2018 European Nuclear Physics Conference

September 2nd-7th, 2018: Bologna, Italy
San Domenico Center

The 3D structure of nucleons

Mariaelena Boglione

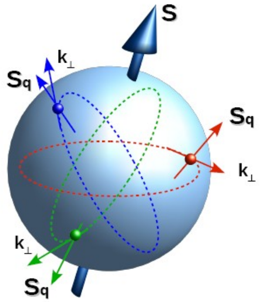
Torino: Mauro Anselmino, Osvaldo Gonzalez, Stefano Melis

Cagliari: Francesco Murgia, Umberto D'Alesio, Carlo Flores

USA: Alexei Prokudin, Ted Rogers, John Collins

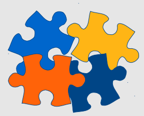
The 3D Structure of the Nucleon

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.



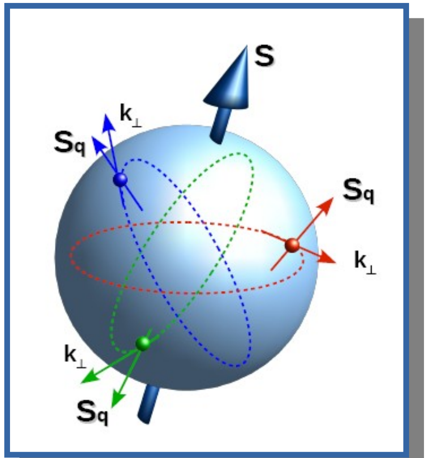
Information on the 3-dimensional structure of the nucleon is embedded in the ***Transverse Momentum Dependent*** distribution and fragmentation functions (***TMDs***).

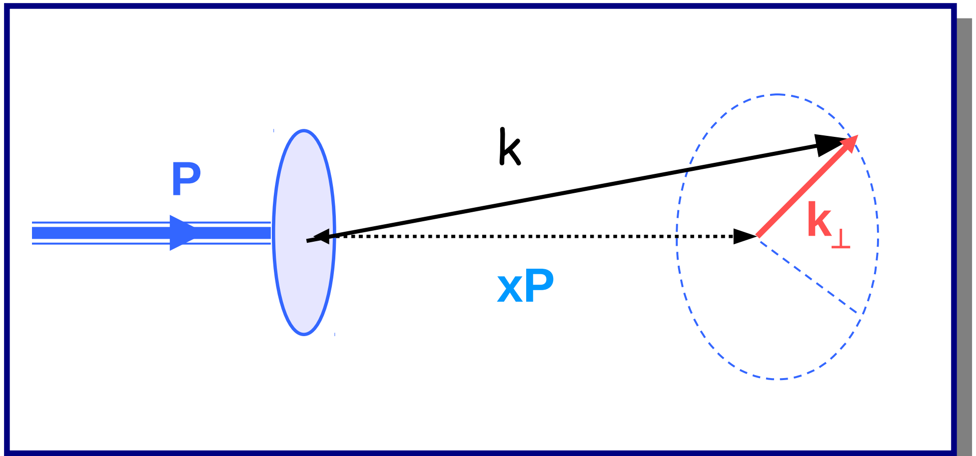
In a very simple **phenomenological** approach, hadronic cross sections and spin asymmetries are generated, within a ***QCD* factorization** framework, as convolutions of **distribution** and (or) **fragmentation** functions with **elementary cross sections**.



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

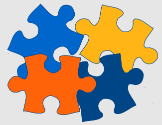
Intrinsic Transverse Momentum





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

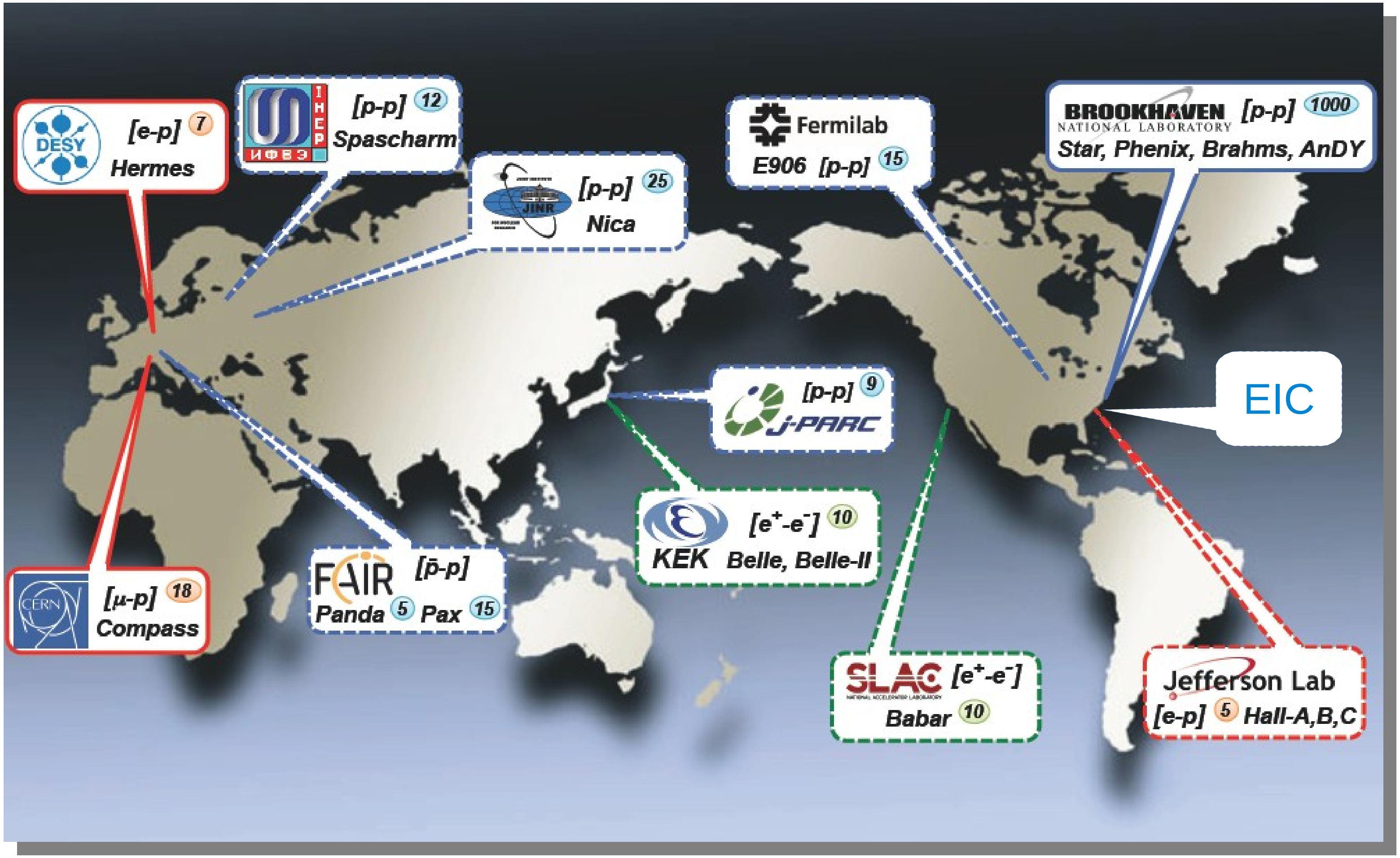
Transverse motion is usually integrated over, but there are important **spin-$k_\perp$** correlations which should not be neglected



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

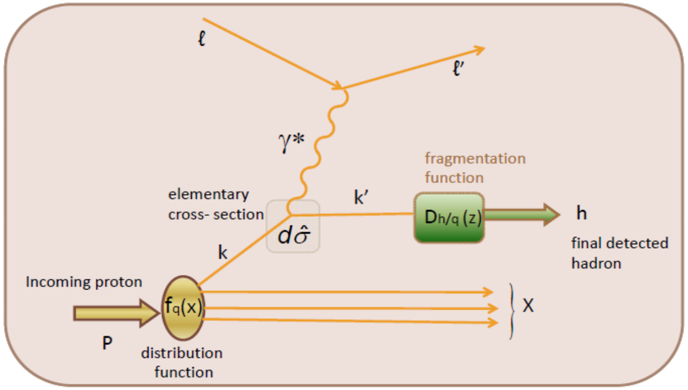
Where can we learn about the 3D structure of matter ?

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



Experimental data for TMD studies

Unpolarized and Polarized SIDIS scattering

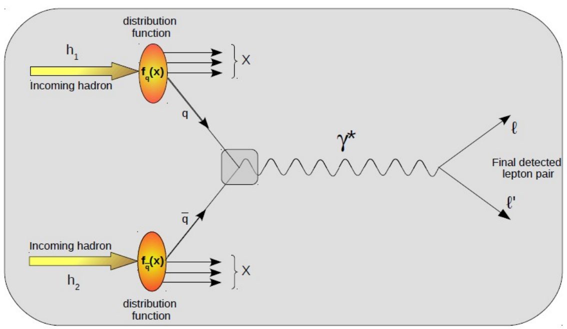


$$\sigma_{SIDIS} = f_q(x) \otimes \hat{\sigma} \otimes D_{h/q}(z)$$

Allows the extraction of TMD distribution and fragmentation functions

Experimental data for TMD studies

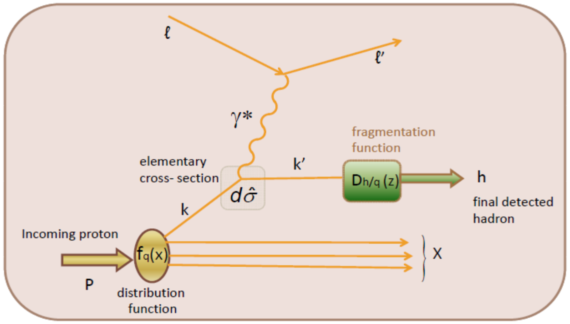
Unpolarized and Polarized Drell-Yan scattering



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

Allows extraction of distribution functions

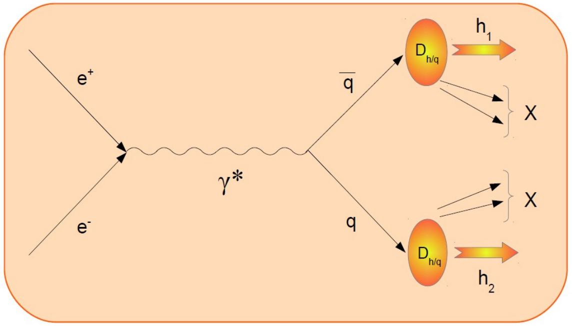
Unpolarized and Polarized SIDIS scattering



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

Allows extraction of distribution and fragmentation functions

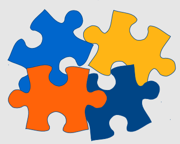
$e^+ e^- \to h_1 h_2 X$

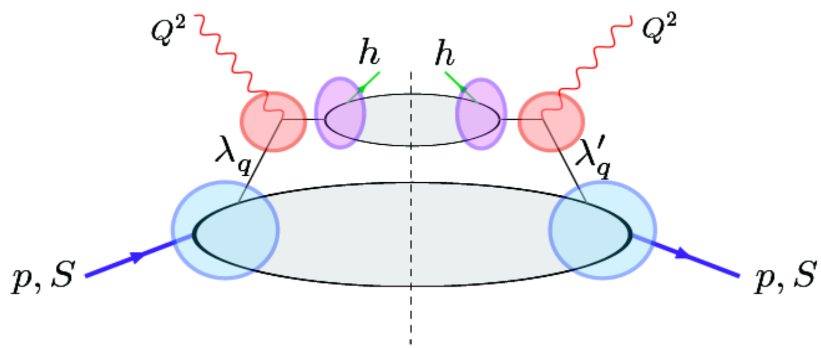


$$\sigma_{h1\,h2}\propto D(z_1)\otimes D(z_2)\otimes\hat\sigma$$

Allows extraction of fragmentation functions

From the theory point of view ...

	***Perturbative QCD*** ***Parton model*** ***Factorization theorems*** ***...***



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

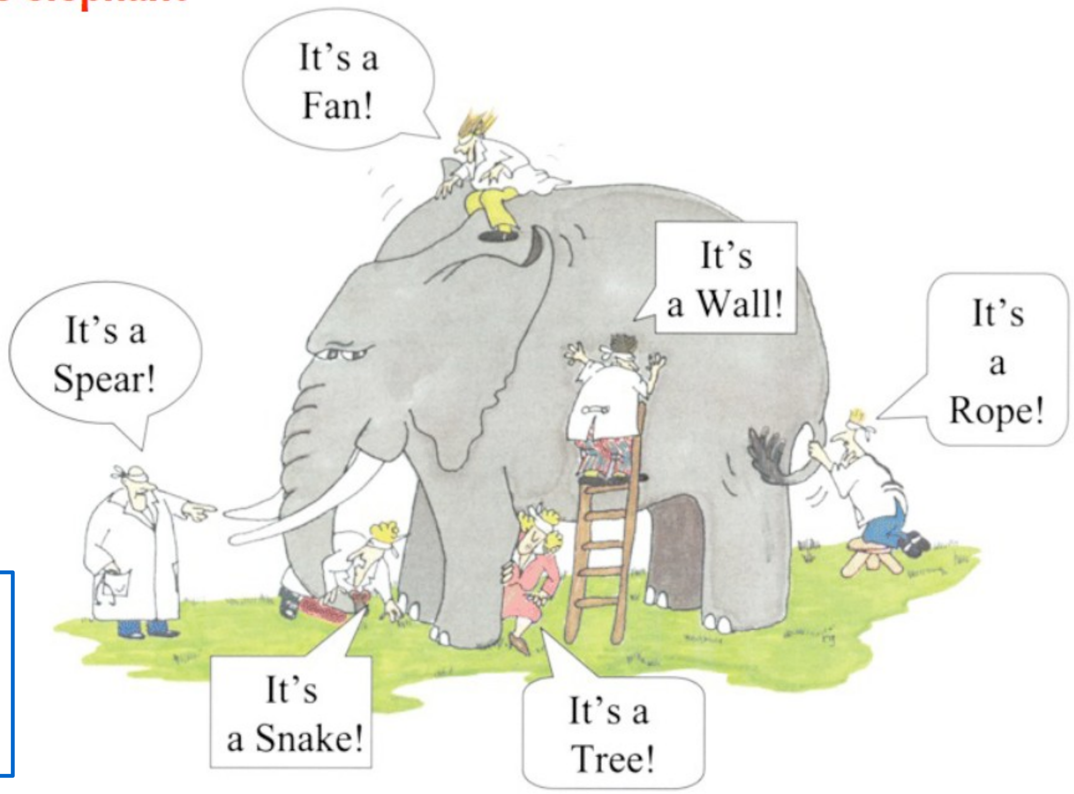
THEORY
- Perturbative QCD
- Factorization theorems
- Resummation
- ...

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

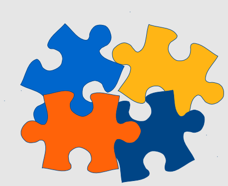
The blind men and the elephant
from H. Avakian



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 ?



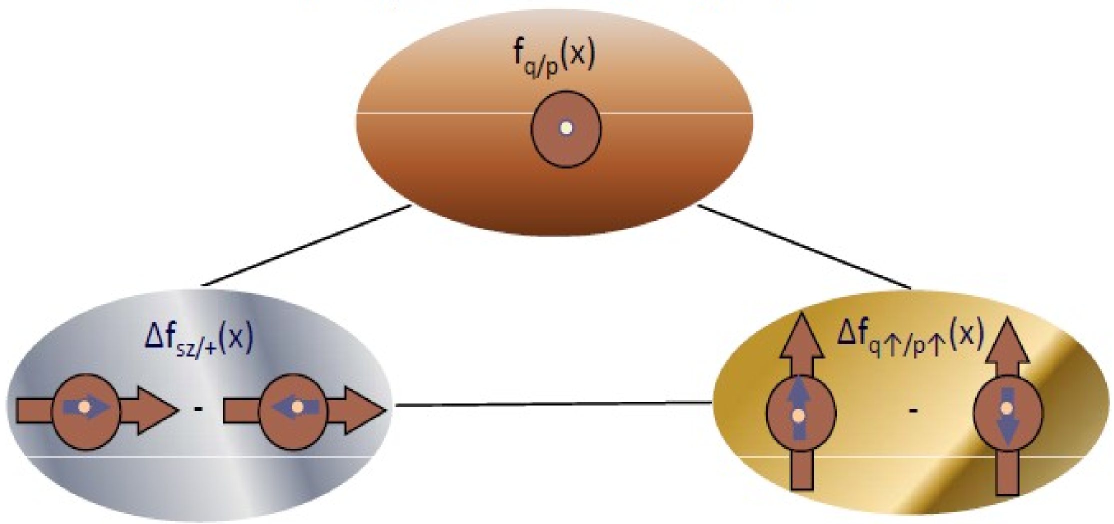
The mechanism which describes how quarks and gluons are bound into hadrons is embedded in the parton distribution and fragmentation functions (PDFs and FFs), the so-called “soft parts” of hadronic scattering processes. These are non-perturbative objects which connect the ideal world of pointlike and 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

