Measurement of antineutrino elastic scattering on free protons in the MINERνA experiment

Noë Roy, on behalf of the MINERνA collaboration

2023

June 21st

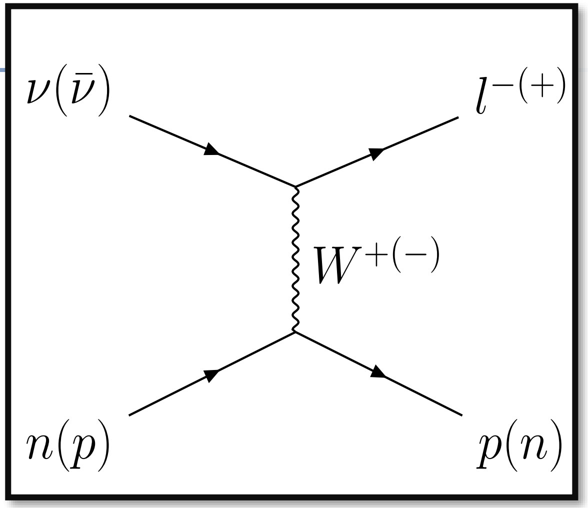
YORK U

Canadian Association of Physicists

Association canadienne des physiciens et physiciennes

MINERνA

Why do we care?



Primary channel of interaction in high energy neutrino experiments: **neutrino scattering on nucleon**

Experiments: oscillation on various type of targets (**CH**, **Ar**, **H_2O**...)

Precise models to predict the expected number of interaction in the detectors → Theoretical computations / Measurements from data

Scattering on free nucleons is be the best way to start building models for heavier nuclei

Don't we know already that cross section?

[Phys. Rep. 3, 261–379]

Llewllyn Smith equation :

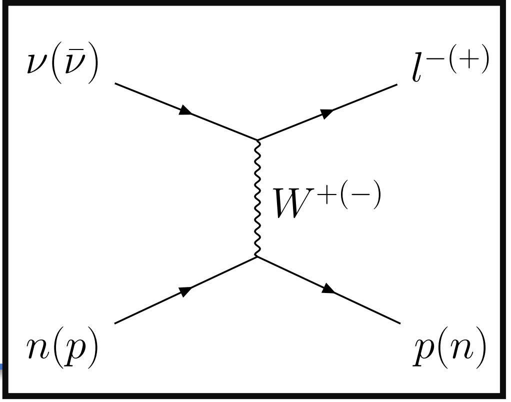
x-section wrt 4 momentum exchange between the neutrino and the nucleon

$$\frac{d\sigma}{dQ^2}\begin{pmatrix}\nu n \to l^- p \\ \bar{\nu} p \to l^+ n\end{pmatrix} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(Q^2) \mp B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right]$$

$$A(Q^2) = \frac{m^2+Q^2}{4M^2}\left[\left(4+\frac{Q^2}{M^2}\right)|F_A|^2 - \left(4-\frac{Q^2}{M^2}\right)|F_V^1|^2 + \frac{Q^2}{M^2}\left(1-\frac{Q^2}{4M^2}\right)|\xi F_V^2|^2 + \frac{4Q^2}{M^2}\mathrm{Re}F_V^{1*}\xi F_V^2 + \mathcal{O}\left(\frac{m^2}{M^2}\right)\right],$$

$$B(Q^2) = \frac{Q^2}{M^2}\mathrm{Re}F_A^*(F_V^1 + \xi F_V^2),$$

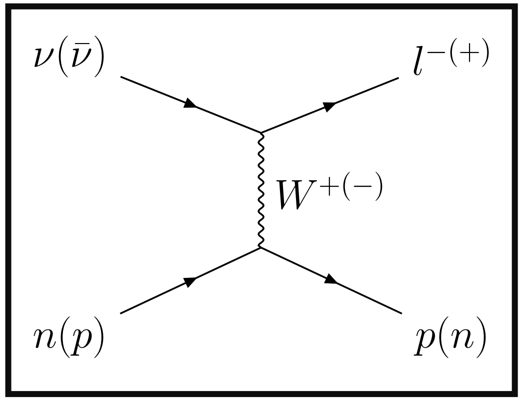
$$C(Q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{4M^2}|\xi F_V^2|^2\right)$$



F_V^1, ξF_V^2: **Electric and magnetic form factors**. Measured with **electron scattering experiment**: A lot of data and well constrained!

F_A: **Axial form factor**, depends on the **weak interaction**. Accessible through **neutrino scattering experiments**: Much less data from scattering.

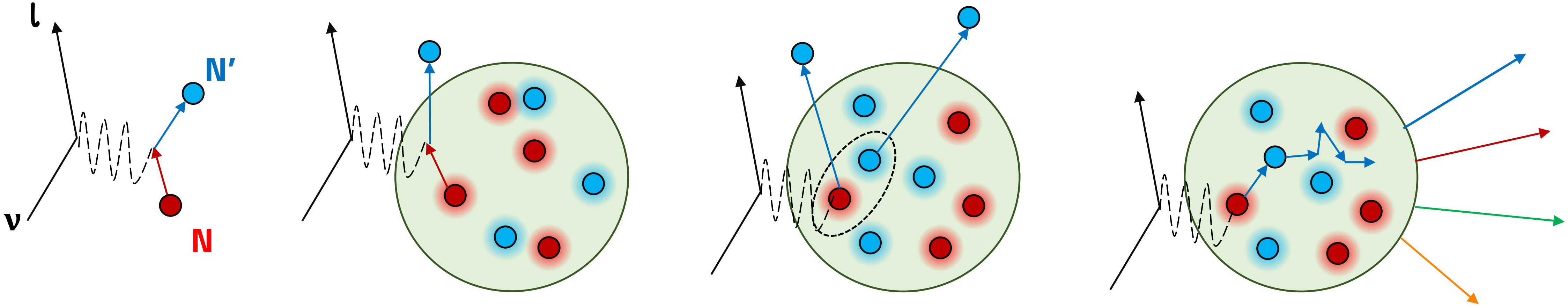
Why “free nucleons”?



Best case scenario:

- Neutrino scattering on a free nucleon
- Charged Current interaction with charged lepton and nucleon in final state
- Energy & Momentum conservation: Final state measurement

BUT

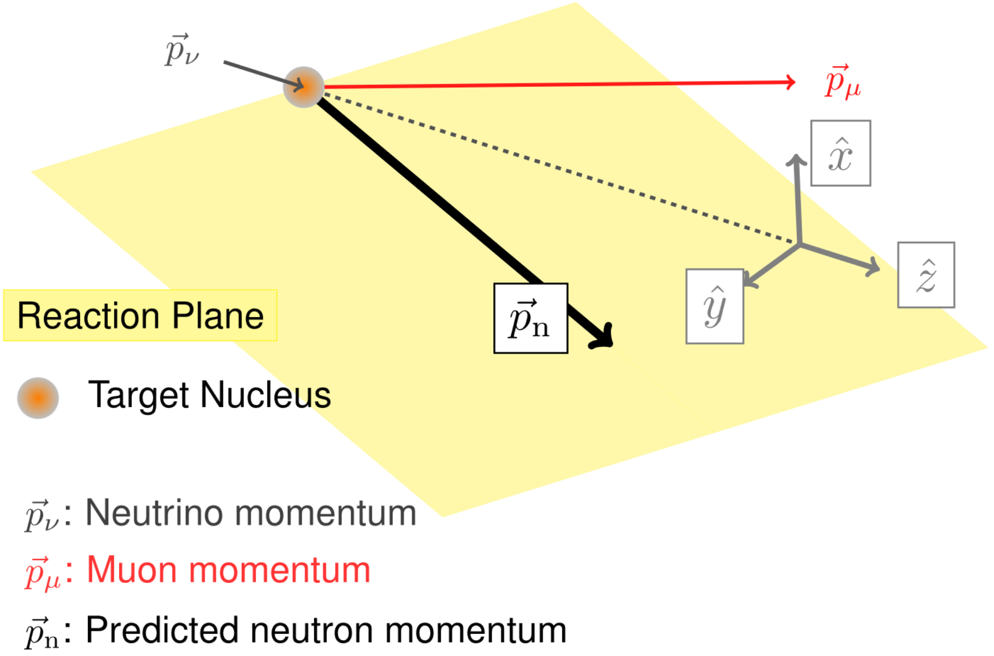


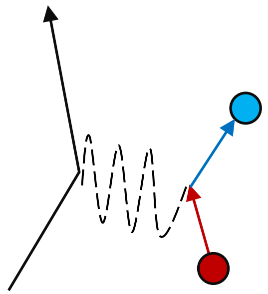
Fermi motion   Short range correlation   Final state interactions

Outgoing neutron in antineutrino scattering

On antineutrino a scattering on H:

- Simple process
- Position neutron direction known from muon measurement





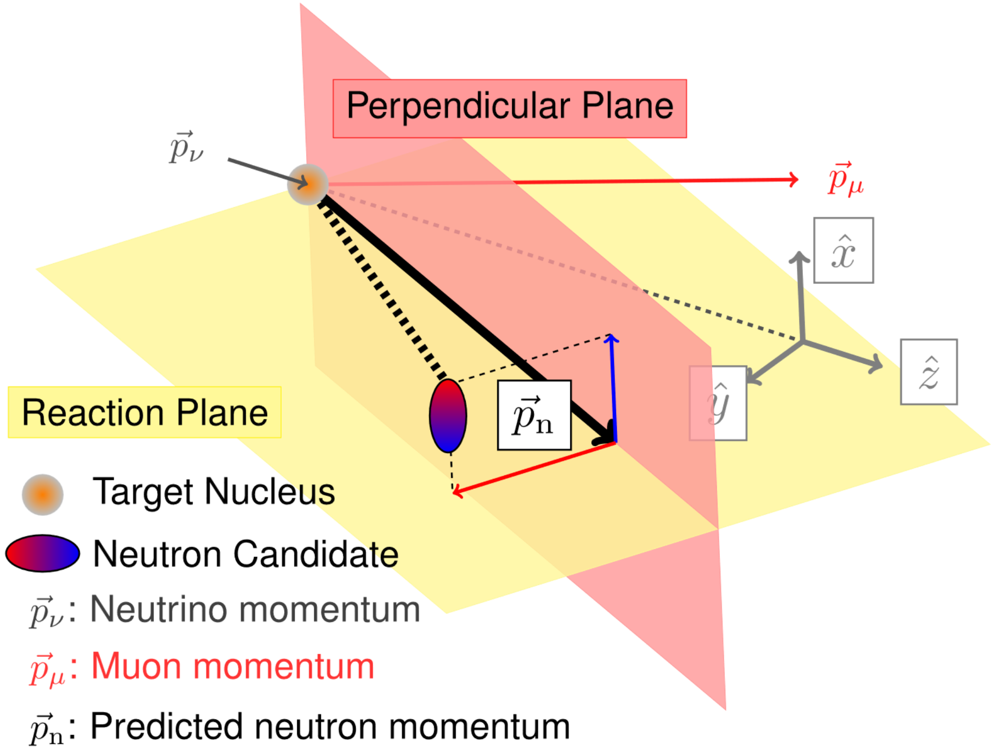
Outgoing neutron in antineutrino scattering

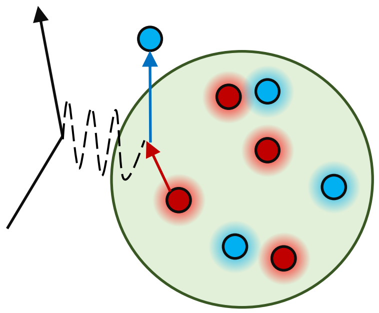
On antineutrino a scattering on H:

- Simple process
- Position neutron direction known from muon measurement

On a scattering on Z>1:

- Initial nucleon momentum
- Final state interaction
- Position of neutron direction deviates from prediction!





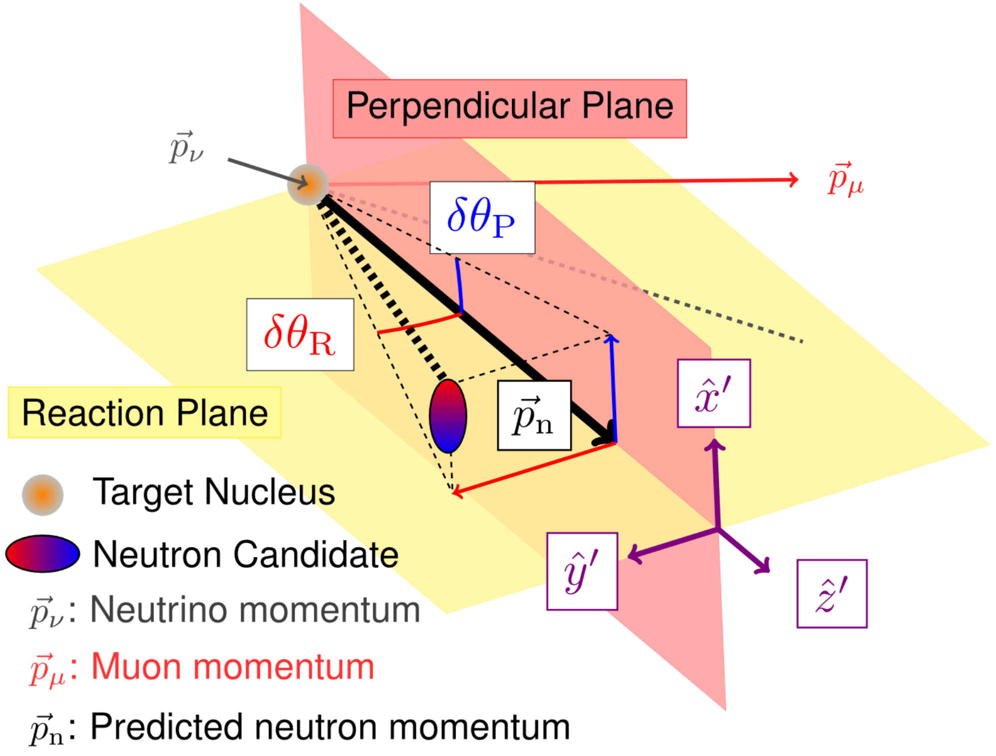
Outgoing neutron in antineutrino scattering

On antineutrino a scattering on H:

- Simple process
- Position neutron direction known from muon measurement

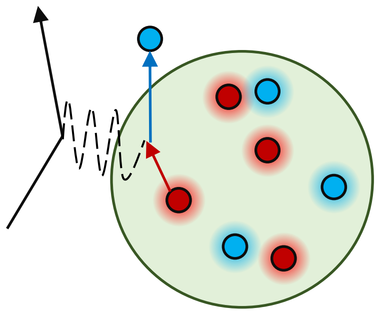
On a scattering on Z>1:

- Initial nucleon momentum
- Final state interaction
- Position of neutron direction deviates from prediction!



Use deviation to separate both interactions:

-Define $\delta\theta_R$ and $\delta\theta_P$ as the deviation between the predicted position and the measured position

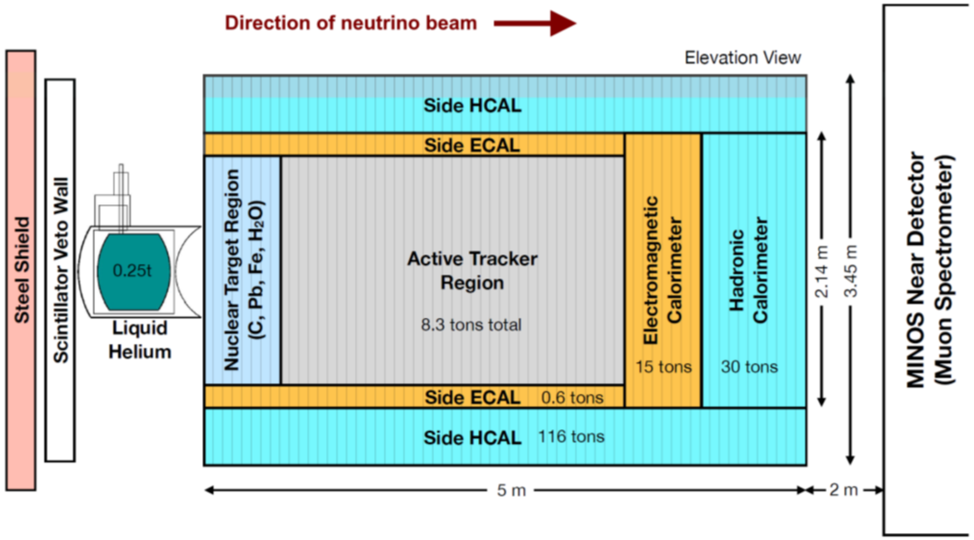


Detecting a neutron with the MINERvA detector

$\overline{\nu_\mu}$ + (C)H -> n + μ^+

- μ^+ leaves a track in the detector and is used to identify the vertex position

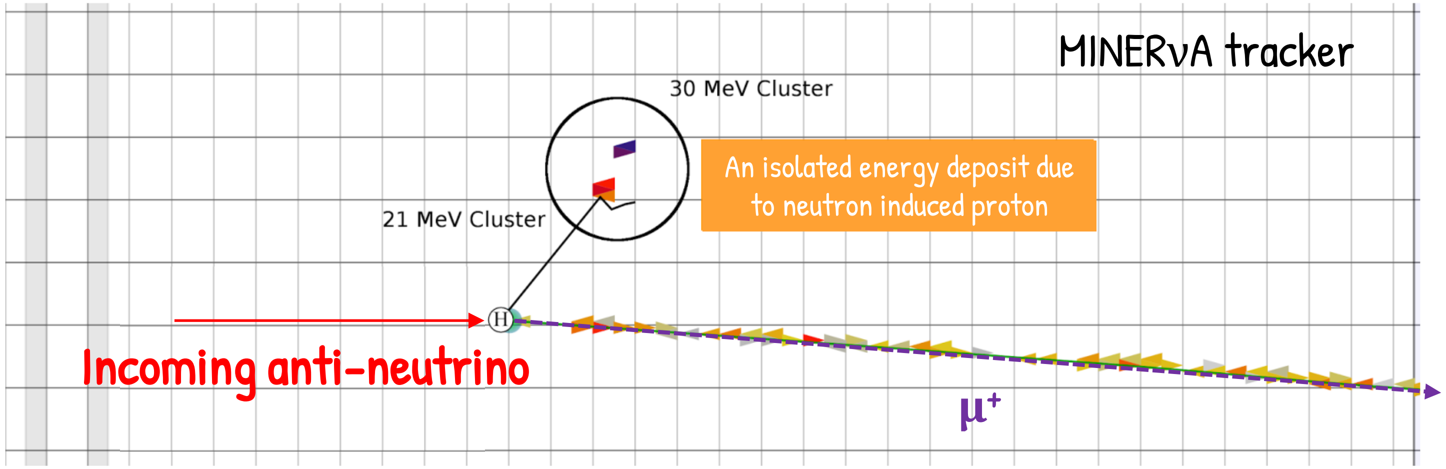
- n interacts knocking off a proton to leave an "isolated energy deposit".



