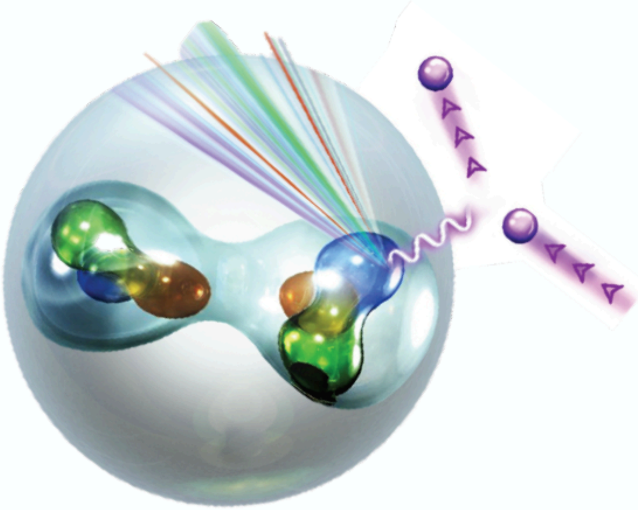
SIDIS fragmentation @ JLAB22

Erez O. Cohen and Harut Avagyan,
Ofer Aviv, Dien T. Nguyen, Florian Hauenstein, Igor Korover,
Or Hen, Eli Piasetzky

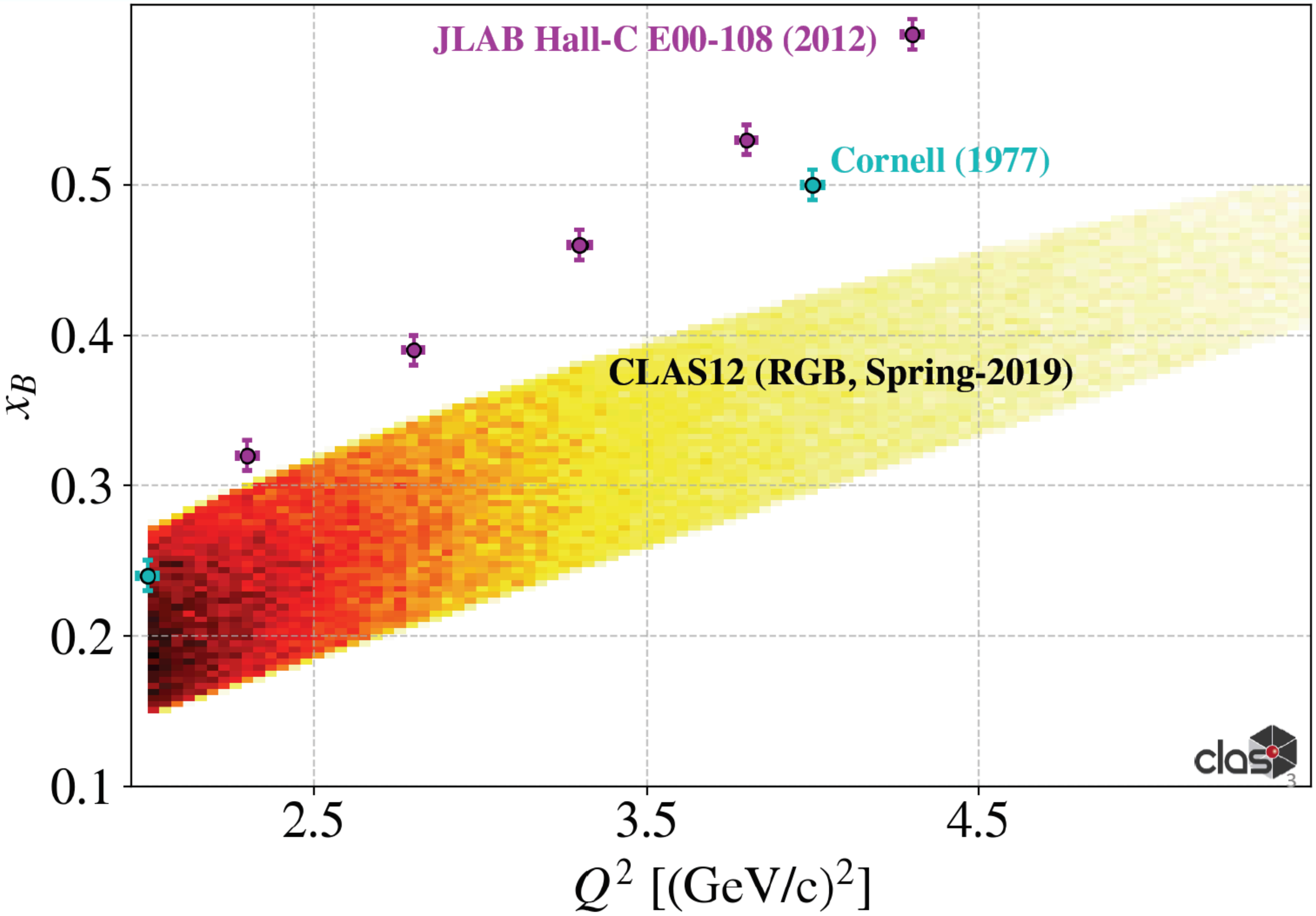
Jan-24, 2023

Motivation

- Looking for a difference between a bound *p* and a free *p*, we study SIDIS off a deuteron
- @12 GeV we observe an approach to the Parton Field-Feynman limit
- @22 GeV this can be verified

