Proton tomography in fixed-target experiments

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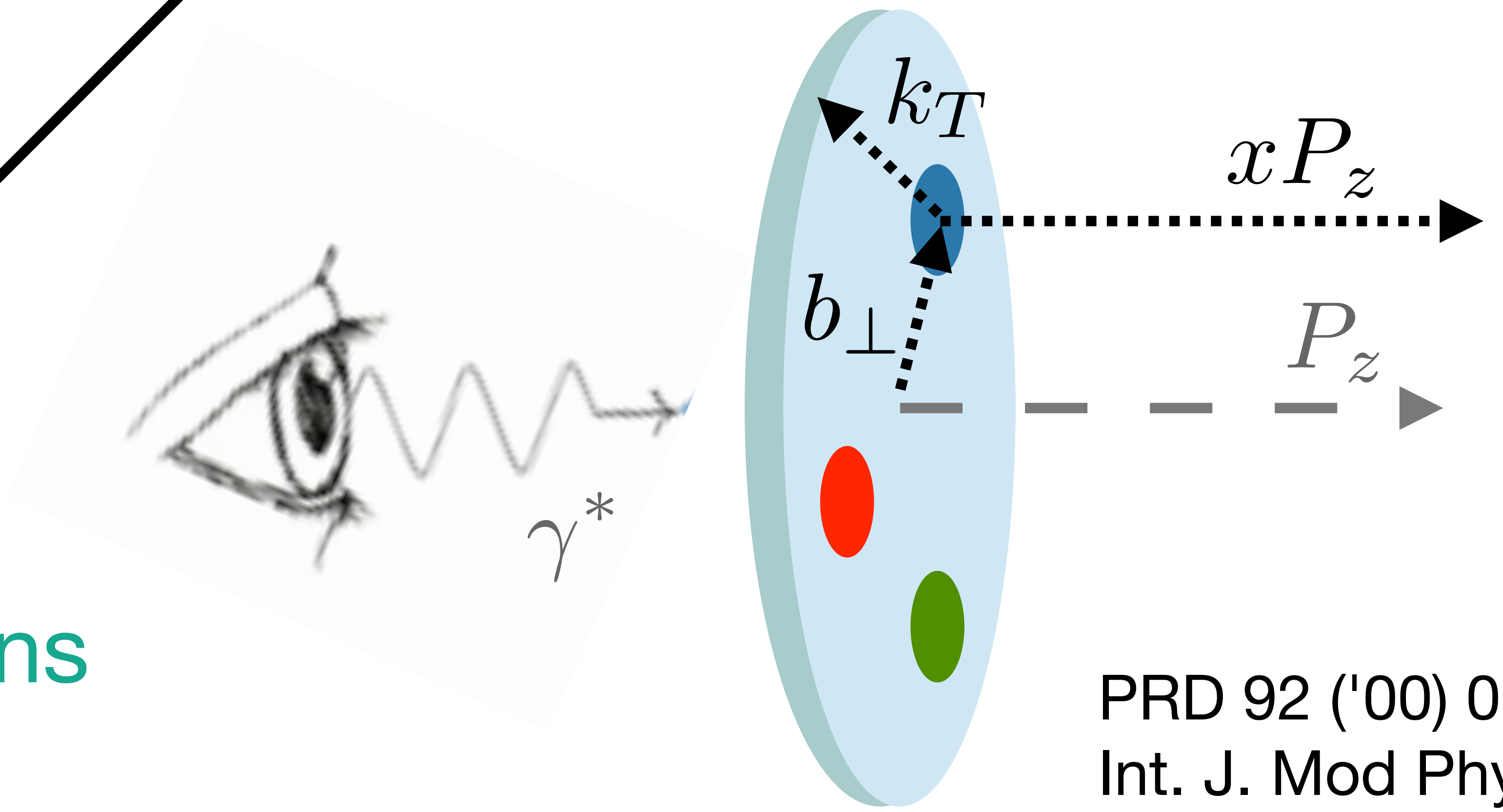
The various dimensions of the nucleon structure

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

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

transverse-momentum dependent (TMD) parton distribution functions (PDFs)



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

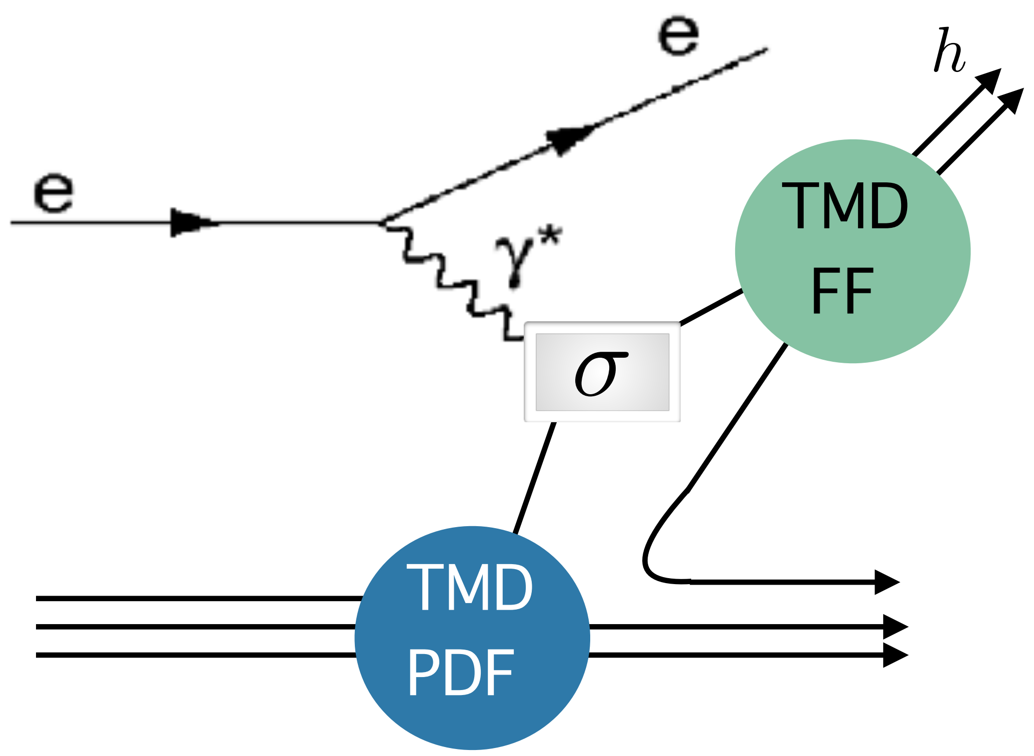
impact-parameter dependent PDFs

PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

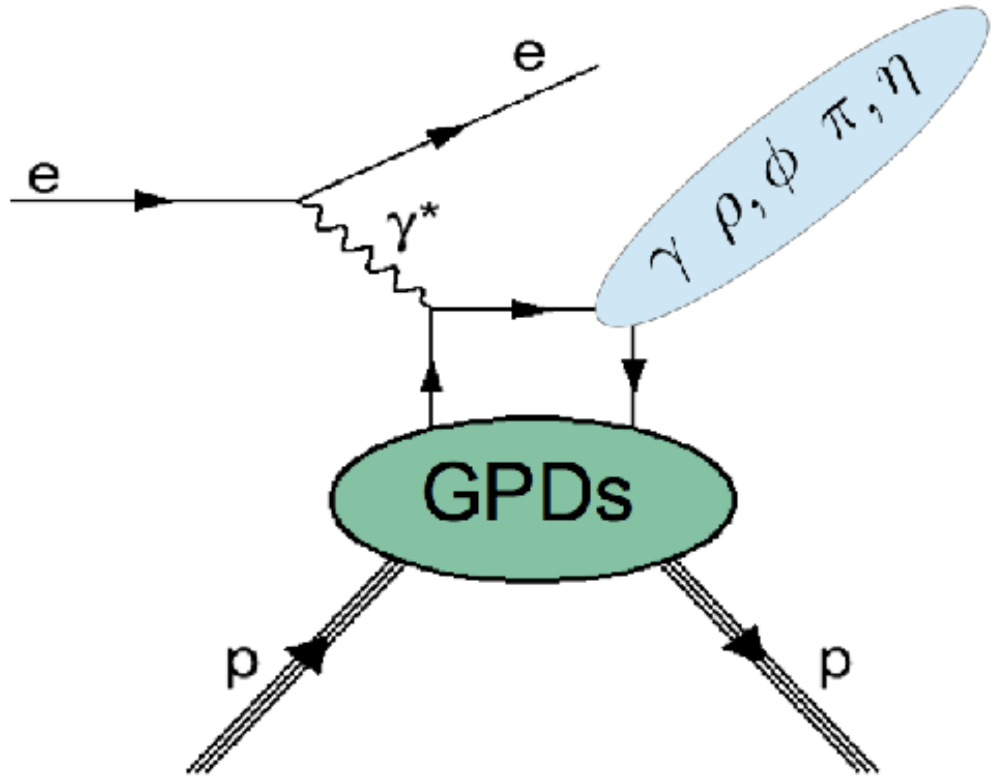
Fourier transform

generalised parton distributions (GPDs)

Semi-inclusive production



Exclusive production



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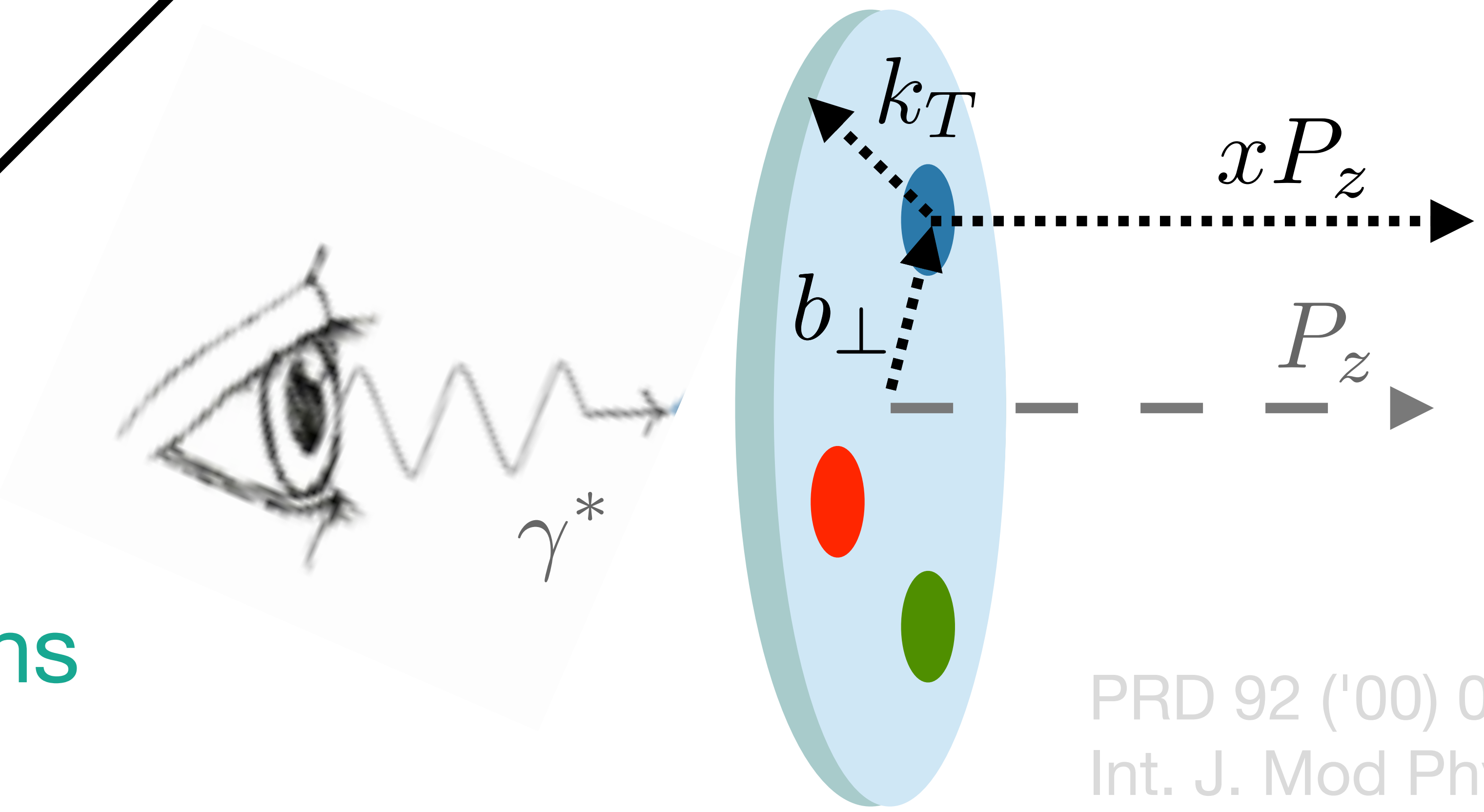

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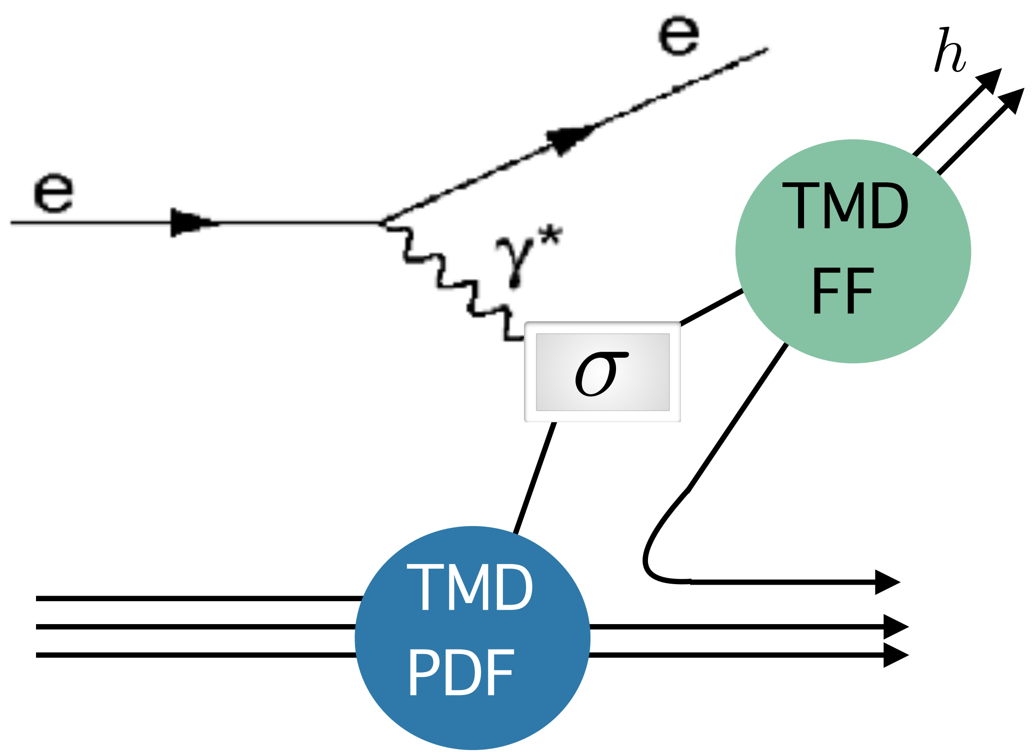
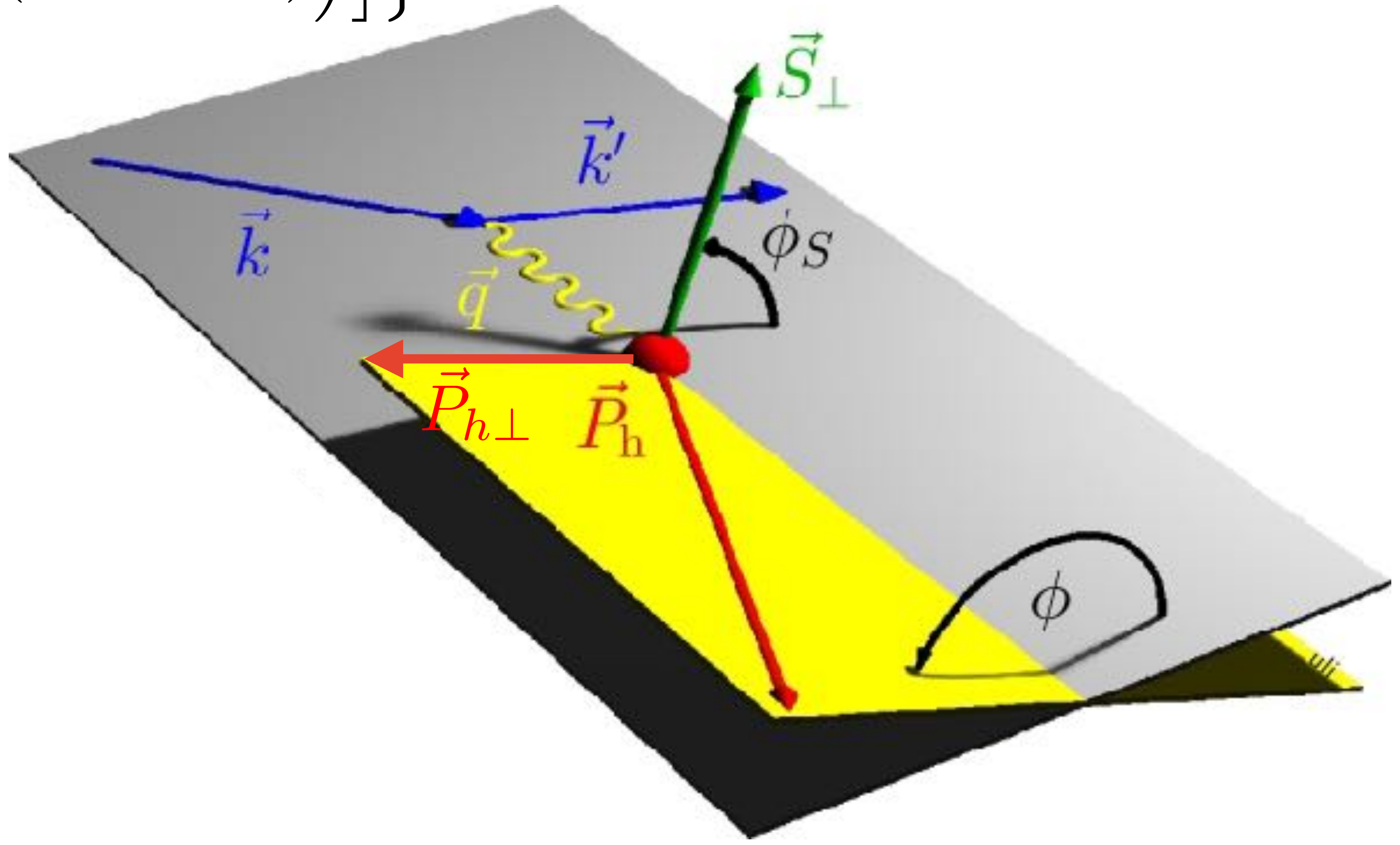


Exclusive production

Semi-inclusive DIS cross section

$$
\begin{aligned}
\sigma^h(\phi,\phi_S) \quad &= \quad \sigma^h_{UU}\Big\{1+2\langle\cos(\phi)\rangle^h_{UU}\,\cos(\phi)+2\langle\cos(2\phi)\rangle^h_{UU}\,\cos(2\phi)\\
&+ \quad \lambda_l\,2\langle\sin(\phi)\rangle^h_{LU}\,\sin(\phi)\\
&+ \quad S_L\Big[2\langle\sin(\phi)\rangle^h_{UL}\,\sin(\phi)+2\langle\sin(2\phi)\rangle^h_{UL}\,\sin(2\phi)\\
&+ \quad \lambda_l\Big(2\langle\cos(0\phi)\rangle^h_{LL}\,\cos(0\phi)+2\langle\cos(\phi)\rangle^h_{LL}\,\cos(\phi)\Big)\Big]\\
&+ \quad S_T\Big[2\langle\sin(\phi-\phi_S)\rangle^h_{UT}\,\sin(\phi-\phi_S)+2\langle\,\sin(\phi+\phi_S)\rangle^h_{UT}\,\sin(\phi+\phi_S)\\
&+ \quad 2\langle\sin(3\phi-\phi_S)\rangle^h_{UT}\,\sin(3\phi-\phi_S)+2\langle\sin(\phi_S)\rangle^h_{UT}\,\sin(\phi_S)\\
&+ \quad 2\langle\sin(2\phi-\phi_S)\rangle^h_{UT}\,\sin(2\phi-\phi_S)\\
&+ \quad \lambda_l\Big(2\langle\cos(\phi-\phi_S)\rangle^h_{LT}\,\cos(\phi-\phi_S)\\
&+ \quad 2\langle\cos(\phi_S)\rangle^h_{LT}\,\cos(\phi_S)+2\langle\cos(2\phi-\phi_S)\rangle^h_{LT}\,\cos(2\phi-\phi_S)\Big)\Big]\Big\}
\end{aligned}
$$



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\end{aligned}
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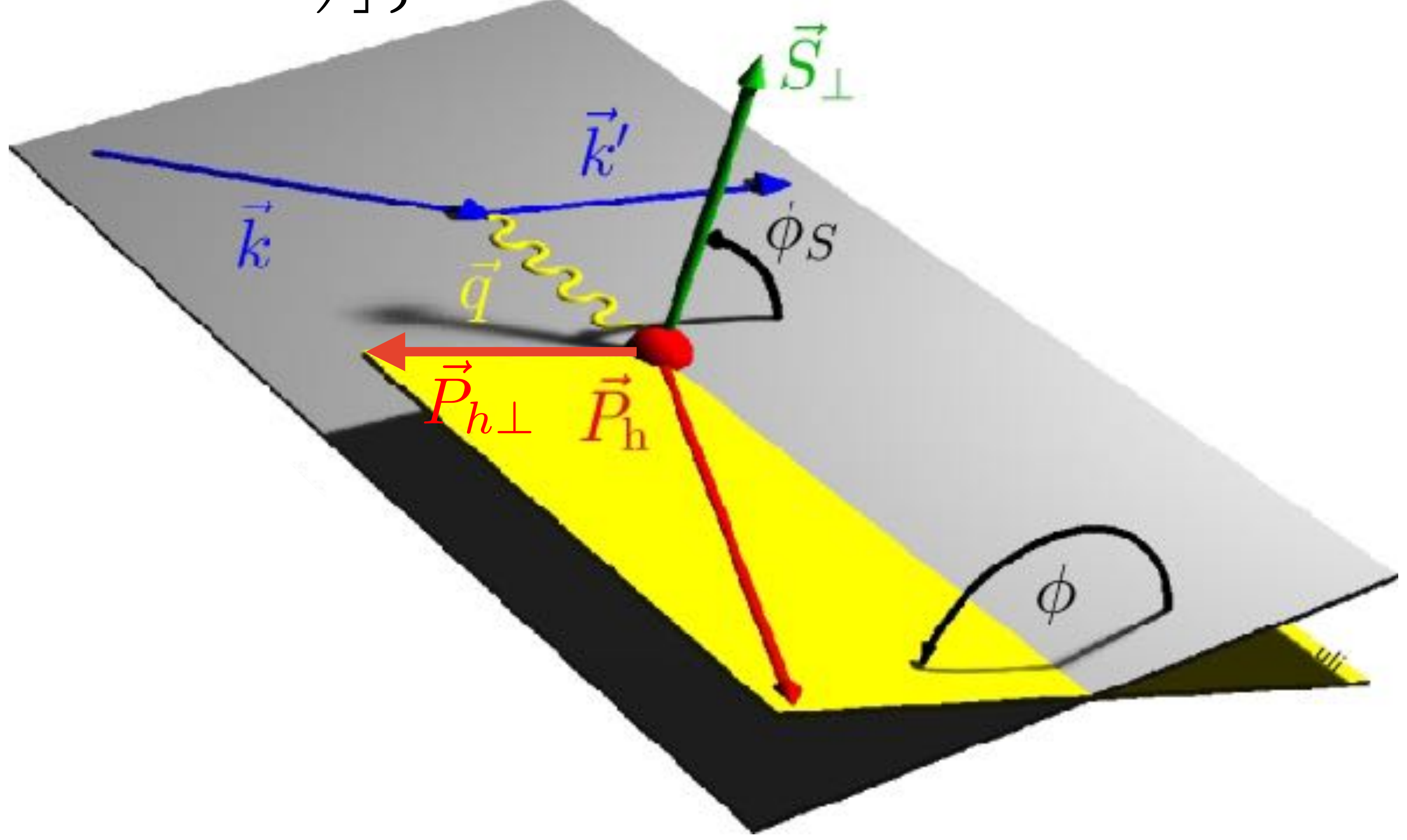
longitudinal target polarisation

transverse target polarisation

beam polarisation

beam polarisation

target polarisation



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longitudinal target polarisation

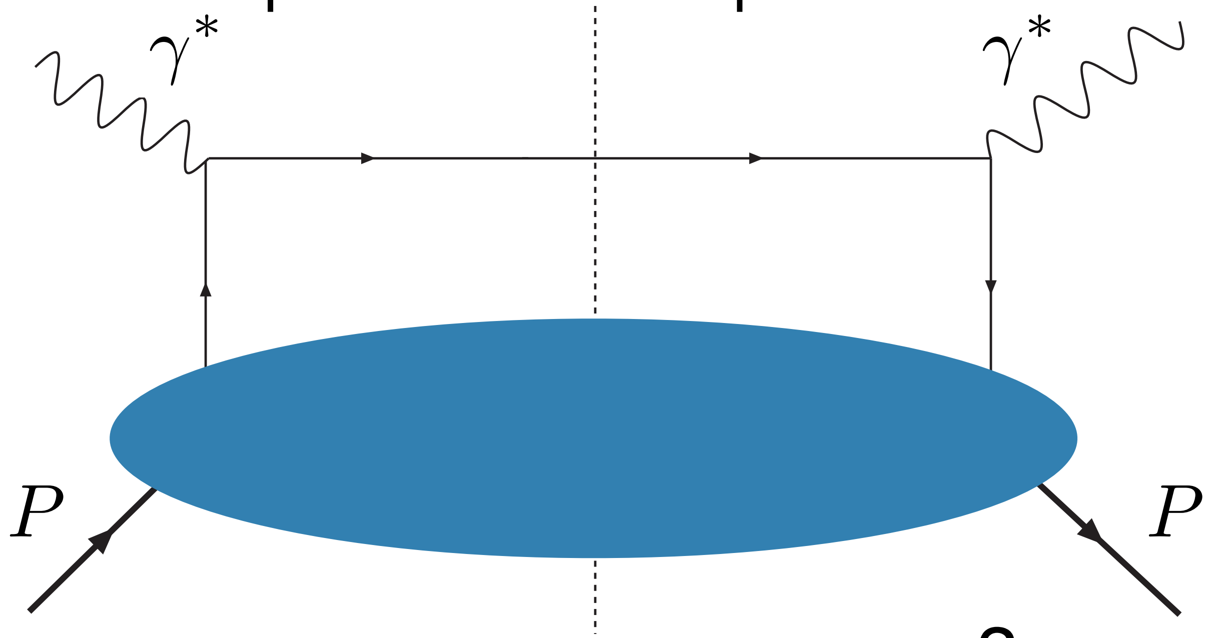
transverse target polarisation

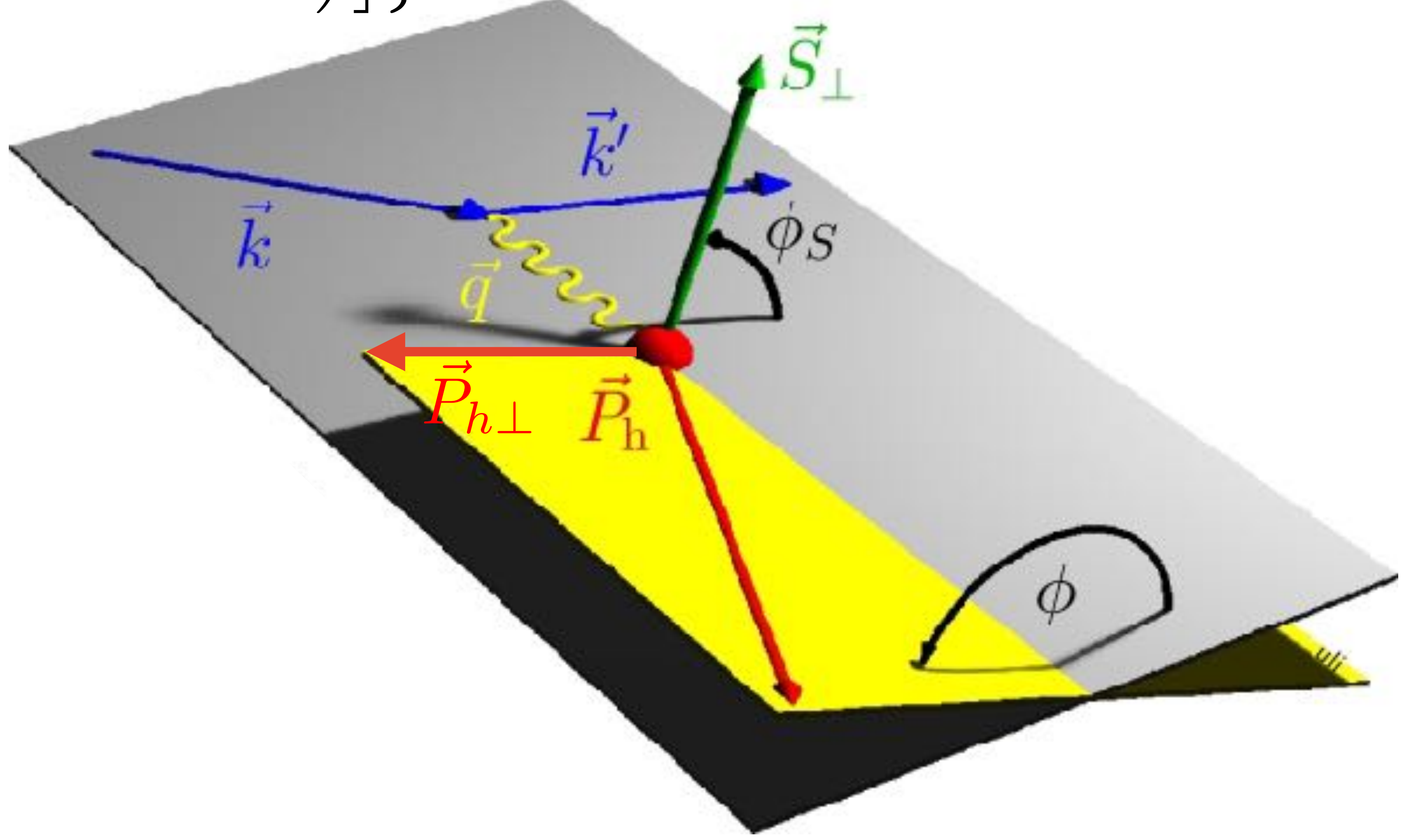
beam polarisation

beam polarisation

target polarisation

leading twist





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longitudinal target polarisation

transverse target polarisation

beam polarisation

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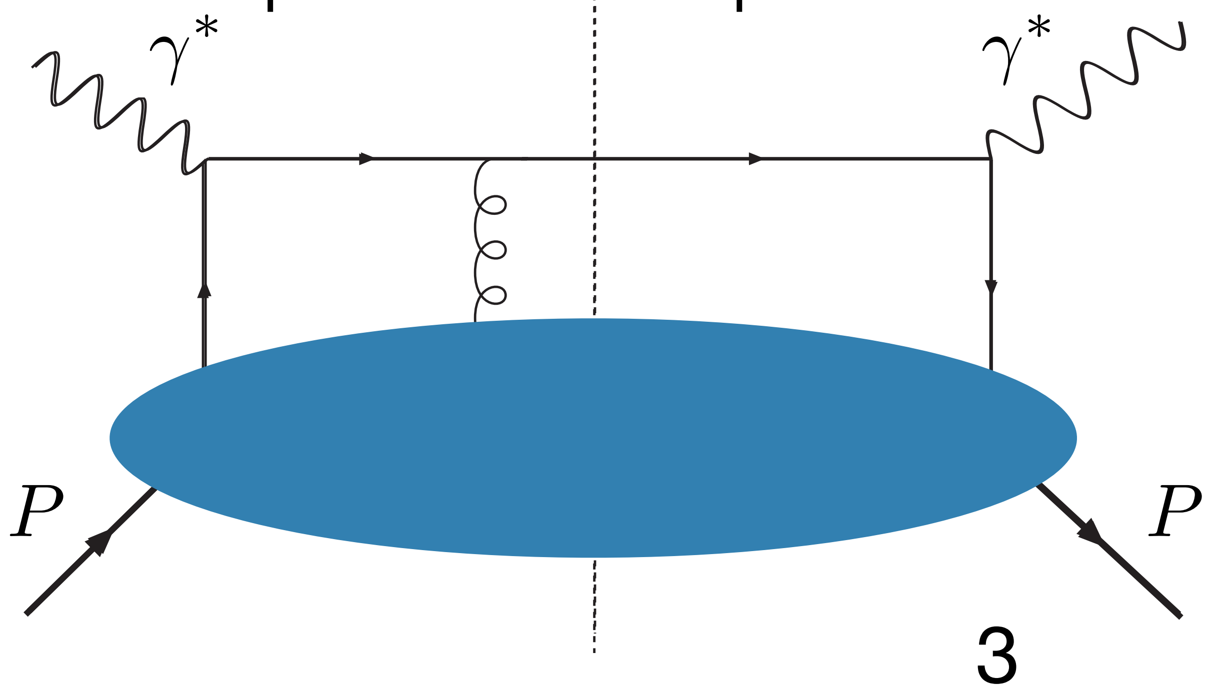
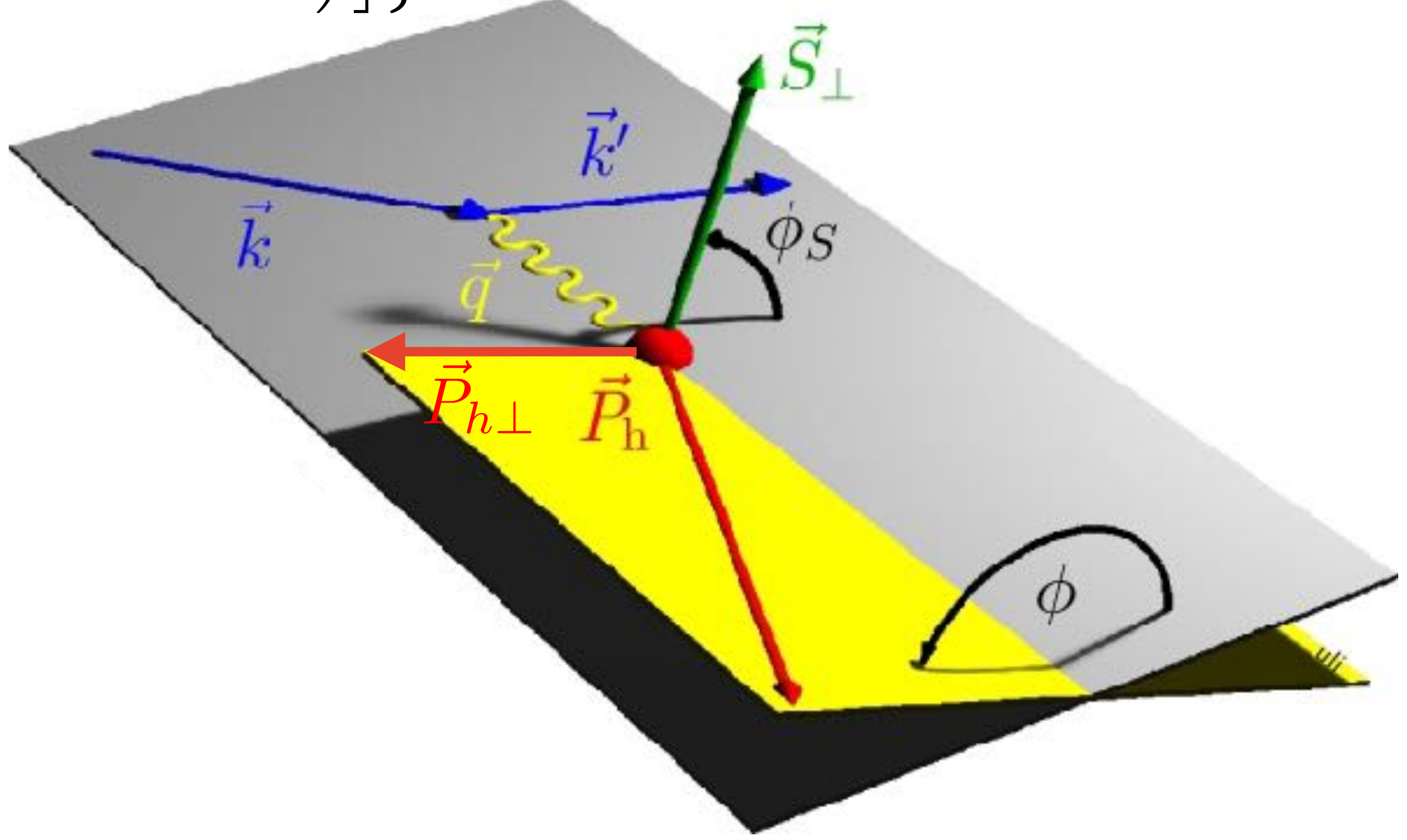
target polarisation

sub-leading twist





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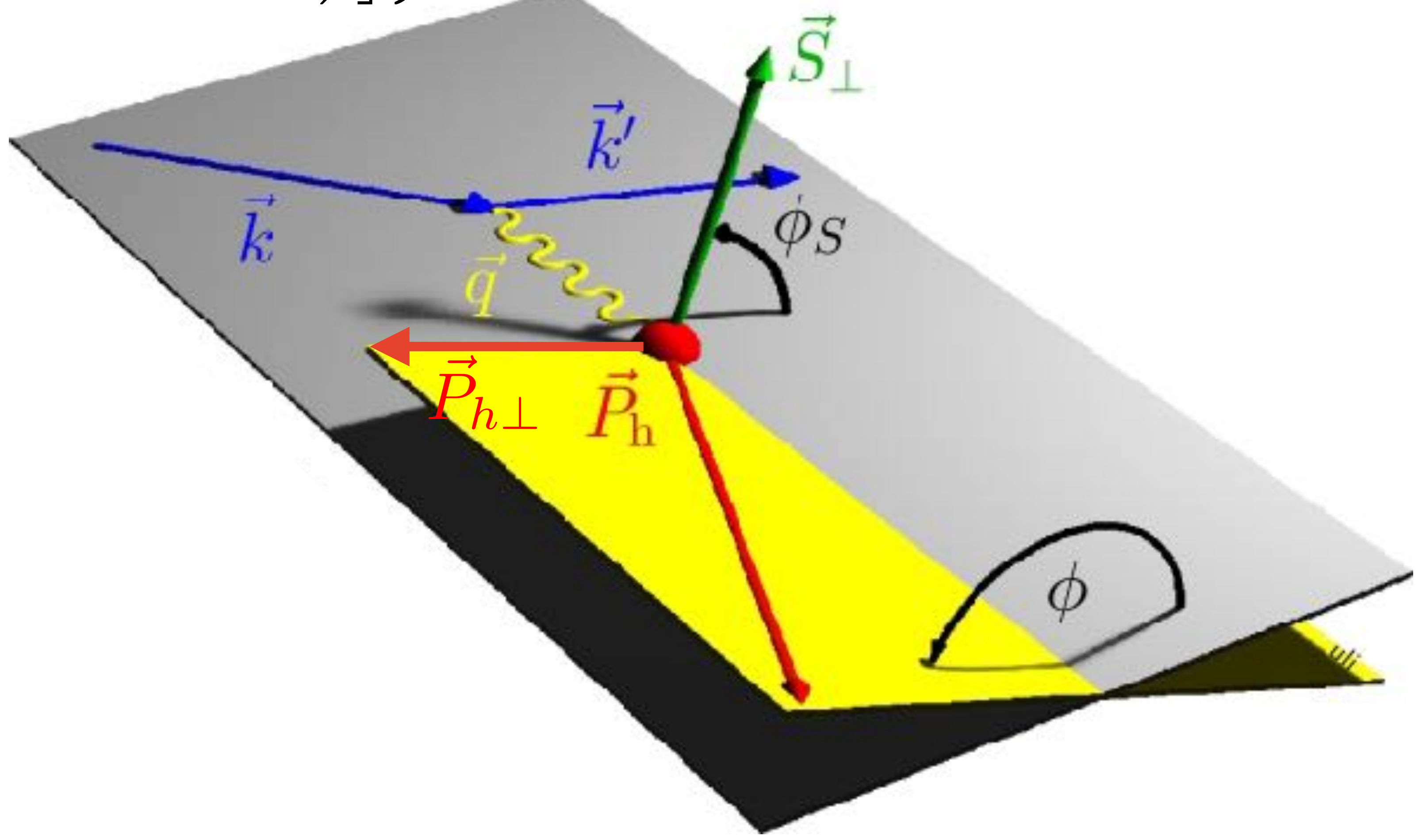
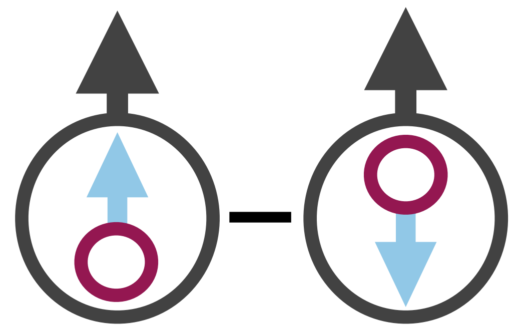
Presented here

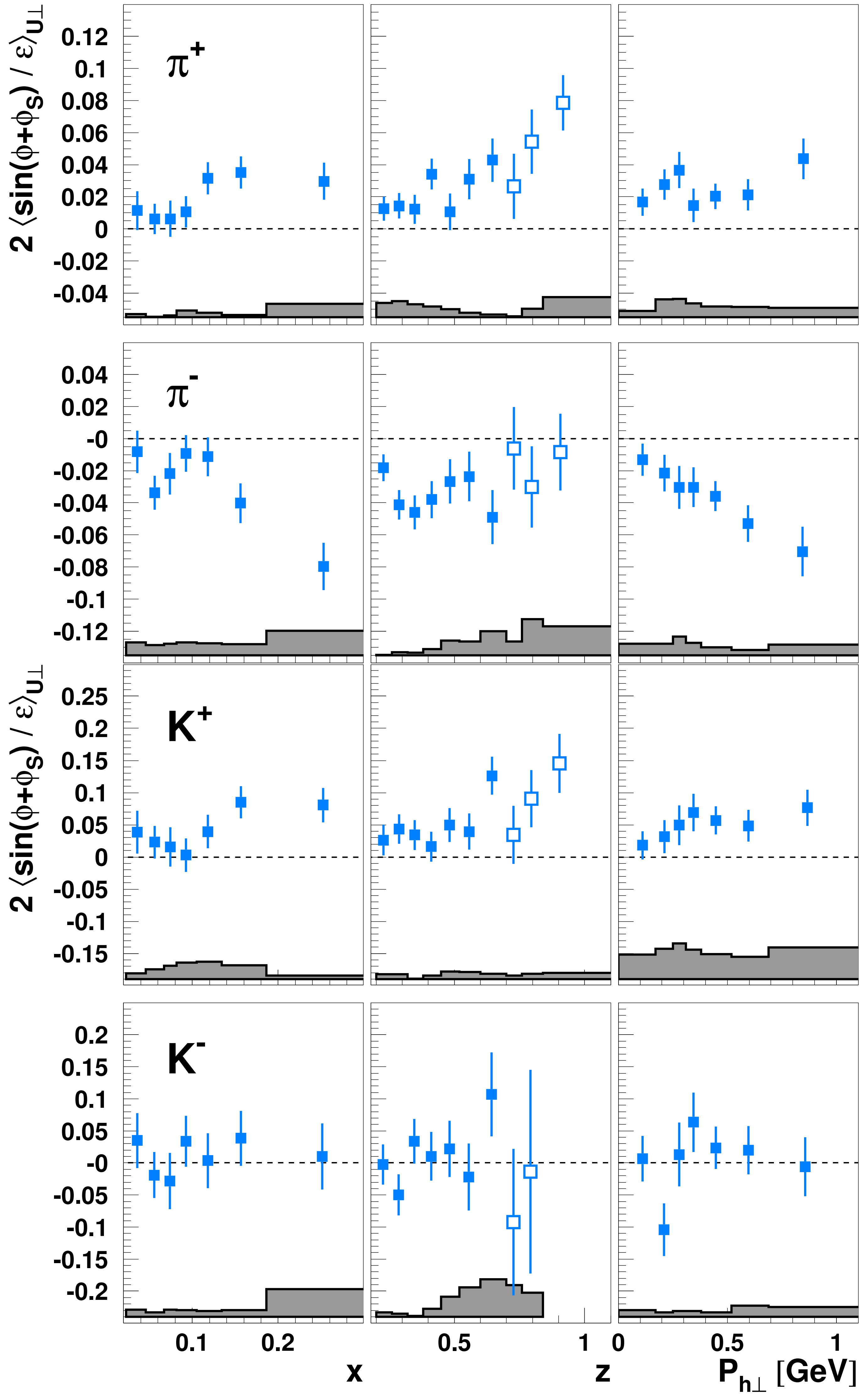


Collins amplitudes



$$\mathscr{C}\left[h_{1T}^{q} \times H_1^{\perp,q}\right]$$

HERMES, JHEP **12**(2020)010



- Oppositely signed amplitudes for π^+ and π^-:

$$H_1^{\perp,u\to\pi^+} \approx -H_1^{\perp,u\to\pi^-}$$

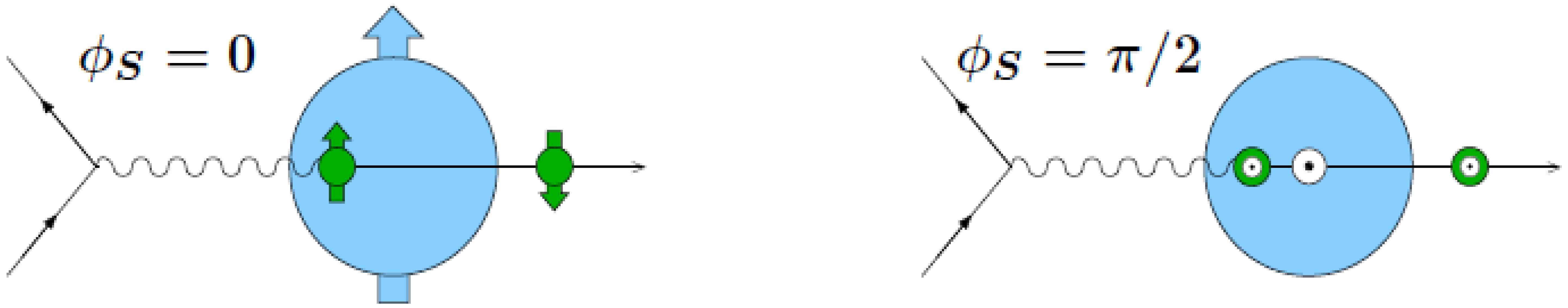
- Amplitudes for K^+ larger than for π^+:

$$H_1^{\perp,u\to K^+} > H_1^{\perp,u\to\pi^+}$$

Artru model

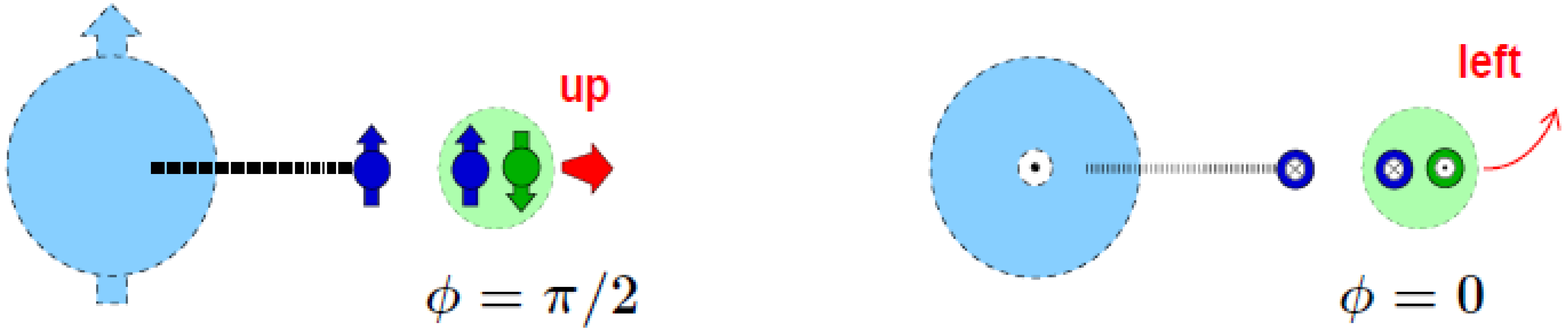
X. Artru et al., Z. Phys. C**73** (1997) 527

polarisation component in lepton scattering plane reversed by photoabsorption:



string break, quark-antiquark pair with vacuum numbers:

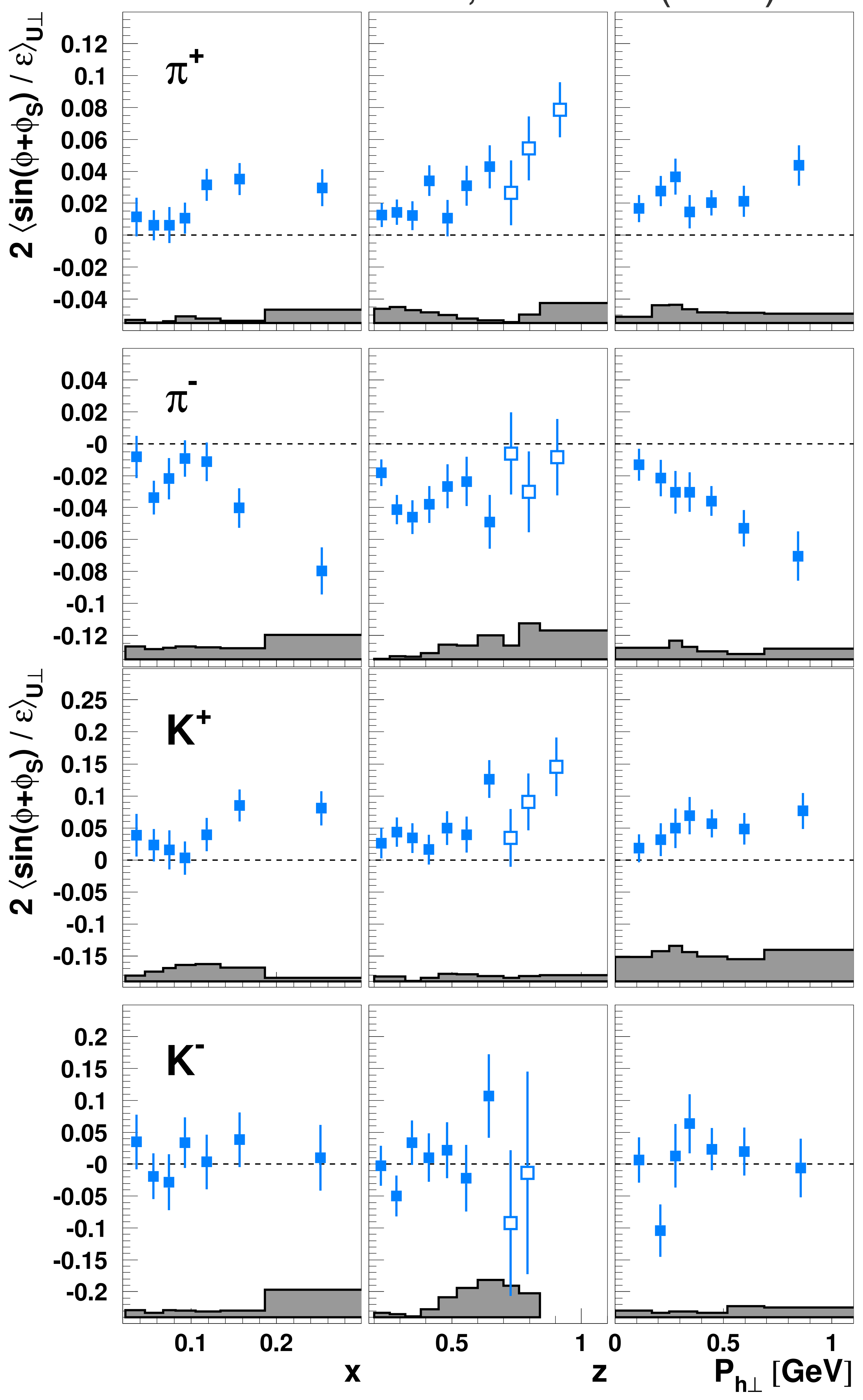
orbital angular momentum creates transverse momentum:

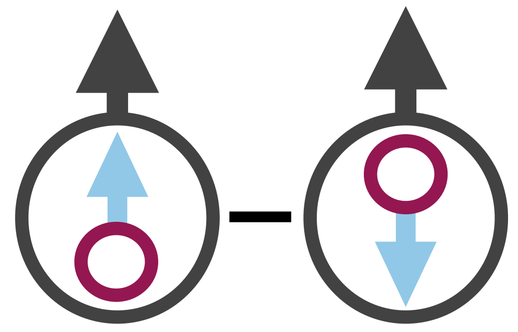


Courtesy U. Elschenbroich

Collins amplitudes

HERMES, JHEP **12**(2020)010





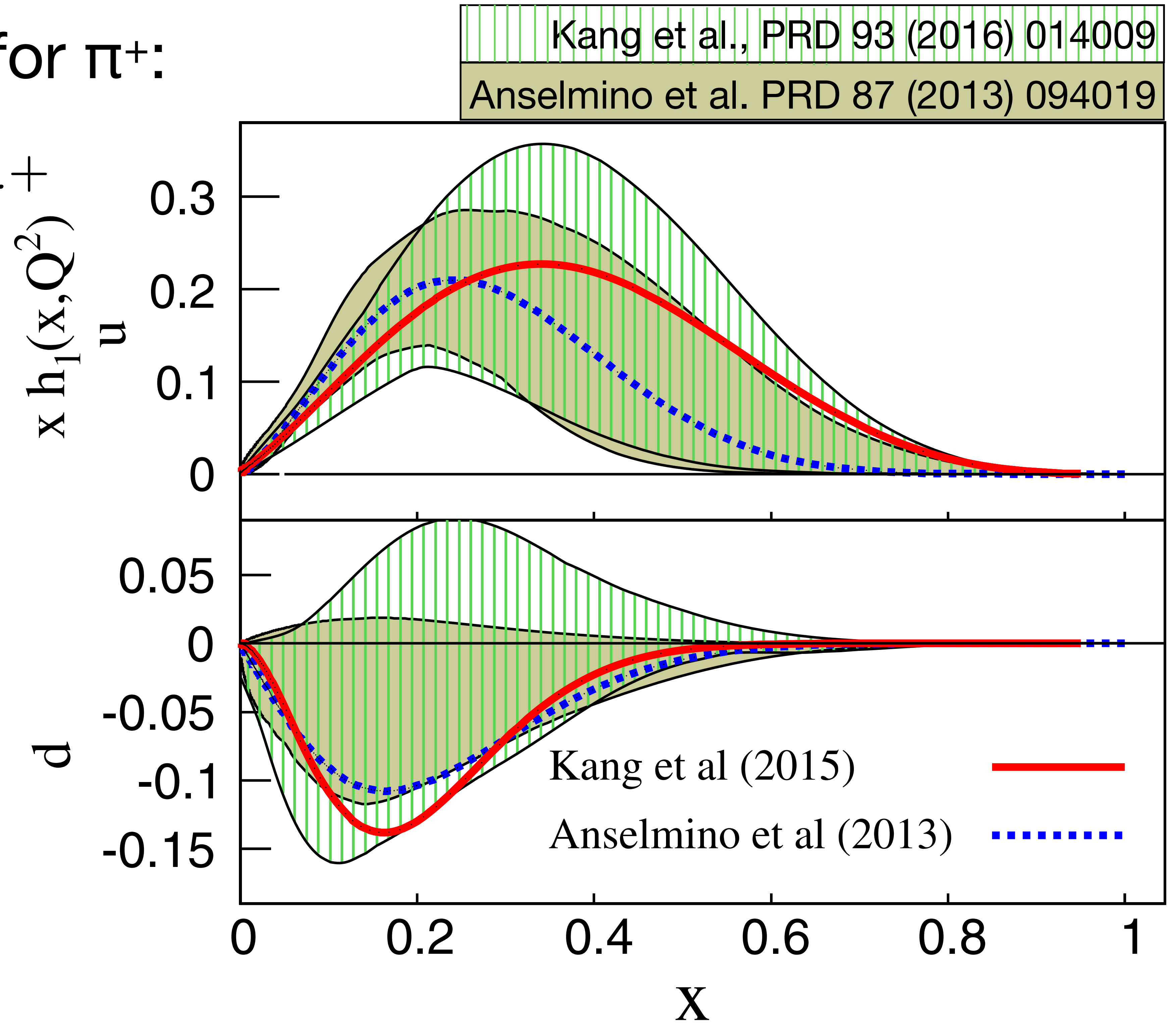
$$\mathscr{C}\left[h_{1T}^{q} \times H_1^{\perp,q}\right]$$

