Overview of recent hermes results

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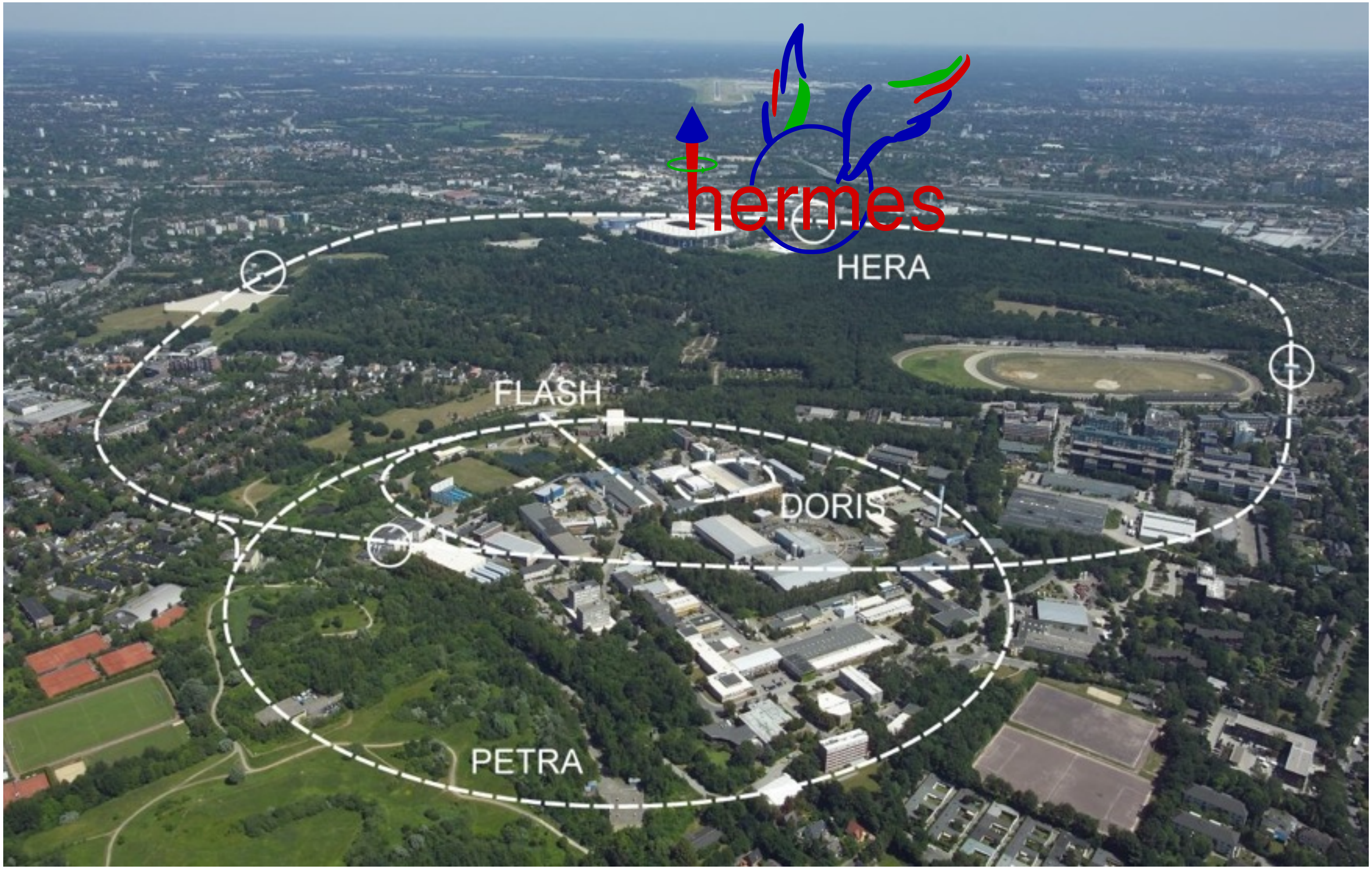
DESY - Hamburg, 11 November 2014

Outline

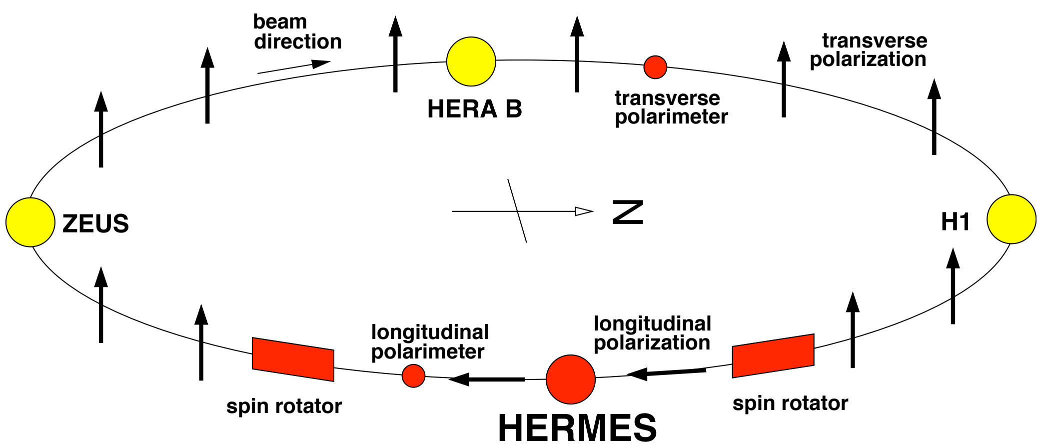
- HERMES experiment
- exclusive ω production
- A_{UT} and A_{LT} in semi-inclusive DIS
- inclusive A_{UT}
- Λ polarization in quasi-real photoproduction

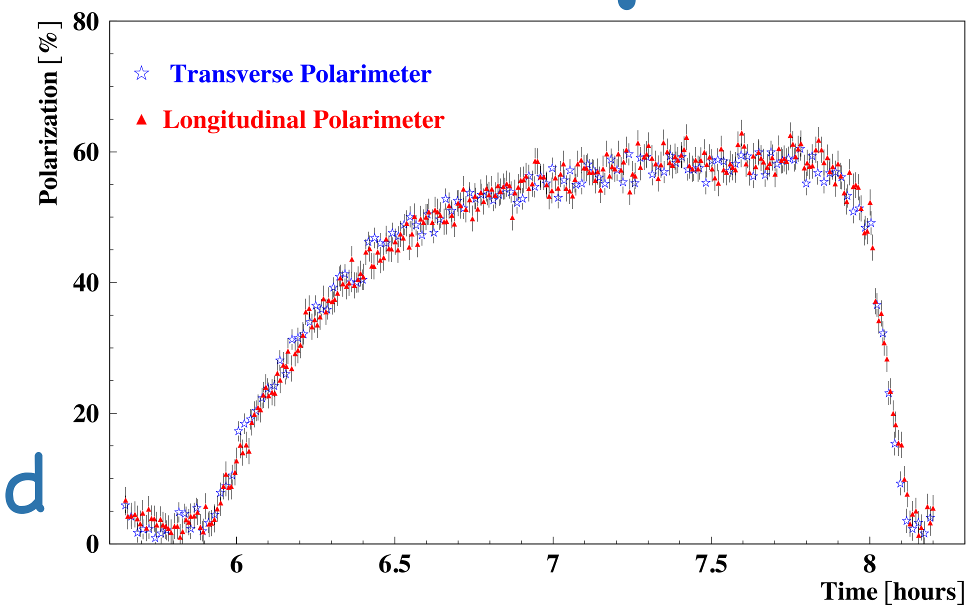
The HERMES experiment

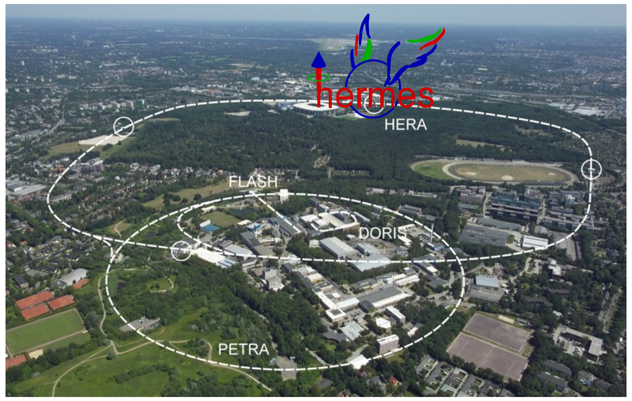


The HERMES experiment

Beam
- e^+/e^-
- 27.6 GeV
- longitudinally polarized







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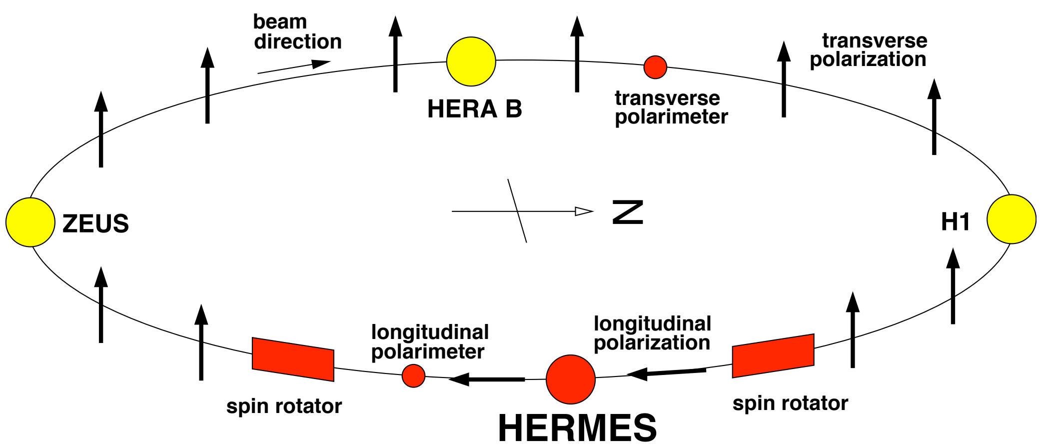
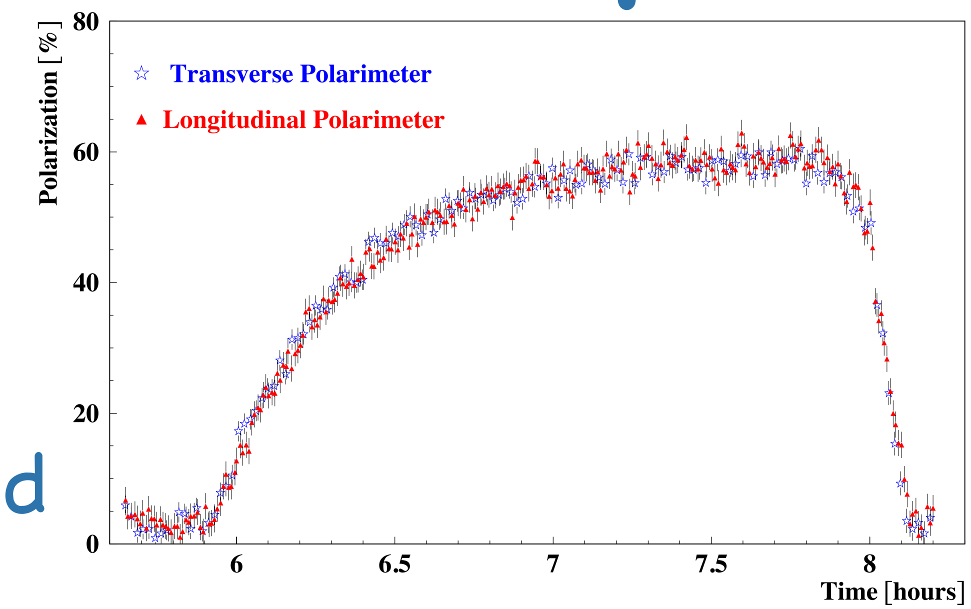
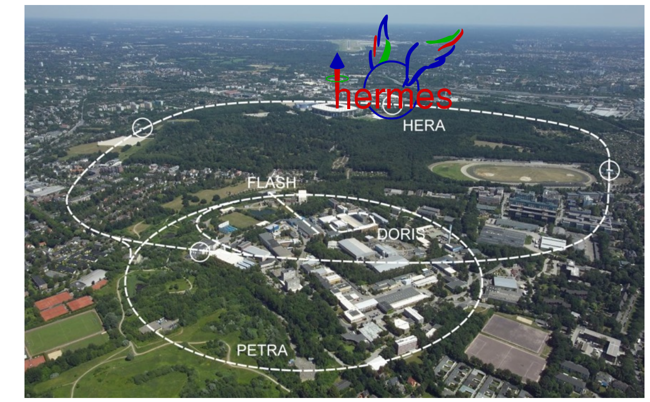
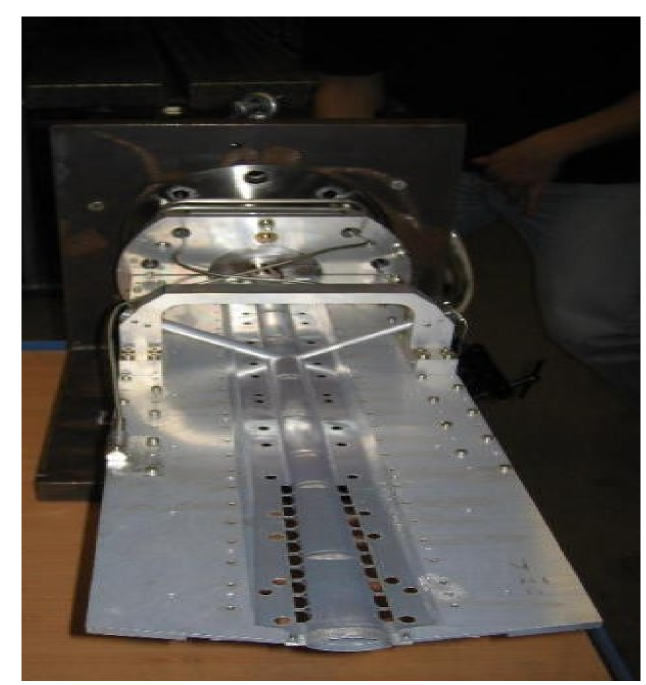






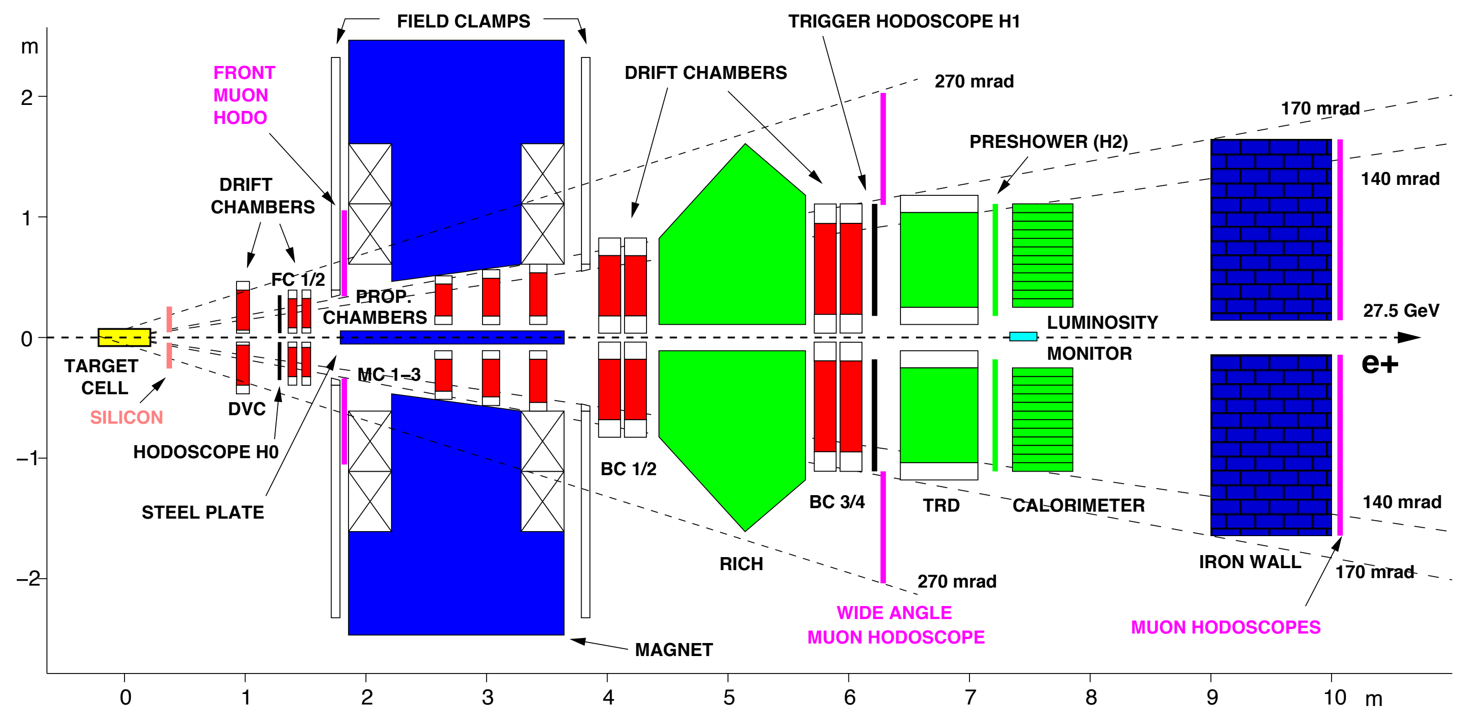
Target

- fixed gaseous target
- transversely polarized H
- longitudinally polaris H, D, He
- unpolarized H, D, He, Kr, ...



The HERMES experiment

data taking from 1995
until 30 June 2007

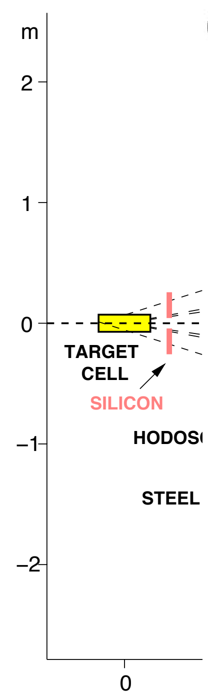


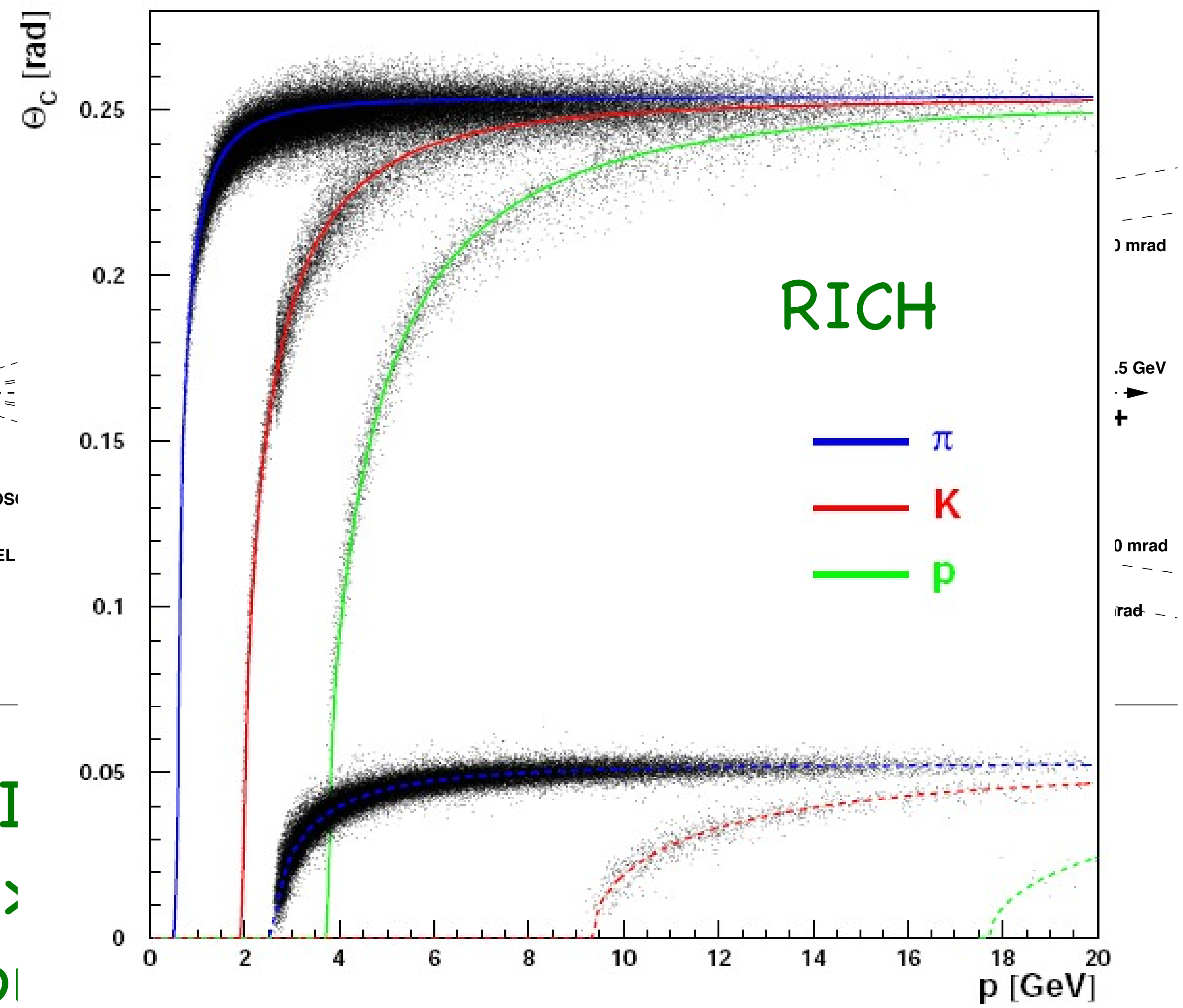
- tracking
  $\delta P/P<2\%$

- lepton-hadron PID
  high efficiency (>98%)
  low contamination (<1%)
- hadron PID: RICH in 2-15 GeV

The HERMES experiment

data taking from 1995
until 30 June 2007





- tracking
  $\delta P/P<2\%$

- lepton-hadron PI
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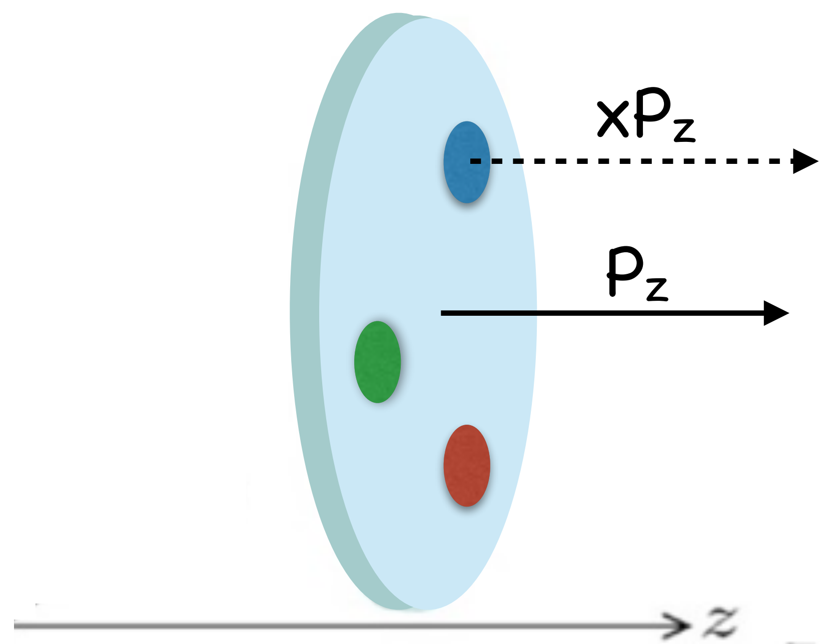
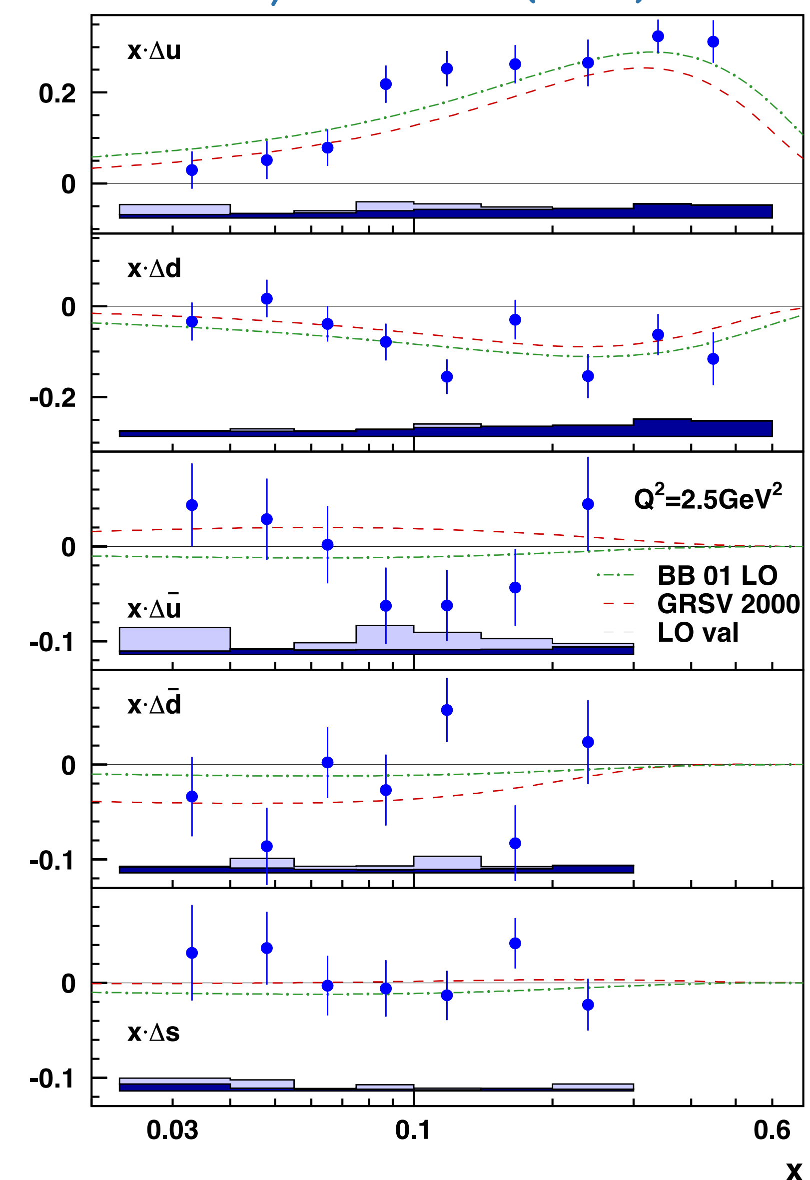
The nucleon in multiple dimensions

