TMD Studies: from JLab to EIC

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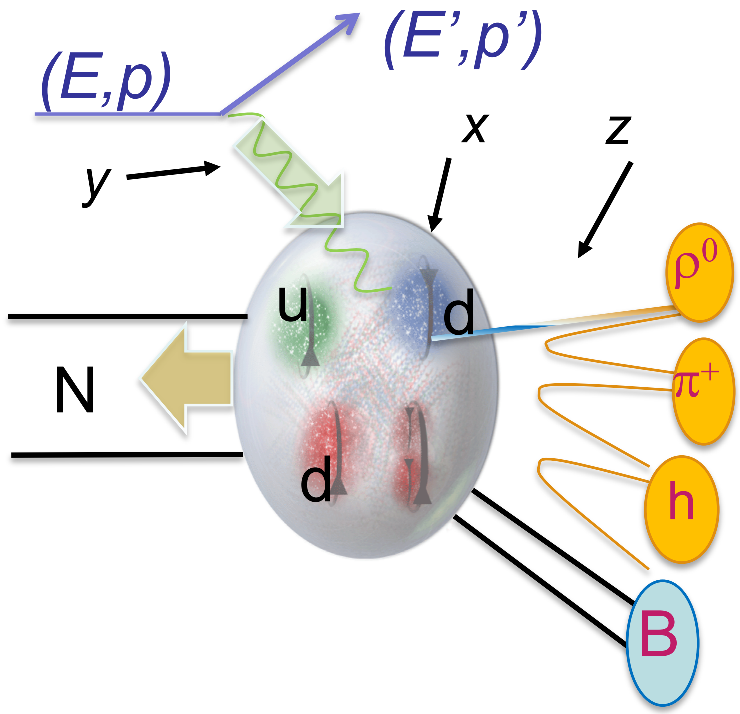
https://jlab.bluejeans.com/268057570

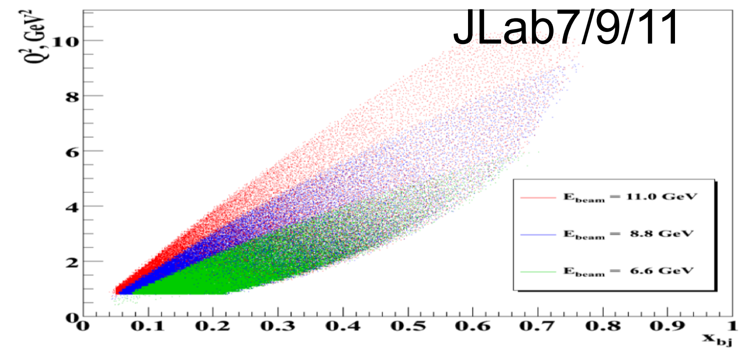
Alessandro Bacchetta (University of Pavia and INFN Pavia) , Haiyan Gao (Duke University) , Harut Avagyan (Jefferson Lab) , Jian-ping Chen (JLab) , Jianwei Qiu (Jefferson Lab) , Kyungseon Joo (University of Connecticut)

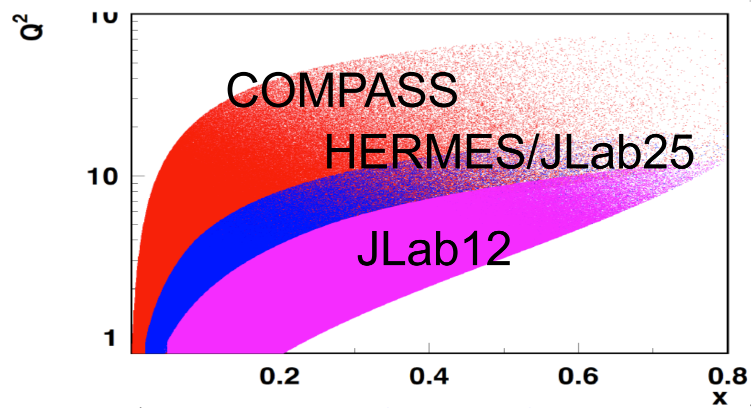
Harut Avakian (JLab)

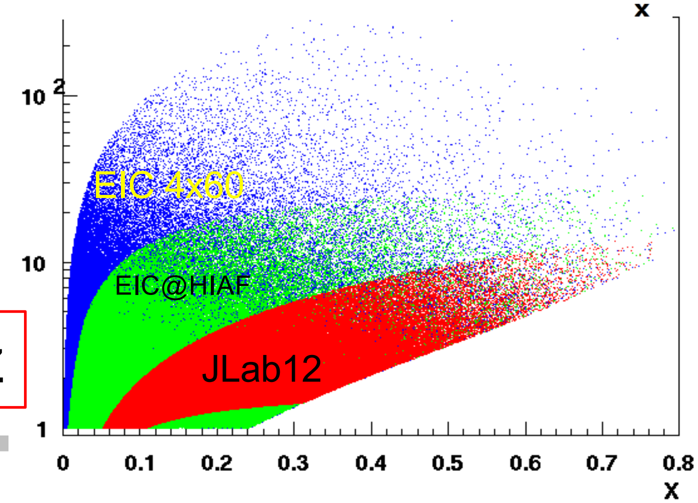
- Evaluation of the SIDIS and the TMD program at large x
- TMD extraction framework, assumptions, approximations, input data, output parameterizations/grids
- Predictions and projections for SSAs (Sivers,…)
- Complementarity of JLab and EIC
- Radiative Corrections and MC simulations
- Upgrade possibilities

SIDIS kinematical coverage and observables









$$\sigma = F_{UU} + P_t F_{UL}^{\sin\phi} \sin 2\phi + P_b F_{LU}^{\sin\phi} \sin\phi \dots$$

$$\int d^2\vec{k}_T d^2\vec{p}_T \delta^{(2)}(z\vec{k}_T + \vec{p}_T - \vec{P}_T)$$

$$F^h_{XY}(x, z, P_T, Q^2) \propto \sum H^q \times f^q(x, k_T, ..) \otimes D^{q\to h}(z, p_T, ..) + Y(Q^2, P_T) + \mathcal{O}(M/Q)$$

beam polarization

target polarization

corrections for the region of large kT~Q

$\boxed{q_T = P_T/z}$

PAC request for reevaluation

From PAC review of CLAS12 Long.Pol. experiment:

…the [DIS/SIDIS] proponents should come back to the PAC after the significance of the different experiments addressing PDFs, <u>helicity PDFs and TMDs has been reevaluated.</u>

estimates of their effects. For example, the TMD description of SIDIS is valid in the small-p_T regime when $p_T^2/(zQ)^2 \ll 1$, and in a recent study [JHEP 06 (2020) 137] finding that $p_T^2/(zQ)^2 \lesssim 0.06$ approximately demarcates the boundary to large p_T, where a description in terms of TMD PDFs may not be trustworthy. By comparison, values for this ratio as large as ~ 2 are often found for the kinematics covered in JLab TMD-oriented proposals. Such observations do not negate the value and importance of the measurements, but they should be addressed directly in the proposals, and their potential impact on interpretation should be discussed more explicitly.

