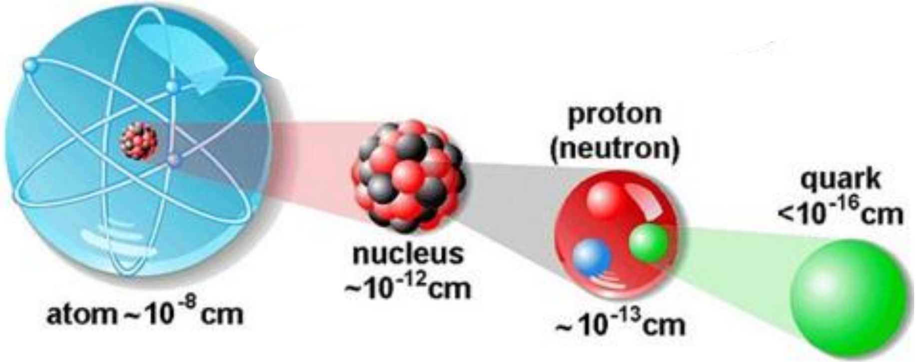
Deeply Virtual Compton Scattering off the Neutron
(6 GeV experiments)

Meriem BEN ALI

LPC Clermont-Ferrand

- ○ Generalized Parton Distributions
- ○DVCS off the neutron motivation
- ○ Experimental setup
- ○ DVCS cross section extraction off the neutron
- ○ Summary

Why study the nucleon structure?



✓ The basic bricks of the atomic nucleus

- ➢ The nucleon is a very complex object (governed by non-perturbative QCD)

Nucleon mass:
= 938 MeV > masse(u + u + d)

✓Problem of "spin crisis"

Nucleon spin (few known components)

$$\frac{1}{2} = \frac{1}{2}\boxed{\Delta\Sigma_q} + \underbrace{\boxed{\Delta\Sigma_g} + \boxed{L_q + L_g}}_{??}$$

~30%

Quarks spin contribution

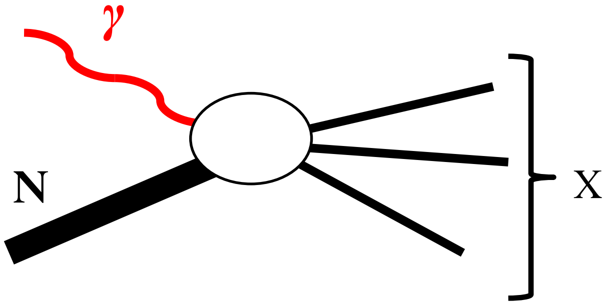
Gluon spin contribution

Quarks and gluons orbital momentum contributions

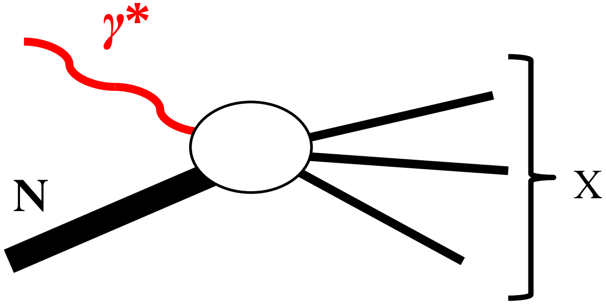
Electromagnetic probe

Advantage: The electromagnetic probe is a powerful tool to probe the internal structure of the nucleon, it is elementary and understood probe

Real Photon : γ



Virtual Photon : γ^*



γ^* **characterized by :**

- ❖ Nonzero and negative squared mass
- ❖ Virtuality $(Q^2=-q^2=-(k-k')^2)$

=

momentum transfer to the nucleon

=

Resolution of the probe $\lambda = 1/\sqrt{Q^2}$

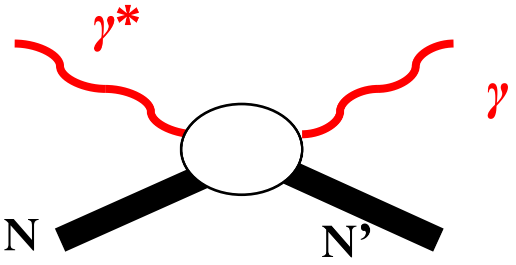
VCS &&Deep VCS

The physical regime depends : the probe virtuality (Q^2) and the center of mass energy (s):

- At low energy

Virtual Compton Scattering

(**VCS**: $\gamma^* p \rightarrow \gamma p$)



γ^* **with low virtuality** **(Q^2)**

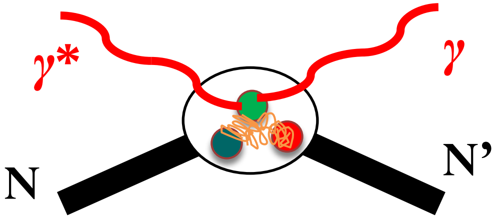
The nucleon is seen as a whole

Generalized Polarizabilities (GPs)

- At high energy ($s \gg M^2$) and large $Q^2 \gg M^2$

Deeply Virtual Compton Scattering

(**DVCS**: $\gamma^* p \rightarrow \gamma p$)

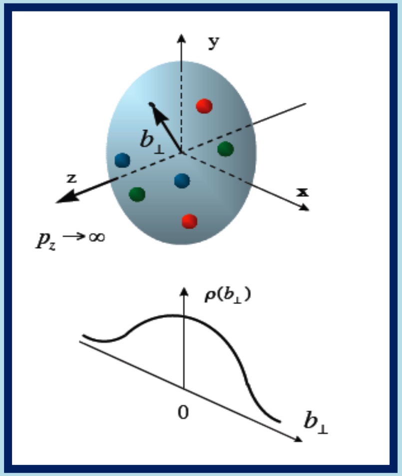


γ^* **with high virtuality** **($Q^2 \gg M^2$)**

Scattering on the partons in the nucleon

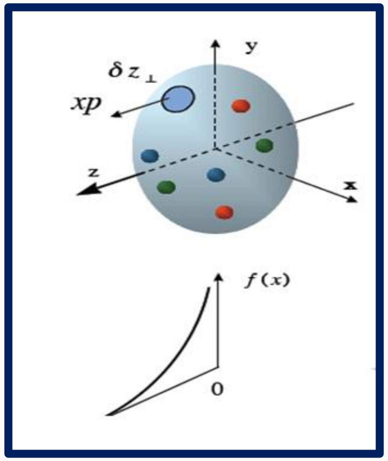
Generalized Parton Distribution (GPDs)

