Exclusive processes at hermes

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Generalized parton distributions

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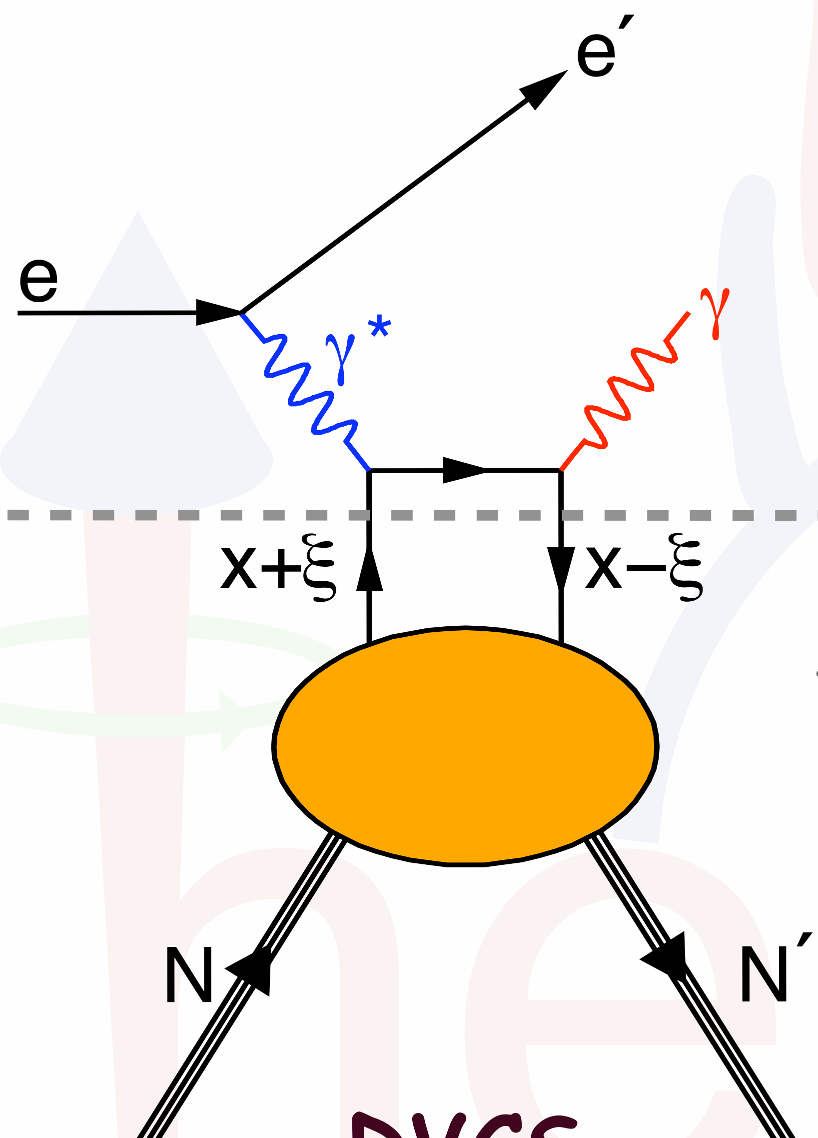
  - ... thanks!
    - ... also to Erik Etzelmüller and Charlotte Van Hulse for "slides support"

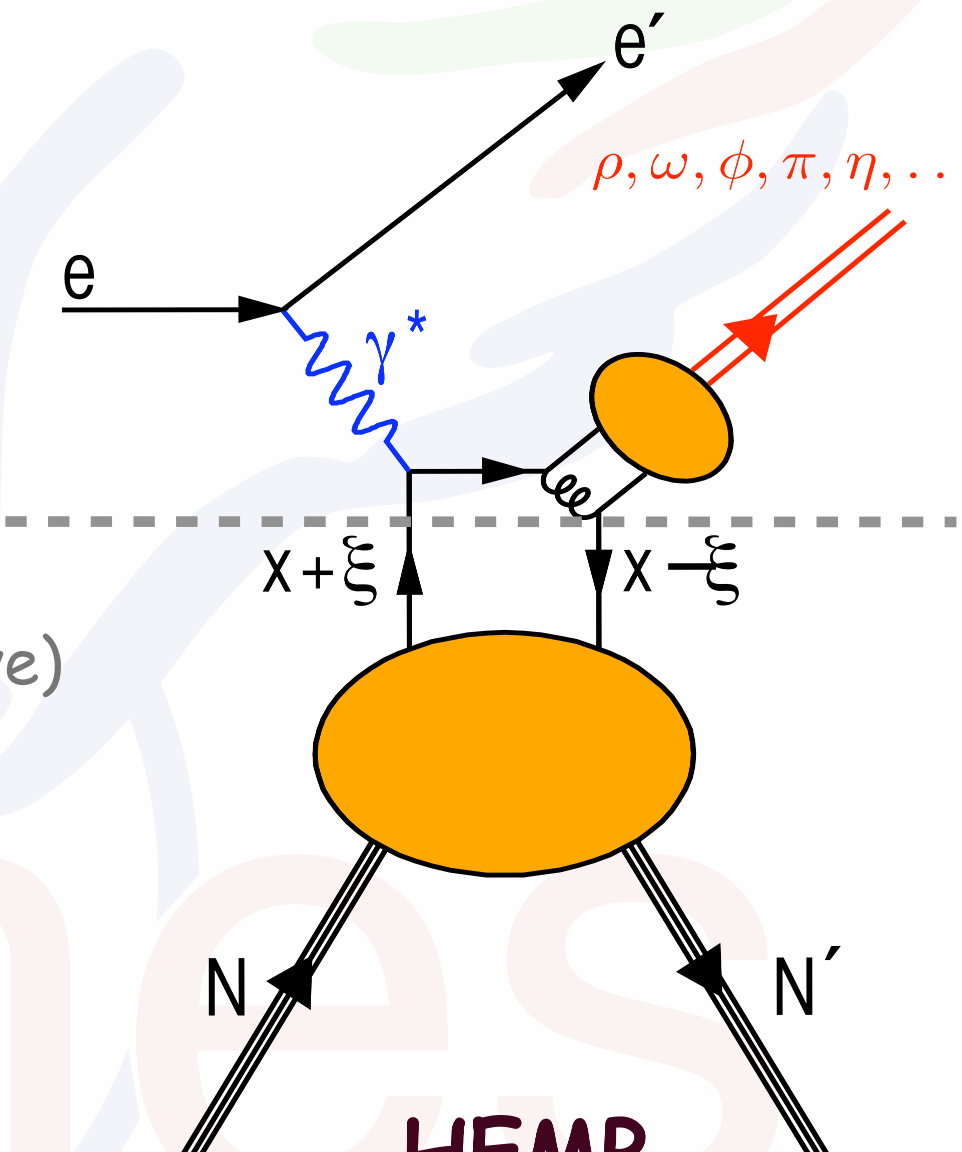
GPDs in exclusive reactions

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



hard scattering process (QED & QCD)

soft (non-perturbative) part (GPDs)



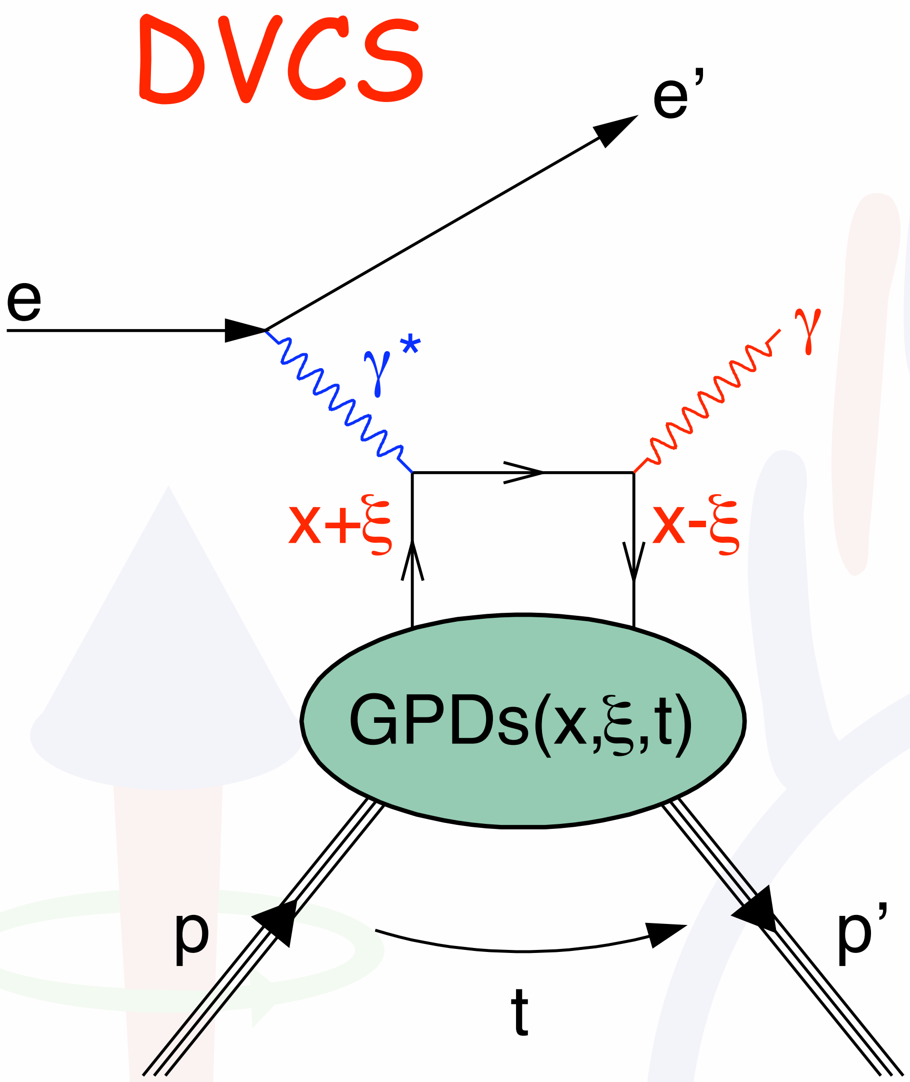
DVCS

deeply virtual Compton scattering

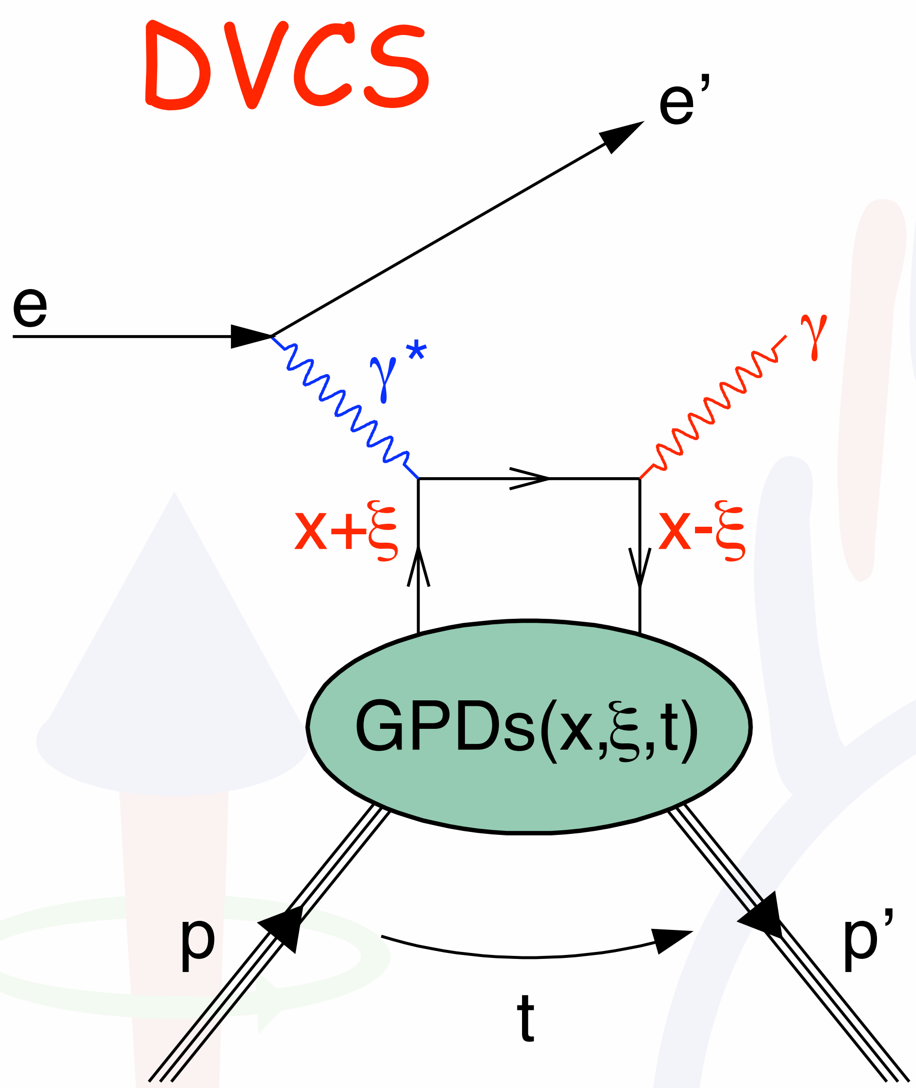
HEMP

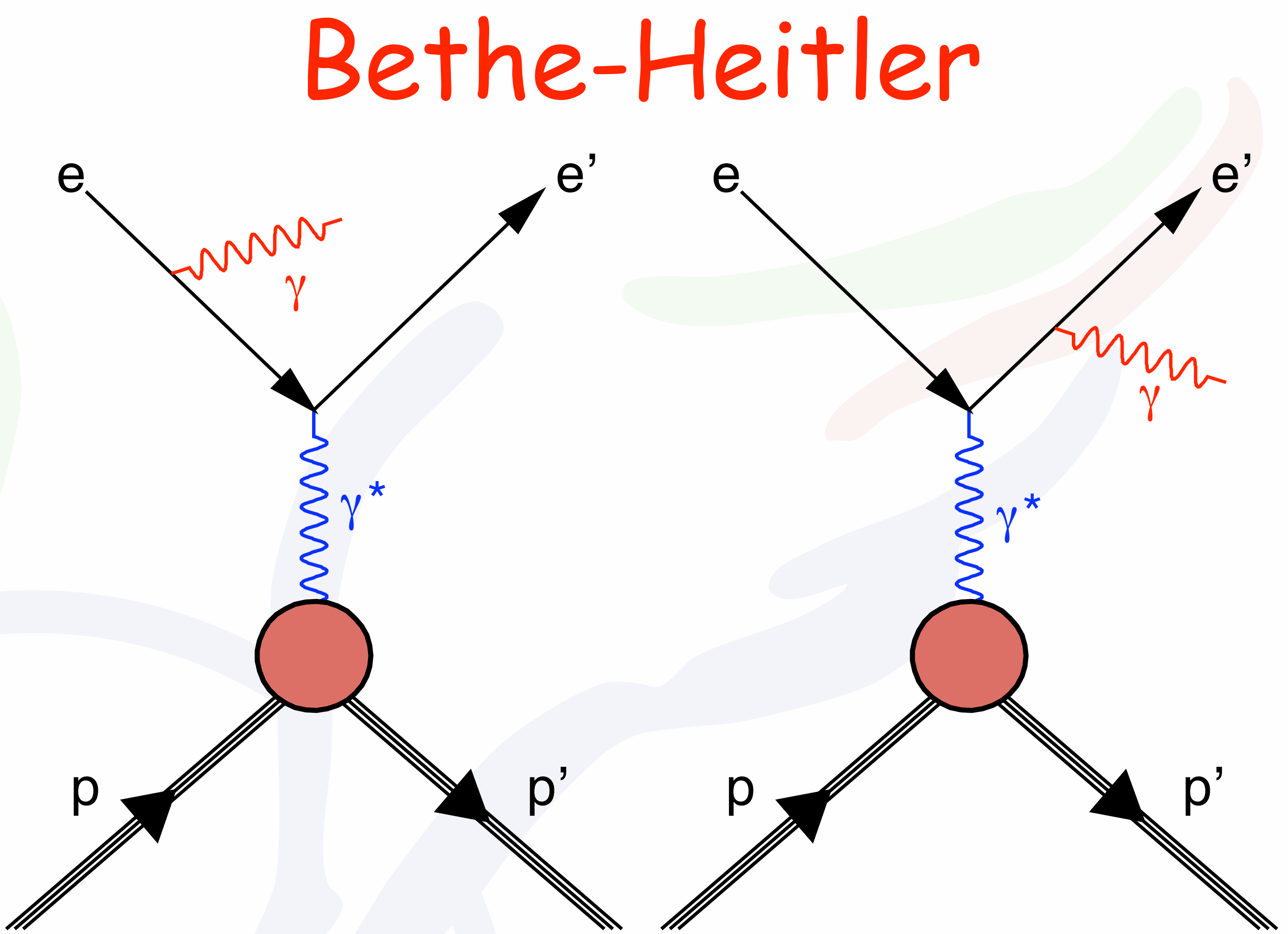
hard exclusive meson production

Real-photon production



Real-photon production

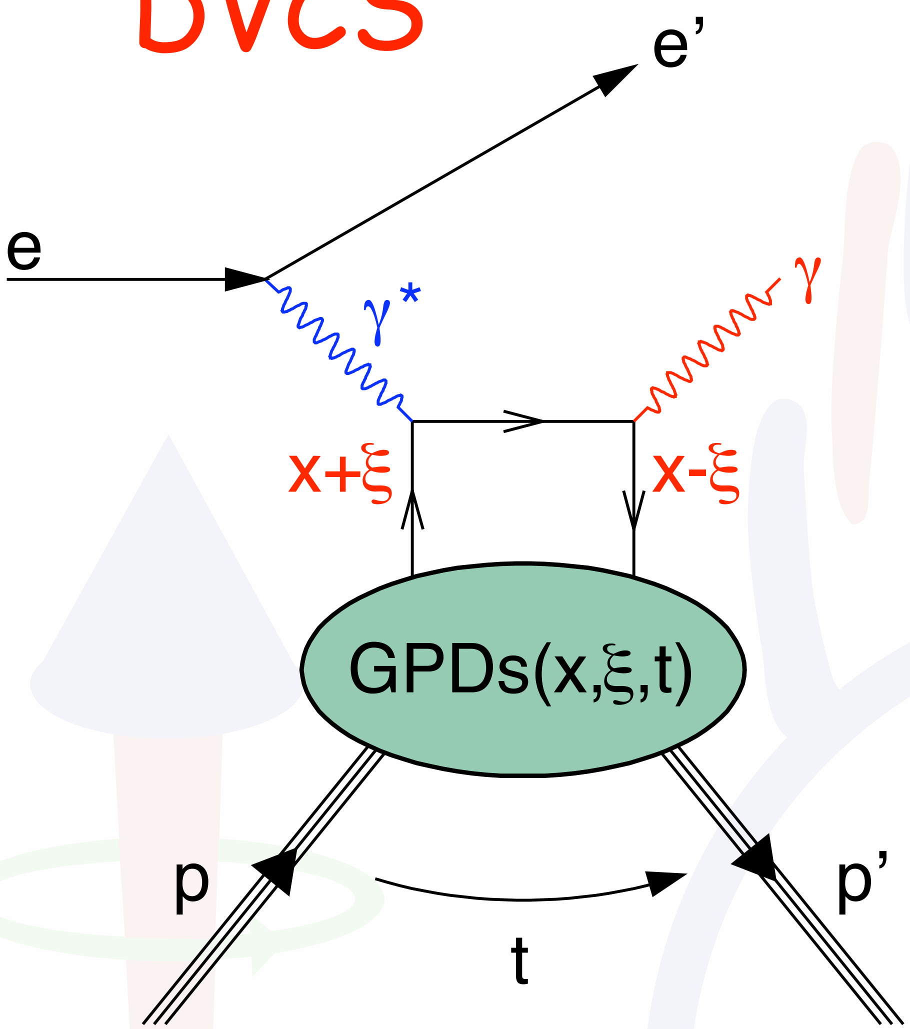




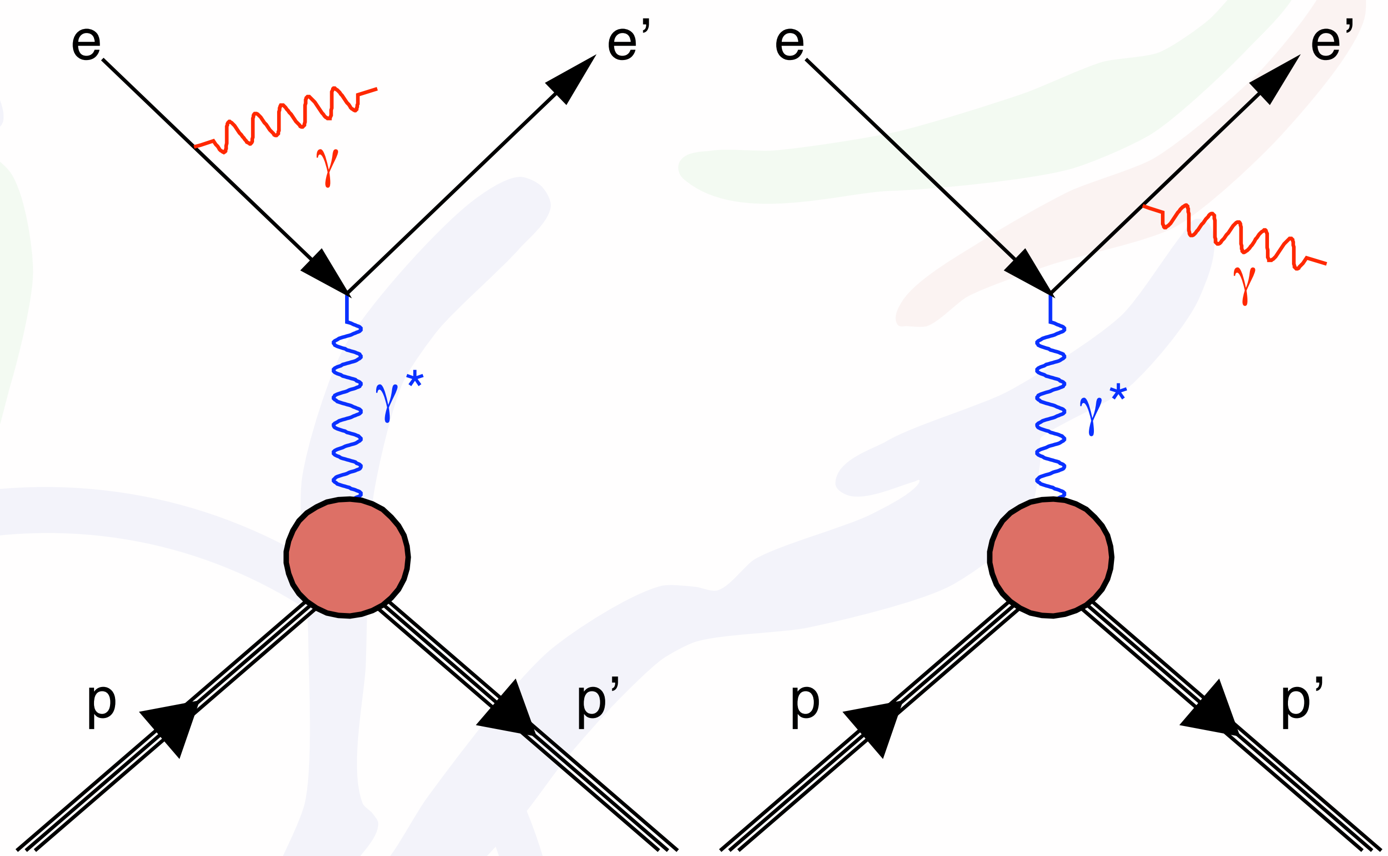
$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\phi} = \frac{y^2}{32(2\pi))^4\sqrt{1+\frac{4M^2x_B^2}{Q^2}}}\left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I}\right)$$

Real-photon production

DVCS



Bethe-Heitler



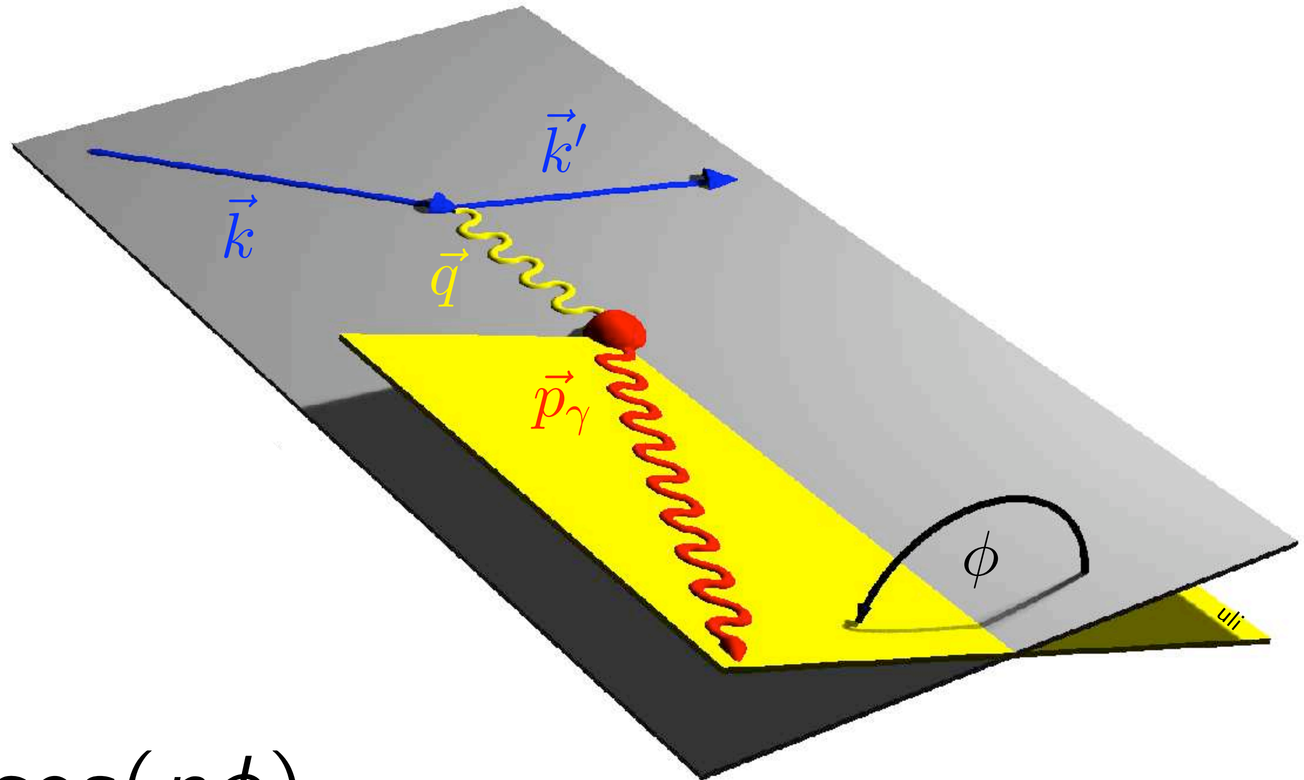
Amplitude of Bethe-Heitler scattering is dominant at HERMES kinematics

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

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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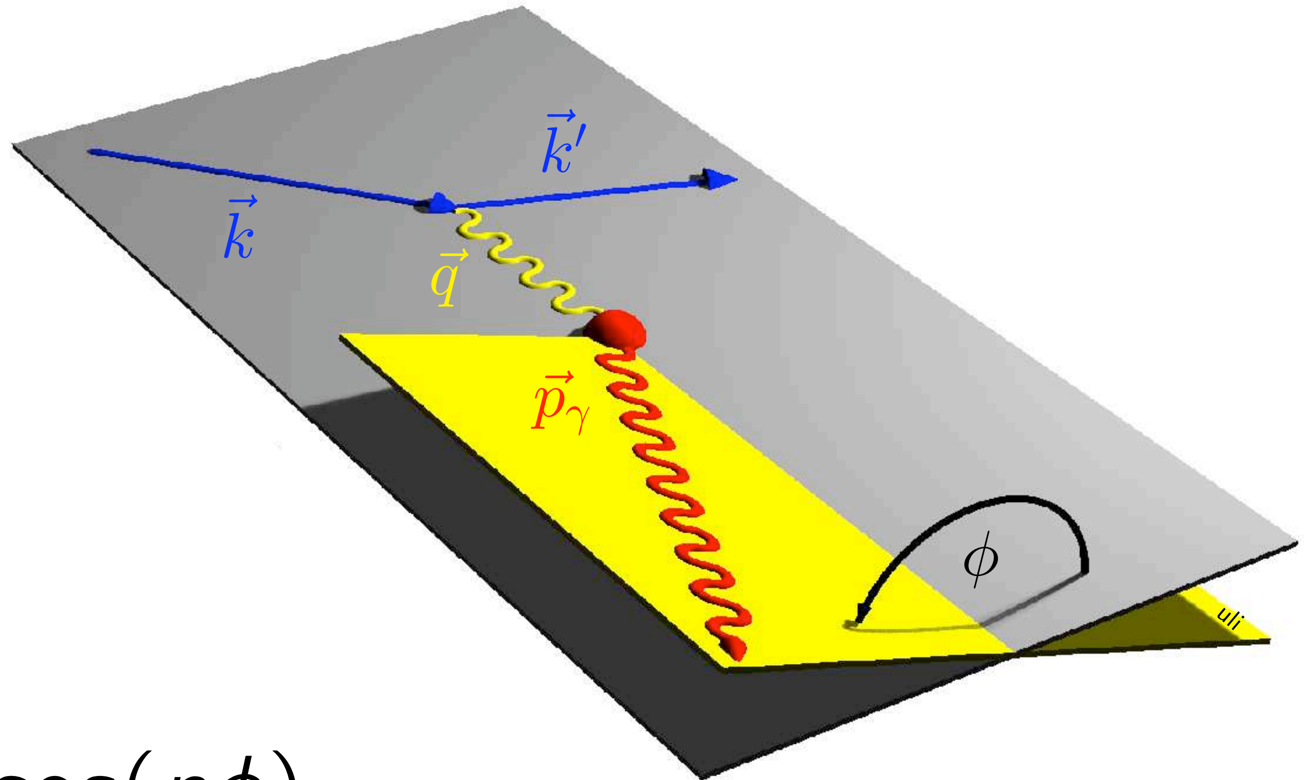

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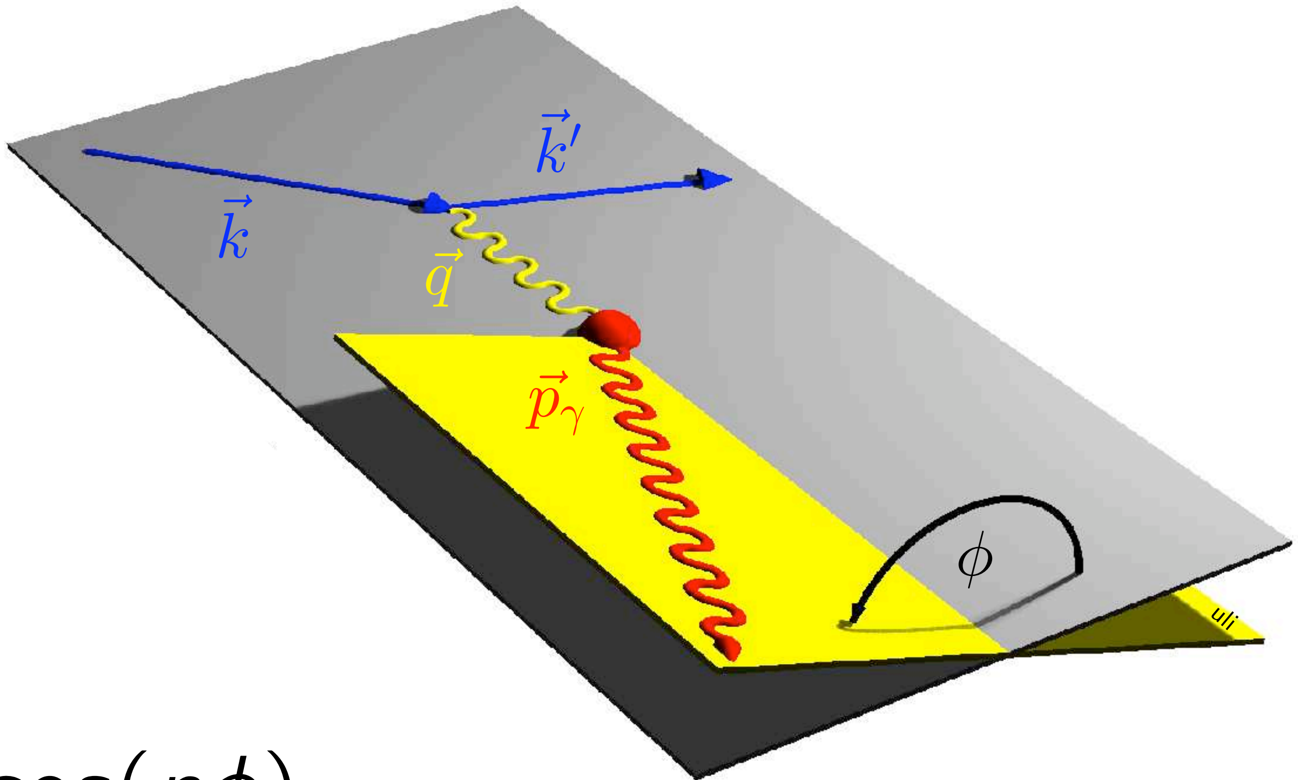

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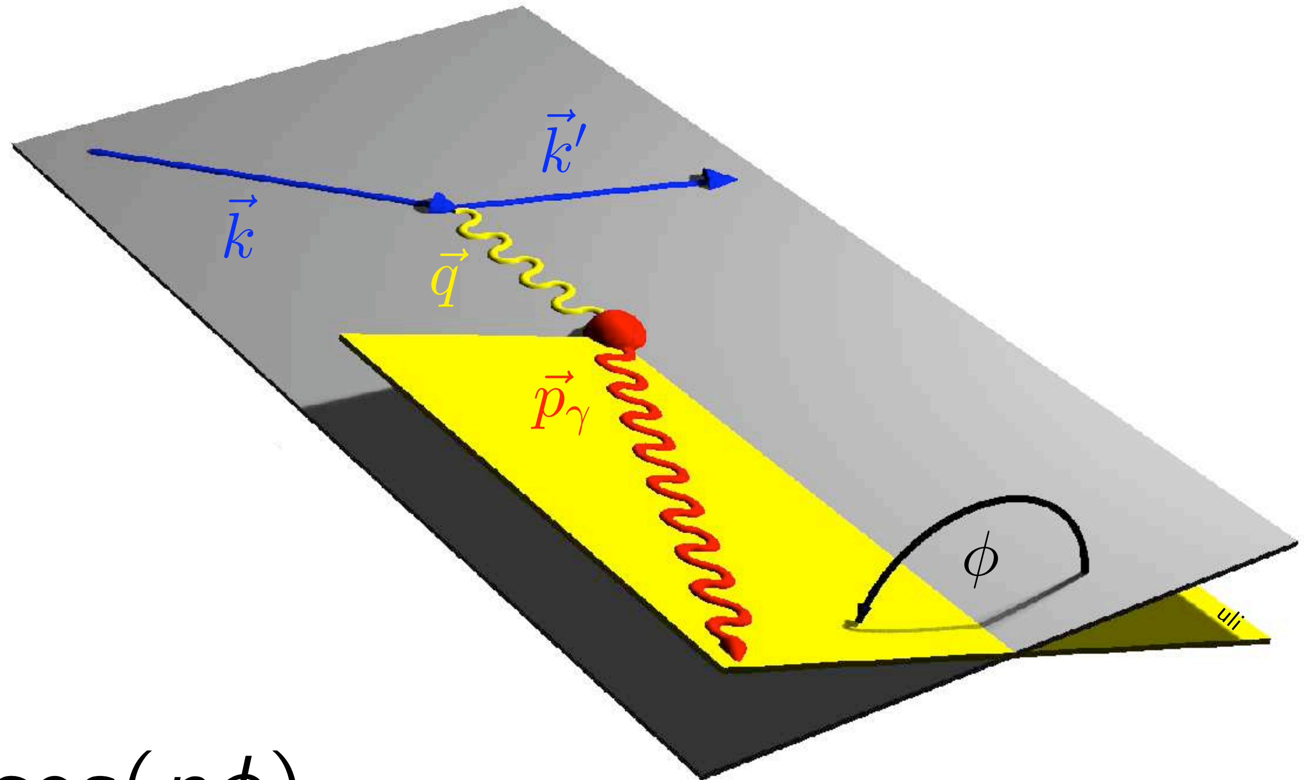
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Azimuthal dependences in DVCS/BH

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



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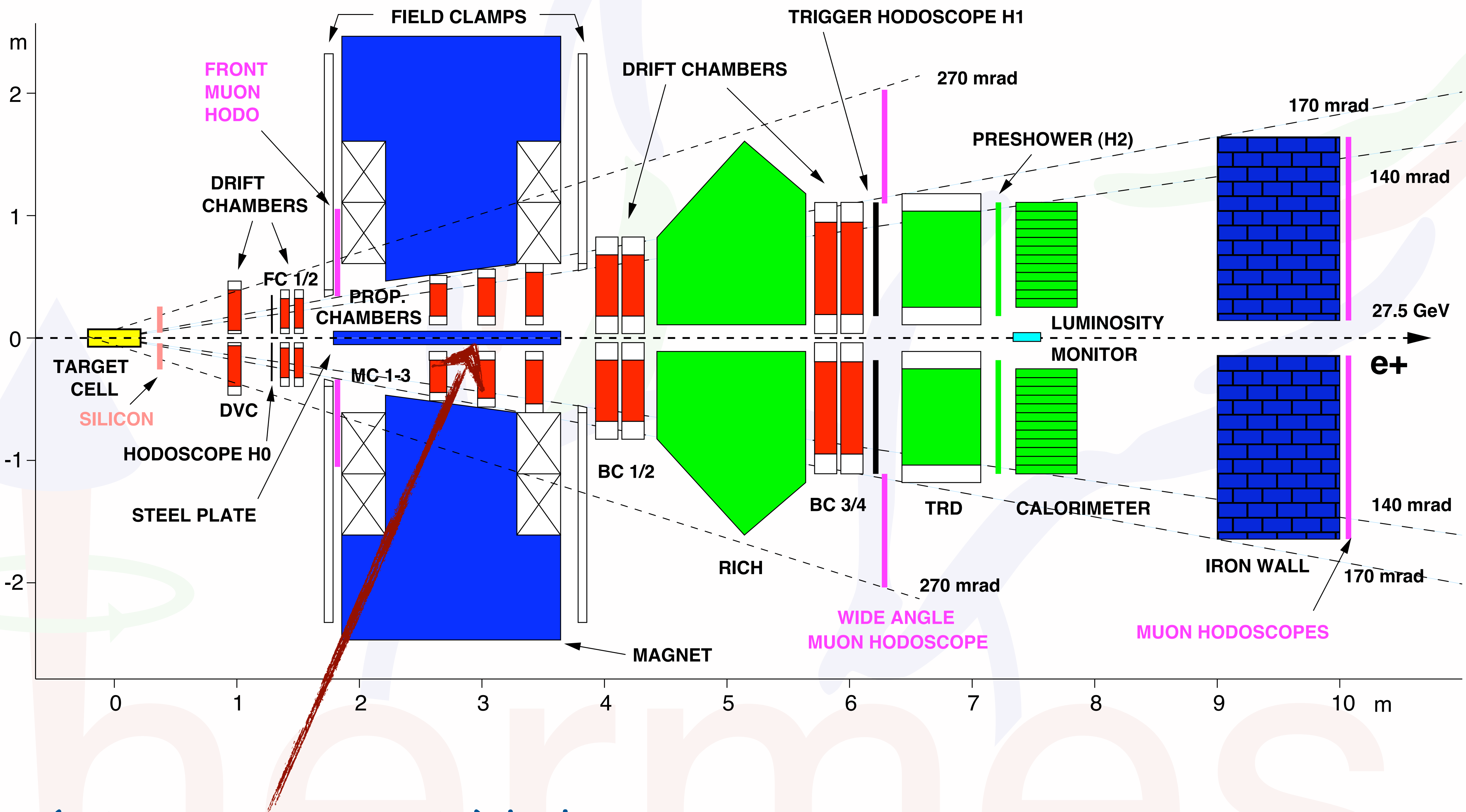
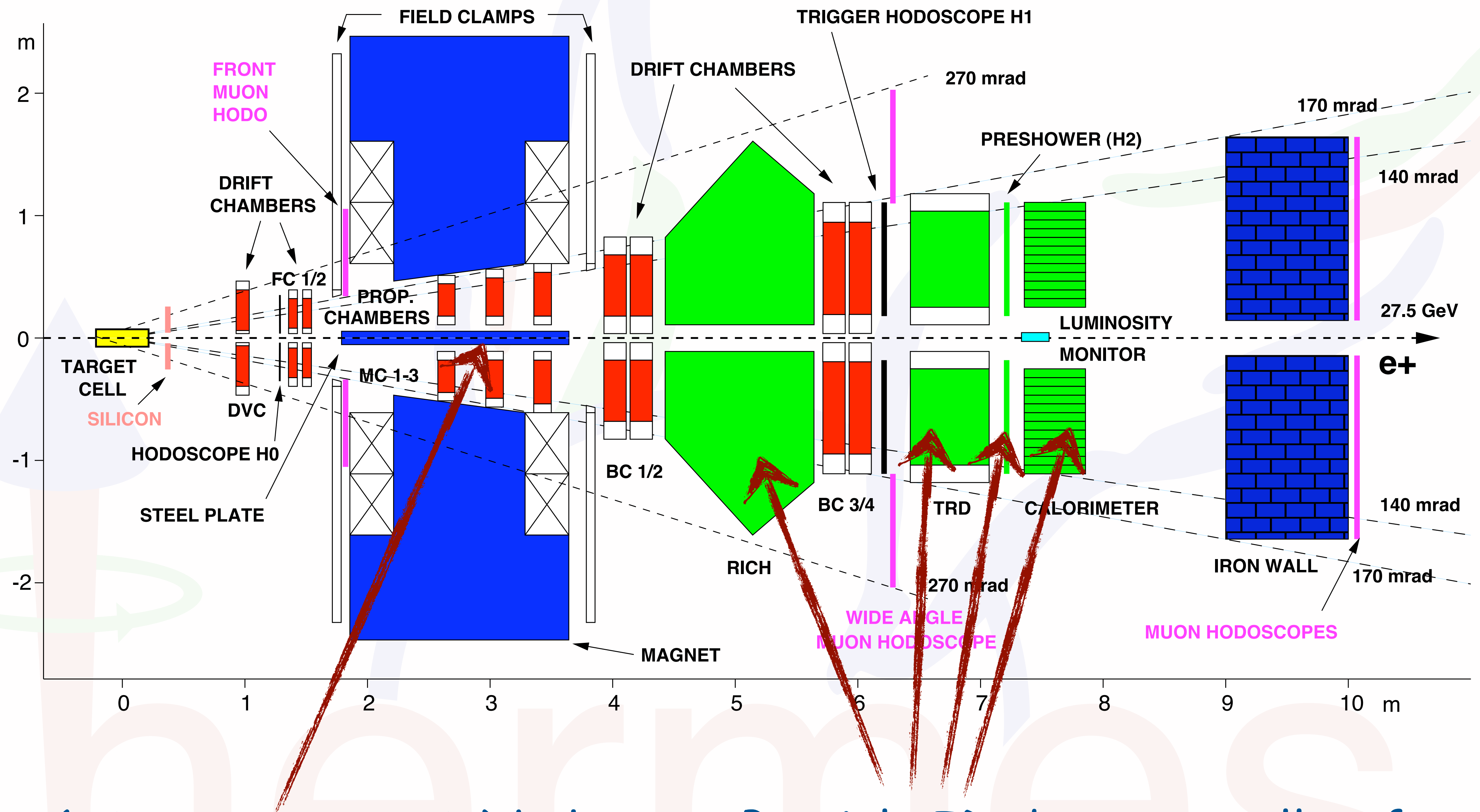
bilinear ("DVCS") or linear ("I") in GPDs