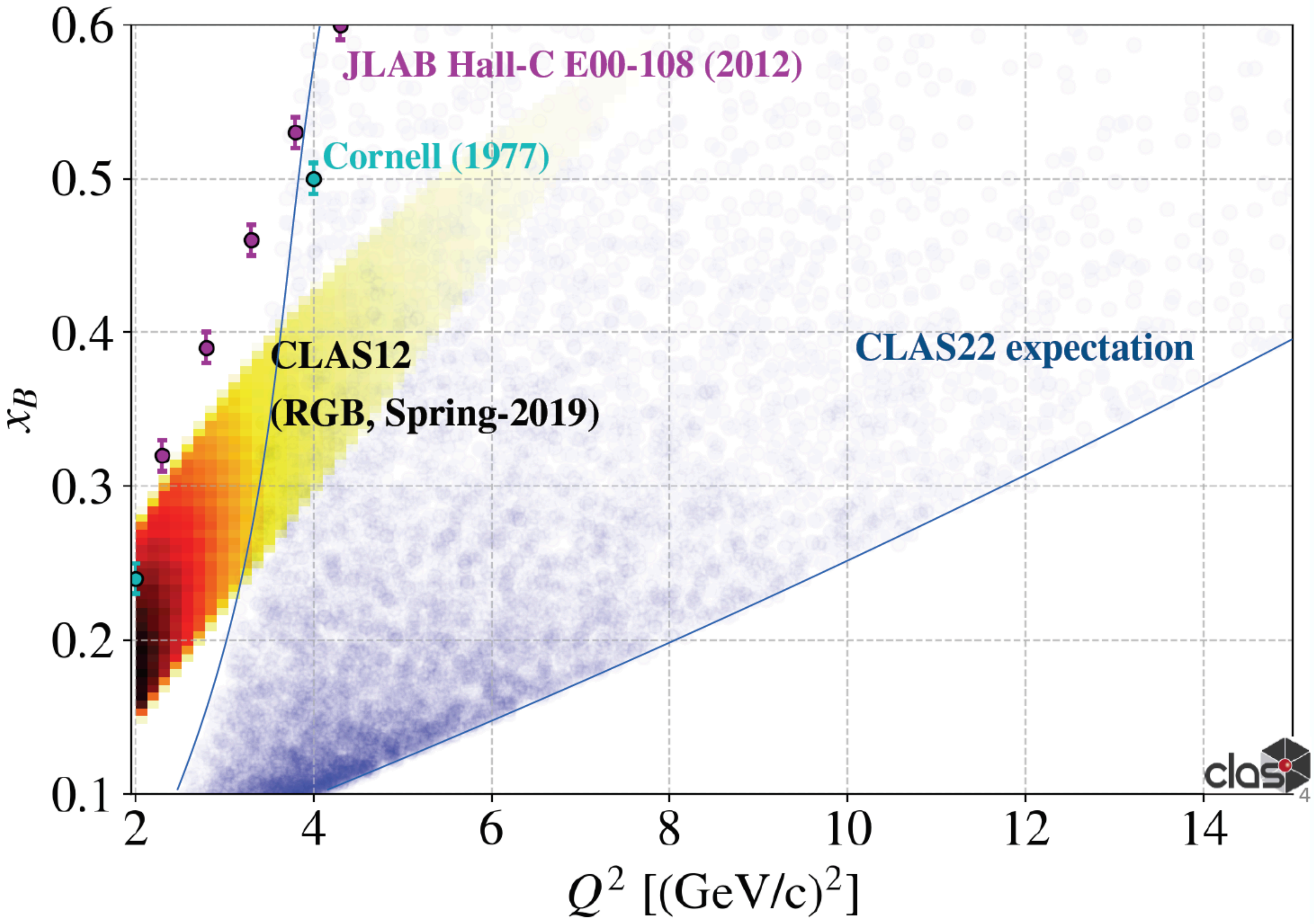


Kinematical coverage

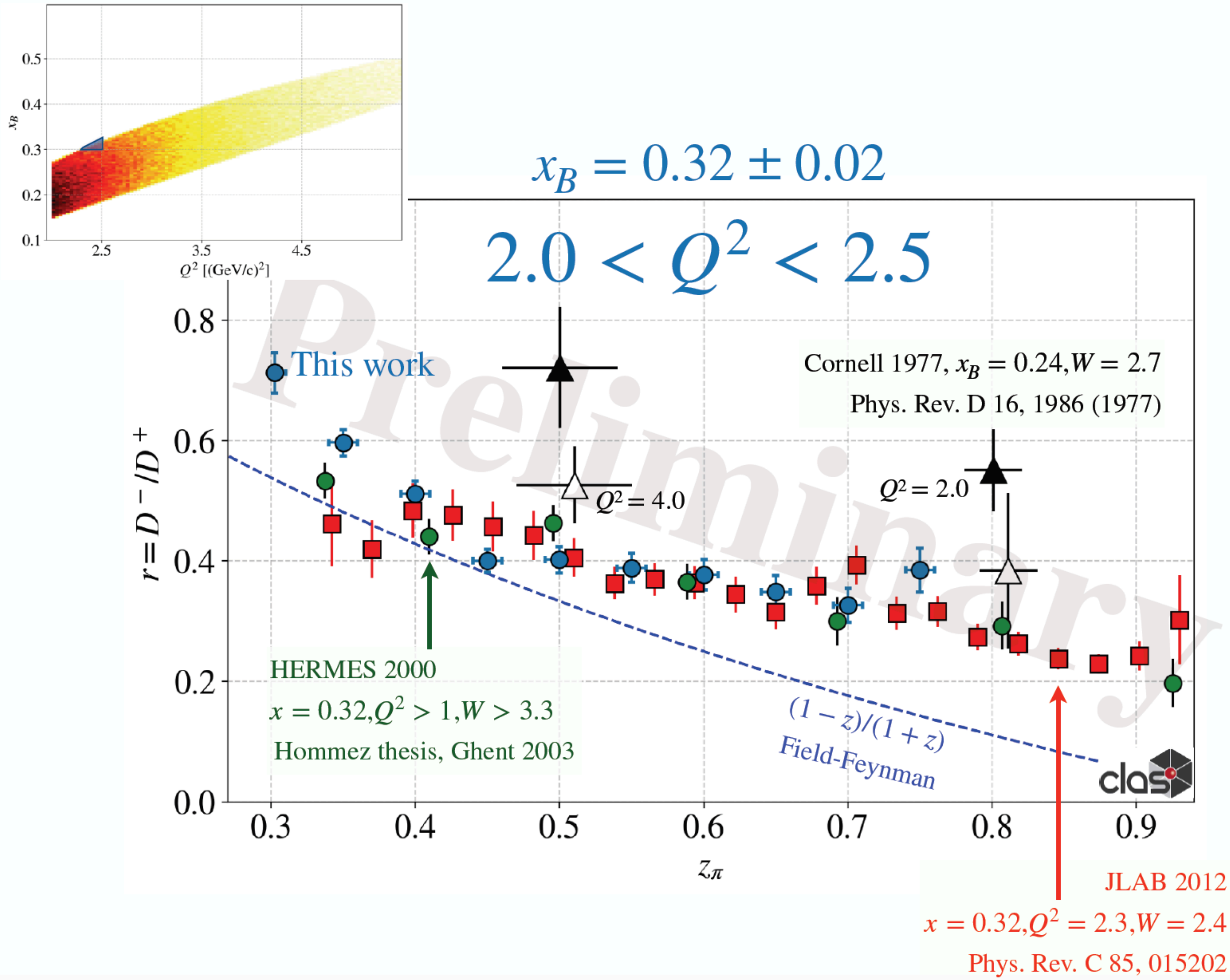


RGB + BAND: 10.2 GeV all data

Kinematical coverage



RGB + BAND: 10.2 GeV all data



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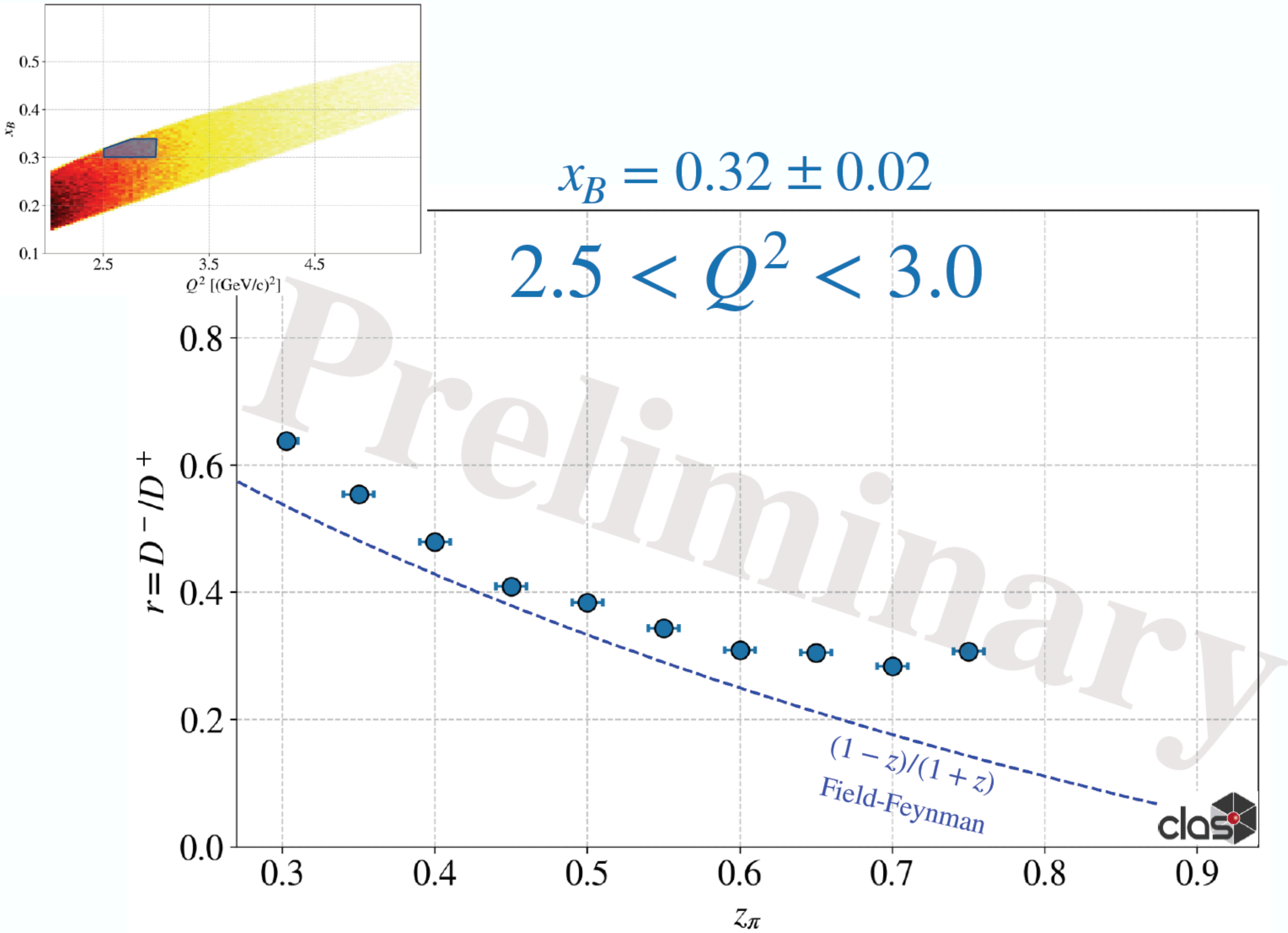
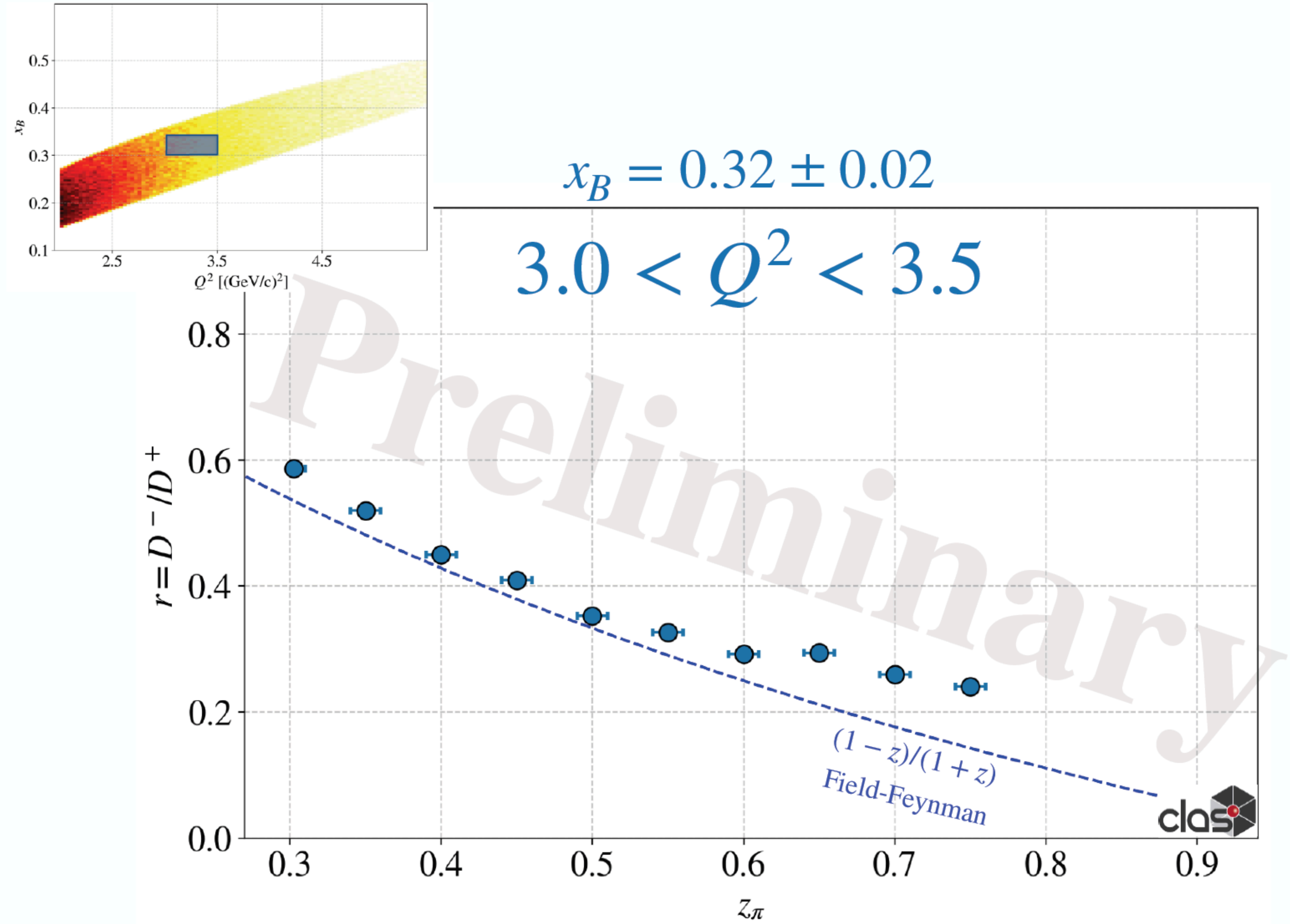


$x_B = 0.32 \pm 0.02$

$2.5 < Q^2 < 3.0$

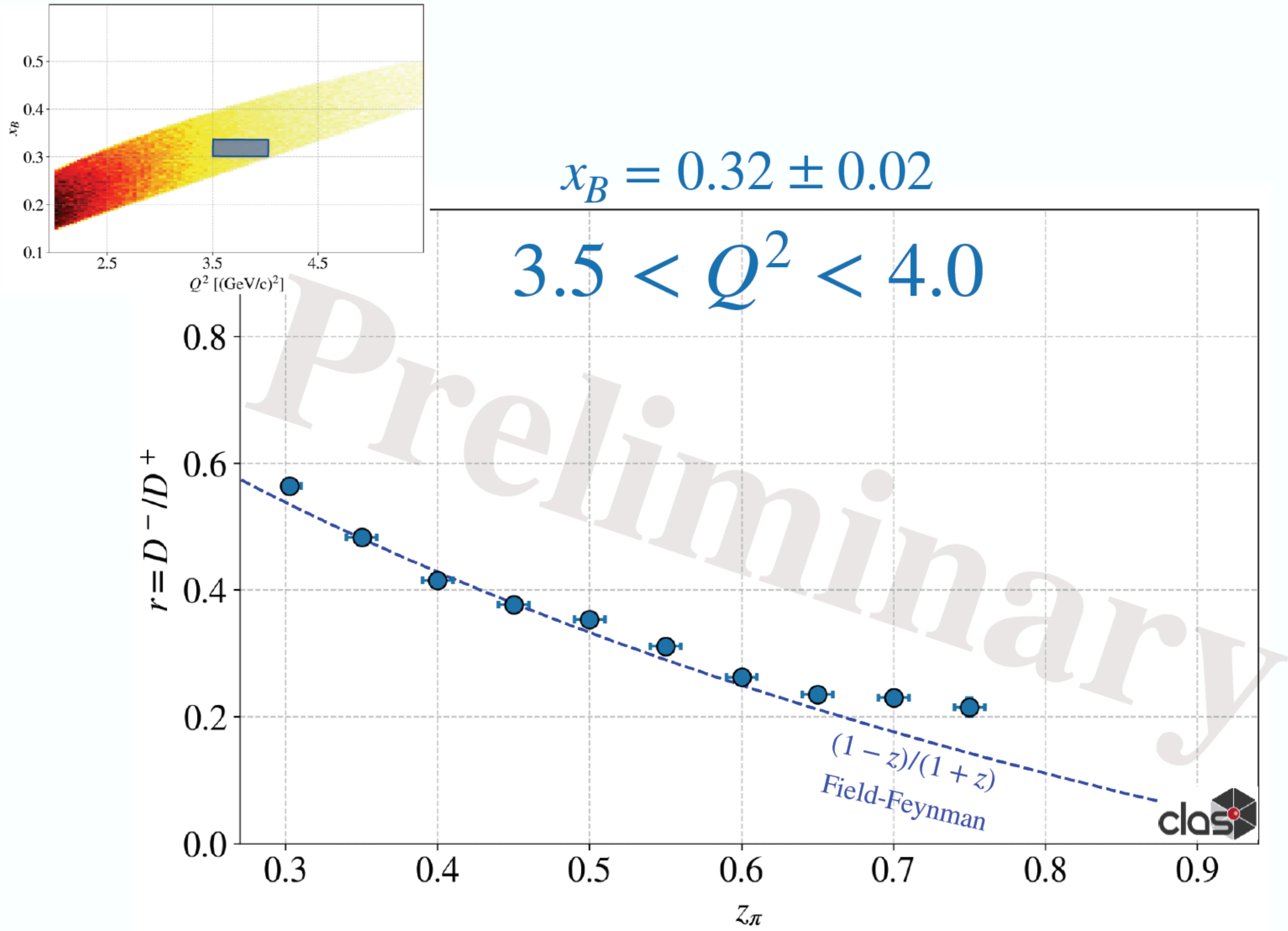
RGB + BAND: 10.2 GeV all data



$$x_B = 0.32 \pm 0.02$$

$$3.0 < Q^2 < 3.5$$

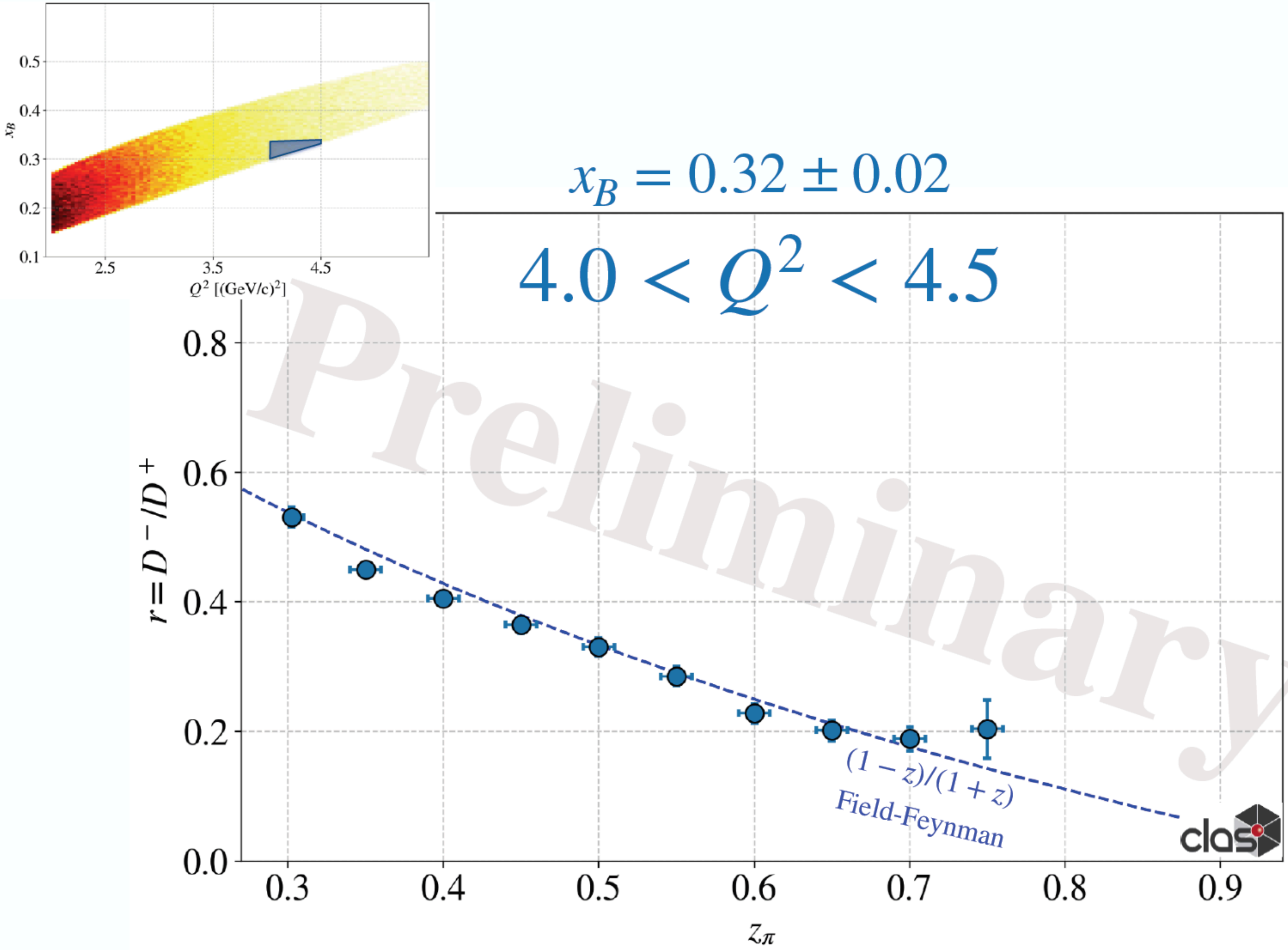
RGB + BAND: 10.2 GeV all data



$x_B = 0.32 \pm 0.02$

$3.5 < Q^2 < 4.0$

RGB + BAND: 10.2 GeV all data



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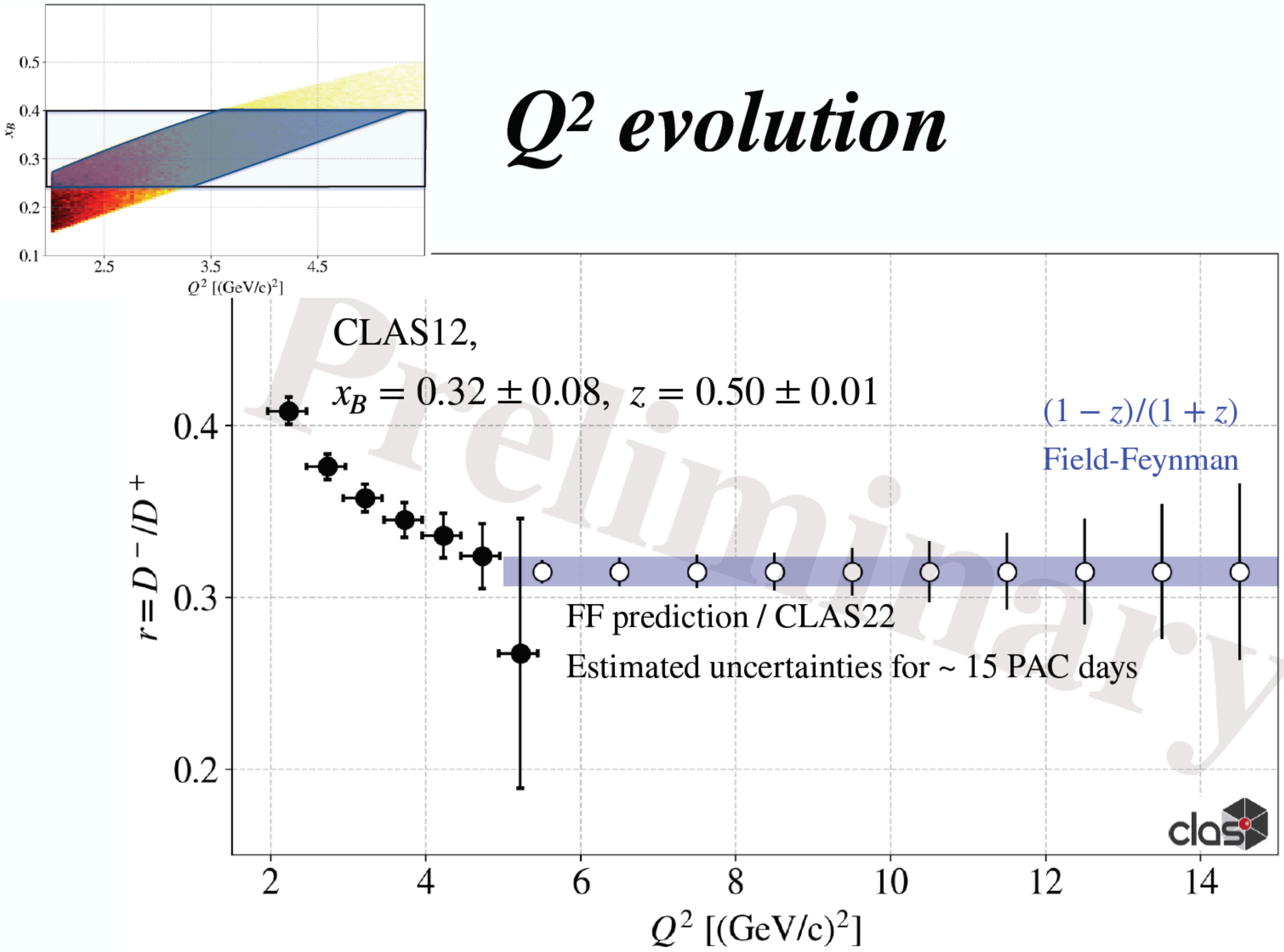
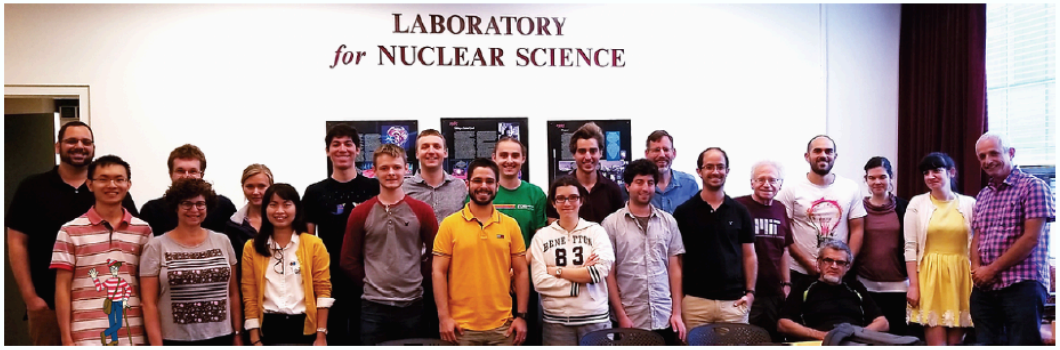
Q^2 evolution



