NuWro - neutrino MC event generator

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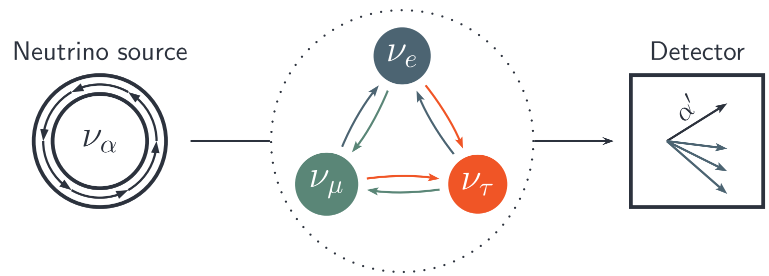
Uniwersytet Wrocławski

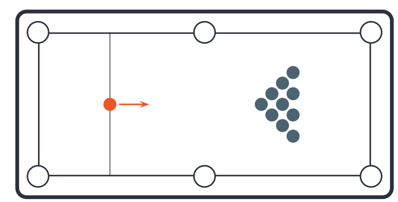
Outline

1. Motivation

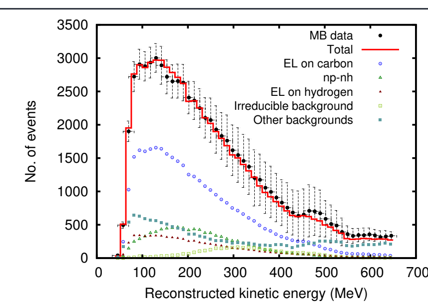


2. NuWro event generator

3. Final State Interactions



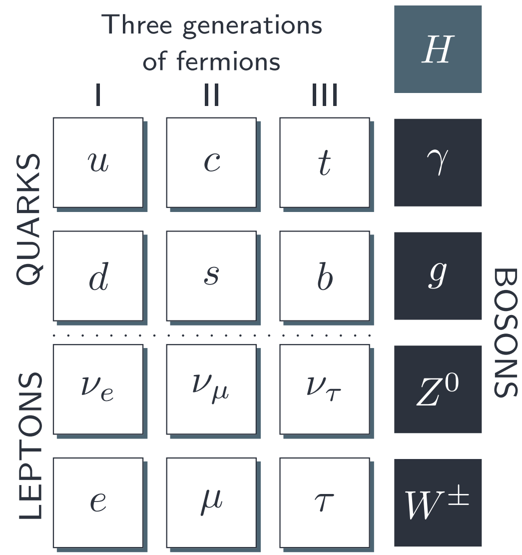
4. MB NCEL data analysis



Introduction

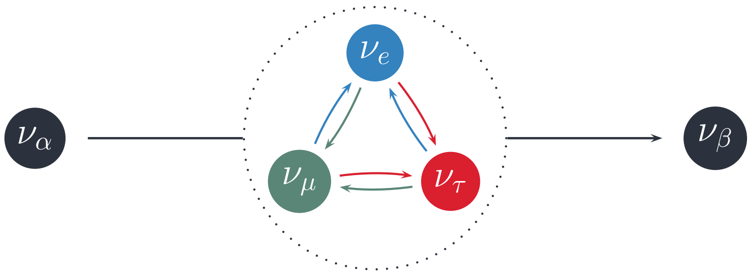
Basic properties of neutrinos

- $\frac{1}{2}$-spin, no electric charge, small mass (extremely hard to detect)



- Interactions with elementary particles
  $\rightarrow$ electroweak theory (Standard Model)
- Interactions with nucleons
  $\rightarrow$ form factors
  $\rightarrow$ parton distribution functions
- Interactions with nuclei $\rightarrow$ nuclear effects
- The neutrino flavor state is a superposition of the mass states:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$



The neutrino produced in α state can be measured in β state. The phenomenon is called neutrino oscillation.

Pontecorvo-Maki-Nakagawa-Sakata matrix

The PMNS matrix defines the mass mixing in the lepton sector:

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$ θ_{ij} - mixing angels δ - CP phase factor

Measurements:

- Solar, reactor and accelerator: $\sin^2(2\theta_{12}) = 0.846 \pm 0.021$
- Atmospheric: $\sin^2(2\theta_{23}) > 0.92$
- Reactor: $\sin^2(2\theta_{13}) = 0.093 \pm 0.008$

δ can be measured if and only if all mixing angles are nonzero. If $\delta \neq 0$ CP is violated.

Probability of oscillation

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) &= \left|\langle \nu_\beta(x) | \nu_\alpha(y) \rangle\right|^2 = \delta_{\alpha\beta} \\ &- 4\sum_{i>j} \mathrm{Re}\left[U^*_{\alpha i} U_{i\beta} U_{\alpha_j} U^*_{j\beta}\right] \sin^2\left(\frac{\Delta {m_{ij}}^2 L}{4E}\right) \\ &+ 2\sum_{i>j} \mathrm{Im}\left[U^*_{\alpha i} U_{i\beta} U_{\alpha_j} U^*_{j\beta}\right] \sin^2\left(\frac{\Delta {m_{ij}}^2 L}{2E}\right) \end{aligned}$$

$$\boxed{\Delta m^2_{ij} \equiv m_i^2 - m_j^2}$$

L - traveled distance (fixed), E - neutrino energy (will be discussed)

Measurements:

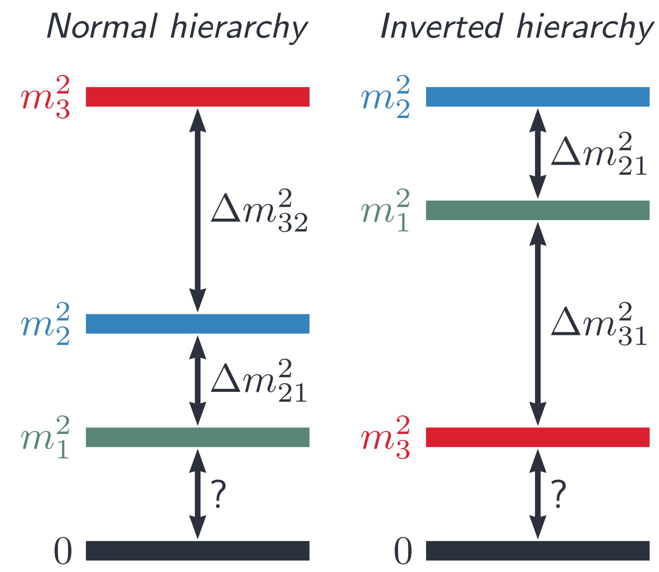
- Solar neutrinos: $\Delta m^2_{21} = (7.53 \pm 0.18) \cdot 10^{-5} eV^2$
- Atmospheric neutrinos: $|\Delta m^2_{32}| = (2.44 \pm 0.06) \cdot 10^{-3} eV^2$

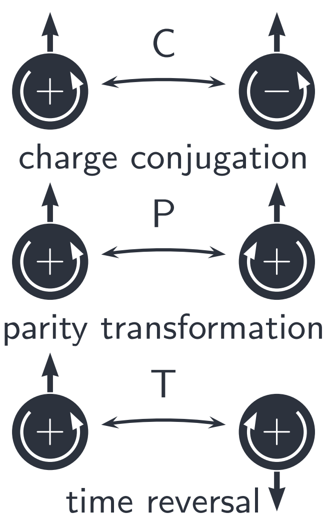
Neutrino oscillation

The probability of neutrino oscillation depends on:

- What we want to measure:
  - three mixing angles - already measured
  - the difference between squared mass of the mass states - the sign of Δm^2_{32} is still unknown, what is the mass hierarchy?
  - the CP phase factor - is the CP symmetry broken?

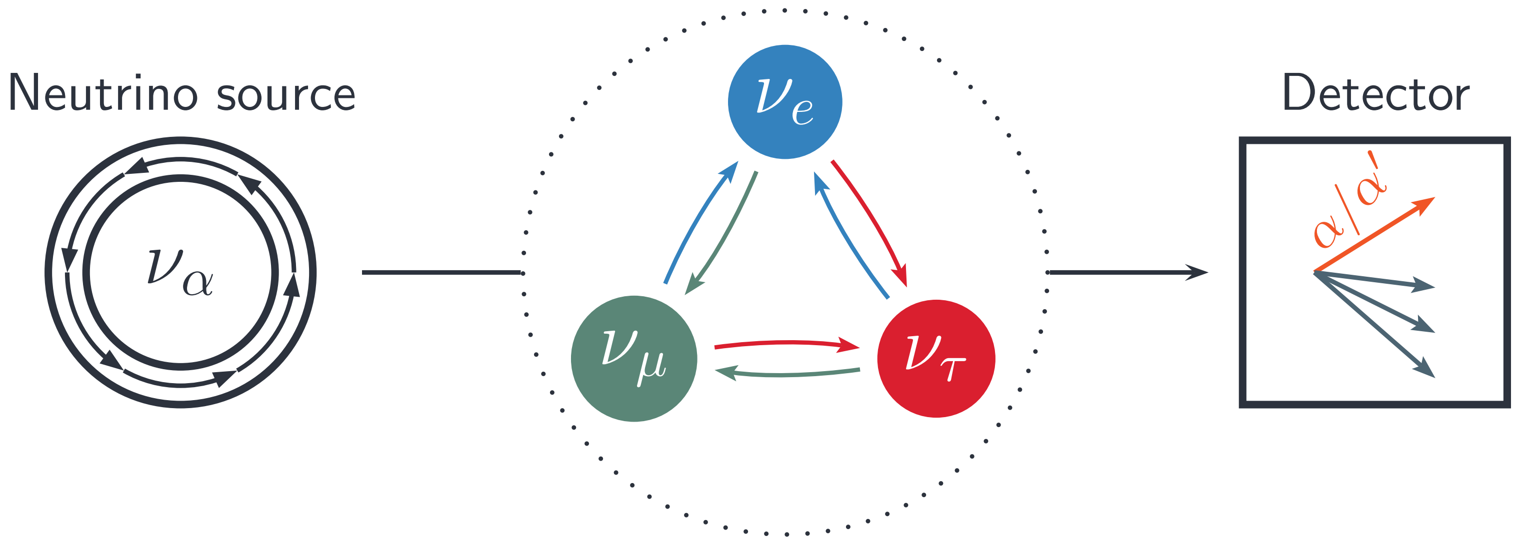
$$P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = P(\nu_\beta \to \nu_\alpha) \stackrel{?}{=} P(\nu_\alpha \to \nu_\beta)$$





- What we need to know:
  - the distance traveled by a neutrino
  - **neutrino energy** - this is a problem

How to measure neutrino oscillation?



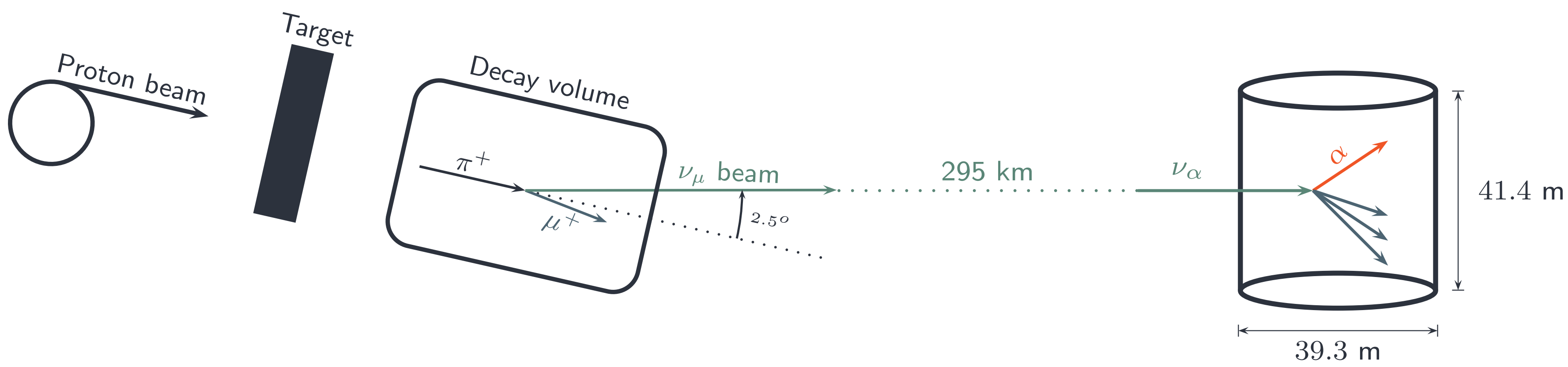
Disappearance method

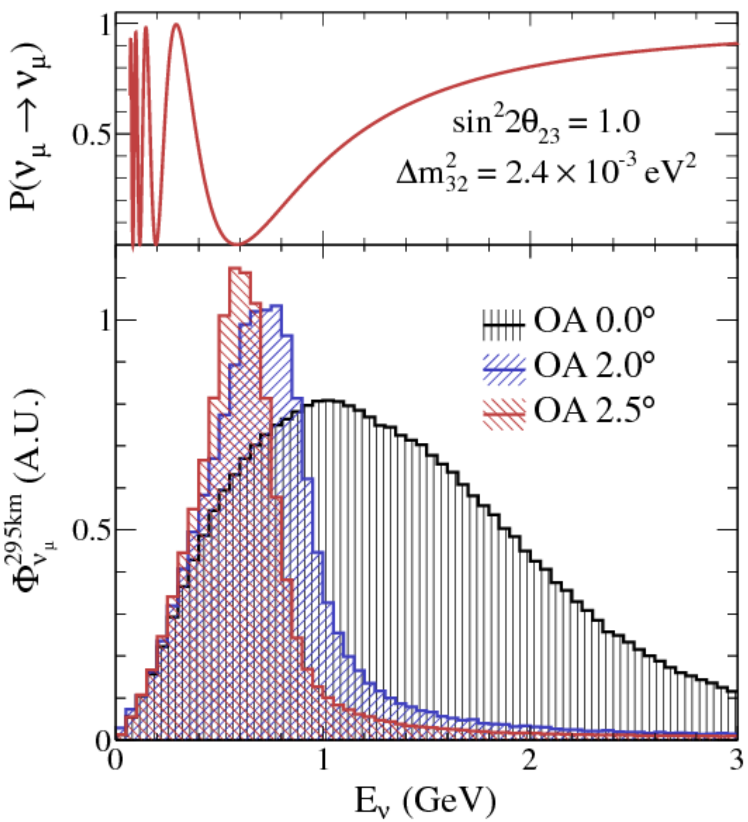
Number of α-flavor neutrinos ⟷ Number of α-flavor charged leptons

Appearance method

Number of α-flavor neutrinos ⟷ Number of α'-flavor charged leptons

Example: T2K

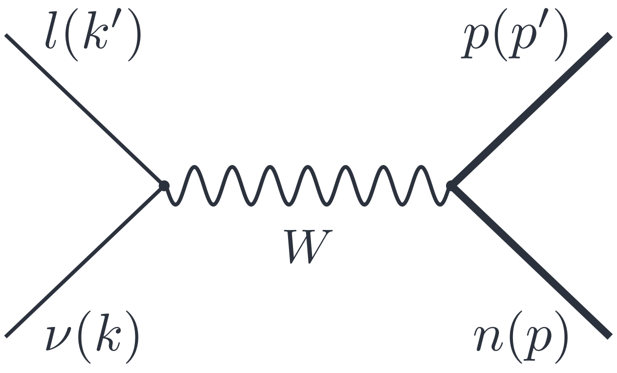




- Off-axis beam
- Cherenkov detector (Super-Kamiokande)
- 50 000 tons of ultra-pure water
- Only charged leptons and final state charged hadrons are visible
- The neutrino energy is unknown

The problem with neutrino energy reconstruction

In the case of neutrino scattering off nucleon at rest neutrino energy can be calculated from lepton kinematics:



Quasi-elastic scattering

$$M_p^2 = p'^2 = (p + k - k')^2$$

$$\begin{aligned} M_p^2 &= m_l^2 + M_n^2 - 2M_n E_l \\ &+ 2E_\nu (M_n - E_l + |\vec{p}_l| \cos\theta_l) \end{aligned}$$

$$E_\nu = \frac{M_p^2 - M_n^2 - m_l^2 + 2M_n E_l}{2(M_n - E_l + |\vec{p}_l| \cos\theta_l)}$$

$$\begin{aligned} k &= (E_\nu, 0, 0, E_\nu) \\ k' &= (E_l, \vec{p}_l) \\ p &= (M_p, 0, 0, 0) \\ p' &= p + q \\ q &= k - k' \end{aligned}$$

