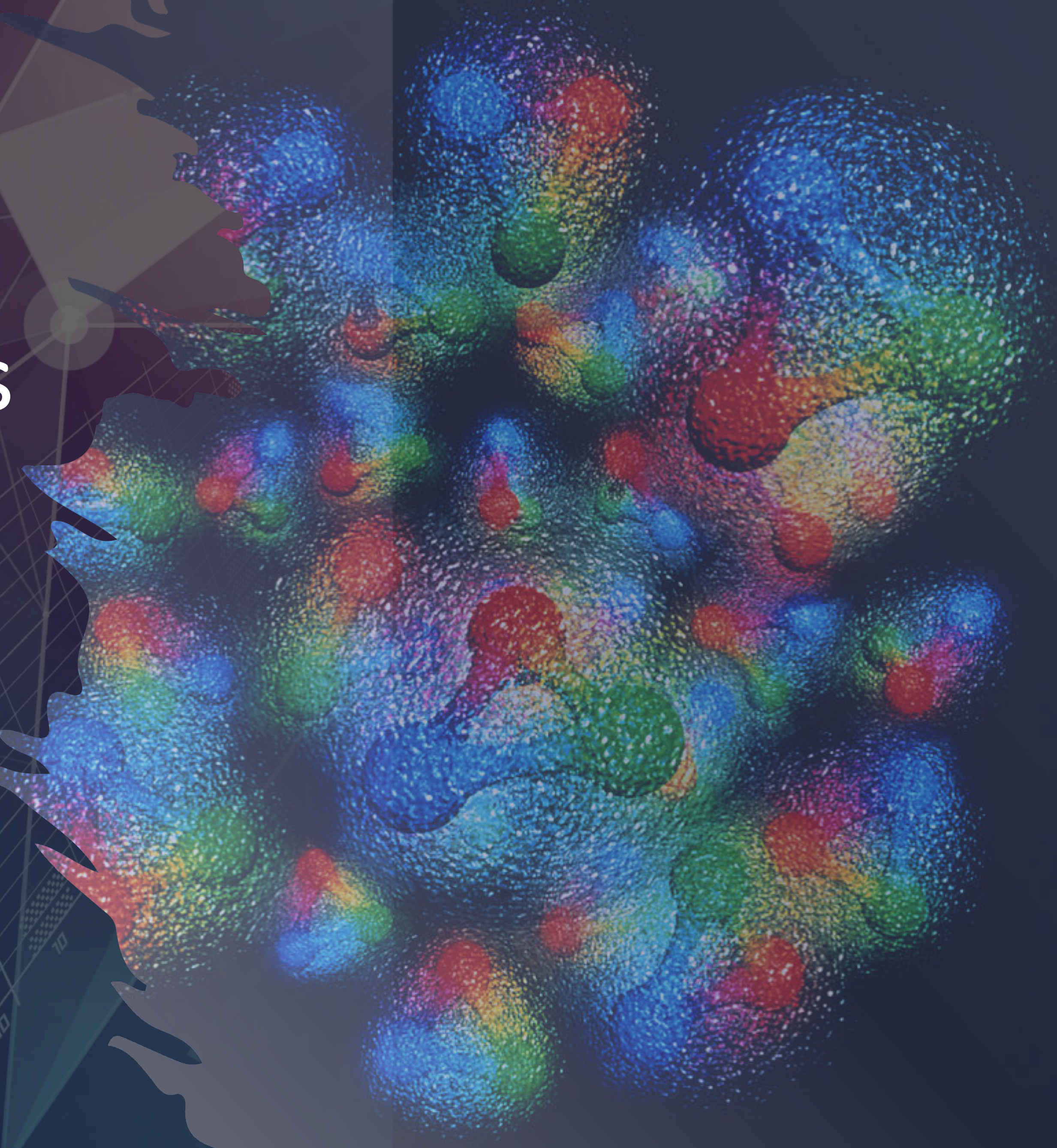
Unique opportunities and complementarities at EIC 2nd detector

Simonetta Liuti



UNIVERSITY OF VIRGINIA 1819
DEPARTMENT OF ENERGY • UNITED STATES OF AMERICA
CENTER for NUCLEAR FEMTOGRAPHY

Concrete steps towards 2nd detector
(started in 2022, see R. Fatemi and A. Deshpandhe's contributions)

December 6-8, 2022
CFNS, Stony Brook
"Incubator" workshop organized by
EIC 2nd detector committee

Spring 2023
Establishment of
Physics Program Committee

May 17-19, 2023
Temple U.
1st International Workshop on EIC 2nd detector

https://indico.bnl.gov/event/17693/

https://indico.bnl.gov/event/18414/

Aim of this talk

- ✓ **Overview** of the physics discussed at the workshops
- ✓ **Basic message**: The EIC 2nd detector committee is also a **venue for gathering the communities' contributions**, whether in the form of ideas, or more technical proposal

Renee Fatemi
Klaus Dehmelt
Charles Hyde
Sangbaek Lee
Simonetta Liuti
Marco Radici (ex officio)
Bjoern Schenke
Ernst Sichterman
Pawel Nadel Turonski
Thomas Ulrich
Anselm Vossen

Some features of the 2nd detector in IR8

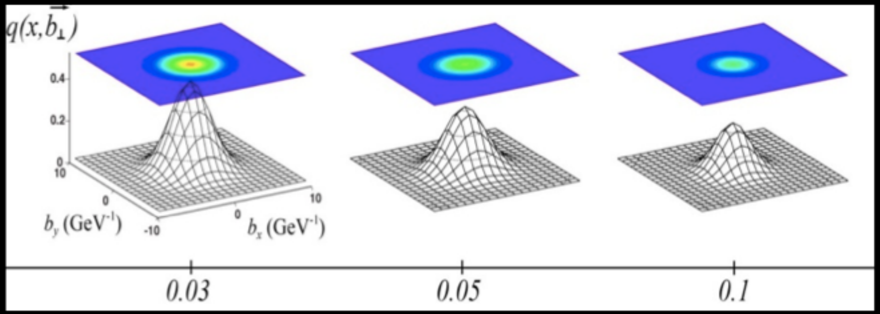
(R. Fatemi)

- **HIGH INTENSITY MAGNETIC FIELD:** charged particles momentum reconstruction

- **EXTENDED COVERAGE:** precision electromagnetic calorimetry – Deeply Virtual Exclusive Experiments

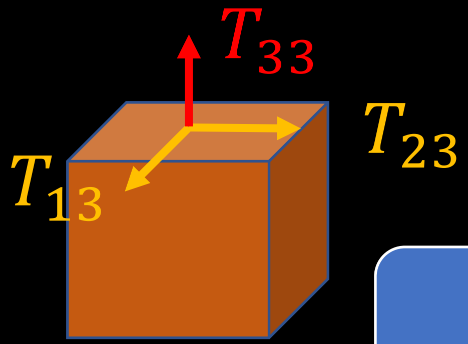
- **SECONDARY FOCUS:** tagging all ion fragments with extended acceptance at low p_T/ low x protons – DVCS from nuclei

- **ENHANCED MUON ID** (in backward and barrel region): TCS and other DVES and diffractive reactions
-
- **BACKWARD HADRONIC CALO** - Low-x physics, reconstruction of current jets in the approach to saturation