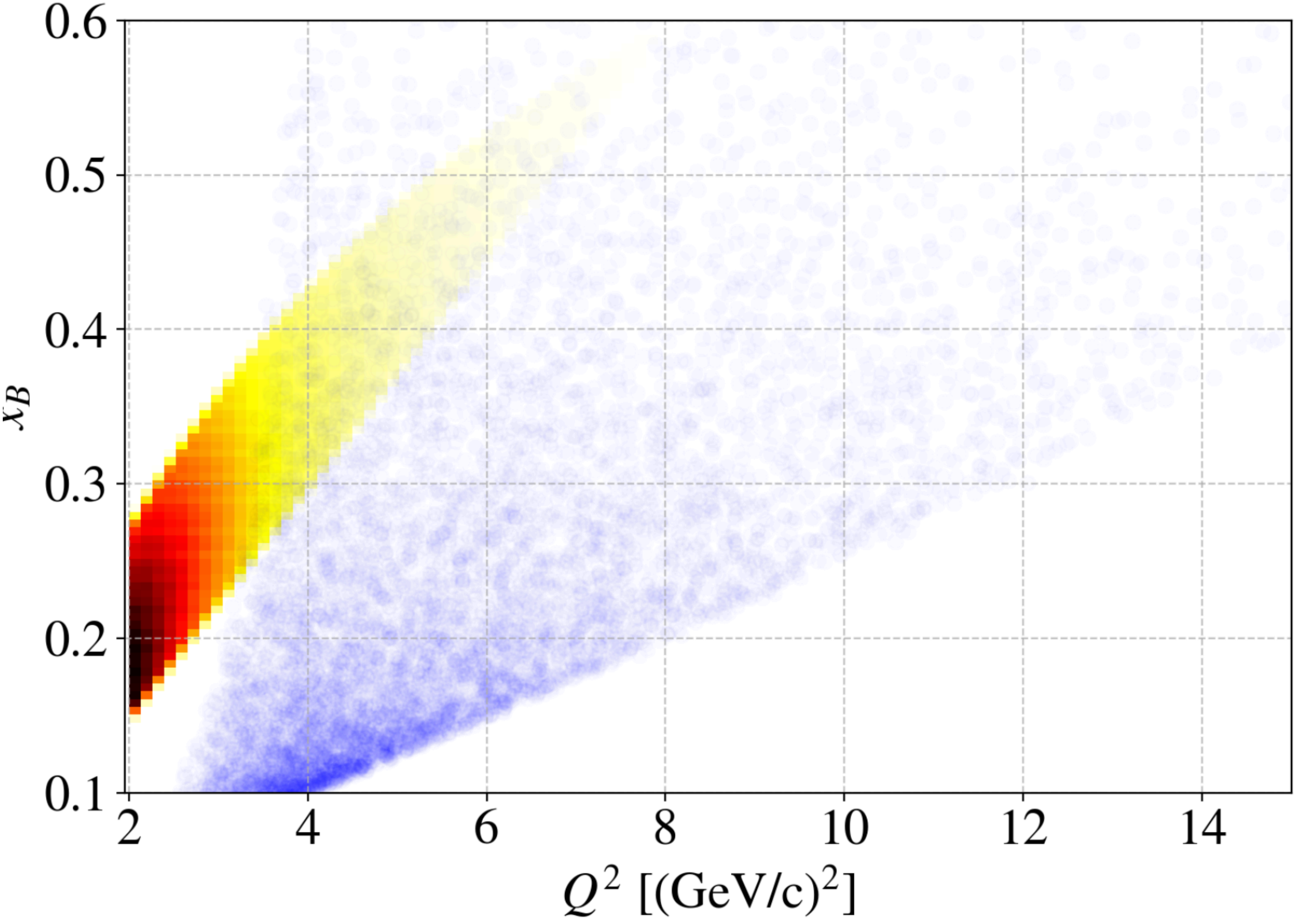
RGB + BAND: 10.2 GeV all data

Thank you for your time

+ Erez O. Cohen, Ofer Aviv,
and Eli Piasetzky from TAU



cohen.erez7@gmail.com


0.6
0.5
0.4
0.3
0.2
0.1
x_B
2
4
6
8
10
12
14
Q^2 [(GeV/c)^2]

Azimuthal asymmetries on proton at COMPASS: Q^2- dependence

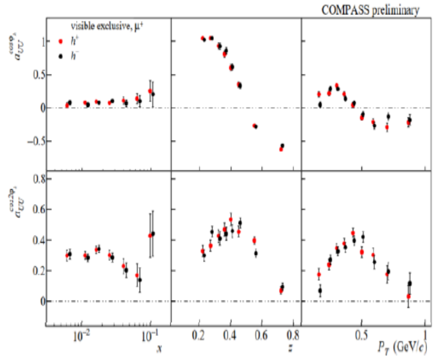
Andrea Moretti

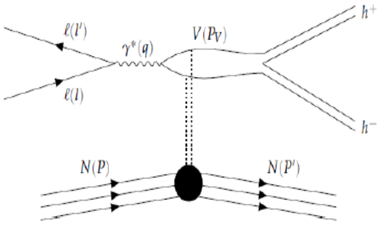
Science at the Luminosity Frontier: Jefferson Lab at 22 GeV Workshop – Jefferson Lab 23-26/01/2023

Azimuthal asymmetries at COMPASS (proton 2016)

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\varphi_h dP_T^2} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\cdot\left(F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}F_{UU}^{\cos\varphi_h}\cos\varphi_h+\varepsilon F_{UU}^{\cos 2\varphi_h}\cos 2\varphi_h+\lambda_l\sqrt{2\varepsilon(1-\varepsilon)}F_{LU}^{\sin\varphi_h}\sin\varphi_h\right)$$

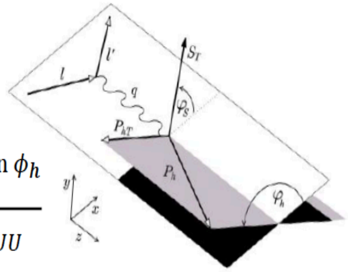
Exclusive hadrons: *discarded* (visible part) or *subtracted* (not visible part, Monte Carlo)





Fit of the **amplitude of the modulation in the azimuthal angle** of the hadrons

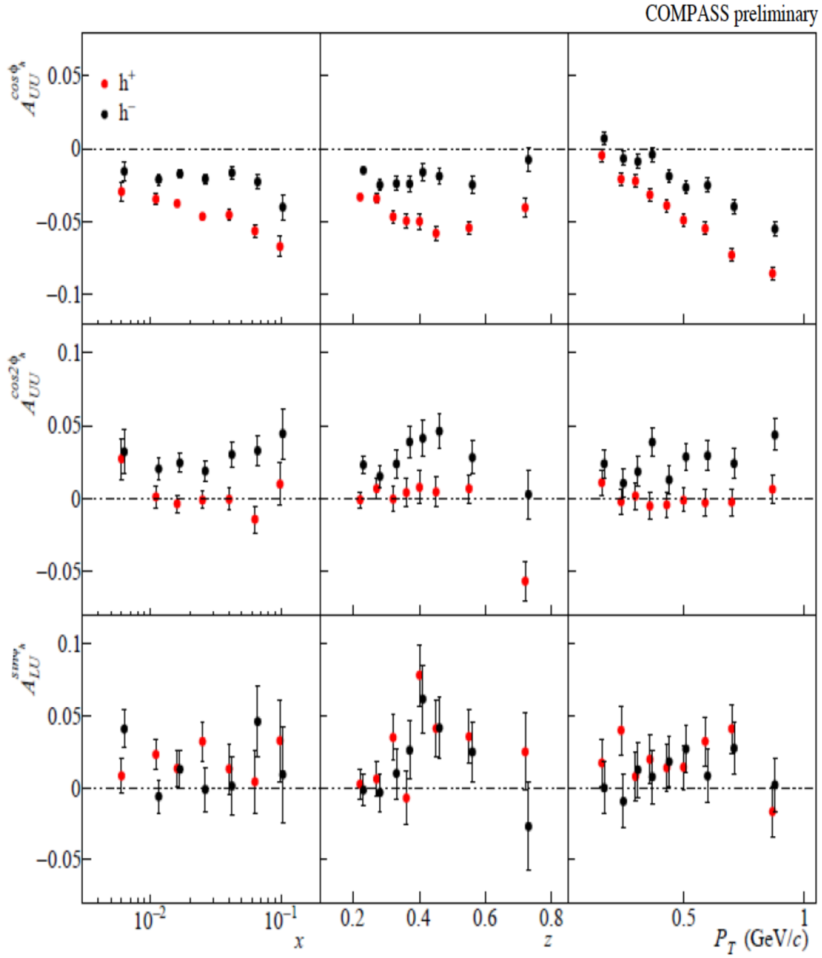
- as a function of x, z or P_T (1D)
- with a simultaneous binning (3D)



Azimuthal asymmetries: defined as the following ratios

$$A_{UU}^{\cos\phi_h} = \frac{F_{UU}^{\cos\phi_h}}{F_{UU}} \qquad A_{UU}^{\cos 2\phi_h} = \frac{F_{UU}^{\cos 2\phi_h}}{F_{UU}} \qquad A_{LU}^{\sin\phi_h} = \frac{F_{LU}^{\sin\phi_h}}{F_{UU}}$$

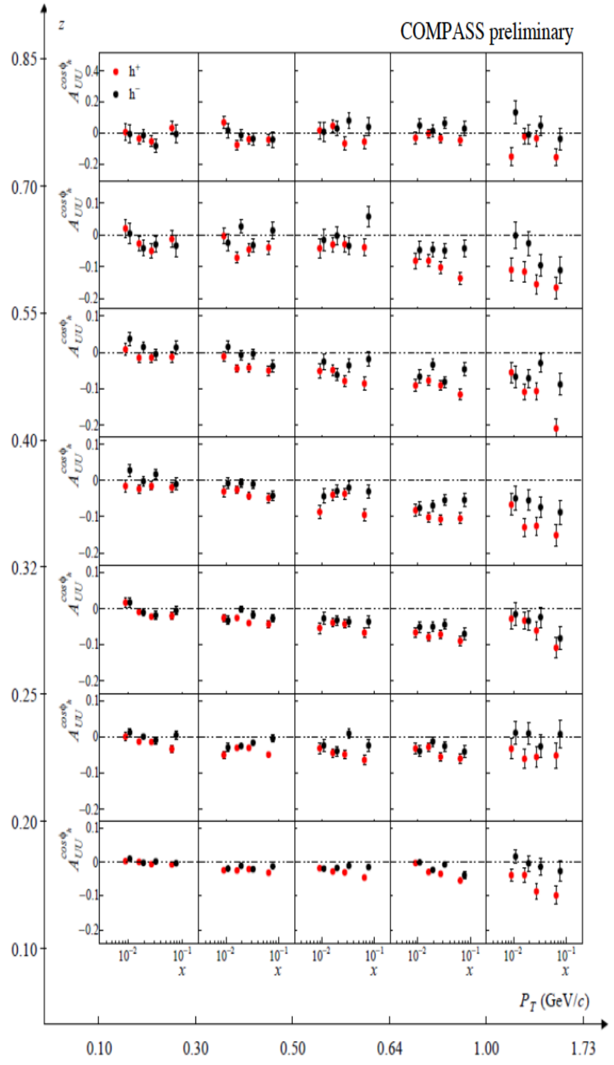
- **Strong kinematic dependences**
- **Interesting differences** between positive and negative hadrons, as observed in previous measurements by COMPASS on deuteron and by HERMES



The error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim \sigma_{stat}$ (1D)

Q^2- dependence of $A_{UU}^{cos\phi_h}$

The error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim 0.5\, \sigma_{stat}$ (3D)



3D azimuthal asymmetries for positive and negative hadrons

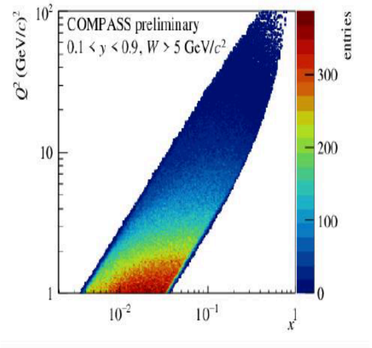
Clear signal, strong dependence on P_T; compatible with zero at high z.
In agreement with COMPASS deuteron results.

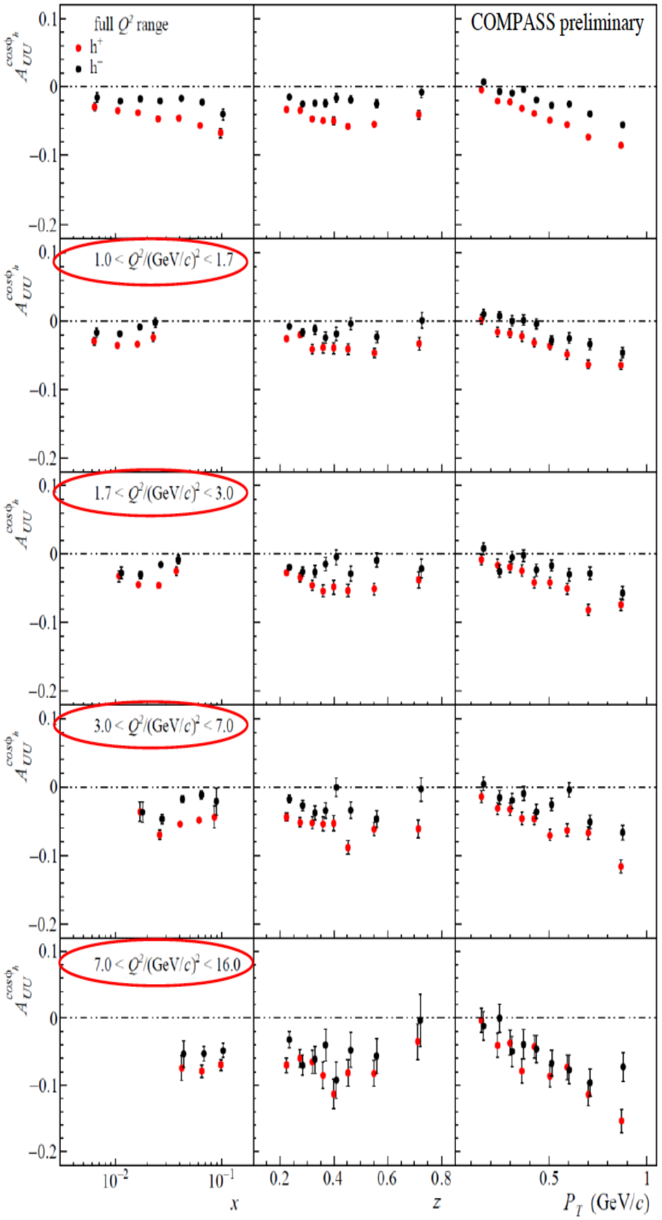
Expectation from Cahn effect:

$$A_{UU|Cahn}^{\cos\phi_h} = -\frac{2zP_T\langle k_T^2\rangle}{Q\,\langle P_T^2\rangle}$$

Binning in Q^2

- The $A_{UU}^{cos\phi_h}$ asymmetry is observed to increase with Q^2 ***unexpected!***
- The difference between positive and negative hadrons decreases with Q^2.
- **Almost no Q^2 dependence for $A_{UU}^{cos2\phi_h}$**





