

DIS 23 - WG5 summary (Spin & 3D Structure)

Lansing, MI
March 31, 2023

Jim Drachenberg (ACU)
Caroline Riedl (UIUC)
Jakub Wagner (NCBJ)
(WG5 conveners)

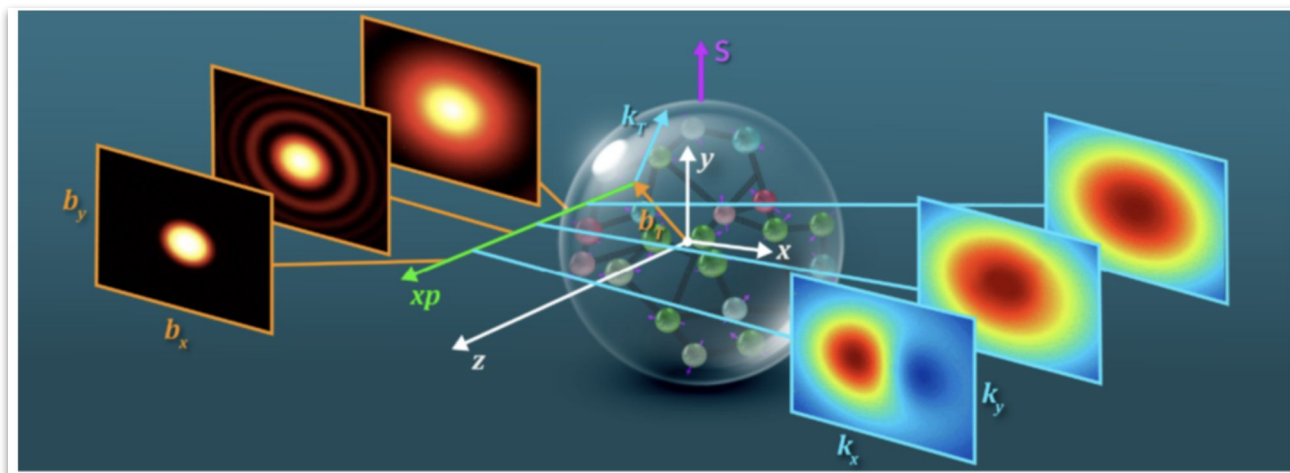


Nucleon spin & 3D structure

- Spin puzzle
- Longitudinal structure
- 3D Structure of the nucleon - tomography & OAM
 - Generalized parton distributions (GPDs)
 - Transverse momentum dependent (TMD) PDFs & fragmentation functions (FFs)

$$\frac{1}{2} = \frac{1}{2} \sum_q \Delta q + \Delta g + L_q + L_g$$

proton spin	quark helicity	gluon helicity	quark and gluon orbital motion
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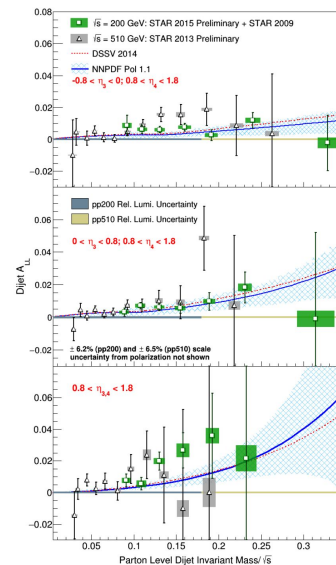


See also & in particular [Maria Zurek's spin plenary talk on Monday](#) !

Image taken from White Paper of
QCD Town Meeting 2022,
<https://arxiv.org/abs/2303.02579>

Longitudinal Spin Structure

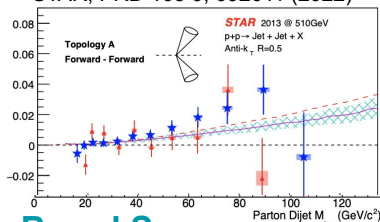
Zilong Chang p+p directly taps **gluonic subprocesses at LO** → excellent tool to constrain $\Delta g(x)$



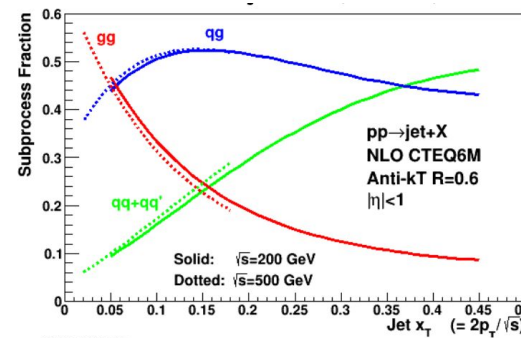
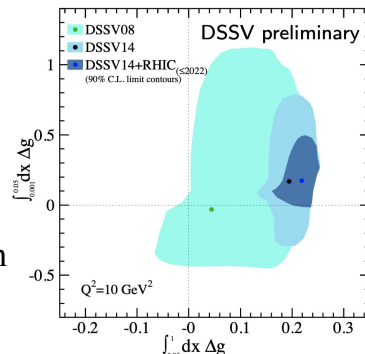
STAR presented preliminary A_{LL} for dijets at 200 and 510 GeV

- Measured at midrapidity and for $0.8 < \eta < 1.8$
- Reach lower x by pushing to higher \sqrt{s} and higher η
- Dijets enable much tighter constraints on x → shape of $\Delta g(x)$
- Last RHIC longitudinal spin data collected in 2013 and 2015

STAR, PRD 105 9, 092011 (2022)

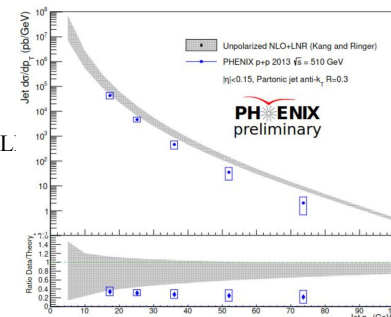


Bernd Surrow



PHENIX presented data at 510 GeV for

- Forward η cross section
- Midrapidity inclusive jet cross sect and A_{LL}
- Midrapidity direct- γ cross sect and A_{LL}
- Midrapidity charged pion A_{LL}
- Cross sections probe spin-averaged PDFs (jet, direct- γ) and FF (η)
- A_{LL} probes $\Delta g(x)$