The problem with neutrino energy reconstruction

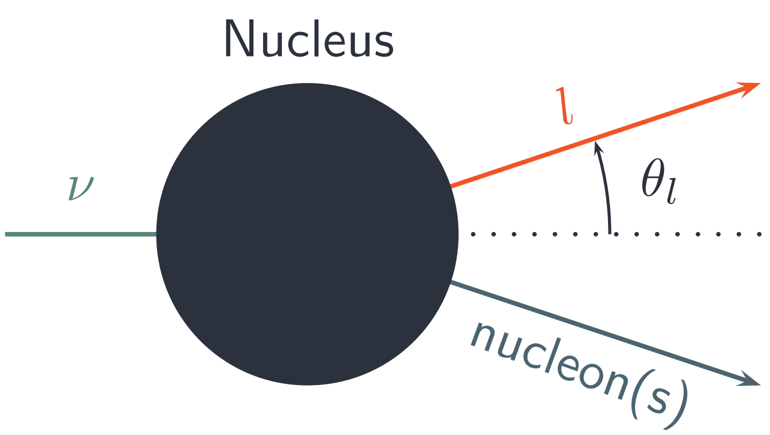
- Usually, the energy reconstruction procedure is based on quasi-elastic neutrino-nucleon scattering:

$$E_\nu^{REC} = \frac{M_p^2 - (M_n - E_B)^2 - m_l^2 + 2(M_n - E_B)E_l}{2(M_n - E_B - E_l + |\vec{p}_l|\cos\theta_l)}$$

Impulse Approximation

No Fermi motion

Binding Potential



The problem with neutrino energy reconstruction

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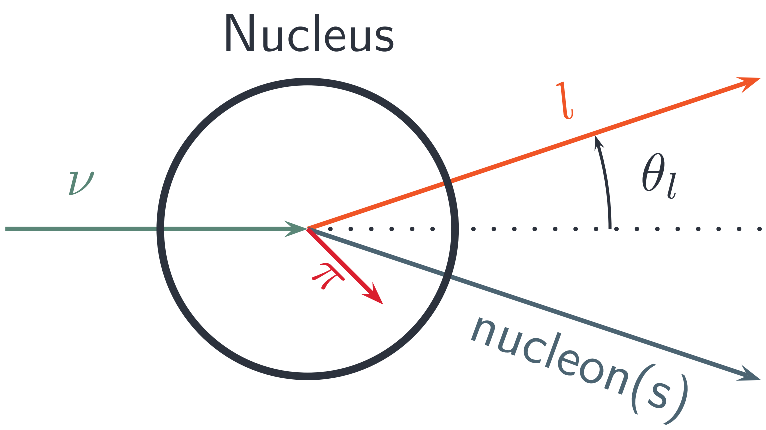
Never judge an event

by its final state particles!

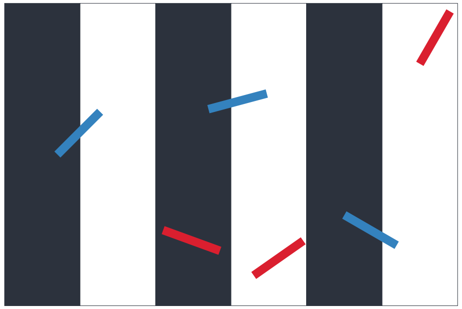


Monte Carlo generators

Buffon's needle problem

Suppose we have a floor made of parallel strips of wood, each the same width, and we drop a needle onto the floor. What is the probability that the needle will lie across a line between two strips?

Georges-Louis Leclerc,
Comte de Buffon
18th century



blue are good

red are bad

Monte Carlo without computers

If needle length (l) $<$ lines width (t):

$$P = \frac{2l}{t\pi}$$

which can be used to estimate π:

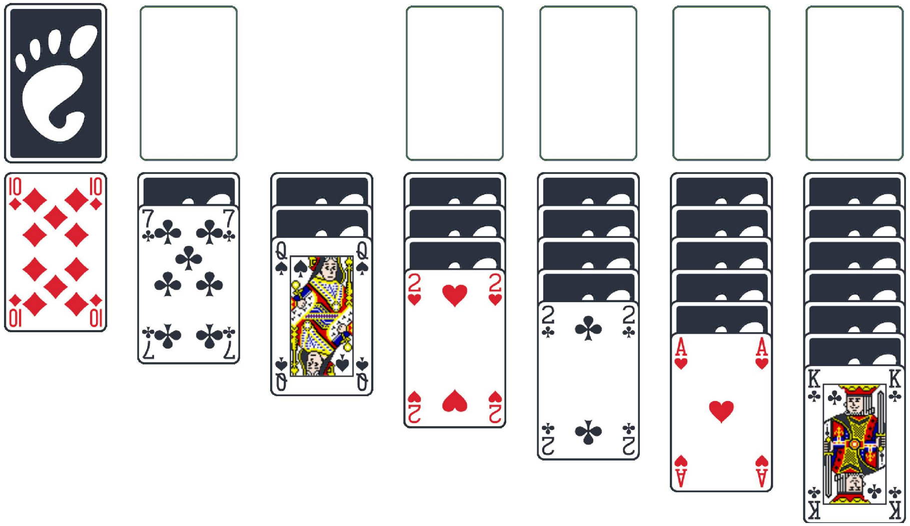
$$\pi = \frac{2l}{tP}$$

MC experiment was performed by Mario Lazzarini in 1901 by throwing 3408 needles:

$$\pi = \frac{2l \cdot 3408}{t \cdot \#red} = \frac{355}{113} = 3.14159292$$

From Solitaire to Monte Carlo method

- Stanisław Ulam was a Polish mathematician
- He invented the Monte Carlo method while playing solitaire
- The method was used in Los Alamos, performed by ENIAC computer



- What is a probability of success in solitaire?
    - Too complex for an analytical calculations
    - Lets try $N = 100$ times and count wins
    - With $N \to \infty$ we are getting closer to correct result

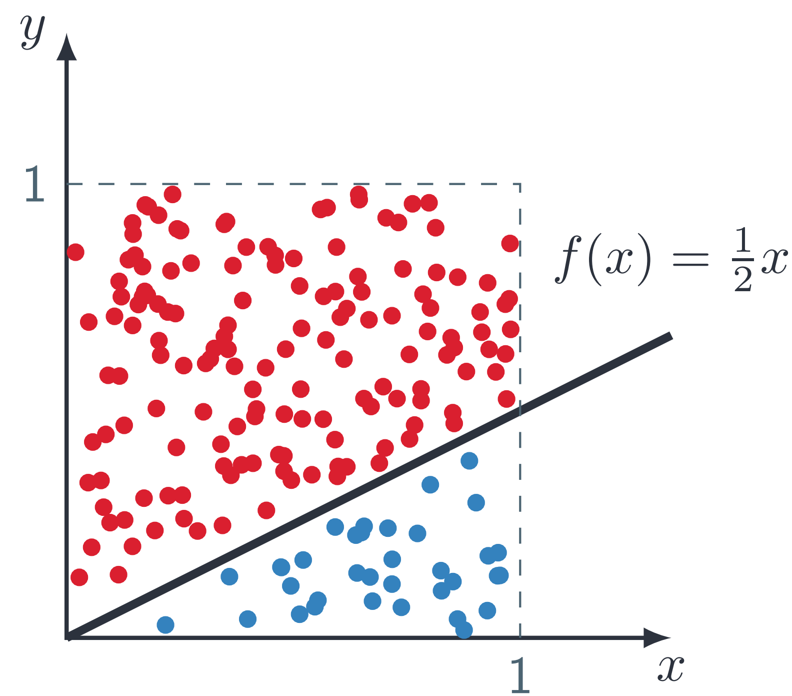
MC integration (hit-or-miss method)

Lets do the following integration using MC method:

$$\int_0^1 f(x)dx = \int_0^1 \left(\frac{1}{2}x\right) dx = \frac{1}{2}\frac{x^2}{2}\Big|_0^1 = \frac{1}{4}$$

- take a random point from the $[0,1] \times [0,1]$ square
- compare it to your $f(x)$
- repeat N times
- count n points below the function
- you results is given by

$$\int_0^1 f(x)dx = P_\square \cdot \frac{n}{N} = \frac{n}{N}$$



MC integration (crude method)

Lets do the following integration using MC method once again:

$$\int_0^1 f(x)dx = \int_0^1 \left(\frac{1}{2}x\right) dx = \frac{1}{2}\frac{x^2}{2}\Big|_0^1 = \frac{1}{4}$$

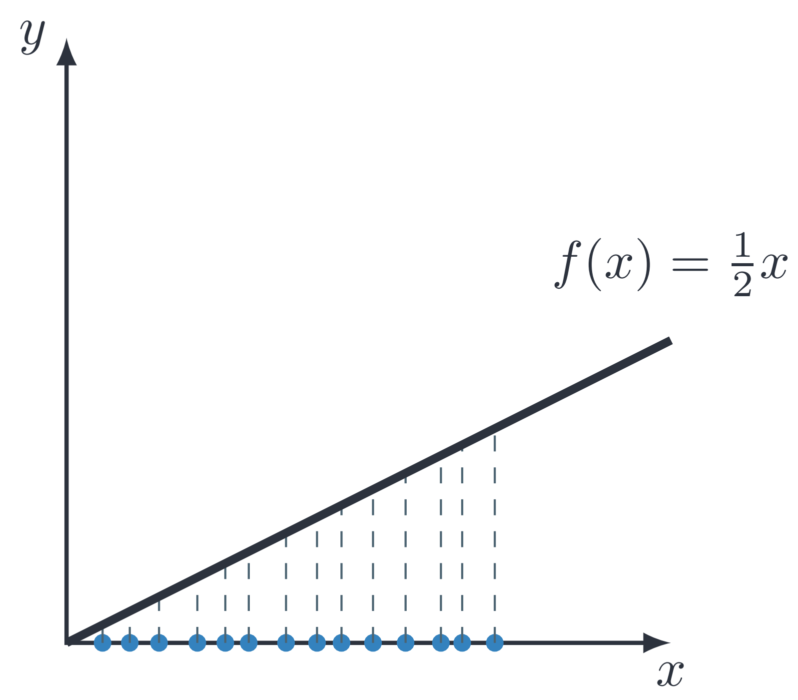
- One can approximate integral

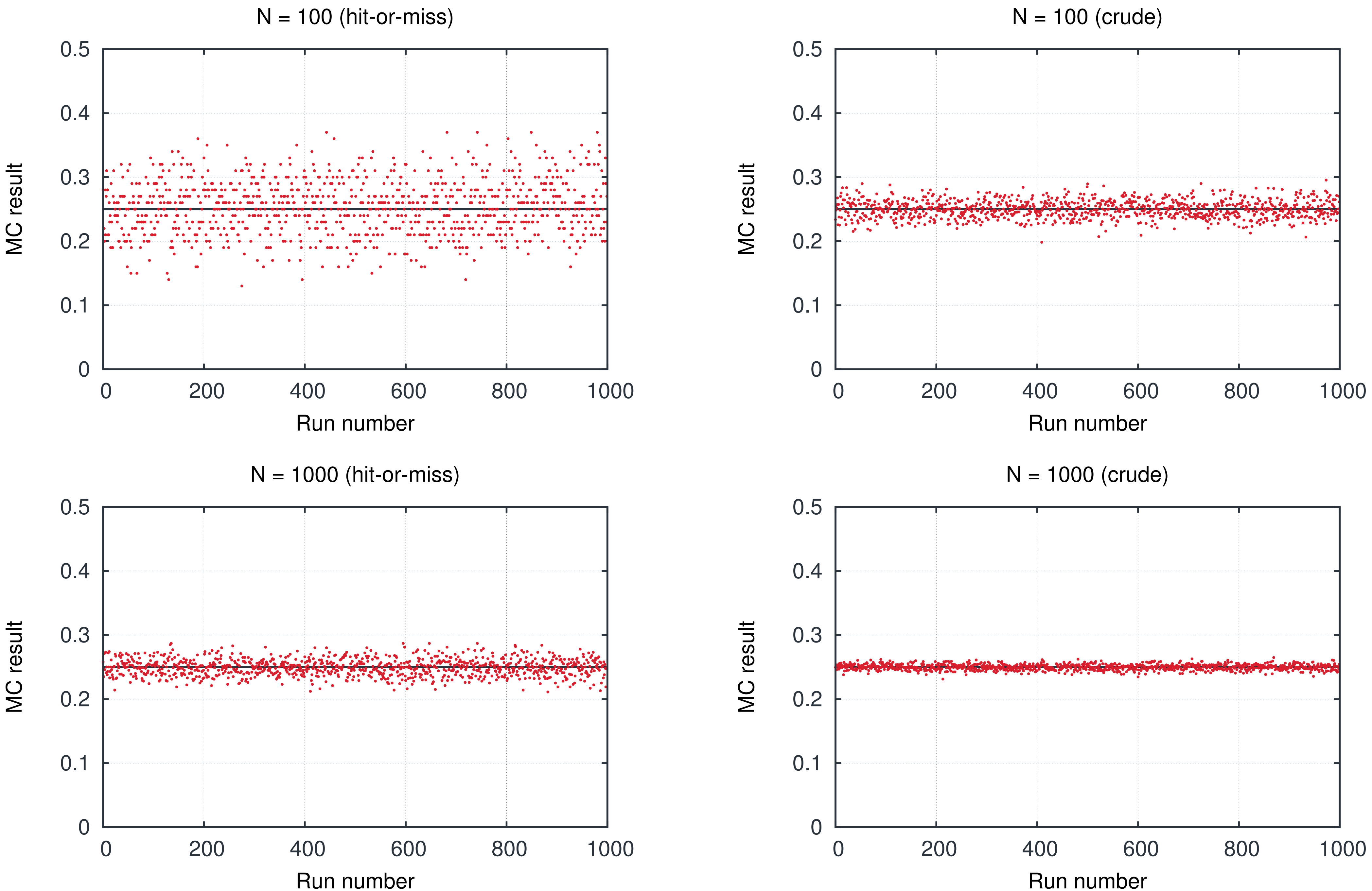
$$\int_a^b f(x)dx \approx \frac{b-a}{N}\sum_{i=1}^{N} f(x_i)$$

  where x_i is a random number from $[a, b]$

- It can be shown that crude method is more accurate than hit-or-miss

- We will skip the math and look at some comparisons




N = 100 (hit-or-miss)
N = 100 (crude)
N = 1000 (hit-or-miss)
N = 1000 (crude)
MC result
Run number
0
0.1
0.2
0.3
0.4
0.5
200
400
600
800
1000

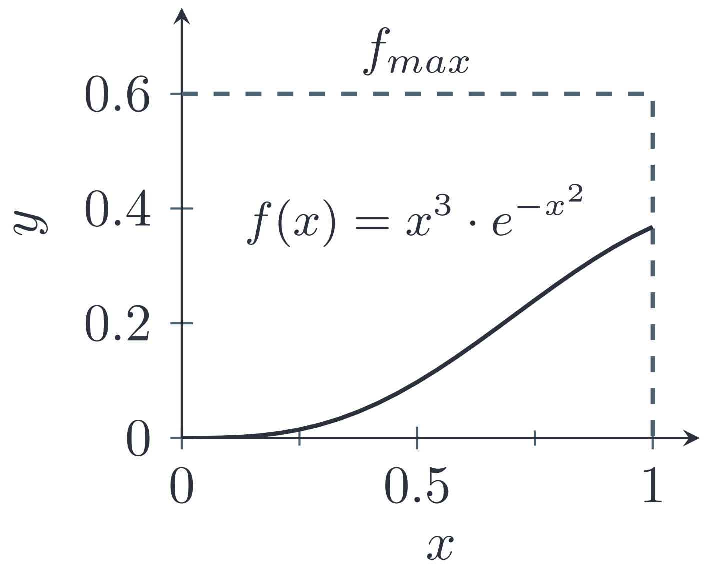
Acceptance-rejection method

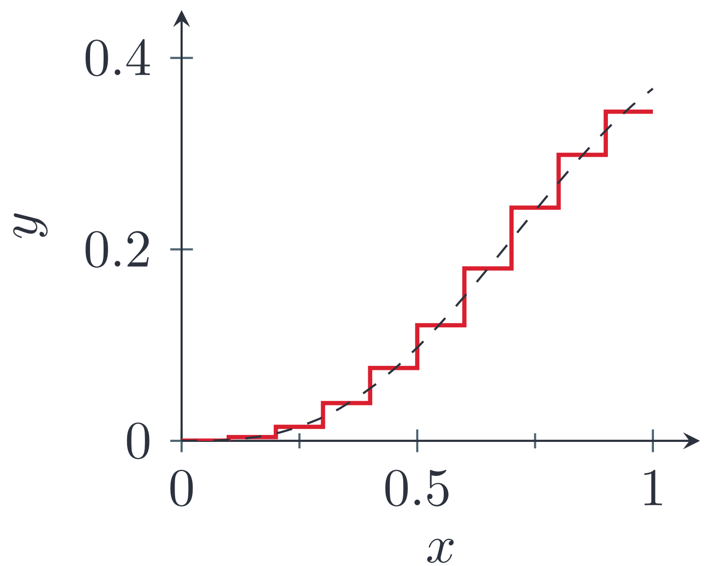
For generating events according to a distribution.