HERMES (1998-2005) schematically



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

HERMES (1998-2005) schematically



two (mirror-symmetric) halves
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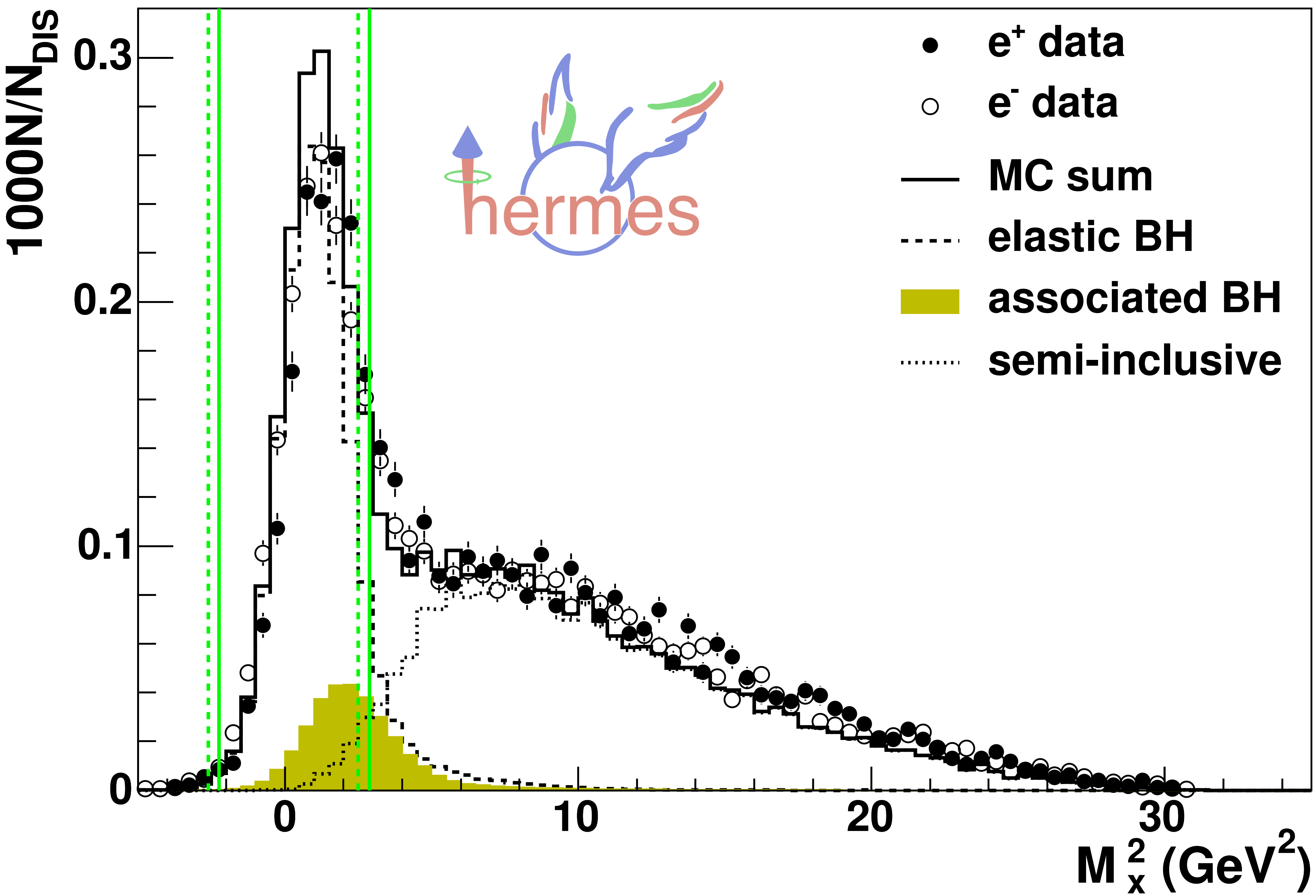
coverage

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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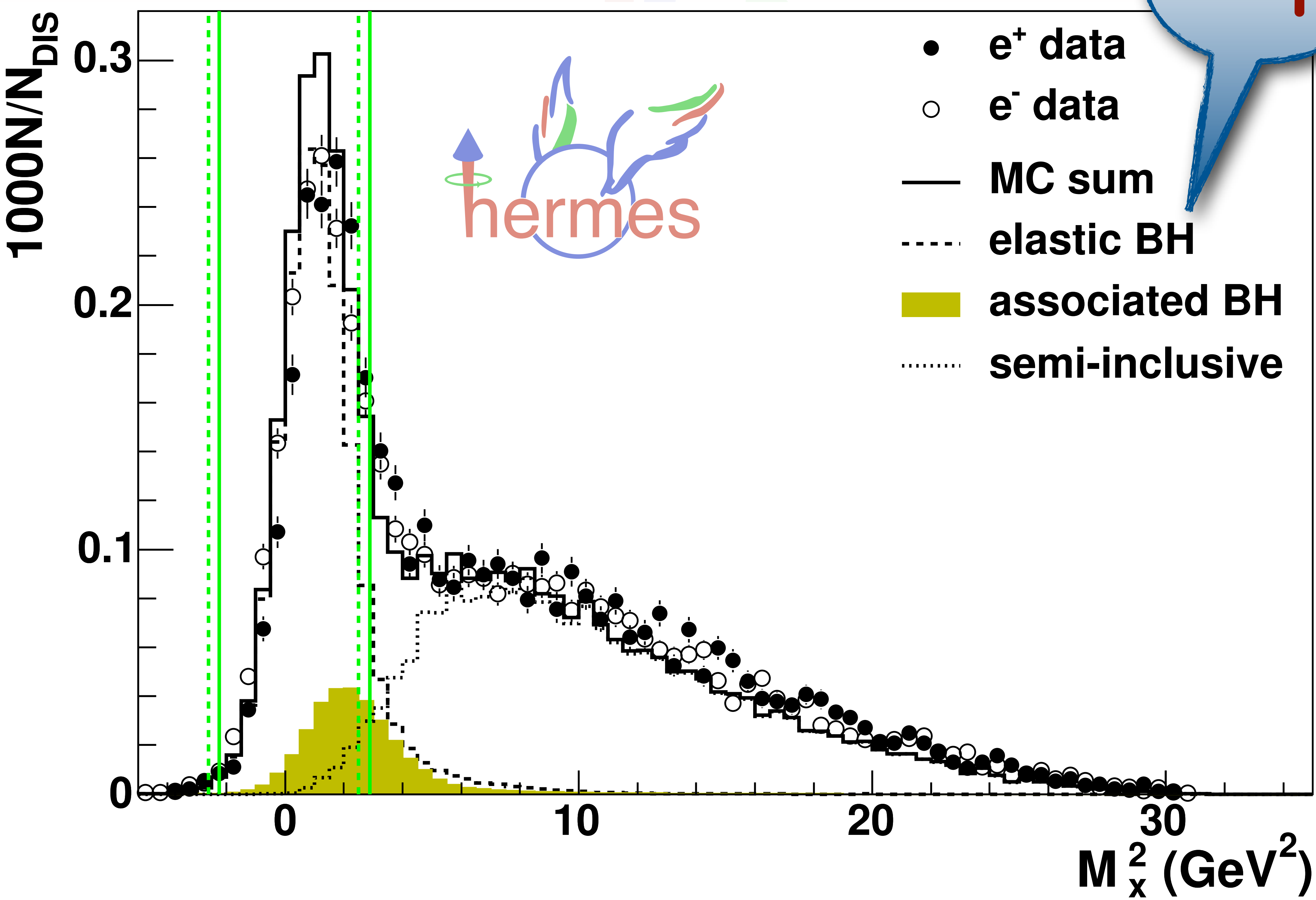
X=p



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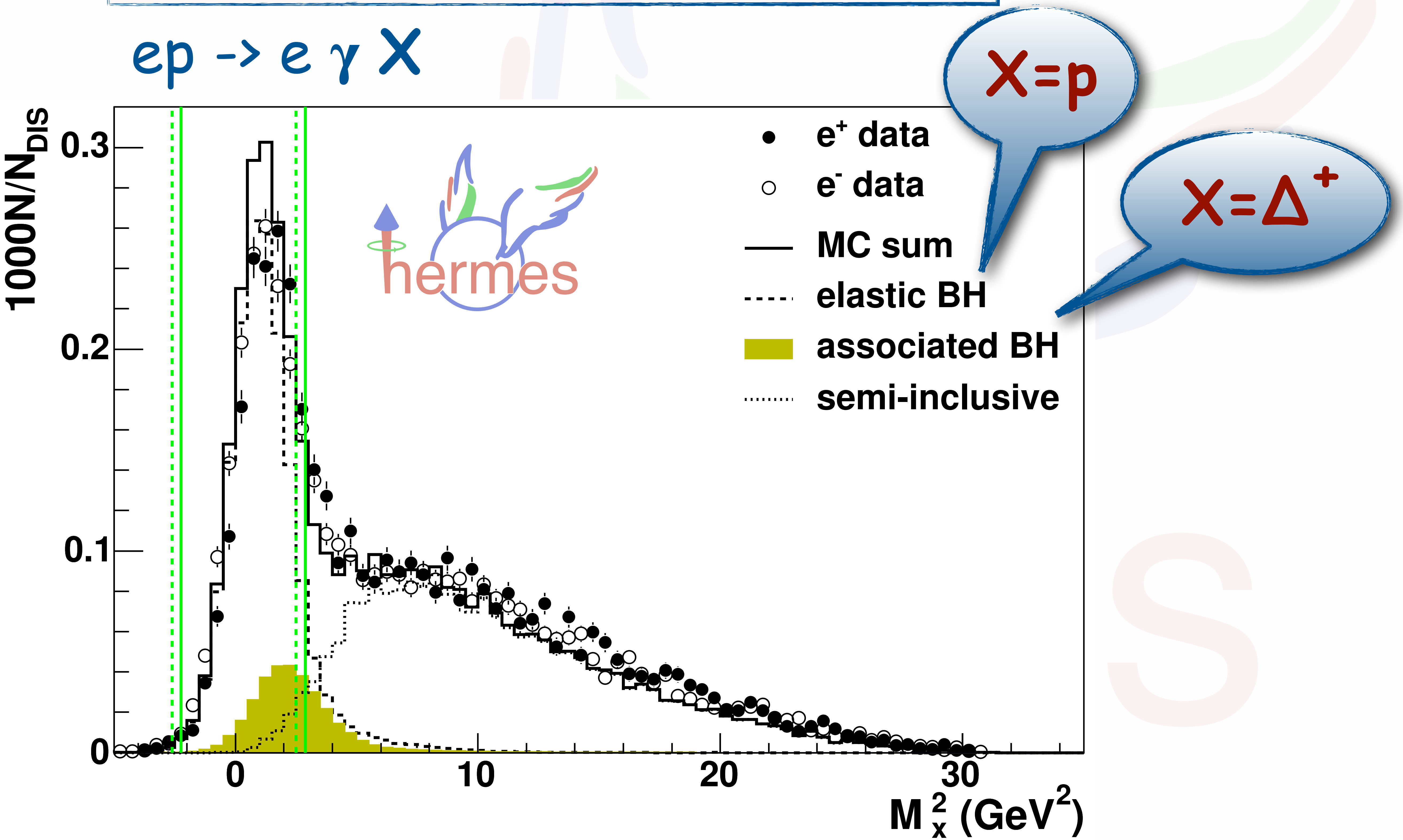

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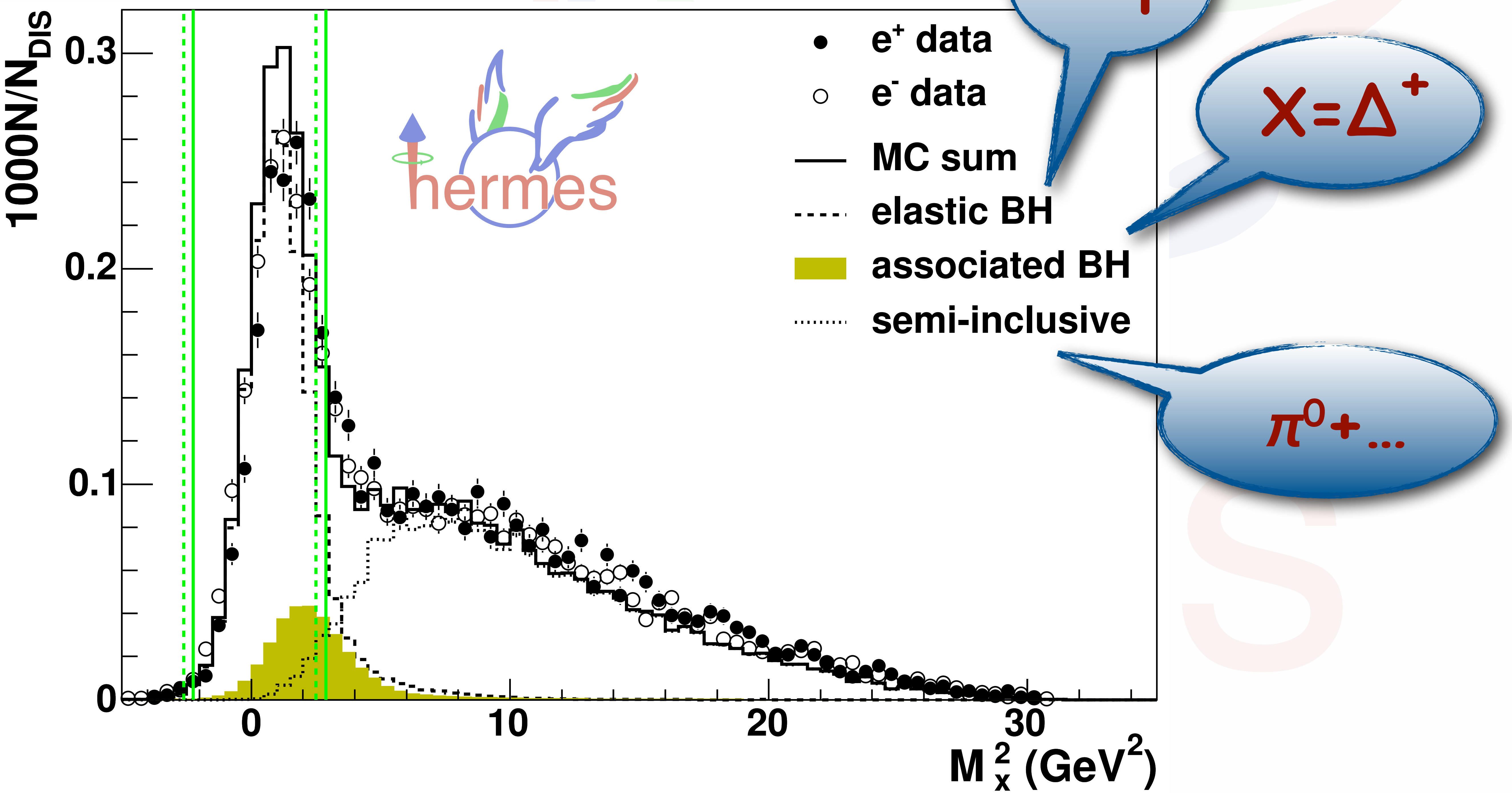
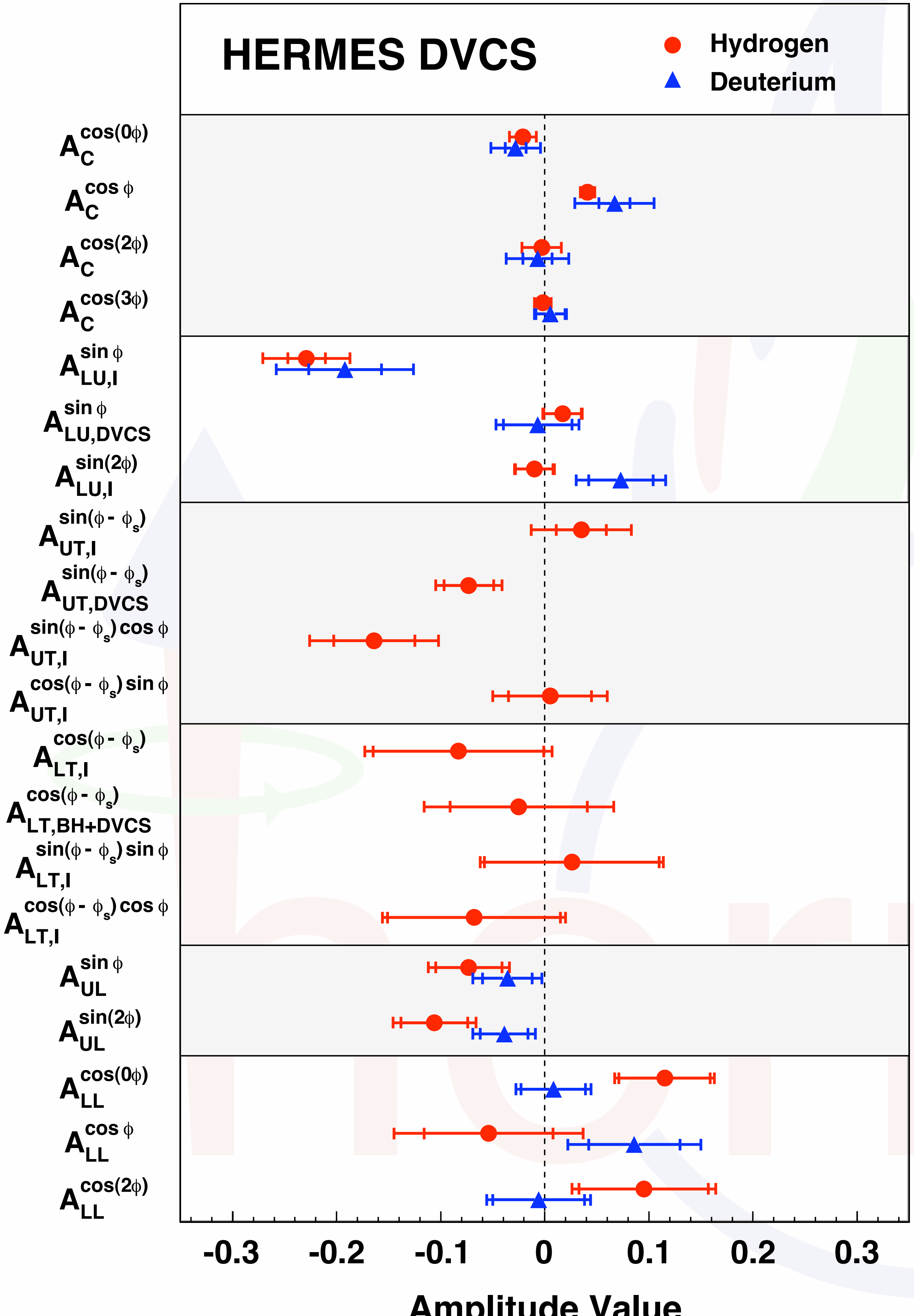


A wealth of azimuthal amplitudes



Beam-charge asymmetry:

GPD H

PRD 75 (2007) 011103
NPB 829 (2010) 1
JHEP 11 (2009) 083
PRC 81 (2010) 035202
PRL 87 (2001) 182001
JHEP 07 (2012) 032

Beam-helicity asymmetry:

GPD H

Transverse target spin asymmetries:

GPD E from proton target

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

Longitudinal target spin asymmetry:

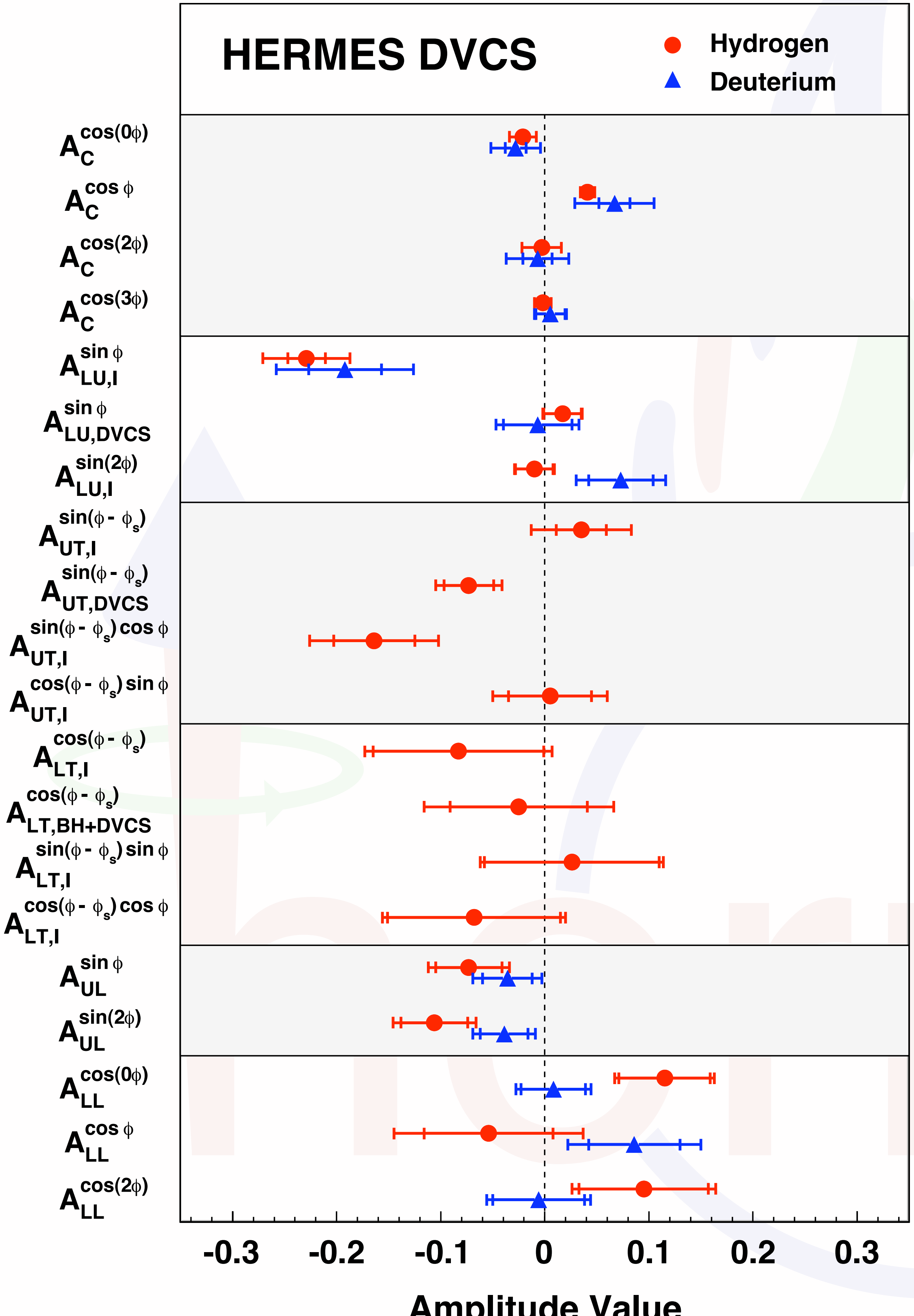
GPD $\tilde{H}$

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

Double-spin asymmetry:

GPD $\tilde{H}$

A wealth of azimuthal amplitudes



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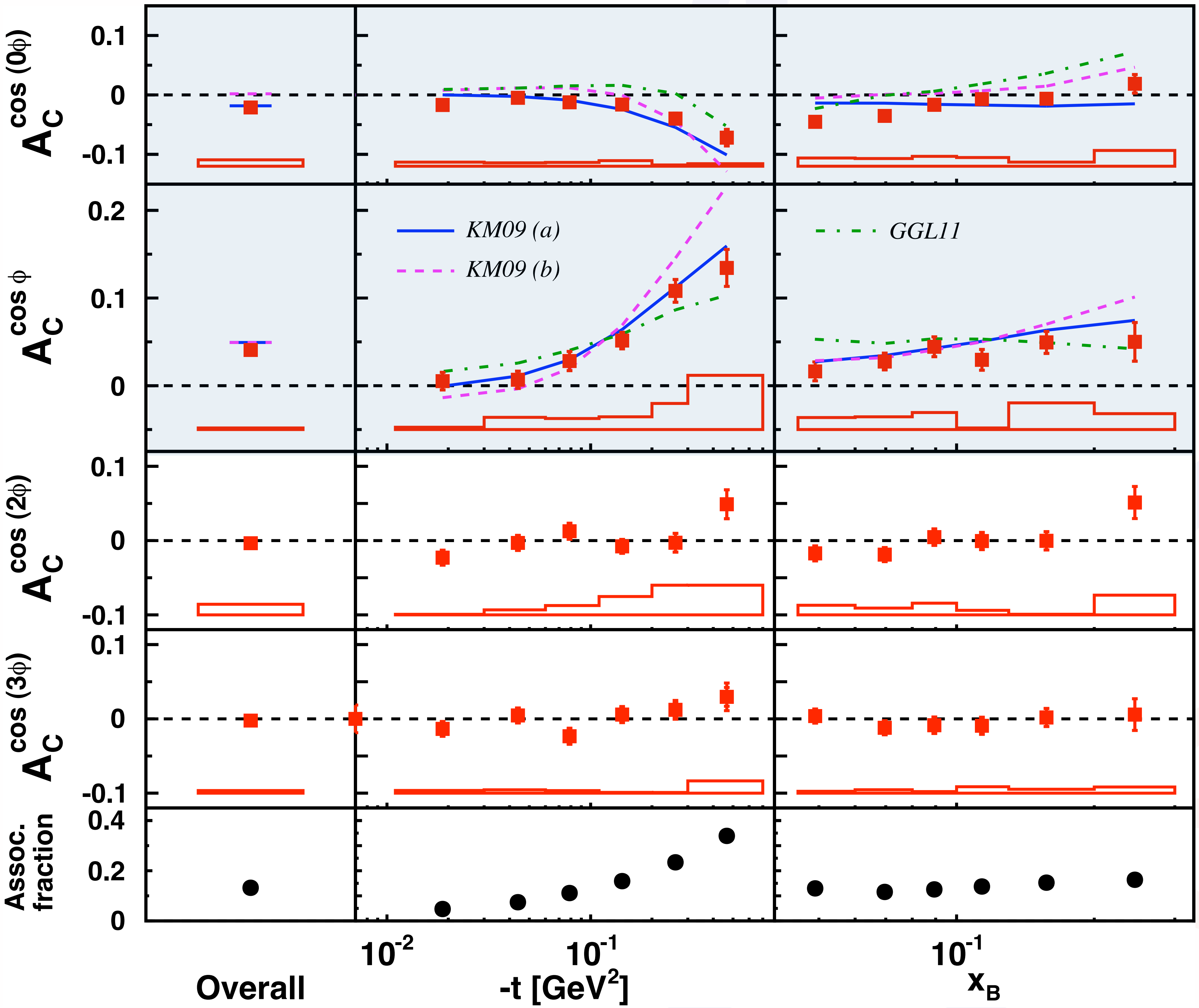
NPB 842 (2011) 265

complete data set!

Beam-charge asymmetry

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



constant term:

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

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

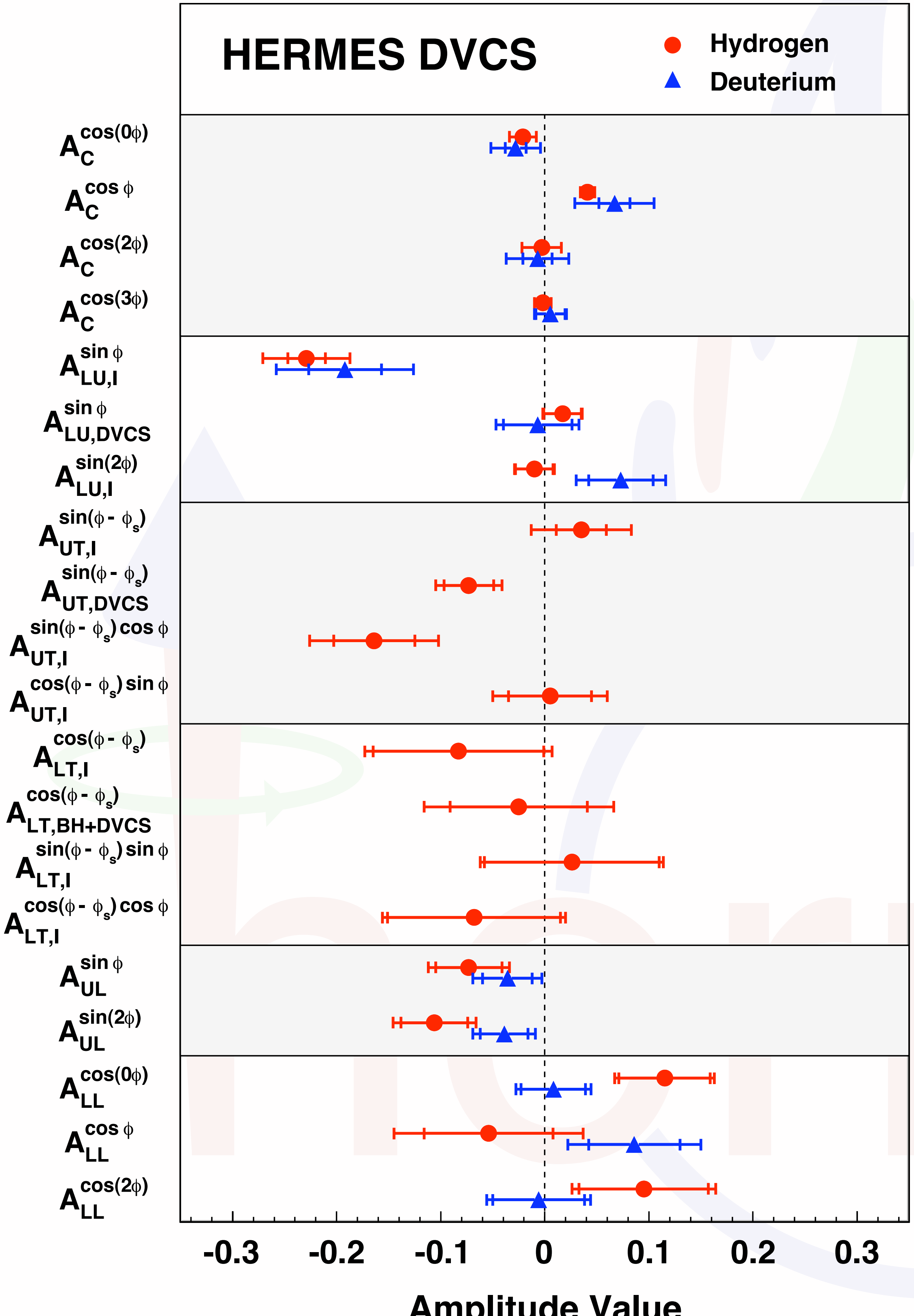
[higher twist]

[gluon leading twist]

Resonant fraction:

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

A wealth of azimuthal amplitudes



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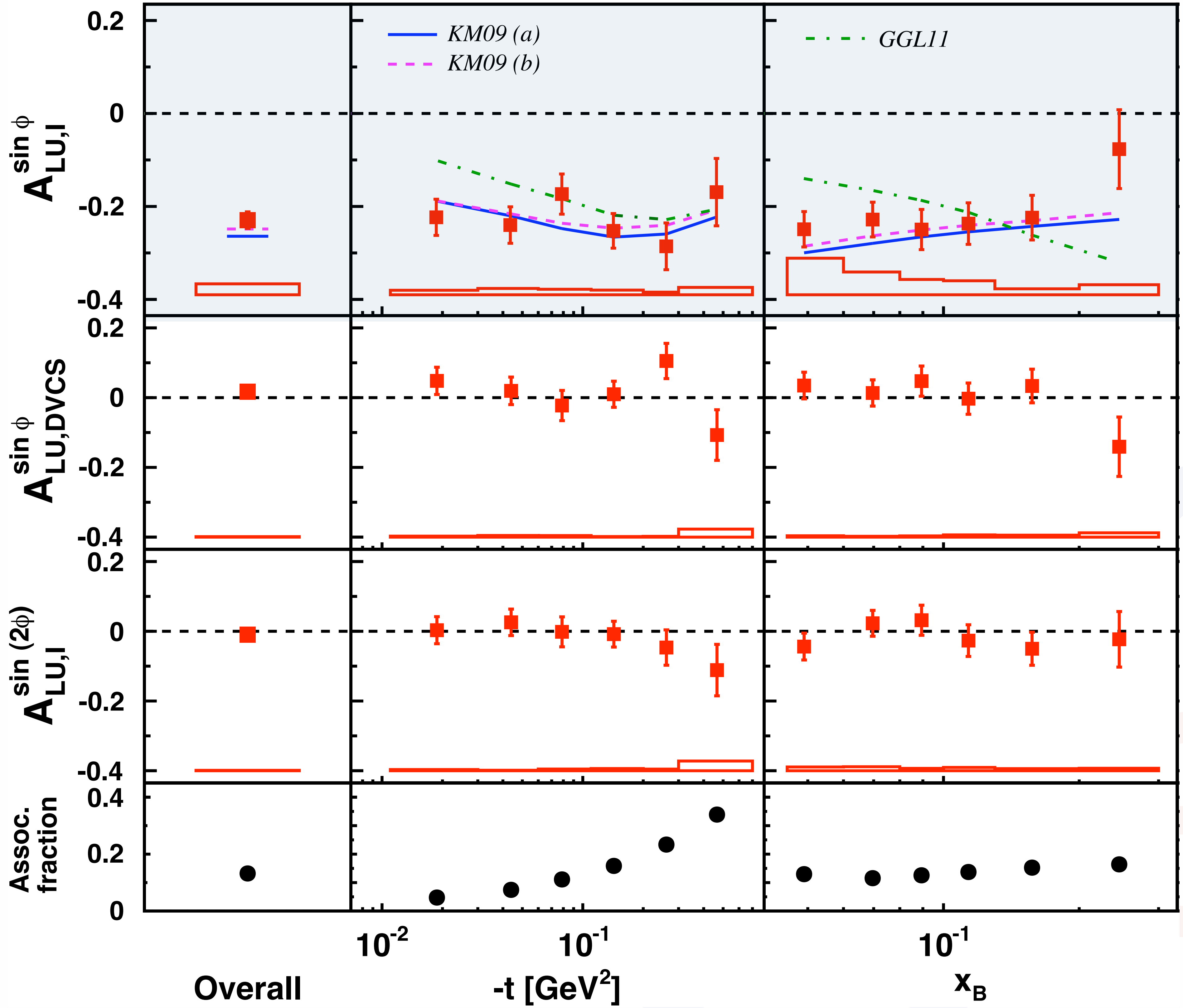
Beam-spin asymmetry

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



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

[higher twist]

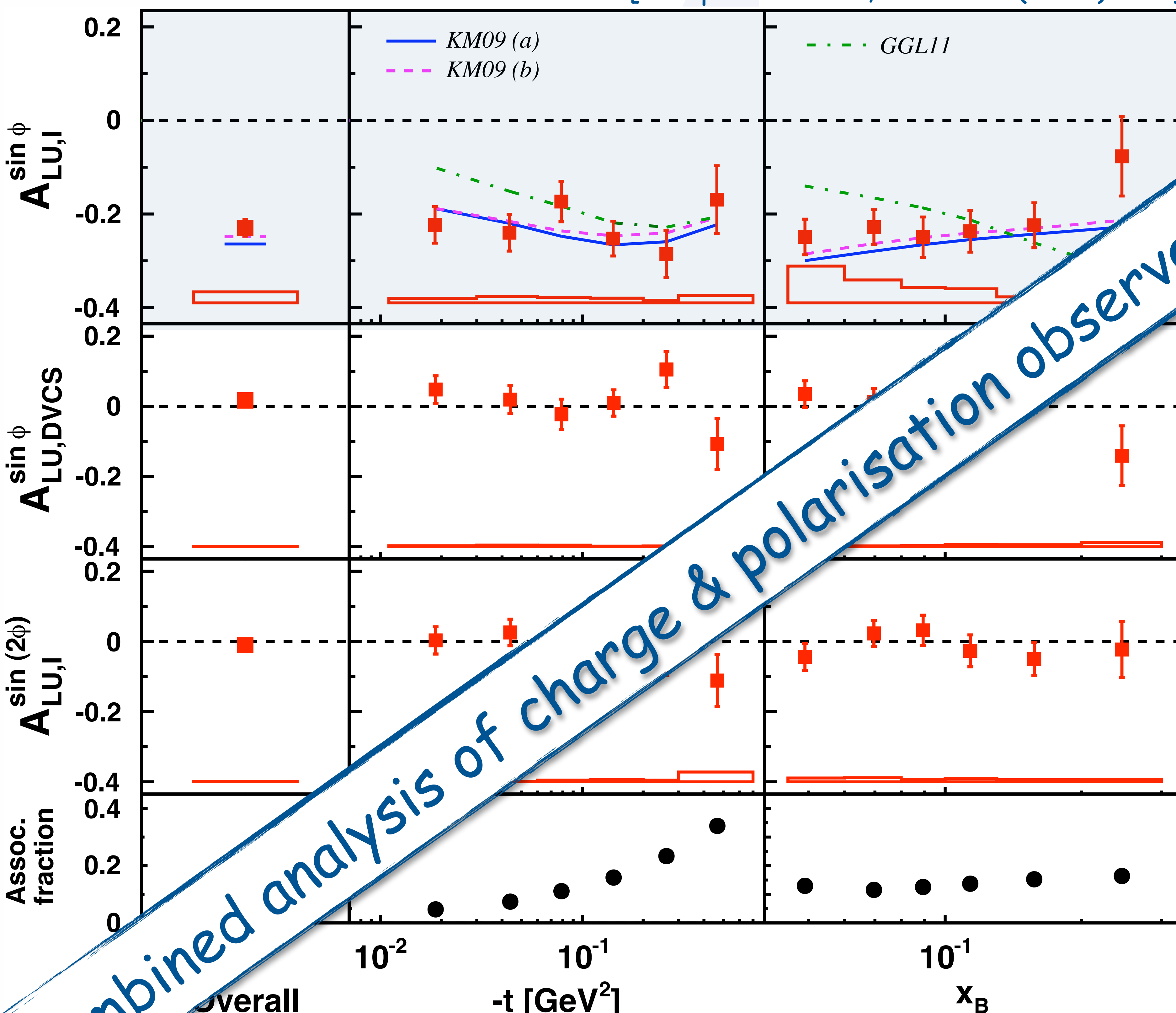
Resonant fraction:

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

complete data set!

Beam-spin asymmet

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



combined analysis of charge & polarisation observables unique to HERA!

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

[higher twist]

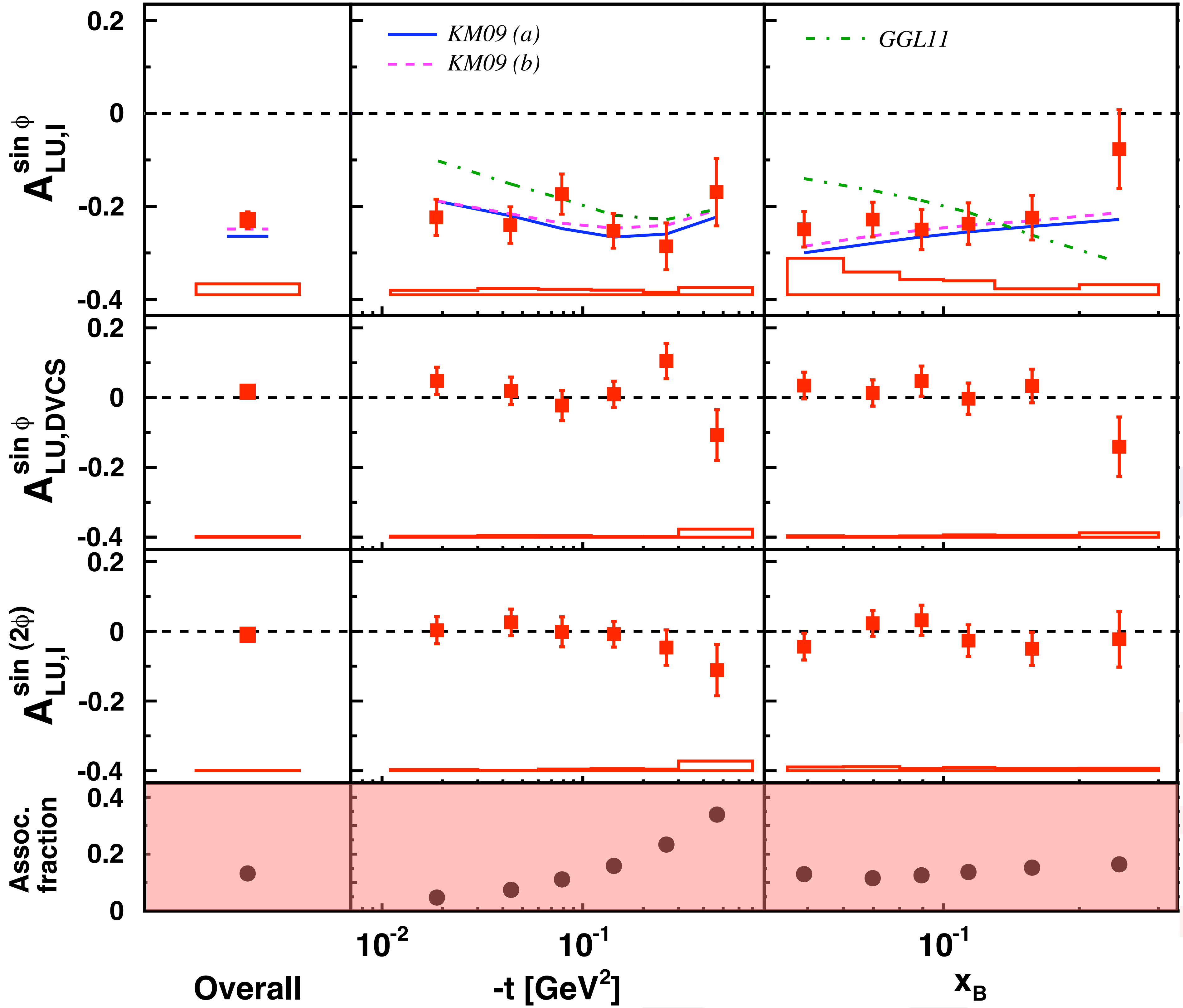
Resonant fraction:

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

complete data set!

