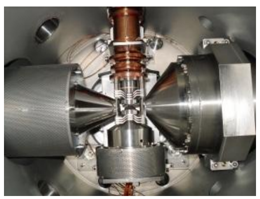
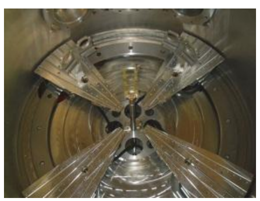
Laboratoire de physique corpusculaire

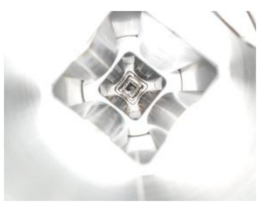


DVCS off the Neutron in Jlab Hall A
(6 GeV experiments)



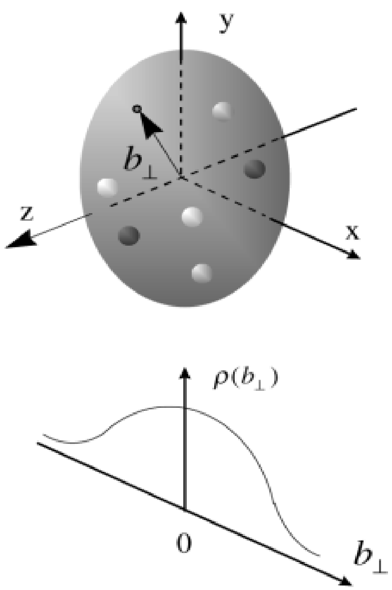
Meriem BENALI

Faculte des Sciences de Monastir (Tunisia)

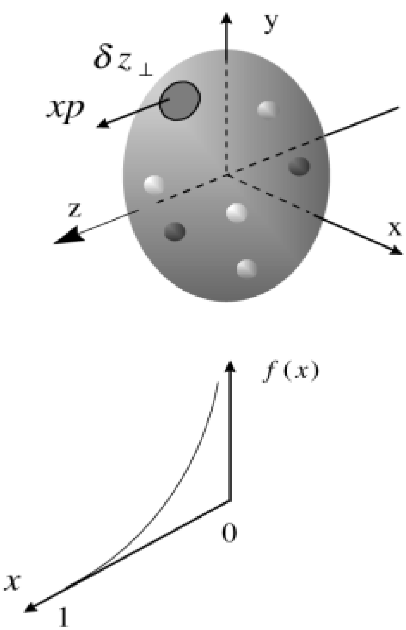


Generalized Parton Distribution GPDs

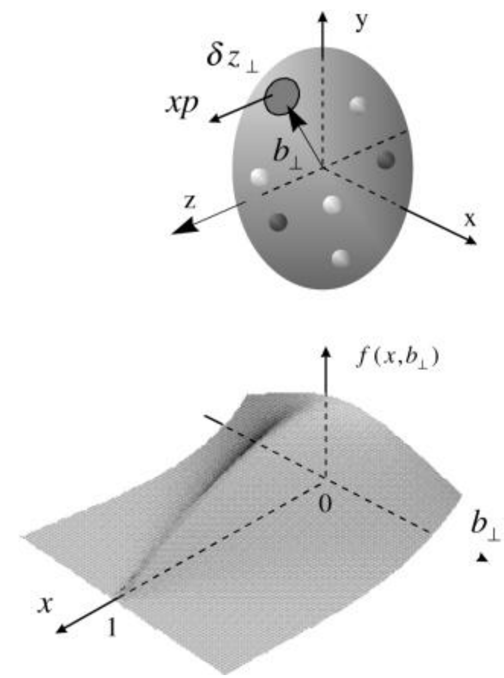
Elastic Scattering



Deep inelastic scattering



Deep exclusive scattering



Form Factors
(Transverse position of partons)

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

Generalized Parton Distribution GPDs

Two independent informations about the nucleon structure → Correlate → **3-D picture of the nucleon**

Generalized Parton Distribution GPDs

At leading order, 8 GPDs for each flavor quark *f*:

- **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 at (ξ=t=0)**

$$H^q(x,0,0)\begin{cases} = q(x)\ ; & x>0 \\ = -\bar{q}(x) & x<0 \end{cases}$$

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

$$\tilde{H}_T^q(x,0,0)\begin{cases} =\delta q(x)\ ; & x>0 \\ = \delta\bar{q}(-x)\ ; & x<0 \end{cases}$$

➢ **Link to Form Factors (∀ ξ)**

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

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

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

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

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

Generalized Parton Distribution GPDs

At leading order, 8 GPDs for each flavor quark *f*:

- **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

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

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

➢Solving the problem of the "spin puzzle"

$$\frac{1}{2} = \underbrace{\boxed{\frac{1}{2}\Delta\Sigma_q + L_q}}_{J_q} + J_g$$

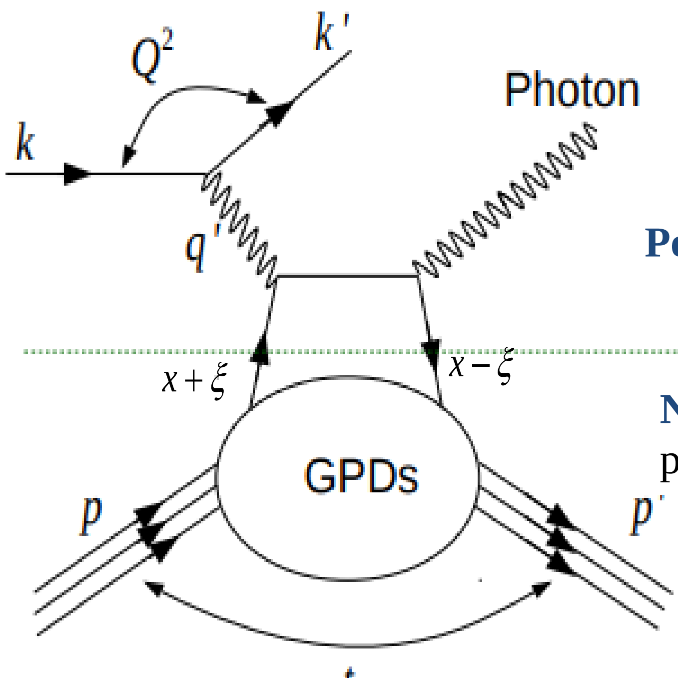
quark spin contribution
(~30% of total spin)

quark orbital ???
angular momentum

How to access 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

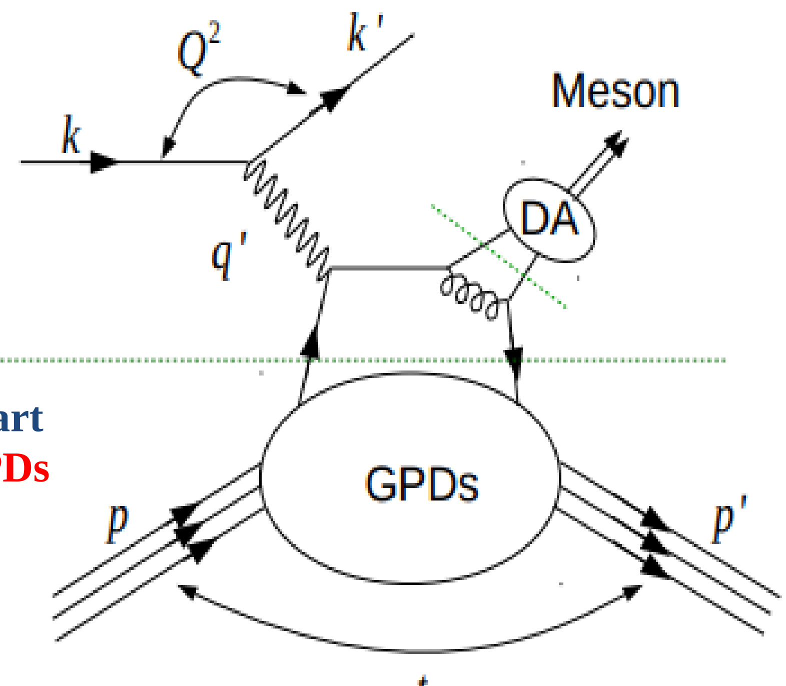
$$\begin{cases} Q^2 = -(k-k')^2 \to \infty \\ \nu = (k_0 - k'_0) \to \infty \end{cases} \quad \textbf{and fixed} \quad x_B = \frac{Q^2}{2M\nu}$$



