Recent results on π^0 measurements at $E\nu$~<6 GeV> in the MINERνA experiment

Noë Roy, on behalf of the MINERνA collaboration

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YORK U

Canadian Association of Physicists
Association canadienne des physiciens et physiciennes

MINERνA

What do we want to study?

Less than a hundred years ago, neutrinos were thought to be undetectable…

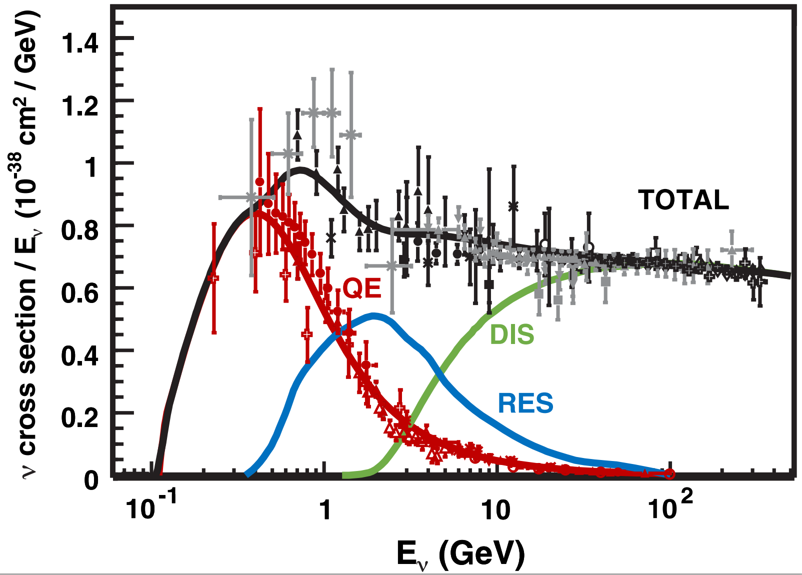
Thanks to the development of detection methods on various neutrino sources, we've come a long way!

A large physics field was opened for us

Accelerator neutrino experiment are a great way to have a controllable & high statistics neutrino source.

However : with neutrinos at the O(100 MeV/GeV) energy scale, final states can get crowded with…

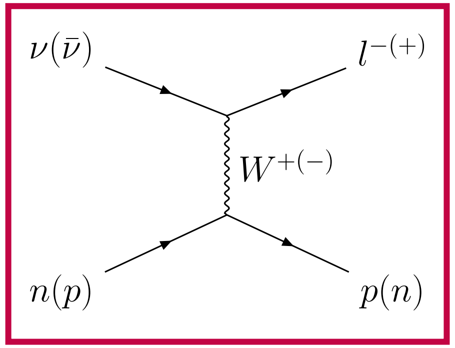
[Rev. Mod. Phys. 84, 1307]

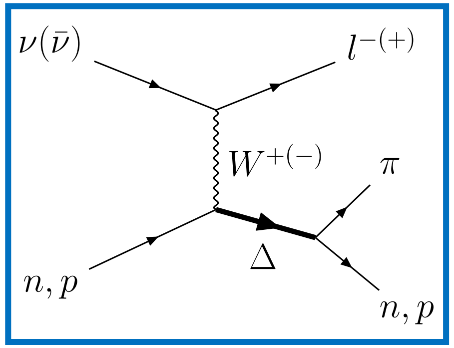


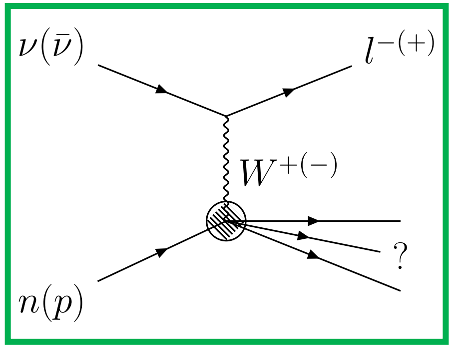
- **Charge Current (Quasi)-Elastic scattering**
- **Resonant Pion production**
- **Deep inelastic scattering**

-> Require already a good tagging/tracking technology

How do things get messy?







Ideal world:

- Neutrino interacts on a free nucleon
- All the particles in the final state particles are reconstructed
- Initial creation process inferred

Channel of interaction	Final states
CCQE	l^- + p
Pion resonance	l^- + π + Np
DIS	l^- + Nπ + Mp

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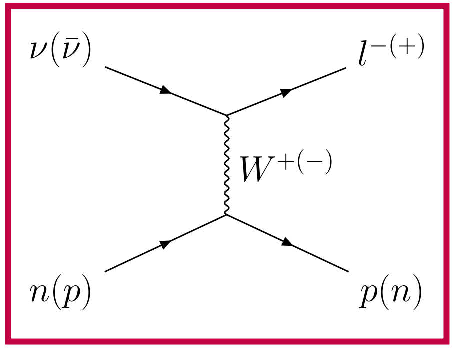

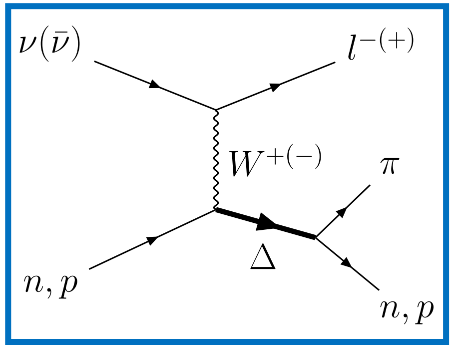

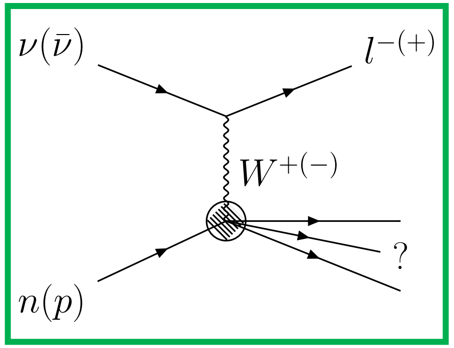

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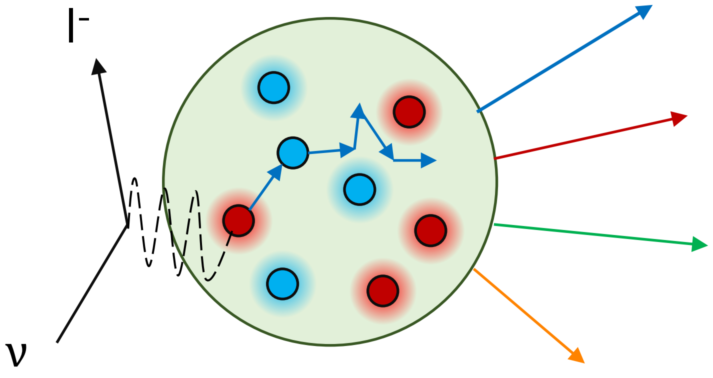
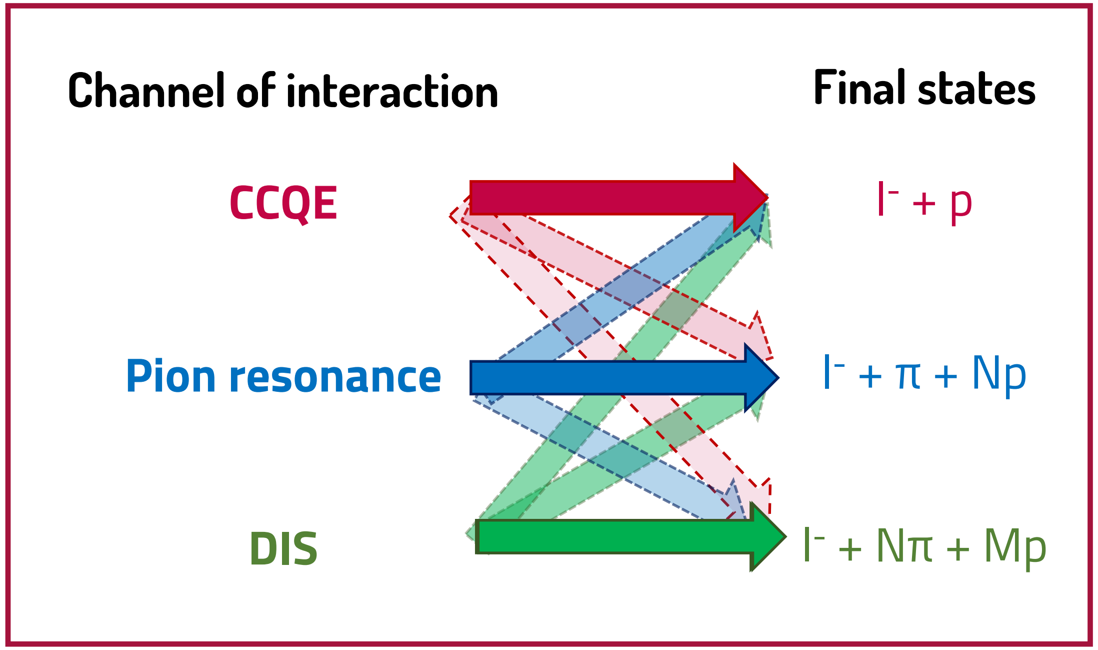
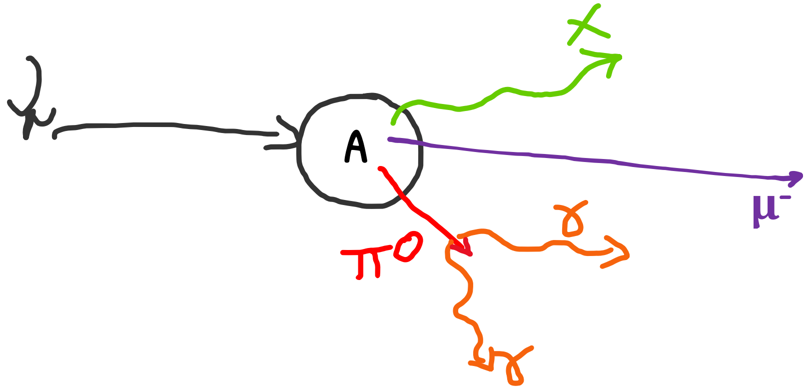


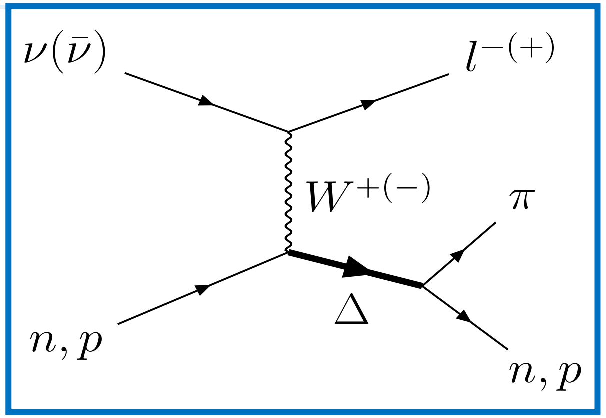
Final state interactions



Need to produce interaction models based on theory + data to simulate the neutrino interactions!

