

# WG6 - Spin Physics Summary Talk



## WG6 Conveners:

Tanja Horn (Catholic University of America)

Zhongbo Kang (University of California)

Charlotte Van Hulse (University of the Basque Country)

# Thanks to all speakers!

- Experiment
- Theory
- WG6+WG7 Joint

## TMDs & FFs and GPDs:

Andrew Puckett  
Kalyan Allada  
Edward Kinney  
Barbara Badelek  
Wally Melnitchouk  
Marcin Stolarski  
Cristian Pisano  
Marco Radici  
Leonard Gamberg  
Emanuele Roberto  
Nocera  
Nobuo Sato

Daria Sokan  
Carlos Munoz-Camacho  
David Hamilton  
Tanja Horn  
Charlotte van Hulse  
Pawel Sznajder  
Renaud Boussarie  
Franck Sabatie  
Jakub Wagner  
Andrea Ferrero

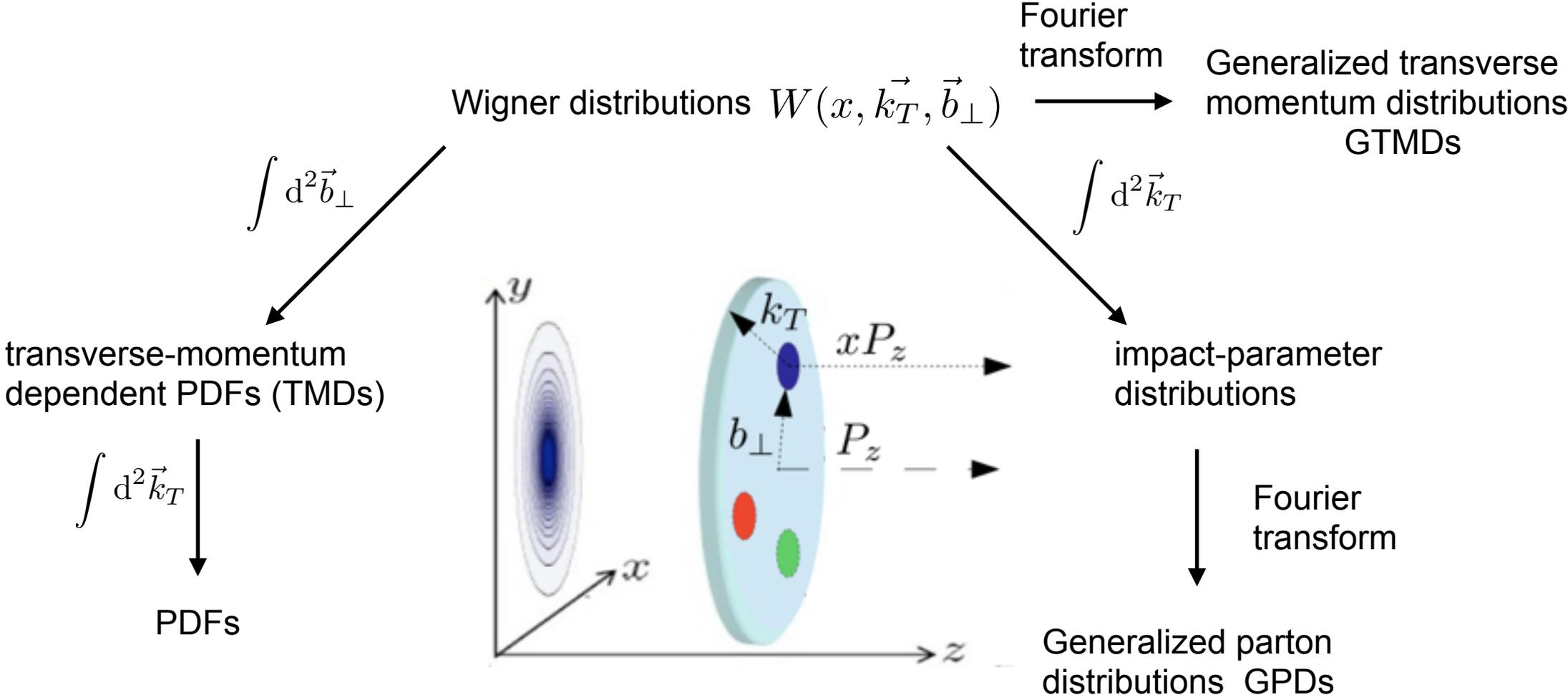
Bakur Parsamyan  
Adam Szabelski  
Jian Zhou  
James Drachenberg  
Marie Boer  
Michael Skoby  
Qinghua Xu  
Bernd Surrow  
Anselm Vossen  
Jincheng Mei  
Shohini Bhattacharya  
Asmita Mukherjee  
Shunzo Kumano  
Gaku Mitsuka

**Total talks: 37+6**

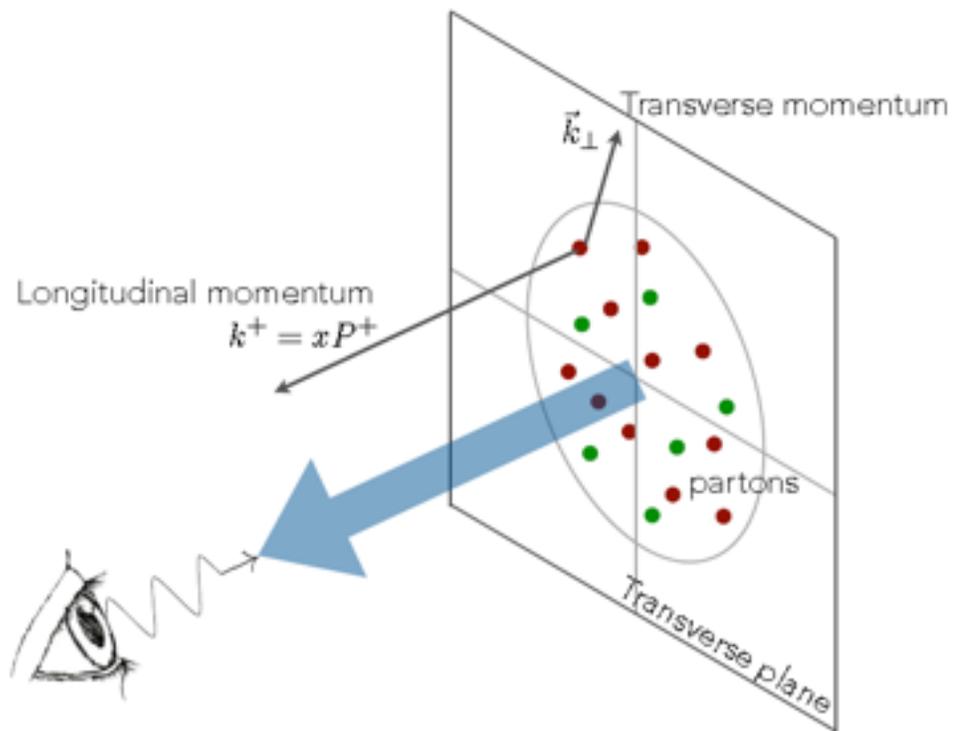
## Future Experiments (Joint WG6+WG7)

Wim Cosyn  
Tanja Horn  
Brian Page  
Kazuhiro Tanaka  
Yong Zhao  
Tom Daal  
Nobuo Sato