- Oppositely signed amplitudes for π⁺ and π⁻:

$$H_1^{\perp,u\to\pi^+} \approx -H_1^{\perp,u\to\pi^-}$$

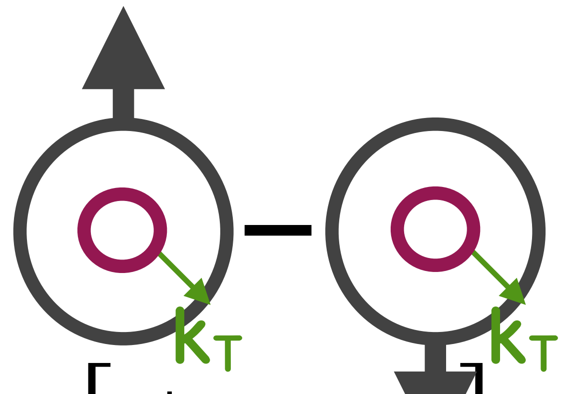
- Amplitudes for K⁺ larger than for π⁺:

$$H_1^{\perp,u\to K^+} > H_1^{\perp,u\to\pi^+}$$



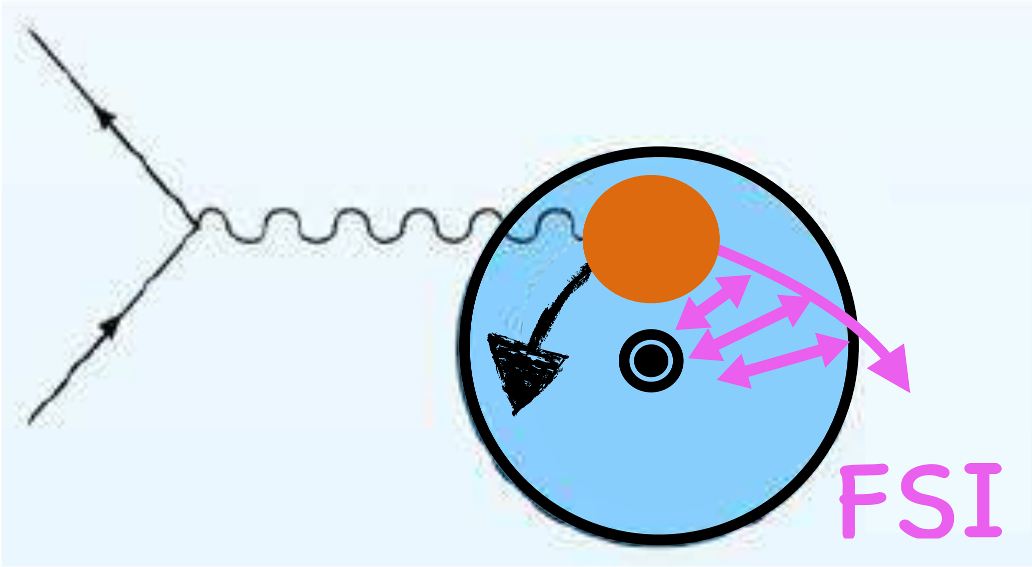
data from Belle, Babar, COMPASS, HERMES, Jefferson Lab Hall A

Sivers amplitudes



$$\mathscr{C}\left[f_{1T}^{\perp,q}\times D_1\right]$$

- Sivers function:
  - requires non-zero orbital angular momentum
  - final-state interactions $\longrightarrow$ azimuthal asymmetries



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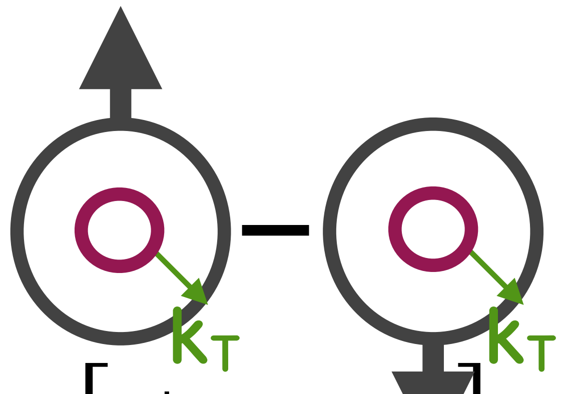

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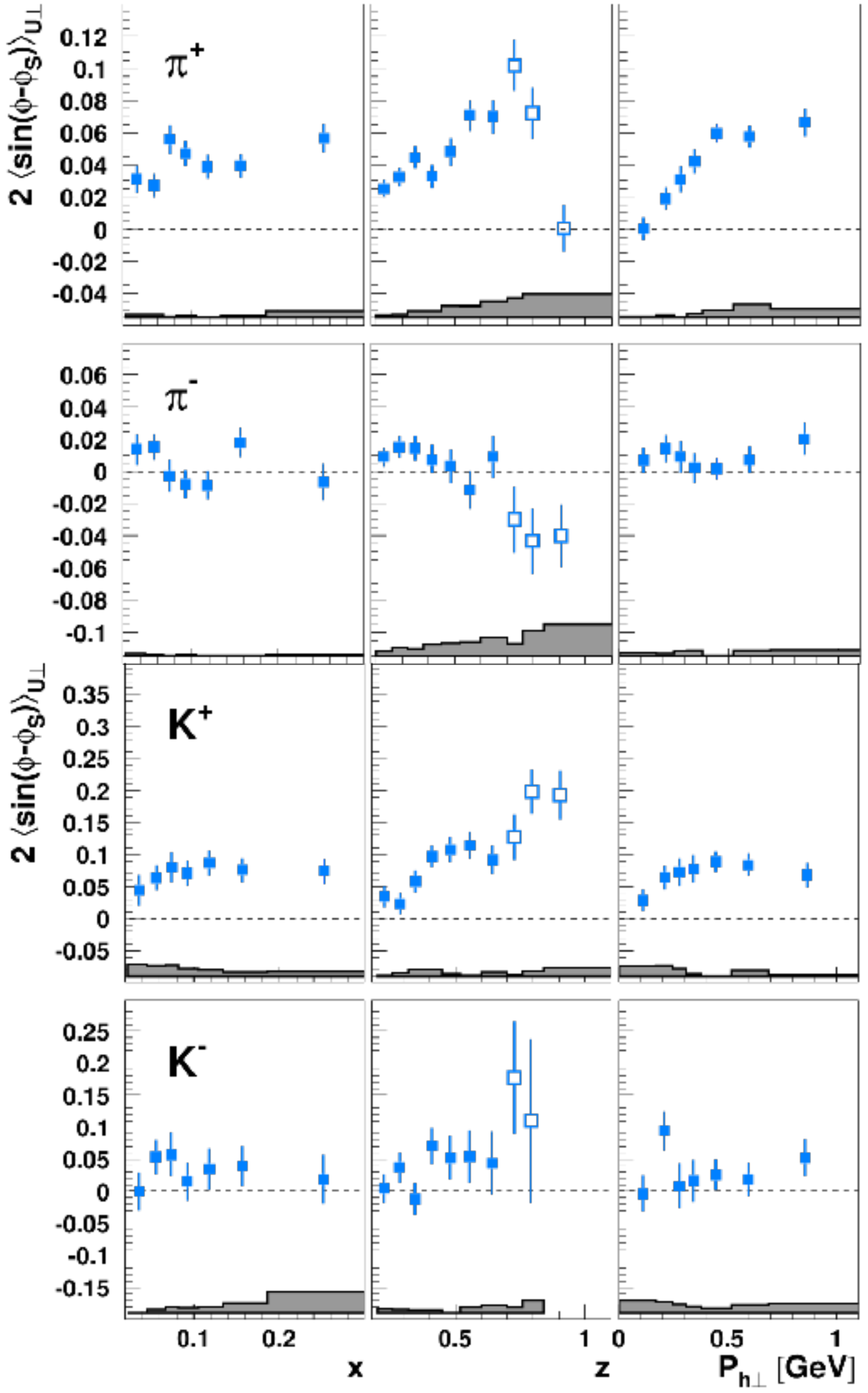
HERMES, JHEP **12**(2020)010



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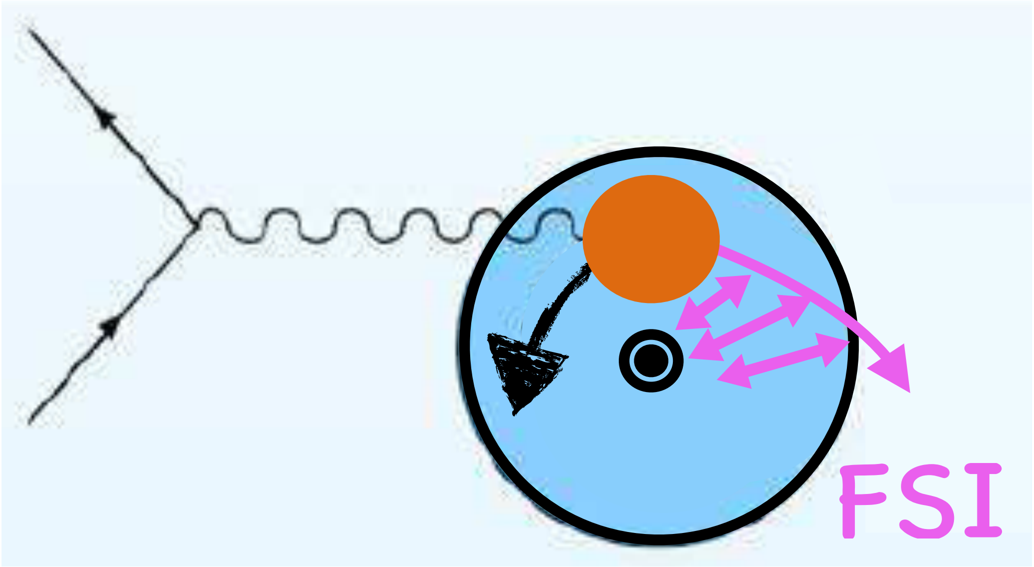

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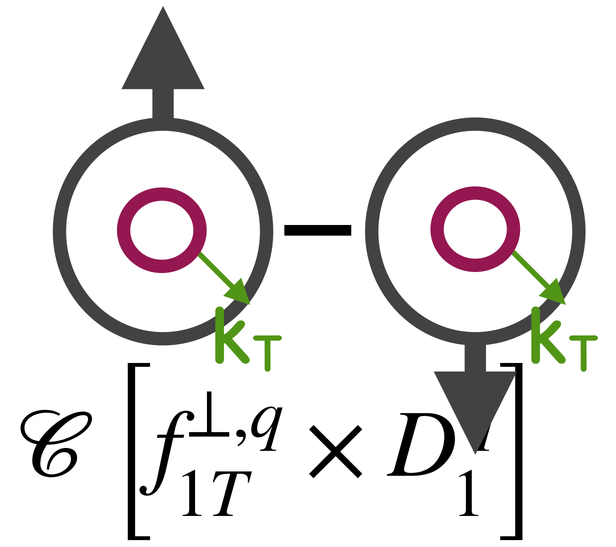

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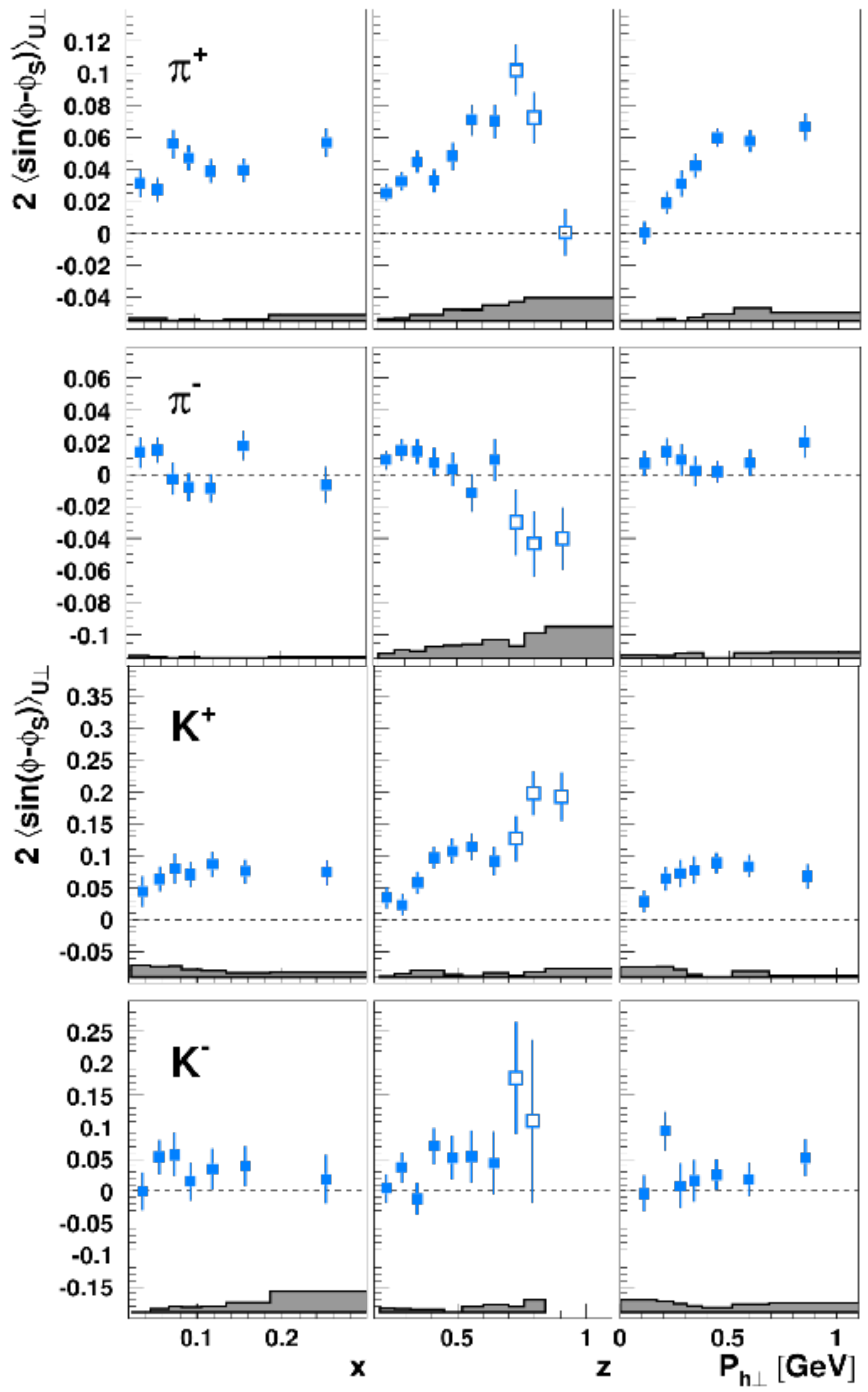

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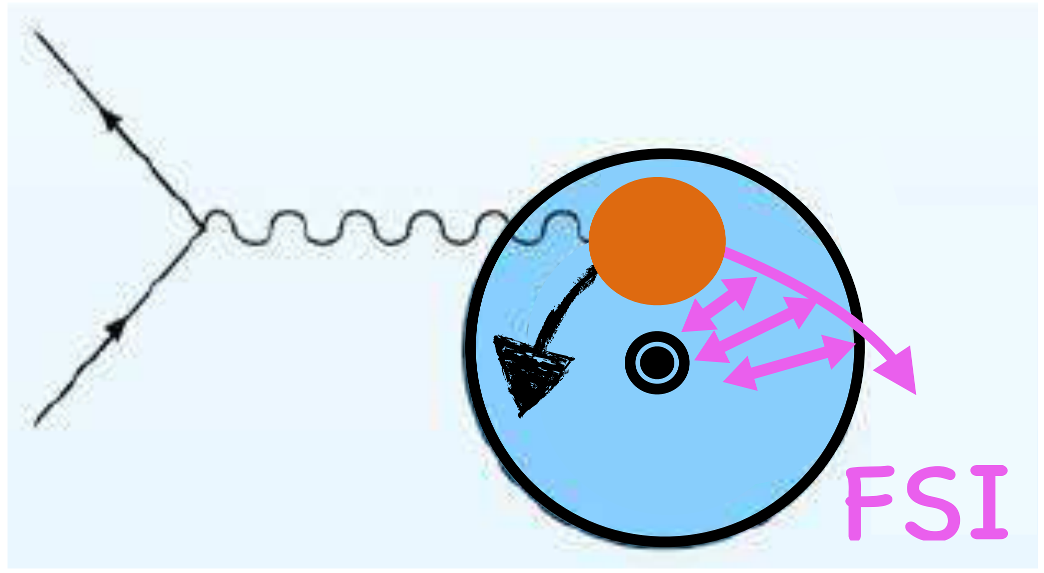
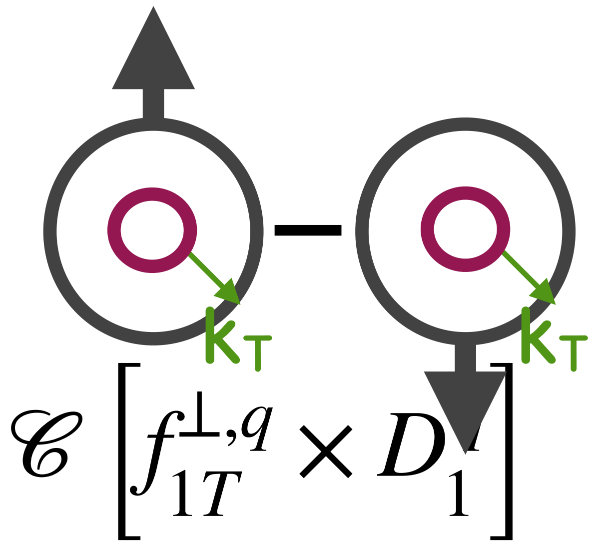
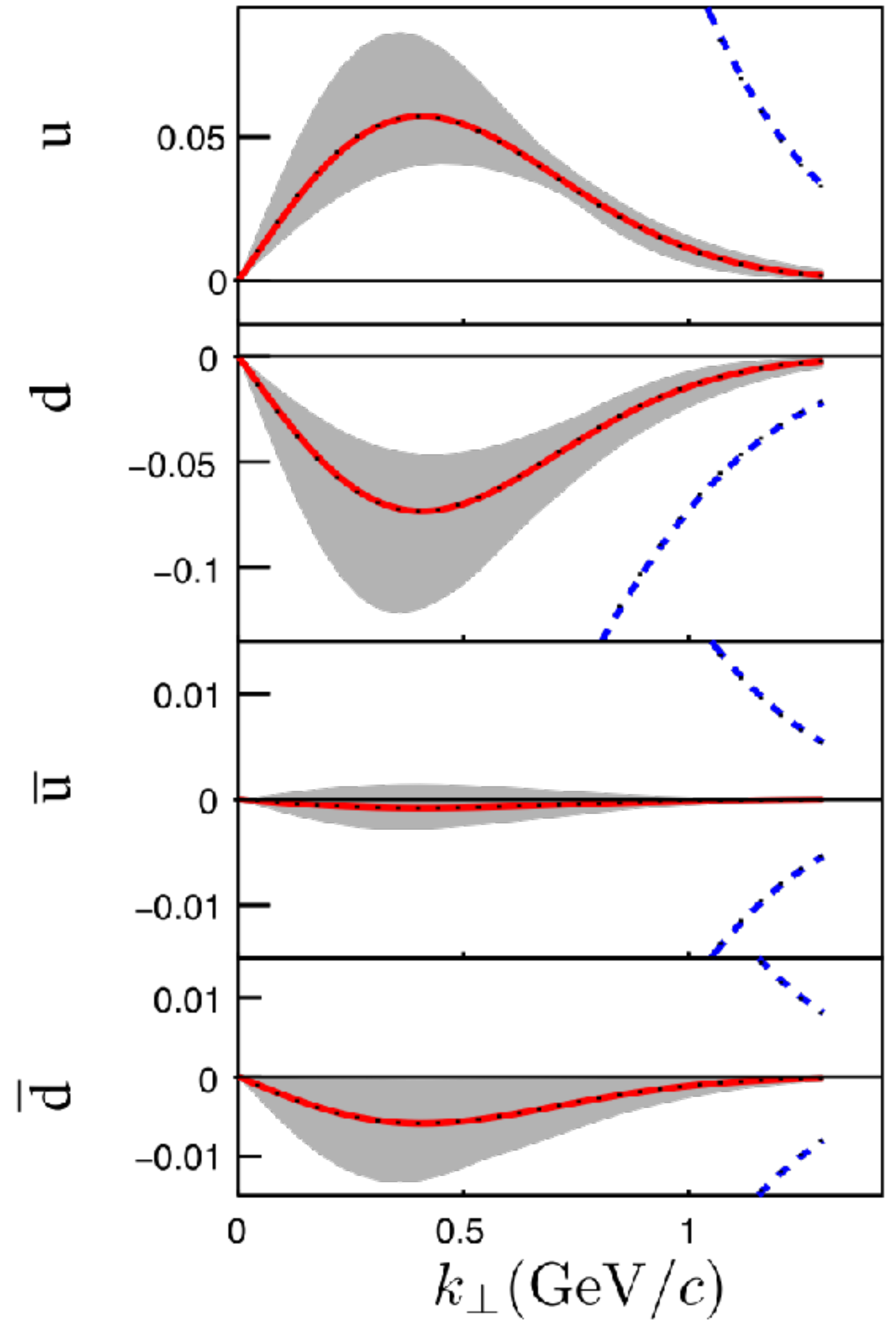


- π^+:
  - positive -> non-zero orbital angular momentum
- π^-:
  - consistent with zero → u and d quark cancelation

Sivers amplitudes



M. Anselmino et al., JHEP **04** (2017) 046



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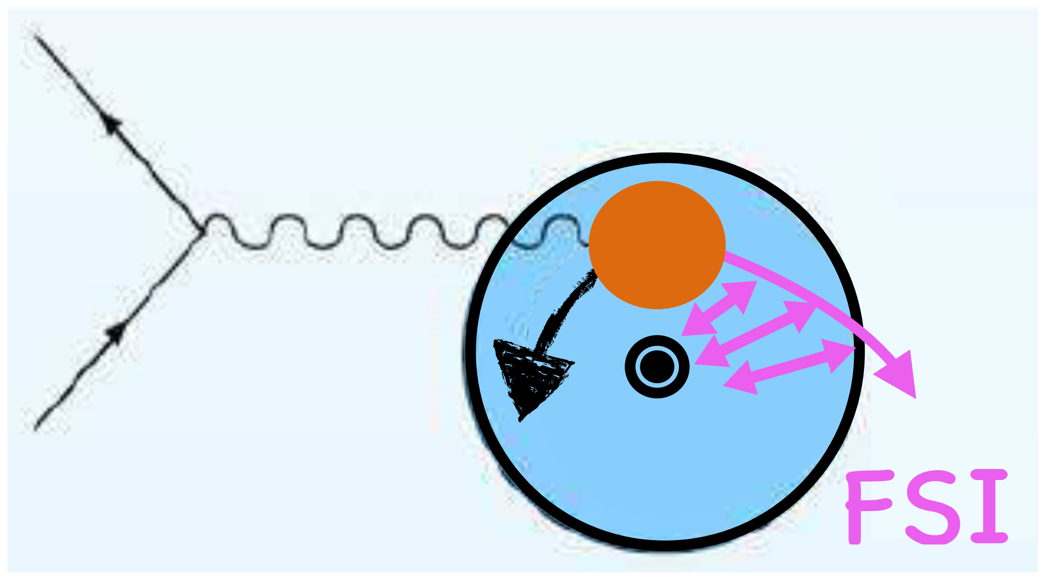

- π^+:
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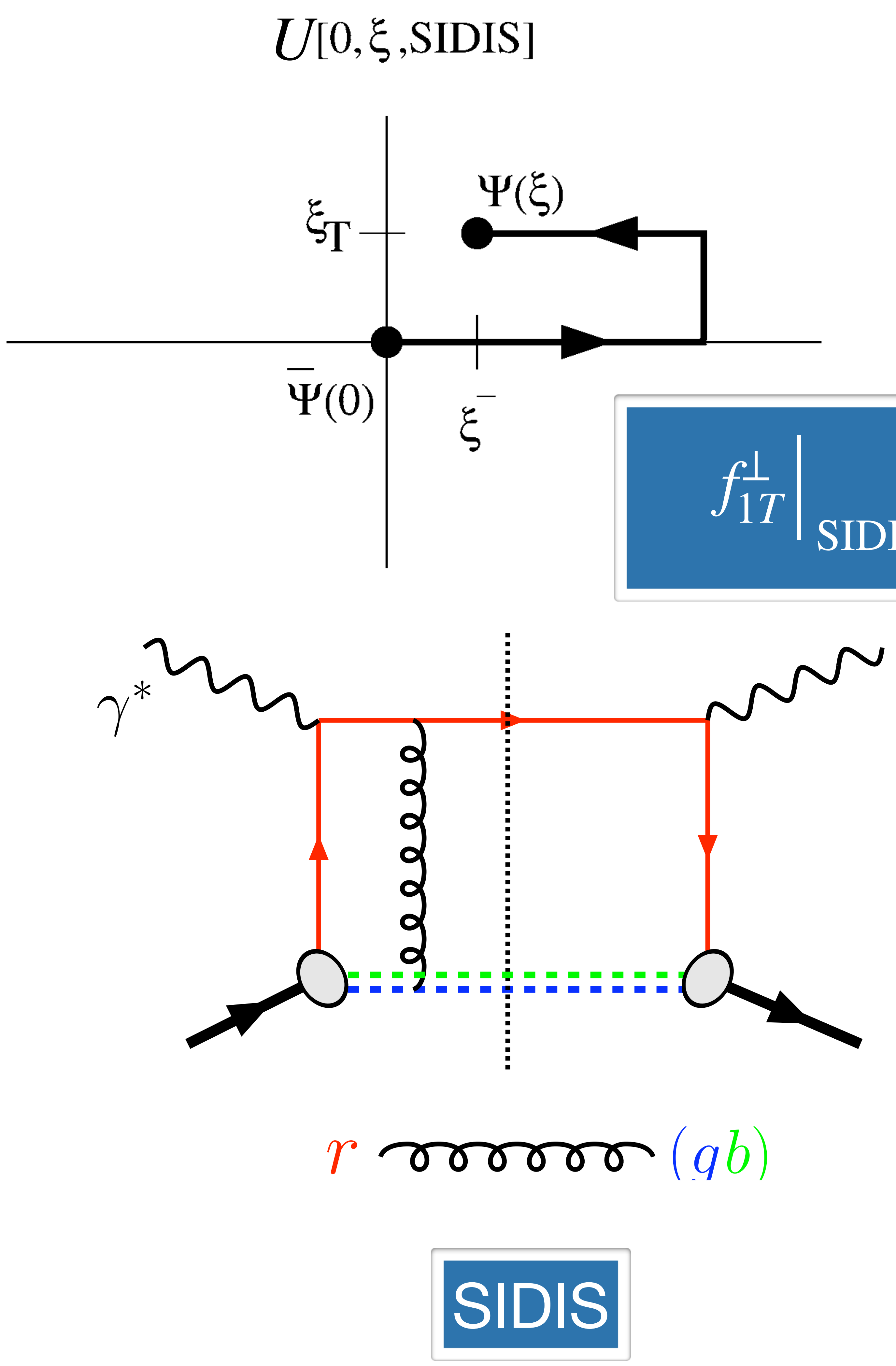
  - consistent with zero → u and d quark cancelation

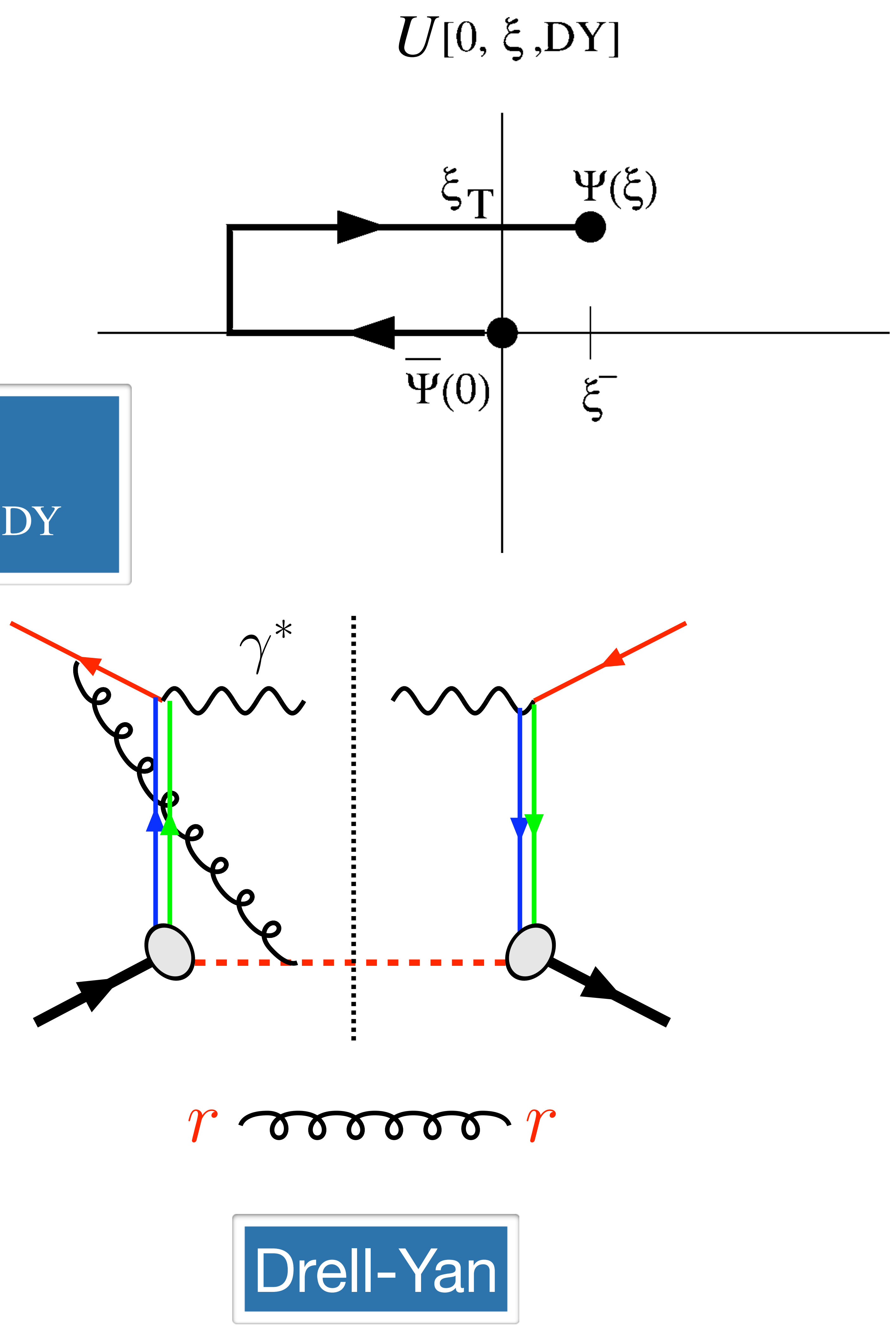
Predicted Sivers sign change for SIDIS and Drell-Yan

J. C. Collins, Phys. Lett. B 536 (2002) 43

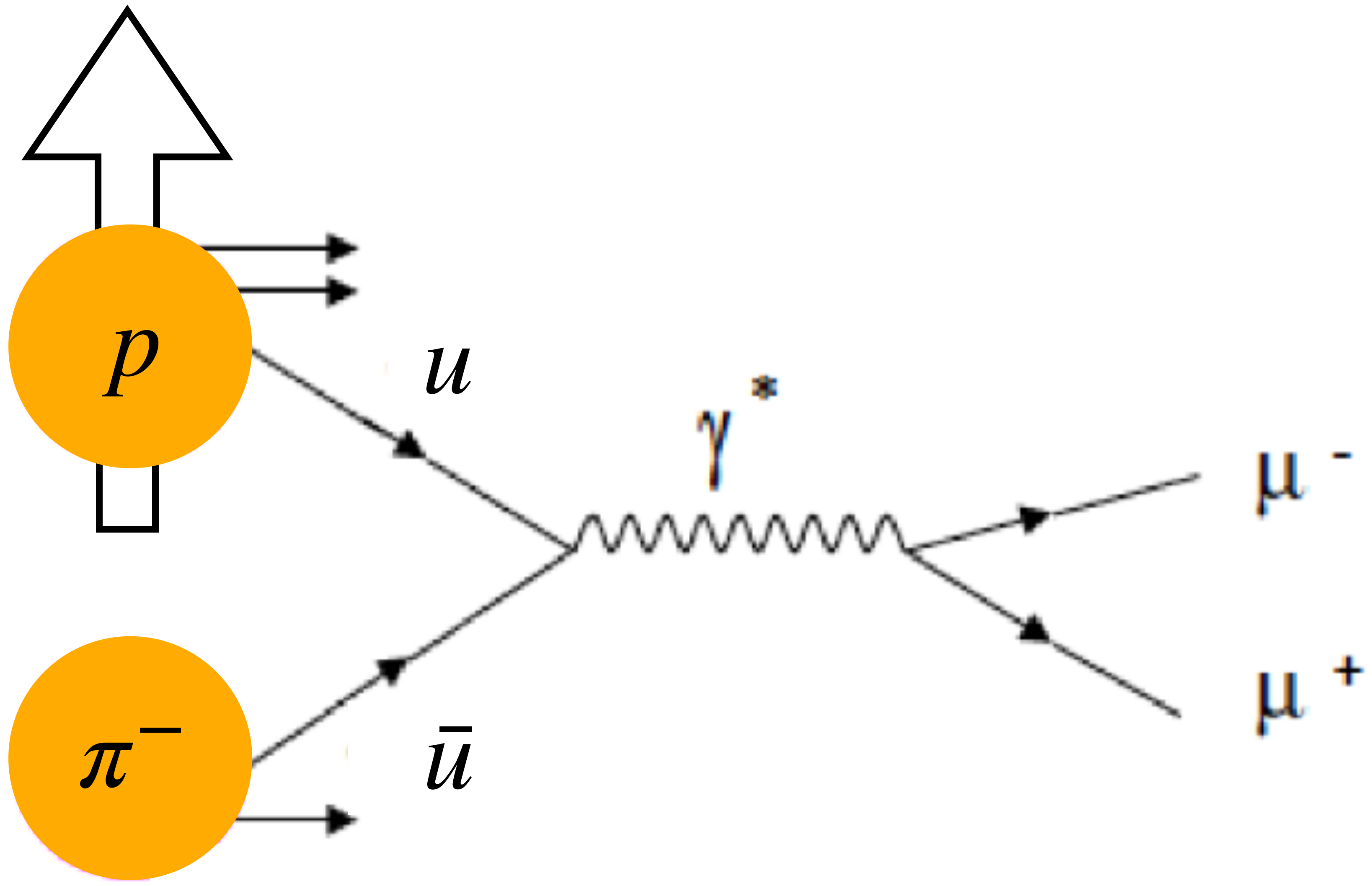
$$\Phi_{ij}(p,P,S) = \frac{1}{(2\pi)^4}\int d^4\xi\, e^{ip\cdot\xi}\langle P,S|\,\bar\psi_j(0)\,U_{[0,\xi]}\,\psi_i(\xi)\,|P,S\rangle$$



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



Experimental access to Sivers in Drell-Yan



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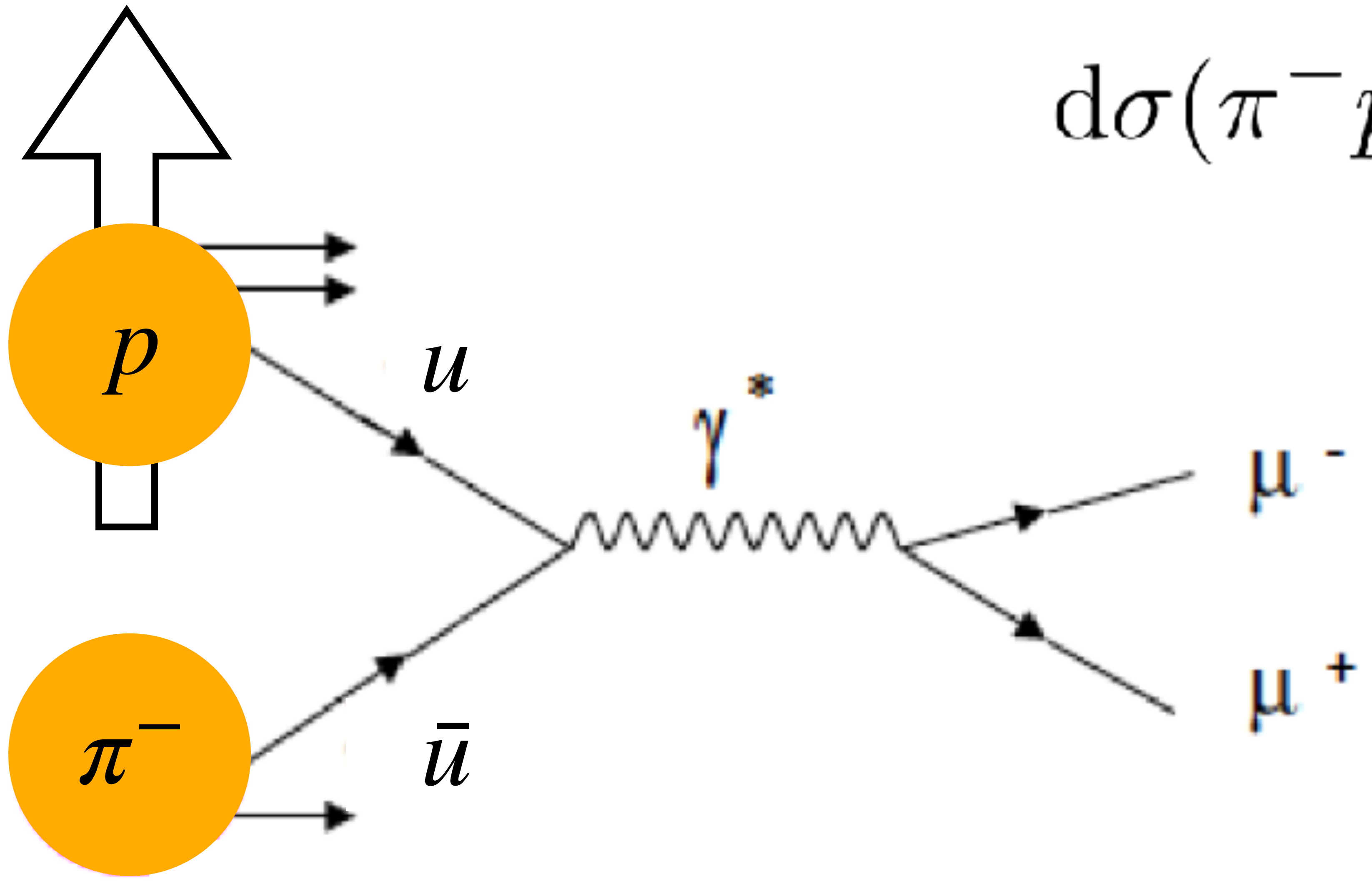
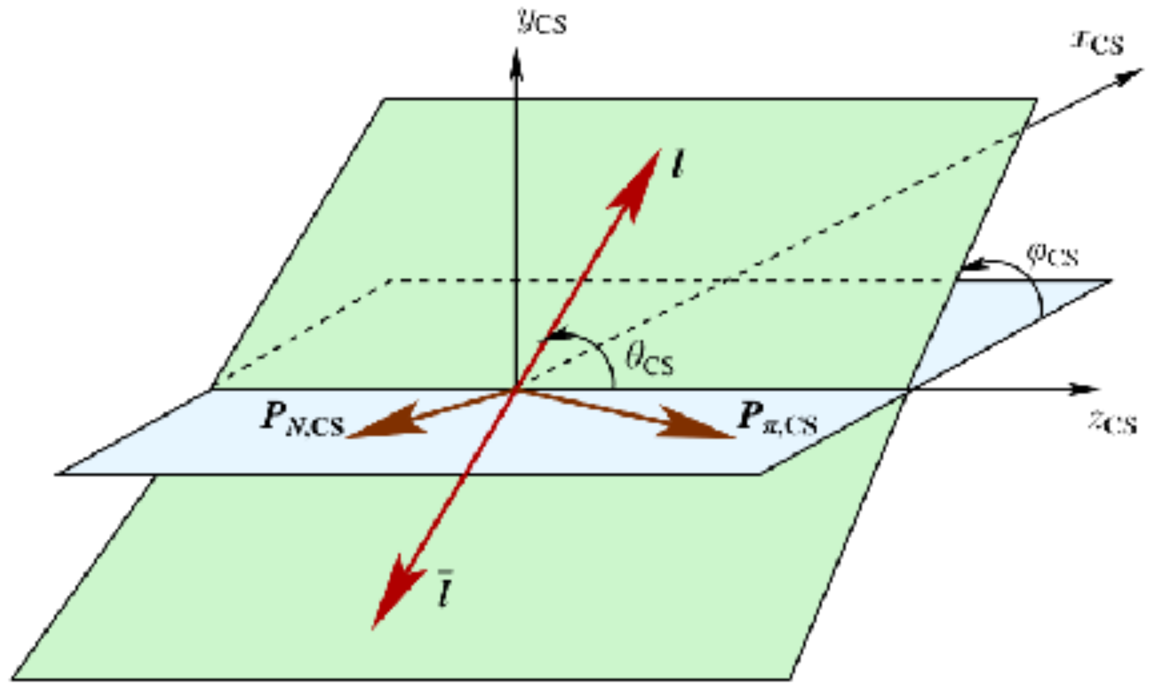
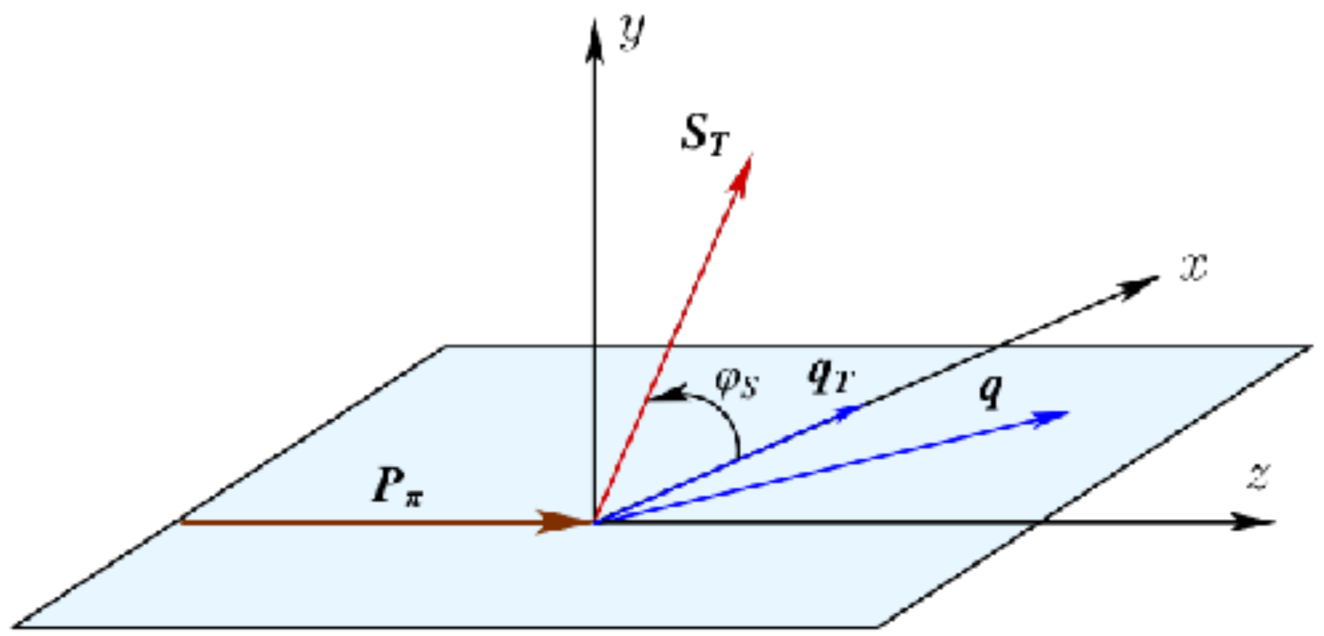


$$
\begin{aligned}
d\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) \sim\ & 1 + \bar{h}_1^\perp \otimes h_1^\perp \cos(2\phi) \\
& + |S_T| \ \bar{f}_1 \otimes f_{1T}^\perp \sin\phi_S \\
& + |S_T| \ \bar{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi + \phi_S) \\
& + |S_T| \ \bar{h}_1^\perp \otimes h_{1T} \sin(2\phi - \phi_S)
\end{aligned}
$$





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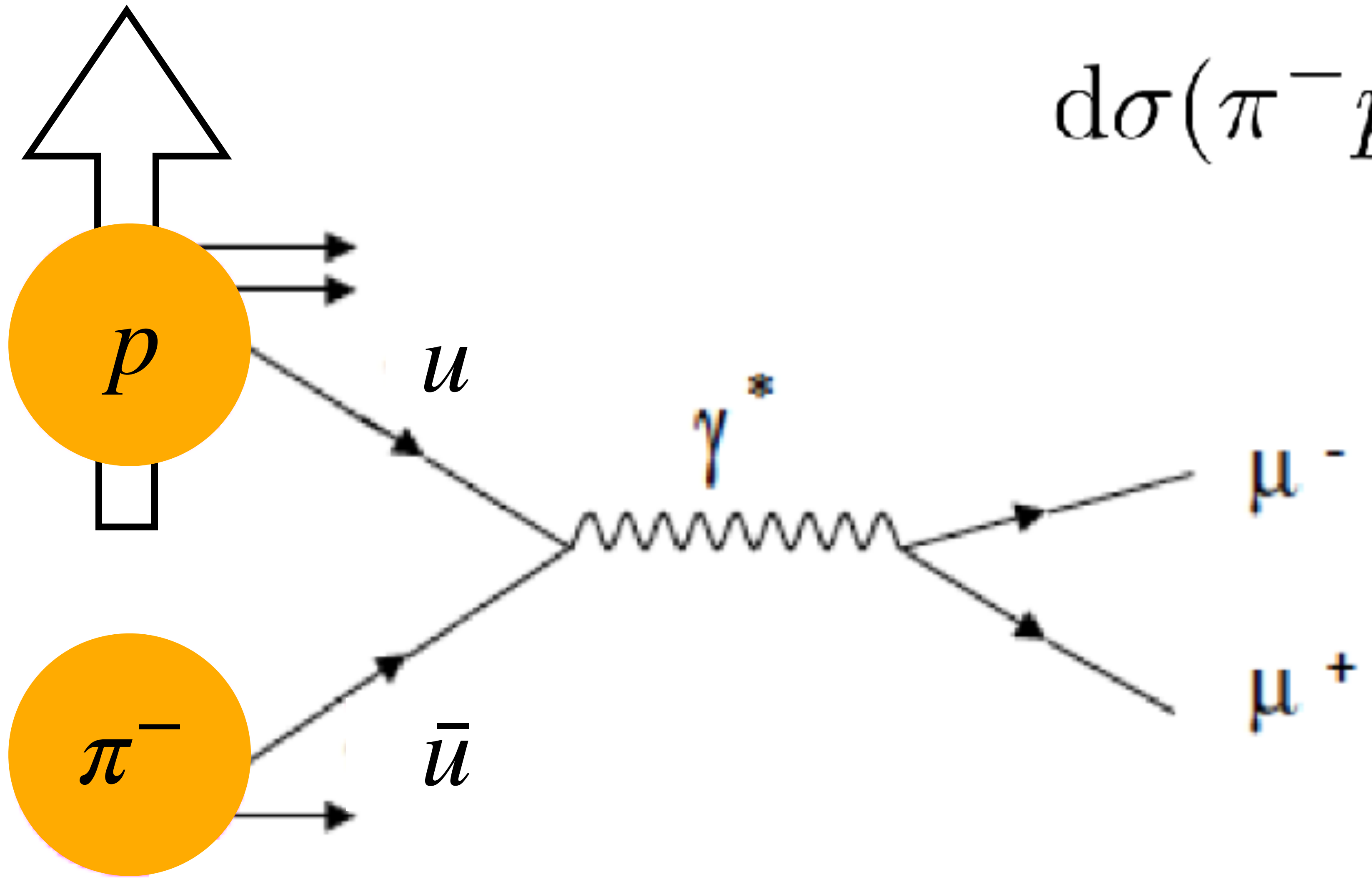

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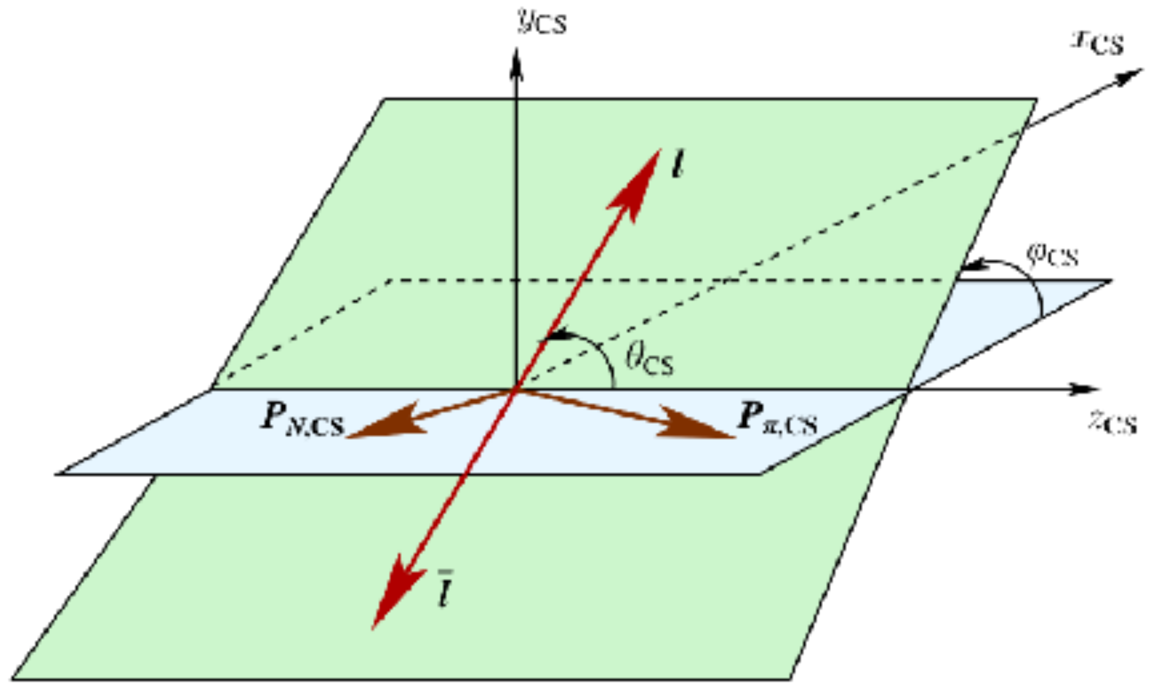
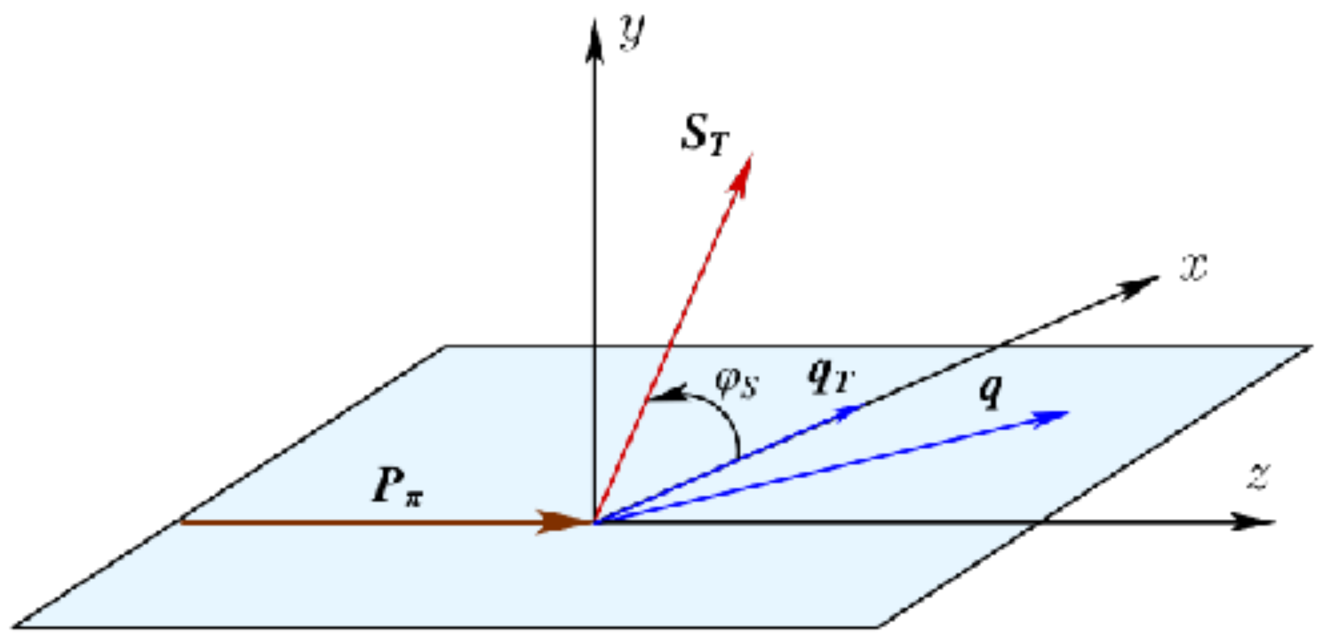
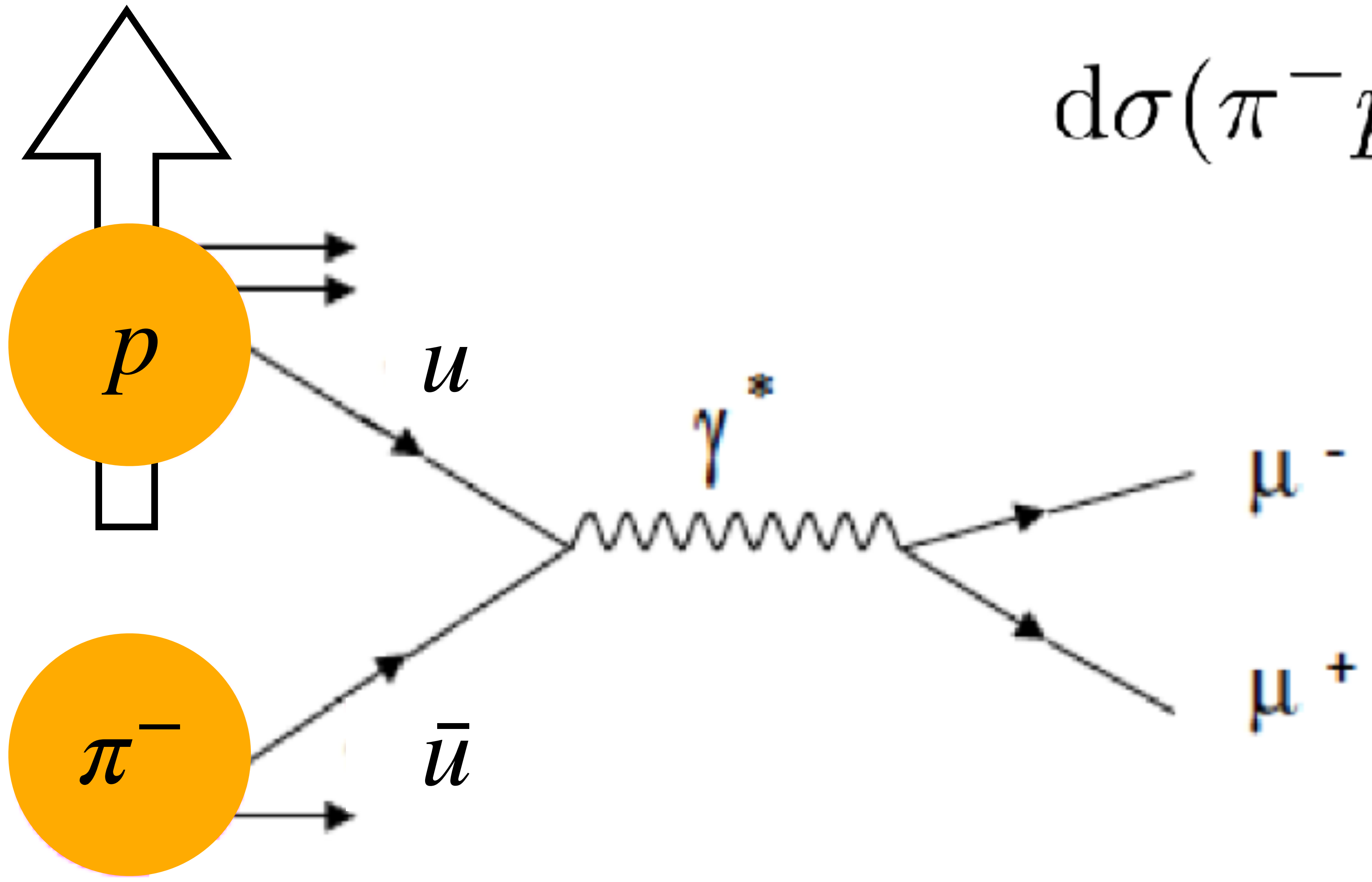
$$