Indication of a gap between theory and experiment?

Understand the source, and evaluate the impact of q_T limitations!

Impact of the q_T/Q cut

JLab/HERMES/COMPASS/EIC talks

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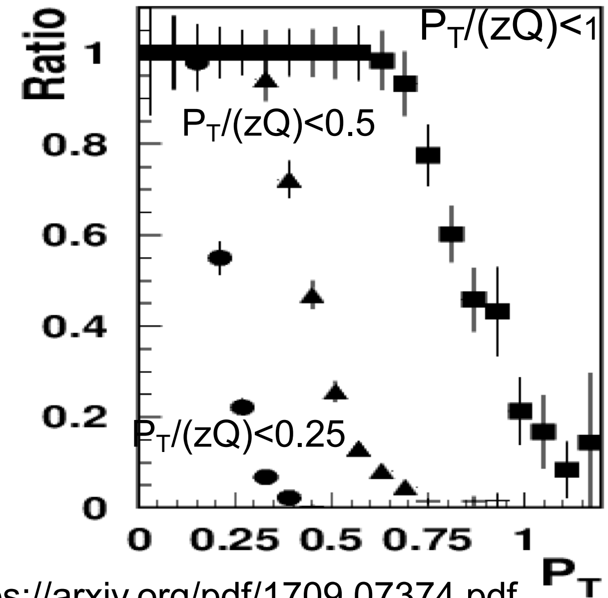
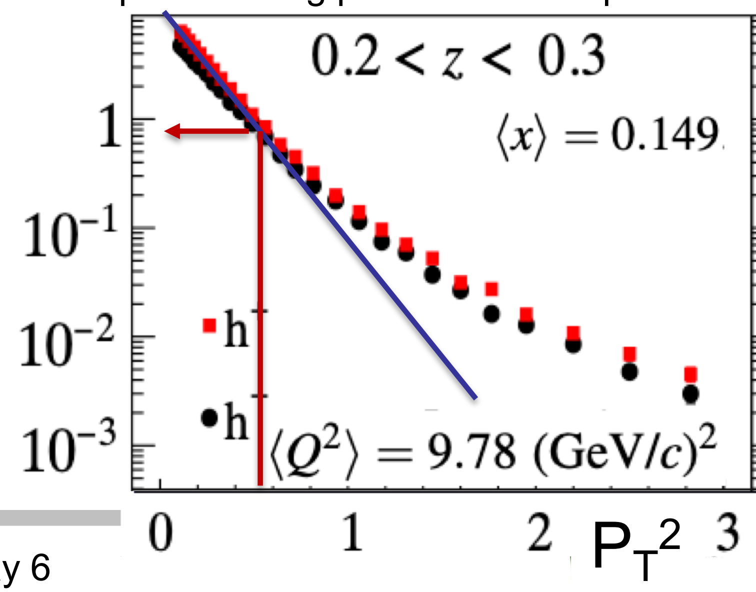
JLab12



https://arxiv.org/pdf/1709.07374.pdf



The $q_T=P_T/z$ cut, as formulated:

1) Enhances large z region (ex. Exclusive Events)
2) Suppresses high P_T (sensitive to k_T), where all kind of azimuthal modulations are large
3) Cuts not only most of the JLab data, but practically all accessible in polarized SIDIS large P_T samples , including ones from HERMES (Schnell) COMPASS (Parsamyan) and EIC(Dilks).

TMD extractions, parameterizations, grids

Important note from theorists: parametrizations should be used in the kinematics they are applicable. Validations mostly done for given Fragmentation Functions, by variations of experimental data within errors(TMD extraction talks).

How to validate the TMD parameterization in 3D (discussion session):

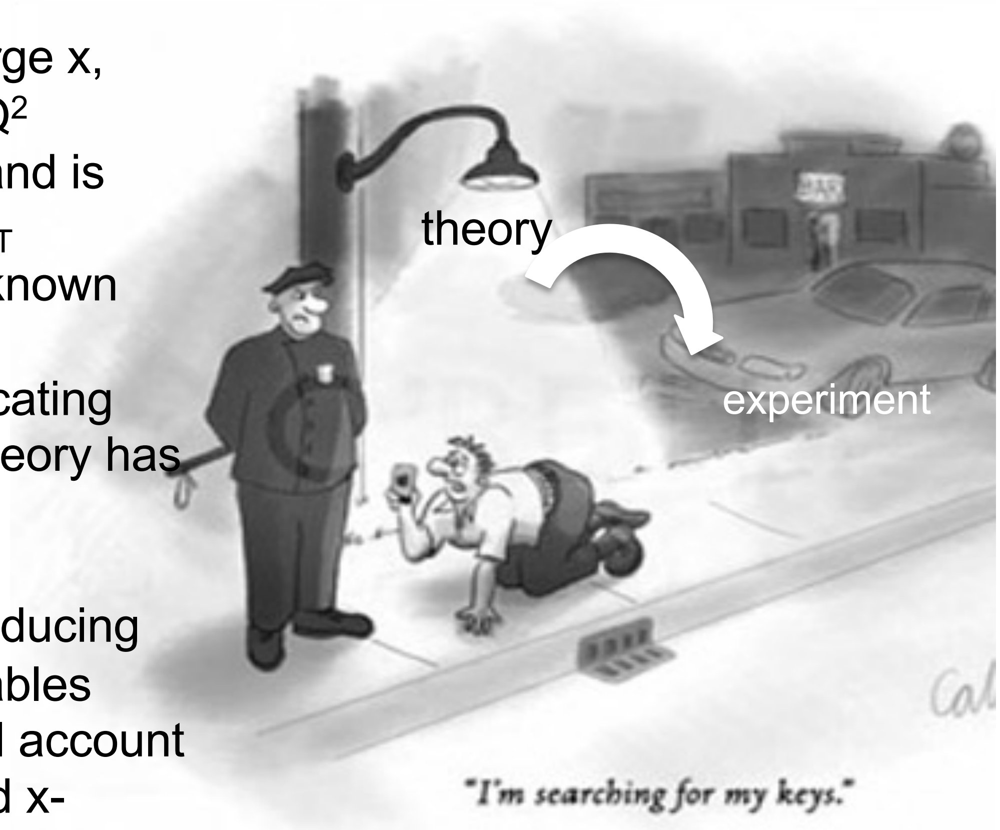
- Compare kinematic dependences with new data (ex. P_T,Q^2-dependences)
- Compare kinematical dependences with direct calculations and lattice
- Compare kinematical dependences with other extractions
- Compare kinematical dependences with QCD inspired model predictions
- Common sense & intuition about non-perturbative kinematics

