

Tuning the GENIE neutrino event generator with Professor

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on behalf of the GENIE Collaboration

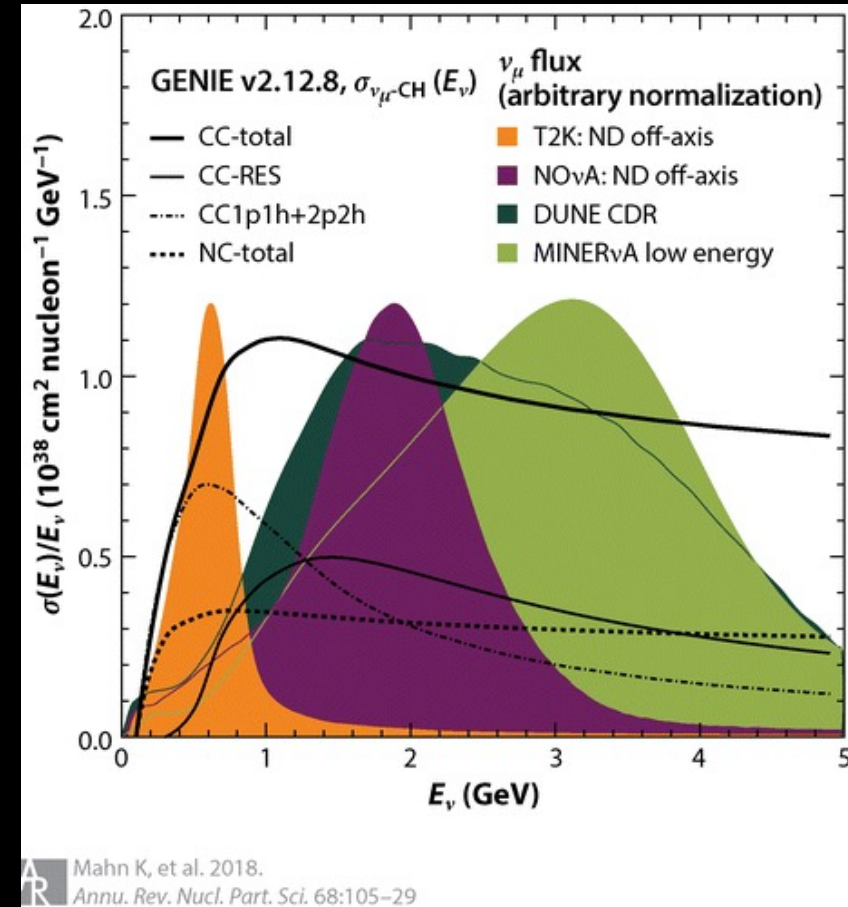
Workshop on Neutrino Event Generators
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Simulating neutrino interactions for accelerator experiments

Neutrino experiments rely on simulations to **reconstruct the neutrino energy** and **estimate systematic uncertainties**

- **Models are not complete**
 - Limited phase space coverage
 - Do not handle transition between different kinematic regions
 - Can fail to describe hadronic final states
 - Nuclear effects are factorized out
- **Lack of model systematic uncertainties estimates from theorists**



The GENIE Event Generator

- GENIE seeks to model neutrino interactions for all probes and targets across the kinematic region of interest for neutrino experiments
- It provides a number of comprehensive model configurations (CMCs)
 - Each configuration consists of a self consistent set of interaction models
 - Theoretical inputs are used to simulate specific processes at specific parts of the phase space
 - **Relies on empirical approaches to extrapolate in other kinematic regions and provide exclusive final-state information**



Examples of empirical models in GENIE CMC's

- **Parameterization of vector and axial form factors**
 - Electron and neutrino scattering data
- **Simulation of pion production on free nucleon interactions**
 - Hydrogen and deuterium data from bubble chamber experiments
- **Neutrino induced hadronization (AGKY model)**
 - Hadronization data from bubble chamber experiments
- **Final-state interaction models**
 - Hadron-nucleus data

Lack of MC/Data description

- The Shallow Inelastic Scattering (SIS) region is modelled as:

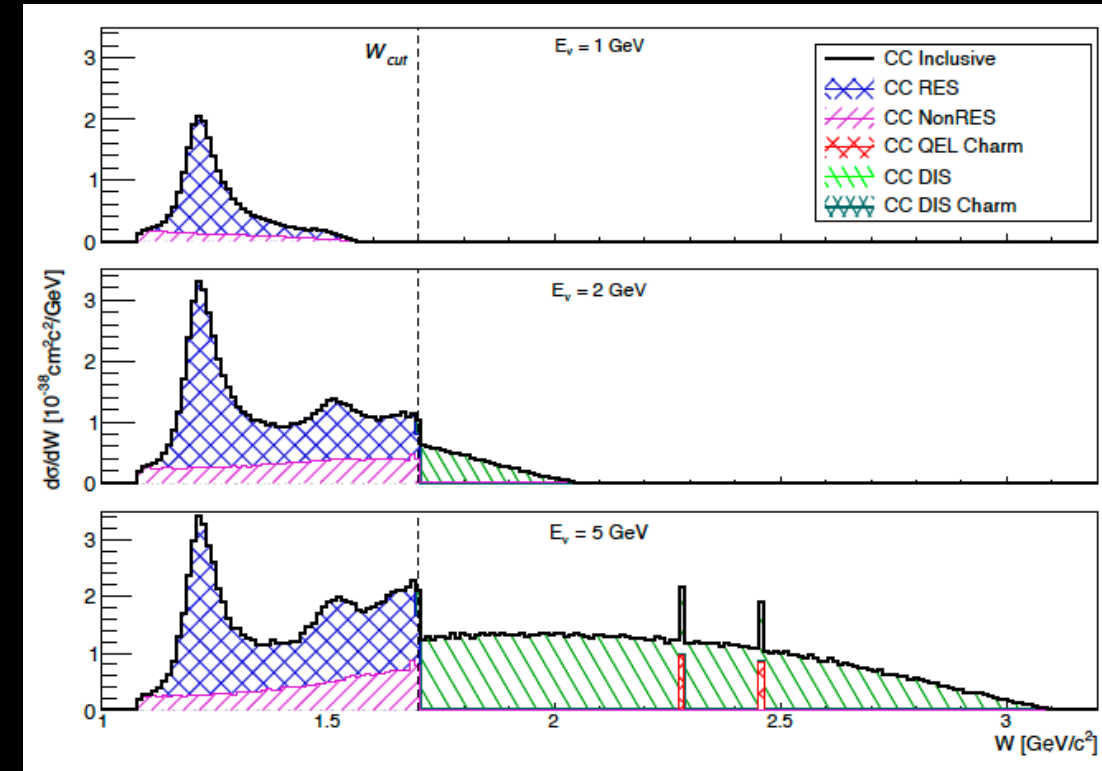
[PhysRevD.104.072009](https://arxiv.org/abs/2007.07209)

$$\frac{d^2\sigma^{inel}}{dQ^2 dW} = \begin{cases} \frac{d^2\sigma^{RES}}{dQ^2 dW} + \frac{d^2\sigma^{Non-RES}}{dQ^2 dW} & \text{for } W < W_{cut} \\ \frac{d^2\sigma^{DIS}}{dQ^2 dW} & \text{for } W \geq W_{cut} \end{cases}$$

$$\frac{d^2\sigma^{Non-RES}}{dQ^2 dW} = \frac{d^2\sigma^{DIS}}{dQ^2 dW} \cdot \Theta(W_{cut} - W) \cdot \sum_m f_m(Q^2, W)$$

Free parameters

- The Resonant contribution is modelled from Rein-Sehgal or Berger-Sehgal
- The non-resonant background is modelled using the Deep-Inelastic-Scattering model (Bodek and Yang) extrapolated at $W < W_{cut}$



