Summary of the International Workshop

A path towards TMD extraction

TMDe2015

XV International Conference on Science, Arts and Culture

ICTP, Trieste, Italy, 2th-4th September 2015

edited by Anna Martin

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1 TMDe2015 - A path towards TMD extraction

The Workshop "TMDe2015 - A path towards TMD extraction" took place at the Adriatico ICTP Guest House, in Grignano, Trieste (Italy), from 2^{th} to 4^{th} September 2015. It was a hosted activity of the ICTP, the "Abdus Salam International Centre for Theoretical Physics" and organised in the framework of ECSAC, the "European Centre for Science Arts and Culture".

TMDe2015 was organised by the Italian community working in the field with the aim of gathering together physicists representative of the different experimental and theoretical collaborations in order to review and discuss the state of the art, the near future perspectives, new ideas and possibilities on a hot topic in hadron physics: the extraction of transversity and transverse momentum dependent parton distribution functions (TMD PDFs) from semi-inclusive deep inelastic scattering (SIDIS) data.

Transversity and TMD PDFs are new and crucial elements for the understanding of the nucleon structure in terms of the quark and gluon degrees of freedom in quantum chromodynamics (QCD) beyond the collinear approximation. They are being intensively studied since 30 years by a large international community of theoreticians and experimentalists.

These new PDFs can be accessed in several different reactions like SIDIS, Drell-Yan processes and hard proton-proton scattering. SIDIS has a key role because of the clear interpretation of the observables, the availability of experimental facilities and the large statistics which can be collected in a reasonable time.

The first results from SIDIS measurements with transversely polarised deuteron and proton targets were produced by the COMPASS and HERMES experiments in 2005, when the theoretical framework on TMD PDFs was already well established. The experimental evidence by HERMES that both the Collins and the Sivers asymmetries on proton were different from zero was a milestone in the field. Those measurements, together with the Belle results on e^+e^- annihilation into hadrons immediately allowed for the first extractions of the Sivers and transversity functions for the u and d quark, and of the Collins fragmentation functions. In the following 10 years new e^+e^- results came from the Belle, BABAR and BES experiments. A large amount of results from SIDIS with unpolarised and polarised targets has been produced by the COMPASS, HERMES and Jefferson Lab experiments. Particularly relevant has been the measurement with transversely polarised protons finally done by COMPASS in 2007 and 2010, which confirmed the persistence at high energies of the Collins and the Sivers asymmetries. Today a relatively large set of precise results exists for these two asymmetries and pioneering measurements of all the TMD-related asymmetries have been performed.

On the theoretical side, the new experimental findings stimulated a remarkable effort which allowed important new developments. By now solid predictions to test the theoretical framework exist, a much deeper understanding of the role of transverse momentum has been achieved, and new fields, like the Q^2 evolution of the TMD functions, have been attacked. More SIDIS data, covering the quark valence region today badly measured and/or at larger energies, and results in different reactions are clearly needed to have definite answers for many of these topics.

The year 2015 somehow marks the transition from the first to the second phase of the investigation, in particular from the experimental point of view. The pioneering experiments HERMES, COMPASS and the Jefferson Lab experiments have finished the foreseen data taking with polarised target but the analysis of the collected data is still ongoing. New generation high precision SIDIS experiments are in preparation at the new 12 GeV facility at Jefferson Lab and the first result on transverse spin observables are expected in less than five years. The proposal for an Electron Ion Collider, which will allow for precision SIDIS measurements at much higher energy, is well advanced.

Thus 2015 was a particularly suitable year to organise a mini-Workshop fully dedicated to the extraction of transversity and TMD PDFs from SIDIS data, where discuss all the achievements and the problems. The ambitious goal of TMDe2015 was to track the road towards further progress creating the opportunity to critically review the state of the art, to openly discuss the major limitations of the existing data and theoretical description, to single out relevant measurements still undone with the already collected data, to optimise future measurements, and improve the collaboration among the different physicists communities.

TMDe2015 has been organised as an as a working group meeting, a three days full immersion in the specific topic with a few introductory talks and most of the time left for discussions and short contributions. The participants were asked to share their experience, discuss methodologies and propose new ideas in particular on
- TMD evolution and higher twist effects,
- p_T distributions, azimuthal dependencies in unpolarised SIDIS,
- azimuthal asymmetries in transversely and longitudinally polarized SIDIS,
- TMD fragmentation functions in e^+e^- and SIDIS processes,
- new data analysis methods,
with focus on TMD extraction.

The Workshop has been attended by 42 researches (students, PhD students, post-doc and senior physicists) deeply involved in the different experimental (BABAR, Belle, BES, COMPASS, HERMES, Jefferson Lab and RHIC experiments) and theoretical Collaborations coming from Europe, United States, China, Australia, Armenia.

The wide range and high level participation, the active and enthusiastic attendance at the different sessions, and the quite informal environment (an almost self-organised Workshop) have allowed for very stimulating and constructive discussions among theoreticians and experimentalists. Many aspects have been clarified and, as obvious, many question have been left open for future similar initiatives. Important inputs for new analysis of existing data, for the future measurements, and for phenomenological and theoretical developments are been given. The new ideas put forward during the Workshop will hopefully develop in the future and constitute the basis for more deep future collaborations. To conclude, TMDe2015 has been a fruitful experience which should be repeated regularly in the future being topical meetings like this complementary to and as relevant as the standard Workshops.

More information and additional material can be found in the following sections:
2. List of participants, page 3,
3. Scientific programme and Timetable, page 4,
4. Short summaries of the talks, page 7,
and all the presentations can be found in the Indico web page of the Workshop:
https://indico.cern.ch/event/386033/

Acknowledgments
We would like to thank all the participants for their very active contribution to the success of the Workshop, ECSAC and ICTP for the support and for taking care of the logistics, and all the sponsors for making TMDe2015 possible.

2 Participants

Mauro Anselmino	Torino University and INFN
Fabio Anulli	INFN Sezione di Roma
Elke-Caroline Aschenauer	BNL
Harut Avakian	Jefferson Lab
Vincenzo Barone	University of Piemonte Orientale and INFN
Andrea Bianconi	Brescia University
Mariaelena Boglione	Torino University and INFN
Franco Bradamante	INFN Trieste
Andrea Bressan	Trieste University and INFN
Federico Alberto Ceccopieri	IFPA, Universite de Liege
Marco Contalbrigo	INFN Ferrara
Shuddha Shankar Dasgupta	Trieste University and INFN
Rolf Ent	Jefferson Lab
Leonard Gamberg	Penn State University
Isabella Garzia	INFN Ferrara
Gary Goldstein	Tufts University
Albi Kerbizi	Trieste University
Aram Kotzinian	INFN Torino and ErPhI Armenia
Krzysztof Kurek	National Centre for Nuclear Research (PL)
Tianbo Liu	Duke University and DKU
Simonetta Liuti	University of Virginia
Bo-Qiang Ma	Peking University
Anna Martin	Trieste University and INFN
Hrayr Matevosyan	University of Adelaide
Jan Matousek	Prague Charles University and INFN
Stefano Melis	Torino University
Marco Mirazita	INFN Laboratori Nazionali di Frascati
Francesco Murgia	INFN Cagliari
Barbara Pasquini	University of Pavia and INFN
Michael Pesek	Prague Charles University
Cristian Pisano	University of Antwerp
Silvia Pisano	INFN Laboratori Nazionali di Frascati
Marco Radici	INFN Pavia
Patrizia Rossi	Jefferson Lab
Giulio Sbrizzai	Trieste University and INFN
Ignazio Scimemi	Universidad Complutense (ES)
Sergio Scopetta	Perugia University and INFN
Andrea Signori	VU University Amsterdam - Nikhef
Adam Szabelski	National Centre for Nuclear Research (PL)
Fulvio Tessarotto	INFN Trieste
Charlotte Van Hulse	University of the Basque Country
Anselm Vossen	Indiana University
Christian Weiss	Jefferson Lab

3 Scientific Program and Timetable

The scientific programme has been organised in seven sections:

Session 1	TMD evolution *chairpersons: Mauro Anselmino, Barbara Pasquini*
Session 2	Higher twist and target fragmentation effects *chairpersons: Vincenzo Barone, Marco Mirazita*
Session 3	TMDs from unpolarised SIDIS data *chairpersons: Alessandro Bacchetta, Silvia Pisano, Patrizia Rossi*
Session 4	TMDs from azimuthal asymmetries in transversely and longitudinally polarized SIDIS *chairpersons: Mauro Anselmino, Marco Contalbrigo*
Session 5	TMD fragmentation functions in e^+e^- and SIDIS processes *chairpersons: Franco Bradamante, Andrea Bressan, Marco Radici*
Session 6	New data analysis methods ("4π" and multiD measurements, weighted asymmetries,use of generators ...) *chairpersons: Alessandro Bacchetta, Anna Martin, Marco Radici*
Session 7	New channels ($\Lambda, J/\Psi$, high p_T hadron pairs, ...) production in SIDIS *chairpersons: Franco Bradamante, Andrea Bressan, Marco Radici*

In line with the aims of the Workshop, only few 30' talks were given in order to introduce the different topics from the theoretical and from the experimental point of view. They were overview talks, summarising the status, the main recent progress, the perspectives and the difficultie without entering in too deep details. In each session, all the rest of the time was left free for general discussions and for short presentations on more specific item. In total there were 11 overview talks and 21 short communications, i.e. 32 speakers out of 42 participants. The discussions were particularly stimulating and took all the available time. Unfortunately the summaries by the chairpersons, expected each day, could not take place.

The detailed timetable with the list of presentations is given in the following. The symbols "**" or "*" indicate that a short write-up of the contribution has been kindly prepared by the speaker or that the written abstract was available. The slides of all talks are available in https://indico.cern.ch/event/386033/contributions/speakers .

Timetable

September 2

Welcome	ICTP (video), S. Dalla Torre (INFN Trieste), F. Bradamanate (ECSAC)		

Session 1: TMD evolution

	M. Anselmino	TMD evolution -The next stage in the 3D imaging of the nucleon	
Overviews	I. Scimemi	TMD evolution: an overview	
	S. Melis	Phenomenological implementations of TMD evolution	
Talks	A. Signori	Effects of TMD evolution and partonic flavor on e^+e^- annihilation into hadrons	**

Session 2: higher twist, and target fragmentation effects

Overviews	H. Avakian	Disentangling different effects, from higher twist to target fragmentation	**
Talks	V. Barone	The target fragmentation region of SIDIS: a few remarks	
	F. A. Ceccopieri	Λ production in the DIS target-fragmentation region	**
	M. Mirazita	Λ production in the DIS target-fragmentation region: the CLAS12 program	

Session 3: TMDs from unpolarised SIDIS data

Overviews	R. Ent	TMDs from unpolarised SIDIS data - Experimental overview	
	C. Weiss	Unraveling hadron transverse momentum in SIDIS: Dynamics, present data, future measurements	**
Talks	M. Boglione	Multiplicities, azimuthal asymmetries, ...	
	G. Sbrizzai	Hadron distributions vs p_T at COMPASS	

September 3

Session 4: TMDs from azimuthal asymmetries in transversely and longitudinally polarized SIDIS

Overviews	A. Bressan	Experiments: status and perspectives	
	M. Boglione	Phenomenology: status and perspectives	**

Session 4: TMDs from azimuthal asymmetries in transversely and longitudinally polarized SIDIS (cont.)

Talks	A. Martin	Point by point extraction of the transversity distribution	*
	S. Scopetta	An update on the extraction of neutron SSAs from ^{3}He data	**
	B-Q. Ma	The pretzelosity of the nucleon	
	G. Goldstein	Transversity from GPDs	**
	C. Pisano	Collins asymmetries in $p^\uparrow p \rightarrow$ jet π X	*

Session 5: TMD fragmentation functions in e^+e^- and SIDIS processes

Overviews	M. Radici	Phenomenology: status and perspectives	
	A. Vossen	Asymmetry measurements in e^+e^-: methods, open points and perspectives	**
Talks	I. Garcia	Collins asymmetries in e^+e^- annihilation	*
	F. Bradamante	Interplay between the Collins and the di-hadron asymmetries	*
	A. Kotzinian	Dependence of 2h SIDIS structure functions on $\Delta\phi$	*
	H. Matevosyan	Transverse Spin Effects in Two Hadron Electroproduction	*

September 4

Session 6: New data analysis methods (multiD and "4π" measurements, weighted asymmetries, use of generators ...)

Overviews	L. Gamberg	Bessel and p_T weighted asymmetries	
	M. Contalbrigo	"4π" and multiD measurements	**
Talks	S. Liuti	PDF extraction with neural network	
	A. Bianconi	Adaptation of a generator to TMD analysis	**

Session 7: New channels: Λ, J/Ψ, high p_T pairs … production in SIDIS

Talks	A. Szabelski	The Gluon Sivers effect measurement at COMPASS from high- p_T hadron pairs	
	F. Murgia	Estimating the gluon Sivers function from A_N data in polarized pp collisions at RHIC	*
	J. Matousek	Sivers asymmetry from J/Ψ production at COMPASS	

4 Short summaries of the talks

In this last section the short summaries (or abstracts) of the talks [1] are collected in order to give hints on the present status, the perspectives, and the amount of work which is being done in investigating the different aspects related to Transversity and TMD extraction.

