Measurement of the generalized polarizabilities of the proton by virtual Compton scattering at MAMI

ANALYSIS OF MAMI DATA « VCSQ2 » EXPERIMENT

AT $Q^2 = 0.2\ GeV^2$

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Introduction

Generalized Polarizabilities
Virtual Compton Scattering
Analysis techniques
World data and goal of the experiment

Design of the experiment

Preliminary results

Introduction : GPs

Nucleon electromagnetic polarizabilities

- How the internal structure is deformed in an applied electromagnetic field
- Extreme proton stiffness

Generalized polarizabilities

- Polarizabilities depend on the four-momentum transfer Q² when we have a virtual photon
- For example the Fourier transform electric GP leads to the charge distribution modification

⟶ **VCS to measure GPs**

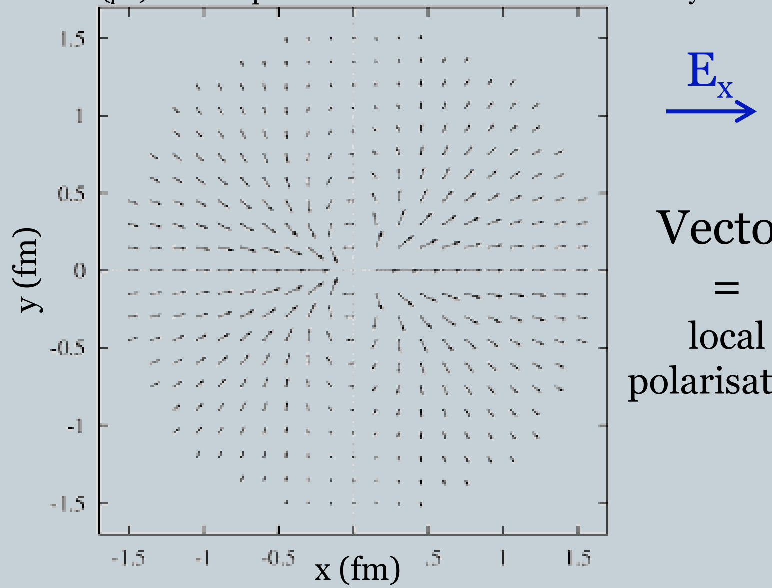
V.Olmos de Leon et al. Eur.Phys. J. A10 (2001) 207

$$\alpha_E = (12.1 \mp 0.3_{stat} \mp 0.5_{syst})10^{-4} fm^3$$

$$\beta_M = (1.6 \mp 0.4_{stat} \mp 0.6_{syst})10^{-4} fm^3$$

S.Scherer, AIP Proc. Conf. 768 (2005) 110.

HBChPT O(p^3) Electric polarization in the nucleon induced by the field E_x

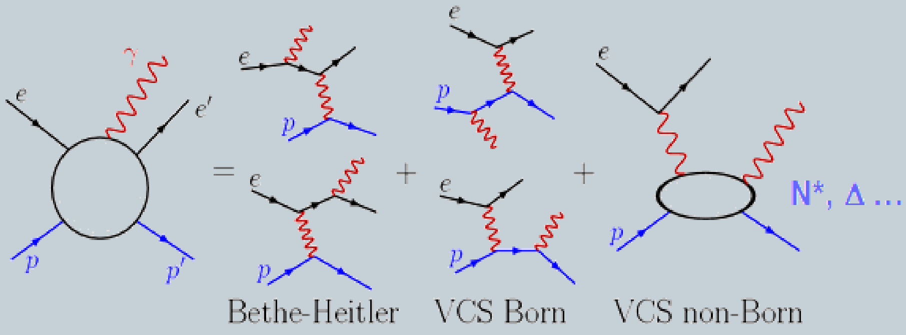


Vector = local polarisation

Virtual Compton Scattering

Photon electroproduction amplitude

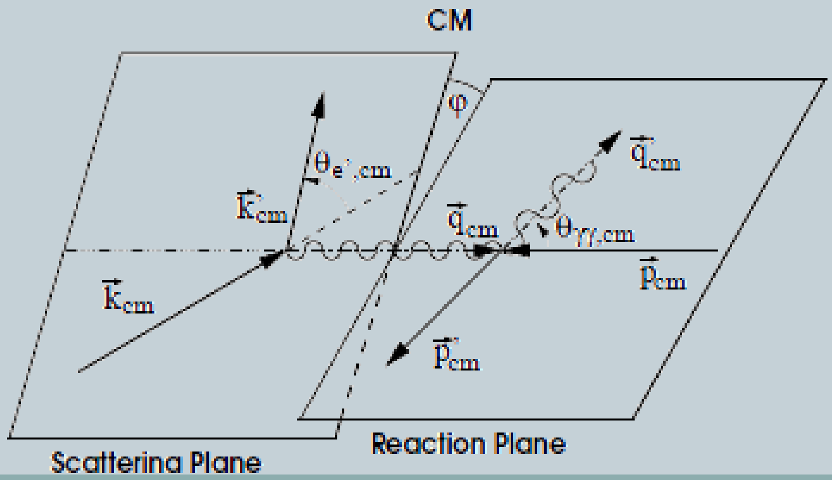
- $ep \rightarrow ep\gamma$
- A sum of contributions
- Bethe-Heitler and Born (BH+B) amplitudes depend on elastic protons form factors
- At low energy non-Born is parameterized by **6** GPs



D.Drechsel et al PRC57,941 (1998)
PRC58,1751(1998)

Center of mass kinematics

- $(q_{cm}, q'_{cm}, \varepsilon, \theta_{\gamma\gamma cm}, \varphi)$
  - q & q' modulus of initial and final photon
  - ε usual polarization parameter of the virtual photon
  - θ polar angle
  - φ azimuthal angle



Analysis techniques for VCS : LEX

Low-energy expansion :

