υ_μ CC1π cross section on carbon and water using T2K on-axis detectors

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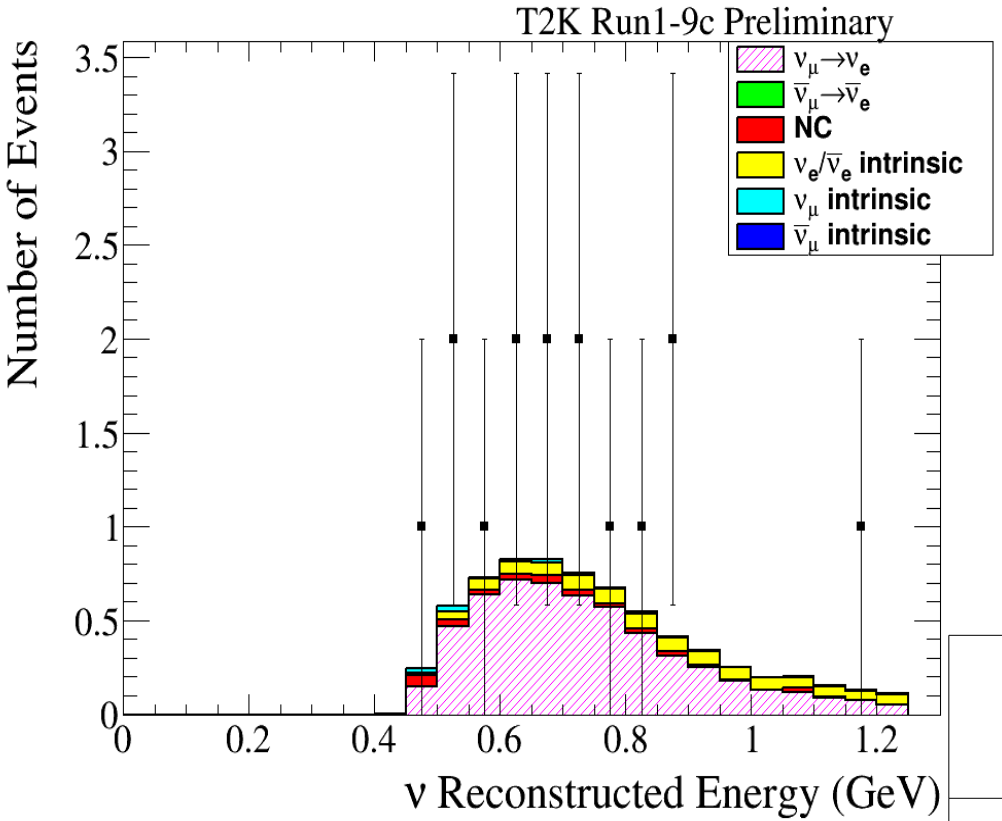
Motivations

Use of CC1π channel to search for oscillation is increasing.
→ T2K, Nova and future Hyper-K, DUNE

T2K far detector



But CC1π poorly known vs CC0π :

- Resonance model → RS ? Sobczyk ? Minoo ?
- Resonant mass value
- FSI models?

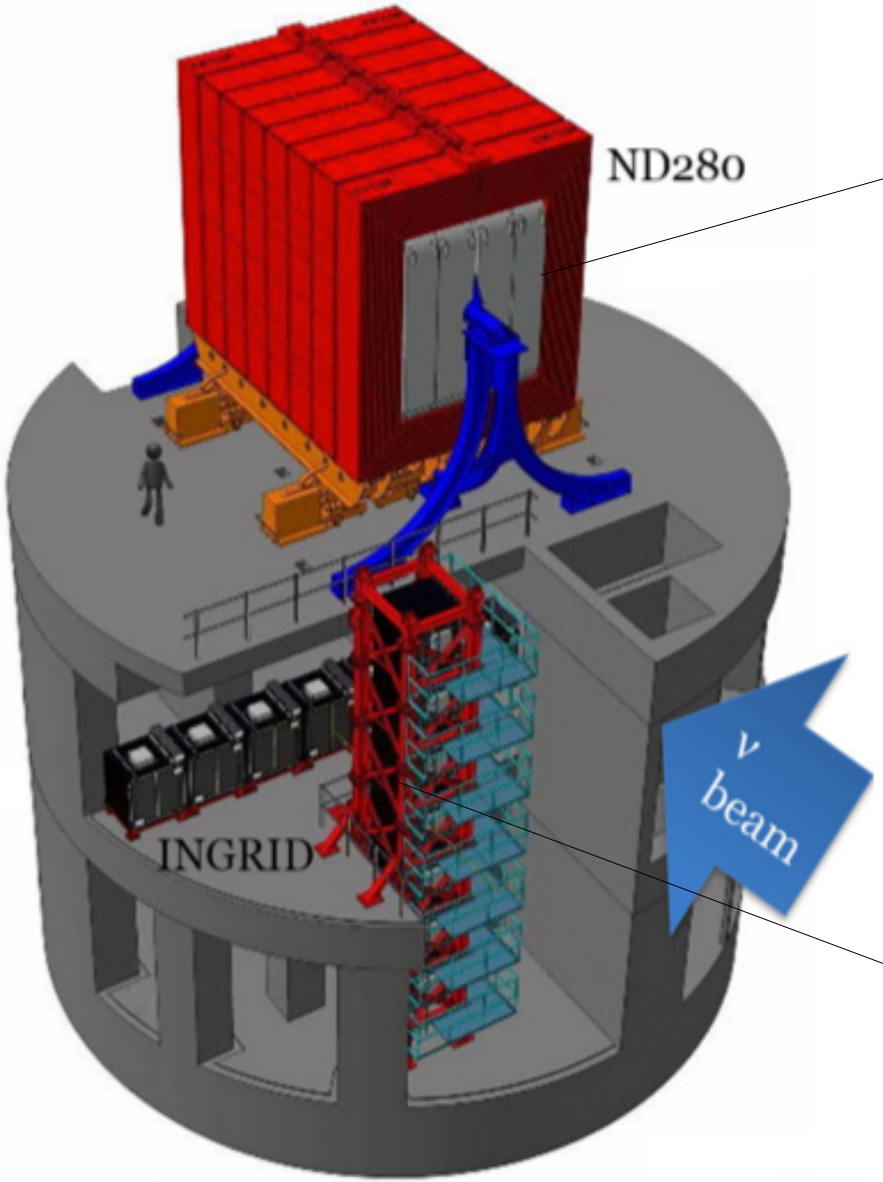
Main channel @T2K

	ν_μ CCQE-like	ν_e CCQE-like	ν_e CC1π^+-like
Uncertainty	4.9 %	9.6 %	18.7 %

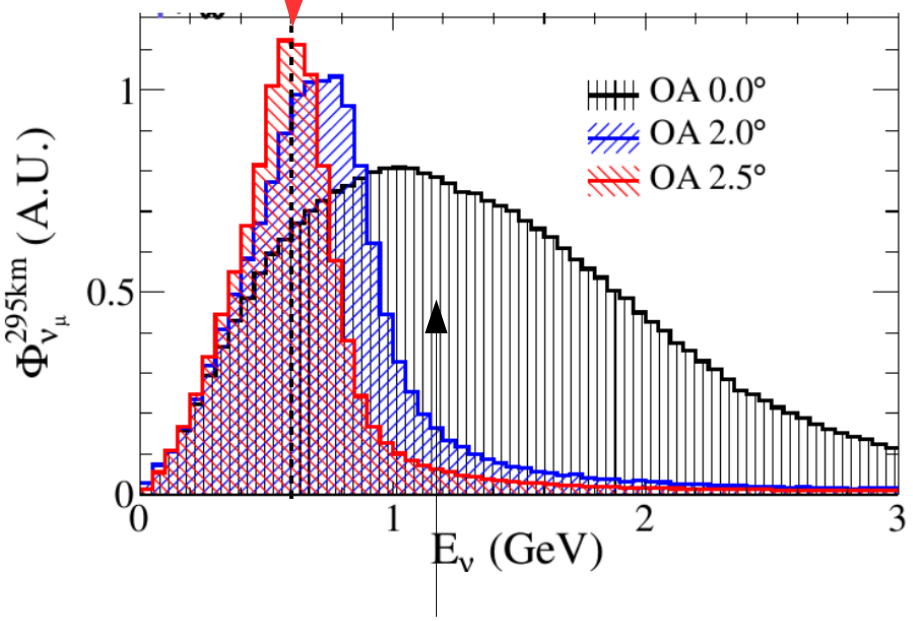
Goal : provide a more accurate CC1π measurement on H_2O & CH