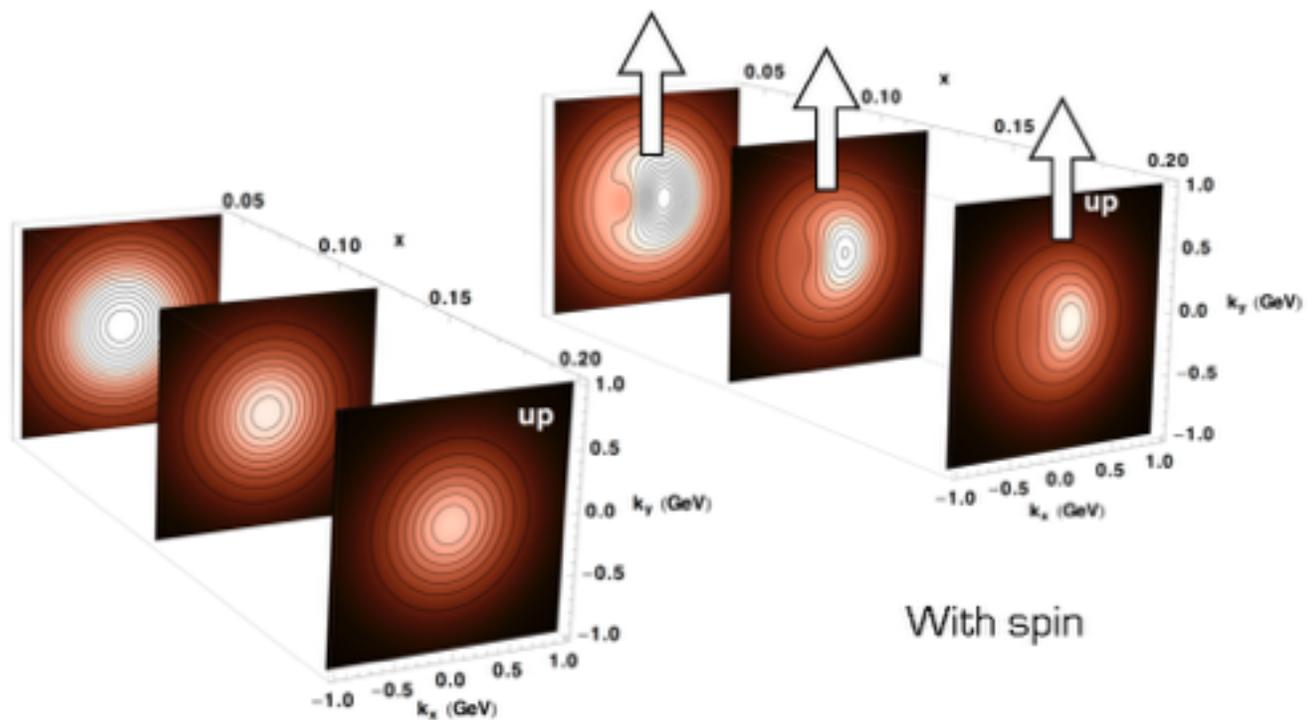
# The proton in multiple dimensions



# Transverse Momentum Distributions - 3D!



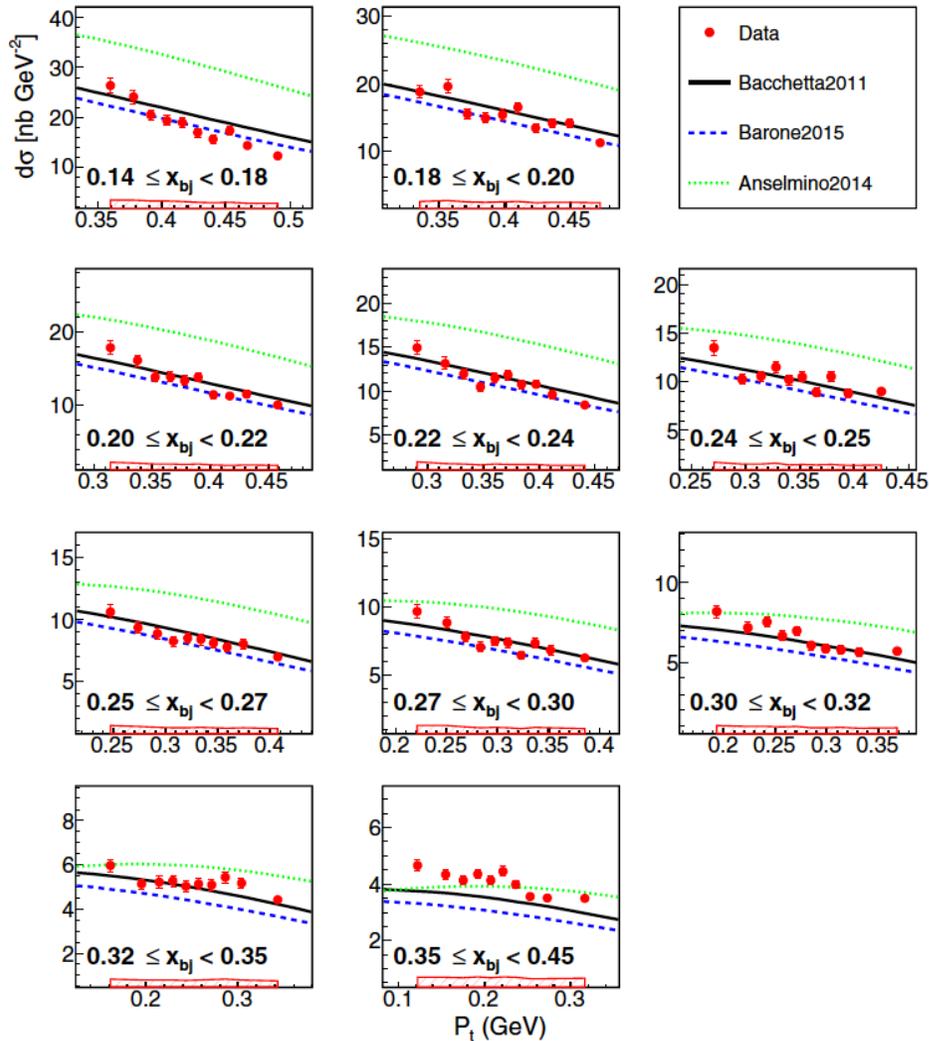
3D Maps of partonic distributions



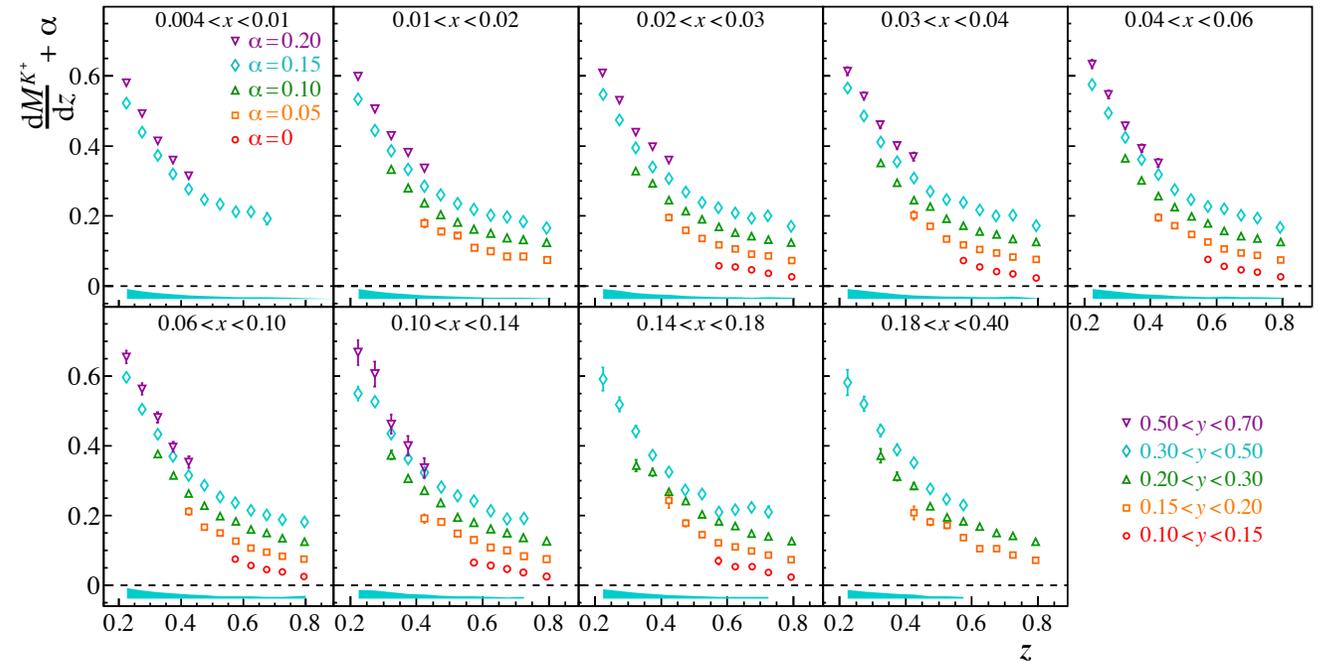
# SIDIS measurements - unpolarized

[Andrew Puckett, Marcin Stolarski, Anselm Vossen]

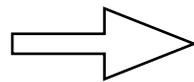
## □ Hall A: $e^+{}^3\text{He} \rightarrow e\pi^\pm X$ cross section



## □ COMPASS $\pi^\pm$ and $K^\pm$ multiplicities



$K^+/K^-$  multiplicity ratios @ large  $z \neq$  LO  
large  $v$  dependence



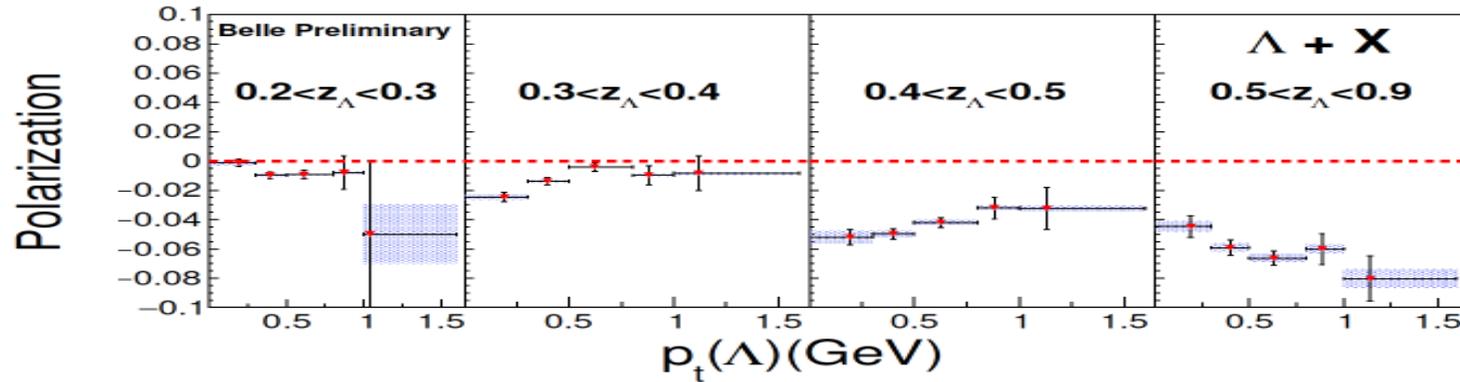
Constrain spin-independent FF

## □ New di-hadron measurements in $e^+e^-$ from Belle

# Transverse $\Lambda$ polarization measurements: polarized FFs

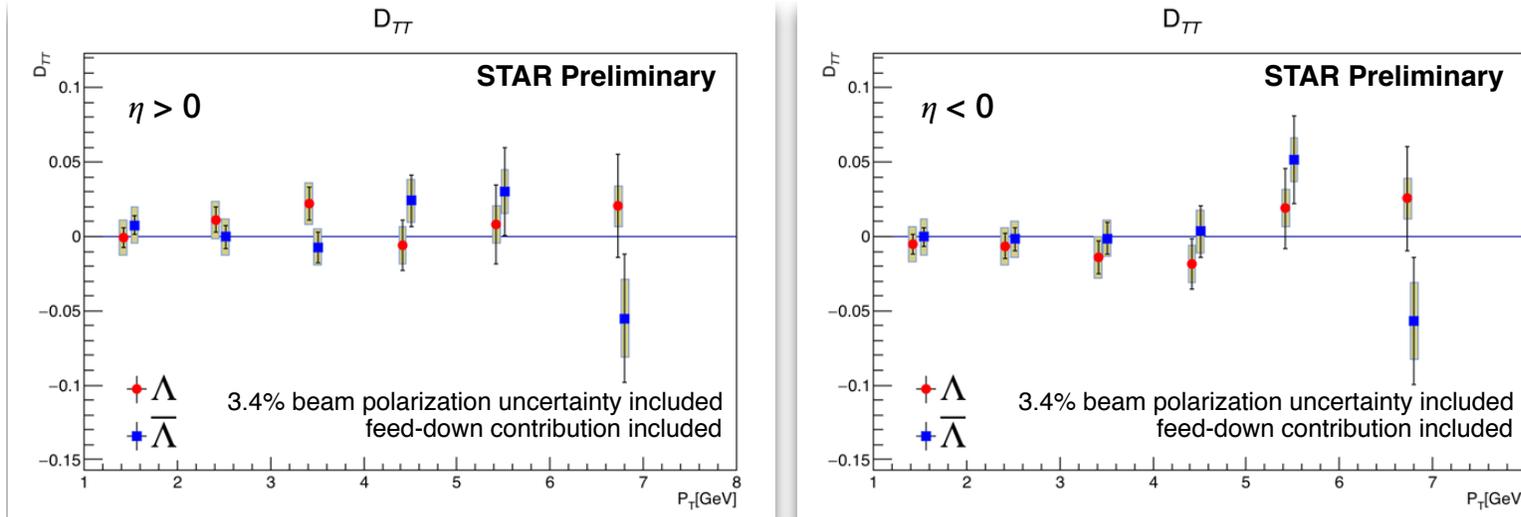
[Anselm Vossen, Jincheng Mei]

