Exclusive processes at hermes

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Generalized parton distributions

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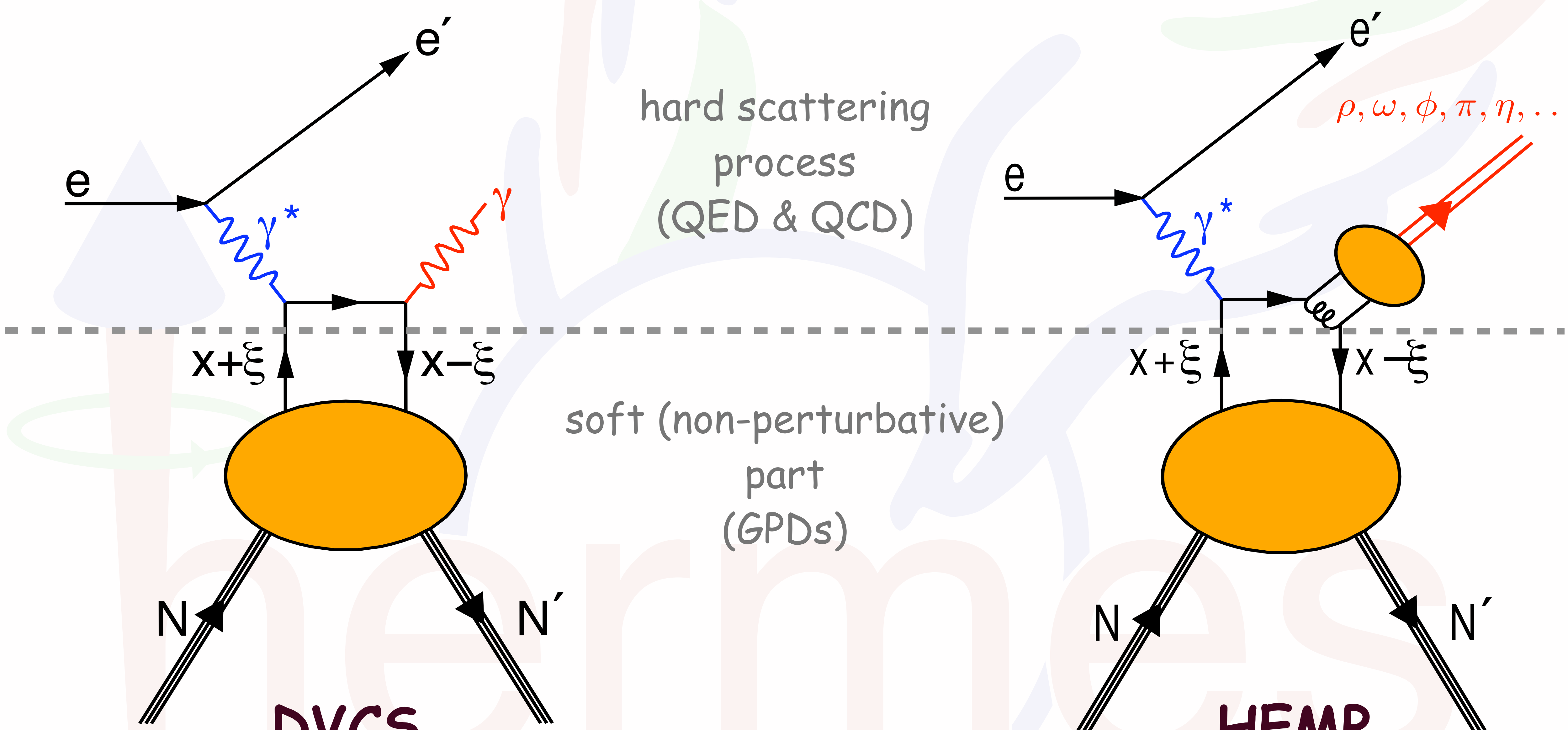
  - ... thanks!

    - ... also to Erik Etzelmüller and Charlotte Van Hulse for "slides support"

GPDs in exclusive reactions

Experimentally GPDs can be accessed through measurements of hard exclusive lepton-nucleon scattering processes.



DVCS

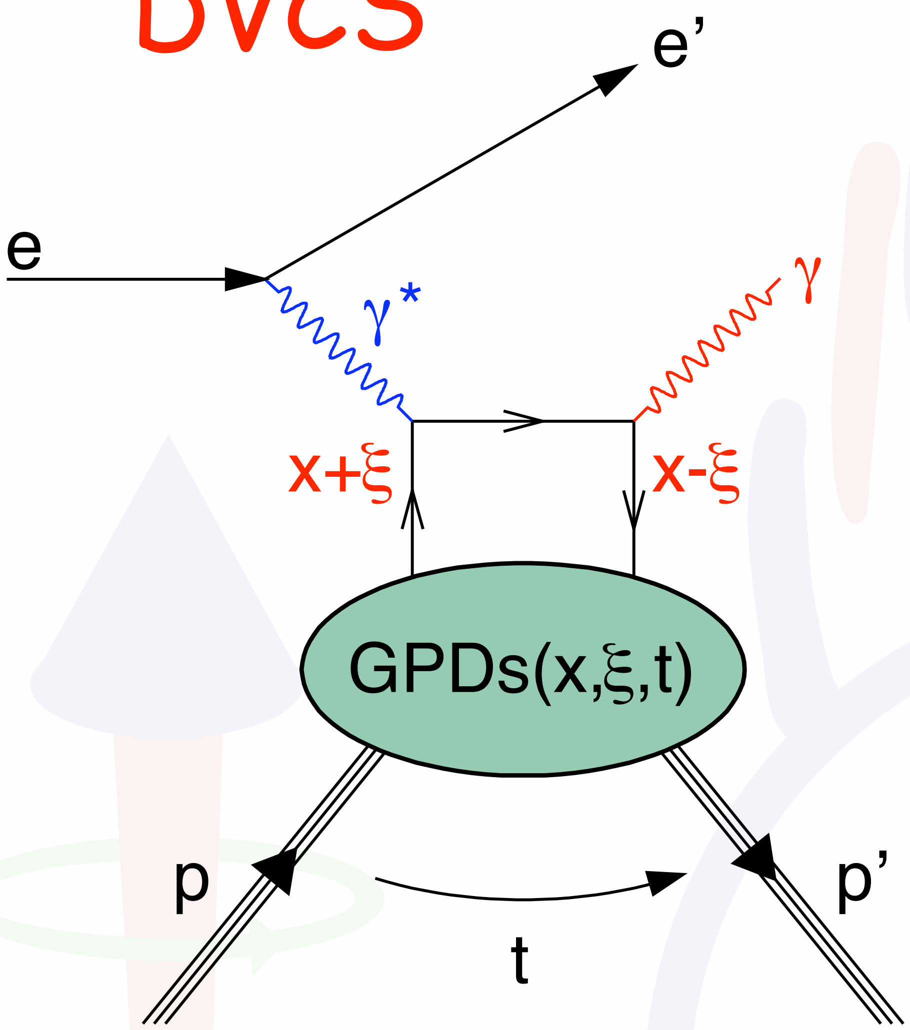
deeply virtual Compton scattering

HEMP

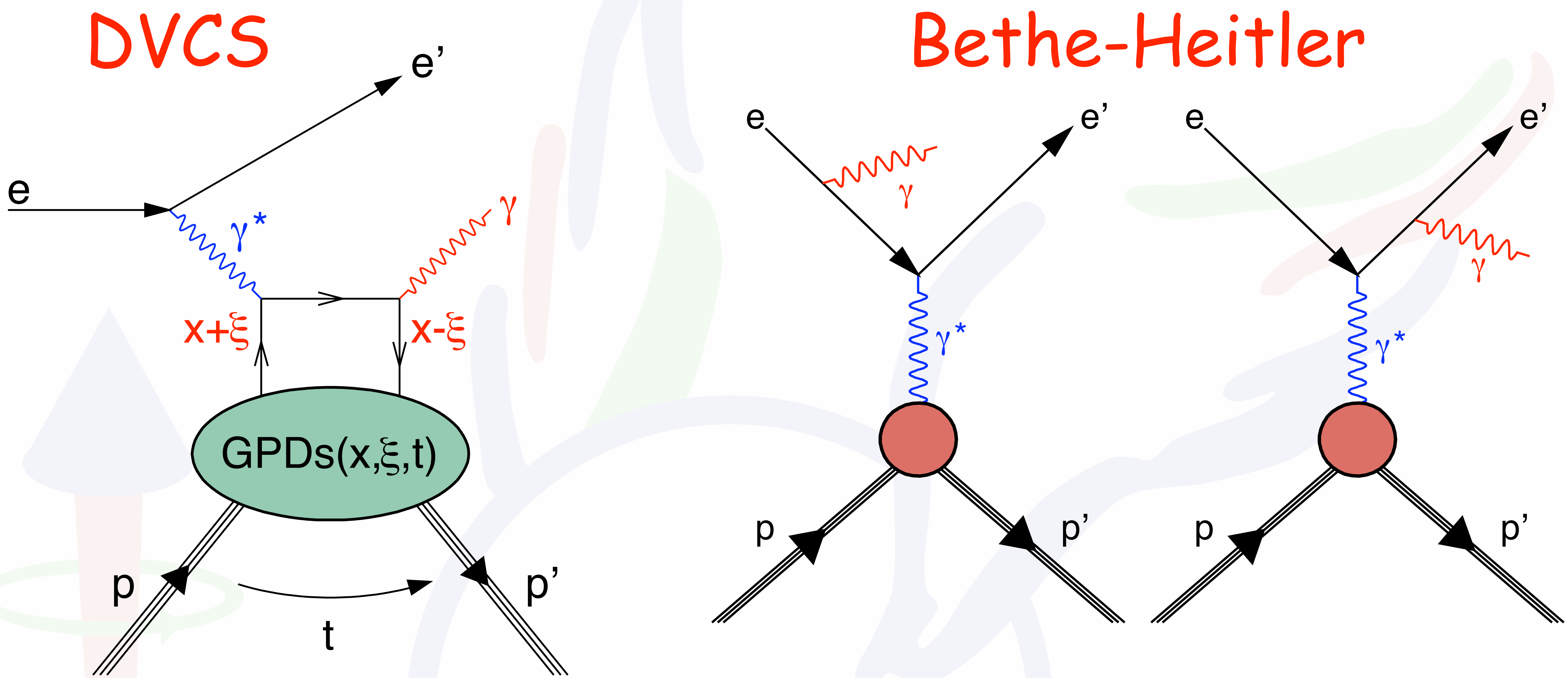
hard exclusive meson production

Real-photon production

DVCS



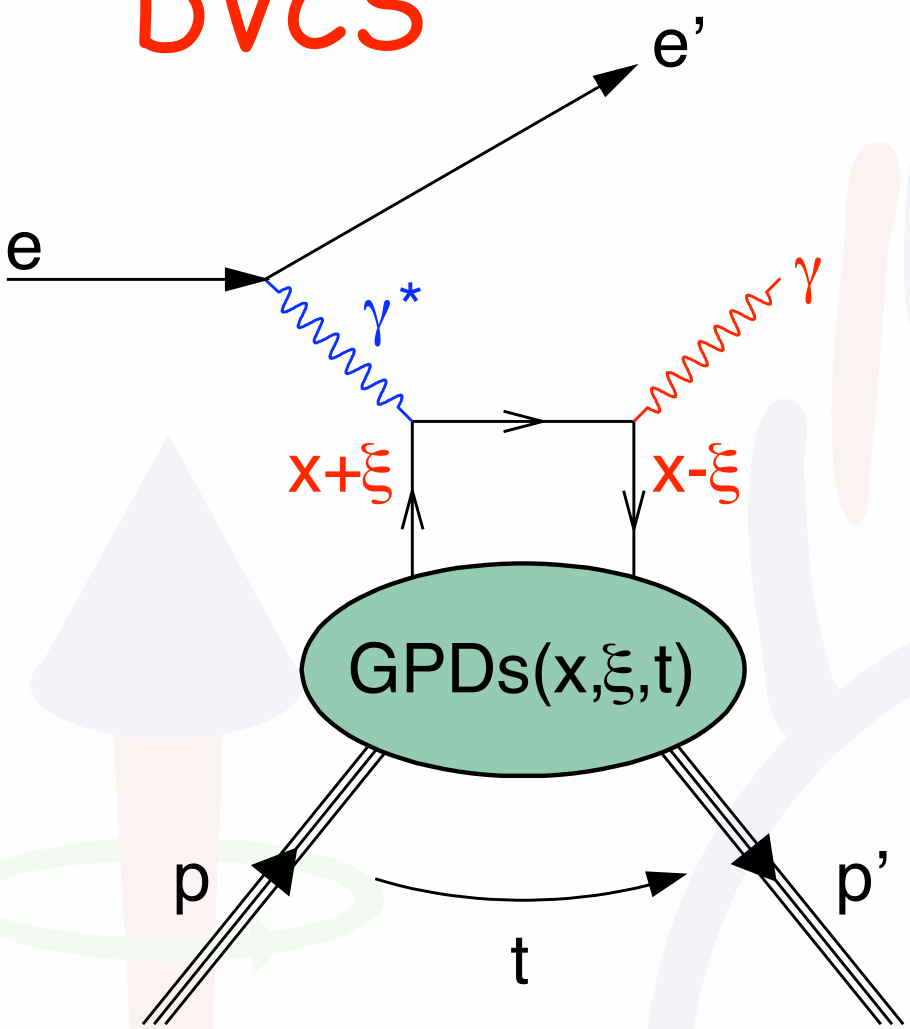
Real-photon production



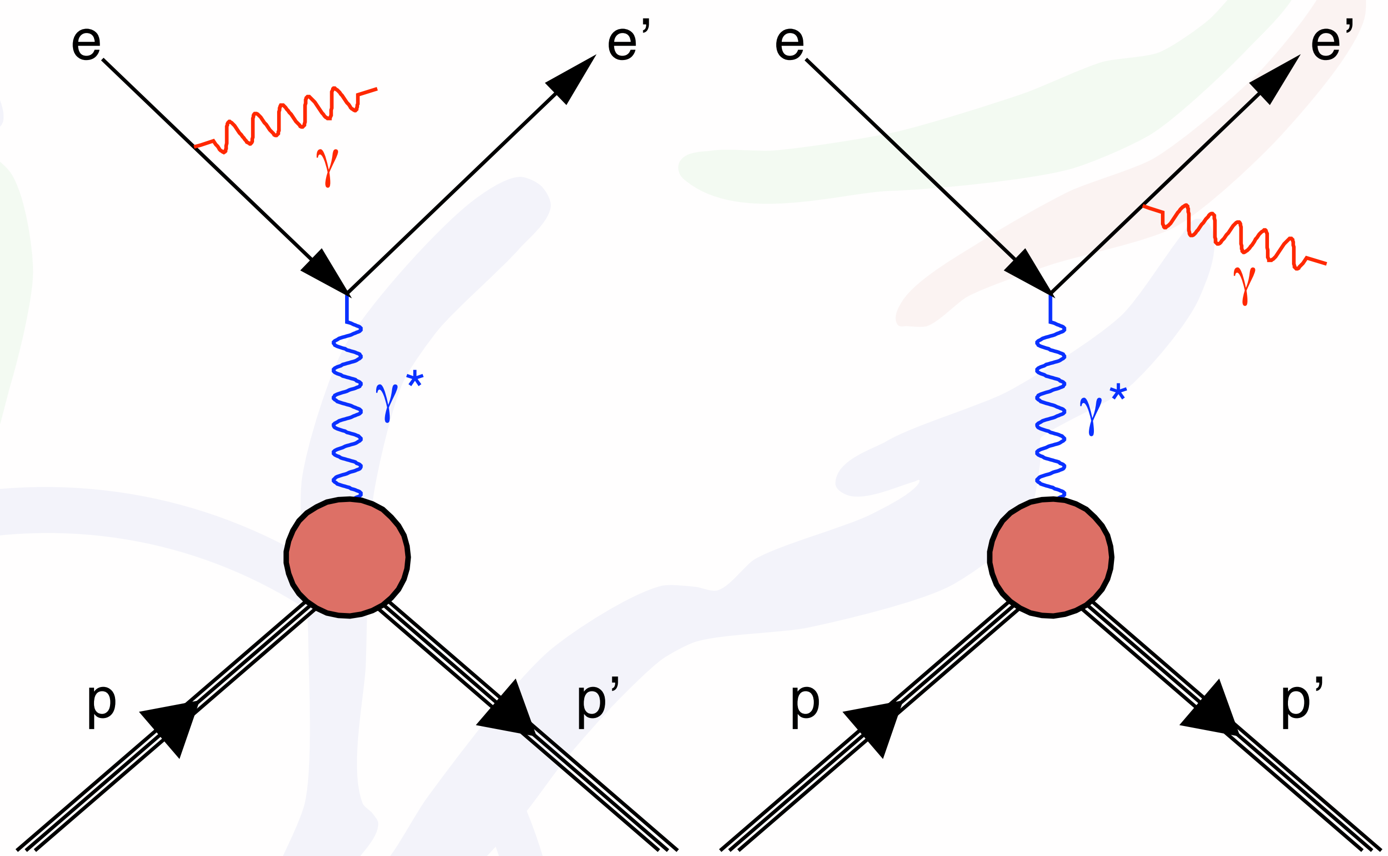
$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\phi} = \frac{y^2}{32(2\pi))^4\sqrt{1+\frac{4M^2x_B^2}{Q^2}}}\left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I}\right)$$

Real-photon production

DVCS



Bethe-Heitler



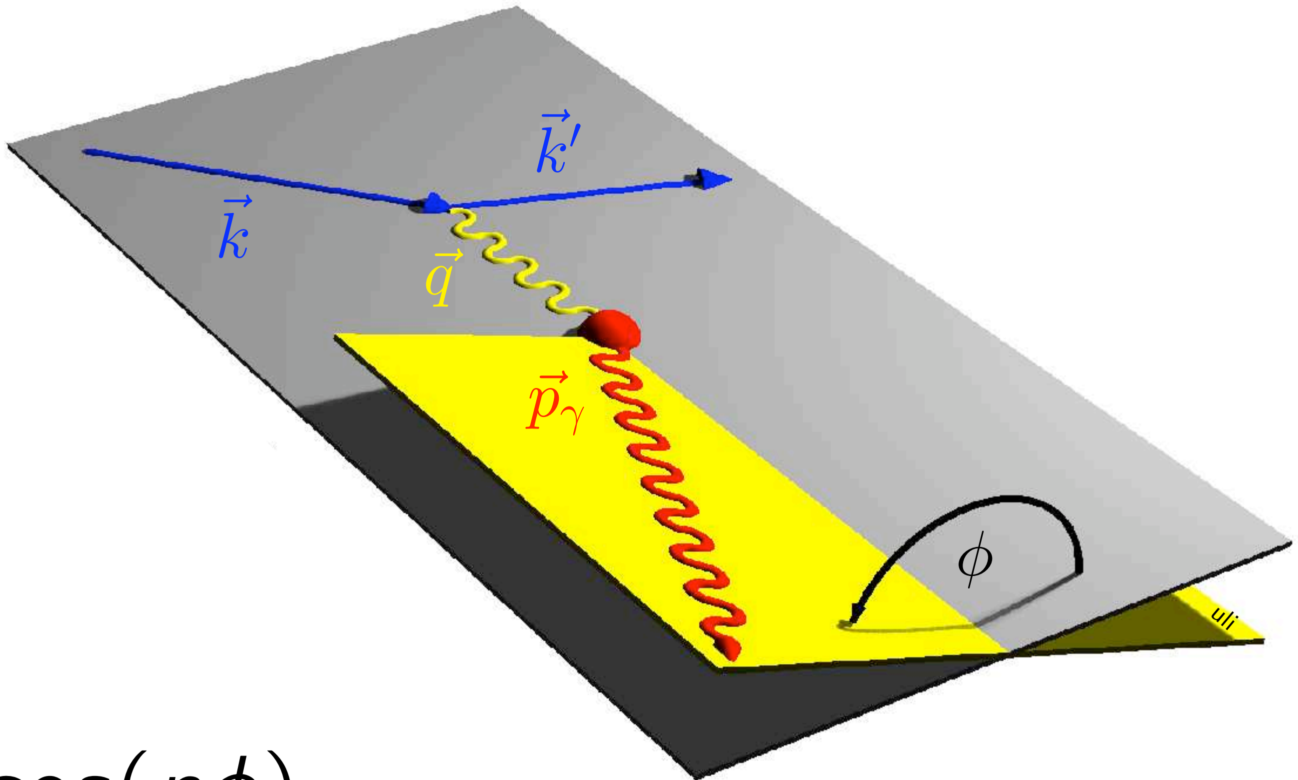
Amplitude of Bethe-Heitler scattering is dominant at HERMES kinematics

$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} = \frac{y^2}{32(2\pi))^4\sqrt{1+\frac{4M^2x_B^2}{Q^2}}} \left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \boxed{\mathcal{I}}\right)$$

DVCS amplitude is amplified by BH in the interference term

Azimuthal dependences in DVCS/BH

- beam polarization P_B
- beam charge C_B
- here: unpolarized target



Fourier expansion for ϕ:

$$|\mathcal{T}_{\mathrm{BH}}|^2 = \frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi)$$

calculable in QED

(using form-factor measurements)

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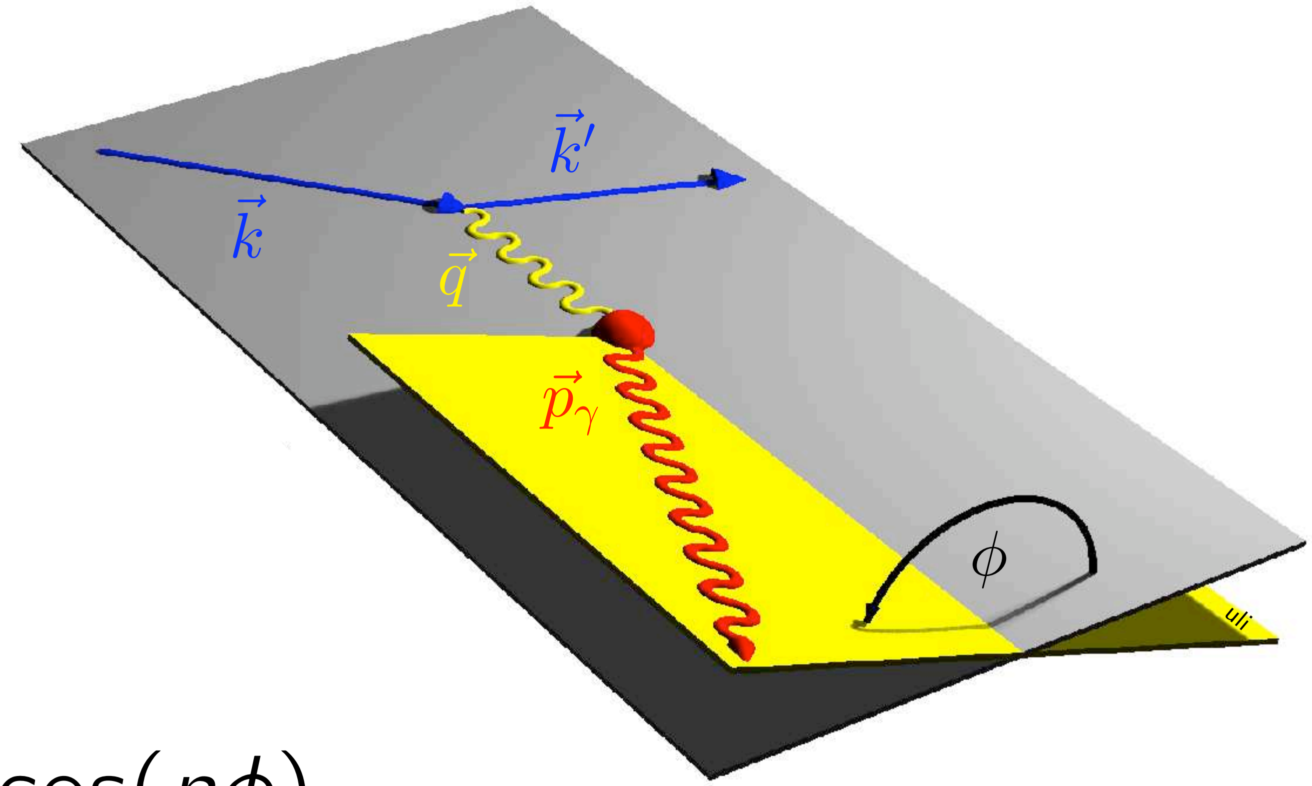

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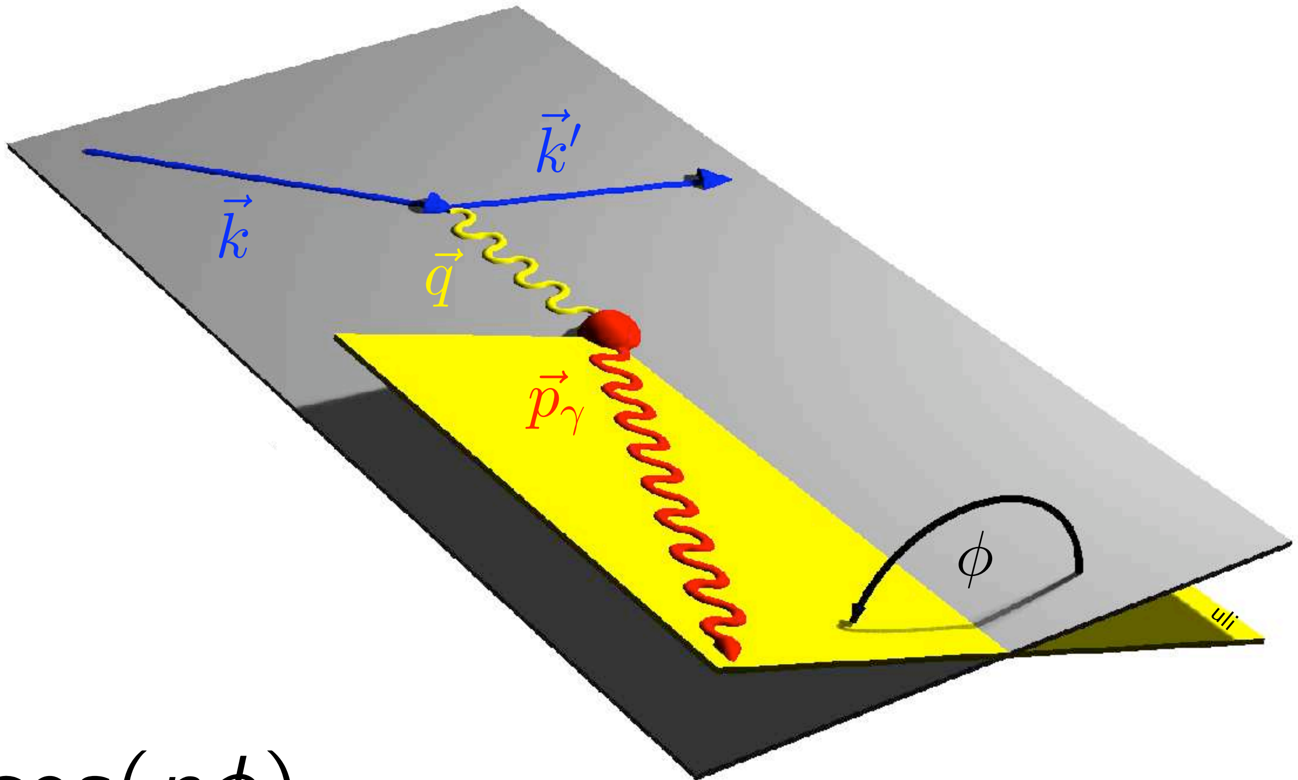

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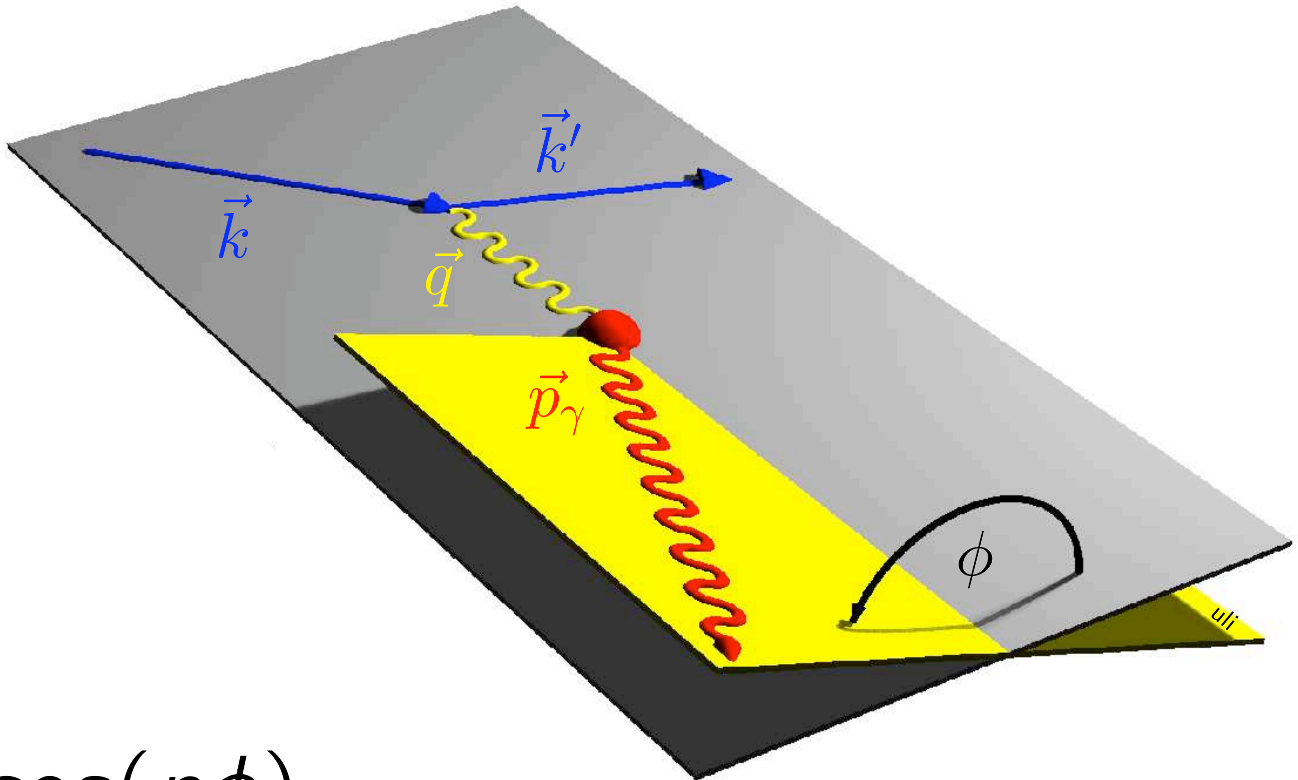
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Azimuthal dependences in DVCS/BH

- beam polarization P_B
- beam charge C_B
- here: unpolarized target



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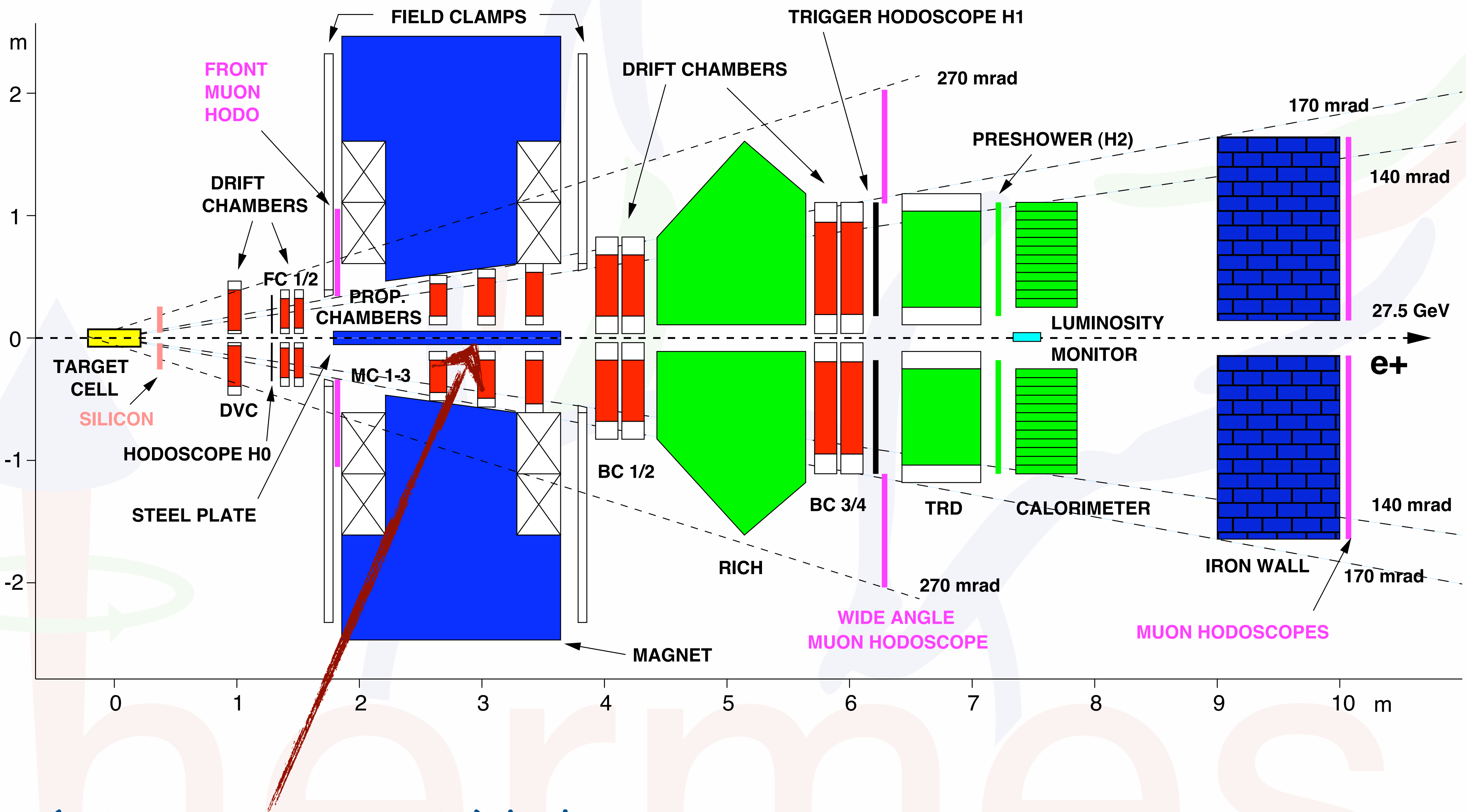
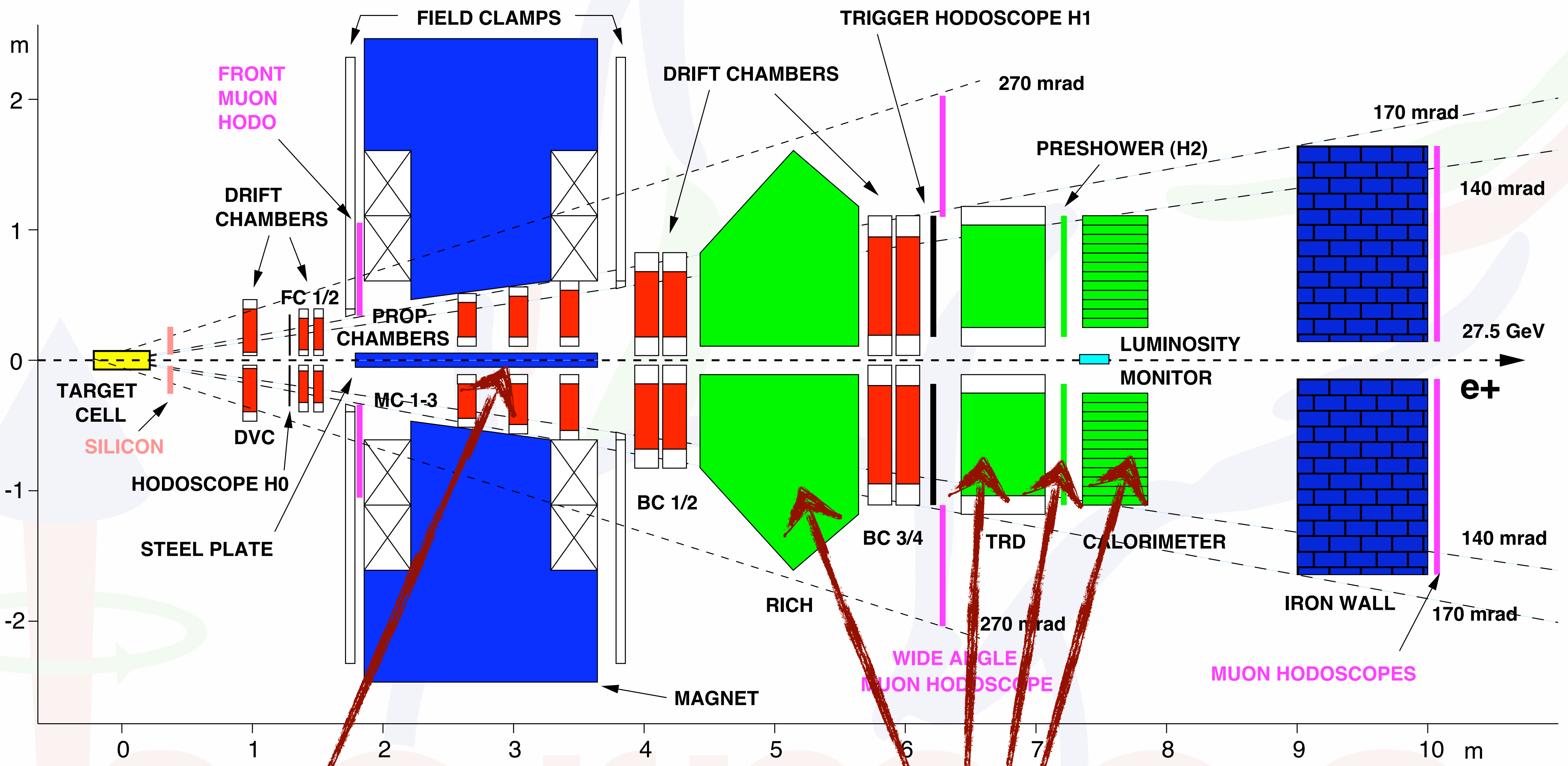
bilinear ("DVCS") or linear ("I") in GPDs

HERMES (1998-2005) schematically



two (mirror-symmetric) halves
-> no homogenous azimuthal coverage

HERMES (1998-2005) schematically



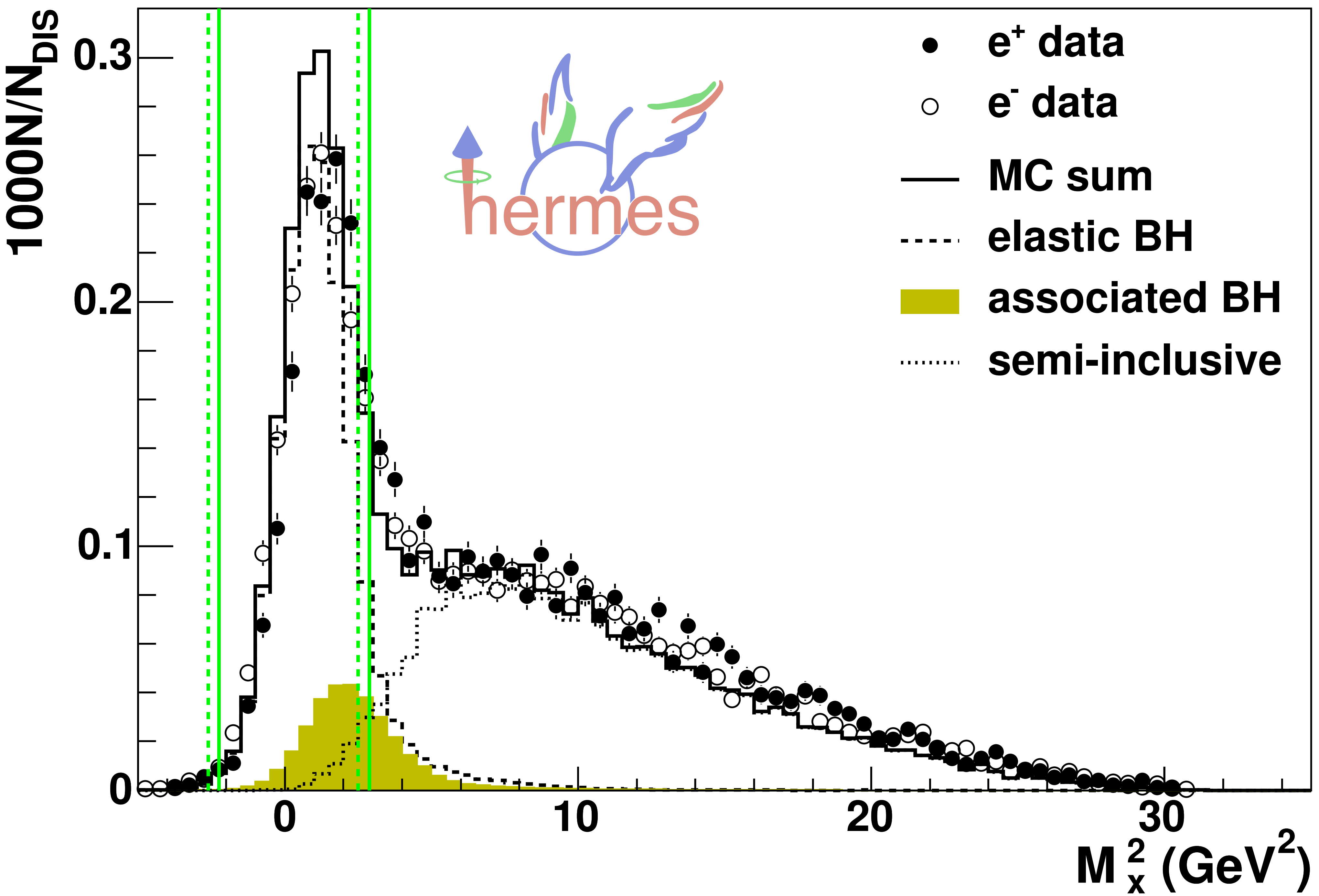
two (mirror-symmetric) halves
-> no homogenous azimuthal coverage

Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination 2GeV<p<15GeV

Exclusivity: missing-mass technique

$$M_x^2 = (k - k' + P_0 - P_\gamma)^2 = M^2 + 2M(\nu - E_\gamma) + t$$

ep -> e γ X



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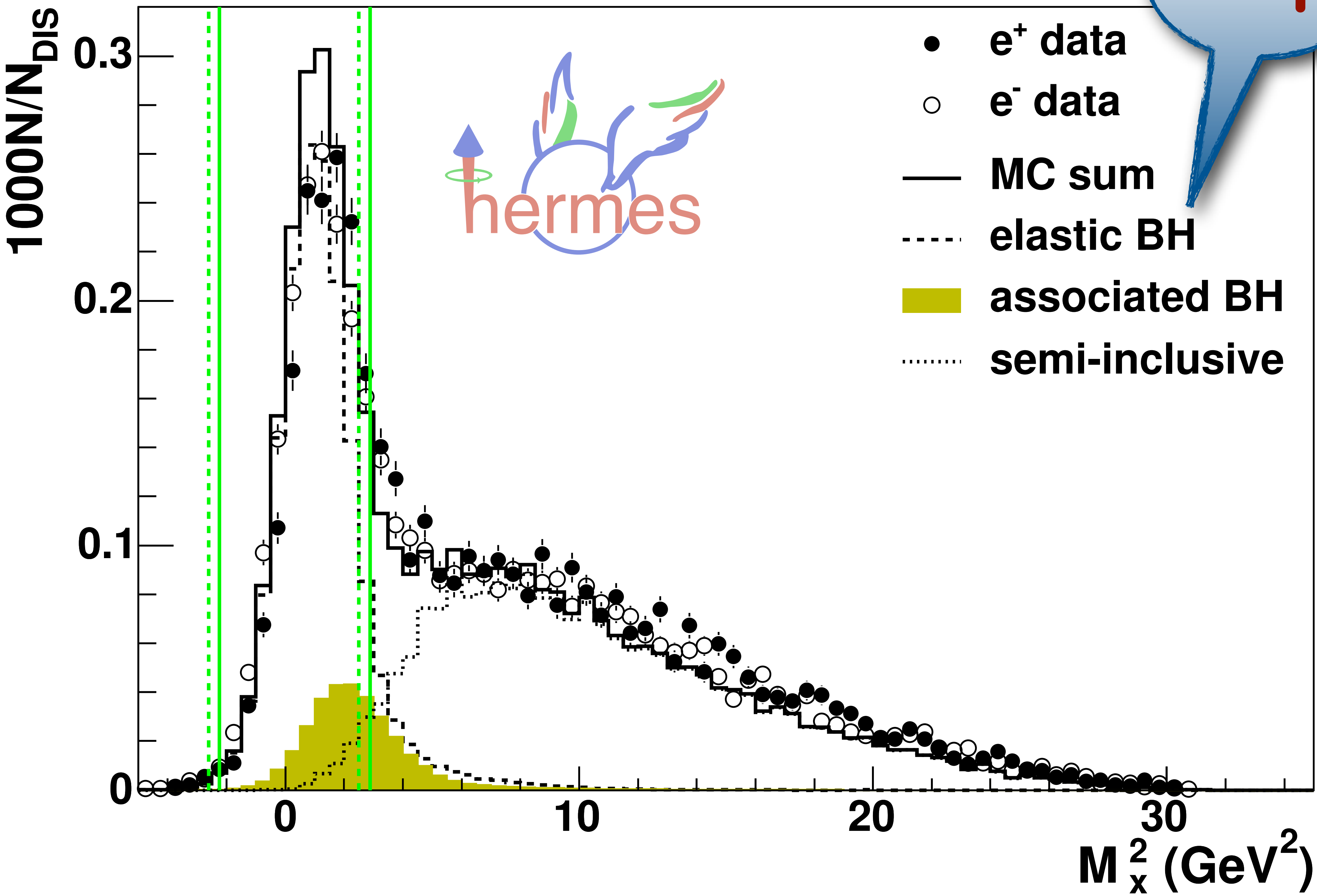
X=p



