Beam Spin Asymmetry in Deeply Virtual Meson Production off the Scalar Target

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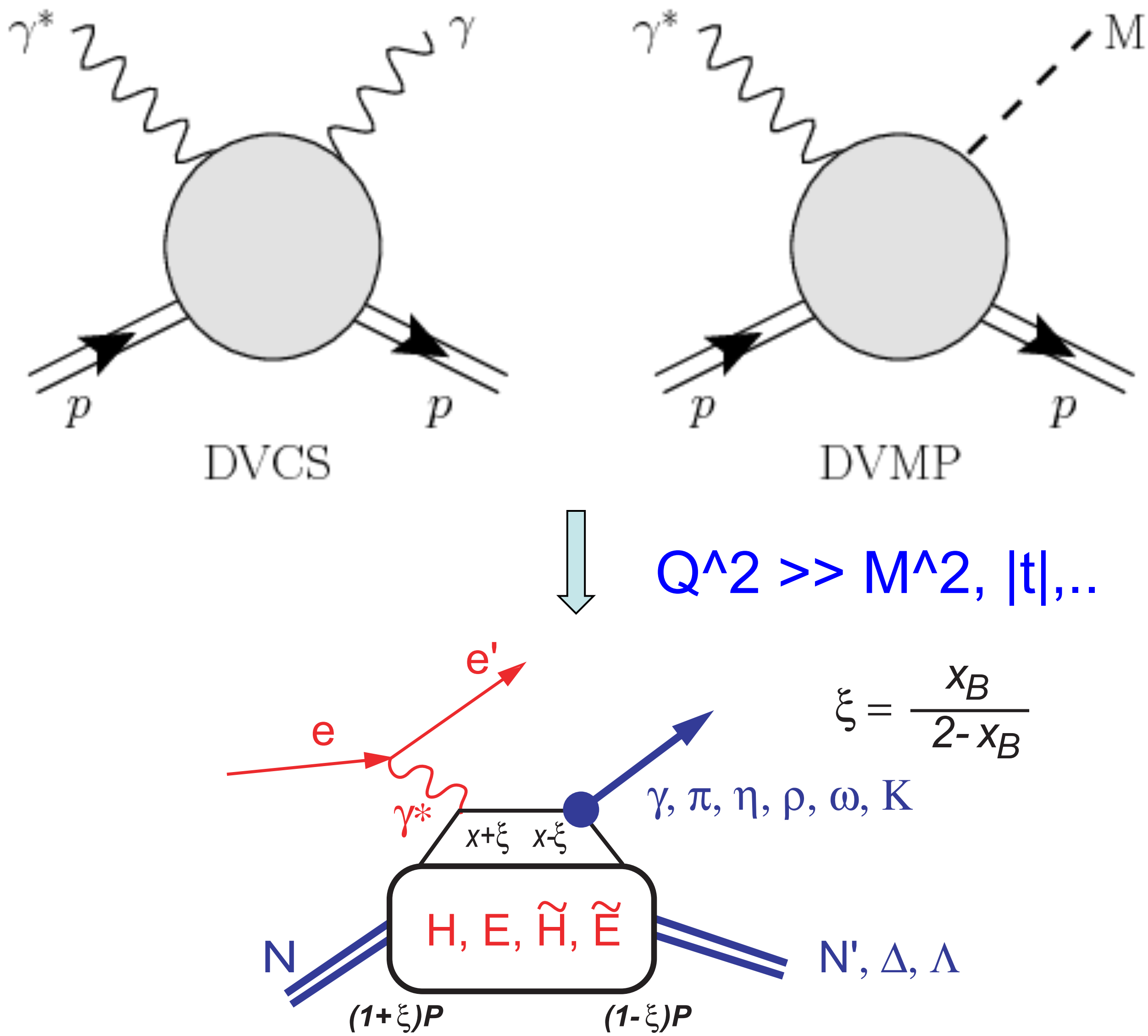
The Nature of Hadron Mass and Quark-Gluon Confinement from JLab Experiments in the 12-GeV Era

APCTP, July 2, 2018

Outline

- Proton GPDs in DVCS and DVMP
- 5-Fold Differential Cross Section (Notations)
- Hadronic Currents in Meson Production off the Scalar Target (0^{++} vs. 0^{-+})
- Benchmark BSA for π^0 production off ^{4}He
- Generalized Compton Form Factors of ^{4}He
- Conclusion and Outlook

