Search for Possible Neutrino Radiative Decay and Monte Carlo Simulations in Modern Physics

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Abstract

Pursuing the idea of a possible radiative decay from neutrino mass damped oscillations, the experiment NOTTE searched for new limits on the lifetime of the heavy neutrino radiative decay. I will cover all the essential parts involving the above experiment: the theoretical and experimental approaches, expectations versus results and conclusions. The theoretical predictions for NOTTE were achieved through basic Monte Carlo simulations. To understand why a ***basic*** *Monte Carlo simulation was used and considering the impact of the method in the modern physics, I will introduce the audience to general Monte Carlo simulations, from understanding its basic concept to the modern times development of the method, going through the main problems involving this method and their possible solutions.*

Now it's the time to flee!!! ;)

Neutrino Oscillations Through Total Eclipse

References and further reading...

1. S. Cecchini, D. Centomo, G. Giacomelli, R. Giacomelli, M. Giorgini, L. Patrizii, V. Popa, **C. G. Serbanut** - New Lower Limits on the Lifetime of Heavy Neutrino Radiative Decay (arxiv:0912.5086v1[hep-ex]: http://arxiv.org/PS_cache/arxiv/pdf/0912/0912.5086v1.pdf)
2. S. Cecchini, D. Centomo, G. Giacomelli, R. Giacomelli, V. Popa, **C. G. Serbanut** and R. Serra - Search for neutrino radiative decays during total solar eclipse (hep-ex/0402014v1: http://arxiv.org/PS_cache/hep-ex/pdf/0402/0402014v1.pdf)
3. S. Cecchini, D. Centomo, G. Giacomelli, R. Giacomelli, V. Popa, **C. G. Serbanut** and R. Serra - Search for possible neutrino radiative decays during the 2001 total solar eclipse (hep-ex/0402008: http://arxiv.org/pdf/hep-ex/0402008)
4. S. Cecchini, D. Centomo, G. Giacomelli, V. Popa and **C. G. Serbanut** - Monte Carlo simulation of an experiment looking for radiative solar neutrino decays (hepph/ 0309107: http://arxiv.org/pdf/hep-ph/0309107)

Neutrino Flavour Framework

$$\{\, \nu_e,\ \nu_\mu,\ \nu_\tau \,\} \qquad \longleftrightarrow \qquad \{\, \nu_{m_1},\ \nu_{m_2},\ \nu_{m_3} \,\}$$

$$\nu_{l=e,\mu,\tau} = \sum_{j=1}^{3} c_{lj}\, \nu_{m_j} \qquad \longleftrightarrow \qquad \nu_{m_{j=\overline{1,3}}} = \sum_{l=e,\mu,\tau} c'_{jl}\, \nu_l$$

$$M = m_{in},\ \ m = m_{out},\ \ \nu_j = \nu_{m_j},\ \ m_j > m_{j+1}$$

$$\Delta m^2_{1(2|3)} = 2.5 \times 10^{-3} eV^2 \qquad \Delta m^2_{23} = 6 \times 10^{-5} eV^2$$

$$\sin^2\theta_{(3|2)1} \simeq 0.1 \qquad \sin^2\theta_{32} \simeq 0.74$$

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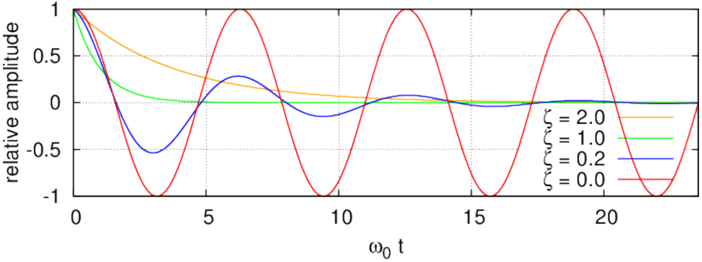
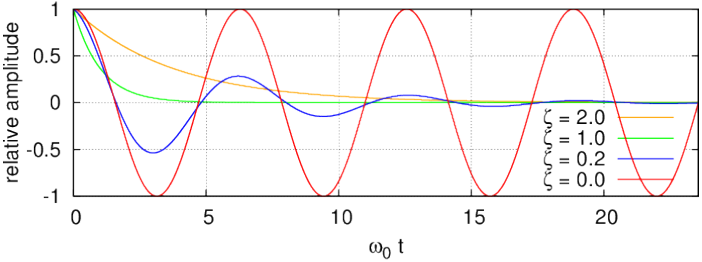
Neutrino Decay: Damped Oscillations



$$\ddot{x} + 2\zeta\omega_0\dot{x} + \omega_0 x = 0$$

Neutrino Decay: Damped Oscillations



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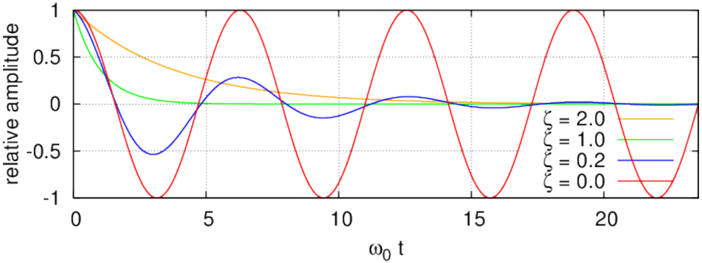