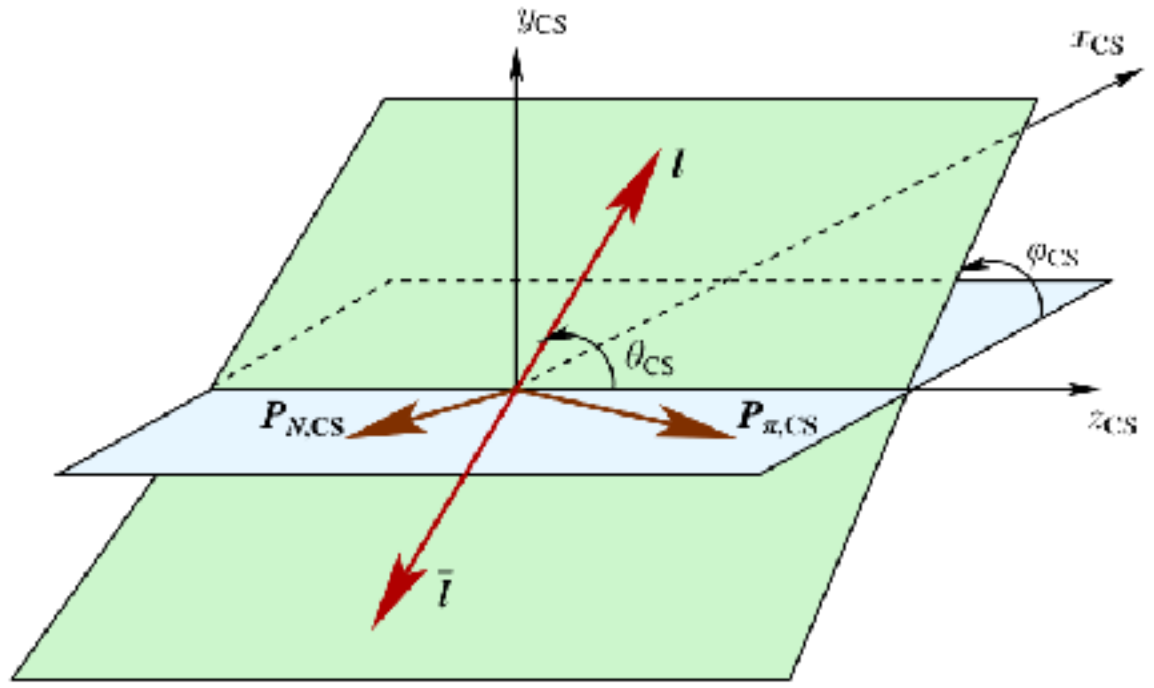


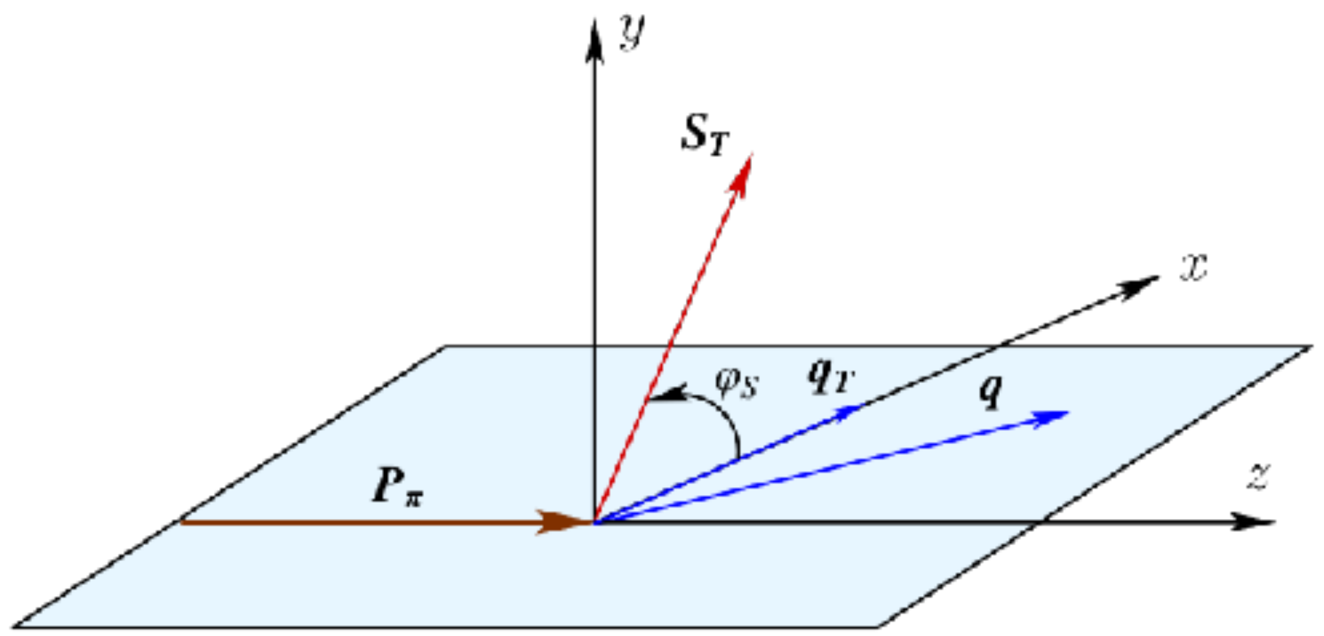


Experimental access to Sivers in Drell-Yan



$$
\begin{aligned}
d\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) \sim\; & 1 + \bar{h}_1^\perp \otimes h_1^\perp \cos(2\phi) \\
& + |S_T|\; \bar{f}_1 \otimes f_{1T}^\perp \sin\phi_S \\
& + |S_T|\; \bar{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi + \phi_S) \\
& + |S_T|\; \underbrace{\bar{h}_1^\perp}_{\pi^-} \otimes \underbrace{h_{1T}}_{p} \sin(2\phi - \phi_S)
\end{aligned}
$$





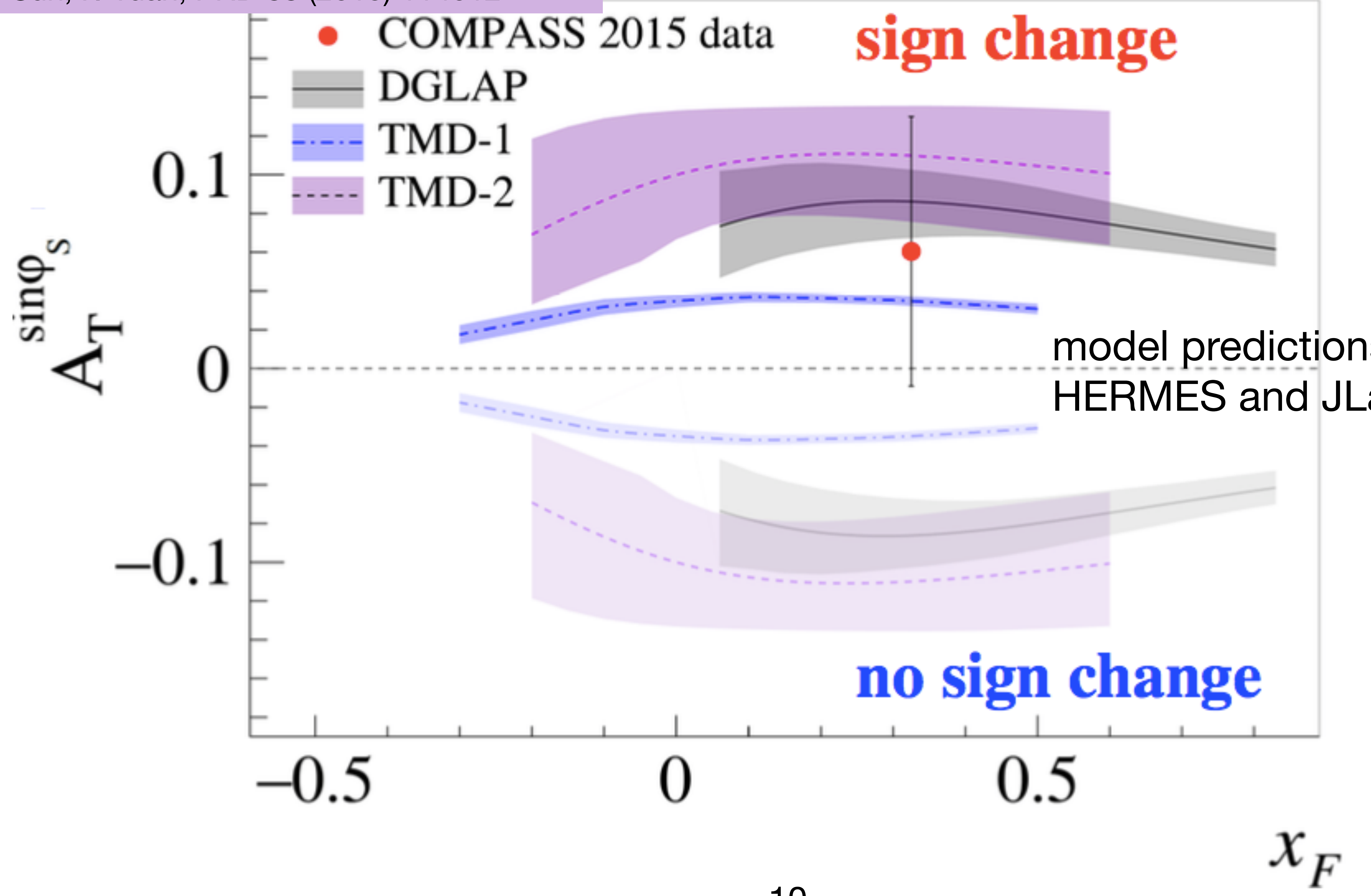
Investigation of the Sivers sign change in $p^{\uparrow}\pi^{-}$ collisions

M. Anselmino et al., JHEP **04** (2017) 046

M. G. Echevarria et al. PRD **89** (2014)074013

P. Sun, F. Yuan, PRD **88** (2013) 114012

COMPASS, PRL **119** (2017) 112002



model predictions based on COMPASS, HERMES and JLab semi-inclusive DIS data

Investigation of the Sivers sign change in $p^{\uparrow}\pi^{-}$ collisions

M. Anselmino et al., JHEP **04** (2017) 046

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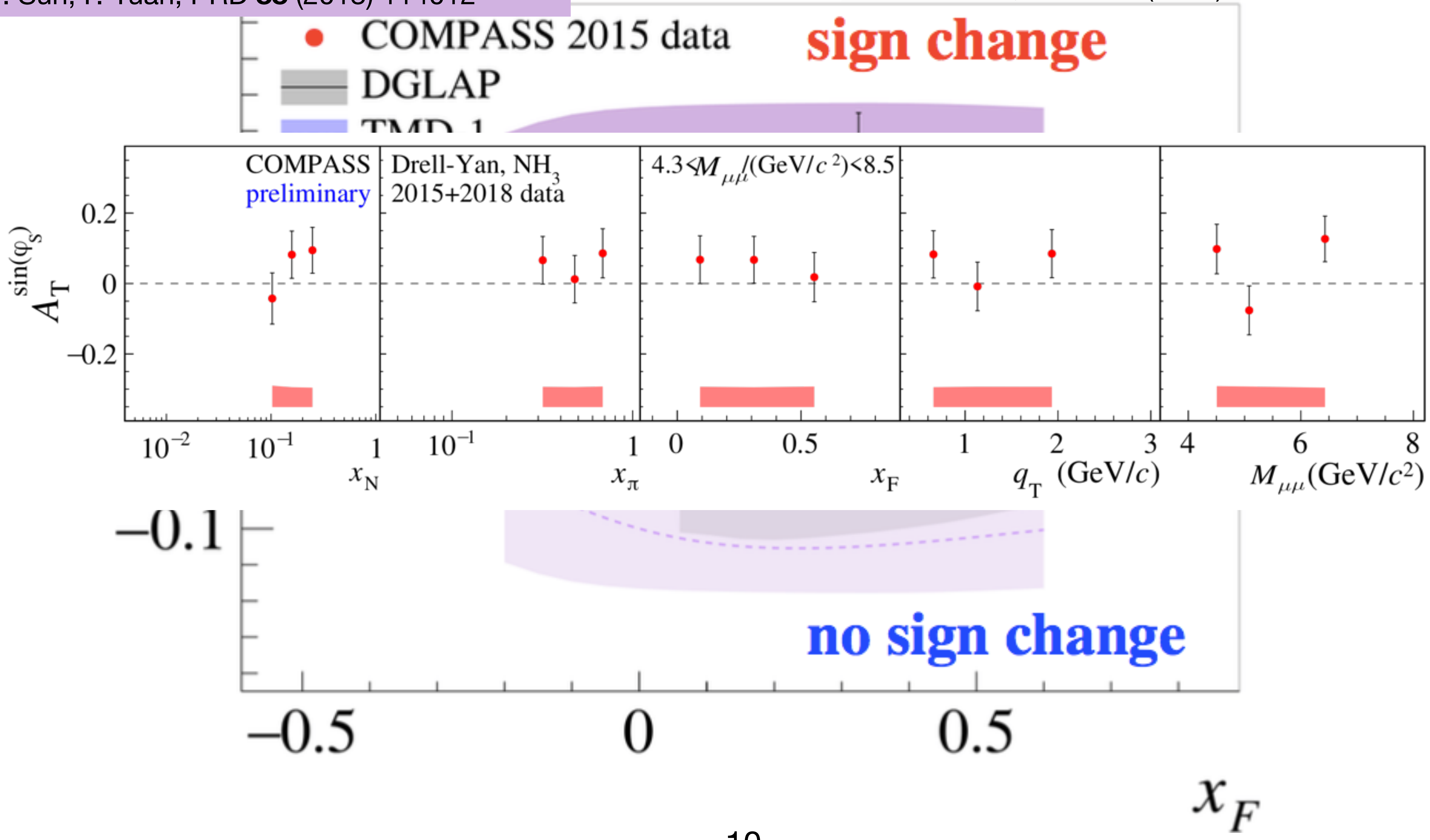
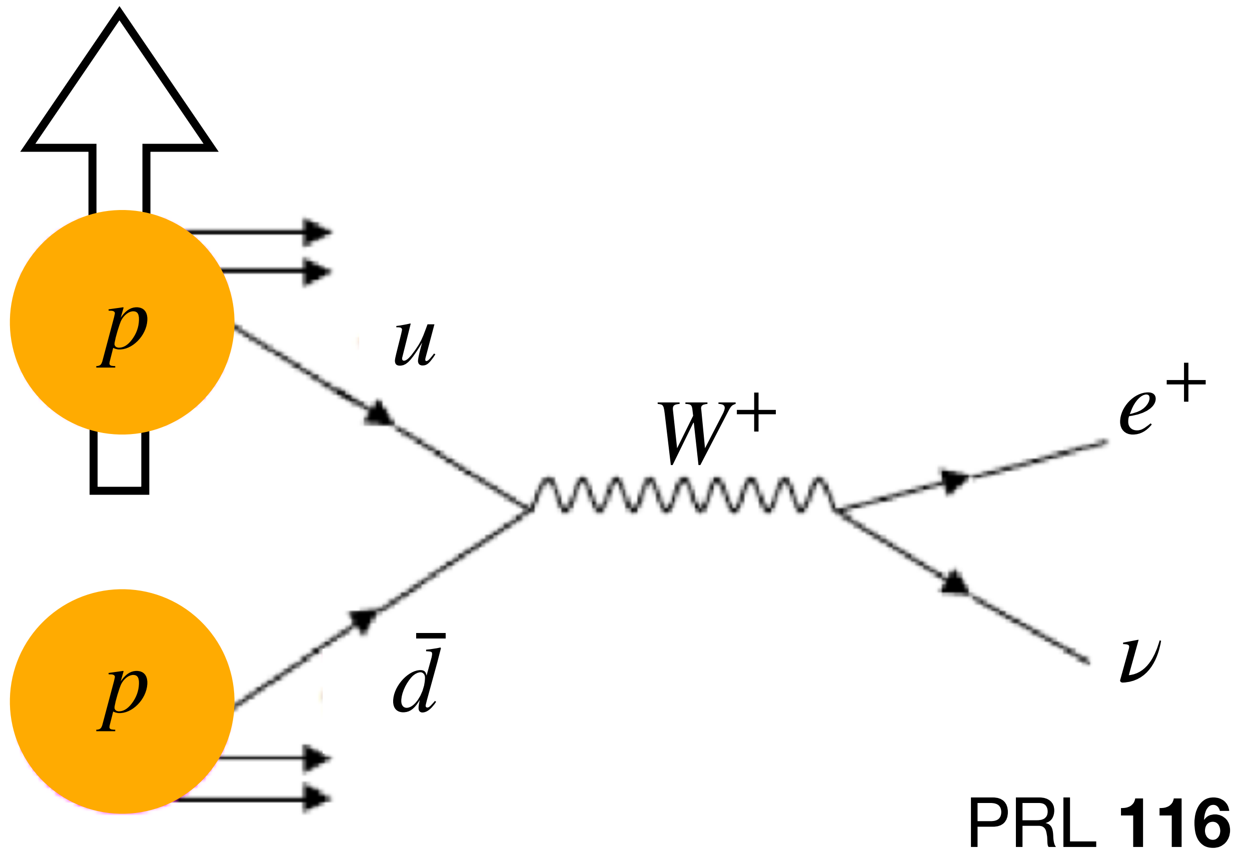
COMPASS, PRL **119** (2017) 112002

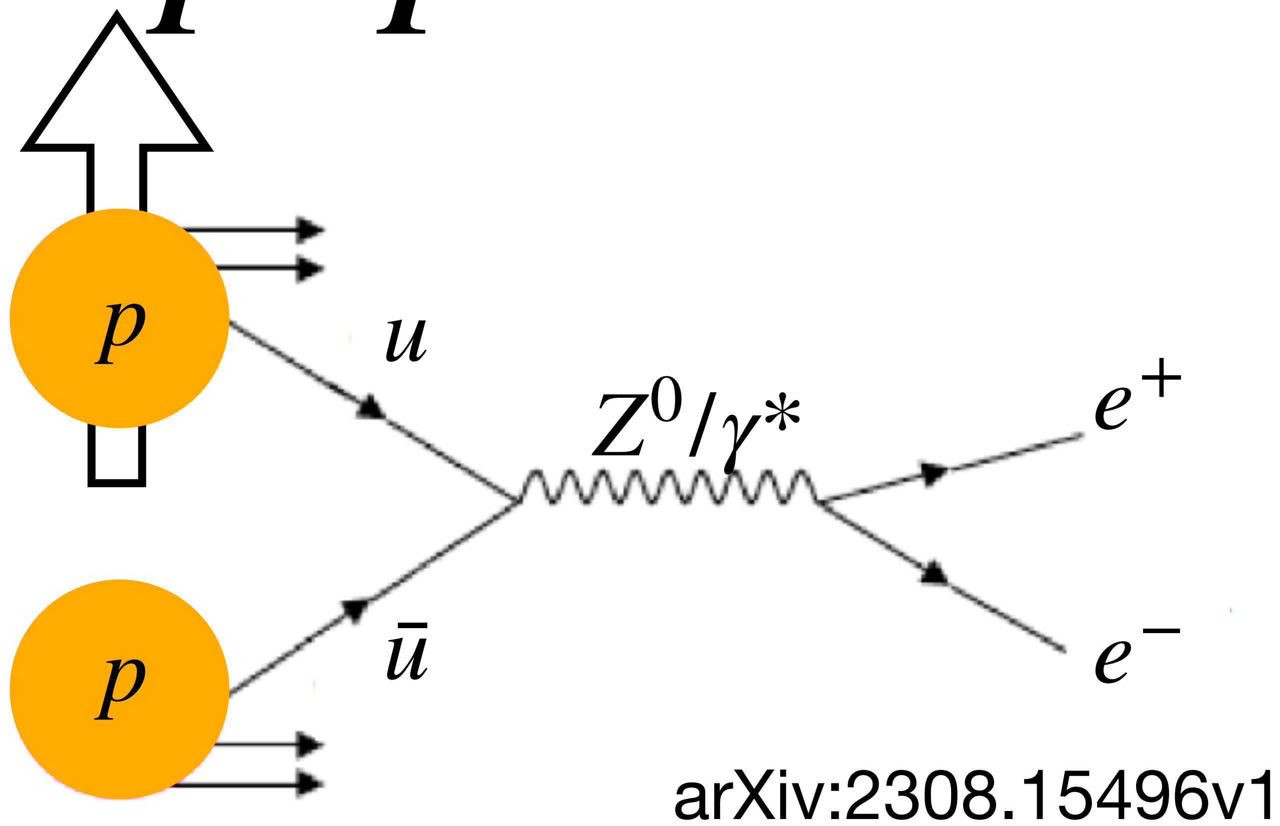


on COMPASS,

inclusive DIS data

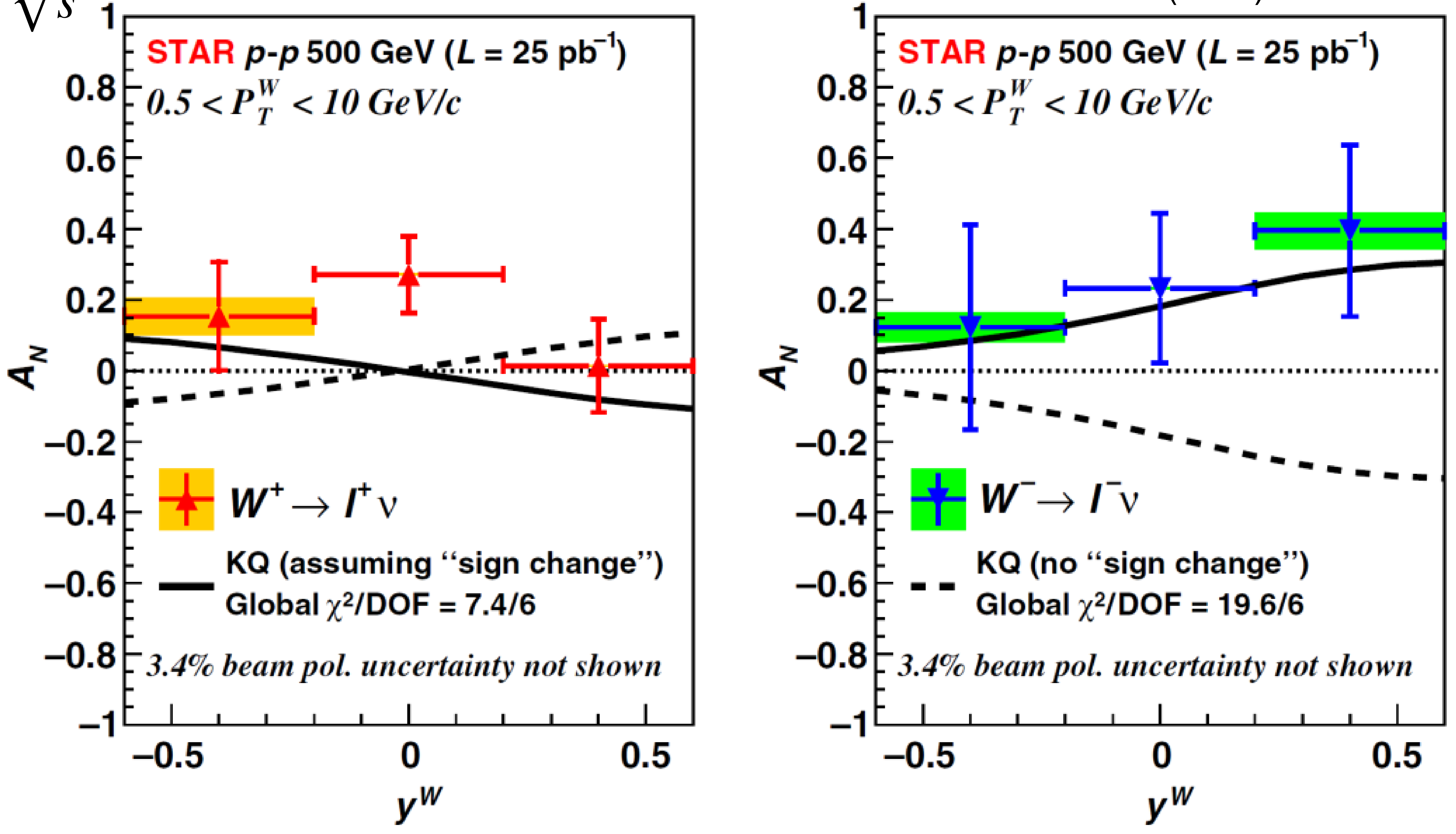
Investigation of the Sivers sign change in $p^{\uparrow}p$ collisions



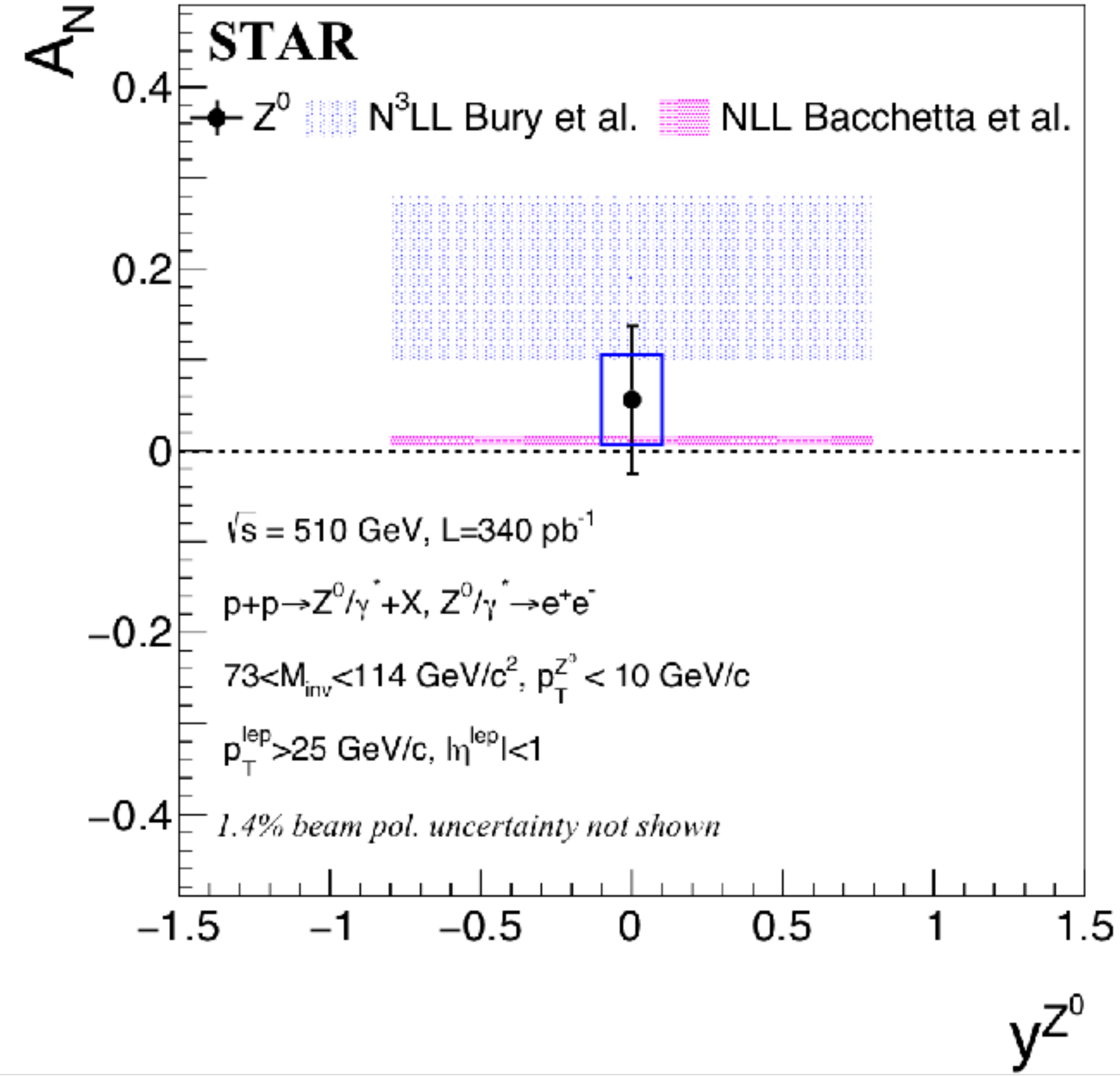


$$x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y}$$

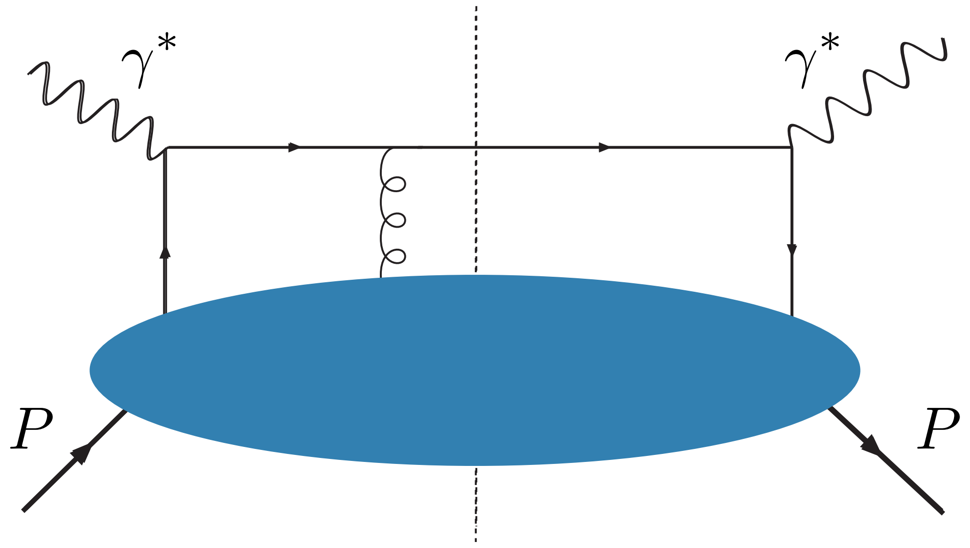
PRL **116** (2016) 132301



arXiv:2308.15496v1

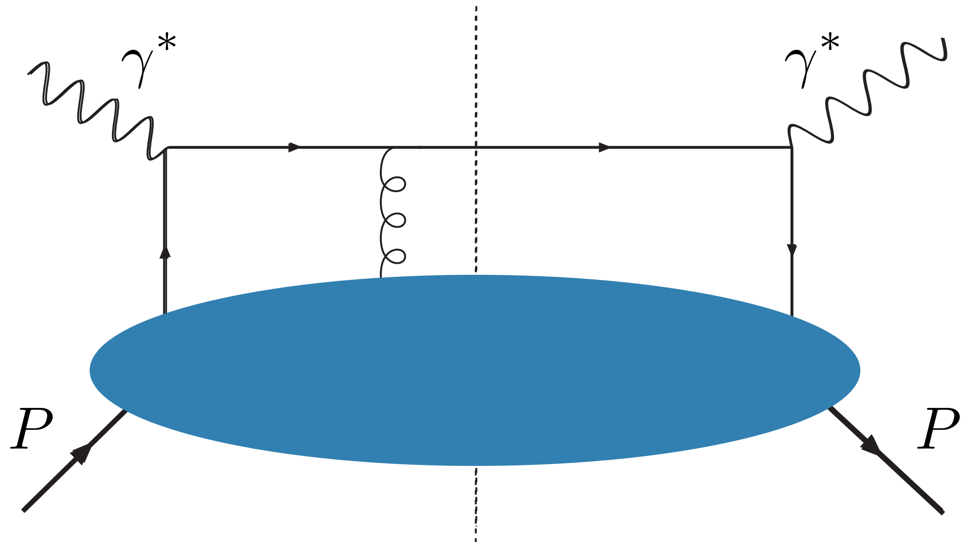


Twist-3: $\langle\sin(\phi)\rangle_{LU}^{h}$



$$\langle\sin(\phi)\rangle_{LU}^{h} \propto \mathcal{C}\left[h_1^{\perp} \times \tilde{E}, e \times H_1^{\perp}, g^{\perp} \times D_1, f_1 \times \tilde{G}^{\perp}\right]$$

Twist-3: $\langle \sin(\phi) \rangle_{LU}^{h}$

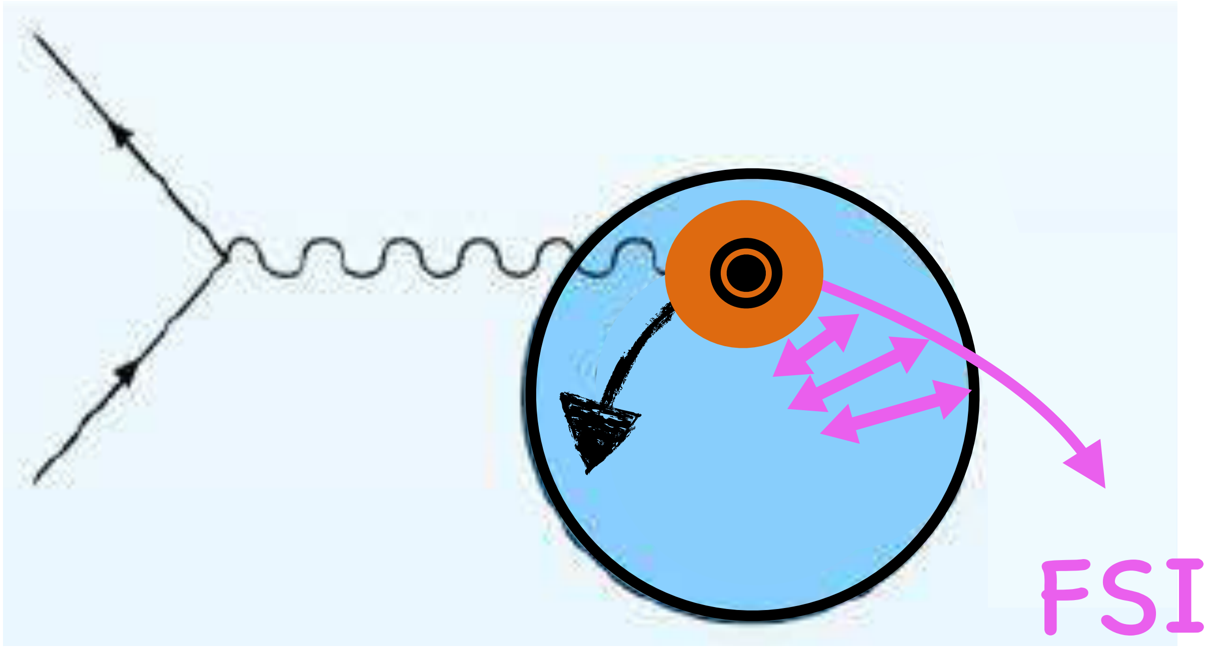


$$\langle \sin(\phi) \rangle_{LU}^{h} \propto \mathcal{C}\left[h_1^{\perp} \times \tilde{E}, e \times H_1^{\perp}, g^{\perp} \times D_1, f_1 \times \tilde{G}^{\perp}\right]$$

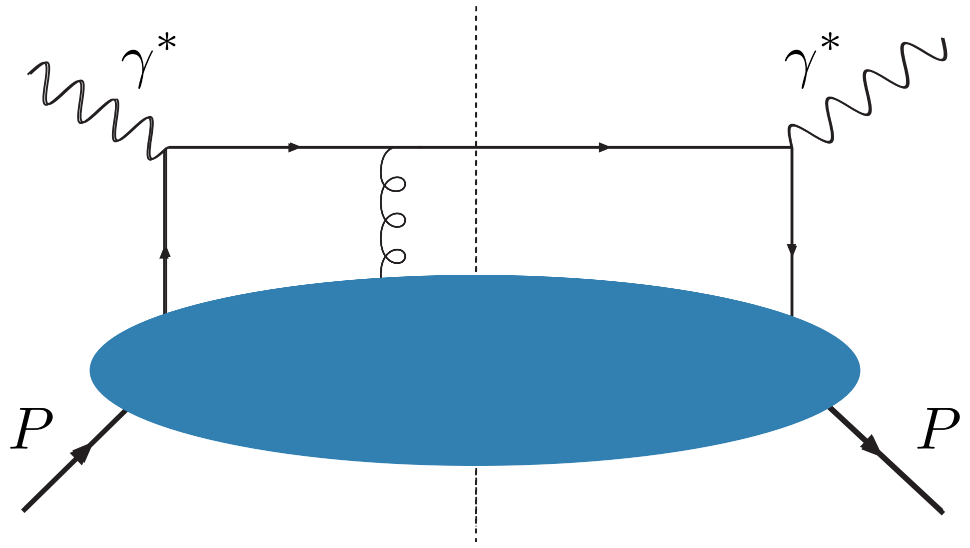
Boer-Mulders PDF

Chiral-odd T-even twist-3 FF

Boer-Mulders PDF



Twist-3: $\langle \sin(\phi) \rangle^{h}_{LU}$

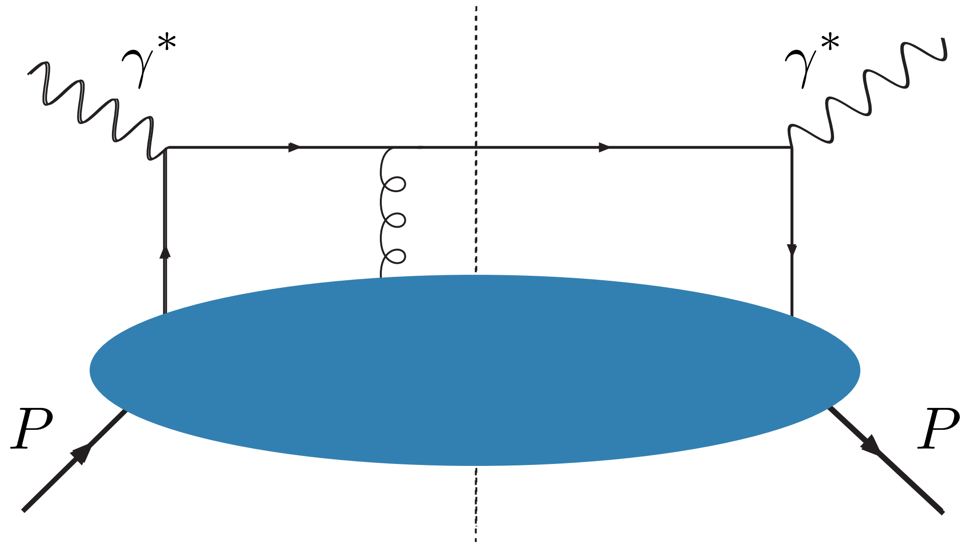


$$\langle \sin(\phi) \rangle^{h}_{LU} \propto \mathcal{C}\left[h_1^{\perp} \times \tilde{E}, e \times H_1^{\perp}, g^{\perp} \times D_1, f_1 \times \tilde{G}^{\perp}\right]$$

Chiral-odd T-even twist-3 PDF

Collins FF

Twist-3: $\langle \sin(\phi) \rangle^h_{LU}$



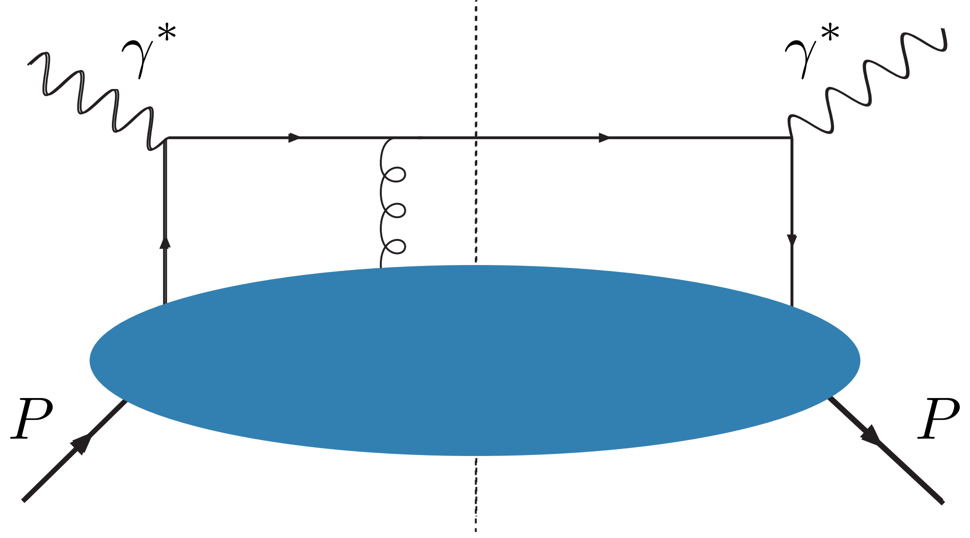
$$\langle \sin(\phi) \rangle^h_{LU} \propto \mathcal{C}\left[h_1^\perp \times \tilde{E}, e \times H_1^\perp, g^\perp \times D_1, f_1 \times \tilde{G}^\perp\right]$$

Chiral-odd T-even twist-3 PDF

Collins FF

$$e(x) = e^{\mathrm{WW}}(x) + \bar{e}(x)$$

Twist-3: $\langle \sin(\phi) \rangle_{LU}^{h}$



$$\langle \sin(\phi) \rangle_{LU}^{h} \propto \mathcal{C}\left[h_1^{\perp} \times \tilde{E}, e \times H_1^{\perp}, g^{\perp} \times D_1, f_1 \times \tilde{G}^{\perp}\right]$$

Chiral-odd T-even twist-3 PDF

Collins FF

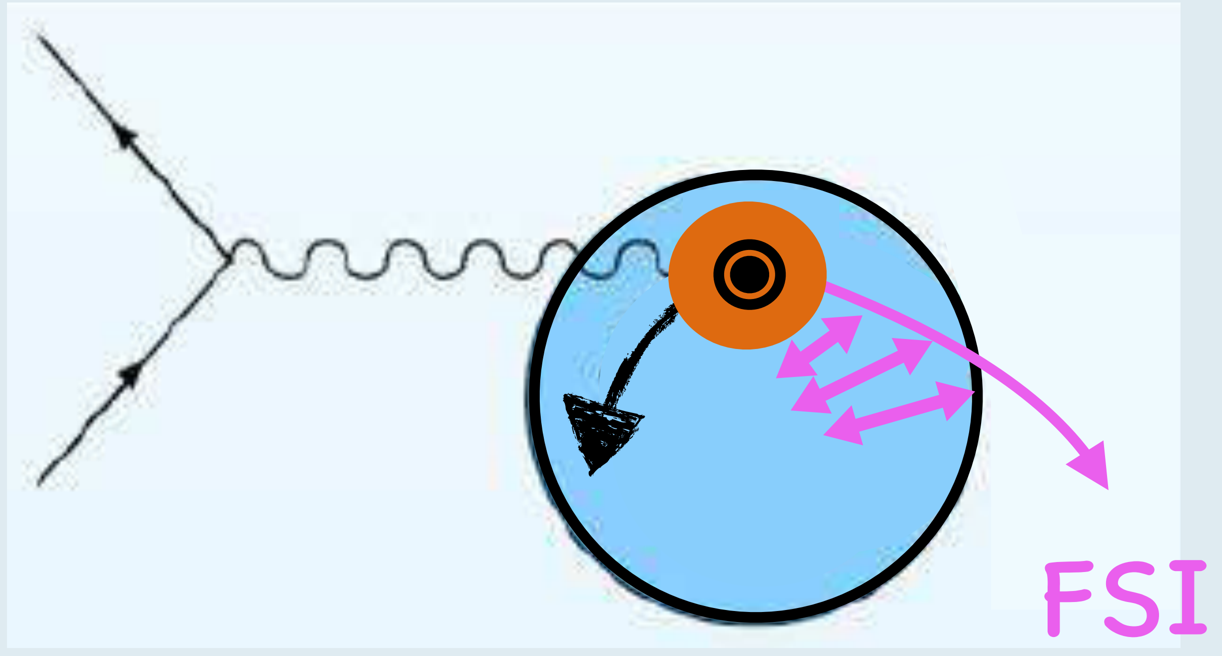
$$e(x) = e^{\mathrm{WW}}(x) + \bar{e}(x)$$

$$e_2 \equiv \int_0^1 dx\, x^2 \bar{e}(x)$$

→ force on struck quark at t=0

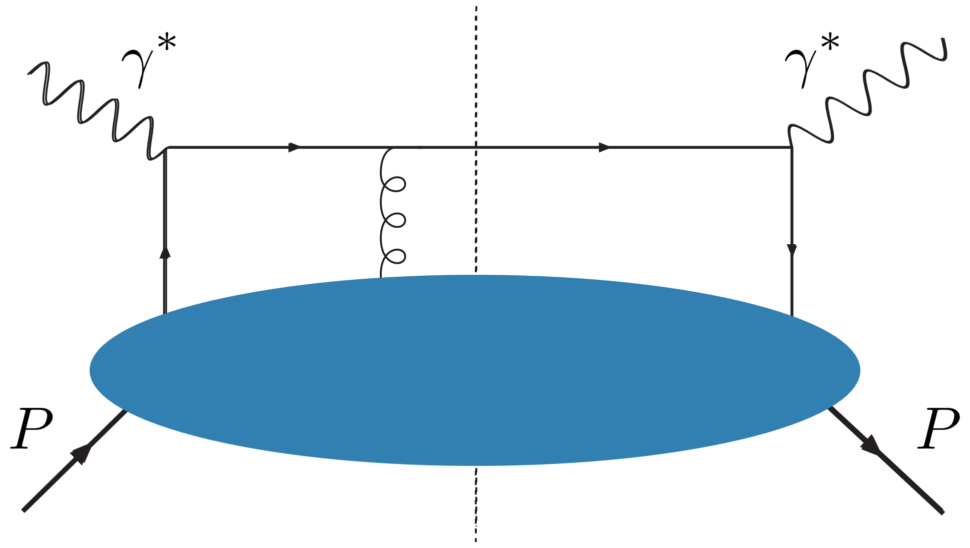
M. Burkardt, arXiv:0810.3589

Boer-Mulders PDF



FSI: t=0→∞

Twist-3: $\langle \sin(\phi) \rangle^h_{LU}$

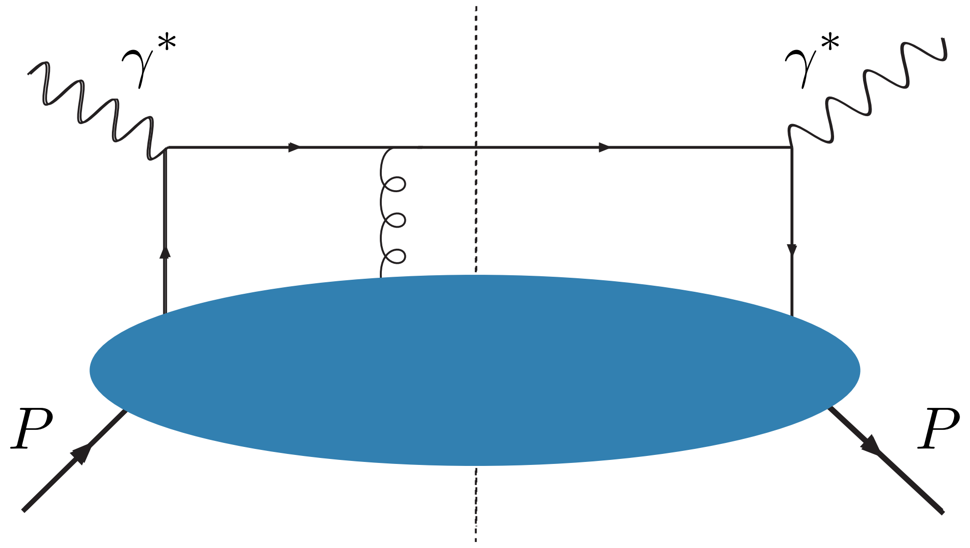


$$\langle \sin(\phi) \rangle^h_{LU} \propto \mathcal{C}\left[h_1^\perp \times \tilde{E}, e \times H_1^\perp, g^\perp \times D_1, f_1 \times \tilde{G}^\perp\right]$$

Chiral-even T-odd twist-3 PDF

spin-independent FF

Twist-3: $\langle \sin(\phi) \rangle_{LU}^{h}$



$$\langle \sin(\phi) \rangle_{LU}^{h} \propto \mathcal{C}\left[h_1^{\perp} \times \tilde{E}, e \times H_1^{\perp}, g^{\perp} \times D_1, f_1 \times \tilde{G}^{\perp}\right]$$

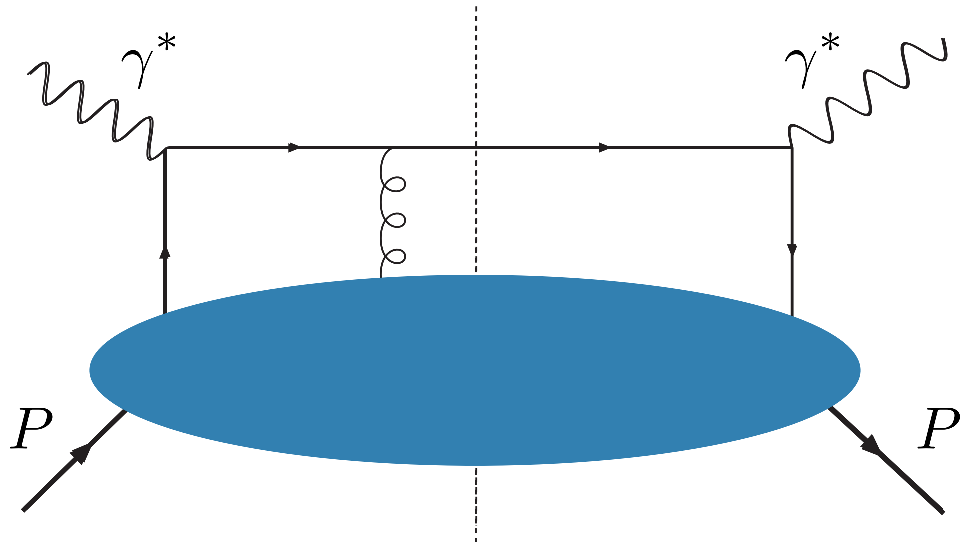
Chiral-even T-odd twist-3 PDF

spin-independent FF

Only term to survive in TMD single-jet inclusive DIS

$$e + p \rightarrow e' + \mathrm{jet} + X$$

Twist-3: $\langle\sin(\phi)\rangle^h_{LU}$

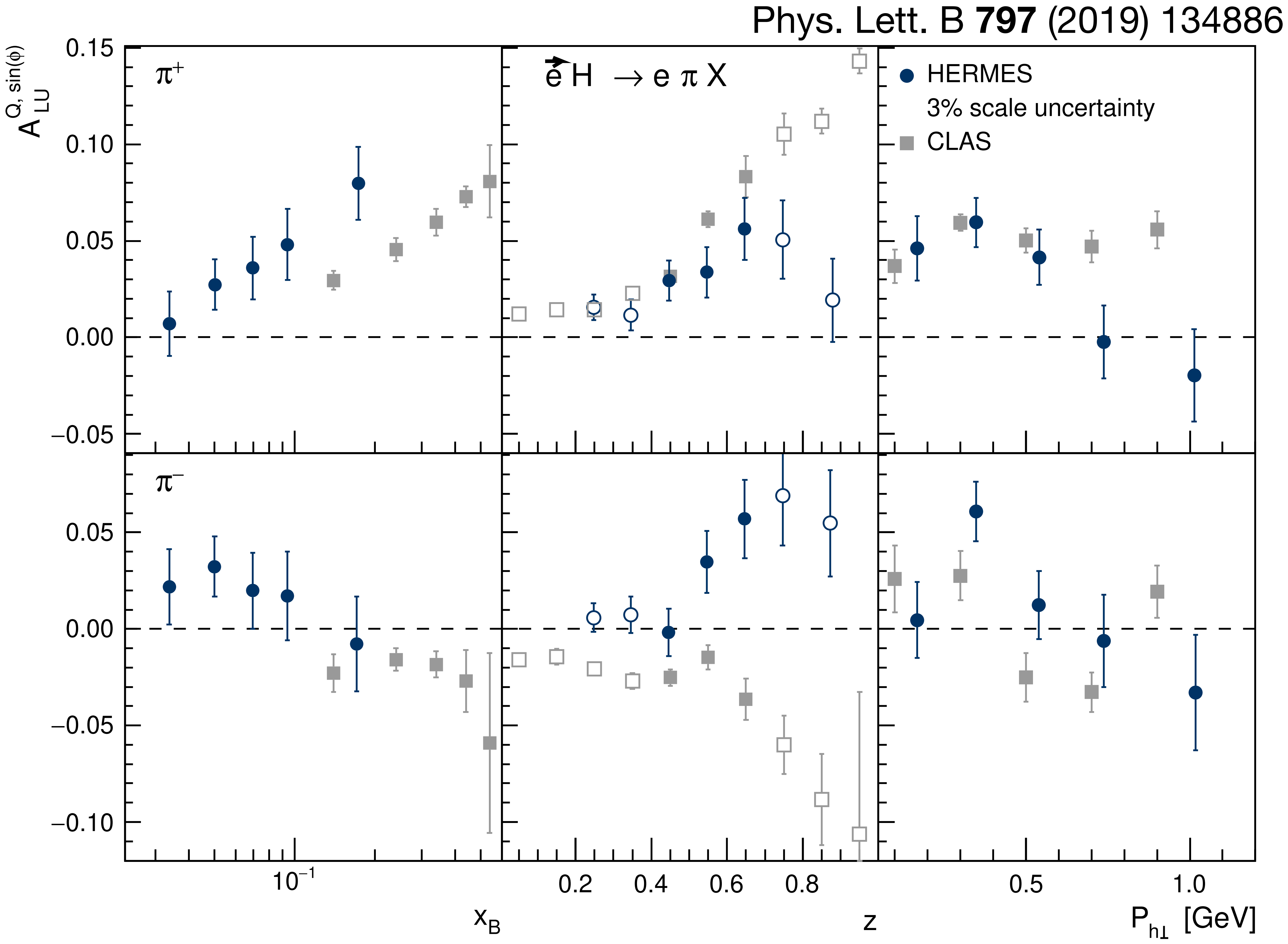


$$\langle\sin(\phi)\rangle^h_{LU} \propto \mathcal{C}\left[h_1^\perp \times \tilde{E}, e \times H_1^\perp, g^\perp \times D_1, f_1 \times \tilde{G}^\perp\right]$$

spin-independent PDF

chiral-even, T-odd twist-3 FF

Twist-3: $\langle \sin(\phi) \rangle^h_{LU}$

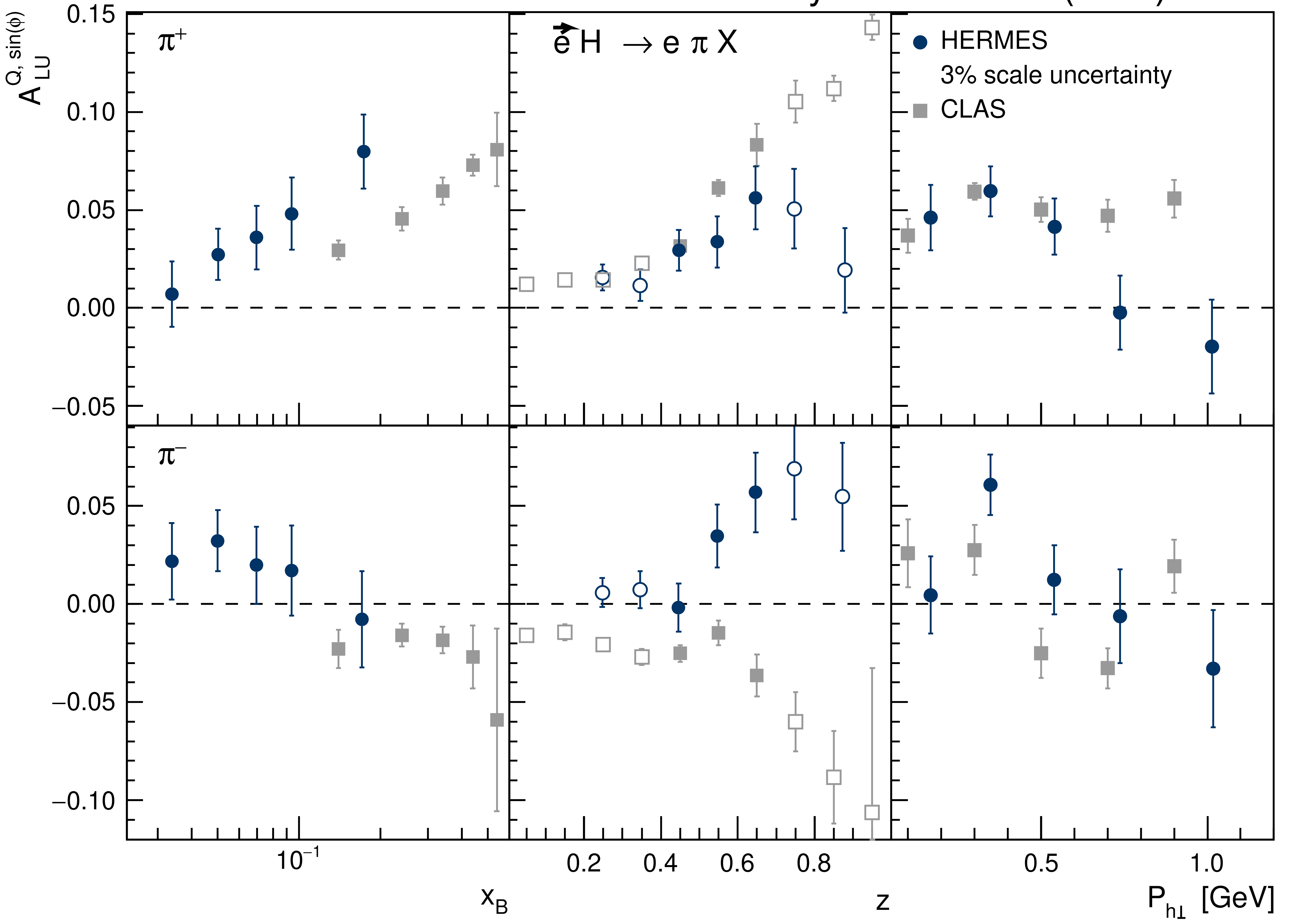


- Opposite behaviour for π^- z projection due to different x range probed
- CLAS probes higher x region: more sensitive to $e \times H_1^\perp$?