Lack of MC/Data description

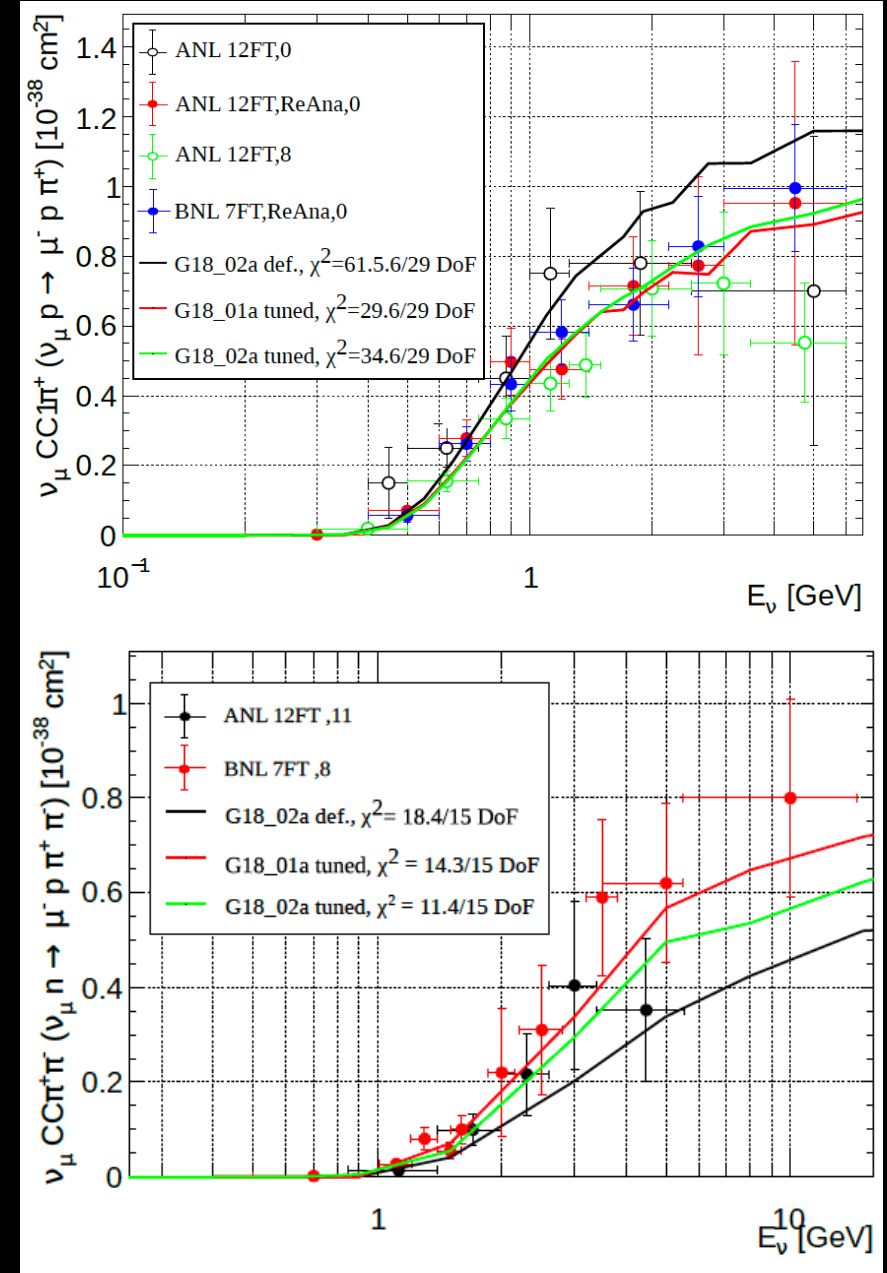
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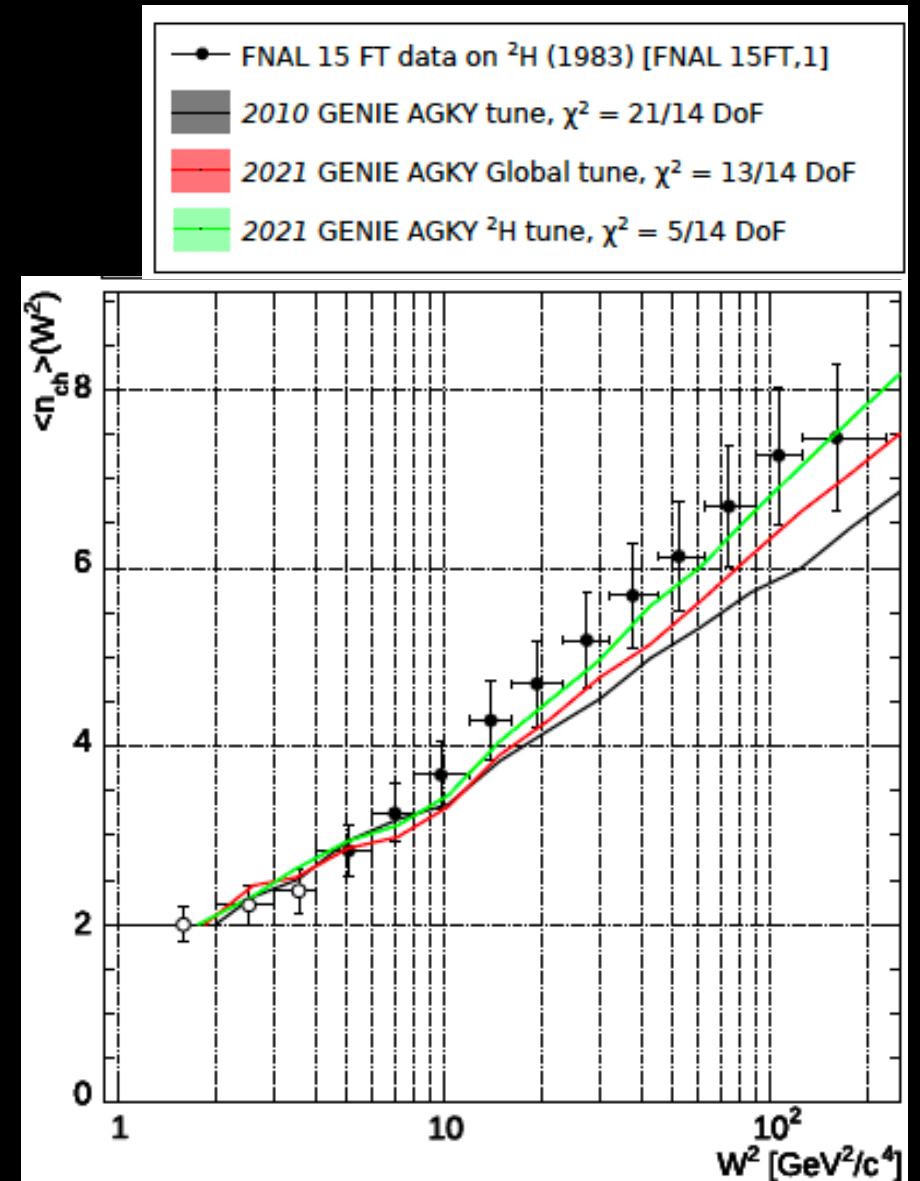
Free parameters

- Tuning is essential to address double counting**
- Untuned GENIE (G18_02a def) fails to describe one and two pion production data on free nucleon



Lack of MC/Data description

- Hadronization is handled with the AGKY model [Eur.Phys.J.C63:1-10,2009]
 - Low-W empirical model for SIS/DIS events at $W < 2.3 \text{ GeV}/c^2$
 - PYTHIA 8 for events with $W > 3 \text{ GeV}/c^2$
 - Transition region in the $2.3 < W < 3 \text{ GeV}/c^2$ region
 - Probability of using Low-W with respect to PYTHIA changes linearly with W
- **The untuned model fails to describe neutrino hadronization data and it does not provide with model uncertainties**
 - AGKY can't be tuned using standard Reweighting procedures