Beam-spin asymmetry

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



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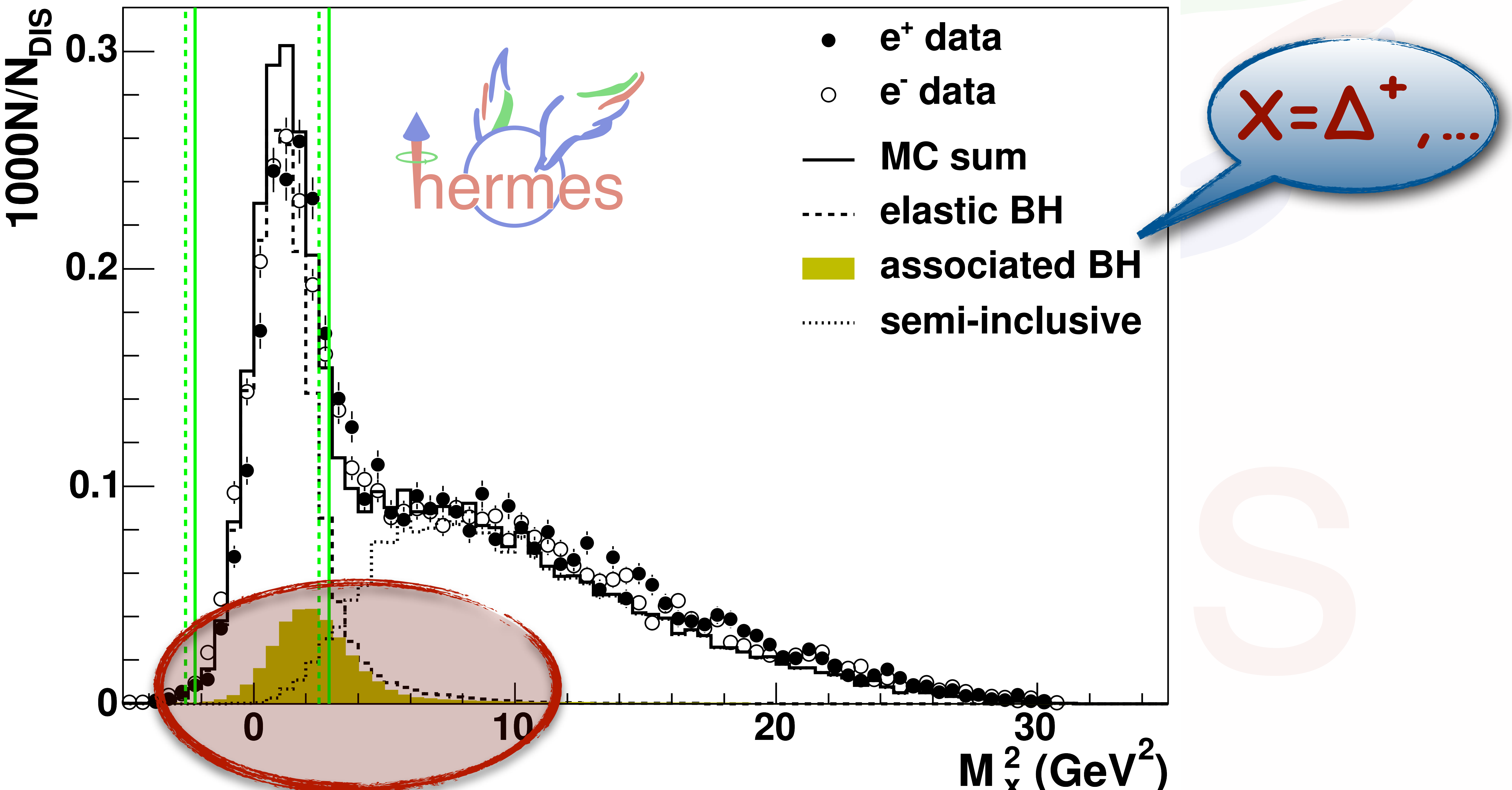
[higher twist]

Resonant fraction:

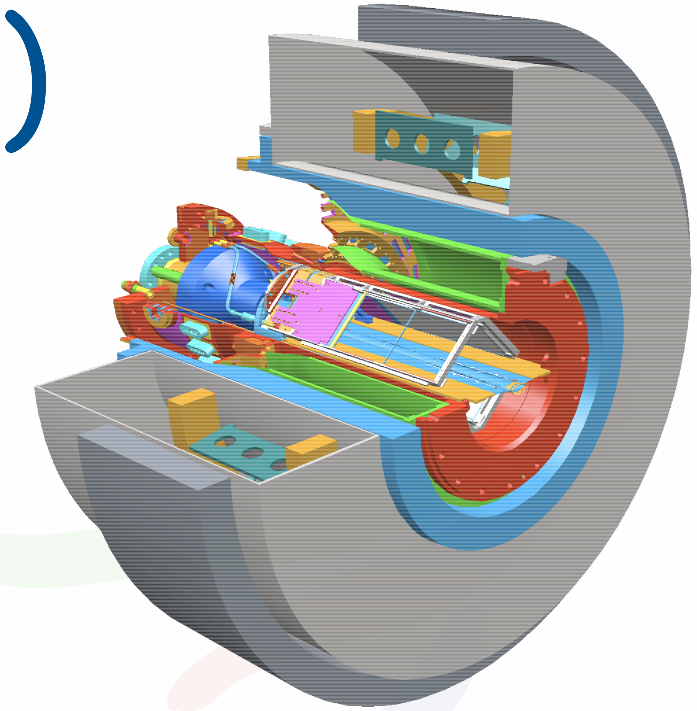
$ep \to e\Delta^+\gamma$

Exclusivity: missing-mass technique

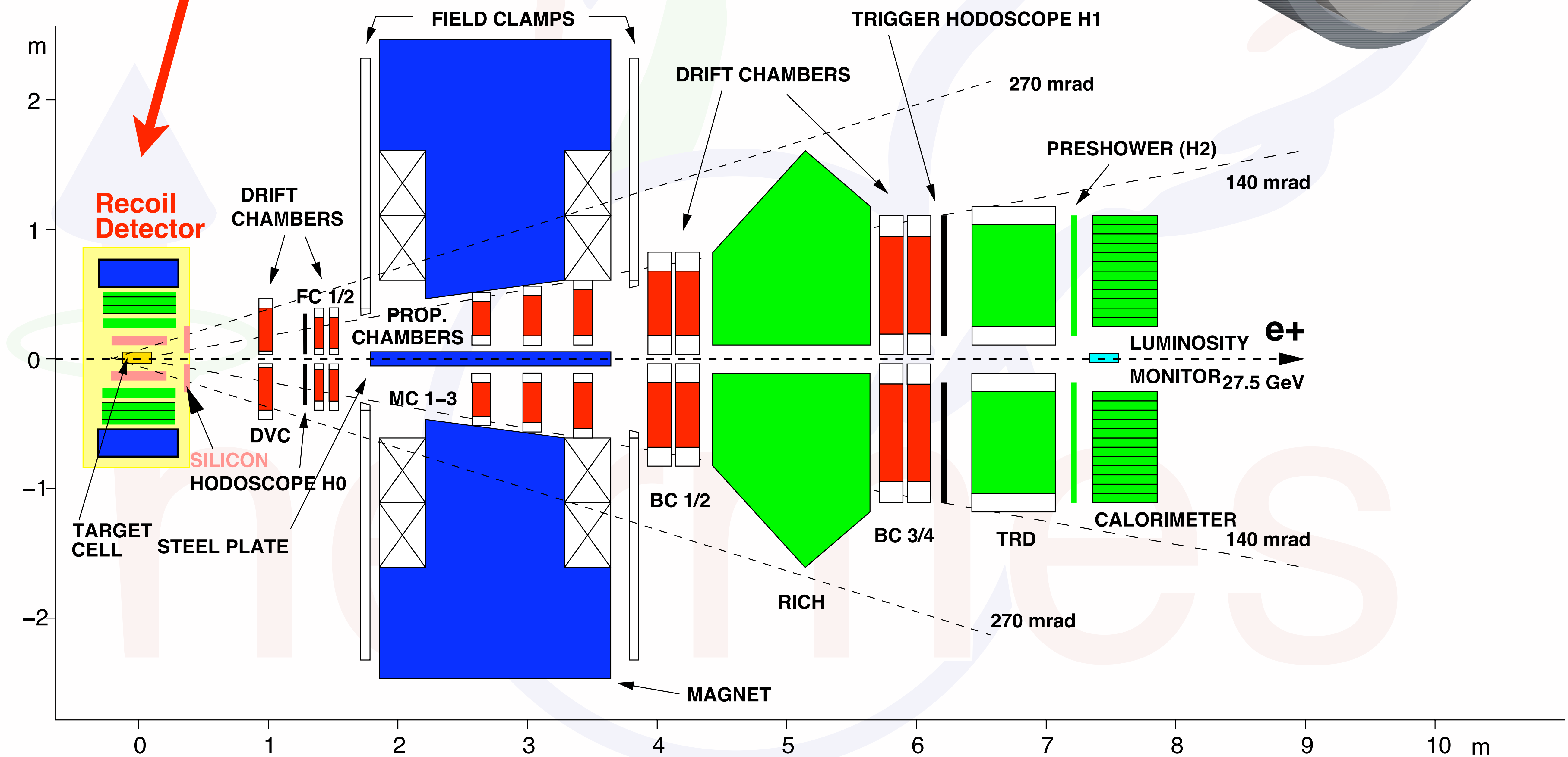
ep -> e γ X



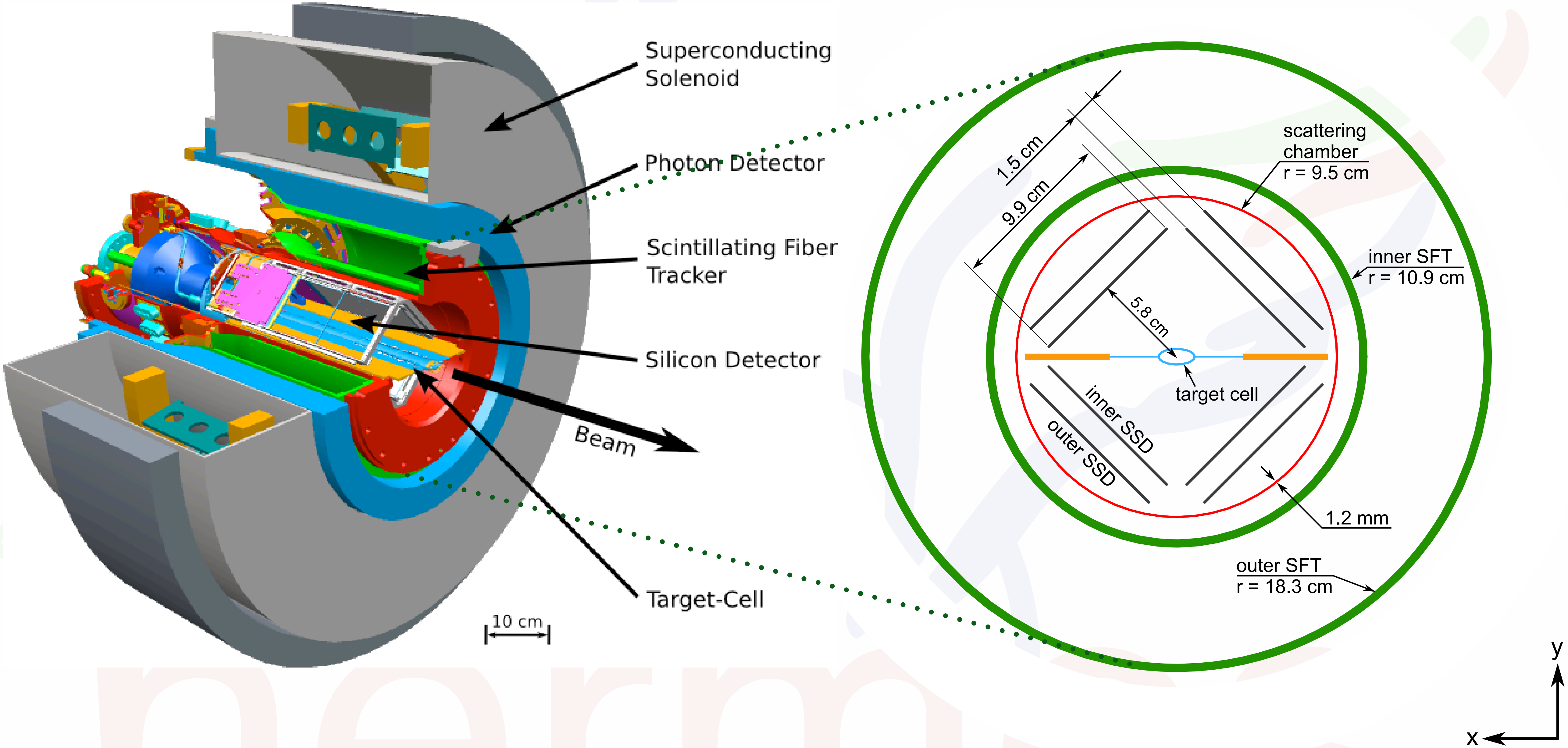
HERMES detector (2006/07)



detection of recoiling proton



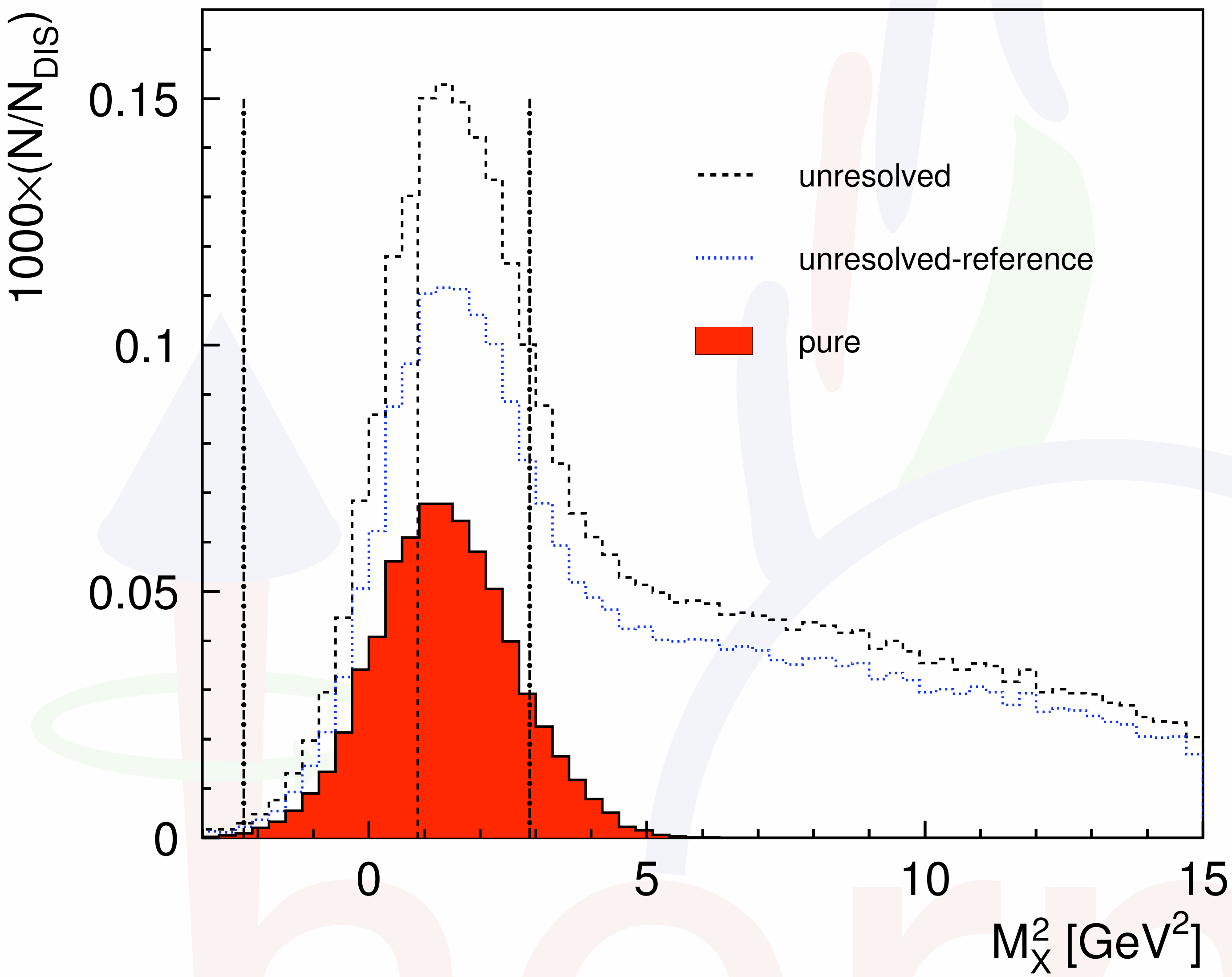
The HERMES Recoil detector

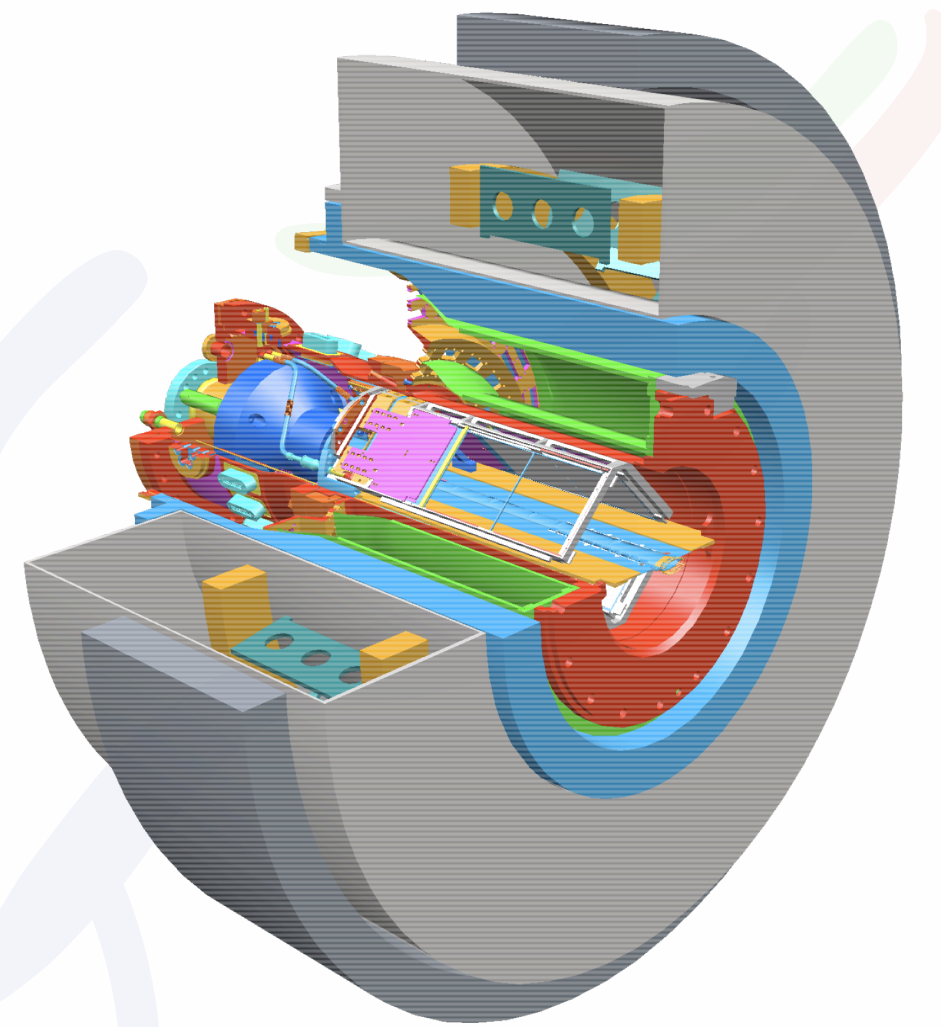


Enables the measurement of the recoiling charged particle and therefore full ep→epγ event reconstruction

HERMES detector (2006/07)

kinematic fitting





- All particles in final state detected → 4 constraints from energy-momentum conservation
- Selection of pure BH/DVCS (ep→ep γ) with **high efficiency** (~83%)
- Allows to suppress background from associated and semi-inclusive processes to a negligible level (<0.2%)

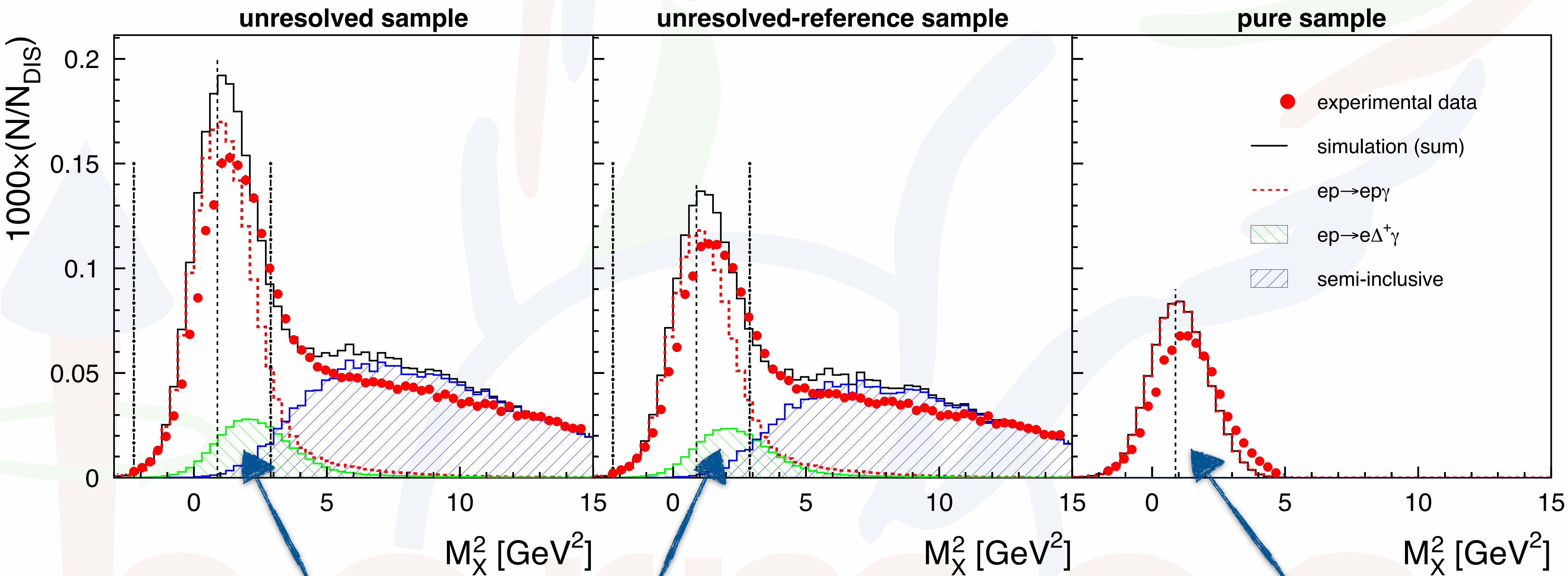
Exclusivity with recoil detector

forward spectrometer only

similar background

measured proton

same kinematic acceptance



associated processes (ep→e γ Δ^+)

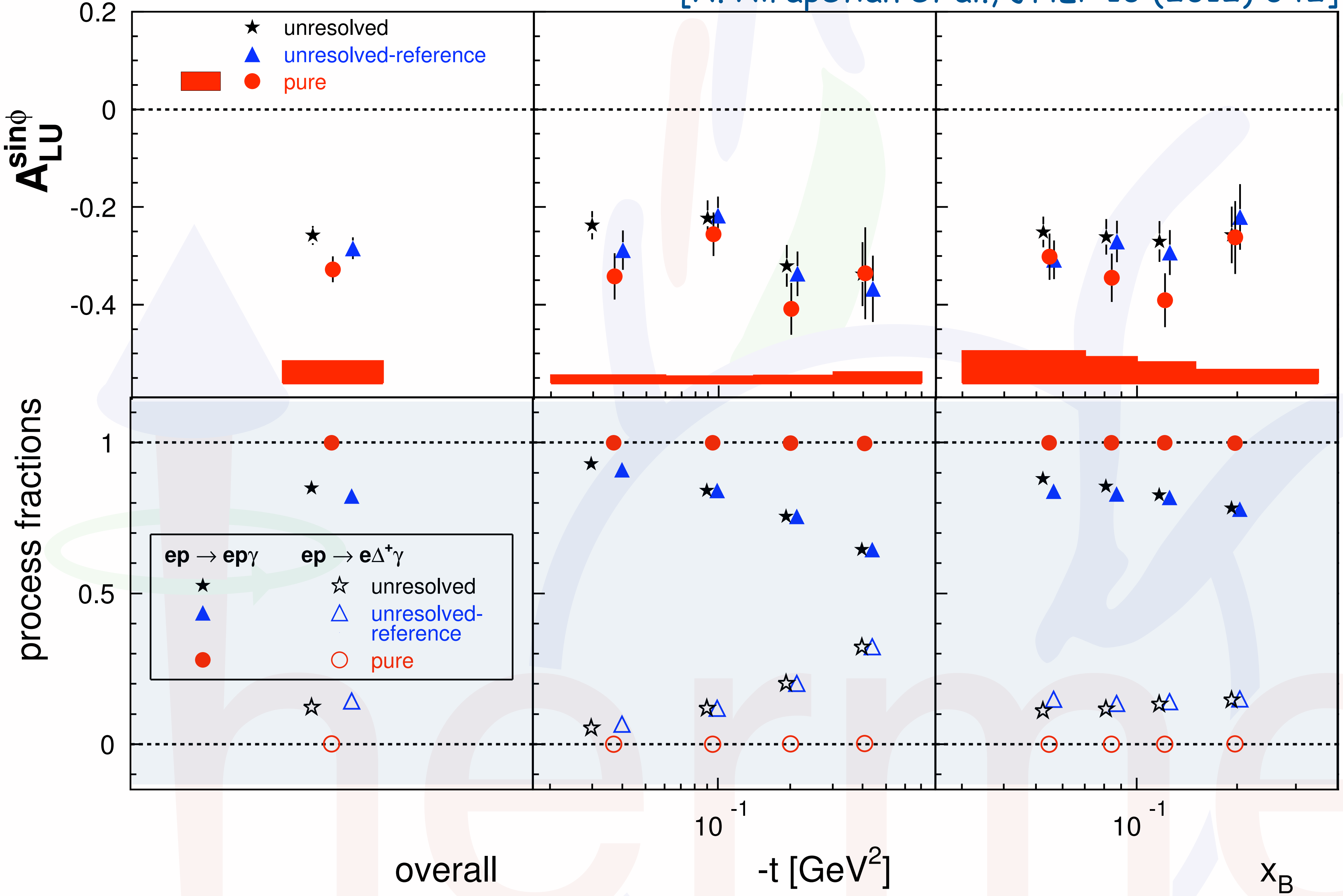
pure ep→e γ p

Missing mass:

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

Single-charge BSA with recoil proton

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

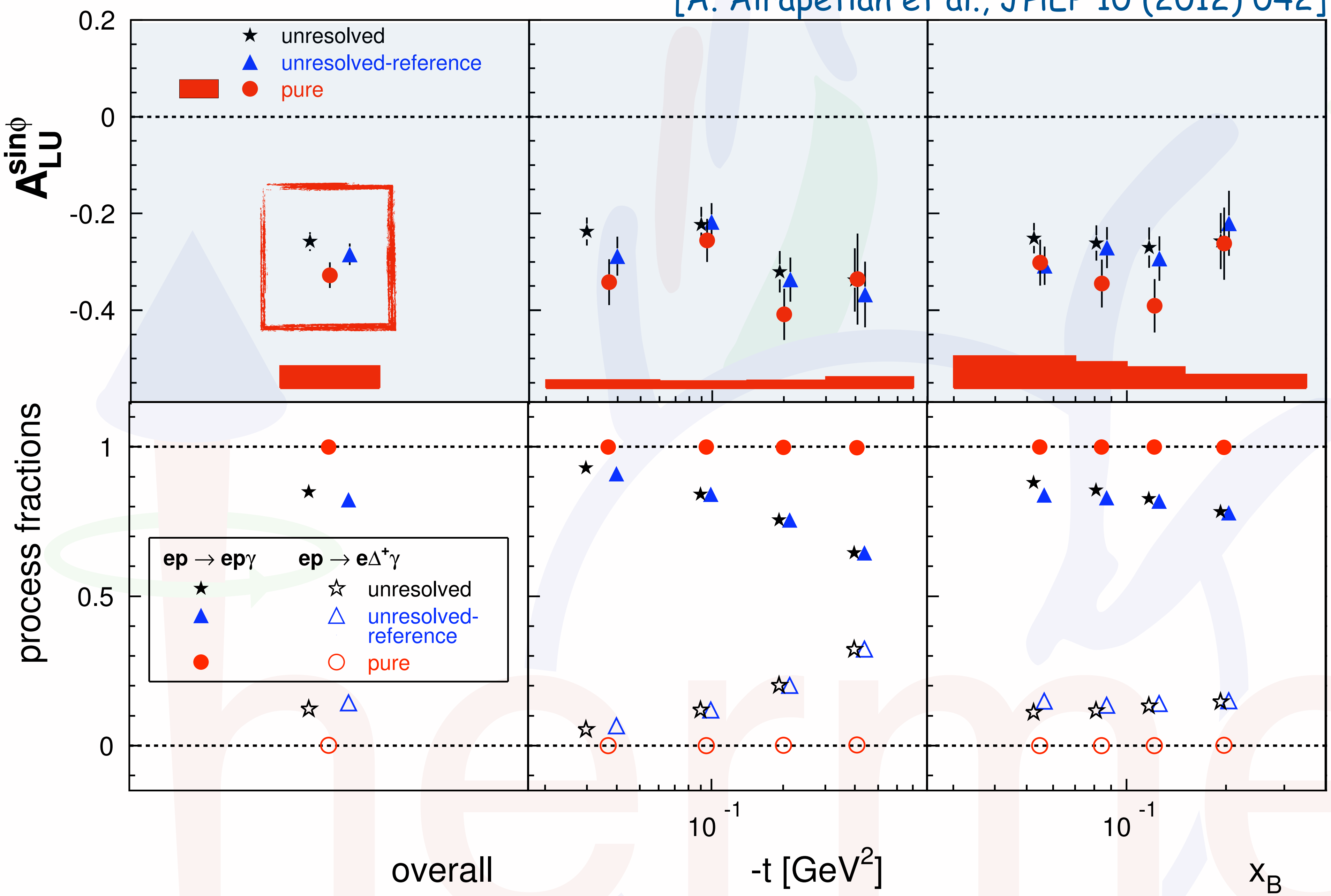


basically **no contamination**

-> 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

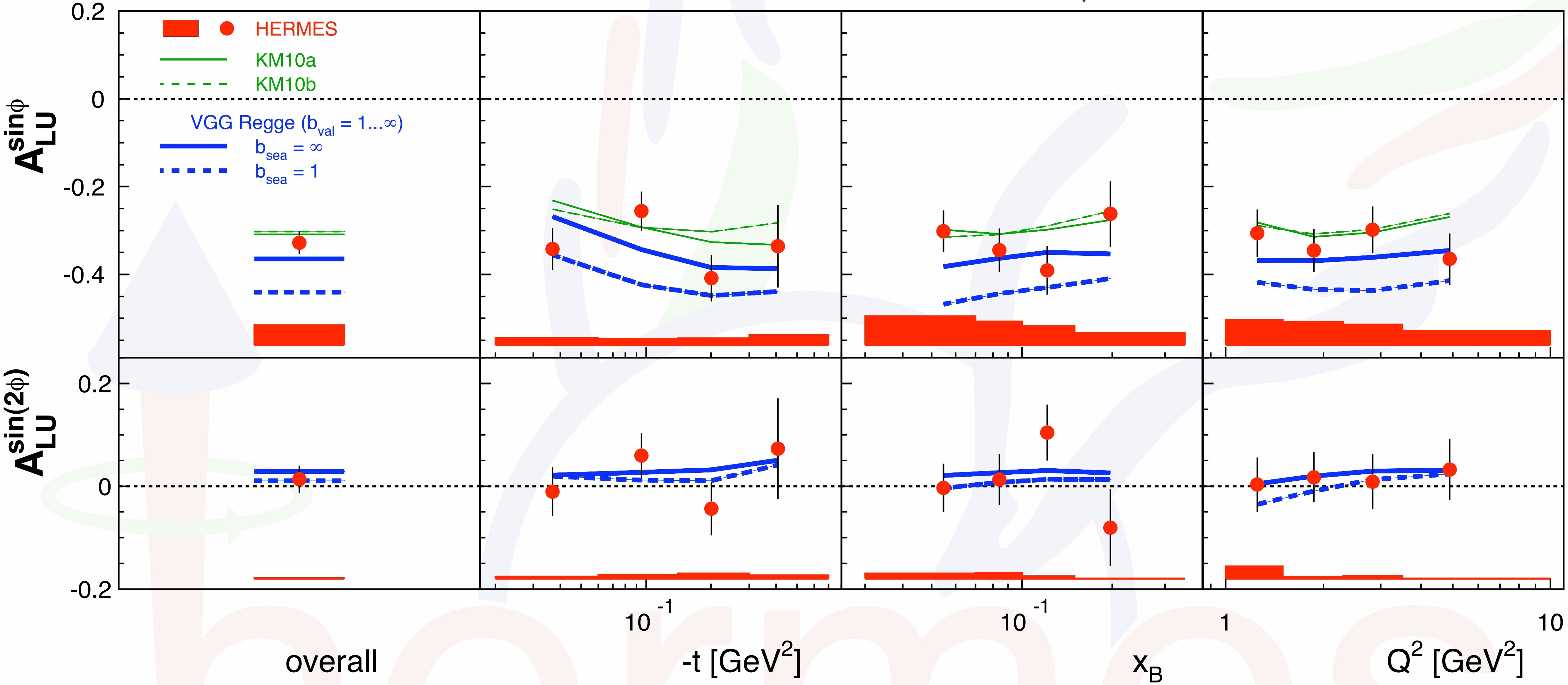
(-> assoc. in traditional analysis mainly dilution)

basically **no contamination**

-> clear interpretation

Single-charge BSA with recoil proton

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



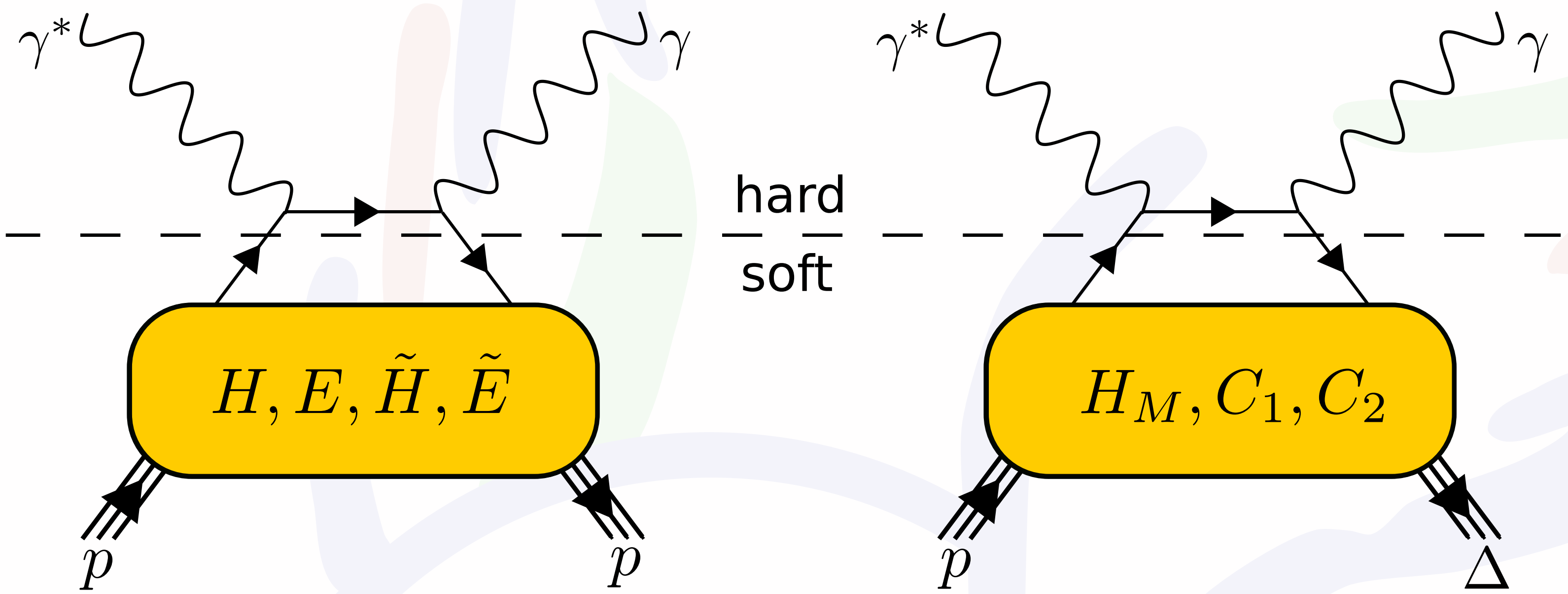
good agreement with models

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.

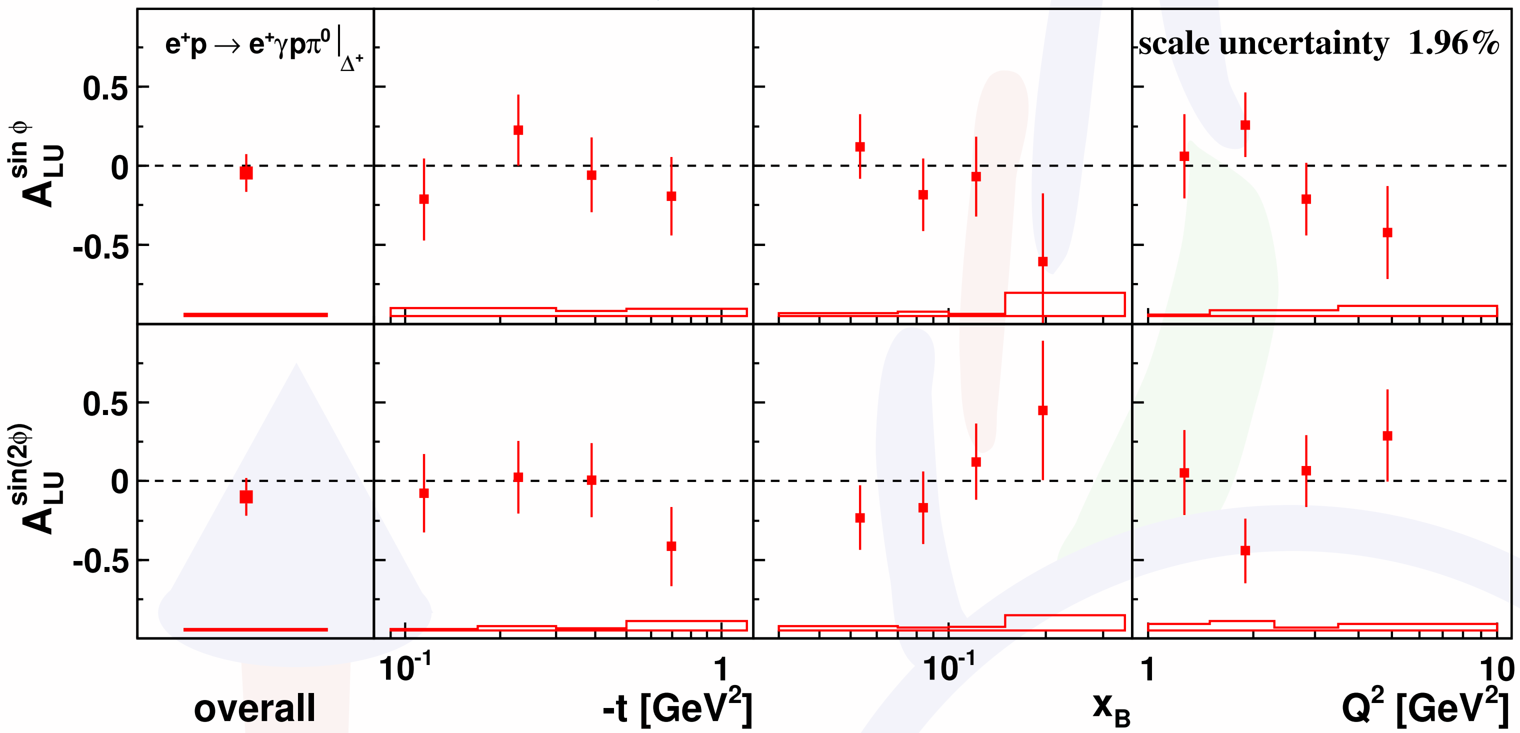


In the large-N$_c$ limit the remaining N→Δ GPDs can be related to the N→N iso-vector GPDs:

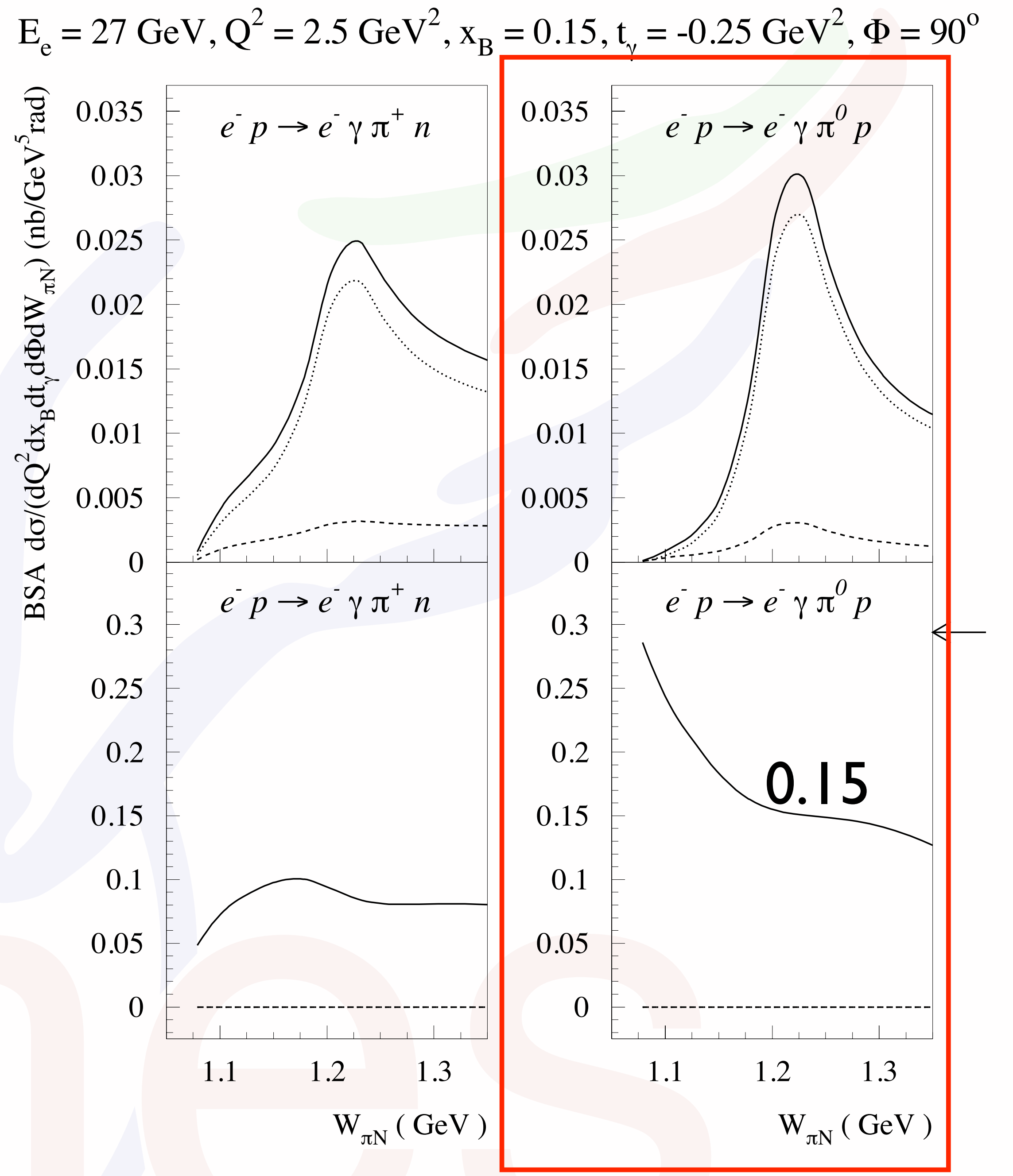
$$\boxed{\begin{aligned} H_M(x,\xi,t) &= \frac{2}{\sqrt{3}}\left[E^u(x,\xi,t) - E^d(x,\xi,t)\right], \\ C_1(x,\xi,t) &= \sqrt{3}\left[\tilde{H}^u(x,\xi,t) - \tilde{H}^d(x,\xi,t)\right], \\ C_2(x,\xi,t) &= \frac{\sqrt{3}}{4}\left[\tilde{E}^u(x,\xi,t) - \tilde{E}^d(x,\xi,t)\right] \end{aligned}}$$

Beam-spin asymmetries ep→e γ pπ⁰

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



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



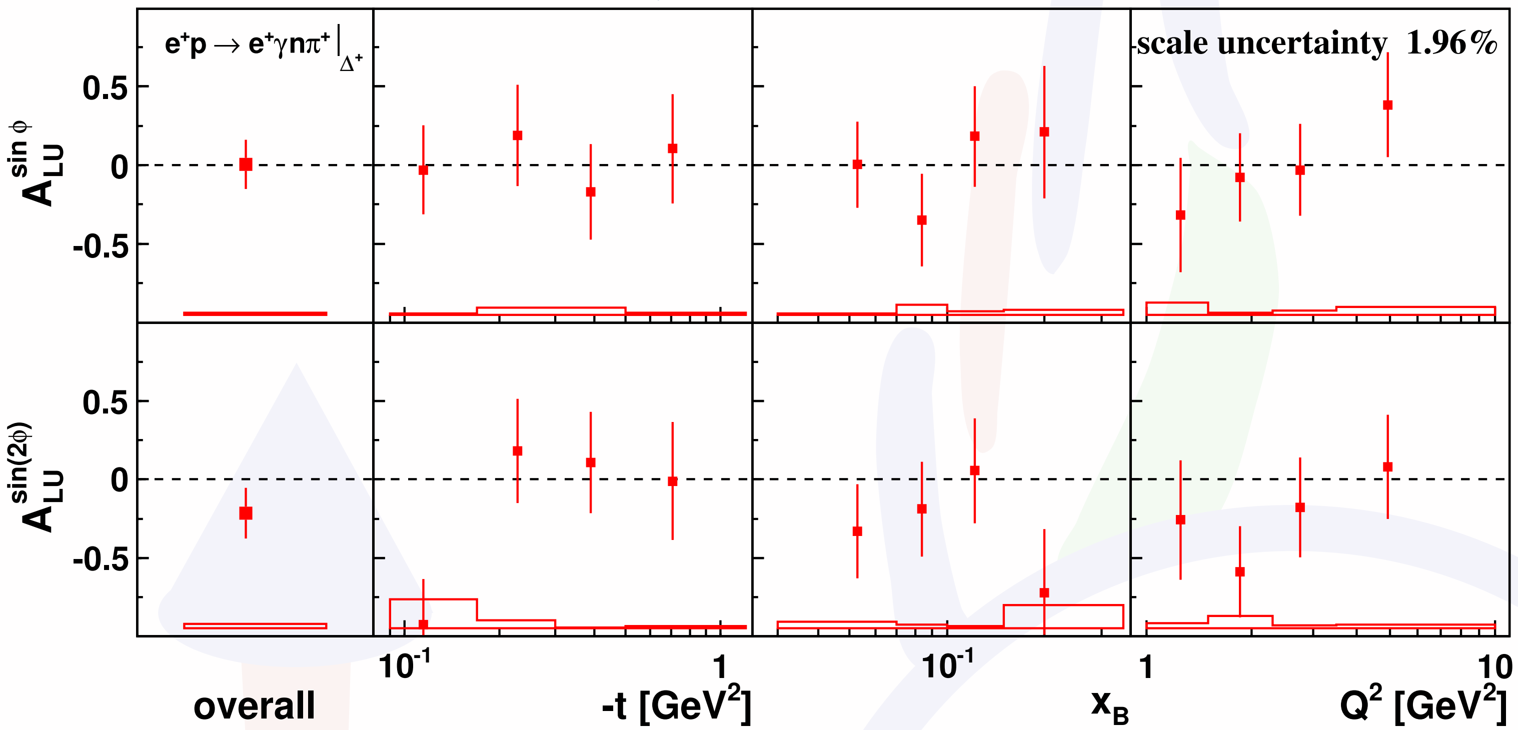
Shown amplitudes corrected for background (only overall fractions are listed here):

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

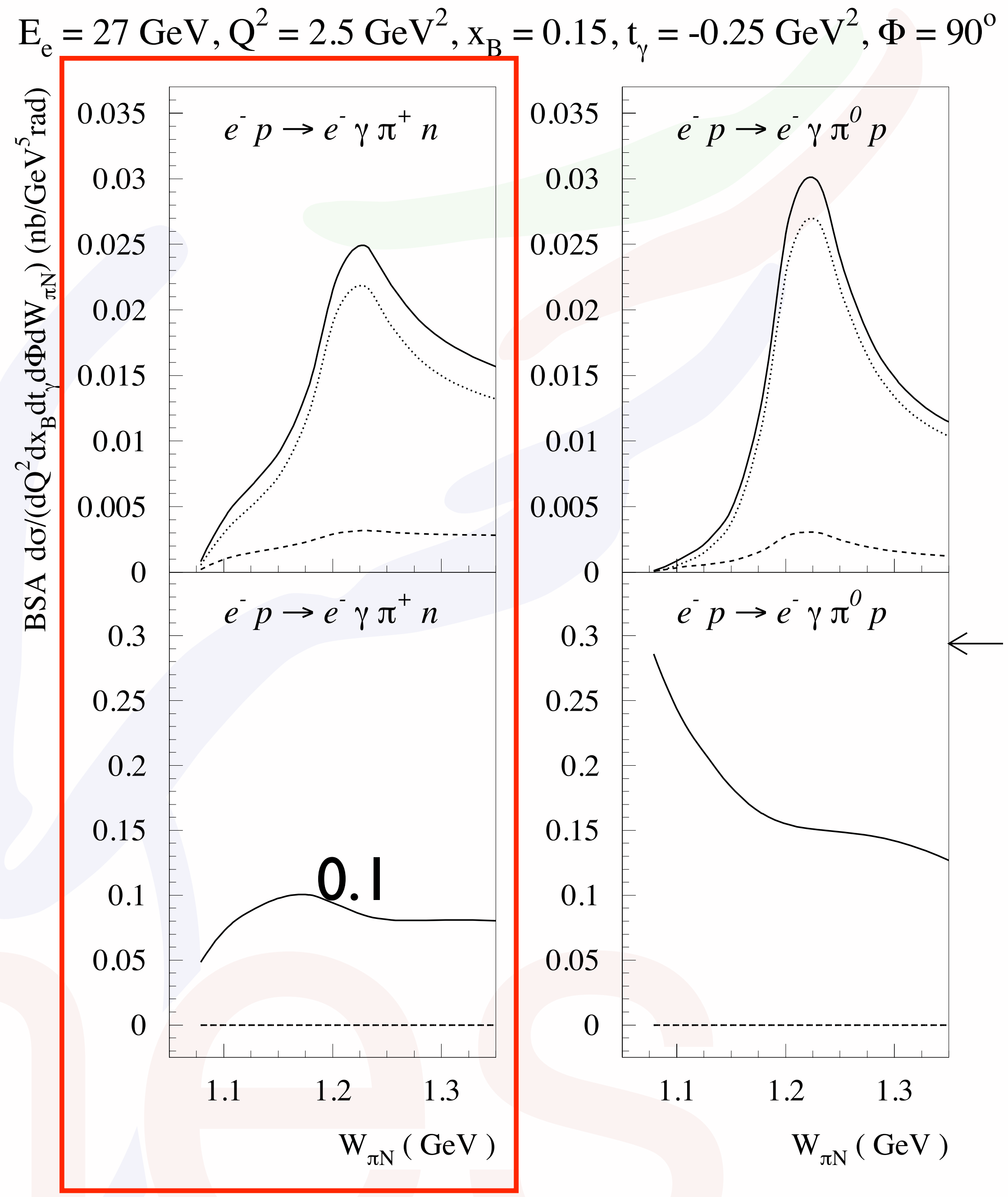
opposite sign conventions!