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



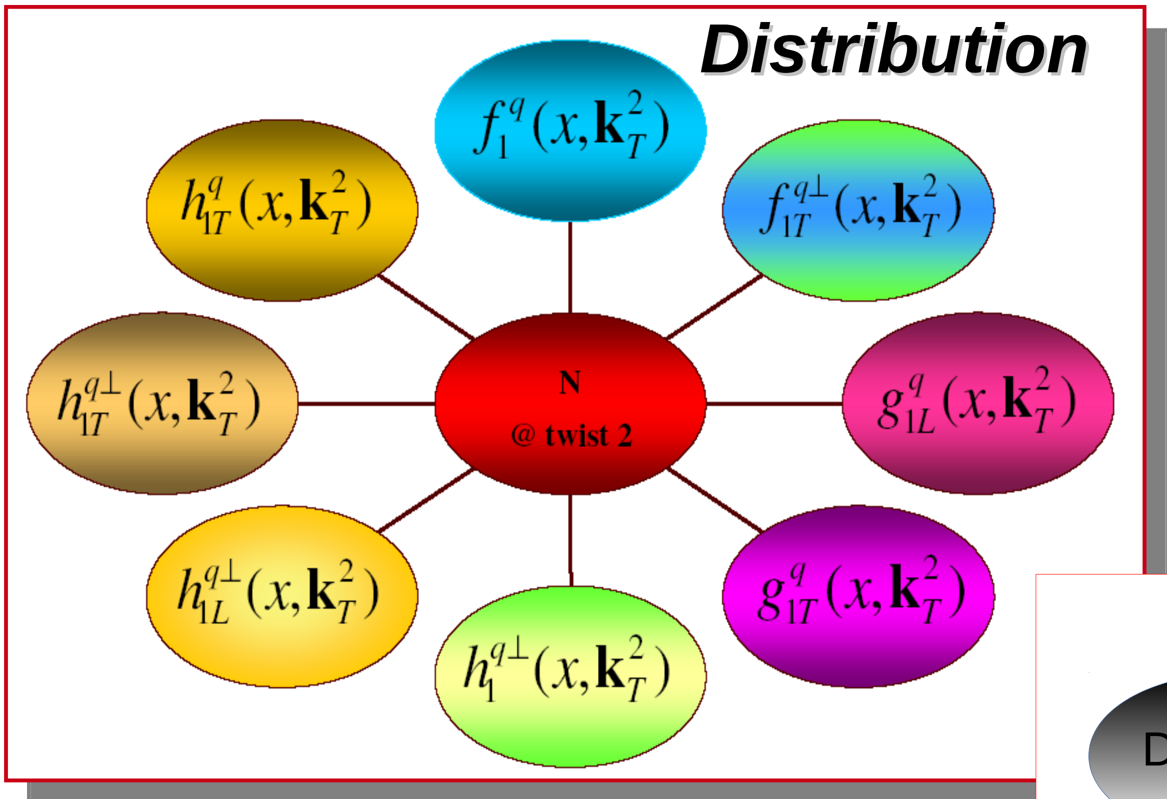
Helicity distribution functions

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

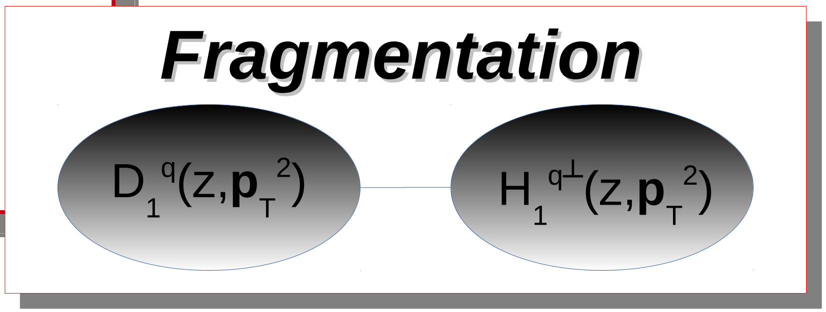
Transversity distribution functions

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

TMD distribution and fragmentation functions



Correlations between spin and transverse momentum



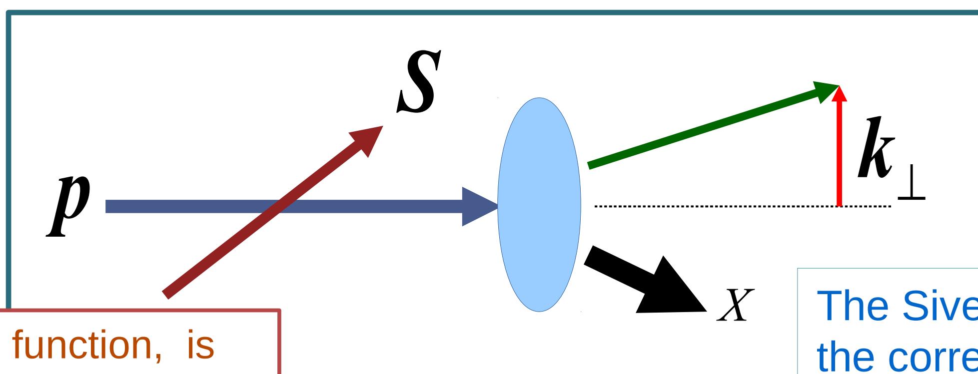
The Sivers function

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

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

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

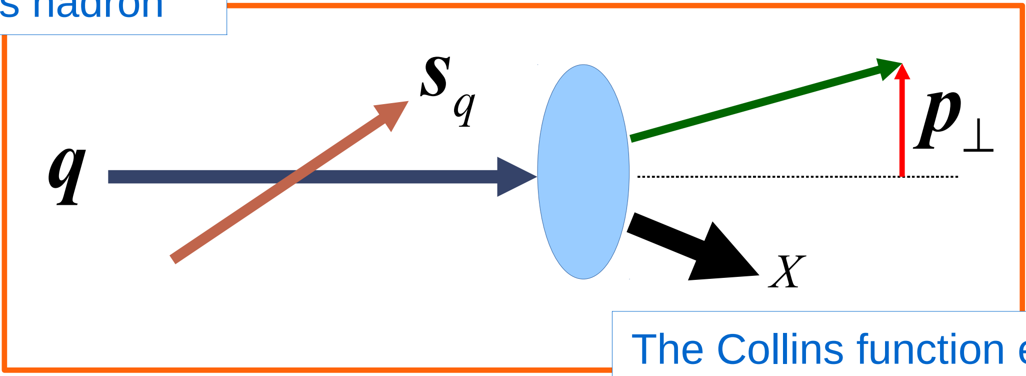
The Collins function

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

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

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

- Polarized TMDs are best studied in polarized processes, most commonly they are extracted from spin or azimuthal asymmetries.

- However, to compute these asymmetries in a reliable way, we must be able to reproduce the unpolarized cross sections in the best possible way, over the largest possible range in q_T.

Unpolarized TMDs ...
… where it all begins

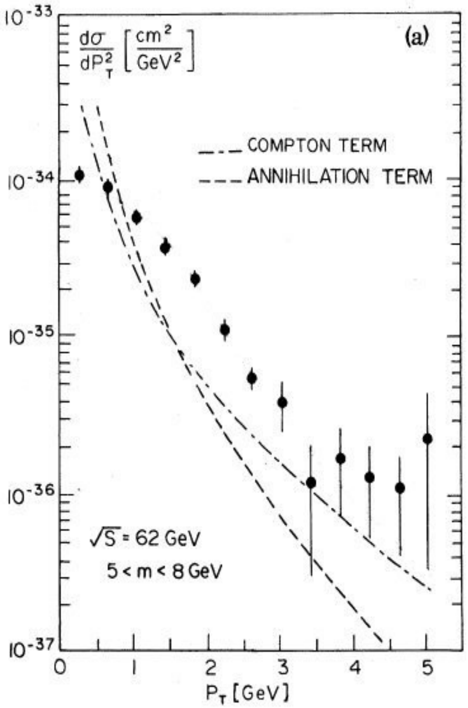
Naive TMD approach

- Calculating a cross section which describes a hadronic process over the whole q_T range is a highly non-trivial task

Let's consider Drell Yan processes (for historical reasons)

- Fixed order calculations cannot describe DY data at **small q_T**:

At Born Level the cross section is vanishing
At order α_s the cross section is divergent...



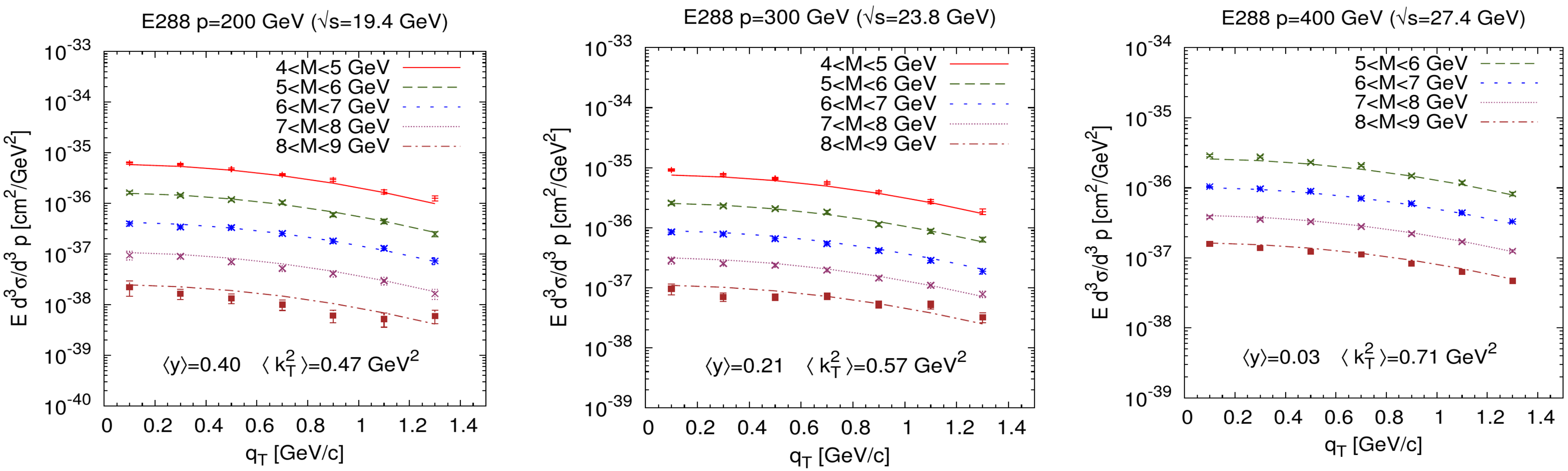
$$q_T \to 0$$

$$\frac{1}{\sigma_0}\frac{d\sigma}{dq_T^2} = \frac{2C_F}{2\pi q_T^2}\alpha_s \ln\left(\frac{M^2}{q_T^2} - \frac{3}{2}\right)$$

Naive TMD approach

$$\frac{d\sigma}{dP_T^2} \propto \frac{\alpha_{em}}{M^2} \sum_q f_{q/h_1}(x_1) \bar{f}_{q/h_2}(x_2) \frac{\exp(-P_T^2/\langle P_T^2\rangle)}{\pi \langle P_T^2 \rangle}$$

- Considering the same DY process at different energies:

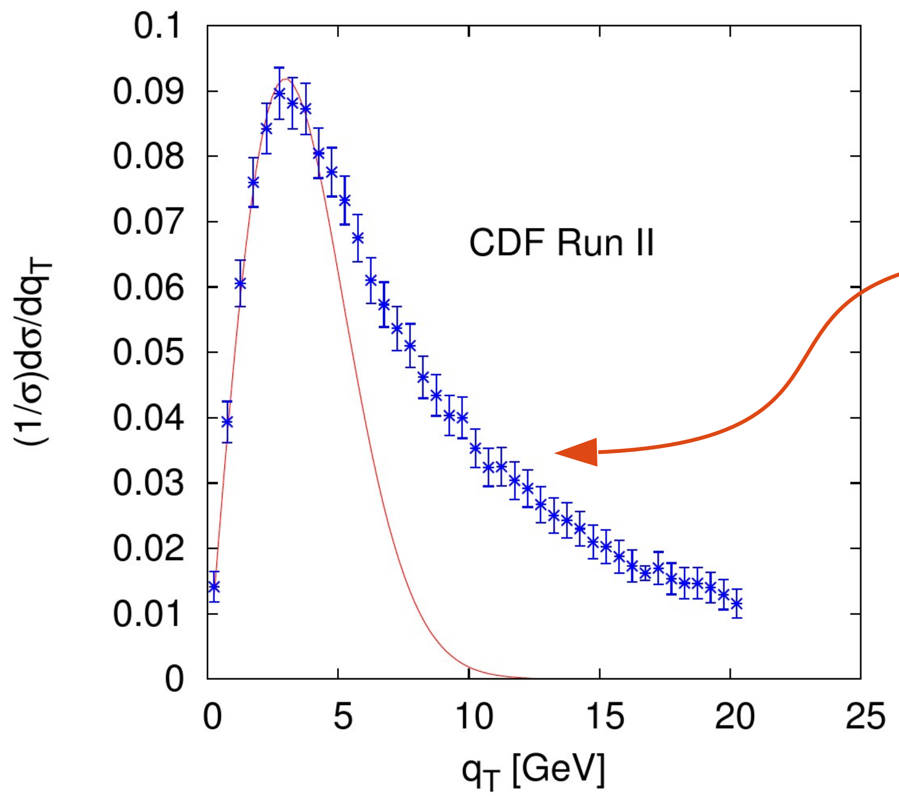


Each data set is Gaussian but with a different width

Drell-Yan phenomenology

- Does the q_T distribution behave like a Gaussian ?

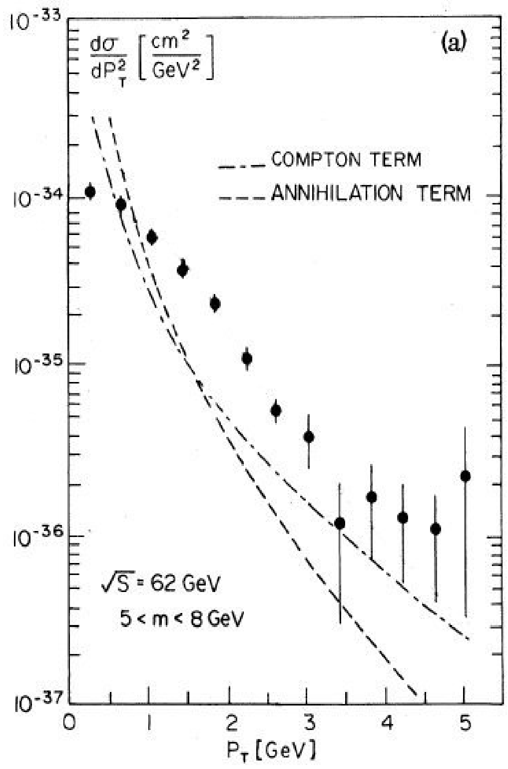
$$\frac{d\sigma}{dP_T^2} \propto \frac{\alpha_{em}}{M^2} \sum_q f_{q/h_1}(x_1) \bar{f}_{q/h_2}(x_2) \frac{\exp(-P_T^2/\langle P_T^2\rangle)}{\pi\langle P_T^2\rangle}$$



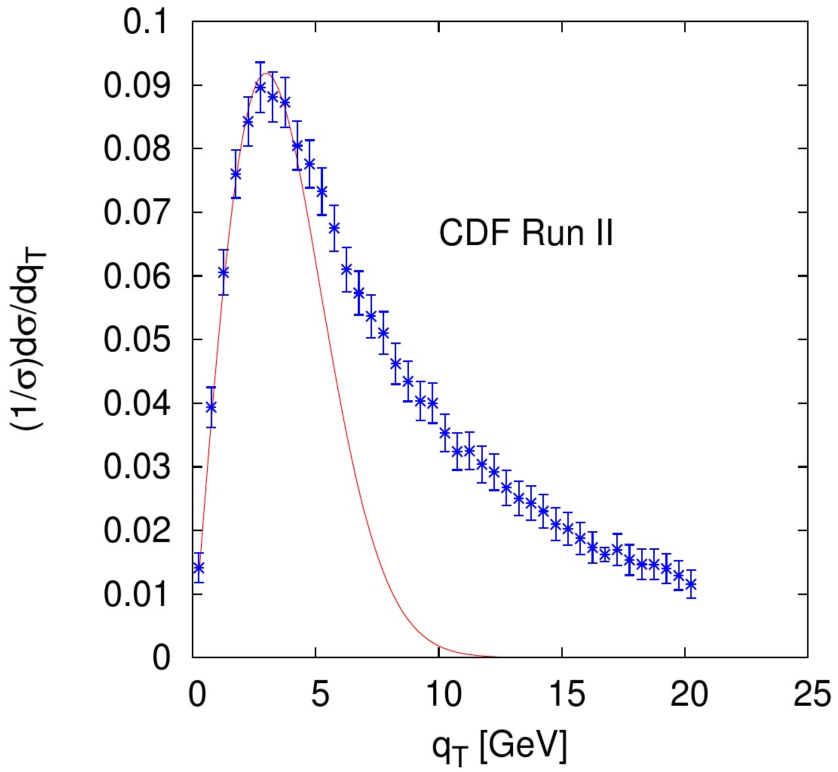
Clearly this is not a Gaussian tail !

Drell-Yan phenomenology

Fixed order calculations cannot describe correctly DY cross sections at small q_T



DY cross sections do not show a Gaussian behaviour at large q_T

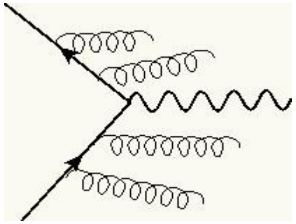


Resummation / TMD factorization

- Fixed order calculations cannot describe correctly DY/SIDIS data at small q_T

$$\frac{1}{\sigma_0}\frac{d\sigma}{dq_T^2} = \frac{2C_F}{2\pi q_T^2}\alpha_s \ln\left(\frac{M^2}{q_T^2} - \frac{3}{2}\right)$$

- These divergencies are taken care of by TMD evolution/resummation



The cross section is written in **b_T space**:

$$\frac{1}{\sigma_0}\frac{d\sigma}{dQ^2 dy dq_T^2} = \int \frac{d^2\boldsymbol{b}_T e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T}}{(2\pi)^2}\sum_j \overbrace{e_j^2 W_j(x_1,x_2,b_T,Q)}^{\text{Resummed term}} + \overbrace{Y(x_1,x_2,q_T,Q)}^{\text{Finite term}}$$

Resummation / TMD factorization

$$\frac{1}{\sigma_0}\frac{d\sigma}{dQ^2 dy dq_T^2} = \int \frac{d^2\boldsymbol{b}_T e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T}}{(2\pi)^2}\sum_j \overbrace{e_j^2 W_j(x_1,x_2,b_T,Q)}^{\text{Resummed term}} + \overbrace{Y(x_1,x_2,q_T,Q)}^{\text{Finite term}}$$

$$\boxed{Y = \sigma^{FO} - \sigma^{ASY}}$$

- The W term is designed to work well at low and moderate q_T, when $q_T \ll Q$. (Actually, W is devised to work down to $q_T \sim 0$, however collinear-factorization works up to $q_T > M$; therefore, TMD-factorization and collinear-factorization can be simultaneously applied only when $q_T \gg M$).
- The W term becomes unphysical when $q_T \geq Q$, where it becomes negative (and large).
- The Y term corrects for the misbehaviour of W as q_T gets larger, providing a consistent (and positive) q_T differential cross section.
- The Y term should provide an effective smooth transition to large q_T, where fixed order perturbative calculations are expected to work.

Resummation / TMD factorization

- Example: the CSS resummation scheme:

at small b_T OPE works
→ collinear PDFs

$$W_j(x_1,x_2,b_T,Q) = \exp\left[S_j(b_T,Q)\right]\sum_{i,k} C_{ji}\otimes f_i(x_1,C_1^2/b_T^2)\; C_{\bar{j}k}\otimes f_k(x_2,C_1^2/b_T^2)$$

$$S_j(b_T,Q) = -\int_{C_1^2/b_T^2}^{Q^2}\frac{d\kappa^2}{\kappa^2}\left[A_j(\alpha_s(\kappa))\ln\left(\frac{Q^2}{\kappa^2}\right)+B_j(\alpha_s(\kappa))\right]$$

$$\mu = \frac{C_1}{b_T}$$

At large b_T the scale μ becomes too small!