GENIE's global analysis with Professor

GENIE develops a global analysis of scattering data for tuning and uncertainty characterization of comprehensive neutrino interaction models

- **Goals:**
 - Perform a global tune that improves data/MC agreement
 - Avoid double-counting in transition region
 - Estimate data-driven uncertainties
- **Requirements:**
 - Tune all aspects of event generators, **including non-reweightable processes**
 - The software can accommodate neutrino, hadron nucleon and electron scattering data
- **Summary of previous GENIE tunes:**
 - Neutrino-Nucleon Cross-Section Model Tuning in GENIE v3 [[PhysRevD.104.072009](#)]
 - Hadronization Model Tuning in GENIE v3 [[PhysRevD.105.012009](#)]
 - Neutrino-nucleus $CC0\pi$ cross-section tuning in GENIE v3 [[PhysRevD.106.112001](#)]

This talk focuses on the global analysis software

GENIE's global analysis with Professor

- The GENIE global analysis software is based on the Professor concept
 - Professor is extensively used in the collider community
- GENIE's global analysis software is adapted to the needs of the neutrino community
 - Has diversified from the standard Professor software
- The GENIE Generator package interfaces with GENIE tuning software via GENIE Comparisons software
- Professor is not available in UPS but it can be installed on the FNAL grid
- **The Professor concept can be used to tune other event generators**



<https://professor.hepforge.org>

GENIE's global analysis with Professor

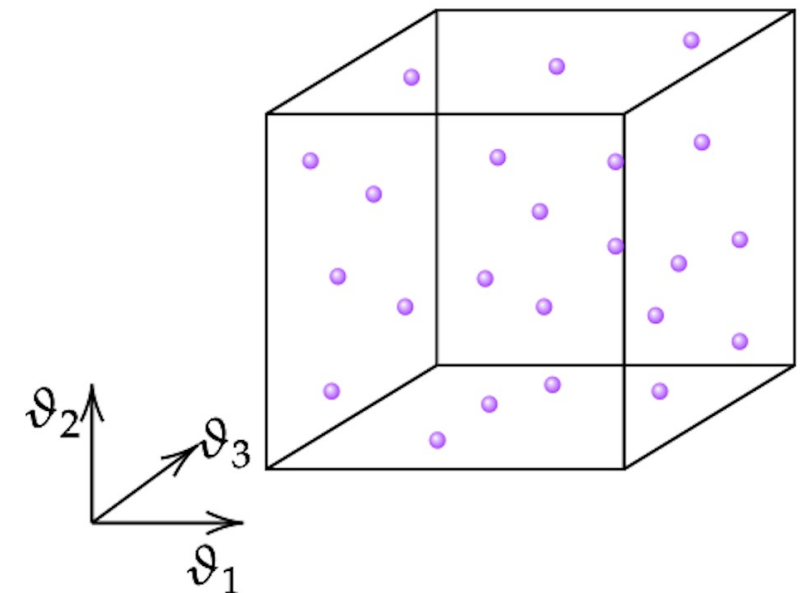
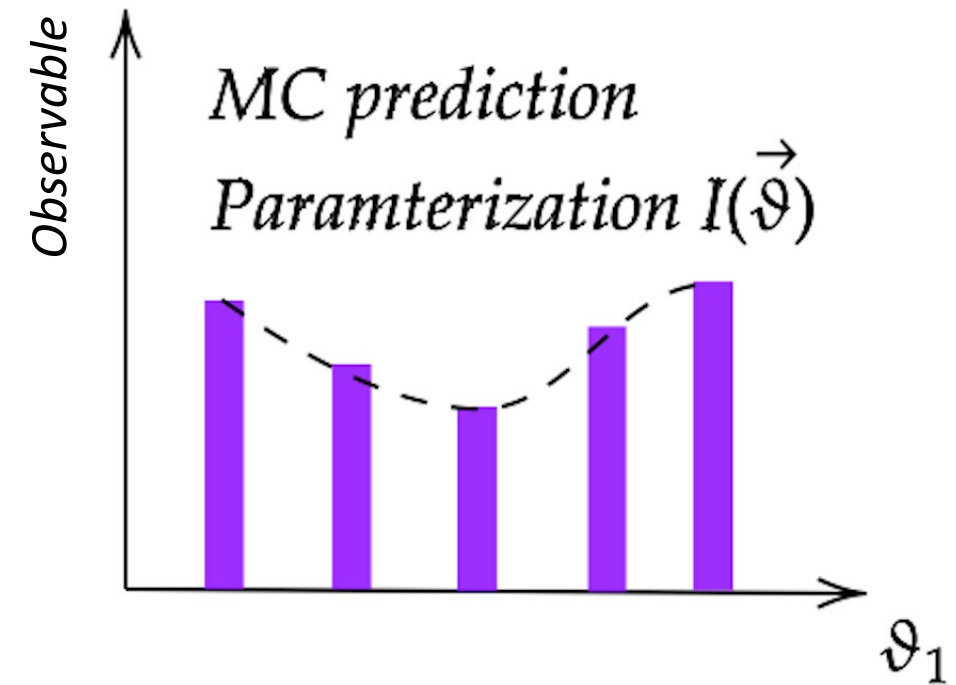
- Professor's concept:
Parameterization instead of full MC
- Main take-aways:
 - The MC response for a given observable is parameterized as a function of the parameters phase-space
 - We call this the response function
 - The minimization of the likelihood is done with the parameterized response function



<https://professor.hepforge.org>

General Tuning Workflow

1. Select the parameters to tune and define physical phase-space
2. Define your observable in terms of bins
3. Evaluate observable bin's behaviour with brute force
4. Use sampled points to parameterize bin's behaviour with an N-Dimensional polynomial
5. Minimize using parameterization instead of full MC



Selection of parameters of interest

- The selection of parameters will depend on the interaction process you want to tune
- **The parameters to tune are directly used in the cross-section computation**
- For instance, we might want to tune M_A^{QEL} :

