Accessing gluons in the nucleon: ϕ eletroproduction with the CLAS12 experiment

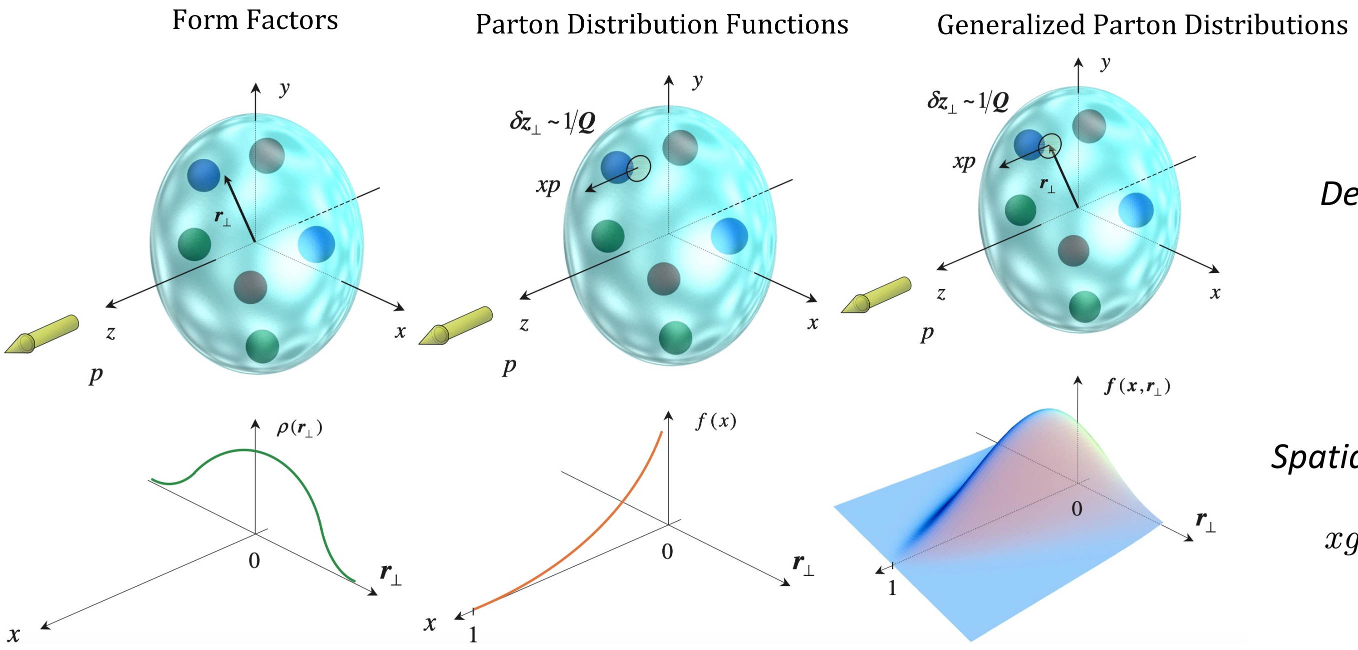
Towards improved hadron femtography with hard exclusive reactions

20 July 2026

M. Ronayette, for the CLAS collaboration

Summary

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.

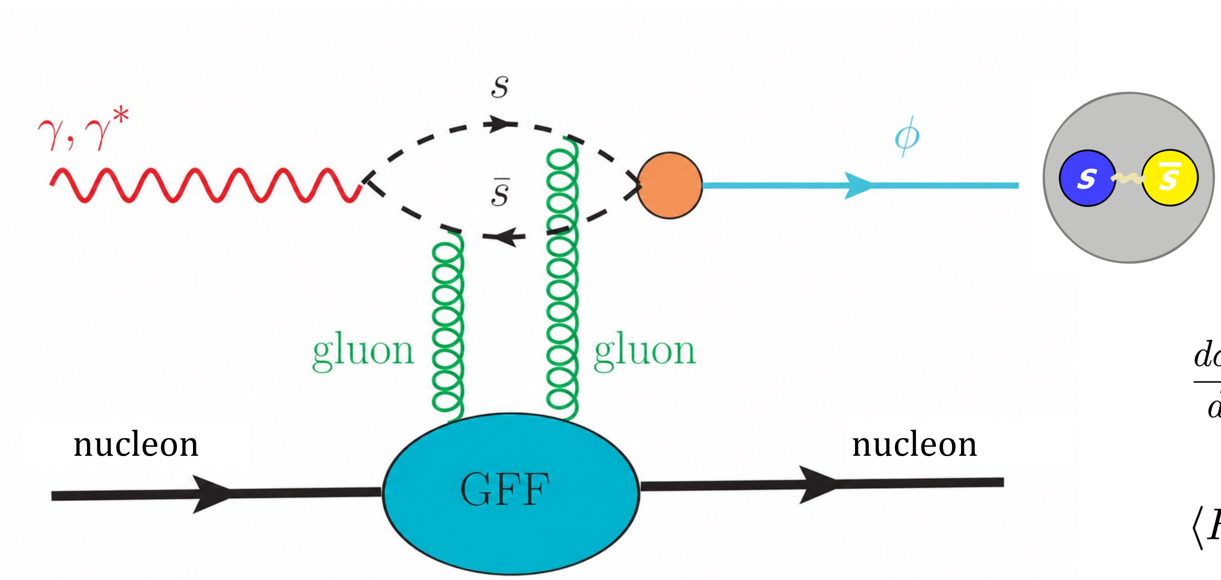
Density of gluons carrying momentum fraction x :

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

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



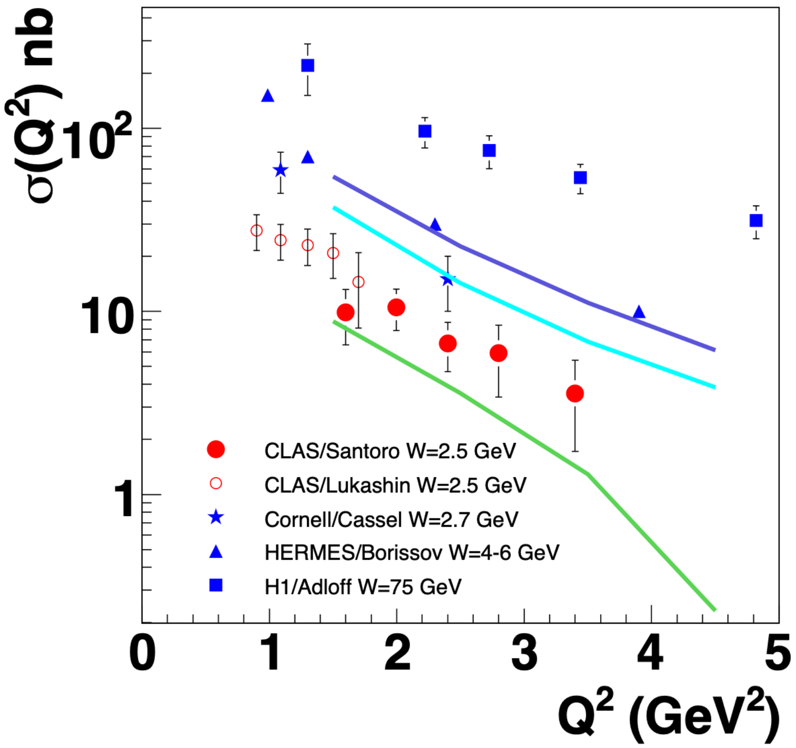
$$\frac{d\sigma_L}{dt} = \frac{\alpha_{\text{em}}}{Q^2}\frac{x_B^2}{1-x_B}\left[(1-\xi^2)|\langle H_g\rangle|^2 + \text{terms in } \langle E_g\rangle\right]$$

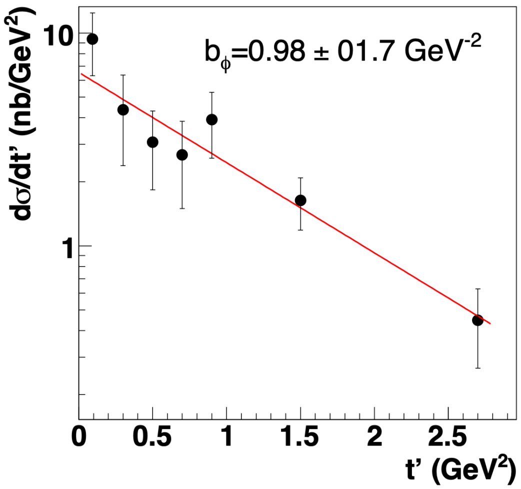
$$\langle H_g\rangle \equiv \frac{3\pi f_\phi}{27}\int_{-1}^{1} dx\ H_g(x,\xi;t)\ K(x,\xi,Q^2)$$

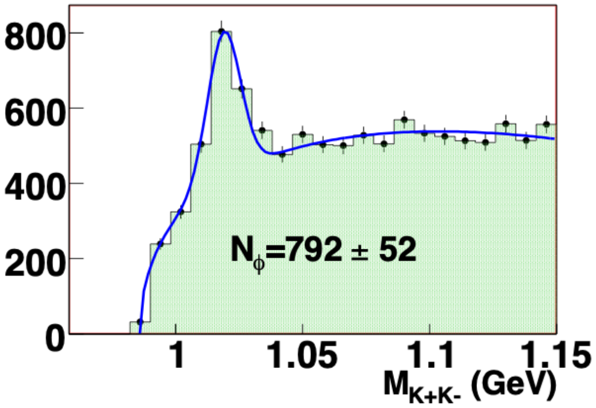
⟶ Since the contribution of the strange quark-antiquark pairs inside the nucleon is small, gluons play a major role in the creation of the ϕ meson.

⟶ Extracting the ϕ electroproduction cross section makes it possible to probe the gluon content of the nucleon.

Previous results with CLAS6





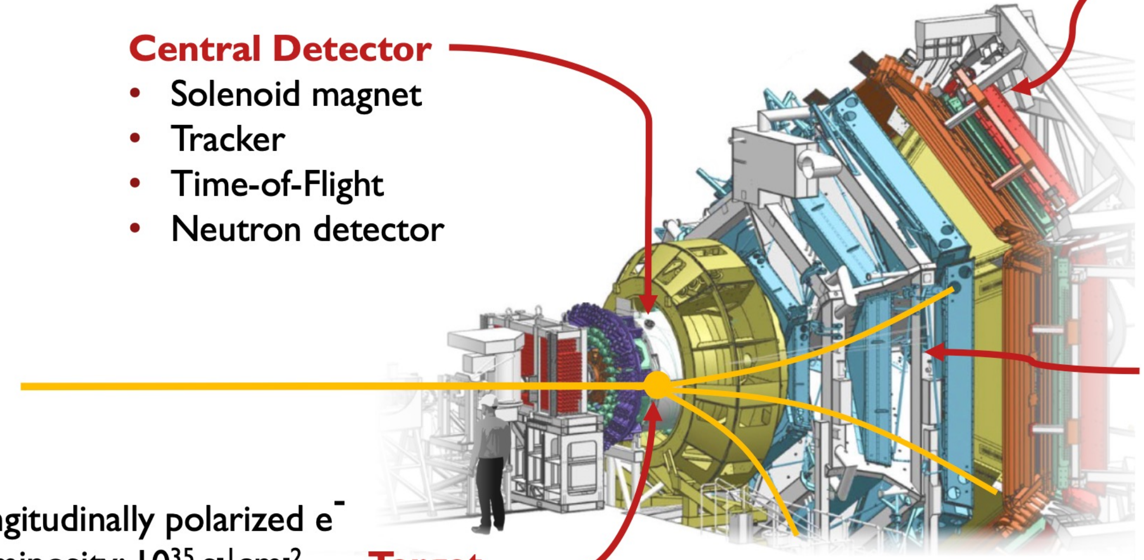


*Plots from J. P. Santoro et al. (CLAS), "Electroproduction of phi(1020) mesons at 1.4 < Q**2 < 3.8 GeV**2 measured with the CLAS spectrometer," Phys. Rev. C 78, 025210 (2008), arXiv:0803.3537 [nucl-ex].*

The CLAS12 Experiment

Central Detector
- Solenoid magnet
- Tracker
- Time-of-Flight
- Neutron detector

Forward Detector
- Torus magnet
- Drift Chambers
- Time-of-Flight
- Calorimeters
- Cherenkov counters



Forward Tagger
- Calorimeter
- Time-of-Flight
- Tracker

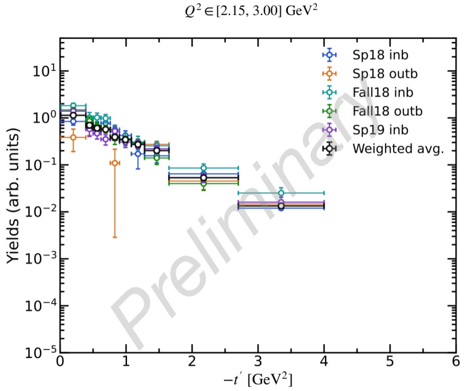
Beam
- 85% longitudinally polarized e^-
- Max. luminosity: $10^{35}\ s^{-1}cm^{-2}$
- Energy: 6.5 / 7.5 / ~10.6 GeV

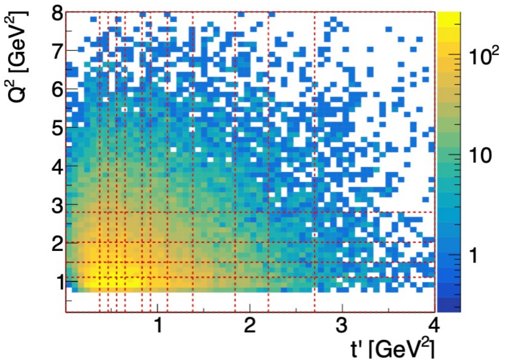
Target
- Proton
- Deuterium
- Longitudinally pol. H/D
- Nuclear targets

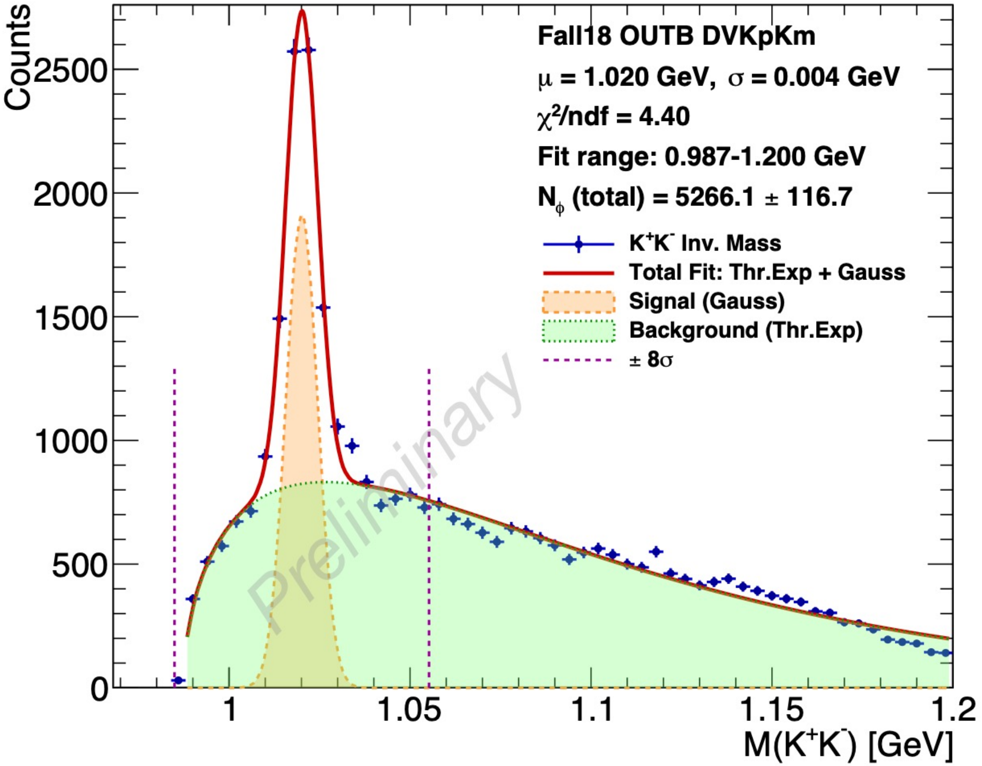
Figure from P. Chatagnon – Probing the proton fundamental properties with exclusive reactions at Jefferson Lab

ϕ electroproduction on the proton

- e p → e' p' **ϕ**
- In **$K^+ K^-$** channel : e p → e' p' $K^+ K^-$ (Br ~49.2%)
- Use a liquid **dihydrogen** target.
- Beam energy : **10.2** and **10.6** GeV.







