proton and quarks are spin-½ particles

Quarks are confined inside an extended proton and move – the motion creates Orbital Angular Momentum

Can this motion be correlated with the spin of the proton?

Sivers function and angular momentum

quark and gluon contribution to the nucleon spin

$$J^{q,g} = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x \left(\underbrace{H^{q,g}(x,0,0)}_{\text{unpolarized PDF}} + \underbrace{E^{q,g}(x,0,0)}_{\text{not directly accessible}} \right)$$

A. Bacchetta, M. Radici, Phys. Rev. Lett. 107 (2011) 212001

Assume

$$\boxed{\begin{aligned} f_{1T}^{\perp(0)a}(x;Q_L^2) &= -L(x)E^a(x,0,0;Q_L^2) \\ f_{1T}^{\perp(0)a}(x,Q) &= \int d^2\boldsymbol{k}_\perp\, \widehat{f}_{1T}^{\perp a}(x,k_\perp;Q) \end{aligned}}$$

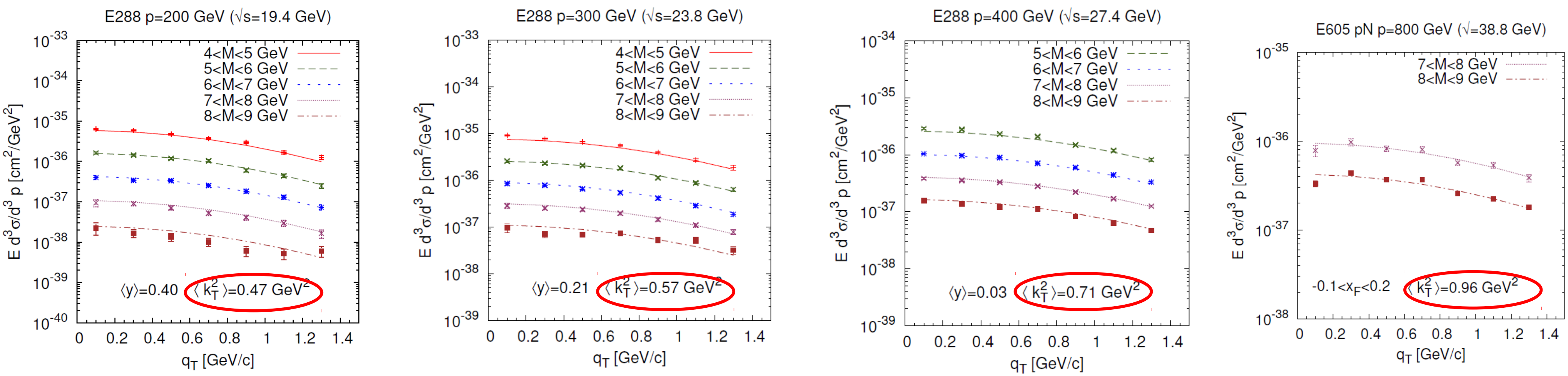
L(x) = Lensing function

- Parameterize the Sivers and Lensing function
  (can be extracted from models or by fitting data)
- Obtain $E^q(x)$
- Estimate J: $J^u \sim 0.23$, $J^{q\neq u} \sim 0$ at $Q^2 = 2.4$ GeV^2

Is the $k_\perp$ TMD distribution Gaussian ?

Drell-Yan phenomenology

Stefano Melis preliminary studies



The fit on E288 and E605 Drell-Yan data is performed by assuming a gaussian $k_\perp$ dependence with a DGLAP evolution of the factorized

$$\widehat{f}_{q/p}(x, k_\perp; Q) = f_{q/p}(x; Q)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$$

The gaussian width is fitted independently for each different energy data set.

Notice that $<k_\perp^2>$ grows as energy grows

Schweitzer, Teckentrup, Metz, Phys.Rev. D81 (2010) 094019
D'Alesio, Murgia, Phys. Rev. D70 (2004) 074009

Extracting the unpolarized TMD Gaussian widths from SIDIS data

Let's see whether the Gaussian approximation works in the most simple case ...

Extracting the unpolarized TMD Gaussian widths from SIDIS multiplicities

M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261

- Data: Hermes (p and d targets, π^+, π^-, K^+, K^- production)

  2660 data points in (x, z, P_T, Q^2 bins)

  A. Airapetian et al., Phys. Rev. D87 (2013) 074029

  Compass (d target, h^+, h^- production)

  18627 data points in (x, z, P_T, Q^2 bins)

  C. Adolph et al., Eur. Phys. J. C73, 2531 (2013)

- Parameterizations:

$$\widehat{f}_{q/p}(x, k_\perp; Q) = f_{q/p}(x; Q)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$$

CTEQ6L (DGLAP evolution)

1 free parameter
(no evolution)

$$D_{h/q}(z, p_\perp) = D_{h/q}(z)\,\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle},$$

DSS (DGLAP evolution)

1 free parameter
(no evolution)

Extracting the unpolarized TMD Gaussian widths from SIDIS multiplicities

In the simplest form of this model:

Flavor-independent average transverse momenta

No x-dependence

No z-dependence

Two parameters in total

Gaussian model:

$$\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle.$$

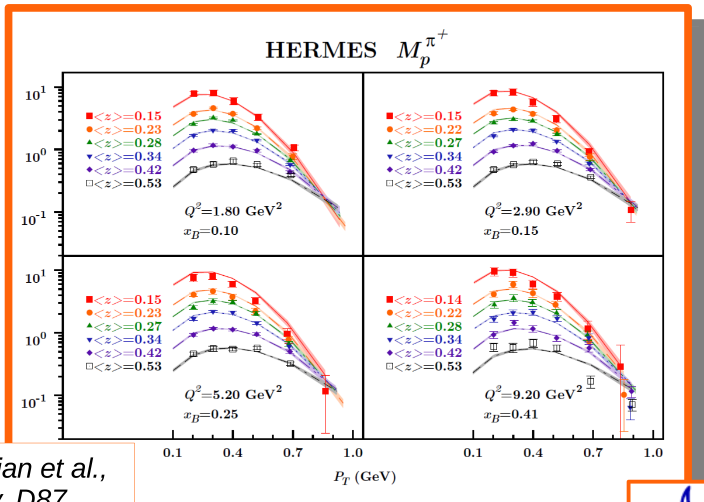
$$\sigma \propto \frac{1}{\pi \langle P_T^2 \rangle} e^{-P_T^2/\langle P_T^2 \rangle}$$

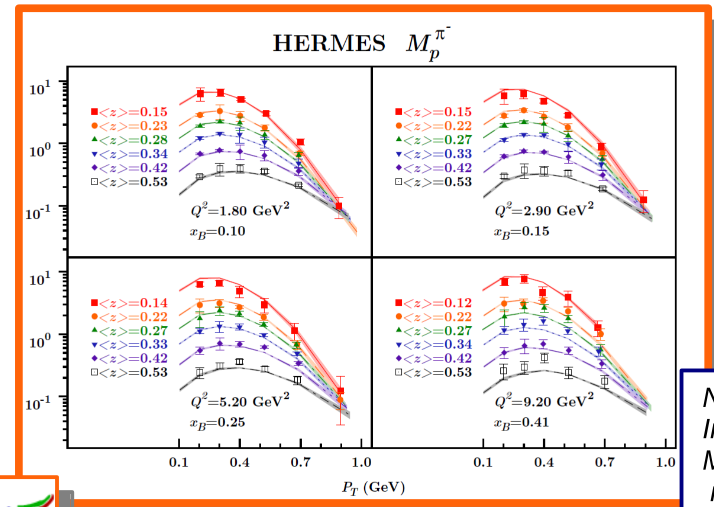
Normalization

Gaussian width

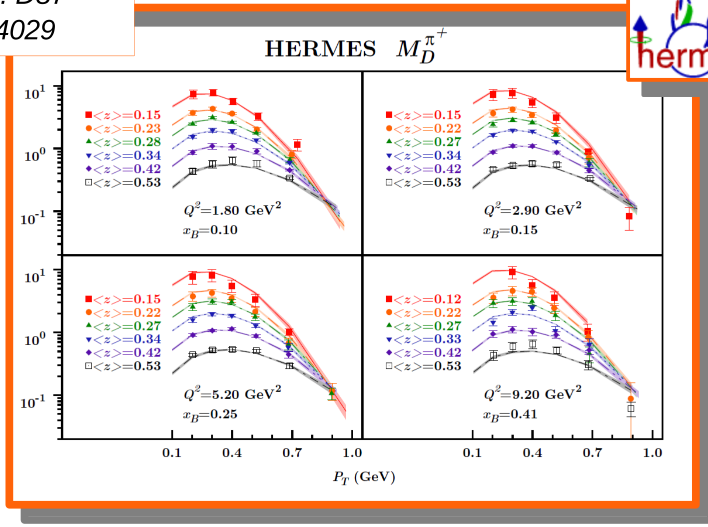
Extracting the unpolarized TMD Gaussian widths from SIDIS multiplicities

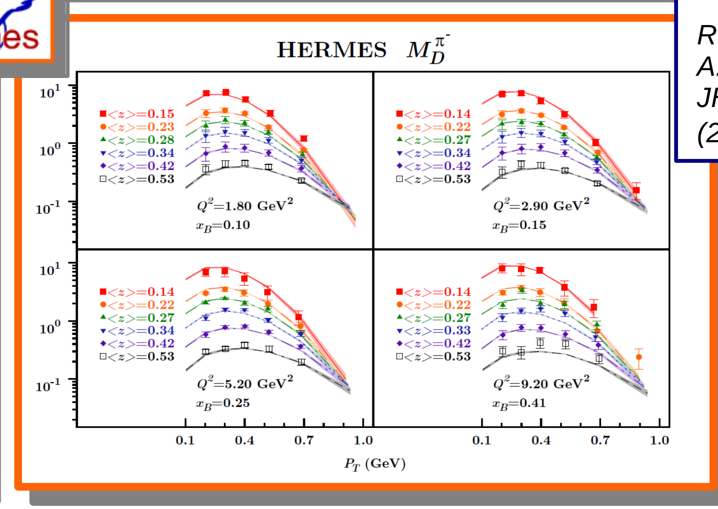
M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261