## □ Belle



behaviour at intermediate  $z$  unexpected

## □ STAR

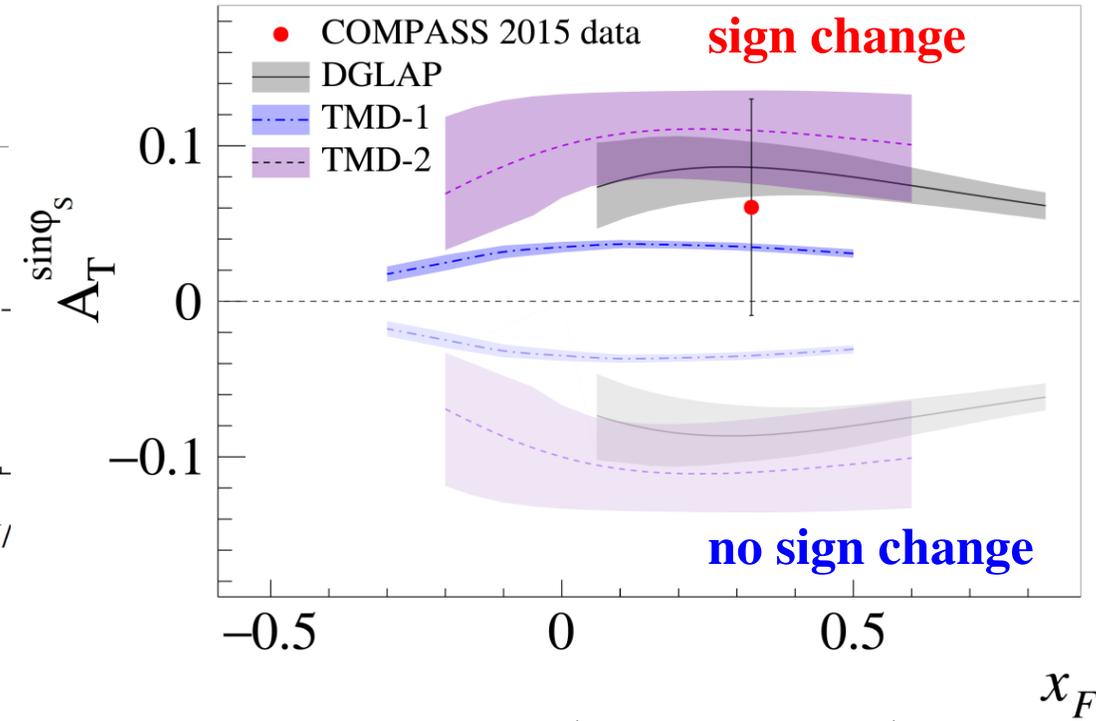
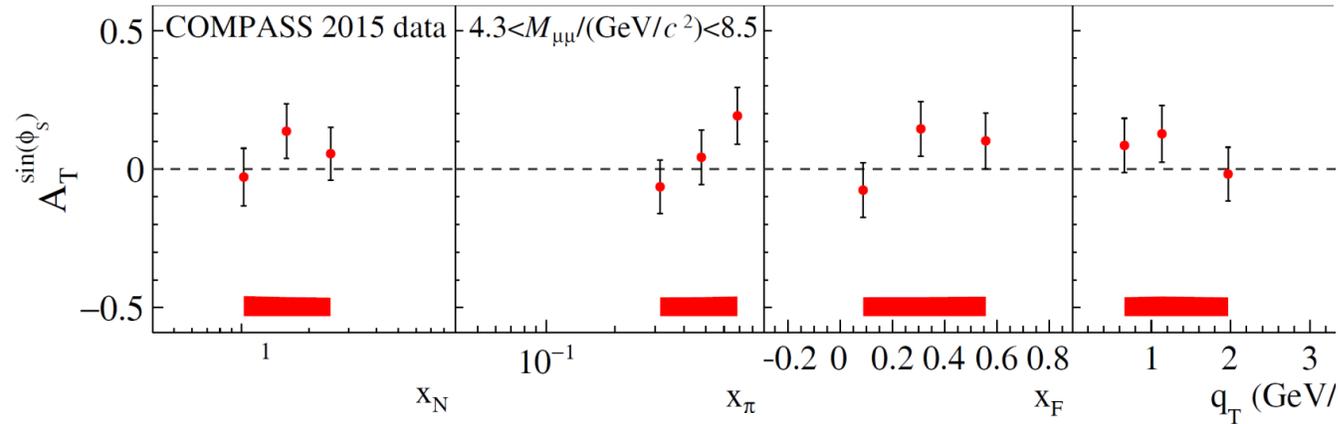


$\Lambda, \bar{\Lambda}$  consistent with zero

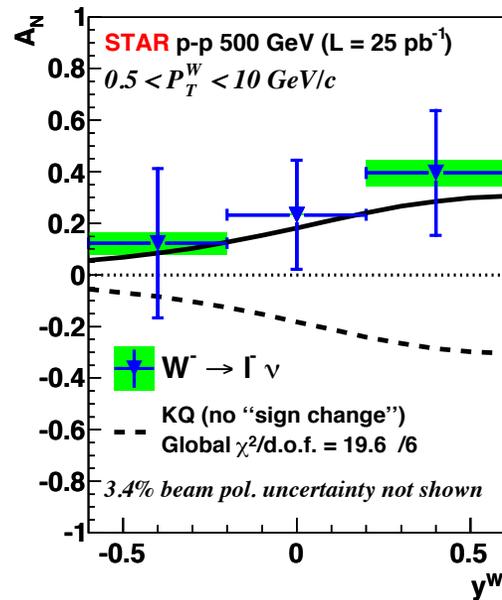
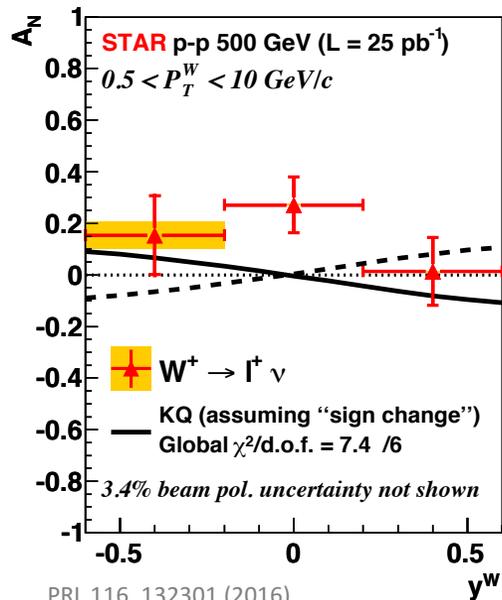
# Sivers SIDIS and Drell Yan

[Bakur Parsamyan, James Drachenberg]

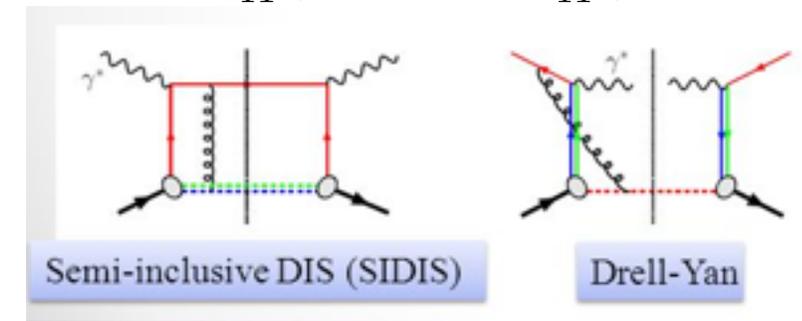
## COMPASS: first Sivers Drell-Yan measurement



