Overview of HERMES results

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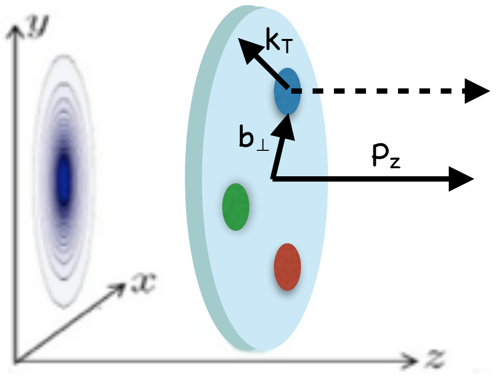
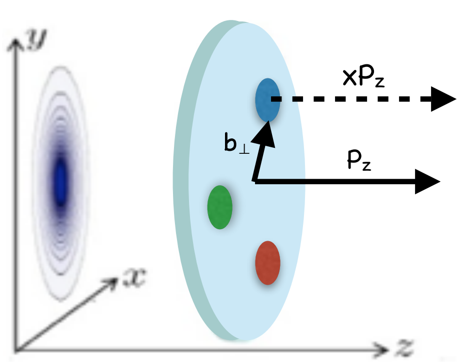
POETIC VI
7-11 September 2015
Palaiseau, France

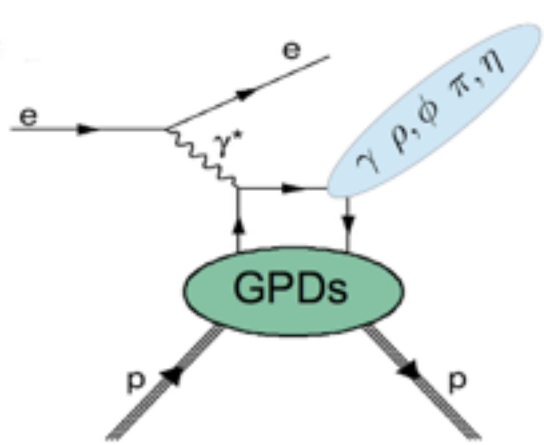
Outline



- 3D picture of the nucleon:
  - exclusive ω production: SDMEs and A_{UT}
  - A_{UT} and A_{LT} in semi-inclusive DIS
- Bose-Einstein correlations in DIS
- Λ polarization in photoproduction

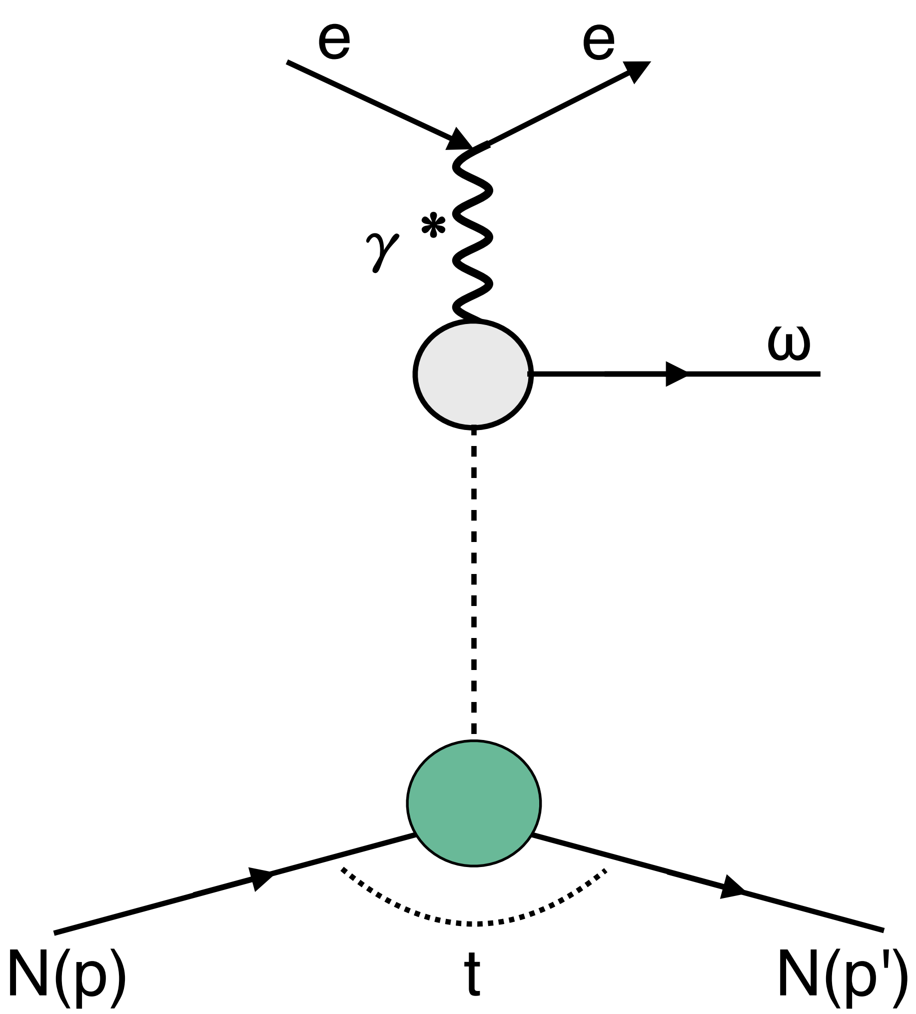
Exclusive ω production



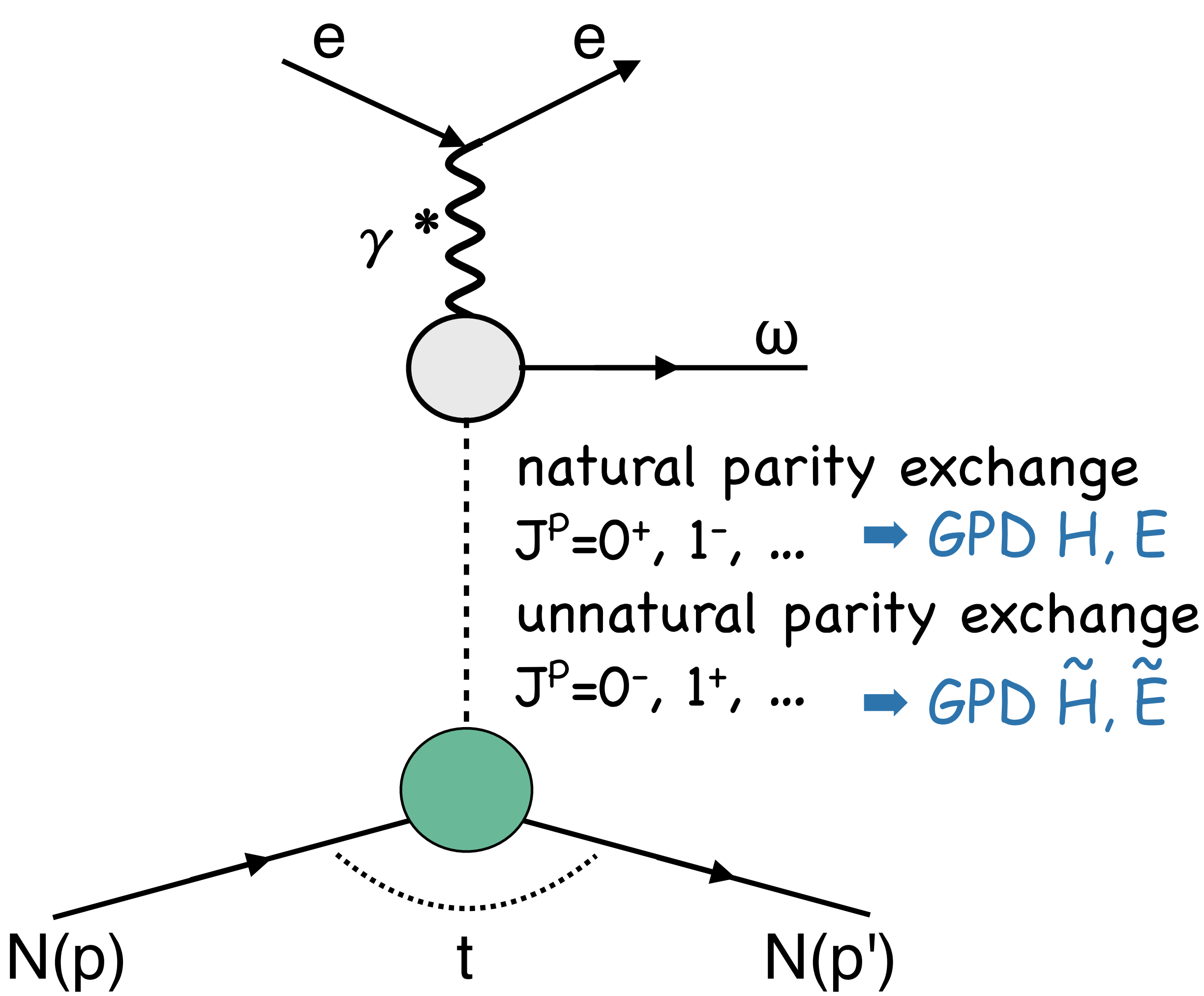


- SDMEs:
  - unpolarized & longitudinally polarized e^+/e^- beam
  - unpolarized H & D target
- A_{UT}:
  - unpolarized e^+/e^- beam
  - transversely polarized H target

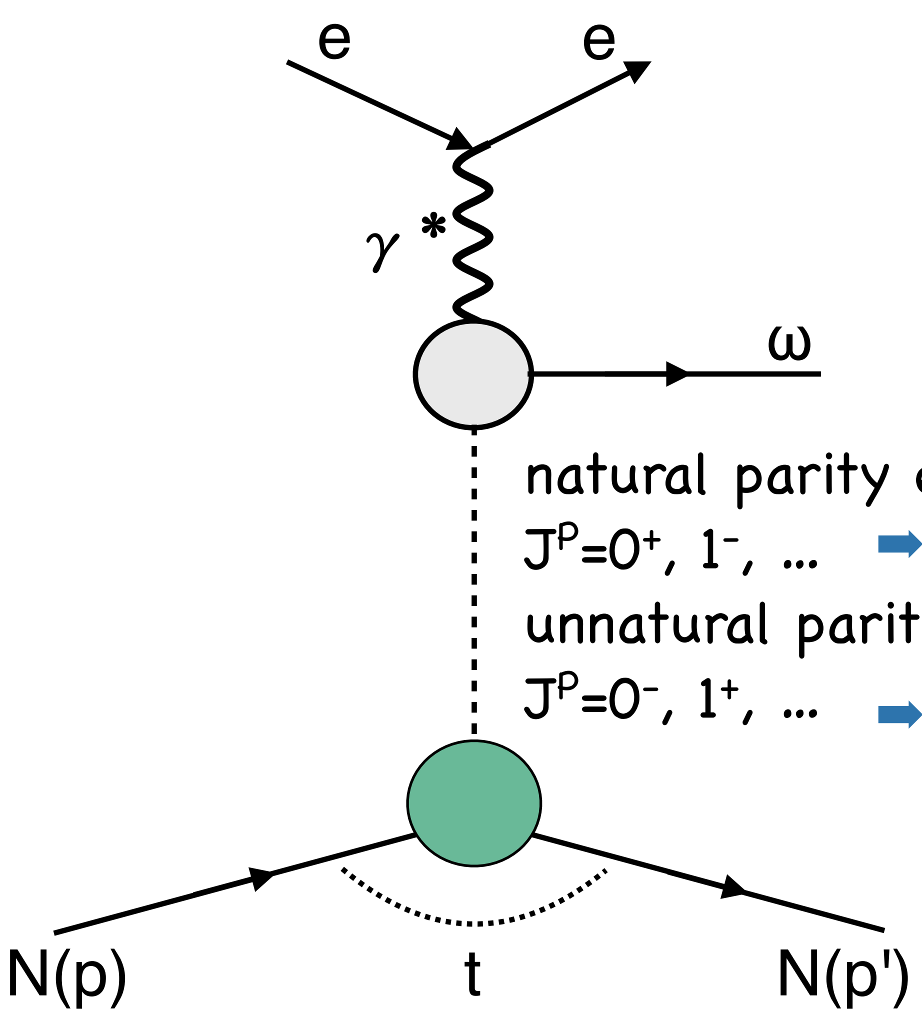
Exclusive ω production



Exclusive ω production



Exclusive ω production



natural parity exchange

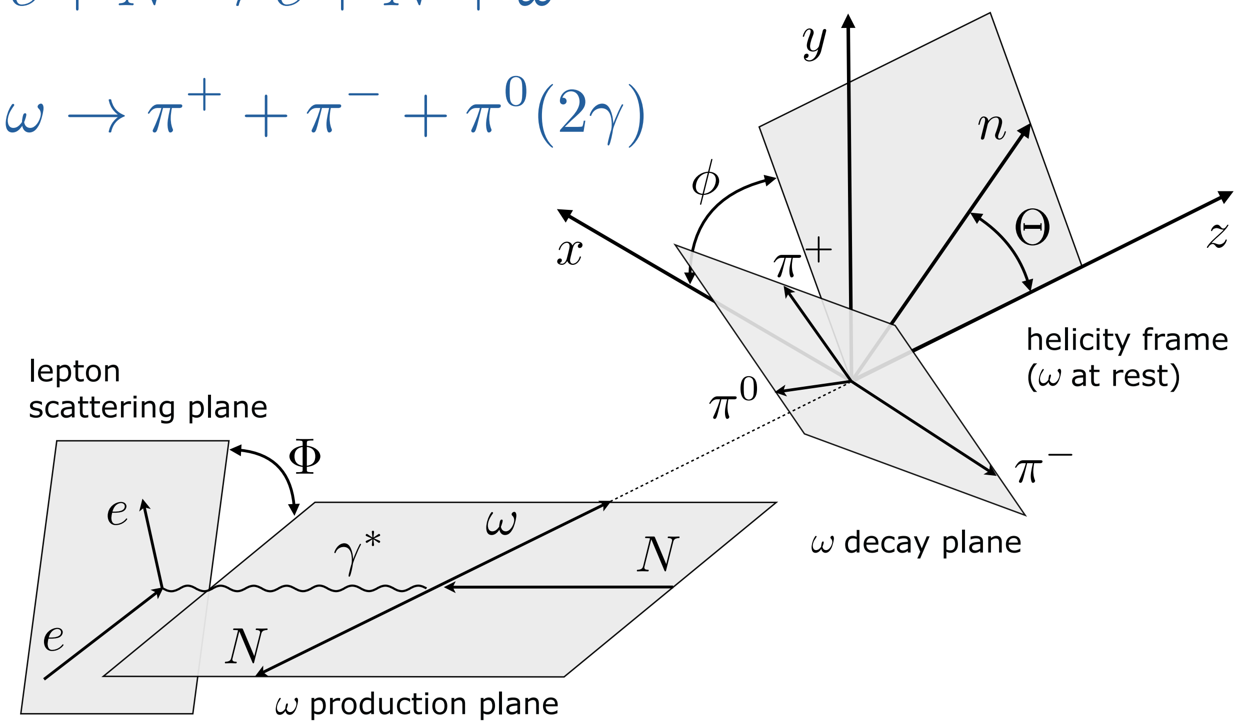
$J^P = 0^+, 1^-, \ldots$ ➡ GPD H, E

unnatural parity exchange

$J^P = 0^-, 1^+, \ldots$ ➡ GPD $\tilde{H}$, $\tilde{E}$

$e + N \rightarrow e + N + \omega$

$\omega \rightarrow \pi^+ + \pi^- + \pi^0(2\gamma)$



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

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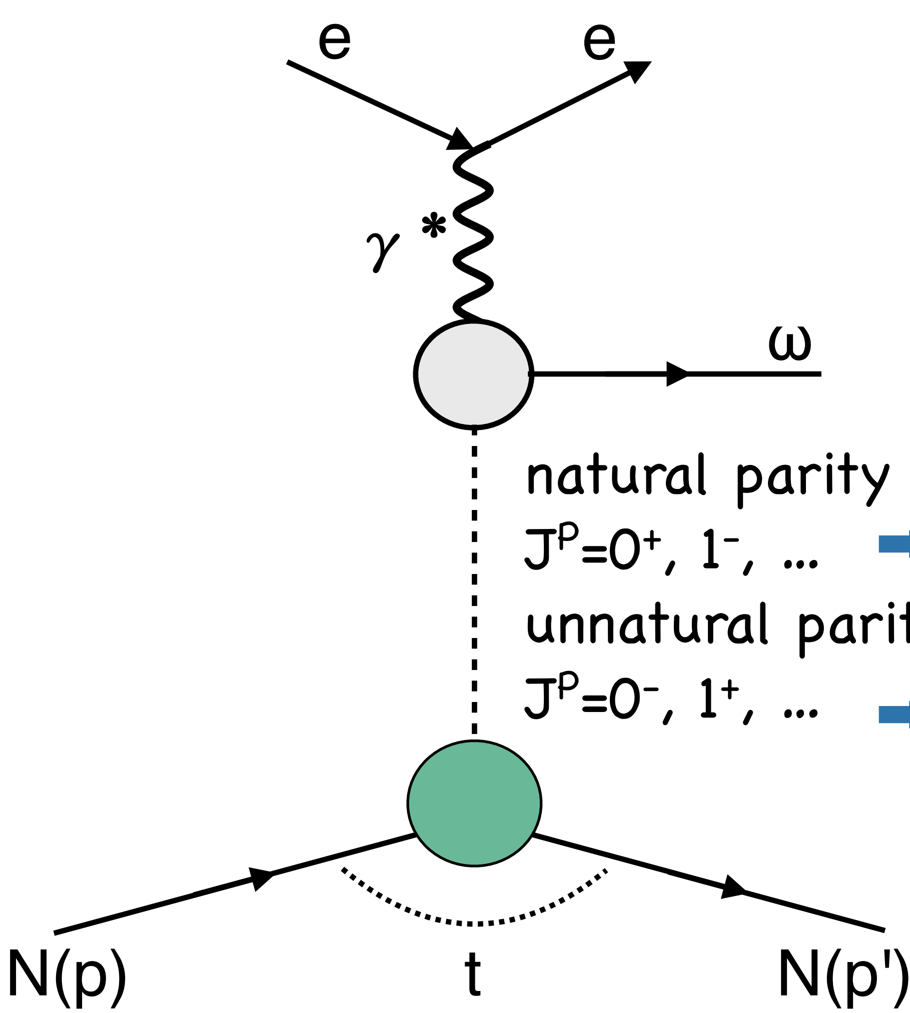
Spin density matrix elements (SDMEs)

describing final spin state of ω

and transverse target-spin asymmetries (A_{UT})