- Evaluate $f_{max} \geq \max(f)$

  Note: $f_{max} > \max(f)$ will affect performance, but the result will be still correct

- Generate random x
- Accept x with $P = \frac{f(x)}{f_{max}}$
  - generate a random u from $[0, f_{max}]$
  - accept if $u < f(x)$

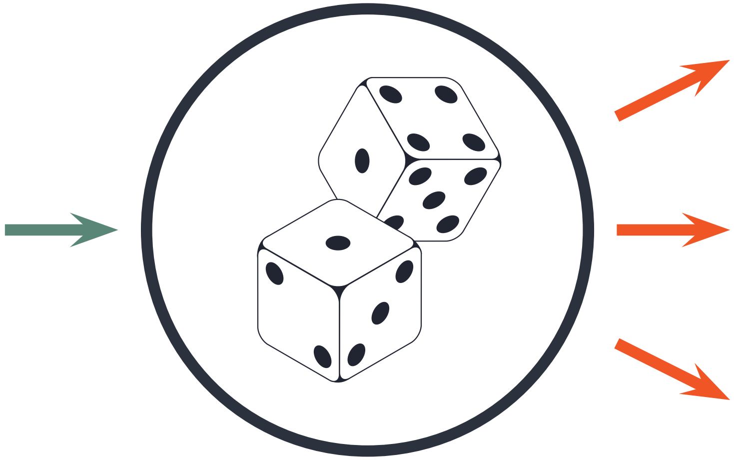




Monte Carlo event generators

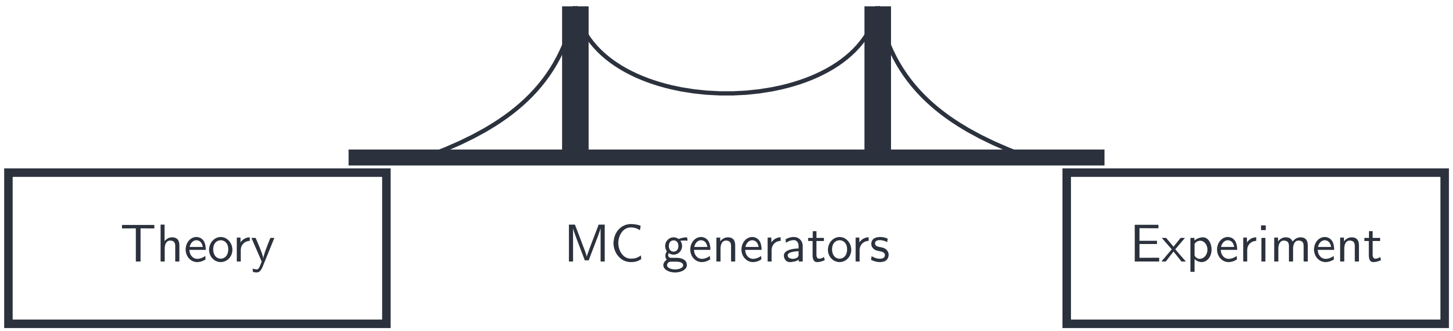
- Monte Carlo generators basically do two things:
  - integrate cross section formulas
  - generate events using accept-reject method

  with many optimization tricks



- Physicists have been using them since ENIAC
- Some common generators used in neutrino community:
  - transport of particles through matter: **Geant4**, **FLUKA**
  - neutrino interactions: **GENIE**, **GIBUU**, **NEUT**, **NUANCE**, **NuWro**

Why do we need them?

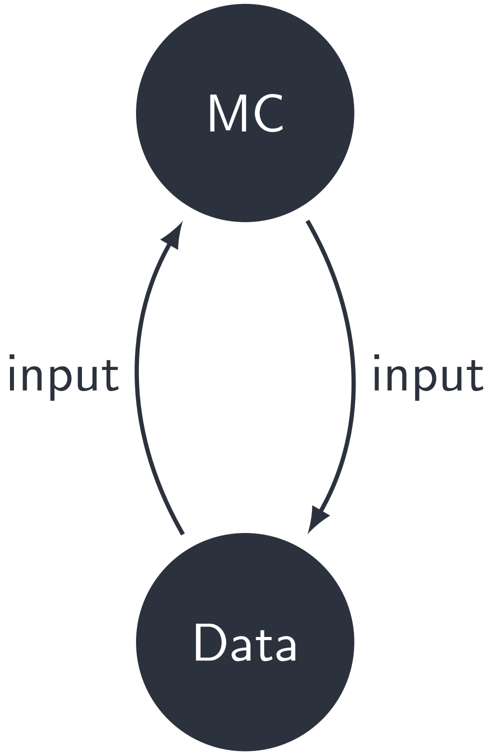


- Monte Carlo event generators connect experiment (what we see) and theory (what we think we should see)
- Any neutrino analysis relies on MC generators
- From neutrino beam simulations, through neutrino interactions, to detector simulations
- Used to evaluate systematic uncertainties, backgrounds, acceptances...

What is the main problem?

"You use Monte Carlo until you understand the problem"
Mark Kac

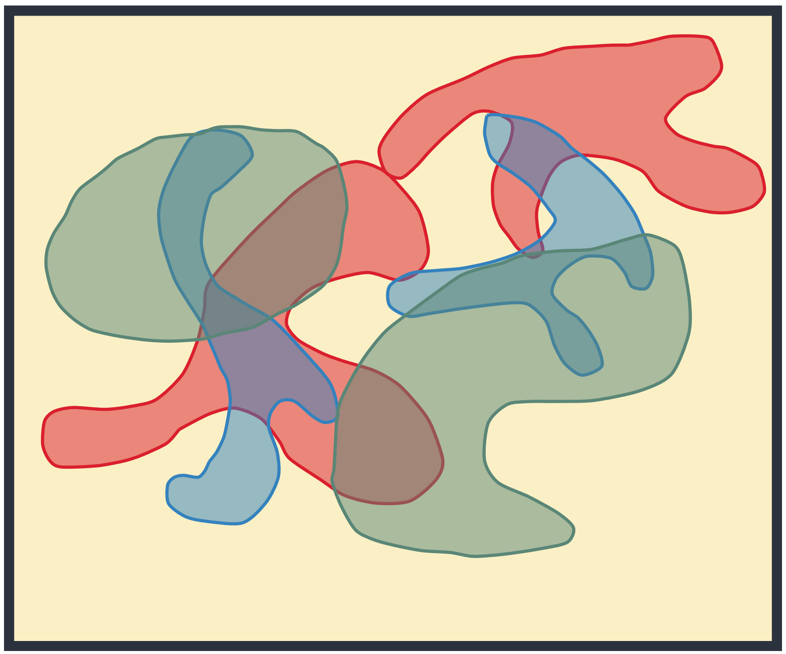
- In perfect world MC generators would contain "pure" theoretical models
- In real world theory does not cover everything
- Neutrino and non-neutrino data are used to tune generators



How to build generator

INGREDIENTS:

Phase space



theory | ν data | other data

educated guesses

RECIPE:

NuWro

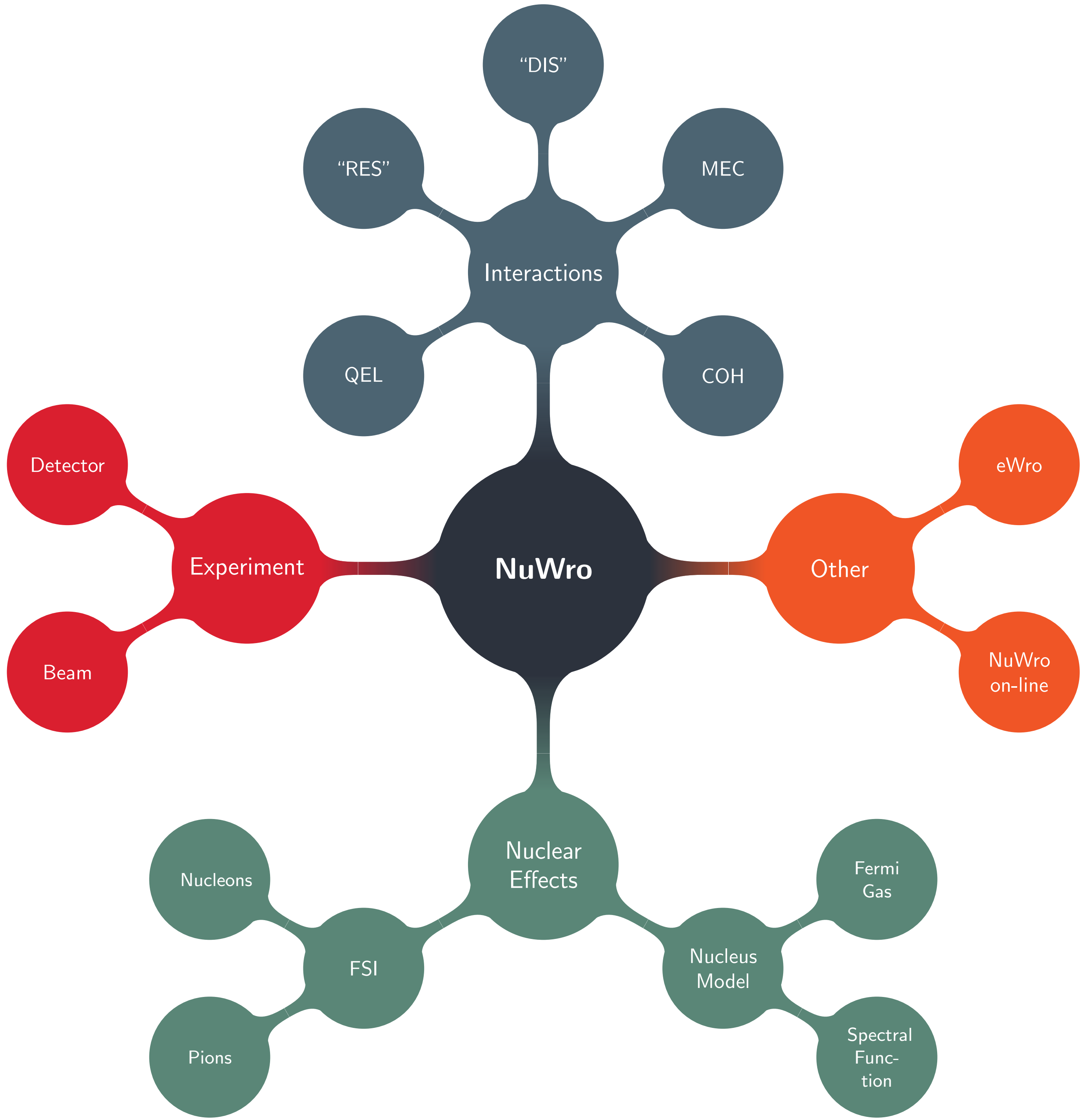
NuWro MC event generator

NuWro

Monte Carlo neutrino event generator

formerly known as WroNG

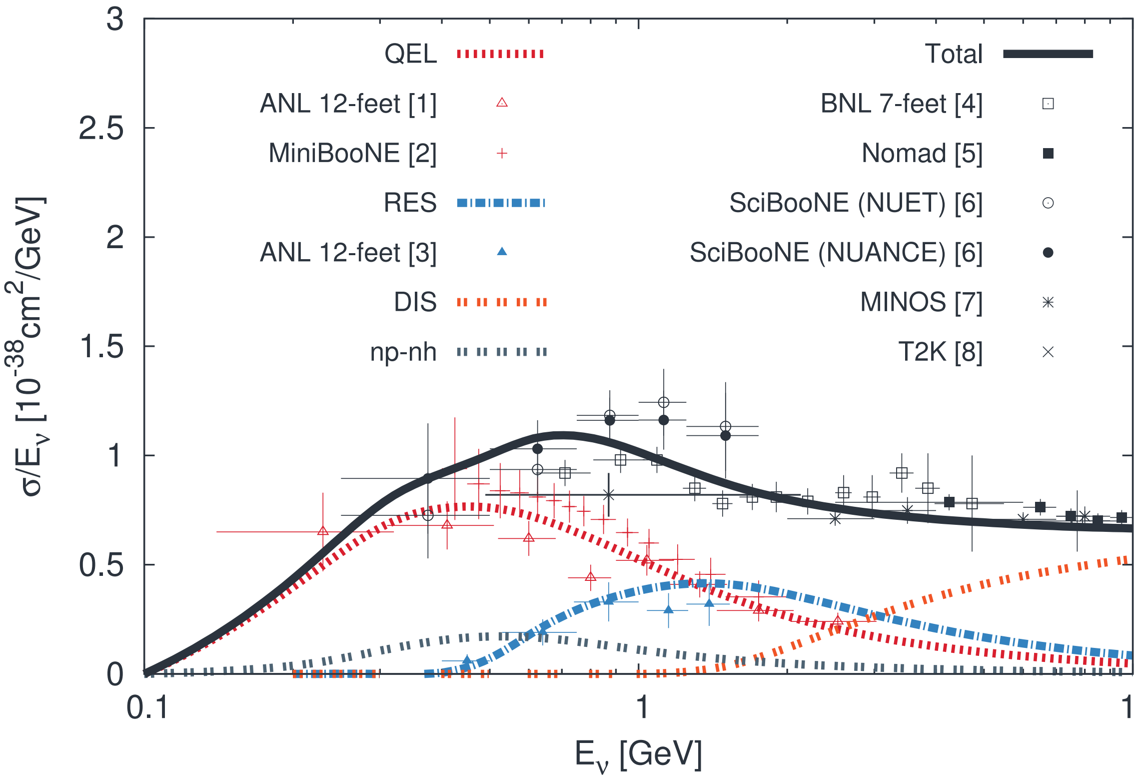
- It has been developed at Wroclaw University since 2006
  - Currenly involved: Jan Sobczyk, Cezary Juszczak, Krzysztof Graczyk, Tomasz Golan, Kajetan Niewczas
  - Significant contribution: Jarosław Nowak, Jakub Żmuda, Artur Kobyliński, Maciej Tabiszewski, Paweł Przewłocki, Patrick Stowell, Luke Pickering
- The authors were encouraged by prof. Danuta Kiełczewska
- The open source code: `https://github.com/nuwro/`


NuWro
Interactions
"DIS"
"RES"
MEC
QEL
COH
Experiment
Detector
Beam
Other
eWro
NuWro on-line
Nuclear Effects
FSI
Nucleons
Pions
Nucleus Model
Fermi Gas
Spectral Func- tion

Implemented dynamics

- All major interaction channels are implemented, for charged and neutral current, covering neutrino energy region from a few hundreds MeV (Impulse Approximation limit) to several TeV:

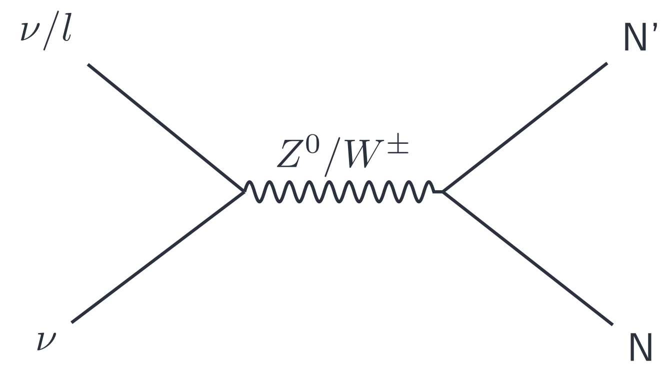
QEL	(quasi-)elastic scattering
RES	pion production through a Δ resonance excitation
DIS	more inelastic processes
COH	coherent pion production
np-nh	two body current contribution

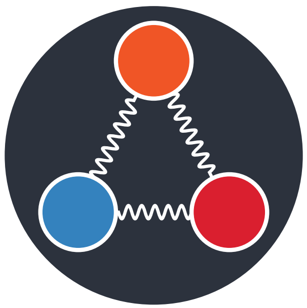


[1] PRD 19 (1979) 2521
[2] PRD 81 (2010) 092005
[3] PRD 16 (1977) 3103
[4] PRD 25 (1982) 617
[5] PLB 660 (2008) 19
[6] PRD 83 (2011) 012005
[7] PRD 81 (2011) 072002
[8] PRD 87 (2013) 092003

(Quasi-)elastic scattering

- Llewellyn-Smith model is used for charged current quasi-elastic scattering
- Not much difference here between generators (but default parameters)



