CNUGS Summer School

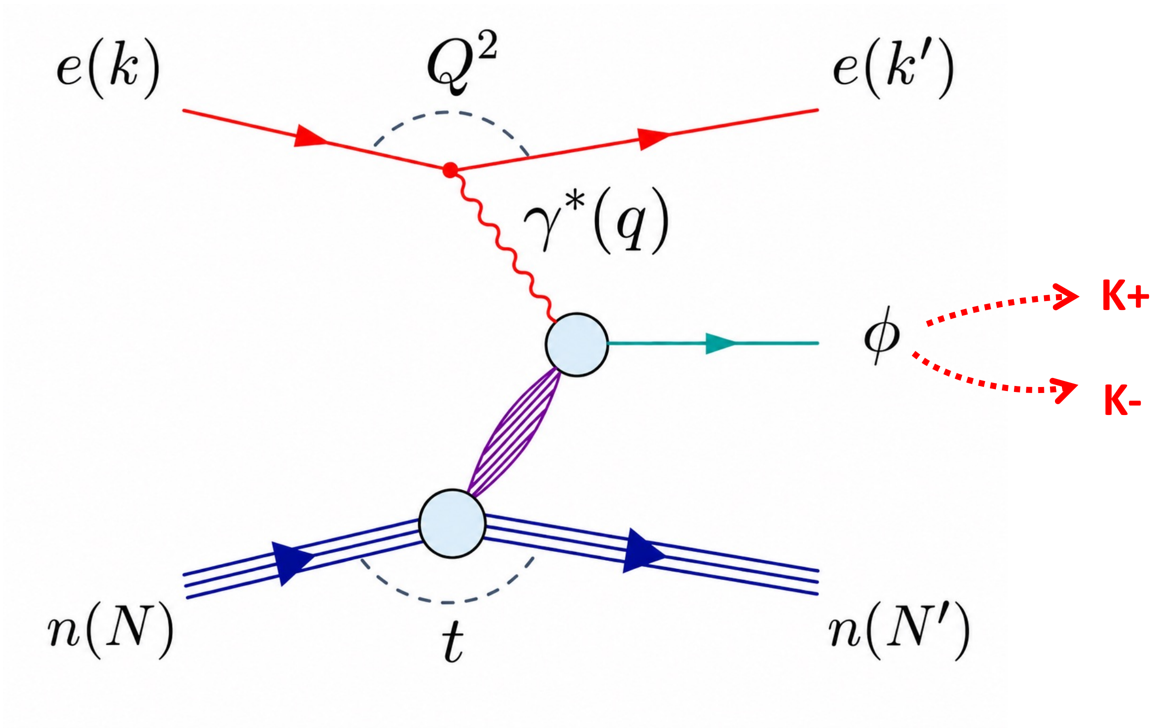
ϕ electroproduction on the neutron with CLAS12

10 June 2026

M. Ronayette, P. Chatagnon

1. Introduction and motivations
2. CLAS12 experiment
3. Extraction of the number of events
4. Generator for Monte Carlo simulations
5. Acceptance correction
6. Proton contamination
7. Preleminary results on the differential cross section

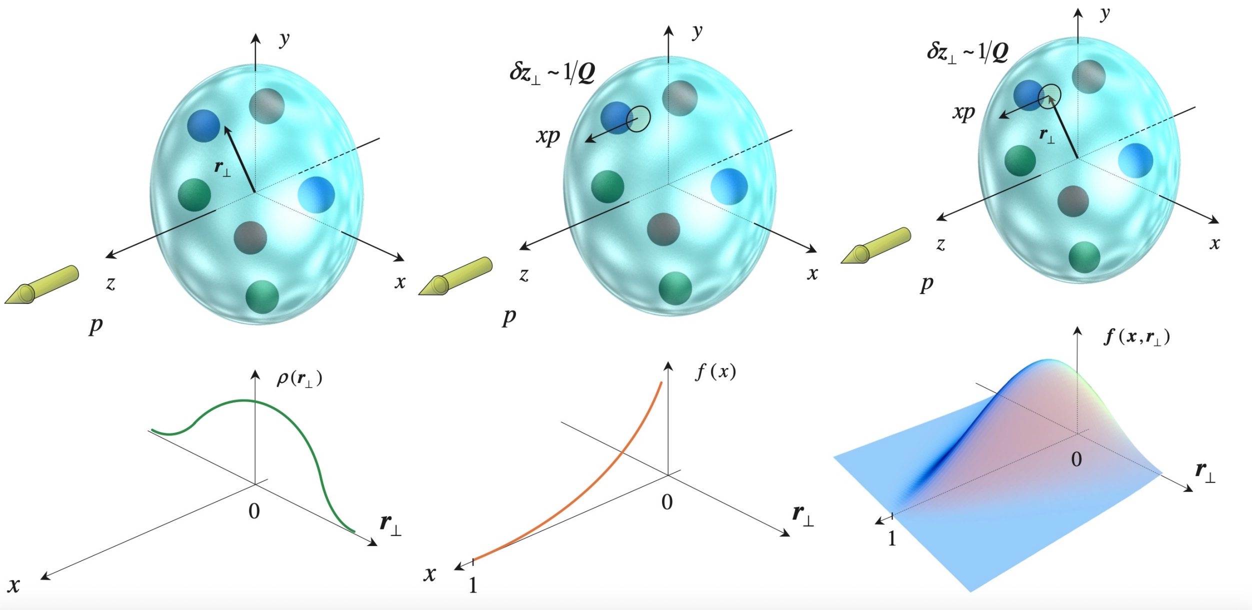
Introduction and motivations



Analysis objective :

Measurement of the **cross section** of the **ϕ electroproduction** on **neutron** in the **$K^+ K^-$** channel with **deuterium** target.

Introduction and motivations



The interpretation of GPDs as a tomography of the nucleon

Figure from A.V. Belitsky and A. V. Radyushkin. Unraveling hadron structure with GPDs.

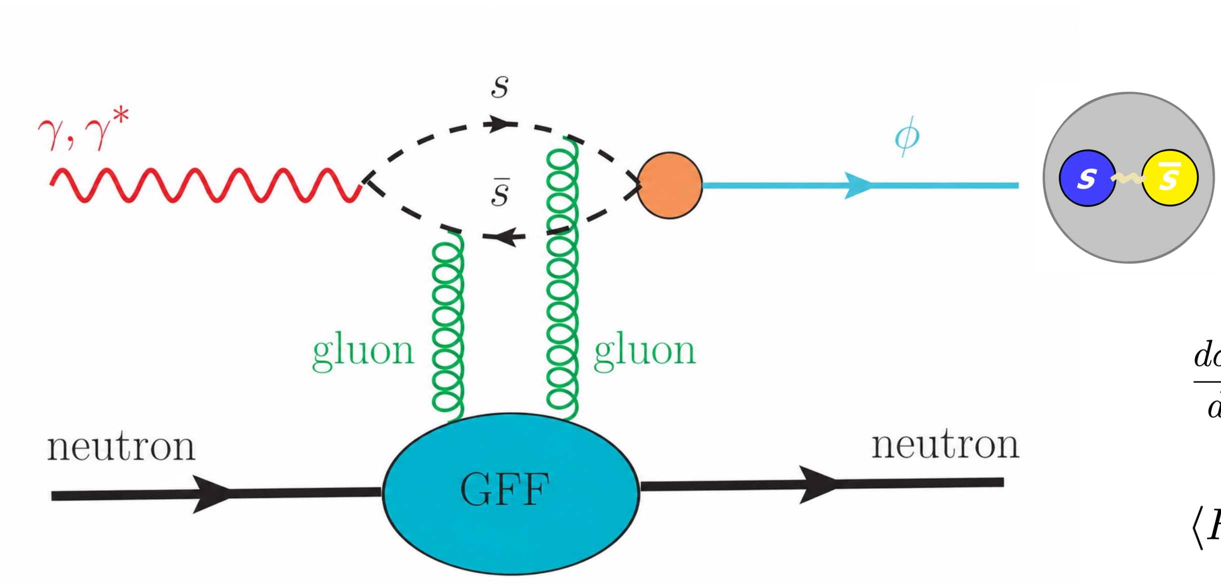
Density of gluons carrying momentum fraction x :

$$H_g(x, \xi = 0, t = 0) \quad = \quad xg(x)$$

Spatial profile of the distribution of gluons at given x :

$$xg(x, b) \ \equiv \ \int \frac{d^2\Delta_T}{(2\pi)^2} \, e^{i\boldsymbol{\Delta}_T \boldsymbol{b}} \, H_g(x, \xi = 0, t = -\boldsymbol{\Delta}_T^2)$$

Introduction and motivations



$$\frac{d\sigma_L}{dt} = \frac{\alpha_{\text{em}}}{Q^2}\frac{x_B^2}{1-x_B}\left[(1-\xi^2)|\langle H_g\rangle|^2 + \text{terms in } \langle E_g\rangle\right]$$

$$\langle H_g\rangle \equiv \frac{3\pi f_\phi}{27}\int_{-1}^{1} dx\ H_g(x,\xi;t)\ K(x,\xi,Q^2)$$

⟶ Since the contribution of the sea of quark-antiquark pairs inside the neutron is negligible, gluons play a major role in the creation of the s s̄ pair.

⟶ Extracting the ϕ electroproduction cross section makes it possible to probe the gluon content of the neutron (integrals of GPDs).

CLAS12 Experiment

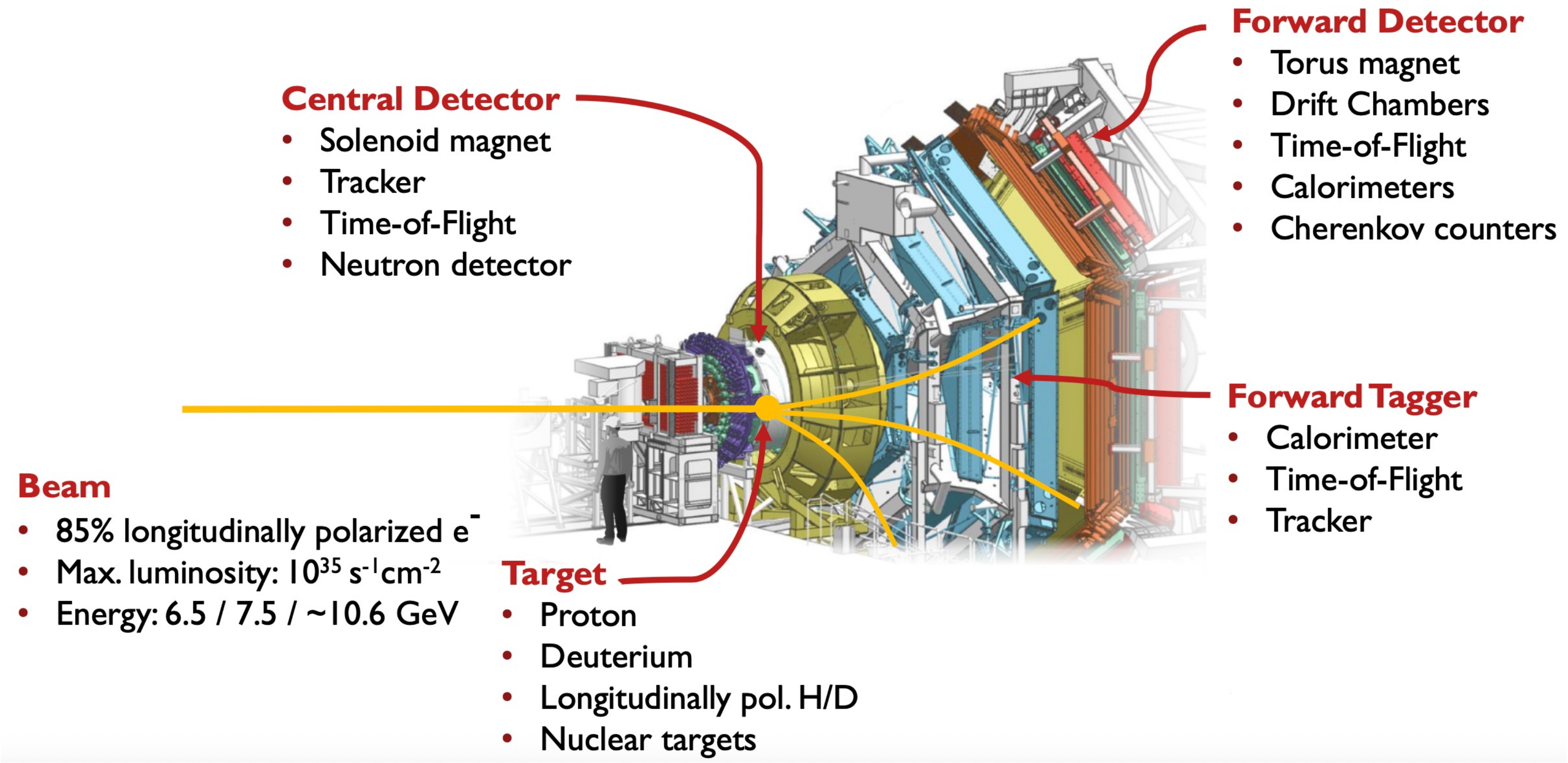
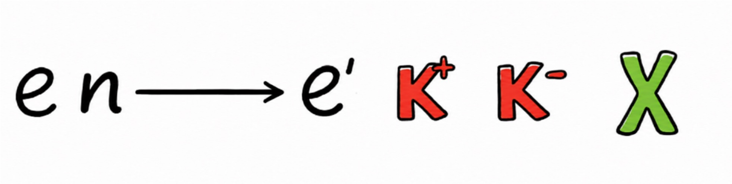
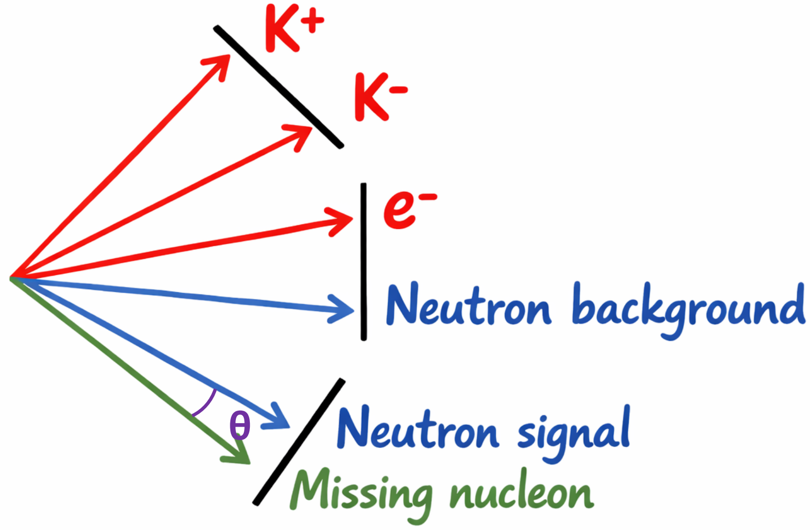


Figure from P. Chatagnon – Probing the proton fundamental properties with exclusive reactions at Jefferson Lab

Extraction of the number of event



- Select the best neutron wich minimize the angle between the missing nucleon and the neutron and verify that the angle θ between both is less than 5 °.
- Also we need **0 proton** detected to reduce contamination.



Additional cuts :

$Q^2 > 1.0\ GeV^2$	$P_{electron} > 2\ GeV$	$\theta_{neutron} > 4\ °$	$P_{neutron} > 0.25\ GeV$	$-0.5 < Miss_{tot}^2 < 0.5\ GeV^2$

Extraction of the number of event

Fit performed using RooFit.

Signal model :

The signal is described by a Gaussian function :

$$S(M_{inv}) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left(-\frac{(M_{inv}-\mu)^2}{2\sigma^2}\right)$$

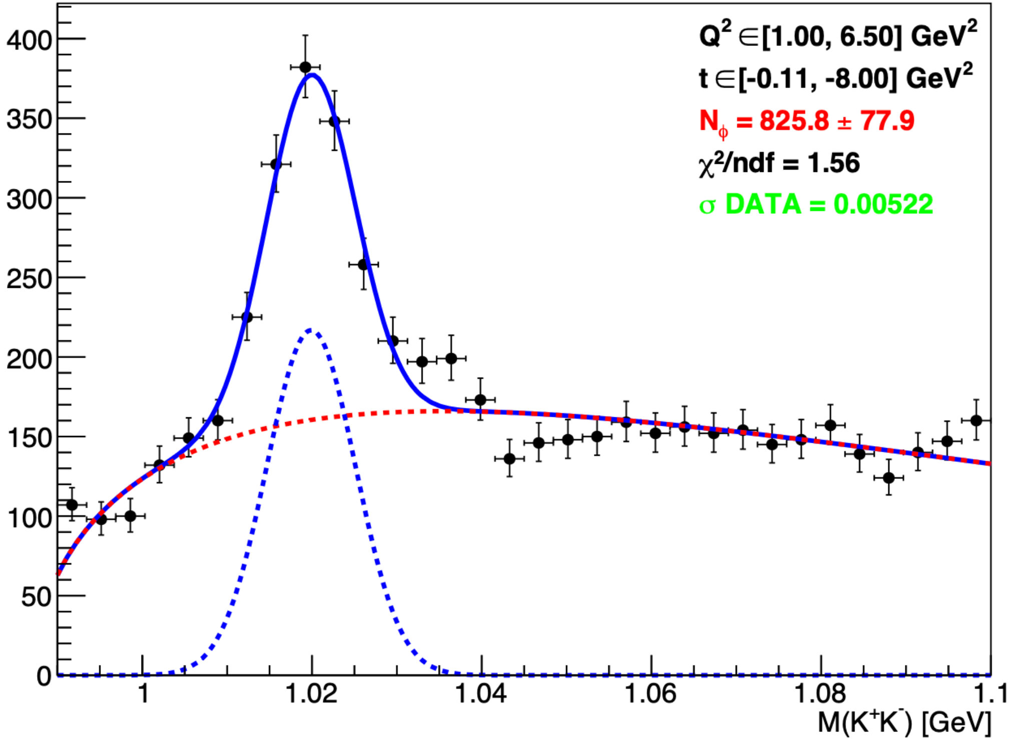
Background model :

The background is modeled using a threshold function multiplied by an exponential polynomial :

$$B(M_{inv}) = \sqrt{M_{inv}^2 - 4m_K^2}\ \exp\left(a_0 M_{inv} + a_1 M_{inv}^2\right)$$

where :

- m_K is the kaon mass,
- a_0 and a_1 are free parameters of the fit.