A. Airapetian et al., Phys. Rev. D87 (2013) 074029





NO flavour dep. In distr. fns., MILD flavour dep. in fragm. fns,

Results agree with A. Signori et al., JHEP 1311 (2013) 194

$$\langle k_\perp^2 \rangle = 0.57 \pm 0.08 \text{ GeV}^2$$

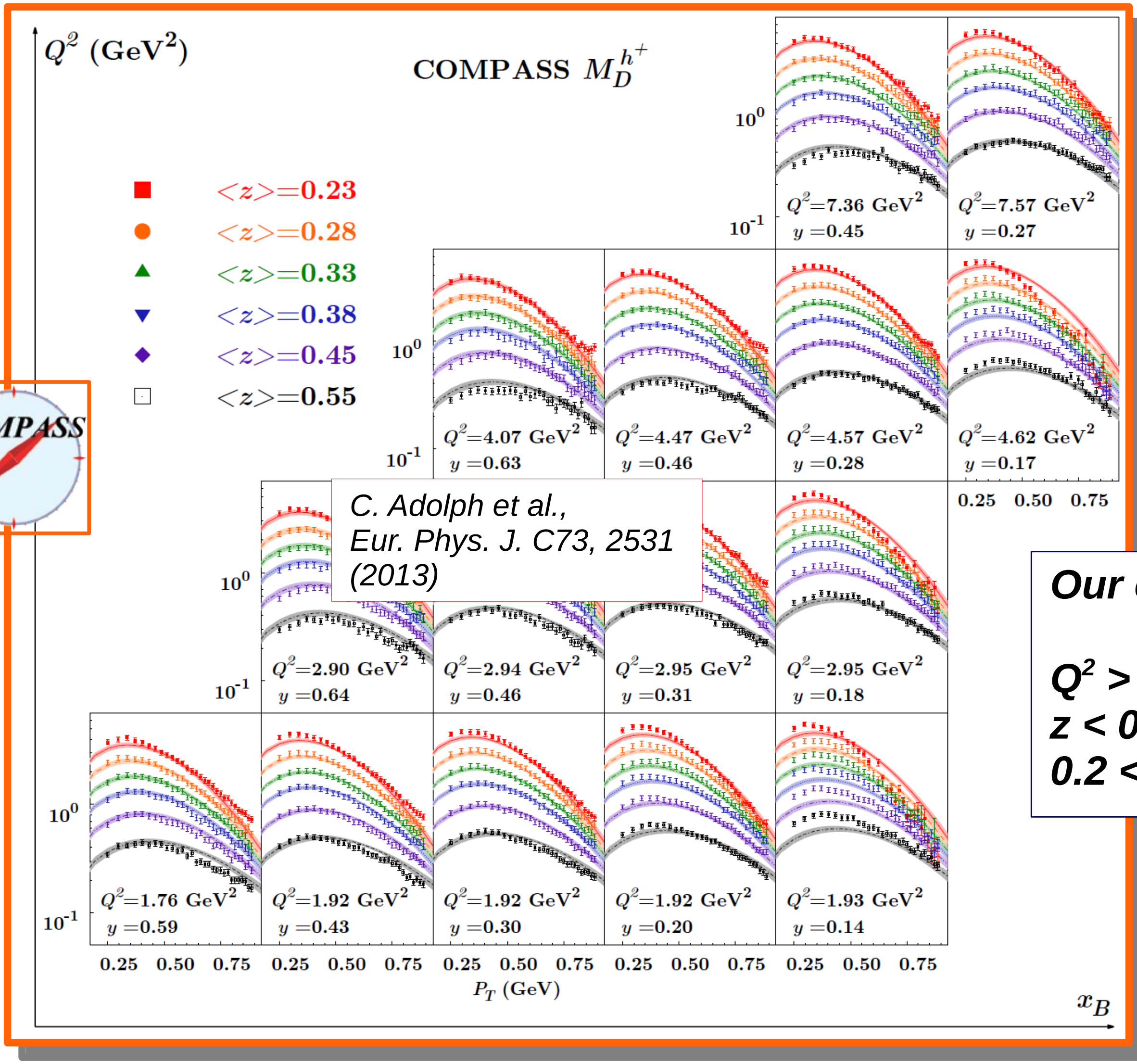
$$\langle p_\perp^2 \rangle = 0.12 \pm 0.01 \text{ GeV}^2$$

$$\chi^2_{\rm dof} = 1.69$$

Extracting the unpolarized TMD Gaussian widths from SIDIS multiplicities

M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261

$$\langle k_\perp^2 \rangle = 0.60 \pm 0.14 \text{ GeV}^2$$
$$\langle p_\perp^2 \rangle = 0.20 \pm 0.02 \text{ GeV}^2$$
$$\chi^2_{\rm dof} = 3.42$$
$$N_y = A + B\,y$$



C. Adolph et al., Eur. Phys. J. C73, 2531 (2013)

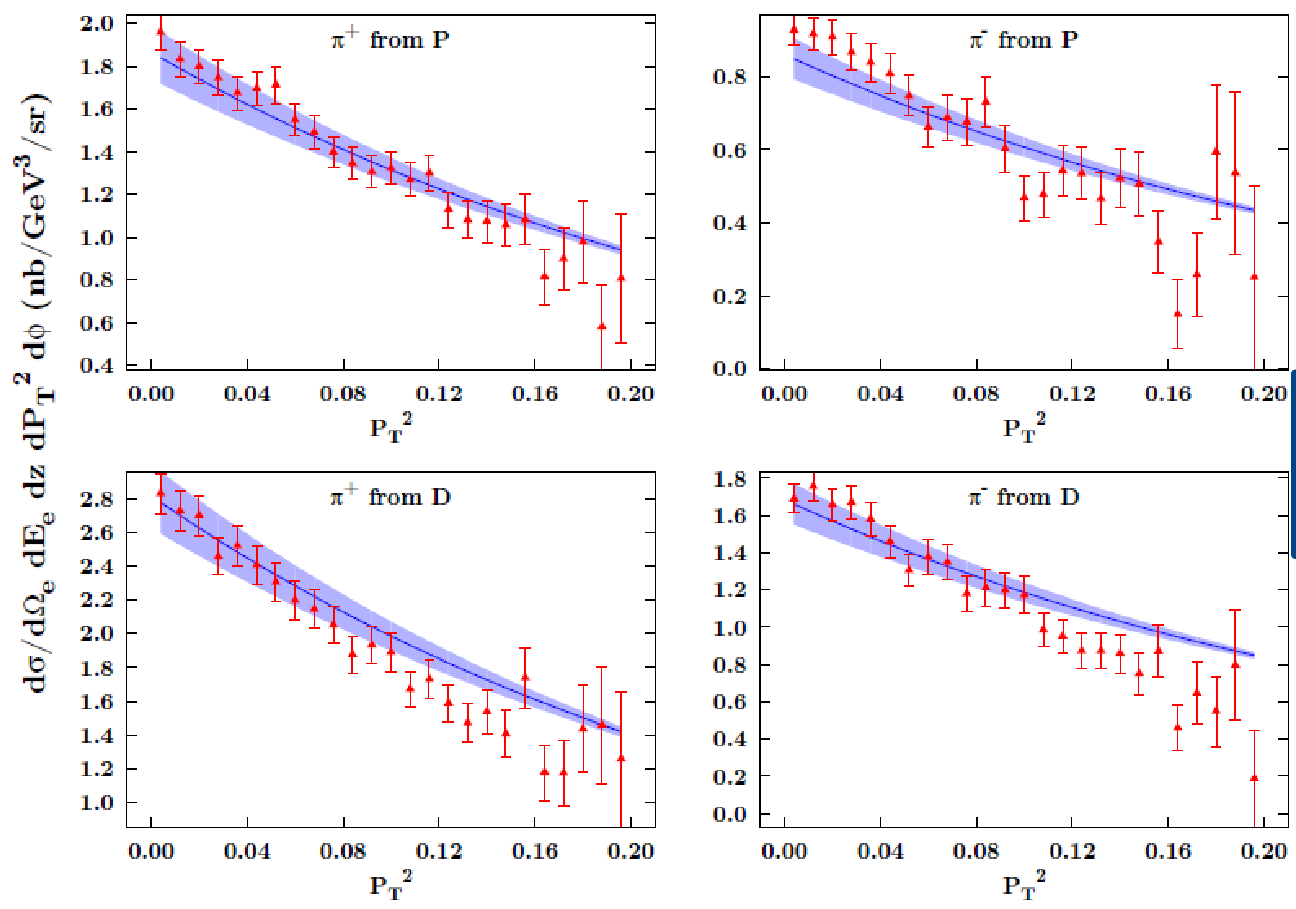
NO flavour dep. In distr. fns., NO flavour dep. in fragm. fns,

Our cuts:

Q^2 > 1.6 GeV^2
z < 0.6
0.2 < P_T < 0.9

Comparison with Jlab data HALL C

M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261

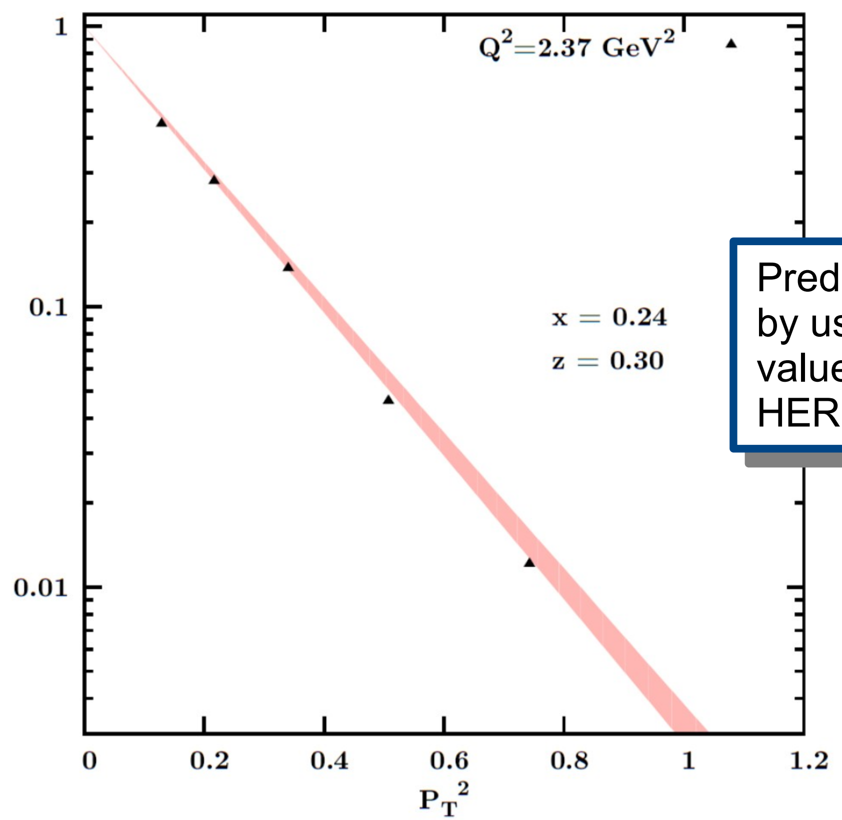


Predictions obtained by using the parameter values extracted from HERMES multiplicities

R. Asaturyan et al., Phys. Rev. C85, 015202 (2012)

Comparison with Jlab data CLAS 6

M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261



Predictions obtained by using the parameter values extracted from HERMES multiplicities

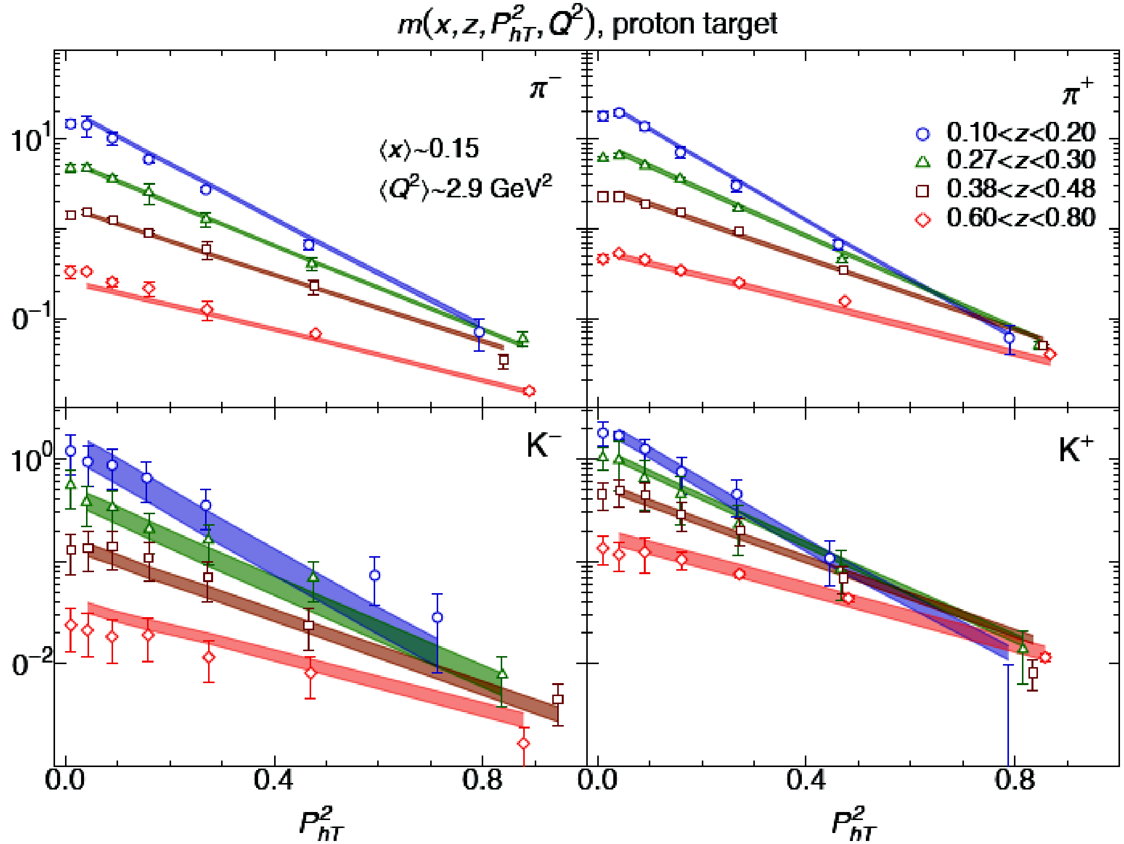
M. Osipenko et al., Phys. Rev. D80, 032004 (2009)

proton target global χ^2 / d.o.f. $= 1.63 \pm 0.12$
no flavor dep. 1.72 ± 0.11

5/7 parameters
Much more complex parametrization of x and z dependence

π^-
1.80 ± 0.27
1.83 ± 0.25

K^-
0.78 ± 0.15
0.87 ± 0.16



π^+
2.64 ± 0.21
2.89 ± 0.23

K^+
0.46 ± 0.07
0.43 ± 0.07

A. Signori, A. Bacchetta, M. Radici, G. Schnell, JHEP 1311 (2013) 194

What about $k_\perp$ Gaussians then ?

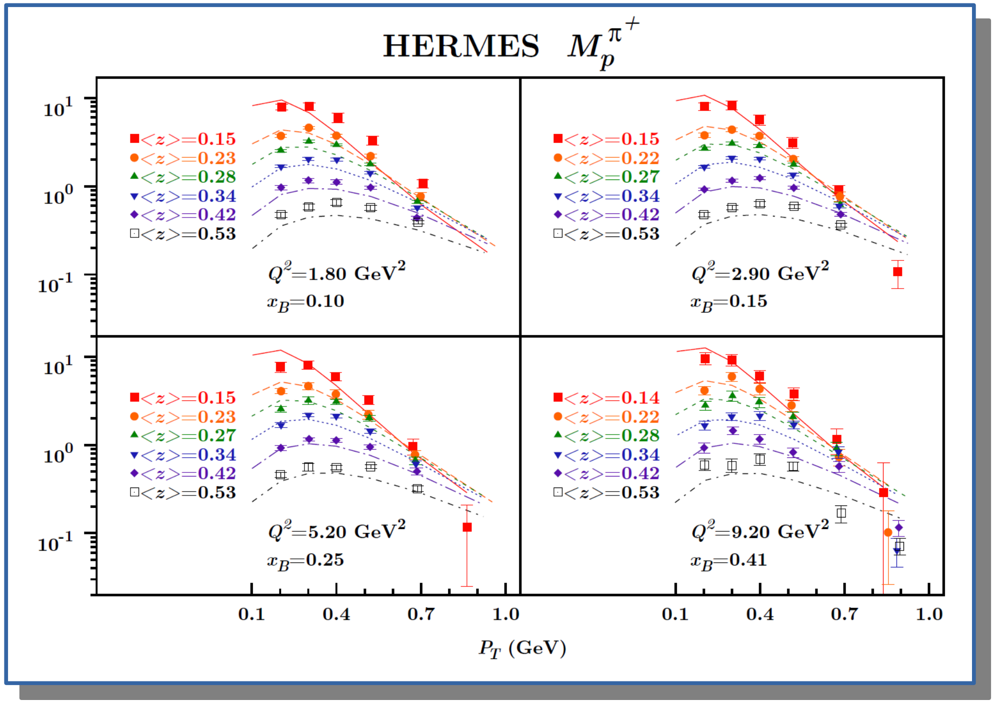
- Gaussian $k_\perp$ distributions seem to describe the data pretty well.
- However, one could legitimately wonder whether other distributions could do better.

- Drop the x - $k_\perp$ factorization hypothesis and use a quark-diquark like model for the unpolarized TMDs
- Perform the same fits again and compare with the results obtained with Gaussian distributions
- **We find that the description of data significantly worsen !**

What about $k_\perp$ Gaussians then ?

V. Barone, M. Boglione, O. Gonzalez, S. Melis, PRELIMINARY

Vaguely inspired to A. Bacchetta, F. Conti, M. Radici, Phys.Rev. D78 (2008) 074010



$$f(x,k_\perp) = f(x)\frac{6L^6}{\pi(2\mu^2+L^2)}\frac{k_\perp^2+\mu^2}{(k_\perp^2+L^2)^4}$$

$$L^2 = xM_s^2 + (1-x)\Lambda^2 - x(1-x)M_p^2$$

$$\mu^2 = (m + xM_p)^2$$

$$D(z,p_\perp) = D(z)\frac{6\tilde{L}^6}{\pi(2\nu^2+\tilde{L}^2)}\frac{p_\perp^2+\nu^2}{(p_\perp^2+\tilde{L}^2)^4}$$

$$\tilde{L}^2 = (1-z)M_h^2 + z(\tilde{M}_s^2 - \tilde{\Lambda}^2) + z^2\tilde{\Lambda}^2$$

$$\nu^2 = \left(\tilde{M}_s - (1-z)\tilde{m}\right)^2$$

$$\chi^2_{dof} = 6.96$$

$$M_s^2 = 0.43 \qquad \Lambda^2 = 0.25^\dagger$$

$$\tilde{M}_s^2 = 1.11 \qquad \tilde{\Lambda}^2 = 0.00*$$

$$\langle k_\perp^2\rangle = \frac{L^2(2L^2+\mu^2)}{L^2+2\mu^2}$$

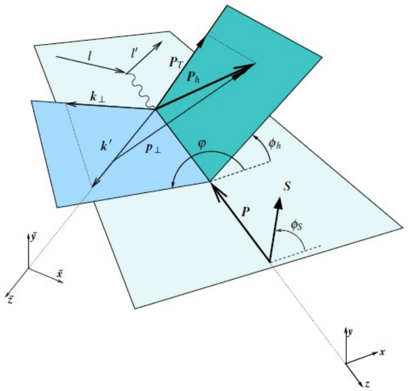
$$\langle p_\perp^2\rangle = \frac{\tilde{L}^2(2\tilde{L}^2+\nu^2)}{\tilde{L}^2+2\nu^2}$$

