Experimental overview on TMDs
at fixed-target experiments

- Introduction to TMDs
- Experiments and results
- Putting them together

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COMPASS

clas

hermes

Jefferson Lab
Hall A

NSF

APRIL MEETING 2016

April 16–19
Salt Lake City, Utah

Photo: Kennecott Utah Copper Mine

The current picture of the proton

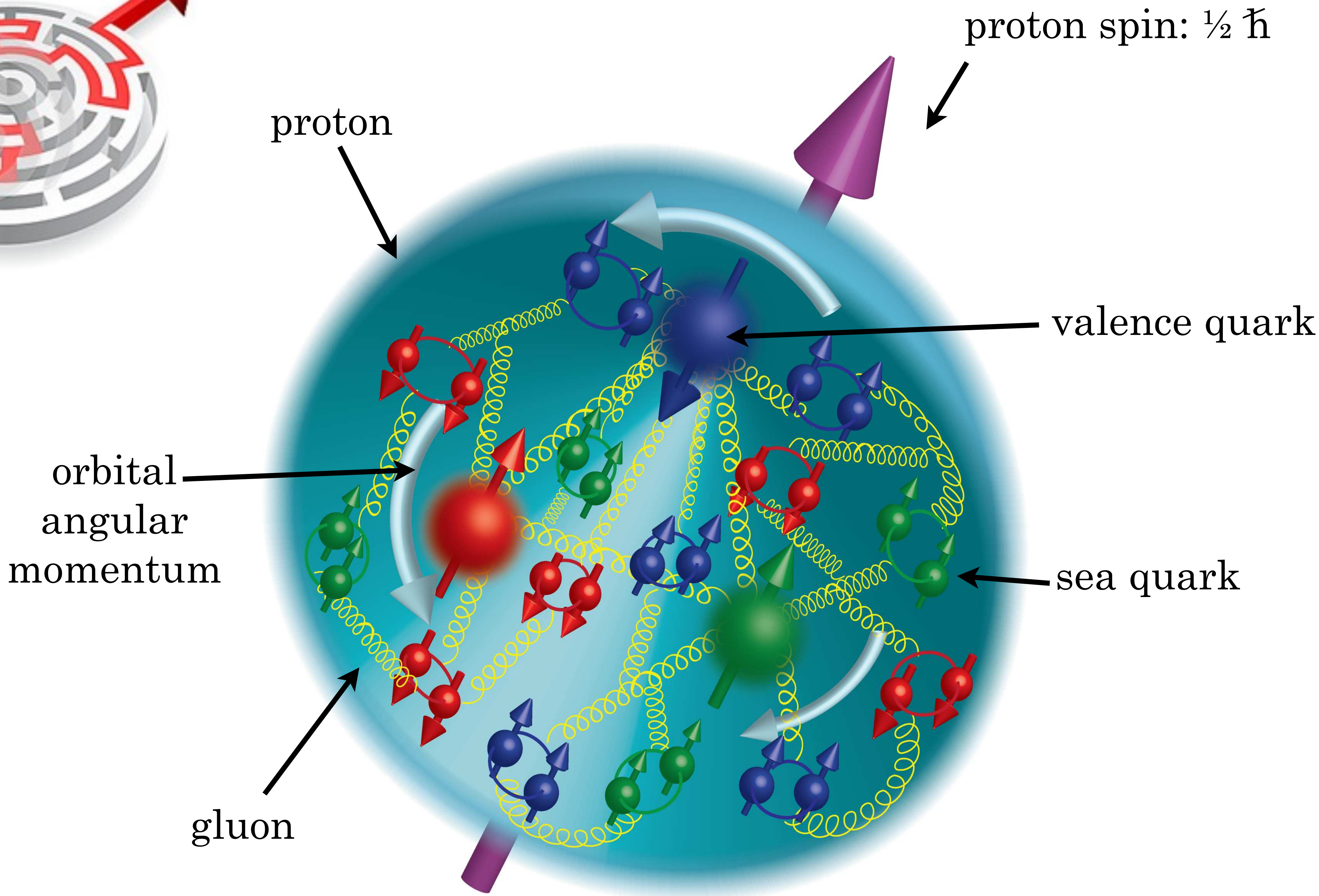
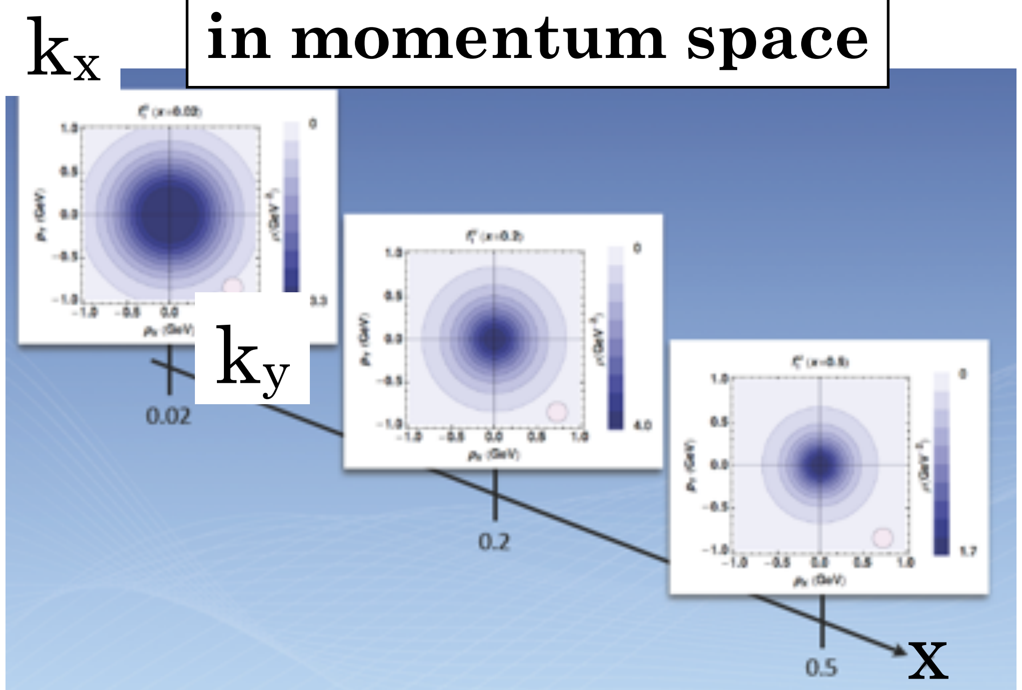


Figure courtesy of: "Electron Ion Collider: The Next QCD Frontier. Understanding the glue that binds us all". arXiv:1212.1701

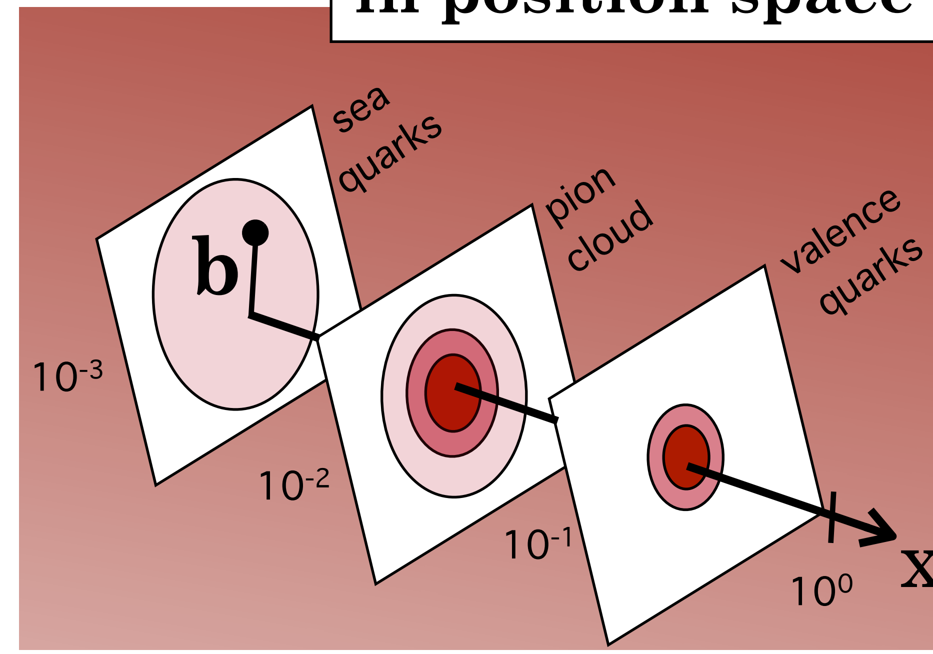
Nucleon tomography

in momentum space



Correlation between spin and transverse momentum

in position space



Correlation between longitudinal momentum and transverse position

Transverse Momentum dependent PDFs

TMDs
$f(x,k_T)$

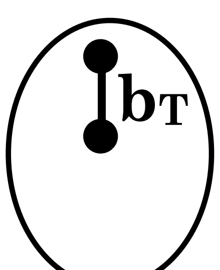
GPDs
$H(x,\xi,t)$

Generalized Parton Distributions

k_T-integration

ξ=0, t=0

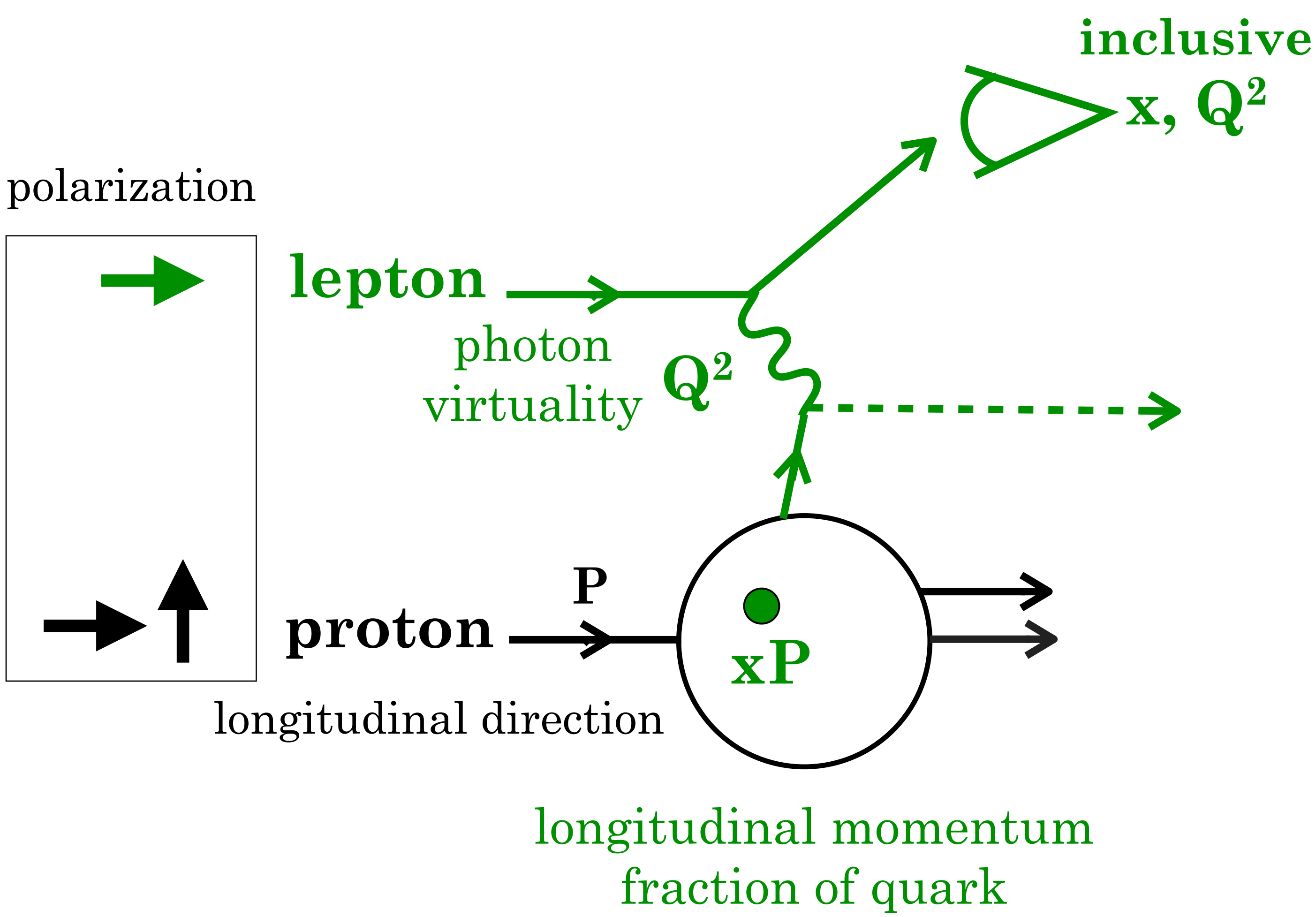
b = impact parameter:
FT(t↔b) ↔
$H(x,\xi=0,b)$
$\mathbf{k_T \equiv 0}$



FT(k_T↔b_T) ↔
$f(x,b_T)$
t≡0

(collinear)
PDFs q(x), 1D

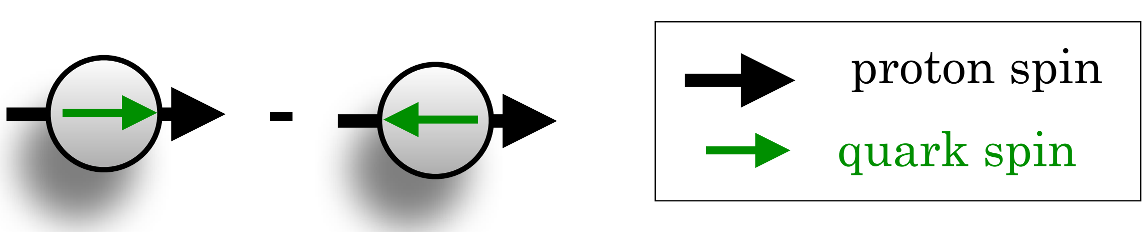
Deep Inelastic Scattering (DIS): $\ell\, N \rightarrow \ell\, (h) X$

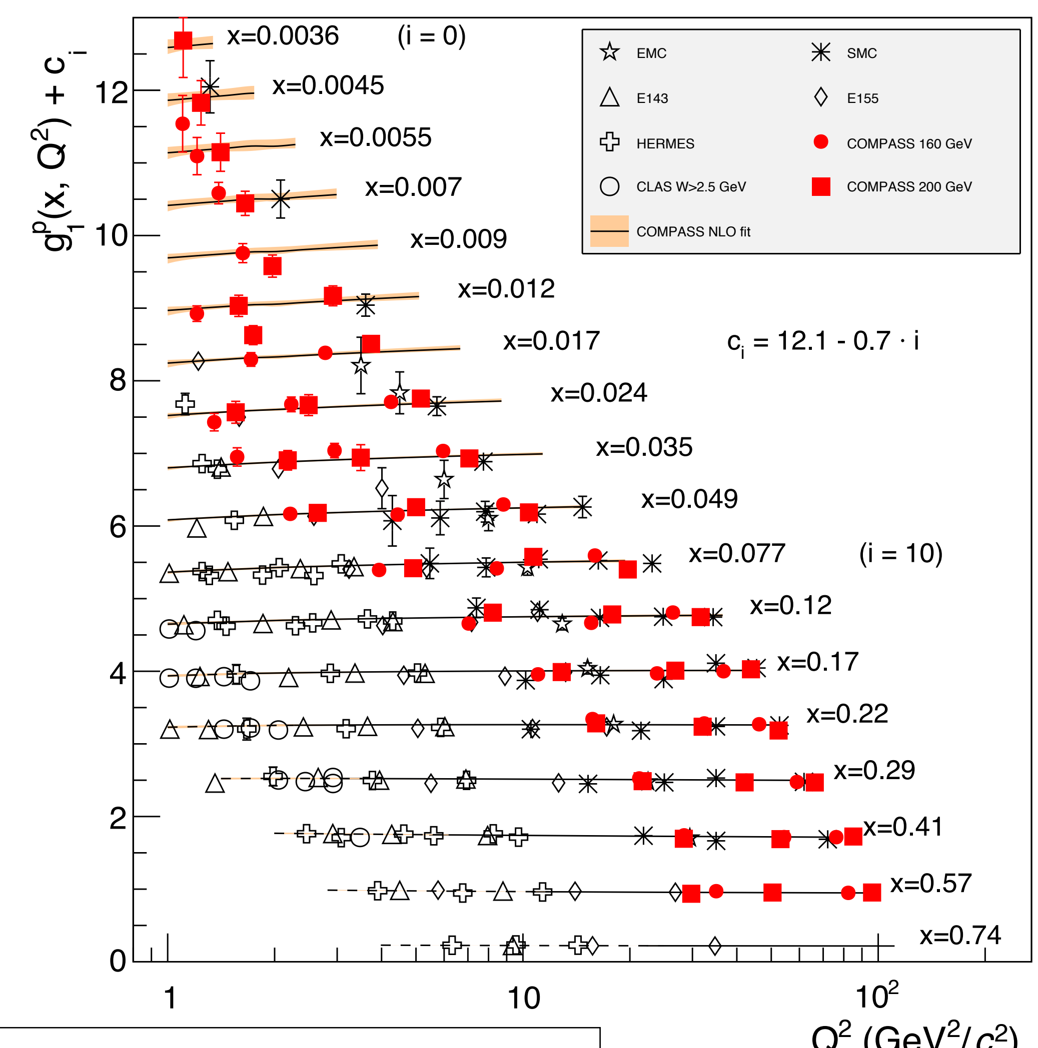


Example: “**spin structure function**”

$$g_1(x, Q^2)$$

Longitudinal momentum- and spin structure of the proton well known.





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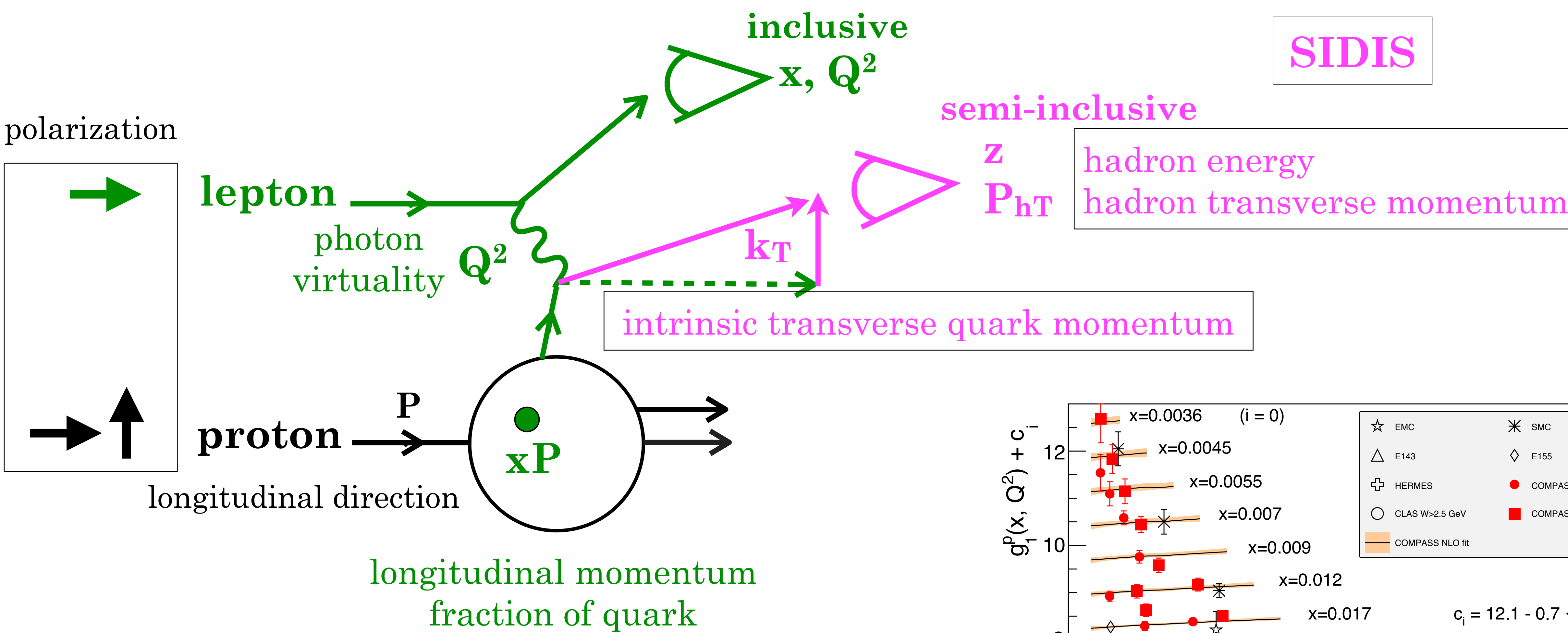
Deep Inelastic Scattering (DIS): ℓ N→ ℓ (h)X



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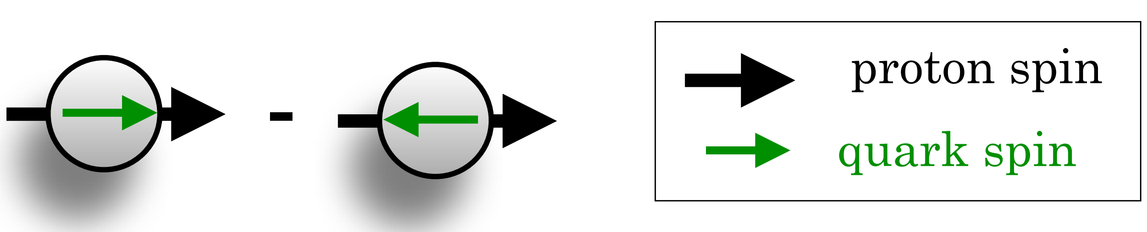

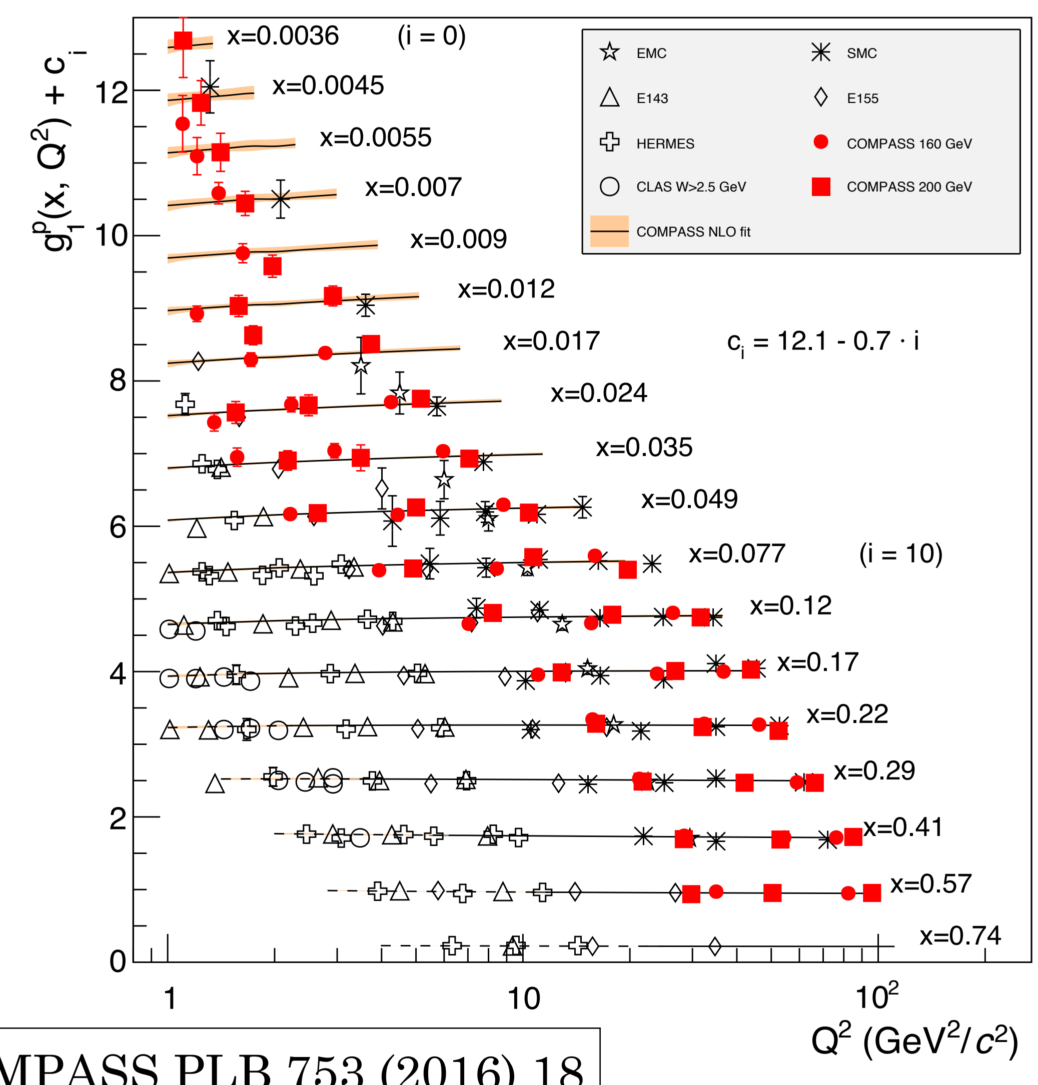

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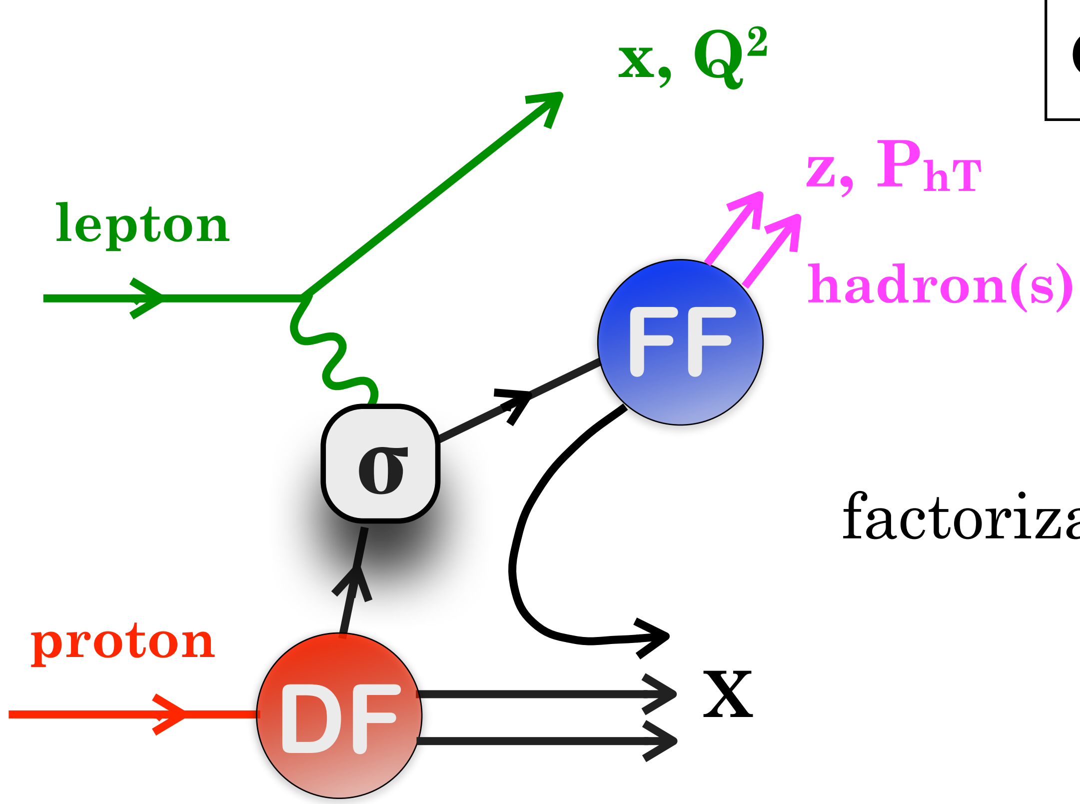
Factorization of DIS cross section



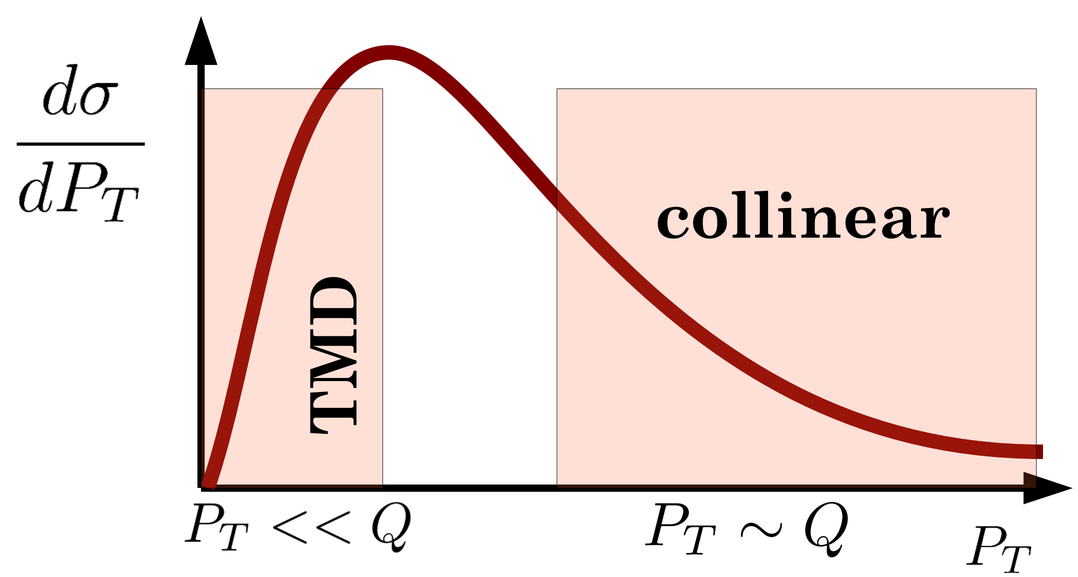
$$\sigma^{\ell p \to \ell h X} = \Sigma_q \left(DF \otimes \sigma^{\ell q \to \ell q} \otimes FF\right)$$

TMD Fragmentation Functions (FF)

factorization -

TMD Distribution Functions (DF)

TMD factorization
2-scale problem
f(x, k_T; Q²)



Collinear factorization
1-scale problem
f(x; Q²)

courtesy Alexei Prokudin 2015/16

The SIDIS cross section: "harmonic(ϕ, ϕ_S)·DF ⊗ FF"

Cahn-effect + BM ⊗ Collins

Worm-gear (Kotzinian-Mulders) ⊗ Collins

BM ⊗ Collins

$$\sigma(\phi,\phi_S) \equiv \frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\, F_{UU}^{\cos\phi} + \epsilon\cos(2\phi)\, F_{UU}^{\cos(2\phi)} + \lambda_e\left[\sqrt{2\epsilon(1-\epsilon)}\sin\phi\, F_{LU}^{\sin\phi}\right] +$$

$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi\, F_{UL}^{\sin\phi} + \epsilon\sin(2\phi)\, F_{UL}^{\sin(2\phi)}\right] + S_L\lambda_e\left[\sqrt{1-\epsilon^2}\, F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi\, F_{LL}^{\cos\phi}\right]$$

$$+|S_T|\Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S)\, F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)\, F_{UT}^{\sin(3\phi-\phi_S)}$$

$$+\sqrt{2\epsilon(1+\epsilon)}\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S)\, F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+|S_T|\lambda_e\left[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)\, F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S)\, F_{LT}^{\cos(2\phi-\phi_S)}\right]\Big\},$$

Sivers ⊗ D1

Worm-gear ⊗ D1

Transversity ⊗ Collins

Pretzelosity ⊗ Collins

- $F_{XY[Z]}$ = structure function. X=beam, Y= target polarization, [Z= virtual-photon polarization]. X, Y ∈ {U, L, T} (Unpolarized, Longitudinally, Transversely)
- λ_e = helicity of the lepton beam
- S_L and S_T = longitudinal and transverse target polarization
- ε = ratio of longitudinal and transverse photon fluxes

Bacchetta et al., JHEP 02, 093 (2007)

TMD(PDF)s

legend *nucleon moves to the right.*

nucleon (**N**) — nucleon spin

unpolarized quark (**Q**) — quark spin

quark k_T

TMDs surviving integration over k_T. "Collinear analysis"

naive time-reversal odd TMDs

N \ Q	U	L	T
U	f_1 number density		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ worm-gear	h_1 transversity; $h_{1T}^\perp$ pretzelosity

chiral odd TMDs

→ **Chiral symmetry breaking** of the QCD nucleon wave function

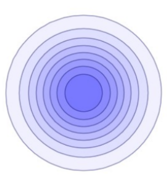
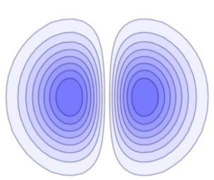
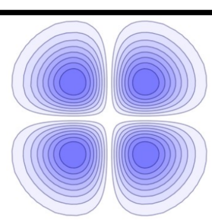
8 **TMD(PDF)s** needed at leading twist description.
Analog table for **fragmentation functions** (capital letters except for UU=D_1)

Flavor indices and kinematic dependences skipped for simplicity.

Proton "orbitals"

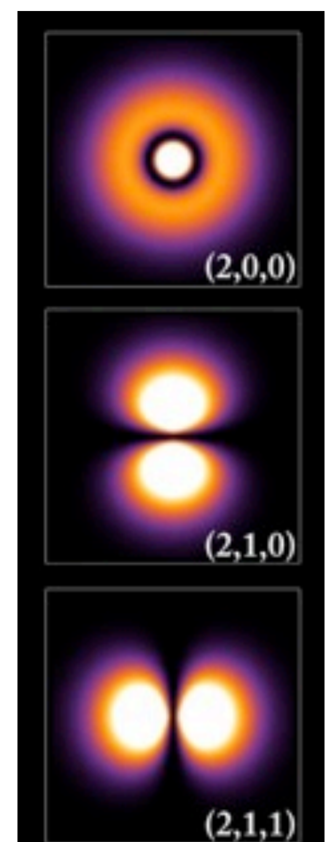
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Courtesy A. Prokudin.

Modulation		proton waves
	monopole	S
	dipole	S, P interference
	quadrupole	D

- Understand the bound system and its excitation levels.
- Spin-orbit correlations in QCD similar to those in QED (H-atom).
- "Proton (hyper)fine structure"

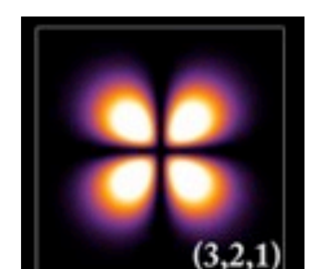
H-atom wave function



$\psi_{\mathrm{nlm}}(r, \theta, \phi)$

orbital angular momentum

spin



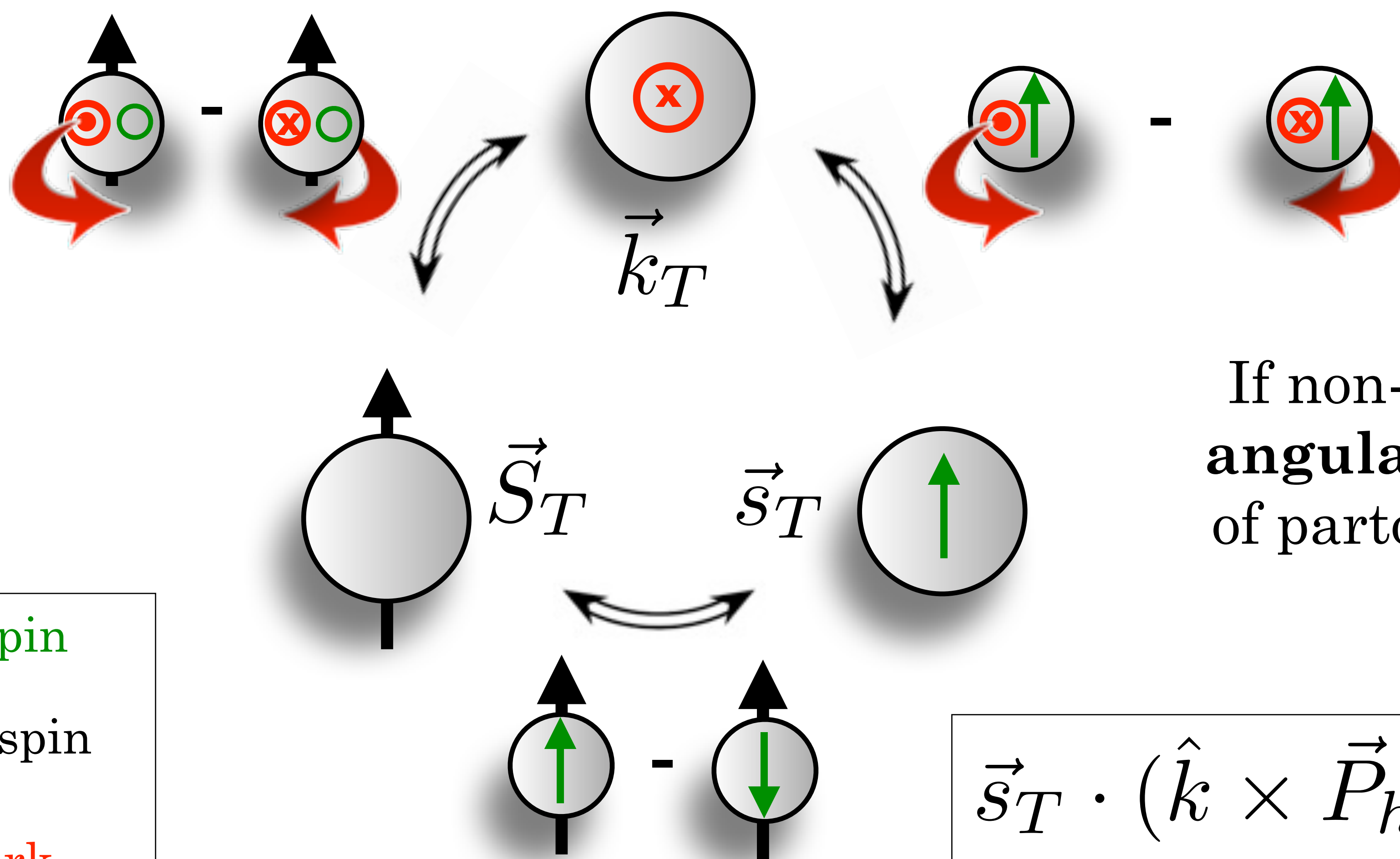
Reversal of spin- and momentum vectors only

Naive time-reversal odd TMDs

Describe strength of **spin-orbit correlations** $\vec{S} \cdot (\vec{p_1} \times \vec{p_2})$ ← no Lorentz vector under T-odd

$\vec{S}_T \cdot (\widehat{P} \times \vec{k}_T)$ — Sivers function

$\vec{s}_T \cdot (\widehat{P} \times \vec{k}_T)$ — Boer-Mulders function



If non-zero: indicate **orbital angular momentum (OAM)** of partons inside the nucleon.

$\vec{s}_T$ quark spin

$\vec{S}_T$ nucleon spin

quark transv. mom.

$\vec{k}_T$ $\widehat{P}$ (longitudinal direction)

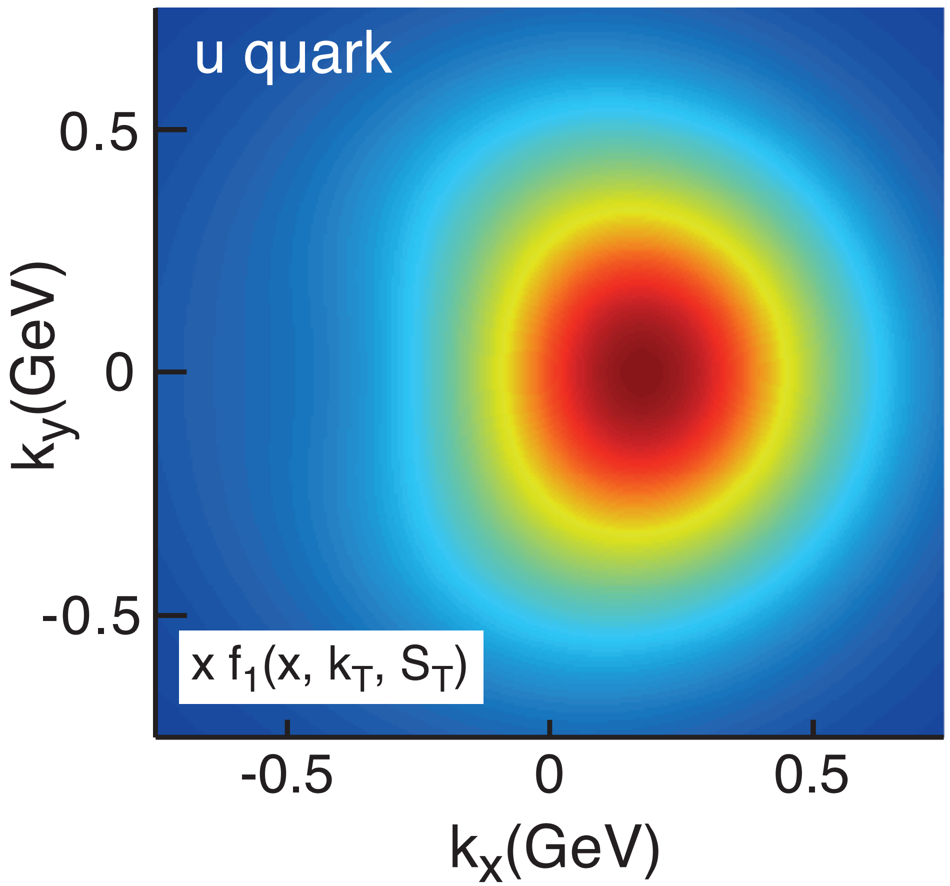
Transversity ⊗ $\vec{s}_T \cdot (\hat{k} \times \vec{P}_{hT})$ Collins function = chiral-even factor in cross section

chiral-odd PDF (spin-spin correlation)

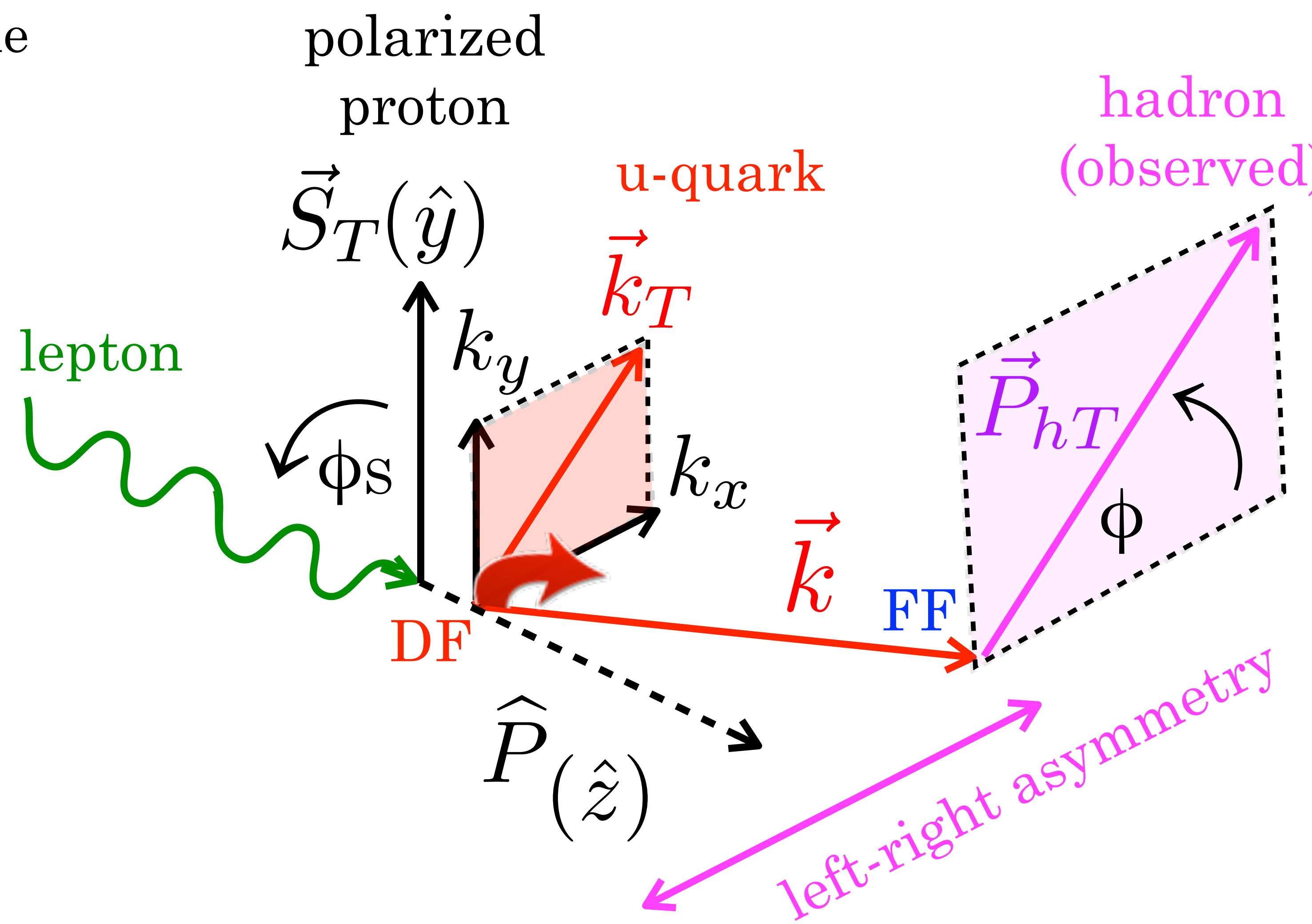
chiral-odd FF

What is measured?