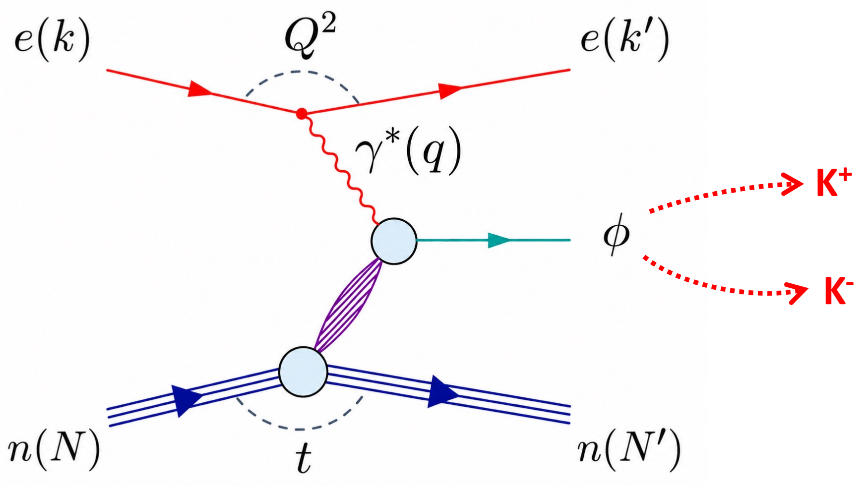
*Plots from **Bhawani Singh**.*

ϕ electroproduction on the neutron

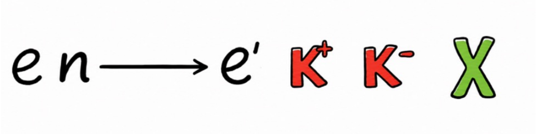
Analysis objective :

Measurement of the **cross section** of the **ϕ electroproduction** on neutron.

- e n → e' n' **ϕ**
- Through **$K^+ K^-$** channel : e n → e' n' $K^+ K^-$ (Br ~49.2%)
- With a liquid **deuterium** target.
- Beam energy between **10.2** and **10.6** GeV.

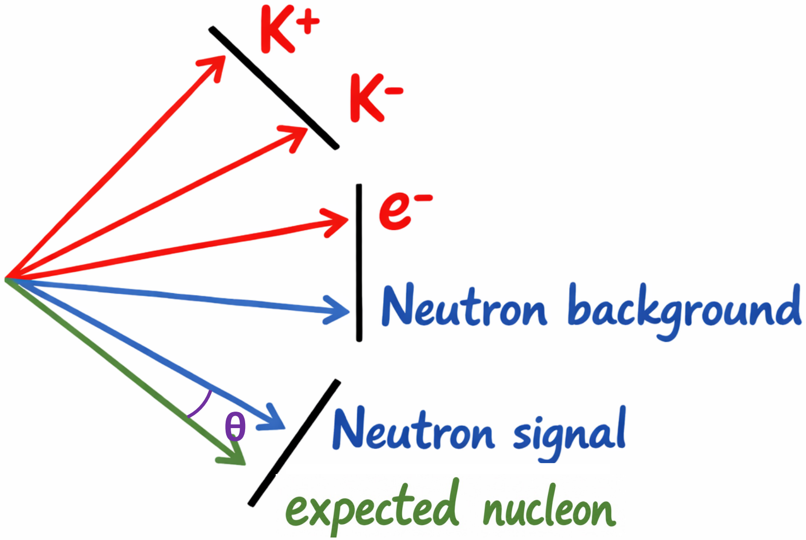


Neutron identification

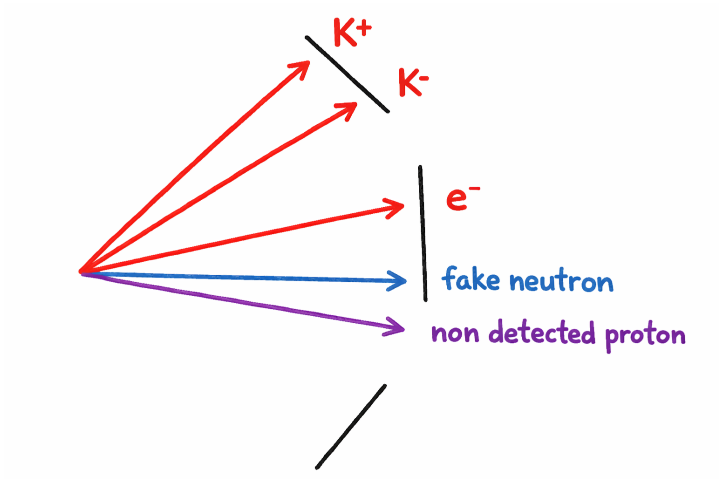


- Select the best neutron wich minimize the angle between the expected nucleon and the neutron and verify that the angle θ between both is less than 5 °.

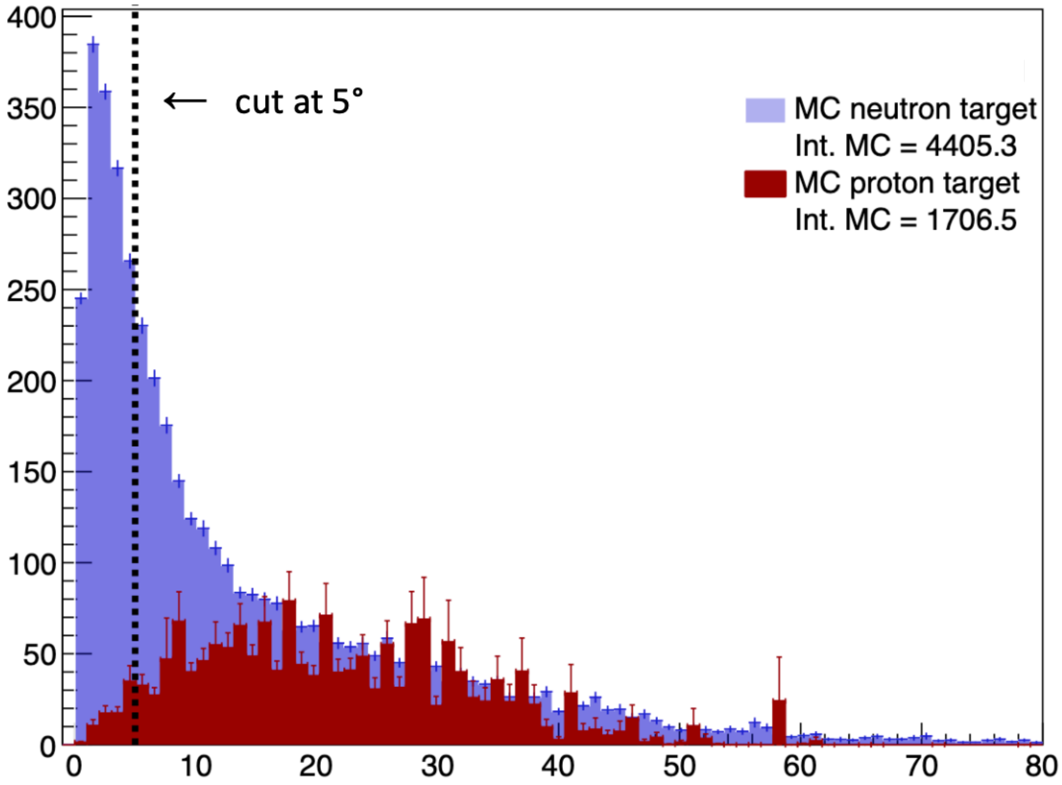
- Also we need **0 proton** detected to reduce contamination.



Proton contamination

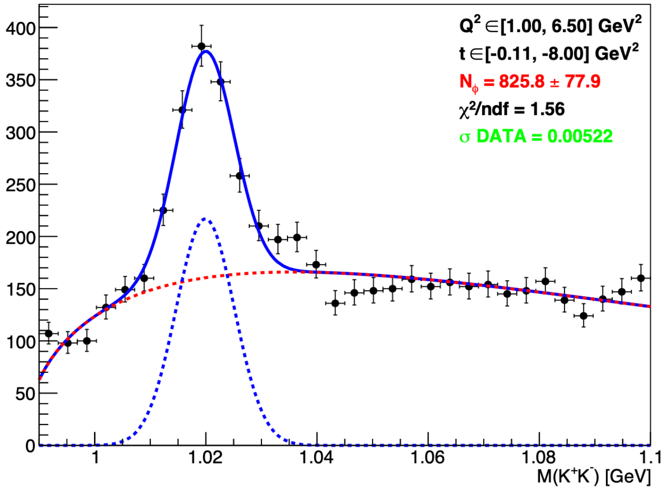


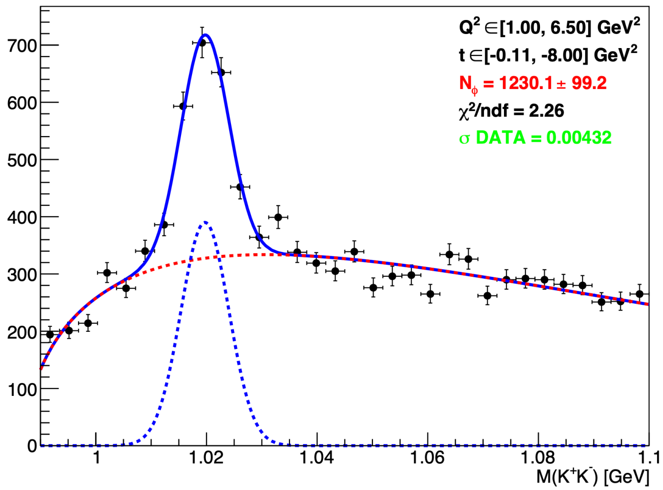
Contamination when the expected nucleon is a non detected proton and there is a fake neutron signal who pass the cut on the angle.

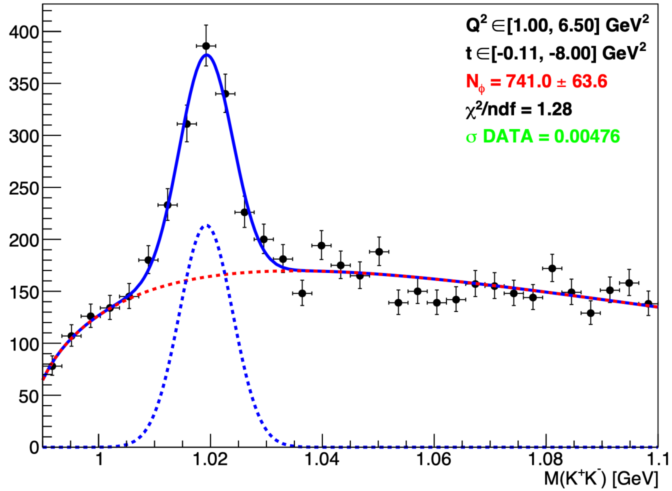


Angle between the expected nucleon and the neutron detected [deg]

Yields







Fall 2019 outbending

Q = 12.1 mC and Eb = 10.4 GeV

Spring 2019 inbending

Q = 63.4 mC and Eb = 10.2 | 10.6 GeV

Spring 2020 inbending

Q = 28.3 mC and Eb = 10.2 GeV

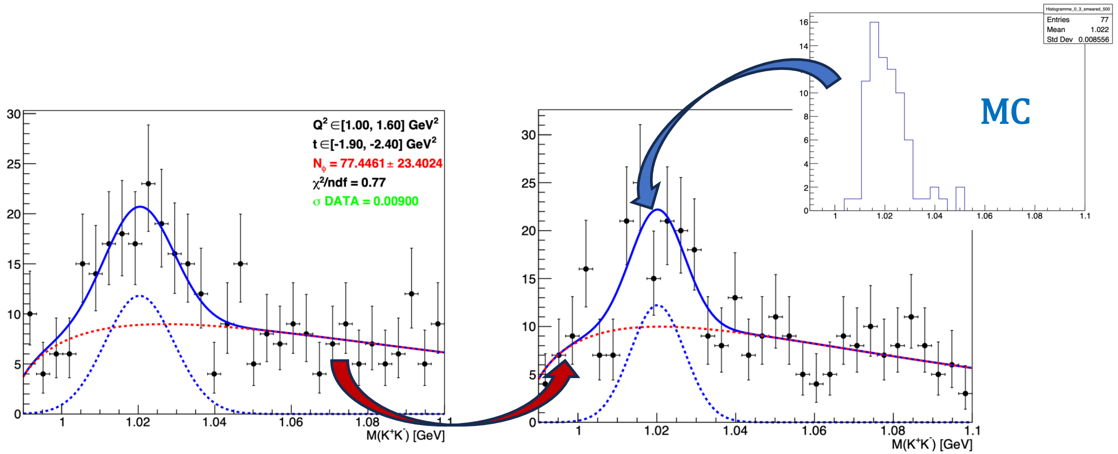
→ The outbending configuration provides a higher yield (relative to the accumulated charge) because it collects more low-Q^2 events.

Acceptance correction

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

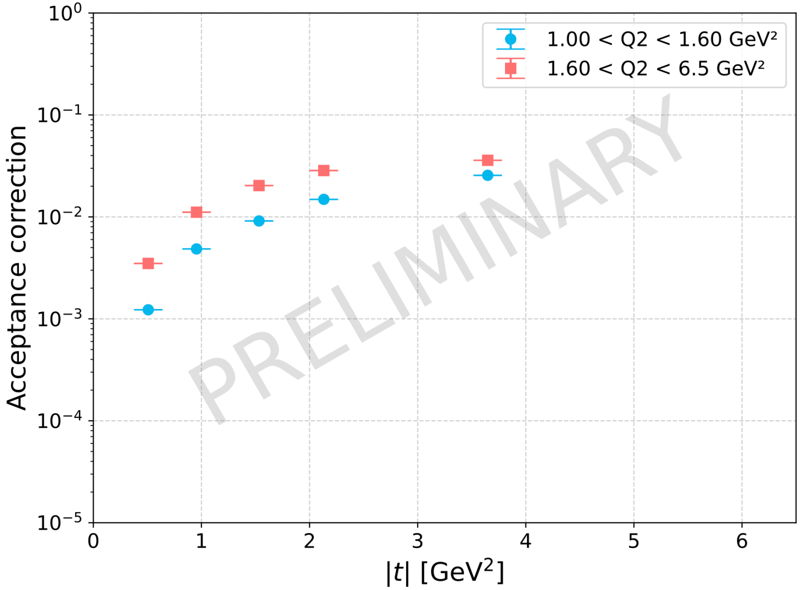
Contribution the geometry and the efficiency.

Contribution from the resolution of the fit.



DATA

MC Pseudo-exp



Preliminary results on the neutron

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

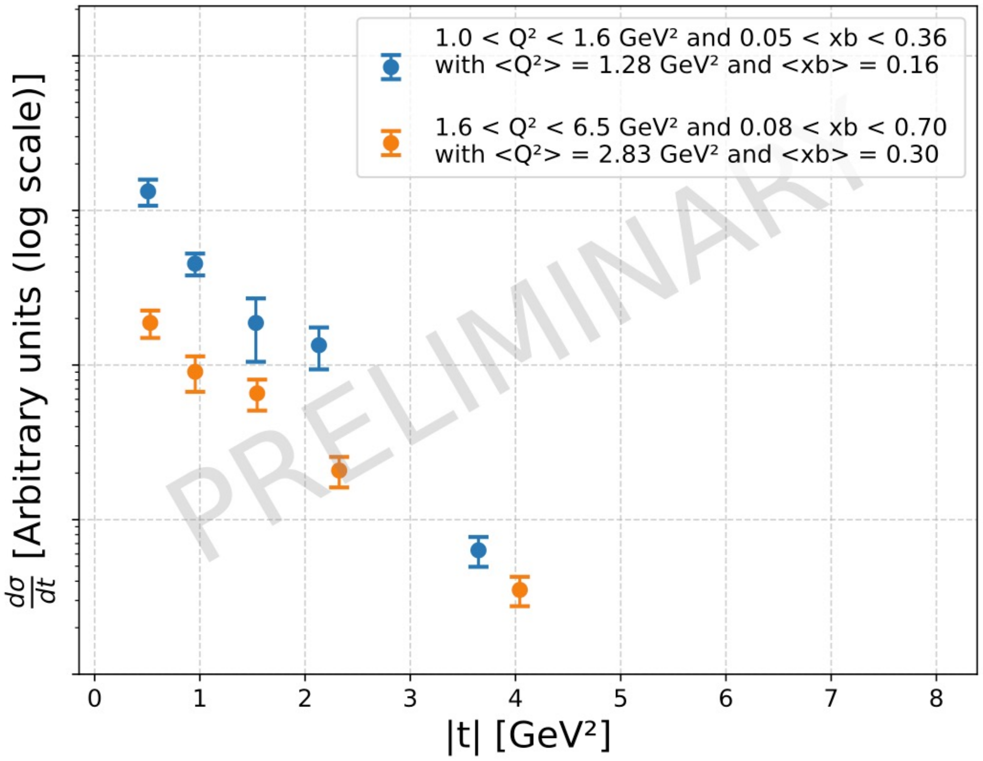
$$\frac{d^3\sigma}{dQ^2 dx_B dt} = \Gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt}(Q^2, x_B, t) + \epsilon\frac{d\sigma_L}{dt}(Q^2, x_B, t)\right]$$

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 $\gamma^* n \rightarrow n'\phi$ is given by :