Simultaneous extraction of transversity and the Collins function

Simultaneous extraction of transversity and the Collins function

Anselmino, Boglione, D'Alesio, Melis, Murgia, Prokudin, Phys.Rev. D87 (2013) 094019

Anselmino, Boglione, D'Alesio, Gonzalez, Melis, Murgia, Prokudin, in preparation



SIDIS

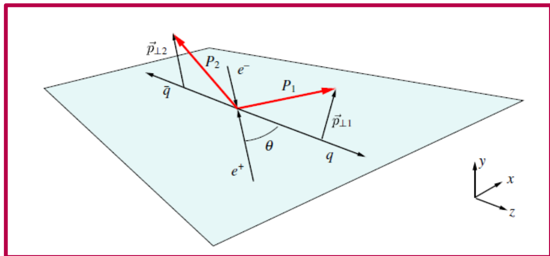
$$A_{UT}^{\sin(\phi+\phi_S)} \equiv 2\,\frac{\int d\phi\, d\phi_S\, [d\sigma^\uparrow - d\sigma^\downarrow]\,\sin(\phi+\phi_S)}{\int d\phi\, d\phi_S\, [d\sigma^\uparrow + d\sigma^\downarrow]}$$

$$d\sigma^\uparrow - d\sigma^\downarrow = \sum_q h_{1q}(x, k_\perp) \otimes d\Delta\hat{\sigma}(y, \boldsymbol{k}_\perp) \otimes \Delta^N D_{h/q^\uparrow}(z, \boldsymbol{p}_\perp)$$

Transversity **Collins**

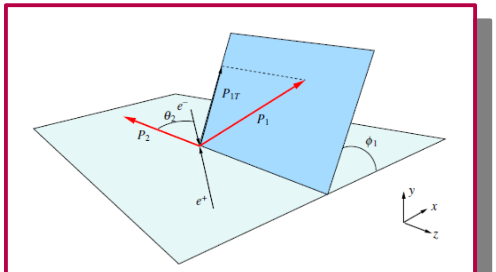
$e^+ e^- \to h1\, h2\, X$

A_{12} – thrust axis method



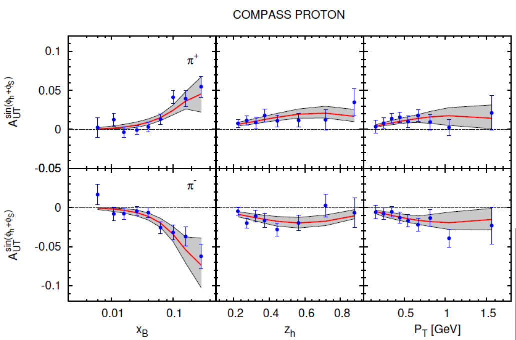
$$\frac{\sum_q e_q^2\, \Delta^N D_{h_1/q^\uparrow}(z_1)\, \Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)}{\sum_q e_q^2\, D_{h_1/q}(z_1)\, D_{h_2/\bar{q}}(z_2)}$$

A_0 – hadron plane method



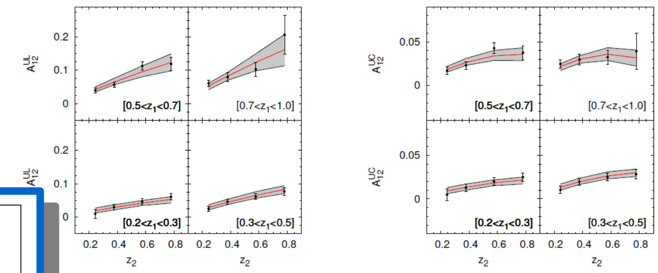
Simultaneous extraction of transversity and the Collins function

Anselmino, Boglione, D'Alesio, Melis, Murgia, Prokudin, Phys.Rev. D87 (2013) 094019

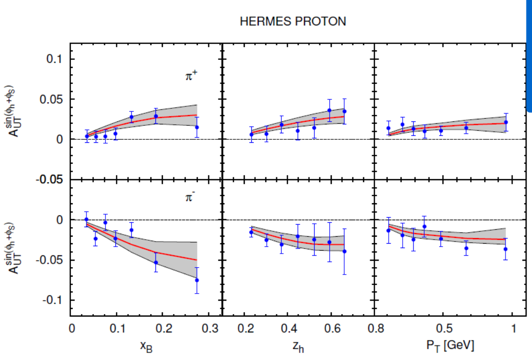


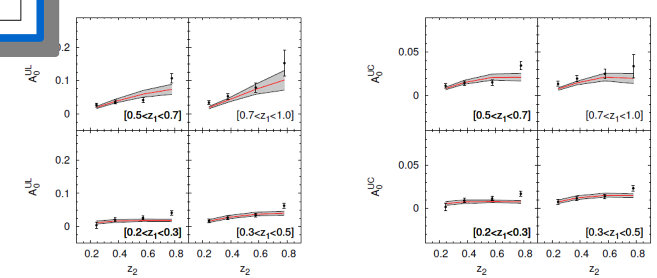
SIDIS

	FIT DATA 178 points	SIDIS 146 points	A_{12}^{UL} 16 points	A_{12}^{UC} 16 points	A_0^{UL} 16 points	A_0^{UC} 16 points
Standard Parameterization $\chi^2_{\rm d.o.f} = 0.80$	$\chi^2_{\rm tot} = 135$	$\chi^2 = 123$	$\chi^2 = 7$	$\chi^2 = 5$	$\chi^2 = 44$ NO FIT	$\chi^2 = 39$ NO FIT
Standard Parameterization $\chi^2_{\rm d.o.f} = 1.12$	$\chi^2_{\rm tot} = 190$	$\chi^2 = 125$	$\chi^2 = 20$ NO FIT	$\chi^2 = 12$ NO FIT	$\chi^2 = 35$	$\chi^2 = 30$
Polynomial Parameterization $\chi^2_{\rm d.o.f} = 0.81$	$\chi^2_{\rm tot} = 136$	$\chi^2 = 123$	$\chi^2 = 8$	$\chi^2 = 5$	$\chi^2 = 45$ NO FIT	$\chi^2 = 39$ NO FIT
Polynomial Parameterization $\chi^2_{\rm d.o.f} = 1.01$	$\chi^2_{\rm tot} = 171$	$\chi^2 = 141$	$\chi^2 = 44$ NO FIT	$\chi^2 = 27$ NO FIT	$\chi^2 = 15$	$\chi^2 = 15$



$e^+ e^- \to h1\, h2\, X$





SIDIS data are fitted with excellent χ^2

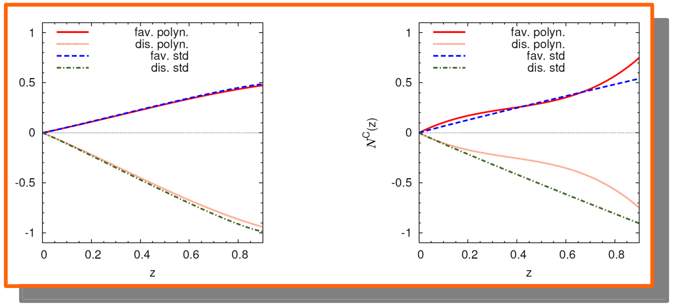
There seems to be some tension In the fit between BELLE A_{12} and A_0

Tension between BELLE A_0 and A_{12} ?

Anselmino, Boglione, D'Alesio, Melis, Murgia, Prokudin, Phys.Rev. D87 (2013) 094019

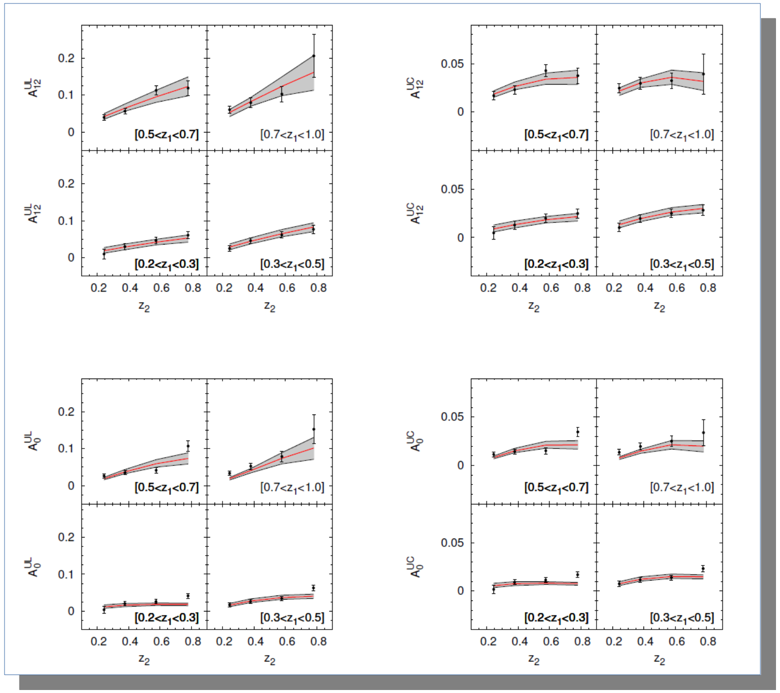
Standard parameterization of the Collins function

$$\mathcal{N}_q^C(z) = N_q^C \, z^{\gamma}(1-z)^{\delta}\, \frac{(\gamma+\delta)^{(\gamma+\delta)}}{\gamma^{\gamma}\delta^{\delta}}$$

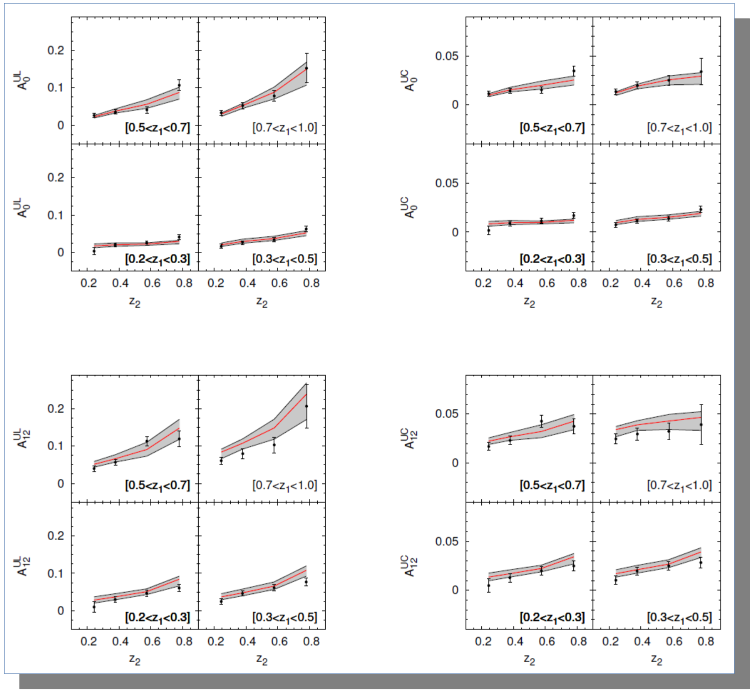


Polynomial parameterization of the Collins function

$$\mathcal{N}_q^C(z) = N_q^C \, z\,[(1-a-b) + a\,z + b\,z^2]$$



Fit of A_{12} with standard param.