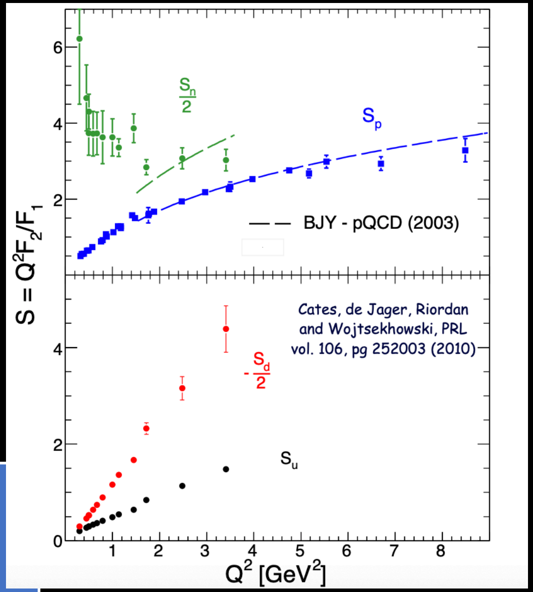
Fourier transforms of GPDs (M. Defurne)

Imaging the nuclear initial state



QCD Energy Momentum Tensor content

Gluon dynamics and flavor/color symmetries



At the same time, role of complementarity:

"Motivations for Two Detectors at a Particle Collider",

Paul D. Grannis and Hugh E. Montgomery,
arXiv:2303.08228

Instances where two independent experiments were critical for confirmation of major new discoveries

- ✓ Tevatron top quark discovery (CDF and D0)
- ✓ LHC Higgs discovery
- ✓ Cases where independent measurements ***provided critical protection*** against incorrect results (ghost muons, Omega b observation …)
- ✓ Instances where ***unconfirmed result remains in limbo*** because two-detector system is not in place (W mass….)

❖ Two competitive and independent collaborations make vigorous confirmation of each other's new results and weed out erroneous claims.

Outstanding new questions

Jets in nuclei

Felix Ringer , Helen Caine, Ivan Vitev

Deeply virtual exclusive experiments

Yoshi Hatta , Feng Yuan, Vadim Guzey, Yakub Wagner, Zhite Yu, Bjoern Schenke, Brandon Kriesten, Stefan Diehl, Matteo Rinaldi, Pawel Sznajder, Pierre Chatagnon, Charles Hyde, Marie Boer, Spencer Klein, Jianwei Qiu, SL

Quark and gluon TMDs in nucleons and nuclei

Yuri Kovchegov, John Terry, F.G. Celiberto,, Ralf Seidl, Elena Boglione,

Target fragmentation

Yang Tin Chien, R Elayavalli, Christian Weiss

Backward photoproduction via baryon exchange and baryon stopping

Spencer Klein, Z.Xu

Current target correlations and quantum entanglement

Dima Kharzeev, Dennis Sivers

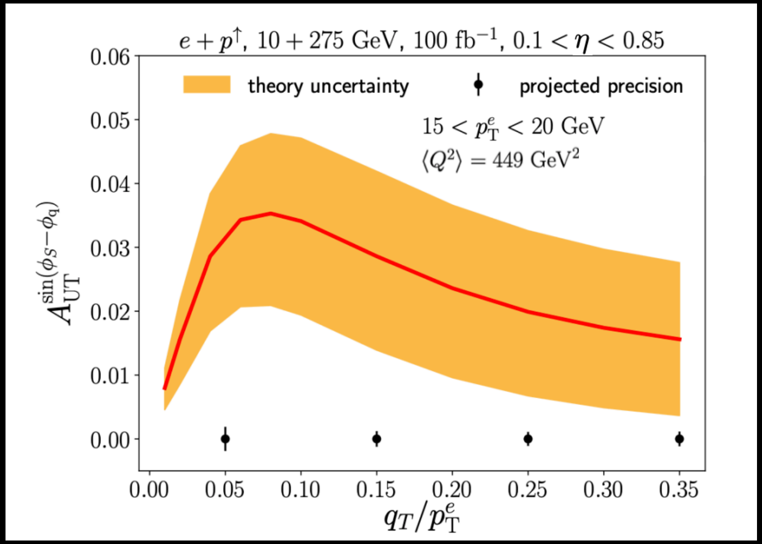
This is a partial list…..many other equivalently valid contributions …..

Open questions on Understanding Jets in Nucleons and Nuclei

Felix Ringer: **Emphasize <u>Far forward</u> detection capabilities, ML-based approach**

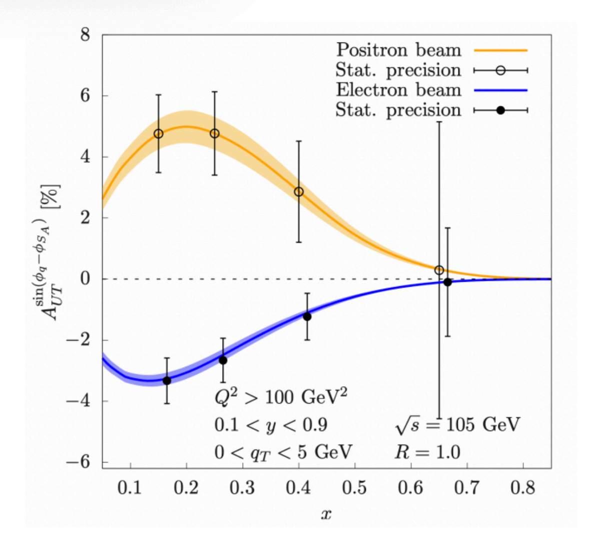
Electron jet correlations

$$\vec{q}_T = \vec{p}_T^{\,e} + \vec{p}_T^{\,\mathrm{jet}}$$



Neutrino jet correlations (flavor separation)

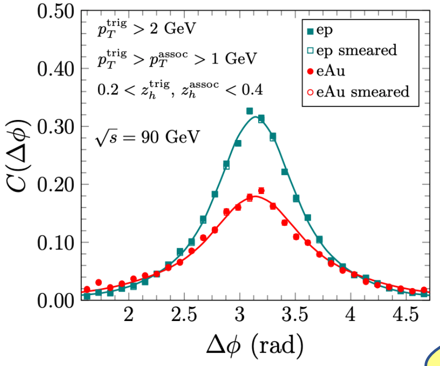
$$\vec{q}_T = \vec{p}_T^{\,\nu} + \vec{p}_T^{\,\mathrm{jet}}$$



- Helen Caines

Access to the gluon Wigner distribution,
Probing the linearly polarized Weizsaecker-Williams gluon TMDs
Probing the gluon Sivers function

Opportunities at the EIC



Events with inelasticity $0.6 < y < 0.8$
Pairs $|\eta| < 3.5$
Integrated luminosity 10 fb^{-1}/A
stat uncertainties smaller than markers

RHIC
- Similar Moderate-Q^2-low x
- Similar collision energy
- Complimentary probes (e vs p)

LHC
- High Q^2 - low x
- Complimentary probes (e vs p)

EIC
- Study wide range of ion beams from deuterons to heavy nuclei (Au, Pb, U)

Definitive measurements at EIC?