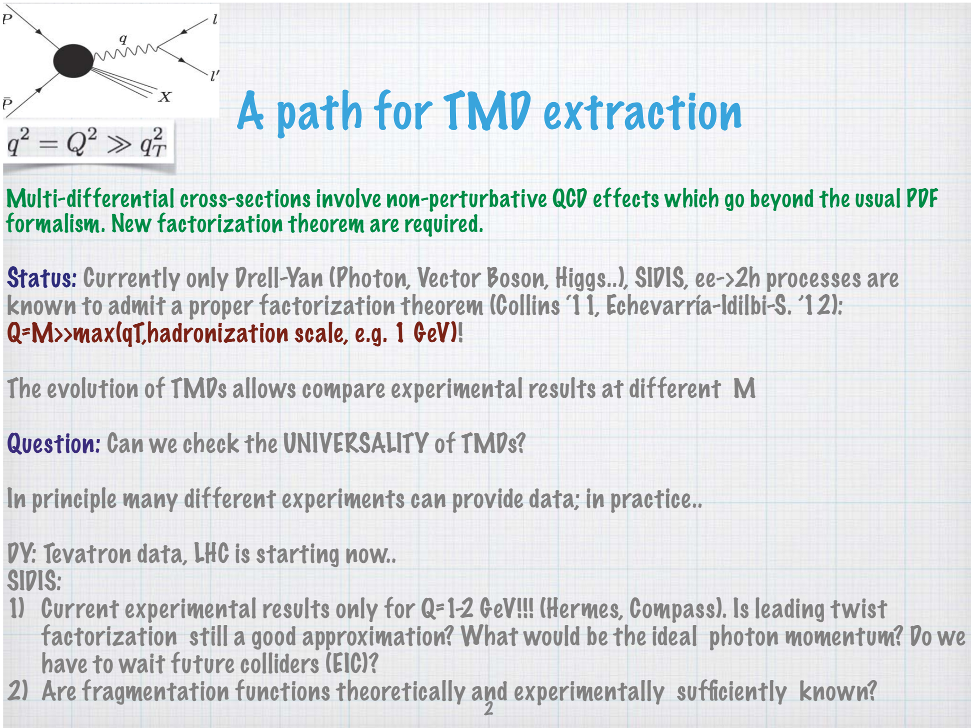
Index of authors

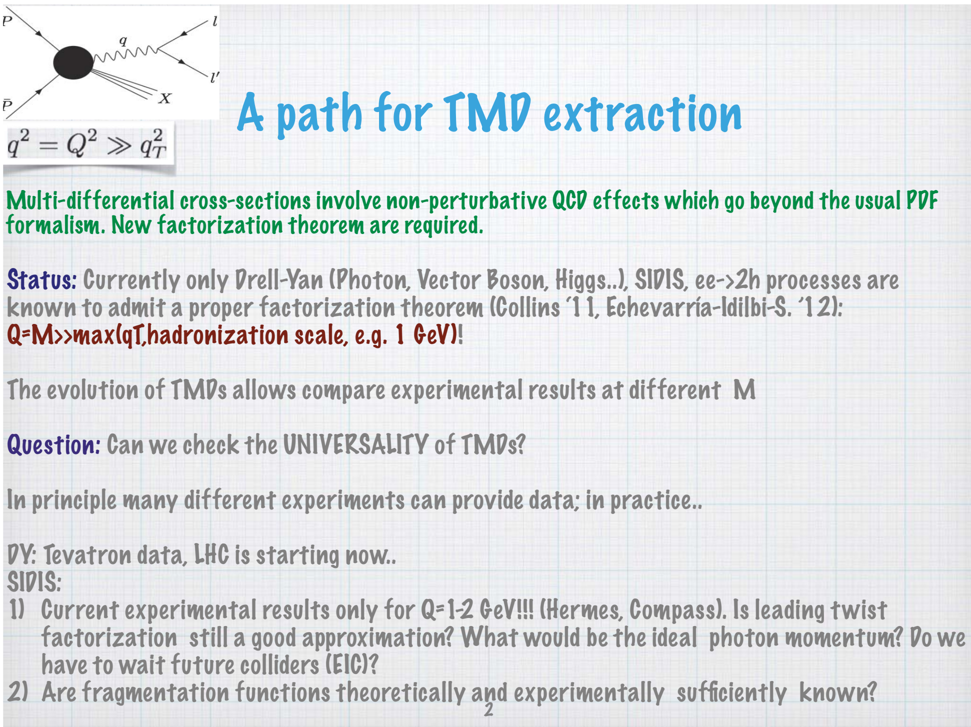
[1] The missing summaries (and abstracts) of the overview talks have been replaced by two slides chosen by the editors of this summary.

TMD evolution: overview of the theory

Ignazio Scimemi

Universidad Complutense (ES)





Phenomenological implementations of TMD evolution

Stefano Melis

Torino University, Torino, Italy

Conclusion I

- TMD evolution can describe DY data. The predictions are robust at the mass of Z and transverse momenta of $5<q_T<30$ GeV. Lower transverse momenta need a non perturbative modeling

- Present SIDIS data are at low energy therefore
  1) the non-pertubative behavior is dominant.
  2) the perturbative part could be not under control (i.e. Higher order terms may be large)
  3) The region of matching and that of resummation cannot be clearly separated.

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Conclusion II

- Different approaches can describe the Sivers asymmetry because the non pertubative behavior is probably dominant

- We do not have a full NLO and NLL fit of SIDIS data yet. We need to know well the twist 3 Qiu-Sterman functions and their (NLO) collinear evolution... which is not close

- Contrary to unpolarized PDF we do not know the collinear T_F Can we study T_F in SIDIS? (i.e. at large q_T, maybe at EIC?)

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Evolution and flavor effects in $e^+e^- \to h_1 h_2 X$

Alessandro Bacchetta [1,2], Miguel G. Echevarra [3,4], Piet J. Mulders [3,4],
Marco Radici [1], Andrea Signori [3,4 a]

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I. INTRODUCTION AND MOTIVATION

Among the goals of the workshop "A path towards TMD extractions (TMDe2015)" held in Trieste there is the definition of a "standard framework" within the TMD factorization formalism to extract TMD parton distribution functions (PDFs) and TMD FFs from experimental data. This involves the implementation of both the perturbative and the non-perturbative content of the TMD distributions (TMDs), the modeling of the transition between the perturbative and the non-perturbative regions in the q_T-spectra of physical observables and the choices for the model at low transverse momentum. Here, in the spirit of the program described in Ref. [1], we want to elucidate how different choices in the perturbative and non-perturbative part of the TMDs affect the extractions. We calculate the transverse momentum dependence in the production of two back-to-back hadrons in electron-positron annihilation at the medium/large energy scales of Bes-III and Belle experiments. We use the parameters of the transverse-momentum-dependent (TMD) fragmentation functions (FFs) that were recently extracted from the semi-inclusive deep-inelastic-scattering multiplicities at low energy from Hermes. TMD evolution is applied according to different approaches and using different parameters for the non-perturbative part of the evolution kernel, thus exploring the sensitivity of our results to these different choices and to the flavor dependence of parton fragmentation functions. We discuss how experimental measurements could discriminate among the various scenarios. Moreover, we can make realistic tests on the sensitivity to various implementations of TMD evolution available in the literature, since the hard scales involved in e^+e^- annihilation are much larger than the average values explored in SIDIS by Hermes, which is assumed as the starting reference scale.

II. KINEMATICS AND OBSERVABLES

A detailed description of the kinematic setup and the chosen physical observables is given in Ref. [2]. Here we point out that the covariant form of the transverse momentum is the non-collinearity of the photon momentum and the momenta of hadrons h_1 and h_2:

$$q_T^\mu = q^\mu - \frac{P_1^\mu}{z_1} - \frac{P_2^\mu}{z_2} \ . \tag{1}$$

q_T is the transverse momentum of the photon in the frame where h_1 and h_2 are collinear and it reduces to the expression $-P_{hT}/z_1$, involving the hadronic transverse momentum of hadron h_1, in the frame where the virtual photon and h_2 are collinear. Here z_l is the fractional energy transferred to hadron l, M is the mass of hadron 1 and Q^2 is the invariant mass of the hadronic system in the final state. In order to deal with an observable poorly sensitive to perturbative corrections, we choose to investigate TMD multiplicities normalized at a given value of q_T (chosen to be 0):

$$M^{h_1 h_2}(z_1, z_2, q_T^2, y)/M^{h_1 h_2}(z_1, z_2, 0, y) \ . \tag{2}$$

[a] Electronic address: asignori@nikhef.nl - speaker

In analogy with the SIDIS process, we define the multiplicities in e^+e^- annihilation as the differential number of back-to-back pairs of hadrons produced per corresponding single-hadron production:

$$M^{h_1 h_2}(z_1, z_2, q_T^2, y) = \frac{d\sigma^{h_1 h_2}}{dz_1 dz_2 dq_T^2 dy} \Big/ \frac{d\sigma^{h_1}}{dz_1 dy} \ . \tag{3}$$

Then, we study their transverse momentum distribution at large values of the center-of-mass (cm) energy, starting from an input expression for TMD FFs taken from the analysis of Hermes SIDIS multiplicities at low energy performed in Ref. [3]. In this framework, we can extract clean and uncontaminated details on the transverse-momentum dependence of the unpolarized TMD FF, which is a fundamental ingredient of any spin asymmetry in SIDIS and, therefore, it affects the extraction also of polarized TMD distributions.

III. QCD EVOLUTION

In the TMD cross section $d\sigma^{h_1 h_2}$ in (3) (described in details in Ref. [2]) we work in the regime of small transverse momentum $q_T^2 \ll Q^2$, where we expect TMD factorization to hold. For this reason we neglect the contribution from high transverse momentum regions (the so called "Y-term" and fixed order calculation, see Ref. [4]). We also do not consider higher-twist effects. The core of $d\sigma^{h_1 h_2}$ lies in the convolution [product] of two unpolarized TMD FFs $D_1^{q\to h_1}$ and $D_1^{\bar{q}\to h_2}$ in transverse momentum [position] space. The definition of TMD FFs is intrinsically related to the TMD factorization theorem: they depend on 4 variables,

$$D_1^{q\to h_l}(z_l, b_T; \mu, \zeta) \ , \tag{4}$$

where z_l is the collinear fractional energy, b_T is the Fourier conjugated of the transverse momentum q_T, μ is the renormalization/factorization scale through which renormalization group evolution is implemented and ζ is connected to a rapidity cutoff introduced to split the soft function and define the TMD distributions (Refs. [4, 5]). The "evolution" with μ and ζ (crucial for phenomenology) is a byproduct of the TMD factorization theorem. Applying an operator product expansion (OPE) on the b_T-spectrum the TMD FF reads:

$$D_1^{j\to h_l}(z_l, b_T; \mu, \zeta) = \left\{ \sum_{k=q,\bar{q},g} C_{jk}(z_l, b_T; \mu, \zeta) \otimes d_1^{k\to h_l}(z_l; \mu) \right\} F_{NP}^{j\to h_l}(z_l, b_T; \zeta) \ . \tag{5}$$

d_1 is the collinear fragmentation function, C_{jk} are the perturbatively calculable Wilson coefficients. Note that the non-perturbative model F_{NP} to account for the low transverse momentum spectrum is assumed to be kinematic- and flavor-dependent. In particular we rely on a Gaussian hypothesis in momentum space at the input scale ζ_i (see Refs. [2, 3, 6]), which in b_T-space reads:

$$F_{NP}^{j\to h_l}(z_l, b_T; \zeta_i) = \frac{1}{z_l^2} \exp\left\{ - \left[\frac{\langle P_\perp^2 \rangle_{j/h_l}(z_l)}{4 z_l^2} + g_{np}(b_T) \ln \frac{\zeta_i}{Q_0^2} \right] b_T^2 \right\} \ , \tag{6}$$

where $P_\perp$ is the transverse momentum acquired during the fragmentation process with respect to the quark momentum and Q_0^2 is a parameter (see Ref. [3]). Possible forms of g_{np} are specified in Ref. [2]. Since the observable defined in (2) is not drastically sensitive to corrections arising from QCD evolution we choose to work at the parton model level (with no α_s corrections in the hard part and in the Wilson coefficients C_{jk}) and at Next-to-Leading-Log (NLL) order of accuracy in the perturbative Sudakov form factor (see Ref. [2]). Under these assumptions the hard part reduces to 1 and the C_{jk} coefficients to delta distributions involving the (anti)quark flavors multiplied by the perturbative Sudakov quark form factor. In this treatment we assume for the final value of the evolution scales $\mu_f^2 = \zeta_f = Q^2$ (where Q^2 is the hard scale of the process), whereas for the initial value we have $\mu_i^2 = \zeta_i$ and we explore the phenomenological impact of choosing μ_i equal to μ_b and Q_i (where $\mu_b = 2e^{-\gamma_E}/\hat{b}$).