Deeply Virtual Compton Scattering (DVCS)

Perturbative part (calculable)

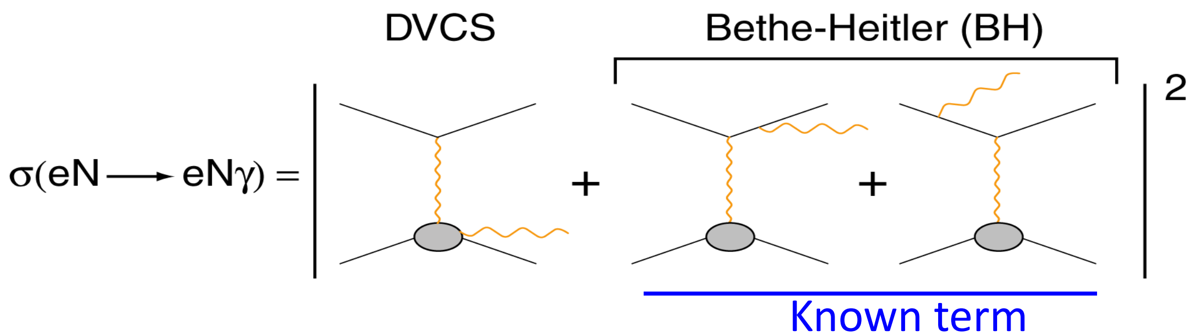
Non perturbative part parameterized by **GPDs**



Deeply Virtual Meson Production (DVMP)

5

Deeply Virtual Compton Scattering



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

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

→Known (fully calculable with nucleon FFs)

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

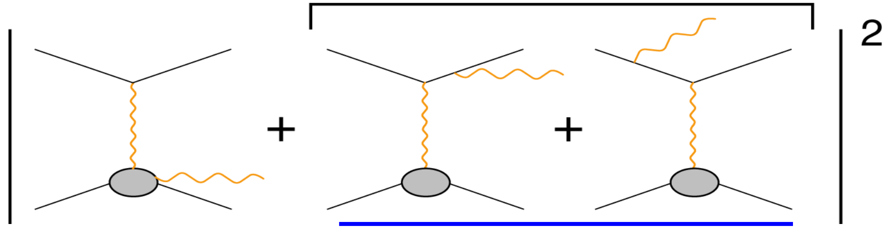
The **polarized cross-section difference** accesses the imaginary part of the interference and therefore **GPDs at x=±ξ**

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

Deeply Virtual Compton Scattering

DVCS Bethe-Heitler (BH)

σ(eN ⟶ eNγ) =



Known term

At leading order (LO**) and leading twist (LT) (twist-2):**

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

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

Known (fully calculable with nucleon FFs)

Bilinear combination of Compton Form Factors CFFs

$$C^{DVCS}(\mathcal{F},\mathcal{F}^*) \propto 4(1-x_B)\mathcal{H}\,\mathcal{H}^* - f(x_B,Q^2,t)(\mathcal{H}\,\mathcal{E}^* + \mathcal{E}\,\mathcal{H}^*) + \ldots$$

Linear combination of CFFs

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

$$\begin{cases} \Re e(\mathcal{H}) = \sum_q P\int_{-1}^{1} dx \left(\frac{1}{x-\xi} \pm \frac{1}{x+\xi}\right) \mathcal{H}^q(x,\xi,t) \\ \Im m(\mathcal{H}) = -\pi \sum_q e_q^2 \left(\mathcal{H}^q(x=\xi,\xi,t) - \mathcal{H}^q(x=-\xi,\xi,t)\right) \end{cases}$$

GPDs

BMK : Belitsky et al. Phys.Rev.D82:074010,2010

BMP : Braun et al. Phys.Rev.D89:074022,2014

We can extract 8 GPDs observables at LO/LT: $\Re e$ and $\Im m \left(\mathcal{F} \in \left\{\mathcal{H}, \tilde{\mathcal{H}}, \mathcal{E}, \tilde{\mathcal{E}}\right\}\right)$

Deeply Virtual Compton Scattering

Access to GPDs via **the unpolarized cross section :**

- Subtract the known contribution of BH

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

Known
(fully calculable
with nucleon FFs)

Deeply Virtual Compton Scattering

Access to GPDs via **the unpolarized cross section :**

- Studying the φ and E_{beam} dependence of I and $|T^{DVCS}|^2$ at fixed x_B, Q^2 and t allows to deduce some observables

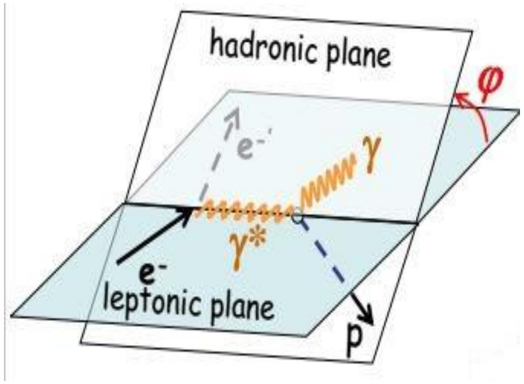
$$d^4\overleftarrow{\sigma} + d^4\overrightarrow{\sigma} = 2\Re e(T^{DVCS}.T^{BH}) + \left|T^{DVCS}\right|^2 + \left|T^{BH}\right|^2$$

$$\left|T^{DVCS}\right|^2 \propto \Gamma^{DVCS} E^2_{beam}\left[c_0^{DVCS}(\mathcal{F}) + c_1^{DVCS}(\mathcal{F})\cos\phi + \dots\right]$$

$$2\Re e(T^{DVCS}.T^{BH}) \propto \Gamma^{I} E^3_{beam}\left[c_0^{I}(\mathcal{F}) + c_1^{I}(\mathcal{F})\cos\phi + c_2^{I}(\mathcal{F})\cos 2\phi + c_3^{I}(\mathcal{F})\cos 3\phi + \dots\right]$$

$$\mathcal{F} \in \left\{\mathcal{H}, \tilde{\mathcal{H}}, \mathcal{E}, \tilde{\mathcal{E}}\right\}$$

: Compton Form Factors CFFs



Motivation (DVCS off the neutron)

❖ DVCS off the **neutron** : $F_1(t) \ll F_2(t)$

$$c^{\mathrm{I}}(\mathcal{F}) = \cancel{F_1(t)\mathcal{H}} + \frac{x_B}{2-x_B}(\cancel{F_1(t)} + F_2(t))\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2(t)\mathcal{E}$$

➢ **Sensitive to GPD E (**least constrained GPD) and which is important to access quarks orbital momentum via Ji's sum rule:

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

❖ Neutron has different flavors from the proton => GPDs flavor separation:

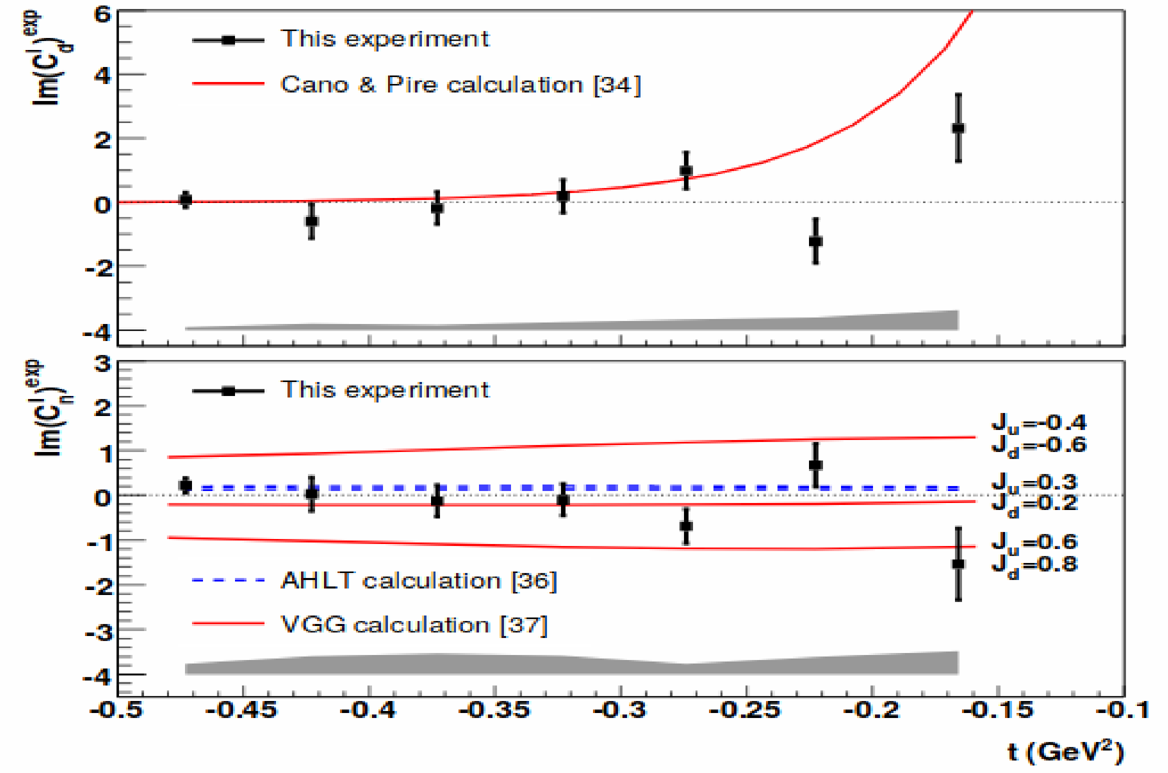
$$H^p(\xi,\xi,t) = \frac{4}{9}H^u(\xi,\xi,t) + \frac{1}{9}H^d(\xi,\xi,t) \qquad H^n(\xi,\xi,t) = \frac{4}{9}H^d(\xi,\xi,t) + \frac{1}{9}H^u(\xi,\xi,t)$$

DVCS off the neutron (Experiment E06-106)

E03-106: pioneer experiment of the DVCS off the neutron (2004):

Polarized cross section difference was determined at: **Q^2=1.91 GeV^2; x_B=0.36, E_{beam}=5.75 GeV**

M. MAZOUZ *et al.,* Phys. Rev. Lett. 99:242501, 2007



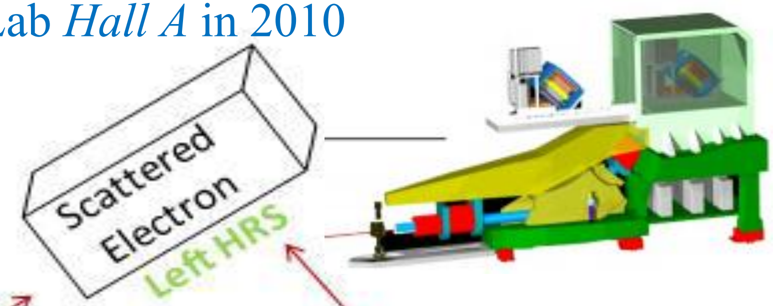
Unpolarized cross section could not be extracted (huge systematic uncertainties)

Next experiment

Experimental setup

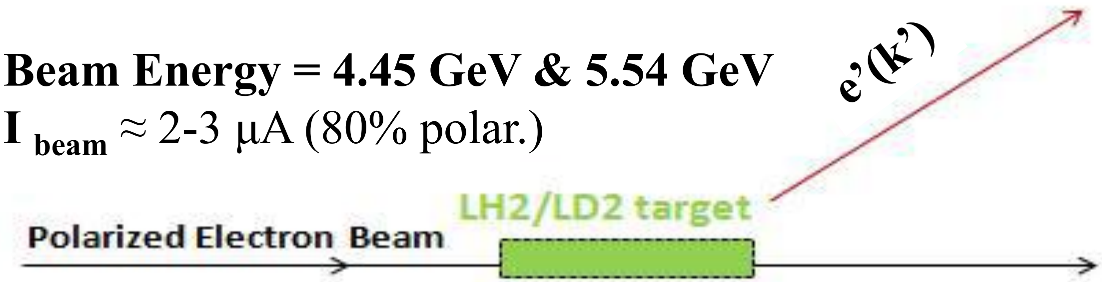
The **E08-025** (n-DVCS) experiment was performed at JLab *Hall A* in 2010

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



Beam Energy = 4.45 GeV & 5.54 GeV

I **beam** ≈ 2-3 μA (80% polar.)



DVCS events are identified with M_x^2

$$ep \rightarrow e\gamma p$$

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

P(p')

Recoil nucleon not detected

γ(q')

Electromagnetic Calorimeter

❖The data were taken at two kinematics (Kin2high and Kin2low):

- ✓**Q^2 = 1.75 GeV^2**
- ✓ **x_{Bj} = 0.36**
- ✓ **t ~ [-0.5 , -0.1] GeV^2**
- ✓ **Maximal luminosity = 3. $10^{37} cm^{-2} s^{-1}$**

- 13 X 16 PbF2 blocs (density 7.77 g/cm^3)
- block size : 3x3 cm^2 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 && π^0 contamination subtraction

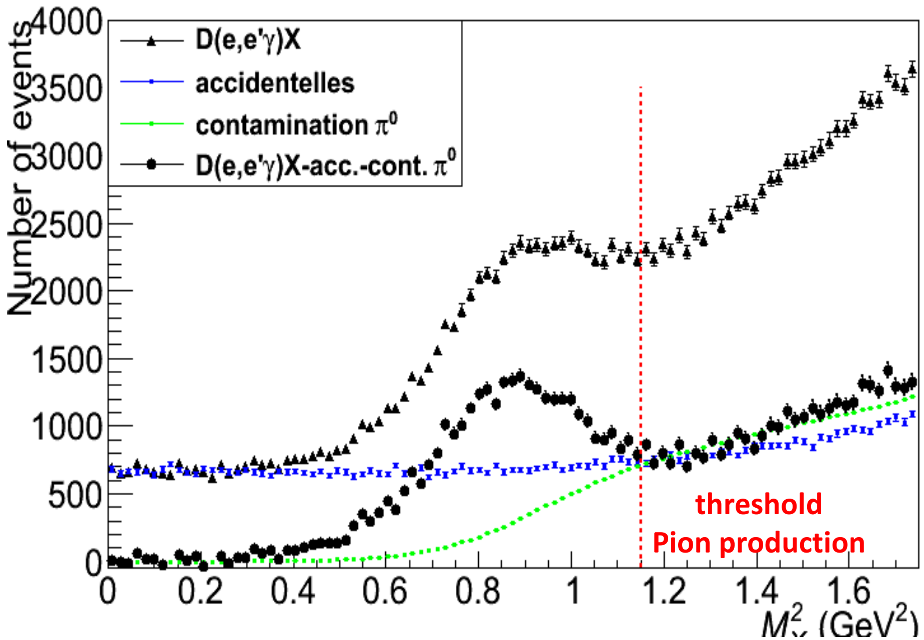
The raw data: detect e' and γ in coincidence (eN→e' γ X)

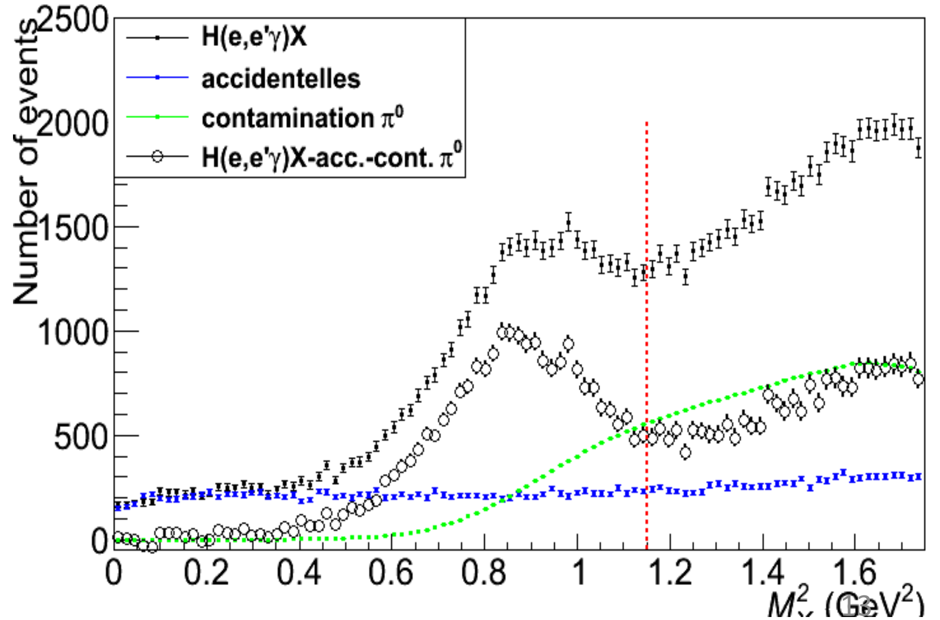
•1 track in the HRS and 1 cluster in the calorimeter (energy> 1 GeV)