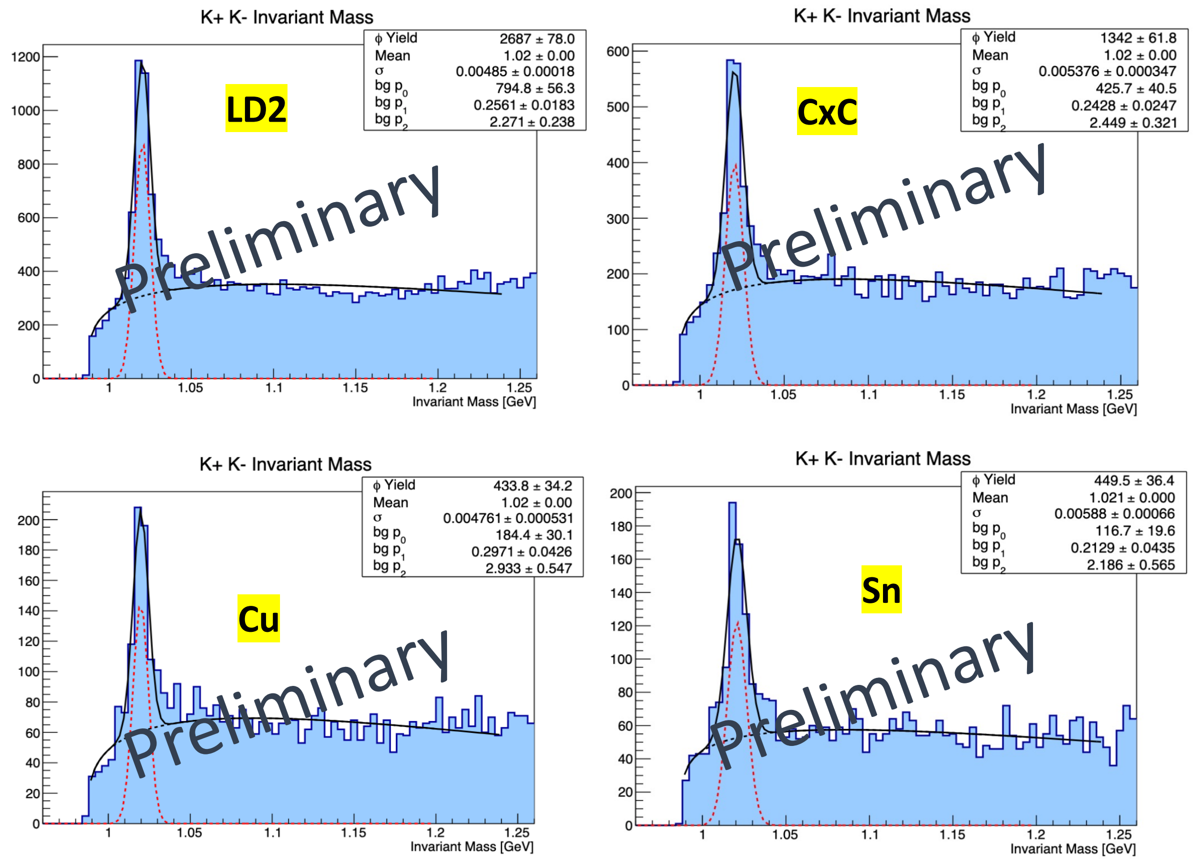
$$\frac{d\sigma}{dt}(Q^2, x_B) = \frac{1}{\Gamma(Q^2, x_B, E)} \cdot \frac{d^3\sigma}{dQ^2 dx_B dt}$$

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



With **Fall2019** outbending data

Incoherent ϕ production on nuclear targets



- Two datasets RG-D (2023), and RG-E (2024), yield estimation with ~10% of RG-D.
- Incoherent production : e p K^+ K^- in the final state.

Expected final yields on full RG-D dataset

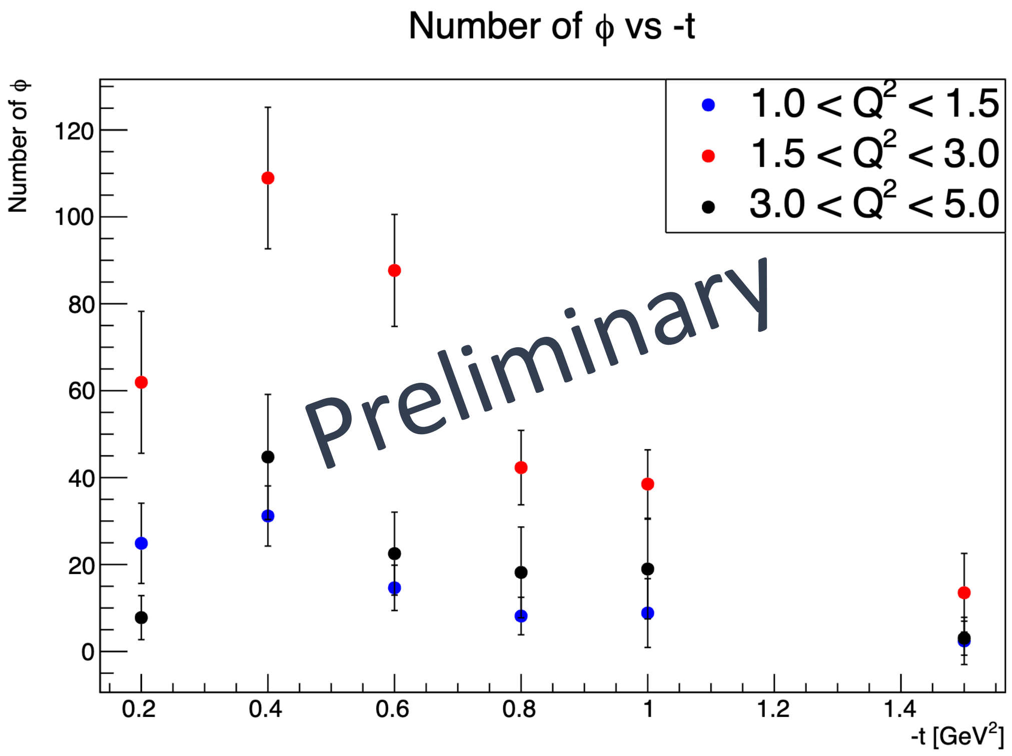
- LD2: ~ 25000
- CxC: ~13000
- Cu: ~ 4500
- Sn: ~ 4500

Aim to probe:

- Cross section ratios (function of x).
- Impact of nuclear system on the gluonic structure of the proton.
- Model dependent FSI contribution.

Plots from Richard Tyson.

Coherent ϕ production on deuterium



Detect **e d K$^+$ K$^-$** to tag coherent production on the deuteron.

Main dataset with LD2 target (RG-B).

Two other datasets to be investigated (RG-D, RG-E) as they also include D2 targets.

Very preliminary analysis, will optimise PID and detection strategy to increase statistics

Aim to probe **Q^2** and **t** dependence of cross section.

Plots from Richard Tyson.

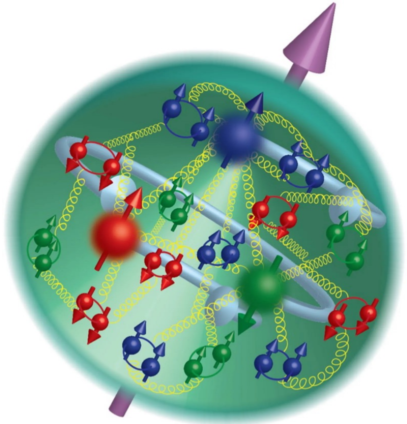
Conclusion and outlook

- The ϕ electroproduction analysis on the **proton** is well advanced, with the extraction of the Spin Density Matrix Elements (SDMEs) currently underway.

- The **neutron** analysis is progressing toward the first measurement of exclusive ϕ electroproduction on the neutron with CLAS12.

- Future studies on **nuclear targets** will investigate how the gluonic structure of nucleons is modified in the nuclear medium through exclusive ϕ meson production.

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

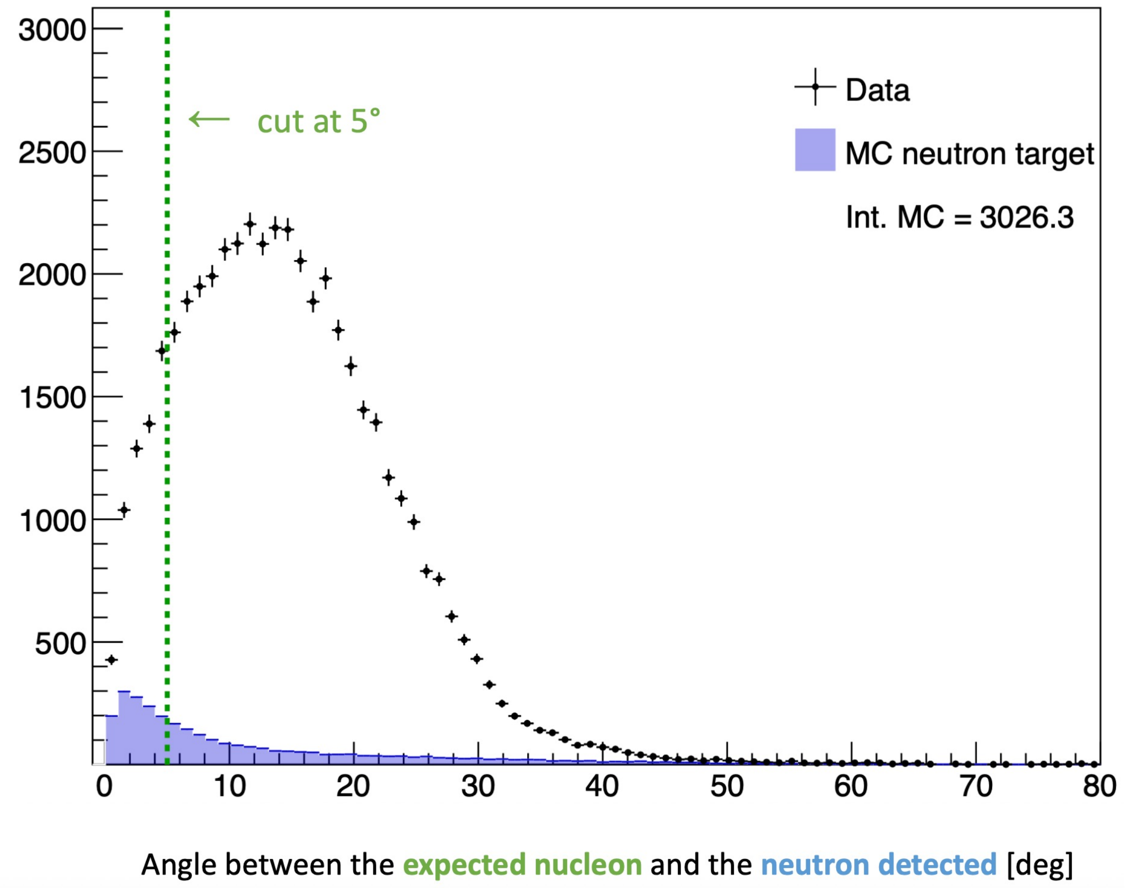


Thanks!

Backup

Backup slides

Exclusivity cuts and kinematics cuts

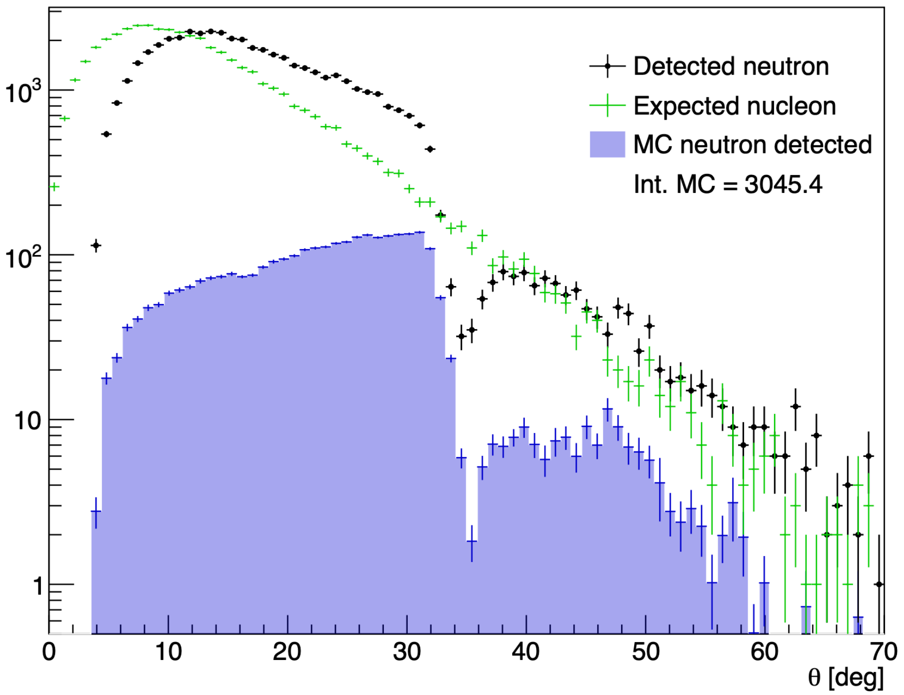


Expected nucleon : missing particle of e n → e' K^+ K^- X

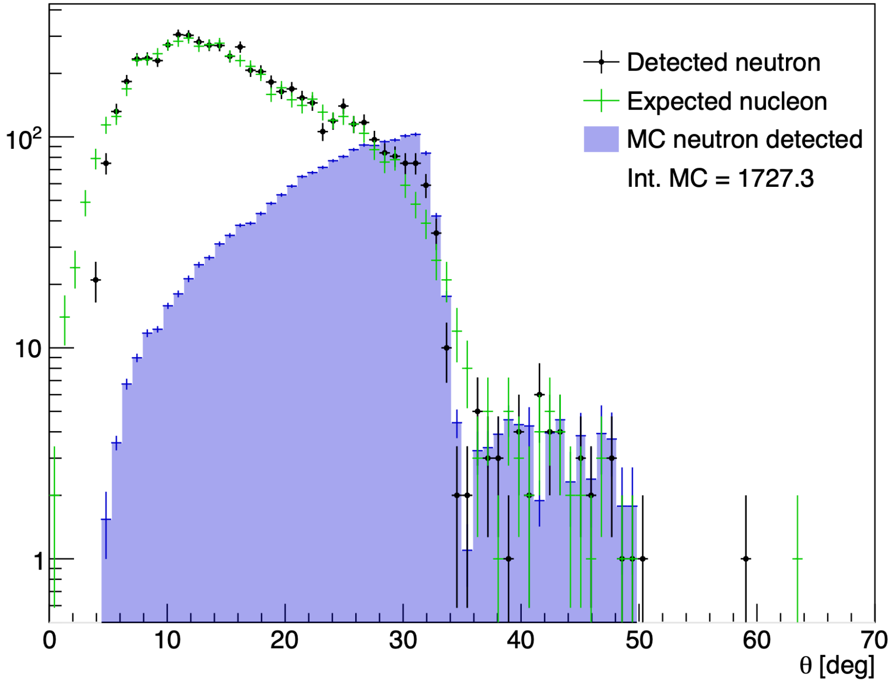
- Cut at 5° correctly select true neutron.
- The choice of this cut depend of the smearing in the MC.
- A cut at 10° will be tested in the future.