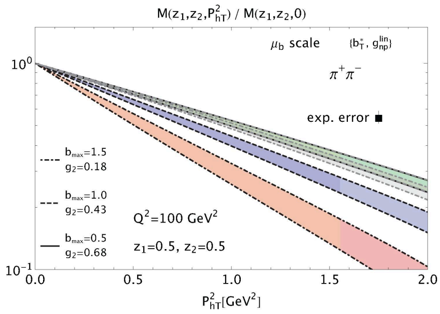

FIG. 1: The normalized multiplicity at $z_1 = z_2 = 0.5$ as a function of $P_{hT}^2 = z_1^2 q_T^2 \equiv (0.5)^2 q_T^2$ at the Belle scale $Q^2 = 100$ GeV^2 for the "μ_b scale" evolution scheme and with the $\{b_T^*, g_{\rm np}^{\rm lin}\}$ prescription for the transition to the non-perturbative regime (see Ref. [2]). The uncertainty bands correspond to various choices of the non-perturbative parameters of evolution [2]: $\{b_{\rm max} = 1.5, g_2 = 0.18\}$ for the band with dot-dashed borders, $\{b_{\rm max} = 1, g_2 = 0.43\}$ for the one with dashed borders, $\{b_{\rm max} = 0.5, g_2 = 0.68\}$ for the one with solid borders. The latter is accompanied by a light-gray band with dot-dashed borders, that represents the result with the same parameters but with the choice $\mu_b/2$ for the renormalization scale, and by an overlapping light-gray band with dashed borders for the choice $2\mu_b$. An experimental error of 7% is also indicated.

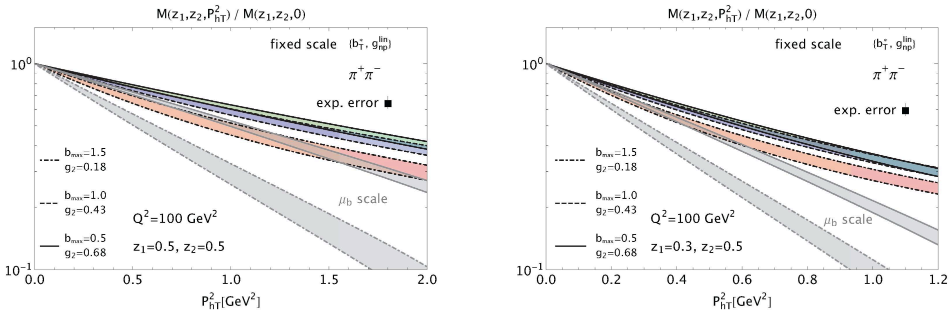

FIG. 2: The same as in Fig. 1 but evaluated at $\mu_i = Q_i$. Left panel (a) displays predictions at $z_1 = z_2 = 0.5$. The right panel (b) for $z_1 = 0.3$ and $z_2 = 0.5$. The additional light-gray bands with dot-dashed and solid borders are the result related to the $\mu_i = \mu_b$ evolution scheme for $\{b_{\rm max} = 1.5, g_2 = 0.18\}$ and $\{b_{\rm max} = 0.5, g_2 = 0.68\}$, respectively.

IV. A SELECTION OF RESULTS

In Fig. 1 we show the sensitivity of normalized multiplicity for $\pi^+\pi^-$ production to the parameters involved in the non-perturbative Sudakov form factor and in the separation between low and high transverse momenta ($\{b_{\rm max}, g_2\}$). It is interesting to notice how different values for $\{b_{\rm max}, g_2\}$ can generate different multiplicities. Assuming an experimental uncertainty of 7% (as in Fig. 1) we could in principle be able to discriminate between different non-perturbative scenarios. They grey band in Fig. 1 also shows the stability of the results under variations of the renormalization scale μ considering the values $\{0.5\mu_{\hat{b}}, \mu_{\hat{b}}, 2\mu_{\hat{b}}\}$. This proves that the observable defined in (2) is not deeply sensitive to corrections from perturbative QCD (which needs anyway to be accounted for in a proper treatment).

In Fig. 2 we can appreciate the effects due to different choices for the initial value of the renormalization scale μ_i. The grey bands correspond to $\mu_i = \mu_b$ whereas the colored ones correspond to $\mu_i = Q_i$. The latter choice produces always larger distributions. This is due to the fact that $\mu_i = \mu_b$ suppresses the perturbative content, canceling terms proportional to $\ln \mu_i/\mu_b$. We can argue if it is possible to discriminate between the two prescriptions. From Fig. (2)a it seems it is not, since the two overlap for different choices of the non-perturbative parameters $\{b_{\rm max}, g_2\}$. But taking into account both the $\{b_{\rm max}, g_2\}$- and the z-dependence (as in Fig. (2)b), there exist values of P_{hT} where it is possible to discriminate between the μ_b and the Q_i prescriptions.

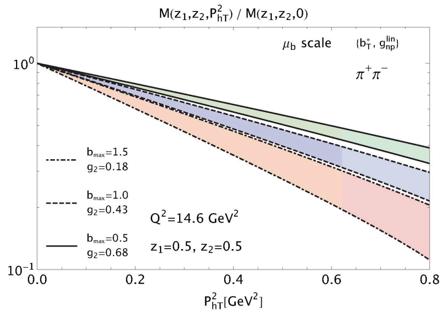

FIG. 3: The same as Fig. 1 but evaluated at $Q^2 = 14.6$ GeV^2.

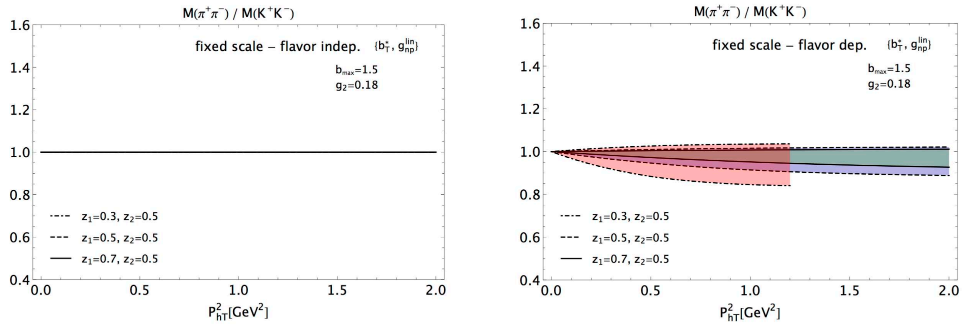

FIG. 4: The ratio of normalized multiplicities between the $\{\pi^+\pi^-\}$ final state and the $\{K^+K^-\}$ final state at $z_2 = 0.5$ and $y = 0.2$ as a function of $P_{hT}^2 = z_1^2 q_T^2$ at the Belle scale $Q^2 = 100$ GeV^2 for $\mu_i = Q_i$, for the evolution parameters $\{b_{\max} = 1.5, g_2 = 0.18\}$, and with the $\{b_T^*, g_{\rm np}^{\rm lin}\}$ prescription for the transition to the non-perturbative regime. Uncertainty bands with dot-dashed, dashed, and solid borders for $z_1 = 0.3$, 0.5, 0.7, respectively. Left panel (a) for flavor independent intrinsic parameters of input TMD FF, right panel (b) for flavor dependent ones.

In Fig. 3 we show how the multiplicity looks like at $Q^2 = 14.6$ GeV^2 (hard scale at the BES-III experiment), a lower energy scale with respect to the one used in Fig. 1 ($Q^2 = 100$ GeV^2, related to Belle experiment). Figs. 1 and 3 together show the complementarity of medium and high Q^2 values: studying the $\pi^+\pi^-$ multiplicity at $Q^2 = 14.6$ GeV^2 is not useful to discriminate among different non-perturbative scenarios (as in Fig. 1) because the bands related to $\{b_{\max}, g_2\}$ values are almost overlapping. Nevertheless, it could be important in order to pin down some of the non-perturbative replicas of the intrinsic transverse momentum $\langle P_\perp^2 \rangle_{k/h_l}$ values (see [3]) within each band related to $\{b_{\max}, g_2\}$.

In Fig. 4 we study ratios of normalized multiplicities, since these quantities have a good sensitivity to the flavor of the involved quarks. Fig. 4 displays the behavior of the ratio between $\{\pi^+\pi^-\}$ and $\{K^+K^-\}$ multiplicities choosing $\mu_i = Q_i$. The latter condition implies that the only source of b_T- or q_T- dependence in the cross section is the non-perturbative model at low transverse momentum. If we assume the model to be flavor/hadron independent, it factors out and cancel in the ratio. As a consequence the observable is flat in P_{hT} (see Fig. 4a). Flavor dependent models, contrary, bring different contributions for different flavor/hadron combinations. For this reason they combine in the ratio producing a specific non-flat q_T-dependence as displayed in Fig. 4b. The width of the bands arises from the different replicas of the flavor dependent intrinsic parameters $\langle P_\perp^2 \rangle_{k/h_l}$. Qualitatively the results are similar setting $\mu_i = \mu_b$. In this case, though, the differences between the flavor dependent and independent cases are more difficult to separate because the transverse momentum dependence induced by the non-perturbative model combines with the $\mu_b \sim b_T^{-1}$ dependence in the collinear fragmentation functions.

V. CONCLUSIONS

We can summarize the previous observations as follows: the way we implement QCD evolution affects the extraction of non-perturbative information; this is very important in defining a framework for the extraction of TMD distributions. At Belle kinematics ($Q^2 = 100$ GeV^2) we could discriminate evolution schemes (see Fig. 2) and pin-down non-perturbative evolution parameters $\{b_{\max}, g_2\}$ (see Fig. 1) . Moreover, annihilation at BES kinematics ($Q^2 = 14.6$ GeV^2) could be useful to select non-perturbative intrinsic parameters of TMD FFs (see Fig. 3). Annihilation to different final states $\{\pi^{\pm}, K^{\pm}\}$ can be very useful to constrain flavor dependence of TMD FFs (see Fig. 4). Knowledge of unpolarized TMD FFs helps in constraining both (un)polarized TMD PDFs and polarized TMD FFs.

Acknowledgments

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Disentangling different effects, from higher twist to target fragmentation

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Studies of spin-azimuthal asymmetries in semi-inclusive and hard exclusive production of photons and hadrons have been widely recognized as key objectives of the JLab 12 GeV upgrade and a driving force behind construction of the Electron Ion Collider. Several proposals have been already approved by the JLab PAC intending to extract Generalized Parton Distributions (GPDs), and Transverse Momentum Distributions (TMDs) from various observables accessible in hard scattering. There exist data on spin-azimuthal distributions of hadrons in semi-inclusive DIS, providing access to TMDs and GPDs, accumulated in recent years by several collaborations, including HERMES [1] COMPASS [2], BELLE, BaBar and Halls A, B and C at JLab. After the first few years of running of JLab12, a significantly greater set of data will be available.

The extraction of TMDs and GPDs from different single and double spin azimuthal asymmetries requires reliable and model independent procedure for flavor decomposition of underlying 3D partonic distributions. Various assumptions involved in preliminary extraction of TMDs and GPDs from available data, have yet to allow credible estimates of systematic errors associated with those assumptions. Some TMDs have been already phenomenologically extracted, mainly from analyzing azimuthal distributions of single hadrons in SIDIS. To obtain a full picture about the 3D momentum structure of the partons in the nucleon from high to low x, it is important to connect the theoretical approaches to extract TMDs including evolution.

The studies of 3D PDFs in general, and TMDs in particular, require a lot more attention to uncertainties due to input parametrizations, as more degrees of freedom and bigger number of input parameters may generate uncontrolled model uncertainties. This makes the development of a framework for testing different extraction procedures a high priority task for the community involved in studies of 3D PDFs. Development of realistic Monte-Carlo generators accounting for TMD evolution effects, spin-orbit and quark-gluon correlations will be a great support for a multifaceted effort to study the fundamental 3D structure of matter.

Standard global fitting methodologies and error analysis which have been developed during the decades of PDF measurements, provide a starting point for the analysis of 3D PDFs. The main challenges in precision measurements of hard scattering processes include clear understanding of leading twist QCD fundamentals (Y-term, matching at large P_T..), higher twist effects, TMD fragmentation functions and also correlations of hadron production in target and current fragmentation regions. In addition the unambiguous interpretation of any SIDIS experiment (JLab in particular) in terms of leading twist transverse momentum distributions, requires detailed understanding of effects of finite energies, finite phase space (target and hadron mass corrections,..) as well as radiative corrections to all involved observables, which themselves introduce azimuthal modulations which can couple to similar modulations from Born cross section and detector acceptances, complicating credible estimates of systematic errors. Target mass corrections may be significant at large-x, already in collinear framework [3]. Development of consistent approach for accounting the target mass corrections in studies of TMDs and GPDs will be crucial for precision studies of 3D PDFs.

Recent studies have shown that especially in the region of large x, where little or no direct experimental information is available, the uncertainty related to the choice of parametrization and methodology may be as large or larger than the statistical uncertainty [4, 5]. Compared to PDFs, the status of TMD extractions is still in an “exploratory stage.” Phenomenology efforts have been summarized recently by introduction of a library of fits and parametrizations for transverse-momentum-dependent parton distribution functions (TMD PDFs) and fragmentation functions (TMD FFs) together with an online plotting tool, TMDplotter [6].