- Ivan Vitev

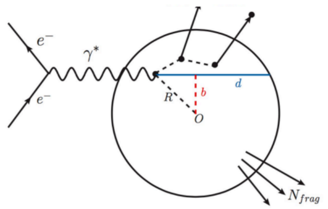
Parton showers in cold nuclear matter

Renormalization group analysis of modifications of hadronization

Centrality dependent light and heavy meson (and jet) production in eA

Jet substructure modification in eA (charge and momentum sharing distributions)

$\times D^{h/j}(z,\mu)$,



Z. Kang et al. (2016)

W. Chang et al. (2022)

Centrality dependent measurements emphasize the dynamical nature of nuclear effects

BeAGLE – centrality can be determined from the neutrons detected in the ZDC, <d>

Robust with respect to nuclear effects – shadowing, particle formation times

Deeply virtual exclusive experiments: quark and gluon angular momentum and the origin of the spin crisis

$$J_q + J_g = L_q + \frac{1}{2}\Sigma_q + J_g = \frac{1}{2}$$

This sum rule has longitudinal and transverse components, how do we access them through observables/quark and gluon distributions?

Fundamental role of deuteron through:

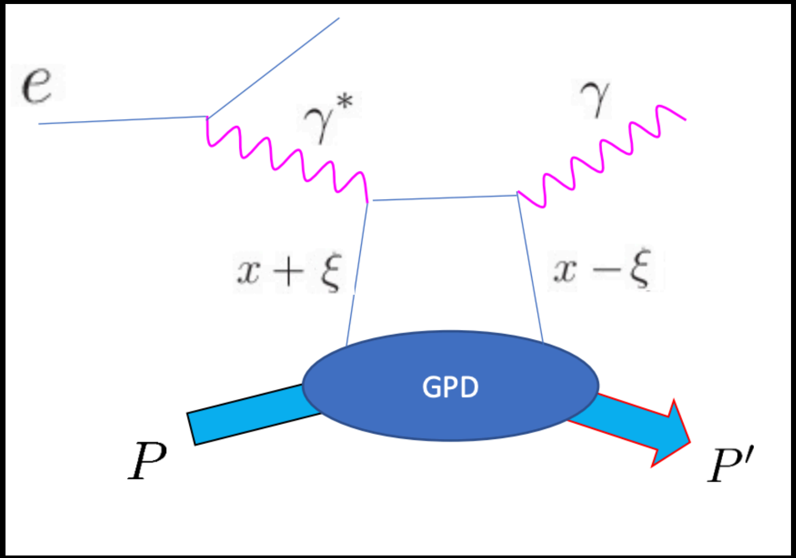
1. Extension of sum rule to spin 1 and interpretation of observables (SL)
2. Additional tensor-like observables

Y. Hatta

$$xE_g(x) = \int d^2k_\perp[-f_{1,1}(k_\perp) + 2f_{1,3}(k_\perp) + \frac{k_\perp^2}{M^2} f_{1,2}(k_\perp)]$$

$$\sim \left(\frac{1}{x}\right)^{4\ln 2\bar{\alpha}_s}$$

BFKL Pomeron behavior, the same as unpol gluon PDF!



From

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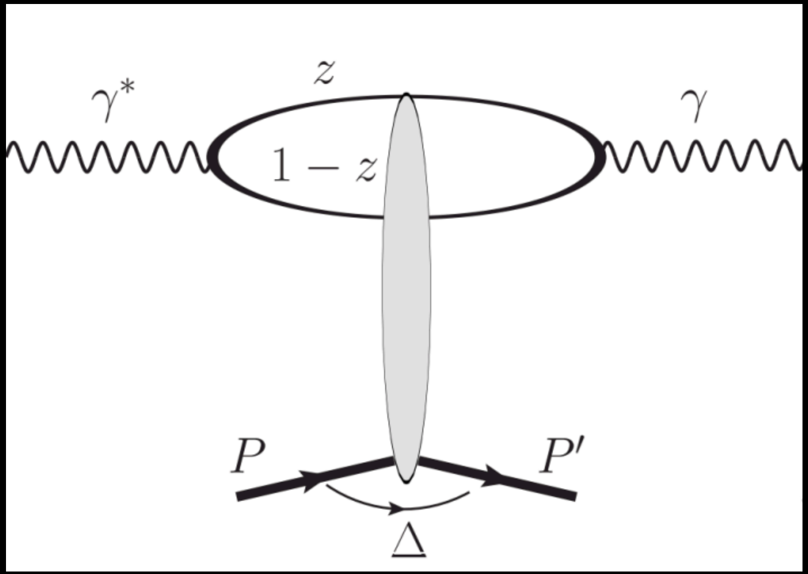
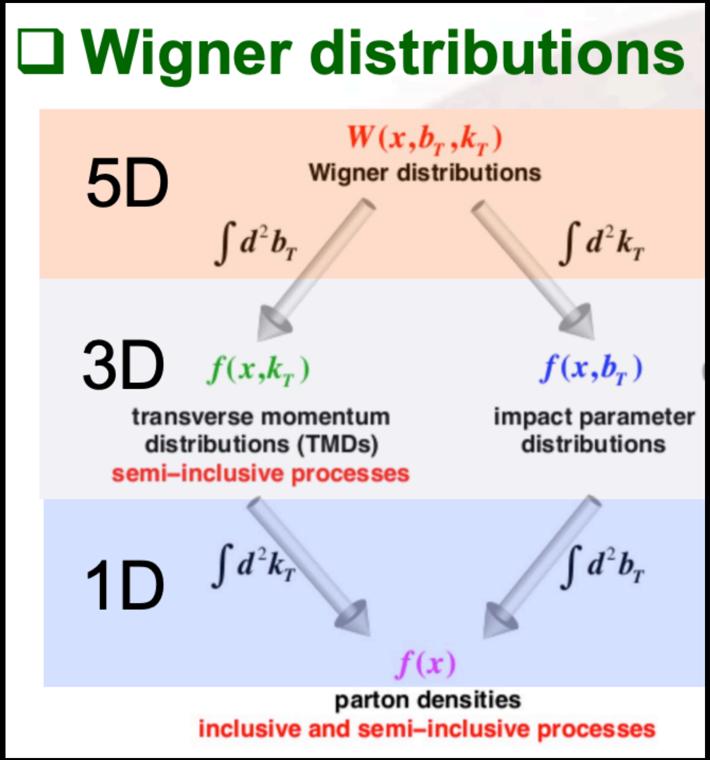
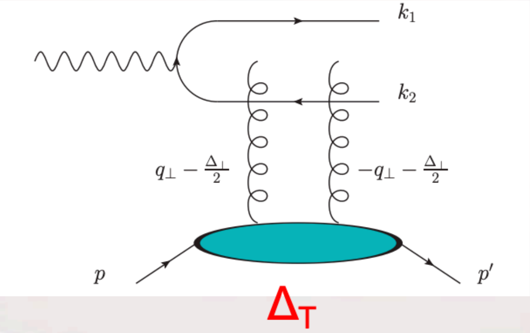


To

Feng Yuan



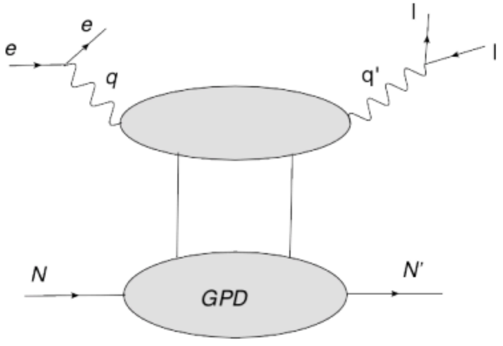
- To avoid the soft gluon radiation contribution, we need to reconstruct nucleon/nucleus recoil momentum to study the tomography