Exclusivity cuts and kinematics cuts

Neutron lab frame polar angle $\theta_{neutron}$



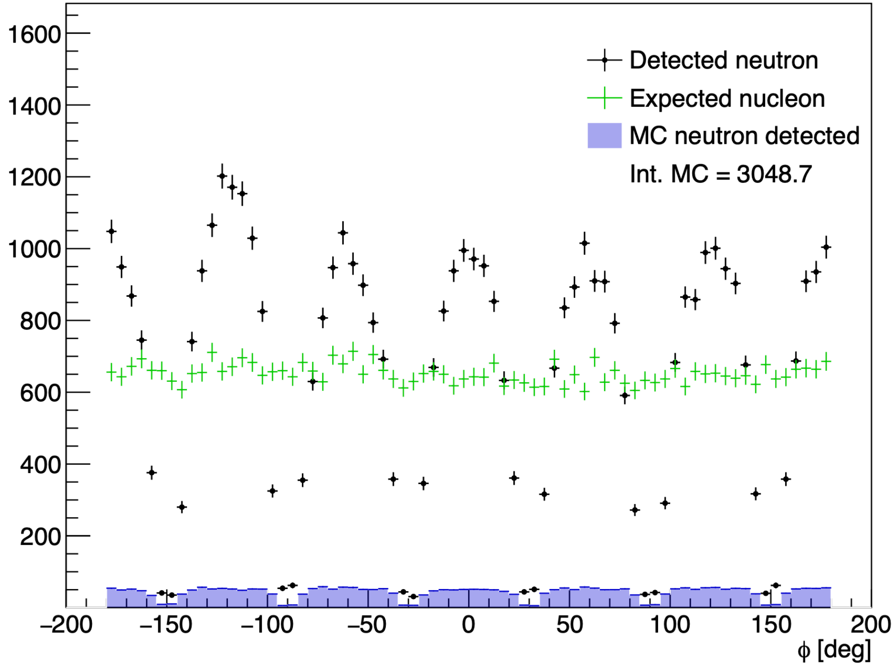
Neutron lab frame polar angle $\theta_{neutron}$



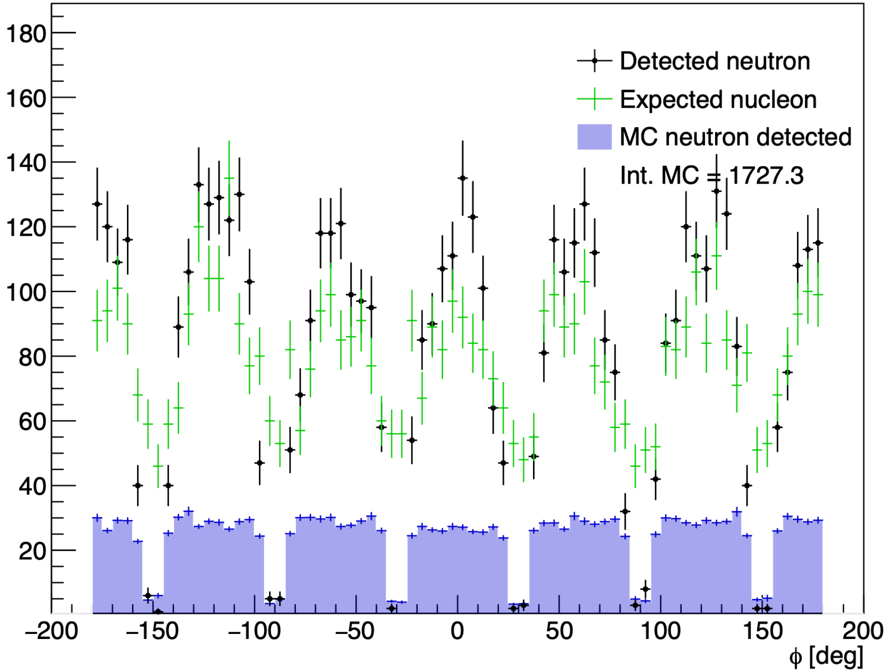
Before (left) and after (right) the cut on the angle between the expected nucleon and the detected neutron

Exclusivity cuts and kinematics cuts

Neutron lab frame azimuthal angle $\Phi_{neutron}$



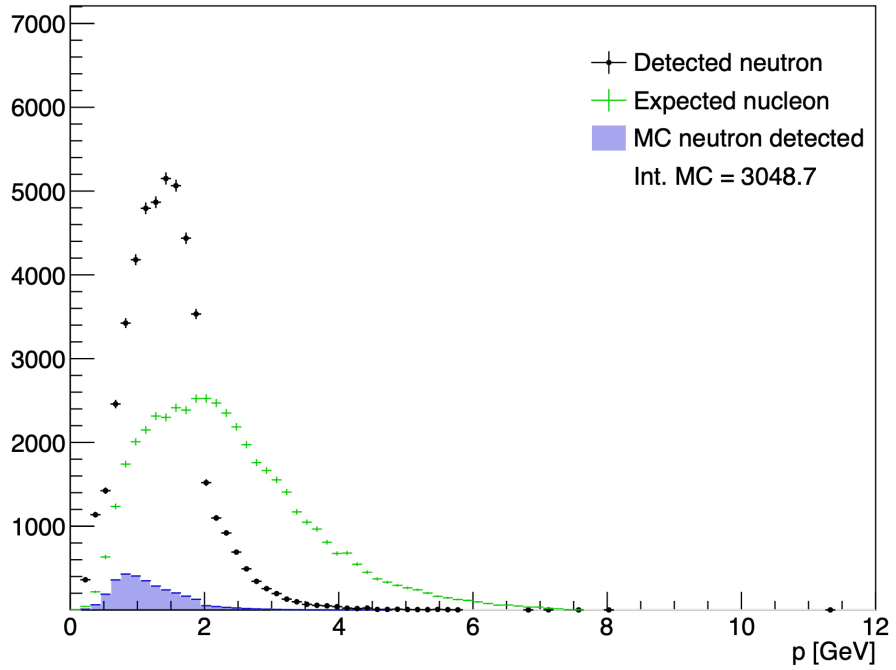
Neutron lab frame azimuthal angle $\Phi_{neutron}$



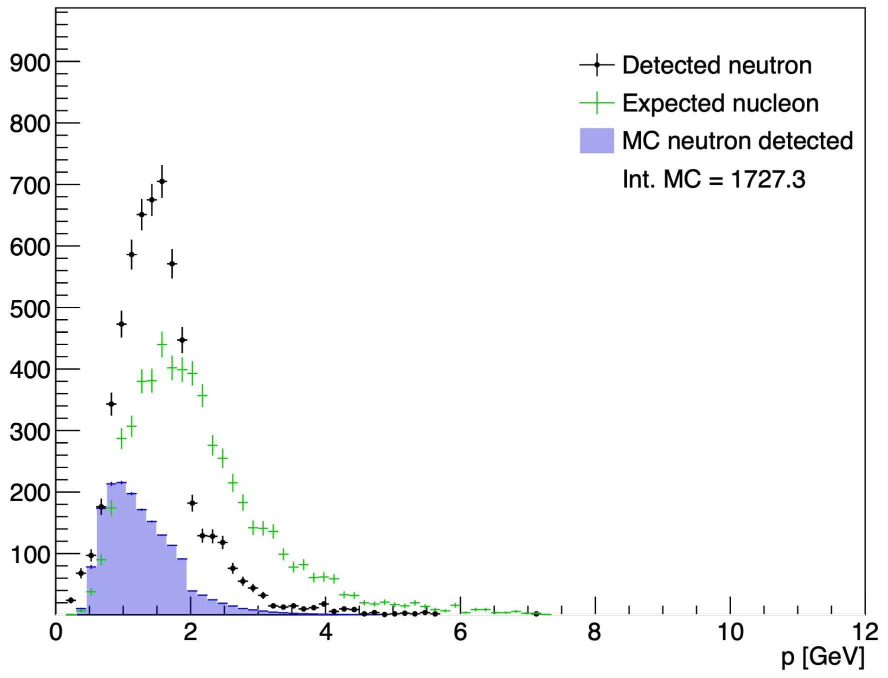
Before (left) and after (right) the cut on the angle between the expected nucleon and the detected neutron

Exclusivity cuts and kinematics cuts

Neutron lab frame momentum

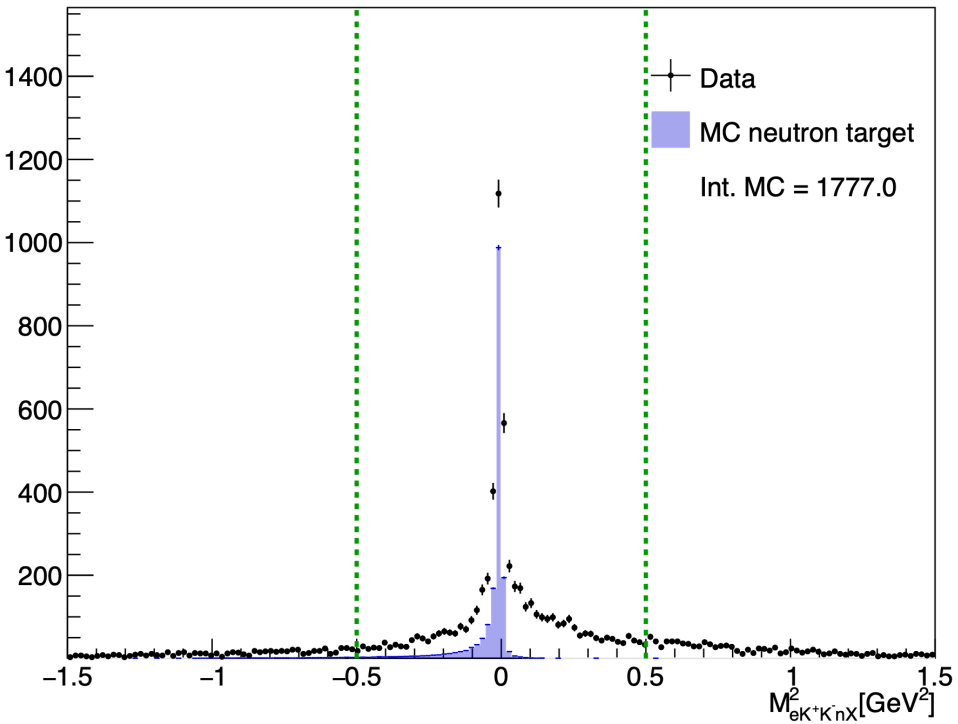


Neutron lab frame momentum



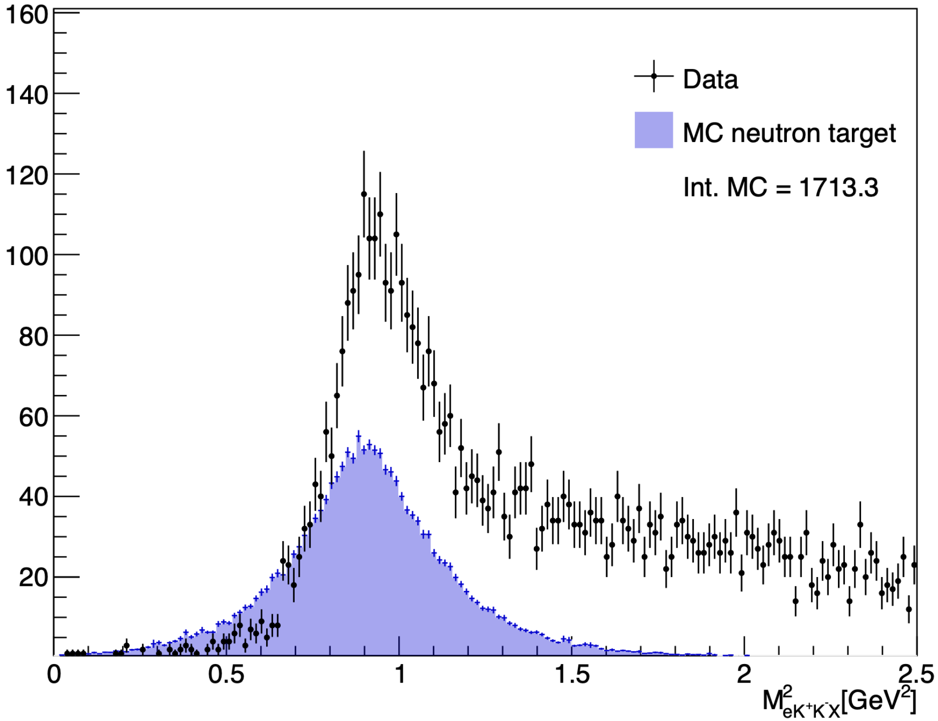
Before (left) and after (right) the cut on the angle between the expected nucleon and the detected neutron

Exclusivity cuts and kinematics cuts



e n → e' n K^+ K^- **X**

(After all previous cuts)



e n → e' K^+ K^- **X**

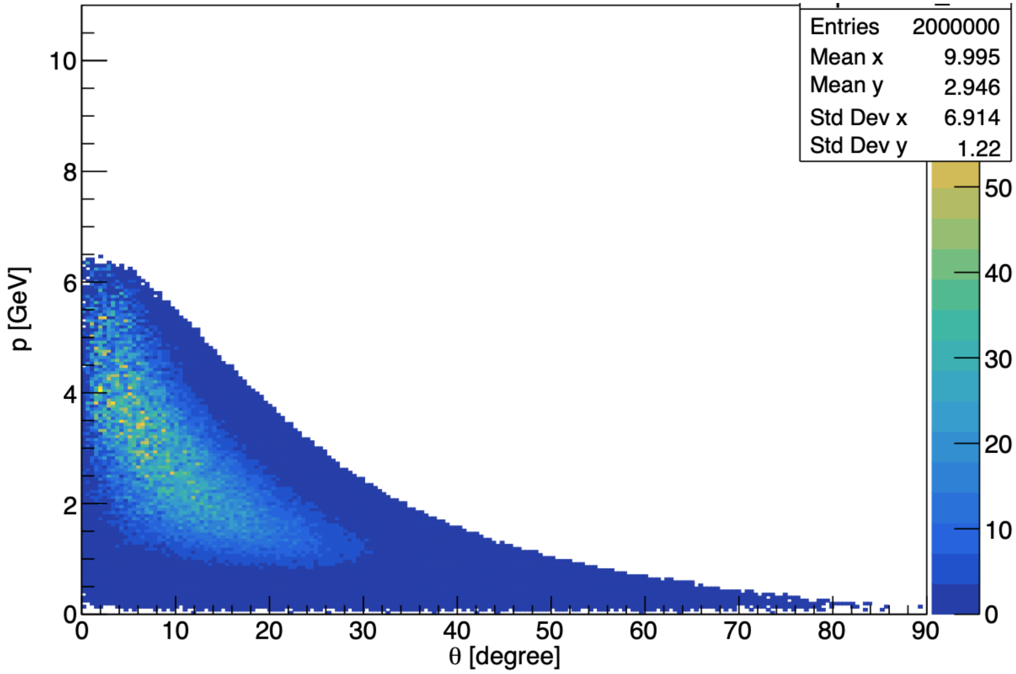
(After all previous cuts and the cut on the total missing mass)

Exclusivity cuts and kinematics cuts

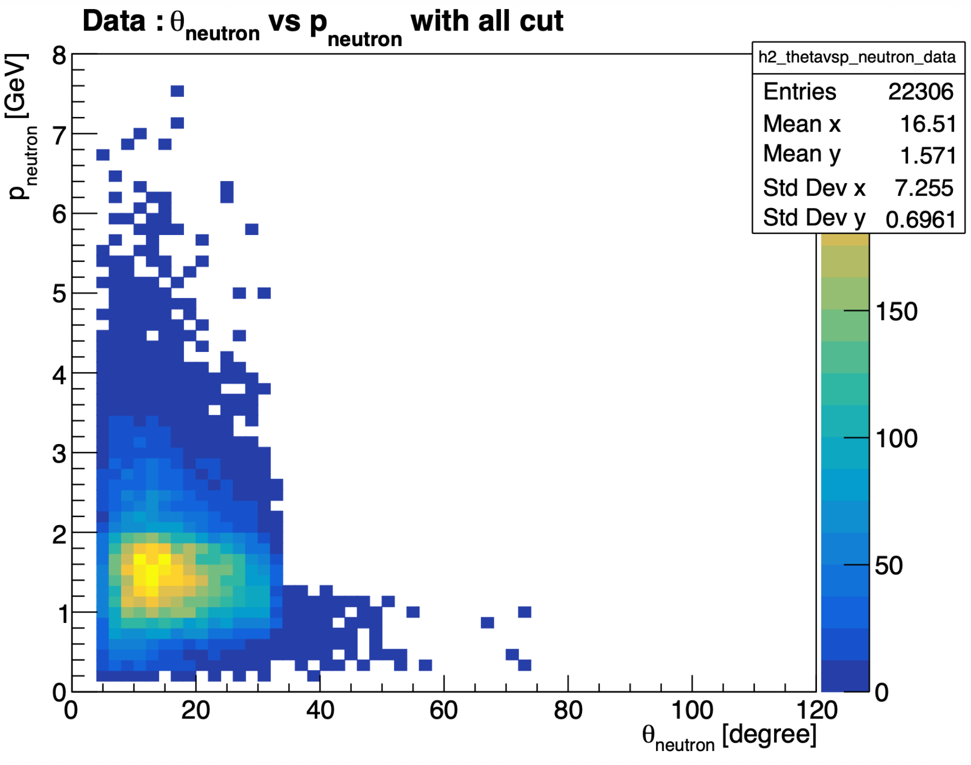
Two justifications to cut K+ K- in CD :

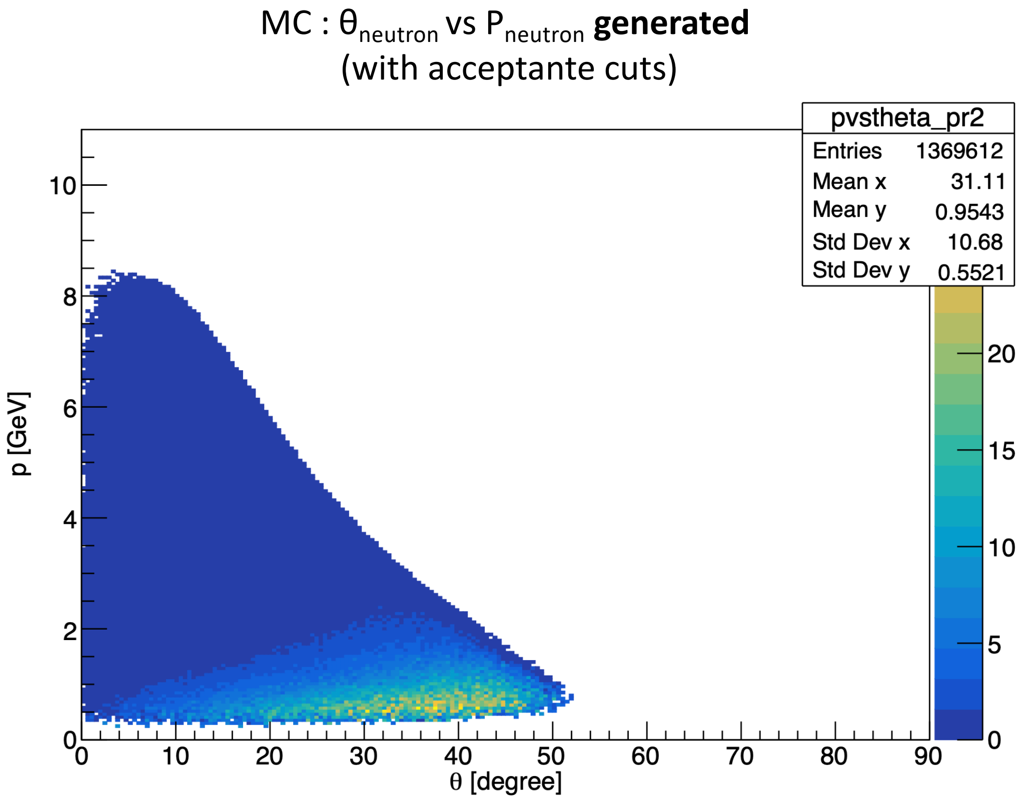
- Reconstruction of kaons in the CD is less good than in the FD
- The generator predict few events in the CD