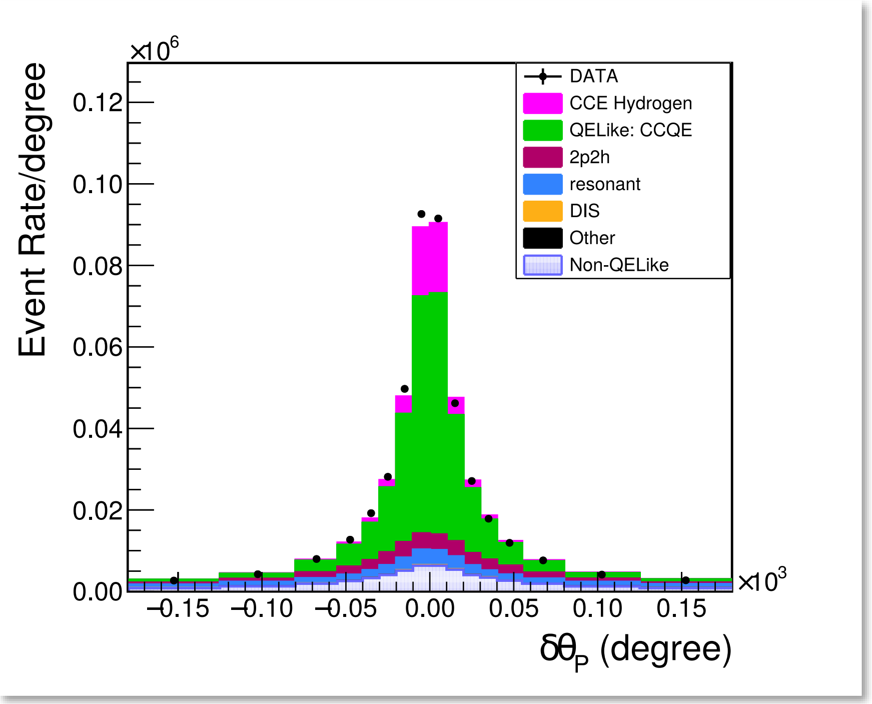
Event selection:
- No Hadronic tracks (charged mesons or pions)

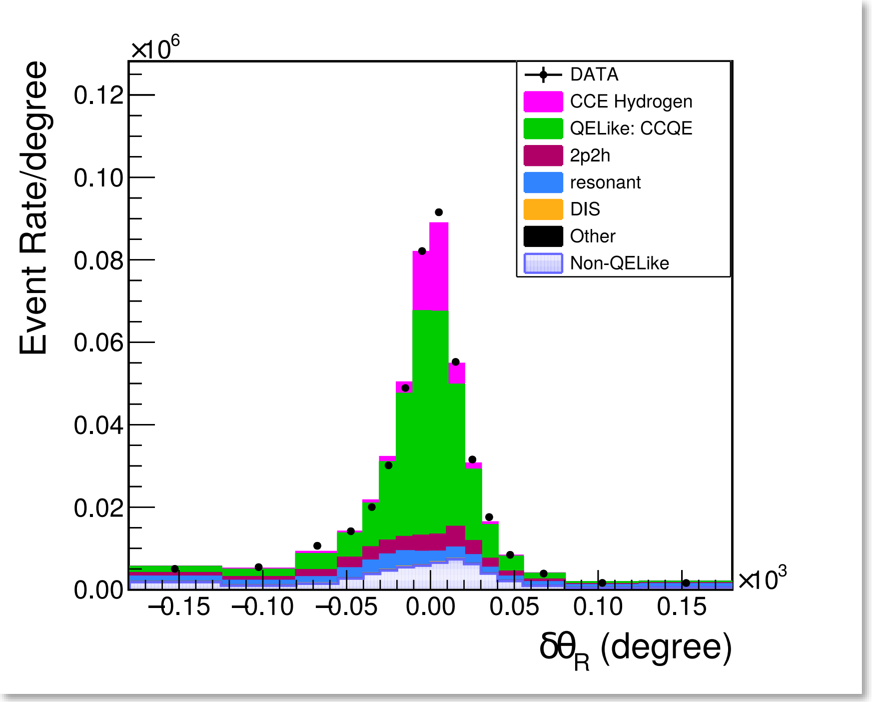
Neutron candidate:
- 10 cm away from the muon axis

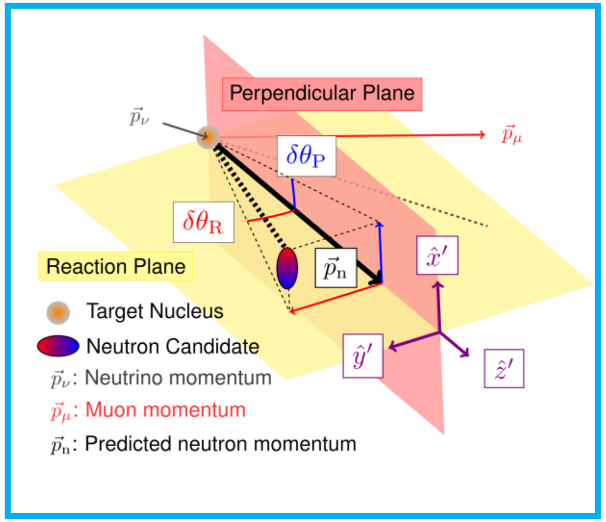
Muon candidate:
- Muon energy [1.5; 20] GeV
- $\theta\mu < 20°$ wrt the neutrino beam



Deviation angles measurement







Data and Monte-Carlo distribution of the deviation angles

Elastic scattering on **H** centered on 0 with little deviation

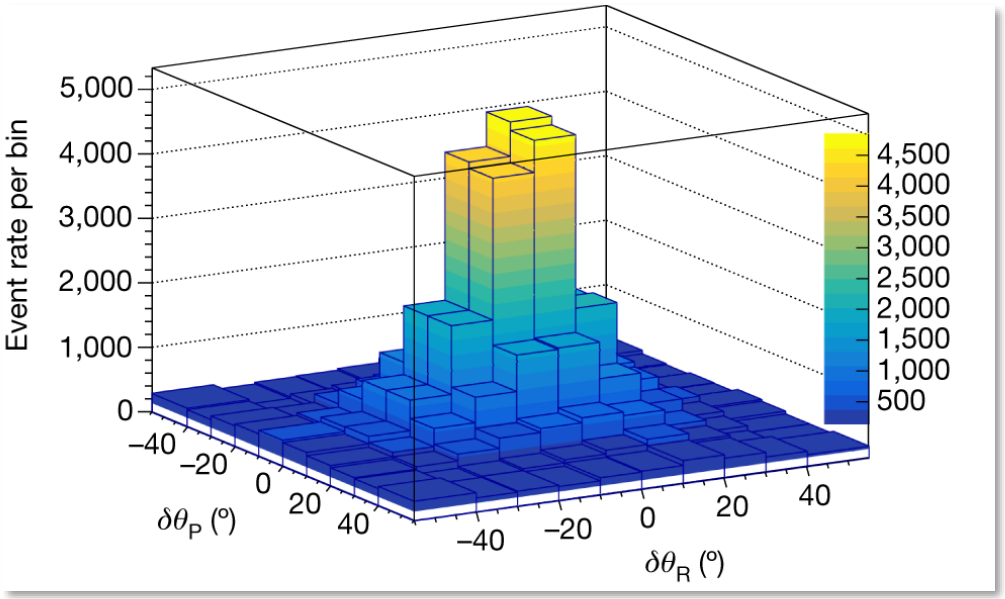
Quasi elastic scattering (**QE-Like**) on **Carbon**: Centered on 0 with some smearing

Other type of background (not simple scattering)

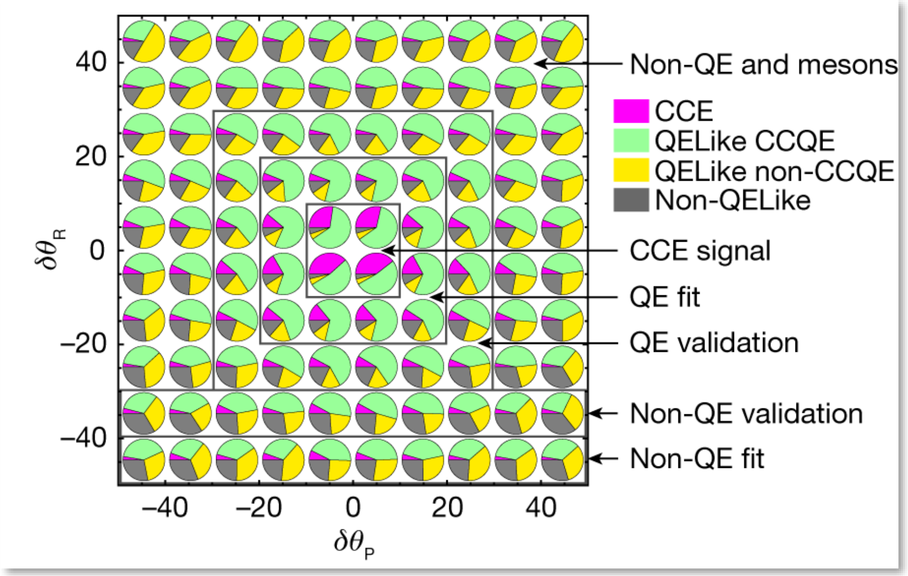
Clear difference between H and C scattering but signal/background ratio is not good, need to get smarter !

