Electroproduction of $f_0(980)$ and $f_2(1270)$ off the proton with the CLAS detector

Brice Garillon, Ph.D.

1. Introduction and physics motivations
2. Experimental setup
3. Cross sections for $f_0(980)$ and $f_2(1270)$ electroproduction
4. Moments Analysis of 2-pion electroproduction
5. Conclusions

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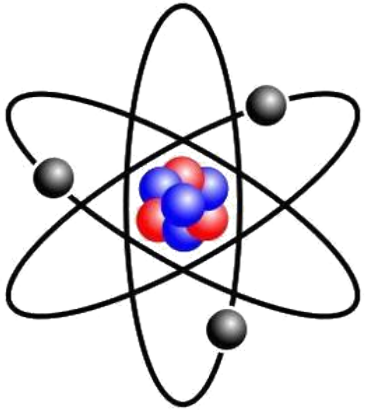
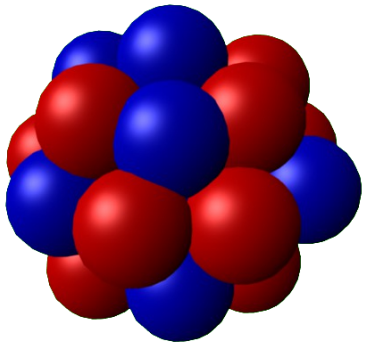
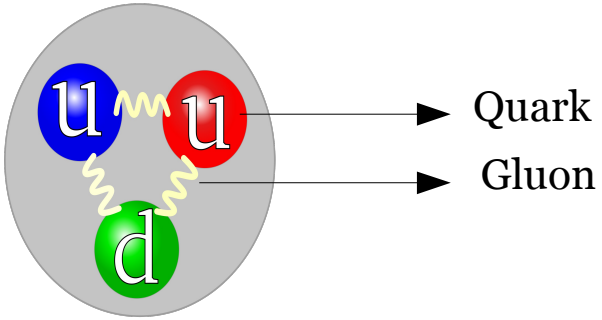
Visible matter at subatomic scale



Atom
10^{-10} m



Nucleus
10^{-11} m



Nucleon
10^{-16} m

Parton
10^{-18} m

- **Strong interaction :** Interaction between **quarks** and **gluons**.

- In the Standard Model, the strong interaction is described by Quantum Chromodynamics (QCD).
  → Each quark or gluon carry a colour charge (r,g,b).
  → **Hadron :** bound state of quarks and gluons, colour singlet.

- To this day , QCD cannot be solved analytically for bound states.

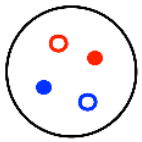
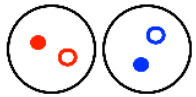
- **Quark model** (Gell-Mann, Zweig 1963-64)
  → One half spin = **Baryon = qqq**
  → Integer spin = **Meson = $q\bar{q}$**

The $f_0(980)$ and $f_2(1270)$

	$f_0(980)$	$f_2(1270)$
J^{PC}	0^{++} (scalar)	2^{++}(tensor)
Isospin	0	0
Mass (MeV)	990±20	1275±1.2
FWHM (MeV)	40-100	185.1±3
Main decay channel	$\pi^+\pi^-$	$\pi^+\pi^-$

- **$f_0(980)$**

  Scalars : 5 observed I=0 states vs. 2 predicted (2 nonets) in the quark model.
  →Some states are different from $q\bar{q}$.
  $\Phi \rightarrow \gamma f_0 \rightarrow \gamma\pi^0\pi^0$: Important strangeness content.
  $f_0(980)$: candidate for an **exotic state**[1] :

  - Tetraquark[2] ($q\bar{q}q\bar{q}$) 
  - $K\bar{K}$ Molecule[3] 

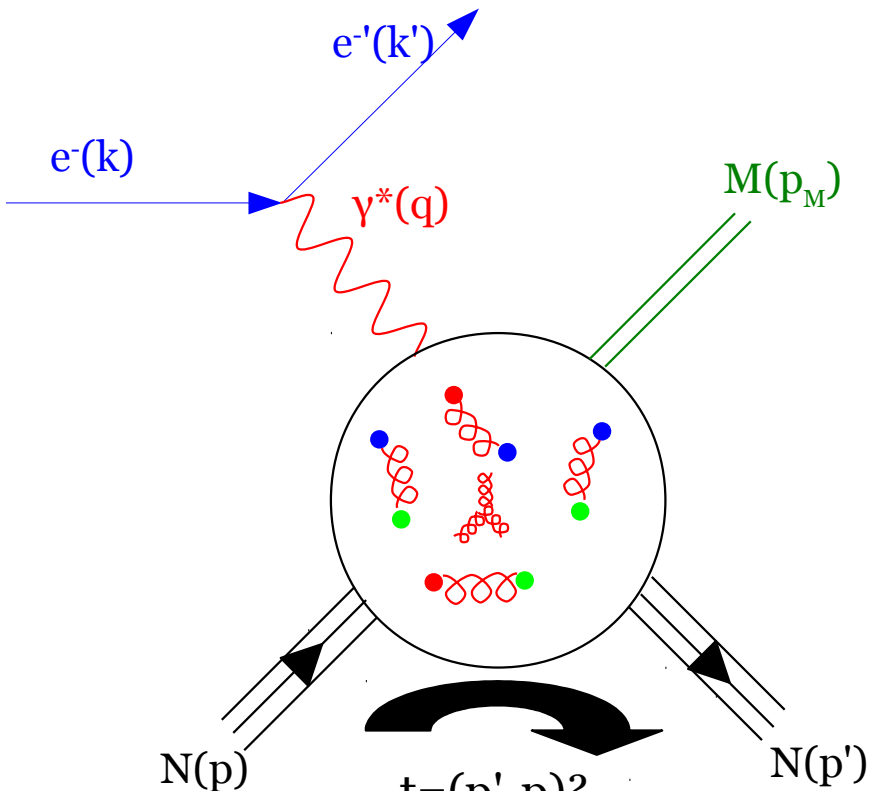
- **$f_2(1270)$**

  → Compatible with quark model predictions.
  → Dynamically generated by vector meson-vector meson interactions [4] ?

- Studies from πN scattering, e^+e^- and $p\bar{p}$ collisions, photoproduction γp[5].

[1] A.Donnachie, Yu.S.Kalashnikova, arXiv:0806.3698v1
[2] R.L. Jaffe, Phys. Rev. D 15, 267 (1977)
[3] T.Barnes, Phys. Lett. B 165, 434 (1985)
[4] E.Oset *et al* , Eur. Phys. Journal A, 44, 2, p.305-311
[5] M. Battaglieri *et al*, Phys.Rev. D80 (2009) 072005

Meson electroproduction



Meson electroproduction
(1-photon exchange)

- The electron interacts with the nucleon via an exchange of a **virtual photon γ***
  → Perturbative QED
  (α_{EM}=1/137<<1)

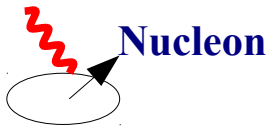
- **Q^2=-(e'-e)² Virtuality**
  → Q^2=0 : Photoproduction
  → Compton Wavelength **: $\lambda \propto 1/\sqrt{Q^2}$**
  Spatial resolution on the probed nucleon

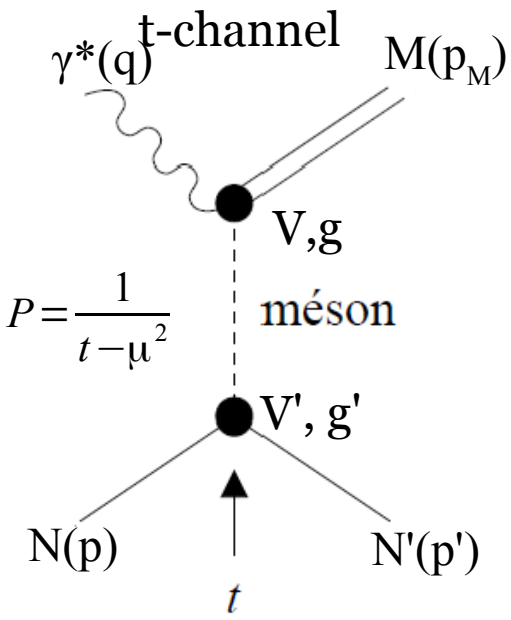
Cross sections for exclusive γ*p → pf_0/f_2 have never been measured!

- **Q^2 and t-dependences might give hints on the nature of f_0 and f_2.**

γ*N → N'M mechanisms

Low Q^2
Particle exchange





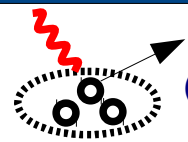
Mandelstam variables

$$t=(q-p_M)^2$$
$$u=(q-p')^2$$
$$s=(q+p)^2$$

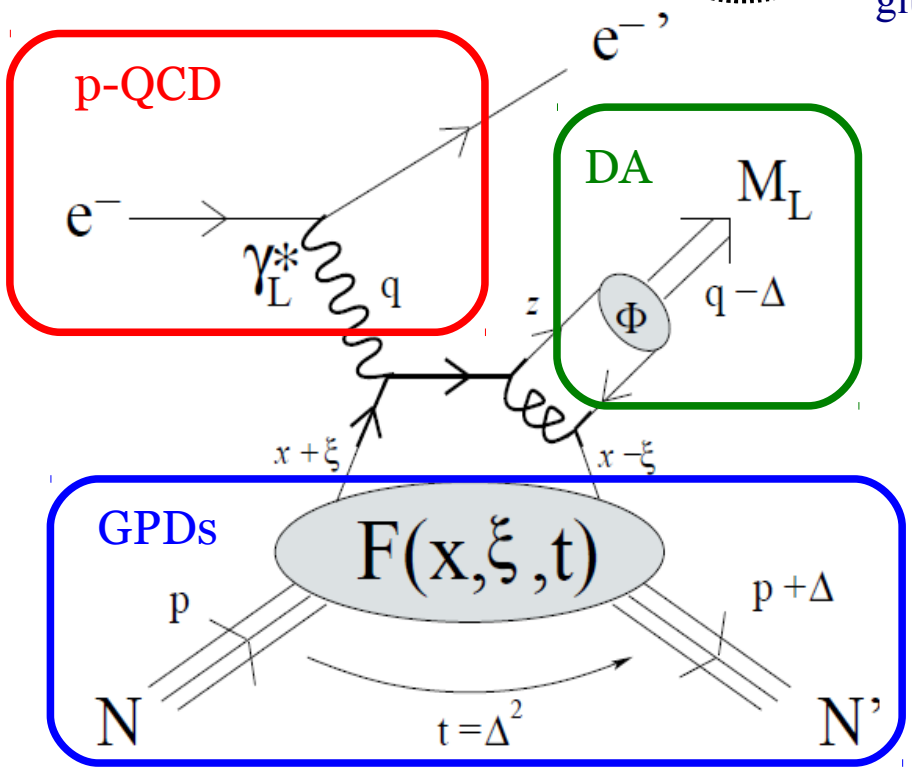
- **t channel exchange dominant** for the f_0 and f_2 production.

- Amplitude :
  A~gVPg'V'
  P : Propagator.
  V,V': Vertices
  g,g' : Coupling constants

High Q^2
DVMP



(quarks or gluon)



(Q^2, υ → ∞ et x_B constants), t << Q^2
Longitudinally polarized photon.

- **Factorisation** theorem **:**
  →"Hard" scattering
  → Distribution Amplitude (DA)
  → 4 Generalized Parton Distributions (GPDs) H,E, $\tilde{H}$ et $\tilde{E}$(x, ξ, t)
  Correlation between the transverse position of a quark and its longitudinal momentum fraction.

The exclusive $ep \rightarrow ep\pi^+\pi^-$ final state

- **The f_0 and f_2 are analysed in their main decay channel :**

  $f_0 \rightarrow \pi^+\pi^-$ (dominant) and $f_2 \rightarrow \pi^+\pi^-$ (85%)

- The exclusive final state $e'p'\pi^+\pi^-$ comes from several processes :

$ep \rightarrow e'p'$ M ► **$\pi^+\pi^-$**

$ep \rightarrow e'$ N* $\pi^{+/-}$ ► **$p'\pi^{-/+}$**

$ep \rightarrow e'p'\pi^+\pi^-$

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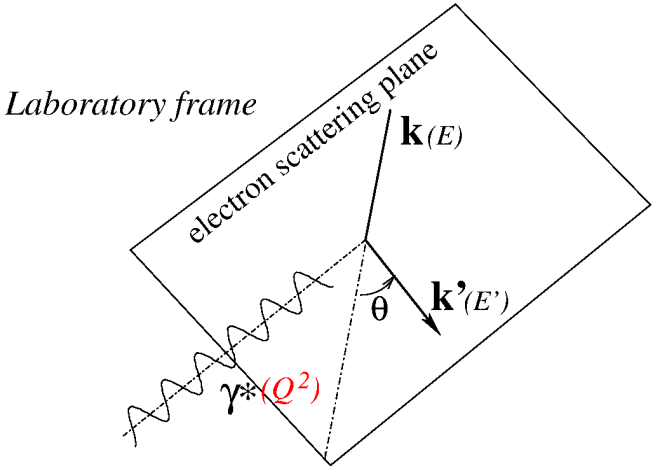
The unpolarized cross section is described by 7 independent kinematic variables :



- **Q^2** Virtuality of the virtual photon (γ^*) .
  $\nu = (E-E')$

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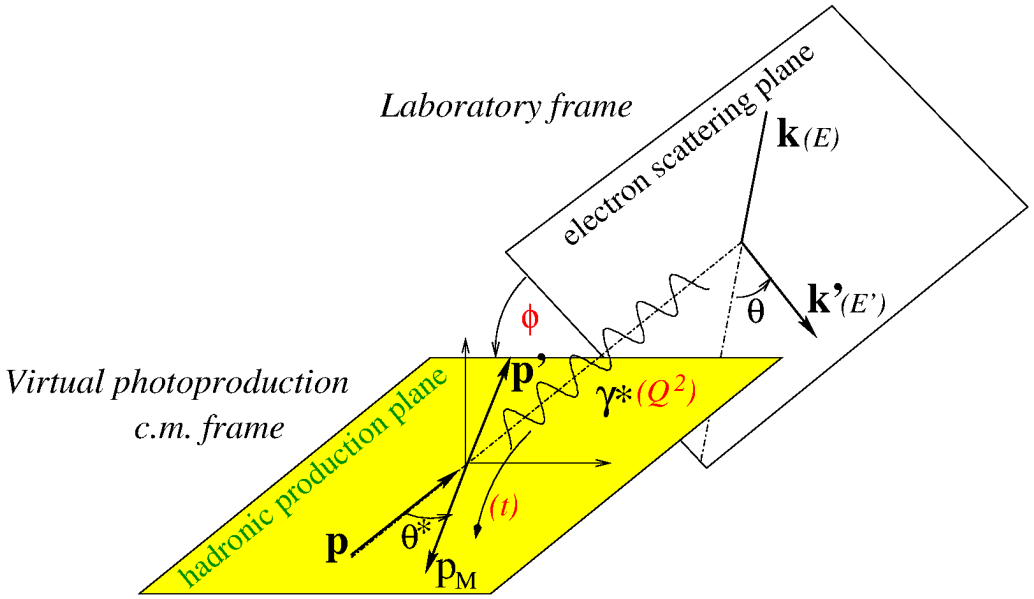

Q^2 Virtuality of the virtual photon (γ*) .
$\nu=(E-E')$

$x_B=Q^2/2M_p\nu$ Bjorken variable
(~ 1/**W**, energy of (γ*,p) center of mass frame)

t Momentum transfer to the nucleon

Φ Azimuthal angle between the leptonic plane (γ*,e') and the hadronic plane (γ*,p').

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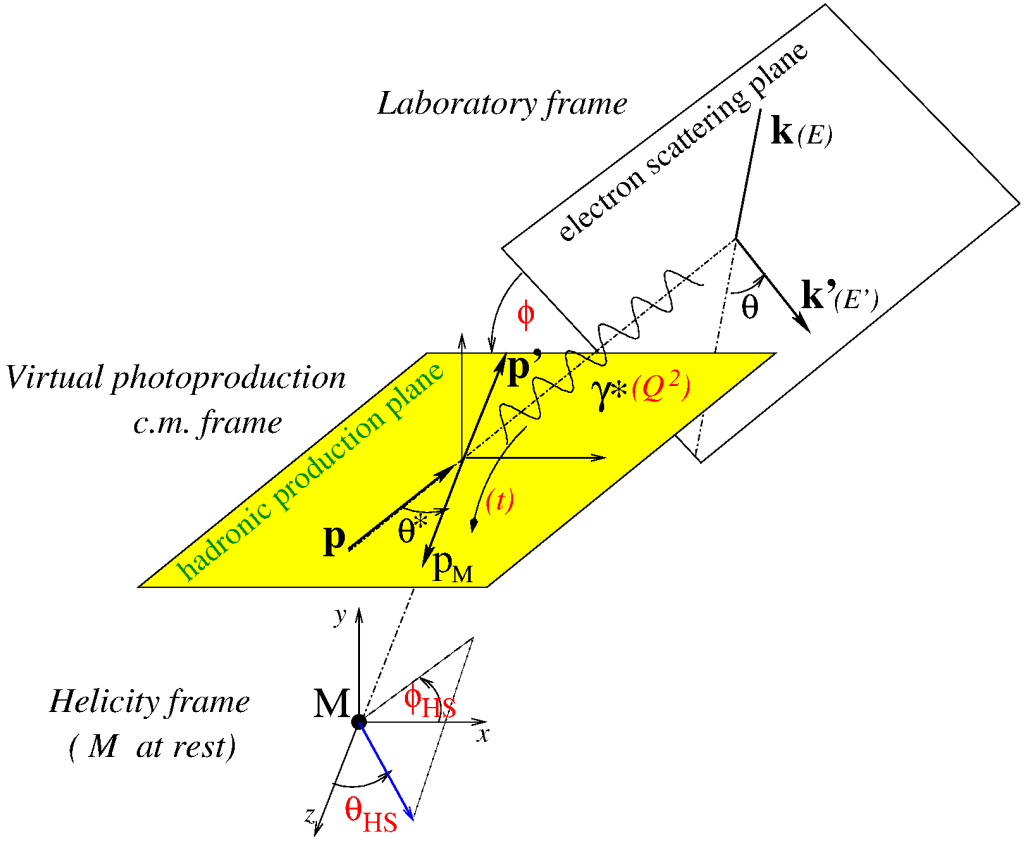

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$Cos(\theta_{\pi+})$, $\Phi_{\pi+}$ π^+ angles in the helicity rest frame of the meson.

$M_{\pi+\pi-}$ $\pi^+\pi^-$ invariant mass

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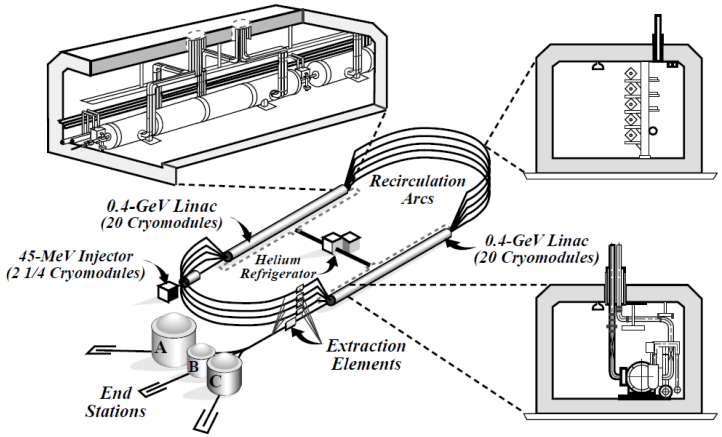
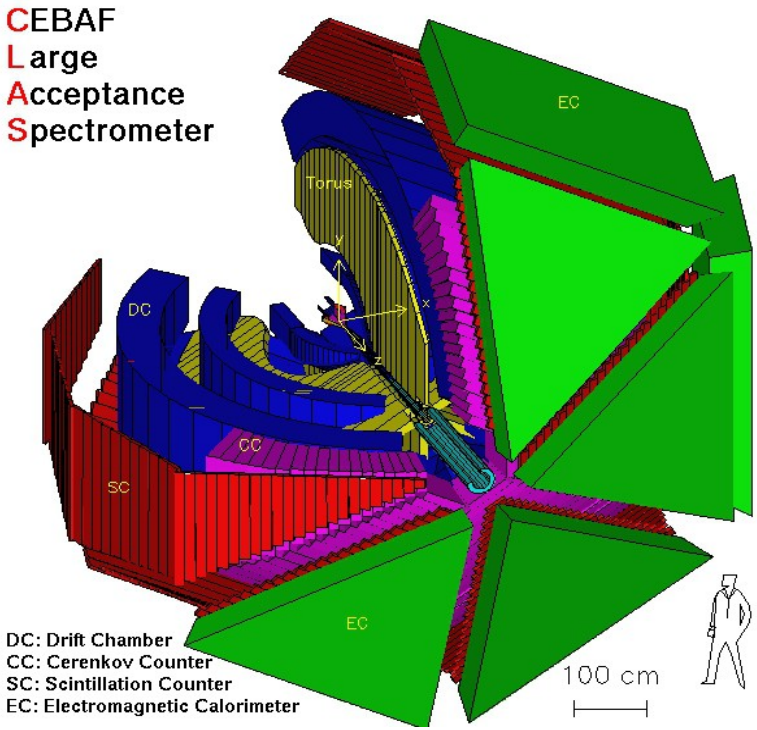
The experimental setup

Jefferson Laboratory

- CEBAF (2012) : E_{max} = 6 GeV, I_{max} = 200 µA
- Distributed to 3 experimental Halls A, B and C (2012).



CLAS (Hall B, 1997-2012)



- Large acceptance spectrometer ("4π") .
- Split by the toroidal magnet (B_{max}=2.5T) into 6 azimuthal sectors. Each sector included :
  - → **3 regions of Drift Chambers(DC)** : Charged particles momenta. (Δp/p<0.5% for 1 GeV/c)
  - → **Cherenkov Counters(CC)** : π/e^- separation up to 2.5 GeV/c. (8°< θ <45°)
  - →**Electromagnetic Calorimeters (EC)** : electron and neutral particle identification.
  - → **Scintillator Counters (SC)** : Particle identification by time-of-flight measurement (8°< θ <140°, Δt = 80 to 160 ps) .

e1-6 (2001)

→ Electron beam : E_{mean} = 5.754 GeV, I_{mean} = 7 nA

→ Target : LH_2 (length=5 cm, diameter=1.5 cm)

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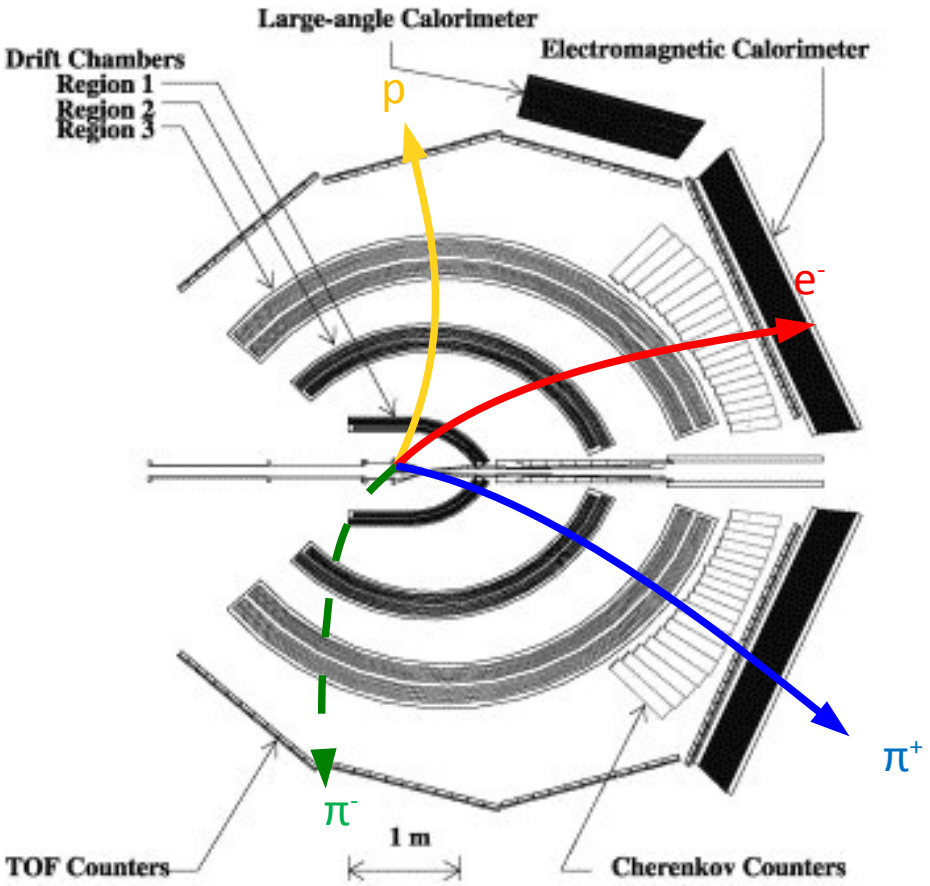
Selection of exclusive e'p'$\pi^+\pi^-$



e^- identification

→ p_{e^-}>0.8 GeV/c
→Z-Vertex selection within the target volume (DC)
→ Ficudial cuts (EC et CC).
→ Energy sample fraction (EC)
→ Track matching between DC,CC and SC.

p and π^+ identification

→ $p_{q>0}$ >0.2 GeV/c
→ Fiducial cuts (DC)
→Time-of-flight (SC) :
Measured velocity

$$\Delta\beta_m = \beta_{mes} - \beta_{calc}(m) = \frac{l}{ct}\ (\text{SC}) - \frac{p}{\sqrt{p^2+m^2}}\ (\text{DC})$$

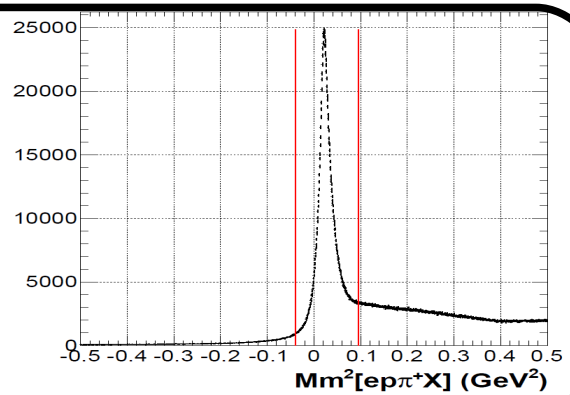
Predicted velocity for a particle with given mass m.

Exclusivity

→Selection on π^- **peak** in missing mass spectrum **Mm[epπ^+X]**

$$-0.05 \le Mm^2[ep\pi^+X] \le 0.08\ \text{GeV}^2$$

→ Z-Vertex selection within the target volume
→ Cherenkov noise removed for p_{e^-}<1.5 GeV/c



Differential cross sections $\sigma^{\gamma^* p \to p\pi^+\pi^-}$

Reduced cross section

$$\frac{d^2\sigma^{\gamma^* p \to p\pi^+\pi^-}}{d\,\eta\, dM_{\pi^+\pi^-}} = \frac{1}{\Gamma_V(Q^2, x_B)} \frac{d^4\sigma^{ep \to p\pi^+\pi^-}}{dQ^2 dx_B d\,\eta dM_{\pi^+\pi^-}}$$

Γ_V Virtual photon flux factor

η : A kinematic variable among $(-t, \Phi, \cos\theta_{HS})$, or none.