CommonParam.xml used in spline generation:

```
<param_set name="QuasiElastic">
  <!--
  P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 P12 P13 P14 P15 P16 P17 P18 P19 P20 P21 P22 P23 P24 P25 P26 P27 P28 P29 P30 P31 P32 P33 P34 P35 P36 P37 P38 P39 P40 P41 P42 P43 P44 P45 P46 P47 P48 P49 P50 P51 P52 P53 P54 P55 P56 P57 P58 P59 P60 P61 P62 P63 P64 P65 P66 P67 P68 P69 P70 P71 P72 P73 P74 P75 P76 P77 P78 P79 P80 P81 P82 P83 P84 P85 P86 P87 P88 P89 P90 P91 P92 P93 P94 P95 P96 P97 P98 P99 P100 P101 P102 P103 P104 P105 P106 P107 P108 P109 P110 P111 P112 P113 P114 P115 P116 P117 P118 P119 P120 P121 P122 P123 P124 P125 P126 P127 P128 P129 P130 P131 P132 P133 P134 P135 P136 P137 P138 P139 P140 P141 P142 P143 P144 P145 P146 P147 P148 P149 P150 P151 P152 P153 P154 P155 P156 P157 P158 P159 P160 P161 P162 P163 P164 P165 P166 P167 P168 P169 P170 P171 P172 P173 P174 P175 P176 P177 P178 P179 P180 P181 P182 P183 P184 P185 P186 P187 P188 P189 P190 P191 P192 P193 P194 P195 P196 P197 P198 P199 P200 P201 P202 P203 P204 P205 P206 P207 P208 P209 P210 P211 P212 P213 P214 P215 P216 P217 P218 P219 P220 P221 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P2180 P2181 P2182 P2183 P2184 P2185 P2186 P2187 P2188 P2189 P2190 P2191 P2192 P2193 P2194 P2195 P2196 P2197 P2198 P2199 P2200 P2201 P2202 P2203 P2204 P2205 P2206 P2207 P2208 P2209 P2210 P2211 P2212 P2213 P2214 P2215 P2216 P2217 P2218 P2219 P2220 P2221 P2222 P2223 P2224 P2225 P2226 P2227 P2228 P2229 P2230 P2231 P2232 P2233 P2234 P2235 P2236 P2237 P2238 P2239 P2240 P2241 P2242 P2243 P2244 P2245 P2246 P2247 P2248 P2249 P2250 P2251 P2252 P2253 P2254 P2255 P2256 P2257 P2258 P2259 P2260 P2261 P2262 P2263 P2264 P2265 P2266 P2267 P2268 P2269 P2270 P2271 P2272 P2273 P2274 P2275 P2276 P2277 P2278 P2279 P2280 P2281 P2282 P2283 P2284 P2285 P2286 P2287 P2288 P2289 P2290 P2291 P2292 P2293 P2294 P2295 P2296 P2297 P2298 P2299 P2300 P2301 P2302 P2303 P2304 P2305 P2306 P2307 P2308 P2309 P2310 P2311 P2312 P2313 P2314 P2315 P2316 P2317 P2318 P2319 P2320 P2321 P2322 P2323 P2324 P2325 P2326 P2327 P2328 P2329 P2330 P2331 P2332 P2333 P2334 P2335 P2336 P2337 P2338 P2339 P2340 P2341 P2342 P2343 P2344 P2345 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P2512 P2513 P2514 P2515 P2516 P2517 P2518 P2519 P2520 P2521 P2522 P2523 P2524 P2525 P2526 P2527 P2528 P2529 P2530 P2531 P2532 P2533 P2534 P2535 P2536 P2537 P2538 P2539 P2540 P2541 P2542 P2543 P2544 P2545 P2546 P2547 P2548 P2549 P2550 P2551 P2552 P2553 P2554 P2555 P2556 P2557 P2558 P2559 P2560 P2561 P2562 P2563 P2564 P2565 P2566 P2567 P2568 P2569 P2570 P2571 P2572 P2573 P2574 P2575 P2576 P2577 P2578 P2579 P2580 P2581 P2582 P2583 P2584 P2585 P2586 P2587 P2588 P2589 P2590 P2591 P2592 P2593 P2594 P2595 P2596 P2597 P2598 P2599 P2600 P2601 P2602 P2603 P2604 P2605 P2606 P2607 P2608 P2609 P2610 P2611 P2612 P2613 P2614 P2615 P2616 P2617 P2618 P2619 P2620 P2621 P2622 P2623 P2624 P2625 P2626 P2627 P2628 P2629 P2630 P2631 P2632 P2633 P2634 P2635 P2636 P2637 P2638 P2639 P2640 P2641 P2642 P2643 P2644 P2645 P2646 P2647 P2648 P2649 P2650 P2651 P2652 P
```

Selection of parameters of interest

- The selection of parameters will depend on the interaction process you want to tune
- **The parameters to tune are directly used in the cross-section computation**

- **Benefits of this approach:**

- Any parameter involved in the cross-section or event generation algorithms can be tuned
- Can tune non-reweightable parameters
 - Hadronization, final-state interaction (including cascade FSI models), etc...
- New parameterizations are added directly in the GENIE Generator
- The results of the tune can be easily included in GENIE CMC's to be run out-of-the-box by users
 - Complex configurations are handled with tune tags: [Example of nuclear tune configuration \(GPRD18_10a\)](#)

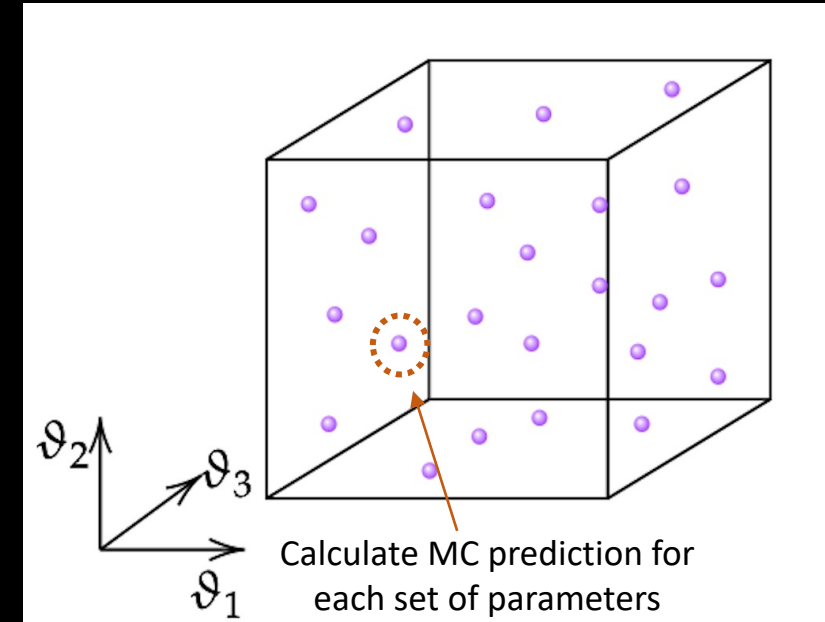
Sampling of phase-space

- Once the set of parameters is selected ($\vartheta_1, \vartheta_2, \dots, \vartheta_{N_\vartheta}$), the next step is to define the parameters phase-space
 - Ideally, the best-fit result should lie around the middle of the phase-space
- In order to parameterize the response-function with an N-dimensional polynomial, we uniformly sample the phase space with

$$N_{MC \text{ Samples}} = \frac{(N_\vartheta + N)!}{N_\vartheta! N!} \cdot 1.5$$

N_ϑ	4 th order polynomial	5 th order polynomial
2	22	31
5	189	378
10	1500	4500
13	3570	12852

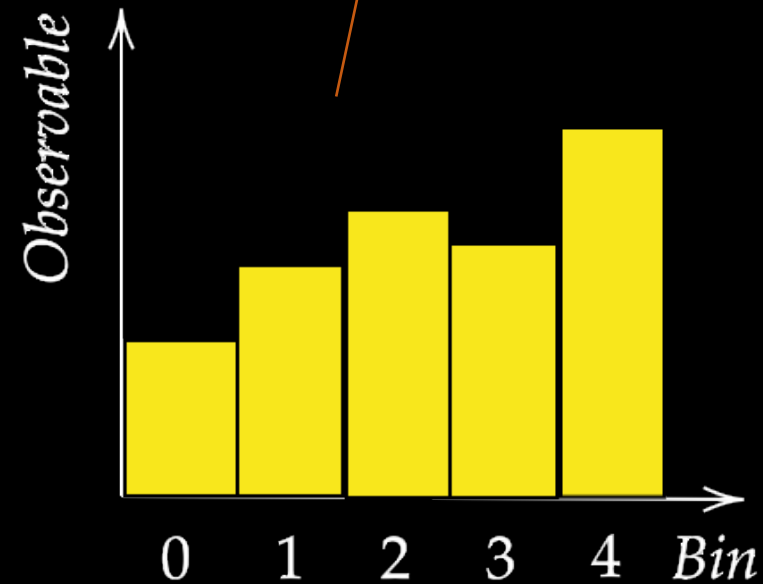
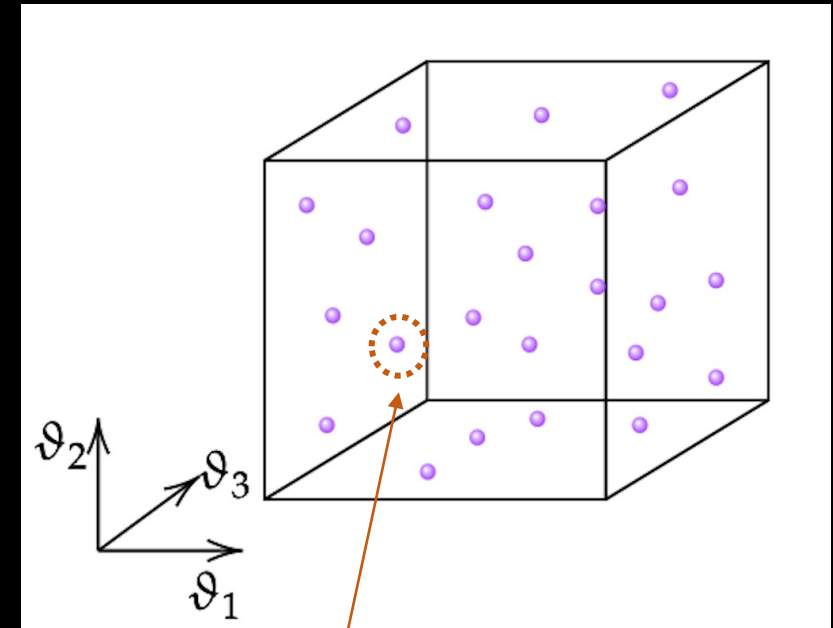
N_ϑ dimensions phase-space