Non-trivially connected to the physical region: $Q^2 \gg q_T^2 \simeq \Lambda^2_{QCD}$

- **All TMD evolution schemes require a model to deal with the non-perturbative region**

- **Working in b_T space makes phenomenological analyses more difficult, as we lose intuition and direct connection with "real world experience". (Experimental data are in q_T space).**

Non perturbative region

- This is a perturbative scheme. All the scales must be frozen when reaching the non perturbative region:

$$b_T \longrightarrow b_* = \frac{b_T}{\sqrt{1 + b_T^2/b_{max}^2}} \qquad\qquad \mu = \frac{C_1}{b_T} \longrightarrow \mu_b = C_1/b_*$$

- Then we define a non perturbative function for large b_T:

$$\frac{W_j(x_1, x_2, b_T, Q)}{W_j(x_1, x_2, b_*, Q)} = F_{NP}(x_1, x_2, b_T, Q)$$

Perturbatively calculable, but process dependent

Non-perturbative, must be inferred from experiment, but universal

$$W_j(x_1, x_2, b_T, Q) = \sum_{i,k} \exp\left[S_j(b_*, Q)\right] \left[C_{ji} \otimes f_i\left(x_1, \mu_b\right)\right] \left[C_{\bar{j}k} \otimes f_k\left(x_2, \mu_b\right)\right] F_{NP}(x_1, x_2, b_T, Q)$$

$b_*, \; \mu_b$

b_T

$$C_1 = 2\exp(-\gamma_E)$$

Collins, Soper, Sterman, Nucl. Phys. B250, 199 (1985)

TMD regions

- For this scheme to work, 4 distinct kinematic regions have to be identified
- They should be large enough and well separated

TMD evolution		Matching region (Y factor)	Fixed Order collinear QCD
$q_T \sim \lambda_{QCD}$	$q_T << Q$	$q_T \sim Q$	$q_T \geq Q$
Intrinsic q_T	Soft gluon radiation		Hard gluon emission

CSS for DY processes

To perform phenomenological studies we need a non perturbative function.

$$F_{NP}(x_1, x_2, b_T, Q)$$

Davies-Webber-Stirling (DWS) $\exp\left[-g_1 - g_2 \ln\left(\frac{Q}{2Q_0}\right)\right] b^2;$

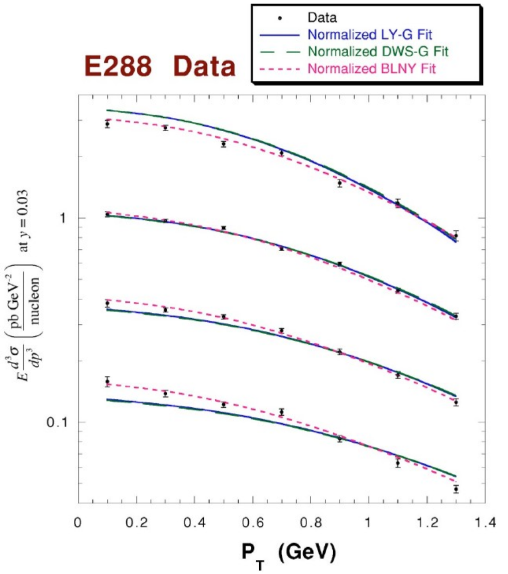
Ladinsky-Yuan (LY) $\exp\left\{\left[-g_1 - g_2 \ln\left(\frac{Q}{2Q_0}\right)\right] b^2 - [g_1 g_3 \ln(100 x_1 x_2)] b\right\};$

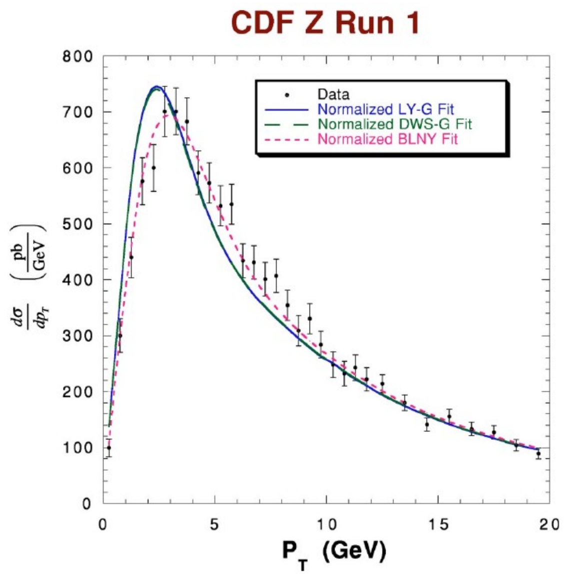
Brock-Landry-Nadolsky-Yuan (BLNY) $\exp\left[-g_1 - g_2 \ln\left(\frac{Q}{2Q_0}\right) - g_1 g_3 \ln(100 x_1 x_2)\right] b^2$

Nadolsky et al., Phys.Rev. D67,073016 (2003)

CSS for DY processes

Nadolsky et al.* analyzed successfully
low energy DY data and Z_0 production data
using different parametrizations





Parameter	DWS-G fit	LY-G fit	BLNY fit
g_1	0.016	0.02	0.21
g_2	0.54	0.55	0.68
g_3	0.00	-1.50	-0.60
CDF Z Run-0 N_{fit}	1.00 (fixed)	1.00 (fixed)	1.00 (fixed)
R209 N_{fit}	1.02	1.01	0.86
E605 N_{fit}	1.15	1.07	1.00
E288 N_{fit}	1.23	1.28	1.19
DØ Z Run-1 N_{fit}	1.01	1.01	1.00
CDF Z Run-1 N_{fit}	0.89	0.90	0.89
χ^2	416	407	176
χ^2/DOF	3.47	3.42	1.48

$b_{max} = 0.5\ \text{GeV}^{-1}$

Nadolsky et al., Phys.Rev. D67,073016 (2003)

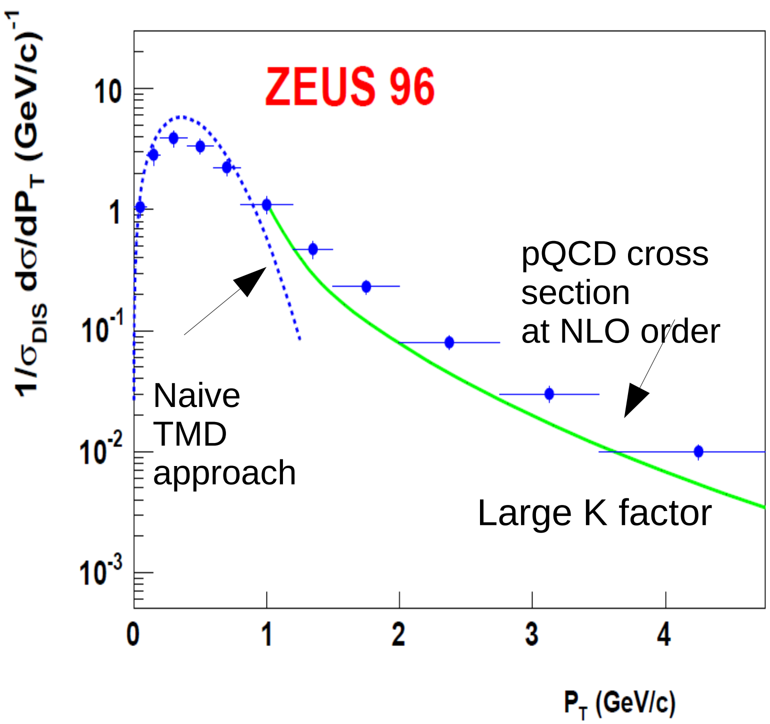
$$+$$

SIDIS processes

$$\ell + p \to \ell' + h + X$$

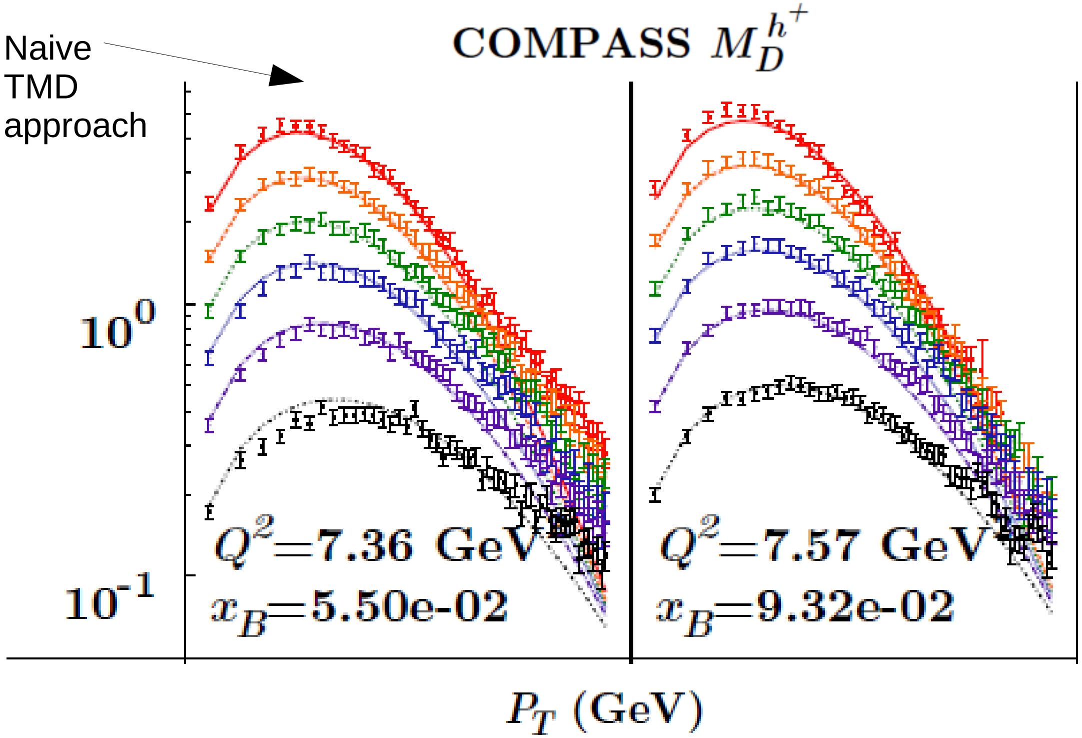
Resummation in SIDIS

- As mentioned above
  - fixed order pQCD calculation fail to describe the SIDIS cross sections at small q_{T},
  - the cross section tail at large q_T is clearly non-Gaussian.



Anselmino, Boglione, Prokudin, Turk, Eur.Phys.J. A31 (2007) 373-381

ZEUS Collaboration (M. Derrick), Z. Phys. C 70, 1 (1996)



Anselmino, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (2014) 005

COMPASS, Adolph et al., Eur. Phys. J. C 73 (2013) 2531

Need resummation of large logs and matching perturbative to non-perturbative contributions

Naive TMD approach

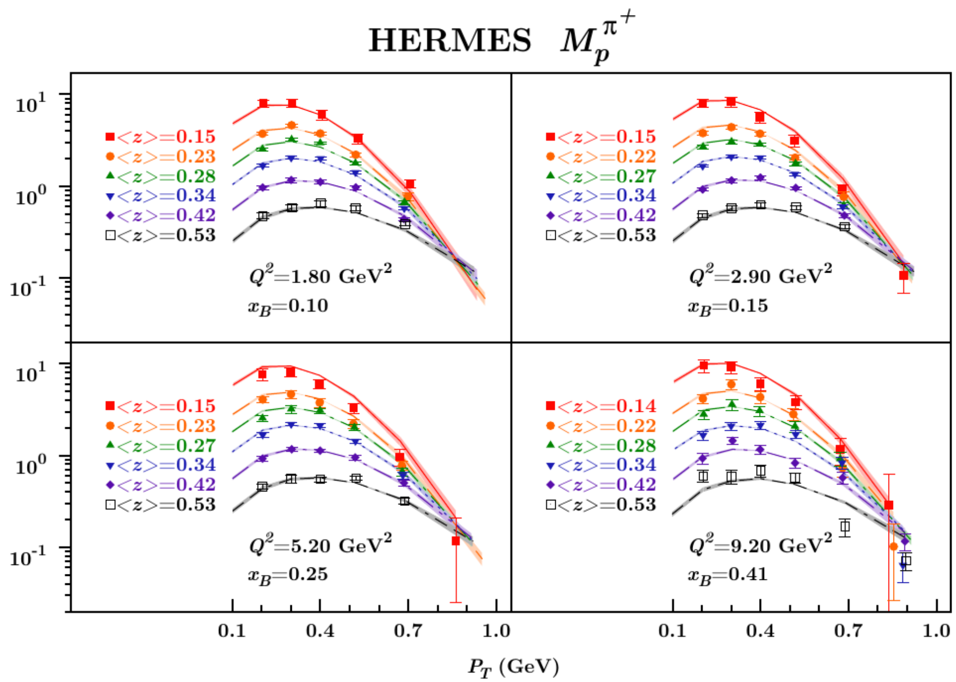
M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261

- Simple phenomenological ansatz can reproduce low q_T data

$$f_{q/p}(x, k_\perp) = f(x)\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle} \qquad D_{h/q}(z, p_\perp) = D_{h/q}(z)\,\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}$$

$$F_{UU} = \sum_q e_q^2\, f_{q/p}(x_B)\, D_{h/q}(z_h)\frac{e^{-P_T^2/\langle P_T^2\rangle}}{\pi\langle P_T^2\rangle}$$

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



Airapetian et al, Phys. Rev. D 87 (2013) 074029

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

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

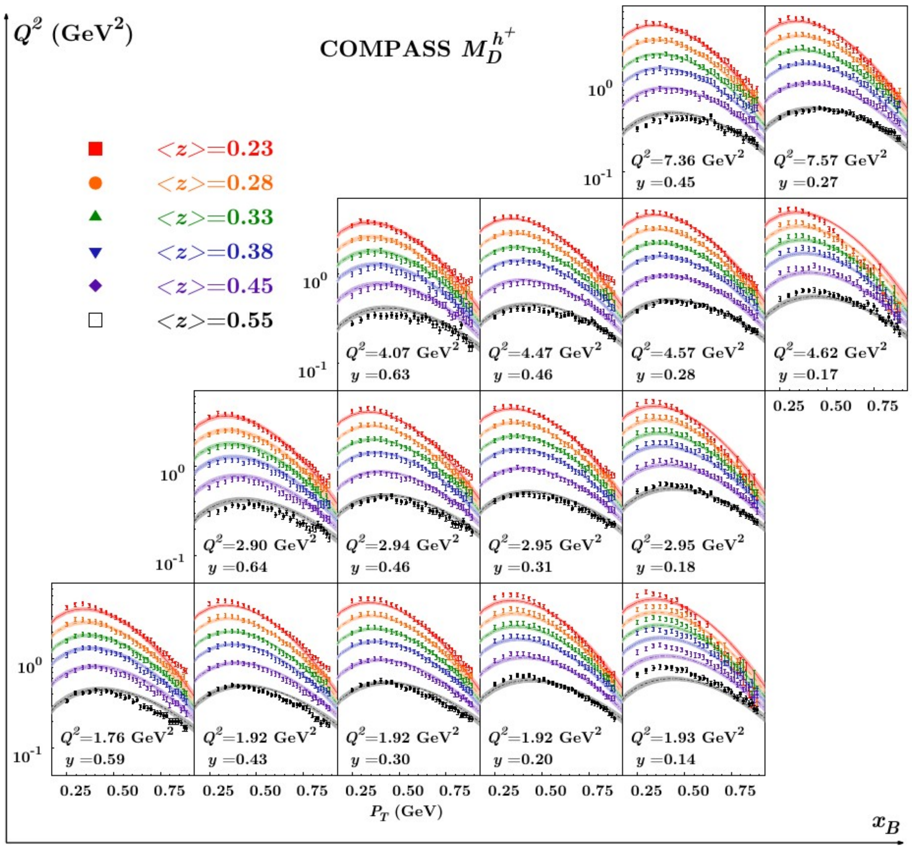
$$\chi^2_{\mathrm{dof}} = 1.69$$

Naive TMD approach

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

$$F_{UU} = \sum_q e_q^2 \, f_{q/p}(x_B) \, D_{h/q}(z_h) \frac{e^{-P_T^2/\langle P_T^2 \rangle}}{\pi \langle P_T^2 \rangle}$$

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



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

Fit over 6000 data points with 2 free parameters

$$N_y = A + B\, y$$

"The point-to-point systematic uncertainty in the measured multiplicities as a function of p_T^2 is estimated to be 5% of the measured value. The systematic uncertainty in the overall normalization of the p_T^2-integrated multiplicities depends on z and y and can be as large as 40%".

Erratum Eur.Phys.J. C75 (2015) 2, 94

Extracting the unpolarized TMD Gaussian widths from SIDIS multiplicities: flavour dependence

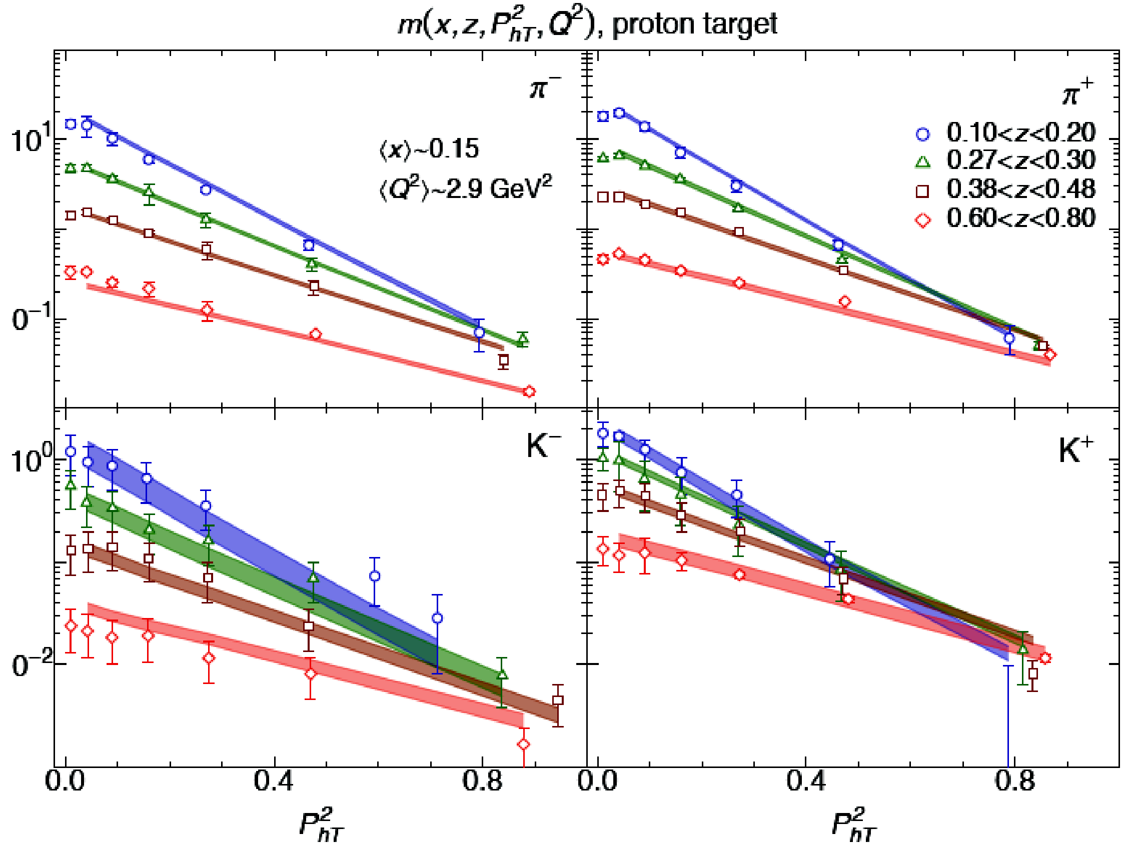
A. Signori, A. Bacchetta, M. Radici, G. Schnell, JHEP 1311 (2013) 194

proton target global χ^2 / d.o.f. = 1.63 ± 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