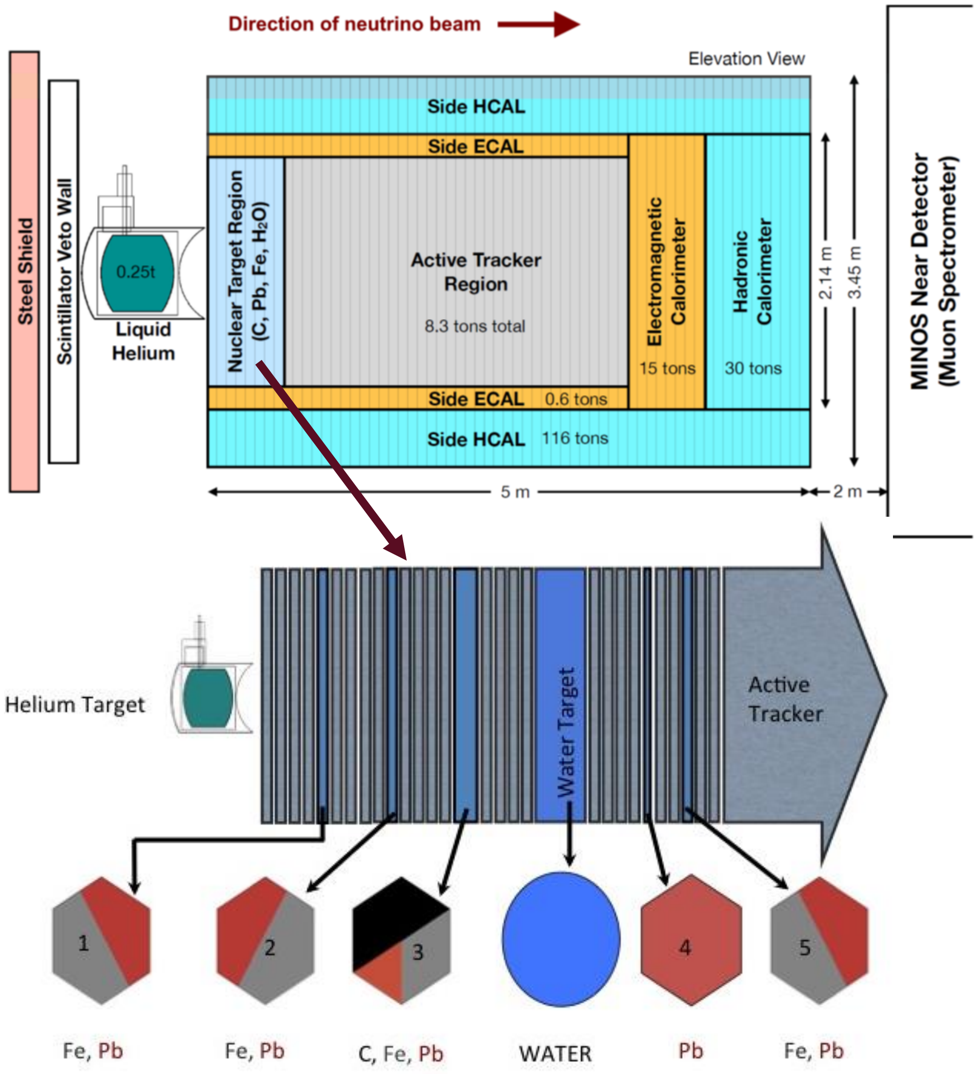
Why study neutral pions?





- Neutral pions produced mostly by Δ resonance production inside the nuclei target
- π^0 are neutral particle, can can only be detected with their decay products
- If the gammas are missed or if we just see 1 gamma and 1 proton in the final state, can be miss-classed as another type of interaction
- Understanding all channels of interactions of neutrinos is essential!

The MINERνA experiment



High resolution scintillator detector located at Fermilab in the NuMI beamline

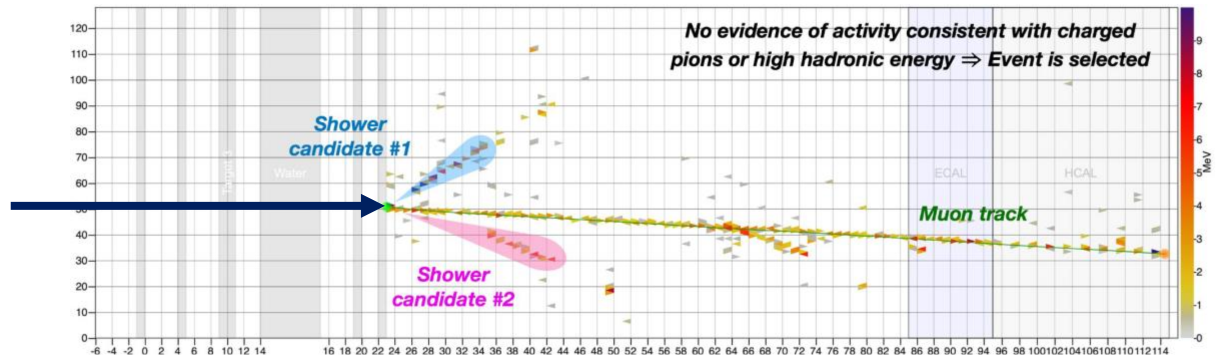
Beamline produces muon (anti) neutrinos that interact in the detector

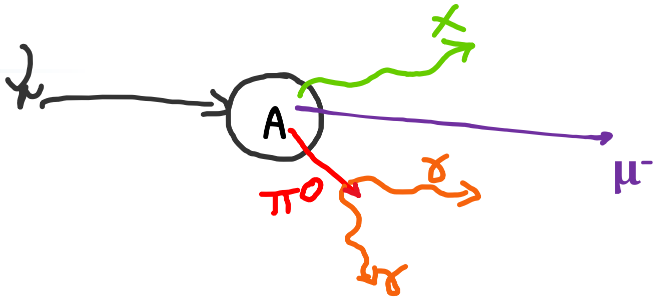
Detector composed of a plastic **scintillator Tracker (CH)** and of **nuclear targets** (Fe, C, Pb, Water)

Measuring the evolution of x-section with different Z will help generalizing cross section models

Here, x-section measured on **Pb** and **Fe**

What does a π^0 look like in MINERνA?





Perfect case scenario:

Muon track tagged by MINOS near detector

2 showers consistent with gammas from π^0

Showers are identified with Angle scan algorithm and with their geometrical features.

No charged pion activity or High energy hadronic energy

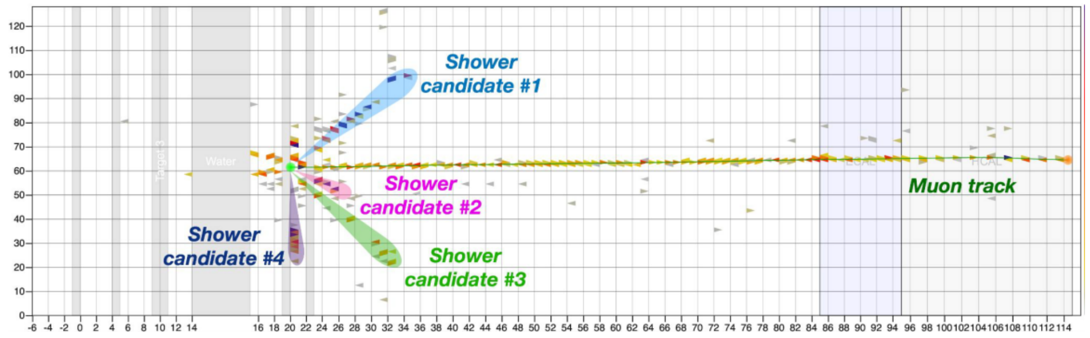
Some limitations:

Protons & pions can mimic shower signature

Hadronic energy lost inside passive materials (targets)

Interactions can get busy -> Larger background

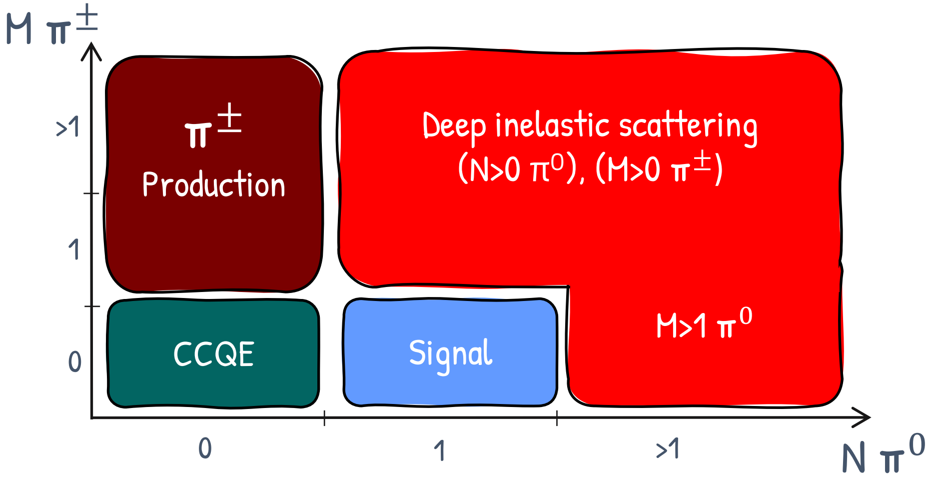
Final selection: at least one shower candidate