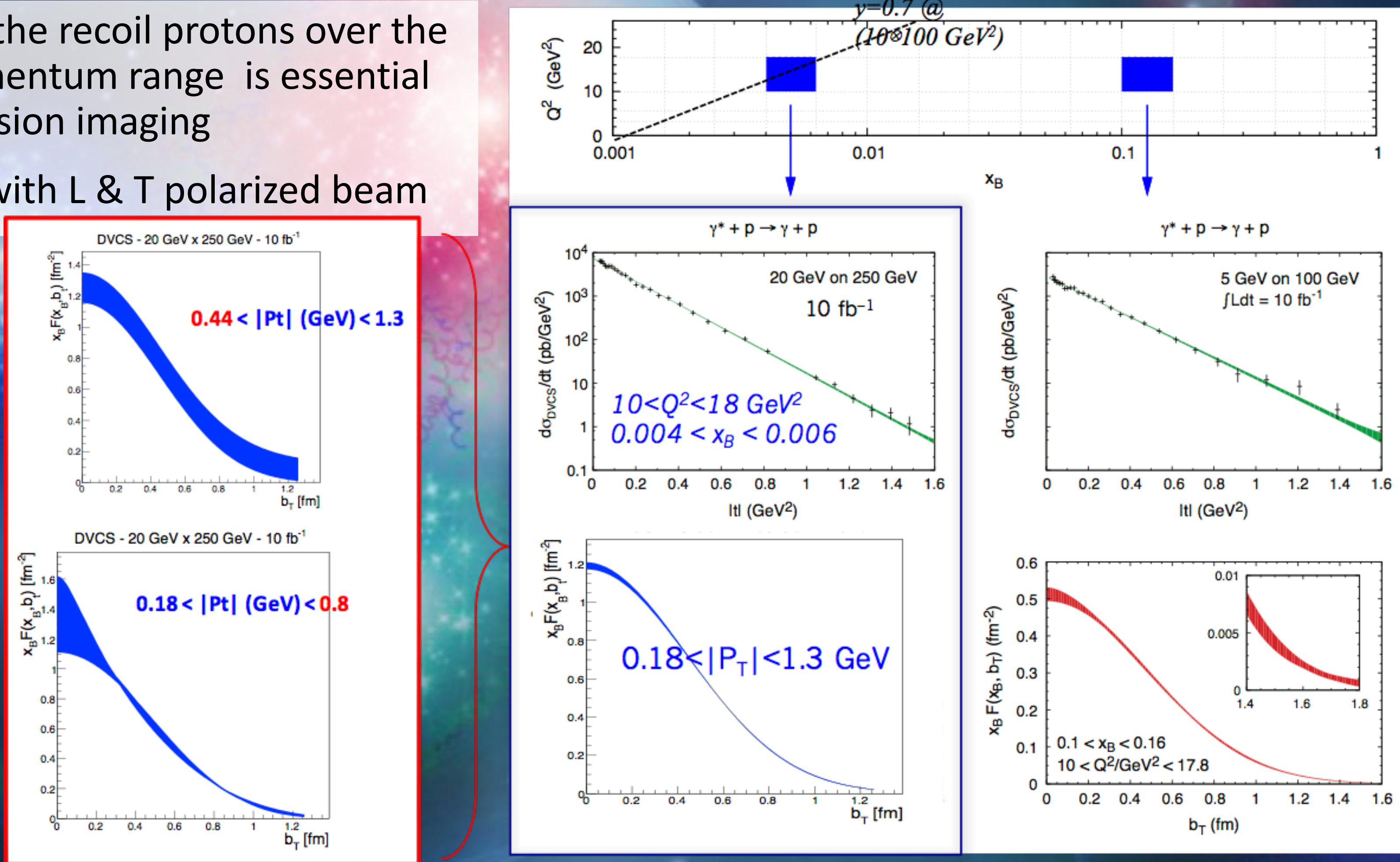


H, E - unpolarized, H̃, Ẽ - polarized GPD

The GPDs Define Nucleon Structure

DVCS on the Proton at the EIC:
Transverse Imaging vs x_B

- Tagging the recoil protons over the full momentum range is essential for precision imaging
- Repeat with L & T polarized beam



In[277]:=

```
Flatten[{{{"Q^2", "xBj", "k", "k'", "the", "thq", "thq'", "thp'", "q'", "t/Q^2"}},
  Table[Block[{M = 0.938, Q = Sqrt[pars[[i, 1]]], xBj = pars[[i, 2]], Eb = pars[[i, 3]],
    the = pars[[i, 4]] Pi / 180, thetaC = 20 Pi / 180, thq = ArcCos[costhetaqT2]},
   {Q^2, xBj, Eb, PeT1, the 180 / Pi, thq 180 / Pi, ArcCos[costhqf] 180 / Pi, ArcCos[
     costhpf] 180 / Pi, qfT3mu[[1]], MandeltT2 / Q^2}], {i, 1, 12}]}, 1] // MatrixForm
```

Out[277]//MatrixForm=

Q^2	xBj	k	k'	the	thq	thq'	thp'	q'	t/Q^2
1.9	0.36	5.75	2.93669	19.3	18.0503	11.9997	69.6549	2.65582	-0.1555
3.	0.36	6.6	2.15792	26.5	11.6529	6.69292	66.0322	4.23202	-0.131356
4.	0.36	8.8	2.87723	22.9	10.3184	5.96439	64.4845	5.66645	-0.120212
4.55	0.36	11.	4.26285	17.9	10.6859	6.58293	64.1816	6.45567	-0.116055
3.1	0.5	6.6	3.2951	22.5	19.5262	14.4829	60.4087	3.0229	-0.170658
4.8	0.5	8.8	3.68273	22.2	14.4748	10.3331	57.1229	4.76891	-0.13615
6.3	0.5	11.	4.28358	21.1	12.4174	8.76649	55.3539	6.31422	-0.119765
7.2	0.5	11.	3.32409	25.6	10.1755	6.74662	53.737	7.24243	-0.112945
5.1	0.6	8.8	4.26908	21.2	17.7604	13.7928	51.4698	4.06193	-0.172513
6.	0.6	8.8	3.46951	25.6	14.8072	11.1302	49.5692	4.82846	-0.156969
7.7	0.6	11.	4.1592	23.6	13.0416	9.77439	48.0193	6.28128	-0.136317
9.	0.6	11.	3.00426	30.2	10.1946	7.16227	46.0515	7.39496	-0.125229

Table III in E12 - 06 - 114, Julie Roche et al.