Generalized Parton Distribution GPDs



❖ Elastic Scattering

Form Factors
(Transverse position of partons)



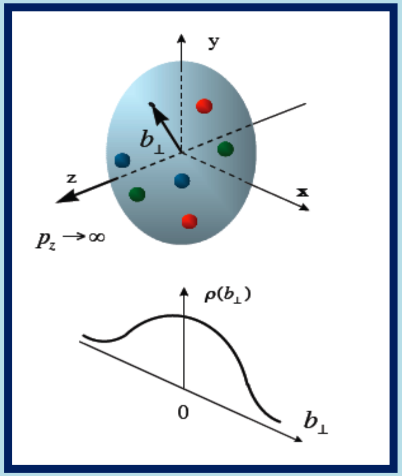
❖ Deep ($Q^2 >> M^2$) Inelastic Scattering (**DIS**)

Parton Distribution Function (PDFs)
(Longitudinal momentum distribution of the partons in the nucleon)

Non-correlated informations about the nucleon structure and they do not allow multi-dimensional description

Some exclusive reactions of deep inelastic scattering (like the DVCS) can measure new quantities: **(Generalized Parton Distribution GPDs)**

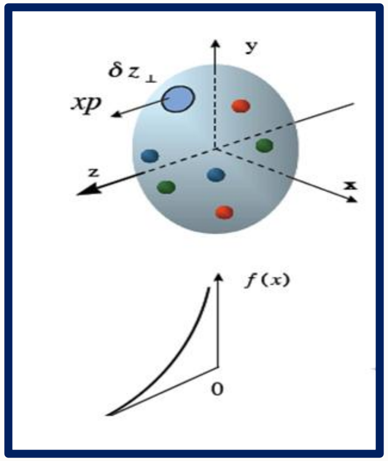
Generalized Parton Distribution GPDs



- ❖ Elastic Scattering

Form Factors

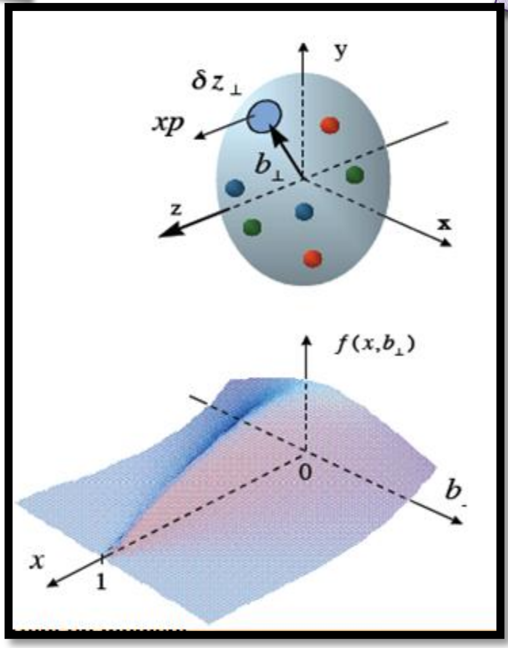
(Transverse position of partons)



- ❖ Deep ($Q^2 >> M^2$) Inelastic Scattering **(DIS)**

Parton Distribution Function (PDFs)

(Longitudinal momentum distribution of the partons in the nucleon)



Exclusive reactions of deep inelastic scattering (DVCS)

Generalized Parton Distribution GPDs:

3-D picture of the nucleon with access to correlations between transverse spatial distribution (2d) and longitudinal momentum distributions (1d)

Generalized Parton Distribution GPDs

At leading order

4 chiral even GPDS **:** $H^f(x,\xi,t), E^f(x,\xi,t), \tilde{H}^f(x,\xi,t), \tilde{E}^f(x,\xi,t)$ Conserve the parton helicity

4 chiral odd (transversity) GPDs**:** $H_T^f(x,\xi,t), E_T^f(x,\xi,t), \tilde{H}_T^f(x,\xi,t), \tilde{E}_T^f(x,\xi,t)$ Flip the parton helicity

❖ **Link to Parton distribution functions**

(ξ=t=0)

$$H_q(x,0,0) \begin{cases} = q(x)\ ; \quad x>0 \\ = -\bar{q}(x)\ x<0 \end{cases}$$

$$\tilde{H}_q(x,0,0) \begin{cases} = \Delta q(x)\ ; \quad x>0 \\ = \Delta\bar{q}(-x)\ ; \quad x<0 \end{cases}$$

➢ **Link to Form Factors (∀ ξ)**

$$\sum_q e_q \int_{-1}^{1} dx H_q(x,\xi,t) = F_1(t)$$

$$\sum_q e_q \int_{-1}^{1} dx E_q(x,\xi,t) = F_2(t)$$

$$\sum_q e_q \int_{-1}^{1} dx \tilde{H}_q(x,\xi,t) = G_A(t)$$

$$\sum_q e_q \int_{-1}^{1} dx \tilde{H}_q(x,\xi,t) = G_p(t)$$

➢ Access to **quark angular momentum, via Ji sum rule [X. Ji 1997]:**

$$\frac{1}{2}\int_{-1}^{+1} dx\, x[H_q(x,\xi,t=0)+E_q(x,\xi,t=0)] = J_q = \frac{1}{2}\Delta\Sigma_q + L_q$$

➢Solving the problem of the "spin crisis"

