Unraveling light nuclei with deeply virtual Compton scattering processes:

from models to event generator

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and in collaboration with
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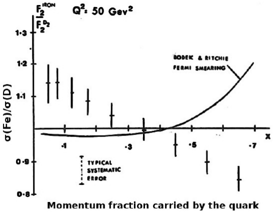
The nuclear medium modifies the structure of bound nucleons

The European Muon Collaboration found
$R(x) = \frac{F_2^A(x)}{F_2^d(x)} \neq 1$, $x = \frac{Q^2}{2M\nu} \in \left[0; \frac{M_A}{M}\right]$



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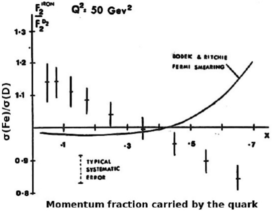

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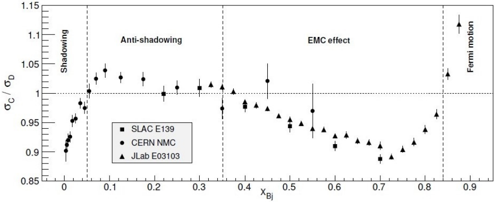

- $x \leq 0.05$: "Shadowing region"
- $0.3 \leq x \leq 0.85$: "EMC region"
- $0.85 \leq x \leq 1$: "Fermi motion region"

Collinear information led to many models but not yet to a complete explanation

(e.g., see **Cloët et al. JPG (2018)**, for a recent report)

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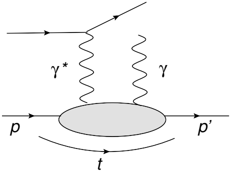
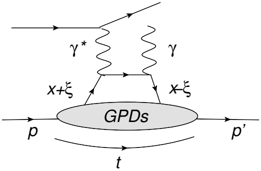
- **Exclusive electro-production of a real photon** $\rightarrow$ *clean access to* ***Generalized Parton Distributions*** (factorization property, i.e. $-\Delta^2 \ll Q^2$)





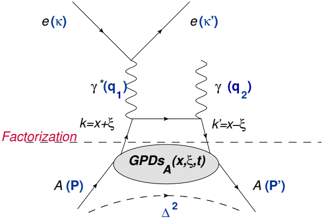
GPDs depend on: $\left(a^{\pm} = \frac{a_0 \pm a_3}{\sqrt{2}}; \bar{P} = \frac{P+P'}{2} \text{and } \bar{k} = \frac{k+k'}{2}\right)$

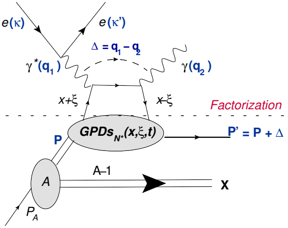
- Δ^2 =t= $(P' - P)^2$
- Q^2 = $-(\kappa - \kappa')^2$
- ξ = $-\frac{\Delta^+}{2\bar{P}^+} \approx \frac{x_B}{2-x_B}$, with $x_B = \frac{Q^2}{2M\nu}$
- x = $\frac{\bar{k}^+}{\bar{P}^+}$

Deeply Virtual Compton Scattering off nuclei

- **Exclusive processes** $\rightarrow$ *3-dimensional structure function*
- **Exclusive electro-production of a photon** $\rightarrow$ *clean access to Generalized Parton distributions* (factorization property, i.e. $-\Delta^2 \ll Q^2$)
- **Two DVCS channels in nuclei**:

- **Coherent channel** $\rightarrow$ GPDs of the **whole nucleus**
- **Incoherent channel** $\longrightarrow$ GPDs of the **bound nucleon**





ALERT: for the rigorous GPD formalism see, e.g., **Ji, PRL (1997)**, **Diehl, Phys. Rept. (2003)**, **Belitsky et al., Phys. Rept. (2005)**

- GPDs are defined in terms of **non-diagonal matrix elements of non-local operators**

$$\frac{1}{2}\int\frac{dz^-}{2\pi}e^{ix\bar{P}^+z^-}\langle P'S'|\bar{\psi}\Big(-\frac{z^-}{2}\Big)\gamma^+\psi\Big(\frac{z^-}{2}\Big)|PS\rangle$$
$$=\frac{1}{2\bar{P}^+}\left[\mathbf{H_q(x,\xi,t)}\bar{u}(P',S')\gamma^+u(P,S)+\mathbf{E_q(x,\xi,t)}\bar{u}(P',S')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u(P,S)\right]$$