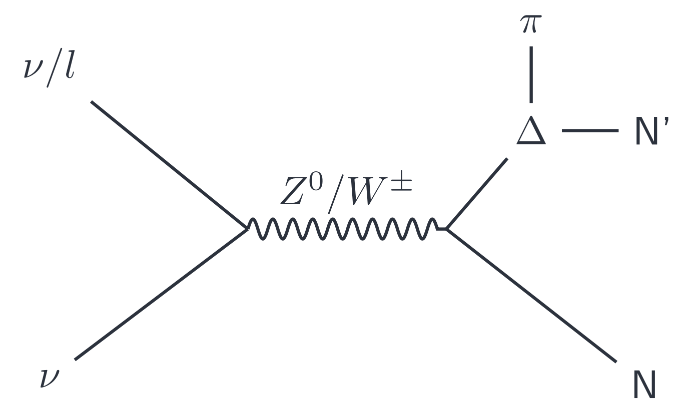


- Nucleon structure is parametrized by form factors

- Vector $\rightarrow$ Conserved Vector Current (CVC)
- Pseudo-scalar $\rightarrow$ Partially Conserved Axial Current (PCAC)
- Axial $\rightarrow$ dipole form with one free parameter (axial mass, M_A)

Resonance pion production

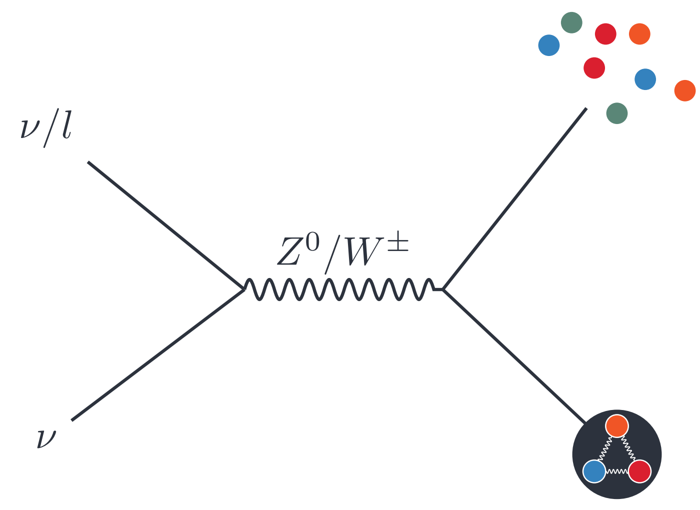
- Most of generators (like NEUT and GENIE) uses Rein-Sehgal model



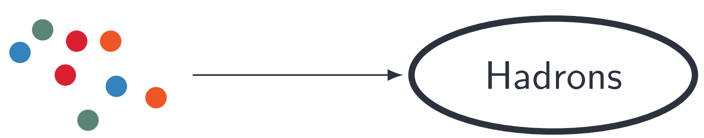
- RS model describes single pion production through baryon resonances below $W = 2$ GeV
- In NuWro Adler-Rarita-Schwinger formalism is used to calculate Δ resonance explicitly
- Non-resonant background is estimated using quark-parton model

Deep inelastic scattering [DIS]

- Quark-parton model is used for deep inelastic scattering
- Bodek-Young modification to the parton distributions at low Q^2 is included by most generators

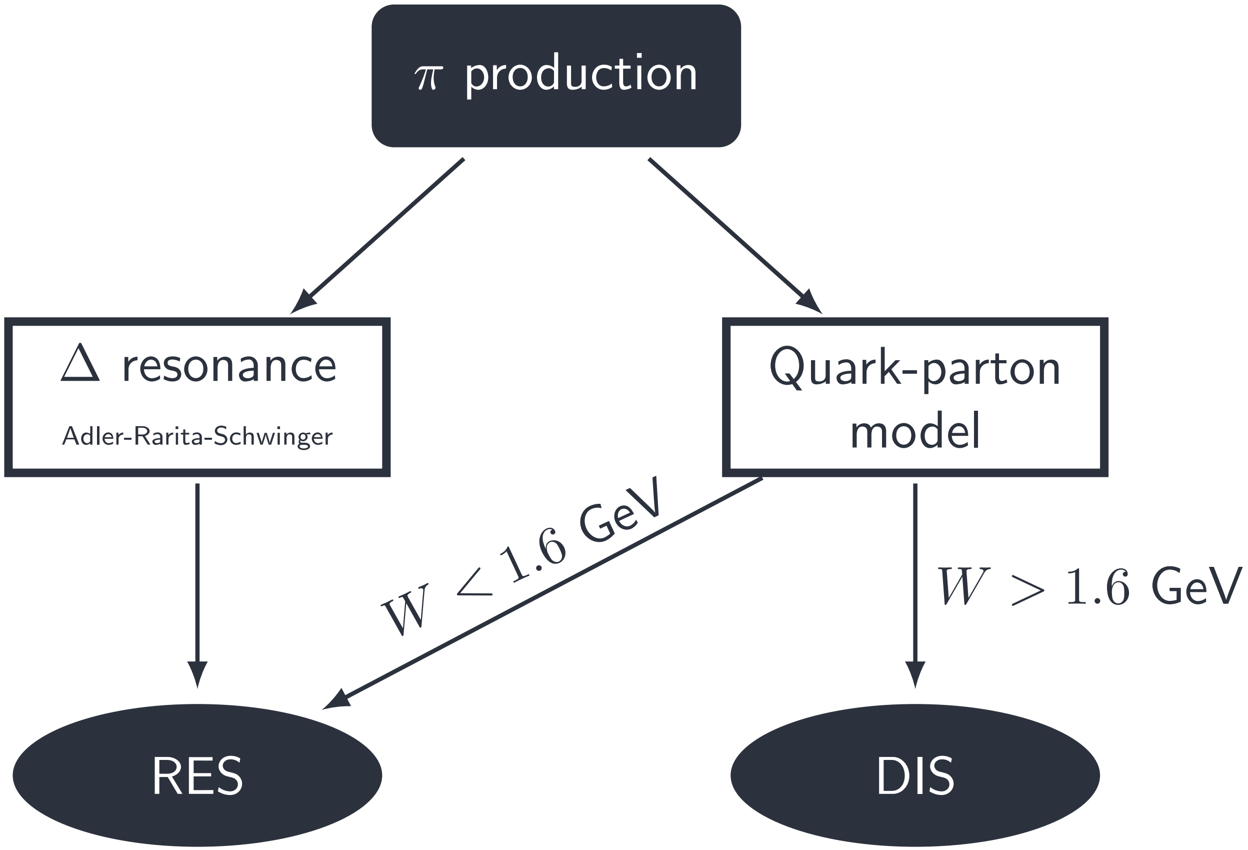


Hadronization



- Hadronization is the process of formation hadrons from quarks
- Pythia is widely used at high invariant masses

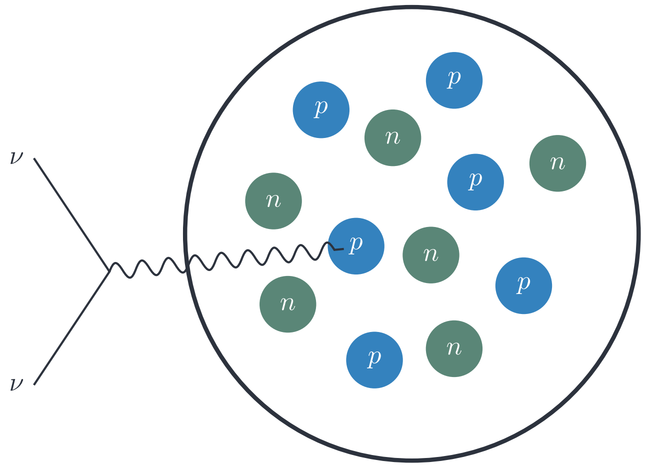
Pion production in NuWro



RES/DIS distinguish is arbitrary for each MC generator!

Impulse approximation

- In impulse approximation neutrino interacts with a single nucleon



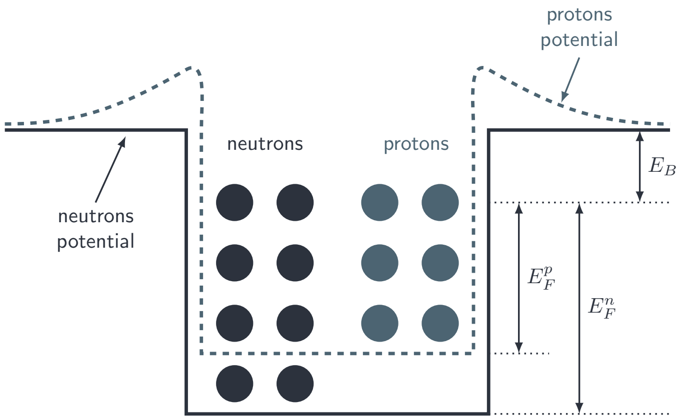
- If $|\vec{q}|$ is low the impact area usually includes many nucleons
- For high $|\vec{q}|$ IA is justified
- Squares of transition matrices are summed up and interference terms are neglected

$$\sigma^A = \sum_{i=1}^{Z} \sigma_p + \sum_{i=1}^{A-Z} \sigma_n$$

- High $|\vec{q}|$ means more than 400 MeV. However, IA is always assumed

Fermi gas

Nucleons move freely within the nuclear volume in constant binding potential.

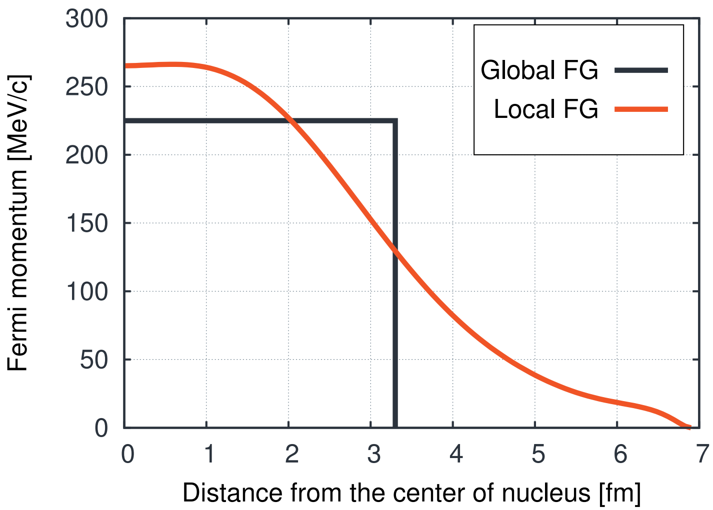


Global Fermi Gas

$$p_F = \frac{\hbar}{r_0}\left(\frac{9\pi N}{4A}\right)^{1/3}$$

Local Fermi Gas

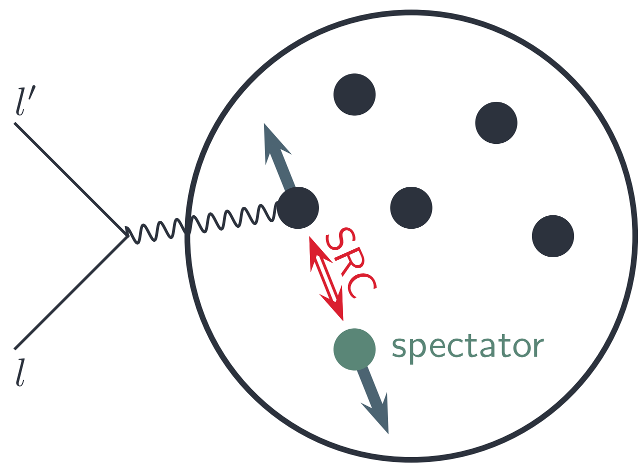
$$p_F(r) = \hbar\left(3\pi^2\rho(r)\frac{N}{A}\right)^{1/3}$$

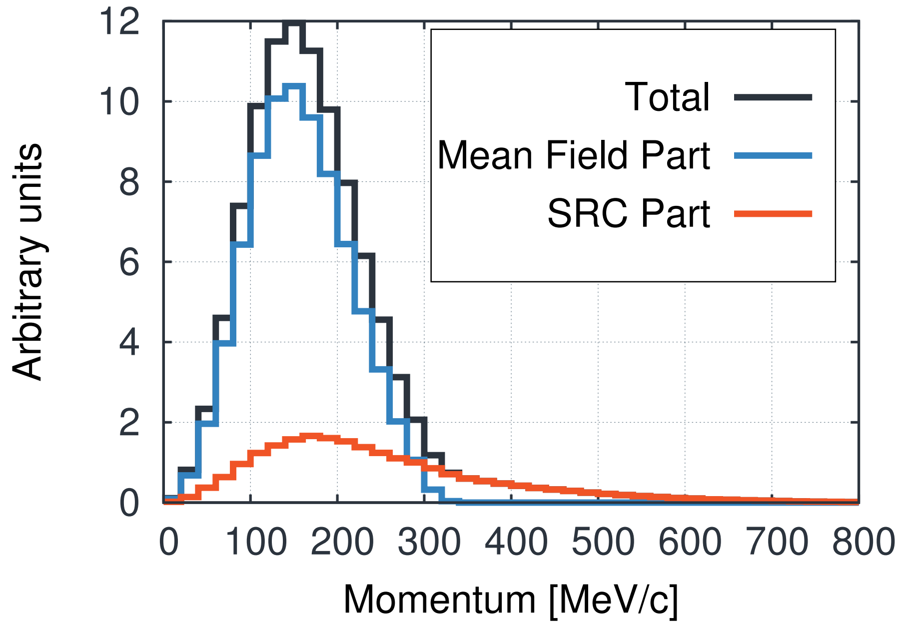


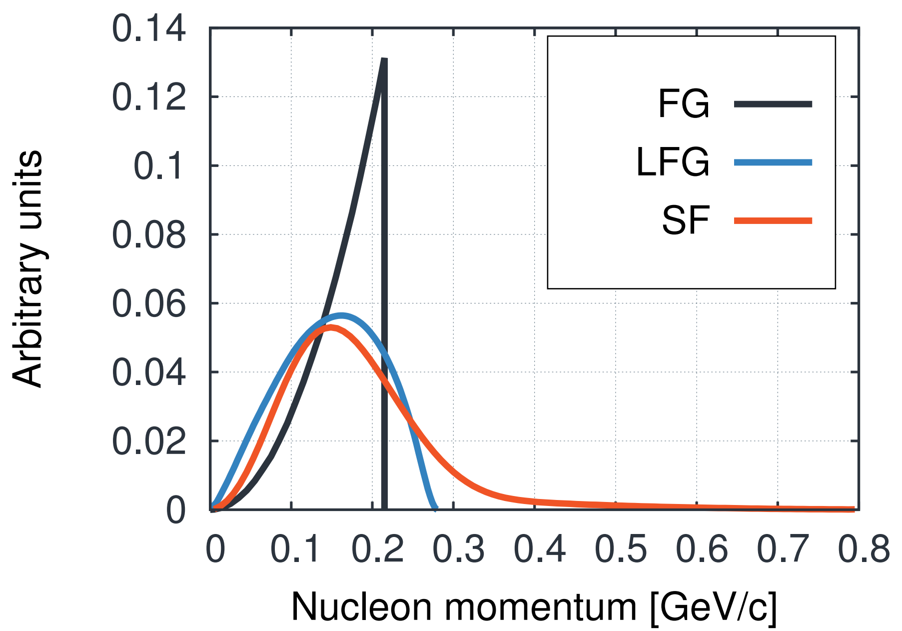
Spectral function

The probability of removing of a nucleon with momentum $\vec{p}$ and leaving residual nucleus with excitation energy E.

$$P(\vec{p}, E) = P_{MF}(\vec{p}, E) + P_{corr}(\vec{p}, E)$$







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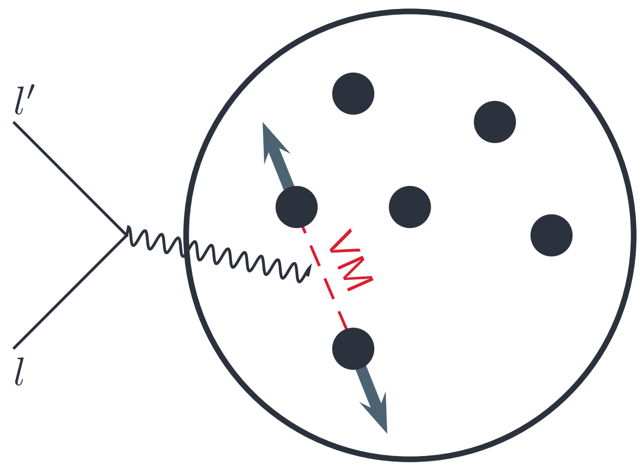
Two-body current interactions