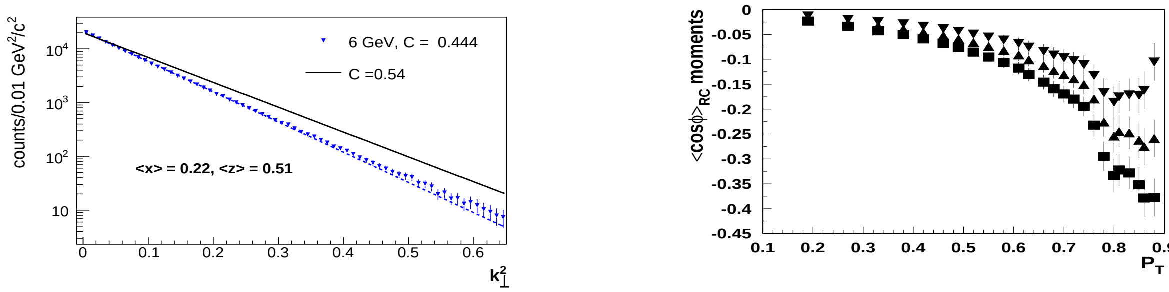

Figure 1: Left panel: MC generated distributions implementing Gaussian function (solid line). The down triangles show the outcome for distributions from the MC at 6 GeV initial lepton energy, in comparison with the fit (dashed curve) with Gaussian function with a smaller width [7, 8] Right panel: Sensitivity of the $\cos\phi$-moment generated by radiative effects to ϕ-dependence of three different structure functions with $\cos\phi$ input amplitudes equal to -5% (squares), -10% (triangles up), and -15% (triangles down) calculated from haprad2.0 [9] as a function of the transverse momentum of a pion in SIDIS in JLab12 kinematics at $x = 0.3$ and $z = 0.3$.

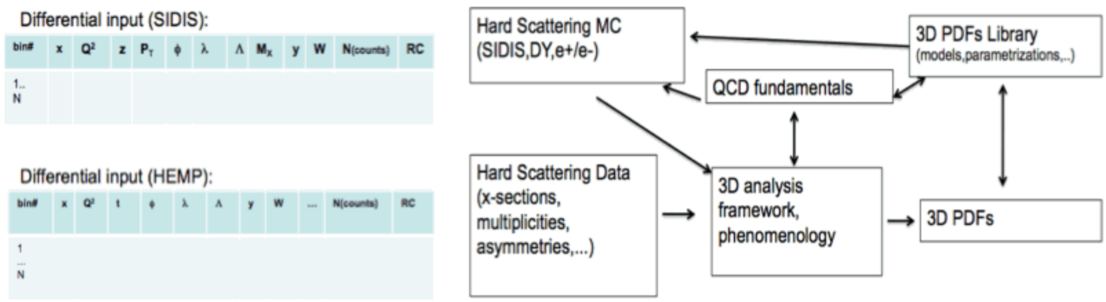

Figure 2: The suggested data input(left) and the diagram for analysis framework with validation using the MC.

Further progress in the interpretation of the quantitative description of azimuthal, spin-orbit, and polarization phenomena in SIDIS at JLab 12 and EIC, and other processes (DY at RHIC, DY at COMPASS) will require novel MC technologies. Studies of the effects of limited energy on the available phase space to generate high P_T SIDIS events have been performed for JLab and COMPASS kinematics using a multidimensional generator [7], starting from the initial transverse momenta of quarks and accounting for the energy conservation across the production process, indicating significant deformations of final distribution, compared to the respective initial input Gaussian distribution. A possible effect of limited phase space, shown for CLAS kinematics in Fig. 1, may have been also observed by the Torino group [10] in attempts to describe P_T-distributions measured in JLab Hall-C experiment [11] by using parameters extracted from fits to HERMES multiplicities.

In experiments, one measures a convolution of cross section and detector acceptance. Accounting for all the relevant azimuthal moments in the MC generators, used for detector acceptance studies, it will be crucial for properly handling of the radiative effects. As a matter of fact, the radiative effects in SIDIS also generate azimuthal moments which may couple with the moments in the Born cross section and produce more complex azimuthal structure in the observed cross section [12, 9]. Azimuthal moments generated by radiative effects may be comparable to modulations in the Born cross sections and they are very sensitivity to different input ϕ-dependent structure functions. Cosine moments generated by radiative effects, for three different input structure functions are shown on Fig.1.

As it is becoming increasingly clear, observables which are constructed by taking ratios are not ideal grounds for studies of TMDs, and in particular transverse momentum of TMDs and their evolution effects, which are the most intriguing part of 3D non-perturbative partonic distributions, and more effort should be made towards measuring properly normalized SIDIS and e+e-, and Drell-Yan cross sections (both unpolarized and polarized)[13]. The simplest input to the analysis framework could be a table of counts in a given five (semi-inclusive DIS with x, Q^2, z, P_T, ϕ) dimensional or four (hard exclusive meson/photon production with x, Q^2, t, ϕ) bins (see Fig. 2) of specific set of events (ex. $e\pi^+X$) with given states of incoming (lepton), λ, and target (proton), Λ, polarizations. The size of the bins should only be limited by the detector resolution and resources available for MC simulation of corresponding acceptances, required to get the acceptance corrected counts. Given the complexity of the extraction process, a realistic MC with solid fundamentals will be important part of the global 3D analysis framework, including the data analysis, phenomenology and extended 3D PDF library (see Fig.2) enabling validation of the whole extraction chain.

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Λ production in the DIS target fragmentation region

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The description of the particle production in the target fragmentation region of Semi-Inclusive Deep Inelastic Scattering (SIDIS) requires the introduction of fracture functions [1]. Such distributions simultaneously encode information both on the parton partecipating the hard scattering and on the fragmentation of the spectator system into the observed hadron. Their scale dependence can be calculated in perturbative QCD [1] an a dedicated factorisation theorem [2] guarantees that they are universal distributions, at least in the context of SIDIS. Among baryons, Λ hyperons are predominantly produced in the SIDIS target fragmentation region. A first attempt to determine Λ fracture functions by performing a QCD fit to a variety of Semi-Inclusive Λ production data collected in lepton-nucleon scattering has been recently presented in Ref. [3]. By using this set of Λ fracture functions, we have presented in Ref. [4] predictions for Λ observables in the target fragmentation region of neutral current (NC) Deep Inelastic Scattering (DIS) focusing on CLAS@12 GeV kinematics. As an example, we present in Fig. (1) the normalised single differential cross sections as a function of x_F in x_B and Q^2 bins on hydrogen and deuterium targets. This input from the experimental side could be valuable to test the key feature of the underlying theory, notably the Q^2 dependence, and the implementation hadron mass corrections. It may also validate many of the assumptions of the proposed phenomenological model and improve our knowledge of Λ fracture functions allowing fits with high precision data.

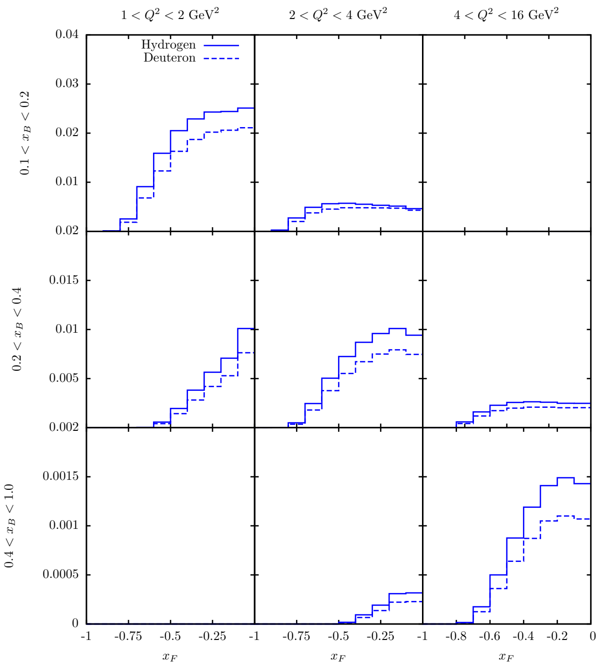

Figure 1: Normalised single differential cross sections as a function of x_F, $1/\sigma_\Omega^{\rm DIS} d\sigma^\Lambda/dx_F$, in various bins of x_B and Q^2. Distributions for hydrogen and deuteron targets are presented and correspondingly normalised.

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TMDs from unpolarised SIDIS data
Experimental overview

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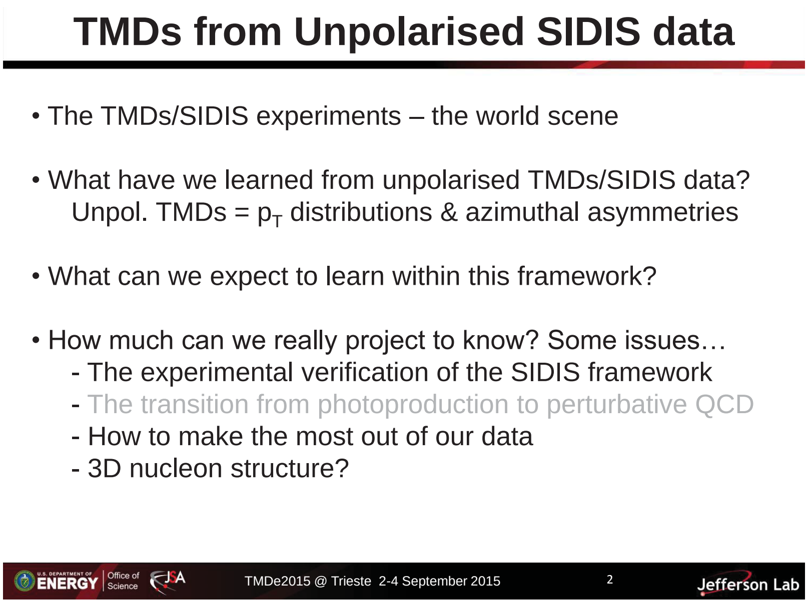

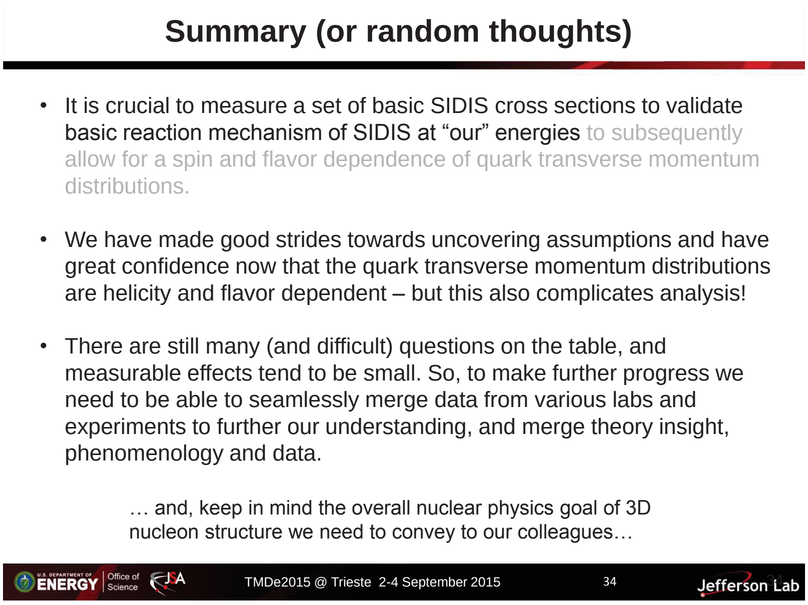

Explaining hadron transverse momentum in SIDIS: Multiplicity data and non-perturbative dynamics

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Understanding the dynamical origin of hadron transverse momenta in semi-inclusive deep-inelastic scattering (SIDIS) and related processes has become a central problem of nucleon structure physics. Much progress has been made applying formal methods of QCD factorization to hadron transverse momentum distributions in DIS at $P_{Th} \ll Q$, using the Collins–Soper–Sterman (CSS) approach to account for the effects of Sudakov–suppressed QCD radiation (TMD factorization); see [1, 2] for a review. Many questions remain, however, regarding the practical application of these methods, such as: (a) Region of applicability: Corrections to the factorized approximation; effective scale where perturbative radiation becomes relevant. (b) Structure of TMD parton distribution functions (PDFs) and fragmentation functions (FFs) at low scales: Relation to inclusive PDFs/FFs; relation to hadronic structure; differences between valence and sea PDFS, favored and unfavored FFs. (c) Transition from low to high Q^2: Matching TMD factorization with a hadronic description of hadron spectra. These questions need to be addressed before TMD factorization can be applied to extract information about nucleon structure in QCD. New insights could come from two directions: Empirical studies of hadron multiplicity data and their kinematic dependences, and theoretical studies of models of non-perturbative dynamics generating transverse momentum.