Use MC validation: generate pions with probabilities from extracted SFs for a given experiment, including the RC and compare multiplicities and SSAs with a given experiment (accounting phase space limitations & correlations between variables)

$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}\big(M/Q\big)$$

Nucleon structure, TMDs and SSAs

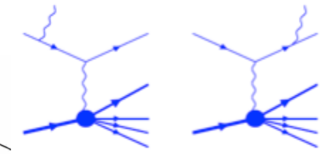
- Large effects observed at relatively large x, relatively large P_T and relatively low Q^2
- Theoretical framework works better, and is “trustworthy” at higher Q^2 and lower P_T
- TMD Fragmentation functions poorly known and understood (R. Seidl)
- Higher twist SSAs are significant, indicating strong quark-gluon correlations, but theory has issues
- Real experiments have “phase space limitations” due to finite energies, introducing correlations between kinematical variables
- Impact of radiative corrections with full account of azimuthal moments in the polarized x-sections still in development

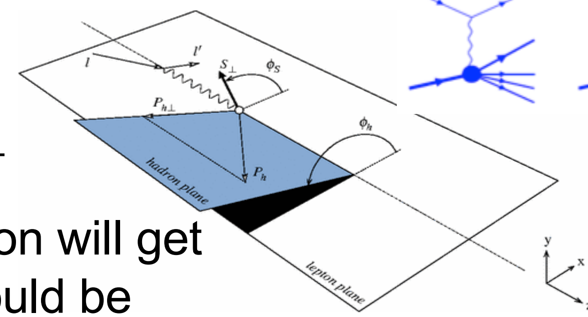


Testing and understanding of the current TMD framework with all its assumptions and approximations, in kinematics safe for formalism is certainly important
The main goal is the study of non-perturbative QCD, through spin-orbit correlations, where they are significant enough to be measurable

Experiments measure the full x-section with RC

Tianbo Liu
Igor Akushevich





$$\sigma = \sigma_{UU} + \sigma_{UU}^{\cos\phi} cos\phi + S_T \sigma_{UT}^{\sin\phi_S} \sin\phi_S +$$

Due to radiative corrections, ϕ-dependence of x-section will get multiplicative R_M and additive R_A corrections, which could be calculated from the full Born (σ_0) cross section for the process of interest

$$\sigma_{Rad}^{ehX}(x,y,z,P_T,\phi,\phi_S) \rightarrow \sigma_0^{ehX}(x,y,z,P_T,\phi,\phi_S) \times R_M(x,y,z,P_T,\phi) + R_A(x,y,z,P_T,\phi,\phi_S)$$

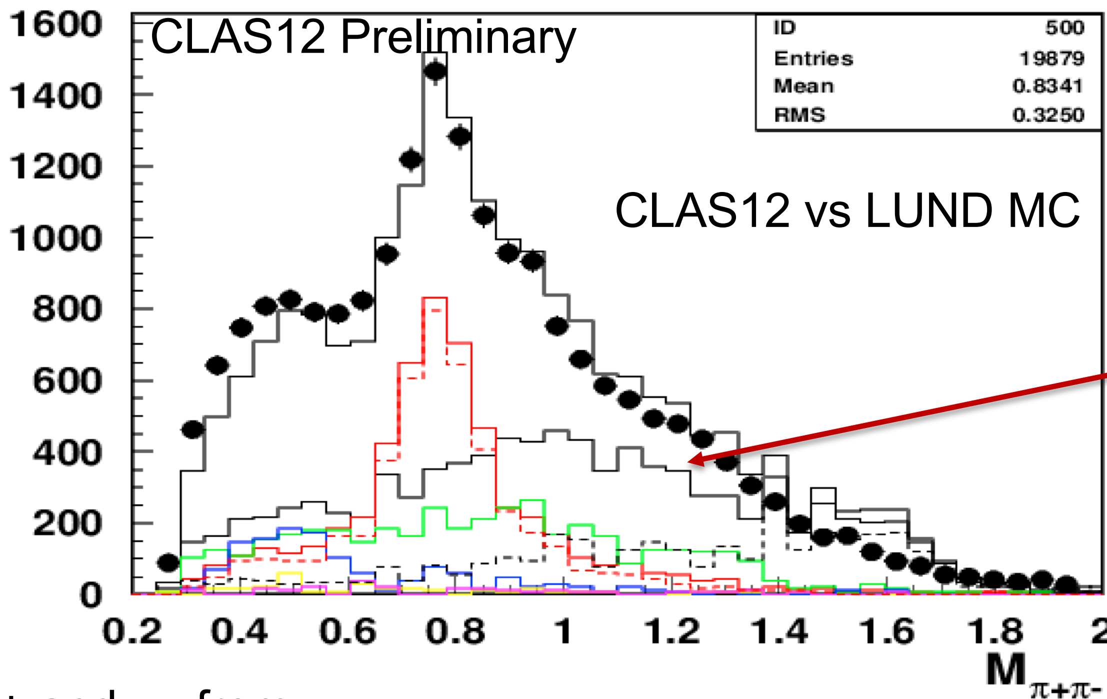
Due to radiative corrections, ϕ-dependence of x-section will get more contributions

•Some moments will modify

•New moments may appear, which were suppressed before in the x-section

Hadronization and Vector Mesons

A. Kerbizi
D. Byer



High P_T pions at large $M\pi\pi$

π+ from		π+ and π– from
red solid	ρ0	red dashed
black solid	string	black dashed
green solid	ρ+	
blue solid	ω	

Dominant fraction of inclusive pions come from VM decays

theory

The situation should be worse at higher energies where diffractive VMs contribute more

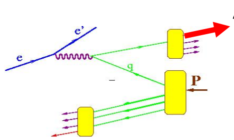
Does it matter for q_T if pions are from VM decays?