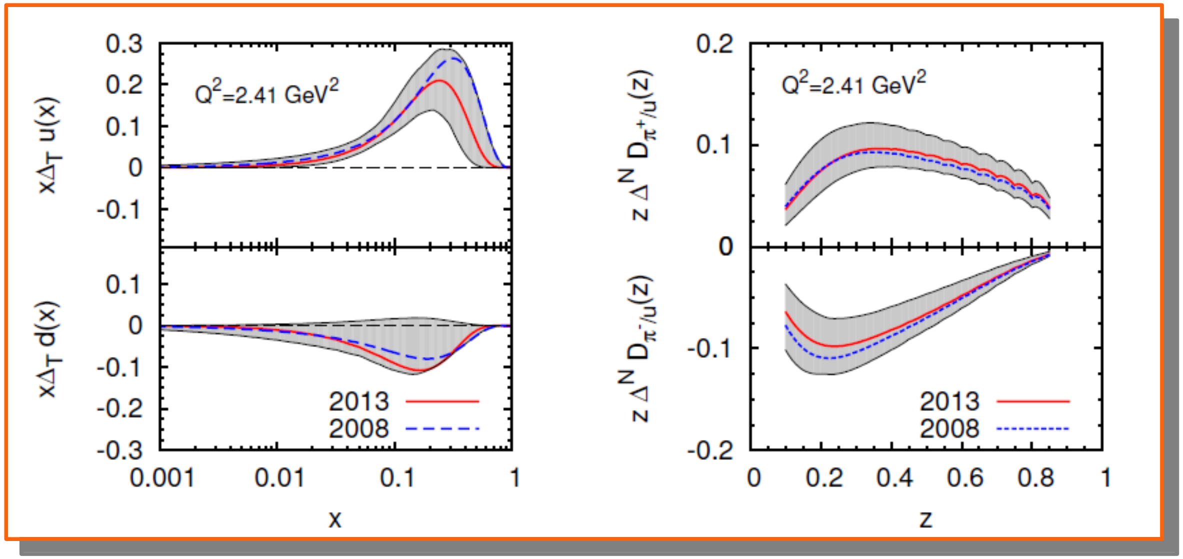


Fit of A_0 with polynomial param.

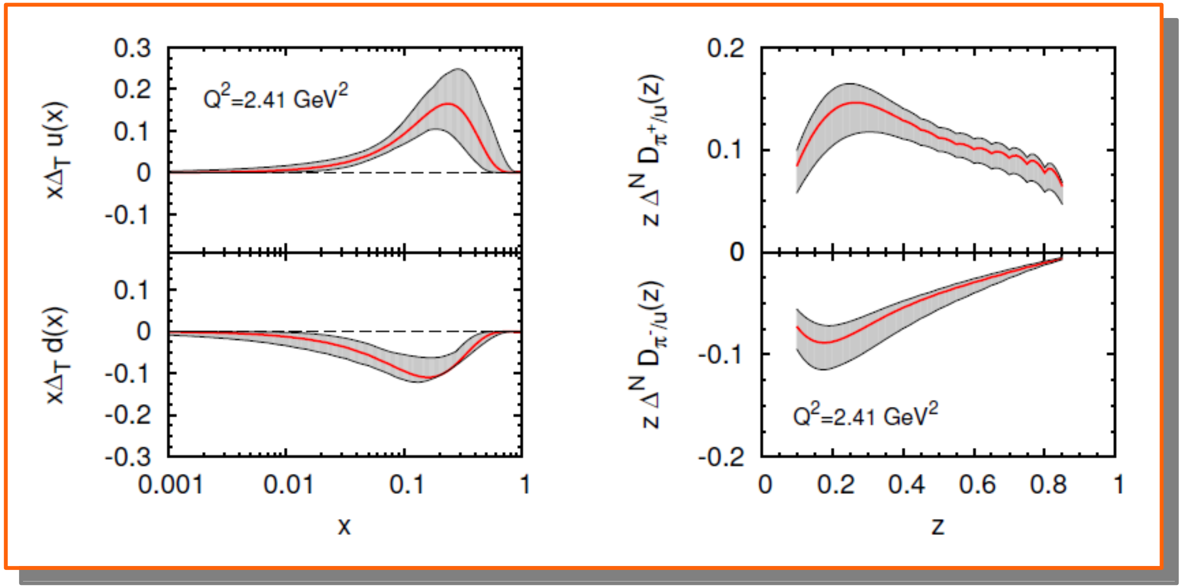
Simultaneous extraction of transversity and the Collins function

Anselmino, Boglione, D'Alesio, Melis, Murgia, Prokudin, Phys.Rev. D87 (2013) 094019