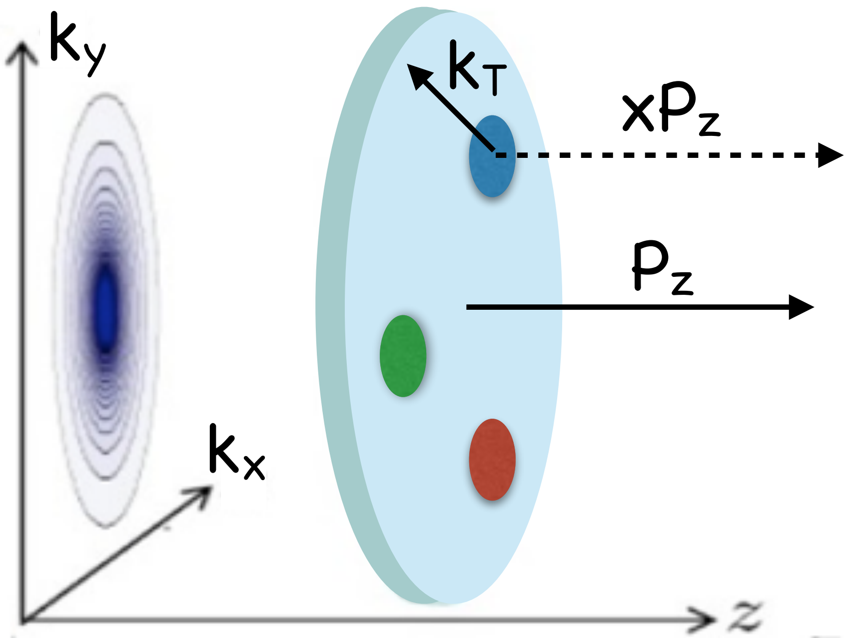


Phys. Rev. D 71 (2005) 012003



The nucleon in multiple dimensions

transverse-momentum dependent PDFs (TMD PDFs)



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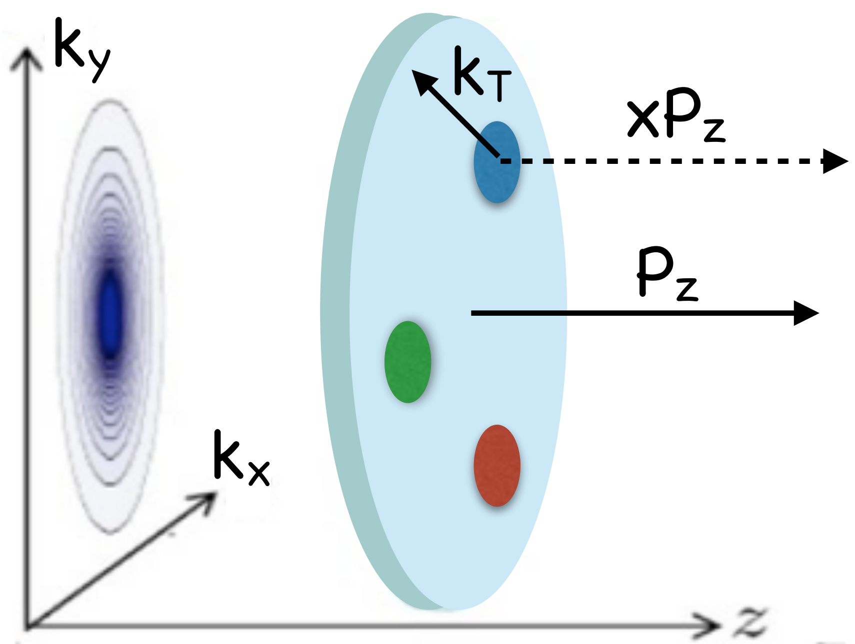
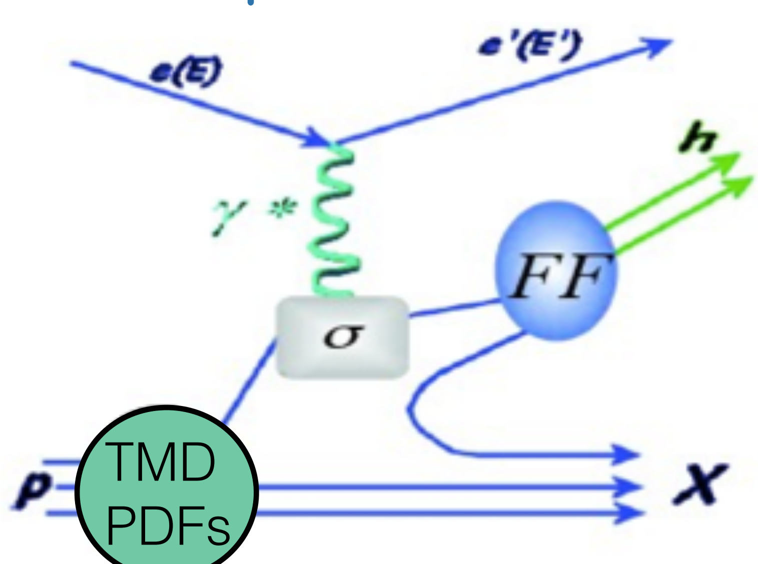


semi-inclusive deep-inelastic scattering (DIS)



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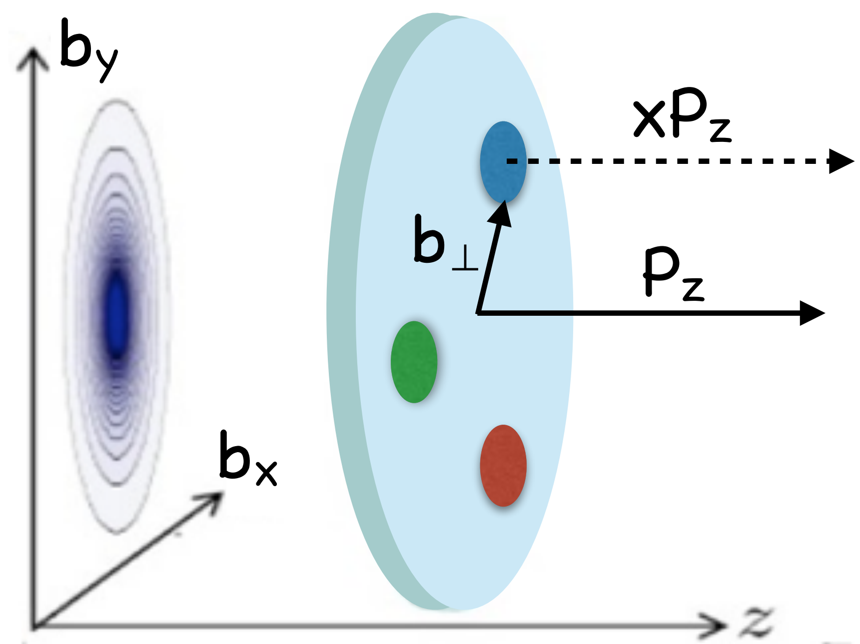


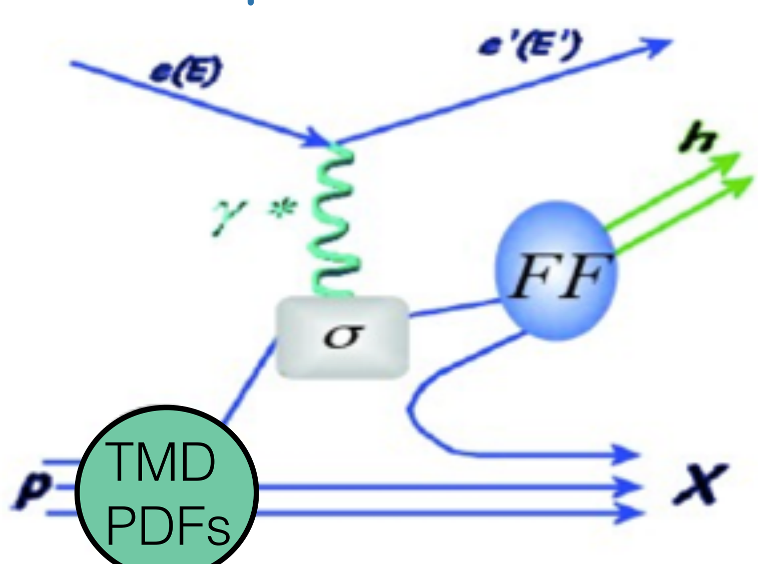
transverse-momentum dependent PDFs (TMD PDFs)

impact-parameter distributions

Fourier transform

generalized parton distributions (GPDs)

semi-inclusive deep-inelastic scattering (DIS)



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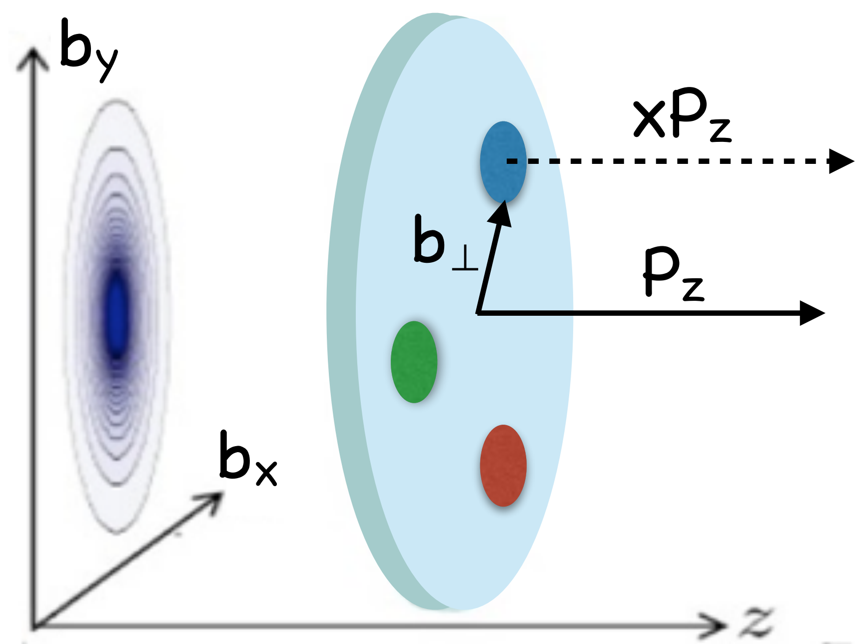

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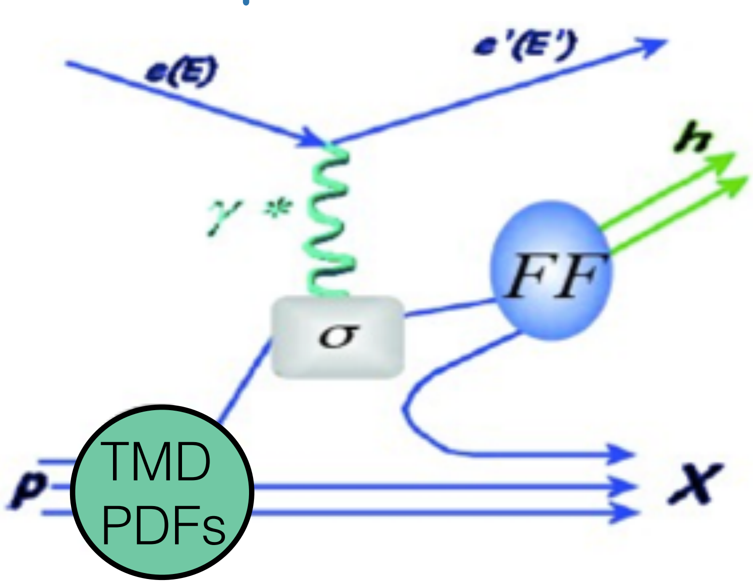
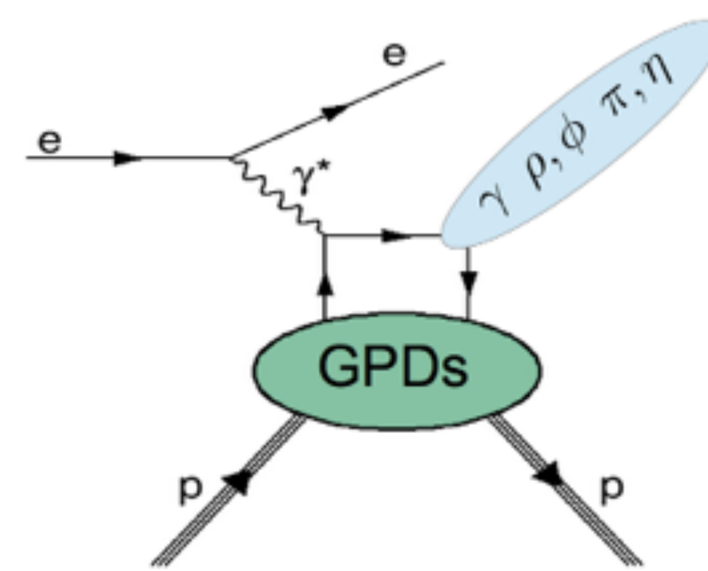


hard exclusive reactions

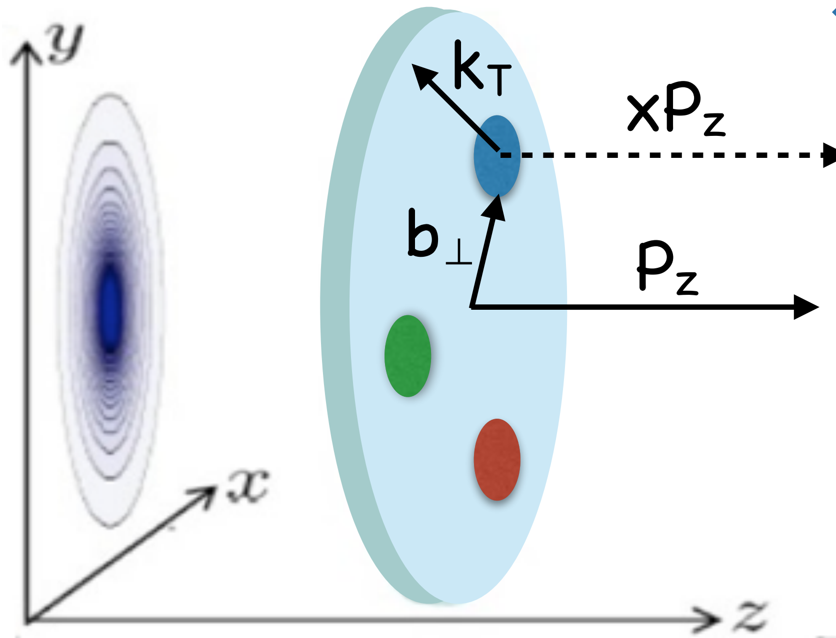


The nucleon in multiple dimensions

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

$\int d^2\vec{k}_T$



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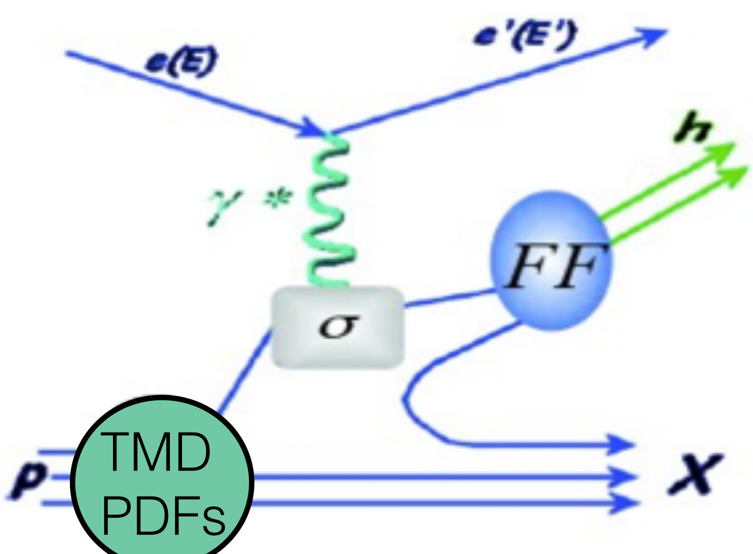

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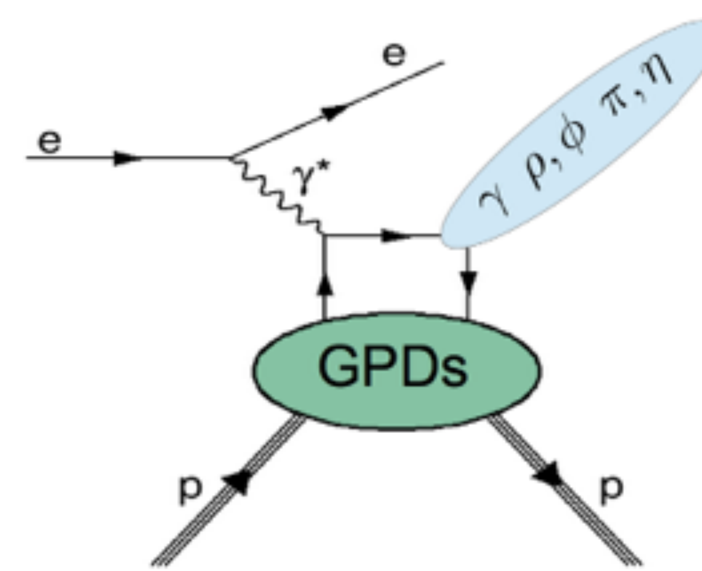
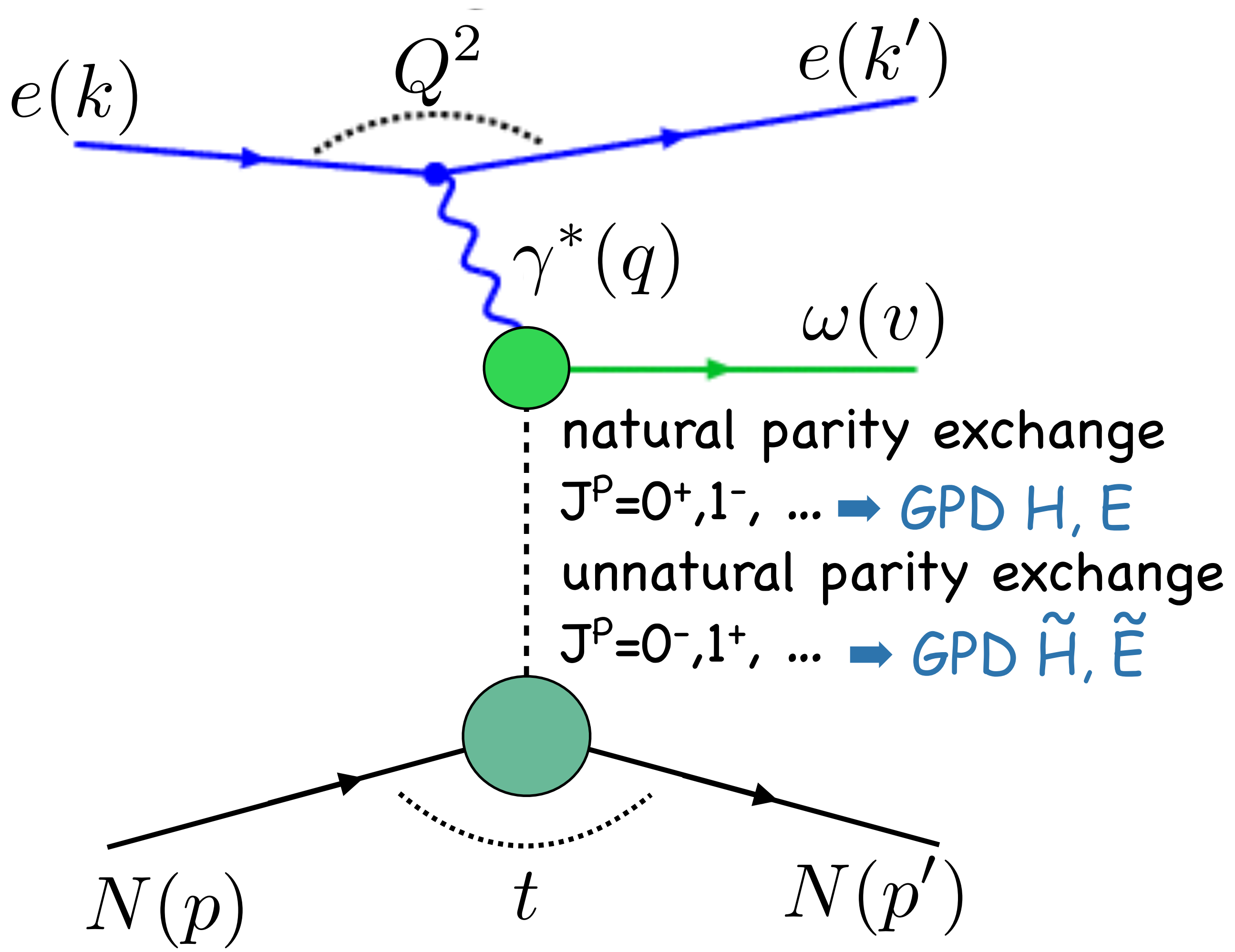
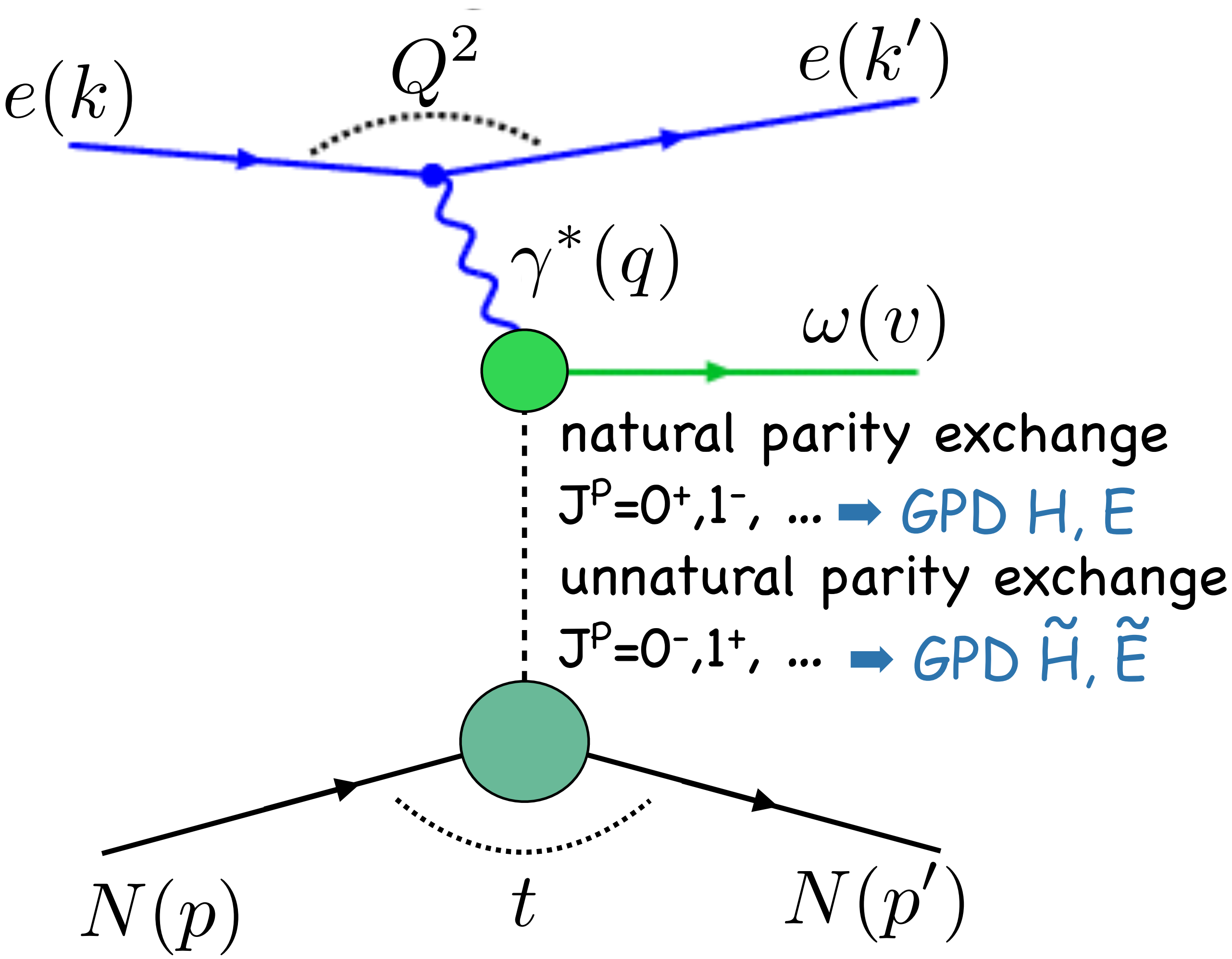