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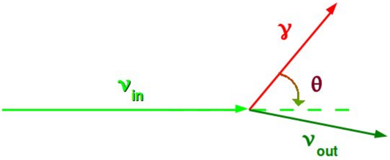
a way to interpret: $E_1 - W = E_2 \Rightarrow E_1 = E_2 + W$

neutrino decay: $\nu_{in} \to \nu_{out} + \gamma$

$$|\nu(x)\rangle = \sum_{i=1}^{3} k_i\, |\nu_i(x)\rangle \quad \longrightarrow \quad |\nu(x)\rangle = \sum_{\substack{i=1 \\ i\neq in}}^{3} k_i'\, |\nu_i(x)\rangle$$

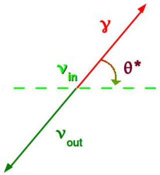
Neutrino Decay: Kinematics



$$\nu_{in} \rightarrow \nu_{out} + \gamma$$

$$\begin{aligned}
\text{t-channel: } E_{out}^2 - \vec{p}_{out}^{\,2} &= (E_{in} - E_\gamma)^2 - (\vec{p}_{in} - \vec{p}_\gamma)^2 \\
E_{out}^2 - \vec{p}_{out}^{\,2} &= E_{in}^2 - \vec{p}_{in}^{\,2} + E_\gamma^2 - \vec{p}_\gamma^{\,2} - 2 \cdot E_{in} \cdot E_\gamma + 2 \cdot \vec{p}_{in} \cdot \vec{p}_\gamma \\
E^2 - \vec{p}^{\,2} &= m^2; \quad m_\gamma = 0; \quad \vec{p}_{in} \cdot \vec{p}_\gamma = |\vec{p}_{in}| \cdot |\vec{p}_\gamma| \cdot \cos\theta \\
m^2 &= M^2 - 2 \cdot E_{in} \cdot E_\gamma + 2 \cdot |\vec{p}_{in}| \cdot E_\gamma \cdot \cos\theta \\
2 \cdot E_\gamma \cdot (E_{in} - |\vec{p}_{in}| \cos\theta) &= M^2 - m^2 \\
E_\gamma &= \frac{\Delta m^2}{2} \frac{1}{E_{in} - |\vec{p}_{in}| \cos\theta}
\end{aligned}$$

Neutrino Decay: Dynamics



$$\nu_{in} \rightarrow \nu_{out} + \gamma$$

$$\tau = 1/\Gamma$$

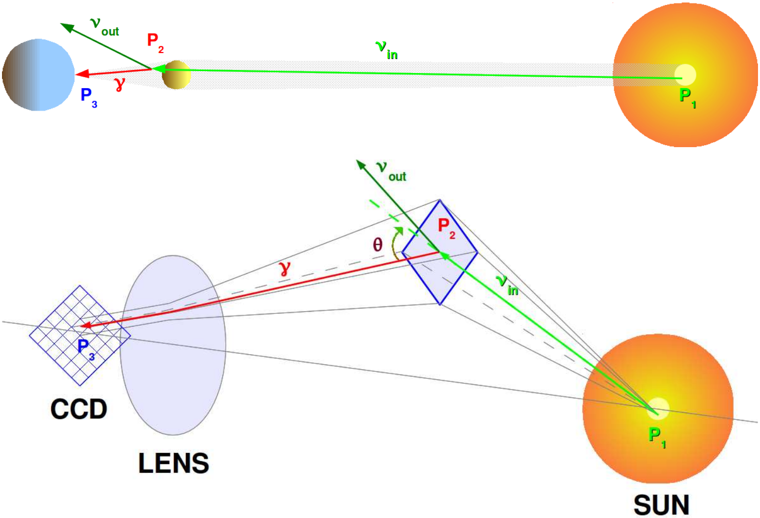
definition: $$\frac{\mathrm{d}\Gamma}{\textit{phase-space element}} = \frac{\textit{final states combinatorial factor}}{2} \cdot \frac{\textit{decay amplitude}}{M}$$