→ Selection of exclusive $e'p'\pi^+\pi^-$ events in experimental data

For each $ep\pi^+\pi^-$ selected event

Weighing by the factor $w_k = \frac{1}{\Gamma_V\, Acc_{\text{Corr Rad}}\, Eff_{CC}}$

Projection onto a $\mathbf{M_{\pi\pi}}$ dependent distribution, in a given (Q^2, x_B, η) bin

Each (Q^2, x_B, η, M) normalized by $\frac{1}{L_{\text{int}} \cdot \Delta V \cdot F_{\text{Corr Vol}} \cdot F_h}$

- $\mathbf{Acc_{Corr\ Rad}(Q^2, x_B, t, \Phi, \cos\theta_{HS}, \varphi_{HS}, M_{\pi\pi})}$ CLAS acceptance, corrected from radiative effects. Computed with **Monte Carlo simulations**.
- $\mathbf{Eff_{CC}(p_{e^-}, Q^2, x_B)}$ Loss of good events after electron-ID cut.
- $\mathbf{L_{int} = 30\ fb^{-1}}$ Integrated luminosity. Integrated beam charge measured with Faraday cup.
- $\mathbf{\Delta V = \Delta Q^2 \Delta x_B \Delta\eta \Delta M_{\pi\pi}}$ Bin volume.
- $\mathbf{F_{corrVol}(Q^2, x_B, \eta)}$ Bin volume fraction occupied by $ep\pi^+\pi^-$ phase space events
- $\mathbf{F_h}(Q^2, x_B, \eta, M)$ Correction to the acceptance, in a $(Q^2, x_B, \eta, \mathbf{M_{\pi\pi}})$ bin.

Monte Carlo simulations

→ Acceptance correction

Genev
epπ⁺π⁻ Monte Carlo event generator

↓ Generated epπ⁺π⁻

GSIM
CLAS simulation package

↓ ADC/TDC

GPP (GSIM Post-Processing)
Smearing and inefficiencies to reproduce real data

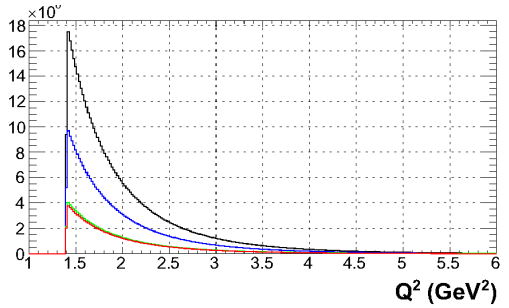
↓ ADC/TDC

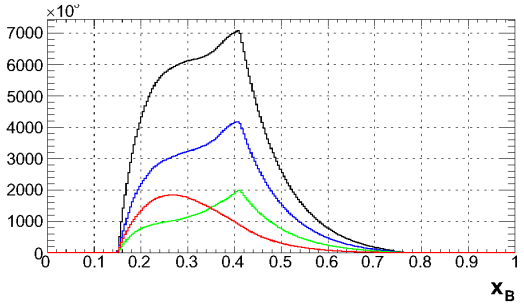
Recsis
Reconstruction
(ADC/TDC → Physical variables)

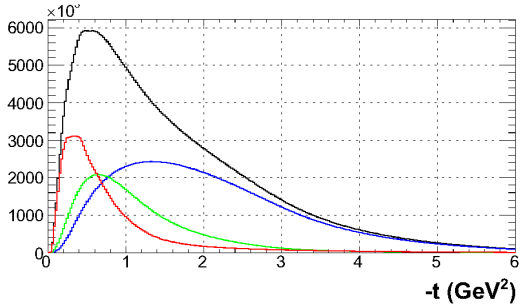
↓ epπ⁺π⁻ accepted by CLAS

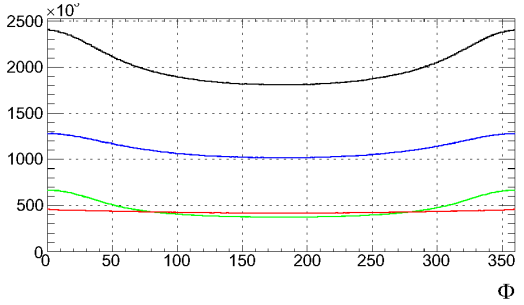
Event selection
Same algorithm as in the real data
(except for the CC related cuts)

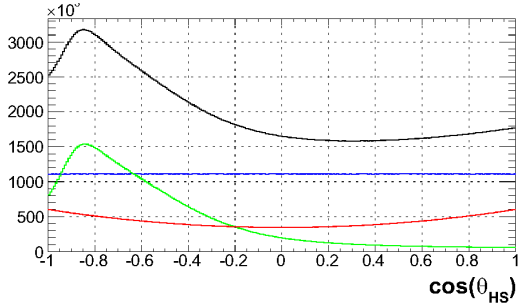
Generated MC
- **Total (240 M)**
- **Non resonant epπ⁺π⁻ (45%)**
- **ep → epρ⁰ (25%)**
- **ep → epΔ⁺⁺π⁻ (30%)**

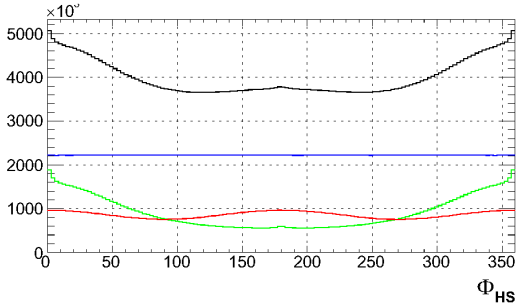


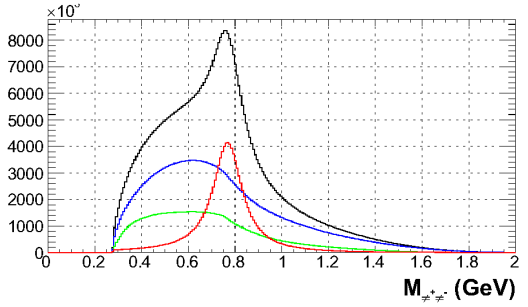












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Event selection
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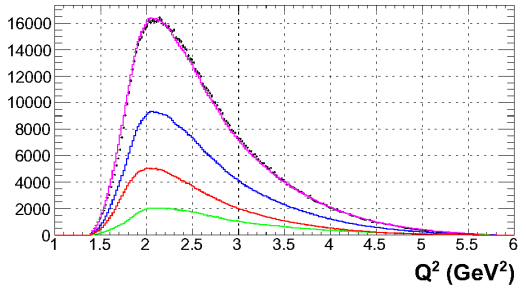
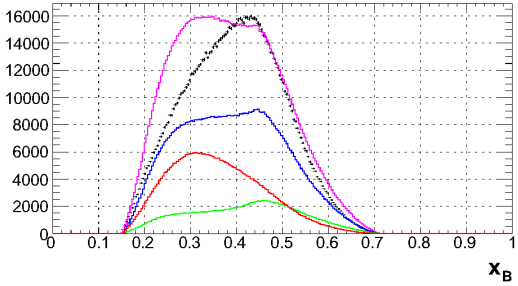
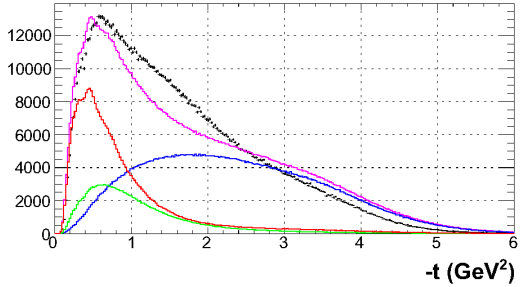
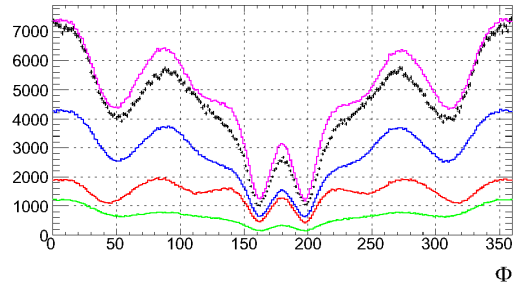
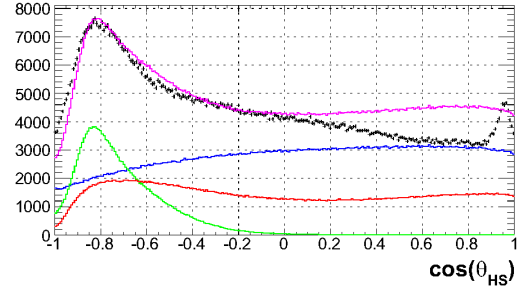
– **Data**
– **Reconstructed MC (Normalised to data)**
– **Non resonant epπ⁺π⁻**
– **ep → epρ⁰**
– **ep → epΔ⁺⁺π⁻**

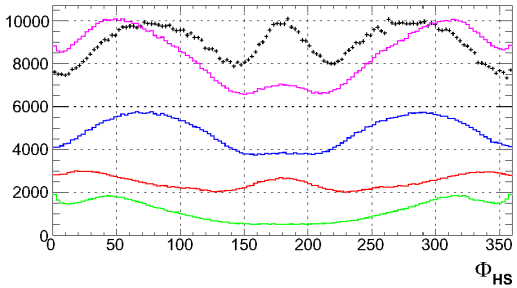


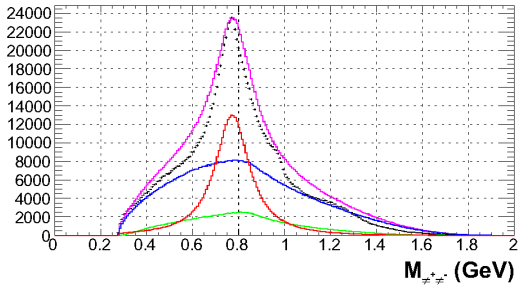








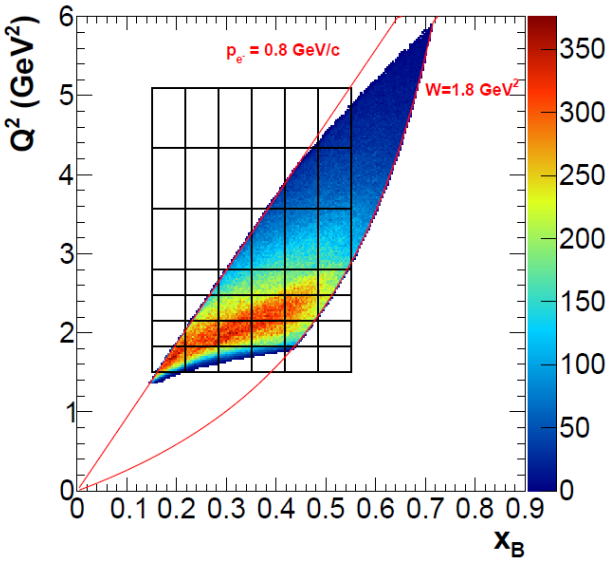




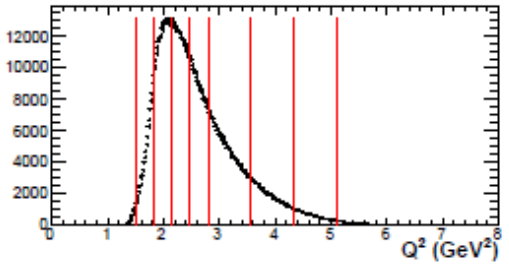
Binning of the phase space

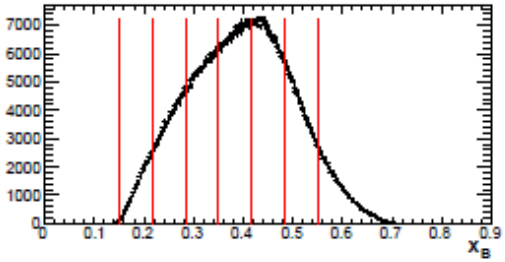
$W > 1.8\,\mathrm{GeV}$,
$p_{e^-} > 0.8\,\mathrm{GeV/c}$

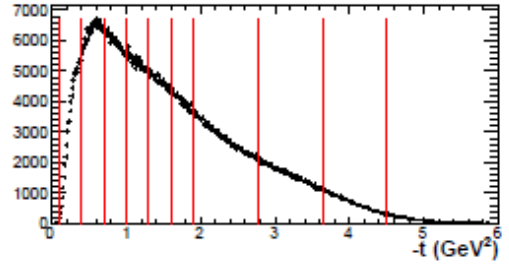
Variable	Unit	Intervals	Nb. bins	Bin width
Q^2	GeV^2	1.50-2.80 2.80-5.10	4 3	0.33 0.76
x_B	-	0.15-0.55	6	0.06
-t	GeV^2	0.1-1.90 1.90-4.30	6 3	0.30 0.80
Φ	°	0-360	7	51.4
$\cos\theta^{HS}_{\pi+}$	-	-1. à 1.	7	0.28
$\Phi^{HS}_{\pi+}$	°	0-360	7	51.4
$M_{\pi+\pi-}$	GeV	0.26-2.00	45	0.04

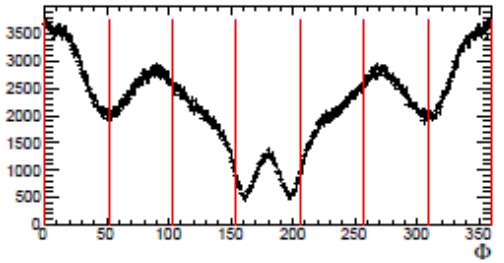


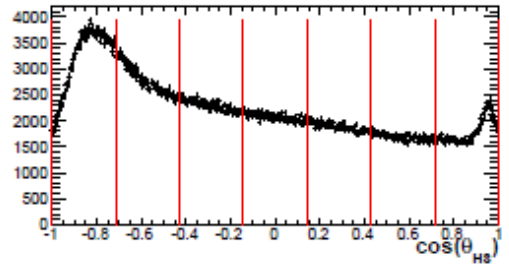
Experimental data

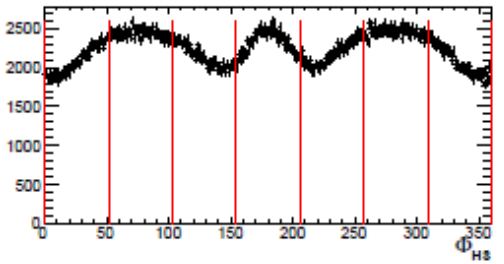


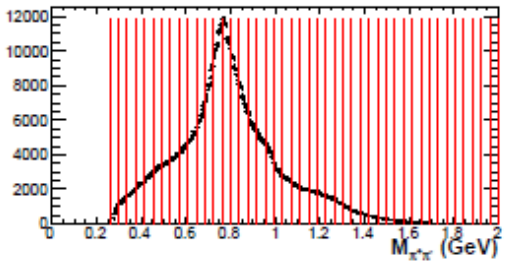




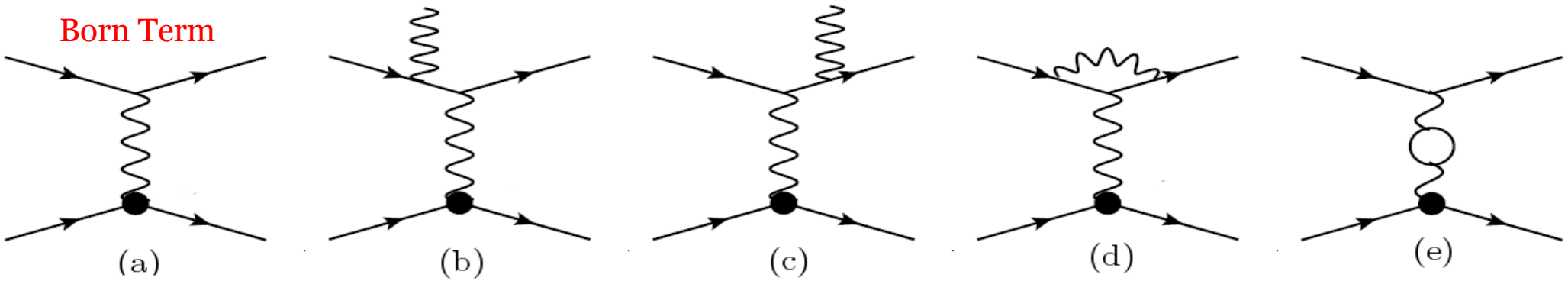


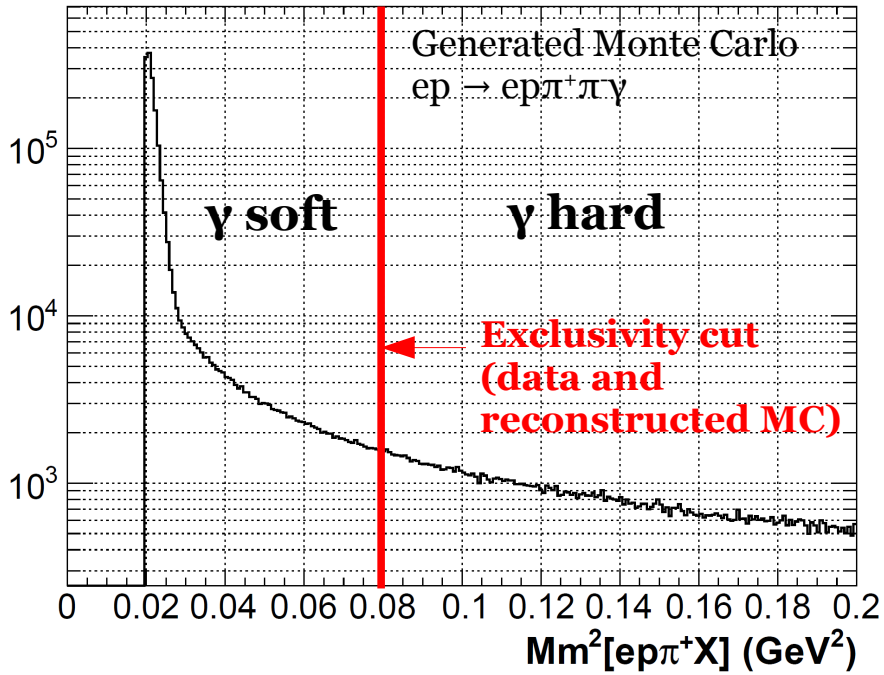






Radiative corrections





- The e^- radiates photons easily.
- "Hard" photons
  "soft" photons : Low energy emissions and/or reabsorbed immediately (**still in data after exclusivity cut**).
- Mo and Tsai. (fig. b) to e)) radiative effects embedded in GENEV, calculated for ep → ep process.
- Born cross section : $\sigma_{Born} = F_{Rad} * \sigma_{\text{Born+diagrams b) to e)}}$

  → Radiative correction factor:

$$F_{rad} = \frac{Gen_{\text{non rad}}}{Gen_{\text{rad soft}}} \quad (\sim 5 \text{ to } 20\%)$$

Acceptance corrected from radiative effects

- Acc = Geometrical acceptance*CLAS detection efficiency

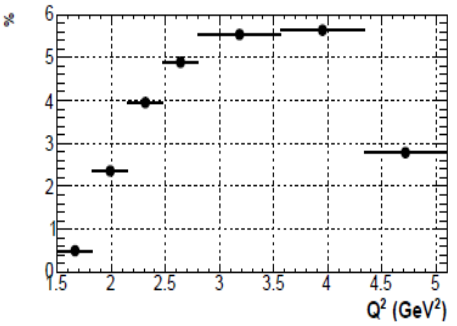
$$Acc = \frac{Rec_{Rad\ soft}}{Gen_{Rad\ soft}}$$

$Rec_{Rad\ soft}$ ← Nb. of MC events reconstructed by CLAS in a bin.

$Gen_{Rad\ soft}$ ← Nb. of MC events generated in a bin.

→Computed with MC simulations.

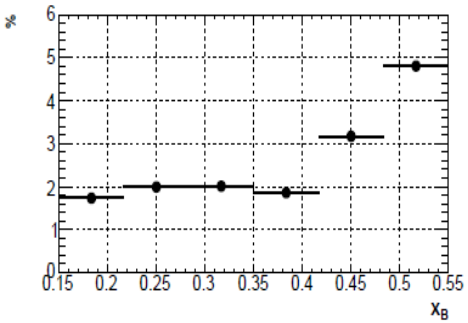
Integrated acceptance
(mean : 2.5%)

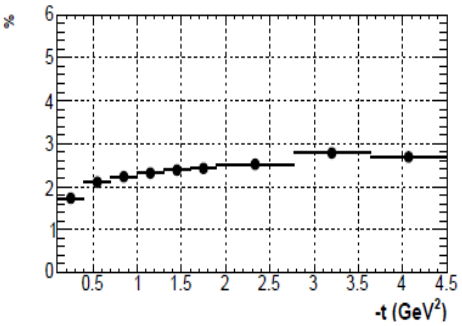


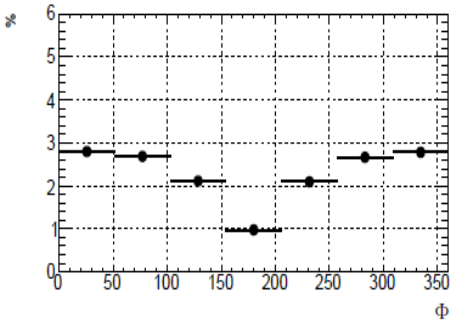
- Acceptance and radiative corrections computed **in a single effective term $Acc_{Corr\ Rad}$**

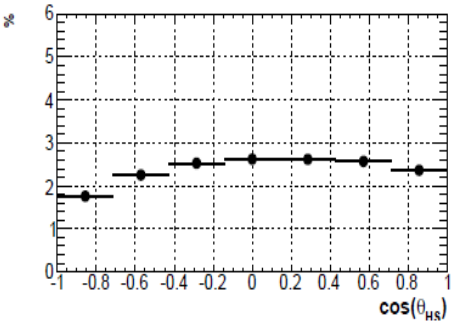
$$\sigma^{\gamma p\pi^+\pi^-}_{Born} = \frac{N^{\gamma p\pi^+\pi^-}_{Rad\ soft} \cdot F_{RAD}}{L_{int} \cdot Eff_{cuts} \cdot Acc}$$

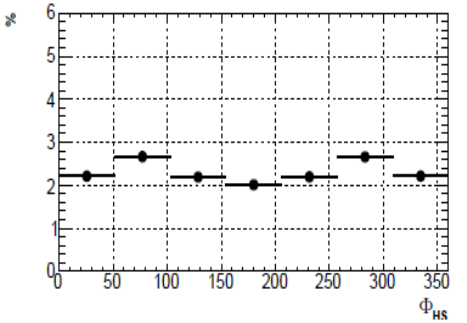
$$Acc_{Corr\ Rad} = \frac{Rec_{Rad\ soft}}{Gen_{non\ rad}}$$

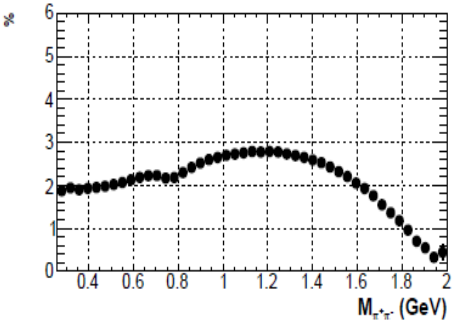










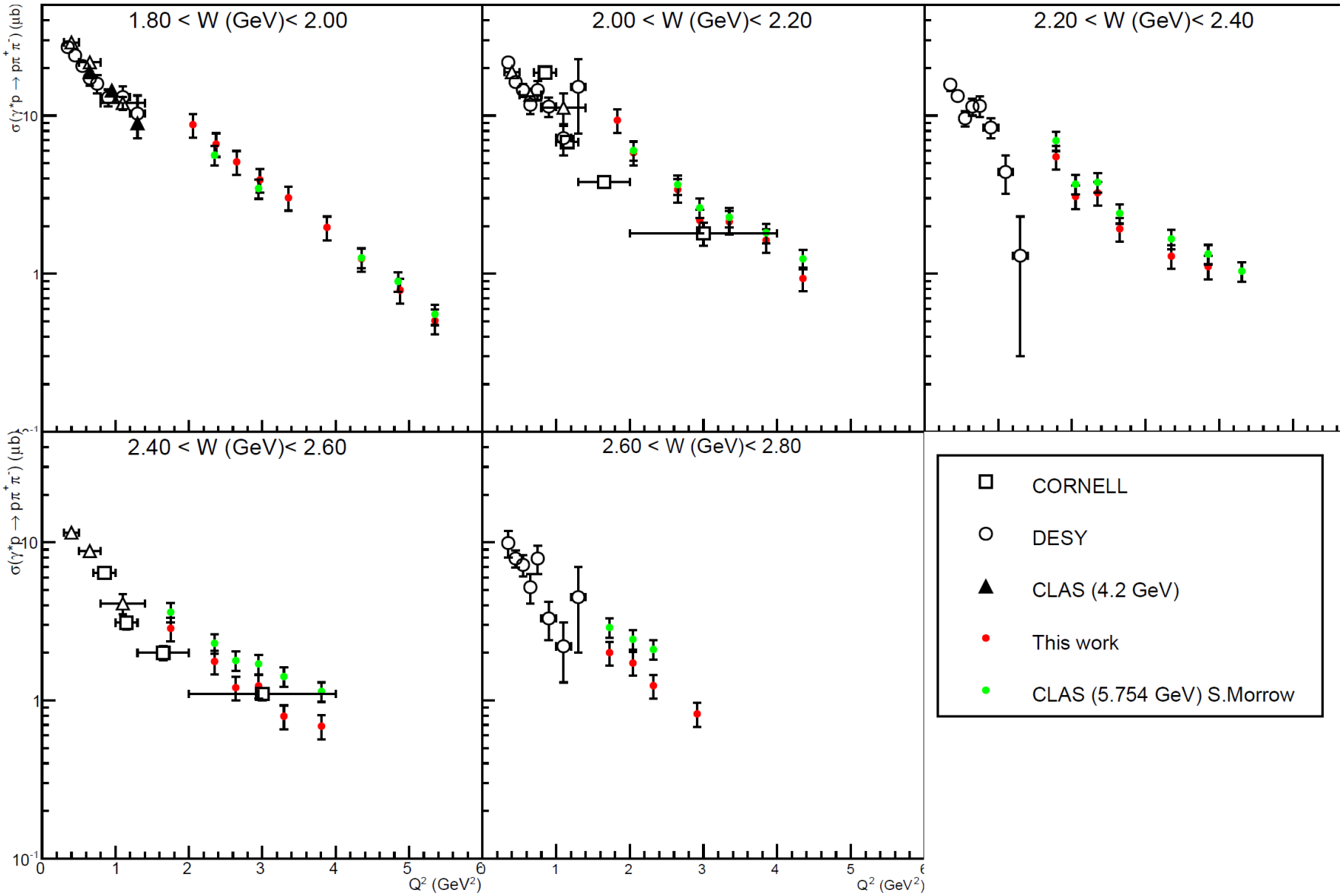


$Rec_{Rad\ soft}$ $ep\pi^+\pi^-\gamma_{soft}$ reconstructed by CLAS and selected in a bin .

$Gen_{non\ rad}$ $ep\pi^+\pi^-$ generated without radiative effects in a bin.