## STAR: exploratory Sivers sign-change measurement



$$f_{1T}^{\perp q} |_{SIDIS} = -f_{1T}^{\perp q} |_{DY}$$

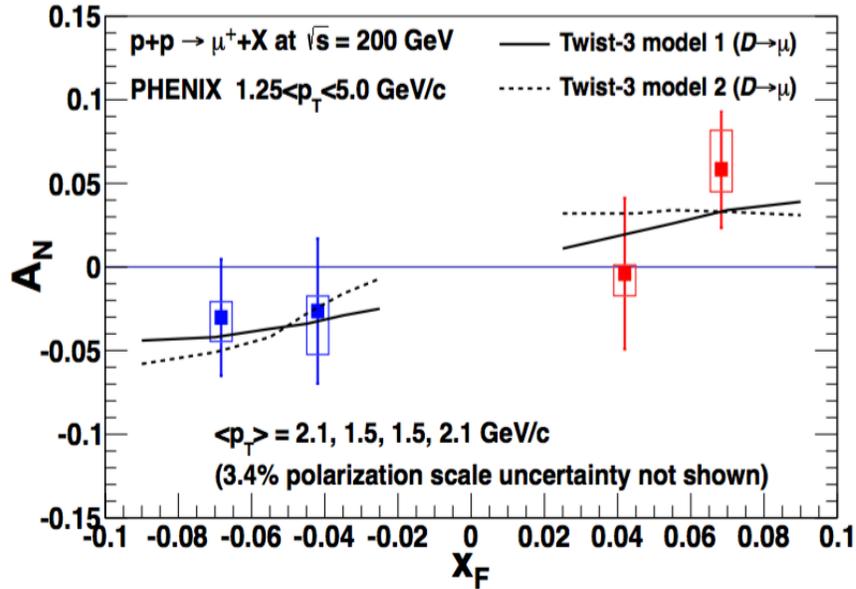


Measurements from PHENIX to come

# More TMDs

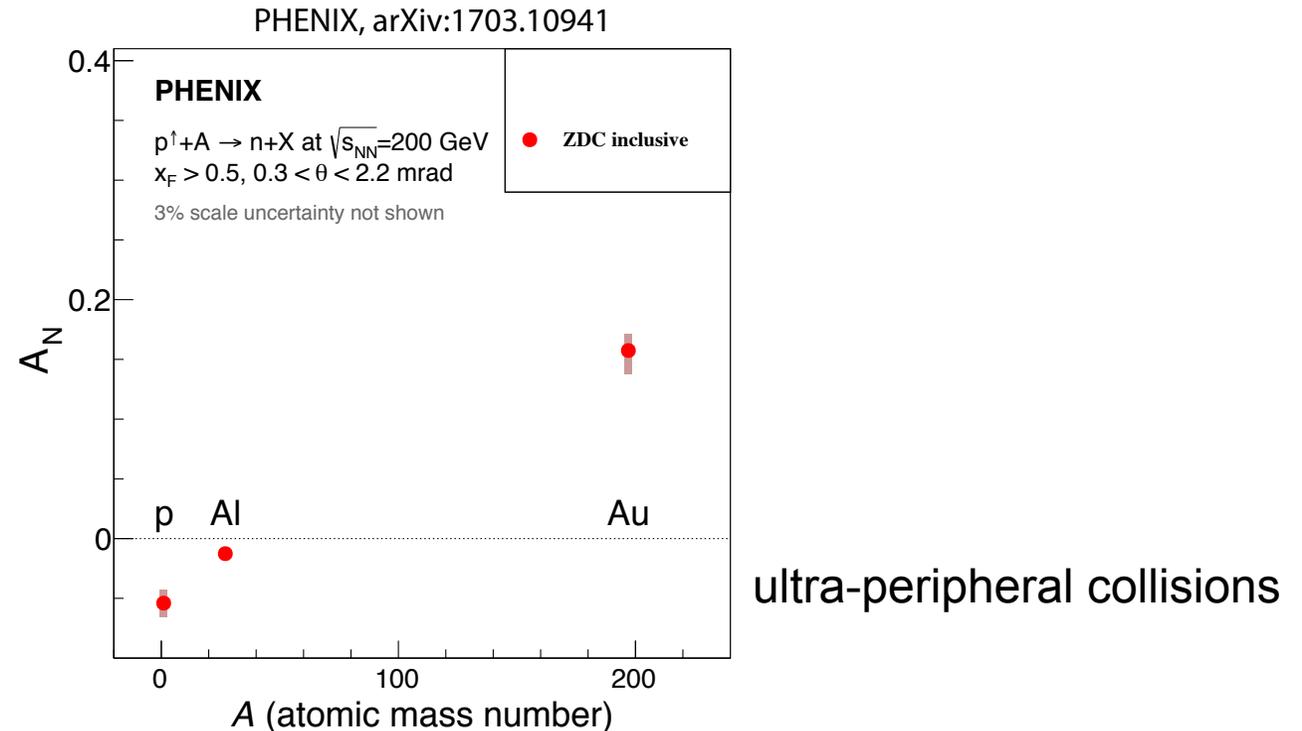
[Marie Boer, Adam Szabelski, Bakur Parsamyan, Gaku Mitsuka, Mike Skoby]

- ❑ Phenix gluon Sivers: Heavy flavour - D meson decay into  $\mu^+$



- ❑ COMPASS - gluon Sivers
- ❑ COMPASS - full set of single/di-hadron SSAs on longitudinally polarized target
- ❑ factorization-breaking and color-entanglement studies at PHENIX

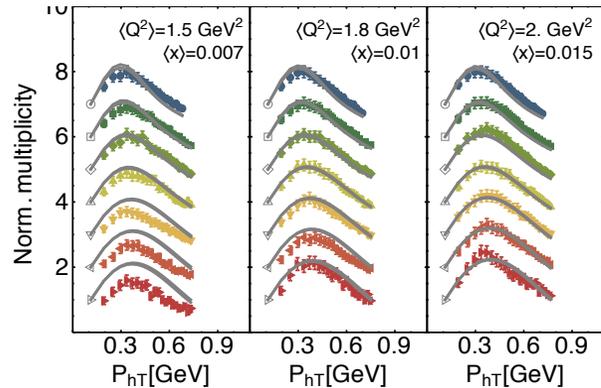
- ❑ Large  $pA \rightarrow nX$  asymmetries PHENIX



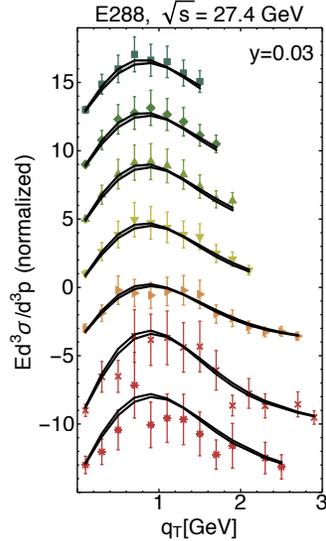
# Fits and extractions

[Cristian Pisano, Marco Radici, Leonard Gamberg, Emanuele Nocera, Nobuo Sato]

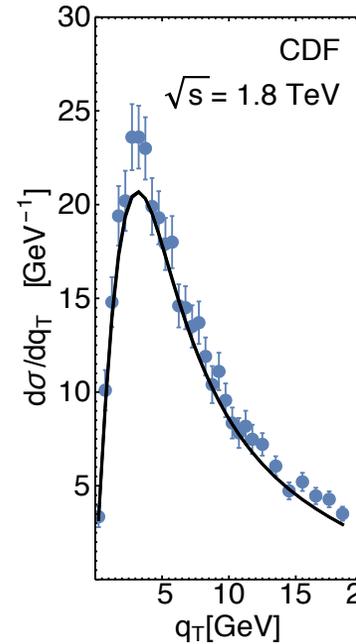
## First global fit - unpolarized TMD PDFs & FFs



SIDIS (HERMES & COMPASS)



Drell-Yan  
(Fermilab)



Z-boson (CDF & D0)

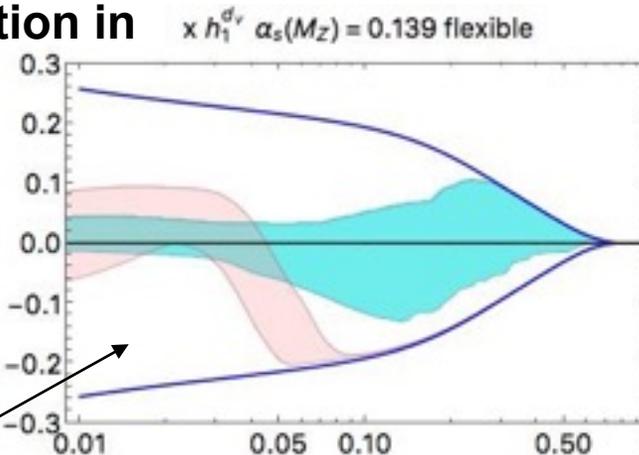
- ❑ Matching collinear and TMD factorization
- ❑ NNFF1.0: fragmentation functions
- ❑ First Monte Carlo analysis of fragmentation functions
- ❑ Test of fragmentation functions in Pythia
- ❑ Validation of TMD factorization and evolution

## Transversity from di-hadron production in SIDIS, $e^+e^-$ , pp

old fit

new fit (pp STAR data added)

Soffer bound

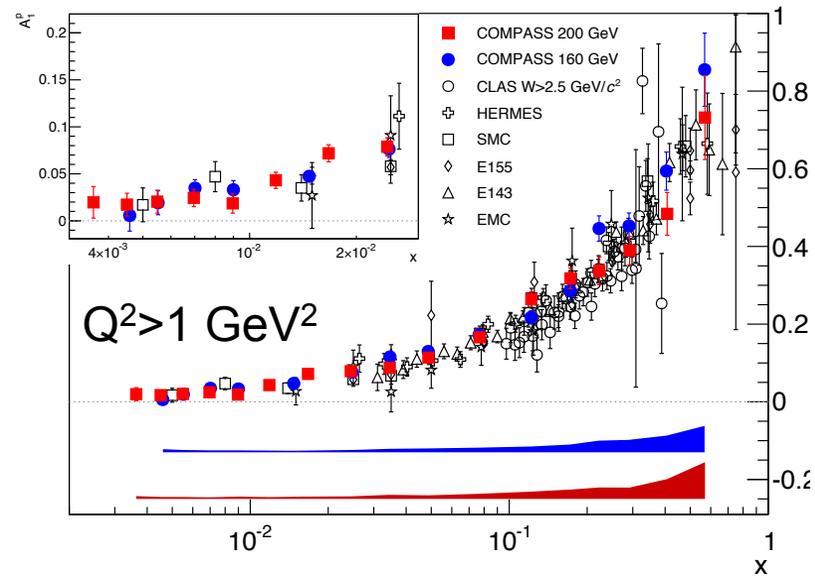


# Helicity PDFs

[Barbara Badelek, Wally Melnitchouk, Qinghua Xu, Bernd Surrow]