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

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



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

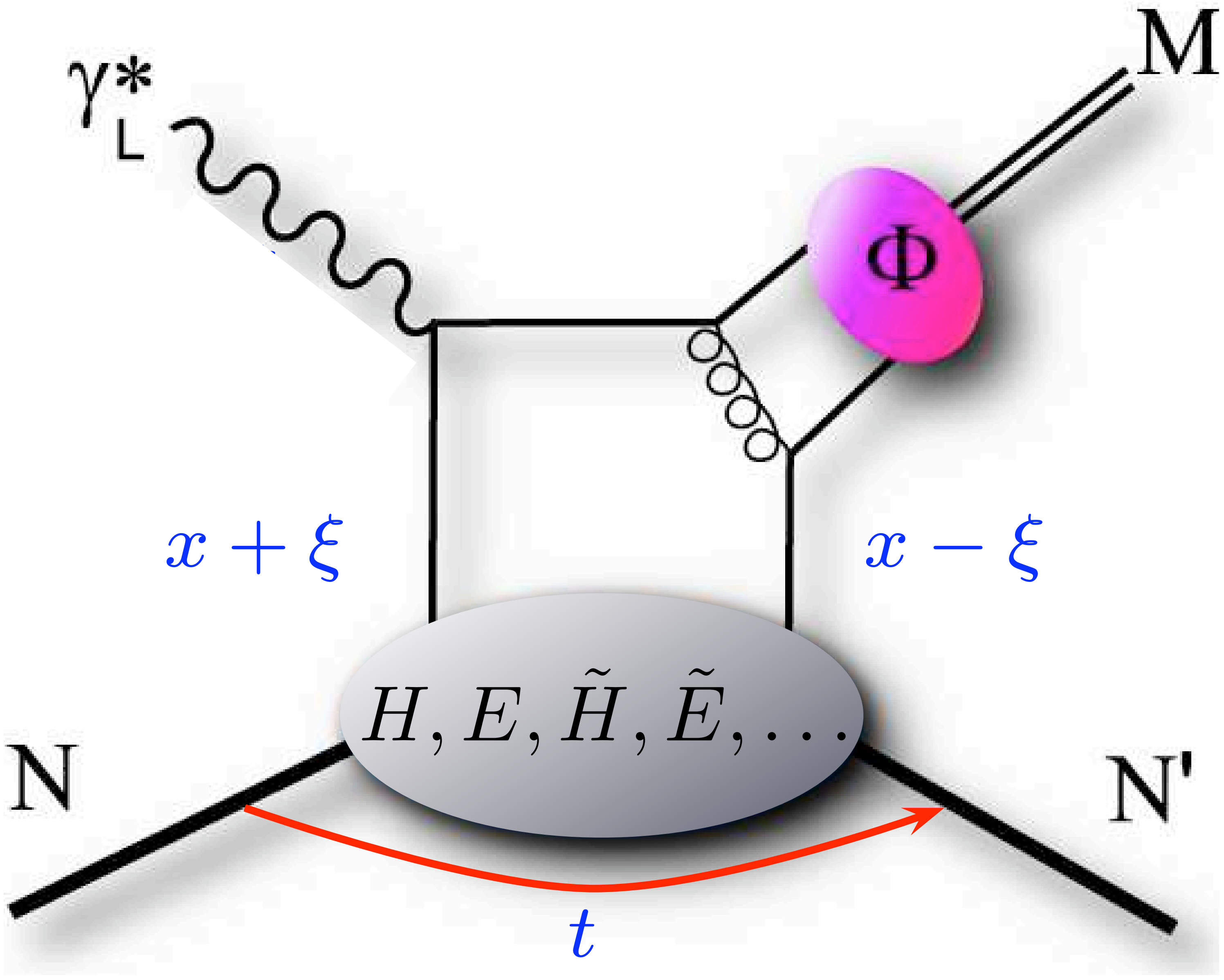


Shown amplitudes corrected for background (only overall fractions are listed here):

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

opposite sign convention!

Exclusive meson production



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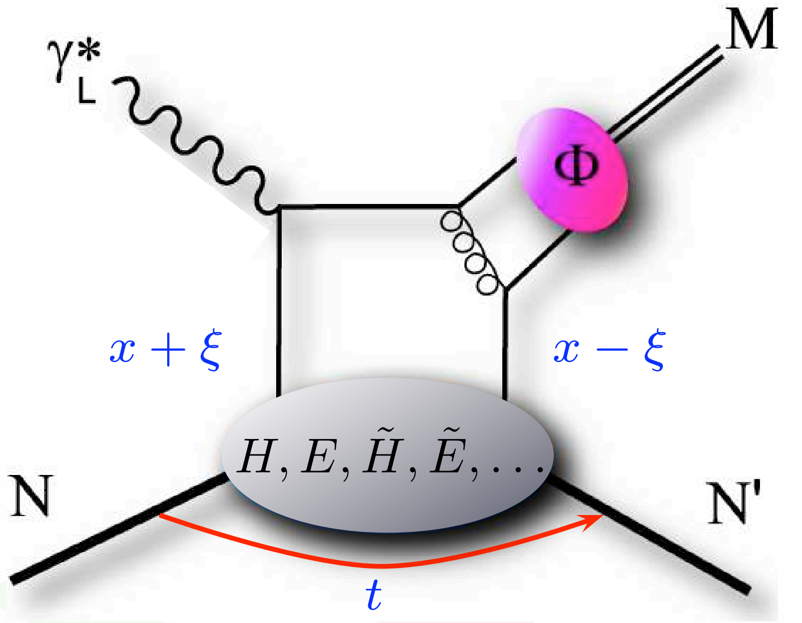
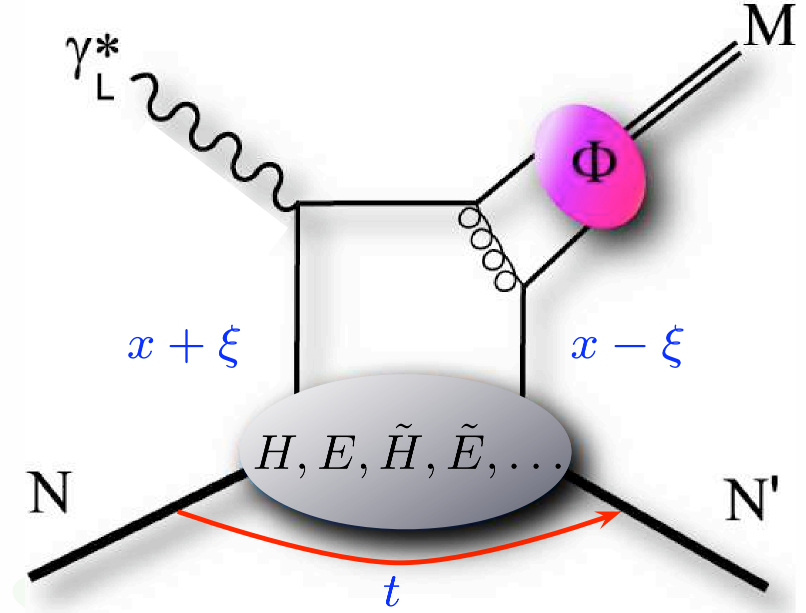


- GPDs convoluted with meson amplitude

Exclusive meson production

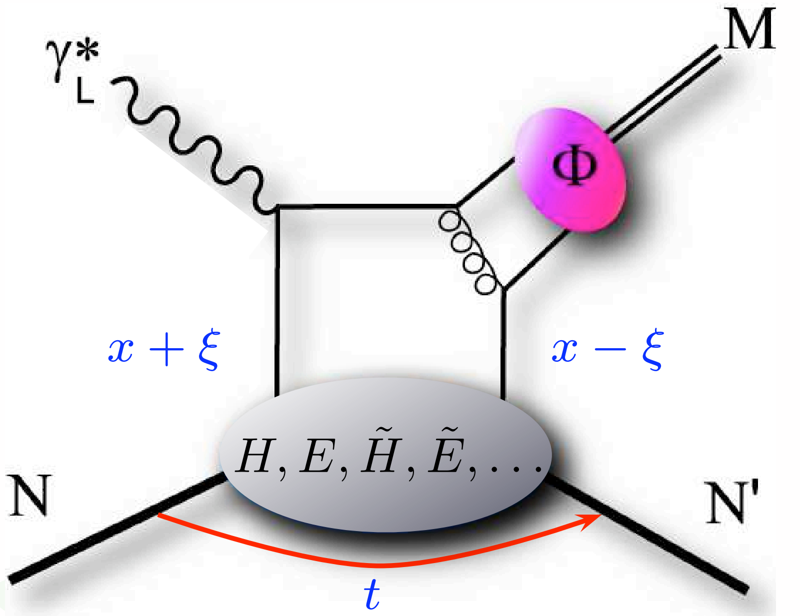


- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations

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

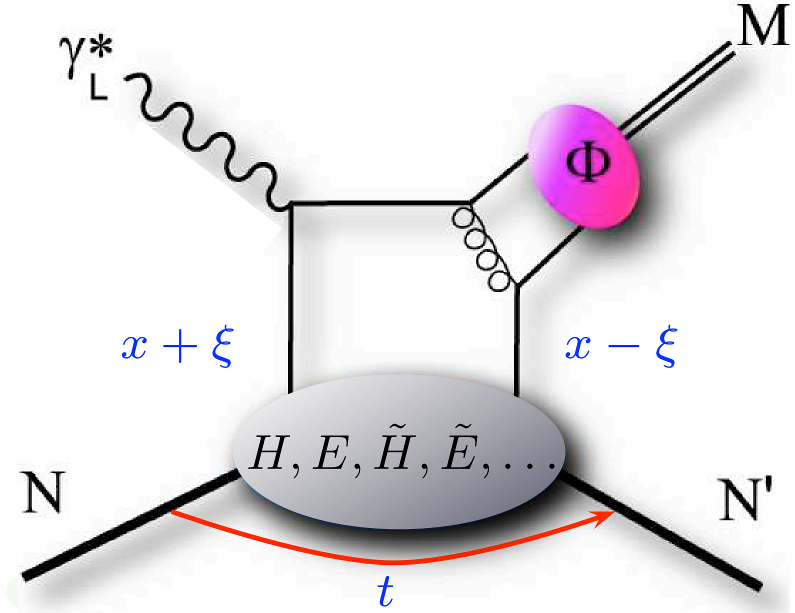
- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
- factorization proven for longitudinal photons



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



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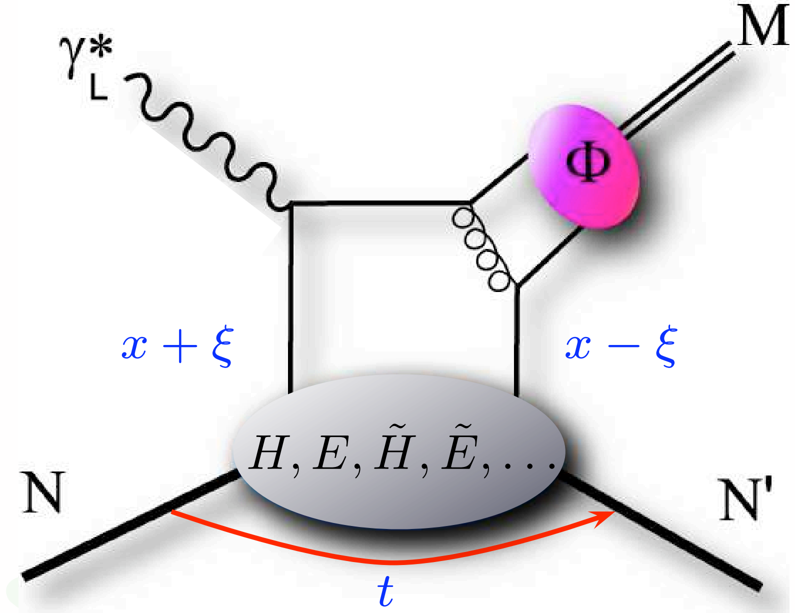

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J/ψ	g

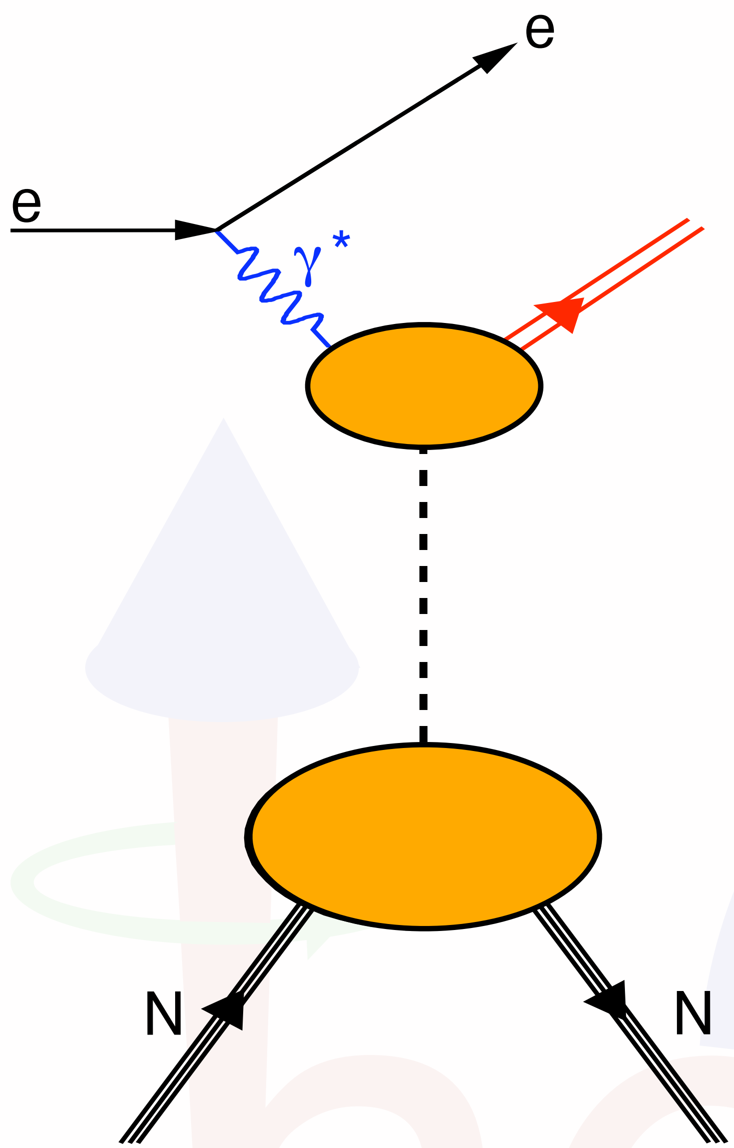
- GPDs convoluted with meson amplitude
- access to various quark-flavor combinations
- factorization proven for longitudinal photons
- generalized to transverse photons in GK model
- vector-meson cross section:

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

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

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

“Regge phenomenology”



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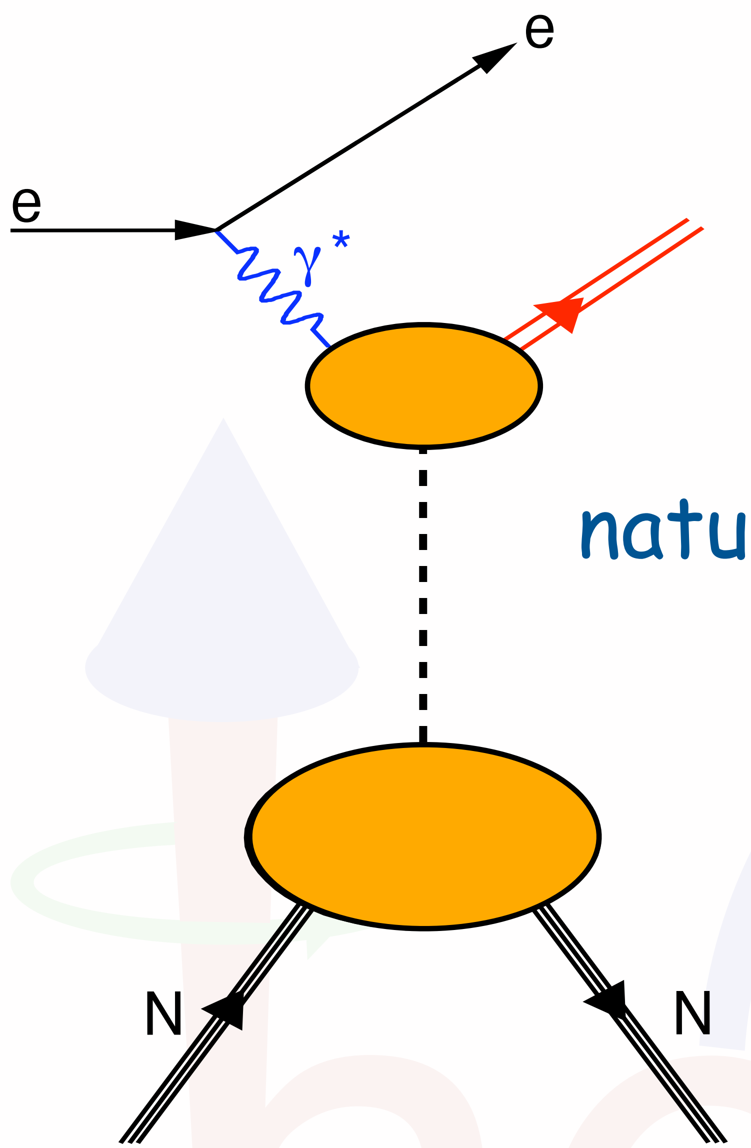
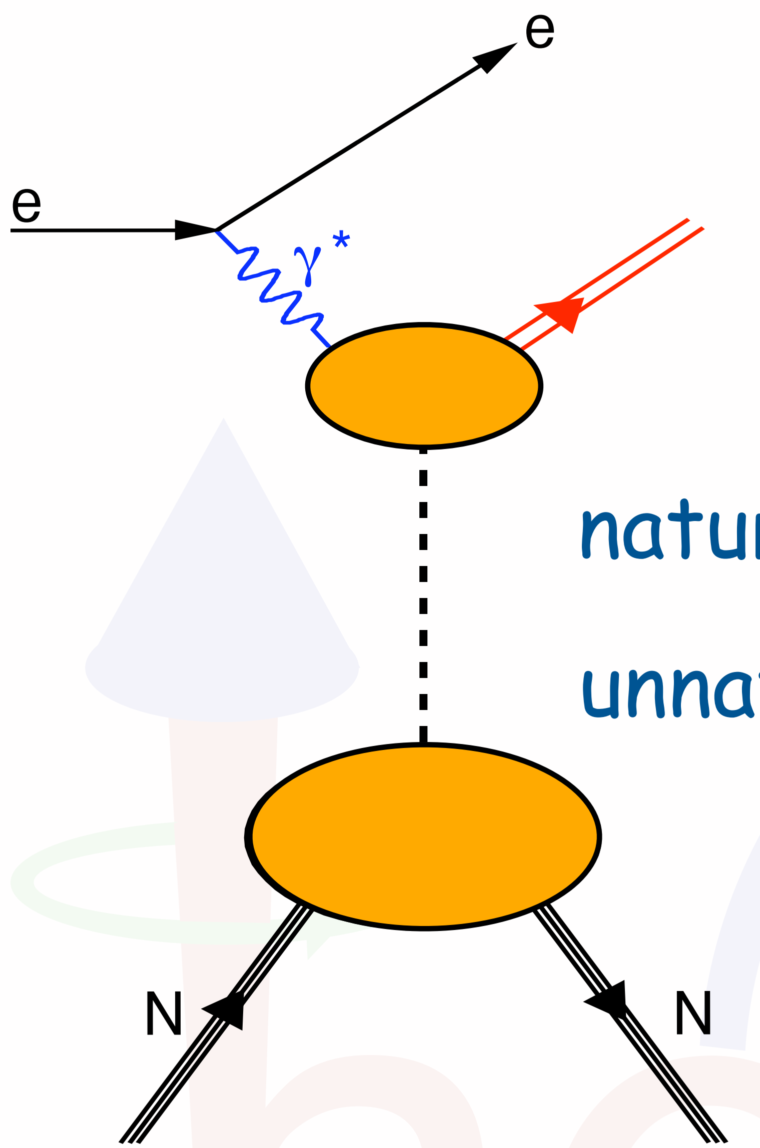


natural-parity exchange $J^P = 0^+, 1^-, \ldots$ GPDs H&E

“Regge phenomenology”

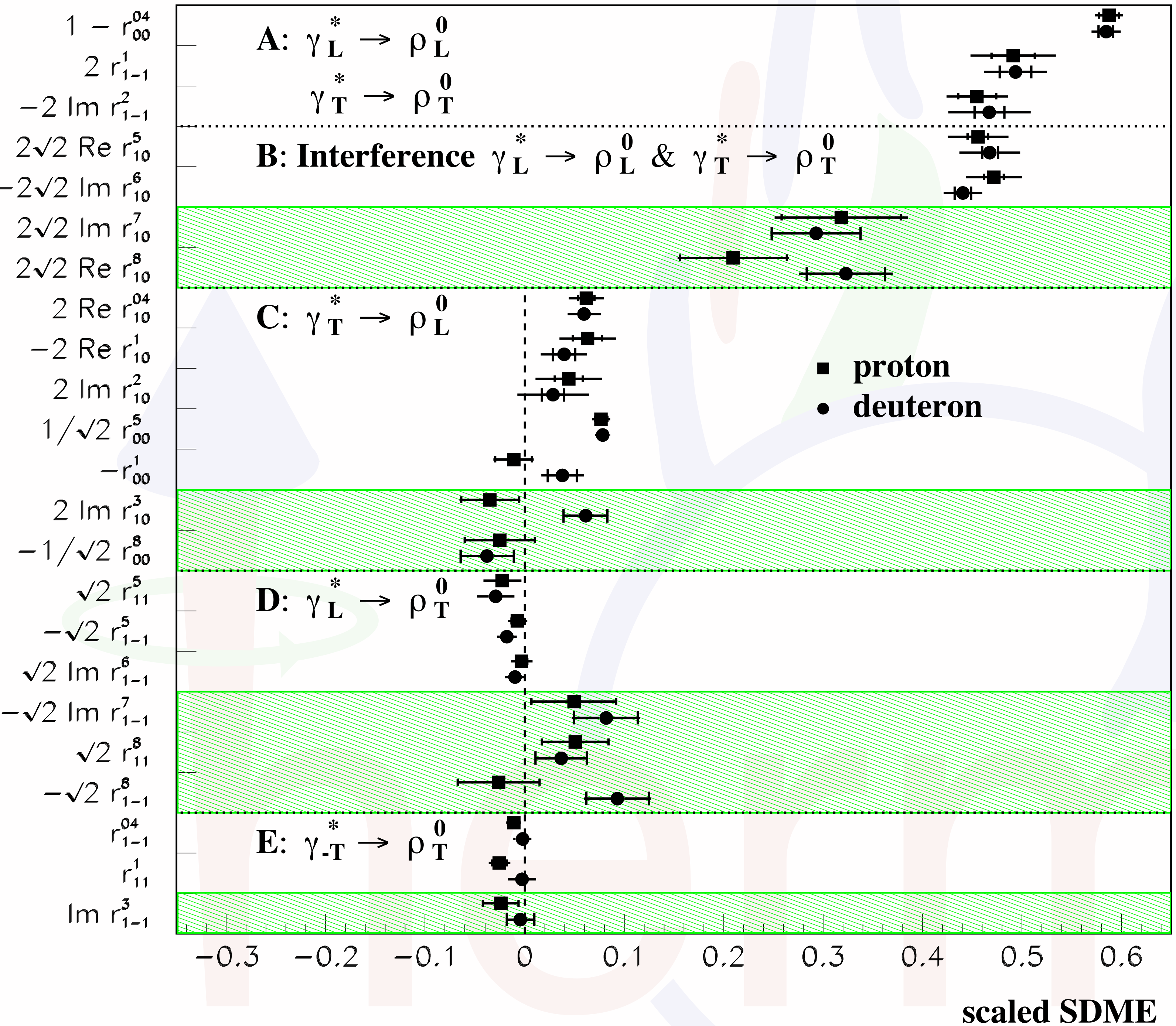


natural-parity exchange $J^P = 0^+, 1^-, \ldots$ GPDs H&E

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

ρ^0 SDMEs from HERMES

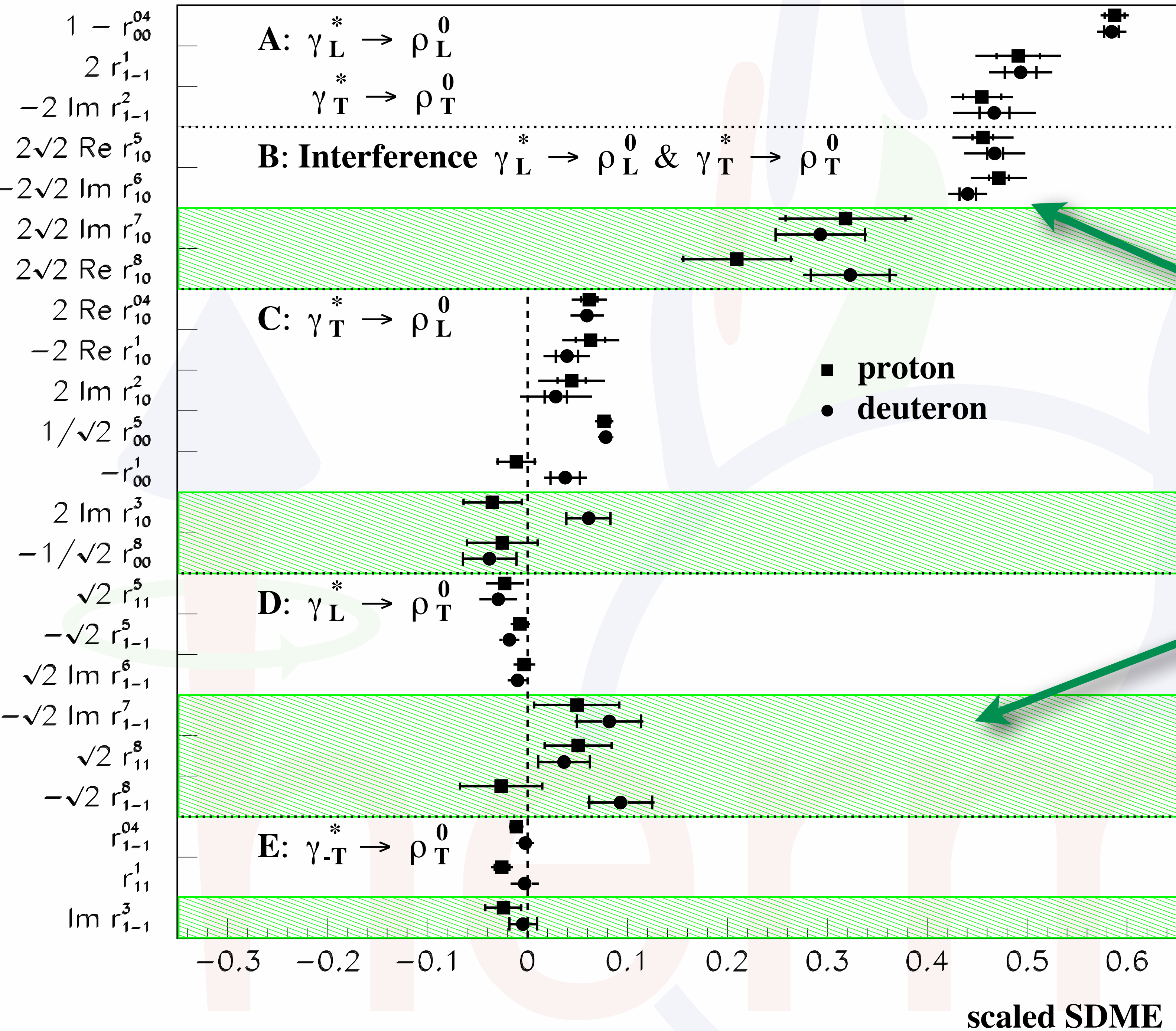
[A. Airapetian et al., EPJ C62 (2009) 659]



target-polarization independent SDMEs

ρ^0 SDMEs from HERMES

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

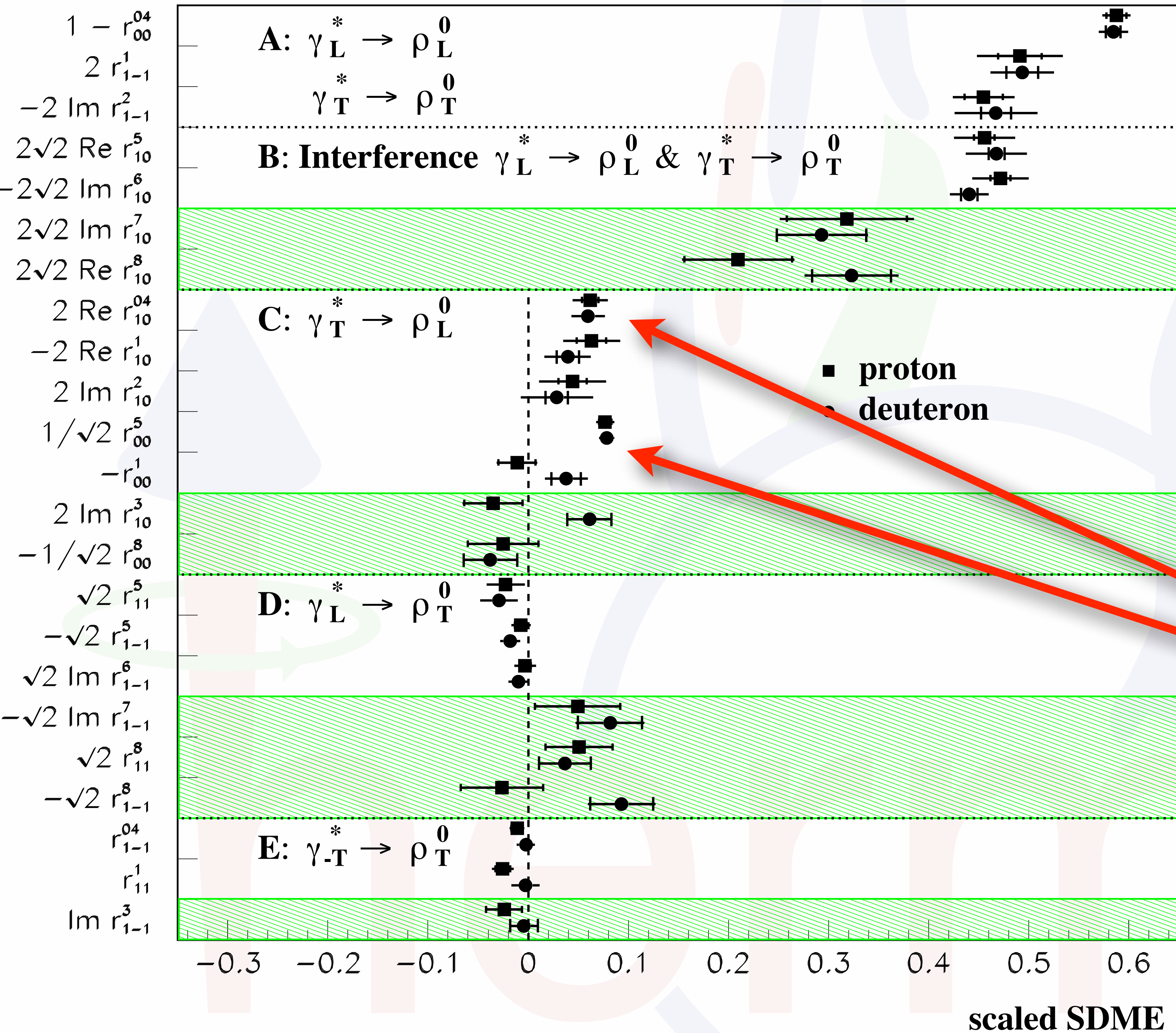


helicity non-flip much larger than helicity-flip and double helicity-flip

target-polarization independent SDMEs

ρ^0 SDMEs from HERMES

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

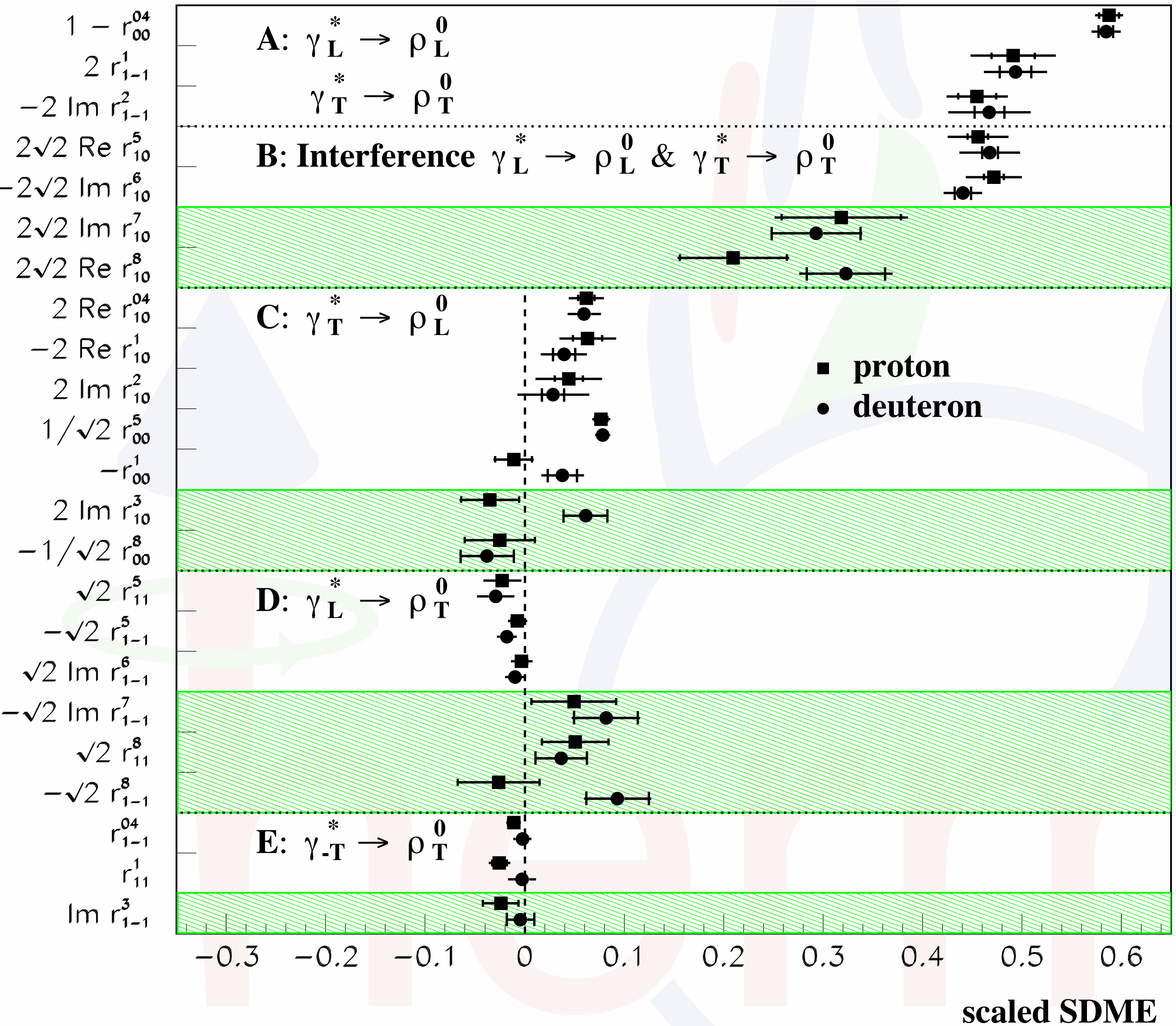


clear breaking of s-channel helicity conservation

target-polarization independent SDMEs

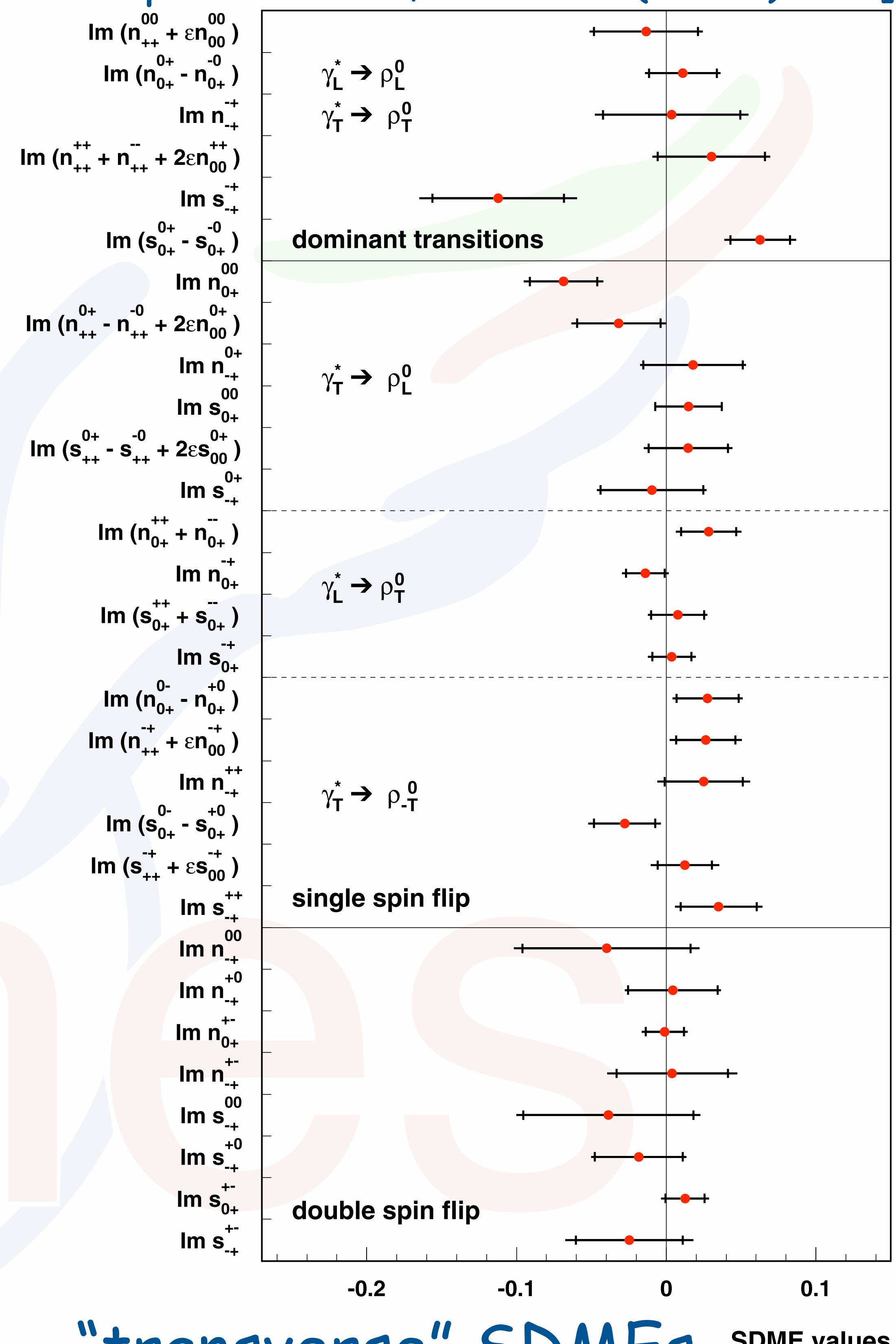
ρ^0 SDMEs from HERMES

[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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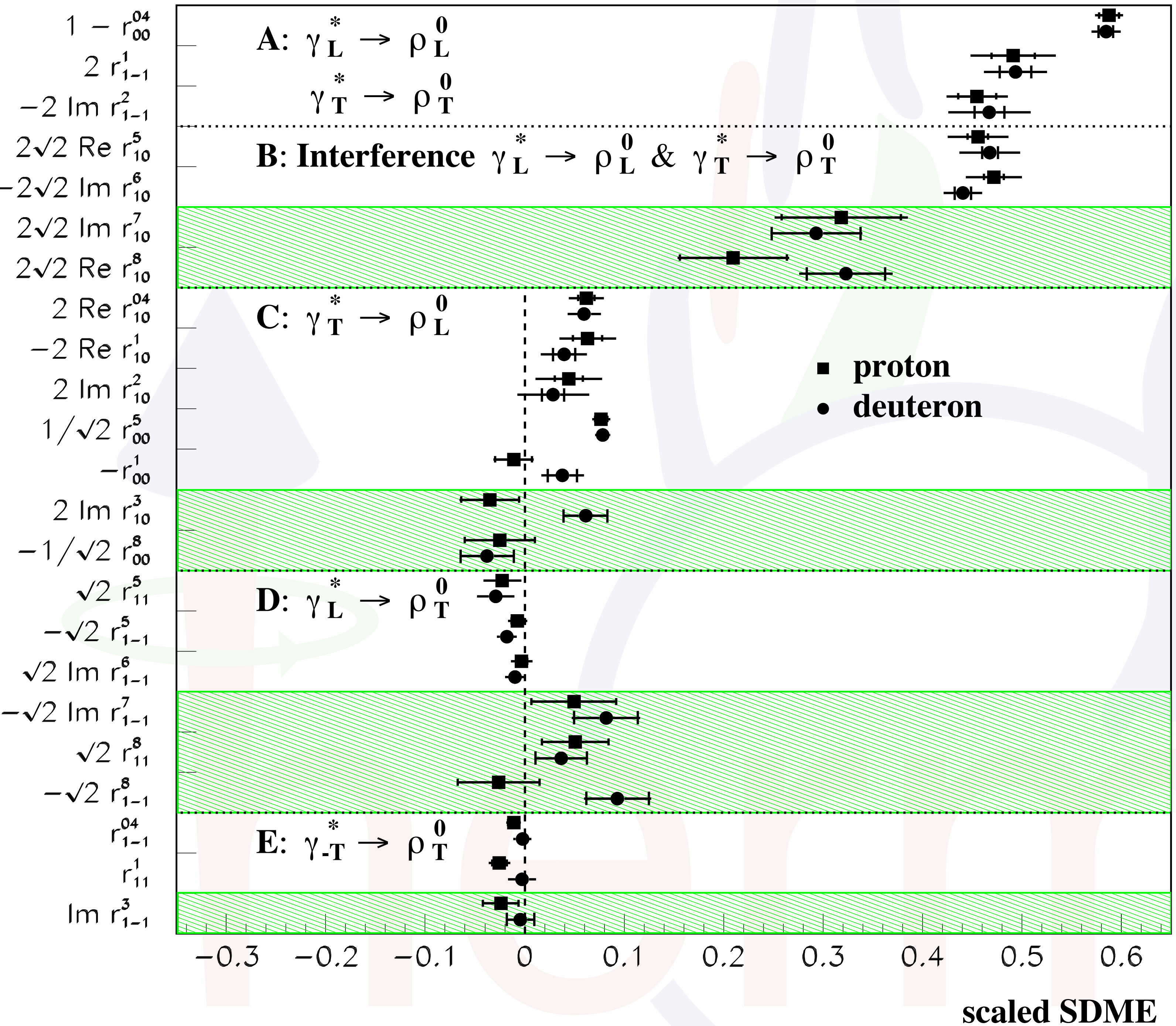