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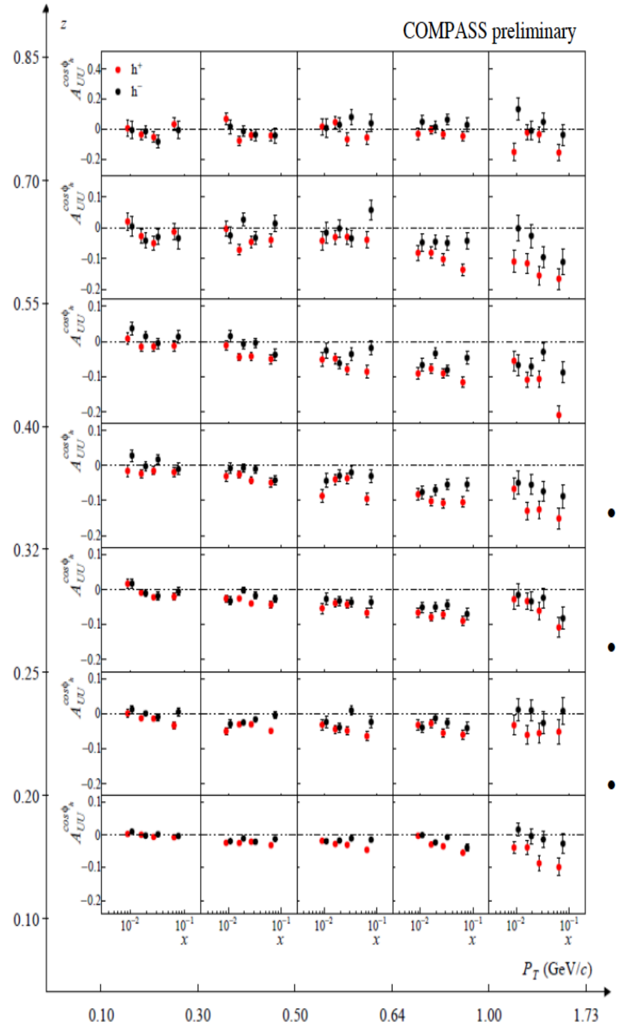
The error bars correspond to the statistical uncertainty only. $\sigma_{syst} \sim 0.5\,\sigma_{stat}$ (3D)



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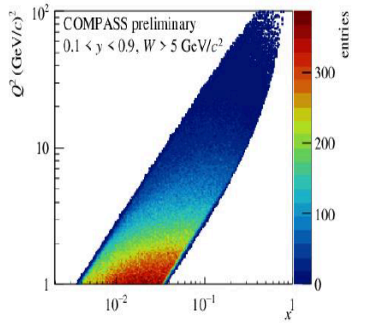
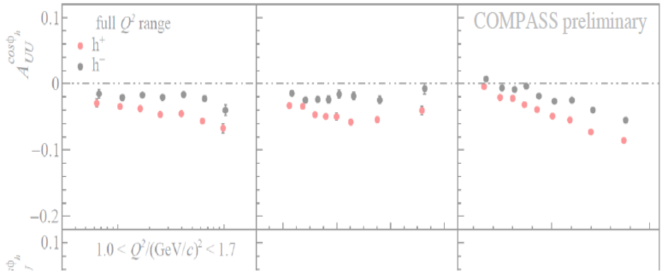
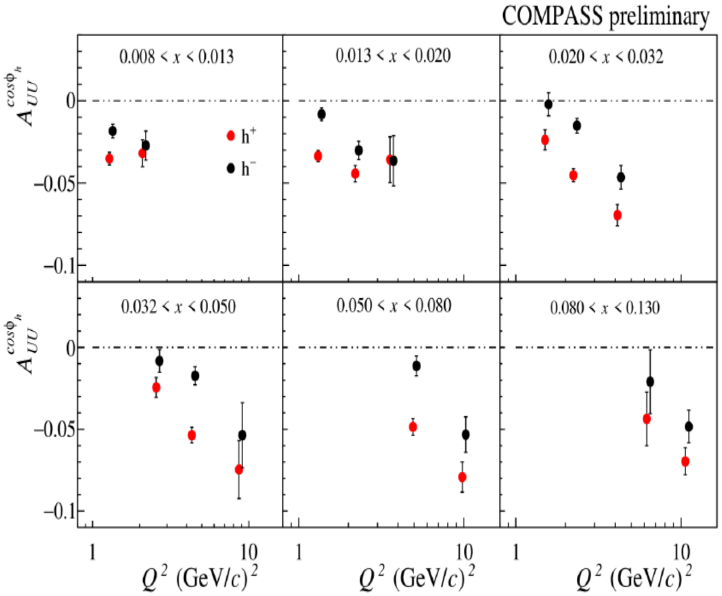
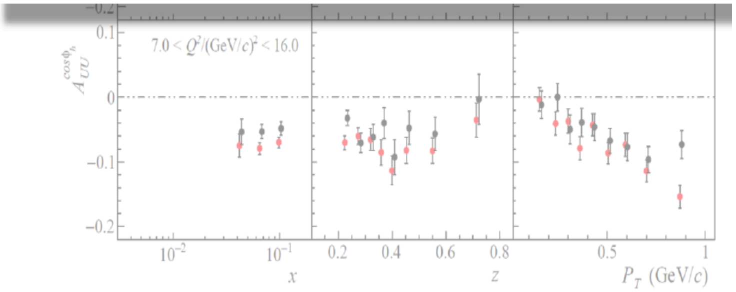








Conclusions and Perspectives

Azimuthal asymmetries

Very interesting observables to access the nucleon structure in unpolarized SIDIS

- **COMPASS** has produced results using a **deuteron** (published 2014) and **proton** target (new)

- Intriguing investigations of their properties:
  rich kinematic dependences, h^+h^- differences, …

A lot to be understood and/or addressed

- Difference between positive and negative hadrons in azimuthal asymmetries
- Kinematic dependences (sometimes *counterintuitive* for azimuthal asymmetries)
- Role of twist-3 contributions beyond Cahn
- Impact of radiative corrections – not included in the results shown here
  may give a relevant contribution to the Q^2 dependence
- Possible role of vector mesons inclusively produced in SIDIS

Science at the Luminosity Frontier: Jefferson Lab at 22 GeV

01/23 – 01/25 2023

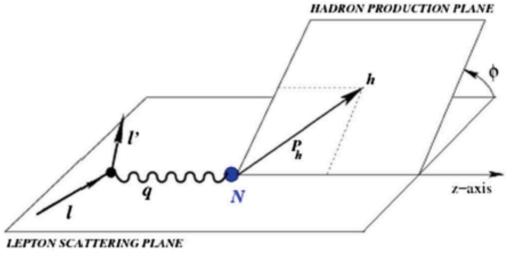
Understanding the scale dependence of spin and azimuthal asymmetries: beam SSAs

Stefan Diehl

Justus Liebig University Giessen
University of Connecticut

January 24, 2023

Physics motivation



SIDIS cross section for an unpolarized target:

$$\frac{d\sigma}{dx_B\, dQ^2\, dz\, d\phi_h\, dp_{h\perp}^2} = K(x,y,Q^2)\Big\{F_{UU,T} + \varepsilon F_{UU,L}$$

$$+\sqrt{2\,\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\sin\phi_h \underline{F_{LU}^{\sin\phi_h}}\Big\}$$

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^\perp + \frac{M_h}{M}f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(xg^\perp D_1 + \frac{M_h}{M}h_1^\perp\frac{\tilde{E}}{z}\right)\right)$$

twist-3 FF

twist-3 FF

Collins FF

twist-3 t-odd dist. funcion

Boer-Mulders

twist-3 pdf

unpolarized dist. function

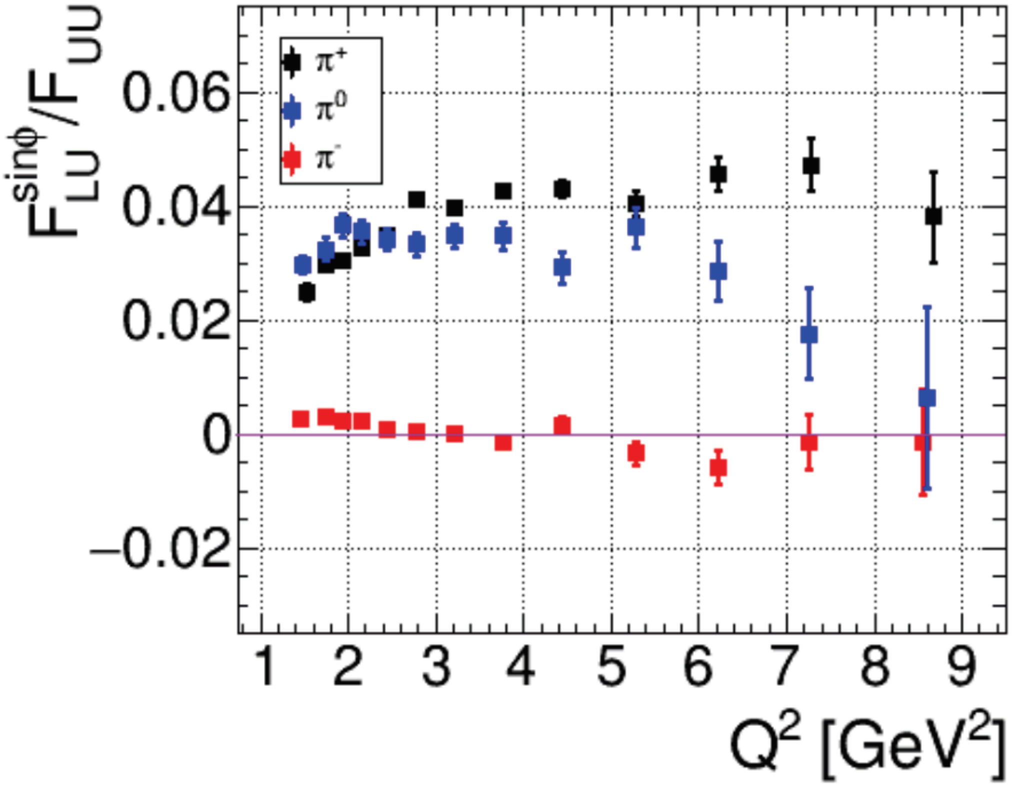
➔ A convolution of 4 TMDs and 4 fragmentation functions

$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{\boxed{A_{LU}^{\sin\phi}}\sin\phi}{1 + A_{UU}^{\cos\phi}\cos\phi + A_{UU}^{\cos(2\phi)}\cos(2\phi)}$$

$$A_{LU}^{\sin\phi} = \sqrt{2\varepsilon(1-\varepsilon)}\,\frac{F_{LU}^{\sin\phi}}{F_{UU}}$$

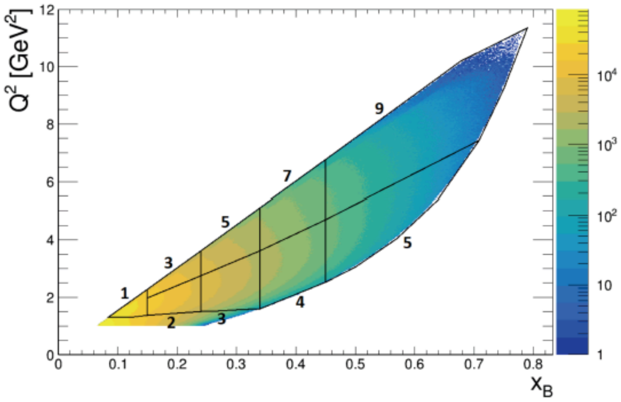
➔ Twist-3 quantity ➔ 1/Q suppression expected!

Pion beam SSAs in the 1D case

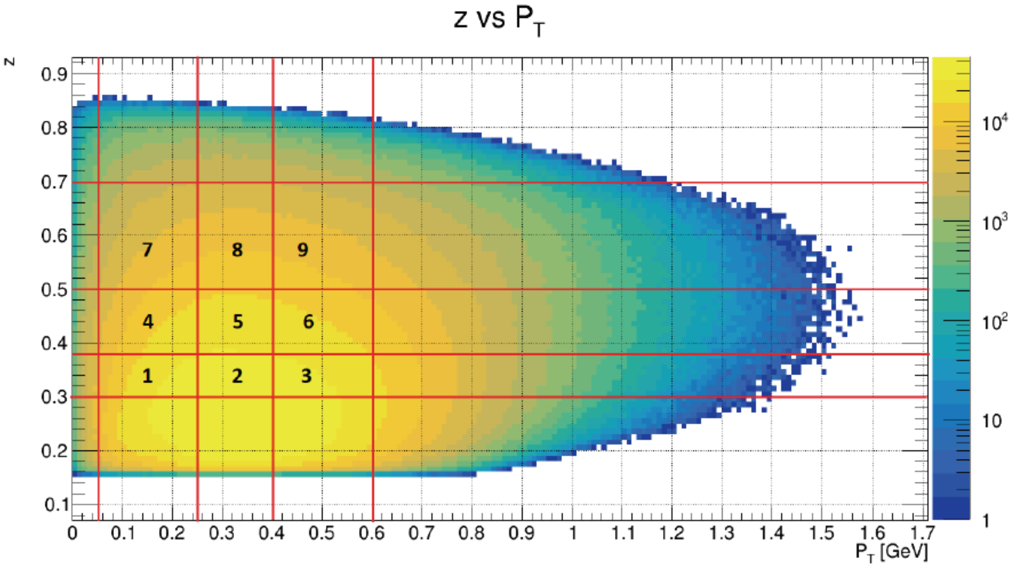


z-P_T and x_B inetgarted case

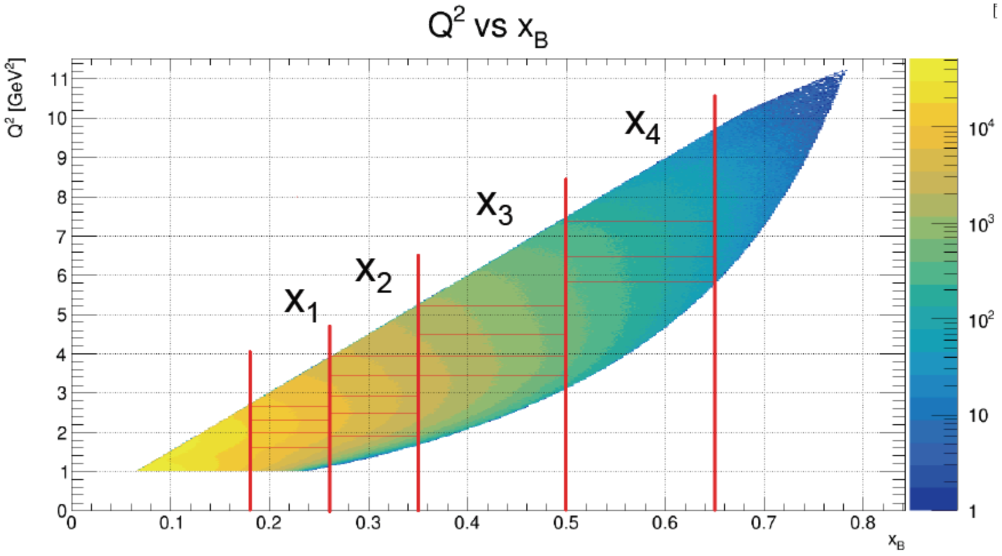
➔ Bahaviour dominated by x_B dependence (as observed in models)