T2K near detectors

Located at 280m from the target

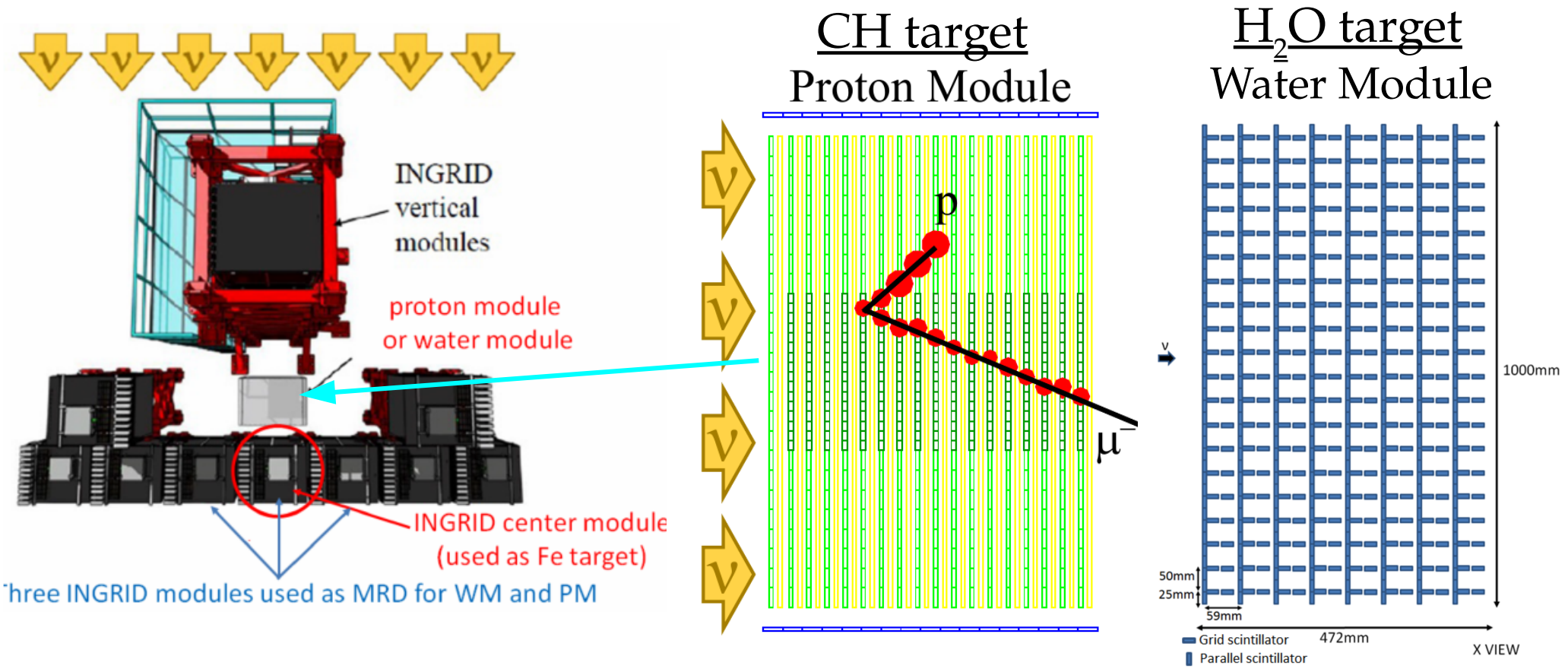


ND280 off-axis near detector



INGRID on-axis near detector

Strategy to measure CC1π cross-section



H_2O and Plastic detectors installed at same position but different periods

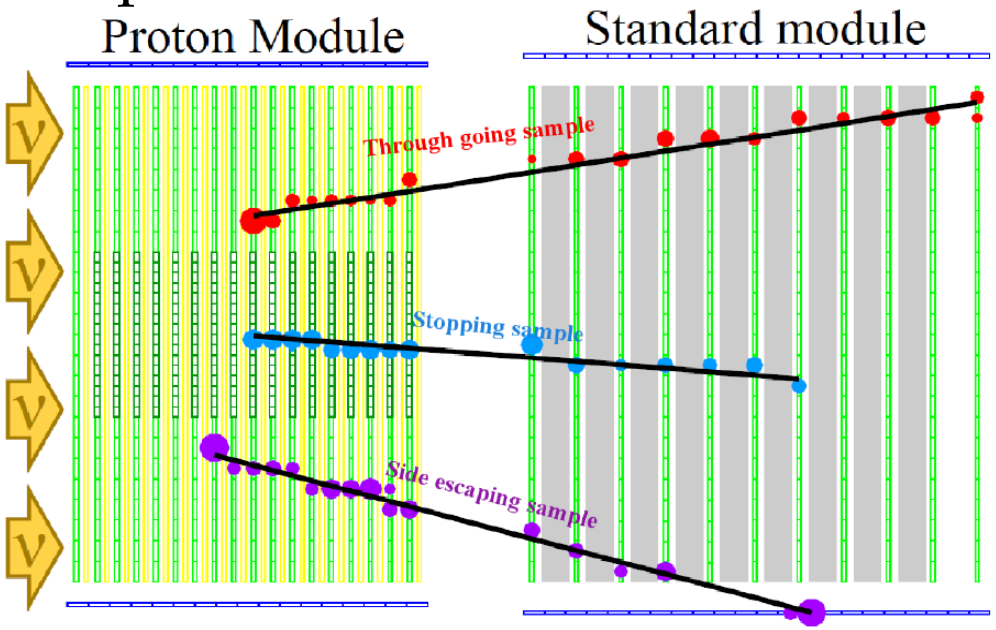
- Proton Module (PM) : 5.9 x 10^{20} POT ν-mode data in 2010 - 2013
- Water Module (WM) : 7.2 x 10^{20} POT ν-mode data in 2016 – 2017

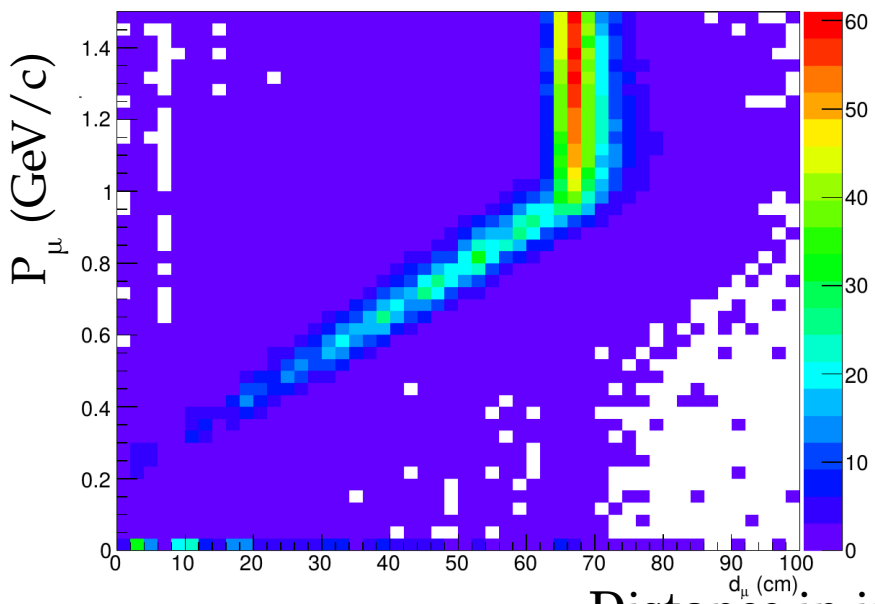
Double differential cross section

- Aim to maximize model constraints

  → Measurement differential in muon kinematics p_μ, θ_μ

- Use penetration distance of muon in iron to determine p_μ.





Distance in iron

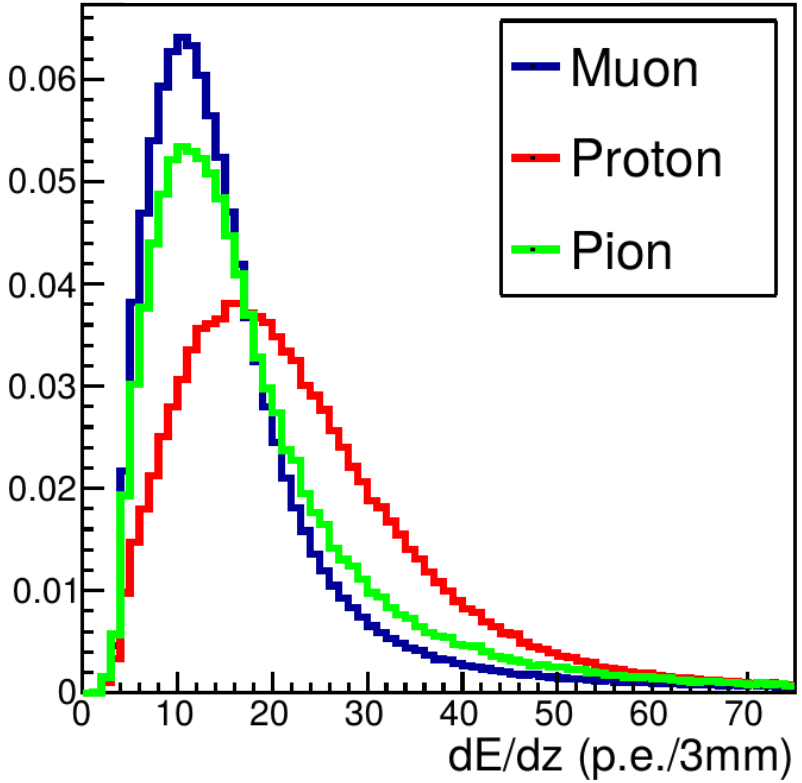
	p_μ range/ resolution	θ_μ range/ resolution
Through-going μ	> 1 GeV/c	0 – 50° / 5°
Stopping μ	0.4 – 1 /0.1 GeV /c	0 – 50° / 5°

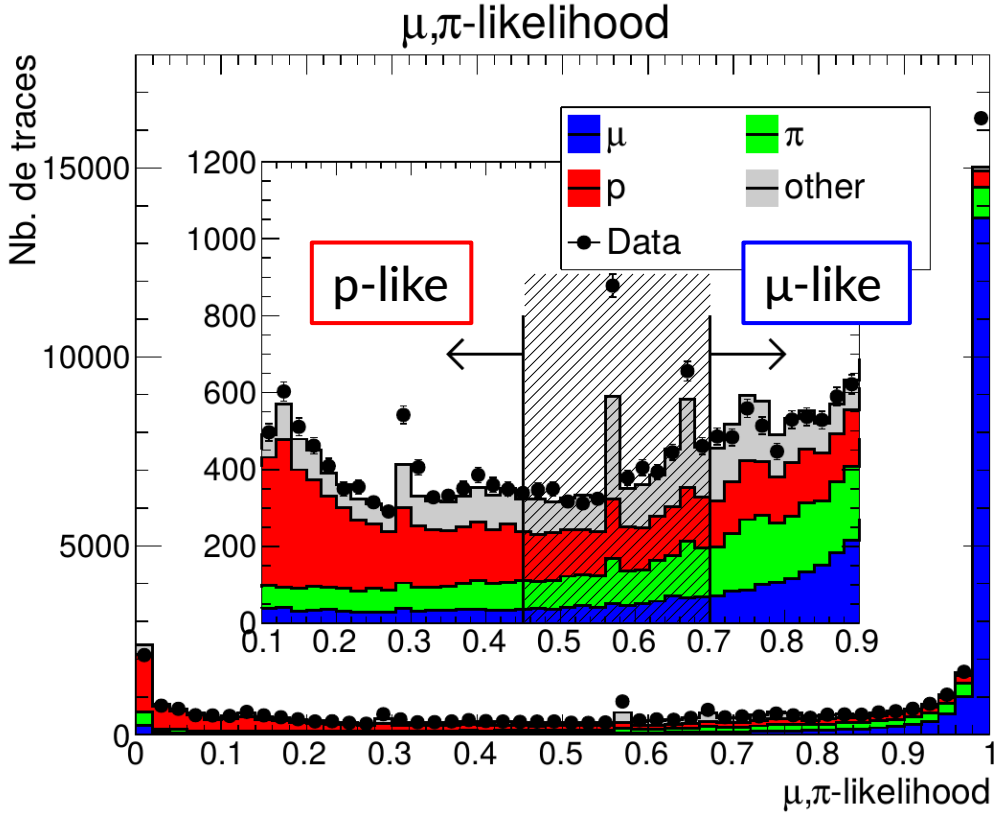
CC1π selection tool

- Based on a PID to avoid cross-section model dependency.

μ,π-likelihood: $\mathbb{P}(\mu,\pi|\{\mathrm{d}E/\mathrm{d}z\}) = \dfrac{\mathbb{P}(\{\mathrm{d}E/\mathrm{d}z\}|\mu,\pi)\,\mathbb{P}(\mu,\pi)}{\mathbb{P}(\{\mathrm{d}E/\mathrm{d}z\})}$