→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

Spectrum : $M_X^2 = (e + N - e' - \gamma)^2$





Selection of the n-DVCS events

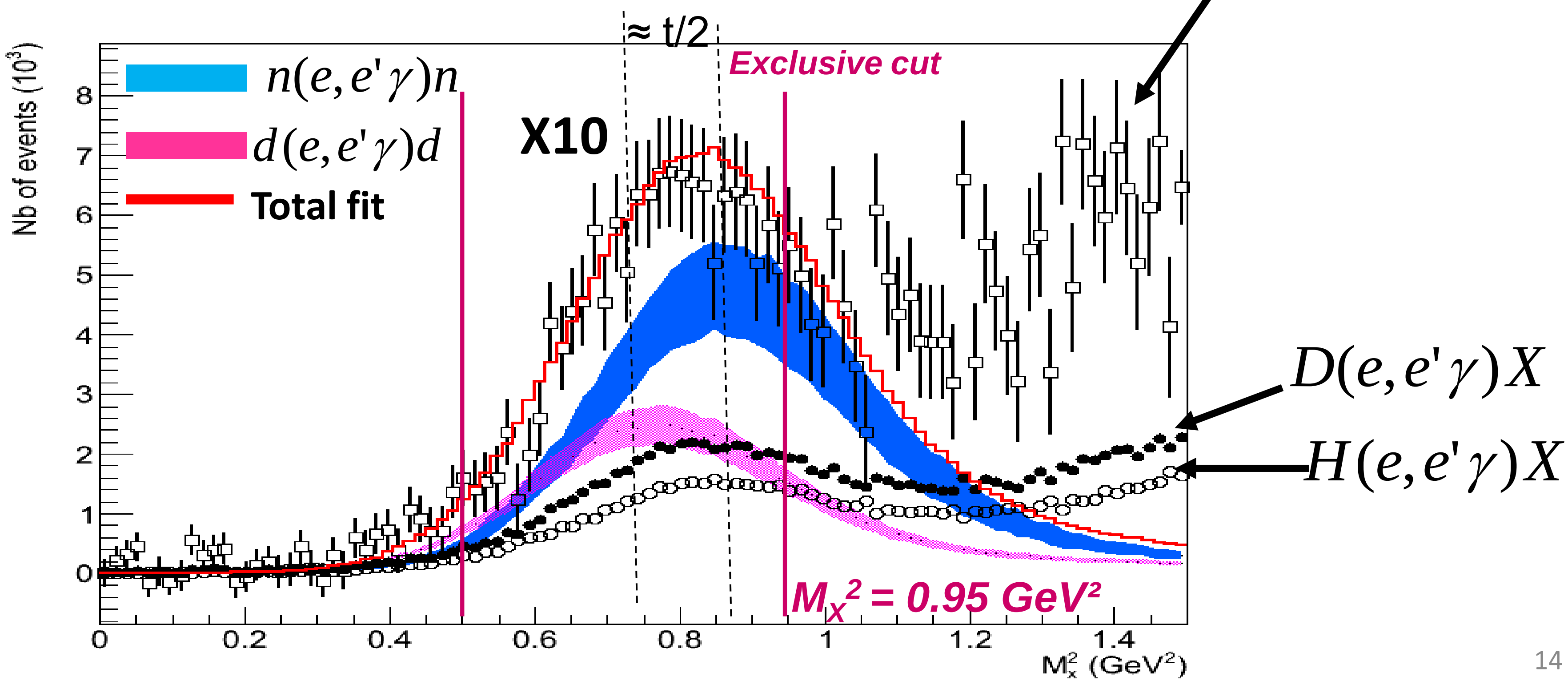
After

- 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

$$D(e,e'\gamma)X - H(e,e'\gamma)X = \boxed{n(e,e'\gamma)n} + \boxed{d(e,e'\gamma)d} + \ldots$$

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



Adjusting the simulation to the experimental data

Experimental data

+

simulated data:

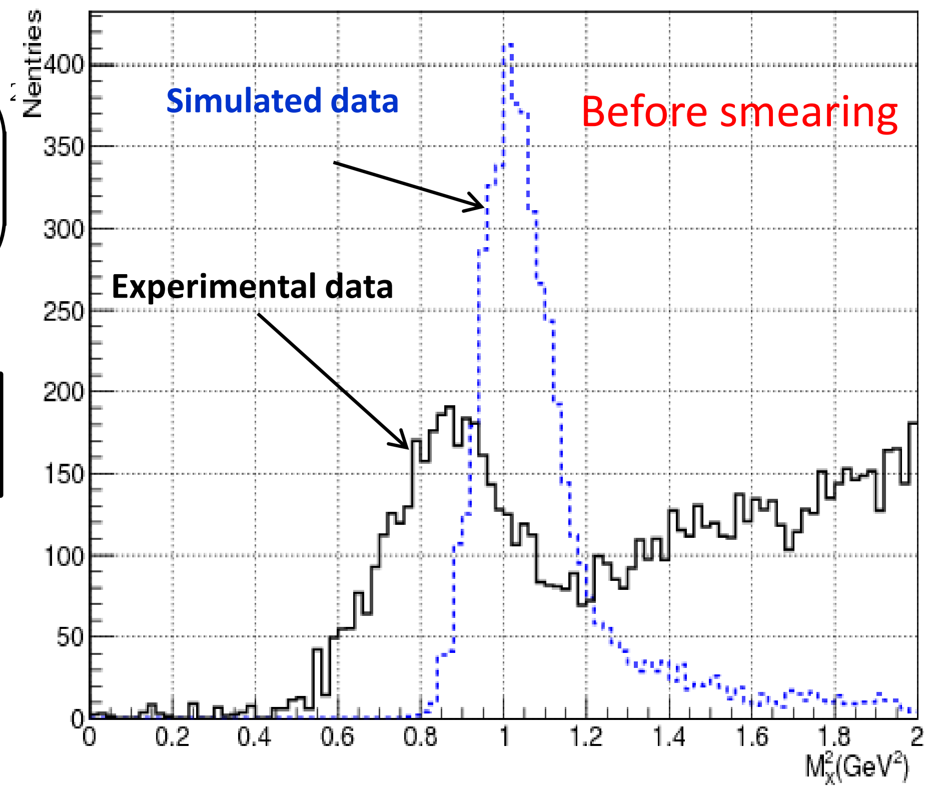
1- have the same cuts applied to the experimental data