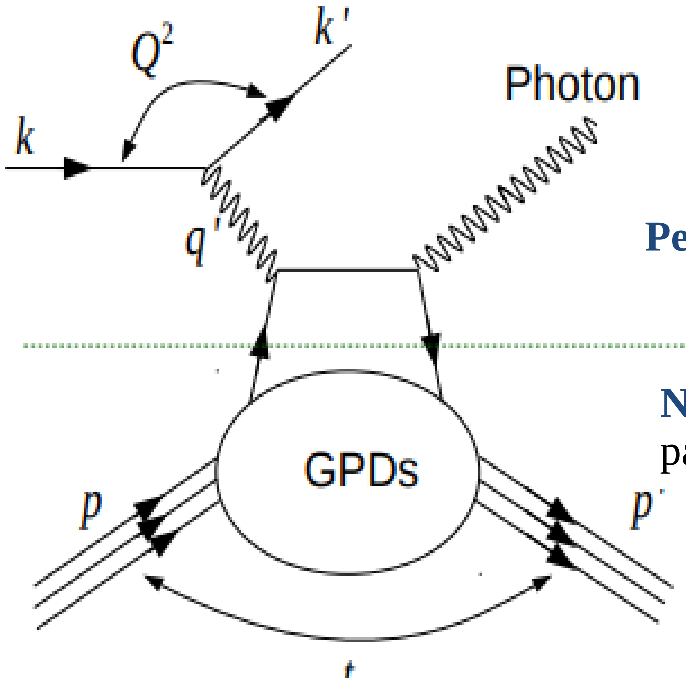
$$\frac{1}{2} = \frac{1}{2}\boxed{\Delta\Sigma_q} + \boxed{\Delta\Sigma_g} + \overset{??}{\boxed{L_q + L_g}}$$

How access to GPDs ?

The deep exclusive processes in the Bjorken regime are the simplest process which can be described in terms of GPDs by measuring its cross section

$$\begin{cases} Q^2 = -(k-k')^2 \rightarrow \infty \\ \nu = (k_0 - k'_0) \rightarrow \infty \end{cases}$$

and fixed $x_B = \dfrac{Q^2}{2M\nu}$



Deeply Virtual Compton Scattering

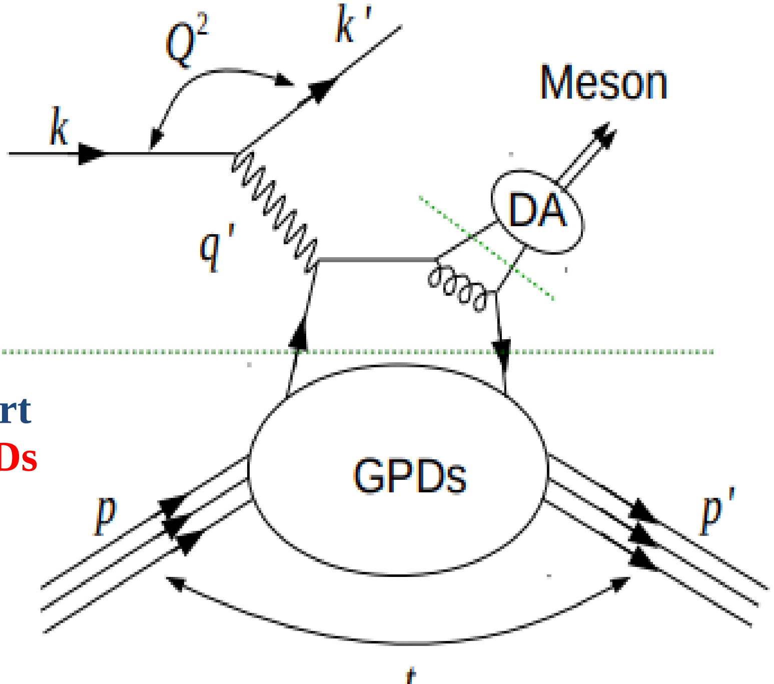
(**DVCS**)

Perturbative part

(calculable)

Non perturbative part

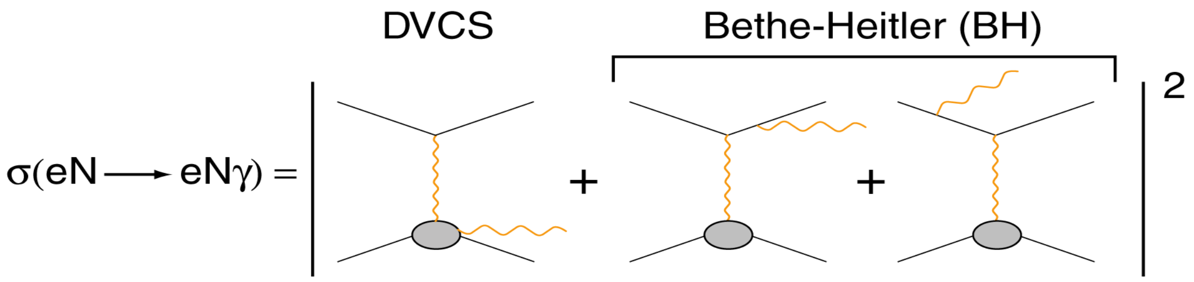
parameterized by **GPDs**



Deeply Virtual Meson Production

(DVMP)

Deeply Virtual Compton Scattering



Known term

$$d^4\overleftarrow{\sigma} - d^4\overrightarrow{\sigma} = 2\underline{\Im\mathrm{m}(T^{DVCS}.T^{BH})}$$

$$d^4\overleftarrow{\sigma} + d^4\overrightarrow{\sigma} = 2\underline{\Re e(T^{DVCS}.T^{BH})} + \underline{\left|T^{DVCS}\right|^2} + \boxed{\left|T^{BH}\right|^2}$$

Known

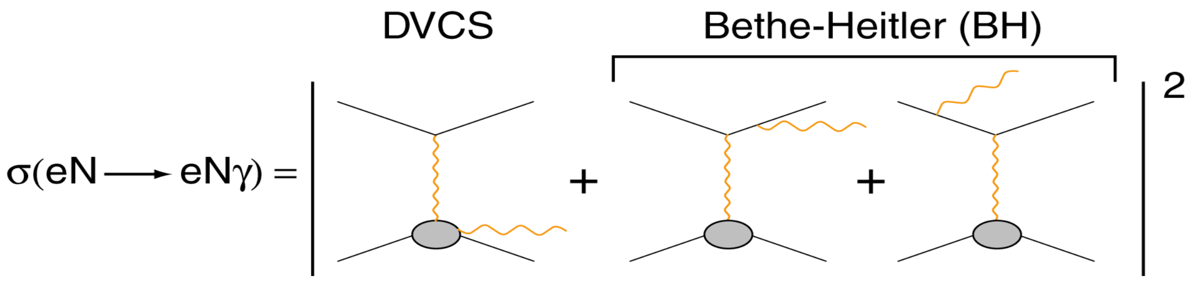
(fully calculable with nucleon FFs)