Jlab 12 GeV Exclusive Kinematics

Review

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CONCEPTUAL ISSUES CONCERNING GENERALIZED PARTON DISTRIBUTIONS

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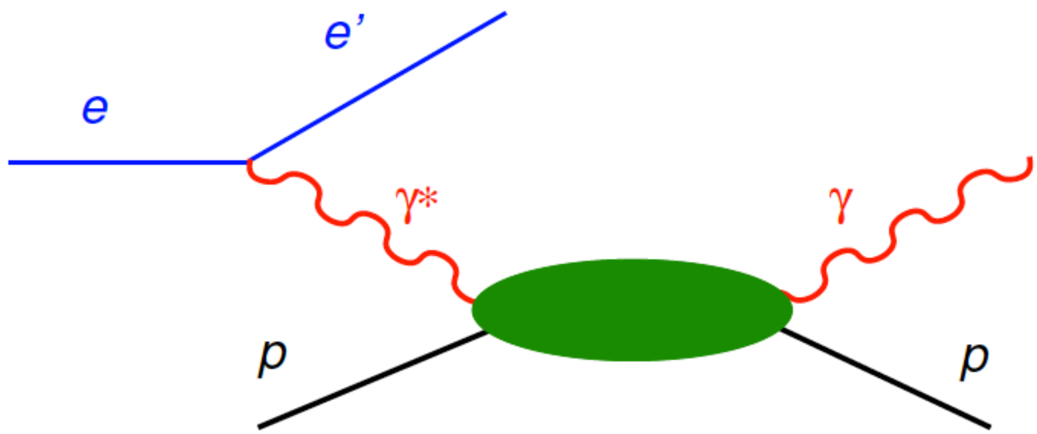
Number of Independent Amplitudes in VCS