Jakub Wagner

Double DVCS

Belitsky & Muller, PRL 90, PRD 68, Guidal & Vanderhaeghen, PRL 90



(c)

$$\gamma^*(q_{in})N(p) \to \gamma^*(q_{out})N'(p')$$

DDVCS allows us to access GPDs away from the diagonal x= ξ

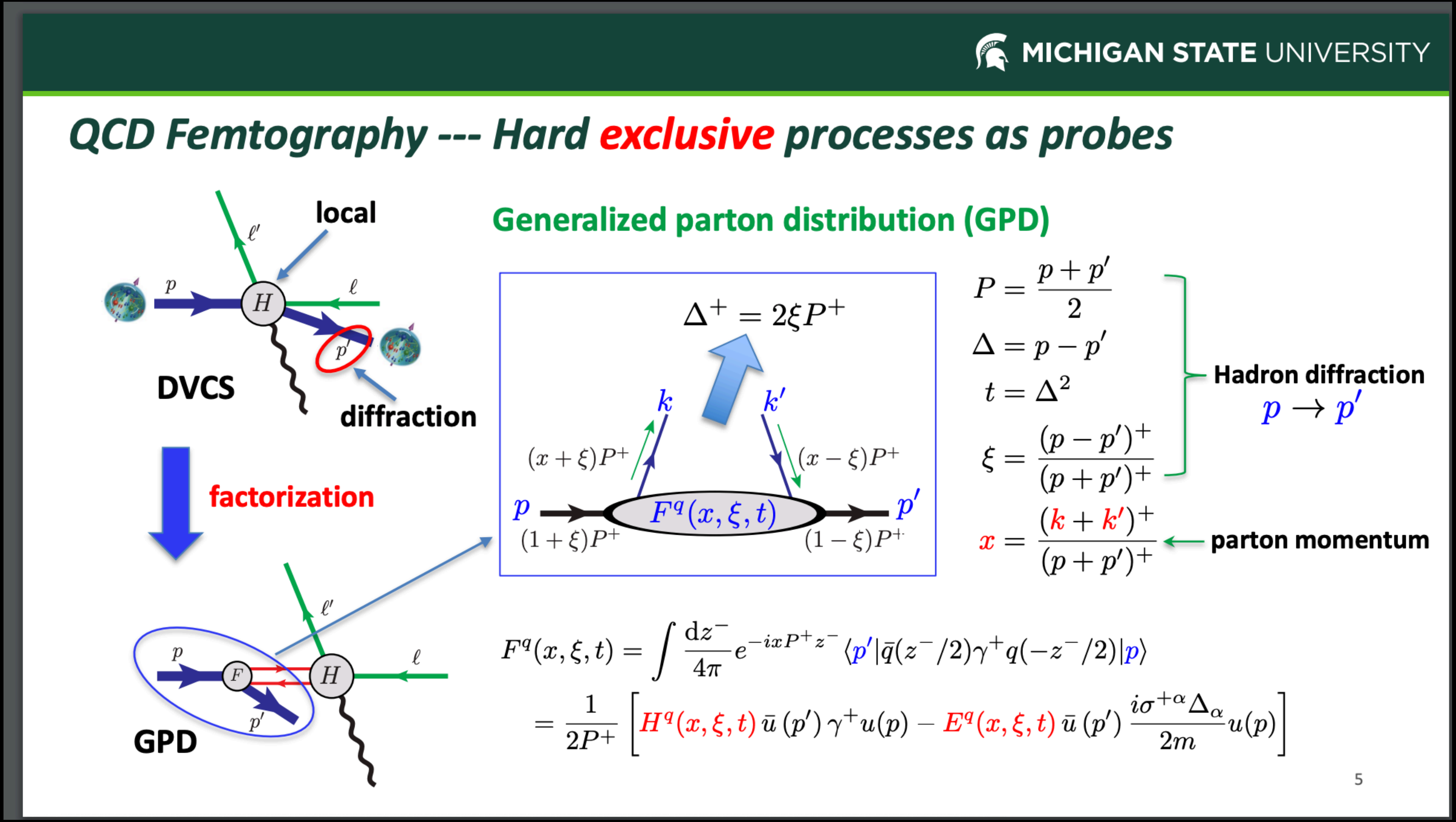
$$\mathrm{CFF} \sim \mathrm{PV}\left(\int_{-1}^{1} dx \frac{1}{x-\rho}\mathrm{GPD}(x,\xi,t)\right) - \int_{-1}^{1} dx\, i\pi\delta(x-\rho)\mathrm{GPD}(x,\xi,t) \pm \cdots$$

DDVCS can provide unique information, but is very challenging experimentally.
But recent measurement of TCS should also make us more optimistic about DDVCS!

We need muon detection!

Zhite Yu and Jianwei Qiu

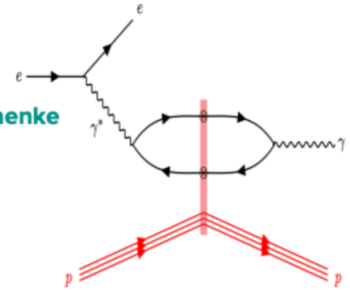
Diffractive scattering background allows us to circumvent factorization issues with exclusive multi-particle finals states!



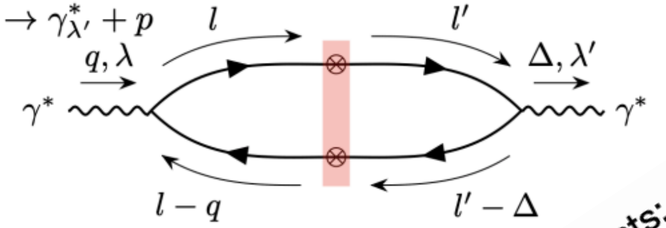
Bjoern Schenke

DVCS in the CGC

H. Mäntysaari, K. Roy, F. Salazar, B. Schenke
Phys.Rev.D 103 (2021) 9, 094026



LO diagram in CGC



Helicity preserving amplitude

$$\langle \mathcal{M}_{\pm1,\pm1}\rangle_Y \sim \int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\int_{\boldsymbol{r}_\perp} D_Y(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp)\int_z e^{-i\boldsymbol{\delta}_\perp\cdot\boldsymbol{r}_\perp}\Big[(z^2+\bar{z}^2)\ \varepsilon_f K_1(\varepsilon_f r_\perp)\varepsilon'_f K_1(\varepsilon'_f r_\perp)$$
$$+ m_f K_0(\varepsilon_f r_\perp) m_f K_0(\varepsilon'_f r$$

Helicity flip amplitude

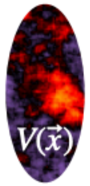
$$\langle \mathcal{M}_{\pm1,\mp1}\rangle_Y \sim e^{\pm 2i\phi_\Delta}\int_{\boldsymbol{b}_\perp} e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\int_{\boldsymbol{r}_\perp} e^{\pm 2i\phi_{r\Delta}} D_Y(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp)\int_z e^{-i\boldsymbol{\delta}_\perp\cdot\boldsymbol{r}_\perp} z\bar{z}\ \varepsilon_f K_1(\varepsilon_f r_\perp)\varepsilon'_f K_1(\varepsilon'_f r_\perp)$$