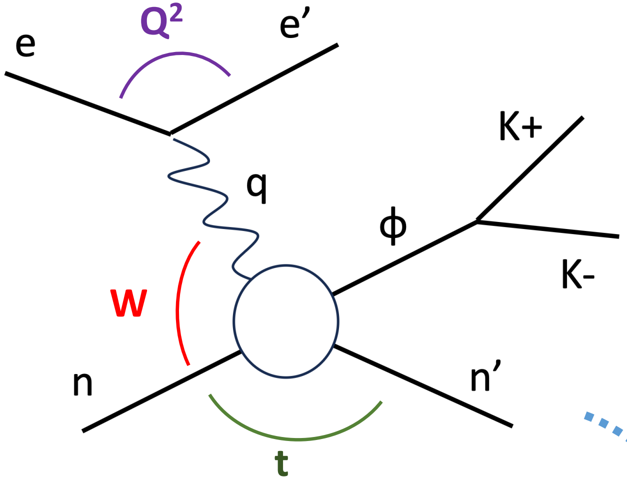


Fall2019 outbending

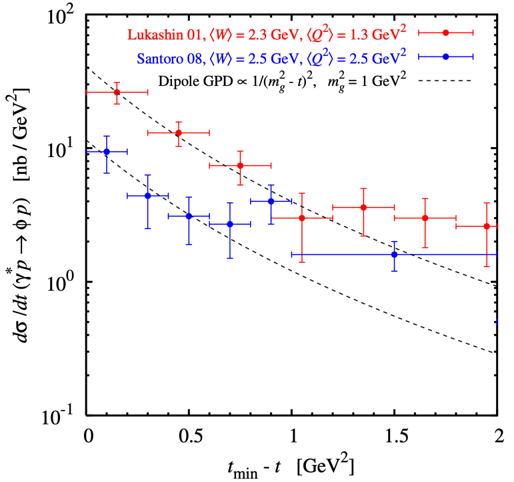
Q = 12.1 mC

Generator for MC simulation

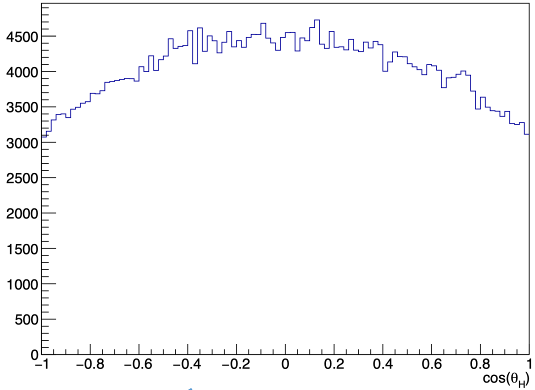
1) kinematics



2) Cross section

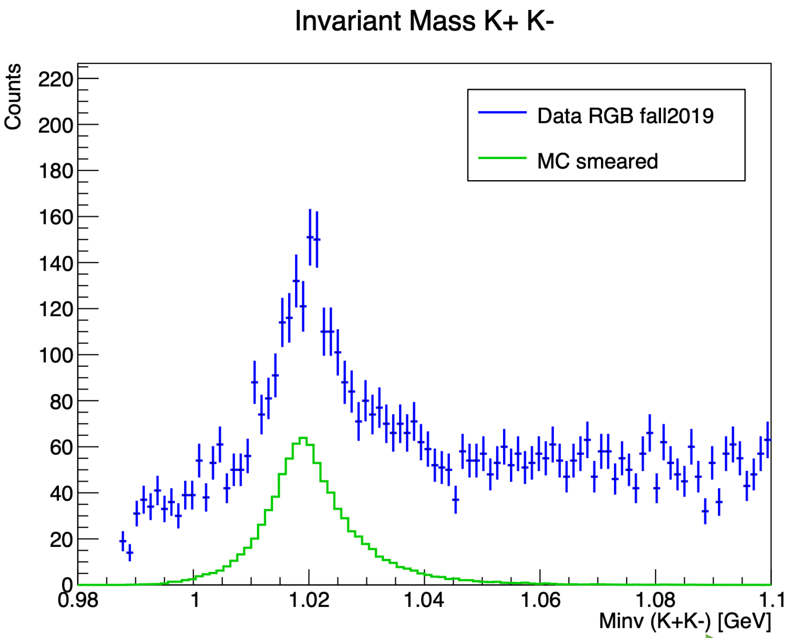


3) SDME



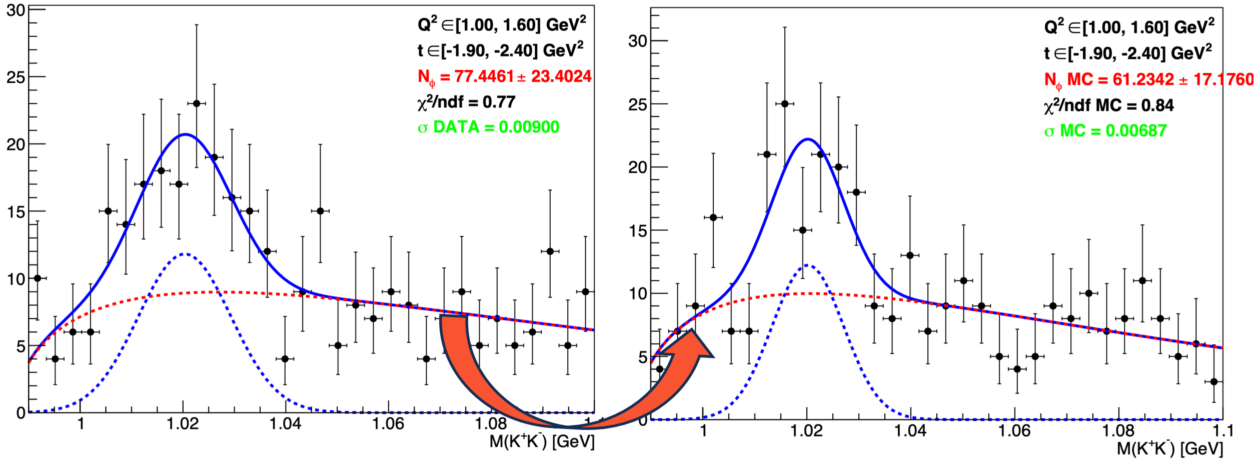
$$Total\ weight = Phase\ Space * \frac{d^3\sigma}{dt dQ^2 dx_b} * SDME * BR_{\phi \to K^+K^-}$$

Comparison MC vs Data



In green, the reconstructed event after simulation with GEMC, the GEANT4 simulation of CLAS12.

DATA **MC**



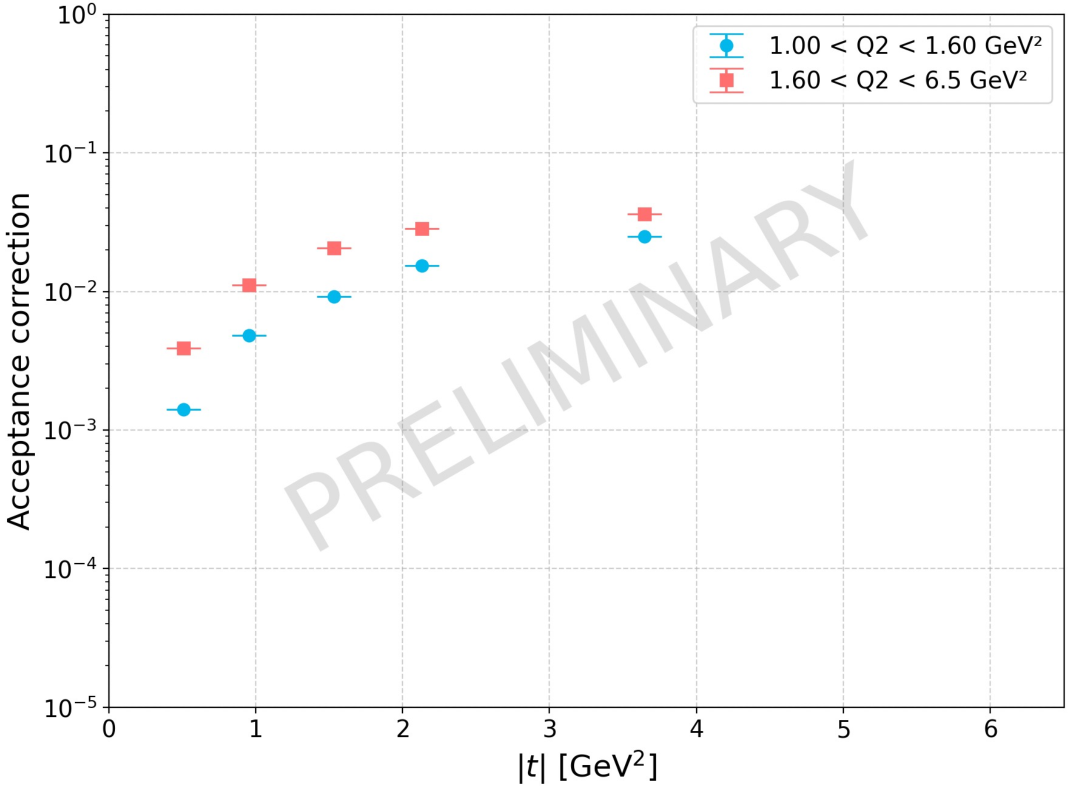
Random fill from the distribution of data background to take this into acount in our MC.

Acceptance correction

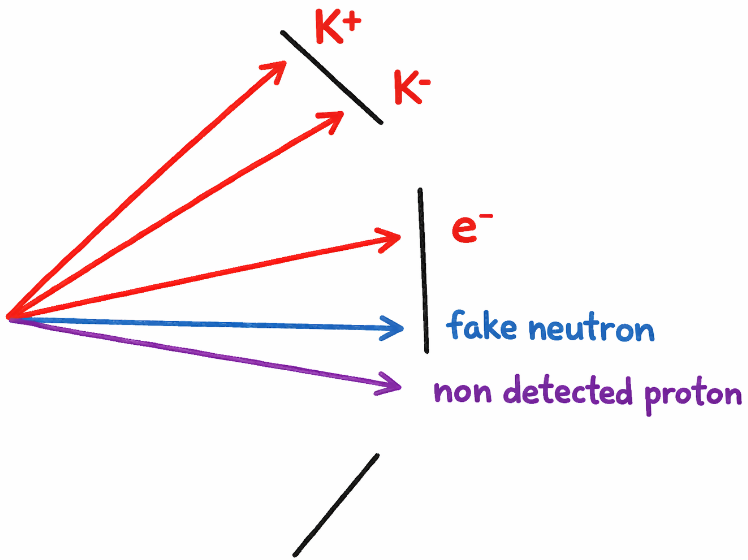
$$A = \frac{N_{rec}}{N_{gen}} * \frac{N_{fit}}{N_{random}}$$

Contribution from the model, the geometry and the efficiency.

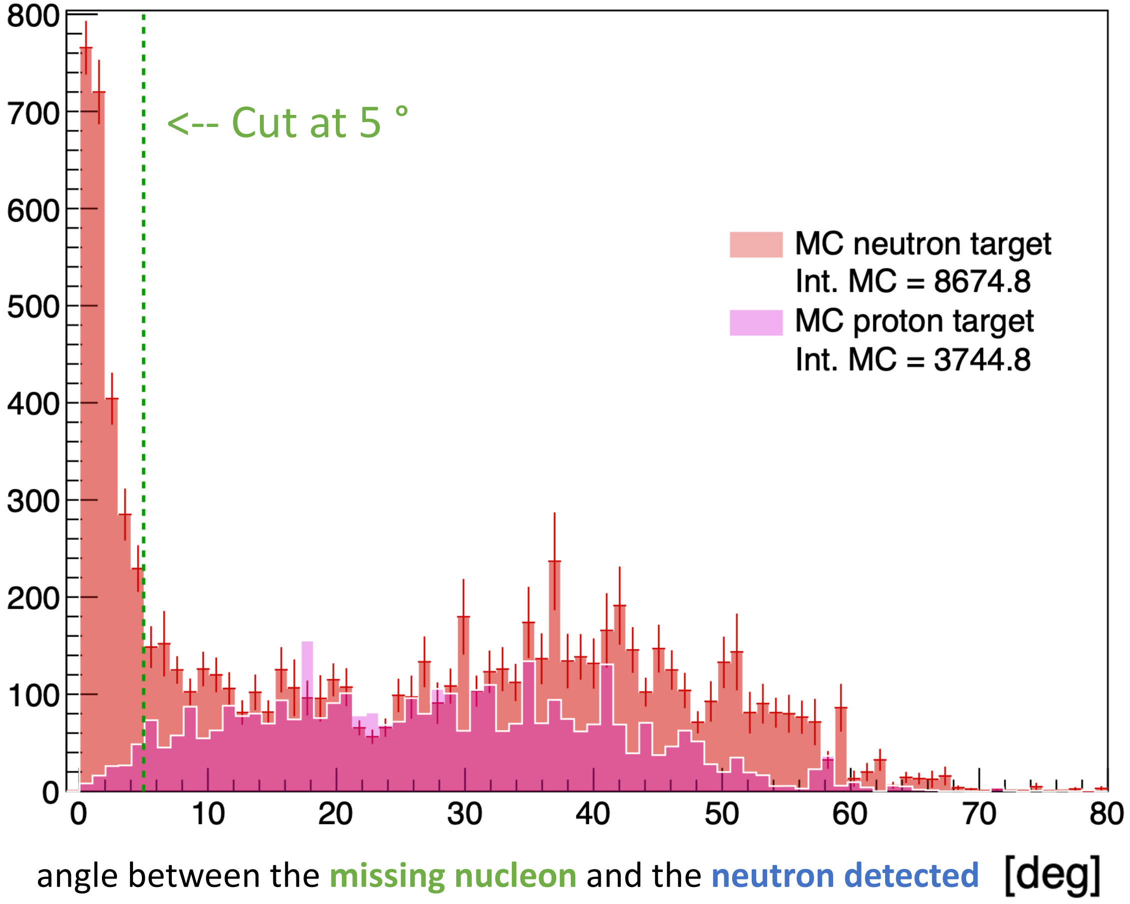
Contribution from the resolution of the fit.



Proton contamination estimation



Contamination when the missing nucleon is a non detected proton and there is a fake neutron signal who pass the cut on the angle



Preliminary differential cross section

The differential cross section of this reaction $e\,n \to e'\,n'\phi$ is :

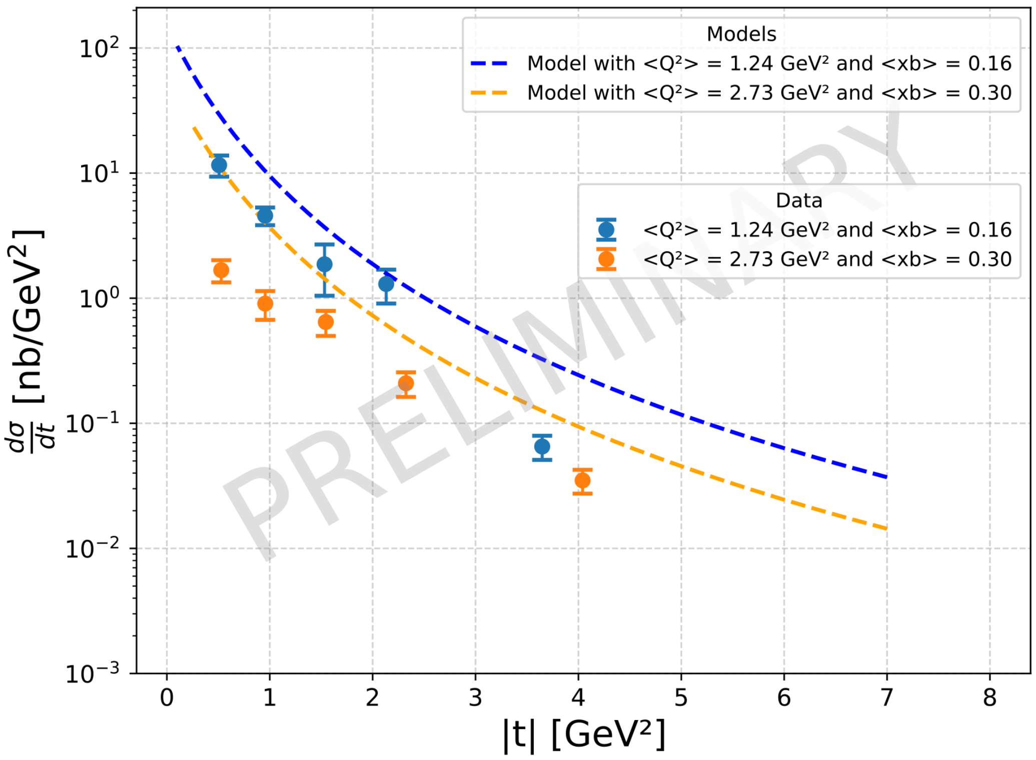
$$\frac{d^3\sigma}{dQ^2 dx_B dt} = \Gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt}(Q^2, x_B, t) + \epsilon\frac{d\sigma_L}{dt}(Q^2, x_B, t)\right]$$

with $\Gamma \equiv \frac{\alpha}{8\pi}\frac{Q^2}{m_N^2 E^2}\frac{1-x_B}{x_B^3}\frac{1}{1-\epsilon}.$ the virtual photon flux factor.

The reduced differential cross section of this reaction $\gamma^* n \to n'\phi$ is given by :

$$\frac{d\sigma}{dt}(Q^2, x_B) = \frac{1}{\Gamma(Q^2, x_B, E)} \cdot \frac{d^3\sigma}{dQ^2 dx_B dt}$$

$$\frac{d\sigma}{dt}(Q^2, x_B) = \frac{\Delta N}{\Gamma \cdot \Delta x_B \cdot \Delta Q^2 \cdot \Delta t \cdot f \cdot L \cdot Acc \cdot Br}$$

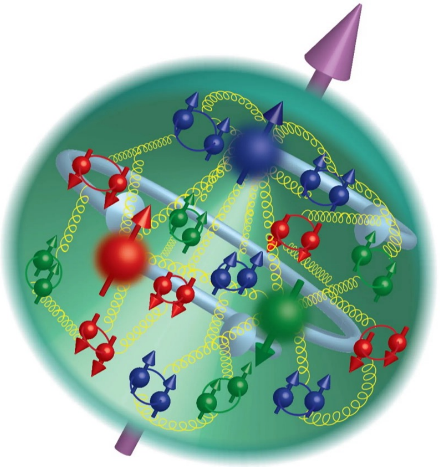


Conclusion and outlook

Next steps in the ϕ analysis :

- Improve the MC simulations (fermi motion, efficiency corrections for the kaons...)
- Develop momentum corrections for the kaons.

- Stay tuned for the final results, which will soon provide a first probe of the **gluons** inside the **neutron**!



Thanks!