Understanding the backgrounds

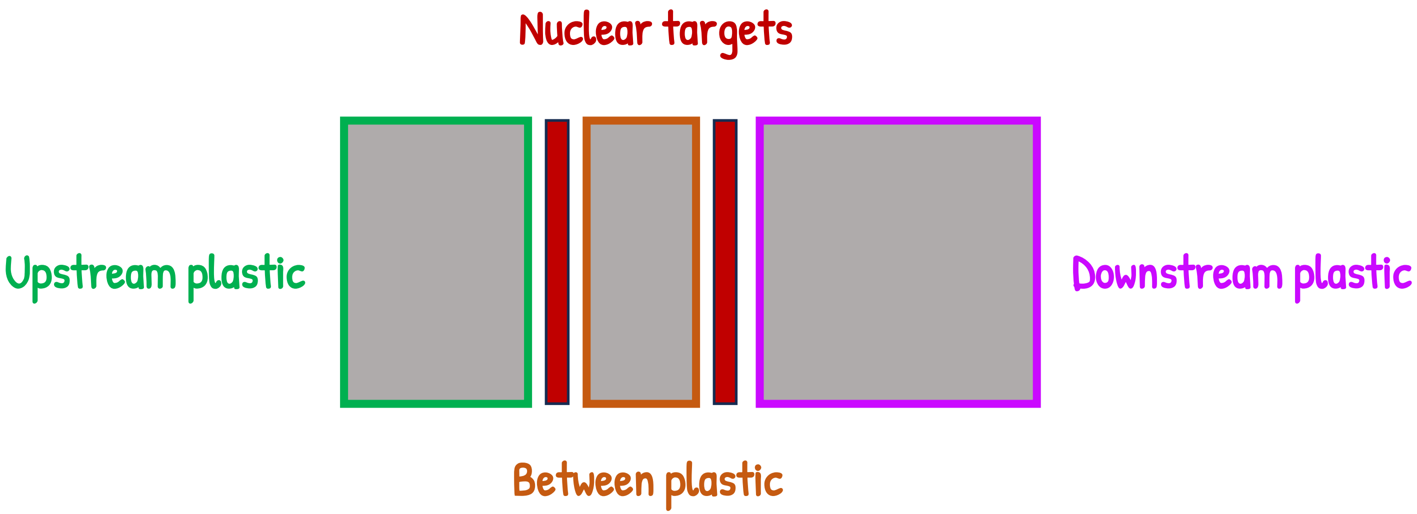
Physics background

- (More than 1 π^0) OR (1 π^0 and more than 1 $\pi^\pm$)
- No π^0 and some $\pi^\pm$
- No pions



"Plastic" background

Neutrinos that interact in **plastic scintillator** and not **targets**



Our selected data is made of the "Signal" and all the different types of background.

We know that the neutrino generator does not reproduce perfectly well the physics

Use the selection in "sidebands" to constrain our backgrounds

Understanding the backgrounds

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- (More than 1 π^0) OR (1 π^0 and more than 1 $\pi^\pm$)
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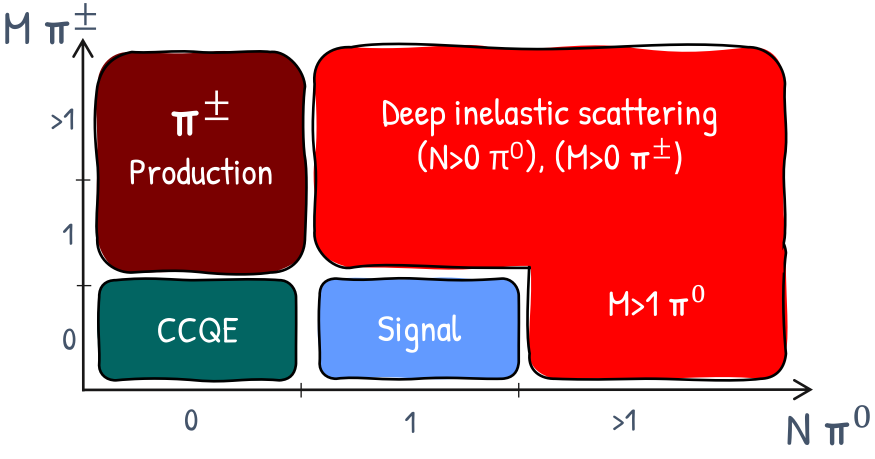

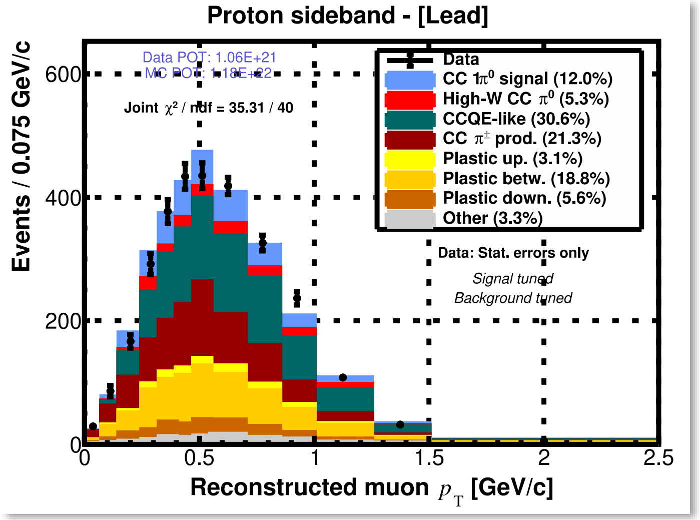

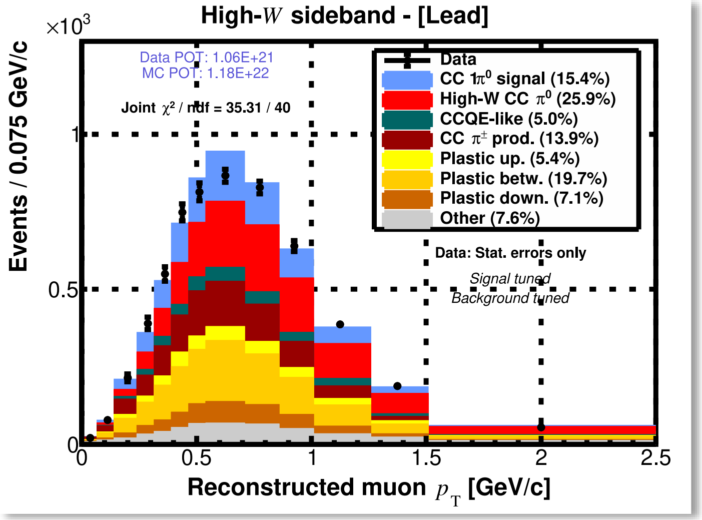

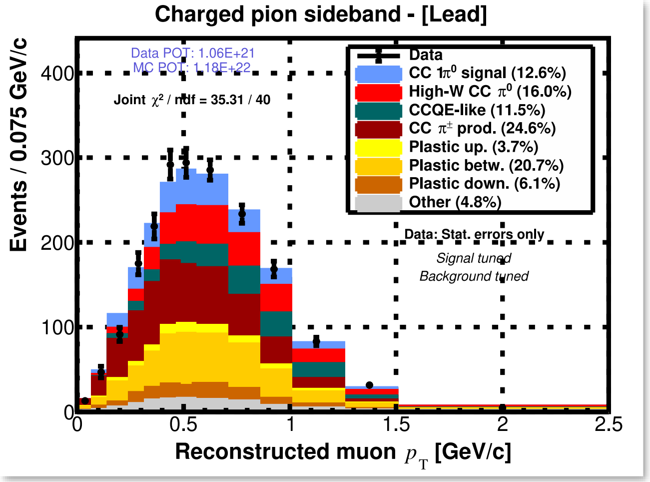

Physics sidebands:

- High hadronic invariant mass (W) events -> More likely to be DIS events
- Michel electron in the event -> As Michel electrons are produced by $\pi^\pm$ decay chain
- Gamma shower dE/dx consistent with proton -> If the gamma shower is in fact a proton

Selection inside the "sidebands" to constrains our model with data/MC simultaneous fits.