Empirical studies using hadron multiplicity data. The unpolarized differential hadron multiplicities in SIDIS and their kinematic dependences (W or x, Q^2, z, P_{Th}) are the basic material for exploring the mechanisms of hadron production and the origin of transverse momentum. The HERMES and COMPASS experiments have now published multiplicity data that enable many interesting studies [3, 4]. It is important that the data be presented such that they permit fully differential studies of the kinematic dependences in a flexible binning. Particular questions that should be addressed are:
(a) Unfavored vs. favored quark fragmentation. The QCD description of SIDIS data requires knowledge of the behavior of favored and unfavored FFs in transverse momentum and z, especially at $z > 0.5$ where major differences are expected. Favored and unfavored FFs can be separated empirically using combinations of charged pion multiplicities, with minimal additional assumptions. In LO factorization the sum/difference of charged pion multiplicites, $M(\pi^+) \pm M(\pi^-)$, are proportional to the sum/difference of favored and unfavored FFs, $D_{\text{fav}}(z) \pm D_{\text{unfav}}(z)$ [5]. Particularly instructive is the difference $M(\pi^+) - M(\pi^-)$ for the deuteron target, which is free of strange quark contributions and gives direct access to $D_{\text{fav}}(z) - D_{\text{unfav}}(z)$. Studies using HERMES data show that the ratio $D_{\text{unfav}}(z)/D_{\text{unfav}}(z)$ is surprisingly large at $z > 0.5$, challenging conventional understanding of quark fragmentation [6]. Further studies should be performed to confirm this observation and clarify its origin. The approach can be extended to study also the transverse momenta in unfavored and favored FFs.
(b) Soft dynamics in P_{Th} distributions. An important question is the role of soft (hadronic) dynamics in generating the P_{hT} distributions of hadrons observed in SIDIS at $Q^2 \gg 1\,\text{GeV}^2$. It determines what part of the hadron P_{hT} distributions in the QCD description should be attributed to genuinely non-perturbative dynamics, and what variations one should expect from perturbative CSS-type radiation. The role of soft dynamics can be studied by comparing the SIDIS hadron P_{hT} distributions at $Q^2 \sim 1\,\text{GeV}^2$ with those measured in hadro– or photoproduction experiments at the same energy. Similar studies of the "soft–to–hard transition" were performed for inclusive cross sections at HERA and proved to be most instructive in determining the boundary of DGLAP

evolution and the properties of the initial distributions; see [7] for a review. They would be equally instructive in the case of P_{hT} distributions and CSS evolution. They complement studies of P_{hT} distributions in SIDIS at the highest possible scales $Q^2 \gg 1\,\mathrm{GeV}^2$ aiming to find direct evidence of CSS evolution.

Models of non-perturbative dynamics. Models of non-perturbative QCD can play an important role in explaining the properties of TMD PDFs and FFs at a low scale. Of particular importance is the effect of dynamical chiral symmetry breaking in QCD, which is caused by non-perturbative interactions at distance scales $\rho \sim 0.3\,\mathrm{fm}$, much smaller than the typical hadronic size $R \sim 1\,\mathrm{fm}$. The effect of such interactions on the TMD PDFs in the nucleon has been studied in [8]. It is found that sea quarks have intrinsic transverse momenta up to $p_T \sim \rho^{-1}$, much larger than those of valence quarks at $p_T \sim R^{-1}$. The large intrinsic sea quark p_T have a characteristic spin–flavor dependence and occur in the flavor–singlet unpolarized $(\bar{u}+\bar{d})$ and the flavor-nonsinglet polarized sea $(\Delta\bar{u} - \Delta\bar{d})$. These predictions could be tested experimentally by separating valence and sea quark TMDs in semi-inclusive DIS, e.g., by combining charged pion or kaon multiplicity data. Indications for $p_T(\text{sea}) > p_T(\text{valence})$ are seen in a comparison of dilepton P_T distributions in pp and $\bar{p}p$ collisions [9]. Chiral symmetry breaking also suggests that the natural starting scale for CSS evolution in TMD PDFs is $Q^2 \sim \rho^{-2} \sim (600\,\mathrm{MeV})^2 \gg \Lambda^2_{\mathrm{QCD}}$ [10].
The non-perturbative interactions associated with chiral symmetry breaking also affect the process of quark fragmentation into pions and kaons [11]. Theoretical efforts should aim to develop a unified framework incorporating chiral symmetry–breaking interactions in the TMD PDFs and FFs, including the non-perturbative final–state interactions inherent in these structures ("gauge link"). Such a framework could be of considerable help in explaining the dynamical origin of hadron P_{Th} distributions in SIDIS.
More direct tests of chiral–symmetry–breaking interactions might be possible through measurements of hadron P_{Th} correlations between the current and target fragmentation regions of SIDIS, which attest to the presence of small–size correlated $q\bar{q}$ pairs in the nucleon (short–range correlations); see [8] for details. Such measurements would be possible with JLab 12 GeV and a future EIC and are an attractive option for future studies.

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TMDs from azimuthal asymmetries in transversely and longitudinally polarized SIDIS Experiments: status and perspectives

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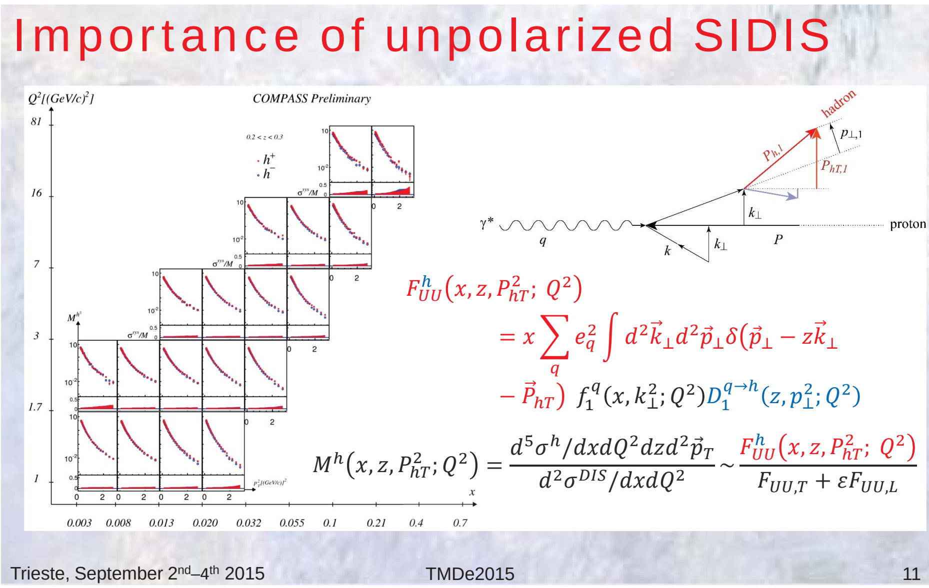

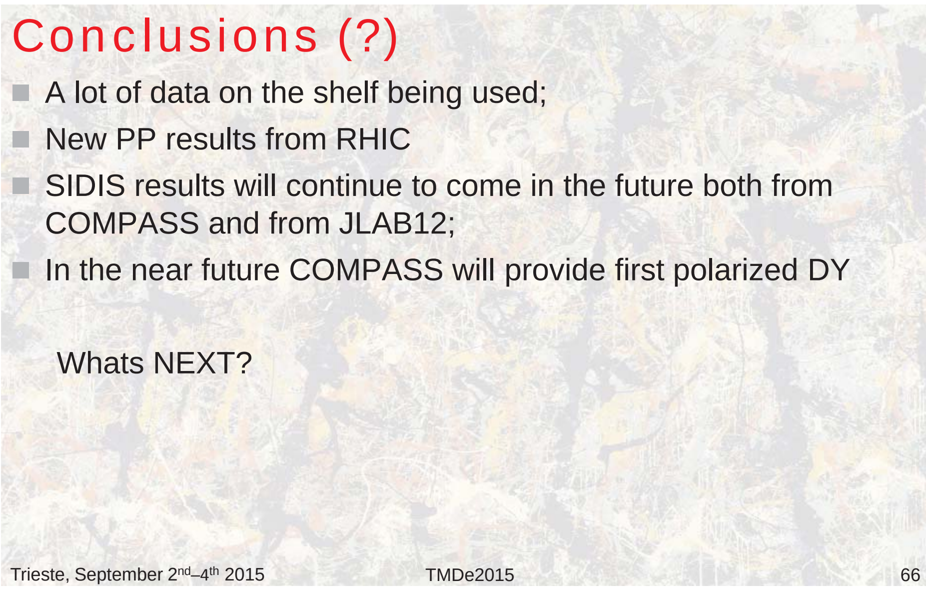

TMDs from azimuthal asymmetries in transversely and longitudinally polarized SIDIS Phenomenology: status and perspectives

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Our knowledge of the 3-dimensional partonic structure of the nucleon in momentum space is encoded, at leading-twist, in eight Transverse Momentum Dependent Parton Distribution Functions (TMD-PDFs). They depend on two variables, the light-cone momentum fraction, x, of the parent nucleon's momentum carried by a parton and the parton transverse momentum, $\boldsymbol{k}_\perp$, with respect to the direction of the nucleon's motion. At a low resolution scale Q^2 the transverse momentum $\boldsymbol{k}_\perp$ may be associated with the intrinsic motion of confined partons inside the nucleon. For polarised nucleons and partons there is a further dependence on the spins of the nucleon and the parton. In addition, the QCD radiation of gluons induces a dependence on the scale Q^2 at which the nucleon is being explored.

Similarly, the hadronisation process of a parton into the final hadron is encoded in the Transverse Momentum Dependent parton Fragmentation Functions (TMD-FFs) which, in addition to spin, depend on the light-cone momentum fraction, z, of the fragmenting parton carried by the hadron and the hadron transverse momentum, $\boldsymbol{p}_\perp$, with respect to the parton direction. For final spinless or unpolarised hadrons there are, at leading-twist, two independent TMD-FFs.

So far, among the polarised leading twist TMD-PDFs and TMD-FFs, the Sivers distribution and the Collins fragmentation function have clearly shown their non negligible effects in several different experimental measurements [1, 2, 3, 4, 5].

Unraveling the intrinsic transverse momentum dependence of TMDs is very important. The explicit dependence of the TMDs on their corresponding momentum fractions x or z is relatively easy to access, as most measured observables (cross sections, multiplicities, asymmetries) are given as functions of x or z, although still in a limited range. Instead, the transverse momentum dependence is much more involved, as $k_\perp$ and $p_\perp$ are never observed directly but only through convolutions. Asymmetries alone are not sufficient for a complete study of the Collins transverse momentum dependence, as they require the knowledge of the unpolarised TMD fragmentation functions, which appear in the denominator of the asymmetry.

Information on TMD-PDFs can be extracted from Drell-Yan (DY) processes, where two such distributions appear convoluted in the cross section. Unfortunately, very little data is presently available on polarised DY scattering. TMD-FFs, instead, can be studied by analysing $e^+e^- \to h_1\, h_2\, X$ processes, where two TMD fragmentations functions appear convoluted. At the moment, only asymmetry measurements are available. However, for a direct extraction of the $p_\perp$ dependence of the unpolarised FFs, one would need to measure transverse momentum dependent cross sections or multiplicities in $e^+e^- \to h_1\, h_2\, X$ reactions. These would, in turn, allow a safe extraction of the $p_\perp$ dependence of the Collins function from e^+e^- asymmetries.

SIDIS processes, like those measured in the HERMES and COMPASS experiments, have been and still are of paramount importance. In fact, their cross sections include the convolution between one TMD-PDF and one TMD-FF, so that they can be used to complement and bridge the information obtained, separately, from DY and e^+e^-. Unfortunately, in SIDIS processes, the $k_\perp$ and $p_\perp$ dependences are strongly correlated and cannot be disentangled unambiguously.

It is therefore clear that only global, simultaneous analyses of all available data from different experiments from DY, SIDIS and e^+e^- scattering (possibly covering wide kinematical ranges) can help us to successfully unravel the $k_\perp$ and $p_\perp$ dependences of TMDs, and lead us to the complete understanding of the 3D structure of nucleons.

Along these lines, we have performed a global analysis of SIDIS and $e^+e^- \to h_1\, h_2\, X$ scattering processes, using the most recent available world data, which I will briefly describe in what follows.

The Collins fragmentation function can be studied in Semi-Inclusive Deep Inelastic Scattering (SIDIS) experiments, where it appears convoluted with the transversity distribution, and where, being dependent on $\boldsymbol{p}_\perp$, it induces a typical azimuthal modulation, the so-called Collins asymmetry. Clear signals of this asymmetry were observed experimentally, see Refs. [1, 3, 4]. The Collins fragmentation functions also induce azimuthal angular correlations between hadrons produced in opposite jets in e^+e^- annihilation. Consequently, a simultaneous analysis of SIDIS and e^+e^- data allows the combined extraction of the transversity distribution and the Collins FFs [6, 7, 8].

We have adopted a phenomenological model for TMD–PDFs and FFs in a scheme where the cross section is written as the convolution of two TMDs with the corresponding partonic cross section. The z-dependent part of our TMDs evolves in Q^2 while the transverse momentum dependent part is Q^2 independent. This model has proven to work surprisingly well, allowing to describe a wide variety of observables: from the SIDIS unpolarised multiplicities [9, 10] to SIDIS Sivers and Collins effects [8, 11, 12]. However, a proper treatment of unpolarised as well as polarised TMDs would require the use of TMD evolution [13]. In fact, one expects that, as Q^2 grows, gluon radiations will change the functional form of the $k_\perp$ and $p_\perp$ dependence: in particular, the widths of the TMDs will generically grow with Q^2. The TMD approach is valid in the region in which $q_T \ll Q$, where $q_T \simeq P_T/z$ and Q^2 are the transverse momentum and the virtuality of the probing photon, respectively. Available SIDIS data cover the region from low to moderate Q^2. For instance the average values of Q^2 of the SIDIS data considered in the present analysis are between 2.4 and 3.2 GeV^2, while the typical transverse momentum P_T of the final hadron is between 0.1 and 1.5 GeV. Clearly, in this region, it is difficult to guarantee $q_T \ll Q$.