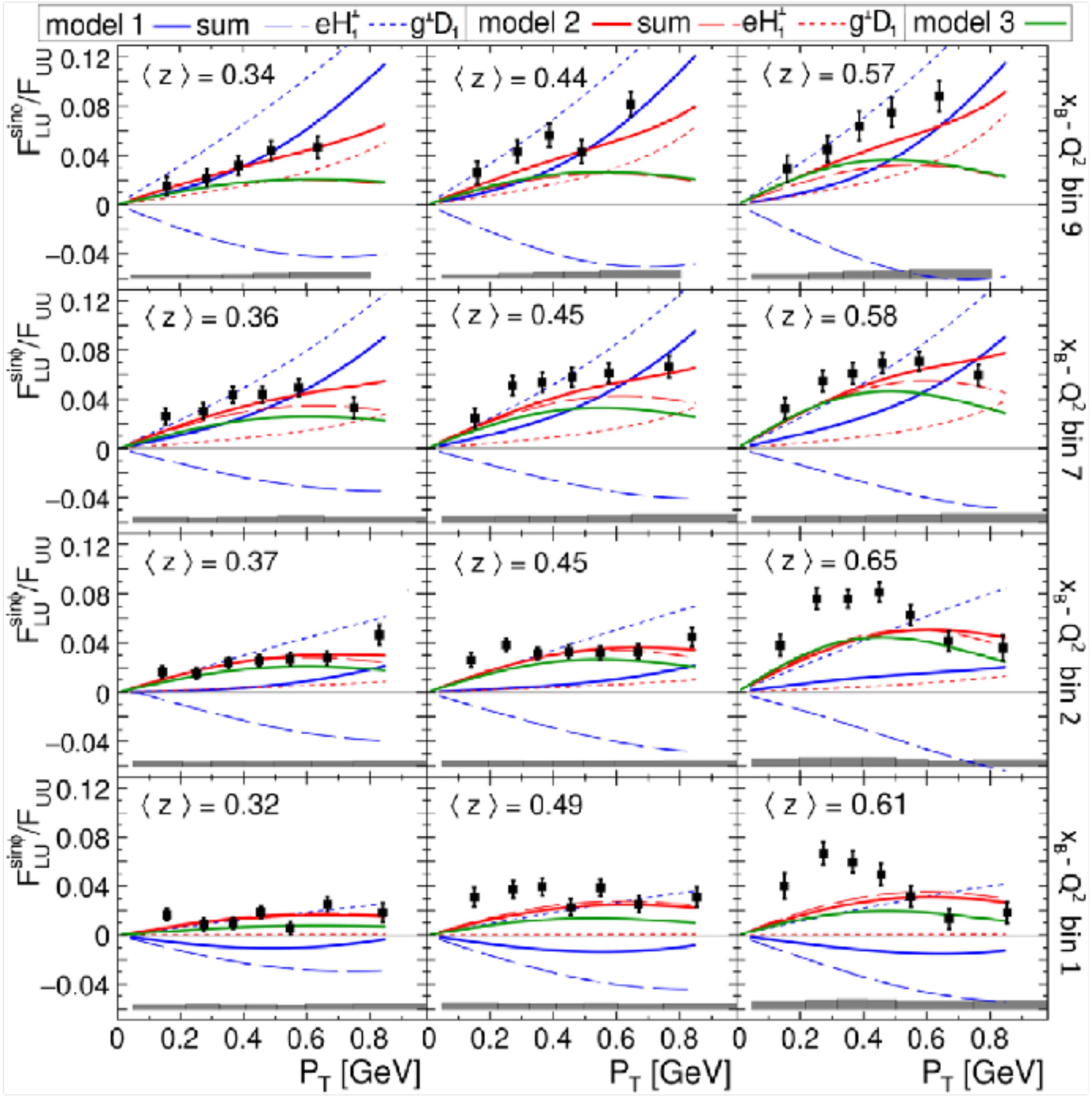
$$\langle \sin(\phi) \rangle^h_{LU} \propto \mathcal{C}\left[h_1^\perp \times \tilde{E}, \boxed{x\, e \times H_1^\perp}, x\, g^\perp \times D_1, f_1 \times \tilde{G}^\perp\right]$$

Twist-3: $\langle\sin(\phi)\rangle^h_{LU}$

Phys. Lett. B **797** (2019) 134886



CLAS12, Phys. Rev. Lett. **128** (2022) 062005



- Opposite behaviour for π⁻ z projection due to different x range probed
- CLAS probes higher x region: more sensitive to $e \times H_1^\perp$?

$$\langle\sin(\phi)\rangle^h_{LU} \propto \mathcal{C}\left[h_1^\perp \times \tilde{E}, \boxed{x\, e \times H_1^\perp}, x\, g^\perp \times D_1, f_1 \times \tilde{G}^\perp\right]$$

Gluons

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g,\ h_{1T}^{\perp g}$

- In contrast to quark TMDs,
  gluon TMDs are almost unknown

- Accessible through production of dijets,
  high-P_T hadron pairs, quarkonia

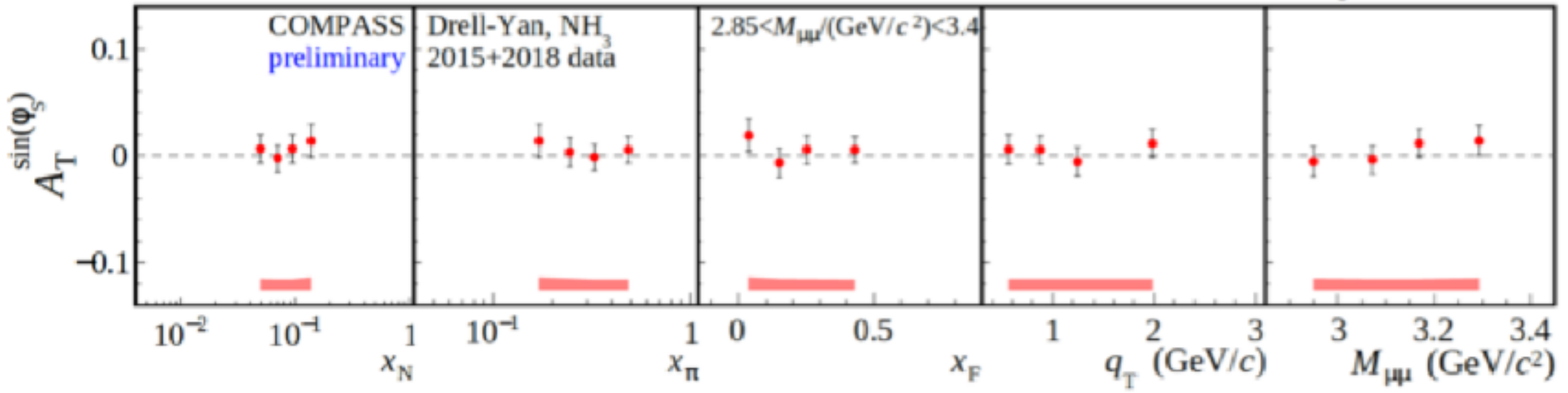
Gluons

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_{1T}^g, $h_{1T}^{\perp g}$

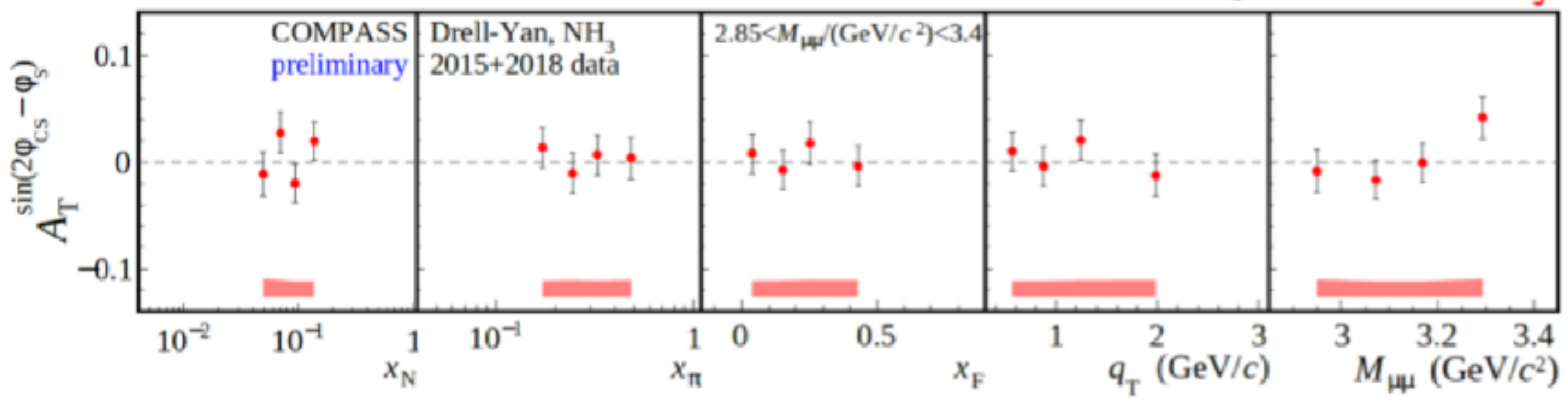
- In contrast to quark TMDs, gluon TMDs are almost unknown
- Accessible through production of dijets, high-P_T hadron pairs, quarkonia

Drell-Yan with lepton pair in J/ψ mass region:
$q\bar{q}$ annihilation or gluon-gluon fusion

Number density⊗Sivers

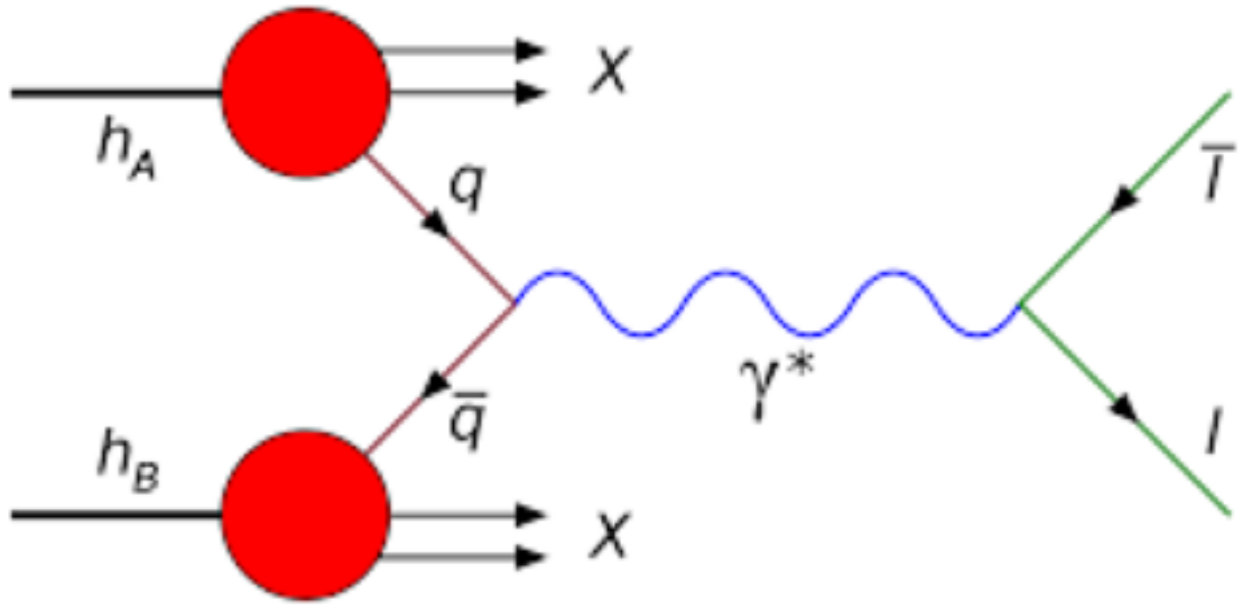


Boer-Mulders⊗Transversity



Upcoming experiments probing TMDs

AMBER
Apparatus for Meson and Baryon
Experimental Research

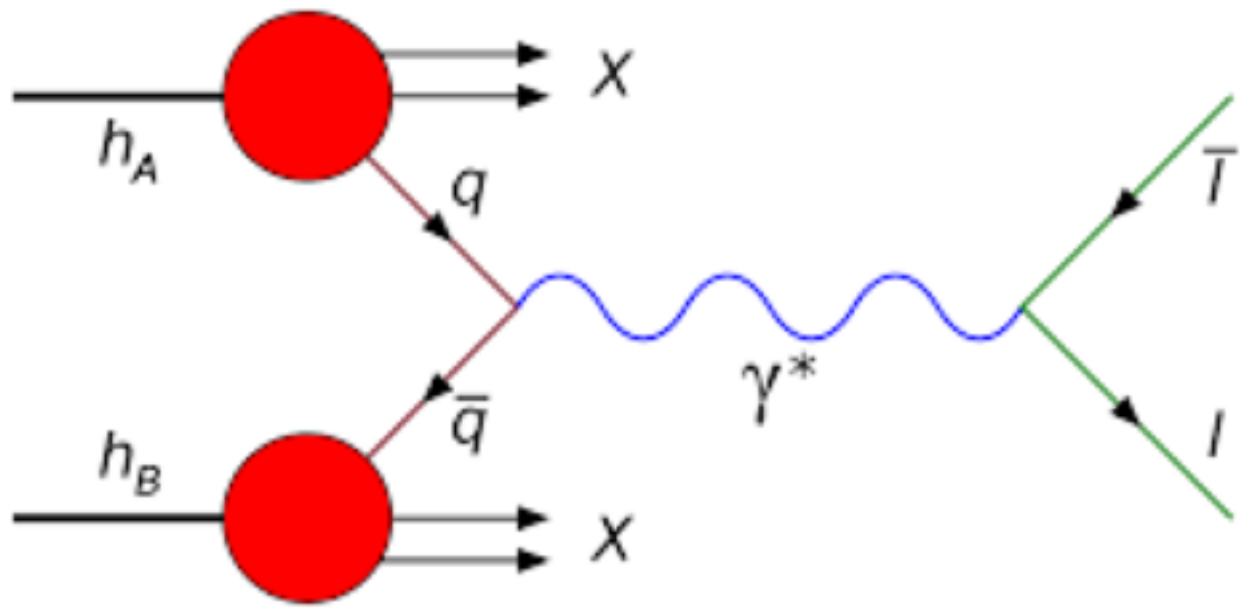


Meson structure

Upcoming experiments probing TMDs

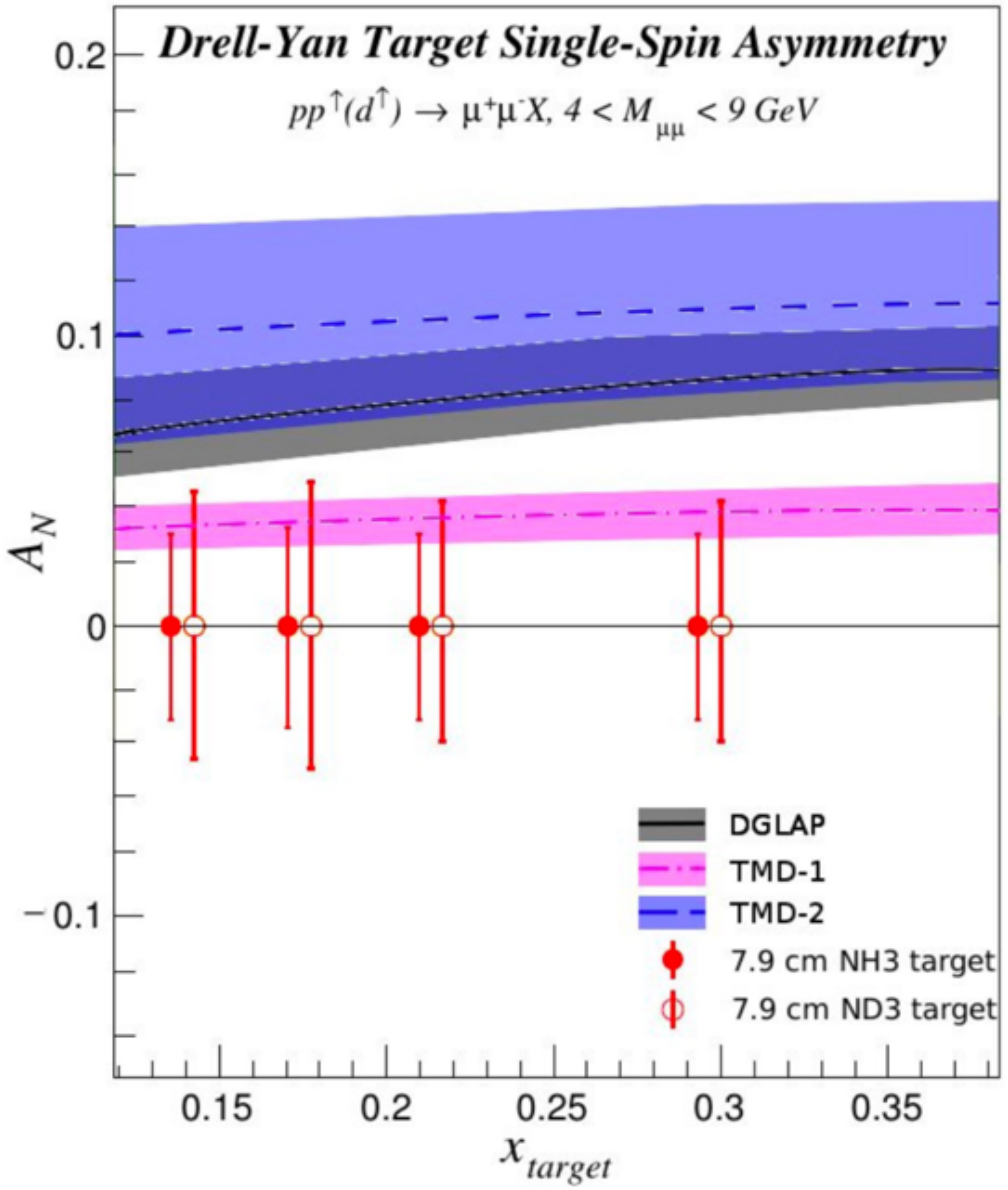
AMBER

Apparatus for Meson and Baryon Experimental Research



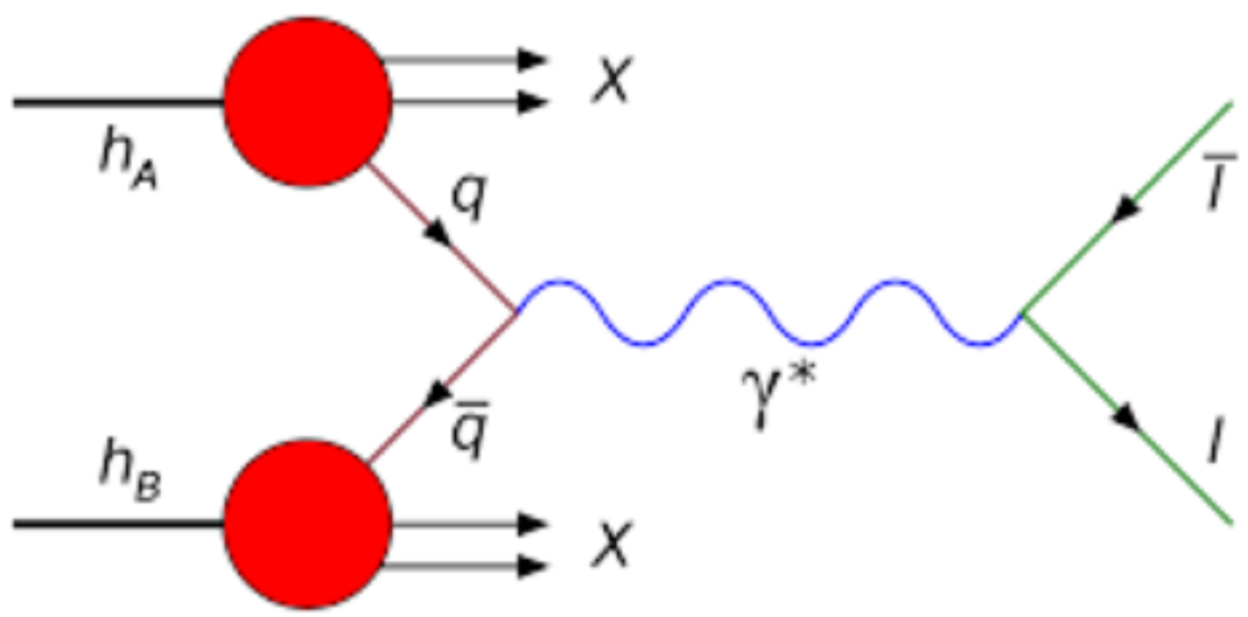
Meson structure

SpinQuest ⟶ Sivers function



Upcoming experiments probing TMDs

Apparatus for Meson and Baryon Experimental Research



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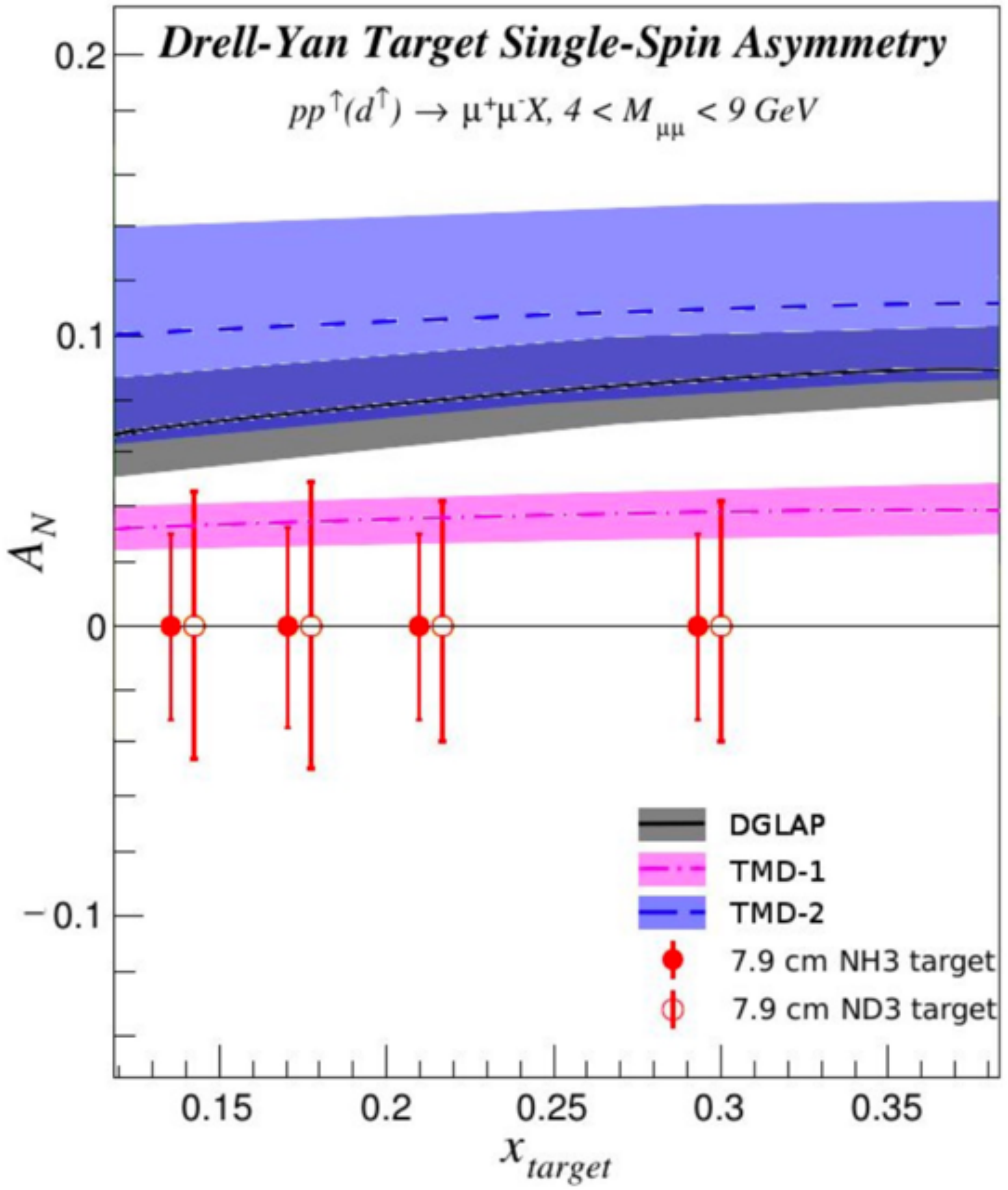
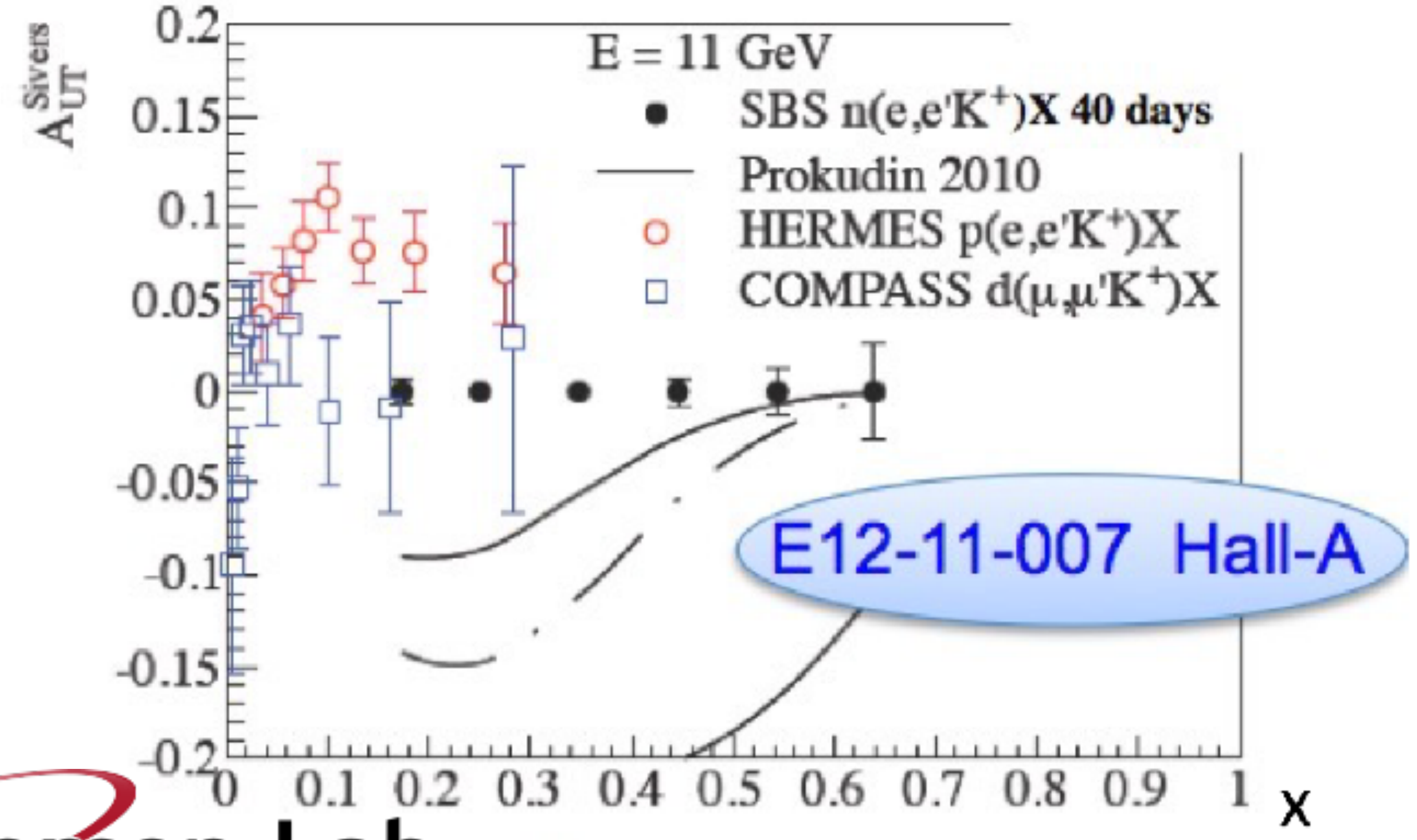
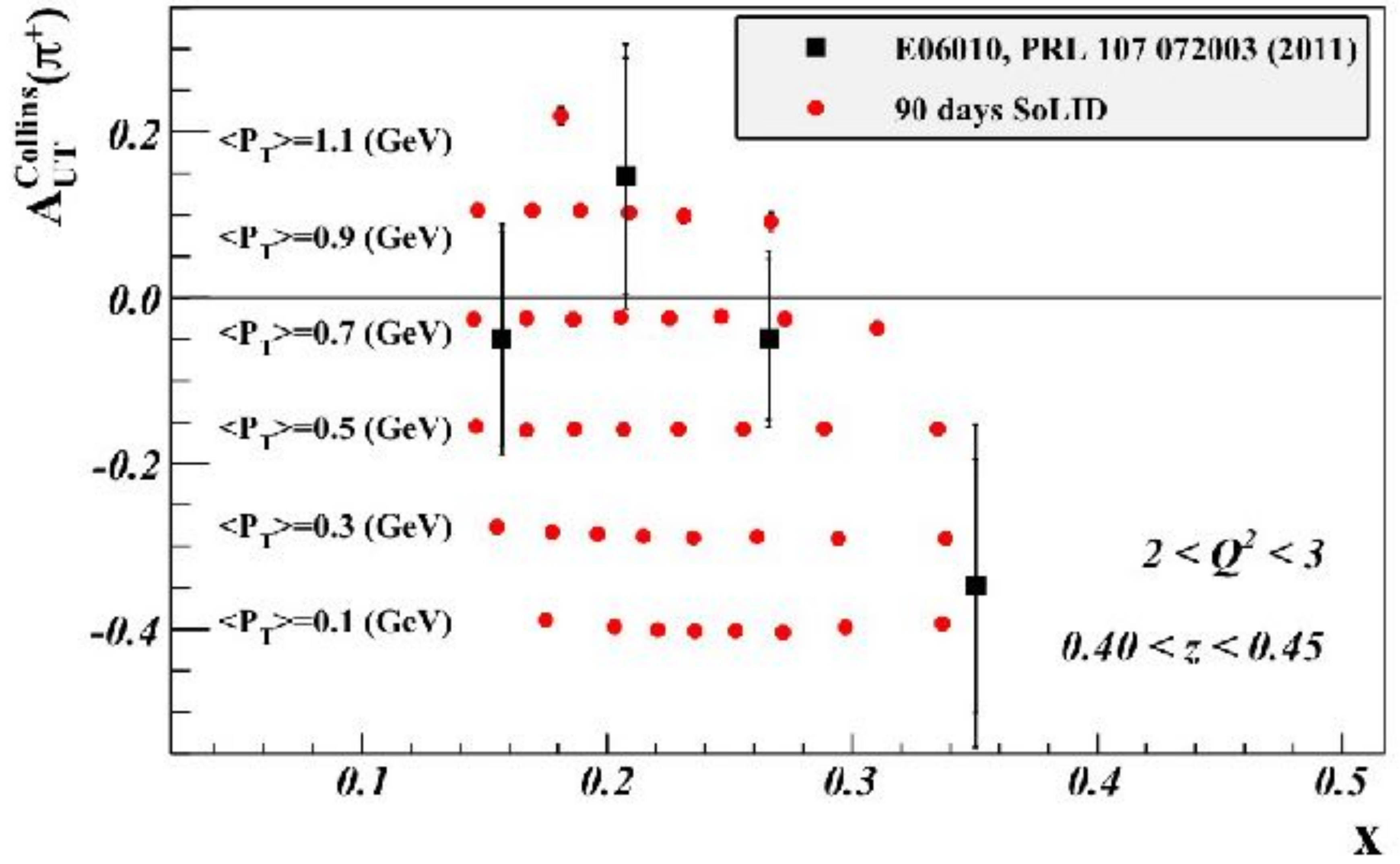




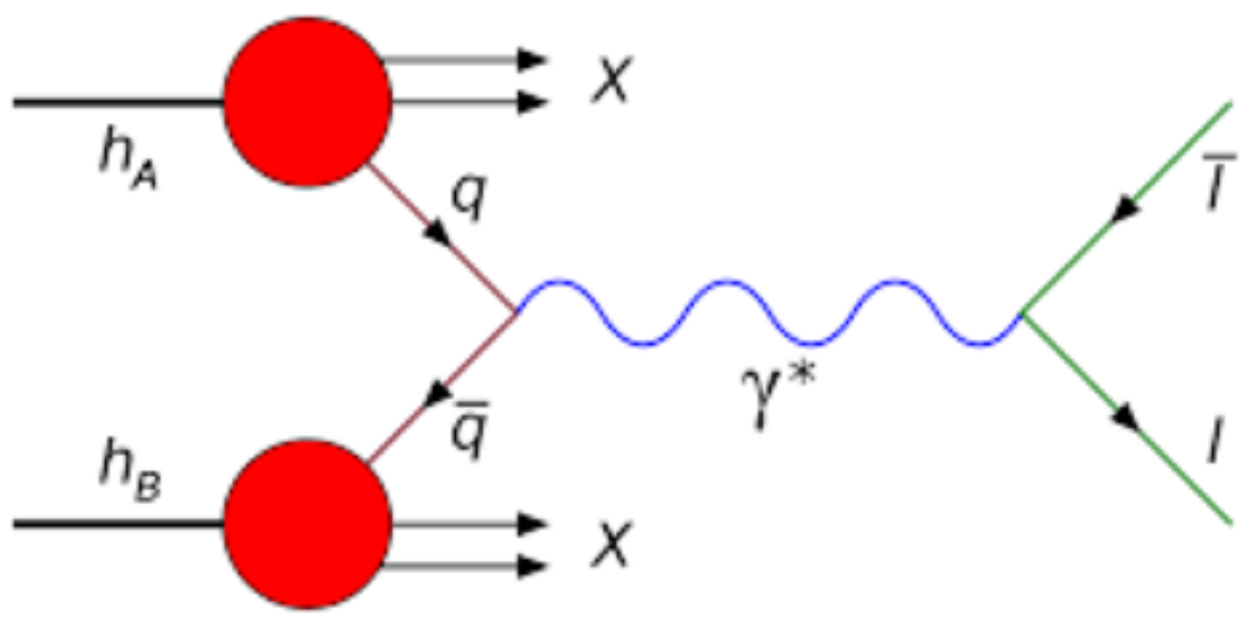
Jefferson Lab



Upcoming experiments probing TMDs

AMBER

Apparatus for Meson and Baryon Experimental Research



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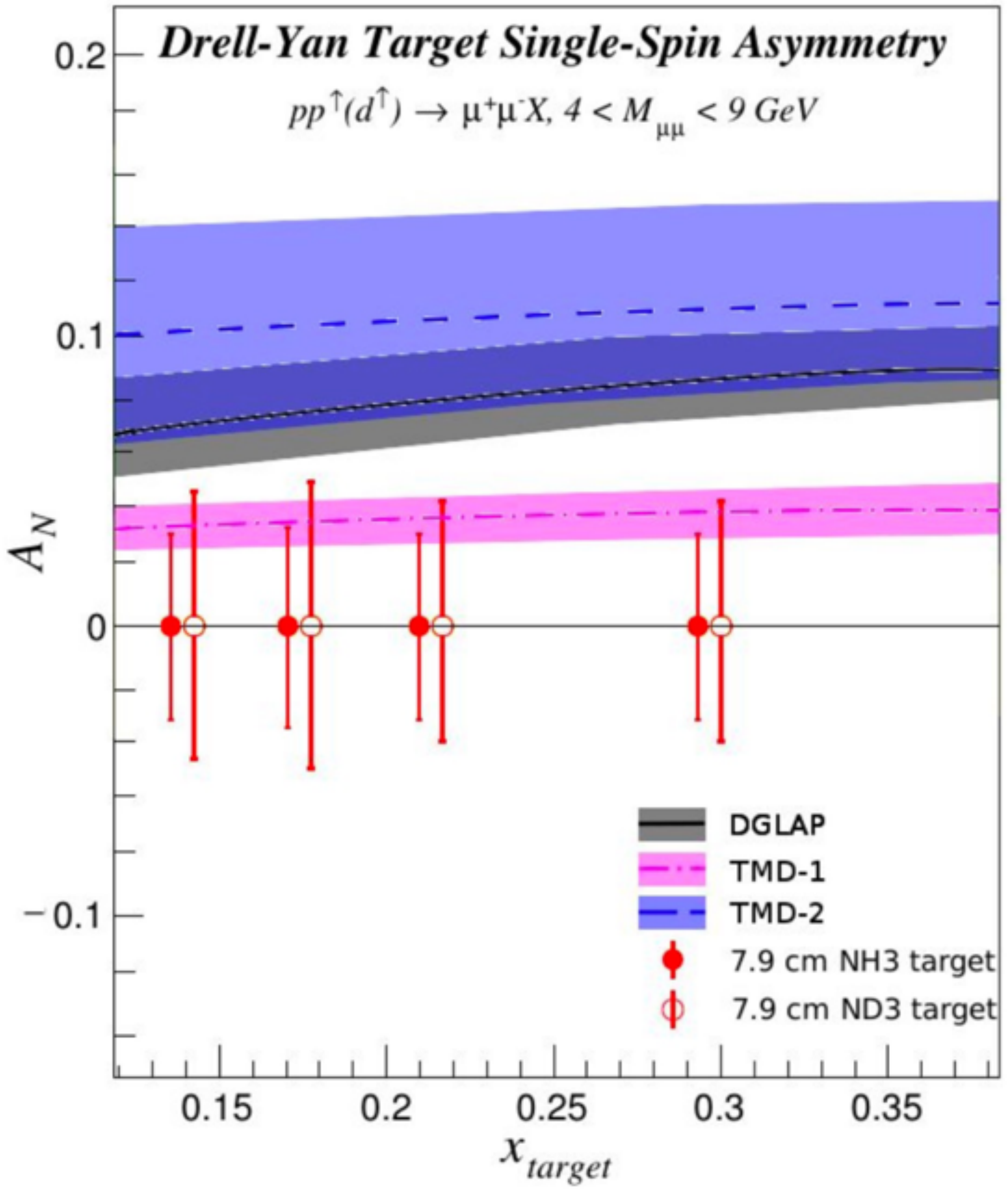
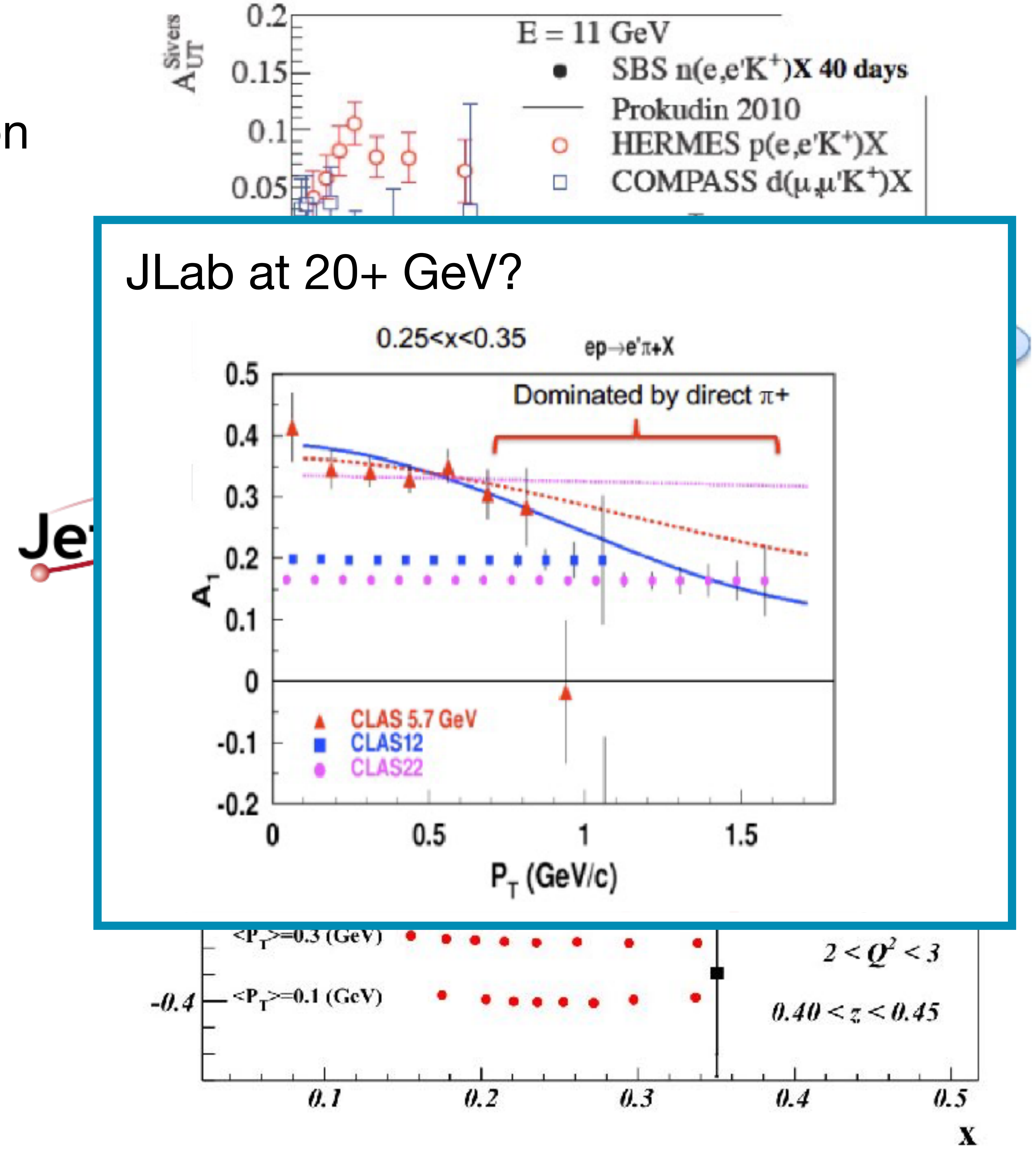


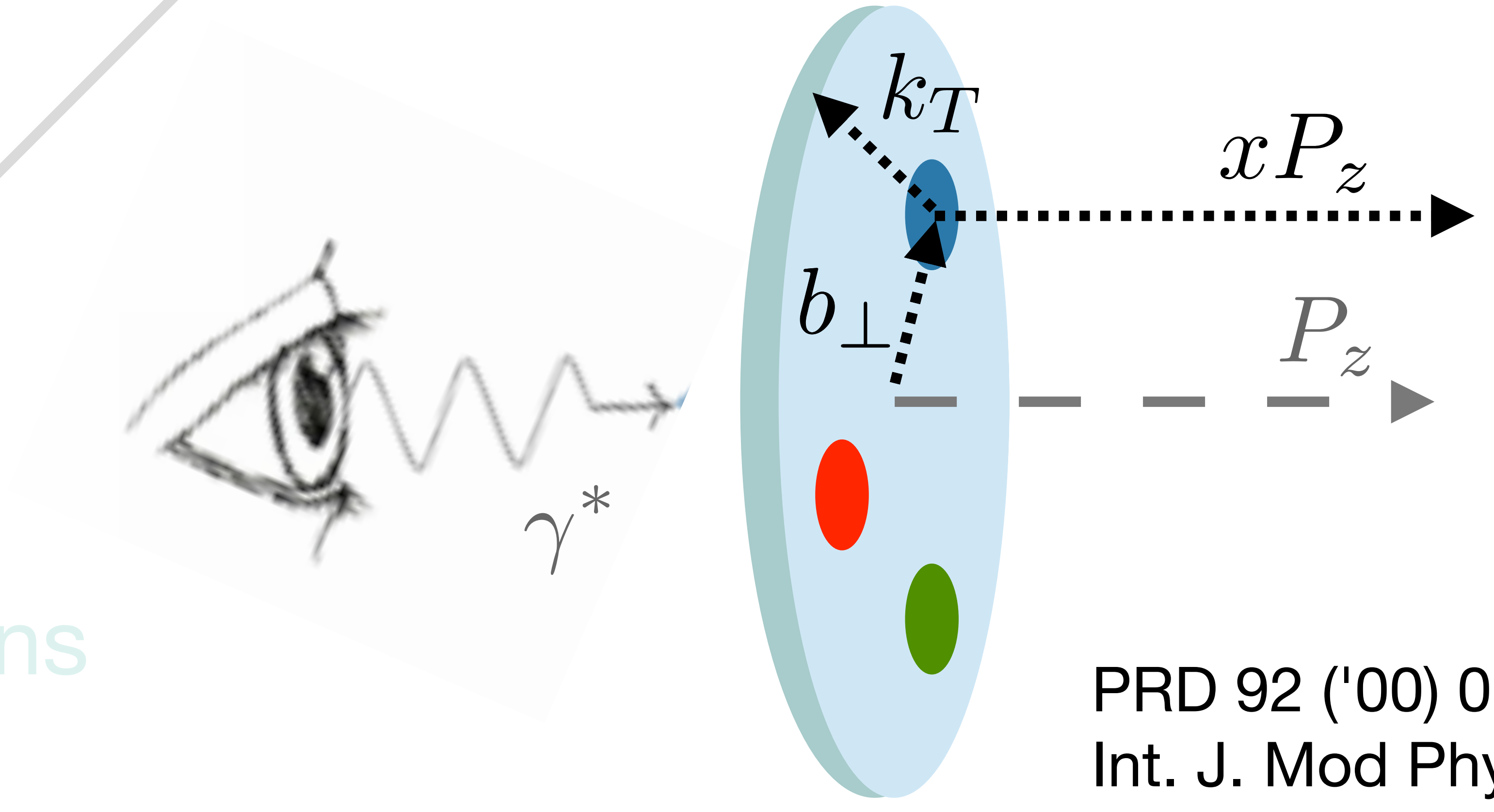


The various dimensions of the nucleon structure

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

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

transverse-momentum dependent (TMD) parton distribution functions (PDFs)



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

impact-parameter dependent PDFs

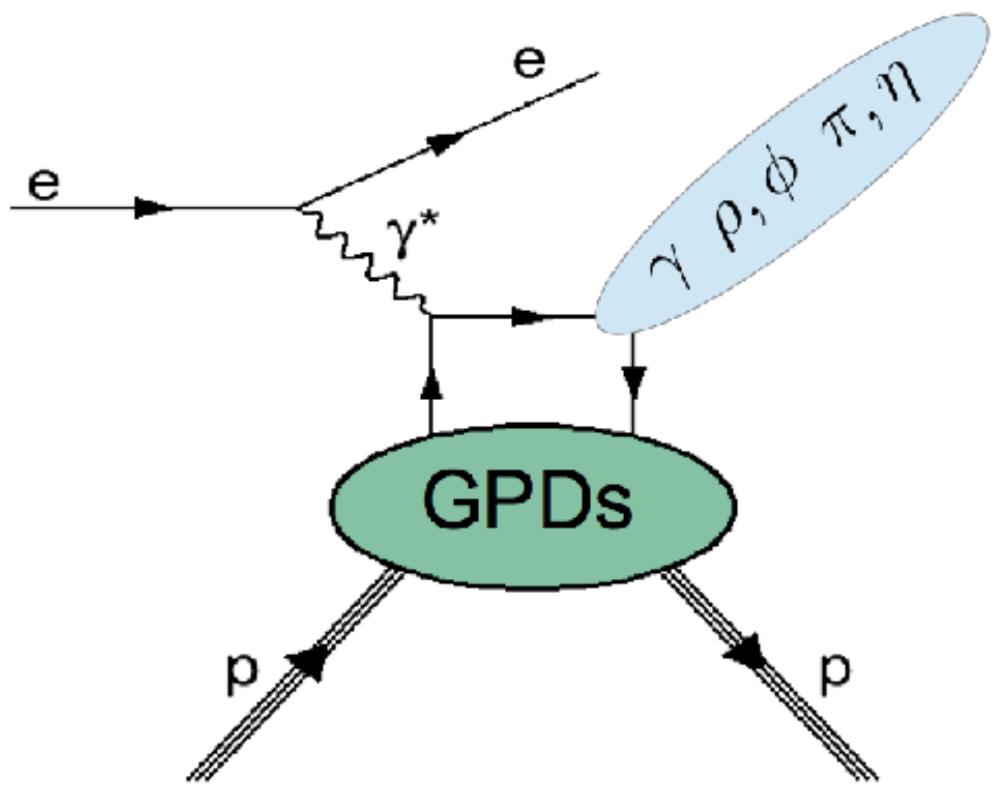
PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

Fourier transform

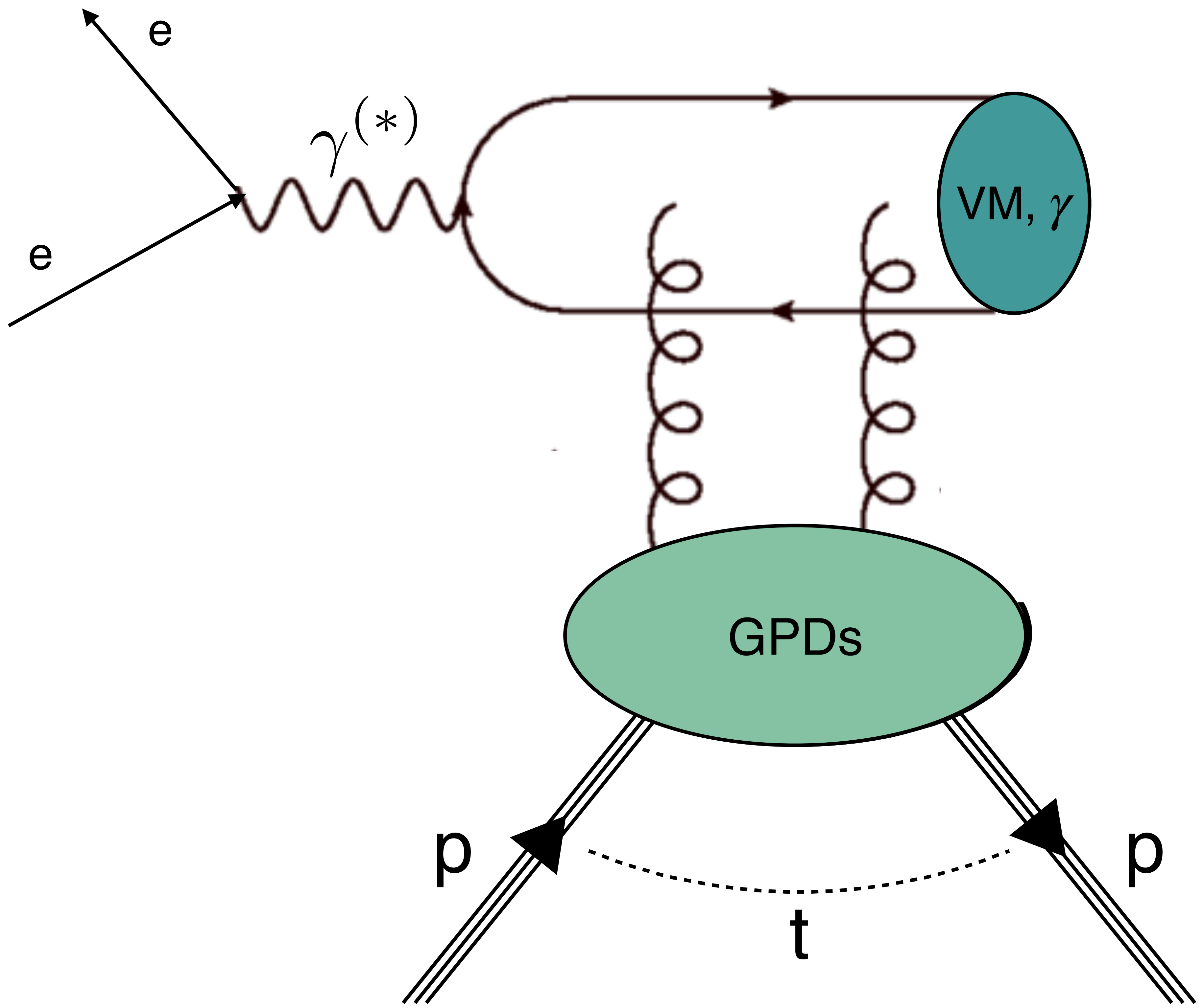
generalised parton distributions (GPDs)

Semi-inclusive production

Exclusive production



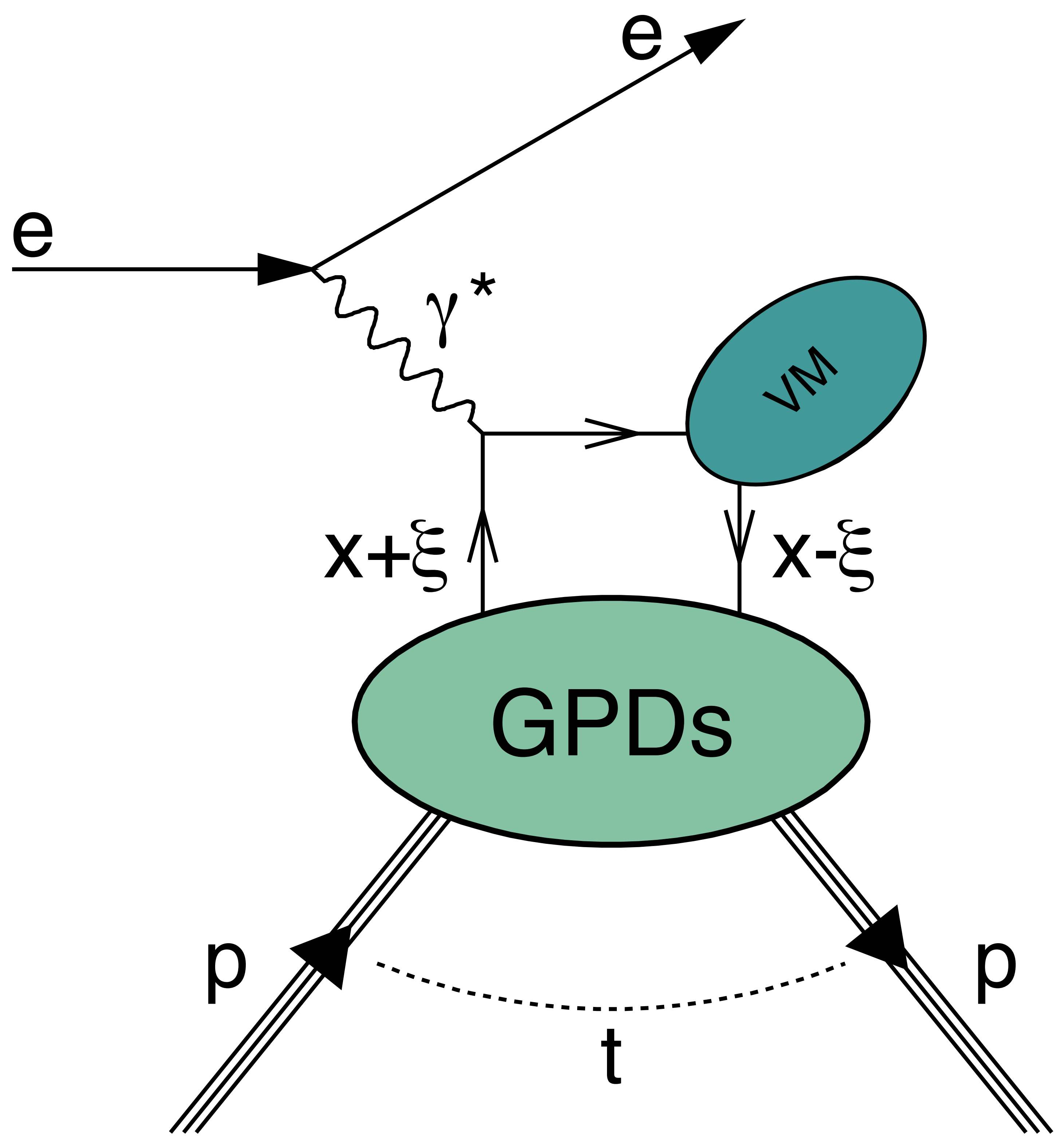
Exclusive vector-meson production



Target polarization state

- unpolarized target: nucleon-helicity-non-flip GPDs H, $\tilde{H}$ and $\bar{E}_T$=2H_T+$\tilde{E}_T$.
- transversely polarised target: nucleon-helicity-flip GPDs E, $\tilde{E}$ and H_T.