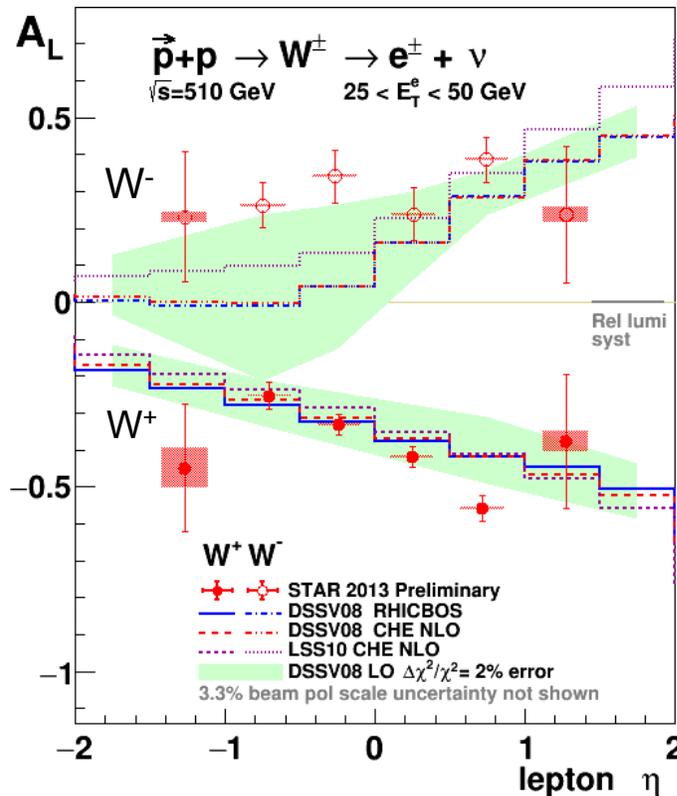
## COMPASS

full data set for  $g^1_p(x)$  and  $g^1_d(x)$   
at  $Q^2 < 1 \text{ GeV}^2$  and  $Q^2 > 1 \text{ GeV}^2$

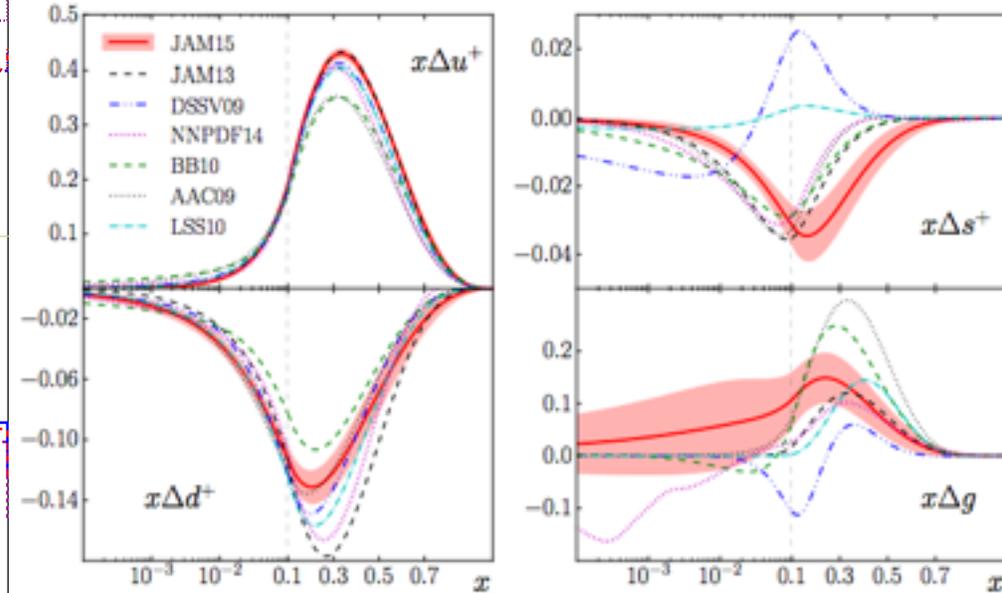


$g^1_p(x) > 0$  at low  $x$   
 $g^1_d(x) \approx 0$  at low  $x$

## STAR



## MC analysis of PDFs

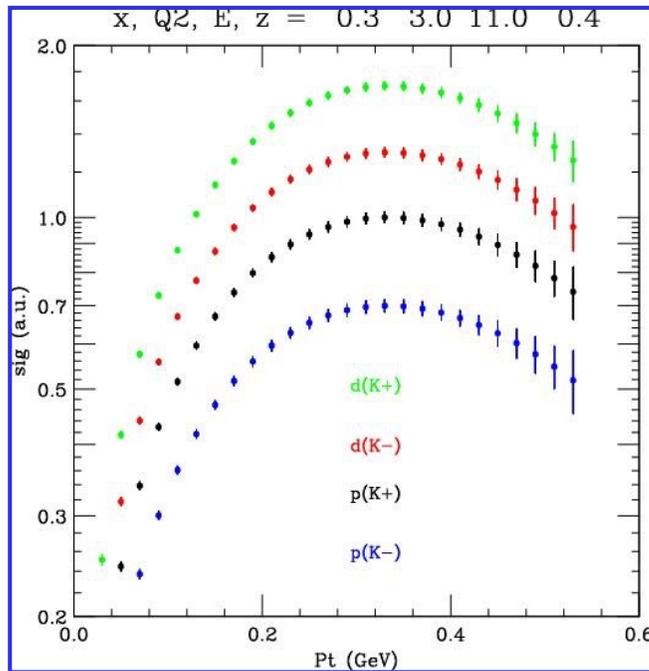


$\Delta u$  and  $\Delta d$  similar to earlier results  
 $\Delta s < 0$   
 $\Delta g$  similar to recent DSSV fits

# Near future

[Andrew Puckett, Kalyan Allada, Edward Kinney, James Drachenberg]

- Hall C:**  
 precision measurements of  $\pi^\pm, \pi^0, K^\pm$  SIDIS cross sections at low  $P_{h\perp}$   
 L/T separation of  $\pi^\pm$  cross section

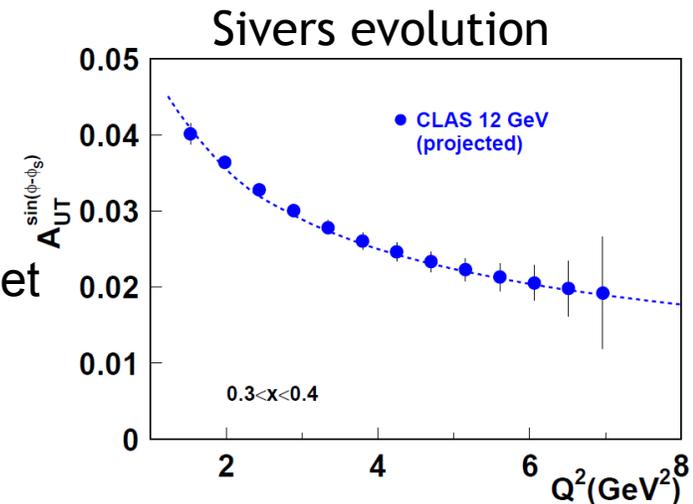


## STAR:

Sivers/twist-3 in  $W, \gamma$ , Drell-Yan  
 More on Collins and IFF  
 Collins from  $p^\uparrow + A$

## CLAS12 - large acceptance

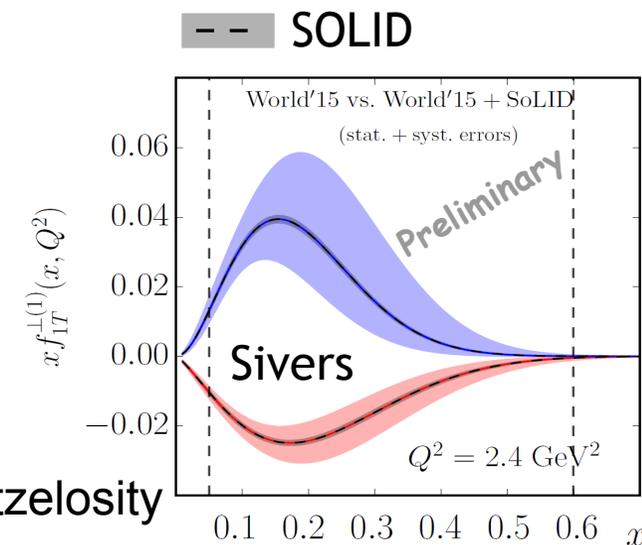
$\sigma_{UU}$  and  $A_{LU}$  from H/D  
 $A_{UL}$  and  $A_{LL}$  from  $NH_3/ND_3$   
 transversely polarized proton target



## Hall A

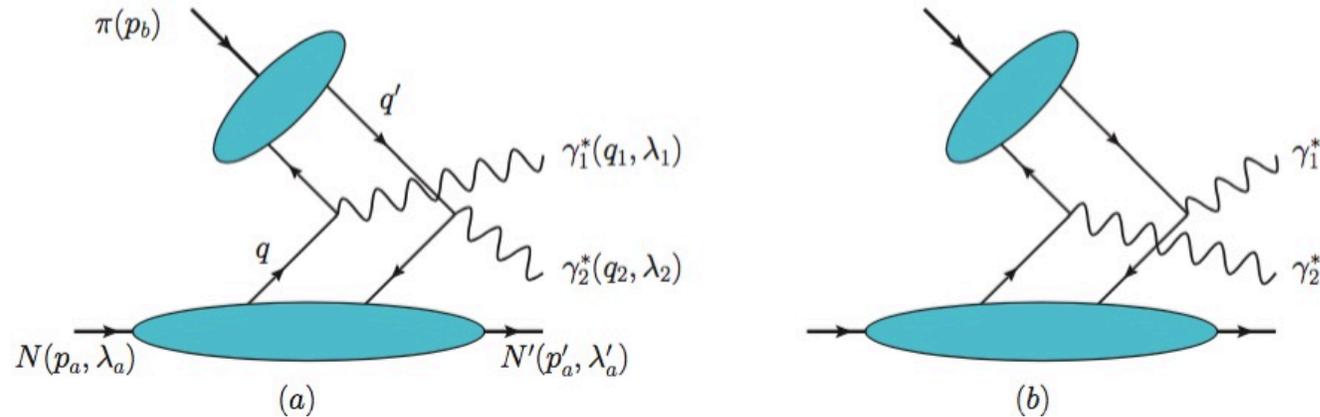
$e + ^3He \rightarrow eX\pi^\pm, 0, eXK^\pm$   
 $A_{UT}$  Collins, Sivers, Pretzelosity