Main goal of the workshop

•Define validation procedures for 3D TMD extractions, to make credible projections, to optimize future measurements
•Combining experiment, lattice, theory to pin down the very complex 3D structure of nucleon

HAVE A VERY PRODUCTIVE WORKSHOP!

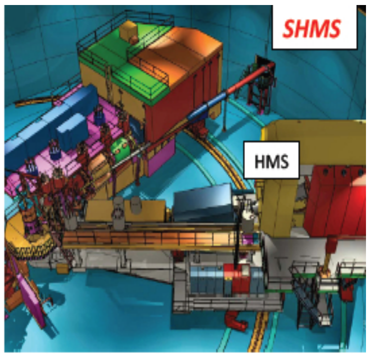
Support slides

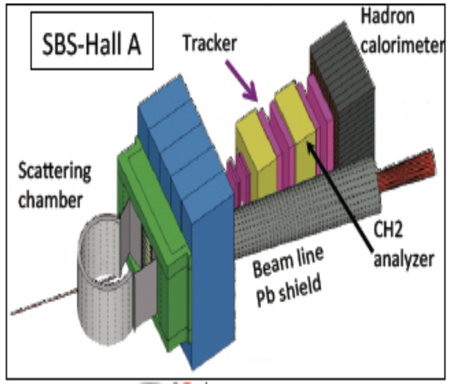


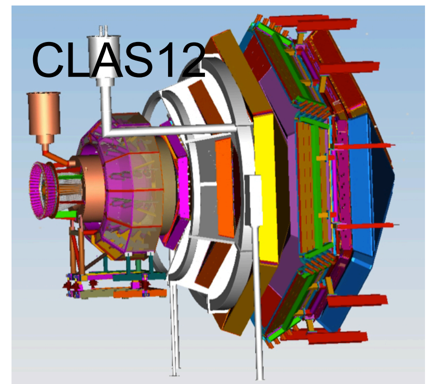
SIDIS at JLab12

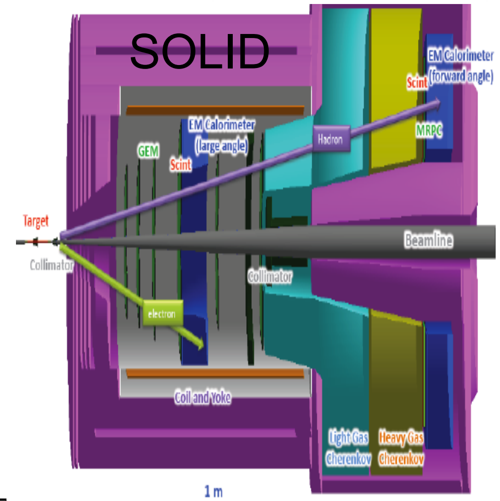
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

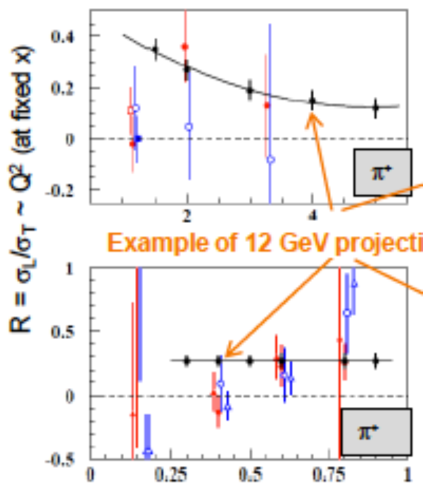
Complementary measurements with different targets