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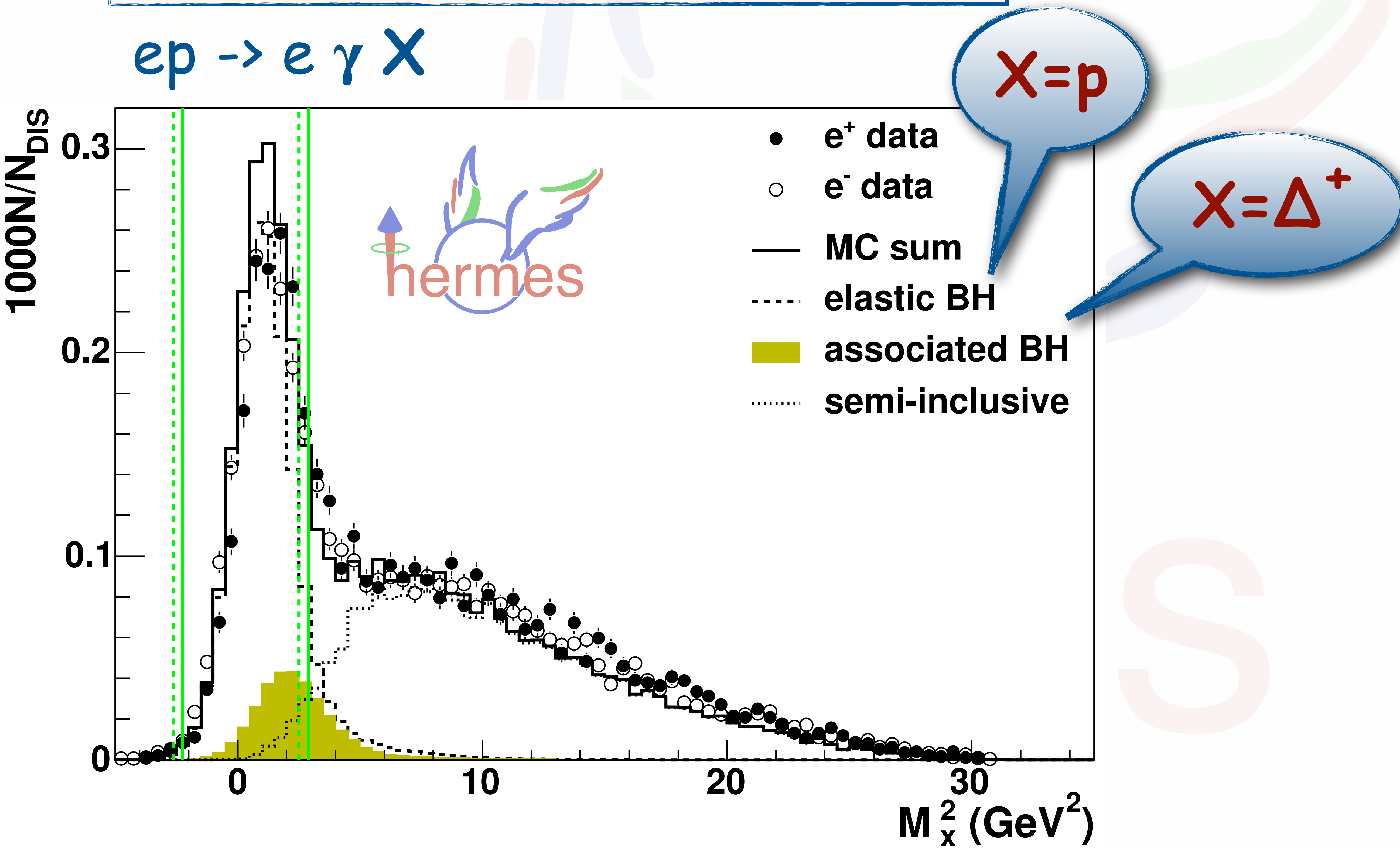

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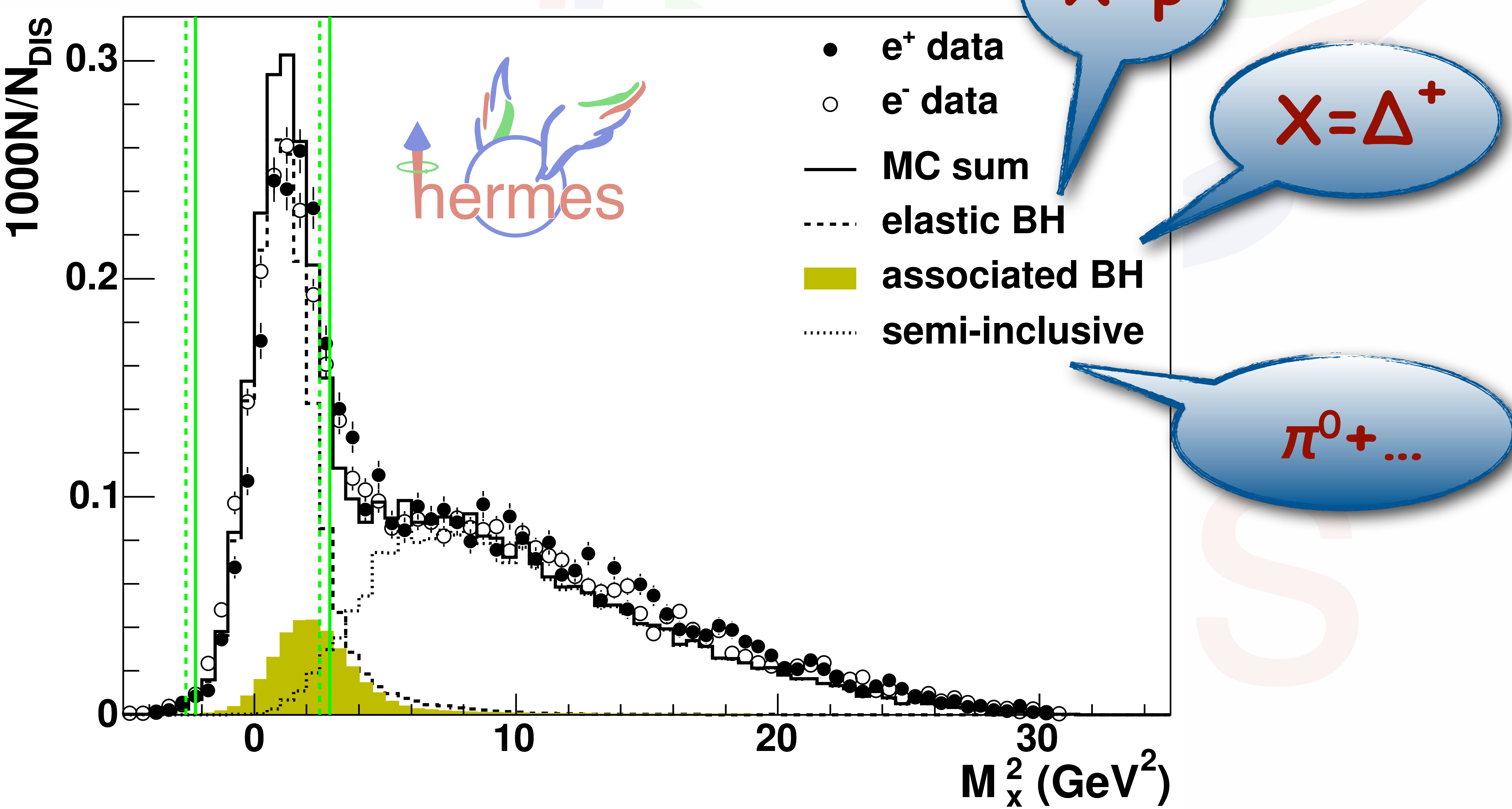
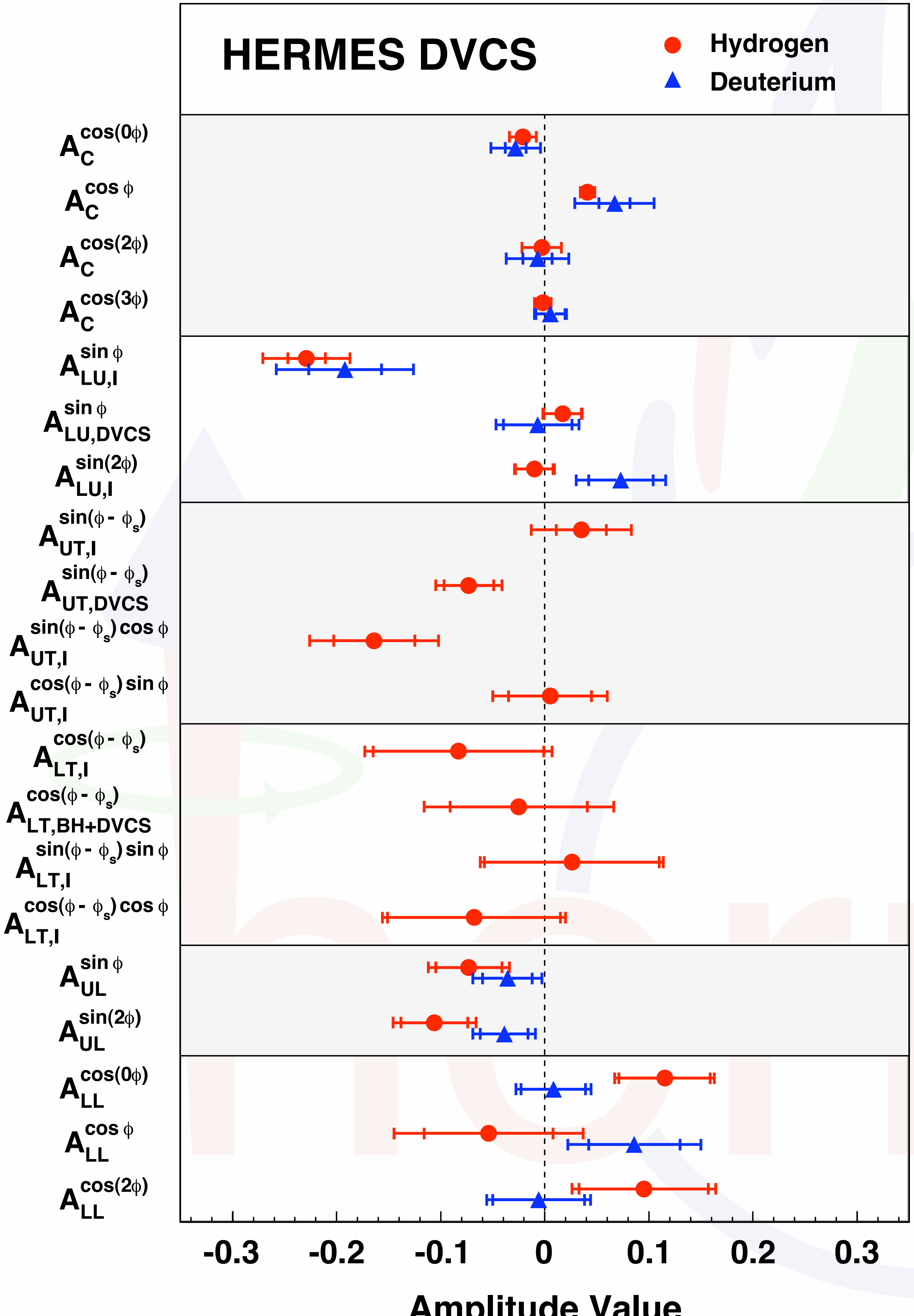


A wealth of azimuthal amplitudes



Beam-charge asymmetry:

GPD H

PRD 75 (2007) 011103
NPB 829 (2010) 1
JHEP 11 (2009) 083
PRC 81 (2010) 035202

Beam-helicity asymmetry:

GPD H

PRL 87 (2001) 182001
JHEP 07 (2012) 032

Transverse target spin asymmetries:

GPD E from proton target

JHEP 06 (2008) 066
PLB 704 (2011) 15

Longitudinal target spin asymmetry:

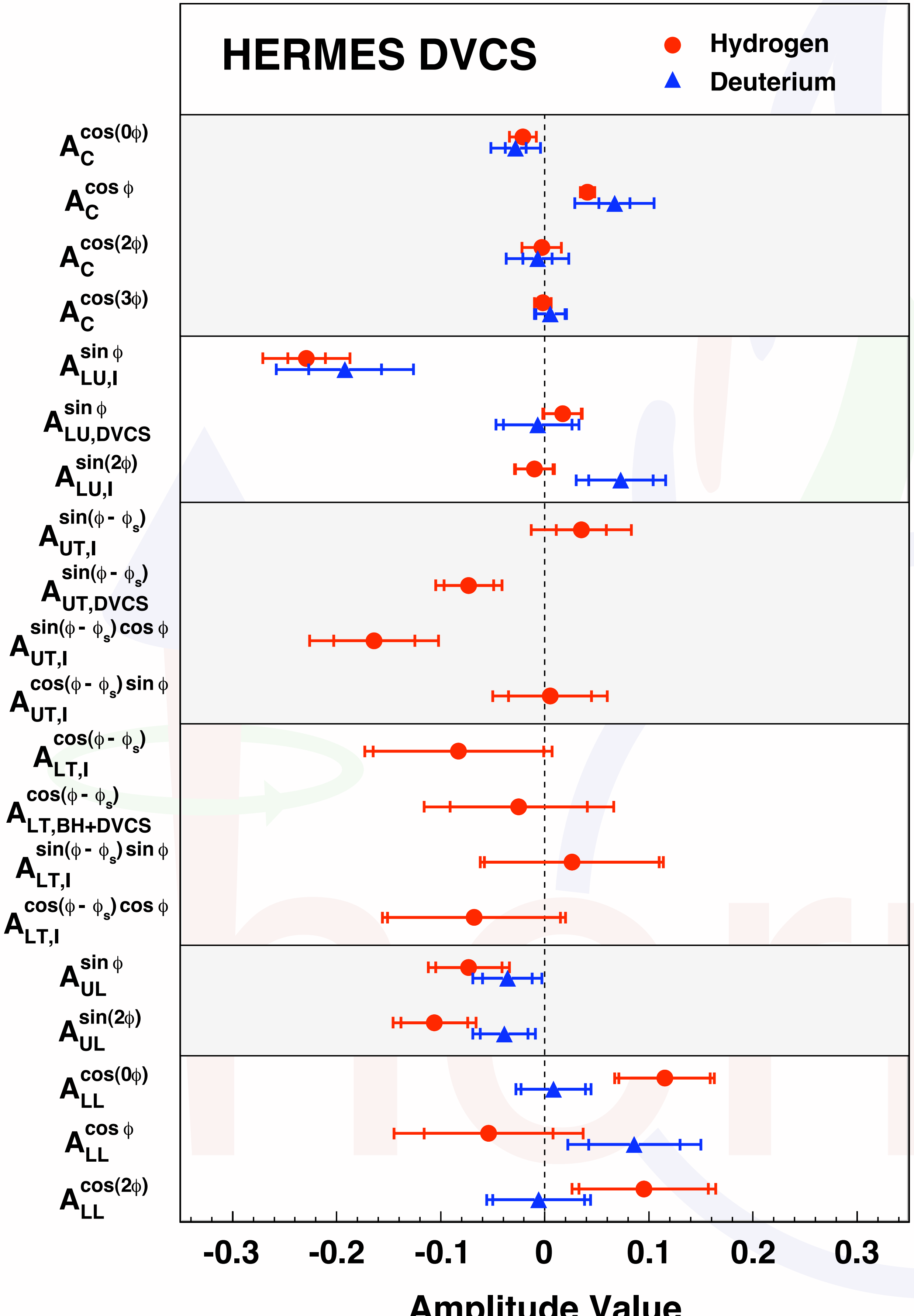
GPD $\tilde{H}$

JHEP 06 (2010) 019
NPB 842 (2011) 265

Double-spin asymmetry:

GPD $\tilde{H}$

A wealth of azimuthal amplitudes



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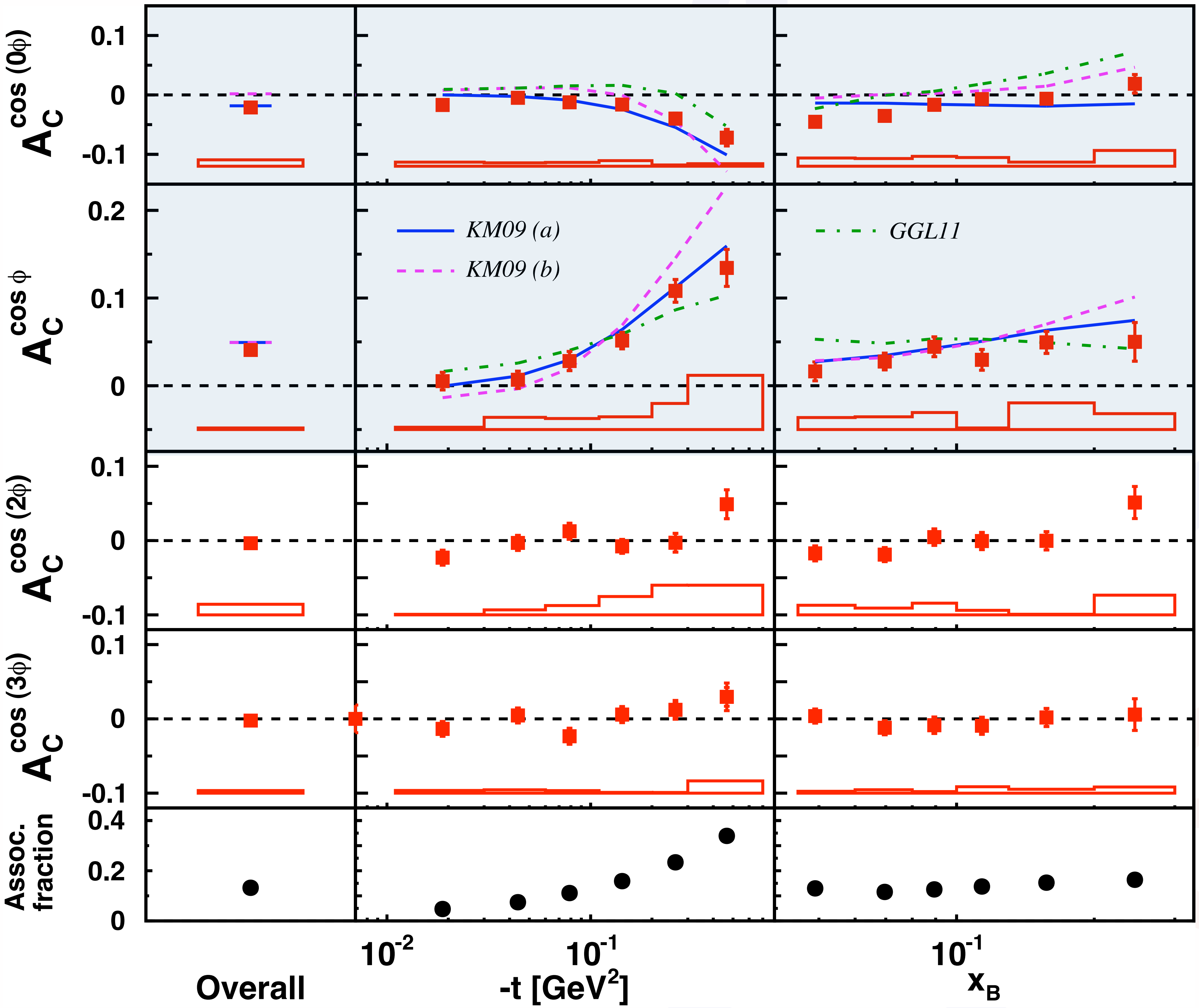
complete data set!

Beam-charge asymmetry

[Airapetian et al., JHEP 07 (2012) 032]



constant term:

$\propto -A_C^{\cos\phi}$

$\propto \mathrm{Re}[F_1\mathcal{H}]$

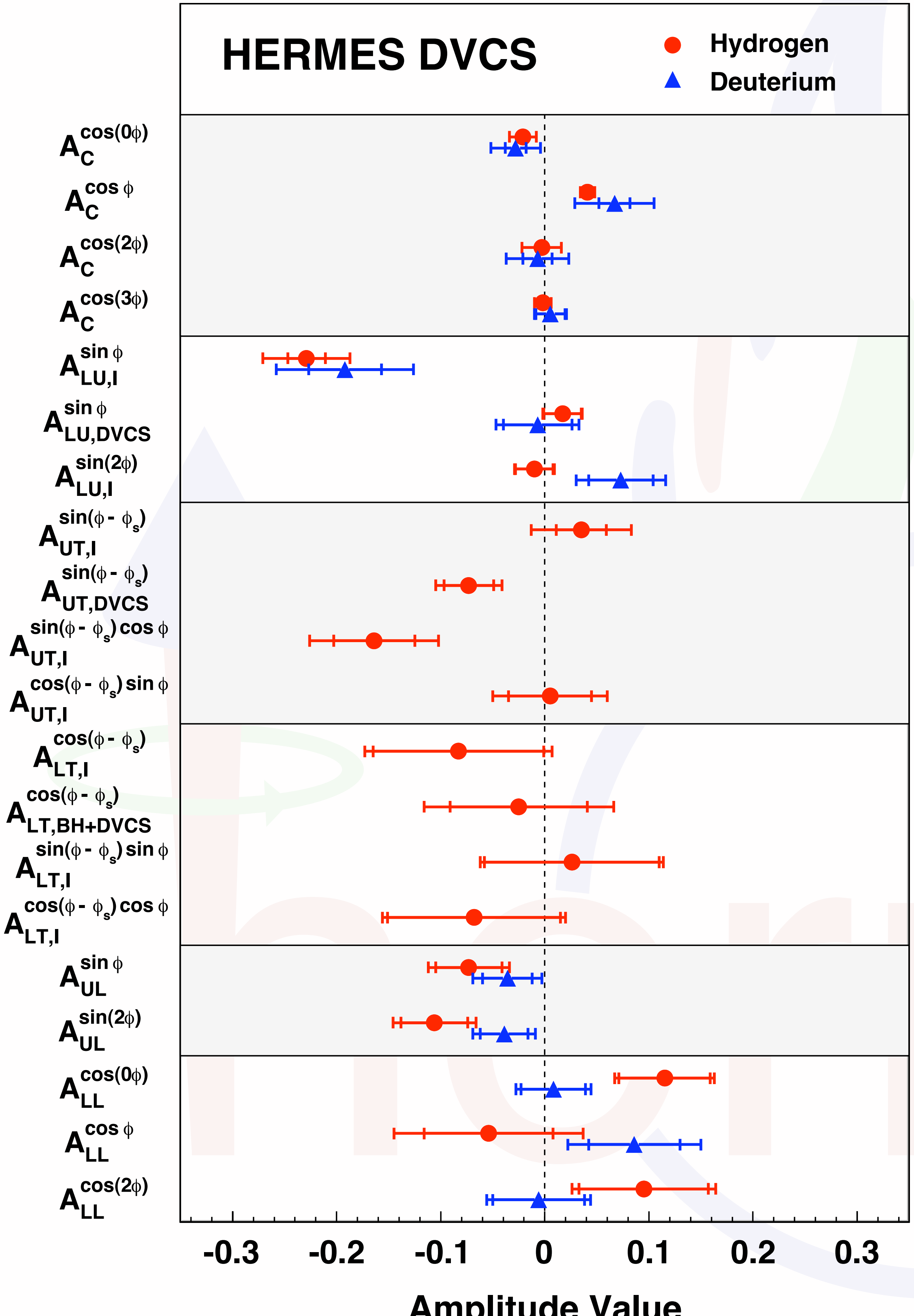
[higher twist]

[gluon leading twist]

Resonant fraction:

$ep \to e\Delta^+\gamma$

A wealth of azimuthal amplitudes



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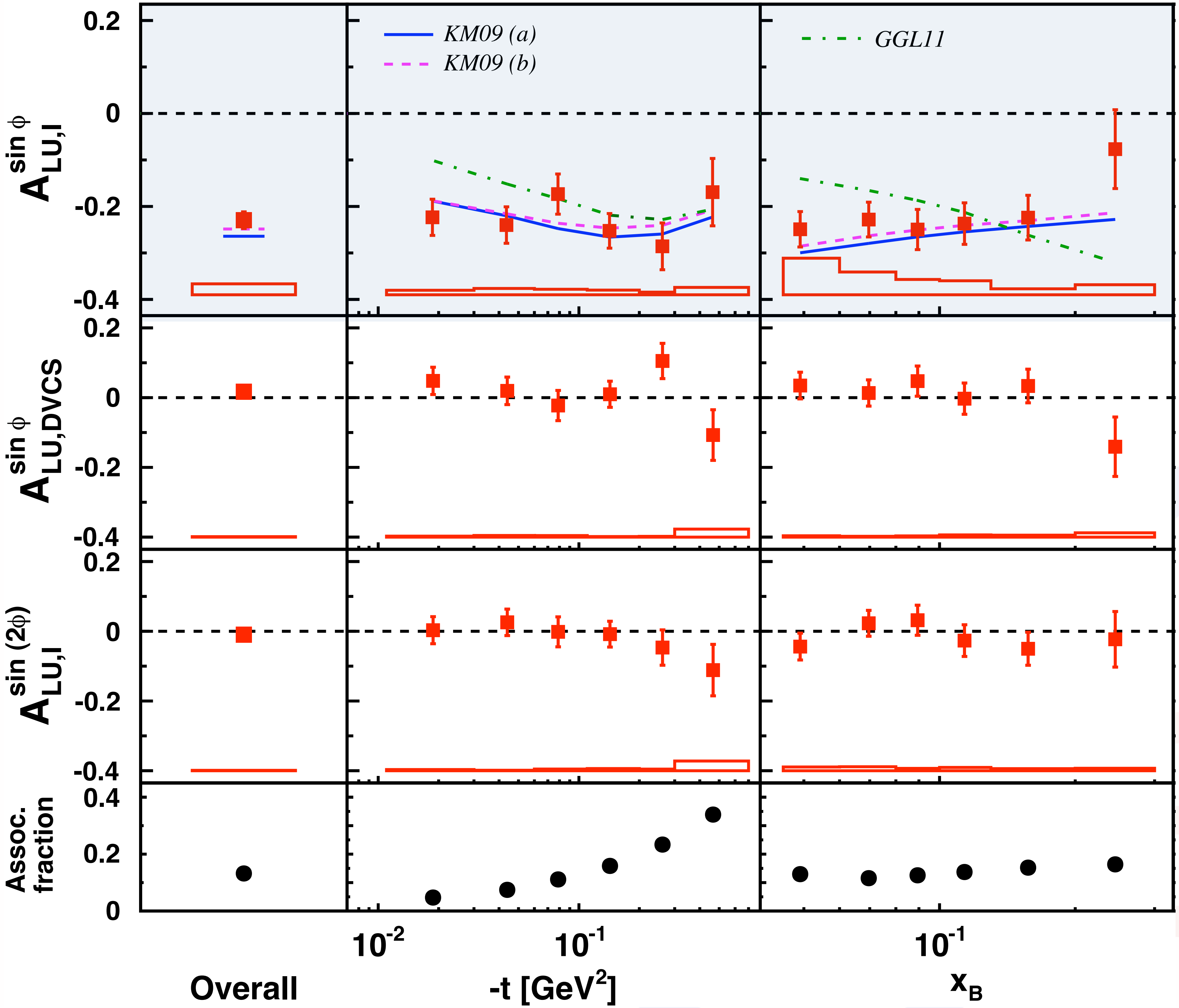
Beam-spin asymmetry

[Airapetian et al., JHEP 07 (2012) 032]



$\propto \mathrm{Im}[F_1\mathcal{H}]$

[higher twist]

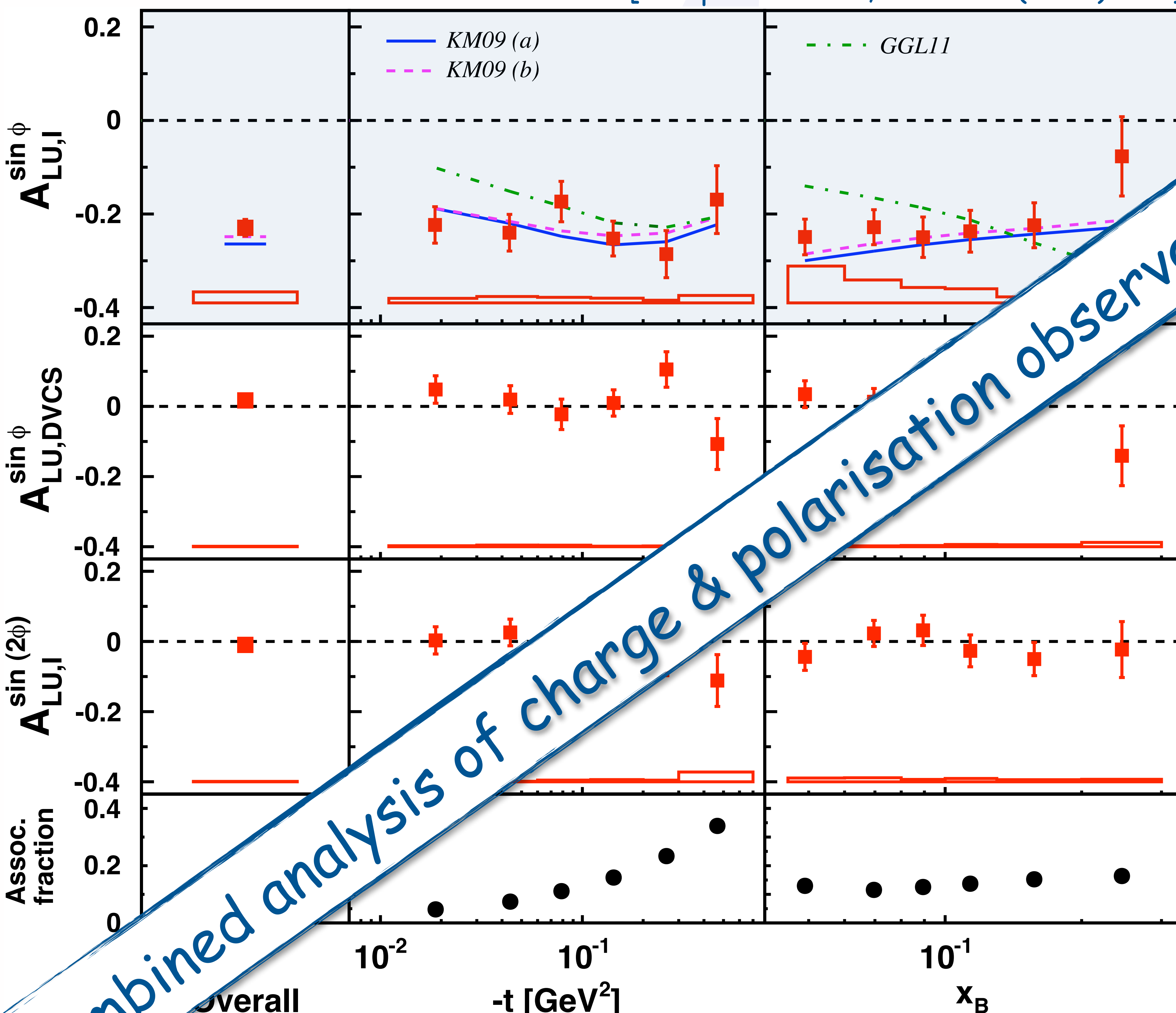
Resonant fraction:

$$\boxed{ep \to e\Delta^+\gamma}$$

complete data set!

Beam-spin asymmetry

[Airapetian et al., JHEP 07 (2012) 032]



combined analysis of charge & polarisation observables unique to HERA!

$\mathrm{Im}[F_1\mathcal{H}]$

[higher twist]

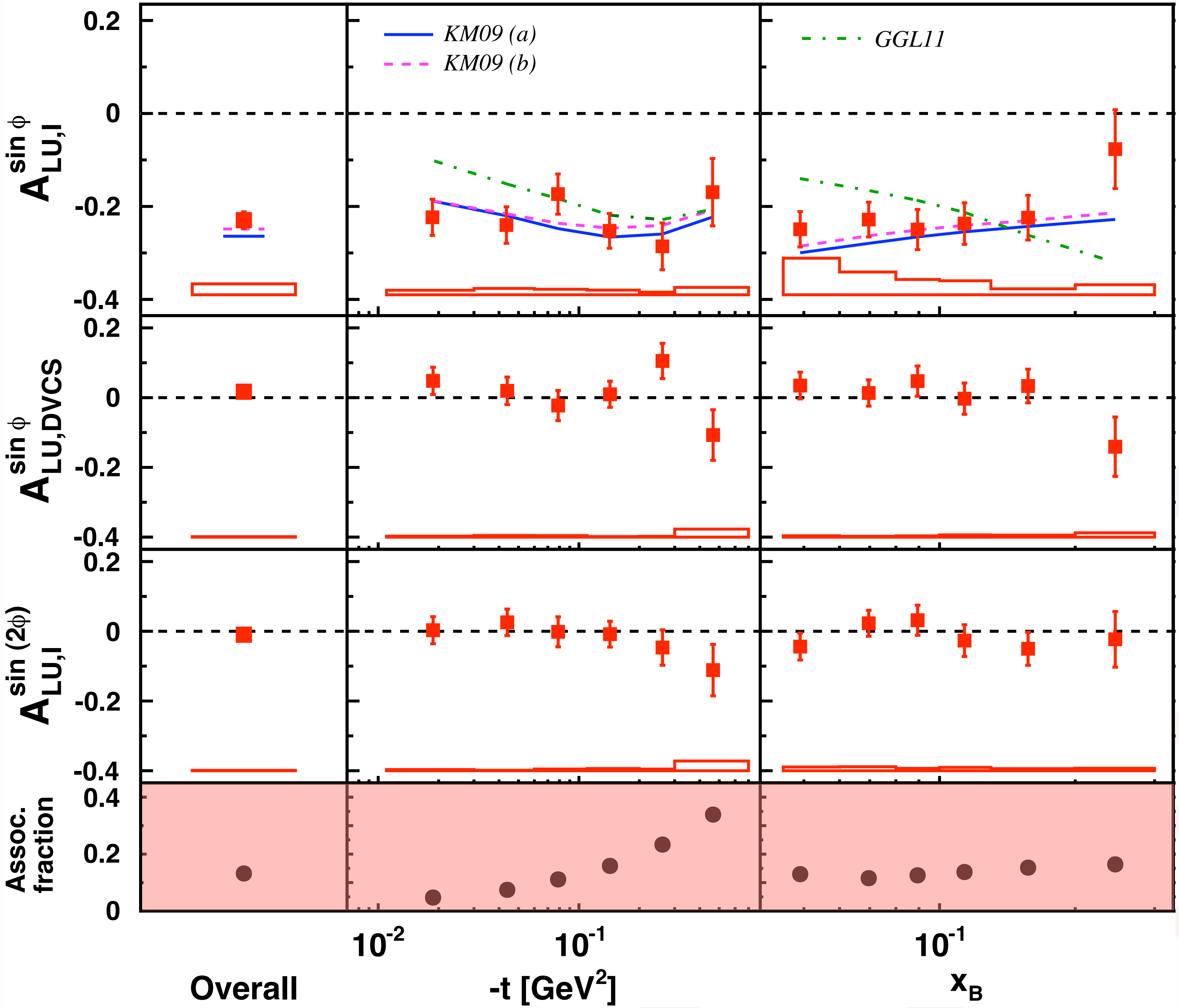
Resonant fraction:

$$ep \to e\Delta^+\gamma$$

complete data set!

Beam-spin asymmetry

[Airapetian et al., JHEP 07 (2012) 032]



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[higher twist]

Resonant fraction:

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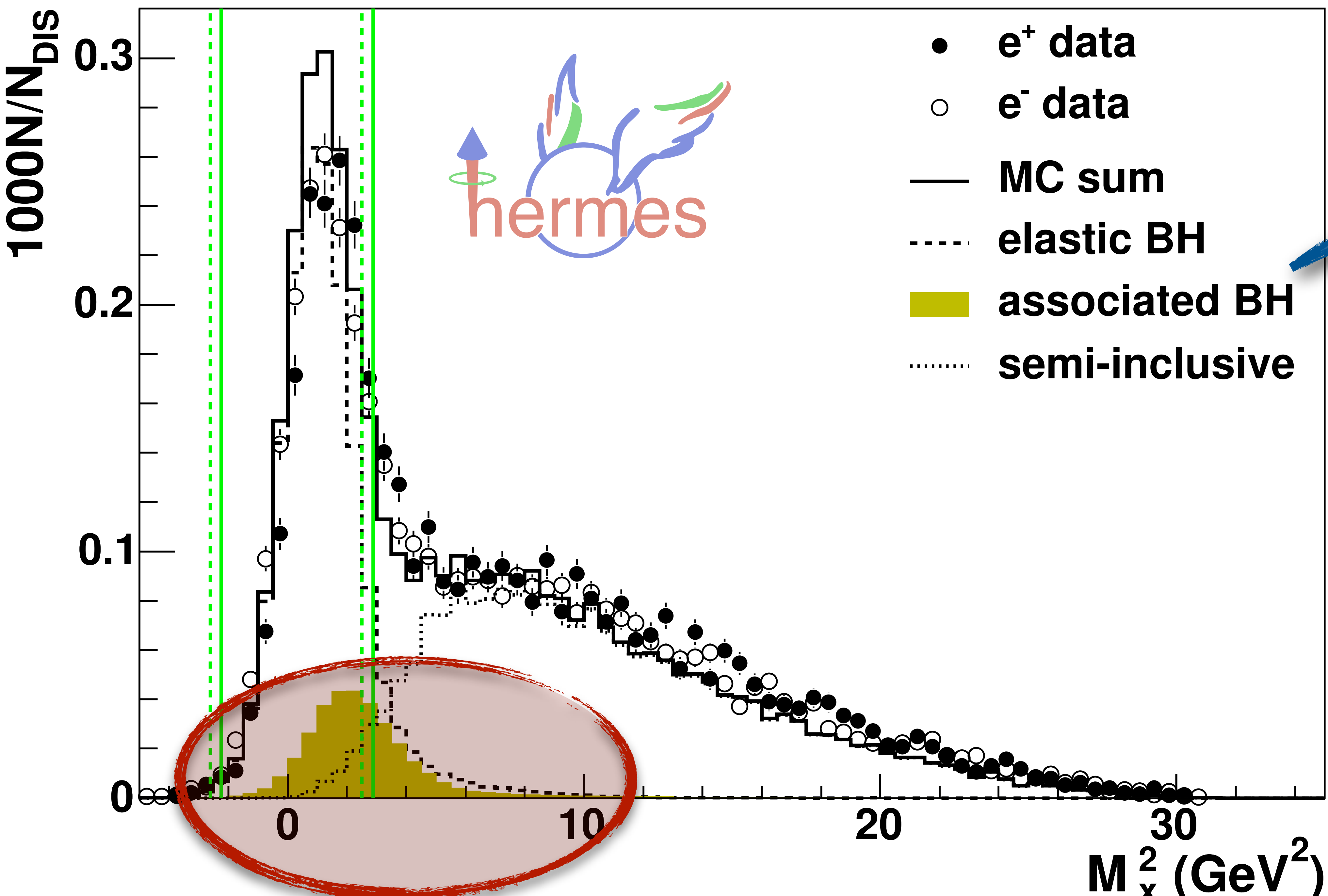
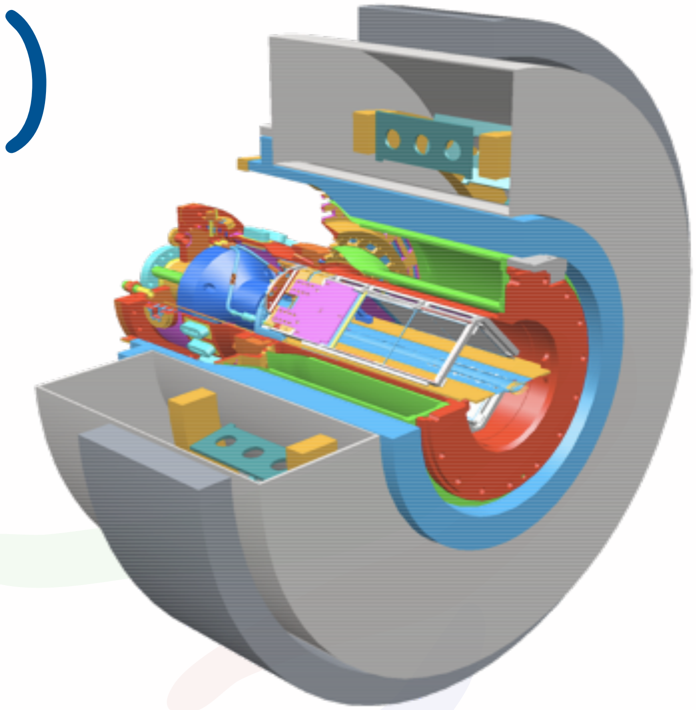
Exclusivity: missing-mass technique

ep -> e γ X

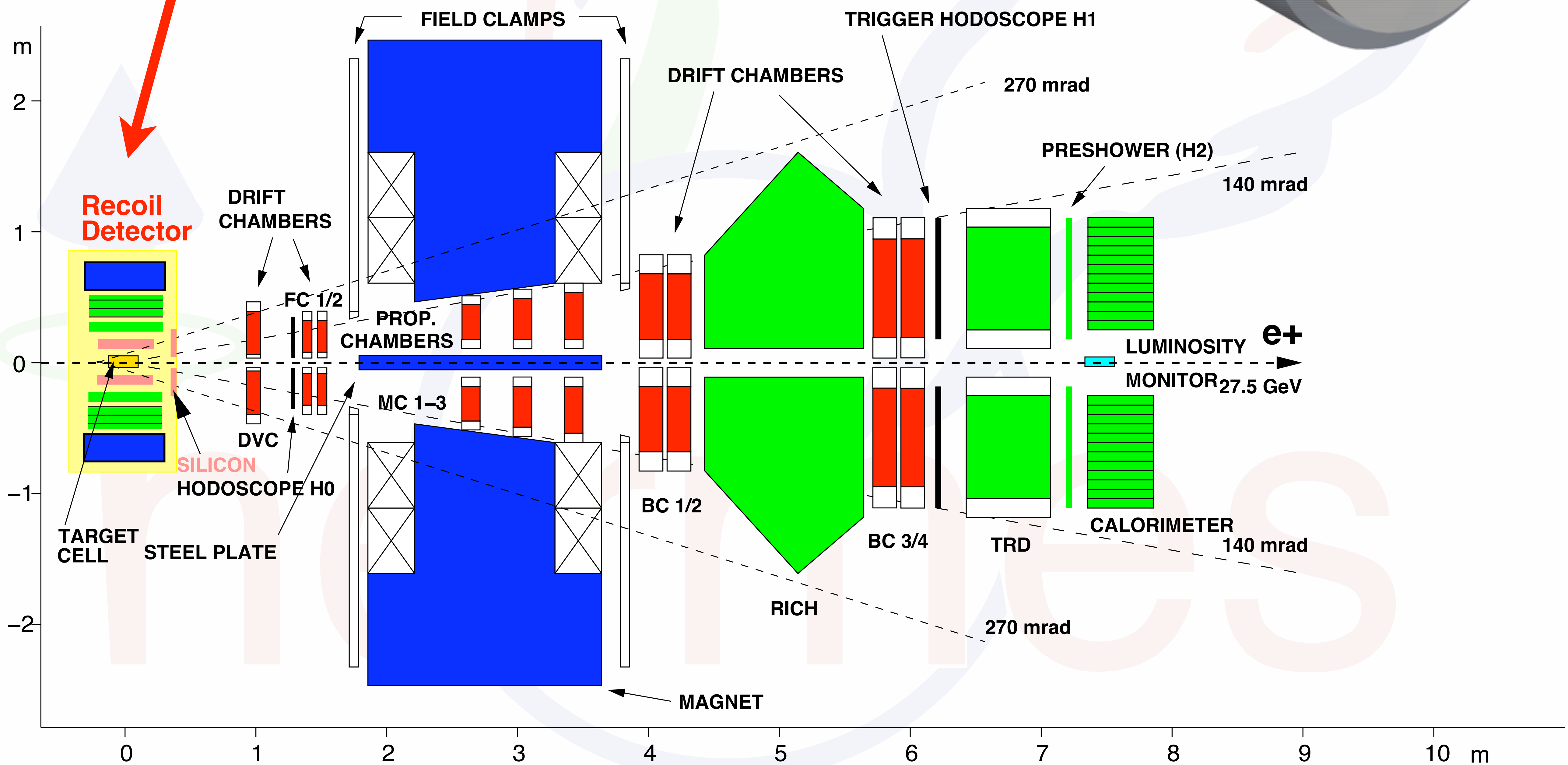


X=Δ+,...