Let's look in 2 dimensions!

Total event rate



Monte-Carlo Fractions

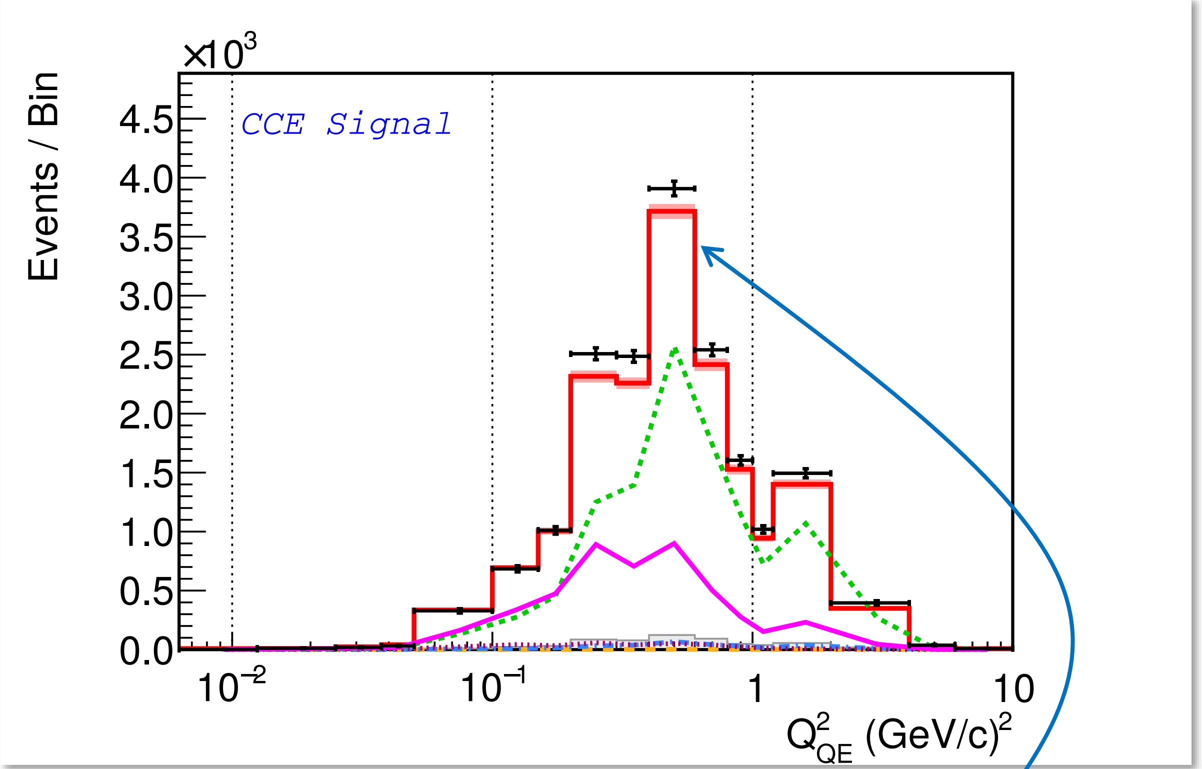


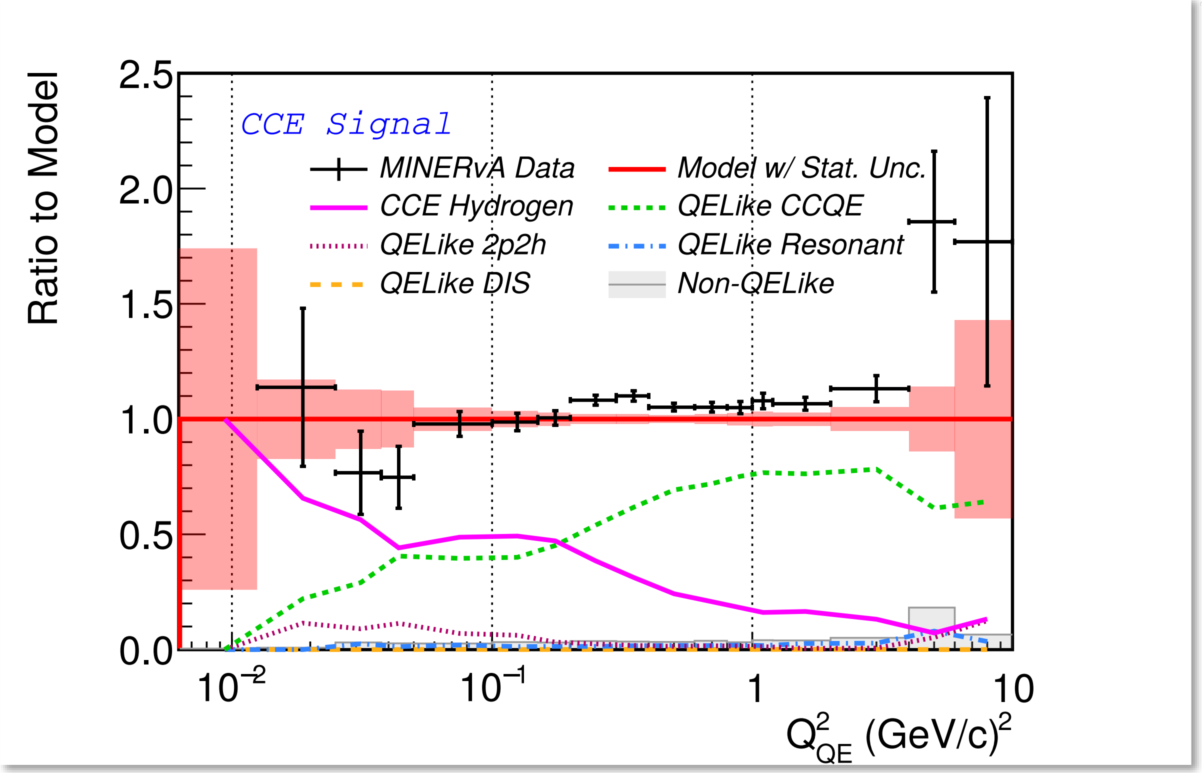
The ($\delta\theta_P$, $\delta\theta_R$) 2D space can be used to improve the signal – background ratio!

Center region used for signal selection

Outer regions used for background constraints and fit validation

Extracting a cross section



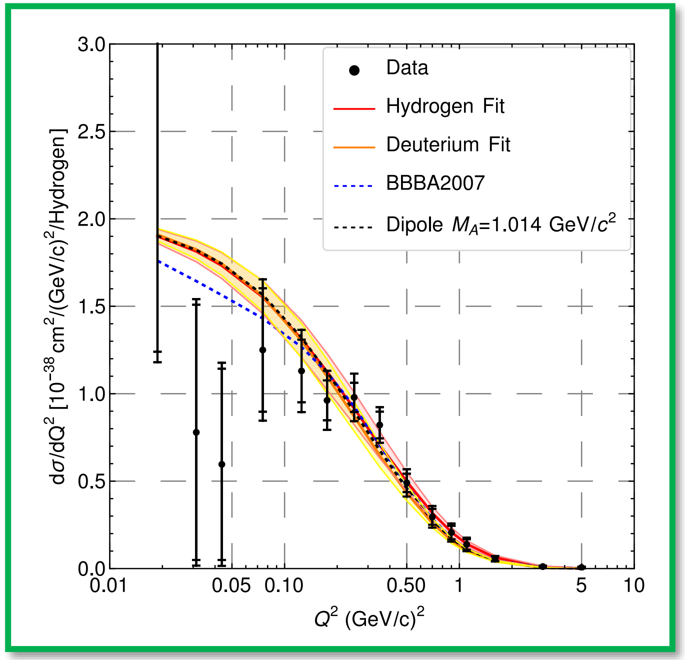


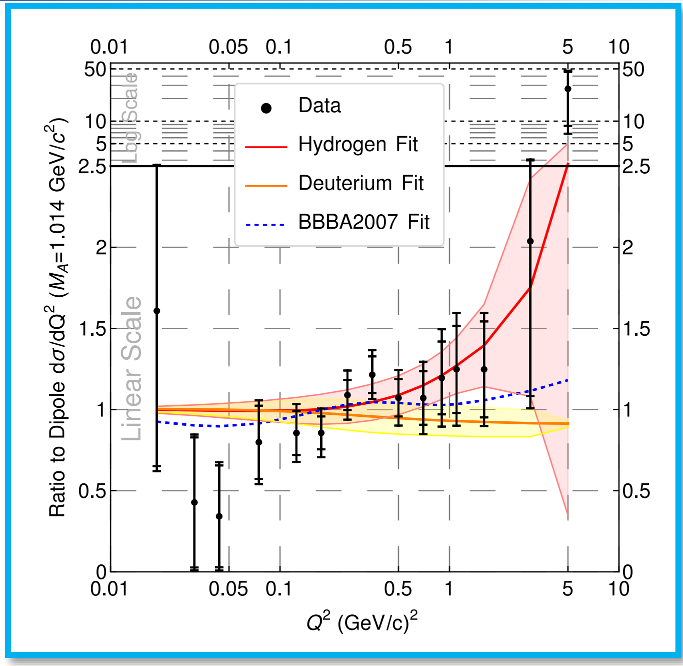
$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\right)_i = \frac{\sum_j U_{ji}\left(N_j^{\mathrm{data}} - N_j^{\mathrm{bkg-pred}}\right)}{\Phi N_H \epsilon_i (\Delta Q^2)_i}$$