Sivers effect generates distorted distribution of unpolarized quarks in the transversely polarized proton.



EIC "White Paper" arXiv:1212.1701, based on M. Anselmino et al., J. Phys. Conf. Ser. 295, 012062 (2011), arXiv:1012.3565



$$A_{\mathrm{UT}}(\phi) = \frac{1}{f S_T} \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)}$$

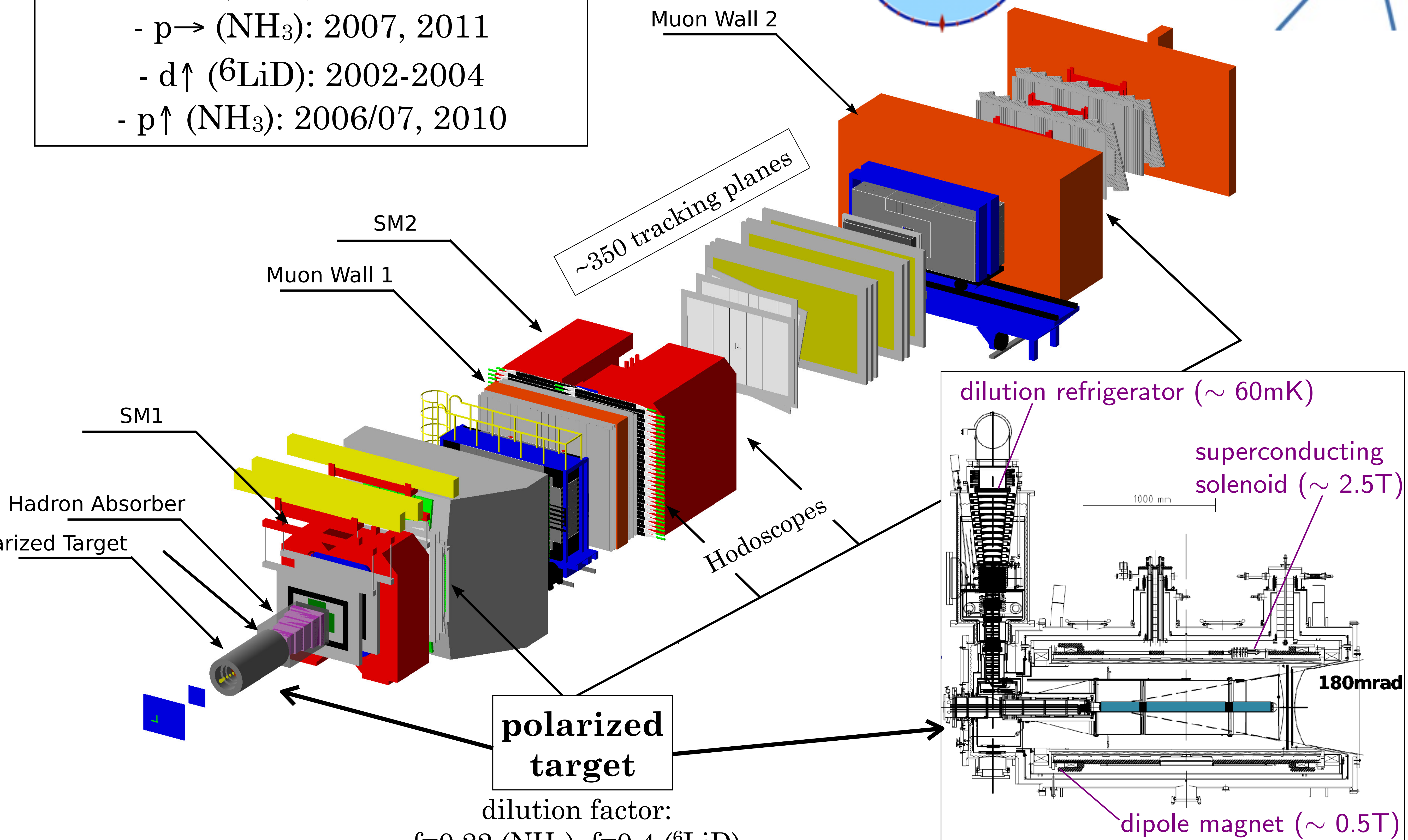
Spin-orbit correlations $\vec{S} \cdot (\vec{p_1} \times \vec{p_2})$

induce observable single-spin asymmetries. Different harmonic modulation for each TMD, e.g. sin(ϕ-ϕs)

SIDIS: polarized muon beams of 160/200 GeV on solid targets

- d→ (^{6}LiD): 2002-2006
- p→ (NH_3): 2007, 2011
- d↑ (^{6}LiD): 2002-2004
- p↑ (NH_3): 2006/07, 2010

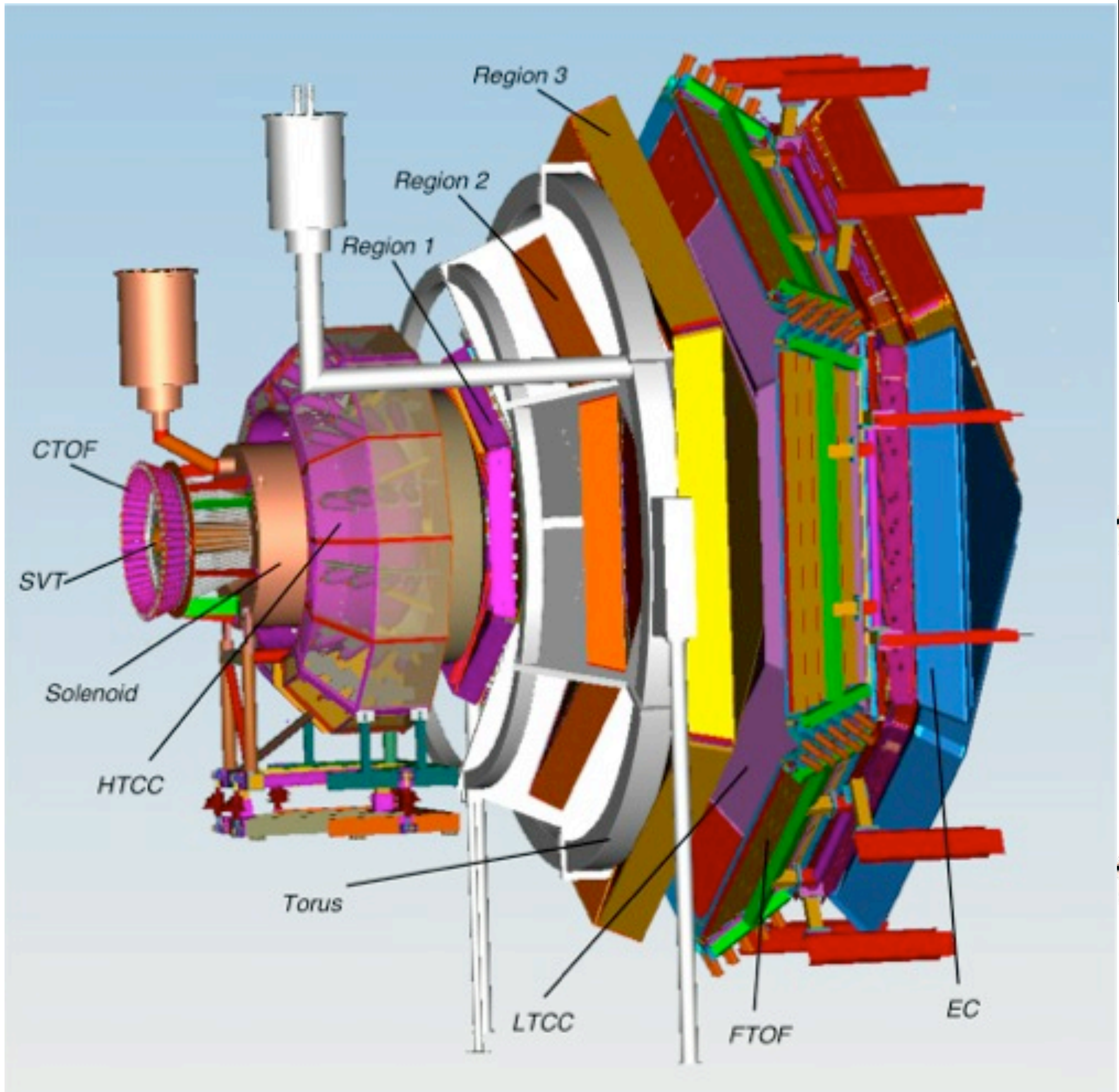
COMPASS at CERN



polarized target

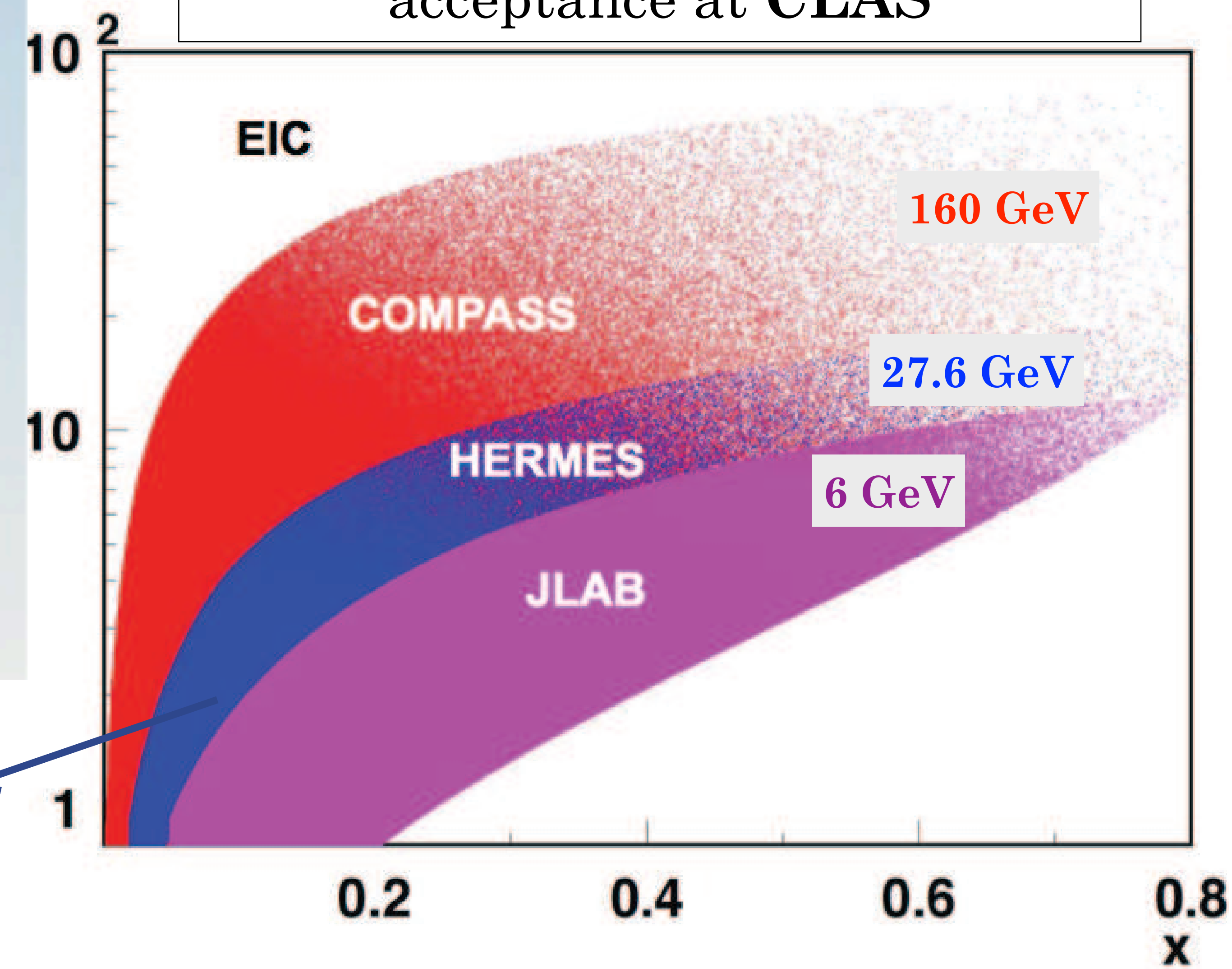
dilution factor:
f=0.22 (NH_3), f=0.4 (^{6}LiD)

at Hall B / Jefferson Lab



- Polarized electrons of 6 / 11 GeV
- Unpolarized and longitudinally polarized targets (2001 / 2005 / 2009)
- Transversely polarized target (CLAS12)
- Lumi ~$10^{34}cm^{-2}sec^{-1}$

Hall A at JLab complementary: very high luminosity vs. very large acceptance at **CLAS**

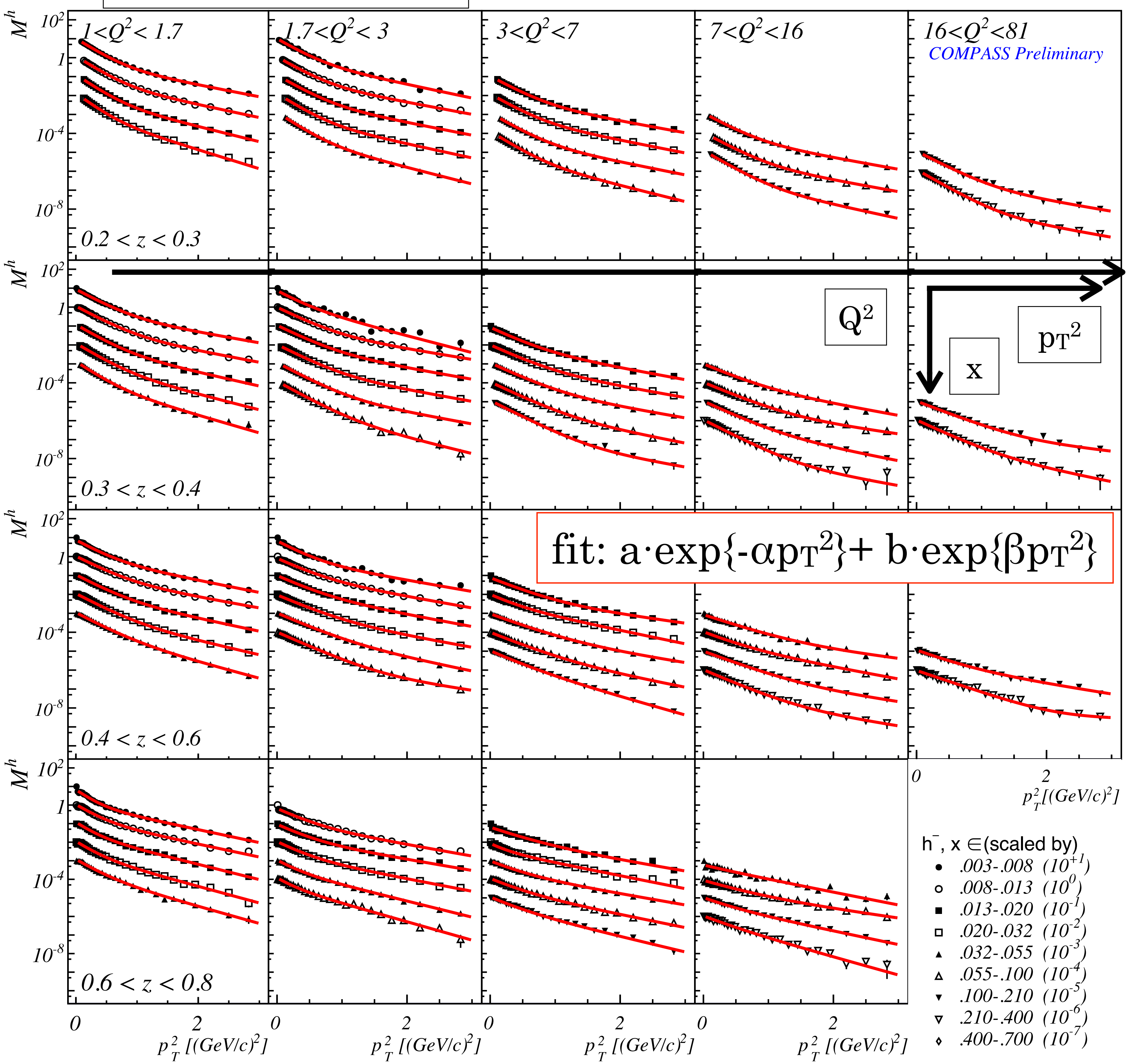


HERMES: spin experiment at HERA/ DESY 1995-2007, polarized electrons of 27.6 GeV on (un)polarized gas targets

p_T^2-dependent hadron multiplicities

negative hadrons (*positive hadrons not shown*)

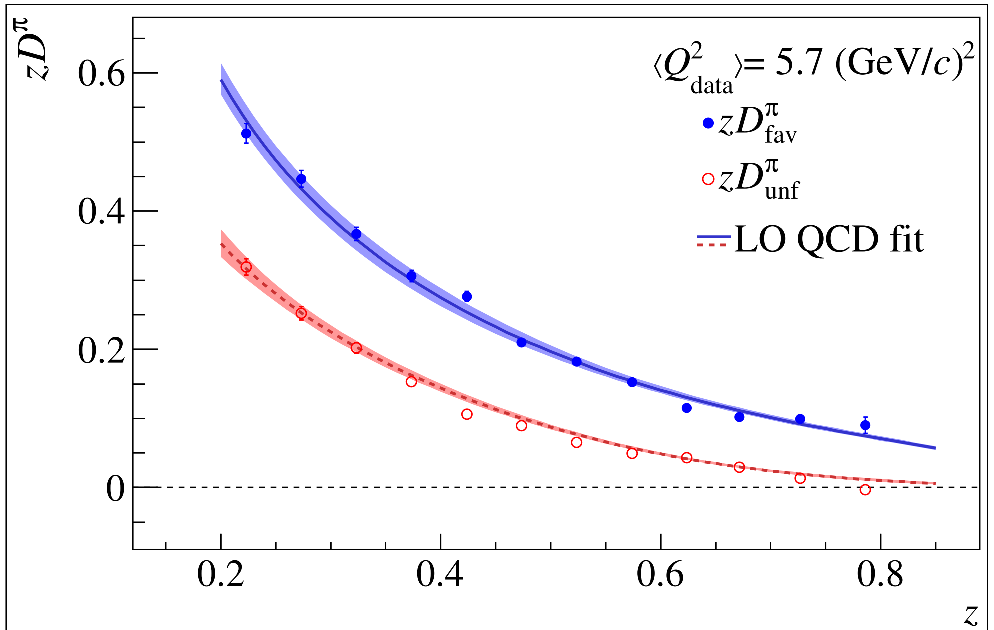
COMPASS d



$$\frac{dN^h}{dN^{DIS}} \propto \sum_q e_q^2 q D_q^h$$

Flavor dependence of spin-independent TMD distribution and fragmentation functions. In total 4,918 data points. Valuable input for TMD evolution studies.

At high-x and high-z:
$h^+ > h^- \Rightarrow D_u^{\pi^+} > D_u^{\pi^-}$



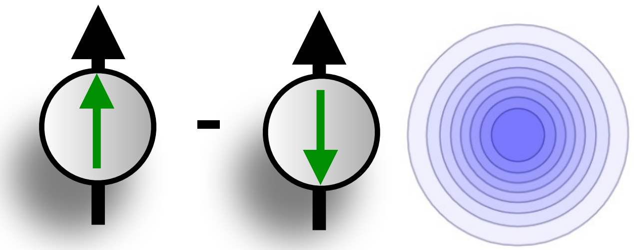
From: differential multiplicities for $\pi^+\pi^-$ and h^+h^- binned in x, y, z.

COMPASS hep-ex/1604.02695, submitted to PLB.

not (yet) corrected for diffractive vector mesons

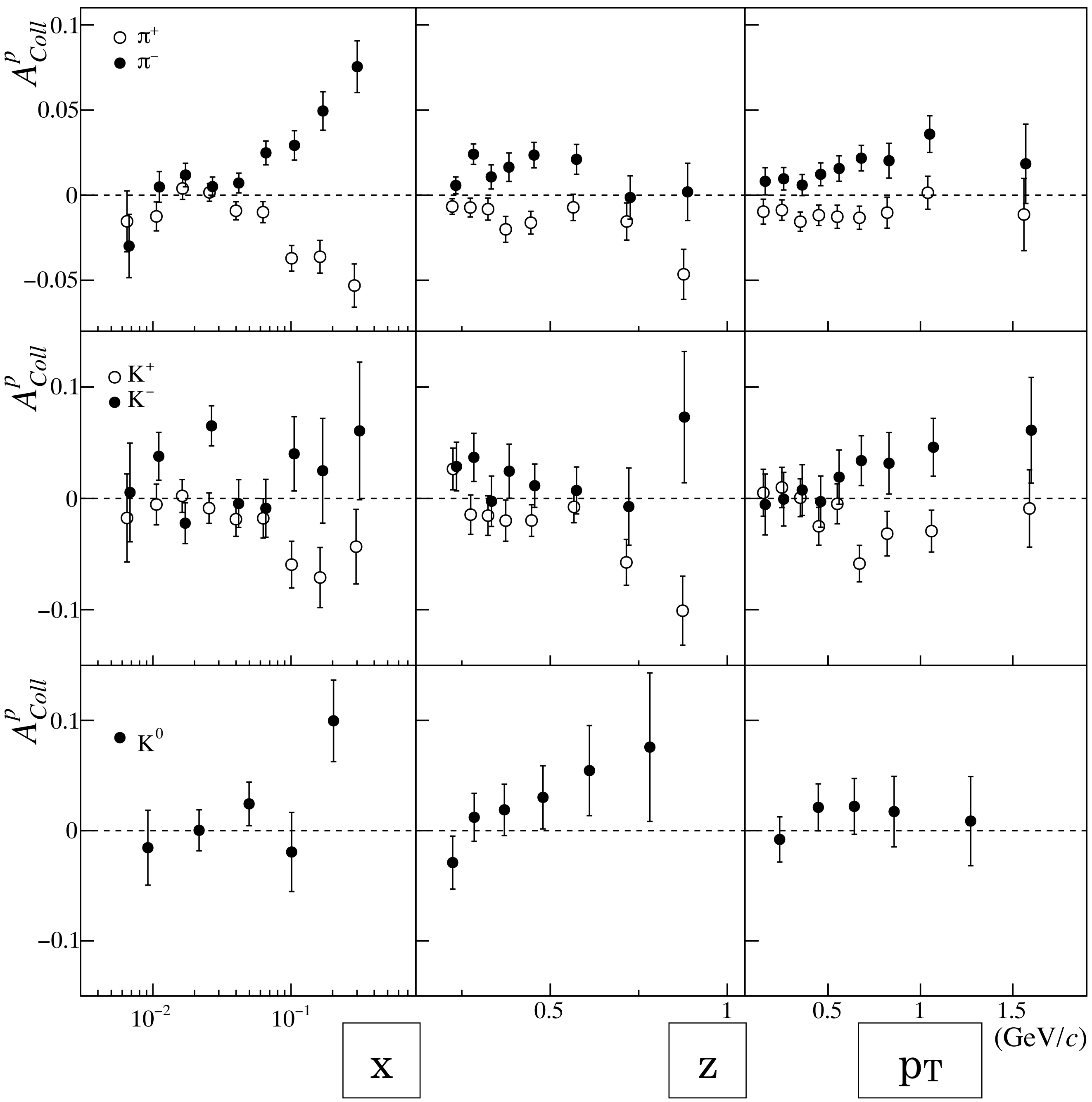
Collins asymmetry

Transversity ⊗ Collins



$\ell\, N^{\uparrow} \rightarrow \ell\, hX$

COMPASS p↑



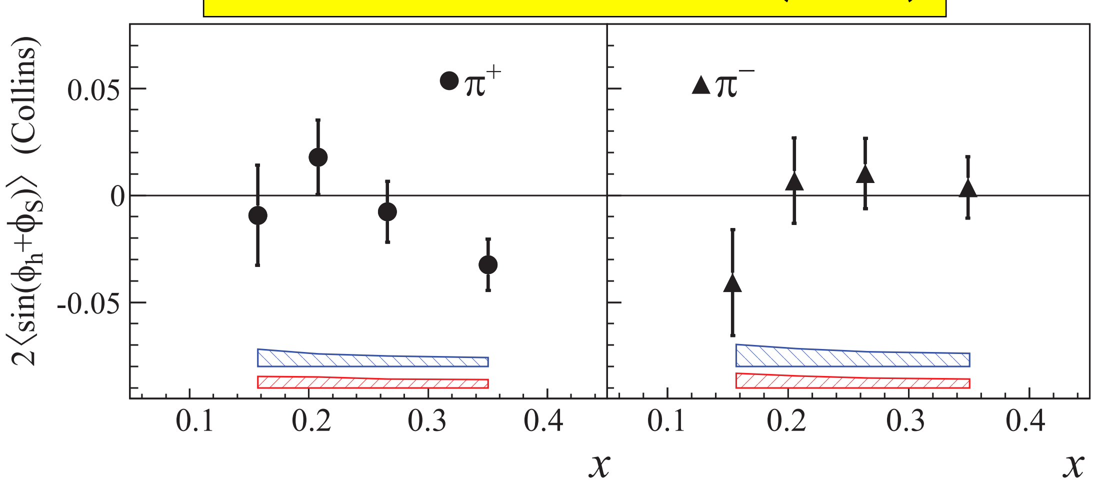
COMPASS PLB 744 (2015) 250 (this plot)

HERMES PLB 693 (2010) 11 (not shown) **HERMES p↑**

Collins Fragmentation Function describes spin-dependent hadronization of a transversely polarized quark into hadrons.

- $\pi^+ <0$, $\pi^- >0$. → favored ($u \rightarrow \pi^+$, $d \rightarrow \pi^-$) & unfavored ($u \rightarrow \pi^-$, $d \rightarrow \pi^+$) Collins FF of similar size but opposite sign.
- HERMES similar
  → no evolution effect (no Q^2 dependence)
- COMPASS d↑ & Hall-A ^{3}He: null
- e+e– collider (BELLE and BABAR): confirm trend

Hall-A neutrons (^{3}He)

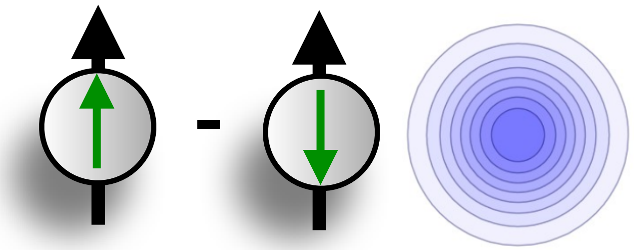


(kaons not shown)

Hall A PRL 107 (2011) 072003

Collins asymmetry

Transversity ⊗ Collins



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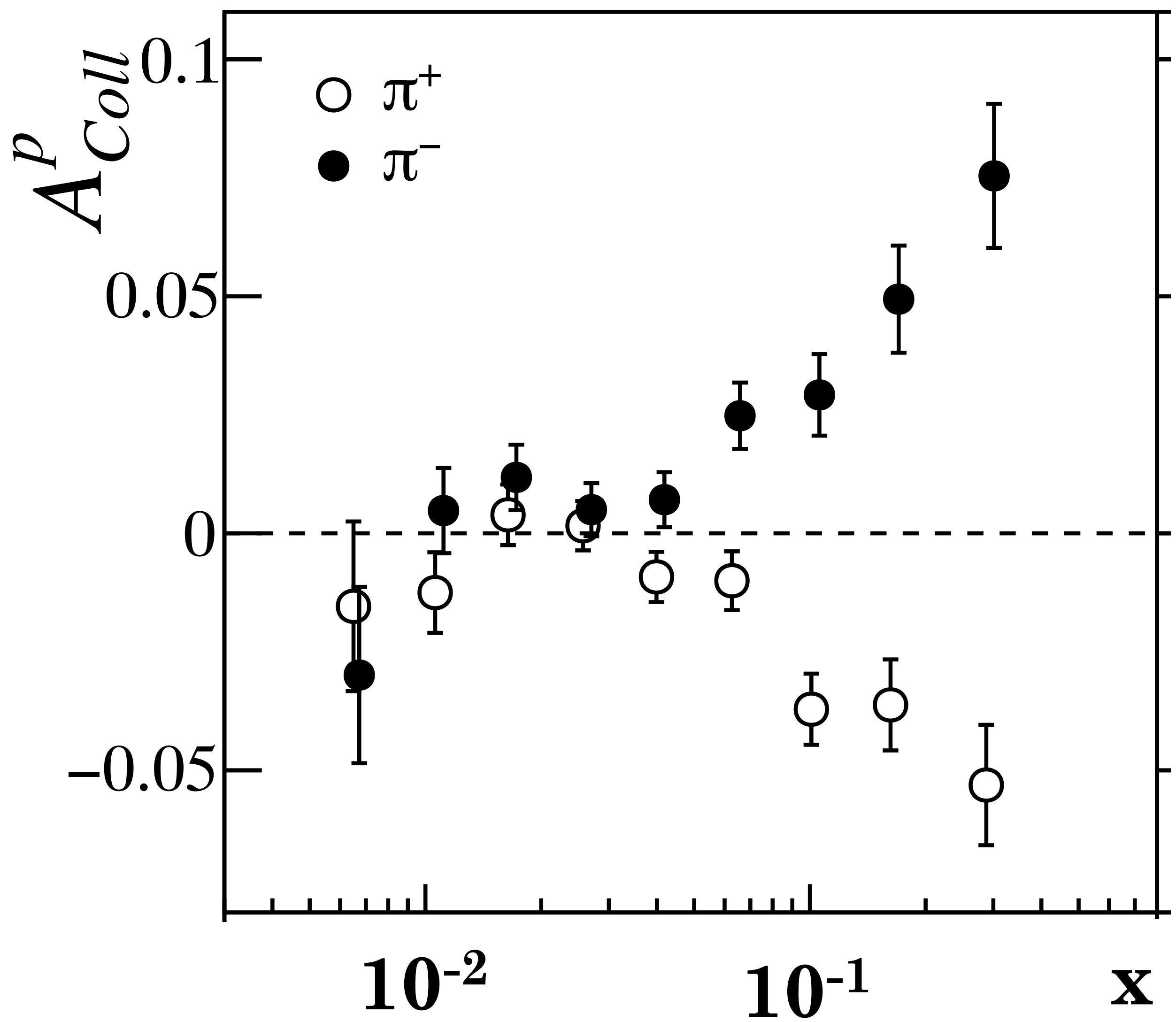
COMPASS p↑



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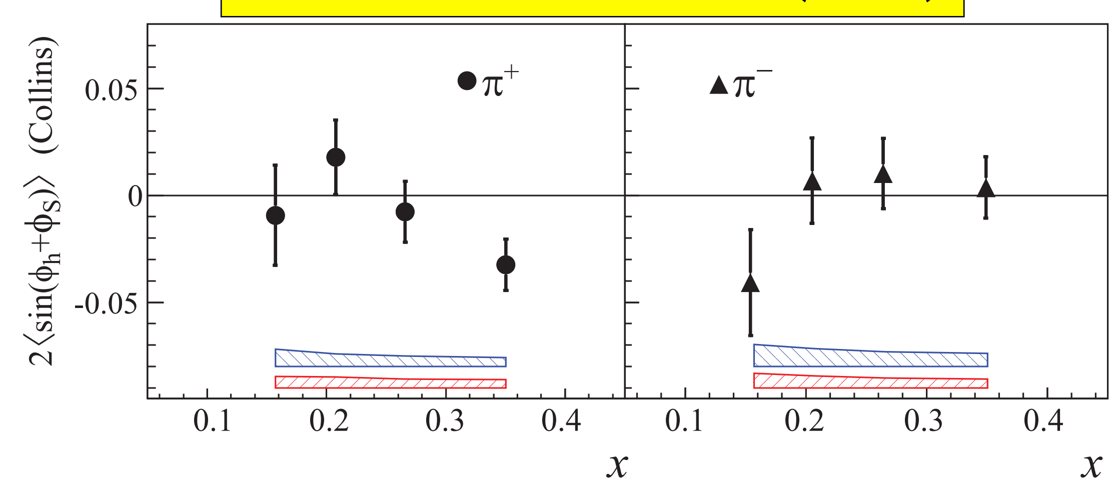


COMPASS PLB 744 (2015) 250 (this plot)

HERMES PLB 693 (2010) 11 (not shown) **HERMES p↑**

(kaons not shown)

Hall A PRL 107 (2011) 072003

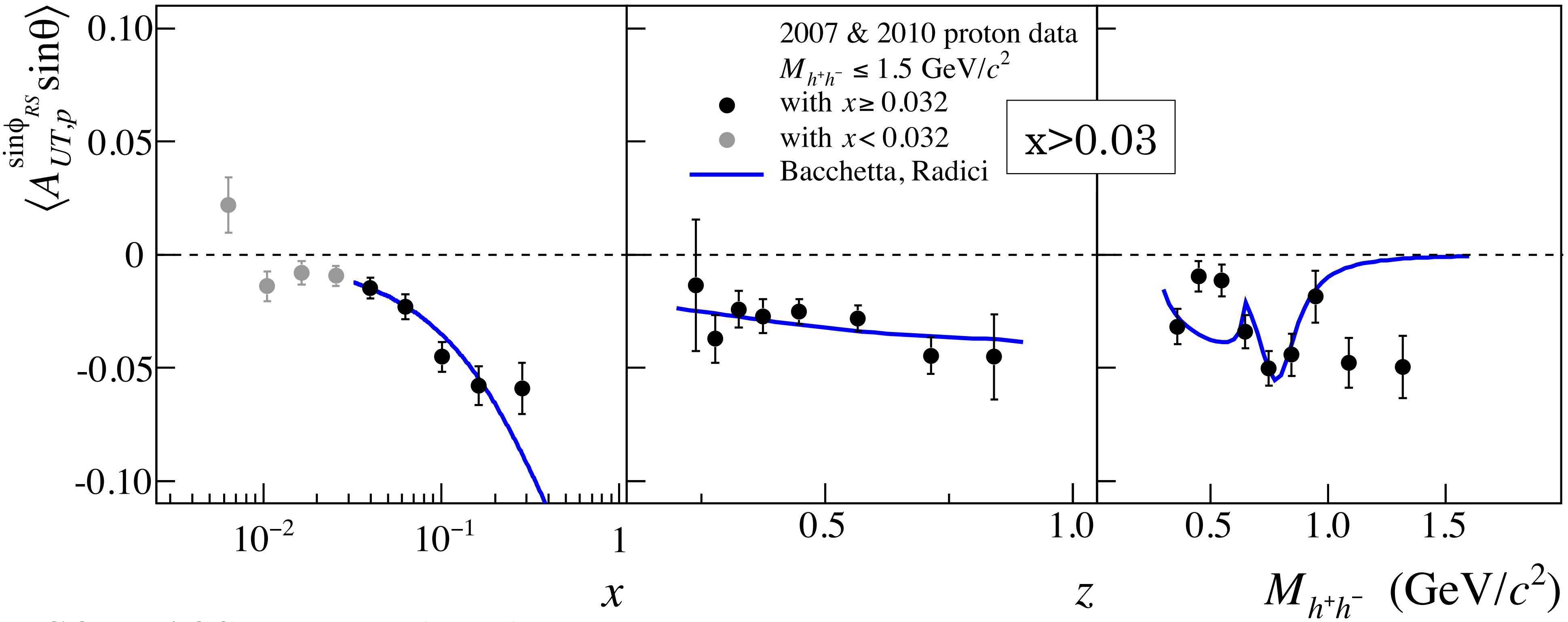
Di-hadron asymmetry

Transversity ⊗ Interference FF

(collinear analysis - no quark k_T)

$\ell\, N^{\uparrow} \rightarrow \ell\, h^+ h^- X$

COMPASS p↑

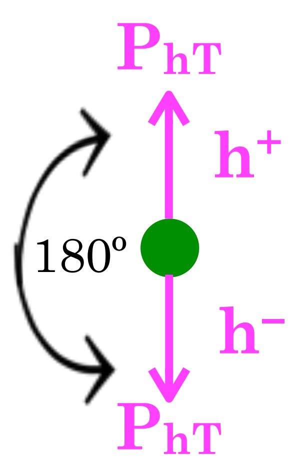


Di-hadron-, or interference FF from interference of different channels of the fragmentation process into the two-hadron system.

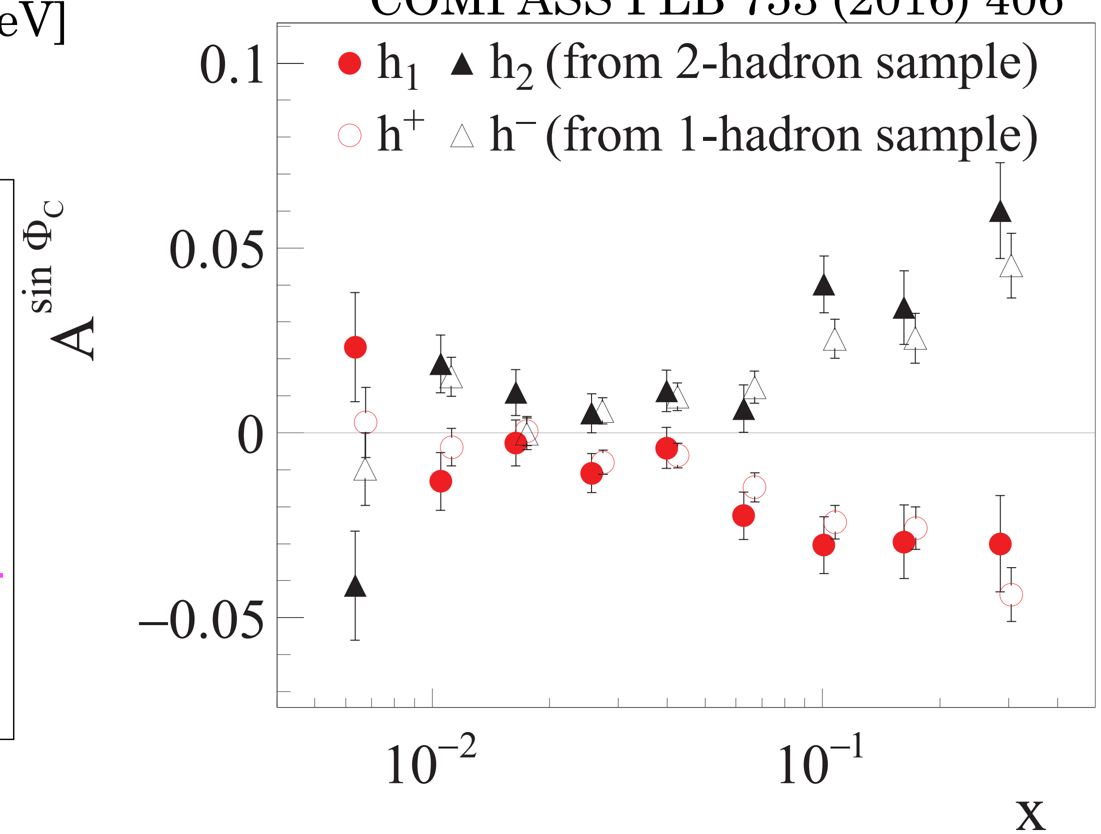
COMPASS PLB 736 (2014) 124

Solid curve: Bacchetta, Radici priv. comm. &
M. Anselmino et al., Nucl. Phys. Proc. Suppl. 191 (2009) 98–107.