P.Guichon et al Nucl.Phys.A591 (1995)

$$d^5\sigma(ep\gamma) = d^5\sigma_{BH+B} + \underbrace{(\Phi q'_{cm}) \times [v_{LL}.\left(\boldsymbol{P_{LL}} - \frac{\boldsymbol{P_{TT}}}{\boldsymbol{\varepsilon}}\right) + v_{LT}.(\boldsymbol{P_{LT}})]}_{\text{Interference NB} \Leftrightarrow \text{BH+B}} + \boldsymbol{\mathcal{O}}({q'}^2_{cm})$$

- Structure functions can be determined by measuring the deviation of σ_{exp} from σ_{BH+B}
- Structure functions lead to electric and magnetic GPs if one fixes spin-flip GPs with a theoretical model
- Valid only below the pion production threshold (q'=126 MeV/c)
- Find a phase space region where the effect of $\boldsymbol{\mathcal{O}}({q'}^2_{cm})$ is small enough to be neglected

$$P_{LL} - \frac{P_{TT}}{\varepsilon} = \frac{4M_p}{\alpha}.G_E^P(Q^2).\boldsymbol{\alpha_E(Q^2)} + [spinflip]$$

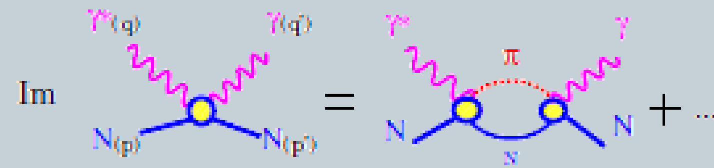
$$P_{LT} = \frac{-2M_p}{\alpha}\sqrt{\frac{q^2{}_{cm}}{Q^2}}.G_E^P(Q^2).\boldsymbol{\beta_M(Q^2)} + [spinflip]$$

Analysis techniques for VCS : DR

Dispersion relation model

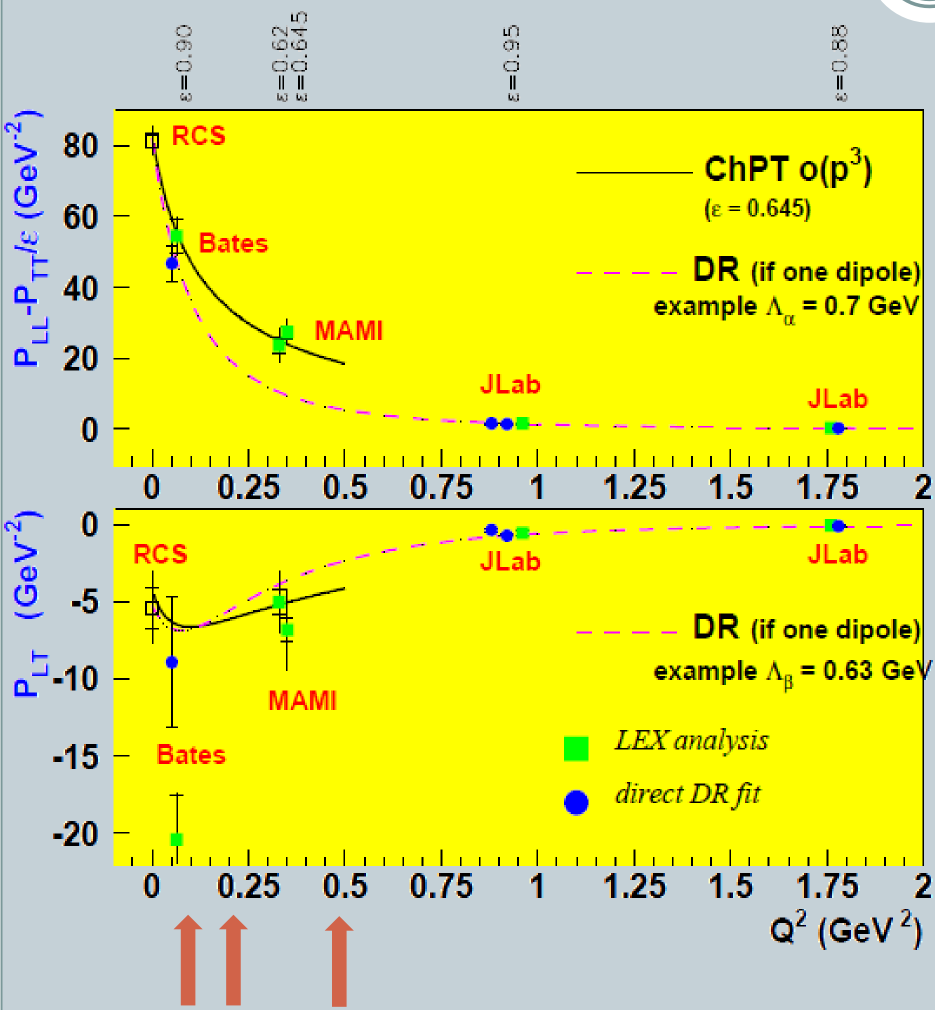
B.Pasquini et al., Eur.Phys.J. A 11 (2001)

- VCS amplitude is given by dispersion integrals
- $\gamma^* N \to \pi N$ diagrams calculated with MAID model



LEX	DR
❖ Calculation is valid only below the pion threshold	❖ Calculation is valid even above the pion threshold
❖ Structure functions are found by fitting experimental data and leads to GPs	❖ $\alpha_E(Q^2)$ & $\beta_M(Q^2)$ are directly described through free parameters Λ_α & Λ_β
❖ Spin GPs have to be deduced from a model	❖ Spin GPs are predicted by the DR model

World Data and goal of the experiment



- Structure functions contain $\alpha_E(Q^2)$ & $\beta_M(Q^2)$
- Heavy Baryon Chiral Perturbation Theory at order p^3 curve follows the data at low Q^2
- The enhancement of $\alpha_E(Q^2)$ at low Q^2 is not fitted by the DR calculation assuming one single dipole