Similar expressions for other amplitudes: $\langle \mathcal{M}_{0,0}\rangle_Y$ $\langle \mathcal{M}_{\pm1,0}\rangle_Y$ $\langle \mathcal{M}_{0,\pm1}\rangle_Y$

$$D_Y(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp) = 1 - \frac{1}{N_c}\left\langle \mathrm{Tr}\left[V\left(\boldsymbol{b}_\perp + \frac{\boldsymbol{r}_\perp}{2}\right)V^\dagger\left(\boldsymbol{b}_\perp - \frac{\boldsymbol{r}_\perp}{2}\right)\right]\right\rangle_Y$$

Again, the same Wilson lines

22



$$\boldsymbol{\delta}_\perp = \left(\frac{z-\bar{z}}{2}\right)\boldsymbol{\Delta}_\perp$$

Some requirements:
- Separate coherent and incoherent diffraction (for all | t |)
- Measure jets to low p_T to be sensitive to saturation effects
- Measure angular dependencies down to the percent level

Brandon Kriesten

Outstanding questions

2. How do we separate twist two and twist three components?

Twist -3 GPDs

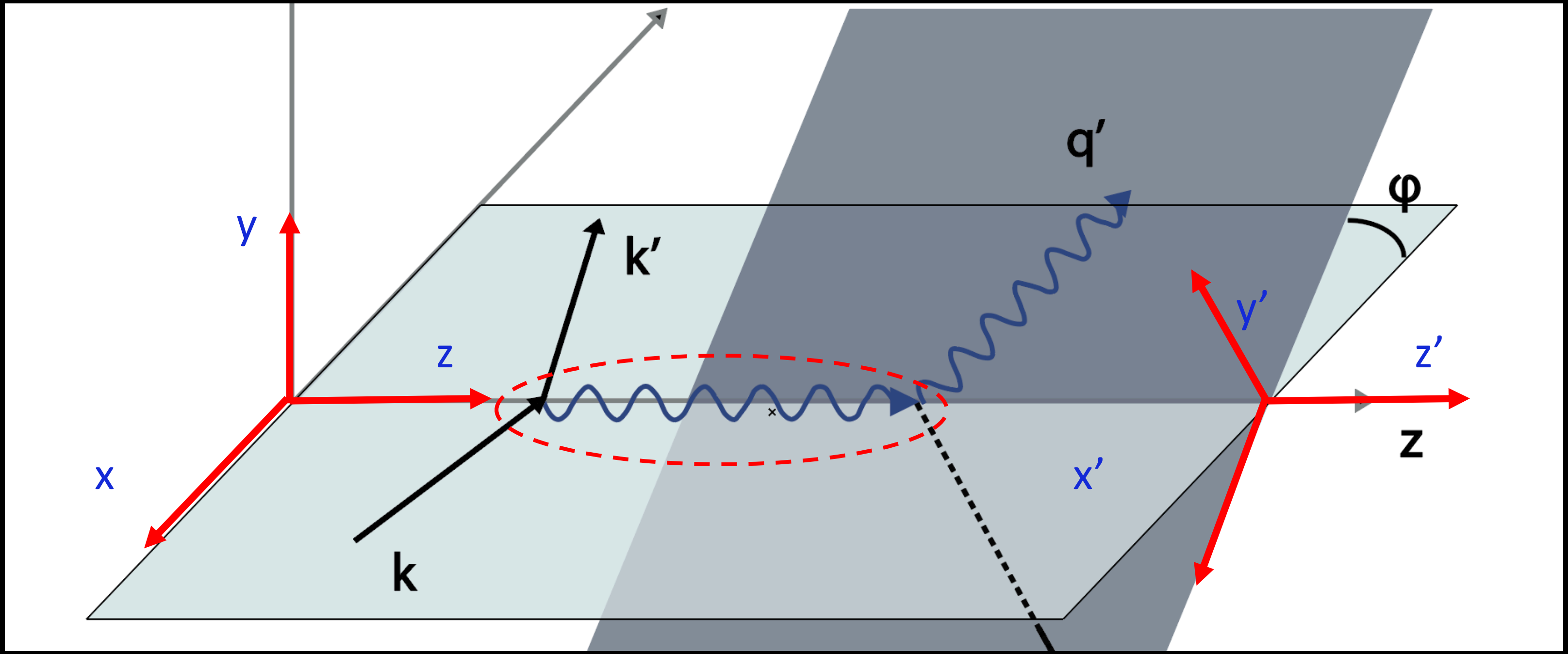
GPD	$P_q P_p$	TMD	Ref.[1]
$H^\perp$	UU	$f^\perp$	$2\widetilde{H}_{2T} + E_{2T}$
$\widetilde{H}_L^\perp$	LL	$g_L^\perp$	$2\widetilde{H}'_{2T} + E'_{2T}$
$H_L^\perp$	UL	$f_L^{\perp\,(*)}$	$\widetilde{E}_{2T} - \xi E_{2T}$
$\widetilde{H}^\perp$	LU	$g^{\perp\,(*)}$	$\widetilde{E}'_{2T} - \xi E'_{2T}$
$H_T^{(3)}$	UT	$f_T^{(*)}$	$H_{2T} + \tau \widetilde{H}_{2T}$
$\widetilde{H}_T^{(3)}$	LT	g'_T	$H'_{2T} + \tau \widetilde{H}'_{2T}$

(*) T-odd

B. Kriesten and S. Liuti, *Phys.Rev. D105 (2022),* arXiv 2004.08890

[1] Meissner, Metz and Schlegel, JHEP(2009)

To disentangle twitw 2 and twist 3 GPDs one needs to perform **L/T separations:** understand the cross section and its detailed ϕ dependence



DVCS

DVCS formalism

- B. Kriesten et al, *Phys.Rev. D* 101 (2020)
- B. Kriesten and S. Liuti, *Phys.Rev. D105 (2022),* arX 2004.08890
- B. Kriesten and S. Liuti, Phys. Lett. B829 (2022), arXiv:2011.04484

ML

- J. Grigsby, B. Kriesten, J. Hoskins, S. Liuti, P. Alonzi and M. Burkardt, Phys. Rev. D104 (2021)

GPD Parametrization for global analysis

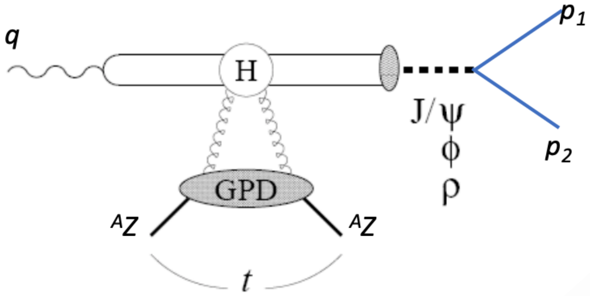
- B. Kriesten, P. Velie, E. Yeats, F. Y. Lopez and SL, *Phys. Rev D 105 (2022)*, arXiv:2101.01826

Charles Hyde

Nuclear DVCS and DVMP

Resolving momentum transfer to nucleus

- Must measure independent of ion beam momentum spread
  - $t = \Delta^2$
  - Measure $\Delta^\mu = (q-q')^\mu = (q-p_1-p_2)^\mu$



- Vector Mesons
  - Charged particle decays
  - Resolution from tracking.
- Neutral channels require high-resolution EMCal
  - $e\,^ZA \rightarrow e\,^ZA\,\gamma$
  - $e\,^ZA \rightarrow e\,^ZA\,\omega$