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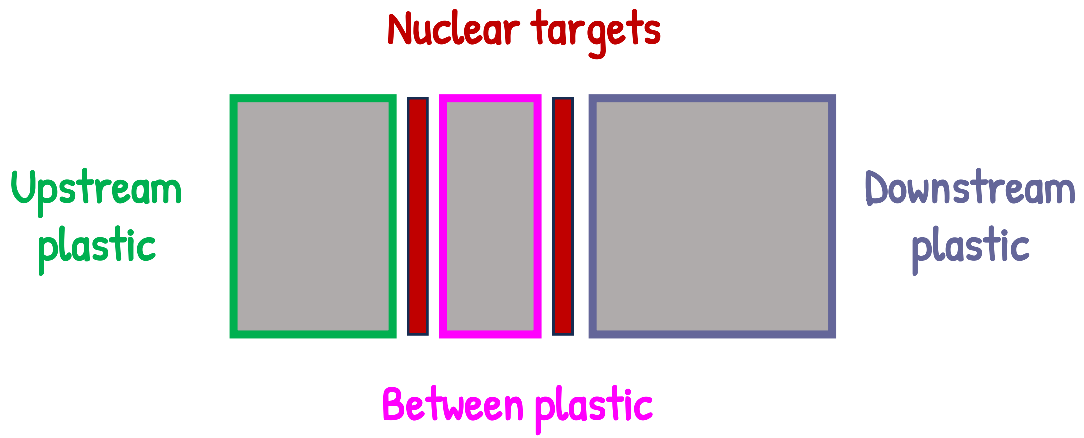
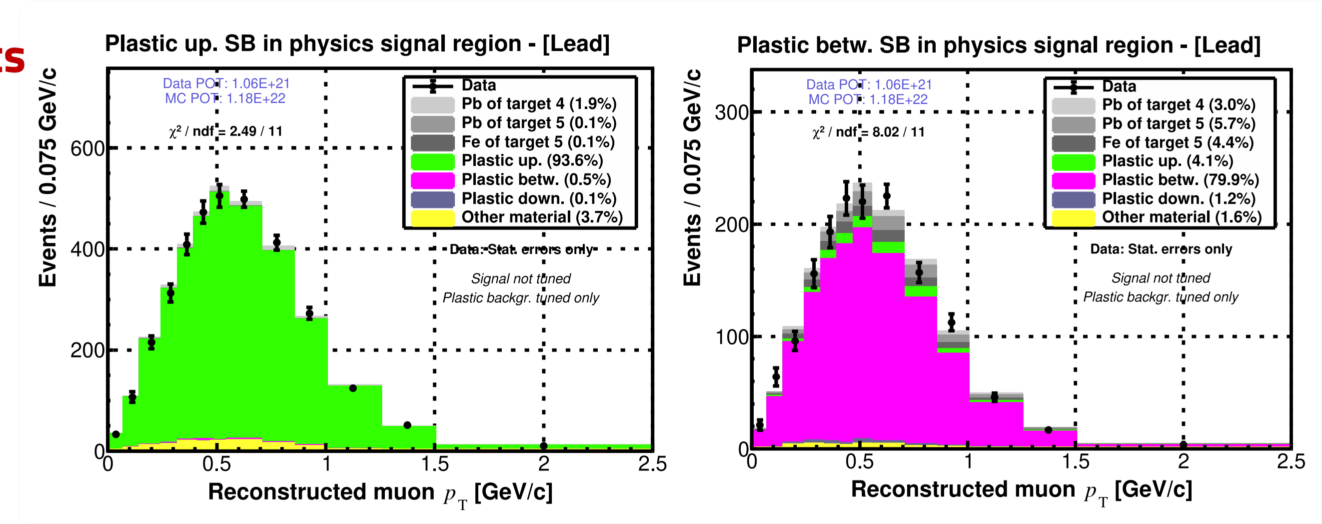
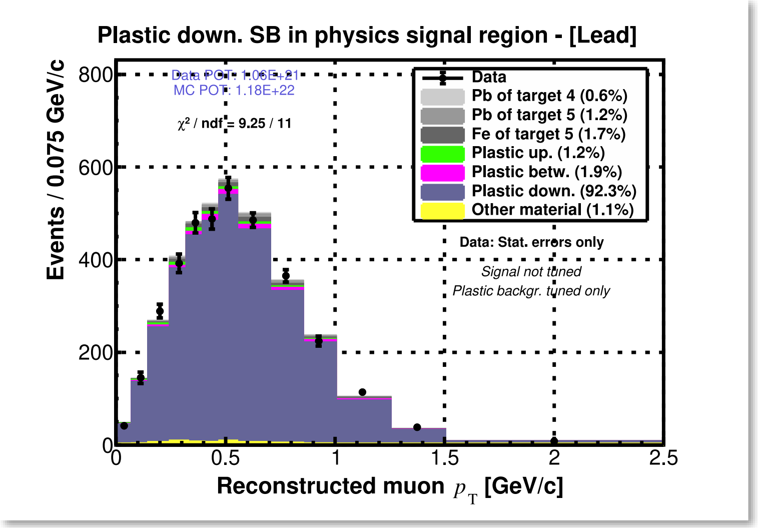




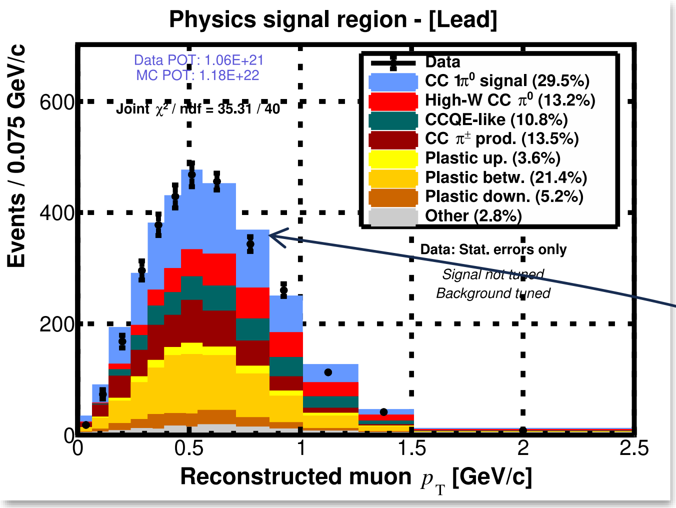
Plastic sidebands:

Selection of interactions in the **3 plastic regions**



Selection inside the "sidebands" to constrains our backgrounds with data/MC simultaneous fits.

Extraction of a cross section

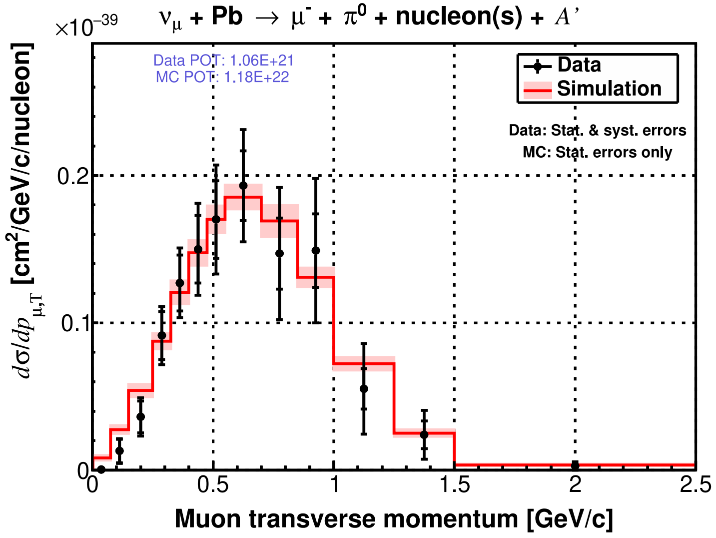


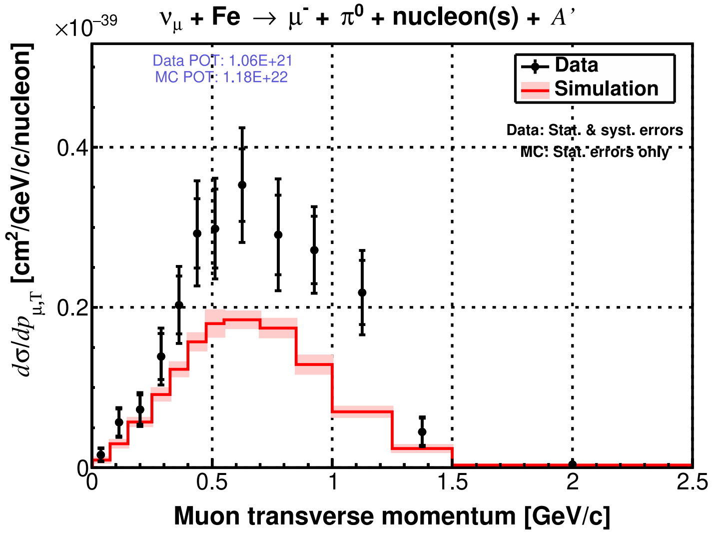
$$\left(\frac{d\sigma}{dp_{\mu,T}}\right)_i = \frac{\sum_j U_{ji}\left(N_j^{\mathrm{data}} - N_j^{\mathrm{bkg-pred}}\right)}{\Phi N_T \epsilon_i (\Delta p_{\mu,T})_i}$$

What do we need to extract a cross section ?

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

We have everything we need!



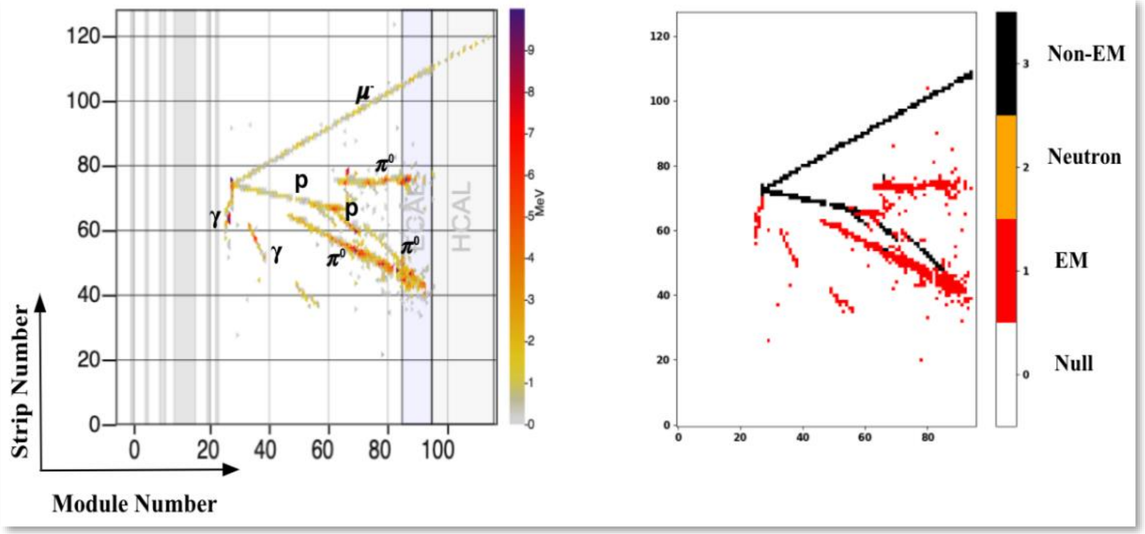


We see a large difference in x-section Pb vs Fe: Final state interaction effects.