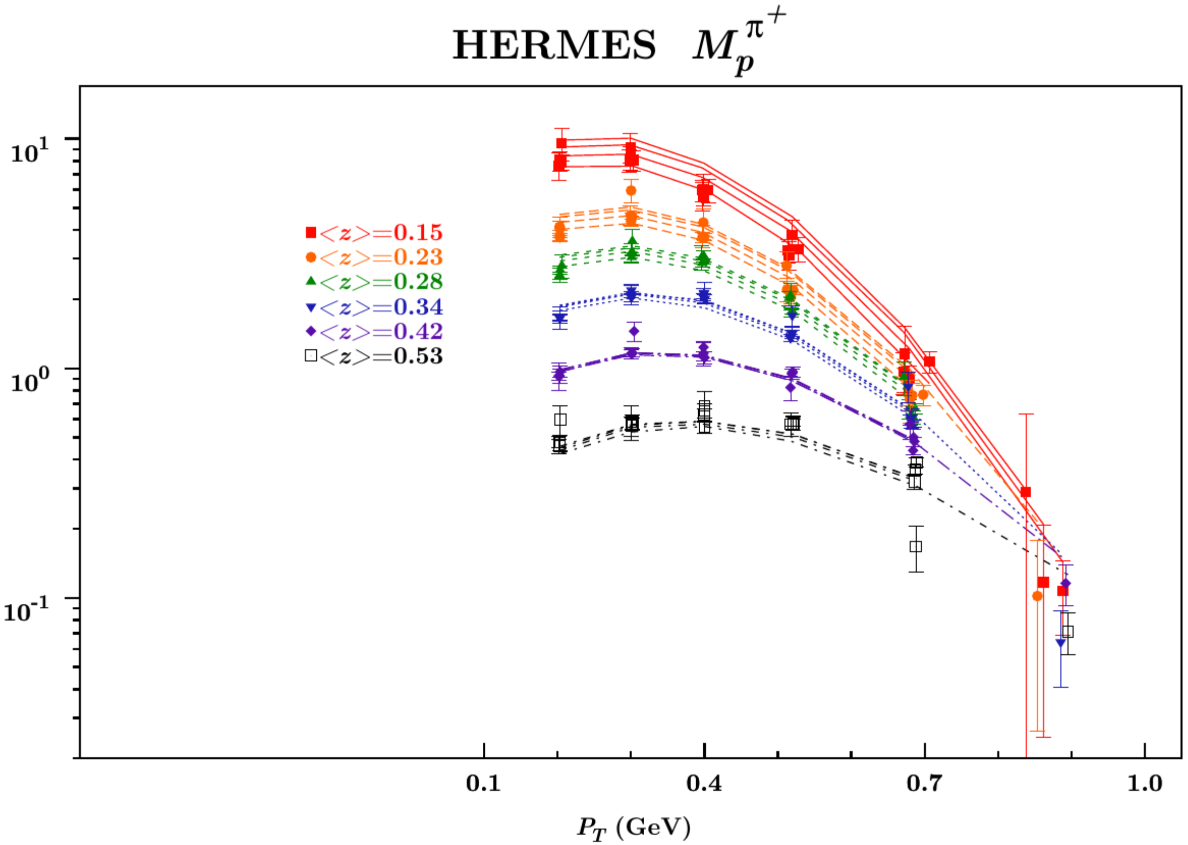
π^+
2.64 ± 0.21
2.89 ± 0.23

K^+
0.46 ± 0.07
0.43 ± 0.07

Q^2 dependence of HERMES data...

$$F_{UU} = \sum_q e_q^2\, f_{q/p}(x_B)\, D_{h/q}(z_h) \frac{e^{-P_T^2/\langle P_T^2\rangle}}{\pi \langle P_T^2\rangle}$$

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



Anselmino et al. JHEP 1404 (2014) 005

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

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

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

All four bins have been overlapped in the same panel

Hard to decouple the Q^2 dependence from HERMES data alone

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.

Resummation of large logarithms

- To ensure momentum conservation, write the cross section in the Fourier conjugate space

$$\delta^2(\boldsymbol{q}_T - \boldsymbol{k}_{1T} - \boldsymbol{k}_{2T} - \ldots\ldots - \boldsymbol{k}_{nT} + \ldots) = \int \frac{d^2\boldsymbol{b}_T}{(2\pi)^2} e^{-i\boldsymbol{b}_T\cdot(\boldsymbol{q}_T - \boldsymbol{k}_{1T} - \boldsymbol{k}_{2T} - \ldots\ldots - \boldsymbol{k}_{nT} + \ldots)}$$

$$\boxed{\frac{1}{\sigma_0}\frac{d\sigma}{dQ^2 dy dq_T^2} = \left[\int \frac{d^2\boldsymbol{b}_T e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T}}{(2\pi)^2} X_{div}(b_T)\right] + Y_{reg}(q_T)}$$

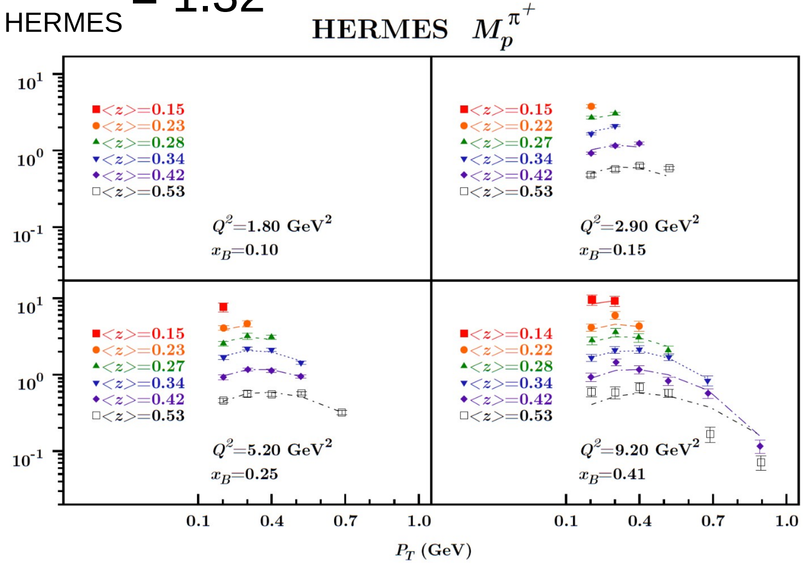
$$X_{div}(b_T) \longrightarrow W(b_T) = \exp\left[S(b_T)\right] \times (\text{PDFs and Hard coefficients})$$

$$\boxed{\frac{d\sigma^{total}}{dx\,dy\,dz\,dq_T^2} = \pi\sigma_0^{DIS}\int \frac{d^2\boldsymbol{b}_T e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T}}{(2\pi)^2} \underbrace{W^{SIDIS}(x,z,b_T,Q)}_{\text{Resummed part}} + \underbrace{Y^{SIDIS}(x,z,q_T,Q)}_{\text{Regular part}}}$$

Fit of HERMES and COMPASS data
Attempting "Resummation" in SIDIS ...

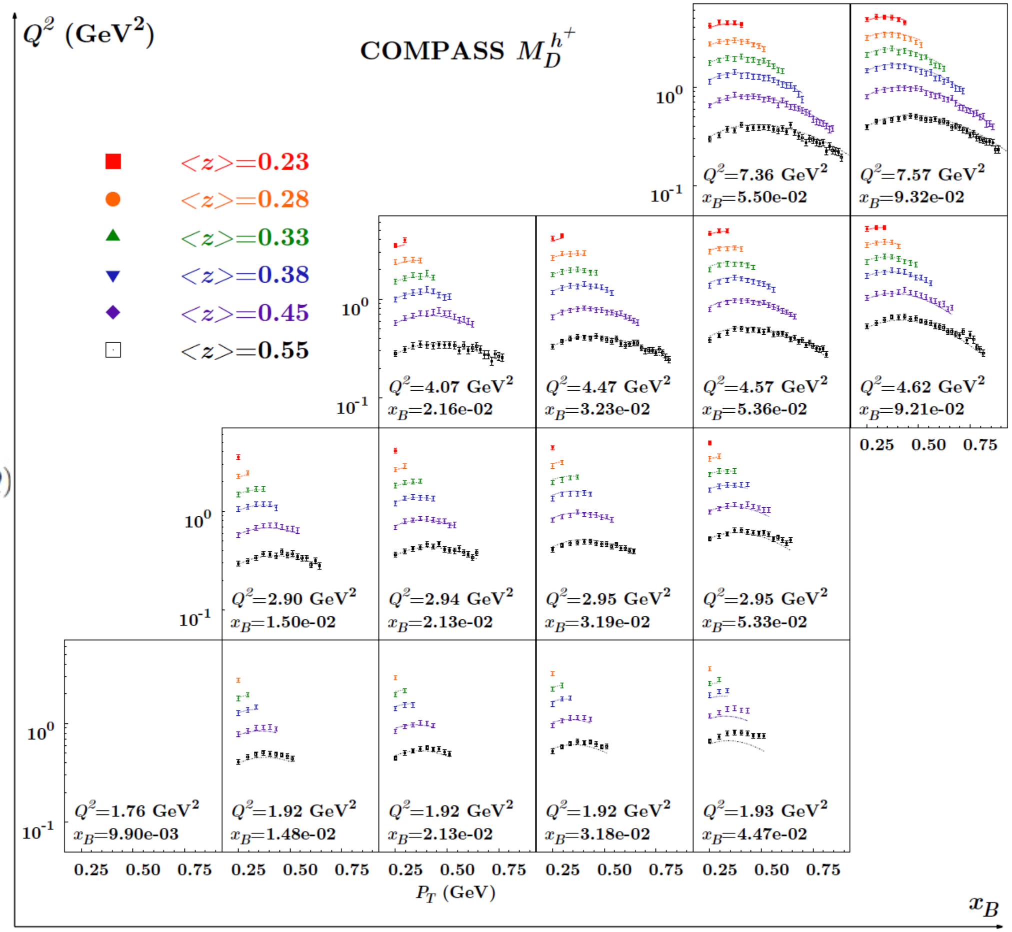
J. Osvaldo Gonzalez Hernandez, work in progress

$\chi^2_{\text{HERMES}} = 1.32$



$\chi^2_{\text{tot}} = 1.17$

$\chi^2_{\text{COMPASS}} = 1.12$



$$\frac{d\sigma}{dx\,dy\,dz\,dq_T^2} = \pi\sigma_0^{DIS}\left\{\int \frac{d^2\mathbf{b_T}e^{i\mathbf{q_T}\cdot\mathbf{b_T}}}{(2\pi)^2} W^{SIDIS}(x,z,b_*,Q,C_1,C_2,C_3)F_{NP}^{SIDIS}(x,z,b_T,Q) \cancel{+Y^{SIDIS}(x,z,q_T,Q,C_4)}\right\},$$

Y-term is neglected

$$F_{NP}^{SIDIS}(x,z,Q) = \exp\left\{\left[-\frac{g_1+g_{1f}/z^2}{2} - g_2\ln(Q/(2Q_0)) - g_1 g_3\ln(10x)\right] b_T^2\right\}$$

N ~ 2 (One overall normalization parameter is required)
g1 ~ 0.5 (too large compared to the value extracted from DY data)
g2 ~ 0.5
g3 ~ - 0.03

Global fits

A. Bacchetta, F. Delcarro, C. Pisano, M. Radici, A. Signori, JHEP06 (2017) 081

Extraction of partonic transverse momentum distributions from semi-inclusive deep-inelastic scattering, Drell-Yan and Z-boson production

Alessandro Bacchetta,[a,b] Filippo Delcarro,[a,b] Cristian Pisano,[a,b] Marco Radici[b] and Andrea Signori[c]

[a] *Dipartimento di Fisica, Università di Pavia, via Bassi 6, I-27100 Pavia, Italy*
[b] *INFN Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy*
[c] *Theory Center, Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, VA 23606, U.S.A.*
E-mail: alessandro.bacchetta@unipv.it, filippo.delcarro@pv.infn.it, cristian.pisano@unipv.it, marco.radici@pv.infn.it, asignori@jlab.org

JHEP06(2017)081

Abstract: We present an extraction of unpolarized partonic transverse momentum distributions (TMDs) from a simultaneous fit of available data measured in semi-inclusive deep-inelastic scattering, Drell-Yan and Z boson production. To connect data at different scales, we use TMD evolution at next-to-leading logarithmic accuracy. The analysis is restricted to the low-transverse-momentum region, with no matching to fixed-order calculations at high transverse momentum. We introduce specific choices to deal with TMD evolution at low scales, of the order of 1 GeV^2. This could be considered as a first attempt at a global fit of TMDs.

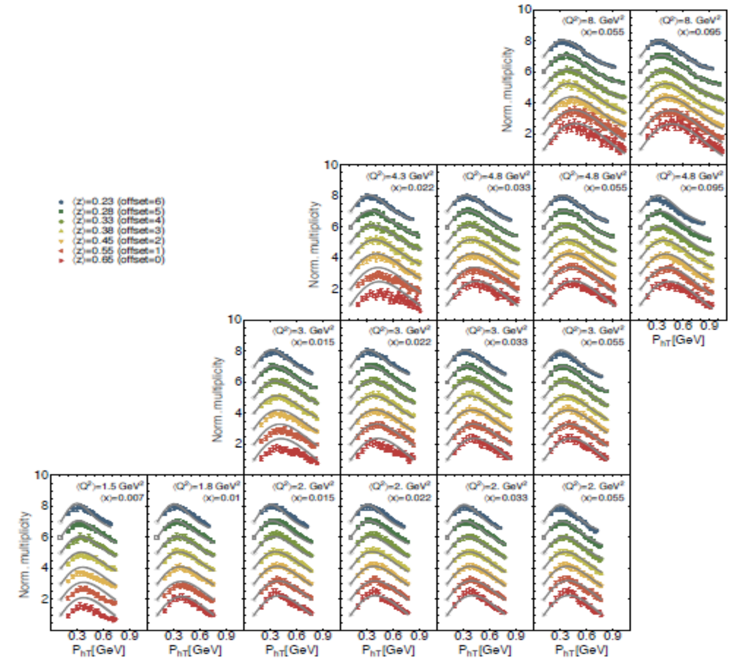


Figure 5. COMPASS multiplicities for production of negative hadrons (π^-) off a deuteron for different $\langle x \rangle$, $\langle z \rangle$, and $\langle Q^2 \rangle$ bins as a function of the transverse momentum of the detected hadron P_{hT}. Multiplicities are normalized to the first bin in P_{hT} for each $\langle z \rangle$ value (see (3.1)). For clarity, each $\langle z \rangle$ bin has been shifted by an offset indicated in the legend.

$$\chi^2_{tot} = 1.55$$

- Y-term is neglected
- Sum of two Gaussian k_T distributions is introduced

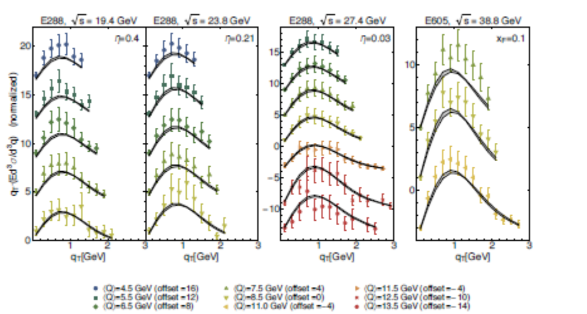


Figure 7. Drell-Yan differential cross section for different experiments and different values of $\sqrt{s}$ and for different $\langle Q \rangle$ bins. For clarity, each $\langle Q \rangle$ bin has been normalized (the first data point has been set always equal to 1) and then shifted by an offset indicated in the legend.

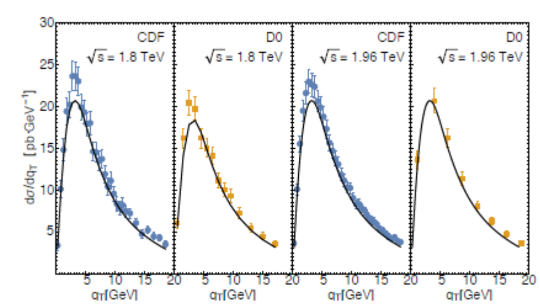
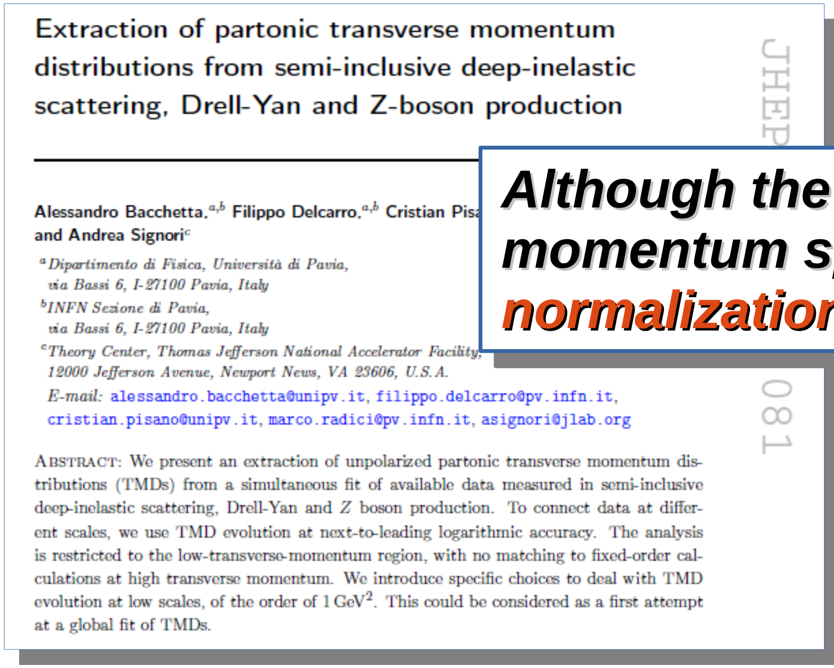


Figure 8. Cross section differential with respect to the transverse momentum q_T of a Z boson produced from $p\bar{p}$ collisions at Tevatron. The four panels refer to different experiments (CDF and D0) with two different values for the center-of-mass energy ($\sqrt{s}$ = 1.8 TeV and $\sqrt{s}$ = 1.96 TeV). In this case the band is narrow due to the narrow range for the best-fit values of g_2.

Global fits

A. Bacchetta, F. Delcarro, C. Pisano, M. Radici, A. Signori, JHEP06 (2017) 081



Extraction of partonic transverse momentum distributions from semi-inclusive deep-inelastic scattering, Drell-Yan and Z-boson production

Alessandro Bacchetta,[a,b] Filippo Delcarro,[a,b] Cristian Pisa[…]
and Andrea Signori[c]
[a]Dipartimento di Fisica, Università di Pavia, via Bassi 6, I-27100 Pavia, Italy
[b]INFN Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy
[c]Theory Center, Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, VA 23606, U.S.A.
E-mail: alessandro.bacchetta@unipv.it, filippo.delcarro@pv.infn.it, cristian.pisano@unipv.it, marco.radici@pv.infn.it, asignori@jlab.org

Abstract: We present an extraction of unpolarized partonic transverse momentum distributions (TMDs) from a simultaneous fit of available data measured in semi-inclusive deep-inelastic scattering, Drell-Yan and Z boson production. To connect data at different scales, we use TMD evolution at next-to-leading logarithmic accuracy. The analysis is restricted to the low-transverse-momentum region, with no matching to fixed-order calculations at high transverse momentum. We introduce specific choices to deal with TMD evolution at low scales, of the order of 1 GeV^2. This could be considered as a first attempt at a global fit of TMDs.