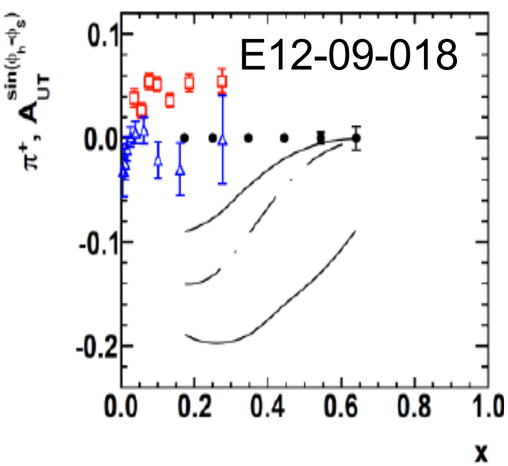


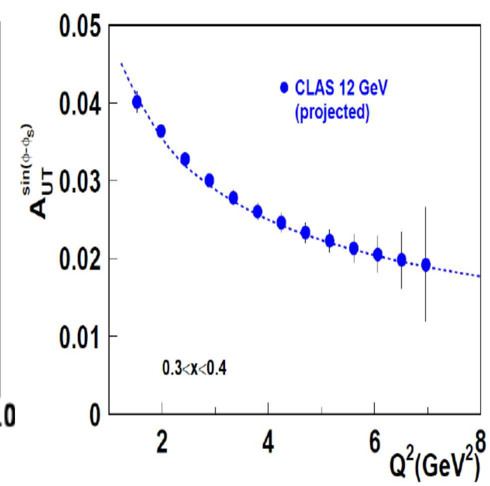


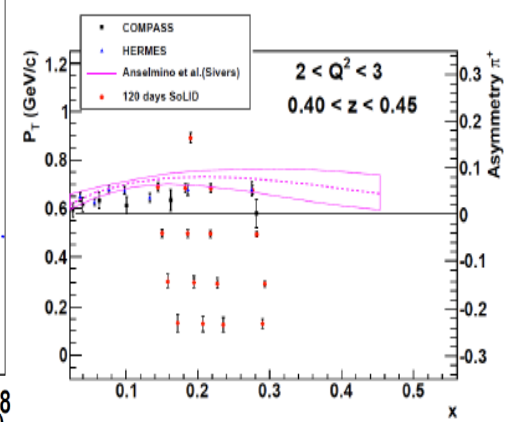










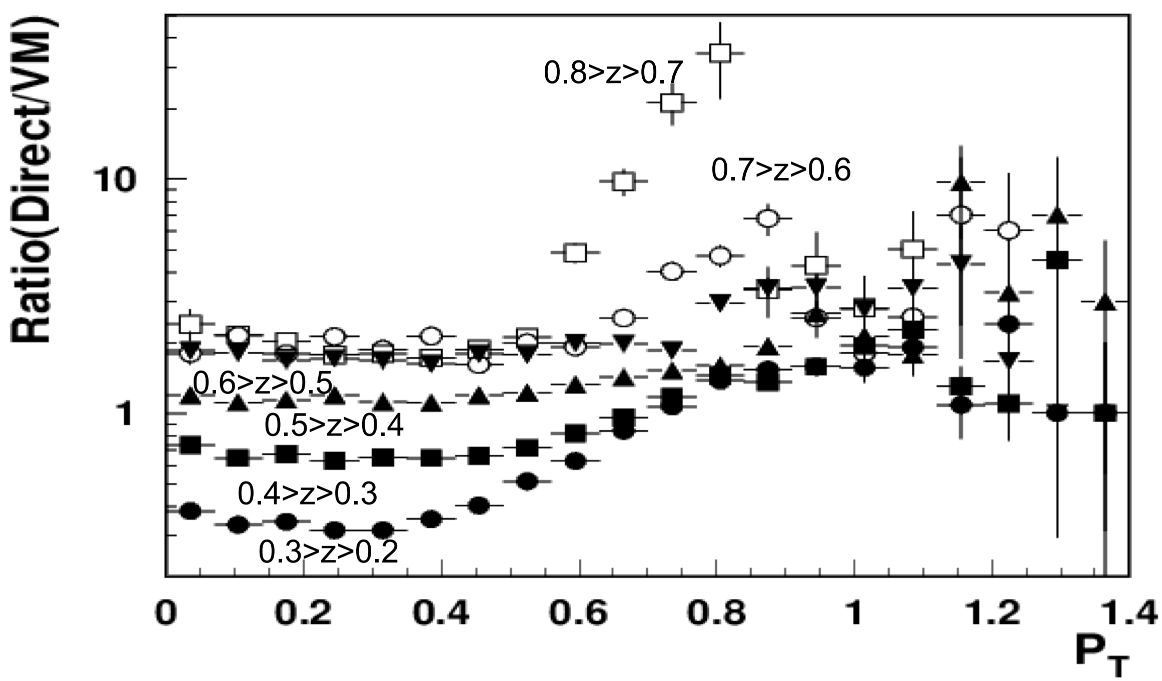


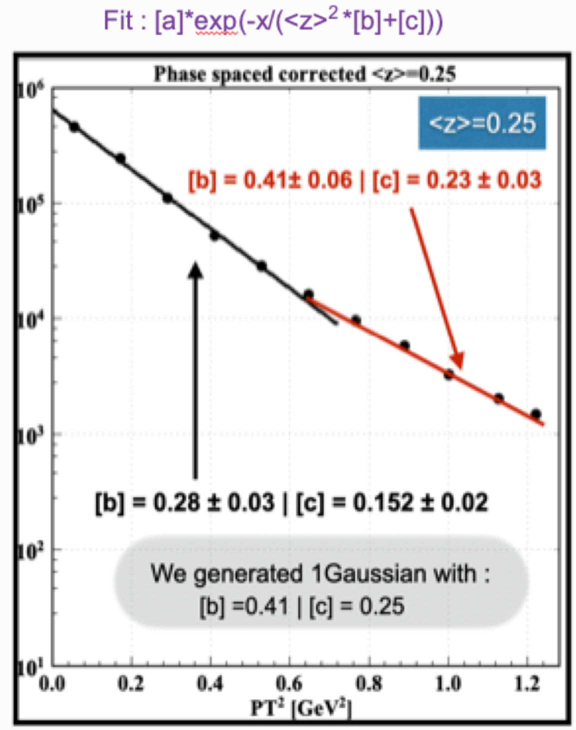
Combination of high resolution measurements from spectrometers combined with large acceptance data from CLAS12 and SOLID would allow to pin down all TMDs in the valence region

CLAS12 Multiplicities: the role of high P_T

LUND MC at 12 GeV using a single Gauss for all hadrons

G. Angelini (GW)





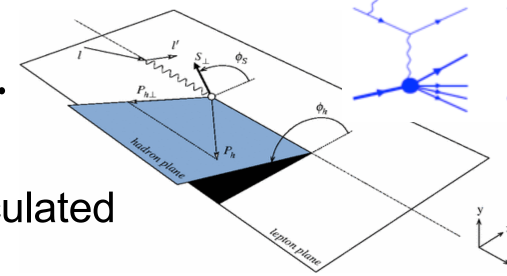
- Corrections due to phase space (energy needed to produce a hadron with a given z,P_T at given x,Q^2) are detector and model independent
- Corrections due to fraction of fragmentation VMs and diffractive VMs are model dependent, but can be extracted from MC (work in progress)

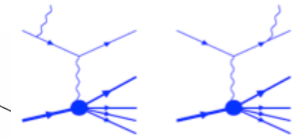
At low z, only the high P_T shows the generated Gaussian transverse momentum distribution.

Experiment measure the full x-section with RC

I. Akushevich et al (LDRD-2018)

$$\sigma = \sigma_{UU} + \sigma_{UU}^{\cos\phi} cos\phi + S_T \sigma_{UT}^{\sin\phi_S} \sin\phi_S + \ldots$$





Due to radiative corrections, ϕ-dependence of x-section will get multiplicative R_M and additive R_A corrections, which could be calculated from the full Born (σ_0) cross section for the process of interest

$$\sigma_{Rad}^{ehX}(x,y,z,P_T,\phi,\phi_S) \to \sigma_0^{ehX}(x,y,z,P_T,\phi,\phi_S) \times R_M(x,y,z,P_T,\phi) + R_A(x,y,z,P_T,\phi,\phi_S)$$

Due to radiative corrections, ϕ-dependence of x-section will get more contributions
- Some moments will modify
- New moments may appear, which were suppressed before in the x-section

Simplest rad. correction

$$R(x,z,\phi_h) = R_0(1 + r\cos\phi_h)$$

Correction to normalization

$$\sigma_0(1 + \alpha\cos\phi_h)R_0(1 + r\cos\phi_h) \to \sigma_0 R_0(1 + \alpha r/2)$$