$$\vdots$$

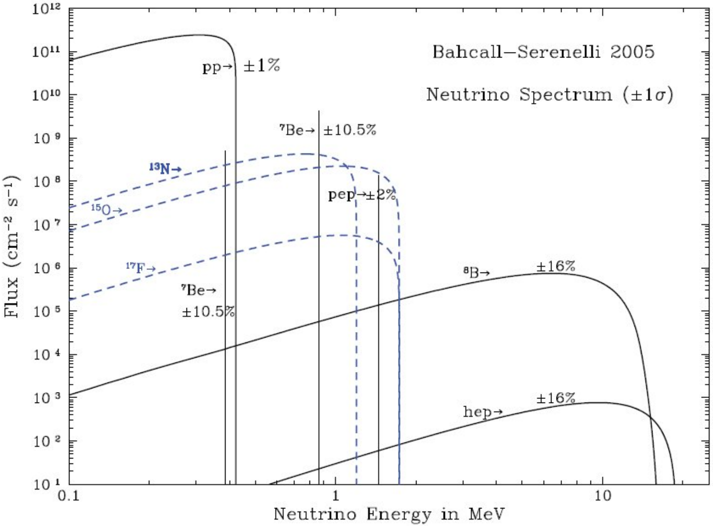
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\left(\cos\theta^*\right)} = \frac{\alpha_e^2}{\pi^2}\left[\frac{M}{\left(\Delta m^2\right)^3}\left(m^2 + M^2 + m \cdot M\right)\right]\left(1 + \alpha \cdot \cos\theta^*\right)$$

NOTTE Geometry Model

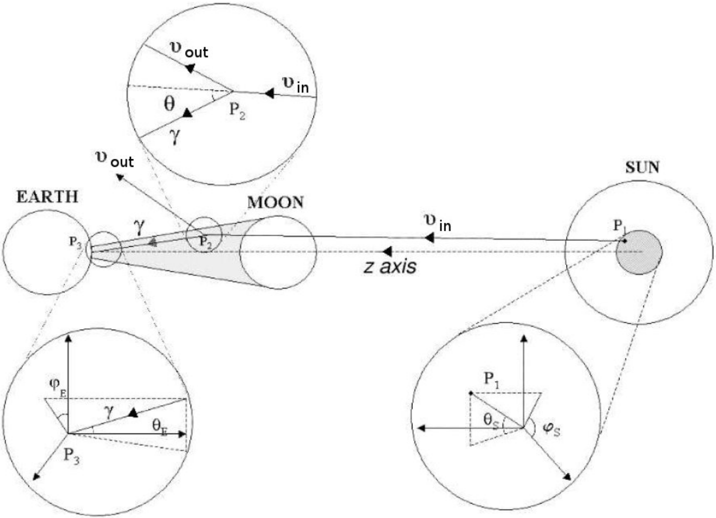
Legend: θ = azimuthal angle



Standard Solar Model

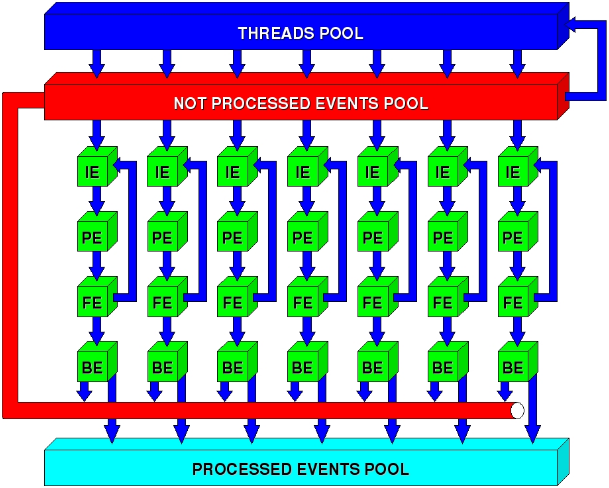


NOTTE Monte Carlo Simulation: Event Geometry



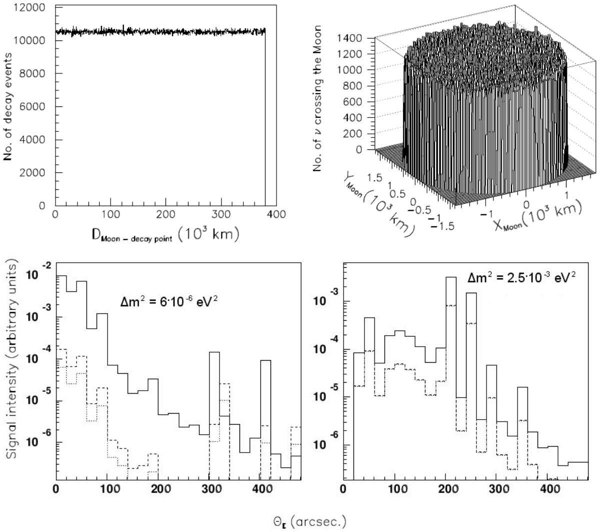
NOTTE Monte Carlo Simulation: Dataflow

IE - initializing the event; PE - processing the event; FE - finalizing the event; BE - buffering the event