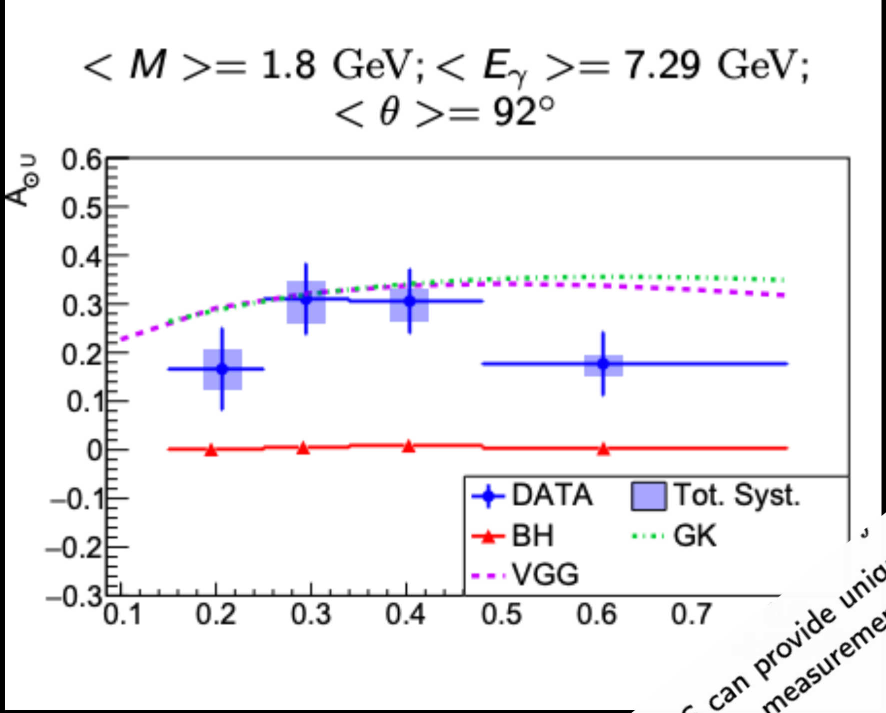
IR-8 High-Dispersion focus in downstream ion beam line enables

100% tagging of break-up nuclei ≤ A-1 up to $^{90}_{40}Zr$

- Tagging of ≤ A-2 daughter nuclei beyond Zr in IR-8
- Region from $^{16}_{8}O$ to $^{90}_{40}Zr$ not accessible for A-1 in IR-6

Pierre Chatagnon

First TCS measurement @Jlab

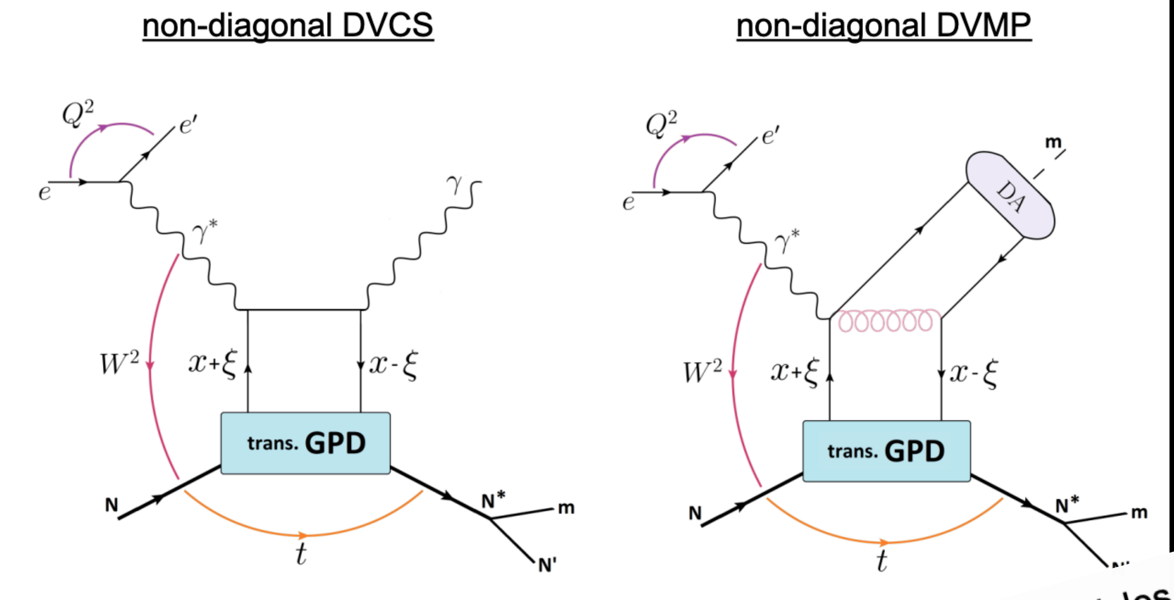


DDVCS can provide unique information, but is very challenging experimentally.
But recent measurement of TCS should also make us more optimistic about DDVCS!

We need muon detection!

Stefan Diehl

Non-diagonal DVCS / DVMP



factorisation expected for: $-t/Q^2$ small, Q^2 > M

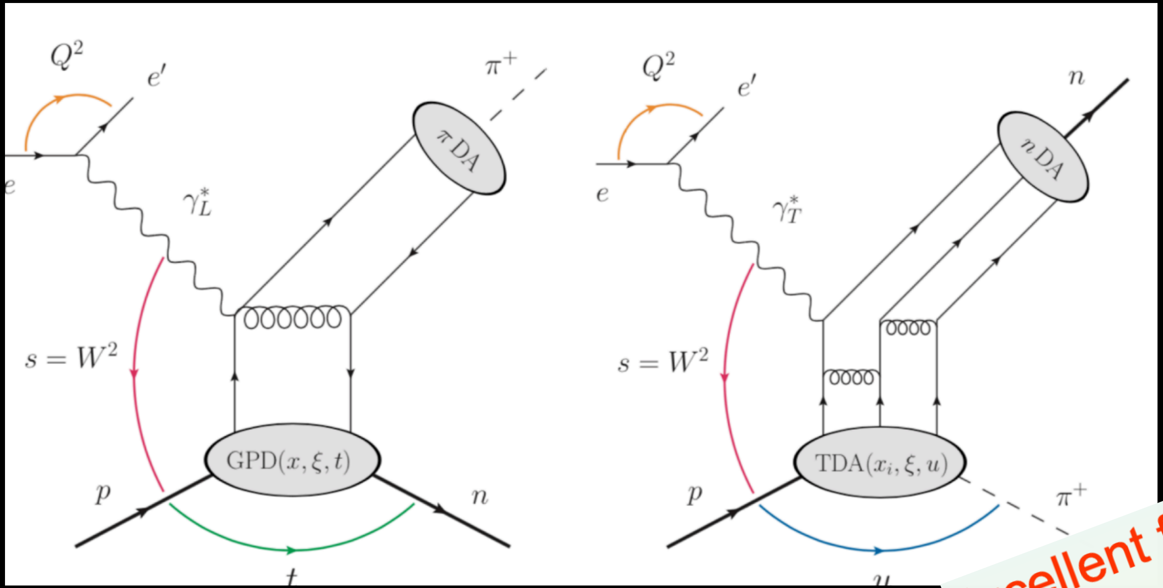
➔ Deacy particles, especially the meson can have very low momenta

➔ Low momentum threshold needed in the backward region!

➔ For p π^0 a backward coverage for photons and for n π^+ a neutron detection is needed!