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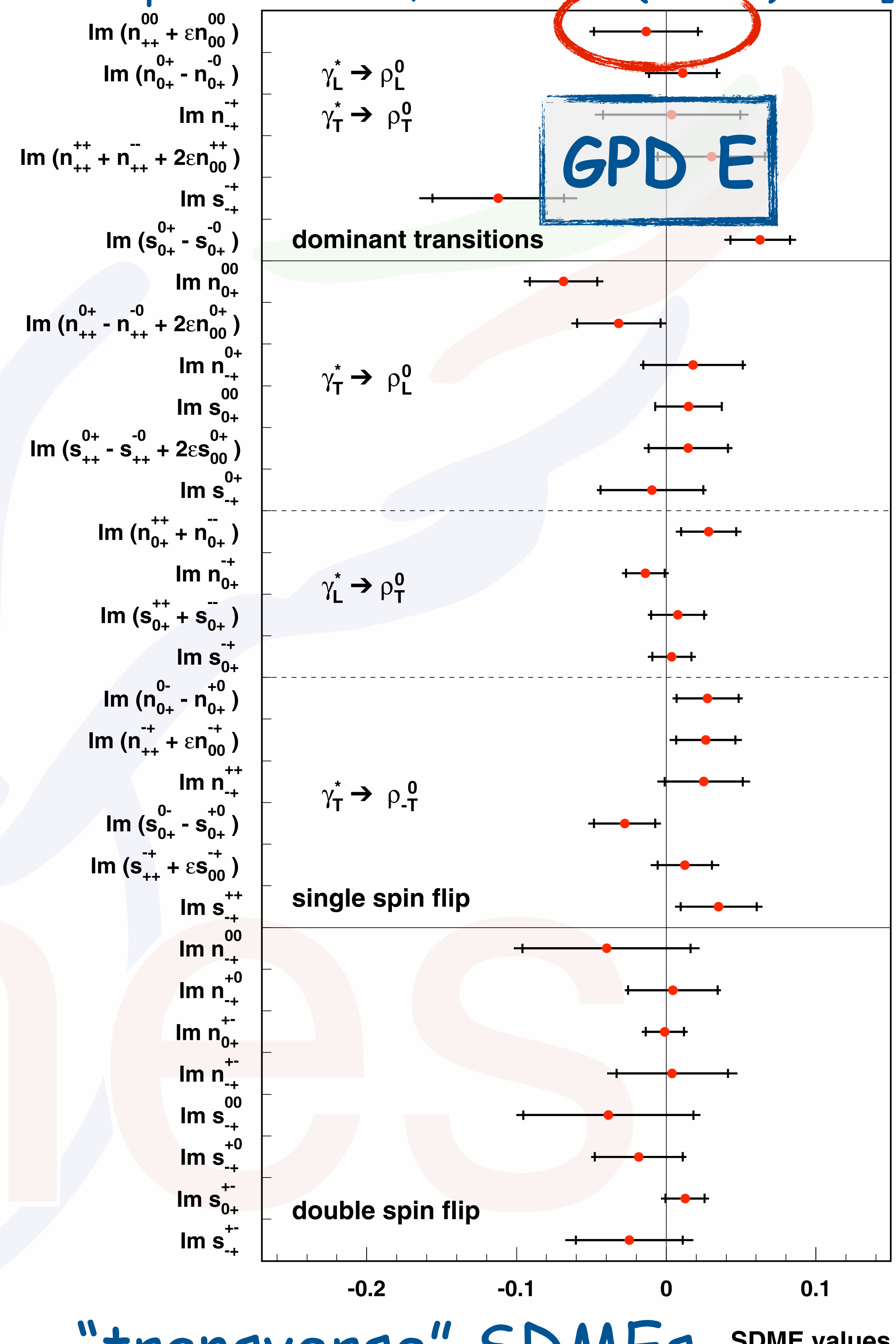

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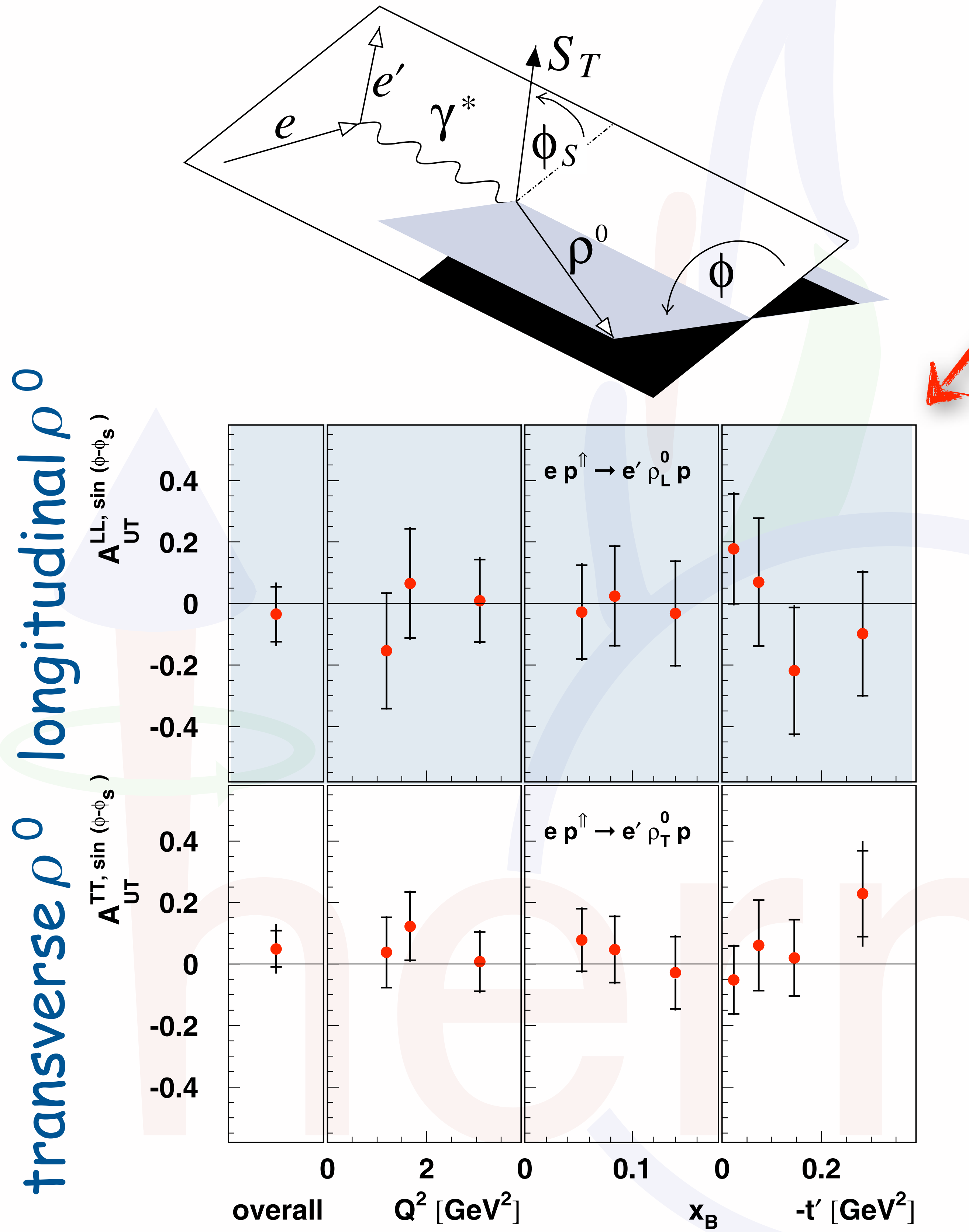

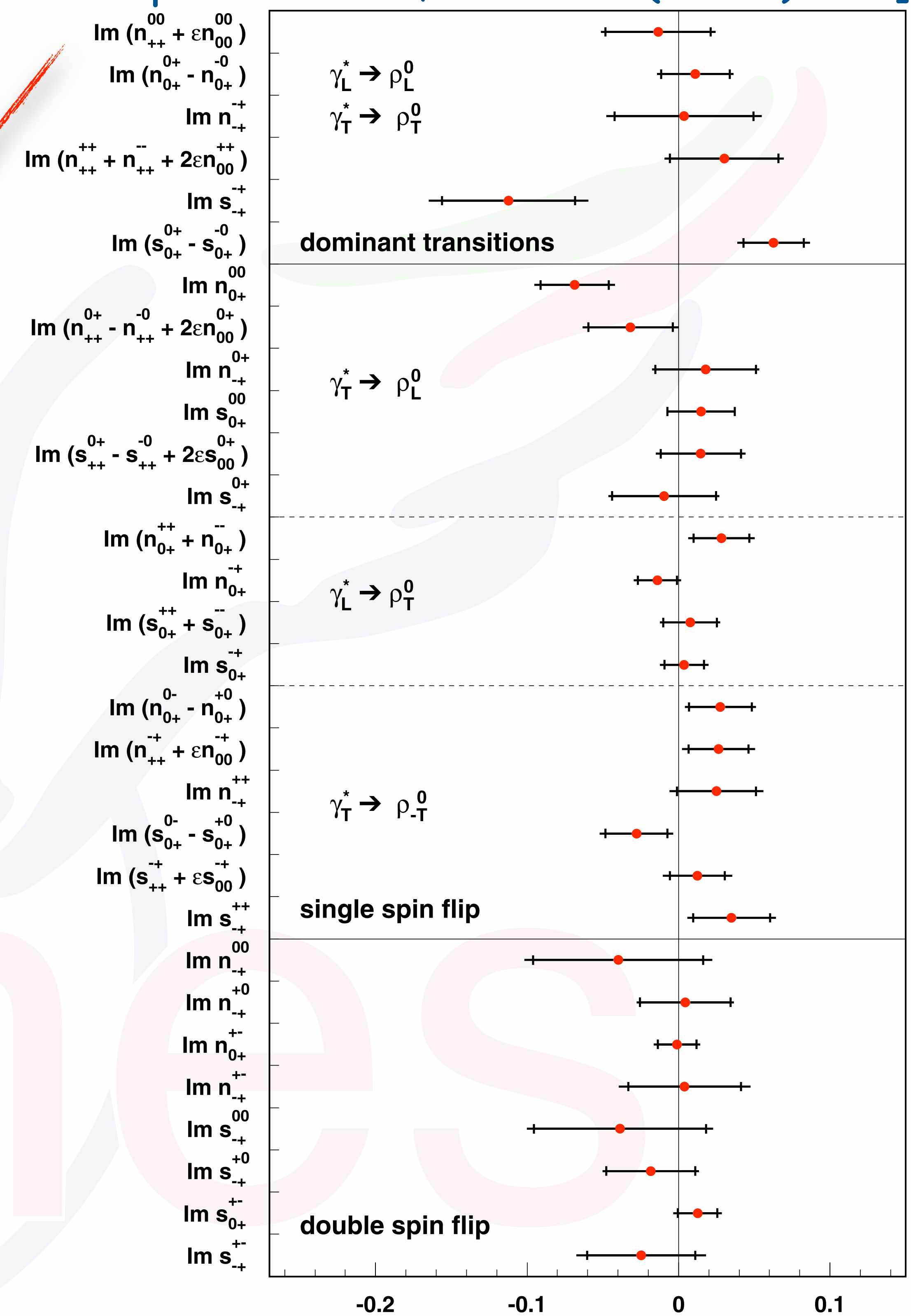

"transverse" SDMEs

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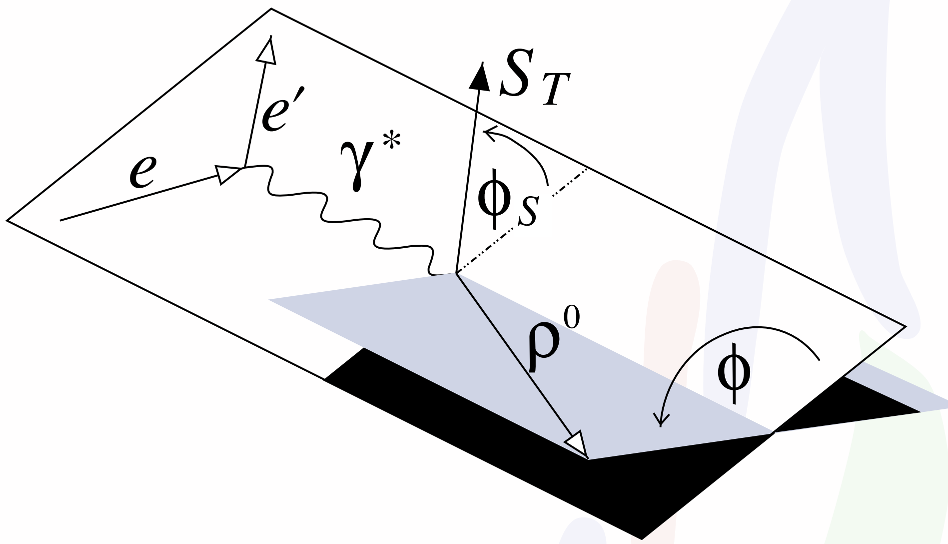
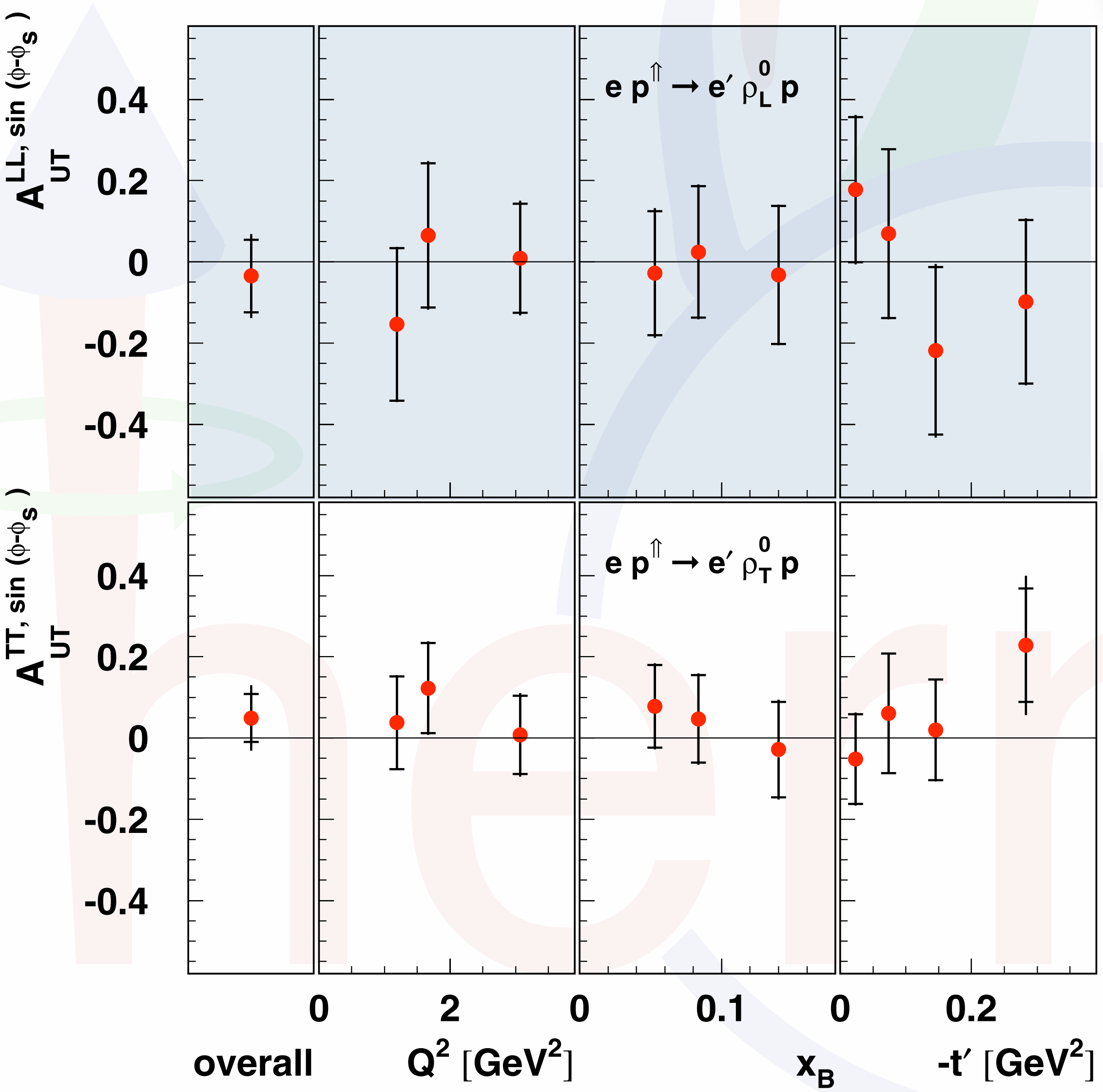
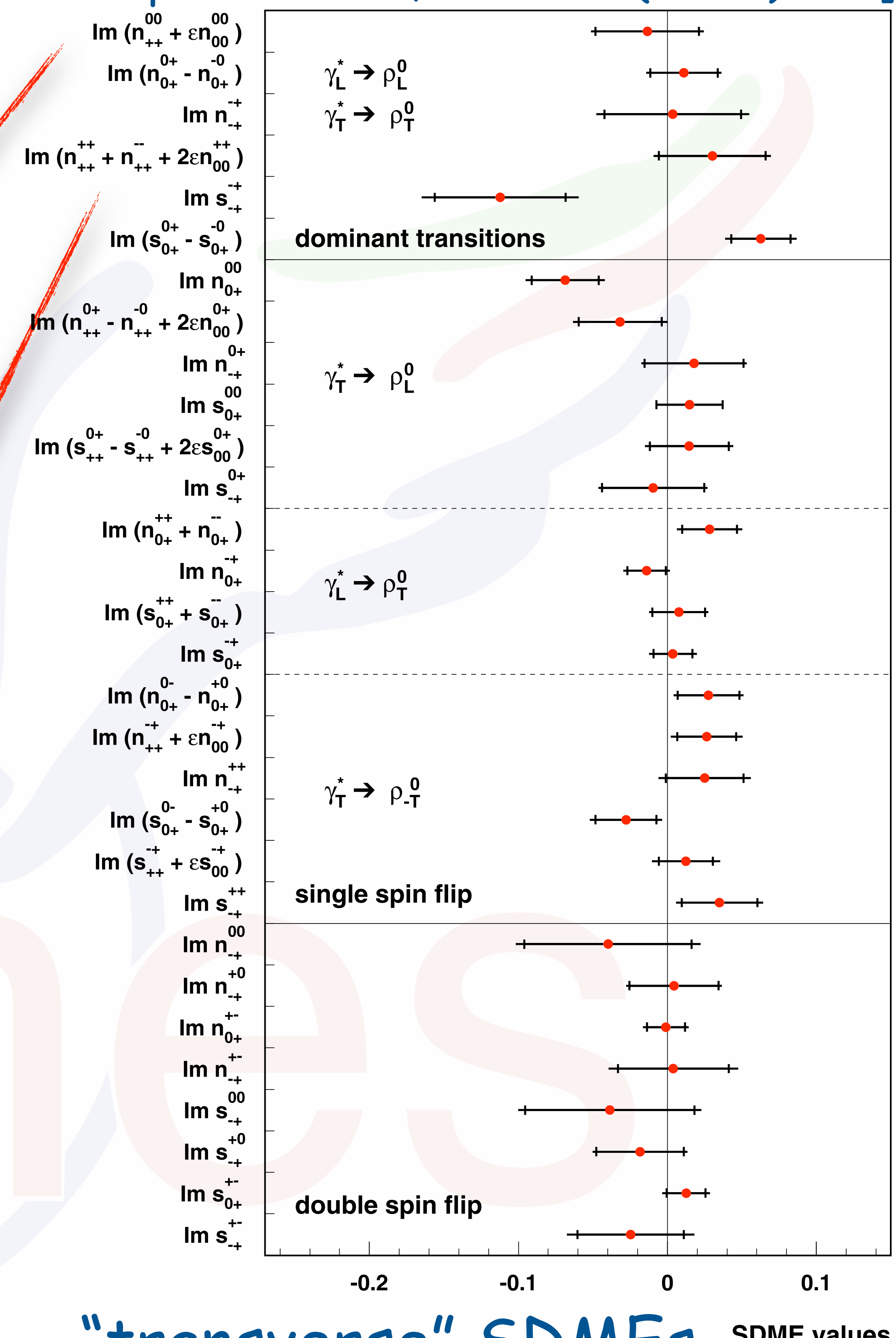


longitudinal ρ^0

transverse ρ^0

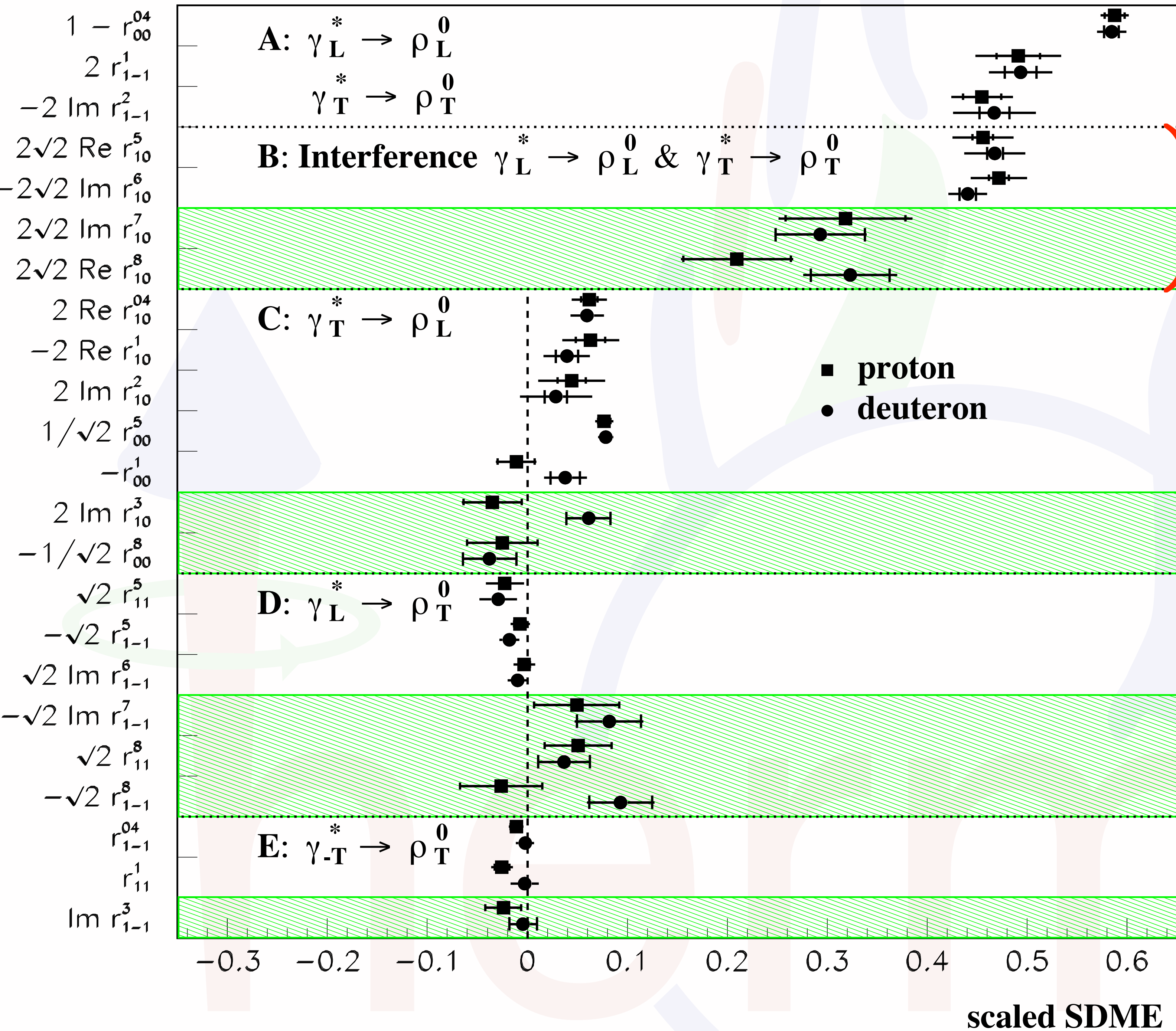




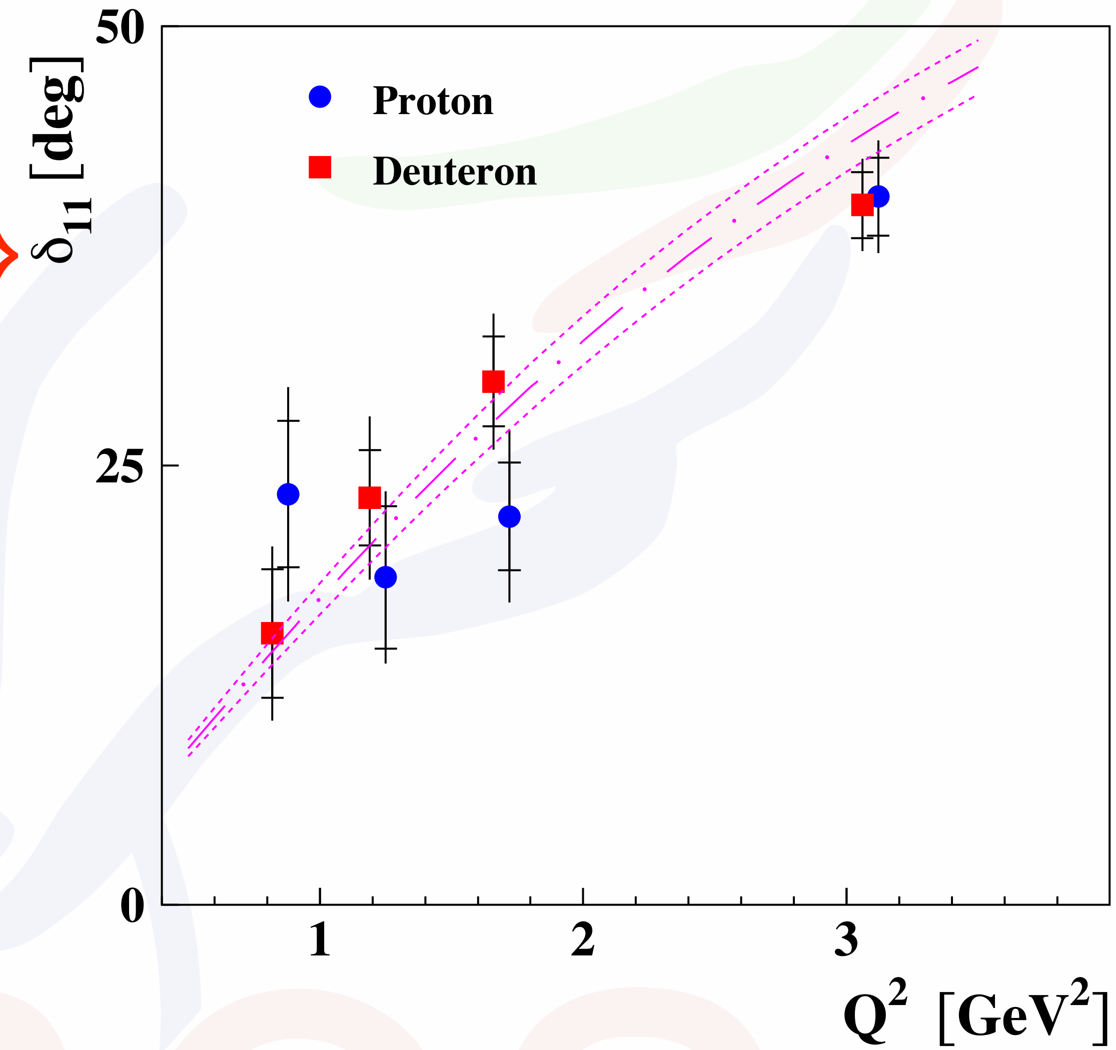
"transverse" SDMEs

ρ^0 SDMEs from HERMES: challenges

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



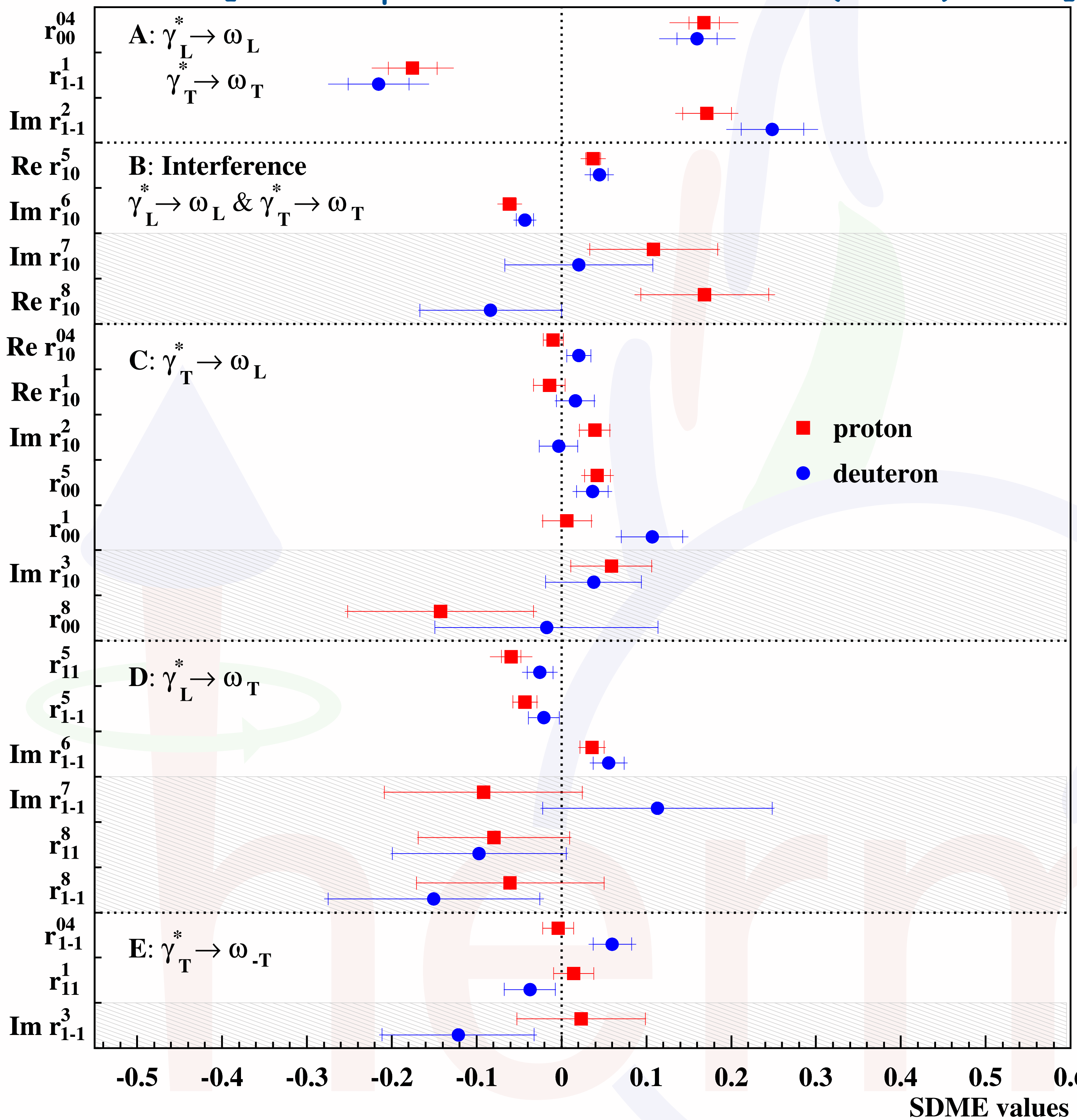
[A. Airapetian et al, EPJ C71 (2011) 1609]



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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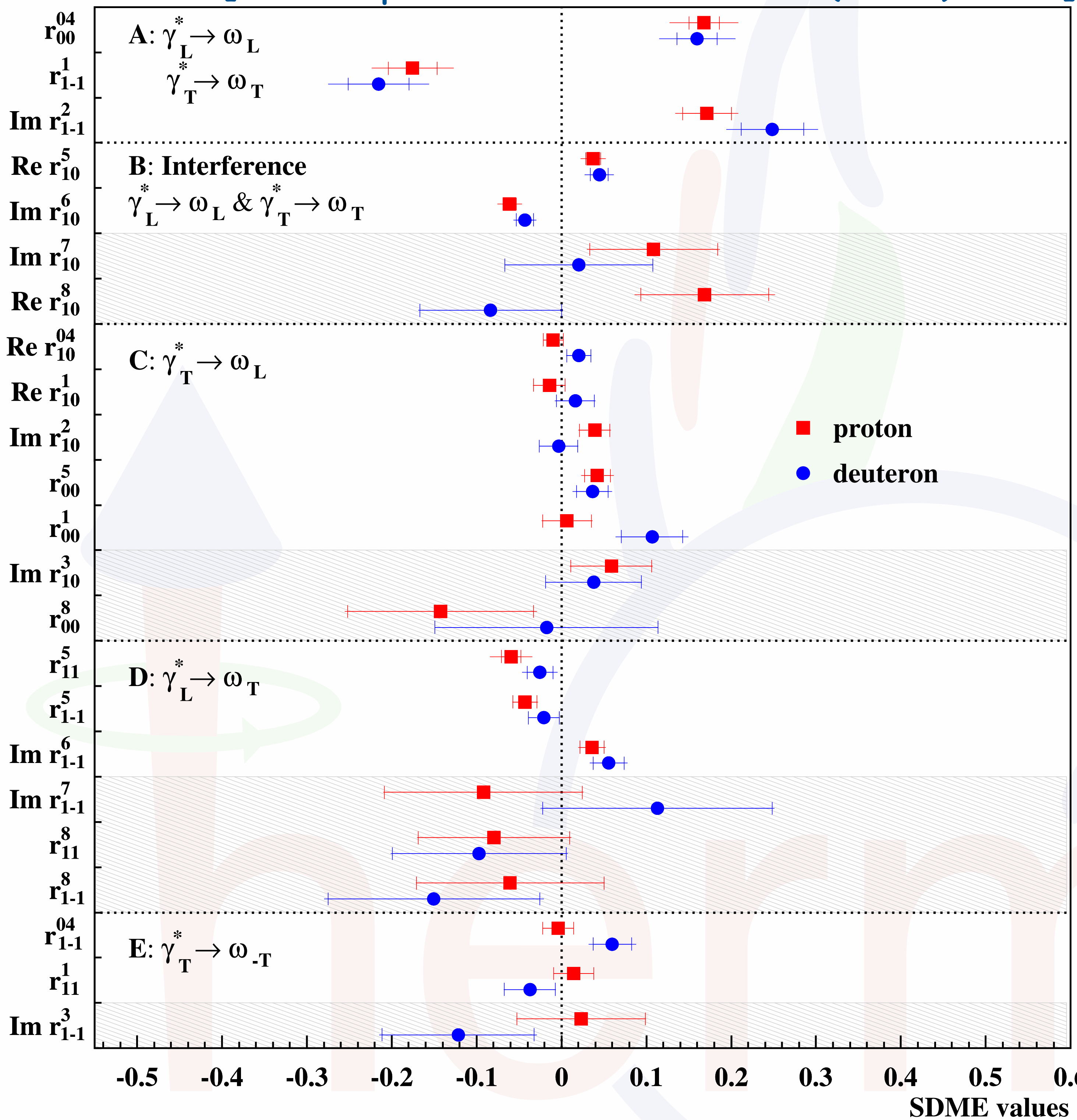