GPDs without quarks helicity flip

GPDs in a nutshell

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- **GPDs without quarks helicity flip** + **GPDs with quarks helicity flip**
- Split the **quark** an the **gluon** contributions

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- **GPDs without quarks helicity flip** + **GPDs with quarks helicity flip**
- Split the **quark** an the **gluon** contributions
  - a system of spin S has $2(2S+1)^2$ quark GPDs and $2(2S+1)^2$ gluon GPDs

$\longrightarrow$ **4(2S+1) x 4(2S+1) GPDs**

GPDs in a nutshell

- GPDs are defined in terms of **non-local matrix elements**
- **Polinomiality property**, e.g. the first moment yields the **form factor**

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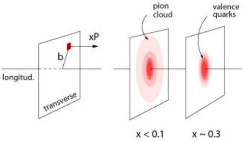
- GPDs have a **probabilistic interpretation** in the impact parameter space

$$\rho_q(x, \vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp \cdot \vec{\Delta}_\perp} H_q(x, 0, \Delta_\perp^2)$$



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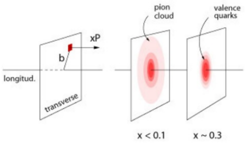

- GPDs are **universal objects**, linked to the **Compton Form Factors**

$$\mathcal{H}_q(\xi,t) = \int_0^1 dx\, C(x,\xi)\Big(H_q(x,\xi,t) - H_q(x,-\xi,t)\Big)$$

where $C(x,\xi) = \frac{1}{x+\xi} + \frac{1}{x-\xi}$ in DVCS

Issues when dealing with nuclei

When dealing with **nuclear targets**, keep in mind that:

- for **light nuclei** the Schrödinger equation can be exactly solved accounting for **realistic NN potentials** and **3-body forces**

- at LO, the number of GPDs is $\mathbf{2(2S+1)^2}$ (to halve in DVCS)

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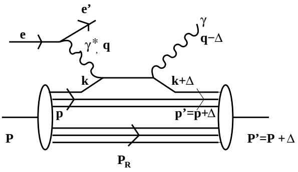
^{4}**He is a golden target** because:

- it is a typical few body system and it is theoretically well known
- $J^{\pi}_{^4He} = 0^+$ and $I_{^4He} = 0 \implies$ **only one** chiral-even **GPD** at LO
- Experiments at JLab using ^{4}He target (CLAS coll., coherent (**PRL 119, 202004 (2017)**) and incoherent (**PRL 123, 032502 (2019)**) DVCS)
- good perspectives at **JLab12** and the **EIC**

Making Impulse approximation models

Impulse approximation to the handbag approximation

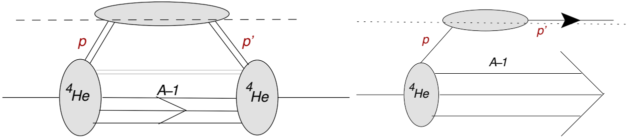


- Only nucleonic degrees of freedom
- The bound proton is **kinematically** off-shell

$$p_0 = M_A - \sqrt{M^{*2}_{A-1} + \vec{p}^2} \simeq M - E - T_{rec} \longrightarrow \mathbf{p^2 \neq M^2}$$

where the ***removal energy*** is $E = |E_A| - |E_{A-1}| - E^*$

- Possible final state interaction (**FSI**) effects are neglected
- Convolution formulas (for the cross section, for the GPD...) between nuclear $\Big($**spectral functions** obtained with **realistic potential and 3-body forces**, i.e. Argonne 18 (Av18) + Urbana IX $\Big)$ and nucleonic ingredients



Coherent DVCS off ^{4}He

Our formalism for the nuclear GPD (S. F., S.Scopetta, M. Viviani, PRC 98 (2018) 015203)

In **IA**, a convolution formula for the chiral even GPD H_q of the helium-4 can be obtained in terms of:

- **GPDs of the inner nucleons**

$$H_q^{^4He}(x,\xi,\Delta^2) = \sum_N \int_{|x|}^{1} \frac{dz}{z} h_N^{^4He}(z,\xi,\Delta^2)\, \mathbf{H_q^N}\left(\frac{x}{\zeta},\frac{\xi}{\zeta},\Delta^2\right)$$