Standard. param. of the Collins function

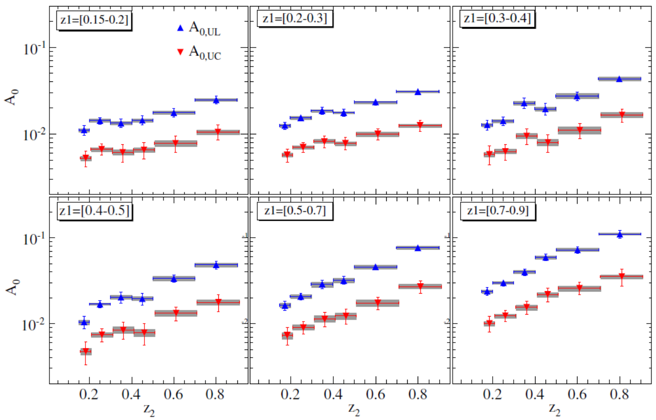


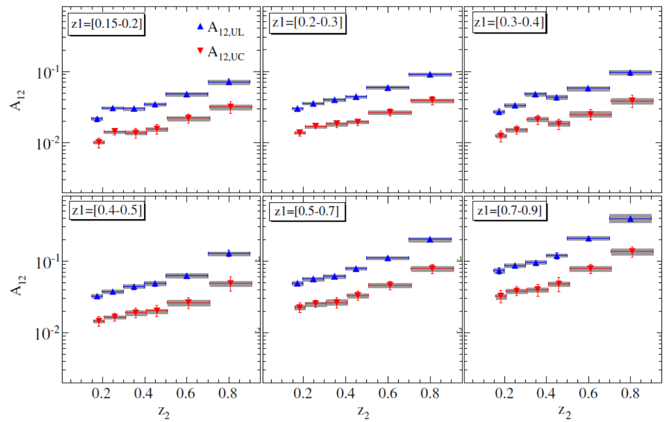
Polynom. param. of the Collins function



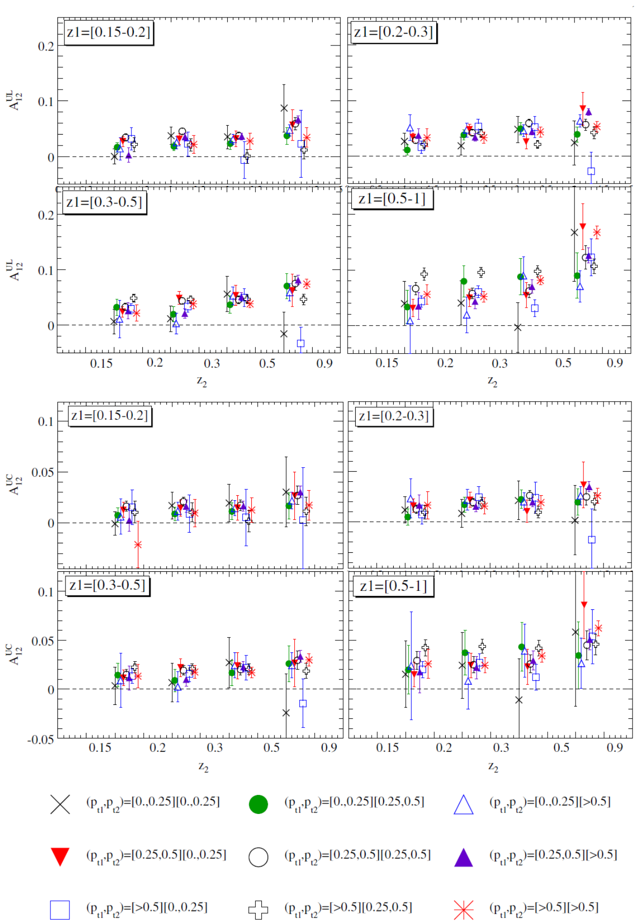
New BaBar data

BaBar measurements of A_0 and A_{12} as a function of z_1 and z_2

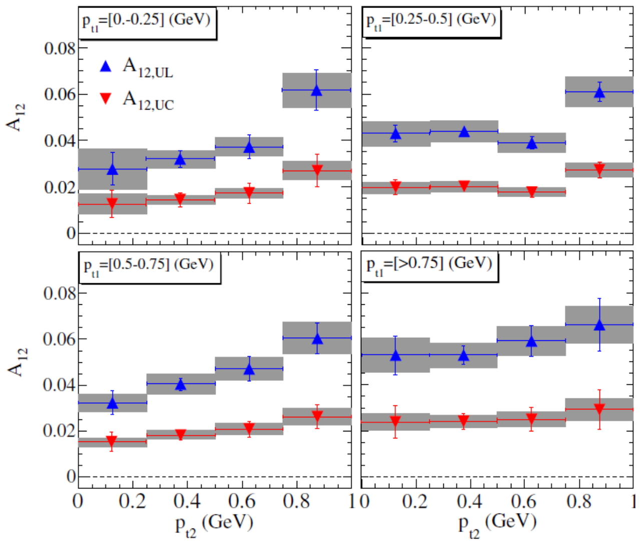


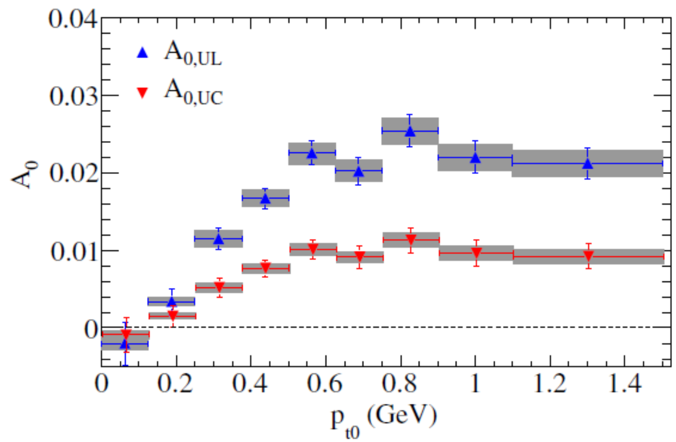


BaBar multidimensional data on A_{12} in bins of (z_1, z_2, p_{t1}, p_{t2})



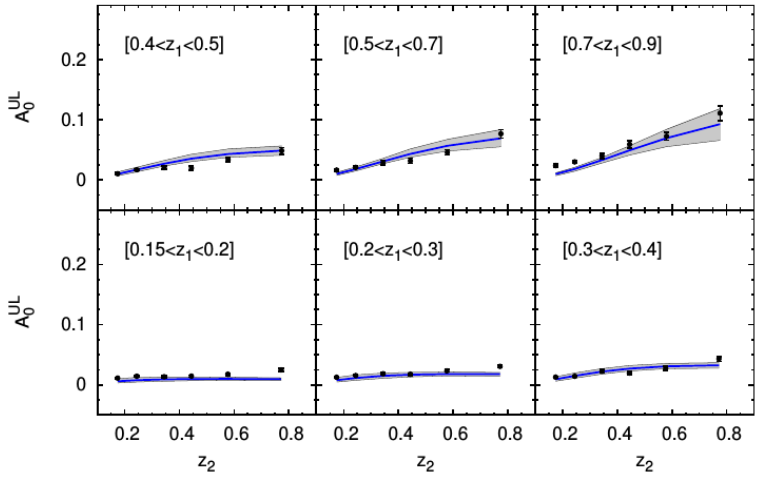
BaBar measurements of A_0 and A_{12} as a function of p_{t0}, p_{t1} and p_{t2}

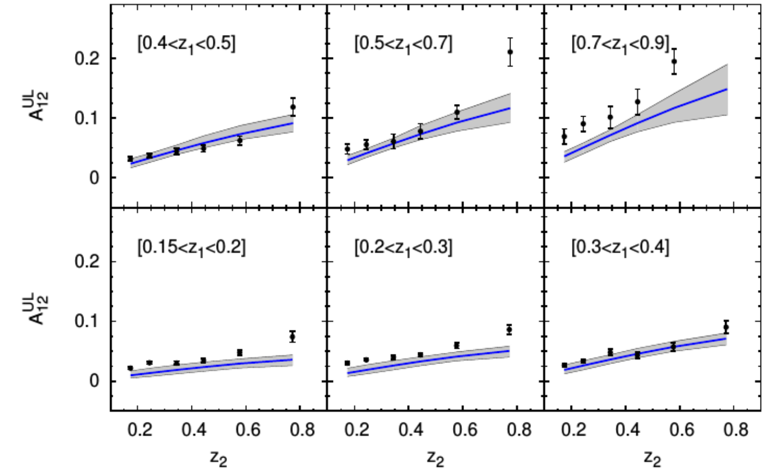


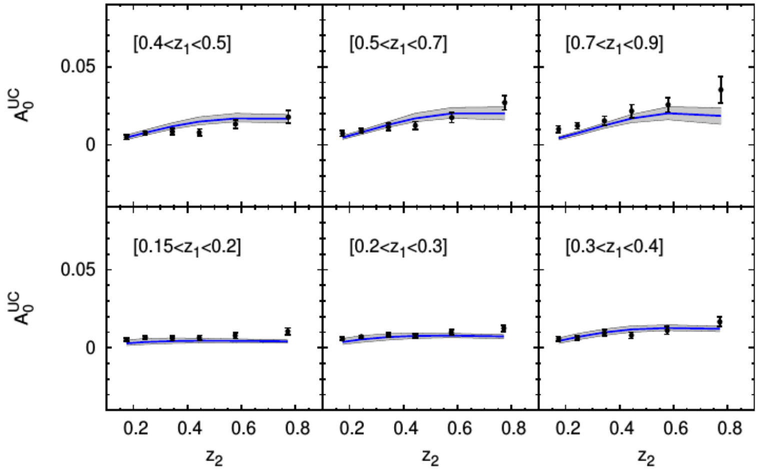


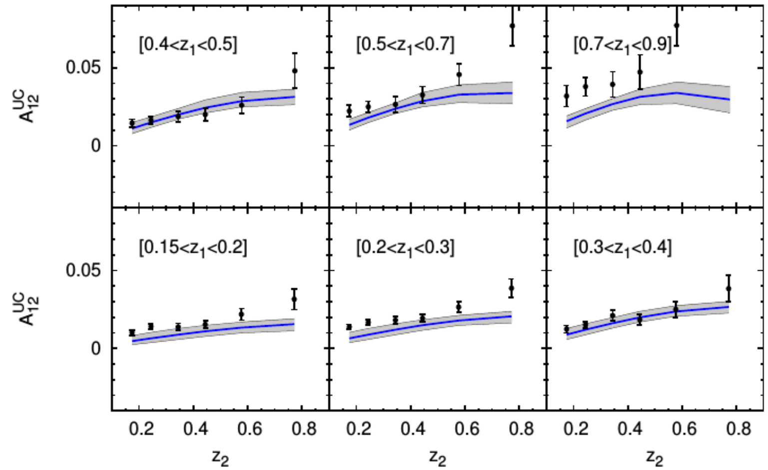
Our predictions compared to BaBar data

Predictions obtained by using the parameters extracted by best-fitting BELLE A_{12} experimental data with the standard parametrization of the Collins function are compared to BaBar measurements of A_0 and A_{12} as a function of z_1 and z_2



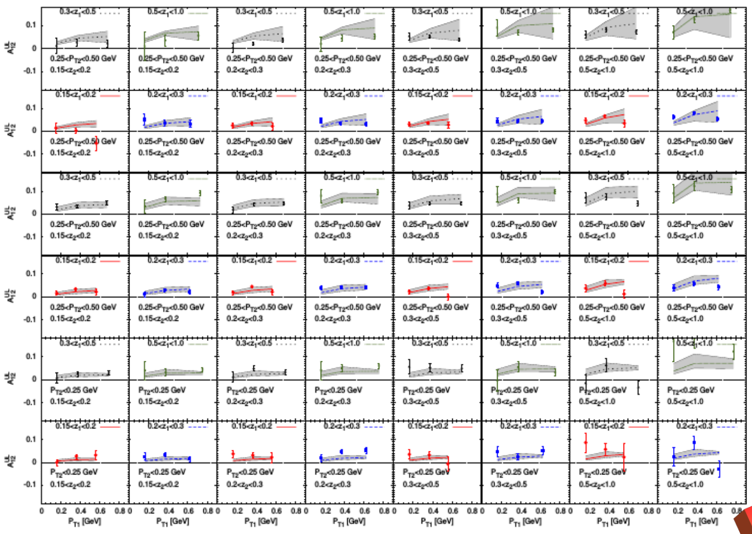


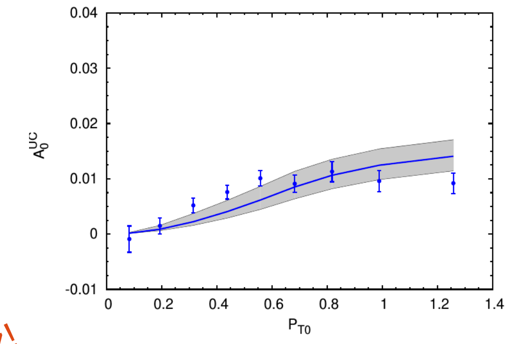




Our *predictions* compared to BaBar data

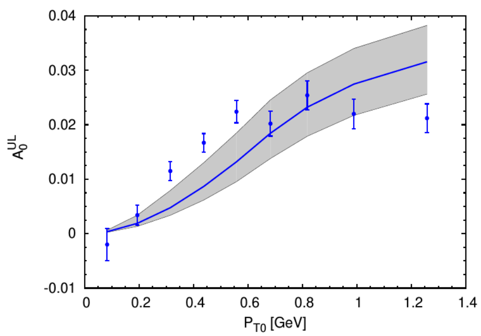
Anselmino, Boglione, D'Alesio, Gonzalez, Melis, Murgia, Prokudin, in preparation





Preliminary

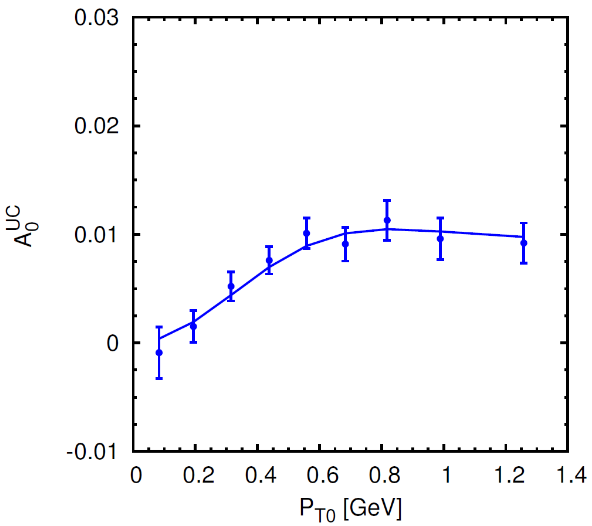
Very many thanks to S. Melis and O. Gonzalez!