NOTTE Monte Carlo Simulation: Tests and Expected Signal

Legend: θ_E = azimuthal angle from Earth

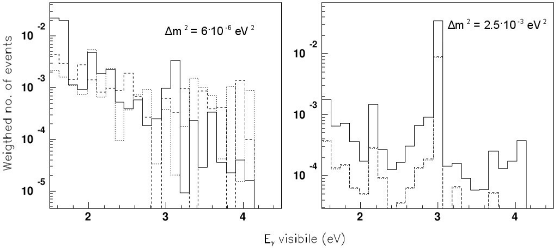


NOTTE Monte Carlo Simulation: Expected Photon Energy

Legend: continuous line: $m = 0.001eV$; dashed line: $m = 0.01eV$; dotted line: $m = 0.1eV$

$$E_\gamma = \frac{\Delta m^2}{2} \frac{1}{E_{in} - |\vec{p}_{in}| \cos\theta}$$

where E_γ is the photon energy, Δm^2 is the neutrino squared mass difference, E_{in} is the energy of the incoming neutrino, $\vec{p}_{in}$ is the three-dimensional momentum for the incoming neutrino and θ is the azimuthal angle.



Total Solar Eclipse 2001: Experimental Setup

TSE: duration = 3.5 minutes, location = Zambia

Legend: ADU = Acquisition Digital Unit

(a)

(b)

(a) Digital videocamera: $10\times$ $(+2\times)$ optical zoom, 1 pixel = 10"$\times$10", 4149 frames, 1 ADU = 7.3×10^4 photons;

(b) A small Matsukov - Cassegrain telescope (coupled to a digital camera): ϕ = 90 mm, f = 1250 mm, 1 pixel = 1.14"$\times$1.14", 10 pictures, 1 ADU = 8.9×10^2 photons.

Total Solar Eclipse 2001: Expected Probability Density

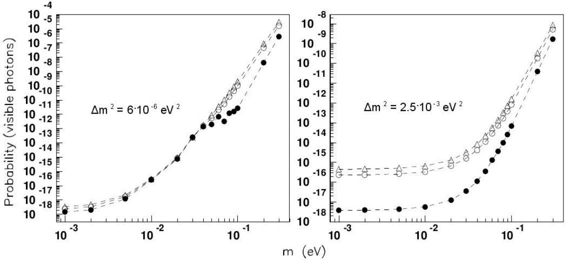
Legend: light triangles: $\alpha = -1$; light circles: $\alpha = 0$; dark circles: $\alpha = +1$

$$\frac{d\Gamma}{d(\cos\theta^*)} = K\left(1 + \alpha \cdot \cos\theta^*\right)$$

where α depends on the incoming neutrino chirality (0 for Majorana particle, ∓ 1 for *left* and *right* projections for the Dirac particle), θ^* is the CM value of the azimuthal angle and the constant

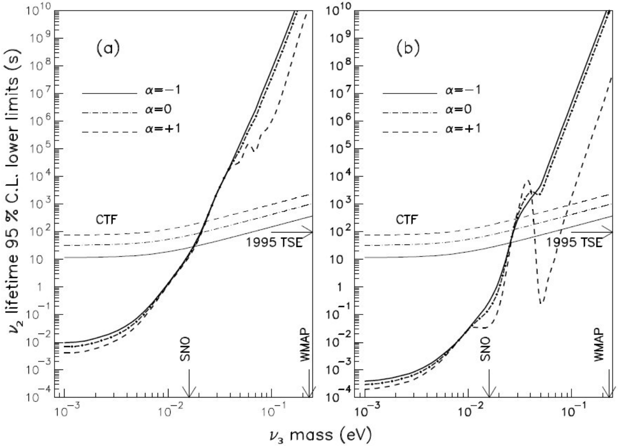
$$K = \frac{\alpha_e^2}{\pi^2} \frac{M}{\left(\Delta m^2\right)^3} \left(M^2 + m^2 + M \cdot m\right)$$

with α_e^2 the electromagnetic constant and $M, \ m$ the incoming and outgoing, respectively, neutrino masses.