- **light-cone momentum distribution**

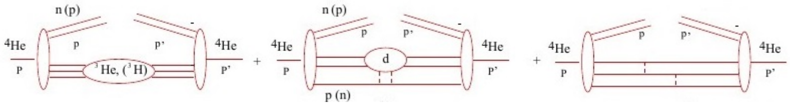
$$h_N^{^4He}(z,\Delta^2,\xi) = \frac{M_A}{M}\int dE \int_{p_{min}}^{\infty} dp \int_0^{2\pi} d\phi\, p\, \tilde{M}\, P_N^{^4He}(\vec{p},\vec{p}+\vec{\Delta},E)$$

$$\tilde{M} = \frac{M}{M_A}\left(M_A + \frac{\Delta^+}{\sqrt{2}}\right), \mathbf{H_q^N} = \sqrt{1-\xi^2}[H_q^N - \frac{\xi^2}{1-\xi^2}E_q^N]$$

One needs the **non-diagonal spectral function** and the **nucleonic GPDs** (we used the **Goloskokov-Kroll** models **(EPJ C (2008)-EPJ C (2009))**

Modelling the spectral function

$$P_N^{^4He}(\vec{p},\vec{p}+\vec{\Delta},E) = \rho(E) \sum_{\alpha\,\sigma} \langle P+\Delta| -p\,E\,\alpha, p+\Delta\,\sigma\rangle\langle p\,\sigma_N, -p\,E\,\alpha|P\rangle$$



$$P^{^4He}(\vec{p},\vec{p}+\Delta,E) =\simeq a_0(|\vec{p}|)a_0(|\vec{p}+\vec{\Delta}|)\delta(E) + \sqrt{n_1(|\vec{p}|)n_1(|\vec{p}+\vec{\Delta}|)}\delta(E-\bar{E})$$

- the total momentum distribution is $n(p) \propto \int d\vec{r}_1 d\vec{r}_1' e^{i\vec{p}\cdot(\vec{r}_1-\vec{r}_1')}\rho_1(\vec{r}_1,\vec{r}_1')$
- the ground momentum distribution is $n_0(|\vec{p}|) = |a_0(|\vec{p}|)|^2$ with

$$a_0(|\vec{p}|) \approx \langle \Phi_{^3He/^3H}|\Phi_{^4He}\rangle \,.$$

- the **excited momentum distribution** is

$$\mathbf{n_1}(|\vec{p}|) = n(|\vec{p}|) - n_0(|\vec{p}|)$$

- $\boldsymbol{n(p), n_0(p)}$ have been evaluated within the Av18 NN interaction **(Wiringa et al., PRC (1995))** + UIX 3-body forces **(Pudliner et al., PRL (1995))**
- $\bar{E}$ is the average excitation energy of the recoiling system (the model for the excited part of the diagonal s.f. **M. Viviani et al., PRC (2003)** is a realistic update of the model by **Ciofi et al., PRC (1996)**, i.e. $P_1^{\text{our model}} = N(p)P_{exc}^{\text{Ciofi's model}}$)

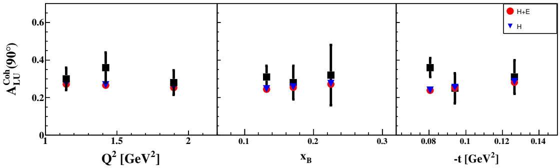
Coherent DVCS: A_{LU} (S. F., S.Scopetta, M. Viviani, PRC 98 (2018) 015203)

Beam spin asymmetry as a function of azimuthal angle

$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$

- $\alpha_i(\phi)$ are kinematical coefficients from **A. V. Belitsky et al., PRD (2009)**
- $H^{^4He}(x,\xi,t) = \sum_{q=u,d,s} \epsilon_q^2 H_q^{^4He}(x,\xi,t)$ comes **from our model**
  - $\Im m\mathcal{H}_A(\xi,t) = H^{^4He}(x=\xi,\xi,t) - H^{^4He}(x=-\xi,\xi,t)$
  - $\Re e\mathcal{H}_A(\xi,t) = \text{Pr}\int_{-1}^{1} dx\, \frac{H^{^4He}(x,\xi,t)}{x-\xi+i\epsilon}$

Results of our model (PRC(2018)) ● *VS* **JLab data** (**Hattawy et al., PRL (2017)**)

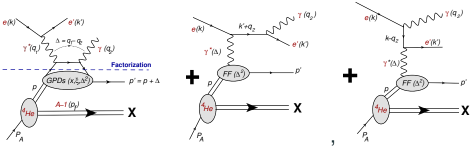


$A_{LU}^{Coh} \equiv A_{LU}(\phi = 90^o)$ *is shown in the experimental* Q^2*,* x_B *and* $-t$ *bins*