- helicity-conserving SDMEs dominate

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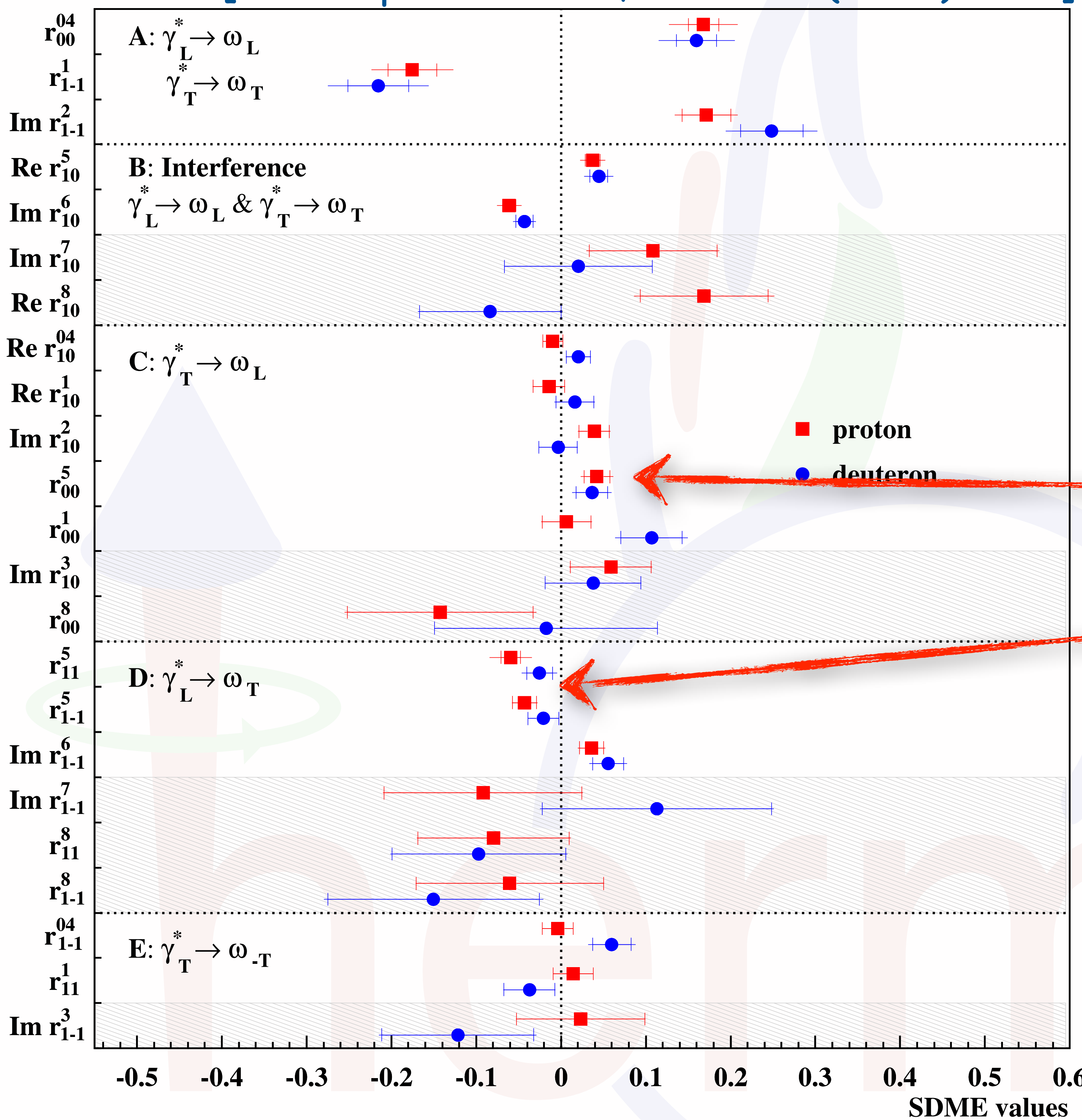
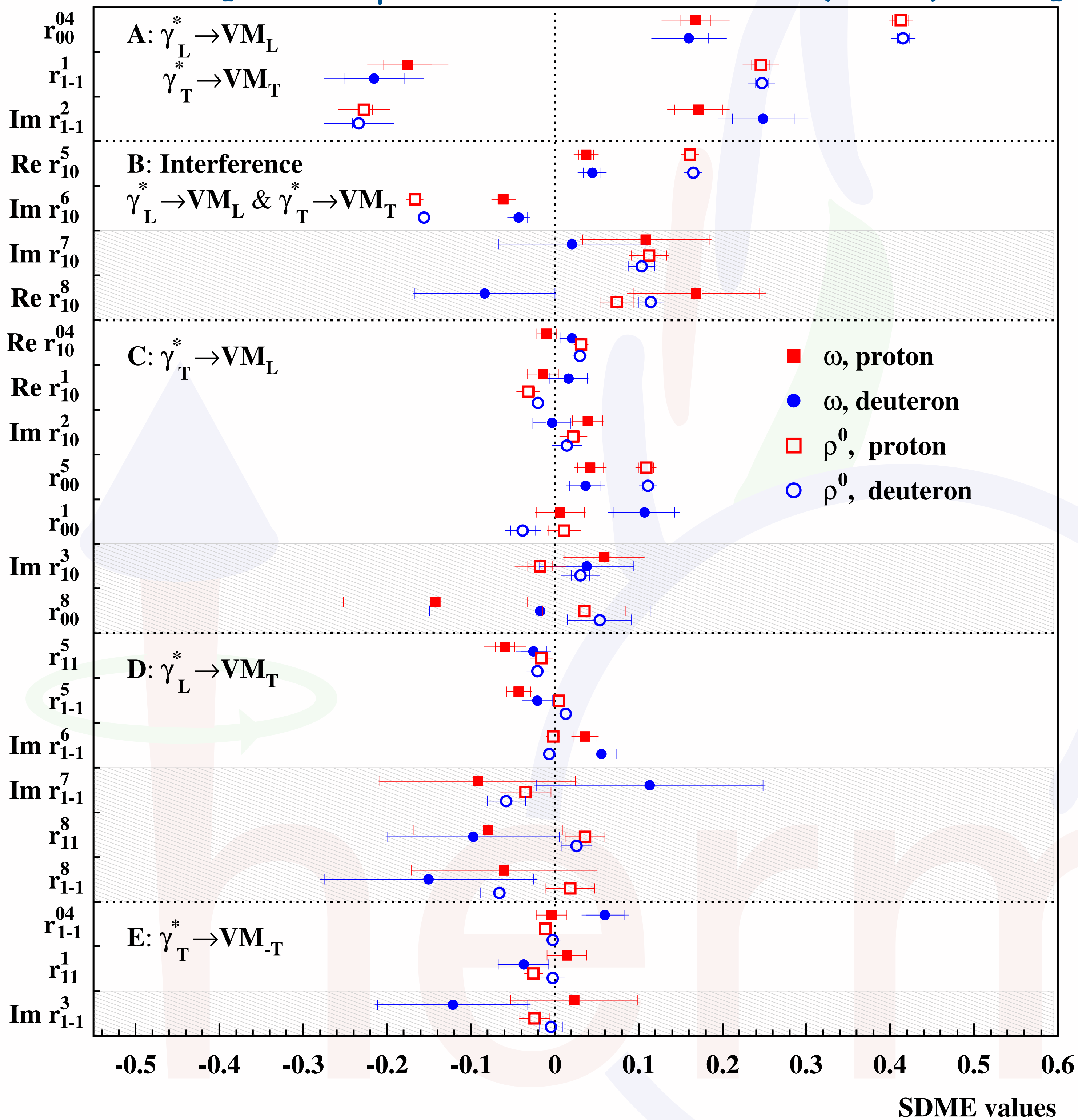
[A. Airapetian et al., EPJ C74 (2014) 3110]



- 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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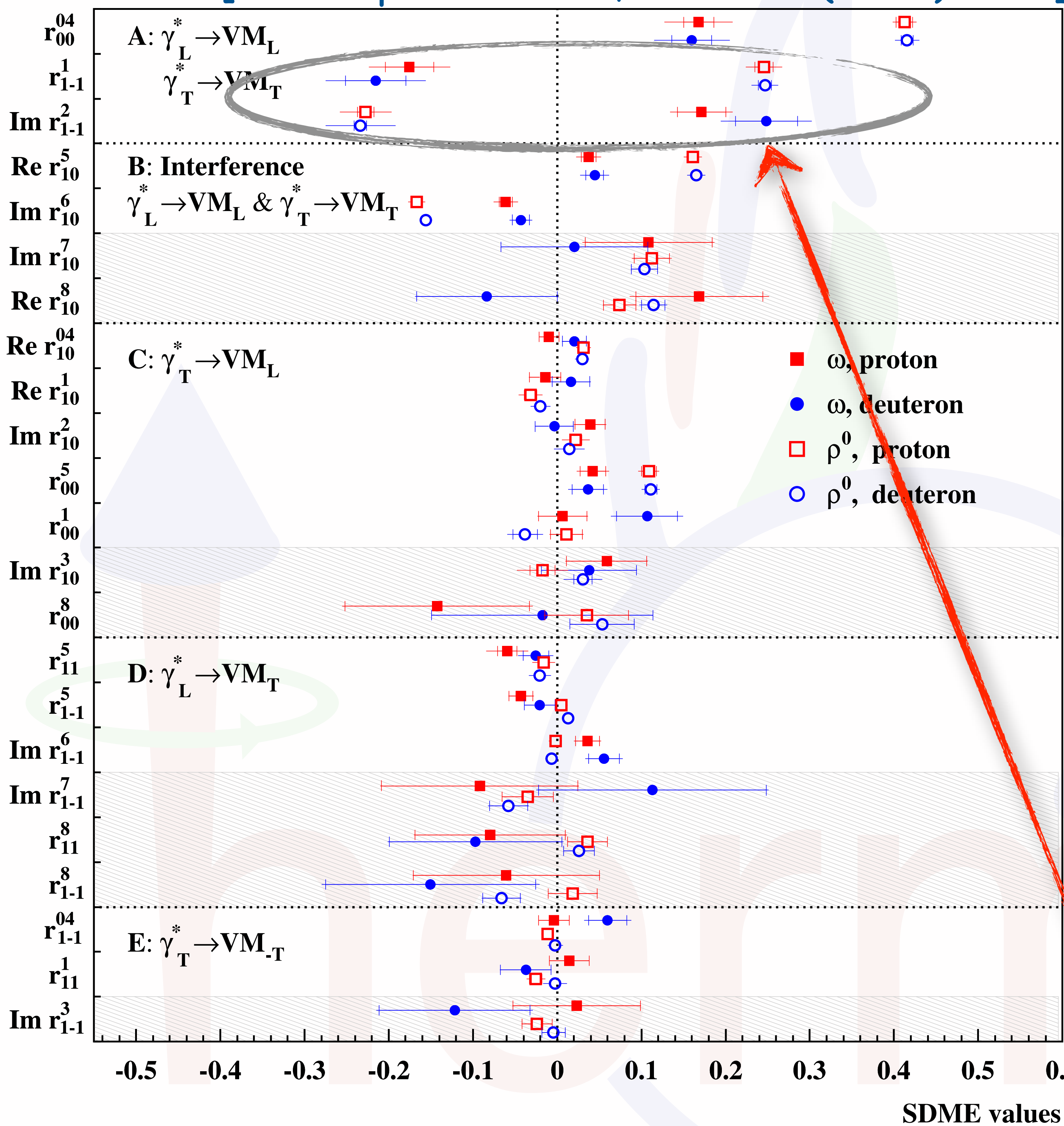

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- hardly any violation of SCHC, except maybe for
  - r^5_{00}
  - $r^5_{11} + r^5_{1\text{-}1} - \Im r^6_{1\text{-}1}$
- interference smaller than for ρ^0 ...
- ... and opposite signs for $r^1_{1\text{-}1}$ & $\Im r^2_{1\text{-}1}$

(un)natural-parity exchange contributions

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

UPE contribution NPE contribution

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

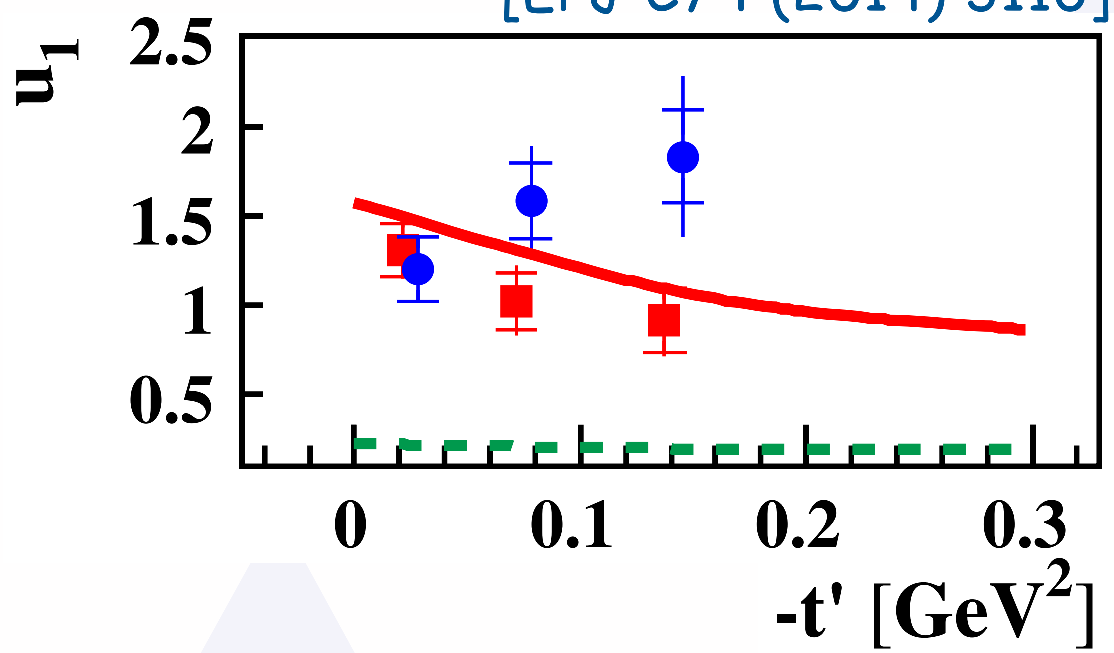
$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^1_{11} - 2r^1_{1-1}$$

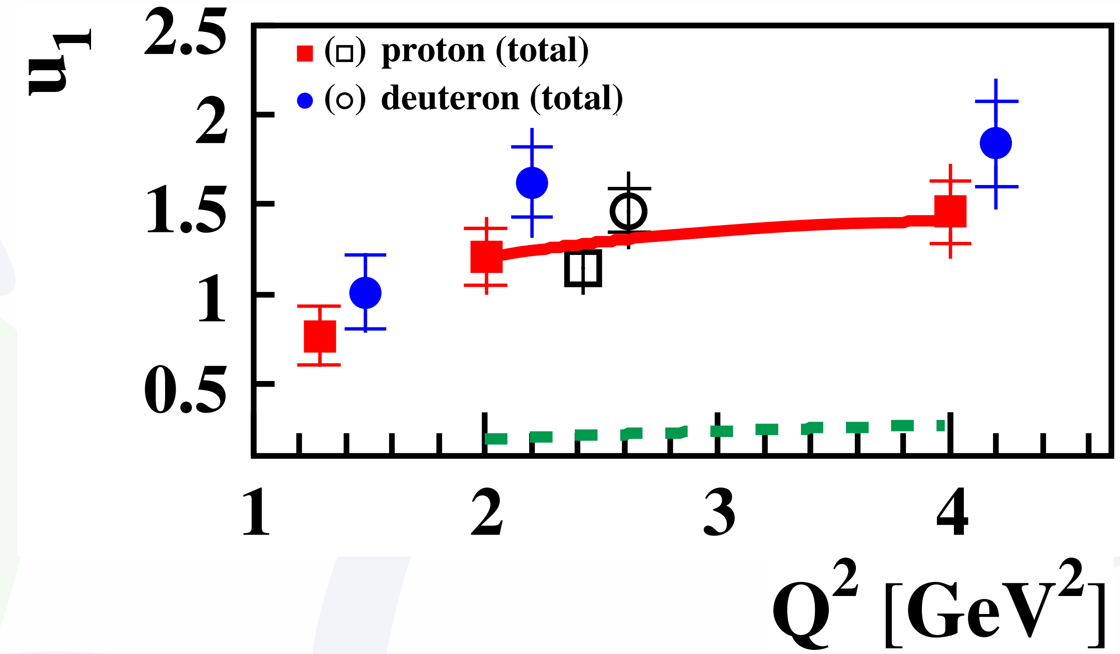
$$u_2 = r^5_{11} + r^5_{1-1}$$

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

test of UPE

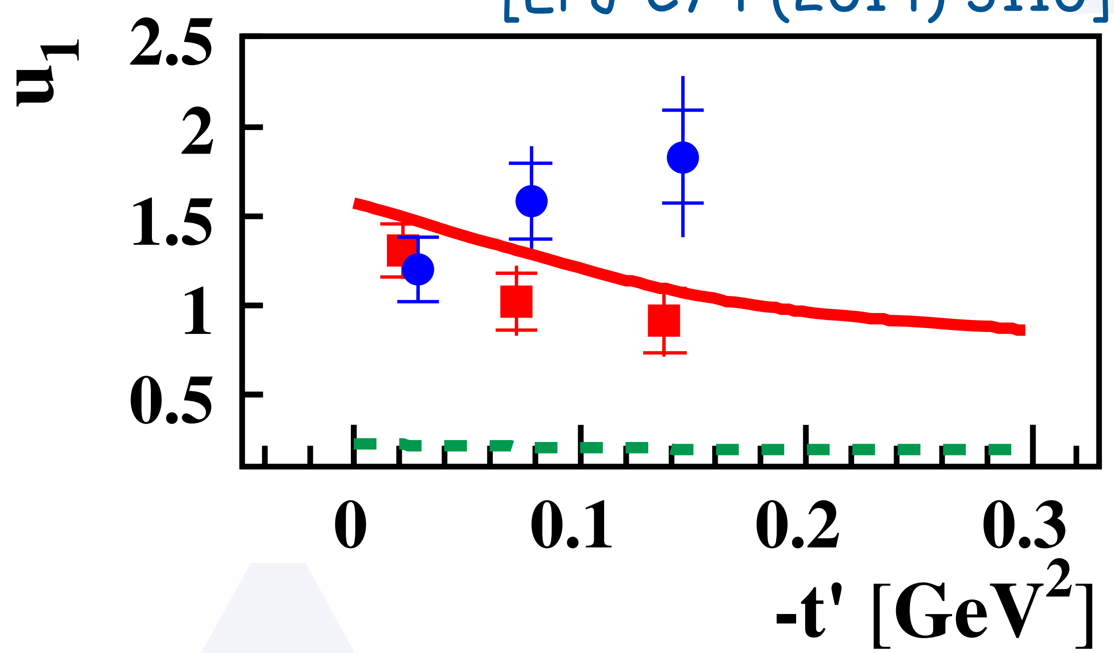
[EPJ C74 (2014) 3110]

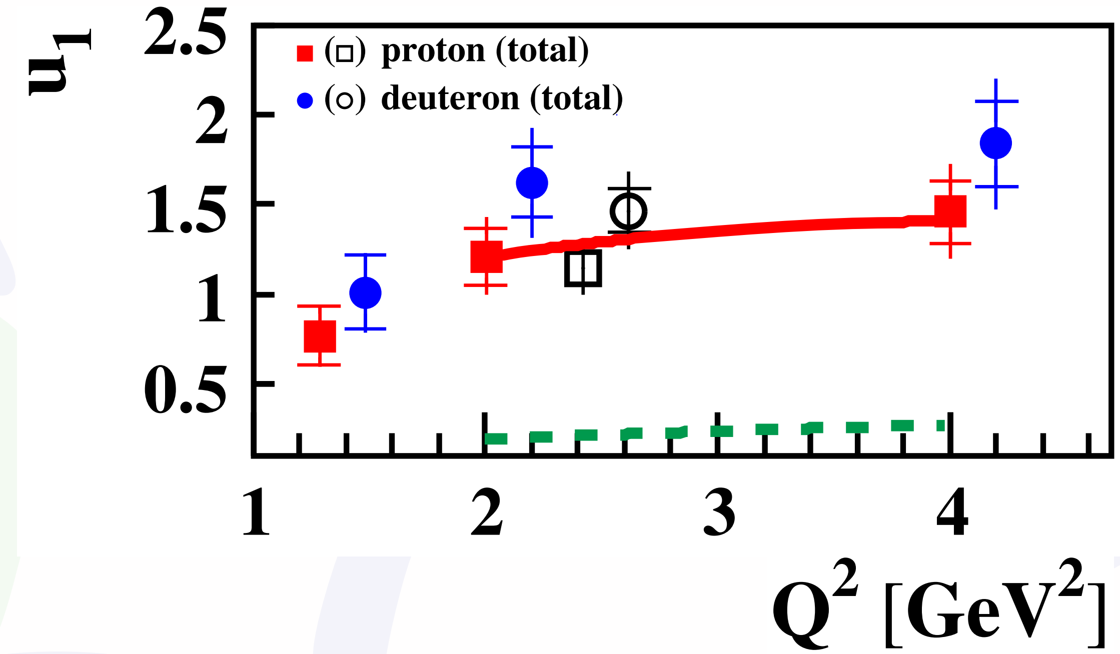




test of UPE

[EPJ C74 (2014) 3110]

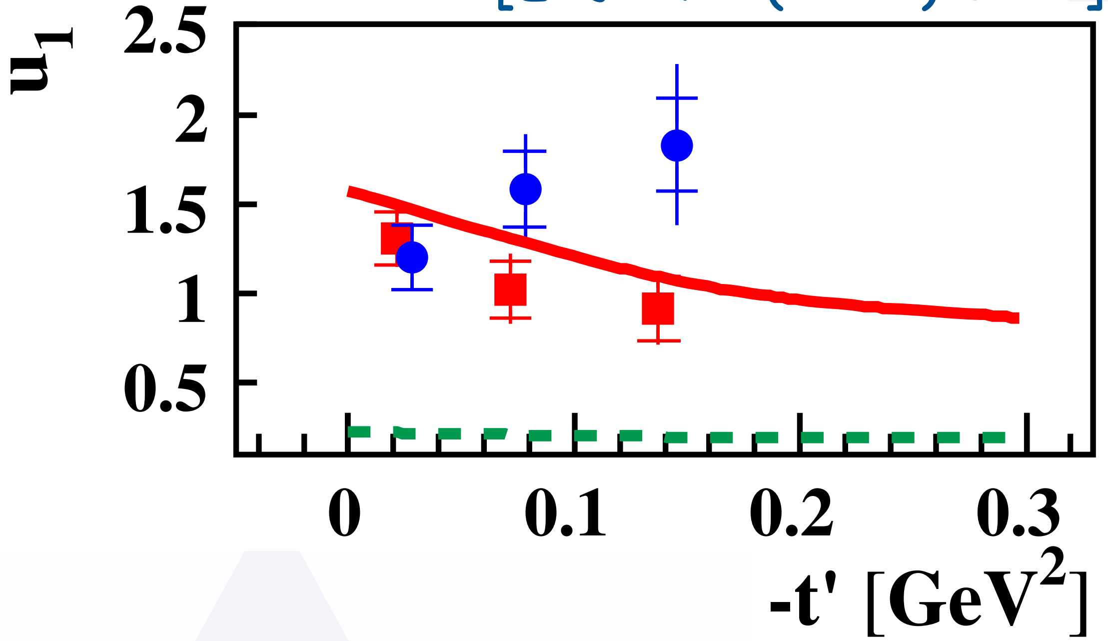


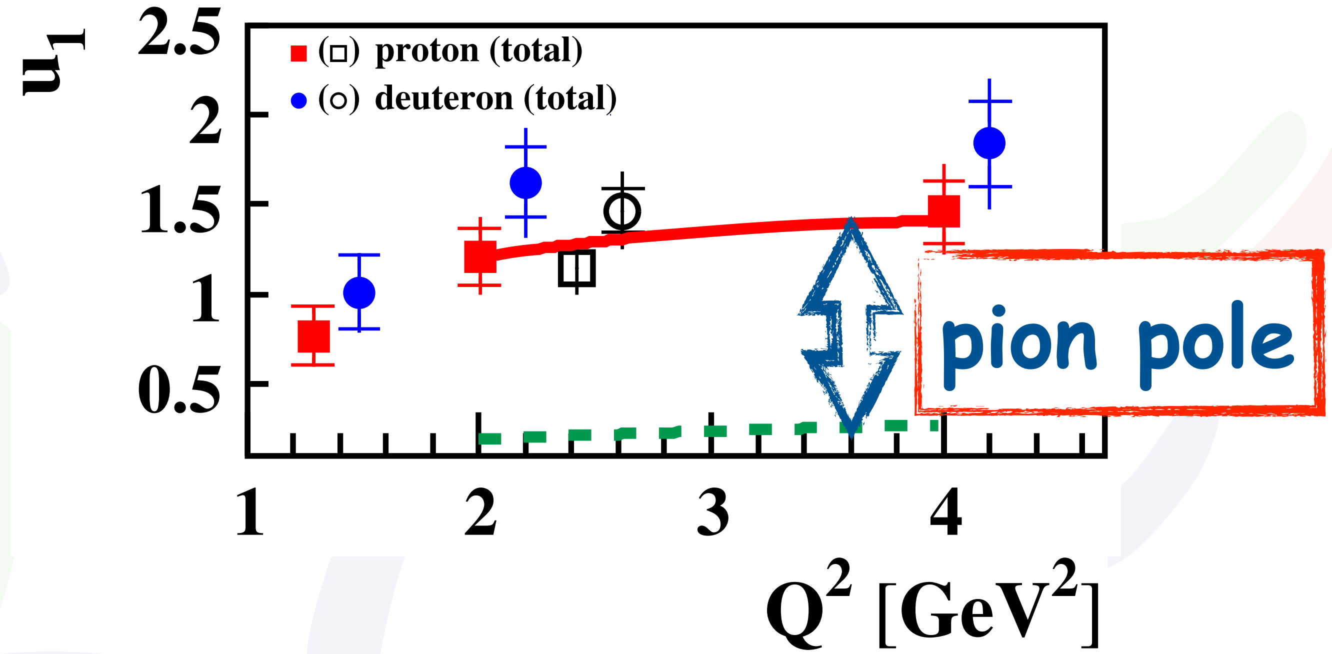


- large UPE contributions

test of UPE

[EPJ C74 (2014) 3110]



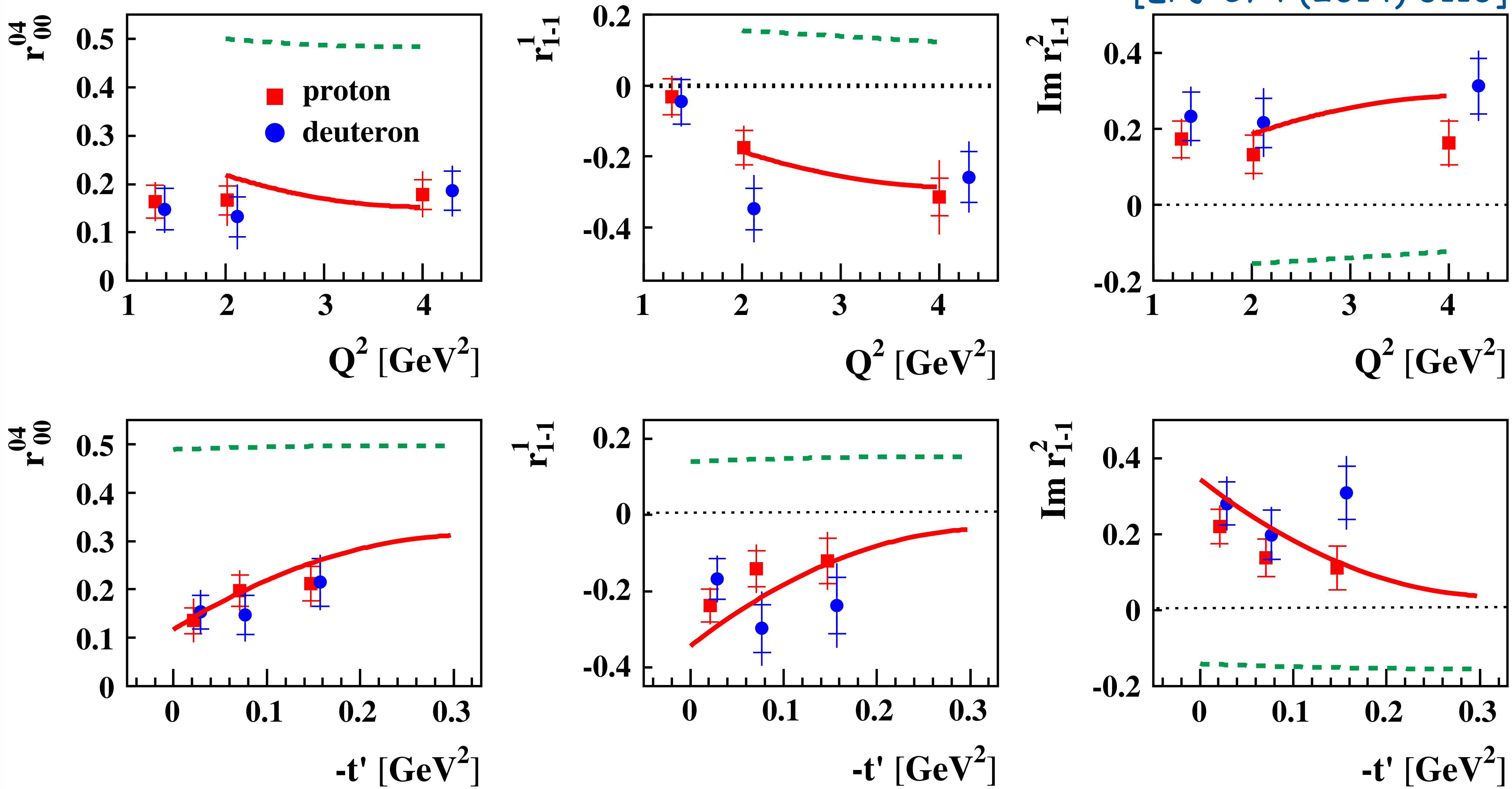


- large UPE contributions
- modified GK model [EPJ A50 (2014) 146] can describe data when including
  - pion pole contribution (red curve)
  - corresponding $\pi\omega$ transition form factor (fit to these data)

impact of pion-pole contr. on SDMEs

- "class-A" - helicity-conserving transitions

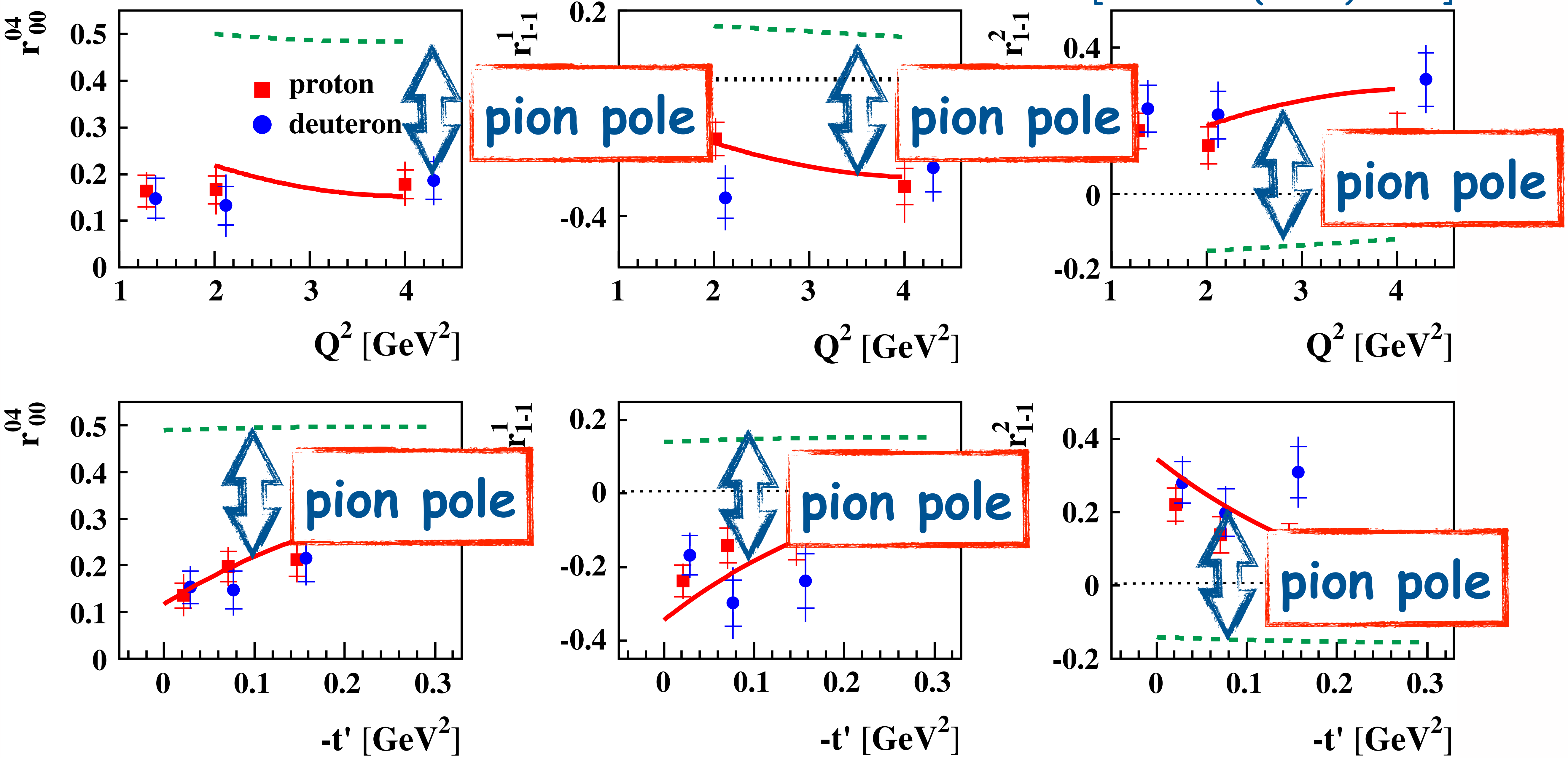
[EPJ C74 (2014) 3110]



impact of pion-pole contr. on SDMEs

- "class-A" - helicity-conserving transitions

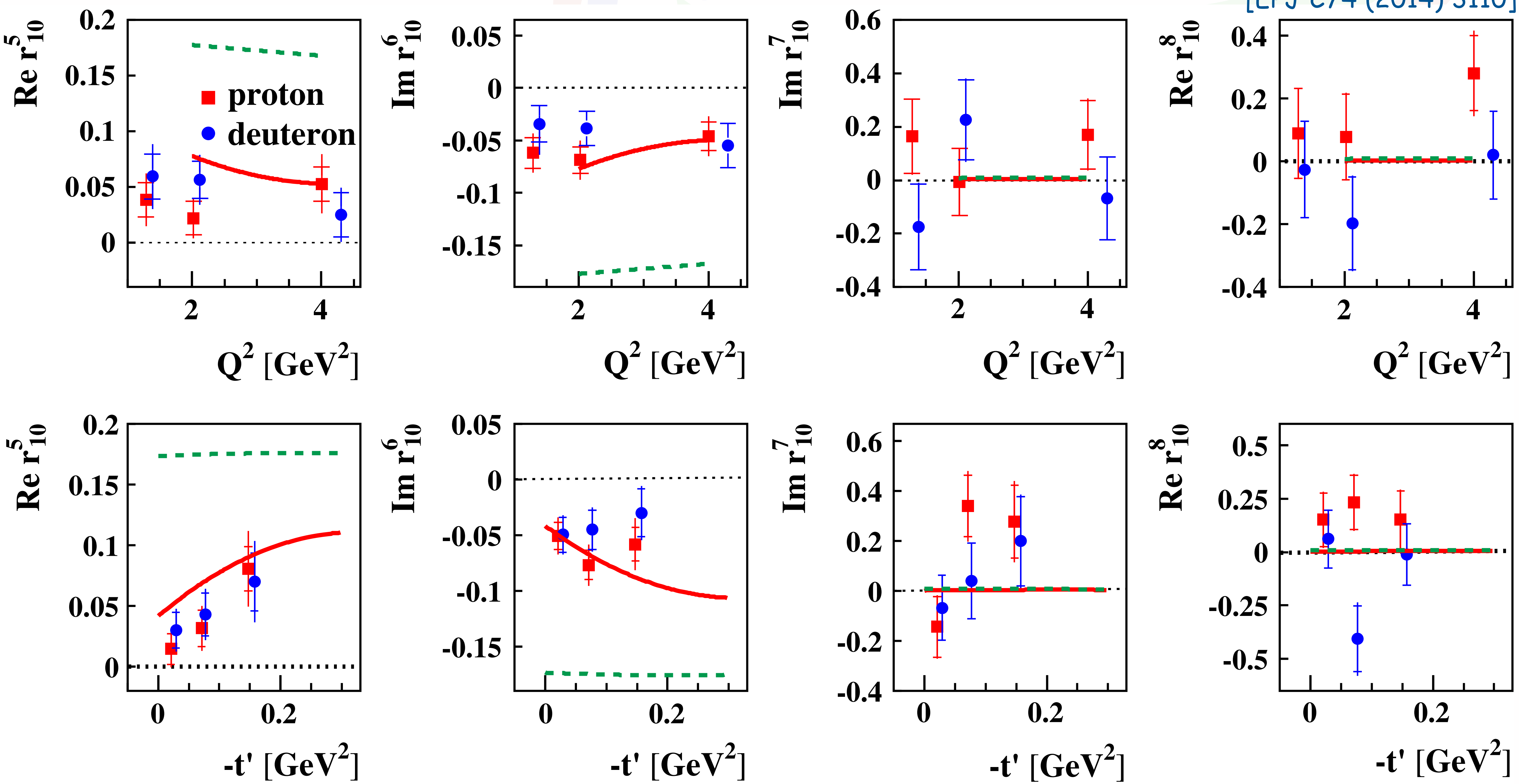
[EPJ C74 (2014) 3110]



impact of pion-pole contr. on SDMEs

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

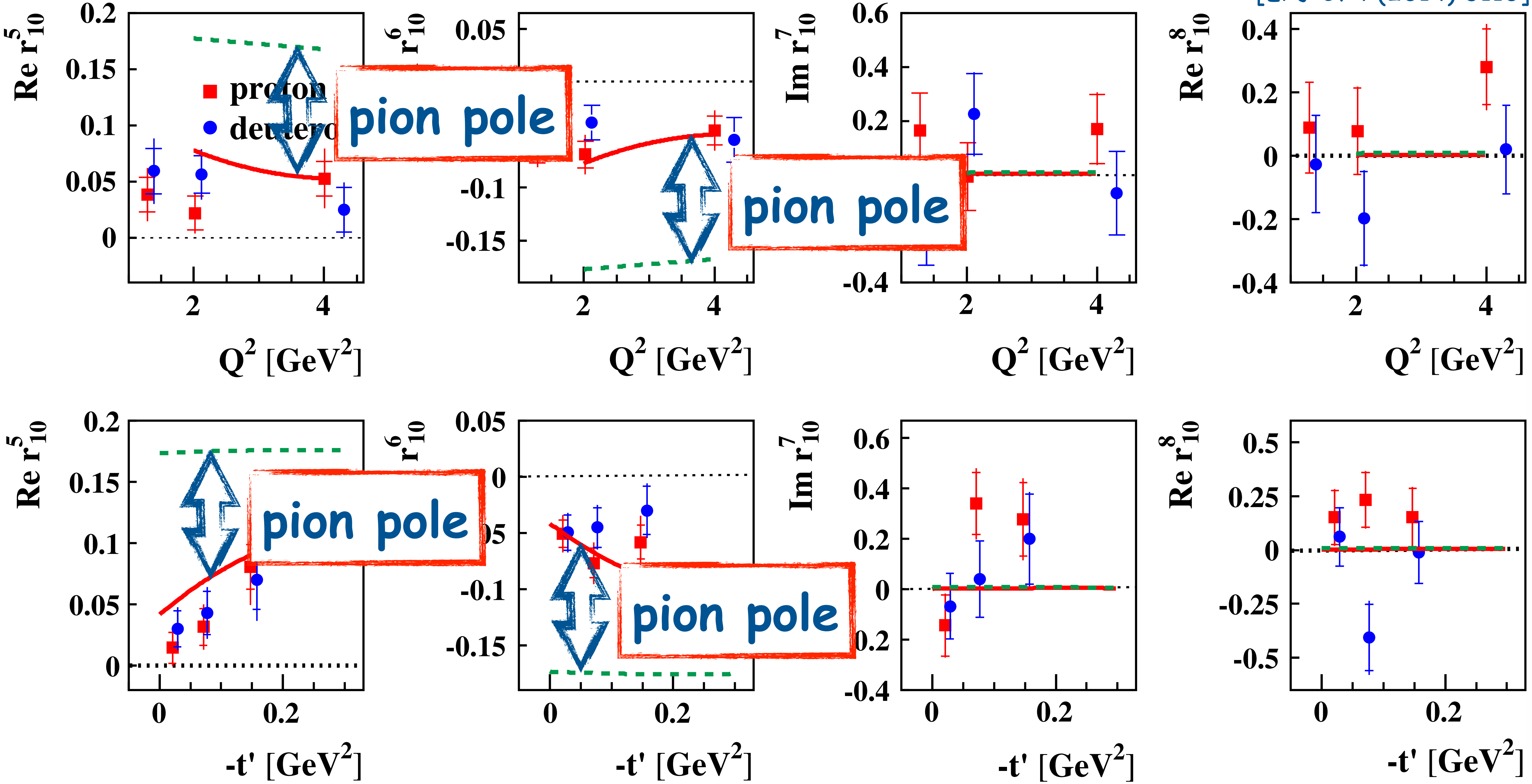
[EPJ C74 (2014) 3110]



impact of pion-pole contr. on SDMEs

- “class-B” - interference of helicity-conserving transitions

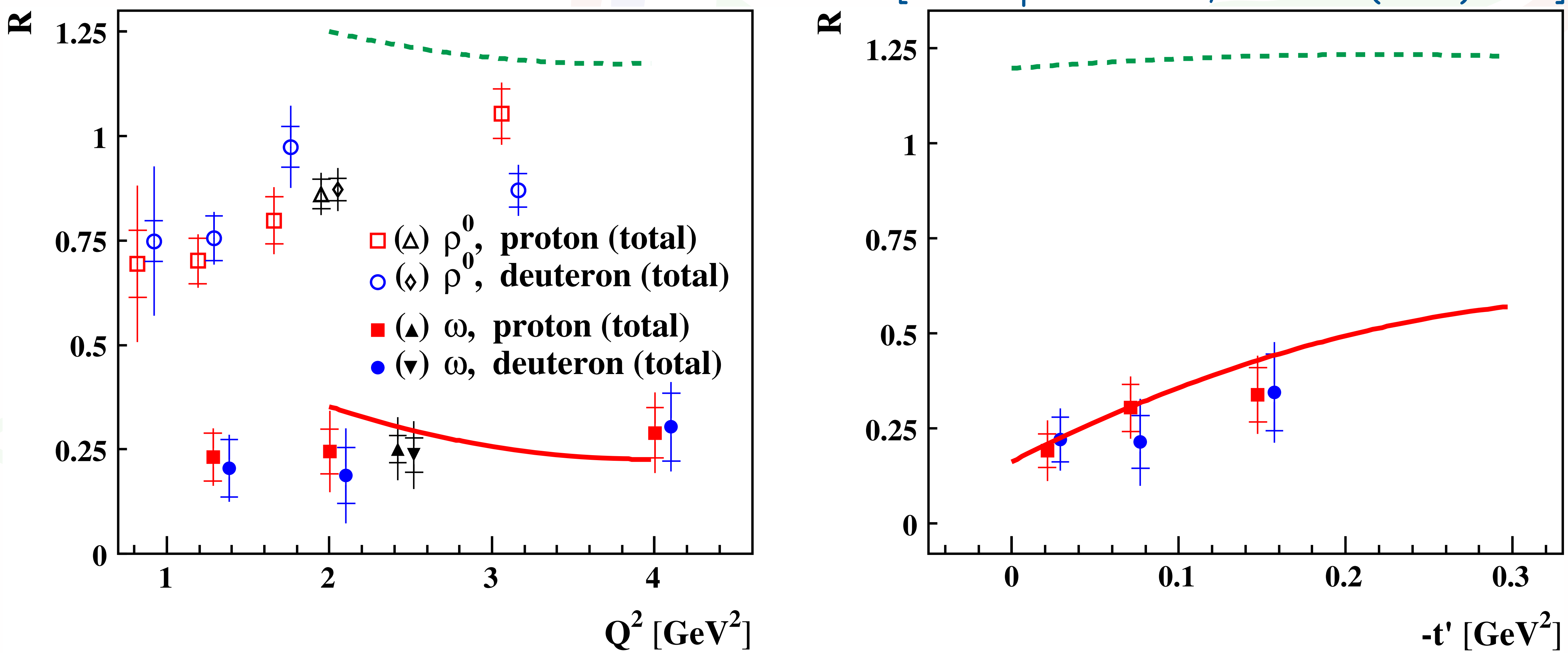
[EPJ C74 (2014) 3110]



long.-to-transverse cross-section ratio

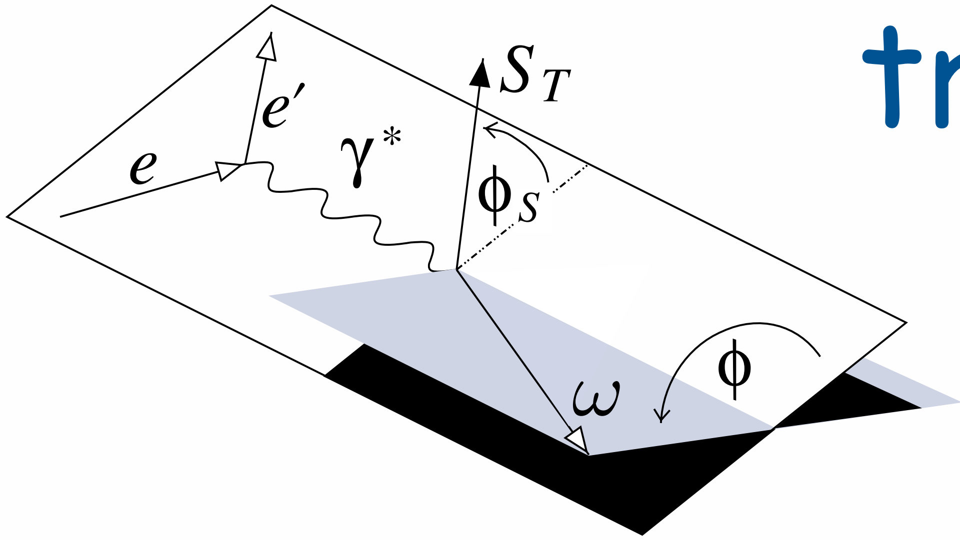
$$R = \frac{d\sigma(\gamma^*_L \to \omega)}{d\sigma(\gamma^*_T \to \omega)} \approx \frac{1}{\epsilon} \frac{r^{04}_{00}}{1 - r^{04}_{00}}$$