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

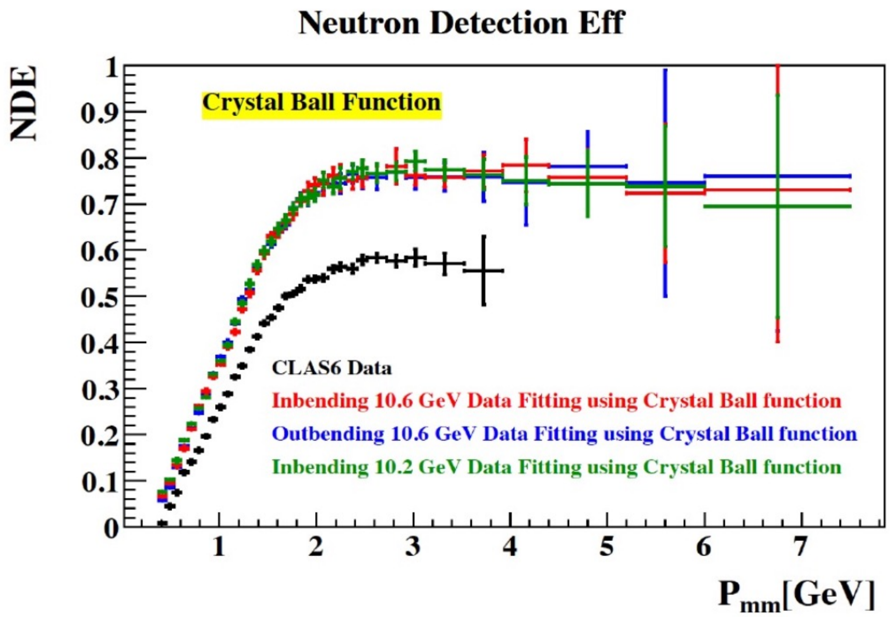


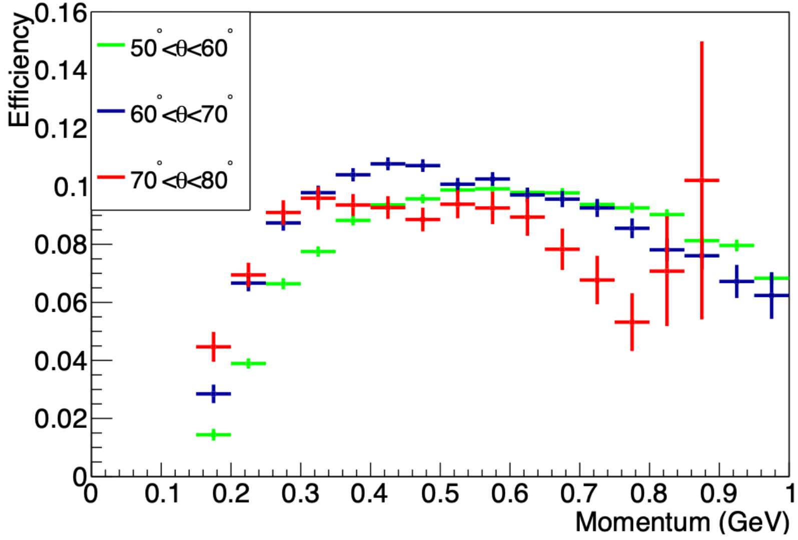
Exclusivity cuts and kinematics cuts





Exclusivity cuts and kinematics cuts



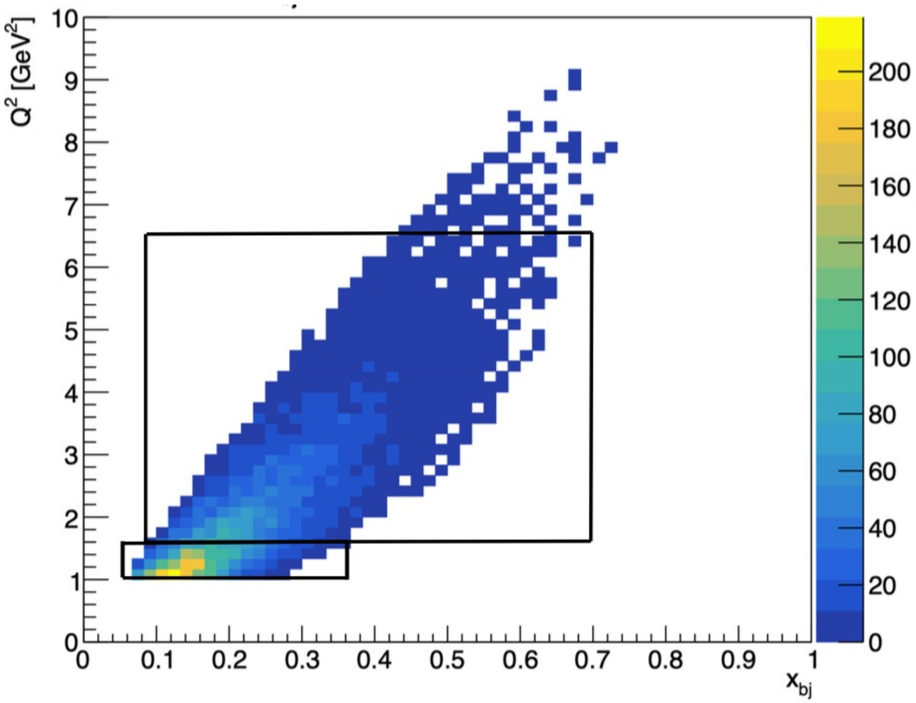


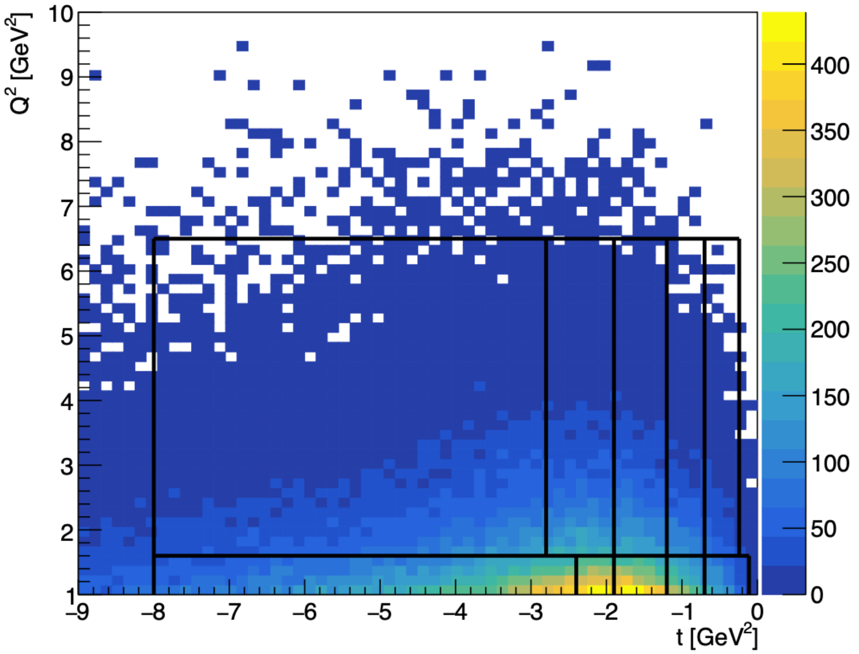
P. Chatagnon's plot

Neutron detection efficiency in the FD

Neutron detection efficiency in the CND

Phasespace

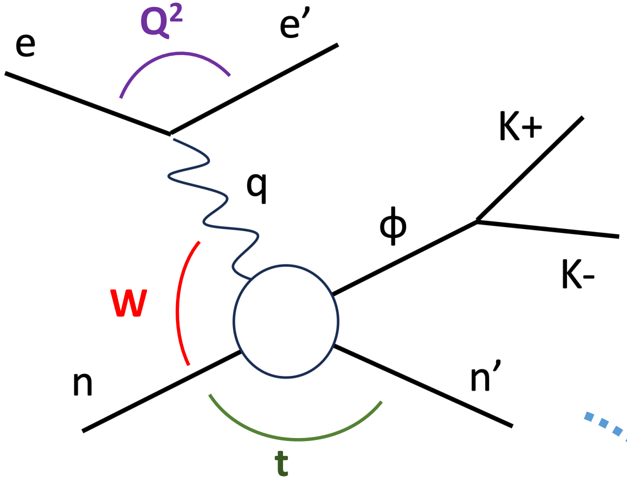




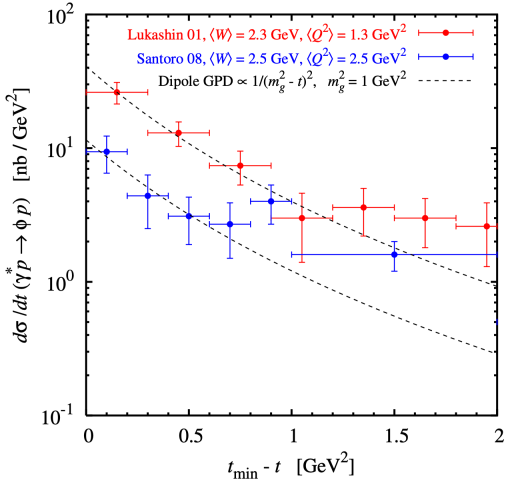
- t binning for the two bins in Q^2

Generator for MC simulation

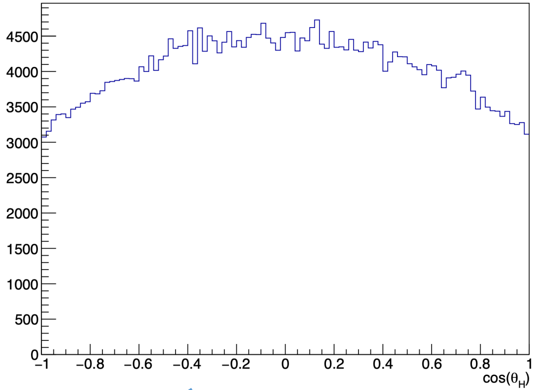
1) kinematics



2) Cross section



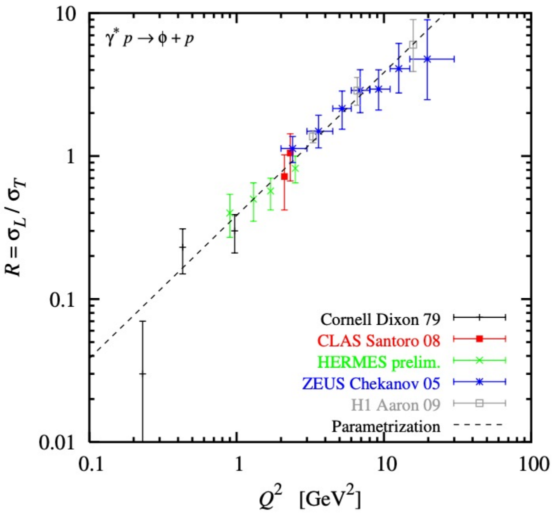
3) SDME



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

Generator for MC simulation (SDME)

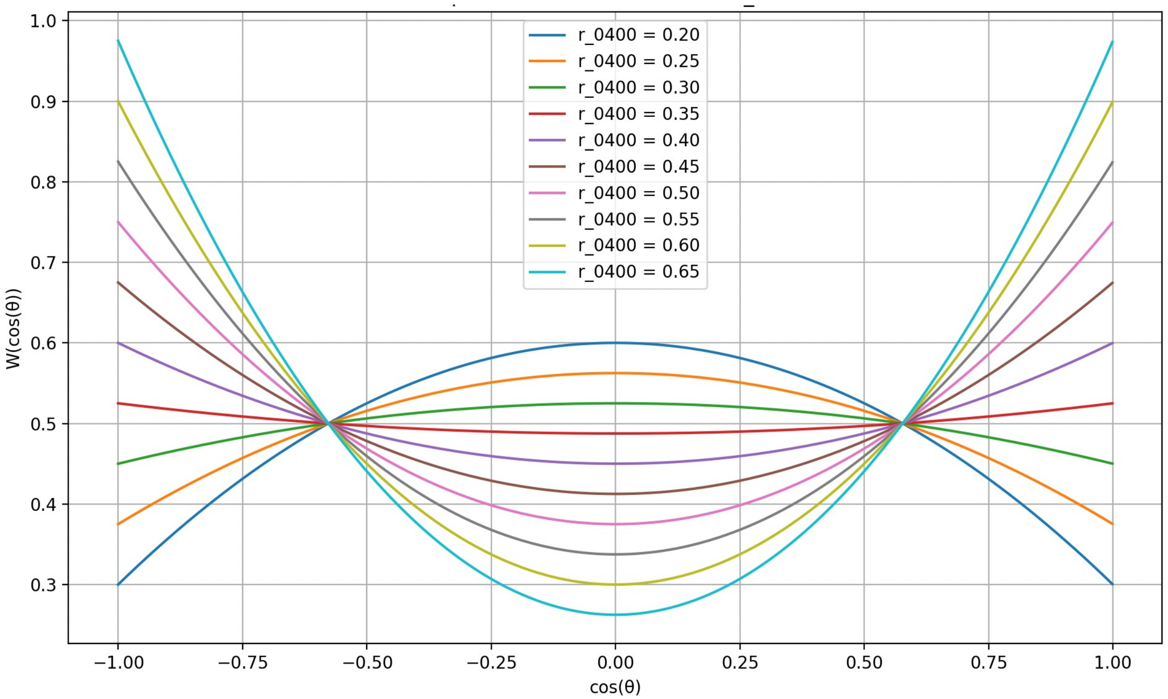
$$W(\cos\theta_H) = \frac{3}{4}\left[\left(1 - r_{00}^{04}\right) + \left(3r_{00}^{04} - 1\right)\cos^2\theta_H\right]$$



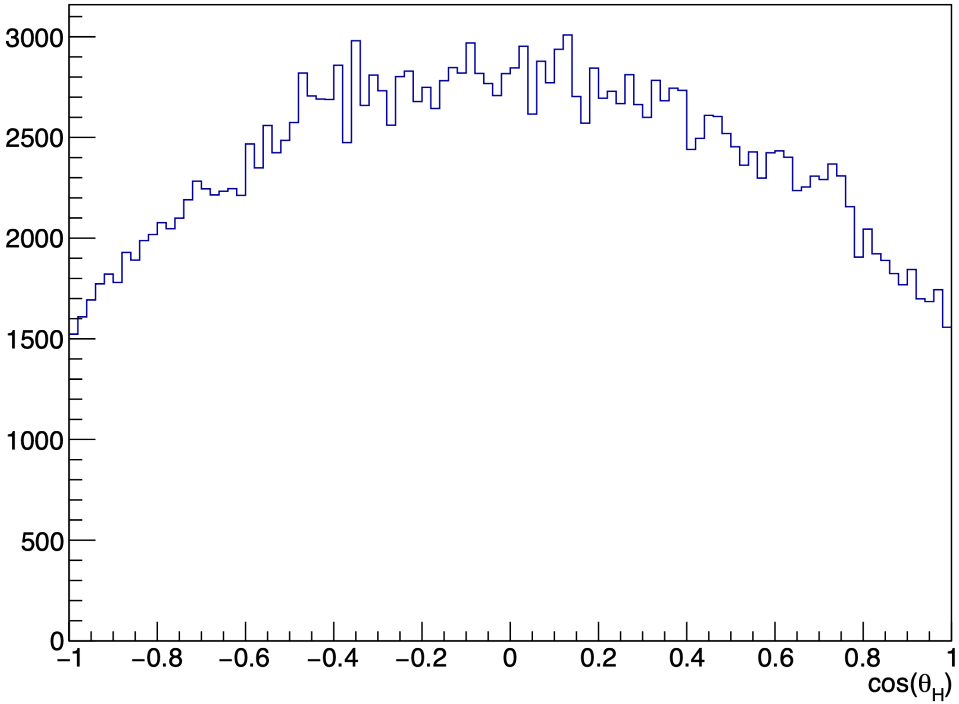
$$R = \frac{r_{00}^{04}}{\epsilon(1 - r_{00}^{04})}.$$