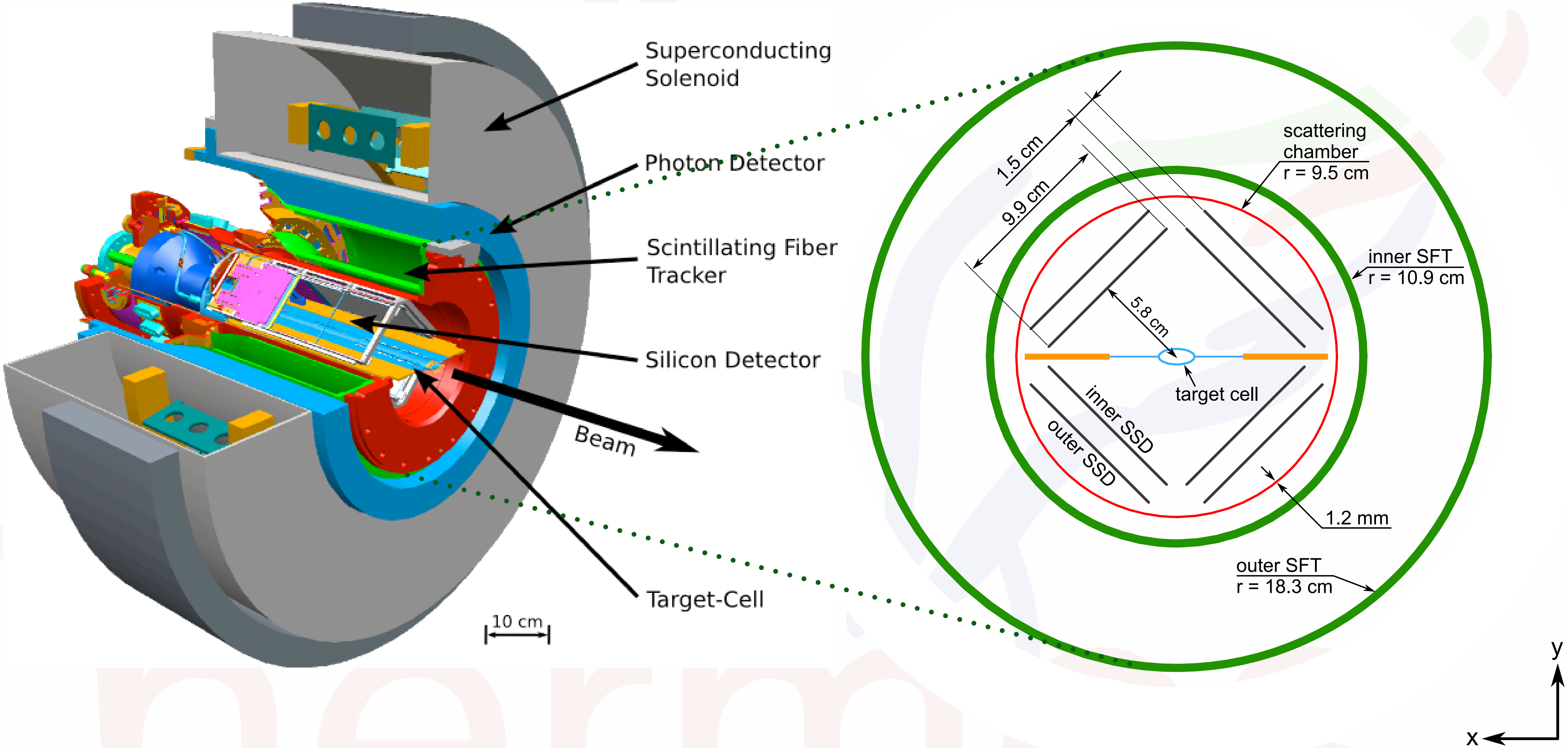
HERMES detector (2006/07)



detection of recoiling proton



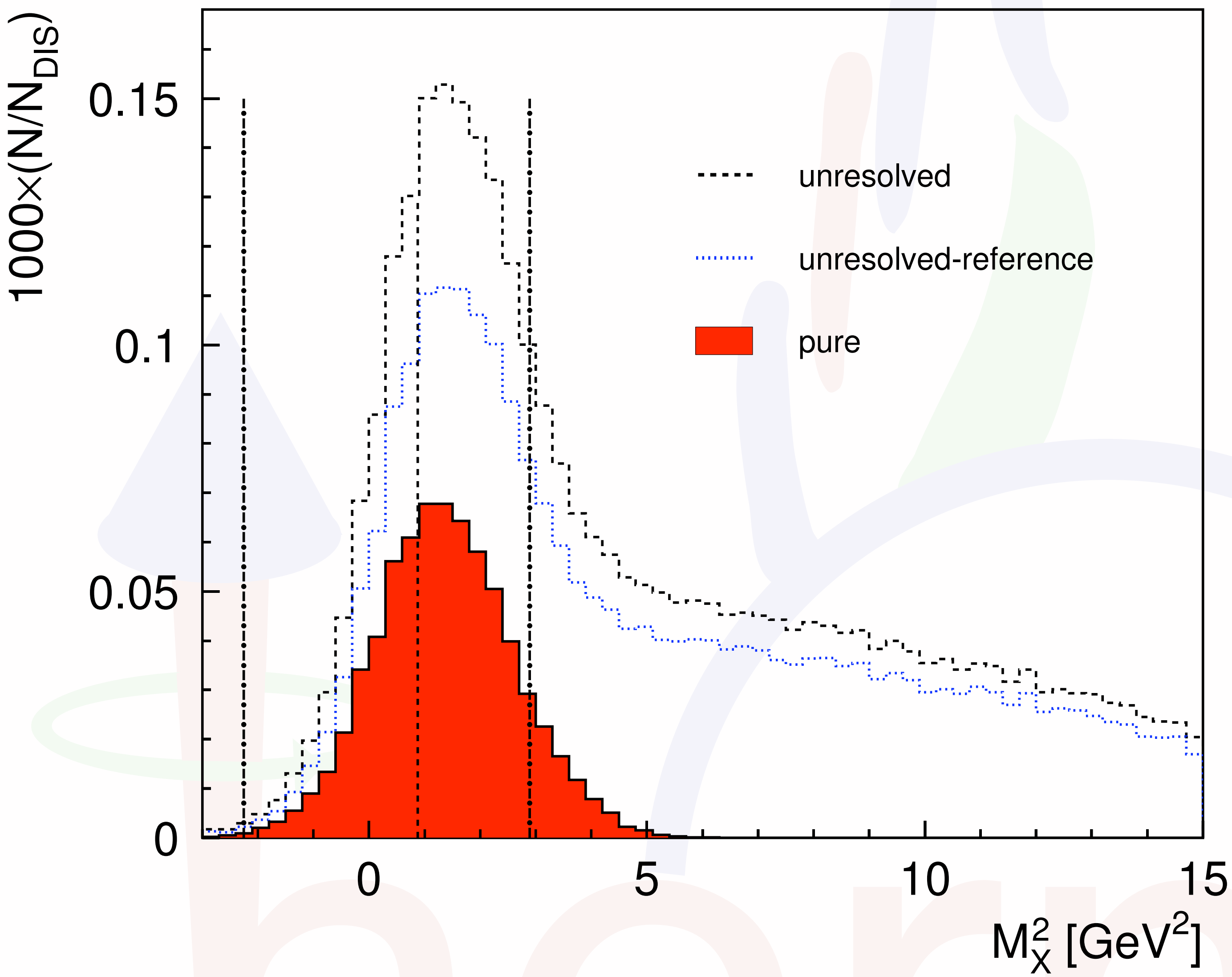
The HERMES Recoil detector

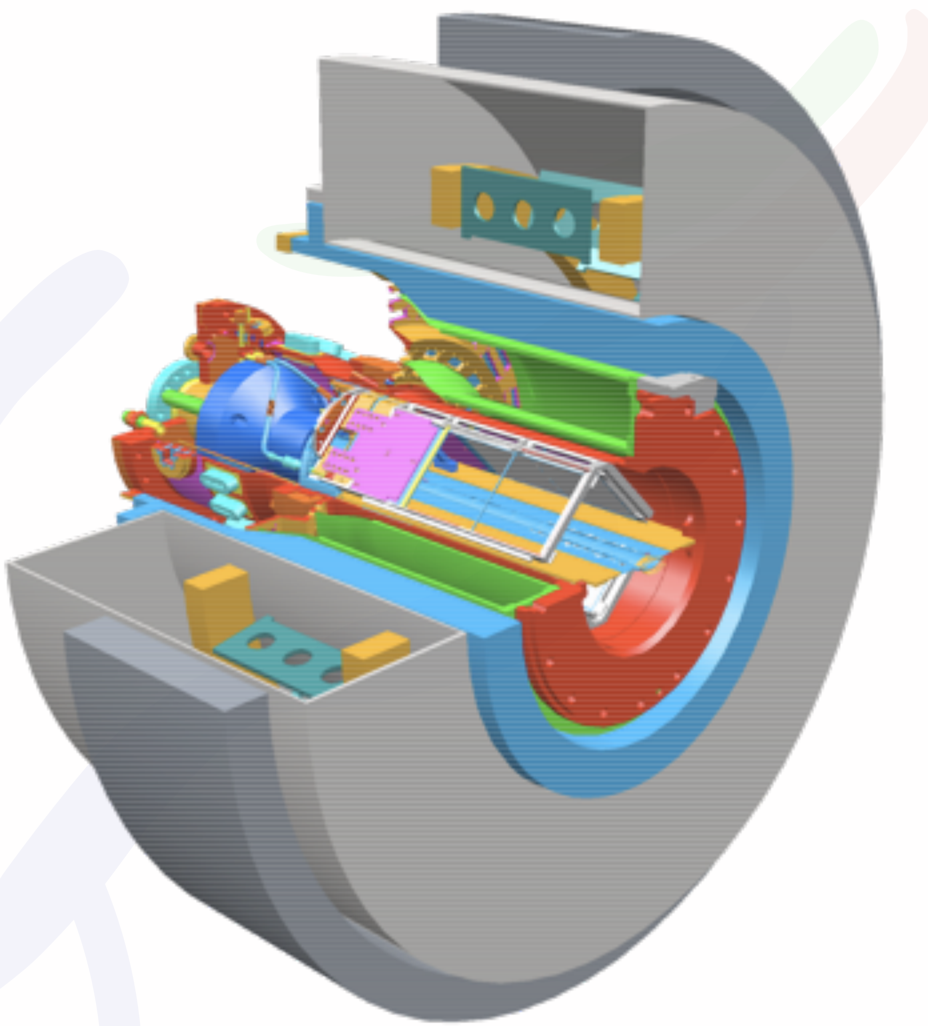


Enables the measurement of the recoiling charged particle and therefore full ep→ep γ event reconstruction

HERMES detector (2006/07)

kinematic fitting





– All particles in final state detected → 4 constraints from energy-momentum conservation

– Selection of pure BH/DVCS ($ep \rightarrow ep\gamma$) with **high efficiency** (~83%)

– Allows to suppress background from associated and semi-inclusive processes to a negligible level (<0.2%)

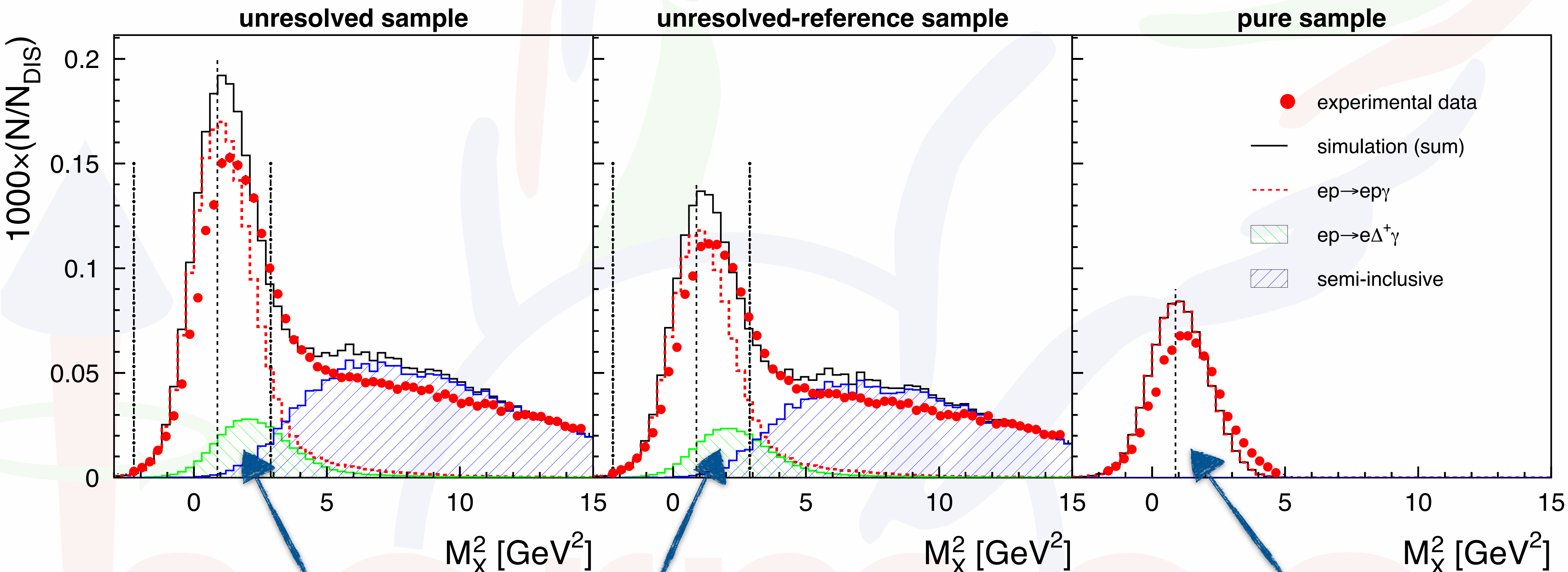
Exclusivity with recoil detector

forward spectrometer only

similar background

measured proton

same kinematic acceptance



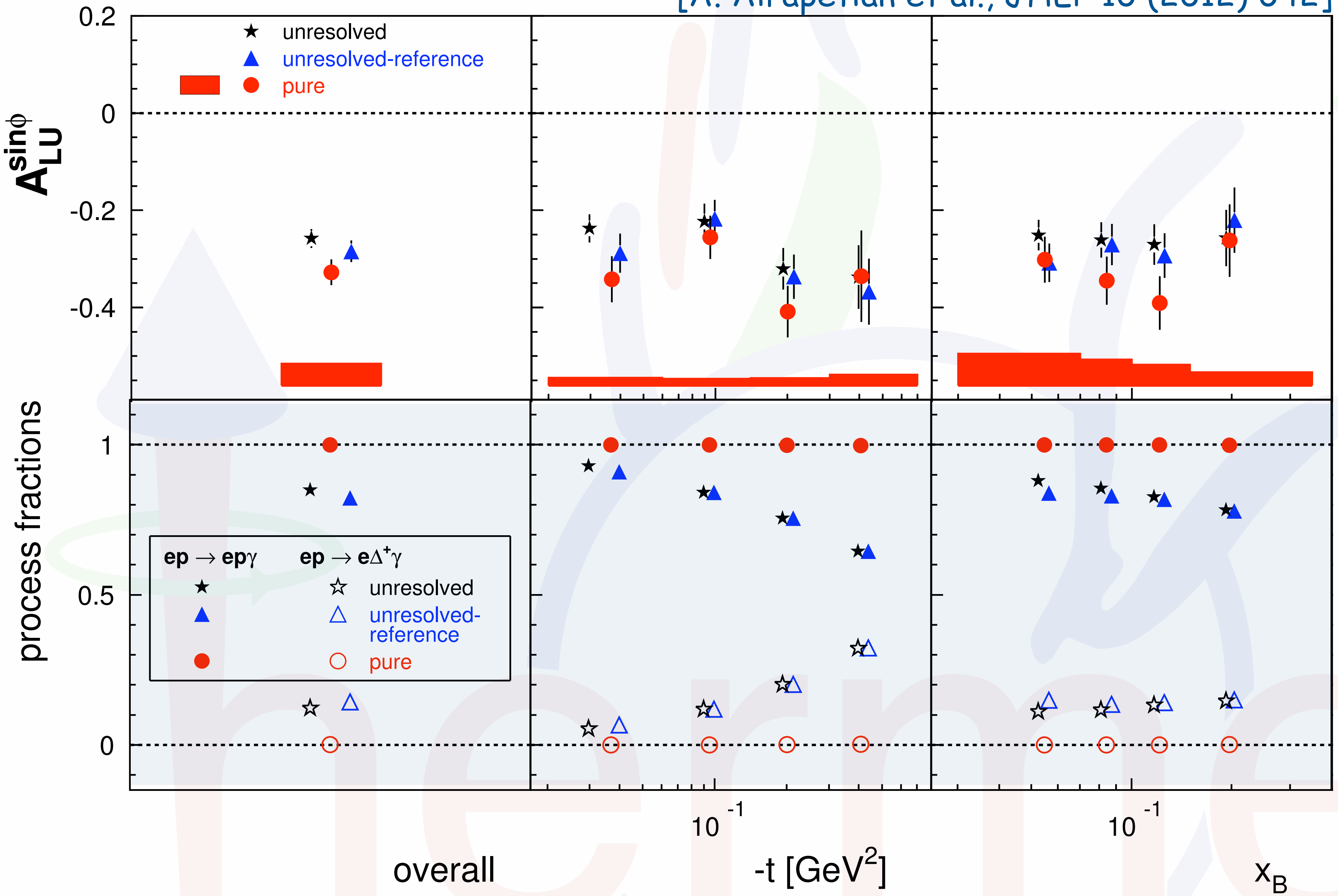
associated processes (ep→e γ Δ^+)

pure ep→e γ p

Missing mass: $$\boxed{M_x^2 = (k - k' + P_0 - P_\gamma)^2 = M^2 + 2M(\nu - E_\gamma) + t}$$

Single-charge BSA with recoil proton

[A. Airapetian et al., JHEP 10 (2012) 042]

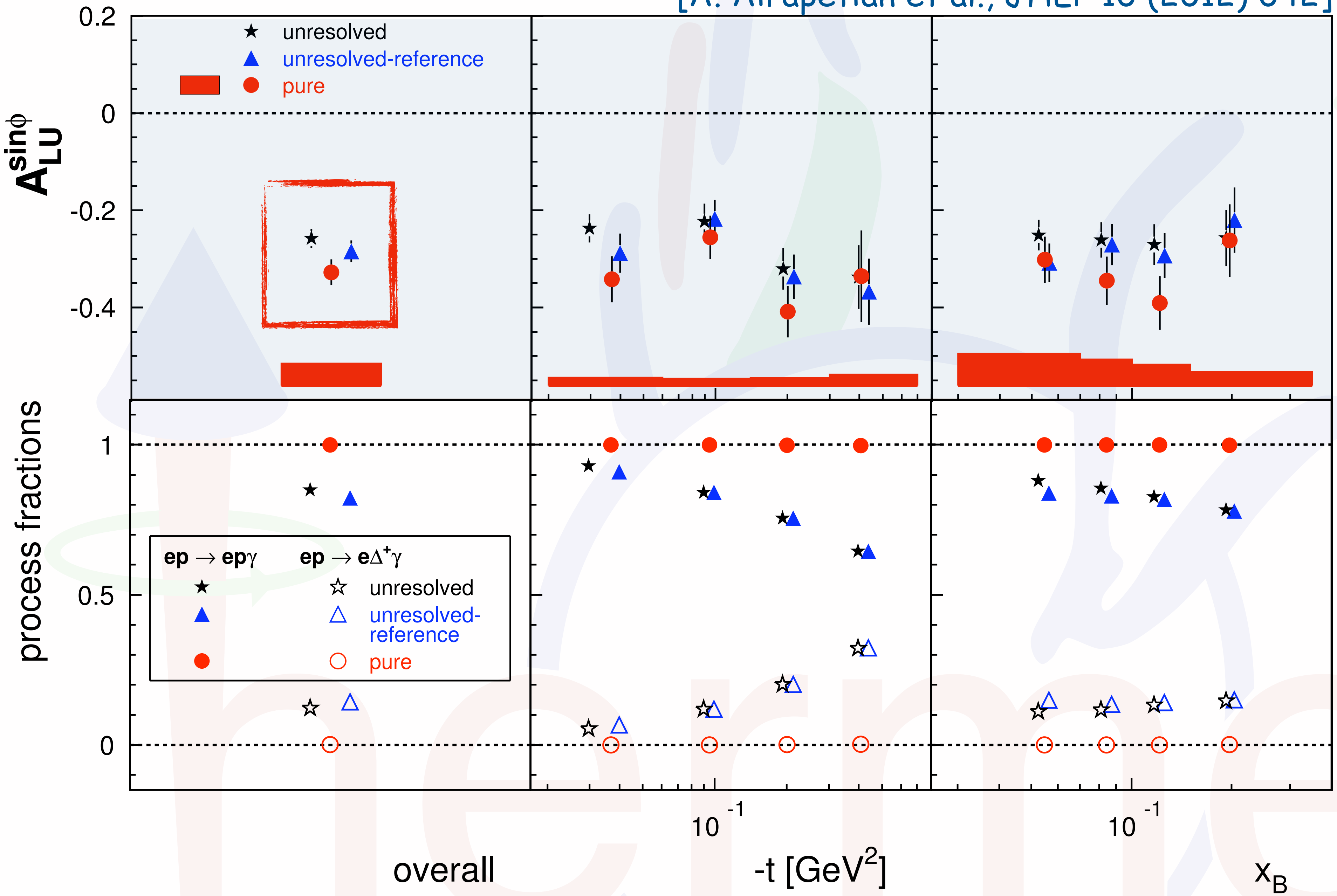


basically **no contamination**

-> clear interpretation

Single-charge BSA with recoil proton

[A. Airapetian et al., JHEP 10 (2012) 042]



Magnitude of the leading asymmetry has increased by 0.054 ± 0.016

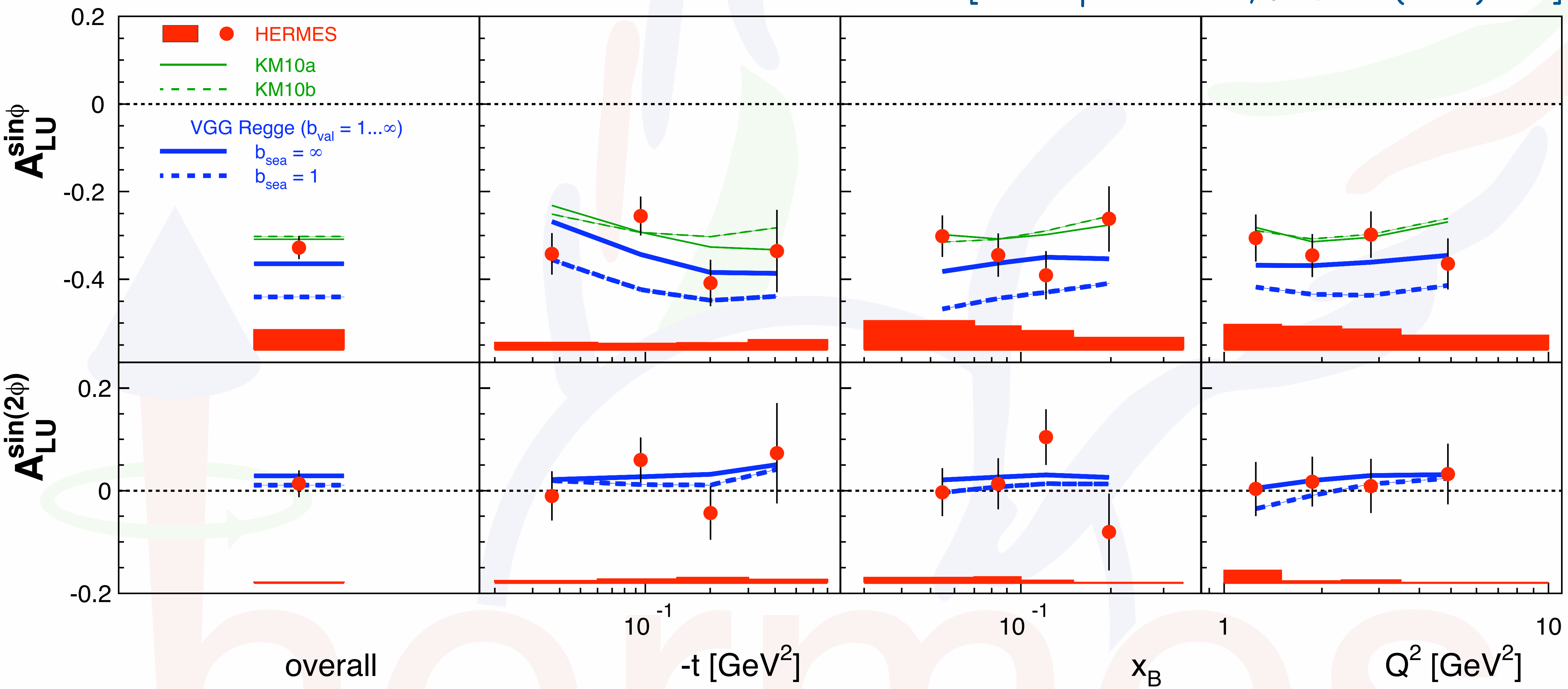
(-> assoc. in traditional analysis mainly dilution)

basically **no contamination**

-> clear interpretation

Single-charge BSA with recoil proton

[A. Airapetian et al., JHEP 10 (2012) 042]

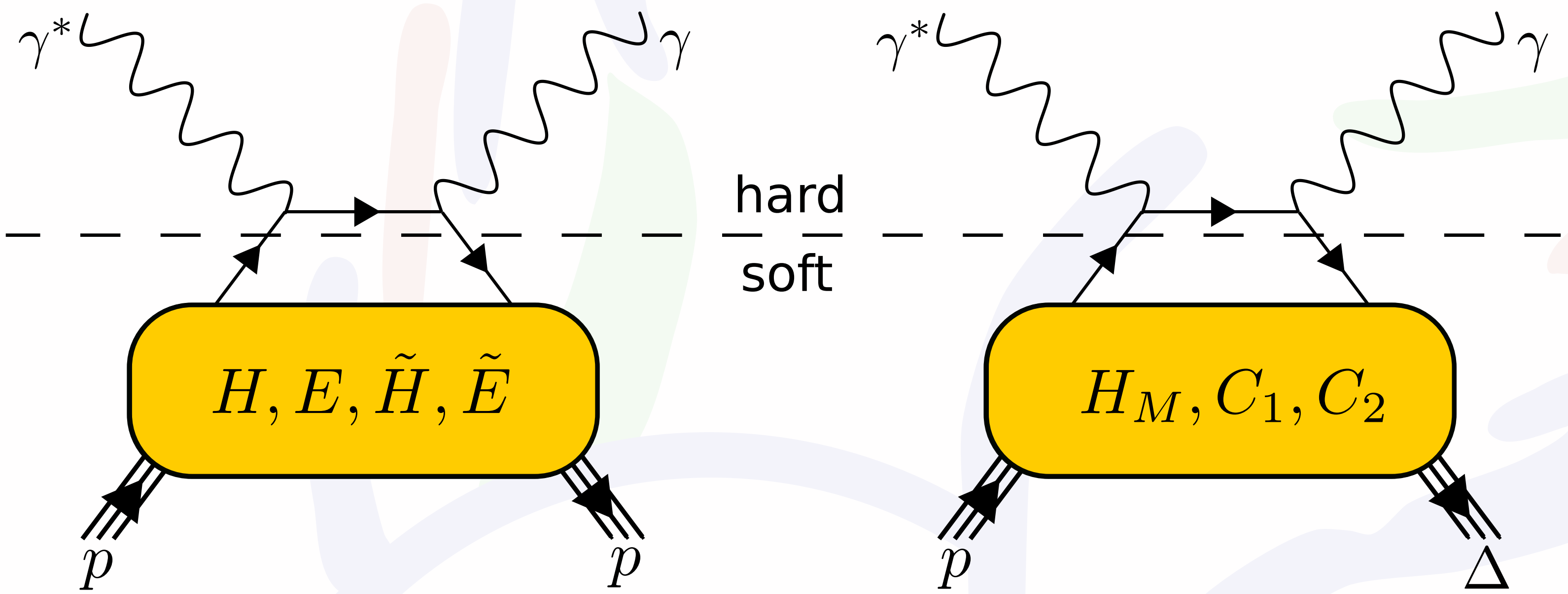


good agreement with models

KM10 - K. Kumericki and D. Müller, Nucl. Phys. B 841 (2010) 1
VGG - M. Vanderhaeghen et al., Phys. Rev. D 60 (1999) 094017

Beam-spin asymmetries ep→e γ Nπ

Besides a better understanding of the unresolved sample, associated DVCS in principle also allows further access to GPDs.

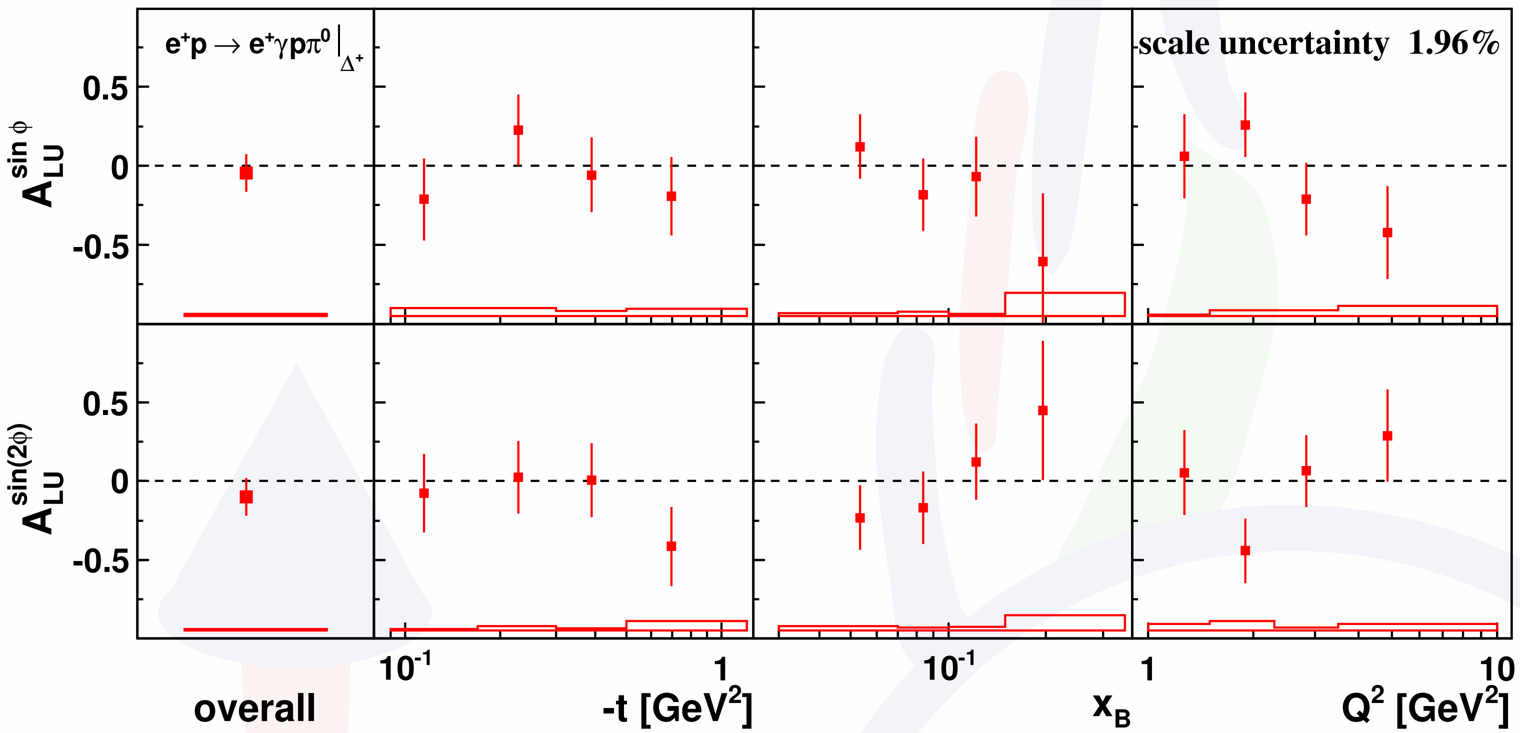


In the large-N$_c$ limit the remaining N→Δ GPDs can be related to the N→N iso-vector GPDs:

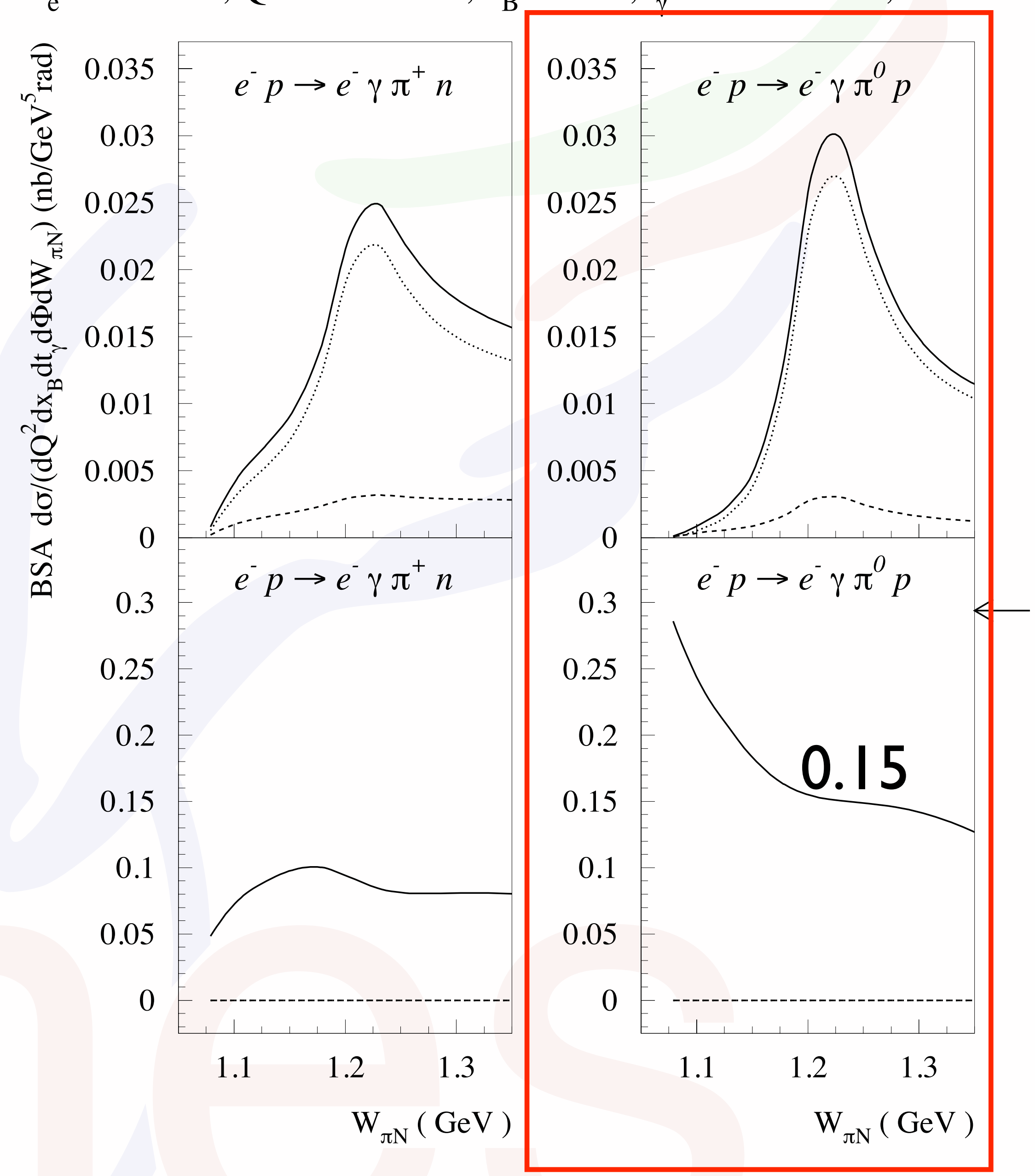
$$\boxed{\begin{aligned} H_M(x,\xi,t) &= \frac{2}{\sqrt{3}}\left[E^u(x,\xi,t) - E^d(x,\xi,t)\right], \\ C_1(x,\xi,t) &= \sqrt{3}\left[\tilde{H}^u(x,\xi,t) - \tilde{H}^d(x,\xi,t)\right], \\ C_2(x,\xi,t) &= \frac{\sqrt{3}}{4}\left[\tilde{E}^u(x,\xi,t) - \tilde{E}^d(x,\xi,t)\right] \end{aligned}}$$

Beam-spin asymmetries $ep \rightarrow e\gamma p\pi^0$

[A. Airapetian et al., JHEP 01 (2014) 077]



[Guichon et al., PRD 68 (2003) 034018]



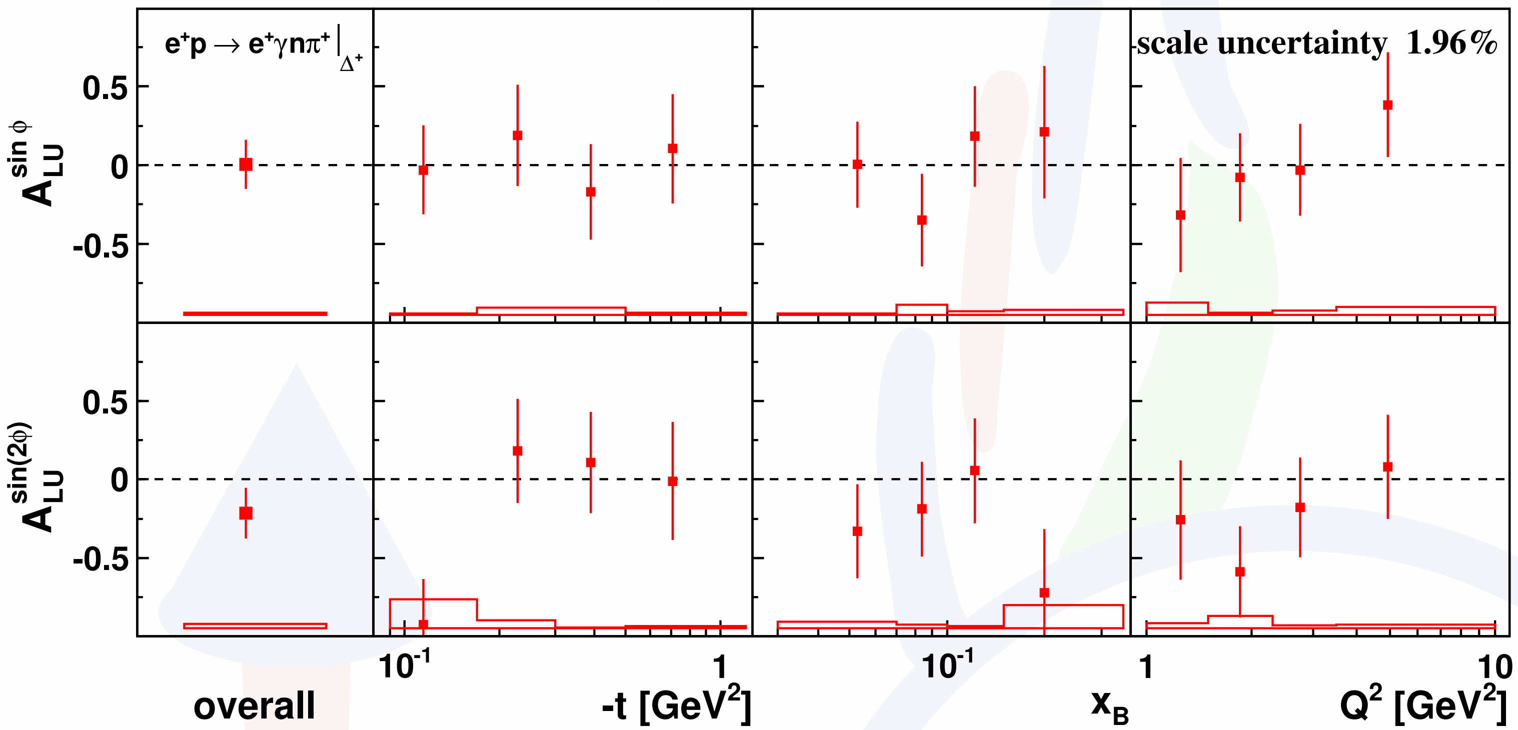
Shown amplitudes corrected for background (only overall fractions are listed here):

Associated DVCS/BH ($ep \rightarrow e\gamma p\pi^0$)	85 ± 1
Elastic DVCS/BH ($ep \rightarrow e\gamma p$)	4.6 ± 0.1
SIDIS ($ep \rightarrow eX\pi^0$)	11 ± 1

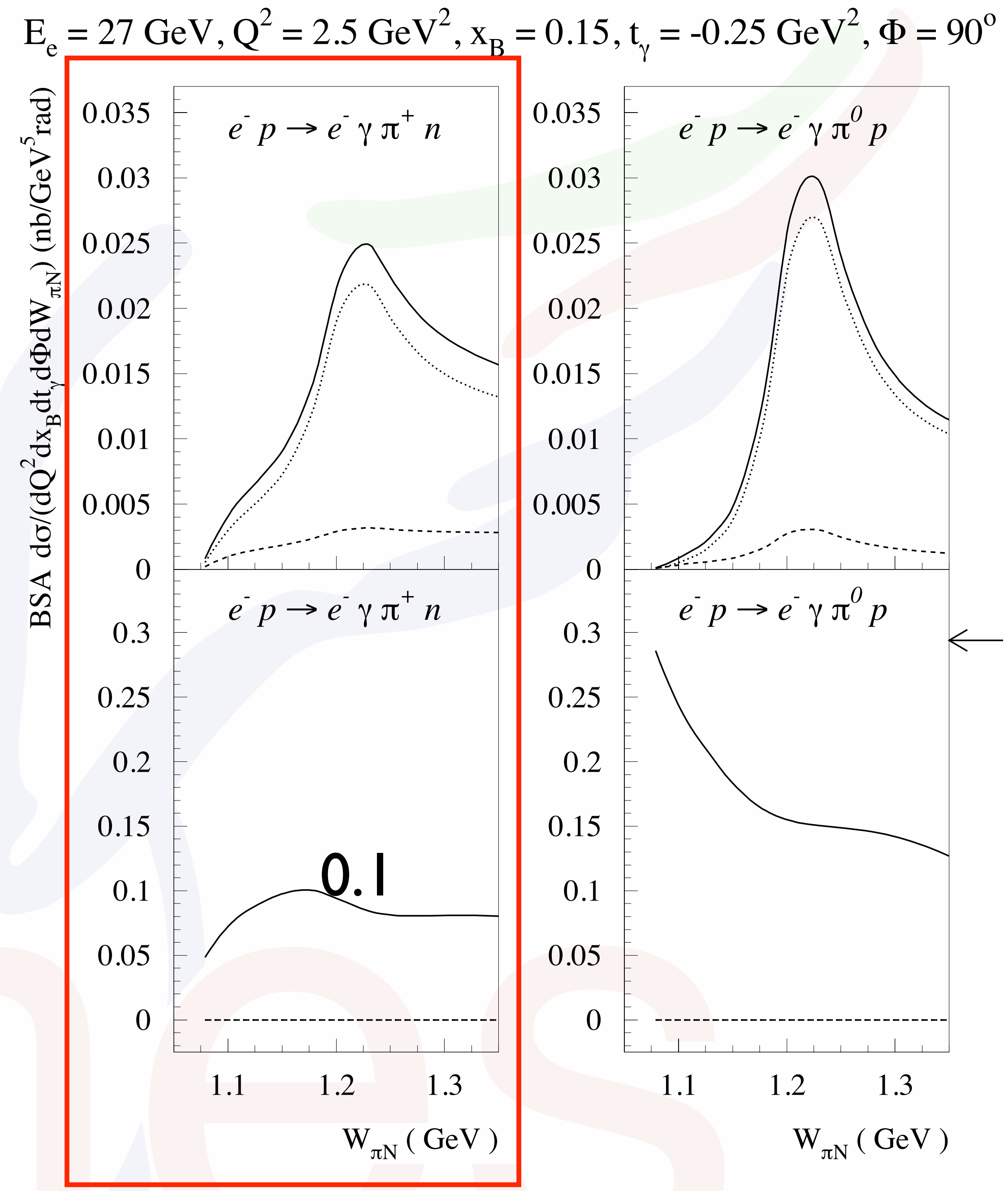
opposite sign conventions!