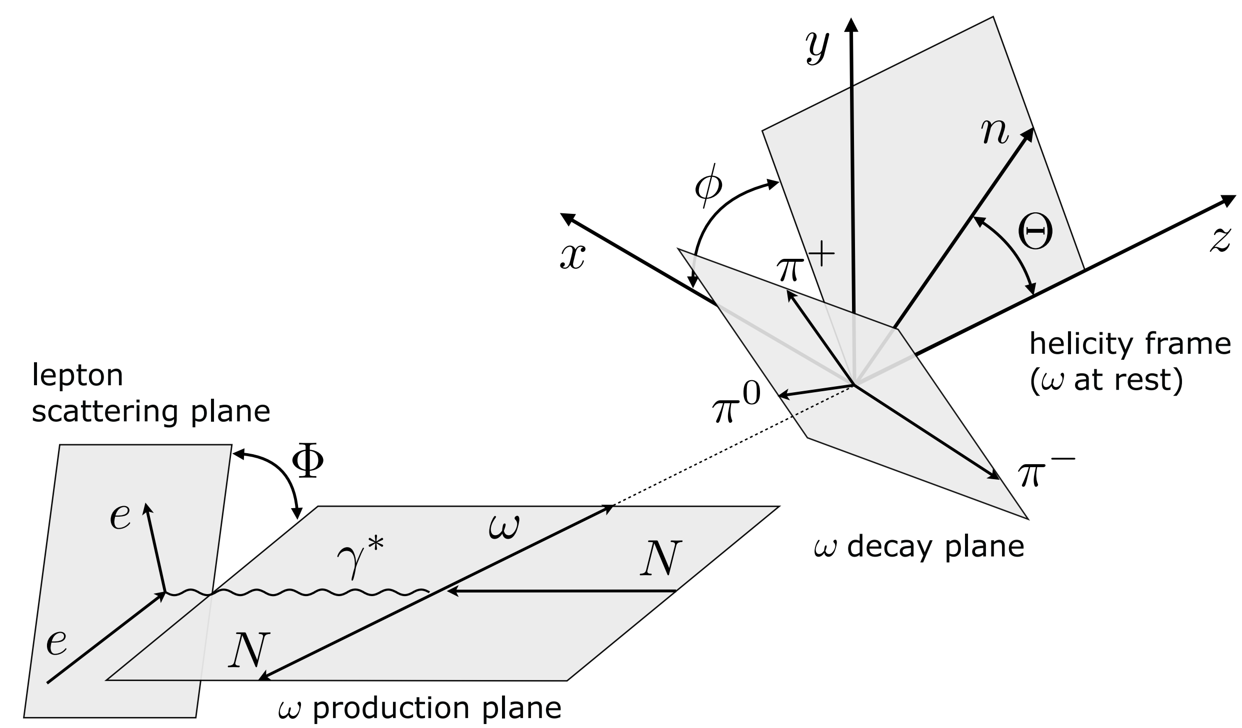
Exclusive ω production

Exclusive ω production



Exclusive ω production



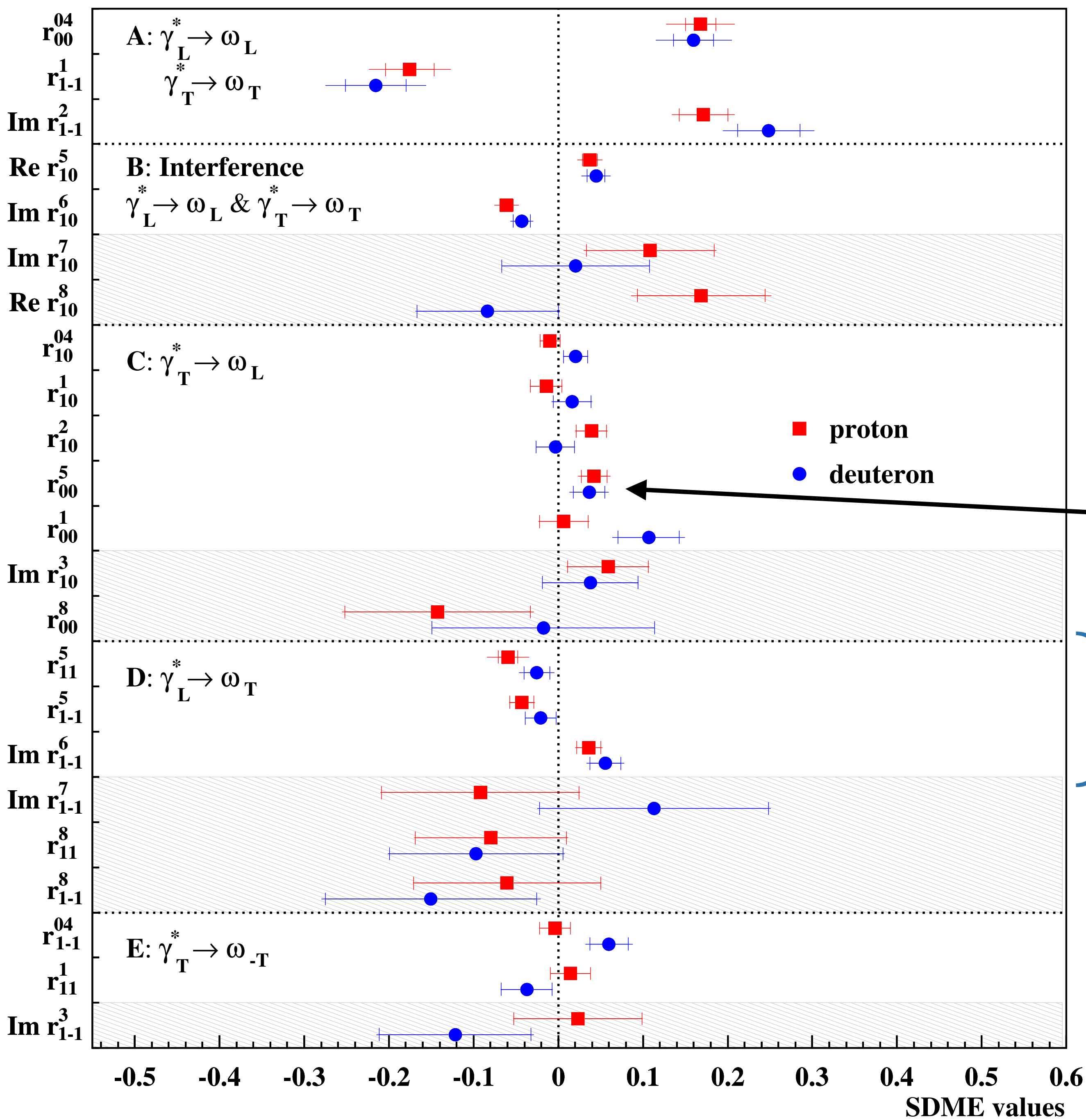


Fit angular distribution $\mathcal{W}(\Phi, \phi, \Theta)$ of ω decay pions

Spin density matrix elements (SDMEs)
describing final spin state of ω

ω SDMEs

arXiv:1407.2119



- 5 classes of SDMEs
- unpolarized and polarized SDMEs
- proton & deuteron similar

- s-channel helicity conservation:
  - fulfilled for class A&B
  - class C - slight violation:

    $r^5_{00} \neq 0$ by $3(2)\sigma$ for p(d)

  - class D - slight violation:

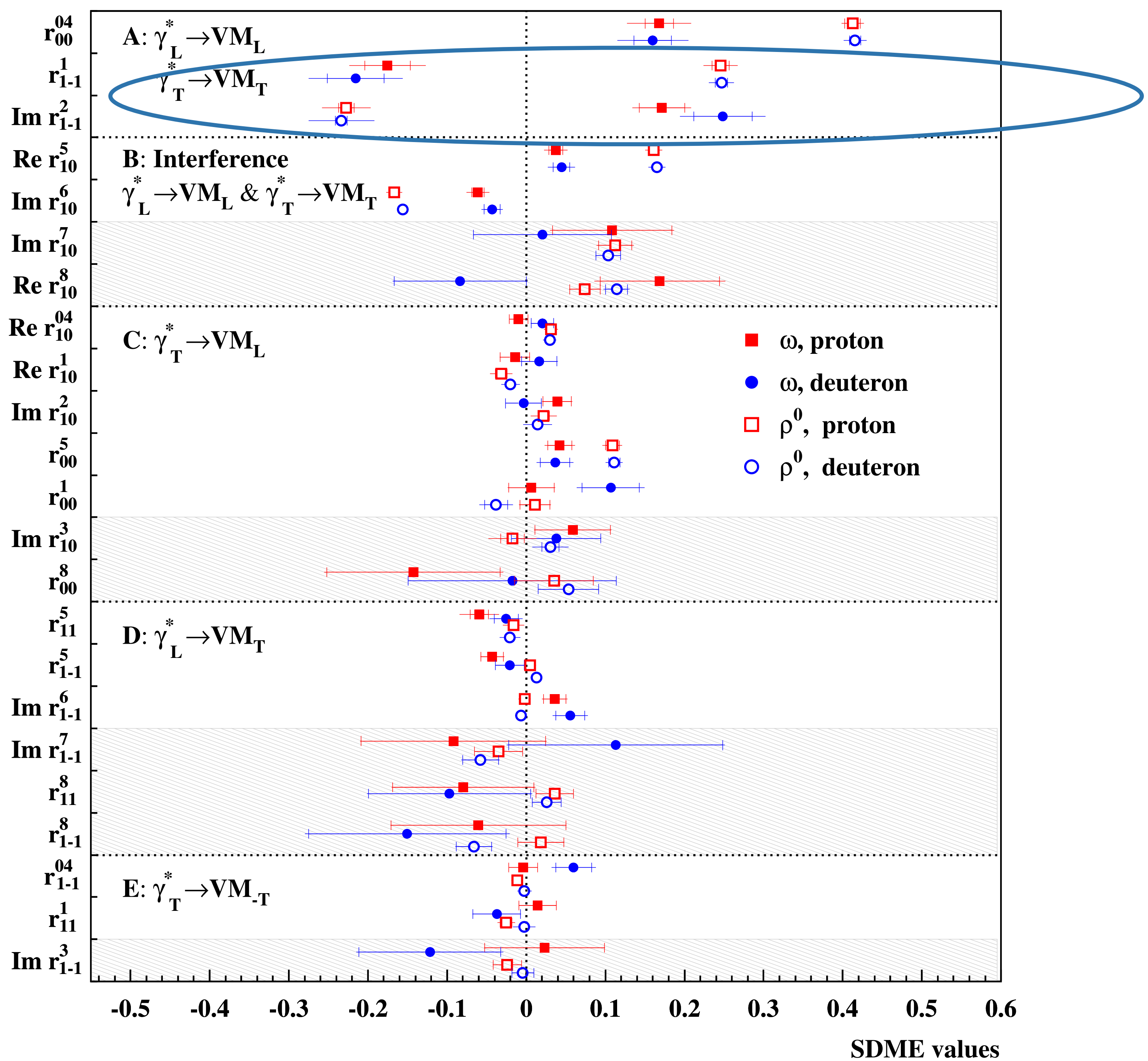
    $r^5_{11} + r^5_{1-1} - \Im r^6_{1-1} =$

    $-0.14 \pm 0.03 \pm 0.04$ for p

    $-0.10 \pm 0.03 \pm 0.03$ for d

Comparison ω and ρ

arXiv:1407.2119



- ω: $r^1_{1-1} < 0 \quad \Im r^2_{1-1} > 0$
- ρ^0: $r^1_{1-1} > 0 \quad \Im r^2_{1-1} < 0$

large unnatural parity exchange for ω production

large natural parity exchange for ρ production

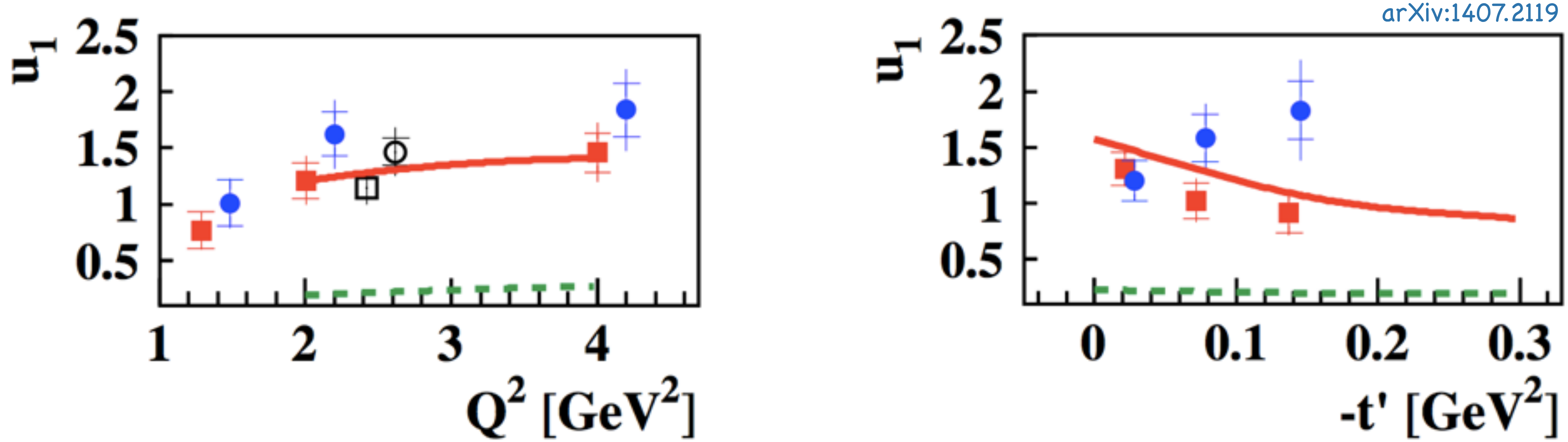
exclusive ρ^0: Eur. Phys. J. C **62** (2009) 659

Test of unnatural parity exchange

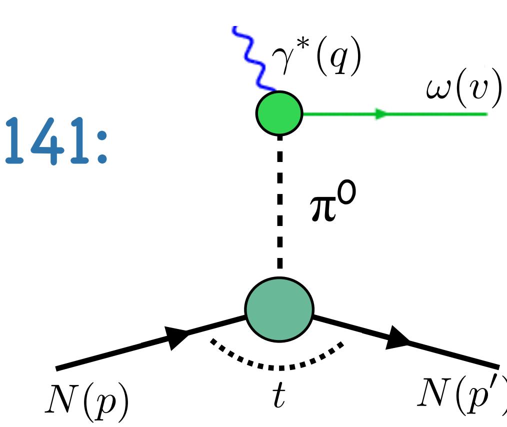
$$u_1 = 1 - r^{04}_{00} + 2\,r^{04}_{1-1} - 2\,r^{1}_{11} - 2\,r^{1}_{1-1}$$

$$\propto 2\,\epsilon |U_{10}|^2 + |U_{11} + U_{-11}|^2$$ (U=unnatural-parity amplitude)

arXiv:1407.2119



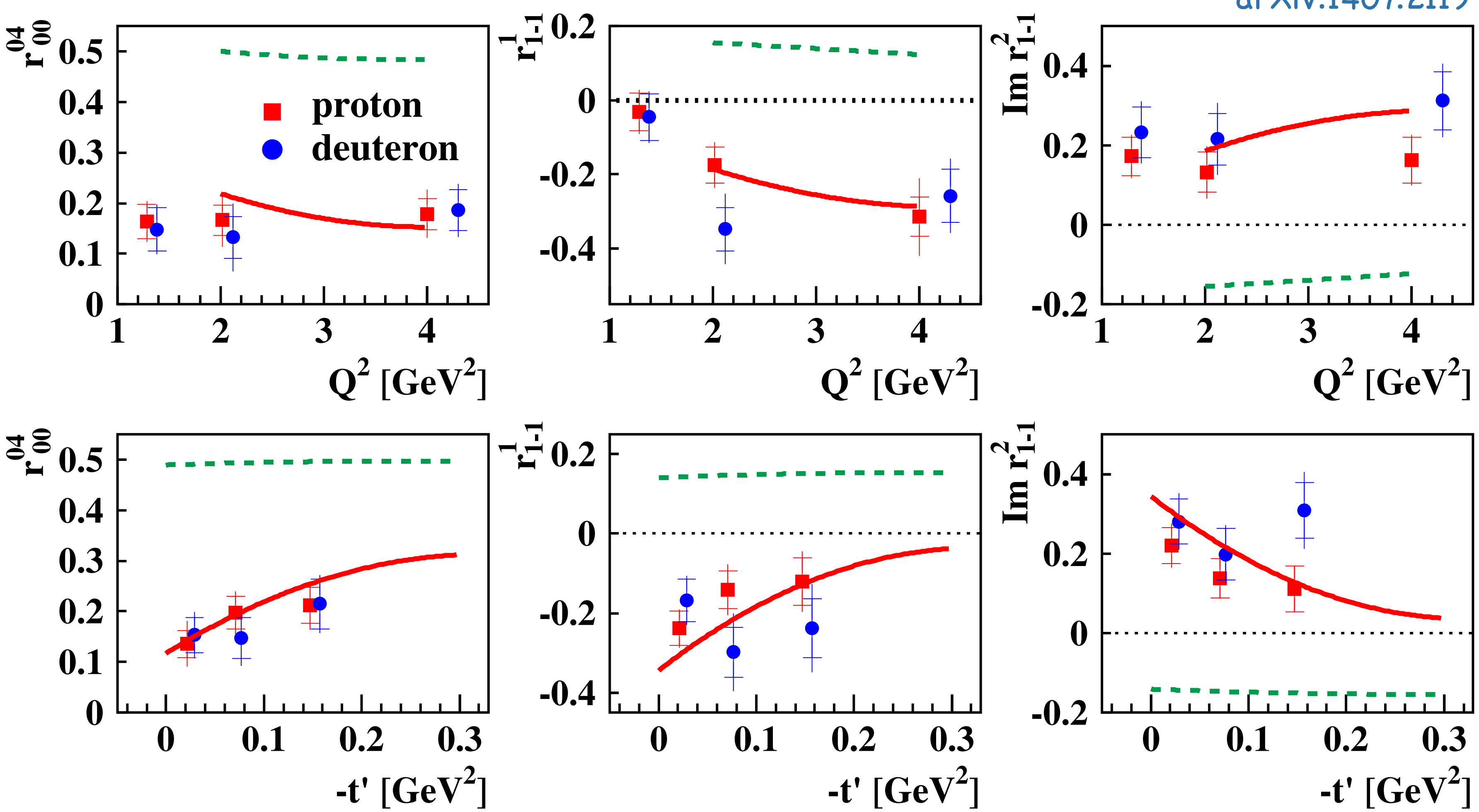
- large unnatural parity exchange
- model for protons - S. Goloskokov and P. Kroll, arXiv. 1407.1141:
  without pion-pole contribution
  with pion-pole contribution



Kinematic dependencies

class A

arXiv:1407.2119

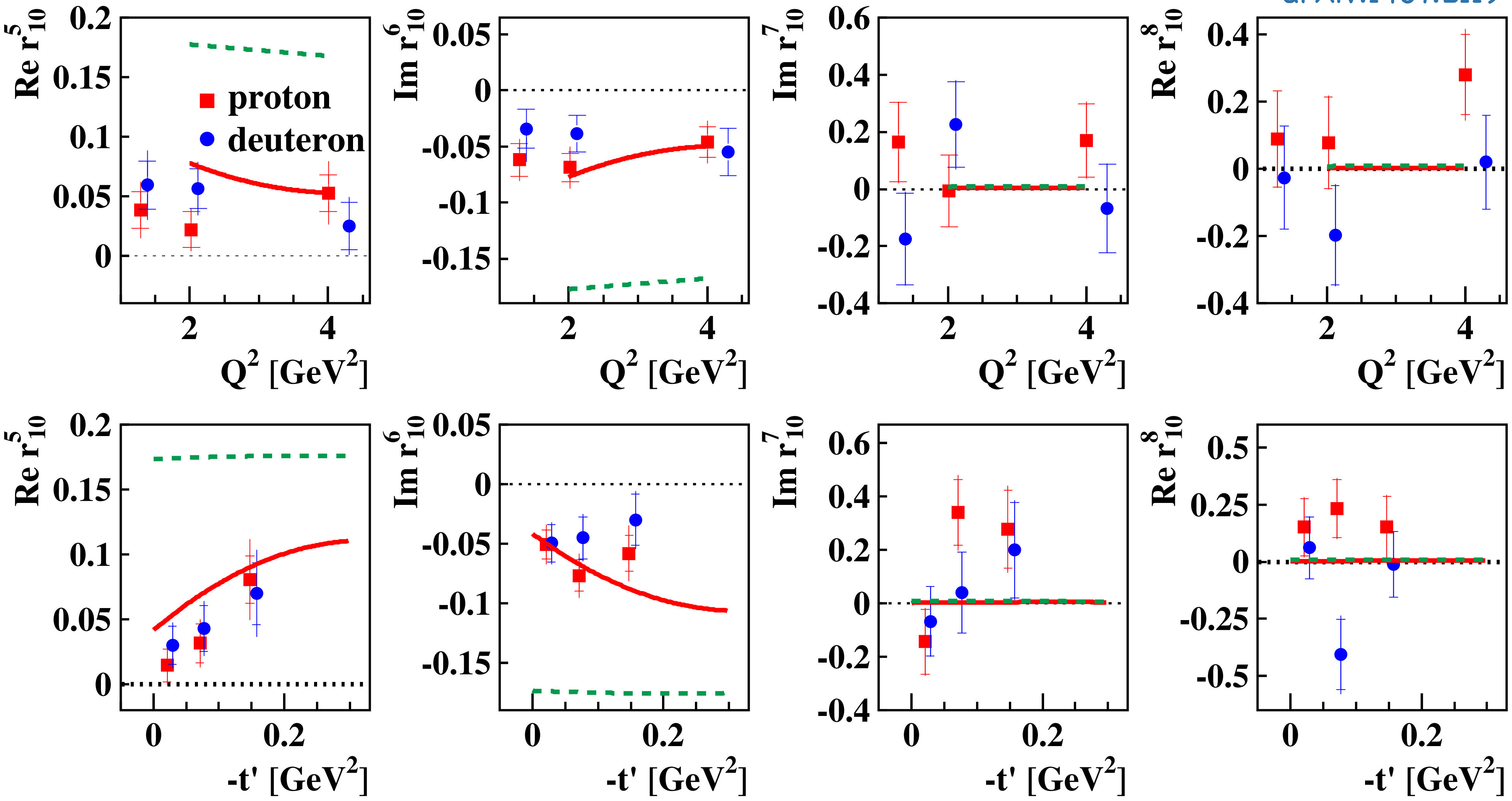


- no clear kinematic dependence observed
- again need for unnatural pion-pole exchange seen!