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

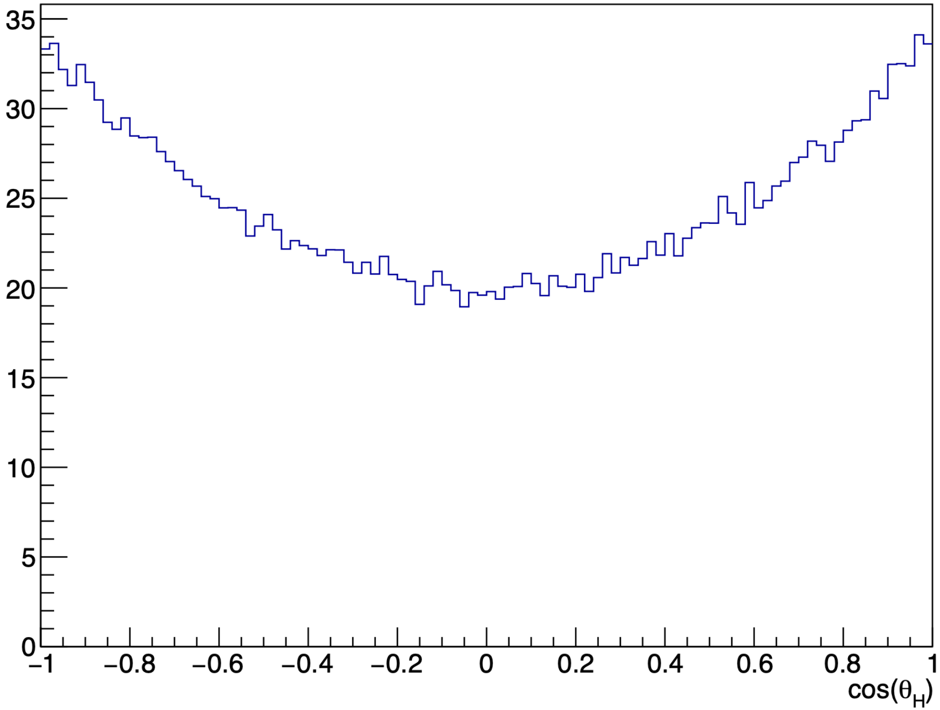
From Proposal to Jefferson Lab PAC39 Exclusive Phi Meson Electroproduction with CLAS12



Generator for MC simulation (SDME generated plots)

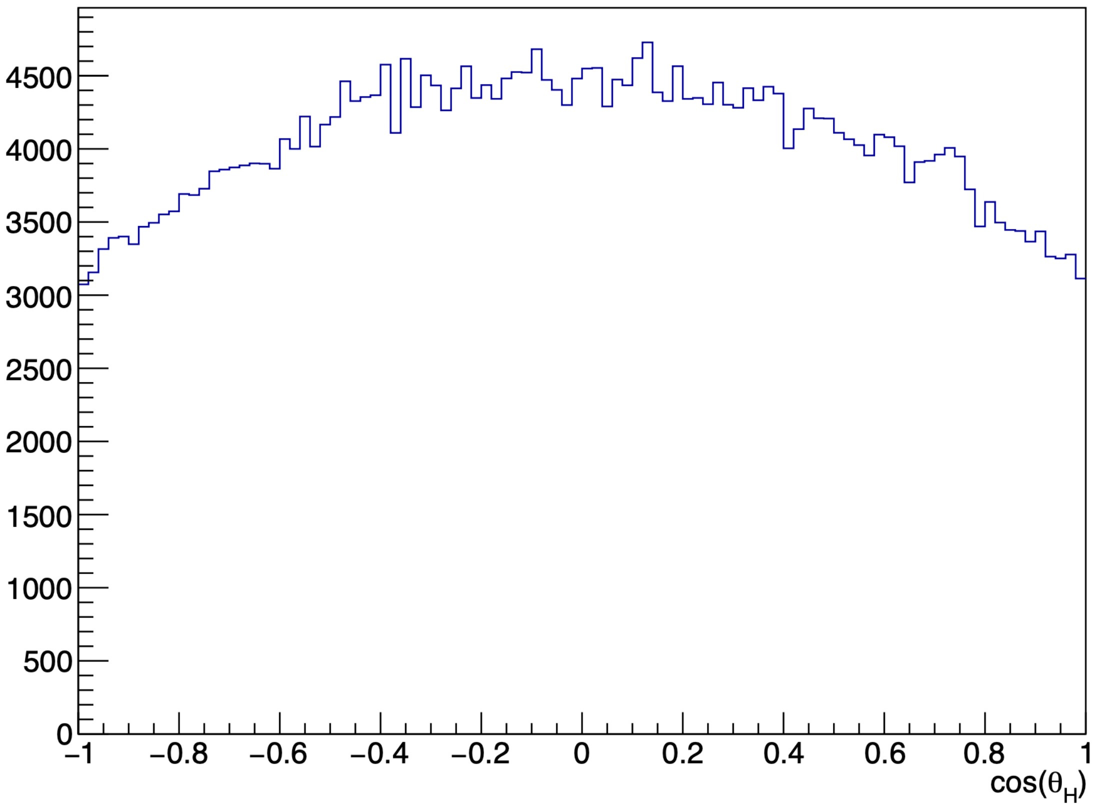


With Q^2 in [1.0 – 1.5] GeV^2



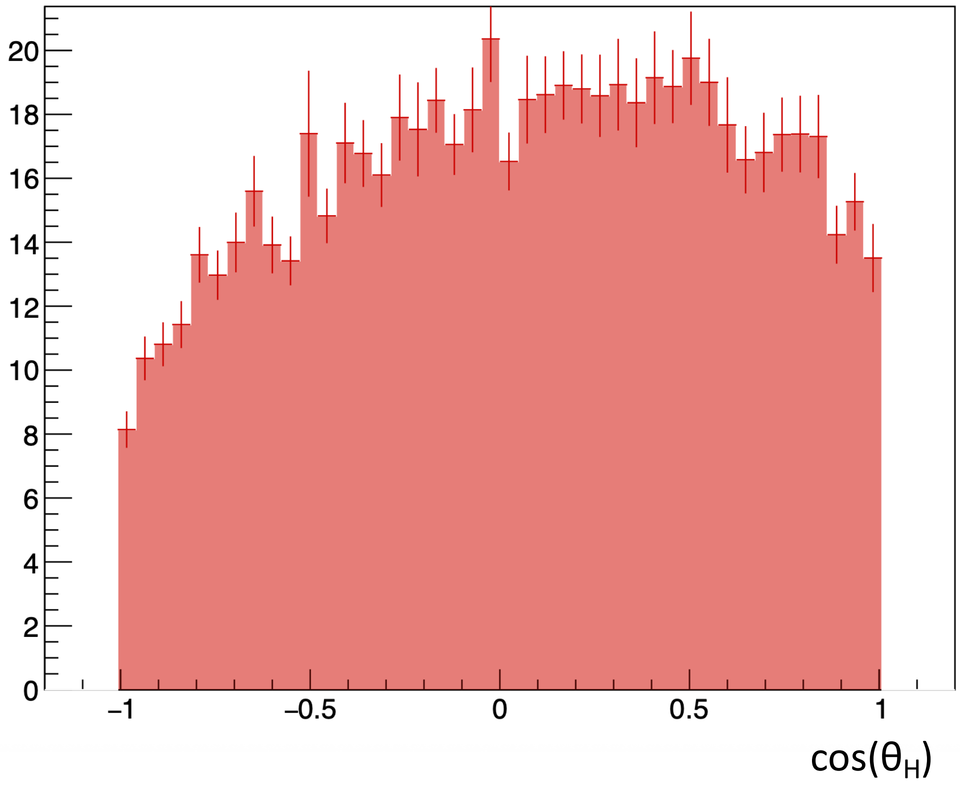
With Q^2 in [5.0 – 6.5] GeV^2

Generator for MC simulation (SDME generated plots)



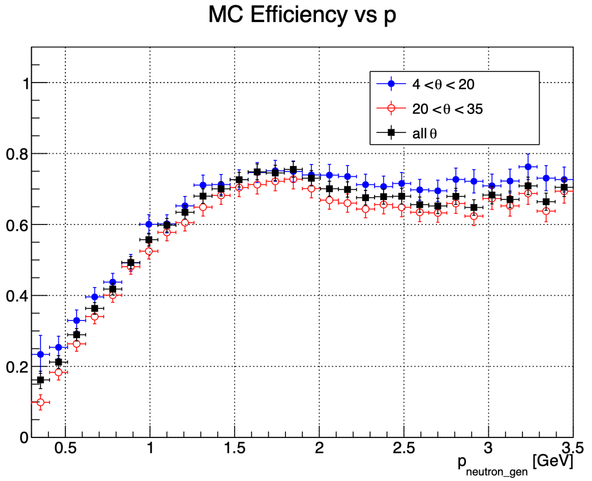
With no cut on Q^2

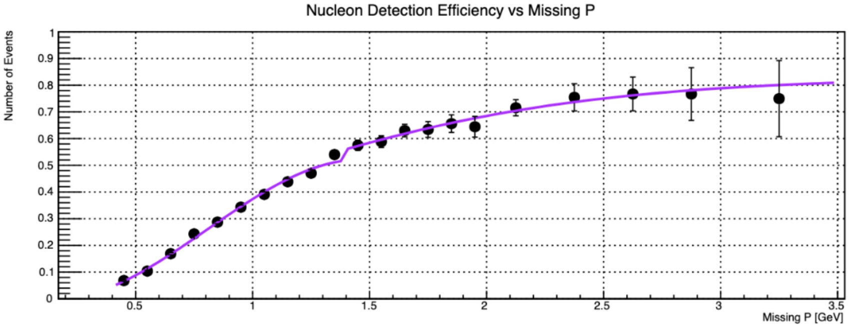
Generator for MC simulation (SDME reconstructed events)

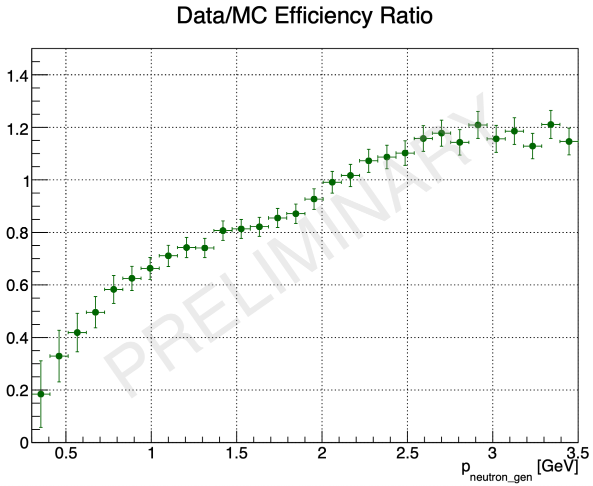


- Reconstructed with Q^2 in [1.0 – 1.5] GeV^2
- You can see acceptance effect when you compare to the generated plot

Efficiency correction factor of neutron







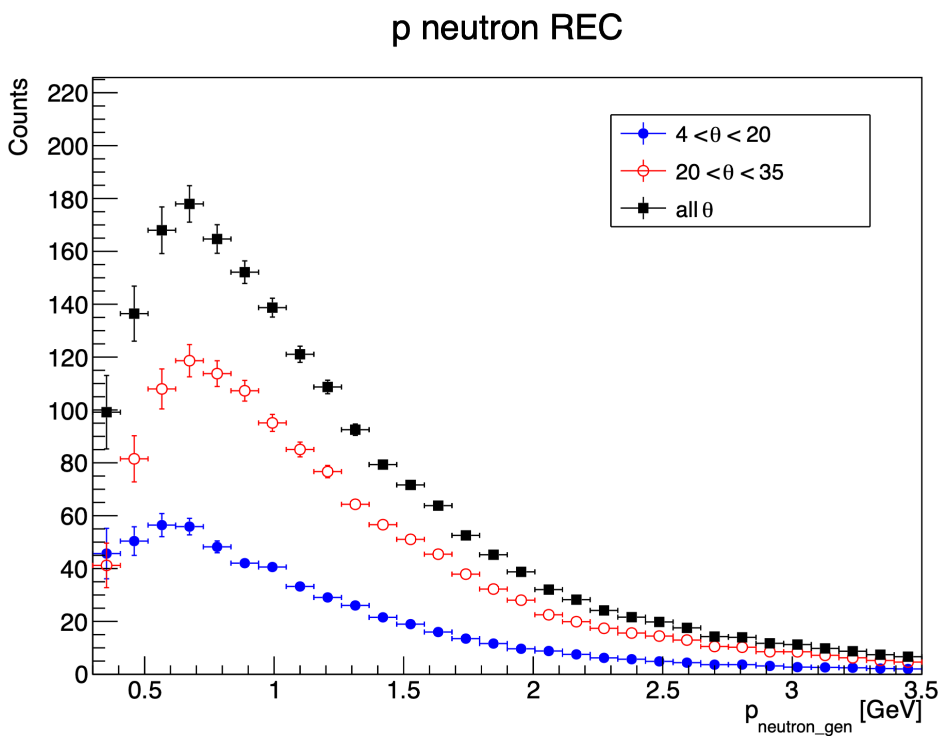
- Neutron efficiency (FD) in **data** from **R. Tyson** release note on J/Psi

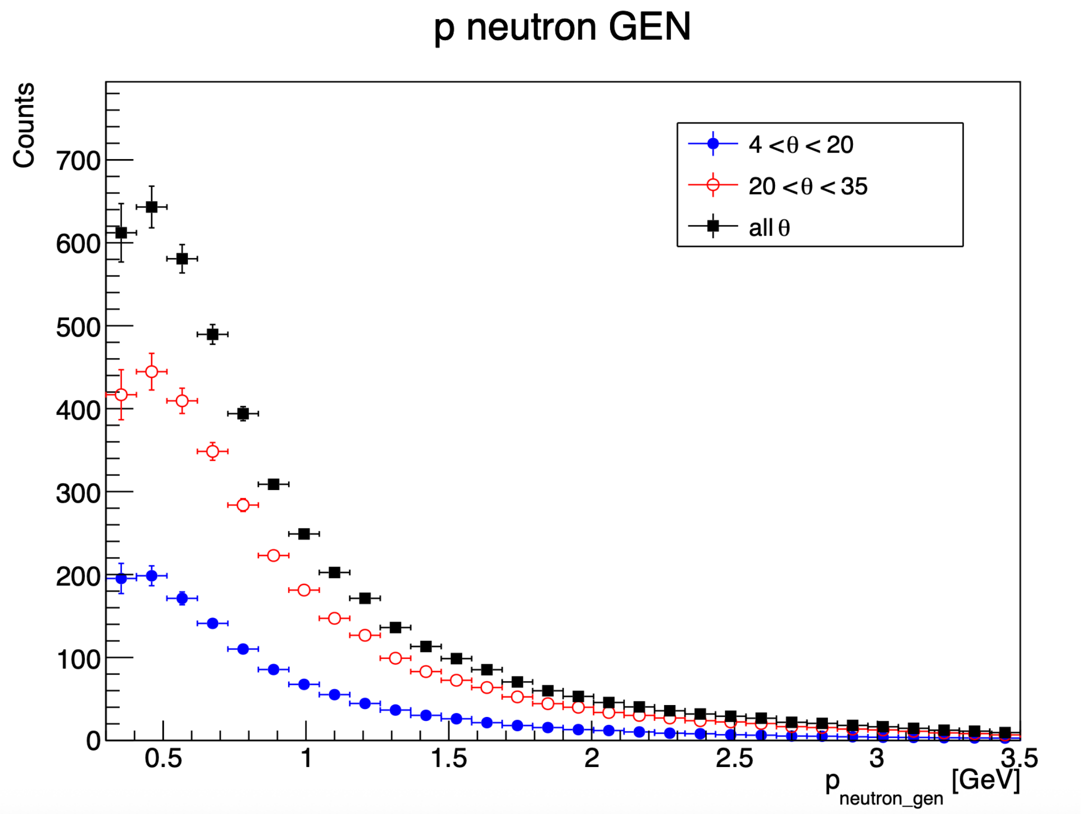
- Neutron efficiency in **MC** : $\frac{N_{rec}(e^- n)}{N_{gen}\,(\text{with } e^- \text{ rec})}$