Incoherent DVCS off ^{4}He

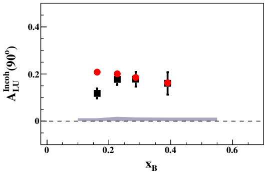
Incoherent DVCS off ^{4}He: S.F., S. Scopetta, M. Viviani, PRC(2021)-PRD(2021)

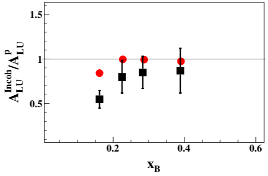
$$d\sigma^{\pm} \approx \int d\vec{p} dE P^{^4He}(\vec{p}, E) |\mathcal{A}^{\pm}(\vec{p}, E, K)|^2$$



$$A_{LU}^{Incoh}(K) = \frac{\mathcal{I}^{^4He}(K)}{T_{BH}^{2\,^4He}(K)} = \frac{\int_{exp} dE\, d\vec{p}\, P^{^4He}(\vec{p}, E)\, g(\vec{p}, E, K)\, \mathcal{I}(\vec{p}, E, K)}{\int_{exp} dE\, d\vec{p}\, P^{^4He}(\vec{p}, E)\, g(\vec{p}, E, K) T_{BH}^2(\vec{p}, E, K)}$$

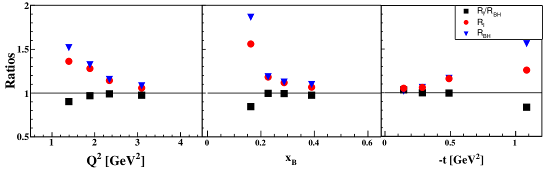
- nuclear effects affect the motion of the proton in the nuclear medium (no modifications to the functional form of the GPDs and FFs)
- in $\mathcal{I}(\vec{p}, E, K) \propto \Im m\mathcal{H}(\xi', \Delta^2, Q^2)$, we used the nucleon **GPD model** evaluated for $\xi' = \frac{\mathbf{Q^2}}{(\mathbf{p}+\mathbf{p'})(\mathbf{q_1}+\mathbf{q_2})}$





What kind of nuclear effects we are describing? Let us consider the *super ratio*

$$A_{LU}^{Incoh}/A_{LU}^{p} = \frac{\mathcal{I}^{^4He}}{\mathcal{I}^{p}} \frac{T_{BH}^{2\ p}}{T_{BH}^{2\ ^4He}} = \frac{R_{\mathcal{I}}}{R_{BH}} \propto \frac{(nucl.eff.)_{\mathcal{I}}}{(nucl.eff.)_{BH}},$$

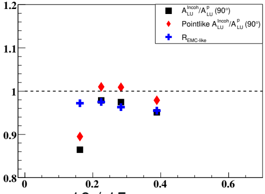


These effects are due to the ***dependence on the 4-momenta components*** *of the bound proton entering the amplitudes.*
This behaviour hasn't to do with a modification of the ***parton structure!***

It is confirmed by:

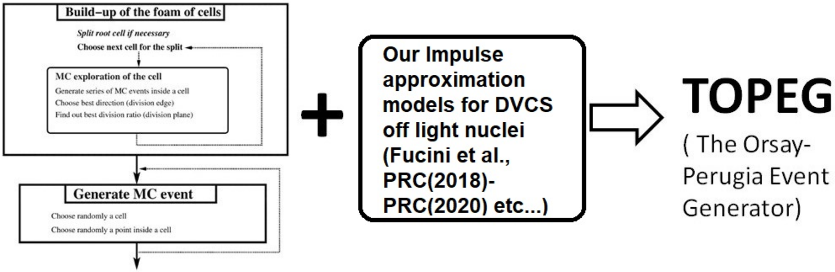
- the ratio $A_{LU}^{Incoh}/A_{LU}^{p}$ for **"pointlike" protons**
- the **"EMC-like" trend**

$$R_{EMC-like} = \frac{1}{\mathcal{N}} \frac{\int_{exp} dE\, d\vec{p}\, P^{^4He}(\vec{p},E)\, \Im m\, \mathcal{H}(\xi',\Delta^2)}{\Im m\, \mathcal{H}(\xi,\Delta^2)}$$



From models to event generation

TOPEG is a Root based generator (**S. Jadach (2005)**) + **our model** for the coherent/incoherent DVCS off light nuclei