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

3- takes into account the radiative corrections

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

$$\boxed{\textbf{Cross Section} \quad \sigma^{exp}}$$



Adjusting the simulation to the experimental data

Experimental data

+

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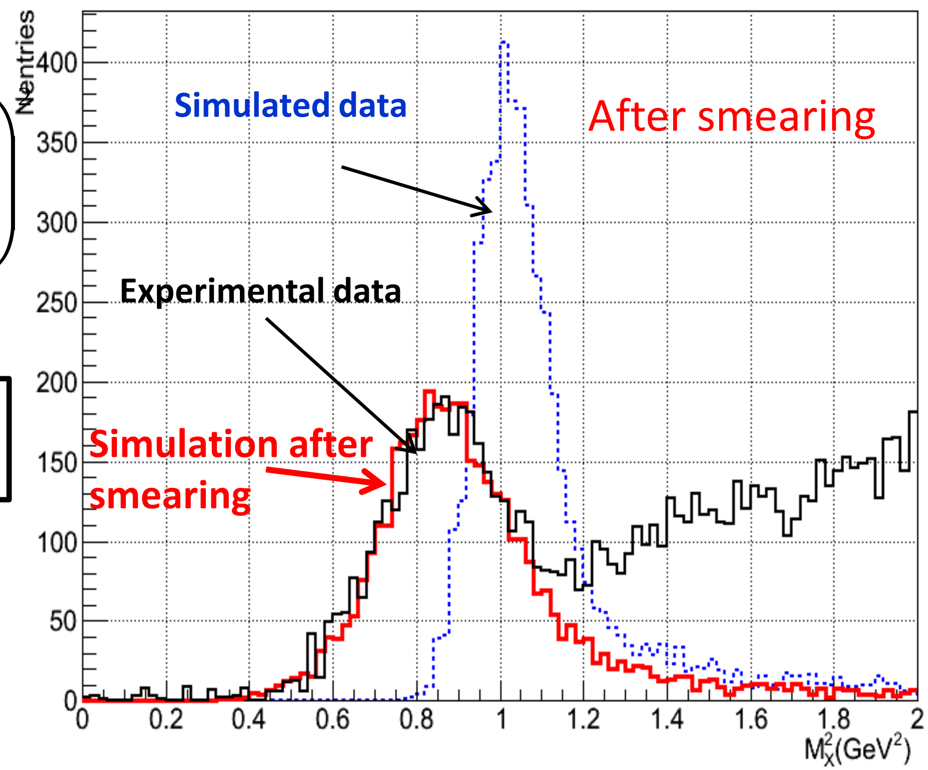
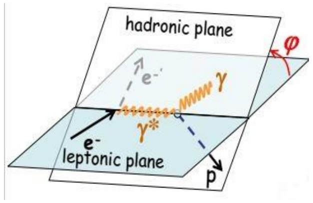
Adjustment : $$\chi^2 = \sum_{e=0}^{Nbin} \left(\frac{N_e^{sim} - N_e^{exp}}{\Delta\sigma_e^{exp}} \right)$$

Cross Section σ^{exp}



n-DVCS cross section (+d-DVCS)



Binning : **12 × 2 × 5 × 30** bins in φ, E , t and M_X^2

- **Dependence in φ ➔ Separate the different neutron LO/LT CFFs observables Xin (neutron) (or Xid (coherent deuton))**

- **Binning in M_X^2 ➔ Separate n(e,e'γ)n and d(e,e'γ)d contributions**
  M_X^2 d ≈ M_X^2 n + t/2

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

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

BH _neutron contribution

BH_coherent deuteron contribution

Kinematical factor

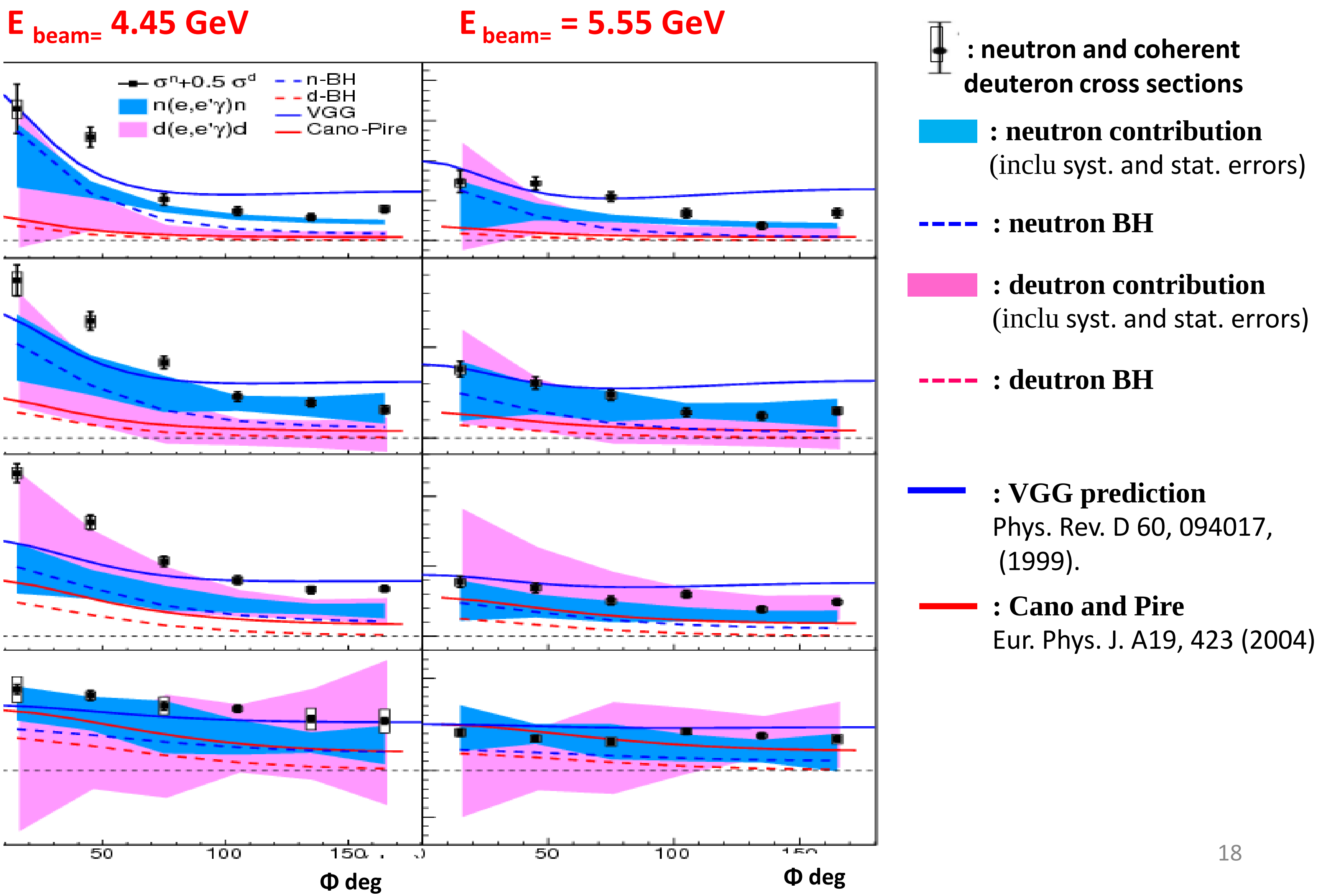
(DVCS²+I) neutron Contribution

(DVCS²+I) Coherent deuteron Contribution

The observables we want to extract:
the linear combinations of CFFS
which contain GPDs

n-DVCS cross section (+d-DVCS)

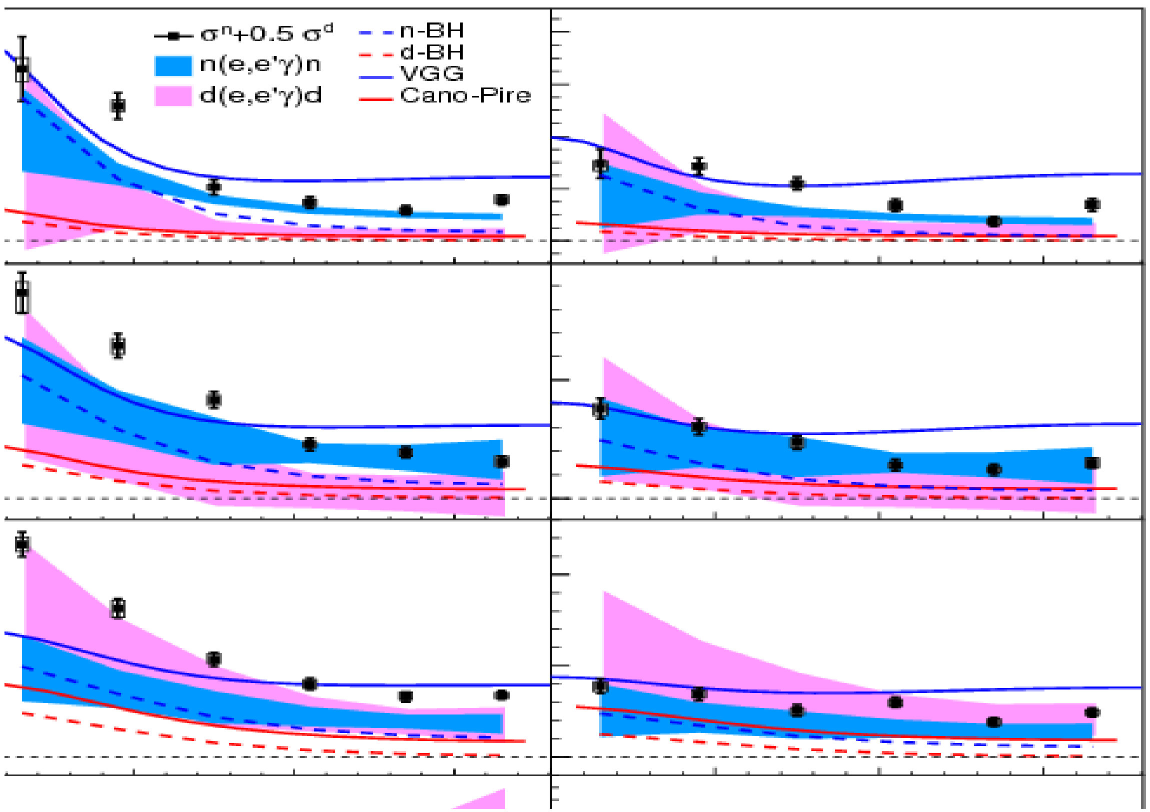
Unpolarized cross section as a function of ϕ, E and t bins :



n-DVCS cross section (+d-DVCS)