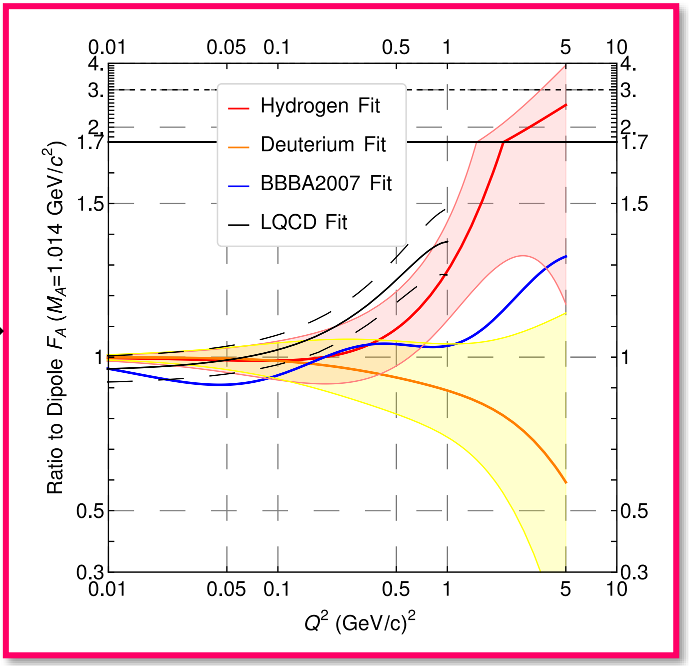
We have everything!

- Unfolding matrix from Data – MC studies
- Efficiency from Data – MC studies
- Flux from models and neutrino-electron scattering measurements
- Number of Hydrogen targets from the detector qualification
- **Measured signal** from data – predicted background

Cross section and Axial form factor







Comparison of our result (Hydrogen fit) with various models:

Deuterium Fit[1]: Deuterium scattering data in Bubble chamber

BBBA2007[2]: Deuterium and pion production electroproduction data

Dipole model: $F_A(Q^2) = F_A(0)\left(1+\frac{Q^2}{M_A^2}\right)^{-2}$ used in neutrino generators

Our measurement favors higher cross sections for higher Q^2

From x-section fit of F_A :

Tension with Deuterium fit

Deuterium fit had to be tweaked at higher Q^2 due to the lack of statistics

Agreement with Lattice QCD fit[3] up to 1 GeV

[1] Phys. Rev. D 93, 113015

[2] Eur. Phys. J. C 53 (2008)

[3] Eur. Phys. J. A 55, 196

Conclusion

We have performed a **statistically significant** measurement of antineutrino elastic scattering on free proton.

This is the **first F_A measurement for the last 30 years! ->** ***More details in the Nature article[1]***

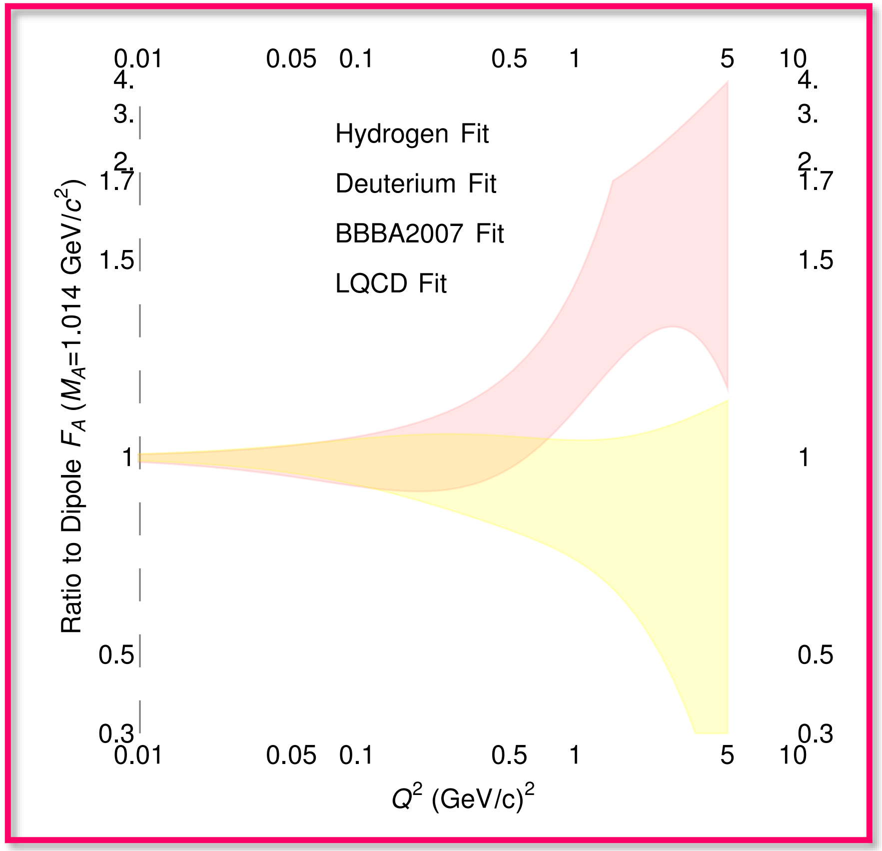
Extracted "proton weak radius": $\sqrt{\langle r_A^2 \rangle}$ = 0.73(17)fm

- Developed algorithm that tag neutron candidates and differentiate scattering on H/C in a CH target
- Extracted a $\overline{\nu_\mu}$-H CCE cross section in the MINERνA tracker
- Fitted the cross section to export the Axial form factor and compared it with different models
- This measurement will help in better understanding axial vector nucleon structure
- See Maria's talk next session for more cross-section measurement in MINERνA

1) Unless indicated otherwise, all the plots were extracted from here

Backup

Cross section measurement



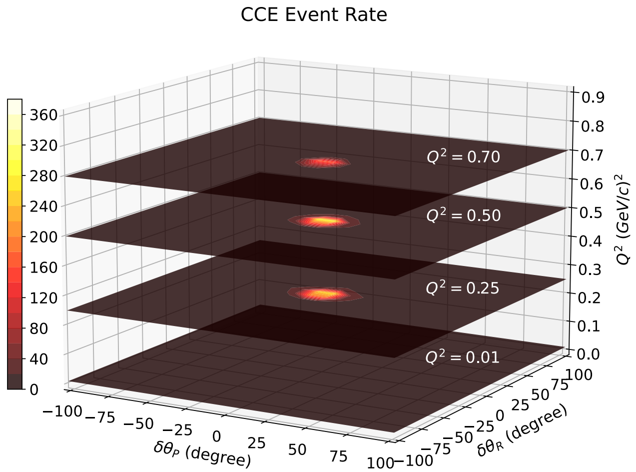
Ratio of $F_A(Q^2)$

Measurement of F_A for different experiments.

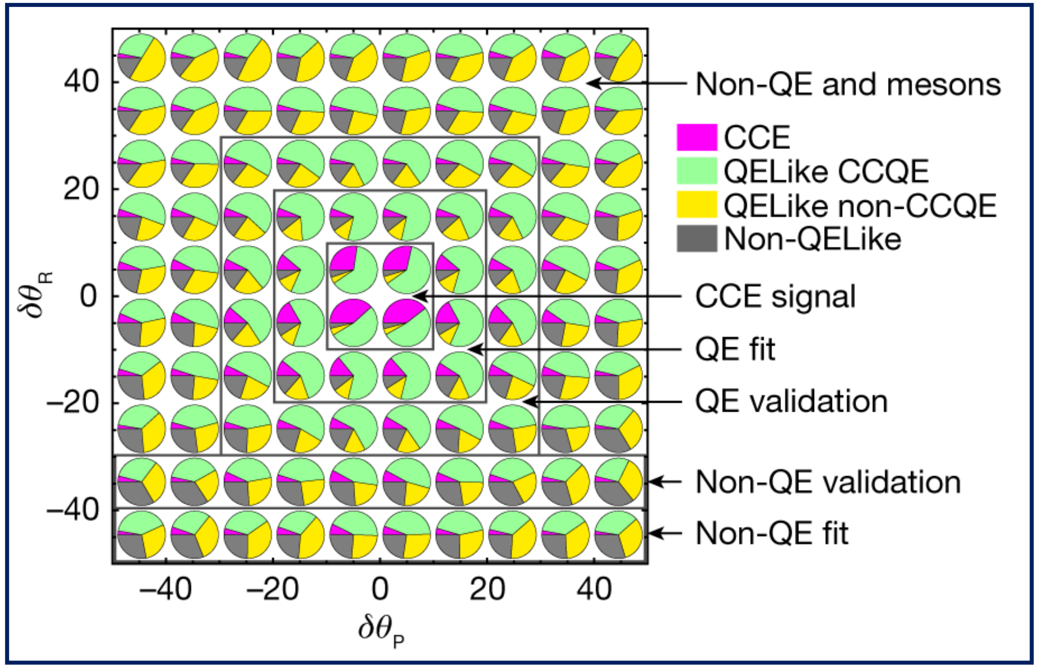
- Lattice QCD fit consistent with out Fitted value up to 1 GeV
- Tension between our fit and deuterium fit.
  - Deuterium fit had to be tweeked at higher Q2 due to the lack of statistics.
- Measurement of proton radius with the limit at 0 of $F_A(Q^2)$
- $\frac{1}{F_A(0)} \frac{dF_A}{dQ^2}\Big|_{Q^2=0} = -\frac{1}{6}\langle r_A^2 \rangle$
- $\sqrt{\langle r_A^2 \rangle}$ = 0.73(17)fm

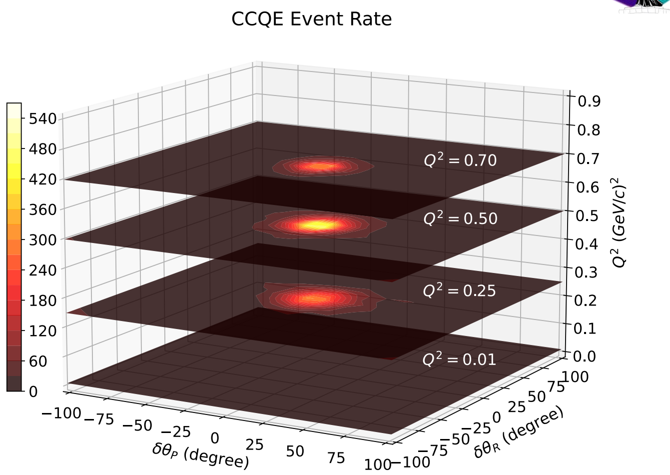
We measured the « proton radius » by throwing anti-neutrino at H atoms without nuclear correction or other theoretical assumption!