Devon Loomis

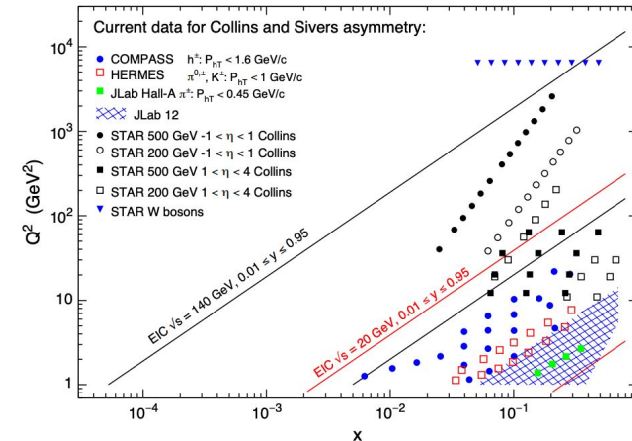
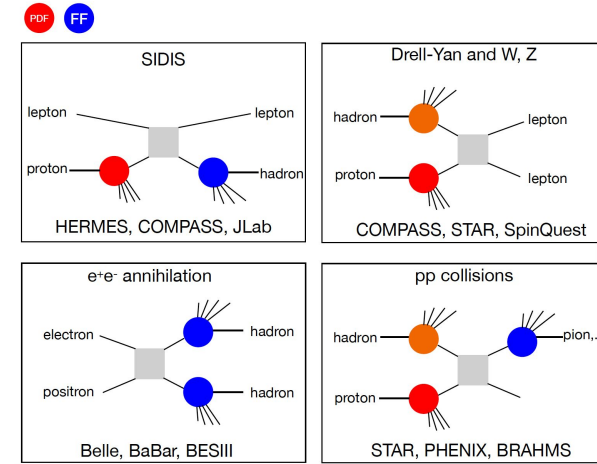
David Ruth (g2p) presented results on the g_1 and g_2 structure functions, published in October in **Nature**

RHIC data add significant constraints to DSSV global analysis:

$$\int \Delta g(x) dx = 0.22 \pm 0.03 \text{ for } x > 0.05 \text{ at } Q^2 = 10 \text{ GeV}^2$$

TMDs - transverse momentum dependent PDFs & FFs

- Multi-dimensional picture of hadrons in **transverse momentum** space
- TMD **fragmentation functions** → information on the **hadronization process** beyond collinear non-perturbative FFs
- Measured in a broad spectrum of collision species & kinematic domains
- **Spin-momentum** and **spin-spin** parton-hadron **correlations** inside the nucleon... **parton orbital angular momentum**
- **Factorization, universality, evolution** (beyond ordinary DGLAP) ... → global analyses



TMD PDFs - hadron-hadron

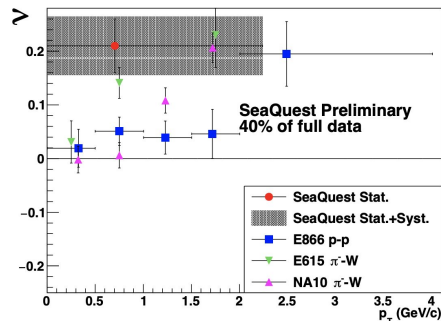
- **COMPASS**, (un)polarized pion-induced Drell-Yan ([Vincent Andrieux](#)). Sivvers asymmetry et al. in DY vs. SIDIS. LT relation. J/ψ asym. and nuclear modification. To come: x-sections on p, W, Al

- **SpinQuest**, polarized proton-induced DY ([Kei Nagai](#)). Commissioning in spring/summer 2023 + 2 years of data taking

- **SeaQuest**, unpolarized proton-induced DY ([Kei Nagai](#)). Angular dependence of DY cross section

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi$$

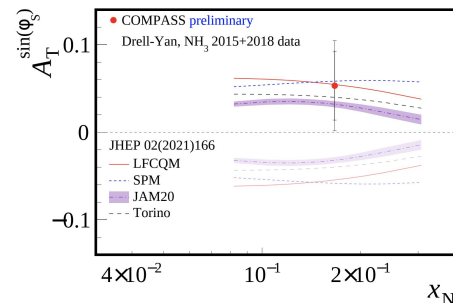
Violation of Lam-Tung relation - could be BM TMD



- **PHENIX**, $p\uparrow p$ and $p\uparrow \text{Au}$ ([Dillon Fitzgerald](#)) nuclear effects in transverse single-spin asymmetry in neutral π & η production. Mid-rapidity, $\sqrt{s}=200$ GeV. [[arXiv:2303.07190](#)], sub. to PRD.

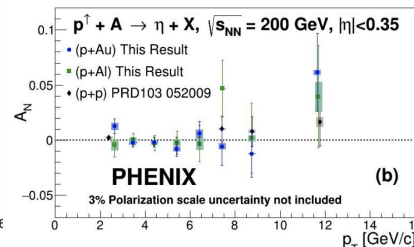
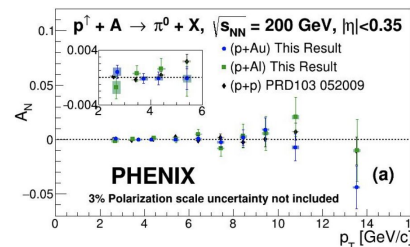
Test of TMD (non-)universality.

Complementarity: SpinQuest sea quark, COMPASS valence quark domain



Sivers effect: spin-orbit correlation between the nucleon transverse spin and parton transverse momentum in the transversely polarized nucleon

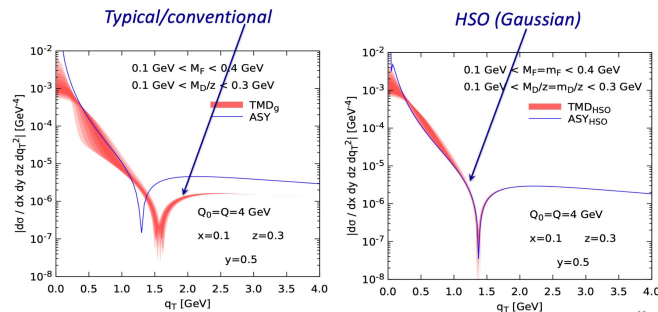
$$\vec{S}_T \cdot (\hat{P} \times \vec{k}_T)$$



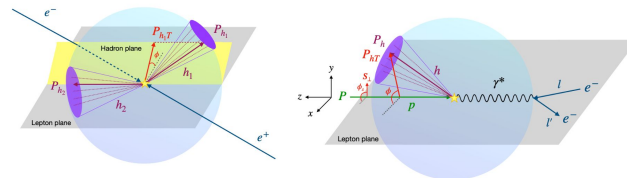
Theory

- TMD factorization re-formulation that works both at small and large transverse momenta (**Ted Rogers**)