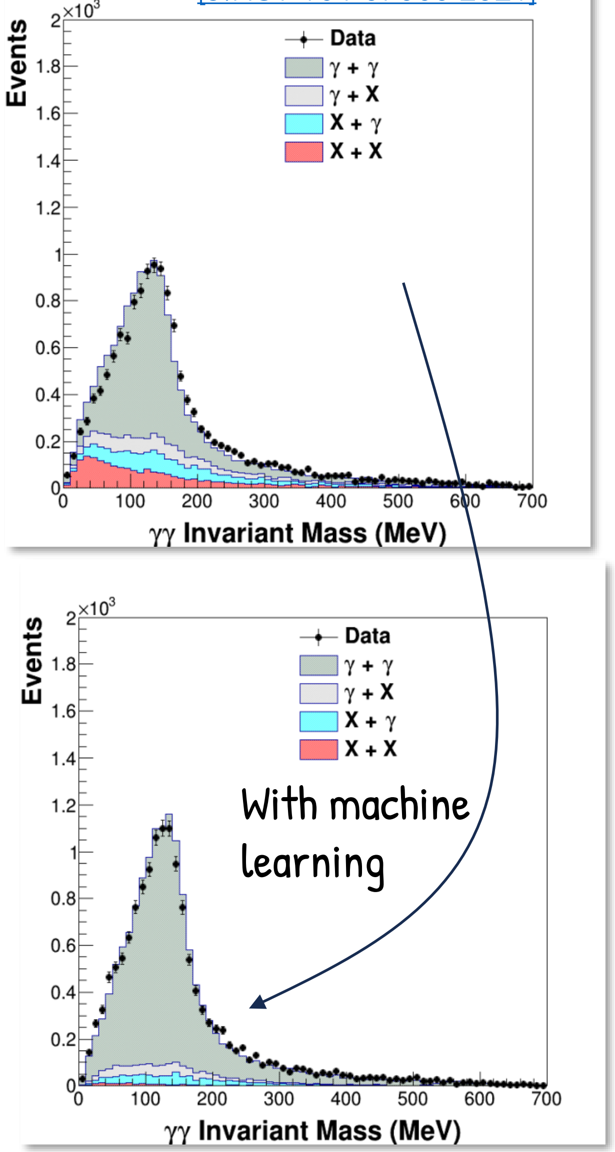
Those data will be useful to try different models of pion productions!

To come: x-section measurement on plastic scintillator

- Events are less crowded as C and H are lighter elements
- No passive materials due to the targets: Better reconstruction of the hadronic kinematics
- Much more statistics
- Developed a Machine learning (ML) algorithm similar to MicroBooNE ML segmentation[1] to distinguish electromagnetic showers from gammas.



[JINST 16 P07060 2021]



[1] Phys. Rev. D 99 (2019) 092001

Conclusion

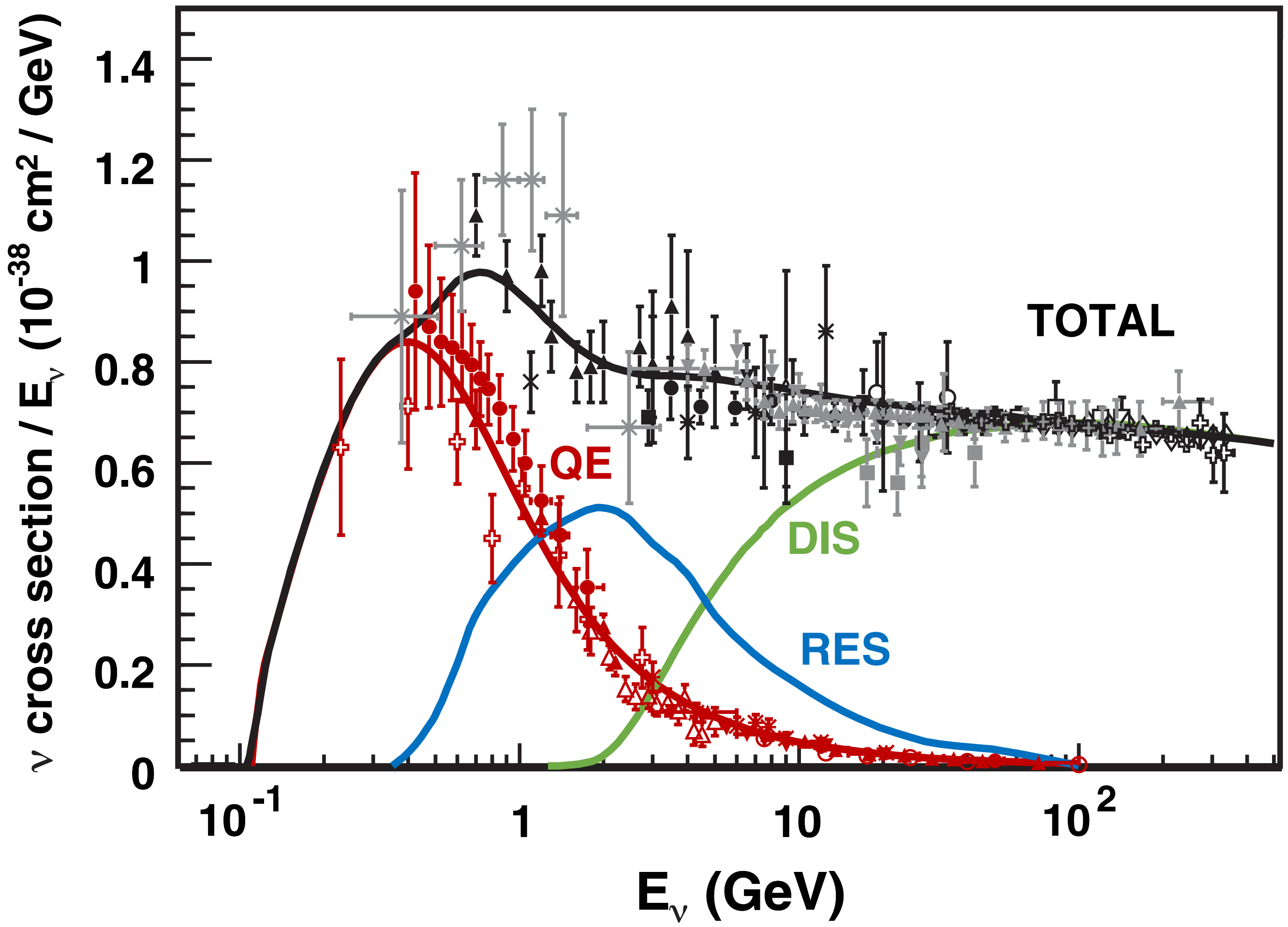
We have performed a measurement of neutral pion production on various targets

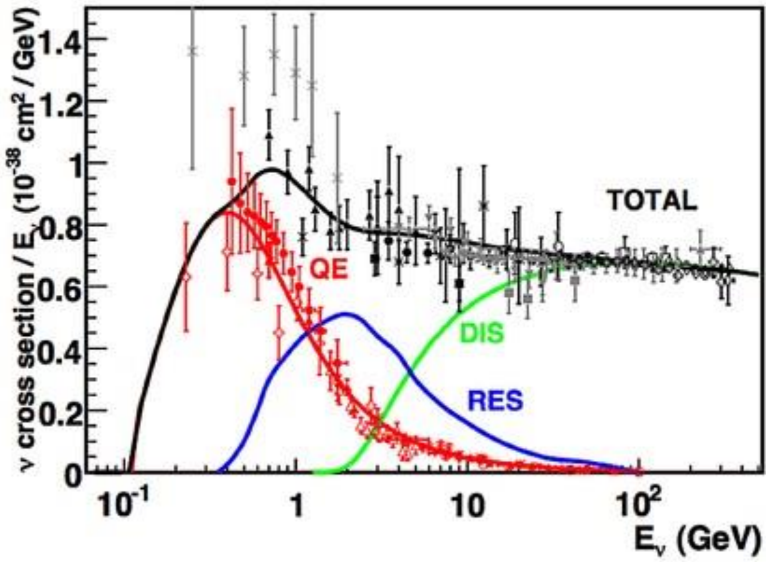
- Developed a method to reconstruct π^0 candidates in the MINERνA detector
- Extracted a cross section for Pb and Fe targets
- Showed variation of the x-section not reproduced by our model
- Article coming soon on those measurement

More results on neutral pion productions with higher statistics on scintillator coming soon to provide more insights on the disagreements.


Thanks for your attention !