Kinematic dependencies

class B

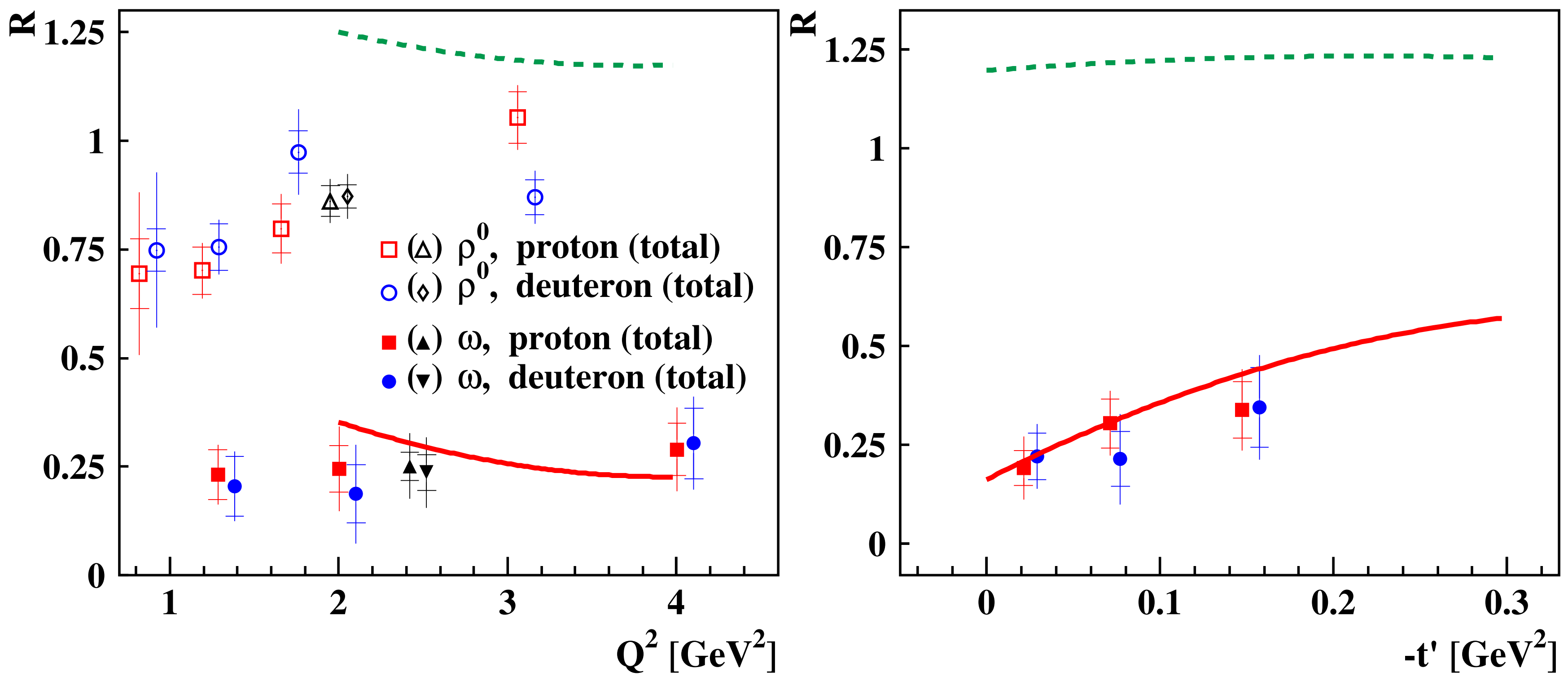
arXiv:1407.2119



- no clear kinematic dependence observed
- need for unnatural pion-pole exchange seen for unpolarized SDMEs

Longitudinal-to-transverse cross-section ratio

$$R = \frac{d\sigma_L(\gamma_L^* \to V)}{d\sigma_T(\gamma_T^* \to V)} \approx \frac{1}{\epsilon}\frac{r_{00}^{04}}{1 - r_{00}^{04}}$$

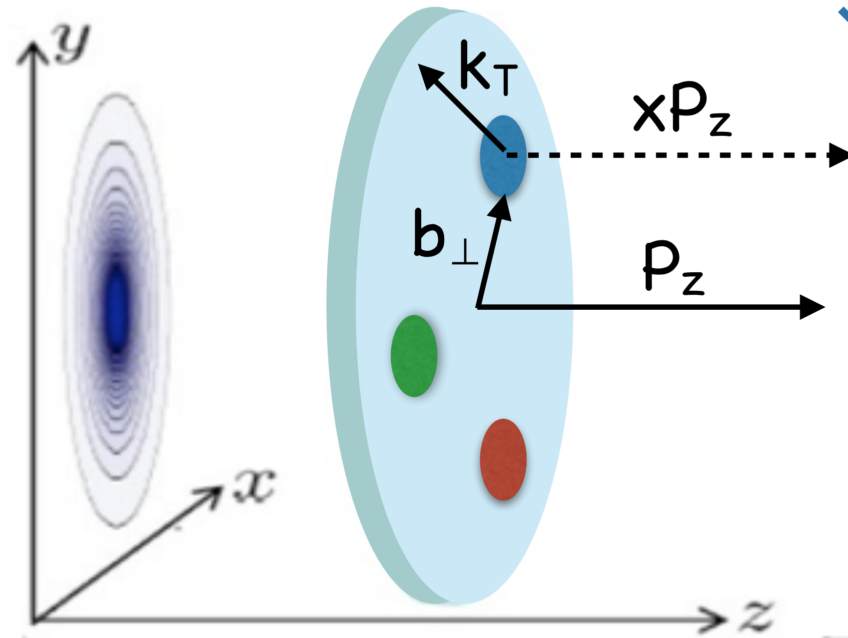


- R≈0.25 for ω, 4x smaller than for ρ
- again need for unnatural pion-pole exchange
- no Q^2 dependence, t' dependence?

The nucleon in multiple dimensions

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$



$\int d^2\vec{k}_T$

transverse-momentum dependent PDFs (TMD PDFs)

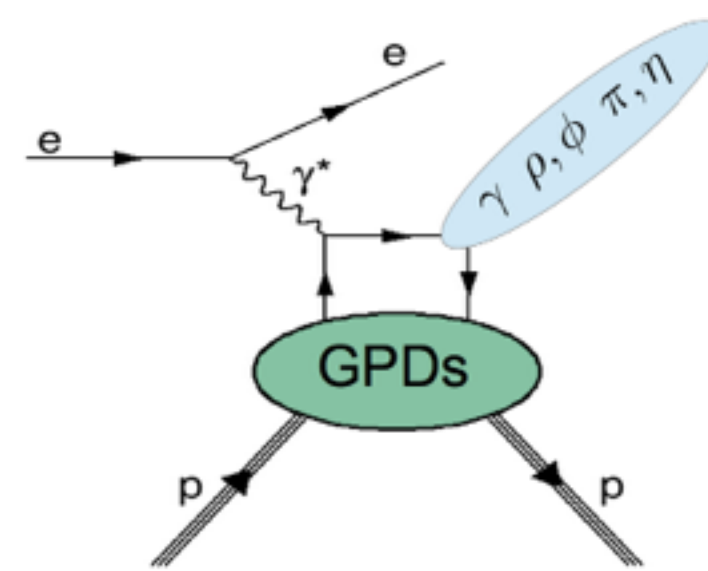
impact-parameter distributions

Fourier transform

generalized parton distributions (GPDs)

semi-inclusive deep-inelastic scattering (DIS)

hard exclusive reactions



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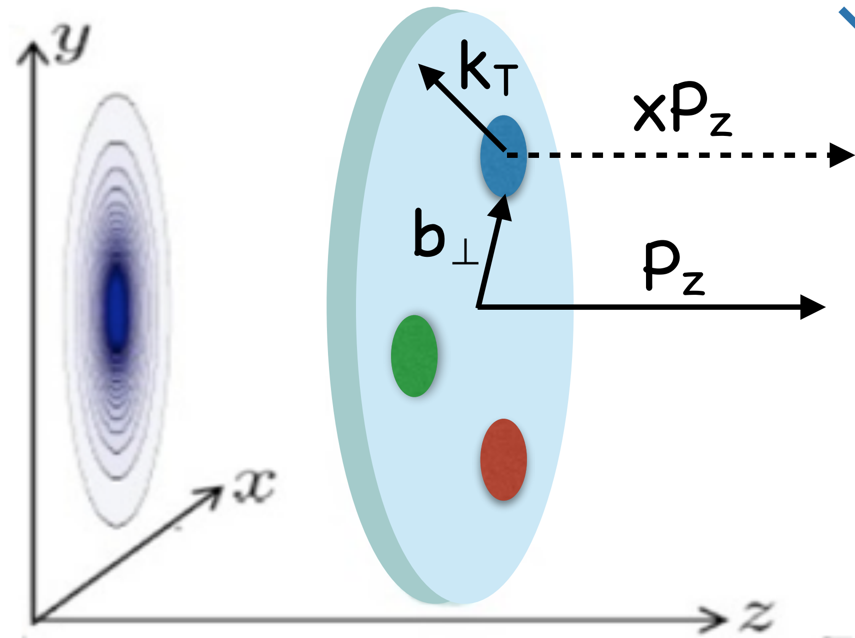

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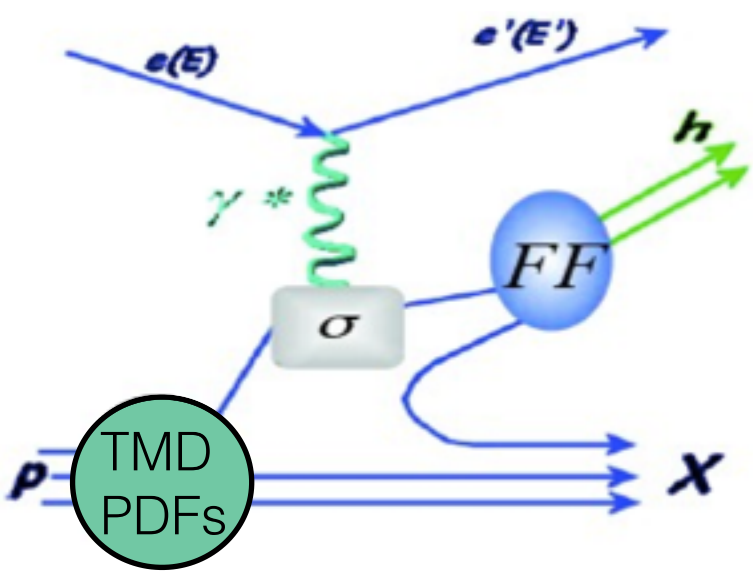
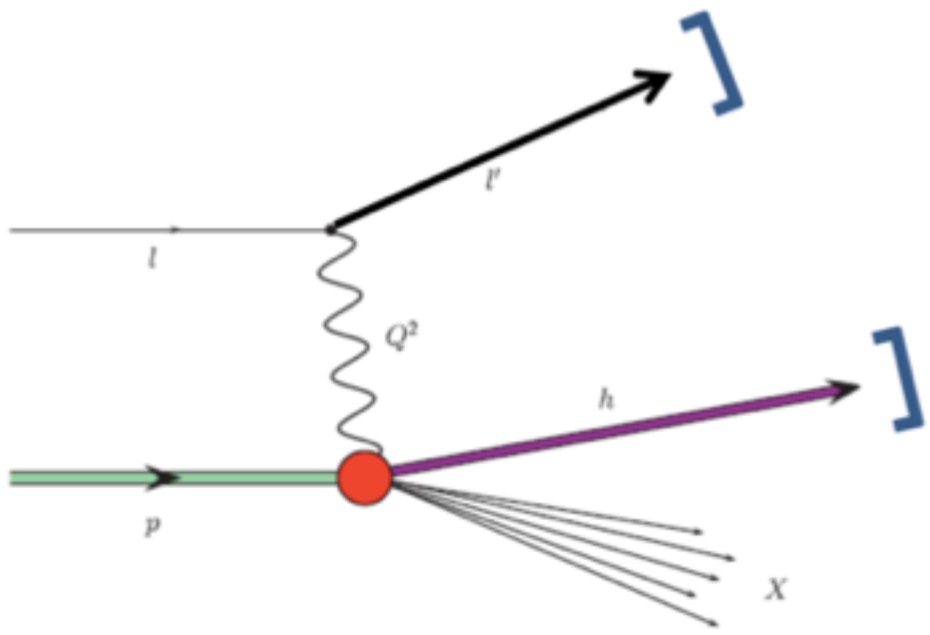
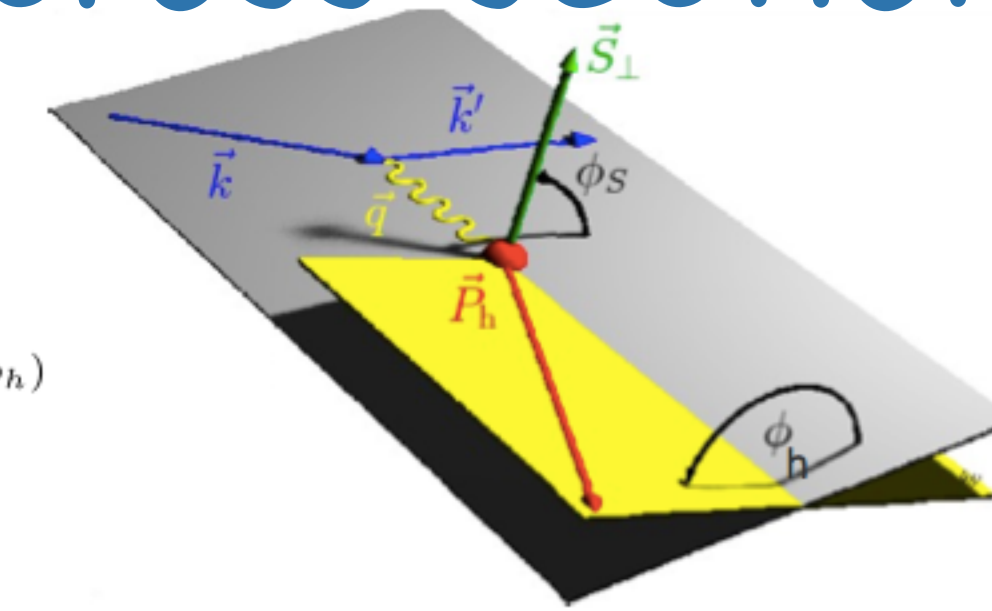


hard exclusive reactions

Semi-inclusive DIS



Semi-inclusive DIS cross section



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

$$\Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi_h)F_{UU}^{\cos(\phi_h)} + \epsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}$$

beam polarization

$$+\lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin(\phi_h)F_{LU}^{\sin(\phi_h)}$$

longitudinal target polarization

$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi_h)F_{UL}^{\sin(\phi_h)} + \epsilon\sin(2\phi_h)F_{UL}^{\sin(2\phi_h)}\right]$$

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

transverse target polarization

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

$$+\quad \epsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

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

$$+S_T\lambda_e\Big[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)}$$

$$+\quad \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

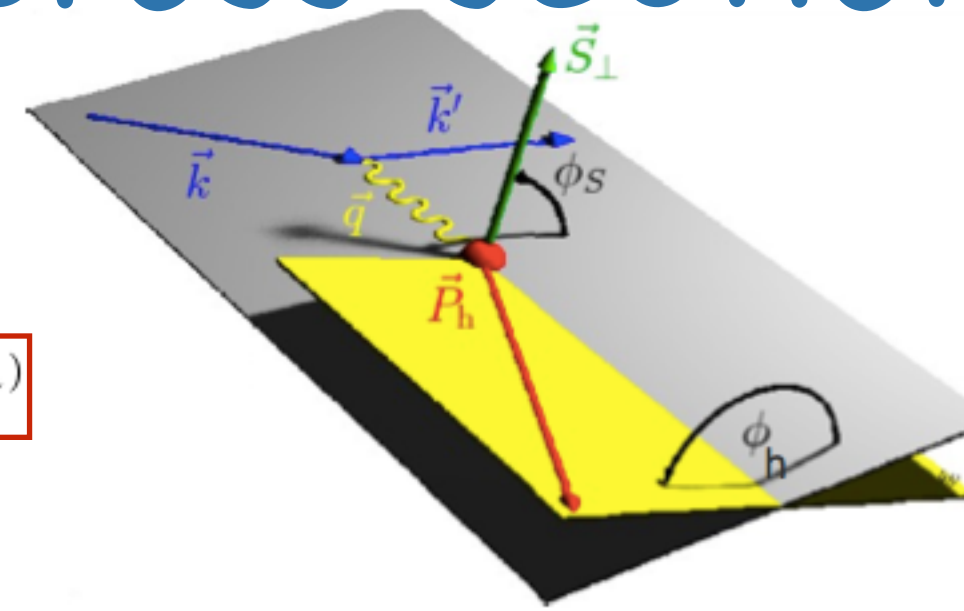
target polarization

structure function $\mathrm{F}_{XY(,Z)}$

beam polarization

(virtual photon polarization)

Semi-inclusive DIS cross section



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$$\Big\{ \boxed{F_{UU,T}} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi_h) F_{UU}^{\cos(\phi_h)} + \epsilon\cos(2\phi_h)\boxed{F_{UU}^{\cos(2\phi_h)}}$$

beam polarization

$$+\lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin(\phi_h)F_{LU}^{\sin(\phi_h)}$$

longitudinal target polarization

$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi_h)F_{UL}^{\sin(\phi_h)} + \epsilon\sin(2\phi_h)\boxed{F_{UL}^{\sin(2\phi_h)}}\right]$$

$$+S_L\lambda_e\left[\sqrt{1-\epsilon^2}\boxed{F_{LL}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_h)F_{LL}^{\cos(\phi_h)}\right]$$

transverse target polarization

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

$$+ \quad \epsilon\sin(\phi_h+\phi_S)\boxed{F_{UT}^{\sin(\phi_h+\phi_S)}} + \epsilon\sin(3\phi_h-\phi_S)\boxed{F_{UT}^{\sin(3\phi_h-\phi_S)}}$$

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

$$+S_T\lambda_e\Big[\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)\boxed{F_{LT}^{\cos(\phi_h-\phi_S)}} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)}$$

$$+ \quad \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

target polarization

structure function $F_{XY(,Z)}$

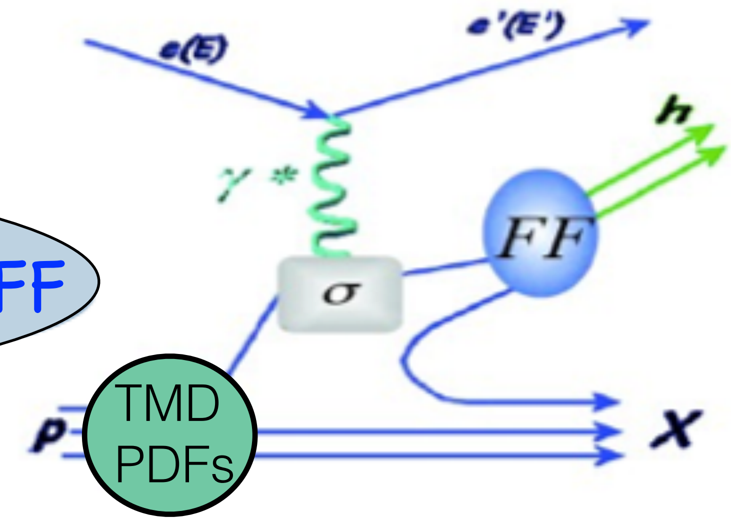
beam polarization

(virtual photon polarization)

leading twist

Semi-inclusive DIS cross section

structure function $F_{XY} \propto$ TMD PDF $\otimes$ TMD FF



transverse momentum distributions (TMDs)

		quark U	quark L	quark T
nucleon	U	f_1		$h_1^\perp$
nucleon	L		g_1	$h_{1L}^\perp$
nucleon	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

fragmentation functions (FFs)

		quark U	quark L	quark T
h	U	D_1		$H_1^\perp$

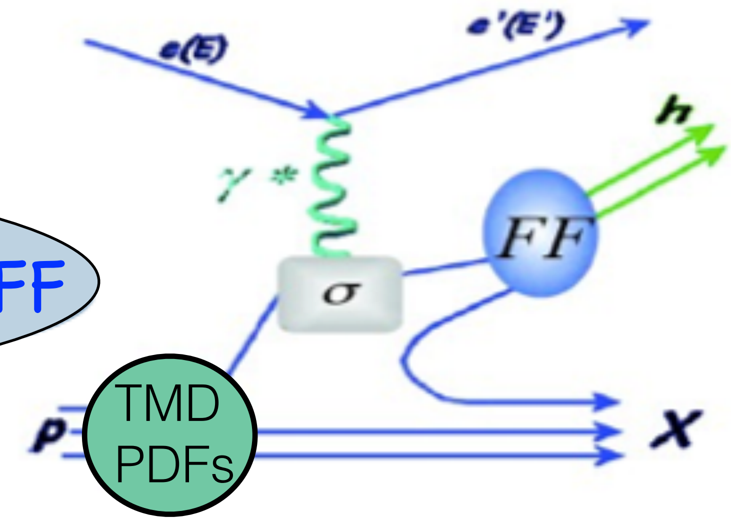
nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

Semi-inclusive DIS cross section

structure function $F_{XY} \propto$ TMD PDF $\otimes$ TMD FF



transverse momentum distributions (TMDs)

		quark U	quark L	quark T
nucleon	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

fragmentation functions (FFs)

		quark U	quark L	quark T
h	U	D_1		$H_1^\perp$

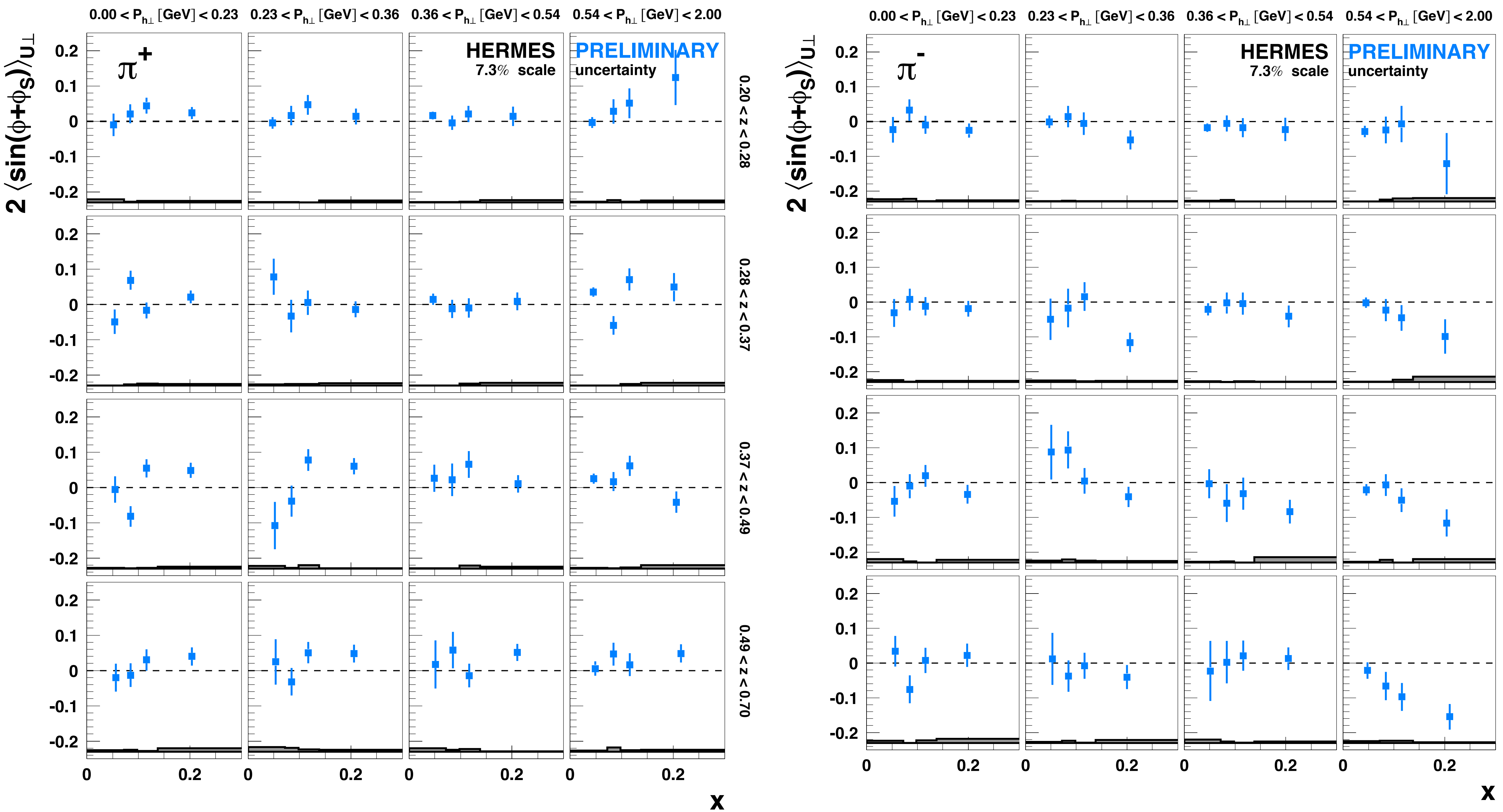
nucleon with transverse/longitudinal spin

quark with transverse/longitudinal spin

quark transverse momentum

Collins amplitudes

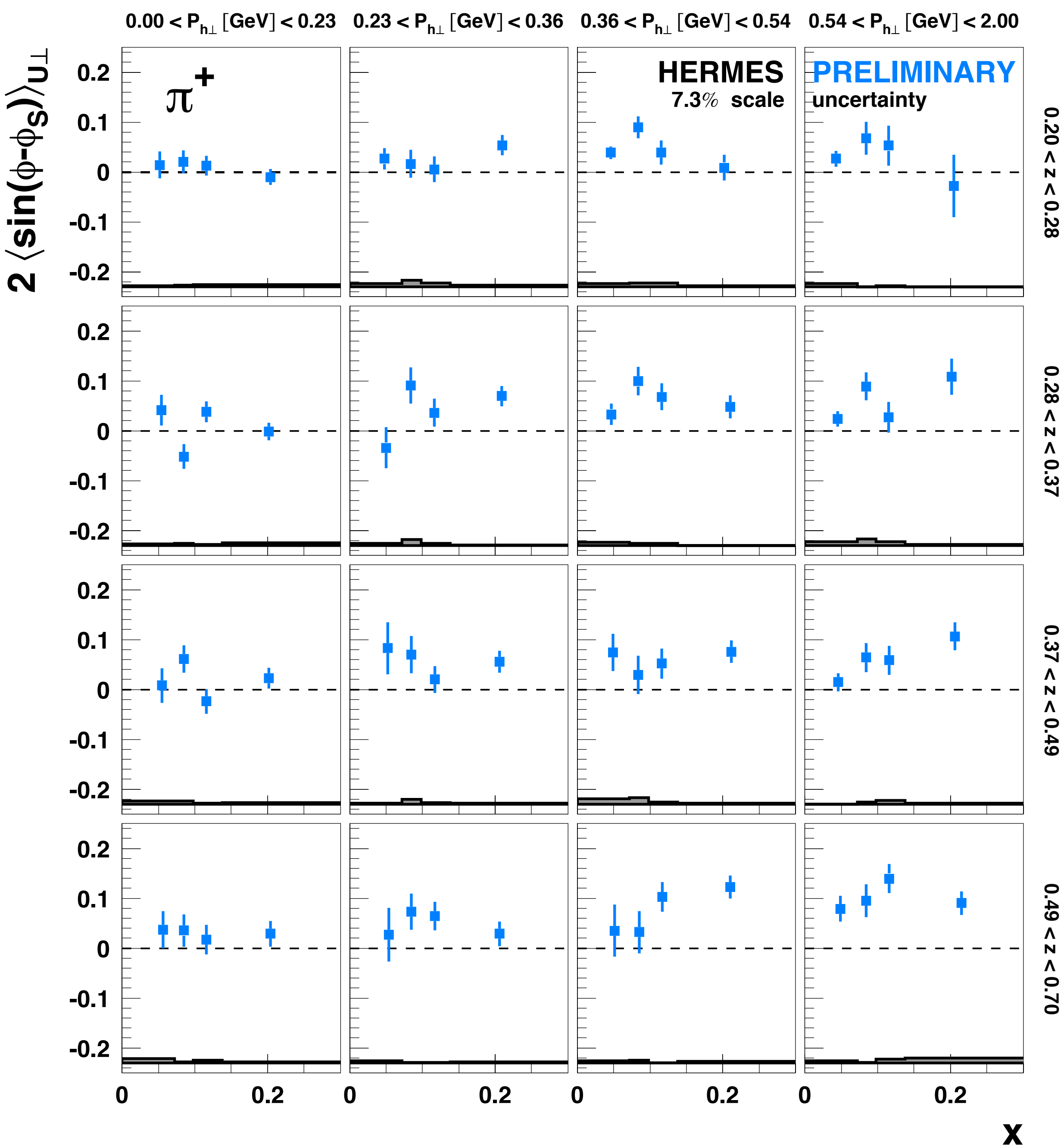
$$F_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1T} \otimes H_1^{\perp}$$