The unpolarized cross section accesses the real part of DVCS and the $|T^{DVCS}|^2$ term which are sensitive to an **integral of GPDs over x**

$$T^{DVCS} \propto \underline{P\int_{-1}^{+1}\frac{GPD(x,\xi,t)}{x-\xi}dx} \pm \underline{i\,\Pi GPD(x=\pm\xi,\xi,t)} + \ldots$$

The **polarized cross-section difference** accesses the imaginary part of DVCS and therefore **GPDs at x=±ξ**

Motivation (DVCS off the neutron)



Known term

$$d^4\overleftarrow{\sigma} - d^4\overrightarrow{\sigma} = 2\Im\mathrm{m}(T^{DVCS}.T^{BH})$$

$$d^4\overleftarrow{\sigma} + d^4\overrightarrow{\sigma} = 2\boxed{\Re e(T^{DVCS}.T^{BH}}) + \left|T^{DVCS}\right|^2 + \boxed{\left|T^{BH}\right|^2}$$

Known (fully calculable with nucleon FFs)

A.V. Belitsky, D. Mueller Phys. Rev., D82:074010, 2010

A linear combination of form factors and Compton form factors

$$\Re e\, C^I(\mathcal{F}) = F_1(t)\Re\mathrm{e}\mathcal{H} - \frac{t}{4M^2}F_2(t)\Re\mathrm{e}\mathcal{E} + \xi(F_1(t)+F_2(t))\Re\mathrm{e}\tilde{\mathcal{H}}$$

$$\Re e(\mathcal{H}) = \sum_f \mathcal{P}\int_{-1}^{+1}dx\left(\frac{1}{x-\xi}\pm\frac{1}{x+\xi}\right)\underline{H^f(x,\xi,t)}$$

GPDs

For the neutron F_1(t)<< F_2(t)

Strong sensitivity to GPD **E** (useful to access the quark angular momentum)

$$\frac{1}{2}\int_{-1}^{+1}dx\, x[H(x,\xi,t=0)+\boxed{E(x,\xi,t=0)]} = J_q = \frac{1}{2}\Delta\Sigma_q + L_q$$

Motivation (DVCS off the neutron)

❖ Measure cross section at different kinematics (2 beam energies)

- ➢ Separate the **$I(T^{BH}T^{DVCS})$** of DVCS and the $|T^{DVCS}|^2$
- ➢ Better constrain theoretical models of GPDs

❖ Measure n-DVCS cross section is important

- ➢ Neutron has different flavors from the proton
- ➢ **Sensitive to GPD E (** The less constrained GPD and which is important to access quarks orbital momentum via Ji’s sum rule**)**

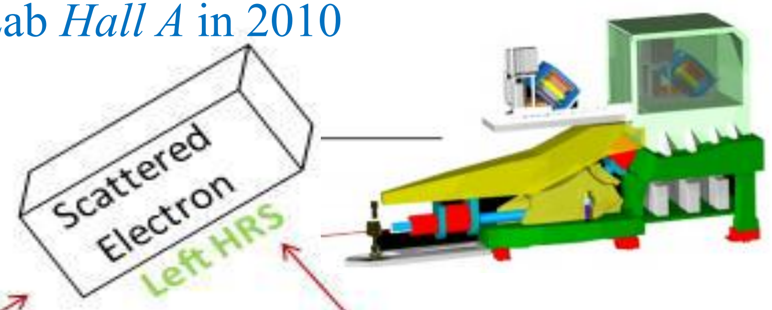
The E08-025 (n-DVCS) experiment **(DVCS on the neutron)**

Q^2 (GeV^2)	**1.75**
x_B	0.36
E_{beam}(GeV)	4.45 (Kin2Low) and 5.54 (kin2high)
Target	LH2 and LD2

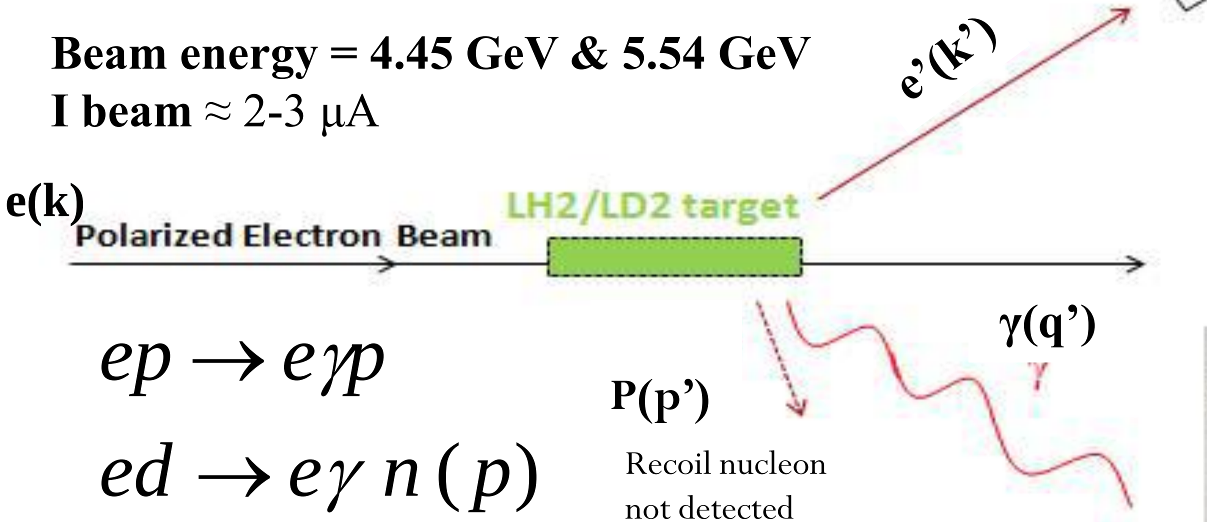
Experimental apparatus

The **E08-025** (n-DVCS) experiment was performed at JLab *Hall A* in 2010

- **Goal : Measure the n-DVCS total cross-sections**



Beam energy = 4.45 GeV & 5.54 GeV
I beam ≈ 2-3 μA



$$ep \to e\gamma p$$

$$ed \to e\gamma\, n\,(p)$$

Recoil nucleon not detected

DVCS events are identified with M_x^2

$M^2x=(k-k'+p-q')^2$

Electromagnetic Calorimeter

- The data were taken at two kinematics (Kin2high and Kin2low):
  - ✓ **$Q^2 = 1.75$ GeV²**
  - ✓ **$x_{Bj} = 0.36$**
  - ✓ **t ~ [-0.5 , -0.1] GeV²**
  - ✓ **Maximal luminosity = 3. 10^{37}cm^{-2}s^{-1}**