JHEP06(2017)081

Although the shape in transverse momentum space is well described, normalization is very problematic

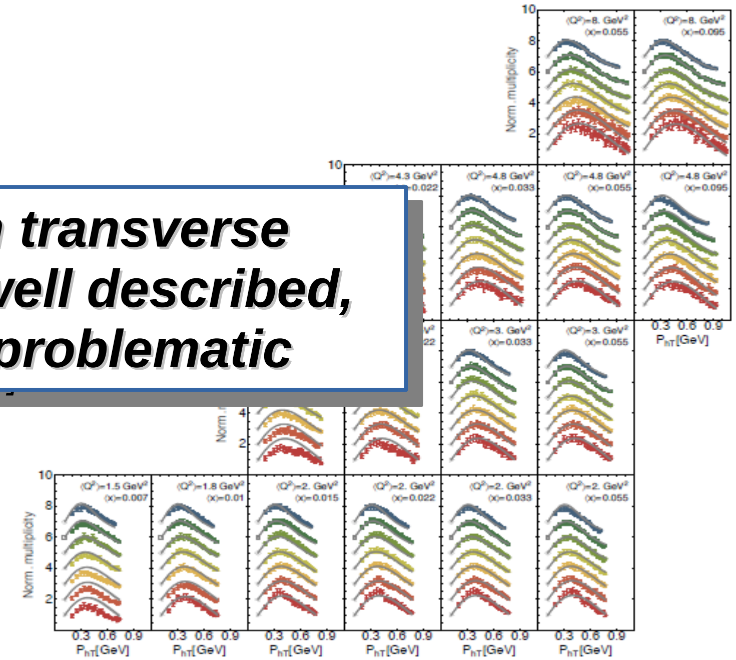


Figure 5. COMPASS multiplicities for production of negative hadrons (π^-) off a deuteron for different $\langle x \rangle$, $\langle z \rangle$, and $\langle Q^2 \rangle$ bins as a function of the transverse momentum of the detected hadron P_{hT}. Multiplicities are normalized to the first bin in P_{hT} for each $\langle z \rangle$ value (see (3.1)). For clarity, each $\langle z \rangle$ bin has been shifted by an offset indicated in the legend.

$$\chi^2_{tot} = 1.55$$

- Y-term is neglected
- Sum of two Gaussian k_T distributions is introduced

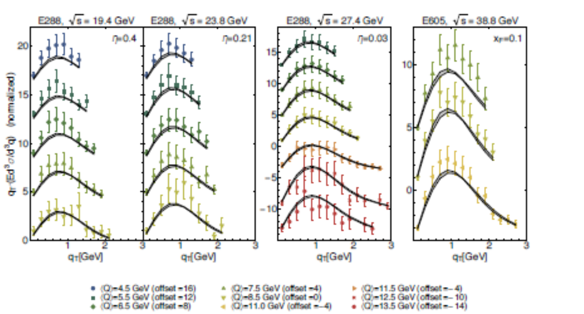


Figure 7. Drell-Yan differential cross section for different experiments and different values of $\sqrt{s}$ and for different $\langle Q \rangle$ bins. For clarity, each $\langle Q \rangle$ bin has been normalized (the first data point has been set always equal to 1) and then shifted by an offset indicated in the legend.

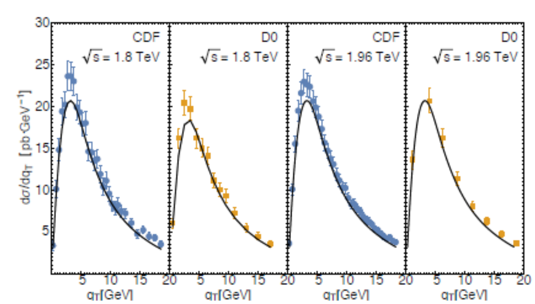
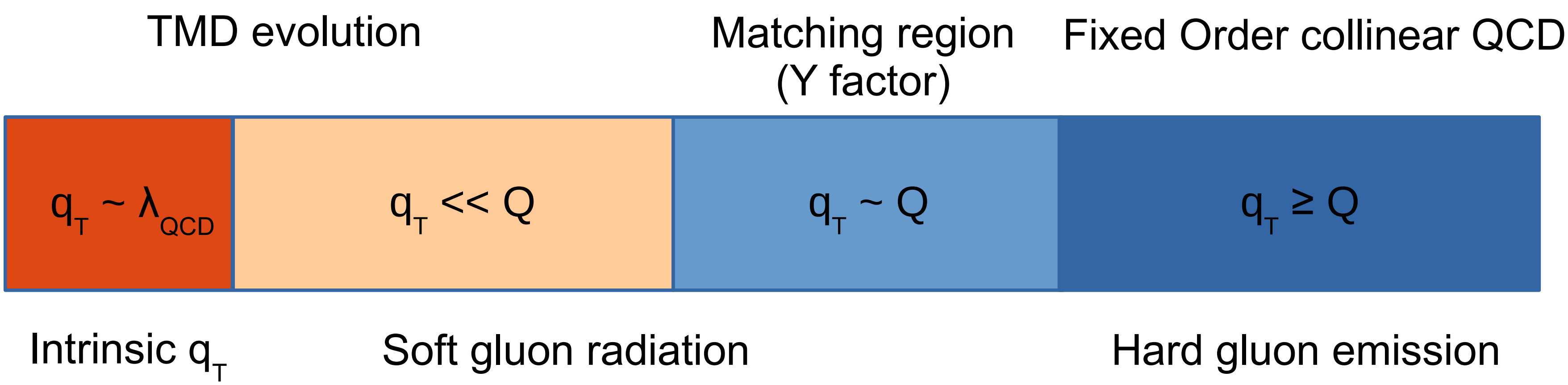


Figure 8. Cross section differential with respect to the transverse momentum q_T of a Z boson produced from $p\bar{p}$ collisions at Tevatron. The four panels refer to different experiments (CDF and D0) with two different values for the center-of-mass energy ($\sqrt{s} = 1.8$ TeV and $\sqrt{s} = 1.96$ TeV). In this case the band is narrow due to the narrow range for the best-fit values of g_2.

What's going on ???

TMD regions

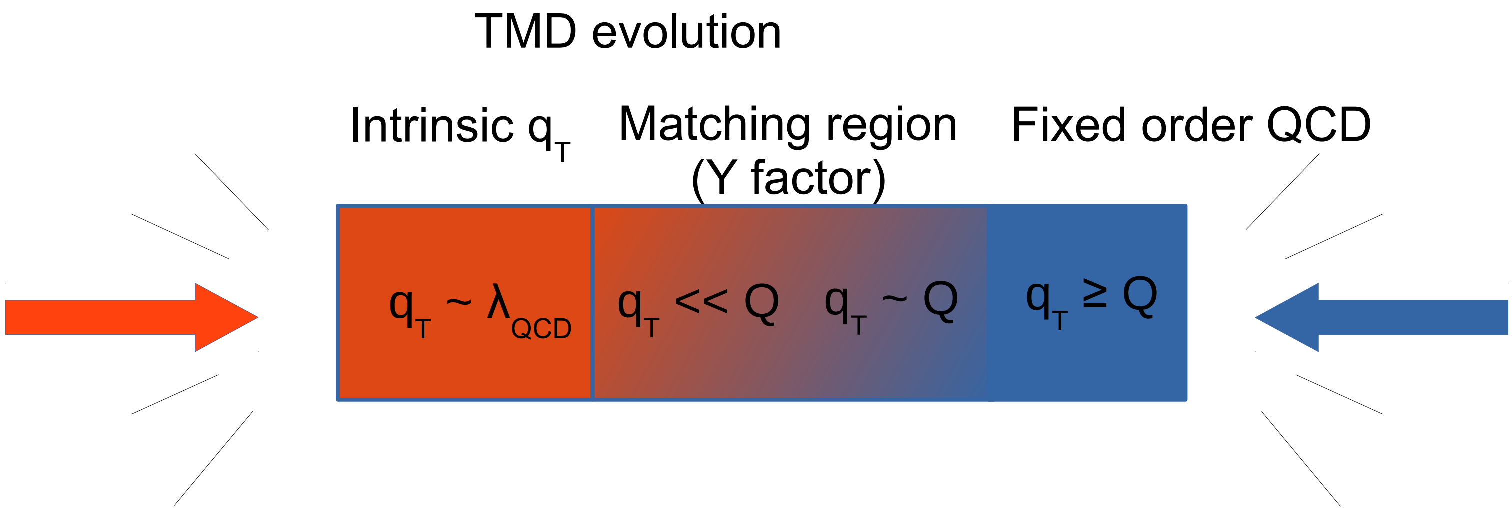
- For this scheme to work, 4 distinct kinematic regions have to be identified
- They should be large enough and well separated



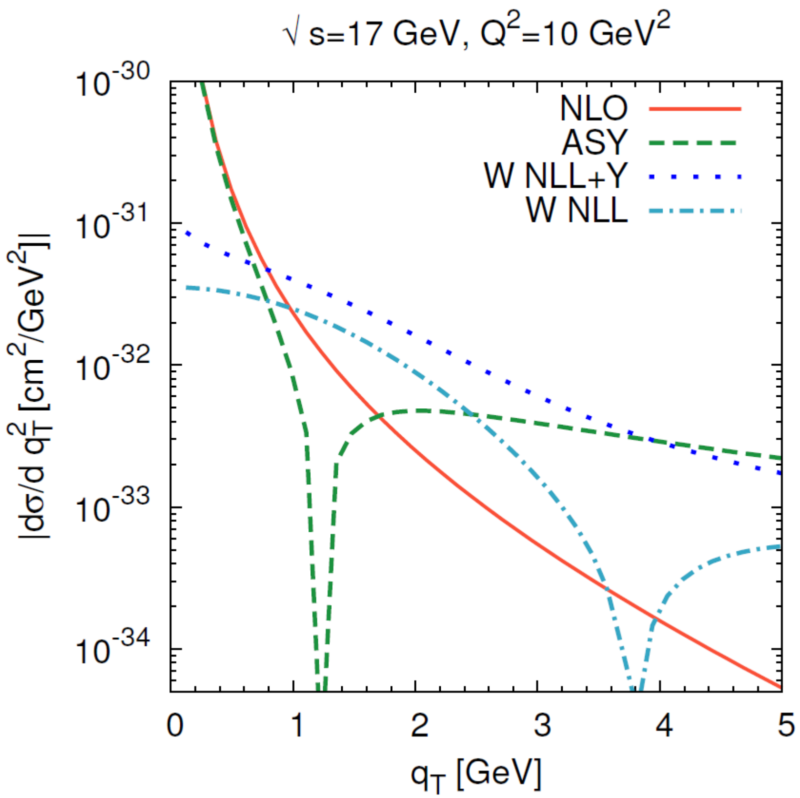
TMD regions

- For this scheme to work, 4 distinct ki … have to be identified
- They should be large … separated

Does not work in SIDIS !



SIDIS - Y factor



- The Y factor is very large (even at low q_T)
- However, it could be affected by large theoretical uncertainties

Boglione, Gonzalez, Melis, Prokudin, JHEP 02 (2015) 095

The Y factor cannot be neglected !!!

- New prescription for Y factor, b* and W

Collins, Gamberg, Prokudin, Rogers, Sato, Wang, Phys. Rev. D 94 (2016) 034014

$$\boxed{\frac{d\sigma^{\rm NLO}}{dx\,dy\,dz\,dq_T^2} = \frac{d\sigma^{\rm ASY}}{dx\,dy\,dz\,dq_T^2} + Y}$$

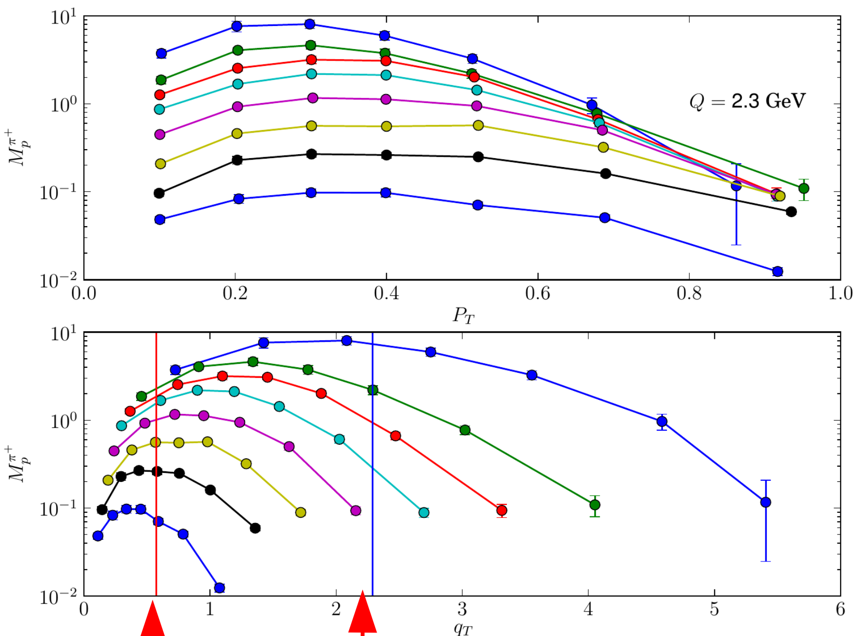
$\sigma^{ASY} = Q^2/q_T^{\ 2}$ [A $\ln(Q^2/q_T^{\ 2})$ + B + C]

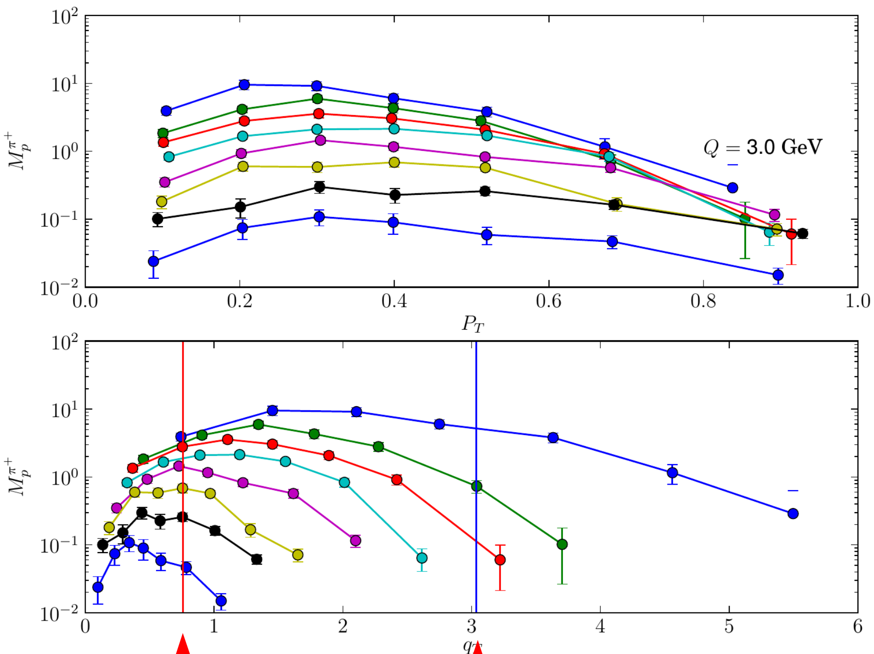
Other issues related to TMD regions ...

- TMD regions are defined in terms of q_T and not in terms of P_T

P_T

$q_T = P_T / z$

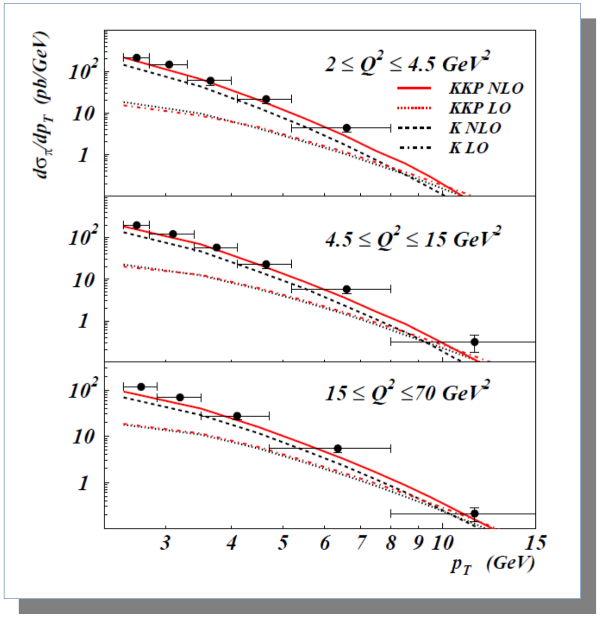




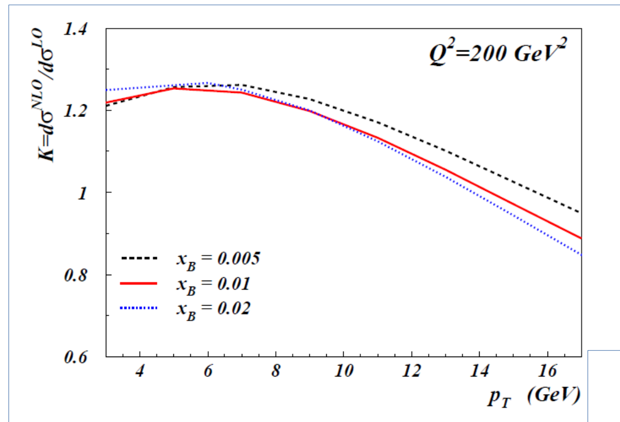
$q_T = Q/4$ $q_T = Q$

$q_T = Q/4$ $q_T = Q$

Normalization and K factor

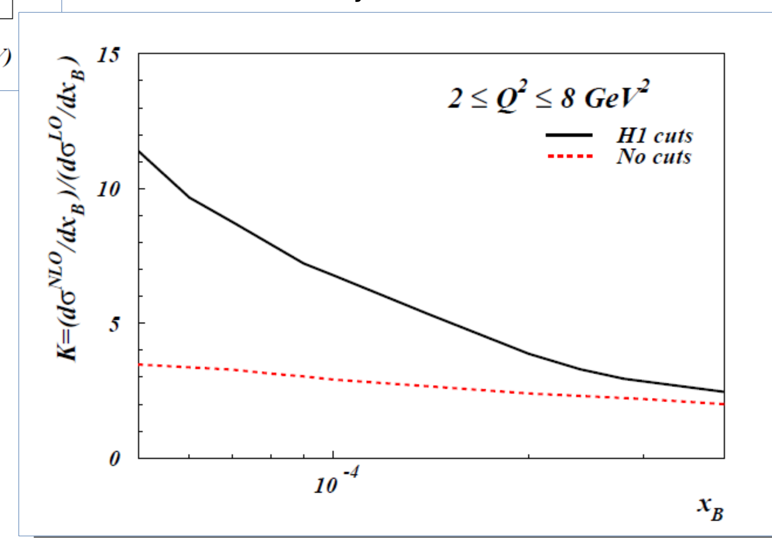


How can we address the normalization problem ???