  → Explore the low-Q^2 domain at new values : *0.1, 0.2* and *0.5* GeV^2 with competitive error bars
- Locate the P_{LT} extremum

Design of the experiment

Guideline

Be able to perform LEX and DR analysis

Good sensitivity to GPs effect

Good sensitivity to each structure function

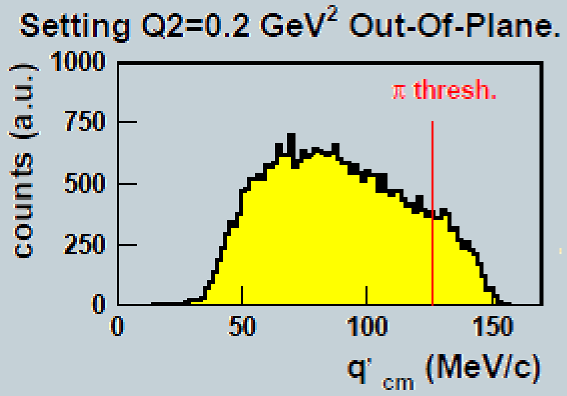
Kinematical setting

Data selection

Design of the experiment : guideline

Be able to perform LEX and DR analysis

- q'_{cm} centered as high as possible below the pion threshold (LEX analysis)
- $\mathcal{O}(q'^{2}_{cm})$ small enough



Good sensitivity to GPs effect

- q'_{cm} as high as possible
- Largest photon polarization ε

Q^2	ε
$0.1\ GeV^2$	0.9
$0.2\ GeV^2$	0.85
$0.5\ GeV^2$	0. 62

Design of the experiment : guideline

Good sensitivity to each structure function

- Find regions where one SF is dominant in the interference term

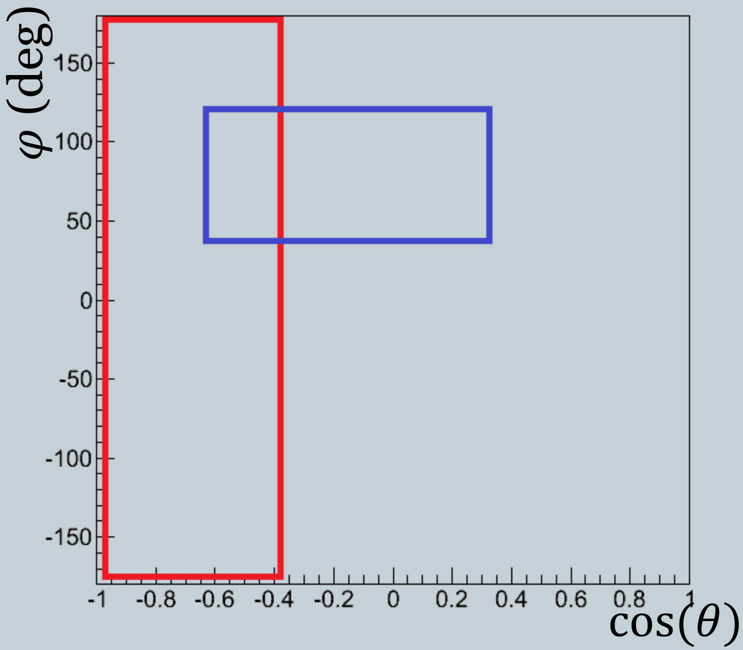
Interference term : $v_{LL}.\left(P_{LL} - \frac{P_{TT}}{\varepsilon}\right) + v_{LT}.(P_{LT})$

- **Out of plane setting** essentially sensitive to $P_{LL} - \frac{P_{TT}}{\varepsilon}$

  $v_{LT} = 0 \quad \text{for} \quad \phi = 90^o \quad \& \quad \theta_{\gamma\gamma cm} = 100^o$

- **In plane setting** essentially sensitive to P_{LT}

  $v_{LL} = 0 \quad \text{for} \quad \theta_{\gamma\gamma cm} = 180^o$



Design of the experiment : Kinematical setting

Kinematical settings

- **Q2-0.2-inp**
- e' detected at 29.9°
- p' detected at 51.8°

setting name	particle in spectrometer	E_{beam} (MeV)	P_B ($\frac{MeV}{c}$)	θ_B (deg.)	OOPB (deg.)	P_A ($\frac{MeV}{c}$)	θ_A (deg.)
q2-0.1-oop	e' in spec.B	877	700	21.9	8.7	345	52.0
q2-0.1-inp	e' in spec.B	877	700	23.0	0.0	420	53.8
q2-0.2-oop	e' in spec.B	1005	784	29.1	7.3	489	52.3
q2-0.2-inp	e' in spec.B	1005	784	29.9	0.0	580	51.8
q2-0.5-oop	e' in spec.A	1035	740	38.7	8.0	647	51.0
q2-0.5-inp	e' in spec.A	1020	750	31.7	0.0	645	51.5

Kinematical variable

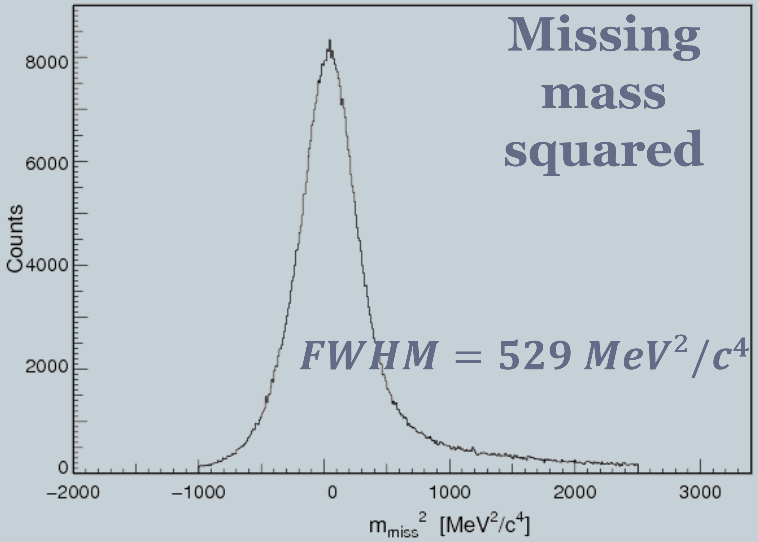
- q' under the pion threshold
- Only backward photons
- All ϕ values