- Interference FF ≈ ½·(Collins[h^+] + (-1)·Collins[h^-])
- Hint at a common physical origin for the Collins mechanism & di-hadron fragmentation function

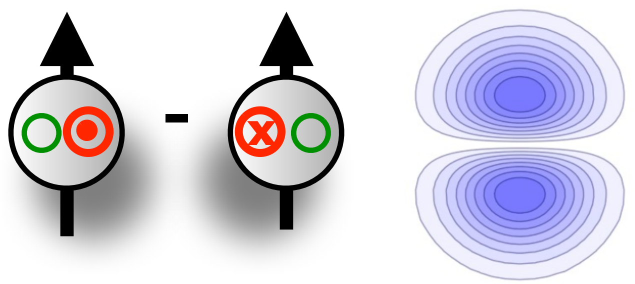


COMPASS PLB 753 (2016) 406

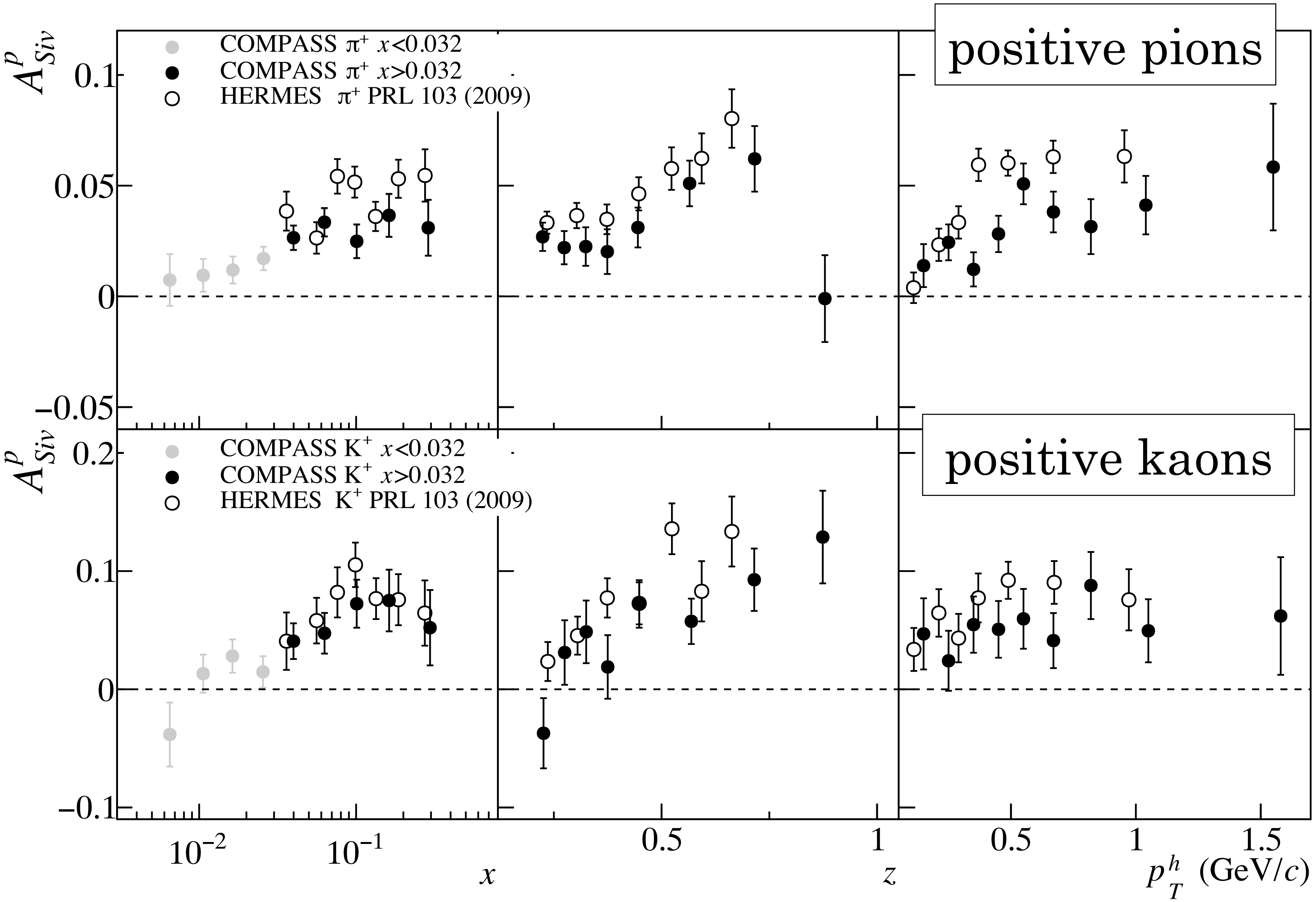


Sivers asymmetry in SIDIS

Sivers ⊗ D1



COMPASS, HERMES p↑



$$\simeq -f_{1T}^{\perp}(x, p_T^2) \otimes D_1^{u\to\pi^+}(z, k_T^2)$$

negative u-quark Sivers function

Null result for negative pions & kaons: **positive d-quark Sivers function**

pion (u,anti-d) < kaon (u, anti-s)
"Role of sea quarks non-negligible?"

● COMPASS PLB 744 (2015) 250

○ HERMES PRL 103 (2009) 152002

Sivers (COMPASS) < Sivers (HERMES): non-trivial Q2-dependence

COMPASS d↑

Null result (u/d-quark cancellation effects)

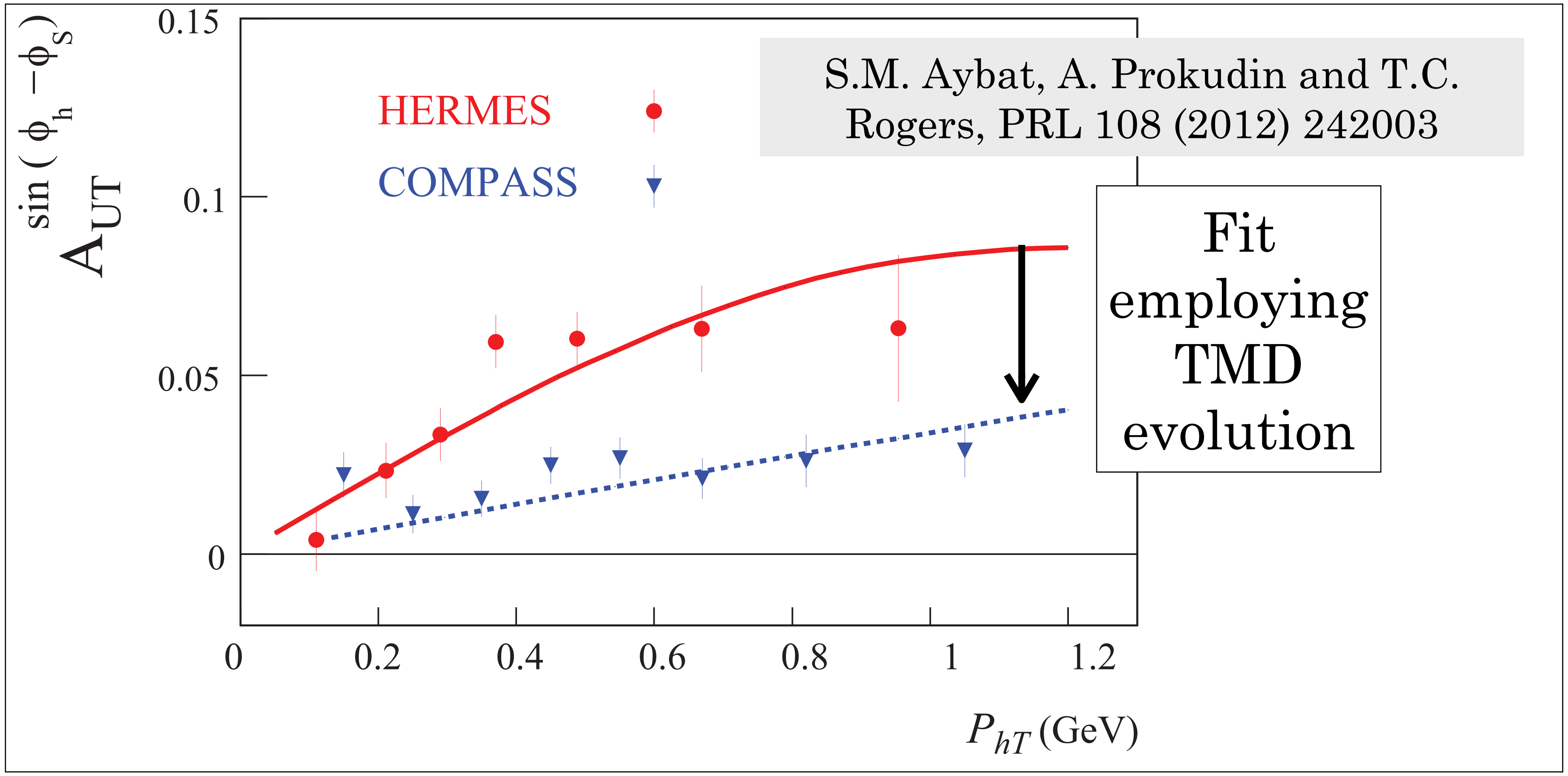
COMPASS Nucl. Phys.B765 (2007) 31

Hall-A neutrons (^{3}He)

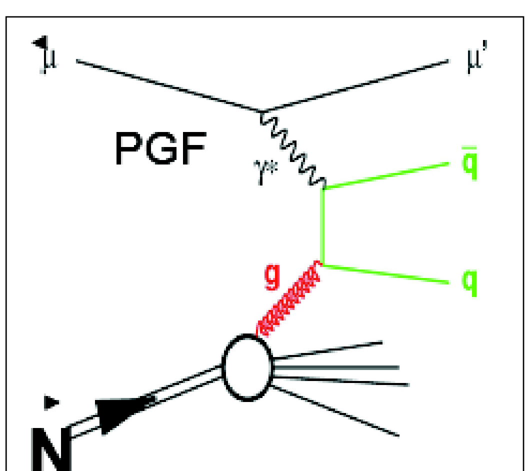
Sivers from positive pions off neutron target negative => d-quark Sivers negative

Hall A Collaboration PRL 107 (2011) 072003

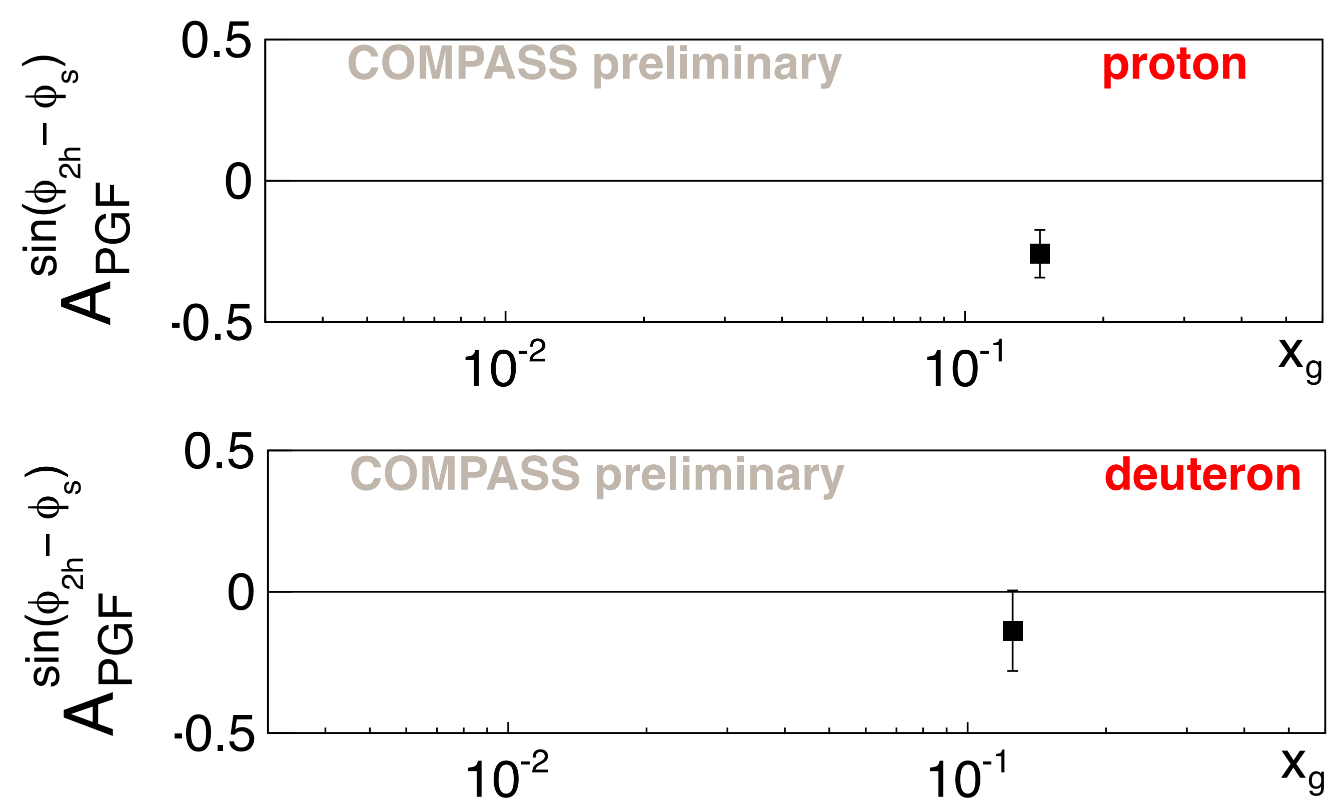
Sivers asymmetry



COMPASS gluon Sivers
from photon-gluon fusion →
experimental signature: 2 high-p_T hadrons

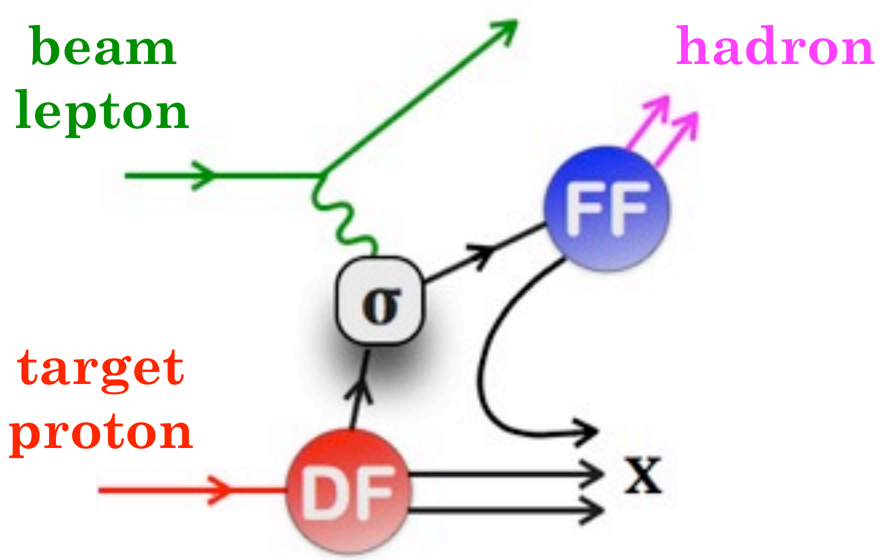


On proton target: Sivers asymmetry negative $A_{PGF}^{\sin(\phi_{2h}-\phi_s)}$ = -0.26+-0.09(stat.) +-0.08(syst.) at <x_g>=0.15



Spin-dependent Drell-Yan measurement at COMPASS

SIDIS

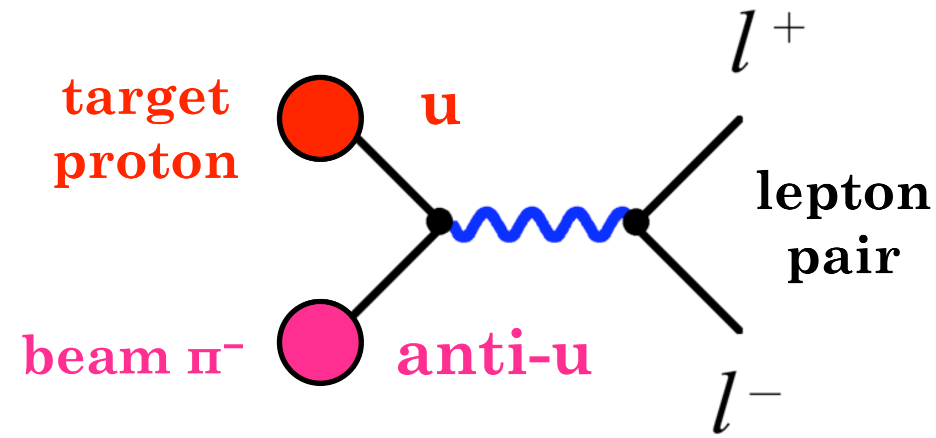


DF ⊗ FF

Universality: naive time-reversal-odd TMDs are expected to have the **same magnitude** but **opposite sign** in DY. Crucial test of TMD framework.

Sivers (SIDIS) = –(1)·Sivers (DY)

Drell-Yan



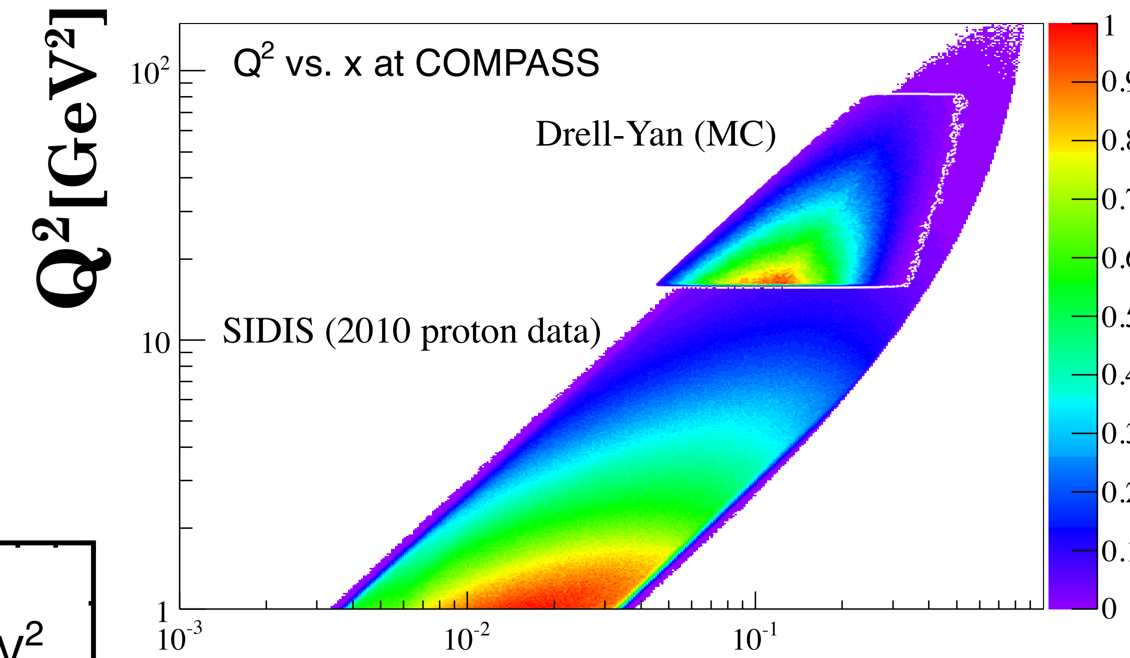
DF ⊗ DF

proton		pion	
$(BM)_p$	⊗	$(BM)_\pi$	first access
$(Sivers)_p$	⊗	$(f_1)_\pi$	
$(Pretzelosity)_p$	⊗	$(BM)_\pi$	
$(Transversity)_p$	⊗	$(BM)_\pi$	

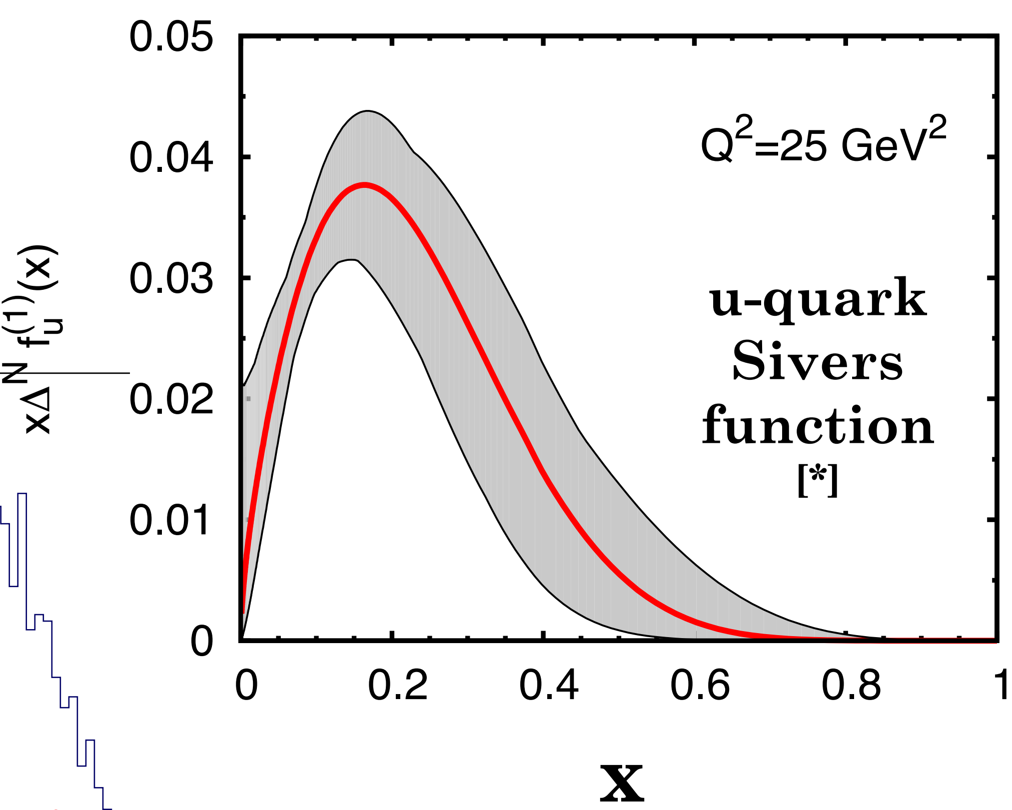
- First spin-dependent DY measurement. **2015 COMPASS results** soon to come! 2nd year of COMPASS polarized DY planned for 2018.
- STAR at RHIC/BNL: Sivers amplitude in W^{+-}/Z^0 production PRL 116, 132301 (2016): "The current data thus favor theoretical models that include a change of sign for the Sivers function relative to […] SIDIS measurements, if TMD evolution effects are small."
- SeaQuest at FNAL: DY w/ polarized target 2018/19

Phase space of COMPASS Drell-Yan data

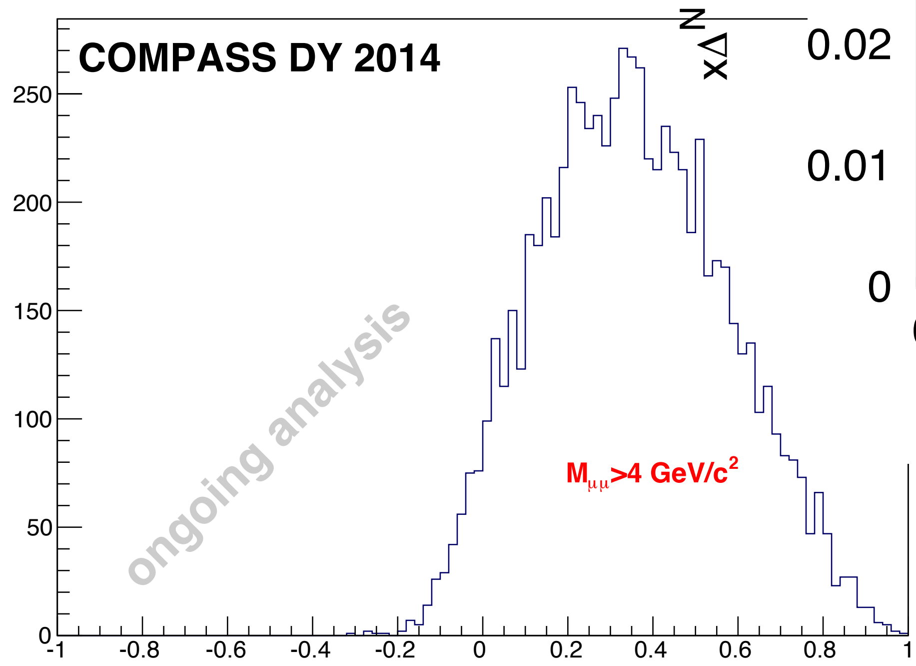
- Unique possibility of measuring **SIDIS** and **Drell-Yan** observables **at the same facility.**
- No need to rely on **uncertainties of TMD evolution.**
- π- on proton probes **valence-quark region** ☛ Sivers function of large magnitude.



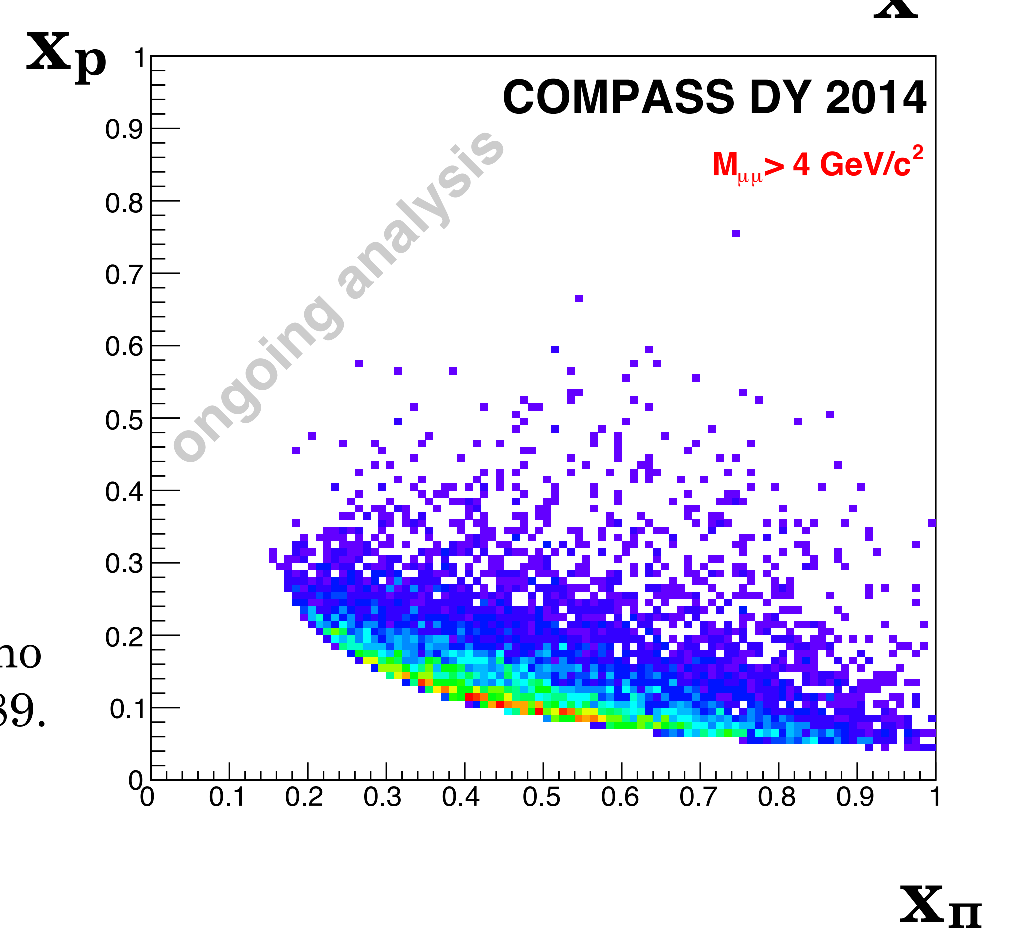
x



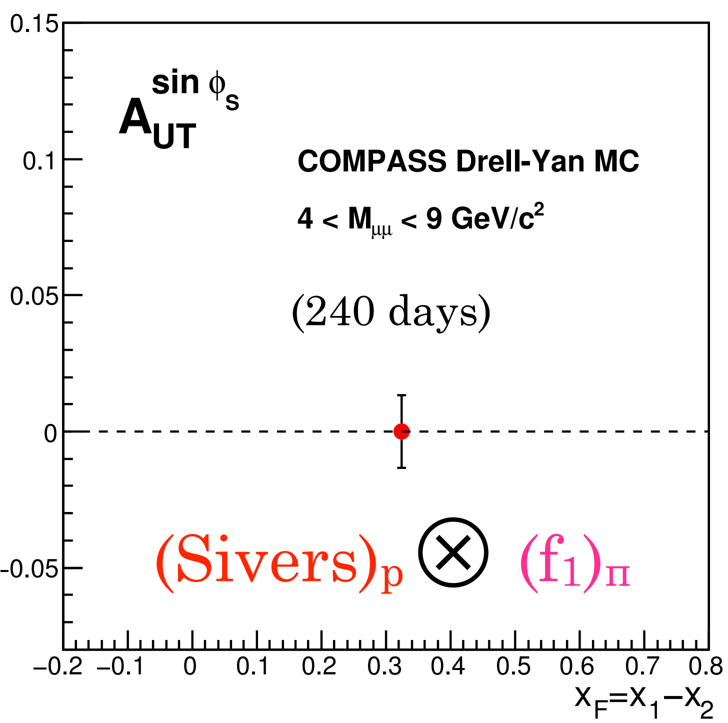
[*] calculated from: M. Anselmino et al., Eur. Phys. J. A39 (2009) 89.

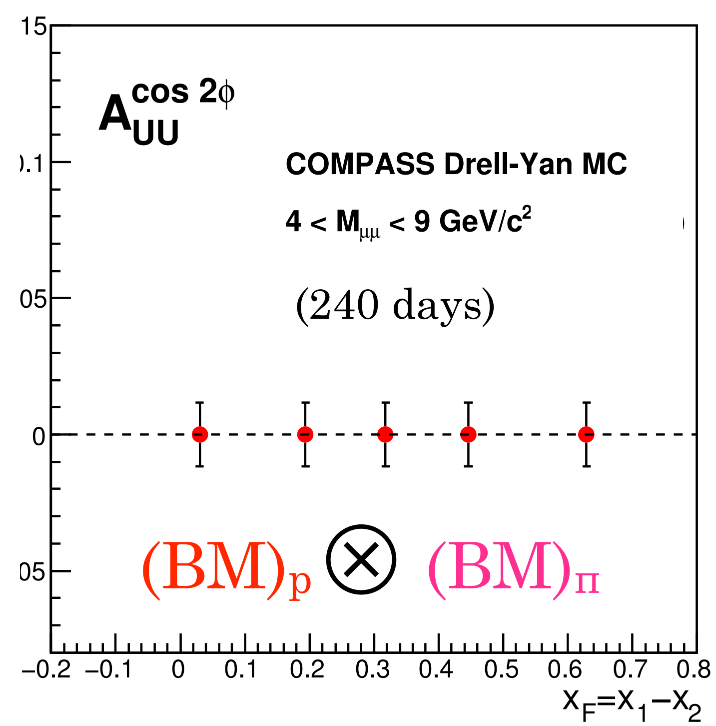


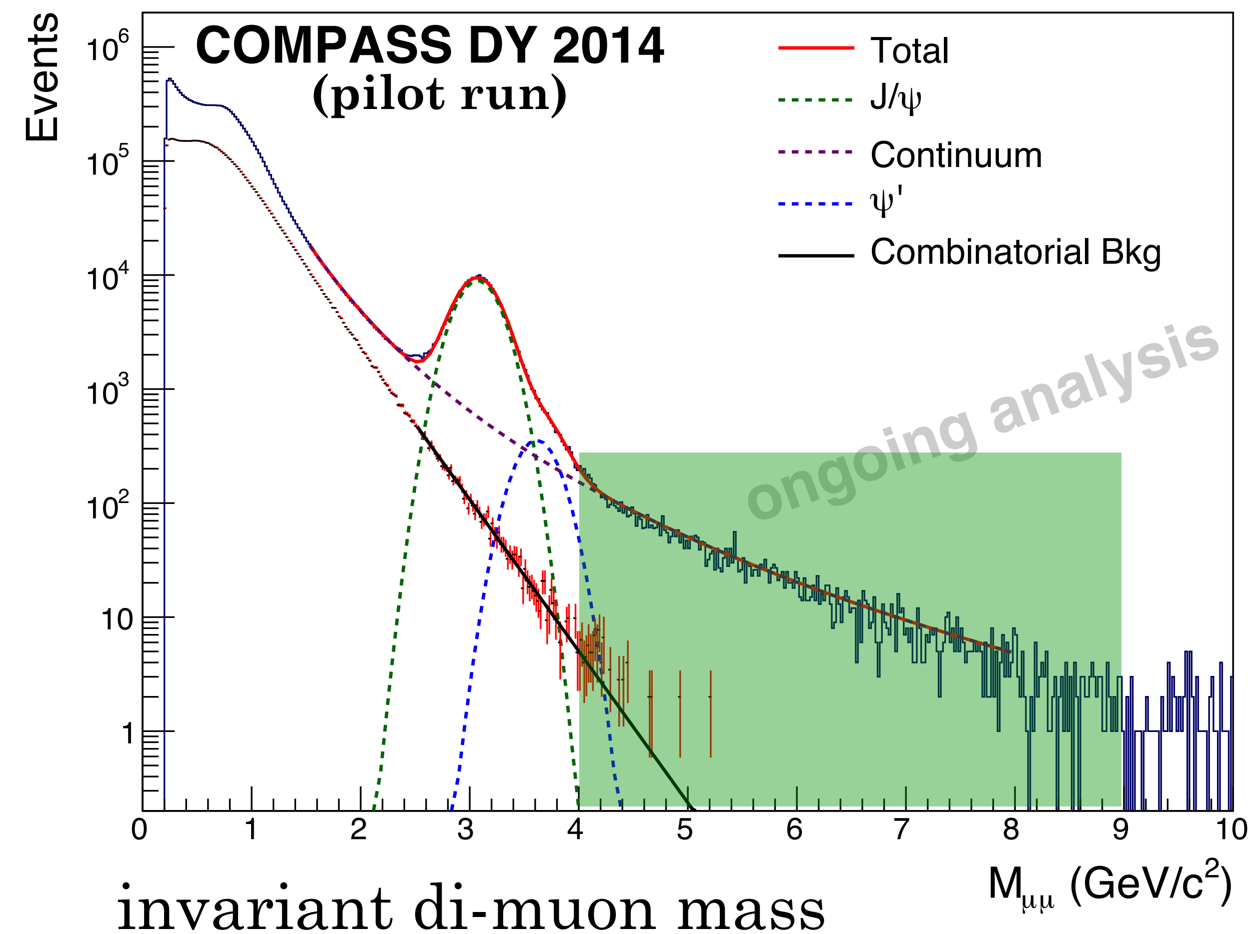
-0.2 0 $x_F = x_\pi - x_p$ 1



COMPASS projections (2015+2018 data)

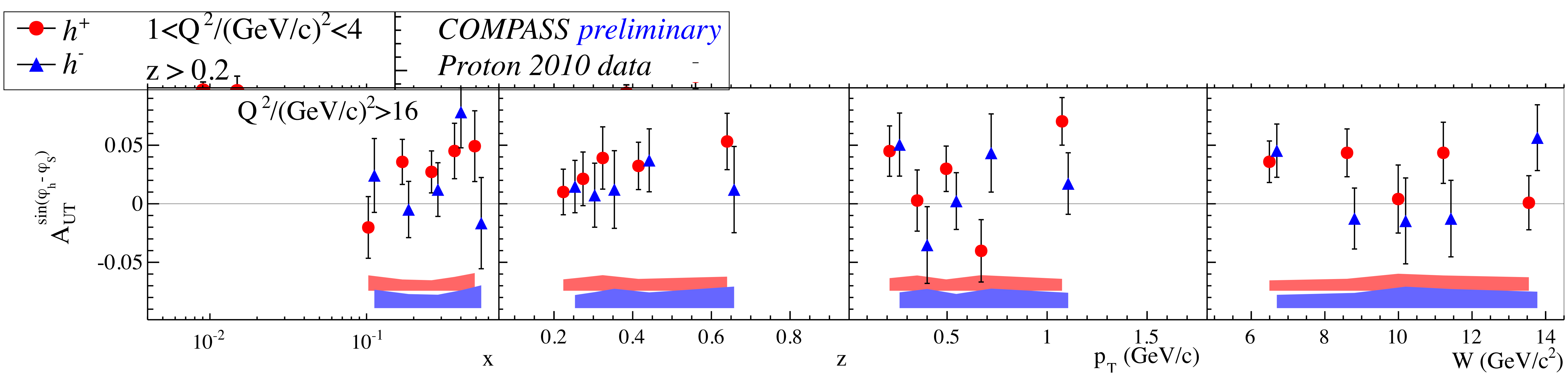




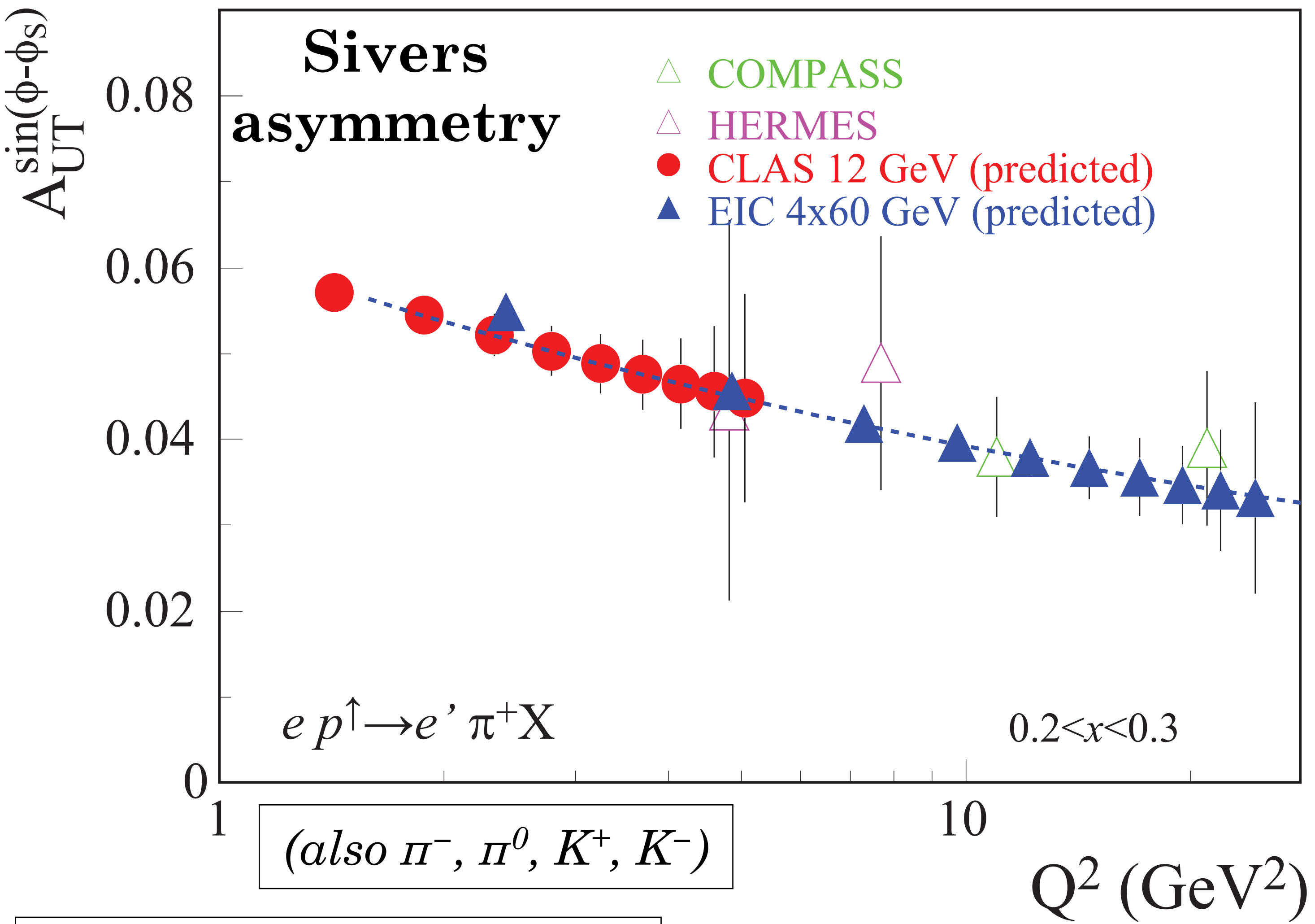


COMPASS SIDIS in DY range:

invariant di-muon mass



Future Sivers and Collins measurements at CLAS-12

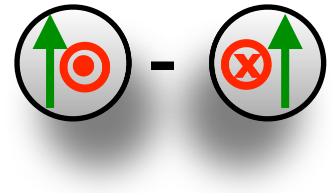


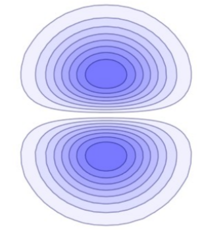
100 days of data taking

- **Transversely polarized HD-Ice target:** with negligible nuclear background and small dilution factor. No strong holding field required.
- **High luminosity and large acceptance** will allow measurements in wide range of x, Q^2, and P_{hT} and a multi-dimensional analysis: extended mapping in several (x, Q^2) bins.
- **Study of TMD evolution.**
- **Constraints of higher-twist contributions** to resolve the observed mismatch between the signs of the moment of the Sivers function extracted from SIDIS data and twist-3 calculations.