Beam-spin asymmetries $ep \to e\gamma n\pi^+$

[A. Airapetian et al., JHEP 01 (2014) 077]



[Guichon et al., PRD 68 (2003) 034018]

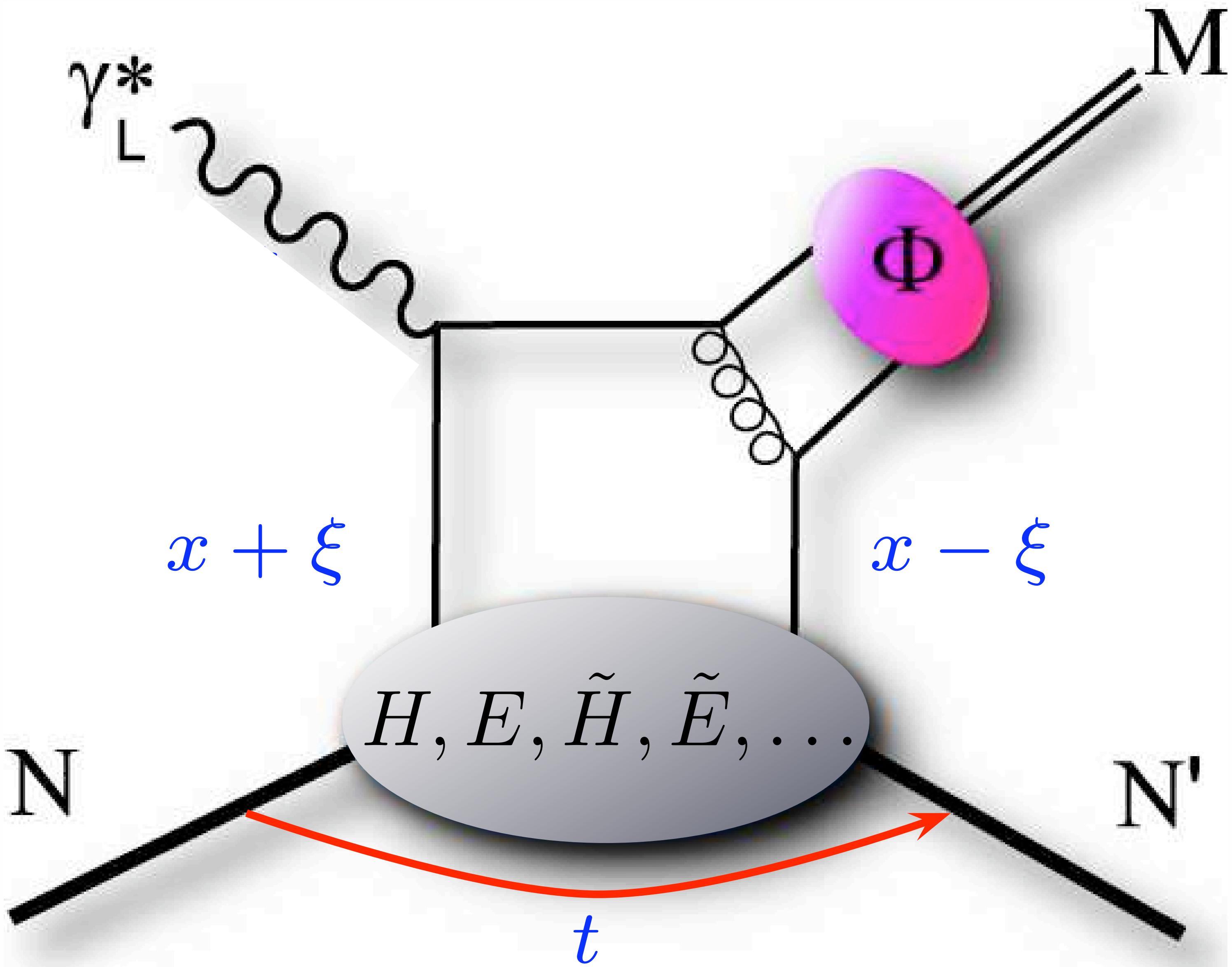


Shown amplitudes corrected for background (only overall fractions are listed here):

Associated DVCS/BH ($ep \to e\gamma n\pi^+$)	77 ± 2
Elastic DVCS/BH ($ep \to e\gamma p$)	0.2 ± 0.1
SIDIS ($ep \to eX\pi^0$)	23 ± 3

opposite sign convention!

Exclusive meson production



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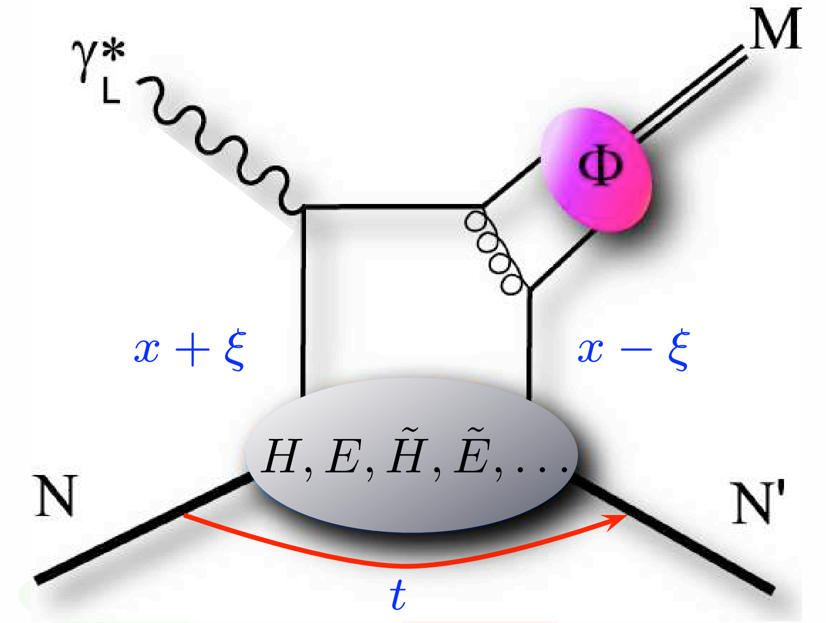

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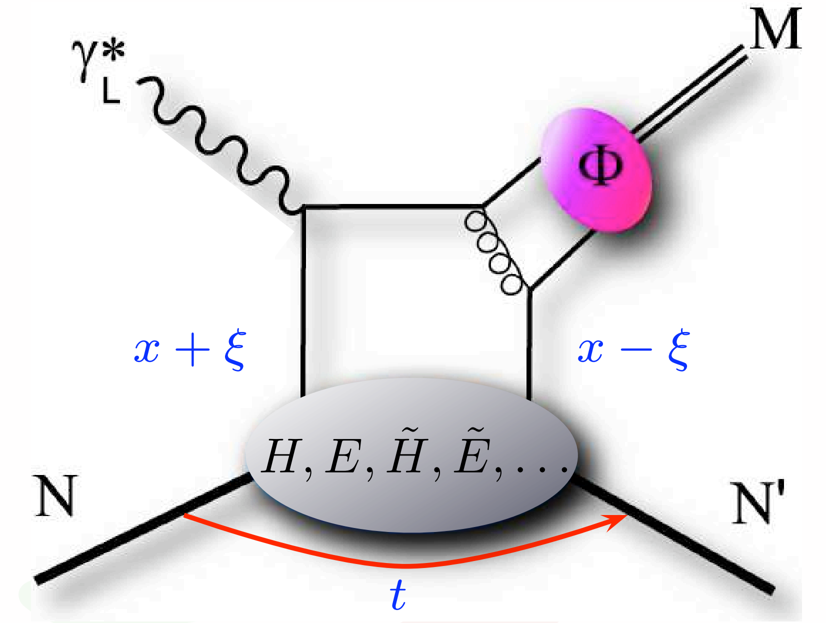
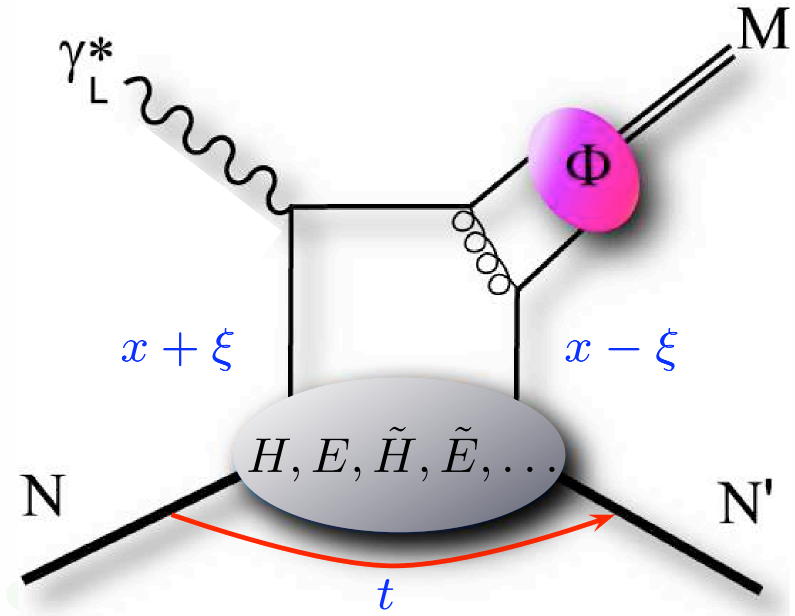


- GPDs convoluted with meson amplitude

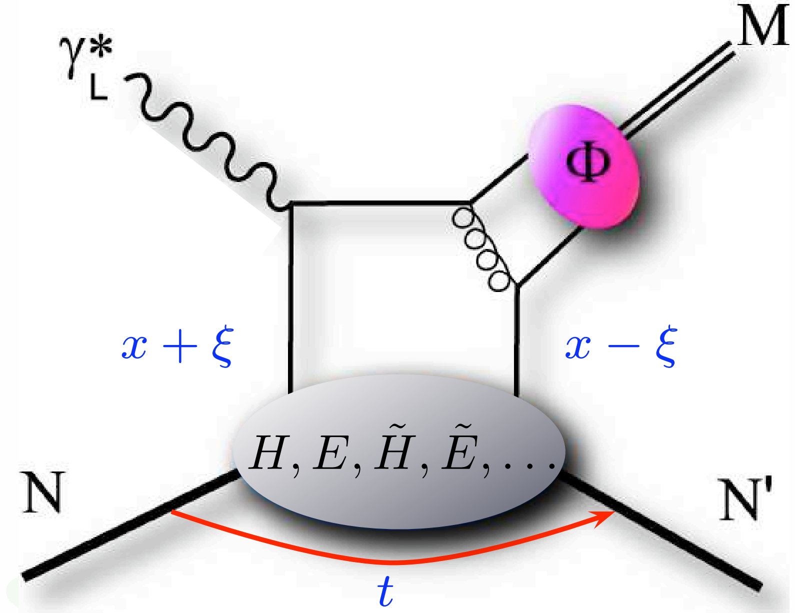
Exclusive meson production



- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$
ρ^0	2u+d, 9g/4
ω	2u−d, 3g/4
ϕ	s, g
ρ^+	u−d
J/ψ	g

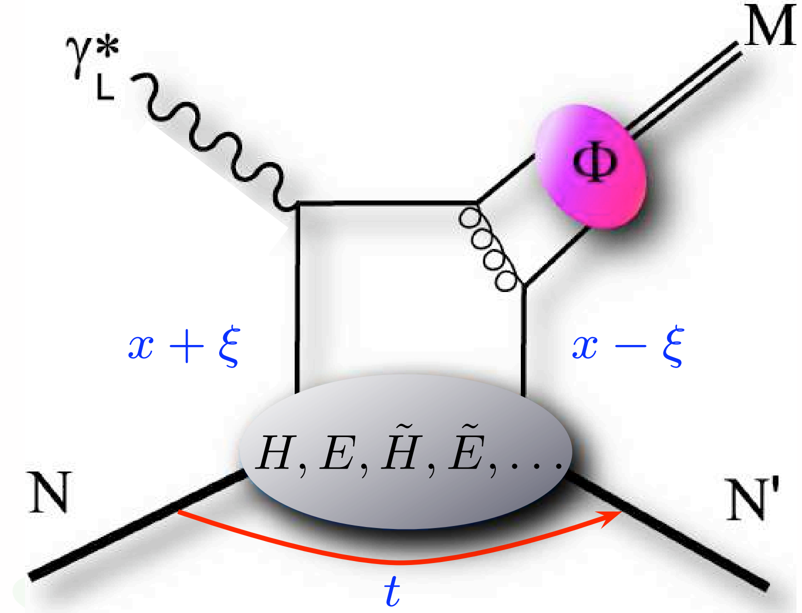
Exclusive meson production



- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
- factorization proven for longitudinal photons

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$
ρ^0	2u+d, 9g/4
ω	2u−d, 3g/4
ϕ	s, g
ρ^+	u−d
J/ψ	g

Exclusive meson production

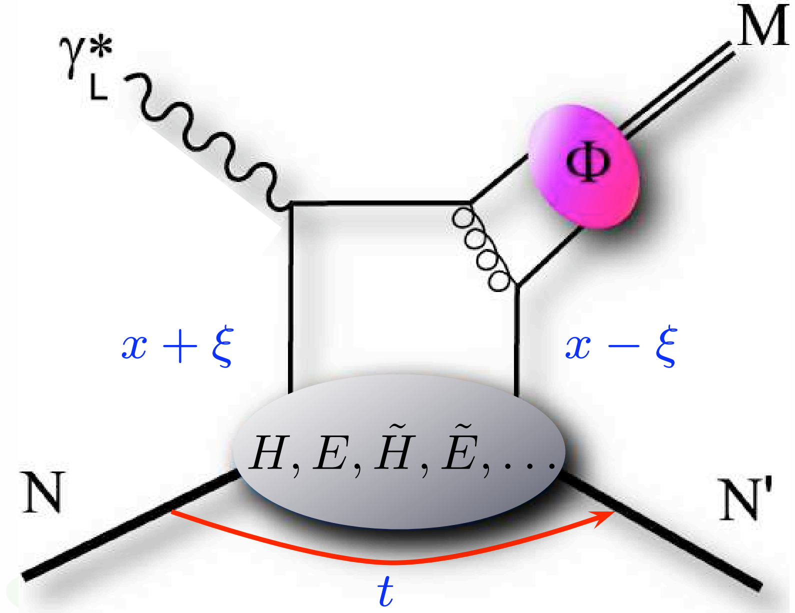


- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
- factorization proven for longitudinal photons
- generalized to transverse photons in GK model

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$

ρ^0	2u+d, 9g/4
ω	2u−d, 3g/4
ϕ	s, g
ρ^+	u−d
J/ψ	g

Exclusive meson production



π^0	$2\Delta u+\Delta d$
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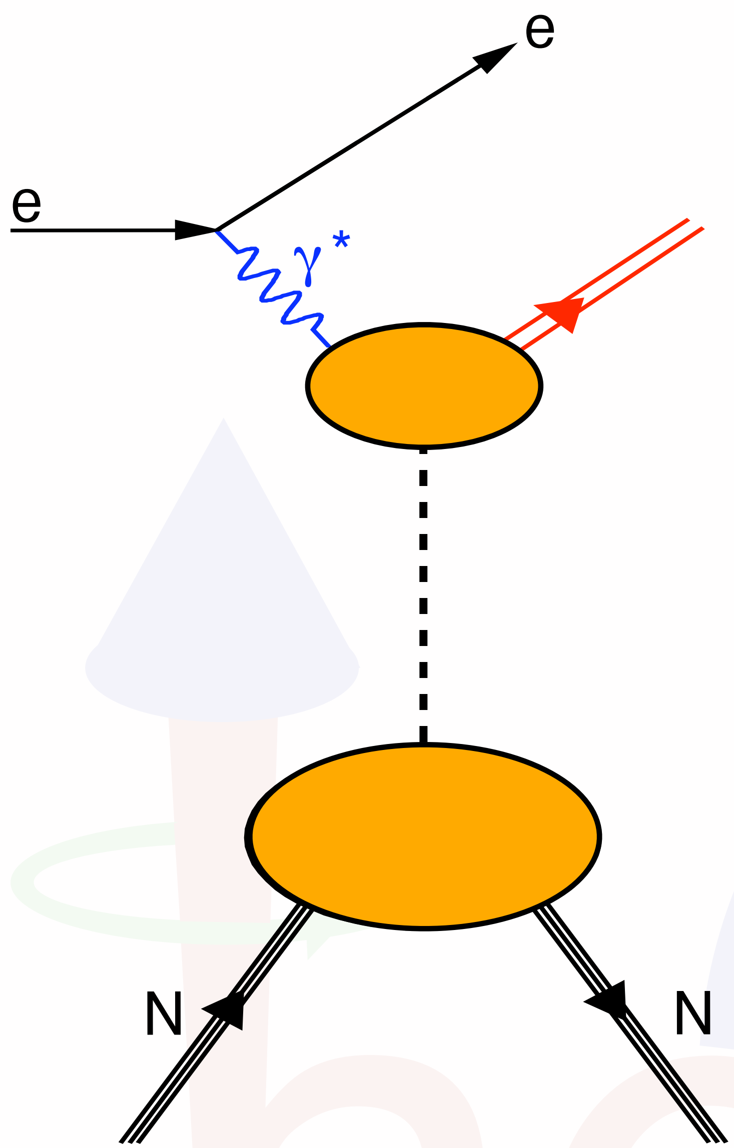
- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
- factorization proven for longitudinal photons
- generalized to transverse photons in GK model
- vector-meson cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_B\,\mathrm{d}Q^2\,\mathrm{d}t\,\mathrm{d}\phi_S\,\mathrm{d}\phi\,\mathrm{d}\cos\theta\,\mathrm{d}\varphi} = \frac{\mathrm{d}\sigma}{\mathrm{d}x_B\,\mathrm{d}Q^2\,\mathrm{d}t} W(x_B, Q^2, t, \phi_S, \phi, \cos\theta, \varphi)$$

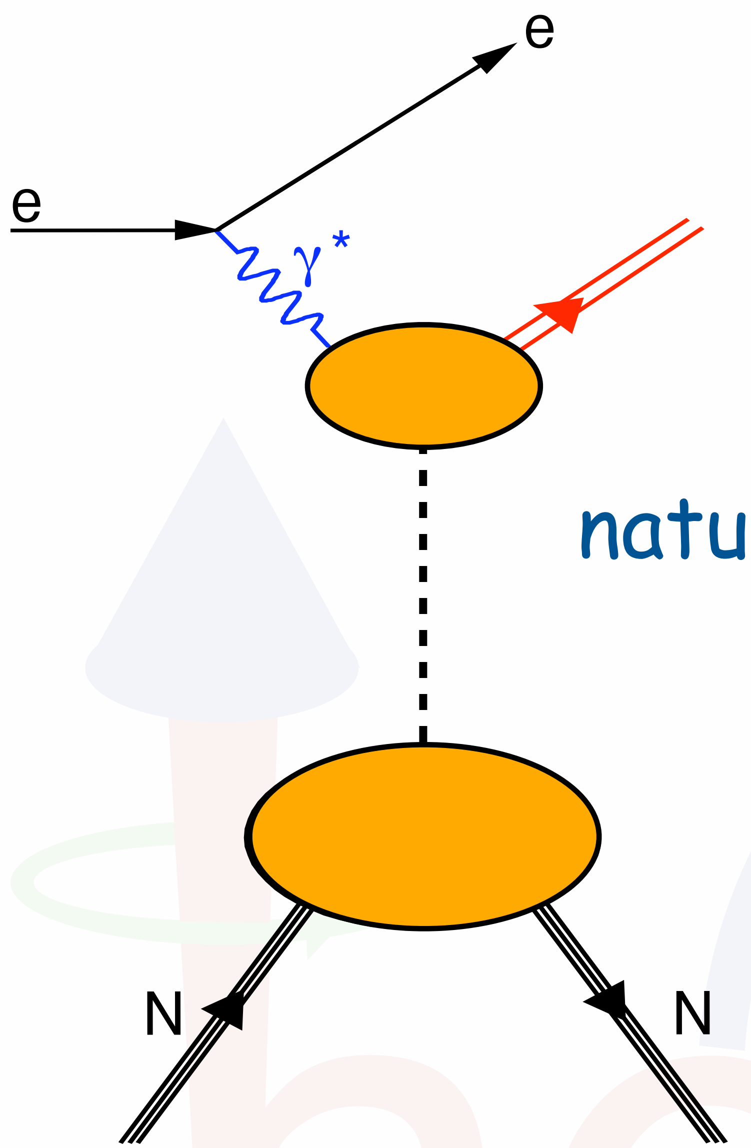
$$W = W_{UU} + P_B W_{LU} + S_L W_{UL} + P_B S_L W_{LL} + S_T W_{UT} + P_B S_T W_{LT}$$

look at various angular (decay) distributions to study helicity transitions (“spin-density matrix elements”)

“Regge phenomenology”

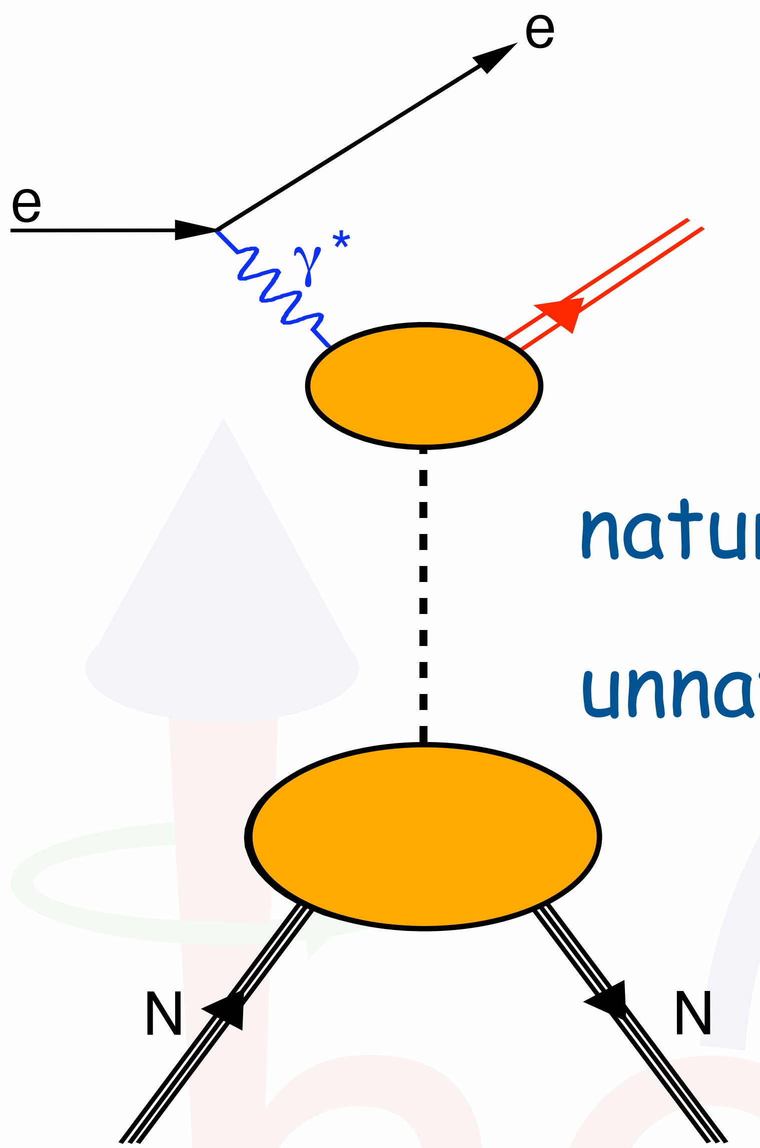


"Regge phenomenology"



natural-parity exchange $J^P = 0^+, 1^-, \ldots$ GPDs H&E

“Regge phenomenology”

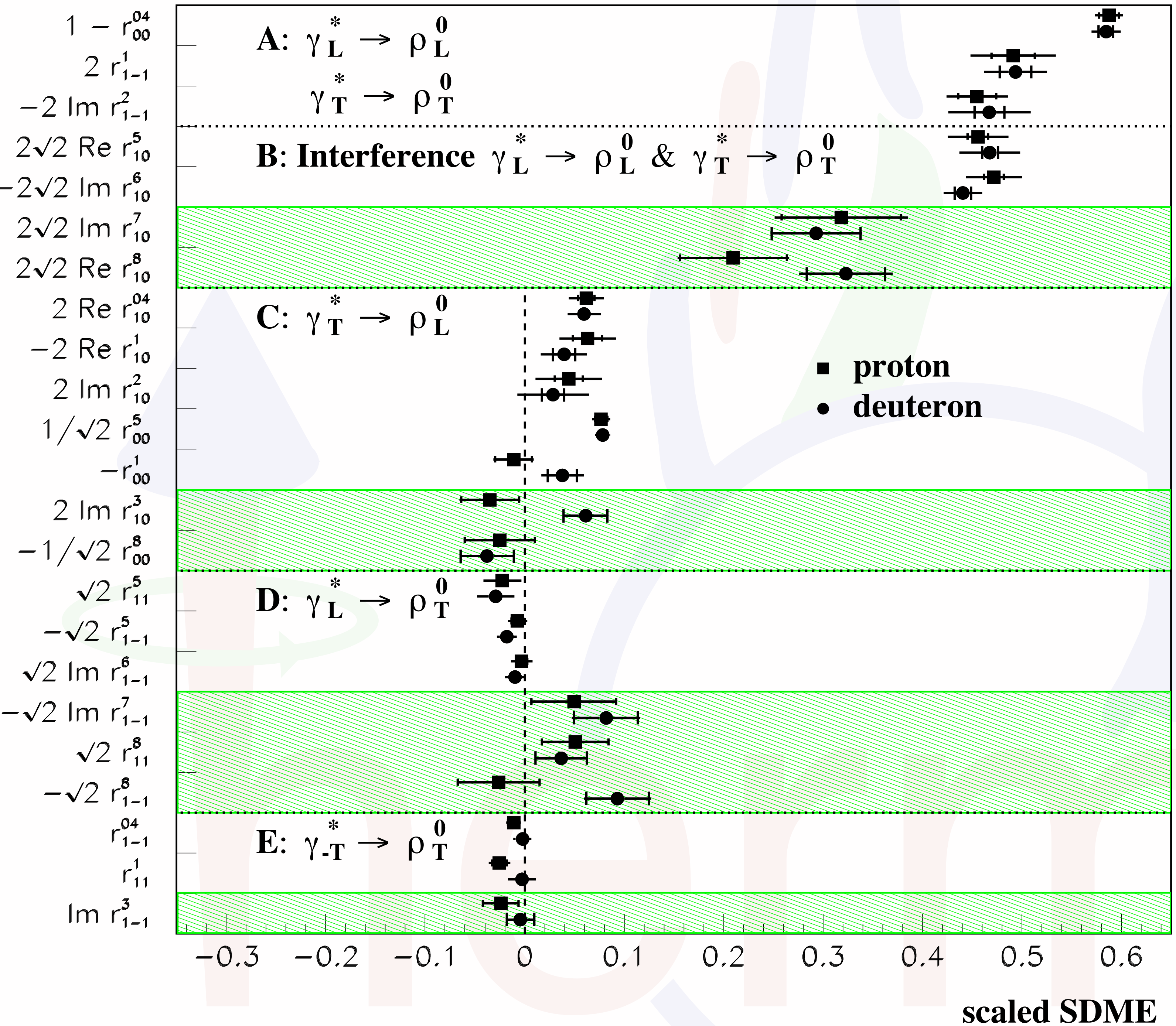


natural-parity exchange $J^P = 0^+, 1^-, \ldots$ GPDs H&E

unnatural-parity exchange $J^P = 0^-, 1^+, \ldots$ GPDs $\tilde{H}$&$\tilde{E}$

ρ^0 SDMEs from HERMES

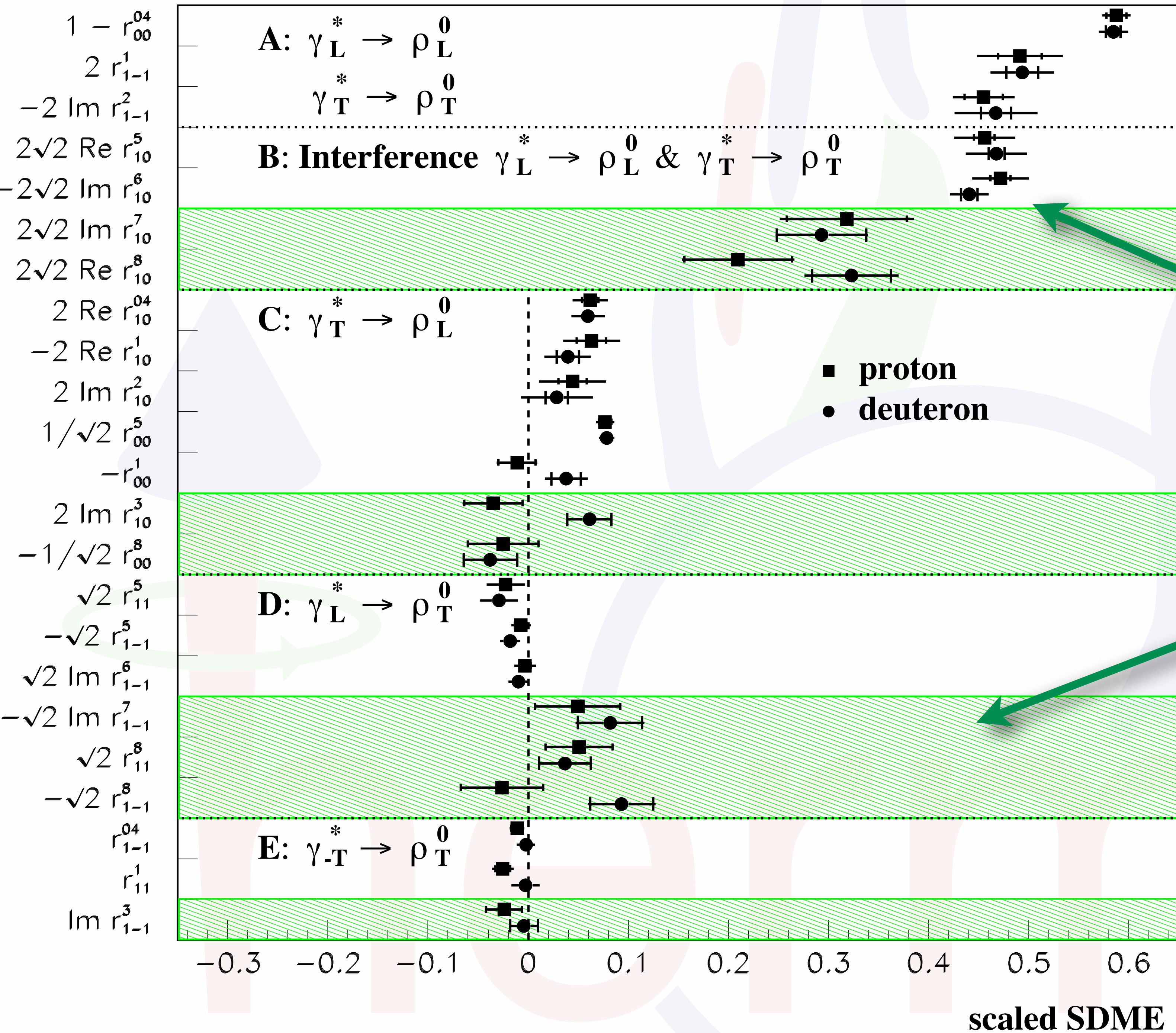
[A. Airapetian et al., EPJ C62 (2009) 659]



target-polarization independent SDMEs

ρ^0 SDMEs from HERMES

[A. Airapetian et al., EPJ C62 (2009) 659]

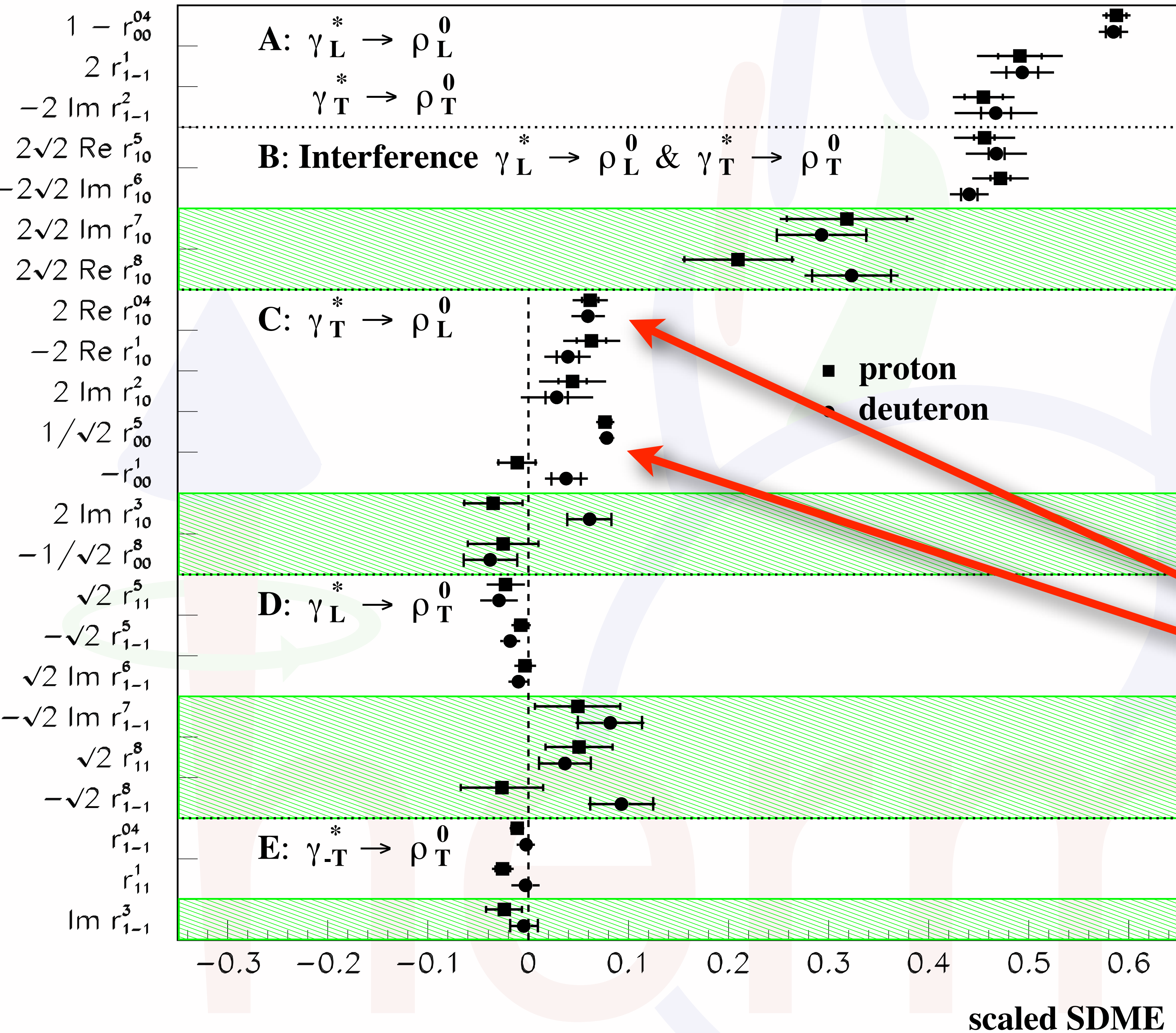


helicity non-flip much larger than helicity-flip and double helicity-flip

target-polarization independent SDMEs

ρ^0 SDMEs from HERMES

[A. Airapetian et al., EPJ C62 (2009) 659]

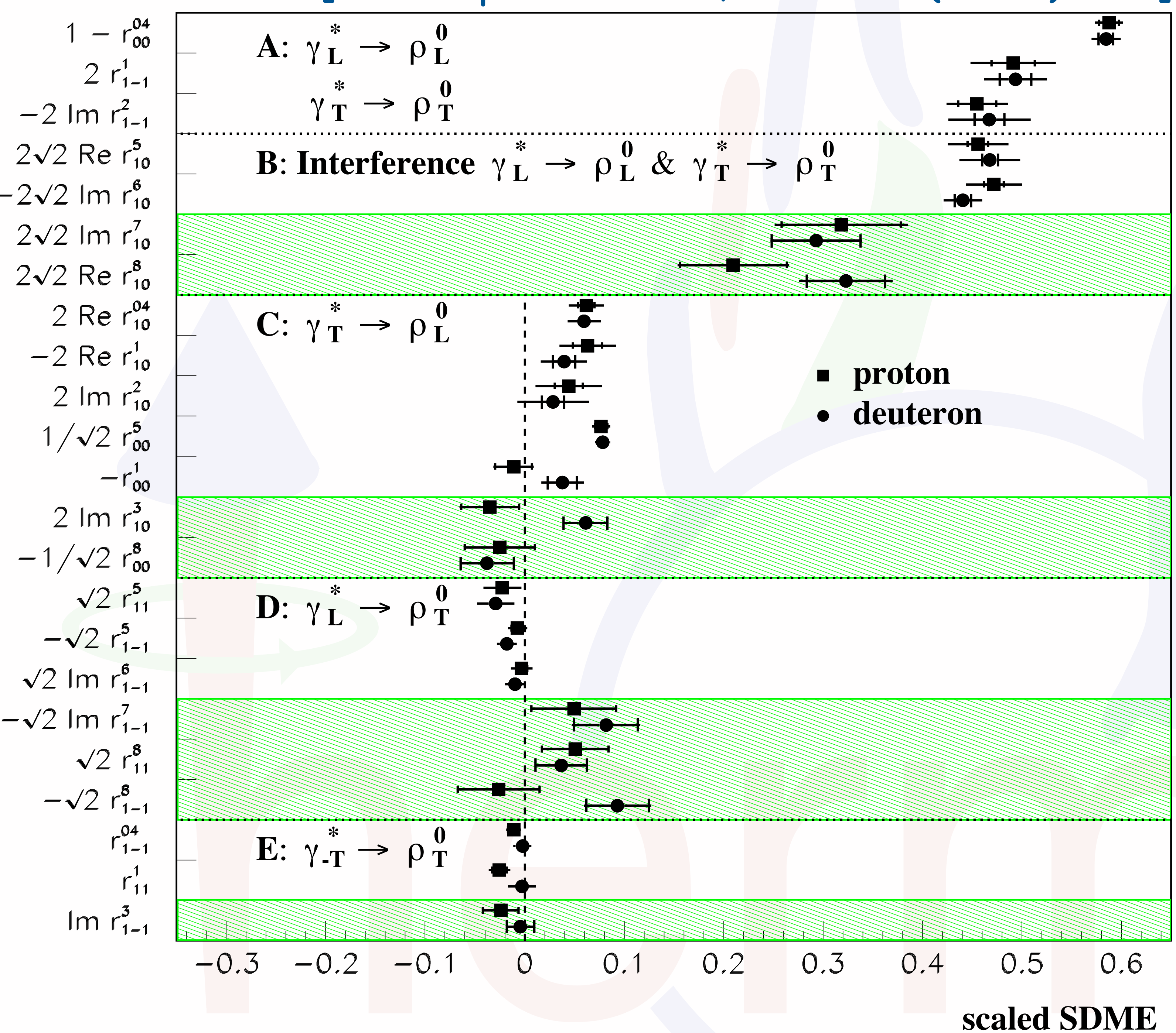


clear breaking of s-channel helicity conservation

target-polarization independent SDMEs

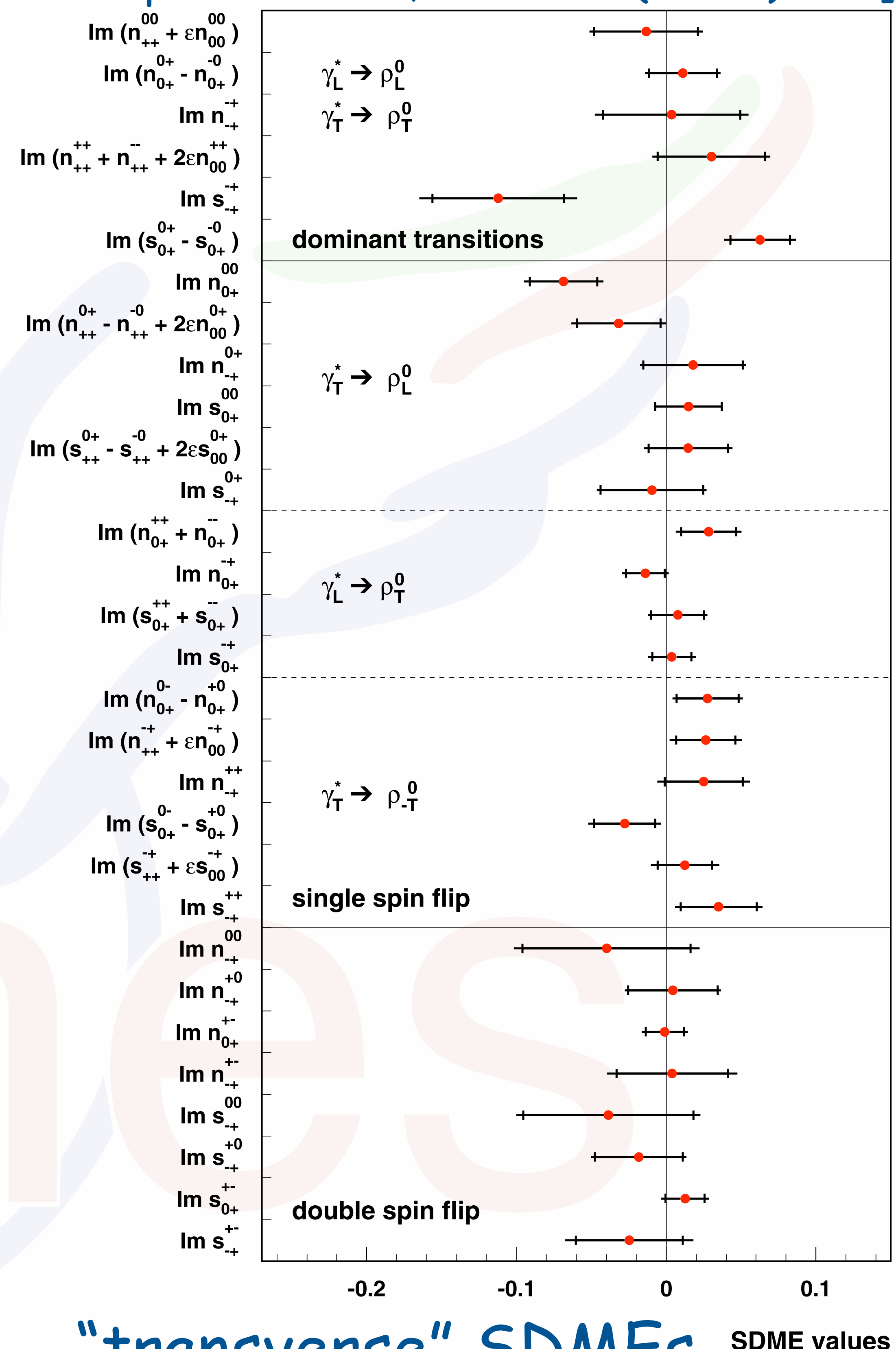
ρ^0 SDMEs from HERMES

[A. Airapetian et al., EPJ C62 (2009) 659]



target-polarization independent SDMEs

[A. Airapetian et al., PLB 679 (2009) 100]



"transverse" SDMEs

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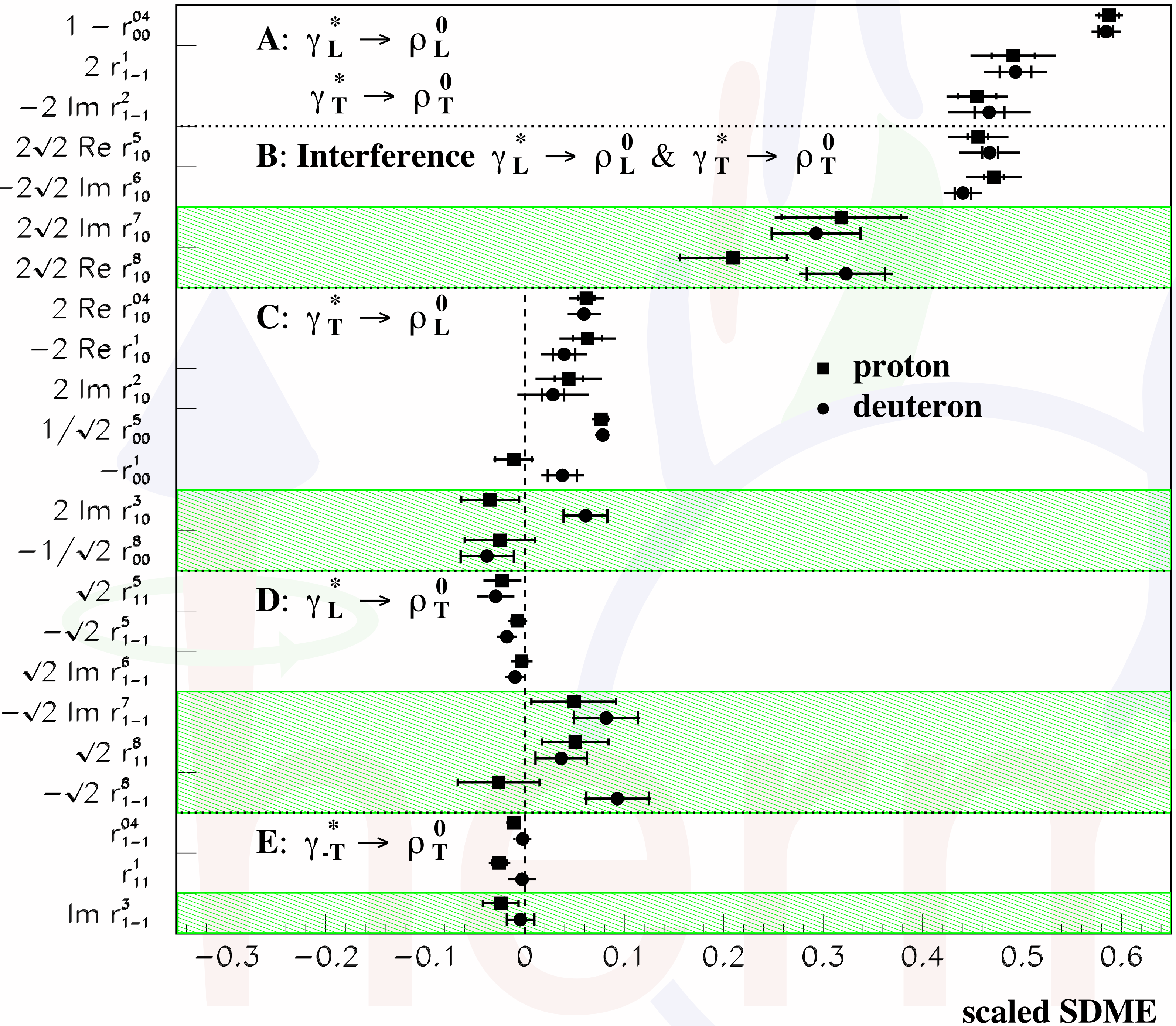
[A. Airapetian et al., EPJ C62 (2009) 659]