Backward photoproduction via baryon exchange and baryon stopping

Spencer Klein



K. Park et al., Phys. Lett. B780, 340 (2018)

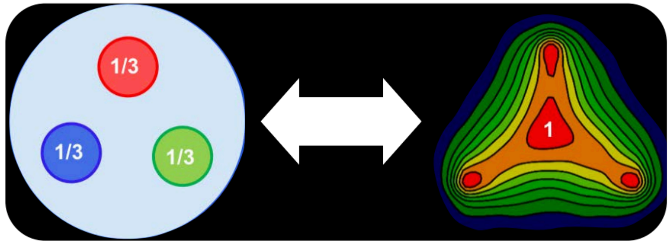
In this approach the baryon recoils but remains intact: baryon stopping?

Excellent far-forward ion-going detectors are required to separate coherent and incoherent photoproduction. Backward production reactions lead to mid-rapidity baryons and far-forward mesons. The later are a detector challenge, requiring more study.

Zhangbu Xu

What carries the baryon quantum number?

Valence Quarks?
Stop the quarks to stop a baryon.



Gluons?
Stop the junction to stop a baryon.

Tracking the origin of baryon number with the EIC

How do we set an experimental test

J. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv: 2205.05685

- Valence quarks carry electric charge; do they also carry a baryon number?
- Electric Charge (Q) vs. baryon (B) stopping in e+A collisions
  - ✓ Naive expectations:

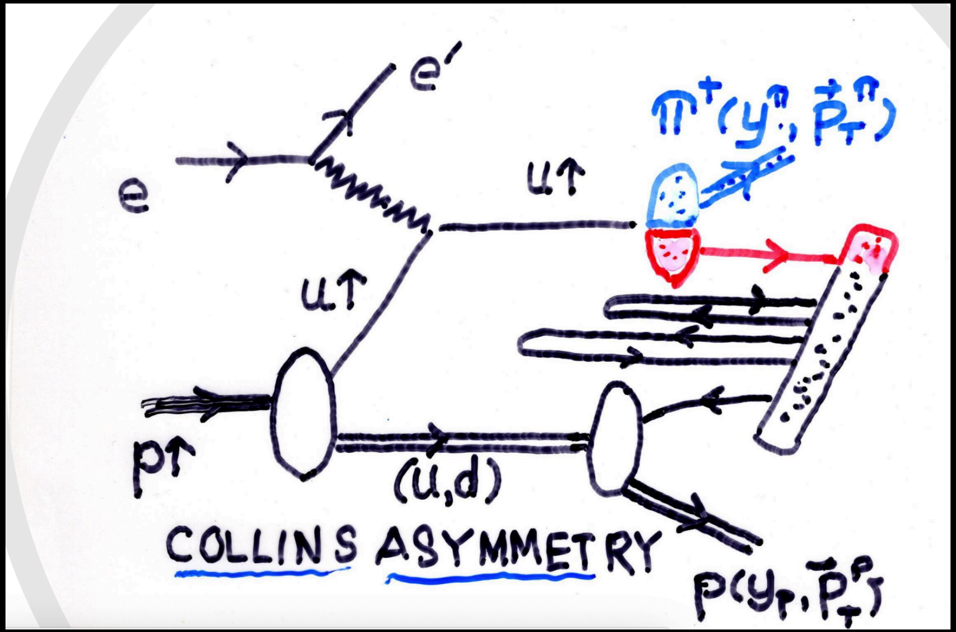
$$R = \frac{B}{Q} \times \frac{Z}{A}$$

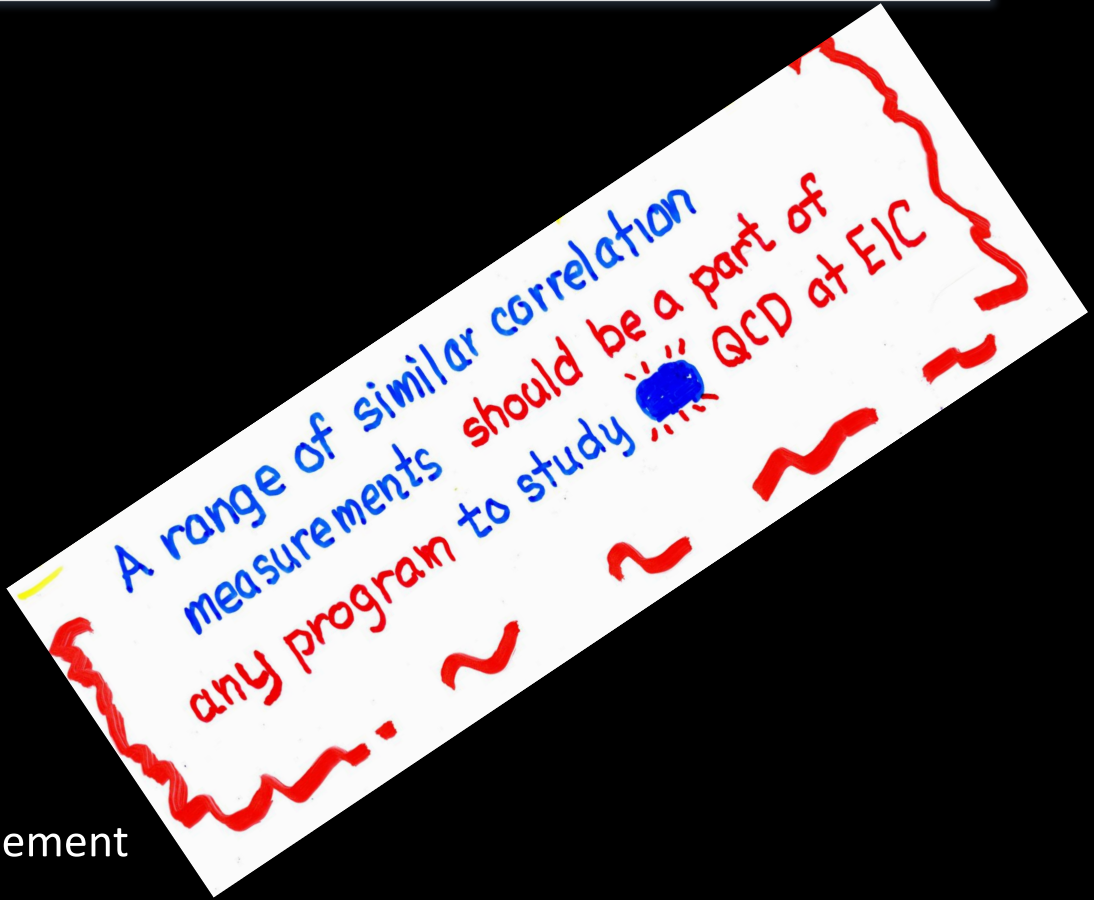
- > 1; gluons carry the flow of baryon number
- < 1; quarks carry the flow of baryon number