Exclusive vector-meson production



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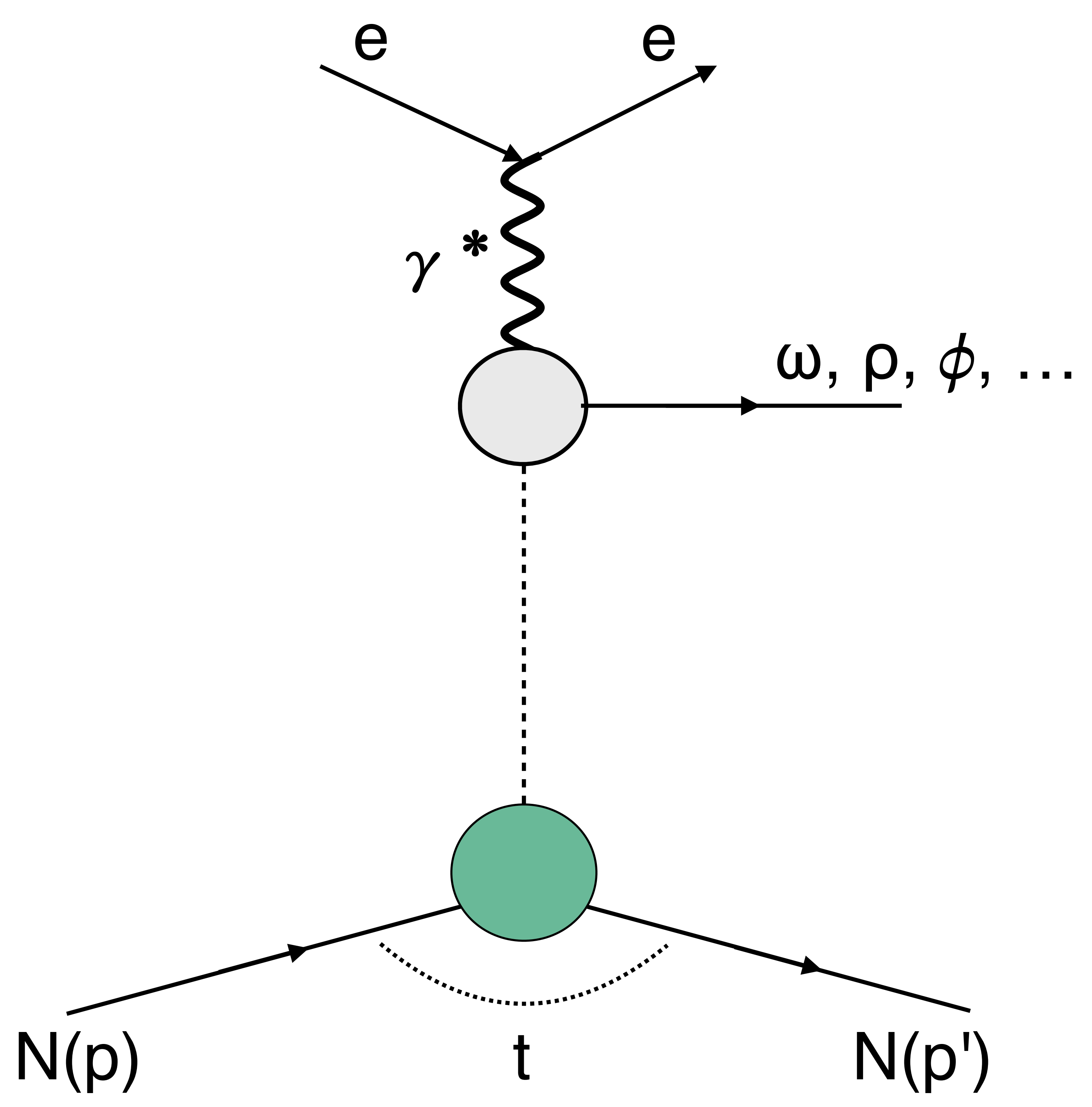

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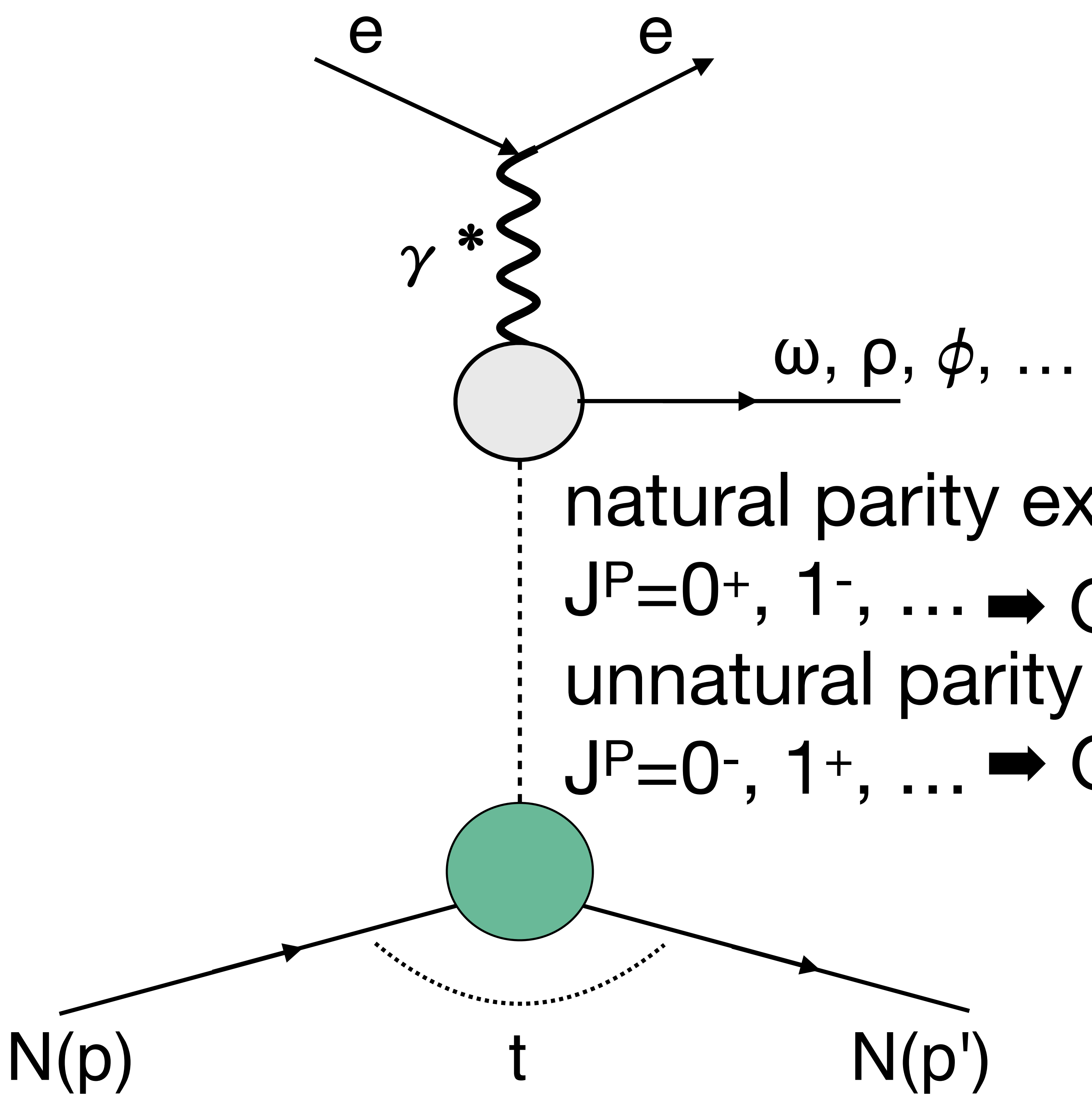

natural parity exchange
$J^P=0^+, 1^-, \ldots$ ➡ GPD H, E, $\bar{E}_T$
unnatural parity exchange
$J^P=0^-, 1^+, \ldots$ ➡ GPD $\tilde{H}$, $\tilde{E}$

Target polarization state

- unpolarized target:
  nucleon-helicity-non-flip GPDs H, $\tilde{H}$ and $\bar{E}_T=2H_T+\tilde{E}_T$.
- transversely polarised target:
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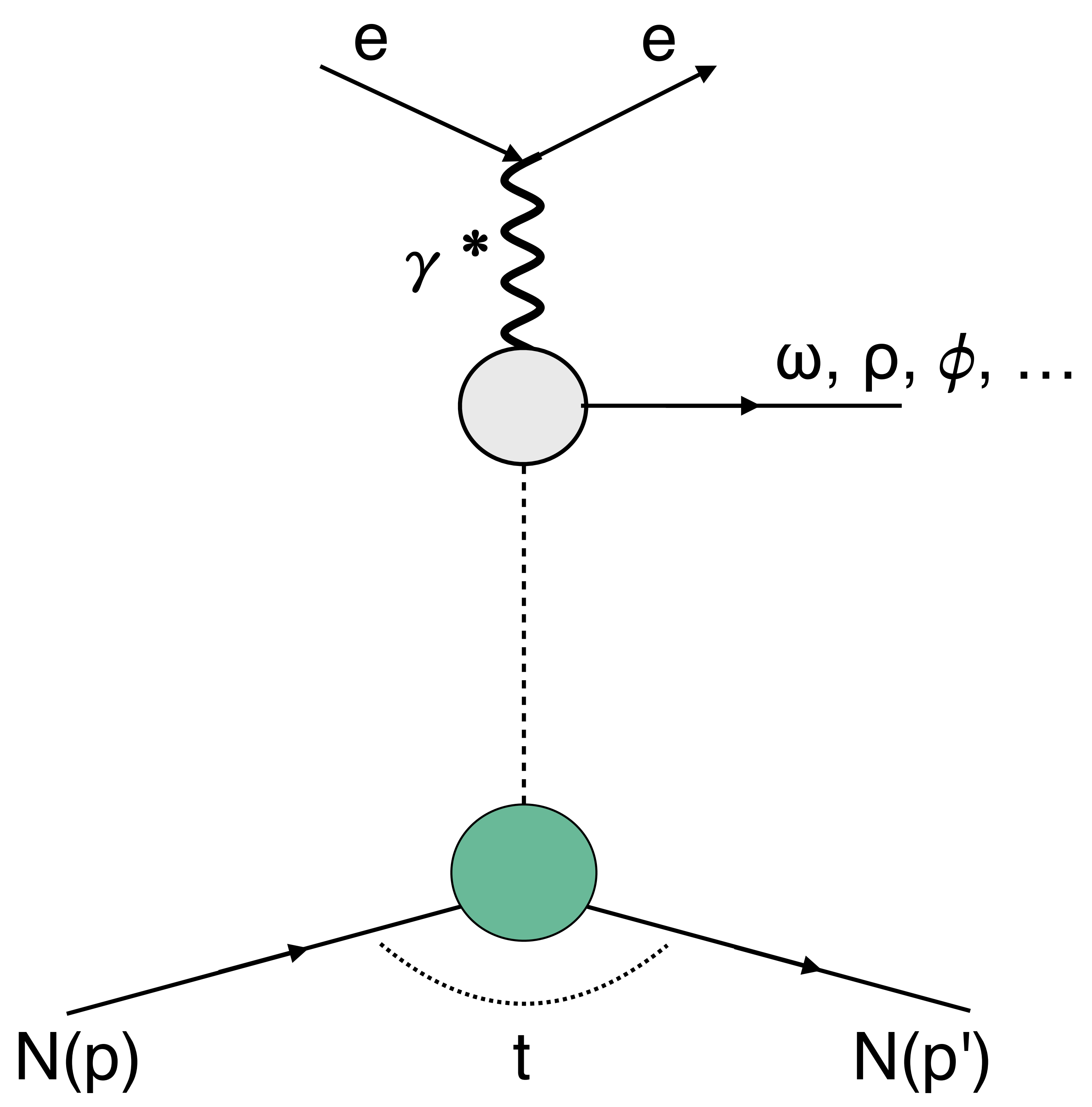
Helicity amplitude ratios and spin-density matrix elements (SDMEs)

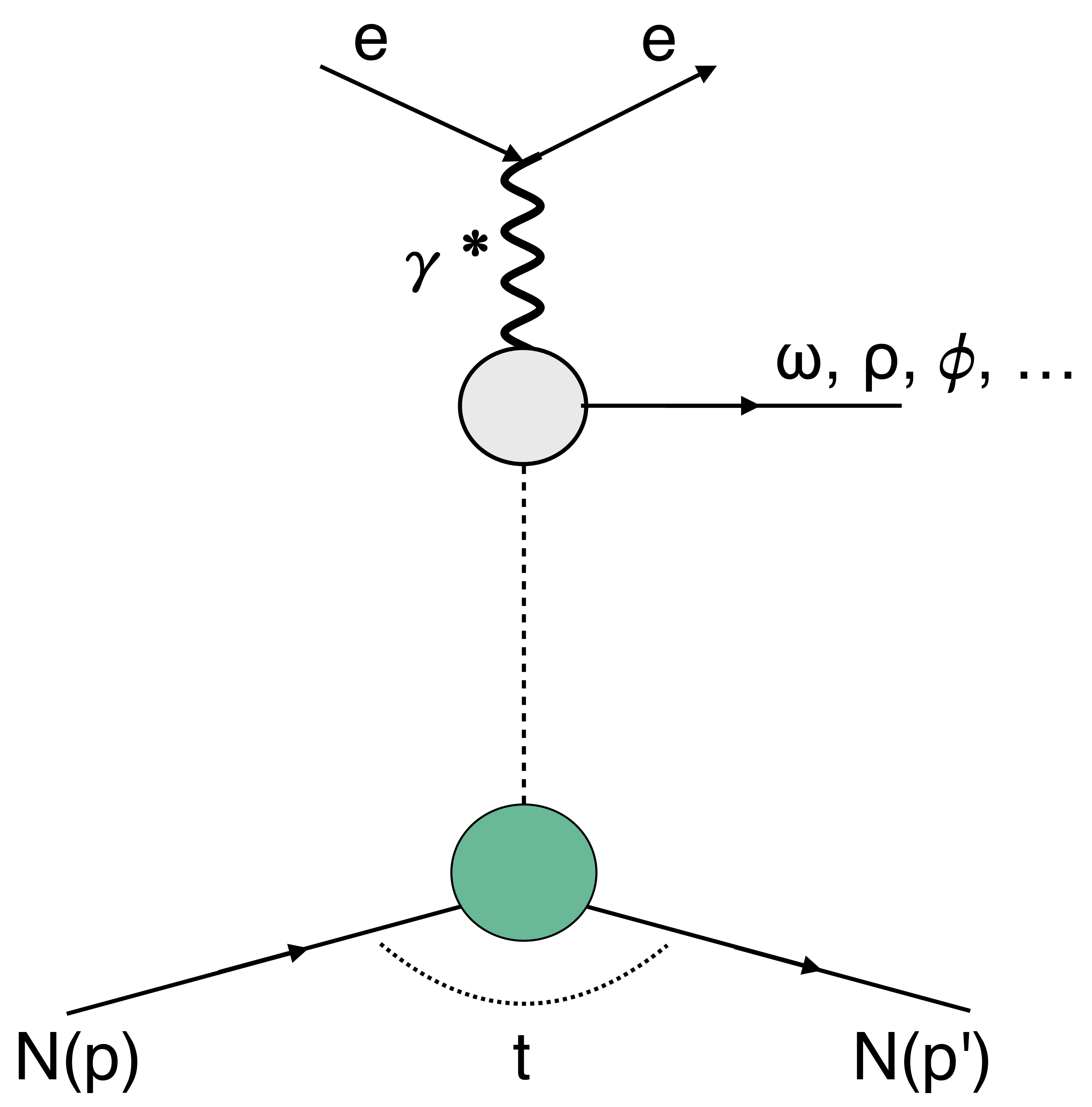
$$\gamma^*(\lambda_\gamma) + N(\lambda_N) \to V(\lambda_V) + N(\lambda'_N)$$



- Helicity amplitude $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$

Helicity amplitude ratios and spin-density matrix elements (SDMEs)

$$\gamma^*(\lambda_\gamma) + N(\lambda_N) \to V(\lambda_V) + N(\lambda'_N)$$

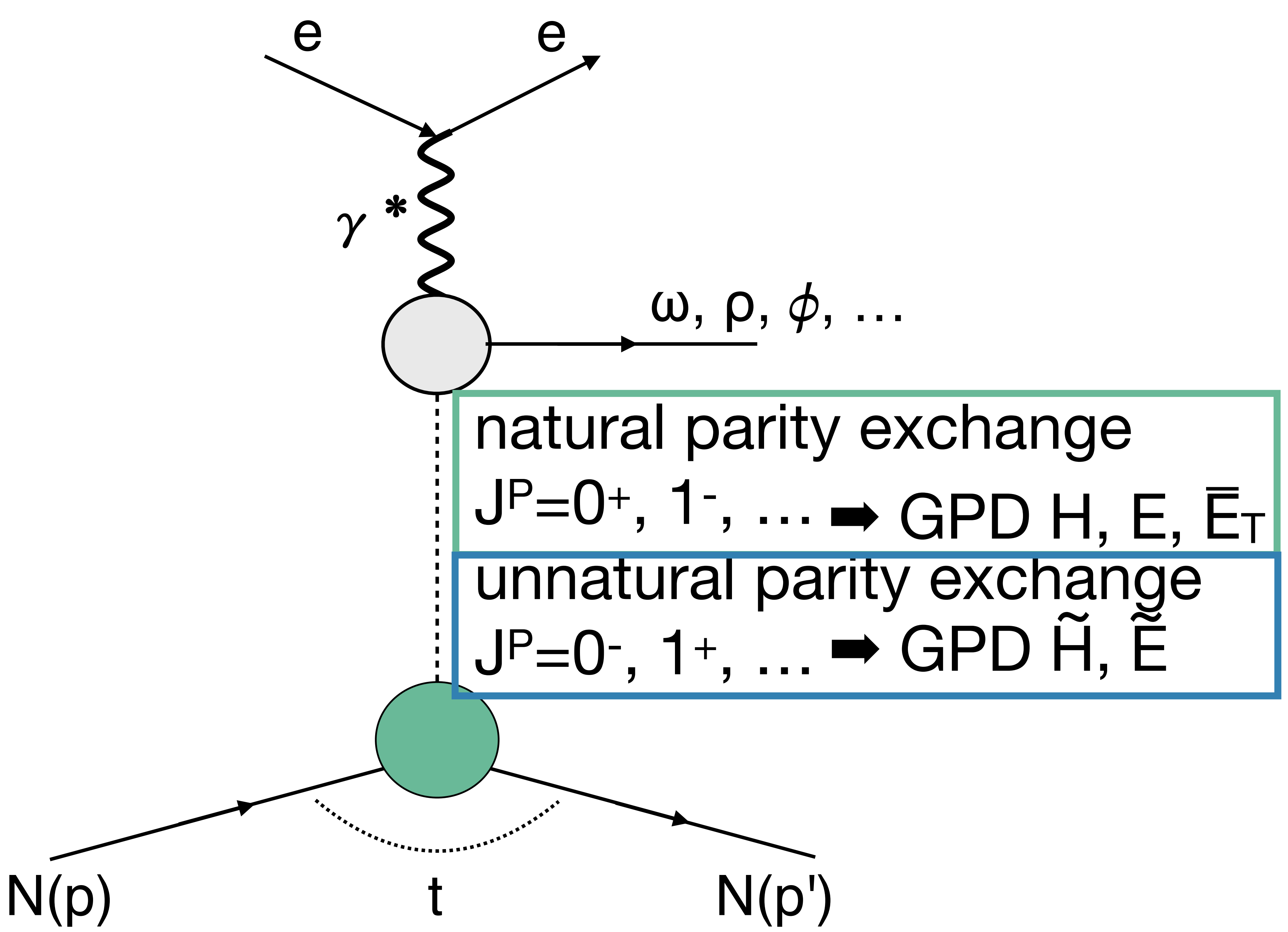


- Helicity amplitude $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$

$$F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$$

Helicity amplitude ratios and spin-density matrix elements (SDMEs)

$$\gamma^*(\lambda_\gamma) + N(\lambda_N) \to V(\lambda_V) + N(\lambda'_N)$$

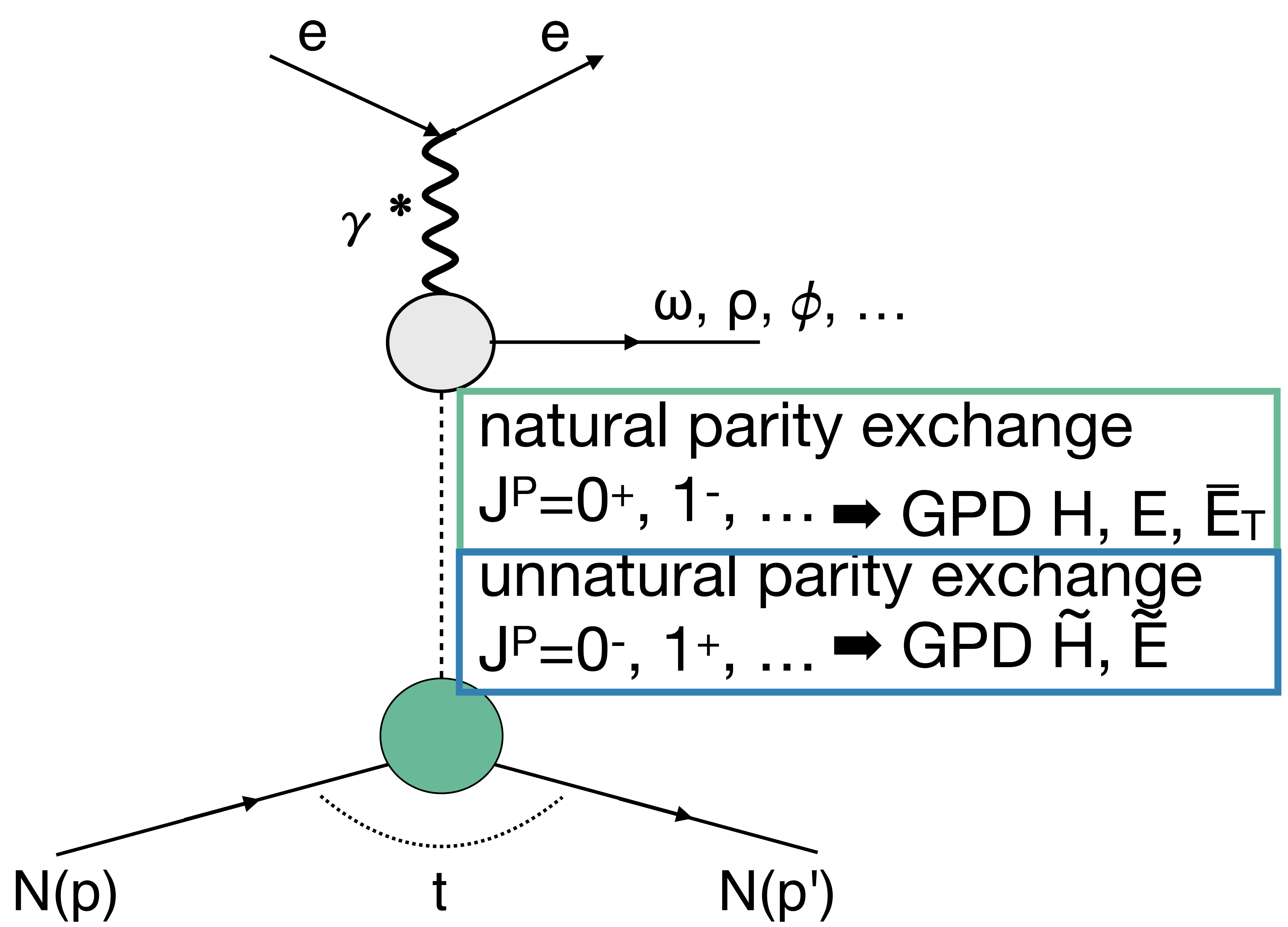


- Helicity amplitude $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$

$$F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = \boxed{T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}} + \boxed{U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}}$$

Helicity amplitude ratios and spin-density matrix elements (SDMEs)

$$\gamma^*(\lambda_\gamma) + N(\lambda_N) \to V(\lambda_V) + N(\lambda'_N)$$



- Helicity amplitude $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$

$$F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = \boxed{T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}} + \boxed{U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}}$$

- Helicity amplitude ratios

$$t^{(n)}_{\lambda_V \lambda_\gamma} = T^{(n)}_{\lambda_V \lambda_\gamma} / T_{0\frac{1}{2}0\frac{1}{2}}$$

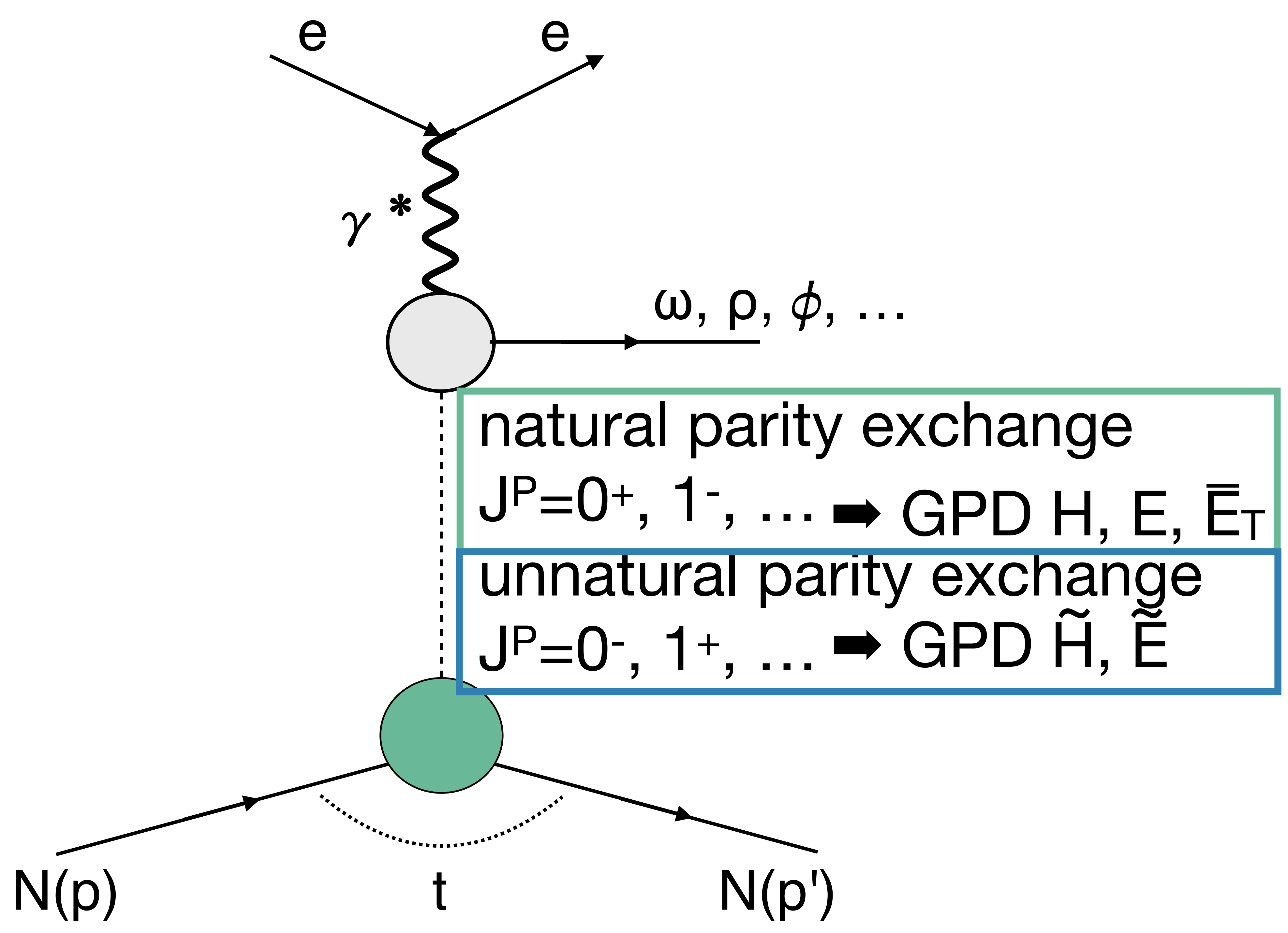
$$u^{(n)}_{\lambda_V \lambda_\gamma} = U^{(n)}_{\lambda_V \lambda_\gamma} / T_{0\frac{1}{2}0\frac{1}{2}}$$

$n = 1 \quad \lambda_N = \lambda'_N$

$n = 2 \quad \lambda_N \neq \lambda'_N$

Helicity amplitude ratios and spin-density matrix elements (SDMEs)

$$\gamma^*(\lambda_\gamma) + N(\lambda_N) \to V(\lambda_V) + N(\lambda'_N)$$



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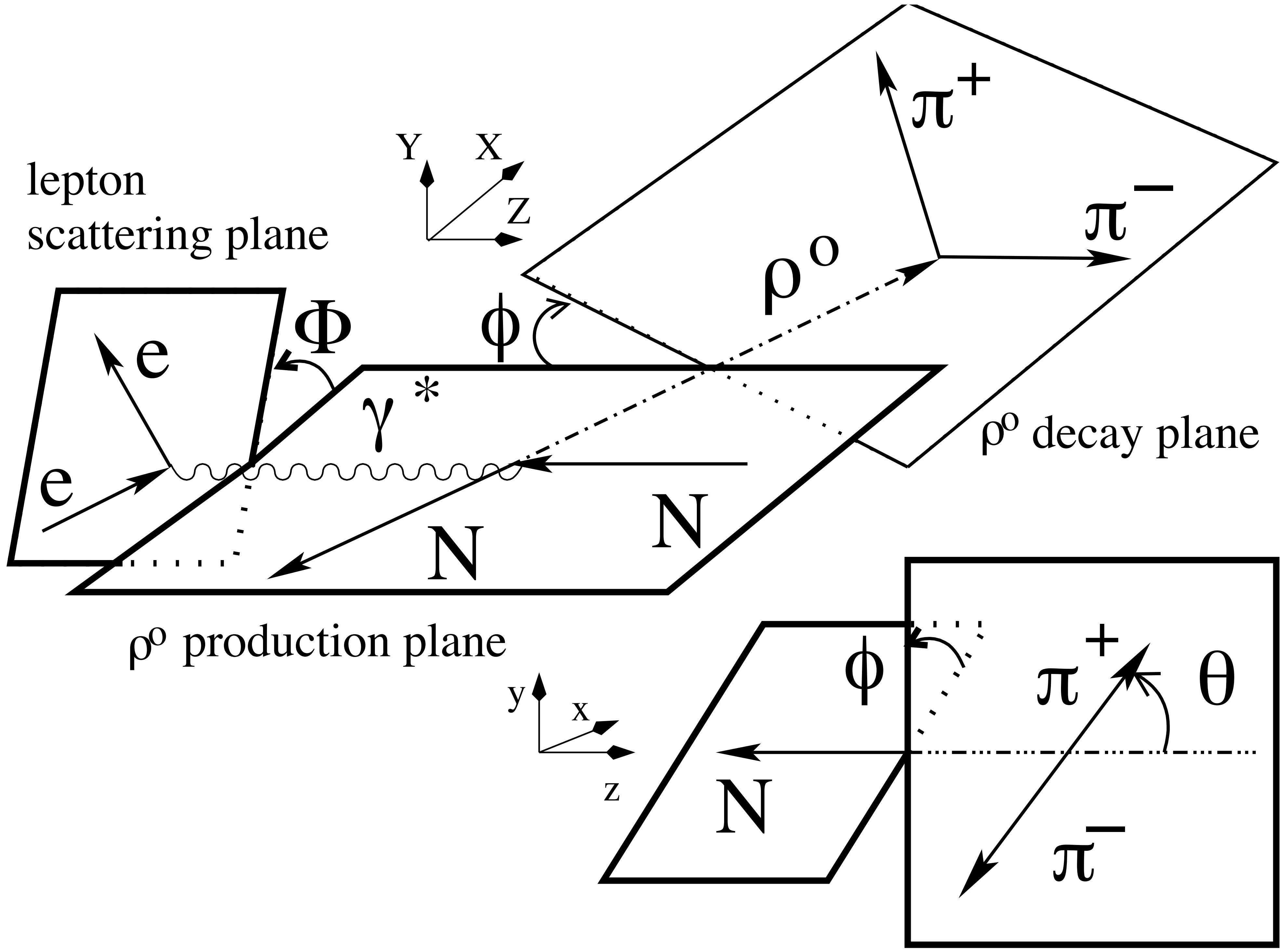
- SDMEs

$$\propto F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \Sigma^{\alpha}_{\lambda_\gamma \lambda'_\gamma} F^*_{\lambda'_V \lambda'_N \lambda'_\gamma \lambda_N}$$

Angular distributions

$l + p \rightarrow l + p + \rho^0 \left(\rightarrow \pi^+ + \pi^- \right)$



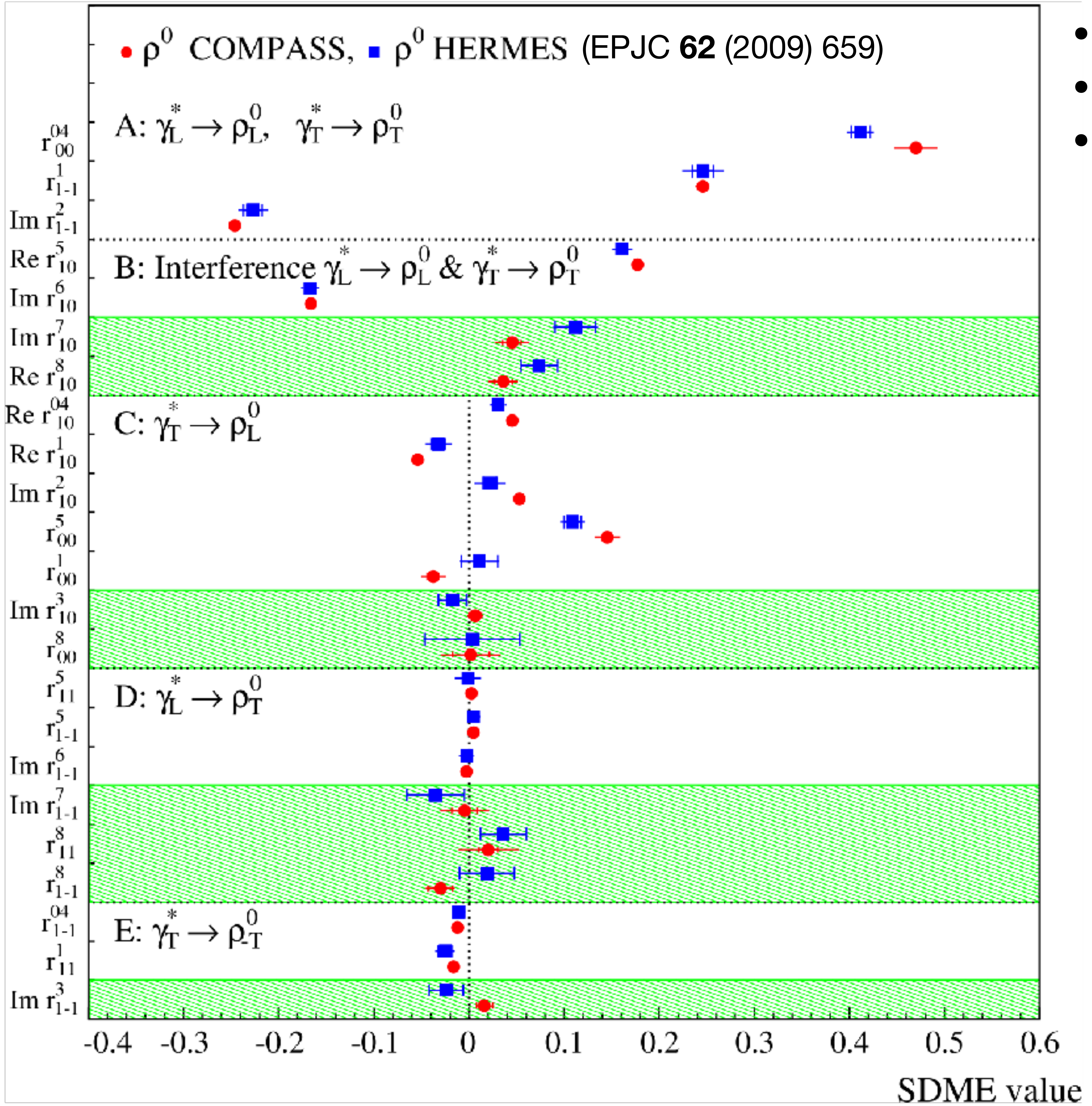
Fit angular distribution of decay pions $\mathcal{W}(\Phi, \phi, \Theta)$ and extract either Spin Density Matrix Elements (SDMEs) or helicity amplitude ratios

ρ^0 SDMEs

HERMES:
$\langle Q^2 \rangle = 1.96$ GeV^2
$\langle W \rangle = 4.8$ GeV^2

COMPASS:
$\langle Q^2 \rangle = 2.40$ GeV^2
$\langle W \rangle = 9.9$ GeV^2

COMPASS: EPJC **83** (2023) 924



- 5 classes of SDMEs
- unpolarised and polarised SDMEs
- proton & deuteron similar

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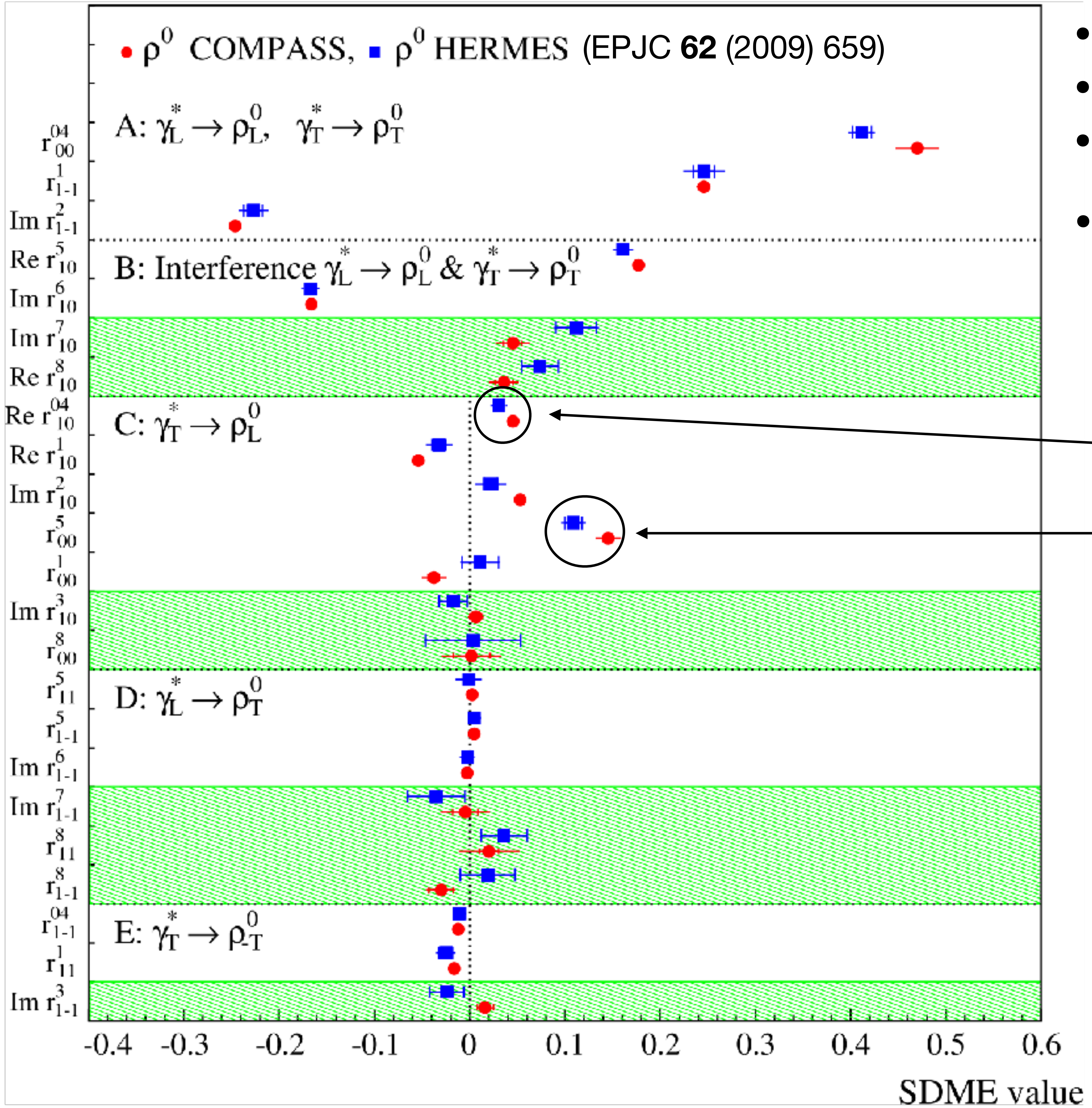

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- s-channel helicity conservation ($\lambda_{\gamma*} = \lambda_{\rho^0}$):
  - fulfilled for class A & B
  - class C - strong violation:

$\Re r^{04}_{10} \neq 0$ by $> 4\sigma$

$\Re r^{5}_{00} \neq 0$ by $> 9\sigma$

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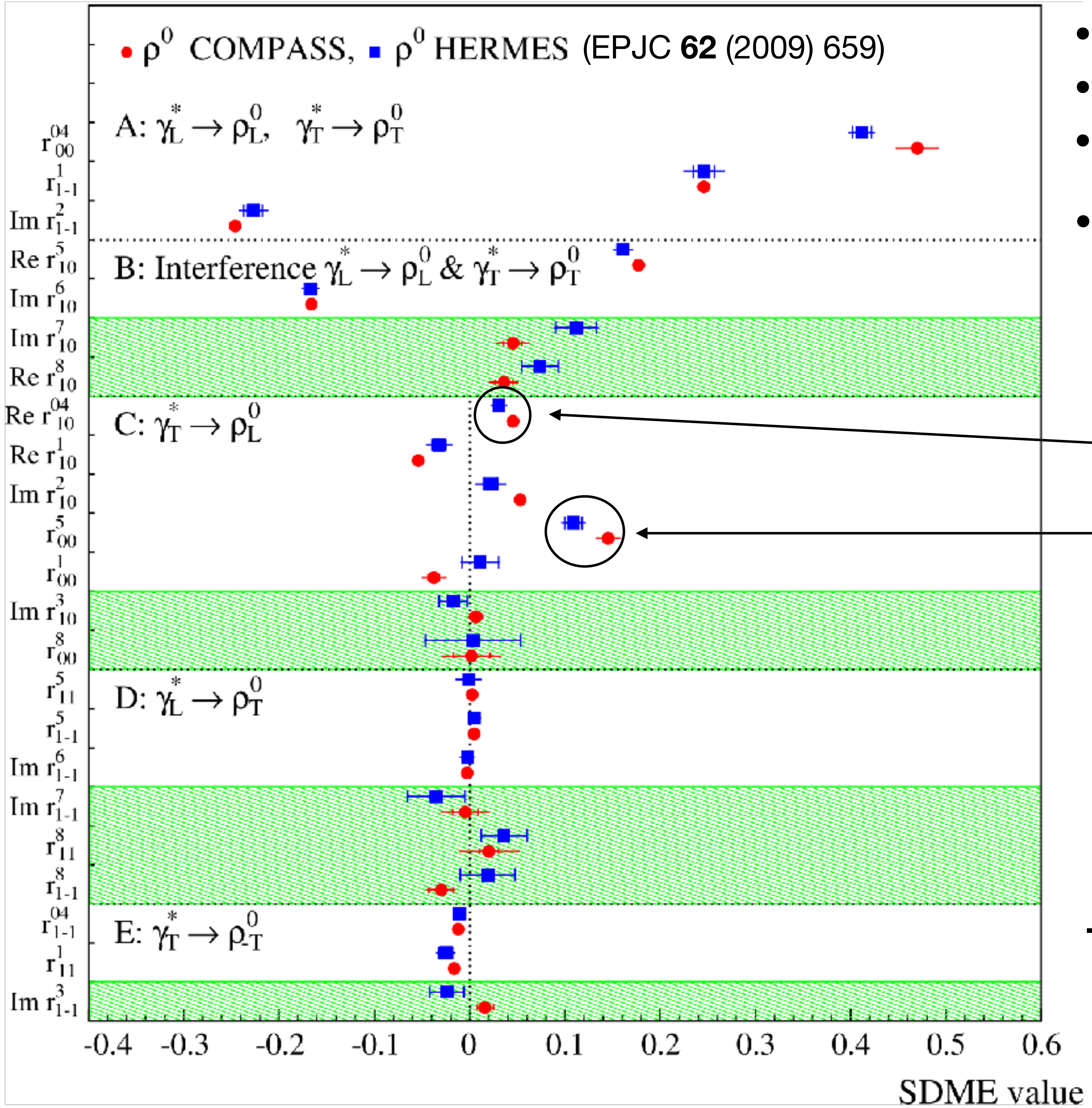

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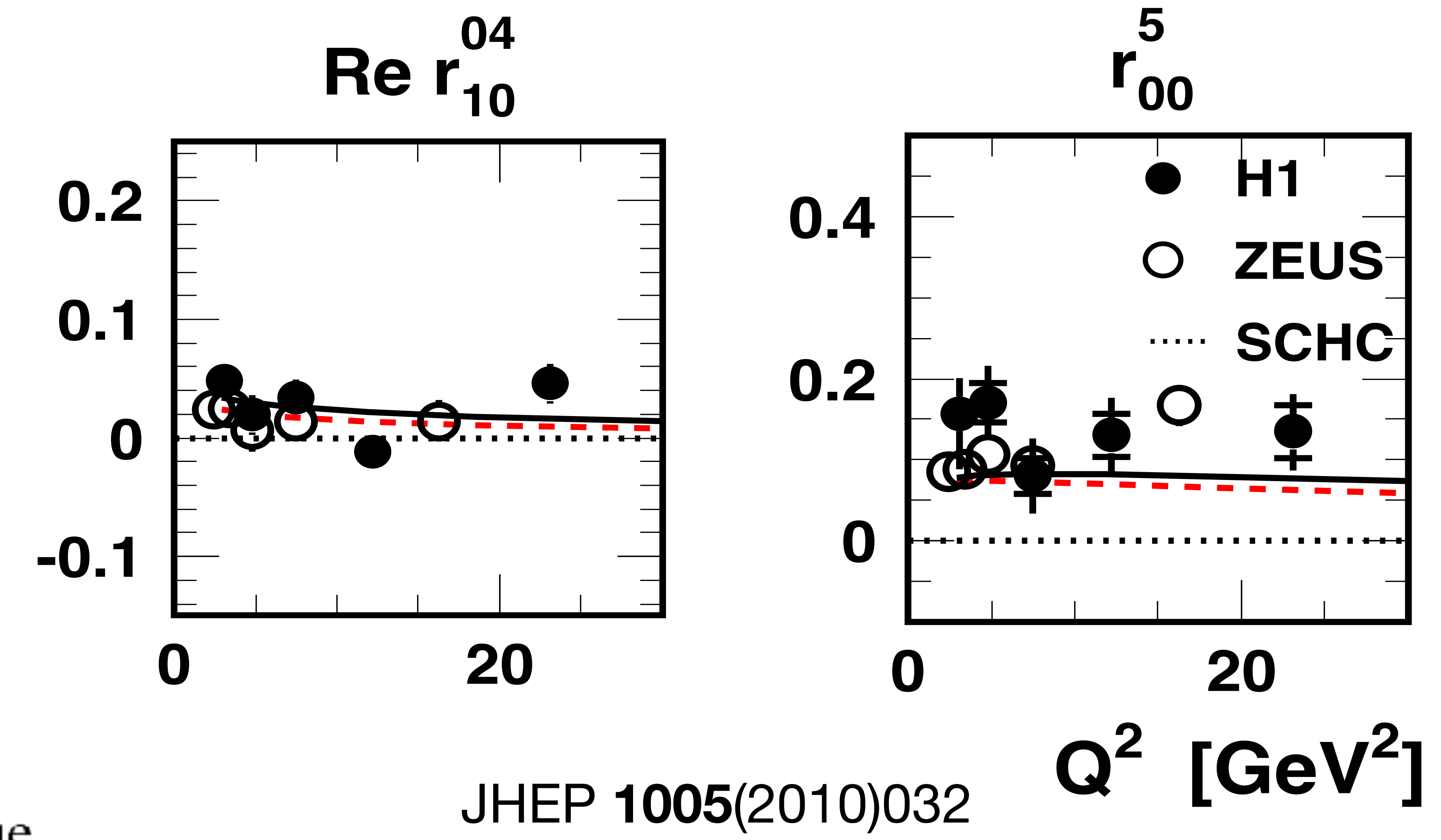

JHEP **1005**(2010)032

Natural and unnatural parity exchange in ρ^0 production

- helicity amplitude ratio – HERMES

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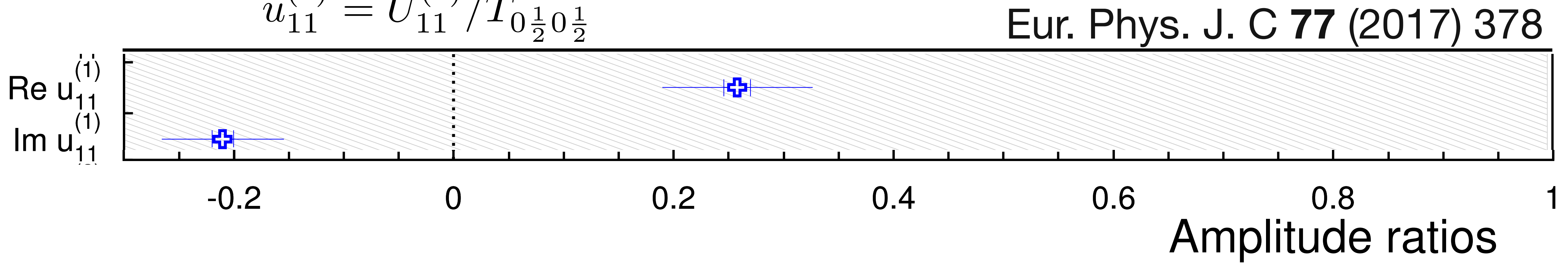

unnatural parity nucleon-helicity non-flip $\neq 0$ by 4σ

cf. quark exchange

COMPASS: $u_1 = 0.047 \pm 0.010 \pm 0.029$

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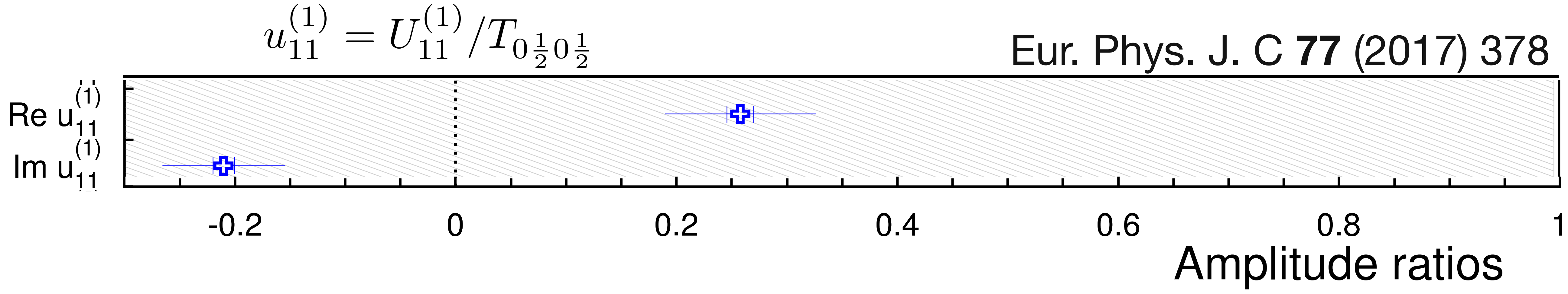