Z.B. Kang et al., Phys. Rev. D83 (2011) 094001

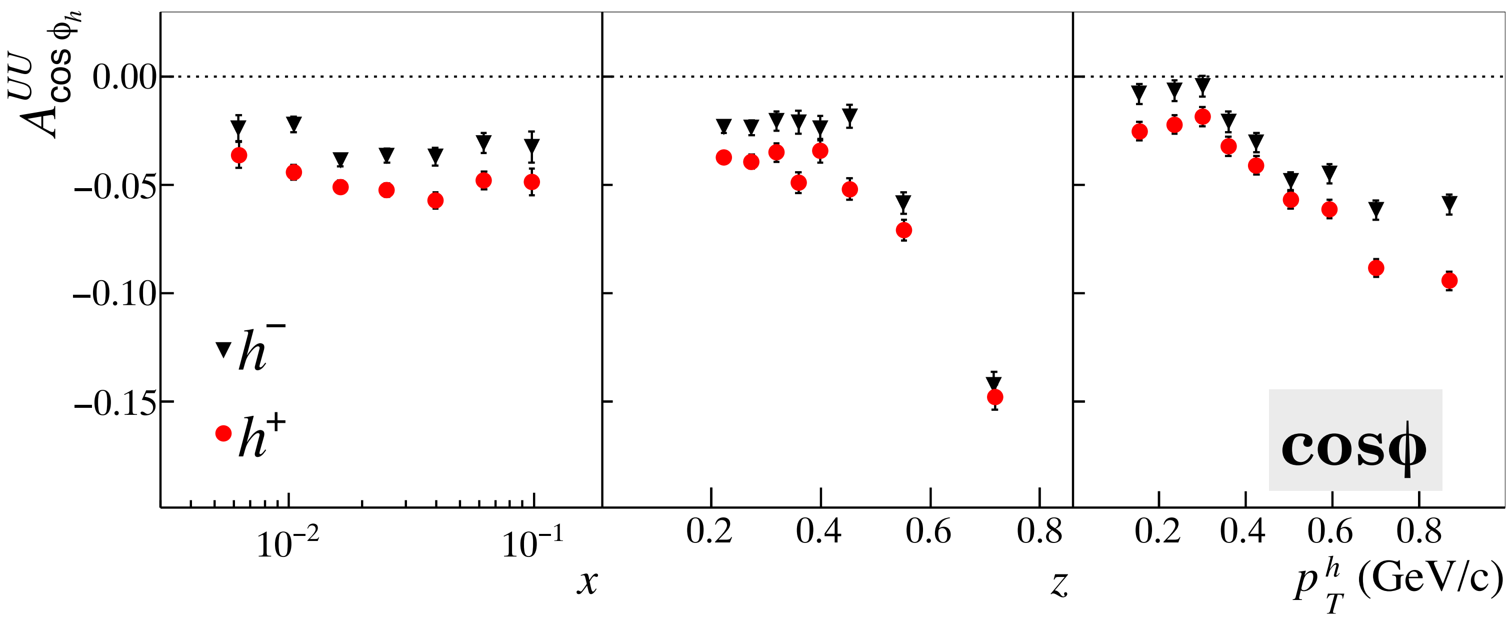
SIDIS Boer-Mulders

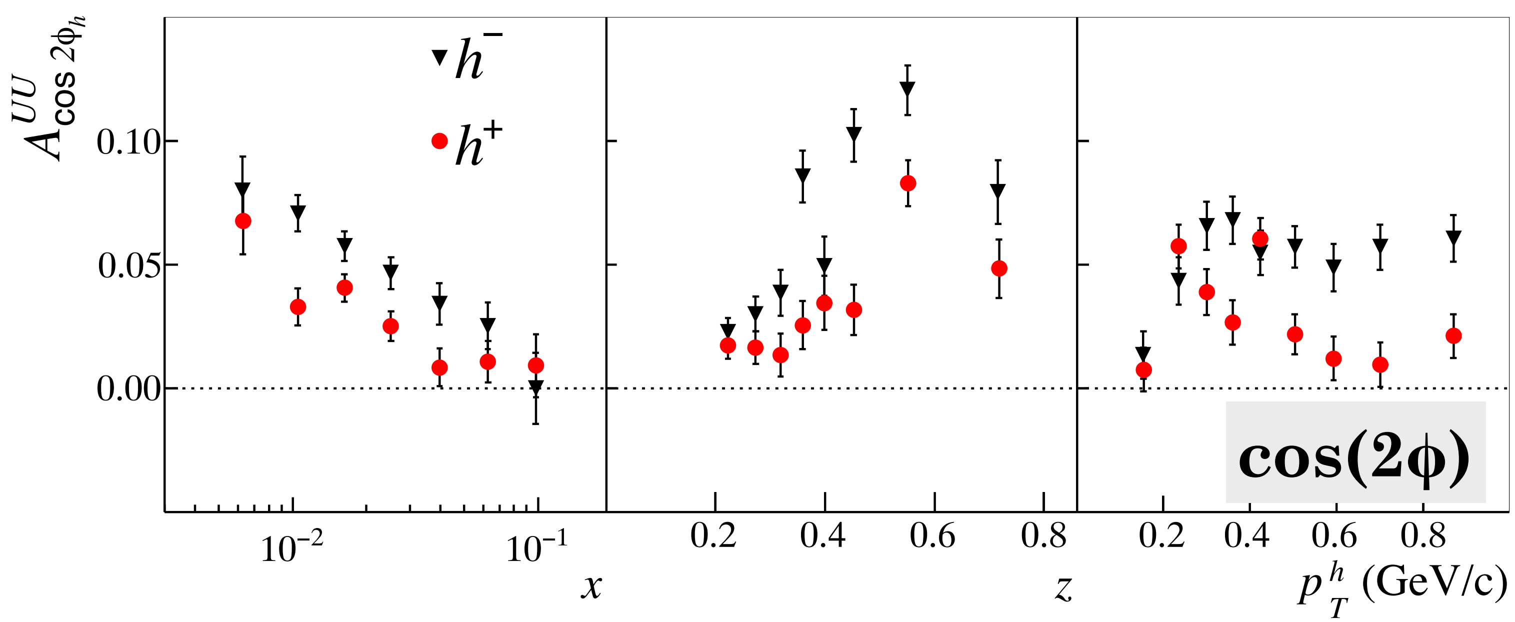




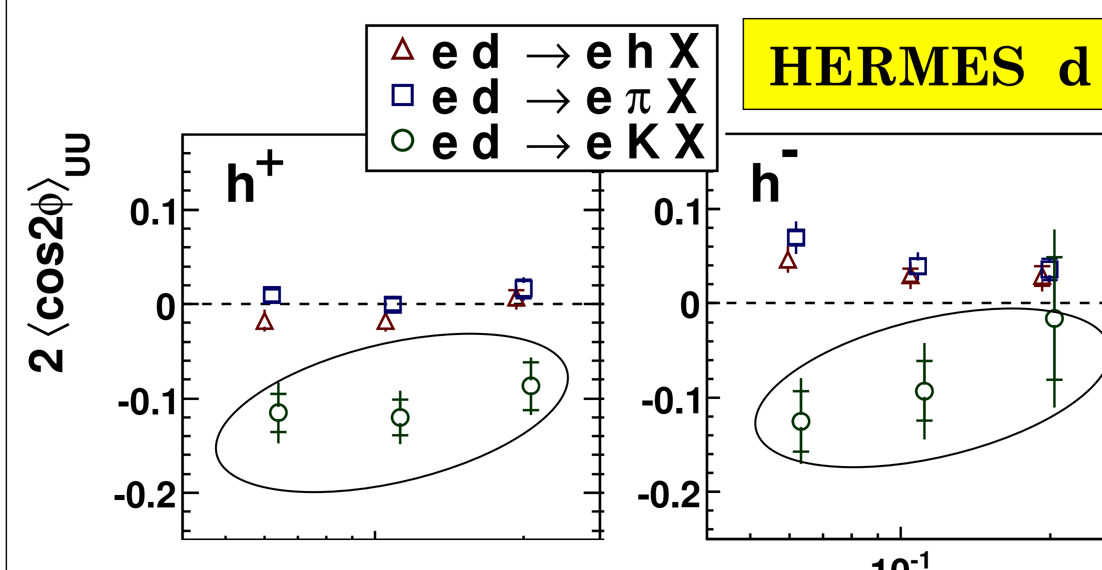
Cahn-effect (cosϕ only)
+ BM ⊗ Collins

COMPASS d COMPASS NPB 886 (2014) 1046





- **Cahn effect** → <k_T> carried by unpol. quarks in unpol. nucleon. **cosϕ modulation** solely from inclusion of non-zero quark k_T.
- h^+ vs. h^-: u-quark dominates & Collins FF has opposite sign of u-quark into positively and negatively charged pions.
- Kaons very different to pions (HERMES)



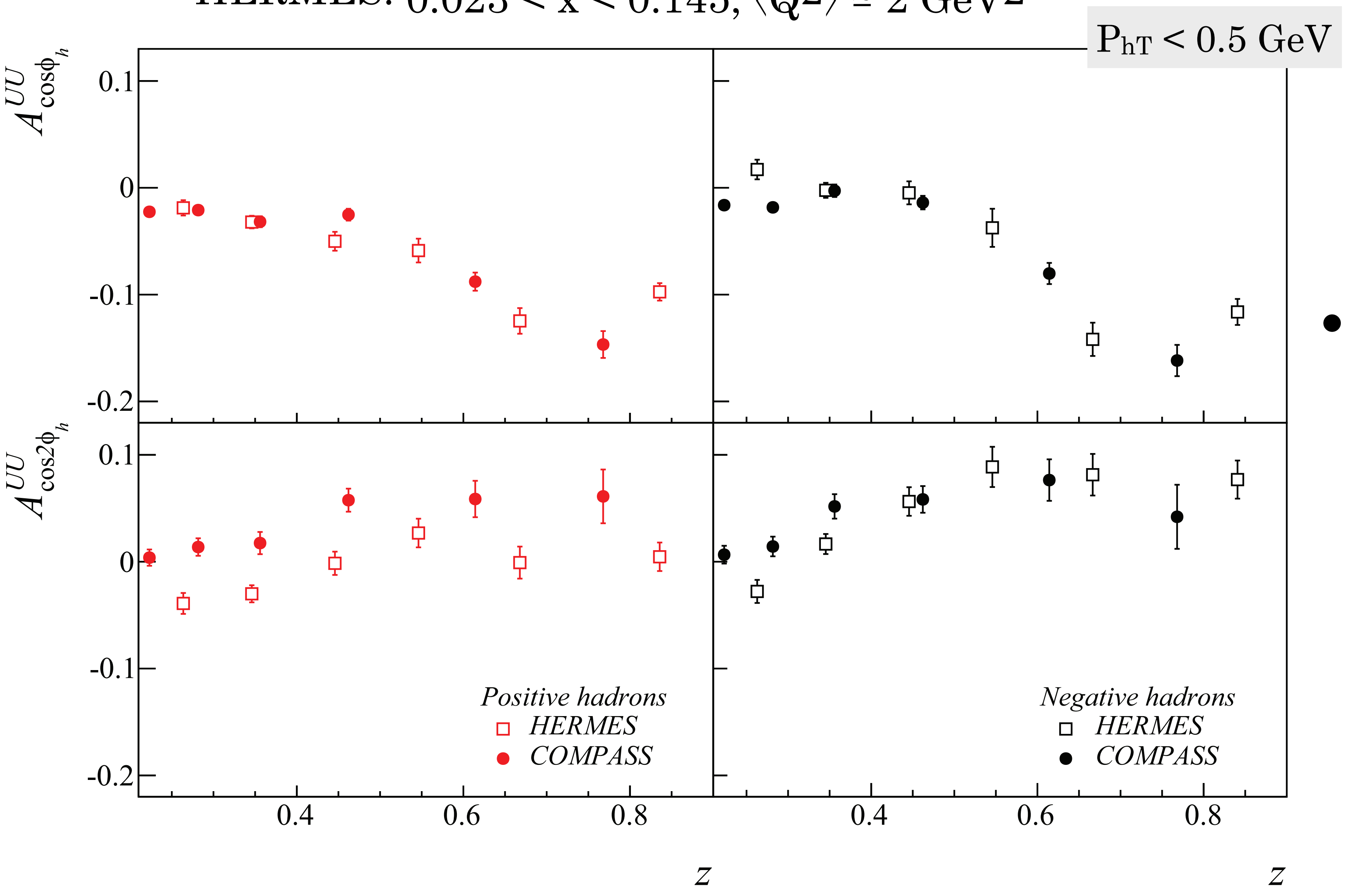
HERMES PRD 87 (2013) 012010

- COMPASS and HERMES: sizable modulations. Results for unidentified hadrons (h) differ.

CLAS p Small cosϕ and cos(2ϕ) modulations.
CLAS PRD 80 (2009) 032004

cos(nϕ) COMPASS vs. HERMES in "almost overlapping kinematics"

COMPASS: $0.02 < x < 0.13$, $\langle Q^2 \rangle \simeq 4$ GeV^2
HERMES: $0.023 < x < 0.145$, $\langle Q^2 \rangle \simeq 2$ GeV^2

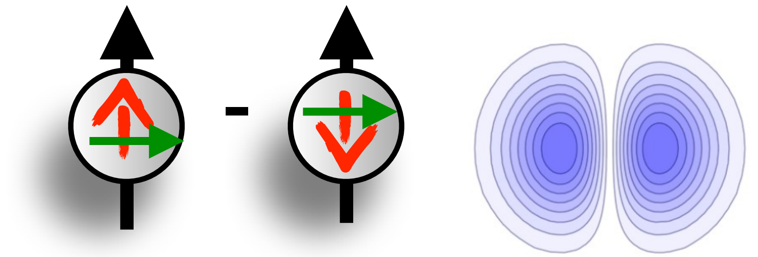


- Full differential analysis using the complete multi-dimensional information is mandatory.

For both experiments, bin-by-bin correction for the ratio of the longitudinal to transverse virtual photon flux before making the weighting average (statistical error only) in x and P_{hT}. All results acceptance corrected.

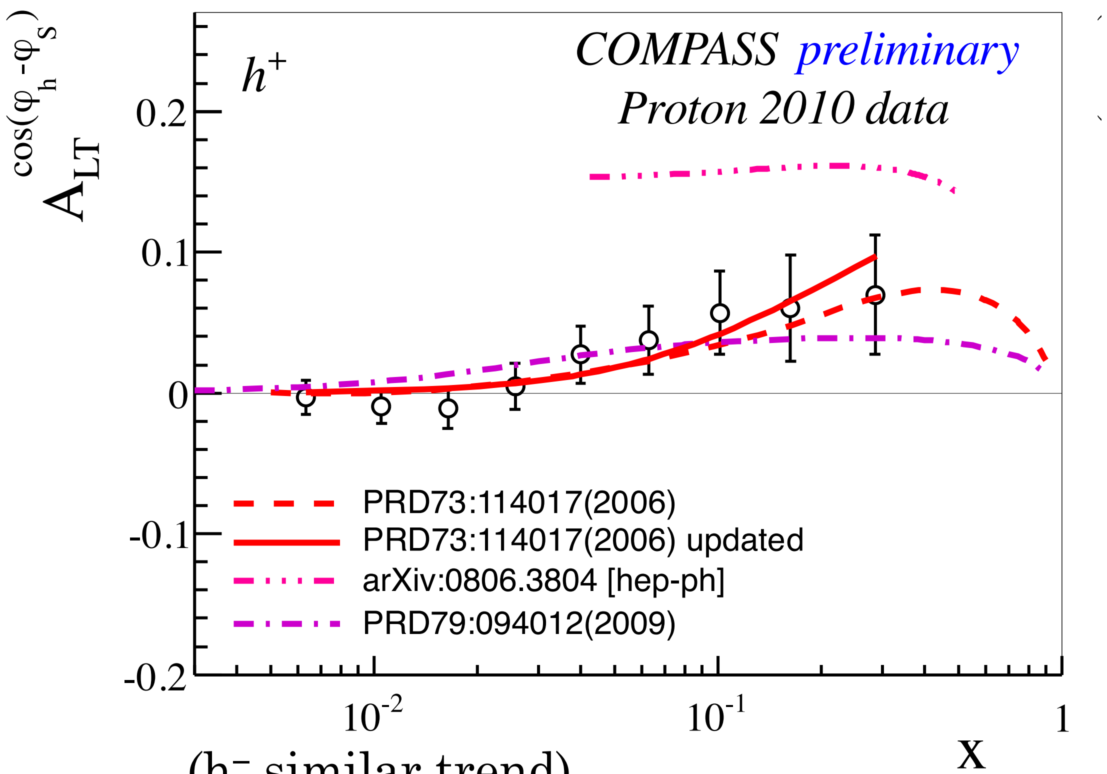
Worm-gear TMD

Worm-gear ⊗ D1



- Related to parton orbital motion - requires interference between wave functions with OAM difference by 1 unit.
- Worm gear TMDs: no “partner GPD”, unlike other 6 TMDs.

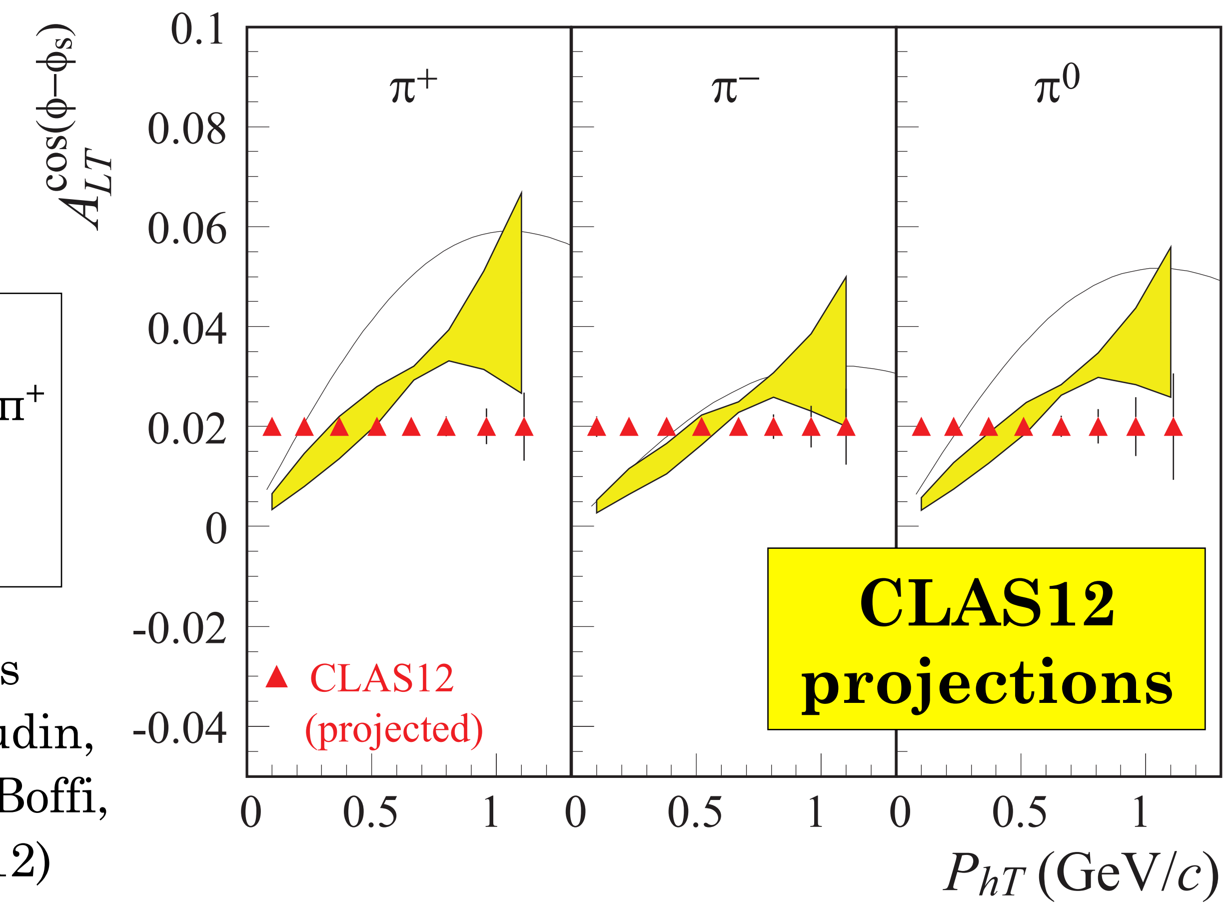
COMPASS p↑



(h^- similar trend)

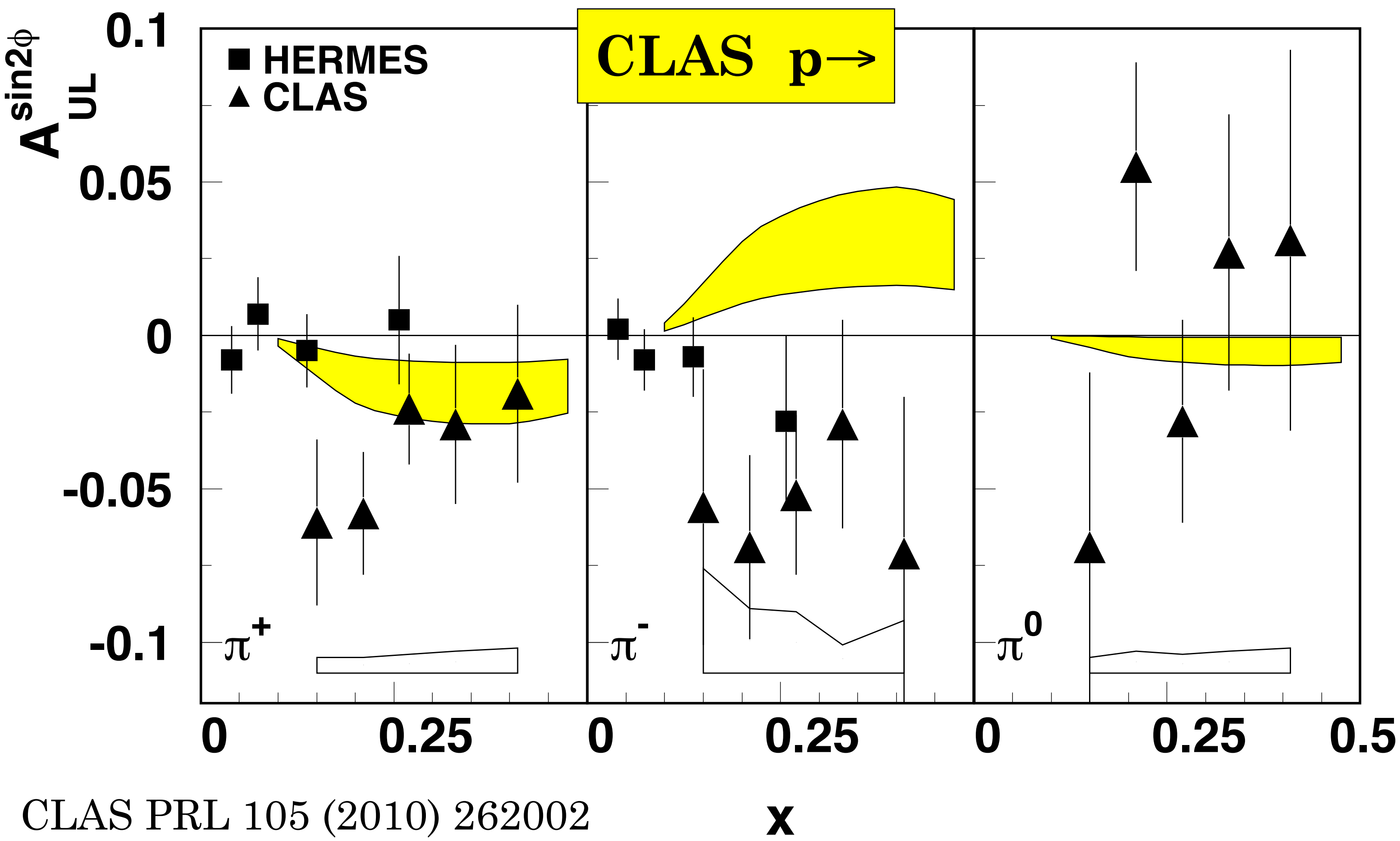
B. Parsamyan, PoS DIS2013 (2013) 231, arXiv:1307.0183

Hall-A n↑	Hall A PRL 108 (2012) 052001 (not shown): neutron result slightly positive for π^-; ≈0 for π^+
HERMES p↑	Preliminary result (not shown): positive trend for π^+ and π^-

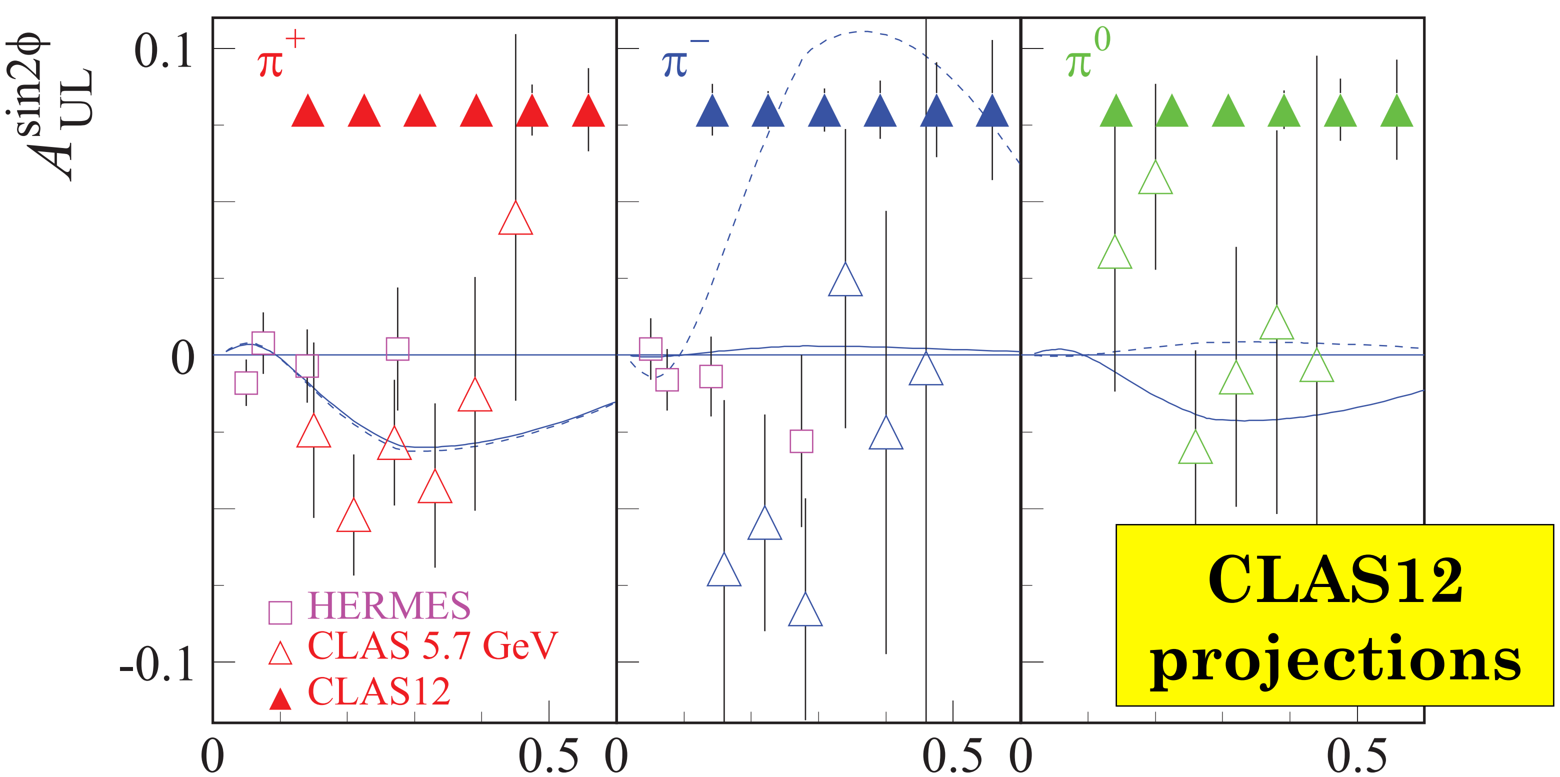


Band: two transverse-momentum dependent Gaussian widths $<k_T^2>$=0.15 and 0.25 GeV^2 (A. Kotzinian, B. Parsamyan, A. Prokudin, PRD 73 (2006) 114017). **Curve**: light-cone constituent model (S. Boffi, A.V. Efremov, B. Pasquini, P. Schweitzer, PRD 79 (2009) 094012)

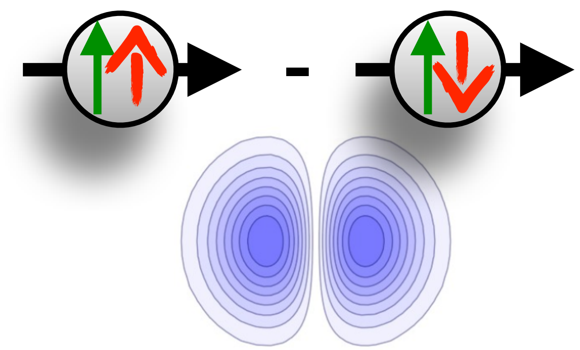
Kotzinian-Mulders worm-gear



CLAS PRL 105 (2010) 262002



Worm-gear (Kotzinian-Mulders) ⊗ Collins



- COMPASS and HERMES results: compatible with zero.

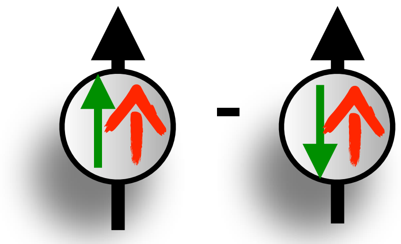
COMPASS (deuteron) EPJ C70 (2010) 39

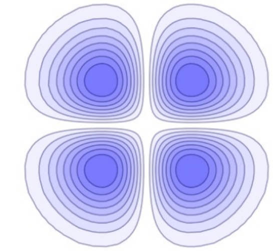
HERMES (proton π+/–) PRL 84 (2000) 4047
HERMES (proton π0) PRD 64 (2001) 097101
HERMES (deuteron) PLB 562 (2003) 182

- CLAS12 measurement will cover wider kinematic range with smaller uncertainties.

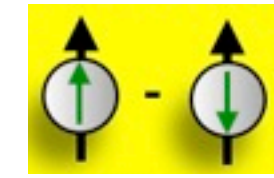
Pretzlosity TMD

Pretzelosity ⊗ Collins





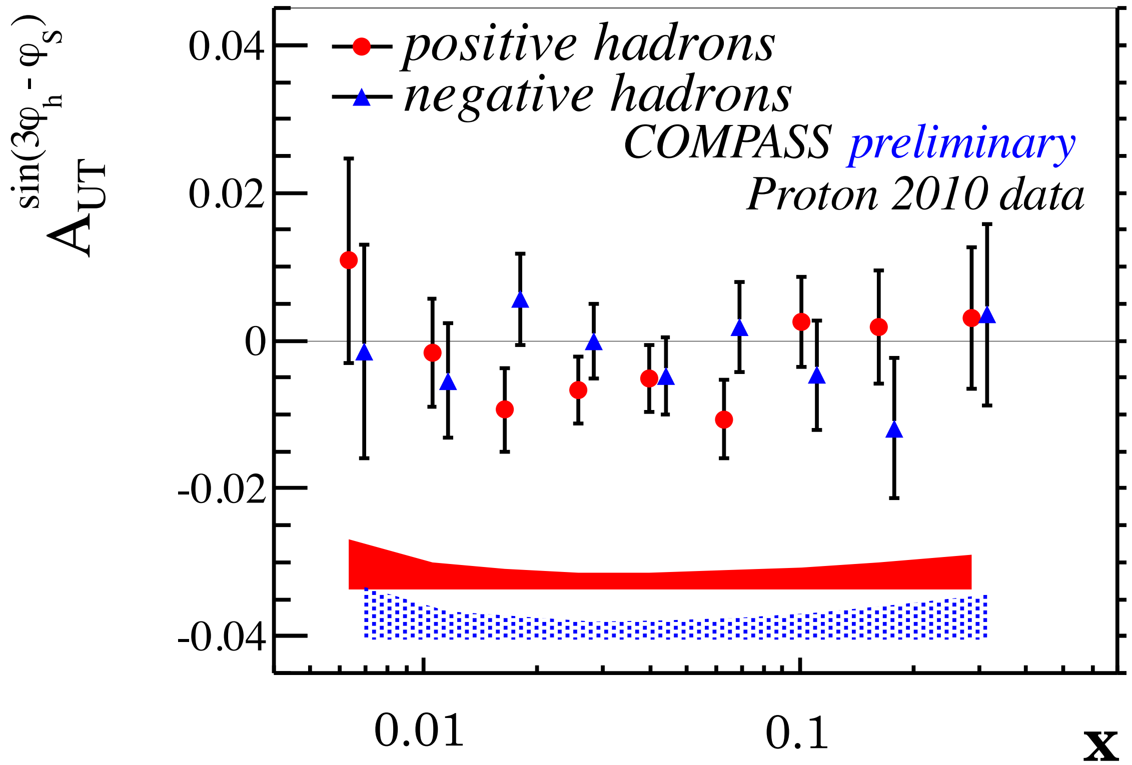
"Quadrupole modulation in momentum space."

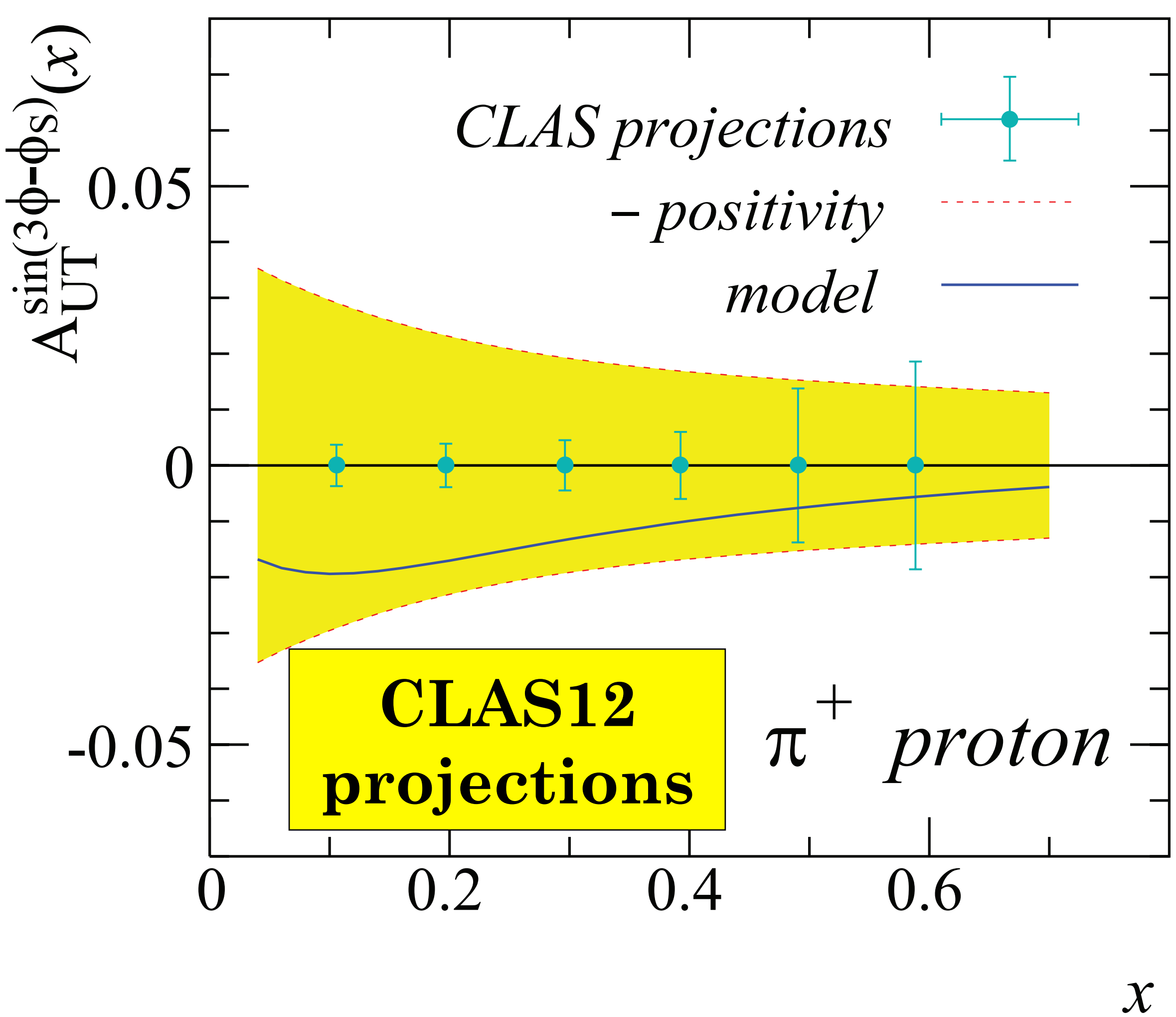


"pretzelosity = helicity minus transversity"
(some models)

=> measure of relativistic motion of quarks inside of proton.

COMPASS p↑





Not shown:

COMPASS d↑ Also compatible with zero.

HERMES p↑

Hall-A n↑

Preliminary results: compatible with zero.

Hall-A SoLID: proposal @ JLab 12

Global analysis of TMD data

- Study kinematic dependences in **multi-dimensional phase-space**
  ⇒ Requires careful choice of ranges and binnings, accounting for experimental acceptances

- **Consistent treatment amongst experiments**
  ⇒ various reactions ↔ address TMD universality
  ⇒ various energy domains ↔ address TMD evolution

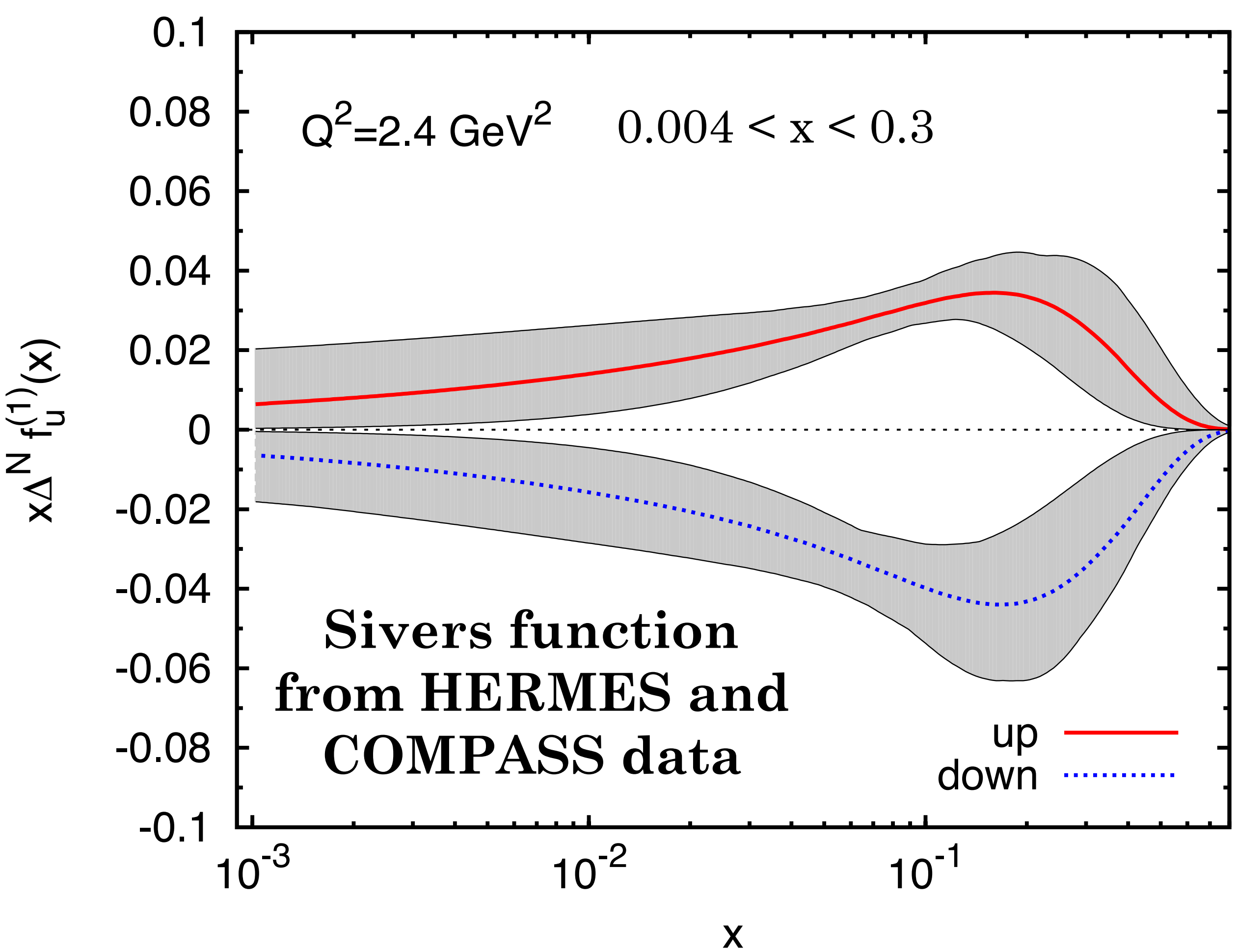
- **Experimental challenges**: results must be as-free-as-possible of acceptance and radiative effects, and of events of diffractive meson production.

- **Quark flavor disentanglement**: use different targets, and identify hadrons.

- Prominent: Sivers and Transversity PDFs, and Collins FF.

- *More: see Zhongbo Kang's talk this session.*

map of valence-quark region: JLab



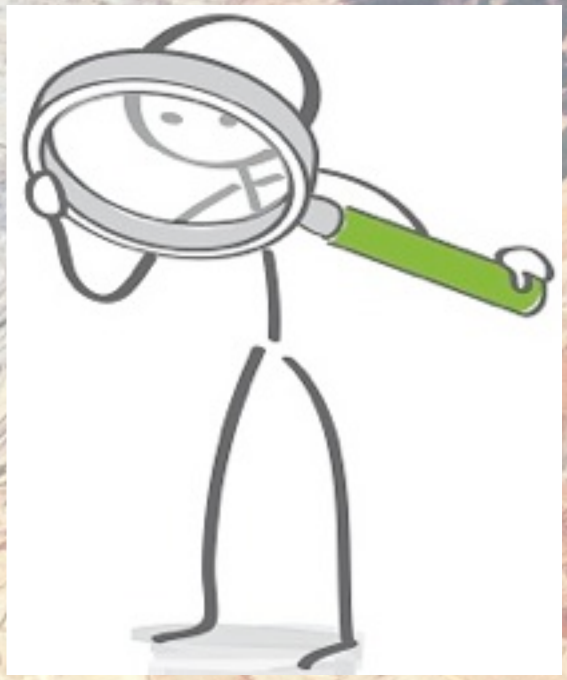
M. Anselmino et al., arXiv:1107.4446 [hep-ph]

Outlook: TMD experiments

- 2016/17 (just starting!): **COMPASS-II SIDIS (2016/17)** on unpolarized target (LH_2)
  - Flavor separation: proton + deuteron data and advanced hadron PID.
  - Mapping in 4 dimensions: x, Q^2, $p_T{}^2$, z; e.g. Boer-Mulders and Cahn-effect
  - Strange-quark distribution function s(x) in so-far uncovered region $0.001 < x < 0.2$

- >2020: **"COMPASS-III" ?** ***Discussions have started.***
  - Different energies for Sivers TMD evolution
  - High-precision mapping
  - Tranversity on deuteron target
  - New structure function → target fragmentation region?

- **JLab 12**
  Several closely-related proposals approved in all three Halls, providing complementary studies with different systematics.
  CLAS12: transversely polarized hydrogen target with access to higher P_{hT} and Q^2 with negligible nuclear background



- ***RHIC*** *results: see Xiaorong Wang, E3.00002*

- *TMDs at an* ***Electron-Ion Collider****: see E. Aschenauer's talk this session.*

Connection with GPDs: Sivers function ↔ GPD E
chiral odd: Transversity ↔ GPD H_T, Boer-Mulders ↔ $2\widetilde{H}_T + E_T$

Summary: TMDs at COMPASS, HERMES & JLab

- The proton structure is being unraveled - similarly exciting situation as in the early 20th century, when the (fine)structure of the hydrogen atom was discovered.
- Huge international effort to measure observables sensitive to the transverse momentum of partons in the nucleon. Parallel effort on the theory side.
- Currently most prominent question: Sivers (et al.) sign switch SIDIS ↔ DY?
- First extraction of TMDs: QCD dynamics is complex.
- Common TMD extraction needed from multi-dimensional observables with high precision →
- - COMPASS-II: 2015-18
  - JLab12: >=2016
  - "COMPASS-III" > 2020?

Thank you to: Harut Avakian, Andrea Bressan, Marco Contalbrigo.

Backup slides

Table of TMD(PDF)s

legend *nucleon moves to the right.*

- nucleon (N)
- unpolarized quark (Q)
- nucleon spin
- quark spin
- quark k_T

N \ Q	U	L	T	
U	f_1 number density		$h_1^\perp$ Boer-Mulders	
L		g_1 helicity	$h_{1L}^\perp$ worm-gear	
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ worm-gear	h_1 transversity	$h_{1T}^\perp$ pretzelosity

TMDs surviving integration over k_T. "Collinear analysis"

naive time-reversal odd TMDs

chiral odd TMDs

(→ **Chiral symmetry breaking** of the QCD nucleon wave function)

Flavor indices and kinematic dependences skipped for simplicity. 8 TMD(PDF)s needed at leading twist description.