The generation of all the samples is the most expensive CPU expensive step
 It can be easily parallelized to minimize computing time
It happens before the actual fit (which takes few minutes to run)

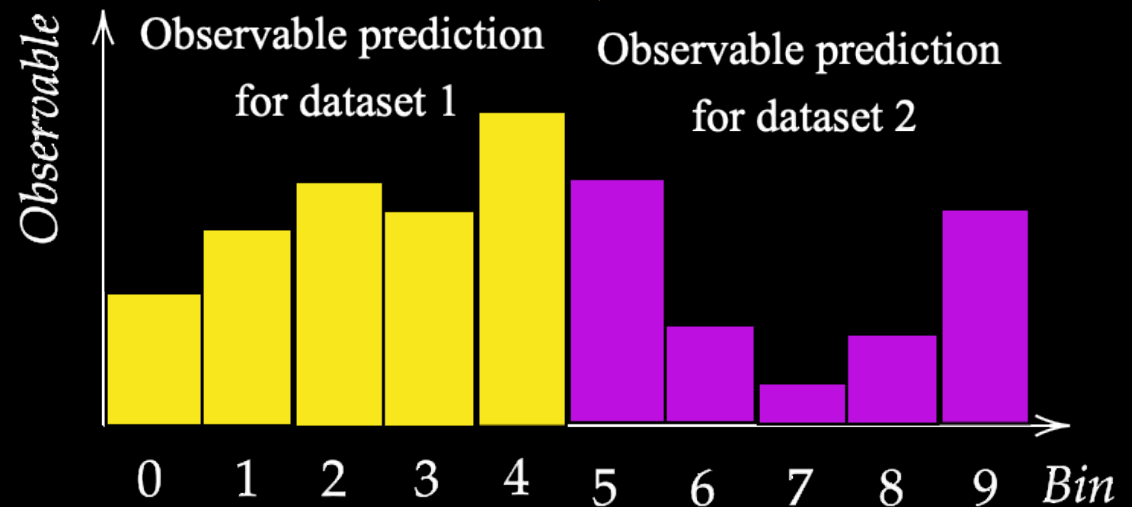
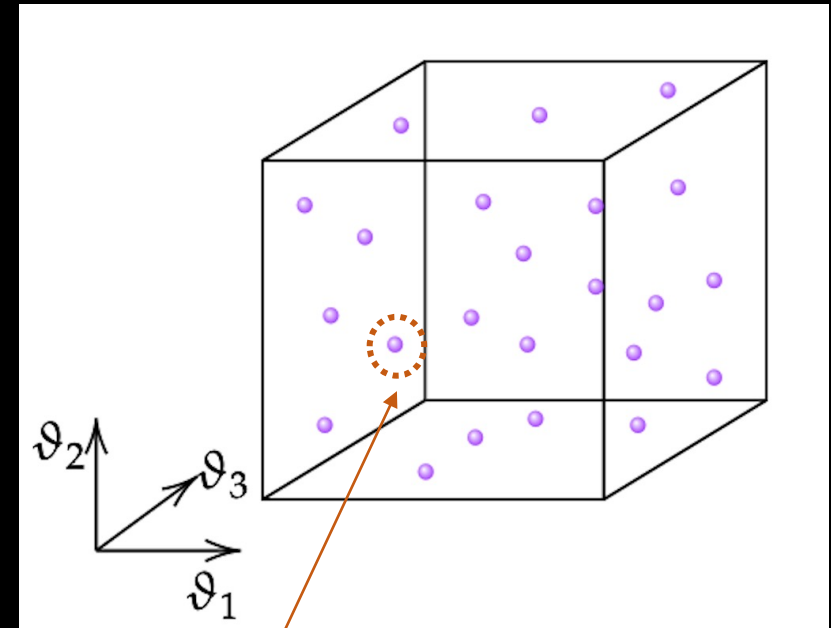
Definition of observable

- The observable is defined as a histogram
 - The most common observable is a differential cross section
 - The observable can correspond to single- and double- differential cross-section measurements
 - Other observables are also compatible, such as hadron multiplicities
 - In each bin, we assume a gaussian distribution
 - **The histogram definition is handled by the internal GENIE database**
 - The observable definition is associated to a data release
- We have a histogram per set of parameters in our N_g -dimensional phase-space



Definition of observable for multiple datasets

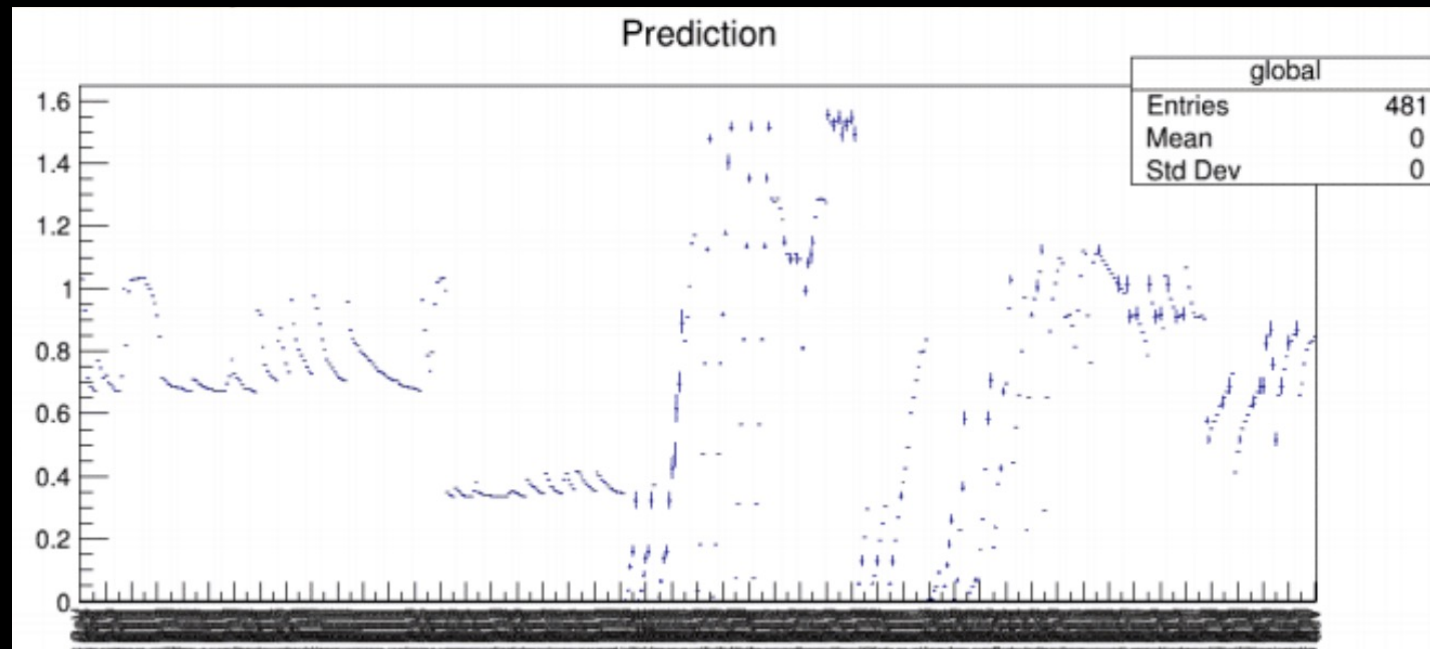
- The observable is defined as a histogram
 - It is possible to use predictions associated to different data releases
 - Each dataset can have a different observable definition
 - All the information is stored in the same 1D-histogram