Exclusive ω production



natural parity exchange

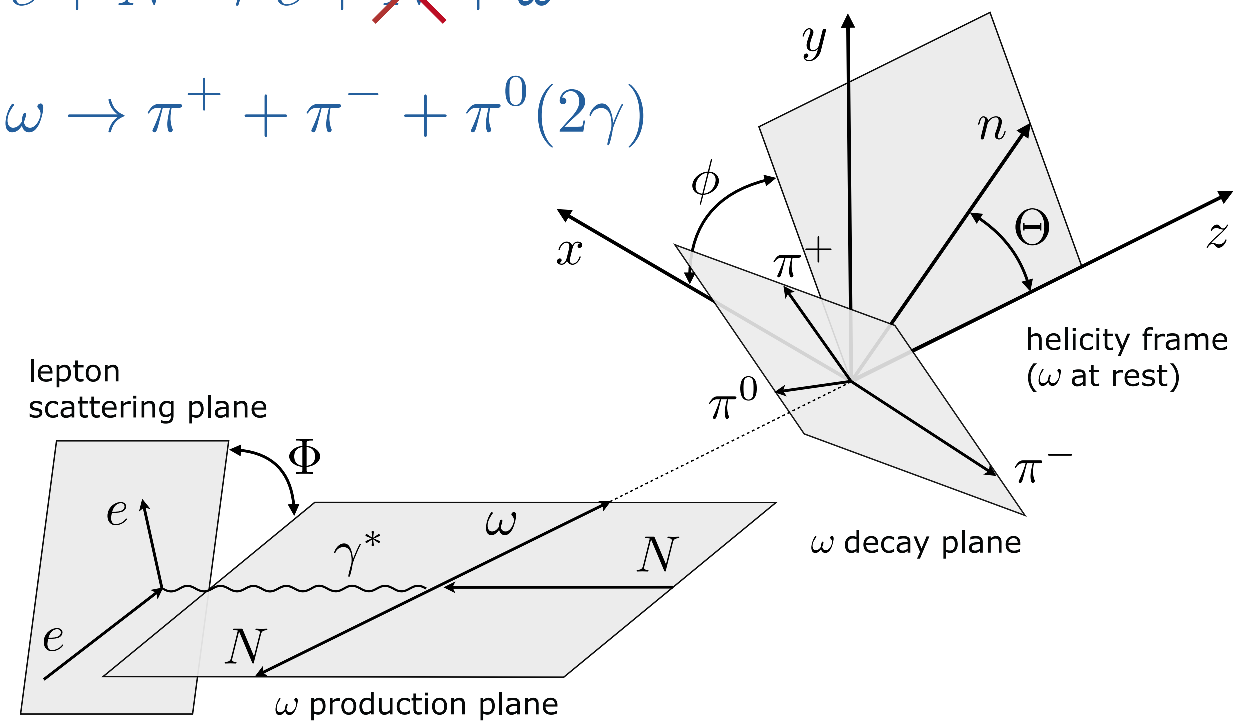
$J^P=0^+, 1^-, \ldots$ ➡ GPD H, E

unnatural parity exchange

$J^P=0^-, 1^+, \ldots$ ➡ GPD $\tilde{H}$, $\tilde{E}$

$e + N \to e + \cancel{N} + \omega$

$\omega \to \pi^+ + \pi^- + \pi^0(2\gamma)$



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

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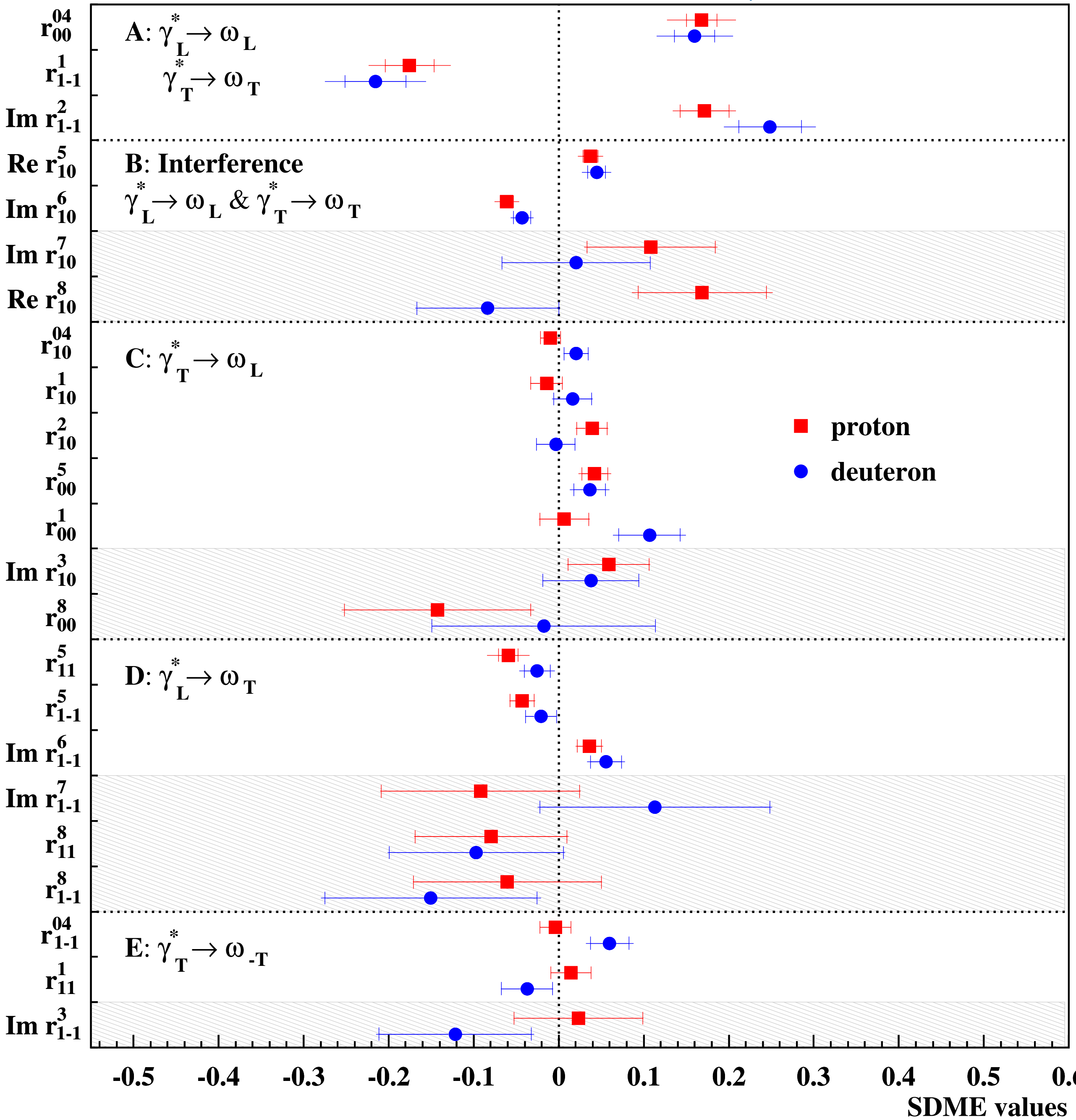
Spin density matrix elements (SDMEs)
describing final spin state of ω
and transverse target-spin asymmetries (A_{UT})

Results ω SDMEs

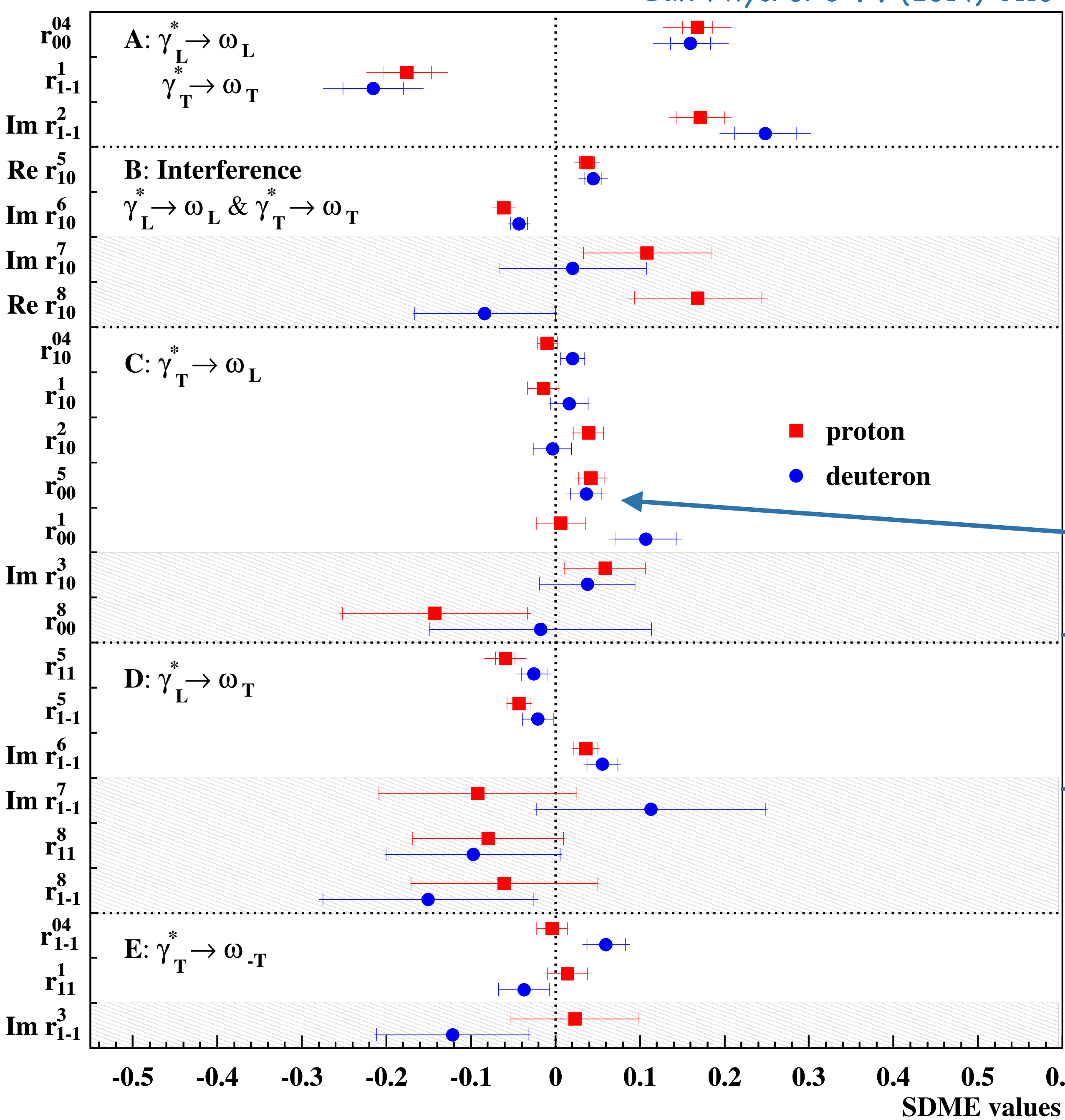
Eur. Phys. J. C **74** (2014) 3110



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

Results ω SDMEs

Eur. Phys. J. C **74** (2014) 3110



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

- s-channel helicity conservation ($\lambda_{\gamma^*} = \lambda_\omega$):
  - 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:

    $r^5_{11} + r^5_{1-1} - \Im r^6_{1-1} \neq 0$

    by $3(2.5)\,\sigma$ for p(d)

Results ω and ρ SDMEs

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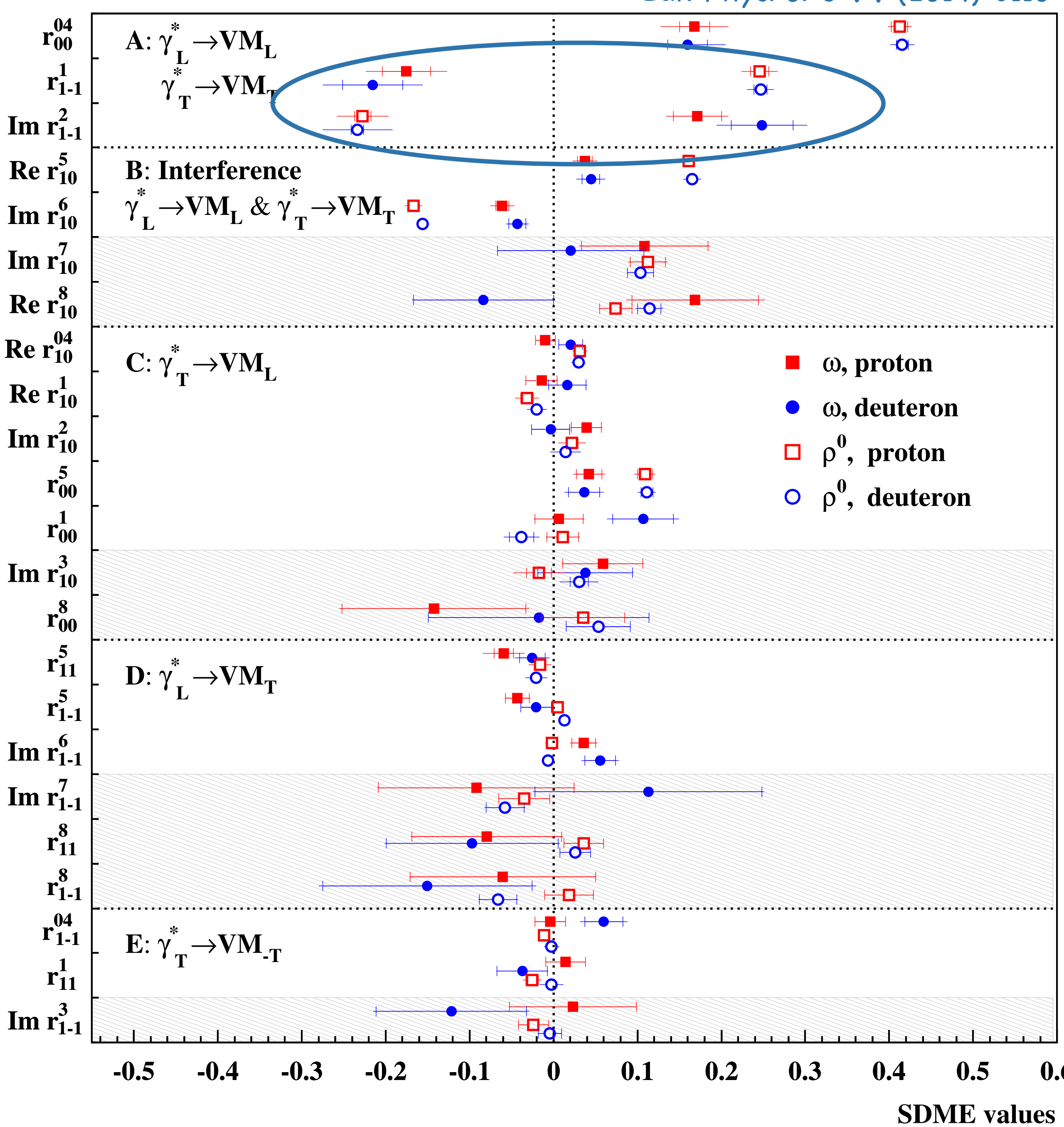