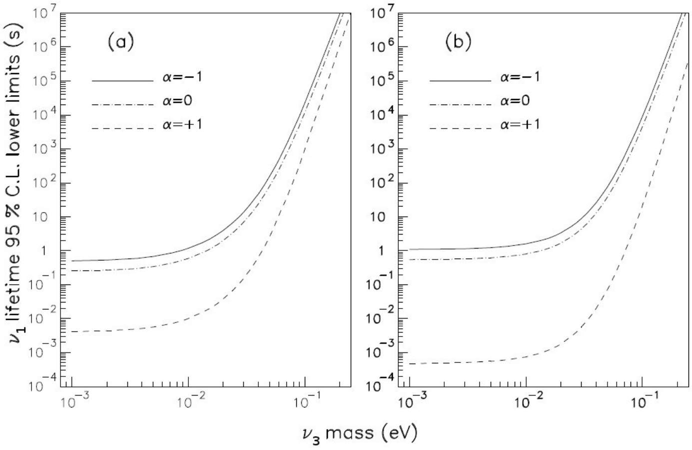
Total Solar Eclipse 2001: Lifetime Lower Limit

Large Mixing Angle: $\sin^2\theta_{32} = 0.74;\ \Delta m^2 = 6 \times 10^{-5}\ eV^2$



Total Solar Eclipse 2001: Lifetime Lower Limit

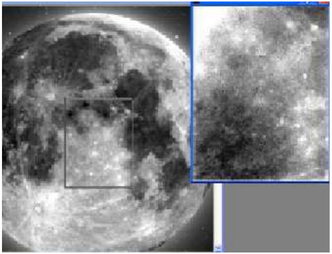
Small Mixing Angle: $\sin^2\theta_{31} \simeq 0.1;\ \Delta m^2 = 2.5 \times 10^{-3}\ eV^2$



Total Solar Eclipse 2006: Experimental Setup

TSE: duration $<$ 2 minutes, location = Lybian Sahara desert

Legend: ADU = Acquisition Digital Unit; 1 frame = 256$\times$256 squared pixels



legend: LH image = example of frame, RH image = integrated luminozity for all frames;

main: A Matsukov - Cassegrain telescope (coupled to a 16 bits Mx916 CCD camera): ϕ = 235 mm, f = 2350 mm, 1 pixel = 1.99”$\times$1.95”, 195 (out of 212) pictures, 1 ADU = 6.1$\pm$0.1 photons;

backup: Digital videocamera: 10$\times$ (+2$\times$) optical zoom, 1 pixel = 10”$\times$10”, 2370 frames, 1 ADU = 7.3×10^4 photons;

backup: A smaller Celestron C5 equipped with Canon 20D: 50 pictures.

Total Solar Eclipse 2006: Expected Probability Density

Large Mixing Angle: $\sin^2\theta_{32} = 0.74;\ \Delta m^2 = 6\times 10^{-5}\ eV^2;$

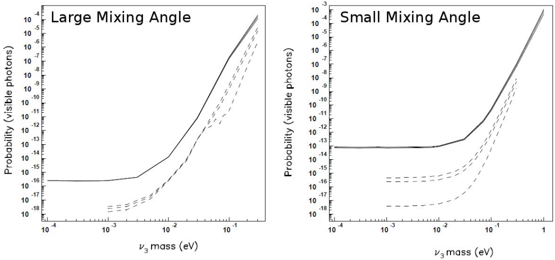
Small Mixing Angle: $\sin^2\theta_{31} \simeq 0.1;\ \Delta m^2 = 2.5\times 10^{-3}\ eV^2$

$$\frac{d\Gamma}{d(\cos\theta^*)} = K\left(1+\alpha\cdot\cos\theta^*\right)$$

where α depends on the incoming neutrino chirality (0 for Majorana particle, ∓ 1 for *left* and *right* projections for the Dirac particle), θ^* is the CM value of the azimuthal angle and the constant

$$K = \frac{\alpha_e^2}{\pi^2}\ \frac{M}{\left(\Delta m^2\right)^3}\ \left(M^2+m^2+M\cdot m\right)$$

with α_e^2 the electromagnetic constant and $M,\ m$ the incoming and outgoing, respectively, neutrino masses. In the figure, the data for TSE 2006 are with solid lines while the data for TSE 2001 are with dashed lines.



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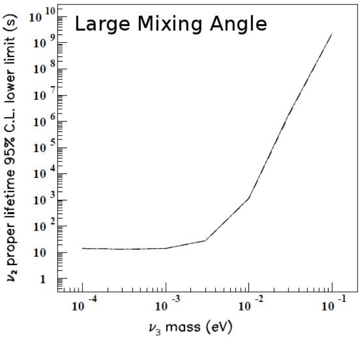
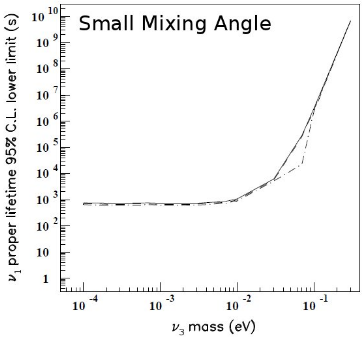




NOTTE: Conclusions

1. We were able to provide only the lower limit for the heavy neutrino because no simulated signal was observed experimentally.
2. For SMA, the limits are estimative because the mixing angle was not known precisely at that time.
3. Even with a better resolution, the lack of a correct definition of ashen light might provide a too high noise.