$$\prod_{\text{hits } i} \mathbb{P}(\mathrm{d}E_i/\mathrm{d}z_i \,|\, \mu,\pi)$$





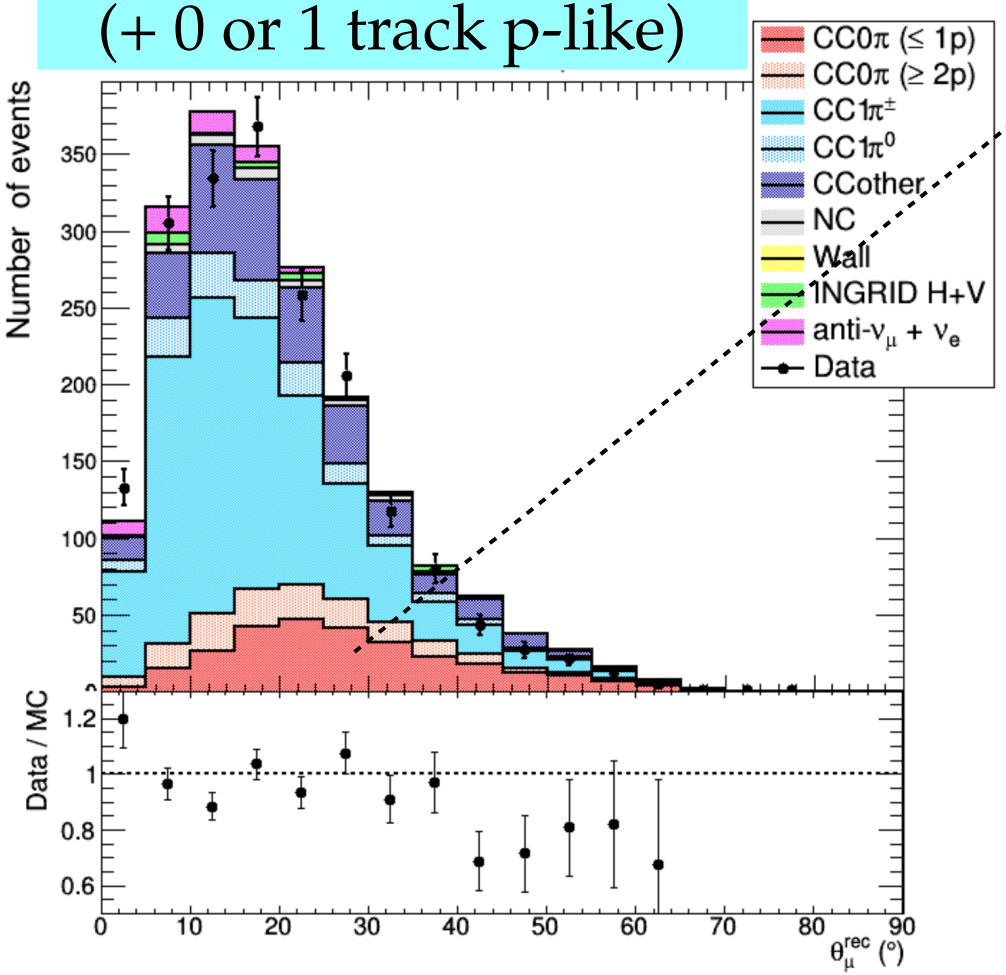
CC1π and CC0π selection results

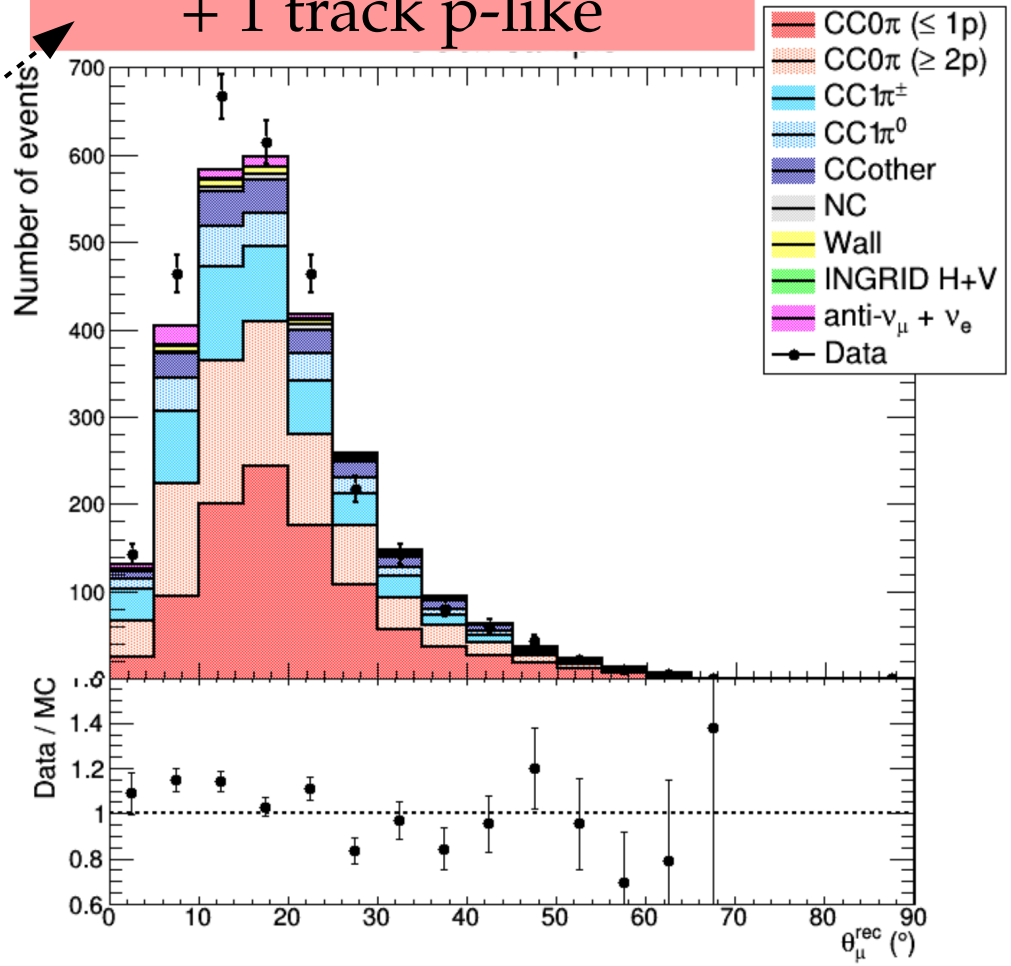
CC 1π : $\nu_\mu + \mathcal{N} \rightarrow \mu^- + \pi^\pm + \mathcal{N}'$

CC 0π : $\nu_\mu + \mathcal{N} \rightarrow \mu^- + \mathcal{N}'$

Signal : 2 tracks μ-like (+ 0 or 1 track p-like)

Side-band : 1 track μ-like + 1 track p-like

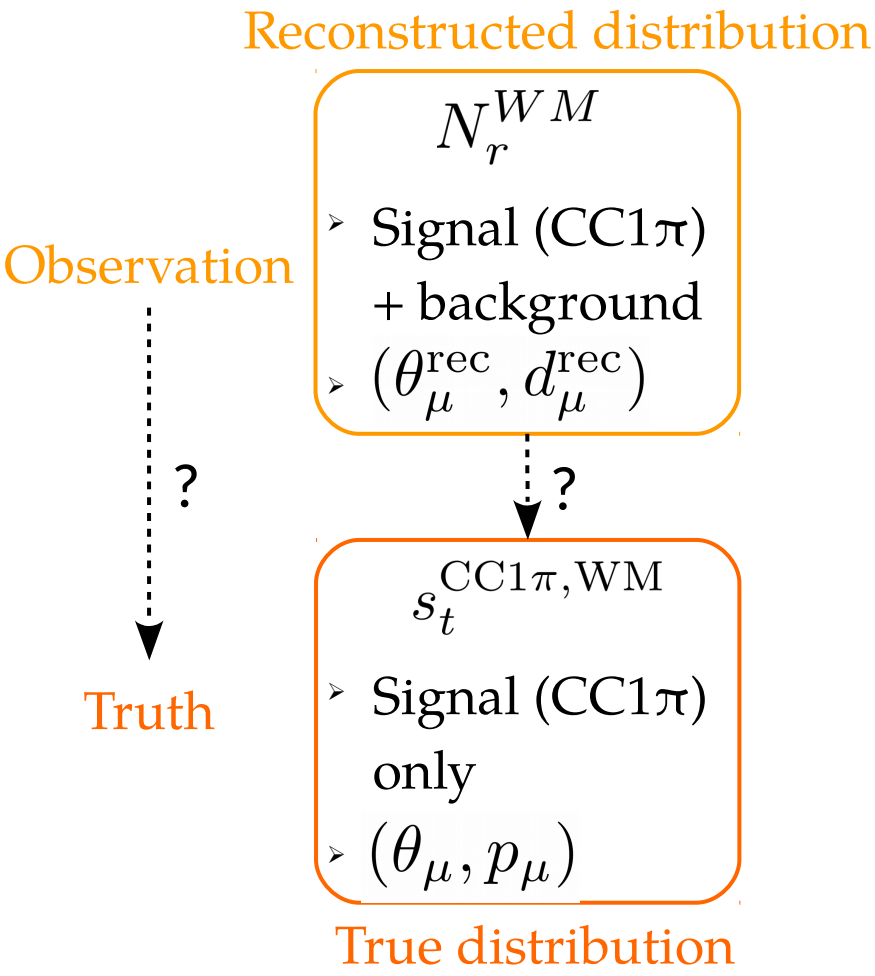


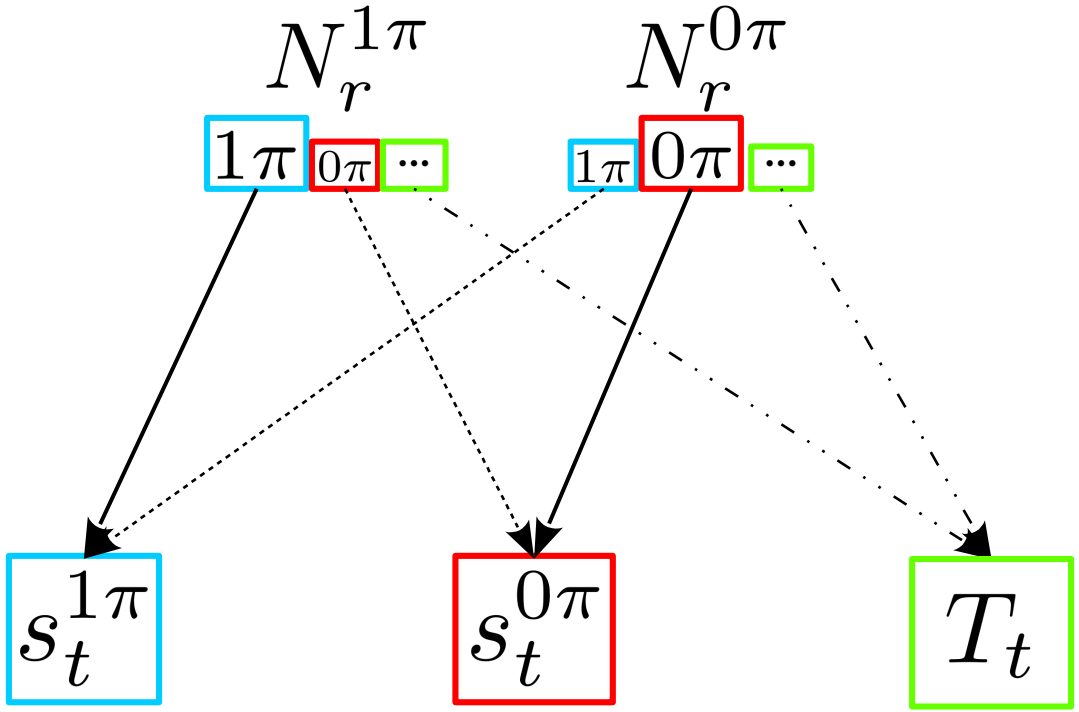


Unsmearing the detector effects

Goal: model independent result in observable variables (θ_μ, p_μ)

→ For everyone external to collaboration to use





→ simultaneous unfolding of signal and sideband

Bayes inspired unfolding

Unsmearing done with a Bayes inspired unfolding matrix

$$U_i^j \equiv P(T_i|O_j) = \frac{P(O_j|T_i) \cdot P(T_i)}{\sum_k P(O_j|T_k) \cdot P(T_k)}$$

Input Data

$$D^{(1)\ true,i} = \sum_j U_j^i \times D^j$$

Likelihood = Detector transfer matrix

Prior on p_μ, θ_μ of CC1π events (NEUT etc.) → Model dependency

Iterative procedure

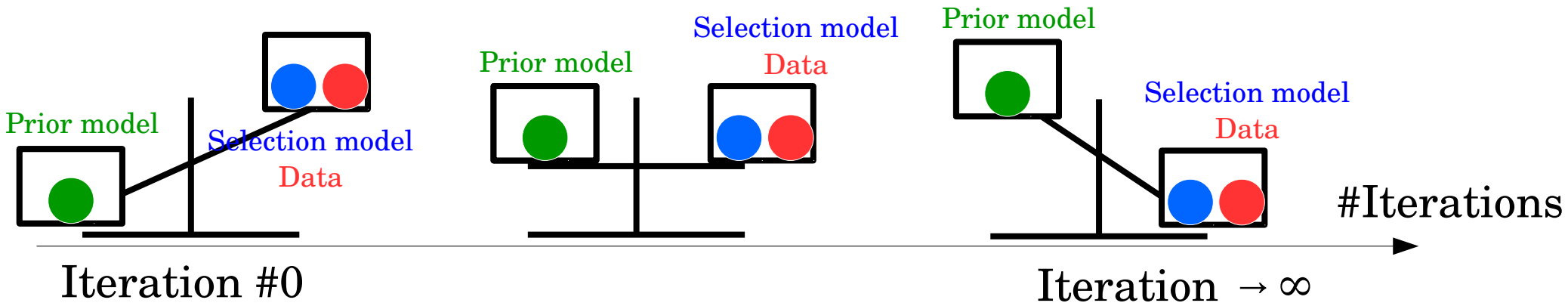
Unsmearing done with a Bayes inspired unfolding matrix

$$U_i^j \equiv P(T_i|O_j) = \frac{P(O_j|T_i) \cdot P(T_i)}{\sum_k P(O_j|T_k) \cdot P(T_k)}$$

Input Data

$$D^{(1)\ true,i} = \sum_j U_j^i \times D^j$$

$$U_i^{j\,(2)} = \frac{P(O_j|T_i) \cdot D^{(1)\ true,i}}{\sum_k P(O_j|T_k) \cdot D^{(1)\ true,k}}$$



How to choose $N_{iterations}$?