Use of the TFoam class to create and memorize a grid and then to generate events

Putting these models in TOPEG

So far, we have results only for the coherent DVCS off ^{4}He (version **1.0** released)

- **JLab**
  - Check for the events generated at the kinematics with 6 GeV electron beam
  - Good also for CLAS 12 GeV
- **EIC**
  - We generated events for the three electron - helium-4 beam energy configurations
    - **(5x41) GeV**
    - **(10x110) GeV**
    - **(18x110) GeV**
- These latter results are included in the **EIC Yellow Report** (e-Print: 2103.05419)

Promising results:

- the NUCLEAR DVCS can be observed at the EIC
- TOPEG is a flexible tool to do the GPDs phenomenology

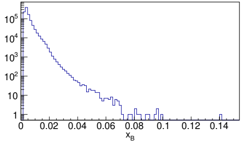
(18 x 110) GeV: kinematical distributions

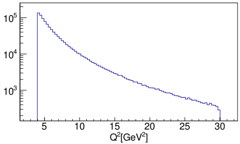
We generated events weighted by the cross section $\frac{d^4\sigma}{dQ^2 dt d\phi dx_B}$

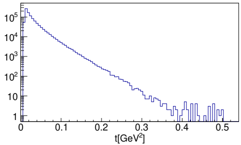
- 1 million events
- in the x-section, we set $\Re e$(CFF)=0 (limitation in the computation time)
- Luminosity: 250 nb^{-1} (**NOT ENOUGH!!**)
- $Q^2 > 2$ GeV^2 , $y < 0.8$, $t_{min} < |t| < t_{min} + 0.5$ GeV^2

For small $|t|$, we expect an enhancement of the cross section for the dominance of the BH process ($\simeq \mathbf{FF^2}$).

$|t_{min}| = \frac{4M^2_{4_{He}}\xi^2}{1-\xi^2}$ with $\xi = \frac{x_B}{2-x_B}$ and $x_B = \frac{Q^2}{y(s-M_{4_{He}})}$







Summing up (i)

Our **workable** approaches allow us to constrain **conventional nuclear effects**: interpret the present data and make predictions for the EIC

- ## Coherent DVCS
  - Improvement of the ^{4}**He spectral function** (fully realistic calculation) **(in slow progress)**
  - Toward the semi-realistic description of the **EMC effect** in the helium-4 **(in progress)**
  - Impact of the **target mass corrections** on the observables **(planned for the very next future)**
  - Inclusion of **shadowing effects**

- ## Incoherent DVCS
  - Same formalism can be used for the **deuteron** **(in progress)**
  - Realistic calculation of $\phi \longrightarrow$ impact on the observables **(in progress)**
  - Introduction of some **final state interaction effects** **(TBD)**

Summing up (ii)

Ongoing developments of **TOPEG**:

- Preliminary results for the **projections for the ^{4}He profiles** toward the **first nuclear tomography** for different transverse momentum thresholds
- Study the impact of **non nucleonic d.o.f.**: is this kind of Physics feasible at the EIC?

- **Tech improvements** to include $\Re\mathrm{e}$(CFF) in the simulations **(in progress)**
- **MultiThreading** to shorten the calculation time **(in progress)**
- Complete the simulation accounting for the **EIC smearing**

- Add **more models, other (light) nuclei**, e.g. ^{3}He
  - **Incoherent** off ^{4}He and off ^{2}H almost ready **(in progress)**
- Write the documentation and then the **version 1.1** is ready

Backup slides

DVCS off deuterium

Incoherent channel

- Nuclear part: momentum distribution (it is exact: instant form or light front)
- Key study also for heavier nuclei

Coherent channel

- 9 quark GPDs
- Formalism already developed and established (see **Cano, Pire EPJA (2004)**)
- there is a connection between the light-cone wave function of the deuteron (helicity amplitudes $\longrightarrow$ **GPDs**) in terms of light-cone coordinates and the ordinary (instant-form) relativistic wave function that fulfills a Schrödinger type equation (we can update the potential)
- we can compute

$$\chi(\vec{k};\mu_1,\mu_2) = \sum_{L;m_L;m_S} \langle \frac{1}{2}\frac{1}{2}1|\mu_1,\mu_2,m_S\rangle\langle L11|m_L m_S \lambda\rangle Y_{L,M_L}(\hat{k})u_L(k)$$