π^+ beam SSAs in the 4D case



select 9 bins in the z-P_T plane



for each of the 9 z-P_T bins, select 4 bins in x_B with 2 - 4 Q² bins

$0.18 < x_B < 0.26$ $0.26 < x_B < 0.35$ $0.35 < x_B < 0.5$ $0.5 < x_B < 0.8$

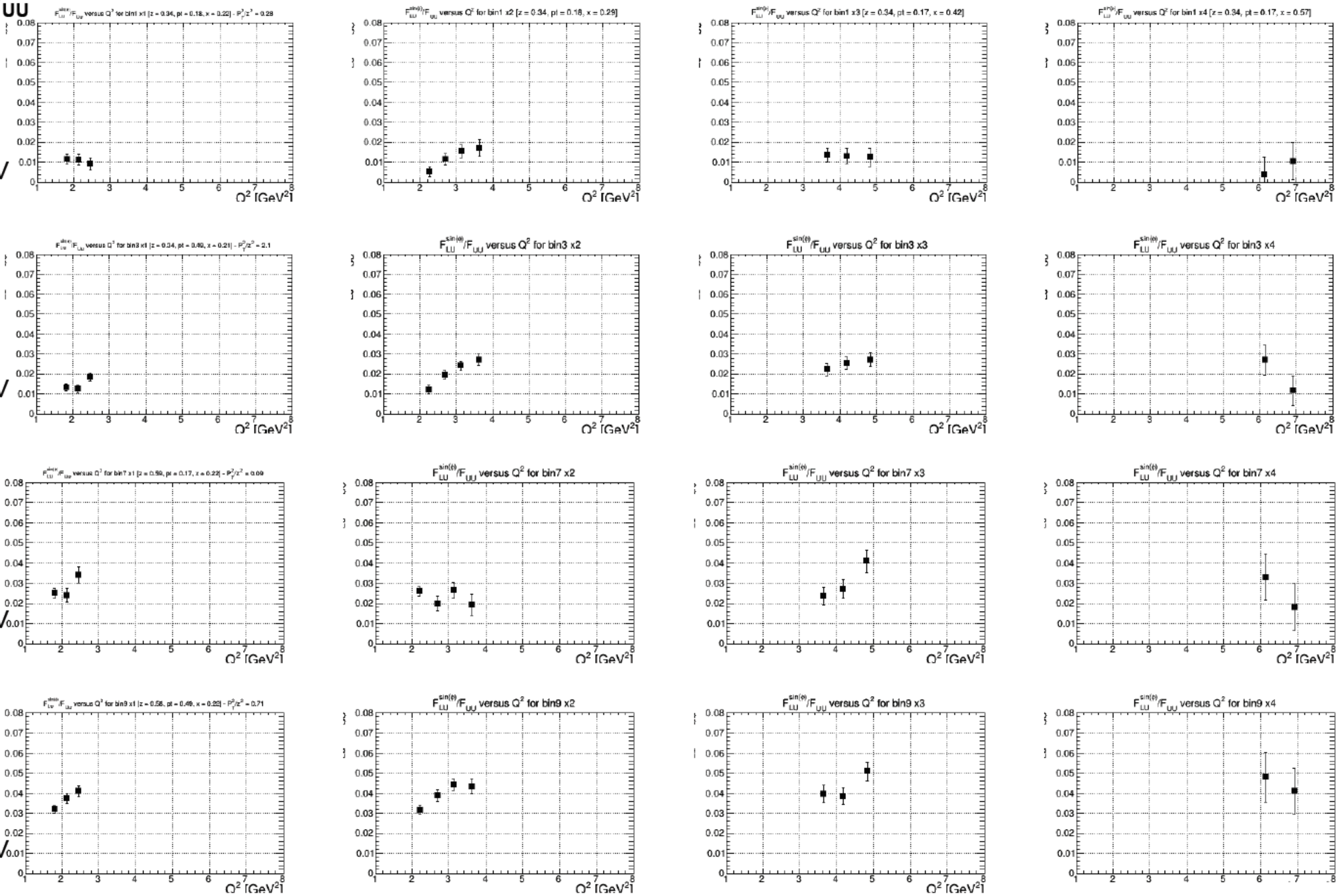
$F_{LU}^{\sin\Phi}/F_{UU}$

bin1
z = 0.34
P_T =
0.18 GeV

bin3
z = 0.34
P_T =
0.49 GeV

bin7
z = 0.58
P_T =
0.17 GeV

bin9
z = 0.58
P_T =
0.49 GeV

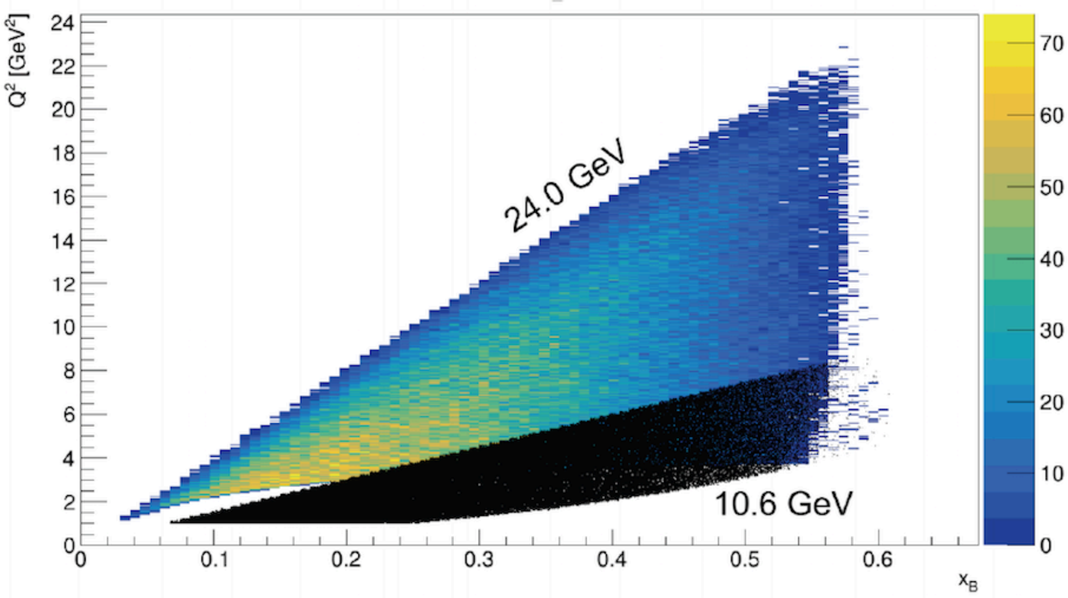


Q^2 [GeV²]

Conclusion and gain from an energy upgrade

➔ At vey **low Q²** an increase with Q² can be observed.
(effect of x_B dependece can not be fully excluded due to rel. wide bins)

➔ At **higher Q²**, statistics and limitted range do not allow a final conclusion



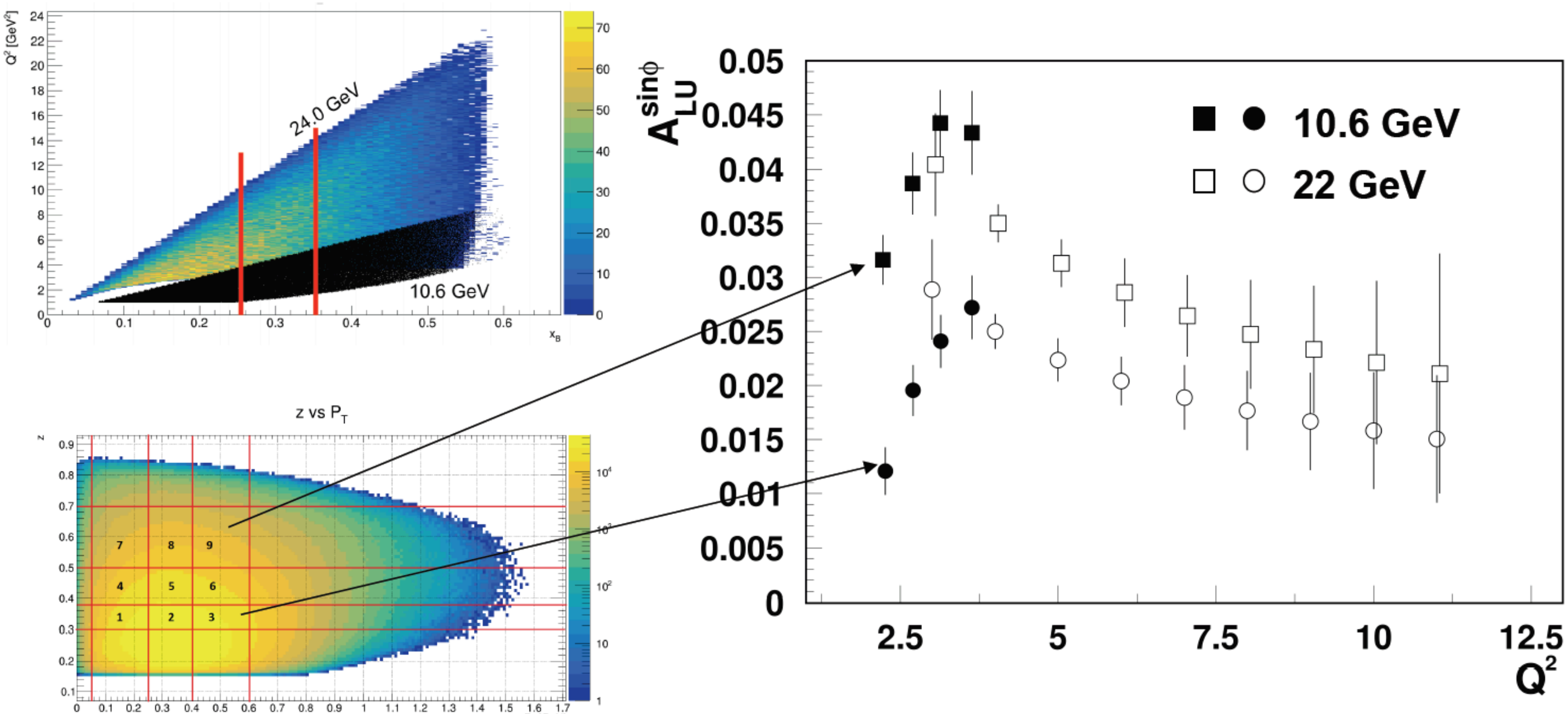
➔ Larger Q² range for different fixed (tight) x_B ranges needed

➔ A 22 / 24 GeV upgrade would allow such studies and help to better understand the onset of factorisation.

➔ Similar effects also observed for cos(ϕ) and cos(2ϕ) moments.

➔ Also here an energy upgarde would be very beneficial to understand the Q² behaviour.

Conclusion and gain from an energy upgrade



H. Avakian

Semi-Exclusive Production of Mesons in SIDIS

Andrei Afanasev
The George Washington University
Washington, DC

Electroproduction: Berger, *Higher-Twist Effects in Deep-Inelastic Scattering,* Phys.Lett B89 (1979) 241; Brandenburg, Khoze, Müller, *Semi-Exclusive Pion Production in Deep-Inelastic Scattering*, Phys.Lett. B347 (1995) 413

Brodsky, Diehl, Hoyer, Peigne, *Semi-exclusive processes: new probes of hadron structure*, Phys.Lett. B449 (1999) 306.

Same mechanism for high-pt photoproduction:

Carlson&Wakely, Phys.Rev.D48:2000-2006,1993

Afanasev, Carlson&Wahlquist, Phys.Lett.B398:393-399,1997; Phys.Rev.D58:054007,1998; Phys.Rev.D61:034014,2000;

Scaling and duality in semi-exclusive processes: Phys.Rev.D62:074011,2000

pQCD applicability

- Large momentum scale is required to make pQCD calculations applicable for specific processes
  - DIS, SIDIS : large Q^2
  - Elastic scattering: large Q^2 (form factors); large p_T (2->2)
  - Deep-exclusive processes (DVCS, DVMP): large Q^2 and/or p_T
  - Wide-angle exclusive photoproduction (Compton, exlusive mesons): small or zero Q^2, large p_T
  - Inclusive photoproduction: small Q^2, large p_T

Berger’s Mechanism

- Berger, Higher-Twist Effects in Deep-Inelastic Scattering, Phys.Lett B89 (1979) 241

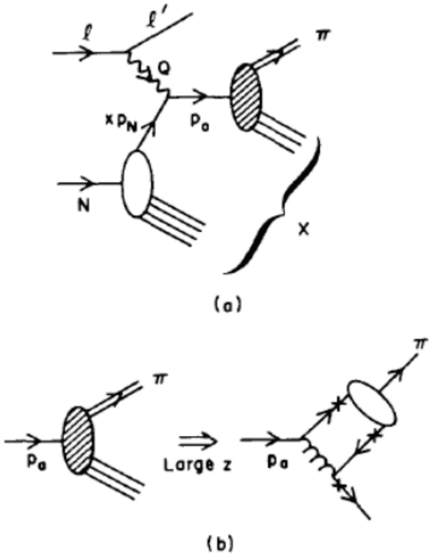


Fig. 1. (a) Sketch of $\ell N \to \ell' \pi X$; Q labels the exchanged γ^* or W. The intermediate quark labeled p_a is off-shell and timelike. The initial quark from the incident nucleon carries four momentum $p_b = xp_N$. (b) On the left is a diagram showing the dissociation of an off-shell virtual quark into a pion plus X. At large p_a^2, its behavior may be represented by the single gluon exchange diagram sketched on the right, in which the quark lines marked with crosses (×) are essentially on-shell. The unshaded oval in the diagram on the right-hand side of fig. 1b represents the unspecified small momentum behavior of the pion wavefunction, represented in this paper simply by the wavefunction at the origin, $\psi_\pi (\boldsymbol{r} = 0)$.

Parton Model + pQCD for high-pT Photoproduction

- Similar to SIDIS, high-pt photoproduction may be described by parton fragmentation; hadron is a part of a jet
- In addition, pQCD predicts existence of a short-distance process in which a hadron (pion) is produced kinematically isolated at high pt, balanced by a opposite-momentum quark jet

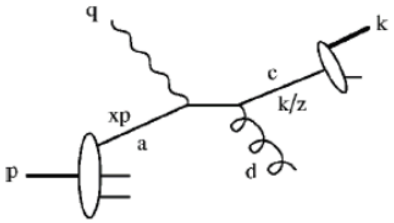


FIG. 2. One diagram for photoproducing π mesons via fragmentation.

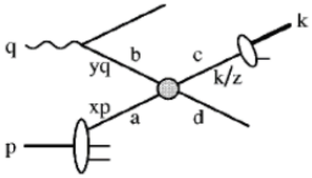


FIG. 4. A resolved photon process.

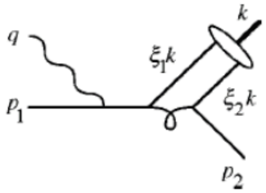


FIG. 3. One of four lowest order perturbative diagrams for direct photoproduction of mesons from a quark. The four diagrams correspond to the four places a photon may be attached to a quark line.

Implications for Experiment

- Direct production enhanced toward high pt

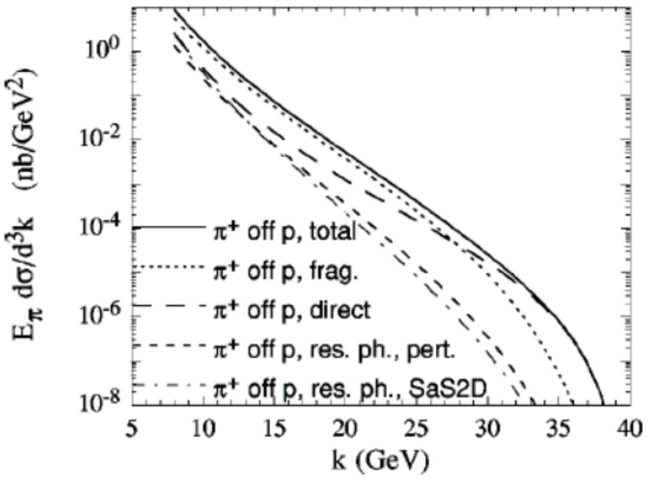


FIG. 5. Comparing fragmentation, direct, and resolved photon processes for $e+p\to\pi^++X$ with $E_e=50$ GeV and $\theta_{\rm lab}=5.5°$.

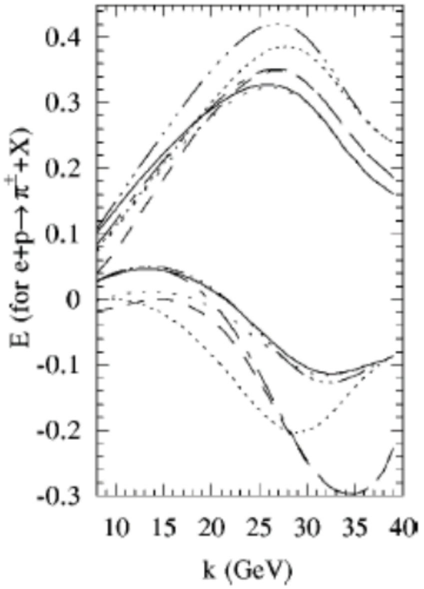


FIG. 9. The asymmetry E for $\vec{\gamma}+\vec{p}\to\pi^\pm+X$, at $E_e=50$ GeV and $\theta_{\rm lab}=5.5°$. This time, the upper six curves are for π^+ production and the lower six curves are for π^- production. As in Fig. 8, for each set of six, there are three curves with the full calculation, with the loose dotted curve using parton distributions from GRSV, the dashed curve using GS-A, and the tight dotted line using the CTEQ with the suggestion of Soffer *et al.* and the BBS polarized gluon distribution. The other three curves have Δg set to zero, with the solid curve using GRSV, the dash-dotted curve using GS, and the dash-triple dot curve using the CTEQ with the suggestion of Soffer *et al.*

Summary and Outlook

- Semi-Exclusive electroproduction:
  - Effects at high –z
  - Effects at high-pt
  - Gives access to QCD mechanism of meson production, by-passing parton fragmentation
    - Same mechanism is assumed for DVMP theory
  - Experimental signature: kinematically isolated hadrons at high-z
  - Why 22 GeV @JLab? Measurements of cross sections – to isolate the semi-exclusive mechanism - require high luminosity; 22 GeV provide a high-momentum scale for perturbative gluon exchange

(Chiral-odd) collinear PDFs in SIDIS

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UNAM (National Autonomous University of Mexico)

“FORDECYT-PRONACES”.