- 13 X 16 PbF2 blocs (density 7.77 g/cm^3)
- Taille d'un bloc : 3x3 cm² x 20 X_0
- Each blok is conected to (PM + base)
- The detection Based on Čerenkov light detection

Selection of the n-DVCS events

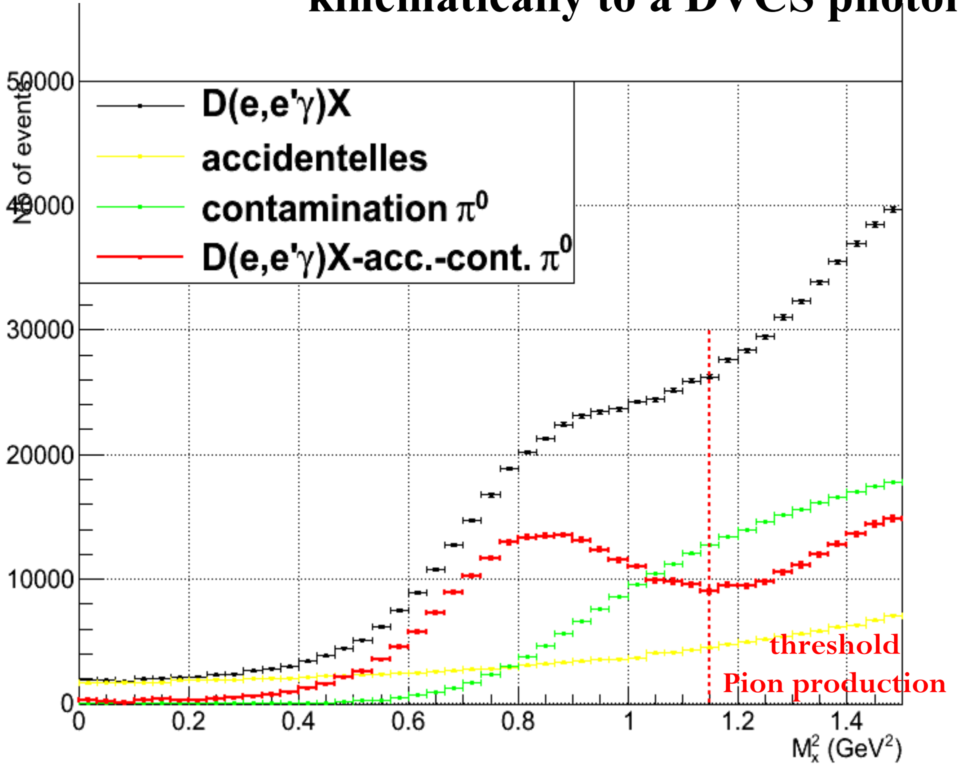
Accidentals subtraction && π^0 contamination subtraction

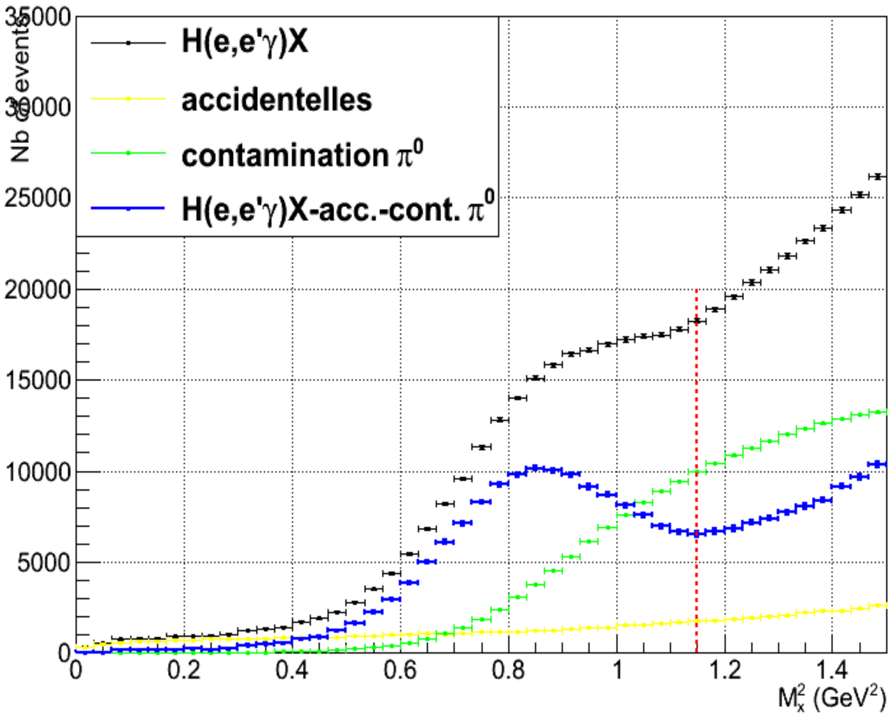
The raw data: detect e' and γ in coincidence (eN→e' γ X)

- 1 track in the HRS and 1 cluster in the calorimeter (energy> 1 GeV)

→The detected photon may be in fortuitous coincidence with the scattered electron

→ The photon detected in the calorimeter may come from the decay of π^0 and resembles kinematically to a DVCS photon : eN→e'π^0 X→e' γ_1 γ_2X