- K factor depends on p_T
- Kinematics cuts can affect the size of K factors … up to a factor 10 !

Stringent cuts on the pion production angle in H1 data suppresses LO and NLO contributions in a different way



Daleo, De Florian, Sassot, Phys.Rev. D71 (2005) 034013

Daleo, De Florian, Sassot, Braz.J.Phys. 37 (2007) 585-590

Aktas et al., H1 Collaboration, Eur. Phys. J. C36 (2004) 441

"The rather large size of the K-factor can be understood as a consequence of the opening of a new dominant ('leading-order') channel, and not to the 'genuine' increase in the partonic cross section [...]. The dominance of the new channel is due to the size of the gluon distribution at small x_B and to the fact that the H1 selection cuts highlight the kinematical region dominated by the $\gamma + g \to g + q + \bar{q}$ partonic process. In particular, without the experimental cuts for the final state hadrons, the gg component represents less than 25% of the total NLO contribution at small x_B."

Daleo, De Florian, Sassot, Phys.Rev. D71 (2005) 034013

Daleo, De Florian, Sassot, Braz.J.Phys. 37 (2007) 585-590

Large transverse momentum behaviour in SIDIS

J.O. Gonzalez-Hernandez, T.C. Rogers, N. Sato, B. Wang, arXiv:1808.04396

Challenges with Large Transverse Momentum in Semi-Inclusive Deeply Inelastic Scattering

J. O. Gonzalez-Hernandez,[1,2,3,*] T. C. Rogers,[1,4,†] N. Sato,[4,‡] and B. Wang[1,4,5,§]

[1] *Department of Physics, Old Dominion University, Norfolk, VA 23529, USA*
[2] *Dipartimento di Fisica, Università di Torino, Via P. Giuria 1, 10125 Torino, Italy*
[3] *INFN-Sezione Torino, Via P. Giuria 1, 10125 Torino, Italy*
[4] *Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606, USA*
[5] *Zhejiang Institute of Modern Physics, Department of Physics, Zhejiang University, Hangzhou 310027, China*

(Dated: 13 August 2018)

We survey the current phenomenological status of semi-inclusive deep inelastic scattering at moderate hard scales and in the limit of very large transverse momentum. As the transverse momentum becomes comparable to or larger than the overall hard scale, the differential cross sections should be calculable with fixed order pQCD methods, while small transverse momentum (TMD factorization) approximations should eventually break down. We find large disagreement between HERMES and COMPASS data and fixed order calculations done with modern parton densities, even in regions of kinematics where such calculations should be expected to be very accurate. Possible interpretations are suggested.

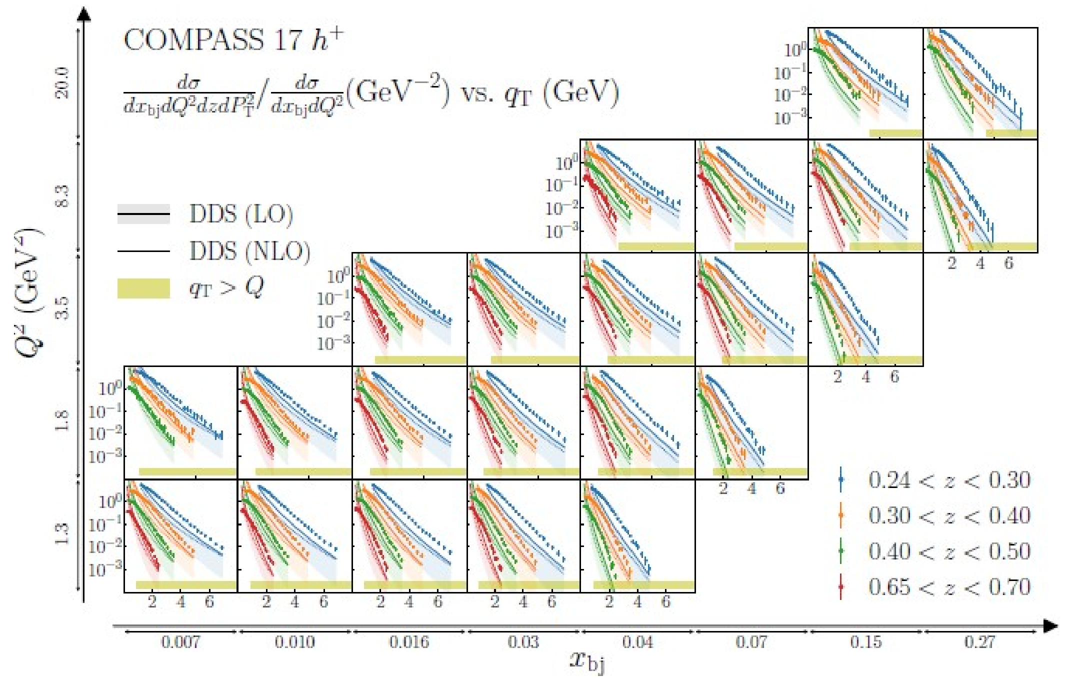


FIG. 4. Calculation of $O(\alpha_s)$ and $O(\alpha_s^2)$ transversely differential multiplicity using code from [22], shown as the curves labeled DDS. The bar at the bottom marks the region where $q_T > Q$. The PDF set used is CJNLO [25] and the FFs are from [26]. Scale dependence is estimated using $\mu = ((\zeta_Q Q)^2 + (\zeta_{q_T} q_T)^2)^{1/2}$ where the band is constructed point-by-point in q_T by taking the min and max of the cross section evaluated across the grid $\zeta_Q \times \zeta_{q_T} = [1/2, 1, 3/2, 2] \times [0, 1/2, 1, 3/2, 2]$ except $\zeta_Q = \zeta_{q_T} = 0$. The red band is generated with $\zeta_Q = 1$ and $\zeta_{q_T} = 0$. A lower bound of 1 GeV is place on μ when $Q/2$ would be less than 1 GeV.

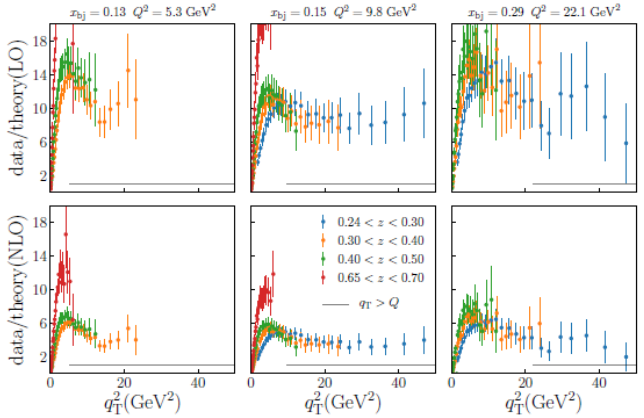


FIG. 5. Ratio of data to theory for several near-valence region panels in Fig. 4. The grey bar at the bottom is at 1 on the vertical axis and marks the region where $q_T > Q$.

There are large discrepancies between data and fixed order calculations. They seem to be generated by collinear PDFs and FFs

Summary

- Naive TMD Models can describe HERMES and COMPASS data at low transverse momentum

- Similarly to DY, the Q^2 dependence is not clearly visible in the shape of the spectrum

- TMD resummation is difficult
  - no information on unpolarized TMD fragmentation functions
  - global fitting is affected by normalization issues
  - Y-term is not included
  - the non-perturbative behaviour seems to be dominant
  - difficult to work in b_T space where we loose phenomenological intuition

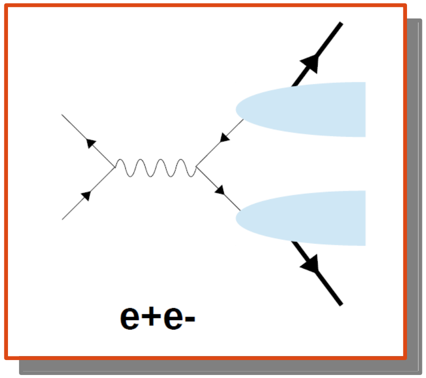
- Fixed order calculation fail to reproduce the correct behaviour of the cross section at large transverse momentum

- Need an extra effort to devise theories/models/prescriptions which simultaneously explain experimental data from different experiments, over a wide range of transverse momentum values

- Need new, high-precision experimental data to be able to perform solid and realistic phenomenological analyses of TMD physics (**EIC** !)

Extracting the unpolarized TMD fragmentation function from e^+e^- data

e^+e^- scattering processes



- Recent data on Collins azimuthal asymmetries from BELLE, BaBar and BES III
- No modern data available (yet) on unpolarized cross sections

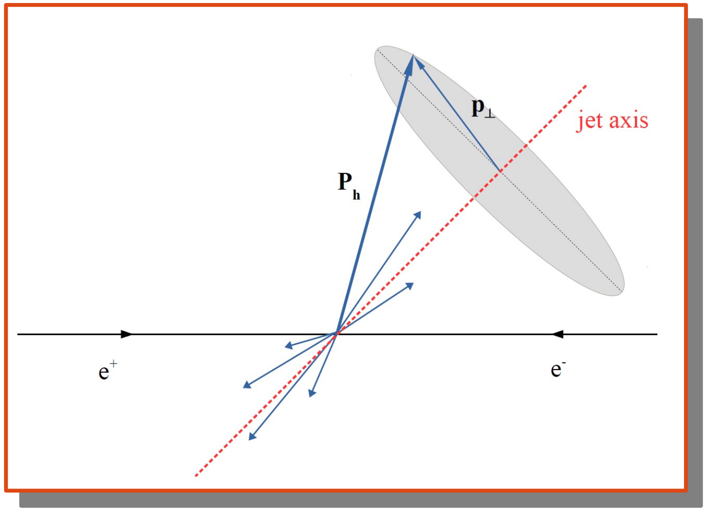
TASSO, MARKII data available for unpolarized $e^+e^- \to h\ X$

- p_T distributions
- Different energies

TMD evolution

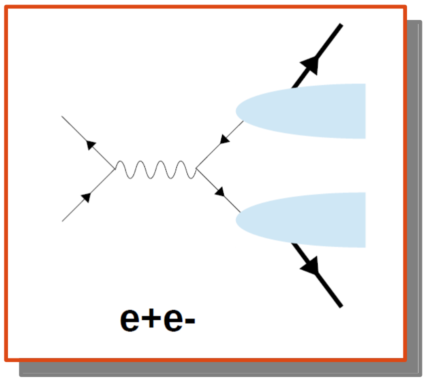
- Integrated over z
- No charge separation

Big limitation

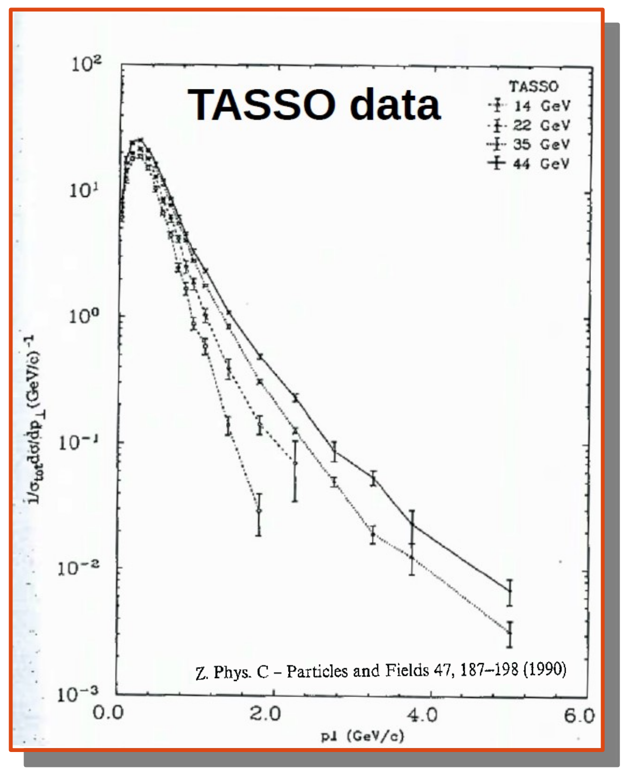


- Direct observation of the hadron momentum component, transverse to the fragmenting parent parton (jet axis)

e^+e^- scattering processes



- Recent data on Collins azimuthal asymmetries from BELLE, BaBar and BES III
- No modern data available (yet) on unpolarized cross sections



TASSO, MARKII data available for unpolarized $e^+e^- \to h\, X$

- p_T distributions
- Different energies

TMD evolution

- Integrated over z
- No charge separation

Big limitation

- Direct observation of the hadron momentum component, transverse to the fragmenting parent parton (jet axis)

Modeling the cross section

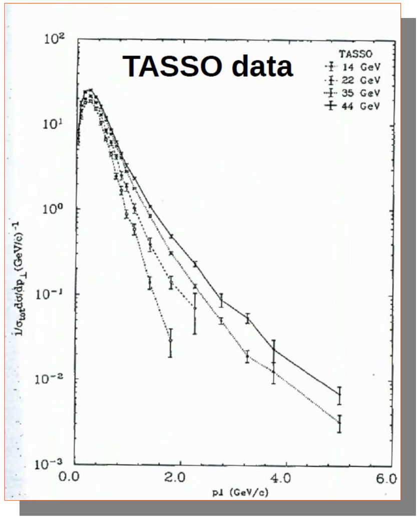
Boglione, Gonzalez-Hernandez, Taghavi, Phys. Lett. B772 (2017) 78-86

Assuming factorization ...

$$\left.\frac{d\sigma^h}{dz\,d^2\boldsymbol{p}_\perp}\right|_{model} = \frac{4\pi\alpha^2}{3s}\sum_q e_q{}^2\, D_q^h(z,\,p_\perp;\,Q^2)$$

$$= \frac{4\pi\alpha^2}{3s}\sum_q e_q{}^2\, D_q^h(z,\,Q^2)\,h(p_\perp)$$

To leading order



Use this ...

To get information about that ...

Issues to investigate:

- Appropriate functional form for $g_{j/p}$
- Scale evolution induced by g_k

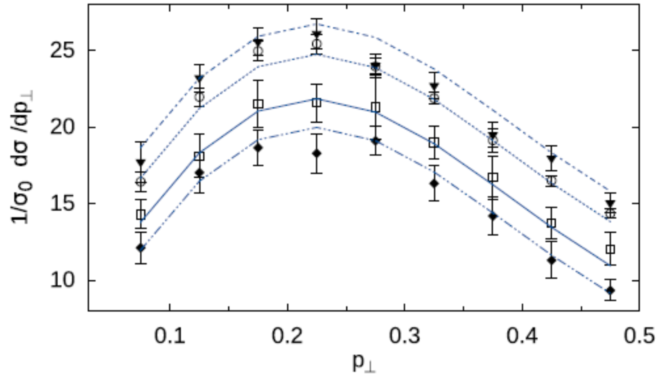
$$\tilde{D}_{h/q}(z,\boldsymbol{b}_\perp;Q) = \sum_i \left[\left(\tilde{C}_{j/q}\otimes\frac{d_{h/j}}{z^2}\right)e^{\Gamma_D(Q)}\right] \exp\left\{g_{j/P}(x,b_\perp) + g_K(b_\perp)\log\left(\frac{Q}{Q_0}\right)\right\}$$

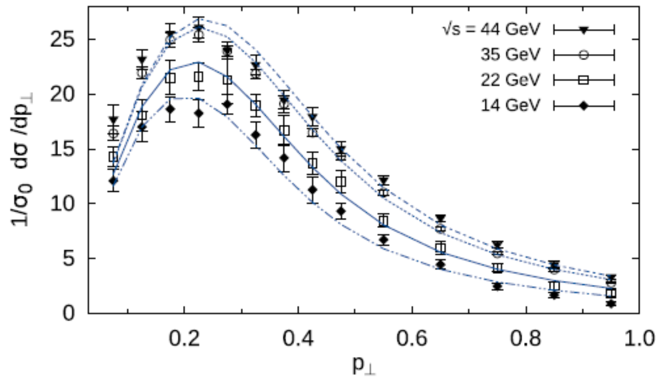
Modeling the $p_\perp$ dependence

Fit of TASSO data,
using **gaussian** $p_\perp$ dependence

1) $\left.\frac{1}{\sigma_0}\frac{d\sigma^h}{dp_\perp}\right|_{model} \longrightarrow \pi\, p_\perp N \left[\int dz \frac{\sum_q e_q^2 D_q^h(z;Q^2)}{\sum_q e_q^2}\right] h(p_\perp) + \delta\, Q$

Normalization problematic !





2) $\langle p_\perp^2 \rangle = 2\, g_1 + 2\, g_2\, z^2 \log\left(\frac{Q}{2\, Q_0}\right)$

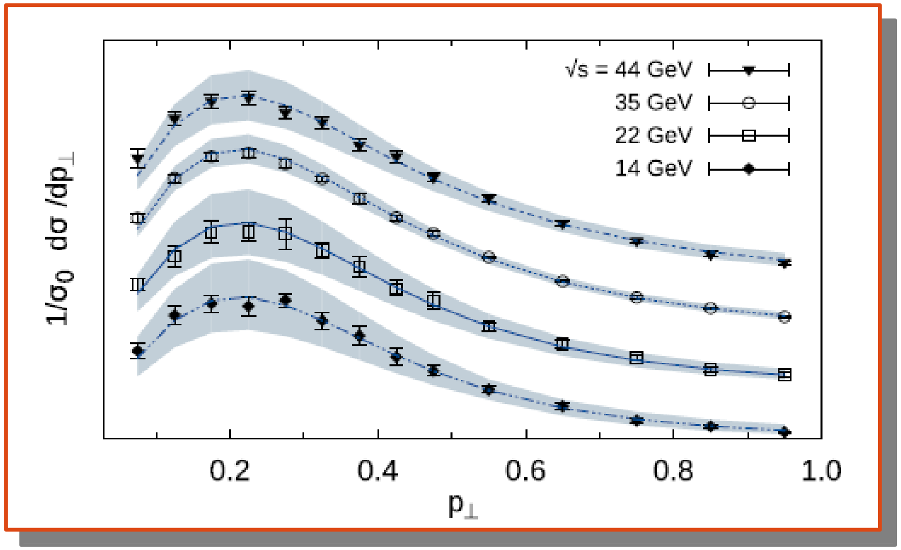
Tension between the shape of the peak and that of the tale

The lack of information about ***z*** hinders a full TMD extraction of the FF.