Unsmearing the detector results

Goal : convergence towards the true value. For fake data/MC :

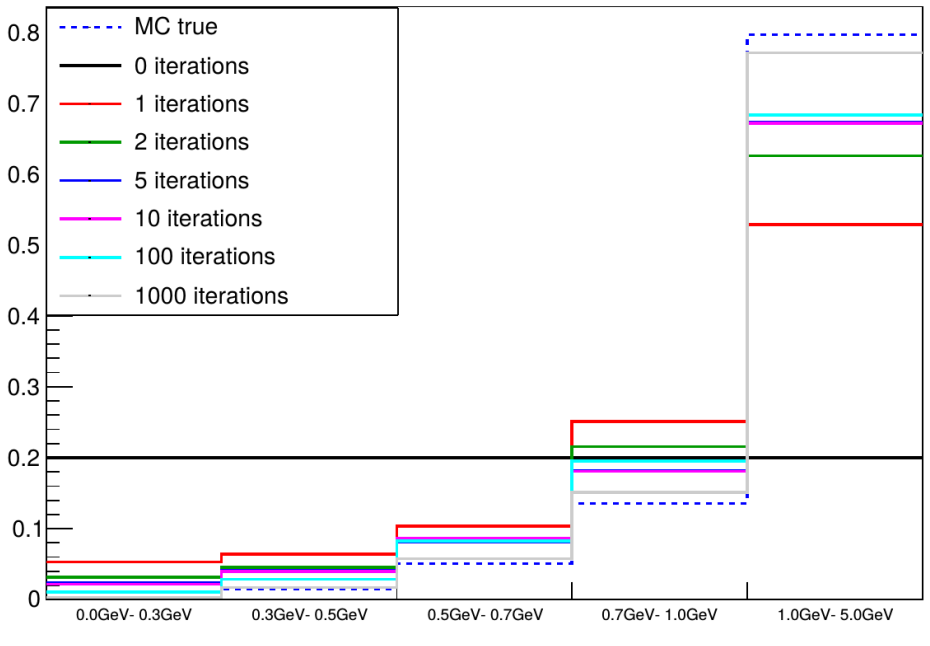
$$\chi^2_T = \sum_{\text{true } p_i,\text{true } \theta_j} \sum_{\text{true } p_k,\text{true } \theta_l} (N^{\text{Unfolded},It\ a}_{i,j} - N^{\text{True}}_{i,j}) \cdot (V^{-1})^{i,j}_{k,l} \cdot (N^{\text{Unfolded},It\ a}_{k,l} - N^{\text{True}}_{k,l})$$

Wish : bias ≪ total uncertainty $\Longrightarrow \frac{1}{N_{bins}}\chi^2_T < 0.2$ Bias ≤ 10 % Uncertainty

Data : impossible to evaluate ''true value'' .

Solution #1 : Define convergence point with simulation / mock data

- Model dependency → may not be optimal for data if ≠ model.
- N_{it} too small: under-estimate bias.
- too big: over-estimate stat. uncertainty



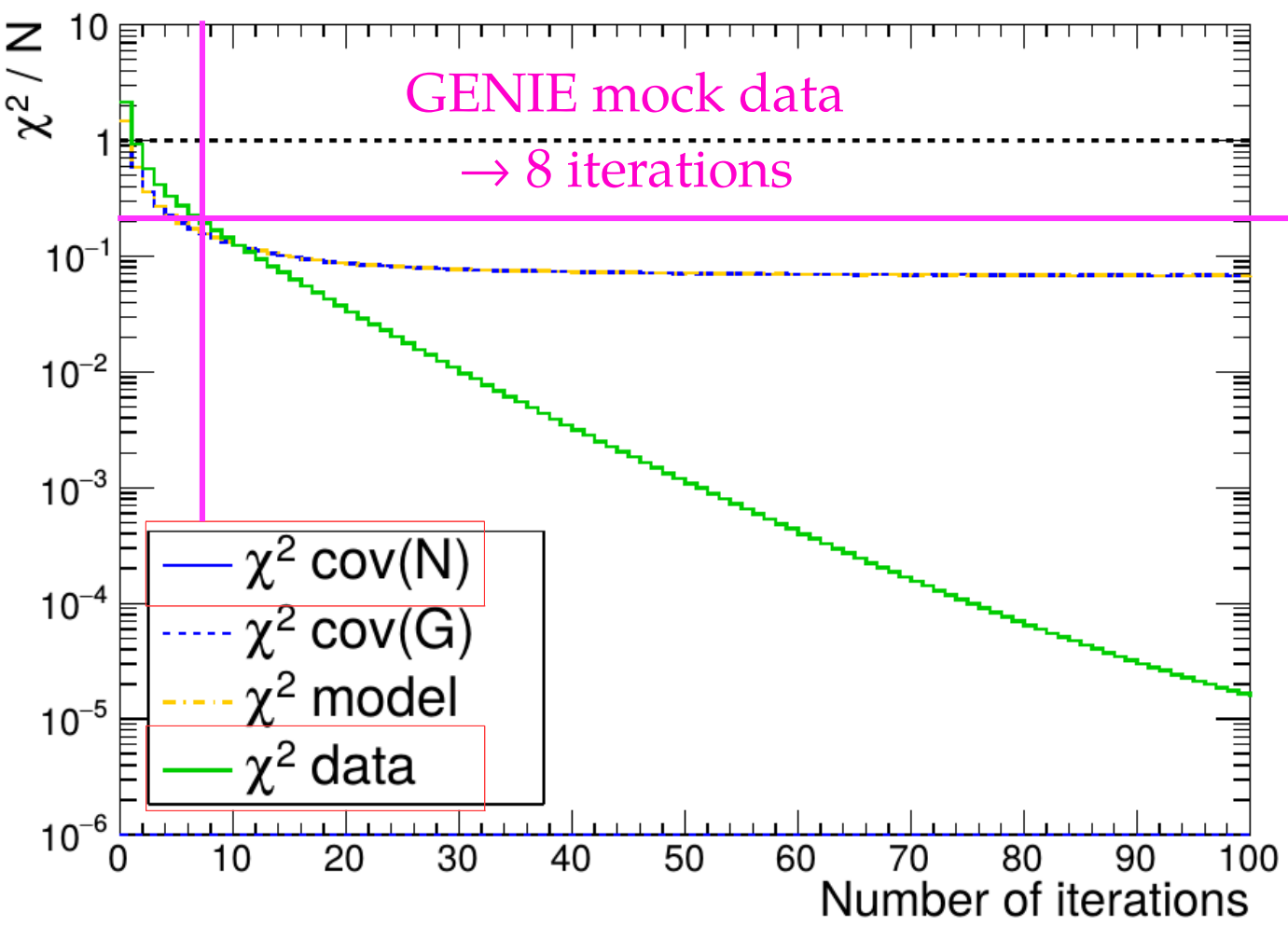
Data driven convergence criterion

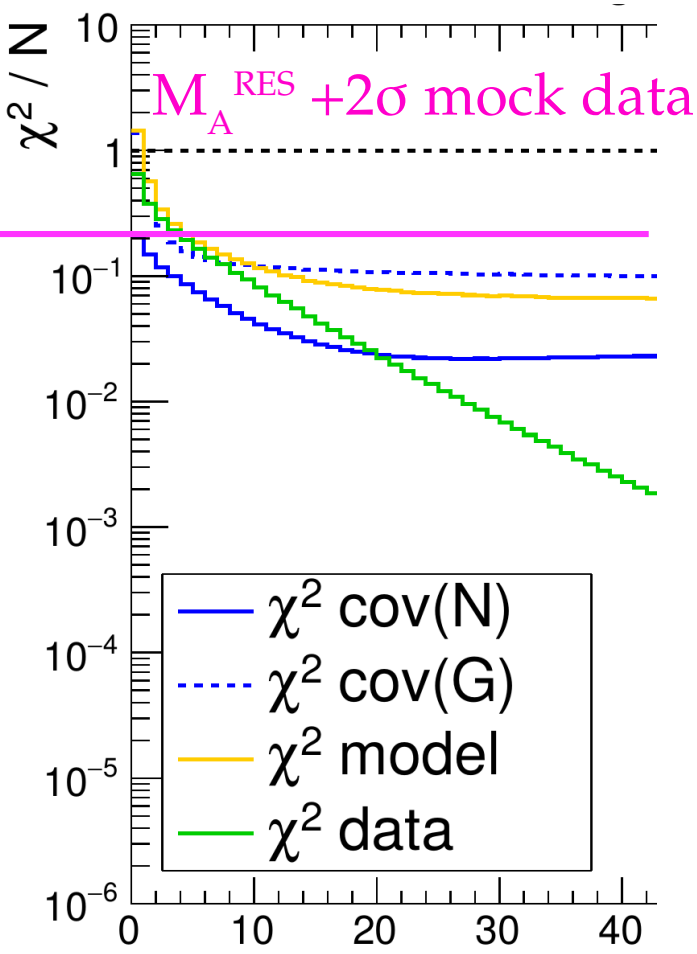
Solution #2 : Convergence towards data final value, N^{∞} (data-driven)

$$\chi^2_{DD} = \sum_{\text{true } p_i,\text{true } \theta_j} \sum_{\text{true } p_k,\text{true } \theta_l} (N^{\text{Unfolded},It\ a}_{i,j} - N^{\text{Unfolded},It\ \infty}_{i,j}) \cdot (V'^{-1})^{i,j}_{k,l} \cdot (N^{\text{Unfolded},It\ a}_{k,l} - N^{\text{Unfolded},It\ \infty}_{k,l})$$

- Analytically : convergence to N^{∞} ⇏ convergence to N^{True}
- Use fake data sets to show that $\frac{1}{N_{bins}}\chi^2_{DD} < 0.25 \Longrightarrow \frac{1}{N_{bins}}\chi^2_{T} < 0.2$
  - PM: 11 iterations and WM: 16 iterations

Mock-data





1. N_{it} data ≫ N_{it} mock data studies (≤ 8)

2. Most mock-data converge for 1 iteration ...

→ *See S. Dolan talk on unfolding*

→ Do not trust MC for unfolding !

→ Essential to use data-driven criterion ?