- ω: $r^1_{1-1} < 0$ and $\Im r^2_{1-1} > 0$
- ρ: $r^1_{1-1} > 0$ and $\Im r^2_{1-1} < 0$

⇩

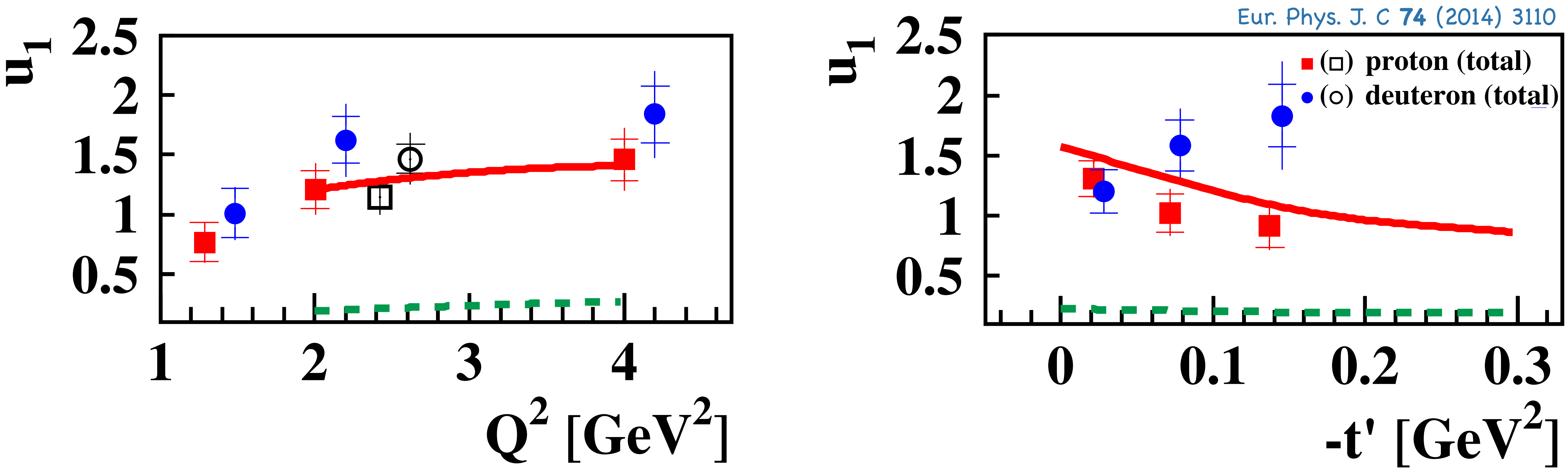
- ω: large unnatural parity exchange
- ρ: large natural parity exchange

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)



- large unnatural parity exchange seen

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)

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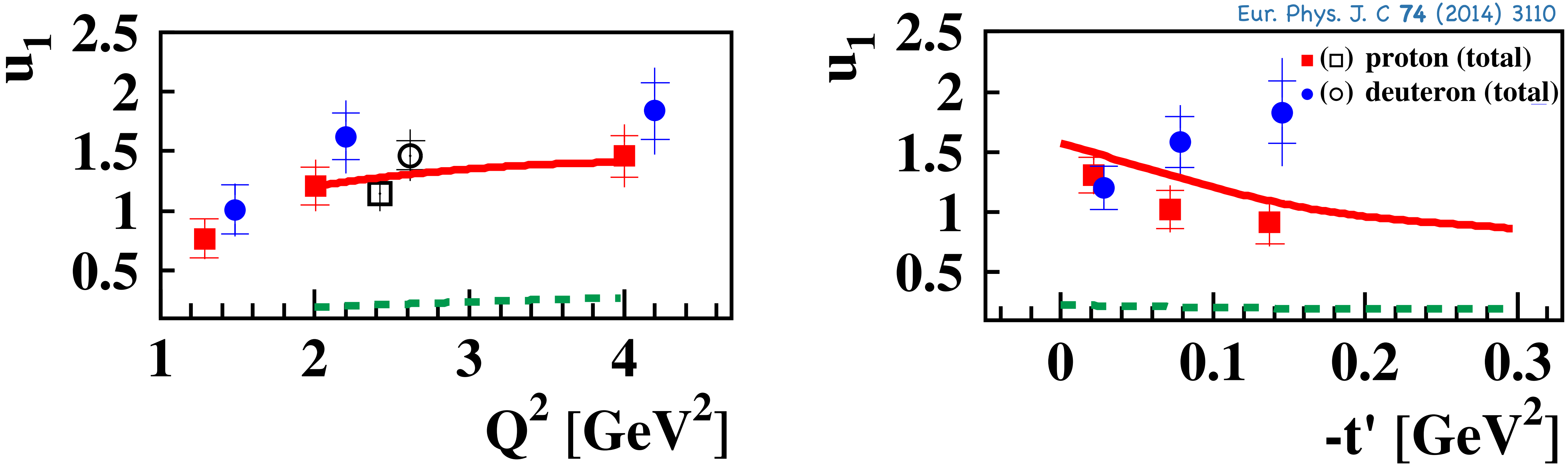
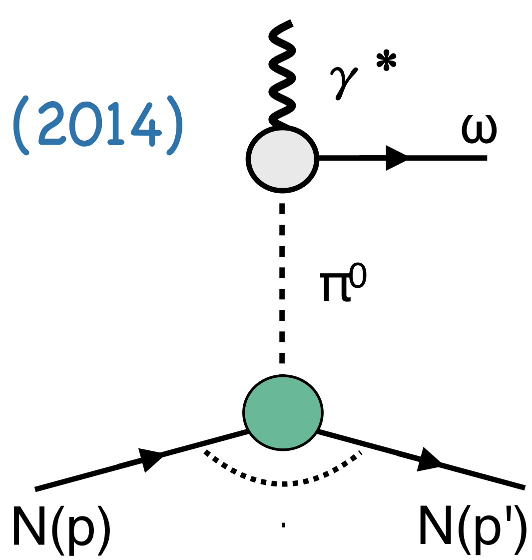


- large unnatural parity exchange seen
- model for protons - S. Goloskokov and P. Kroll, Eur. Phys. J A **50** 146 (2014)
  without pion-pole contribution
  with pion-pole contribution
  pion-pole contribution seems to account completely
  for unnatural-parity exchange



Kinematic dependencies

class A: $\gamma_L^* \to \omega_L$ and $\gamma_T^* \to \omega_T$

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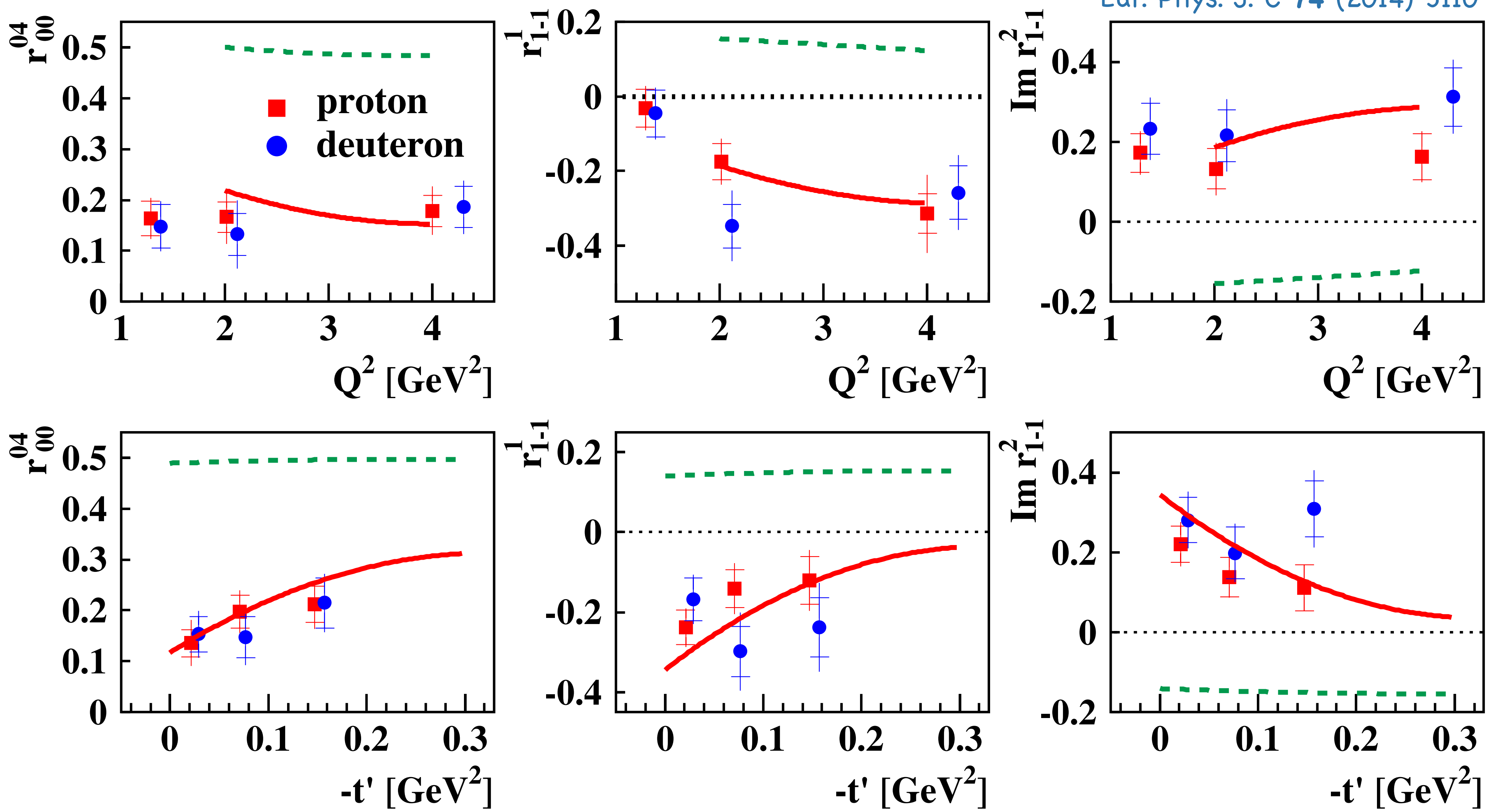

- no pronounced kinematic dependence observed
- again, need for pion-pole contribution observed

Longitudinal-to-transverse cross-section ratio

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

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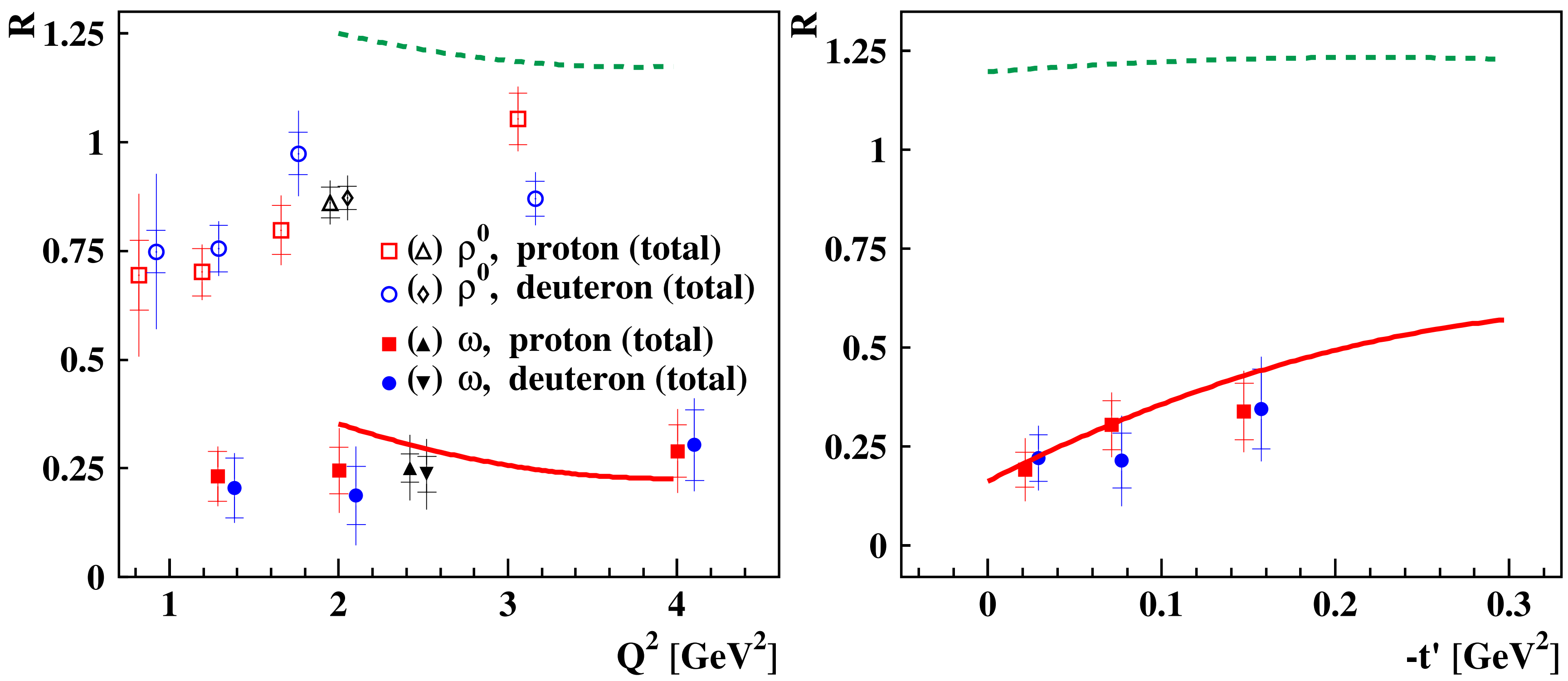
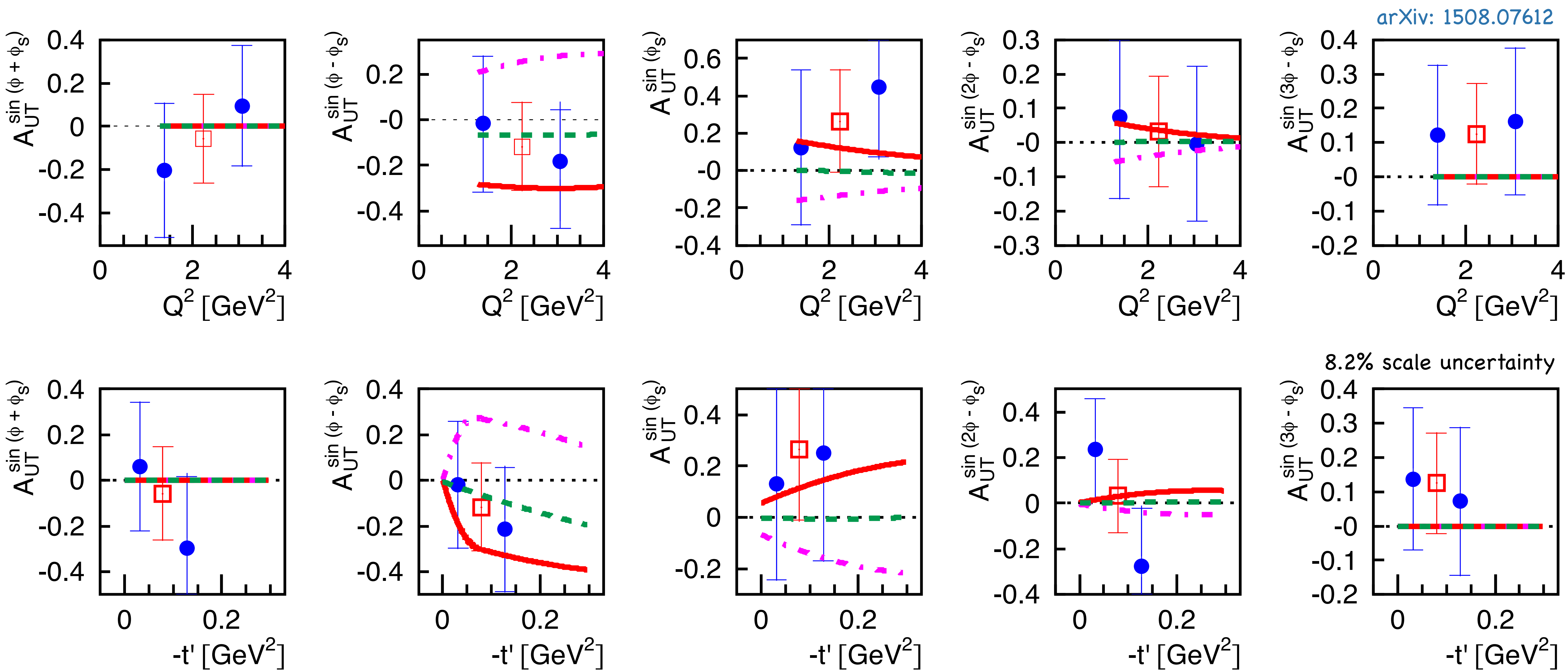