- We are in the fiducial volume for reconstructed and generated event

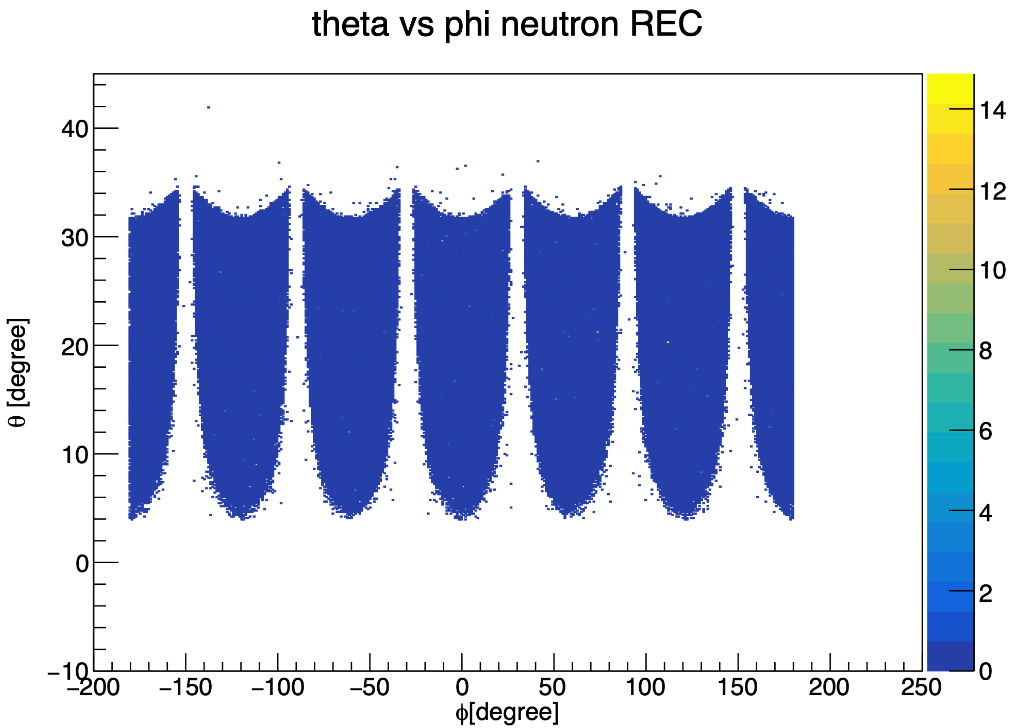
- The ratio between the **MC** and **data** efficiencies gives the **neutron efficiency correction factor**

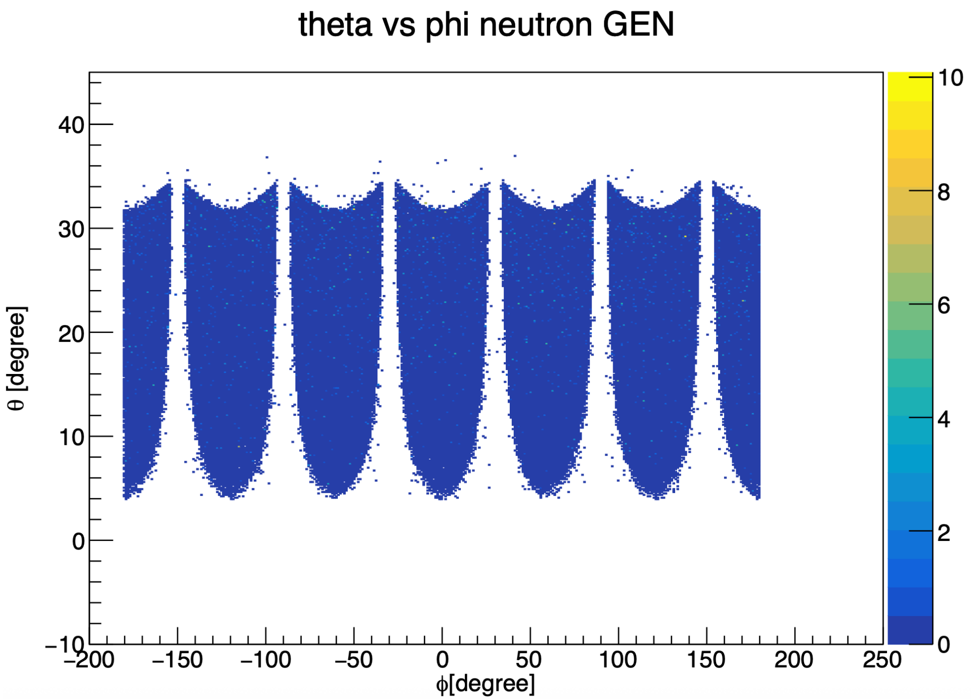
Neutron efficiency correction 1





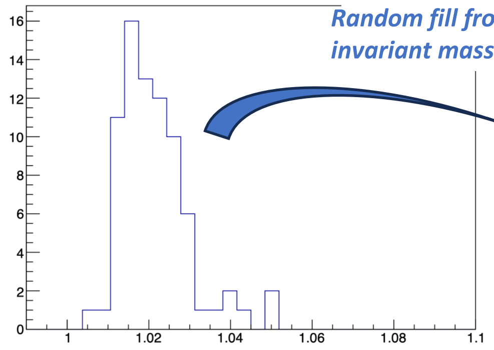
Neutron efficiency correction 2



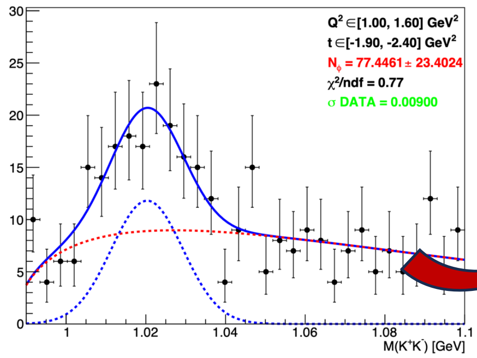


Acceptance correction method for pseudo exp

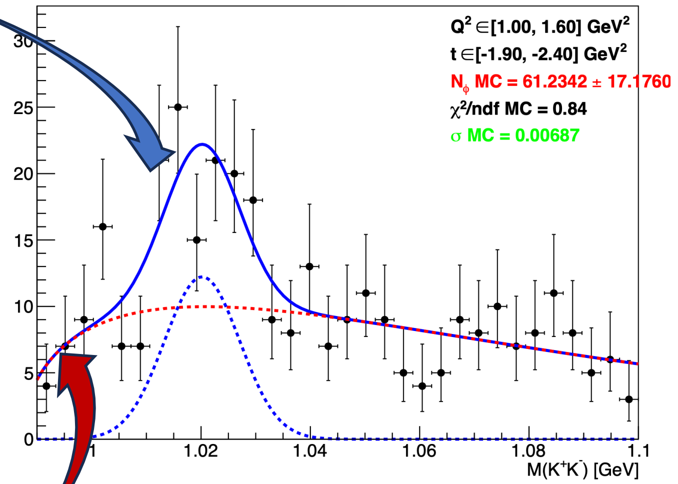
Random fill from the MC reconstructed invariant mass histogram.



MC



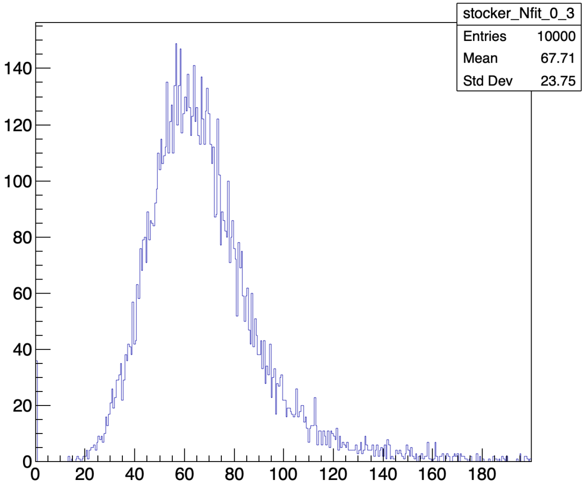
DATA



Pseudo-exp

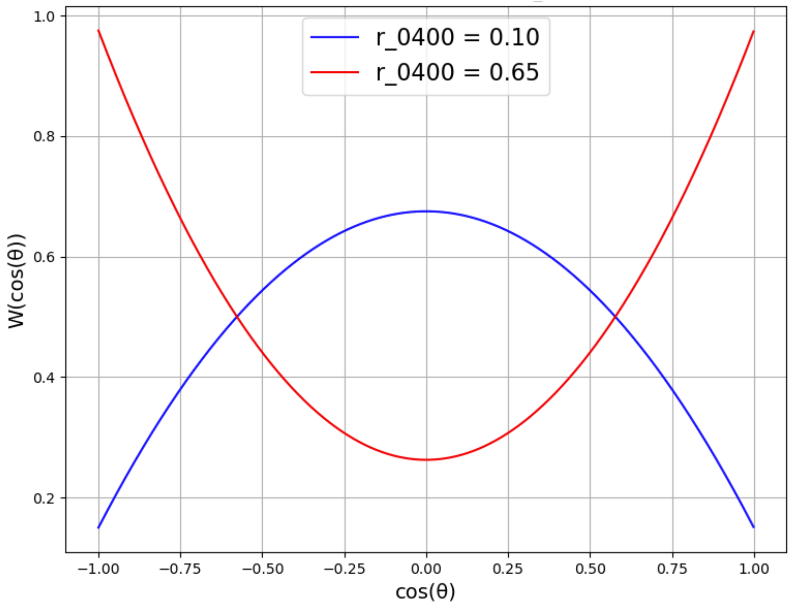
Random fill from the distribution of data background

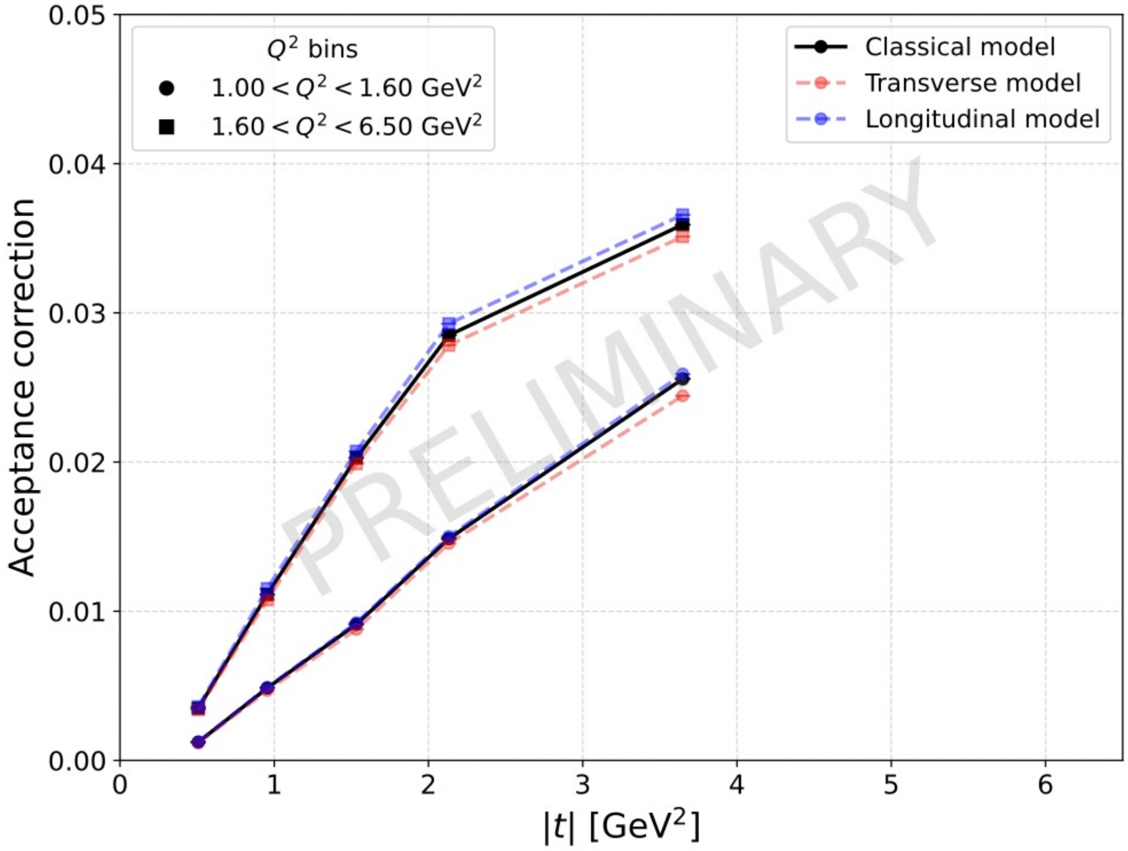
x 10 000



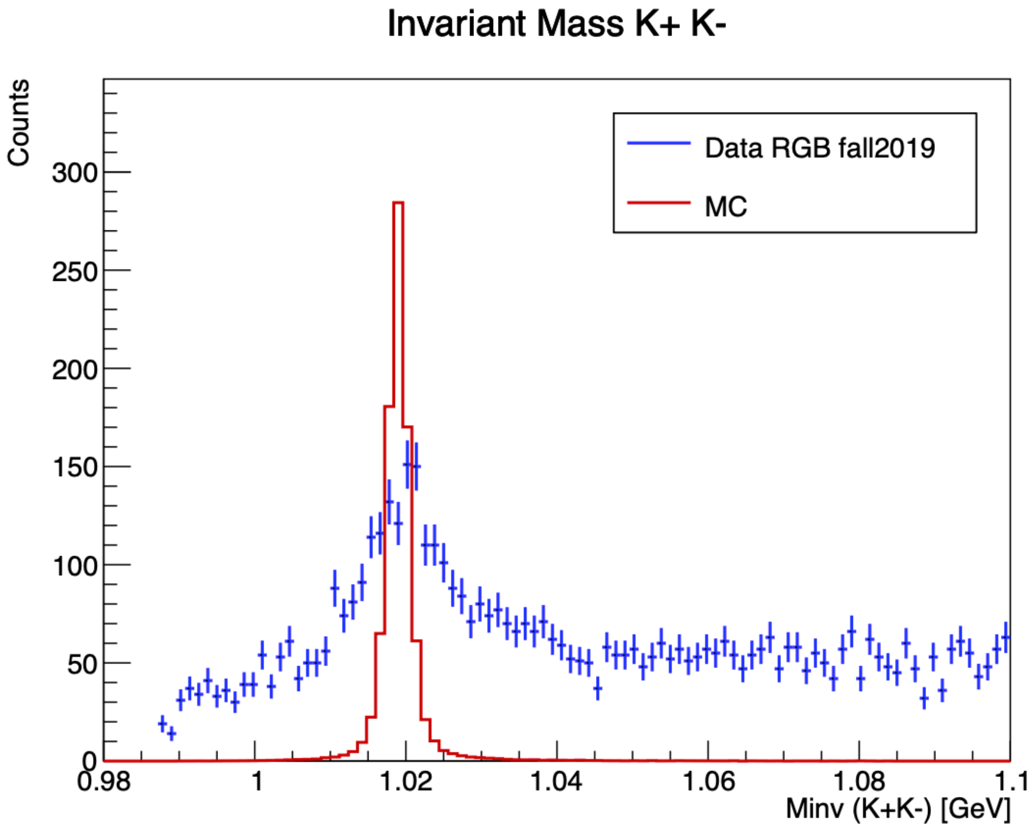
N_{fit}

Acceptance correction sdme impact





Smearing of the kaons



→ We need a smearing of both kaons in the MC

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

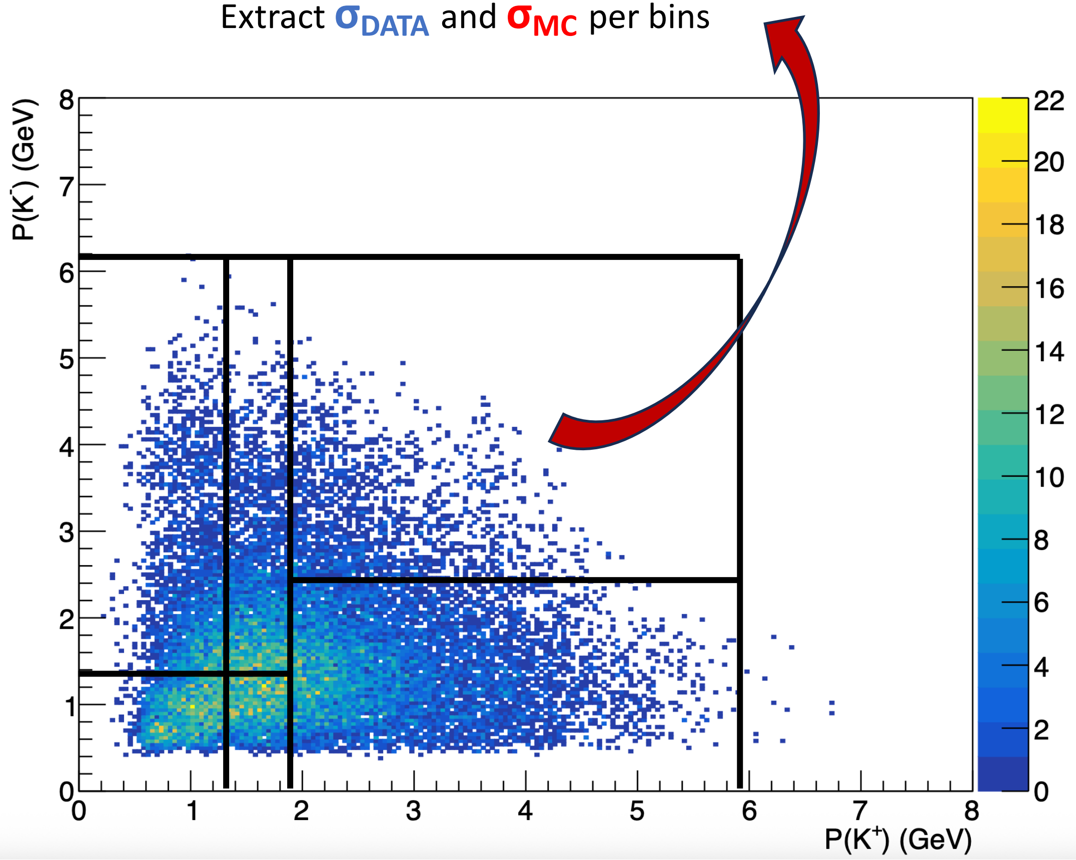
With η_s a random number from a Gaussian centered at 0.