Detector cross sections

CC1π cross section in a given detector :

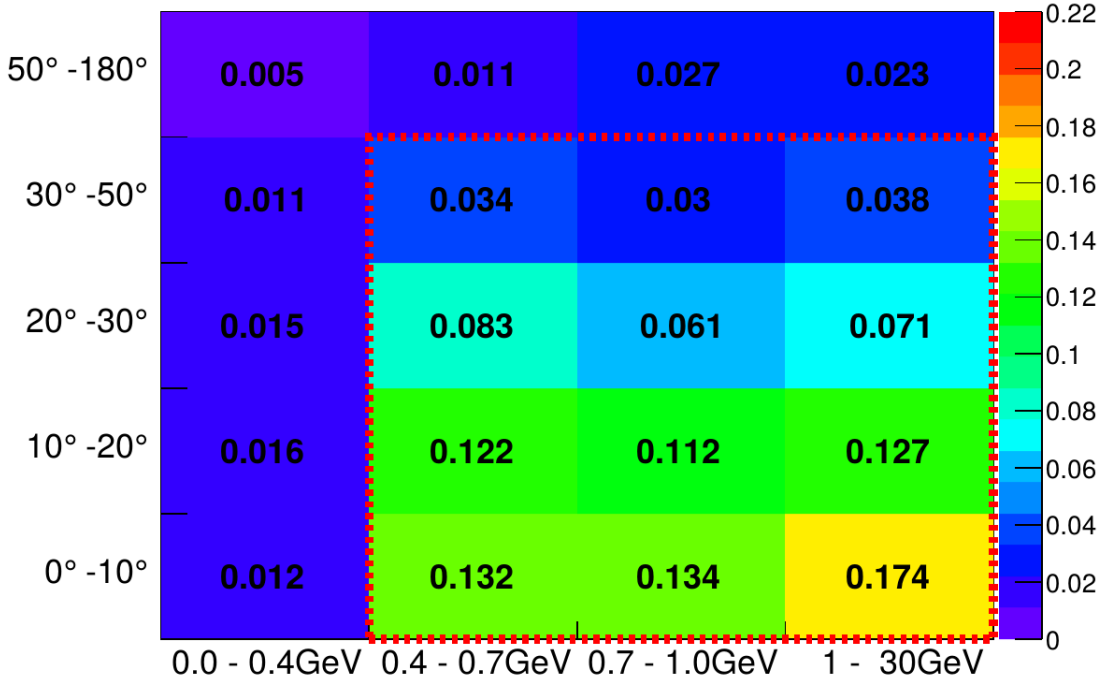
$$\frac{\mathrm{d}^2\sigma_t^{\mathrm{CC1}\pi}}{\mathrm{d}\theta_\mu\,\mathrm{d}p_\mu} \equiv \frac{1}{\Delta\theta_\mu \Delta p_\mu} \cdot \frac{s_t^{\mathrm{CC1}\pi}}{e_t \times \Phi \times T}$$

Number of CC1π events (from unfolding)

Neutrino flux

Target nucleons

(θ_μ, p_μ) Selection efficiency



Accessible phase space:

$\theta_\mu < 50^\circ, \quad p_\mu > 400$ MeV

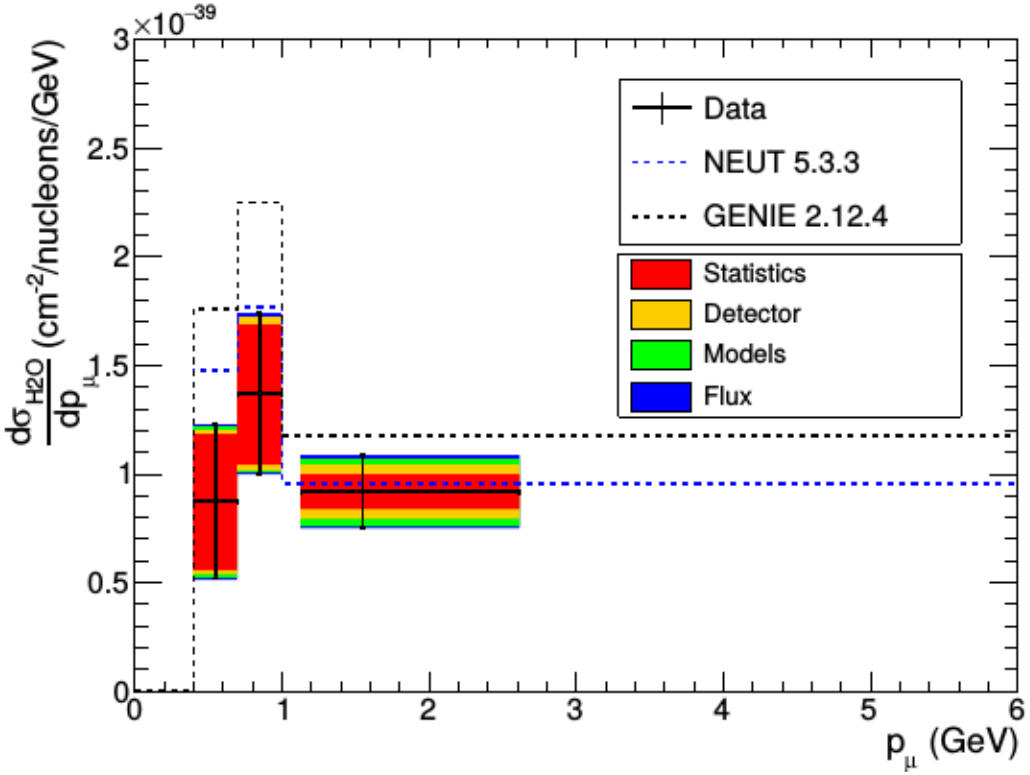
Uncertainties

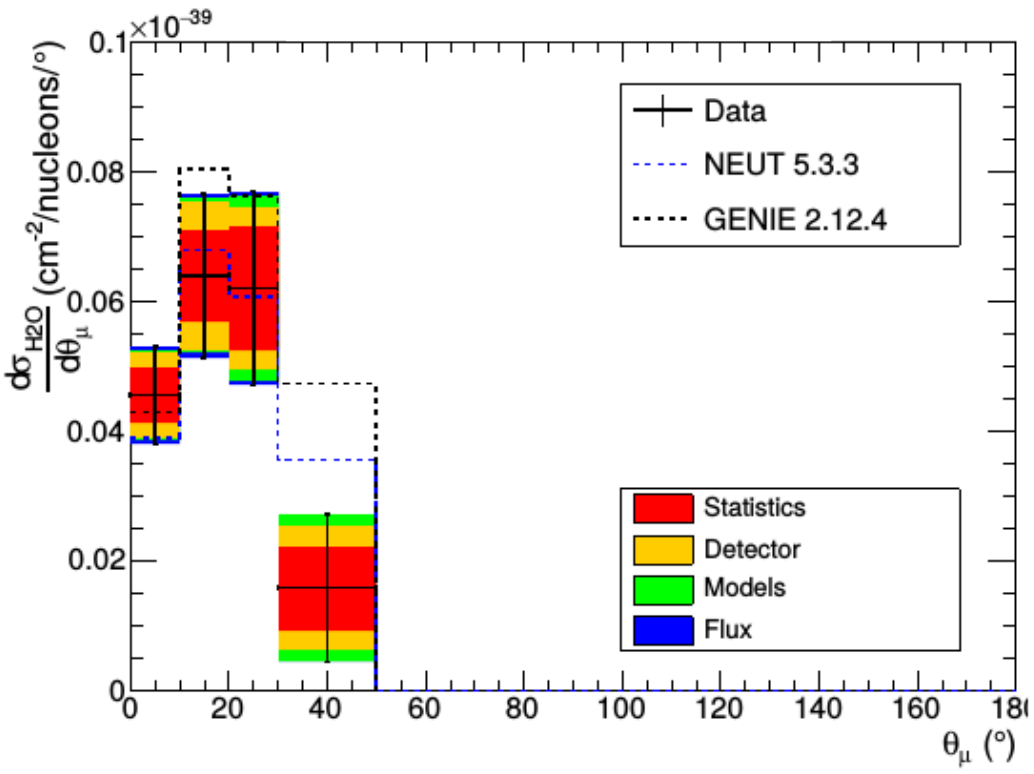
Systematic source	$\Delta\sigma_{CH}(\%)$	$\Delta\sigma_{H_2O}$ (%)	$\Delta\sigma_{H_2O}/\sigma_{CH}(\%)$
Statistics	4.8	8.7	10.8
Flux	6.6	6.8	1.1
Model	7.5	7.6	6.9
Detector	7.9	6.6	9.9
Systematics	12.7	12.1	12.1
Total	13.6	14.9	16.2

Summary of the all uncertainties on the 1-bin cross sections.

Differential result and model comparison

Single differential cross section on water :