- $Acc_{Corr\ Rad}$ computed for each 7D bin (Q^2, x_B, -t, Φ, cos θ_{HS}, φ_{HS}, $M_{\pi+\pi-}$)

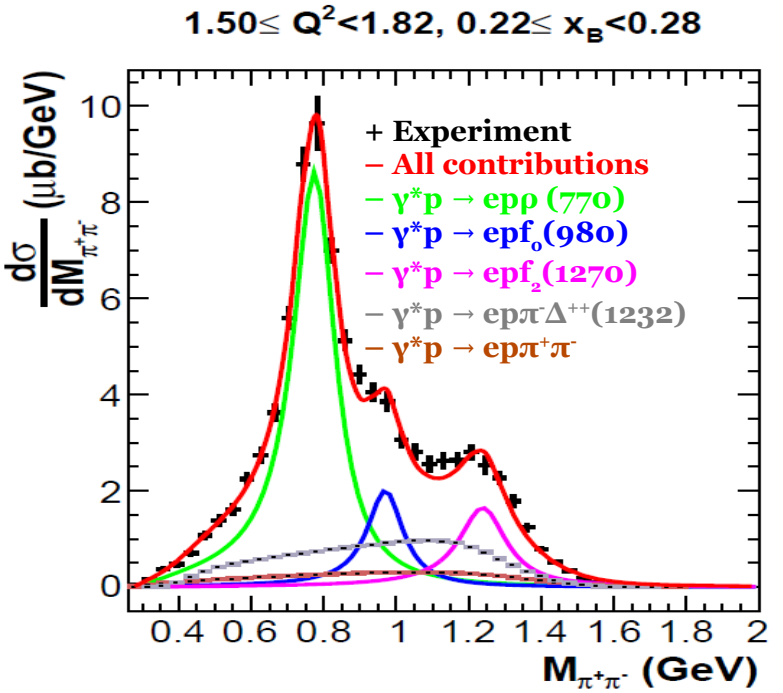
Cross section $\sigma^{\gamma^* p \rightarrow p\pi^+\pi^-}$ in (Q^2, W)

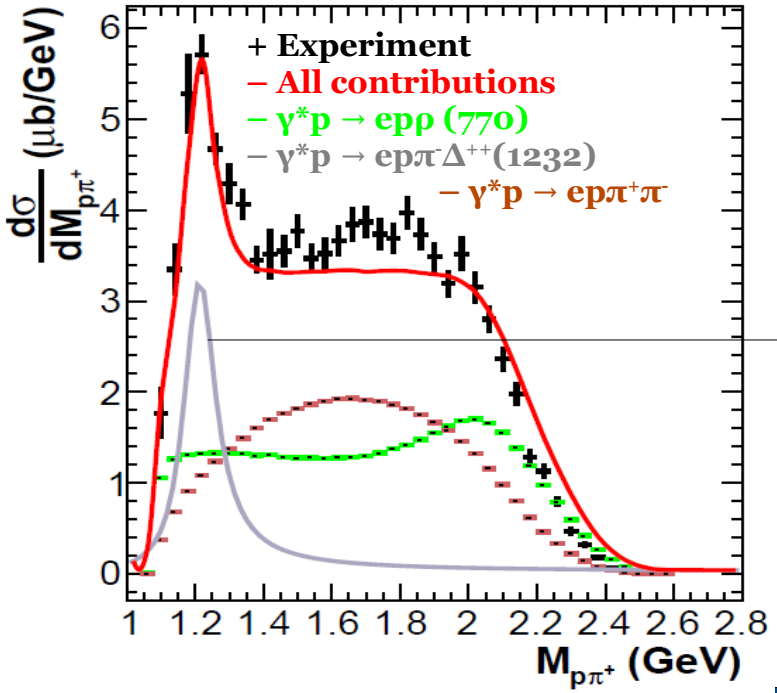


Good agreement with previous CLAS ρ^0 analysis.[1]

[1] S.A. Morrow *et al*, Eur. Phys. J. A 39, 5-31 (2009)

Extraction of f_0 and f_2 signals





- f_0 and f_2 extracted from a **fit** on **reduced cross section spectrum as a function of $M_{\pi+\pi-}$**, in a given (Q^2, x_B, η) bin. η= t, φ, cos θ_{HS} (or nothing).

- Fit model= **incoherent sum of the following contributions** :

  → **3 resonances :**
  Skewed Breit Wigner (BW) for **ρ**, **f_0**, **f_2**

  → 4 parametres :
  -Intensity
  -Centre
  -FWHM
  -Skewness toward lower mass region.

  → **2 backgrounds : non resonant $\pi^+\pi^-$** and **Δ^{++}** .
  Spectra generated with GENEV (no radiative effects).
  → 2 scale parameters (total spectrum fraction):
  $\alpha_{\pi\pi}$ (from 0.01 to 1) et α_{Δ}(<0.2)

Cross section for meson production

$$\sigma^{\gamma^* p \to p\,\mathrm{Meson}} = \frac{\int_0^2 BW_{skew}^{\mathrm{Meson}}\left(M_{\pi^+\pi^-}\right) dM_{\pi^+\pi^-}}{BR^{\mathrm{Meson}\to\pi^+\pi^-}}$$

Branching ratio :
f_0 : 100 %
f_2 : 85%

Systematic errors

$$\frac{\Delta\sigma}{\sigma}=\sqrt{\left(\frac{\Delta\sigma_{\text{stat fit}}}{\sigma}\right)^2+\left(\frac{\Delta\sigma_{\text{syst norm}}}{\sigma}\right)^2+\left(\frac{\Delta\sigma_{\text{syst fit}}}{\sigma}\right)^2}$$

Acceptance and radiative corrections	15 %
Monte Carlo model	5 %
Holes in DC	6 %
CC-cut losses efficiency	1.5 %
Luminosity	3 %
Fitting procedure	Bin by bin

$$\frac{\Delta\sigma_{syst\ norm}}{\sigma}=17\,\%$$

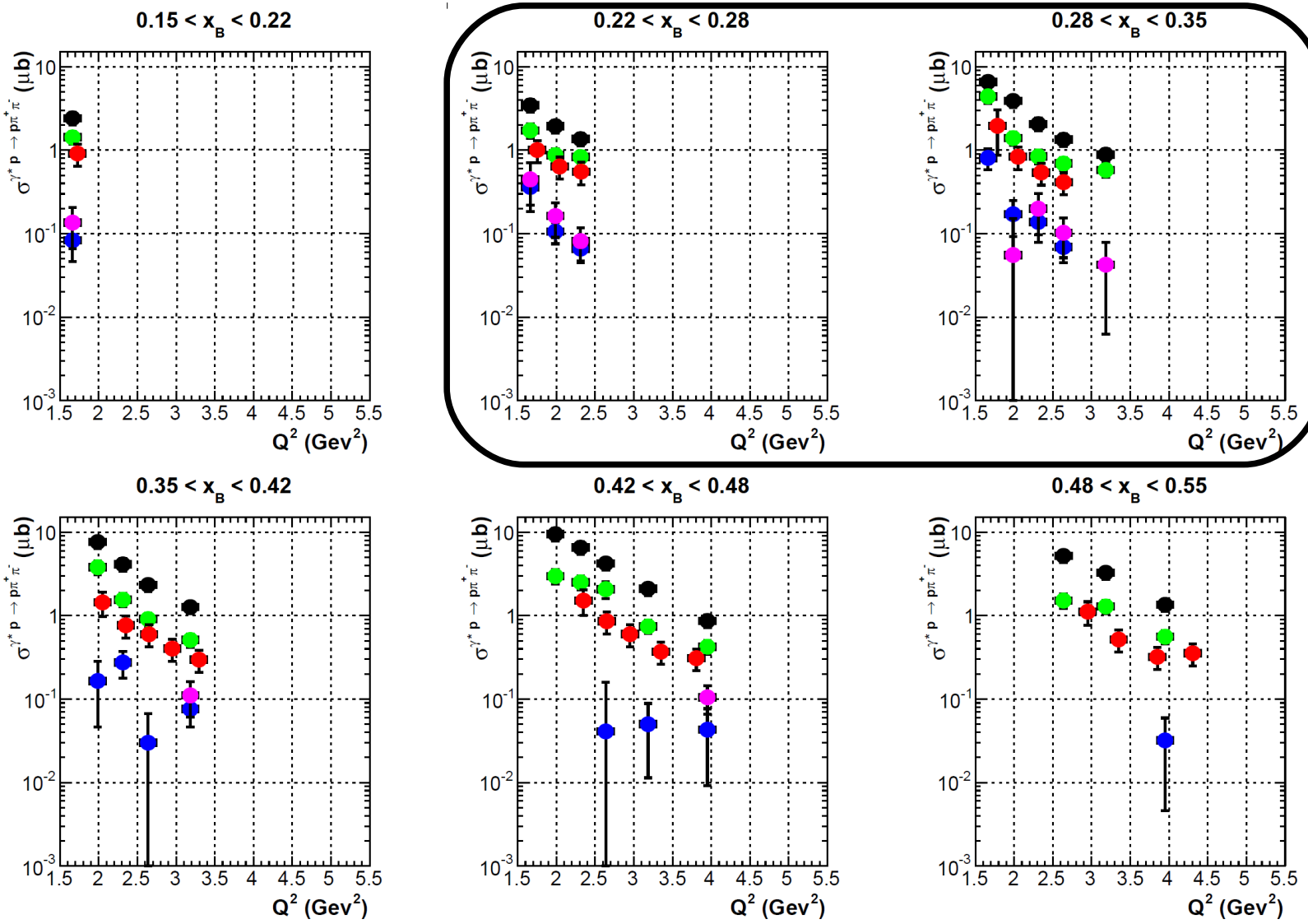
$$\Delta\sigma_{\text{syst fit}}=\sqrt{\frac{1}{4}\sum_{i=1}^{4}(\sigma-\sigma_i)^2}$$

4 systematic variations on fitting procedure :
1) Free Δ^{++} scale parameter.
2)Non resonant background only
3) f_0 and f_2 without skewness
4)+/- 15 % variation on centre and FWHM of f_2 and ρ^0.

Fitting procedure is the main source of systematic error :
For various (Q^2, x_B) bins, ρ^0 : 17 to 22 % f_0: 28 to 150 % f_2 : 44 to 85 %

→ Cross section points with $\Delta\sigma/\sigma_{stat}$> 90 % rejected.

Cross sections in (Q^2, x_B)



+ $\gamma^* p \rightarrow e p \pi^+ \pi^-$
+ $\gamma^* p \rightarrow e p \rho\,(770)$
+ $\gamma^* p \rightarrow e p \rho\,(770)$ (2009)
+ $\gamma^* p \rightarrow e p f_0(980)$
+ $\gamma^* p \rightarrow e p f_2(1270)$

→ Q^2 -scaling

$\rho^0 \sim 1/Q^{6\pm1}$

$f_0 \sim 1/Q^{10\pm1.5}$

$f_2 \sim 1/Q^{10\pm1.8}$

DVMP : $\sigma_L \sim 1/Q^6$

$\sigma_T \sim 1/Q^8$

→ Good agreement on $\sigma^{\gamma p \rightarrow p\rho}$ with previous CLAS ρ^0 analysis.[1]

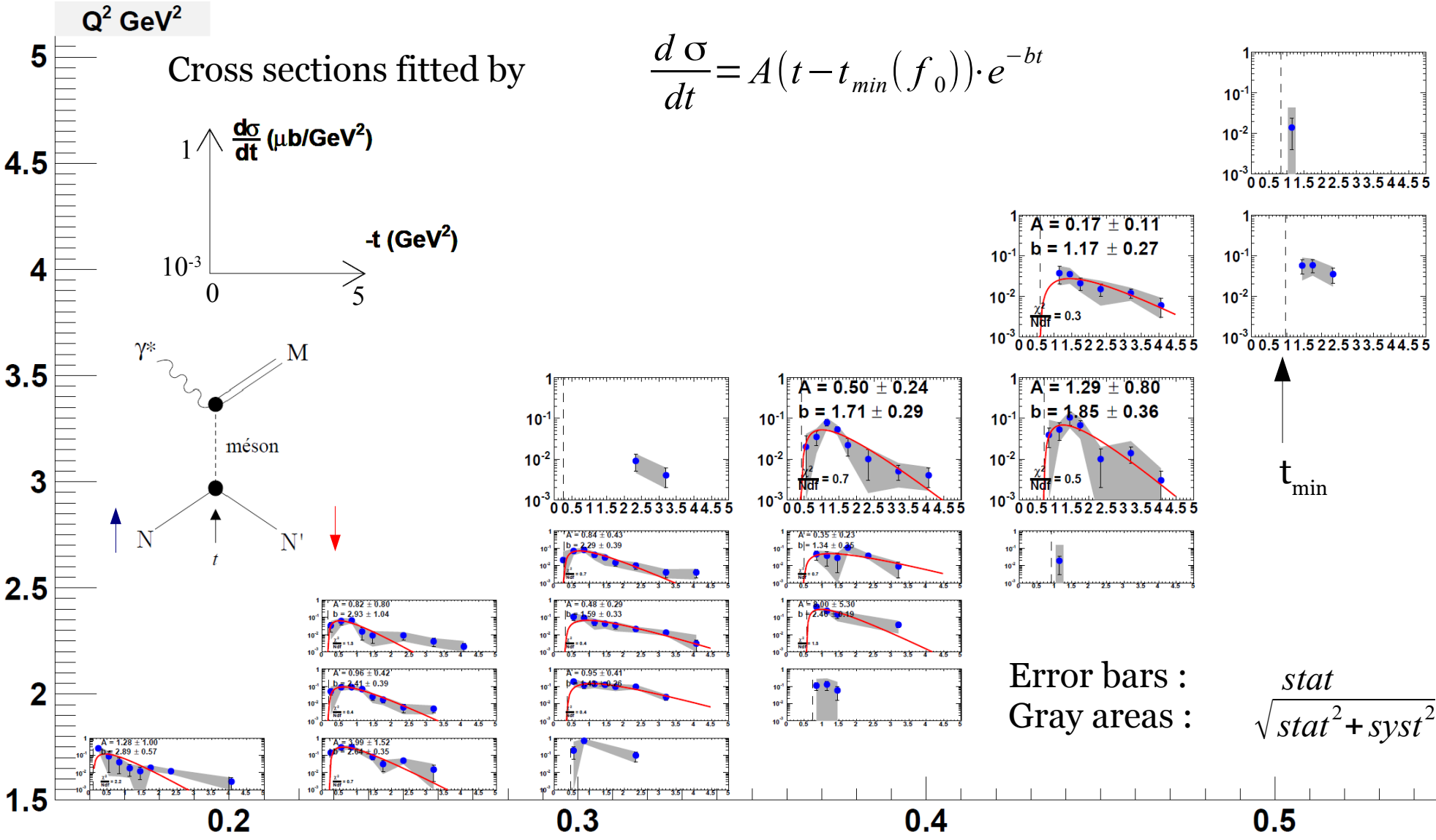
→ f_0 and f_2 seems to follow a different Q^2-scaling from the DVMP one.

[1] S.A. Morrow *et al*, Eur. Phys. J. A 39, 5-31 (2009)

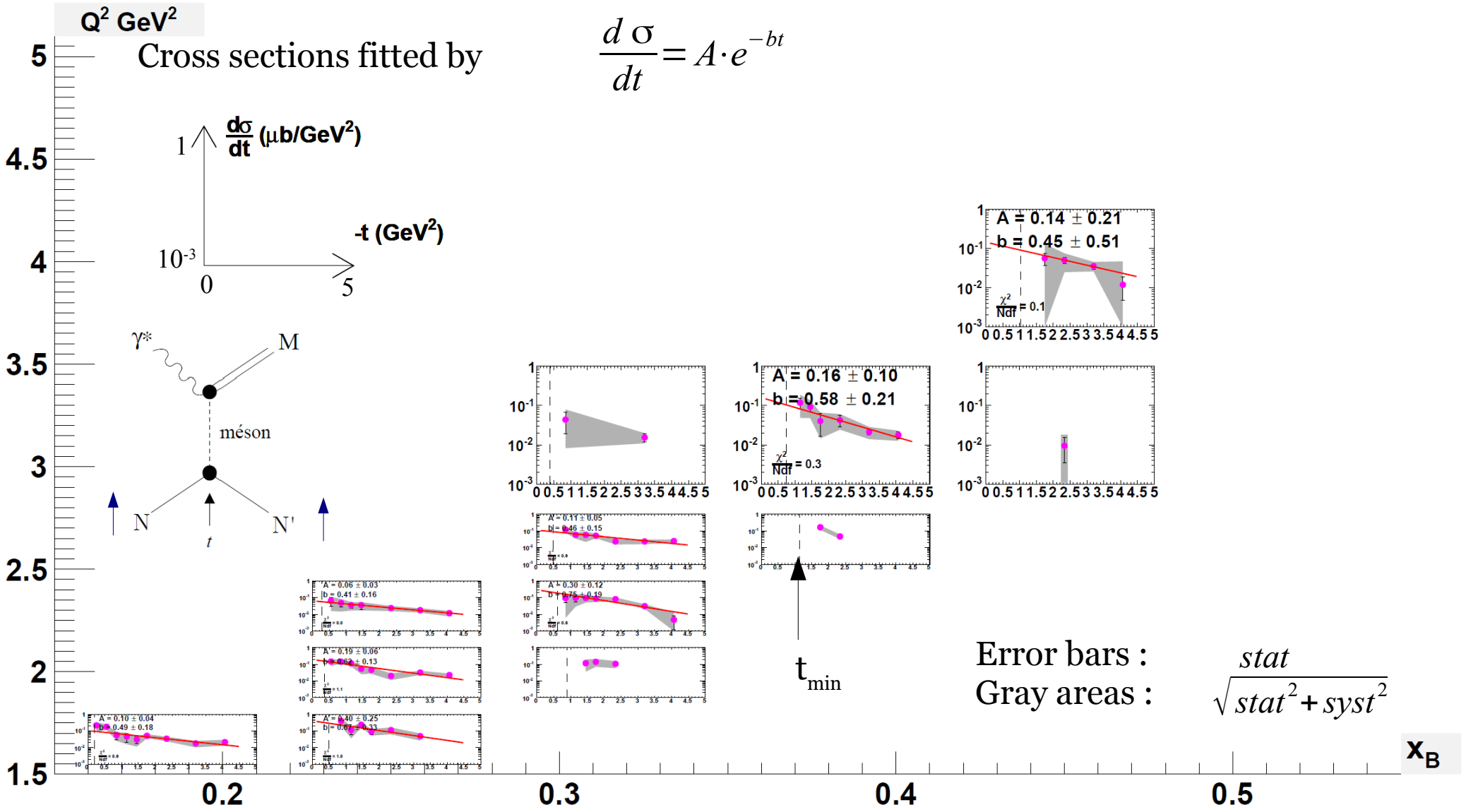
f_0 differential cross sections in (Q^2, x_B, t)

Cross sections fitted by

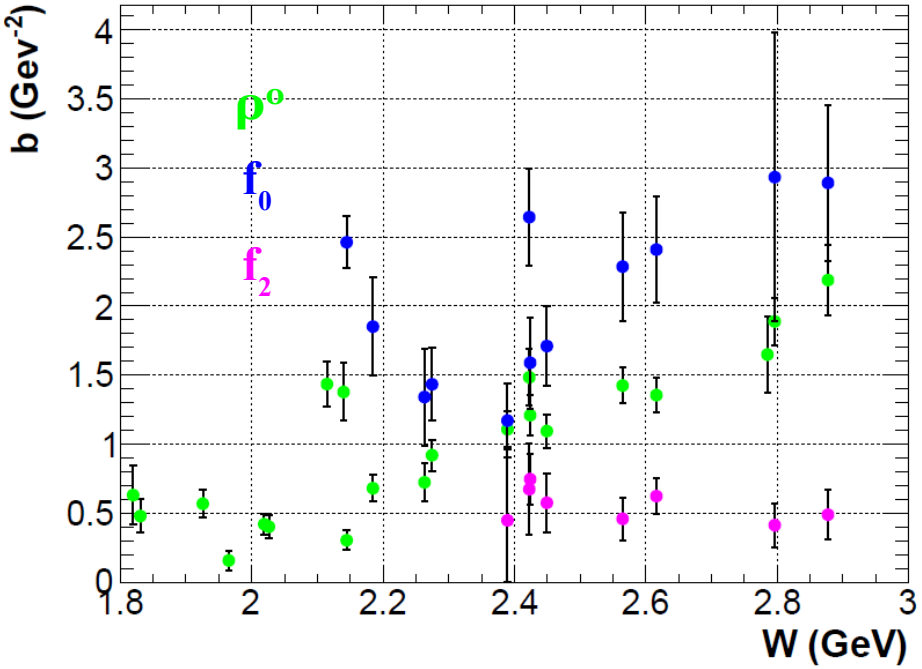
$$\frac{d\sigma}{dt} = A\left(t - t_{min}(f_0)\right)\cdot e^{-bt}$$



f_2 differential cross sections in (Q^2, x_B, t)



Impact parameter b



$$\frac{d\sigma}{dt} \propto Ae^{-bt}$$

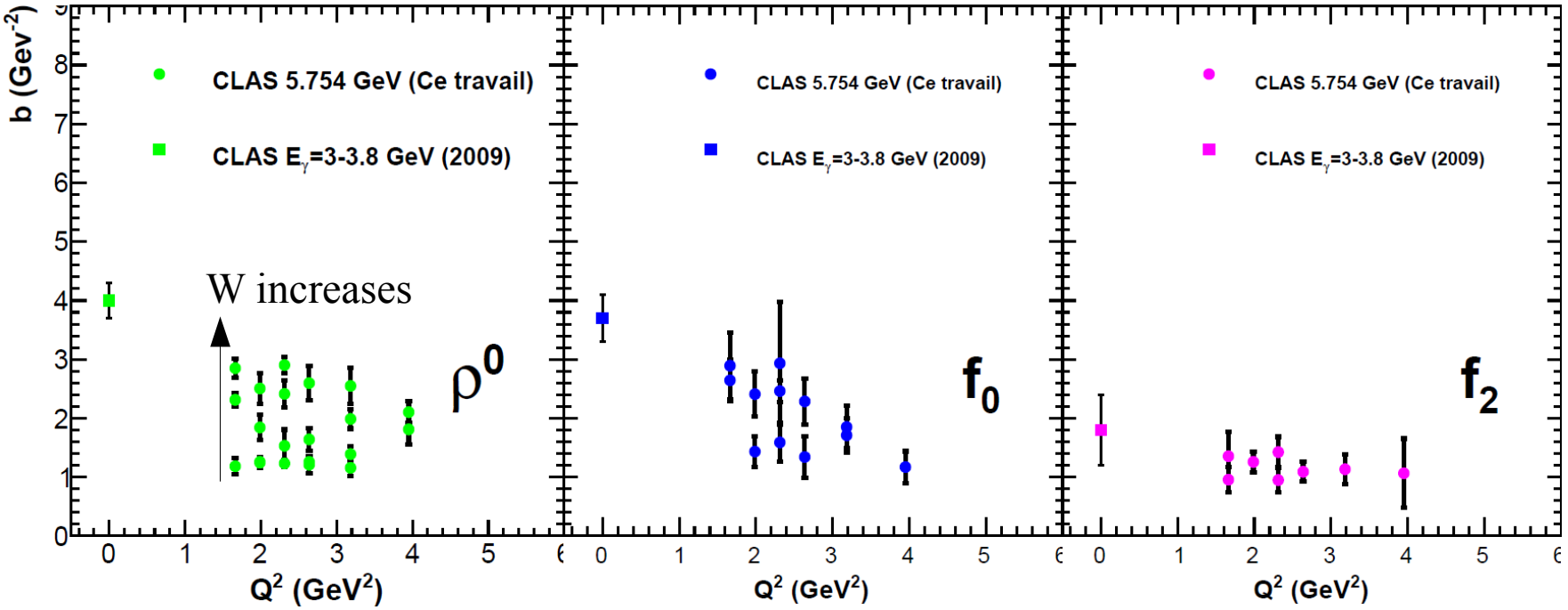
b → Transverse size of γ*p interaction region.

b vs W

- f_0 and ρ^o : Similar behaviour
- f_2 : b constant in the available W region.

b vs Q^2

- b decreases as Q^2 increases.
  → Smaller interaction region with a smaller resolution scale.
- f_2 : Flattest b decrease.
  → Meson mass acts as a resolution scale. ($b_{f_2}(Q^2=0) \sim b_0(Q^2=2\text{-}3\ GeV^2)$)



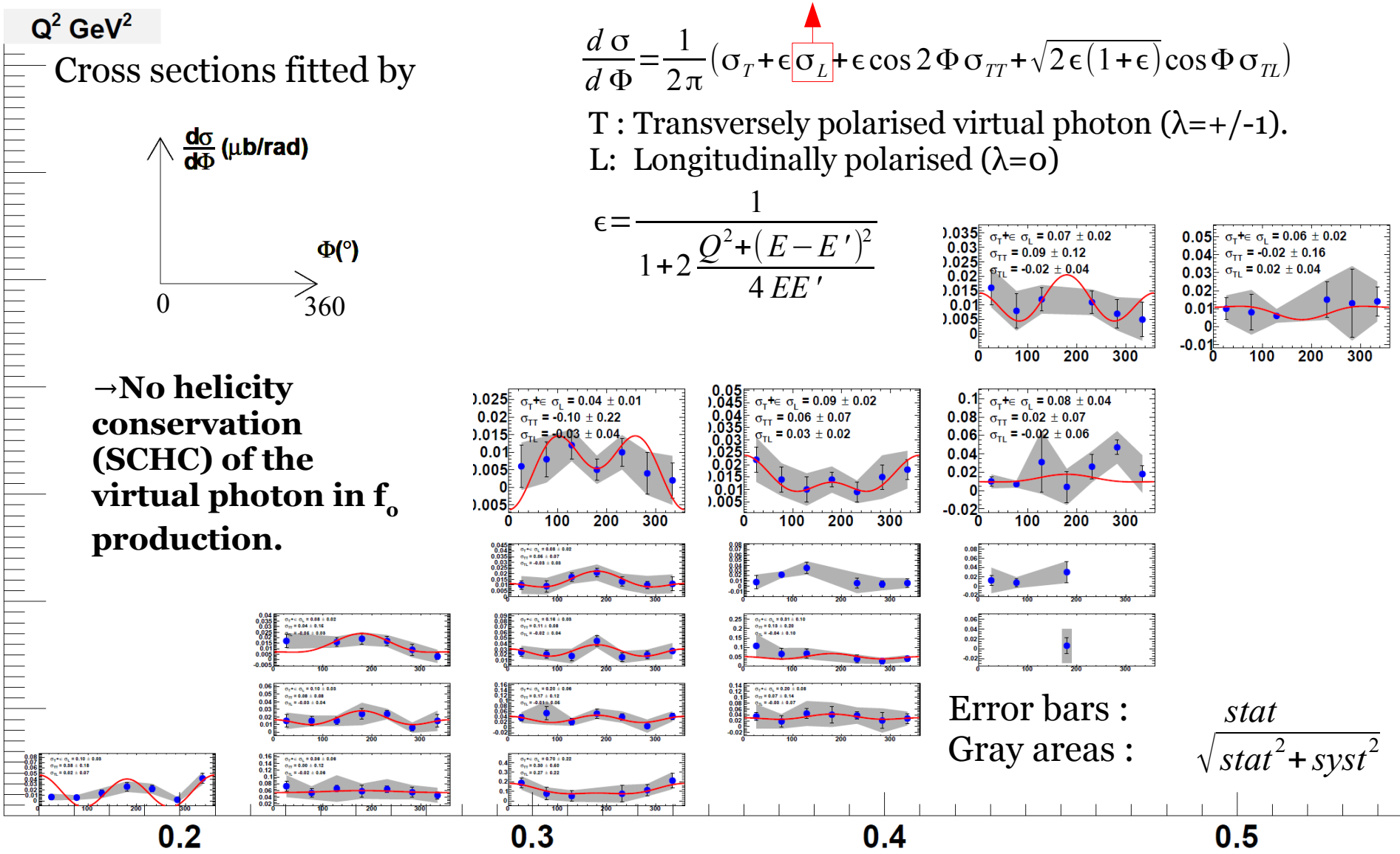
f_o differential cross sections in (Q^2,x_B,Φ)

Factorisation in terms of GPDs

$$\frac{d\sigma}{d\Phi} = \frac{1}{2\pi}\left(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\Phi\,\sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\,\sigma_{TL}\right)$$

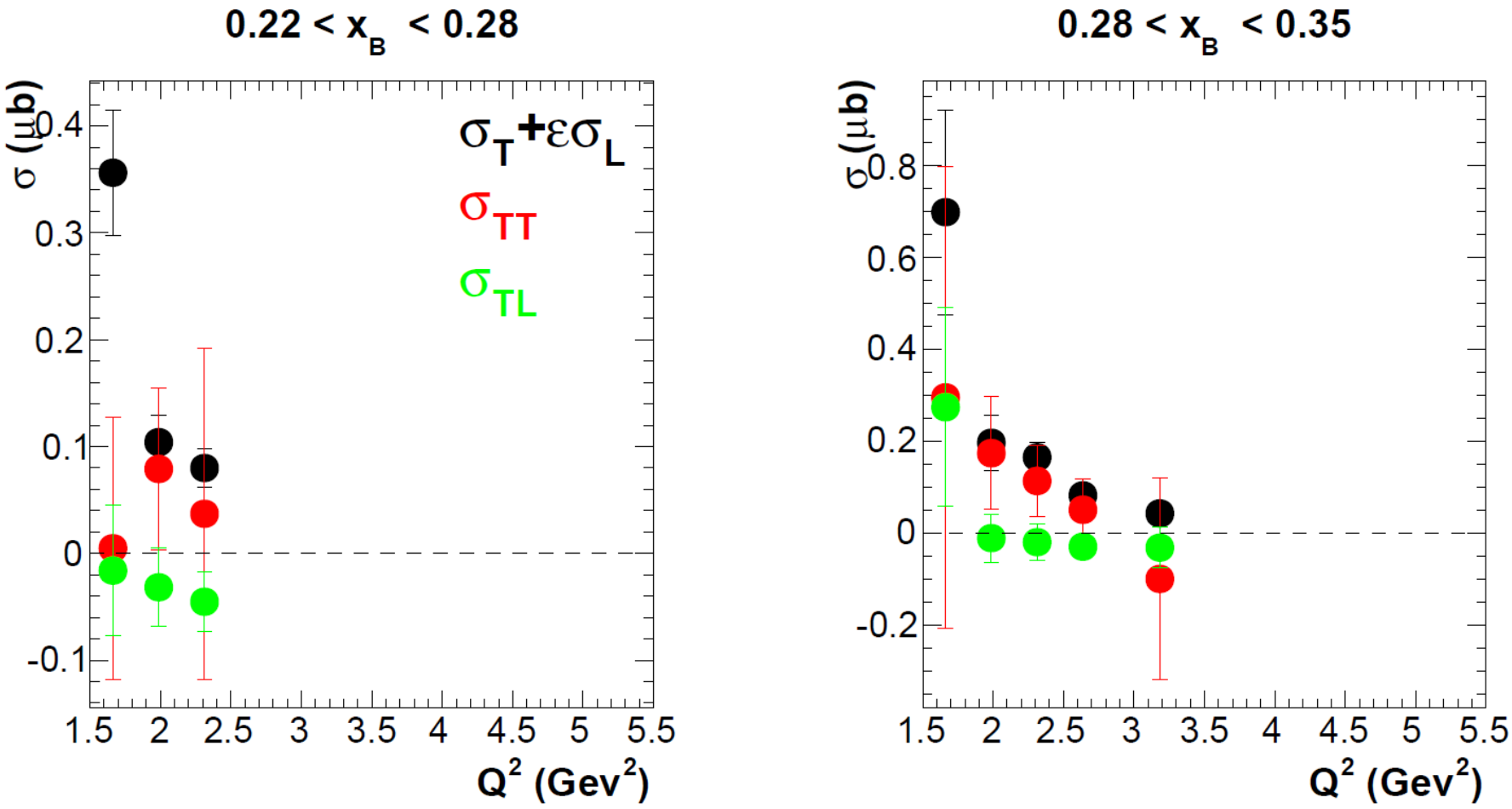
T : Transversely polarised virtual photon (λ=+/-1).
L: Longitudinally polarised (λ=0)

$$\epsilon = \frac{1}{1+2\frac{Q^2+(E-E')^2}{4EE'}}$$



σ_T et σ_L could be extracted by the Rosenbluth technique (measurements at different beam energies, same (Q^2,x_B)).