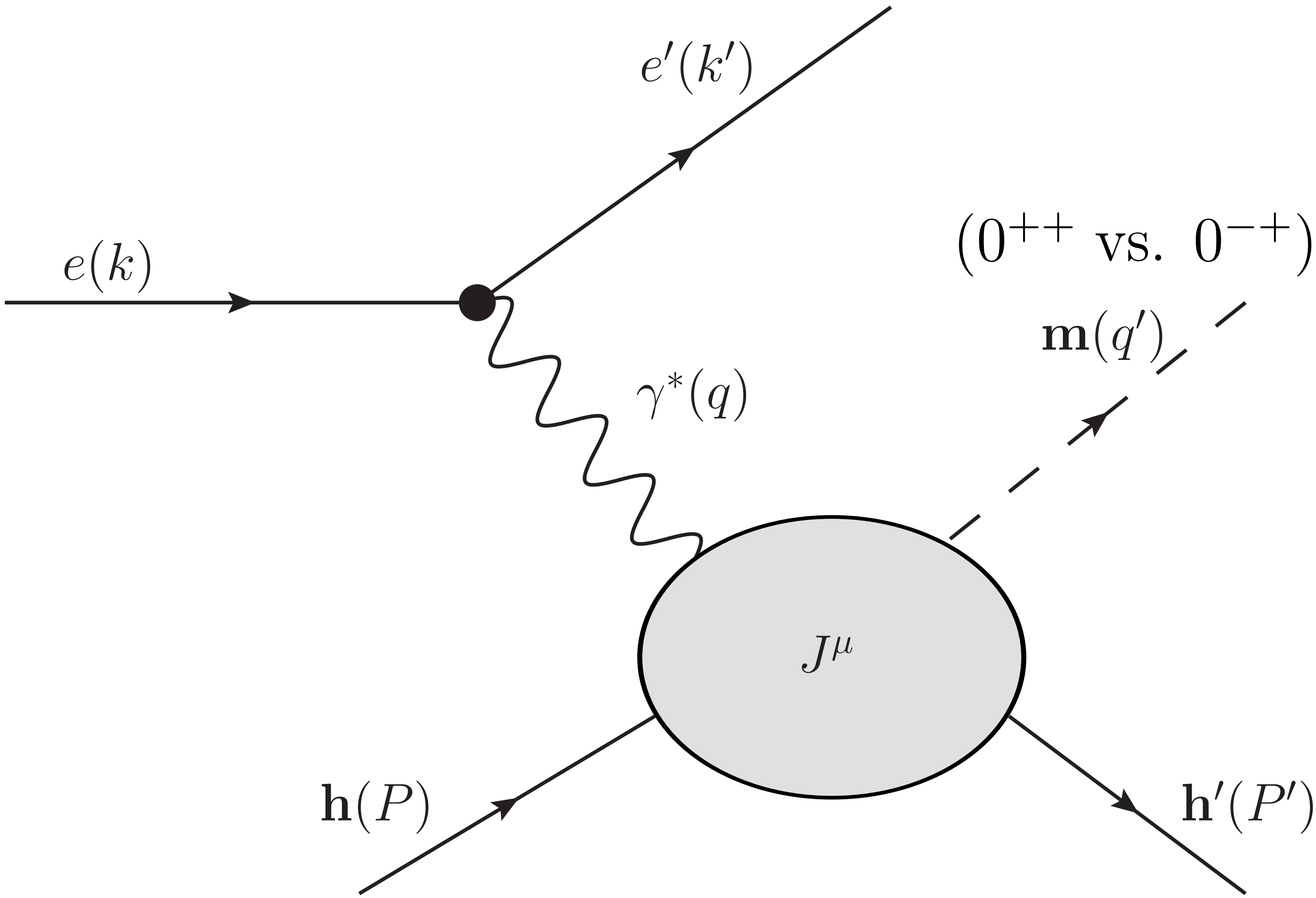


Nucleon Target

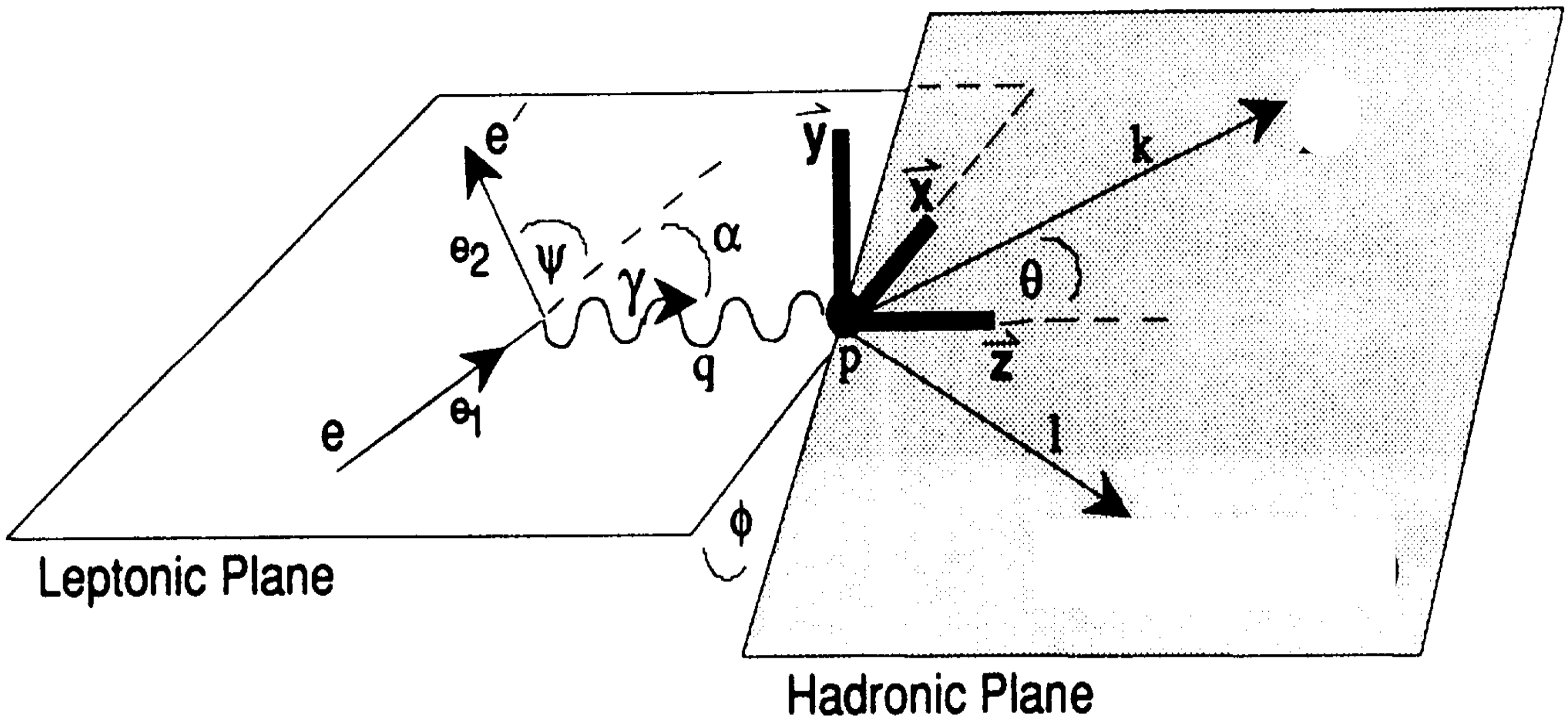
$$3 \times 2 \times 2 \times 2/2 = 12$$

12 independent tensor structures

M.Perrottet, Lett. Nuovo Cim. 7, 915 (1973);
R.Tarrach, Nuovo Cim. 28A, 409 (1975);
D.Drechsel et al.,PRC57,941(1998);
A.V.Belitsky, D.Mueller and A.Kirchner, NPB629, 323(2002);
A.V.Belitsky and D.Mueller, PRD82, 074010(2010)



C.Ji, H.-M.Choi, A.Lundeen, B.Bakker
arXiv:1806.01379 [nucl-th]


e
e
e_2
e_1
ψ
γ
α
q
$\vec{y}$
$\vec{x}$
$\vec{z}$
p
k
l
θ
φ
Leptonic Plane
Hadronic Plane

5-Fold Differential Cross Section

for unpolarized target and without recoil polarization

The following notation of the coincidence cross section will be used in our calculations. Further details can be found in D. Drechsel and L. Tiator, J. Phys. G 18 (1992) 449-497. (scanned version) (click here for a larger image)

$$\frac{d\sigma}{d\Omega_f dE_f d\Omega} = \Gamma \frac{d\sigma_v}{d\Omega}, \quad \Gamma = \frac{\alpha}{2\pi^2} \frac{E_f}{E_i} \frac{k_\gamma}{Q^2} \frac{1}{1-\varepsilon}$$

$$\frac{d\sigma_v}{d\Omega} = \frac{d\sigma_T}{d\Omega} + \varepsilon \frac{d\sigma_L}{d\Omega} + \sqrt{2\varepsilon(1+\varepsilon)} \frac{d\sigma_{LT}}{d\Omega} \cos\phi$$

$$+ \varepsilon \frac{d\sigma_{TT}}{d\Omega} \cos 2\phi + h\sqrt{2\varepsilon(1-\varepsilon)} \frac{d\sigma_{LT'}}{d\Omega} \sin\phi$$

https://maid.kph.uni-mainz.de/maid2007/cross.html

$$d\sigma \equiv \frac{d^5\sigma}{dy\,dx\,dt\,d\phi_{k'}\,d\phi_{q'}} = \kappa\langle|\mathcal{M}|^2\rangle,$$

$$\kappa \equiv \frac{1}{(2\pi)^5}\frac{yx}{32Q^2\sqrt{1+(\frac{2Mx}{Q})^2}}.$$

$$y = P\cdot q/P\cdot k$$

$$t = (P-P')^2$$

$$x = Q^2/(2P\cdot q)$$

$$\epsilon = -\frac{2M^2x^2y^2+2Q^2(y-1)}{2M^2x^2y^2+Q^2(y^2-2y+2)}$$

$$\epsilon_L = \frac{Q^2}{\nu^2}\epsilon$$

$$\langle|\mathcal{M}|^2\rangle = \left(\frac{e^2}{q^2}\right)^2\mathcal{L}^{\mu\nu}\mathcal{H}_{\mu\nu} = \left(\frac{e^2}{q^2}\right)^2\left[\frac{2q^2}{\epsilon-1}\langle|\tau_{fi}|\rangle^2 + 2i\lambda\epsilon^{\mu\nu\alpha\beta}k_\alpha k'_\beta J^\dagger_\mu J_\nu\right]$$