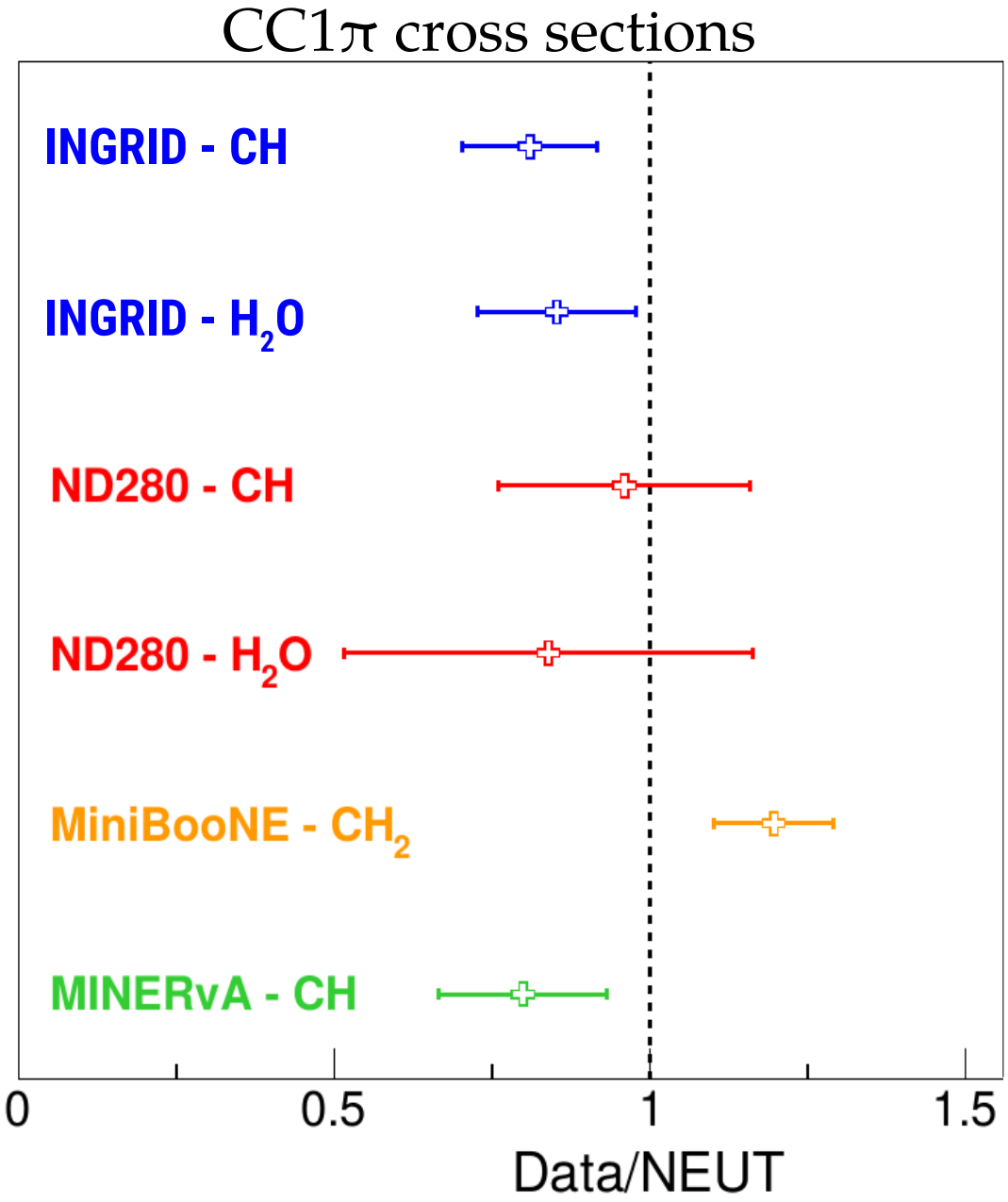




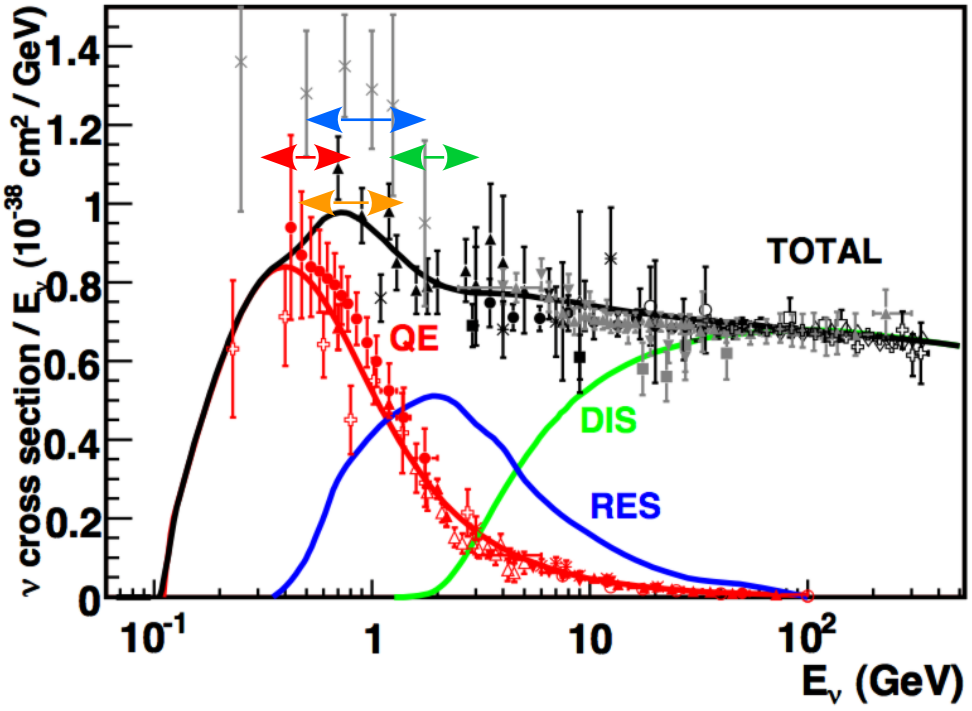
	CH-only	H_2O-only	CH+H_2O
χ^2(Data | NEUT)/NDF	2.0 (2.3σ)	1.3 (1.2σ)	1.3 (1.4σ)
χ^2(Data | GENIE)/NDF	3.7 (4.3σ)	2.6 (3.1σ)	2.4 (3.7σ)

- Our measurement is below NEUT and GENIE.
- NEUT still provides best agreement → High momentum bin

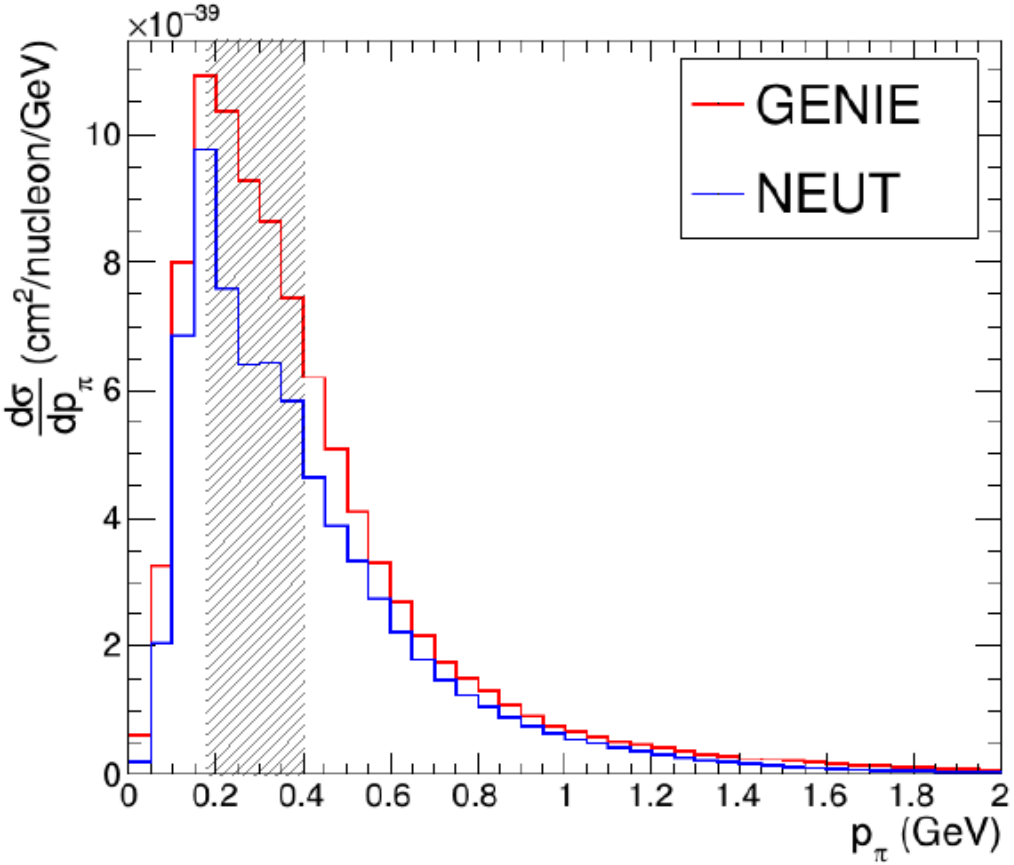
Comparison with other results



- Compatible w/ all other results (< NEUT) but MiniBooNE.
- Most accurate result on H_2O



NEUT and GENIE final state interactions



Incomplete intra-nucleus cascade

Complete intra-nucleus cascade

Intra-nuclear cascade

Interaction w/ free nucleons

$\pi^+ n \rightarrow \pi^+ n$

Nuclear model

$\rho(\boldsymbol{r})$

Higher suppression of π in NEUT

If π absorption is higher in data → should see an increase in CC0π.

Will be refined with a CC0π / CC1π join fit : coming this year.

Conclusions

- High uncertainties on CC1π cross-section → impact oscillations
  → Produce a more accurate measurement of CC1π cross-section on H_2O

- Developed a data-driven unfolding method for the first time to reduce model-dependency.

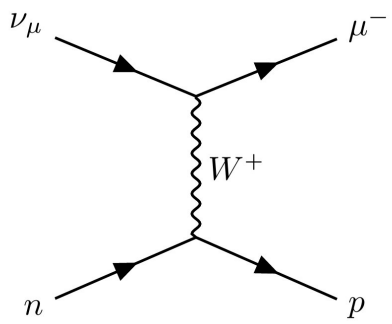
- <u>Take home message :</u>
  - Not using data-driven unfolding → model bias.
  - Our CC1π data shows a deficit → as Minerva and ND280 results.
  - Which agrees considerably better with NEUT than GENIE.

- To investigate its cause properly
  → Is available and will be published for experts (=theorists) to use.
  → Need a CC0π/CC1π join fit → coming this year.

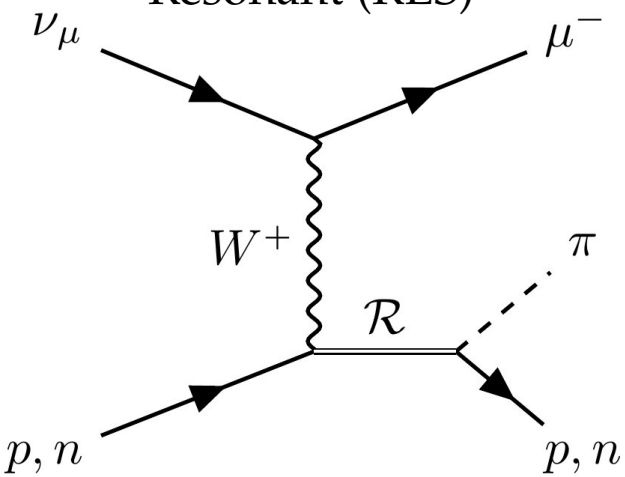
Additional slides

CC1π signal definition

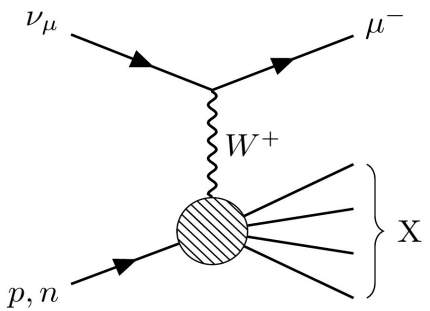
Quasielastic (QE)



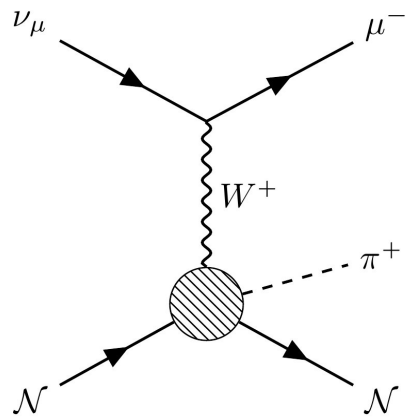
Resonant (RES)



DIS



Coherent (COH)



production of a π

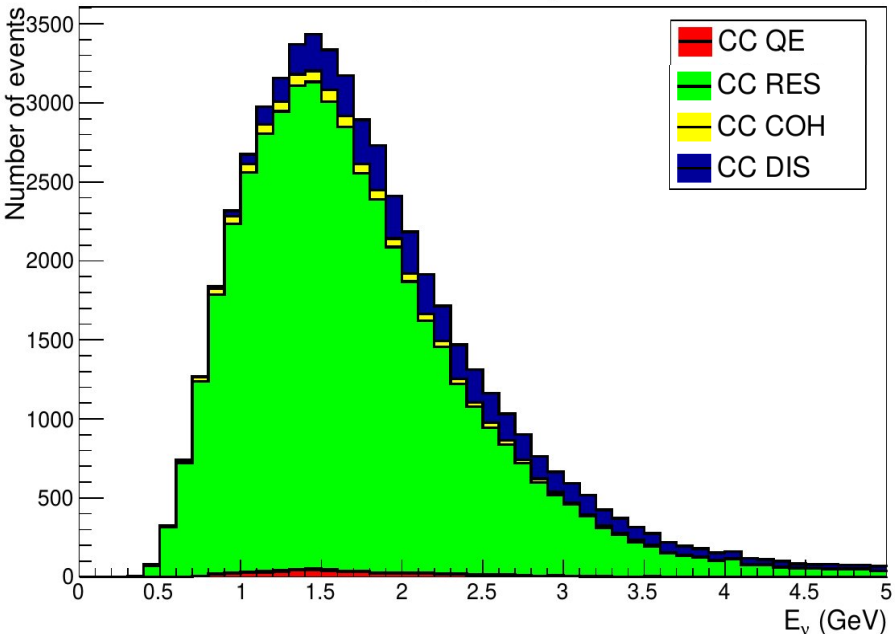
Only a π escapes the nucleus

<u>Observable particles</u>

(escaping the nucleus)