Definition of Observable

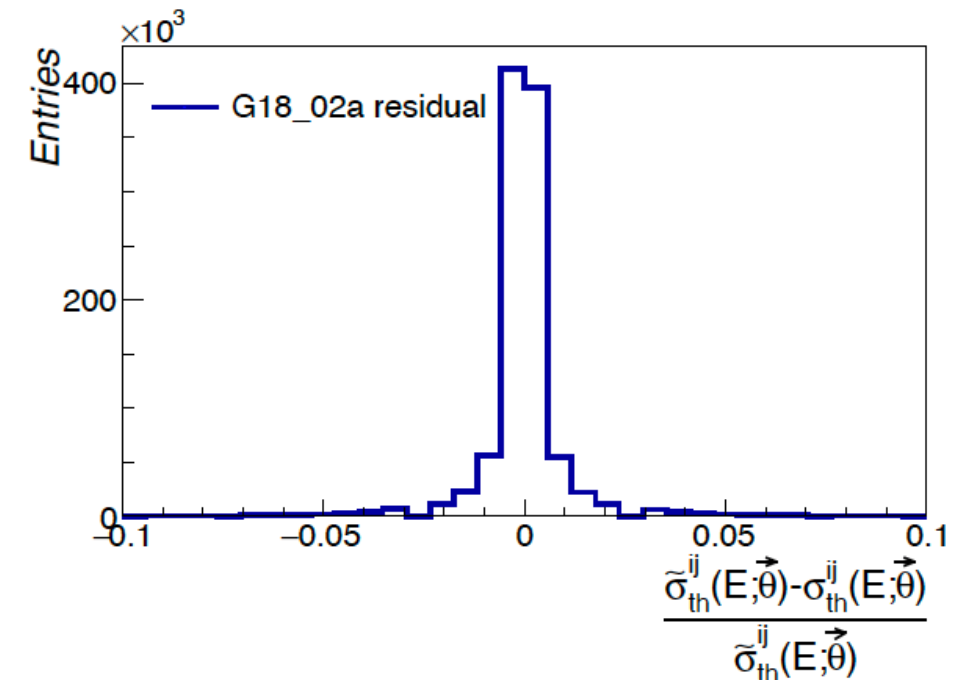
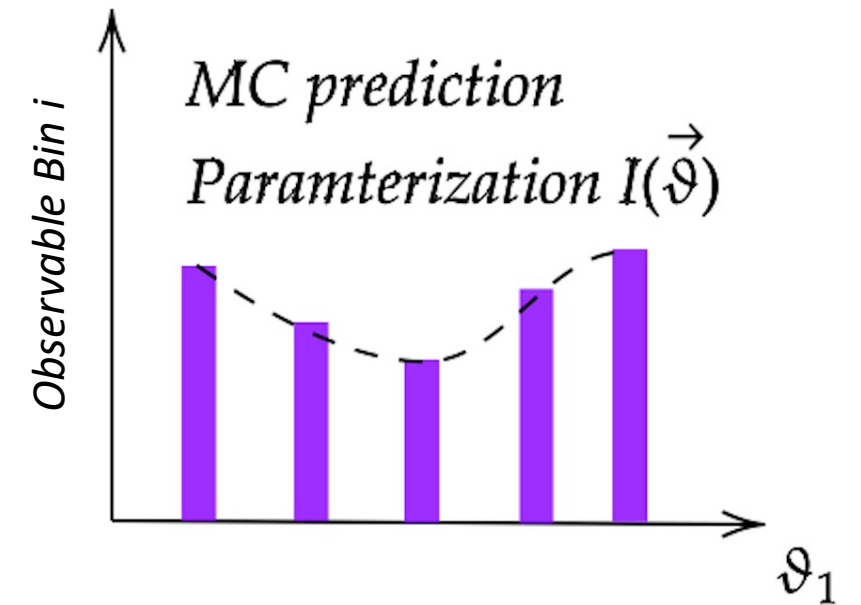
Example from GENIE's free nucleon tune

- Prediction histogram associated to thirty-three datasets [[PhysRevD.104.072009](https://arxiv.org/abs/1907.07209)]
 - The observable corresponds to a series of GENIE Predictions for ν_μ and anti- ν_μ CC inclusive, QEL, single-pion and two-pion production associated to ANL 12 ft, BNL 7ft, BEBC and FNAL bubble chamber data
- This prediction is computed with a single parameter set of our sampled phase space



Parameterization of the MC response function

- For each bin, we parameterize the observable mean value and error dependency on the parameters
- The parameterization is fit against the brute force scan
- The parameterization is an **approximation**
- It is possible to quantify its accuracy with the residual:
 - True prediction - parameterization bin-by-bin



Minimization from parameterization

- The final step is to minimize the parameterisation against the data using `minuit`
- The GENIE tuning software allows us to consider:
 - Correlation between data bins and datasets
 - Bin weights
 - We can use the weights to remove data from the fit
 - Proper treatment for strongly correlated data releases with Peelle's Pertinent Puzzle resolution proposed by:
 - [Jaafar Chakrani et. al. at PoS NuFact2021](#)
 - [Nucl. Instrum. Meth. A 346, 306 \(1994\)](#)
 - Gaussian priors on parameters (θ_0)
 - Uncorrelated and correlated
 - Nuisance parameters $\phi(f)$
 - These can also be constrained with priors

Example from the free-nucleon tune
[\[PhysRevD.104.072009\]](#):

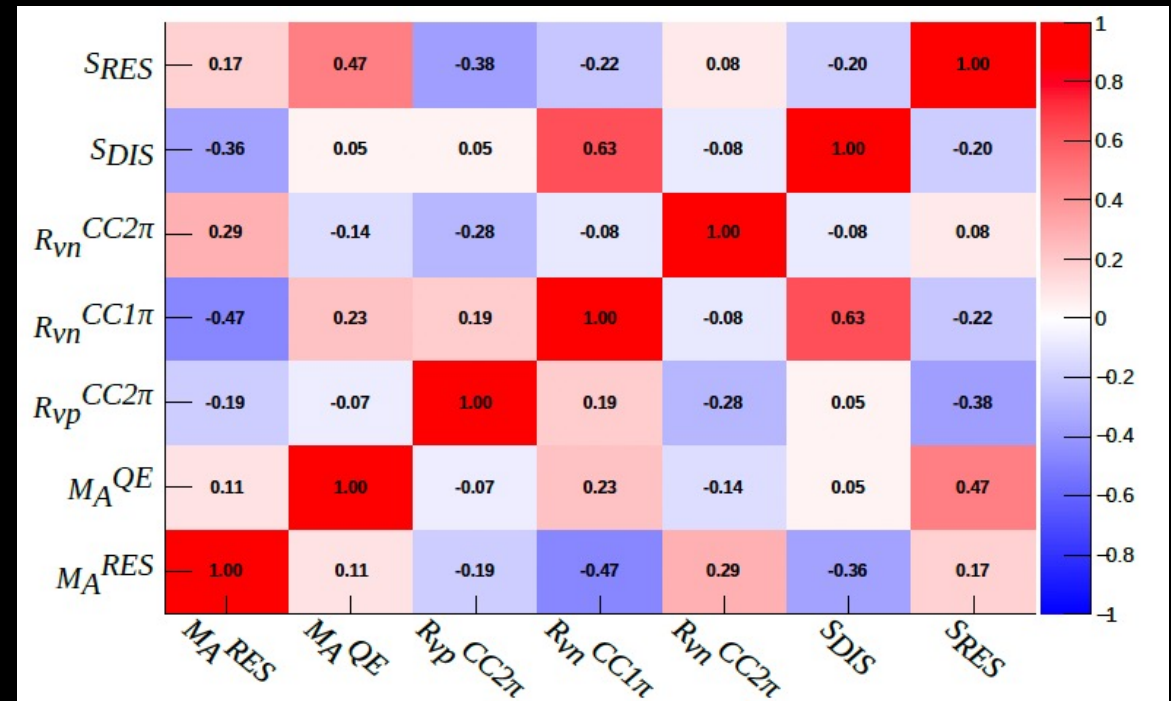
$$\chi^2(\boldsymbol{\theta}, \boldsymbol{f}) = \sum_{i,j,k} w^{ijk} \frac{(\phi_j(\boldsymbol{f}) \tilde{\sigma}_{\text{th}}^{ij}(E_k | \boldsymbol{\theta}) - \sigma_d^{ijk})^2}{(\delta \sigma_{\text{stat}}^{ijk})^2} + (\boldsymbol{\theta} - \boldsymbol{\theta}_0)^T \Sigma_{\boldsymbol{\theta}}^{-1} (\boldsymbol{\theta} - \boldsymbol{\theta}_0) + \sum_j \frac{(f_j - 1)^2}{(\delta f_j)^2}$$