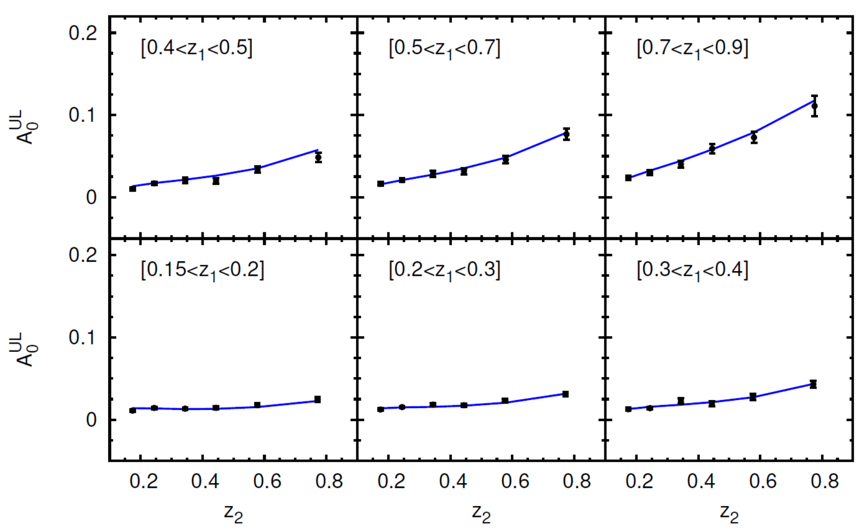


New (preliminary) fits

Anselmino, Boglione, D'Alesio, Gonzalez, Melis, Murgia, Prokudin, in preparation

- Preliminary fits of the new data look very promising (new flexible polynomial parameterization)





- Morover, we are studying different approaches to **scale evolution** for the Collins functions

What about Q^2 evolution ?

$e^+e^- \rightarrow h_1 h_2 X$
BELLE - BaBar
$Q^2 \sim 100\ GeV^2$

SIDIS
HERMES - COMPASS
$Q^2 \sim 3\ GeV^2$

What about Q^2 evolution ?

$e^+e^- \to h_1 h_2 X$
BELLE - BaBar
$Q^2 \sim 100$ GeV^2

SIDIS
HERMES - COMPASS
$Q^2 \sim 3$ GeV^2

Simultaneous fits of SIDIS and $e^+e^- \to h_1 h_2 X$
Involve data sets at very different Q^2 scales

In our computation the Collins TMD function evolves according to DGLAP evolution equations, through its $D_{h/q}(z,p_t,Q^2)$ component

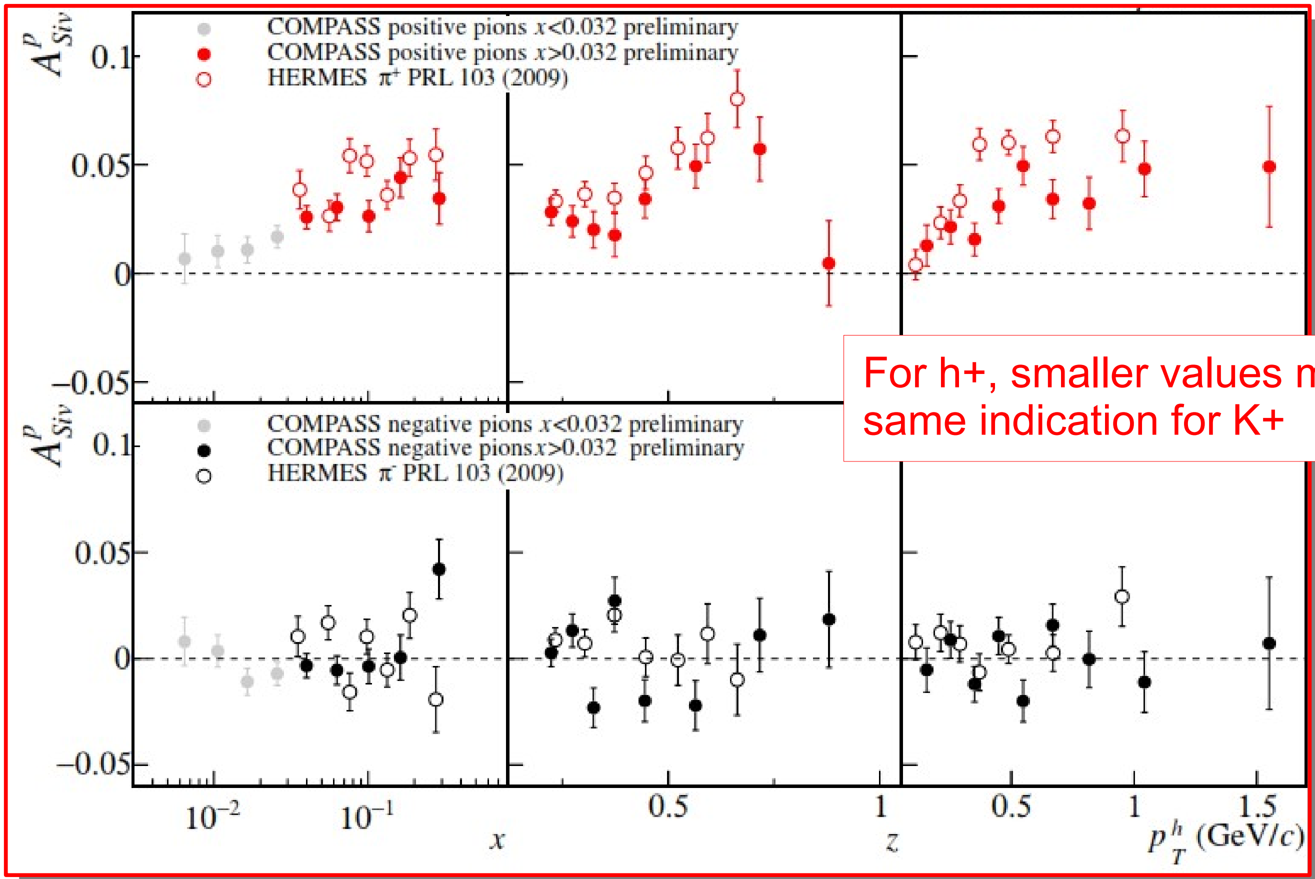
Could TMD evolution be an issue ?
Could TMD evolution affect our results ?

TMD evolution phenomenology

Does most recent SIDIS data suggest TMD evolution ?

Sivers asymmetry on proton (x > 0.032)

Charged pions (and kaons), 2010 data
Comparison with HERMES results



For h+, smaller values measured by COMPASS; same indication for K+

π+

$<Q^2> = 3.2$ GeV^2

$<Q^2> = 2.4$ GeV^2

π-

$<Q^2> = 3.2$ GeV^2

$<Q^2> = 2.4$ GeV^2

Anna Martin

DIS 2013

Does most recent SIDIS data suggest TMD evolution ?

Collins asymmetry on proton (x > 0.032)

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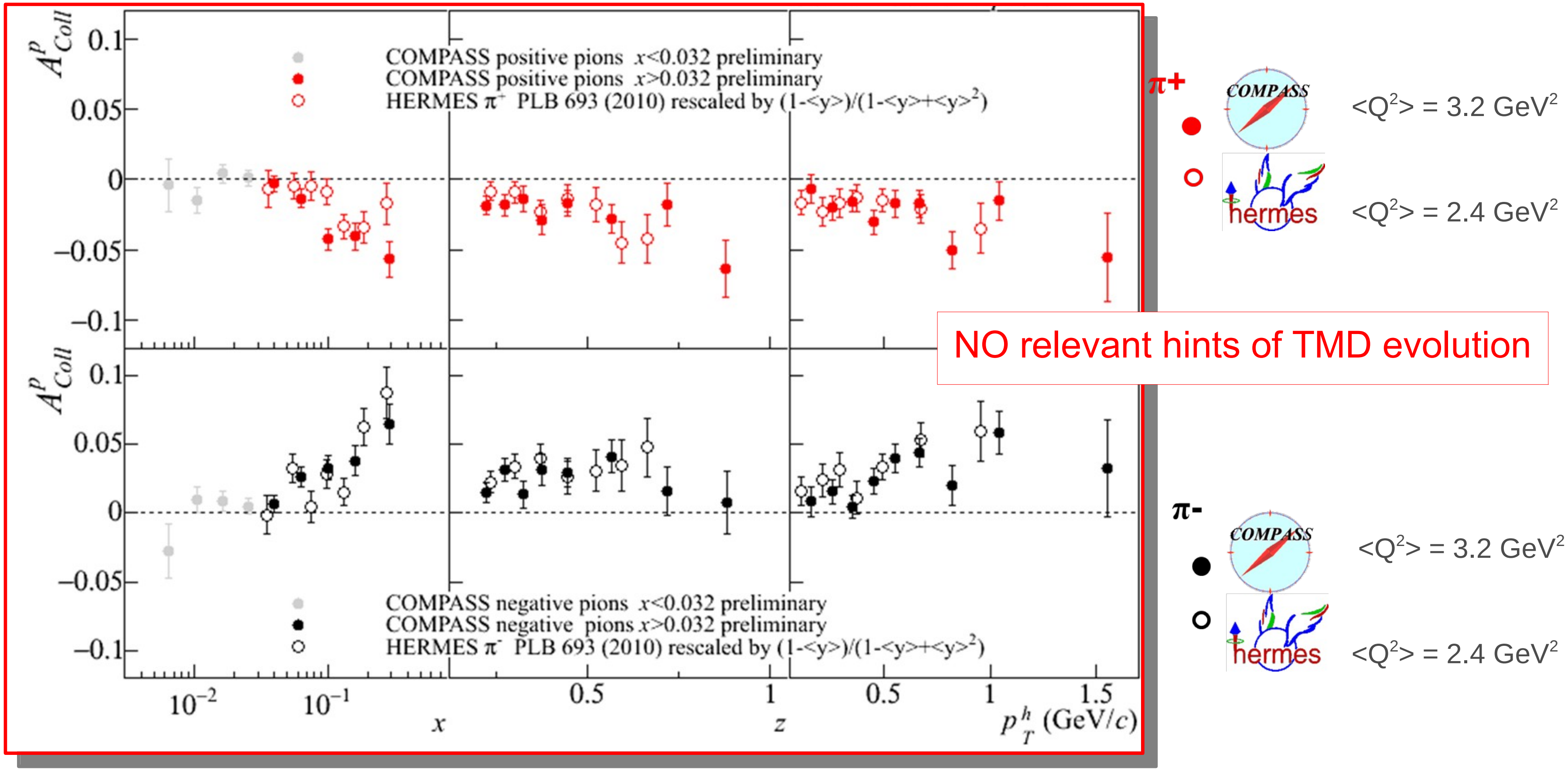