Smoothly transform directly between **nonperturbative** TM dependence at **small** TM ($k_T \approx \Lambda_{QCD}$) & **perturbative** (collinear) TM at **large** TM ($k_T \approx Q$)

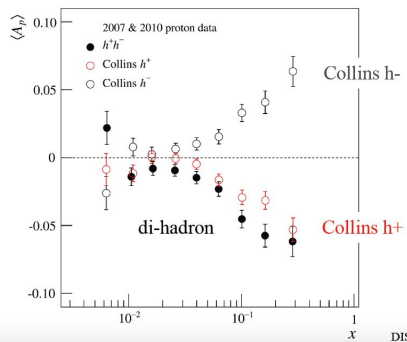


- Collins-type EEC jet function as new probe for TMD PDFs in ee and SIDIS (Fanyi Zhao)**. arXiv.2303.XXXX
EEC (energy-energy correlator) @ back-to-back limit.



Experiment

- COMPASS**, SIDIS (**Caroline Riedl**, for Andrea Moretti) - P_T distributions, Boer-Mulders TMD PDF & Cahn effect; Sivers TMD PDF, **Collins FF** and **IFF**; **new data: d↑ 2022** will bring improved constraints on **d-quark transversity**.



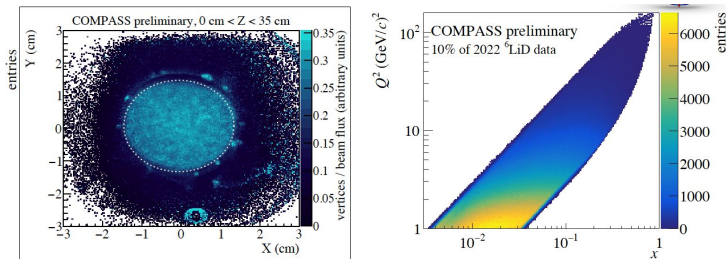
Collins effect: azimuthal modulations of the produced hadron transverse momentum in a transversely-polarized quark fragmentation

$$\text{Collins asymmetry} \sim \text{Transversity} \otimes \text{Collins function}$$

chiral-odd PDF \otimes chiral-odd FF

TMD PDF (x, k_T, Q^2) FF (z, κ_T, Q^2)

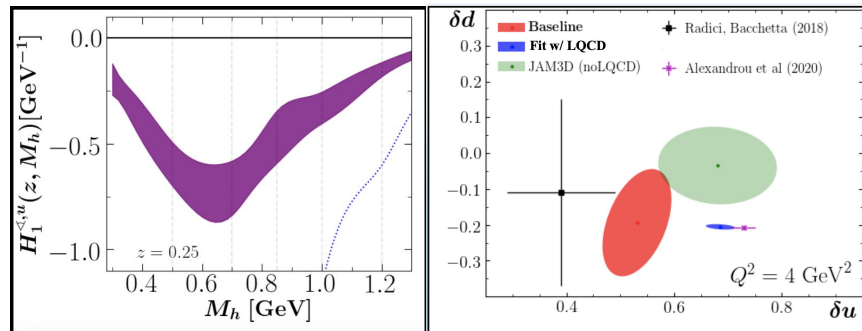
$\vec{s}_T \cdot (\hat{k} \times \vec{P}_{hT})$



Di-hadron fragmentation functions

Theory

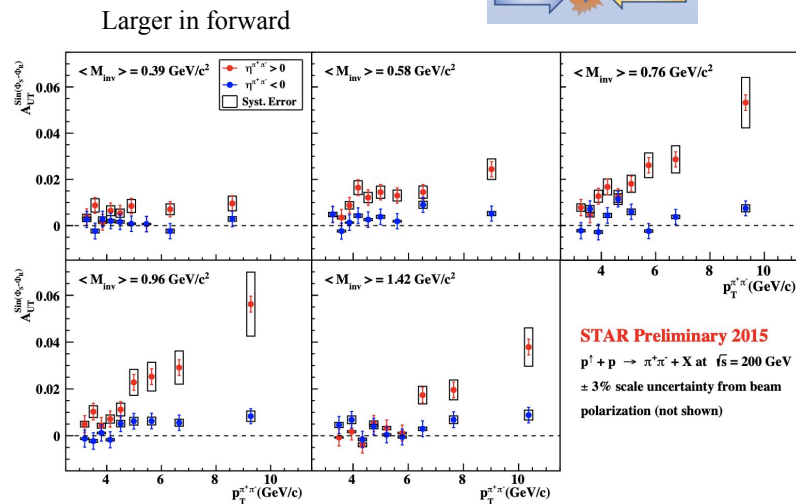
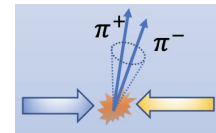
- Revisited the definition, interpretation and **evolution** of **di-hadron FFs = DiFFs**. ([Andreas Metz](#)) Needed to extract info on transversity TMD from SIDIS and pp data. Gluonic DiFFs.
- Simultaneous global extraction of **DiFF**, transversity PDFs, and **tensor charge** ([Christopher Cocuzza with JAM collaboration](#)) from ee, SIDIS & pp data. Include or not lattice result.



- Hadronization dynamics from the spectral representation of the gauge invariant quark propagator ([Caroline Costa](#))