Target fragmentation/current target correlations

Dennis Sivers

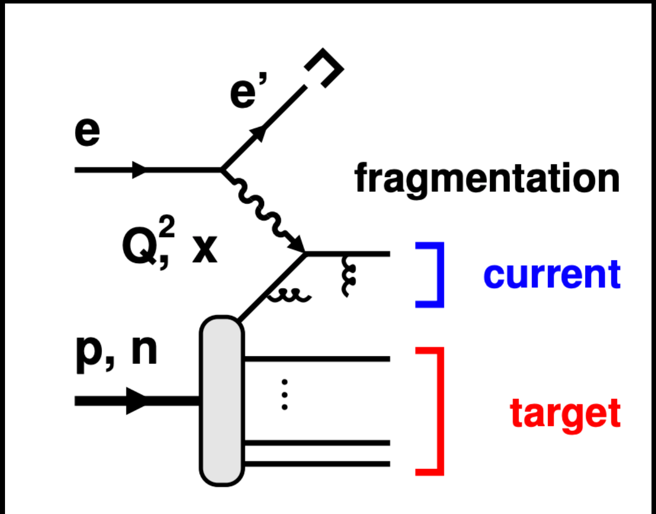
Quantum Entanglement in Transverse Spin Asymmetry (with G.Goldstein and SL)

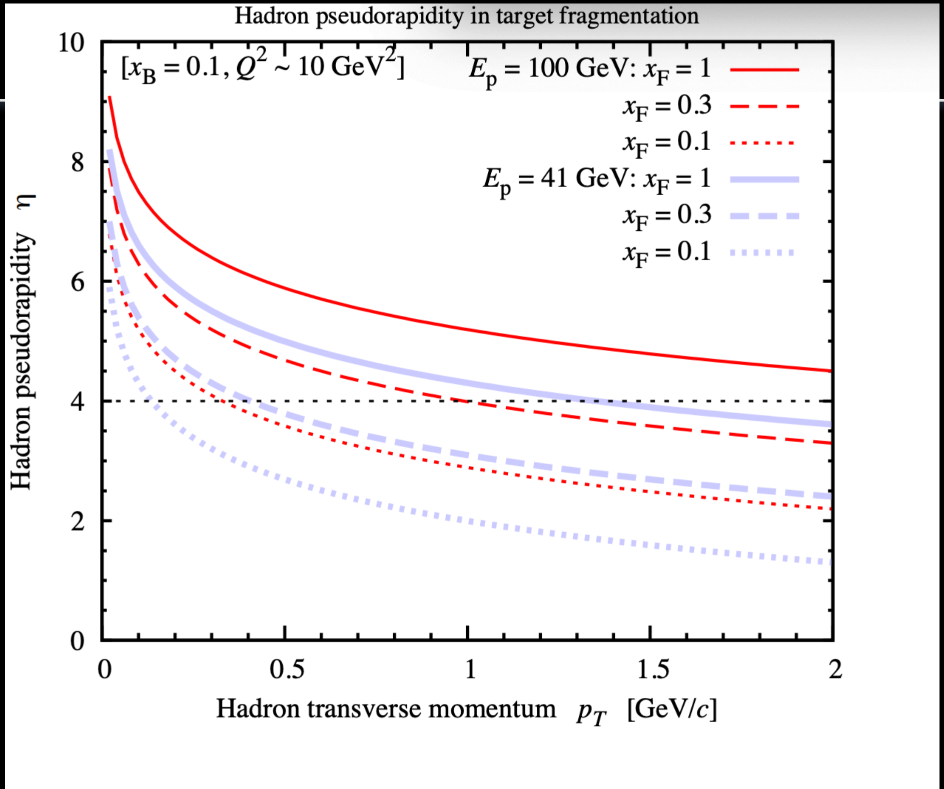




Non-perturbative final state interactions signal ordinary entanglement

Christian Weiss





[Weiss et al 2021, prepared for EIC Yellow Report [INSPIRE]]

- Target fragmentation measurements with EIC require detector coverage "between" central $\eta < 3.5$ and far-forward $\eta > 4.5$ systems

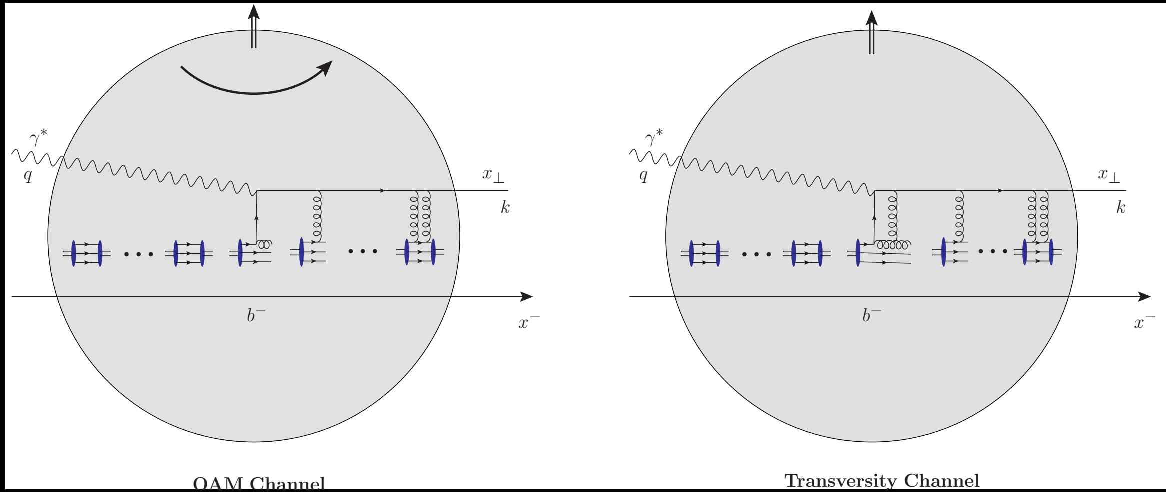
TMDs in nuclei

Yuri Kovchegov

•YK, M. Sievert, *Phys.Rev.D* 89 (2014) 5, 054035; e-Print: 1310.5028 [hep-ph]

Are nuclear TMDs simply proportional to the nucleon TMDs, with shadowing corrections like the PDFs?

- To generate a Single Spin Asymmetry (SSA) we need spin-dependence and a complex phase. In a nucleus they may come from three sources:
  - Sivers functions of the (polarized) nucleons: transversity channel
  - Orbital rotation due to OAM (just gives real OAM-dependence)
  - By including extra rescatterings per nucleon (the odderon): this gives a phase but is A-suppressed.



$$\hat{z}\cdot(\underline{J}\times\underline{k})\, f_{1T}^{\perp A}(\bar{x}, k_T) = M_A \int \frac{dp^+\, d^2p\, db^-}{2(2\pi)^3}\, d^2x\, d^2y\, \frac{d^2k'}{(2\pi)^2}\, e^{-i\,(\underline{k}-\underline{k}')\cdot(\underline{x}-\underline{y})}$$

$$\times \left\{ i\, x\, \underline{p}\cdot(\underline{x}-\underline{y})\, A\, W^{OAM}_{unp}\left(p^+, \underline{p}, b^-, \frac{\underline{x}+\underline{y}}{2}\right) f_1^N(x, k'_T) \right.$$

OAM

$$\left. + \frac{1}{m_N}\,\hat{z}\cdot(\underline{S}\times\underline{k}')\, W^{symm}_{trans}\left(p^+, \underline{p}, b^-, \frac{\underline{x}+\underline{y}}{2}\right) f_{1T}^{\perp N}(x, k'_T) \right\} S_{\underline{xy}}[+\infty, b^-]$$

Transversity

Conclusions

The EIC 2nd detector workshops organized so far have **crystallized the interest of our community** emphasizing the 2nd detector's importance for both **complementary measurements** (P. Grannis, H. Montgomery) and a **new set of measurements allowing to test innovative ideas** that rely on specific features for multiparticle detection in fragmentation from nuclei, muon id, reconstruction of current jets at low x ….