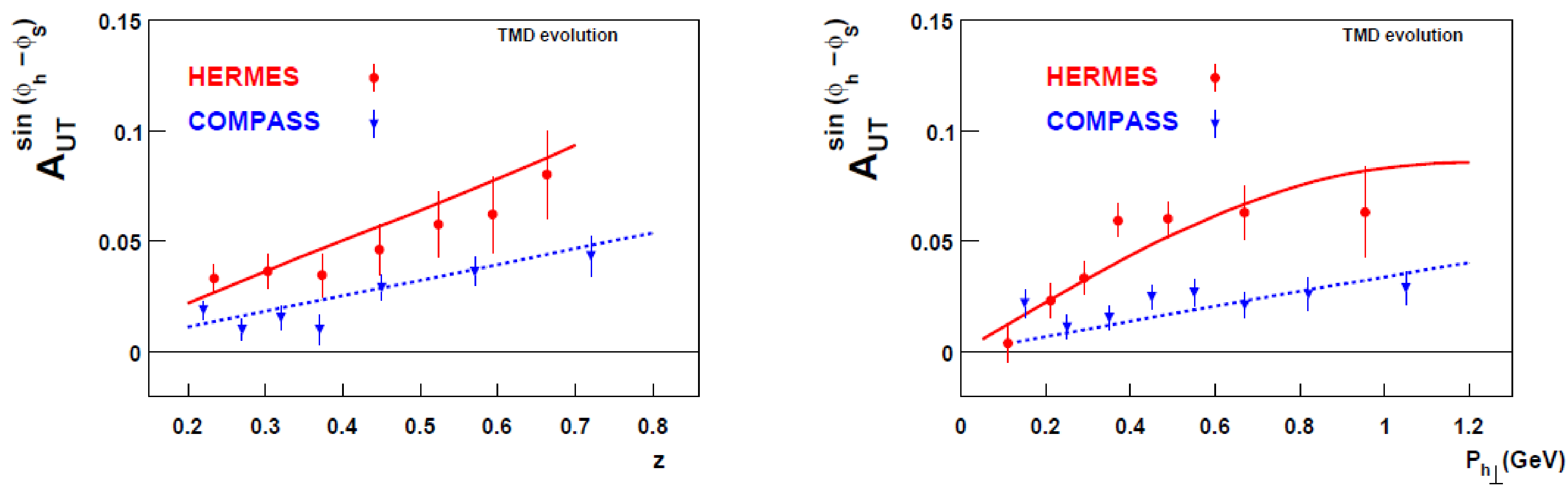
NO relevant hints of TMD evolution

Anna Martin

DIS 2013

Sivers TMD evolution: phenomenological results

Aybat, Prokudin, Rogers, Phys. Rev. Lett. 108, (2011) 242003



$\langle Q^2 \rangle = 2.4\ GeV^2$

Q^2 in the range $[1.3 – 6.2]\ GeV^2$

- No x dependence taken into account
- Sivers A_{UT} calculated at two fixed different values of Q^2: 2.4 and 3.8 GeV^2
- Evolution effects are then compared.

$\langle Q^2 \rangle = 3.8\ GeV^2$

Q^2 in the range $[1.3 – 20.5]\ GeV^2$

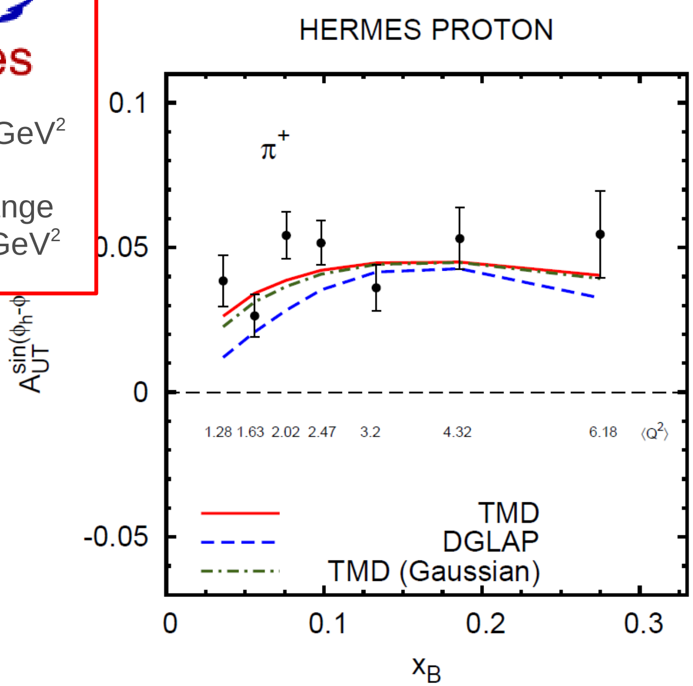
Sivers function from HERMES and COMPASS SIDIS data

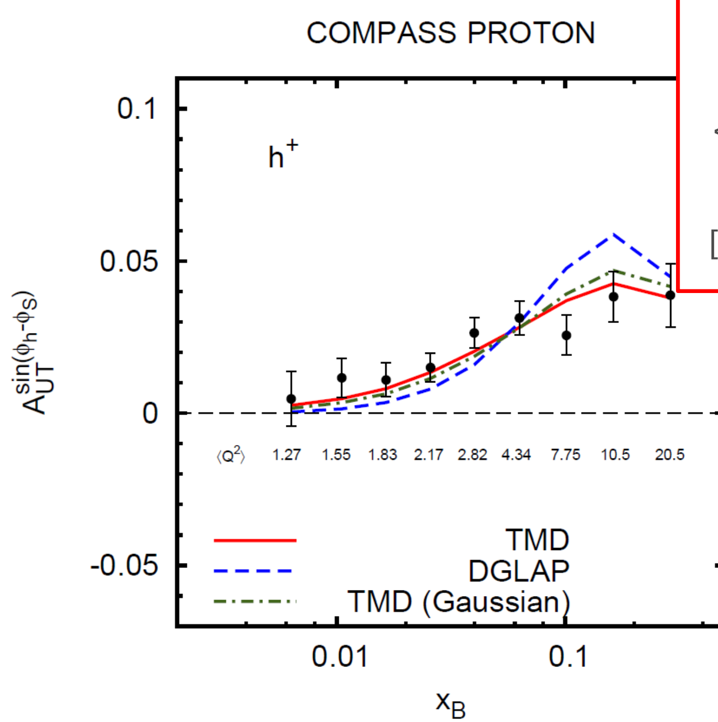
Anselmino, Boglione, Melis, Phys. Rev. D86 (2012) 014028

- Q^2 and x dependence rigorously taken into account
- **2 different fits:**
- TMD-fit (computing TMD evolution equations numerically)
- DGLAP evolution equation for the collinear part of the TMD)

$<Q^2> = 2.4$ GeV^2

Q^2 in the range [1.3 – 6.2] GeV^2





$<Q^2> = 3.8$ GeV^2

Q^2 in the range [1.3 – 20.5] GeV^2

A. Airapetian et al., Phys. Rev. Lett. 103, (2009) 152002

C. Adolph et al., Phys. Lett. B717 (2012) 383

Scale Evolution of unpolarized multiplicities

HERMES and COMPASS multiplicities cover the same range in Q^2 ...

$$\langle k_\perp^2 \rangle = g_1 + g_2 \ln(Q^2/Q_0^2) + g_3 \ln(10\, e\, x)$$
$$\langle p_\perp^2 \rangle = g_1' + z^2 g_2' \ln(Q^2/Q_0^2)$$

$$\langle P_T^2 \rangle = g_1' + z^2 [g_1 + g_2 \ln(Q^2/Q_0^2) + g_3 \ln(10\, e\, x)]$$

- HERMES multiplicities show no sensitivity to these parameters
- COMPASS fitting is much more involved.
  After correcting for normalization,
  we find that the total χ^2 decreases from 3.42 to 2.69.

Conclusions

- $k_\perp$ - Gaussian distributions work reasonably well. However the Gaussian widths appear to depend on the energy (s) of each experiment

- Non perturbative aspects (TMDs) are crucial also for high-energy observable (for instance, Z-production spectrum)

- We have come a long way, but …

What Next ?

- Find theories/models/prescriptions which simultaneously explain all available experimental data from different experiments (Drell-Yan, SIDIS and e+e- scattering) with TMD evolution

- More, new, high-quality data are very much needed to be able to perform solid and realistic phenomenological analyses of TMDs. *EIC* ...