Experiment

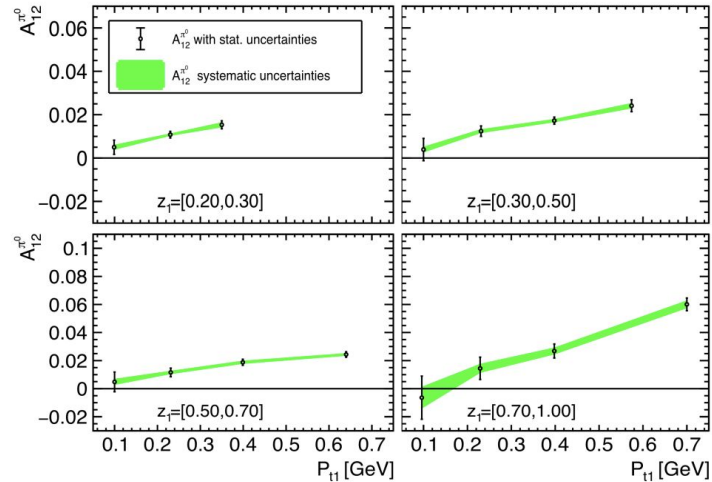
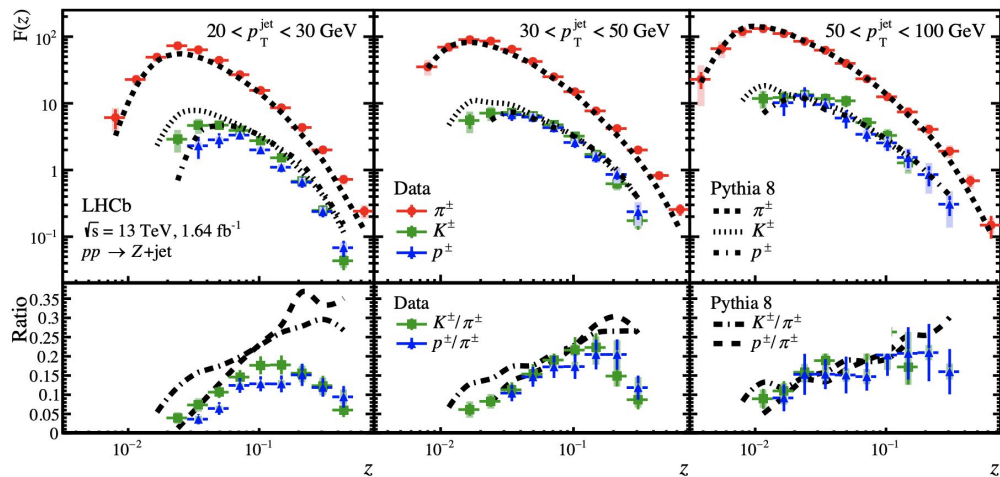
- STAR** di-hadron correlation asym. in $p^\uparrow p \rightarrow \pi^+ \pi^- X$
- **200 GeV new A_{UT}^{2015} pp results & soon results 2012 unpolarized x-section** ([Babu Pokhrel](#))



- 500 GeV 2011 / 510 GeV 2017 ([Navagyan Ghimire](#)) - analysis in progress, expect 4x more statistics

TMD fragmentation functions

- **Belle / Belle2** ongoing FF measurements ([Katherine Parham](#)). Vector and D-meson x-section, new DiFF measurements, T-odd components of jets.
- **LHCb** TMD FF ([Sook Hyun Lee](#)). π , K, p in jets & new light-quark jet FF [arxiv:2208.11691](#) (acc. PRD Lett.). Status of Λ pol.; SMOG & LHC-spin.

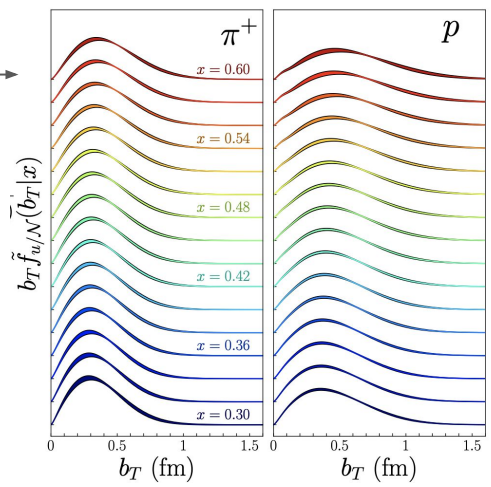
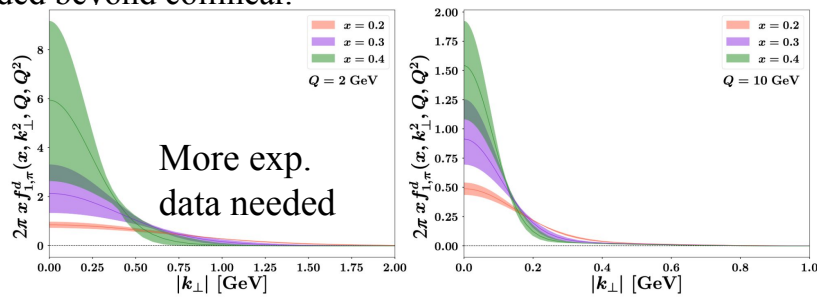
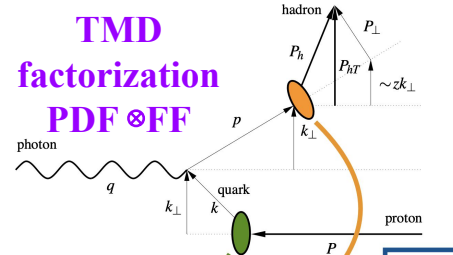


Azimuthal asymmetry of π^0 events binned by fractional energy, z (2019 pub.)

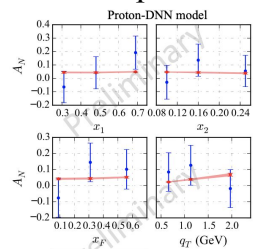
Jet substructure analysis \rightarrow access to TMD-related information

TMDs - global analysis I

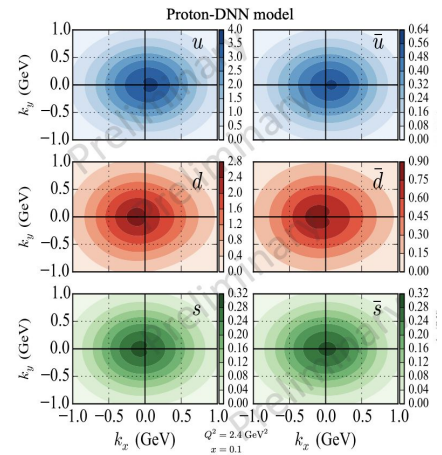
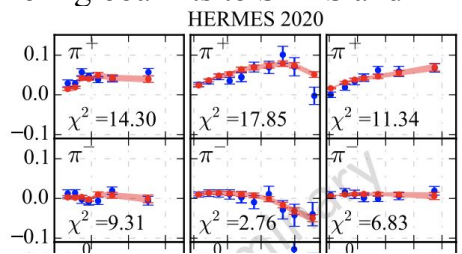
- **Pion and proton TMD PDFs** from DY data ([Patrick Barry](#)). [arXiv:2302.01192](#).
Impact parameter “b*” description.
- **Unpol. TMDs** global extraction at N3LL logarithmic accuracy in the resummation of qT -logarithms ([Matteo Cerutti](#) with **MAP collaboration**). Latest results of ([Pion]MAPTMD22) from SIDIS and DY data, and pion TMD PDFs. Large constant normalization factors needed beyond collinear.