SOLID detector - large acceptance  
 SSA from longitudinally pol. neutron  
 SSA from transversely pol. neutron  
 SSA from transversely pol. proton  
 4D ( $x, Q^2, P_{h\perp}, z$ ) of Collins, Sivers, Pretzelosity



# Possible future measurements

[Jian Zhou, Tom van Daal, Shohini Bhattachary,  
Wim Cosyn, Brian Page,  
Yong Zhao, Asmita Mukherjee]

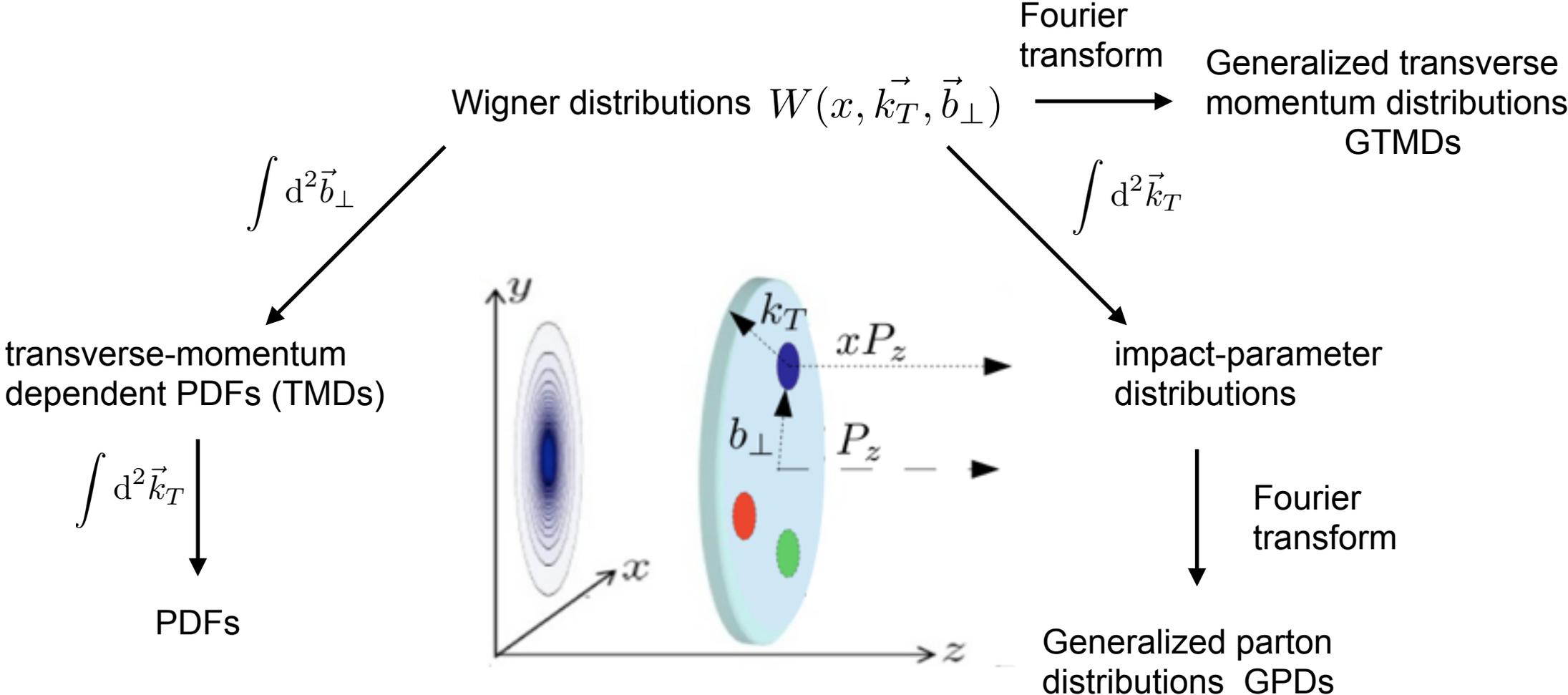


- TMDs at small  $x$
- gluon TMDs at small  $x$  for spin-1 hadrons: deuterons at EIC.
- gluon helicity at EIC via jets
- gluon OAM via exclusive dijet production

- Double Drell Yan: access to quark GTMDs in the ERBL region

➔ quark orbital angular momentum

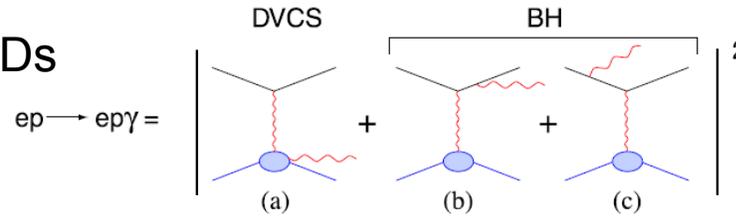
# The proton in multiple dimensions



# Generalized Parton Distributions

Accessed through exclusive processes: DVCS, DVMP, WACS

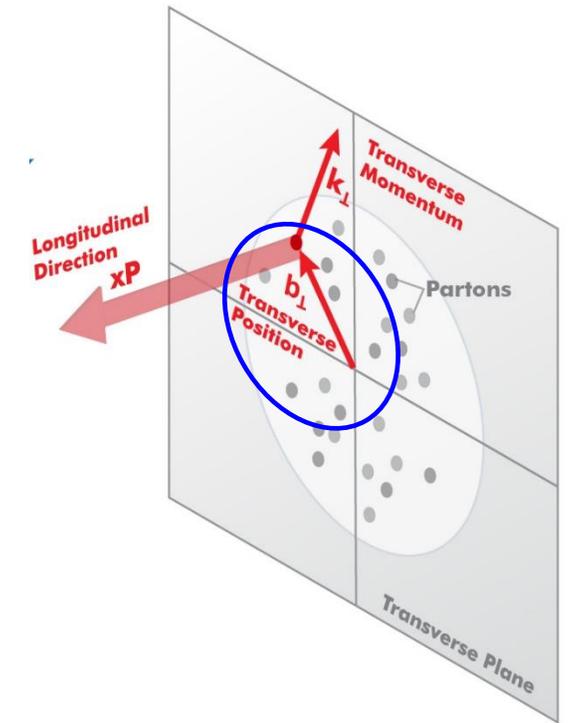
- DVCS is the cleanest way to probe GPDs



At leading twist:

$$d^5 \vec{\sigma} - d^5 \overleftarrow{\sigma} = 2 \Im(T^{BH} \cdot T^{DVCS})$$

$$d^5 \vec{\sigma} + d^5 \overleftarrow{\sigma} = |BH|^2 + 2 \Re(T^{BH} \cdot T^{DVCS}) + |DVCS|^2$$



- Quantum numbers in DVMP probe individual GPD components selectively

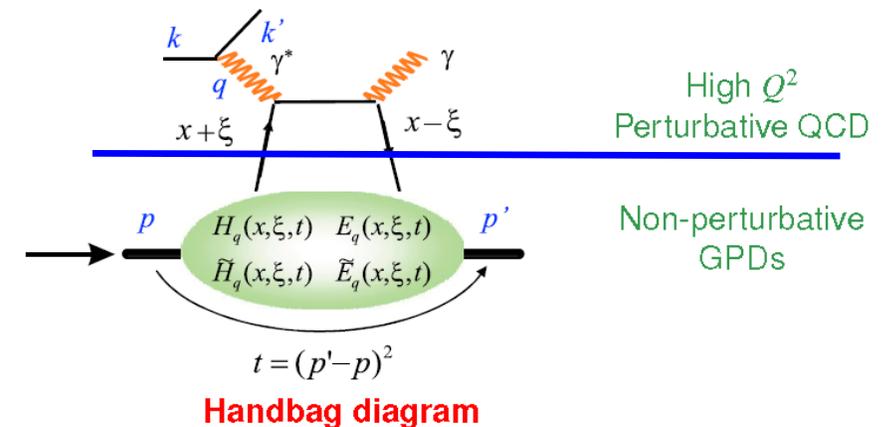
- Vector :  $\rho^0/\rho+/K^*$  select  $H, E$

- Pseudoscalar:  $\pi, \eta, K$  select the polarised GPDs,  $\tilde{H}$  and  $\tilde{E}$

- Need good understanding of reaction mechanism

- QCD factorisation for mesons

- Can be verified experimentally through L/T separated cross sections



# First Measurements

[Daria Sokhan, Carlos Munoz-Camacho, David Hamilton, Tanja Horn, Charlotte van Hulse, Andrea Ferrero, Franck Sabatie]

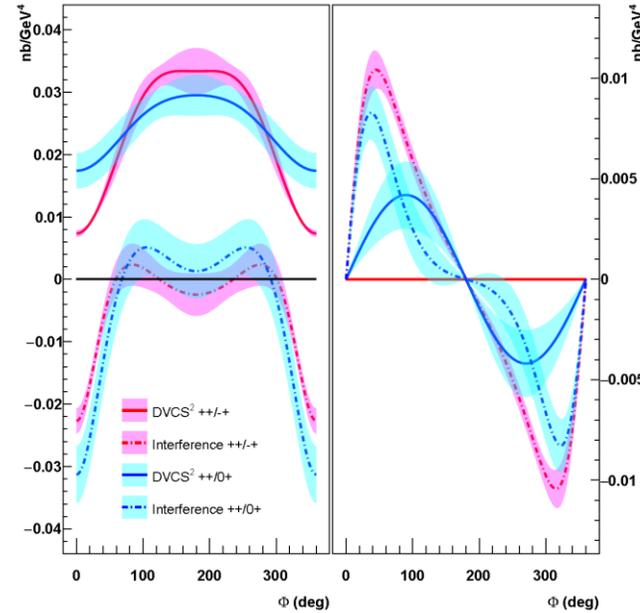
## □ DVCS at 6 GeV JLab and COMPASS:

(un)polarised cross sections,  $A_{LU}$ ,  $A_{UL}$ ,  $A_{LL}$ , measuring the energy dependence of the x-section allows for Rosenbluth type separation,  $t$ -slope of x-section related to transverse squared radius

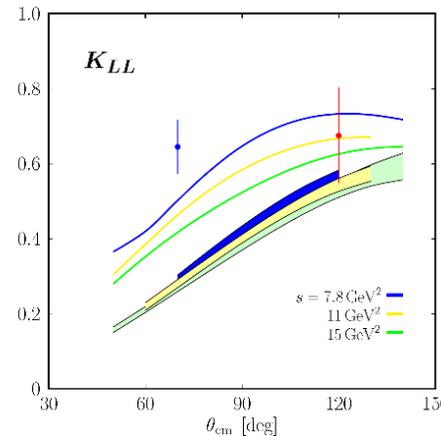
## □ DVMP at 6 GeV Jlab, COMPASS,

**HERMES:**  $\pi^+$   $\chi^-$  sections demonstrate method for QCD factorisation studies,  $\pi^0$  data from proton and neutron show substantial contribution of transverse photons,  $\rho^0$  helicity amplitude ratios small/consistent with zero, new SDMEs partial agreement with GK model

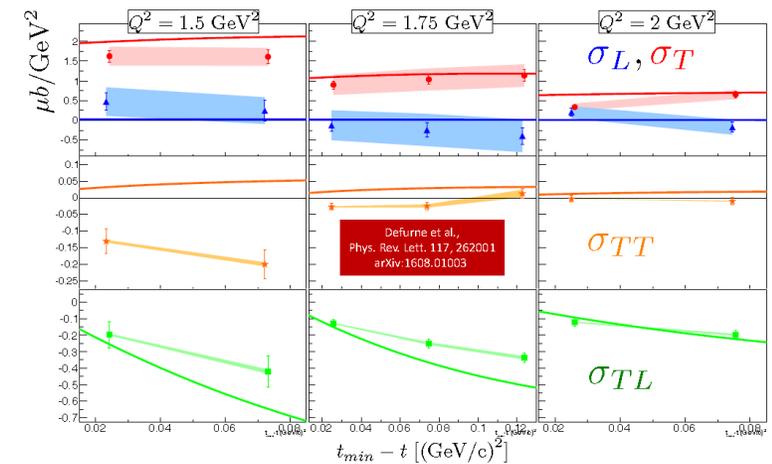
□ Also, access GPDs at large  $t$  from nucleon form factors measured in **Wide-Angle Compton Scattering (WACS) at 6 GeV JLab** through Sum Rules



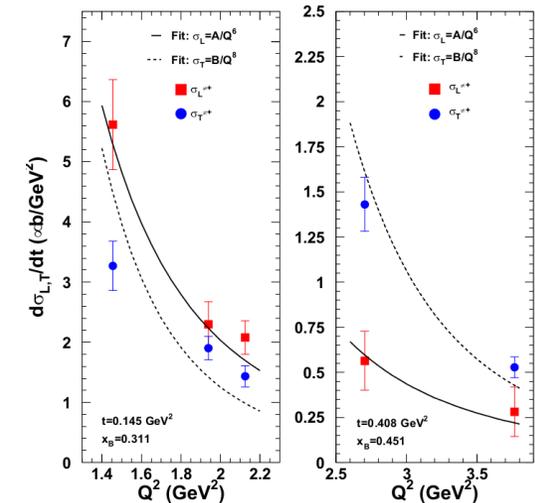
DVCS<sup>2</sup> substantial in cross section



Models in fair agreement with WACS data



Substantial contribution of  $\sigma_T$  in  $\pi^0$  cross section



QCD factorization appears to work in  $\pi^+$

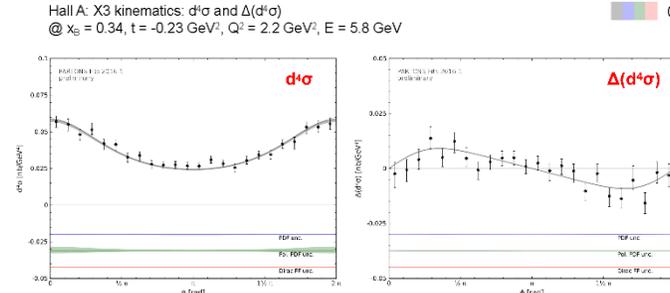
# Setting up a Framework for Global Fits

- ❑ **PARTONS (PARTonic Tomography Of Nucleon Software)**: platform being developed for GPD studies, see: arXiv:hep-ph/1512.06174

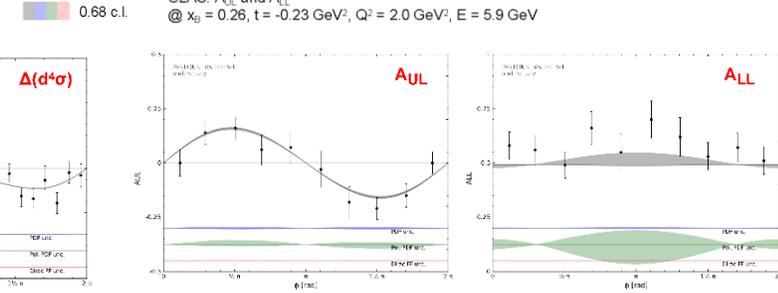
- ❑ **Fits to DVCS data**: successful first attempt to fit high-precision JLab data

- ❑ **Compton Form Factors**: developing new way of fitting with encoded access to tomography, small number of parameters capability to work over wide kinematic range

JLab Hall A



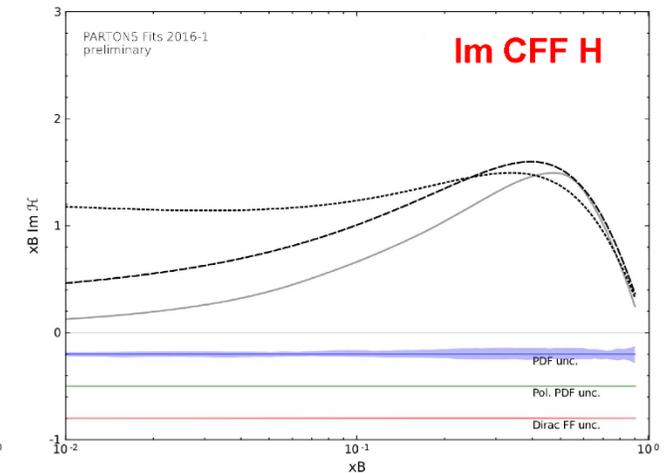
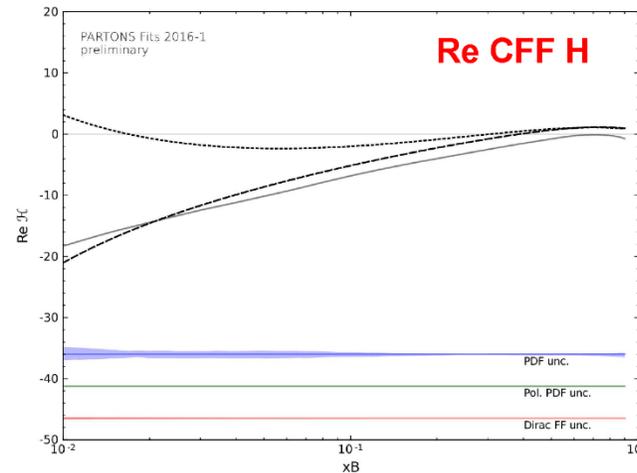
JLab Hall B



Good description of experimental data

Compton form factors for GPD H  
 @  $t = -0.3 \text{ GeV}^2$ ,  $Q^2 = \mu_F^2 = \mu_R^2 = 2 \text{ GeV}^2$

--- VGG  
 ..... GK  
 0.68 c.l.



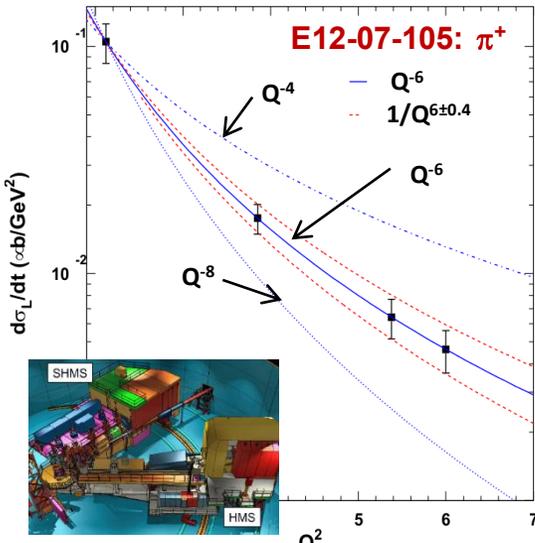
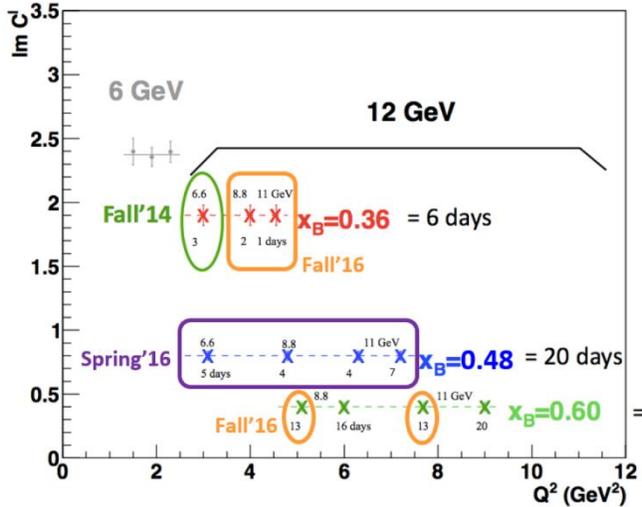
# Near Future: Validation of QCD Factorization

❑ **Scaling tests in DVCS at 12 GeV JLab:**  
 earlier data consistent with scaling over limited  $Q^2$  range, extended  $Q^2$  reach at JLab 12 GeV – 50% of the experiment completed