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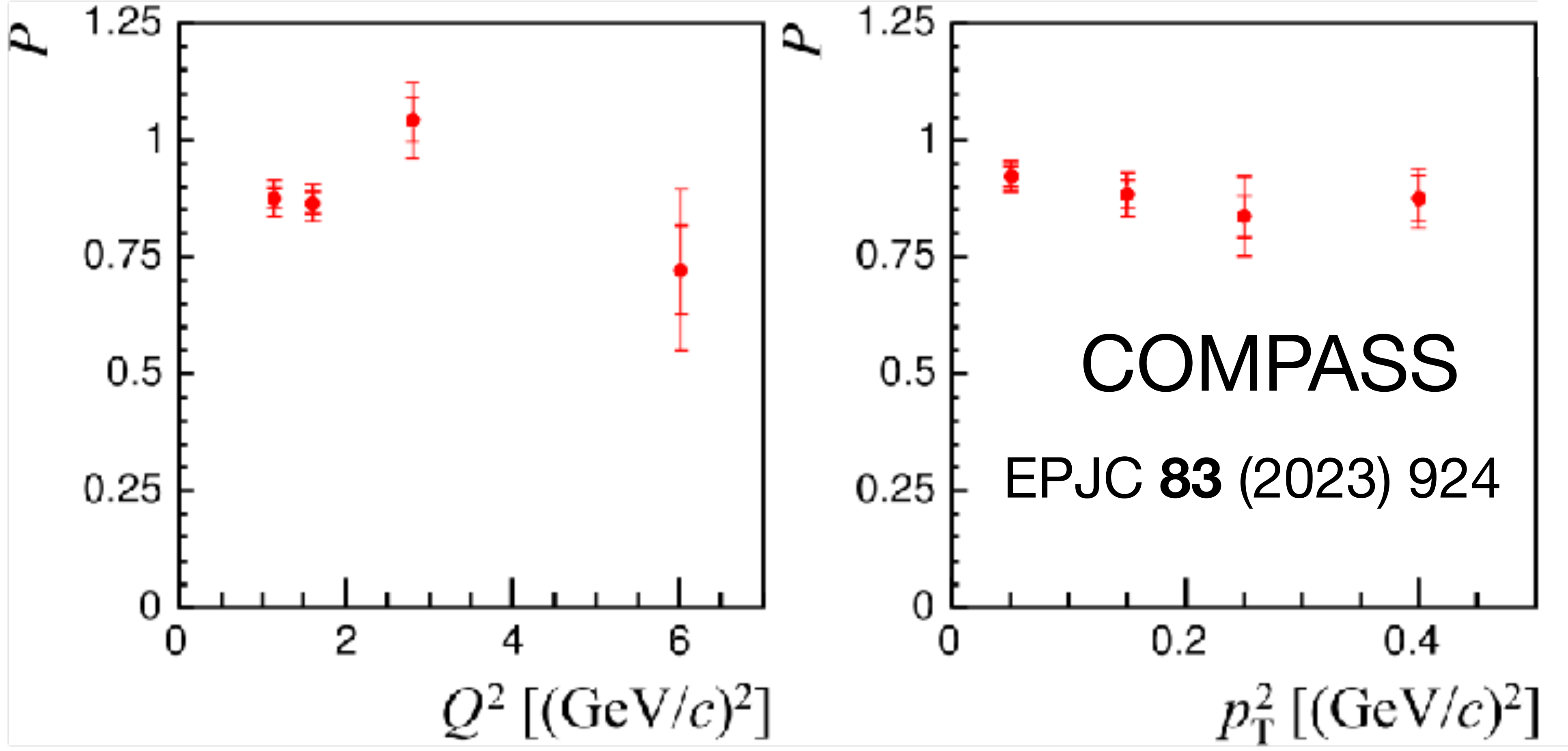
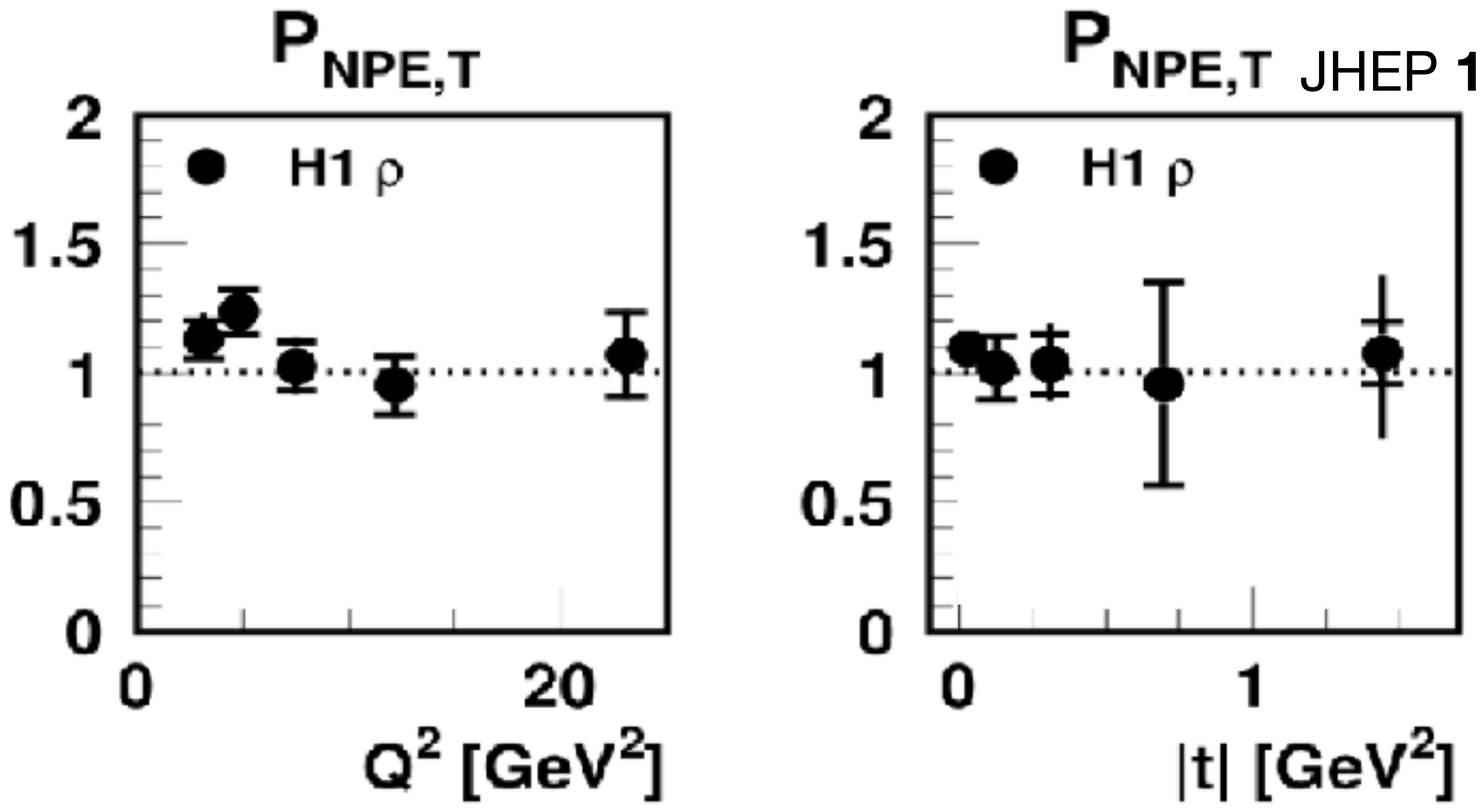
- Asymmetry between natural and unnatural parity exchange

$$P_{NPE,T} = \frac{\sigma_T^N - \sigma_T^U}{\sigma_T^N + \sigma_T^U} \approx \frac{2r^1_{1-1}}{1 - r^{04}_{00} - 2r^{04}_{1-1}}$$





JHEP **1005**(2010)032

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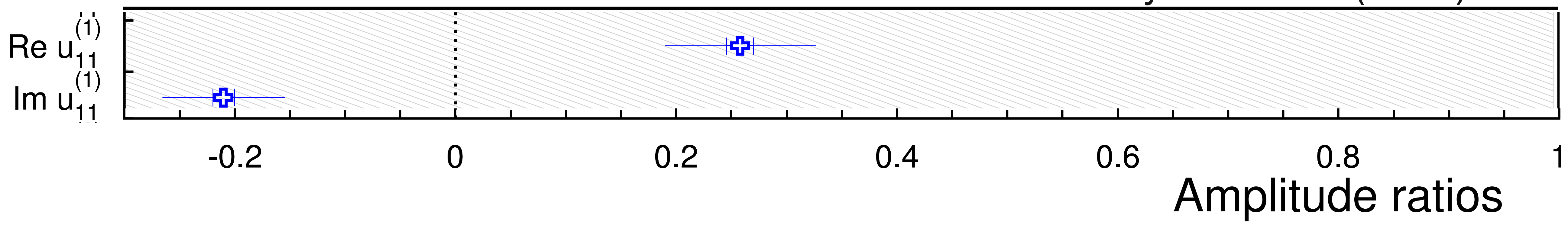

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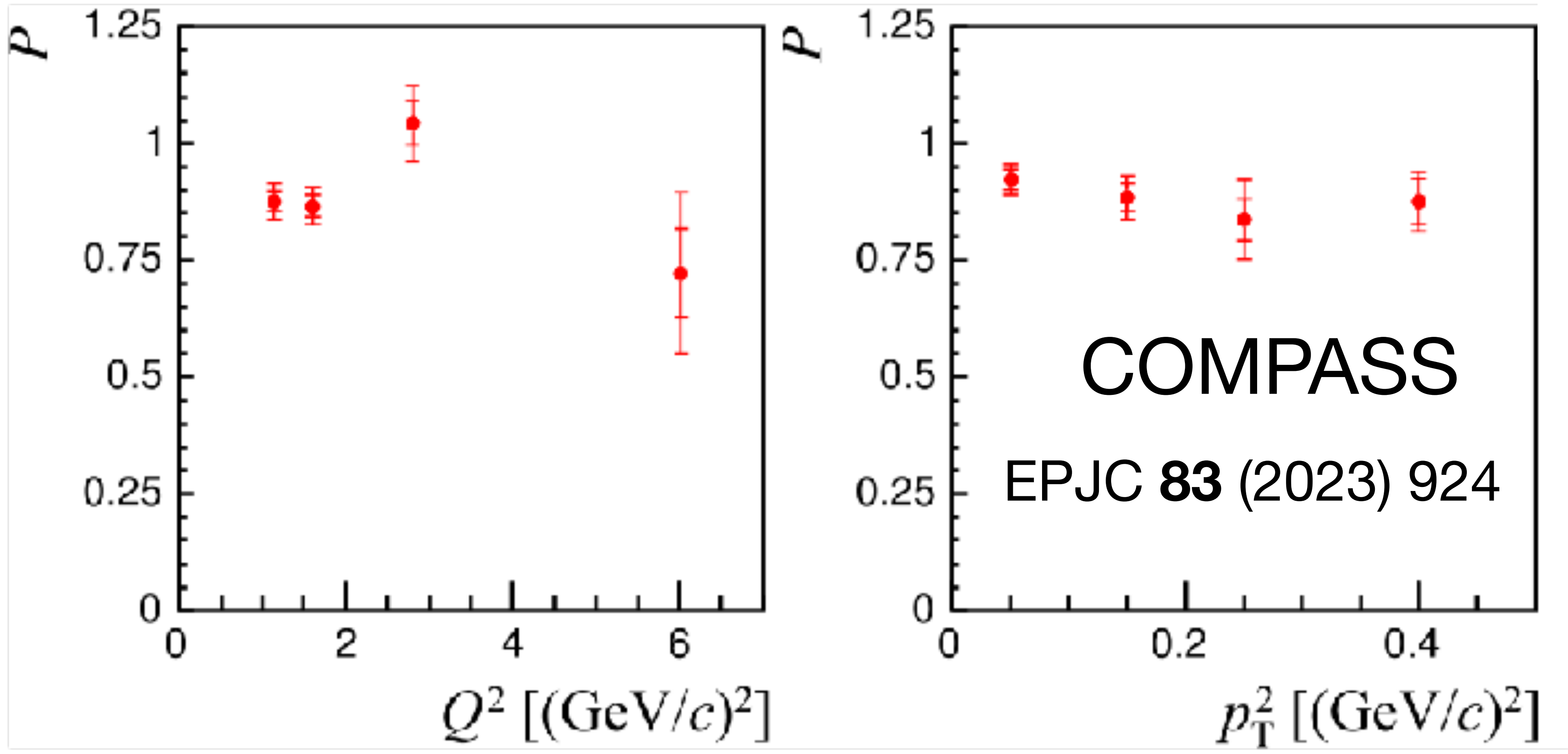
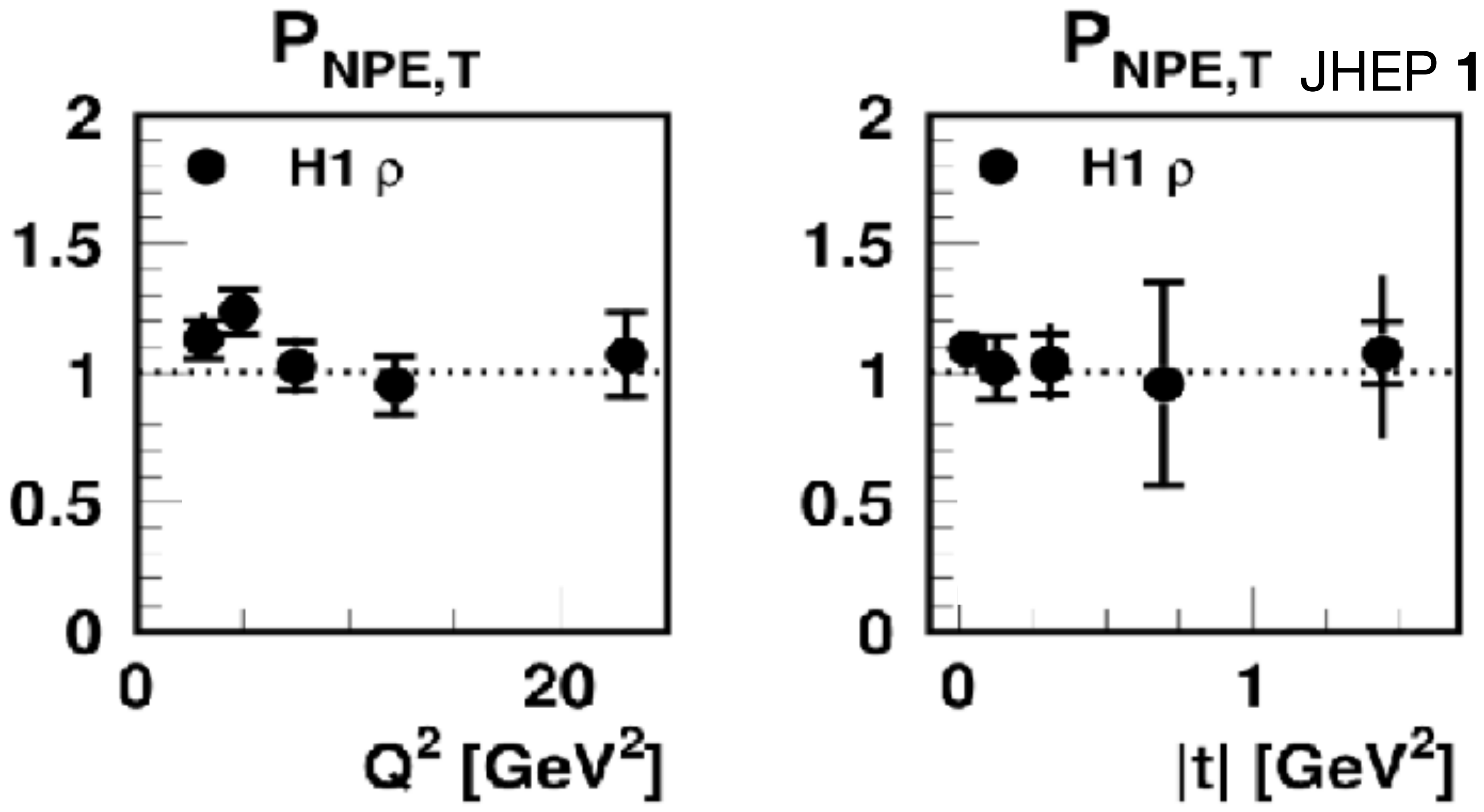




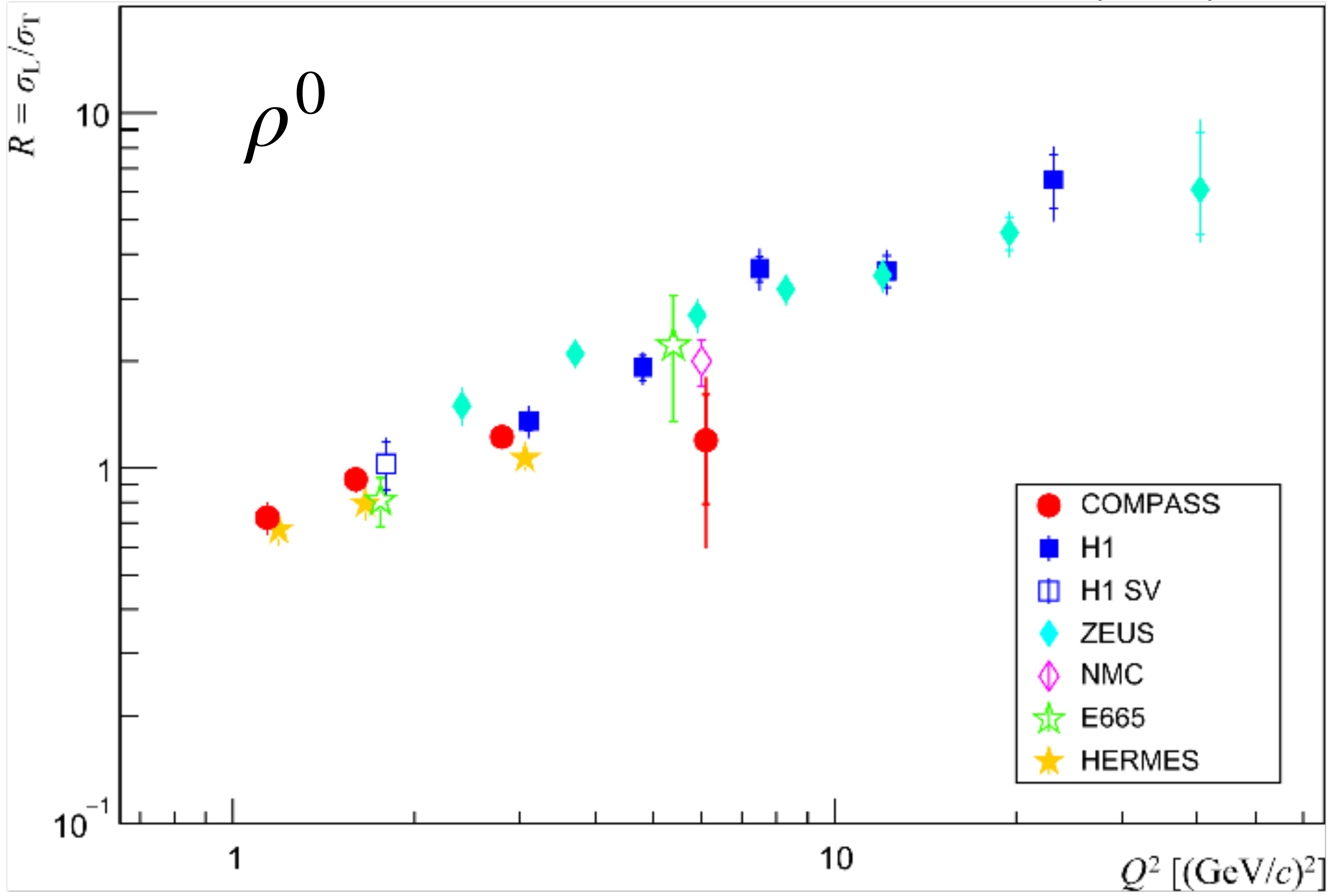
JHEP **1005**(2010)032

diffraction ~ 2 gluon exchange → NPE

Longitudinal-to-transverse cross section ratio

$$R = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1-r_{00}^{04}} = \frac{d\sigma(\gamma_L^* \to V_L^*) + \frac{1}{\epsilon}\, d\sigma(\gamma_T^* \to V_L)}{d\sigma(\gamma_T^* \to V_T) + \epsilon\, d\sigma(\gamma_L^* \to V_T)} \overset{\text{SCHC}}{=} \frac{d\sigma(\gamma^*{}_L)}{d\sigma(\gamma^*{}_T)}$$

EPJC **83** (2023) 924



Longitudinal-to-transverse cross section ratio

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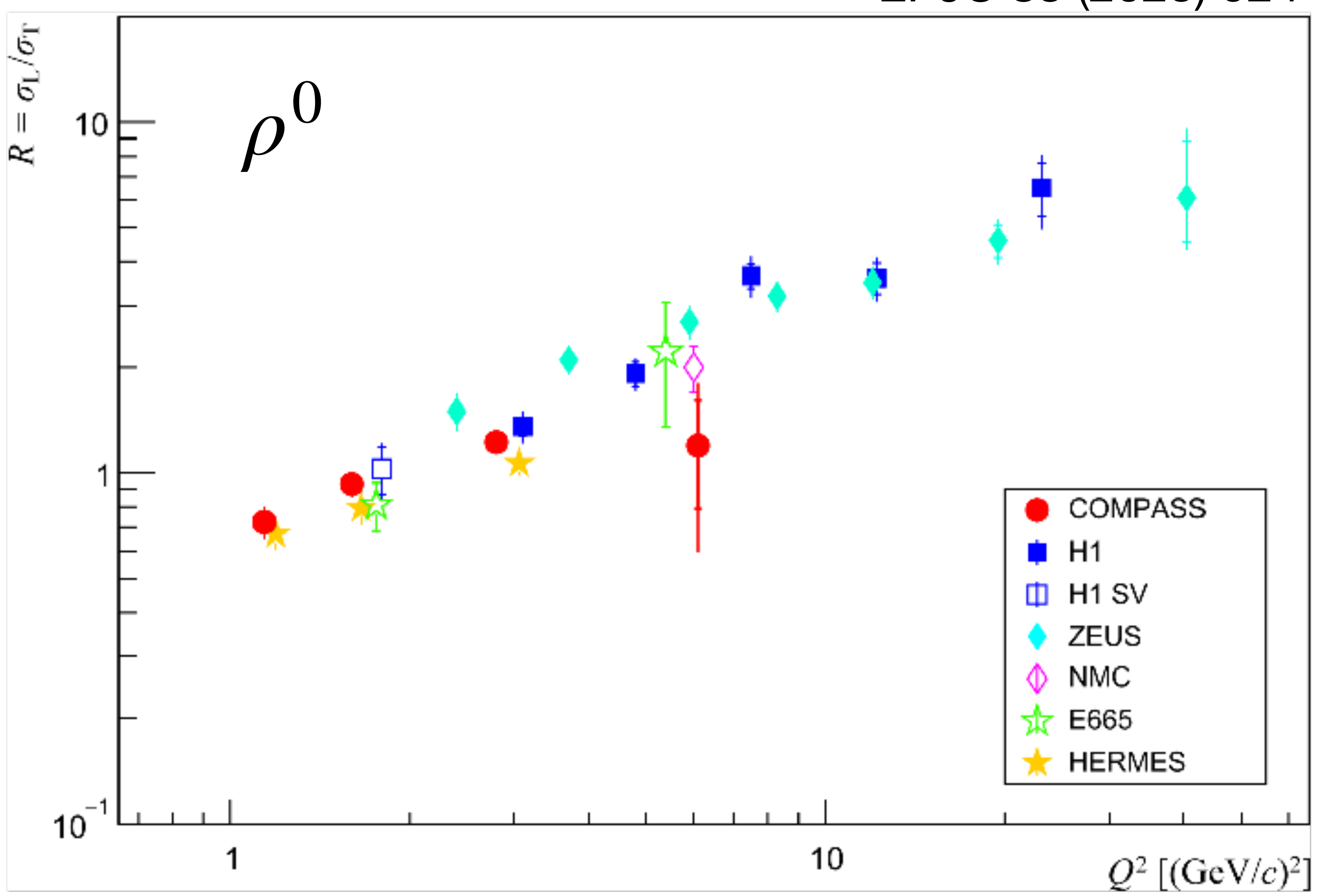
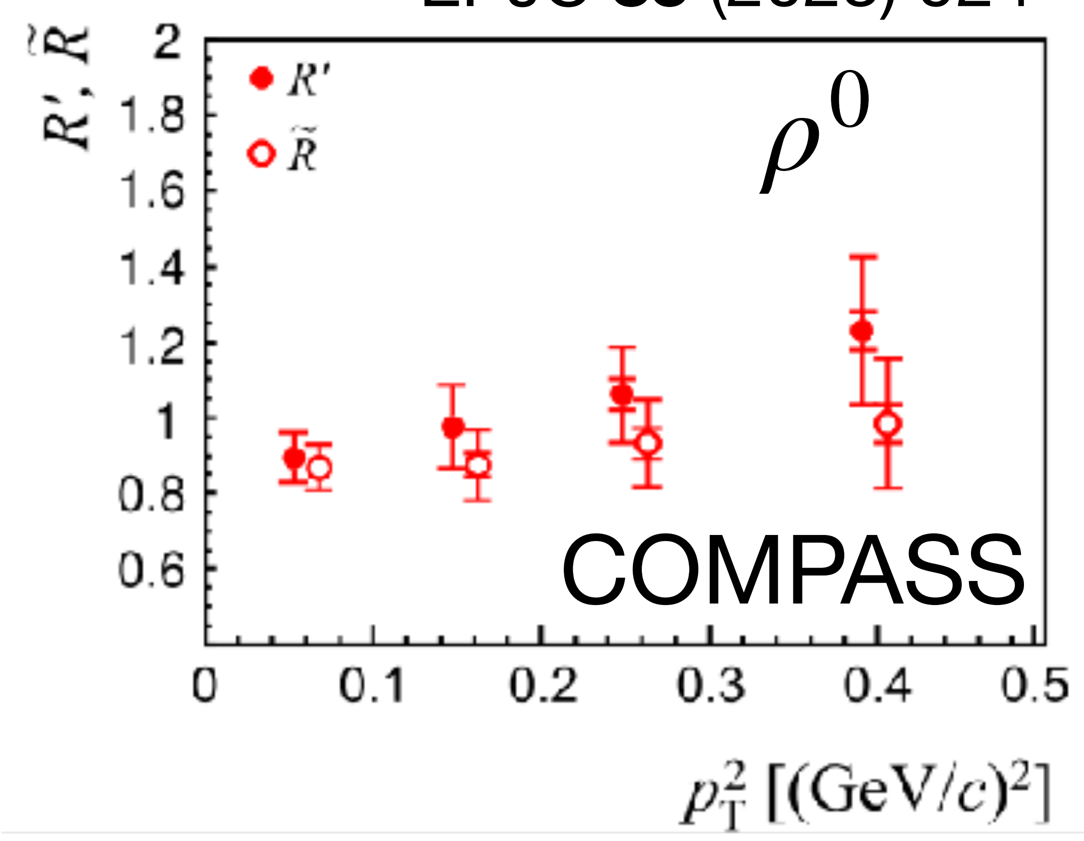
EPJC **83** (2023) 924

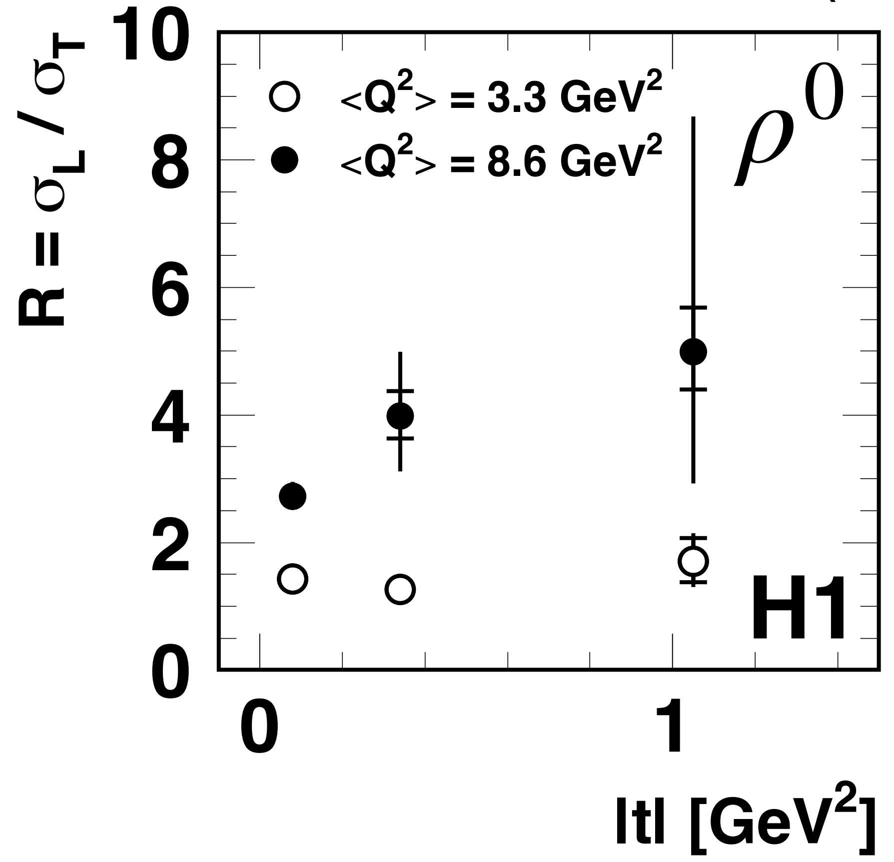


$$R(t) \propto e^{-(b_L - b_T)|t|}$$

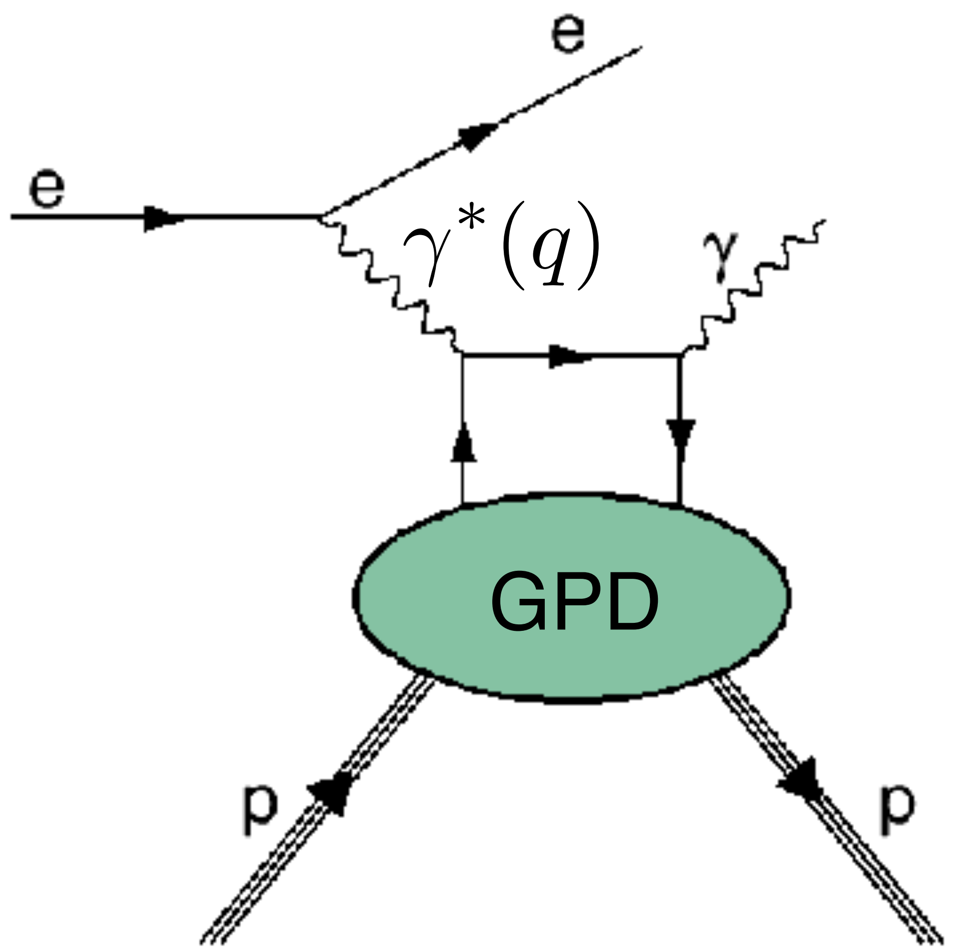
EPJC **83** (2023) 924



JHEP 1005(2010)032



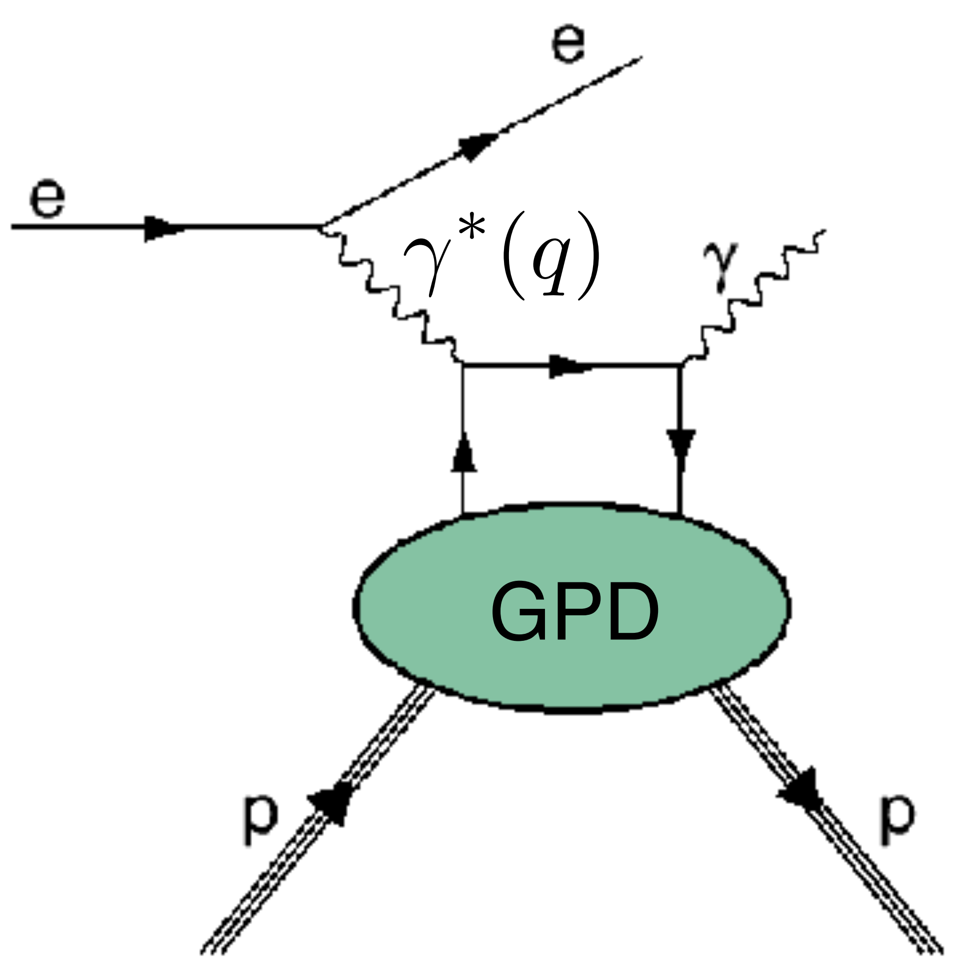
Deeply virtual Compton scattering



DVCS

hard scale = large Q^2

Deeply virtual Compton scattering



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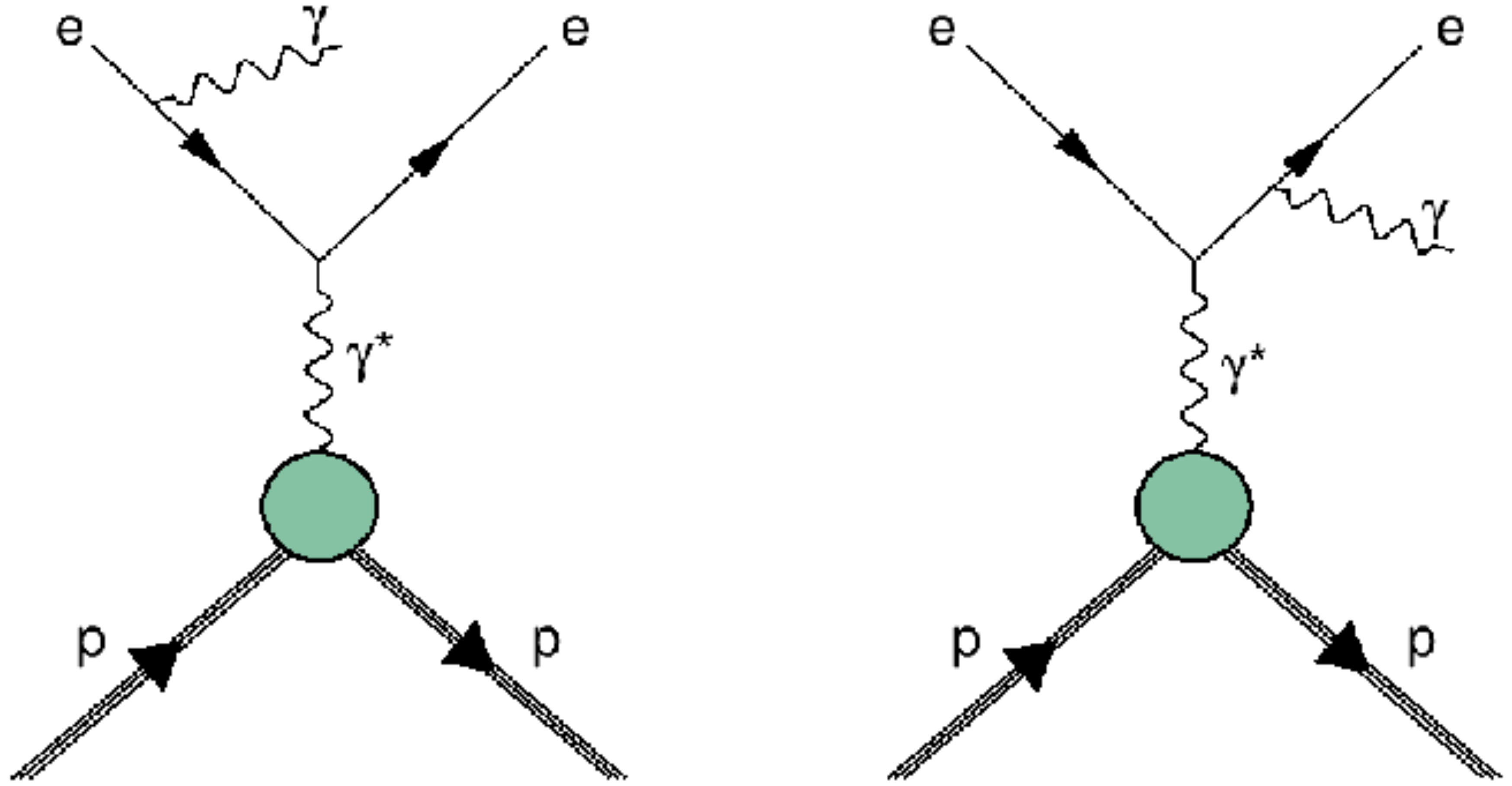
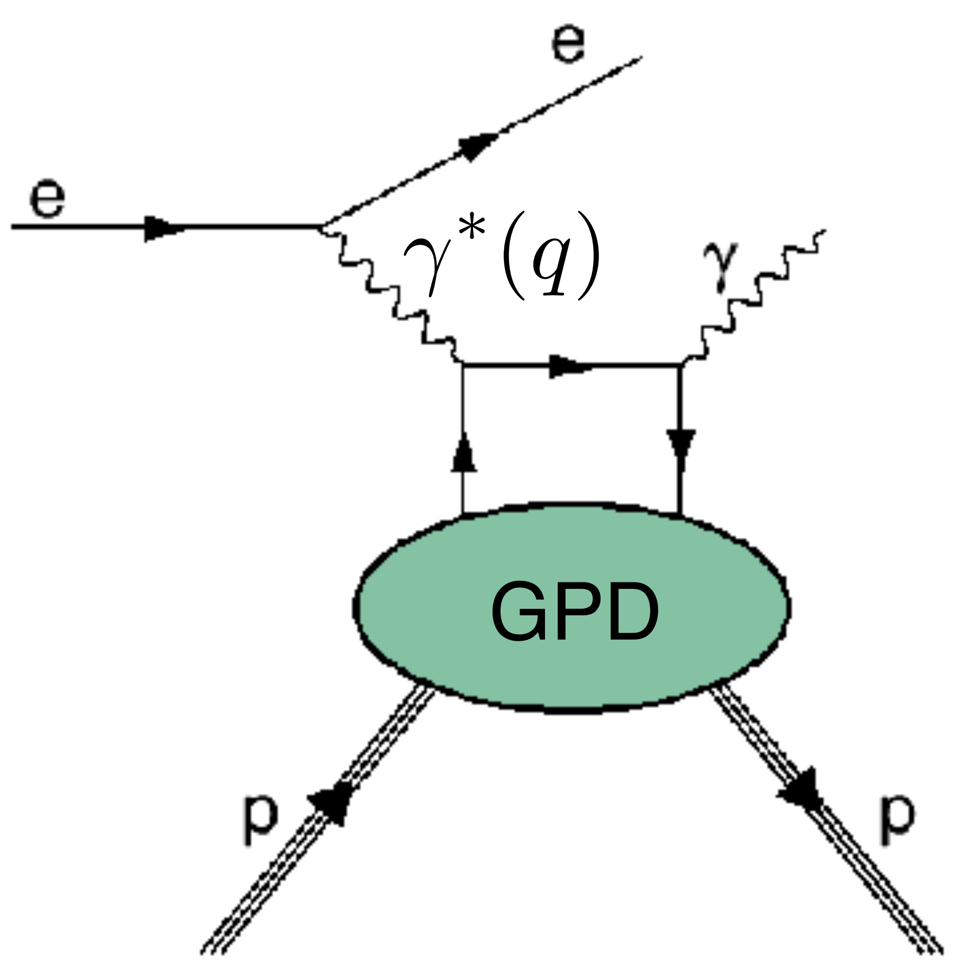


Bethe-Heitler

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH}$$

Deeply virtual Compton scattering



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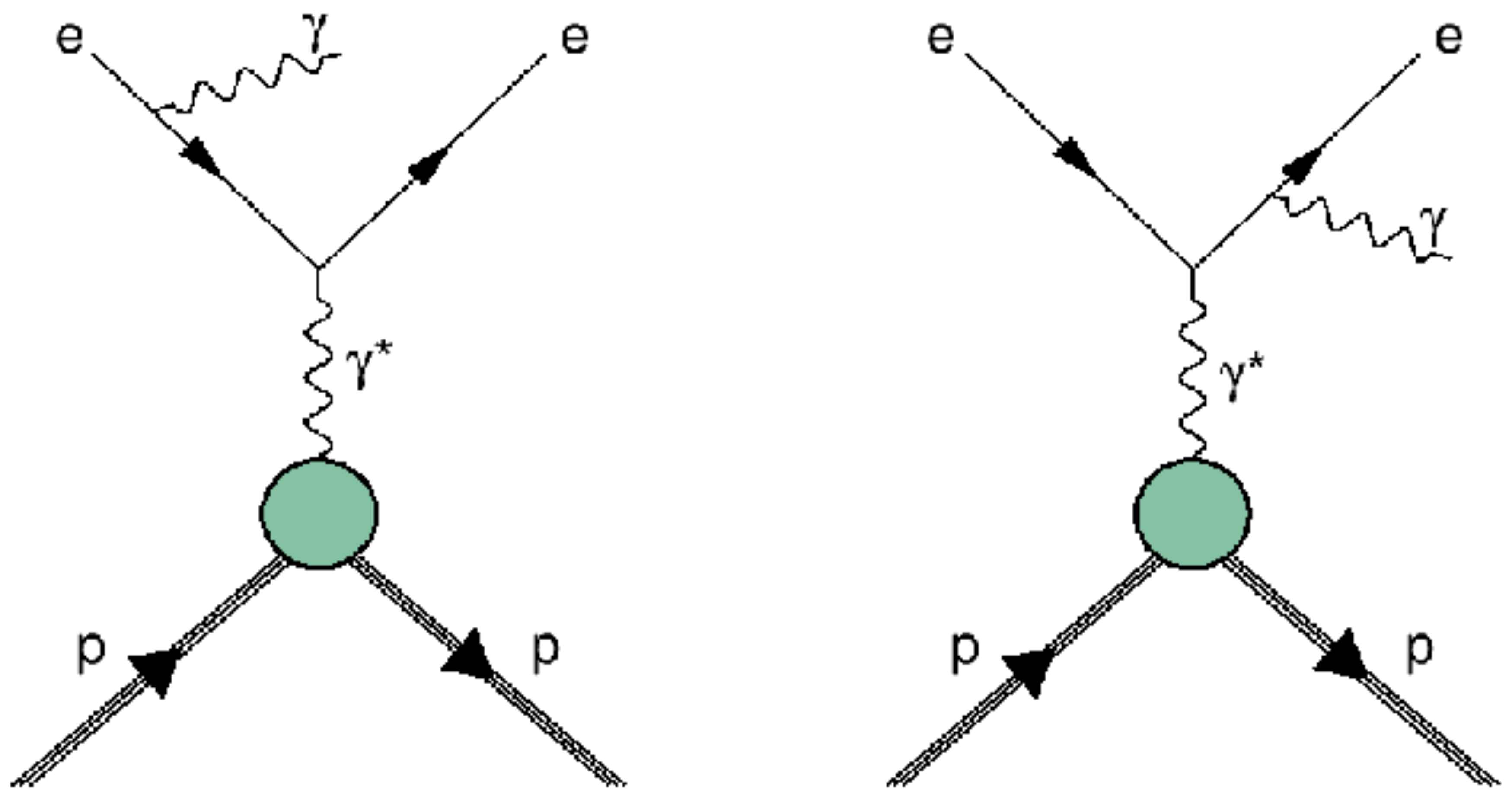

Bethe-Heitler

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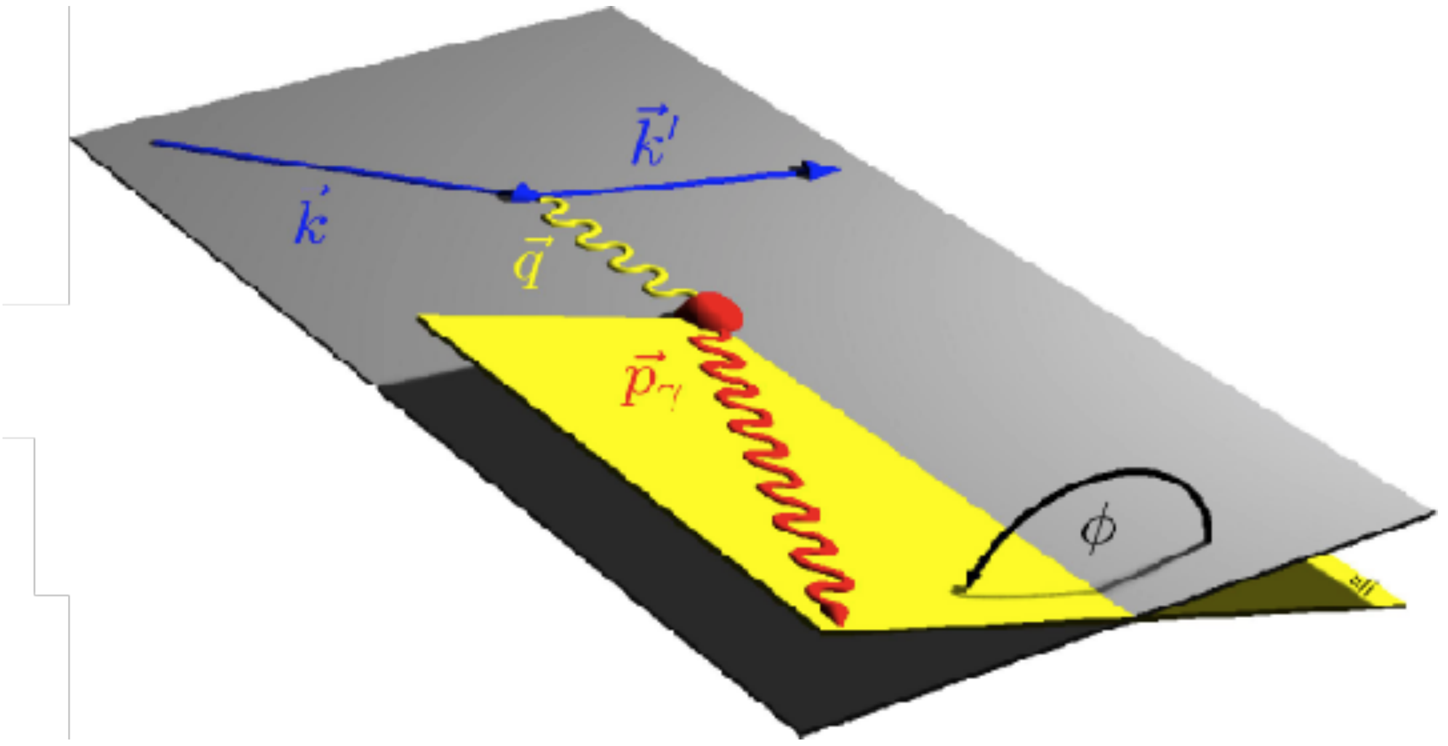
Interference term for unpol. nucleon, longitudinally pol. lepton beam

$$\mathcal{I} = \frac{-e_l K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\,\mathcal{P}_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right\}$$

coefficients: linear in GPDs

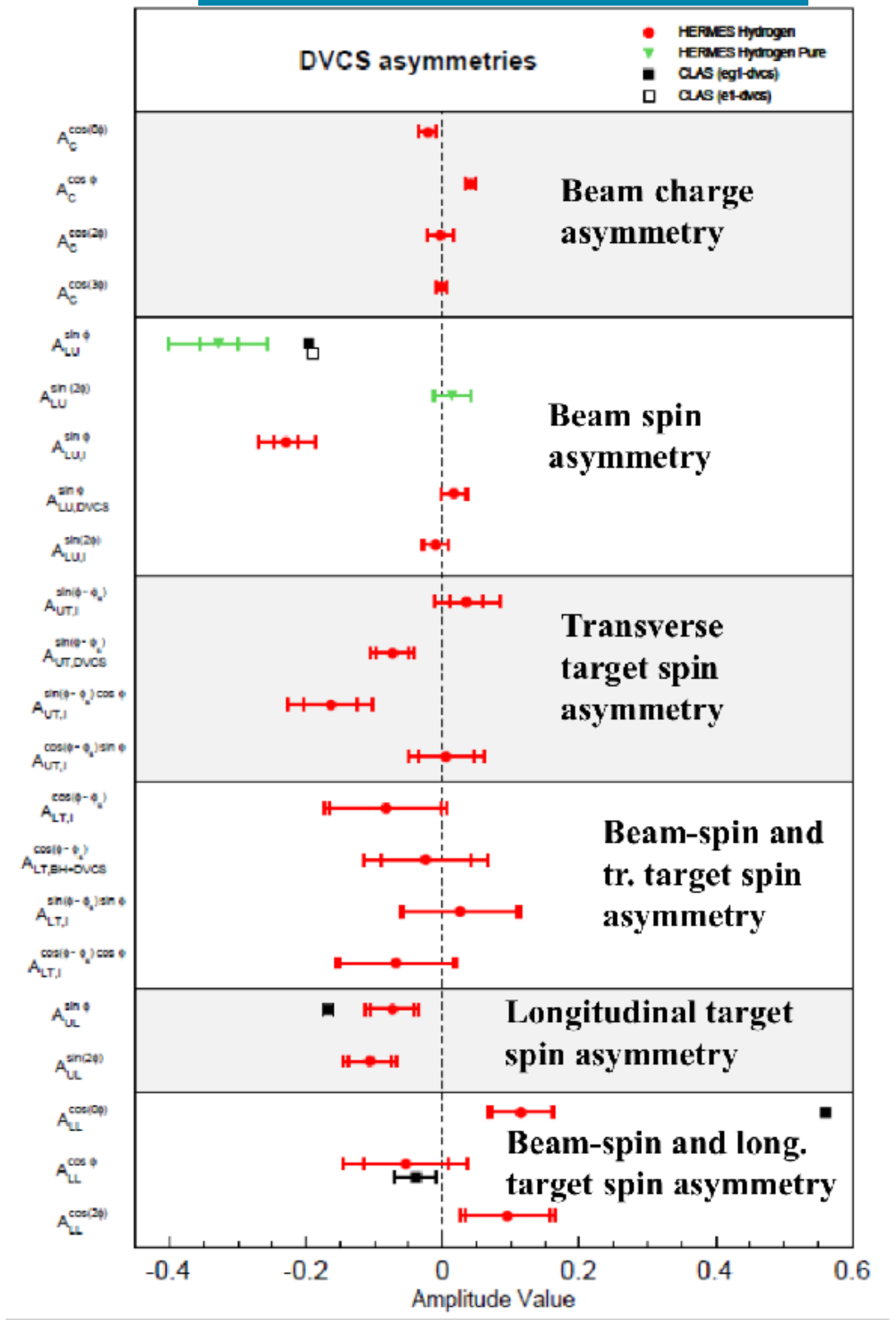
beam charge

beam polarization



Deeply virtual Compton scattering on proton target

Pioneering measurements



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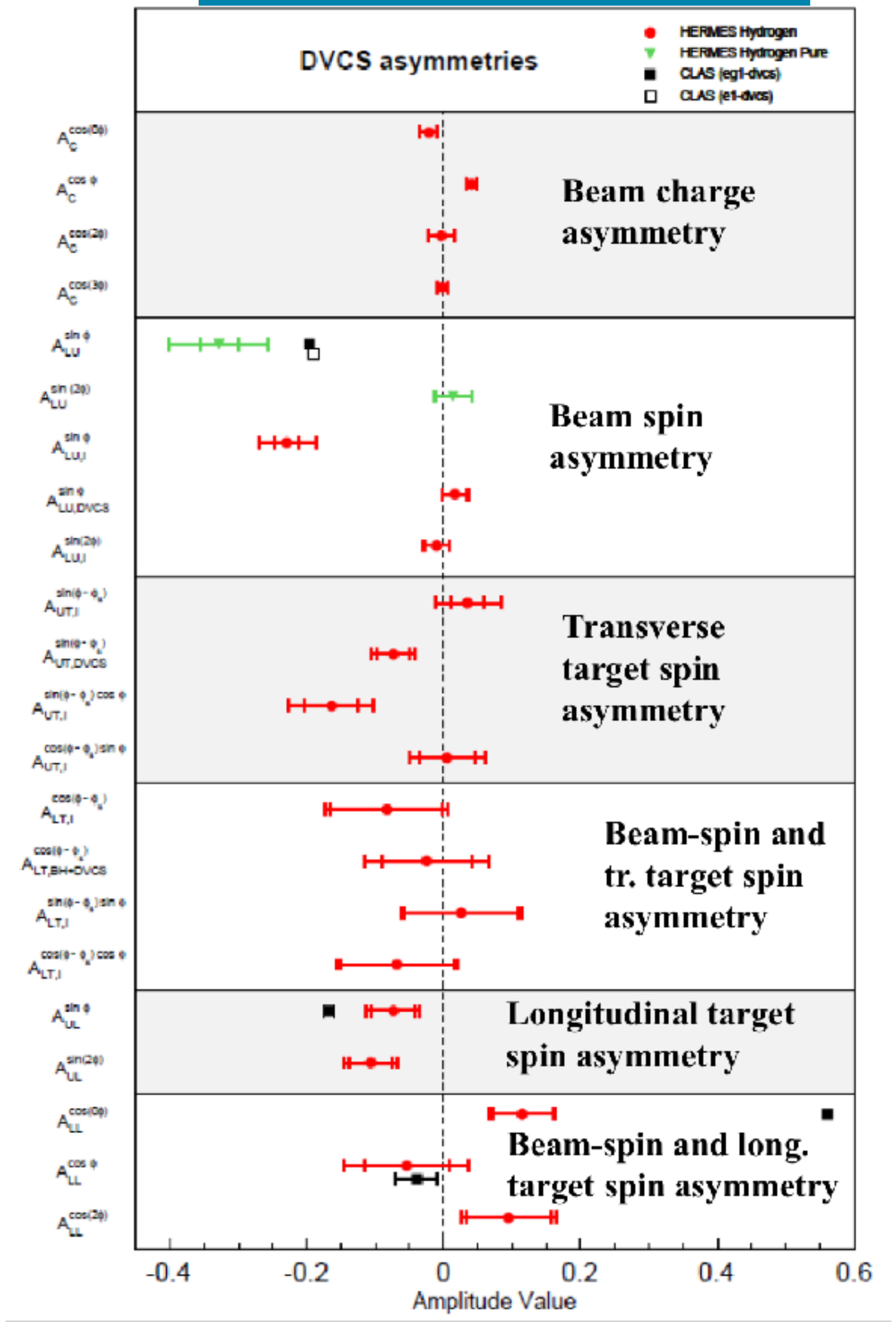
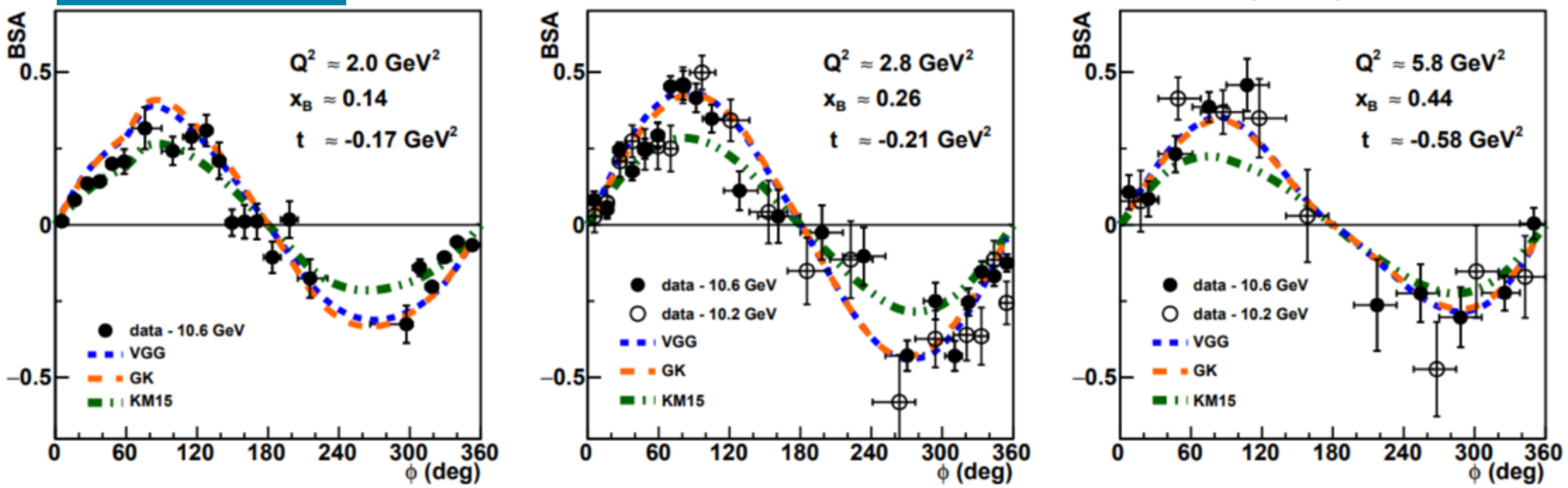