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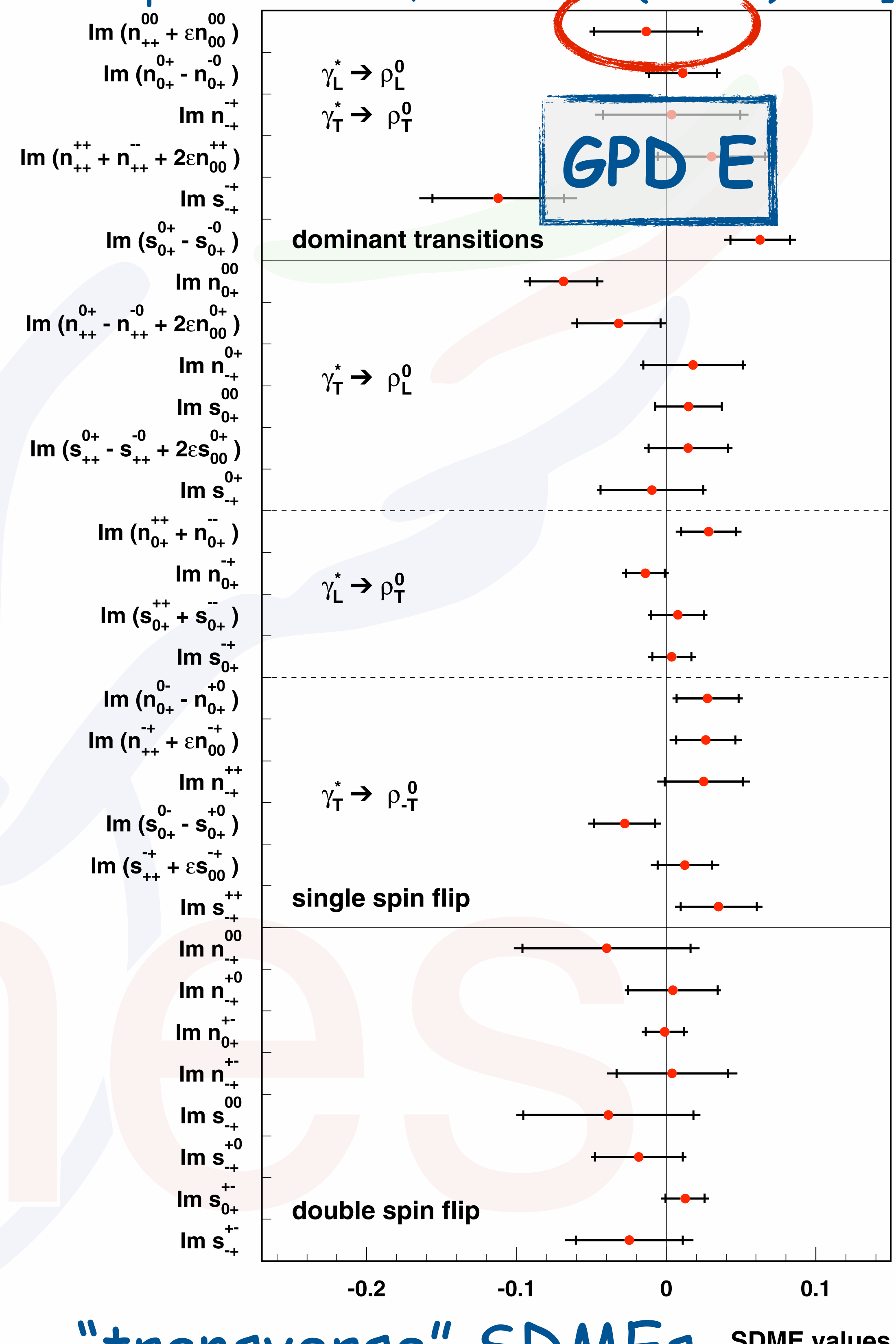

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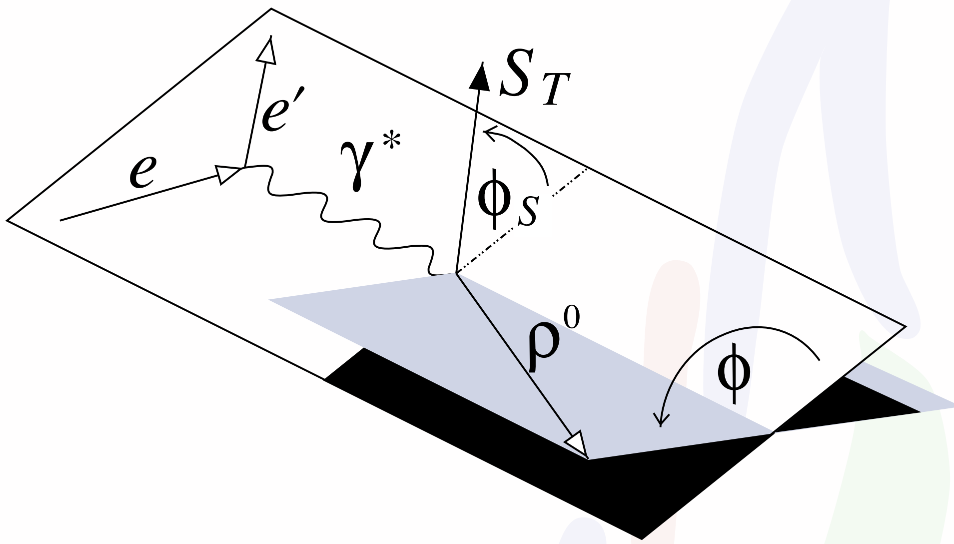
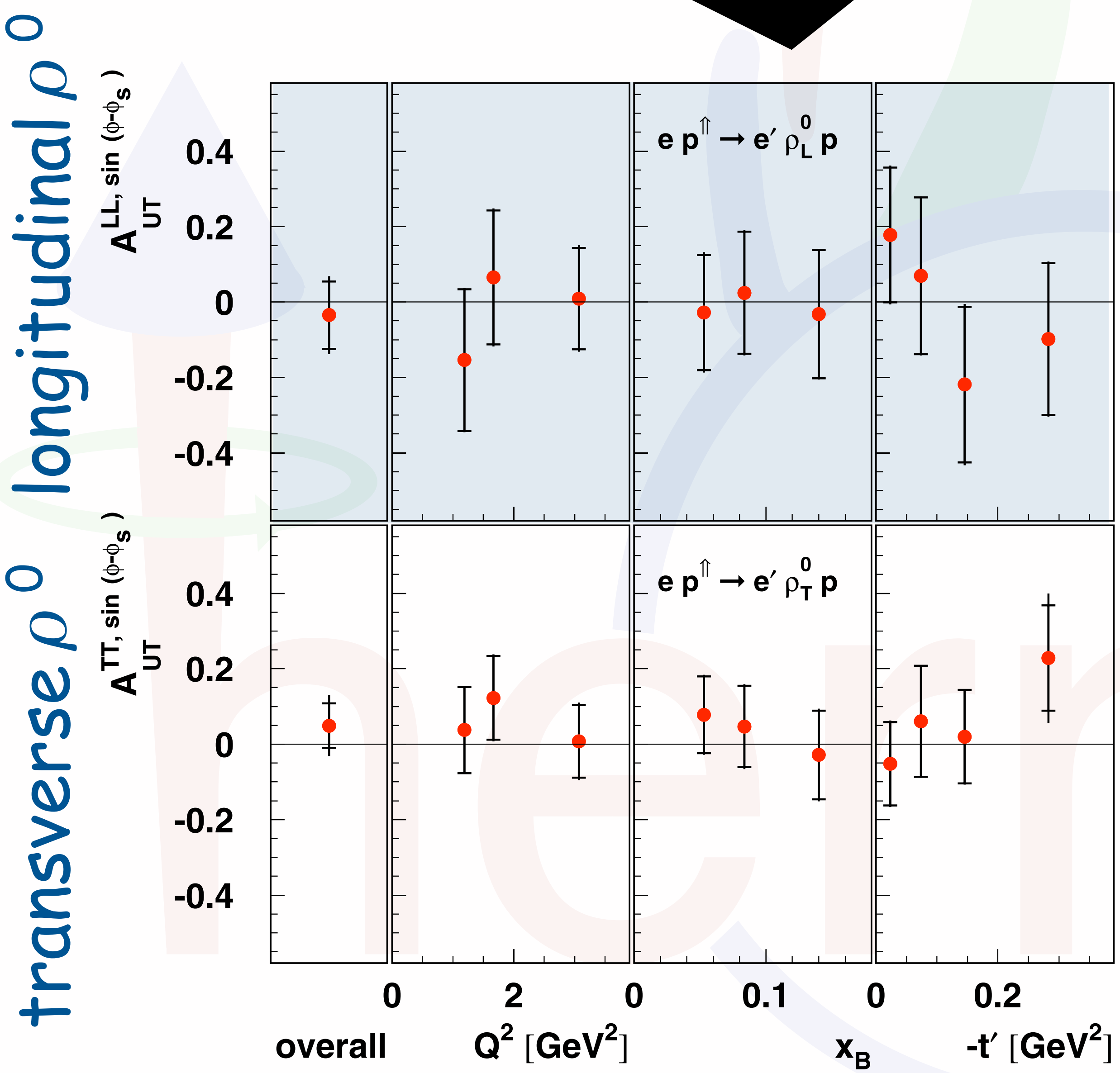
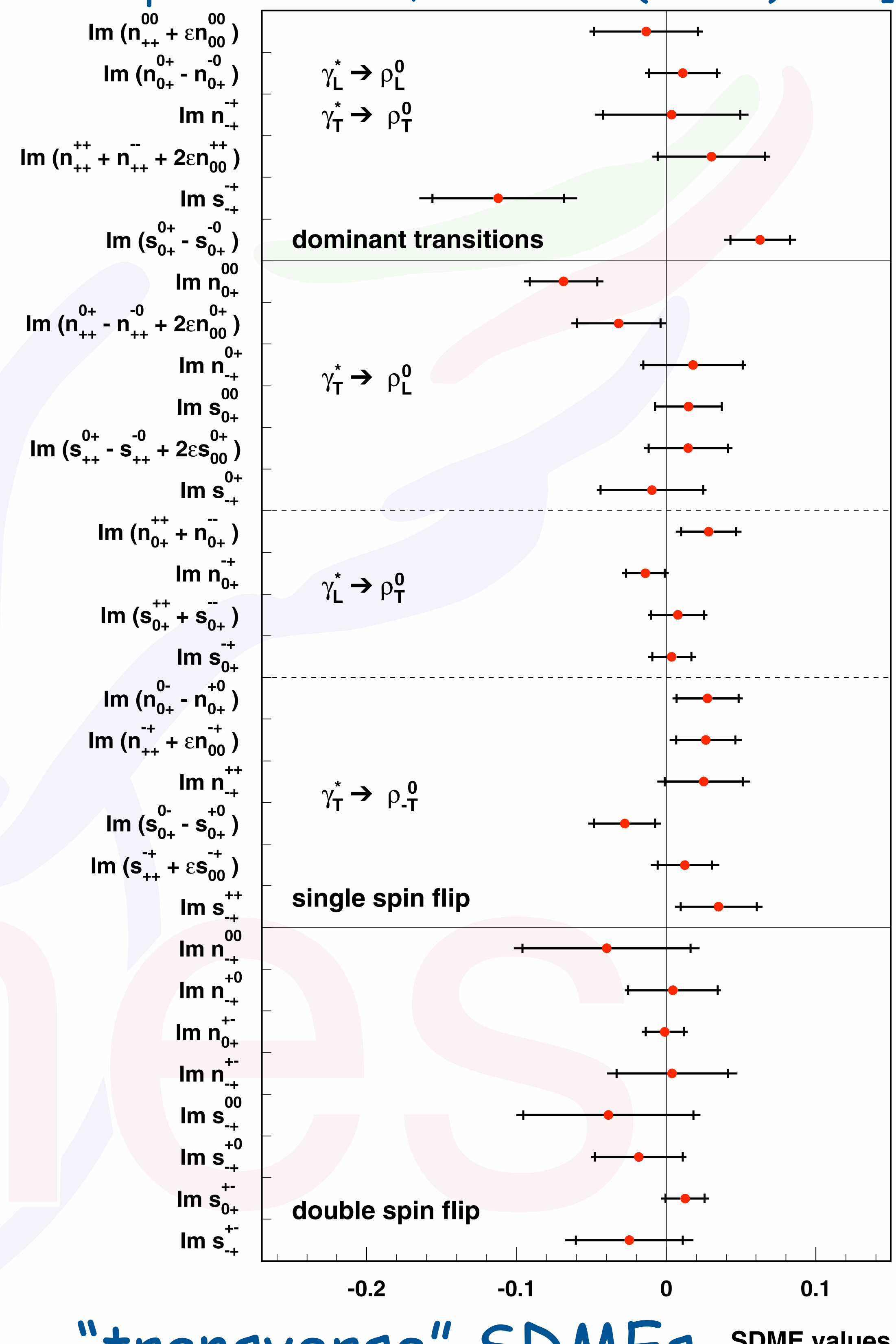
ρ^0 SDMEs from HERMES

[A. Airapetian et al., PLB 679 (2009) 100]







"transverse" SDMEs

ρ^0 SDMEs from HERMES

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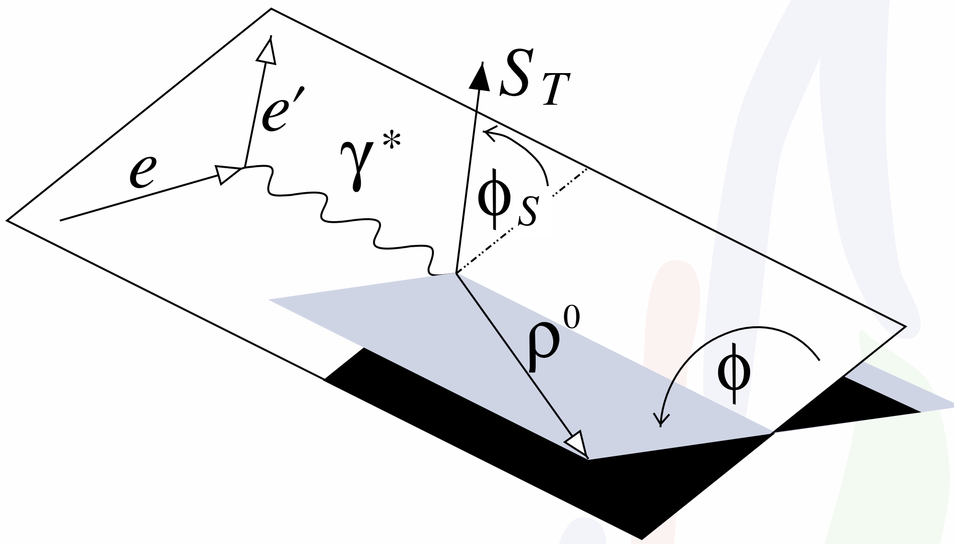
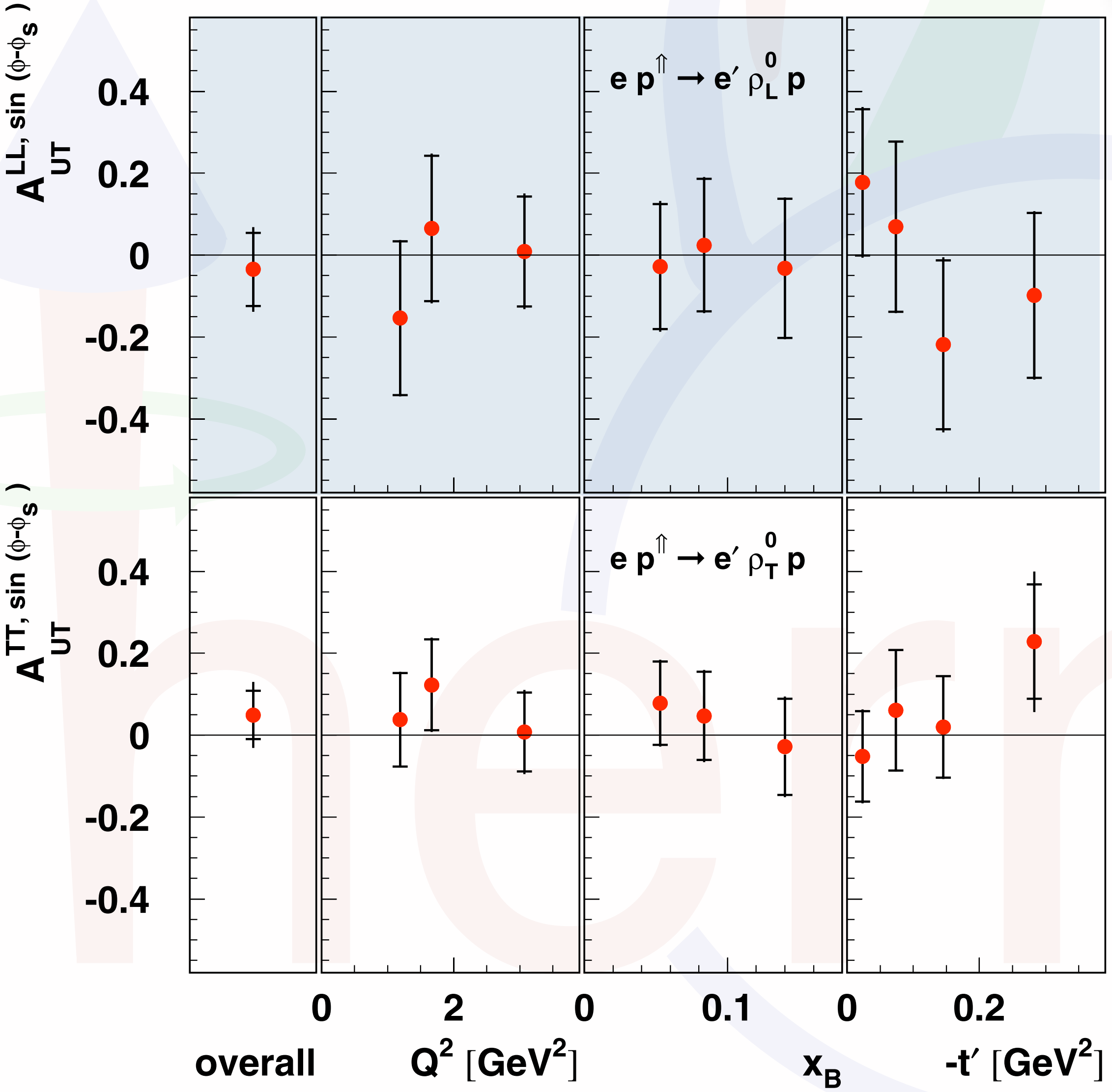
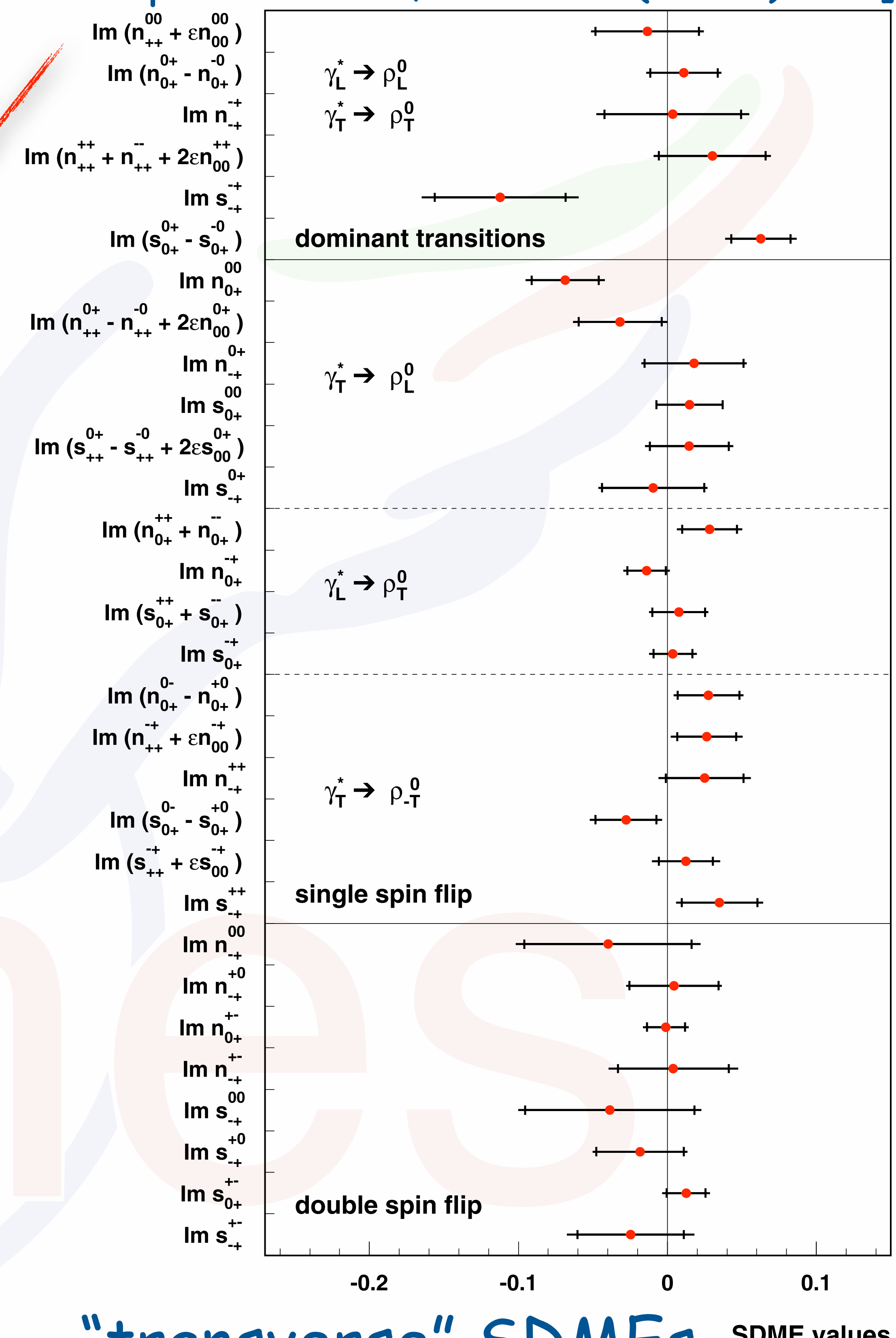


longitudinal ρ^0

transverse ρ^0





"transverse" SDMEs

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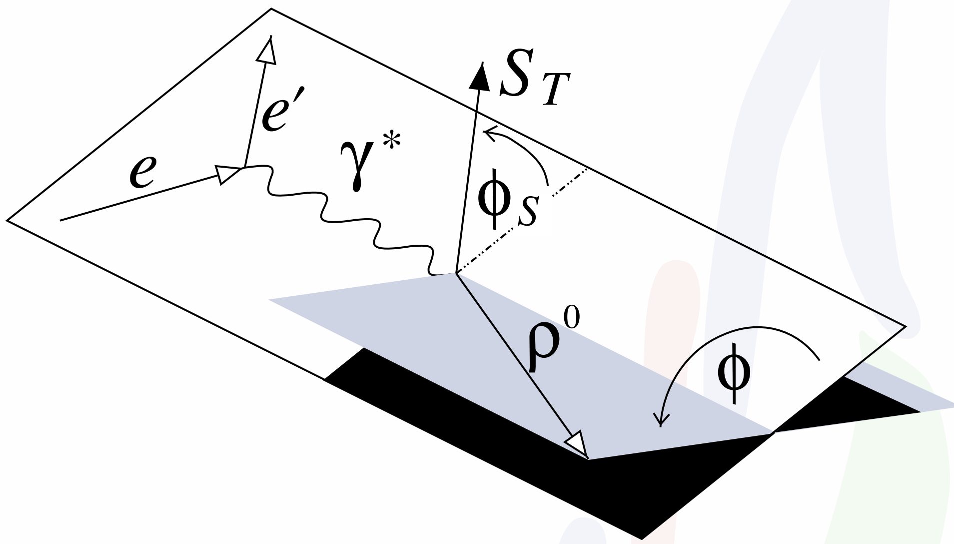
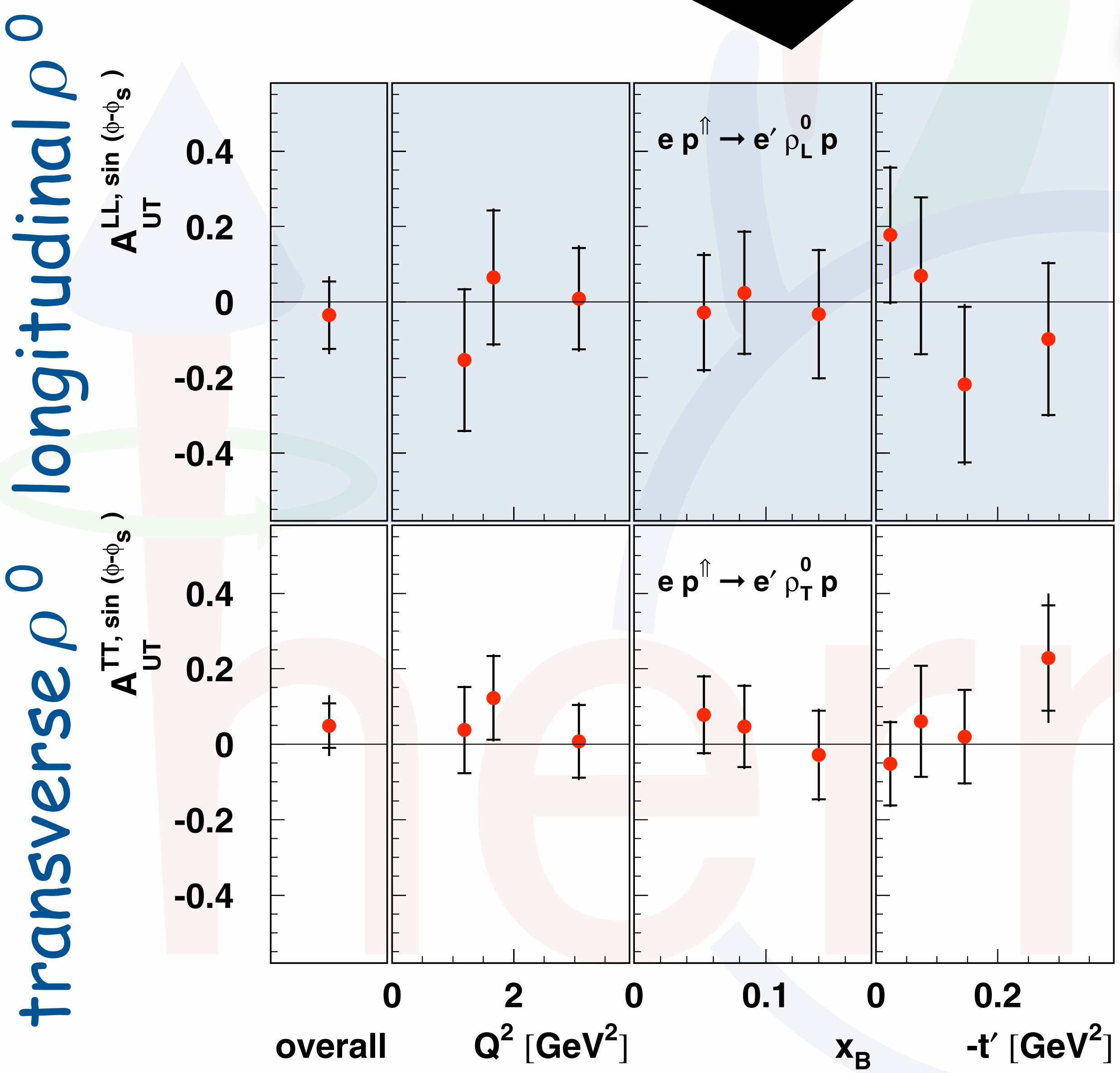
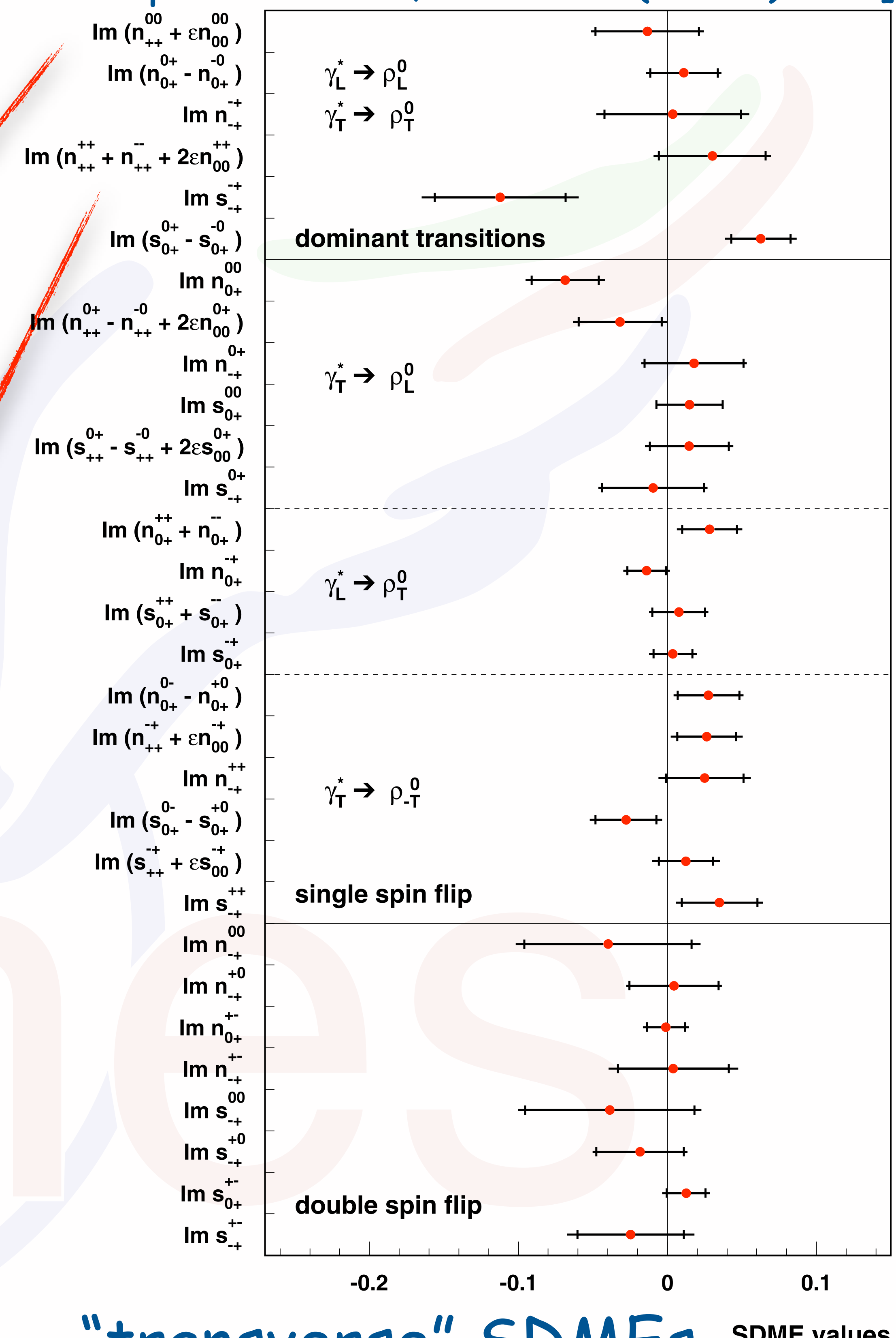


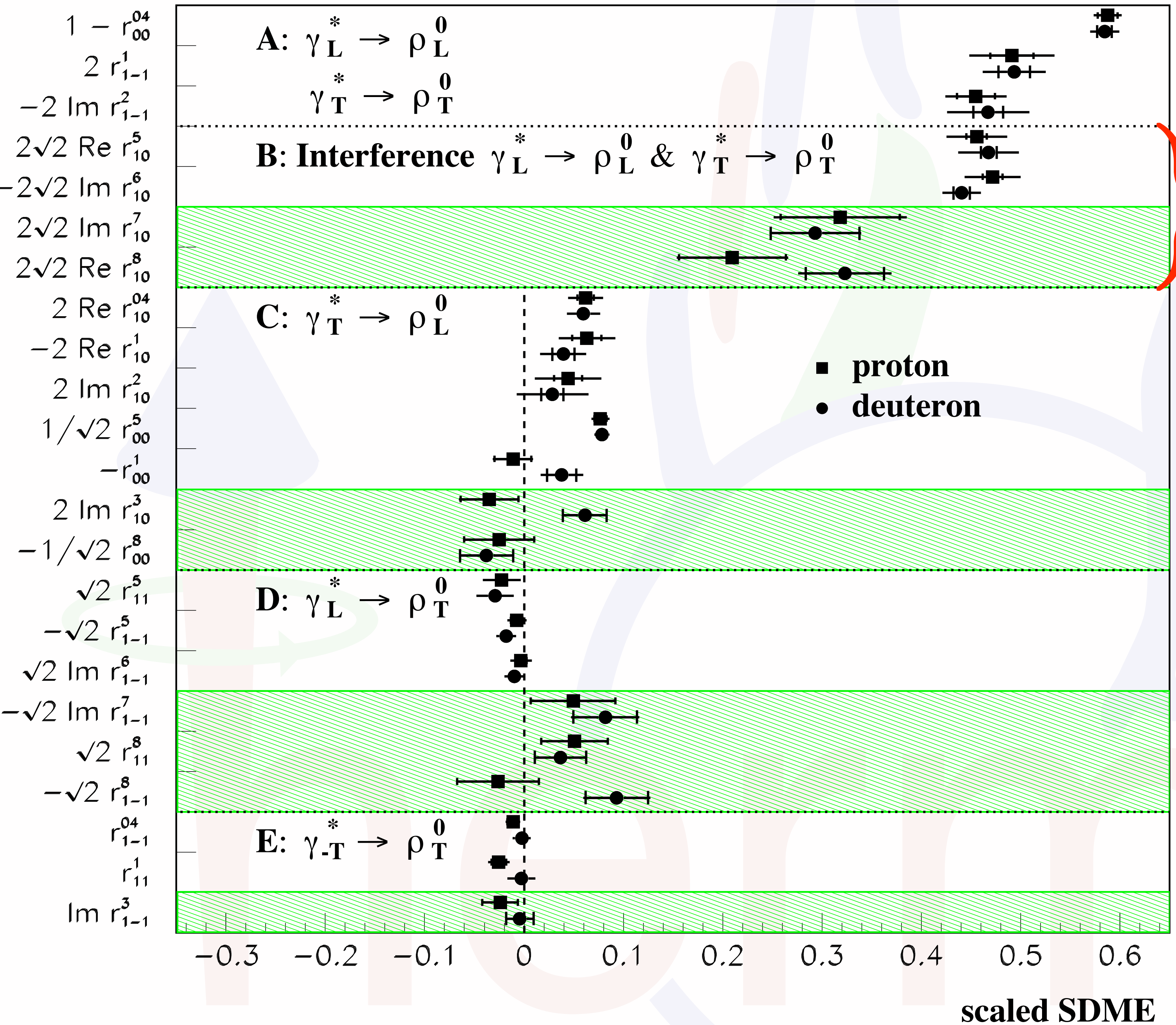




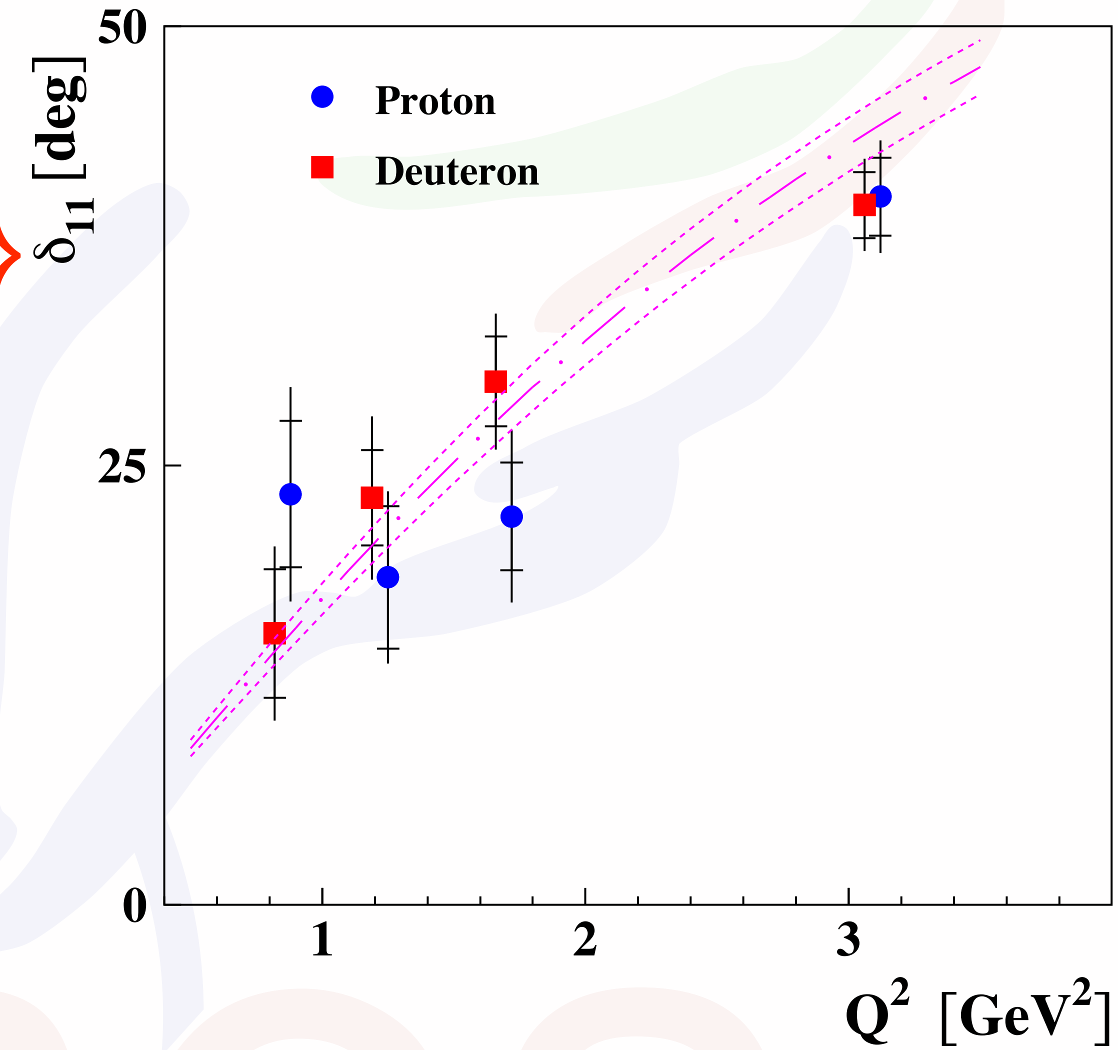
"transverse" SDMEs

ρ^0 SDMEs from HERMES: challenges

[A. Airapetian et al., EPJ C62 (2009) 659]



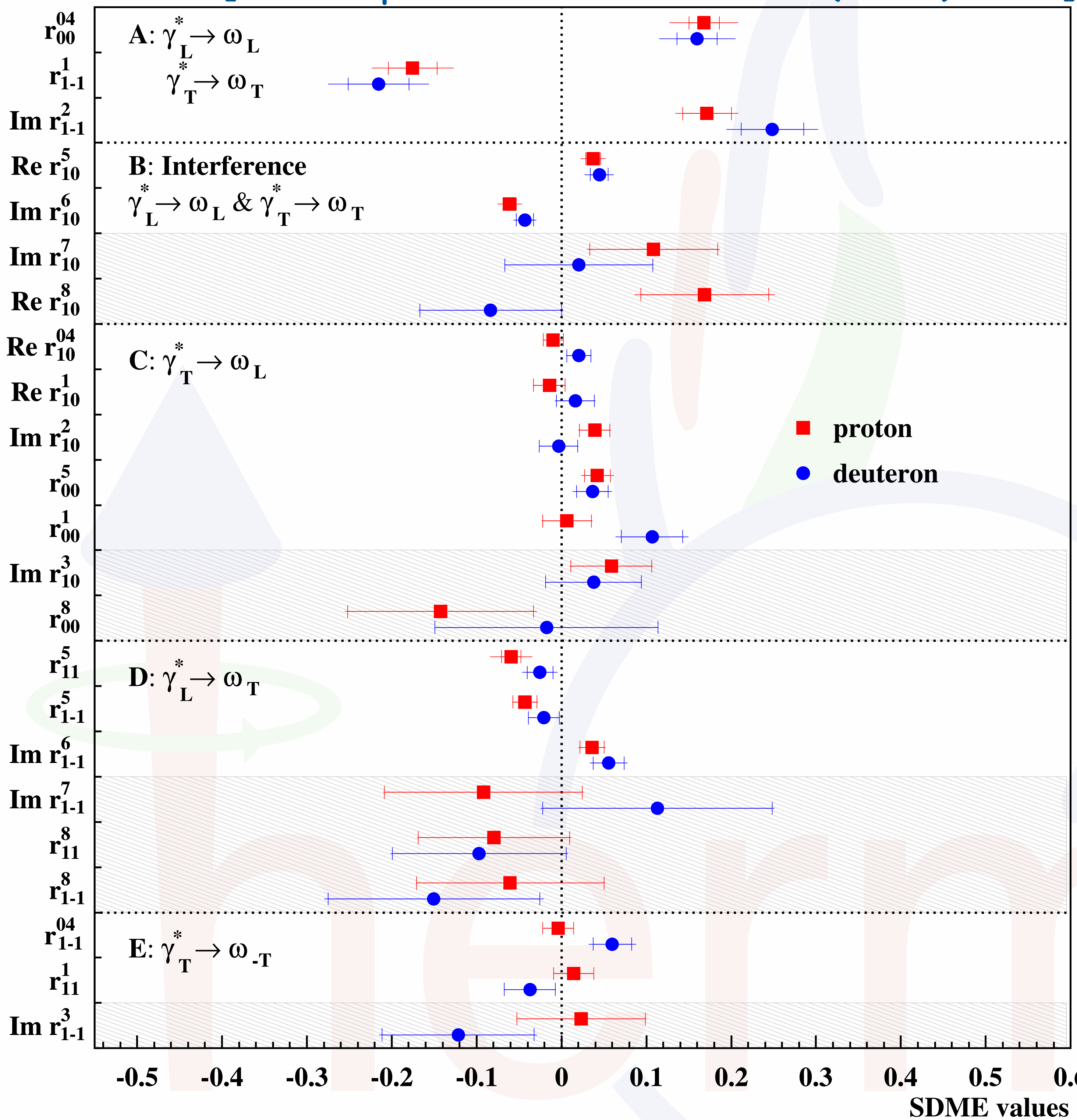
[A. Airapetian et al, EPJ C71 (2011) 1609]



Extraction of SDMEs and helicity amplitude ratios at HERMES for ρ mesons challenges GPD-based calculations (giving small values)

… ω production

[A. Airapetian et al., EPJ C74 (2014) 3110]