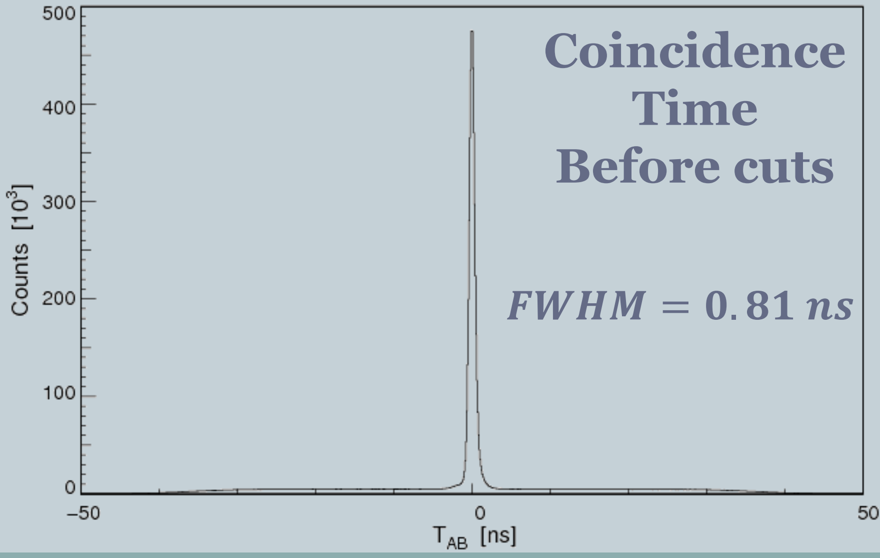
setting name	Q^2 (GeV^2)	$\tilde{Q}^2$ (GeV^2)	ϵ	q_{cm} (MeV/c)	q'_{cm} (MeV/c)	$\theta_{\gamma\gamma cm}$ (deg.)	ϕ (deg.)
q2-0.1-oop	0.10	0.10	0.90	322	100 [60,150]	100 [70,140]	90 [60,120]
q2-0.1-inp	0.10	0.10	0.90	322	100 [60,150]	150 [125,180]	- - [0,360]
q2-0.2-oop	0.21	0.20	0.85	458	95 [40,150]	100 [60,150]	90 [60,120]
q2-0.2-inp	0.21	0.20	0.85	458	95 [40,150]	150 [115,180]	- - [0,360]
q2-0.5-oop	0.50	0.45	0.62	757	100 [40,180]	100 [40,150]	90 [60,150]
q2-0.5-inp	0.50	0.45	0.62	757	100 [70,150]	100 [50,140]	180 [130,230]

Design of the experiment : data selection

p(e,e'p ')γ

- The photon is measured via the missing mass
- Only electron and proton in coincidence are selected
- The data are clean even before selection





Preliminary Results

Cross section measurement and Phase space
VCSSIM and Analysis matching

Some observables
Optics matter

Phase space selection

BH peaks
DR and LEX agreement

Cross section
Structure functions

Cross section measurement & Phase space

Experimental five-fold cross section calculation :

$$d^5\sigma(P_0)_{exp} = \frac{N_{exp}}{N_{sim}} \times \frac{\mathcal{L}_{sim}}{\mathcal{L}_{exp}} d^5\sigma_{sim}(P_0)$$

- $\mathbf{P_o}$ is a point of the phase space $\left(q_{cm}, q'_{cm}, \varepsilon, \theta_{cm}, \varphi\right)$

  FIXED $q_{cm} = 458\ MeV/c$

  FIXED $\varepsilon = 0.85$

  3D BIN
  - $q'_{cm} \in$ [50,75] / [75,100] / [100,125] / [125,150] MeV/c
  - $\theta_{cm} \in$ one of the 40 bins between $\cos(\theta_{cm}) = -1$ and $\cos(\theta_{cm}) = 1$
  - $\varphi \in$ one of the 36 bins between -180^0 and 180^0

- $\boldsymbol{N_{exp}}$ is the experimental number of events in a phase space bin
- $\boldsymbol{\mathcal{L}_{exp}}$ is the total experimental luminosity
- $\boldsymbol{N_{sim}}$ is the simulated number of events in a phase space bin
- $\boldsymbol{\mathcal{L}_{sim}}$ is the simulated luminosity