CONACYT
Consejo Nacional de Ciencia y Tecnología

Instituto de Física
UNAM

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JLab22

01/24/23

Asymmetries in SIDIS

Denominator of asymmetries rely on first term in the expansion of their unpolarized structure function.

$$A \propto \frac{\sigma^{\lambda_{\mathrm{T/B/\ldots}}} - \sigma^{-\lambda_{\mathrm{T/B/\ldots}}}}{\sigma^{\lambda_{\mathrm{T/B/\ldots}}} + \sigma^{-\lambda_{\mathrm{T/B/\ldots}}}}$$

For dihadron SIDIS, the denominator calls for the unpolarized PDF:

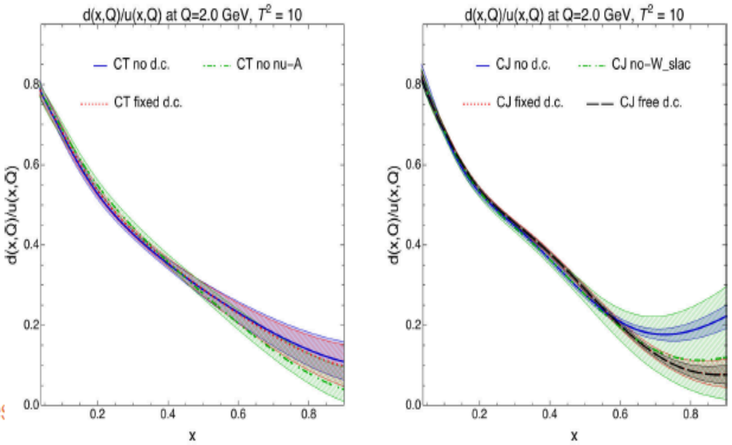
$$\sum_q e_q^2\, f_1^q(x;Q^2) D_{1,ss+pp}^q(z,m_{\pi\pi};Q^2)$$

Unpolarized PDFs:
(large x, low Q^2) is either in the extrapolation region for high-energy global analyses —CT, MSHT, NNPDF
or requires non-perturbative corrections related to the resonance region, e.g. TMC, HT — CJ, JAM.

Change in degrees of freedom.
Increased complexity on which most SIDIS-based extractions at low Q^2 will rely.

Can JLab22 help tackle the denominator?

Comparison of CTEQ-TEA (CT) and CTEQ-JLab (CJ) analyses [Accardi et al, EPJC81]



Why is it important, *e.g.*, for dihadron SIDIS?

From e^+e^-, we've extracted the ratio of pol/unpol DiFFs:

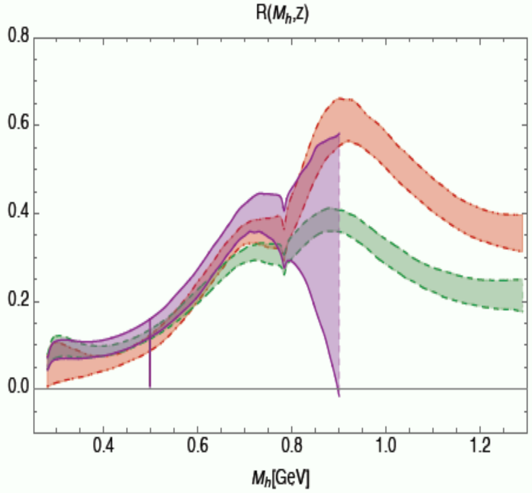
chiral-odd DiFF

$$\boxed{R(z, M_h) = \frac{|\boldsymbol{R}|}{M_h} \frac{H_1^{\sphericalangle u}(z, M_h; Q_0^2)}{D_1^u(z, M_h; Q_0^2)}}$$

unpolarized DiFF

and, up to normalization, the unpol. DiFFs.

[Radici, AC, Bacchetta, JHEP 05 (2015)]



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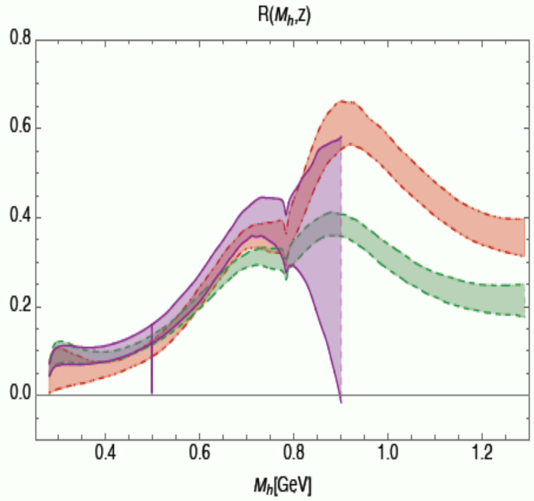
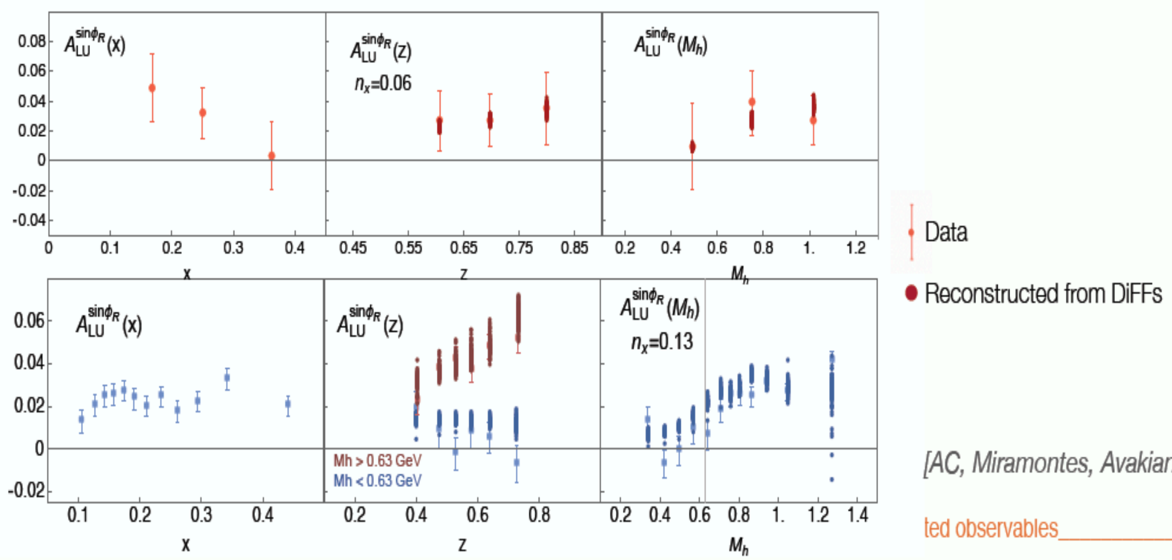


Factorizable dihadron variables:

Consistency check on SIDIS (z, M_h) dependence at CLAS & CLAS12

Determination of the integral of the PDF part, here $e^P(x) \to n_x$, from reconstruction



[AC, Miramontes, Avakian, Mirazita, Pisano, PRD]

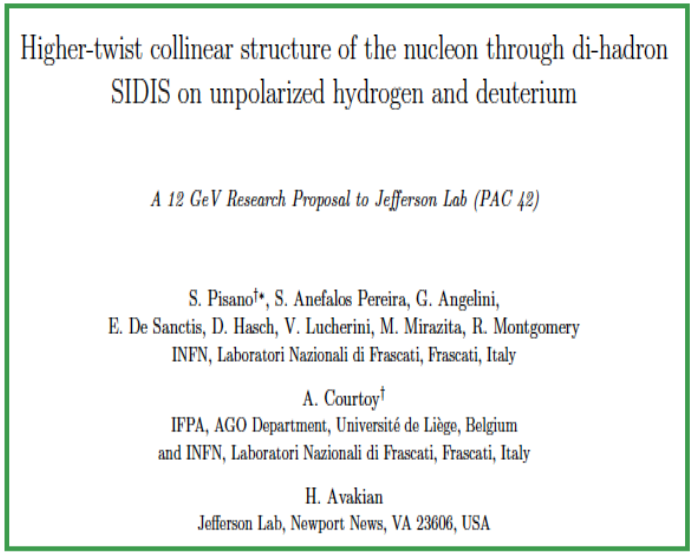
Studies of multiplicities at JLab22

Role of denominator equally important for other asymmetries at low Q^2

$$\sum_q e_q^2\, f_1^{q,\text{lead. power}}(x;Q^2)\, D_1^{q,\text{lead. power}}(\text{rel. variables};Q^2) + \text{non-leading power}$$

From WG2: systematic ways to explore the leading-power PDFs toward lower energies.

(Old) proposal to measure dihadron multiplicities at CLAS12



Higher-twist collinear structure of the nucleon through di-hadron SIDIS on unpolarized hydrogen and deuterium

A 12 GeV Research Proposal to Jefferson Lab (PAC 42)

S. Pisano[†*], S. Anefalos Pereira, G. Angelini,
E. De Sanctis, D. Hasch, V. Lucherini, M. Mirazita, R. Montgomery
INFN, Laboratori Nazionali di Frascati, Frascati, Italy

A. Courtoy[†]
IFPA, AGO Department, Université de Liège, Belgium
and INFN, Laboratori Nazionali di Frascati, Frascati, Italy

H. Avakian
Jefferson Lab, Newport News, VA 23606, USA

$$M^h(z, m_{\pi\pi}, x; Q^2) \;=\; \frac{\sum_q e_q^2\, f_1^q(x;Q^2)\, D_1^q(z, m_{\pi\pi};Q^2)}{\sum_q e_q^2\, f_1^q(x;Q^2)}$$

Separating signals from target and current fragmentation

Timothy B. Hayward

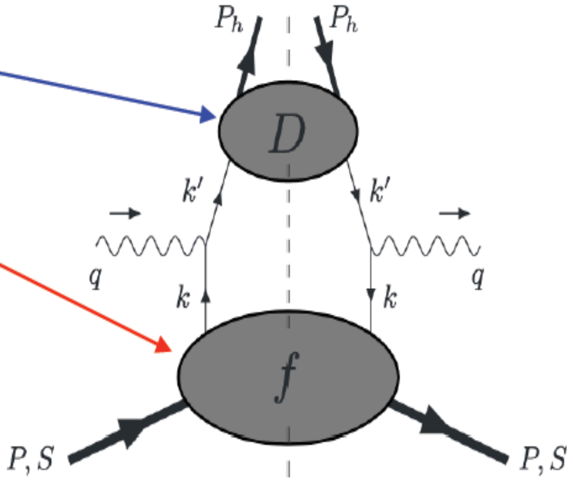
Science at the Luminosity Frontier: Jefferson Lab at 22 GeV Workshop

January 24, 2023

Traditional SIDIS measurements

- Decades of study have led to detailed mappings of the momentum distribution of partons in the nucleon in terms of 1-D and 3-D (TMD) parton distribution functions (PDFs).
- Accessible in SIDIS measurements of cross sections and asymmetries, but rely on the assumption that measured hadrons are produced in the CFR.
- Cross section factorized[1] as a convolution of PDFs and Fragmentation Functions (FFs).

$$\frac{\mathrm{d}\sigma^{\mathrm{CFR}}}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}z_h} = \sum_a e_a^2 \boxed{f_a(x_B)} \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}y} \boxed{D_a(z_h)}$$



M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

- PDFs
  - Probability (leading twist) of finding a particular parton in a certain configuration
  - Confined motion of quarks and gluons inside the nucleus
  - Orbital motion of quarks, correlations between quarks and gluons
- Fragmentation Functions
  - Nonperturbative dynamics of hadronization
  - Probability for a parton to form particular final state hadron
  - Insight into transverse momenta and polarization

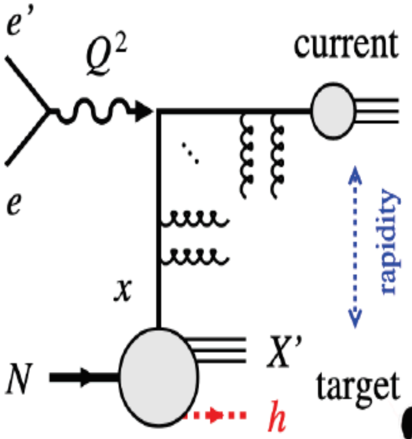
---

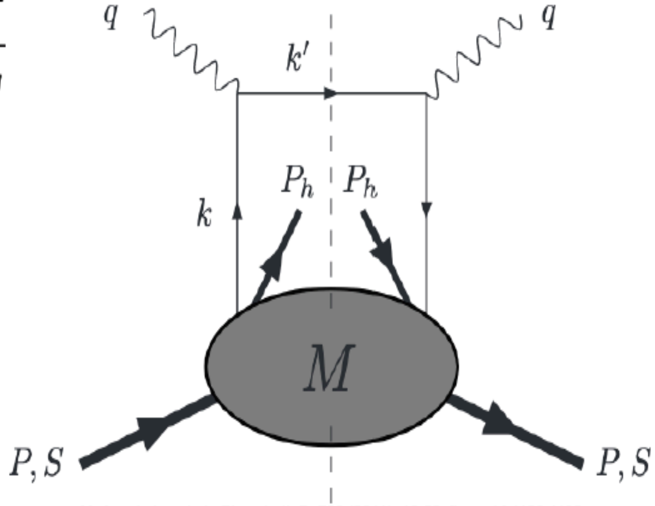
[1] A. Bacchetta et al., JHEP 02 (2007) 093 [hep-ph] 0611265,

The Neglected Hemisphere – Target Fragmentation

- Final state hadrons also form from the left-over target remnant (TFR) whose partonic structure is defined by "fracture functions"[1,2]: the probability for the target remnant to form a certain hadron given a particular ejected quark.
- Understanding the formation of hadrons out of the target remnant allows us to study signals subject to entirely different systematics, test our complete understanding of the SIDIS production mechanisms and could be key for interpreting CFR signals.

$$\frac{\mathrm{d}\sigma^{\mathrm{TFR}}}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}z} = \sum_a e_a^2\,(1-x_B)\boxed{M_a(x_B,(1-x_B)z)}\,\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}y}$$

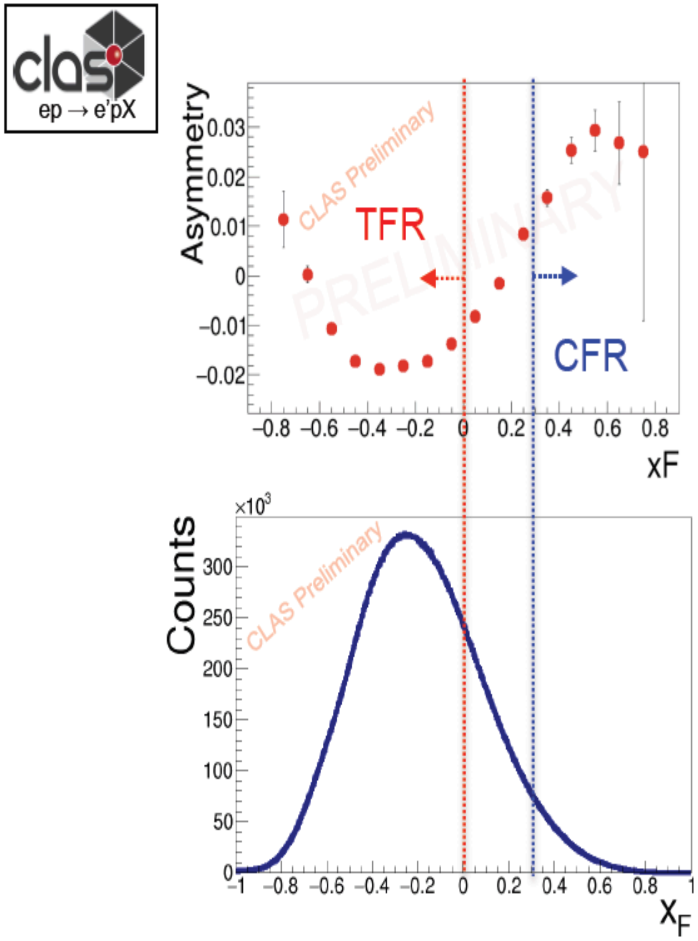




M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

1. L. Trentadue and G. Veneziano, Phys. Lett. B323 (1994) 201,
2. M. Anselmino et al., Phys. Lett. B. 699 (2011), 108-118, [hep-ph] 1102.4214
3. TFR/CFR Fig. from EIC Yellow Report, (2021) [physics.ins-det] 2103.05419

Can We Separate Target and Current?