Two Body Current

2 particles - 2 holes (2p-2h)

Meson Exchange Current (MEC)



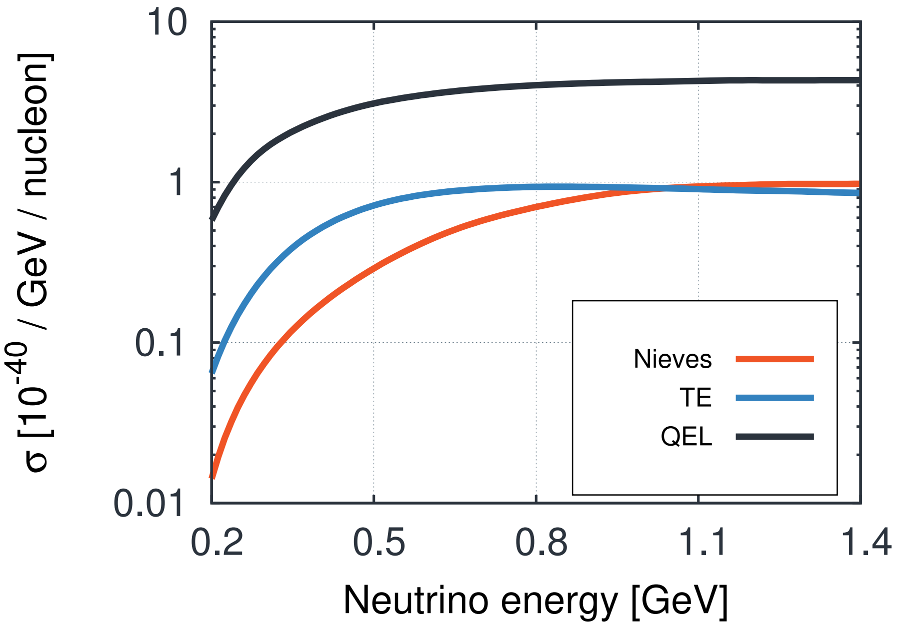
Models in generators

- Nieves model (GENIE, NEUT, NuWro) - CC only
- Transverse Enhancement model (NuWro) - both CC and NC

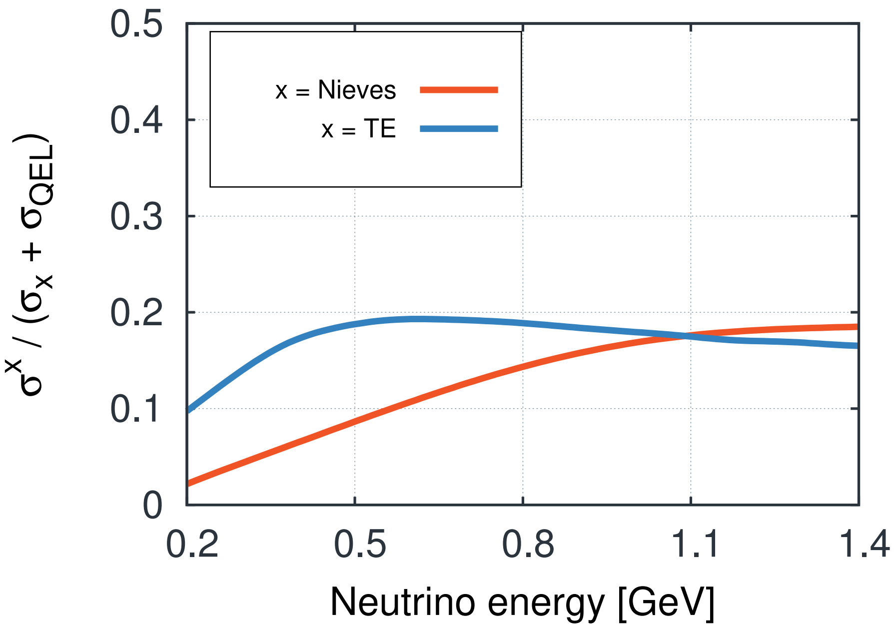
Two-body current interactions

- Nieves model is microscopic calculation
- TE model introduce $2p - 2h$ contribution by modification of the vector magnetic form factors

Total MEC cross section



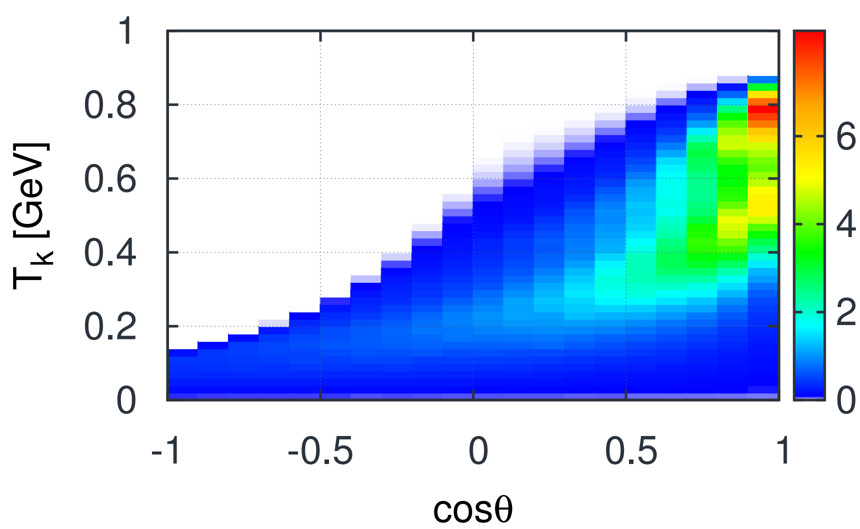
MEC / (QEL + MEC)



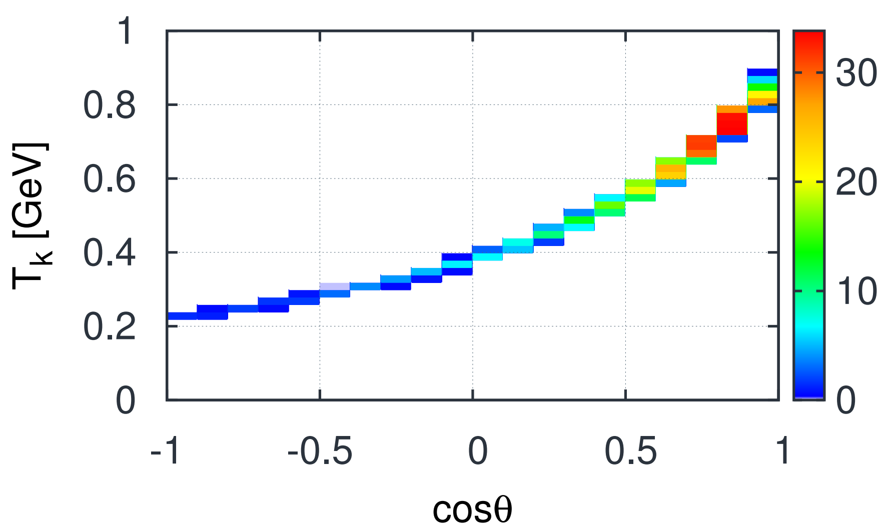
Two-body current interactions

- Both models provide only the inclusive double differential cross section for the final state lepton
- Final nucleons momenta are set isotropically in CMS

Nieves

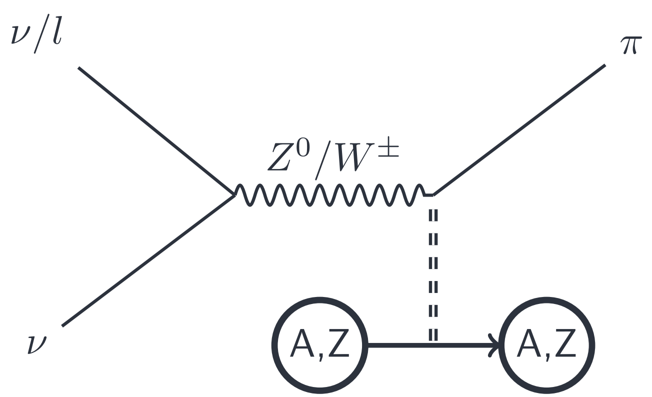


Transverse Enhancement



Coherent pion production

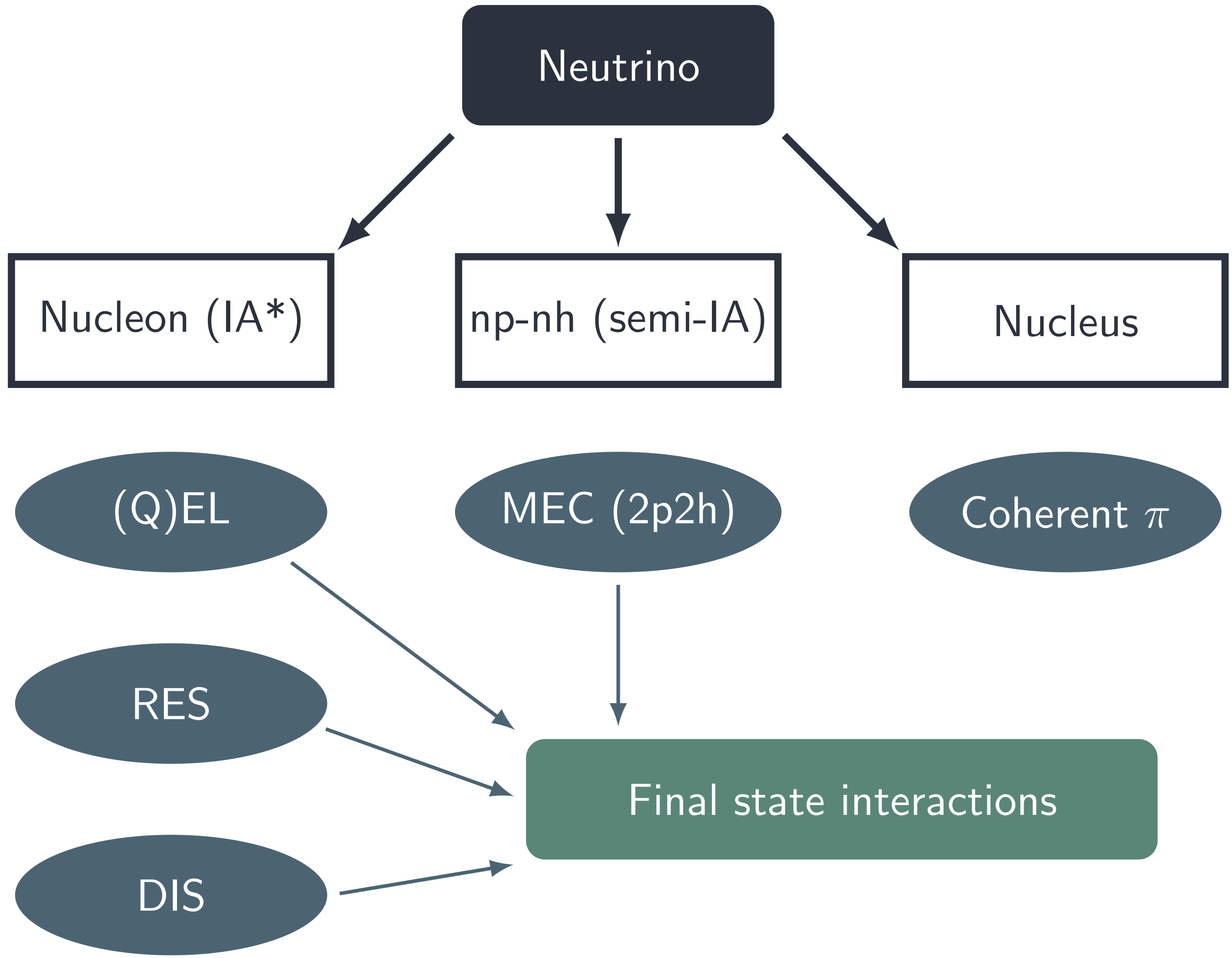
- Rein-Sehgal model is commonly used for coherent pion production
- Note: it is different model than for RES
- Berger-Sehgal model replaces RS (NuWro, GENIE - coming soon)



Comments

- In COH the residual nucleus is left in the same state (not excited)
- The interaction occurs on a whole nucleus - no final state interactions

Neutrino interactions - summary

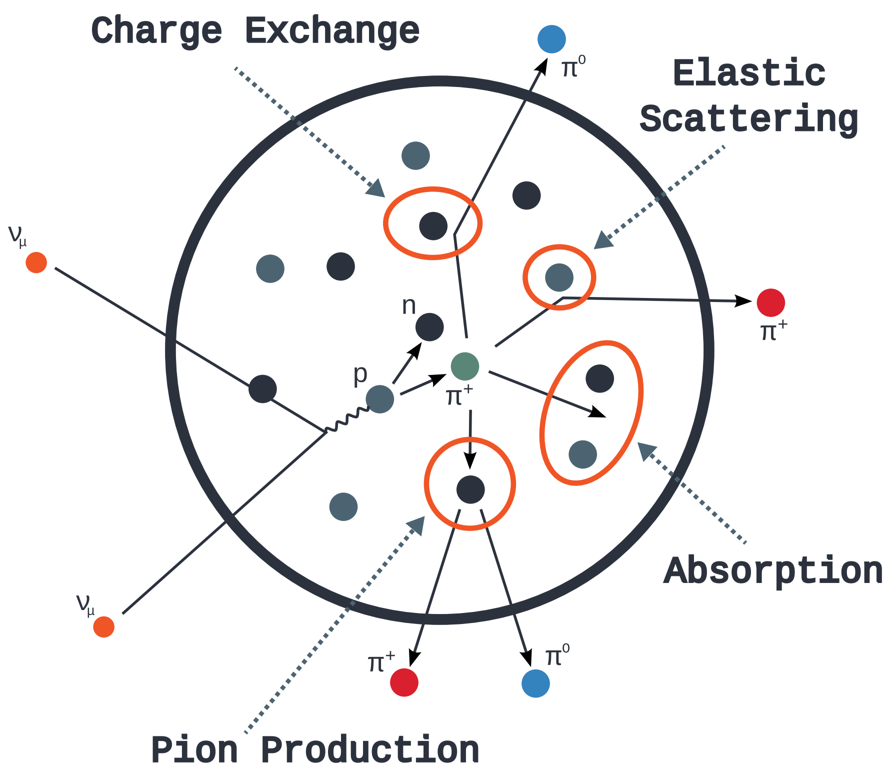


*IA = Impulse Approximation

Final state interactions

Final state interactions

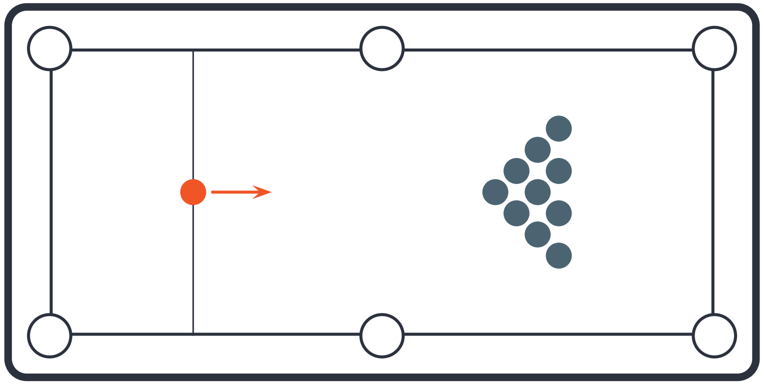
FSI describe the propagation of particles created in a primary neutrino interaction through nucleus



All MC generators (but GIBUU) use intranuclear cascade model

Intranuclear cascade

- In INC model particles are assumed to be classical and move along the straight line.



- The probability of passing a distance λ (small enough to assume constant nuclear density) without any interaction is given by:

$$P(\lambda) = e^{-\lambda/\tilde{\lambda}}$$

$\tilde{\lambda}$ $= (\sigma\rho)^{-1}$ - mean free path

σ - cross section

ρ - nuclear density

Can be easily handled with MC methods.