- R(ω) 4 times smaller than R(ρ)
- no pronounced kinematic dependence observed
- need for pion-pole contribution

Results ω A_{UT}



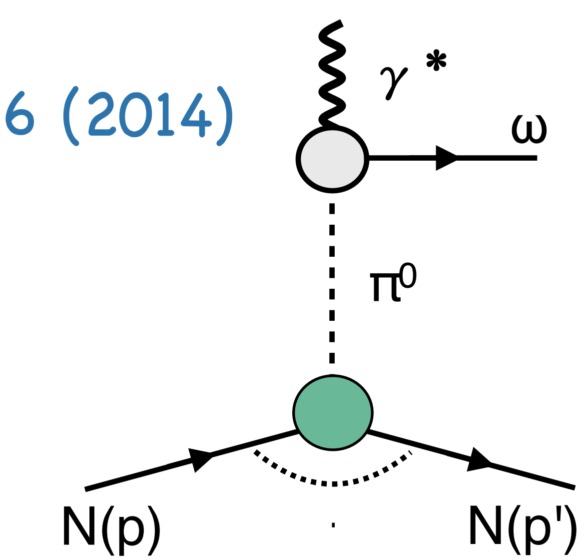
- large unnatural parity exchange seen
- model for protons - S. Goloskokov and P. Kroll, Eur. Phys. J A **50** 146 (2014)

  without pion-pole contribution

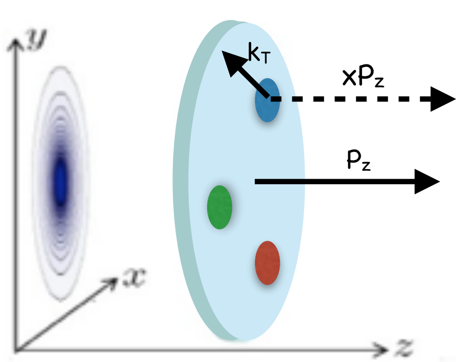
  with pion-pole contribution: πω transition FF > 0

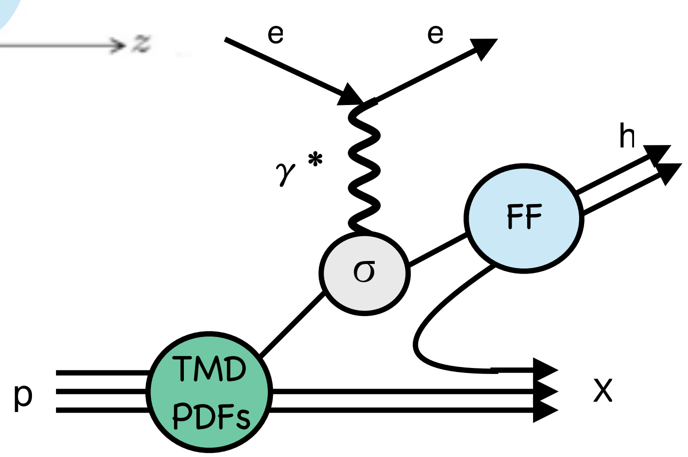
  with pion-pole contribution: πω transition FF < 0

  Positive πω transition FF favoured



Asymmetries in semi-inclusive DIS





- A_{UT} and A_{LT}
  - unpolarized & longitudinally polarized e^+/e^- beam
  - transversely polarized H target
- A_{LU}:
  - longitudinally polarized e^+/e^- beam
  - unpolarized H and D target

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

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

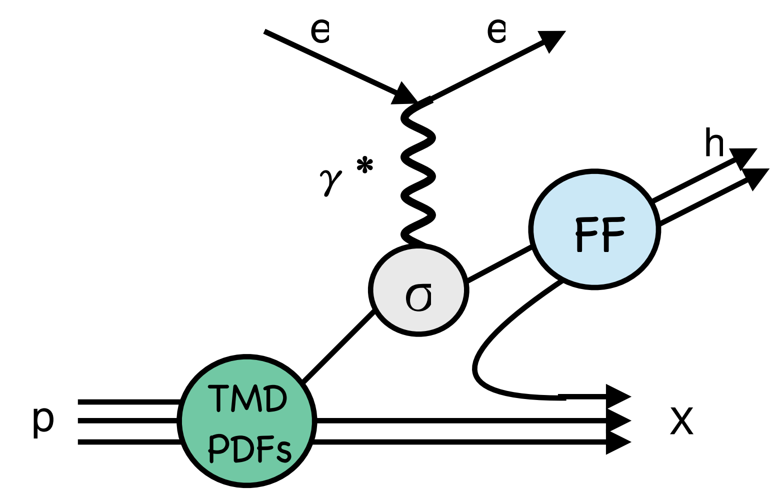
$$+\quad \epsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

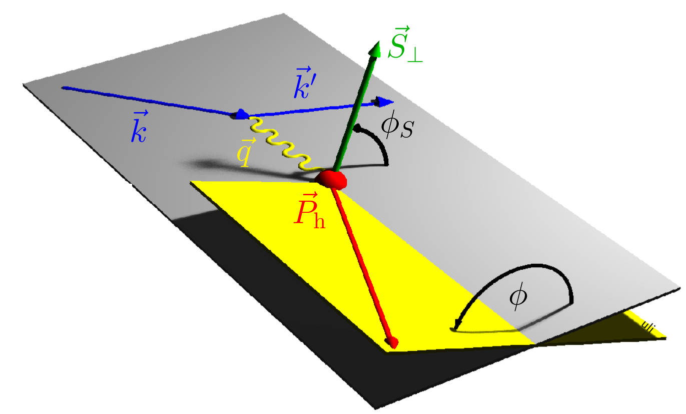
$$+\quad \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

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

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

- structure function $F_{XY(,Z)}$
  X=beam, Y=target, Z=γ^* polarization
- ∝ TMD PDF ⊗ FF





Semi-inclusive DIS cross section

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

beam polarization

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

longitudinal target polarization

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

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

transverse target polarization

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

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

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

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

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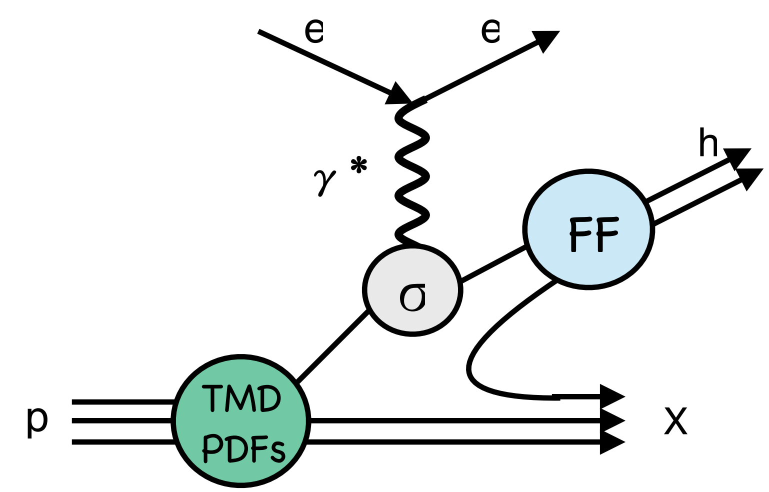
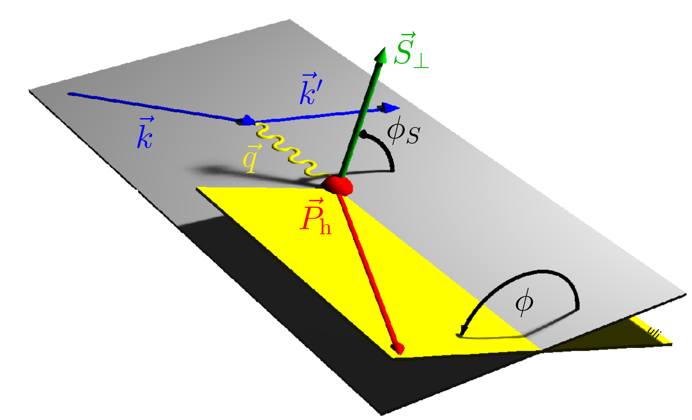
- structure function $F_{XY(,Z)}$
  X=beam, Y=target, Z=γ^* polarization
- ∝ TMD PDF ⊗ FF



- leading twist



Semi-inclusive DIS cross section

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

longitudinal target polarization

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

$$+S_L\lambda_e\left[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1\right.$$

This talk

transverse target polarization

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

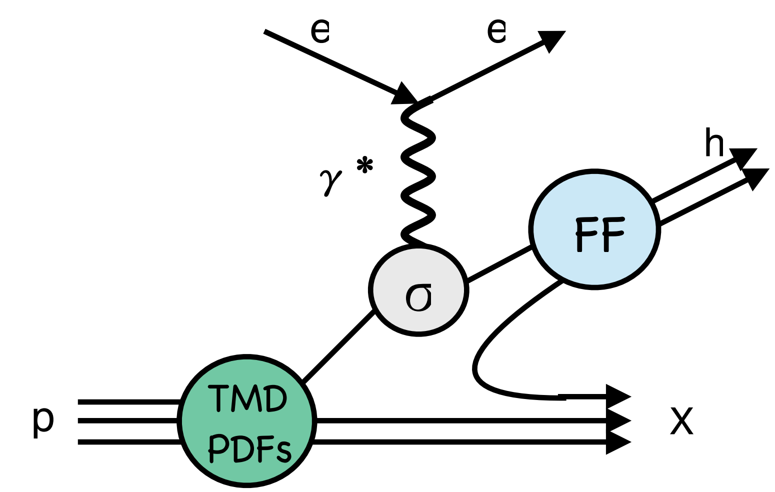
$$+\quad \epsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

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

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

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

- structure function $F_{XY(,Z)}$ X=beam, Y=target, Z=γ^* polarization
- ∝ TMD PDF ⊗ FF



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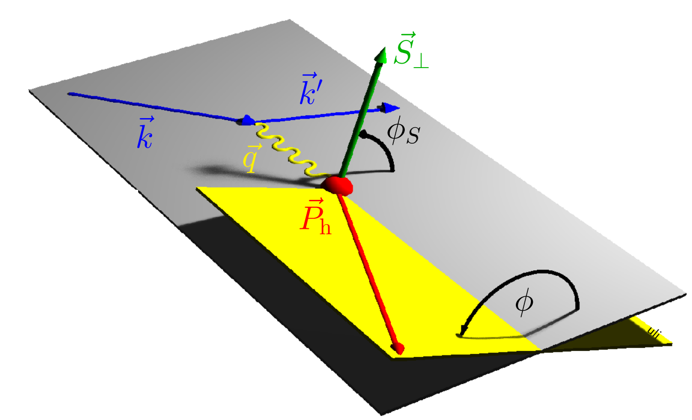
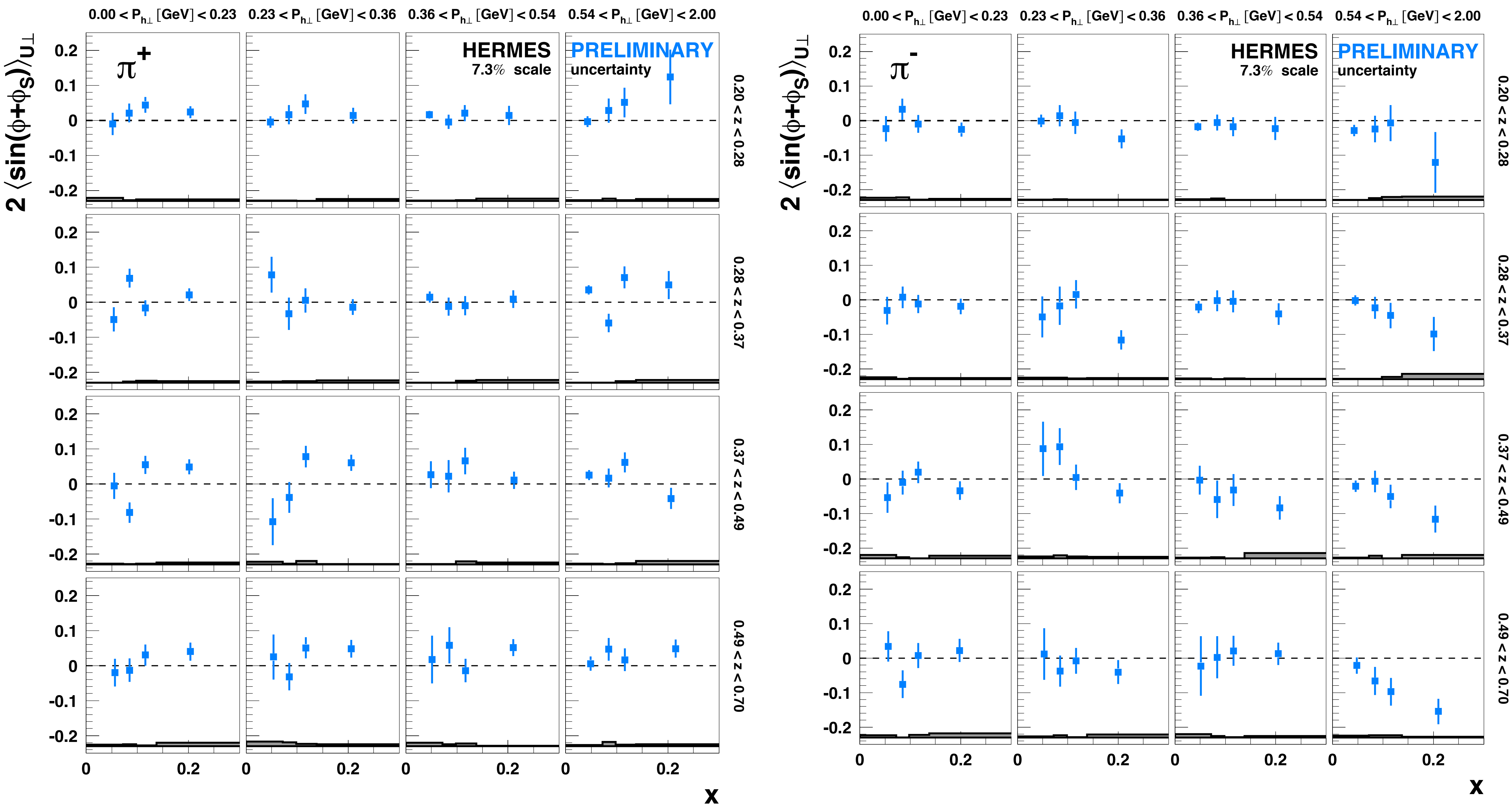


Collins amplitudes

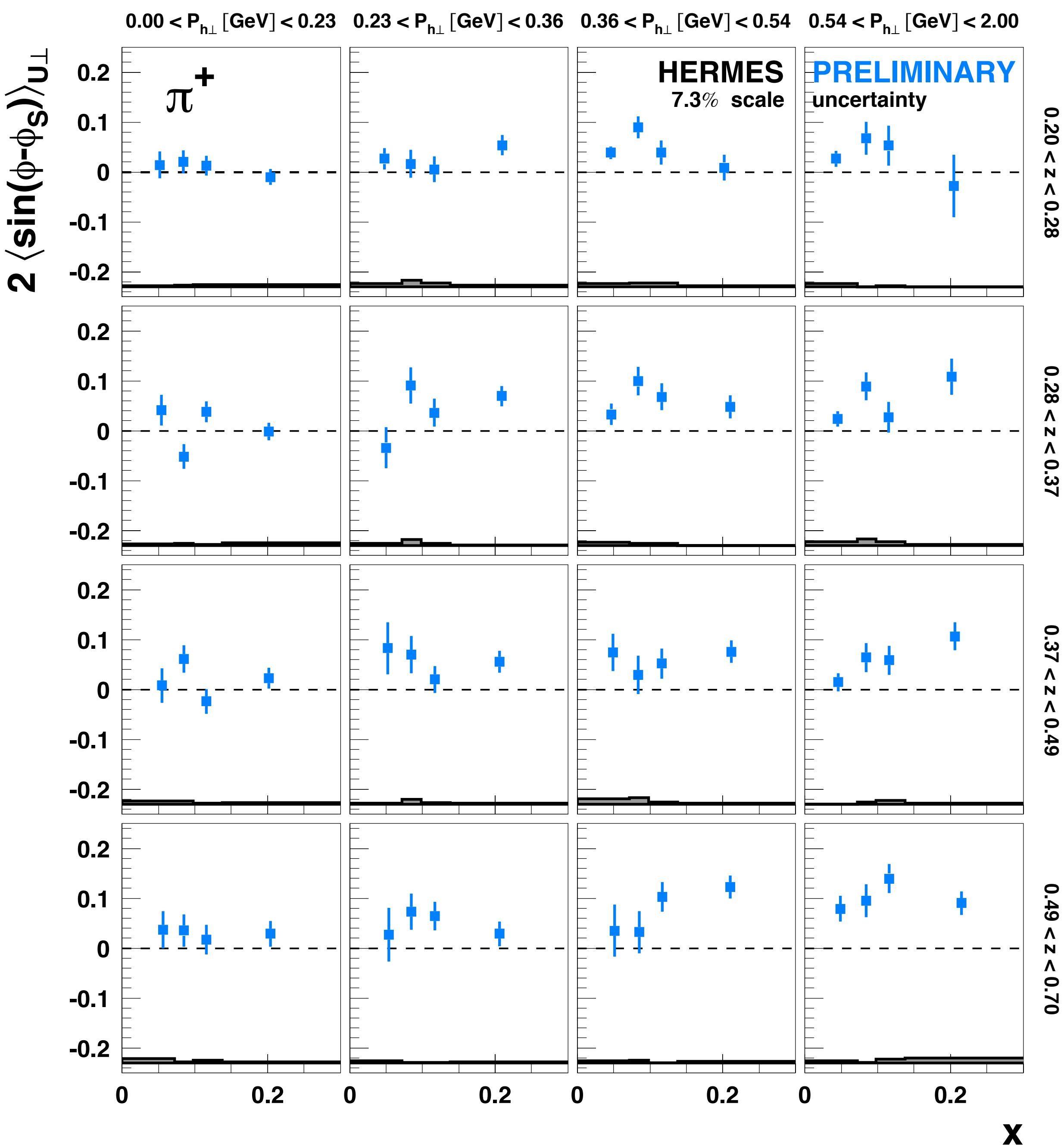
$$F_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1T} \otimes H_1^{\perp}$$