- Modern extraction of **Sivers functions** ([Ishara Fernando](#)) - deep neural network (DNN) model to make predictions of TMD PDFs from global fits to SIDIS and DY data.

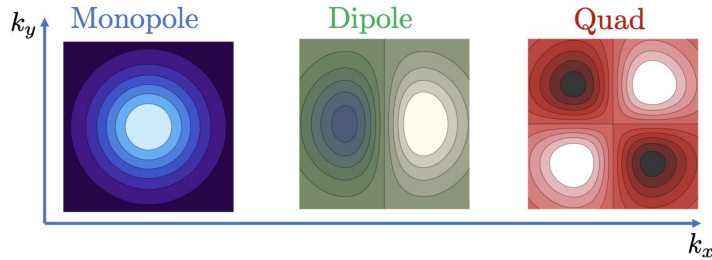


COMPASS
DY



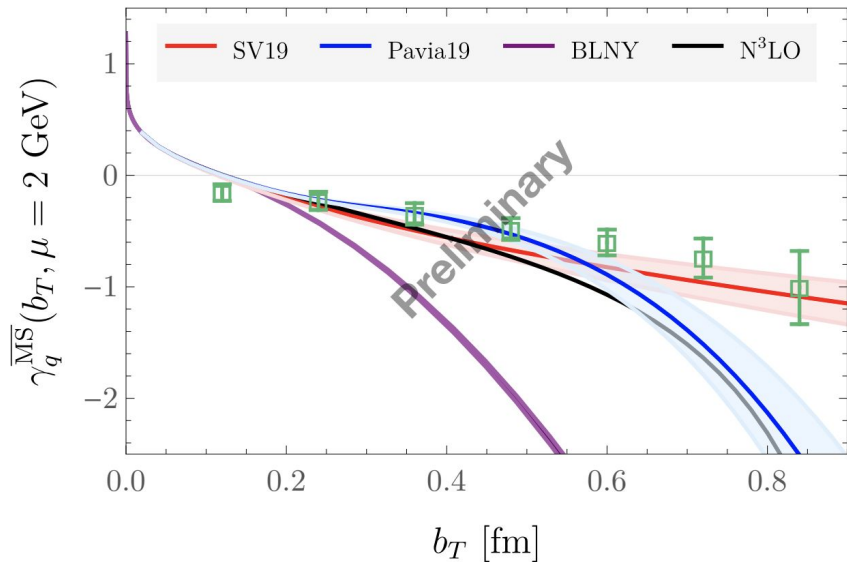
TMDs - global analysis II

- 3D imaging of the nucleon in lattice QCD ([Yong Zhao](#)) - calculation of **quark & gluon TMDs** using large-momentum effective theory (LaMET). Non-perturbative Collins-Soper Kernel, soft factor.



The LP TMDs

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

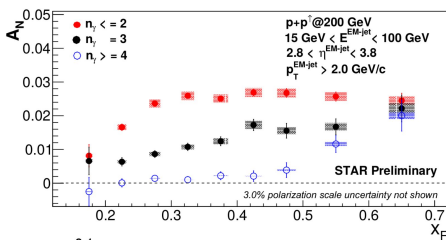


- TMD factorization and resummation** at sub-leading power ([John Terry](#))
Monopole TMDs match to LP PDFs
Dipole TMDs match to NLP PDFs

Large A_N in Forward Hadroproduction

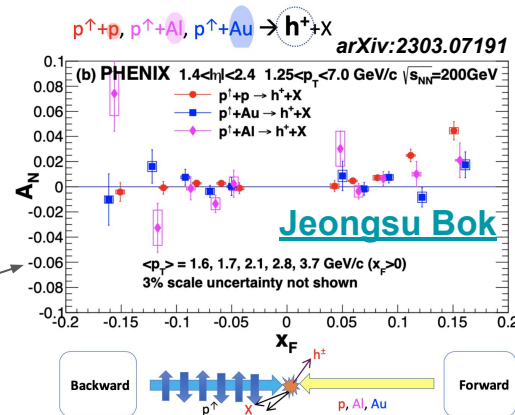
Still searching for **explanation for large A_N in forward production**, e.g., of π^\pm and π^0

- Contributions from higher twist/TMD mechanisms?
- Contributions from diffractive processes?



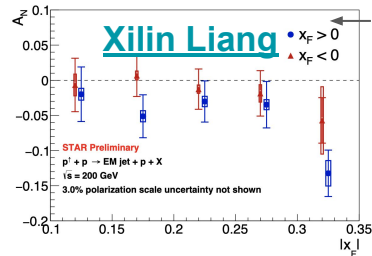
PHENIX presented **new A_N** for $p+p/A \rightarrow h^\pm + X$ at $1.4 < \eta < 2.4$

- A_N increases with x_F and opposite signs for h^+ and h^-
- Partial cancelation in between K^- and π^- in h^- sample
- A_N suppressed in heavier ions (Al, Au)
- Result submitted to PRD: [arXiv:2303.07191](https://arxiv.org/abs/2303.07191)



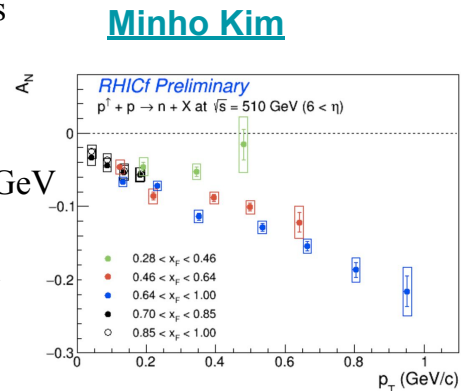
STAR presented **new preliminary A_N** for $p + p \rightarrow \text{EM jet} + X$ at 200 GeV and $2.8 < \eta < 3.8$

- A_N suppressed for higher photon multiplicity
- Measure diffractive contribution by tagging protons in Roman pots
- $p+p \rightarrow \text{EM jet} + p + X$ is *negative* \rightarrow need some theoretical input
- Showed statistical projections for 2017 data set at 510 GeV



RHICf presented **new preliminary A_N** for very forward ($\eta > 6$) neutrons at 510 GeV

- Greatly expand p_T (up to 1.0 GeV/c) with improved position resolution
- RHICf data consistent with PHENIX
- Observe x_F dependence for $p_T > 0.25$ GeV/c
- Showed status of improved background estimation (for publication)