Fit of TASSO data,
using **power law** $p_\perp$ dependence

$$h(p_\perp) = 2(\alpha - 1) M^{2\,(\alpha-1)} \frac{1}{(p_\perp^2 + M^2)^\alpha}$$

1) α extracted separately for each √s value



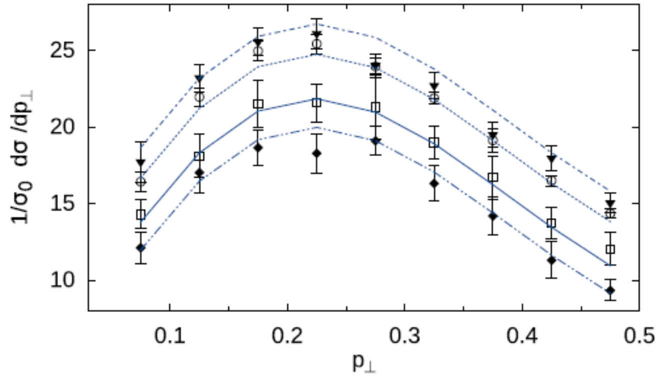
Boglione, Gonzalez-Hernandez, Taghavi,
Phys. Lett. B772 (2017) 78-86

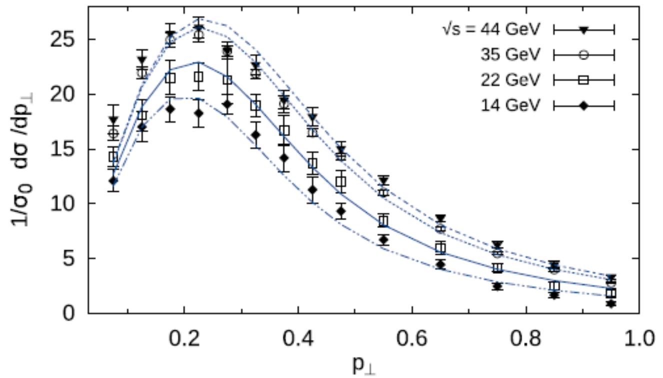
Modeling the $p_\perp$ dependence

Fit of TASSO data,
using **gaussian** $p_\perp$ dependence

$$\frac{1}{\sigma_0}\frac{d\sigma^h}{dp_\perp}\bigg|_{model} \longrightarrow \pi\, p_\perp N \left[\int dz \, \frac{\sum_q e_q^2\, D_q^h(z;Q^2)}{\sum_q e_q^2}\right] h(p_\perp) + \delta\, Q$$

Normalization
problematic





$$\langle p_\perp^2 \rangle = 2\, g_1 + 2\, g_2\, z^2 \log\left(\frac{Q}{2\, Q_0}\right)$$

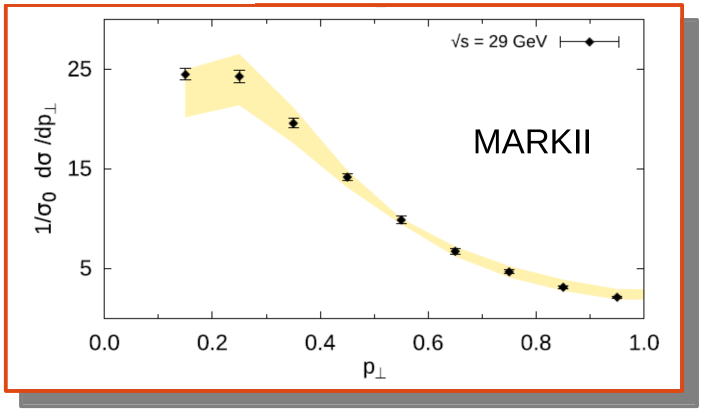
Tension between the shape of
the peak and that of the tale

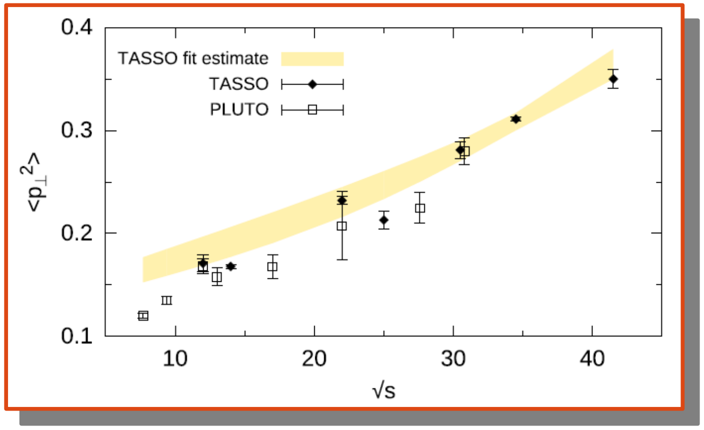
The lack of information about **z** hinders a full TMD extraction of the FF.

Fit of TASSO data,
using **power law** $p_\perp$ dependence

$$h(p_\perp) = 2(\alpha-1)M^{2\,(\alpha-1)}\,\frac{1}{\left(p_\perp^2 + M^2\right)^{\alpha}}$$

$$\alpha = \alpha_0 + \tilde{\alpha}\,\log\left(\frac{Q}{Q_0}\right)$$

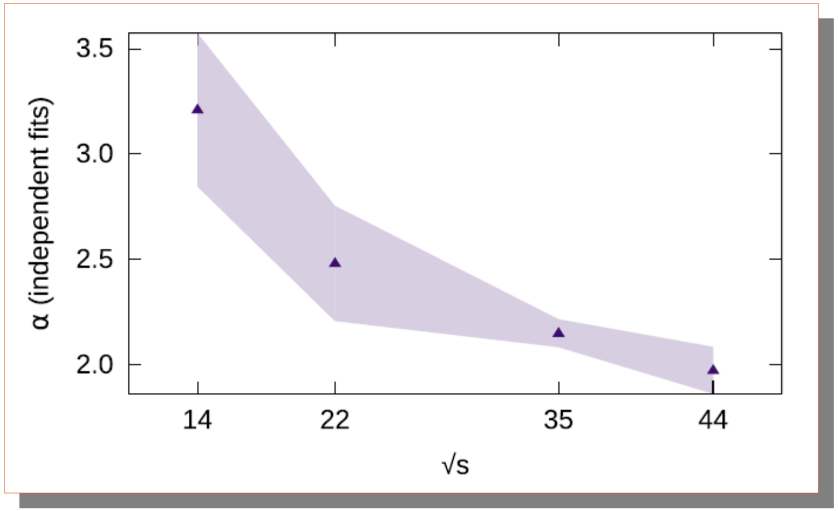




Interpreting our results ...

MODEL

$$h(p_\perp) = 2(\alpha - 1)\mathrm{M}^{2\,(\alpha-1)} \frac{1}{(p_\perp^2 + \mathrm{M}^2)^\alpha}$$



TMD scheme

(under the assumption that integration over z does not alter the structural form of the non perturbative exponential)

$$\mathcal{F}^{-1}\left\{\frac{d\sigma^h}{d^2\boldsymbol{p}_\perp}\right\} \propto \exp\left\{\tilde{g}(b_\perp)\log\left(\frac{Q}{Q_0}\right)\right\}$$

$$b_\perp^{\alpha_0}\,\exp\left\{\tilde{g}(b_\perp)\log\left(\frac{Q}{Q_0}\right)\right\} \propto b_\perp^{\alpha}$$

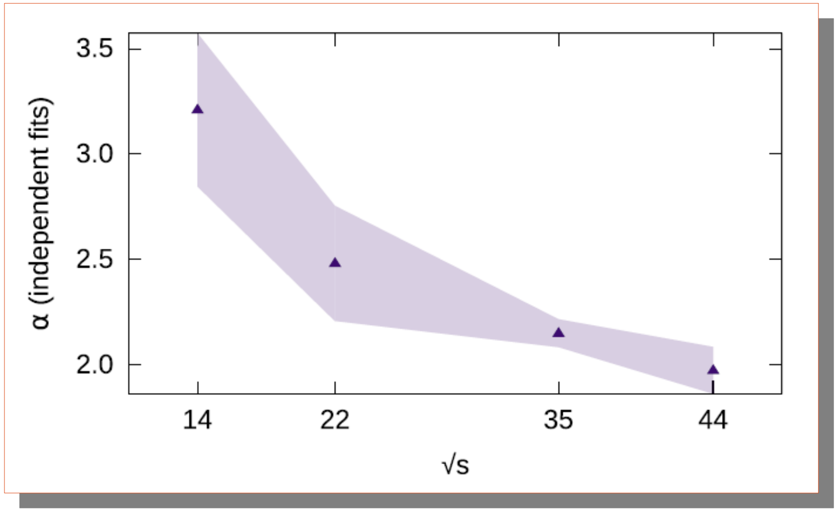
Logarithmic behavior of alpha may be interpreted as a consequence of the **Log** in the definition of the **TMD FF**.

$$\boxed{\begin{gathered} \alpha = \alpha_0 + \tilde{\alpha}\log\left(\frac{Q}{Q_0}\right) \\ g_K(b_\perp) \xrightarrow{\text{large } b_\perp} \tilde{\alpha}\log(\nu\, b_\perp) \end{gathered}}$$

Interpreting our results ...

MODEL

$$h(p_\perp) = 2(\alpha - 1)\mathrm{M}^{2\,(\alpha-1)} \frac{1}{\left(p_\perp^2 + \mathrm{M}^2\right)^\alpha}$$



TMD scheme

(under the assumption that integration over z does not alter the structural form of the non perturbative exponential)

There are caveats on this interpretation:

- it is consistent with theoretical expectations but it is not unique.
- Lack of information on z-dependence of the TMD FF in the TASSO and MARK II measurements (and possible correlations between Q and z of different origin) hinders a more solid conclusion about TMD evolution effects in these data sets.

Logarithmic behavior of alpha may be interpreted as a consequence of the **Log** in the definition of the **TMD FF**.

$$\alpha = \alpha_0 + \tilde{\alpha} \log\left(\frac{Q}{Q_0}\right)$$

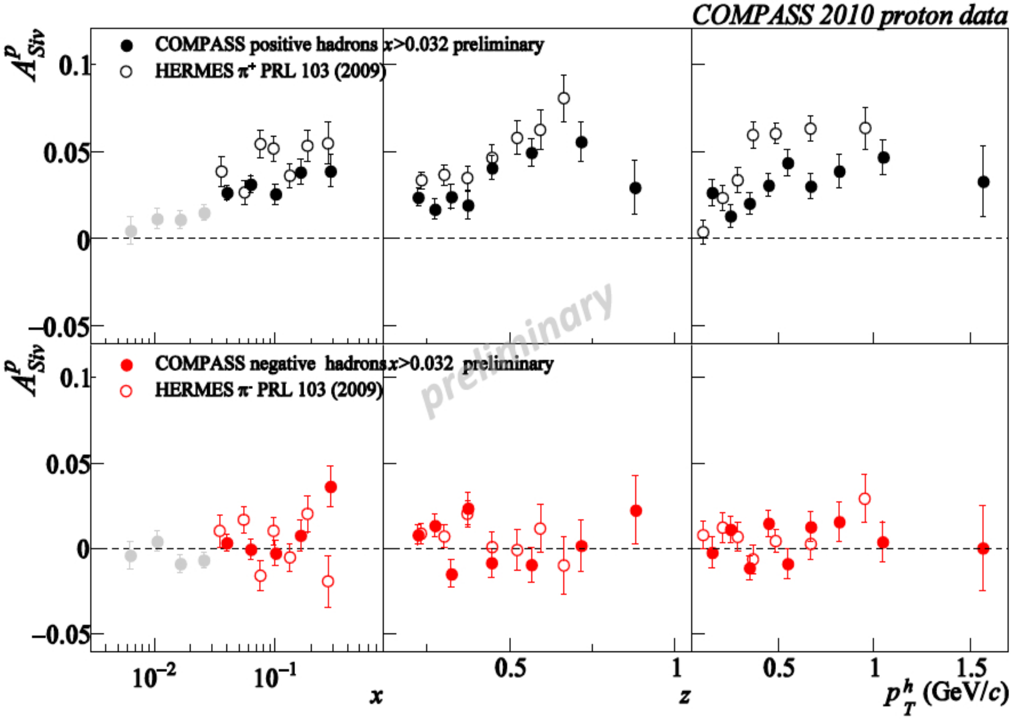
$$g_K(b_\perp) \xrightarrow{\text{large } b_\perp} \tilde{\alpha} \log(\nu\, b_\perp)$$

Extracting the Sivers function from SIDIS data

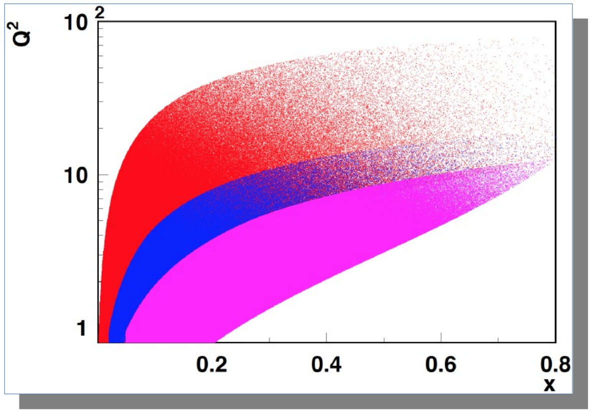
Sivers effect: COMPASS vs. HERMES

Boglione, Gonzalez, Flore, D'Alesio, JHEP 1807 (2018) 148

Apparently …
some tension between
COMPASS and HERMES data



However, COMPASS and HERMES span different ranges in Q^2 and have different $< Q^2 >$.



Kinematics effects
Possible signal of TMD evolution?

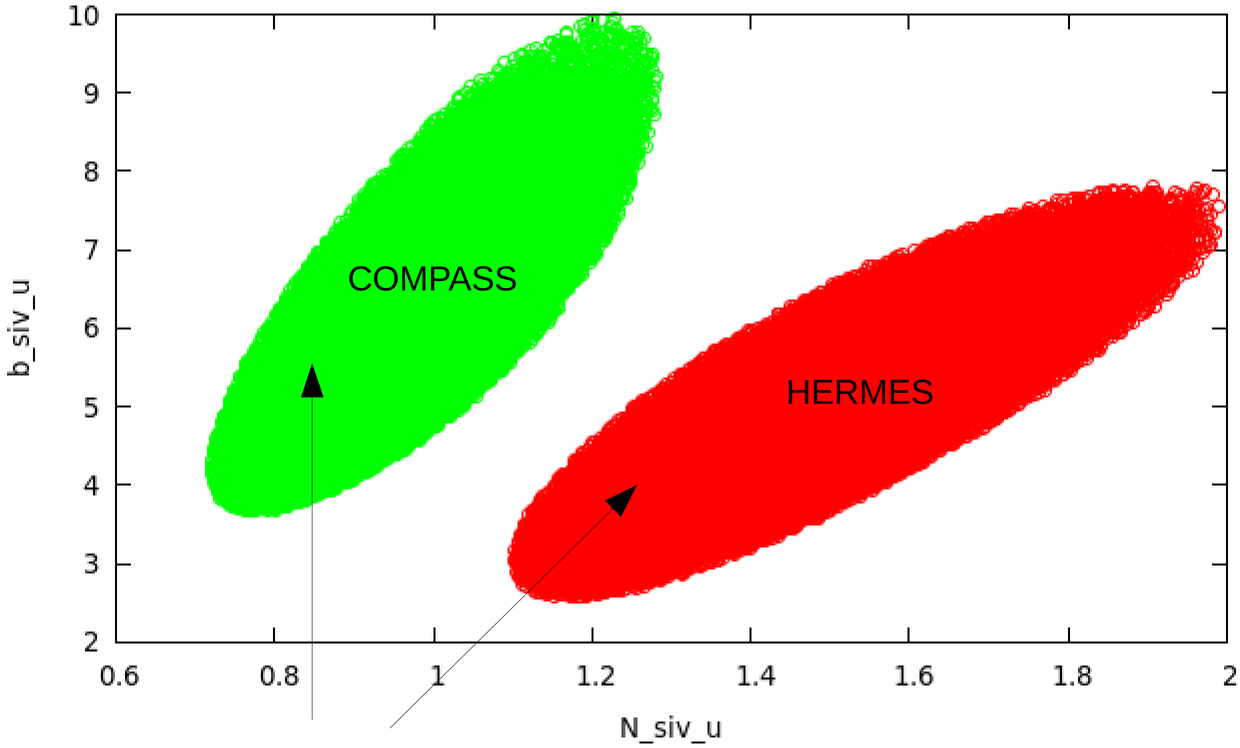
About unpolarized TMDs ...

Boglione, Gonzalez, Flore, D'Alesio, JHEP 1807 (2018) 148

Signal of some tension between independent fit solutions for COMPASS and HERMES data

Start by using a very simple model only 5 parameters and no Q evolution

Use only u flavour and only π+ data



Independent fits

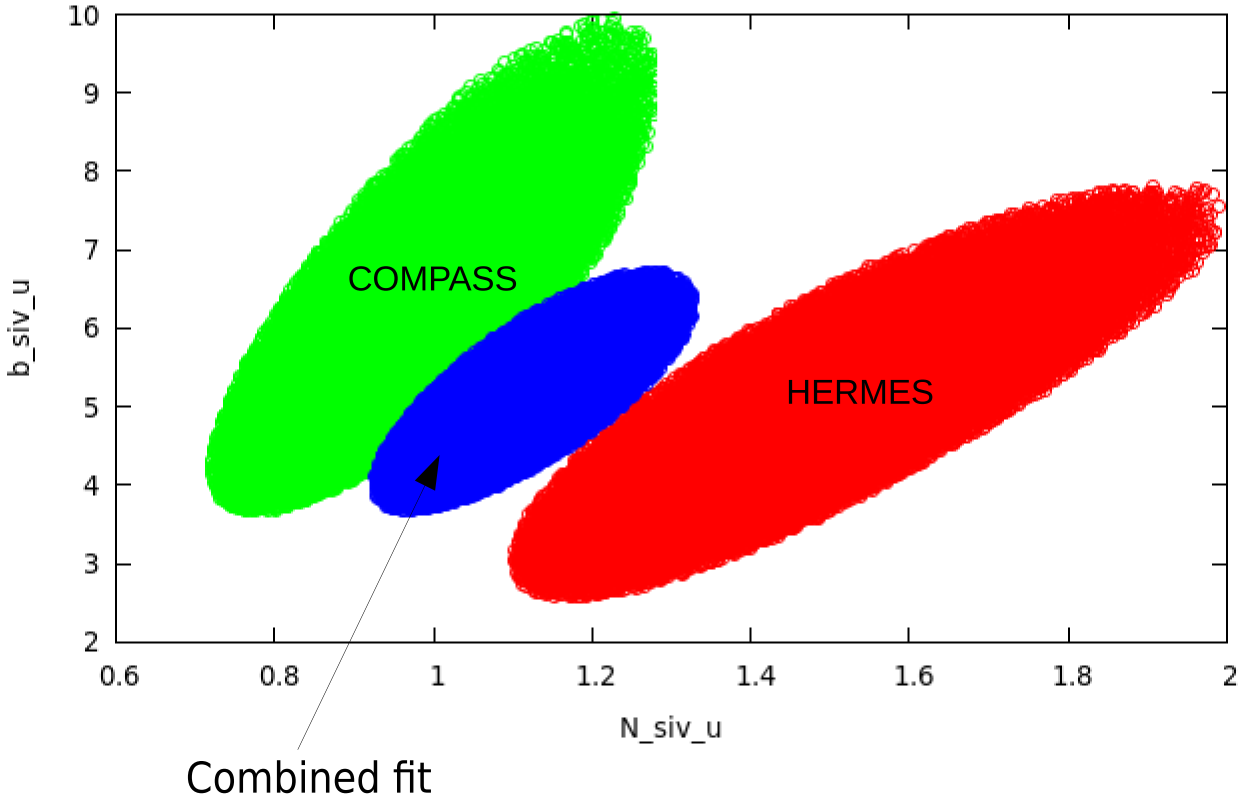
New extraction of the Sivers function

Boglione, Gonzalez, Flore, D'Alesio, JHEP 1807 (2018) 148

Signal of some tension between independent fit solutions for COMPASS and HERMES data