$d\sigma_T$ $d\sigma_{TT}$ $d\sigma_L$ $d\sigma_{LT}$ $d\sigma_{LT'}$

$$\langle|\tau_{fi}|\rangle^2 = \frac{1}{2}(|H_x|^2+|H_y|^2) + \frac{\epsilon}{2}(|H_x|^2-|H_y|^2) + \epsilon_L|H_z|^2 - \sqrt{\frac{1}{2}\epsilon_L(1+\epsilon)}(H_x^*H_z + H_z^*H_x)$$

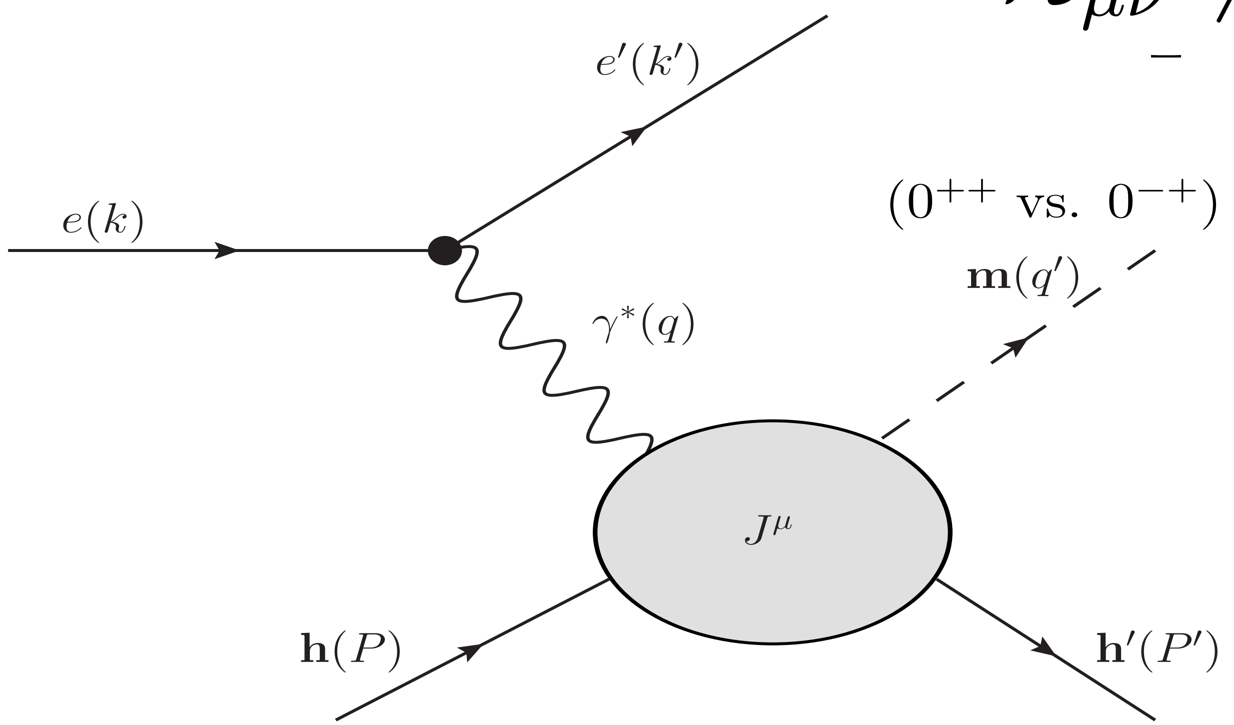
R. Williams, C.Ji, S. Cotanch (= WJC), PRC46, 1617 (1992)

$$\langle |\mathcal{M}|^2 \rangle = \left(\frac{e^2}{q^2}\right)^2 \mathcal{L}^{\mu\nu}\mathcal{H}_{\mu\nu}$$

$$\mathcal{L}^{\mu\nu} = q^2\Big[g^{\mu\nu} + \tfrac{2}{q^2}(k^\mu k'^\nu + k'^\mu k^\nu)\Big] + 2i\lambda\epsilon^{\mu\nu\alpha\beta}k_\alpha k'_\beta$$

$$\mathcal{H}_{\mu\nu} = J^\dagger_\mu J_\nu$$

$$\mathcal{H}_{\mu\nu} \neq \mathcal{H}_{\nu\mu}$$



Pseudoscalar(0^{-+}) Meson vs. Scalar(0^{++}) Meson

$$\epsilon^{\mu\nu\alpha\beta} \quad \text{vs.} \quad d^{\mu\nu\alpha\beta} = g^{\mu\nu}g^{\alpha\beta} - g^{\mu\alpha}g^{\nu\beta}$$

C.Ji & B.Bakker, PoS QCDEV2017,038(2017);
B.Bakker & C.Ji, Few Body Syst. 58,no.1,8(2017)

$$F_{PS}(Q^2, t, x)$$

$$J^\mu_S = (S_q q_\alpha + S_{\bar{P}} \bar{P}_\alpha) d^{\mu\nu\alpha\beta} q_\beta \Delta_\nu$$

$$J^\mu_{PS} = F_{PS}\epsilon^{\mu\nu\alpha\beta} q_\nu \bar{P}_\alpha \Delta_\beta$$

$$F_1 = S_q - S_{\bar{P}}$$

$$F_2 = S_{\bar{P}}$$

$$F_1(Q^2, t, x) \qquad F_2(Q^2, t, x)$$

$$J^\mu_S = F_1(q^2\Delta^\mu - q^\mu q\cdot\Delta) + F_2[(\bar{P}\cdot q + q^2)\Delta^\mu - (\bar{P}^\mu + q^\mu) q\cdot\Delta]$$