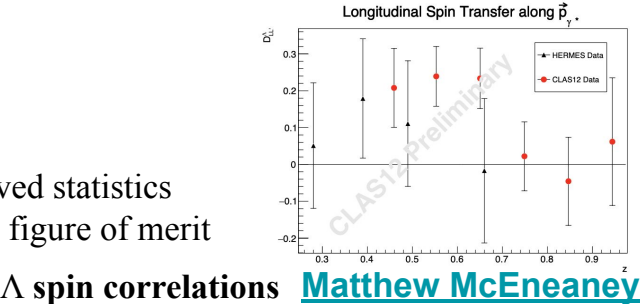
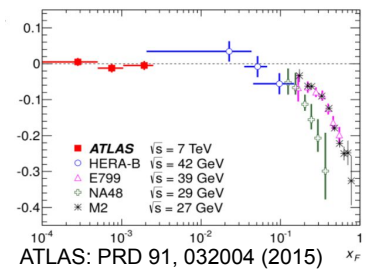
Lambda Production and Heavy Flavor

Lambda polarization in high-energy collisions (pp, pA, ep, ee) increases with x_F and p_T

- Connected to...
 - TMD FF (analogous to Sivers PDF) in unpolarized h+h
 - Transversity TMD PDF (via Collins FF) in transversely polarized DIS
 - Helicity FF with longitudinally polarized beams

Gary Goldstein challenged us to consider **electroproduction of Lambda**

- Address open questions, e.g., Is polarization from fragmentation or from quark-diquark IS / FS interaction?
- Significant role played by non-perturbative QCD

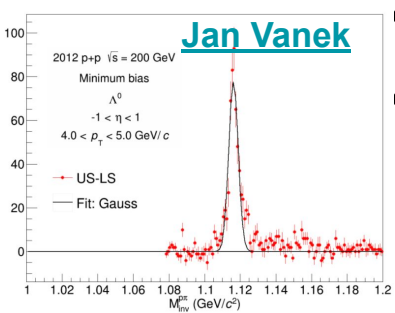


CLAS12 presented preliminary **Lambda spin transfer**

- Consistent with earlier results from HERMES/NOMAD with improved statistics
- Status of using **neural networks** to reduce background and increase figure of merit

STAR presented status of $\Lambda\Lambda$, Λ - anti- Λ , and anti- Λ - anti- Λ **spin correlations**

Matthew McEneaney



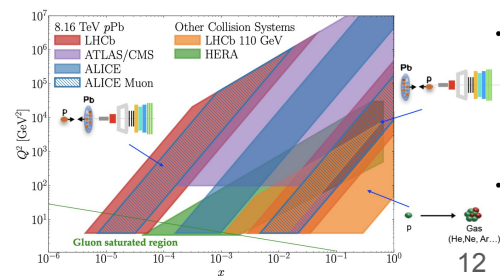
Jan Vanek

- Measure angle between two boosted decay protons from two Λ in the same event
- Show statistical projection for 2012 p+p dataset at 200 GeV

LHCb presented a status of transverse **Lambda Polarization**

- Range of energy + collision species
- Fixed-target mode with SMOG: high $|x_F|$ + lower \sqrt{s}
- Run-3 upgrade gives higher luminosity

Cynthia Nuñez



- Ji sum rule:**

$$J_i = \frac{1}{2} \int_0^1 dx x [H_i(x, \xi) + E_i(x, \xi)]$$

Yoshitaka Hatta

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

BFKL Pomeron behavior, the same as unpol gluon PDF

Implications for GPD modelling

Single spin asymmetry in exclusive J/ψ production

Double spin asymmetry in dijet production at EIC

- Tomography:**

$$\rho(x, r_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-i\Delta_\perp \cdot r_\perp} H(x, 0, \Delta_\perp^2)$$

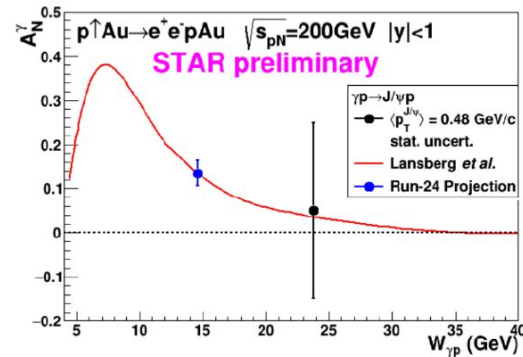
Zaki Panjsheri (presented by S.Liuti)

preliminary results on overlapping of two partons

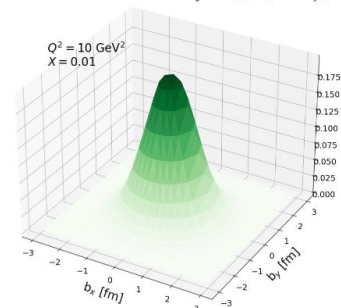
- Energy Momentum tensor:**

$$\begin{aligned} \langle N(p') | T_{q,g}^{\mu\nu} | N(p) \rangle = & \bar{u}(p') \left[A_{q,g}(t) \gamma^{(\mu} \bar{P}^{\nu)} + B_{q,g}(t) \frac{\bar{P}^{(\mu} i \sigma^{\nu)\alpha} \Delta_\alpha}{2M} \right. \\ & \left. + D_{q,g}(t) \frac{\Delta^\mu \Delta^\nu - \eta^{\mu\nu} t}{4M} + \bar{C}_{q,g}(t) M \eta^{\mu\nu} \right] u(p) \end{aligned}$$

Kazuhiro Tanaka - NNLO QCD $\bar{C}_{q,g}(t)$ from trace anomaly constraints
Gravitational form factor related to pressure inside nucleon



Fourier Transform of GPD H₂ vs. b_l [fm] and b_t [fm]



UVA's parametrization

- Factorization:

Shohini Bhattacharya

Revisited QCD factorization for Compton scattering
Observe poles in box diagram from chiral & trace anomalies
Propose possible scenario of pole cancellation
(connected to exchange of eta-mesons & glueballs)

Zhite Yu

Single Diffractive Hard Exclusive Processes (SDHEP)

Systematic simultaneous proof of factorization.

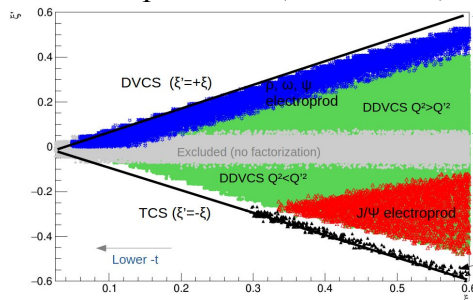
Roadmap for known and more new processes

Enhanced sensitivity to x dependence ($x \neq \pm \xi$ line)

- New channels:

Marie Boër

Potential for new experiments (TCS, DDVCS) at **JLab Hall A & C**



Classification of GPD processes

Electro-production (JLab, EIC, ...)