It is then crucial to test the validity of the TMD approach in this range of Q^2 and q_T by analysing low Q^2 data together with large Q^2 data, and to compare the results obtained by applying a TMD evolution scheme(for example Ref. [14]) to those obtained by not applying any TMD evolution (for example Ref. [15]). In principle this can be done by using e^+e^- Collins asymmetry data, which correspond to a much larger Q^2 and allow the application of the TMD evolution scheme in its range of validity. However, the observables we are analyzing are, in general, ratios or double ratios of cross sections, where strong cancellations of TMD evolution effects can occur. In fact, it turns out that the two different schemes adopted in Refs. [14] and [15] describe the experimental data equally well.

One can also study these Q^2 evolution effects by directly comparing the same azimuthal correlations measured at very different Q^2 values by BaBar–Belle and BESIII [16] Collaborations. Our model predicts almost identical asymmetries for different Q^2. Differences among BESIII and BaBar-Belle [17, 18, 19] asymmetries could be explained by the different kinematical configurations and cuts. Our predictions are in qualitatively good agreement with the present BESIII measurements, indicating that the data themselves do not show any strong sensitivity to the Q^2 dependence in the transverse momentum distribution. Also in this case, the predictions obtained from a TMD evolution approach can describe the data well: this points again to cancellations of the TMD evolution effects which occur in the ratios when computing the measured asymmetries.

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An update on the extraction of neutron SSAs from ^{3}He data

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In the next few years, several experiments involving ^{3}He nuclear targets will be performed at the Jefferson Laboratory (JLab), after the 12 GeV upgrade, with the aim at extracting information on the parton structure of the neutron, mainly in the polarized case. In particular, the three-dimensional neutron structure, described in terms of quark transverse momentum parton distributions (TMDs) [1], will be probed through spin-dependent semi-inclusive deep inelastic electron scattering (SIDIS) off ^{3}He, where a high-energy pion is detected in coincidence with the scattered electron [2]. The experimental observables are, if a transversely polarized ^{3}He target is used, the Sivers and Collins Single Spin Asymmetries (SSAs). Indeed, to clarify the flavour dependence of the involved TMD PDFs and FFs, high precision experiments, involving both protons and neutrons, are needed.

To obtain a reliable information one has to take carefully into account the structure of ^{3}He. An initial study about this problem was reported in Ref. [4], where the plane wave impulse approximation (PWIA) was adopted to describe the reaction mechanism and the ^{3}He structure was treated within the AV18 NN interaction. In the kinematics of the JLab planned experiments, an extraction procedure for the neutron information from ^{3}He data was proven to take safely into account the nuclear effects contained in the PWIA approach, and it has been used already by the experimental collaborations for experiments performed with the 6 GeV electron beam [3]. The interaction in the final state (FSI) between the observed pion and the remnant, which could give a contribution to the SSAs, is not included in the analysis of the PWIA approach of Ref. [4], where FSI are considered only within the two-nucleon spectator pair which recoils. FSI have been taken into account in a recent paper [5], where the distorted spin dependent spectral function of ^{3}He has been introduced, using a Generalized Eikonal Approximation (GEA) approach, along the lines of Ref. [6]. In Ref. [5], the nuclear recoiling system is taken to be a deuteron, so that the approach can be used only in a "spectator" SiDIS process, where a slow recoiling deuteron is detected, and not in the standard SIDIS process where a pion is detected. In the talk we have reported on an updated calculation of the ^{3}He SSAs [7], where the full FSI have been considered using the GEA approach, including any possible nuclear final state in the standard SIDIS process. The results show that the extraction procedure proposed in the PWIA study works also in this more realistic scenario, thanks to specific cancellations of nuclear effects. These results are important for the next generation of SIDIS experiments off transversely polarized ^{3}He targets at JLab [2].

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Transversity from chiral odd generalized parton distributions

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At this workshop there were several presentations of determinations of the transversity Parton Distribution Function (PDF) $h_1(x)$, extracted from SIDIS data (see talks by M. Anselmino, M. Boglione, A. Martin). It is pointed out here that *exclusive* electroproduction of π^0 and η provides another path to extracting transversity and the tensor charge [1, 2]. An accurate experimental extraction of the tensor charge is also important for determining the discovery potential of new physics from precision measurements of neutron beta decay [3]. Deeply virtual exclusive electroproduction of photons (DVCS) or mesons (DVMP) can be specified in terms of Generalized Parton Distributions (GPDs) (for a review see [4]). For pseudoscalar mesons this involves chiral odd GPDs, particularly the *transversity* GPD $H_T(x, \xi, t)$, which, in the limit of the skewdness parameter, ξ, and the momentum transfer between the incoming and outgoing proton, t, going to zero, gives the transversity PDF, $H_T^q(x, 0, 0) = h_1^q(x)$. The first moment of $h_1^q(x)$ for flavor q is the tensor charge δ_q.

In a series of papers [5–8] a flexible parameterization based on a reggeized diquark spectator model was developed in stages to account for all 8 leading twist quark GPDs - 4 chiral even and 4 chiral odd. The chiral even set was constrained by the PDFs f_1^q, g_1^q, and by the nucleon electromagnetic form factors, thereby fixing the masses, the nucleon-quark-diquark couplings, and the parameters contributing to the Regge slope. Using parity relations for the nucleon-quark-diquark wave functions, the corresponding chiral odd set was determined and subsequently compared with DVMP data. The flavor separated transversity distribution can be extracted by taking the forward limit of the GPDs $H_T^{u,d}$ entering π^o and η data as

$$H_T^{\pi^0} = \frac{1}{\sqrt{2}}(e_u H_T^u - e_d H_T^d) \qquad H_T^{\eta} = \frac{1}{\sqrt{6}}(e_u H_T^u + e_d H_T^d - 2e_s H_T^s)$$

where e_q, $q = u, d, s$, is the quark's charge. The results [9] are shown in Fig. 1a compared with the Torino group determination from SIDIS, and the Pavia group determination from dihadron fragmentation. It will be possible to sort these out in the future, with more SIDIS as well as DVMP data.

Different models and analysis methods predict a variety of tensor charges for u and d quarks, some of which are shown in Fig. 1b. The tensor charge is scale dependent, so the points in the figure have been evaluated at different Q^2 values in the few GeV region. However, as our prediction shows, the two different values of Q^2 =1 GeV^2 and 4 GeV^2, are indistinguishable within the theoretical error associated with the current extraction.

Finally, among many possible polarization measurements, the tranverse target spin asymmetries reveal transversity most directly. Fig. 2 shows our prediction for $A_{UT}^{\sin(\phi-\phi_S)}$, ϕ being the angle between the lepton and hadron plane, and ϕ_S the target transverse polarization direction. It will be especially useful for distinguishing among the different model parameterizations of transversity if COMPASS can determine this asymmetry along with other cross sections and azimuthal modulations.

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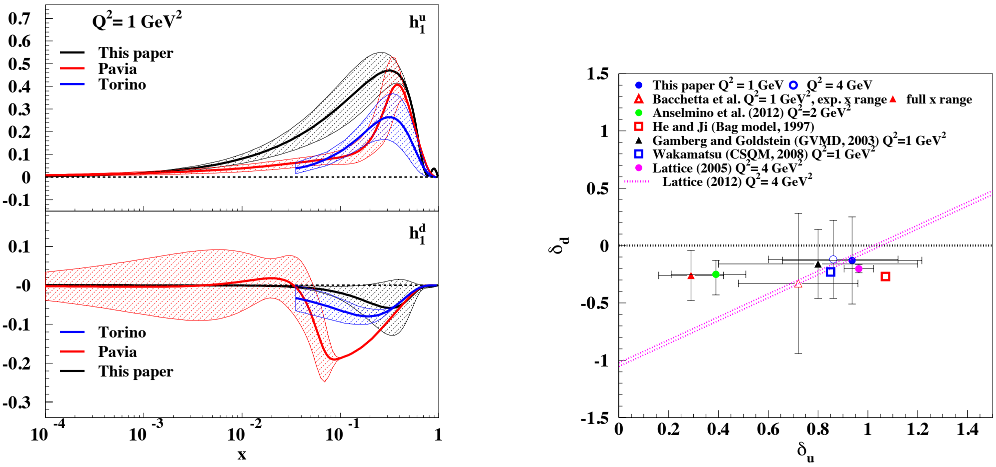

FIG. 1: Left (a): transversity, h_1^q plotted vs. x at Q^2= 1 GeV^2, for the u quarks (upper panel) and for the d quark (lower panel). Besides our analysis, the recent extractions from the Pavia group [10] obtained from dihadron production in a collinear framework, and from the Torino group [11] obtained combining data on polarized SIDIS single hadron production [12, 13], and dihadron production from e^+e^- annihilation [14]. Right (b): Tensor charge values for the d quark, δ_d plotted vs. the u quark, δ_u, as obtained from our analysis of exclusive deeply virtual processes, from the other experimental extractions existing to date: Pavia group [10] (Q^2= 1 GeV^2, flexible set), and Torino group [11], and from different models. The thin band delimited by the dotted curves is the lattice QCD result for the isovector component [15] (Q^2= 4 GeV^2). For our model we also show the effect of PQCD evolution from Q^2=1 GeV^2 to Q^2= 4 GeV^2. Adapted from Ref. [9].

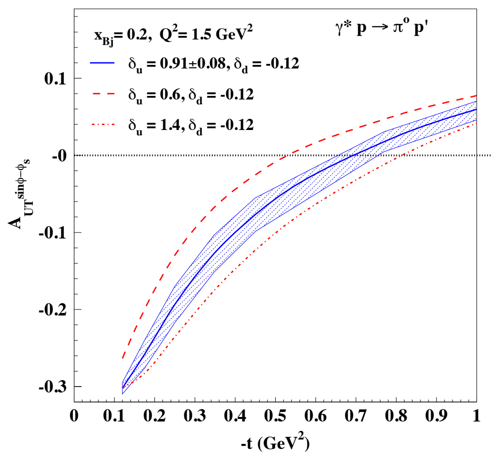

FIG. 2: (Color online) The asymmetry $A_{UT}^{\sin(\phi-\phi_S)}$, plotted vs. $-t$, at x_{Bj} = 0.2, Q^2 = 1.5 for the $\gamma^* p \to \pi^0 p'$ reaction. The error band was obtained by varying the value of the u-quark tensor charge, δ_u, by ± 0.08. The dot-dashed curve corresponds to $\delta_u = 1.4$, and the dashed curve corresponds to $\delta_u = 0.6$. The value of δ_d was kept fixed at -0.12. The graph shows the sensitivity of the asymmetry to variations of the tensor charge, or the precision that is needed in measurements of this quantity in order to reduce the size of the errors from the ones reported in Fig. 1. Adapted from Ref. [9]

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Point by point extraction of the transversity distribution

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A direct and model-independent point-by-point determination of the transversity distributions has been recently performed [1] from single-hadron production and di-hadron production results in semi-inclusive deep inelastic scattering and e^+e^- annihilation.

The extraction is based on some very simple assumptions and does not require any parametrization for the transversity and the Collins functions. The COMPASS results for proton and deuteron (produced in the same x bins and at the same muon beam energy) have been used together with the Belle results on the Collins and di-hadron fragmentation functions.

The results are in agreement with the standard extractions available at that time and are quite interesting. In particular there is an excellent agreement between the valence transversity values obtained from the Collins and from the di-hadron asymmetries. This is not an obvious result since in the point-by-point extraction the convolution over the transverse momenta has been neglected. Also, the results are quite stable with respect to different assumptions on the Q^2 evolution of the relevant fragmentation functions .

The procedure has also allowed the first direct extraction of the transversity distributions of the $\bar{u}$ and $\bar{d}$ quarks shown in fig. 1. They are both compatible with zero, and it is interesting to underline that the accuracy of this result in the case of $\bar{u}$ is comparable to that of the u valence distribution. The large statistical uncertainties in the case of $\bar{d}$ is due to the low statistis deuteron data sample of COMPASS.

The method seems robust, and we are planning to extend it to extract other distribution functions, in particular the Sivers and the Boer-Mulders functions. Its potentialities, and the relevance of data taking in the same kinematics with proton and deuteron targets, foreseen in COMPASS since the beginning, should be kept in mind in planning the new measurements at the future facilities.