(δθ$_P$, δθ$_R$) distributions – sidebands

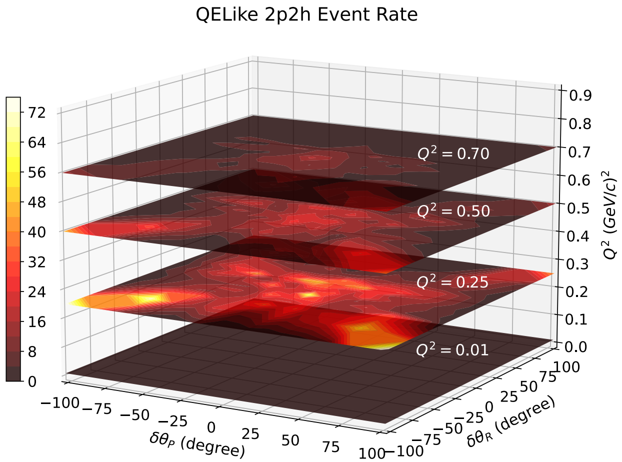


SIGNAL: Elastic on H



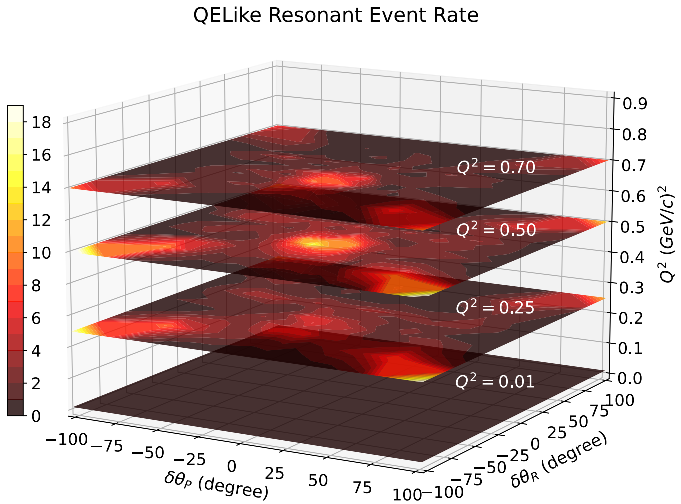


Background: QELike CCQE (on C)



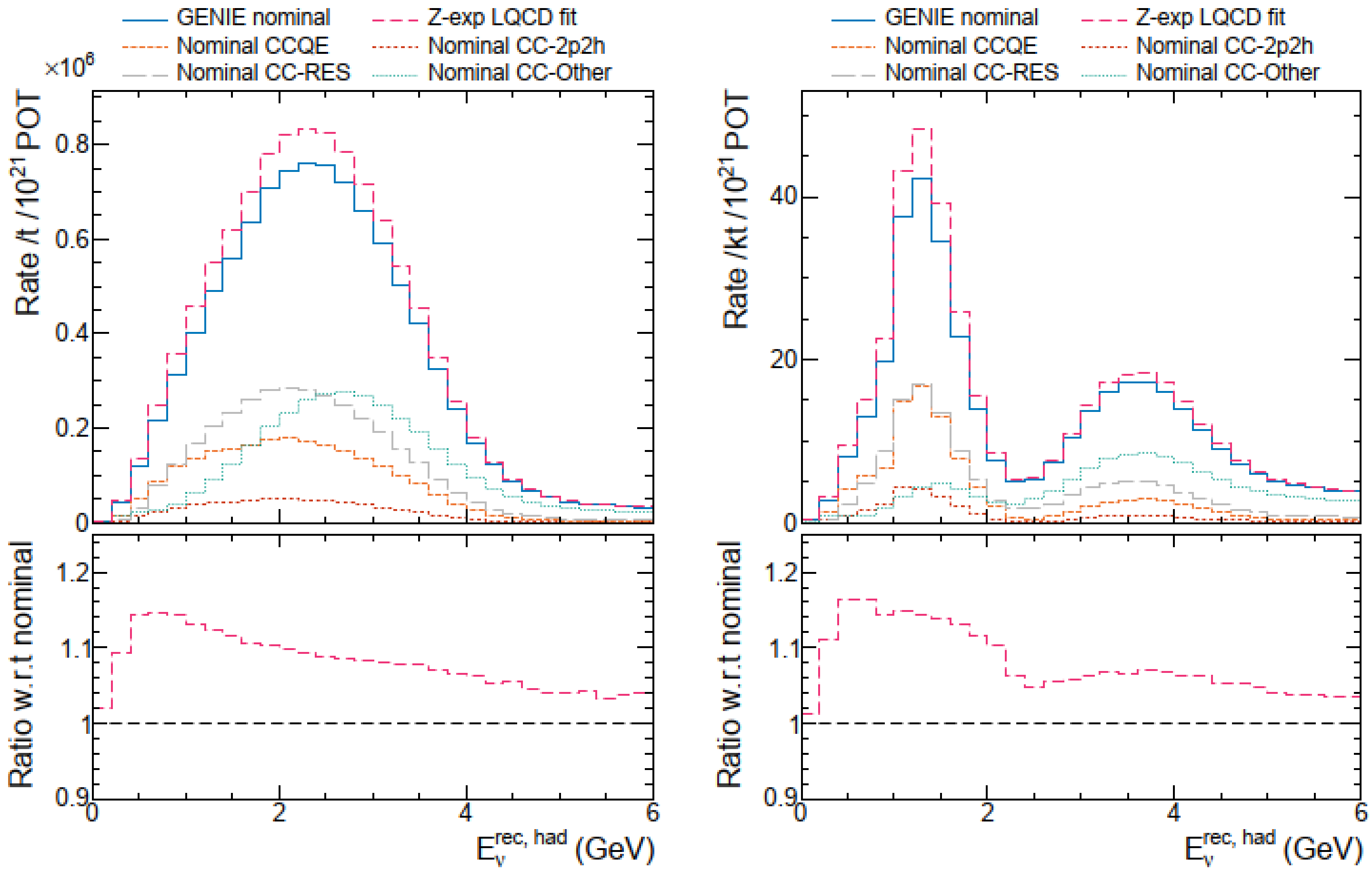
Background: QELike 2p2h

Regions of the 2D angular distribution **used to fit the backgrounds** proportion **in the signal region**.



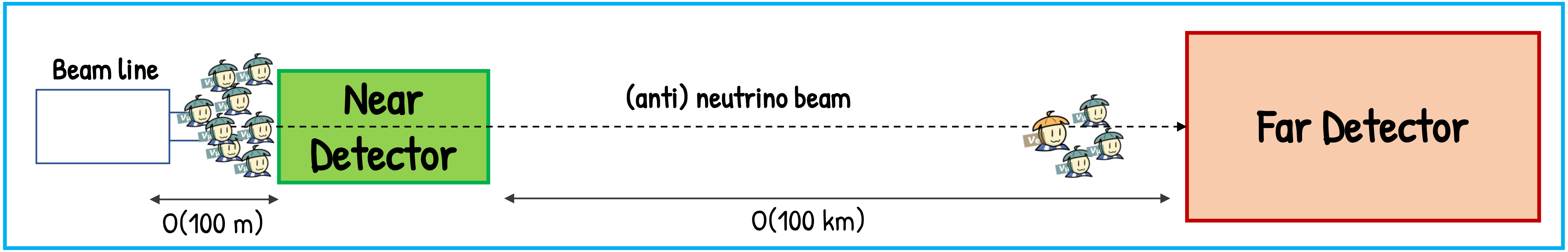
Background: QELike Resonant

Effect on DUNE data (?)