Monte Carlo Simulations

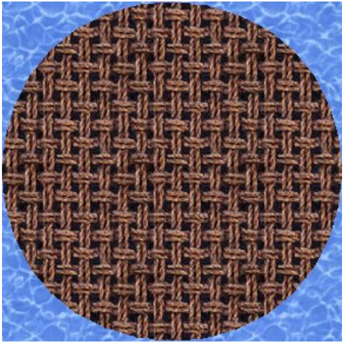
The beginning...

1930 Enrico Fermi first experimented with the Monte Carlo method while studying neutron diffusion, but did not publish anything on it.

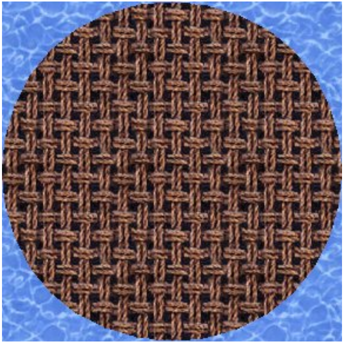
1946 At Los Alamos Scientific Laboratory, Stanislaw Ulam and John von Neumann were investigating radiation shielding and the distance that neutrons would likely travel through various materials. The name is a reference to the Monte Carlo Casino in Monaco where Ulam's uncle would borrow money to gamble.

Monte Carlo Method By Example

Monte Carlo Method By Example



Monte Carlo Method By Example



$$\lim_{\text{high resolution}} \frac{\text{pixels in circle}}{\text{pixels in square}} = \frac{\text{area circle}}{\text{area square}} = \frac{\pi}{4}$$

Monte Carlo Method: Student Approach

Part 1: Monte Carlo at bar

 x 4

divided by

 + 

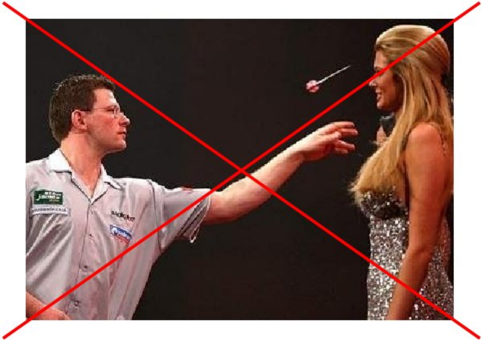
= π

In case you are too good at aiming...

...the beer ensures perfect randomness! If it doesn't work from the first beer, try another... and another...

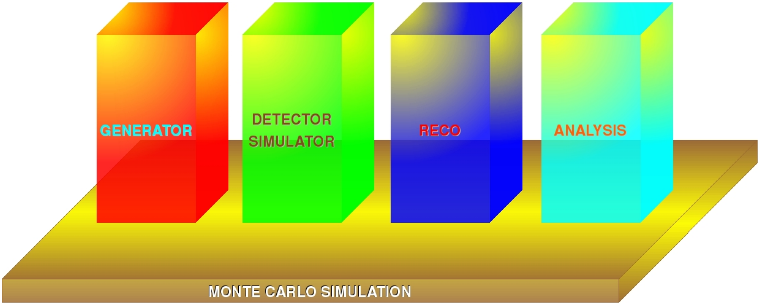
Monte Carlo Method: Student Approach

Part 3: Piece of advice

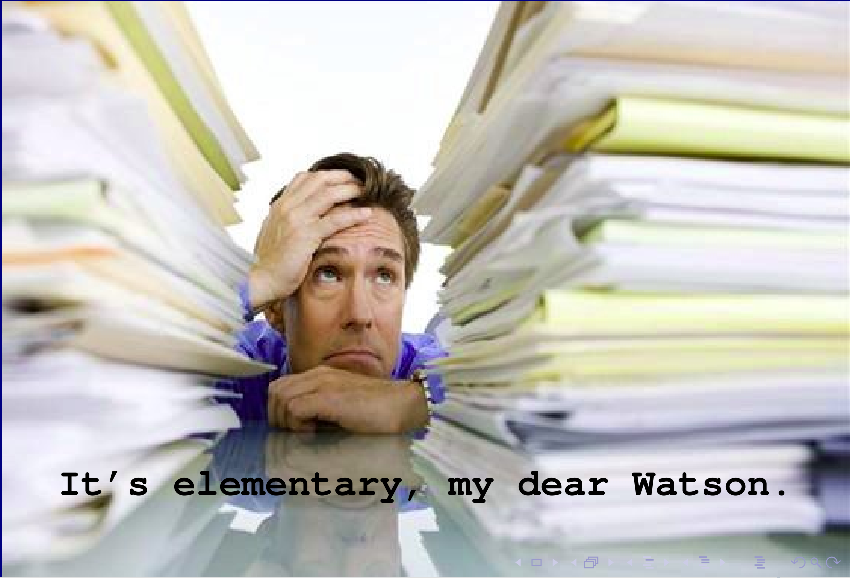


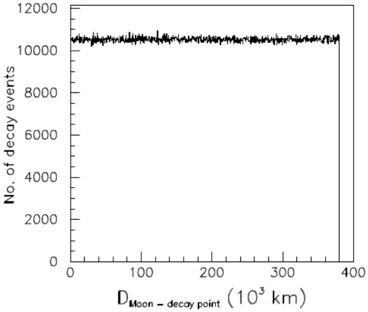
Do not count the shots in your opponent/partner!!!