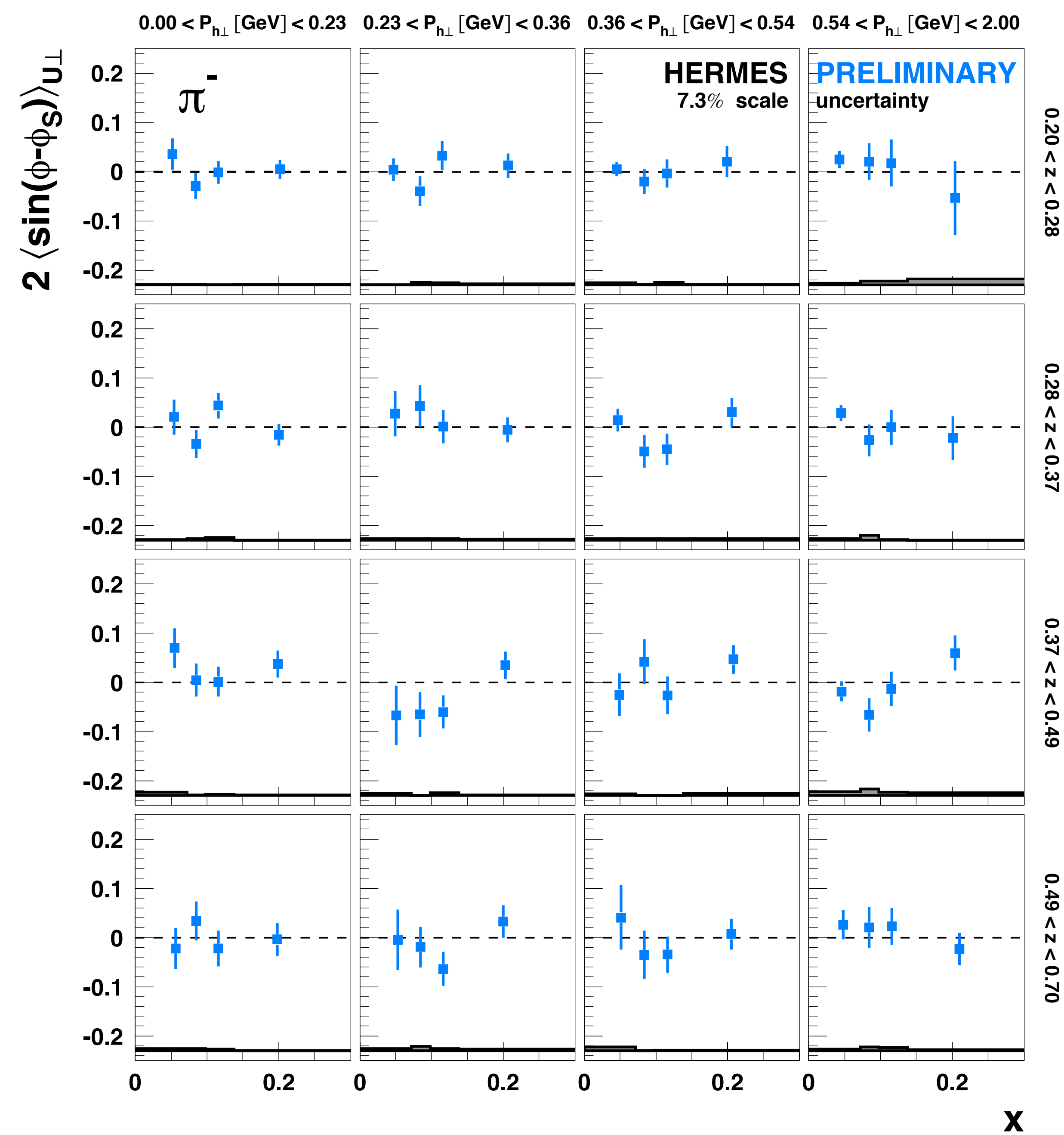


- π^+ amplitudes positive; π^- amplitudes negative
- π^- amplitudes increasing with x at large $P_{h\perp}$

Sivers amplitudes

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

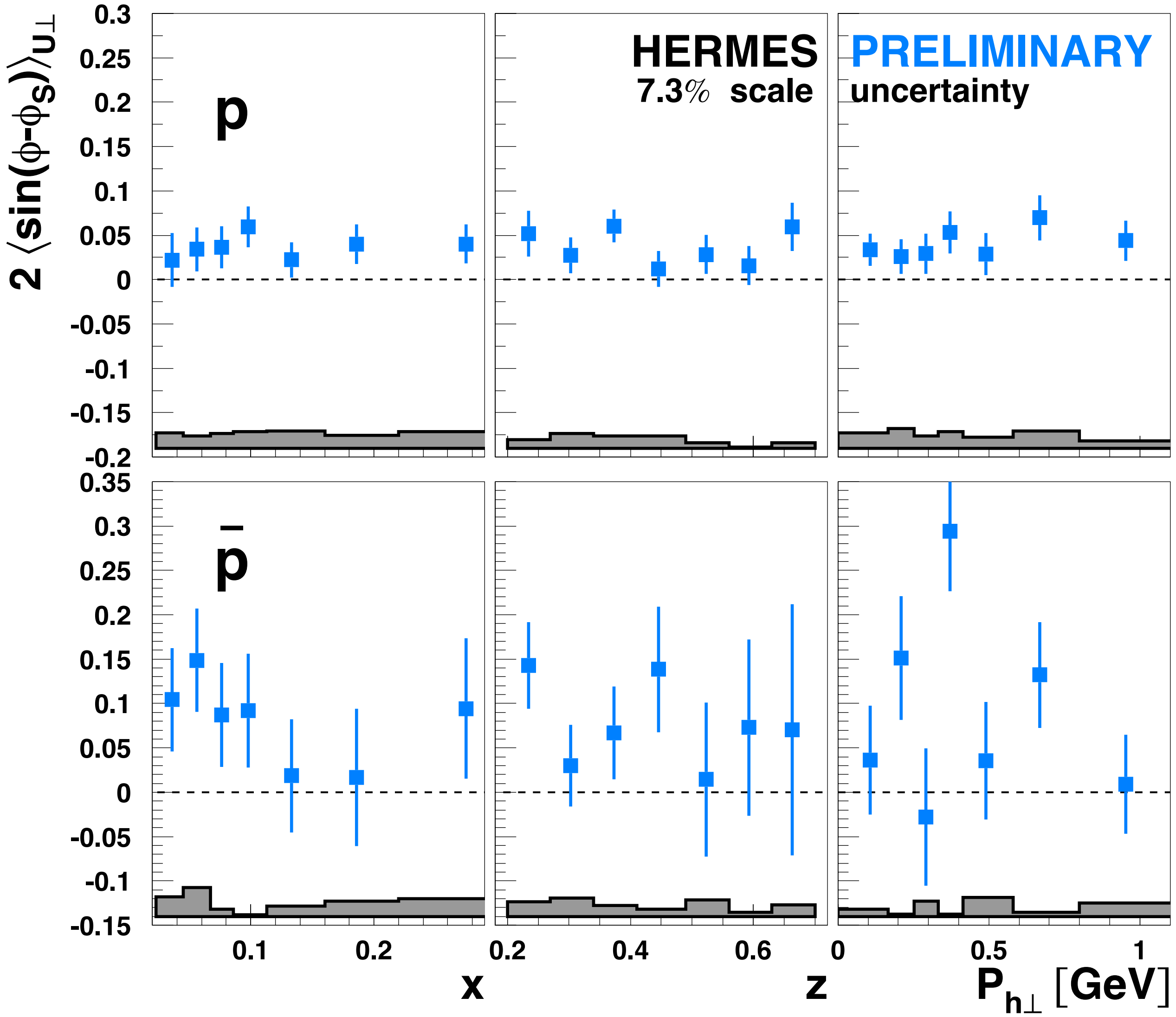


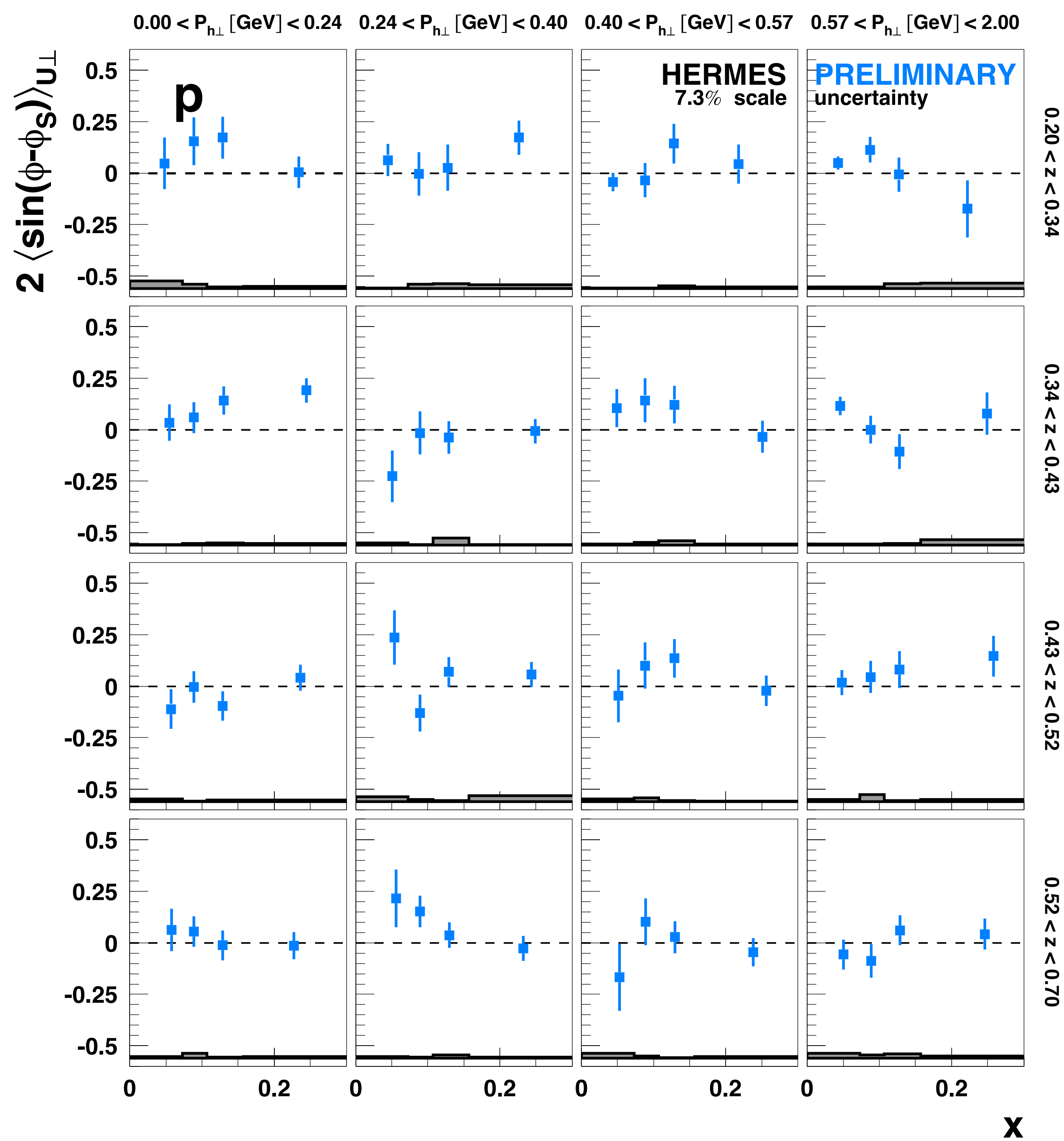


- π^+ amplitudes positive; π^- amplitudes≈0
- π^+ amplitudes increasing with x at large $P_{h\perp}$