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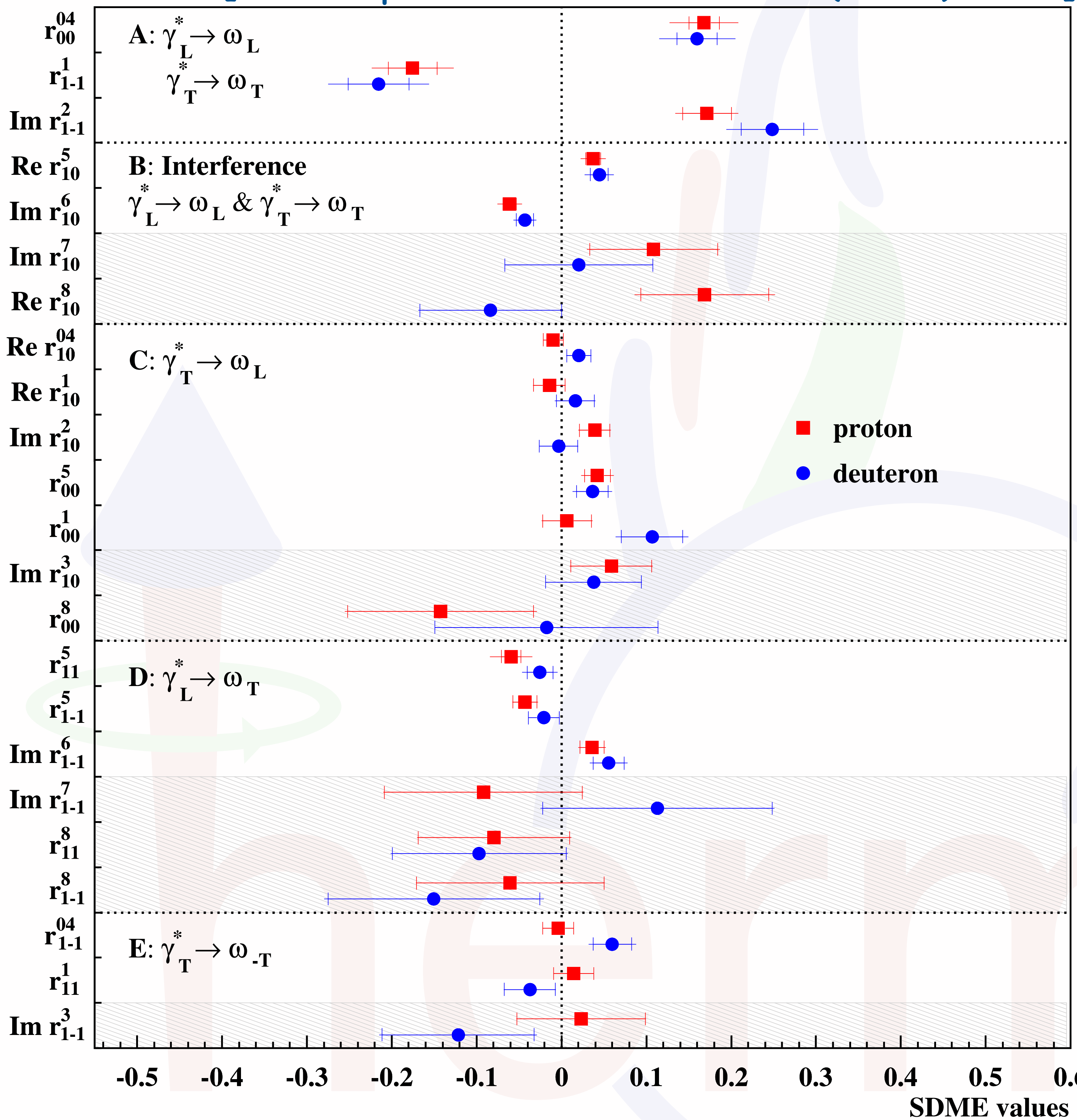
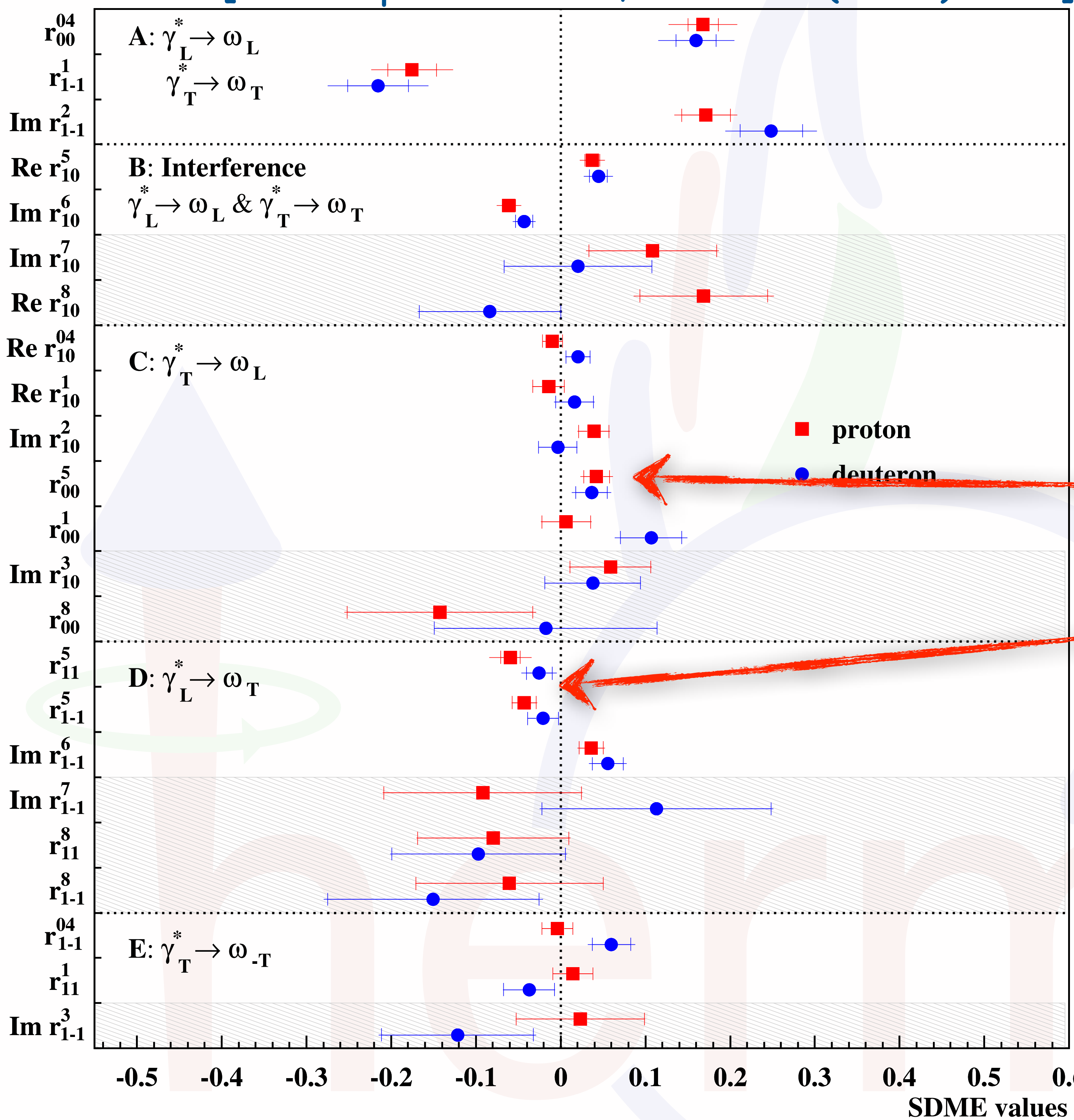
[A. Airapetian et al., EPJ C74 (2014) 3110]



- helicity-conserving SDMEs dominate

... ω production

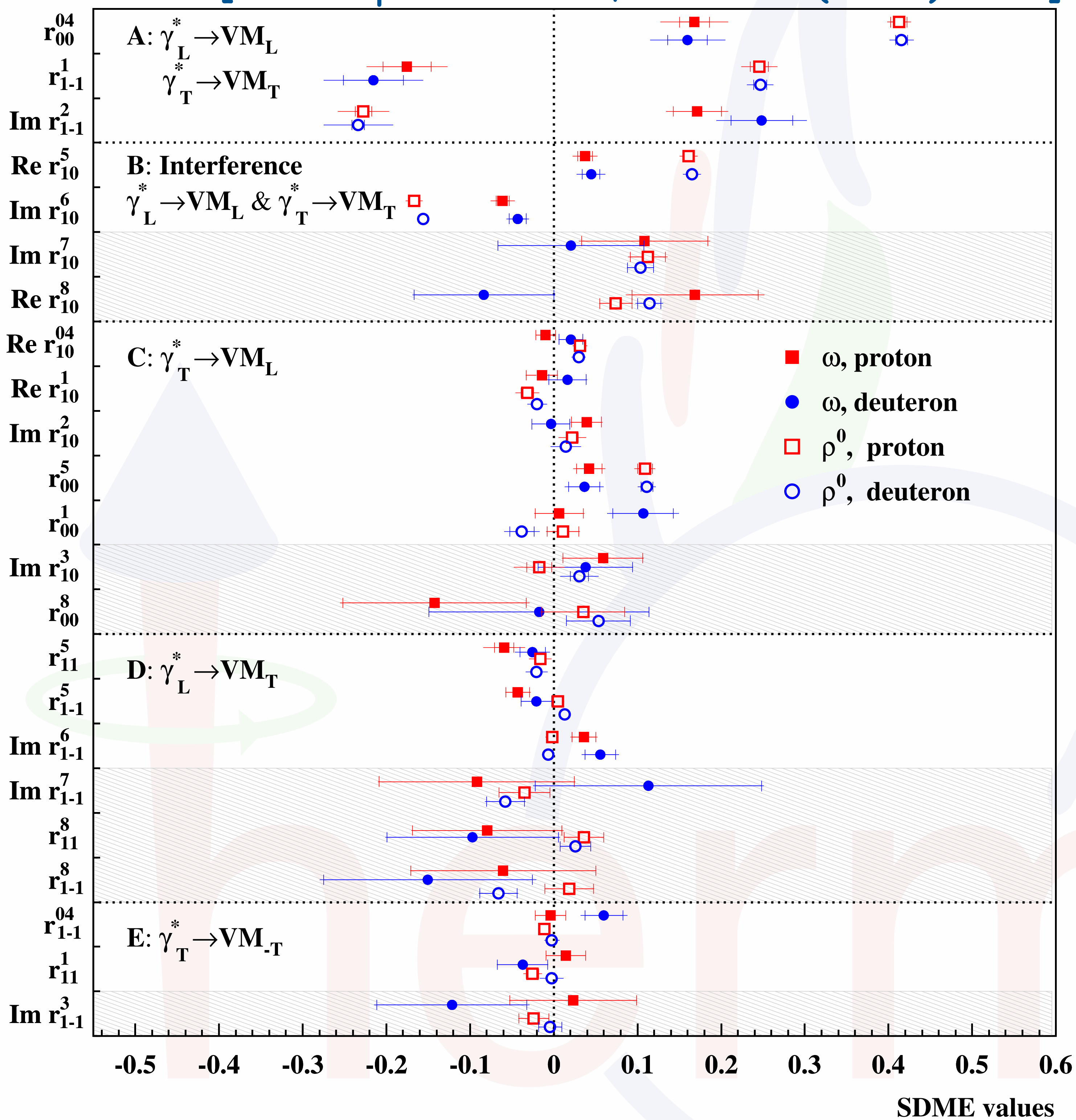
[A. Airapetian et al., EPJ C74 (2014) 3110]



- helicity-conserving SDMEs dominate
- hardly any violation of SCHC, except maybe for
  - r^5_{00}
  - $r^5_{11} + r^5_{1\text{-}1} - \Im\, r^6_{1\text{-}1}$

… ω production

[A. Airapetian et al., EPJ C74 (2014) 3110]



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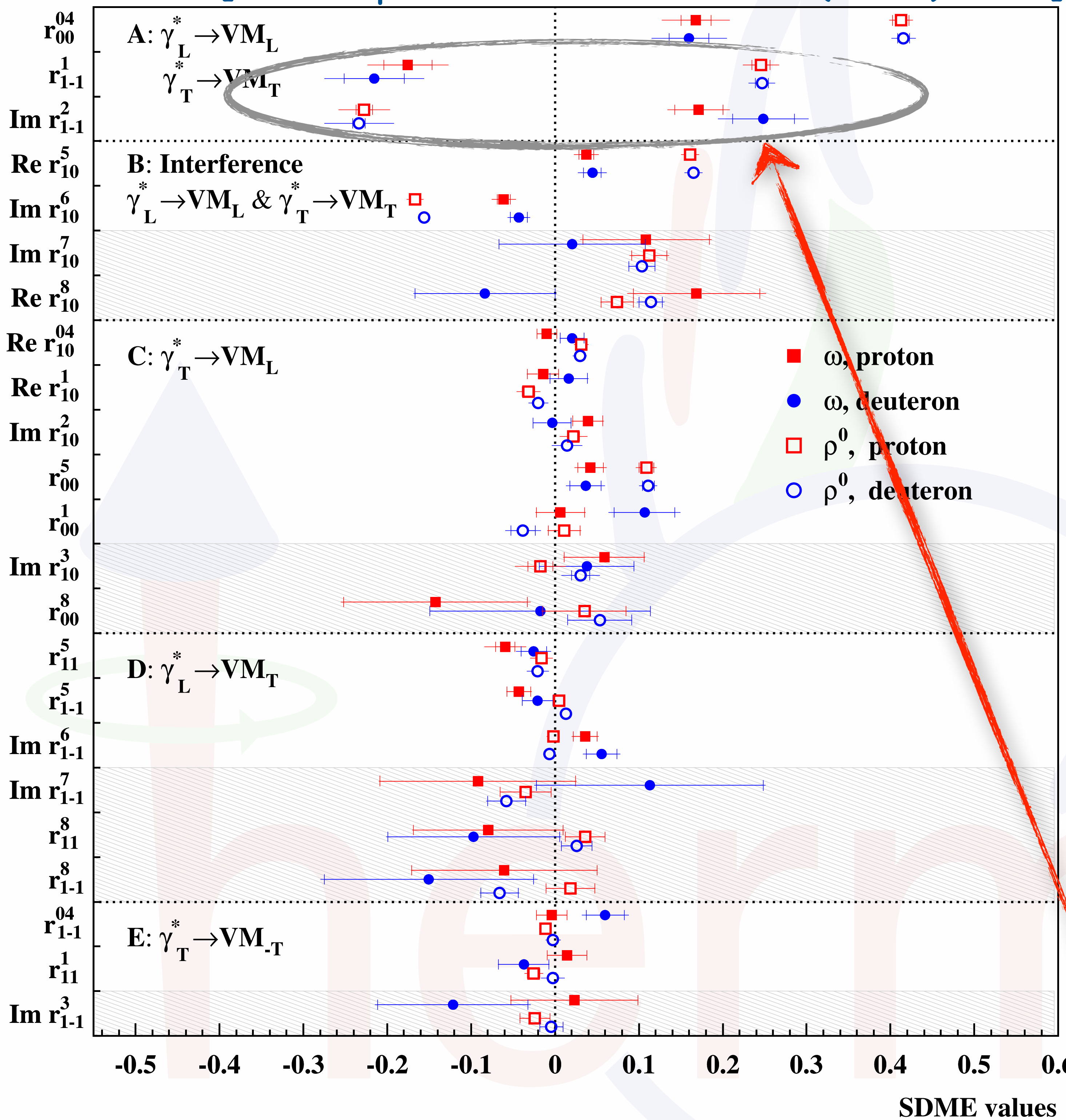
[A. Airapetian et al., EPJ C74 (2014) 3110]



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  - r^5_{00}
  - $r^5_{11} + r^5_{1\text{-}1} - \Im r^6_{1\text{-}1}$
- interference smaller than for ρ^0 …
- … and opposite signs for $r^1_{1\text{-}1}$ & $\Im r^2_{1\text{-}1}$

(un)natural-parity exchange contributions

$$\Im\, r^2_{1-1} - r^1_{1-1} = \frac{1}{\mathcal{N}} \widetilde{\sum} \left(|U_{11}|^2 - |T_{11}|^2 \right)$$

UPE contribution NPE contribution

- positive for omega -> large UPE contributions (unlike for rho)
- can construct various UPE quantities:

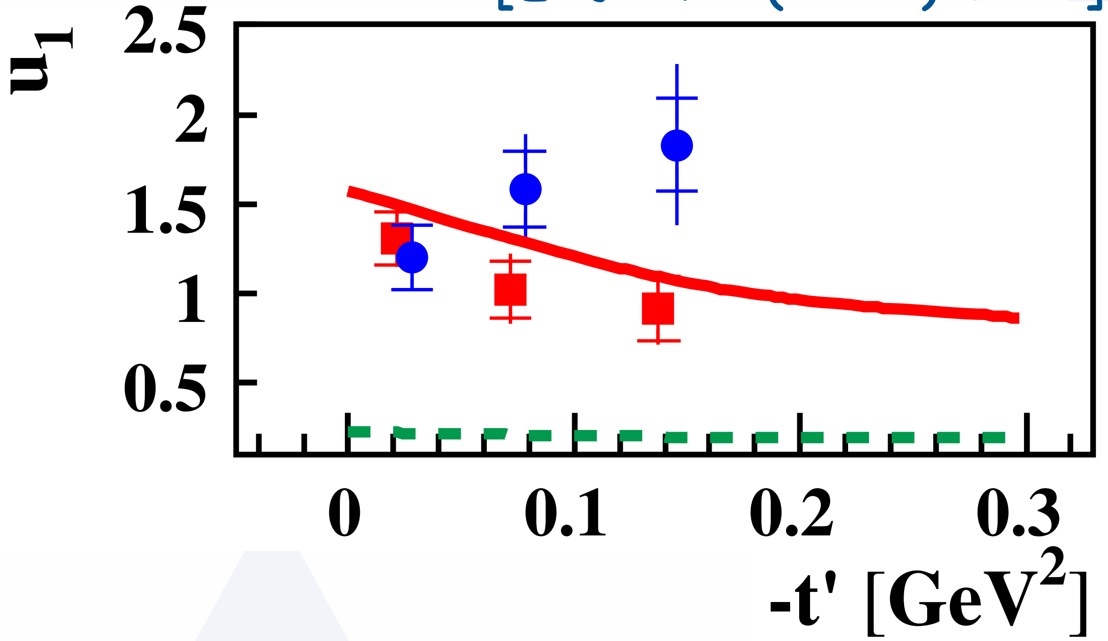
$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^1_{11} - 2r^1_{1-1}$$

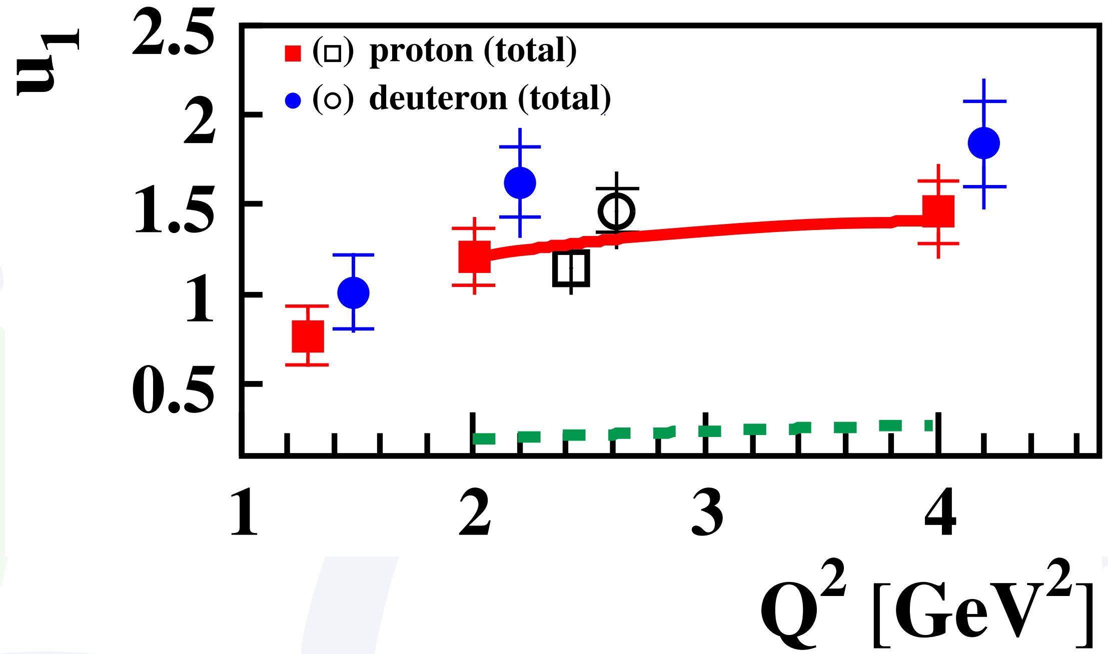
$$u_2 = r^5_{11} + r^5_{1-1}$$

$$u_3 = r^8_{11} + r^8_{1-1}$$

test of UPE

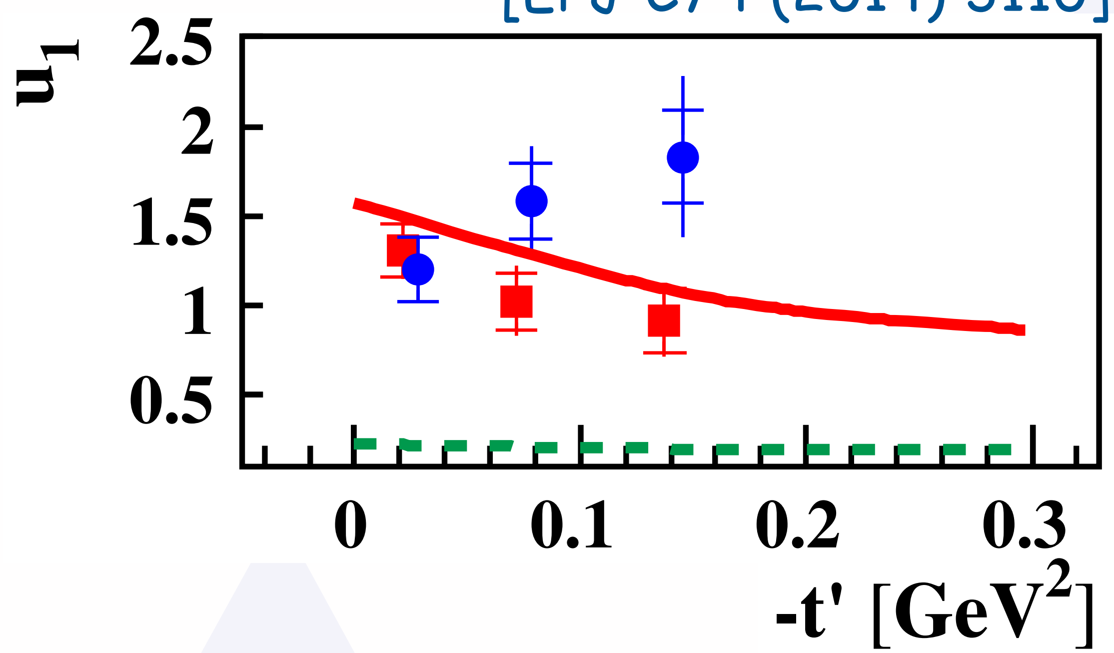
[EPJ C74 (2014) 3110]

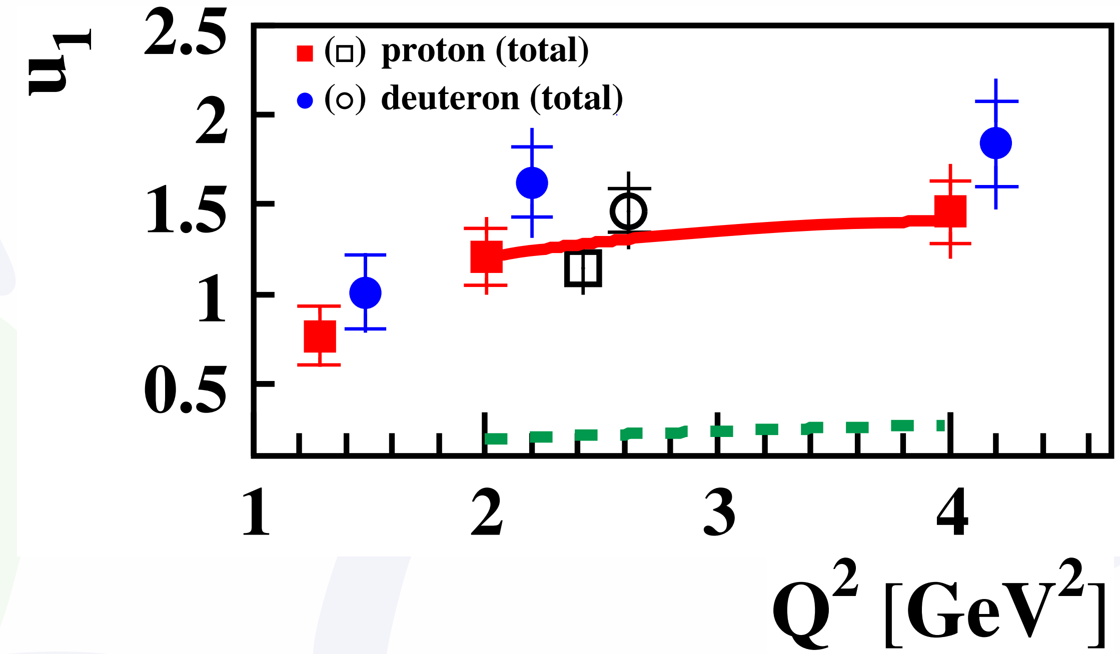




test of UPE

[EPJ C74 (2014) 3110]

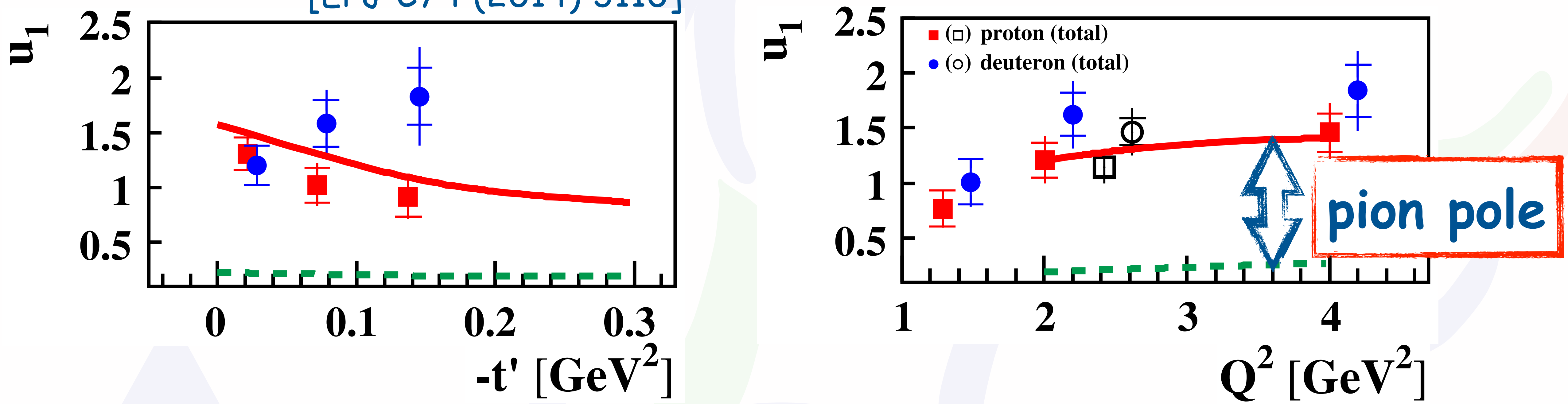




- large UPE contributions

test of UPE

[EPJ C74 (2014) 3110]

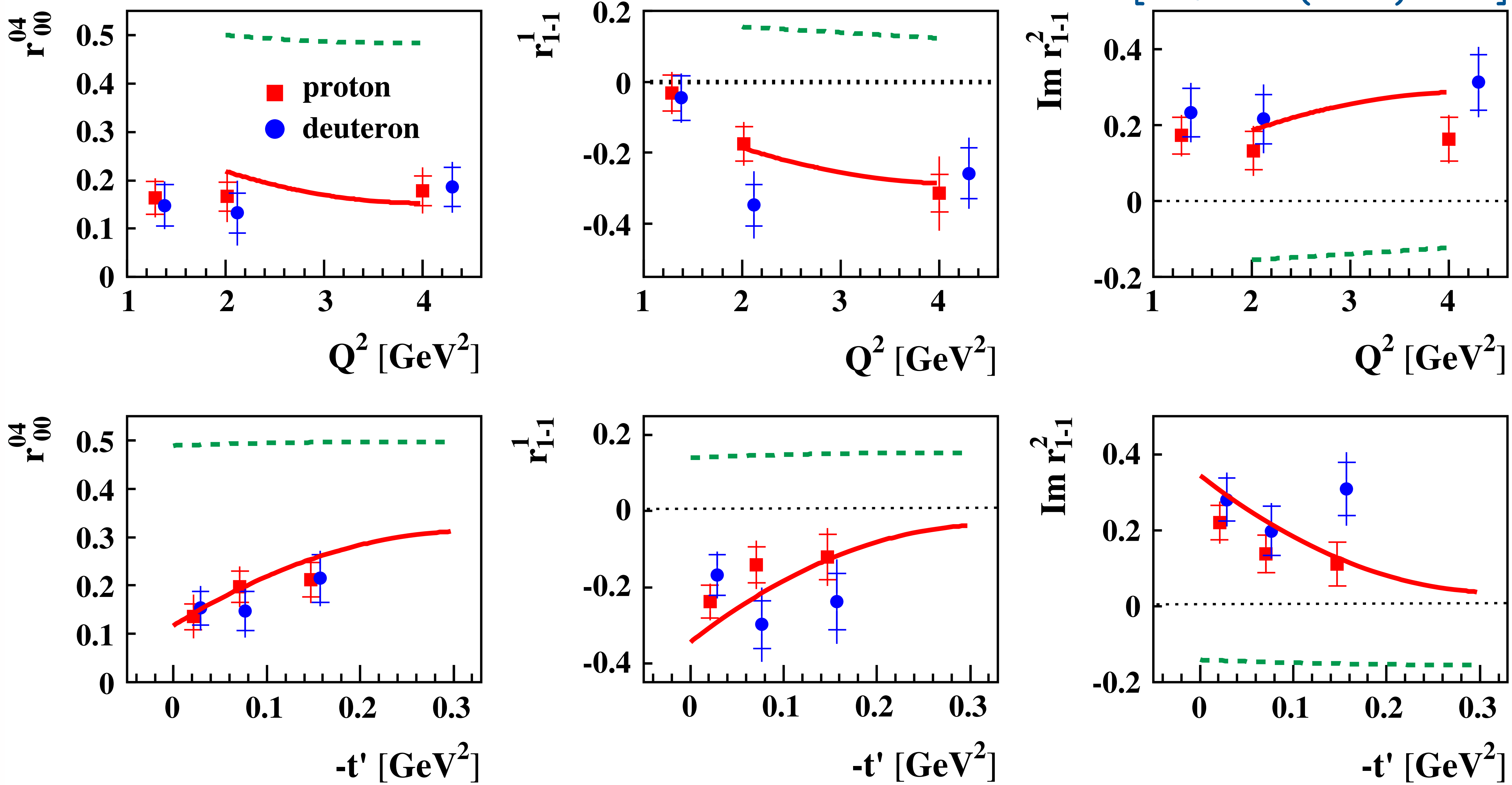


- large UPE contributions
- modified GK model [EPJ A50 (2014) 146] can describe data when including
  - pion pole contribution (red curve)
  - corresponding $\pi\omega$ transition form factor (fit to these data)

impact of pion-pole contr. on SDMEs

- "class-A" - helicity-conserving transitions

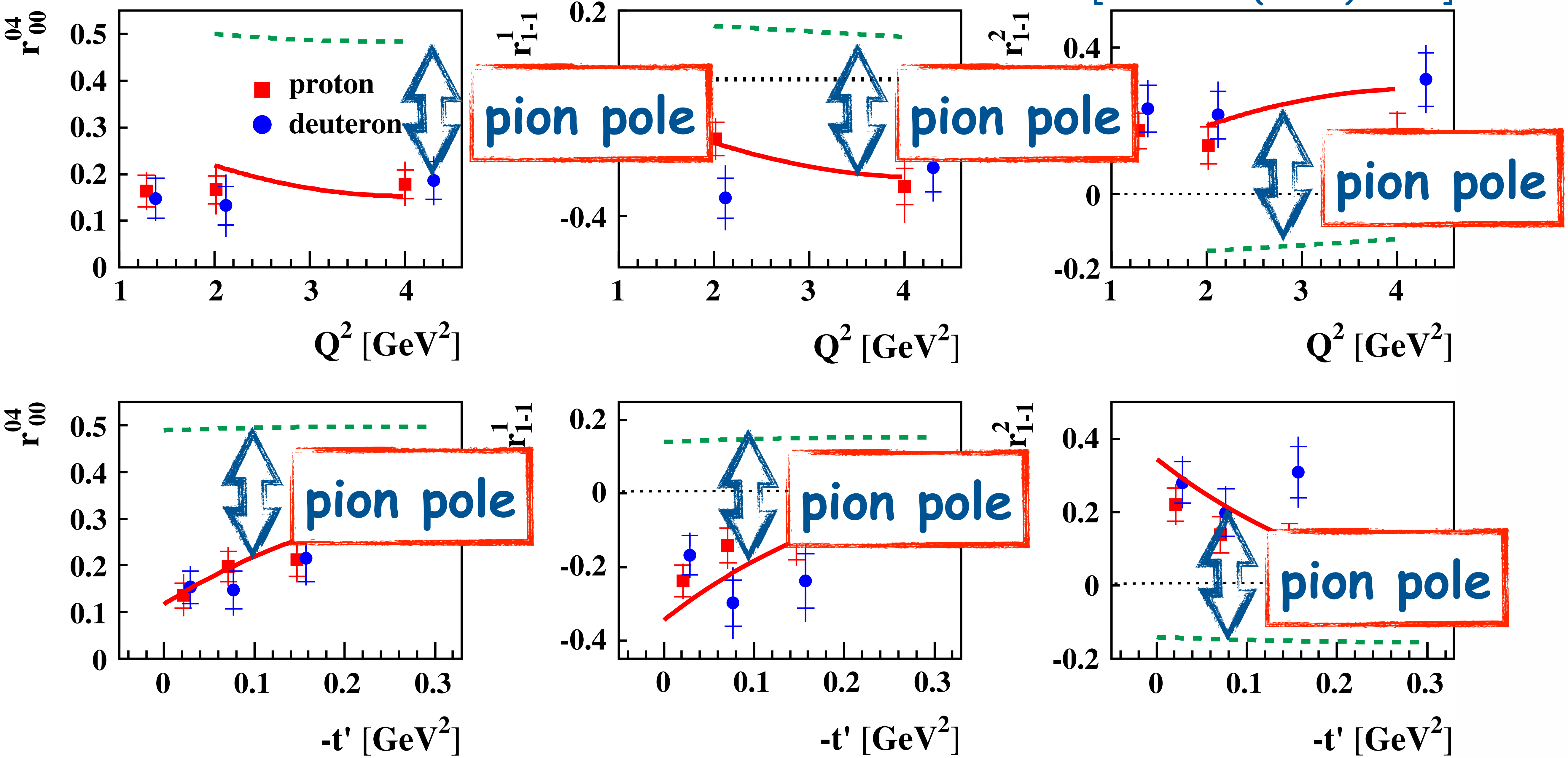
[EPJ C74 (2014) 3110]



impact of pion-pole contr. on SDMEs

- "class-A" - helicity-conserving transitions

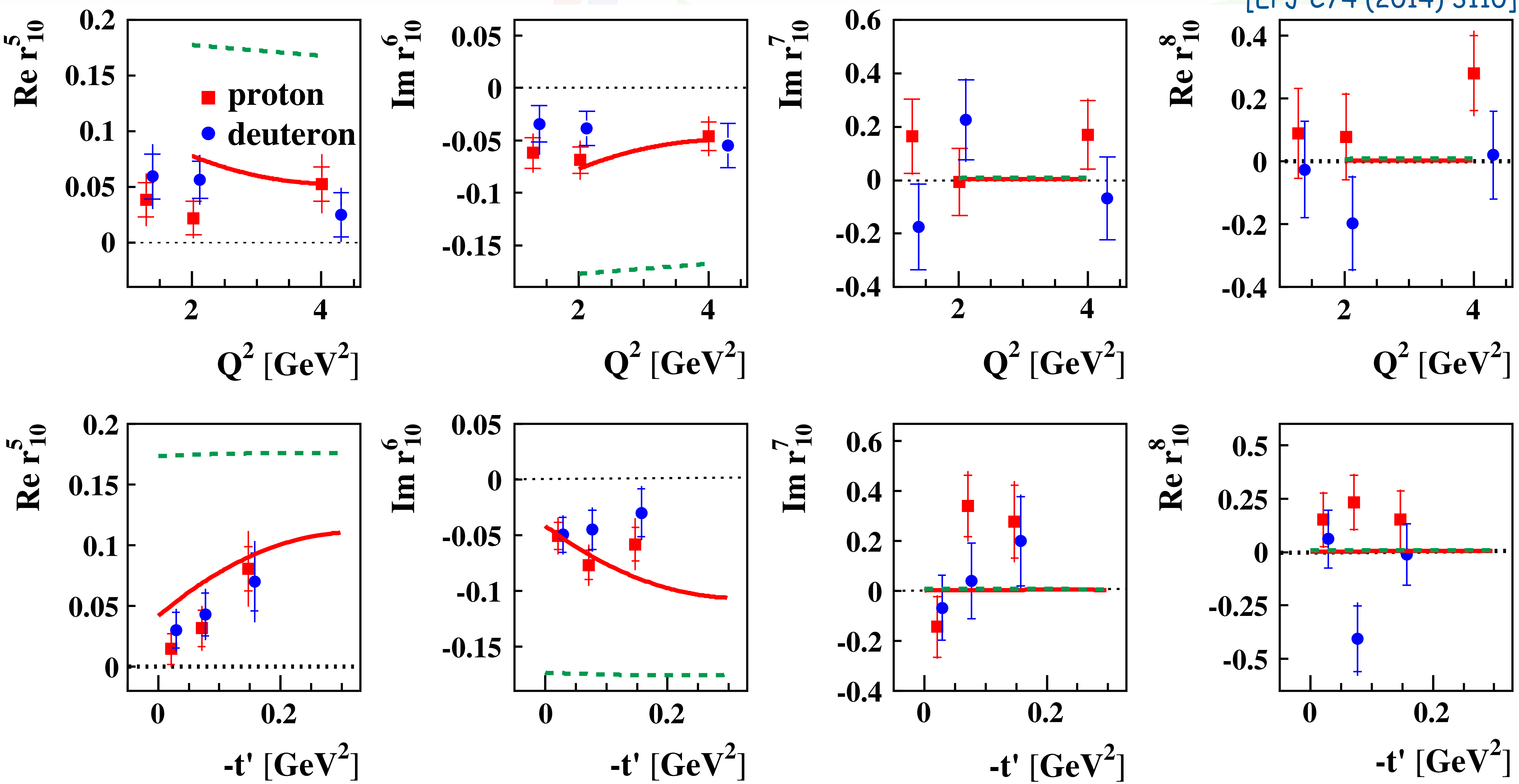
[EPJ C74 (2014) 3110]



impact of pion-pole contr. on SDMEs

- "class-B" - interference of helicity-conserving transitions

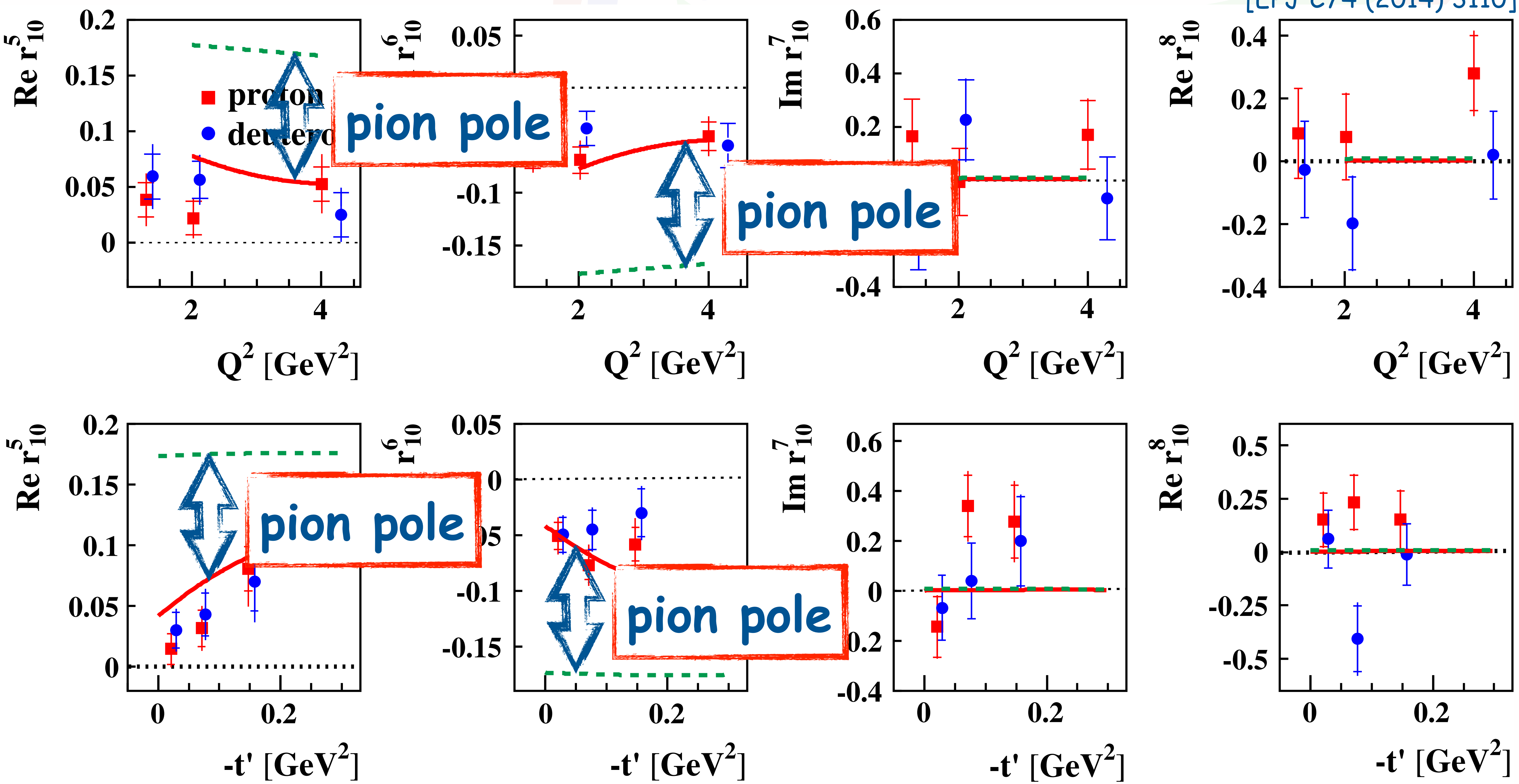
[EPJ C74 (2014) 3110]



impact of pion-pole contr. on SDMEs

- "class-B" - interference of helicity-conserving transitions

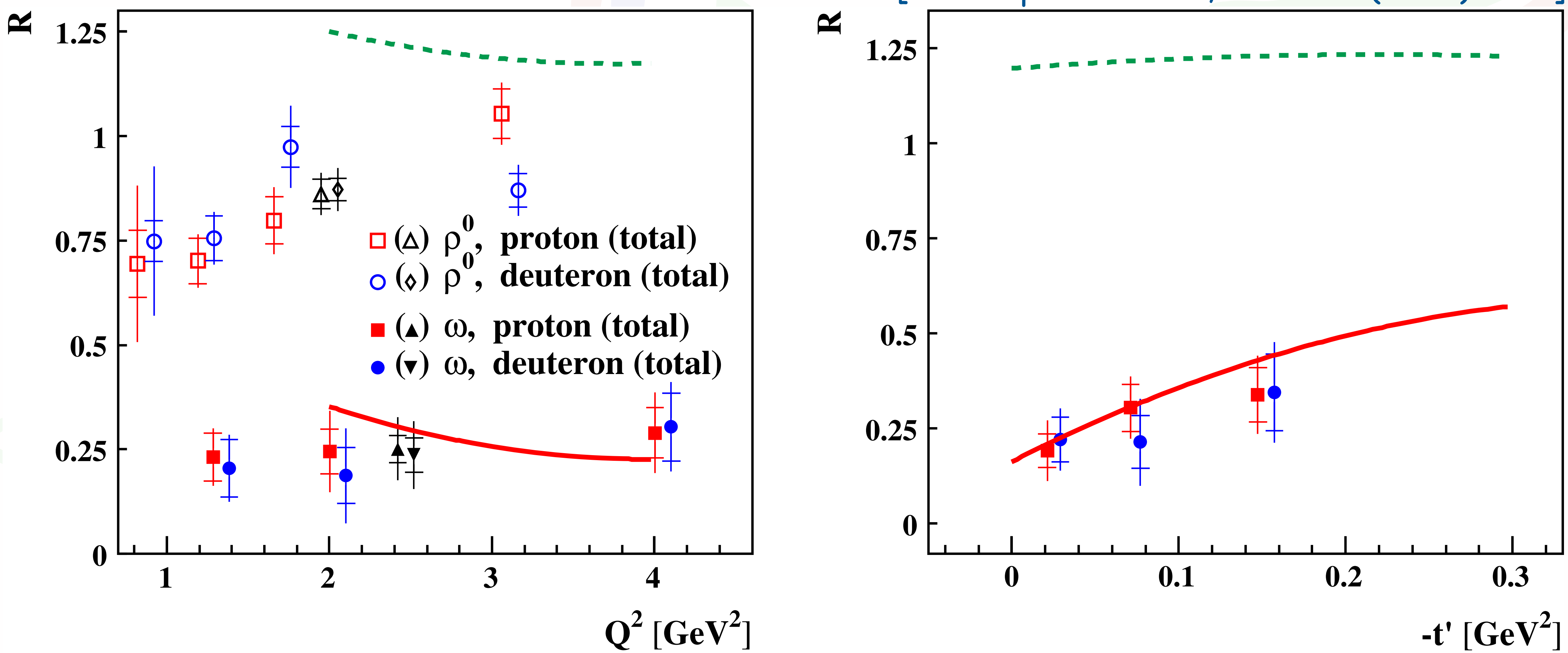
[EPJ C74 (2014) 3110]



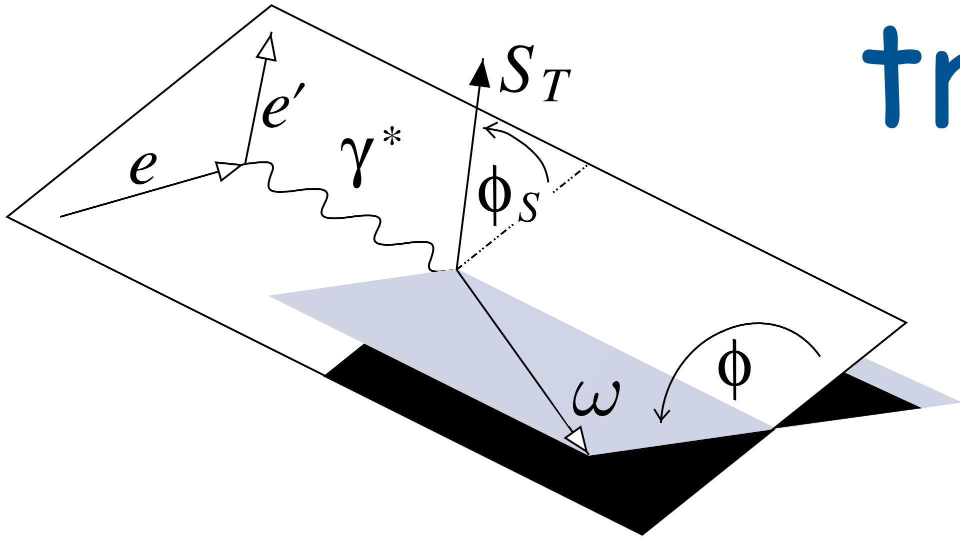
long.-to-transverse cross-section ratio

$$R = \frac{d\sigma(\gamma^*_L \to \omega)}{d\sigma(\gamma^*_T \to \omega)} \approx \frac{1}{\epsilon} \frac{r^{04}_{00}}{1 - r^{04}_{00}}$$