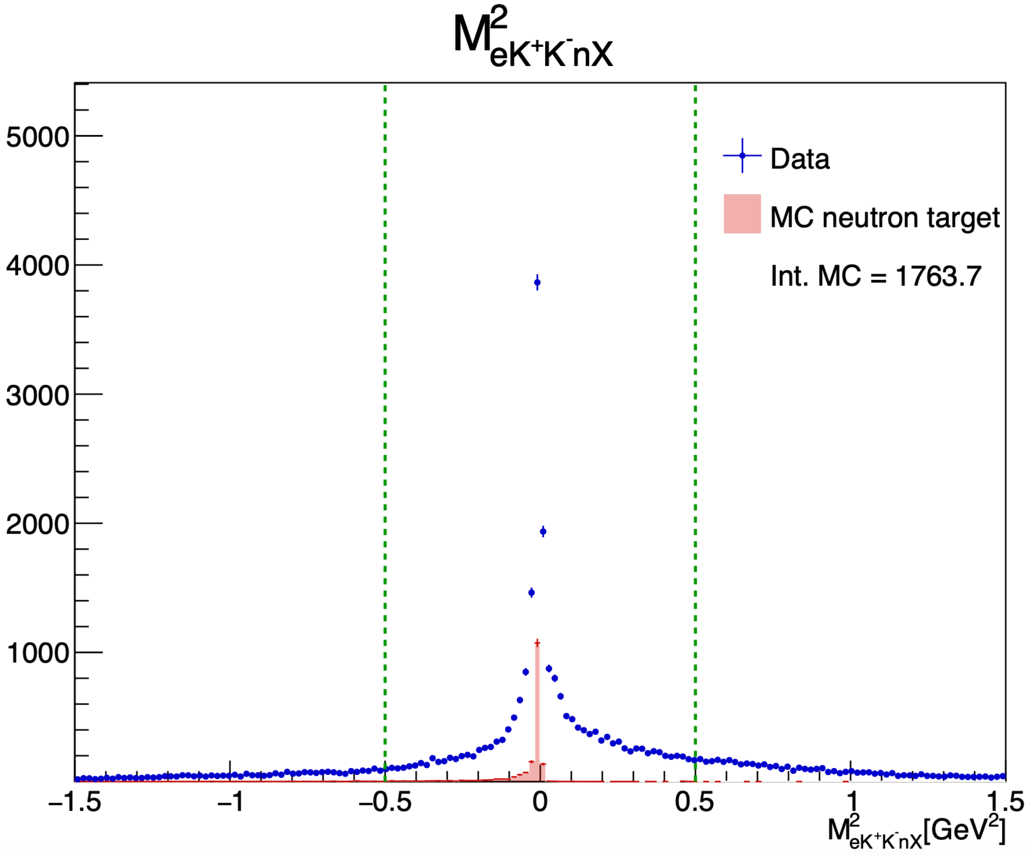
Backup

Backup slides

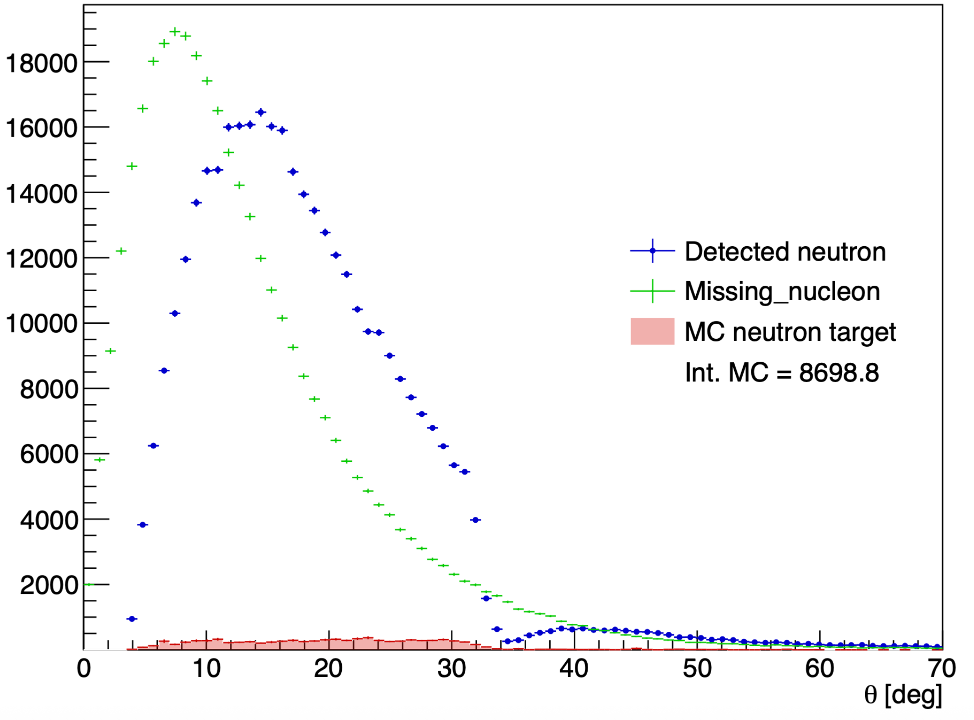
Event selection 1

Total missing mass e n → e’ n’ K^+ K^- X
(after all the previous cut)

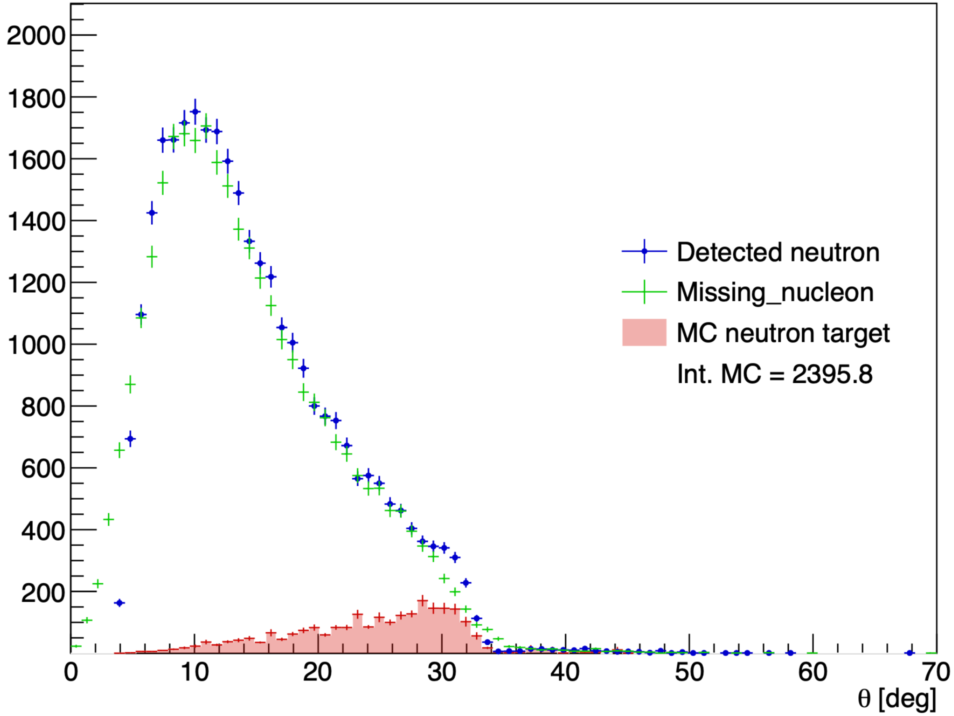
$$-0.5 < M^2_{eK^+K^-nX} < 0.5\, GeV^2$$



Event selection 2 (cut angle between missing nucleon and detected neutron) :

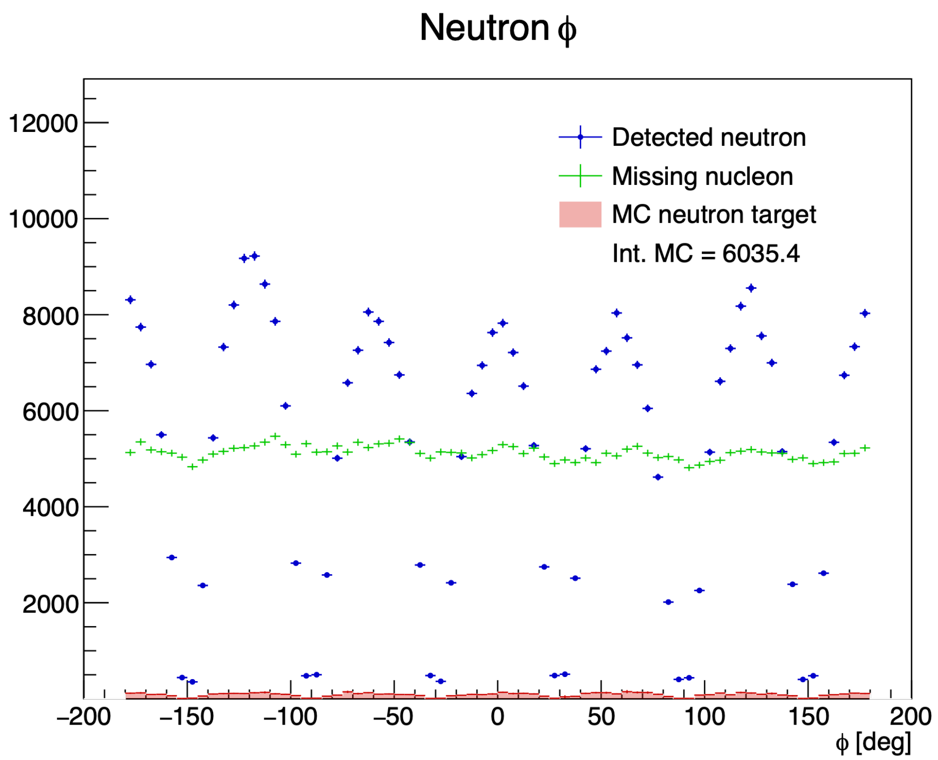


Without the angle cut

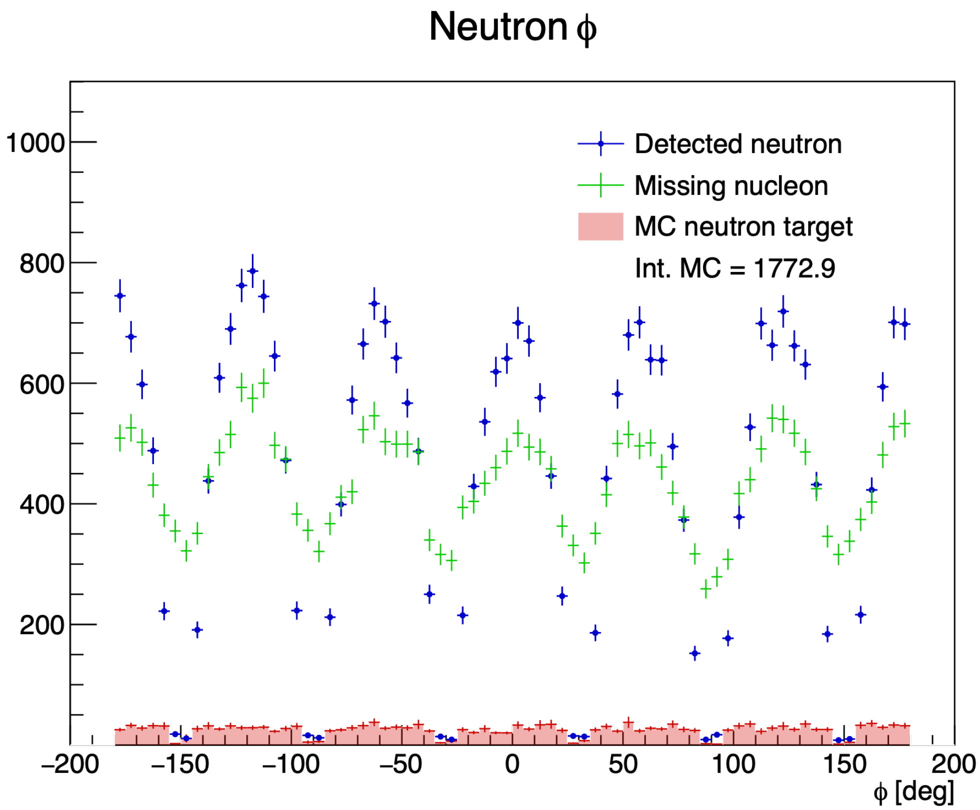


With the angle cut

Event selection 3 (cut angle between missing nucleon and detected neutron) :

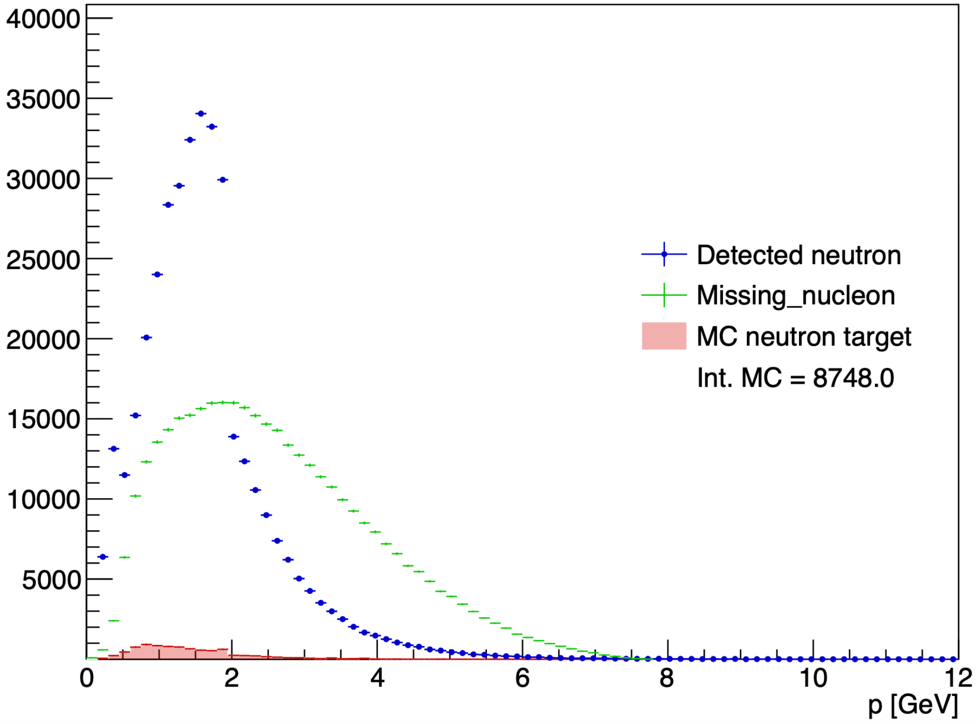


Without the angle cut

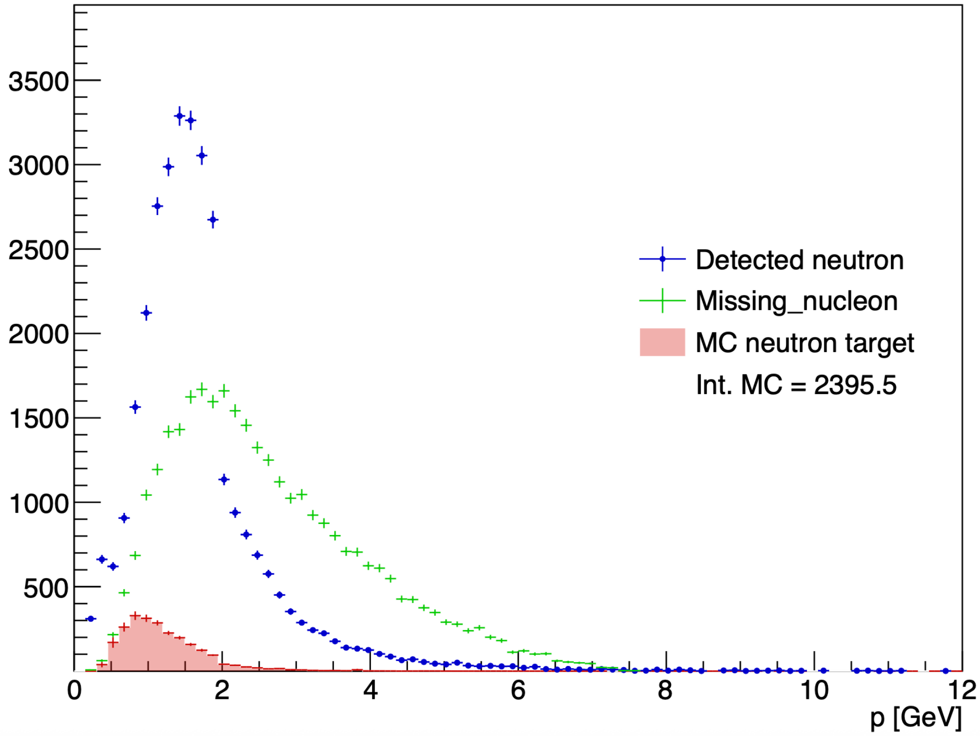


With the angle cut

Event selection 4 (cut angle between missing nucleon and detected neutron) :



Without the angle cut



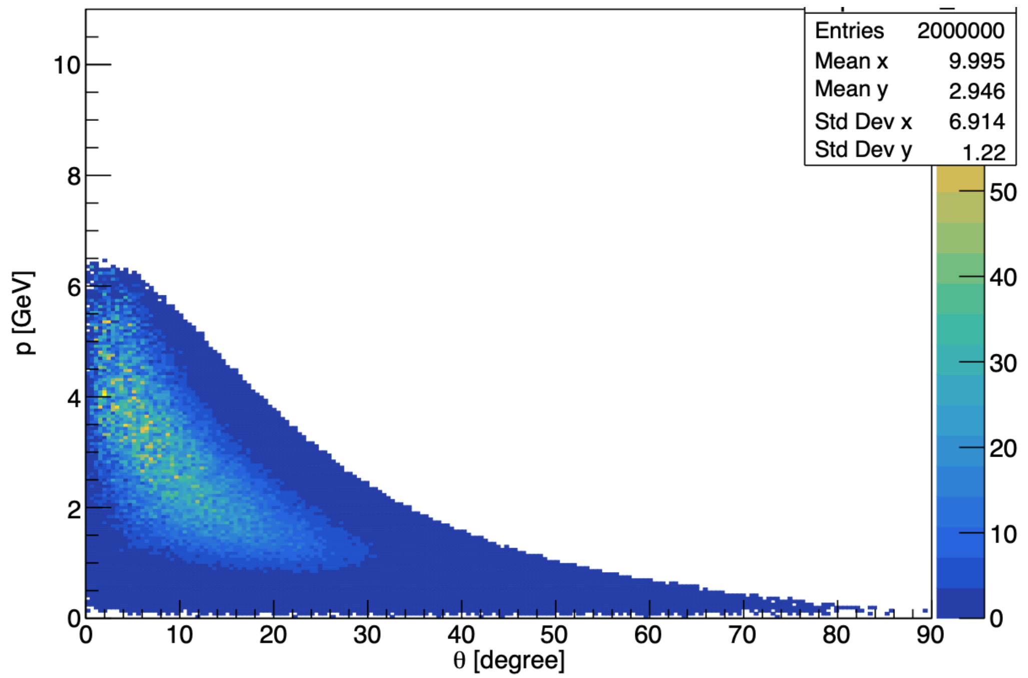
With the angle cut

Event selection 5 (Cut on the status of K^+K^-) :