Most of these features are not present in the Professor software as these were developed by the GENIE Collaboration to tune GENIE against neutrino data

Result of the tune (out-of-the-box)

- Out-of-the-box, we obtain an estimation for the best-fit parameter mean values, uncertainties and correlation between parameters
- Example from the **free nucleon tune paper**: [PhysRevD.104.072009](https://arxiv.org/abs/PhysRevD.104.072009)

Parameter	G18_01a(/b)	G18_02a(/b)
W_{cut}	1.94	1.81
M_A^{QEL}	1.00 ± 0.01	1.00 ± 0.013
M_A^{RES}	1.09 ± 0.02	1.09 ± 0.014
$R_{vp}^{\text{CC1}\pi}$	0.06 ± 0.03	0.008
$R_{vp}^{\text{CC2}\pi}$	1.1 ± 0.2	0.94 ± 0.075
$R_{vn}^{\text{CC1}\pi}$	0.14 ± 0.03	0.03 ± 0.010
$R_{vn}^{\text{CC2}\pi}$	2.8 ± 0.4	2.3 ± 0.12
S_{RES}	0.89 ± 0.04	0.84 ± 0.028
S_{DIS}	1.03 ± 0.02	1.06 ± 0.01
$\chi^2/157 \text{ DoF}$	1.84	1.64

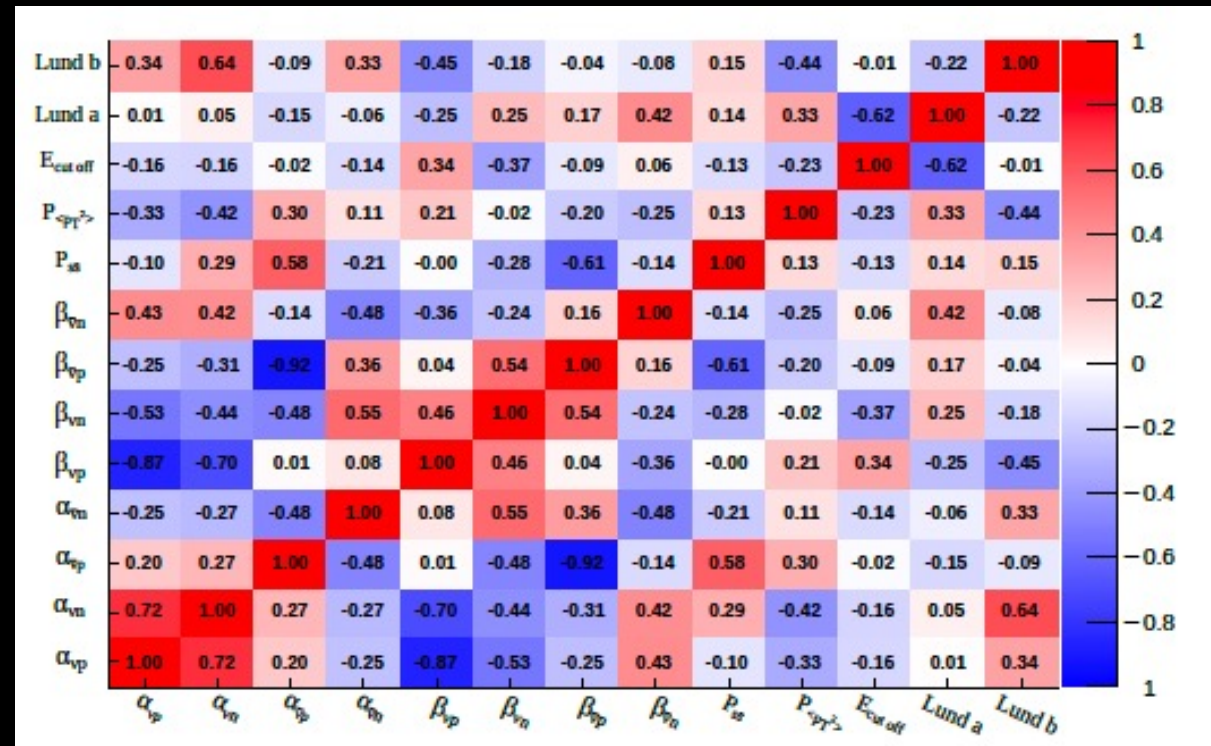


Result of the tune (out-of-the-box)

- Out-of-the-box, we obtain an estimation for the best-fit parameter mean values, uncertainties and correlation between parameters
- Example from the **hadronization tune paper**: [PhysRevD.105.012009](https://arxiv.org/abs/1905.01200)

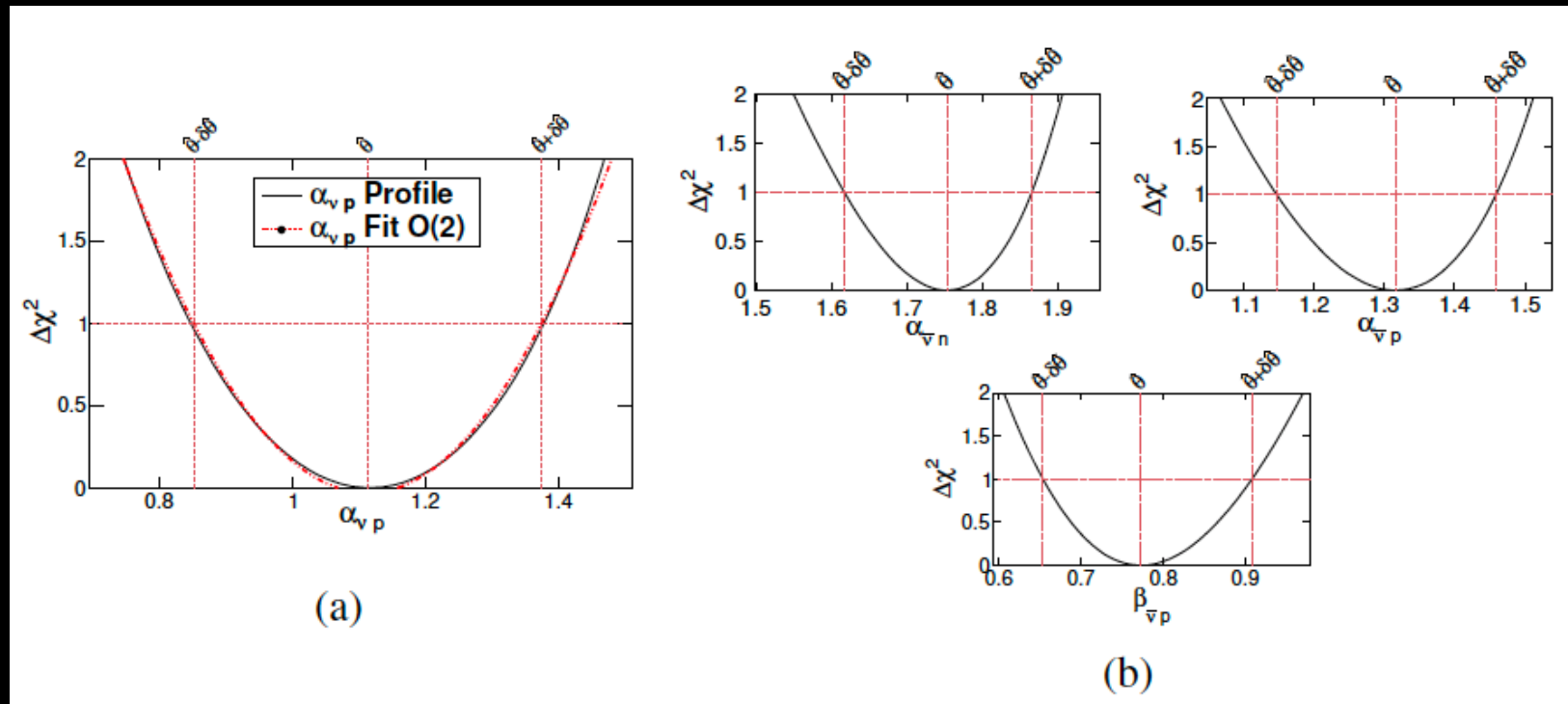
We did tunes of as many as 13 parameters and extract data-driven uncertainties