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



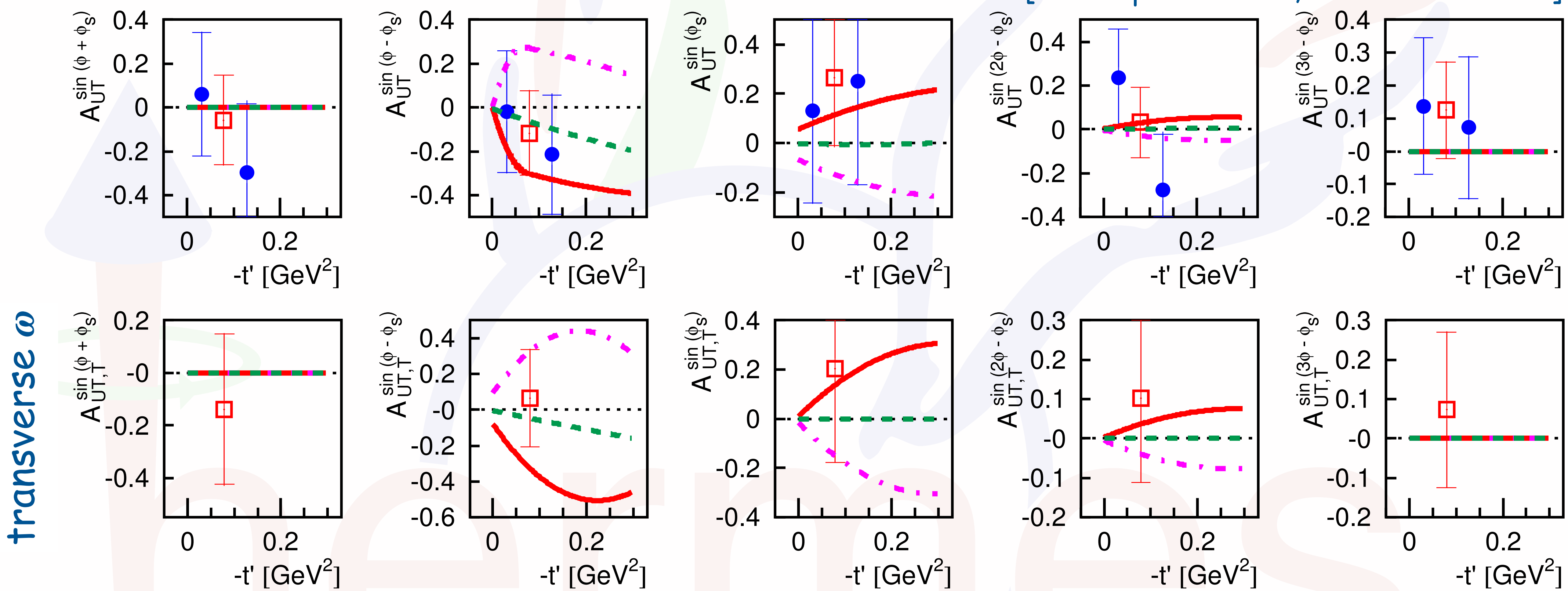
- significantly smaller for ω than for ρ
- important contribution from pion pole

transverse-spin asymmetry



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

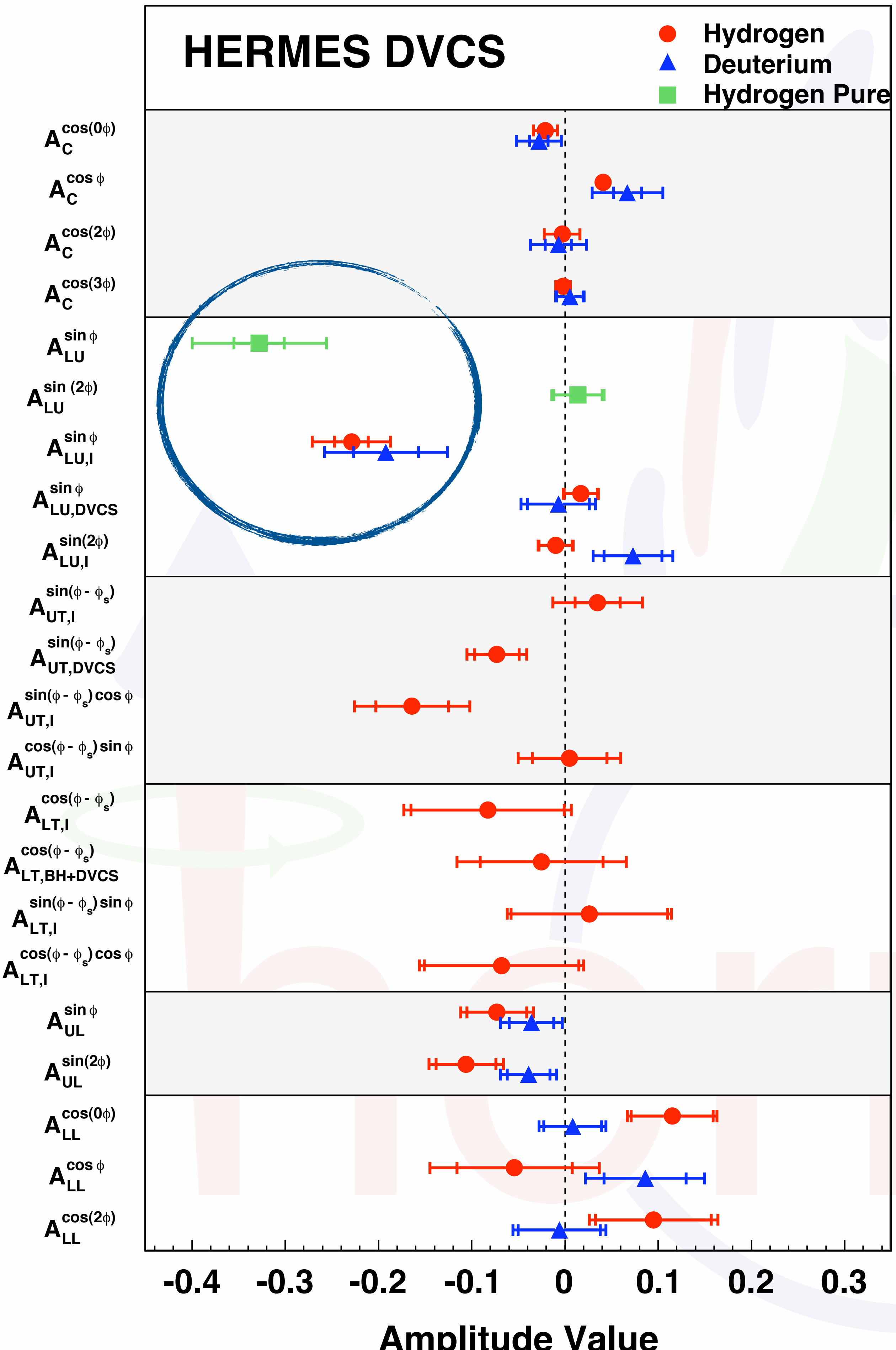
[A. Airapetian et al., arXiv:1508.07612]



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

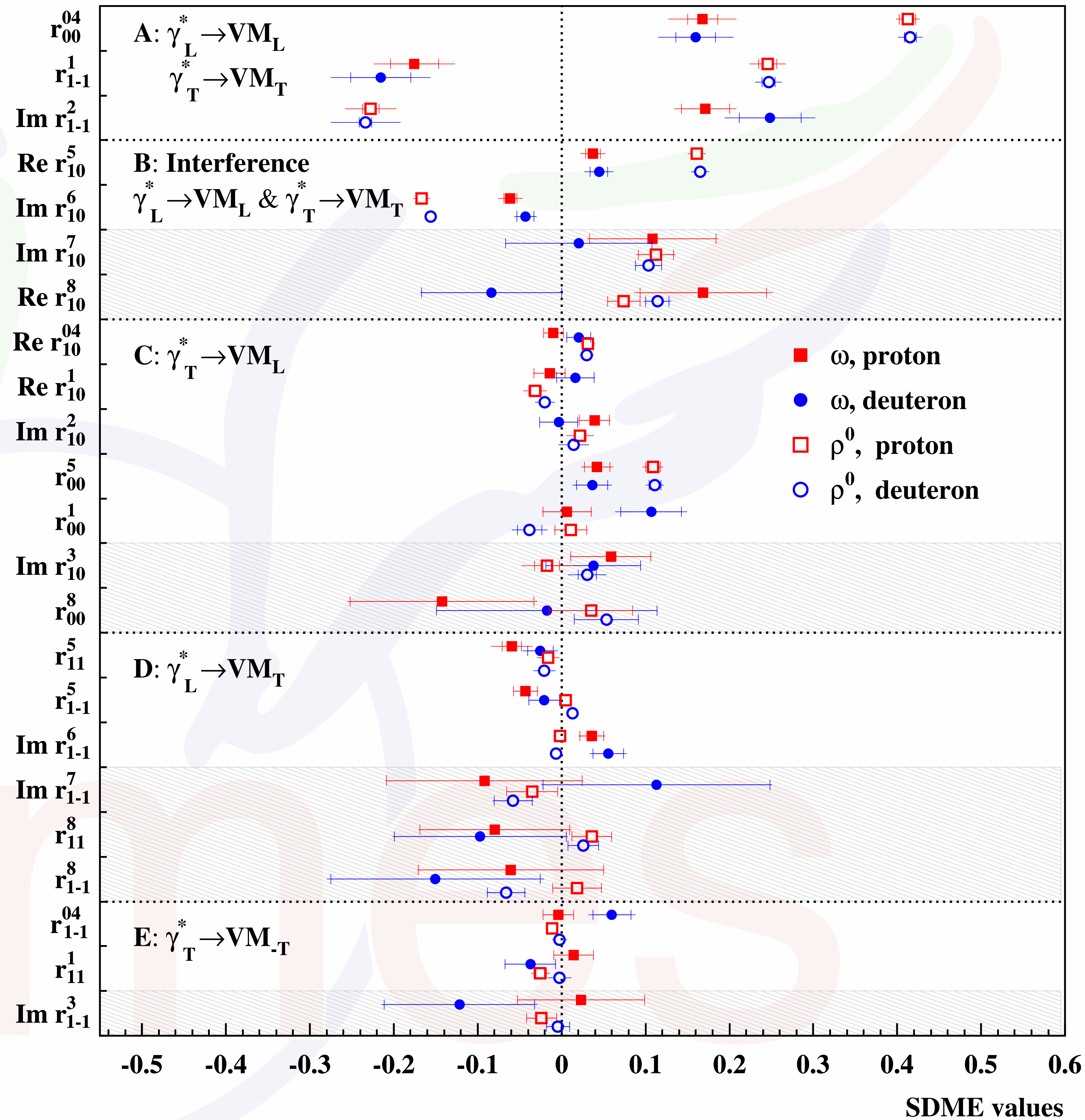
-> assoc. DVCS in "traditional" analysis mainly dilution, supported by **recent results from HERMES [JHEP 01 (2014) 077]:**

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

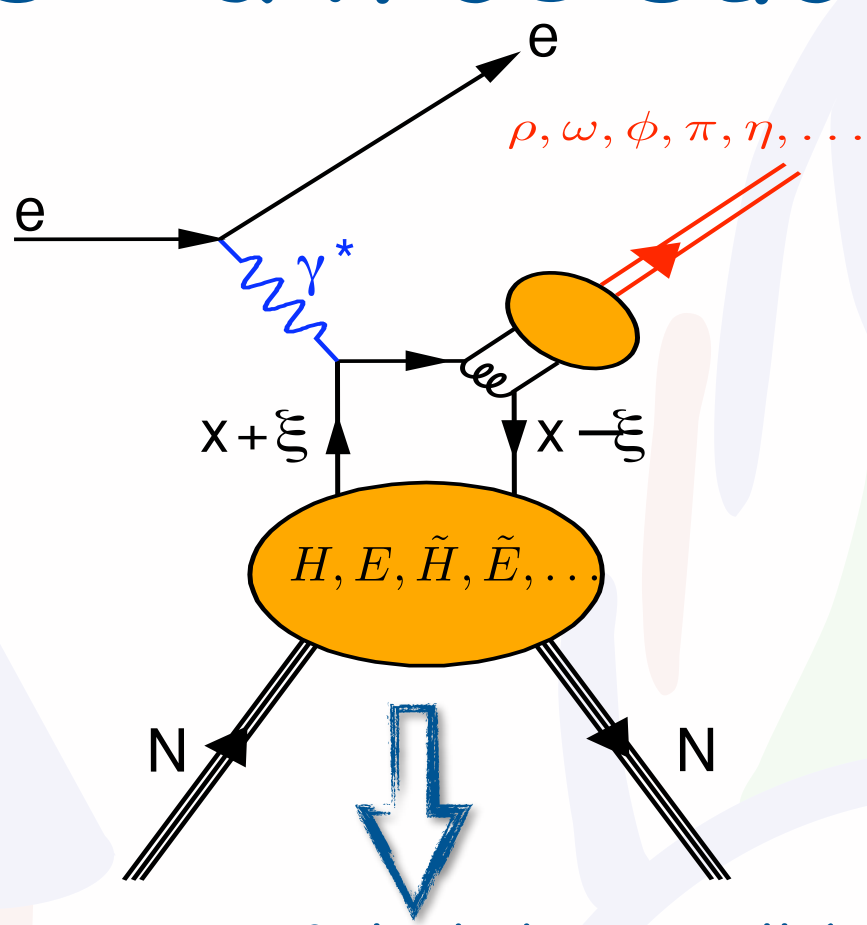
HEMP @ HERMES

- 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 contribution with a preference for positive $\pi\omega$ transition FF

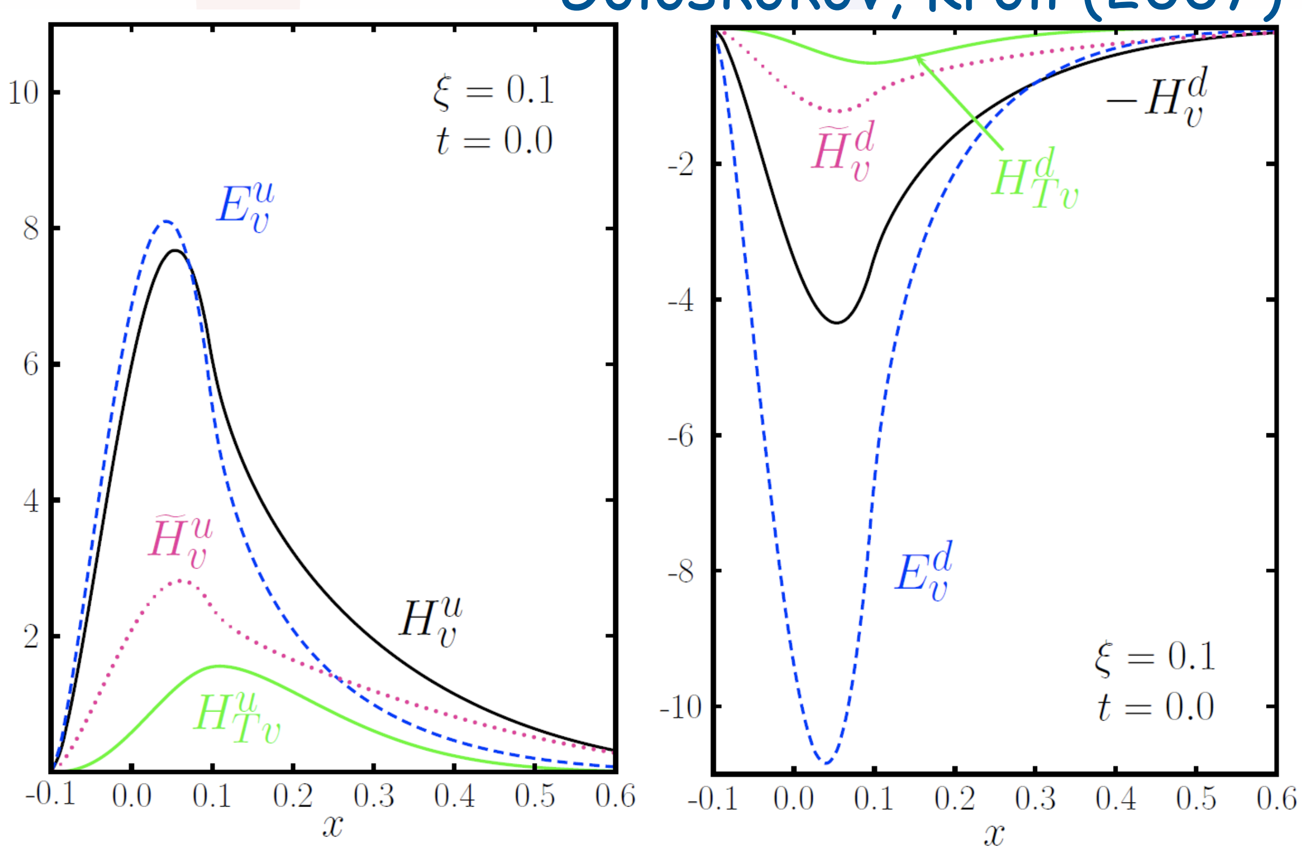
[A. Airapetian et al., EPJ C74 (2014) 3110, EPJ C62 (2009) 659]



GPDs - a nice success story!



Goloskokov, Kroll (2007)



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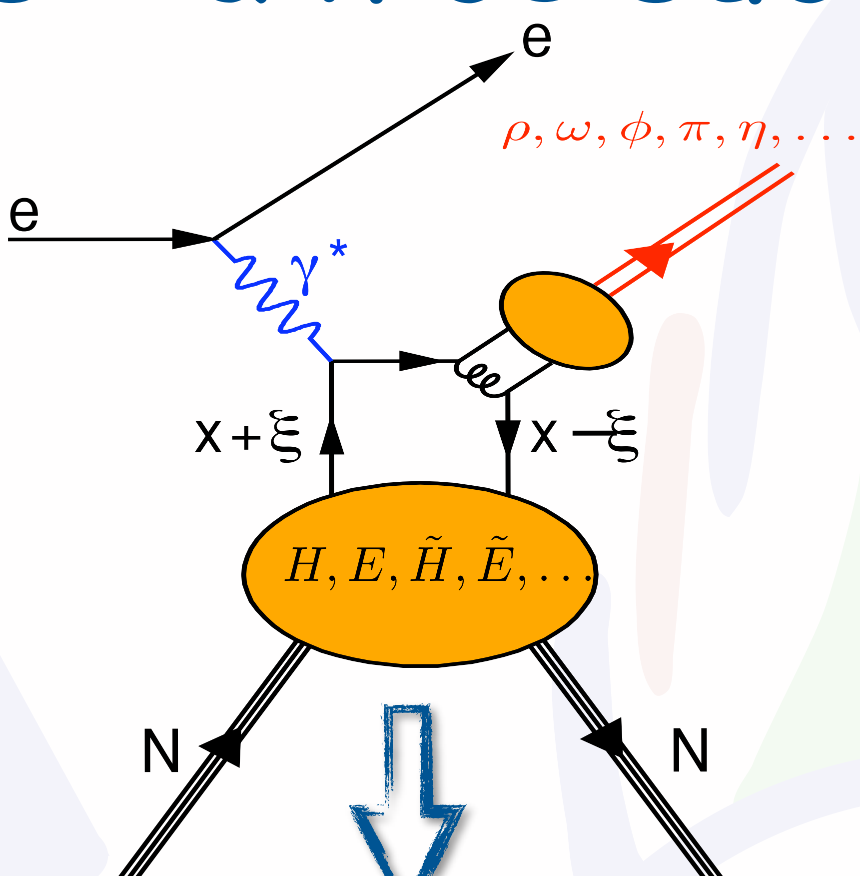

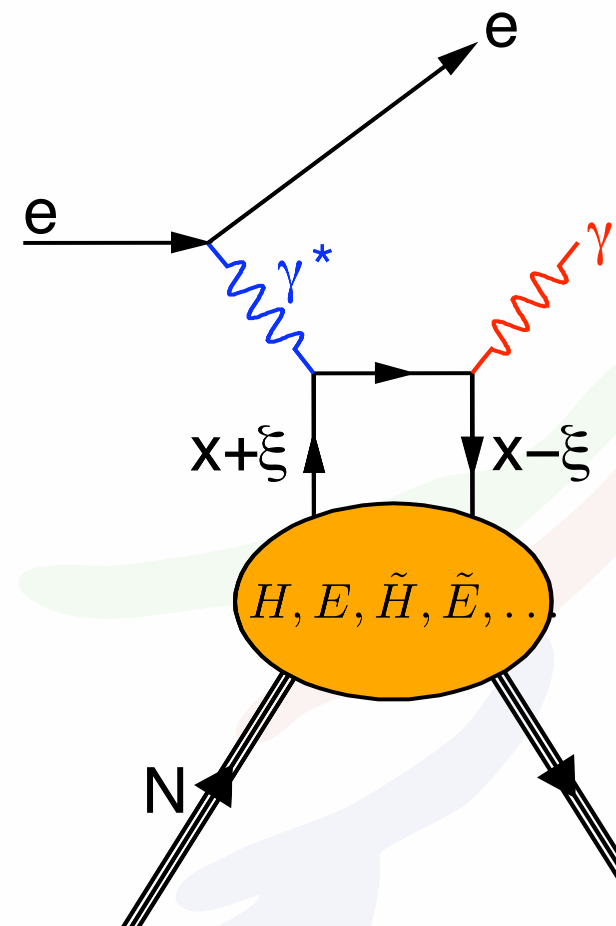

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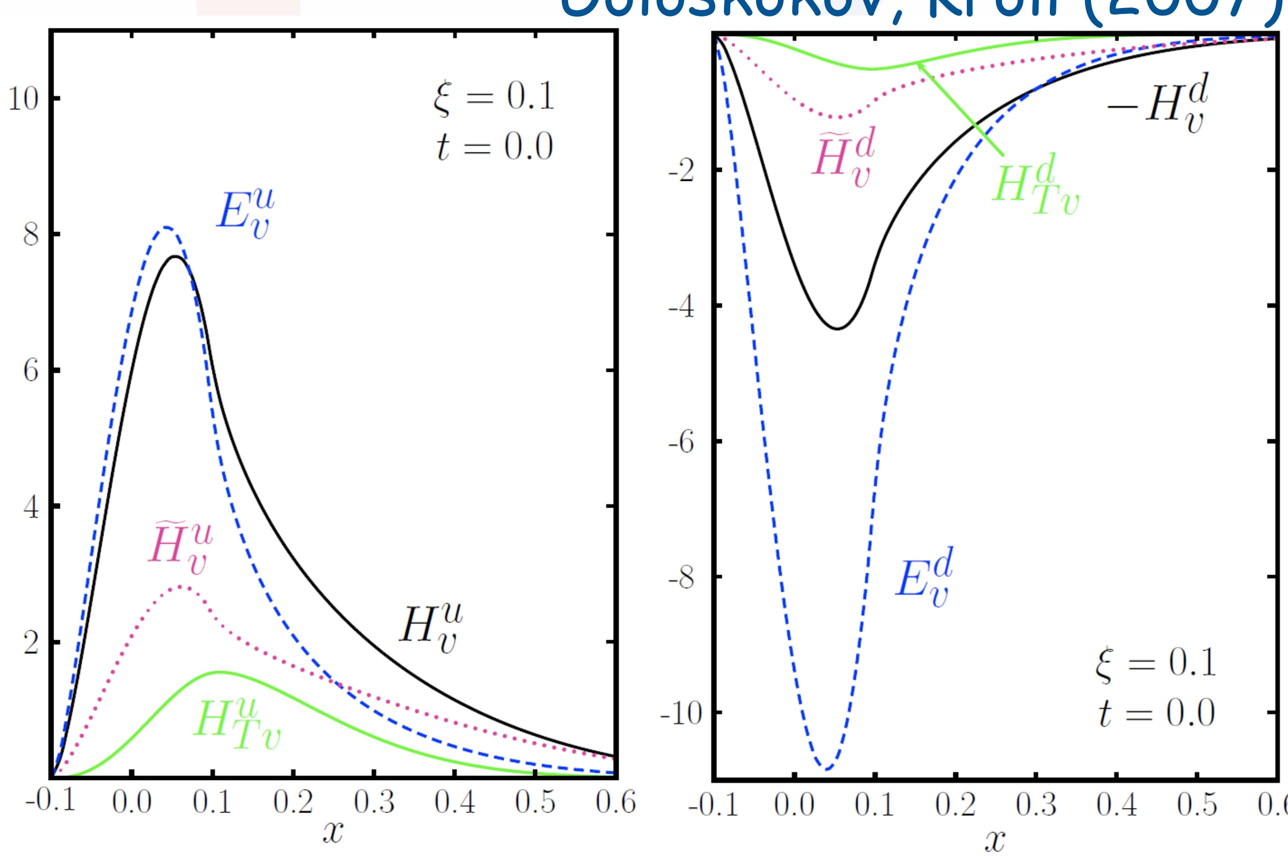
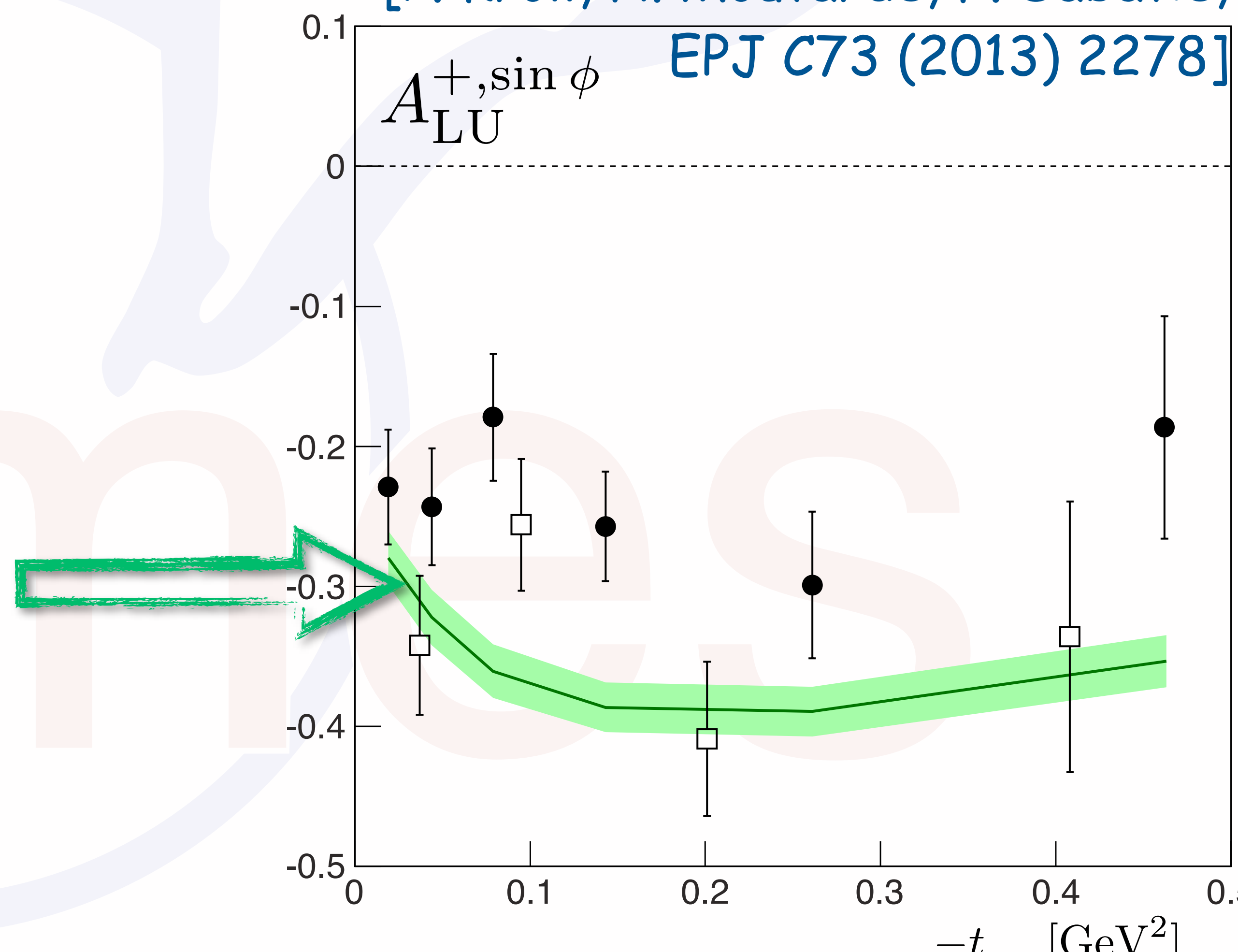
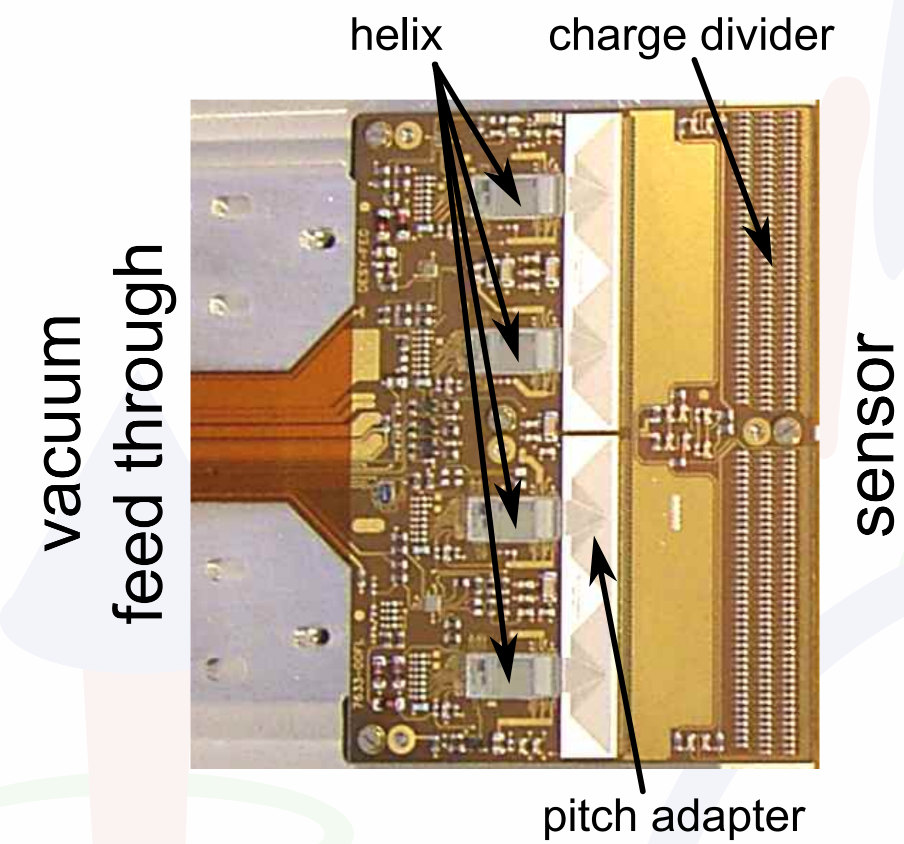


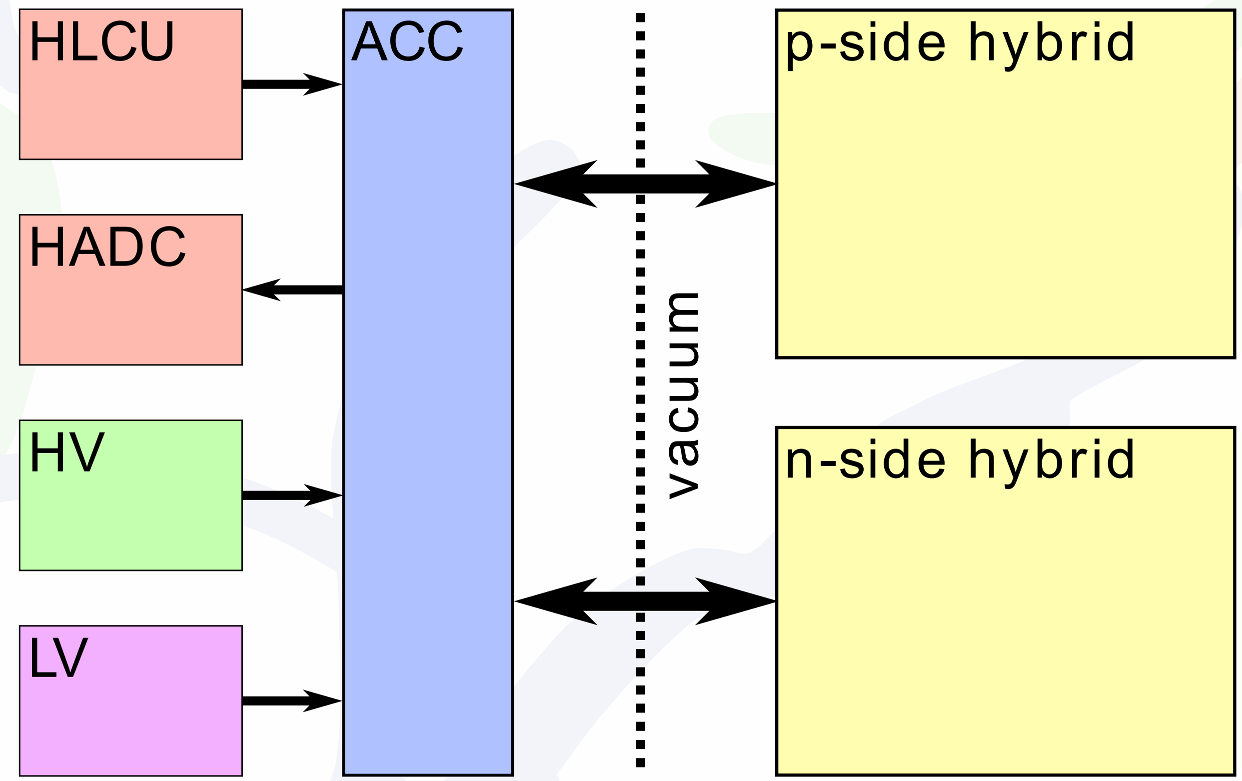
[P. Kroll, H. Moutarde, F. Sabatie, EPJ C73 (2013) 2278]



backup

SSD (silicon strip detector)





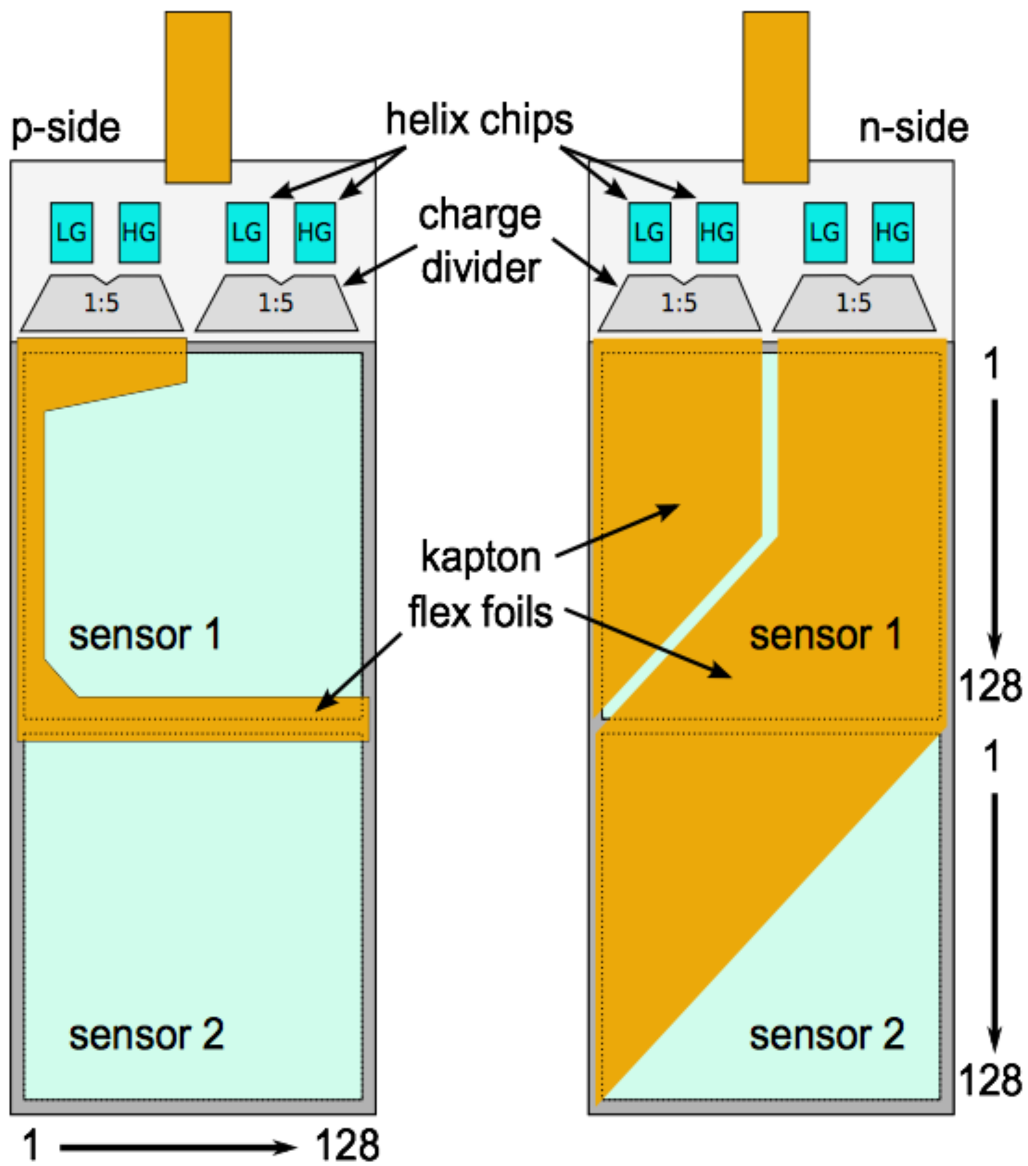
5.8 cm away from lepton beam, 1.5 cm gap

sensor thickness 295 μm - 315 μm

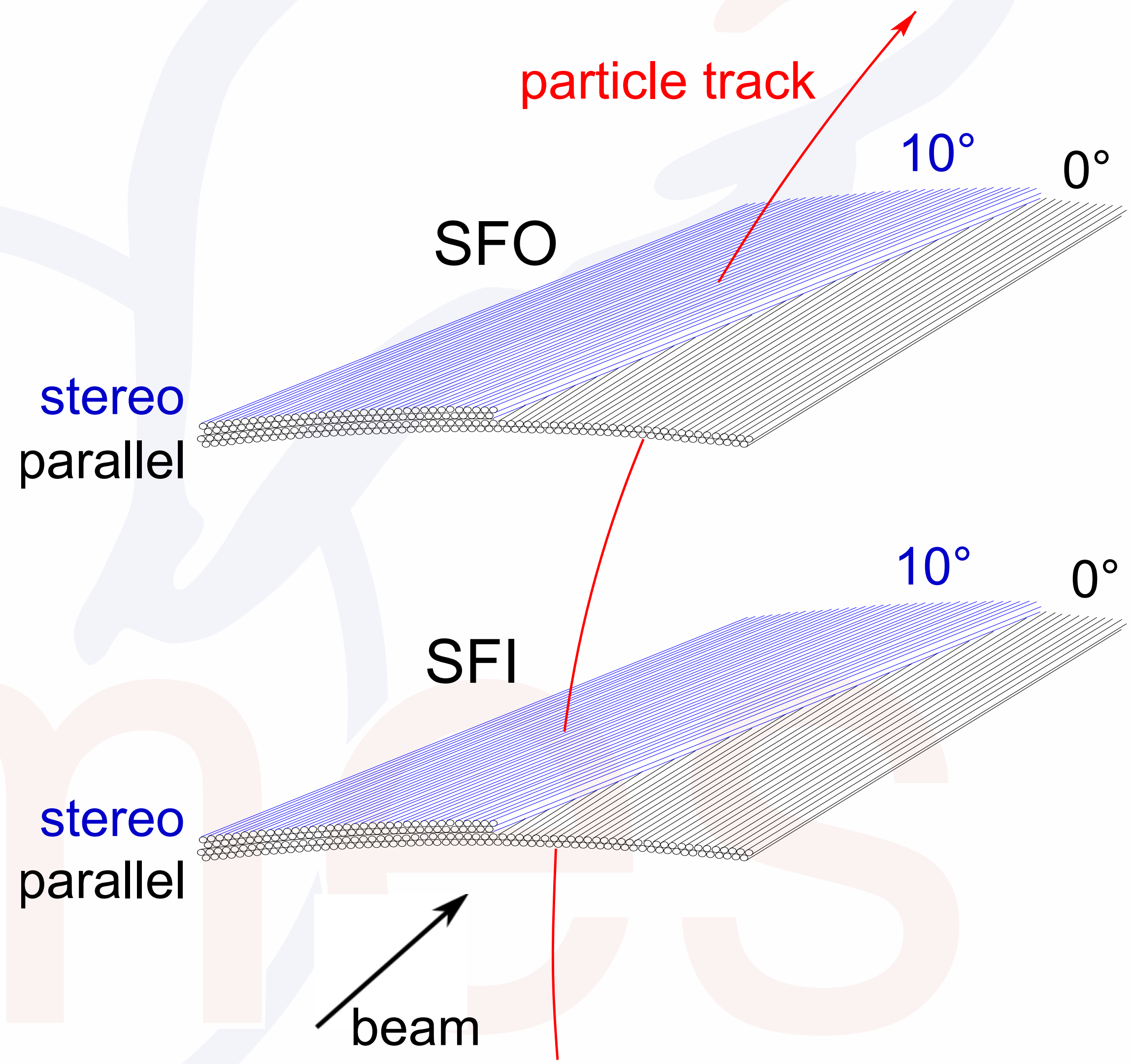
thickness of target cell 75 μm

The HERMES recoil detector

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

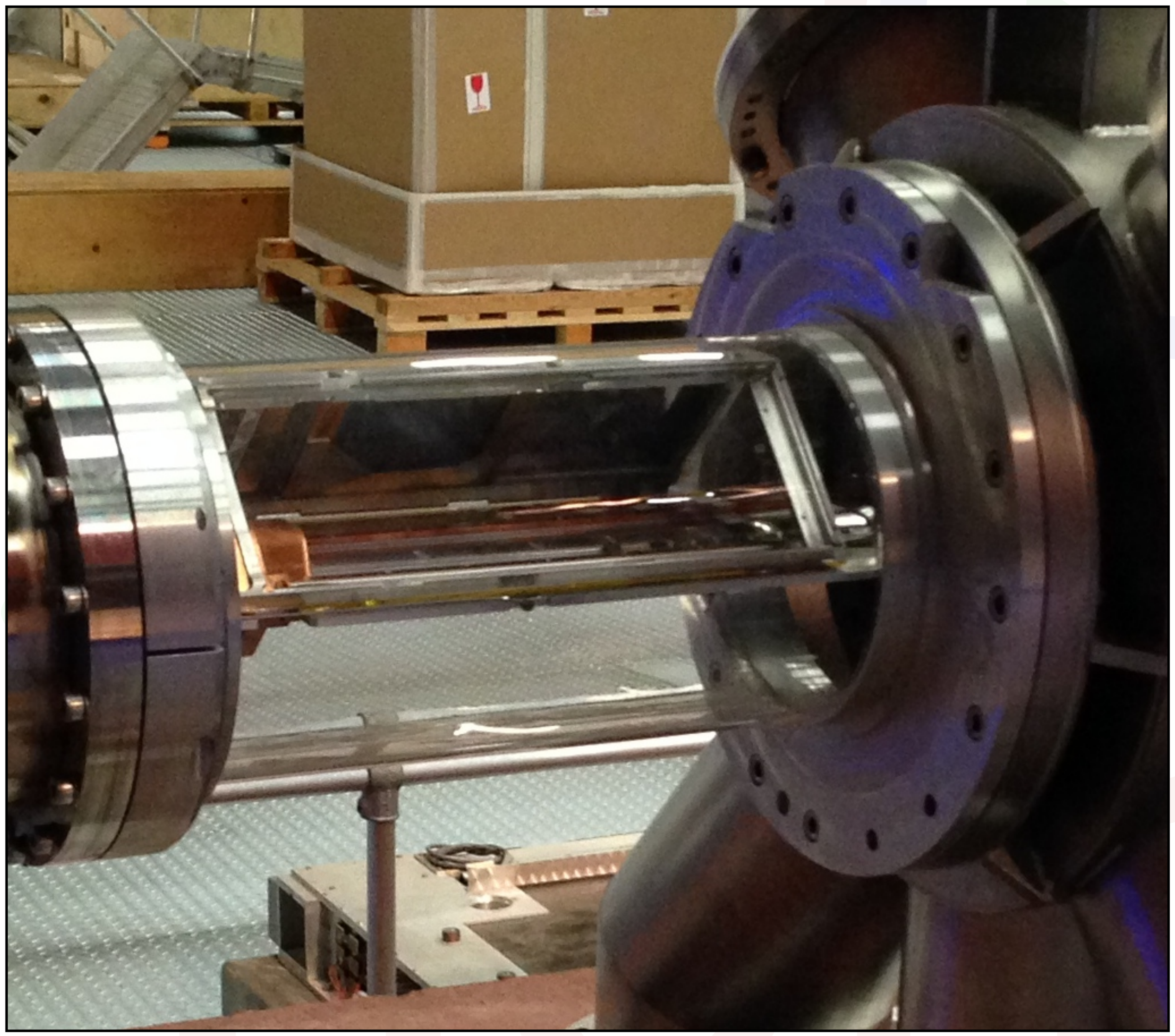


Schematic design of the scintillating fibre tracker (SFT)