Backup


ν cross section / E_ν (10^{-38} cm² / GeV)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^{-1}
1
10
10^{2}
E_ν (GeV)
TOTAL
QE
DIS
RES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However : with neutrinos at the O(100 MeV/GeV) energy scale, final states can get crowded with…

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- **Resonant Pion production**
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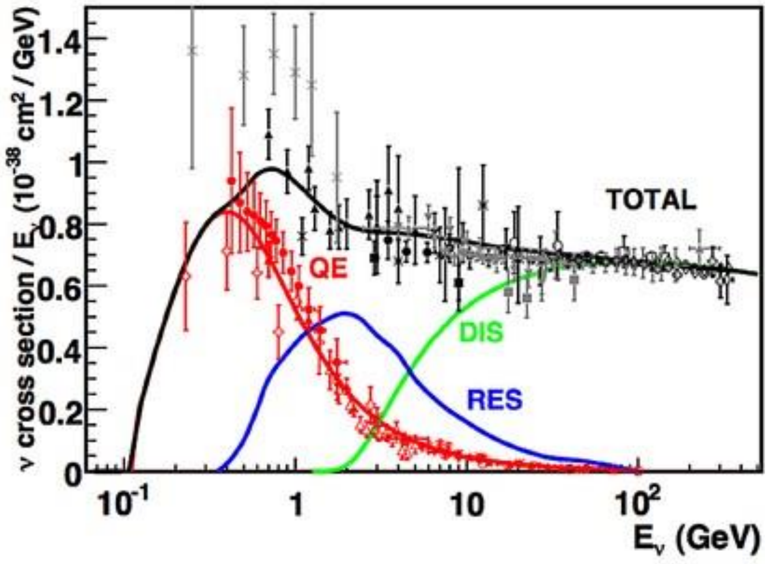
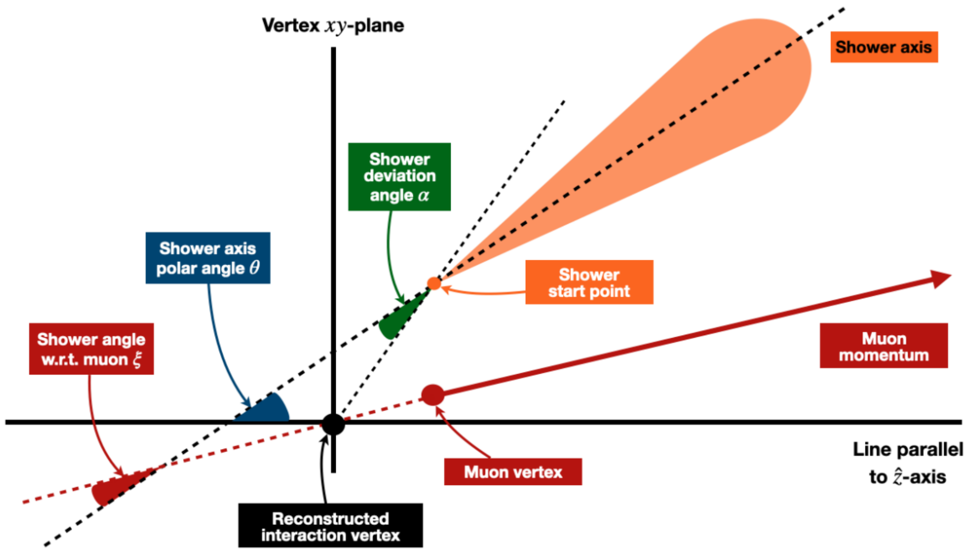
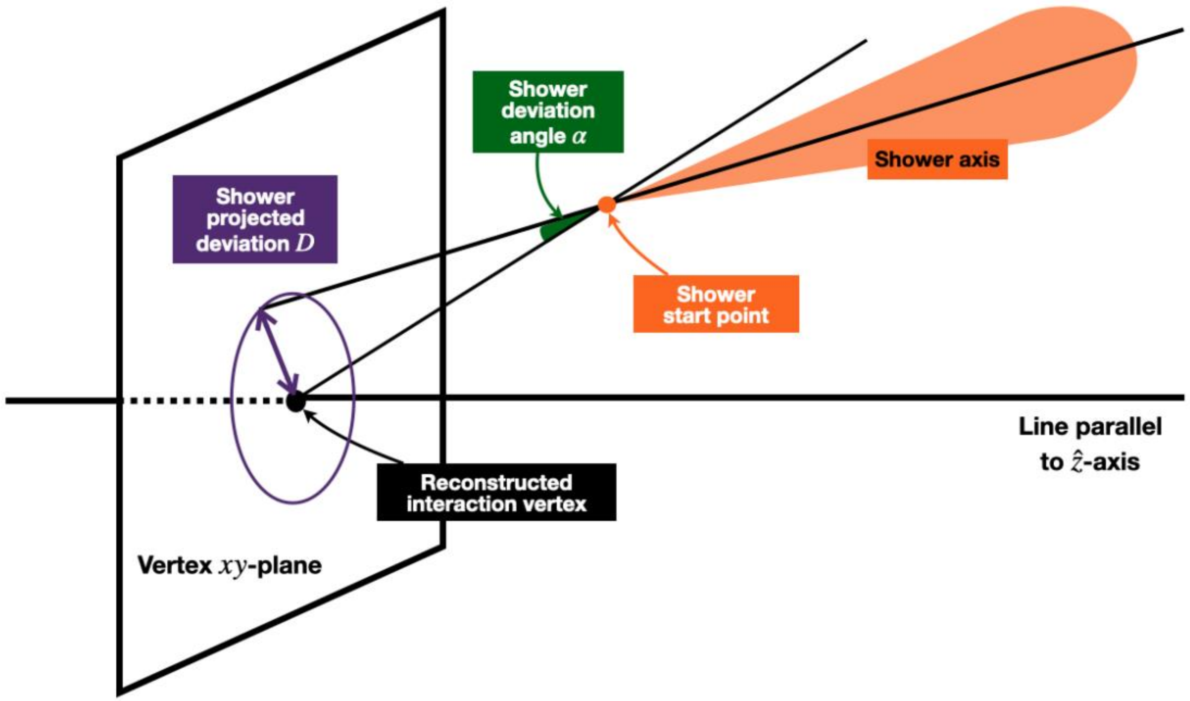
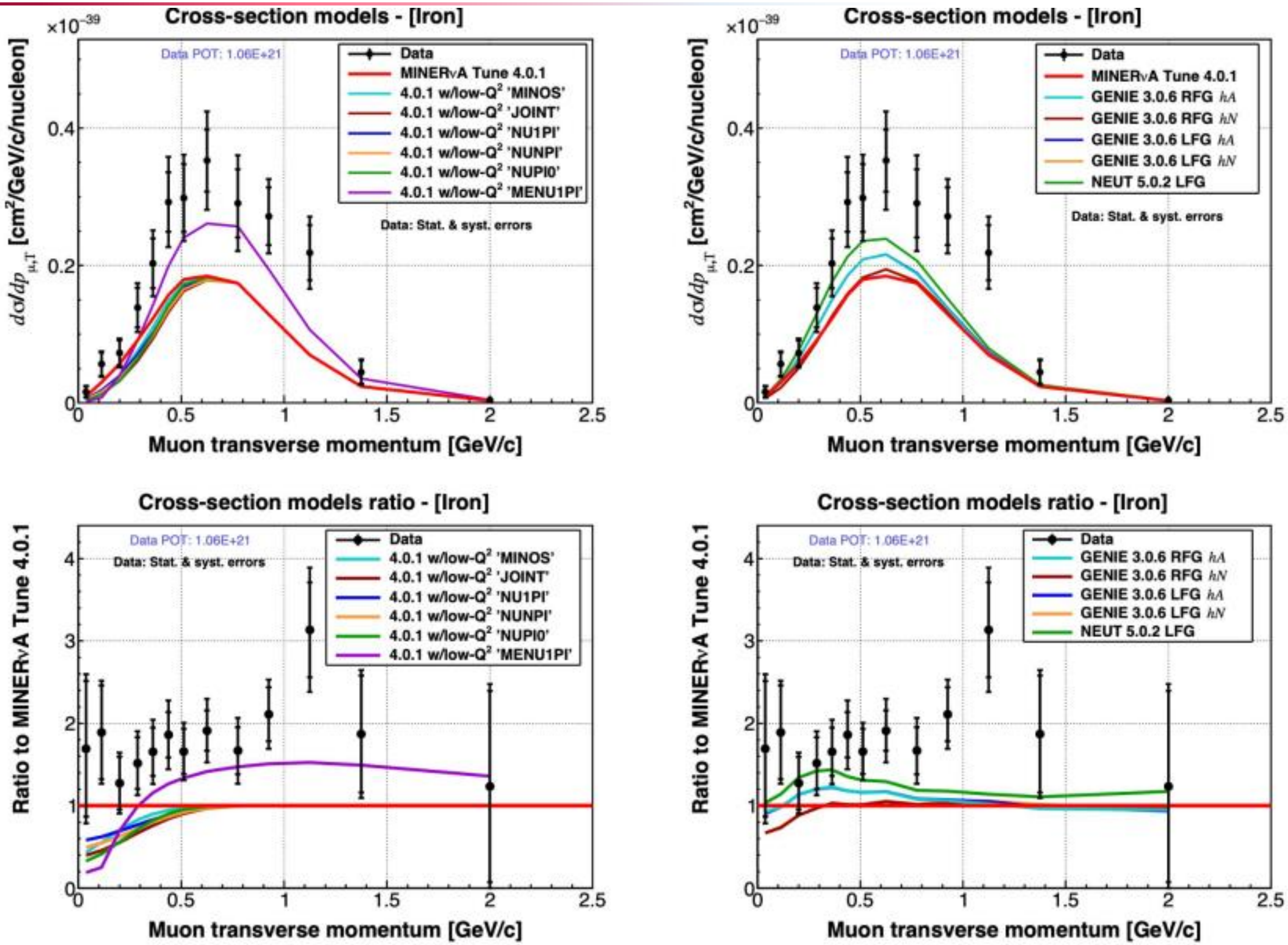