The size of the Gaussian is the parameter δ

$\longrightarrow$ Find two parameters δ_{K+} and δ_{K-}

Smearing of the kaons

Extract σ_{DATA} and σ_{MC} per bins



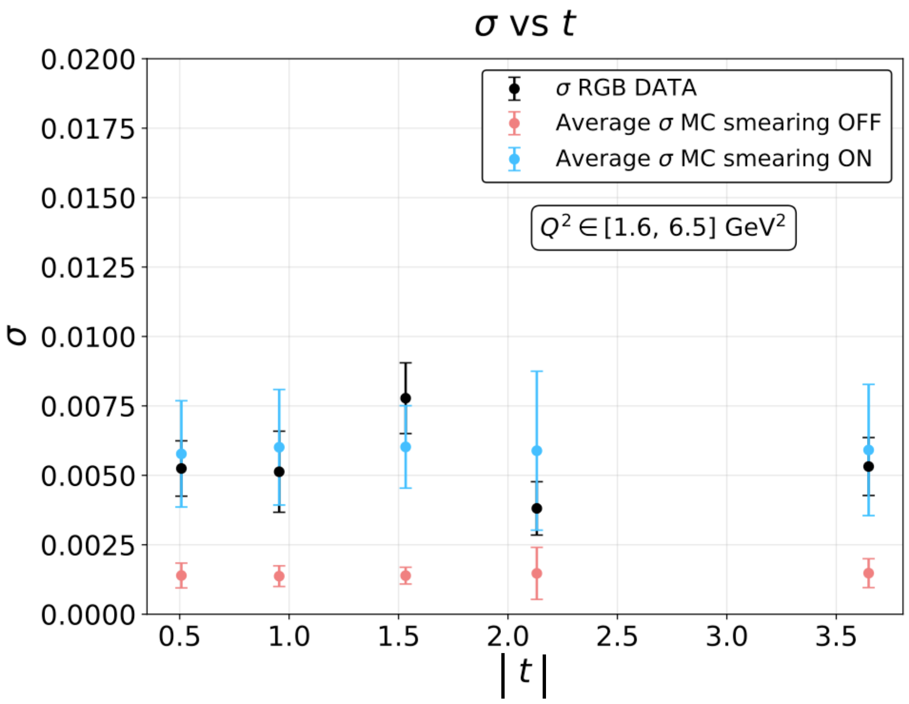
- To extract σ_{DATA} the invariant mass of data in the correponding bin is just fitted and σ_{DATA} correspond to the width of the Gaussian.
- To extract σ_{MC} several pseudos-experiments (like explained before) are permormed. Thus, σ_{MC} correpond to the average of Gaussian width.

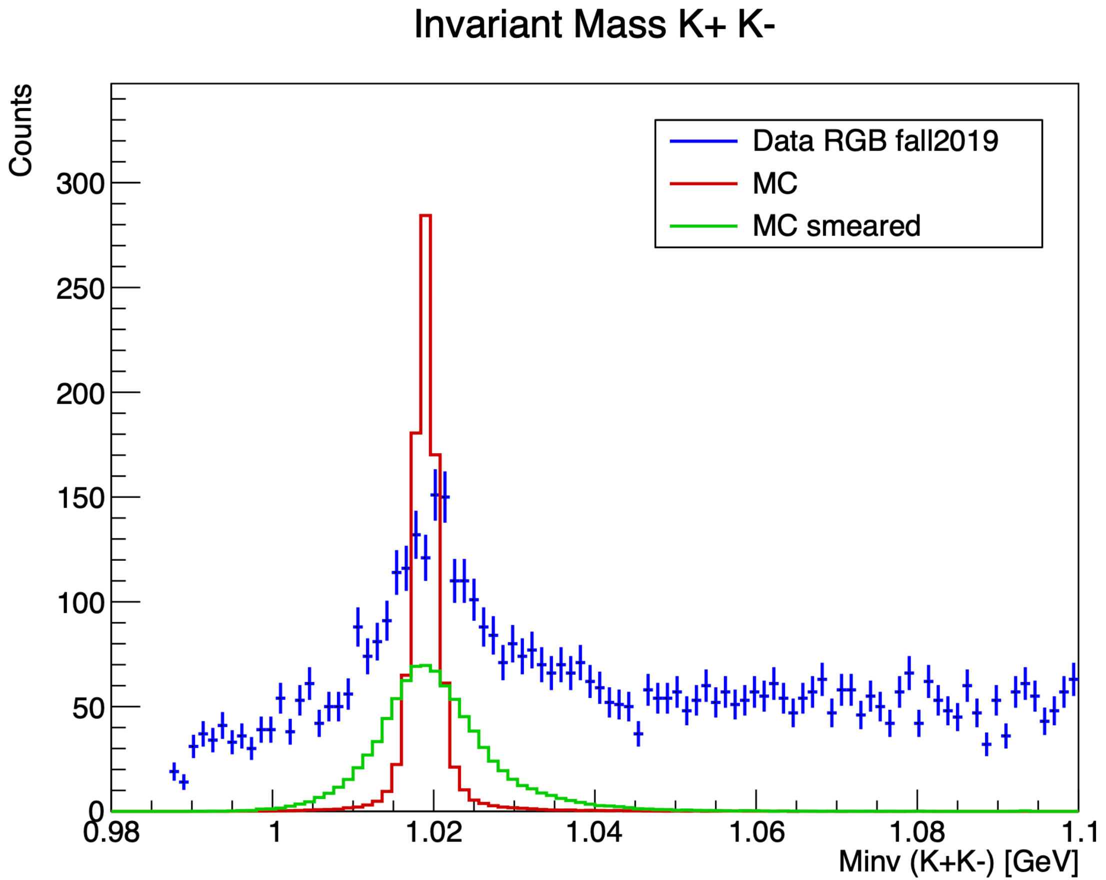
$$\chi^2 = \sum_{bins} \frac{\sigma^2_{data} - \sigma^2_{MC}}{err^2_{\sigma_{data}}}$$

→ Minimise X^2 with Minuit2 or simply with a grid lead to :

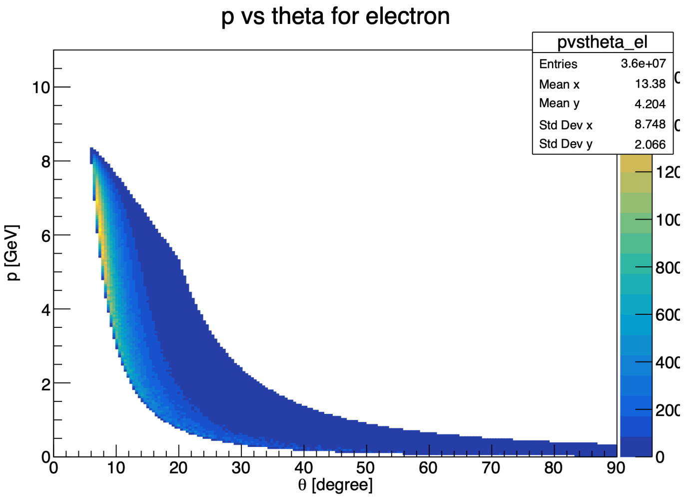
- $\delta_{K+} = 0.077$
- $\delta_{K-} = 0.057$

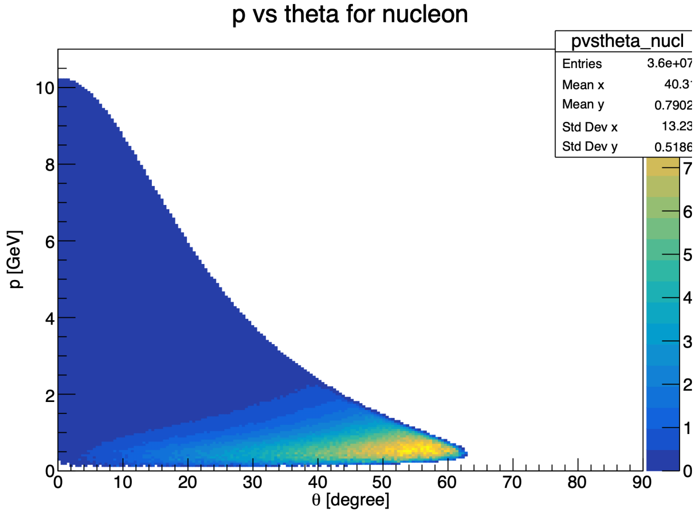
Smearing of the kaons

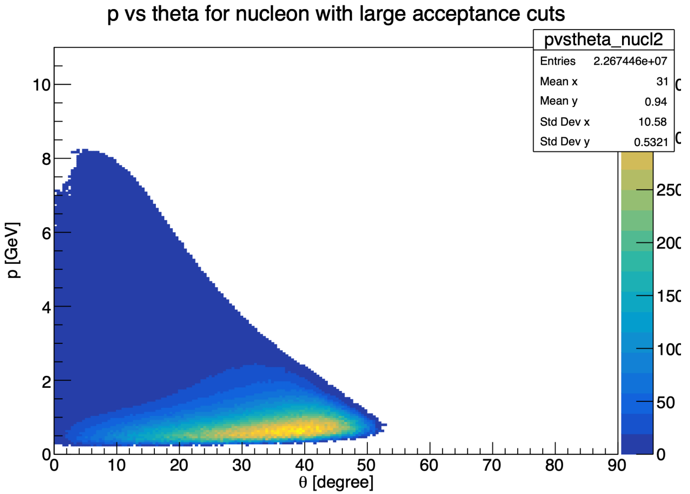




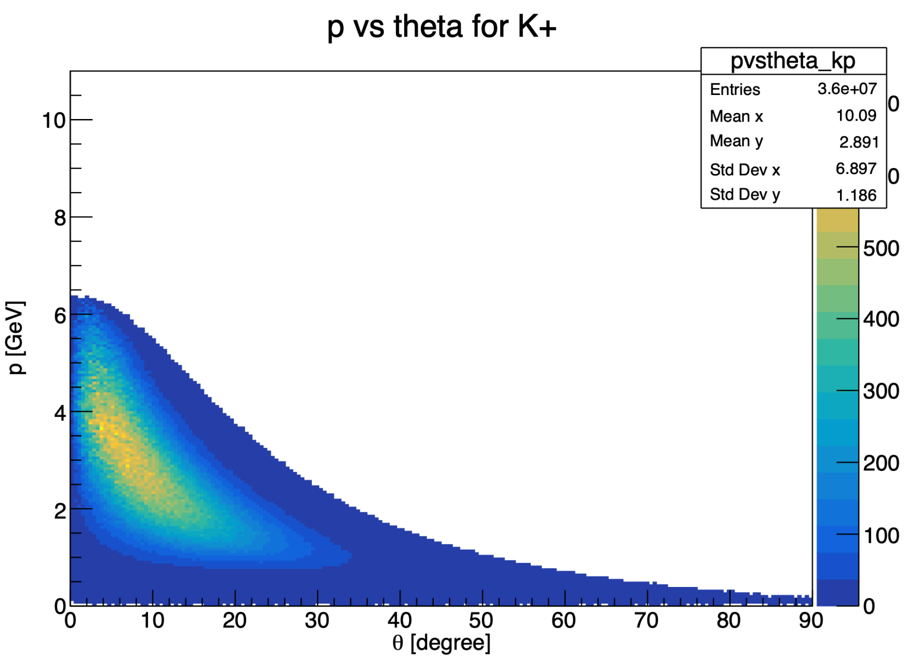
ϕ generator additionals plots 1

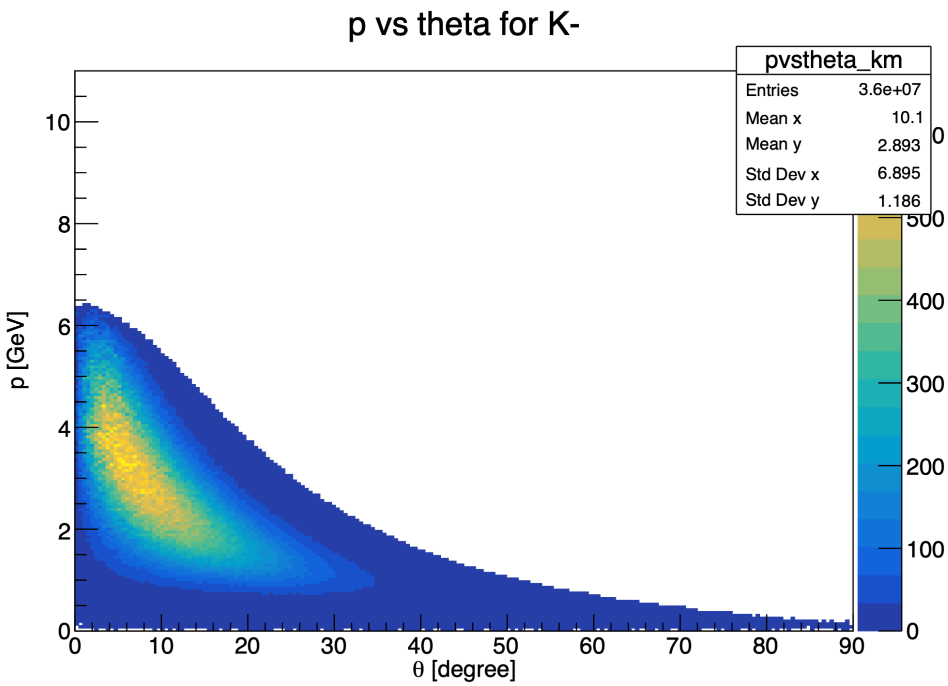




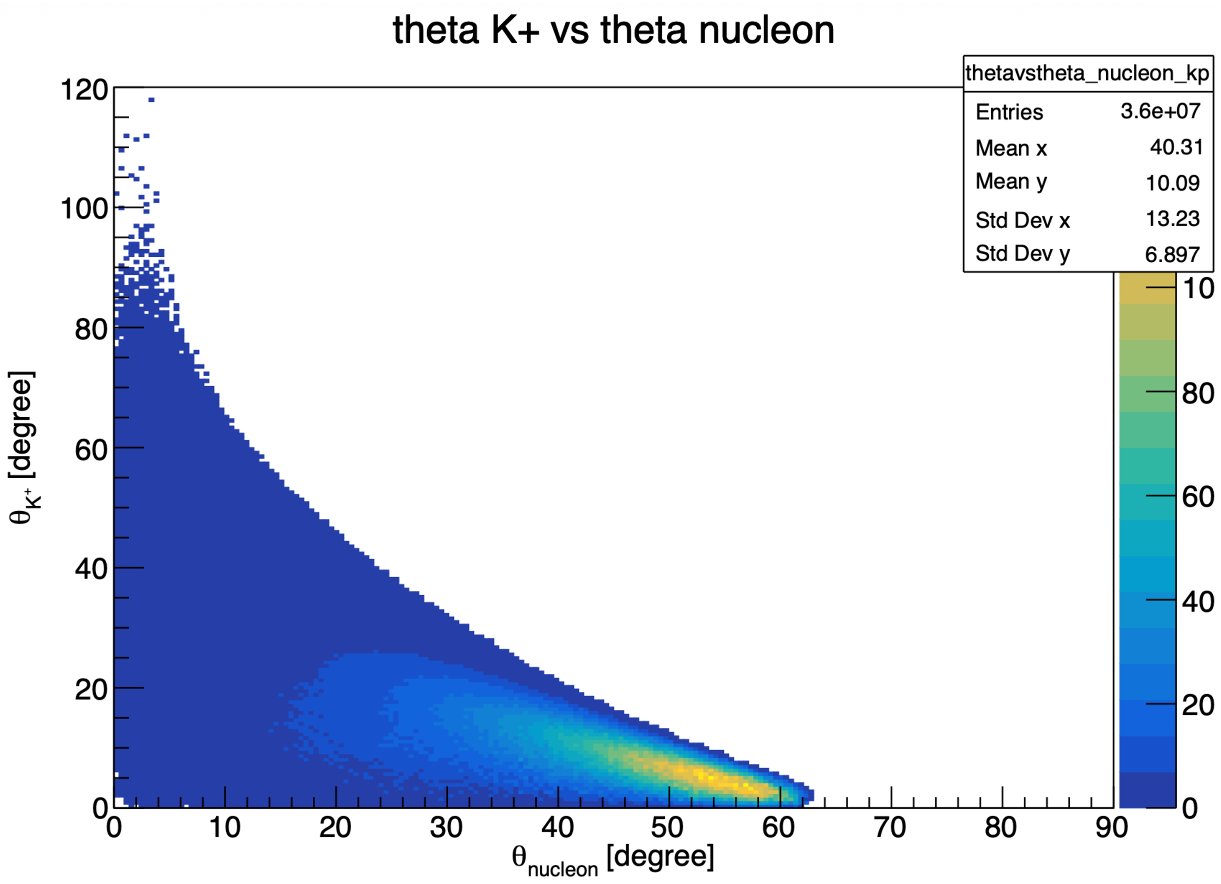


ϕ generator additionals plots 2





ϕ generator additionals plots 3



ϕ generator additionals plots 4