TT and TL interferences of $\gamma^* p \rightarrow p f_0$



- Non negligible contribution from TT response function.
- TT contribution similar to $\gamma^* p \rightarrow p\pi^0$ [1] electroproduction.

[1] I. Bedlinsky et al., Phys. Rev. C 90, 039901 (2014)

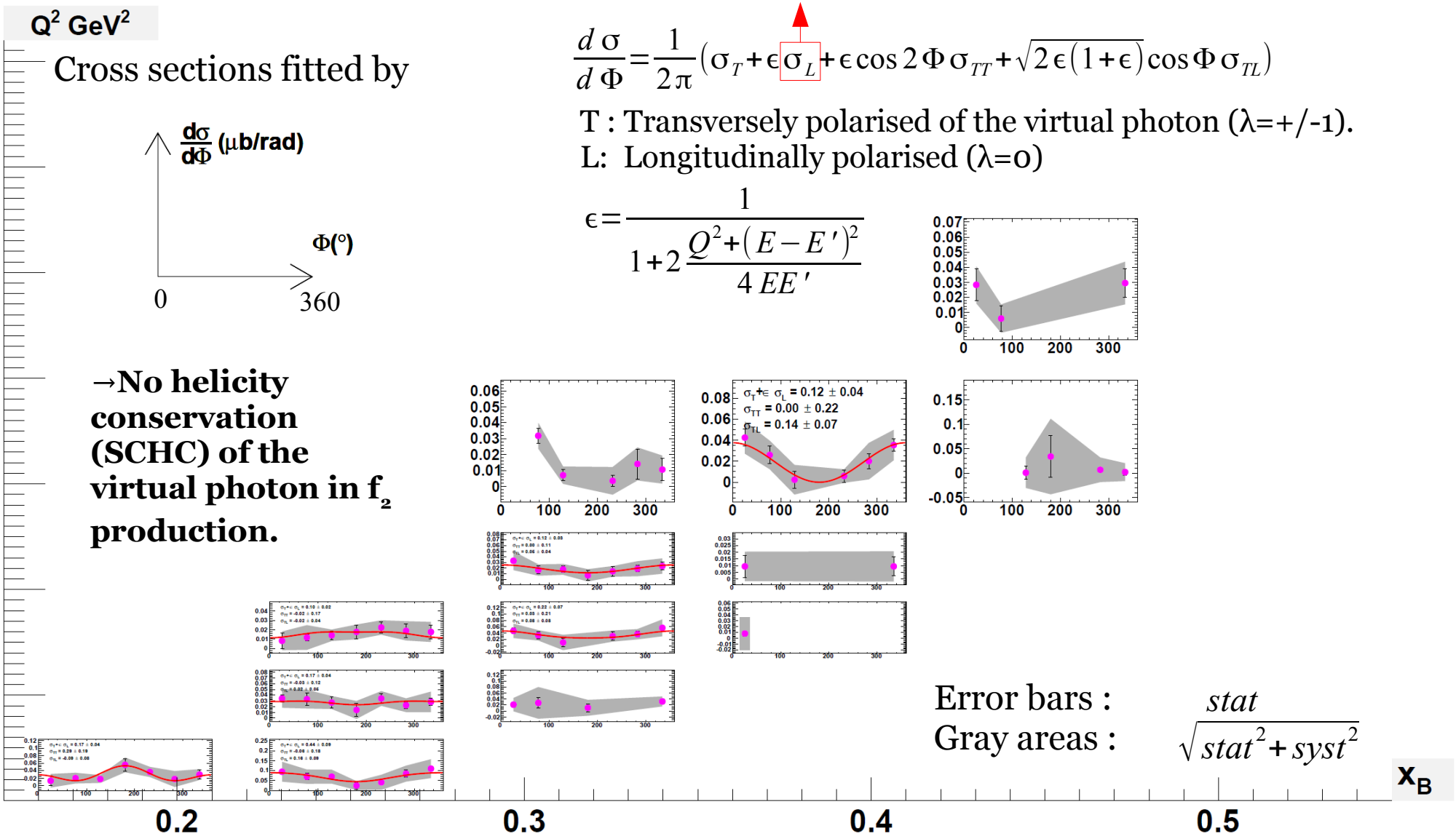
f_2 differential cross sections in (Q^2, x_B, Φ)

Factorisation in terms of GPDs

$$\frac{d\sigma}{d\Phi} = \frac{1}{2\pi}\left(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\Phi\,\sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\,\sigma_{TL}\right)$$

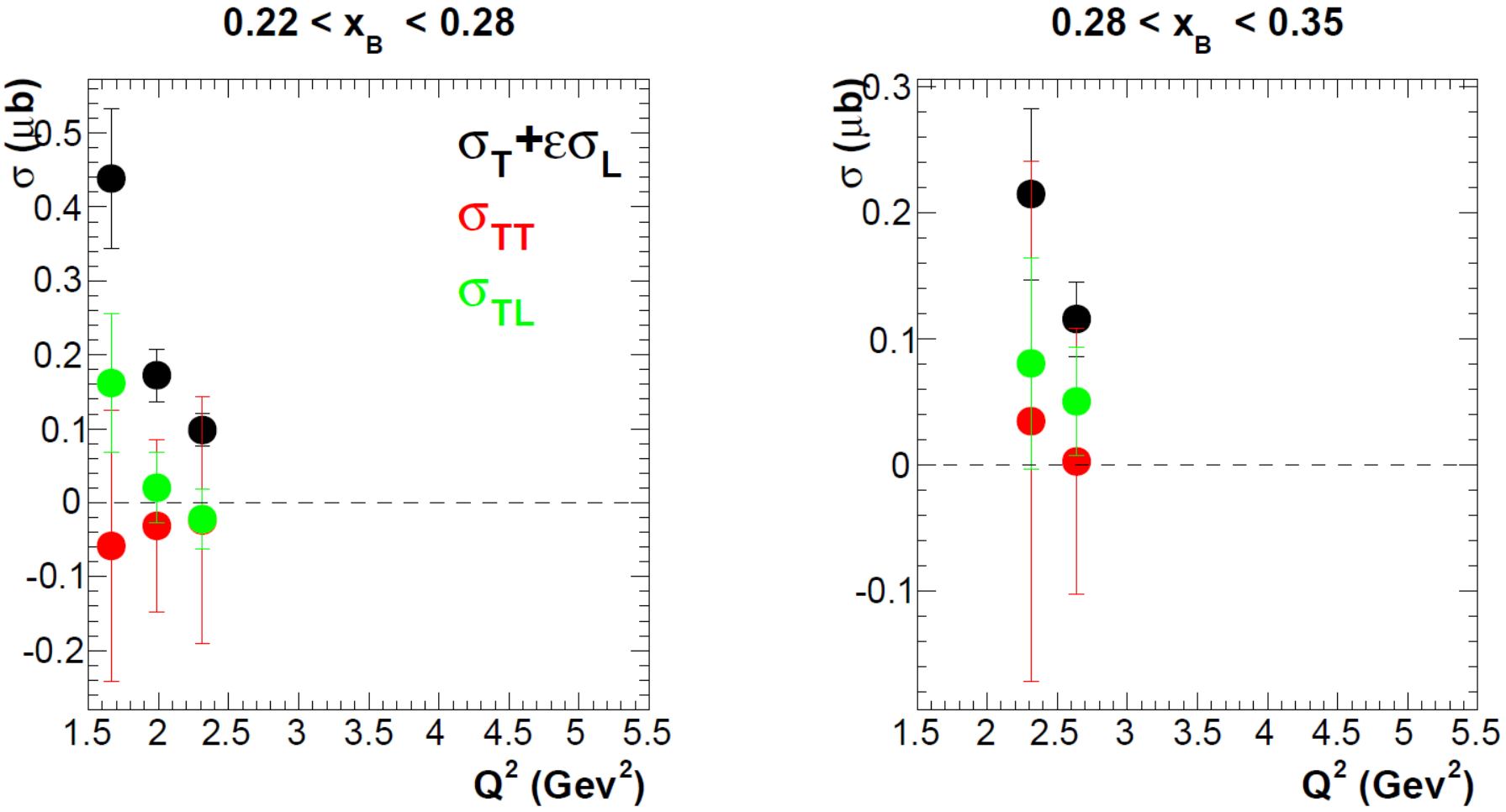
T : Transversely polarised of the virtual photon (λ=+/-1).
L: Longitudinally polarised (λ=0)

$$\epsilon = \frac{1}{1 + 2\frac{Q^2 + (E - E')^2}{4EE'}}$$



σ_T et σ_L could be extracted by the Rosenbluth technique.

TT and TL interferences for $\gamma^* p \rightarrow p f_2$



- Hint of TL response function.
- TL contributions in f_2 mass region in agreement with Legendre moments analysis at HERMES[1].

[1] Airapetian et al. (Collaboration HERMES) Phys. Lett. B 599, 212 (2004)

1.Introduction and physics motivations

2.Experimental setup

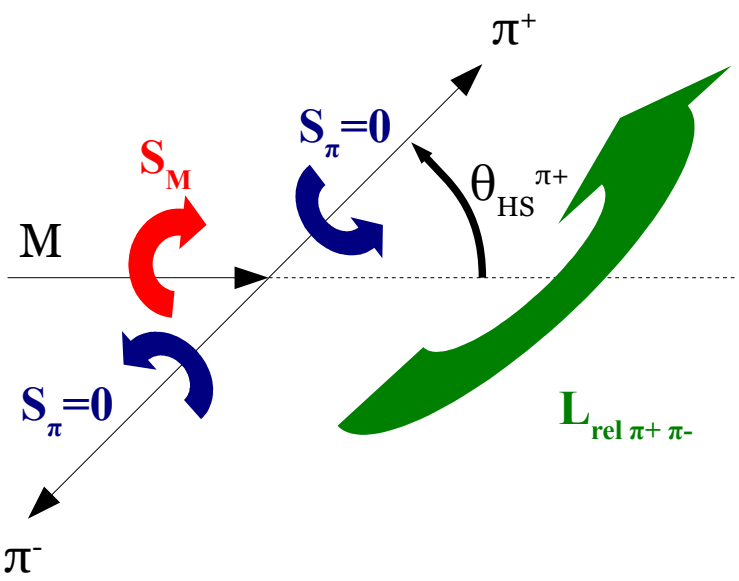
3.Cross section for $f_0(980)$ and $f_2(1270)$

4.Moments Analysis of 2-pion electroproduction

5.Conclusions

Partial Wave Amplitudes

→ f_0 (J=0) and f_2 (J=2) extracted using their spin.



$$S_M = S_{\pi^+\pi^-} + L_{rel}$$

Spin of meson M.

Spin combination of π^+ and π^-. $S_{\pi+\pi-} = 0$

Relative orbital angular momentum of the 2 pions.

→**Spin of M determined by analysis the decay angles of π^+.**

- ep → epππ amplitude decomposed into a **coherent sum of partial wave amplitudes**.

$$\left|A\left(Q^2, x_B, -t, \Phi, \cos\theta, \varphi, M_{\pi^+\pi^-}\right)\right|^2 = \left|\sum_{l=0}^{\infty} \sum_{m=-l}^{m=+l} a_{lm}\left(Q^2, x_B, -t, \Phi, M_{\pi^+\pi^-}\right) \cdot Y_{lm}\left(\cos\theta, \varphi\right)\right|^2$$

l : Relative angular orbital momentum
m : Angular momentum projection along Z_{HS} axis in helicity frame.

Production amplitude

Spherical Harmonics
Decay amplitude

→ First attempt of PWA on ep → epππ with mass independent fits.
(in collaboration with M. Battaglieri, A. Celentano, D.Glazier, V. Mathieu, A. Szczepaniak) :

Pseudo-data : Consistent results in simple cases, fails with realistic ρ → **Parity conservation ?**
Real data : Not enough statistics to perform fit in (Q^2, x_B, t, Φ, M) bins.

Moments of angular distributions

→ **Amplitudes indirectly determined** by analysing **moments** of the decay angular distributions

Moments decomposition[1]

For each $ep\pi^+\pi^-$ event,

$$I(\Theta,\Phi)=\sqrt{4\pi}\sum_{L=0}^{L_{max}}\sum_{M=0}^{L}<Y_{LM}>\Re\left(Y_{LM}(\Theta,\Phi)\right),\ L_{max}=4$$

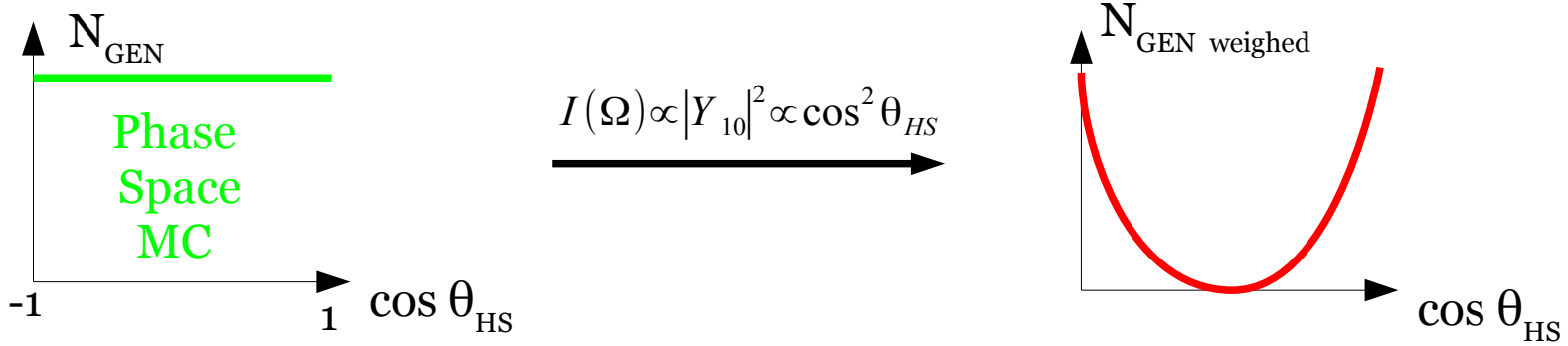
Intensity — **Moment** (0<=M<=L, free parameter) → **Interferences between amplitudes** — Spherical Harmonics

Fit of the intensity (AmpTools)[2]

$$\text{Minimisation of } -\ln L=\underbrace{-\left(\sum_{i}^{n}\ln\left(I(\tau_i,\vec{x})\right)\right)}_{\text{Experimental data}}+\underbrace{\frac{1}{N^{GEN}}\sum_{k=1}^{NREC}I(\tau_i)}_{ep\pi^+\pi^- \text{ Monte Carlo accepted by CLAS (Acceptance correction term)}}$$

$$\tau_i=(\theta,\Phi)\qquad \vec{x}=<Y_{LM}>$$

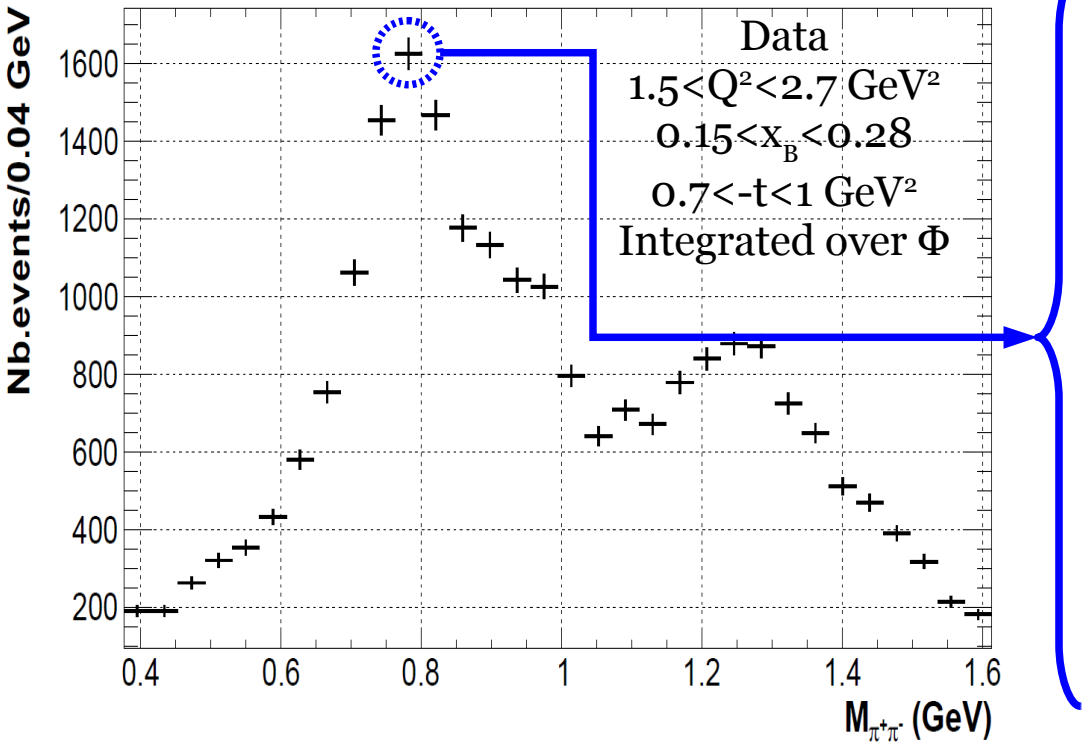
Acceptance corrected angular distribution given by the intensity

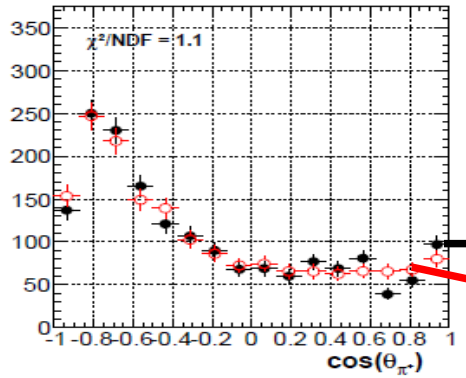


[1] M. Battaglieri *et al*, Phys.Rev. D80 (2009) 072005

[2] http://sourceforge.net/projects/amptools/

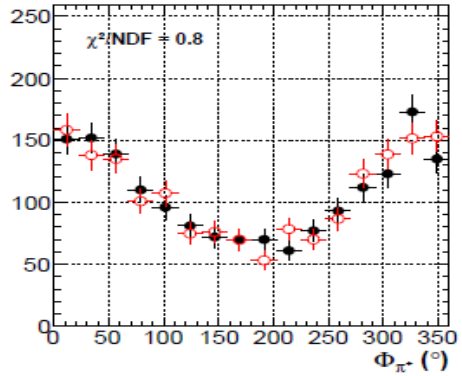
Fit of the moments to the data





Data

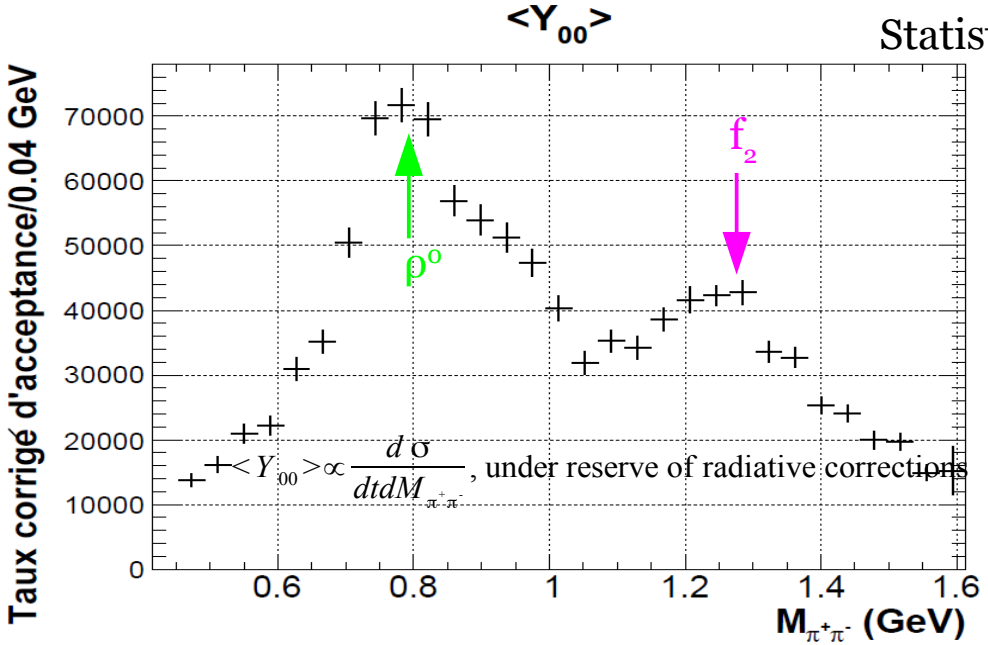
Fitted intensity with CLAS acceptance

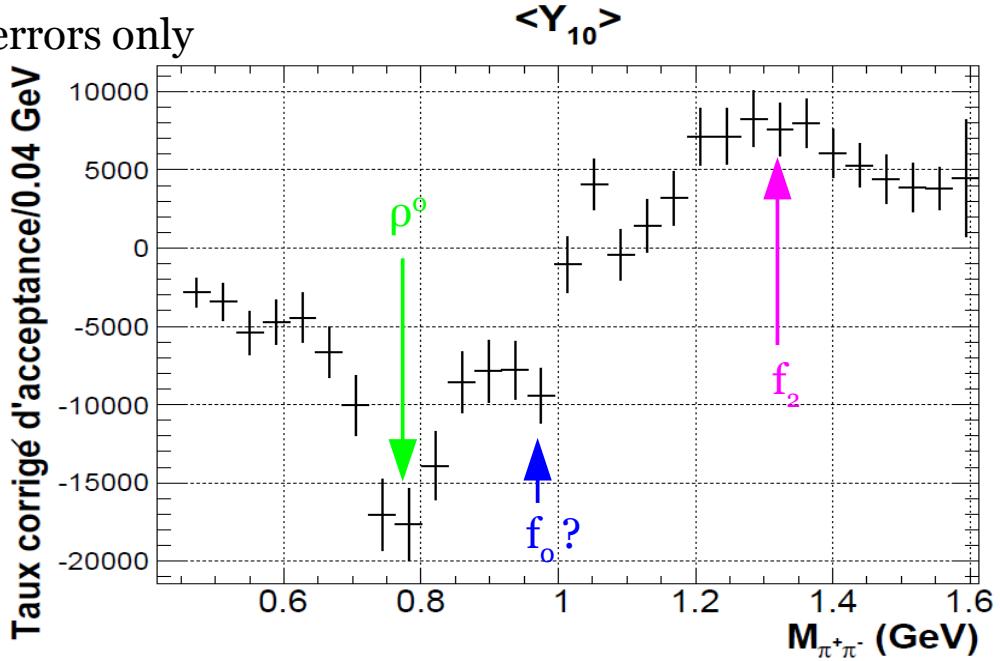


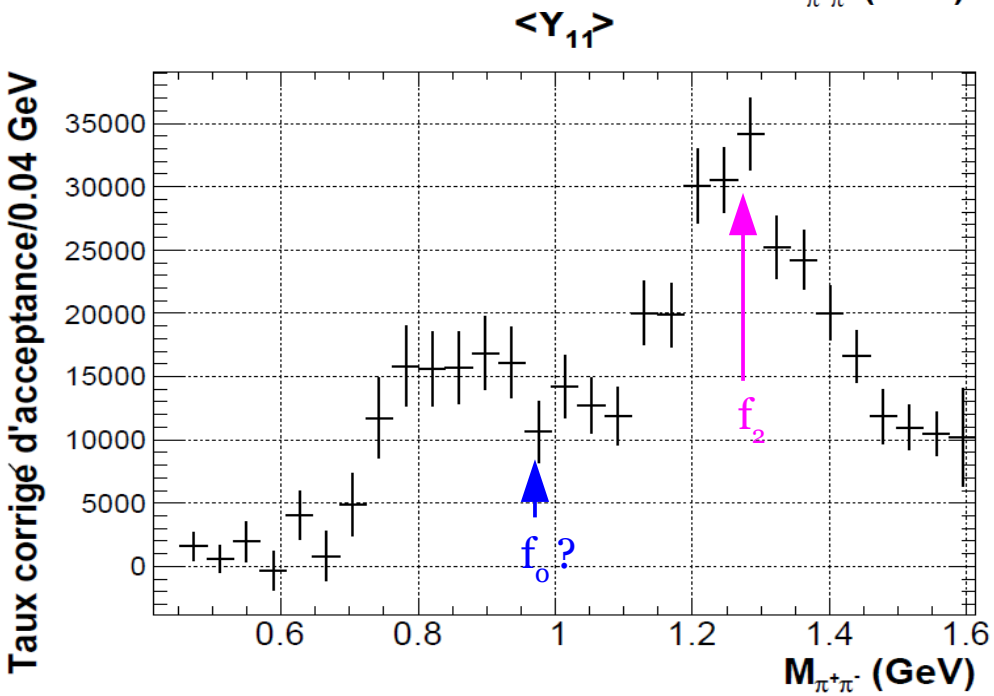
- **Mass independent fit.**
- Several **fit scenarios (8) tried** , 1 with parametres set to 0 and randomly initialised parameters for the others. Kept fit with the **best -ln L.**
- **Fit quality** checked by comparing π^+ angular distributions from the **data** with those predicted by the **intensity reconstructed by CLAS.**
- **Good agreement between the fit and the data.**

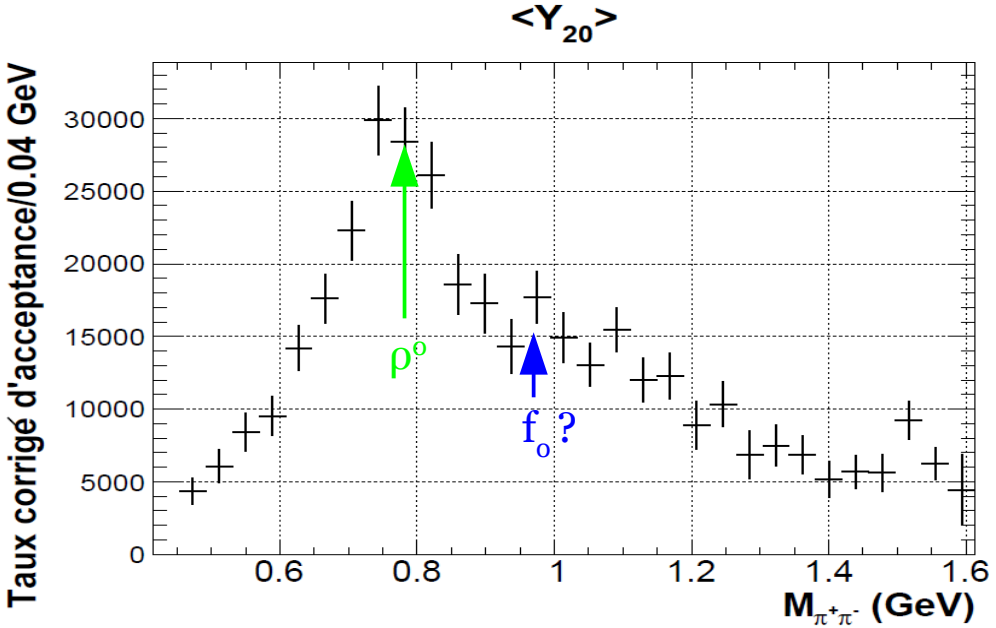
Moments of angular distributions: results

Statistical errors only









→ ρ° and f_2 resonances clearly visible. Possible hint of f_o with a small width (Γ~ 40 MeV).