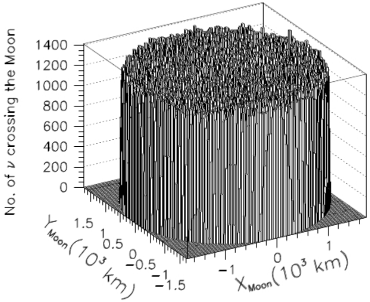
Beam me up, Scotty!



Generator:	Pythia
Detector Simulator:	Geant v.3, Geant v.4, Fluka
Reconstruction:	no generic reconstruction software
Analysis:	no generic analysis software


It's elementary, my dear Watson.



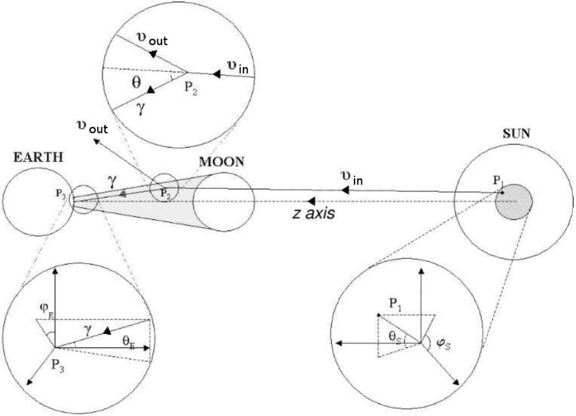


Desired characteristics:

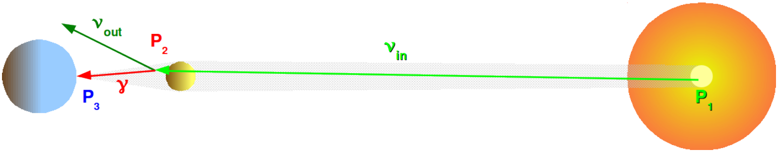
- → large period;
- → fast numerical computation;
- → reproducibility.

Example: RANLUX (Lüscher's 24-bit lagged-fibonacci-with-skipping algorithm)

- → period $\simeq 10^{171}$;
- → 200 - 1750 k ints/second, 150 - 850 k doubles/second;
- → reproducibility based on seed.



$$\cos\left(\text{random}(\theta_E)\right) \neq \text{random}(\cos\left(\theta_E\right))$$



$$\cos\theta = \frac{|\mathbf{P_1P_2}|^2 + |\mathbf{P_2P_3}|^2 - |\mathbf{P_1P_3}|^2}{\mathbf{2} \cdot |\mathbf{P_1P_2}| \cdot |\mathbf{P_2P_3}|}$$

$$\{|P_1P_2|,\ |P_2P_3|,\ |P_1P_3|\} \to \left\{\vec{e}_{P_1P_2},\ \vec{e}_{P_2P_3},\ \vec{e}_{P_1P_3}\right\},\ \{x_k,\ y_k,\ z_k\} = \vec{e}_{P_iP_j}\Big|_{i\neq j} = \frac{\overrightarrow{P_1P_2}}{|P_1P_2|}$$

$$\cos\theta = \frac{\vec{e}_1 \cdot \vec{e}_2}{|\vec{e}_1| \cdot |\vec{e}_2|} \quad \Longrightarrow \quad \cos\theta = \mathbf{x_1 \cdot x_2 + y_1 \cdot y_2 + z_1 \cdot z_2} \quad (\in [\mathbf{0}, \mathbf{1}])$$

$$\left.\begin{aligned} E_\gamma &= \frac{\Delta m^2}{2}\,\frac{1}{E_{in} - |\vec{p}_{in}|\cos\theta} \\ \frac{|\vec{p}|}{E} &= \beta \end{aligned}\right\} \Rightarrow E_\gamma = \frac{\Delta m^2}{2 \cdot E_{in}}\,\frac{1}{1 - \beta_{in} \cdot \cos\theta}$$

$$\left.\begin{aligned} E_{in} \gg M \quad &\Rightarrow \quad \beta_{in} \simeq 1 \\ \theta \to 0 \quad &\Rightarrow \quad \cos\theta \simeq 1 \end{aligned}\right\} \Rightarrow \mathbf{E}_\gamma \to \infty$$