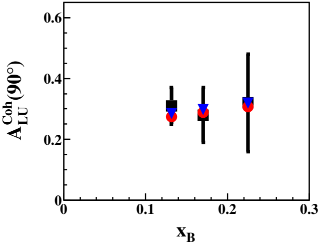
with AV18 and perform a Melosh rotation to relate the spin in the light-front with the spin in the instant-form frame of the dynamics

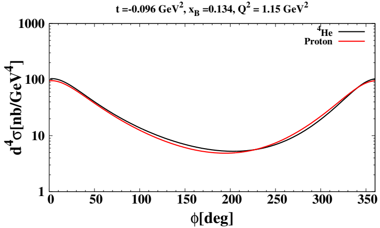
Coherent DVCS off ^{4}He

Model for the only one chiral-even GPD of ^{4}He in **S. Fucini, S.Scopetta, M. Viviani, PRC 98 (2018)**

$$\frac{d^4\sigma^{\lambda=\pm}}{dx_A dt dQ^2 d\phi} = \frac{\alpha^3 x_A y^2}{8\pi Q^4\sqrt{1+\epsilon^2}}\frac{|\mathcal{A}|^2}{e^6}; A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-}$$

$$T^2_{BH} \propto F^2_A(t);\ T^2_{DVCS} \propto \Im m\mathcal{H}^2 + \Re e\mathcal{H}^2;\ I^\lambda_{BH-DVCS} \propto F_A(t)\Im m\mathcal{H}$$

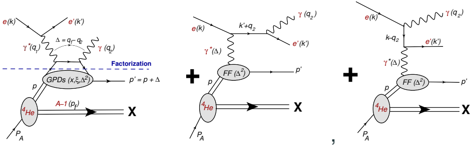




Data from **Hattawy et al., PRL (2017)**; our model including (red dots) or not (blue triangles) the real part of $\mathcal{H}$.
As an illustration, we plot $d^4\sigma_{^4He} \times (F^1_p/F^A_C)^2$ and $d^4\sigma_{proton} * 4$

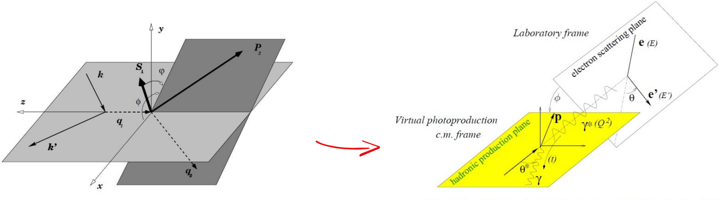
DVCS off bound proton

$$d\sigma^{\pm} \approx \int d\vec{p} dE P^{^4He}(\vec{p}, E) |\mathcal{A}^{\pm}(\vec{p}, E, K)|^2$$



3-momenta components of the final proton can be obtained brute-force solving

$$\begin{cases} \sqrt{|\vec{p}|^2 + |\vec{p}'|^2 + |q_1^z|^2 - 2|\vec{p}||\vec{p}'|\cos\theta_{pp'} - 2|\vec{p}'|q_1^z\cos\theta_N + 2|\vec{p}|q_1^z\cos\vartheta} - p_0 + E_2 - \nu = 0 \\ -\Delta^2 + M^2 + p_0^2 - |\vec{p}|^2 - 2p_0\sqrt{M^2 + |\vec{p}'|^2} + 2|\vec{p}'||\vec{p}|\cos\theta_{\widehat{pp'}} = 0 \end{cases}$$



Numerical sol. (slow the program and there is some instability) $\longrightarrow$ analytical sol.

ϕ is not boost invariant: still studying the impact (5-10%) of this behavior on the x-sections

(18 x 110) GeV: analysis

Is it possible to study the region around the first diffraction minimum in the ^{4}He FF ($t_{\mathrm{dif.\,min}} = -0.48$ GeV^2)?

(18 x 110) GeV: analysis

Is it possible to study the region around the first diffraction minimum in the ^{4}He FF ($t_{\text{dif. min}} = -0.48$ GeV^2)? **YES, we can!**

- 99%+ electrons and photons are in the acceptance of the detector matrix
- This is true for all energy configurations

> Electrons and photons appear in easily accessible kinematics according to the detector matrix requirements (exceptions for small angles photons)

- Acceptance at low -t will be cut passing through the detectors
  - t_{min} is set by the detector features
  - t_{max} is fixed by the luminosity (billion of events to generate)

From left to right, the kinematical distributions of the final particles: electron, photon and ^{4}He