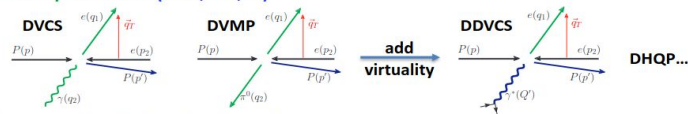
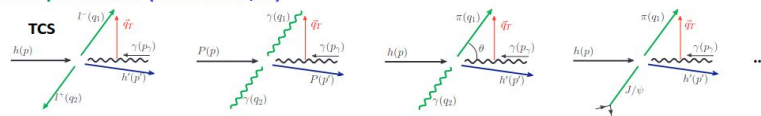
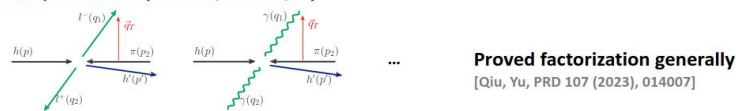


Photo-production (JLab Hall-D, ...)



Meso-production (AMBER, J-PARC, ...)



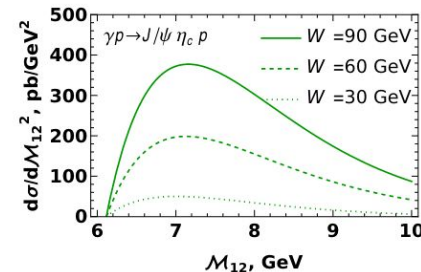
Proved factorization generally
[Qiu, Yu, PRD 107 (2023), 014007]

Marat Siddikov

Exclusive production of heavy quarkonia pair

Sensitive to GPD H_g , E_g behaviour **outside** $x = \pm \xi$ line

Cross-section is large enough for experimental studies

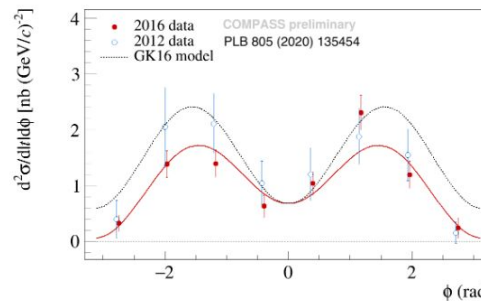
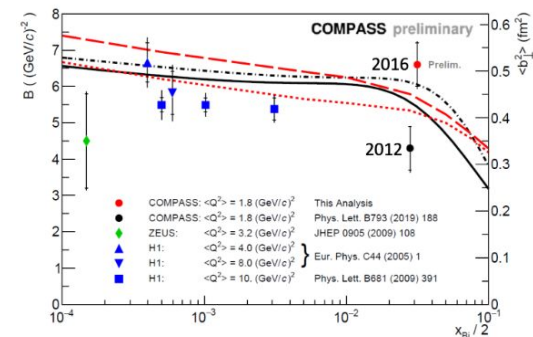
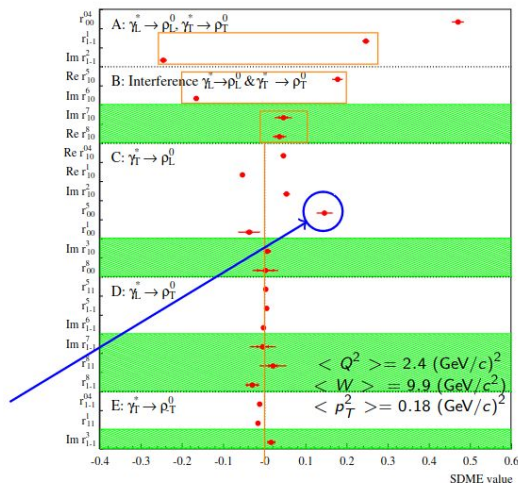


- Anatolii Koval (COMPASS)**

DVCS - 2016/17 dedicated long runs (preliminary, 3 times more data), t -slope π^0 - preliminary results of 2016 measurement, input to GPD models

- Vincent Andrieux (COMPASS)**

Spin Density Matrix Elements of ρ and ω DVMP from 2012 pilot run were shown
Violation of s-channel helicity cons. for $\gamma_T^* \rightarrow V_L$ contribution from chiral-odd GPDs
Ongoing analyses of π^0 , ϕ , ω and J/ψ with 2016/2017 data ($10 \times$ larger)



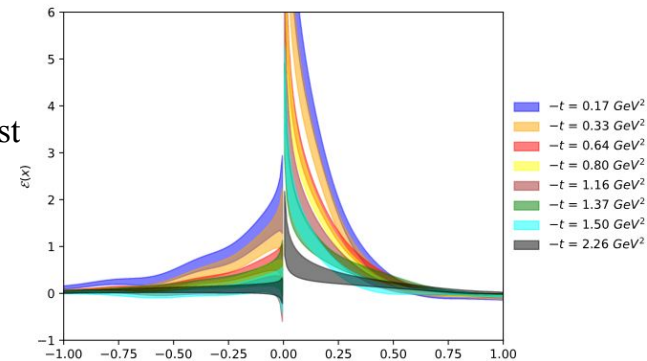
- Kornelija Passek-K.** Wide angle and DVMP pseudoscalar complete twist-3 prediction for PS electroproduction has been obtained
3-body tw3 contr. needed for the gauge invariance, also numerically important
twist-2 (γ_L) NLO available, possibly large and should be included

- Martha Constantinou & Xiang Gao**

Lattice QCD data on GPDs will play an important role in the pre-EIC era
New proposal for **Lorentz inv. decompos.** → reduction of computational cost
First few Mellin moments up to $A_{3,0}$ and $B_{3,0}$ were extracted