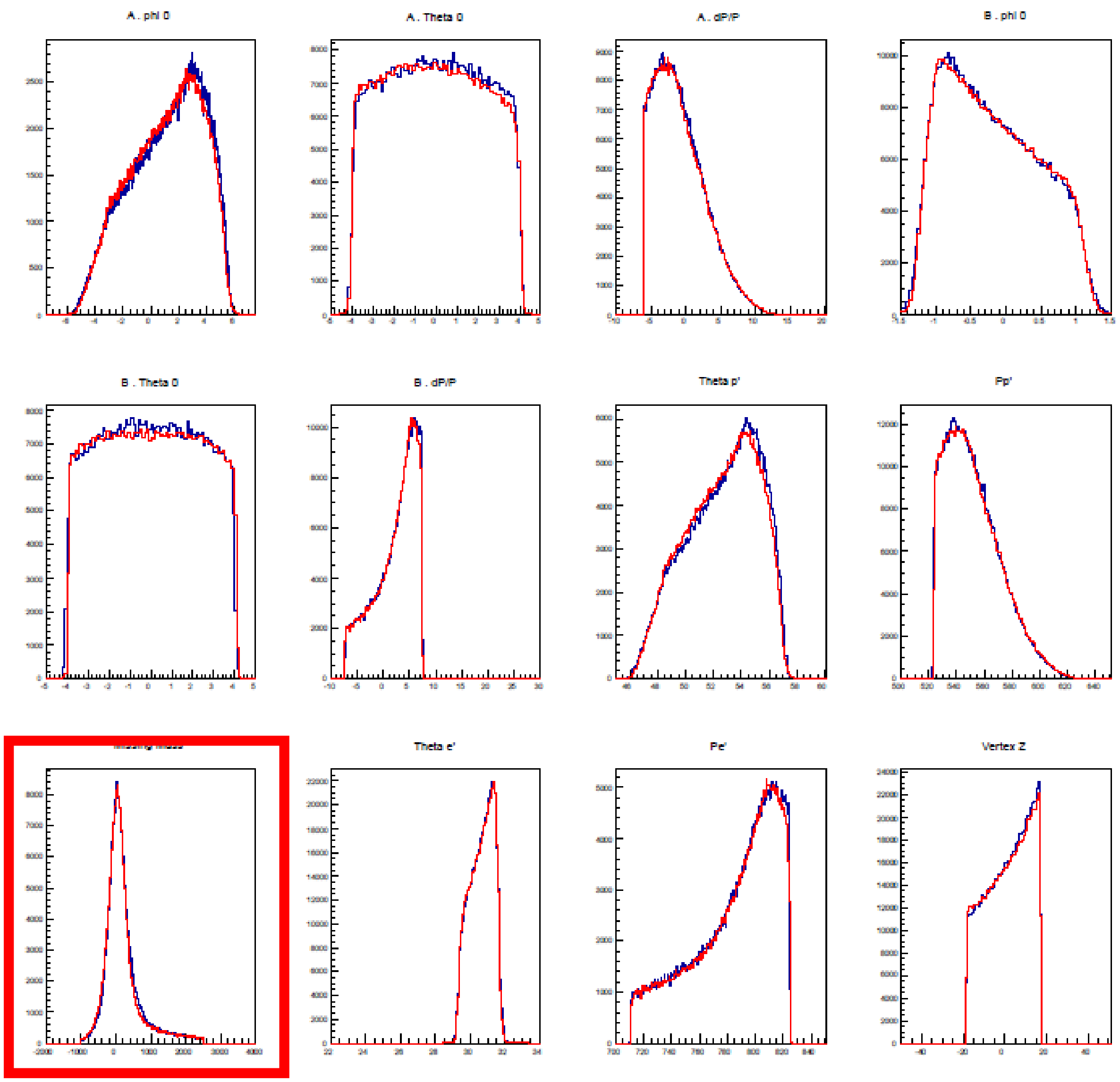
Need of a accurate simulation

VCSSIM versus Analysis

VCSSIM code from P.Janssens (Gent Uni) uses the BH+B cross section calculation from Marc Vanderhaeghen