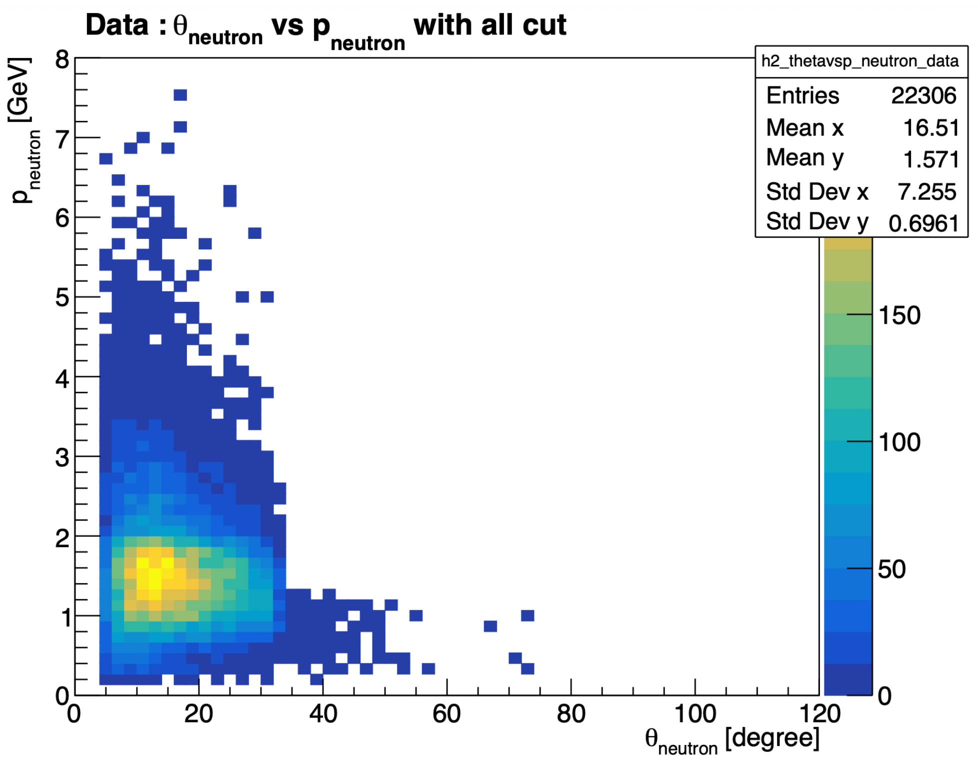
Generated event : p vs theta for K^{+-}

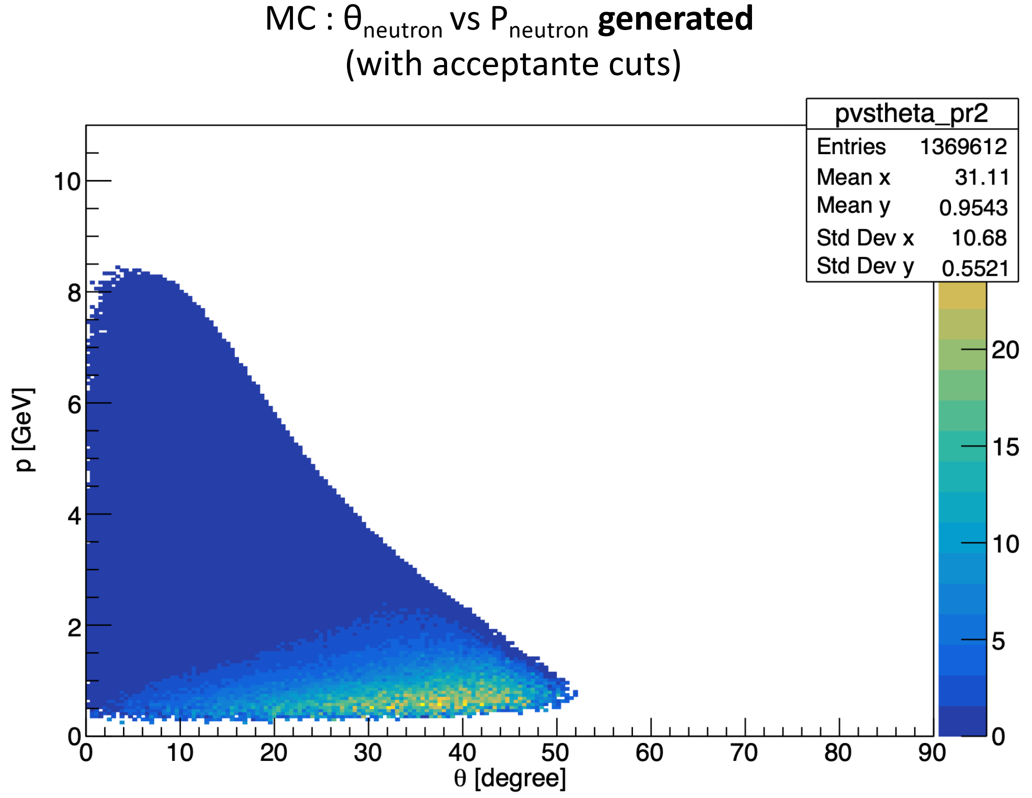
Two justifications to cut K+ K- in CD :

- Reconstruction of kaons in the CD is less good than in the FD
- The generator predict few events in the CD

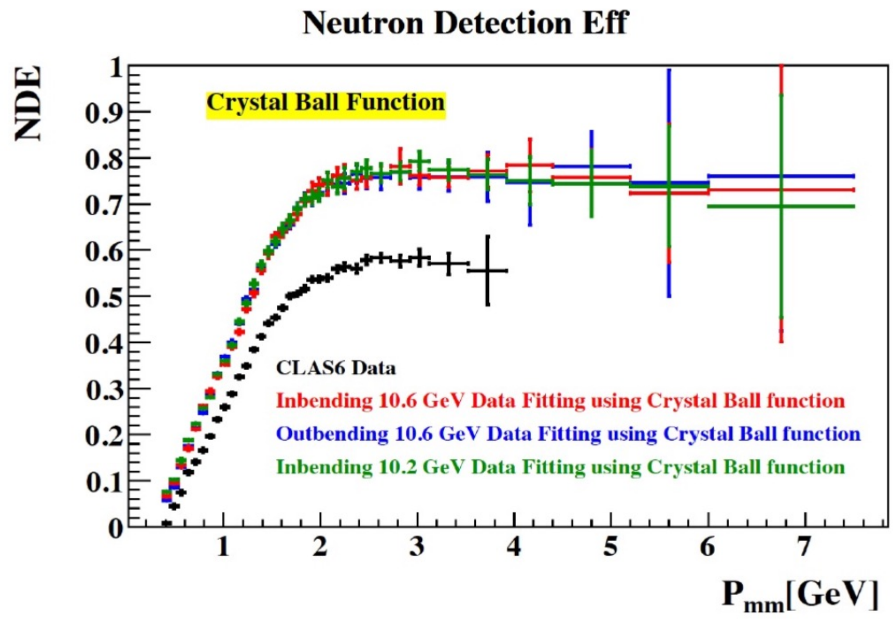


Event selection 6 (Neutron phasespace) :

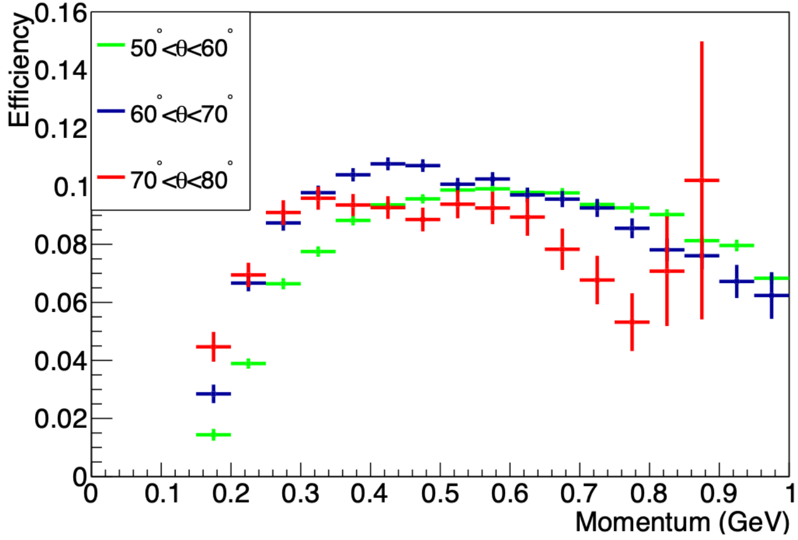




Event selection 7 (Neutron phasespace) :



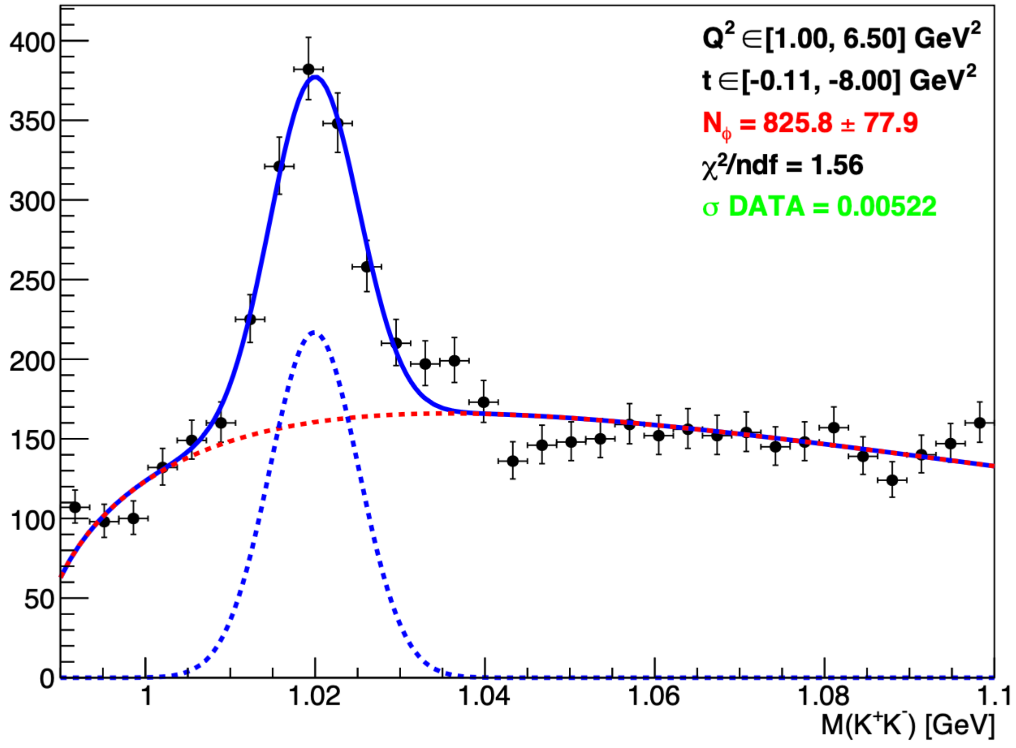
Neutron detection efficiency in the FD



P. Chatagnon's plot

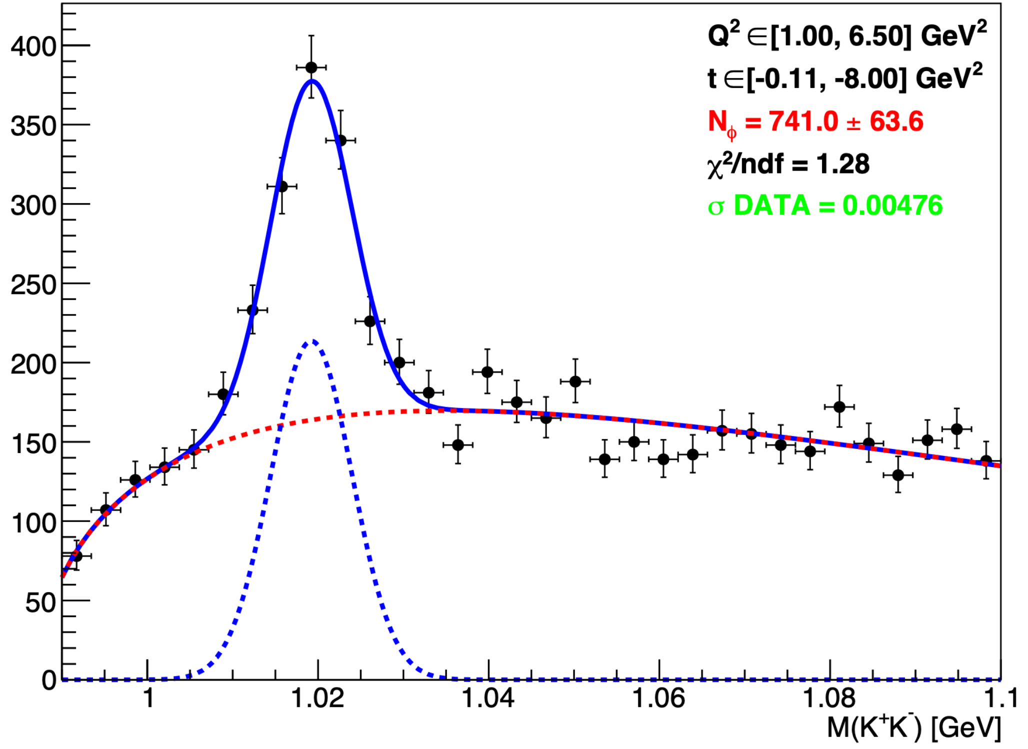
Neutron detection efficiency in the CND

Number of event 1



Fall2019 outbending

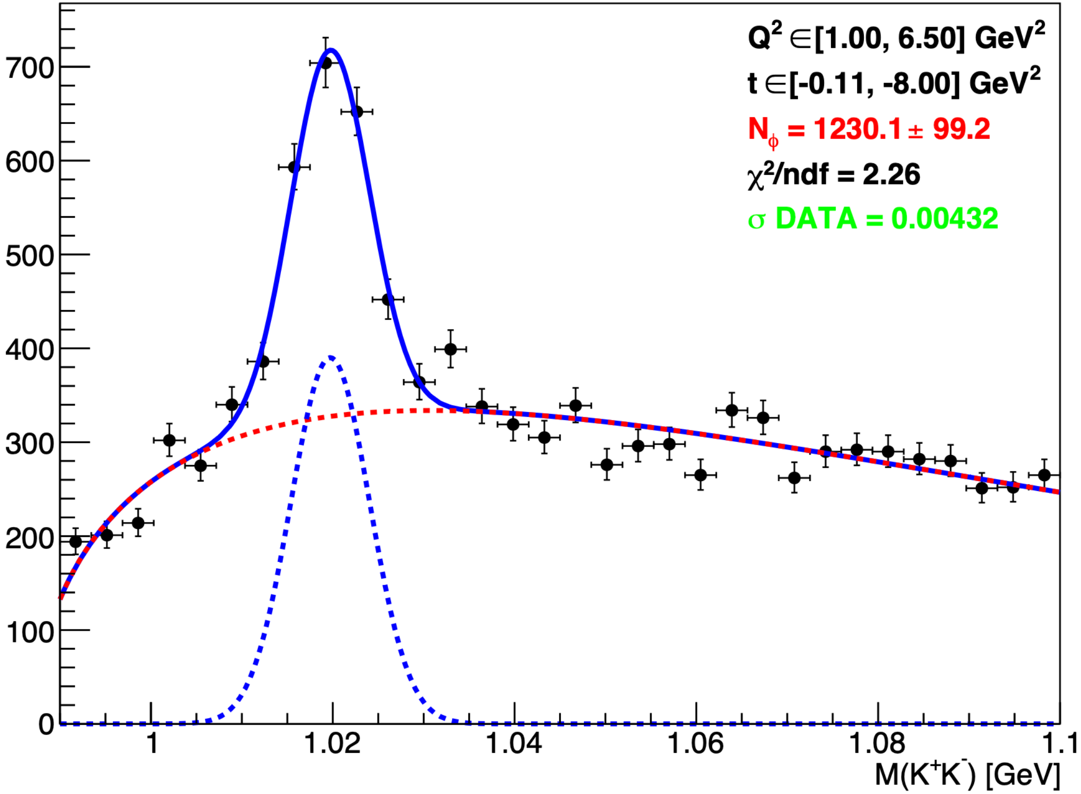
Q = 12.1 mC



Spring2020 inbending

Q = 28.3 mC

Number of event 2



Spring 2019 inbending

Q = 63.4 mC

ϕ generator 1

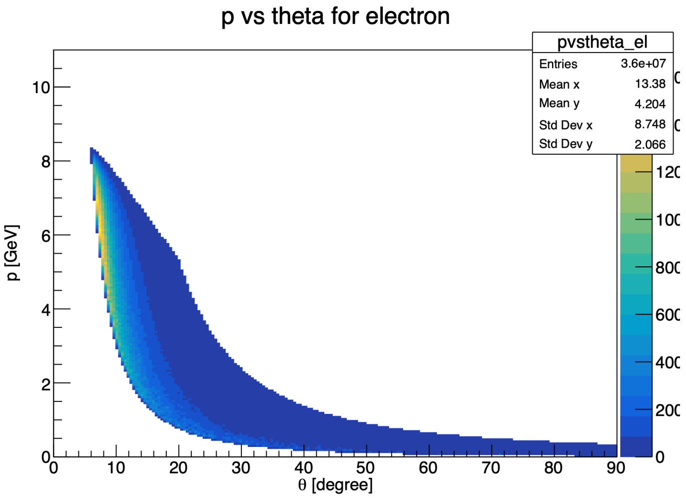
$$weight_{PhaseSpace} = |Q^2_{max} - Q^2_{min}| * |xb_{max} - xb_{min}| * |t_{max} - t_{min}|$$

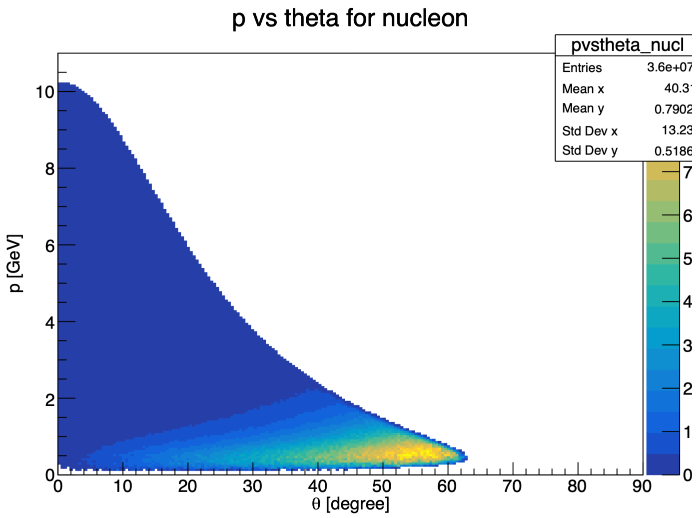
$$\frac{d^3\sigma}{dQ^2 dx_B dt}$$ *From Proposal to Jefferson Lab PAC39 Exclusive Phi Meson Electroproduction with CLAS12*