Parameter	2021 Global Fit
α_{vp}	1.1 ± 0.3
α_{vn}	$1.75^{+0.14}_{-0.11}$
$\alpha_{\bar{v}p}$	$1.32^{+0.16}_{-0.14}$
$\alpha_{\bar{v}n}$	1.11 ± 0.09
β_{vp}	0.79 ± 0.15
β_{vn}	0.5 ± 0.1
$\beta_{\bar{v}p}$	0.8 ± 0.1
$\beta_{\bar{v}n}$	$0.88^{+0.09}_{-0.08}$
P_{ss}	0.27 ± 0.04
$\langle p_{\perp}^2 \rangle$ [GeV ² /c ²]	0.46 ± 0.05
E_{CutOff} [GeV]	0.30 ± 0.04
Lund a	1.53 ± 0.13
Lund b [c ⁴ /GeV ²]	1.16 ± 0.09
87.9/62 DoF	



Parameter error estimation

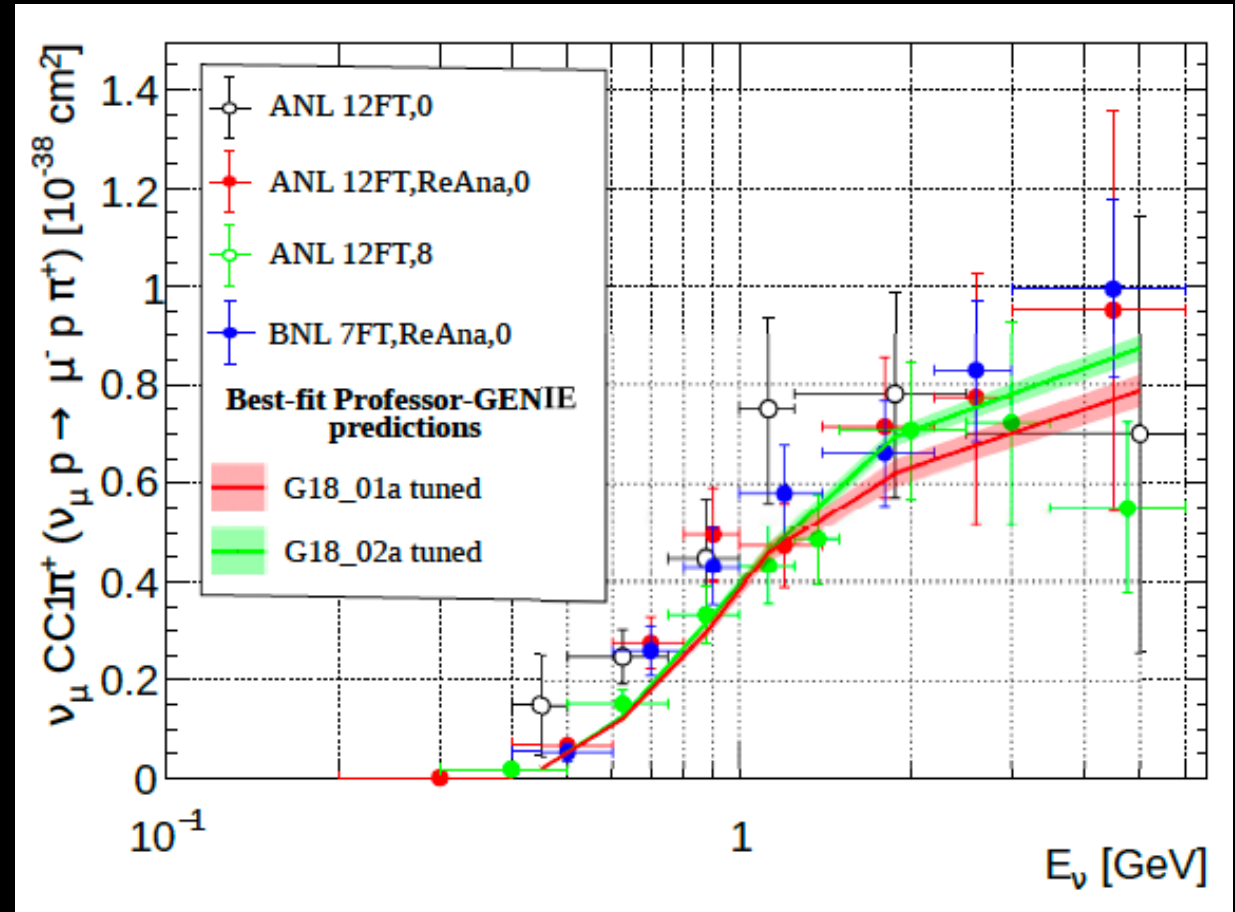
- It is possible to obtain 1D and 2D contours out of the fit
- Asymmetric errors can be extracted from profiles under the $\Delta\chi^2$ condition
- Example from the **hadronization tune paper**: [PhysRevD.105.012009](https://arxiv.org/abs/PhysRevD.105.012009)



Propagation of parameter uncertainties to GENIE Predictions

[PhysRevD.105.012009](#)

- We can propagate the post-fit uncertainty into the parameterization
- It effectively creates a confidence belt out of the tune parameterizations



Conclusions

- GENIE is developing a global analysis software for tuning and uncertainty characterization of comprehensive interaction models
- The software, based on the Professor concept, is based on the minimization of parameterized MC response functions
- **Main features of GENIE's global analysis software:**
 - All event generation models can be tuned, including non-reweightable models such as hN INTRANUKE or the AGKY hadronization model
 - New parameters can be easily added in the MC Event Generator itself
 - The most CPU consuming step (cross-section and event generation of the phase-space) can be parallelized
 - The tuning step itself is fast and can easily be reproduced
 - This tool can be used for other MC event generators

Thank you for your interest

The GENIE Collaboration



Backup slides

Lack of MC/Data description

- G18_10a_02_11b fails to describe MINERvA ν_μ CC0 π data at $0.15 < p_T < 0.7$ GeV/c
 - Valencia model for 1p1h and 2p2h interactions
 - hA FSI model, Berger-Sehgal model for RES
- This has a big consequences on the neutrino energy reconstruction

MINERvA ν_μ CC0 π data