1.Introduction and physics motivations

2.Experimental setup

3.Cross section for $f_0(980)$ and $f_2(1270)$

4.Moments Analysis of 2-pion electroproduction

5.PMT calibration for the Central Neutron Detector (CLAS12)

6.Conclusions

Conclusions

- **First cross section measurements** of excluvie $f_0(980)$ et $f_2(1270)$ electroproduction off the proton.
  → -t, Φ and cos θ_{HS}-dependence studied.

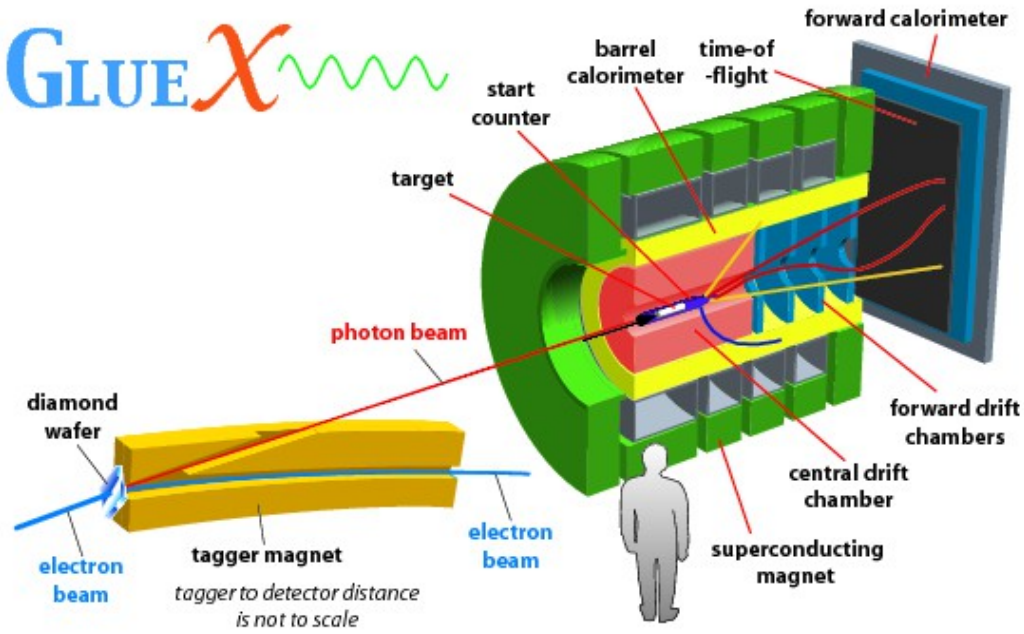
- $f_0(980)$ and $f_2(1270)$ in a region **strongly contaminated by the background**.
  →Large systematic errors.
  Limited by our knowledge of the background.
  Analysis note is ongoing.

- **First** attempt of a **partial waves analysis** on $ep \rightarrow ep\pi^+\pi^-$. **(Work in progress)**
  → Underconstrained fit : partial waves decomposition to be worked out (parity conservation?)
  → Statistics is currently limited, forbiding a fully differential extraction of partial waves amplitudes.
  → How to deal with radiative corrections?

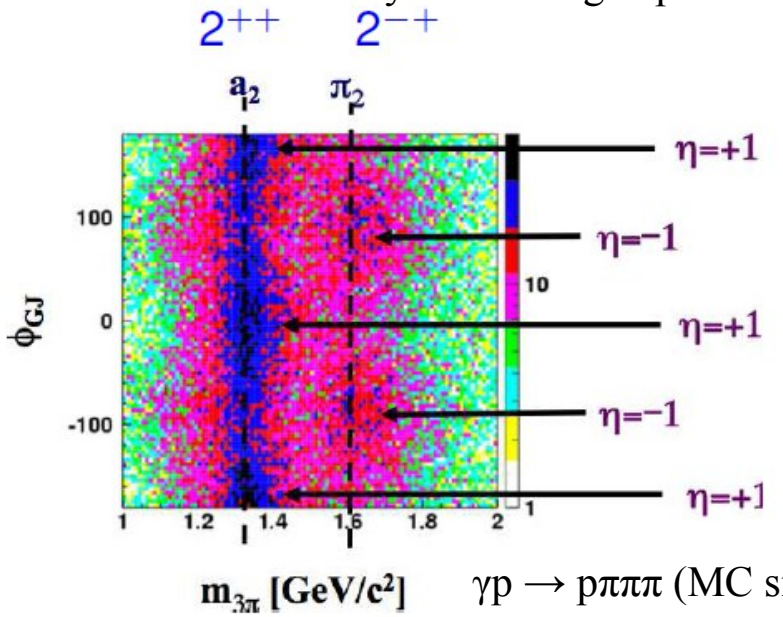
- Alternative analysis by determining **moments of decay angular distributions**.
  → f_2 resonance visible. f_0 to be confirmed with larger statistics
  Analysis limited by the statistics
  (With higher luminosity, analysis with large Q^2, x_B intervals and fine t, Φ, M bins might be possible)

- Central Neutron Detector (CLAS12) : gain calibration of the PMTs

Future prospects



Polarized photon beam
→ Filter on the naturality of exchanged particle.



γp → pπππ (MC simulations)

- GlueX detector :
  → High intensity polarized photon beam
  → Uniform acceptance (azimuthal especiallly)
  → Commissioning under completion

- **Light meson spectroscopy → $f_0(980)$**

  $\gamma p \rightarrow p\pi^+\pi^-$
  → 6 GeV done (first measurement of f_0)
  → Complete the analysis at 12 GeV (achievable with GlueX I ?)

  $\gamma p \rightarrow pK^+K^-$
  → f_0 at treshold
  → K identification improved by addition of DIRC in Hall D(2018)

  $f_0(1500)$ glueball?

- **Search for exotic excitations**

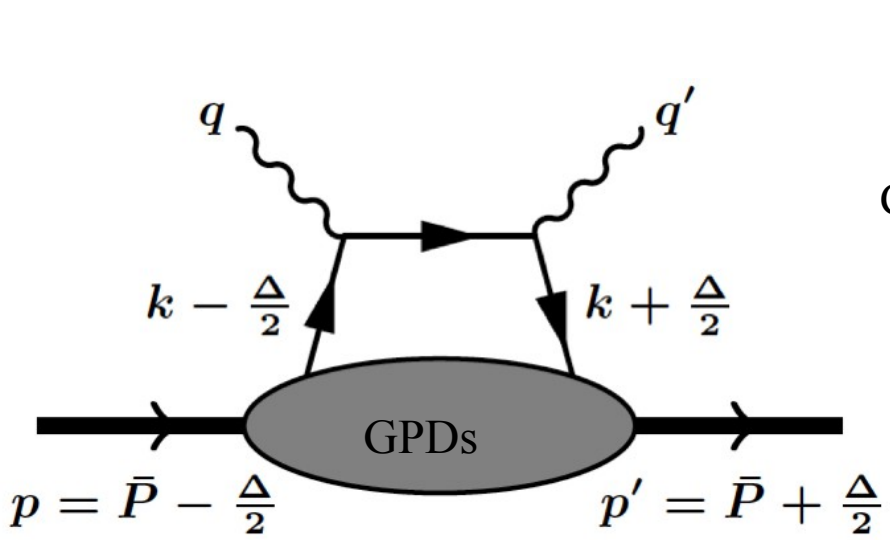
- Early physics expected in 2016:

  → Beam asymmetries
  → Cross sections measurements of known mesons (possibly in PWA)

Thanks for your attention.

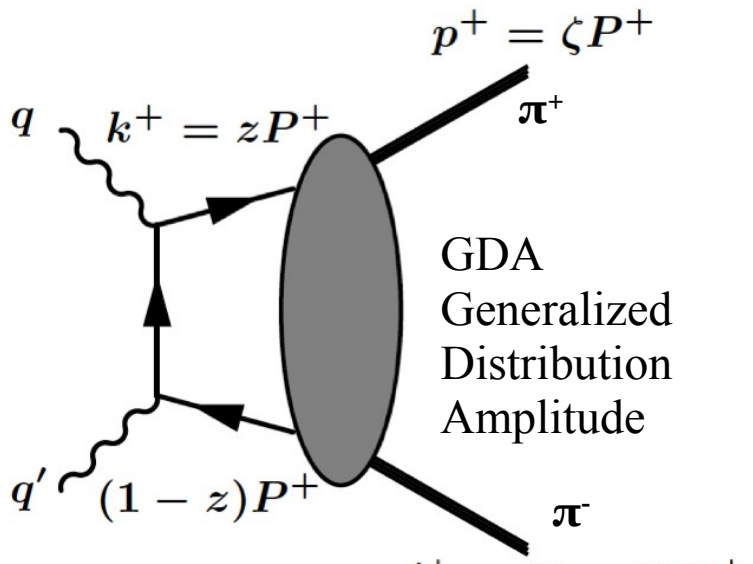
Backup slides

Generalized Distribution Amplitude (GDA)

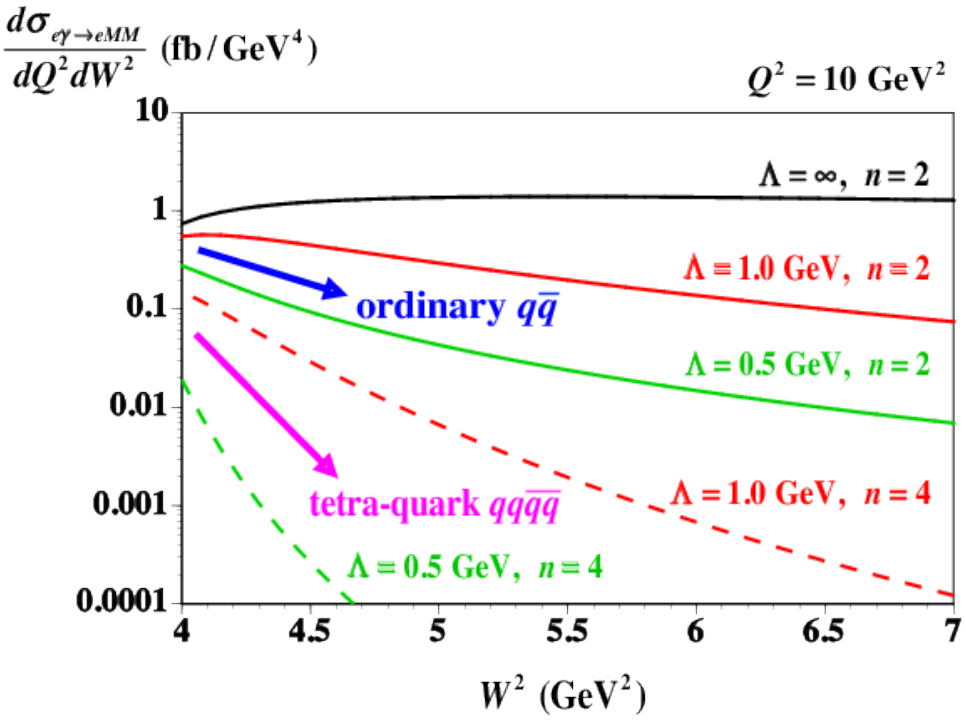


ep → epγ (DVCS)

Crossed diagram



$e^- \gamma \rightarrow e^- + \pi^+ \pi^-$

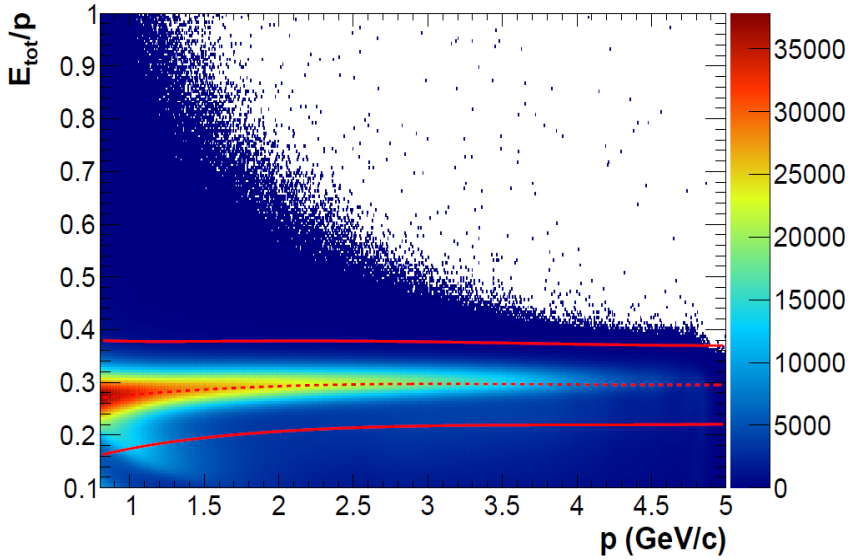


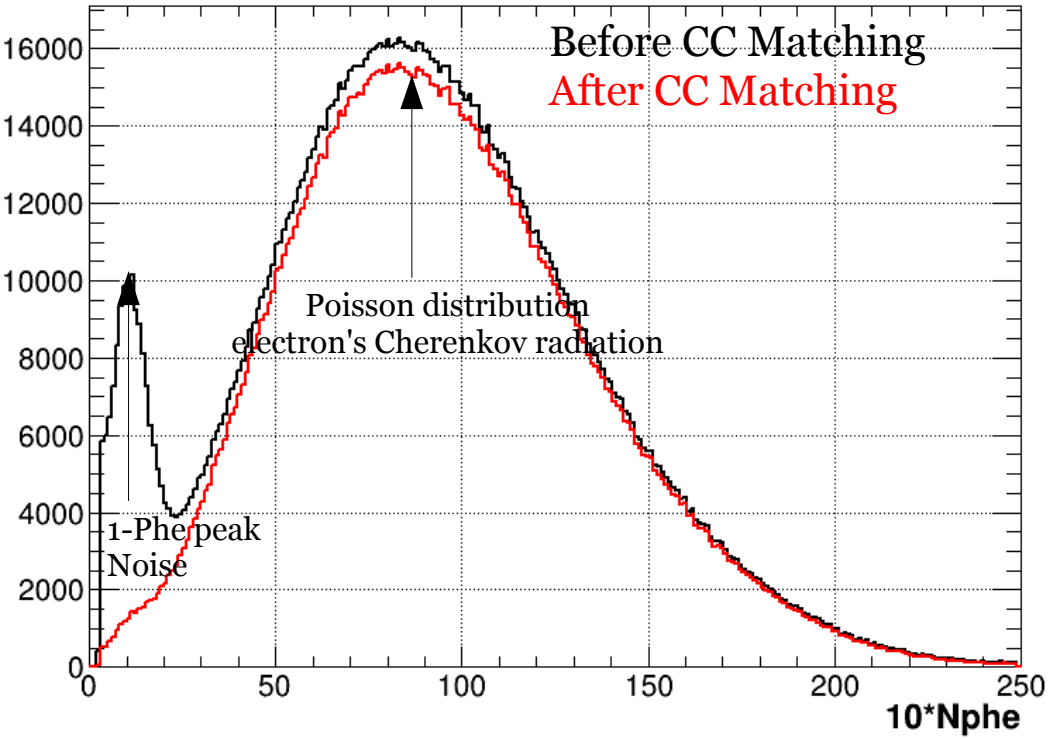
- GDA described **production of hadrons** in a **partonic picture**.
- GDA → Different form factor according to the object's nature ($q\bar{q}$, tetraquark...)
- **Cross sections** depends on the object's **nature** described by the GDA.

Electron identification

Among negative charged tracks (q<0) :

- p>0.8 GeV/c
- Vertex selection within the LH2 target.
- EC and CC fiducial cuts.
- Energy sampling fraction :
  - Total energy deposited/p.
  - Deposited energy fraction in Inner and Outer part of the EC.





Photoelectron emission spectrum from the 2 photomultipliers in module #7 sector 3

"CC Matching"

- Photoelectron emission spectra from CC show a large number of track (**pic 1-Phe**) which are misidentified as e^-.
- Geometrical cuts on the tracks between CC and SC.
- Cuts on the time-of-flight between CC and SC.
- Significant reduction of e^-/π^- contamination

Proton and π^+ identification

Among e-X selected events:

- q<0 and p>0.2 GeV/c
- Fiducial cuts in θ and φ.
- Vertex selection within the target volume.
- **Proton and π^+ identified by time-of-flight measurements :**

Predicted velocity for a particle with given mass m

Target-SC distance

$$\Delta\beta_m = \beta_{mes} - \beta_{calc}(m) = \frac{l}{ct} - \frac{p}{\sqrt{p^2+m^2}}$$

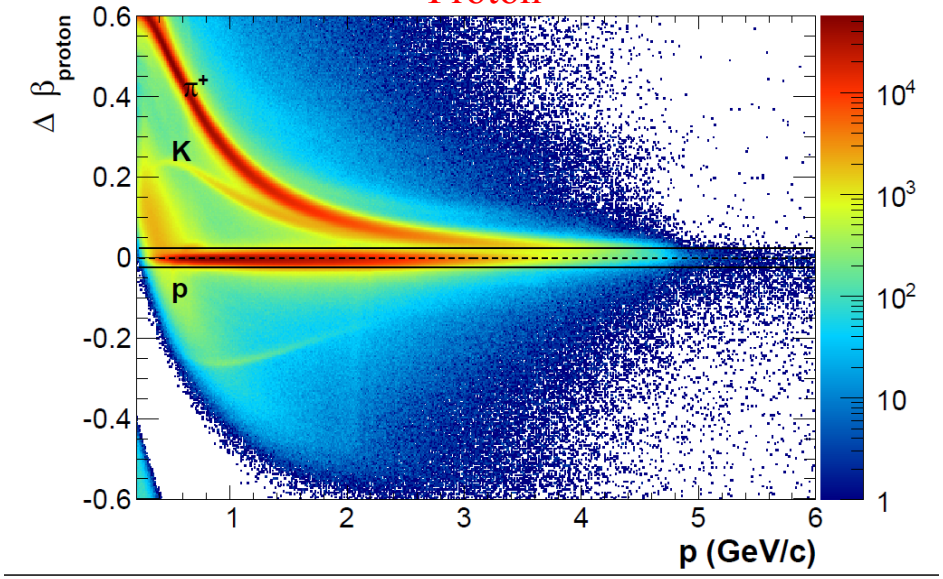
Momentum (DC)

Measured velocity

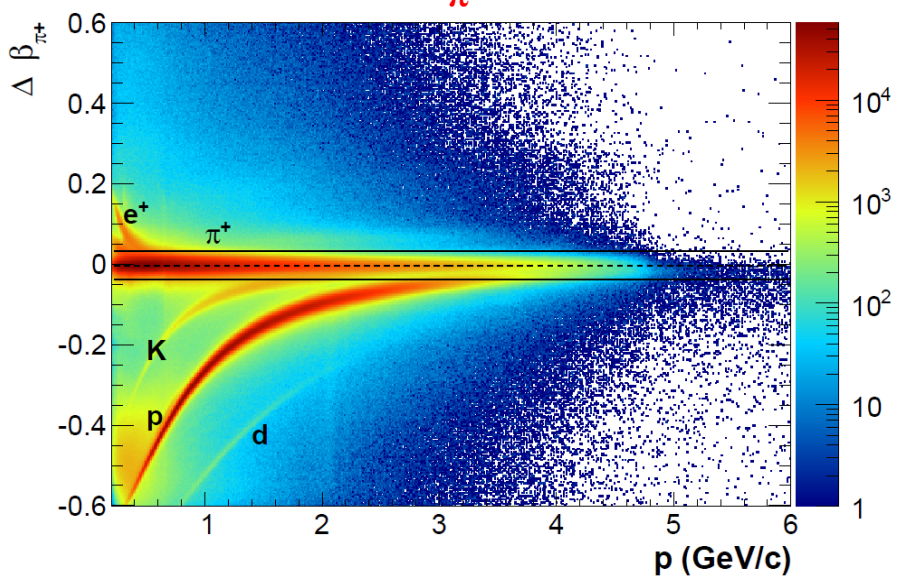
Time of flight (SC)

→ 2.5 σ cuts on $\Delta\beta_p$ and $\Delta\beta_{\pi+}$

Proton



π^+



Exclusive ep → e'p'π⁺π⁻

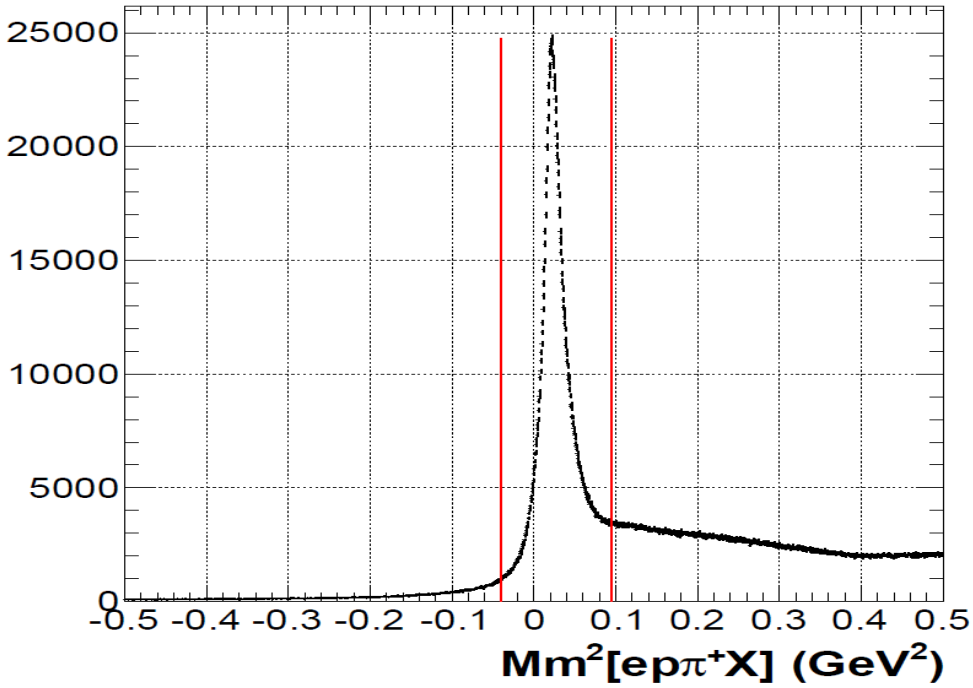
Among $e^-p\pi^+X$ selected events :

- Selection on the missing mass Mm[$e^-p\pi^+X$] :

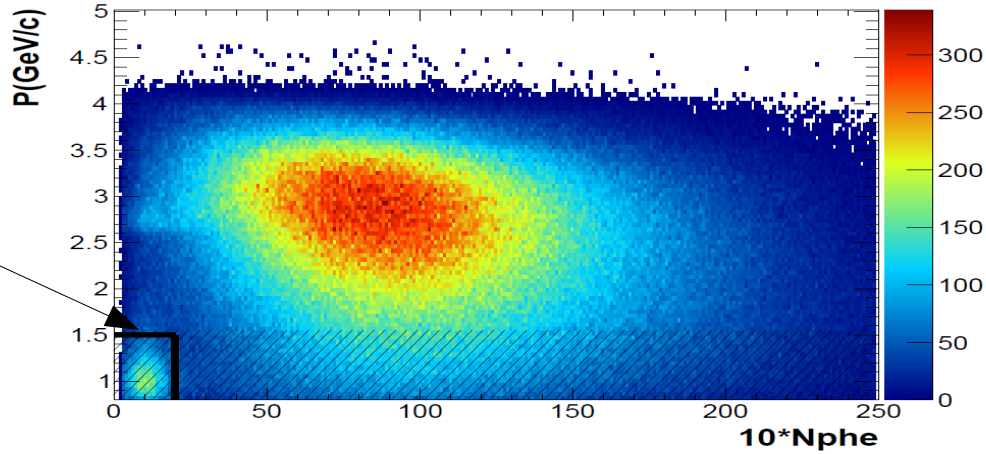
$$p_X = p_p + p_e - (p_{e'} + p_{p'} + p_{\pi^+})$$