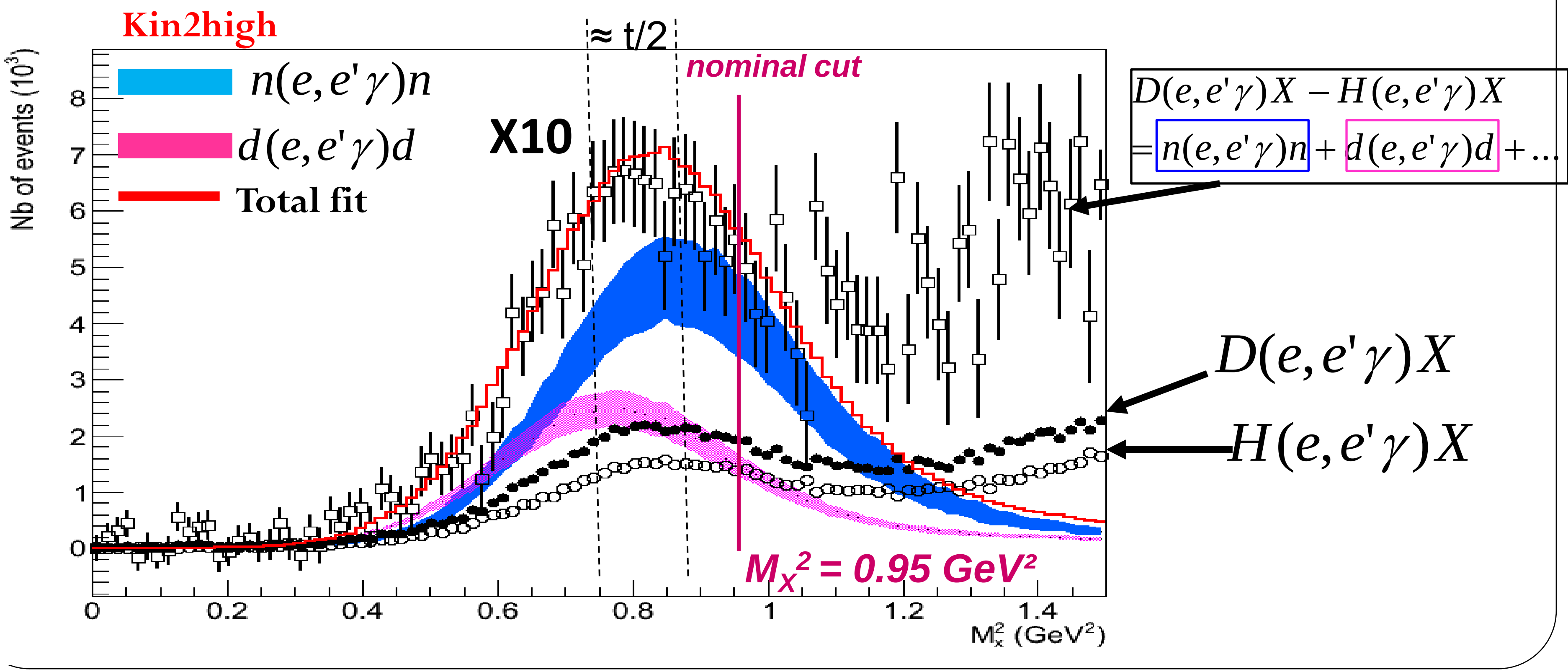
Selection of the n-DVCS events

After

- subtracting the accidentals,
- subtracting single photons coming from π^0 decay (π^0 contamination),
- adding Fermi momentum to H2 data,
- normalizing H2 and D2 data to the same luminosity,

we obtain the difference **($D(e,e'\gamma)X$- $H(e,e'\gamma)X$)**

$$D(e,e'\gamma)pn = p(e,e'\gamma)p + \underbrace{n(e,e'\gamma)n + d(e,e'\gamma)d}$$



Adjusting the simulation to the experimental data

Experimental data obtained

+

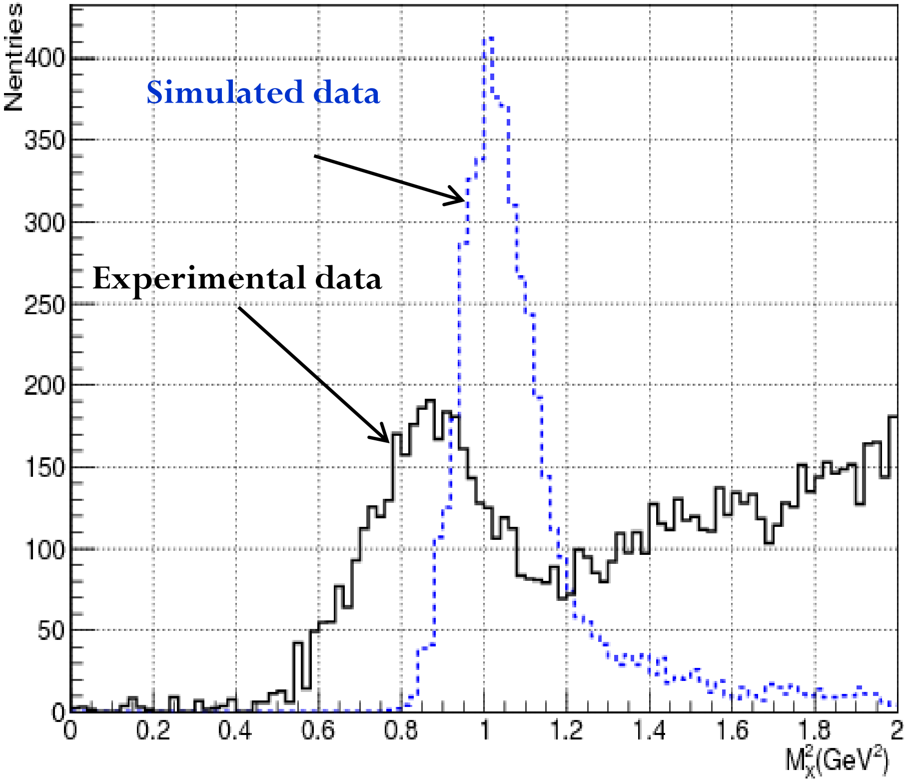
Simulated data:

1- have the same cuts applied to the experimental data

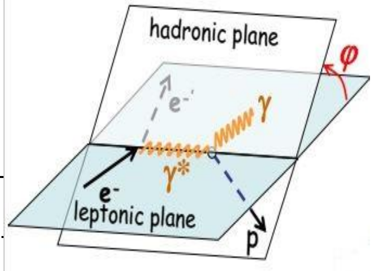
2- have the same resolution and the same calibration that experimental data

Adjustment : $$\chi^2 = \sum_{e=0}^{Nbin} \left(\frac{\boxed{N_e^{sim}} - \boxed{N_e^{exp}}}{\Delta\sigma_e^{exp}} \right)^2$$