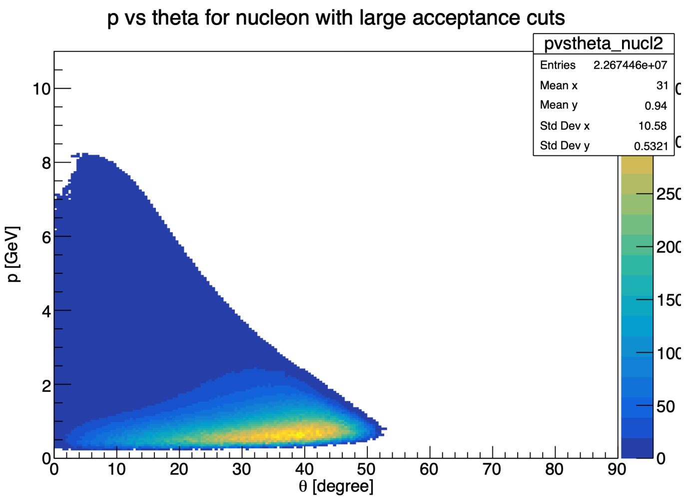
$$\mathrm{BR}(\phi \to K^+K^-) \approx 49.2\%$$

$$totalweight = weight_{phasespace} * weight_{\frac{d^3\sigma}{dt dQ^2 dx_b}} * BR_{\phi \to K^+K^-}$$

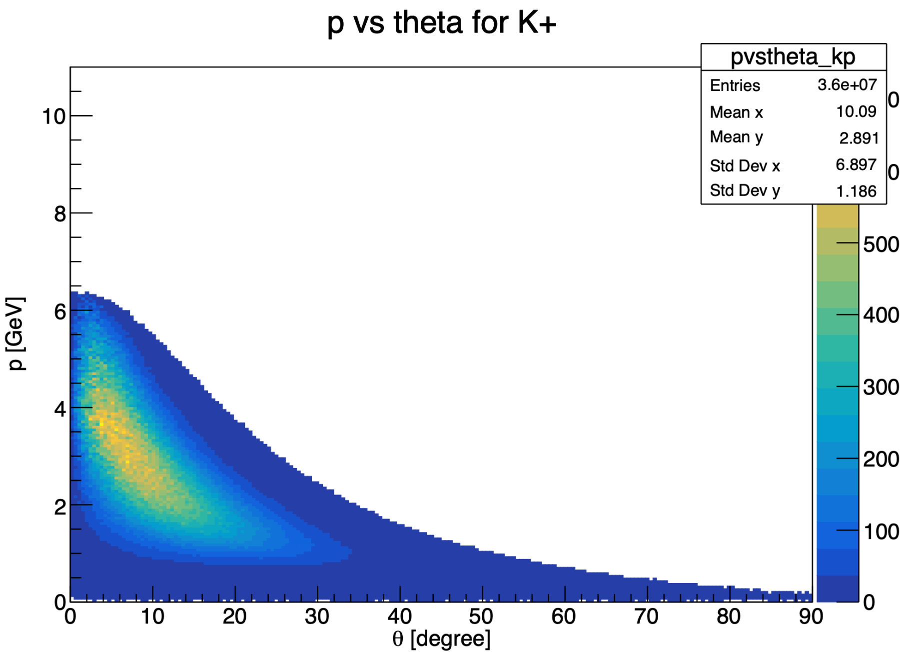
ϕ generator 2

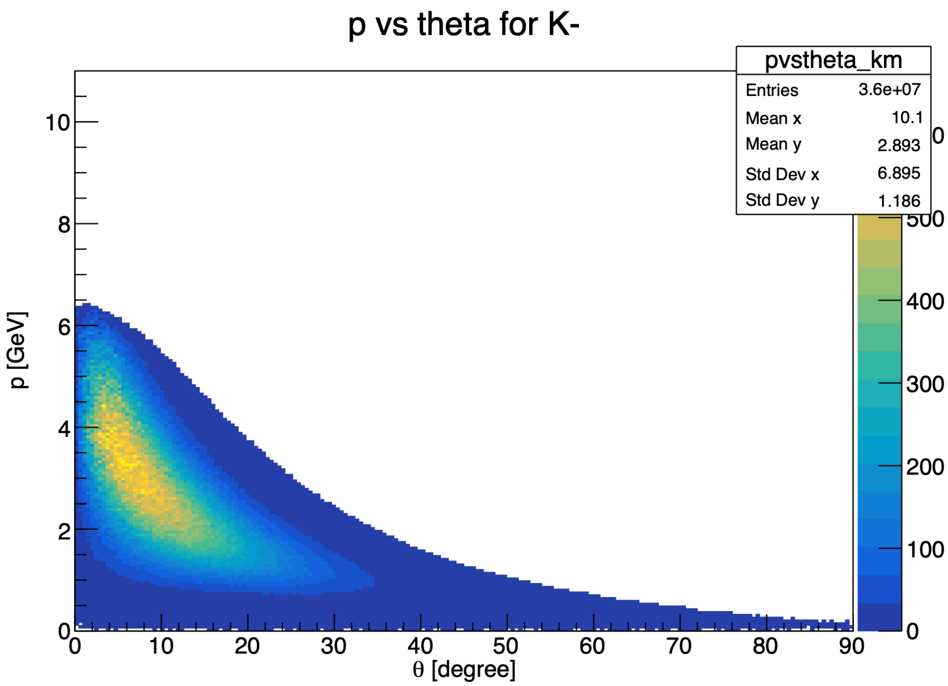




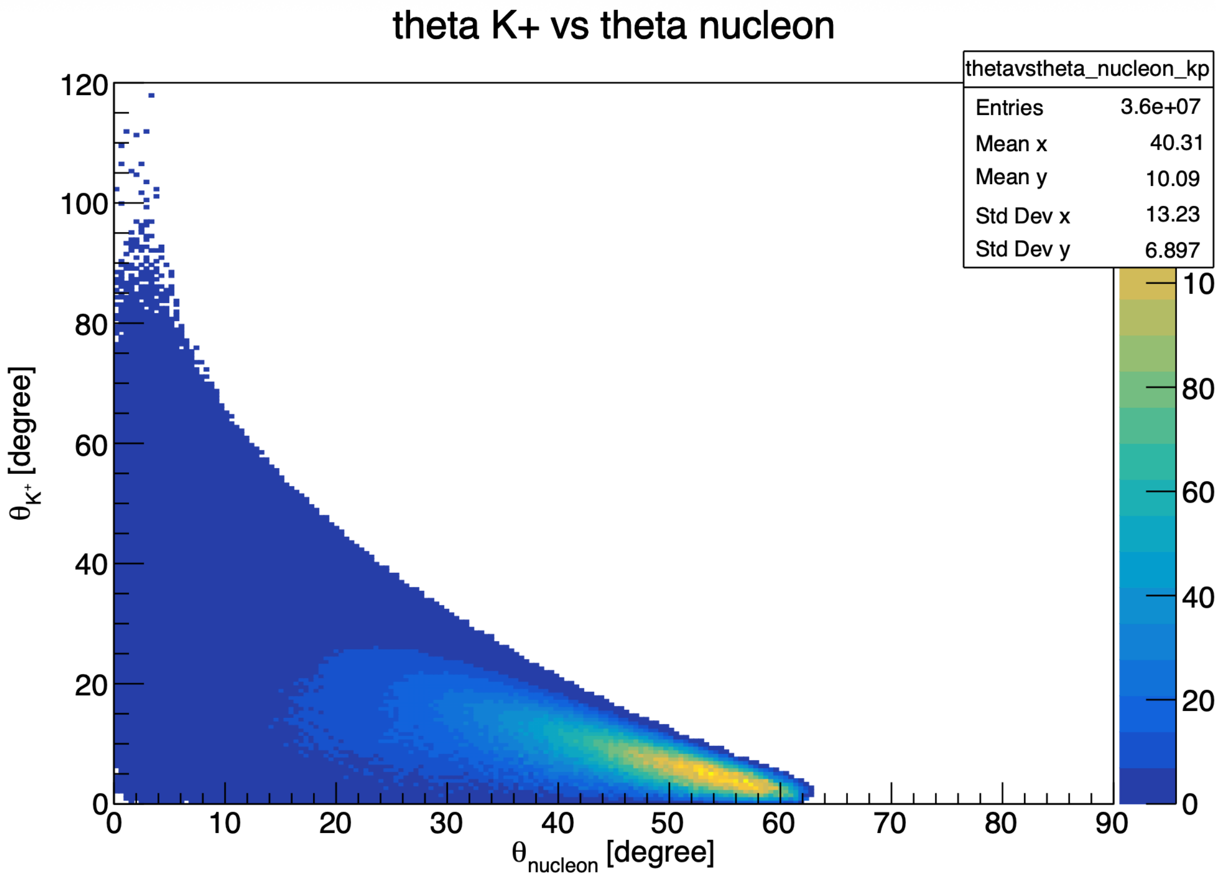


ϕ generator 3

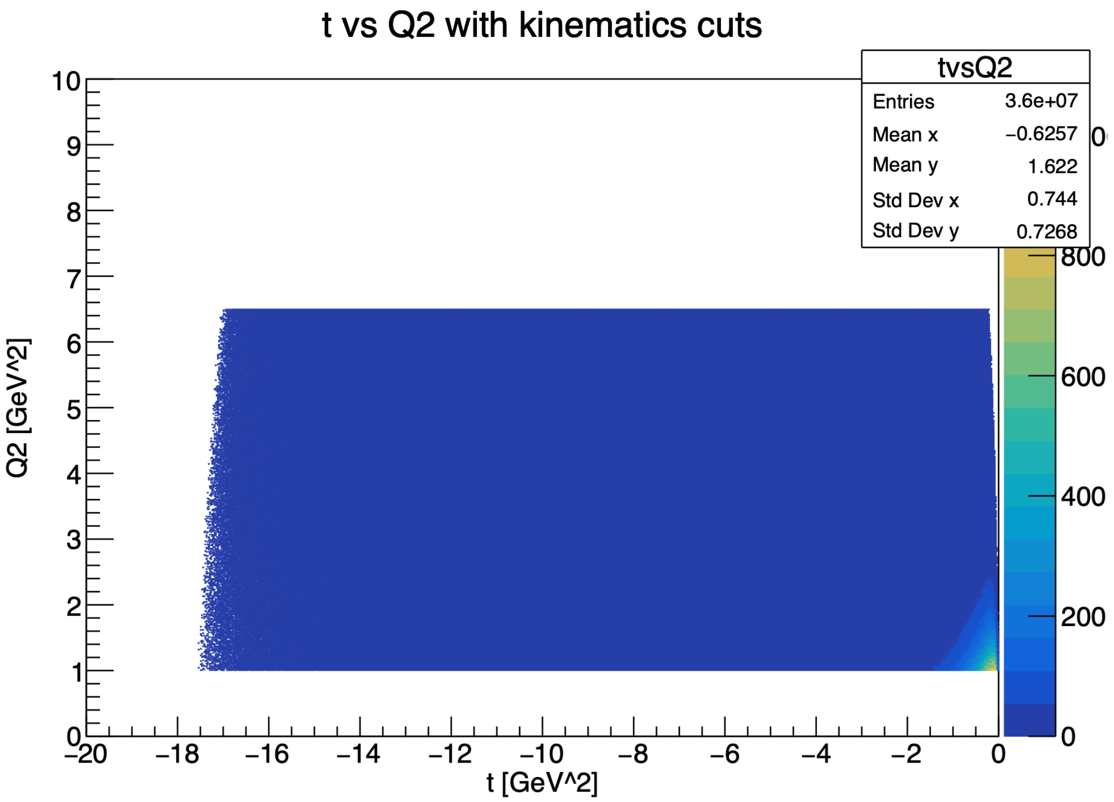


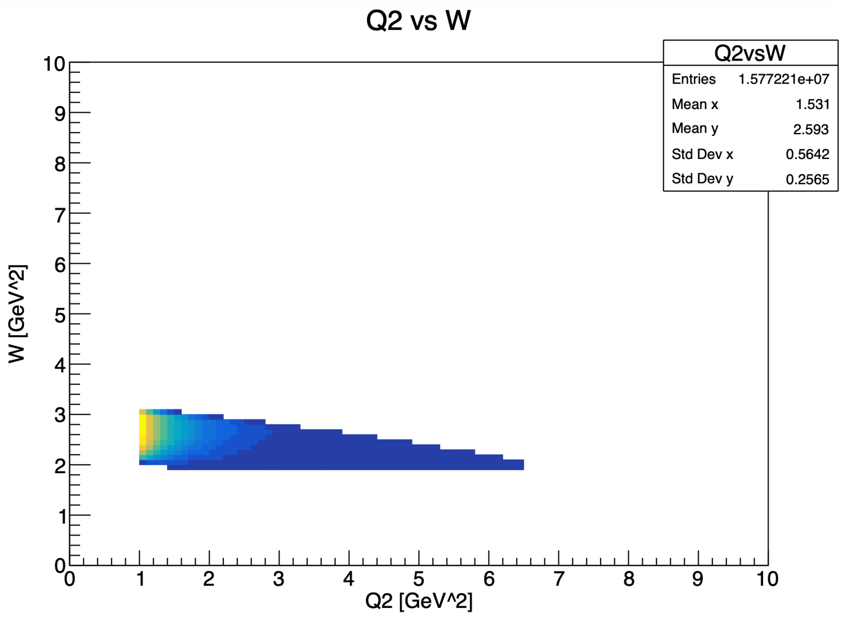


ϕ generator 4

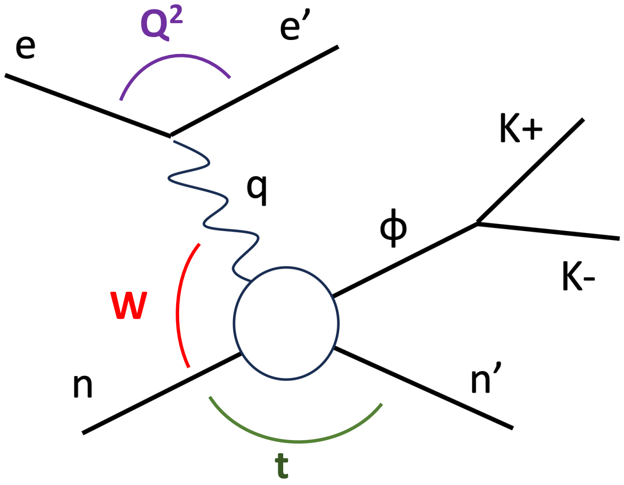


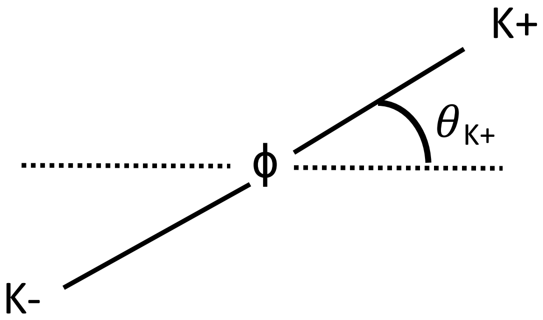
ϕ generator 5





SDME 1



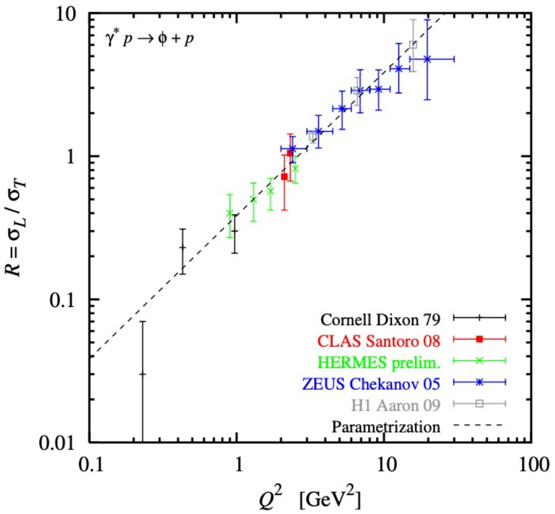


Non isotropic decay of the kaons in the ϕ frame. So we need to add a weight associated to the SDME

$$Total\ weight = Phase\ Space * \frac{d^3\sigma}{dtdQ^2dx_b} * SDME * BR_{\phi \to K^+K^-}$$

SDME 2

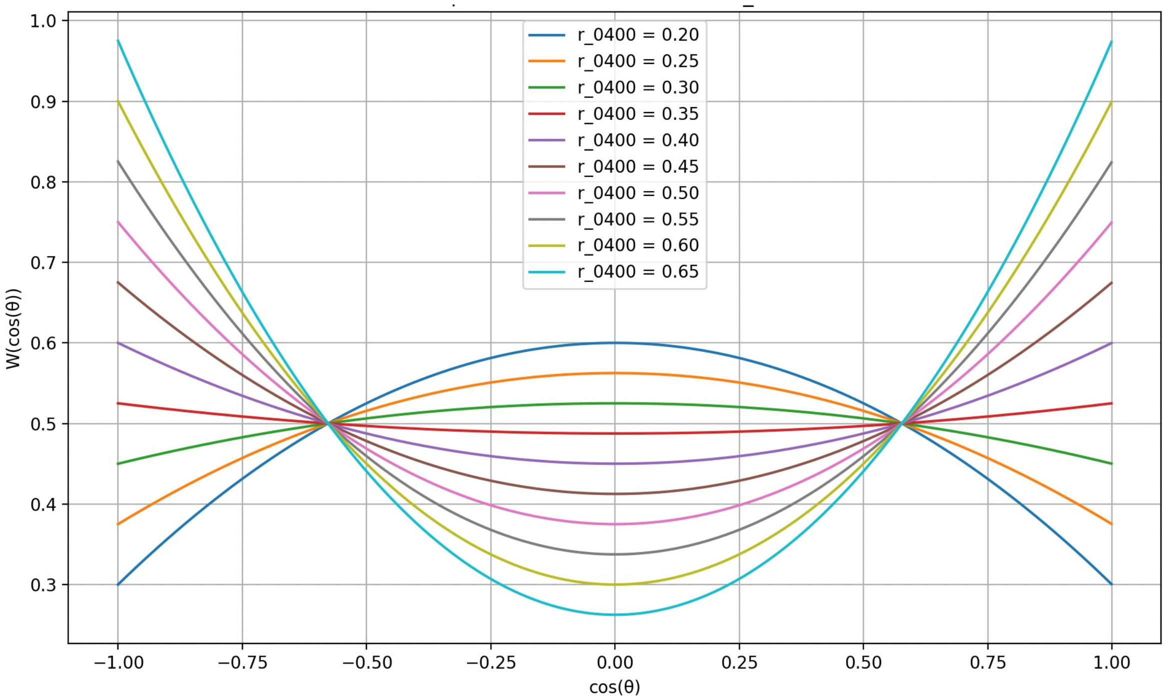
$$W(\cos\theta_H) = \frac{3}{4}\left[\left(1 - r^{04}_{00}\right) + \left(3r^{04}_{00} - 1\right)\cos^2\theta_H\right]$$