Sivers amplitudes

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

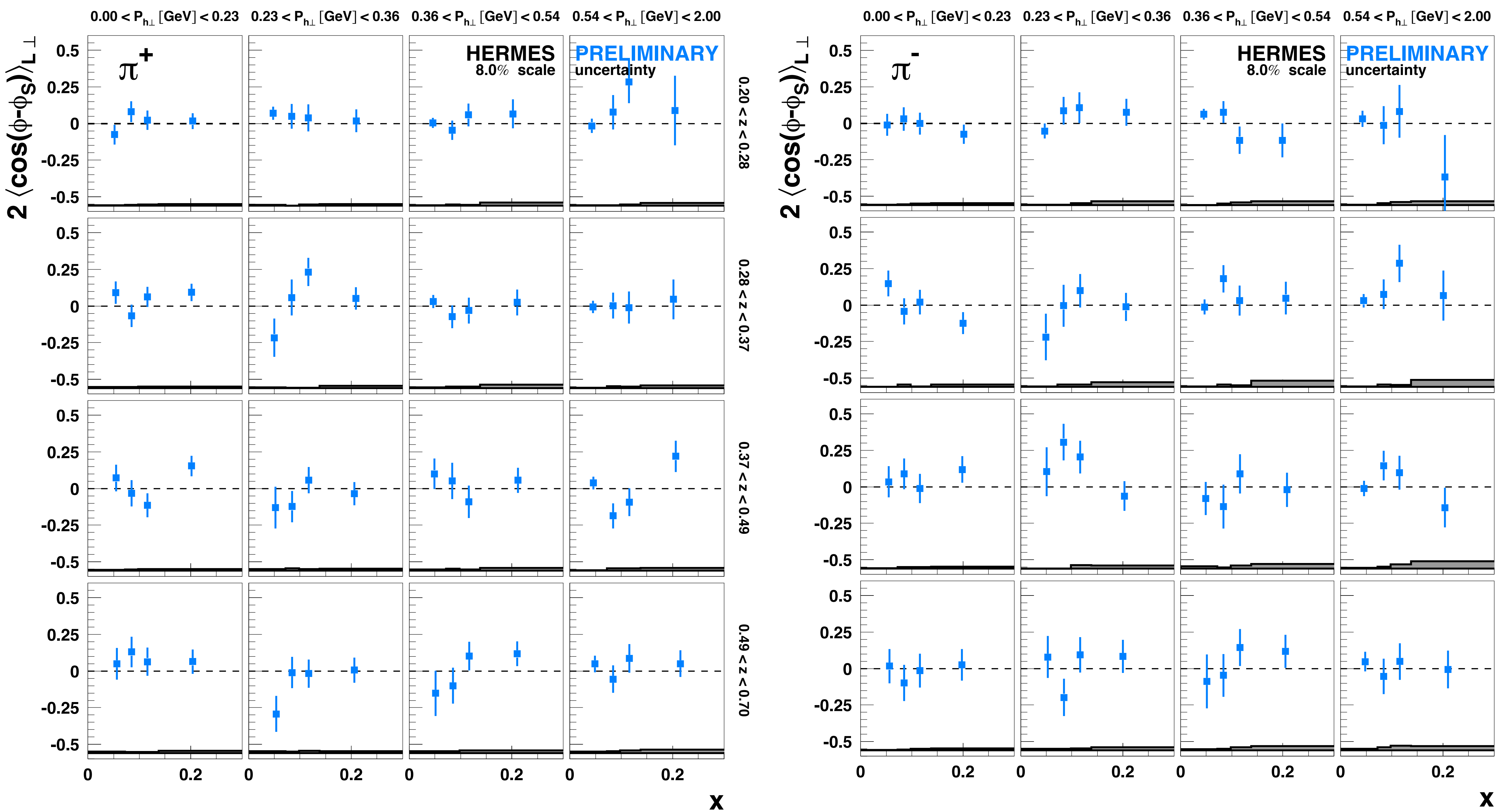




- positive proton amplitudes

Worm-gear amplitudes

$F_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^{\perp} \times D_1$

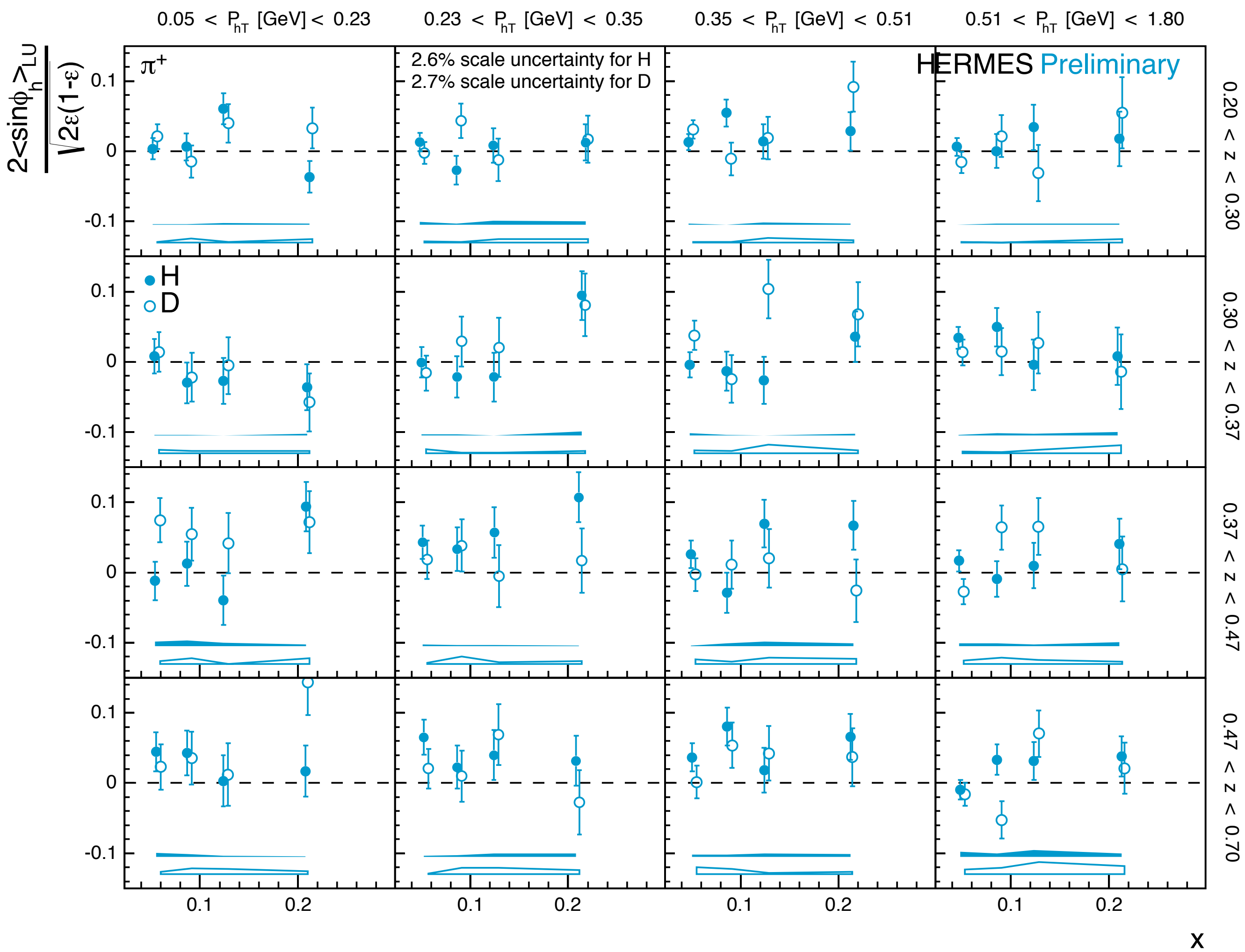


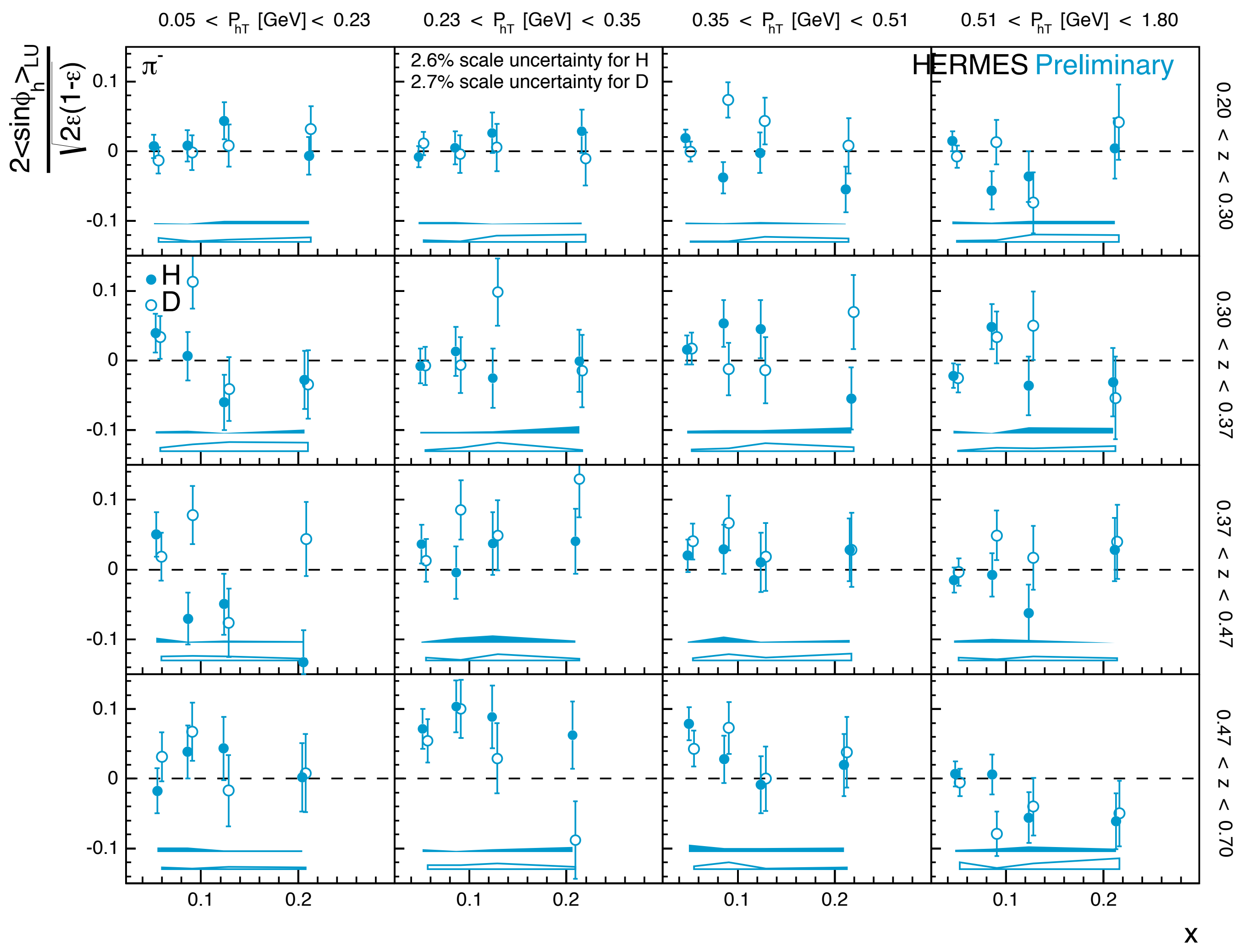
- π^+ and π^- amplitudes≈0

$F_{LU}^{\sin\phi_h}$

higher twist!

$$F_{LU}^{\sin\phi_h} \propto (eH_1^{\perp}; f_1\tilde{G}^{\perp}; g^{\perp}D_1; h_1^{\perp}\tilde{E})$$





Bose-Einstein correlations in DIS

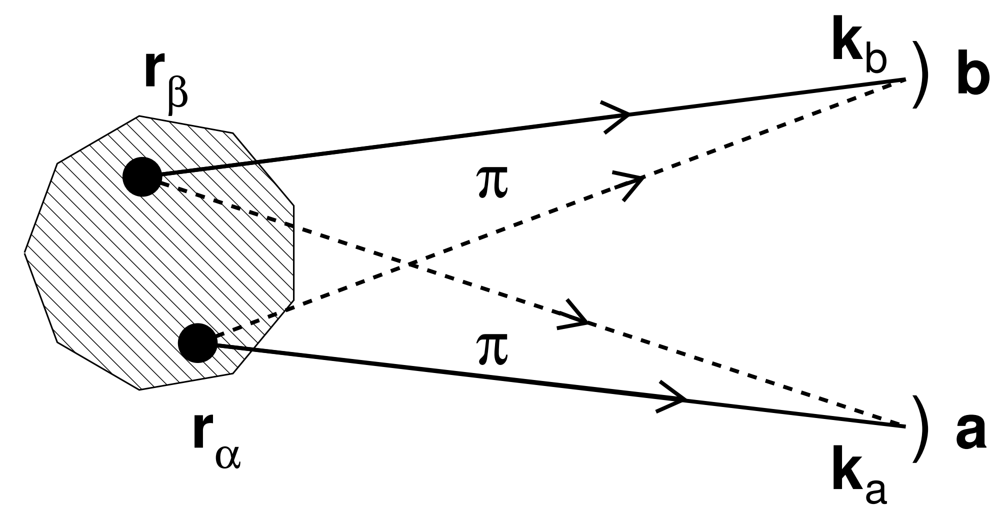
- unpolarized e^+/e^- beam
- H, D, ^{3}He, ^{4}He, N, Ne, Kr, Xe target

Bose-Einstein correlations

- incoherent source of identical bosons
- symmetry of wave function under exchange of identical bosons

⇩

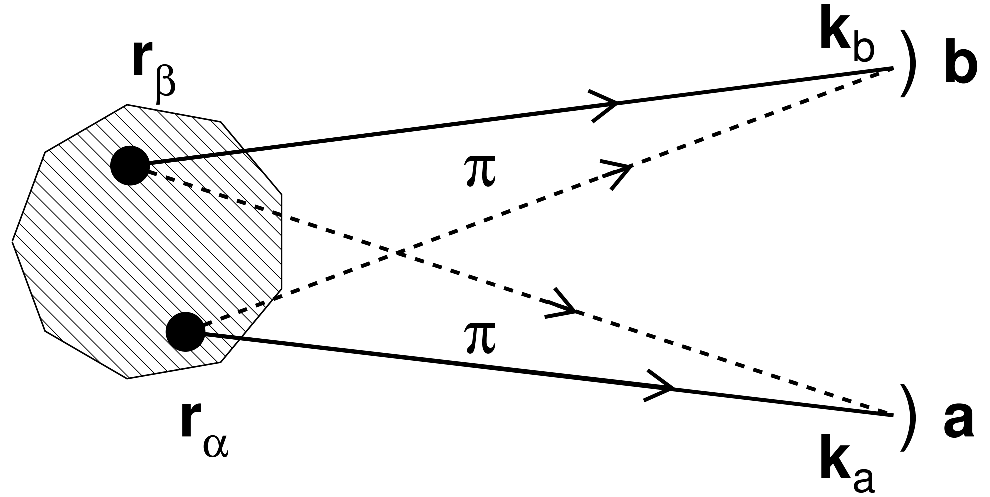
constructive interference



Measurement of source distribution

- measurements of stelar radii by Hanbury Brown and Twiss
- first in particle physics: $p\bar{p}$ collisions
- heavy-ion collisions, study of fireball source distribution
- e^+e^- annihilation
- measurements in DIS are far less abundant

Bose-Einstein correlations



Two-point sources:

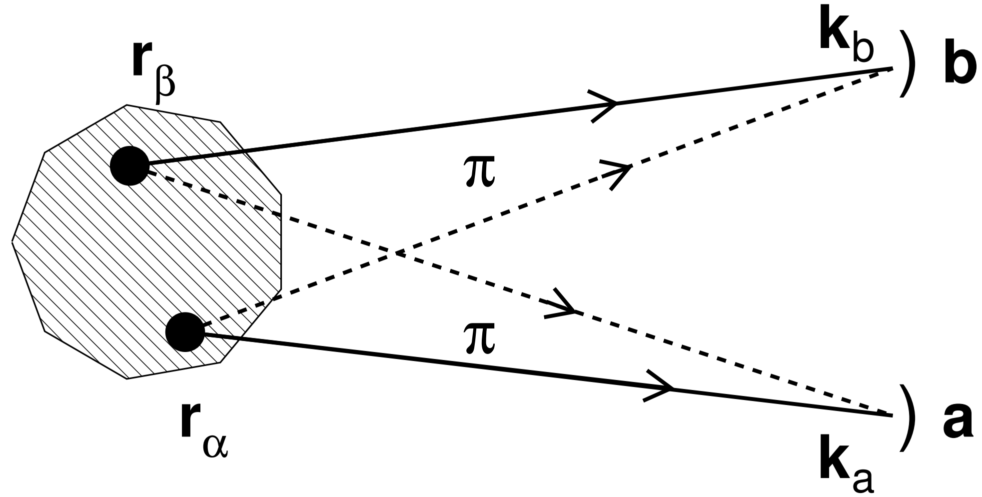
$R(\mathbf{k}_\alpha, \mathbf{k}_\beta) \propto 1 + \cos(\delta\mathbf{k}.\delta\mathbf{r})$

Bose-Einstein correlations

Goldhaber parametrisation of continuous space-time distribution of sources

$$R(T) = 1 + \lambda\,\exp(-T^2 r_G^2)$$

- Gaussian shape of source
- r_G: size of source
- $T^2 = -(p_1 - p_2)^2$
- λ = 0 -> coherent sources; no correlation
  λ = 1 -> completely incoherent sources



Two-point sources:

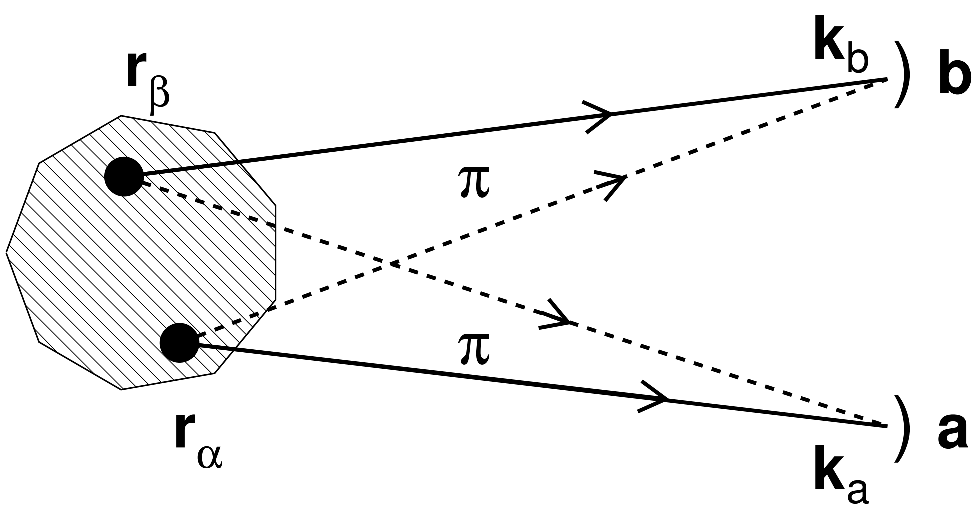
$$R(\mathbf{k}_\alpha, \mathbf{k}_\beta) \propto 1 + \cos(\delta\mathbf{k}.\delta\mathbf{r})$$

Bose-Einstein correlations

Goldhaber parametrisation of continuous space-time distribution of sources

$$R(T) = 1 + \lambda \exp(-T^2 r_G^2)$$

- Gaussian shape of source
- r_G: size of source
- $T^2 = -(p_1 - p_2)^2$
- λ = 0 -> coherent sources; no correlation
  λ = 1 -> completely incoherent sources



Two-point sources:

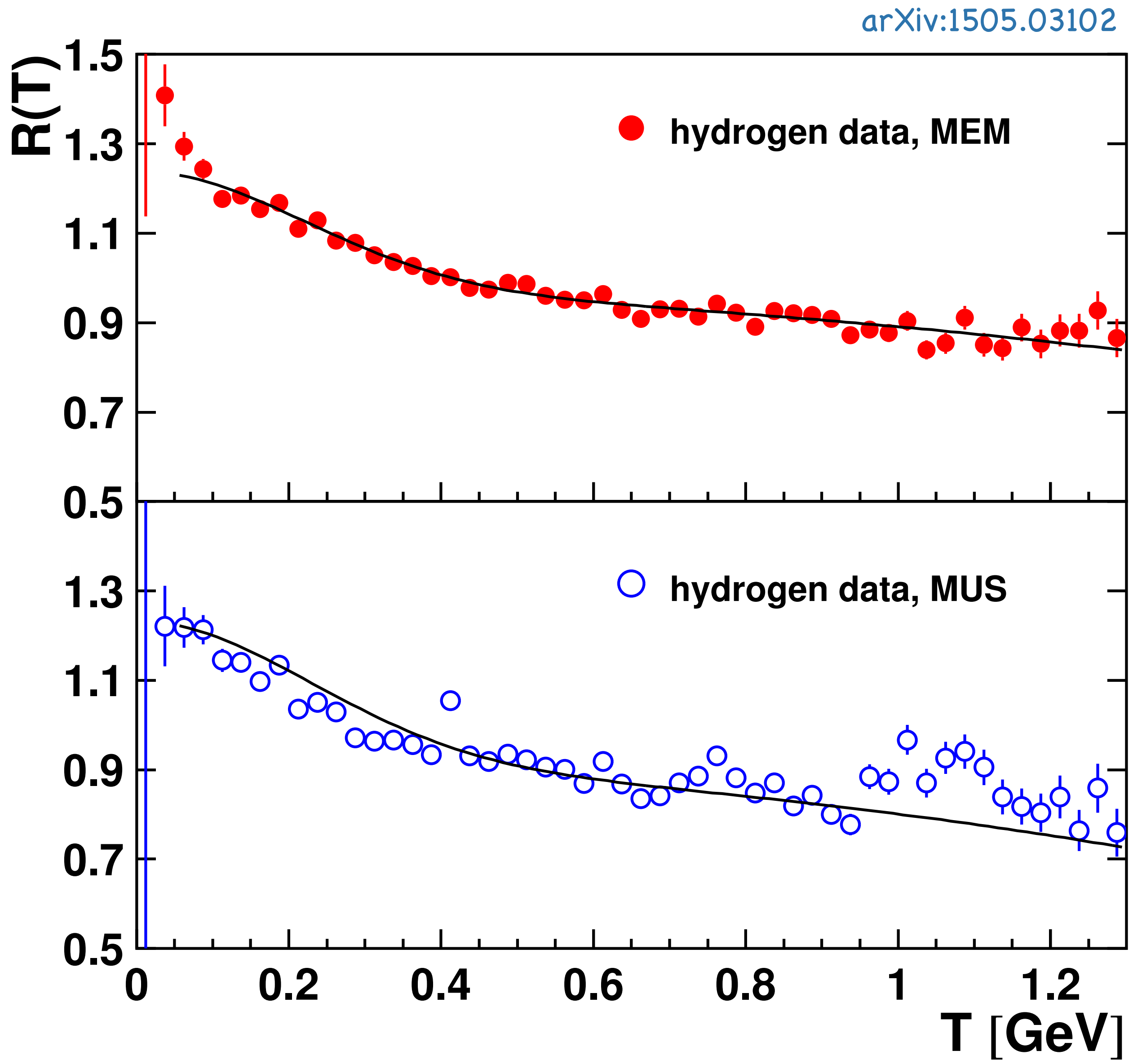
$$R(\mathbf{k}_\alpha, \mathbf{k}_\beta) \propto 1 + \cos(\delta\mathbf{k}.\delta\mathbf{r})$$

Extraction from experimental correlation function from like-sign unidentified hadrons

$$R(p_1, p_2) = D(p_1, p_2)/D_r(p_1, p_2)$$

- reference sample free from BEC, built from
  - unlike-sign pairs (MUS)
  - event mixing (MEM)

Results



MEM

$$r_G = 0.64 \pm 0.03(\mathrm{stat})^{+0.04}_{-0.04}(\mathrm{sys})\ \mathrm{fm}$$

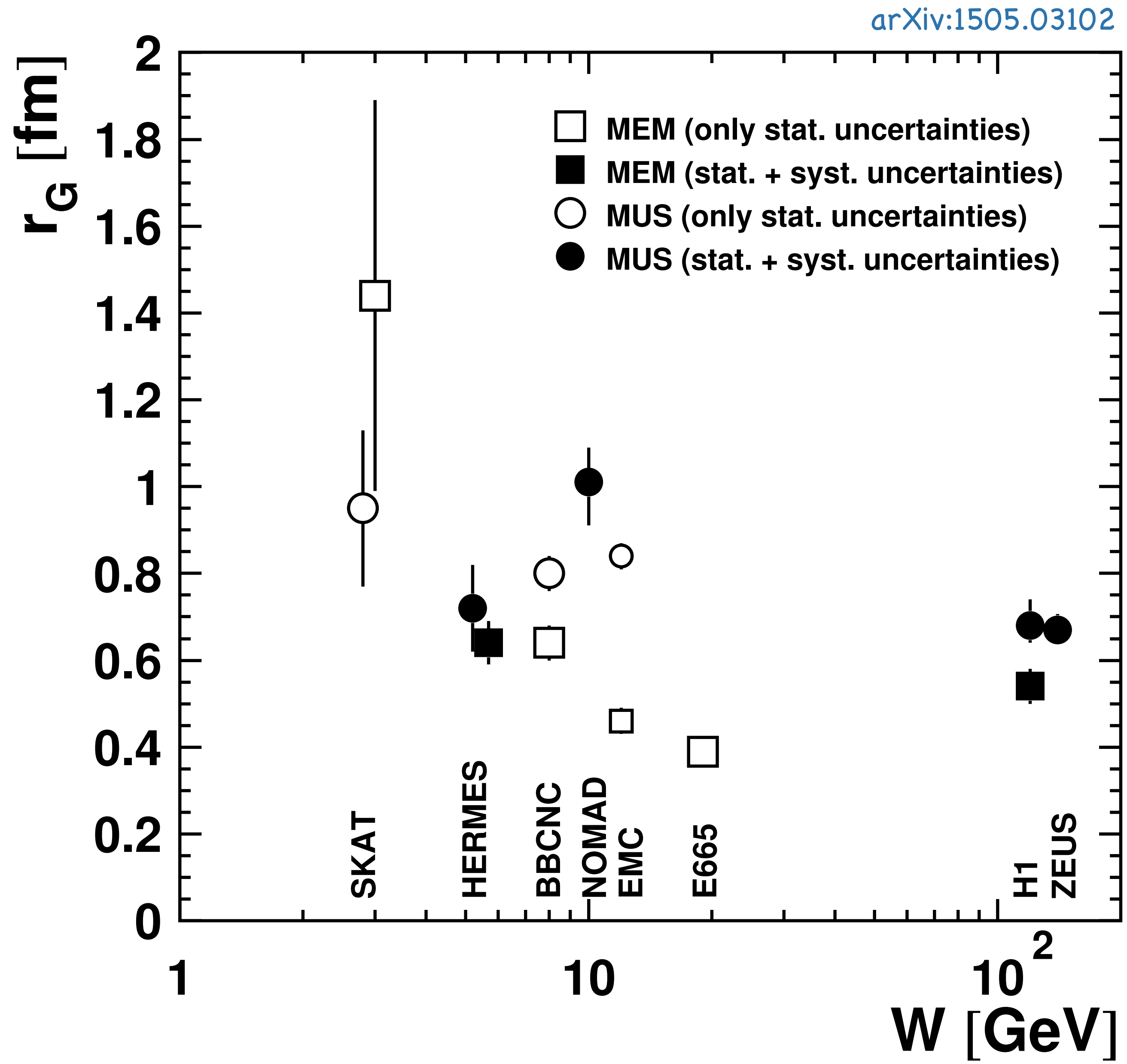
$$\lambda = 0.28 \pm 0.01(\mathrm{stat})^{+0.00}_{-0.05}(\mathrm{sys})\ \mathrm{fm}$$

MUS

$$r_G = 0.72 \pm 0.04(\mathrm{stat})^{+0.09}_{-0.09}(\mathrm{sys})\ \mathrm{fm}$$

$$\lambda = 0.28 \pm 0.02(\mathrm{stat})^{+0.02}_{-0.04}(\mathrm{sys})\ \mathrm{fm}$$

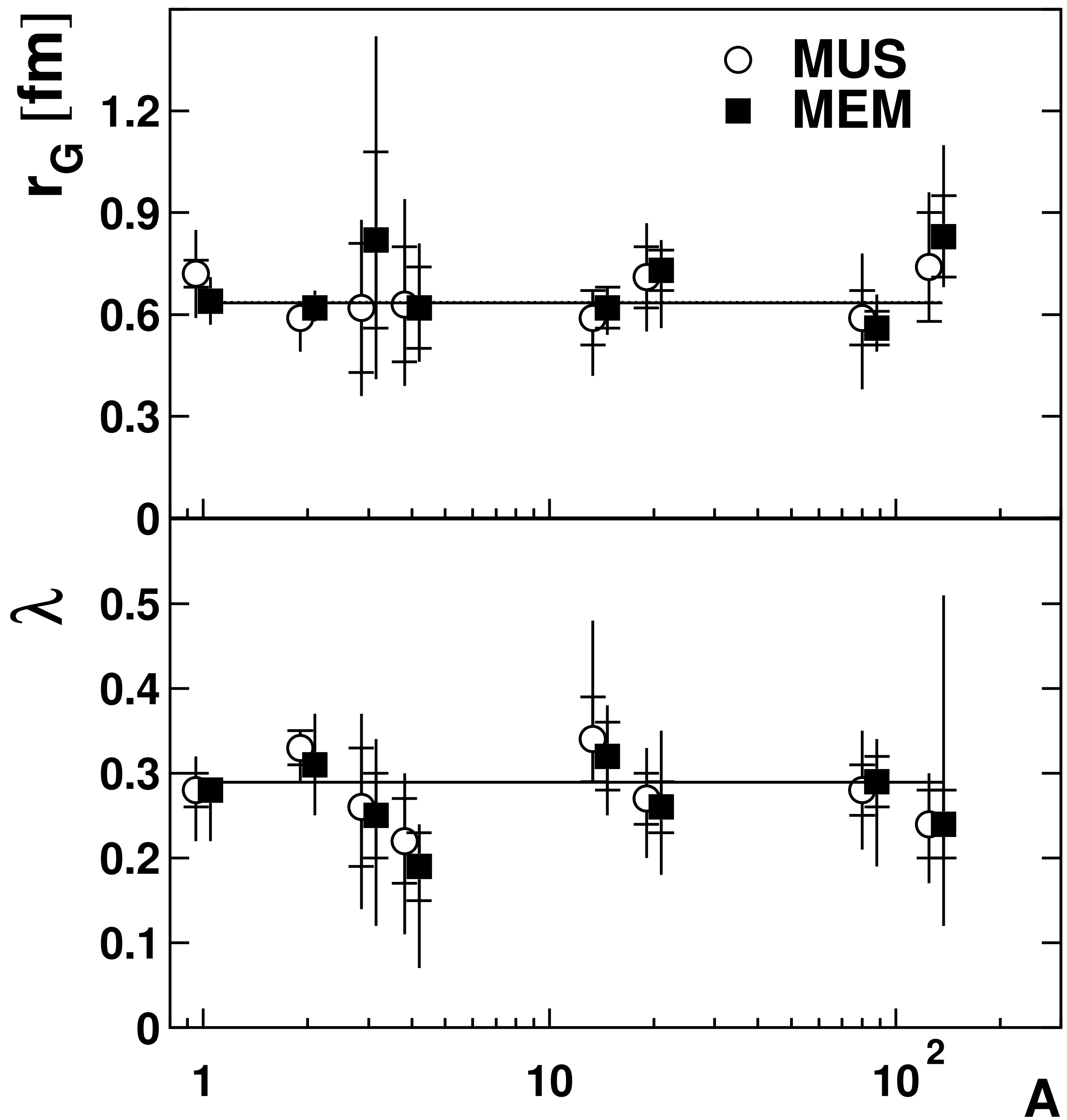
Comparison to other experiments



- general agreement between experiments, with $0.4 \text{ fm} < r_G < 1.0 \text{ fm}$
- HERMES and BBCNC agree well
- MUS values higher than MEM values

Nuclear-mass dependence

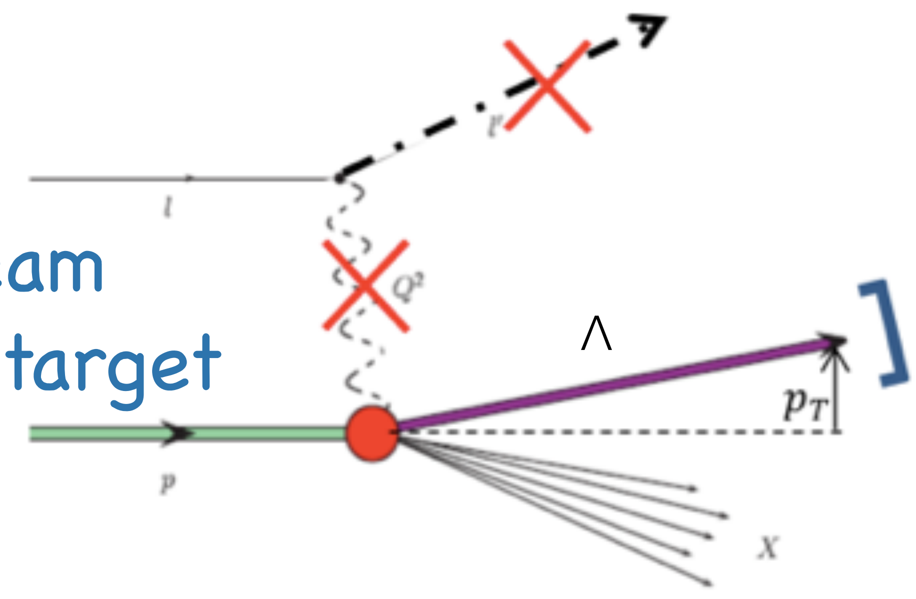
arXiv:1505.03102



- no dependence on nuclear mass A observed

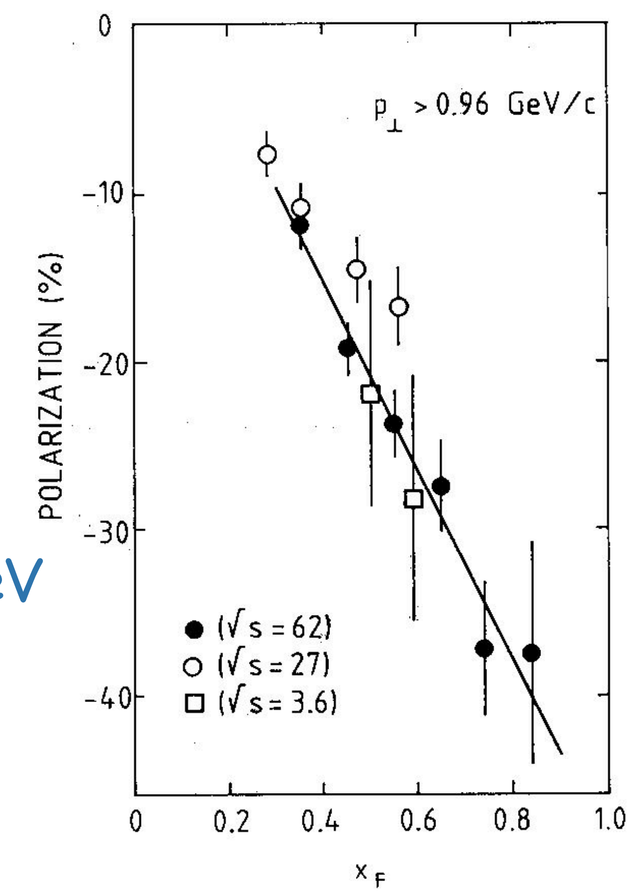
Λ polarization in quasi-real photo-production