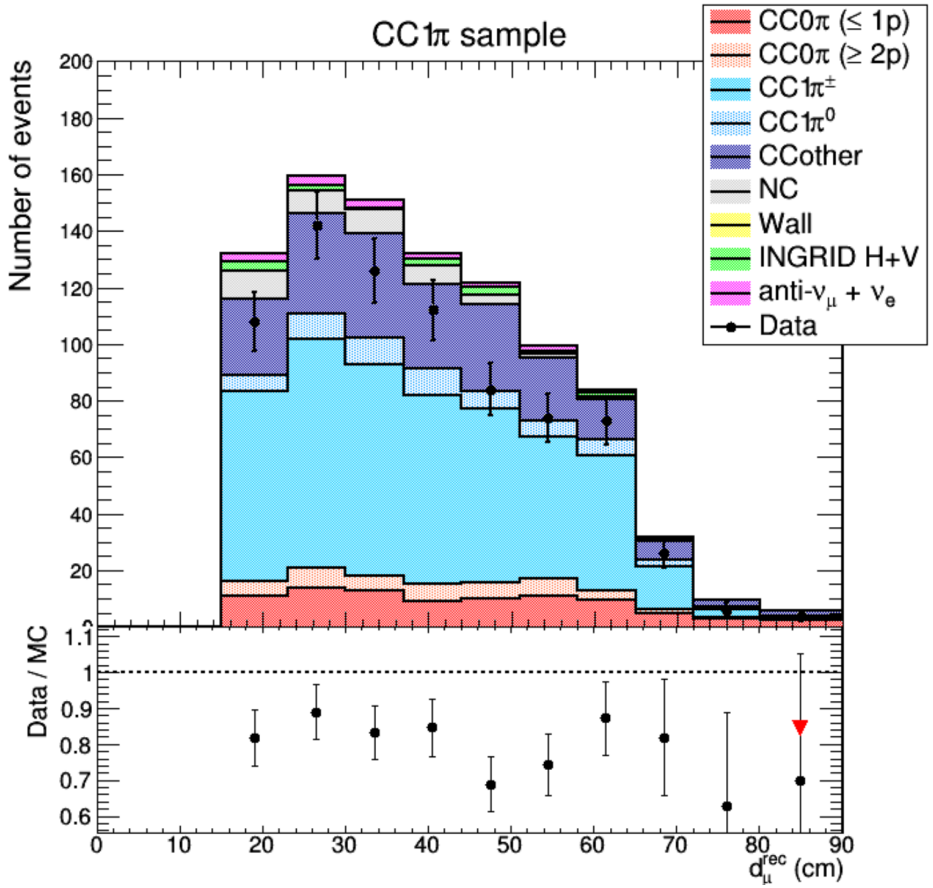
CC $1\pi^{\pm}$

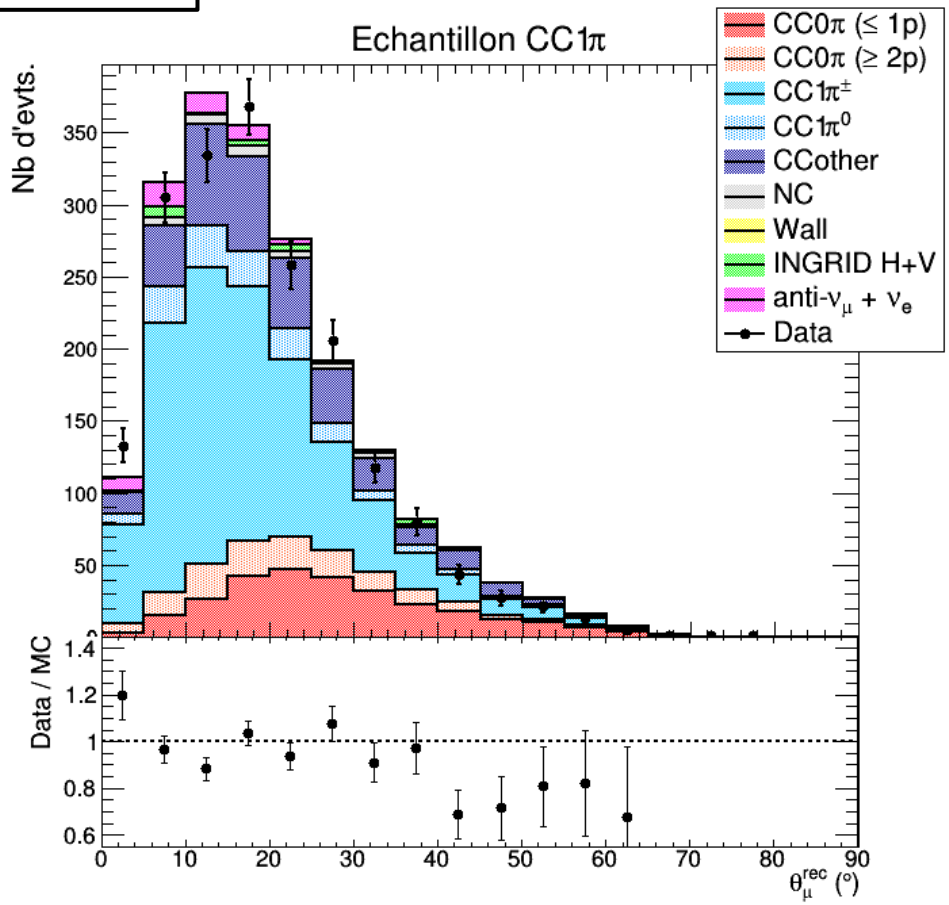
$$\nu_\mu + \mathcal{N} \rightarrow \mu^- + \pi^\pm + \mathcal{N}'$$



CC1π-selected sample, the signal

2 tracks μ-like
(+0 or 1 track p-like)





Cut	Data	Total MC	CC0π	CC1π±	CC1π0	CCOther	NC	Ext.	$\overline{\nu_\mu} + \nu_e$
CC inclusive	34689	34363	14144	7764	2444	5836	1253	1663	1259
CC1π (PID)	4090	5437	994	2454	319	1377	116	31	146
2 or 3 tracks	3513	5016	989	2376	302	1088	100	30	133
μ stop/through	2344	2812	502	1416	166	582	44	14	87

Main contamination → Side band

Cross-section model systematic uncertainties

W/o side-band

Parameter	$\Delta\sigma_{CH}(\%)$	$\Delta\sigma_{H_2O}$ (%)	$\Delta\sigma_{H_2O}/\sigma_{CH}(\%)$
p_F ^{12}C	0.13	0.02	0.11
p_F ^{16}O	-	0.20	0.20
E_B ^{12}C	0.01	< 0.01	0.01
E_B ^{16}O	-	0.01	0.01
MEC norm ^{12}C	4.60	0.08	4.56
MEC norm ^{16}O	-	4.80	4.80
M_A^{QE}	8.62	13.60	4.81
C_A^5	1.01	2.07	1.06
M_A^{RES}	2.75	4.22	1.46
$I = 1/2$ Bkg	2.17	3.19	1.09
CC-other shape	5.91	4.81	1.11
CC-coherent norm ^{12}C	0.82	0.01	0.81
CC-coherent norm ^{12}O	-	0.81	0.81
NC-coherent norm	< 0.01	< 0.01	< 0.01
NC-other shape	0.59	0.81	0.23
FSI π absorption	1.05	0.25	0.88
FSI charge exchange, LE	0.61	0.42	0.19
FSI charge exchange, HE	0.32	0.33	0.01
FSI π QE scattering, LE	2.75	1.28	1.57
FSI π QE scattering, HE	0.76	1.28	0.54
FSI π production	0.53	0.90	0.37
Total	12.4	16.4	8.8

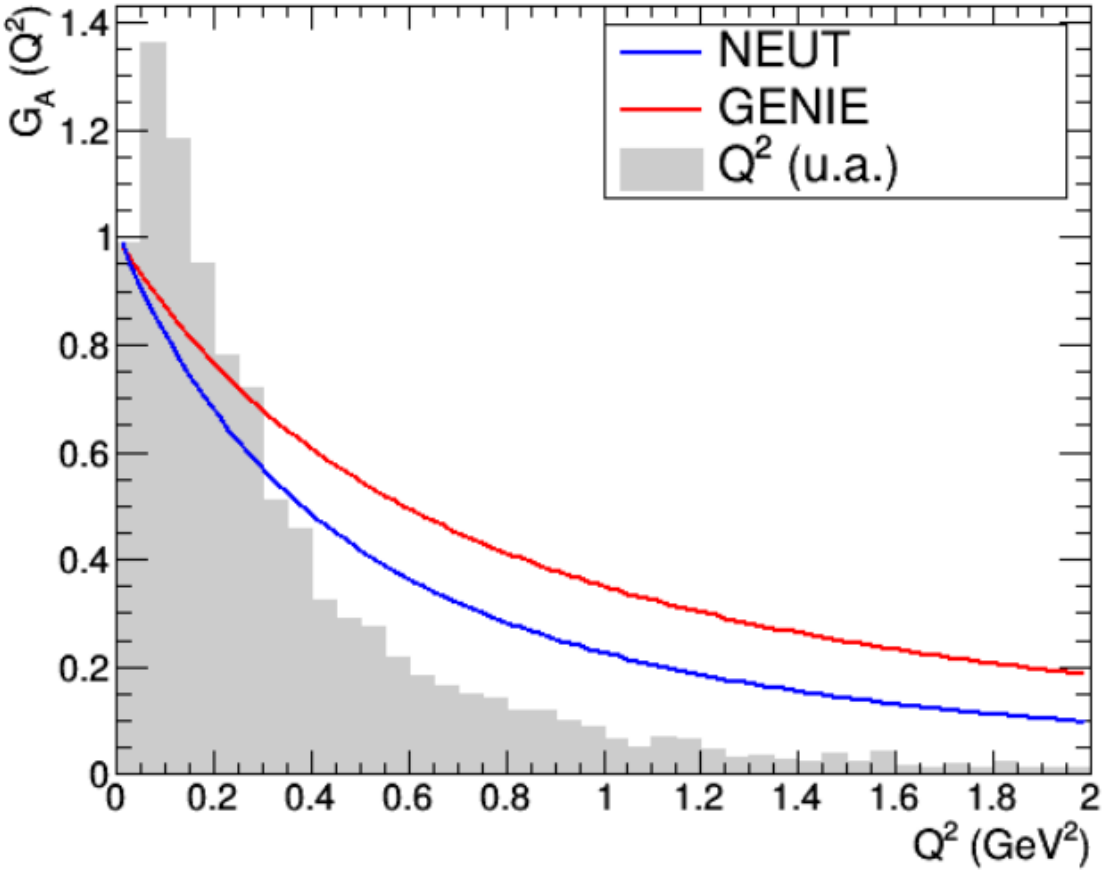
W/ side-band

Parameter	$\Delta\sigma_{CH}(\%)$	$\Delta\sigma_{H_2O}$ (%)	$\Delta\sigma_{H_2O}/\sigma_{CH}(\%)$
p_F ^{12}C	< 0.1	< 0.1	< 0.1
p_F ^{16}O	-	0.2	0.2
E_B ^{12}C	< 0.1	< 0.1	< 0.1
E_B ^{16}O	-	< 0.1	< 0.1
MEC norm ^{12}C	2.1	0.8	2.5
MEC norm ^{16}O	-	3.7	3.7
M_A^{QE}	2.8	5.1	2.1
C_A^5	3.8	2.7	1.1
M_A^{RES}	3.2	1.1	1.9
$I = 1/2$ Bkg	0.3	1.3	0.8
CC-other shape	3.1	0.8	1.7
CC-coherent norm ^{12}C	0.4	< 0.1	0.4
CC-coherent norm ^{12}O	-	0.3	0.3
NC-coherent norm	< 0.01	< 0.1	< 0.1
NC-other shape	0.1	0.3	0.3
FSI π absorption	0.8	1.7	2.4
FSI charge exchange, LE	0.8	0.2	1.0
FSI charge exchange, HE	0.2	0.9	0.7
FSI π QE scattering, LE	2.6	0.4	2.8
FSI π QE scattering, HE	0.8	1.0	0.2
FSI π production	0.5	0.8	0.2
Total	7.5	7.6	6.9

Detector systematic uncertainty

Systematic source	$\Delta\sigma_{CH}(\%)$	$\Delta\sigma_{H_2O}$ (%)	$\Delta\sigma_{H_2O}/\sigma_{CH}(\%)$
Hit Efficiency	0.1	1.2	1.2
Light yield vs. angle	7.2	4.3	9.0
Birks saturation*	2.3	3.2	1.6
External backgrounds*: Wall	1.2	1.4	0.1
INGRID	0.1	0.1	0.1
Secondary interactions	1.1	1.5	2.0
Cross-talk	-	0.7	0.7
Reconstruction	1.3	1.6	2.3
Event pile-up	0.5	0.6	0.8
Target mass	0.4	0.3	0.5
Total	7.9	6.6	9.9