Feynman variable

$$x_F = \frac{p_h^z}{p_h^z(\mathrm{max})} \quad \text{in CM frame } \mathbf{p} = -\mathbf{q}, \qquad -1 < x_F < 1$$

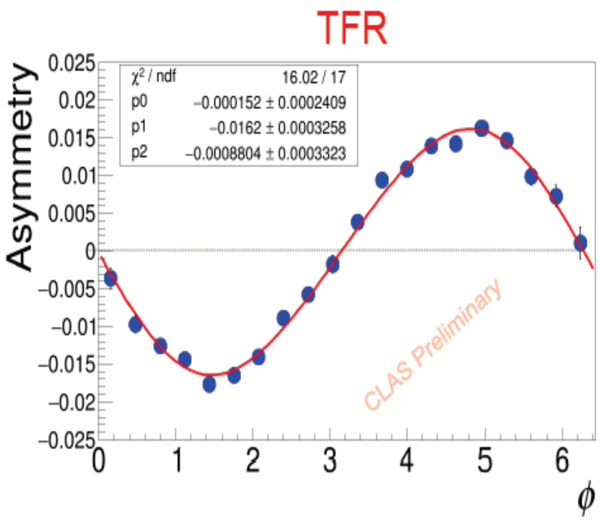
Rapidity

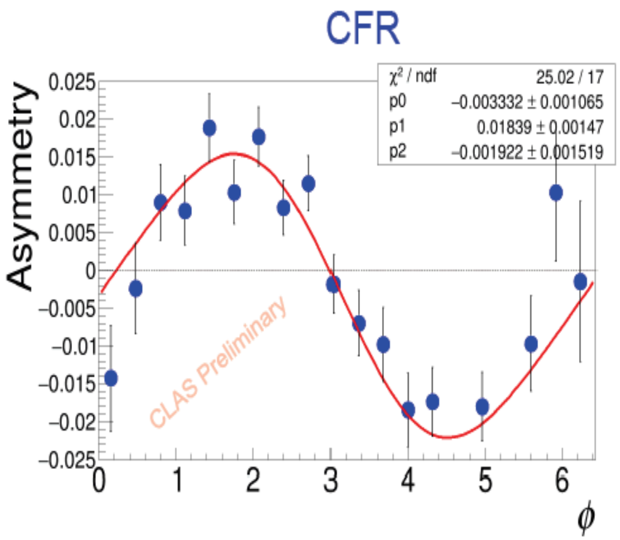
$$y = \frac{1}{2}\log\frac{p_h^+}{p_h^-} = \frac{1}{2}\log\frac{E_h + p_h^z}{E_h - p_h^z}$$

- No clear ***experimental*** definition of what constitutes current production versus target production.
- Structure functions, with different production mechanisms in both regions, give a possible clue.
- Protons (as opposed to mesons) at CLAS12 kinematics give a unique opportunity because they have extensive coverage in both regions.

Separate Signals

ep → e'pX





$$F_{LU}^{\sin\phi} \propto \frac{2M}{Q}\left[\tilde{l}_2^{\perp h} + \ldots \qquad\qquad \right]$$

Need more theory calculations!

$$F_{LU}^{\sin\phi} \propto \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(xeH_1^{\perp} + \frac{M_h}{M}f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{h}\cdot p_T}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

- Sinusoidal modulations (that are probably) coming from the struck quark and the spectator partons appear with roughly equal amplitudes but opposite signs.

Recent progress in the Lattice QCD calculation of TMDs

Science at the Luminosity Frontier: Jefferson Lab at 22 GeV Workshop

Jefferson Lab, Jan. 23—25, 2023

YONG ZHAO

JAN 24, 2023

Argonne NATIONAL LABORATORY

Summary from last JLab 22 GeV Workshop

Targets for lattice QCD studies:

Observables	**Status**
Non-perturbative Collins-Soper kernel	✓, keep improving the systematics
Soft factor	✓, to be under systematic control
Info on spin-dependent TMDs (in ratios)	In progress
Proton v.s. pion TMDs, (x, b_T) (in ratios)	In progress
Flavor dependence of TMDs, (x, b_T) (in ratios)	to be studied
TMDs and TMD wave functions in (x, b_T) space	In progress
Gluon TMDs	to be studied
Wigner distributions/GTMDs (x, b_T)	to be studied

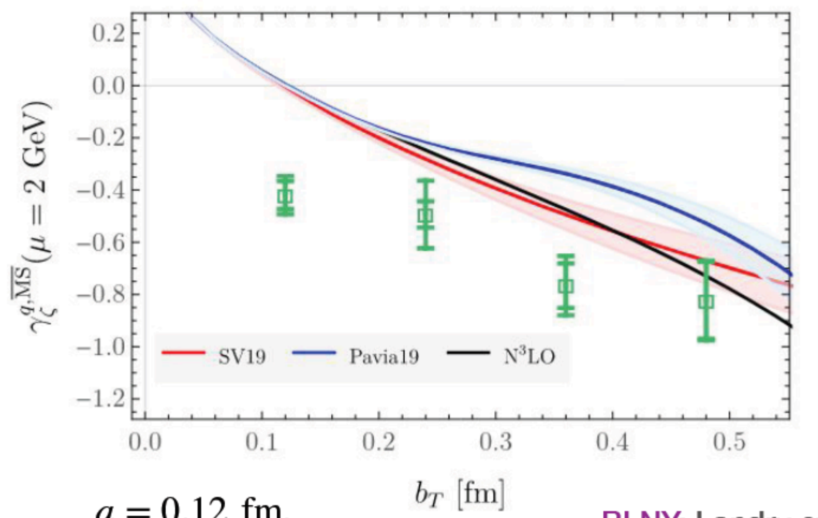
Status of the Collins-Soper kernel calculation

	Lattice setup	Renormalization	Operator mixing	Fourier transform	Matching	*x*-plateau search
SWZ20 PRD 102 (2020) Quenched	$a = 0.06$ fm, $m_\pi = 1.2$ GeV, $P^z_{\mathrm{max}} = 2.6$ GeV	Yes	Yes	Yes	LO	Yes
LPC20 PRL 125 (2020)	$a = 0.10$ fm, $m_\pi = 547$ MeV, $P^z_{\mathrm{max}} = 2.11$ GeV	N/A	No	N/A	LO	N/A
SVZES 21 JHEP 08 (2021)	$a = 0.09$ fm, $m_\pi = 422$ MeV, $P^+_{\mathrm{max}} = 2.27$ GeV	N/A	No	N/A	NLO	N/A
PKU/ETMC 21 PRL 128 (2022)	$a = 0.09$ fm, $m_\pi = 827$ MeV, $P^z_{\mathrm{max}} = 3.3$ GeV	N/A	No	N/A	LO	N/A
SWZ21 PRD 106 (2022)	$a = 0.12$ fm, $m_\pi = 580$ MeV, $P^z_{\mathrm{max}} = 1.5$ GeV	Yes	Yes	Yes	NLO	Yes
LPC22 PRD 106 (2022)	$a = 0.12$ fm, $m_\pi = 670$ MeV, $P^z_{\mathrm{max}} = 2.58$ GeV	Yes	No	Yes	NLO	Yes
ASWZ23 In preparation	$a = 0.12$ fm, $m_\pi = 140$ MeV, $P^z_{\mathrm{max}} = 2.15$ GeV	Yes	Yes	Yes	NLO	Yes

Collins Soper kernel

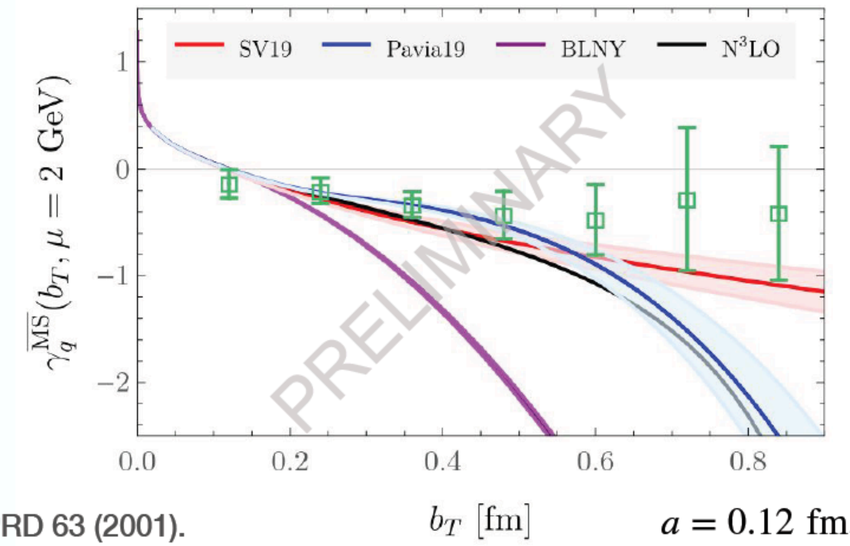
Comparison between lattice results and global fits

P. Shanahan, M. Wagman and YZ (SWZ21), Phys. Rev.D 104 (2021)



$a = 0.12$ fm,
$m_\pi = 580$ MeV,
$P^z_{\mathrm{max}} = 1.5$ GeV

A. Avkhadiev, P. Shanahan, M. Wagman and YZ (ASWZ23), In preparation



BLNY: Landry et al., PRD 63 (2001).
SV19: Scimemi and Vladimirov, JHEP 06 (2020)
Pavia19: Bacchetta et al., JHEP 07 (2020).

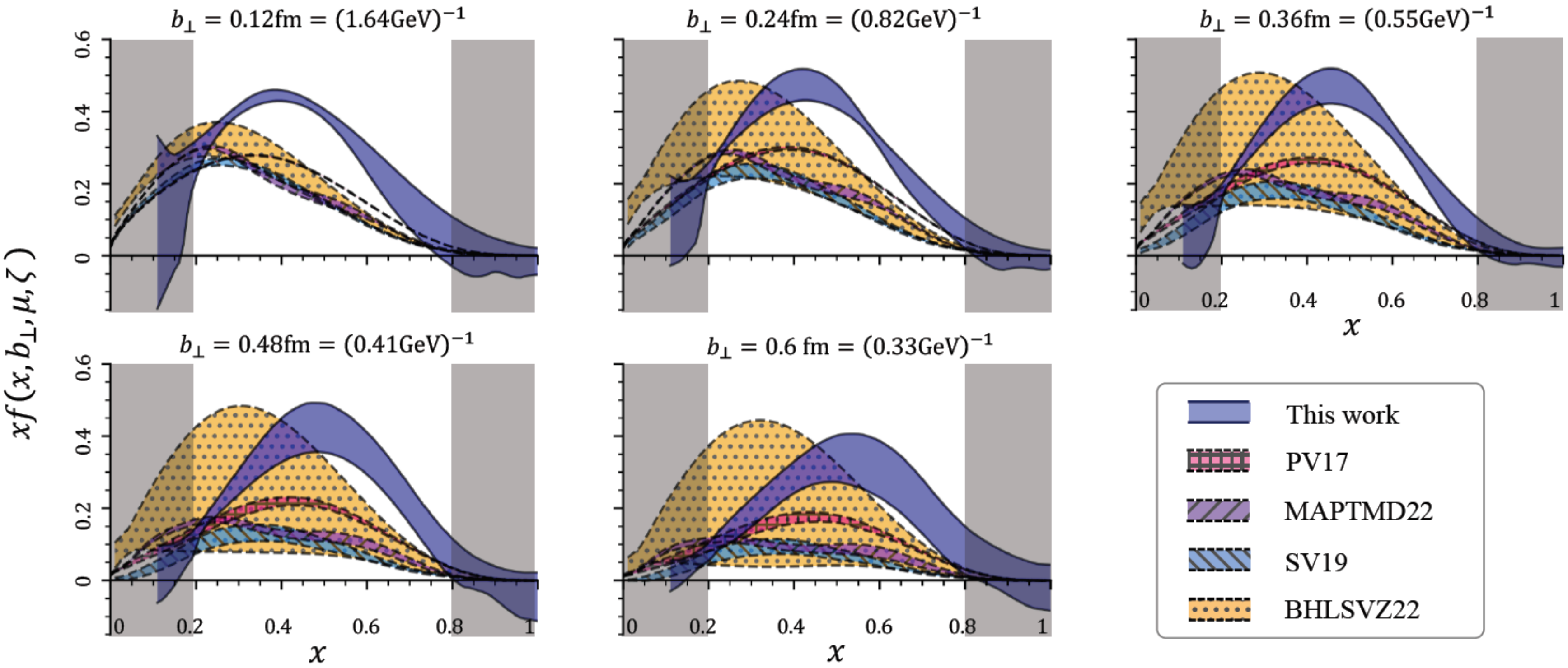
$a = 0.12$ fm,
$m_\pi = 140$ MeV,
$P^z_{\mathrm{max}} = 2.15$ GeV

- Using quasi beam function
- Systematics not quantified

- Using quasi TMD wave function
- Systematics quantified

(x, b_T) dependence of the unpolarized proton TMD

J.-C. He, M.-H. Chu, J. Hua et al., (LPC), arXiv: 2211.02340.

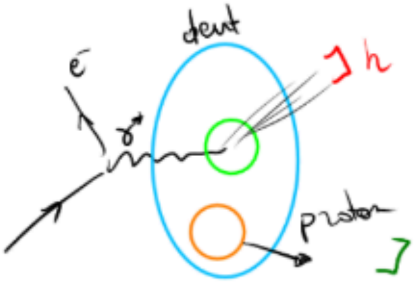


$a = 0.12$ fm,
$m_\pi = \{310,\ 220\}$ MeV,
$P^z_{\text{max}} = 2.58$ GeV

SV19: Scimemi and Vladimirov, JHEP 06 (2020)
Pavia19: Bacchetta et al., JHEP 07 (2020).
MAPTMD22: Bacchetta et al., JHEP 10 (2022).
BHLSVZ22: Bury et al., JHEP 10 (2022).