$$q \;\; ; \;\; \bar{P} = P + P' \;\; ; \;\; \Delta = P - P' = q' - q$$

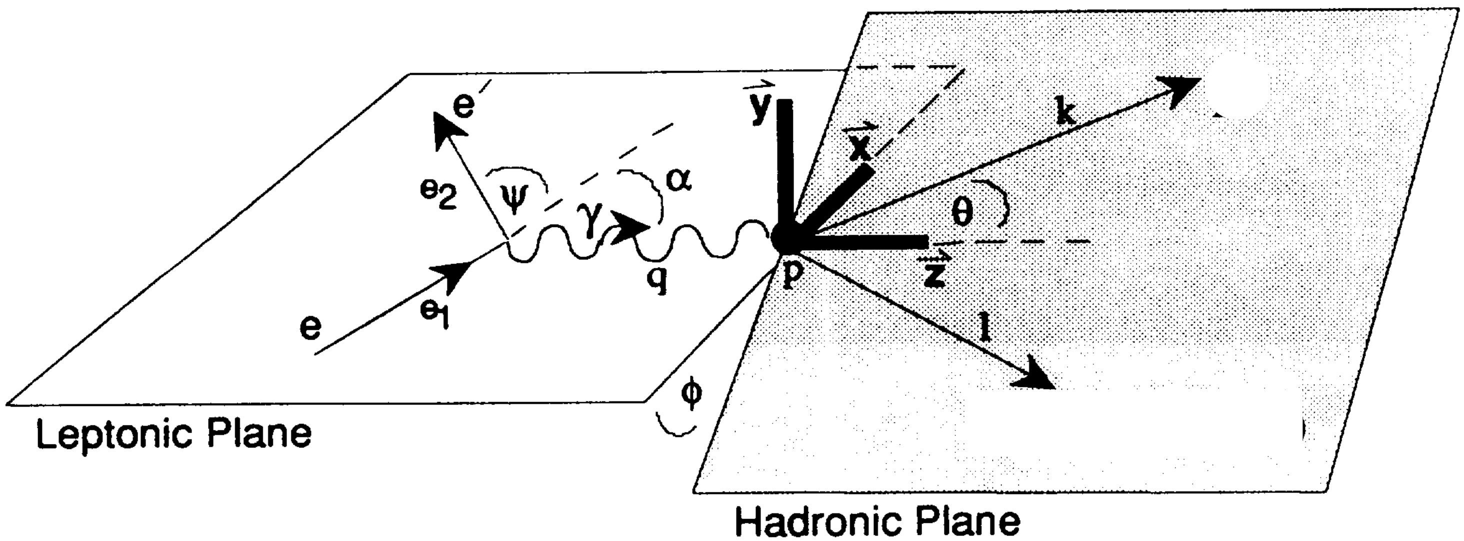
$$\boxed{J^{\mu}_{PS} = F_{PS}\epsilon^{\mu\nu\alpha\beta} q_{\nu} \bar{P}_{\alpha} \Delta_{\beta}}$$

$$\begin{aligned} \mathcal{H}_{\mu\nu} &= J^{\dagger}_{\mu} J_{\nu} \\ &= |F_{PS}|^2 \epsilon_{\mu\alpha\beta\gamma} \epsilon_{\nu\alpha'\beta'\gamma'} q^{\alpha} \bar{P}^{\beta} \Delta^{\gamma} q^{\alpha'} \bar{P}^{\beta'} \Delta^{\gamma'} \\ &= \mathcal{H}_{\nu\mu} \end{aligned}$$

$$\boxed{\epsilon^{\mu\nu\alpha\beta} k_{\alpha} k'_{\beta} \mathcal{H}_{\mu\nu} = 0}$$

$$\frac{d\sigma^{PS}_{\lambda=+1} - d\sigma^{PS}_{\lambda=-1}}{d\sigma^{PS}_{\lambda=+1} + d\sigma^{PS}_{\lambda=-1}} = 0$$

$$J^{\mu}_{PS} = F_{PS}\epsilon^{\mu\nu\alpha\beta} q_{\nu} \bar{P}_{\alpha} \Delta_{\beta}$$



$$H_z = 0$$

$$d\sigma^{PS} = d\sigma^{PS}_{T} + d\sigma^{PS}_{TT}\epsilon\cos 2\phi$$
$$= d\sigma^{PS}_{T}(1 - \epsilon\cos 2\phi)$$

$$d\sigma^{PS}_{T} = \kappa \frac{e^4 |F_{PS}(Q^2, t, x)|^2 \sin^2\theta}{4M^2 x^4 (1-\epsilon)} \left(4M^2x^2 + Q^2\right) \left[x^2\left(t^2 - 4m^2M^2\right) + Q^4 + 2Q^2 tx\right]$$

Scalar Meson Production

$$J_S^\mu = F_1(q^2\Delta^\mu - q^\mu q\cdot\Delta) + F_2[(\bar{P}\cdot q + q^2)\Delta^\mu - (\bar{P}^\mu + q^\mu)q\cdot\Delta]$$

$$d\sigma_\lambda^S = d\sigma_T^S(1+\epsilon\cos(2\phi)) + d\sigma_L^S\epsilon_L + d\sigma_{LT}^S\cos\phi\sqrt{\epsilon_L(1+\epsilon)} + \lambda\, d\sigma_{\rm BSA}^S$$

$$\begin{bmatrix} d\sigma_T^S \\ d\sigma_L^S \\ d\sigma_{LT}^S \\ d\sigma_{\rm BSA}^S \end{bmatrix} = \begin{bmatrix} T_1 & T_2 & T_3 & 0 \\ L_1 & L_2 & L_3 & 0 \\ I_1 & I_2 & I_3 & 0 \\ 0 & 0 & 0 & S_A \end{bmatrix} \begin{bmatrix} |F_1|^2 \\ |F_2|^2 \\ F_{12}^+ \\ F_{12}^- \end{bmatrix}$$