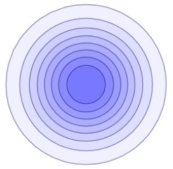
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

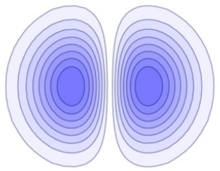
“Im(S×P)” (row U)

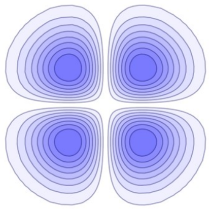
“Re(S×P)” (row L)

↔ **D wave component** ($h_{1T}^\perp$)

“Im(S×P)” (column U) “Re(S×P)” (column L)

$f(x, \mathbf{k}_\perp^2)$  Monopole

$\frac{\mathbf{k}_{\perp i} S_{Ti}}{M} f(x, \mathbf{k}_\perp^2)$  Dipole

$\frac{\mathbf{k}_\perp^i \mathbf{k}_\perp^j - \frac{1}{2}\mathbf{k}_\perp^2 g_T^{ij}}{M^2} f(x, \mathbf{k}_\perp^2)$  Quadrupole

TMD(FF)s

N \ q	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$H_{1T}^\perp$	G_{1T}	H_1 $H_{1T}^\perp$

8 functions describing fragmentation of a quark into spin ½ hadron

Mulders, Tangerman (1995), Meissner, Metz, Pitonyak (2010)

courtesy A. Prokudin

Naive T-odd TMDs

- **Naive time reversal** (no symmetry of QCD Lagrangian): time-reversal operation without interchange of initial and final states, i.e. **reversal of momentum and spin vectors only**.

- At leading twist, the existence of a naively T-odd FF arising from final state interaction effects, was predicted by Collins and is now generally known as the **Collins effect**. In the **fragmentation of transversely polarized quarks** it is responsible for a left-right asymmetry which is due to a **correlation between the spin of the fragmenting quark and the transverse momentum of the produced hadron with respect to the quark direction**.

- Final-state interactions are required for non-vanishing signals for the naive-T -odd TMDs (measured in SIDIS). The associated single-spin asymmetries are caused by the interference of scattering amplitudes involving a helicity flip of only the nucleon, which has to be compensated by orbital angular momentum of the unpolarized quarks.

Chiral-odd TMDs

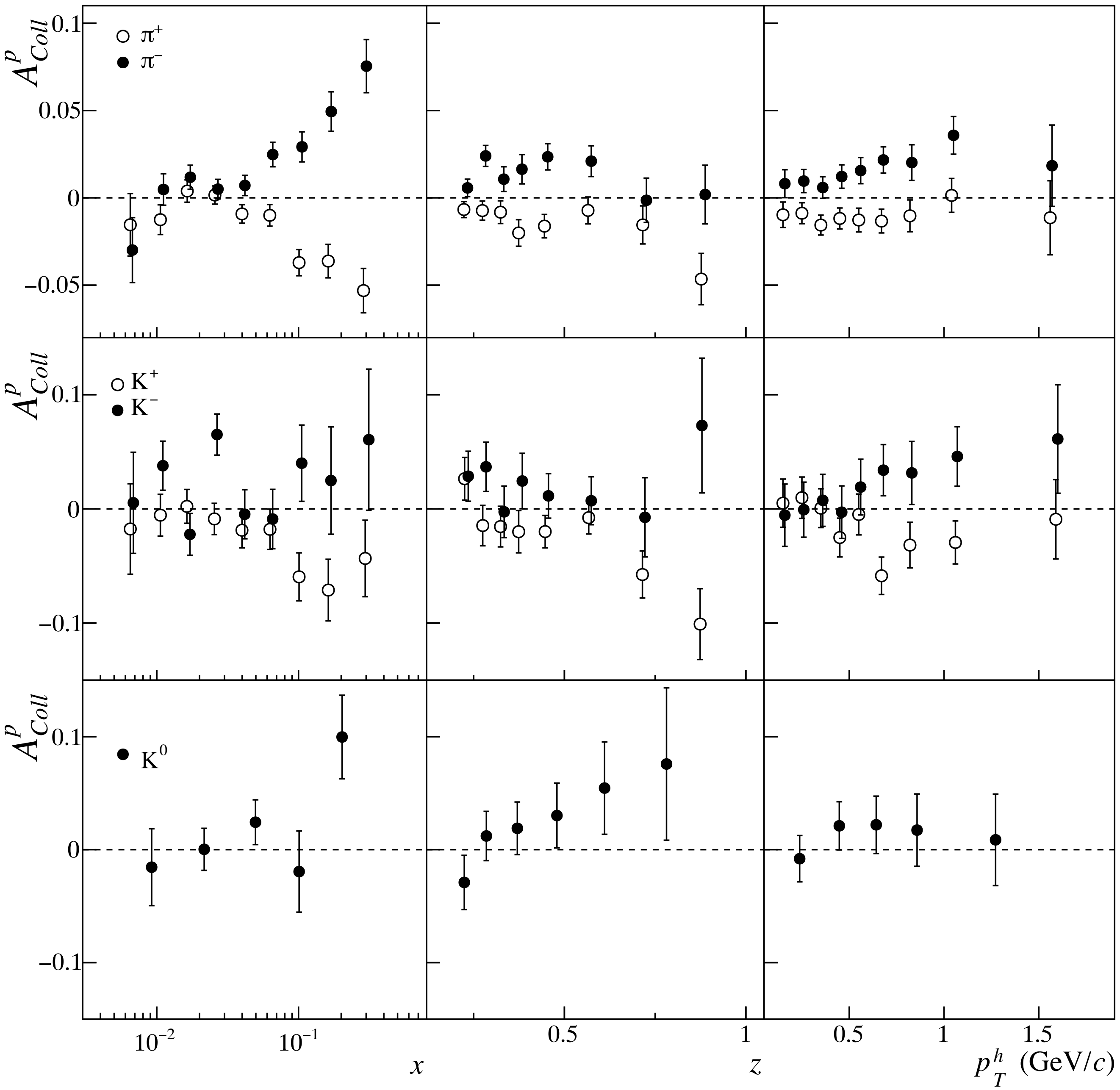
- Although fundamental for the nucleon description, **transversity** has long remained unmeasured due to its chiral-odd nature (in the helicity basis, it corresponds to a **quark helicity flip**), which prevents its measurement in inclusive DIS: the transversity distribution **can only be measured in conjunction with another chiral-odd object**.

- One possibility is represented by SIDIS reactions, where at least one final state hadron is detected in coincidence with the scattered lepton, thus conjugating parton distribution with fragmentation functions (for transversity, the **Collins FF**).

- The TMD distributions for transversely polarized quarks arise from interference between amplitudes with left- and right-handed polarization states, and only exist because of chiral symmetry breaking in the nucleon wave function in QCD. For example, the transversity distribution reflects the quark transverse polarization in a transversely polarized nucleon and is related to the tensor charge of the nucleon.

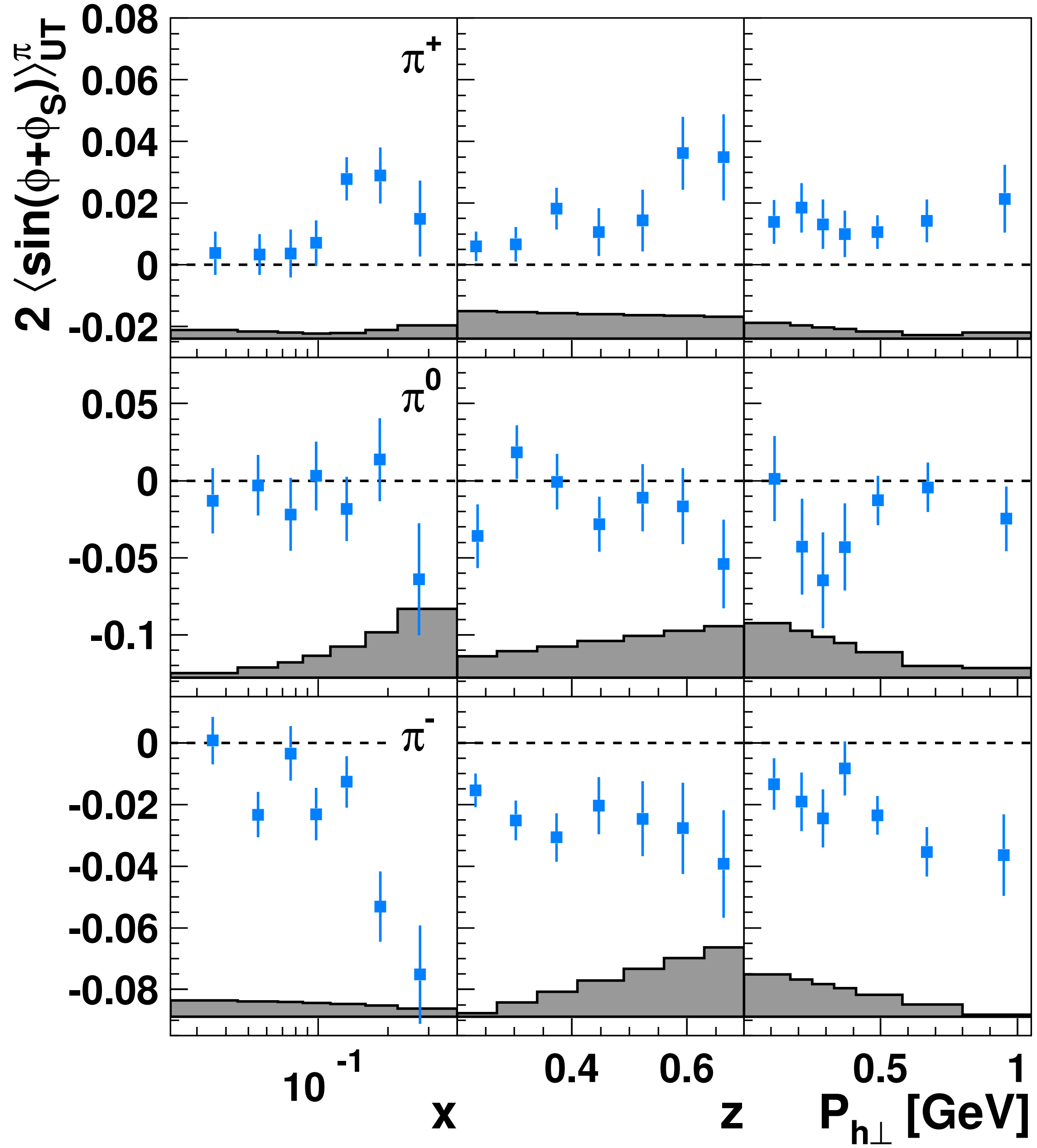
Collins asymmetry in SIDIS

COMPASS



PLB 744 (2015) 250

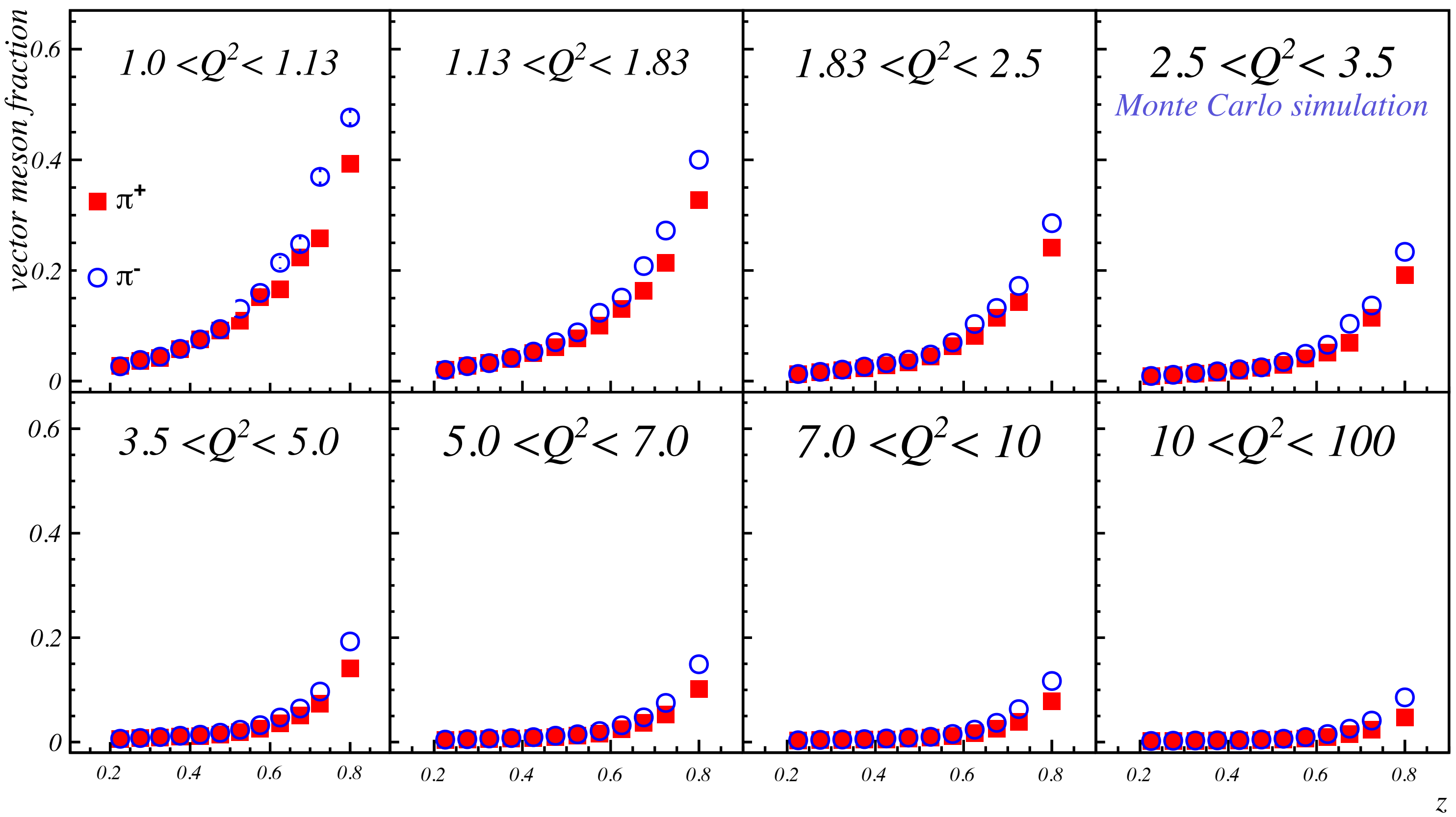
HERMES

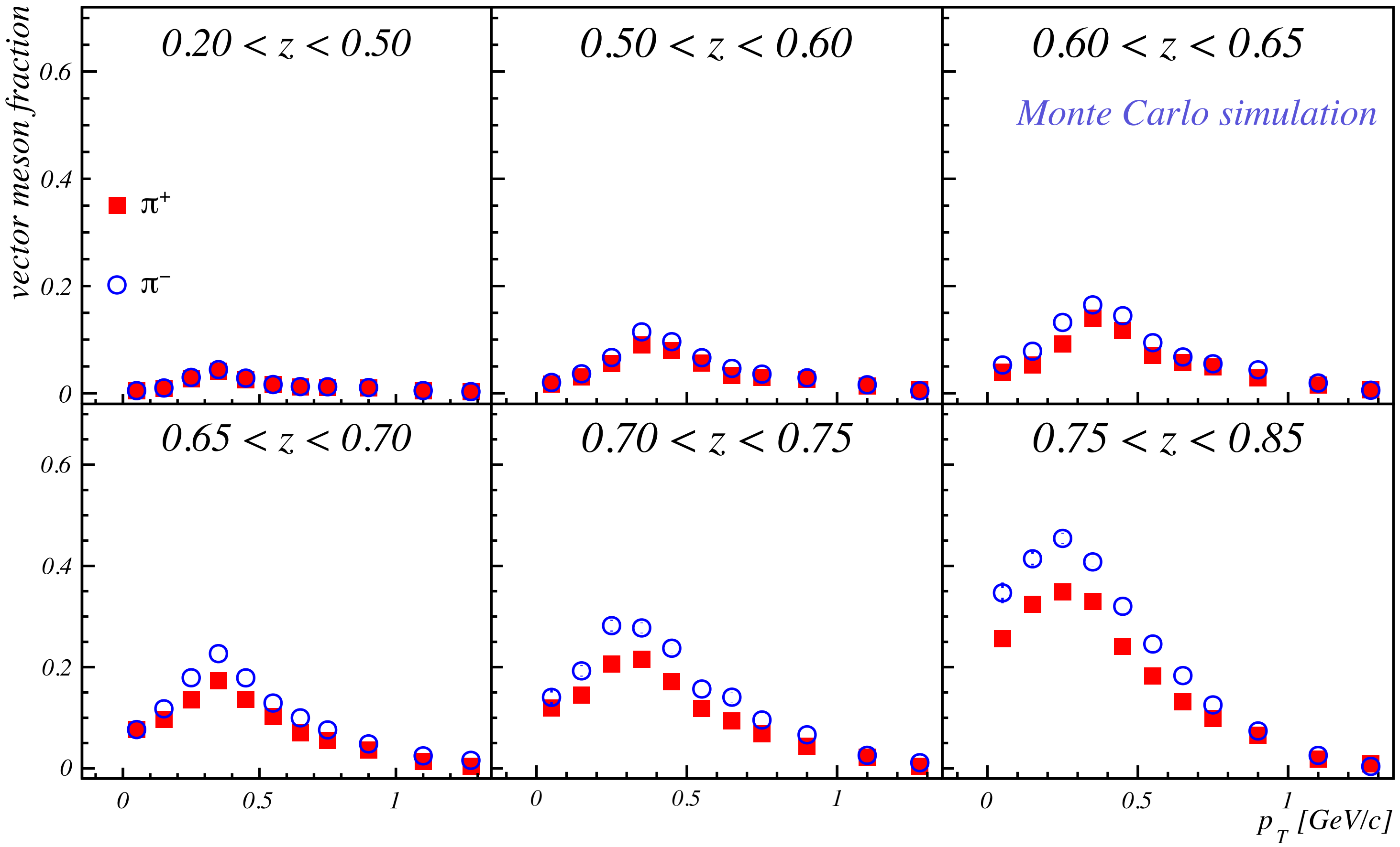


PLB 693 (2010) 11

No effects of evolution (unlike for Sivers case)

Diffractive vector mesons in SIDIS COMPASS data

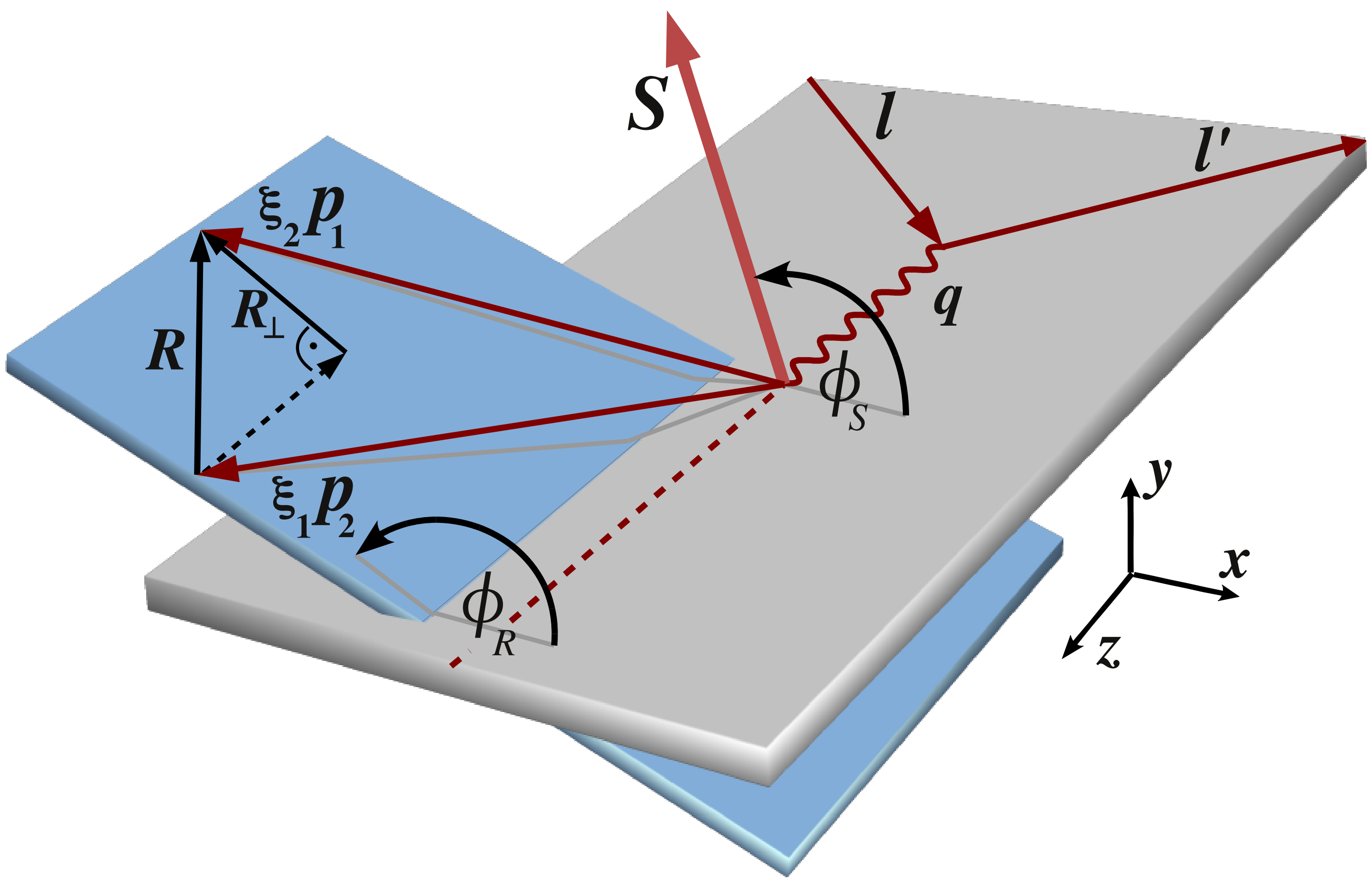




Angle definitions for di-hadron production

$$N_{h^+h^-}(x,\, y,\, z,\, M^2_{h^+h^-},\, \cos\theta,\, \phi_{RS}) \propto \sigma_{UU}\left(1 + f(x,y)\, P_T\, D_{nn}(y)\, A_{UT}^{\sin\phi_{RS}} \sin\theta \sin\phi_{RS}\right)$$

$$A_{UT}^{\sin\phi_{RS}} = \frac{|\boldsymbol{p}_1 - \boldsymbol{p}_2|}{2M_{h^+h^-}} \frac{\sum_q e_q^2 \cdot h_1^q(x) \cdot H_{1,q}^{\sphericalangle}(z,\, M^2_{h^+h^-},\, \cos\theta)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1,q}(z,\, M^2_{h^+h^-},\, \cos\theta)}$$



experimentally extracted quantity:

$A = \langle A_{UT}^{\sin\phi_{RS}} \sin\theta \rangle$, integrated over the angle θ.

θ = polar angle of one of the hadrons in the di-hadron rest frame with respect to the di-hadron boost axis

from COMPASS PLB 736 (2014) 124

Sivers asymmetry (HERMES)

DF $\otimes$ FF

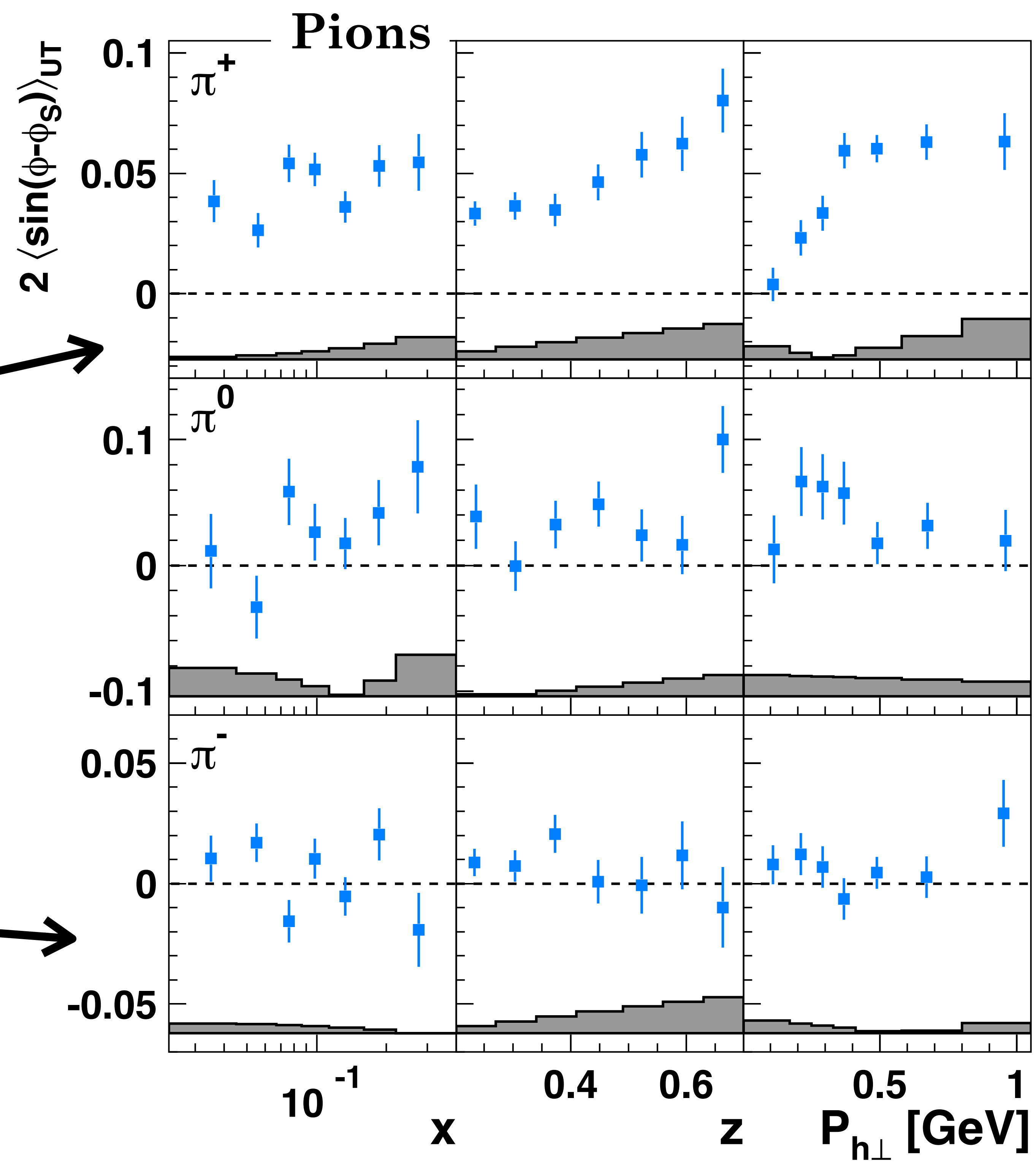
$$2\langle\sin(\phi-\phi_S)\rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2) \otimes_{\mathcal{W}} D_1^q(z,K_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,K_T^2)}$$

☛ π^+ dominated by u-quark scattering:

$$\simeq -f_{1T}^{\perp}(x,p_T^2) \otimes D_1^{u\to\pi^+}(z,k_T^2)$$

☛ u-quark Sivers function < 0

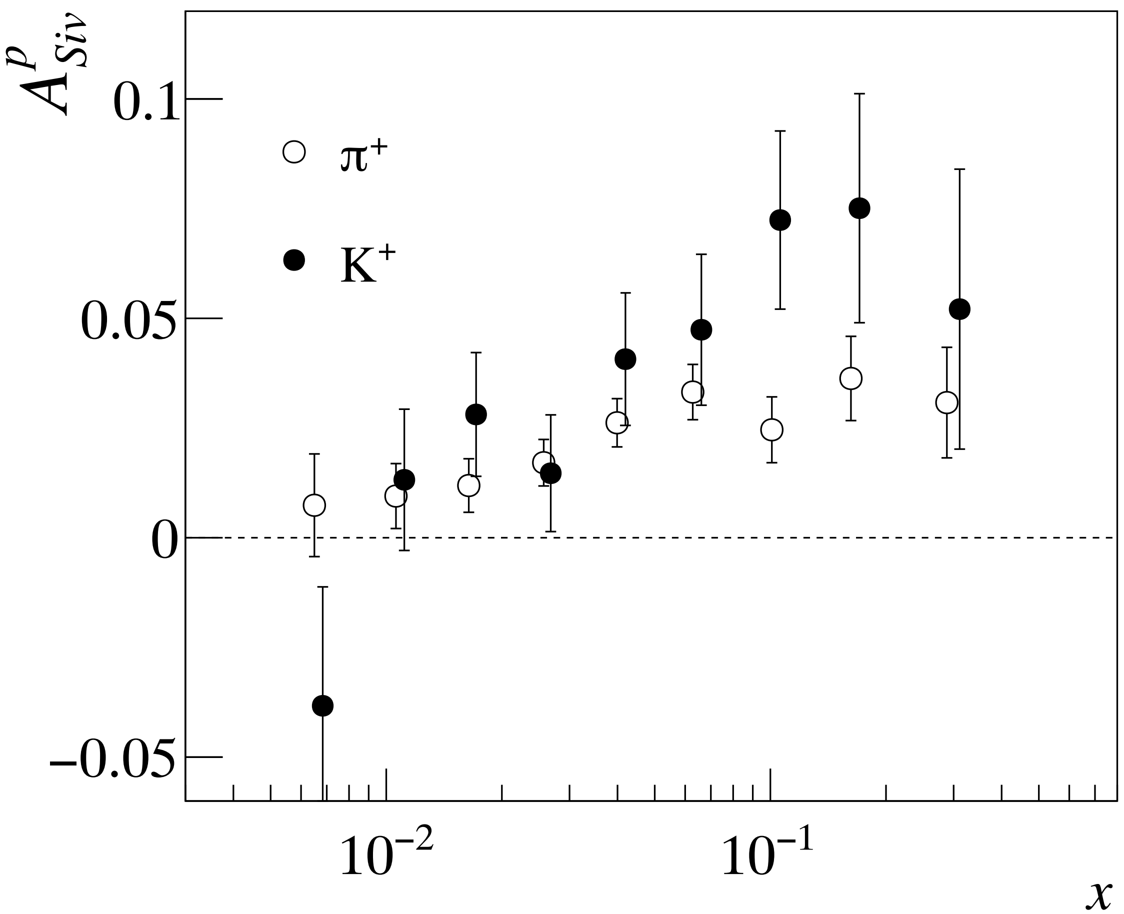
☛ d-quark Sivers function > 0



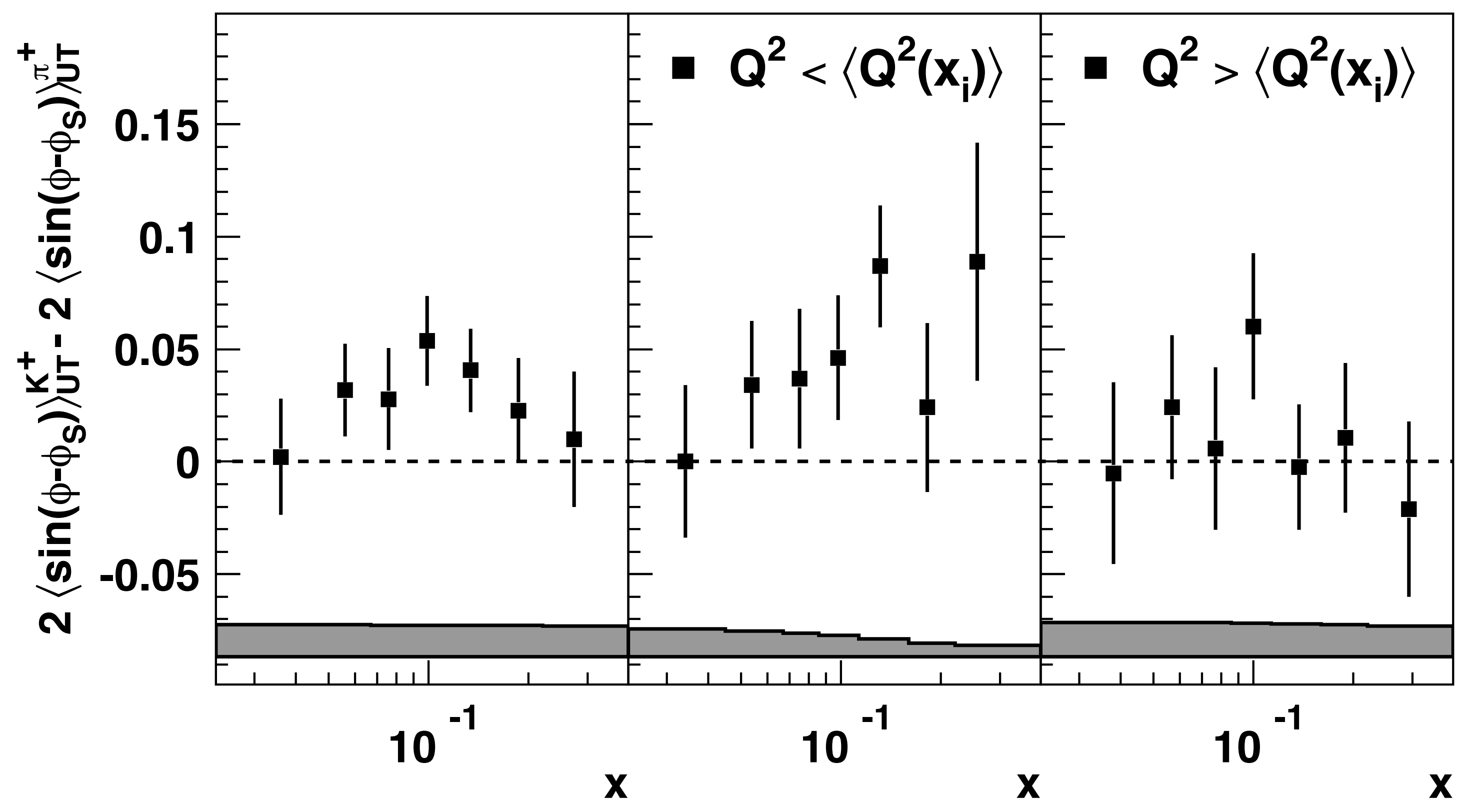
HERMES Phys. Rev. Lett. 103 (2009) 152002

SIDIS Sivers: pions vs. kaons

Role of sea quarks non-negligible!?



COMPASS PLB 744 (2015) 250

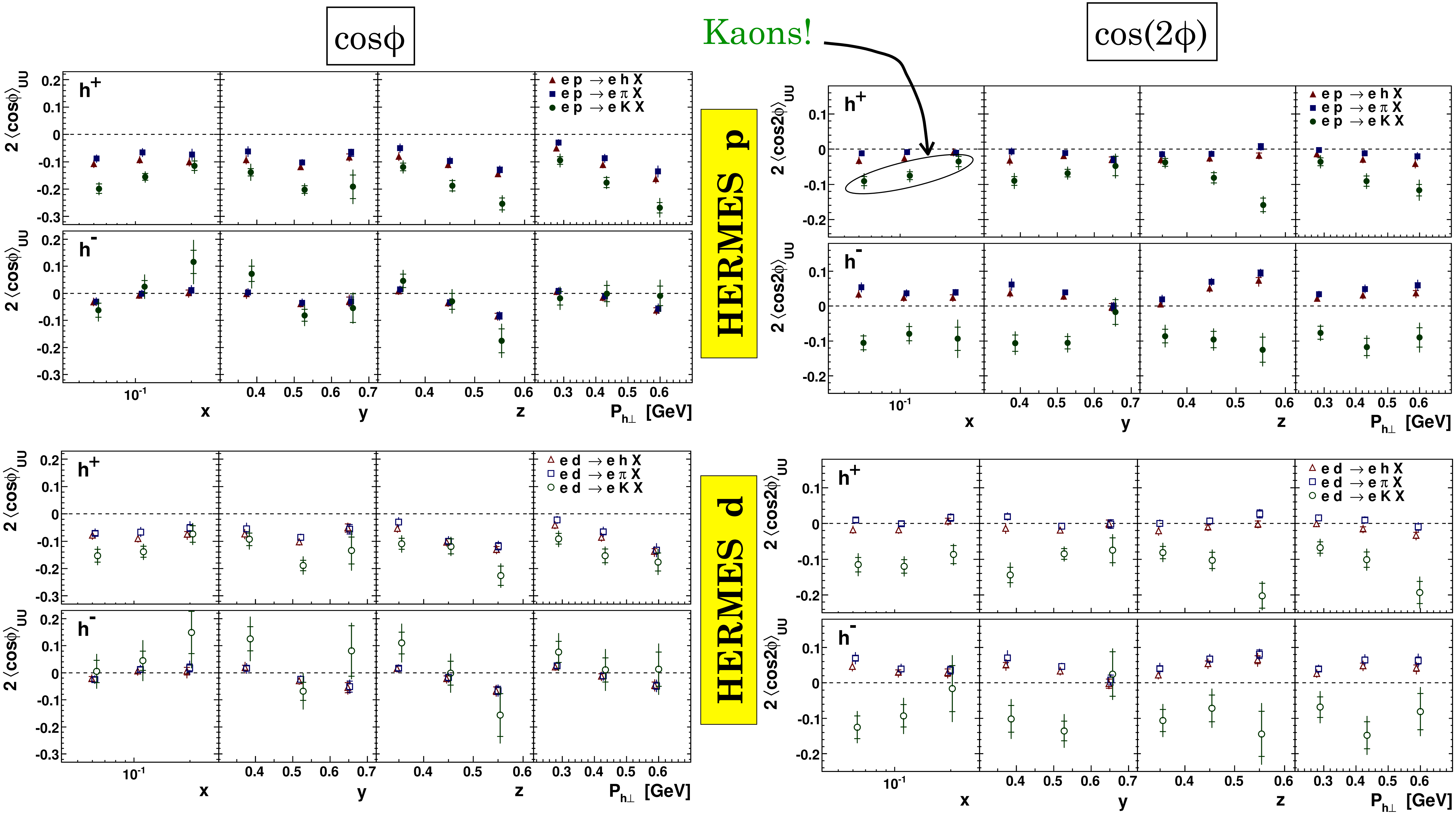


HERMES PRL 103 (2009) 152002

HERMES Boer-Mulders results

HERMES PRD 87 (2013) 012010

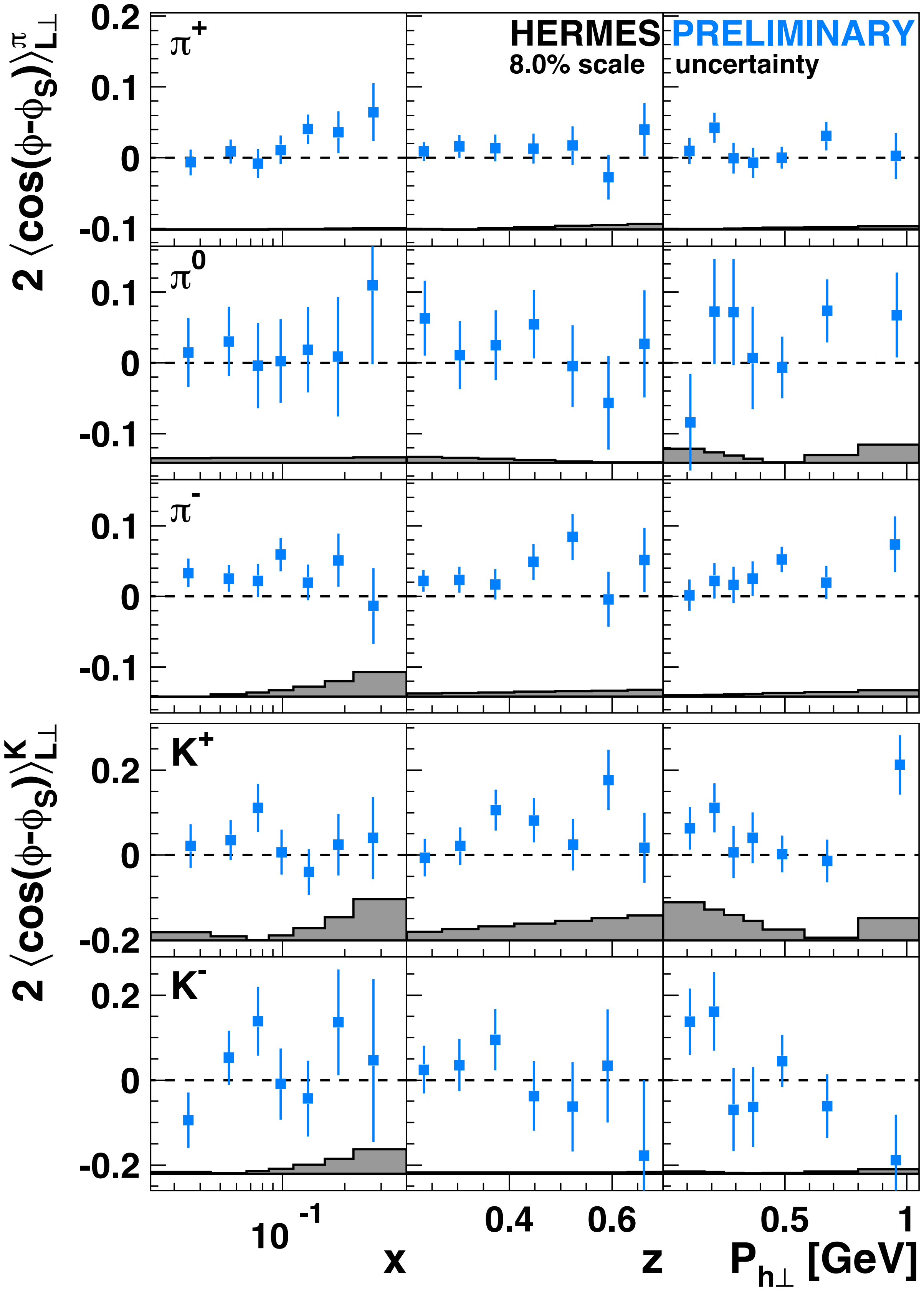
(h, π, and, K shown separately)

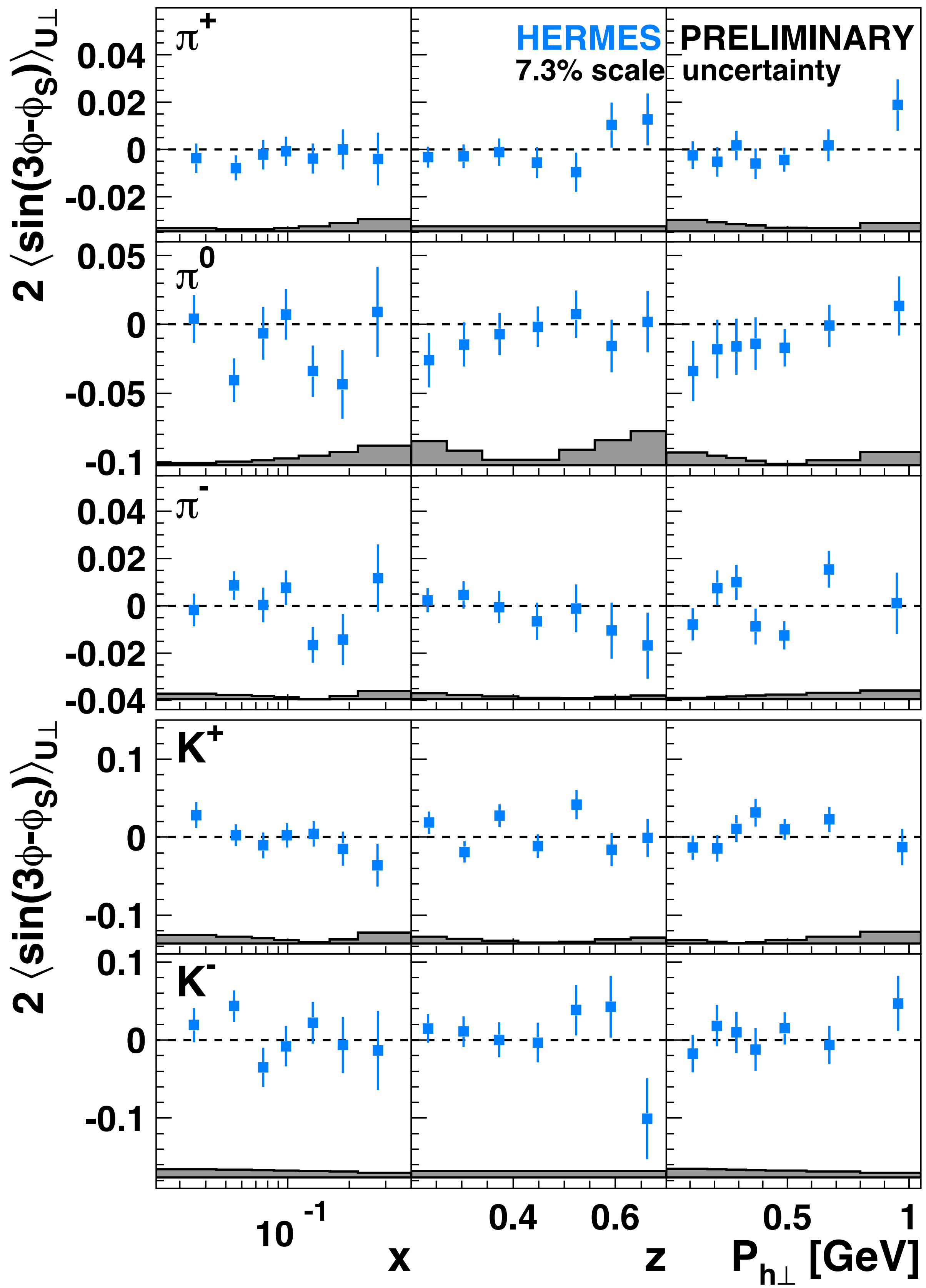


Similarity between p and d results

⇒ indication of same-sign BM for up and down quarks.