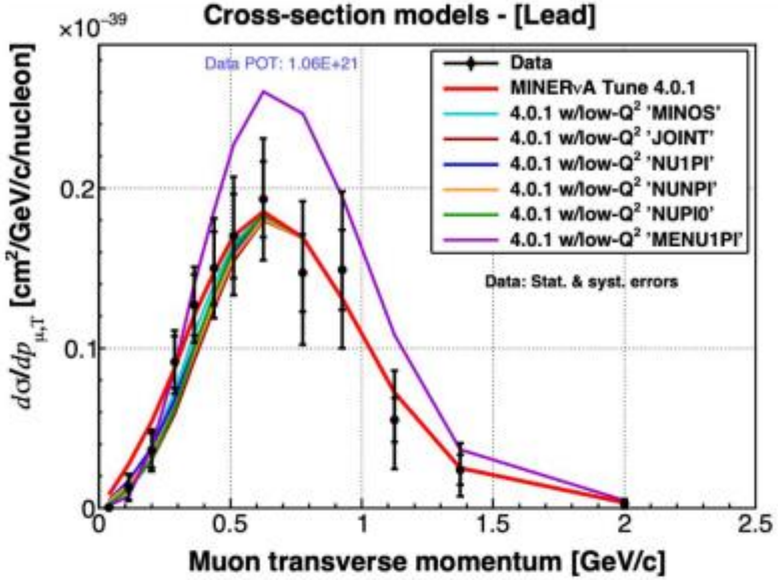
Shower reconstruction direction

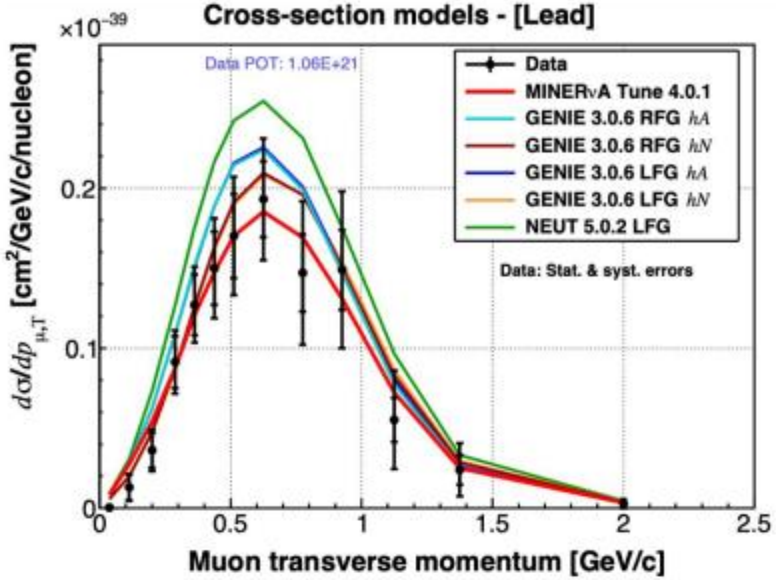




Model comparisons




Cross-section models - [Lead]
×10^-39
Data POT: 1.06E+21
Data
MINERνA Tune 4.0.1
4.0.1 w/low-Q² 'MINOS'
4.0.1 w/low-Q² 'JOINT'
4.0.1 w/low-Q² 'NU1PI'
4.0.1 w/low-Q² 'NUNPI'
4.0.1 w/low-Q² 'NUPI0'
4.0.1 w/low-Q² 'MENU1PI'
Data: Stat. & syst. errors
dσ/dp_μ,T [cm²/GeV/c/nucleon]
Muon transverse momentum [GeV/c]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GENIE 3.0.6 LFG hA
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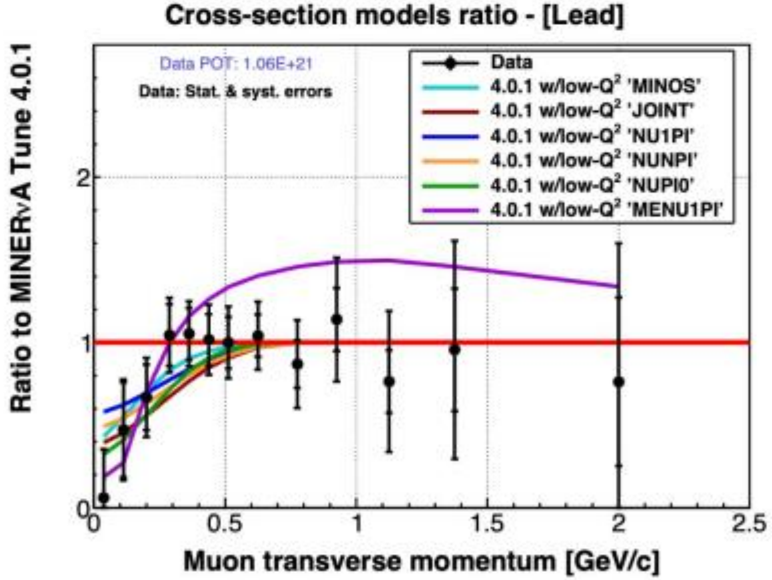
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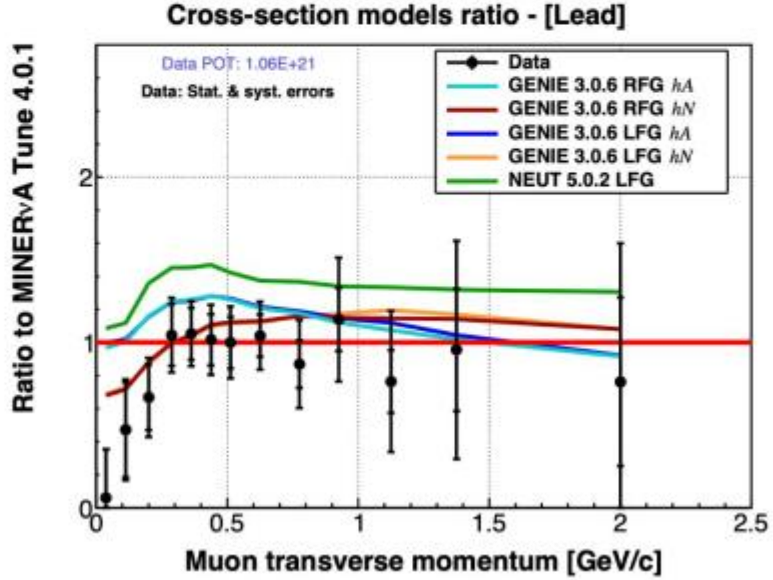
Ratio to MINERνA Tune 4.0.1
Muon transverse momentum [GeV/c]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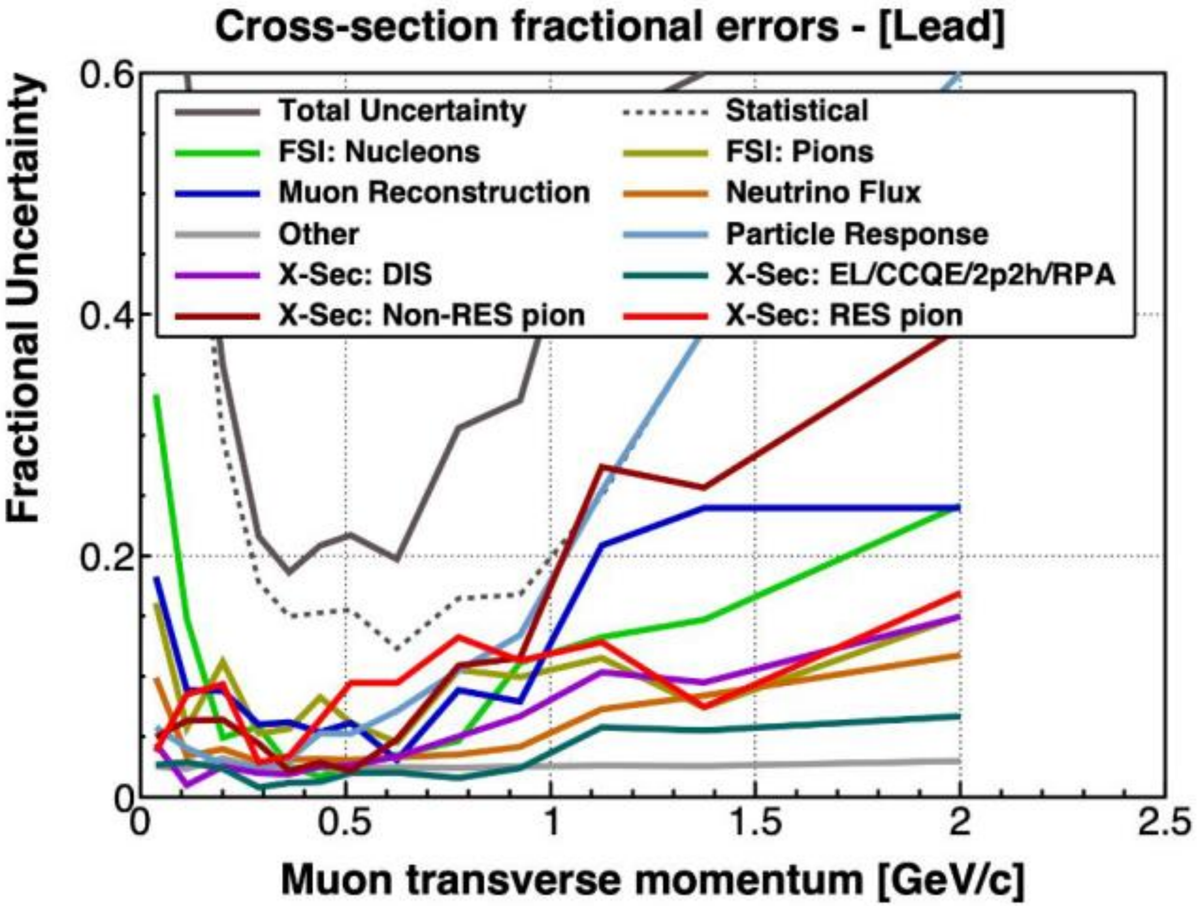
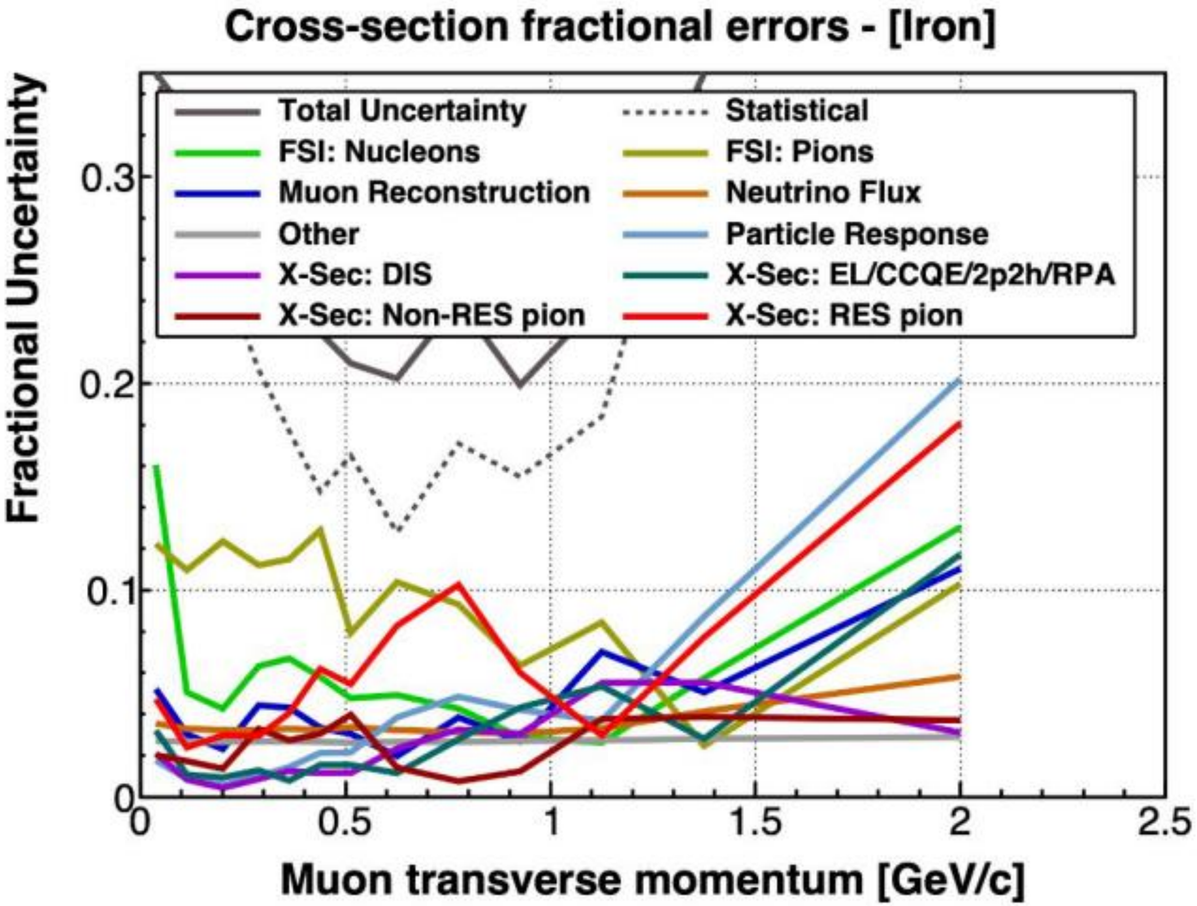
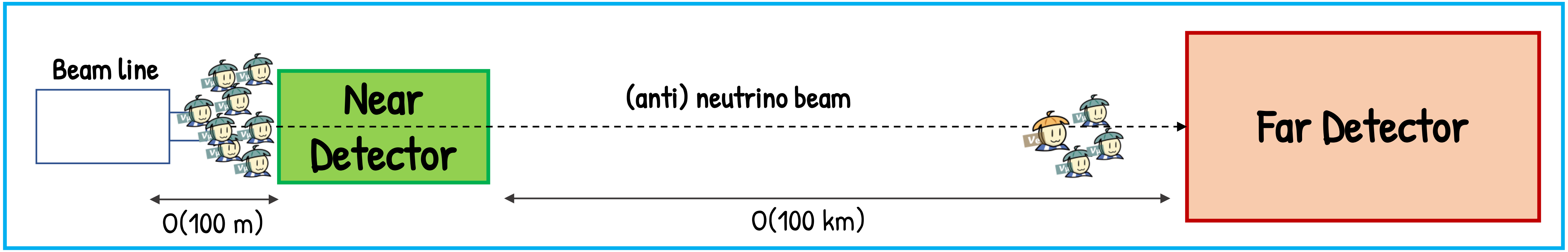
Ratio to MINERνA Tune 4.0.1
Muon transverse momentum [GeV/c]