Correction to SSA

$$\sigma_0(1 + sS_T\sin\phi_S)R_0(1 + r\cos\phi_h) \to \sigma_0 R_0(1 + sr/2S_T\sin(\phi_h - \phi_S) + sr/2S_T\sin(\phi_h + \phi_S))$$

Correction to DSA

$$\sigma_0(1 + g\lambda\Lambda + f\lambda\Lambda\cos\phi_h)R_0(1 + r\cos\phi_h) \to \sigma_0 R_0(1 + (g + fr/2)\lambda\Lambda)$$

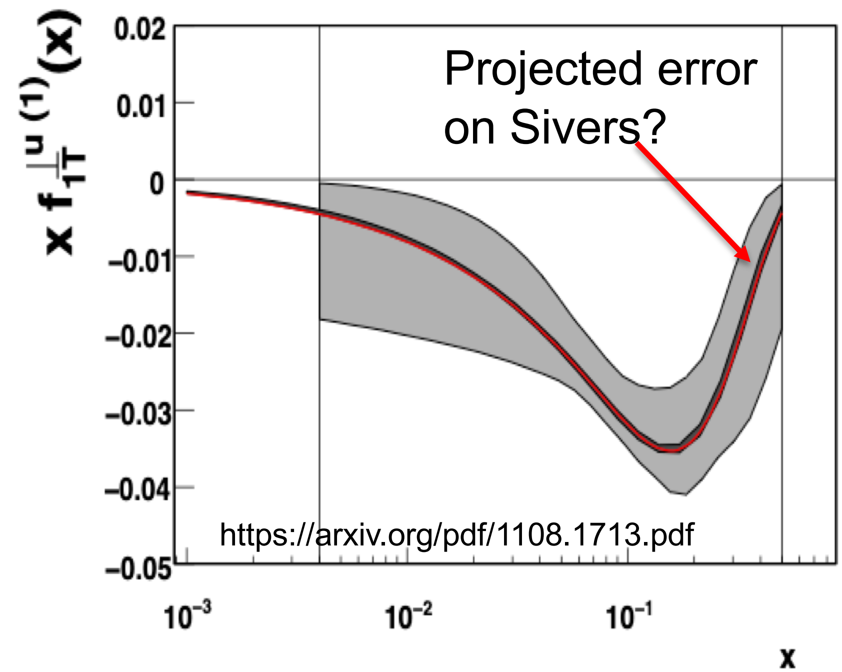
Simultaneous extraction of all moments is important also because of correlations!

Projections for TMDs

"The complementarity between JLab 12 GeV measurements and the EIC has to be fully exploited, and ongoing experiments can play an essential part in this endeavor."

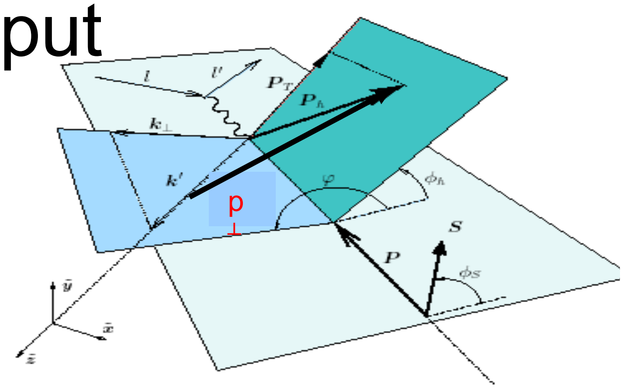
The SIDIS TMD is a major driving force both for JLab12 (possibly JLab25) and the EIC, and it is important to clarify the role of each

Reevaluation by experts in theoretical and experimental studies of TMDs, is needed for the whole SIDIS program to make realistic projections of what two major facilities could do and how they will complement each other



EIC can measure Sivers in SIDIS at x=0.5?

MC Generator to simulate SIDIS output



SIDIS MC in 7D (10D)

$$\frac{d\sigma_{\lambda\Lambda}^{eN\rightarrow e'hX}}{dx\,dQ^2\,dz\,dP_{hT}^2\,d\phi_h\,d\phi_l\,d\phi_s} = \sum_{l=1}^{L} SF_l$$

Theory

Provide a set of SF_l

For a given model/theory based on underlying non-perturbative input and assumptions calculate SF_l