Cross Section σ^{exp}

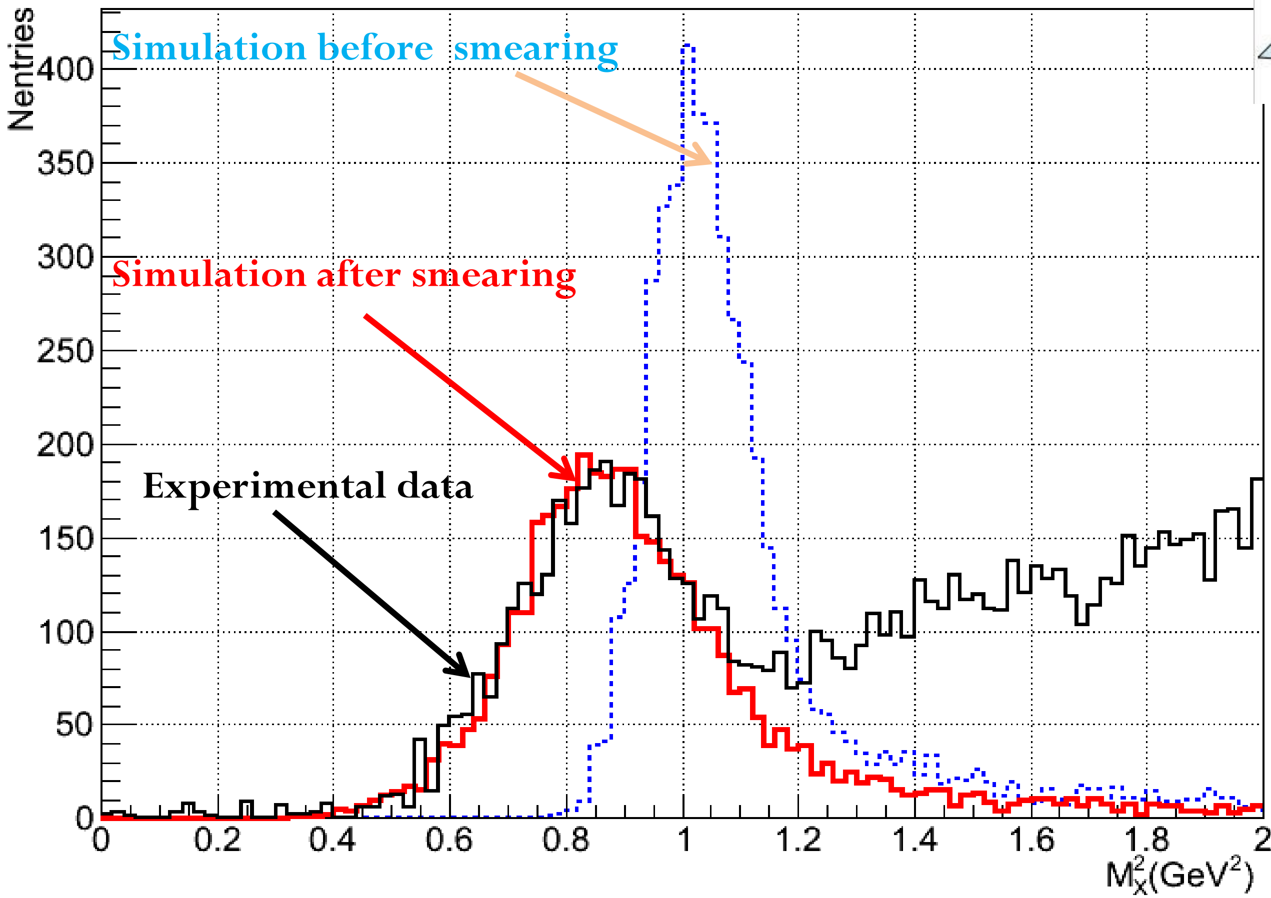


Smearing of the simulation data



Smearing Result

for 1 bin in (t, φ)



Extraction of the cross section

The unpolarized (nDVCS + dDVCS) total cross section (simplified expression) :

$$\frac{d^4\sigma_{(nDVCS\,+\,dDVCS)}}{dQ^2\,dx_B\,dt\,d\varphi} = BH_n + BH_d + \sum_i \Gamma_{in}(E,Q^2,x_B,t,\varphi)\,X_{in} + \sum_i \Gamma_{id}(E,Q^2,x_B,t,\varphi)\,X_{id}$$

Kinematical factor

(DVCS²+I) neutron Contribution

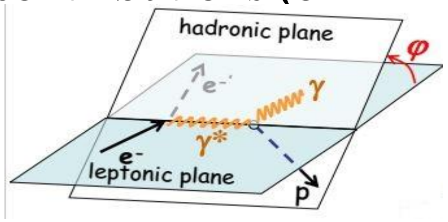
(DVCS²+I) Coherent deuteron Contribution

A.V. Belitsky, D. Mueller Phys. Rev., D82:074010, 2010

<u>Binning</u> :

✓**4 bins in t** (transfer t)

✓**12 bins in φ : Dependence in φ ➔ Separate the different neutron contributions (or coherent deuton contributions)**

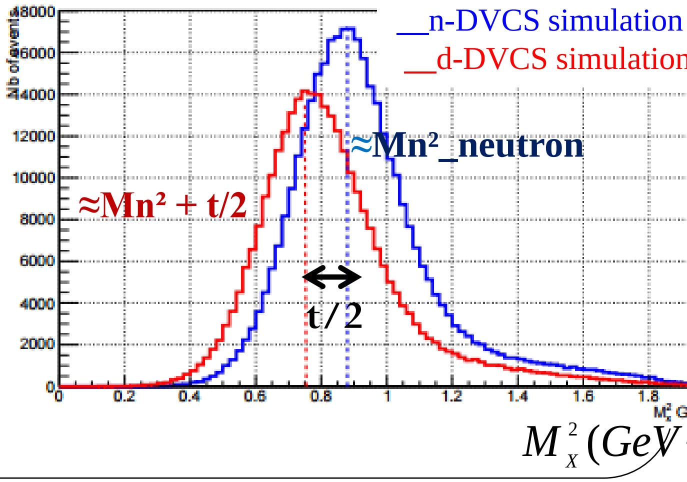


✓**30 bins in M_X^2 : Binning in Mx2 Separate contributions Xin from Xid: Mx²d ≈ Mx²n+t/2**

✓**2 bin in E_{beam}: Rosenbluth separation**

based on data taken with two beam energies.