[A. Airapetian et al., EPJ C74 (2014) 3110]



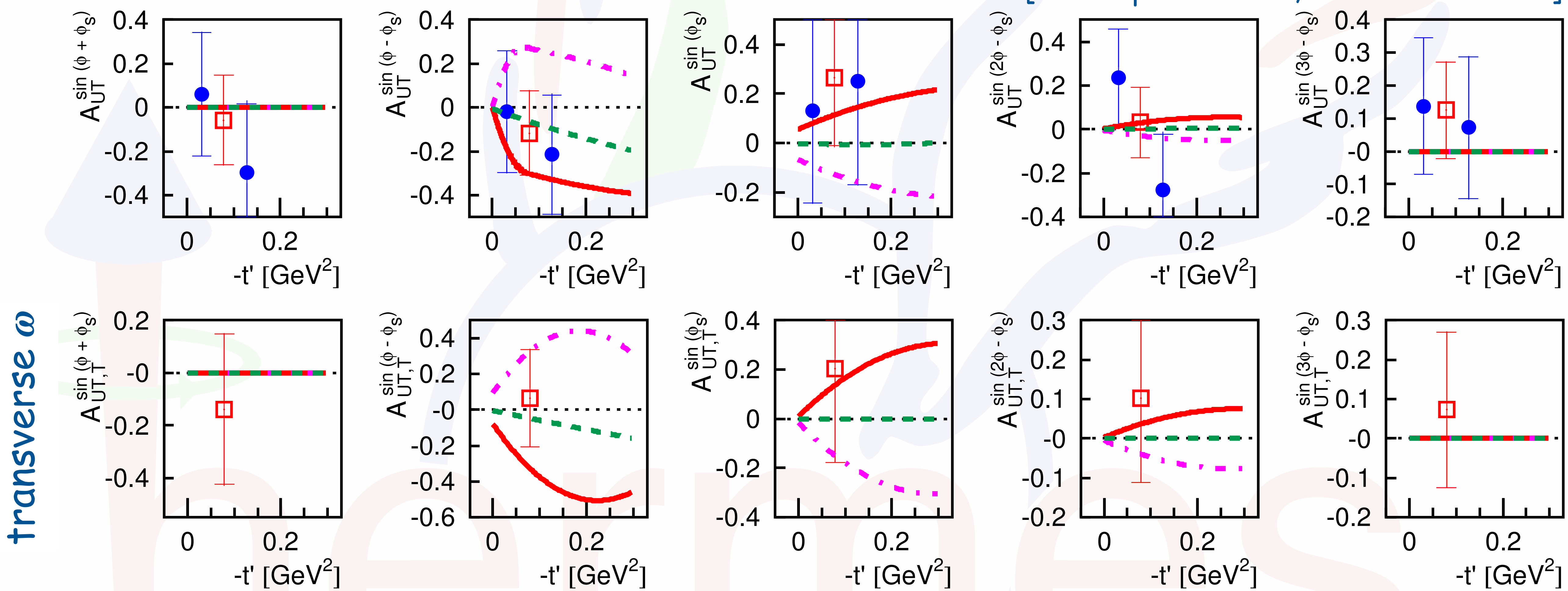
- significantly smaller for ω than for ρ
- important contribution from pion pole



transverse-spin asymmetry

sensitive, in principle, to sign of $\pi\omega$ transition FF

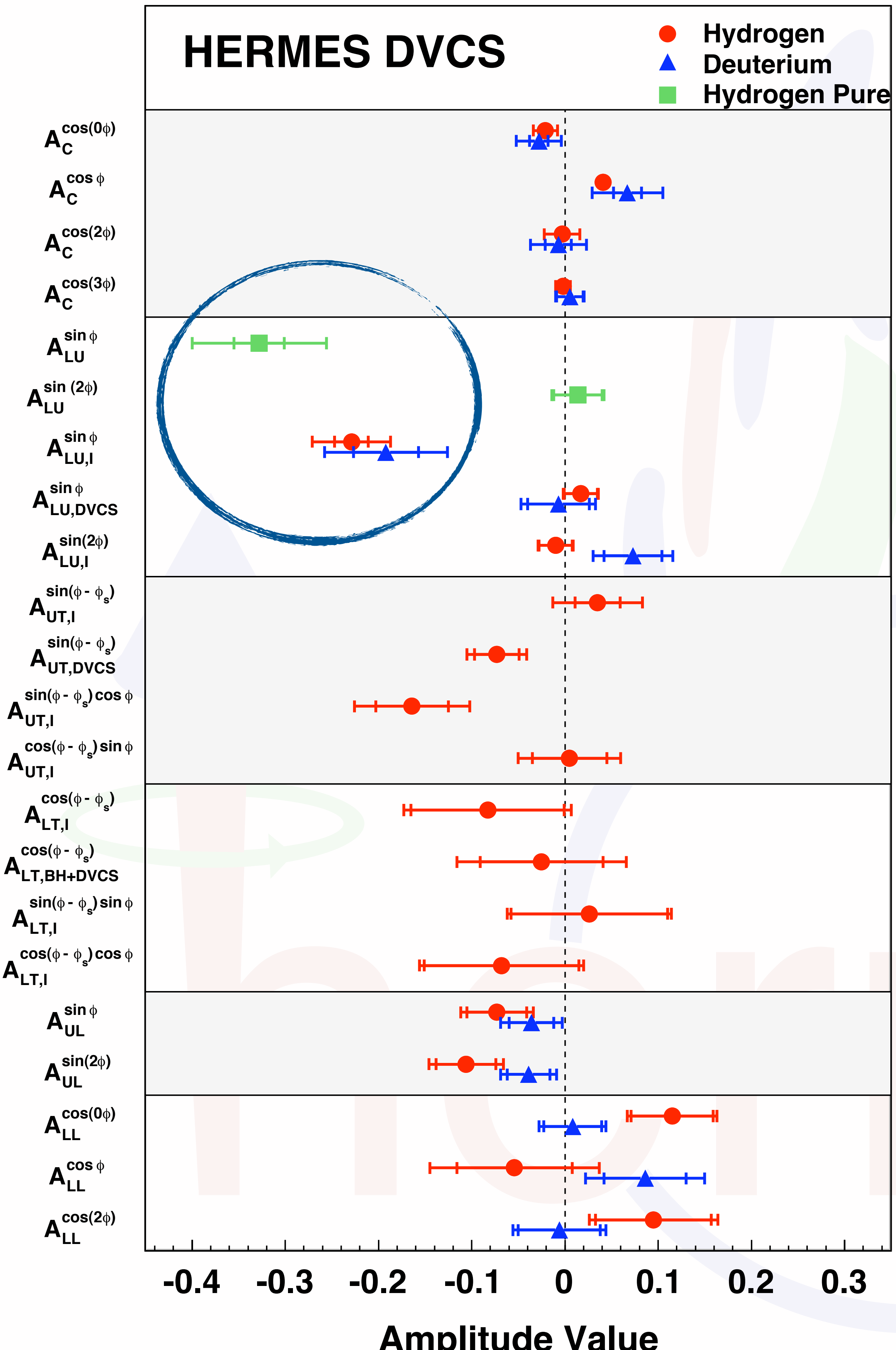
[A. Airapetian et al., arXiv:1508.07612]



slight preference for positive $\pi\omega$ transition FF (red/full line) vs. negative one (magenta/dash-dotted line)

summary

DVCS @ HERMES



HERMES analyzed a wealth of DVCS-related asymmetries on nucleon and nuclear targets

data with recoil-proton detection allows clean interpretation

indication of larger amplitudes for pure sample

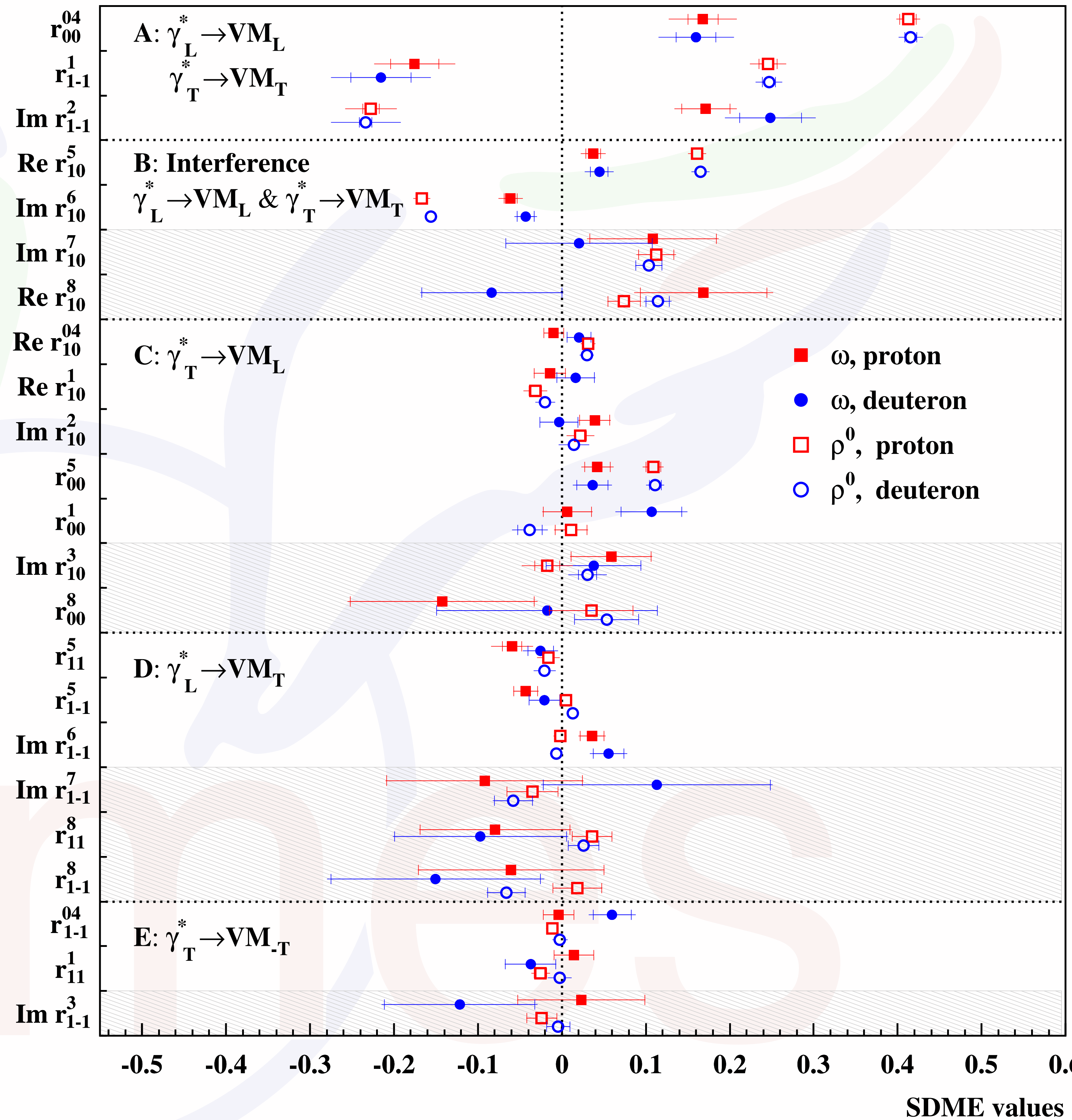
-> assoc. DVCS in "traditional" analysis mainly dilution, supported by **recent results from HERMES [JHEP 01 (2014) 077]:**

assoc. DVCS results consistent with zero but also with model prediction

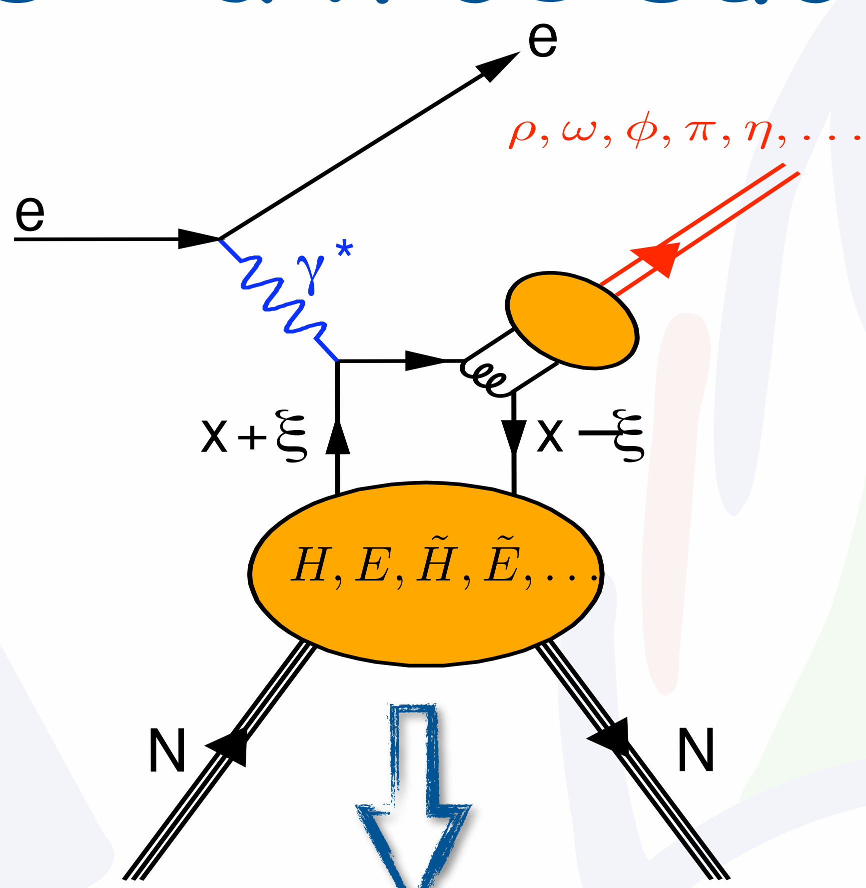
HEMP @ HERMES

- extensive data set on unpolarized and polarized SDMEs in vector-meson production
- (not shown:) cross section and A_{UT} for excl. π^+
- essential input in model building
- recent results on omega production require pion-pole contributions with a preference for positive $\pi\omega$ transition FF

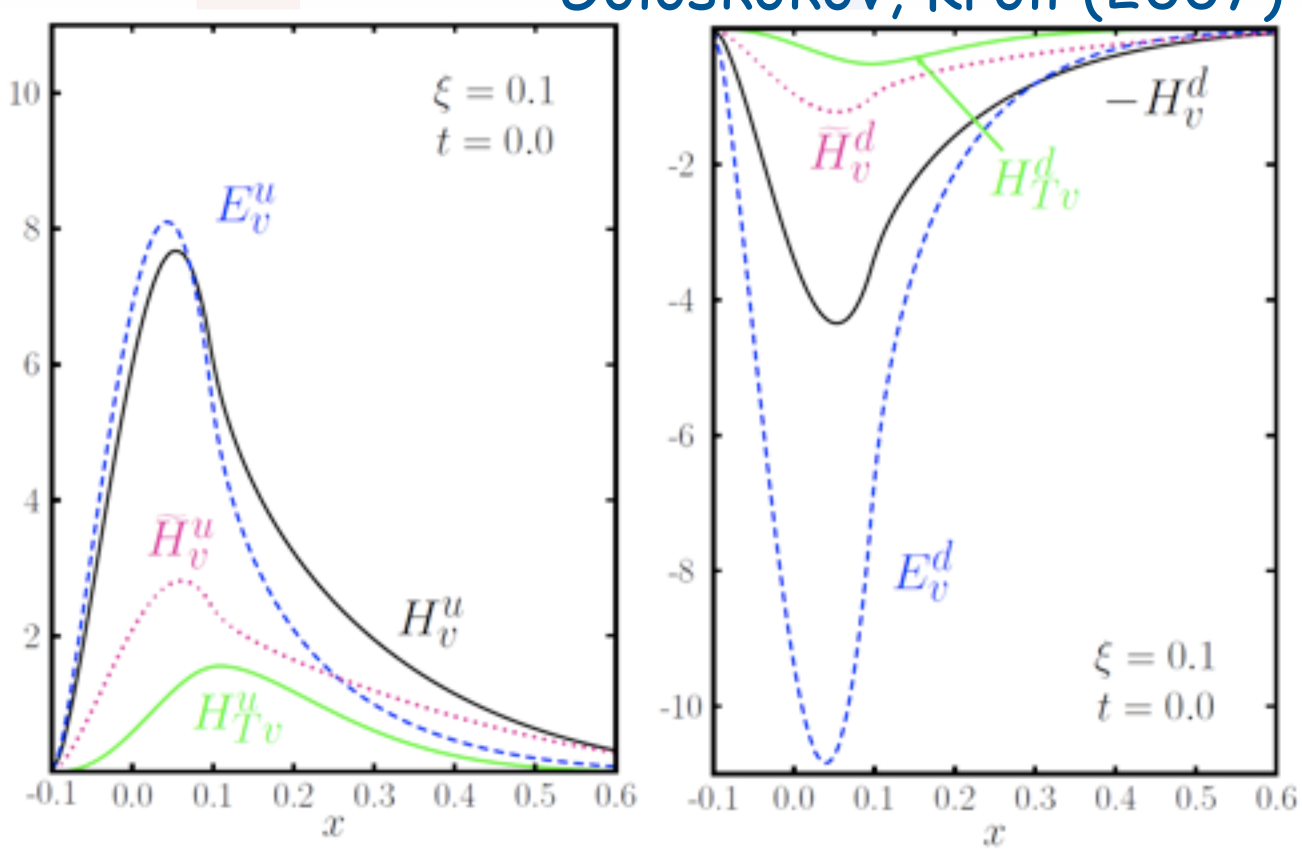
[A. Airapetian et al., EPJ C74 (2014) 3110, EPJ C62 (2009) 659]



GPDs - a nice success story!



Goloskokov, Kroll (2007)



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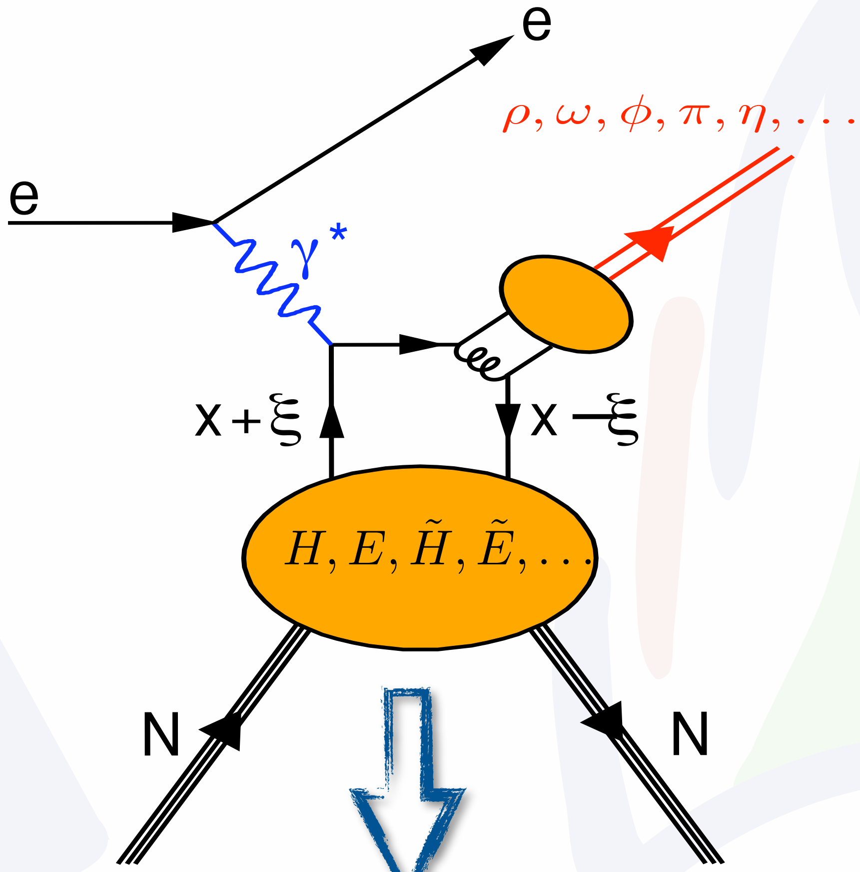

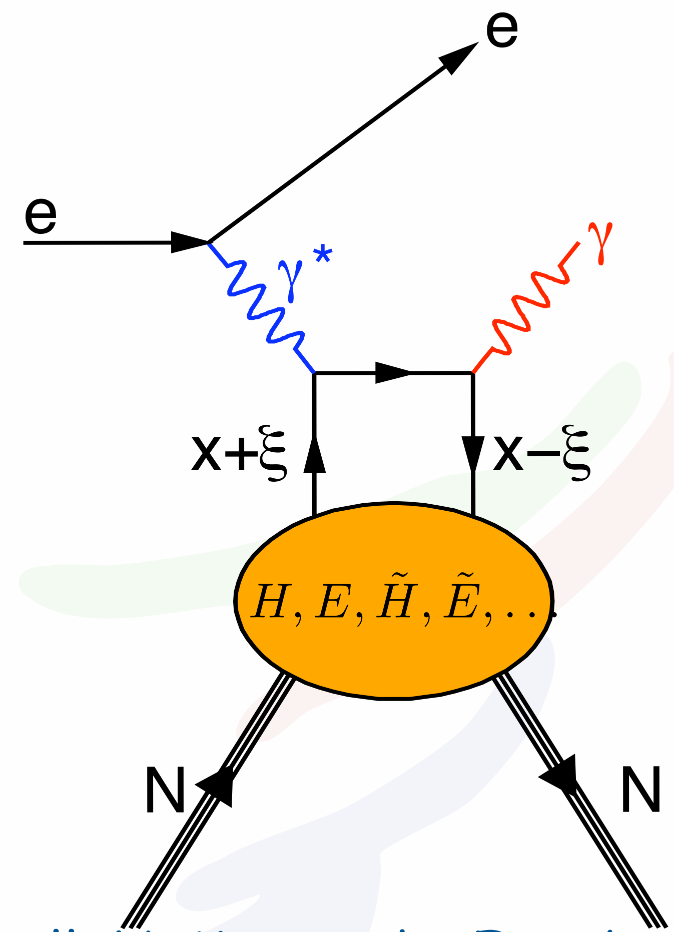

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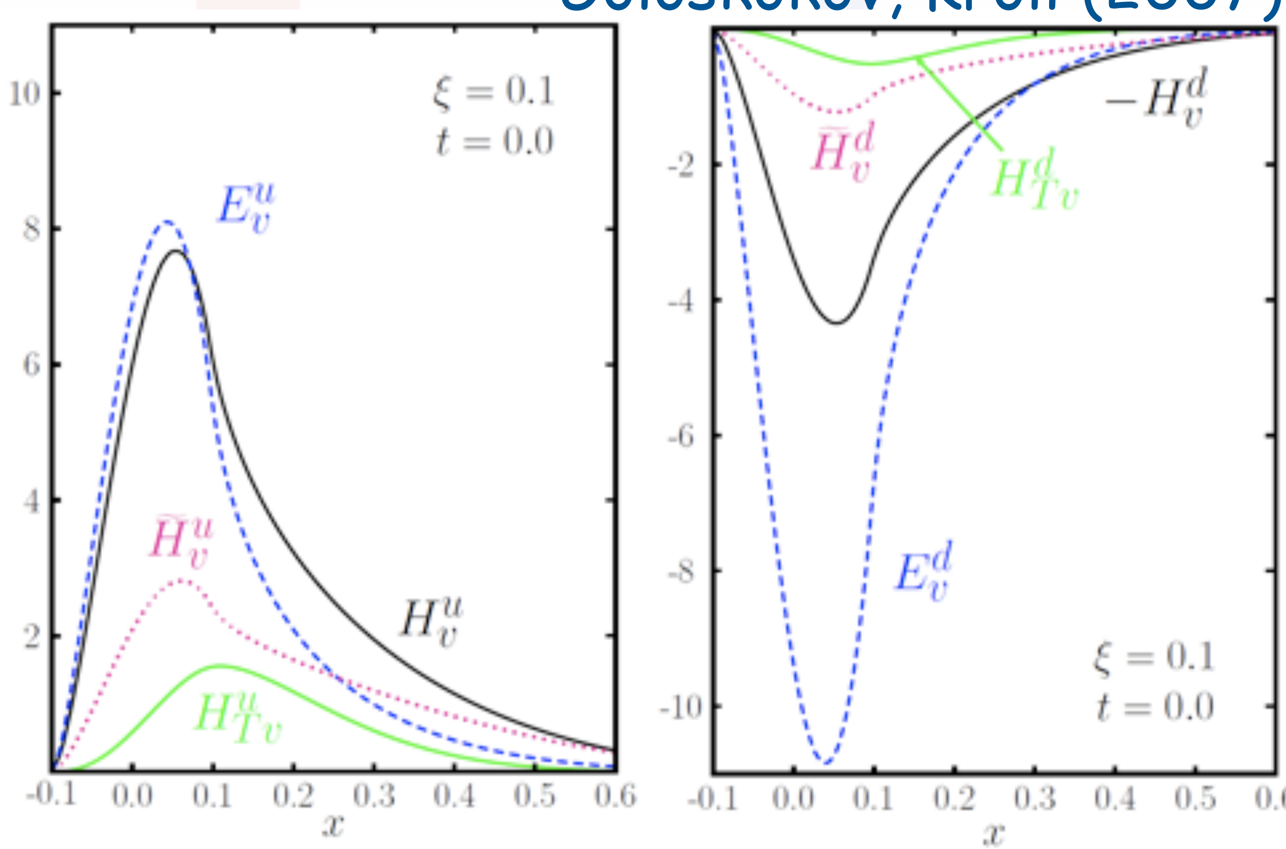
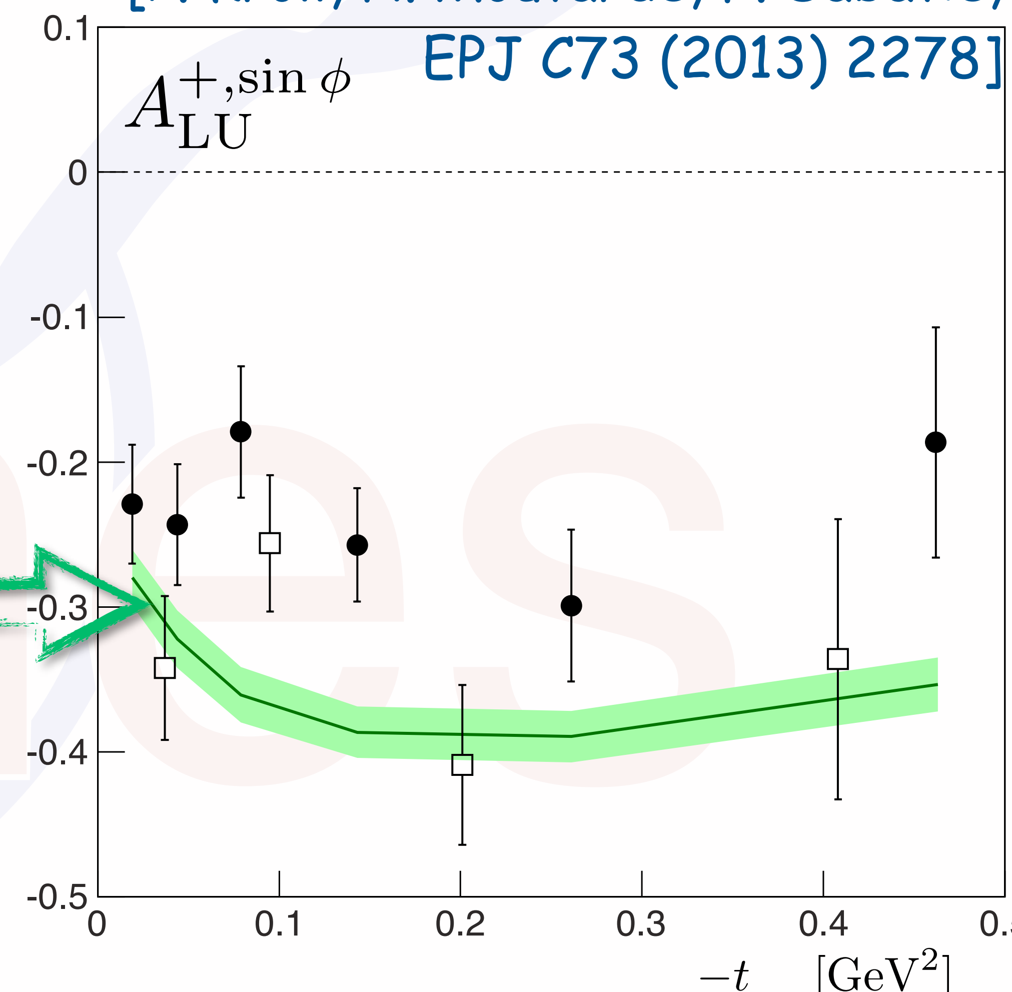
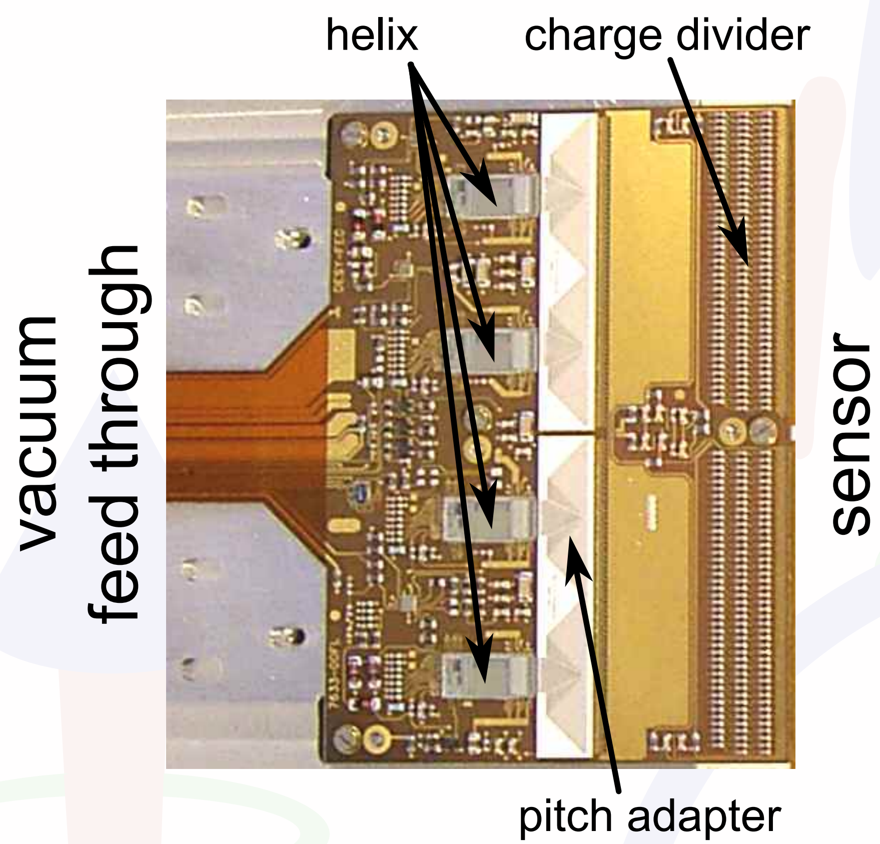


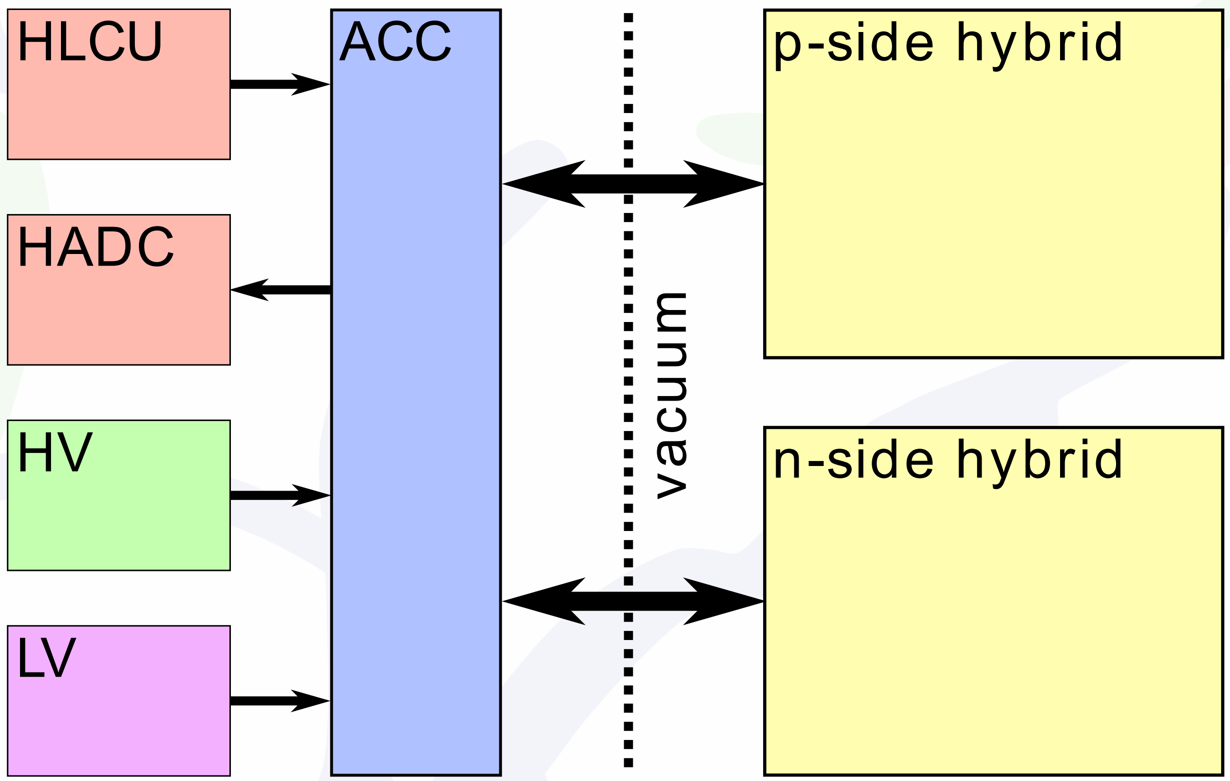
[P. Kroll, H. Moutarde, F. Sabatie, EPJ C73 (2013) 2278]



backup

SSD (silicon strip detector)





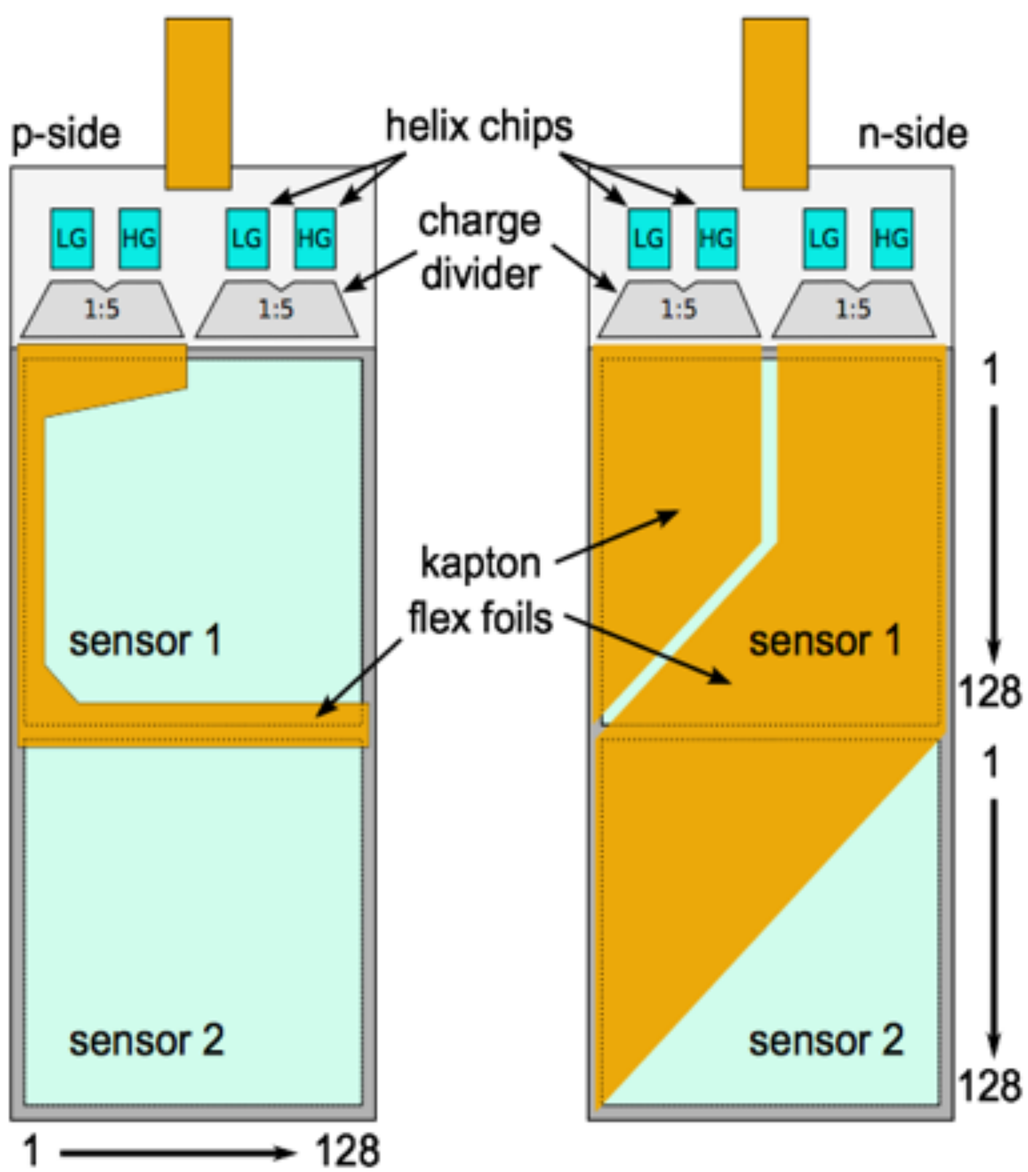
5.8 cm away from lepton beam, 1.5 cm gap

sensor thickness 295 µm - 315 µm

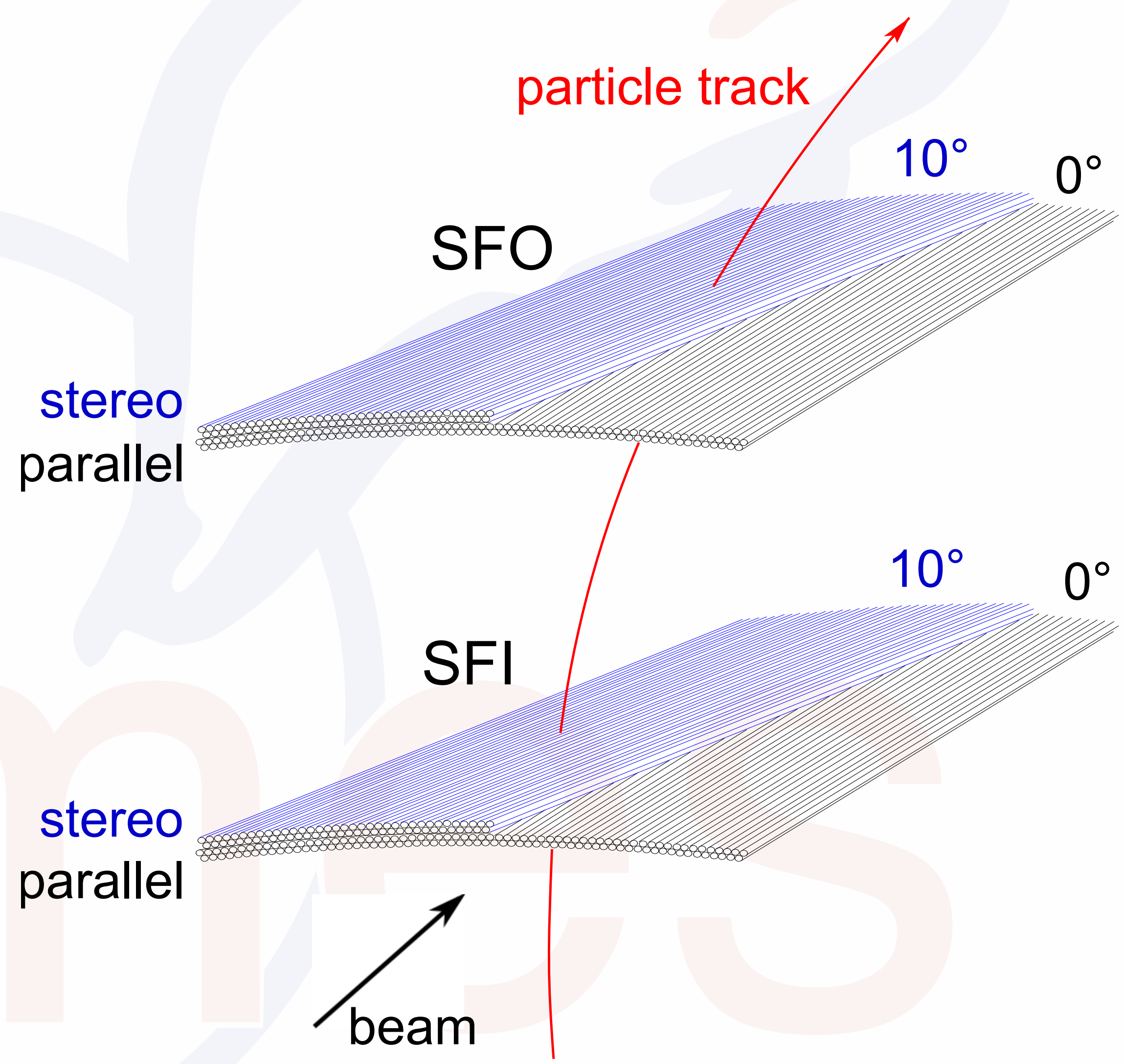
thickness of target cell 75 µm

The HERMES recoil detector

Sketch of front- and backside of a silicon strip detector module (SSD)

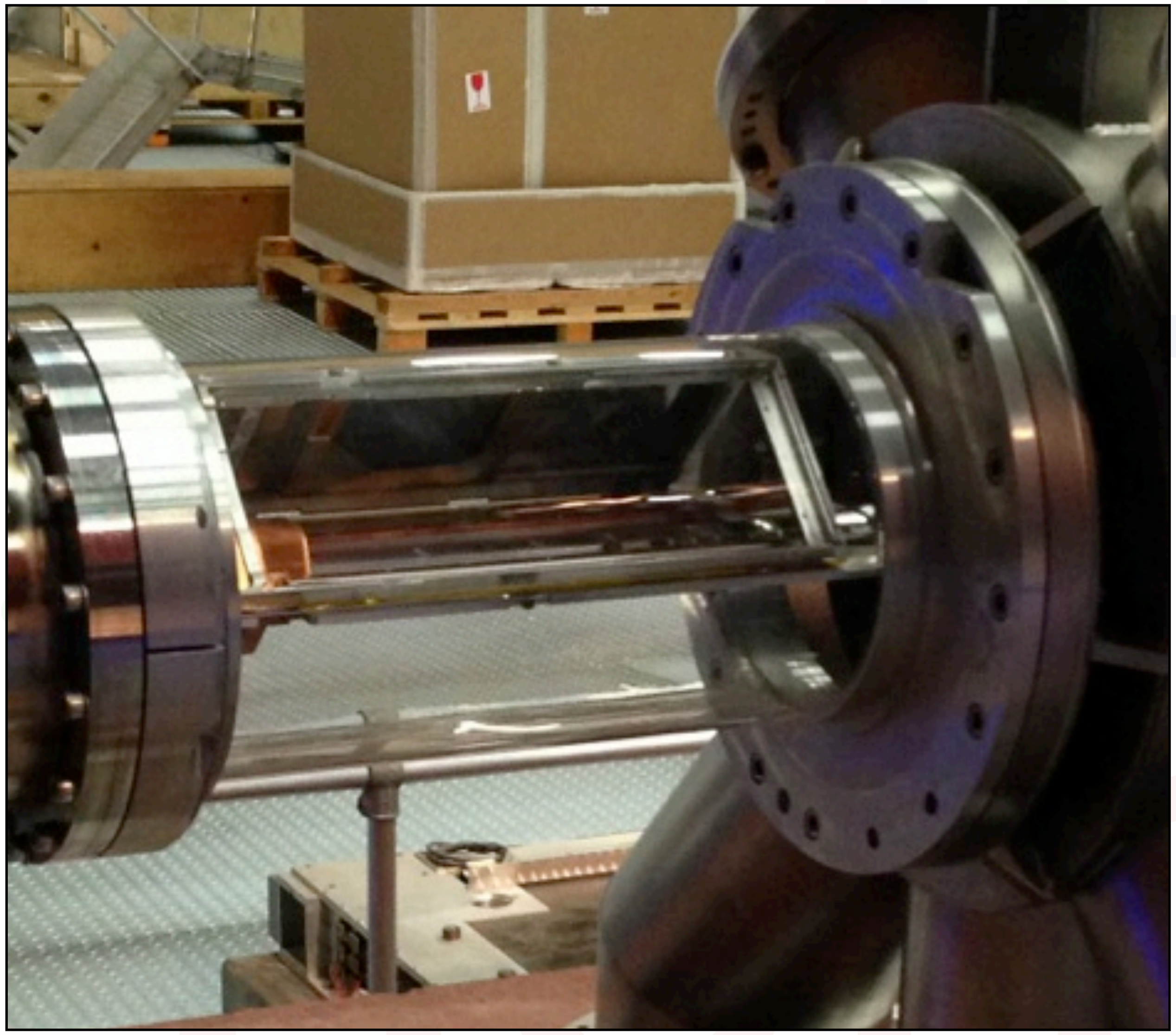


Schematic design of the scintillating fibre tracker (SFT)