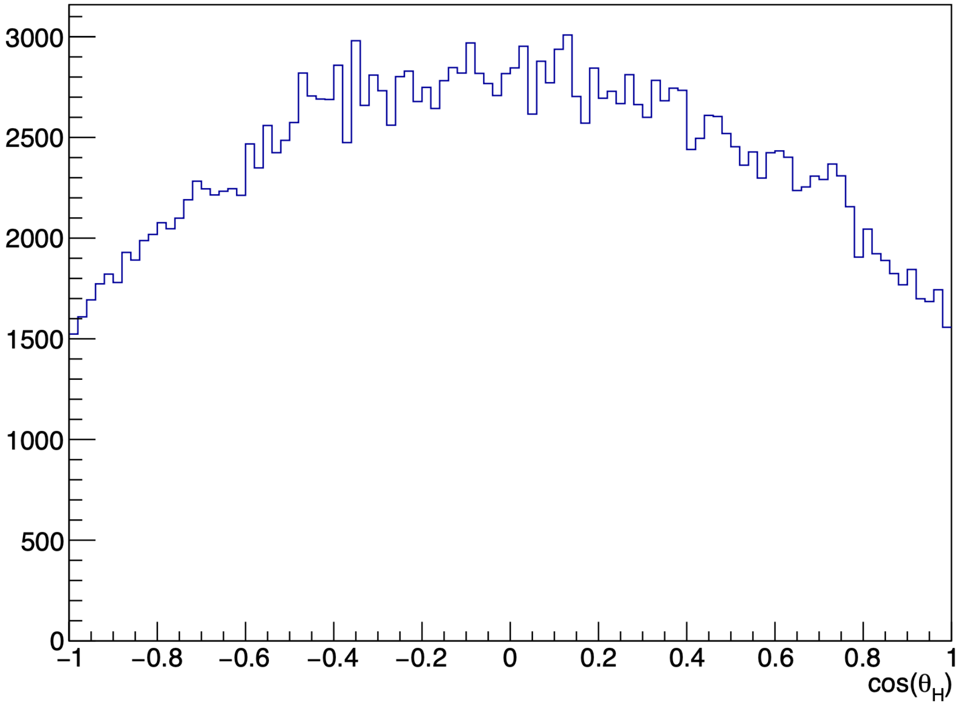
$$R = \frac{r^{04}_{00}}{\epsilon(1 - r^{04}_{00})}.$$

$$R(W,Q^2) = \frac{c_R Q^2}{m^2_\phi}$$

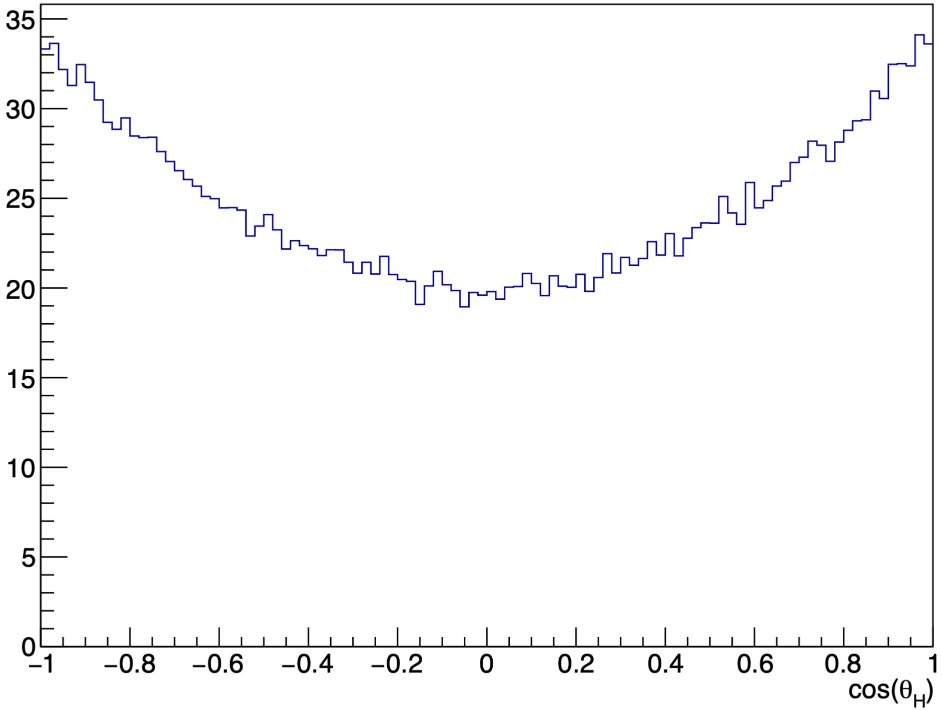
From Proposal to Jefferson Lab PAC39 Exclusive Phi Meson Electroproduction with CLAS12



SDME 3 (generated plots)

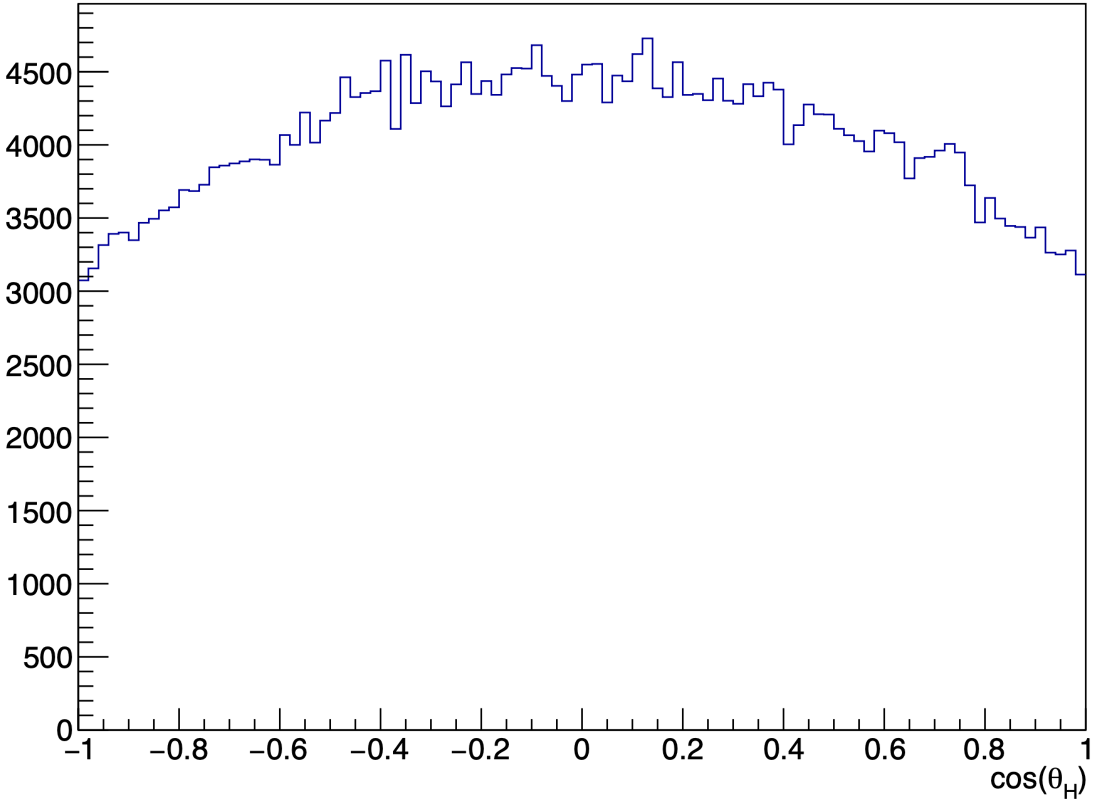


With Q^2 in [1.0 – 1.5] GeV^2



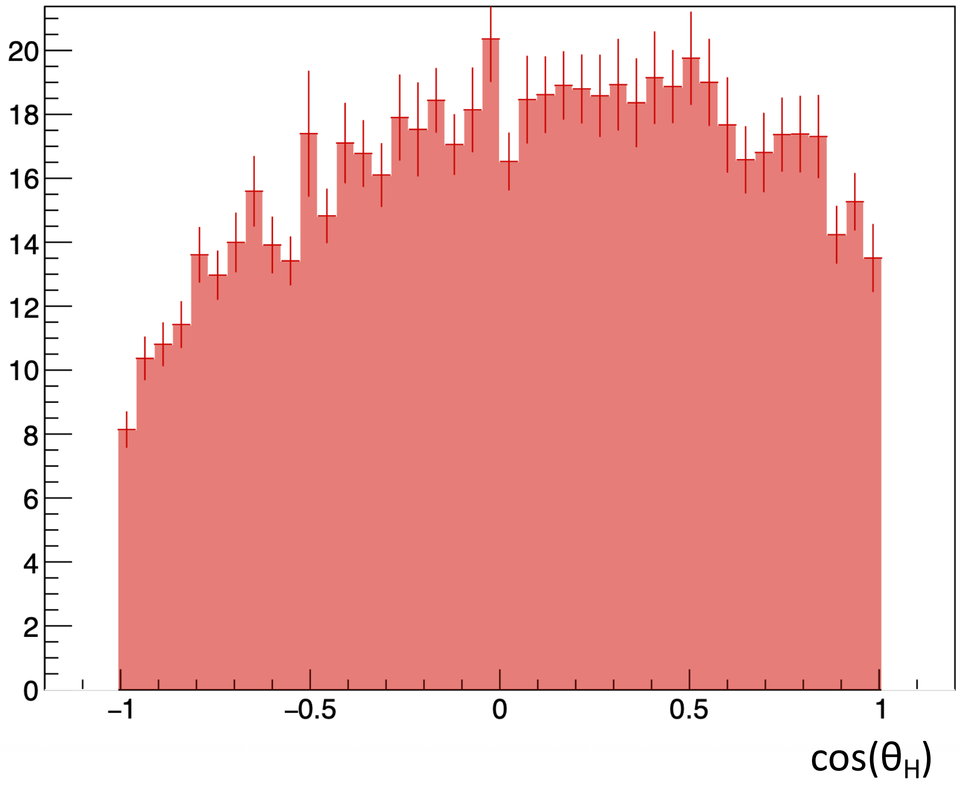
With Q^2 in [5.0 – 6.5] GeV^2

SDME 4 (generated plots)



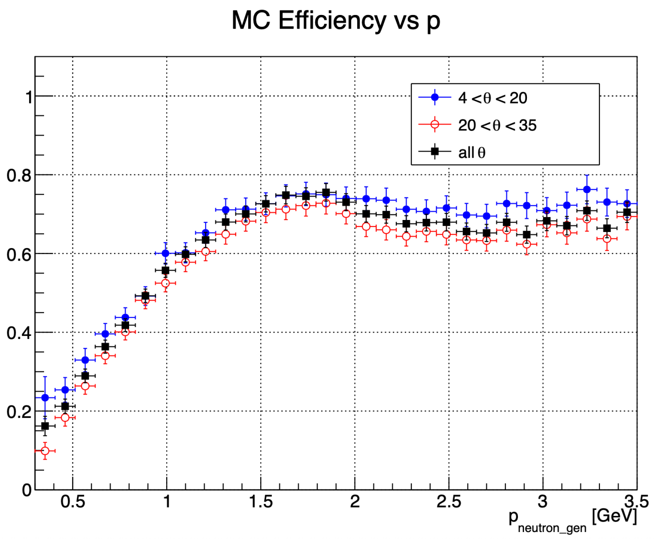
With no cut on Q^2

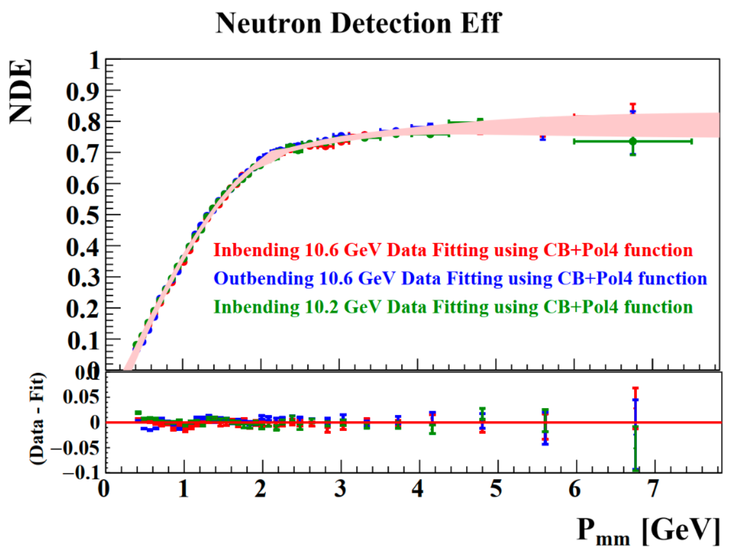
SDME 5 (reconstructed event)

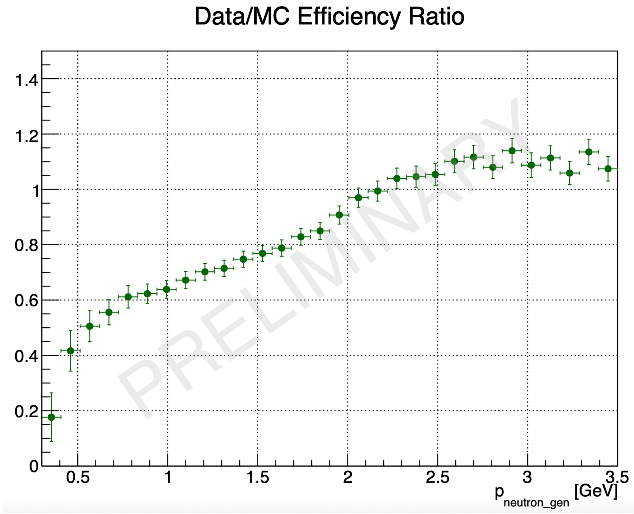


- Reconstructed with Q^2 in [1.0 – 1.5] GeV^2
- You can see acceptance effect when you compare to the generated plot

Efficiency correction for neutron







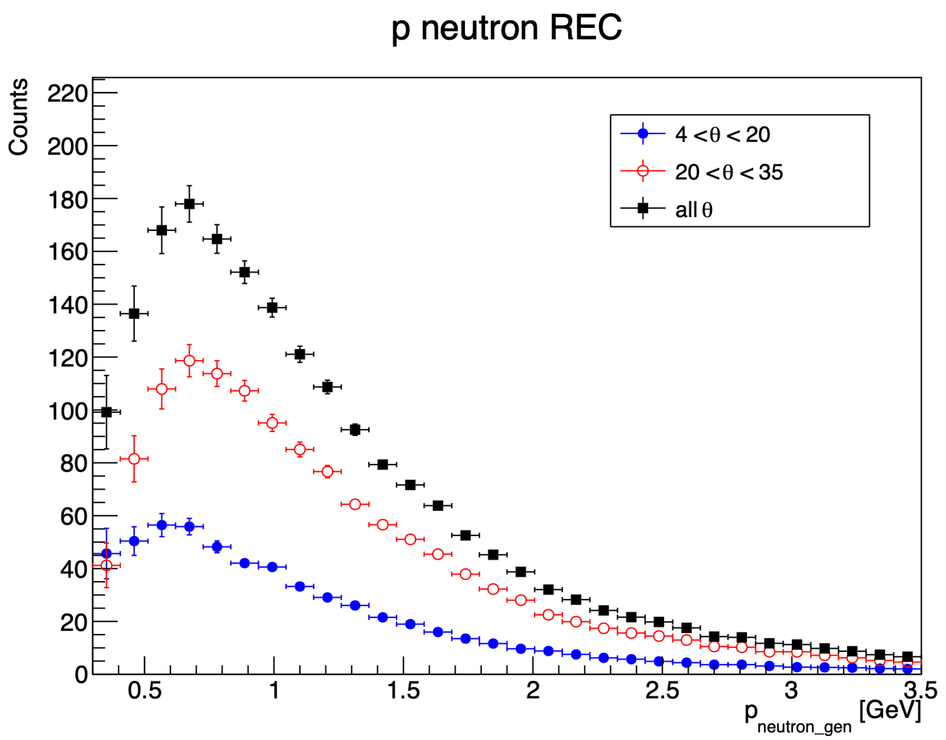
- Neutron efficiency in **MC** : $\frac{N_{rec}(e^- n)}{N_{gen}\ (\text{with } e^- \text{ rec})}$
- We are in the fiducial volume for reconstructed and genrated event

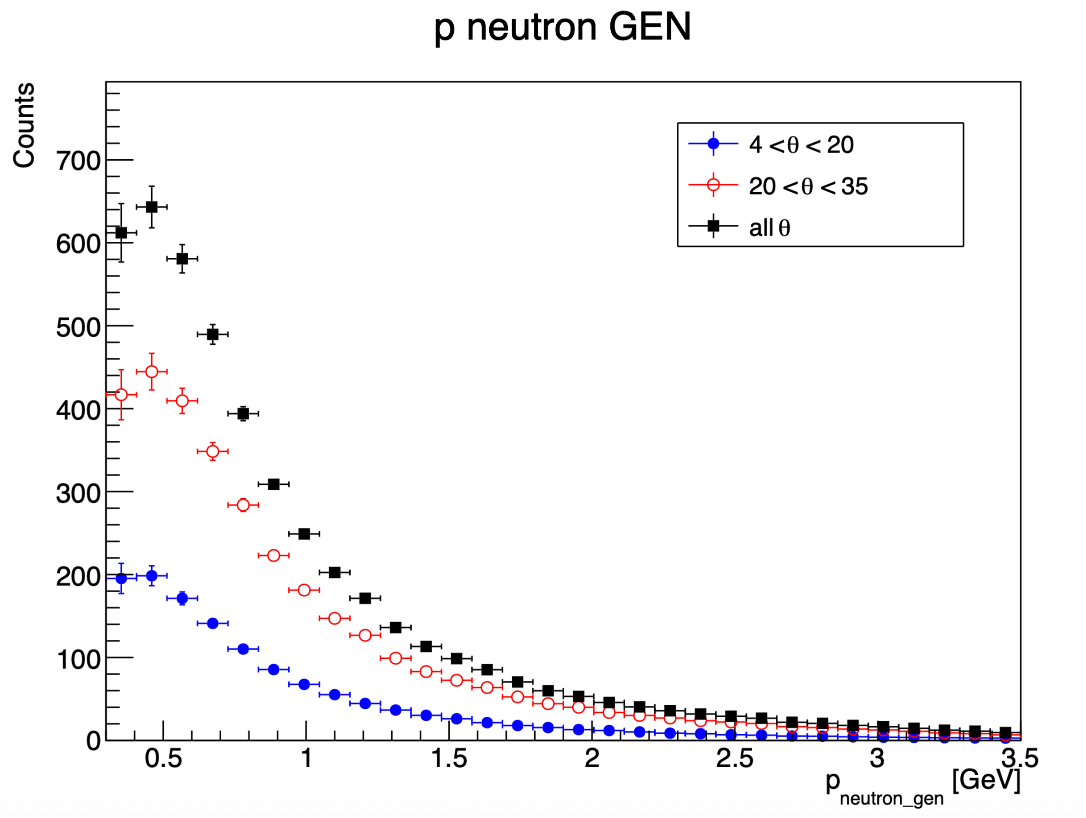
- Neutron efficiency (FD) in **data** from **Lamya Baashen** thesis