Landau Pomeranchuk effect

- The concept of formation time was introduced by Landau and Pomeranchuk in the context of electrons passing through a layer of material.
- For high energy electrons they observed less radiated energy then expected.
- The energy radiated in such process is given by:

$$\frac{\mathrm{d}I}{\mathrm{d}^3k} \sim \left| \int_{-\infty}^{\infty} \vec{j}(\vec{x},t) e^{i(\omega t - \vec{k}\cdot\vec{x}(t))} \mathrm{d}^3x \mathrm{d}t \right|^2$$

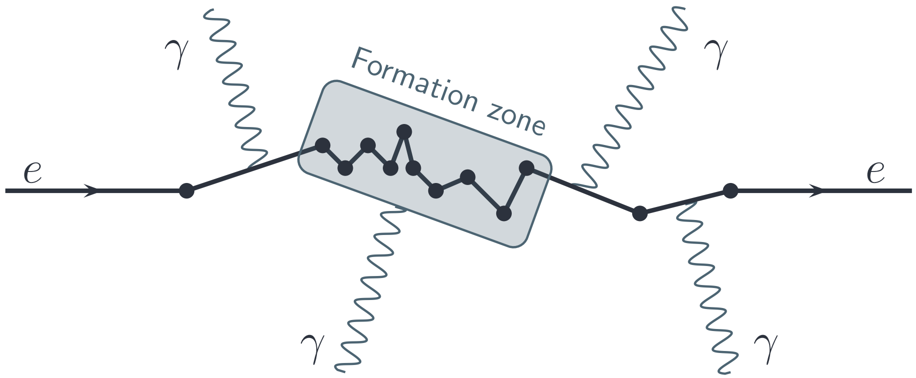
$\vec{x}(t)$ describes the trajectory of the electron.

ω, $\vec{k}$ are energy and momentum of the emitted photon.

Landau Pomeranchuk effect

- Assuming the trajectory to be a series of straight lines (the current density $j \sim \delta^3(\vec{x} - \vec{v}t)$) the radiation integral is:

$$\sim \int_{path} e^{i(\vec{k}\vec{v}-\omega)t}\mathrm{dt}$$



- Formation time is defined as:

$$t_f \equiv \frac{1}{\omega - \vec{k}\vec{v}} = \frac{E}{kp} = \frac{E}{m_e}\frac{1}{\omega_{r.f.}} = \gamma T_{r.f.}$$

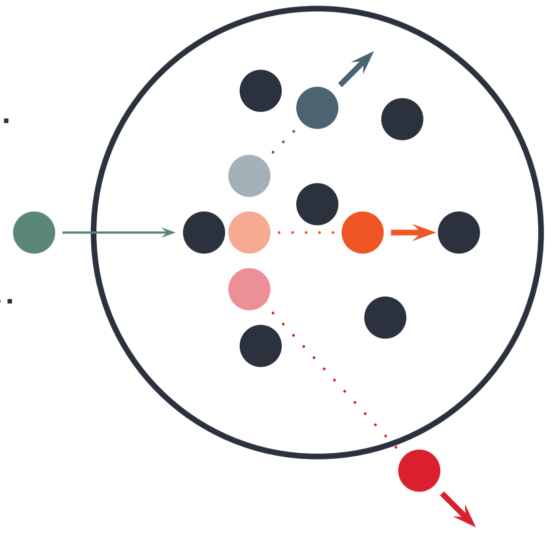
k, p - photon, electron four-momenta
$\omega_{r.f.}$ - photon frequency in the rest frame of the electron

- Formation time can be interpreted as the "birth time" of photon.

- If time between collisions $t >> t_f$, there is no interference and total radiated energy is just the average emitted in one collision multiplied by the number of collisions.

- If $t << t_f$, a photon is produced coherently over entire length of formation zone, which reduces the bremsstrahlung.

Formation time in INC



- One may expect a similar effect in hadron-nucleus scattering.
- In terms of INC it means that particles produced in primary vertex travel some distance, before they can interact.
- There are several parametrization used in MC generators
- Ranft parametrization:

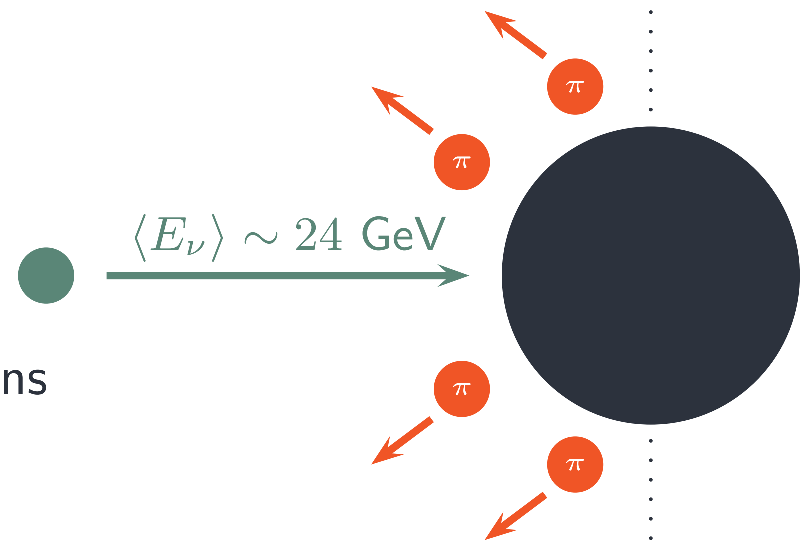
$$t_f = \tau_0 \frac{E \cdot M}{\mu_T^2}$$

where E, M - nucleon energy and mass, $\mu_T^2 = M^2 + p_T^2$ - transverse mass

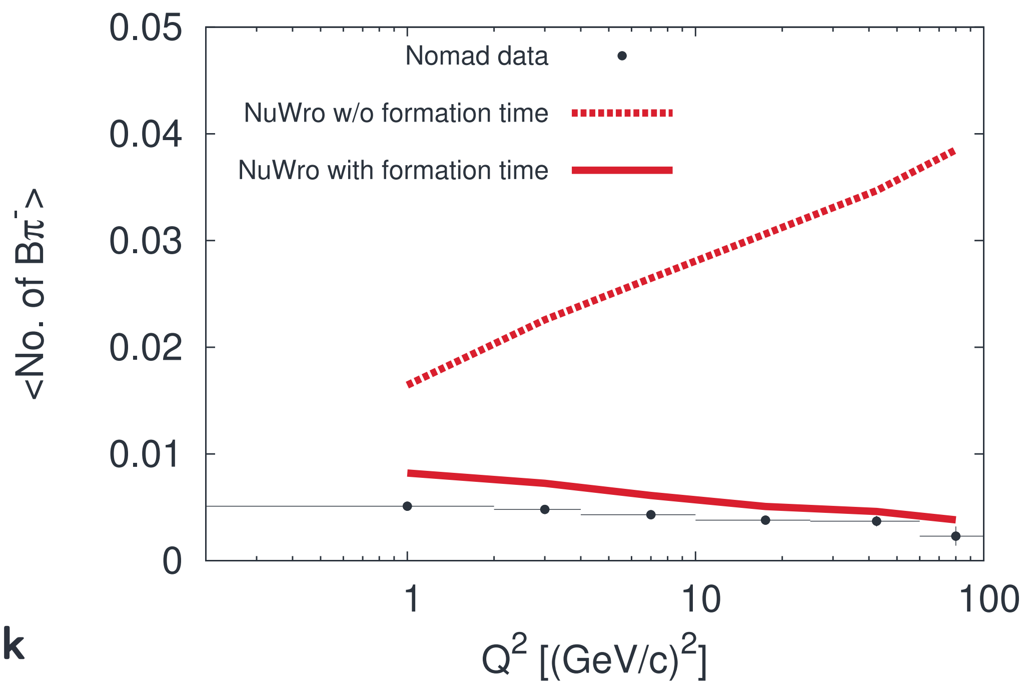
- SKAT parametrization (similar but with $p_T = 0$)
- NEUT and GENIE use SKAT parametrization
- NuWro uses Ranft parametrization for DIS and a model based on Δ lifetime for RES

Comparison with NOMAD data

- Nomad data from Nucl. Phys. B609 (2001) 255.
- The average number of backward going negative pions with the momentum from 350 to 800 MeV/c.

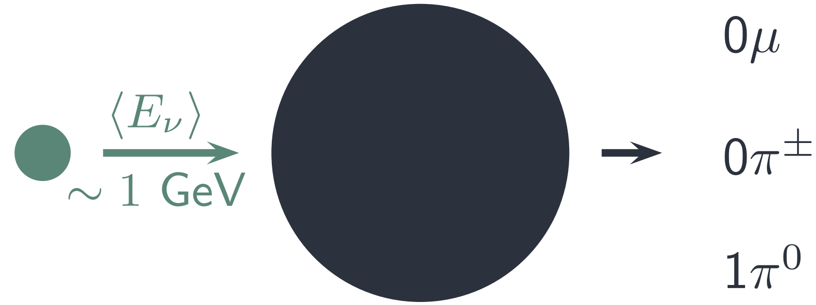


- In this neutrino energy range $B\pi^-$ are an effect of FSI.
- The observable is very sensitive to formation time effect.



Golan, Juszczak, Sobczyk PRC86 (2012) 015505

Comparison with data for NC π^0 production



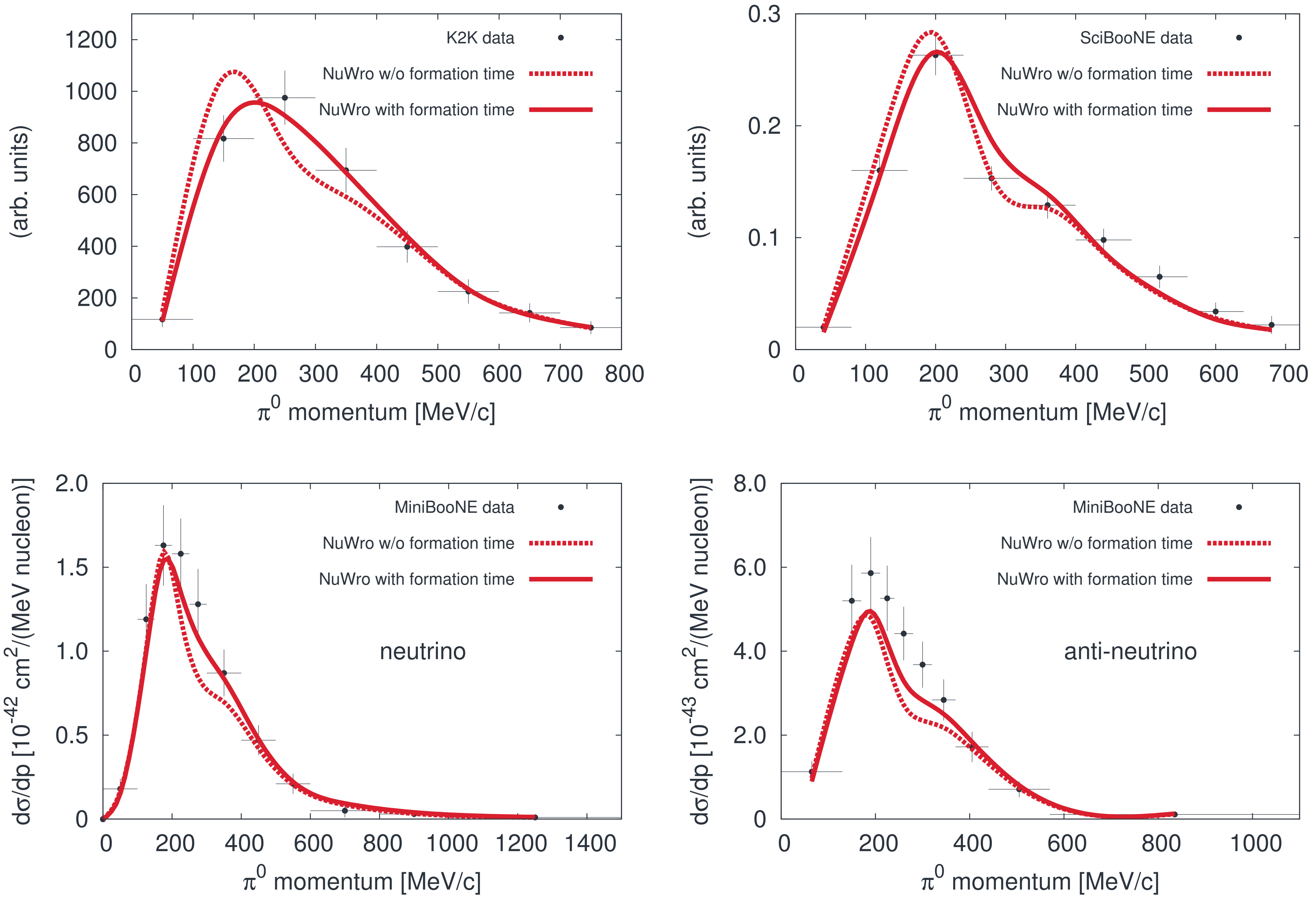
- The cross section for π^0 production through neutral current is measured by K2K [1], MiniBooNE [2] and SciBooNE [3] experiments.
- The signal is defined as: no charged leptons nor charged pions and one neutral pion (or at least one for SciBooNE) in the final state.
- The result depends on primary vertex and FSI, as π can be:
  - produced in primary vertex;
  - produced in FSI;
  - affected by charge exchange;
  - absorbed.

[1] Phys. Lett. B619 (2005) 255

[2] Phys. Rev. D81 (2010) 013005

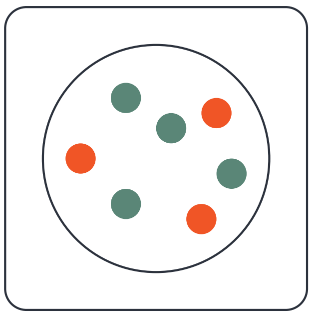
[3] Phys. Rev. D81 (2009) 033004

Comparison with data for NC π^0 production

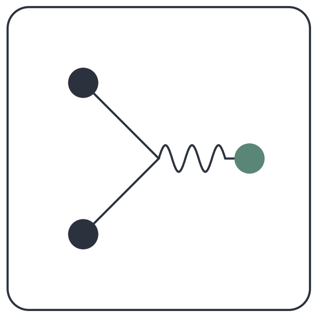


Neutrino-nucleus interactions

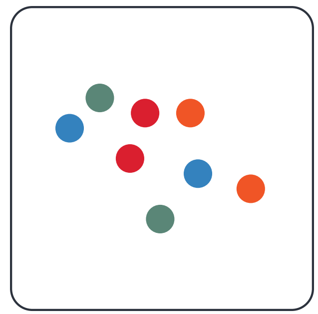
For all channels (but coherent) neutrino interactions are factorized in the following way



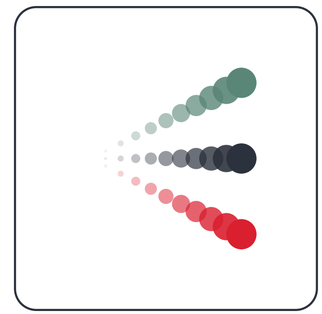
IA



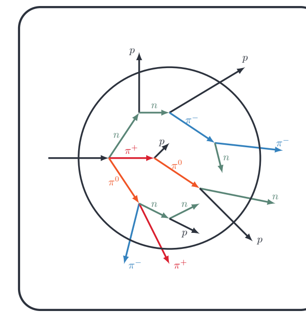
νN



hadronization



formation time



FSI

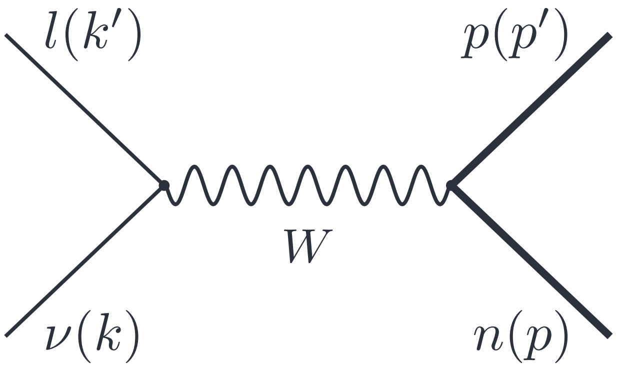
- Is the physics really factorized this way?
- This factorization is common for all generators
- However, some pieces are done in different way

The analysis of MB NCEL data

(Quasi-)elastic neutrino-nucleon scattering

- For (quasi-)elastic neutrino scattering off nucleon the cross section is given by:

$$\sigma \sim |j_\mu h^\mu|^2$$



Quasi-elastic scattering

$$j_\mu = \bar{u}(k')\gamma^\mu (1 - \gamma_5) u(k) \rightarrow \text{lepton current}$$

$$h_\mu = \bar{u}(p')\Gamma^\mu u(p) \rightarrow \text{hadron current}$$

- Leptonic vertex can be calculated from the basis.
- However, due to the complex structure of nucleon, hadronic vertex needs a phenomenological input.
- Γ^μ can be parametrized by the functions of Q^2, called form factors.