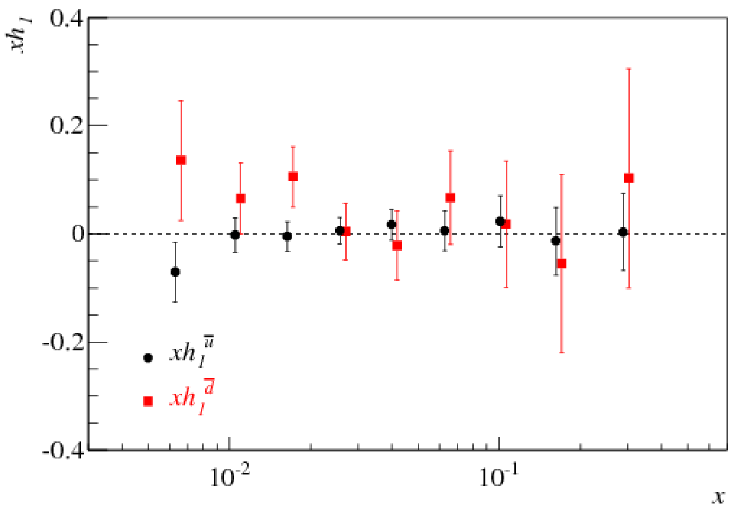

FIG. 1: The transversity distribuitions $xh_1^{\bar{u}}$ and $xh_1^{\bar{d}}$ vs. x [1] from the Collins asymmetries on proton and deuteron.

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TMD fragmentation functions Phenomenology: status and perspectives

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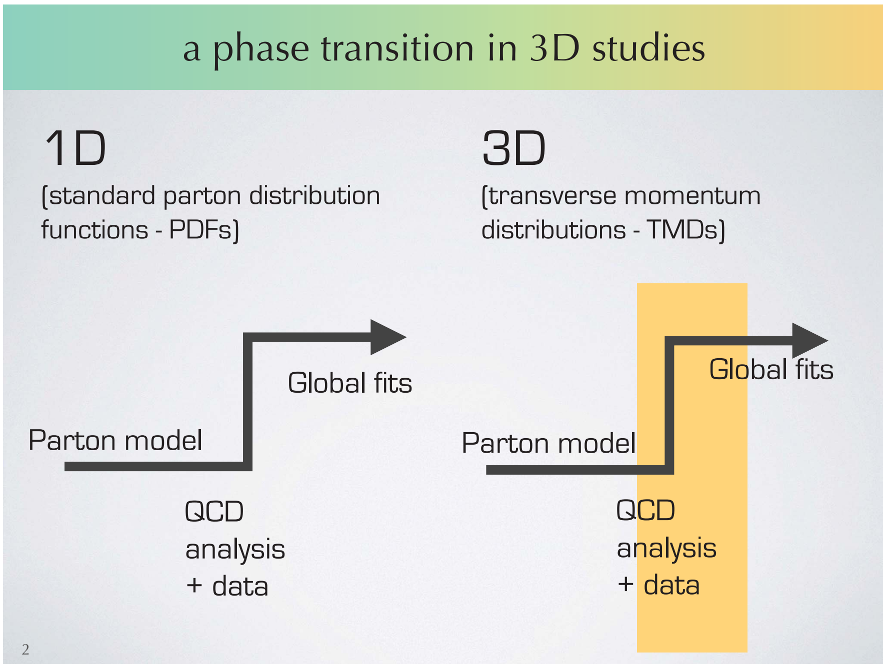

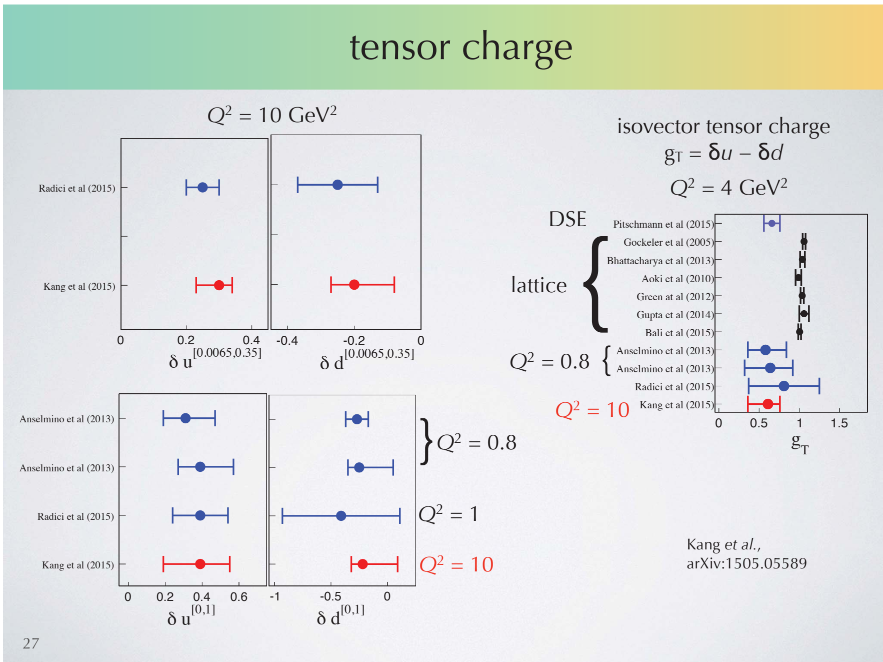

Fragmentation Function Related Measurements in e^+-e^-

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Electron-positron annihilation provides clean access to fragmentation functions and more generally allows the study of the hadronization in QCD. The long history of e^+e^- machines includes experiments at DESY and SLAC around $\sqrt{s}$ of 30 GeV performing pioneering QCD measurements, experiments at CERN and SLAC at $\sqrt{s} = M_Z$ as well as the charm factories CLEO-c and BES. However, only the arrival of the B factories Belle and BaBar made the high precision measurement of spin-dependent correlation measurements in e^+e^- possible and therefore opened the way to extract spin dependent fragmentation functions. First measurements of the Collins effect [1, 2] and di-hadron correlations [3] allowed the first extraction of the respective transverse polarization dependent fragmentation functions and the extraction of transversity [4, 5]. Another milestone was the precise measurement of identified pion and kaon cross-sections [6, 7], which provide important input for the global fit of fragmentation functions [8]. More recently Belle has reported the measurement of di-hadron correlations in back-to-back jets, [9]. This measurement is sensitive to the transverse momentum dependent (TMD) fragmentation function $G_1^\perp$. The fragmentation function $G_1^\perp$ describes the correlation of the intrinsic transverse momentum in the fragmentation process with the quark helicity. Such a correlation is only allowed in the TMD framework and the measurement is therefore an important test of the same. Due to its connection to jet-handedness, $G_1^\perp$ has also interesting connections to local strong parity violating effects [10]. However, the Belle measurement is consistent with zero on the few per-mille level. One interesting future development will be the partial wave decomposition of this asymmetry. It is expected that only a small set of partial waves is contributing to the correlation that Belle measures. However, the measurement is averaging over all partial waves, diluting a potential effect. The path to a multidimensional extraction of observables is also taken for the current generation of Collins and hadron cross-section measurements. Babar showed already pion and kaon Collins results vs. z and p_T [11, 12]. Belle is working on a p_T dependent extraction of the charged pion and neutral meson (π^0, η) Collins effects. It is also worth mentioning the recent measurement of the Collins effect well below the $\sqrt{s} = \Upsilon(4S)$ by BESIII, which was also presented at this meeting. Belle is working on a p_T dependent extraction of the spin averaged cross-section for various charged hadron species. One open question is the experimental definition of the intrinsic transverse momentum p_T. One possibility is the measurement of back-to-back hadrons and use of the p_T imbalance between the hadrons. This quantity is sensitive to the convolution of the p_T dependence of the quark and anti-quark fragmentation functions. Alternatively the p_T can be defined with respect to the thrust axis or the jet axis in back-to-back di-jets. The latter has experimental advantages in correlation measurements, since it minimizes auto-correlations between the hemispheres. Back-to-back hadrons also allow the access to the flavor structure of the fragementation process, while hadrons in the same hemisphere provide access to the di-hadron fragmentation function. Belle recently published [13] the first measurement of di-hadron fragmentation (both, back-to-back and same hemisphere), albeit p_T integrated. Analyses are underway to determine the p_T dependence in back-to-back hadrons as well as using the thrust axis as well as the polarizing Λ fragmentation function. The results and ongoing activities discussed above all pertain to leading twist fragmentation functions. Recently, there has been quite some activity centering on the theory of collinear, polarization dependent twist3 fragmentation functions. However, to this authors knowledge, no experimental observable that is uniquely sensitive to these FFs in e^+e^- has been defined yet. In the near future, the Belle II experiment will allow the measurement of fragmentation function sensitive observables at even higher precision than Belle and BaBar with state-of-the-art PID and vertex detection. This will significantly reduce systematics due to charm contribution and PID uncertainties in particular in multi-kaon final states [14].

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Collins asymmetries in e^+e^- annihilation

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Abstract: Inclusive hadron production cross section and angular distributions in e^+e^- collisions shed light on fundamental questions of hadronization and fragmentation processes. We present measurements of the so called Collins azimuthal asymmetries in inclusive production of hadron pairs in $e^+e^- \to h_1 h_2 X$ annihilation process, where the two hadrons are produced in opposite hemispheres. In particular, we show BaBar preliminary results for KK, and Kπ hadron pair combinations, as well as the Collins asymmetries for pion pairs. We also report the preliminary results from the BESIII experiment, which studies pion pairs azimuthal asymmetries using a data set collected at the center-of-mass energy $\sqrt{s} = 3.65$ GeV. The comparison between asymmetries measured at B factories ($\sqrt{s} = 10$ GeV) and those measured at BESIII can be used as a tool to understand the evolution of the Collins fragmentation function.

Interplay between the Collins and the di-hadron asymmetries

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The recent COMPASS results on the interplay between the Collins asymmetry and the di-hadron asymmetry [1] are briefly presented. The high precision COMPASS measurements on transversely polarized protons showed that in the x-Bjorken region, where the Collins asymmetry is different from zero and sizable, the positive and negative hadron asymmetries exhibit a mirror symmetry and the di-hadron asymmetry is very close to the Collins asymmetry for positive hadrons. These facts have been interpreted as experimental evidence of a close relationship between the Collins and the di-hadron asymmetries, hinting at a common physics origin of the two fragmentation functions, as suggested in the $^3P_0$ recursive string fragmentation model.

In order to better investigate the relationship between the Collins asymmetry and the di-hadron asymmetry the correlations between the azimuthal angles of the final state hadrons produced in the SIDIS process $\mu p \to \mu' h^+ h^- X$ have been studied using the COMPASS data. The investigation has proceeded through three major steps:

1. the Collins asymmetries for positive and negative hadrons have been compared with the corresponding asymmetries measured in the SIDIS process $\mu p \to \mu' h^+ h^- X$, i.e. when in the final state at least two oppositely charged hadrons are detected (2h sample): the Collins asymmetry turned out to be the same, independently of the presence or absence of other hadrons, thus the 2h sample can be used to investigate the interplay among the asymmetries.

2. Using the 2h sample the asymmetries of h^+ and h^- have been measured and their relation has been investigated as function of $\Delta\phi$, the difference of the azimuthal angles of the two hadrons. Also in this case there is a mirror symmetry.

3. The di-hadron asymmetry has been measured as function of $\Delta\phi$ and compared with the h^+ and h^- asymmetries.

Using the original formalism described in the paper it has been possible to calculate the $\Delta\phi$ dependence of the three asymmetries which agree very well with the data providing a simple relation among the relevant structure functions. The $\Delta\phi$ integrated values of the three asymmetries have also been compared and, within statistics they agree with the expectation from the general expression.

As a conclusion the new COMPASS result provides further evidence that both the single hadron and di-hadron transverse-spin dependent fragmentation functions are driven by the same elementary mechanism.

The possible implications on the transversity extraction and the feasibility of the same studies in e^+e^- annihilation are proposed for discussion.

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Dependence of 2h SIDIS structure functions on $\Delta\phi$

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Abstract: The general formalism to study the dependence of 2h SIDIS structure functions on $\Delta\phi$. Examples:
1) Sivers effect in 2h production in CFR.
a) General formula and convolution expressions for SFs
b) Results based on mLEPTO and comparison with released COMPASS data
2) $A_{LU}^{\sin\Delta\phi}$ asymmetry in b2b SIDIS (one hadron produced in the CFR and the second in the TFR). Leading order expression based on fracture and fragmentation functions. Preliminary data from JLab CLASS experiment.

Transverse Spin Effects in Two Hadron Electroproduction

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Abstract: The measurement of various angular single spin asymmetries (SSA) in a single hadron production off a transversely polarized target in semi-inclusive deep inelastic scattering (SIDIS) process allows to access both the Sivers and Collins effects describing the correlations of the the transverse spin and transverse momenta in both parton distribution and fragmentation functions. In our recent work we have explored both Sivers and Collins effects in the two-hadron SIDIS process. We showed that non-vanishing Sivers-effect-induced SSAs exist for modulations involving sines of the azimuthal angles of both the total and the relative transverse momenta of the hadron pair with respect to the the azimuthal angle of the nucleons transverse spin. We have made projections for the sizes of these SSAs for the kinematics of the CLAS12 and EIC experiments. Similarly, in the fragmentation of a transversely polarized quark we used the NJL-jet model to demonstrate that Collins effect generates modulations of the polarized fragmentation function involving the sines of the same azimuthal angles of the hadron pairs transverse momenta, now with respect to the transverse quark spin. Moreover, our results for the Collins effect modulations are consistent with the recent experimental measurements by the COMPASS collaboration. These results help to demonstrate that the experimental measurements in two hadron SIDIS process can provide additional information for precise extractions of Sivers and Collins functions.