SIDIS with tagging

Wim Cosyn (FIU)



- Detection of a hadron in **current** and in **target** fragmentation region
- In *ep* gives access to interactions, correlations within the hadron
    - Kinematic: $x \leftrightarrow z$; p_T
    - Quantum numbers: charge/flavor/spin
- Sensitive to the dynamics of target fragmentation → many topics to explore
- Using light nuclei: tag nuclear fragment
    - Constrain initial nuclear configuration
    - On-shell extrapolation for free neutron TMDs [Sargsian, Strikman PLB 06]
    - At higher momenta study of medium modifications [T. Kutz tomorrow]
- JLab upgrade context
    - Tagging is harder in fixed target (↔EIC)
    - But high-x region
    - Bonus/Alert dedicated detectors
    - Differential measurements will be lumi hungry

Studies of Evolution Properties of Structure Functions in SIDIS

Harut Avakian (JLab)

Science at the Luminosity Frontier: Jefferson Lab at 22 GeV Workshop

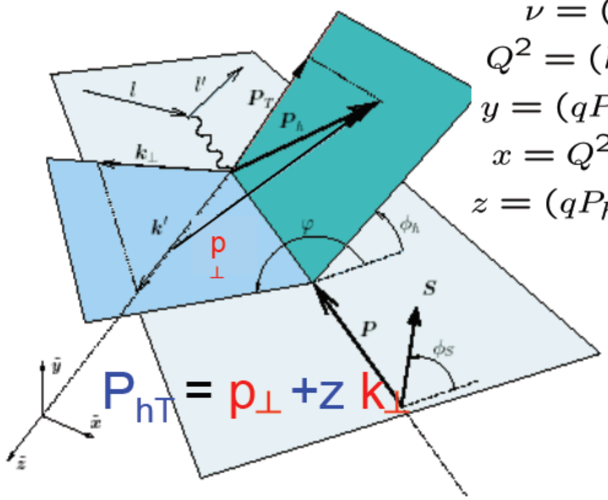
23 Jan 2023, 03:20 → 25 Jan 2023, 22:50 US/Eastern

Understanding the QCD: from observables to QCD dynamics

- Testing the QCD based frameworks for finite energies in SIDIS with experiments with polarized beams and targets
- Studies of evolution properties of observables

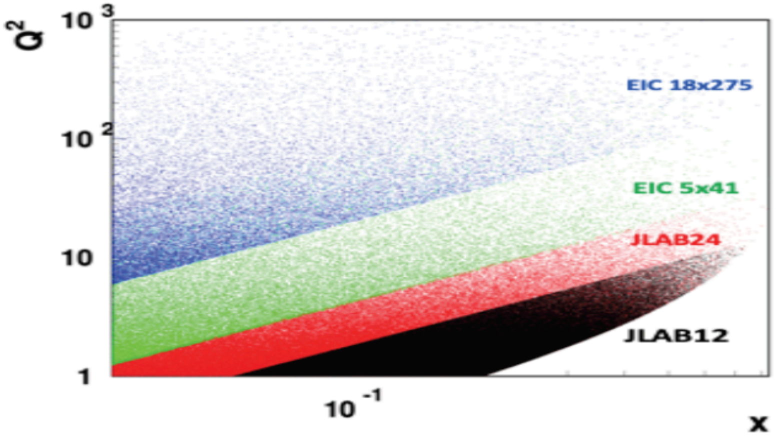
Summary

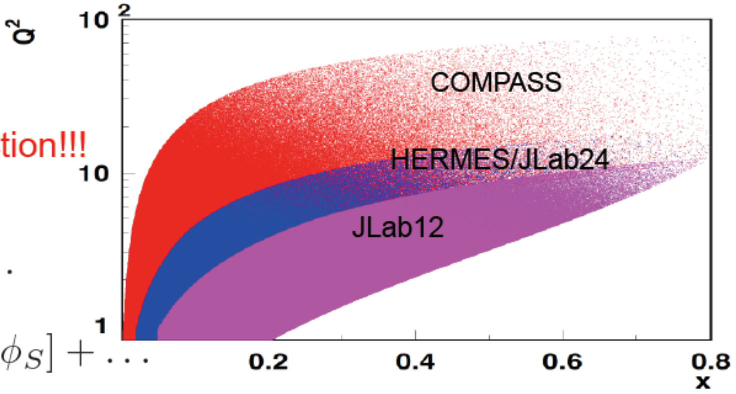
SIDIS kinematical coverage and observables



$$P_{hT} = p_\perp + z\,k_\perp$$

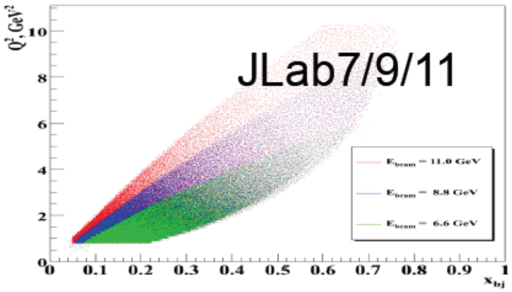
$$\nu = (qP)/M$$
$$Q^2 = (k - k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$





SIDIS experiments measure azimuthal dependence of the cross section!!!

$$\sigma \propto F_{UU} + P_b\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}\sin\phi + P_t\epsilon F_{UL}^{\sin 2\phi}\sin 2\phi + \ldots$$
$$+\epsilon F_{UU,L} + |S_\perp|[F_{UT}^{\sin\phi-\phi_S}\sin(\phi-\phi_S) + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S] + \ldots$$



- Studies of azimuthal modulations give access to underlying 3D partonic distributions
- All azimuthal modulations increase with P_T
- All assumptions involved in description of SFs, should be tested!
- QCD predicts only the Q^2-dependence of 3D PDFs

Theory-Experiment: SIDIS Validation tests

$$\frac{d\sigma^{lN\to l'hX}}{dx_B dQ^2 dz dP^2_{h\perp} d\phi_h} = \frac{\pi\alpha^2 y}{x_B y Q^2(1-\epsilon)}[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \ldots\ldots]$$

$$\left.\begin{array}{l} lN \to l'\pi^+ X \\ lN \to l'\rho^0 X \\ \ldots\ldots\ldots\ldots \end{array}\right\} \; lN \to l'\pi^+ X$$

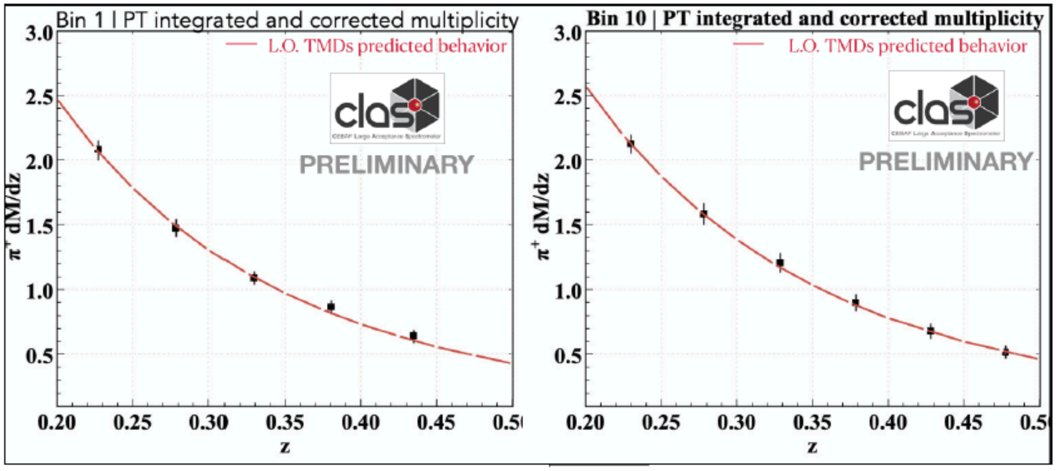
theory

Fragmentation Function
→ probability to produce π+

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

Integrated over transverse momentum are well described by the formalism

the CLAS data at 10.6 GeV follows global fits (also at 6 GeV).



- Challenges starts when measuring dependence on P_T, ($F_{UU,L}/F_{UU,T}$ maybe >1 at large P_T)

TMDs IN Semi-Inclusive DIS

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

$$F_{UU,T}(x,z,P_{hT}^2,Q^2)$$

$$= x\sum_q \boxed{\mathcal{H}^q_{UU,T}(Q^2,\mu^2)} \int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{P}_\perp\, f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2)\, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2)\,\delta(z\boldsymbol{k}_\perp-\boldsymbol{P}_{hT}+\boldsymbol{P}_\perp)$$

$$+Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2)+\mathcal{O}(M^2/Q^2)$$

Major advance in theory in last years

$$\hat{f}_1^a(x,b_T^2;\mu_f,\zeta_f)=\int\frac{d^2\boldsymbol{k}_\perp}{(2\pi)^2}e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp}f_1^q(x,k_\perp^2;\mu_f,\zeta_f)$$

perturbative Sudakov form factor

$$\hat{f}_1^a(x,b_T^2;\mu_f,\zeta_f)=[C\otimes f_1](x,\mu_{b_*})\,e^{\int_{\mu_{b_*}}^{\mu_f}\frac{d\mu}{\mu}\left(\gamma_F-\gamma_K\ \ln\ \frac{\sqrt{\zeta_f}}{\mu}\right)}\left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\rm resum}+g_K}f_{1\,NP}(x,b_T^2;\zeta_f,Q_0)$$

collinear PDF

matching coefficients (perturbative)

Collins-Soper kernel (perturbative and nonperturbative)

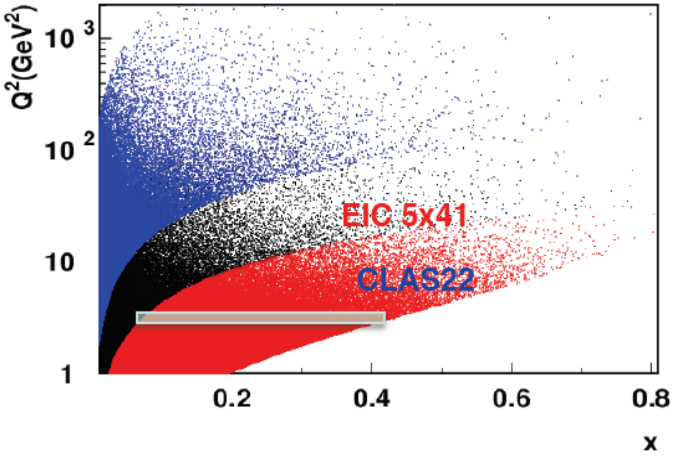
nonperturbative part of TMD

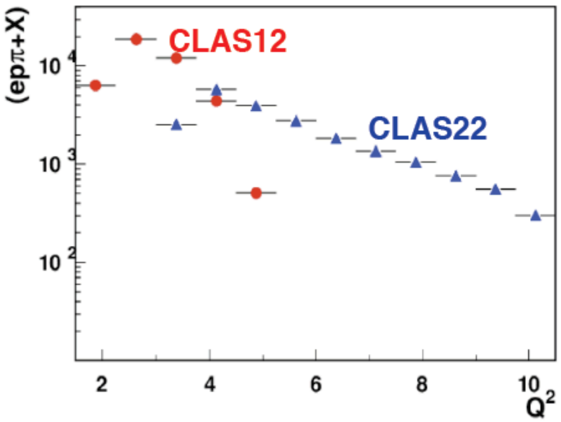
$$\boxed{g_K(b_T^2)}=-g_2^2\frac{b_T^2}{4}$$

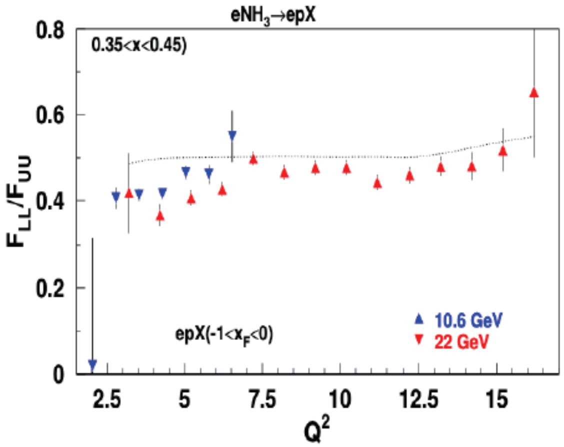
CS kernel discribes the interaction of out-going parton with the confining potential
Provides nonperturbative part of evolution for TMDs

CS-kernel→independent on any other variables

Accessing CS-kernel directly or through extraction of SFs

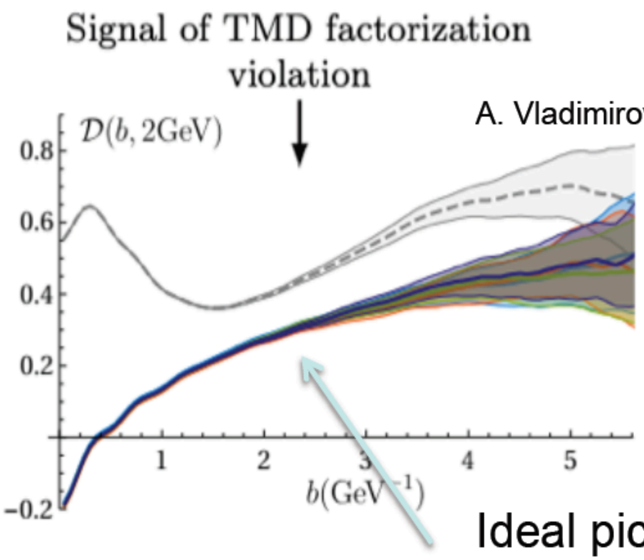






Use slices in Q^2 (good resolution needed)

- Wide Q^2 range and high luminosity is the key for a validating separation of twist-2 contributions



A. Vladimirov

Ideal picture

- Q^2 evolution studies possible, provide superior access to critical Collins-Soper (CS) kernel
- CLAS12 at JLab20+ can provide a wide range in Q^2 combined with high lumi and superior resolution

- Test the CS-kernel from different experiments, and for different kinematics in a given experiment
- Evaluate the systematics due to factorization violation and define possible reasons (some can be easy to fix)

SUMMARY

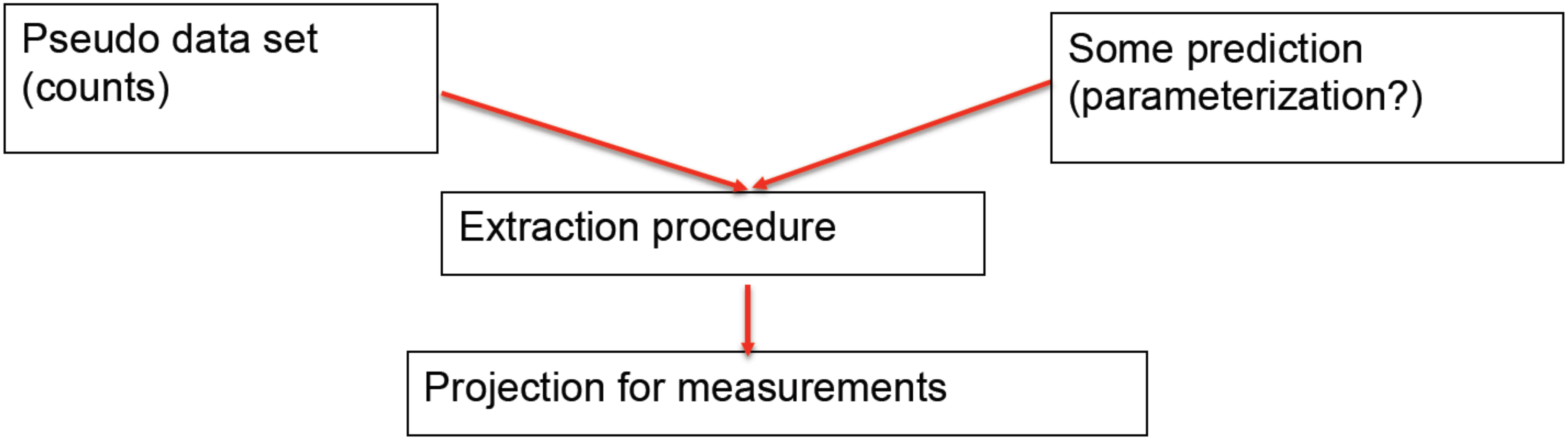
- Studies of QCD dynamics with **controlled systematics** involving Semi-Inclusive DIS, requires detailed understanding of the contributions into the measured cross sections/multiplicities/ asymmetries as a function of all involved kinematical variables (including the P_T and ϕ)

- Evolution studies and understanding the production mechanism will help in defining the validity region of the formalism, which may be much wider than currently anticipated

- To evaluate the systematics of extracted TMDs, it is critical to validate the formalism, and understand main contributions violating the factorized picture based on the dominance of the leading twist contributions, estimate relative contributions

Support slides

Making projections: extraction procedure



Pseudo data set (counts)

Some prediction (parameterization?)

Extraction procedure

Projection for measurements

Extraction procedure should have clear definition of systematics related to assumptions and approximations!!!!

- The role of multidimensional measurements should be well defined, accounted in the extraction
  - The same parameterization used in production of data and extraction of TMDs will have practically unconstrained systematics
  - Using statistical errors from simulation to evaluate the errors on a given TMDs may produce absolutely unrealistic projections (uncontrolled systematics), in particular beyond the actual data coverage used to make parameterizations.

Steps to control systematics in interpretation

- SIDIS, with hadrons detected in the final state, from experimental point of view, is a measurement of observables in 5D space (x,Q^2,z,P_T,ϕ), 6D for transverse target, $+\phi_S$

  Collinear SIDIS, is just the proper integration, over P_T,ϕ,ϕ_S
- SIDIS observations relevant for interpretations of experimental results:
  1. Understanding the kinematic domain where non-perturbative effects of interest are significant (ex. x,P_T-range)
  2. Understanding of P_T-dependences of observables in the full range of P_T dominated by non-perturbative physics is important (also for 1D SIDIS)
  3. Understanding of phase space effects is important (additional correlations)
  4. Understanding the role of vector mesons is important
  5. Understanding of evolution properties and longitudinal photon contributions
  6. Understanding of radiative effects may be important for interpretation
  7. Overlap of modulations (acceptance, RC,…) is important in separation of SFs
  8. Multidimensional measurements with high statistics, critical for separation of different ingredients
- QCD calculations may be more applicable at lower energies when 1)-7) clarified
- Need a realistic chain for MC simulations of SIDIS to produce realistic projections with controlled systematics