NEUT and GENIE form factors



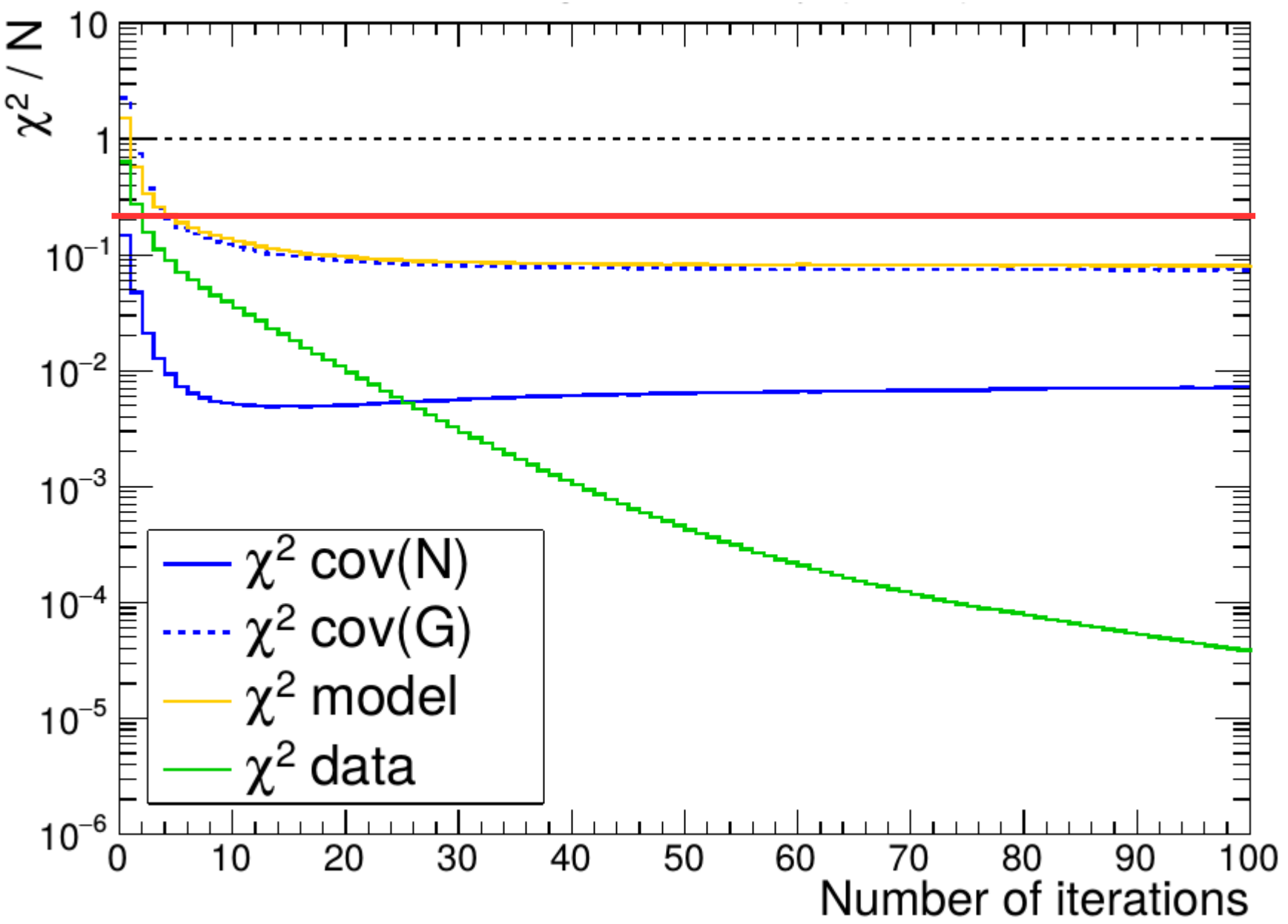
$$G_A^{\mathrm{GS}}(Q^2) = C_A^5(0)\left(1 + \frac{Q^2}{(M_A^{\mathrm{RES}})^2}\right)^{-2}$$

$$C_A^5(0) = 1.01, \quad M_A^{\mathrm{RES}} = 0.95\ \mathrm{GeV}/c^2$$

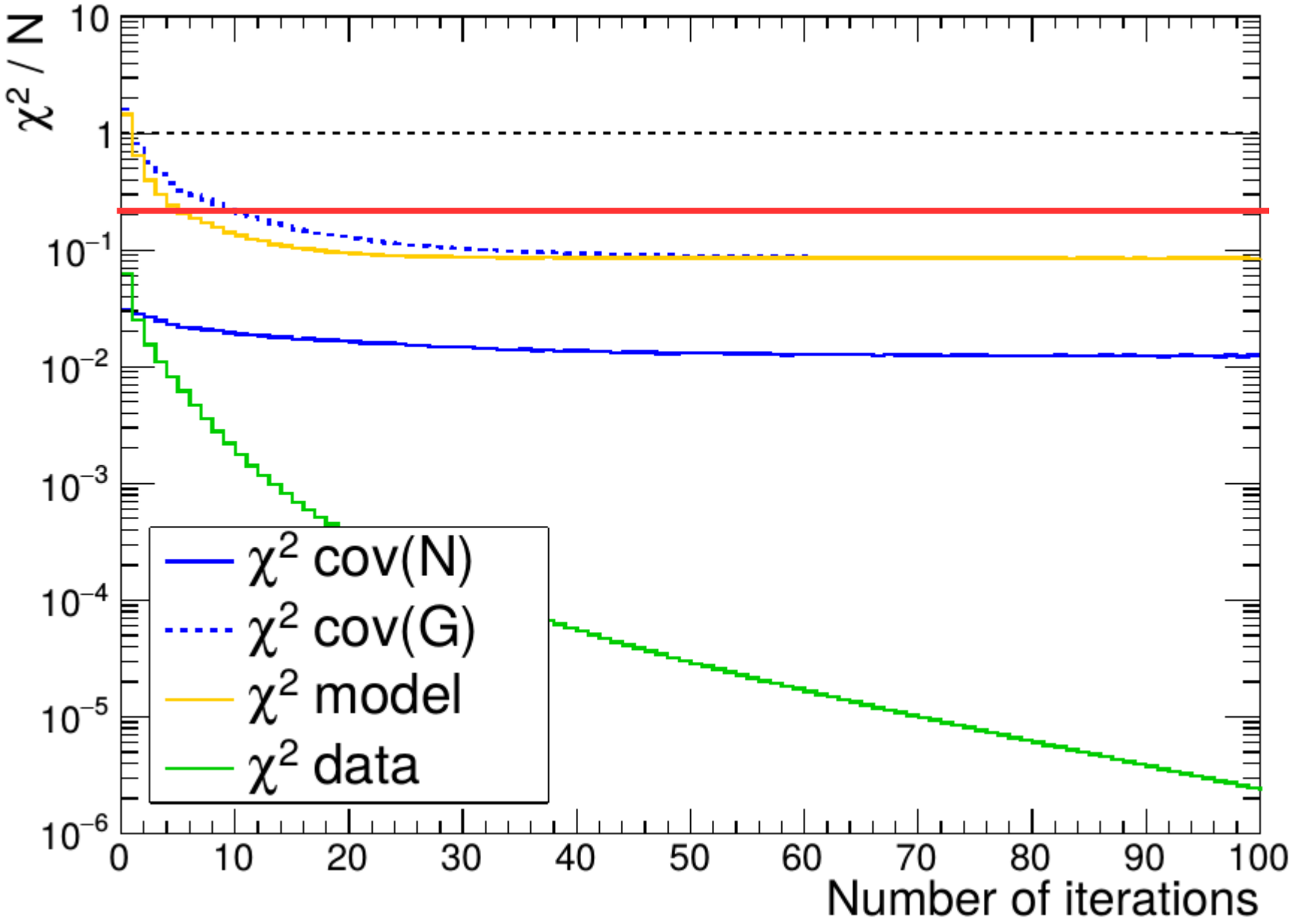
$$G_A^{\mathrm{RS}}(Q^2) = \left(1 + \frac{Q^2}{4m_N^2}\right)^{1/2-n}\left(1 + \frac{Q^2}{(M_A^{\mathrm{RES}})^2}\right)^{-2}$$

$$M_A^{\mathrm{RES}} = 1.12\ \mathrm{GeV}/c^2$$

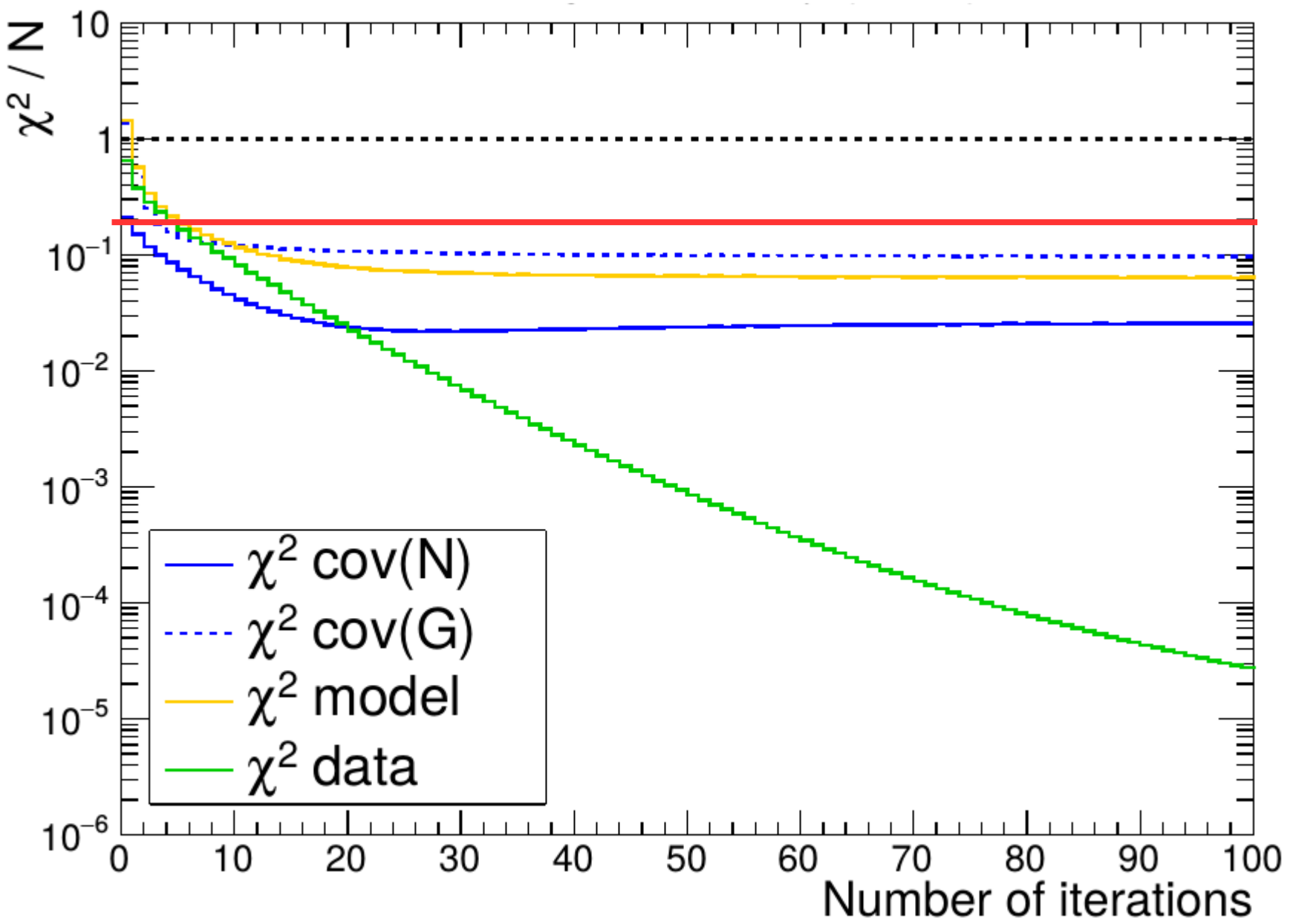
CC-Coherent-varied mock data



MAQE-varied mock data



MARES-varied fake data



GENIE-varied fake data