Form factors

- Hadronic vertex can be expressed in terms of form factors:

$$\Gamma^{\mu}_{NC,p(n)} = \gamma^{\mu} F_1^{NC,p(n)}(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M} F_2^{NC,p(n)}(Q^2) - \gamma^{\mu}\gamma_5 G_A^{NC,p(n)}(Q^2)$$

- Vector form factors are expressed by electromagnetic form factors *(Conserved Vector Current - CVC)*:

$$F_{1,2}^{NC,p(n)}(Q^2) = \pm\frac{1}{2}\left(F^{p}_{1,2}(Q^2) - F^{n}_{1,2}(Q^2)\right) - 2\sin^2\theta_W F_{1,2}^{p(n)}(Q^2) - \frac{1}{2}F^{s}_{1,2}(Q^2)$$

- Axial form factor is assumed to have a dipole form:

axial mass

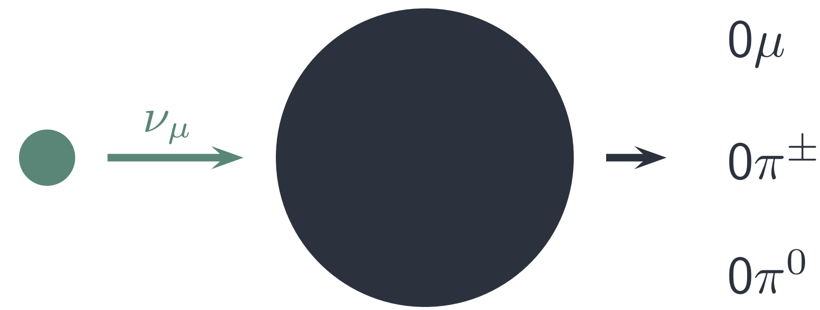
$$G_A^{NC,p(n)}(Q^2) = \pm\frac{1}{2}G_A(Q^2) - \frac{1}{2}G^s_A(Q^2) = (\pm g_A - g^s_A)\left(1 + Q^2/{M_A}^2\right)^{-2}$$

strangeness

different sign for proton/neutron
g^s_A sensitive to $\sigma(\nu p)/\sigma(\nu n)$

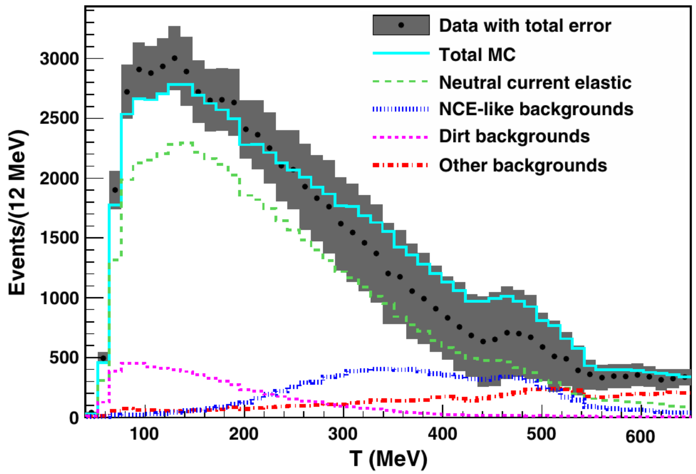
MiniBoonE data for NCEL

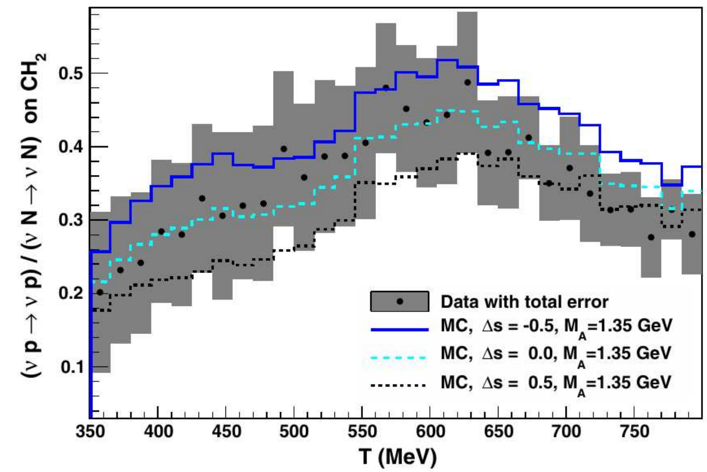
- The cross section for NCEL is measured by MiniBooNE - PRD82 (2010) 092005.



- The signal is defined as: no charged leptons nor any kind of pions in the final state.
- The detector measures the Cherenkov and scintillation light.
- Protons with the kinetic energy of order tens MeV are detectable.
- Neutrons are visible as an effect of interactions with protons (inside or outside the nucleus).
- The M_A and g_A^s is extracted from the measurement.

MiniBoonE data for NCEL





T stands for the total reconstructed energy of all nucleons in the final state.

- Here assume $g_A^s = 0$.
- Best fit for:

$$M_A = 1.39 \pm 0.11 \text{ GeV}$$

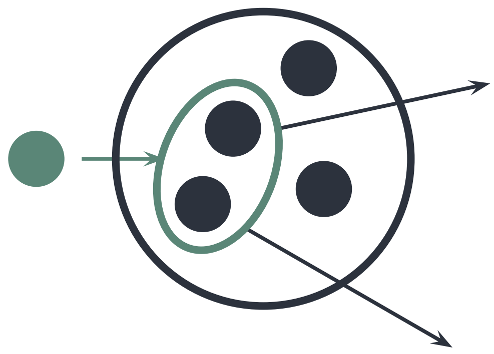
- Inconsistency with older measurements $M_A \sim 1$ GeV.

- Here assume $M_A = 1.35$ GeV.
- Best fit for:

$$g_A^s = 0.08 \pm 0.26$$

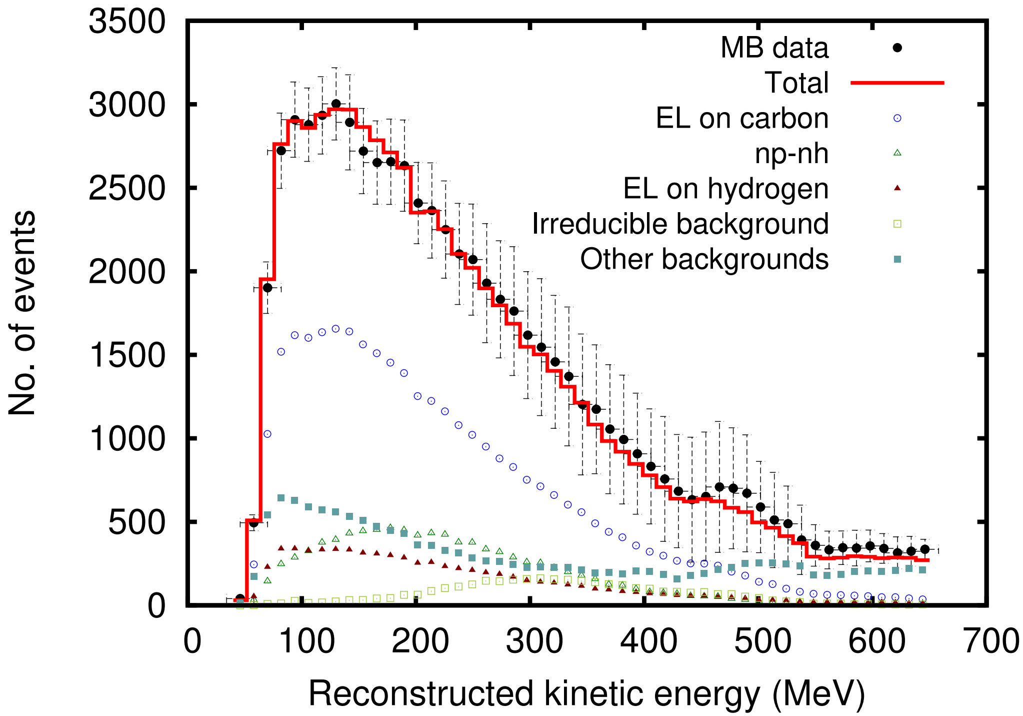
- "$\nu p \to \nu p$" stands for events with proton above Cherenkov treshold.

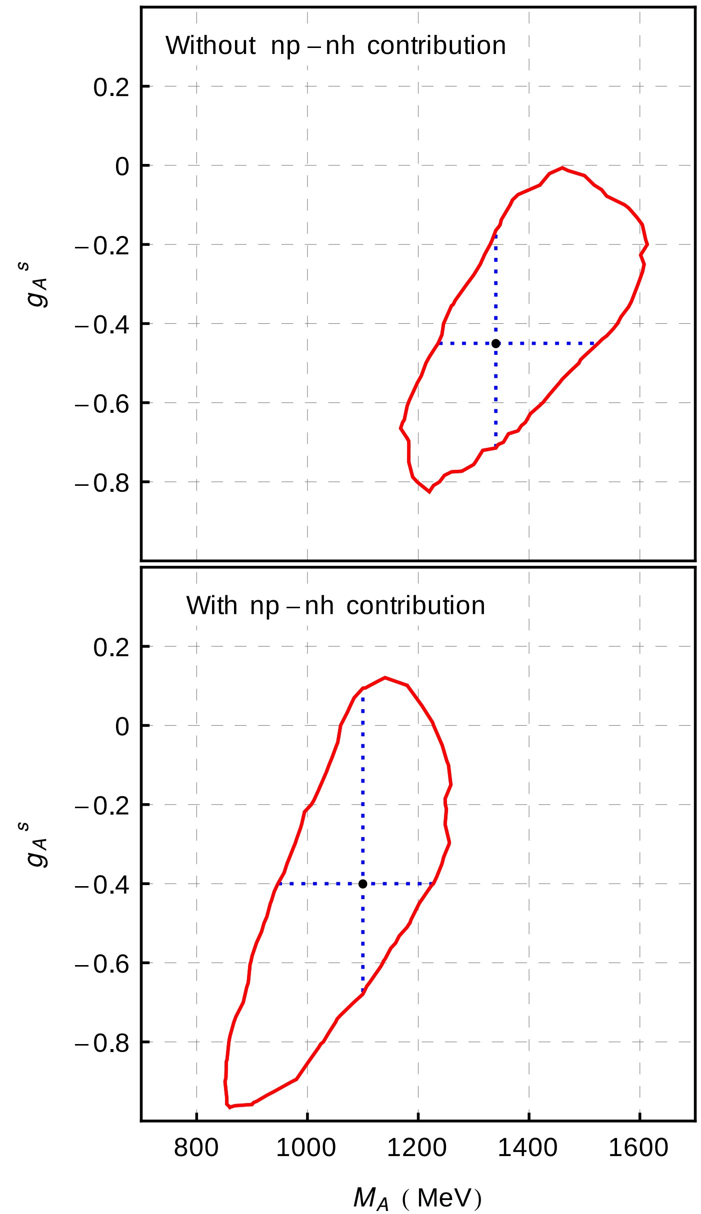
Two body current (or $np-nh$) contribution



- The $np-nh$ interactions occur on at least two nucleons.
- What is the isospin correlation?
- There are no new particles created, so the final state looks the same as in elastic scattering.
- $np-nh$ is not taken into account in MiniBooNE analysis, which may cause the discrepancy with previous measurements of axial mass.
- There are two theoretical models of $np-nh$ (IFIC, Lyon), which take care about proper energy transfer distribution. Unfortunately, both are available only for CC channel.
- The phenomenological Transverse Enhancement (TE) model is used in the calculation. The $np-nh$ contribution is introduced by the modification of the vector magnetic form factors. Lepton kinematics is the same as for elastic scattering.
- The goal is to repeat the analysis with the inclusion if the $np-nh$ contribution.

Simultaneous extraction of M_A and g_A^s





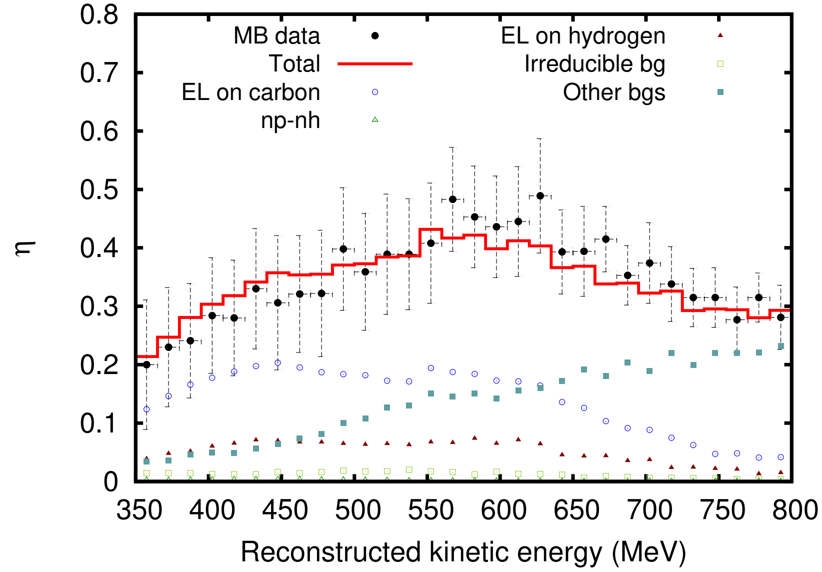
	w/o $np - nh$	with $np - nh$
M_A [GeV]	$1.34^{+0.18}_{-0.10}$	$1.10^{+0.13}_{-0.15}$
g_A^s	$-0.5^{+0.2}_{-0.2}$	$-0.4^{+0.5}_{-0.3}$

Golan, Graczyk, Juszczak, Sobczyk PRC86 (2013) 024612

made in Mathematica

The ratio issue

- The plot is made using best fit values from the last slide.
- It turns out that the ratio is very sensitive on the energy transfer distribution (No. of protons above threshold).



- The Transverse Enhancement does not take care properly of lepton kinematics, which affects the energy distribution of final state nucleons. It is not a proper model to analyze this data.
- This data, however, has a potential to discriminate between IFIC and Lyon models...
- ... when they appear for neutral current channel.

Summary

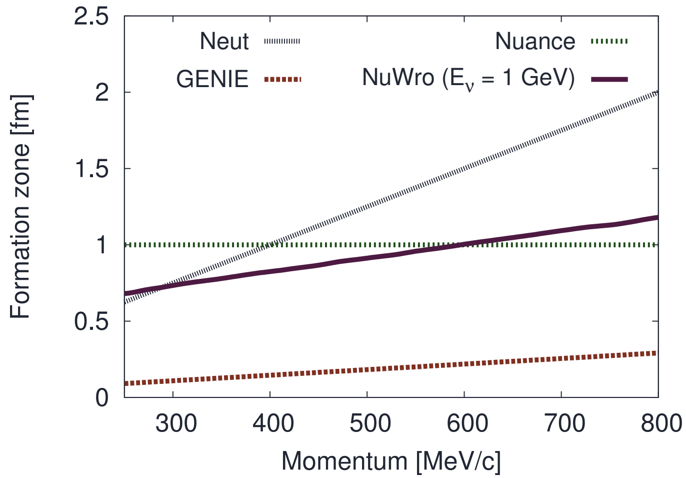
- MC generators are irreplaceable tools in high-energy physics
- People use them before experiment exists (feasibility studies, requirements ...)
- And during data analysis (systematics uncertainties, backgrounds ...)
- NuWro contains all major neutrino-nucleon interaction channels, reliable FSI model and realistic nucleus description - it is a ready tool to use in the investigation of neutrino data

Thank you for the attention!