Cuts around the π-peak:

$$-0.05 \leq Mm^2[ep\pi^+X] \leq 0.08 \ \text{GeV}^2$$

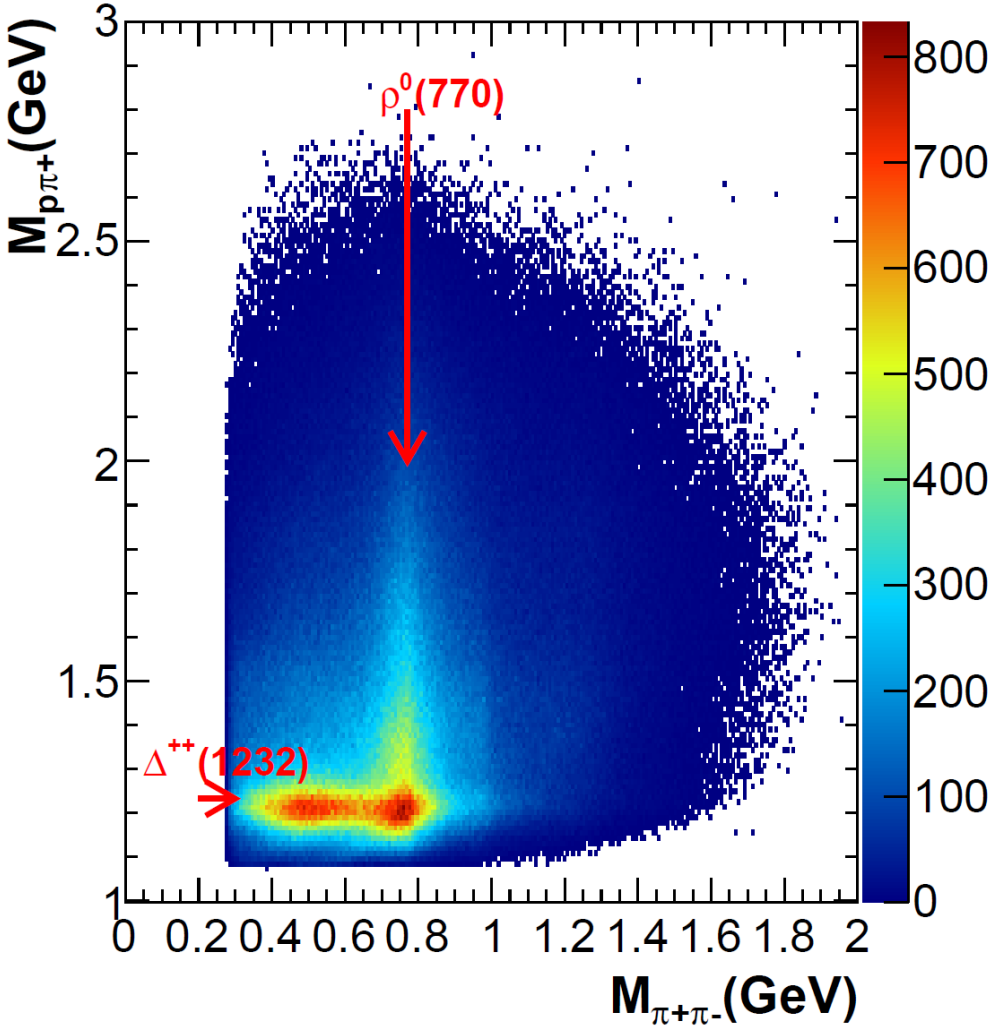


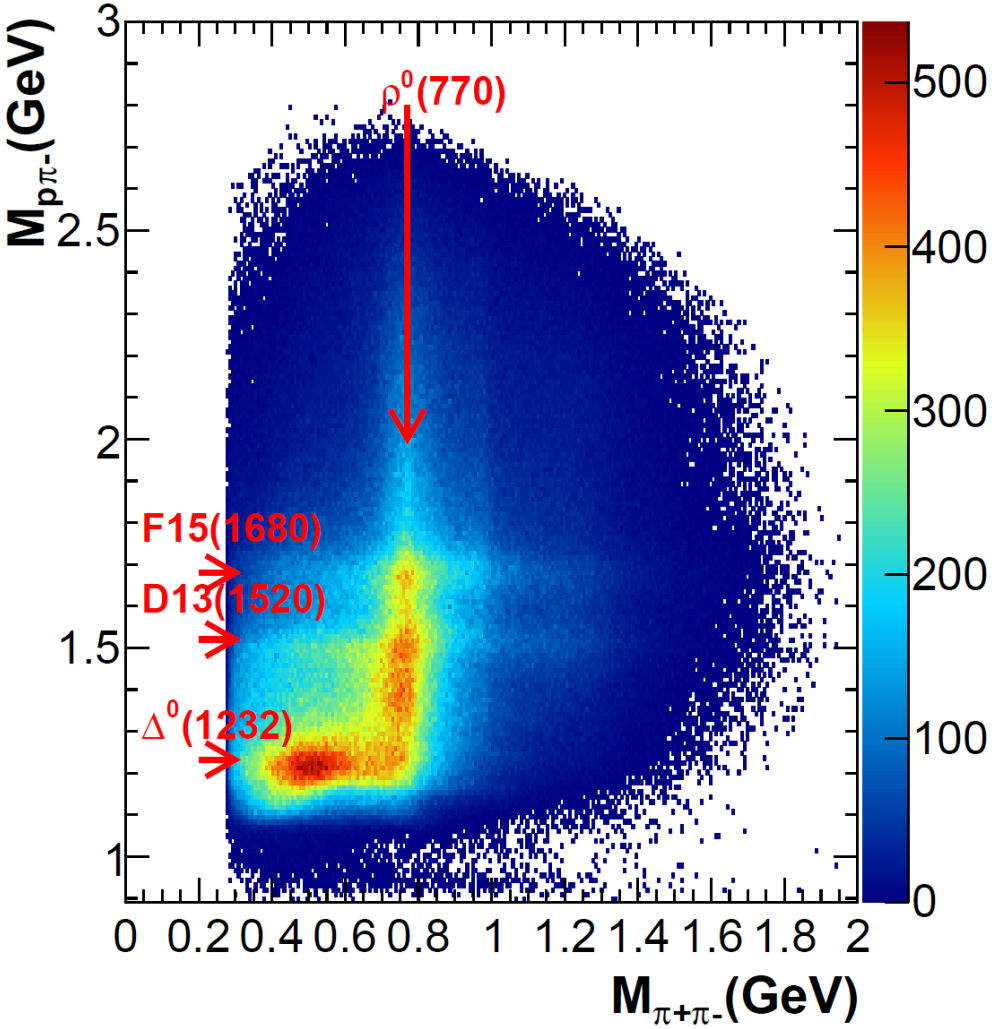
- 1-Phe peak (CC) remains after the missing mass cut for p_{e^-}<1.5 GeV/c.
  → (p_{e^-} ,Nphe)=[0.8;1.5]x[0,300] region excluded



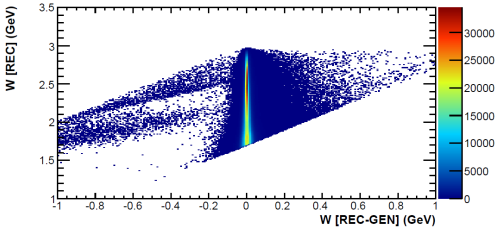
- Cuts on Z vertex difference between the proton and electron, the pion and the electron.

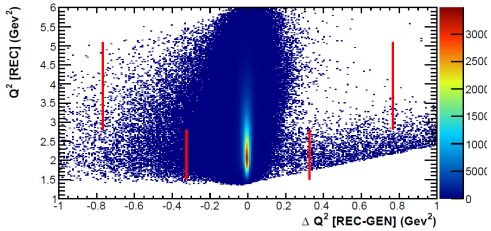
Dalitz plots

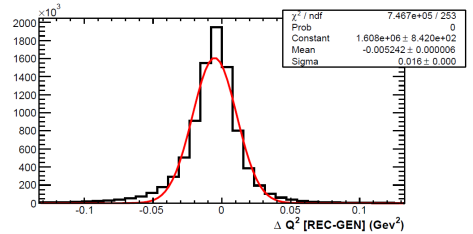


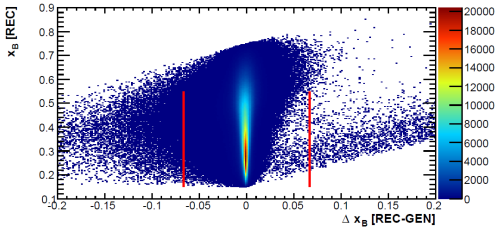


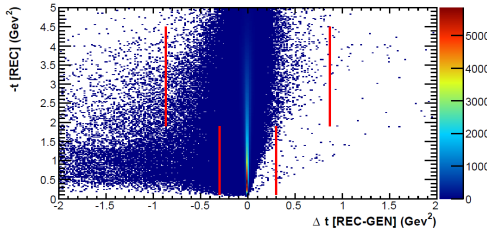
Kinematic resolutions

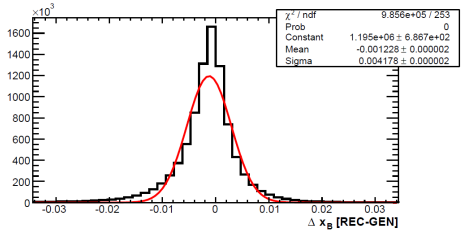


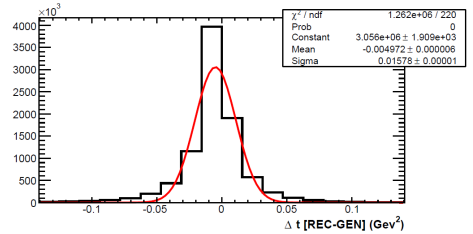


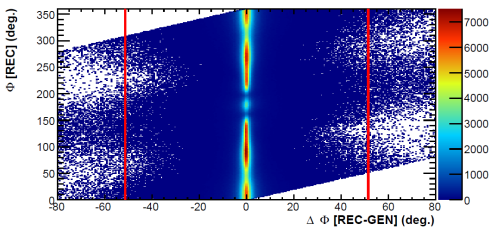


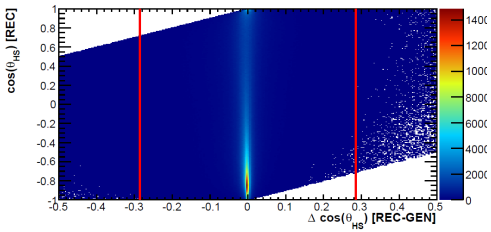


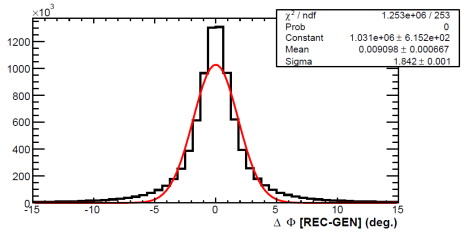


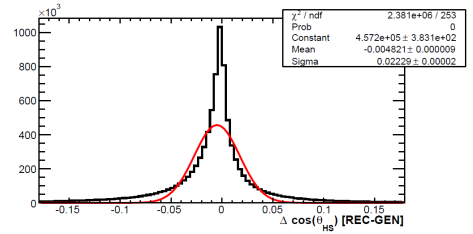


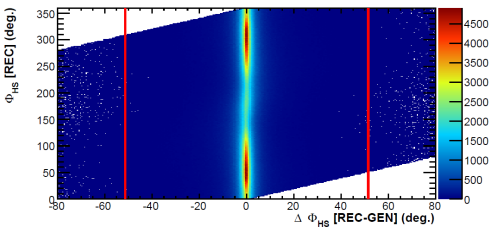


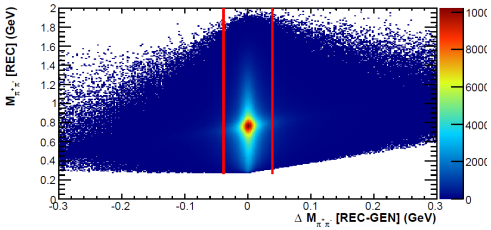


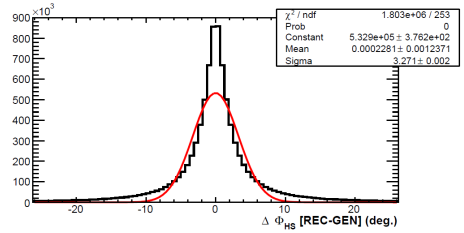


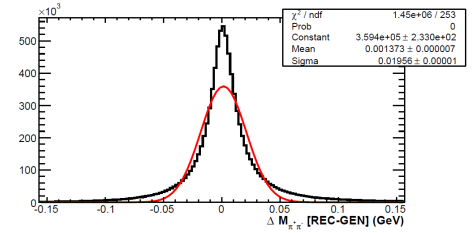






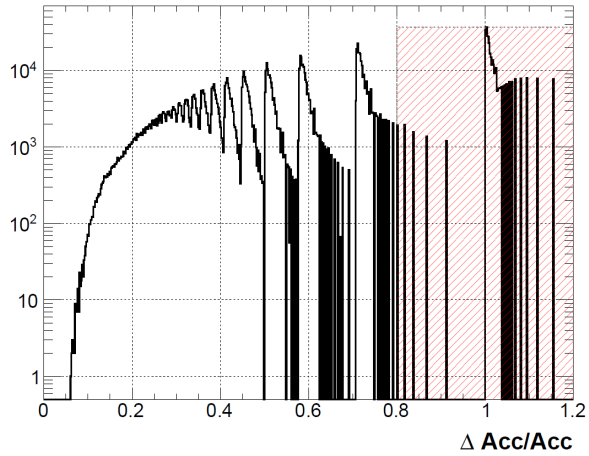






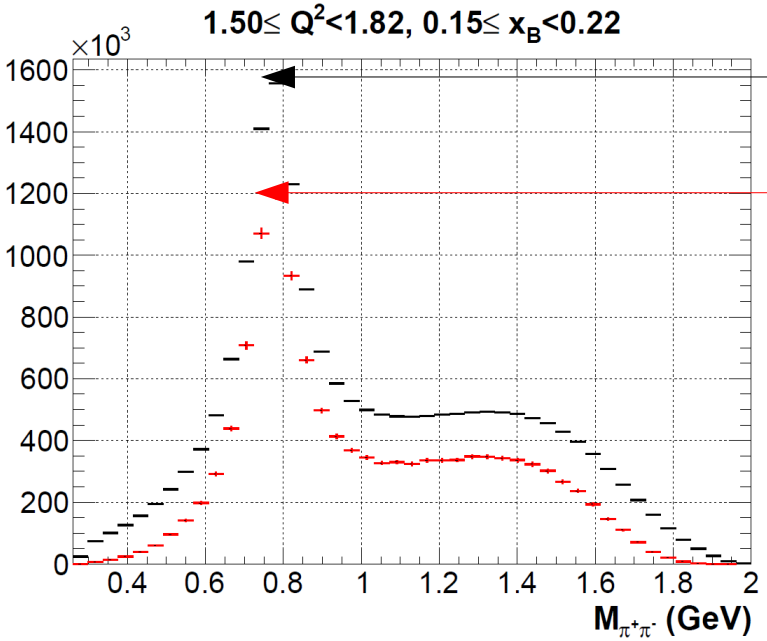
Acceptance correction

- $Acc_{Corr\ Rad}$ computed for each (Q^2, x_B, t, Φ, cos θ_{HS}, Φ_{HS}, $M_{\pi\pi}$) 7D bin and applied as an event-by-event weight.



- 7D bins with large relative error **rejected** :

$$\frac{\Delta Acc}{Acc} < 80\,\%$$



Generated Monte Carlo without radiative effects

Monte Carlo events accepted by CLAS (w/ rad. Effects) , corrected by the 7D acceptance

- 7D acceptance correction on reconstructed MCis not able to retrieve all generated events
  → Hole factor correction $\mathbf{F_h}$

$$F_h(Q^2, x_B, \nu, M_{\pi^+\pi^-}) = \frac{h_{\text{Gen non rad}}(Q^2, x_B, \nu, M_{\pi^+\pi^-})}{h_{\text{Corr Acc 7D}}(Q^2, x_B, \nu, M_{\pi^+\pi^-})}$$

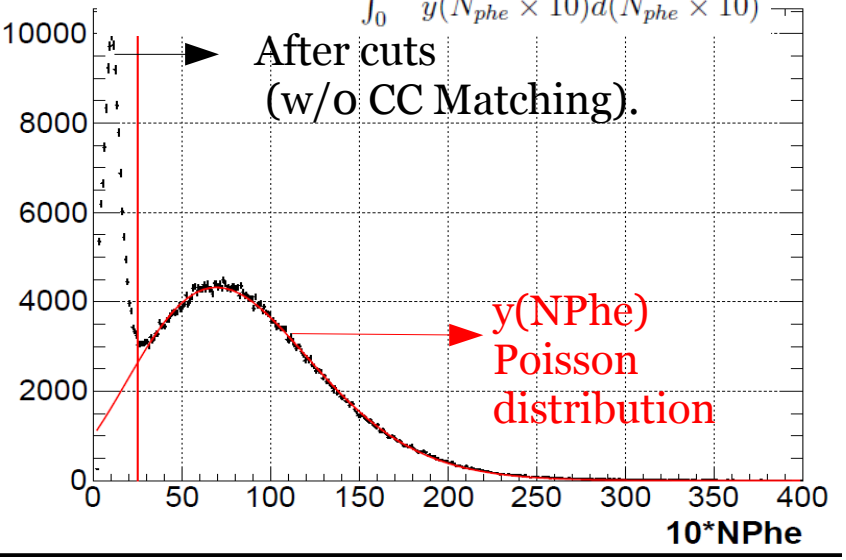
- **(Q^2 , x_B , ν) bins** with a strong hole factor correction are **rejected** :

$$\bar{F}_h(Q^2, x_B, \nu) > 30\,\%$$

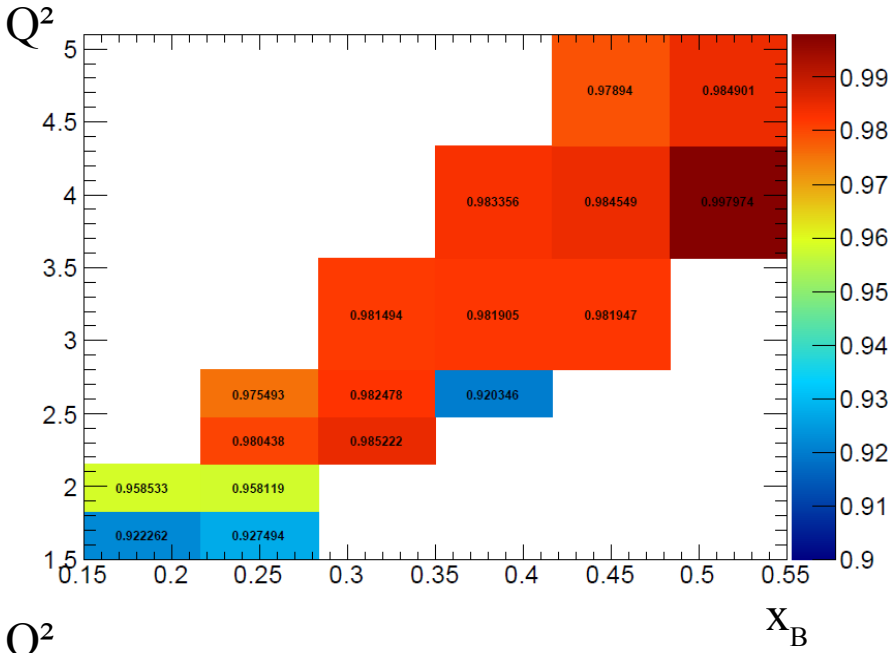
CC_{Eff}

CC selection cuts are applied only to the data
→ Need to estimate the good electrons rejected by these cuts

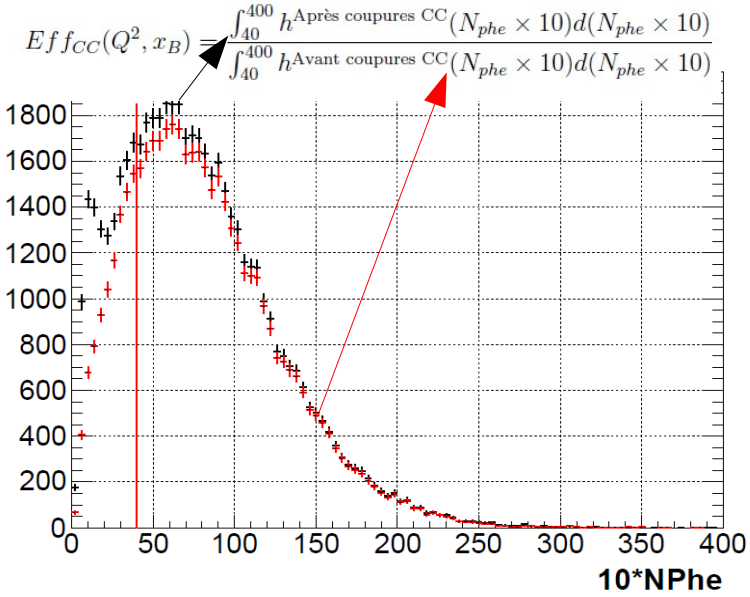
$$Eff_{CC}(Q^2, x_B) = \frac{\int_{25}^{250} y(N_{phe} \times 10) d(N_{phe} \times 10)}{\int_{0}^{250} y(N_{phe} \times 10) d(N_{phe} \times 10)}$$



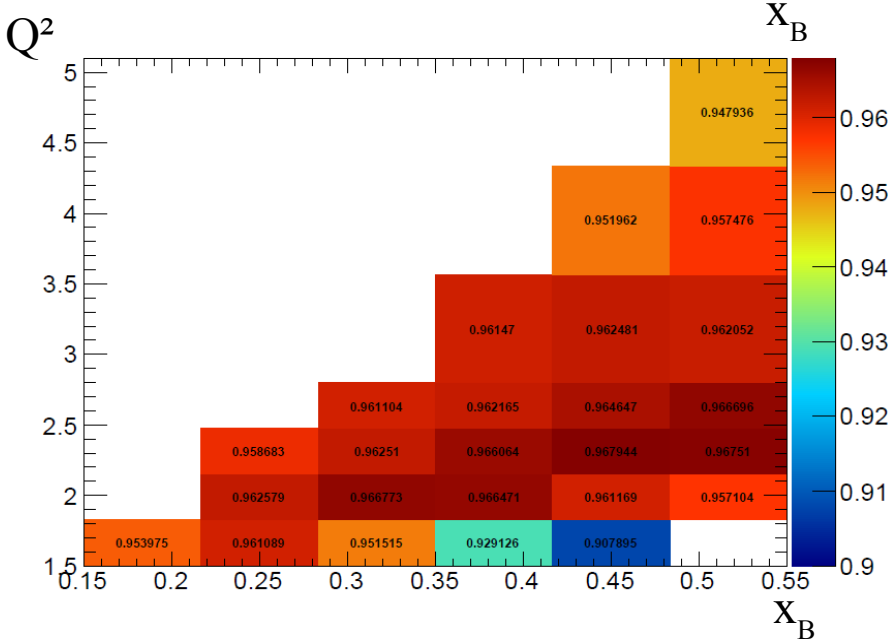
e⁻X
1.82<Q²< 2.15
0.15<x_B< 0.22
p_{e^-}<1.5 GeV/c



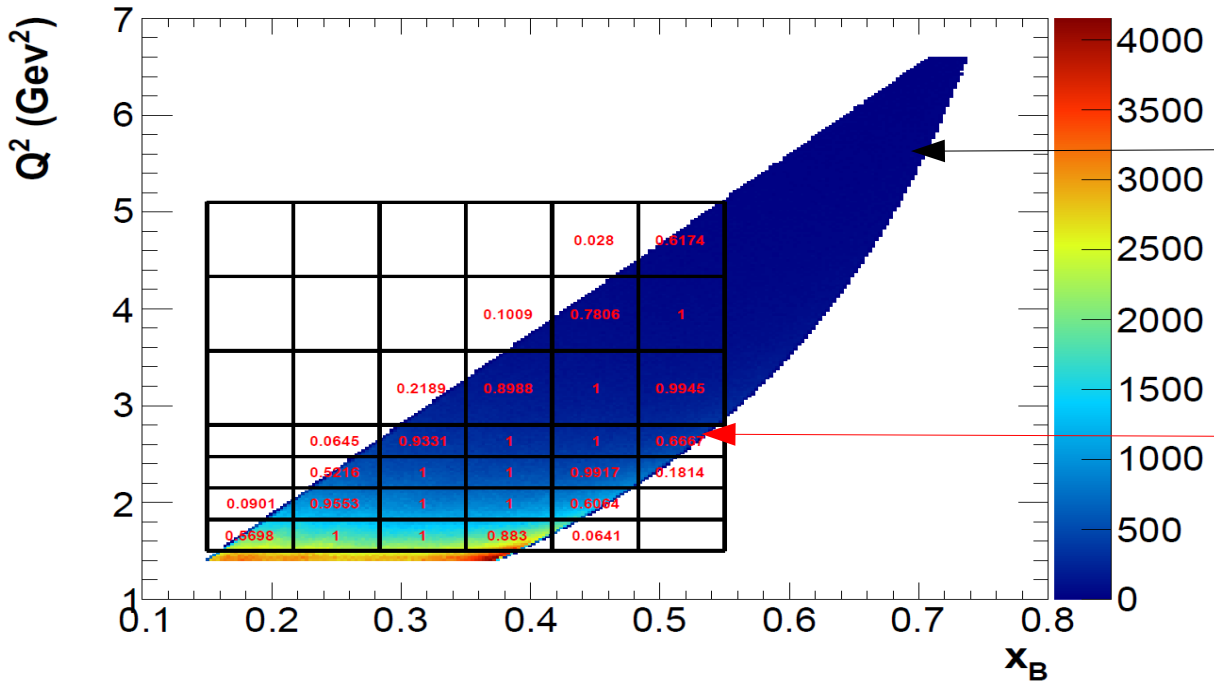
$$Eff_{CC}(Q^2, x_B) = \frac{\int_{40}^{400} h^{\text{Après coupures CC}}(N_{phe} \times 10) d(N_{phe} \times 10)}{\int_{40}^{400} h^{\text{Avant coupures CC}}(N_{phe} \times 10) d(N_{phe} \times 10)}$$



e⁻X
1.82<Q²< 2.15
0.15<x_B< 0.22
p_{e^-}>=1.5 GeV/c



Bin volume correction



Generated phase space MC

Bin volume fraction occupied by the phase space.