$$F_l(x_1, x_2, x_3, ...x_N, P_1, P_2, ...P_M)$$

step-1 $$x_i, Q_i^2 z_i P_{hT}^{i2} \phi_h^i \phi_l^i \phi_s^i$$

step-2 (for a given E_{beam},λ,Λ) $$P_i^{el}, P_i^h$$

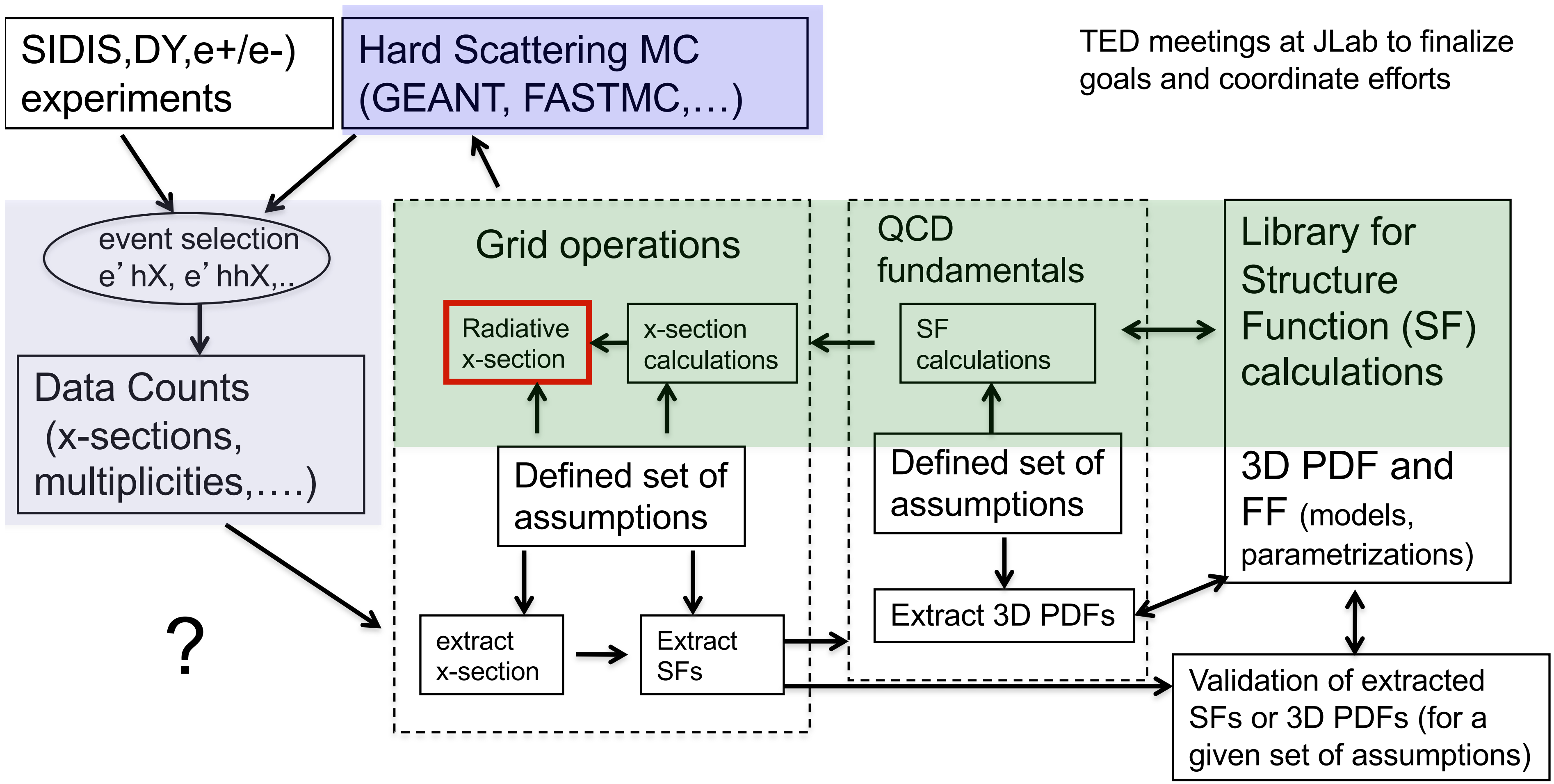
step-3 (detected for a given Detector configuration)

$$x_j, Q_j^2 z_j P_{hT,j}^2 \phi_h^j \phi_l^j \phi_s^j$$

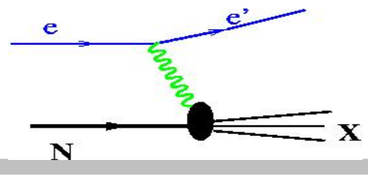
$$F_l(x_1, x_2, x_3, ...x_N, P_1^*, P_2^*, ...P_M^*)$$

Need criteria to compare the input and output parameter spaces (validate)

3D PDF Extraction and VAlidation (EVA) framework

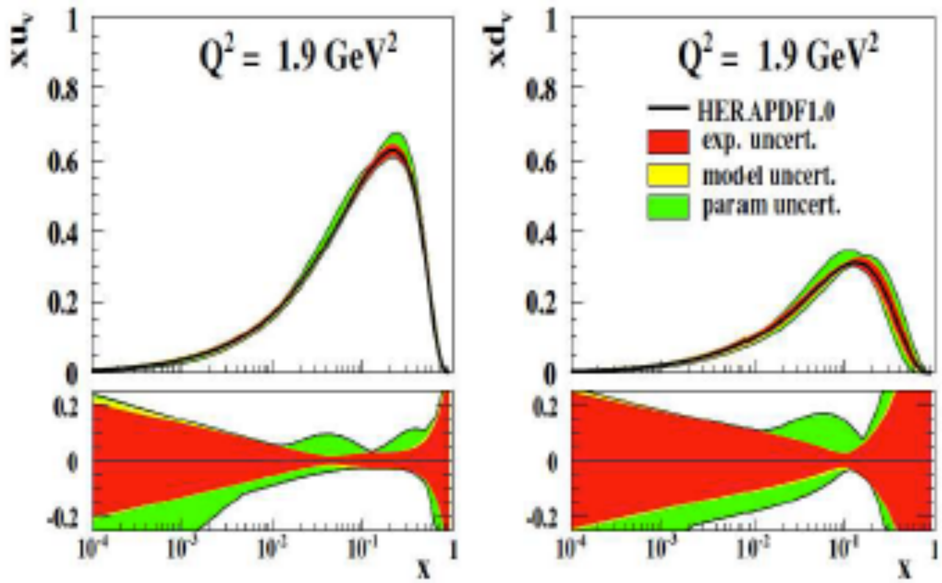


Development of a reliable techniques for the extraction of 3D PDFs and fragmentation functions from the multidimensional experimental observables with controlled systematics requires close collaboration of experiment, theory and computing

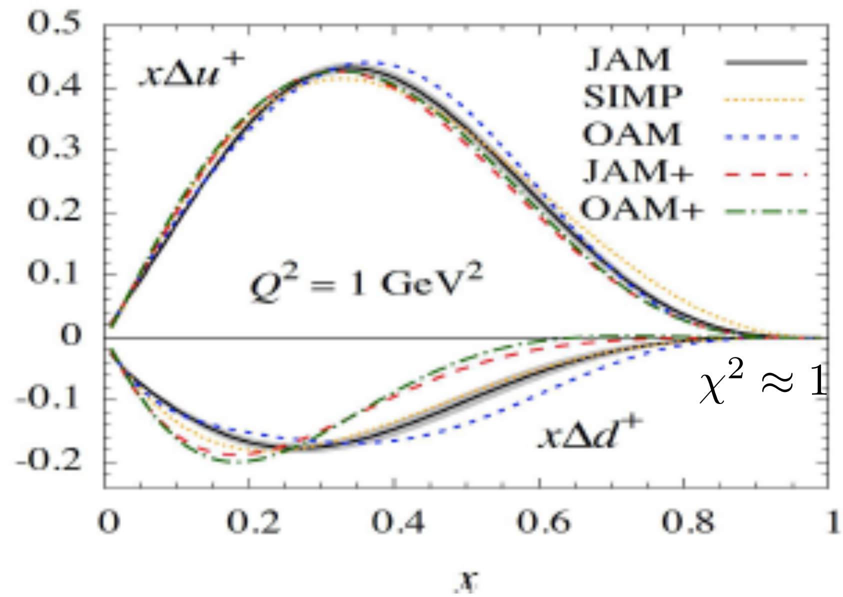


Studies of 1D PDFs

F. Aaron et al., JHEP 1001 (2010)



P. Jimenez-Delgado et al (2014), 1403.3355.



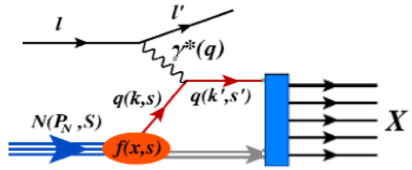
JAM (standard) $$x\Delta q^+(x, Q_0^2) = N\, x^\alpha (1-x)^\beta \,(1 + \epsilon\sqrt{x} + \eta\, x),$$