Fractional uncertainties





Oscillation studies in long baseline neutrino experiments



$$N_{\mu}\,(E_{\nu}) = P(\nu_{\mu} \rightarrow \nu_{\mu})\, \Phi_{\nu}(E_{\nu})\, \sigma(E_{\nu})\, \epsilon(E_{\nu})$$

$P(\nu_{\mu} \rightarrow \nu_{\mu})$: Oscillation probability carried by the PMNS matrix

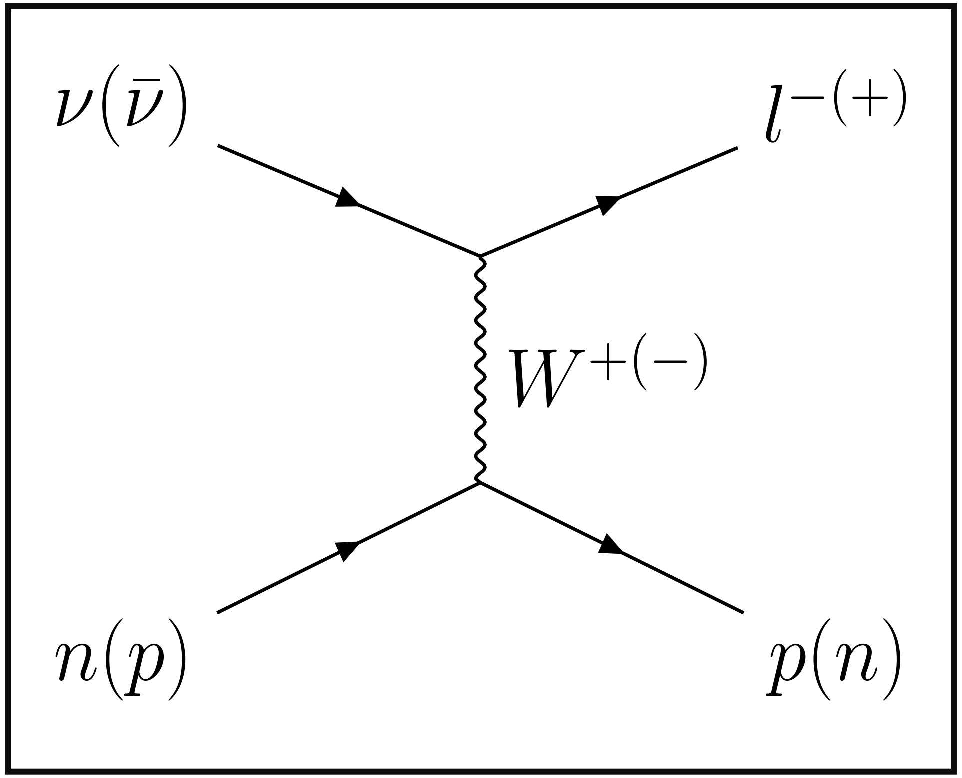
$\Phi_{\nu}(E_{\nu})$: neutrino Flux, constrained by the near detector studies

$\sigma(E_{\nu})$: 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



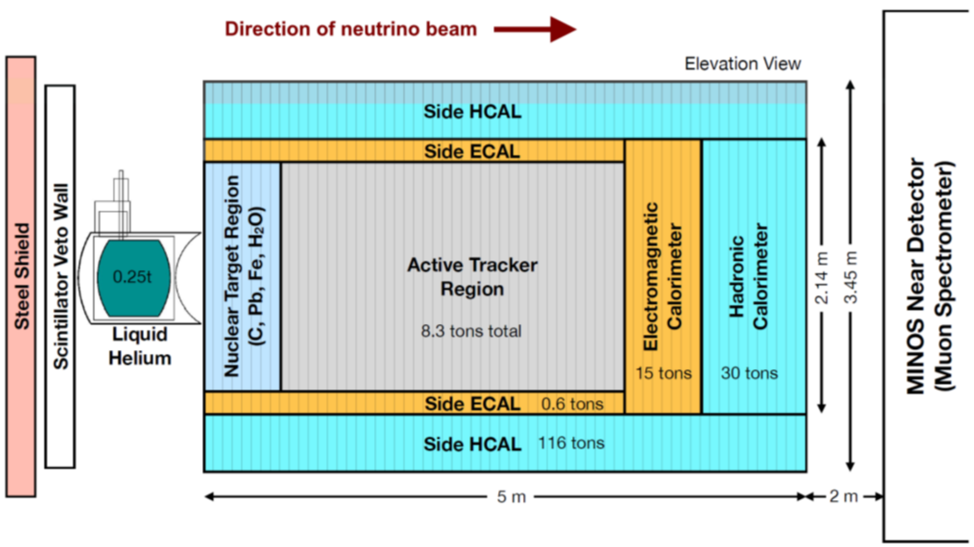
Signal of interest:

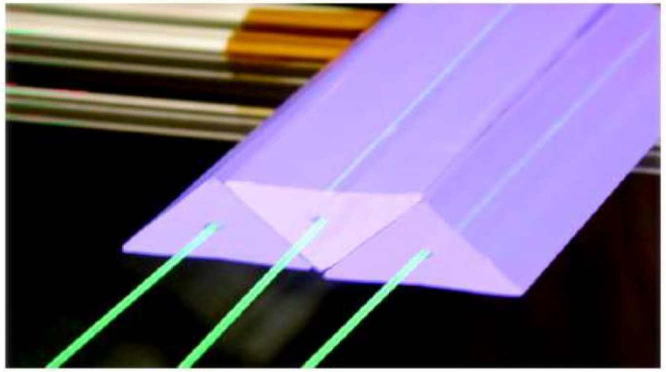
Charged lepton emitted in time & space coincidence with a hadron in the detector.

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