The HERMES recoil detector

The silicon strip detector (SSD)



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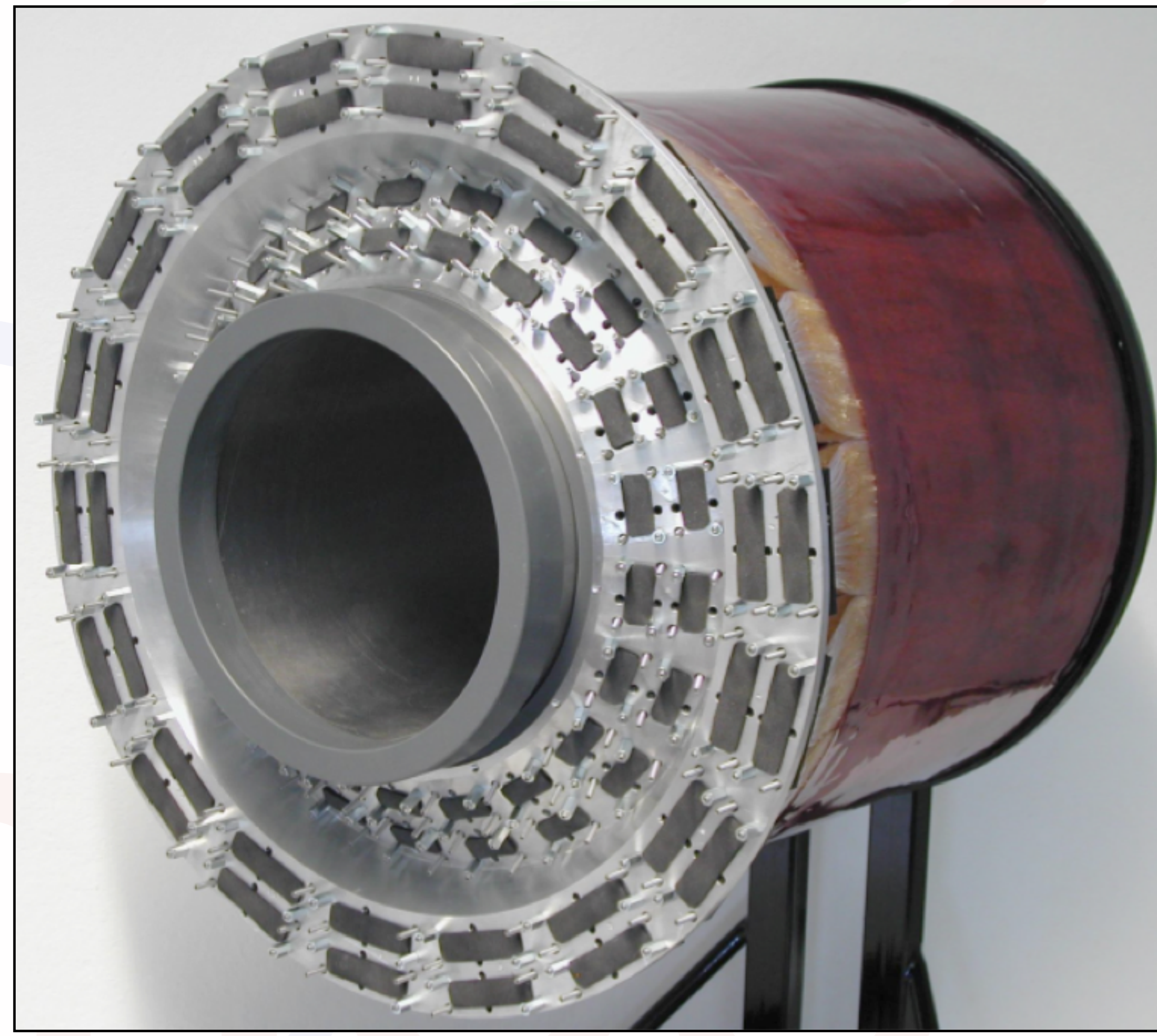
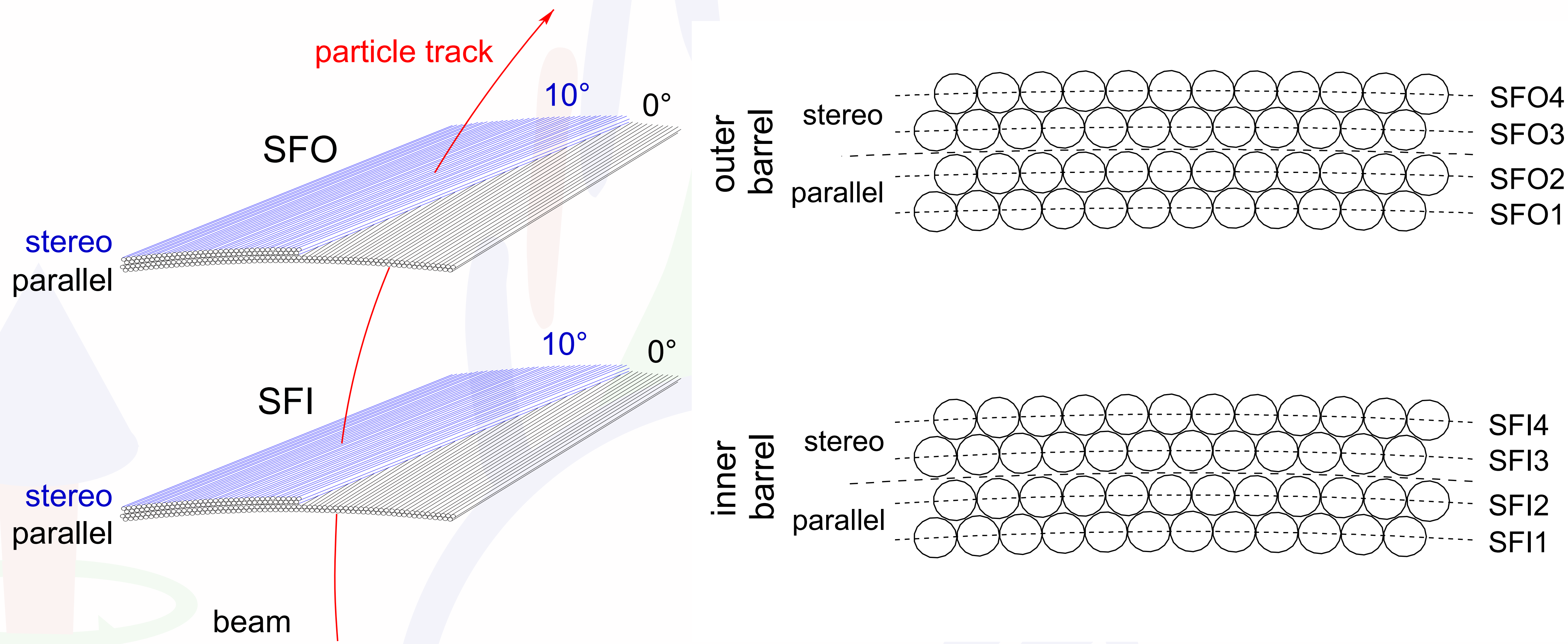


SFT (scintillating fibre tracker)

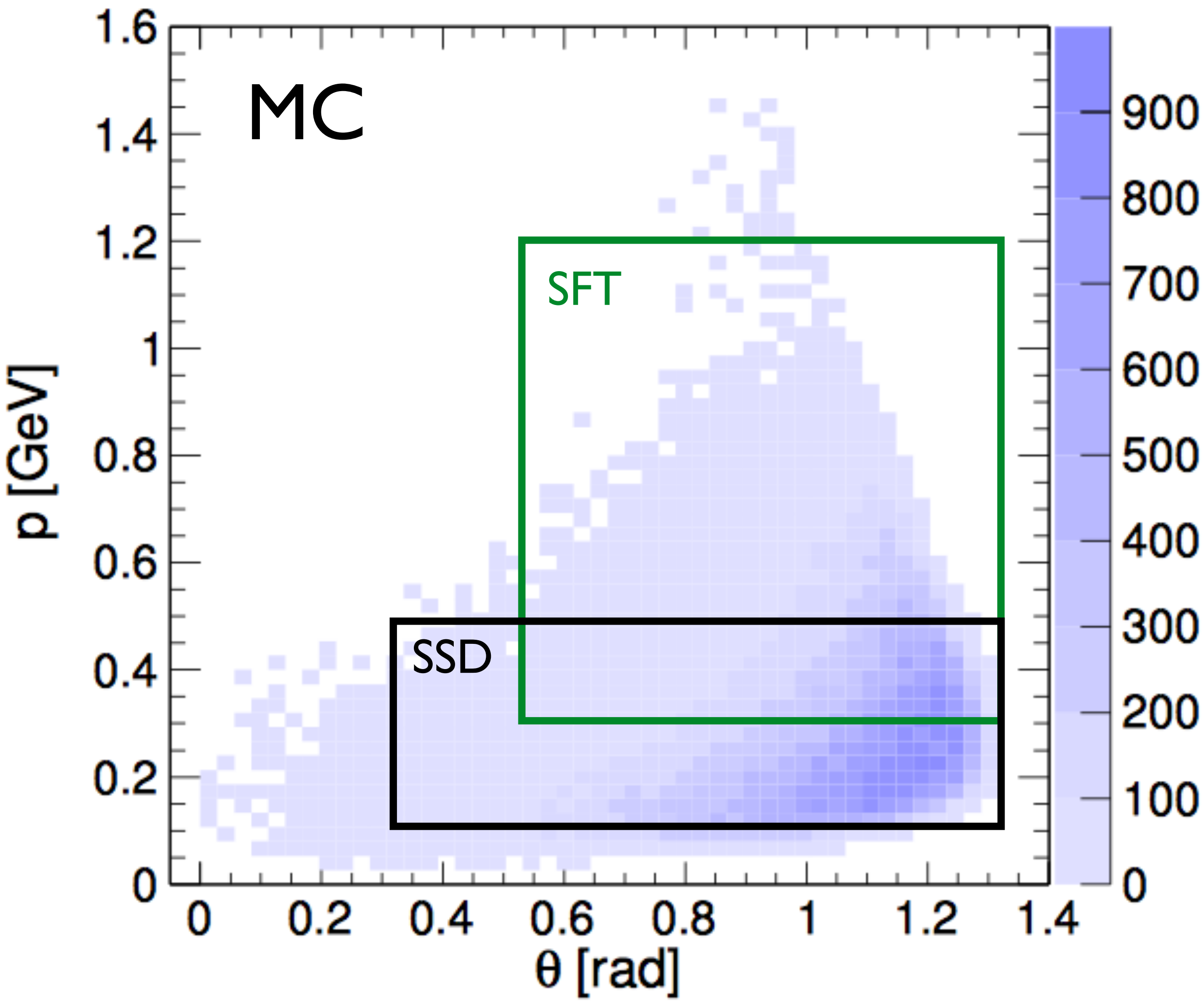


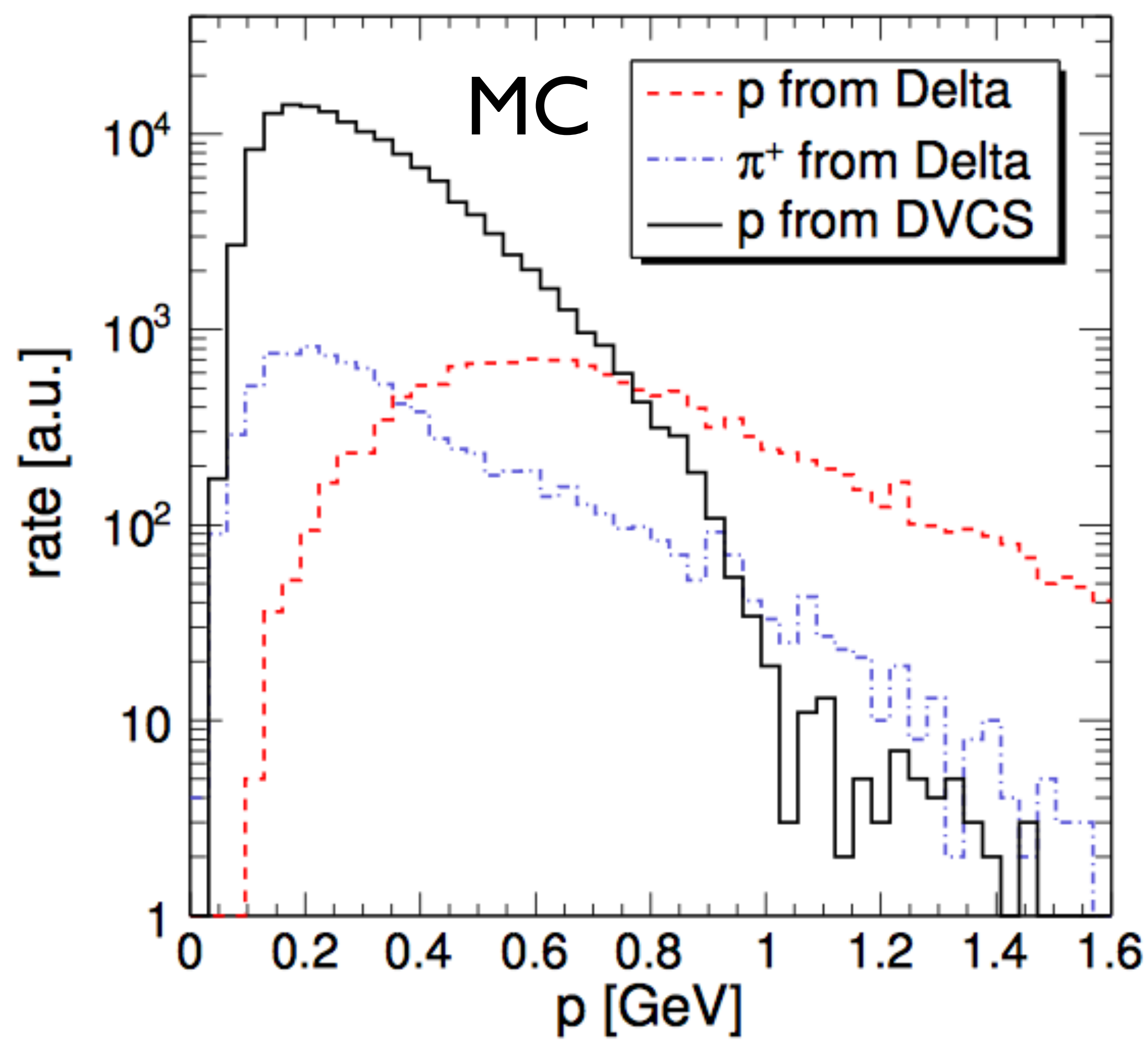
11.5 cm (18.5 cm) inner (outer) radius

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

readout by 64-channel Hamamatsu H7546B MAPMTs

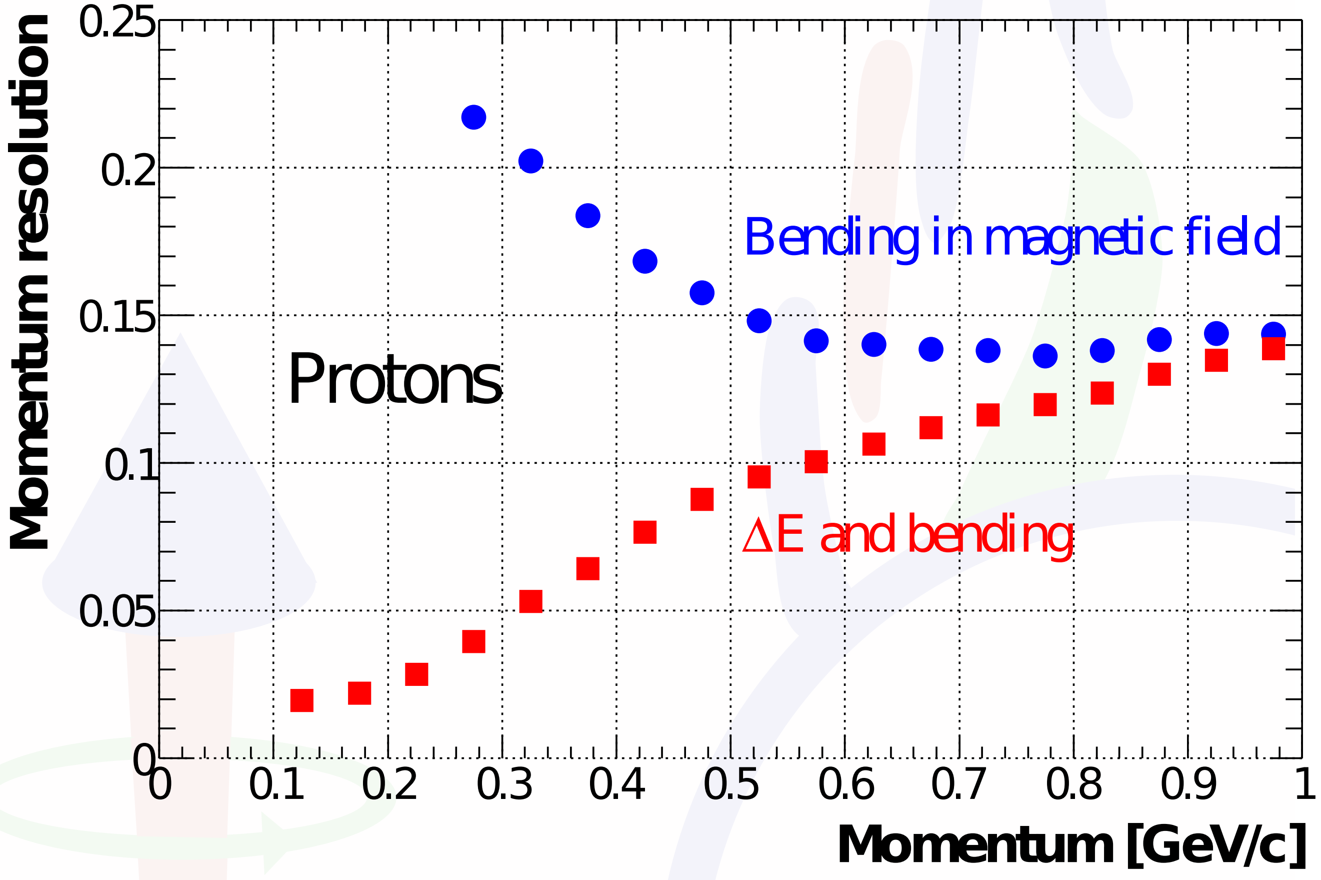
Kinematic coverage of the HERMES RD

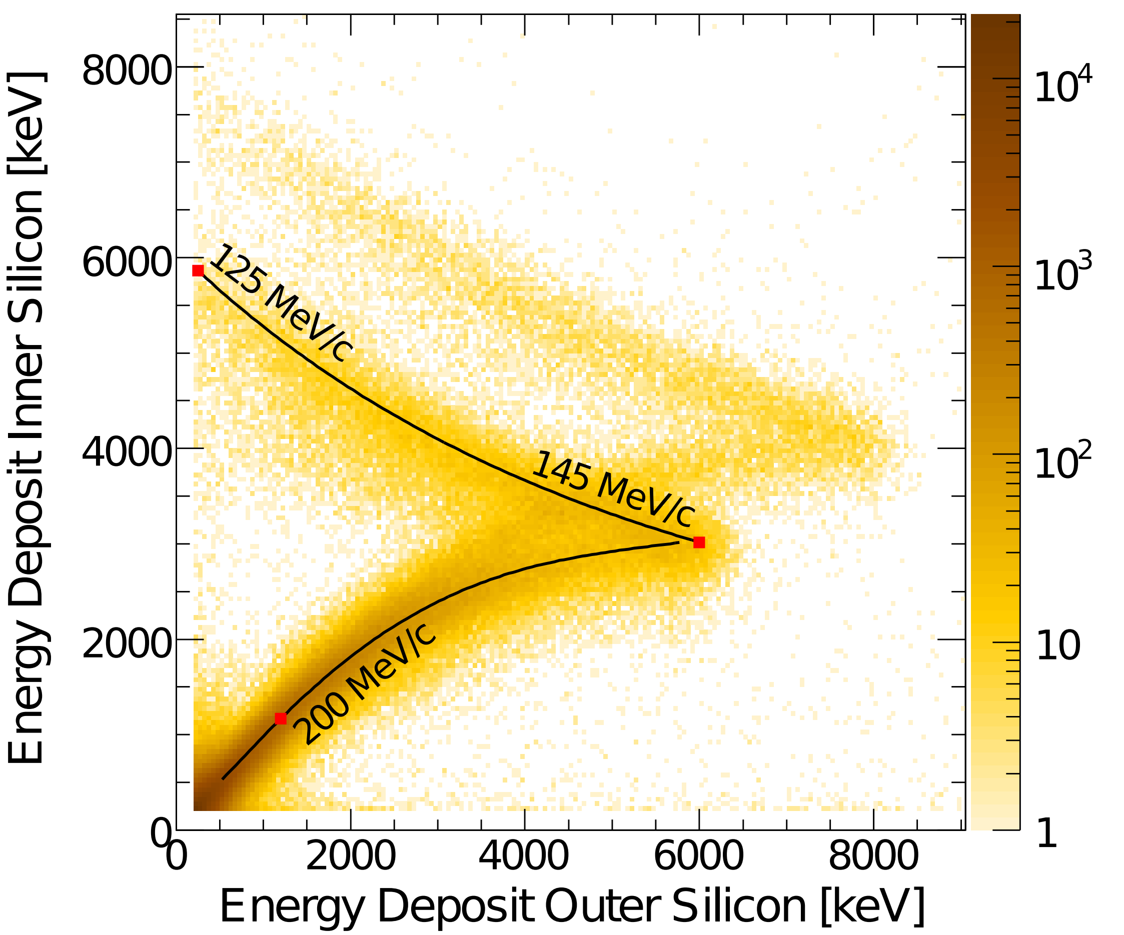




Scintillating fibre tracker (SFT) and silicon strip detector (SSD) complement each other

Recoil-detector tracking



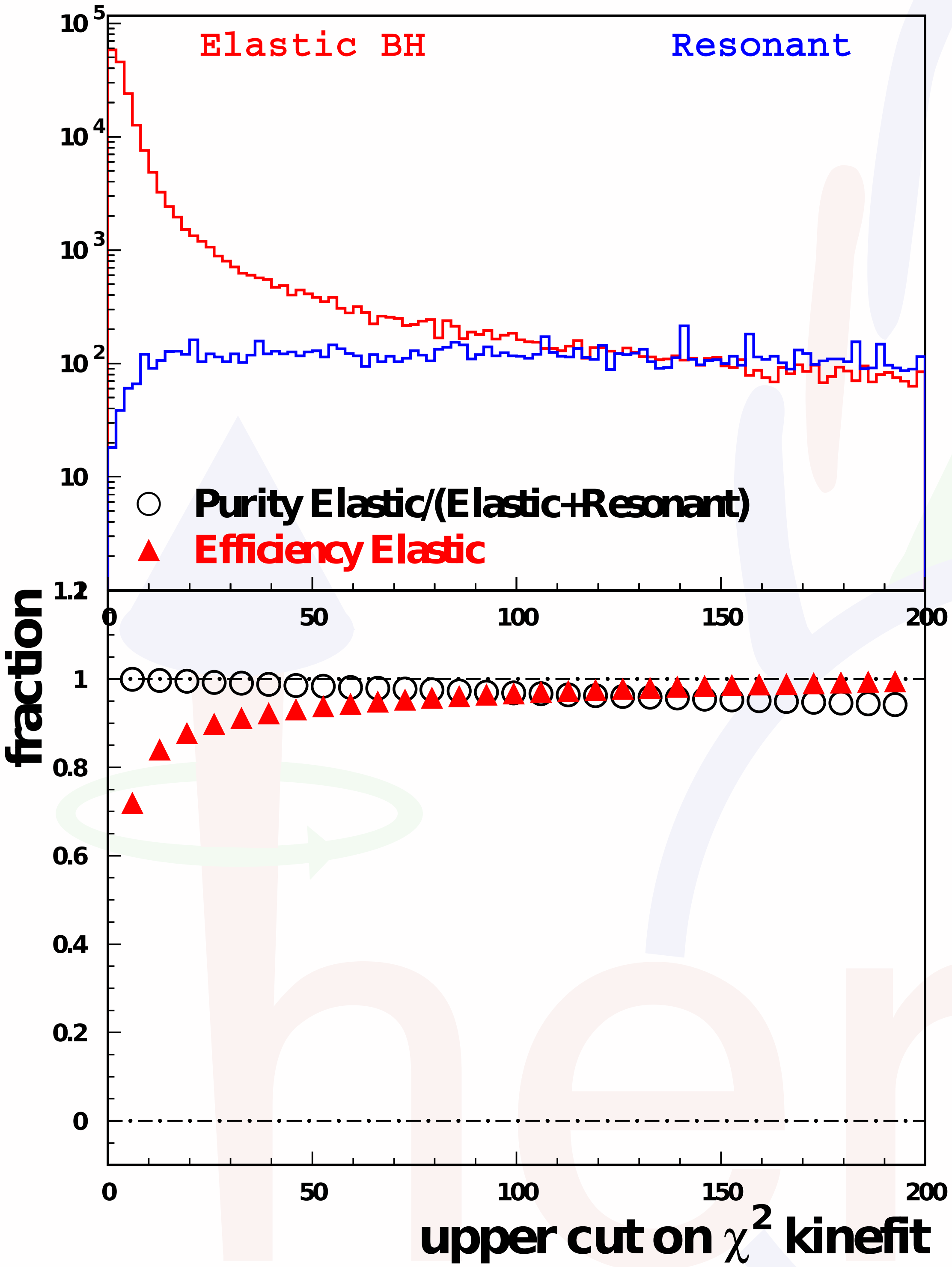


taking energy loss into account improves momentum resolution for low p

azimuthal-angle resolution: 4 mrad

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

Kinematic event fitting

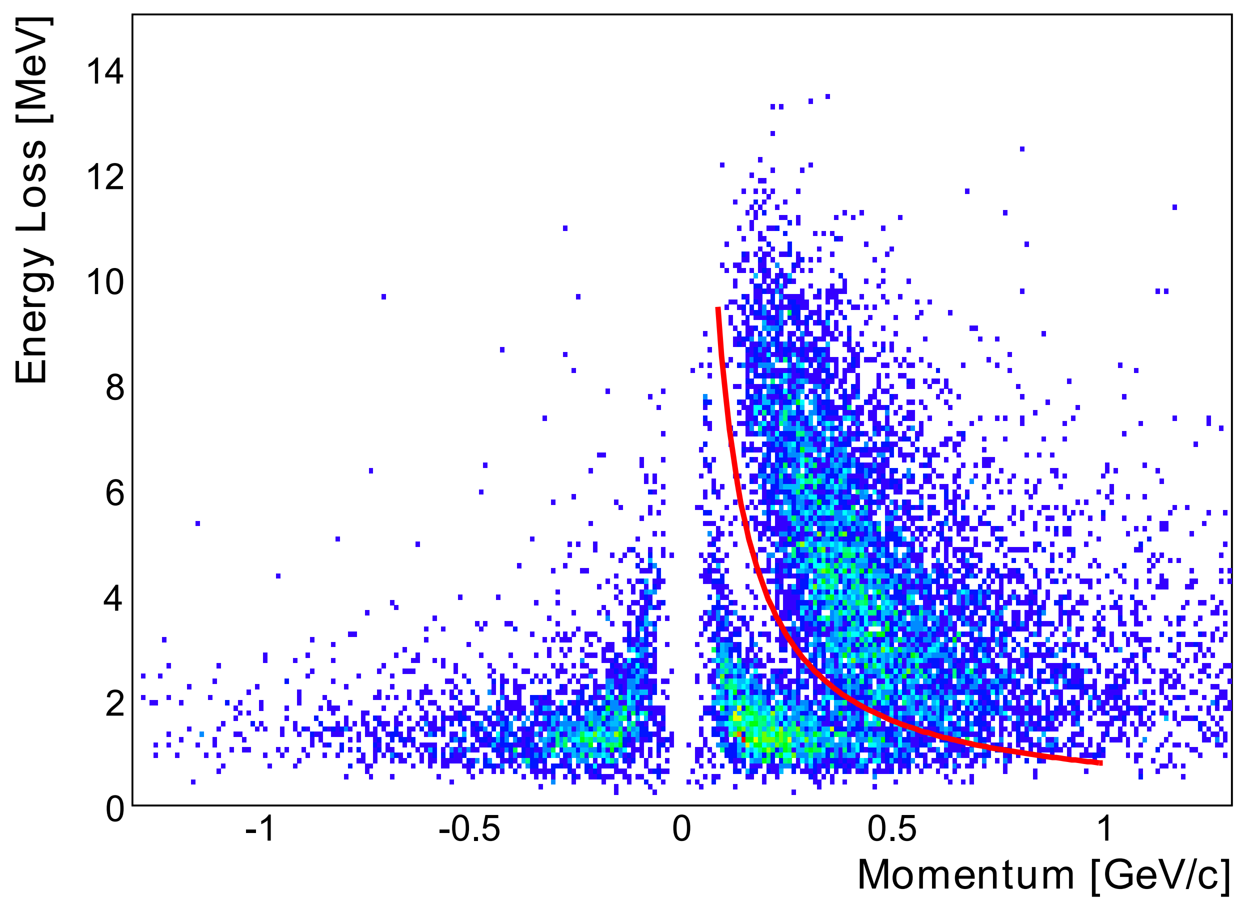


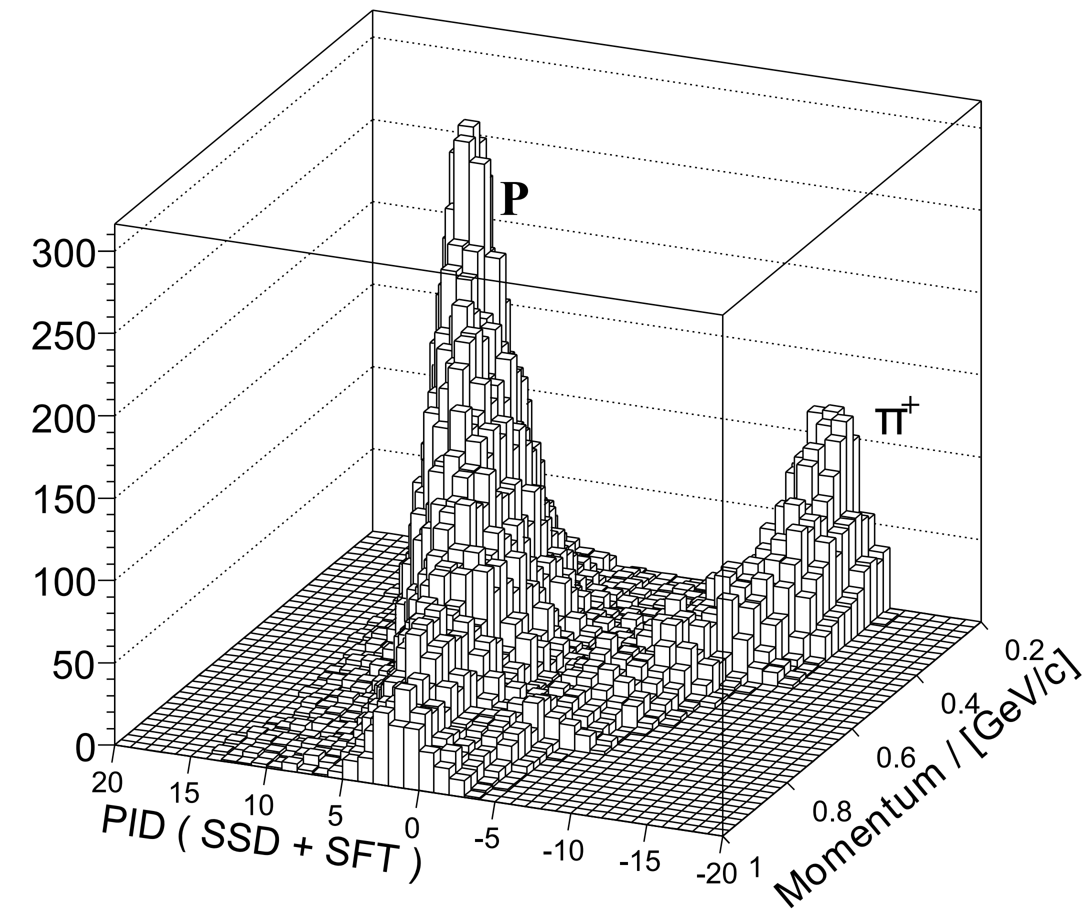
$$\chi^2_{pen} = \sum_{i=1}^{9} \frac{(r_i^{fit} - r_i^{meas})^2}{\sigma_i^2} + T \cdot \sum_{j=1}^{4} \frac{\left[f_j(r_1^{fit}, \ldots, r_9^{fit})\right]^2}{(\sigma_j^f)^2}$$

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



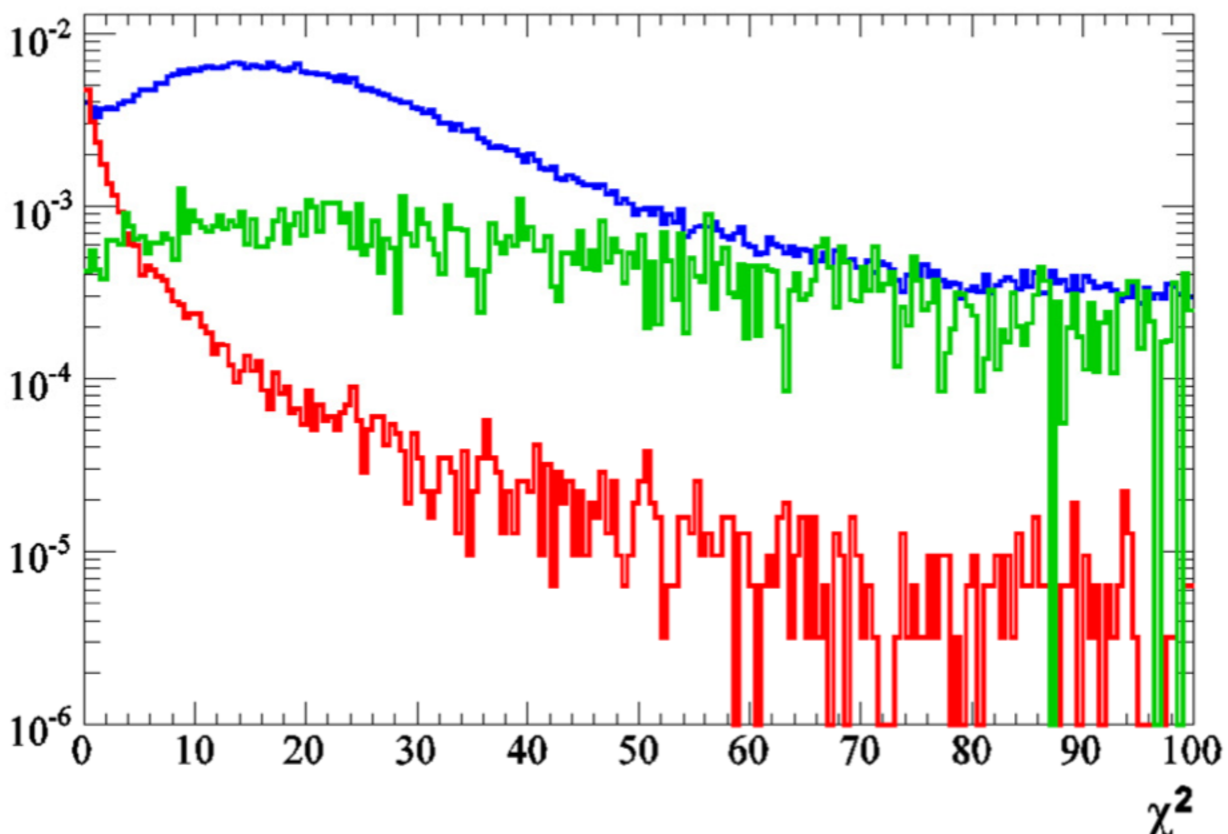


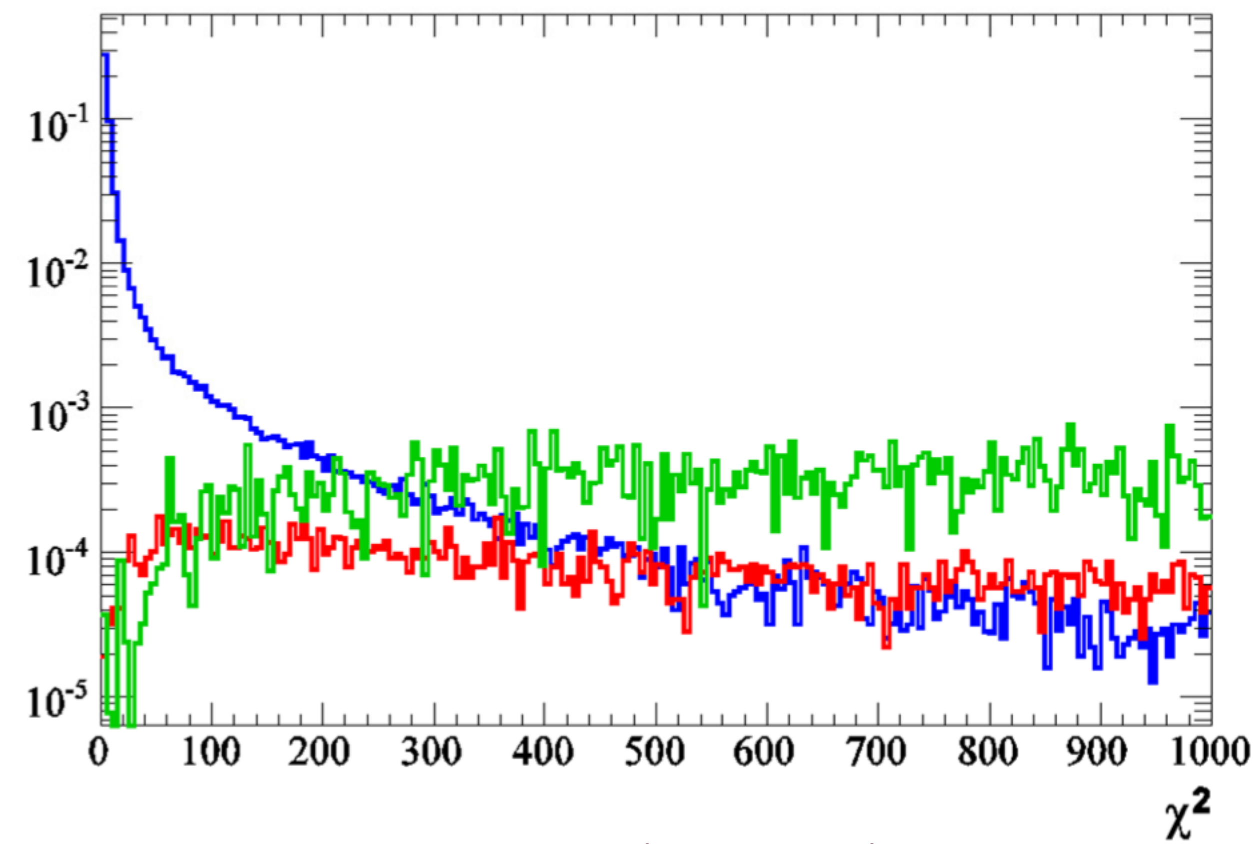
discrimination between protons and positively charged pions

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

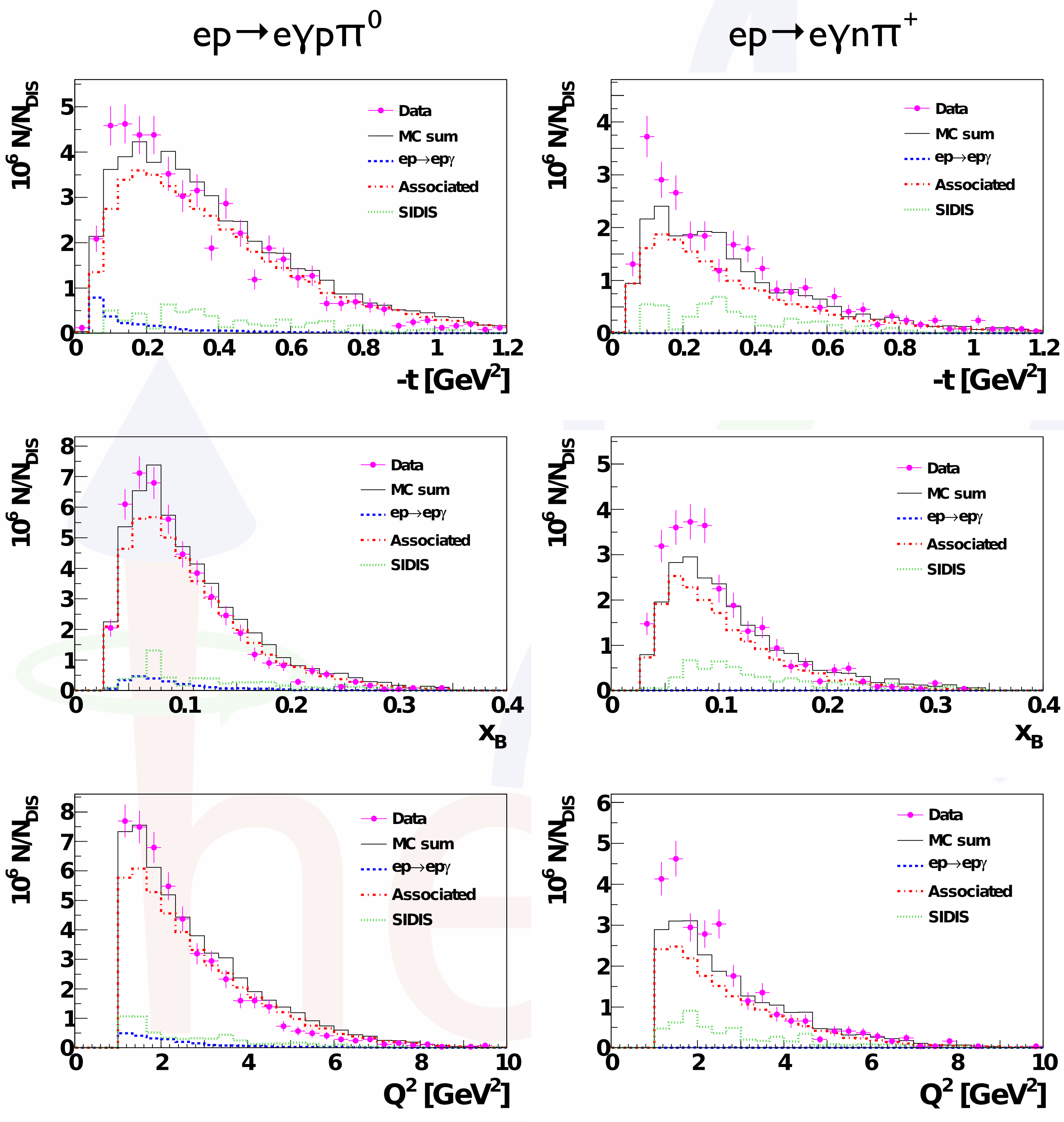
$\chi^2_{ep \rightarrow e\gamma p\pi^0} < 4.6$

$ep \rightarrow e\gamma p$ 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 $ep \rightarrow e\gamma N\pi$ hypothesis therefore not as strong

Additional selection criteria:

- Recoil PID information
- Lower-cut on $ep \rightarrow e\gamma p$ hypothesis