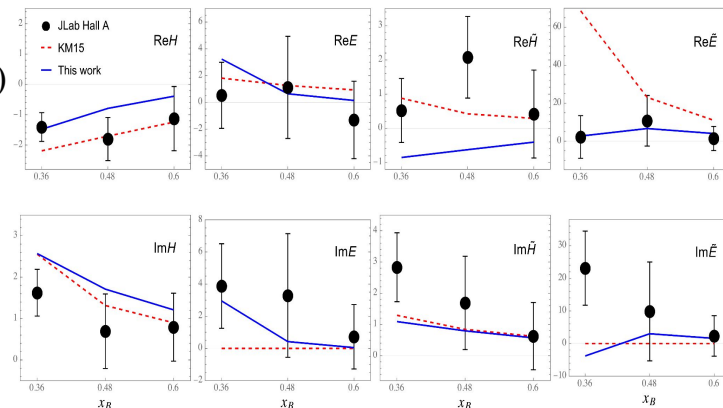
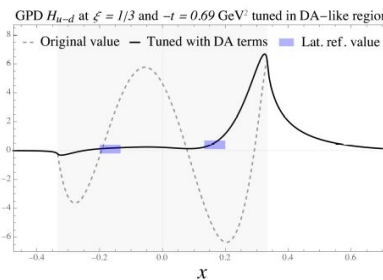
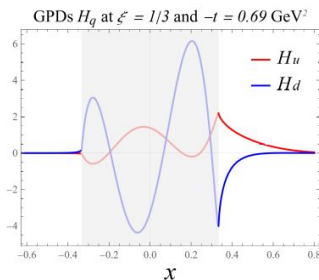
$$\int_{-1}^1 dx x^n H^q(x, \xi = 0, t) = A_{n+1,0}^q(t)$$

$$\int_{-1}^1 dx x^n E^q(x, \xi = 0, t) = B_{n+1,0}^q(t)$$



- Yuxun Guo & M Gabriel Santiago**

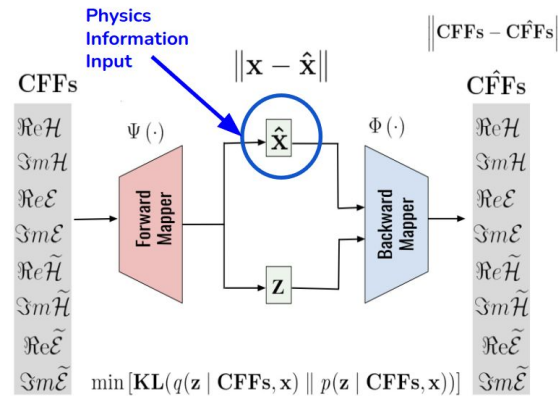
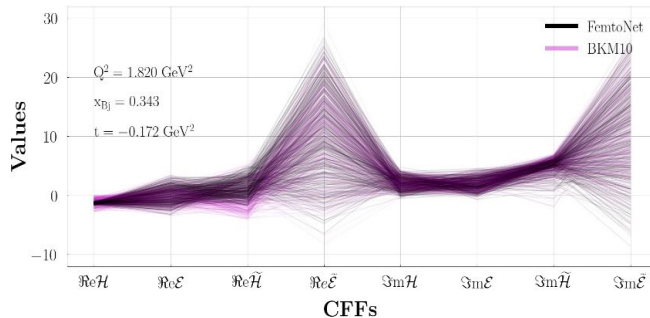
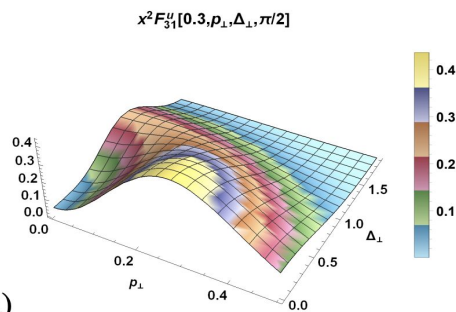
GPDs through **Universal Moment Parameterization (GUMP)**
Inputs: Experimental and **lattice** (crucial to determine the ERBL region)
Preliminary fits of gluon GPDs from ϕ^0 production



GPDs V

- S.Liuti & B.Kriesten**

Progress on **ML-based framework** for the analysis of deeply virtual exclusive scattering experiments to enable the extraction of observables from data with a **faithful representation of uncertainty**



(a)

- Harleen Dahiya**

The **axial-vector form factors** of the light, singly and doubly charmed baryons are investigated in the framework of $SU(4)$ chiral constituent quark model.

- Simone Venturini**

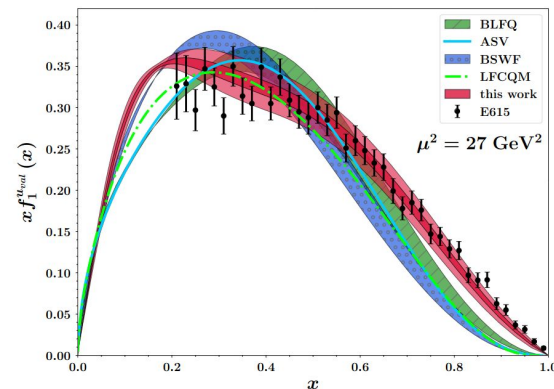
light-front wave functions model for the pion, fit observables sensible to the **pion PDF**, and the exp data of elmag FFs.

Work in progress in the direction of GPDs and TMDs

- Shubham Sharma** (presented by Harleen Dahiya)

higher twist **GTMD** F_{31} for proton in the light-front quark-diquark model

Pion PDFs



Summary: DIS23 WG5 Spin & 3D Structure

WG5 accepted & confirmed abstracts - 49 total

DIS23 - WG5 topical breakdown

Flavor

8.0%

DVCS

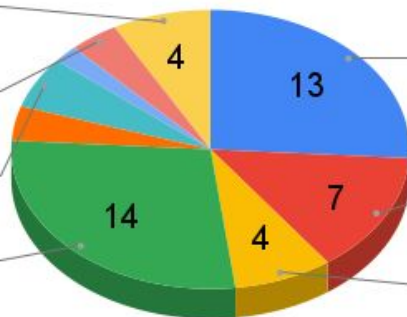
4.0%

ALL

6.0%

GPD

28.0%



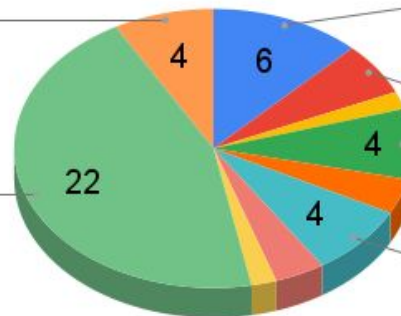
DIS23 - WG5 category breakdown

pheno

8.2%

theory

44.9%



STAR

12.2%

PHENIX

6.1%

JLab

8.2%

COMPASS

8.2%

Thank you to all speakers & session chairs, and to the organizers!

DIS2023: XXX International Workshop on Deep-Inelastic Scattering and Related Subjects (27-31 March 2023): WG5