[Meyer et. al]

Oscillation studies in long baseline neutrino experiments



$$N_\mu\,(E_\nu) = P(\nu_\mu \to \nu_\mu)\,\Phi_\nu(E_\nu)\,\sigma(E_\nu)\,\epsilon(E_\nu)$$

$P(\nu_\mu \to \nu_\mu)$: Oscillation probability carried by the PMNS matrix

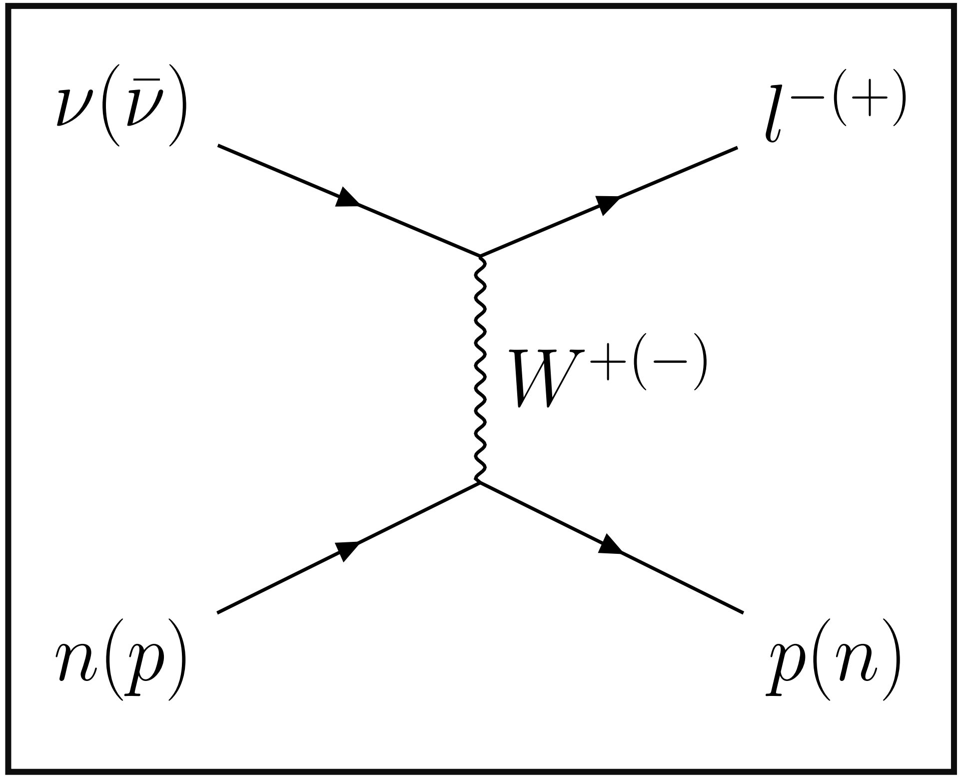
$\Phi_\nu(E_\nu)$: neutrino Flux, constrained by the near detector studies

$\sigma(E_\nu)$: Neutrino cross section, constrained by near detector studies and neutrino interaction models

$\epsilon(E_\nu)$: Detector efficiency, from Data-Monte Carlo studies

How to understand the neutrino cross sections

Main channel of interaction for (anti) neutrinos: (Quasi) elastic scattering



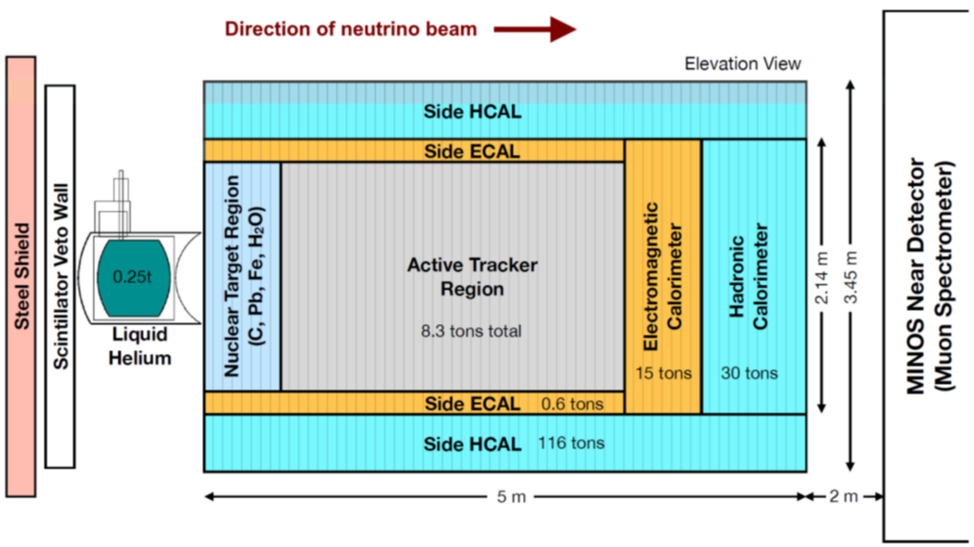
Signal of interest:

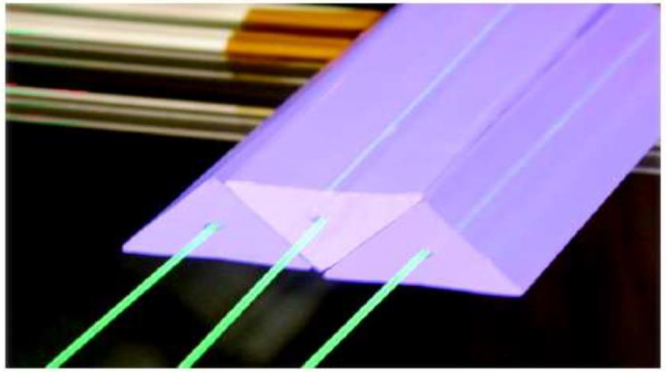
Charged lepton emitted in time & space coincidence with a hadron in the detector.

Different type of detector (**plastic scintillators**, **water Cerenkov**, **time projection chambers**…)

But always the same dominant interaction of interest!

The MINERvA experiment



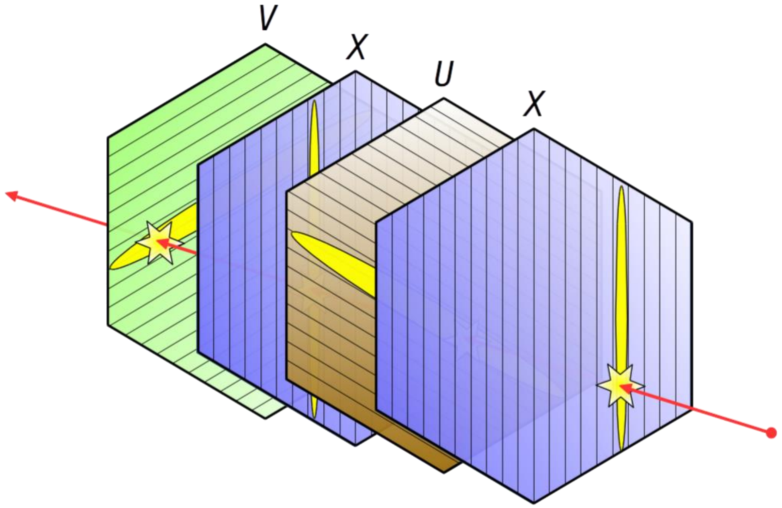


High resolution scintillator detector located at Fermilab in the NuMI beamline

Beamline produces muon (anti) neutrinos that interact in the detector

Detector tracker is composed of hexagonal planes, each constructed from triangular hydrocarbon (CH) strips

The planes are oriented on 3 different directions to be able to get a 3D reconstruction of particles



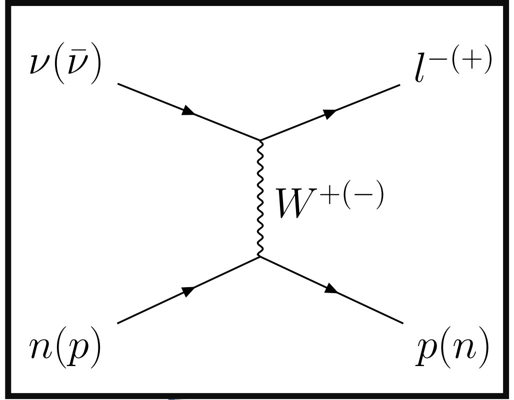
Free nucleon cross-section: Llewllyn Smith equations

$$\frac{d\sigma}{dQ^2}\begin{pmatrix}\nu n \to l^- p \\ \bar{\nu} p \to l^+ n\end{pmatrix} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(Q^2) \mp B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right]$$

$$A(Q^2) = \frac{m^2+Q^2}{4M^2}\left[\left(4+\frac{Q^2}{M^2}\right)|F_A|^2 - \left(4-\frac{Q^2}{M^2}\right)|F_V^1|^2 + \frac{Q^2}{M^2}\left(1-\frac{Q^2}{4M^2}\right)|\xi F_V^2|^2 + \frac{4Q^2}{M^2}\mathrm{Re}F_V^{1*}\xi F_V^2 + \mathcal{O}\left(\frac{m^2}{M^2}\right)\right],$$

$$B(Q^2) = \frac{Q^2}{M^2}\mathrm{Re}F_A^*(F_V^1+\xi F_V^2),$$

$$C(Q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{4M^2}|\xi F_V^2|^2\right)$$



How to measure the cross section ?