Unpolarized cross section as a function of ϕ, E and t bins :

E $_{\text{beam=}}$ 4.45 GeV **E $_{\text{beam=}}$ = 5.55 GeV**



: neutron and coherent deuteron cross sections

: neutron contribution (inclu syst. and stat. errors)

: neutron BH

: deutron contribution (inclu syst. and stat. errors)

: deutron BH

: VGG prediction Phys. Rev. D 60, 094017, (1999).

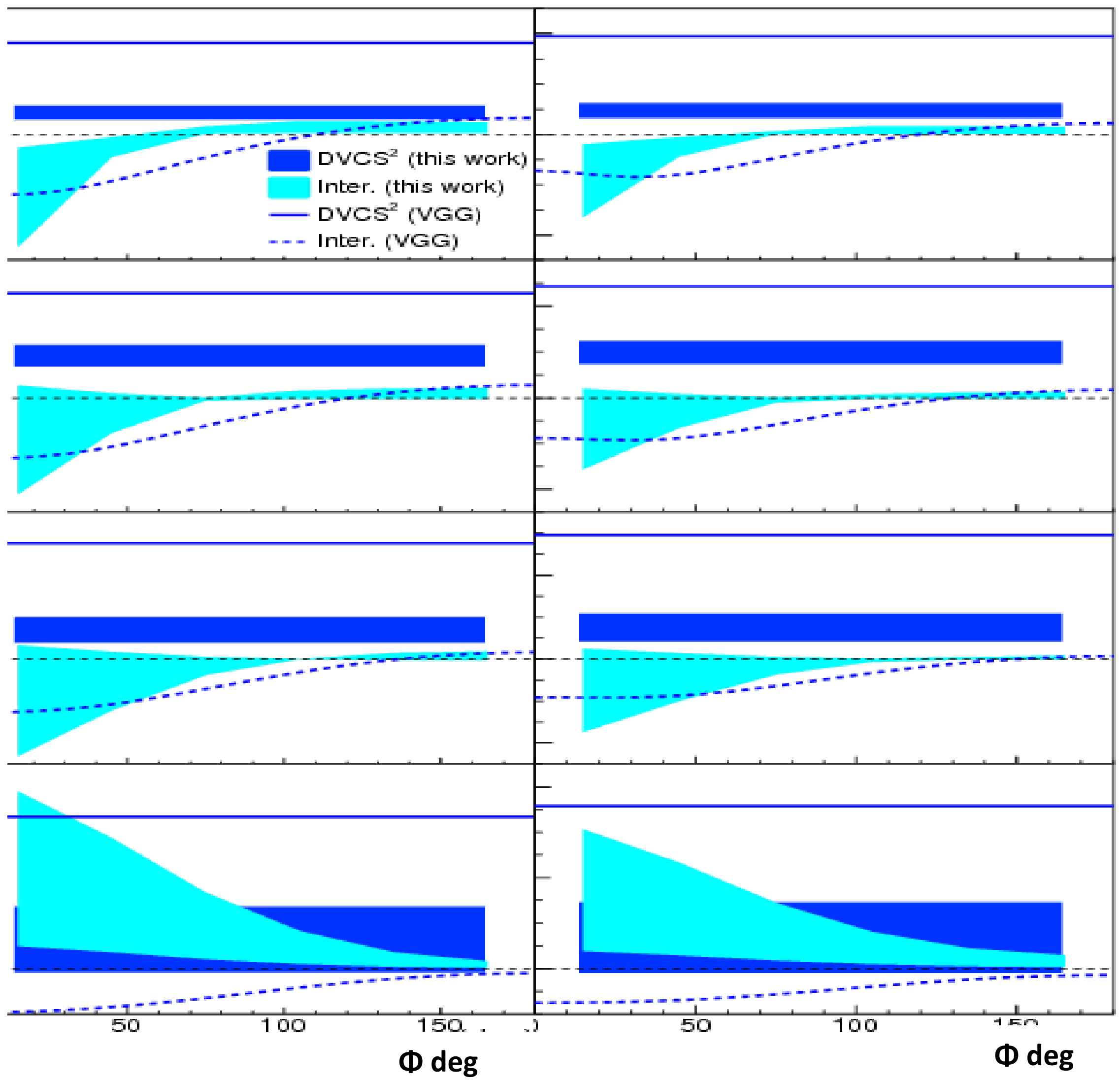
: Cano and Pire Eur. Phys. J. A19, 423 (2004).

- First experimental determination of the unpolarized cross section
- the first experimental evidence of a **positive n-DVCS** signal

n-DVCS cross section (+d-DVCS)

Simultaneous fit of two **E beam** ⇨ **Separate** |DVCS|² and I|DVCS.BH| contributions

E beam= 4.45 GeV **E beam= = 5.55 GeV**



: |DVCS|² **neutron contribution**

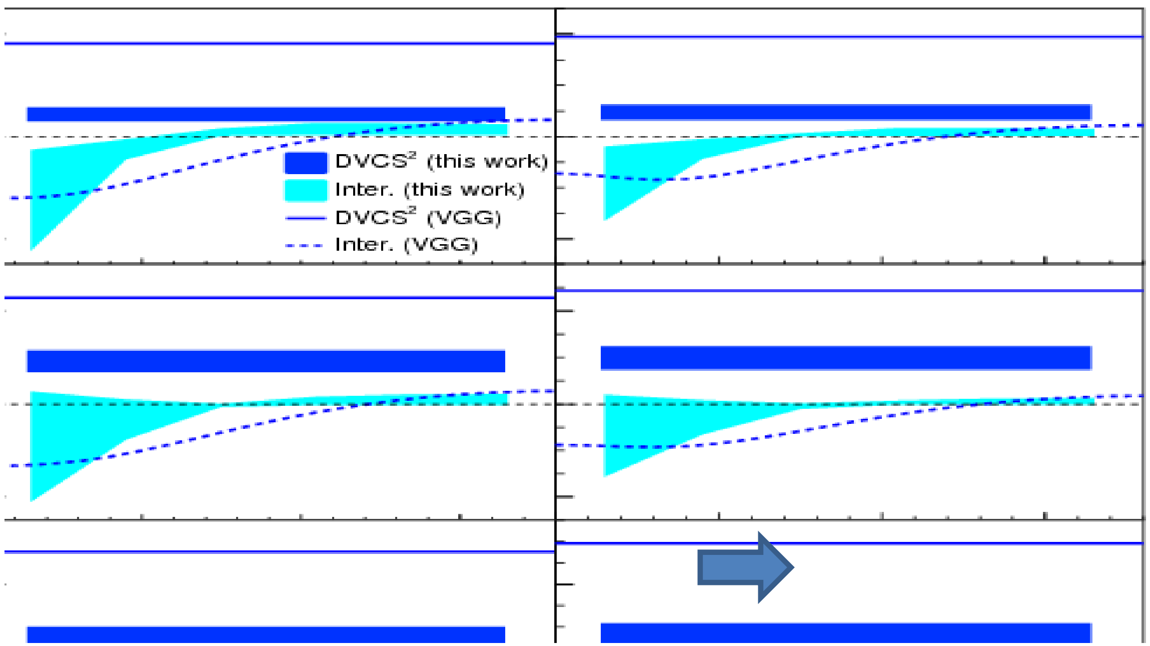
: I|DVCS.BH| **neutron contribution**

: VGG prediction
Phys. Rev. D 60, 094017, (1999).