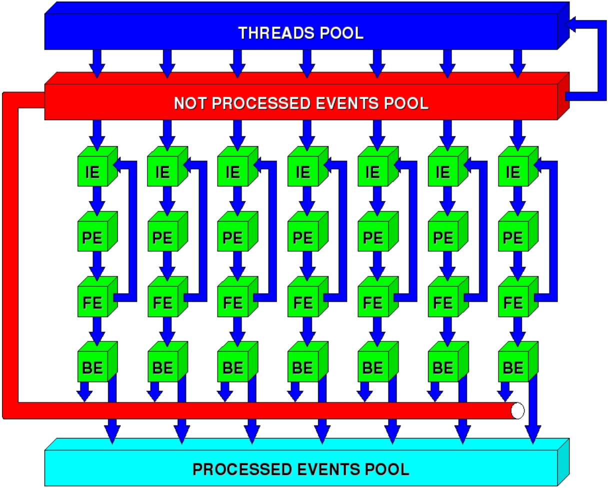
$$\mathbf{E}_\gamma > \mathbf{E}_{\mathbf{in}} || \left(\beta_{\mathbf{in}} \cdot \cos\theta == \mathbf{1}\right)_{\mathbf{precision}} \to \mathbf{E}_\gamma = \mathbf{E}_{\mathbf{in}}$$

1. Use optimized software granulation.
2. Guard only sensitive variables.
3. Optimize the number of computations.
4. Use optimization algorithms (search, vector mapping etc).
5. Choose the right tool for your problem (programming language, database, available written software etc).
6. Buffer your data before starting the write-on-harddisk process.
7. Optimize threads usage.

...and so on

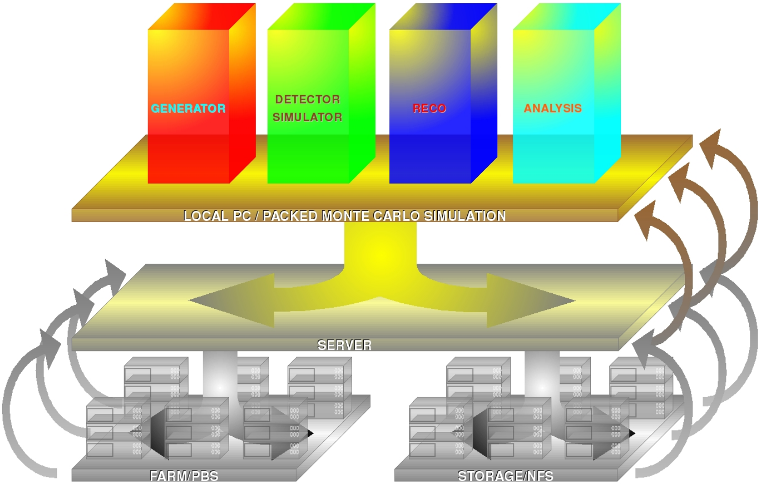
1. Make your software flexible in parameters initialization.
1. Make your software platform quasi-independent (packing).
2. Optimize the number of parallel threads for multi-core multi-processor computing elements or for GPU's.
3. Optimize the number of instances on cluster/farm/grid and balance the load.

"LOCK-FREE" & "PULL" Methods



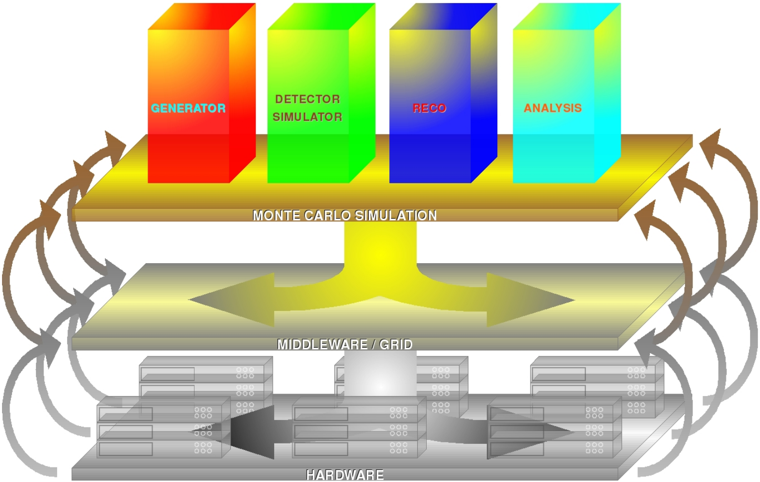
Monte Carlo Simulations: Problems & Solutions

Boost Your Engine: Farm and Centralized Cluster



Monte Carlo Simulations: Problems & Solutions

Boost Your Engine: GRID and Decentralized Cluster



Monte Carlo Simulations: Conclusions

Research life without Monte Carlo method would be:

1. *with less headaches,*
2. *more expensive,*
3. *too short,*
4. *much less fun.*

Thank you for your attention!