(We used the same observables (Xin + Xid) to fit the Data at E_{beam}=4.45 and E_{beam}=5.54 GeV data)



Extraction of the cross section

A χ^2 minimization between the smeared simulation data and experimental data:

$$\chi^2 = \sum_{k=0}^{Nbin} \left(\frac{\boxed{N_k^{sim}} - \boxed{N_k^{data}}}{\sigma_k^{\exp}} \right)^2$$

Number of experimental events in one bin k

The statistical errors in one bin k

$$N_e^{sim} = \boxed{\sum_{v\lambda\ldots} \mathcal{L}\, \Gamma_\lambda(Q^2, x_B, t, \varphi) \frac{\Delta\Gamma}{\mathrm{N}_{\mathrm{gen}}} X_{\lambda v}} P(e,v)$$

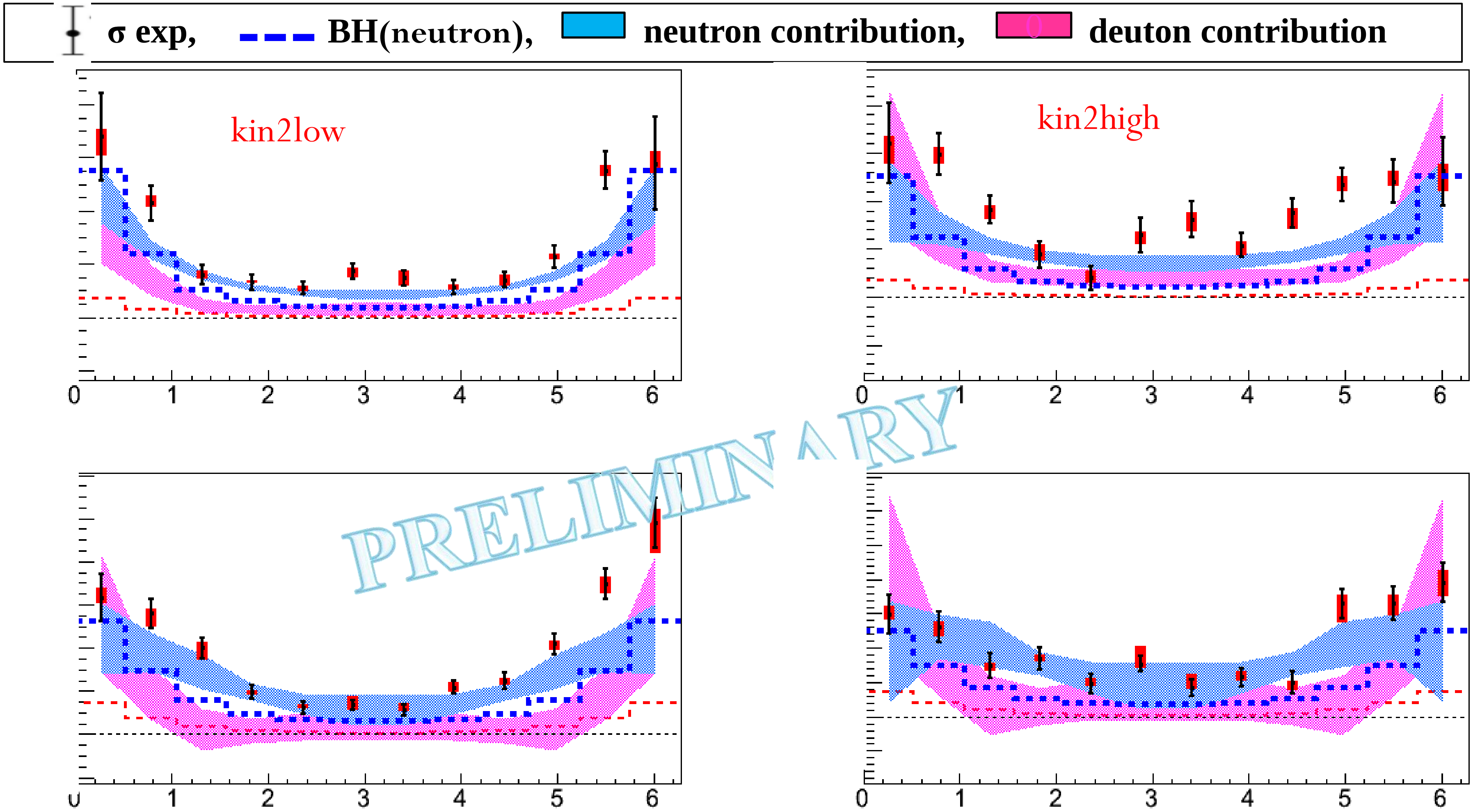
Number of events in the simulation in one experimental bin e

Number of events in the simulation in one Vertex bin v

migration probability of an event at the vertex "v" to an experimental bin "e"

$$\frac{d\chi^2}{dX_{\lambda_0 v_0}} = 0 \Rightarrow X_{\lambda v} \left\{ \begin{array}{l} C^{DVCS}(\mathcal{F},\mathcal{F}^*)_{n/d} \\ \Re e\, C^{\mathrm{I}}(\mathcal{F})_{n/d} \\ \Re e\, C^{\mathrm{I}}(\mathcal{F}_{eff})_{n/d} \end{array} \right. \Rightarrow \boxed{d^4\sigma^{\exp}(e) = d^4\sigma^{Fit}(e) \frac{N^{\exp}(e)}{N^{sim}(e)}}$$

n-DVCS cross section (+d-DVCS)



First experimental determination of the unpolarized $en \to en\gamma$ cross section

$\sigma(n(e,e'\gamma)n) > \sigma(BH_n)$ the first experimental evidence of a **positive n-DVCS** contribution

Conclusion

- **Rosenbluth separation and First measurements (preliminary) of the process unpolarized $n(e,e'\gamma)n$ cross section**

- **Important to constrain GPD E (needed to determine the quark orbital momentum)**

Thank you for your attention