Bessel and p_T weighted asymmetries

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Conclusions cont.

- Propose generalized Bessel Weights to study 3-D structure of the nucleon
- Bessel Weighting solves problem of infinite contribution from large transverse momentum that arise from using "conventional weighting
- Provides a regularization of infinite contributions at lg. transverse momentum when $\mathcal{B}_T^2$ is non-zero
- Soft, Hard CS, eliminated from weighted asymmetries, Sudakov dpnds coupling of *b* & *Q*
- Possible to compare observables at different scales.... could be useful for an EIC

Comments on Weighting

- Using technique of weighting enables one to disentangle in a model independent way the CS in terms of transverse momentum moments of TMDs
- Convert the convolutions in the cross section into simple products
  not a new idea **Kotzinian, Mulders PLB 97, Boer, Mulders PRD 98**
- Bessel Weighting solves problem of infinite contribution from large transverse momentum that arise from using "conventional weighting
  Boer, Gamberg,Musch,Prokudin JHEP 2011
- Explore impact these BWA have on studying the scale dependence of the SIDIS cross section at small to moderate transverse momentum where the TMD framework is expected to give a good description of the cross section **Boer, Gamberg, Musch,Prokudin JHEP 2011**

4π and Multi-D TMDs Measurements

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The main objectives of ongoing and future TMDs studies is the understanding of the internal structure of the nucleon (nucleus) and hadron formation in terms of quarks and gluons, the fundamental degrees of freedom of QCD. By gathering active parton dynamics mechanisms like spin-orbit effects, short-range correlations or momentum broadening through nuclear medium, and making educated guess on parton behaviour, i.e. average transverse momentum and orbital motion, TMDs connect with the ultimate manifestations of the strong-force confinement.

Most of our present understanding derives from inclusive deep inelastic scattering (DIS) experiments performed over the past four decades in different kinematic regimes at fixed-target experiments and collider machines. Based on their large amount of data we have reached a good knowledge of the parton longitudinal-momentum and longitudinal-spin distributions of quarks in the nucleon. Such investigation is based on the so-called collinear factorization of the cross-section into non-perturbative parton distribution functions (PDFs) and fragmentation functions (FFs), a mono-dimensional approach where the given 'longitudinal' direction is the one of the hard probe (the exchanged virtual boson).

In order to describe the rich complexity of the hadron structure one has to take into account the parton transverse degrees of freedom, moving towards the achievement of a 3D comprehension of the parton dynamics. New channels of investigation have been gaining importance as the study of semi-inclusive deep inelastic-scattering (SIDIS) reactions where the hadron produced by the struck quark is observed in conjunction with the scattered lepton probe. The analysis and interpretation of the observables require however an unprecedent level of sophistication as PDFs and FFs appear in convolutions of their own transverse momenta.

This relatively recent field has experienced few exciting years with several first observations of not-zero signals and a correspondingly fast theoretical progresses. Nonetheless few steps are still necessary to eventually enter a mature phase with precise measurements leading to unanmiguous interpretations and rigorous treatments.

The unintegrated SIDIS cross-section has several polarization-dependent terms with specific azimuthal modulations and kinematic dependences that provide independent information on the parton dynamics. The relevant kinematical variables are the one related to the lepton scattering (Bjorken x and exhanged boson virtualy Q^2), the ones related to the leading hadron (the energy fraction z and the transverse momentum $P_{h\perp}$) and the azimuthal angles of the target spin ϕ_S and the produced hadron ϕ_h around the virtual boson axis. Any study aiming to access the 3D parton dynamics has necessarily to deal with all the above variables at once, working in a "multi-D" (multi-dimensional) space. This requires a novel approach able to correctly take into account the underlaining correlations, i.e. avoid cross-talk between the cross-section terms and isolate the leading contributions. Because a complete "4π" angular coverage is pretty hard to obtain in an experiment, a careful choice of ranges and binning taking into account the limits imposed by the experimental apparatus and a verification of the intervals of validity of the dynamics under study have to be performed in the entire multi-D space.

This has to be done consistently among the various experiments in order to be sure to probe the same dynamics over various reactions (to test universality) and energy domains (to assess evolution). A relevant example are the average transverse momentum studies on unpolarized distributions. Precise multi-D results on hadron multiplicities and their azimuthal dependences have been recently released by HERMES [1, 2] and COMPASS [3, 4]. Despite the high-statistics data sets have been collected on both Hydrogen and Deuterium targets and analyzed binned in all the relevant kinematical variables exploiting hadron identification in the final state, no clear indication could have been extracted about a possible flavor dependence. The reason is the convolution of parton distribution and fragmentation functions embedded in the observables, which can be solved only with complementary multi-D fragmentation analyses (ongoing) at e^+e^- colliders.

When dealing with multiple kinematic dependences, one has to consider that any binned analysis has an implicit integration inside the bin phase space which folds together physics and instrumental effects.

As a consequence, acceptance effects does not necessarily cancel even in the so-called spin asymmetries widely used for measuring polarisation-dependent terms of the cross-section, being considered a robust observable where most of the systematics due to instrumental artefacts cancel at first order. This is particularly true in case of mono-dimensional analyses, where the unwanted variables are integrated over in the full range spanned by the experiment. Any consequent phenomenological fit will earn such an underlain approximation. Standard collinear analyses provide a relevant example: in case of not-uniform azimuthal acceptance, an un-integrated analysis is necessary to control the systematics, as unwanted cross-section contributions would survive the incomplete azimuthal angle integration. A fine multi-D binning in all the relevant kinematical variables naturally suppresses the integration effects, however manifests the accetance leaks which can not be anymore neglected. In particular, a limited coverage in the azimuthal angles, which could concentrate into specific corners of the phase space, implies cross-talks between the extracted cross-section moments and the likely appearance of un-physical modulations. As a complete coverage of the azimuthal modulation is quite complicate to obtain for a single experiment, a synergy among various experiment could extend the reach of measurements provide by each of them. In case of partial coverage, an un-binned maximum likelihood method can be used to maximize the sensitivity in extracting the azimuthal dependences.

An abvious goal of multi-D analyses is to disentangle the various kinematical dependences. For example, the dependence on x, a natural choice for parton distributions, should be distinghuised by the one in Q^2, which originates from evolution or subleading contributions. Data at fixed-target experiments range from 1 up to 20 GeV^2, whereas B-factory data are taken at a center-of-mass energy of about 100 GeV^2. In order to extract phenomenological information from a combinet data set, a proper Q^2 evolution has to be taken into account. TMD evolution differs from DGLAP and encloses non-perturbative coefficients which can only be extracted from data themself. Sizeable sub-leading contributions to the cross-section has been identified by all fixed-target experiments, with a sizeable magnitude irrispective of the center-of-mass energy [4, 5, 6]. However, their expected Q^2 dependences has not been clearly proven so far. In the limited phase space accessible at fixed target experiment, the x and Q^2 variables are largely correlated. As a consequence, a complete disentanglement of the two dependencies could be achieved with analysis on high-statistics data sample and common to complementary experiments, an approach foreseen for the upcoming JLab experiments.

In a multi-D analisys each single bin (i.e. kinematical corner) matters and a careful evaluation of the systematics effects, unwanted contributions and range of validity of the TMD study, has to be performed in the multi-D space. In particular, the usual criteria based on uniform selections or statements derived from average values should be superseded to account for possible kinematic correlations. Relevant examples are:

- the TMD factorization is valid in the limit of transverse momentum $P_{h\perp}$ much smaller than the hard scale Q^2, whereas at large $P_{h\perp}$ a collinear factorization holds with higher-twist parton functions; to localize the large tails in the $P_{h\perp}^2/Q^2$ ratio is therefore relevant for the matching with high-$P_{h\perp}$ perturbative calculations;

- to take under control the perturbative part of the cross-section calculations, a high-Q^2 (i.e. several GeV^2) is usually required; in an experiment, the practical upper limit in Q^2 at given x is not defined only by the center-of-mass energy, but also as a result of the balancing with acceptance and luminosity;

- the TMD approach is meant for the so-called SIDIS current region which correspond to the struck quark fragmentation; for a clear interpretation one should avoid kinematic regions influenced by the target remnant fragmentation (Berger criterion at low z) or dominated by a single channel (quasi-exclusive events at high z);

- each cross section term has a kinematic prefactor that depends on the longitudinal to transverse photon flux ratio, i.e. can be interpreted as a depolarization factor, and acts as an analyzing power depending mainly on y; regions with a large depolarization should be isolated as their statistics dilute the signal with N but only improves the error with $\sqrt{N}$, where N is the number of events.

- to get a polarized target is a technological challenge and many experiments use solid state targets (like NH_3, ND_3) with a sizeable dilution from not-polarized heavy-nucleus material: the nuclear effects tipically cause a broadening of the $P_{h\perp}$ distribution, with an effect increasing with $P_{h\perp}$, thus affecting exactly the dependence object of the TMDs study;

- the smearing due to instrumental effects (i.e. on the particle momentum) propagates into the uncertainty of the wanted kinematical variables (i.e. x) in a non linear way depending also on other variables;
- the radiative corrections alter the event kinematics, cause a migration of events between the bins and therefore introduce a cross-talks among the various terms of the SIDIS cross-section Fourier decomposition: to get a proper correction a full knowledge of the hadron tensor (and its full 4D kinematical dependence) is in principle necessary.

A fine binning in all the relevant kinematic variables naturally reduces the correlations between the cross-section and detector acceptance kinematical dependencies. It therefore diminishes one of the major source of systematic uncertainty. However the bin number increases very rapidly in multi-D, moreover unfolding smearing and radiative effects introduces a statistical correlation which inflate the statistical errors in a way that is inversely proportional to the bin size. A multi-D analysis should therefore care about the balancing of the statistical and systematics errors in the multi-D space and is appropriate only for high-luminosity experiments.

In order to project the multi-D information and single-out a specific kinematic dependence, the detailed knowledge of the unpolarized cross-section is in principle required. A cross-section model (which introduce assumptions) or a statistical weighted-average (which folds in the instrumental acceptance) can be used as an effective alternative. In any case the statistical (and systematic) correlation between the projected measurements has to be taken into account.

In summary, the challenge posed by the modern 3D exploration of the strong-force micro-cosmos requires novel multi-D analysis tools and protocols that have not being fully developed yet. These comprise multi-D binning and systematic control, statistical and systematic correlation management, proper physics regime identification, novel ways to present or exploits the outputs. They will be required to superseed the hystorical collinear approximation that, neglecting the transverse degrees of freedom, is largely insensitive to the rich parton dynamics. Such developments will be necessary to exploit the mass of data anticipated by the upcoming or under development facilities, and in preparation of a future EIC.

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Inclusion of partonic transverse spin and TMD in MC generators

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A largely unsolved problem for TMD-including generators is the inclusion of parton-level spin, in particular transverse spin. Some criteria have been developed in the literature, to properly handle these partially unobservable variables in a generator, avoiding the violation of conservation laws, of the Heisenberg principle and entanglement properties. The main practical difficulty is the need of a second-time generation of some variables backward along a chain of steps, so that the generation of a single event becomes a recursive and rather complicated process. Simplified procedures are under consideration by myself and other authors.

What is still missing in the theoretical background is:

- A form for the hard matrix elements, fully dependent on transverse spins.
- A theoretical recipe stating how spin / tensor properties change along the chain of parton branchings.
- A spin-dependent systematic hadronization mechanism, for example a generalization of the Lund string model.
- A well-establish transverse-spin-selective evolution framework, that allows the code to establish a borderline between large angle and collinear branching processes, so to avoid a double counting of the latter (once explicitly, once in evolution).

In addition, several processes that are of interest for such a generator are interference processes between channels that are normally handled as alternative event modalities. Devices to rewrite them as classical probabilistic processes are needed.

The Gluon Sivers effect measurement at COMPASS from high-p_t hadron pairs

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Abstract: The COMPASS collaboration has recently released results of the gluon contribution to the Sivers effect measurement from high-p_t hadron pairs both for proton and deuteron targets. The analysis method is based on the assumption that in the high Q^2 range three processes contribute to the cross section: Leading Process, QCD Compton and Photon Gluon Fusion. The selection of high-p_t hadron pairs enhances the fraction of PGF events in the sample and assures weak kinematic dependence of the asymmetries for each process. A novel approach of event-by-event weighting based on Monte Carlo simulations and with the use of Neural Networks is applied to extract all three asymmetries from the same data sample.

Estimating the gluon Sivers function from A_N data in polarized pp collisions at RHIC

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Abstract: Within a generalized TMD parton model we use the latest highly precise mid-rapidity data on A_N for inclusive neutral pion production in polarized pp collisions by the PHENIX Collaboration to get a first estimate of the still poorly known gluon Sivers distribution. To this end we adopt present information on the quark Sivers functions as extracted from SIDIS data. These results, together with the recent preliminary analysis on the extraction of gluon Sivers asymmetry in SIDIS by the COMPASS Collaboration can help in clarifying the role of the gluon contribution to the Sivers effect. S