JLab 12 GeV

CLAS12 PRL **130** (2023) 21, 211902



Vast extension of statistics: 64 bins in x_B, Q^2, t

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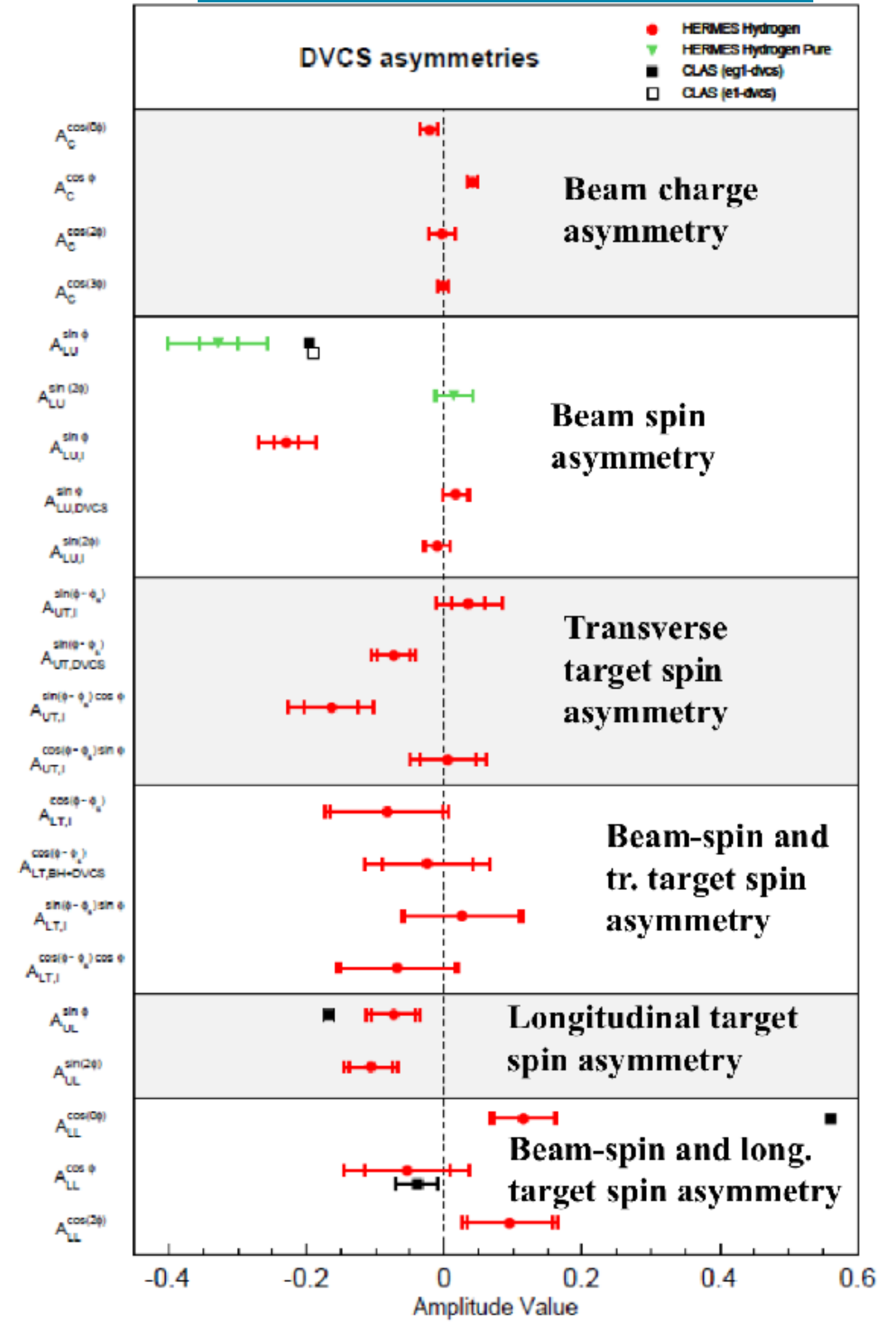

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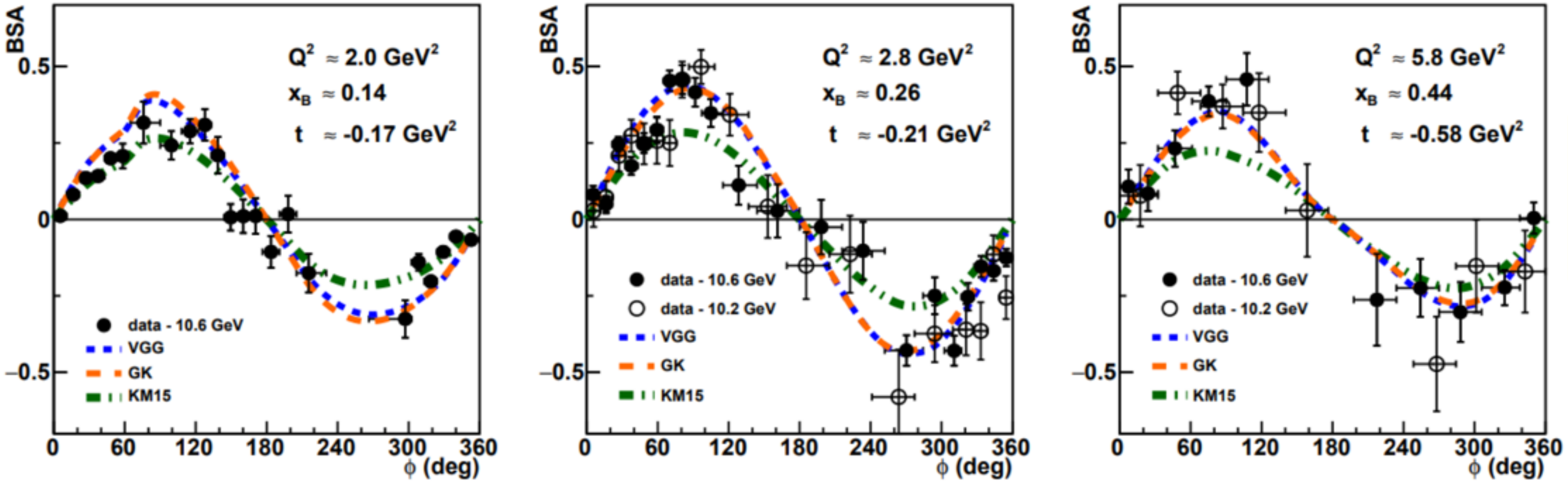

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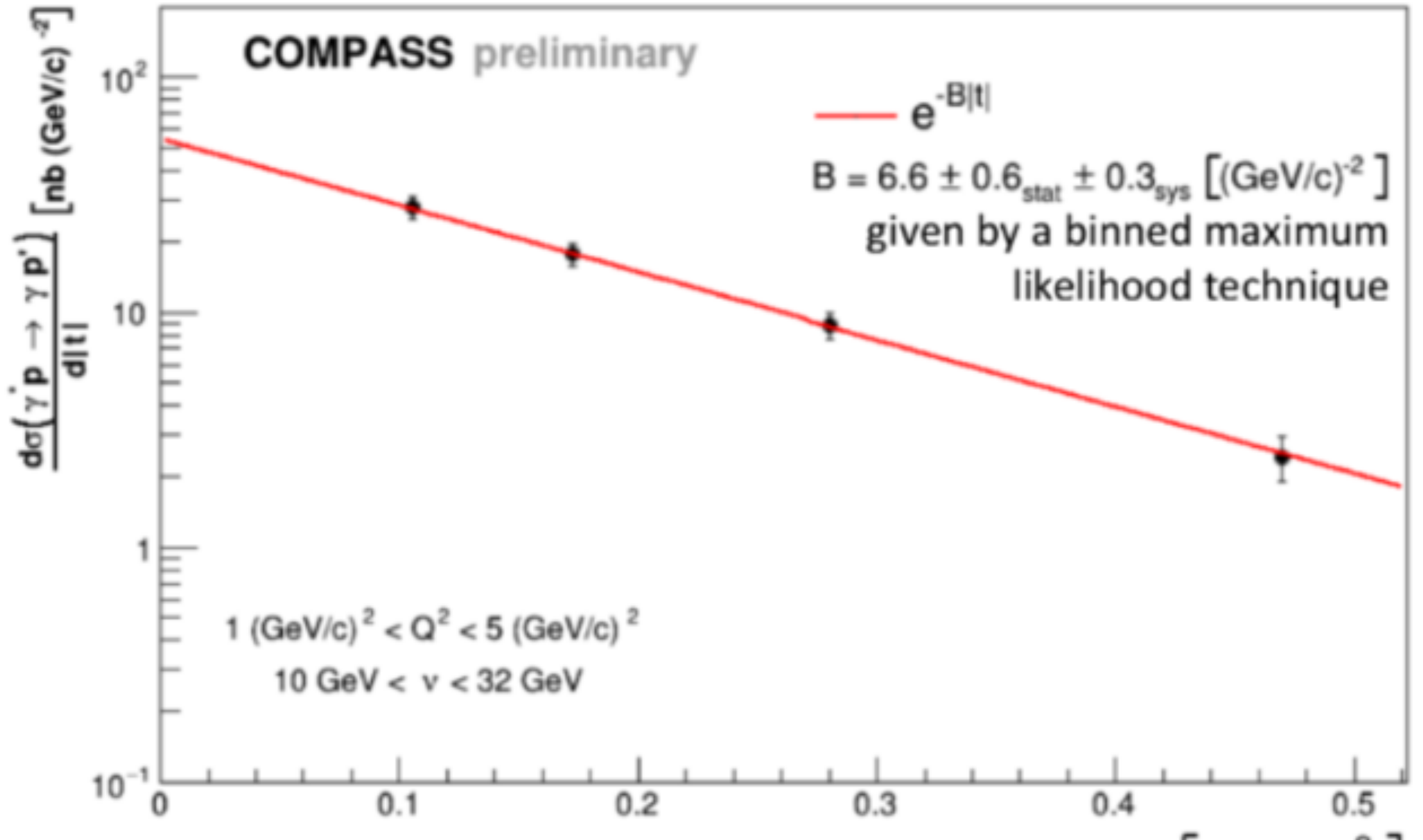
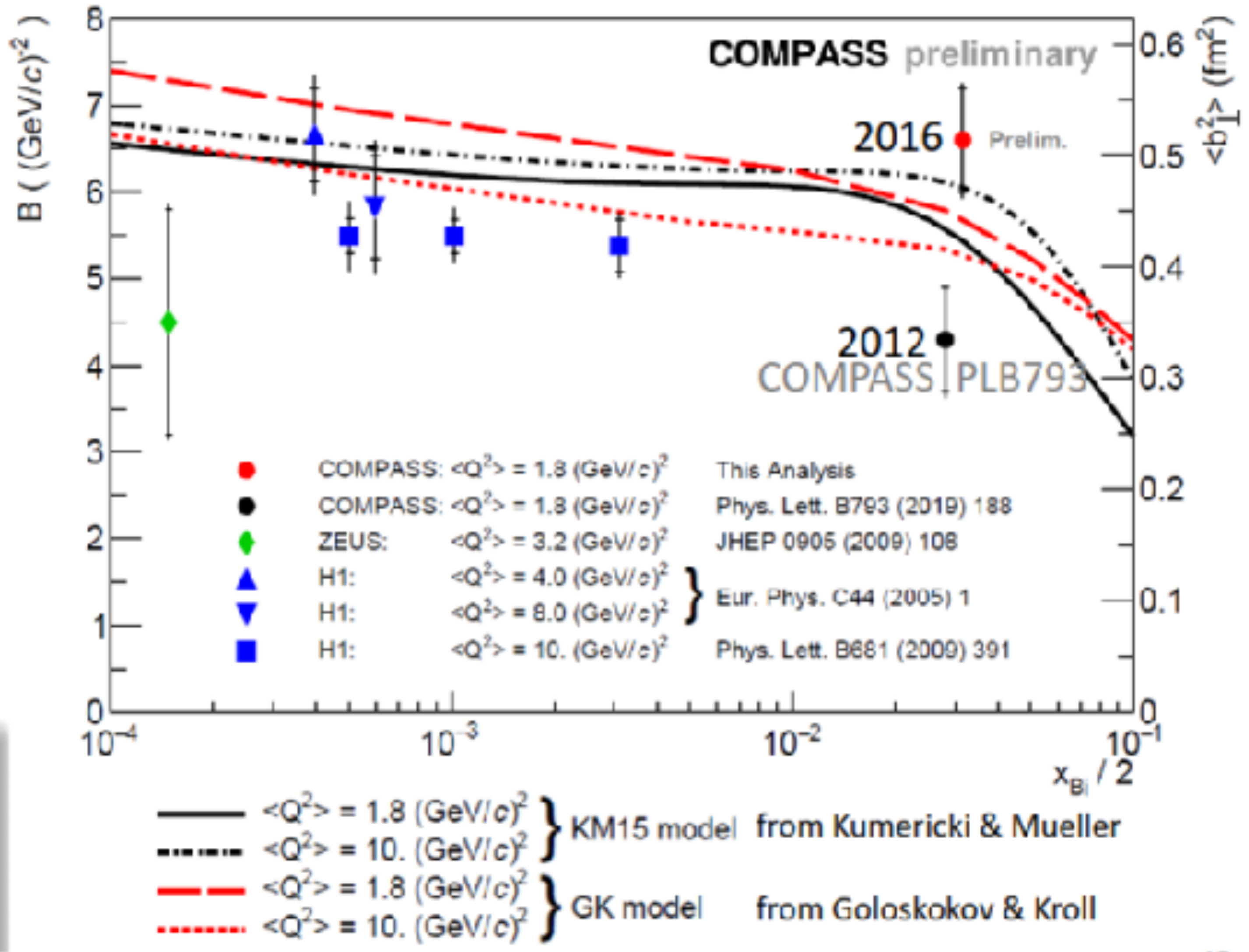
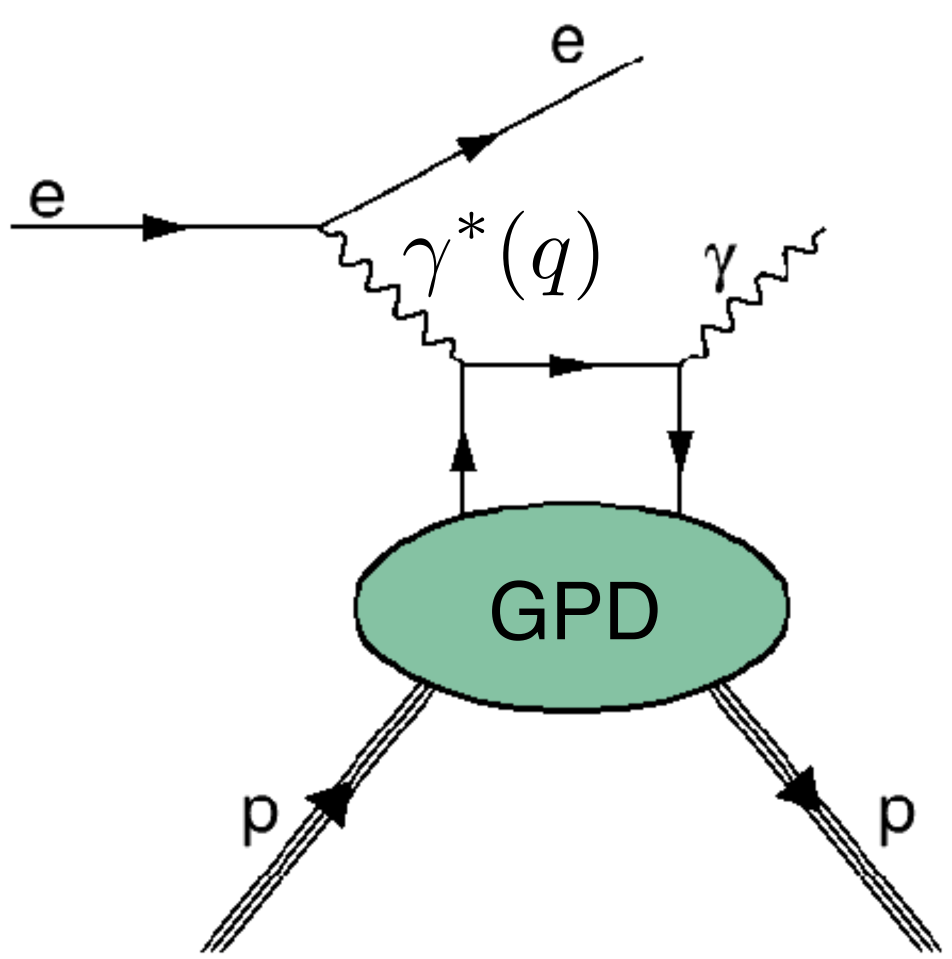
COMPASS





1/3rd of available statistics

Timelike Compton scattering



DVCS

hard scale = large Q^2

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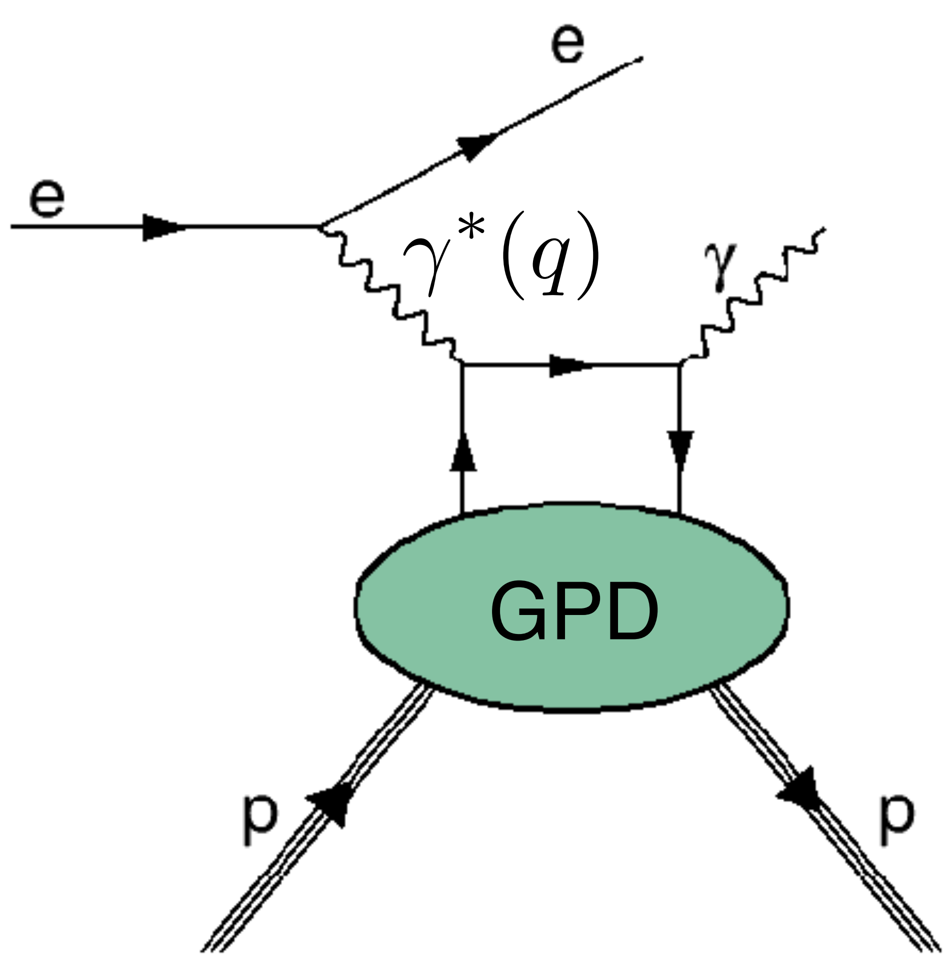

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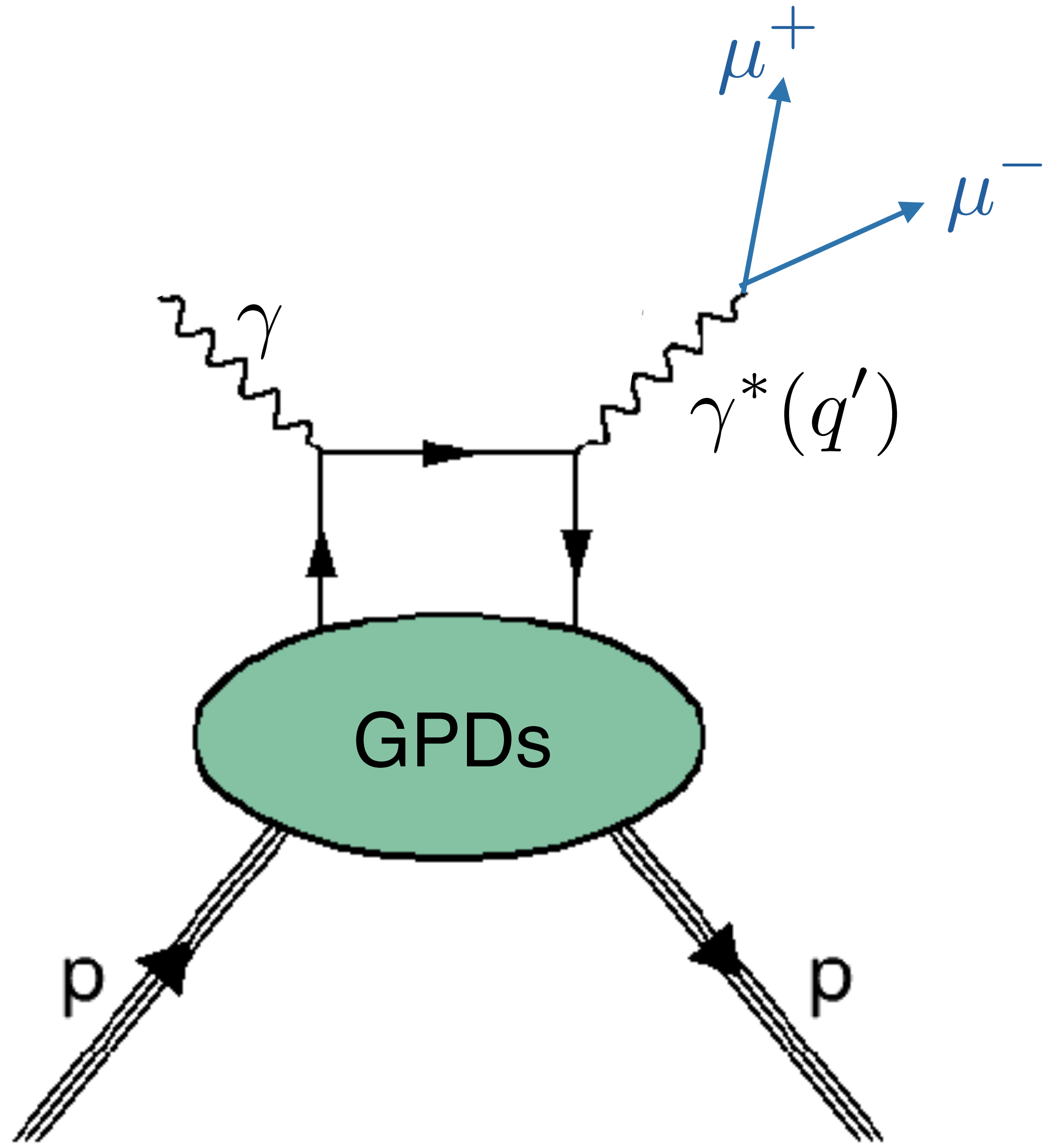
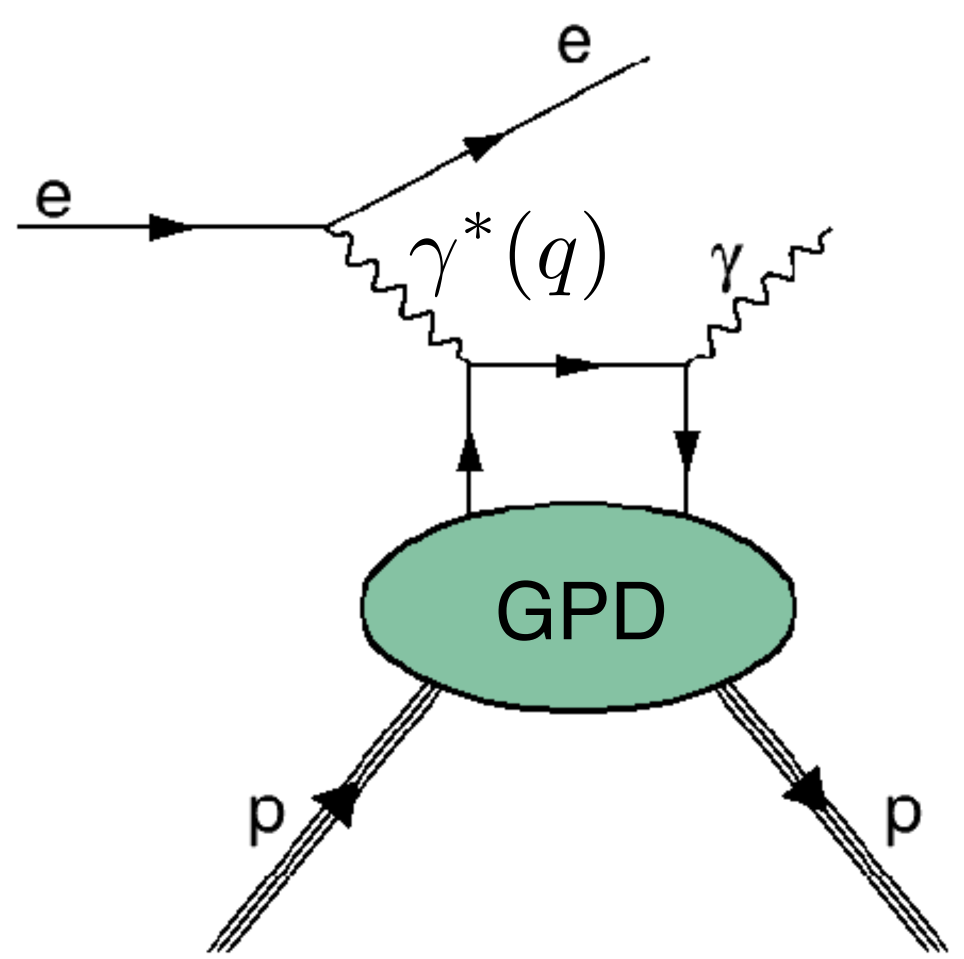


TCS

hard scale = large Q'^2

→ In practice a few GeV^2

Timelike Compton scattering



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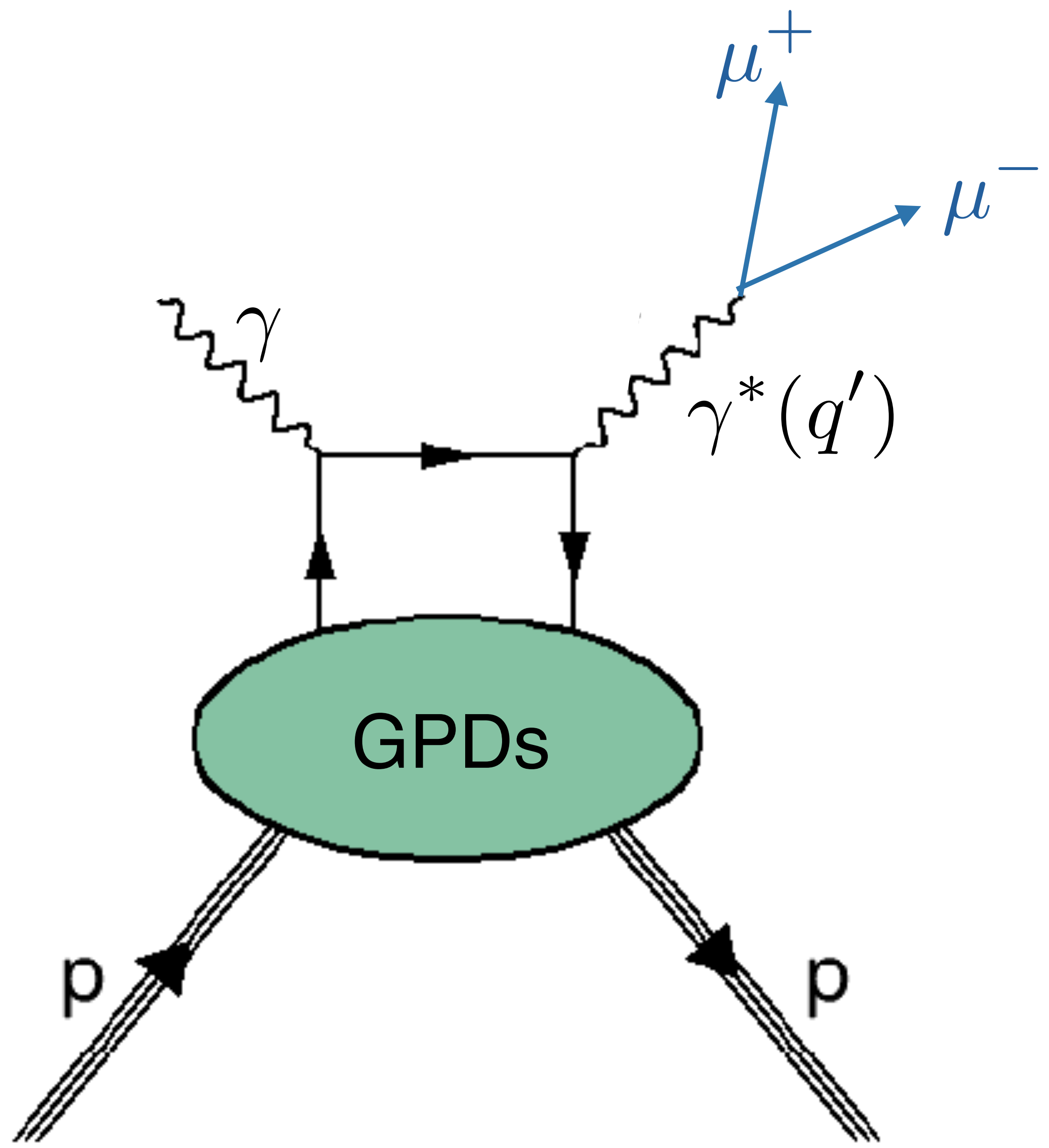

TCS

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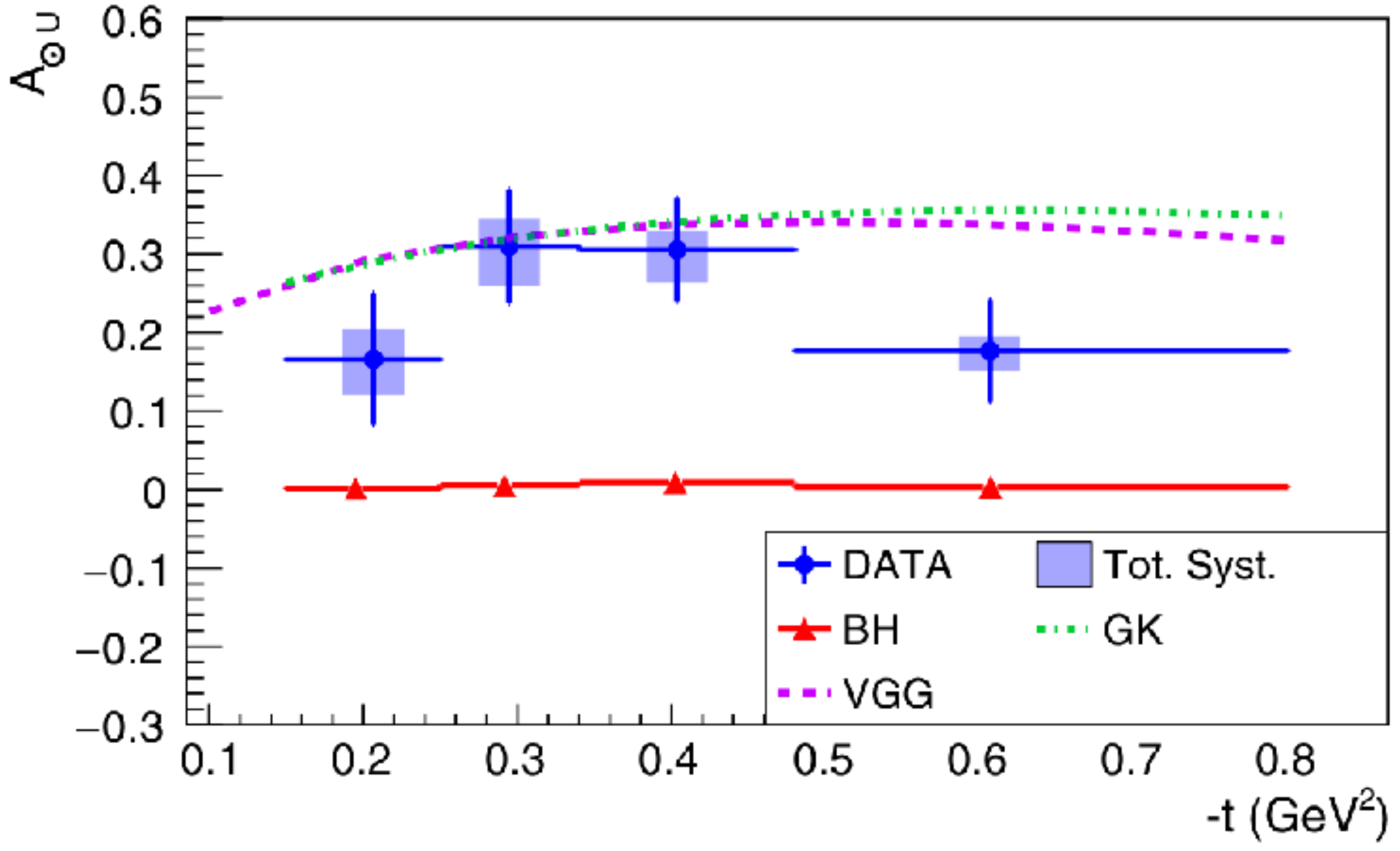
→ In practice a few GeV^2

Compare DVCS and TCS: understand QCD corrections and check universality.

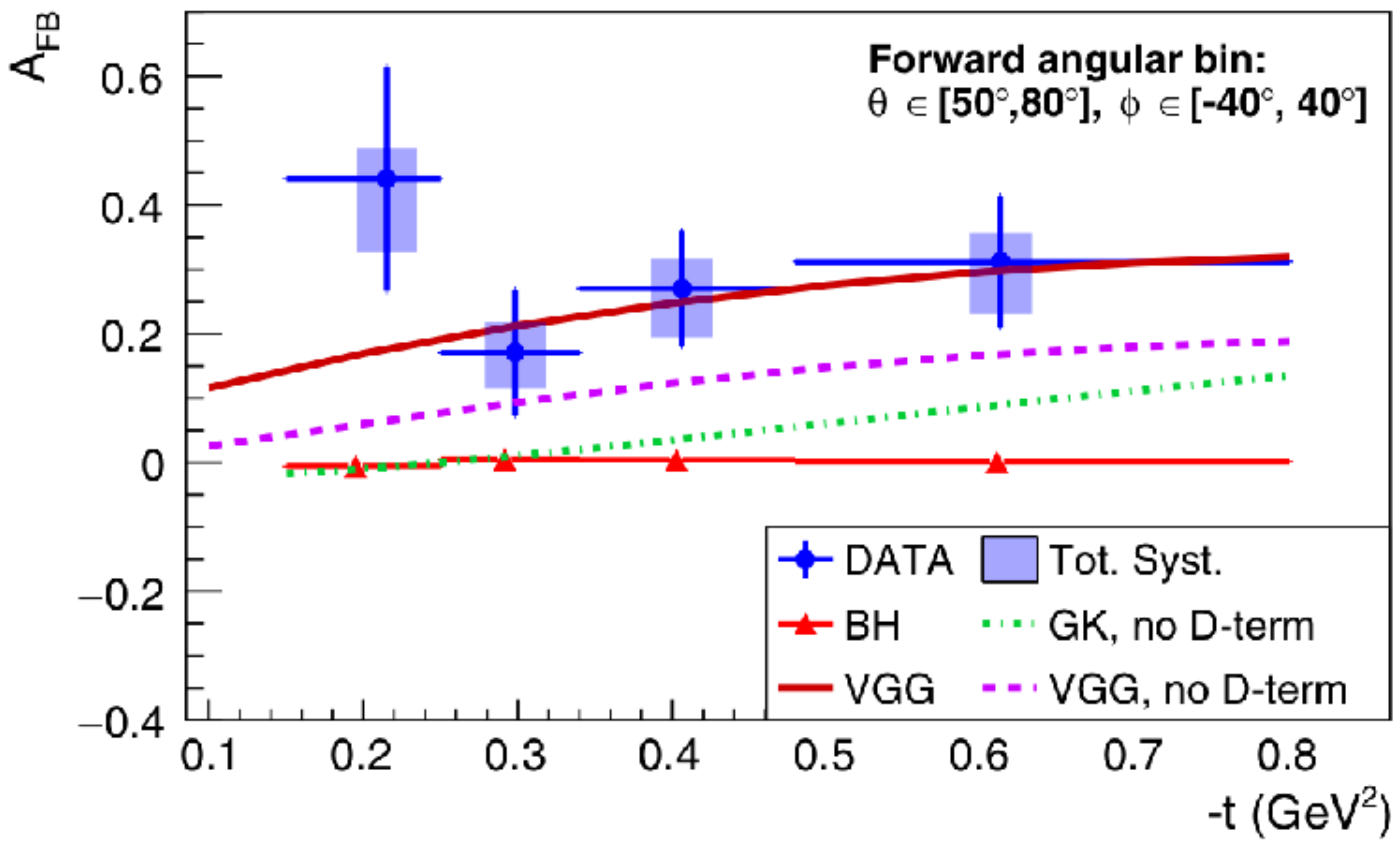
Timelike Compton scattering

Photon polarisation asymmetry



$\sim Im\mathscr{H}$: same information as DVCS

Forward-backward asymmetry



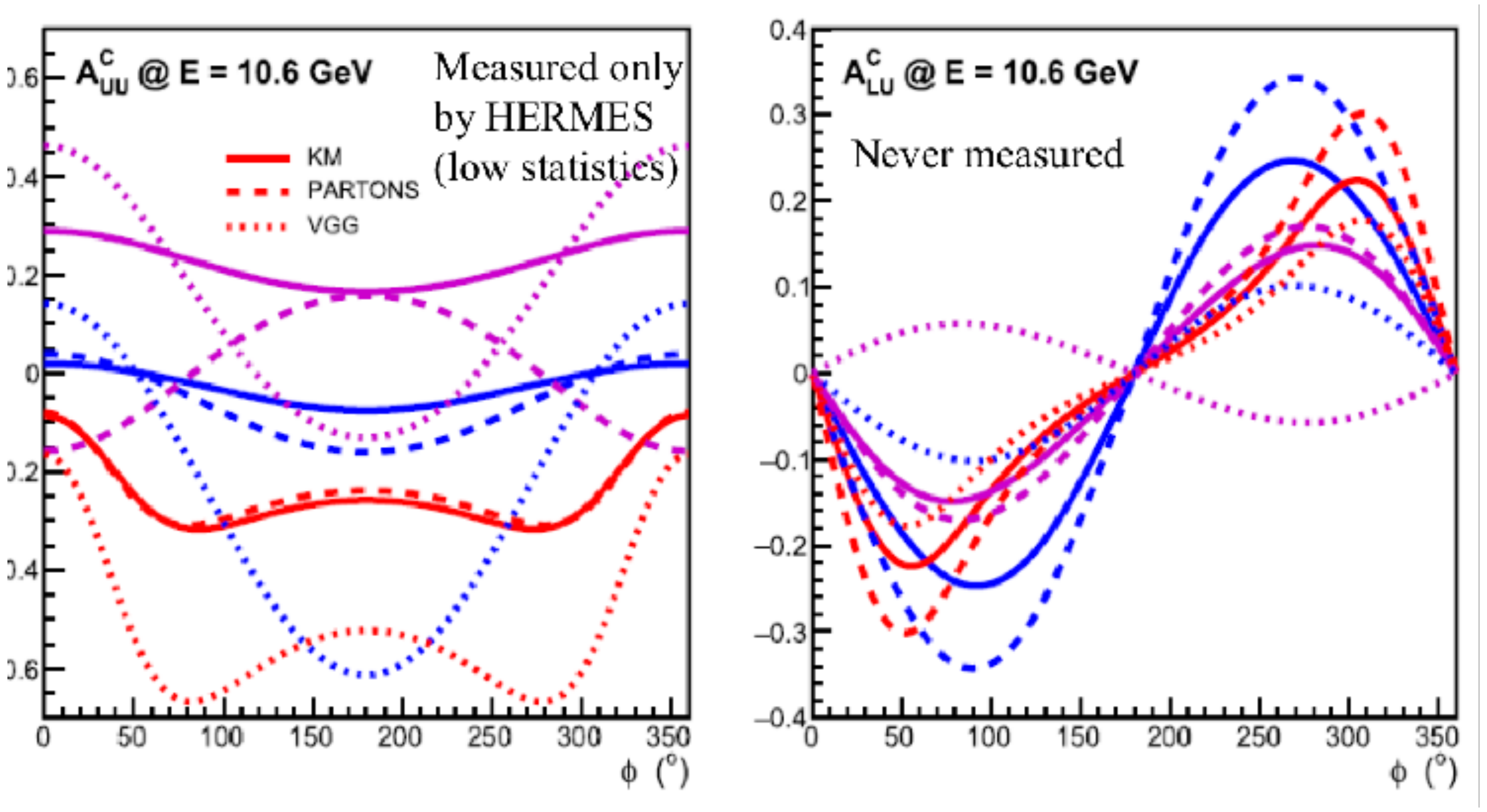
$$A_{\mathrm{FB}}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180° - \theta, 180° + \phi)}{d\sigma(\theta,\phi) + d\sigma(180° - \theta, 180° + \phi)}$$

$\sim Re\mathscr{H}$

Upcoming experiments probing GPDs

- On-going R&D studies for positron beam at JLab (>2030)

PePPO: proof-of-principle for a polarised positrons beam (PRL **116** (2016) 214801)



beam-charge asymmetries: access to $Re\mathscr{H}$

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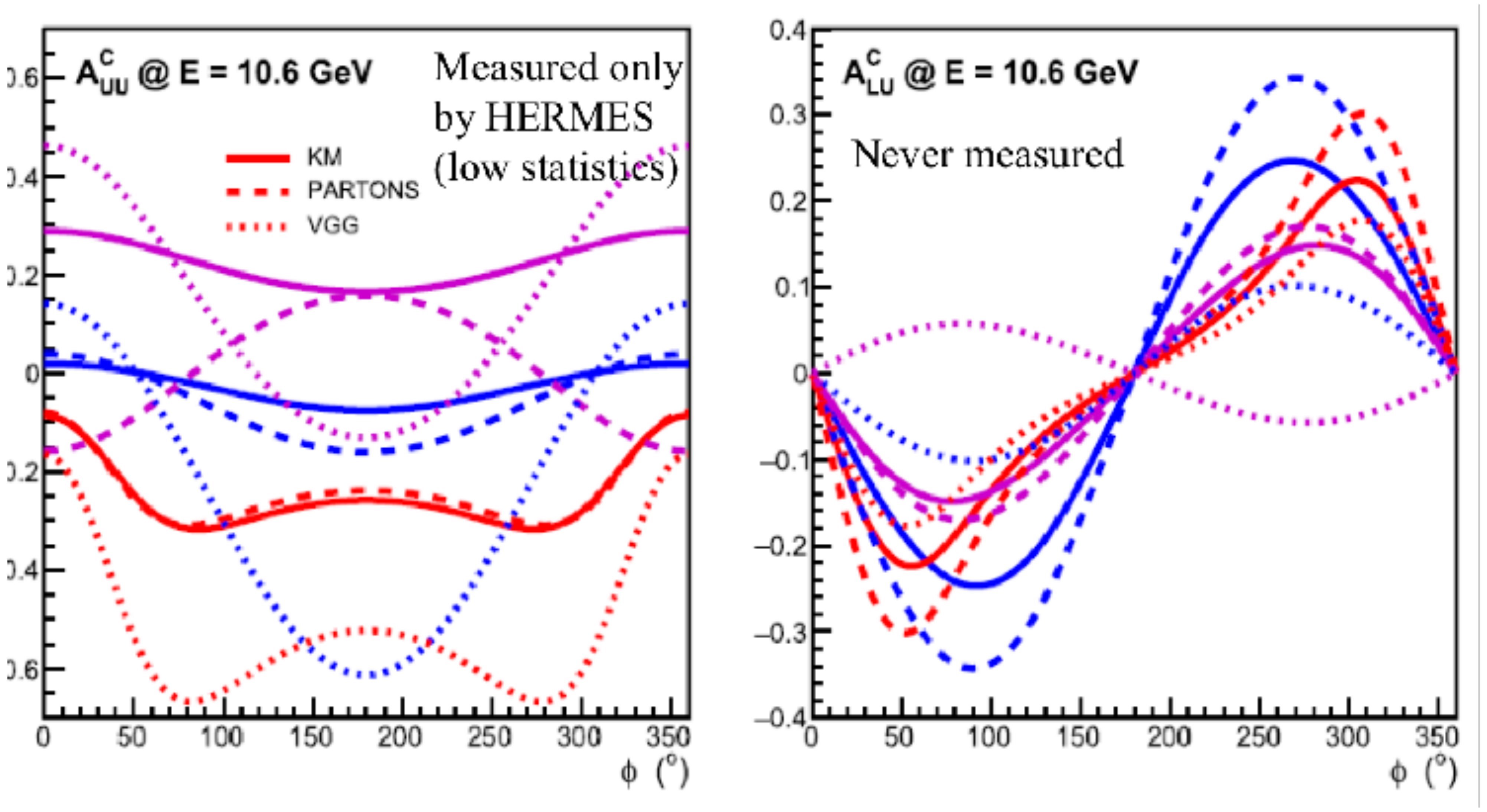

beam-charge asymmetries: access to $Re\mathscr{H}$

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proposal: at SOLID with muon detector added

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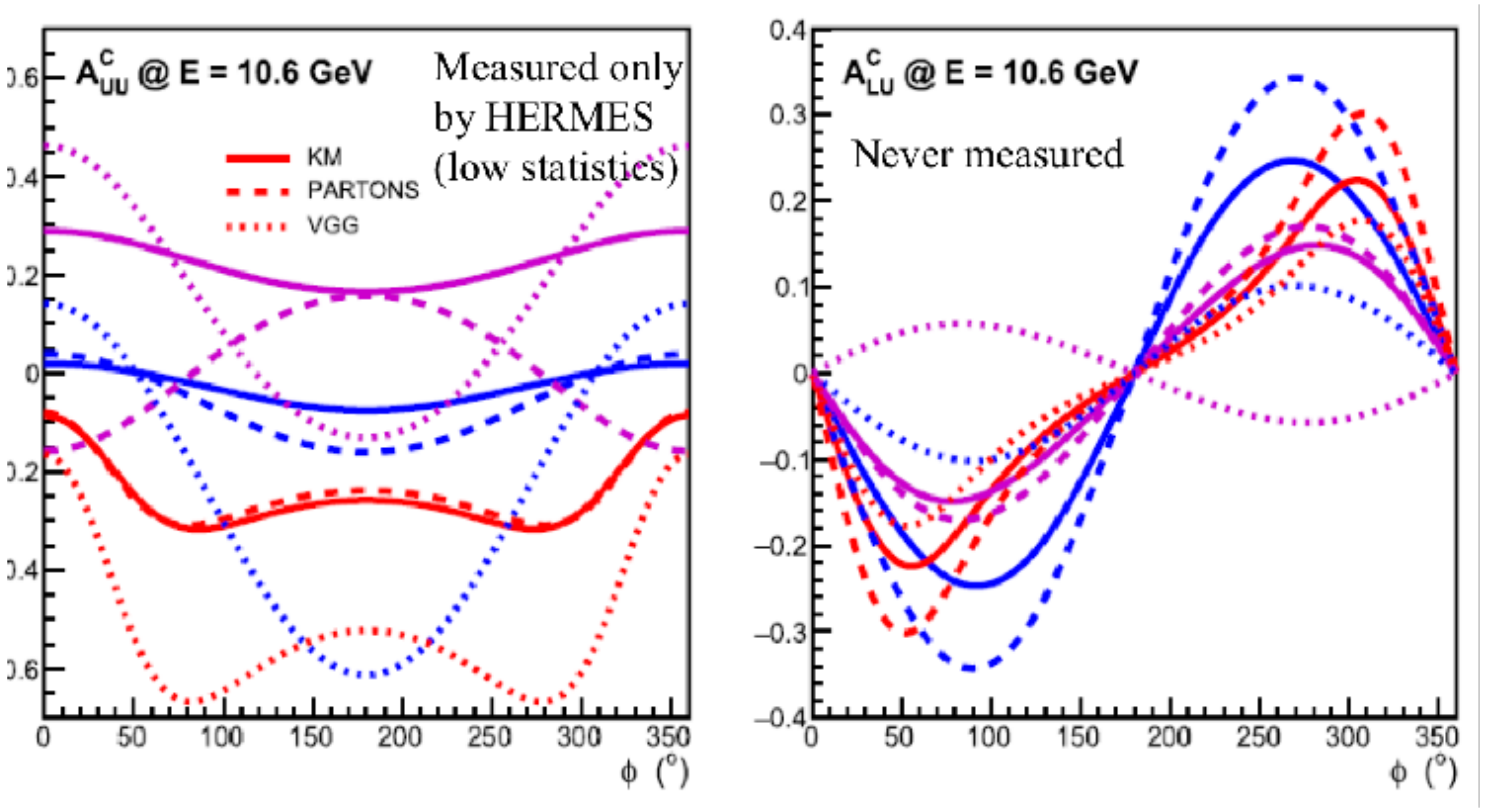

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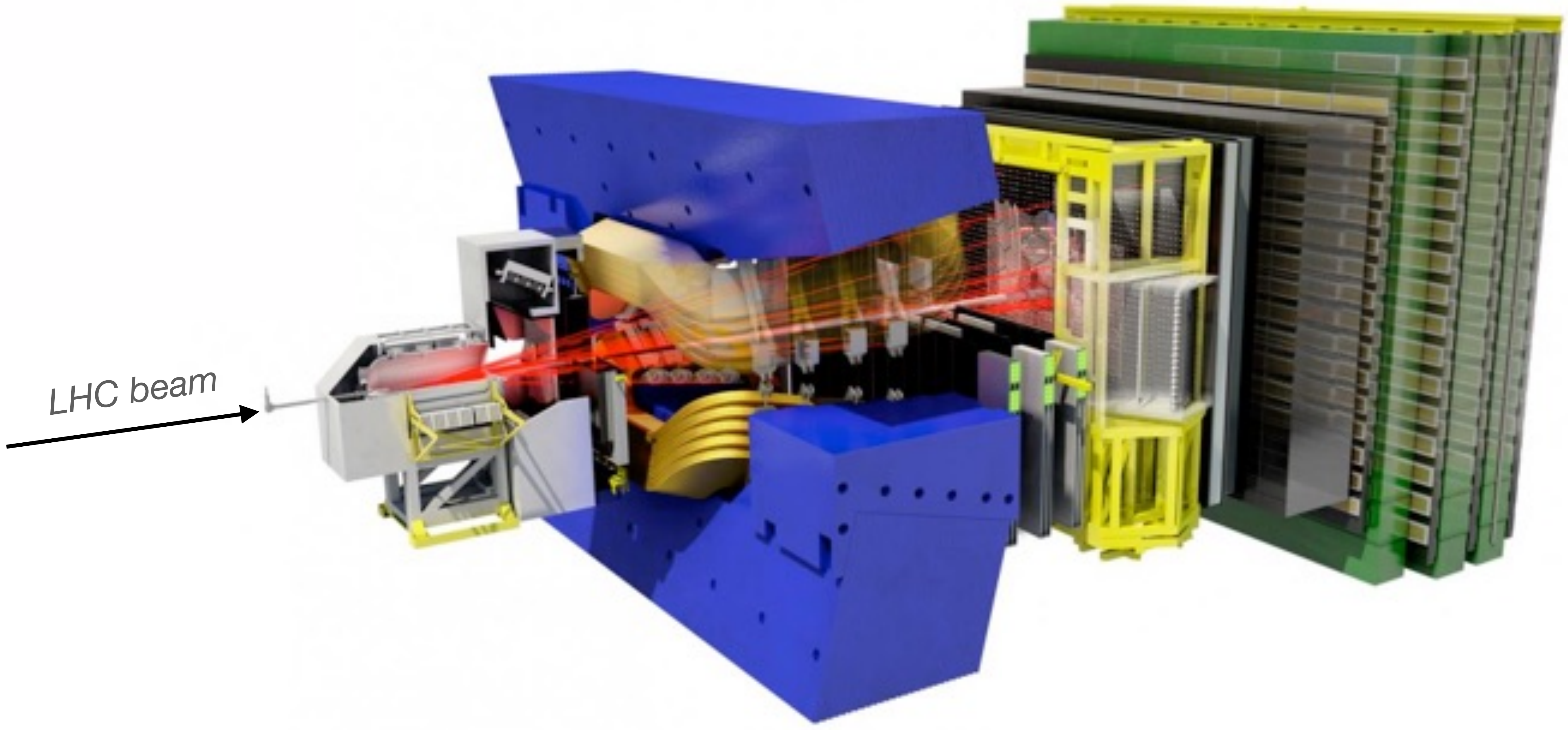
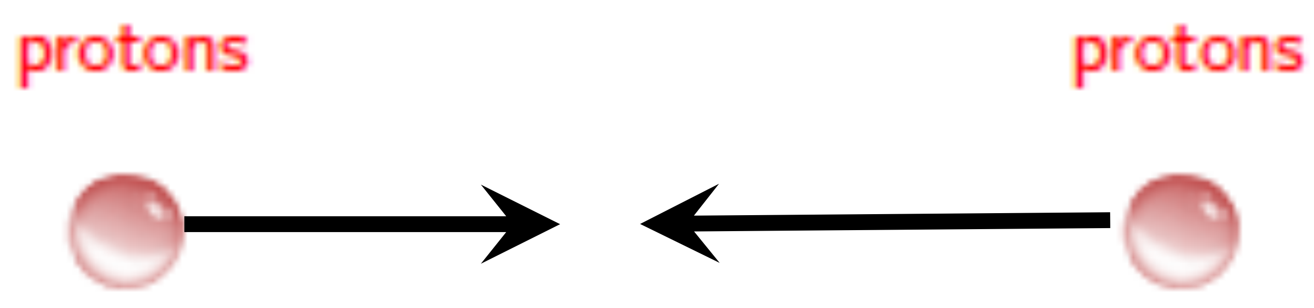
- JLab at 20+ GeV?