(with P_{mm} the missing momentum)

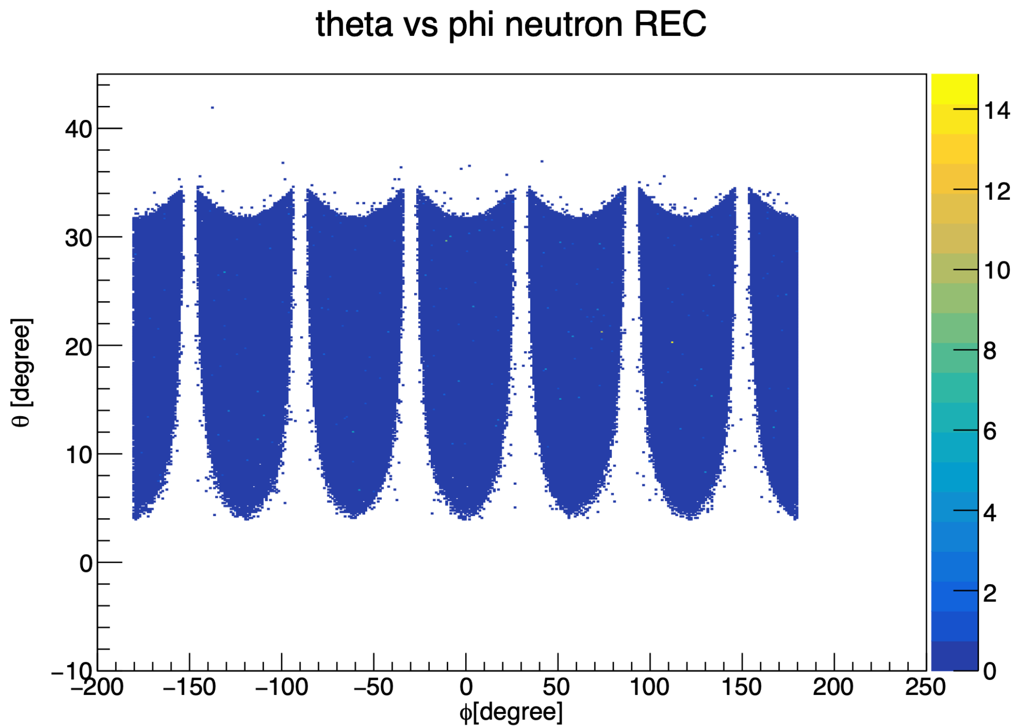
- The ratio between the **MC** and **data** efficiencies gives the **neutron efficiency correction factor**

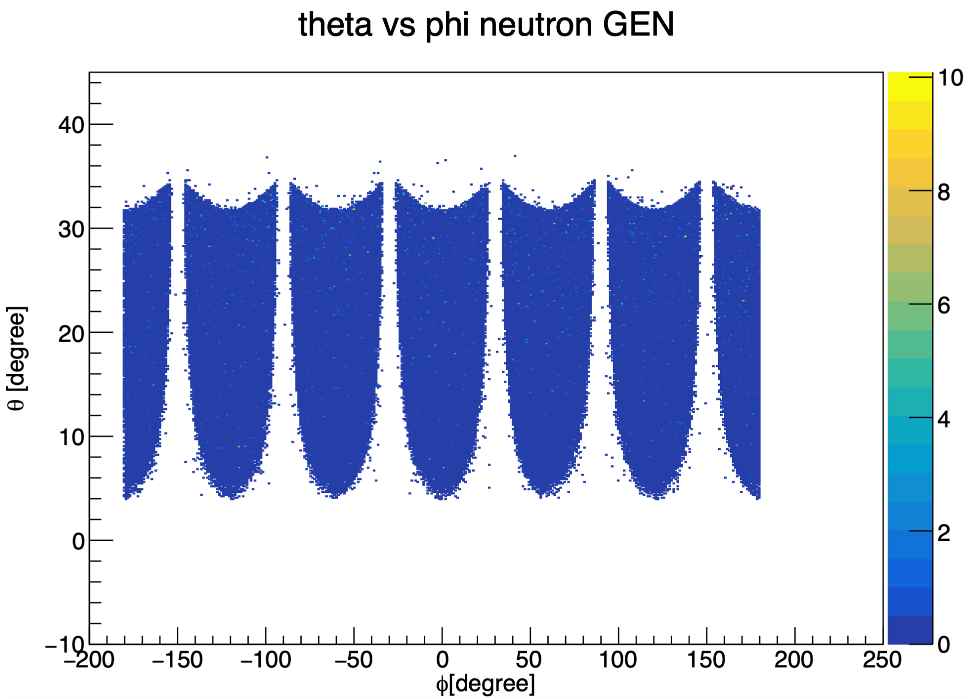
Neutron efficiency correction 1



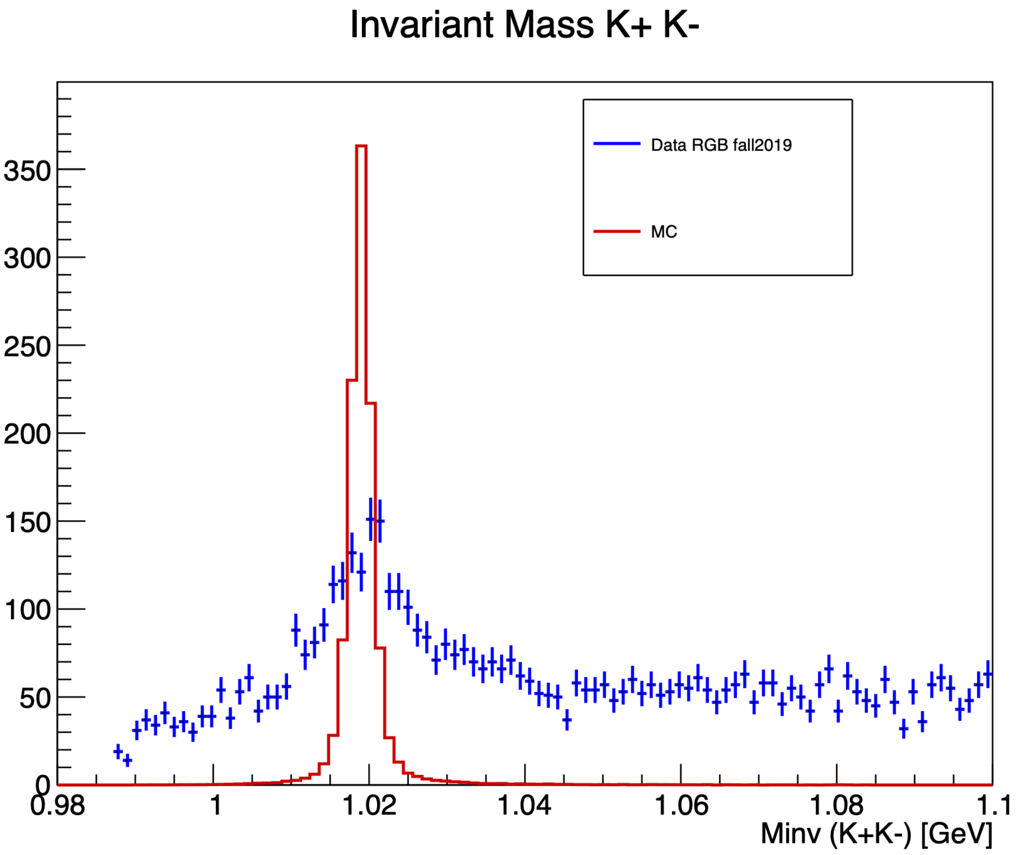


Neutron efficiency correction 2





Smearing of the kaons 1



→ We need a smearing of both kaons in the MC

$$P_{smear} = P \cdot (1 + \eta_s)$$

With η_s a random number from a Gaussian centered at 0.

The size of the Gaussian is the parameter $\delta(P)$

$$\delta_{K+}(P) = A_1\,\Theta(P - P_1)\Theta(P_2 - P) + B_1\,\Theta(P - P_2)\Theta(P_3 - P) + \ldots$$

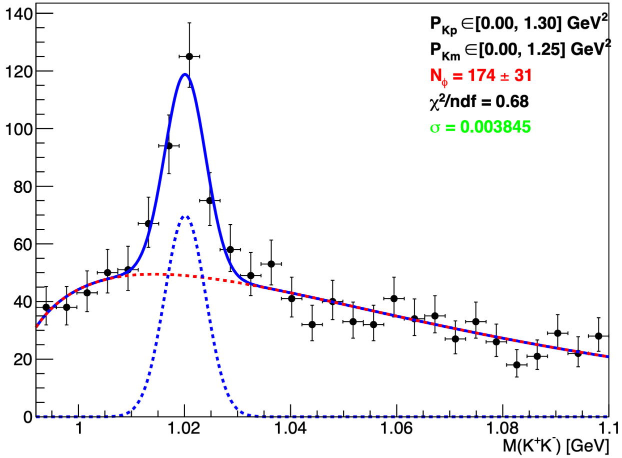
$$\delta_{K-}(P) = A_2\,\Theta(P - P_1)\Theta(P_2 - P) + B_2\,\Theta(P - P_2)\Theta(P_3 - P) + \ldots$$

→ Minimize **σ_{DATA} - σ_{MC}** per bins of momentum to find the parametters A_1, B_1, C_1 ….

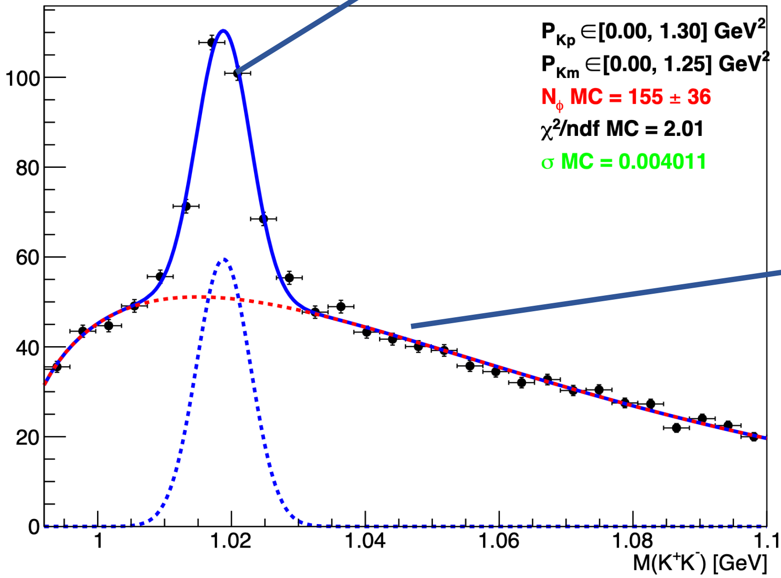
Smearing of the kaons 2

How to extrat σ_{MC} in one bin of momemtum?

Random fill from the MC reconstructed event histogram (with the smearing wich depends of the parametters A_1, B_1, C_1 …)



DATA

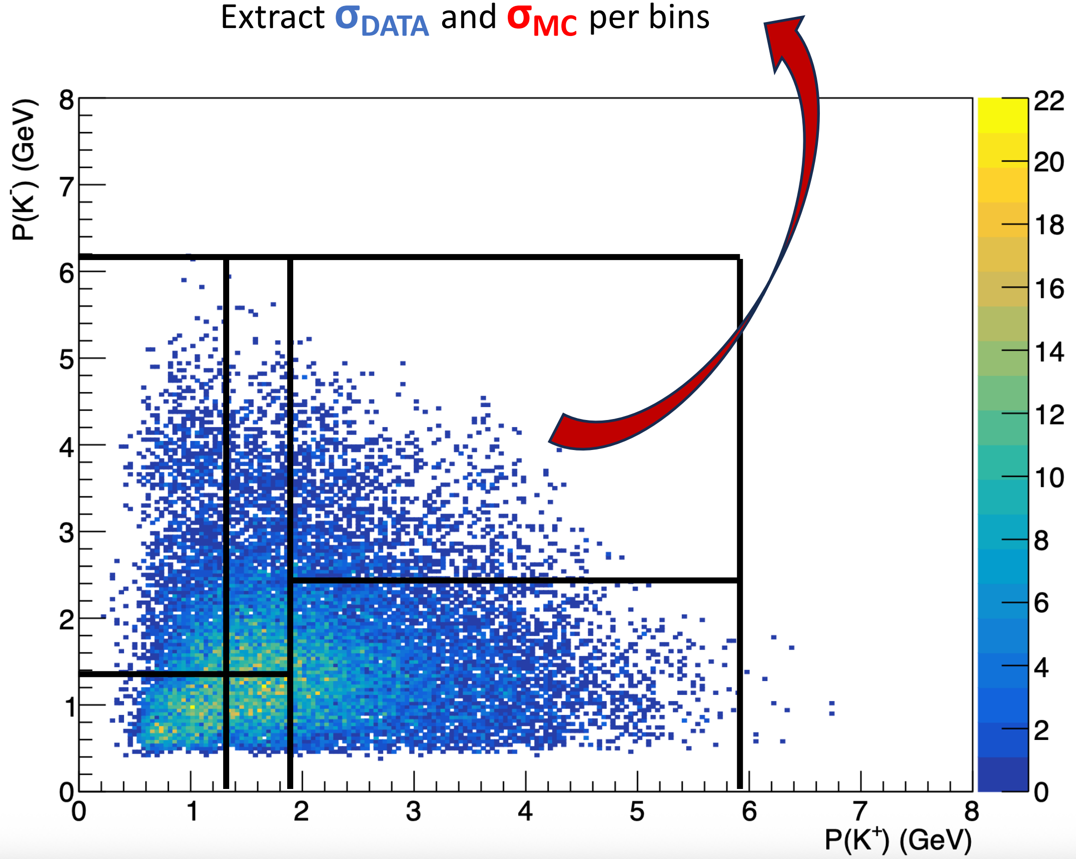


MC

Random fill from the distribution of data background

Smearing of the kaons 3

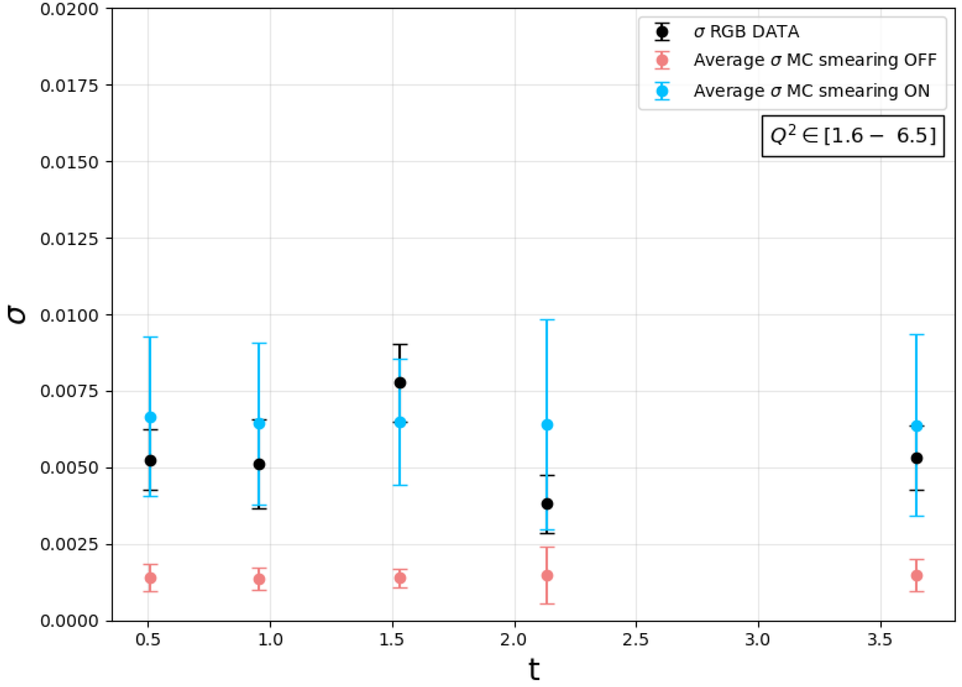
Extract σ_{DATA} and σ_{MC} per bins

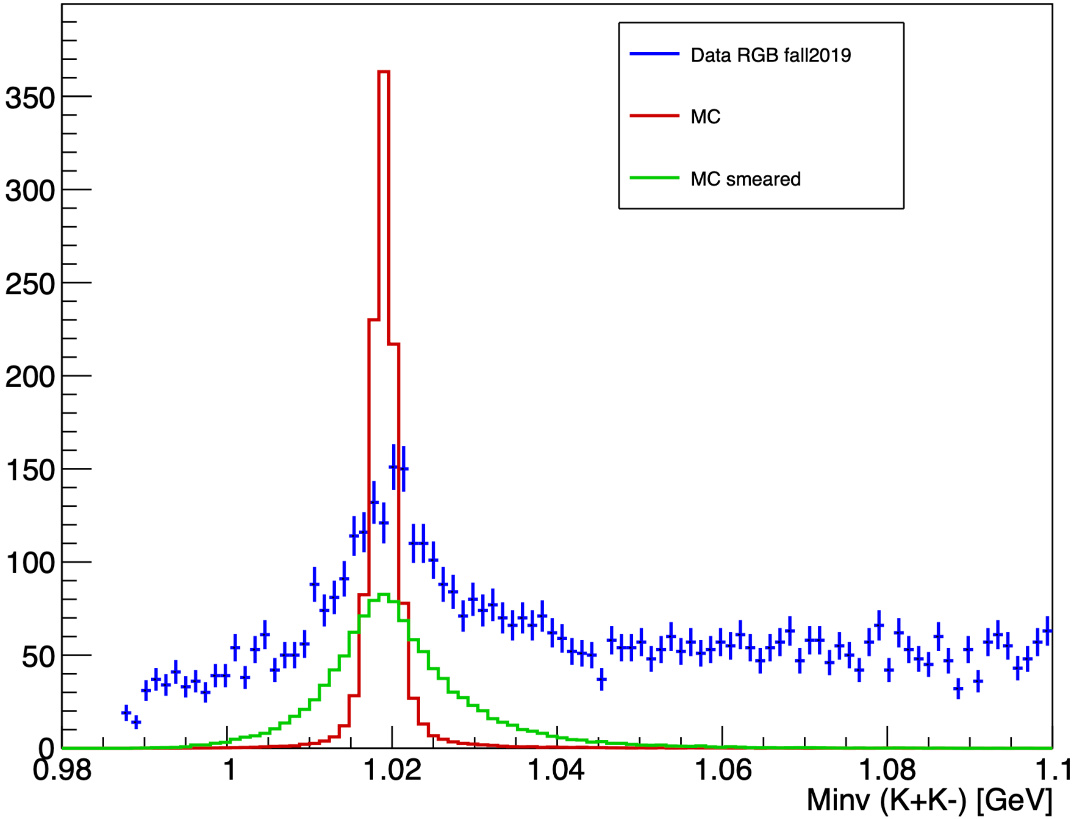


$$X^2 = \sum_{bins} \sigma_{DATA} - \sigma_{MC}$$

→ Minimise X^2 with Minuit2 (Simplex) and find 8 parametters A1, B1, C1, D1, A2, B2, C2, and D2 of the smearing functions

Smearing of the kaons 4





Acceptance 1

$$A = \frac{N_{rec}}{N_{gen}} * \frac{N_{fit}}{N_{random}}$$

Contribution from the model, the geometry and the efficiency.