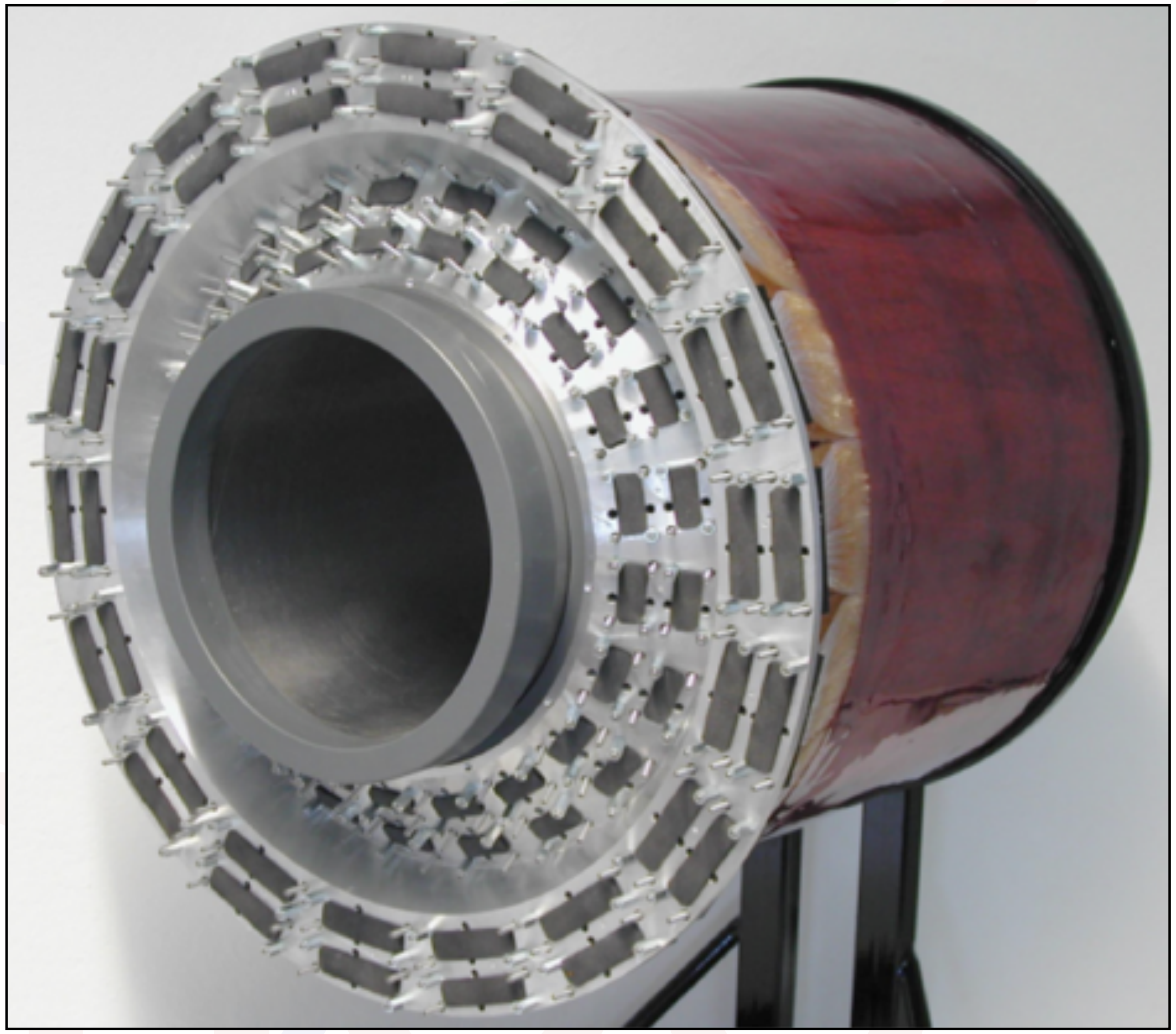


The HERMES recoil detector

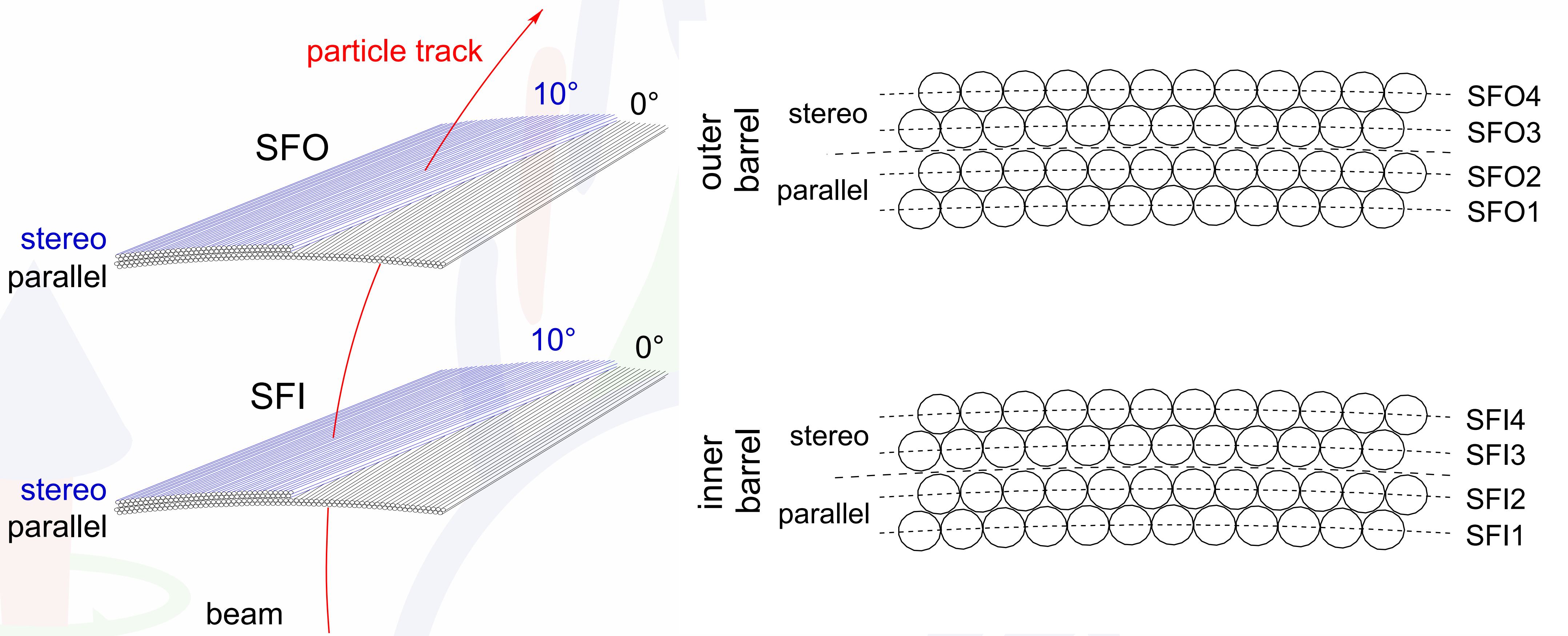
The silicon strip detector (SSD)



The scintillating fibre tracker (SFT)



SFT (scintillating fibre tracker)

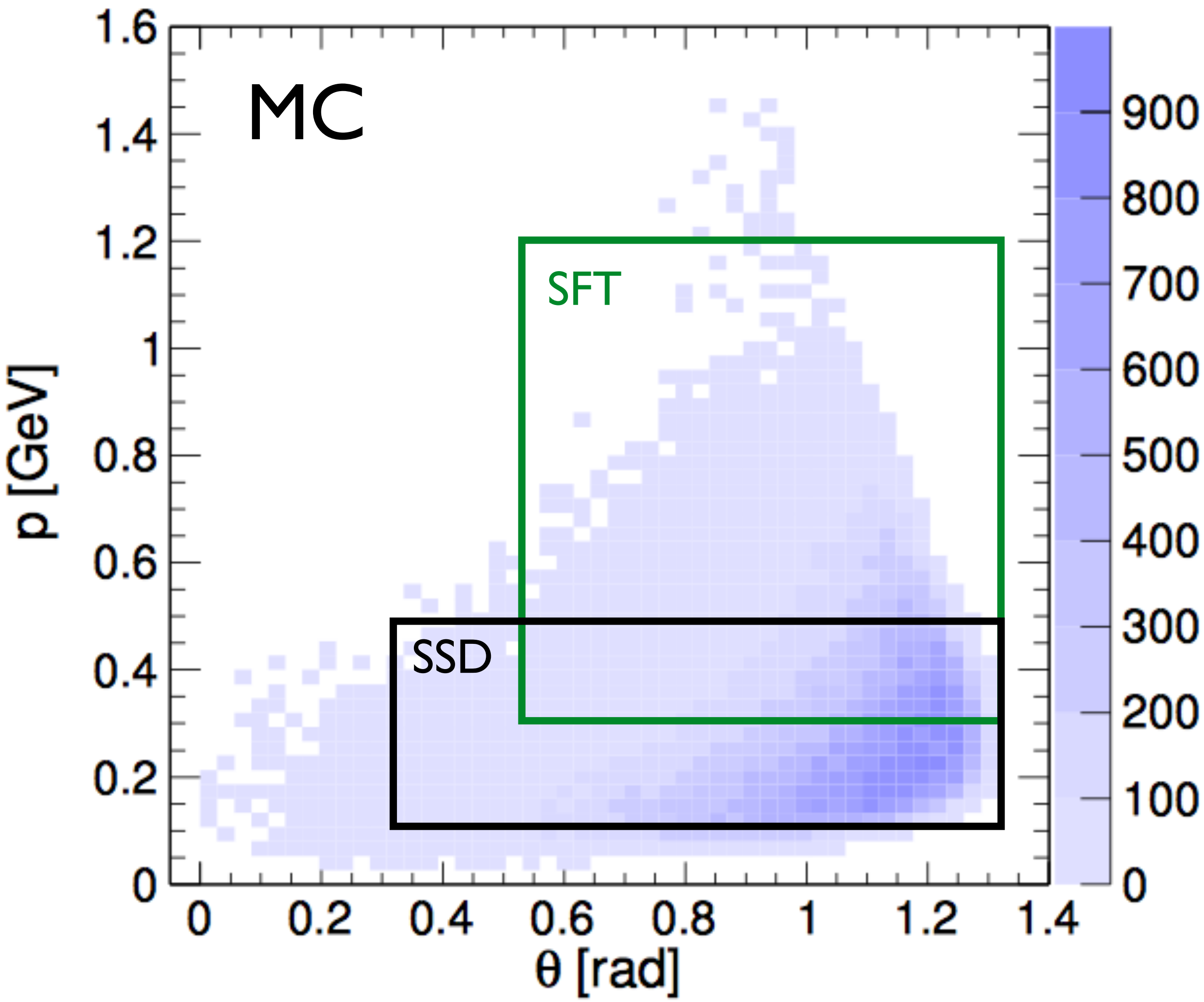


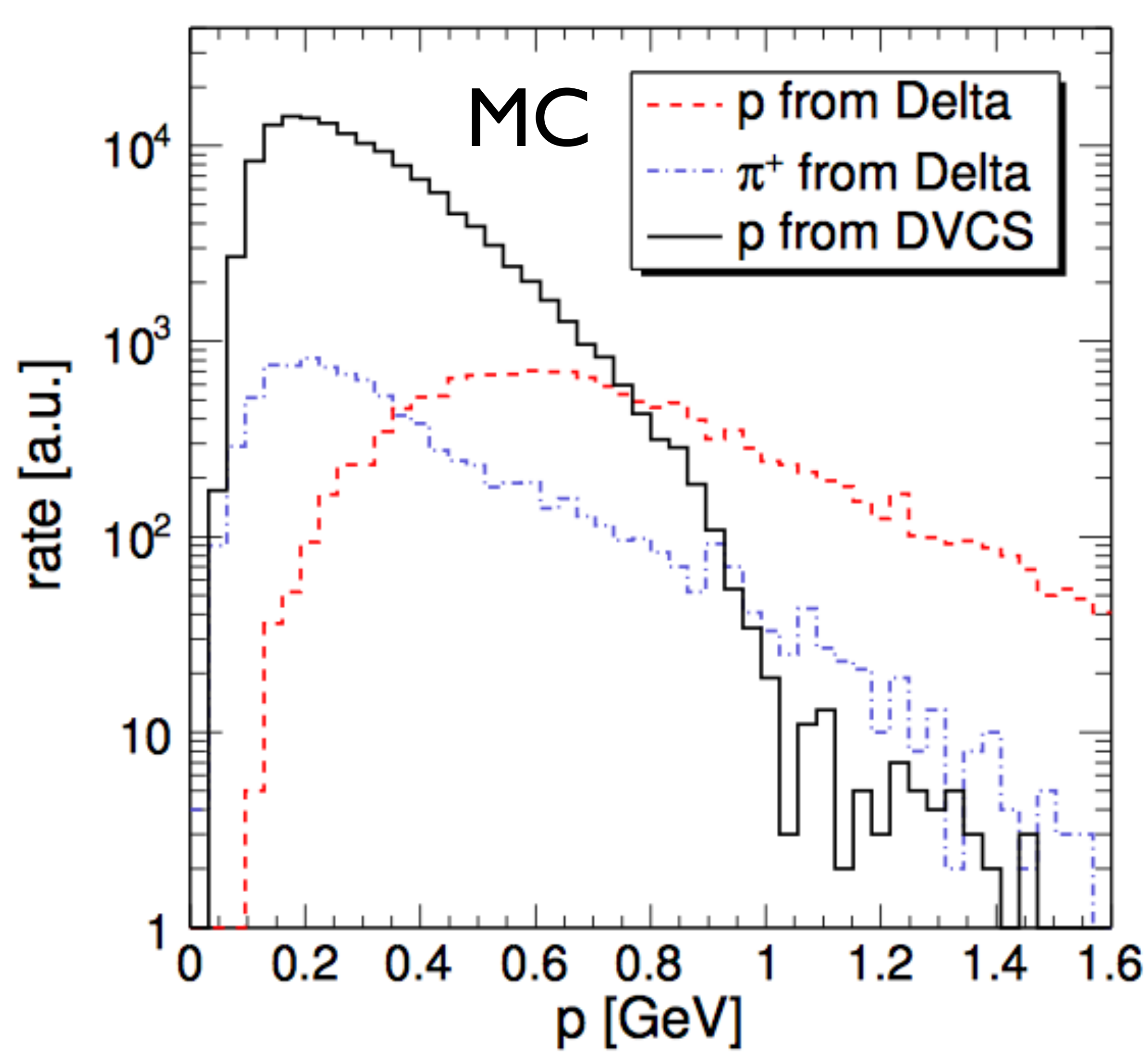
11.5 cm (18.5 cm) inner (outer) radius

1318+1320 (2198+2180) fibers with a diameter of 1 mm each

readout by 64-channel Hamamatsu H7546B MAPMTs

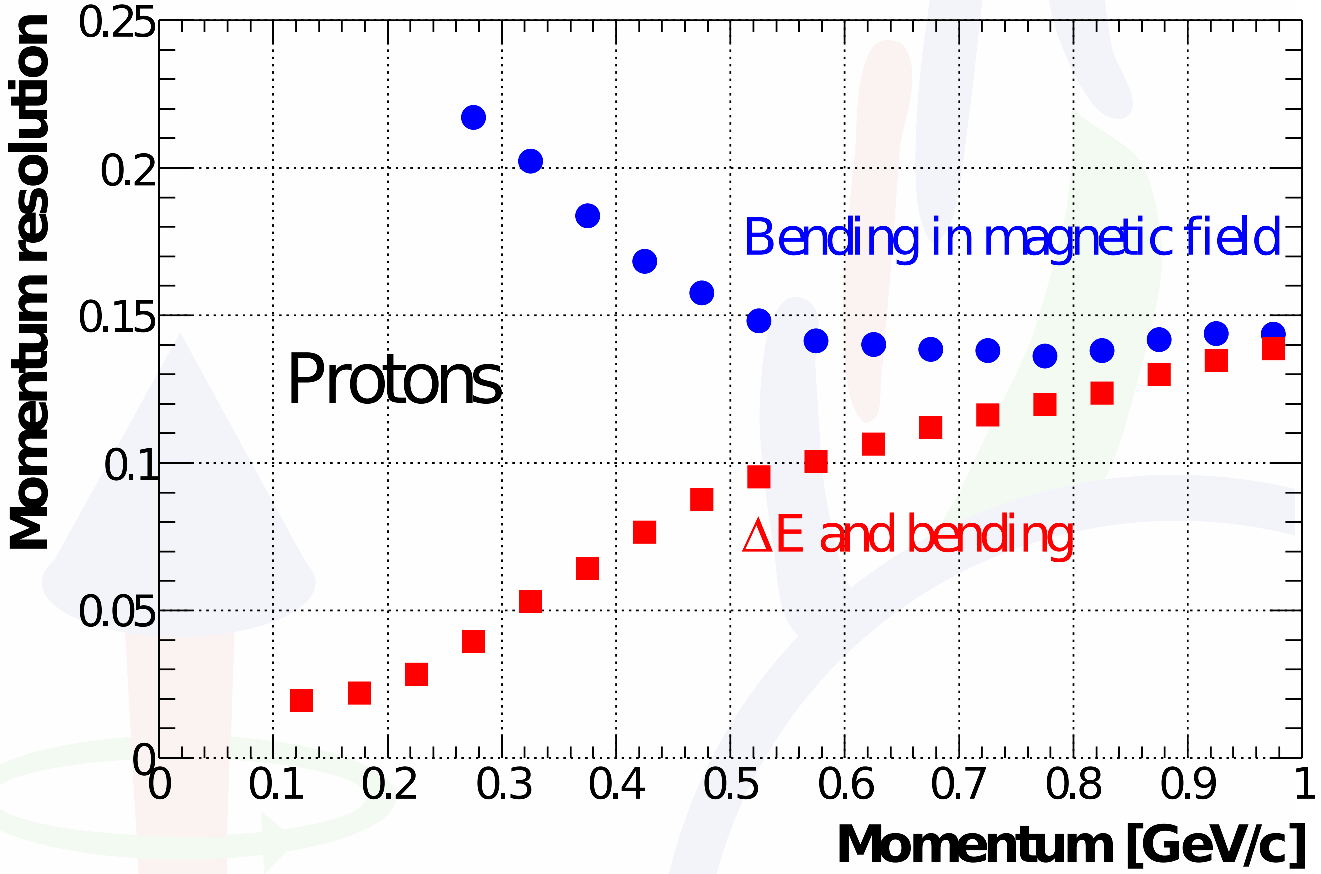
Kinematic coverage of the HERMES RD

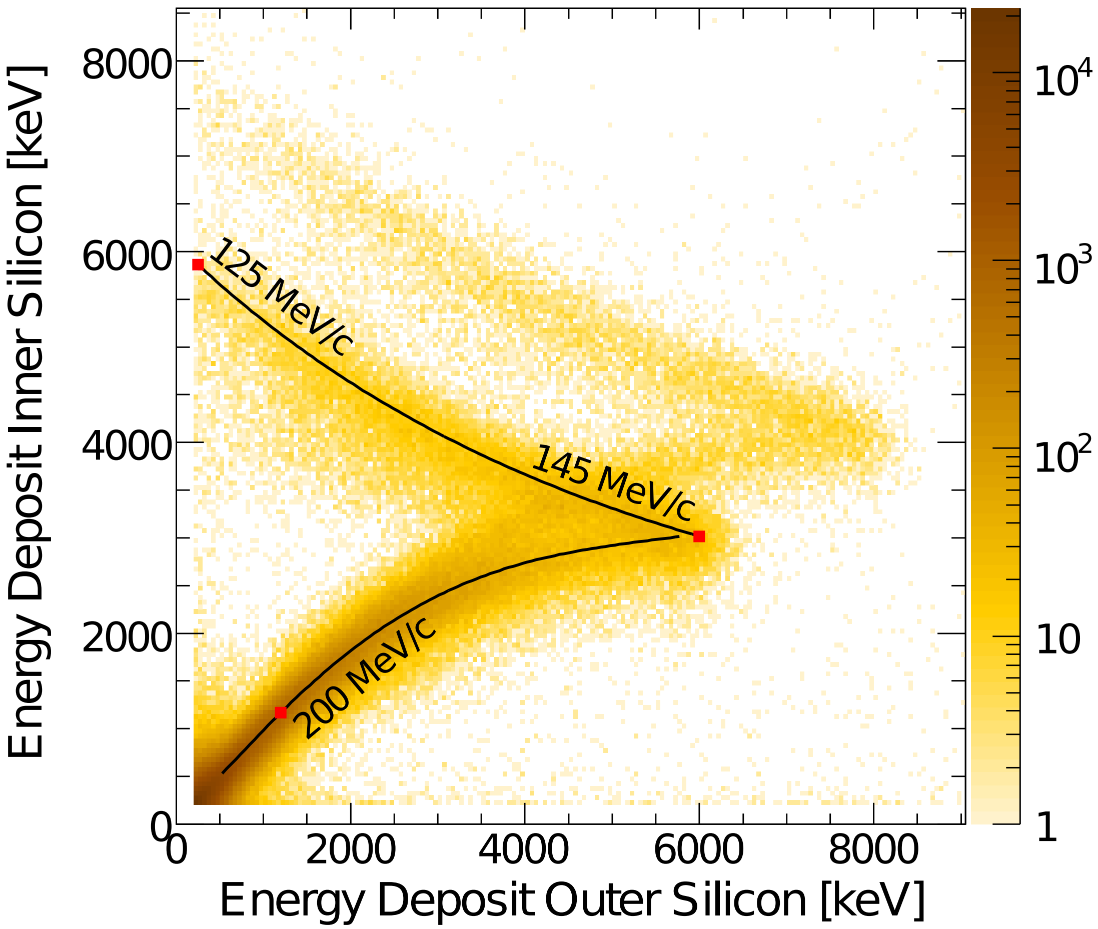




Scintillating fibre tracker (SFT) and silicon strip detector (SSD) complement each other

Recoil-detector tracking



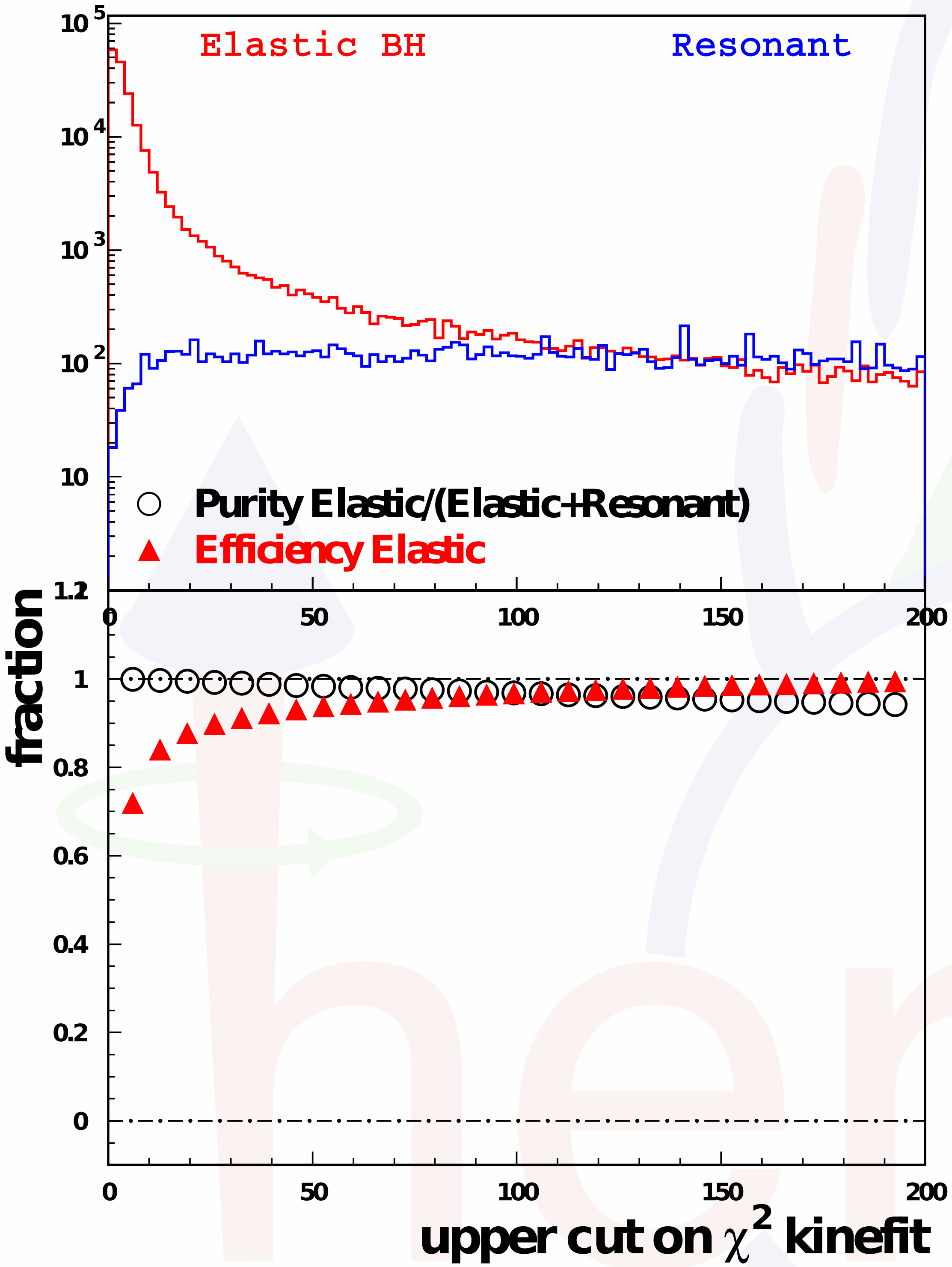


taking energy loss into account improves momentum resolution for low p

azimuthal-angle resolution: 4 mrad

polar-angle resolution: 10 mrad (for p>0.5 GeV)

Kinematic event fitting

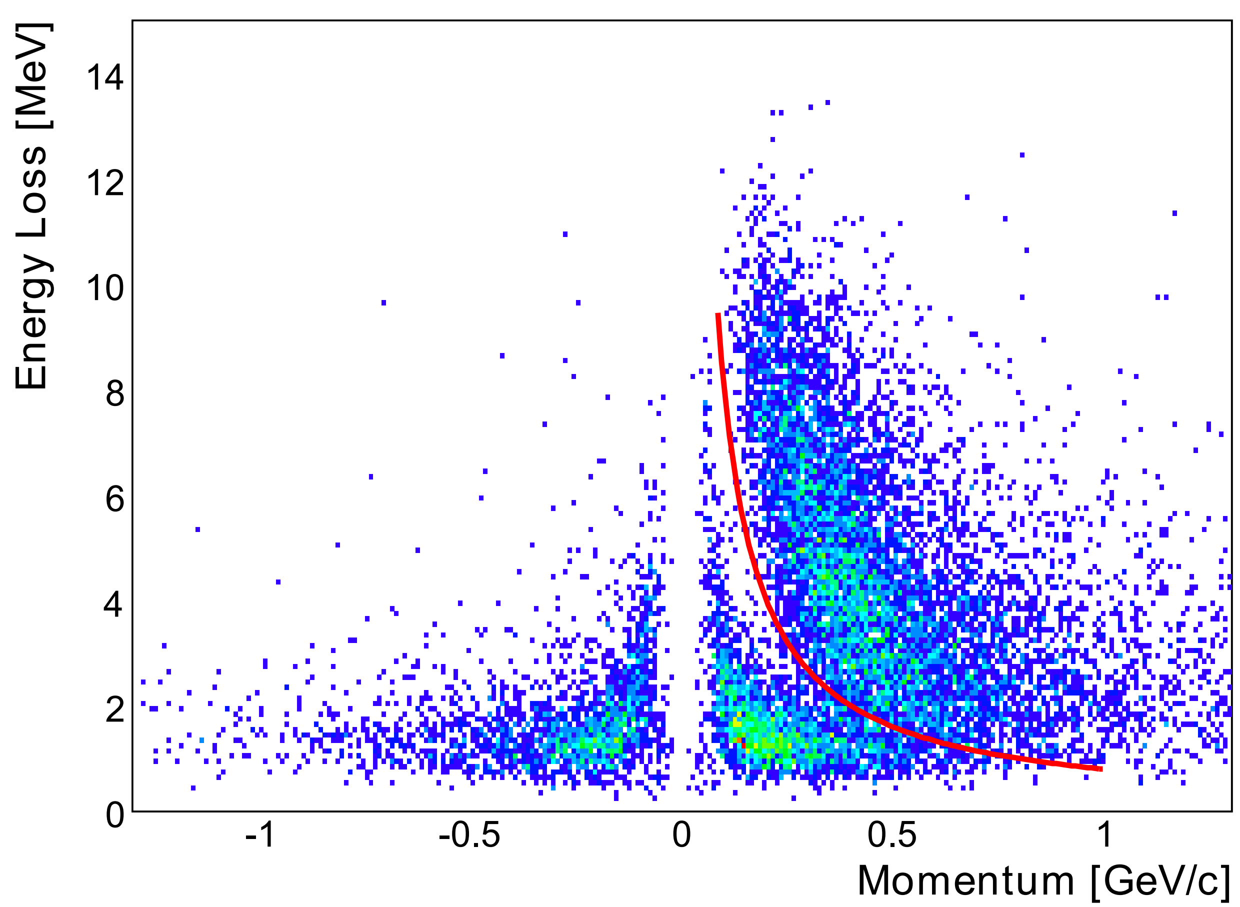


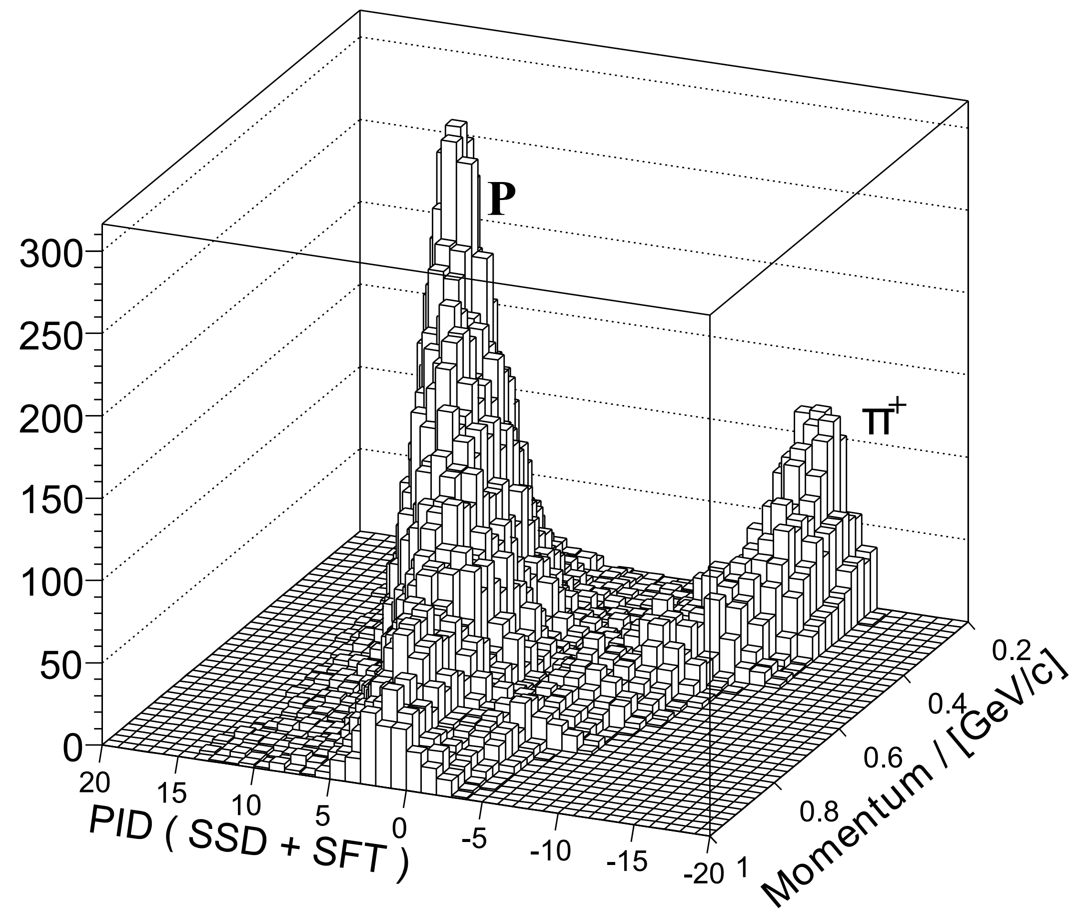
$$\chi^2_{pen} = \boxed{\sum_{i=1}^{9} \frac{(r_i^{fit} - r_i^{meas})^2}{\sigma_i^2}} + \boxed{T \cdot \sum_{j=1}^{4} \frac{\left[\boxed{f_j(r_1^{fit}, \ldots, r_9^{fit})}\right]^2}{(\sigma_j^f)^2}}$$

χ^2-value of interest　penalty term　constraints

- 4-momentum conservation as constraints
- lowest χ^2-value in case of multiple recoil tracks per event
- minimum of 1 % fit probability required, which corresponds to $\chi^2 < 13.7$

Recoil PID



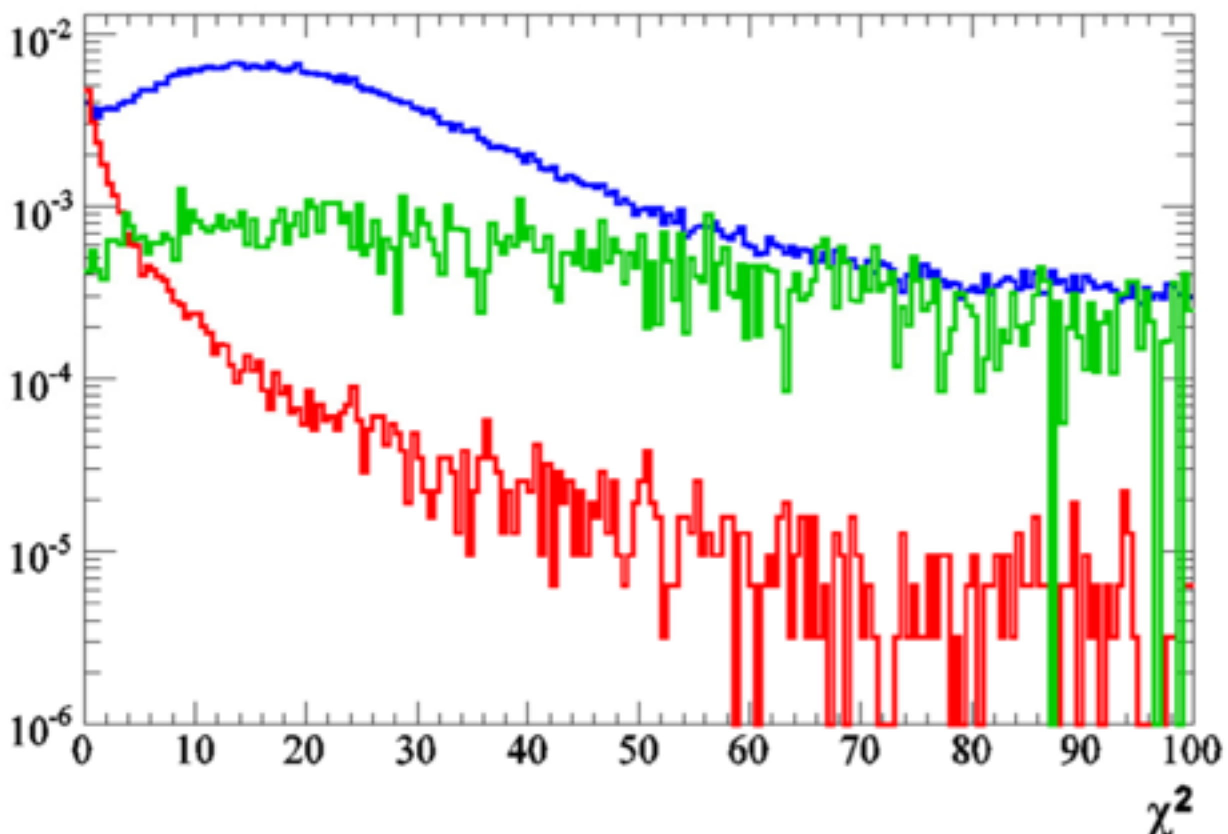


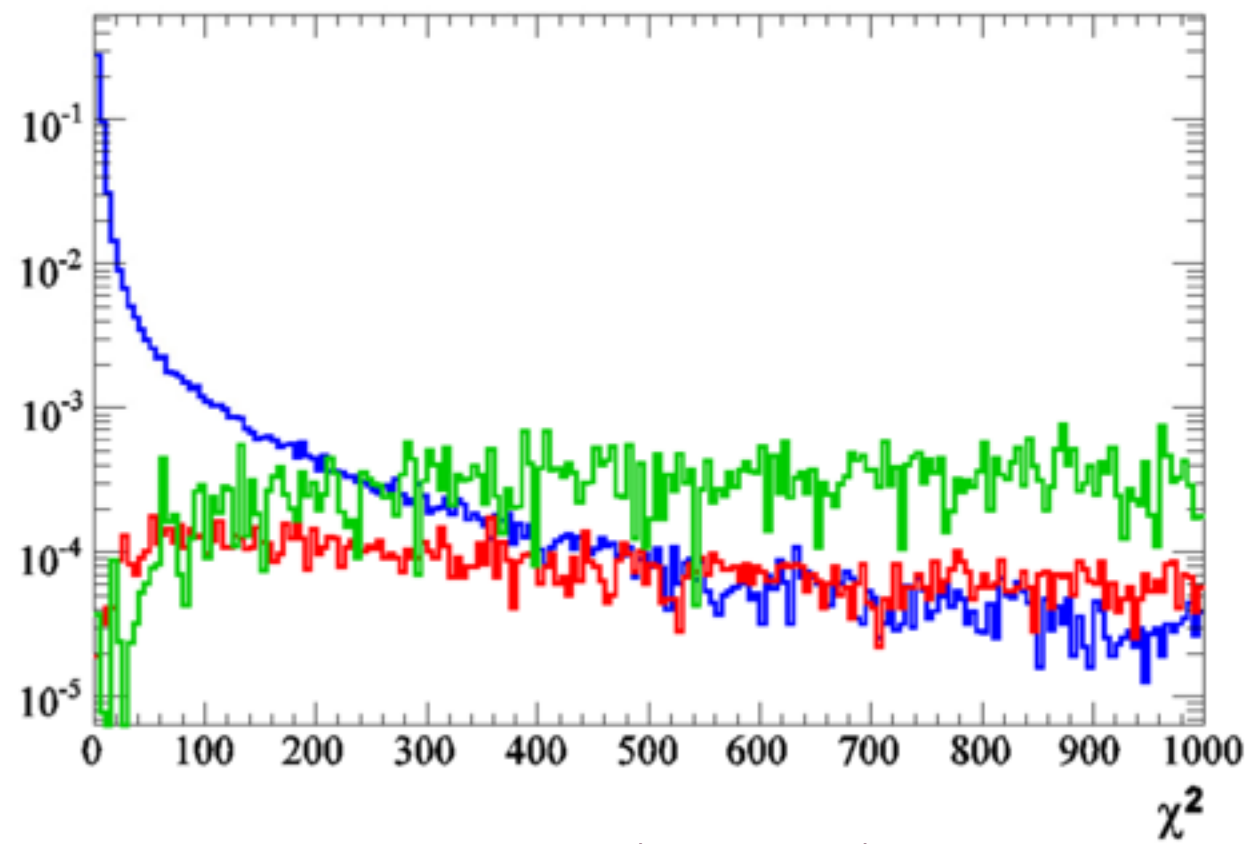
discrimination between protons and positively charged pions

parent distributions were crucial and determined experimentally

Kinematic fitting for $ep \rightarrow e\gamma p\pi^0$

$ep \rightarrow e\gamma p\pi^0$ $ep \rightarrow e\gamma p$ SIDIS





$ep \rightarrow e\gamma p\pi^0$ hypothesis

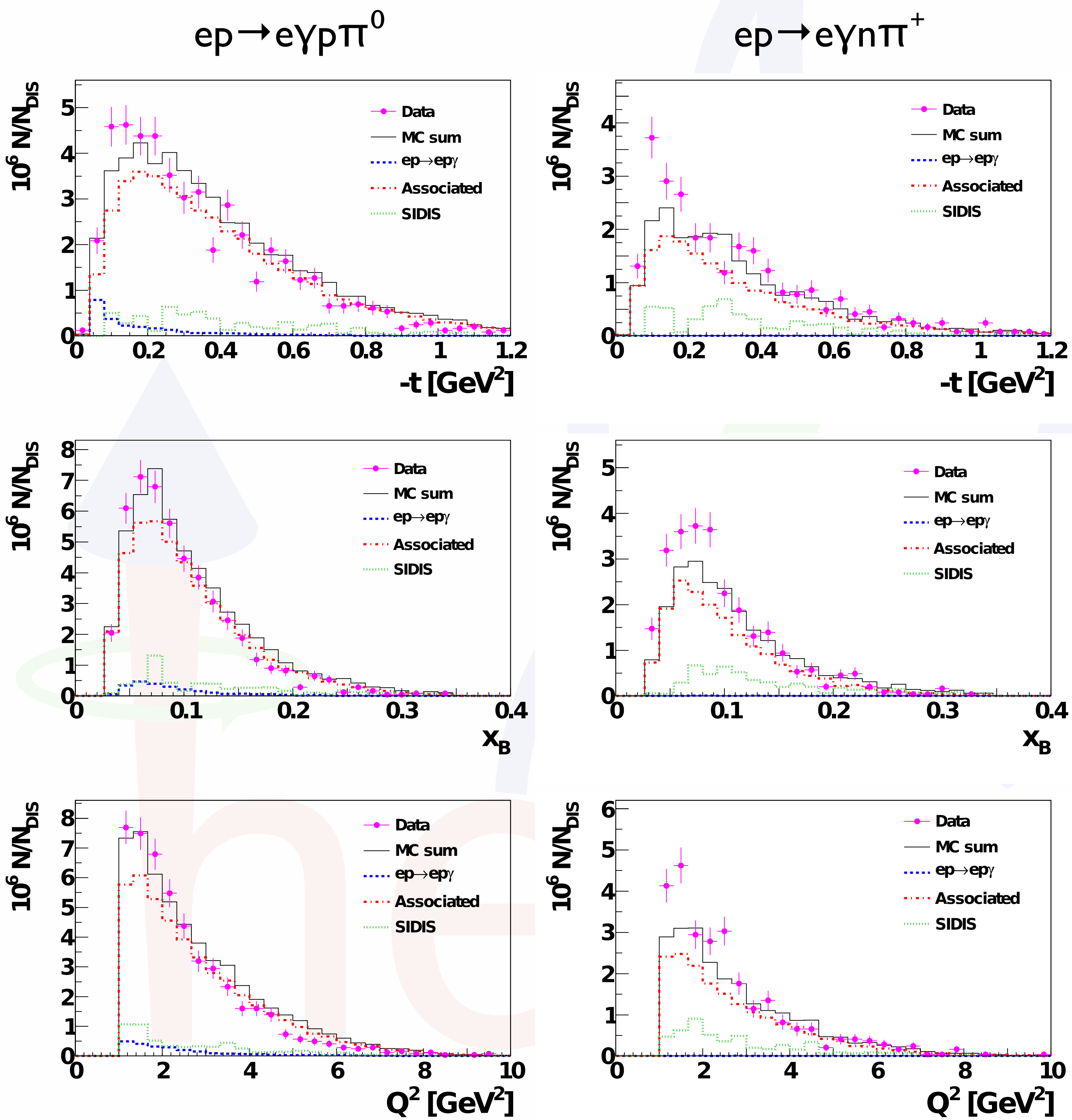
$\chi^2_{ep \rightarrow e\gamma p\pi^0} < 4.6$

$ep \rightarrow e\gamma p$ hypothesis

$\chi^2_{ep \rightarrow e\gamma p} > 50$

Using powerful kinematic fitting of $ep \rightarrow e\gamma p$ hypothesis is crucial for the $ep \rightarrow e\gamma N\pi$ analysis

Selection of associated events



Uncharged particle remains undetected

Kinematic fitting in case of ep→e γ Nπ hypothesis therefore not as strong

Additional selection criteria:

- Recoil PID information
- Lower-cut on ep→e γ p hypothesis