Experiment

Simulation

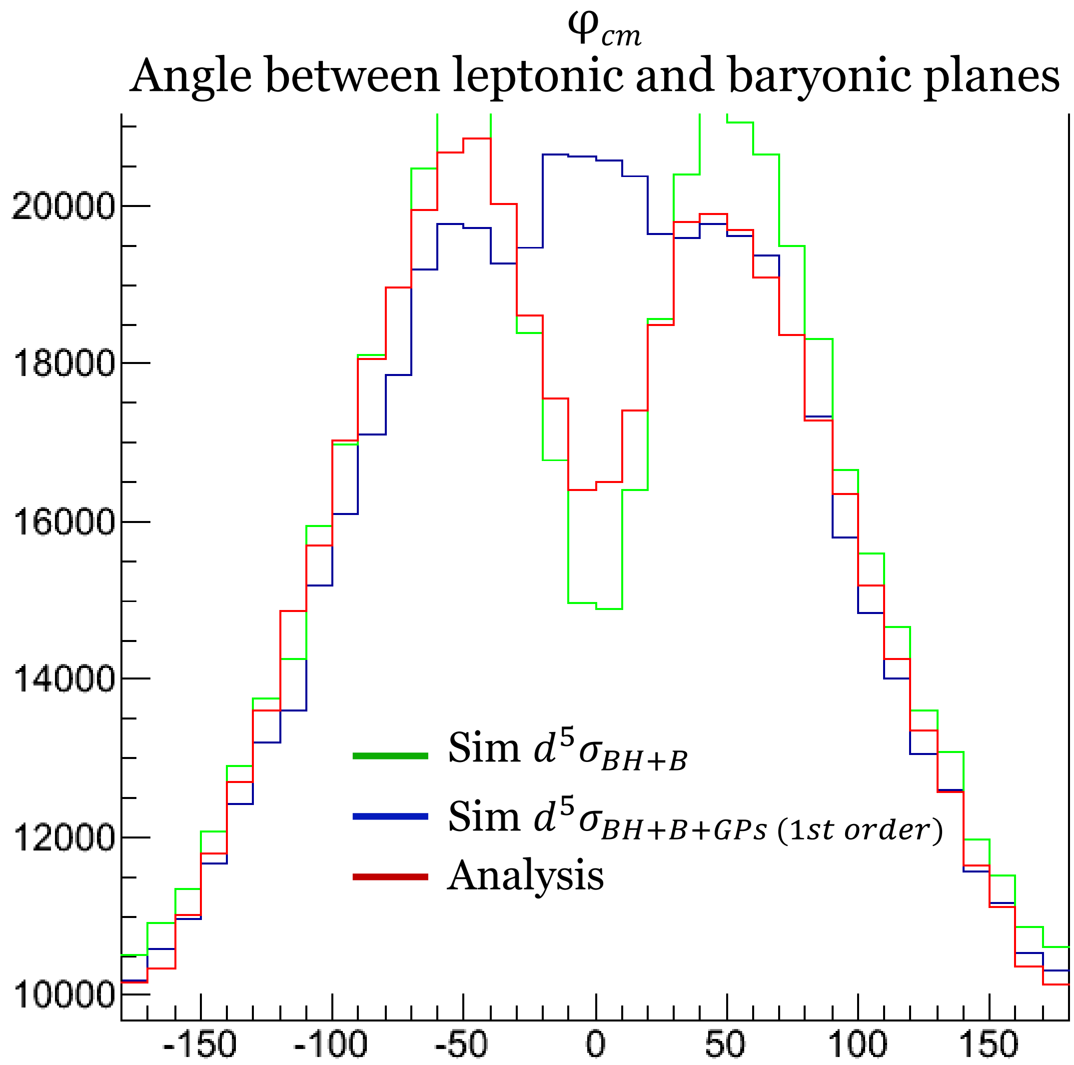


The matching is quite good for many observables but…

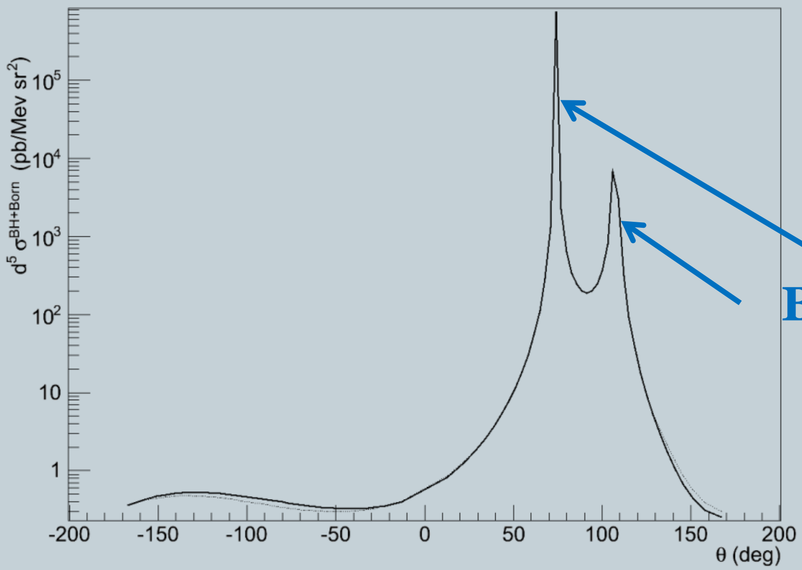
VCSSIM versus Analysis

φ_{cm} distribution

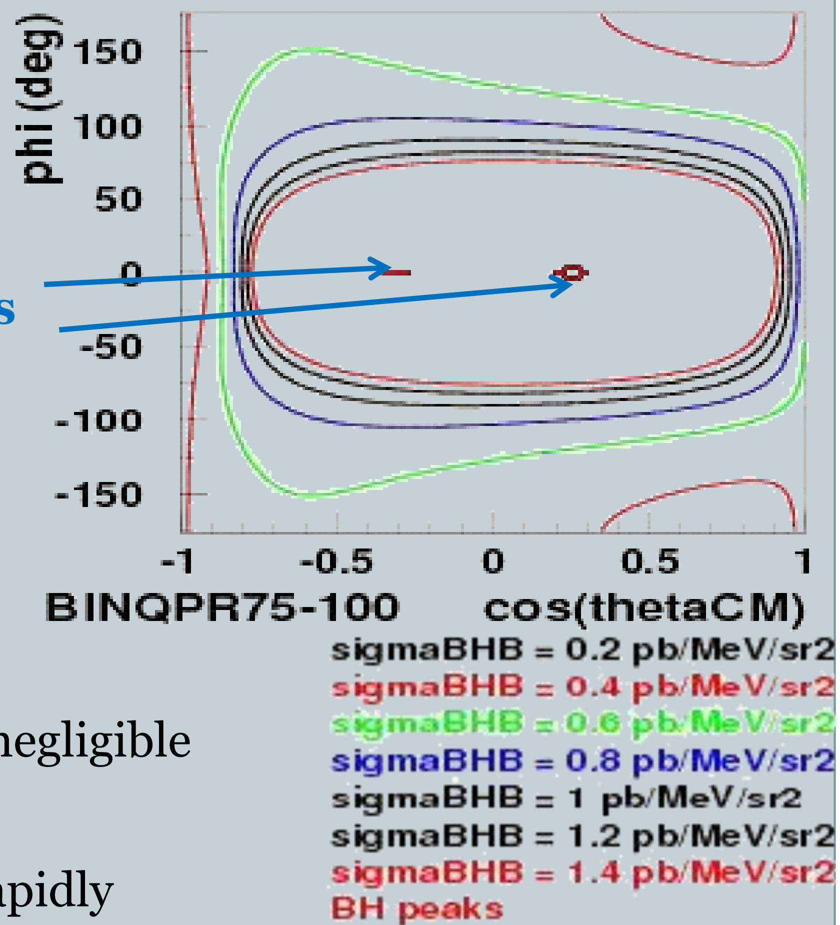
- φ_{cm} is extremely sensitive to polarizabilities effect (difference between simulations)
- The analysis distribution should be symmetric w.r.t φ =0
- The spectrometer optics and offsets need to be optimized
- At φ =0 the first order LEX approach looks wrong (blue distribution is very different from analysis)