n-DVCS cross section (+d-DVCS)

|DVCS|² and I|DVCS.BH| contributions off the neutron as a function of ϕ, E and t bins :

E $_{beam=}$ 4.45 GeV **E $_{beam=}$ = 5.55 GeV**



: |DVCS|² **neutron contribution**

: I|DVCS.BH| **neutron contribution**

: **VGG prediction**
Phys. Rev. D 60, 094017,

- The interference term is compatible with zero within error bars (In agreement with **E03-106 experiment 2004, M. MAZOUZ *et al.*, Phys. Rev. Lett. 99:242501, 2007)**

- The DVCS² has a significant contribution to the cross section (in agreement with proton results at the same kinematics : **M. Defurne et al., Nature Commun. 8, 1408, 2017)**

Conclusion

- **First measurements of the unpolarized cross section of the photon electroproduction off a deuterium target**
- **Rosenbluth separation of the $DVCS^2$ and the interference terms for the neutron and the coherent deuteron**
- **Neutron results: significant deviation of the cross section from the n-BH : a non-zero n-DVCS signal**
- **Deutron results: compatible with d-BH and theoretical expectations**

• A flavor decomposition of the CFFs can be performed by combining proton and neutron data

• The neutron results are sensitive to GPD E and can be exploited to constraint the quark angular momentum

Thank you for your attention

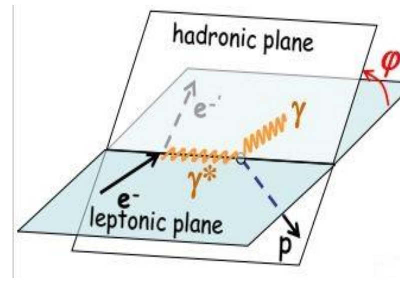
BACK-UP

Extraction of the cross section

➢ **According to the formalism of Muller Belitsky and the differential cross section is:**

$$d^4\sigma = |T^{DVCS}|^2 + 2\,T^{BH}\,\Re e(T^{DVCS}) + |T^{BH}|^2$$

Terme connu



$$|T^{DVCS}|^2 \propto \Gamma_0^{DVCS} C_0^{DVCS} + \Gamma_1^{DVCS} C_1^{DVCS} \cos(\varphi)$$

$$C_0^{DVCS} \propto \Gamma^{DVCS}\, C^{DVCS}(\mathcal{F},\mathcal{F}^*) + \Gamma^{DVCS}\, C^{DVCS}(\mathcal{F}_{eff},\mathcal{F}^*_{eff})$$

1

$$I \propto \Gamma_0^I C_0^I + \Gamma_1^I C_1^I \cos(\varphi) + \Gamma_2^I C_2^I \cos(2\varphi) + \Gamma_3^I C_3^I \cos(3\varphi)$$

$$C_n^I = \Gamma^I\, \Re e\, C_{++}^I(n|\mathcal{F}) + \Gamma^I\, \Re e\, C_{0+}^I(n|\mathcal{F}_{eff}) + \Gamma^I\, \Re e\, C_{-+}^I(n|\mathcal{F}_T)$$

$$\Re e\, C_{++}^I(n|\mathcal{F}) = \Re e\, C^I(\mathcal{F}) + \frac{C_{++}^V(n)}{C_{++}(n)}\, \Re e\, C^{I,V}(\mathcal{F}) + \dots$$

2

$$\Re e\, C_{0+}^I(n|\mathcal{F}_{eff}) = [\dots \Re e\, C^I(\mathcal{F}_{eff})] + \frac{C_{0+}^V(n)}{C_{0+}(n)}\, \Re e\, C^{I,V}(\mathcal{F}_{eff}) + \dots$$

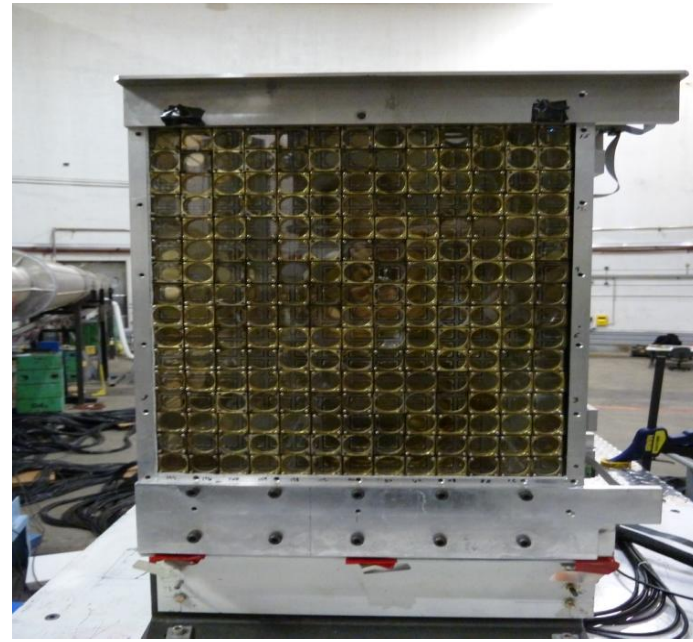
3

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

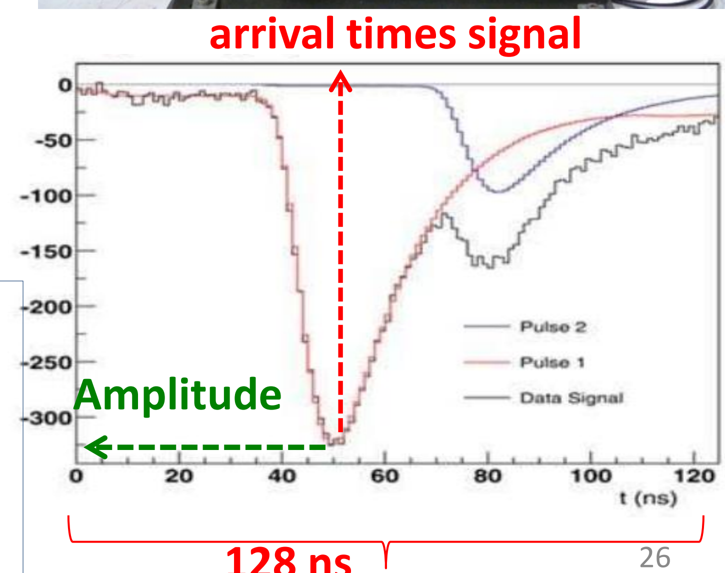
Electromagnetic Calorimeter

Electromagnetic Calorimeter

- 13x16 PbF_2 blocks (Čerenkov light detection)
- Block size: 3x3 cm² x 20 X_0
- short radiation length :
  ->X_0=(1/20) crystal length
- Molière redius=2.2 cm
  -> electromagnetic shower is contained in 9 adjacent blocks
- Each block is connected to (PMT + base + ARS)



✓ recording the input signal on 128 ns (ARS) as in a digital oscilloscope in order to solve the pile up signals.
✓ Digitization and recording of all calorimeter channels for each electron detected in HRS (trigger)
✓The energy deposit determination is based on a wave form analysis of the ARS signals.



blackening blocks under the effects of radiation:
→the gains of the blocks decreases
→ Calibrate the response of the electromagnetic calorimeter

Calorimeter energy calibration

Calibration method

$$eN \rightarrow e'\,\pi^0\,N$$
$$\pi^0 \rightarrow \gamma 1\ \gamma 2 \quad \textbf{(Detected)}$$

The calibration method is based on the comparison between the measured energy of a detected π^0 from $H(e,e'\,\pi^0)p$ events and its expected energy calculated with its scattering angle:

$$\cos(\theta_{\gamma^*\pi 0}) = \frac{\vec{q}_{\gamma^*}.\vec{q}_{\pi 0}}{\|\vec{q}_{\gamma^*}\|.\|\vec{q}_{\pi 0}\|}$$

$$\chi^2 = \sum_{j=1}^{N}\left(E_{\pi}^{j} - \sum_{i=0}^{207} C_i E_i^j\right)^2$$

??