HERMES worm-gear and pretzelosity

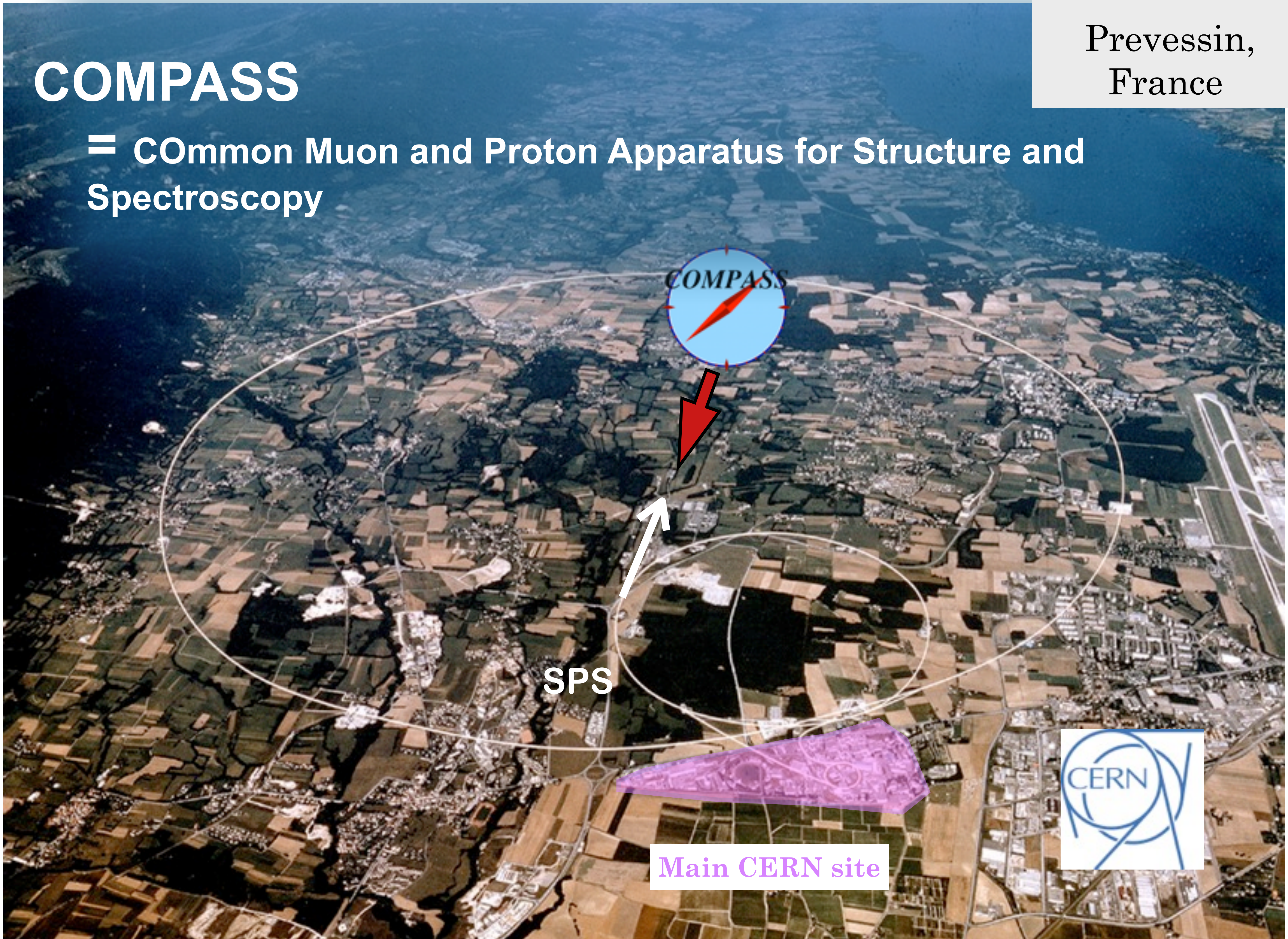




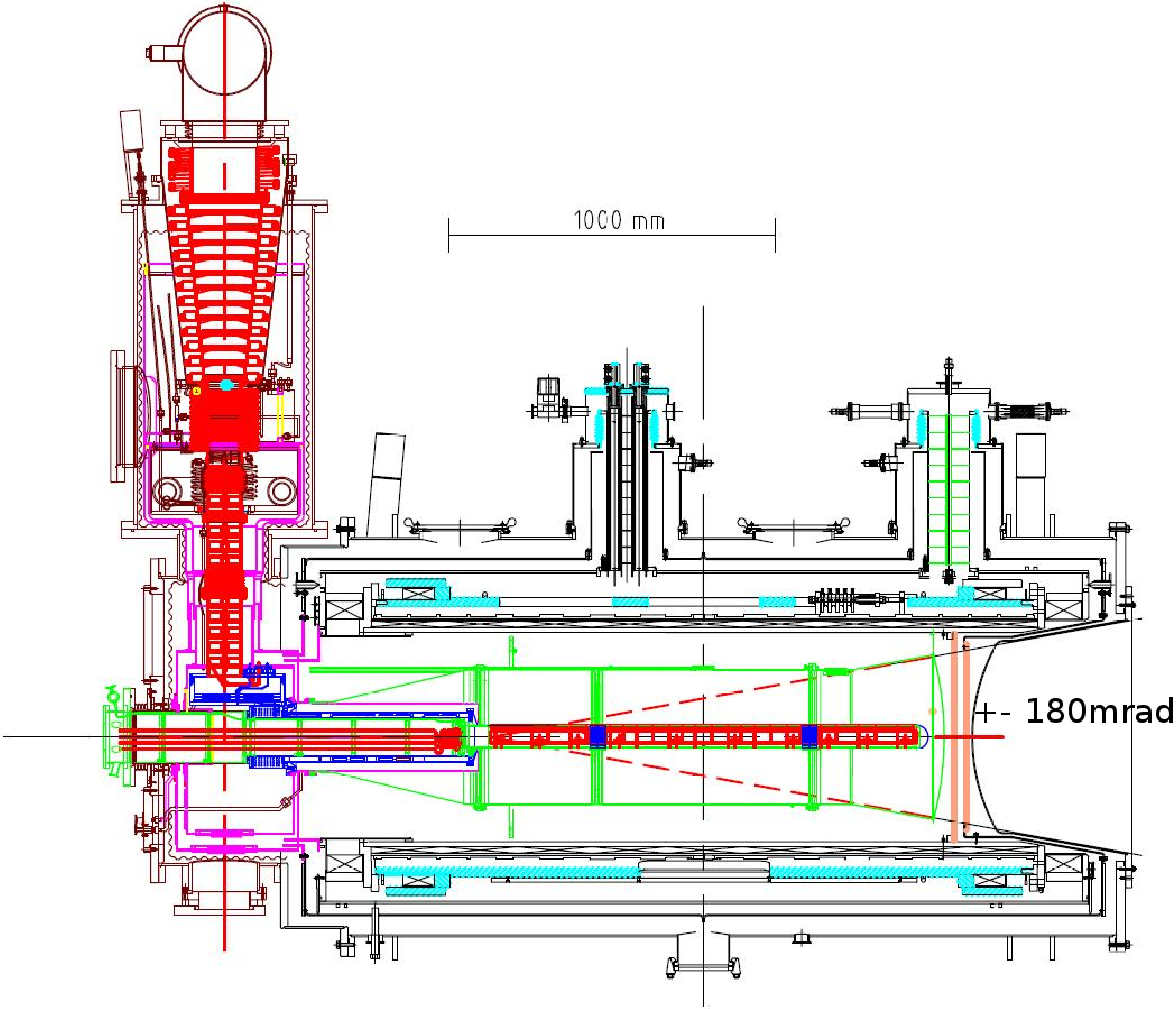
COMPASS at CERN

Geneva, Switzerland /

Prevessin, France

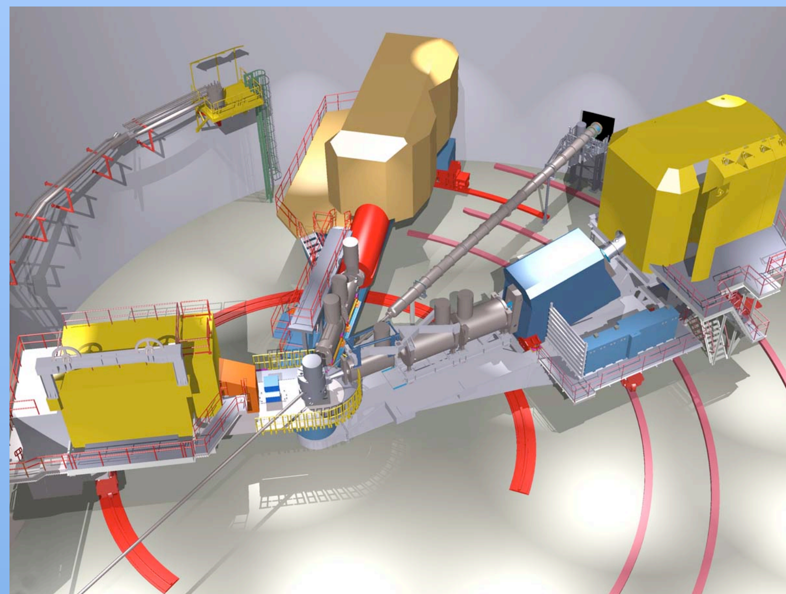


The COMPASS transversely polarized NH_3 target



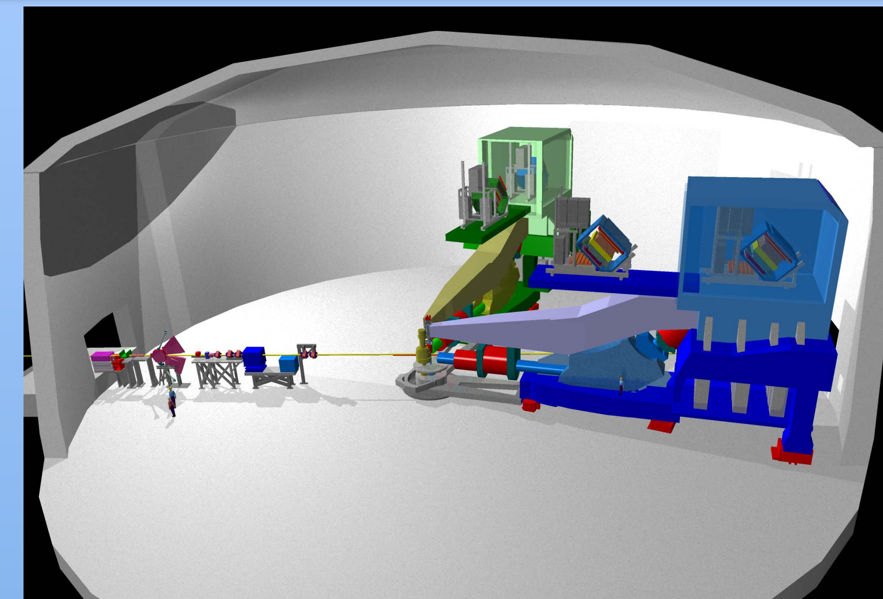
JLab12 Experimental Halls

Hall-C



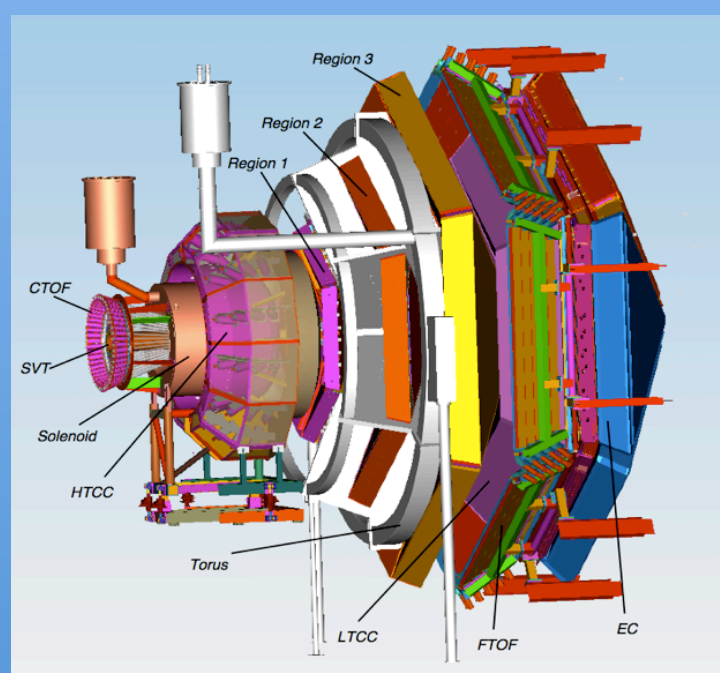
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

Hall-A



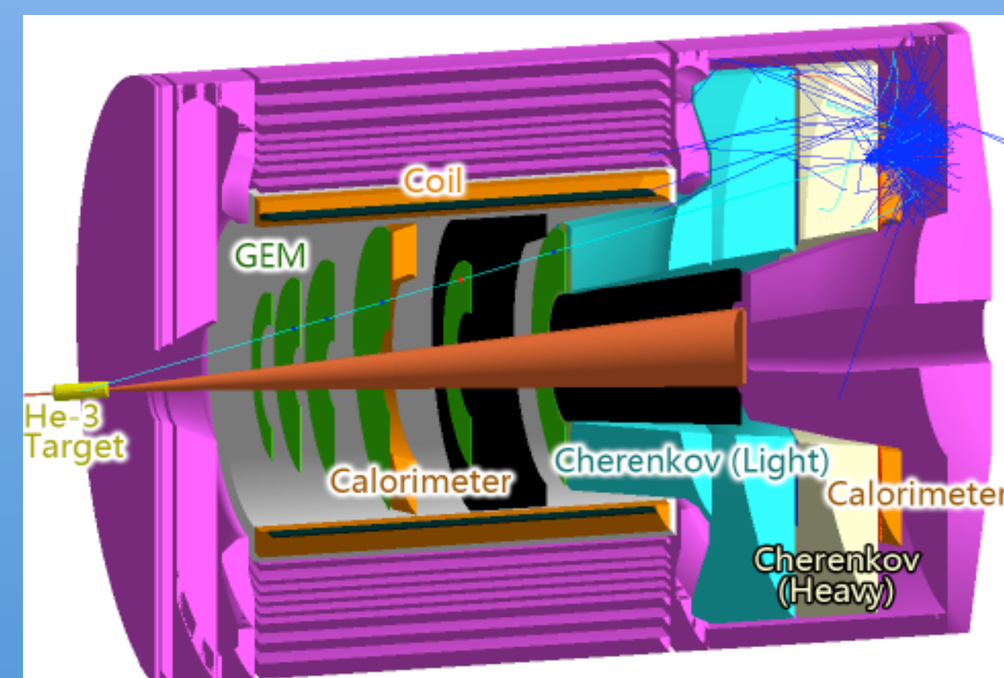
Spectrometer Pair, polarized ^{3}He target
up to to 10^{38} cm^{-2} s^{-1} hadron ID

Hall-B



CLAS12 H,D polarized targets up to 10^{35} cm^{-2} s^{-1}
“complete” acceptance, hadron ID

Hall-A

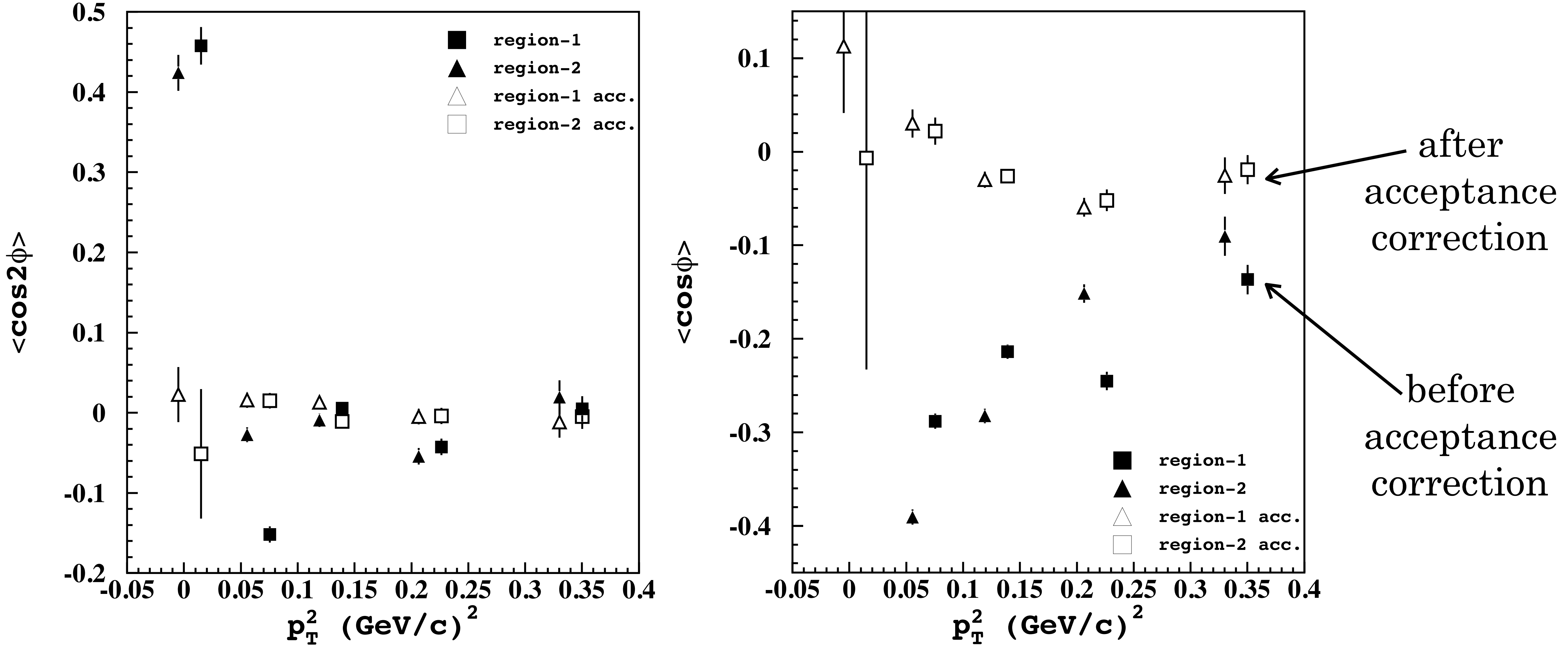


SOLID ^{3}He, NH_3 polarized targets
up to 10^{36} cm^{-2} s^{-1} large acceptance, pion ID

slide courtesy M. Contalbrigo

CLAS cosϕ and cos(2ϕ)

CLAS p



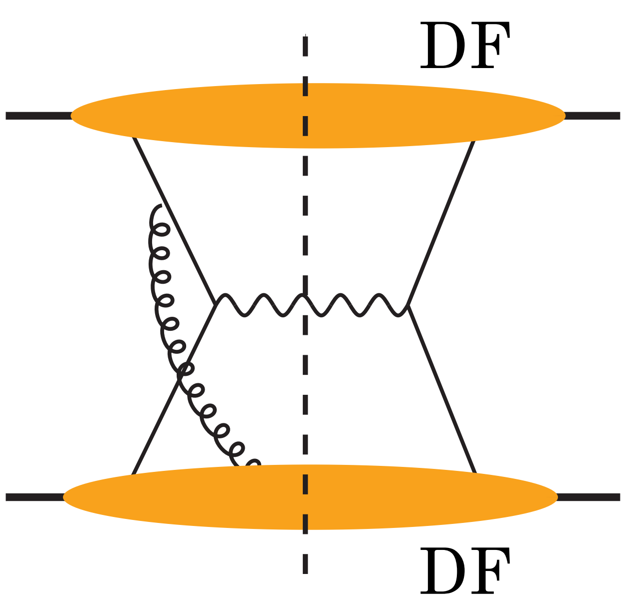
CLAS PRD 80 (2009) 032004

Sign-switch of Sivers function

The path of the Wilson lines depends on the space-time structure of the process in which the TMDs are embedded. The Wilson lines required for Drell-Yan production point to the past, whereas those appearing in the parton distributions for SIDIS point to the future. This reflects the fact that the gluon interactions shown in figure 8 strike a parton before the hard scattering in the Drell-Yan case and after the hard scattering in SIDIS.

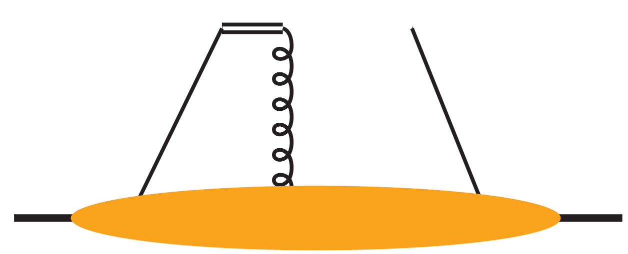
Initial-state interactions

Drell Yan



⇒

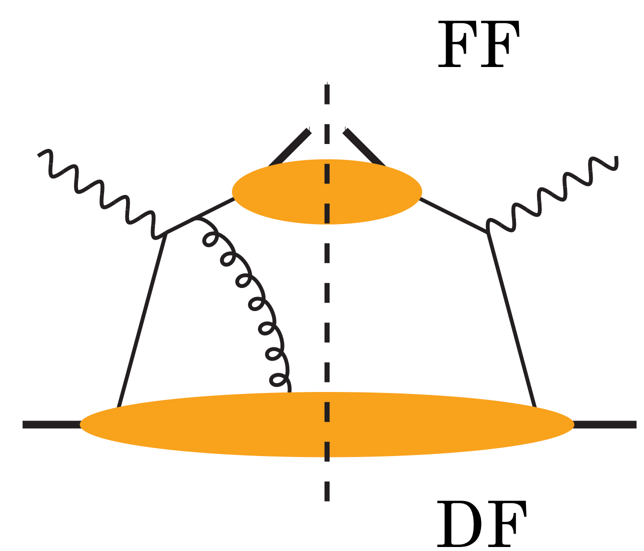
Wilson line



⇐

Final-state interactions

SIDIS

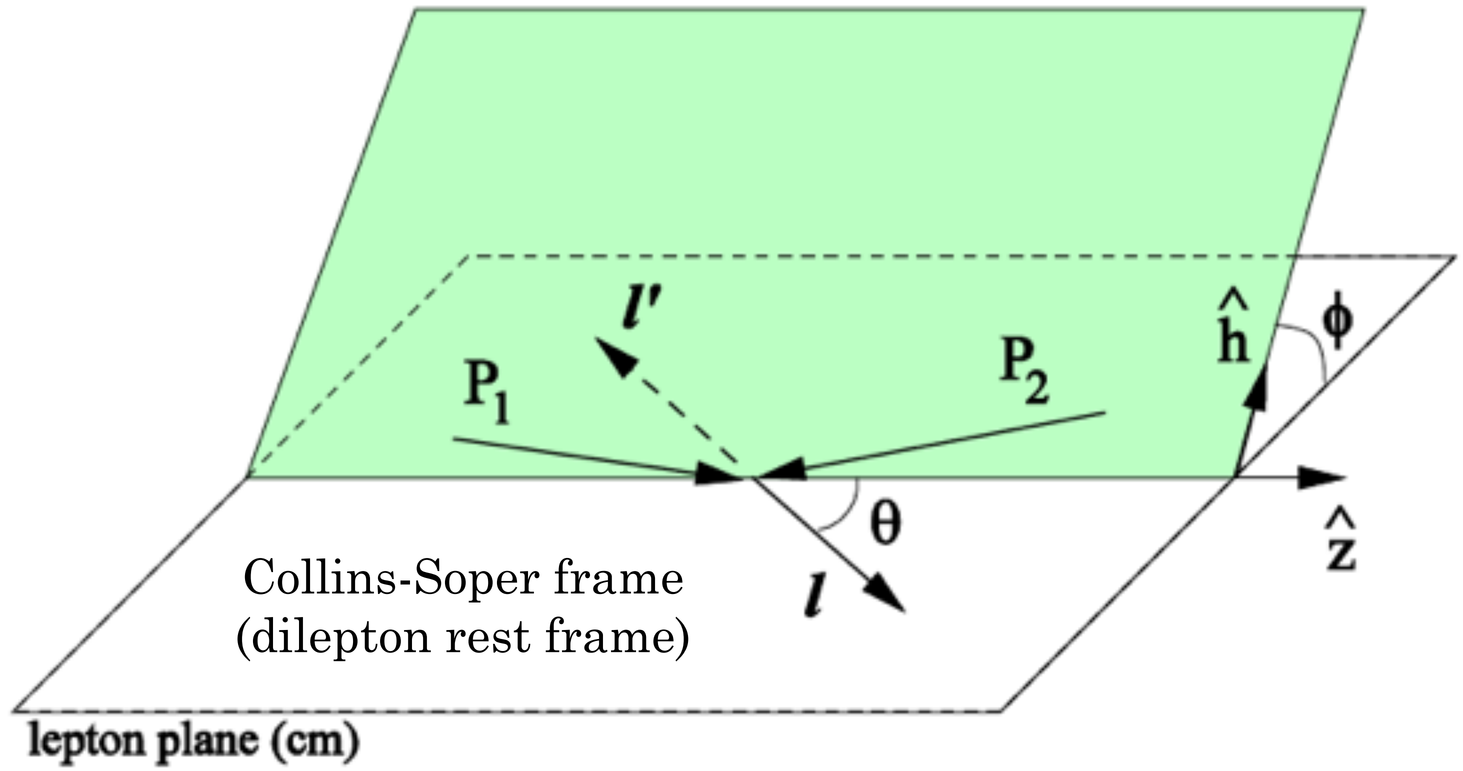


If it were not for the gluon exchange represented by the Wilson line, the Sivers modulation would be zero.

M. Diehl, arXiv:1512.01328

Angular dependence of the Drell-Yan cross section

"no spin"
(spin integrated)



"Naive Drell-Yan" in collinear (k_T=0) qqbar annihilation:

$$\frac{d\sigma}{d\Omega} \propto 1 + \cos^2\theta$$

(1+cos²θ) "naive DY"+ k_T + higher O(α_S)
(presence of gluons will cause quarks to have k_T):

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

$$1 - \lambda = 2\nu$$

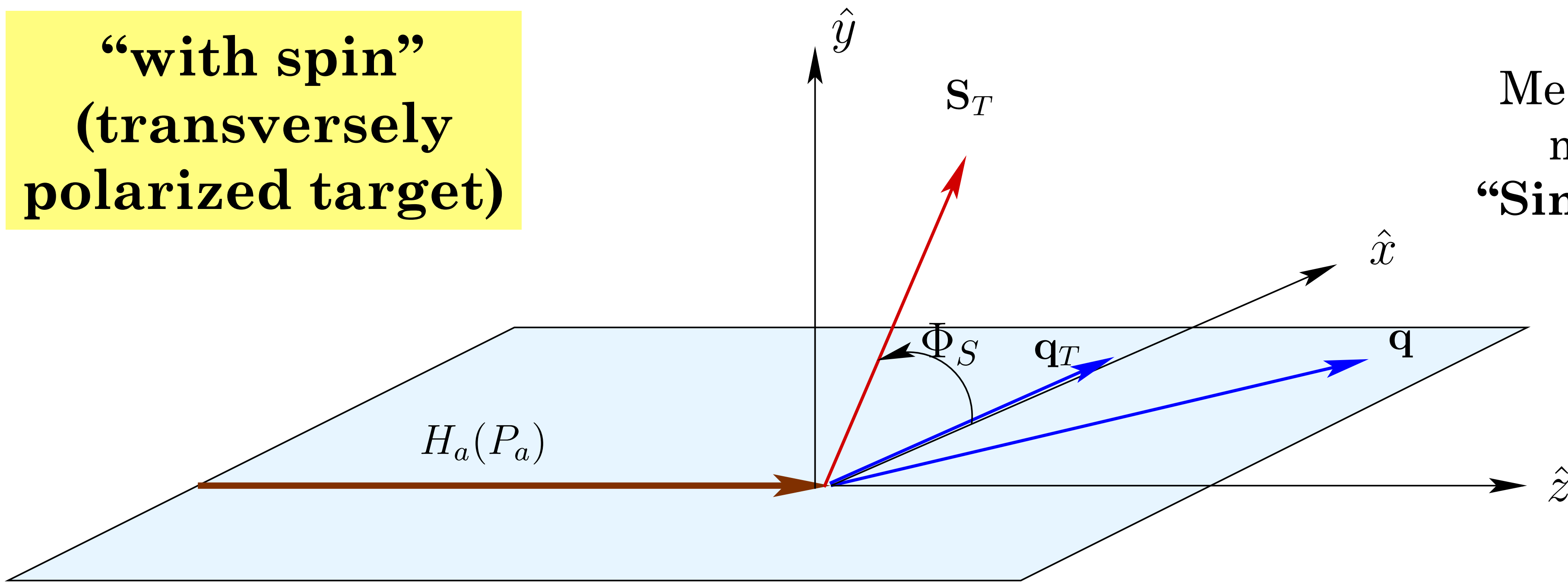
Lam-Tung relation

- *Basic derivation from structure-function formalism.*
- *Consequence of spin-½ nature of quarks.*
- *Expected to be valid also in the presence of QCD corrections.*

C.S. Lam and W.K. Tung, PRD 18 (1978) 2447

Angular dependence of the Drell-Yan cross section

"with spin" (transversely polarized target)



Measure magnitude of azimuthal modulations in cross section:
"Single-Spin Asymmetries" SSA

beam target

Drell-Yan DF $\otimes$ DF

$$d\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) = 1 + \overline{h}_1^\perp \otimes h_1^\perp \cos(2\phi)$$

$$+|S_T| \; \overline{f}_1 \otimes \overline{f}_{1T}^\perp \sin\phi_S$$

$$+|S_T| \; \overline{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi + \phi_S)$$

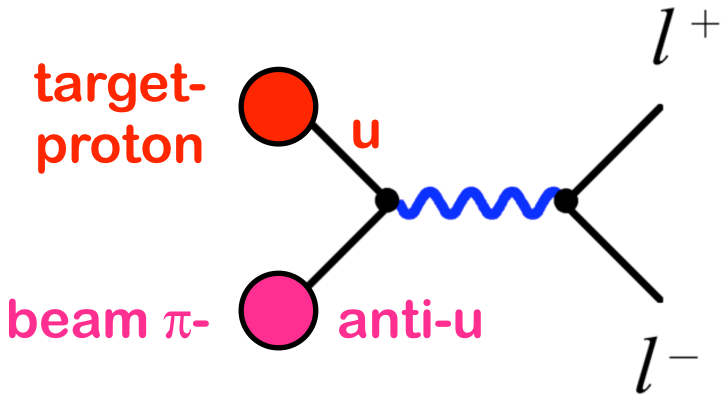
$$+|S_T| \; \overline{h}_1^\perp \otimes h_1 \sin(2\phi - \phi_S)$$

beam		target
(BM)	$\otimes$	**(BM)**
(f_1)	$\otimes$	**(Sivers)**
(BM)	$\otimes$	**(Pretzelosity)**
(BM)	$\otimes$	**(Transversity)**

Why a meson beam?

Drell-Yan DF ⊗ DF

$$\sigma^{\mathrm{DY}} \propto f_{\overline{u}|\pi} \otimes f_{u|p}$$



- **Flavor sensitive**: meson is specific qqbar compound
  - pi-minus on proton: selectively probes u-quark Sivers distribution of the proton
  - no cancellation effects by opposite-sign u- and d-quark Sivers contributions

- Creation of **large-mass di-lepton from valence quarks**: large x
  Proton-induced DY generates di-lepton
  from sea-quark object with small x.

- Mesons as alternative probe to **test meson structure** and **nuclear models** (not accessible in DIS)

pion		proton
$(BM)_\pi$	⊗	$(BM)_p$
$(f_1)_\pi$	⊗	$(Sivers)_p$
$(BM)_\pi$	⊗	$(Pretzelosity)_p$
$(BM)_\pi$	⊗	$(Transversity)_p$

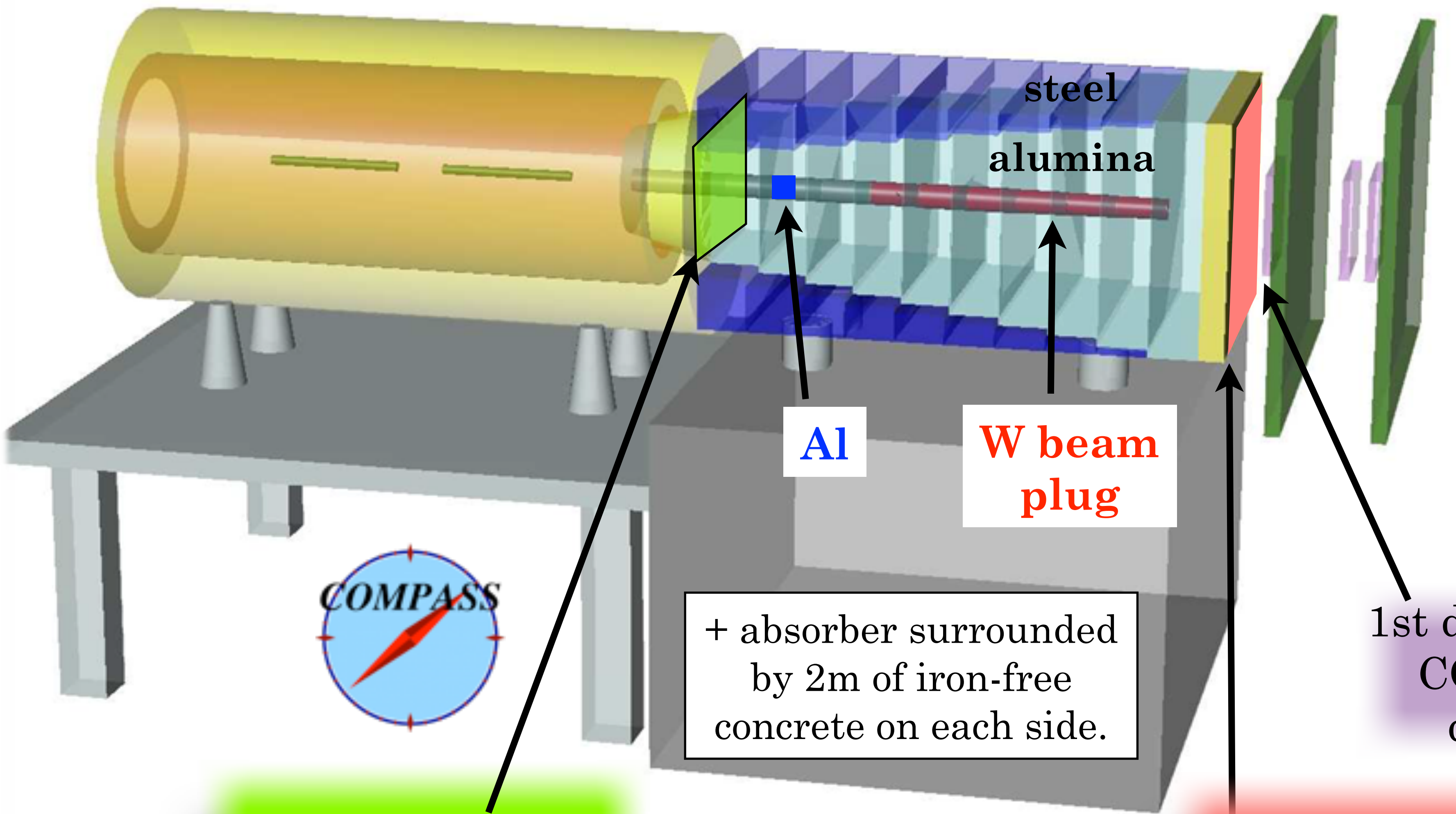
See also: W.-C. Chang and D. Dutta, arXiv:1306.3971,

Transversely polarized NH_3 target & Hadron absorber

To minimize multiple scattering of muons and to maximize stopping power for hadrons.

1. Long. pol.: DNP & 2.5T solenoid
2. Trans. pol: 0.6T dipole

Ammonia beads immersed into liquid helium; dilution factor: f=0.22



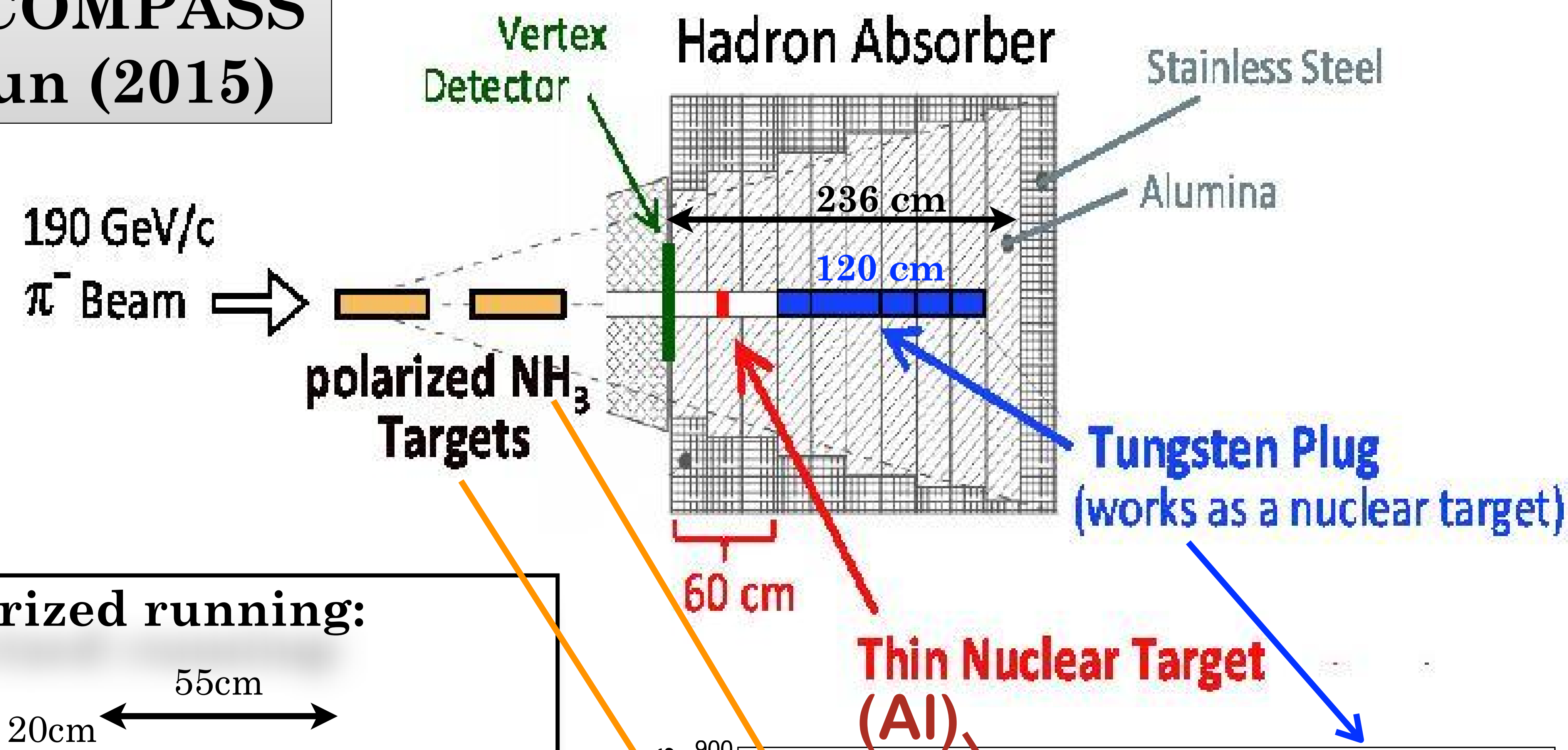
Vertex detector

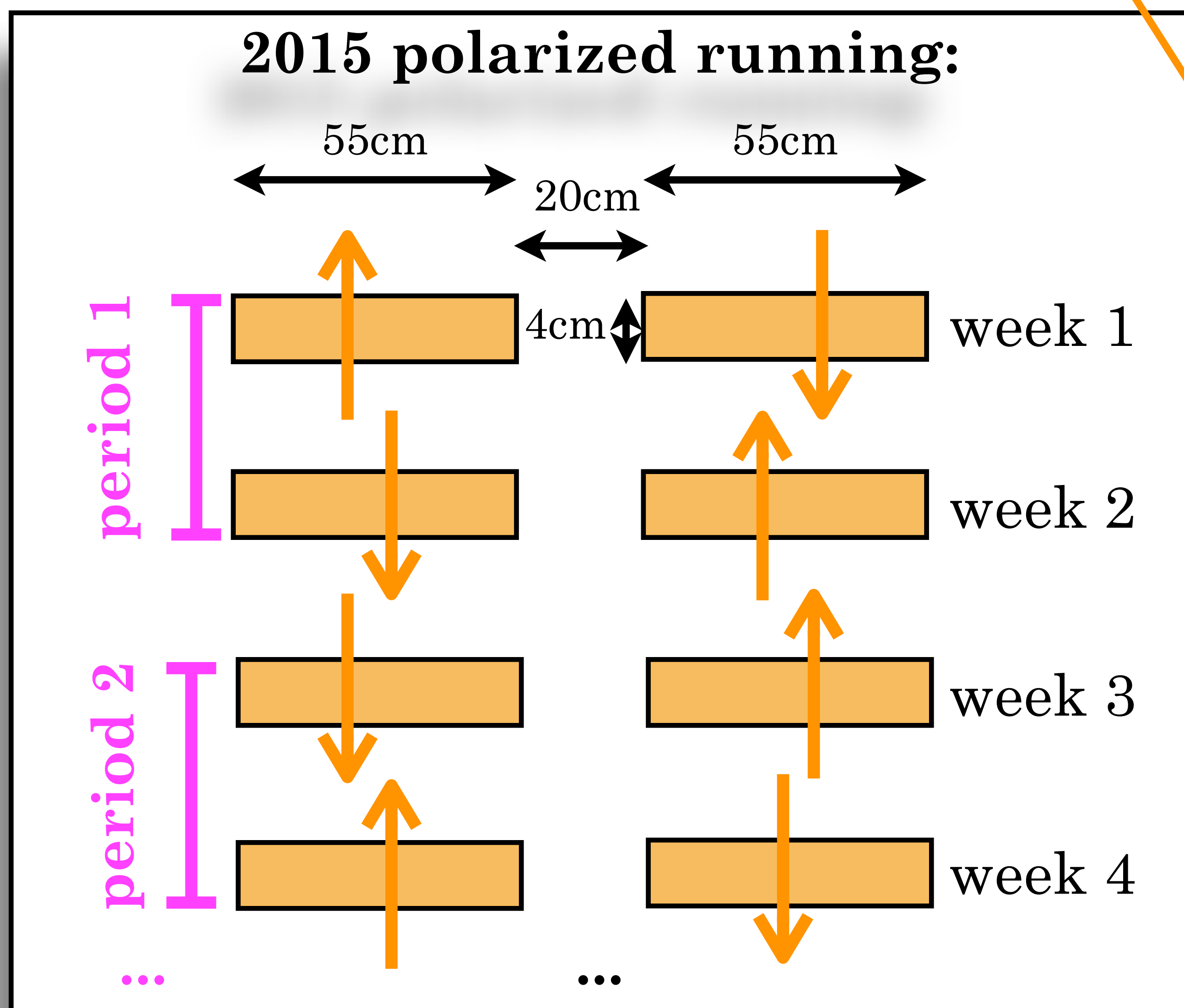
to improve resolution of
- mass & angle of virtual photon
- vertex position.