- unpolarized e^+/e^- beam
- H, D, He, Ne, Kr, Xe target

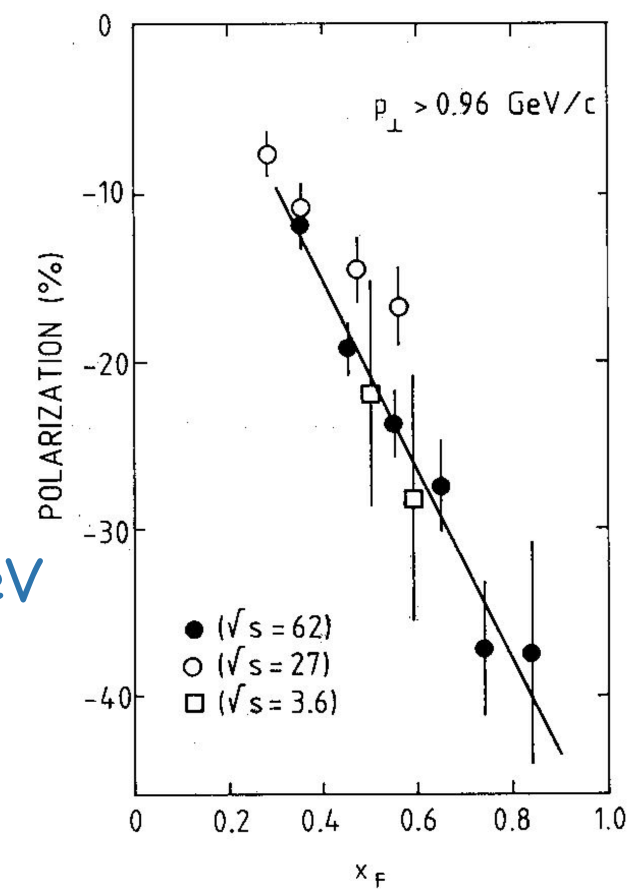


Motivation

- 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



- Large transverse Λ polarization P^Λ observed in unpolarized hadron scattering experiments
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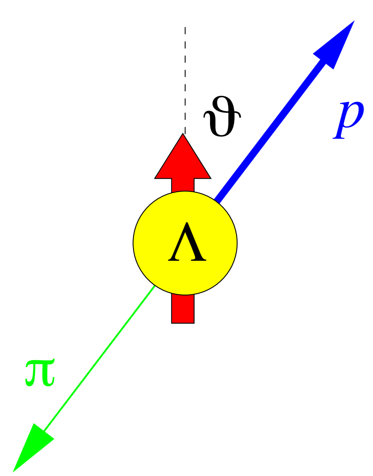
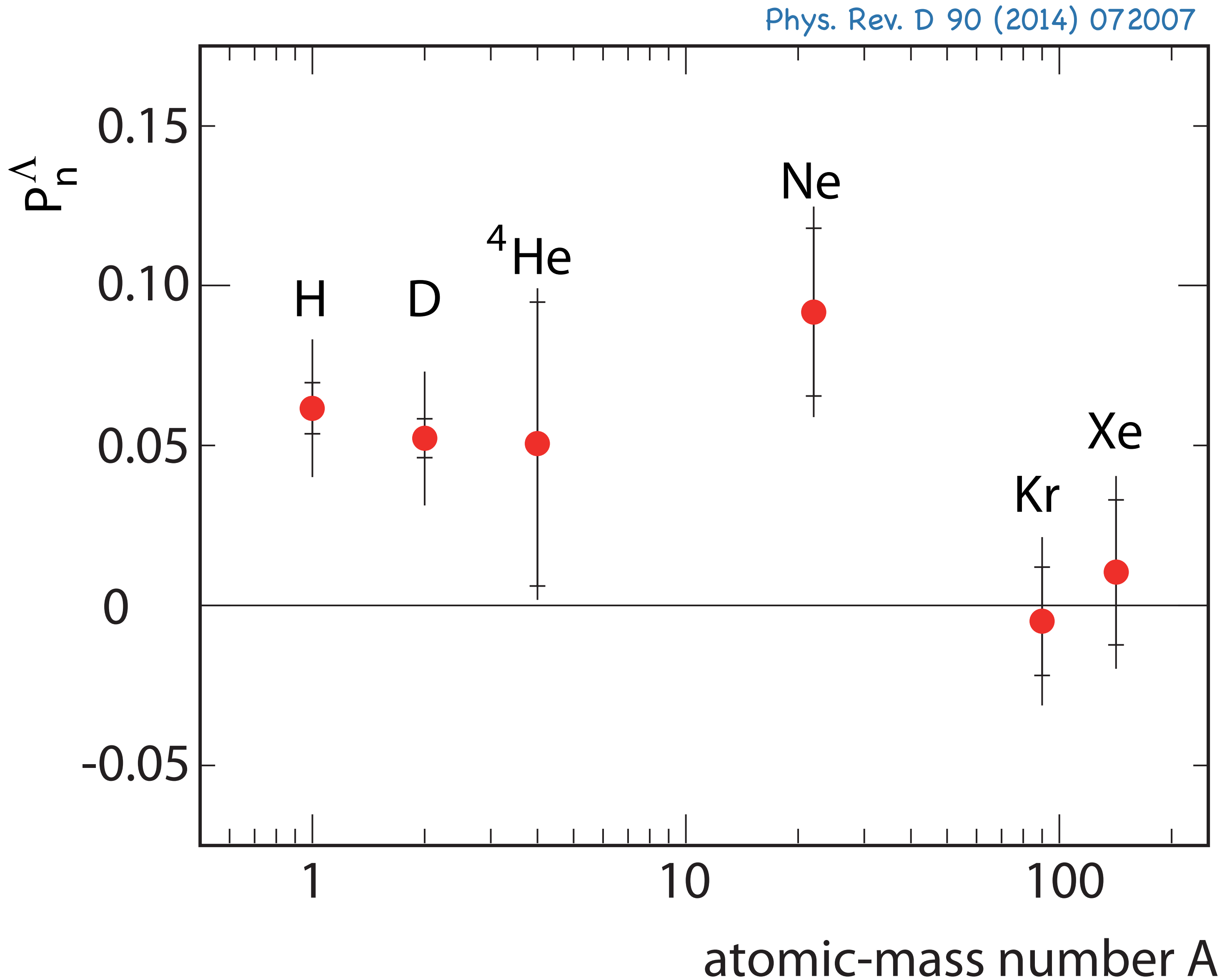
- $ep \to \Lambda^\uparrow X$ scattering?
- SIDIS (high Q^2) $P^\Lambda \propto D_{1T}^\perp$, polarising FF
- current measurement: inclusive ($Q^2 \approx 0$)



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

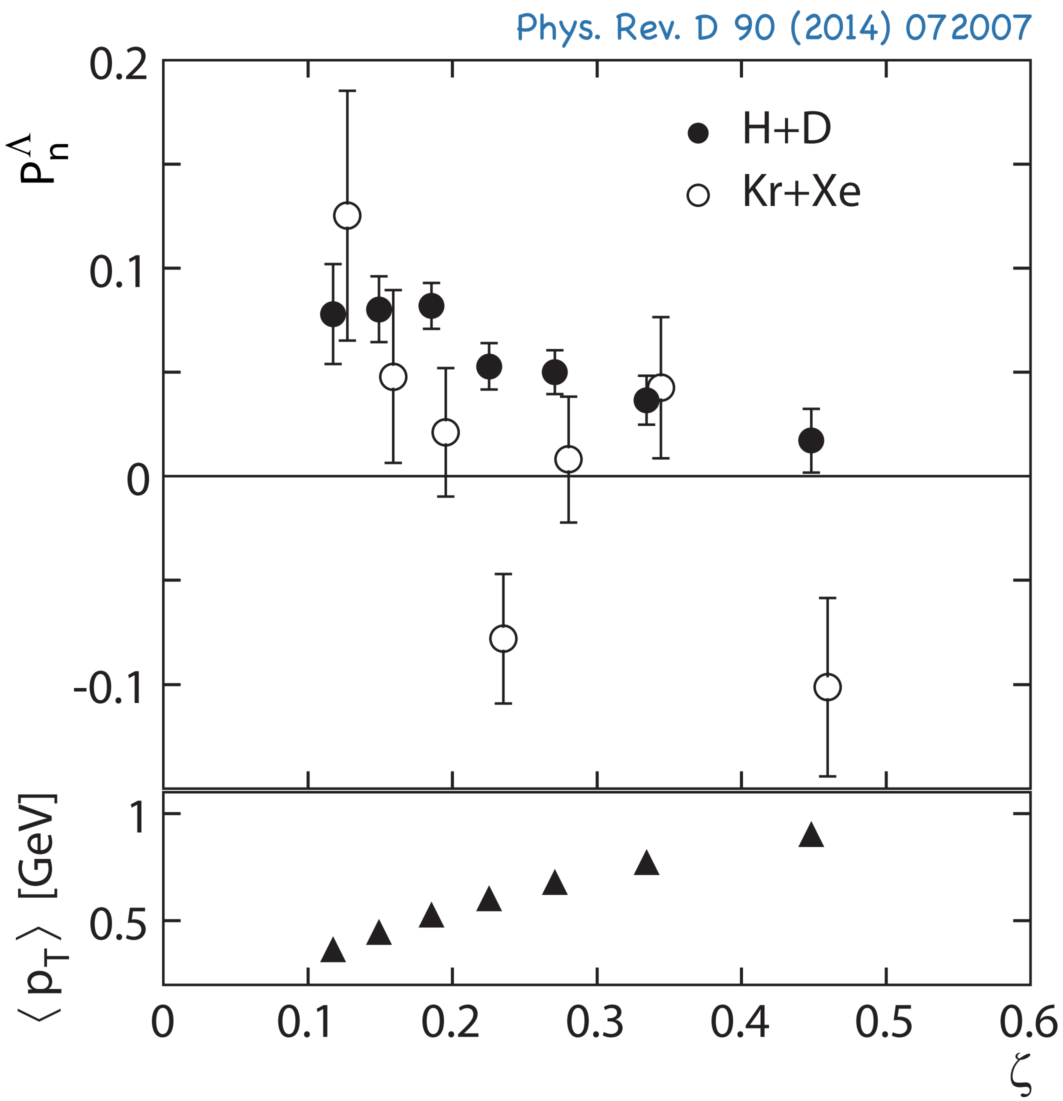
$$\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p}(1 + \alpha P^\Lambda \cos\theta_p)$$

Atomic-mass dependence

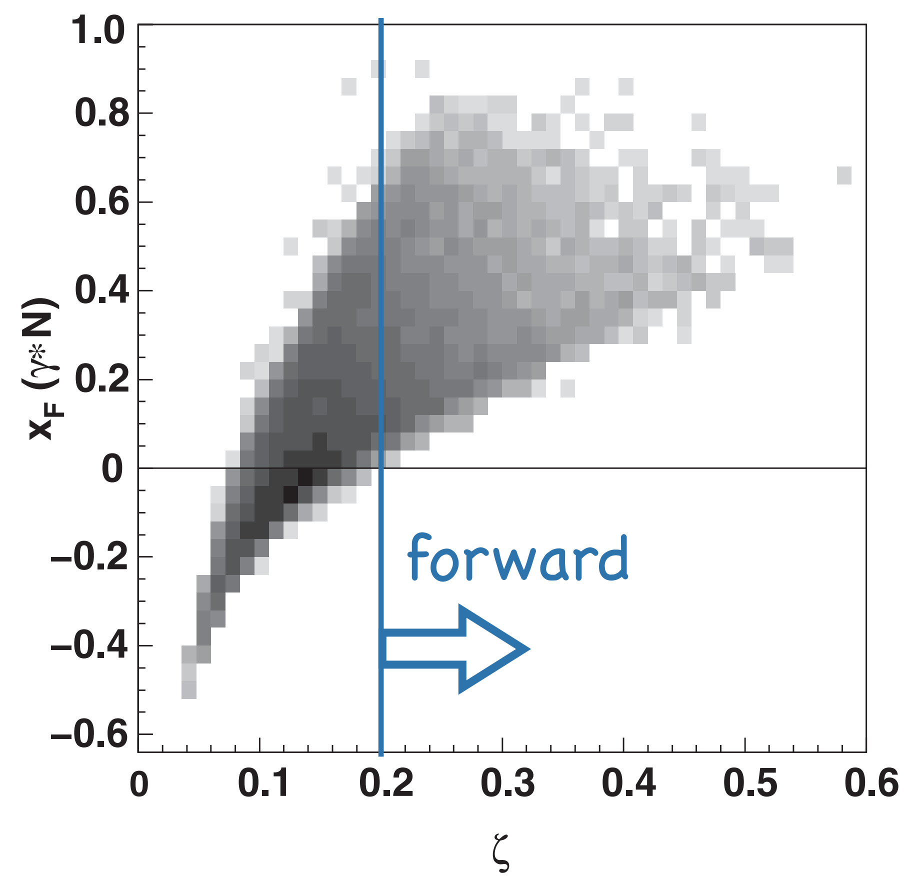


- positive P^Λ for light nuclei
- P^Λ consistent with zero for heavier nuclei

Kinematic dependence



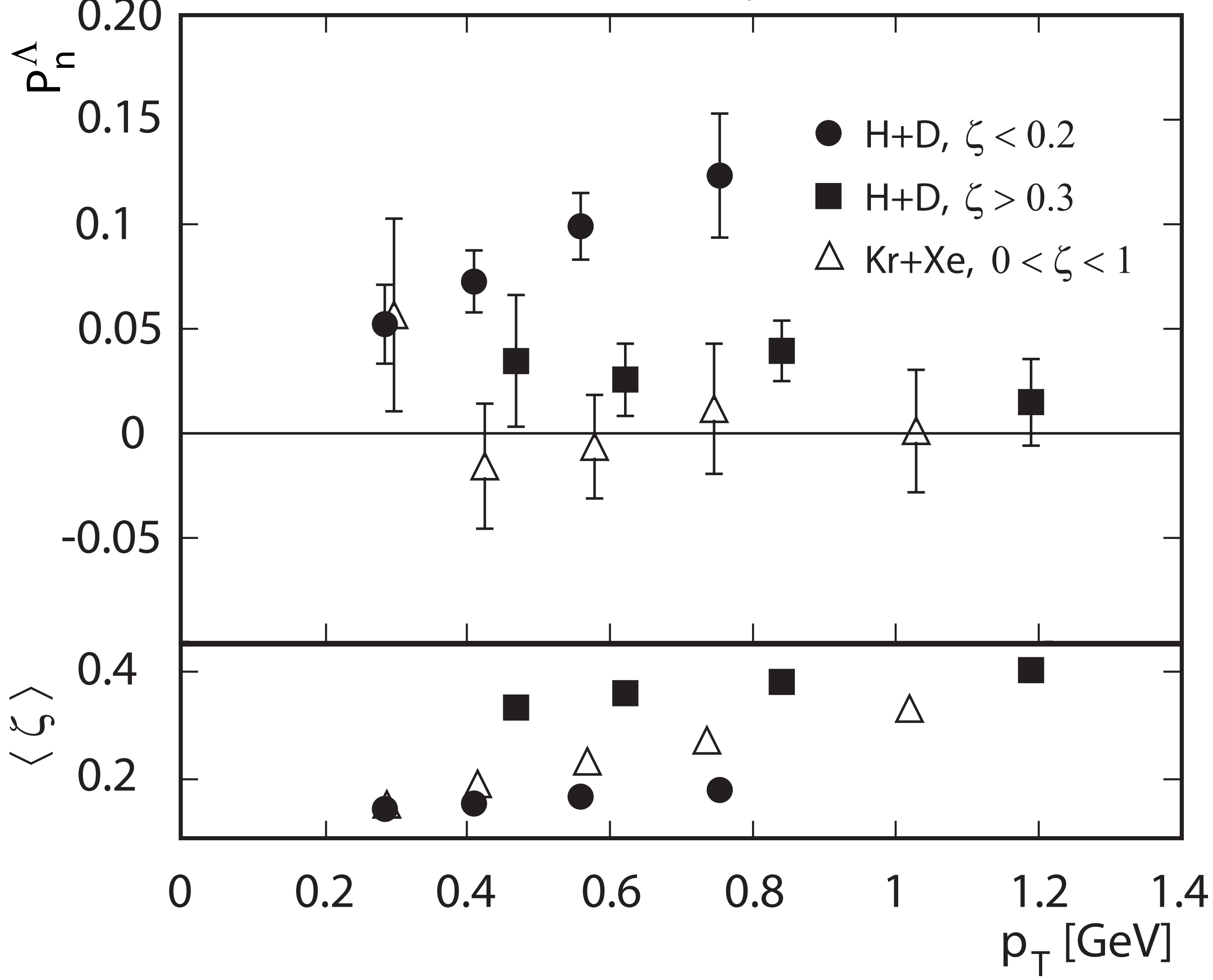
$\zeta = (E_\Lambda + p_{z\Lambda})/(E_e + p_e)$



- H+D: P^Λ larger in backward region ⟶ 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

- 3D picture of the nucleon:
  - ω SDMEs and A_{UT} from exclusive DIS: good model description with inclusion of pion pole.
  - Asymmetries in semi-inclusive DIS: 3D extraction: contribute to understanding of various TMD PDFs @ twist 2 and twist 3.
- Bose-Einstein correlations in DIS: clear signals observed, without evidence for target-mass dependence.
- Λ polarization in quasi-real photoproduction: positive for light nuclei; compatible with zero for Kr and Xe.

Thank you