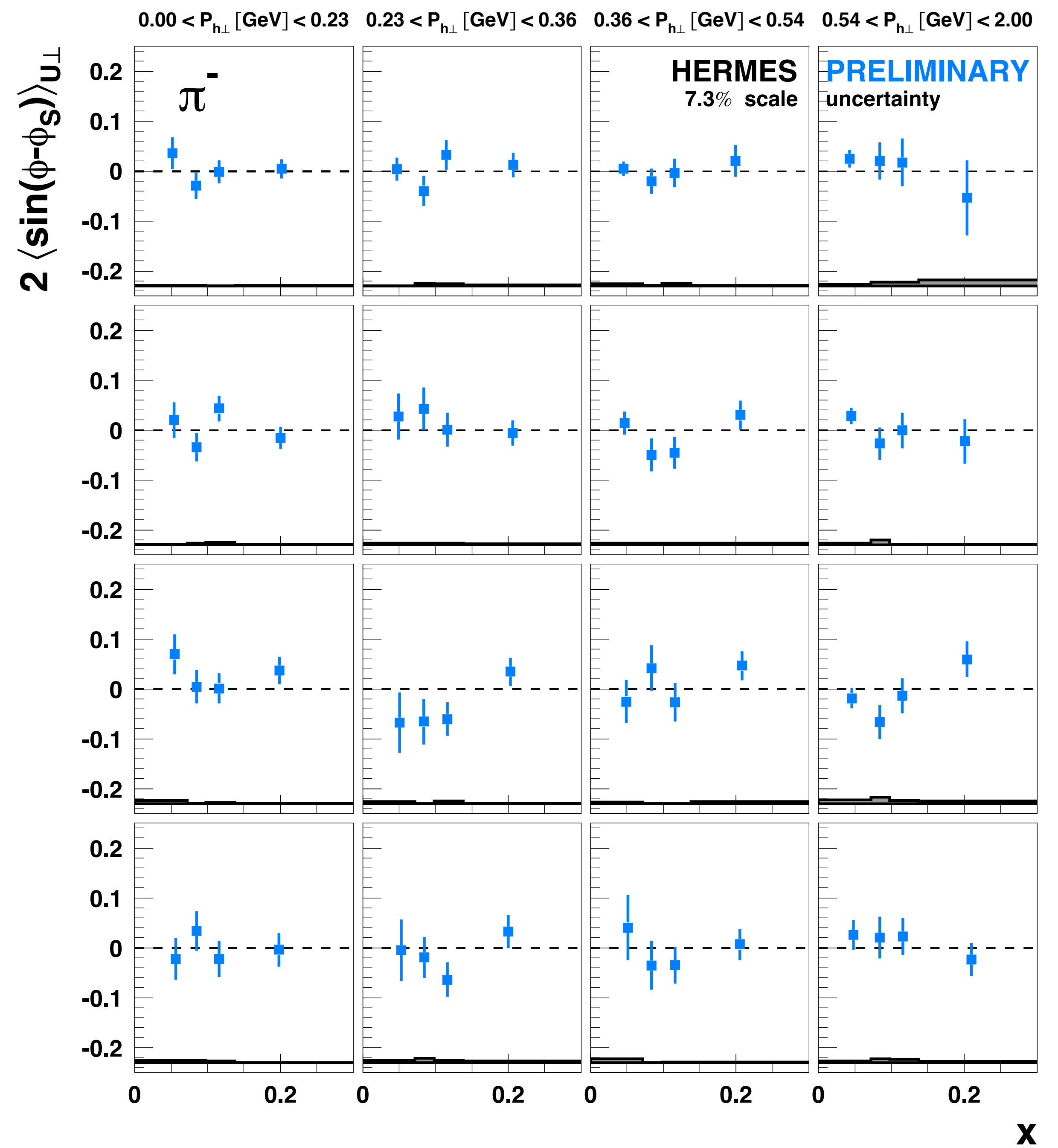


- π^+ amplitudes positive; π^- amplitudes negative
- π^- amplitudes increasing with x at large $P_{h\perp}$

Sivers amplitudes

$$F_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$

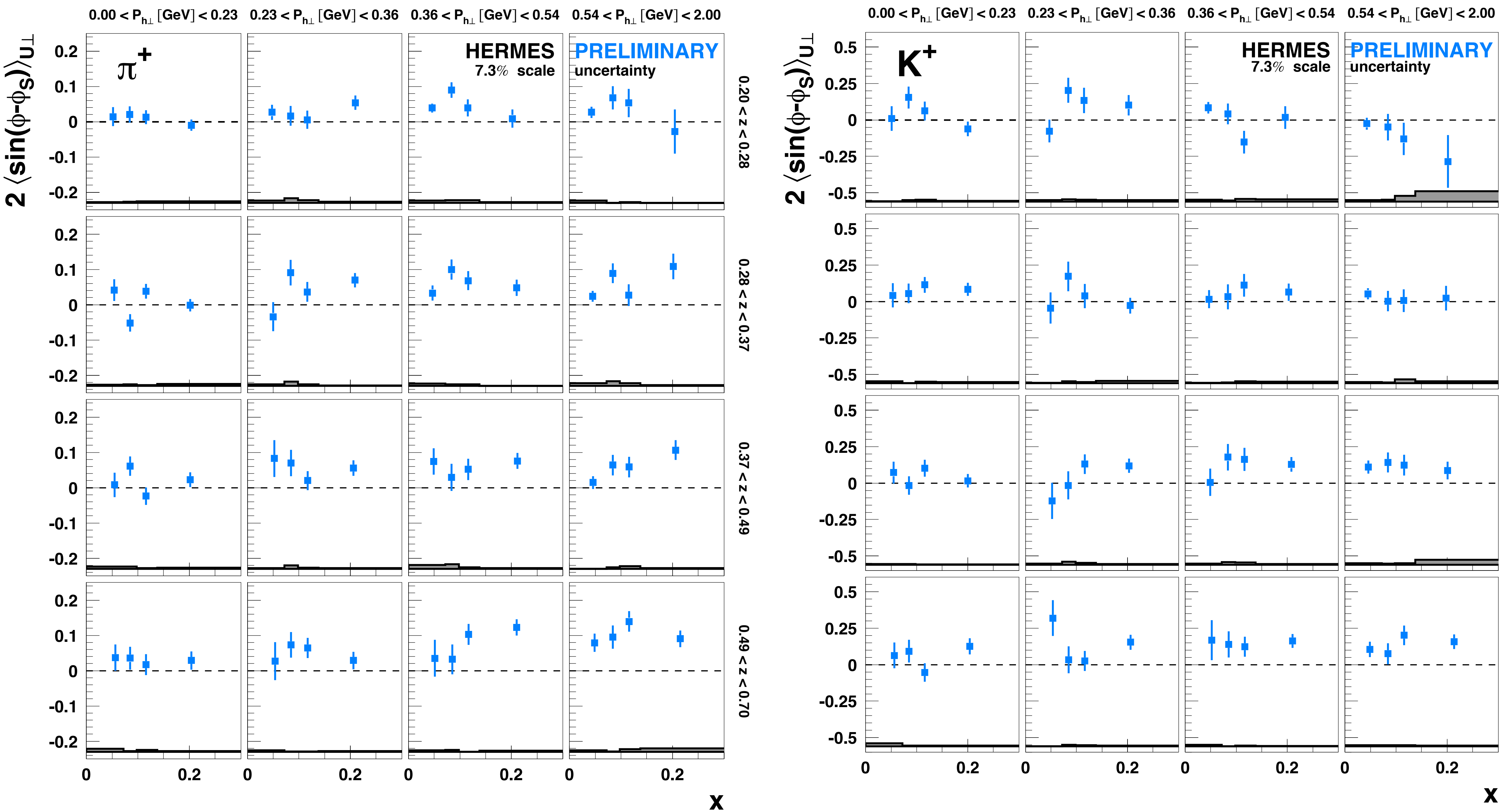




- π^+ amplitudes positive; π^- amplitudes≈0
- π^+ amplitudes increasing with x at large $P_{h\perp}$

Sivers amplitudes

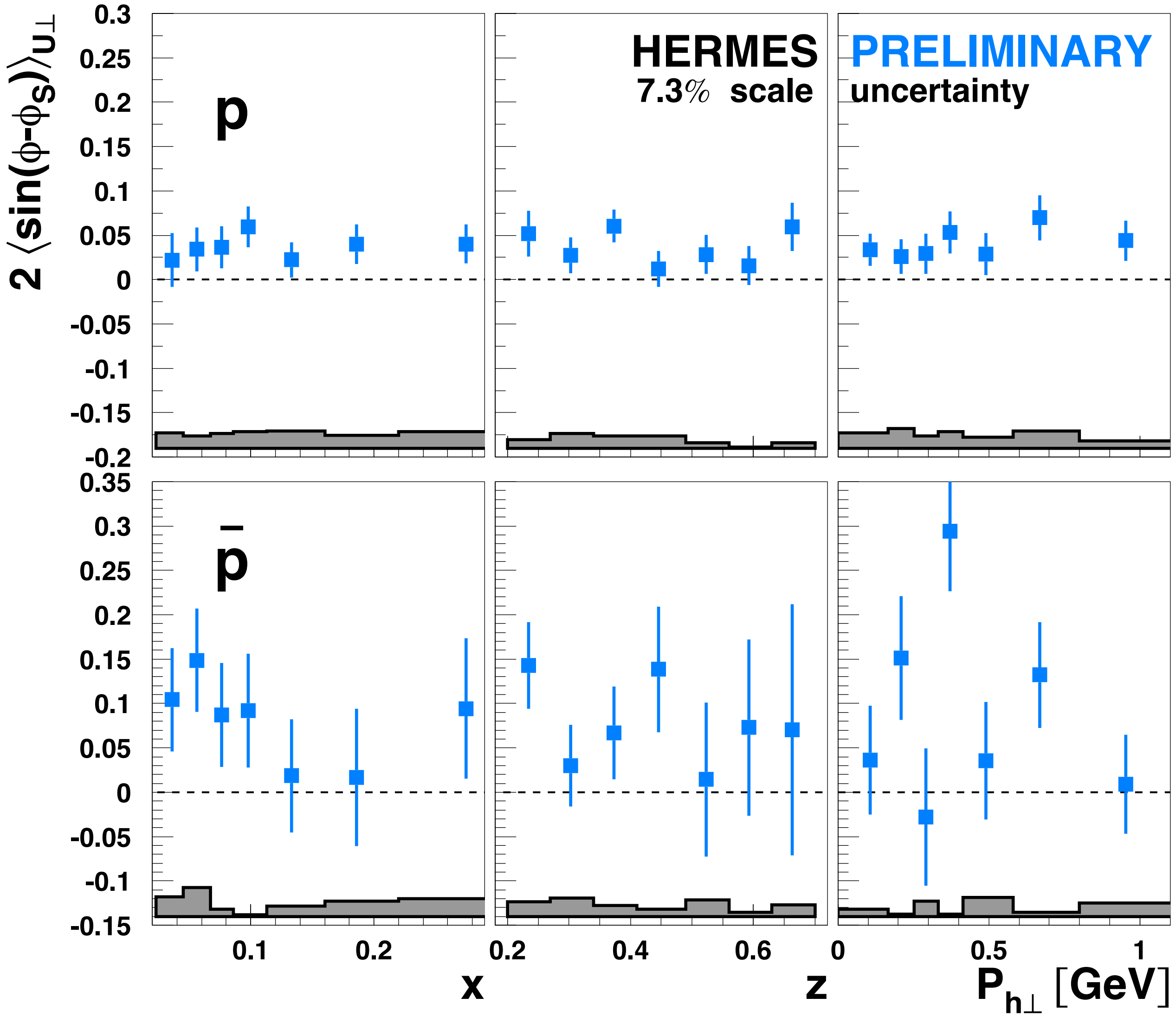
$$F_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$

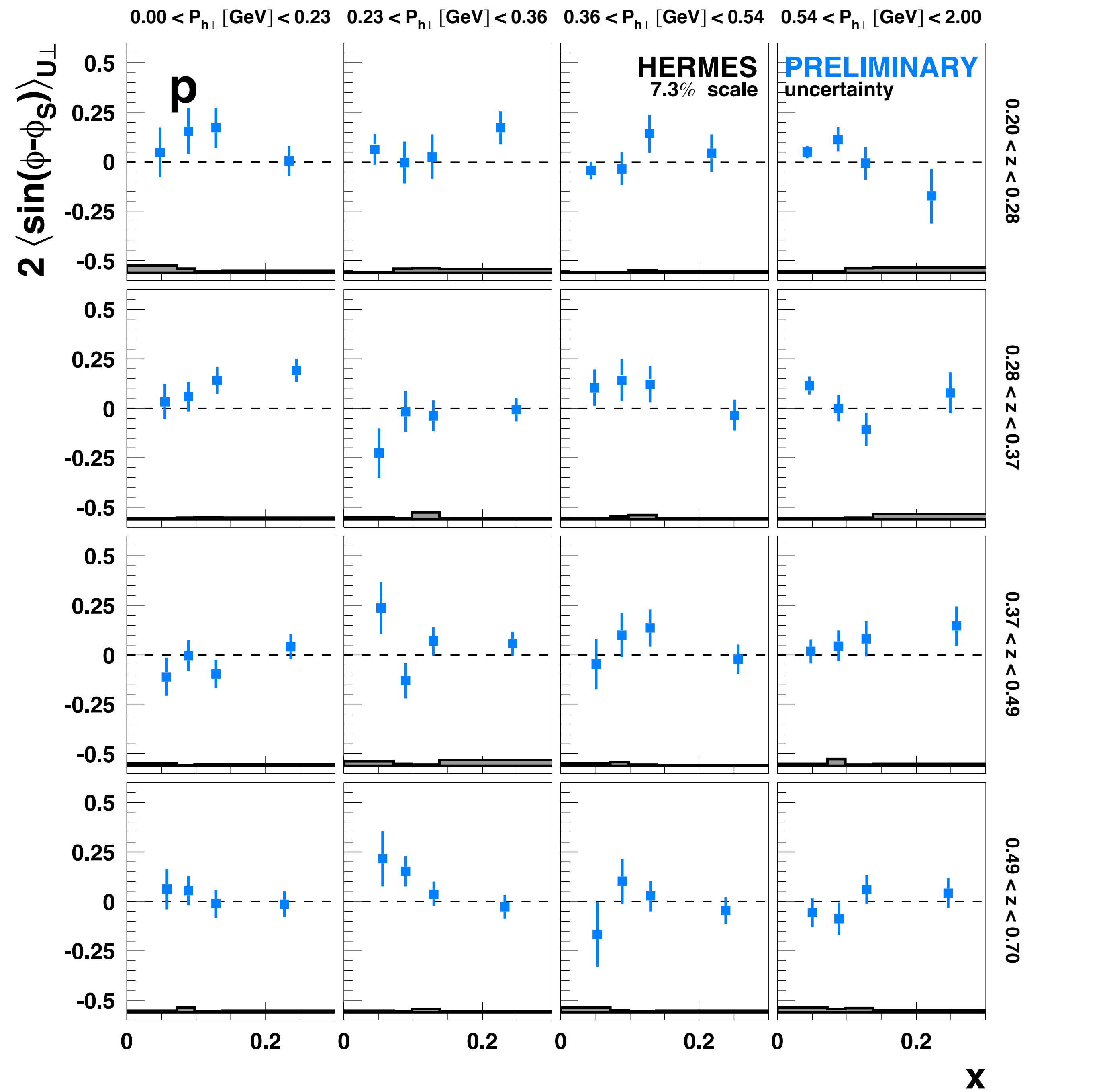


- K^+ amplitudes positive, larger than π^+ $\longrightarrow$ non-trivial role of sea quarks?

Sivers amplitudes

$$F_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$

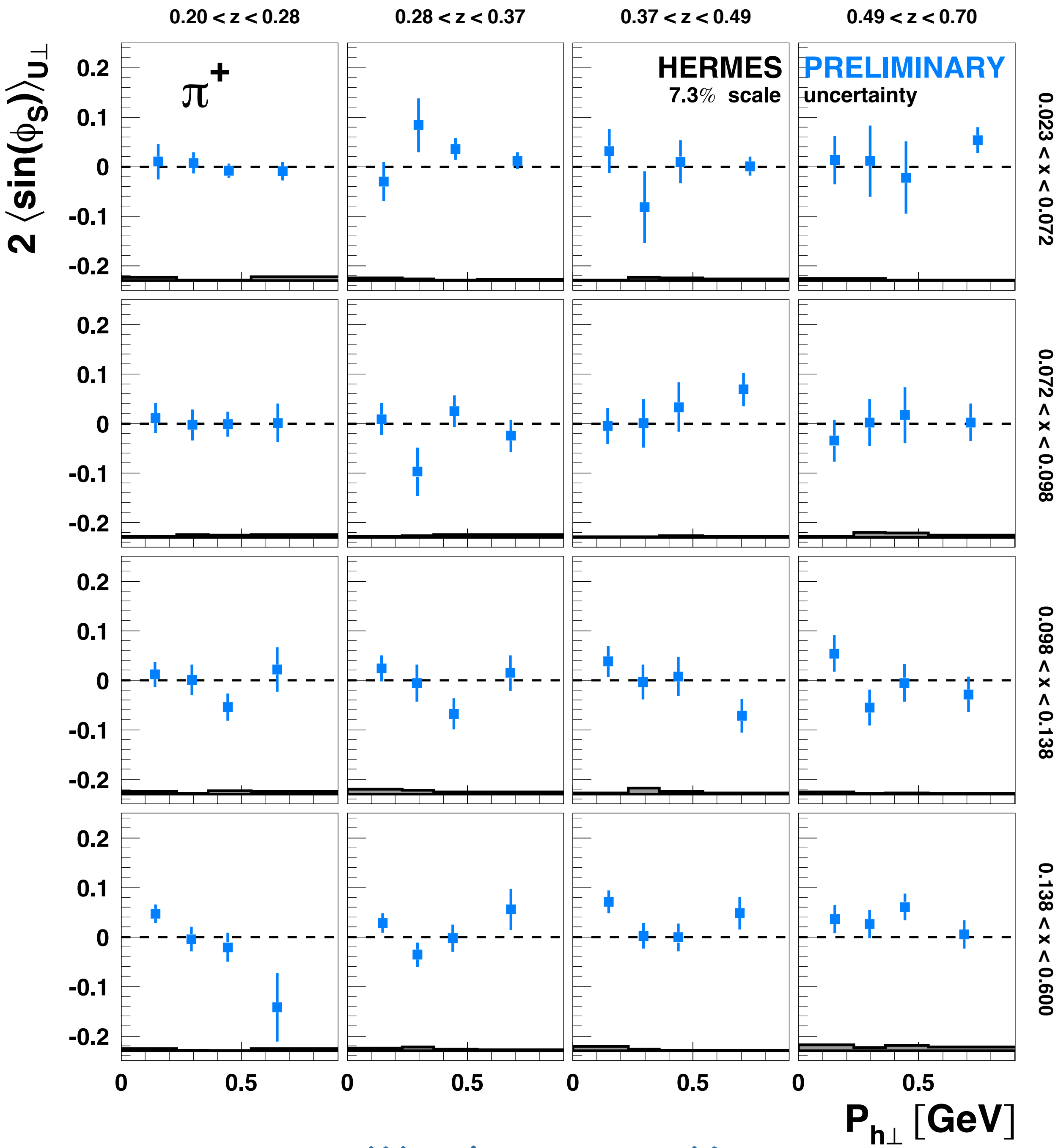


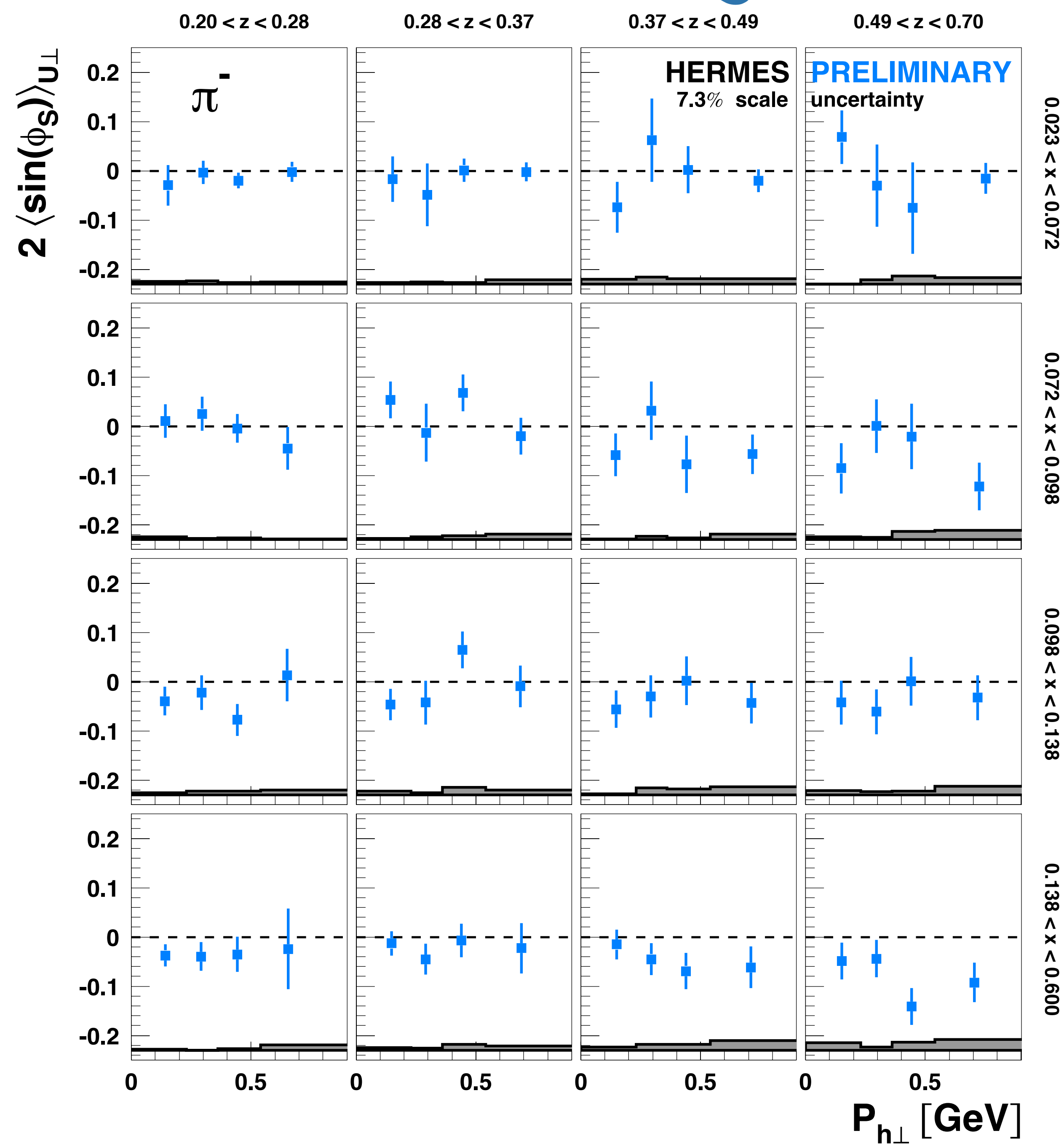


- p amplitudes positive

sinϕ_S

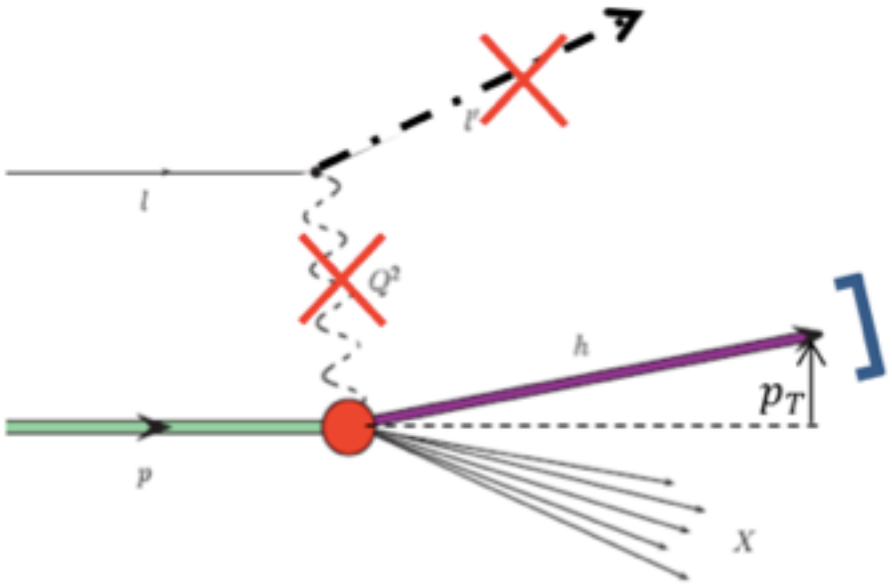
higher twist!