- Most (Q^2,x_B) and (Q^2,x_B,t) cells are not fully filled by the phase space.
- Each cell is **subdivided into 100x100 subcells.**
- Bin volume fraction :

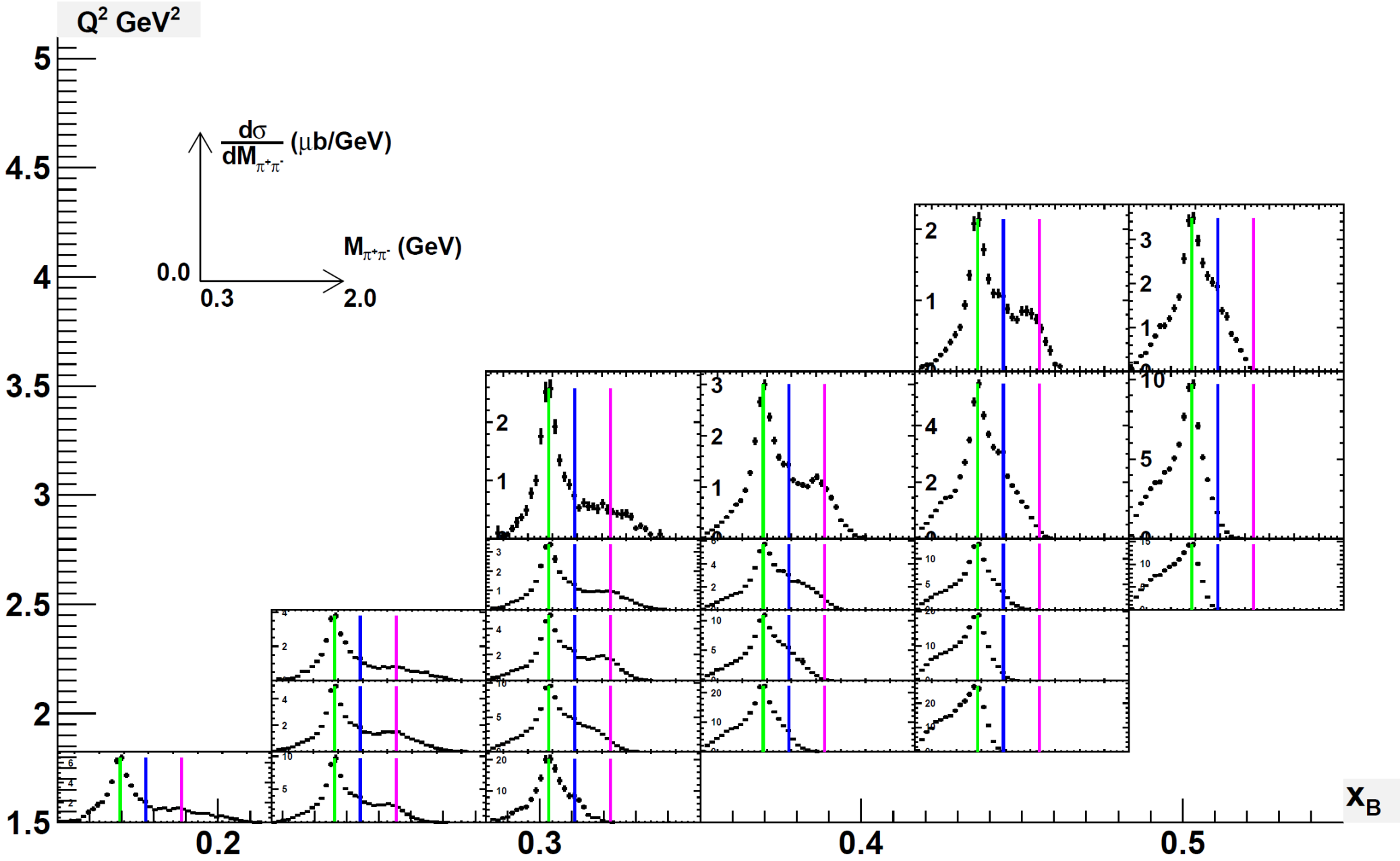
$$F_{\text{Corr Vol}} = \frac{V'}{V}$$

Number of subcells satisfying the cuts :

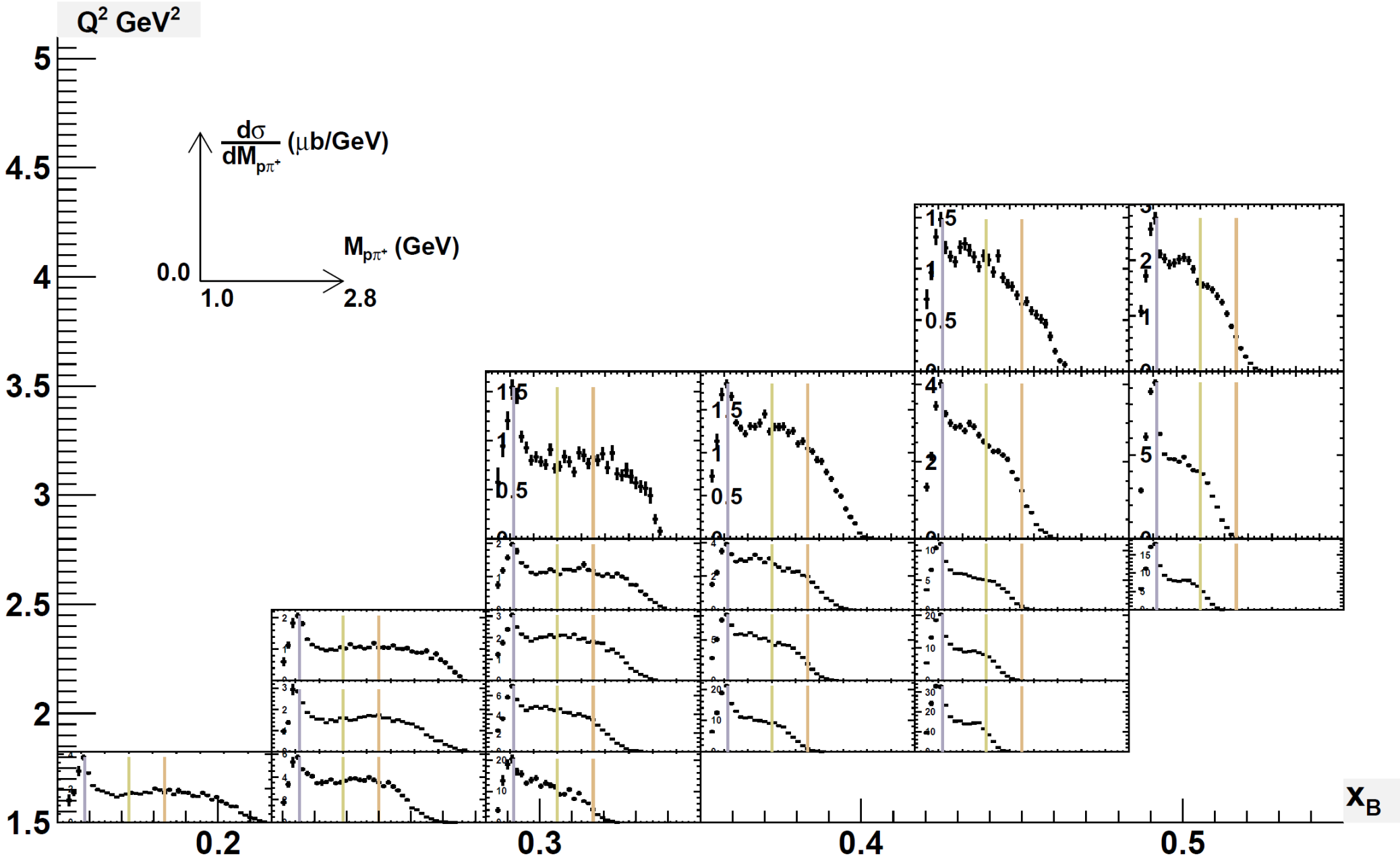
Total number of subcells

$$E_{faisceau} = 5.75\,\text{GeV},$$
$$W > 1.8\,\text{GeV},$$
$$p_{e^-} > 0.8\,\text{GeV/c},\ 10° < \theta_{e^-} < 90°,$$
$$0.1 < \frac{\nu}{E_{faisceau}} < 0.95$$

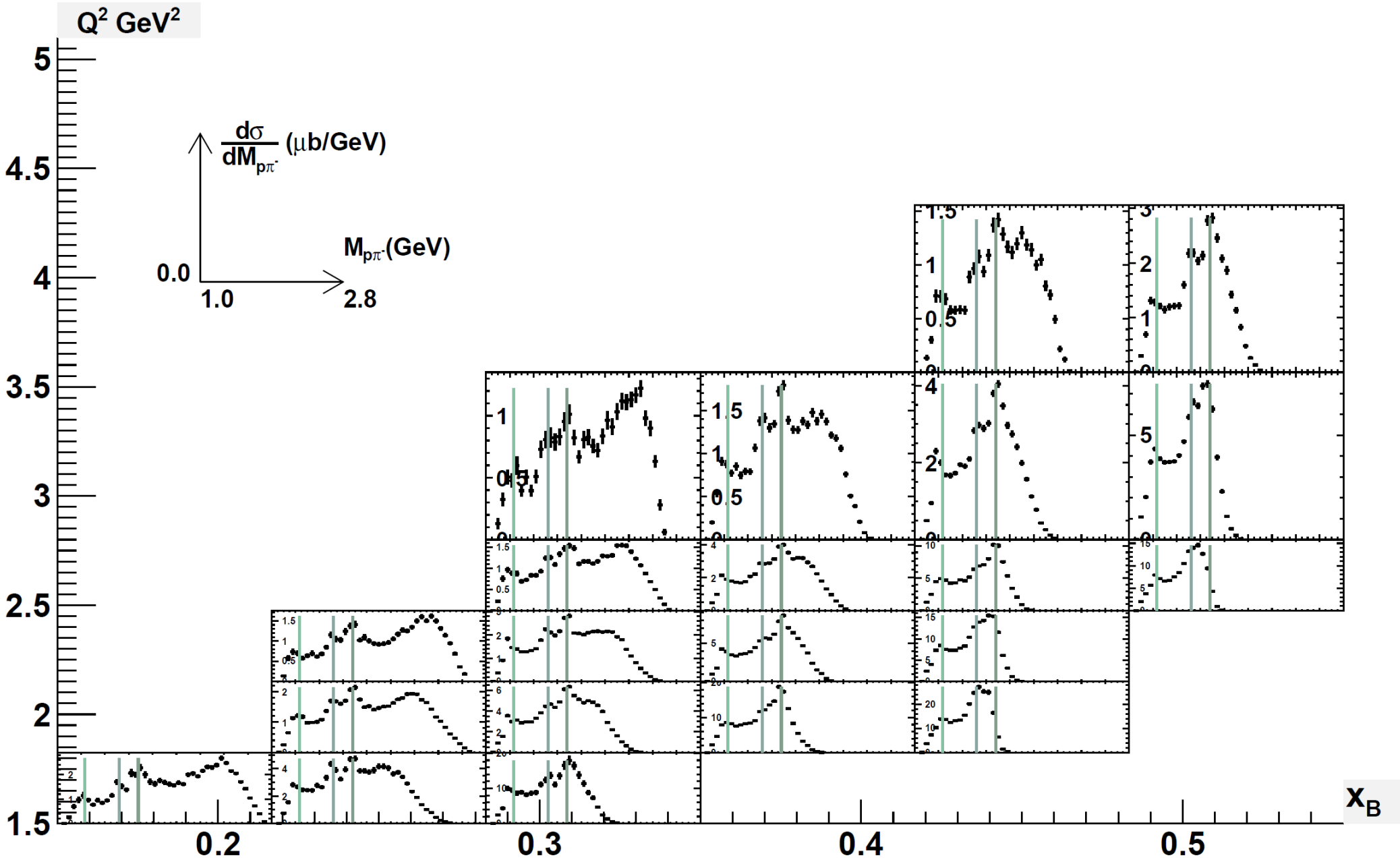
$M_{\pi+\pi-}$ cross sections in (Q^2, x_B)



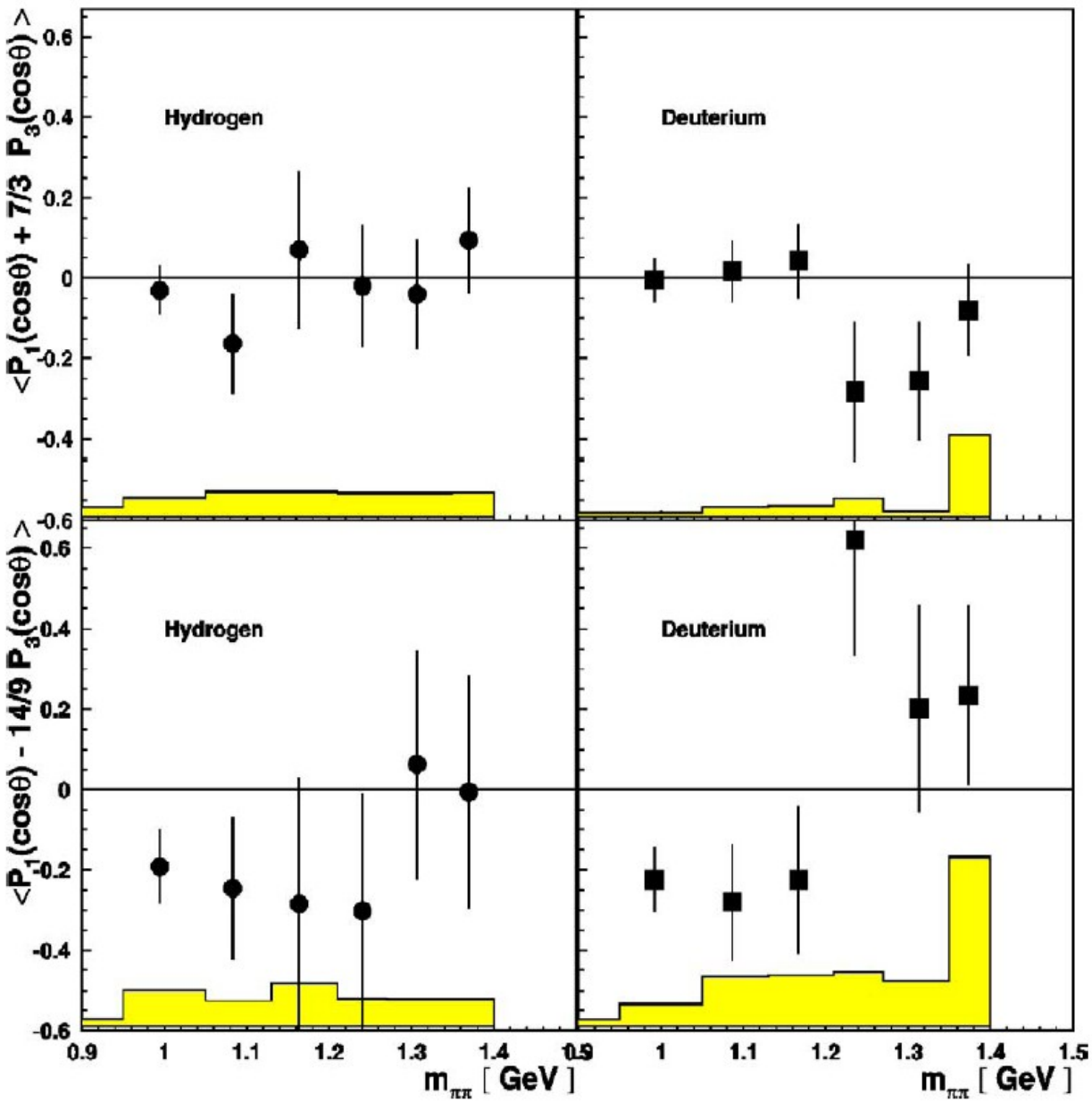
$M_{p\pi+}$ cross sections in (Q^2, x_B)



$M_{p\pi^-}$ cross sections in (Q^2, x_B)



Legendre Moment (HERMES)



Airapetian et al. (Collaboration HERMES)
Phys. Lett. B 599, 212 (2004)

$\langle Q^2 \rangle$ = 3.2 GeV²
$\langle X_B \rangle$ = 0.16
$\langle -t \rangle$ = 0.43 GeV²

→ **Longitudinally polarised photon**

→ **Transversely polarized photon**

Partial Waves Analysis

Parametrization[1]

Pour each $ep\pi^+\pi^-$ event,

$$I(\Theta,\Phi)=\sum_{L=0}^{L_{max}}\sum_{M=-L}^{L} V_{LM}\, Y_{LM}(\Theta,\Phi),\ L_{max}=2,\ |M|\le 1$$

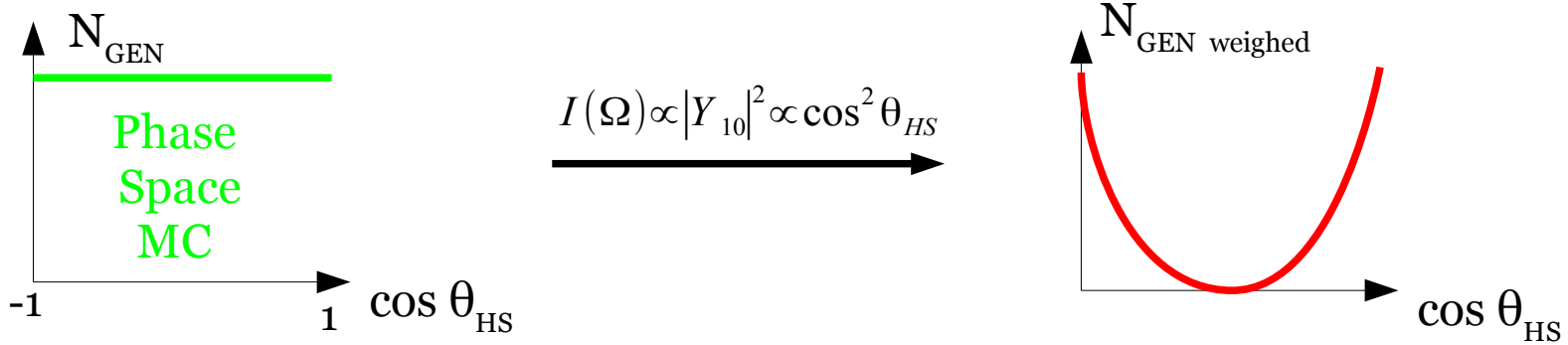
Intensity — **Amplitudes** (free complex parametre) — Spherical Harmonics

Fit of the intensity (AmpTools)[2]

$$\text{Minimisation of } -\ln L=\underbrace{-\left(\sum_{i}^{n}\ln\left(I(\tau_i,\vec{x})\right)\right)}_{\text{Experimental data}}+\underbrace{\frac{1}{N^{GEN}}\sum_{k=1}^{NREC} I(\tau_i)}_{ep\pi^+\pi^- \text{ Monte Carlo accepted by CLAS (Acceptance correction term)}}$$

$$\tau_i=(\theta,\Phi)$$
$$\vec{x}=<Y_{LM}>$$

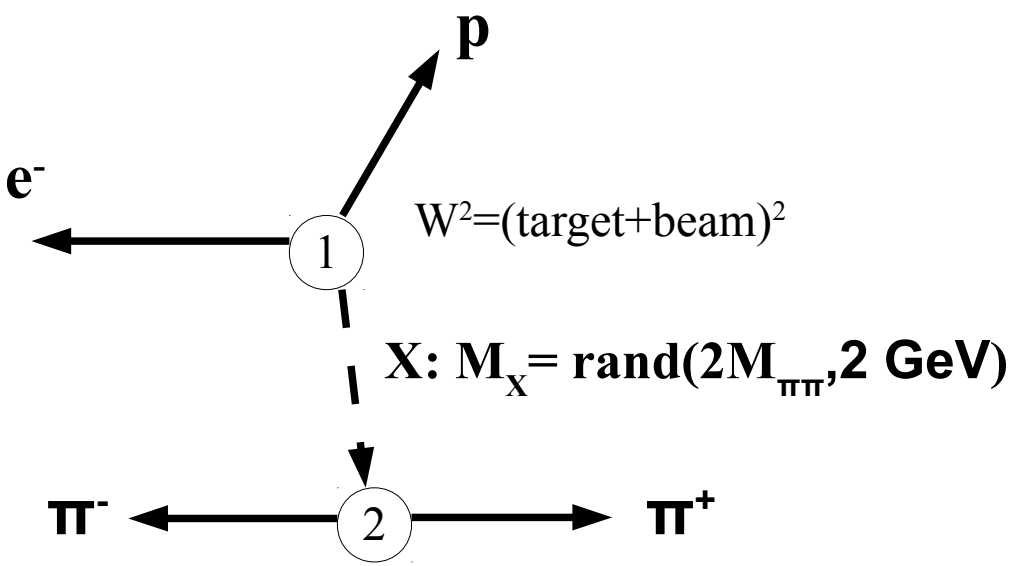
Acceptance corrected angular distribution predicted by the intensity



[1] M. Battaglieri *et al*, Phys.Rev. D80 (2009) 072005

[2] http://sourceforge.net/projects/amptools/

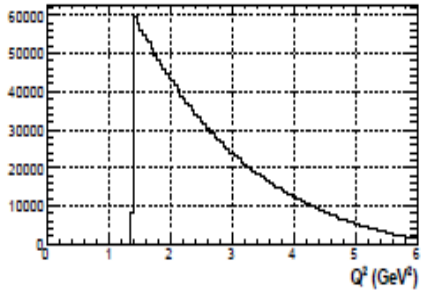
Phase Space MC Generator

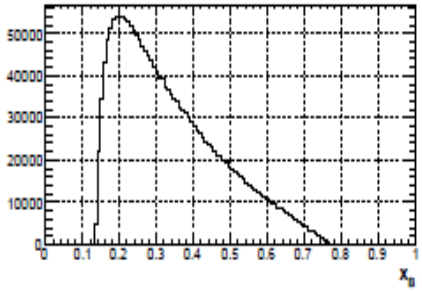


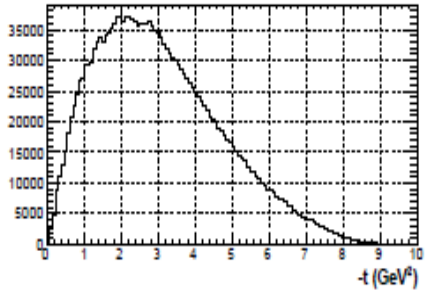
- 3 requirements :
  - Whole phase space covered
  - Uniform decay angular distribution for pion in 2 pion rest frame.
  - Particles generated according to phase space only.

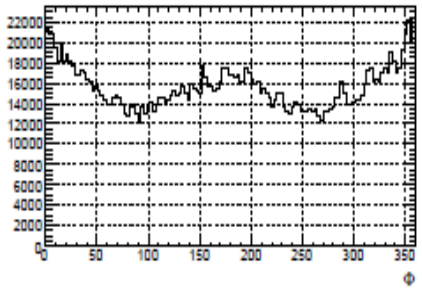
  (Genbod routine).

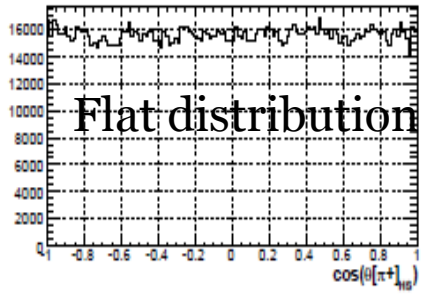
$Q^2>1.4GeV^2$
$W>1.7GeV$

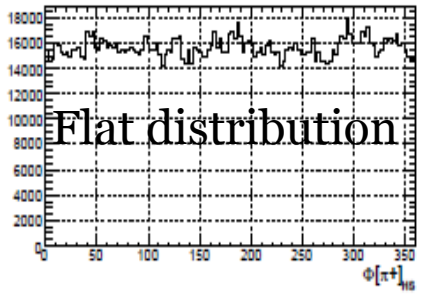


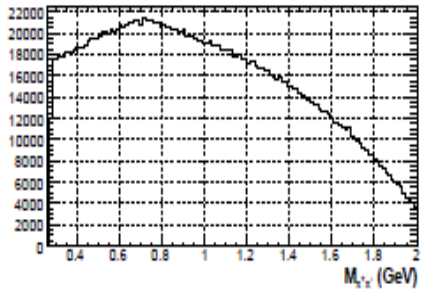




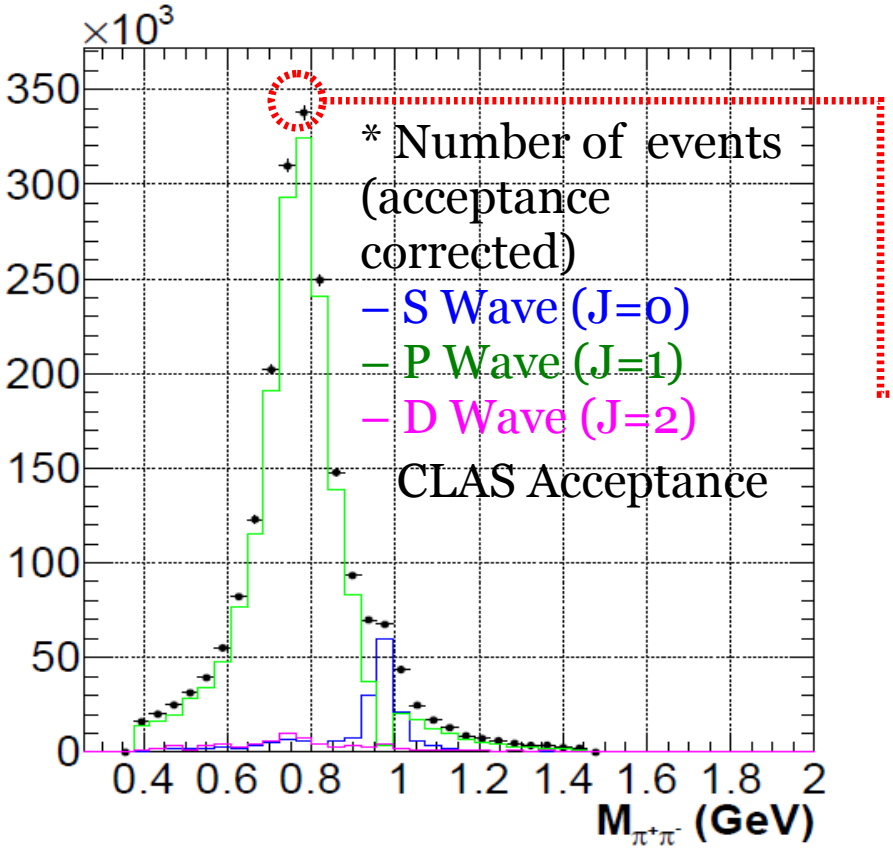


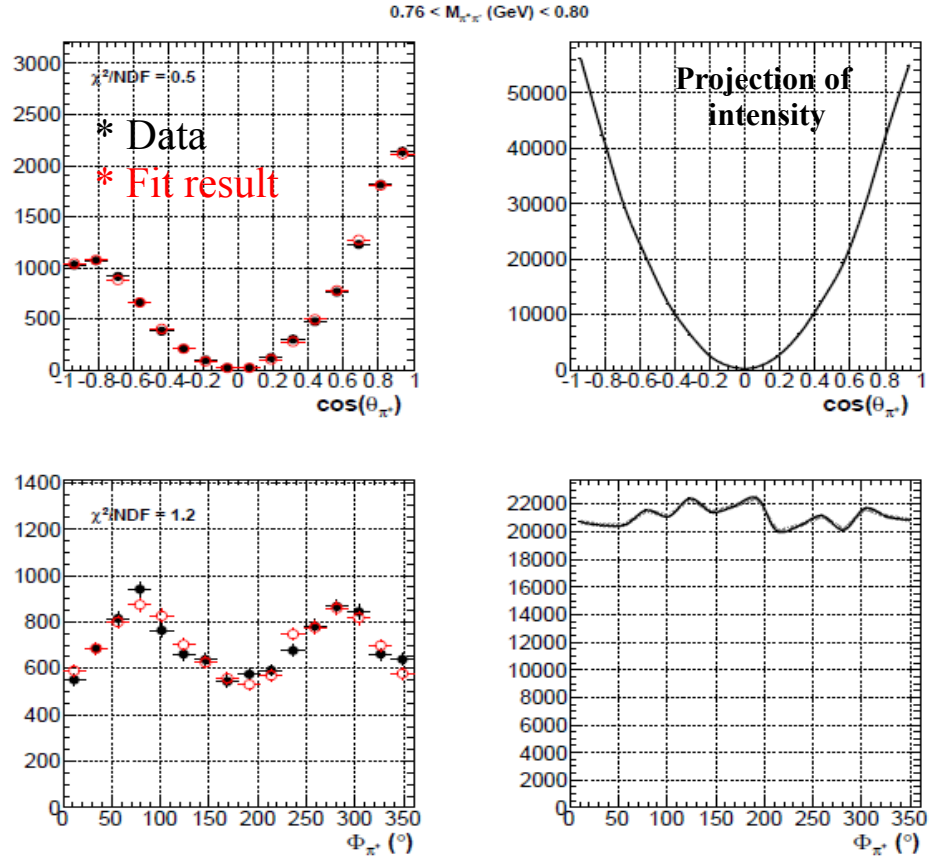






PWA on pseudo-data



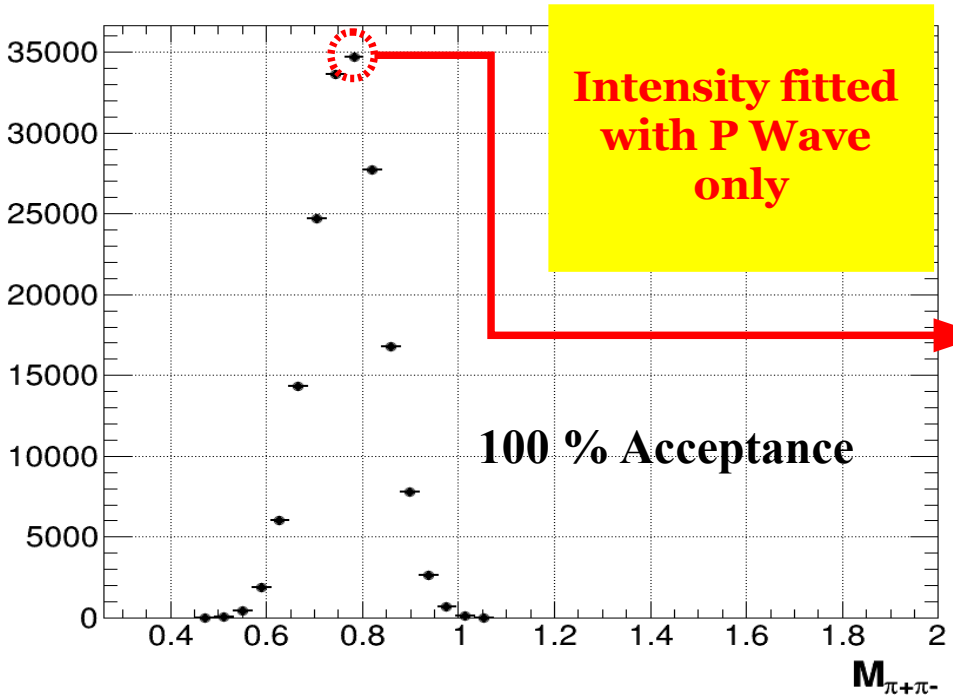


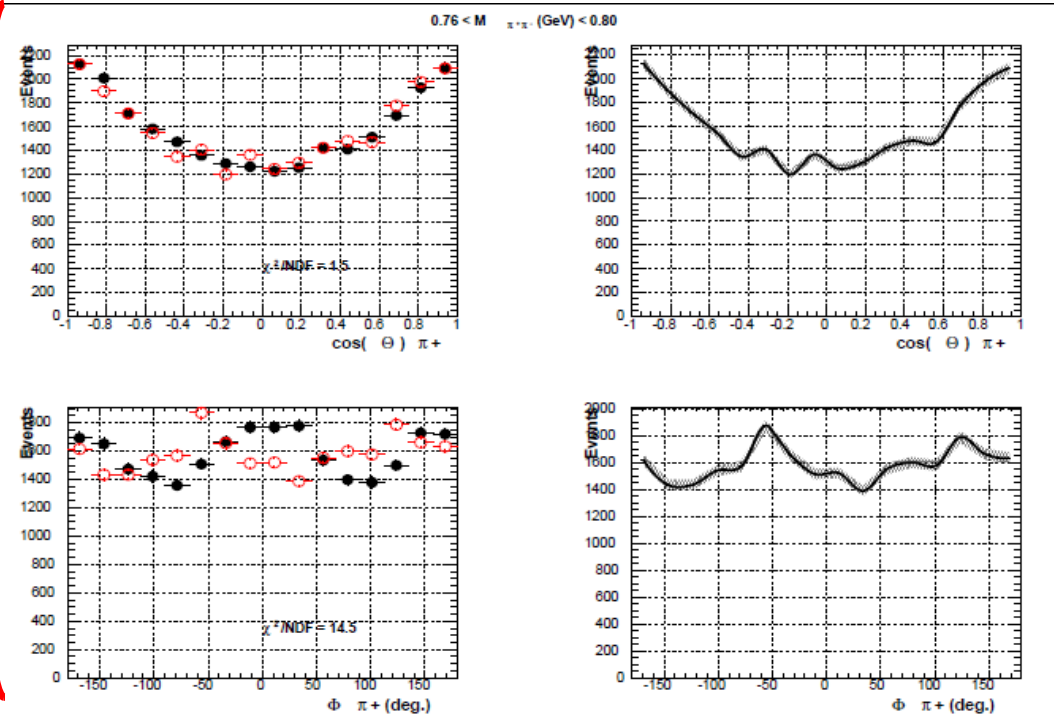
- 85K pseudo-data events extracted from accepted phase space MC with the following intensity :

$$I(\theta_{HS}, \phi_{HS}, M_{\pi^+\pi^-}) = |BW_{\rho^0}(M_{\pi^+\pi^-}).V_{10}Y_{10}(\theta_{HS}, \phi_{HS}) + BW_{f_0}(M_{\pi^+\pi^-}).V_{00}Y_{00}(\theta_{HS}, \phi_{HS}))|^2$$