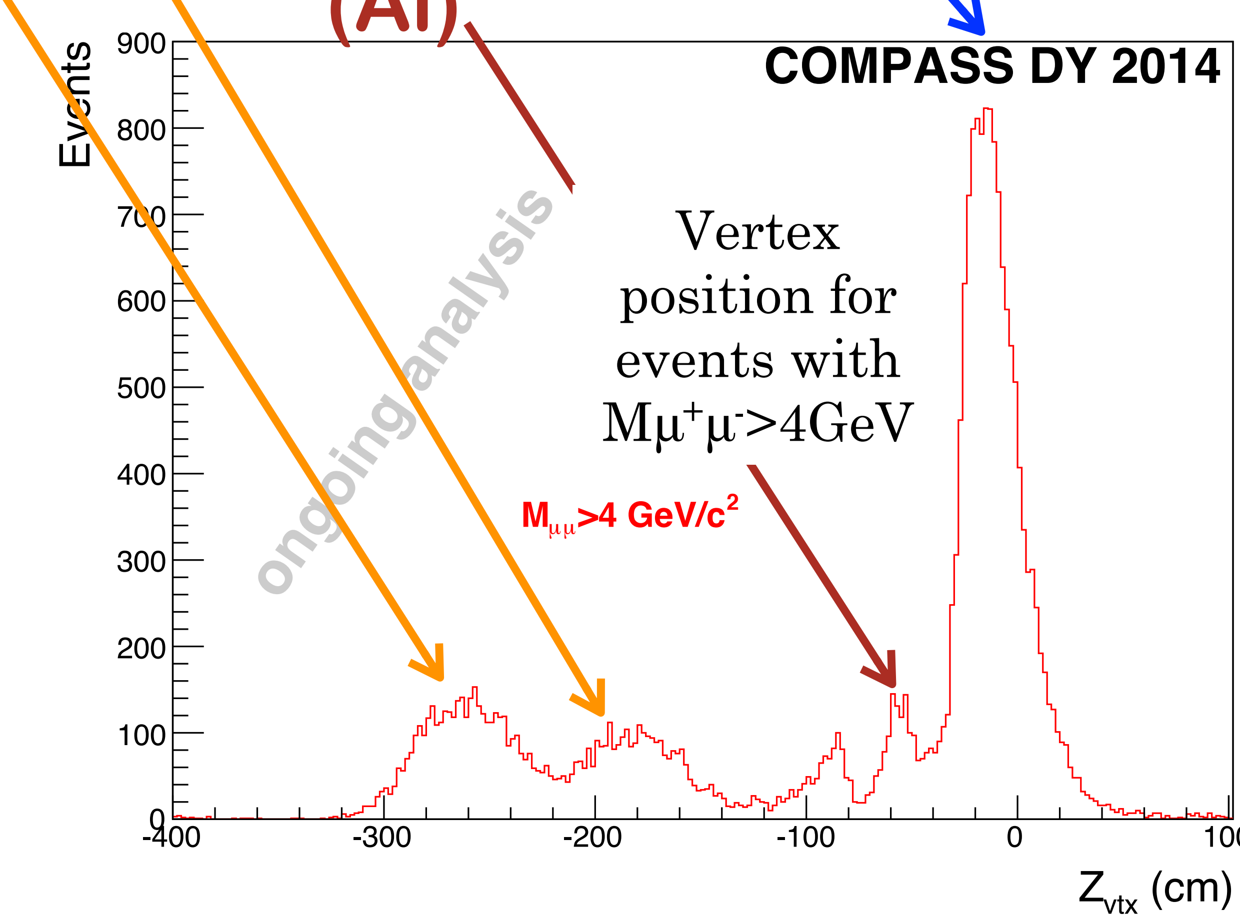
^{6}Li absorber

to prevent flooding of very upstream detectors with charged particles from capture of spallation neutrons ($\Rightarrow \gamma \Rightarrow e^+e^-$).

Targets for COMPASS Drell-Yan run (2015)







Existing COMPASS Drell-Yan data

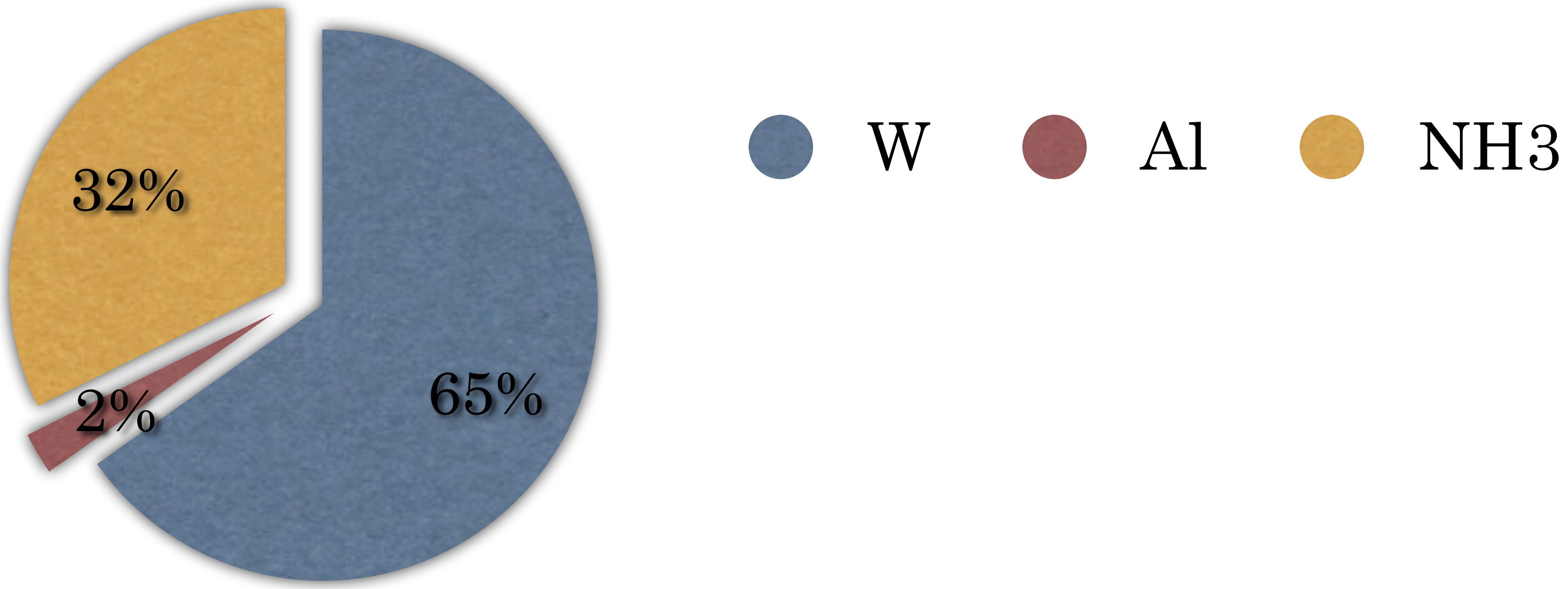
- 2014: **unpolarized proton** (mass 1),
  unpolarized aluminum (mass 27),
  unpolarized tungsten (mass ~183)

→ ***preliminary distributions shown today***

- 2015: **transversely polarized proton**,
  unpolarized aluminum,
  unpolarized tungsten

- Scatter off different targets and record data at the same time.

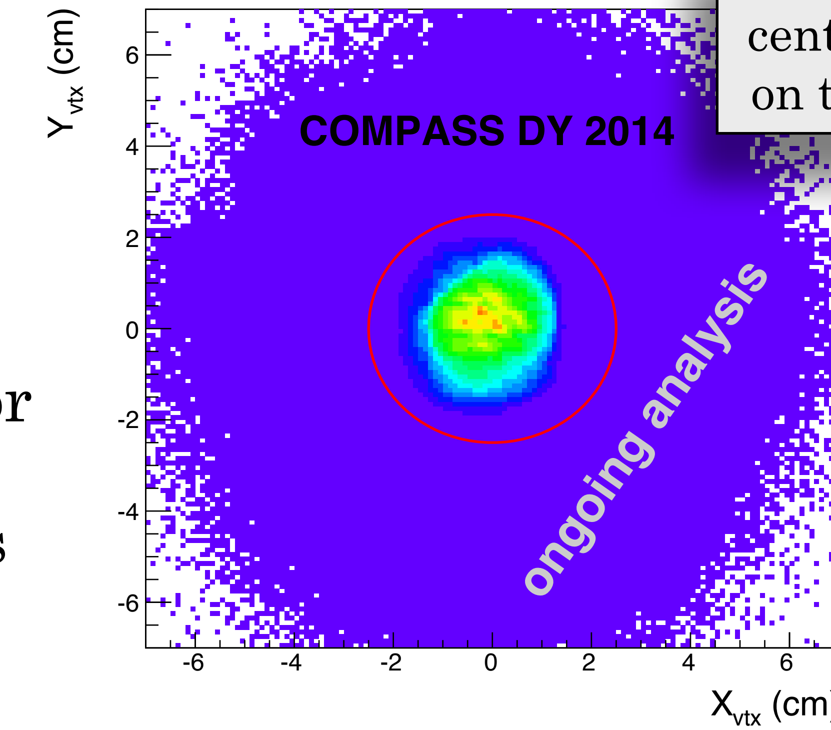
Events with oppositely charged di-muon events (Mμ+μ->4GeV):

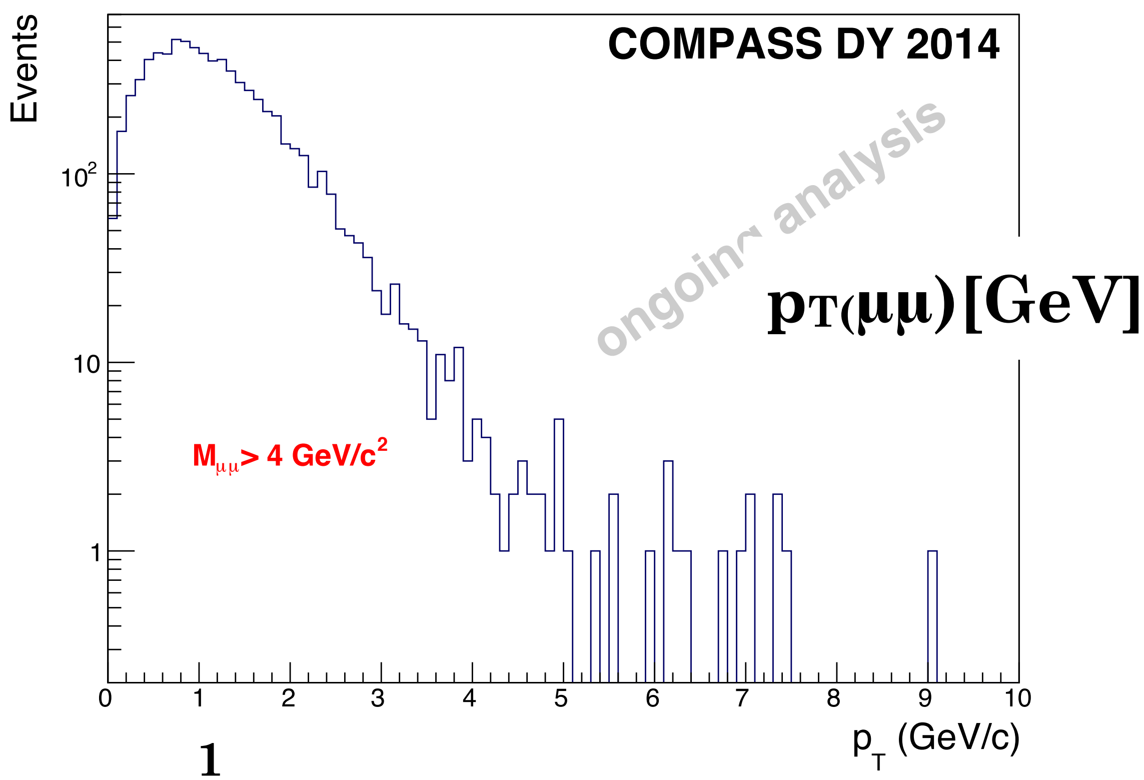


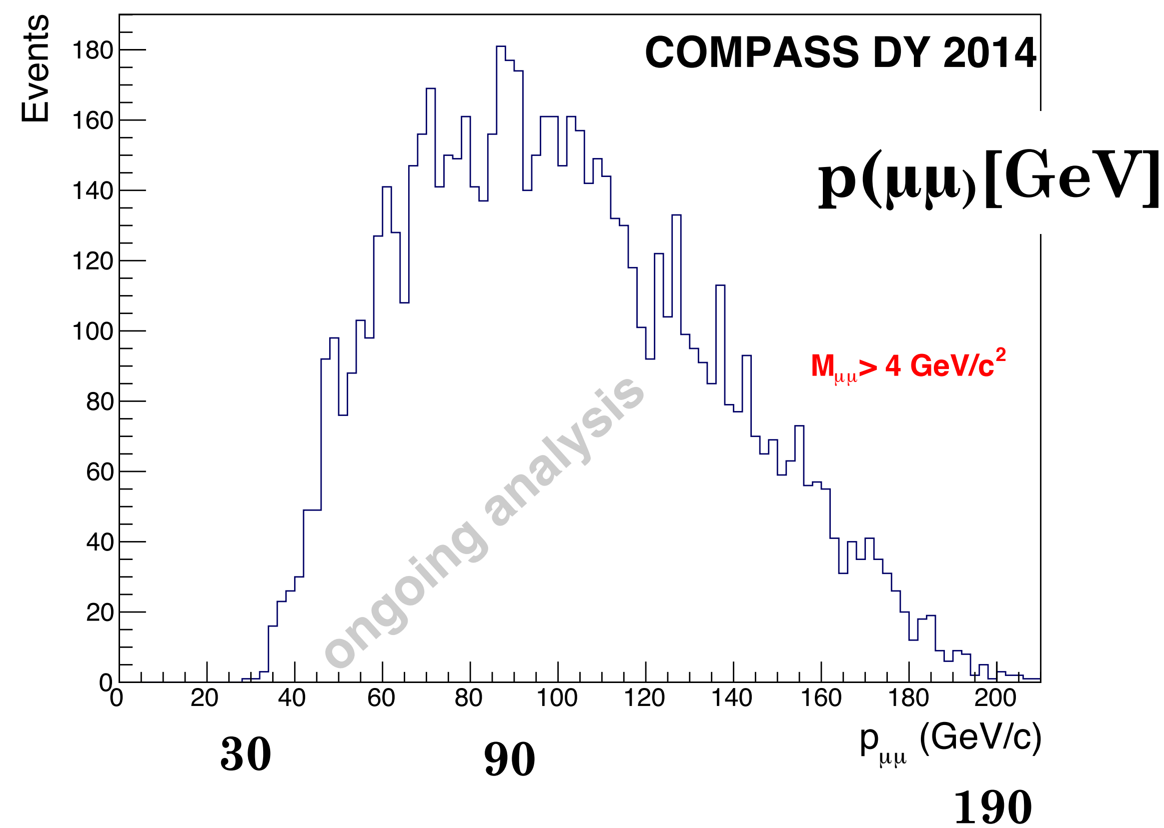
2014 data (DY pilot run) - preliminary

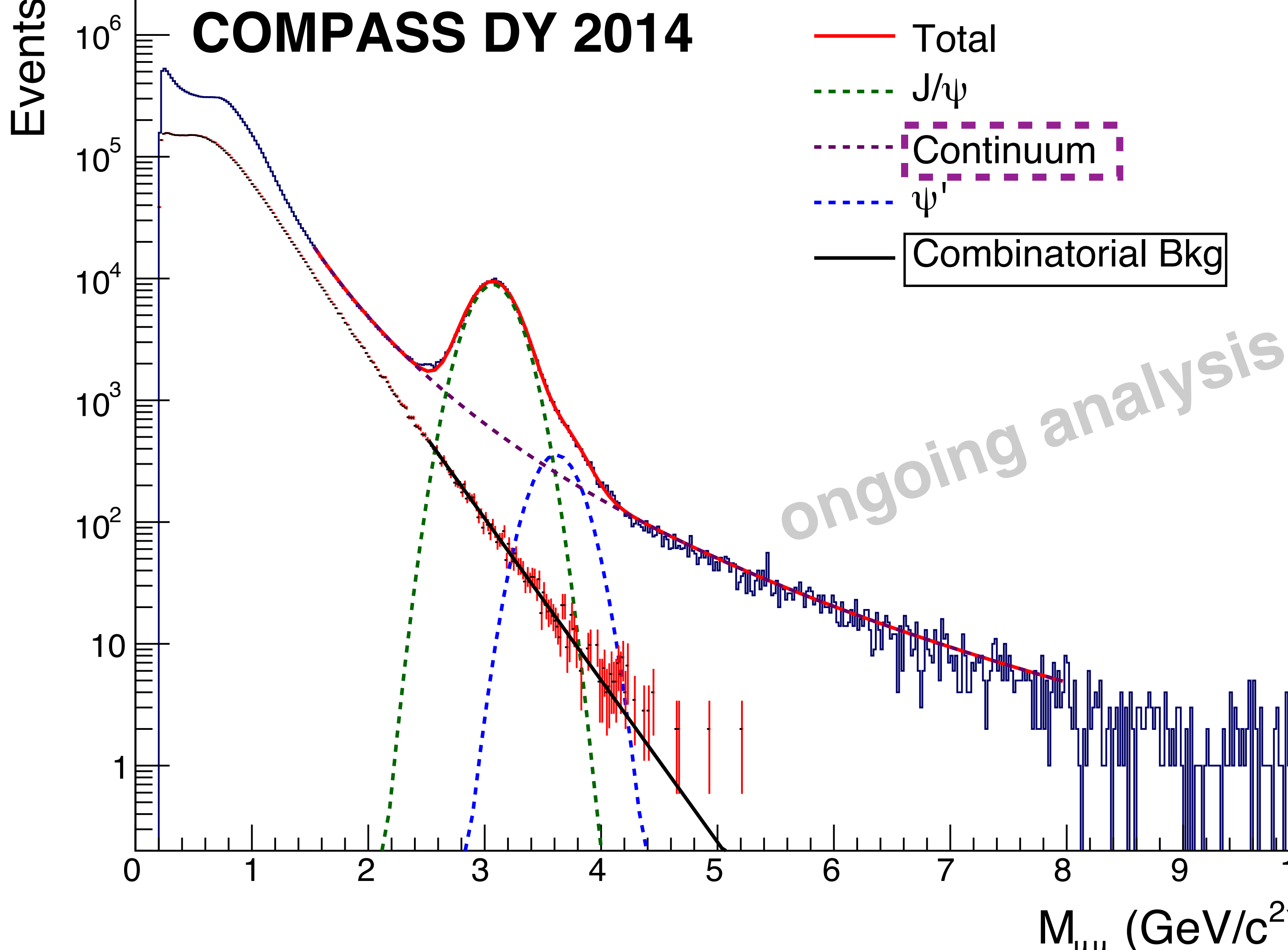
- ~ 2 weeks of stable data taking
- Average beam intensity: 7.3×10^{7} particles /s (up to nominal 10^{8}/s)
- No target polarization, no (usage of) vertex detector
- Statistics (**NH_3 $M\mu^{+}\mu^{-}$>4GeV**): ~7k di-muon events (~9% of 2015 data); ~200k J/ψ.

Beam centering on target







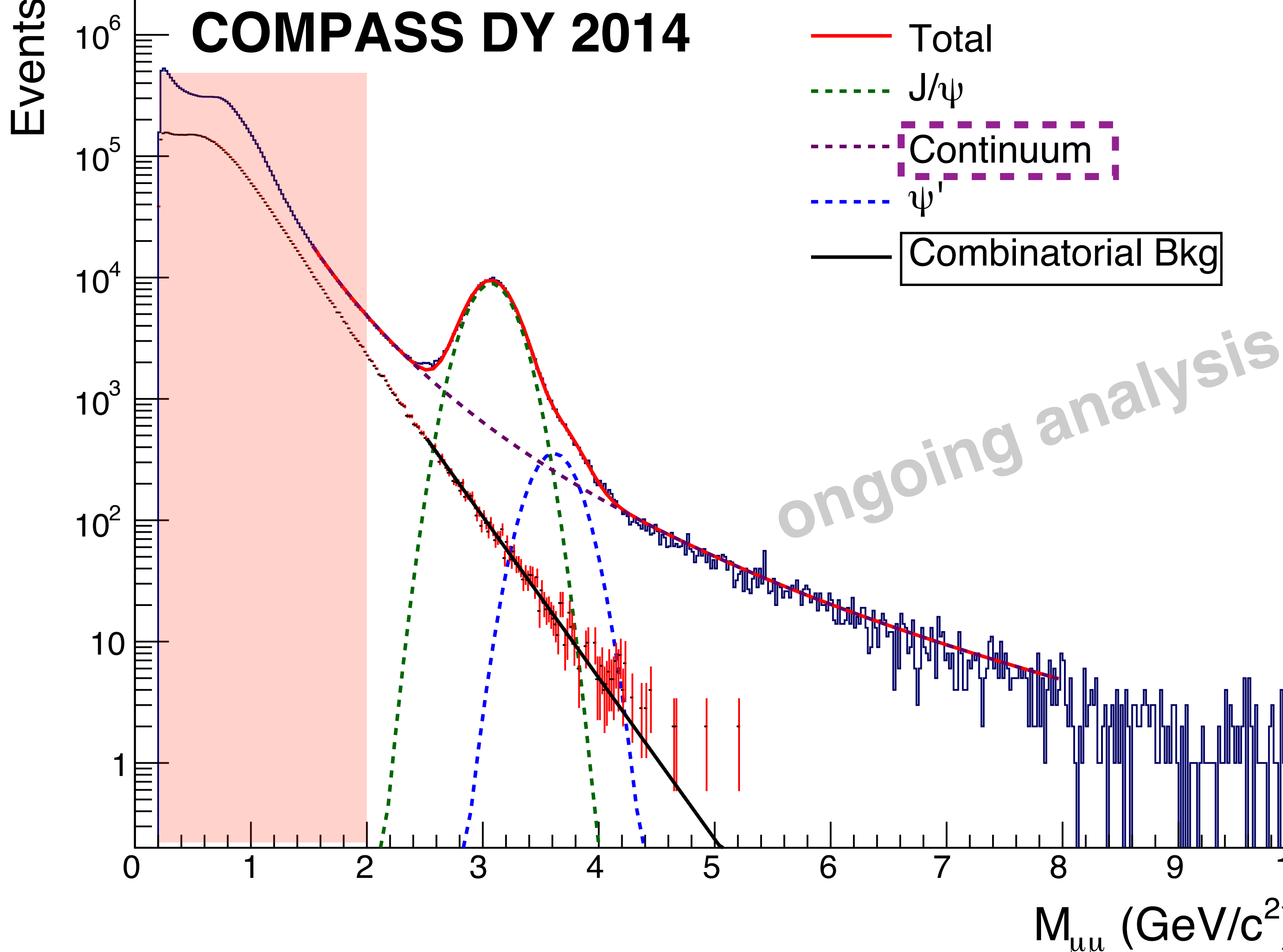


COMPASS di-muon kinematics

Continuum:
- Drell-Yan
- Open charm/bottom decays
- Combinatorial background

Combinatorial background:
- From pion / kaon decays.
- Estimated from like-sign muons.

Mμμ [GeV]	<2	2-2.5	2.5-4		4-9
Q^2 [GeV^2]	1-4	4-6.25	6.25-16		16-81
Region	**“DY low mass”**	**“DY medium mass”**	**“DY J/ψ”**	**“J/ψ”**	**“DY high mass”**
clean?	✗✗ >50% bg	✗	✗ ✗	✗✗	✔ ✔ <10% bg
high DY x-section?	✔ ✔	✔	✔	-	✗
large Sivers?	✗	✗	✗	-	✔



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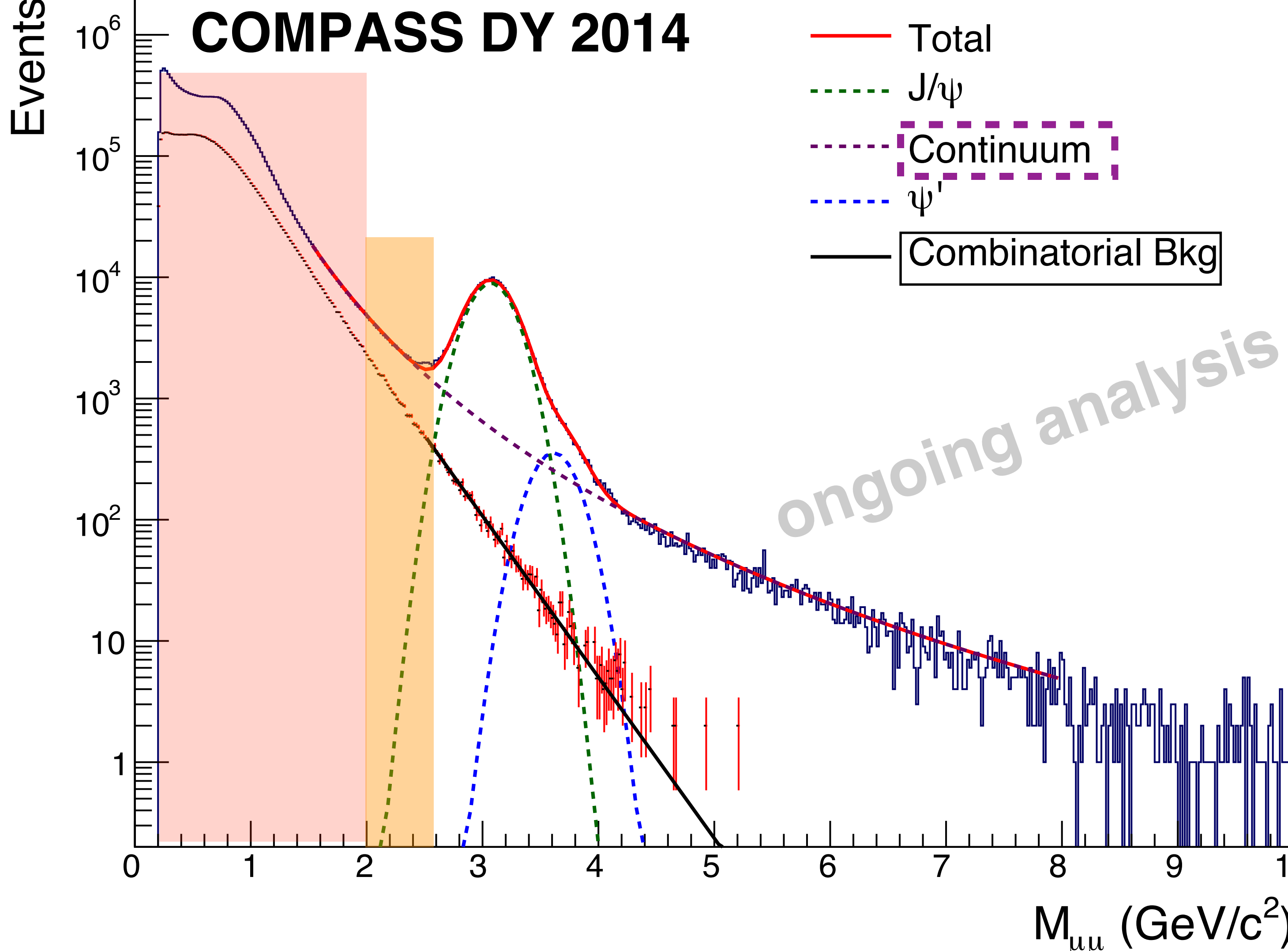
clean?	✘✘ >50% bg	✘	✘ ✘	✘✘	✔ ✔ <10% bg
high DY x-section?	✔ ✔	✔	✔	-	✘
large Sivers?	✘	✘	✘	-	✔



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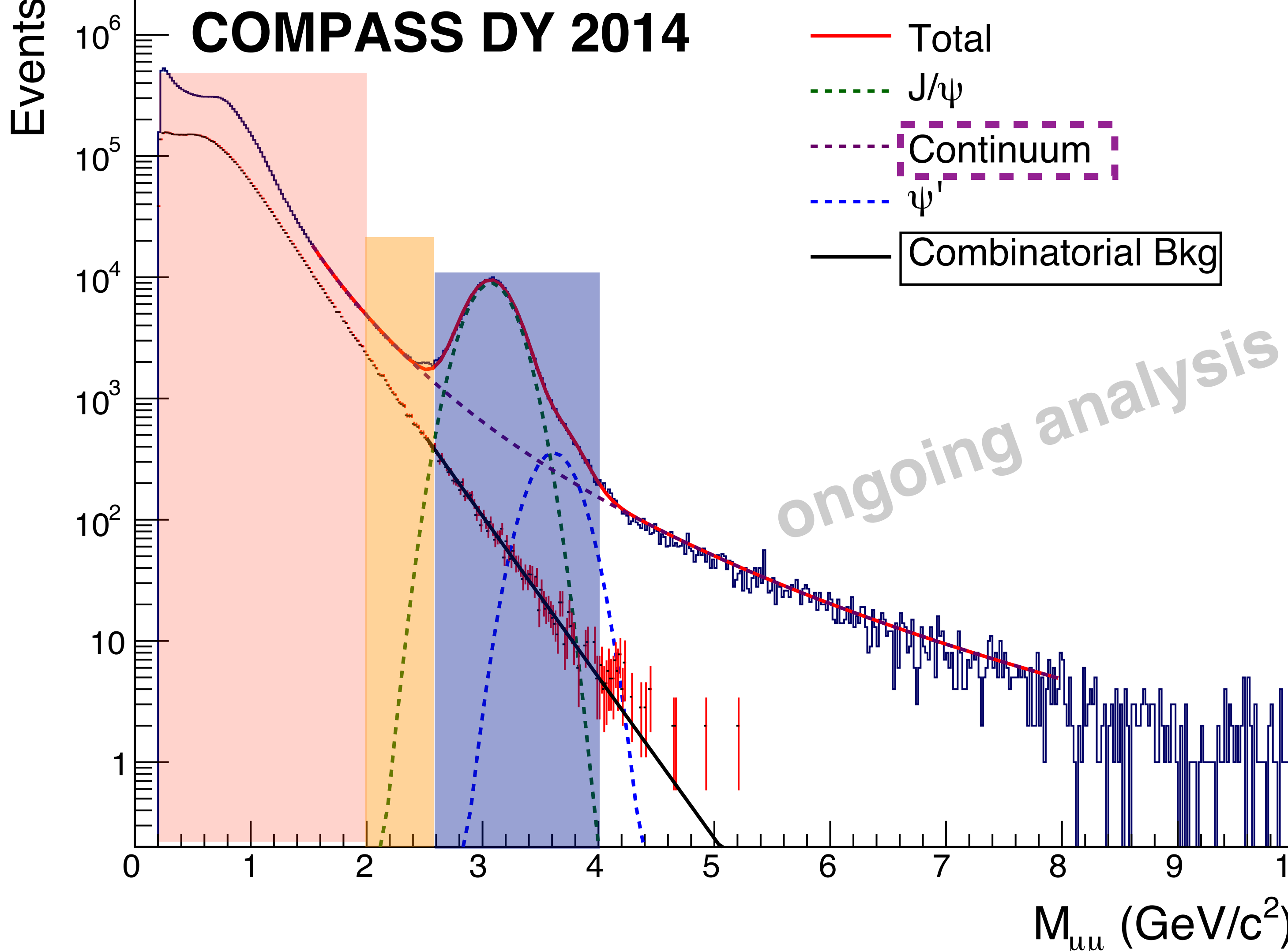
clean?	✗✗ >50% bg	✗	✗ ✗	✗✗	✔ ✔ <10% bg
high DY x-section?	✔ ✔	✔	✔	-	✗
large Sivers?	✗	✗	✗	-	✔



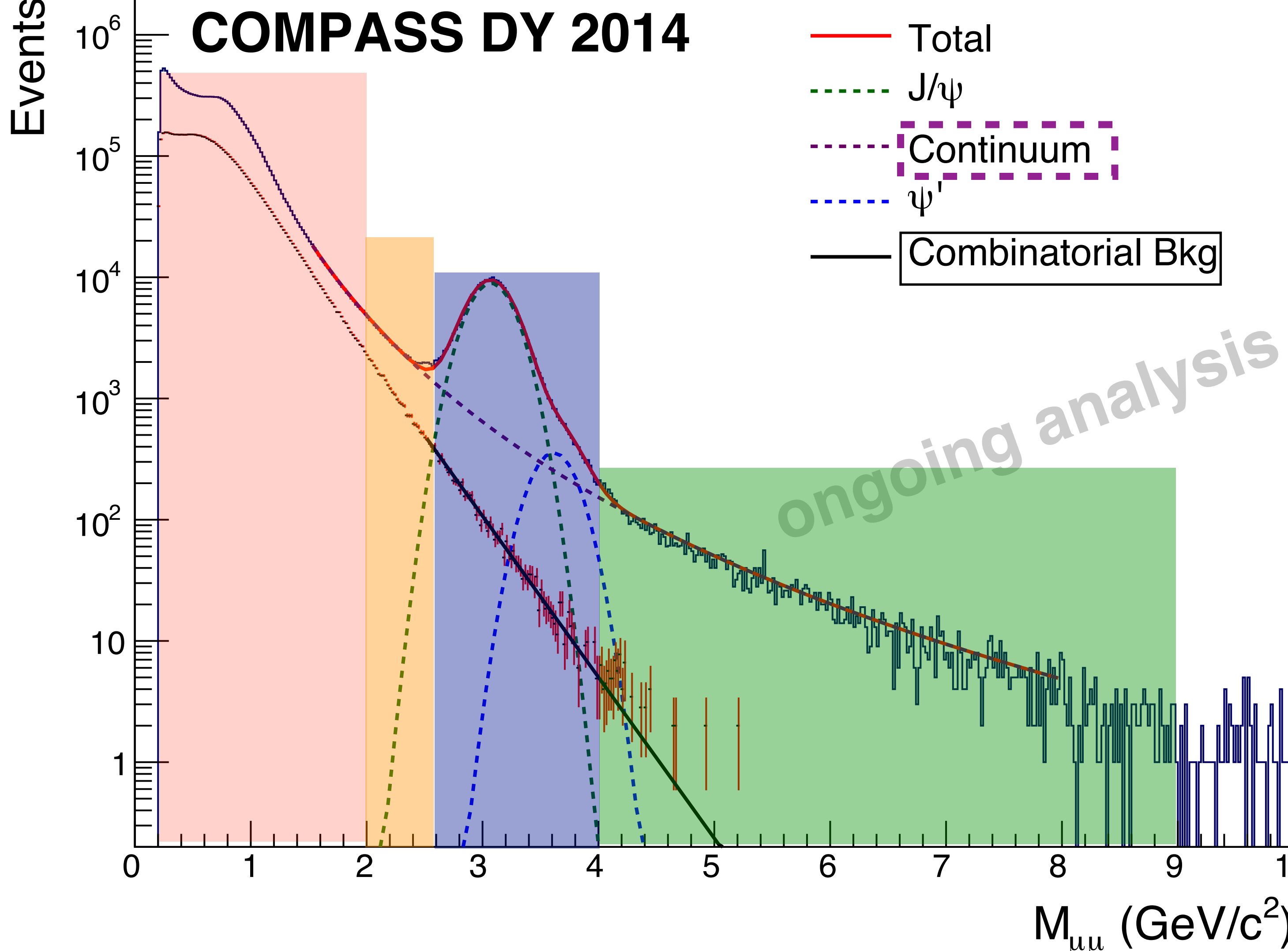
COMPASS di-muon kinematics

Continuum:
- Drell-Yan
- Open charm/bottom decays
- Combinatorial background

Combinatorial background:
- From pion / kaon decays.
- Estimated from like-sign muons.