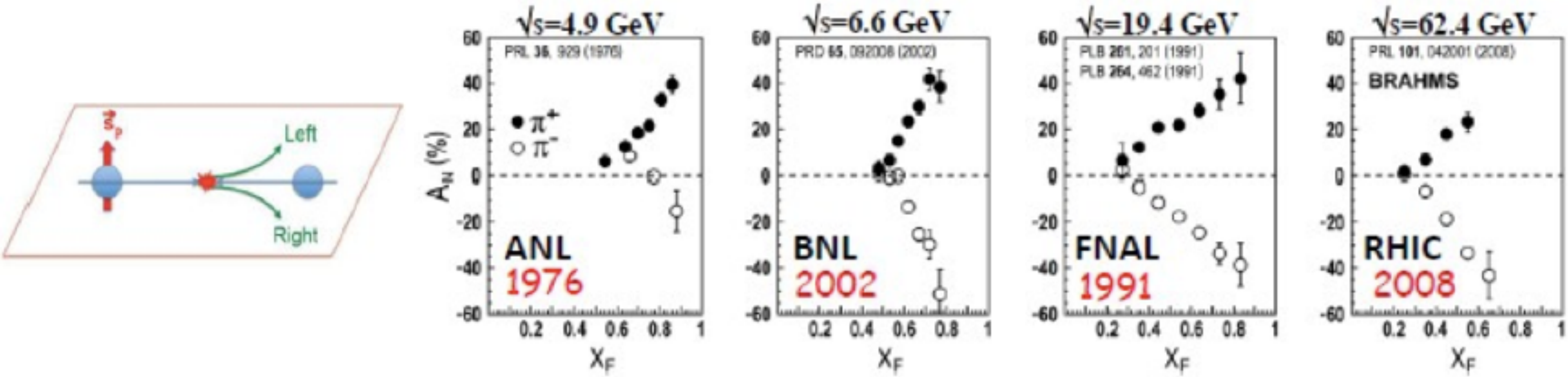
- π^- amplitudes negative

Inclusive transverse target single-spin asymmetry



Motivation

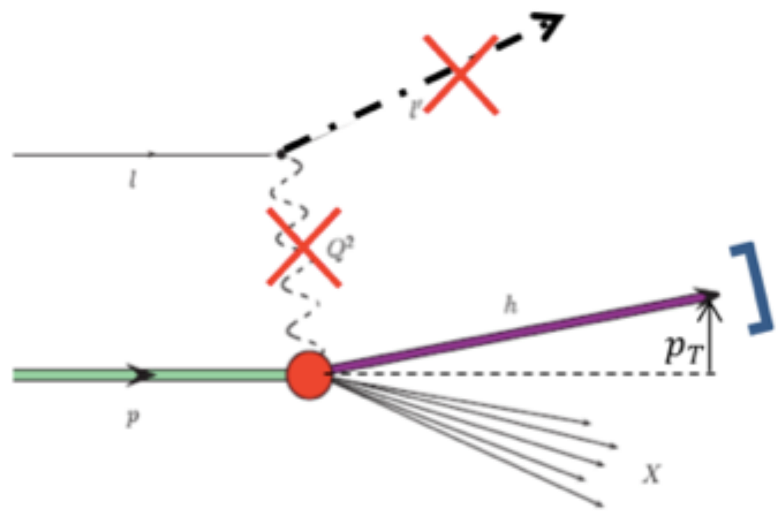
- Large left-right asymmetries (A_N) observed in $p^{\uparrow}p \to hX$ for $\sqrt{s}$ from 4.9 to 500 GeV



- Not interpretable based on collinear factorisation in leading twist
- Possible interpretations are based on
  - TMD PDFs and FFs - mainly Sivers and Collins effect
  - collinear, with higher-twist multiparton correlations
  - combination of both, with different kinematic domains of validity
- Need additional experimental data!

Transverse target spin asymmetry at HERMES

- Inclusive hadron electroproduction $e^{\pm}p^{\uparrow} \to hX$



P_T wrt. lepton beam

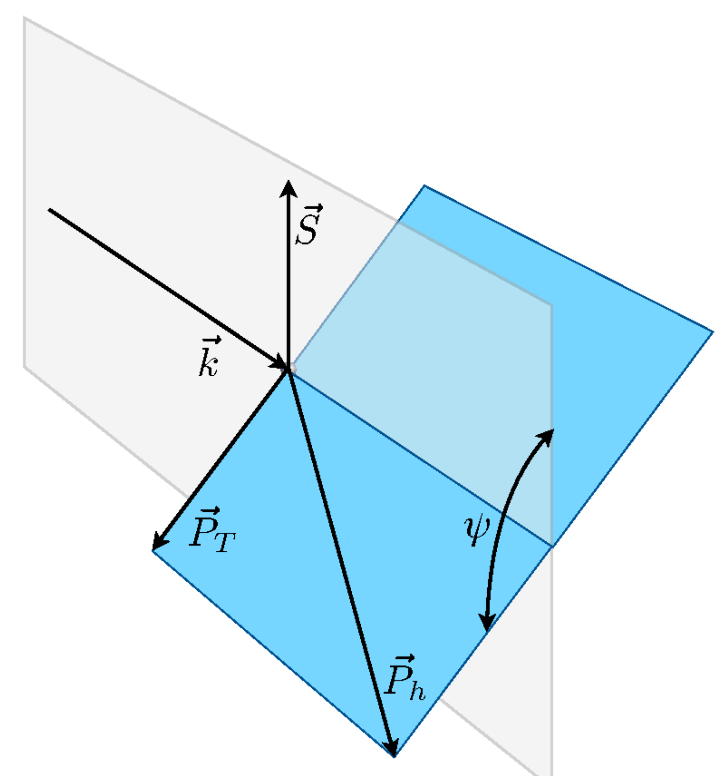
$x_F = P_L/P_{L,max}$ in ep CMS

- Azimuthal asymmetry

$$A_{UT}(x_F, P_T) = A_{UT}^{\sin\psi}(x_F, P_T)\sin\psi$$

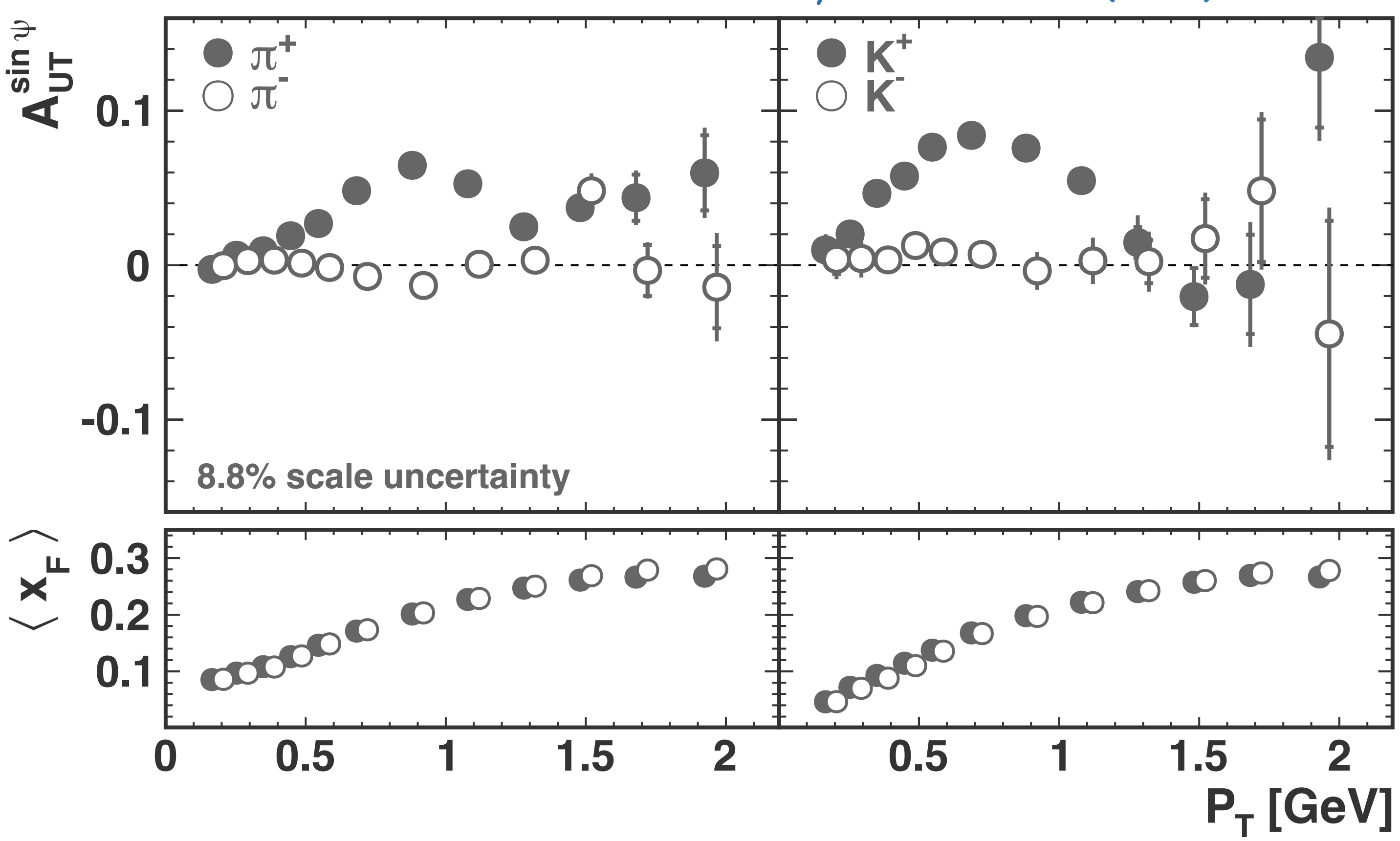
$$A_{UT}^{\sin\psi} = \frac{\pi}{2} A_N$$

at HERMES: $\psi \approx \phi - \phi_S$ (Sivers angle)



P_T dependence

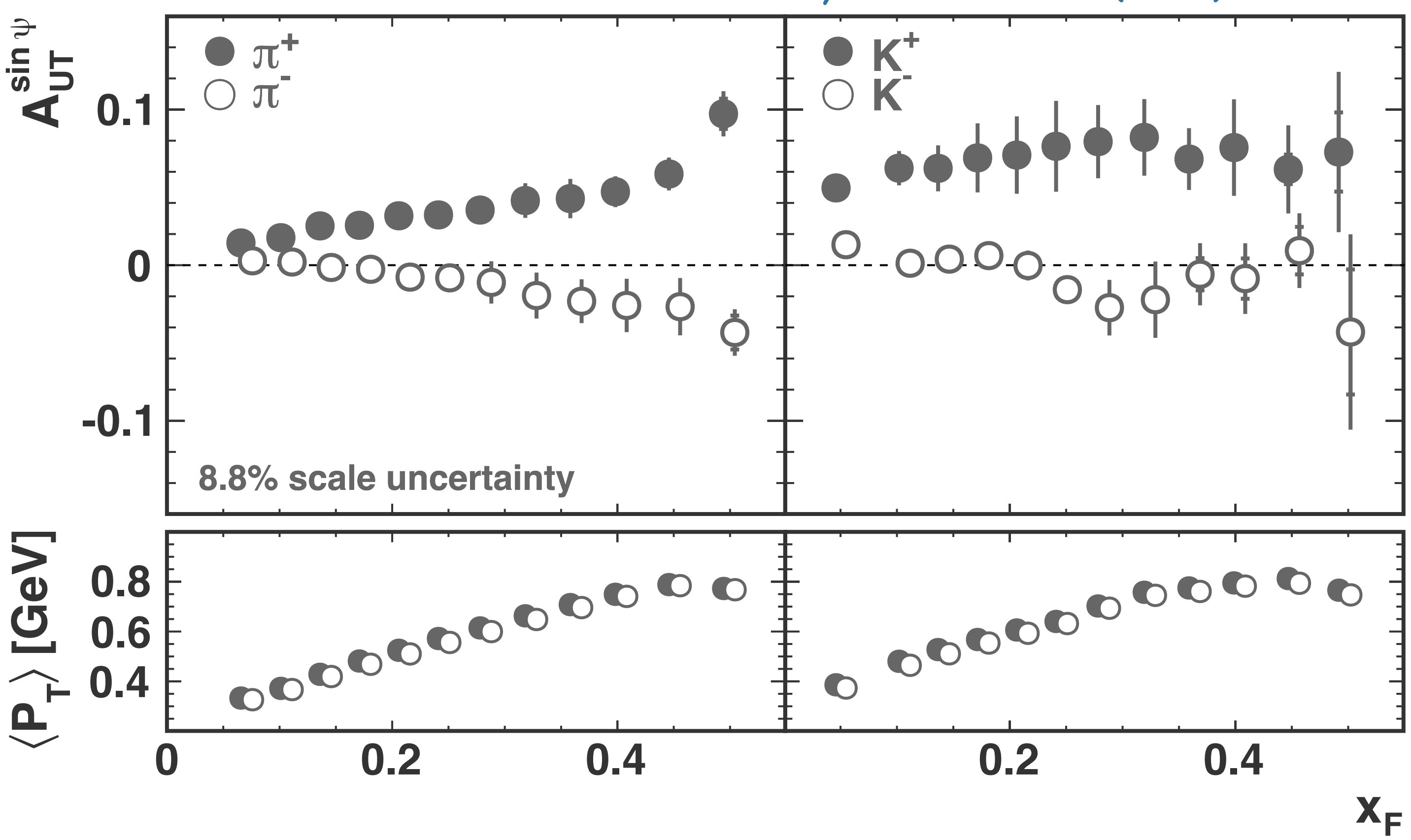
Phys. Lett. B 728 (2014) 183-190



- π^+ and K^+
  - positive
  - larger for K^+ than for π^+
  - varying with P_T
- π^- and K^-
  - small amplitudes

x_F dependence

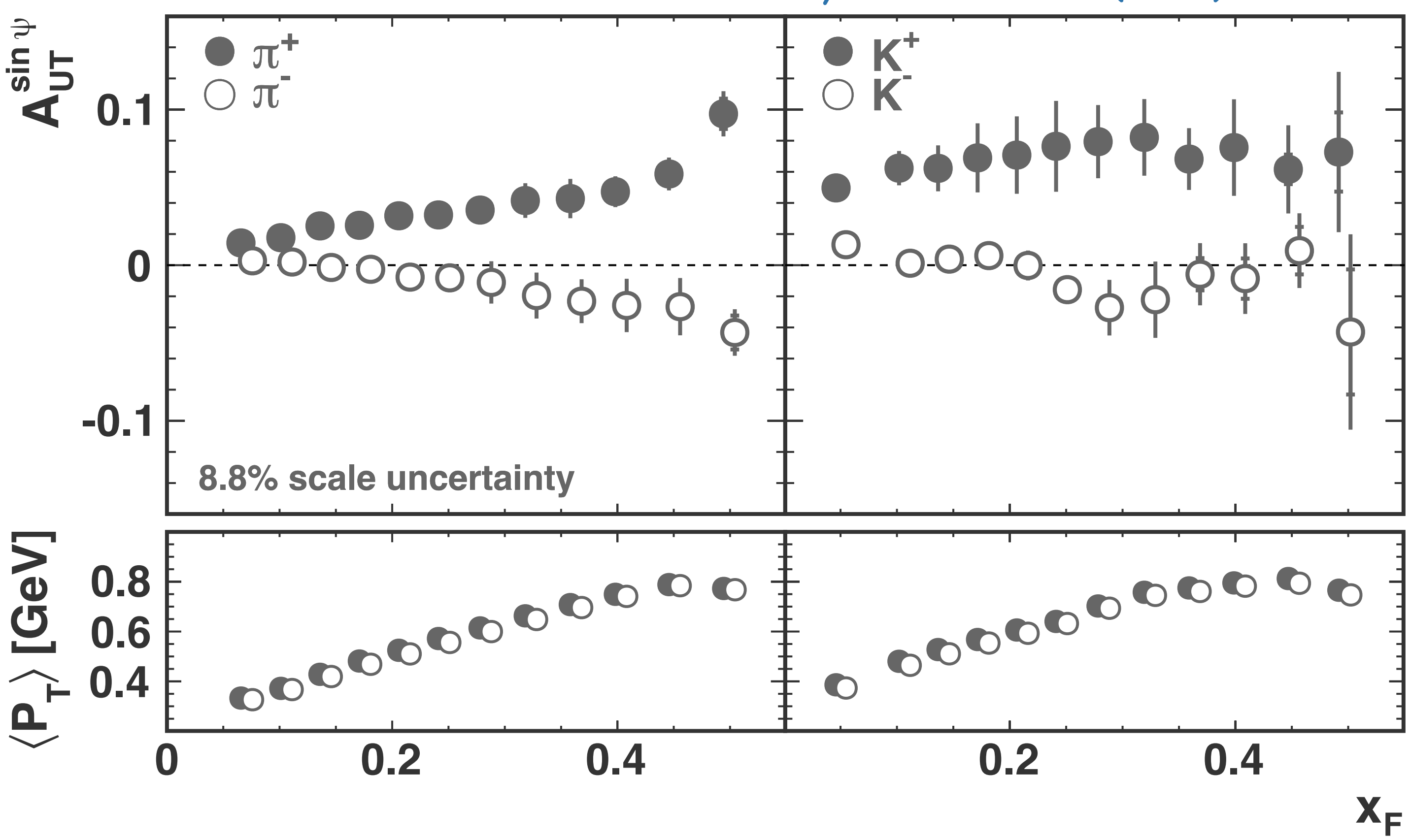
Phys. Lett. B 728 (2014) 183-190



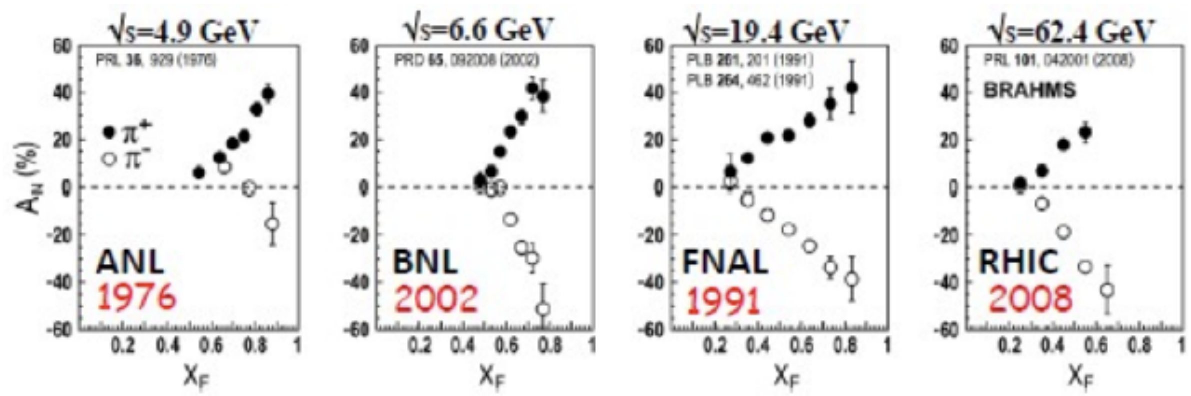
- π^+
  - >0, increasing linearly with x_F
- π^-
  - <0, decreasing linearly with x_F

x_F dependence

Phys. Lett. B 728 (2014) 183-190

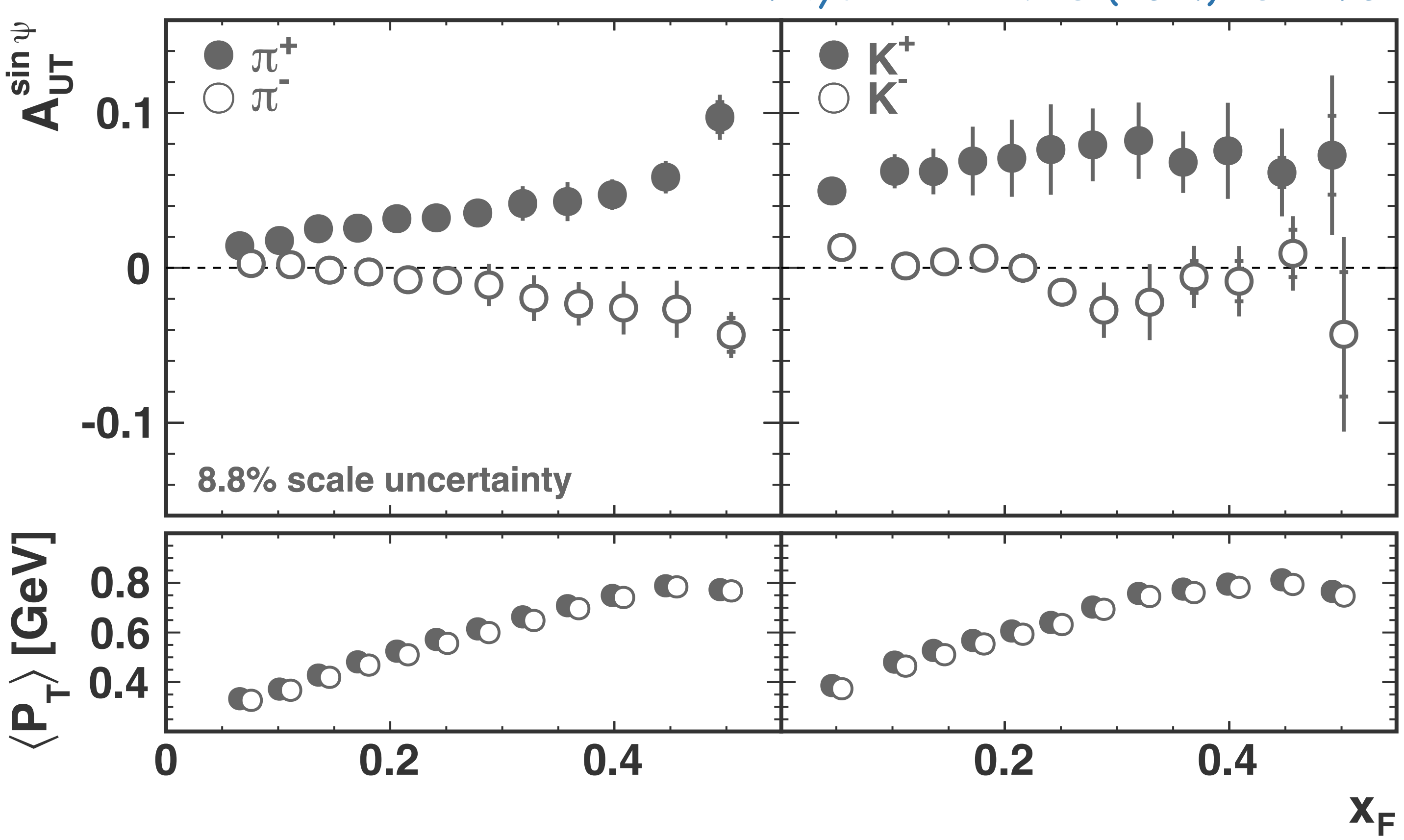


- π^+
  - >0, increasing linearly with x_F
- π^-
  - <0, decreasing linearly with x_F
- π^- and π^+
  - similar behaviour as $p^\uparrow p \to hX$