ρ(770) Breit Wigner Amplitude — 85 — f_0 Breit Wigner Amplitude Γ=70 MeV — 15

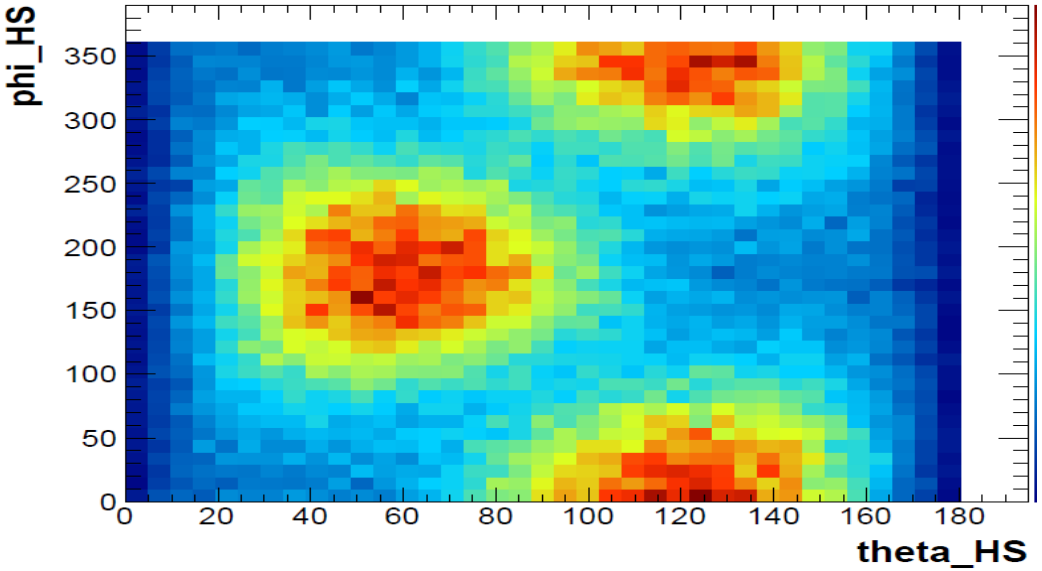
- Good agreement between the fit and the data.
- Fit returns the right contributions of S and P Wave.
- PWA fit procedure in CLAS allows to separate S and P Wave in a simple case.

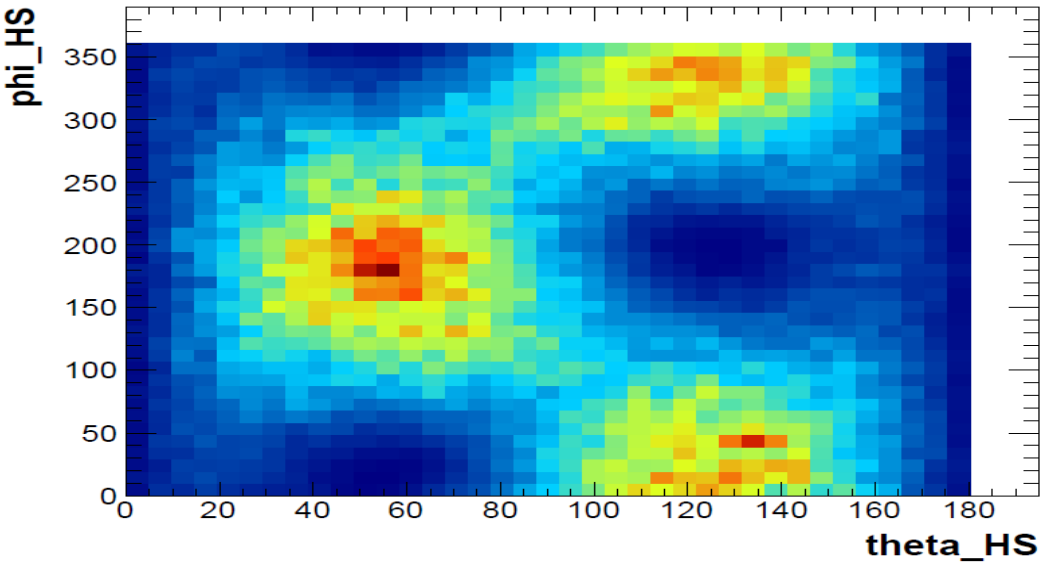




Genev ρ pseudo-data (full mass range)

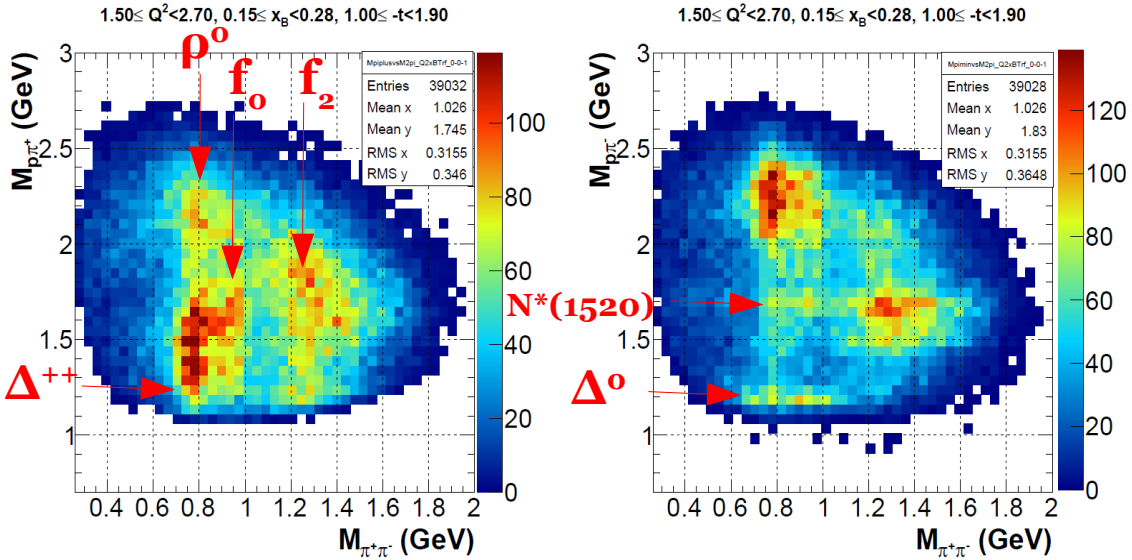
Phase space weighed by the fitted intensity



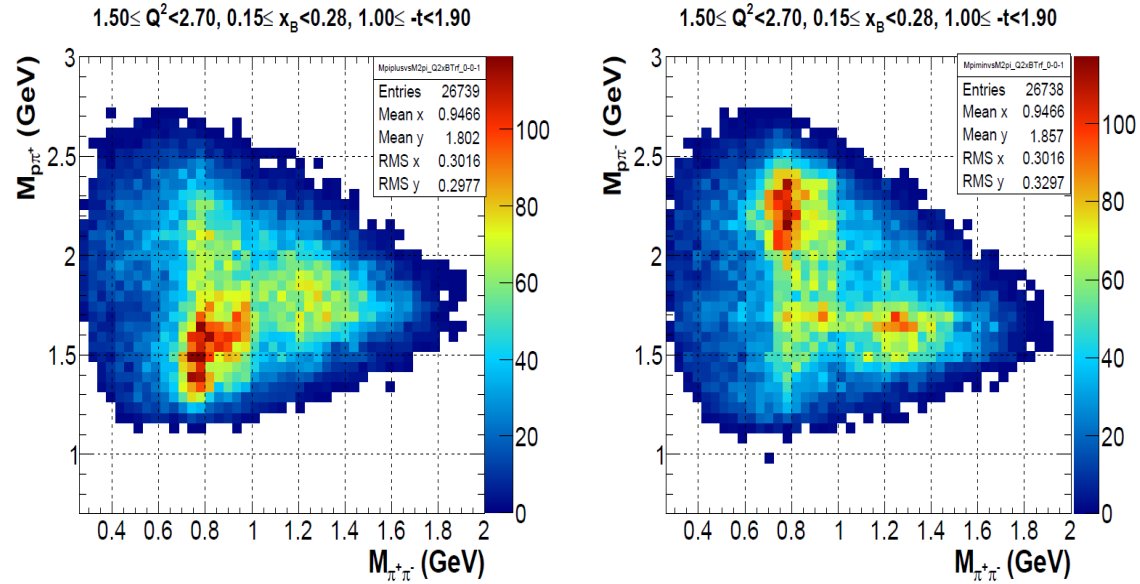


Baryon suppression

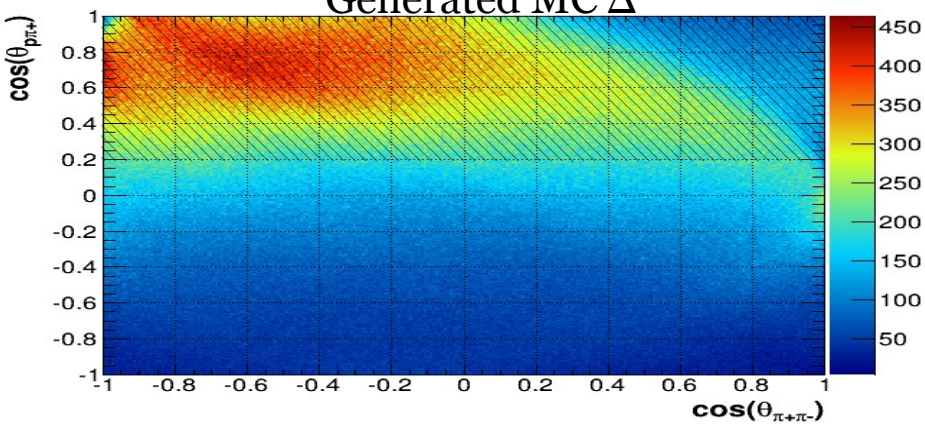
Before cuts



After cuts



Generated MC Δ^{++}

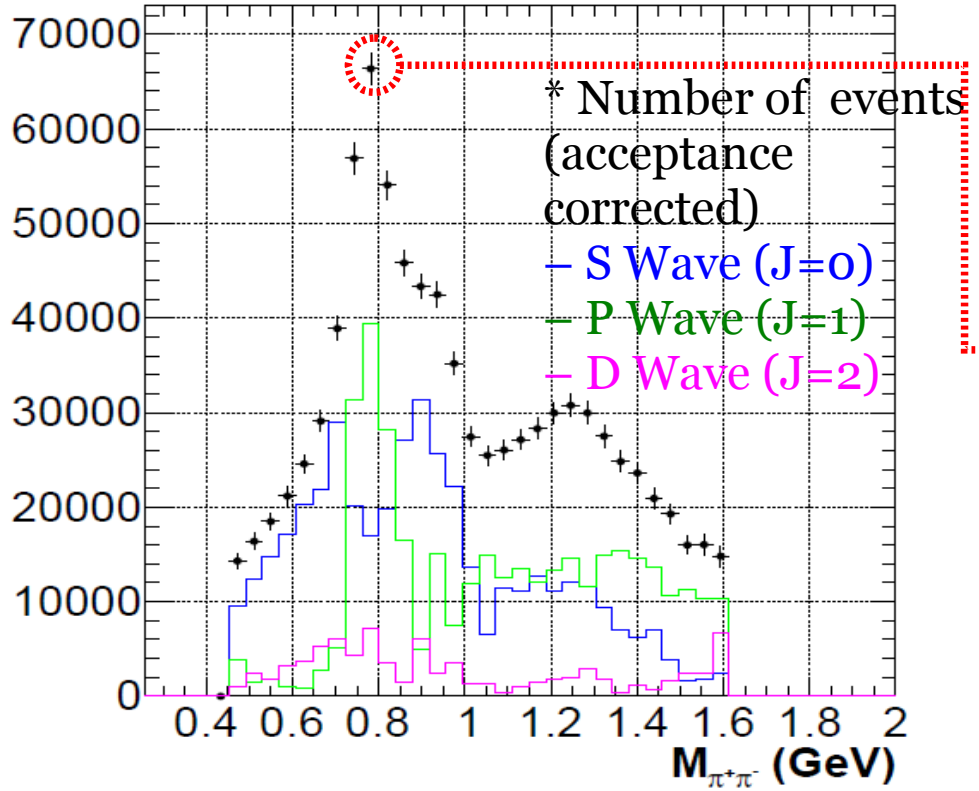


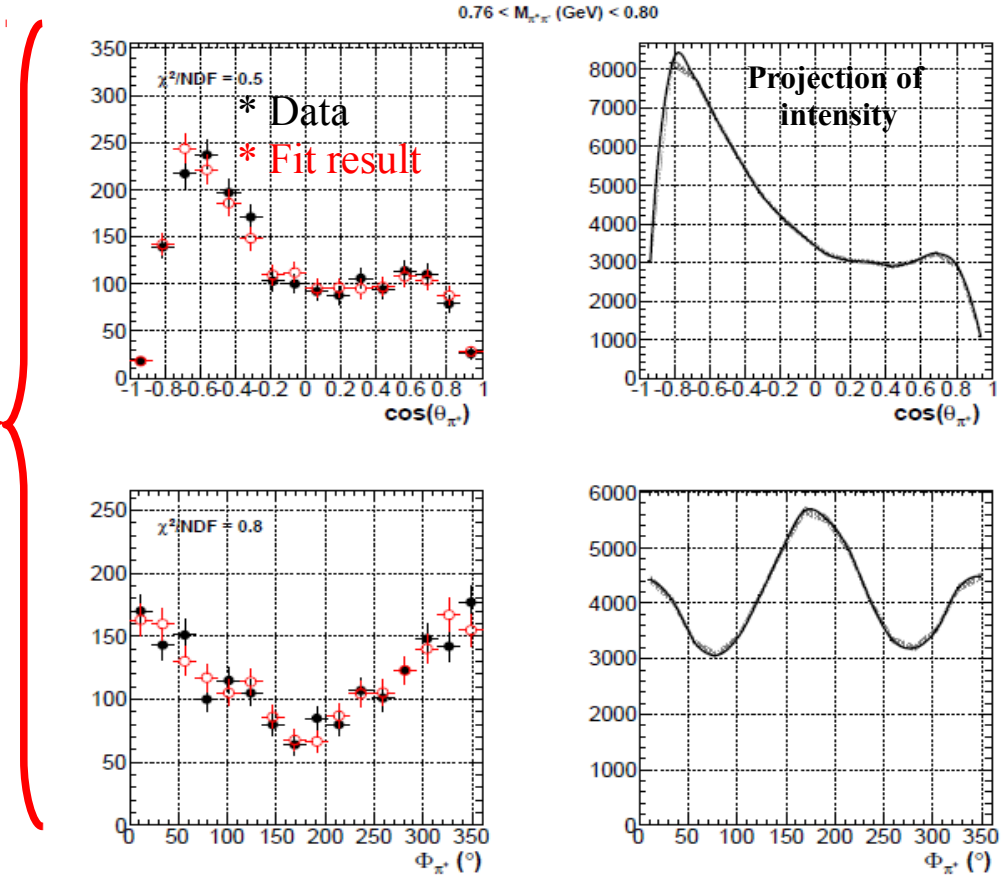
- The π^+ from $ep \rightarrow e\pi N^* \rightarrow ep\pi\pi$ projects onto an infinite set of spherical harmonics.

→ Kinematical cut to remove baryonic resonances

- In a first approximation, proton and π from baryon are collinear ($\cos(\theta_{\text{proton-}\pi})=1$), while $\pi\pi$ from meson are collinear.
  $\cos(\theta[\text{proton-}\pi+])>0.2$
  $\cos(\theta[\text{proton-}\pi-])>0.2$
- **Slight reduction of Δ^{o} and Δ^{++} in the kinematical range considered**

PWA : results



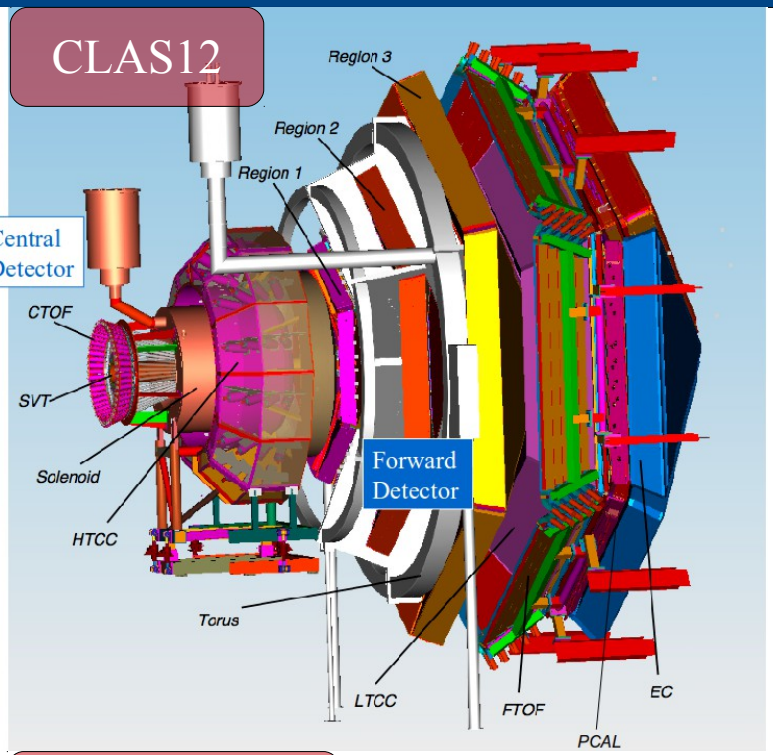


- **Good agreement between 1D angular distribution from the fit and from the data**
- **Unsatisfying results** :

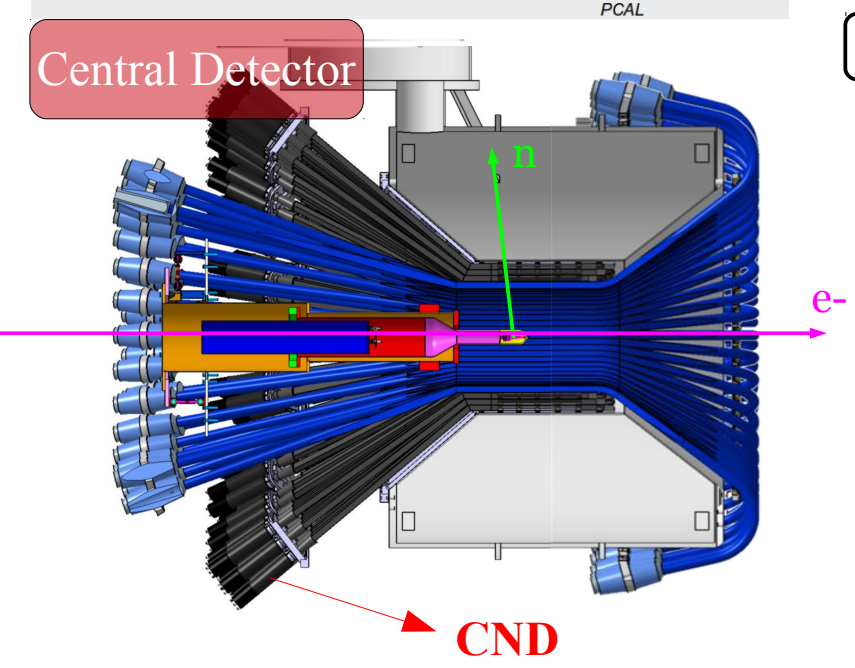
  Not able to establish f_2 resonance in D-Wave.

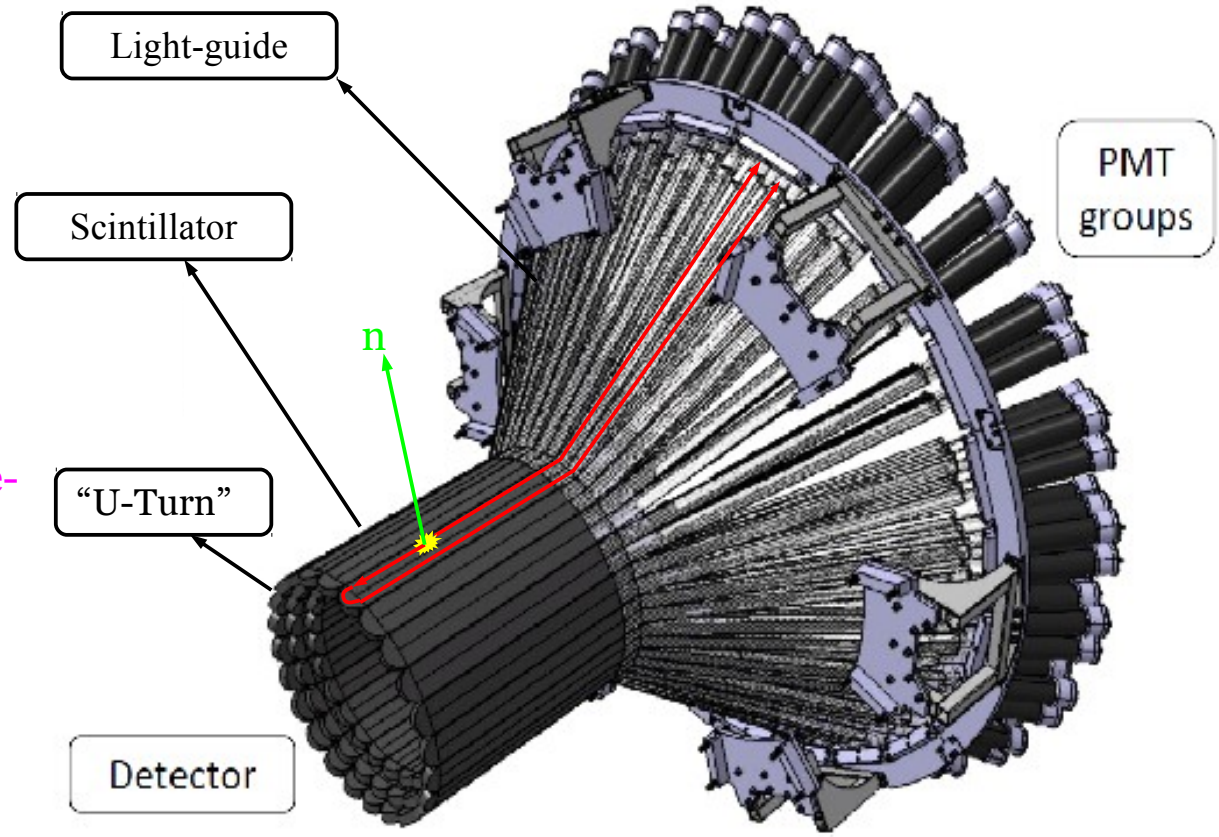
  Peak does appear in ρ (f_0) region in the P (S) wave, but does not have the proper resonance characteristics (mass, FWHM).
- Use of parity conserved amplitude basis may help ?

The Central Neutron Detector (CLAS12)

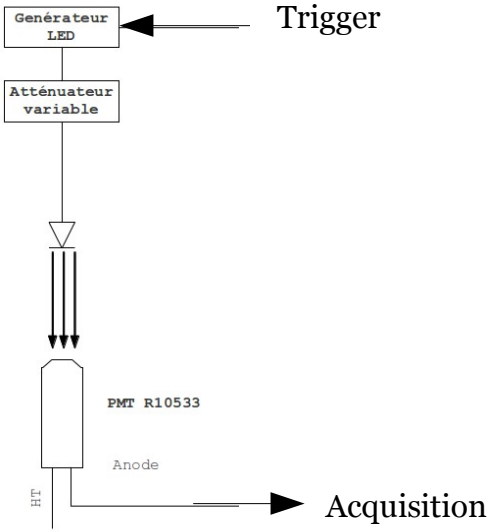


40°<θ<120°
3 radial layers
48 azimuthal segments
Read-out : 144 Hamamatsu R10533 PMTs
Time resolution ~ 130 ps (n/γ separation for $0.2<p_N<1$ GeV/c)





PMT calibration



$$G = \frac{I_k}{I_a}$$

Gain ← G ; I_k → Current of photoelectrons produced at the photocathode

I_a → Anode current

- Gain measured from photoelectron emission spectrum:

$$G(V) = \frac{(\text{peak} - \text{ped}) \cdot \text{charge/ADC channel}}{G_{preamp} \cdot e \cdot N_{phe}}$$

$G(V)$ → Voltage

e → 1.6×10^{-19} C

N_{phe} → Nb. of emitted photoelectron at photocathode

- 144 PMTs calibrated.