$$F_{12}^\pm = F_1F_2^* \pm F_2F_1^*$$

$$\frac{d\sigma_{\lambda=+1}^S - d\sigma_{\lambda=-1}^S}{d\sigma_{\lambda=+1}^S + d\sigma_{\lambda=-1}^S} = \frac{d\sigma_{\rm BSA}^S}{d\sigma_T^S(1+\epsilon\cos(2\phi)) + d\sigma_L^S\epsilon_L + d\sigma_{LT}^S\cos\phi\sqrt{\epsilon_L(1+\epsilon)}}$$

$$\sim\ F_1F_2^* - F_2F_1^*$$

$$
\begin{aligned}
T_1 &= \frac{\kappa e^4 \sin^2\theta Q^2}{4M^2x^2(1-\epsilon)} \left(x^2\left(t^2-4m^2M^2\right)+Q^4+2Q^2tx\right), \\
T_2 &= \frac{\kappa e^4 \sin^2\theta Q^2(x-1)^2}{4M^2x^4(1-\epsilon)} \left(x^2\left(t^2-4m^2M^2\right)+Q^4+2Q^2tx\right), \\
T_3 &= \sqrt{T_1T_2}, \\
L_1 &= \frac{\kappa e^4 Q^4}{8M^2x^2(1-\epsilon)\left(4M^2x^2+Q^2\right)} \left(m^2+Q^2+t(2x-1)\right)^2, \\
L_2 &= \frac{\kappa e^4\left(m^2\left(4M^2x+Q^2\right)+Q^2\left(4M^2x+2tx-3t\right)-4M^2tx+Q^4\right)^2}{8M^2x^2(1-\epsilon)\left(4M^2x^2+Q^2\right)}, \\
L_3 &= \sqrt{L_1L_2}, \\
I_1 &= \frac{\kappa e^4 I_c \tan\theta Q^2\left(m^2+Q^2+t(2x-1)\right)}{2M^2x^2(\epsilon-1)\left(4M^2x^2+Q^2\right)}, \\
I_2 &= \frac{\kappa e^4 I_c \tan\theta (x-1)}{2M^2x^3(\epsilon-1)\left(4M^2x^2+Q^2\right)} \\
&\quad \times\left[m^2\left(4M^2x+Q^2\right)+Q^2\left(4M^2x+2tx-3t\right)-4M^2tx+Q^4\right], \\
I_3 &= \frac{\kappa e^4 I_c \tan\theta}{4M^2x^3(\epsilon-1)\left(4M^2x^2+Q^2\right)}\Bigg[m^2\left(4M^2x^2+Q^2(2x-1)\right) \\
&\quad +Q^2(4M^2x^2+4tx^2-6tx+t)-4M^2tx^2+Q^4(2x-1)\Bigg], \\
S_A &= \kappa e^4 \frac{\sin\theta\sin\phi}{2Mx^2y}\left(m^2+Q^2-t\right) \\
&\times \sqrt{Q^2(y-1)+M^2x^2y^2}\sqrt{x^2\left(t^2-4m^2M^2\right)+Q^4+2Q^2tx},
\end{aligned}
$$

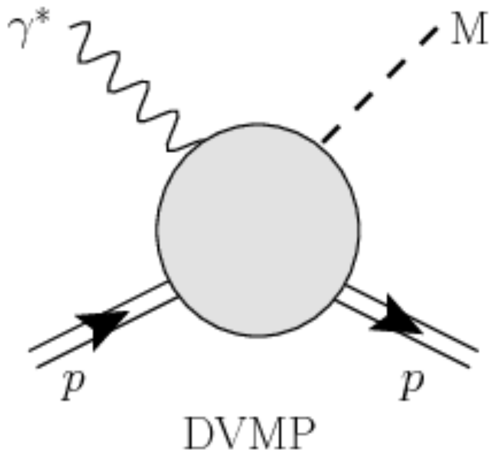
$$F_1 F_2^* - F_2 F_1^* \neq 0$$

as far as at least one of F_1 and F_2 develops an imaginary part.

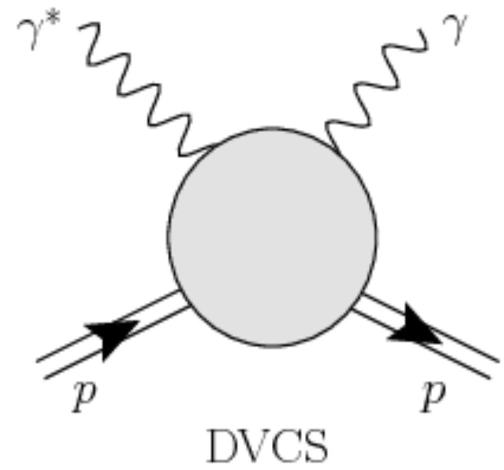
However, if $q = q' - \zeta P$ due to A.V.Radyushkin,PRD56,5524(1996) is imposed, then two form factors merge together: $J_S^\mu = \zeta(F_1 + F_2)(q^2 P^\mu - q^\mu q \cdot P)$

No BSA in that case as $\mathcal{H}_{\mu\nu} = \mathcal{H}_{\nu\mu}$

Thus, BSA measurement of scalar meson production off ^{4}He would be important.



$$d^{\mu\nu\alpha\beta} = g^{\mu\nu} g^{\alpha\beta} - g^{\mu\beta} g^{\nu\alpha}$$



$$\begin{aligned}
G^{\mu\nu}(q'q) &= q'_\alpha d^{\mu\nu\alpha\beta} q_\beta = q' \cdot q\, g^{\mu\nu} - q^\mu q'^\nu, \\
G^{\mu\nu}(qq) &= q_\alpha d^{\mu\nu\alpha\beta} q_\beta = q^2\, g^{\mu\nu} - q^\mu q^\nu, \\
G^{\mu\nu}(q'q') &= q'_\alpha d^{\mu\nu\alpha\beta} q'_\beta = q'^2\, g^{\mu\nu} - q'^\mu q'^\nu, \\
G^{\mu\nu}(\overline{P}q) &= \overline{P}_\alpha d^{\mu\nu\alpha\beta} q_\beta = \overline{P} \cdot q\, g^{\mu\nu} - q^\mu \overline{P}^\nu, \\
G^{\mu\nu}(q'\overline{P}) &= q'_\alpha d^{\mu\nu\alpha\beta} \overline{P}_\beta = \overline{P} \cdot q'\, g^{\mu\nu} - \overline{P}^\mu q'^\nu.
\end{aligned}$$