Bins selection



BH peaks



BH peaks exclusion

Around them the polarizabilities effect is negligible

→ Remove this area

Around them the cross section increases rapidly

→ Put a cut on the cross section gradient

Bins selection

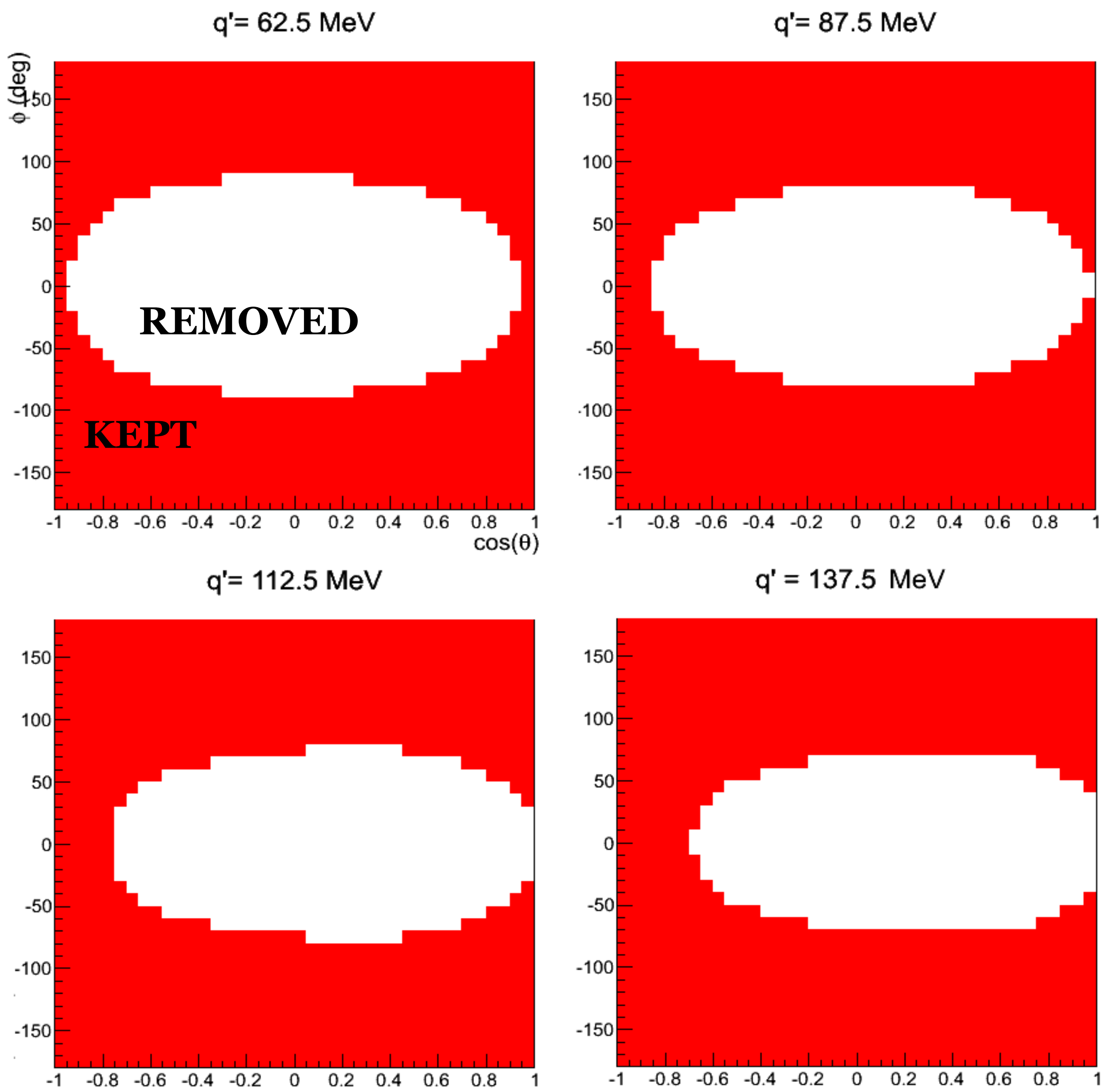
BH peaks exclusion

If

$\overrightarrow{grad}(\sigma) < 0.4\, pb. MeV^{-1}\, sr^{1}$

Bin are kept (red)

- The BH peaks region is removed
- The last q’ bin above the pion threshold is not used for a LEX analysis



Bins selection

The DR and LEX agreement

- The $\mathcal{O}(q'^2_{cm})$ is negligible only in some phase space area

$$\boldsymbol{d^5\sigma(ep\gamma)_{LEX}} = d^5\sigma_{BH+B} + GP_{1st\ order} + \cancel{\mathcal{O}(q'^2_{cm})}$$

- We can write the DR cross section (which includes all orders in q'_{cm}) as :

$$\boldsymbol{d^5\sigma(ep\gamma)_{DR}} \equiv d^5\sigma_{BH+B} + GP_{1st\ order} + \mathcal{O}(q'^2_{cm})$$

$$\left|\frac{\sigma_{LEX} - \sigma_{DR}}{\sigma_{BH+B}}\right| \sim \left|\frac{\mathcal{O}(q'^2_{cm})}{\sigma_{BH+B}}\right|$$

- We explore the phase space regions and calculate both cross sections with : **Equivalent input values of SFs**

LEX	DR
$P_{LL} - \frac{P_{TT}}{\varepsilon} = 25.15\ GeV^{-2}$	$\Lambda_\alpha = 0.85\ GeV$
$P_{LT} = -6.21\ GeV^{-2}$	$\Lambda_\beta = 0.65\ GeV$

- We check higher order impact for each bins with an arbitrary criterion

$$\left|\frac{\sigma_{LEX} - \sigma_{DR}}{\sigma_{BH+B}}\right| \sim \left|\frac{\mathcal{O}(q'^2_{cm})}{\sigma_{BH+B}}\right| < 2\%$$