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\right)_i = \frac{\sum_j U_{ji}\left(N_j^{\mathrm{data}} - N_j^{\mathrm{bkg-pred}}\right)}{\Phi N_H \epsilon_i (\Delta Q^2)_i}$$

Q^2: 4-momentum transfer squared

$\left(\frac{d\sigma}{dQ^2}\right)_i$: Differential cross section in the ith Q^2 bin

ΔQ^2: Width of the ith bin

U_{ij}: Unfolding matrix that carries the detector smearing

N_j^{data}: What we measure

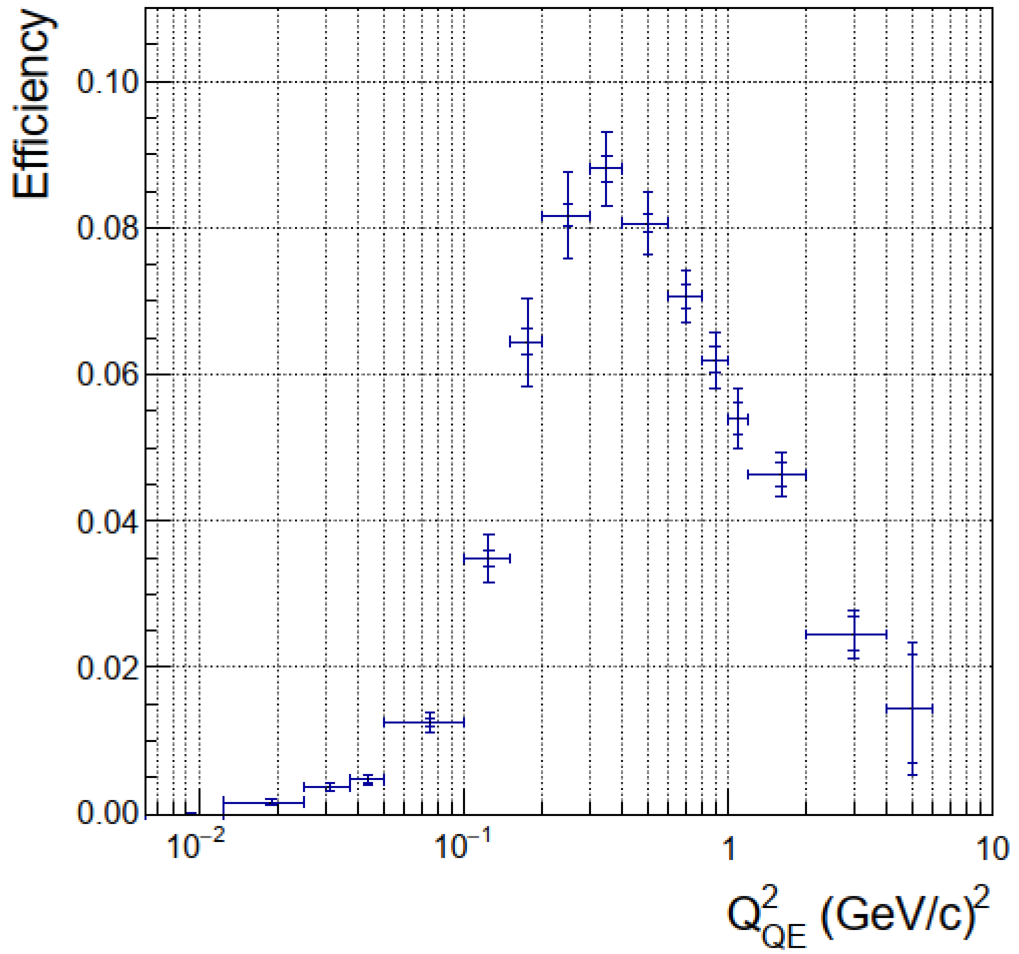
$N_j^{bkg-pred}$: Background prediction from models

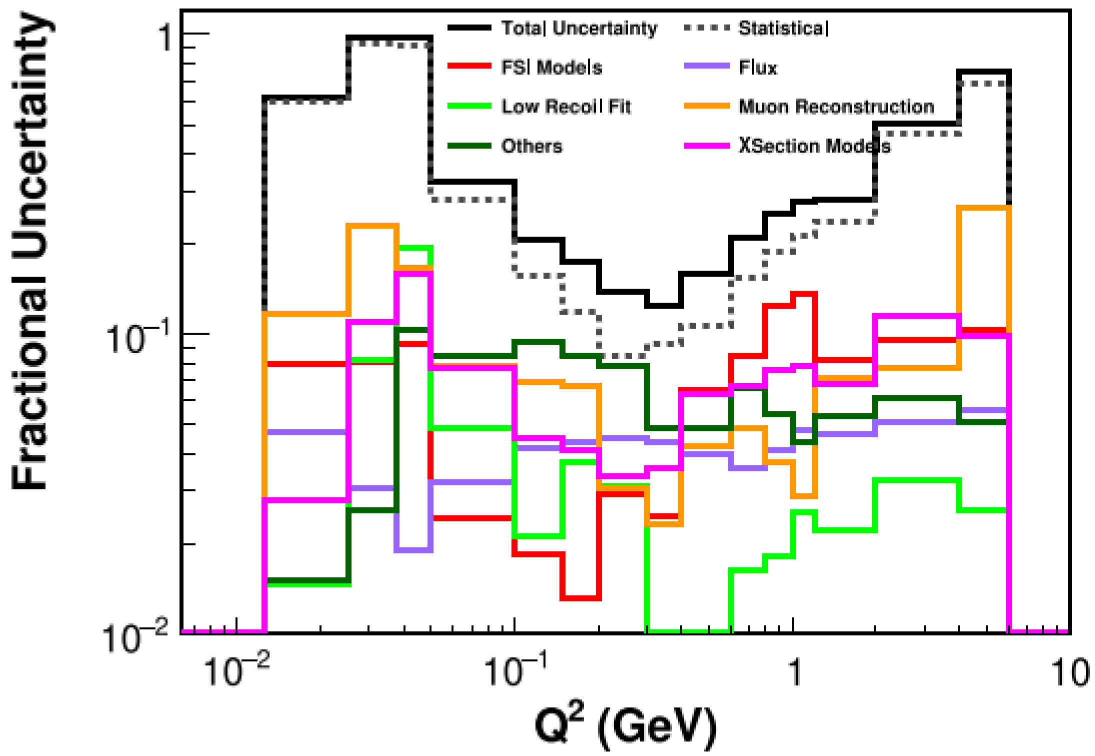
Φ: Flux knowledge

N_H: Number of hydrogen targets

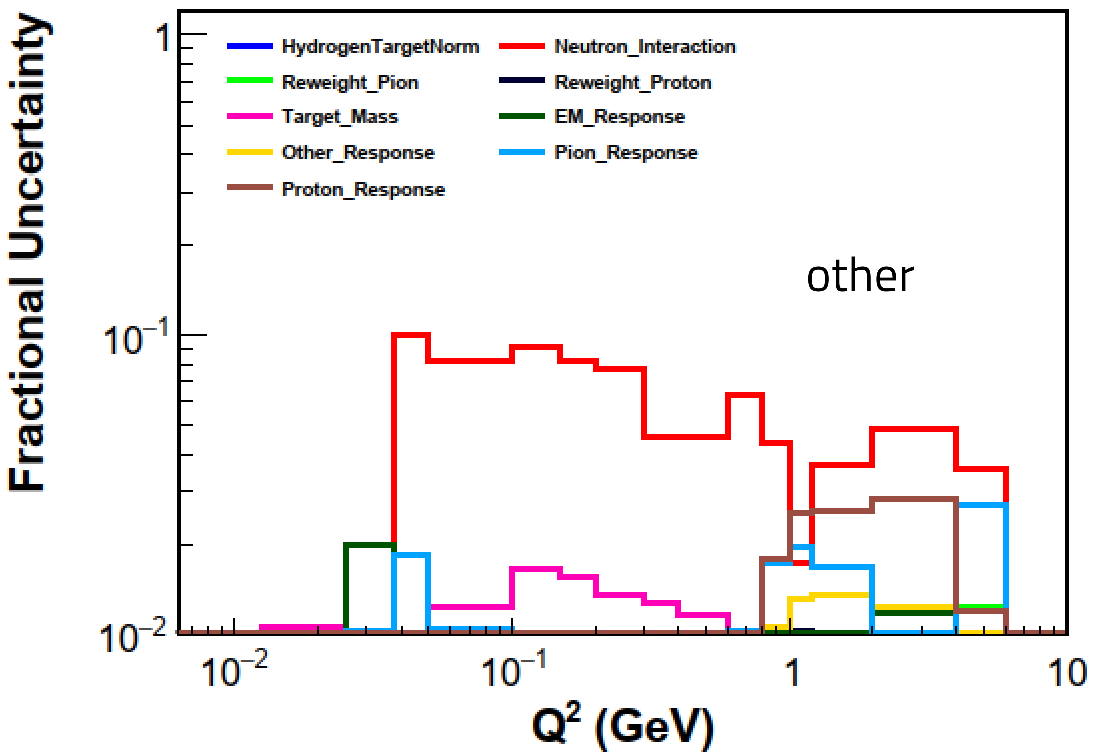
ε_i: signal efficiency

Efficiency





Fractional Uncertainty
Total Uncertainty
Statistical
FSI Models
Flux
Low Recoil Fit
Muon Reconstruction
Others
XSection Models
Q^2 (GeV)



Fractional Uncertainty
HydrogenTargetNorm
Neutron_Interaction
Reweight_Pion
Reweight_Proton
Target_Mass
EM_Response
Other_Response
Pion_Response
Proton_Response
other
Q^2 (GeV)

z-expansion formalism and constraints on a_k

$$F_A(Q^2) = \sum_{k=0}^{k_{\max}} a_k z^k$$

$$z = \frac{\sqrt{t_{\text{cut}} + Q^2} - \sqrt{t_{\text{cut}} - t_0}}{\sqrt{t_{\text{cut}} + Q^2} + \sqrt{t_{\text{cut}} - t_0}}$$

$$\sum_{k=n}^{\infty} k(k-1)\dots(k-n+1)a_k = 0, n \in (0,1,2,3)$$

$$\chi^2 = \Delta X \cdot \text{cov}^{-1} \cdot \Delta X + \lambda \left[\sum_{k=1}^{5} \left(\frac{a_k}{5a_0} \right)^2 + \sum_{k=5}^{k_{\max}} \left(\frac{k a_k}{25 a_0} \right)^2 \right]$$

Central value fit: $k_{\max} = 8, \lambda = 0.13$