$$\begin{aligned}
\tilde{T}^{\mu\nu}_{\text{DNA}} := \sum_{i=1}^{5} \mathcal{S}_i\, \tilde{T}^{(i)\,\mu\nu}_{\text{DNA}} &= \mathcal{S}_1\, G^{\mu\nu}(q'q) \\
&+ \mathcal{S}_2\, G^{\mu\lambda}(q'q')\, G_\lambda{}^\nu(qq) \\
&+ \mathcal{S}_3\, G^{\mu\lambda}(q'\overline{P})\, G_\lambda{}^\nu(\overline{P}q) \\
&+ \mathcal{S}_4\, [G^{\mu\lambda}(q'\overline{P})\, G_\lambda{}^\nu(qq) + G^{\mu\lambda}(q'q')\, G_\lambda{}^\nu(\overline{P}q)] \\
&+ \mathcal{S}_5\, G^{\mu\lambda}(q'q')\overline{P}_\lambda \overline{P}_{\lambda'} G^{\lambda'\nu}(qq).
\end{aligned}$$

Generalized Compton Form Factors : $\mathcal{S}_i,\ i = 1, 2, ..., 5$

Most General Hadronic Tensor for Scalar Target

$$T^{\mu\nu} = G^{\mu\nu}_{qq'} S_1 + G^{\mu\lambda}_{q} G_{q'\lambda}{}^{\nu} S_2 + G^{\mu\lambda}_{q\bar{P}} G_{\bar{P}q'\lambda}{}^{\nu} S_3$$

$$+ (G^{\mu\lambda}_{q\bar{P}} G_{q'\lambda}{}^{\nu} + G^{\mu\lambda}_{q} G_{\bar{P}q'\lambda}{}^{\nu}) S_4 + G^{\mu\lambda}_{q} \bar{P}_{\lambda} \bar{P}_{\lambda'} G^{\lambda'\nu}_{q'} S_5$$

$$G^{\mu\nu}_{qq'} = g^{\mu\nu} q \cdot q' - q'^{\mu} q^{\nu}$$

$$G^{\mu\nu}_{q} = g^{\mu\nu} q^2 - q^{\mu} q^{\nu}$$

$$G^{\mu\nu}_{q'} = g^{\mu\nu} q'^2 - q'^{\mu} q'^{\nu}$$

$$G^{\mu\nu}_{q\bar{P}} = g^{\mu\nu} q \cdot \bar{P} - \bar{P}^{\mu} q^{\nu}$$

$$G^{\mu\nu}_{\bar{P}q'} = g^{\mu\nu} q' \cdot \bar{P} - q'^{\mu} \bar{P}^{\nu}$$

For $q'^2 = 0$, only S_1, S_2 and S_4 contribute.

Metz's approach $S_1 = -B_1, S_2 = B_3, S_3 = -B_2, S_4 = B_4, S_5 = B_{19}$

The method using the projectors introduces a kinematical singularity at $q' \cdot q = 0$. In Tarrach's paper a method is described to remove these kinematic poles. Here we give the final result of that algorithm as obtained in the thesis of Metz[3]. His CFFs are denoted as B_1, B_2, B_3, B_4, and B_{19}. They are implicitly given in terms of the elementary tensor by the following equations:

$$
\begin{aligned}
M^{\mu\nu} &= B_1 M_1^{\mu\nu} + B_2 M_2^{\mu\nu} + B_3 M_3^{\mu\nu} + B_4 M_4^{\mu\nu} + B_{19} M_{19}^{\mu\nu}, \\
M_1^{\mu\nu} &= -q' \cdot q\, g^{\mu\nu} + q^\mu q'^\nu, \\
M_2^{\mu\nu} &= -(\bar{P} \cdot q)^2 g^{\mu\nu} - q' \cdot q\, \bar{P}^\mu \bar{P}^\nu + \bar{P} \cdot q\, (\bar{P}^\mu q'^\nu + q^\mu \bar{P}^\nu), \\
M_3^{\mu\nu} &= q'^2 q^2 g^{\mu\nu} + q' \cdot q\, q'^\mu q^\nu - q^2 q'^\mu q'^\nu - q'^2 q^\mu q^\nu, \\
M_4^{\mu\nu} &= \bar{P} \cdot q\, (q'^2 + q^2)\, g^{\mu\nu} - \bar{P} \cdot q\, (q'^\mu q'^\nu + q^\mu q^\nu) \\
&\quad - q^2 \bar{P}^\mu q'^\nu - q'^2 q^\mu \bar{P}^\nu + q' \cdot q\, (\bar{P}^\mu q^\nu + q'^\mu \bar{P}^\nu), \\
M_{19}^{\mu\nu} &= (\bar{P} \cdot q)^2 q'^\mu q^\nu + q'^2 q^2 \bar{P}^\mu \bar{P}^\nu - \bar{P} \cdot q\, q^2 q'^\mu \bar{P}^\nu - \bar{P} \cdot q\, q'^2 \bar{P}^\mu q^\nu .
\end{aligned}
$$

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[3] A. Metz, *Virtuelle Comptonstreuung un die Polarisierbarkeiten de Nukleons* (in German), PhD thesis, Universität mainz, 1997.

Conclusion and Outlook

- BSA from exclusive π^0 production off ^{4}He is predicted to be absent from the symmetry of general hadronic current structure consideration, which may provide a benchmark for BSA analyses.
- The "DNA" of the most general hadronic tensor structure for scalar target is found and applicable to DVCS and DVMP off 4He .