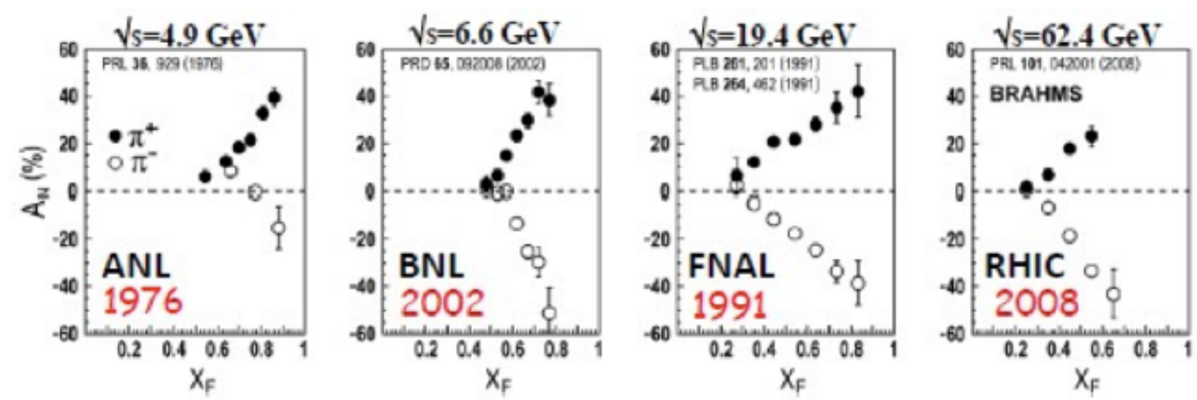


x_F dependence

Phys. Lett. B 728 (2014) 183-190



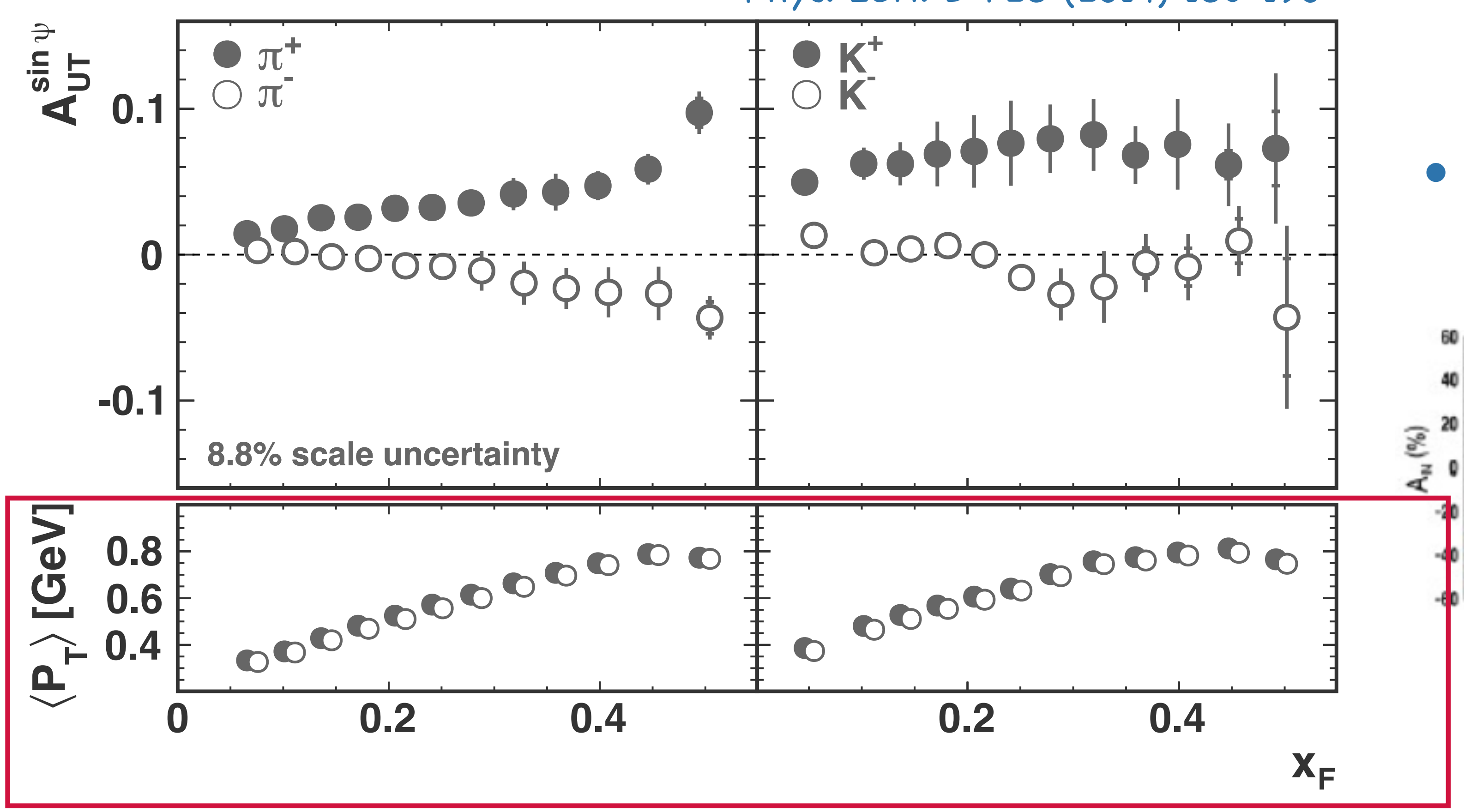
- π^+
  - >0, increasing linearly with x_F
- π^-
  - <0, decreasing linearly with x_F
- π^- and π^+
  - similar behaviour as $p^{\uparrow}p \to hX$



- K^+
  - >0, constant with x_F
- K^-
  - ≈0

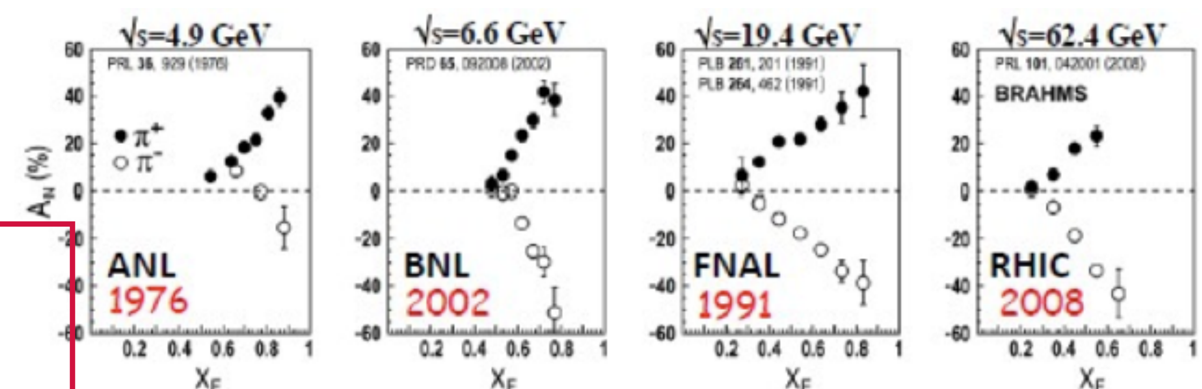
x_F dependence

Phys. Lett. B 728 (2014) 183-190



x_F-P_T correlation ⟶ 2D

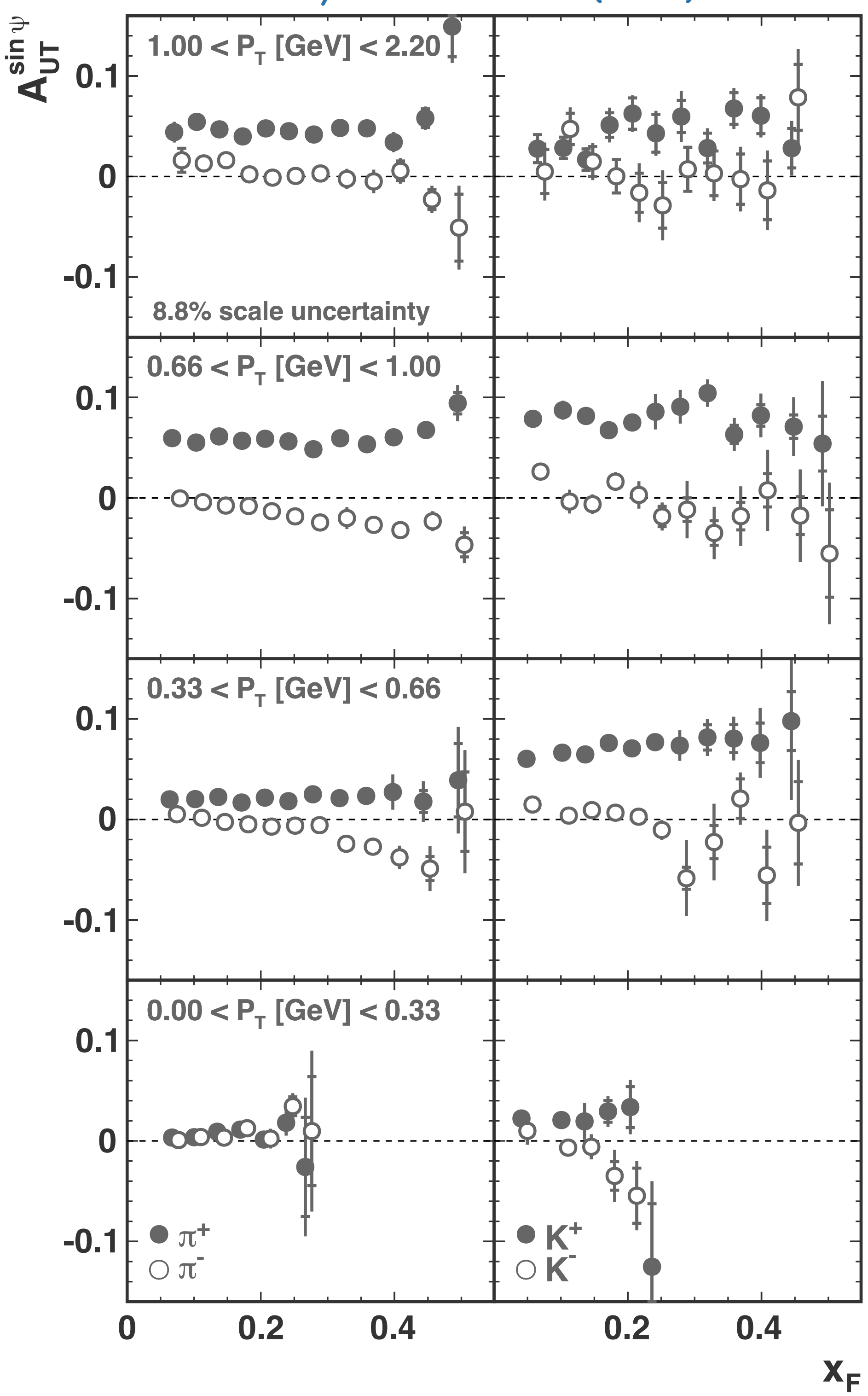
- π^+
  - >0, increasing linearly with x_F
- π^-
  - <0, decreasing linearly with x_F
- π^- and π^+
  - similar behaviour as $p^{\uparrow}p \rightarrow hX$



- K^+
  - >0, constant with x_F
- K^-
  - ≈0

Disentangling x_F and P_T dependence

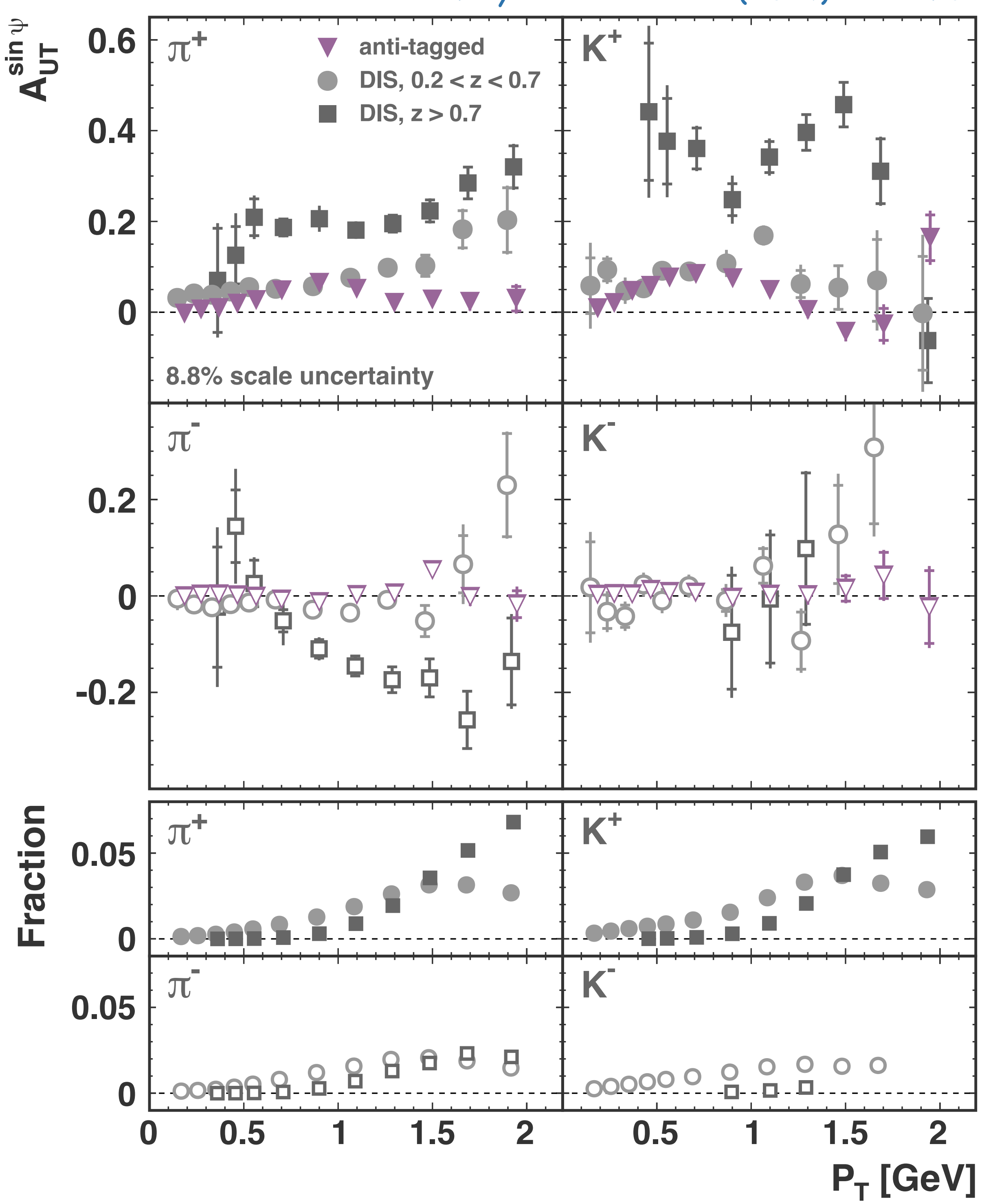
Phys. Lett. B 728 (2014) 183-190



- π^+
  - independent of x_F -> 1D x_F dependence from P_T correlation
- π^-
  - decreasing linearly with x_F As for 1D!
- note: π^- and π^+ from $p^\uparrow p \to hX$
  - linear dependence on x_F remains after slicing in P_T
- K^+
  - ≈ constant/ slightly increasing with x_F
- K^-
  - ≈ constant/ slightly decreasing with x_F

Disentangling sub samples

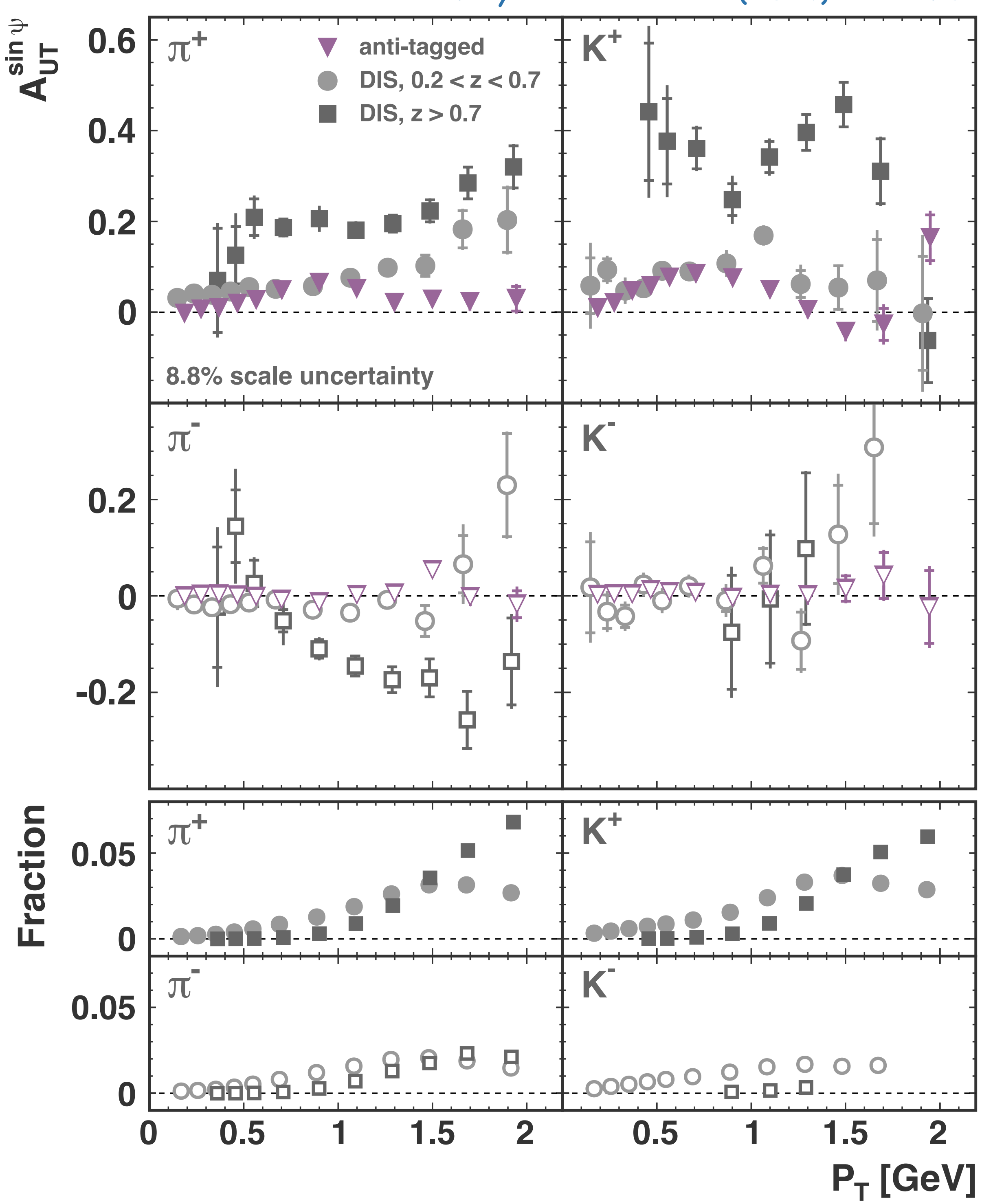
Phys. Lett. B 728 (2014) 183-190



- anti-tagged
  - no scattered $e^{\pm}$ detected
  - mainly $Q^2 \approx 0$
  - hard scale P_T
  - $P_T > \Lambda_{QCD}$: higher twist
  - $P_T \approx \Lambda_{QCD}$: no theory predictions
  - ≈ overall results, 98% of statistics

Disentangling sub samples

Phys. Lett. B 728 (2014) 183-190



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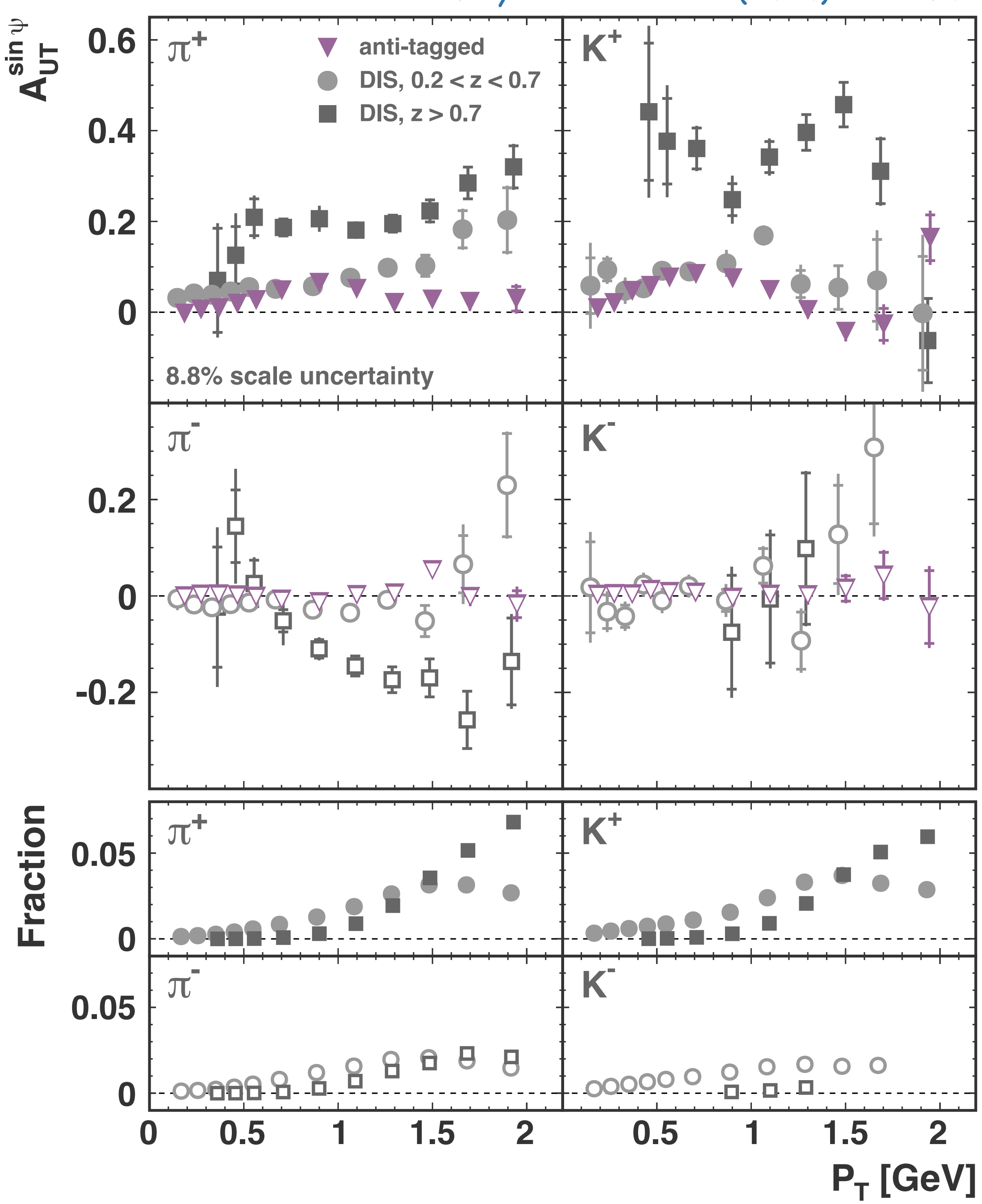
  - ≈ overall results, 98% of statistics
- DIS with 0.2<z<0.7
  - mainly $\langle Q^2 \rangle > P_T$
  - TMD PDF and FF description
  - similar to Sivers amplitudes