Contribution from the resolution of the fit.

N_{rec} : Number of reconstructed event in the MC

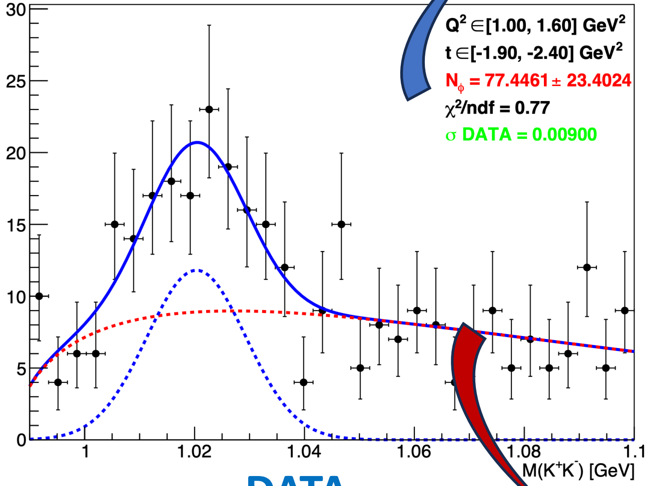
N_{gen} : Number of generated event in the MC

N_{random} : Number of event random fill from the MC reconstructed histogram (equal the number of phi extracted in the data)

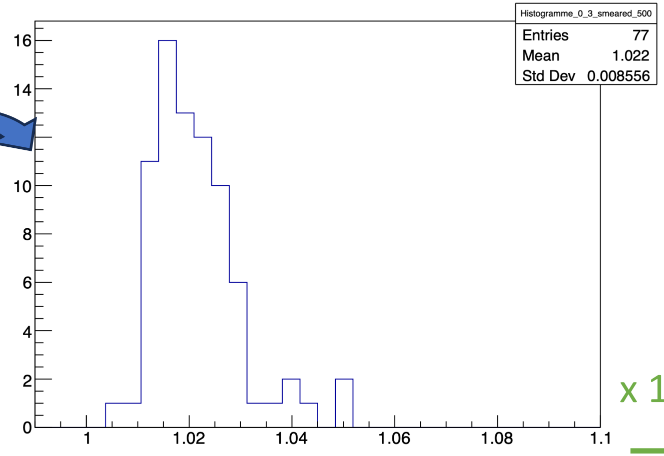
N_{fit} : Number of extracted event with the fit (average of 10000 pseudo-exp)

Acceptance 2

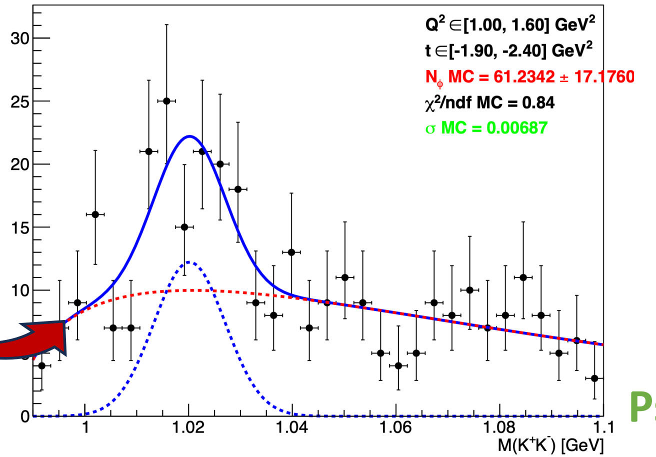
Random fill (with N_{random} equal to the number of ϕ in the data) from the MC reconstructed histogram.



DATA

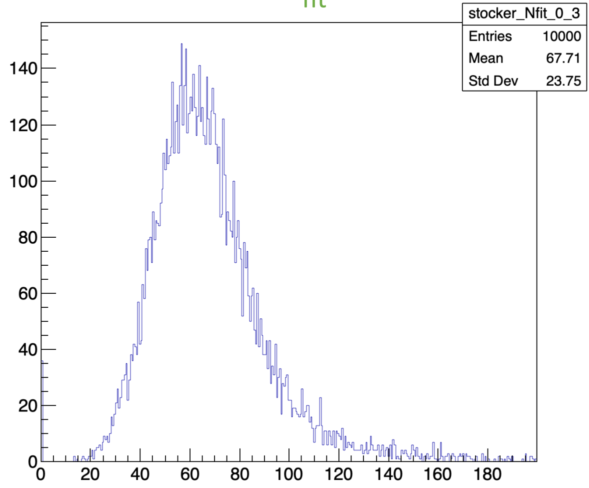


x 10 000



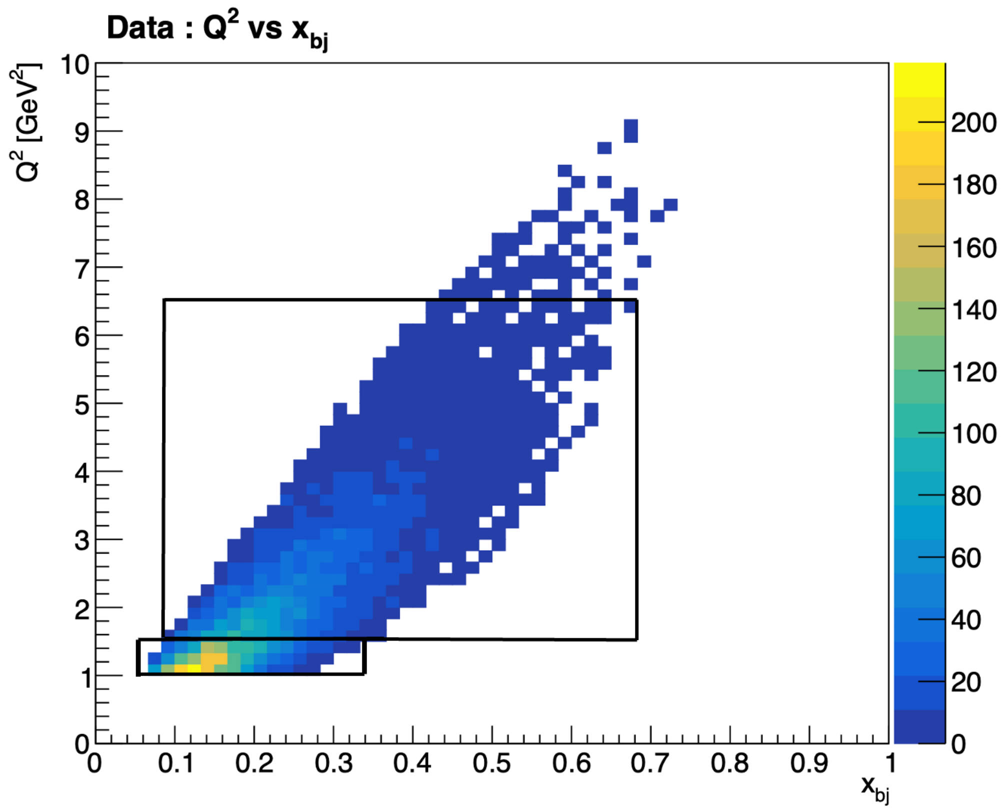
Pseudo-exp

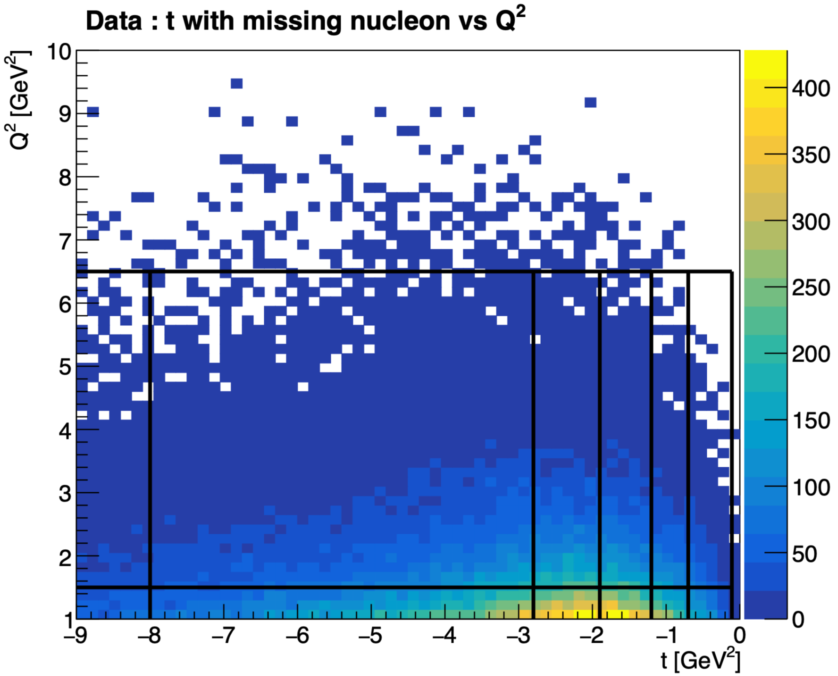
N_{fit}



Random fill from the distribution of data background

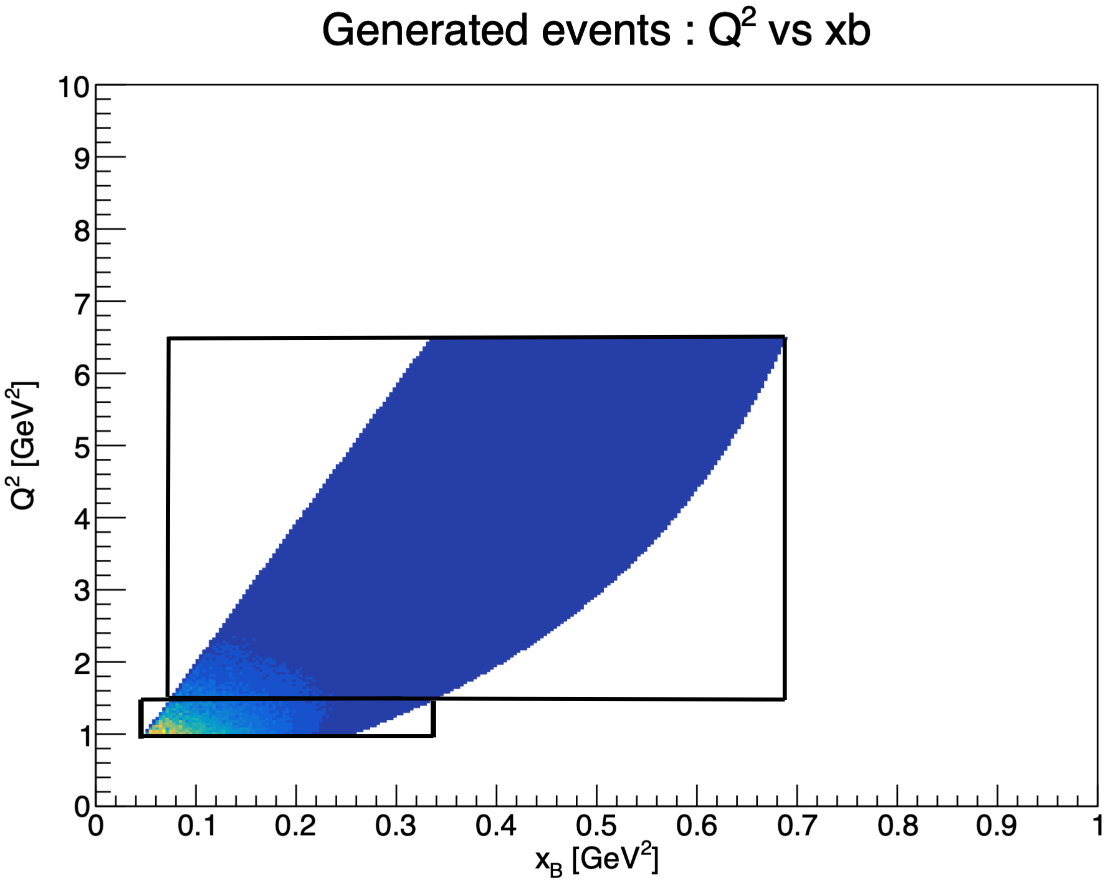
Cross section calculation 1 (binning on Q2, xb, and t)





- t binning for the two bins in Q^2

Cross section calculation 2 (binning correction)

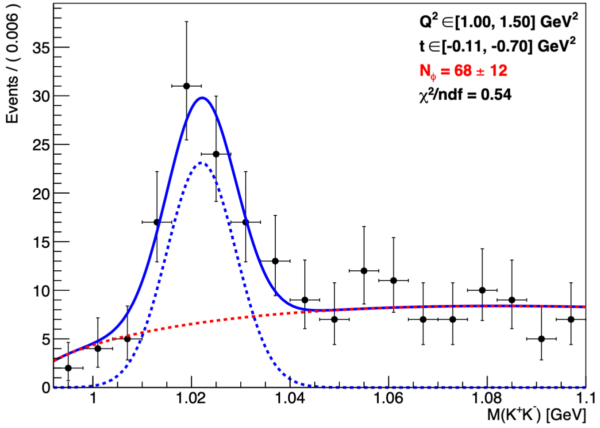


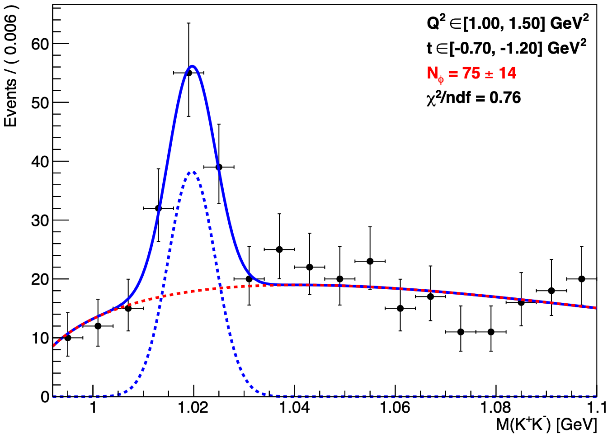
- The correction factor ***f*** is the size of the physical phase space in Q^2 and x_B divide by ΔQ^2 Δxb

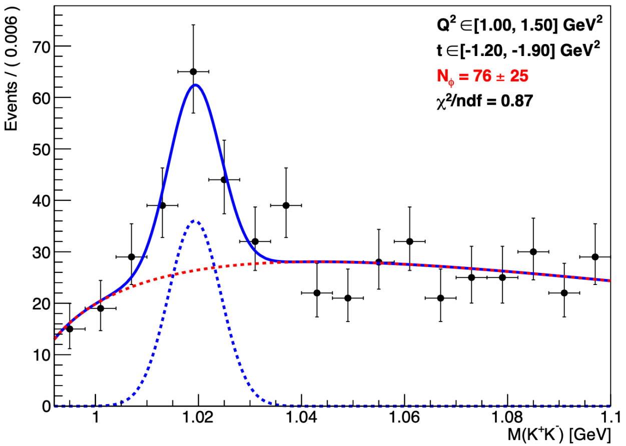
- To determine the size of the physical phase space, we use generated events and divide the number of filled bins by the total number of bins.

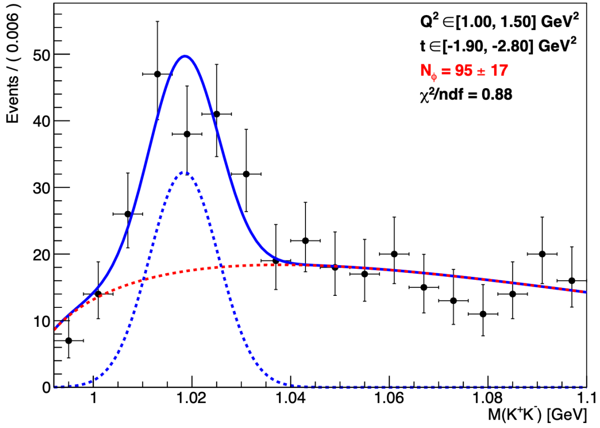
bin	$1.0 < \mathbf{Q^2} < 1.5$ GeV^2 $0.05 < \mathbf{xb} < 0.34$	$1.5 < \mathbf{Q^2} < 6.5$ GeV^2 $0.08 < \mathbf{xb} < 0.7$
f	**0.81**	**0.49**

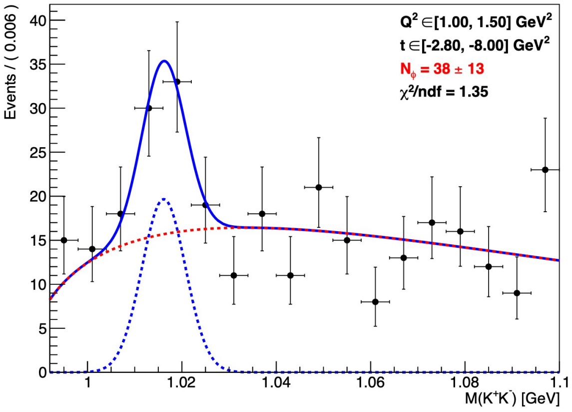
Cross section calculation 3 (all fit data bin1 Q^2)











Cross section calculation 4 (all fit data bin2 Q^2)