Fixed-target at LHCb

JINST 3 (2008) S
IJMPA 30 (2015)



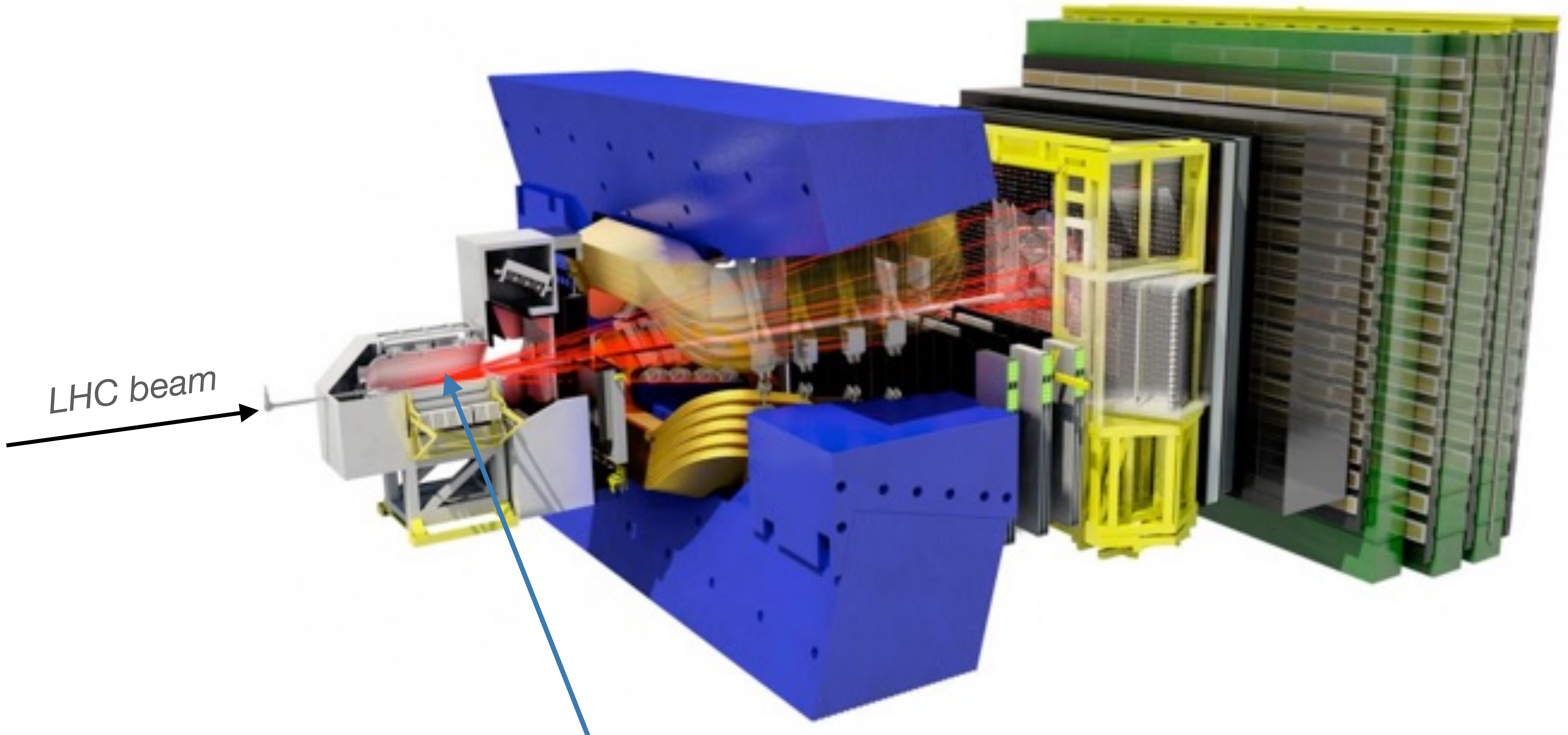


$\sqrt{s} = 13$ TeV

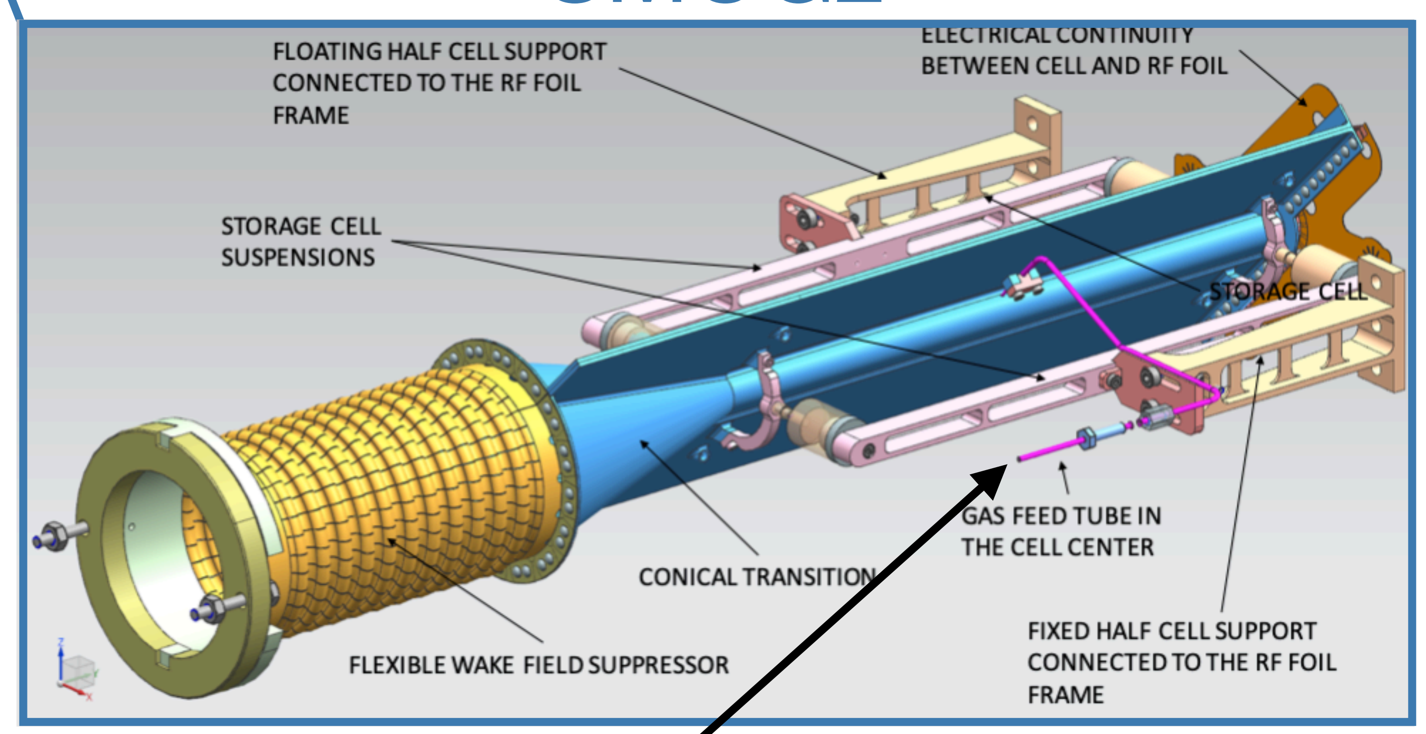
$2 < y_{CM} < 4.5$

Fixed-target at LHCb

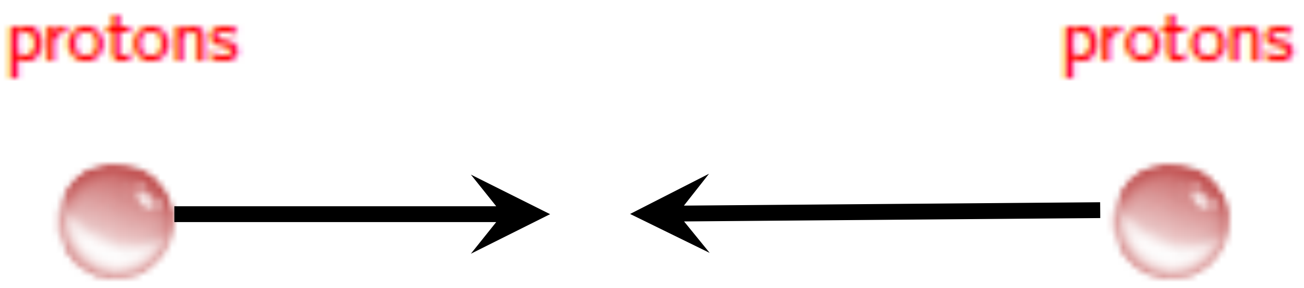
JINST 3 (2008) S…
IJMPA 30 (2015)…



SMOG2



inject gas: He, Ne, Ar, and H_2, D_2



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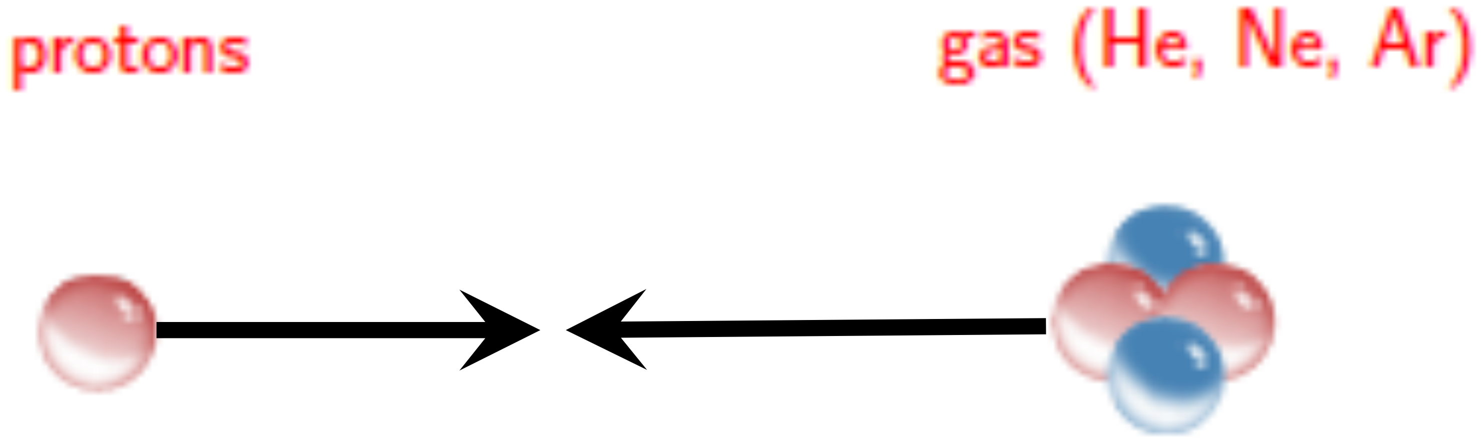
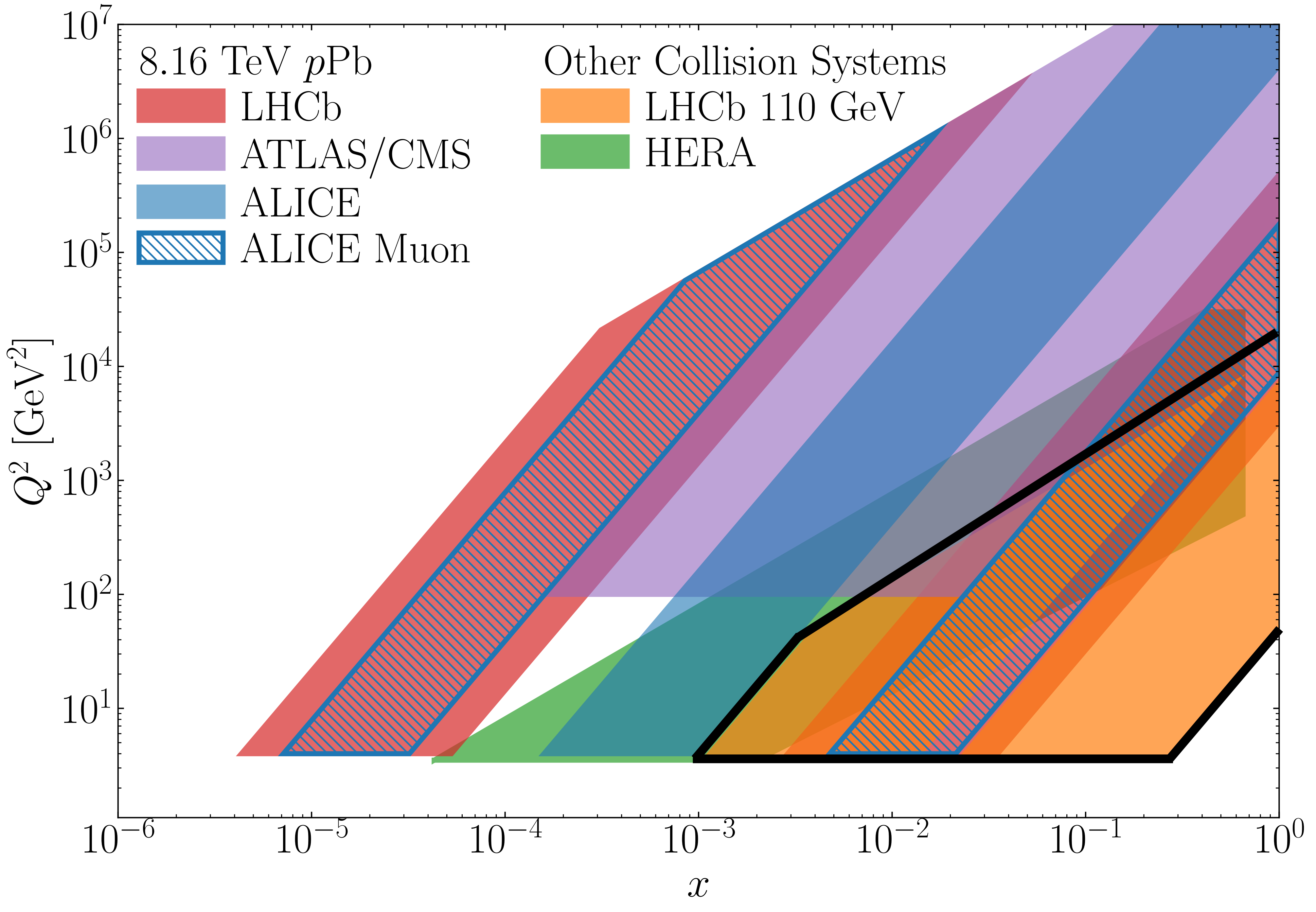


$\sqrt{s_{NN}} = 115$ GeV

$-2.78 < y_{CM} < 0.2$

Fixed-target at LHCb

Access to barely explored high-x region for PDFs, GPDs, TMDs.



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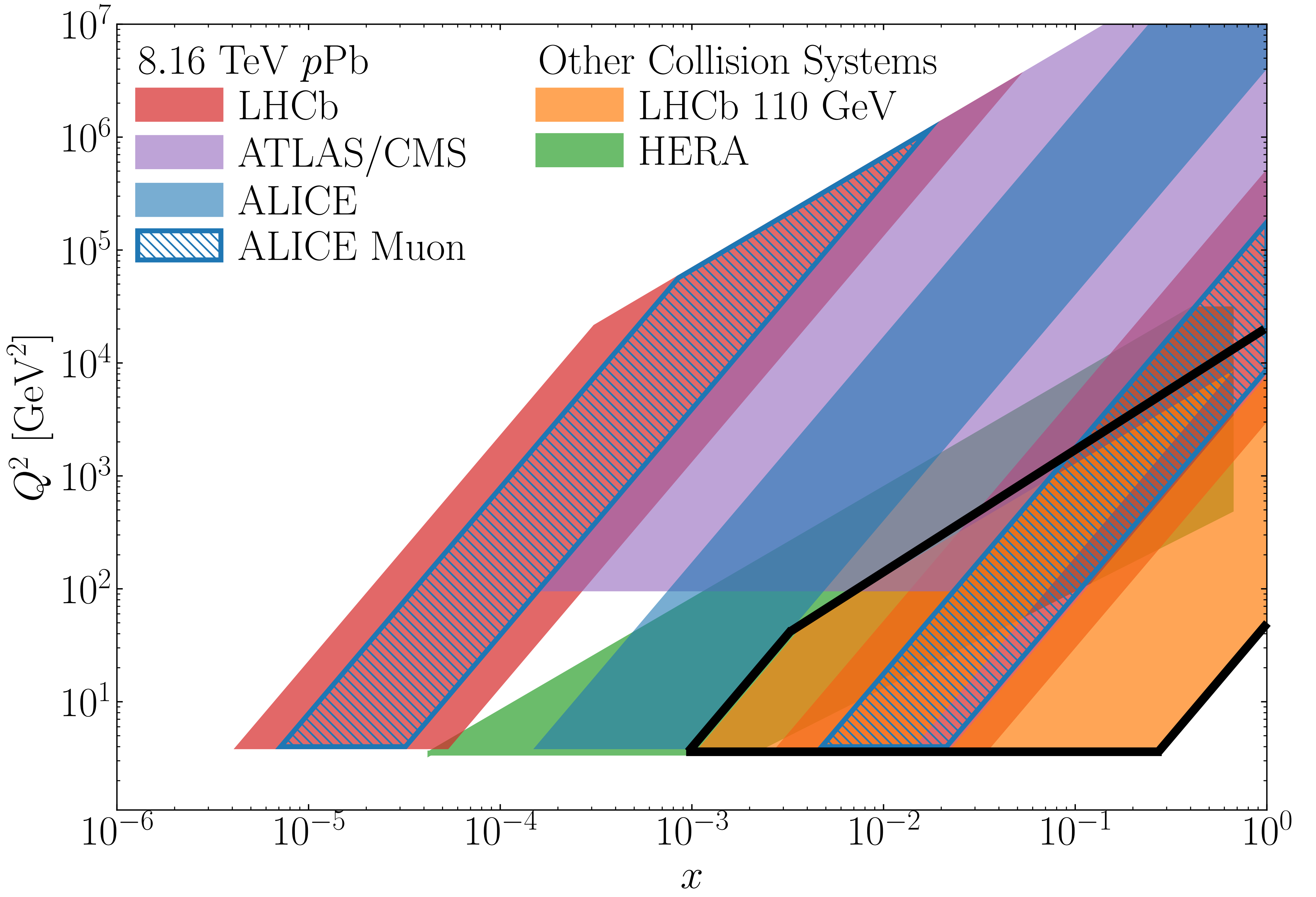

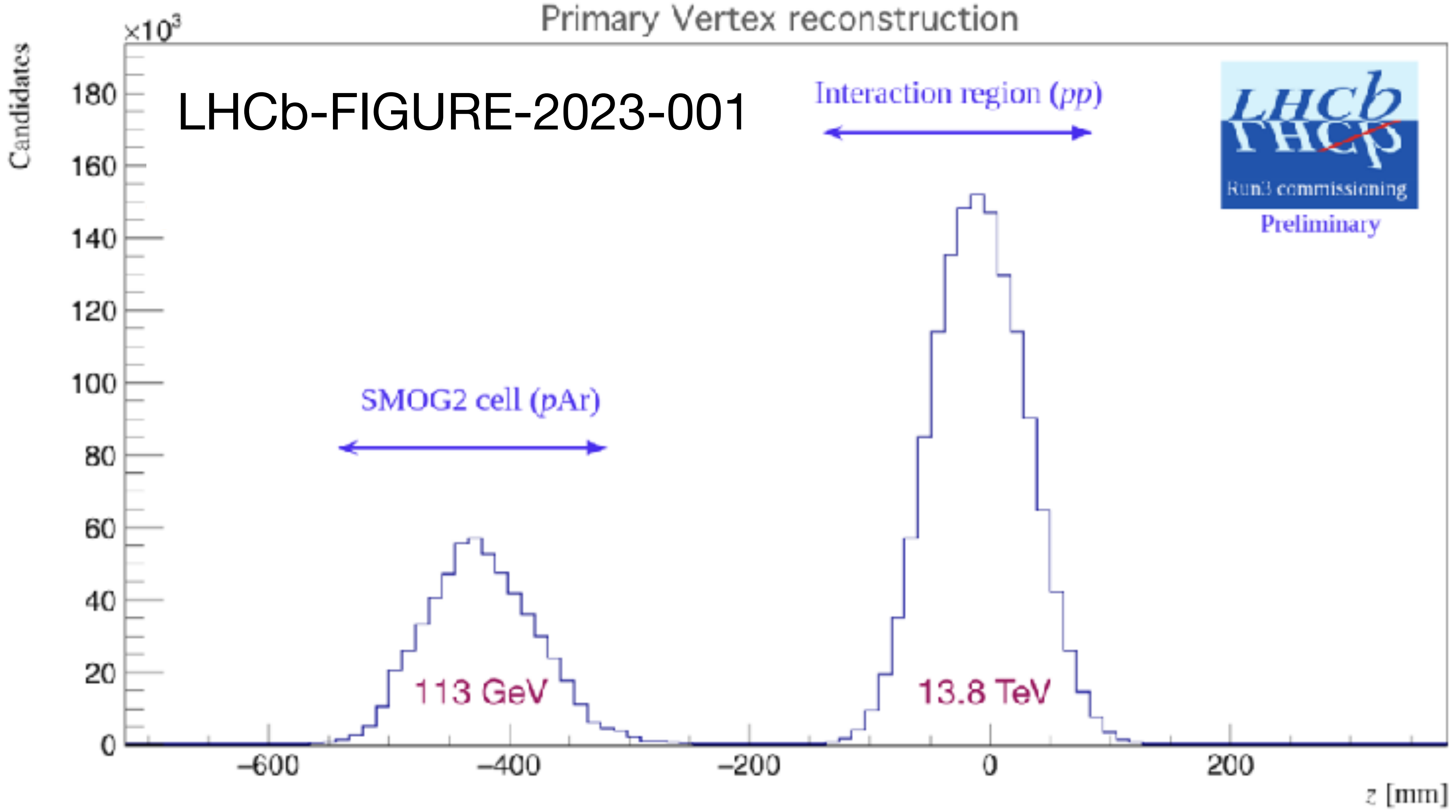

Two well-separated and independent interaction points reconstructed during simultaneous data taking

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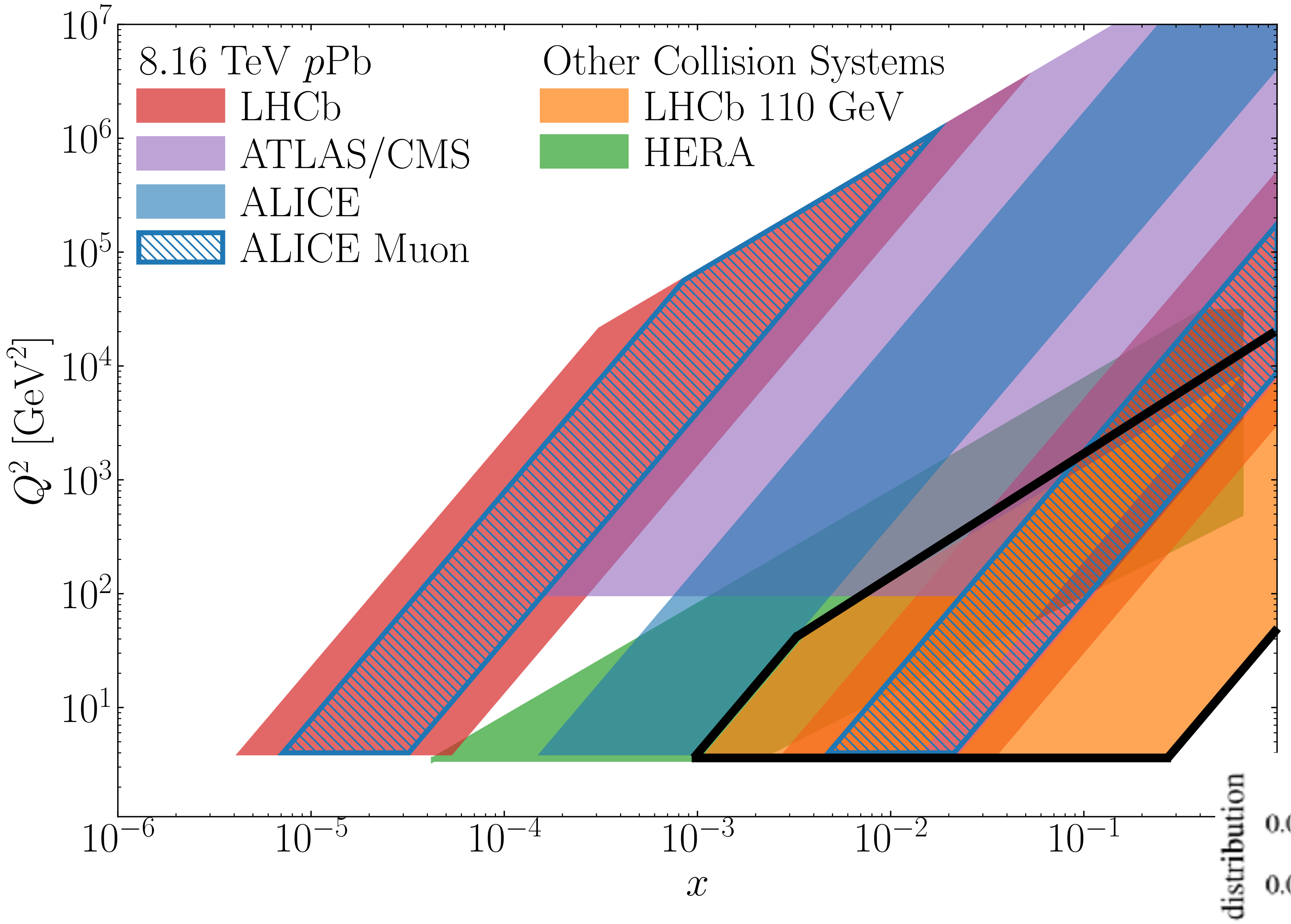

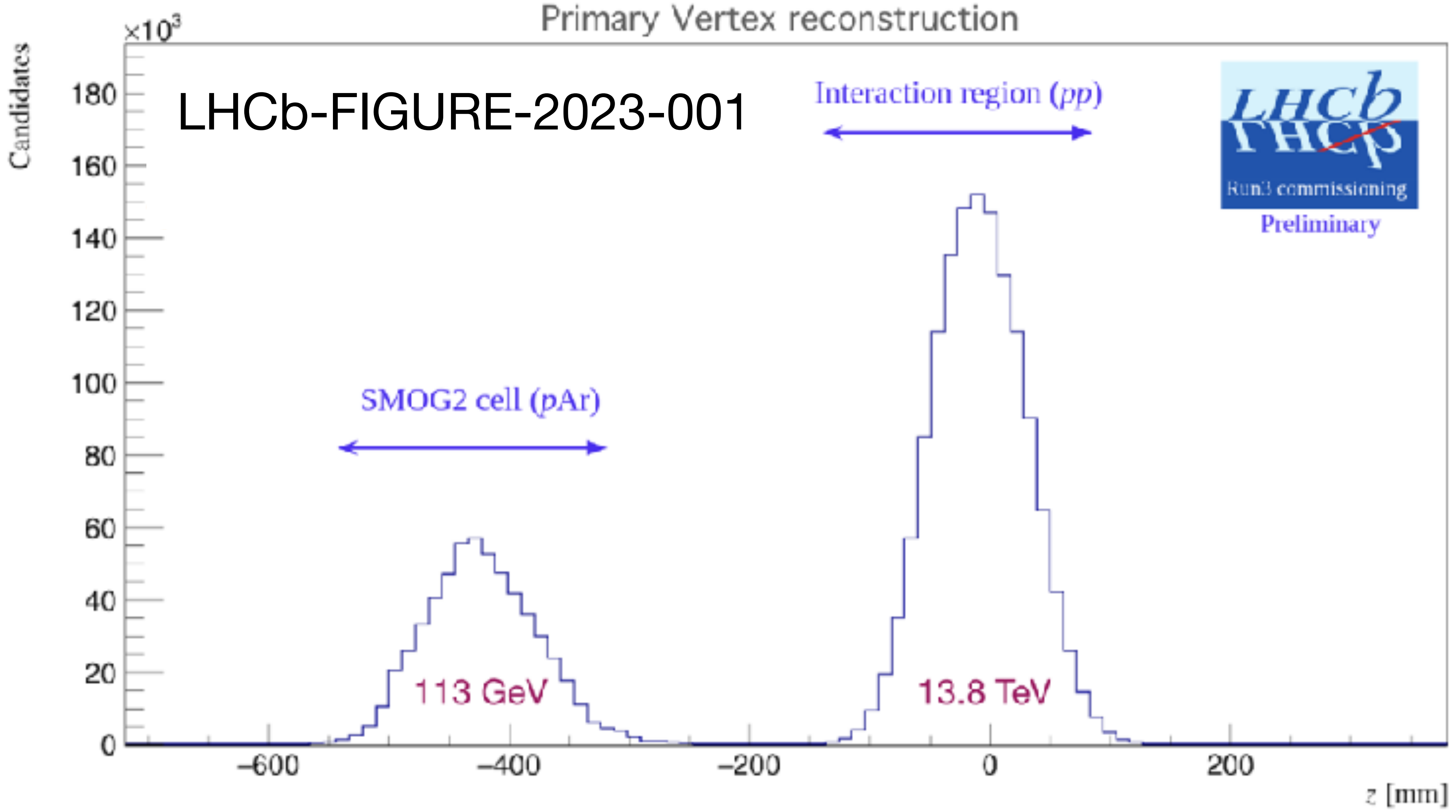

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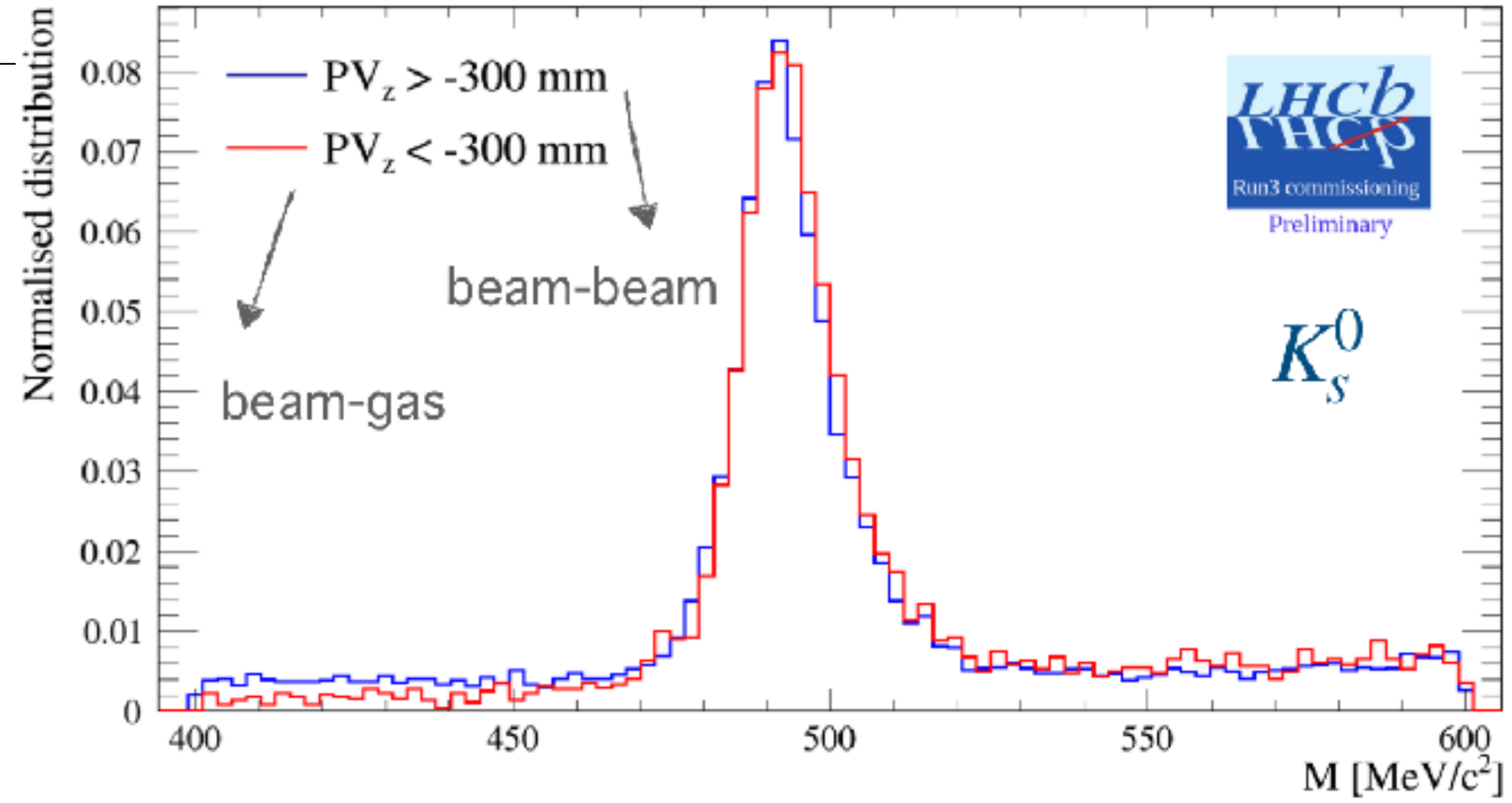
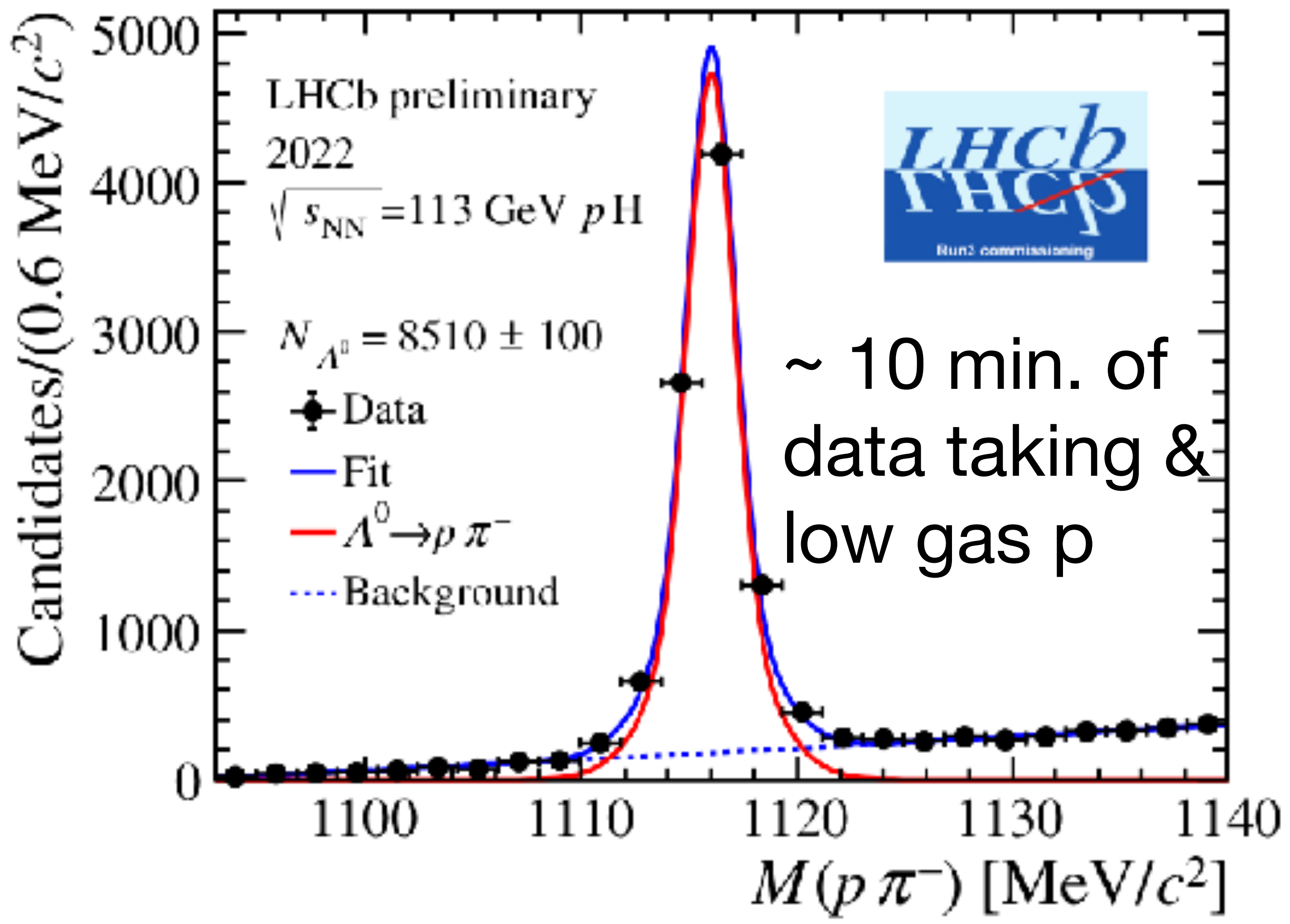
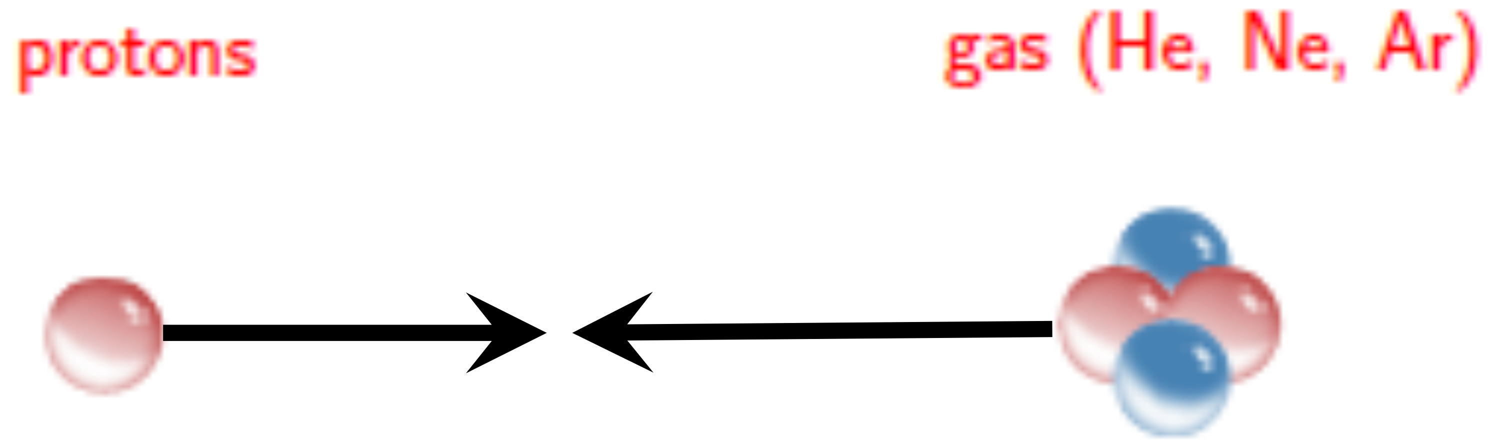




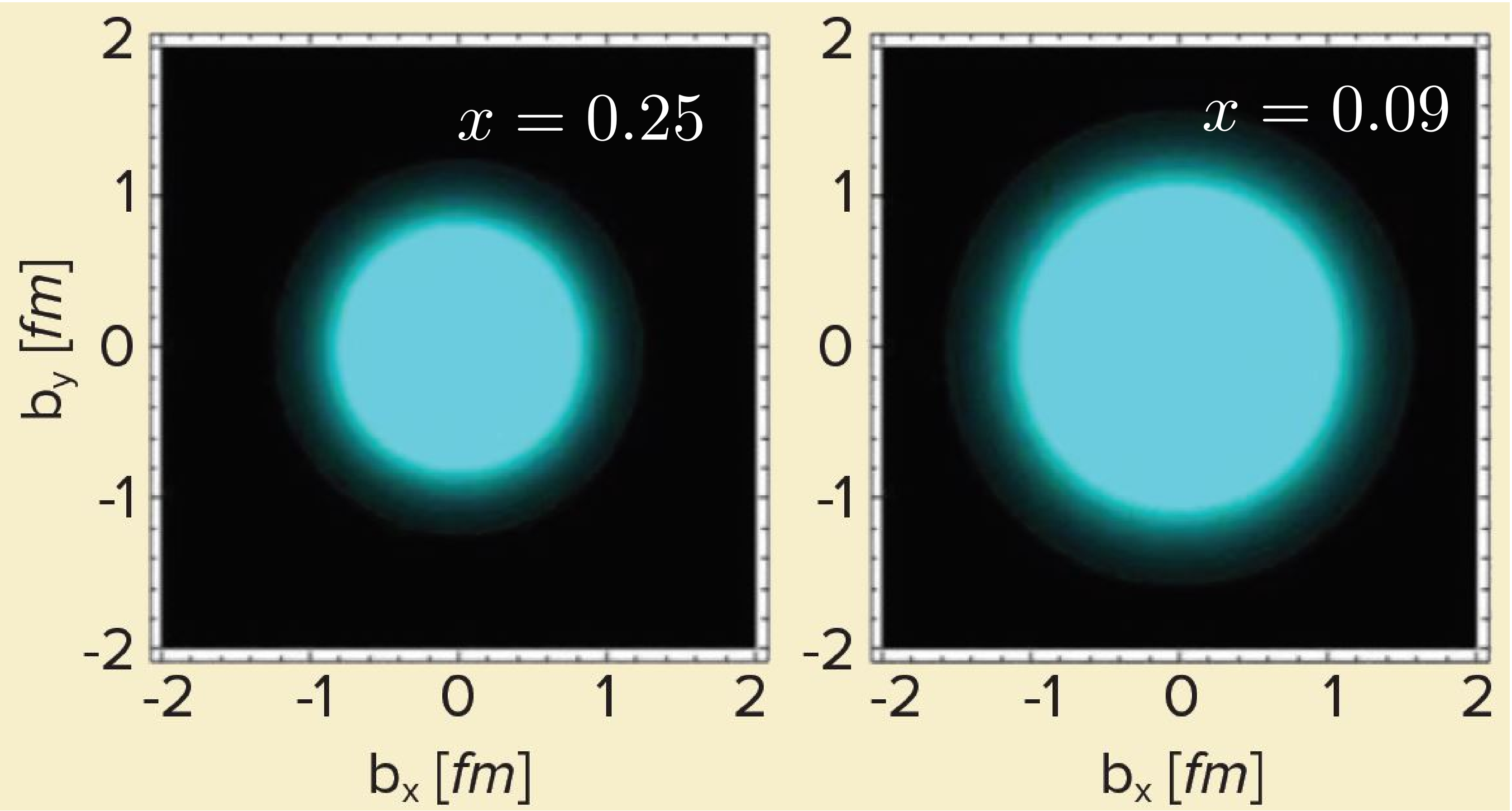
~ 10 min. of data taking & low gas p

Interest of fixed target: LHC run 4

SMOG2

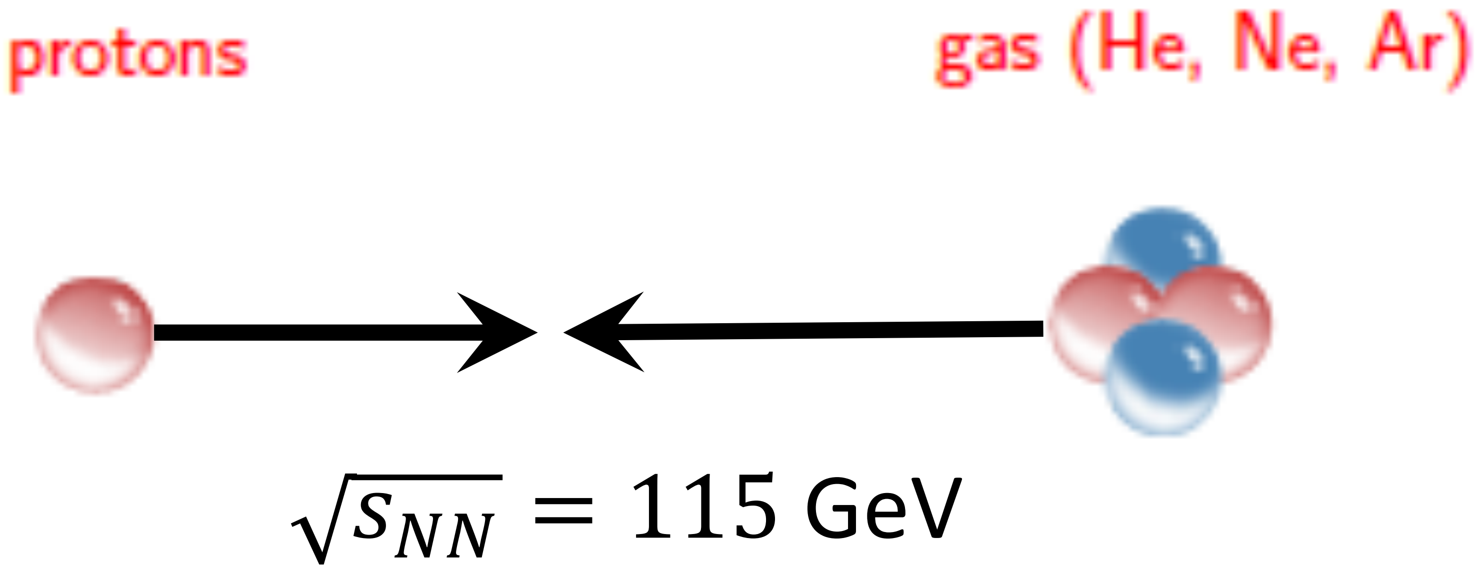


$$\sqrt{s_{NN}} = 115 \text{ GeV}$$

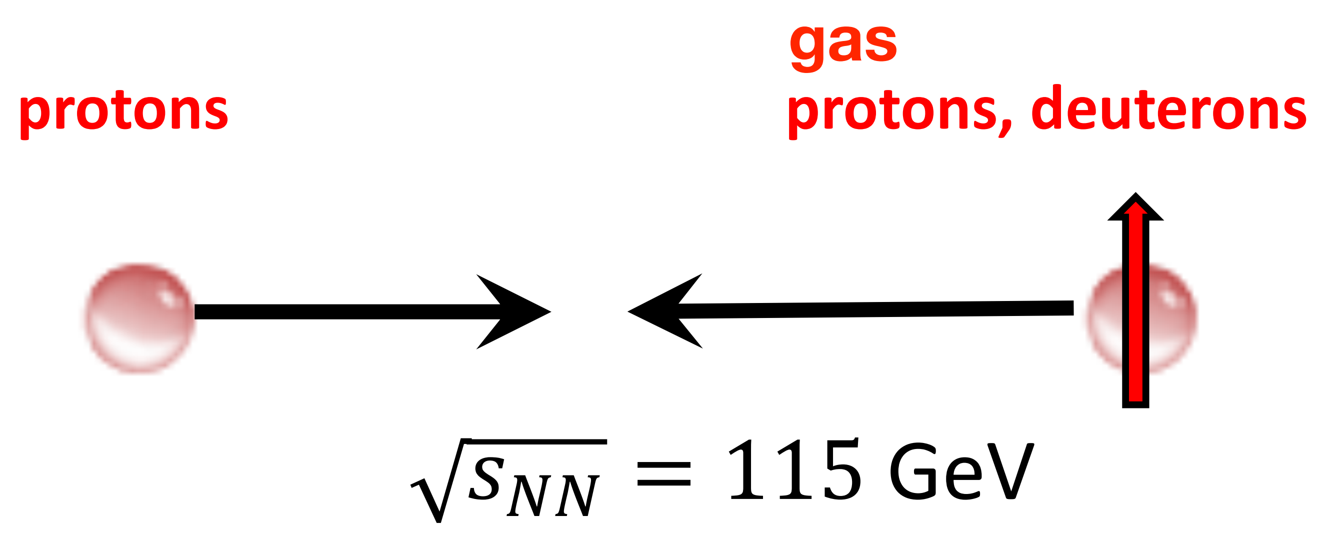


Interest of fixed target: LHC run 4

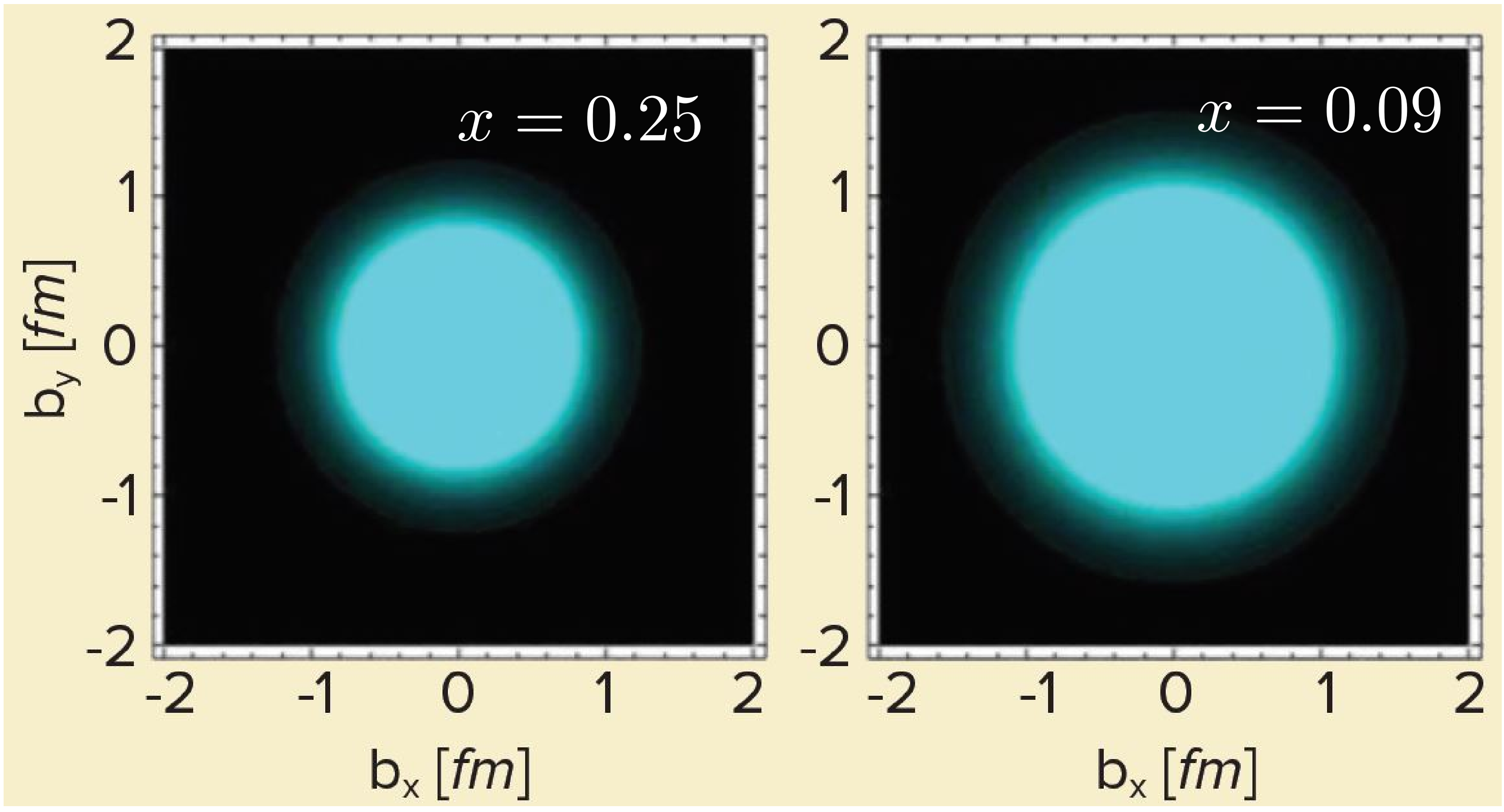
SMOG2

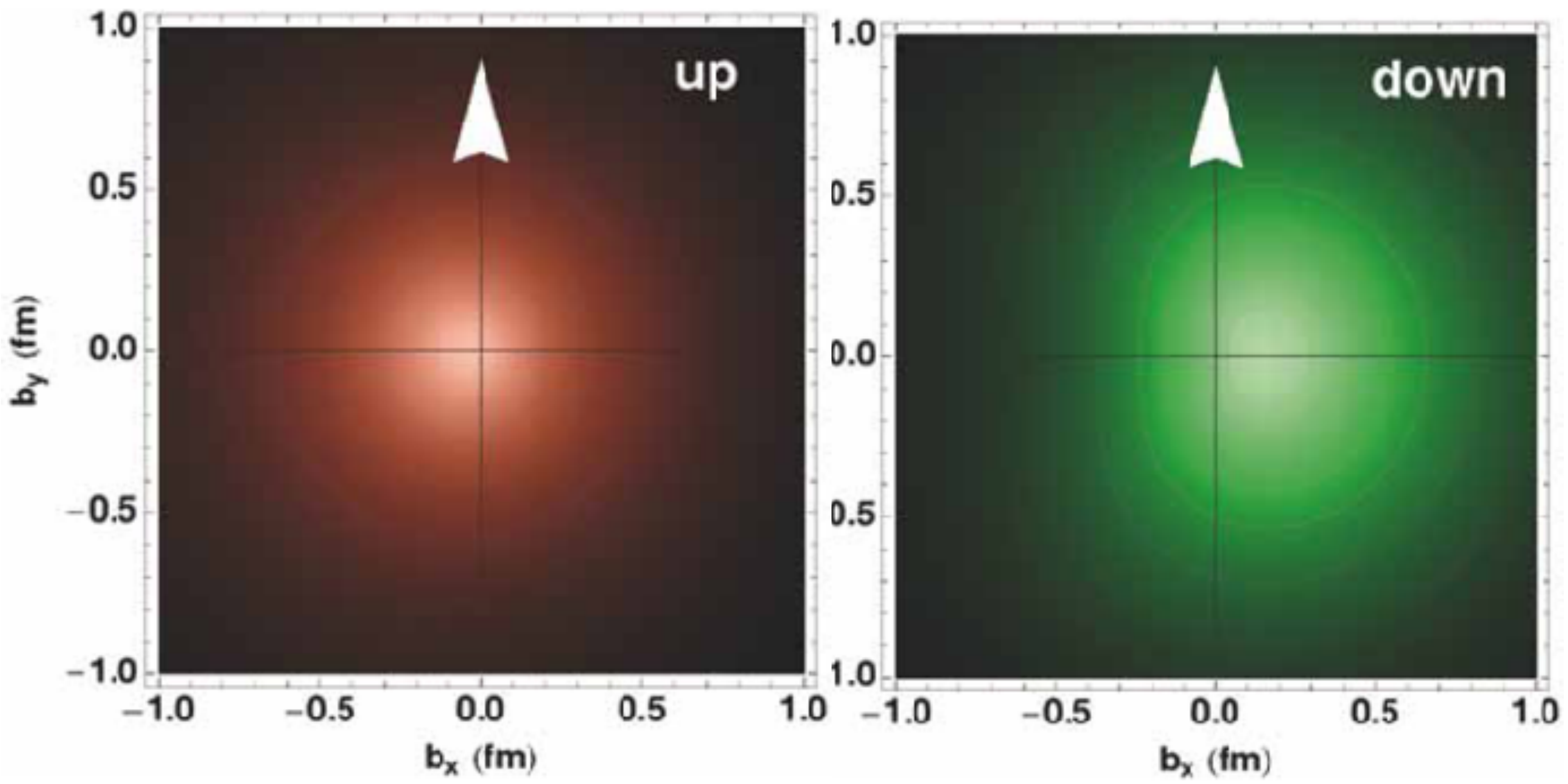


LHCSPIN: transversely polarised gas target



$\longrightarrow$ access to TMDs and GPDs in transversely polarised proton





GPDs H+E

(E $\rightarrow$ distortion and orbital angular momentum)

Summary

- TMD and GPDs: rich field of physics,
  where TMDs have sensitivity to the parton and hadron spin and transverse momentum
  and GPDs probe the (spin-dependent) transverse position and mechanical properties of the nucleon

- Pioneering fixed-target experiments at HERMES, COMPASS, JLab 6 GeV: quark distributions

- Entering era of precision measurements:
  - JLab 12 GeV: unique precision in the valence region
  - LHCb fixed-target programme provides complementary channel, allowing to check our understanding
  - EIC will also provide high-precision data in high-x region