Bins selection

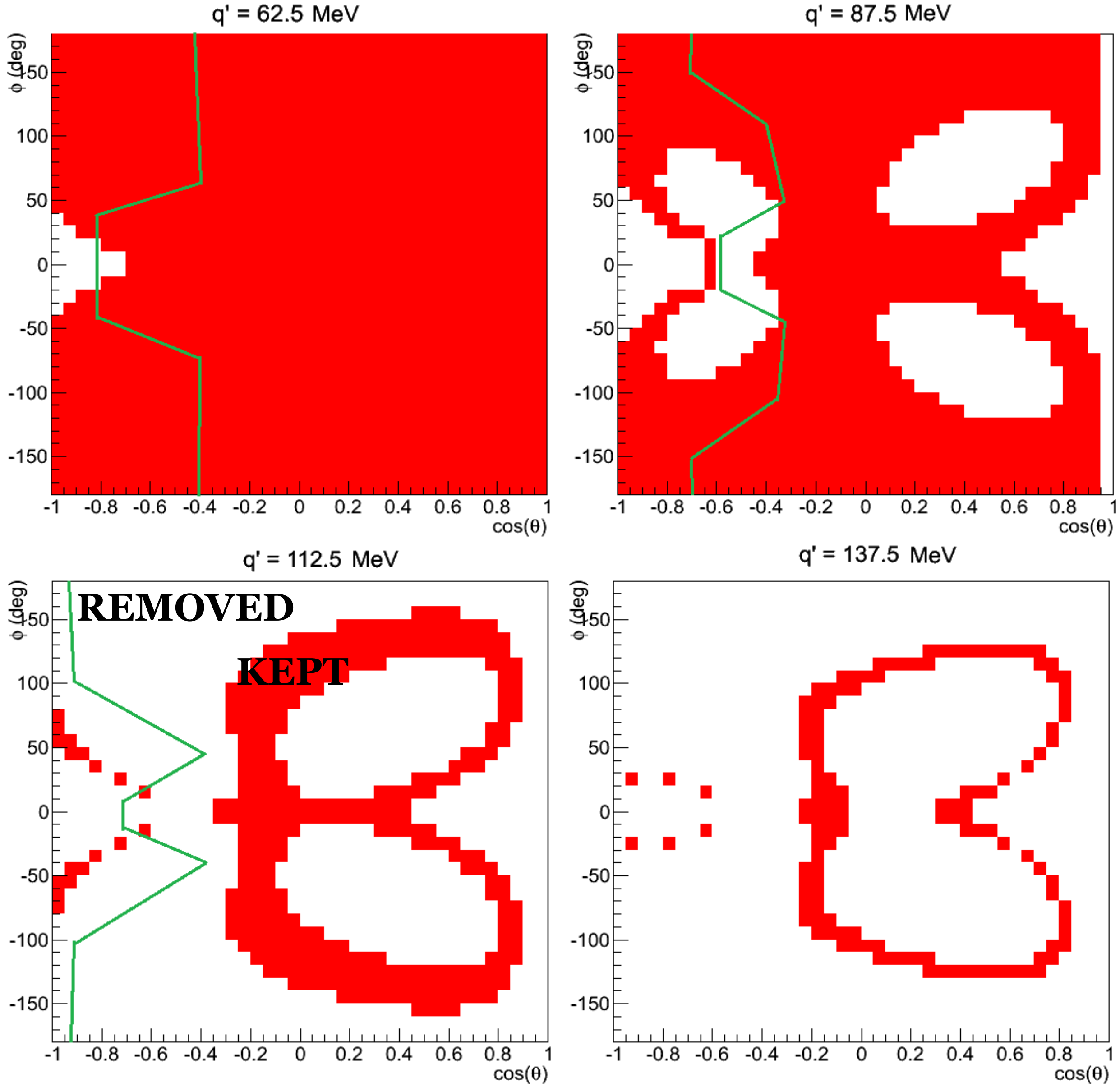
DR and LEX agreement

If

$$\left|\frac{\sigma_{LEX} - \sigma_{DR}}{\sigma_{BH+B}}\right| < 2\%$$

Bins are kept (red)

The green line is the Q2-0.2-inp setting Acceptance



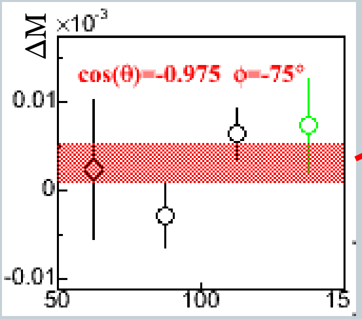
From cross section to structure functions

$$Remind: \quad d^5\sigma(ep\gamma) = d^5\sigma_{BH+B} + (\Phi q'_{cm}) \times \underbrace{\left[v_{LL}.\left(P_{LL} - \frac{P_{TT}}{\varepsilon}\right) + v_{LT}.(P_{LT}) \right]}_{\Psi_0} + \cancel{\mathcal{O}(q'^2_{cm})}$$

ΔM **3D BIN** **φ / θ / q'**

$$\Delta M = \frac{d^5\sigma^{exp} - d^5\sigma^{BH+B}}{q'_{cm} * \phi}$$

$$\lim_{q' \to 0} \Delta M = \Psi_0$$



q'_{cm}

Ψ_o is ΔM averaged over q'_{cm}

3D BIN
Experimental cross section

Ψ_o **2D BIN** **φ / θ**

$$\boxed{\frac{\Psi_0}{v_{LL}} = \frac{v_{LT}}{v_{LL}} \boldsymbol{P_{LT}} + \boldsymbol{P_{LL}} - \frac{\boldsymbol{P_{TT}}}{\boldsymbol{\varepsilon}}}$$

A linear fit by χ^2 minimisation with 2 parameters will lead to SFs

Conclusions

Work in progress

For now :

The fit is exploratory

It can be improved with :

- Optics optimisation
- Global normalisation study
- Other bin selection
- etc

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Thank you