inspired by the OAM
Avakian et al $$x\Delta q^+ = N\, x^\alpha (1-x)^\beta + N'\, x^{\alpha'} (1-x)^{\beta'} \log^2(1-x).$$

- Strong model and parametrization dependence observed already for 1D PDFs
- Different assumptions (positivity requirement,…) may change significantly the PDF (need self consistent fits of polarized and unpolarized target data!!!)

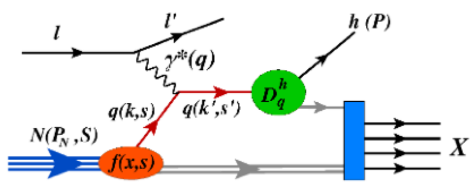
QCD: from testing to understanding

0h DIS



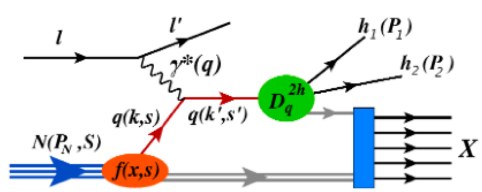
Testing stage:
pQCD predictions, observables in the kinematics where theory predictions are easier to get (higher energies, 1D picture, leading twist, current fragmentation, IMF)

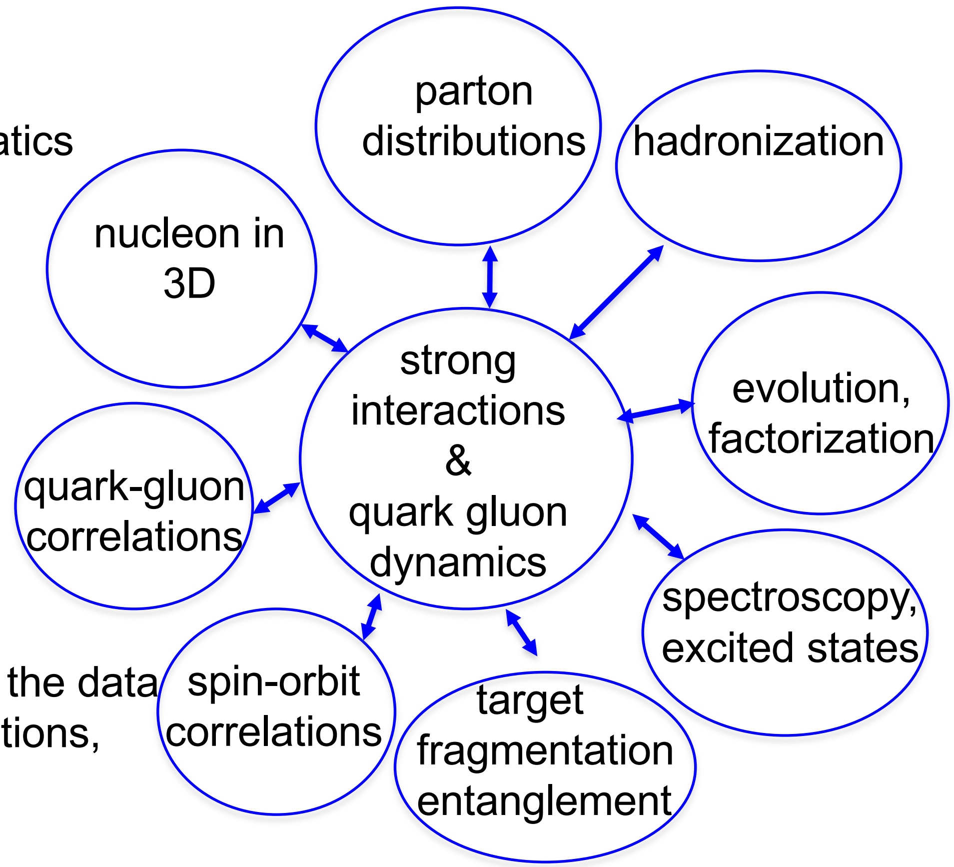
1h SIDIS/DVMP



Understanding stage:
non-perturbative QCD, strong interactions, observables in the kinematics where most of the data is available (all energies, quark-gluon correlations, orbital motion)

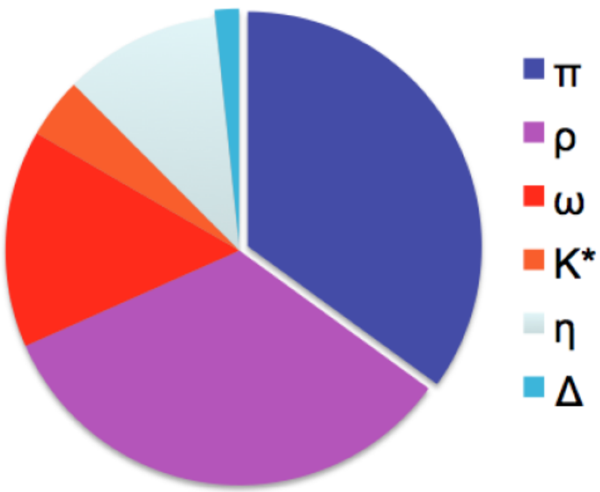
2h SIDIS/DVMP





production in SIDIS provides access to correlations inaccessible in simple SIDIS (BEC,dihadron fragmentation , correlations of target and current regions, entanglement....)

Dihadron production



HERMES-note-96.059

What is the origin of dihadrons?
What is a single hadron?

Matevosyan et al arXiv:1307.8125(NJL-jet)