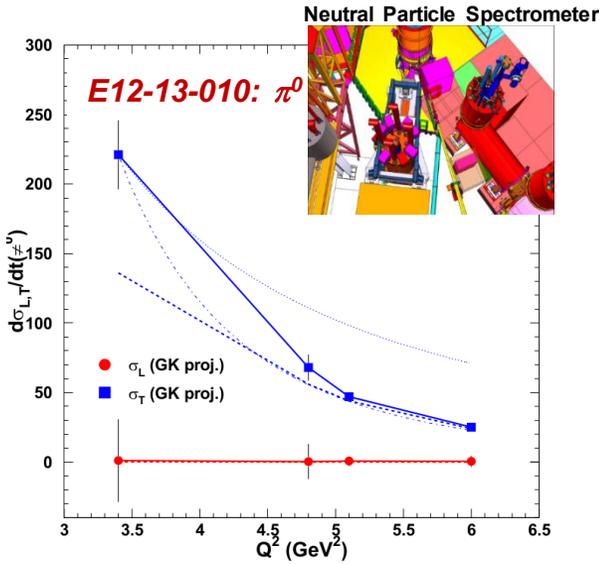
❑ **QCD Factorization tests in DVMP at 12 GeV JLab:** earlier data demonstrated the technique of measuring the  $Q^2$  dependence of L/T separated x-sections, extended reach at JLab 12 GeV for  $\pi^+/\pi^0$  and first time  $K^+$  factorisation tests

❑ **Verifying dominance of transverse photons in DVMP at 12 GeV JLab:** would allow access to transversity GPDs

Scaling test of the DVCS cross section



Search for onset of factorization with precision  $\pi^+$  cross sections

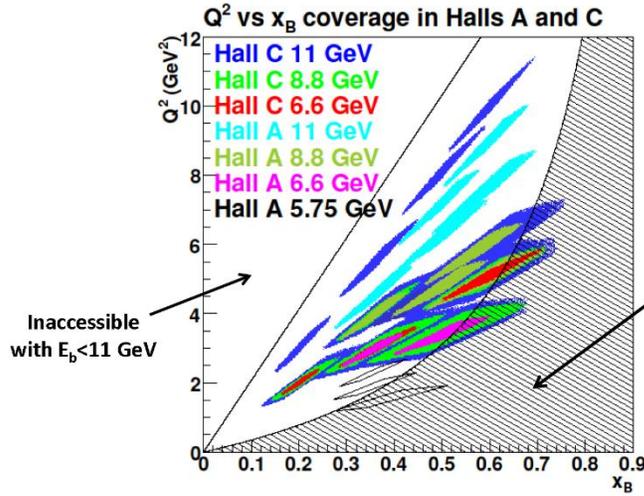


Verifying dominance of  $\sigma_T$  in L/T separated  $\pi^0$

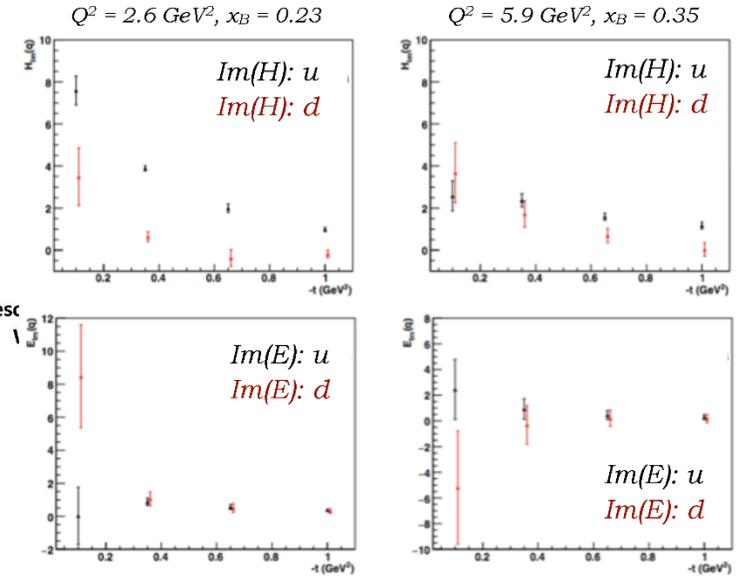
# Near Future Measurements

[Daria Sokhan, Carlos Munoz-Camacho, David Hamilton]

- DVCS cross sections and asymmetries at 12 GeV JLab:**  
 Hall A/C precision cross sections to disentangle higher twist contributions, Hall B longitudinal and transverse asymmetries over wide kinematic range with large acceptance

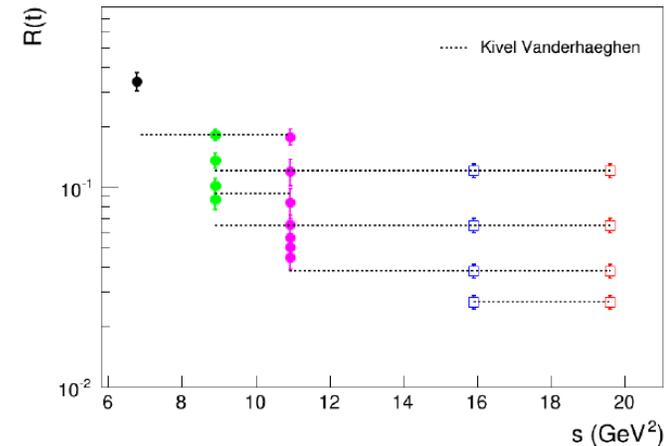


Phase space for DVCS measurements in JLab Hall A/C



Projections for CFF to be extracted from CLAS12

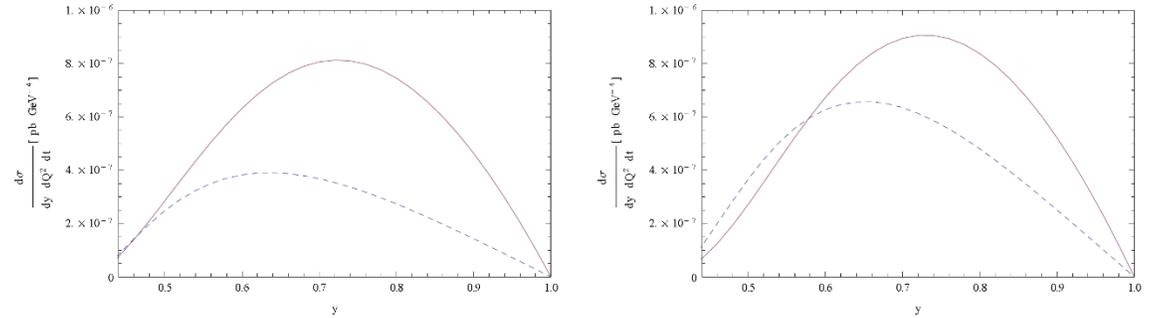
- Wide-Angle Compton Scattering at 12 GeV JLab:** complementary measurements of nucleon form factors at large  $t$  will constrain GPDs, uses Neutral Particle Spectrometer in Hall C



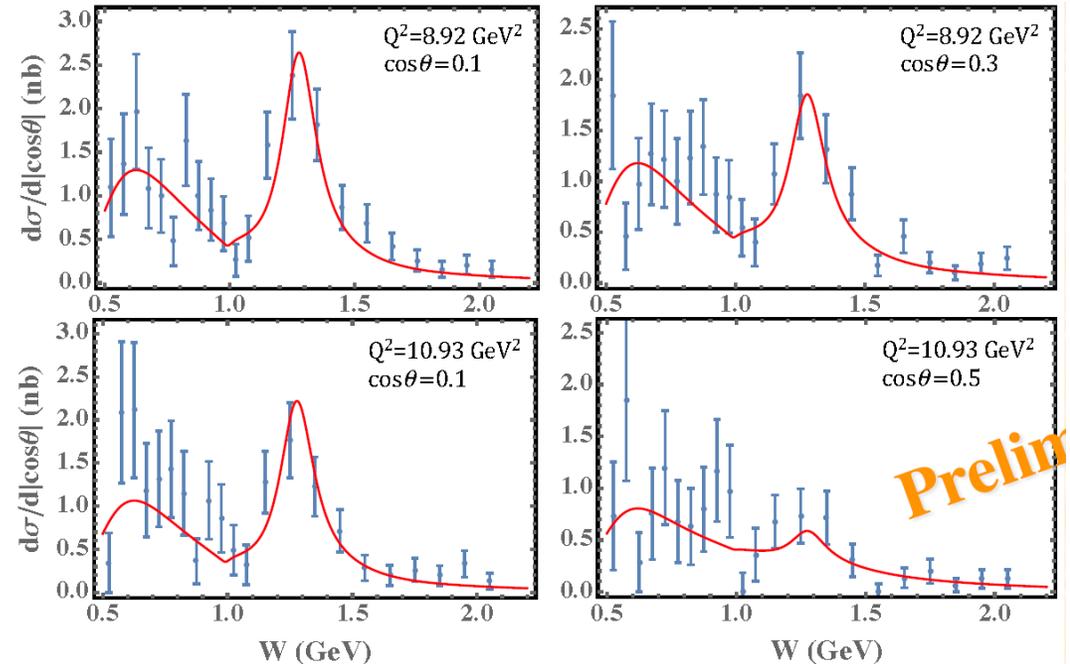
# Possible Future Measurements

[Jakub Wagner, Renaud Boissier, Shunzo Kumano, Kazuhiro Tanaka]

- ❑ **Quark flavour separation through neutrino production of D-mesons:** calculations show that within reach of planned medium and high energy neutrino facilities, gluon contribution important
- ❑ **Polarisation dependence of chiral-even and chiral-odd components:** measurements may be possible at JLab and/or COMPASS, EIC
- ❑ **GPDs for exotic hadrons:** Use GDA and  $s$ - $t$  crossing to access GPDs, first trial to extract GDAs from data, possible at KEKB
- ❑ **Exclusive DY with pion beams:** access GPDs through time-like processes, feasibility studies JPARC



Behaviour of p and n x-section enables separation of u and d quark contributions



Analysis of Belle data on  $\gamma\gamma^* \rightarrow \pi^0\pi^0$