Sum over all events

Sum over all blocks

Calculated energy of pion

Calibration coefficients

measured energy in one block
(elastically calibrated)

After the minimization we get the coefficients for each block i

$$\frac{\partial \chi^2}{\partial C_i} = 0 \Rightarrow [C_i] = [M]^{-1}[B]$$

The momentum of π^0 reconstructed using $\vec{q}_{\gamma 1}$ et $\vec{q}_{\gamma 2}$

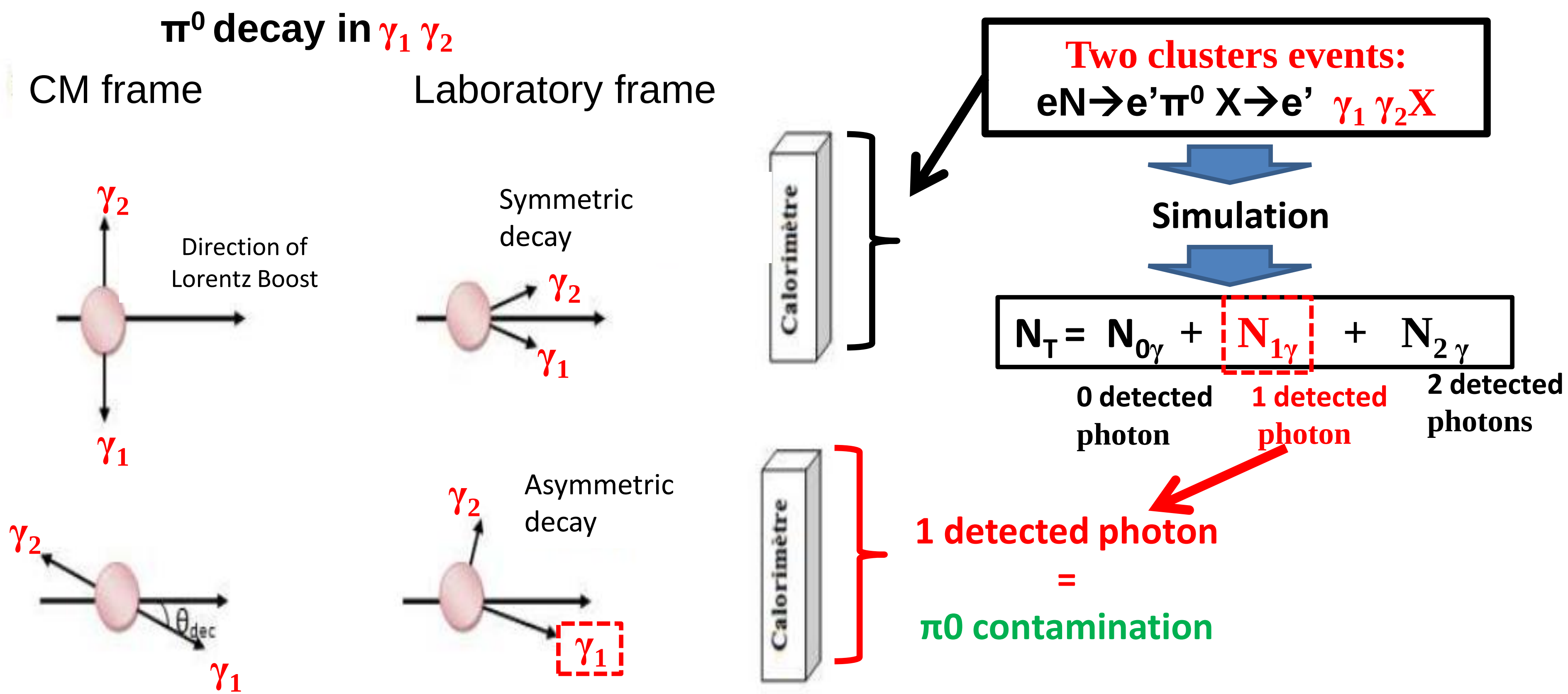
several iterations to get the final coefficients for each block i

$$\Rightarrow C_i^{final} = C_i^{iter1} \times C_i^{iter2} \times \dots C_i^{iter7}$$

Selection of the n-DVCS events

2- π^0 contamination subtraction

→ **The photon detected in the calorimeter may come from the decay of $\pi 0$ and resembles kinematically to a DVCS photon : $eN \rightarrow e'\pi^0 X \rightarrow e' \gamma_1 \gamma_2 X$**



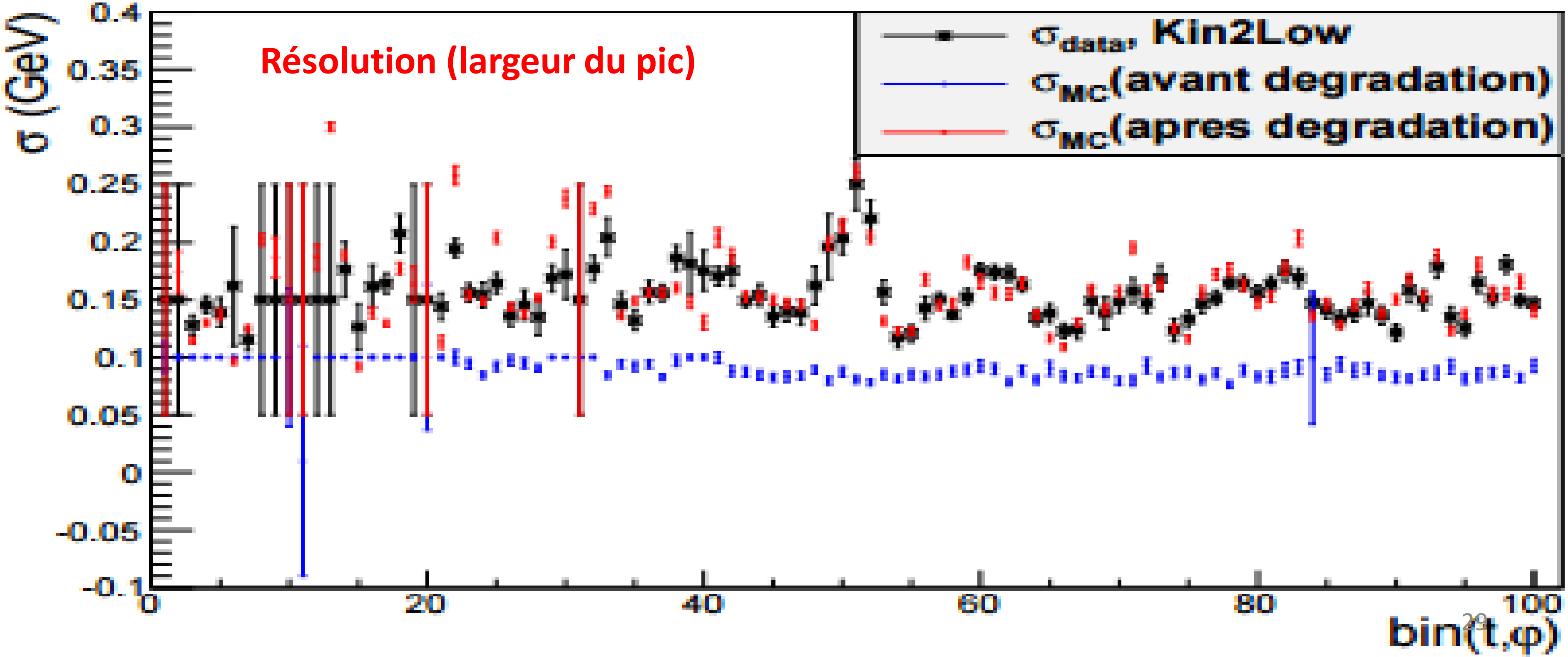
❑ We applied a cut on the blocks of the edges and on the corner of the calorimeter to better estimate the $\pi 0$ contamination (Efficiency = 100% +/- 1)

Smearing of the simulation data

Smearing Result

For 5 in t and 20 in ϕ

- Good agreement between the resolution of the data and the simulation for each bin (t and φ)
- Good agreement between the calibration of the data and the simulation for each bin (t and φ)
- **The first 20 bins are rejected (blocks on board of the calorimeter)**
- **The coefficients of the smearing determined with LH2_data and the p_DVCS simulation are then applied to d_DVCS and n_DVCS simulation.**



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