Start by using a very simple model only 5 parameters and no Q evolution

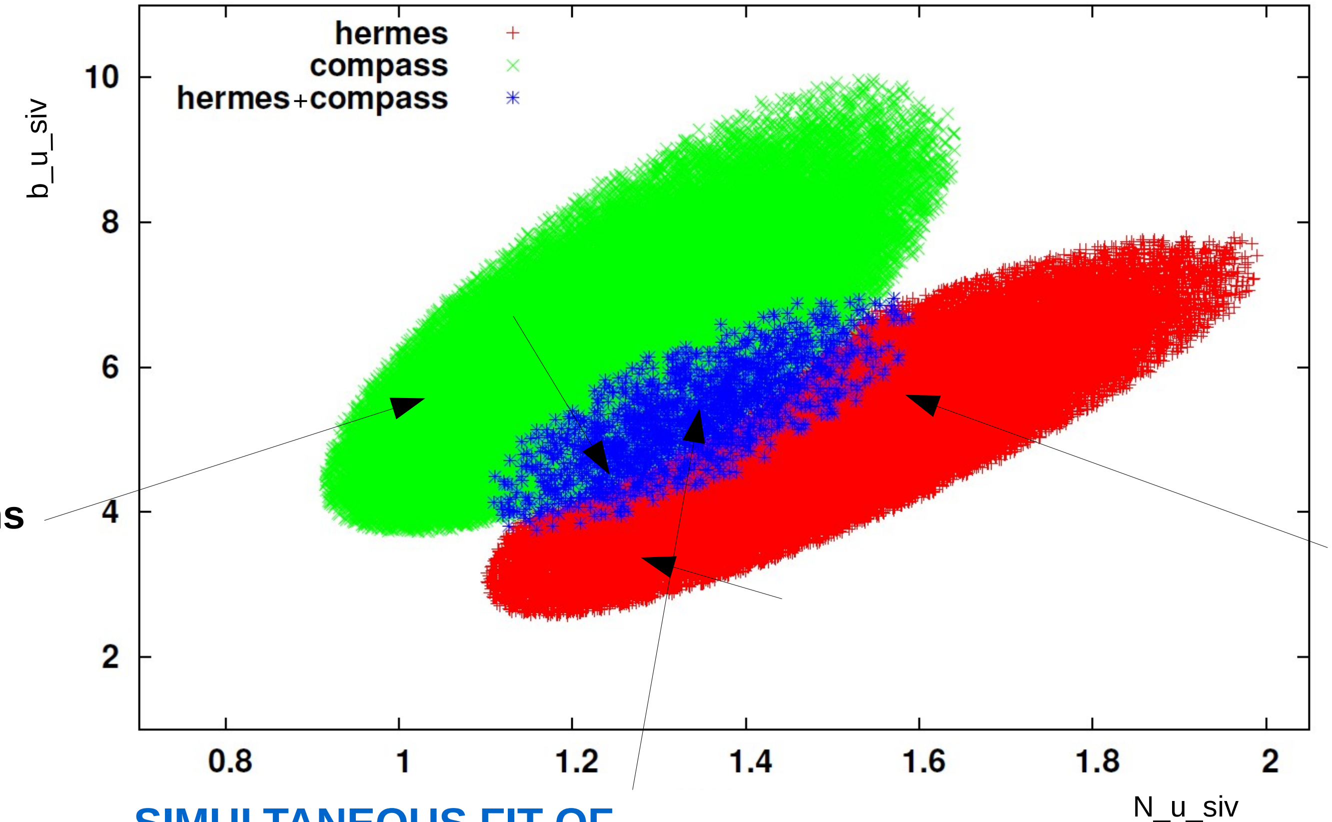
Use only u flavour and only π+ data



New extraction of the Sivers function

Tension relaxes when the asymmetry is computed using the appropriate unpolarized widths for each data set

Reference Fit



COMPASS-2015 (COMPASS widths no-evolution)

HERMES-2009 (HERMES widths no-evolution)

SIMULTANEOUS FIT OF
HERMES-2009 (HERMES widths - no evolution)
COMPASS-2015 (COMPASS widths – no evolution)

New extraction of the Sivers function

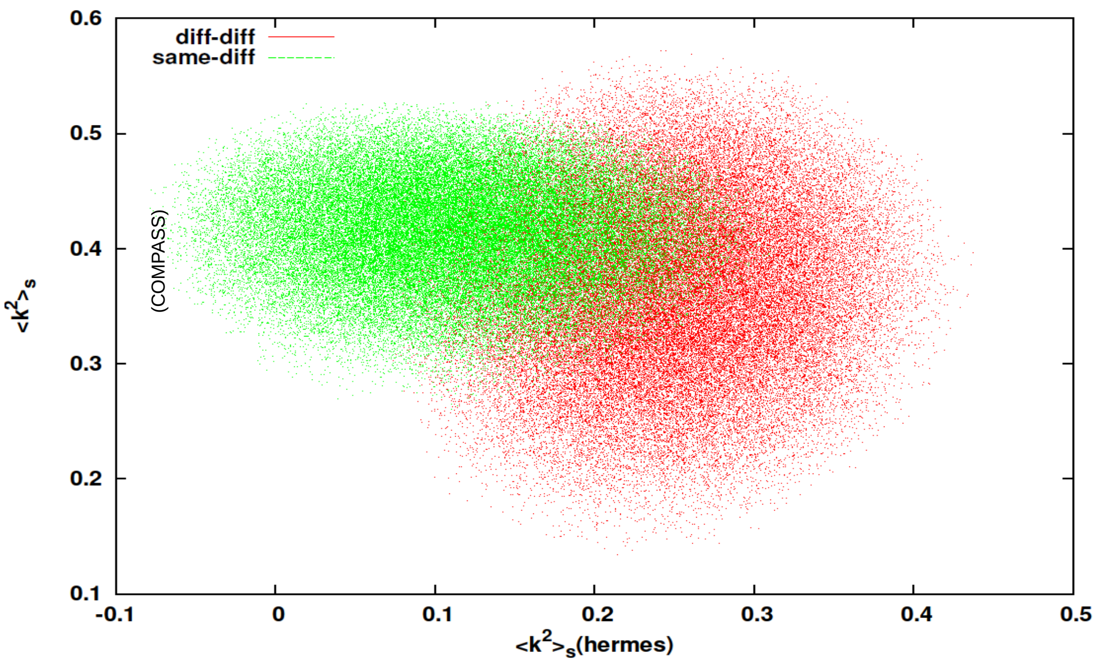
Boglione, Gonzalez, Flore, D'Alesio, JHEP 1807 (2018) 148

If we use different unpolarized widths for HERMES and COMPASS data, do we have to use different **Sivers** widths as well?

Sivers widths: HERMES vs. COMPASS

Allowing for different **Sivers** widths for each experiments, does not improve the quality of the fit, and the extracted values are very similar

No-evolution



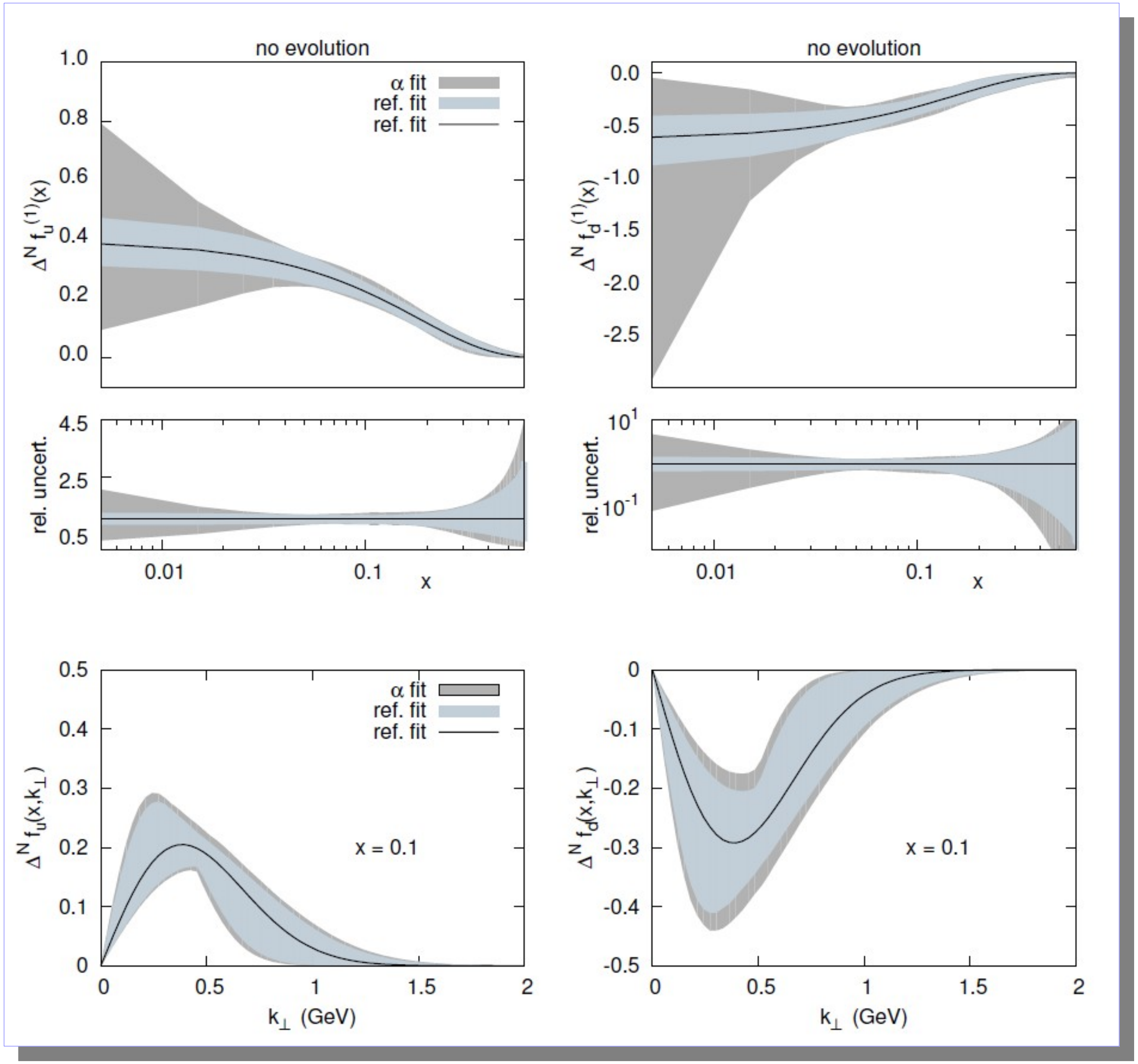
Uncertainty bands – Sivers first moment

Reference Fit
(no-evolution)

Boglione, Gonzalez, Flore, D'Alesio, JHEP 1807 (2018) 148

Study of Low-x Uncertainties
(include α_u and α_d in the parametrization of the Sivers function)

Sivers
First moment
u-contribution



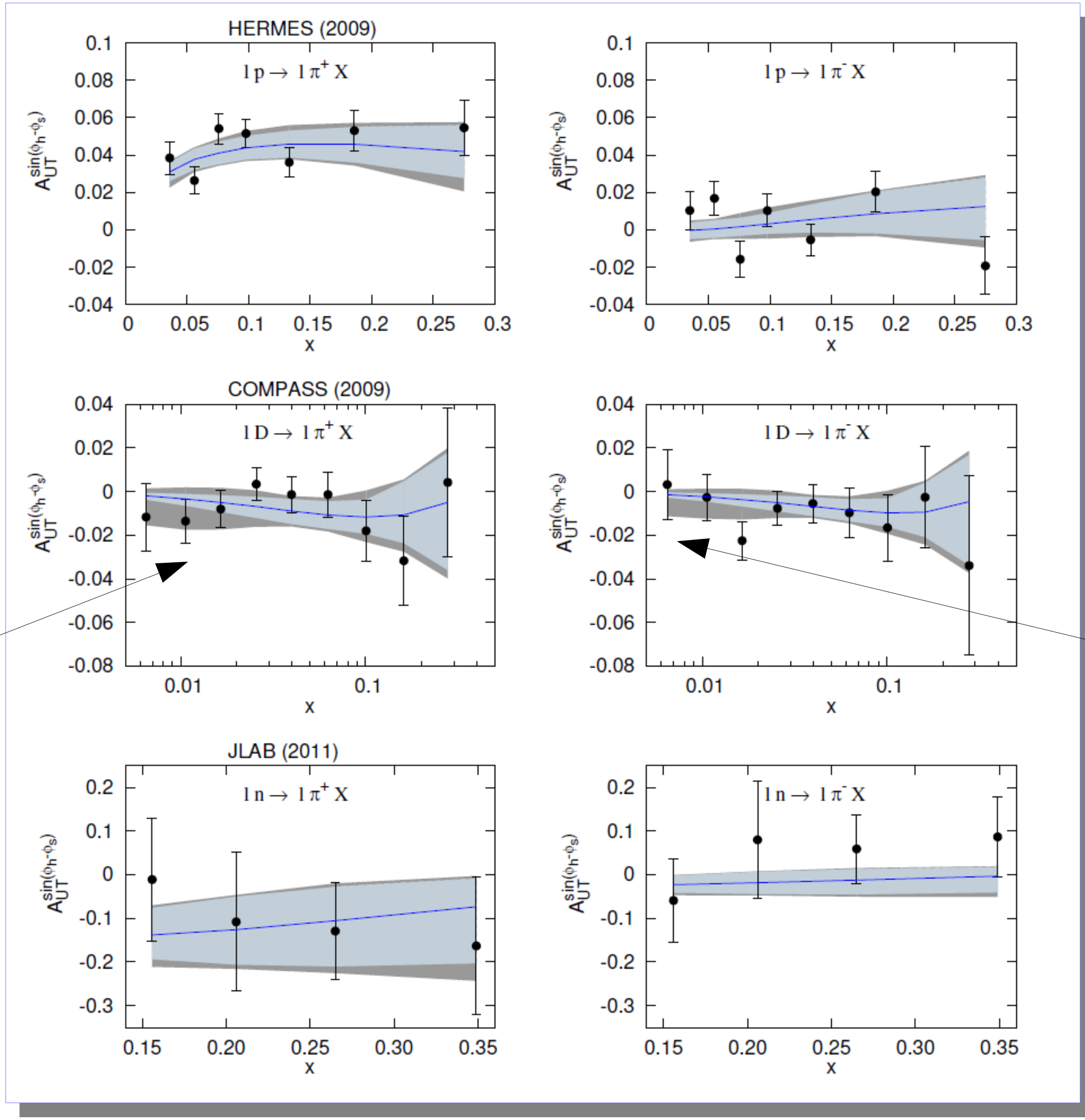
Sivers
First moment
d-contribution

Uncertainty bands – Sivers Asymmetries

Boglione, Gonzalez, Flore, D'Alesio, JHEP 1807 (2018) 148

Reference Fit
(no-evolution)

Uncertainty bands from the reference fit (light-blue) become artificially small at small x.



Study of Low-x Uncertainties
(include α_u and α_d in the parametrization of the Sivers function)

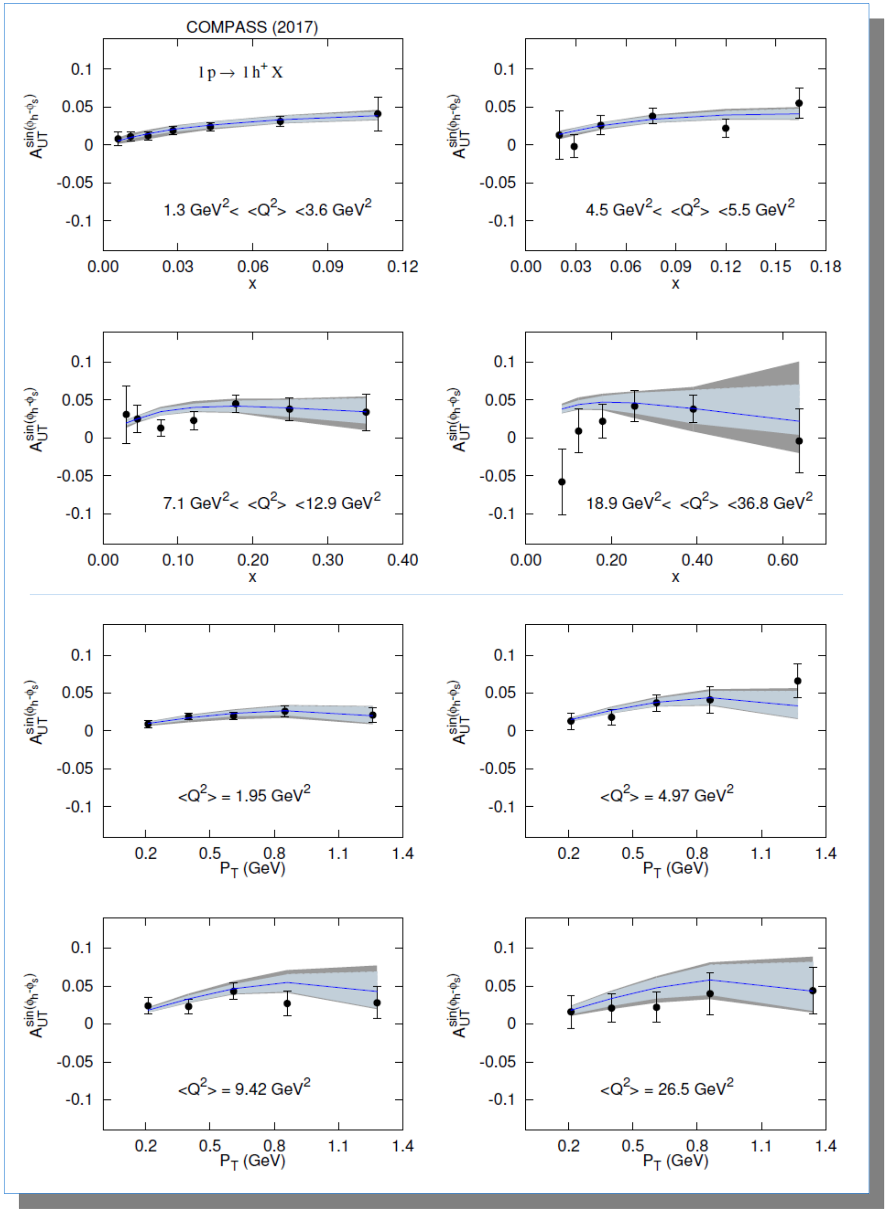
Alpha fit gives better estimates of uncertainties at small x (gray bands).

Uncertainty bands – Sivers Asymmetries

Boglione, Gonzalez, Flore, D'Alesio, JHEP 1807 (2018) 148

Reference Fit
(no-evolution)

Uncertainty bands from the reference fit (light-blue)



Study of Low-x Uncertainties
(include α_u and α_d in the parametrization of the Sivers function)

α-fit gives better estimates of uncertainties at large-x as well (gray bands).