Mμμ [GeV]	<2	2-2.5	2.5-4		4-9
Q² [GeV²]	1-4	4-6.25	6.25-16		16-81
Region	**“DY low mass”**	**“DY medium mass”**	**“DY J/ψ”**	**“J/ψ”**	**“DY high mass”**
clean?	✗✗ >50% bg	✗	✗ ✗	✗✗	✔ ✔ <10% bg
high DY x-section?	✔ ✔	✔	✔	-	✗
large Sivers?	✗	✗	✗	-	✔

COMPASS di-muon kinematics



Continuum:
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Mμμ [GeV]	<2	2-2.5	2.5-4		4-9
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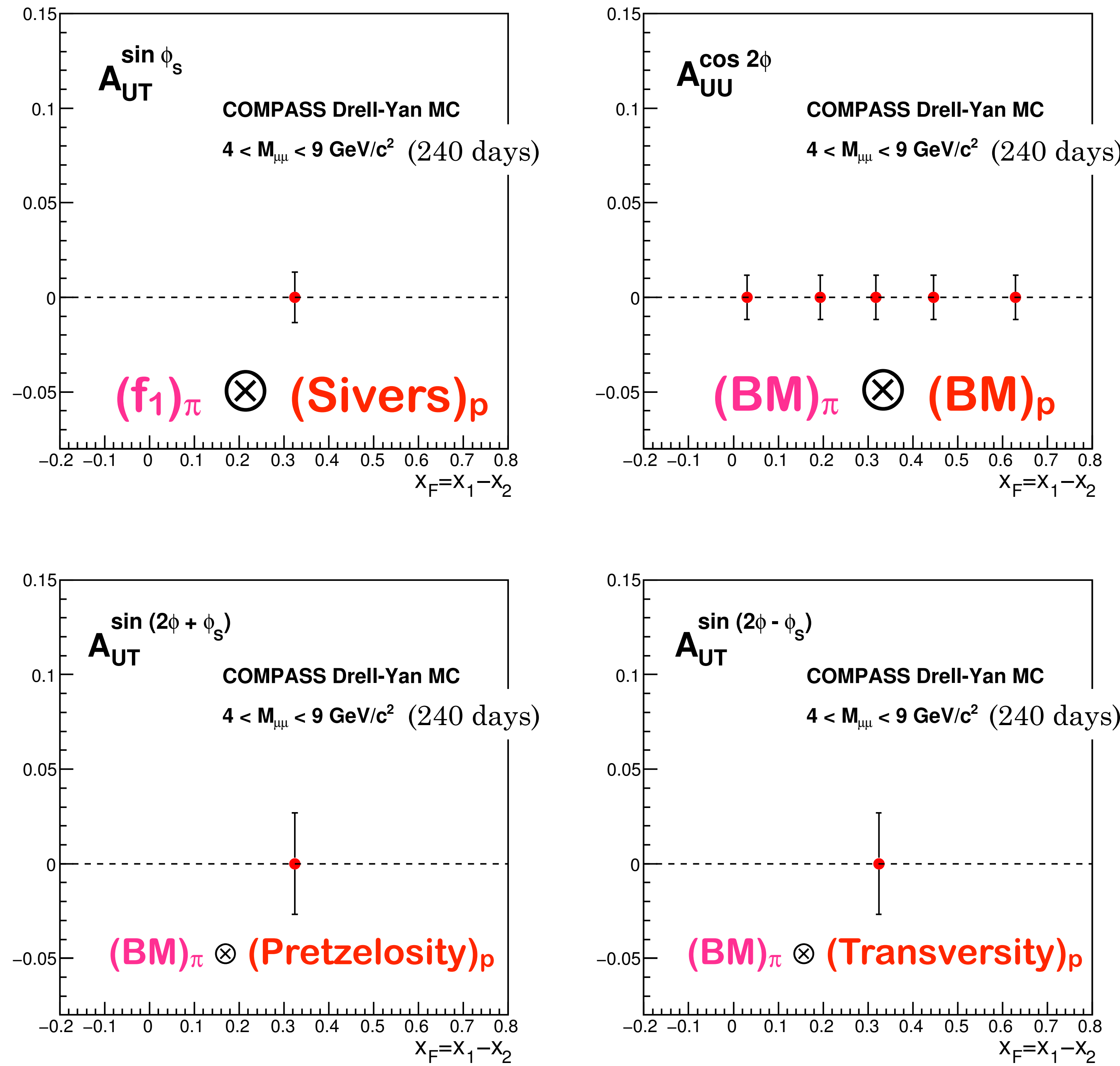
clean?	✗✗ >50% bg	✗	✗ ✗	✗✗	✔ ✔ <10% bg
high DY x-section?	✔ ✔	✔	✔	-	✗
large Sivers?	✗	✗	✗	-	✔

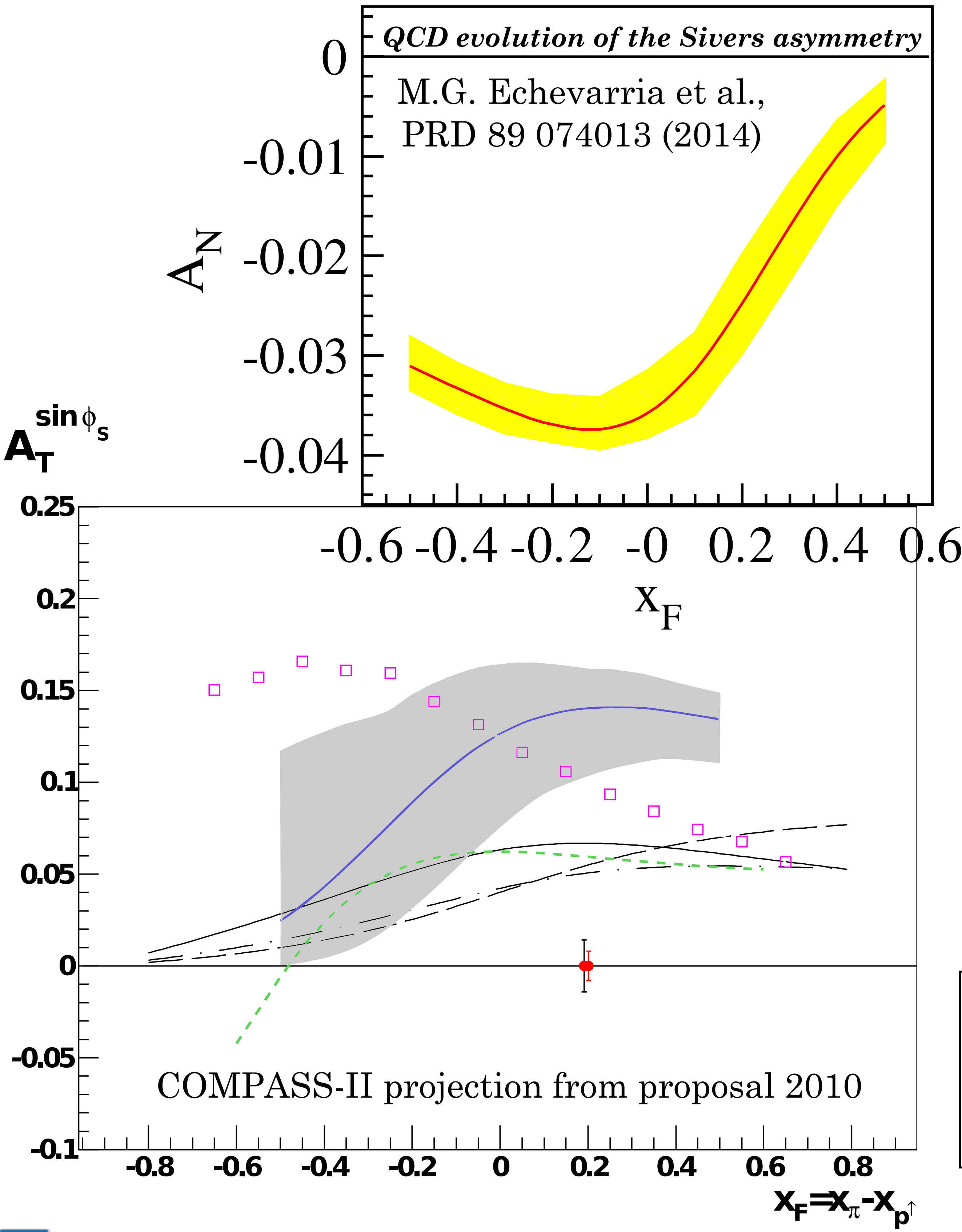
COMPASS Drell-Yan projections (2015+2018 data)

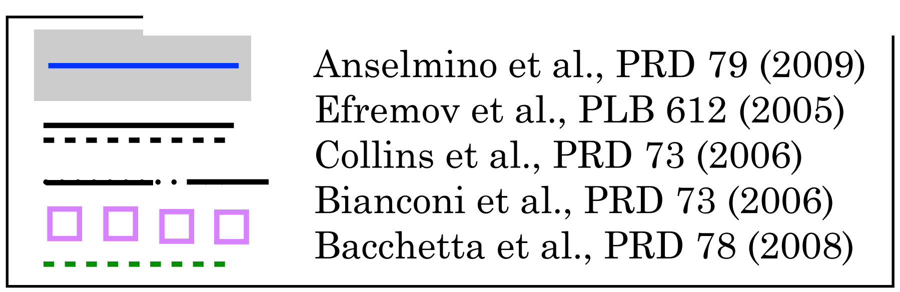
$$d\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) =$$
$$= 1 + \boxed{\bar{h}_1^\perp} \otimes \boxed{h_1^\perp} \cos(2\phi)$$
$$+ |S_T| \boxed{\bar{f}_1} \otimes \boxed{\bar{f}_{1T}^\perp} \sin\phi_S$$
$$+ |S_T| \boxed{\bar{h}_1^\perp} \otimes \boxed{h_{1T}^\perp} \sin(2\phi + \phi_S)$$
$$+ |S_T| \boxed{\bar{h}_1^\perp} \otimes \boxed{h_1} \sin(2\phi - \phi_S)$$

beam pion — target proton



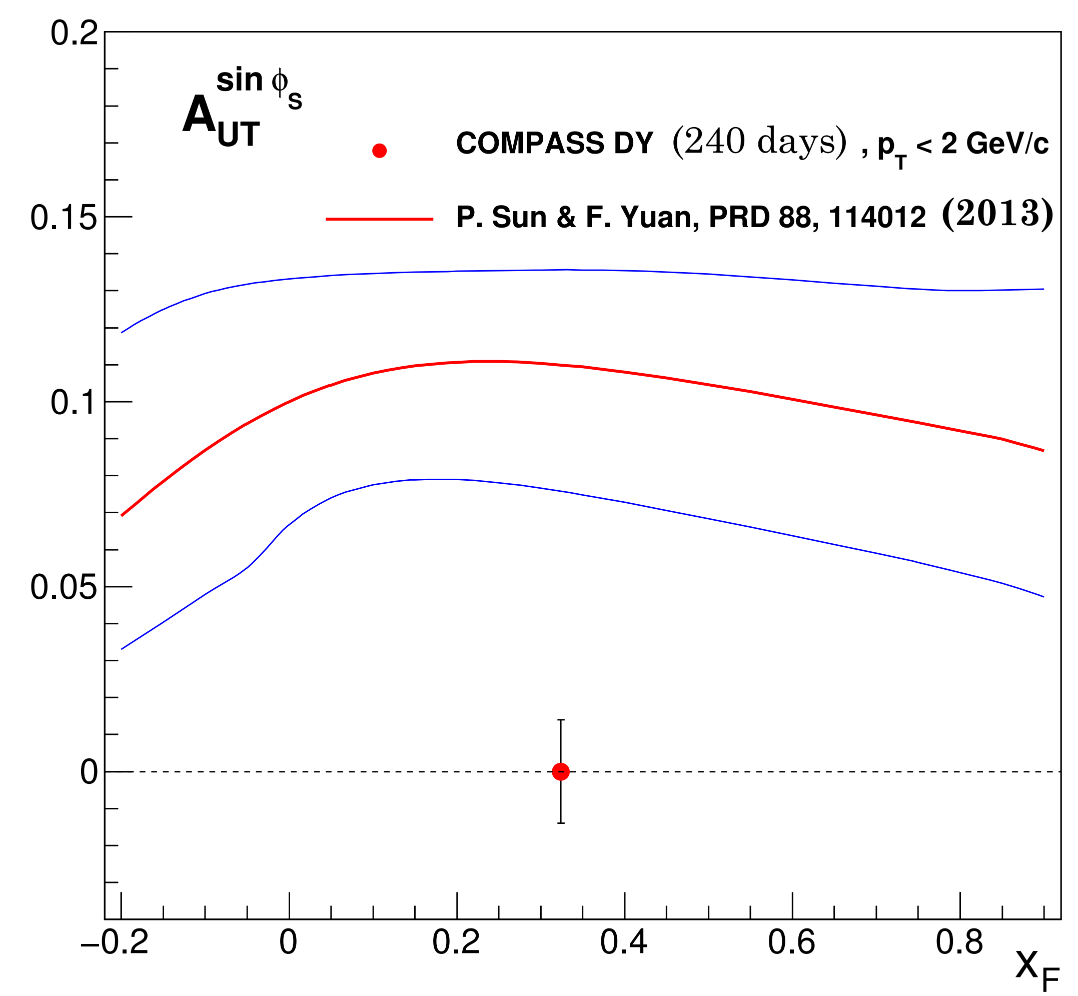
Sivers amplitude: predictions for COMPASS DY



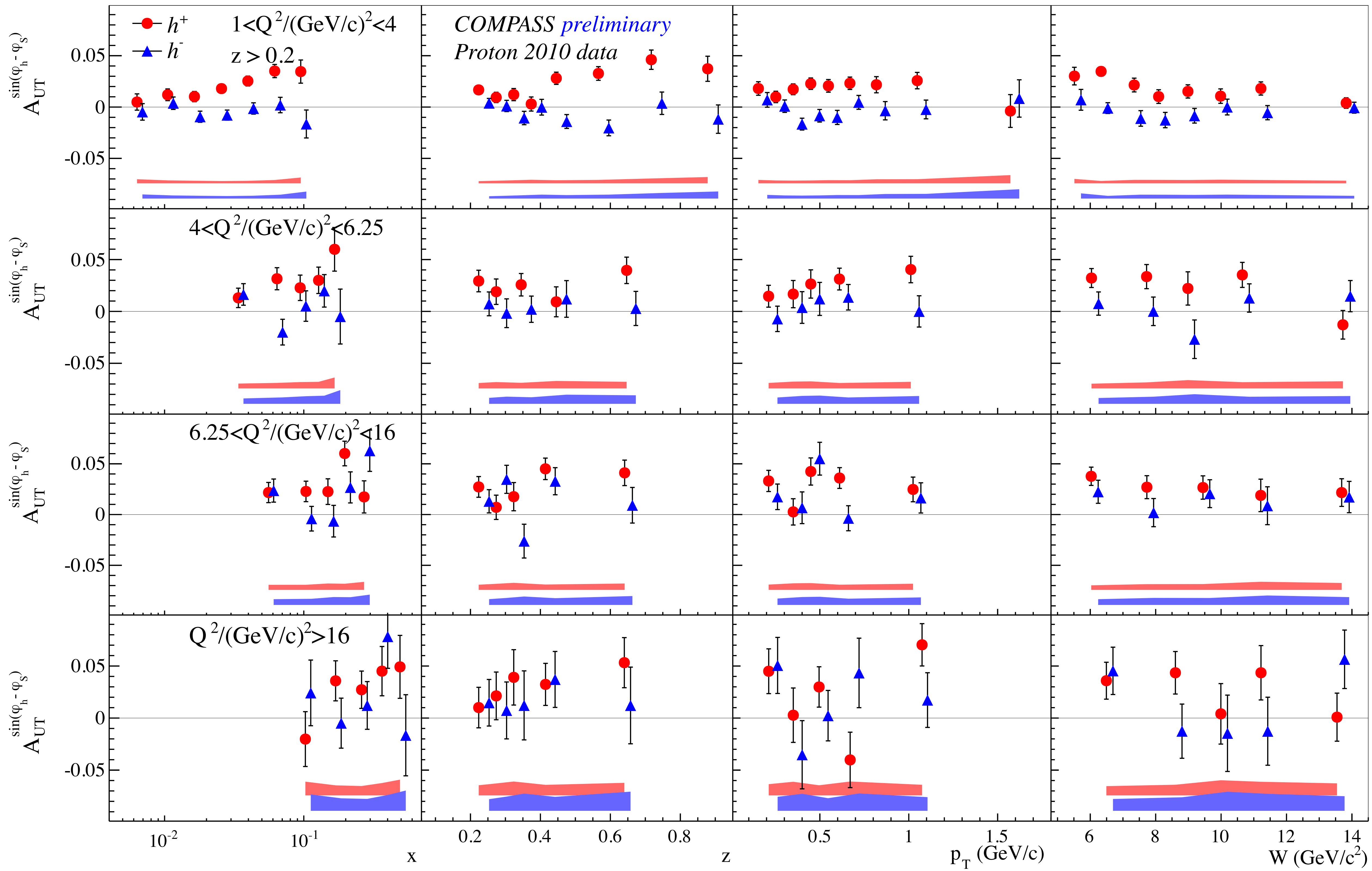


3-15% in absolute size.

Transverse momentum dependent evolution: Matching SIDIS processes to Drell-Yan and W/Z boson production



COMPASS SIDIS Sivers in DY kinematic range



Unpolarized Drell-Yan cross section

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

$$1 - \lambda = 2\nu$$

Lam-Tung relation

Boer and Mulders 1998: distribution function of the unpolarized nucleon with intrinsic k_T dependence.
- Describes correlation between **quark transverse spin and momentum**.
- Induces cos(2Φ) modulation of the DY cross section.

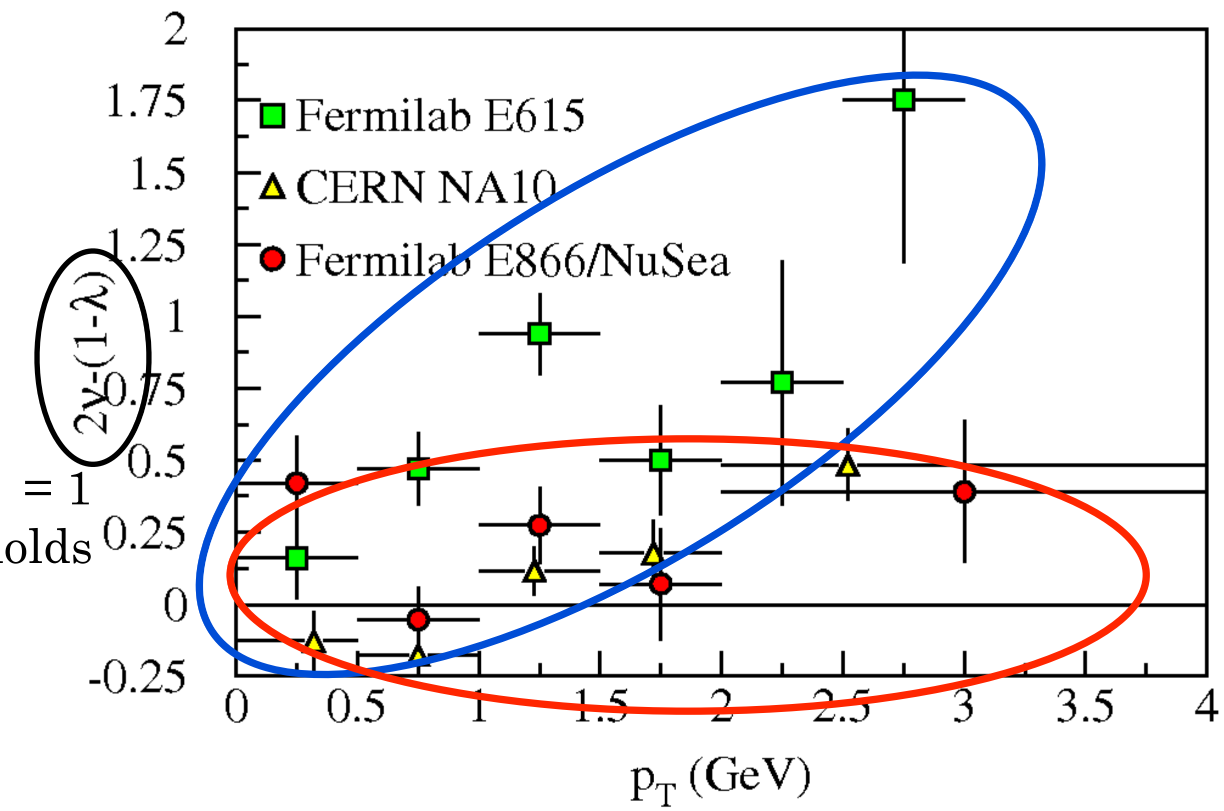
Lam-Tung in proton- and pion-induced DY

$$1 - \lambda = 2\nu$$

- Proton-induced Drell-Yan (E866)
  - consistent with LT-relation
  - no cos(2ϕ) dependence
  - no p_T dependence

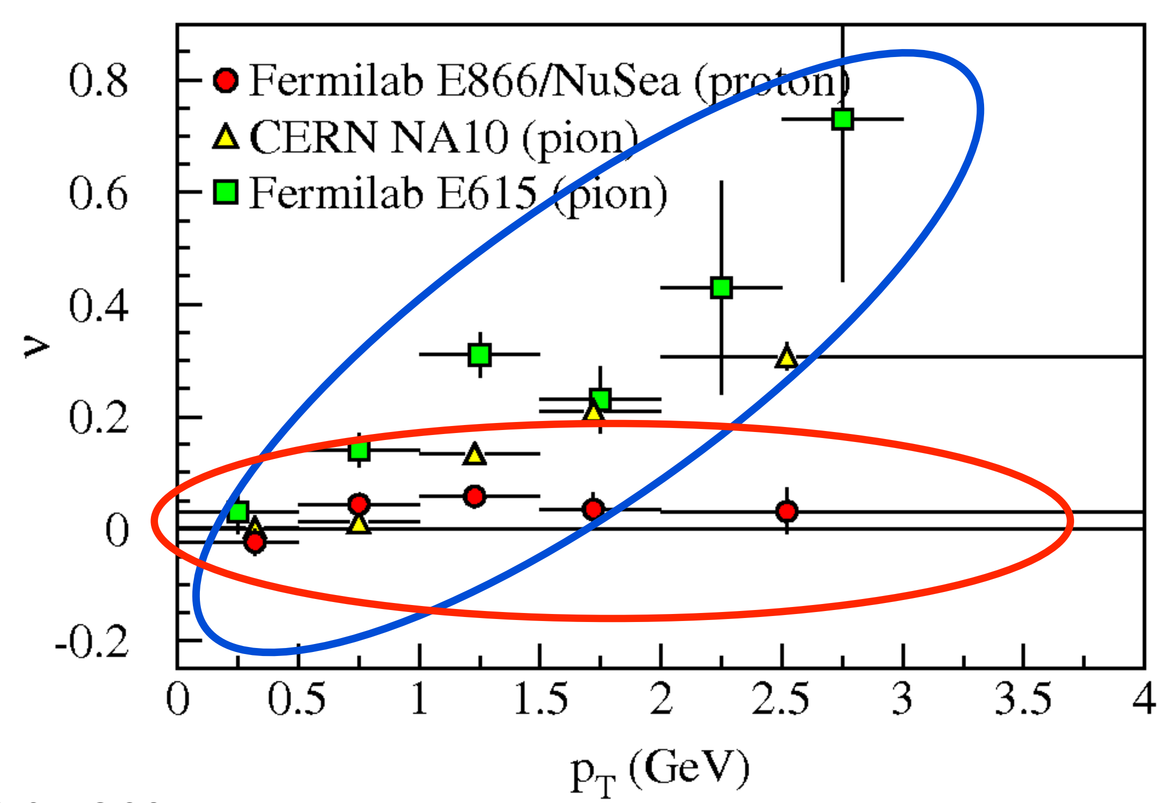
- Pion-induced Drell-Yan (NA10, E615)
  - violates LT-relation
    (independent of nucleus:
    no nuclear effect)
  - large cos(2ϕ) dependence
  - strong with p_T

☛ **One candidate to explain LT violation: BM function**



- Pionic DY probes BM (valence), target=proton
  Protonic DY probes BM (sea), target=proton

  BM (sea) ≪ BM (valence)



☛ study of spin-orbit correlations

see also: P. E. Reimer, arXiv:0704.3621

Spin-orbit correlations from Drell Yan?

- Boer and Mulders 1998: distribution function of the unpolarized nucleon with intrinsic k_T dependence.
  - Describes correlation between quark transverse spin and momentum.
  - Induces cos(2Φ) modulation of the DY cross section.

- Other theoretical interpretations:
  - QCD higher-twist effect causes change of virtual-photon polarization from transversely (λ=1) to longitudinally (λ=-1) polarized for $x_\pi \to 1$?
    - Data taken at different $\sqrt{s}$: pion: 11 GeV and 16 GeV; proton: 39 GeV.
    - Such effect should be seen in E906/SeaQuest data.
  - Spin correlations between annihilating quark and anti-quark?
  - Glauber gluons, QCD instantons, ...

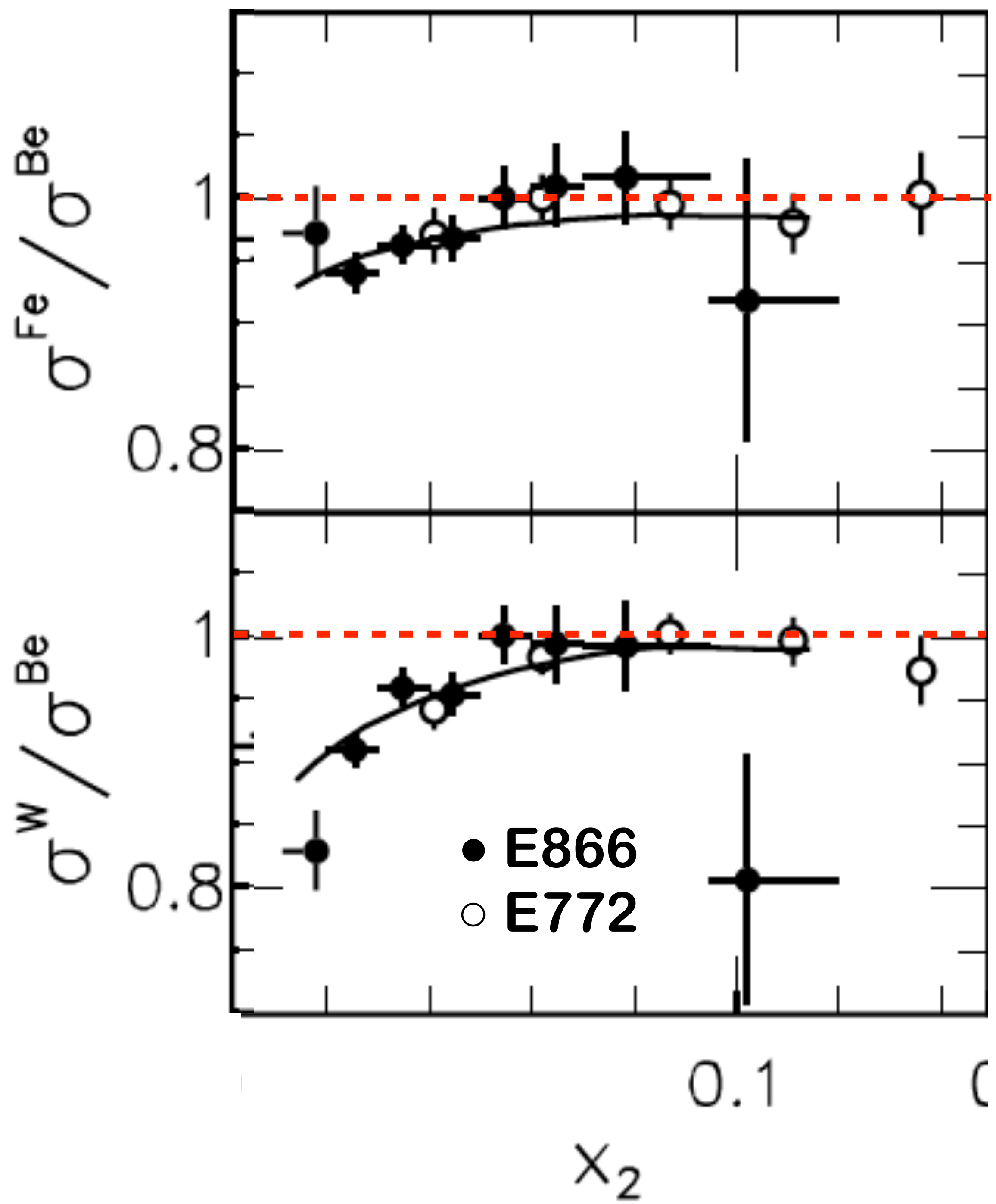
More measurements in wider kinematic range, and kaon/anti-proton beams will help to differentiate the interpretations.

EMC effect in Drell Yan

$$\frac{\sigma^{\mathrm{pA}}}{\sigma^{\mathrm{pd}}} \approx \frac{\overline{u}_{\mathrm{A}}(x)}{\overline{u}_{\mathrm{N}}(x)}$$

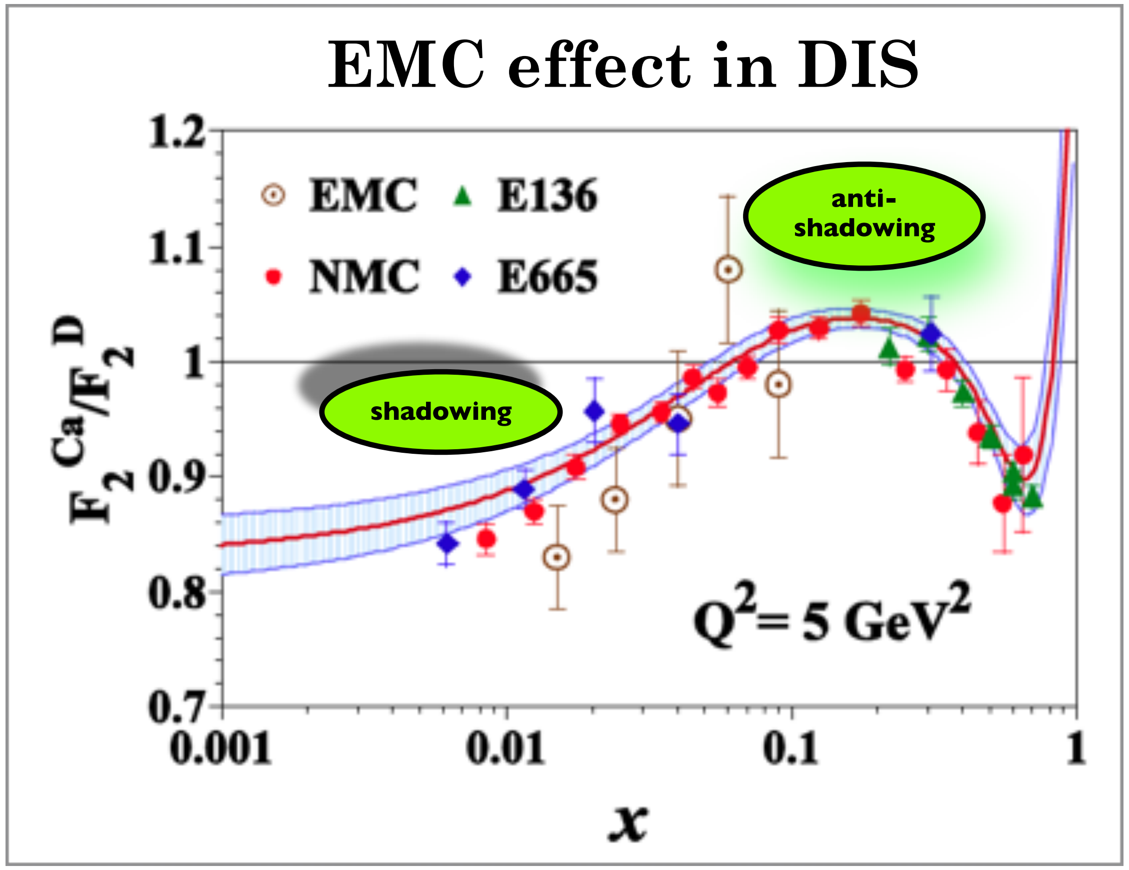
Modification of quark distributions in the nuclear medium

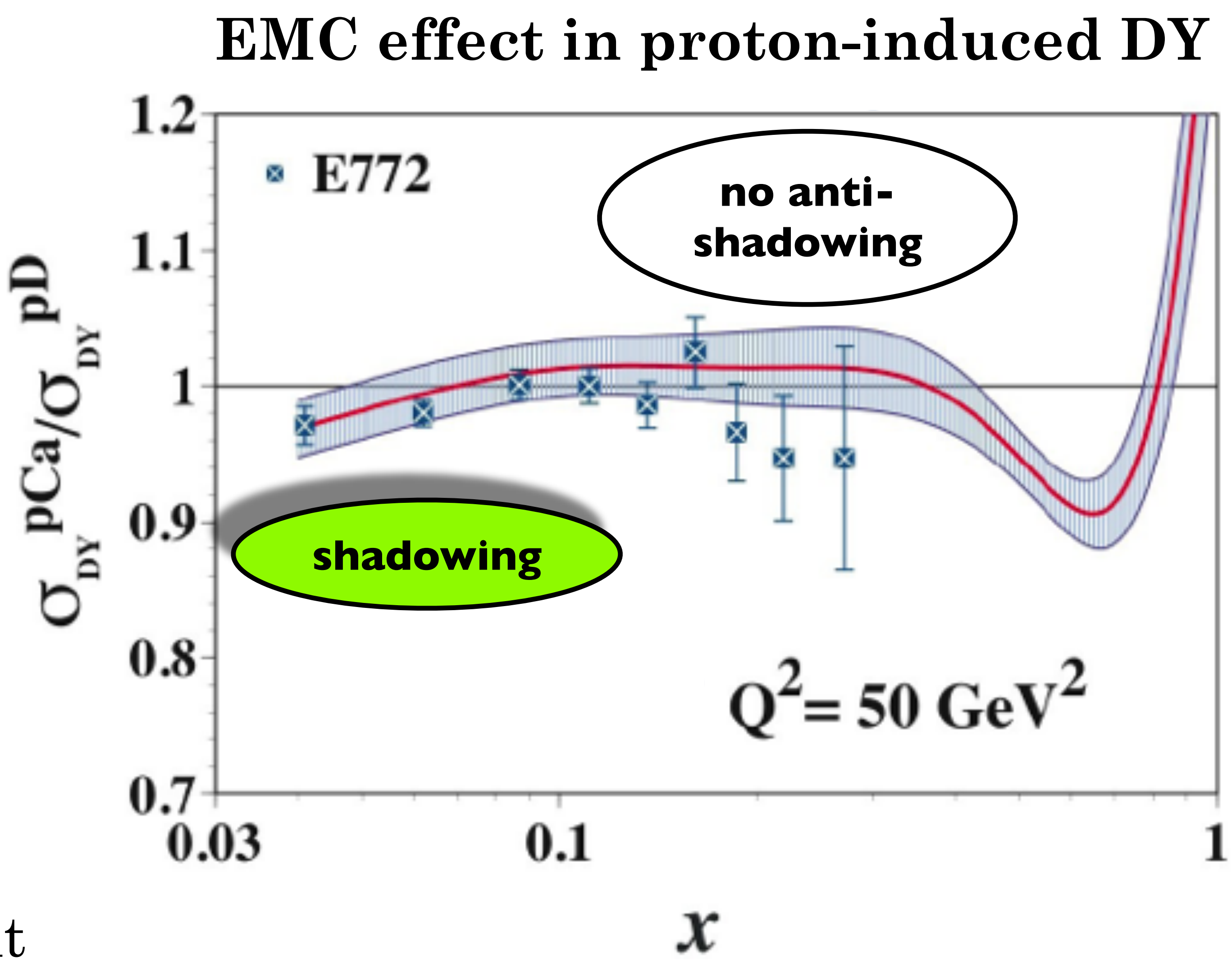
proton-induced DY



E772: PRL 64 (1990) 2479
E866: PRL 83 (1999) 2304

EMC effect in Drell Yan



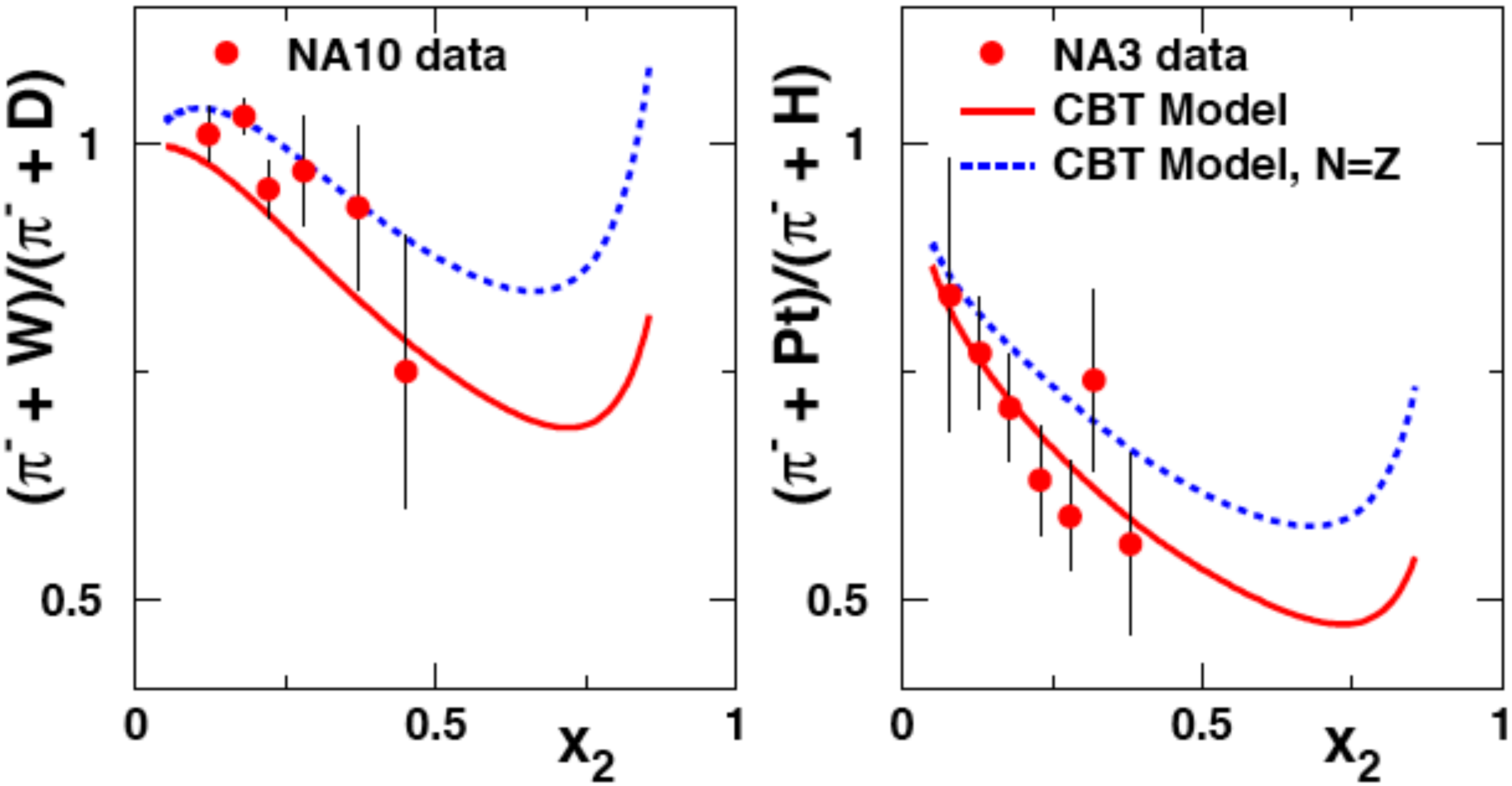


- EMC effect: many models with different input physics. DIS data sufficient as probe?
- DY: no excess pions! Traditional meson-exchange model?
- Contemporary models: large effects for anti-quarks as x increases.

Flavor-dependent EMC effect in pion-induced DY

- Flavor-dependent modification of quark distributions in the nuclear medium?
- Distinguish between different nuclear models
- **Cloet, Bentz, Thomas (CBT) model:**

isovector mean field in a N≠Z nucleus affects u- and d-quarks differently



$$\frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$

flavor-independent EMC effect

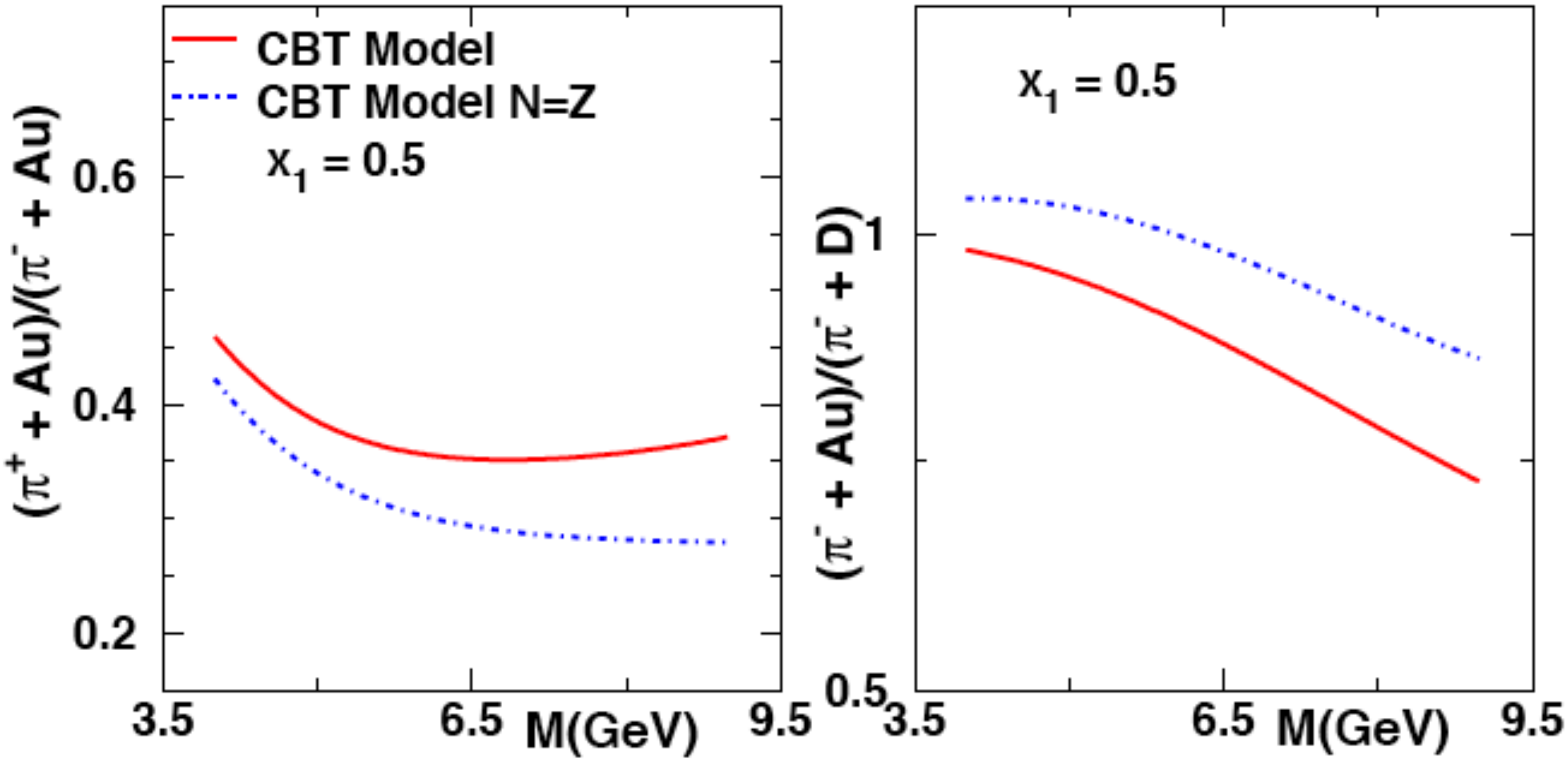
flavor-dependent EMC effect

Dutta, Peng, Cloet, Gaskell, arXiv:1007.3916

$$\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)}$$

Flavor-dependent EMC effect in pion-induced DY

$$\frac{\sigma^{DY}(\pi^+ + A)}{\sigma^{DY}(\pi^- + A)} \approx \frac{d_A(x)}{4u_A(x)} \qquad \frac{\sigma^{DY}(\pi^- + A)}{\sigma^{DY}(\pi^- + D)} \approx \frac{u_A(x)}{u_D(x)}$$



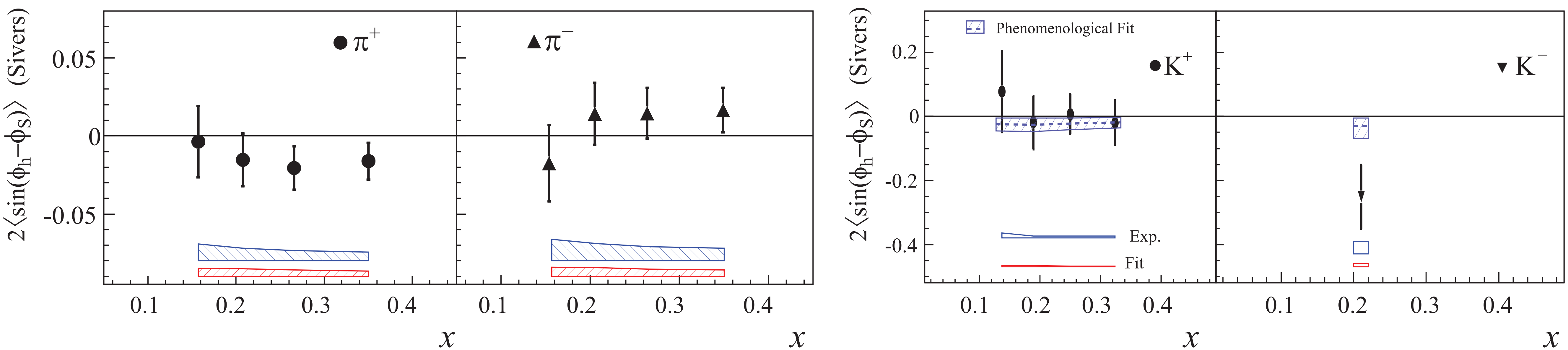
160 GeV
pion beam
@Q^2=25 GeV^2

Important new information from COMPASS-II Drell-Yan data with pion beams

Hall A Sivers

Hall-A neutrons (^{3}He)

Sivers from positive pions off neutron target negative
=> d-quark Sivers negative



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