Disentangling sub samples

Phys. Lett. B 728 (2014) 183-190



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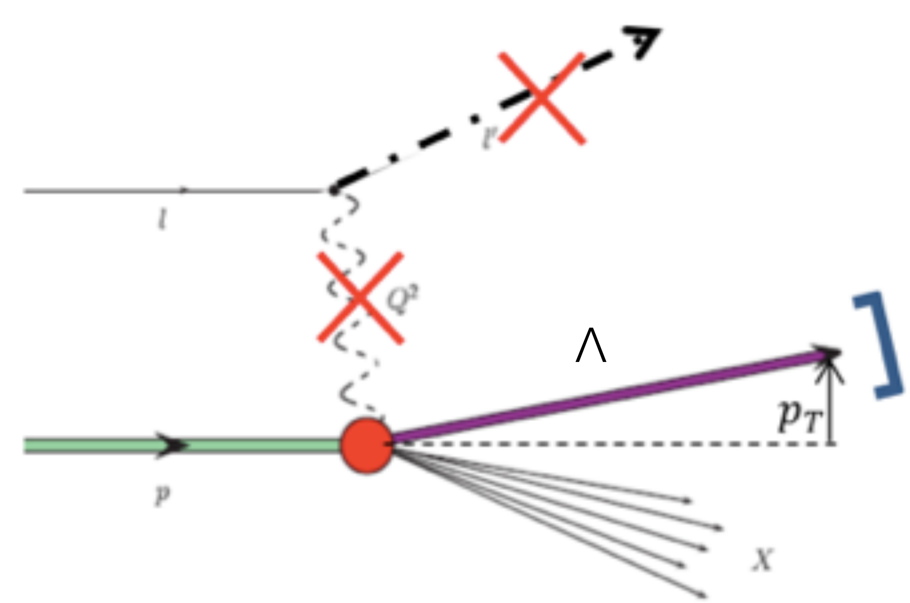
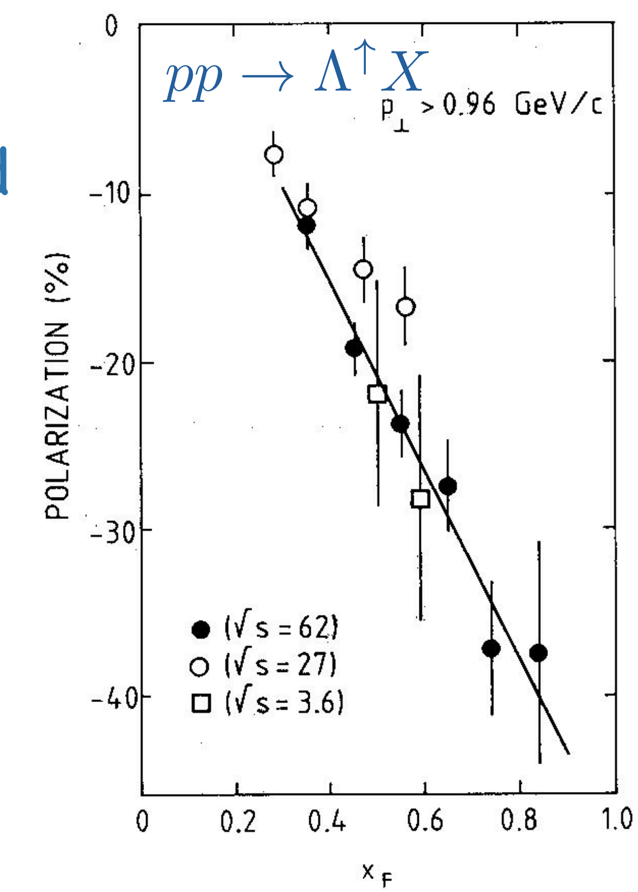
- DIS with 0.2<z<0.7
  - mainly $\langle Q^2 \rangle > P_T$
  - TMD PDF and FF description
  - similar to Sivers amplitudes
- DIS with z>0.7
  - $\langle Q^2 \rangle > P_T$
  - TMD PDF and FF description
  - large asymmetries for $\pi^{\pm}$, K^+
  - exclusive processes (ρ,φ) favoured fragmentation

Transverse Λ polarization in inclusive measurement



Motivation

- Large transverse Λ polarization P^{Λ} observed in unpolarized hadron scattering experiments
- Vast majority: negative polarization values observed, except positive for $K^{-}p$ and $\Sigma^{-}N$
- Magnitude increases with x_F and p_T, reaching plateau for p_T=1 GeV



Motivation

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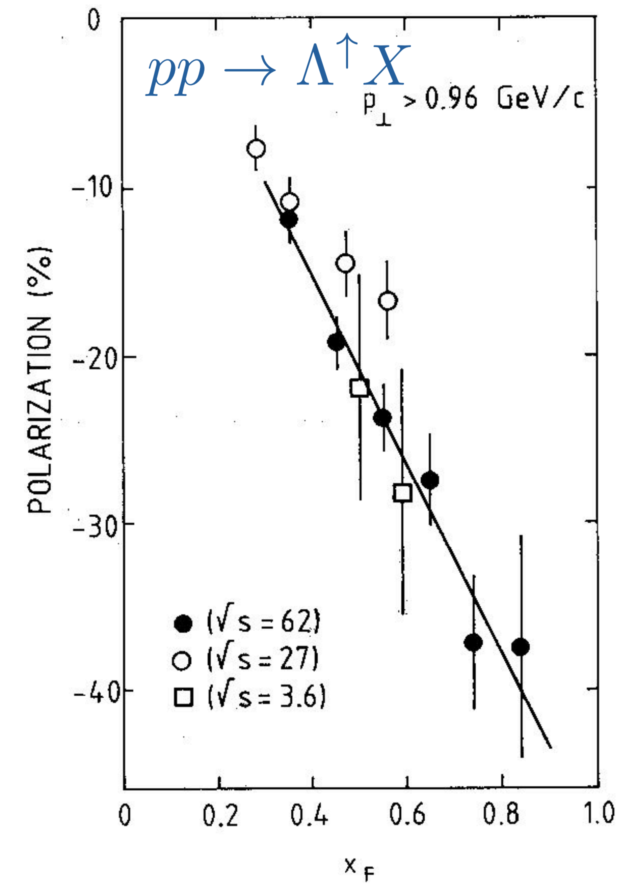
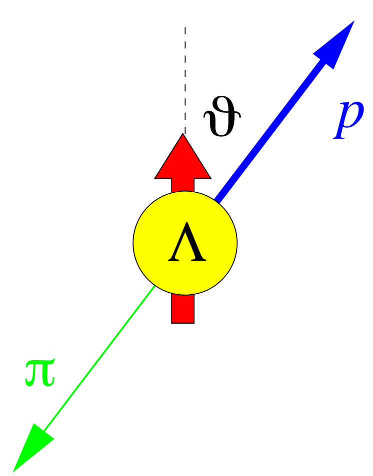


- $ep \to \Lambda^{\uparrow} X$ scattering?
- SIDIS (high Q^2) $P^{\Lambda} \propto D_{1T}^{\perp}$, polarising FF
- current measurement: inclusive ($Q^2 \approx 0$)

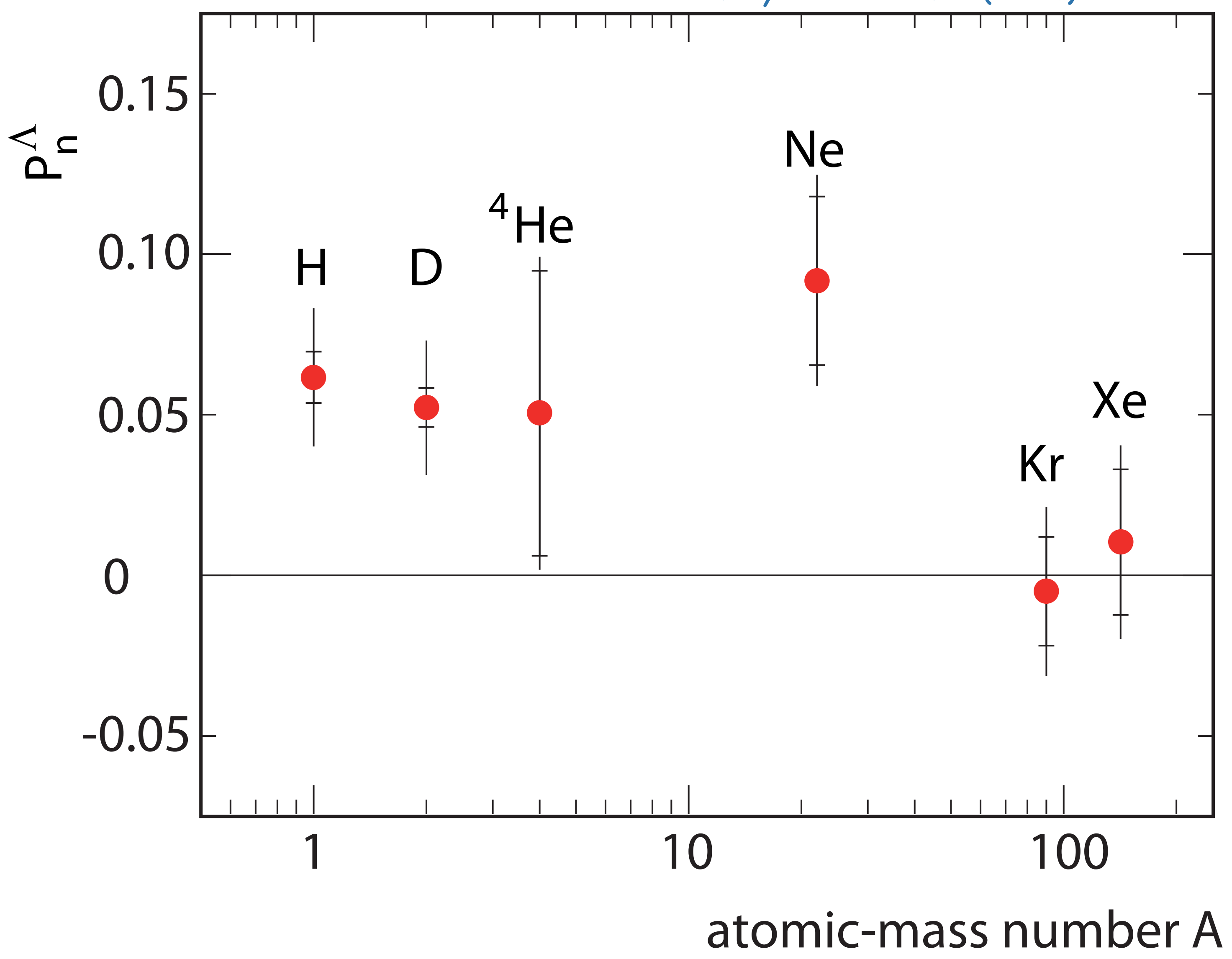


parity-violating weak decay of Λ: in Λ rest frame, proton preferably emitted along Λ spin direction

$$\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p}(1 + \alpha P^{\Lambda} \cos\theta_p)$$

Atomic-mass dependence

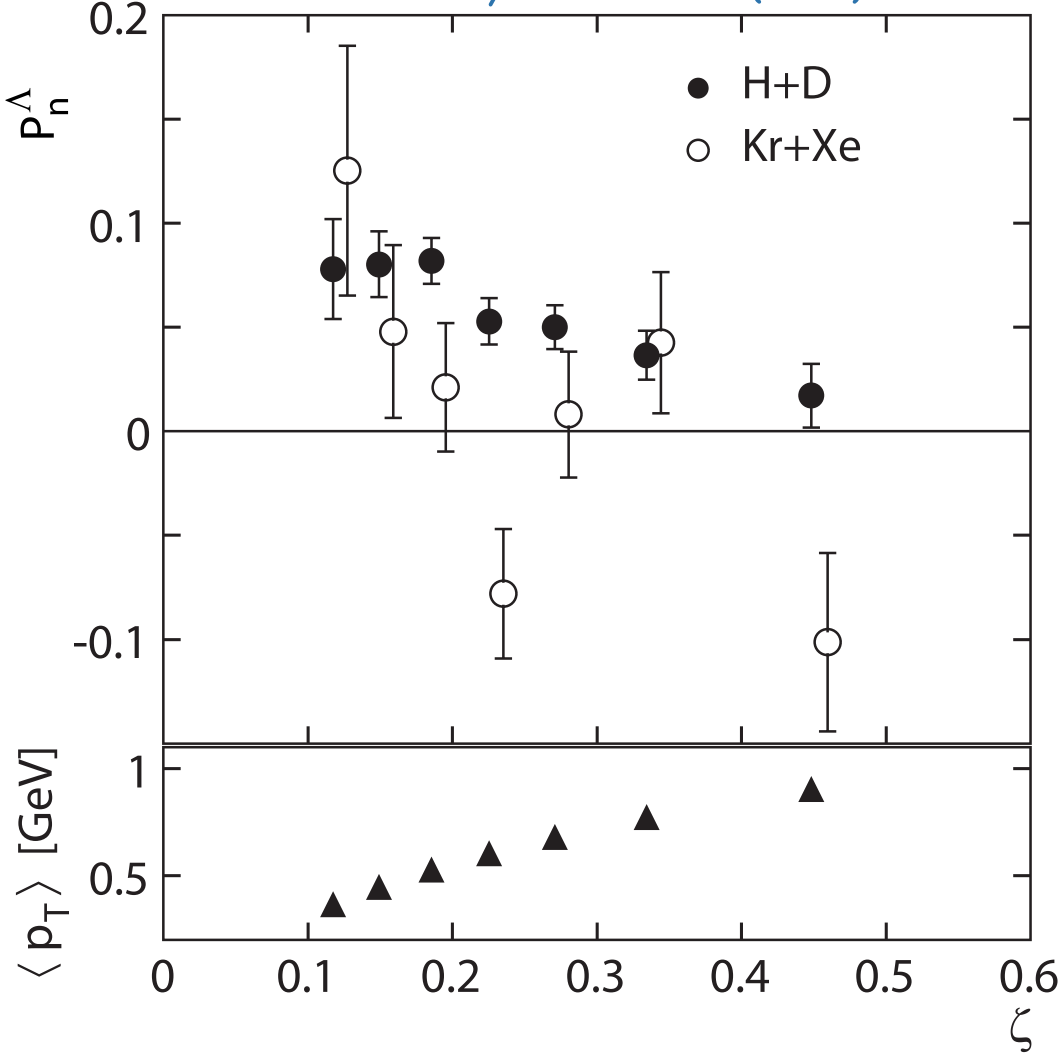
Phys. Rev. D 90 (2014) 072007



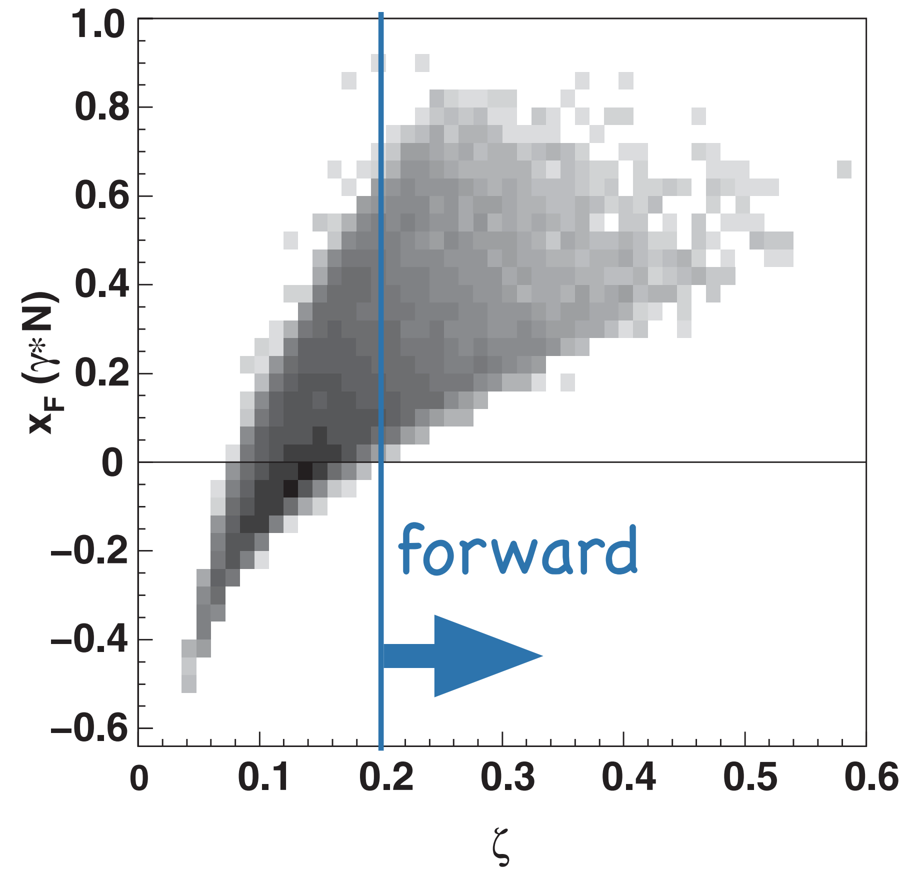
- positive P^Λ for light nuclei
- P^Λ consistent with zero for heavier nuclei

Kinematic dependence

Phys. Rev. D 90 (2014) 072007



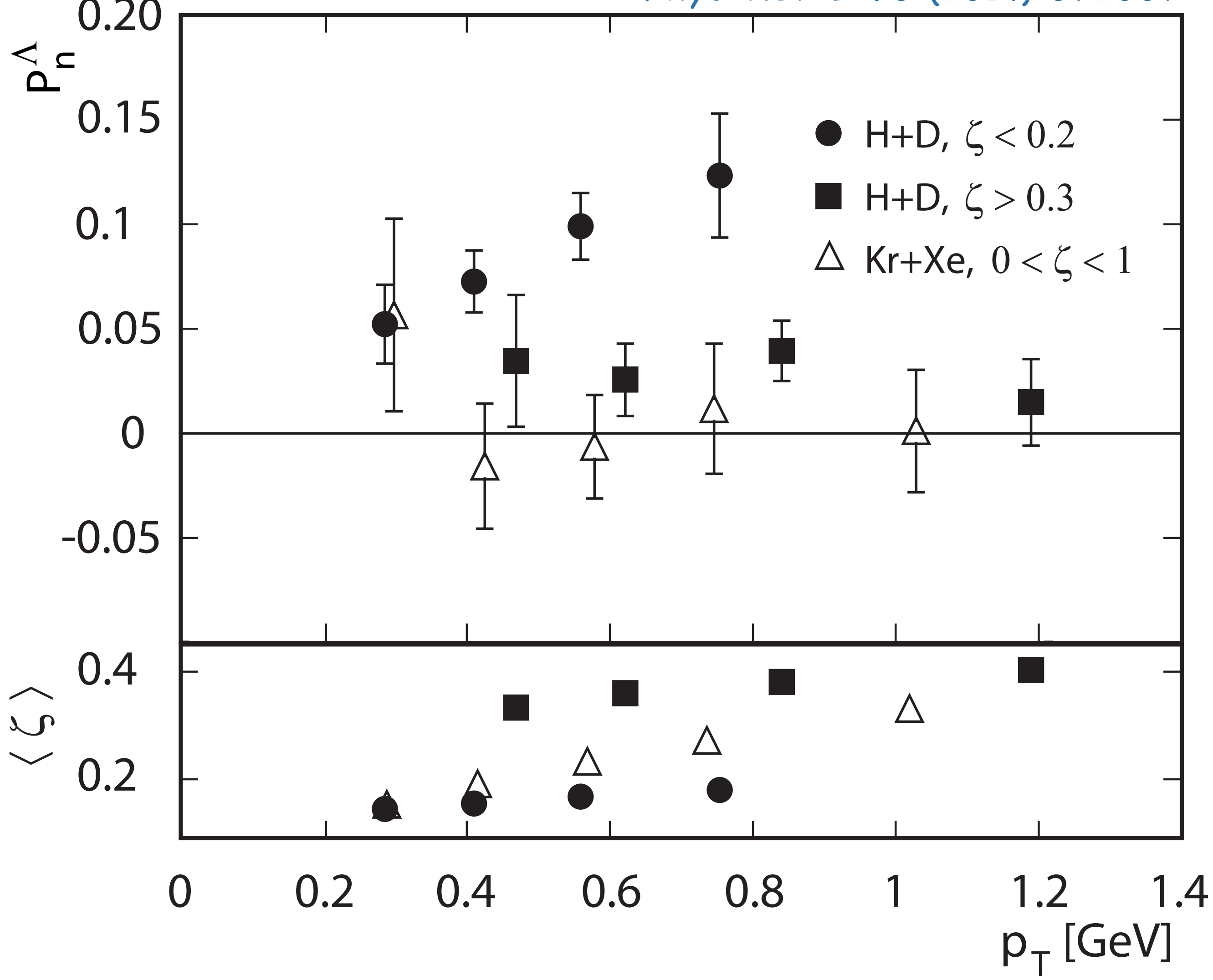
$$\zeta = (E_\Lambda + p_{z\Lambda})/(E_e + p_e)$$



- H+D: P^Λ larger in backward region $\longrightarrow$ possibly influence of current and target fragmentation

Kinematic dependence

Phys. Rev. D 90 (2014) 072007

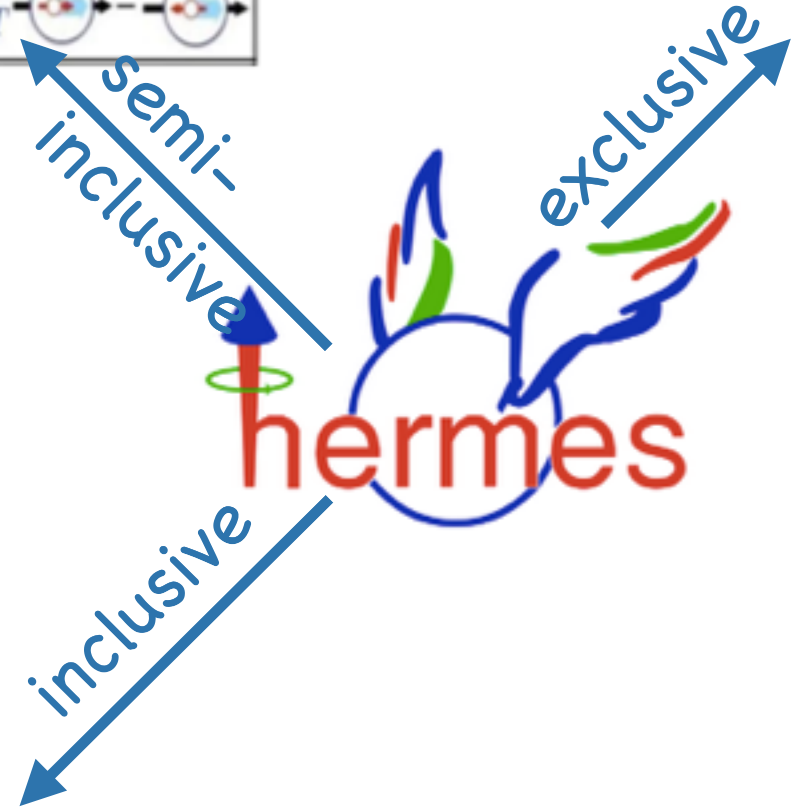


- H+D: P^Λ increases with p_T in backward region, while constant in forward region

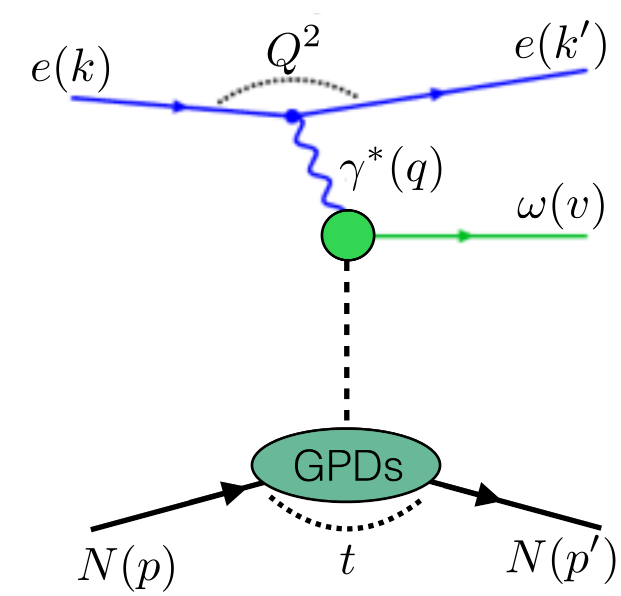
Summary

transverse momentum distributions (TMDs)

nucleon	quark U	quark L	quark T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$



exclusive ω production
arXiv:1407.2119



A_{UT} – Phys. Lett. B **728** (2014) 183-190

P^Λ - Phys. Rev. D 90 (2014) 072007

Thank you for your attention

Back up

Disentangling x_F and P_T dependence