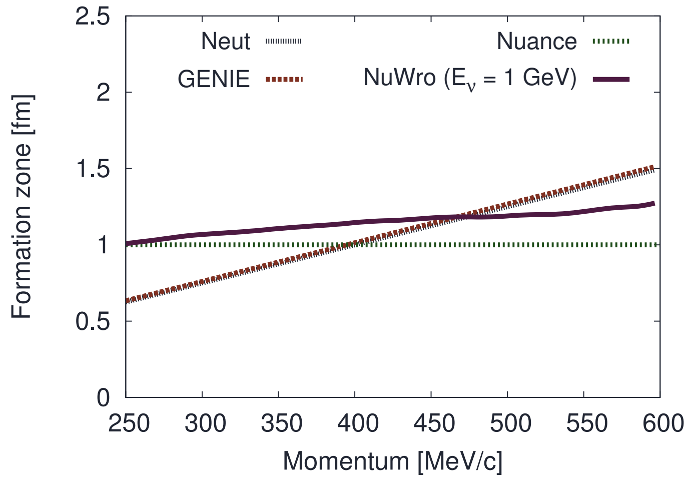
Backup slides

Formation time in MC generators

Formation time for nucleons



Formation time for pions



- NUANCE uses constant formation length $x = 1$ fm.
- NEUT uses SKAT parametrization ($\mu^2 = 0.08 \pm 0.04$ GeV^2):

$$x = \frac{|\vec{p}|}{\mu^2}$$

- GENIE uses Rantf parametrization (assuming transverse momentum $p_T = 0$):

$$x = \tau_0 \frac{E}{M} = \tau_0 \gamma$$

Form factors

$$\Gamma^{\mu}_{CC}(q) = \gamma^{\mu} F_1^V(Q^2) + \frac{i\sigma^{\mu\nu} q_{\nu}}{2M} F_2^V(Q^2) - \gamma^{\mu}\gamma_5 G_A(Q^2) - q^{\mu}\gamma_5 \frac{F_P(Q^2)}{2M}$$

- Vector form factors are expressed by electromagnetic form factors *(Conserved Vector Current - CVC)*:

$$F_{1,2}^V(Q^2) = F_{1,2}^p(Q^2) - F_{1,2}^n(Q^2)$$

- Axial form factor is assumed to have a dipole form:

$$G_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^2)^2}$$

- Pseudoscalar form factor is related to the axial one *(Partially Conserved Axial Current - PCAC)*:

$$F_P(Q^2) = \frac{4M^2}{m_\pi^2 + Q^2} G_A(Q^2)$$

Form factors

$$\Gamma^{\mu}_{NC,p(n)} = \gamma^{\mu} F_1^{NC,p(n)}(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M} F_2^{NC,p(n)}(Q^2) - \gamma^{\mu}\gamma_5 G_A^{NC,p(n)}(Q^2)$$

- Vector form factors are expressed by electromagnetic form factors *(Conserved Vector Current - CVC)*:

$$F_{1,2}^{NC,p(n)}(Q^2) = \pm\frac{1}{2}\left(F^p_{1,2}(Q^2) - F^n_{1,2}(Q^2)\right) - 2\sin^2\theta_W F_{1,2}^{p(n)}(Q^2) - \frac{1}{2}F^s_{1,2}(Q^2)$$

- Axial form factor is assumed to have a dipole form:

$$G_A^{NC,p(n)}(Q^2) = \pm\frac{1}{2}G_A(Q^2) - \frac{1}{2}G_A^s(Q^2)$$

- The axial strange form factor is assumed to have a dipole form:

$$G_A^s(Q^2) = \frac{g_A^s}{\left(1 + Q^2/M_A^2\right)^2}$$

Transverse Enhancement model

- In the Transverse Enhancement model the two body current contribution is introduced by the modification of the vector magnetic form factors:

$$G_M^{p,n} \to \tilde{G}_M^{p,n} = \sqrt{1 + AQ^2 \exp\left(-\frac{Q^2}{B}\right)} G_M^{p,n}(Q^2)$$

- A, B are established from the electron data.
- The cross section for $np - nh$ can be obtained by taking the difference:

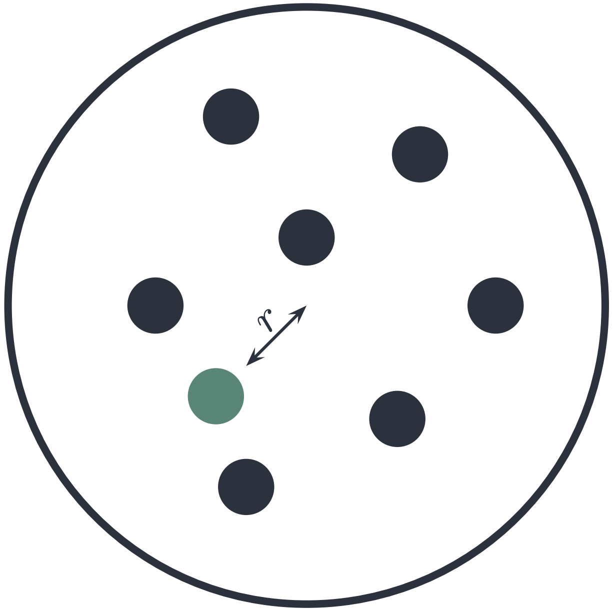
$$\frac{\mathrm{d}^2\sigma^{np-nh}}{\mathrm{d}q\mathrm{d}\omega} \equiv \frac{\mathrm{d}^2\sigma^{QEL}}{\mathrm{d}q\mathrm{d}\omega}(\tilde{G}_M^{p,n}) - \frac{\mathrm{d}^2\sigma^{QEL}}{\mathrm{d}q\mathrm{d}\omega}(G_M^{p,n})$$

- The disadvantage of the model is lepton kinematics (“copied” from the QEL scattering).

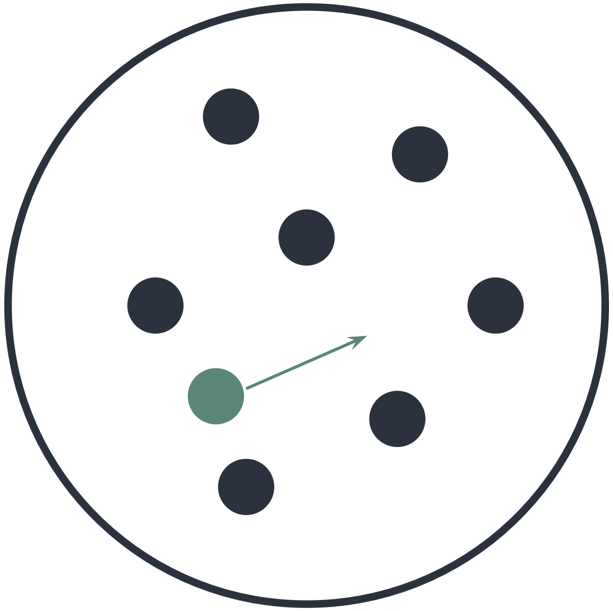
The algorithm for intranuclear cascade

Calculate:

$$\tilde{\lambda}(r) = [\sigma\rho(r)]^{-1}$$



The algorithm for intranuclear cascade



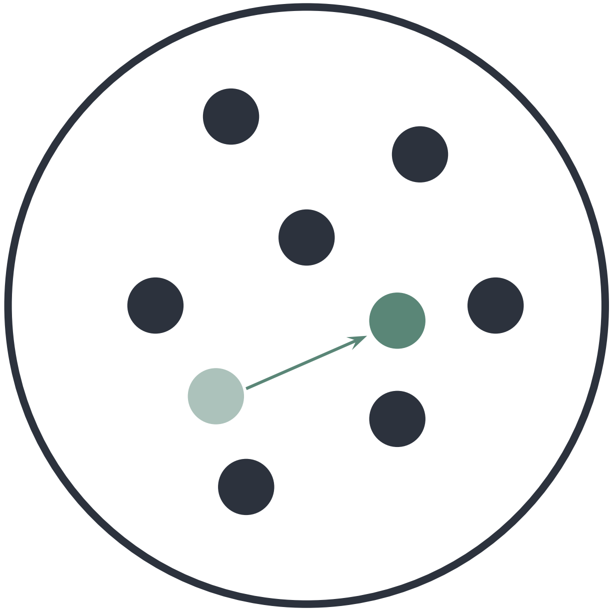
Calculate:

$\tilde{\lambda}(r) = [\sigma\rho(r)]^{-1}$

$\lambda = \tilde{\lambda} \cdot \ln(P)$

$P = \text{rand}[0, 1]$

The algorithm for intranuclear cascade



Calculate:

$\tilde{\lambda}(r) = [\sigma\rho(r)]^{-1}$

→

$\lambda = \tilde{\lambda} \cdot \ln(P)$

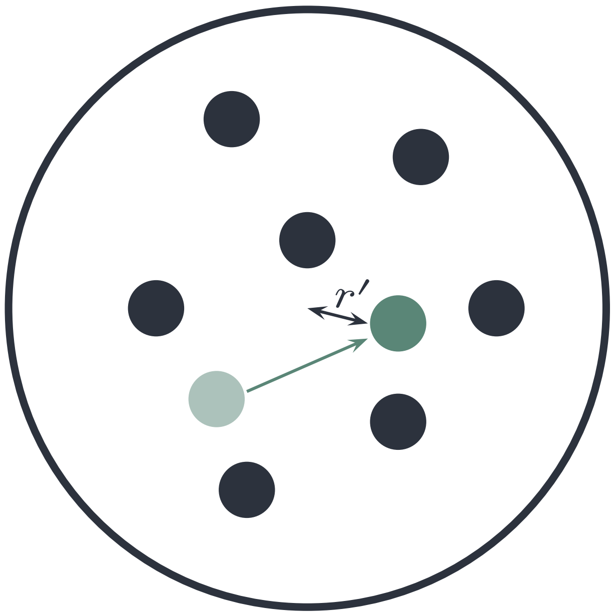
$P =$ rand$[0, 1]$

↓

move particle by

min(λ, λ_{max})

The algorithm for intranuclear cascade



Calculate:
$\tilde{\lambda}(r) = [\sigma\rho(r)]^{-1}$

$\rightarrow$

$\lambda = \tilde{\lambda} \cdot \ln(P)$
$P =$ rand$[0, 1]$

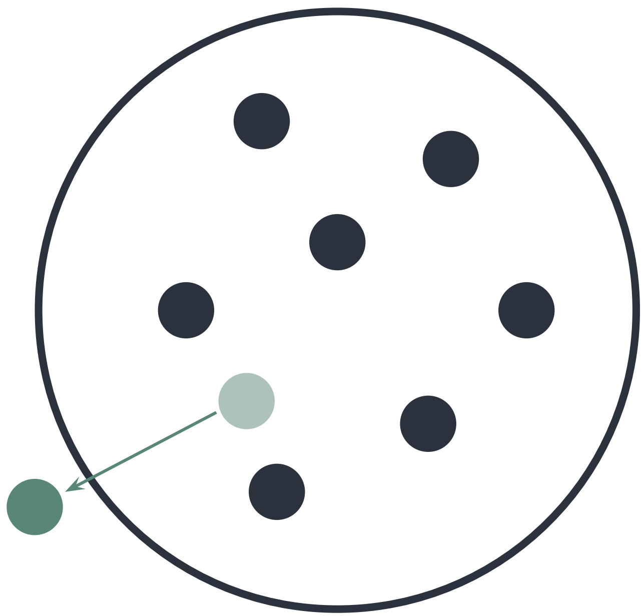
$\downarrow$

move particle by
min(λ, λ_{max})

$\leftarrow$

Check $r' > R$
R - nucleus radius

The algorithm for intranuclear cascade



Calculate:
$\tilde{\lambda}(r) = [\sigma\rho(r)]^{-1}$

$\lambda = \tilde{\lambda} \cdot \ln(P)$
$P =$ rand$[0, 1]$

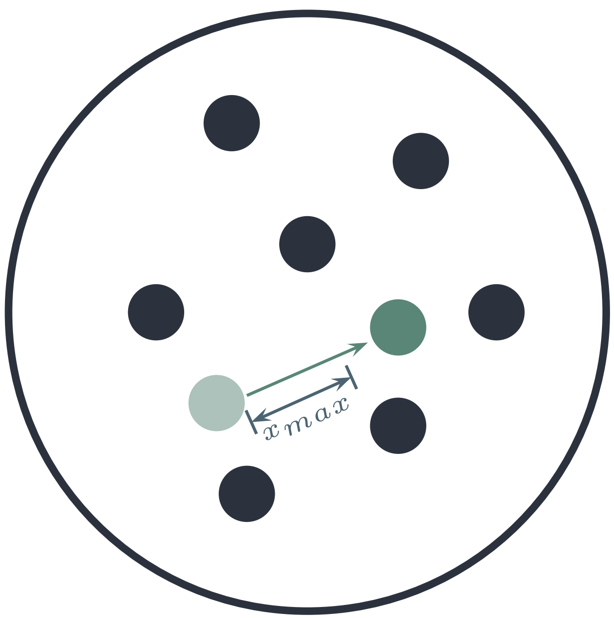
move particle by
min(λ, λ_{max})

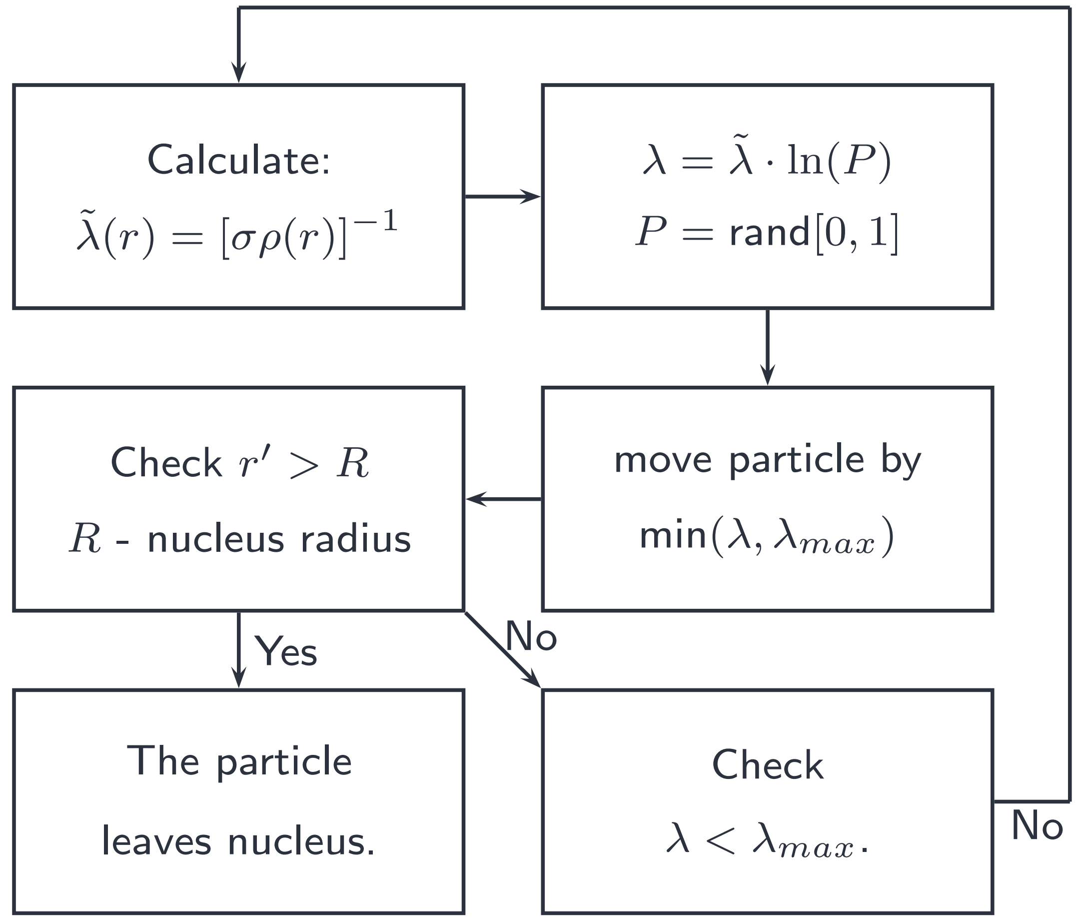
Check $r' > R$
R - nucleus radius

Yes

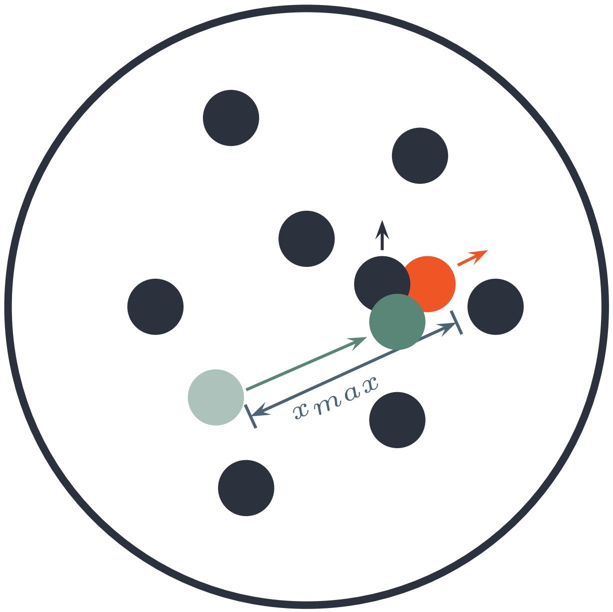
The particle
leaves nucleus.

The algorithm for intranuclear cascade





The algorithm for intranuclear cascade



Calculate:

$\tilde{\lambda}(r) = [\sigma\rho(r)]^{-1}$

$\lambda = \tilde{\lambda} \cdot \ln(P)$

$P =$ rand$[0,1]$

move particle by

min(λ, λ_{max})

Check $r' > R$

R - nucleus radius

Yes

The particle

leaves nucleus.

No

Check

$\lambda < \lambda_{max}$.

No

Yes

Generate

the interaction.

The algorithm for intranuclear cascade