Neutrino directionality measurement with the Double Chooz experiment

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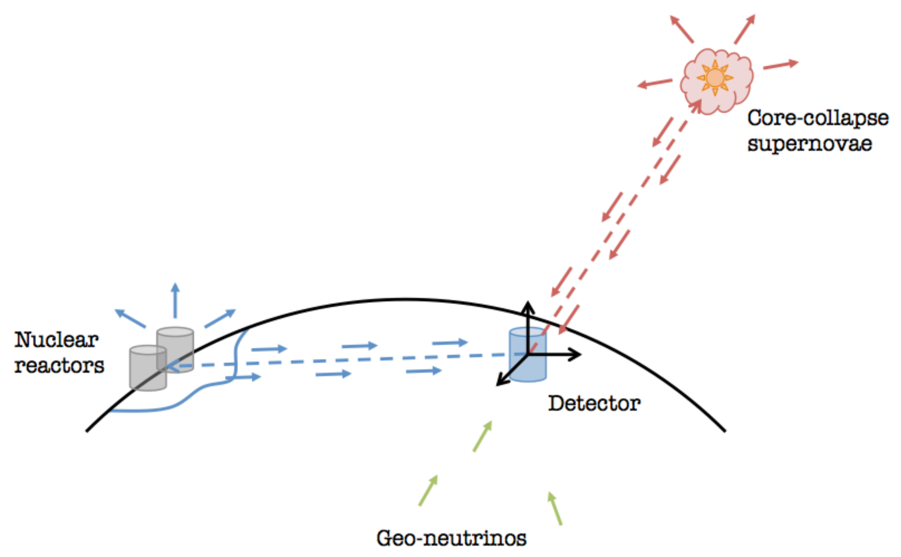
Double Chooz is a reactor neutrino oscillation experiment which studies anti-ν_e emitted from the two nuclear reactors of the Chooz power plant, in the French Ardennes. It aims to measure the neutrino mixing angle θ_{13} thanks to two identical detectors located at different baselines to precisely observe the anti-ν_e disappearance. Thanks to its layout, Double Chooz has the ability to test the feasibility of neutrino directionality measurement by liquid scintillator detector.

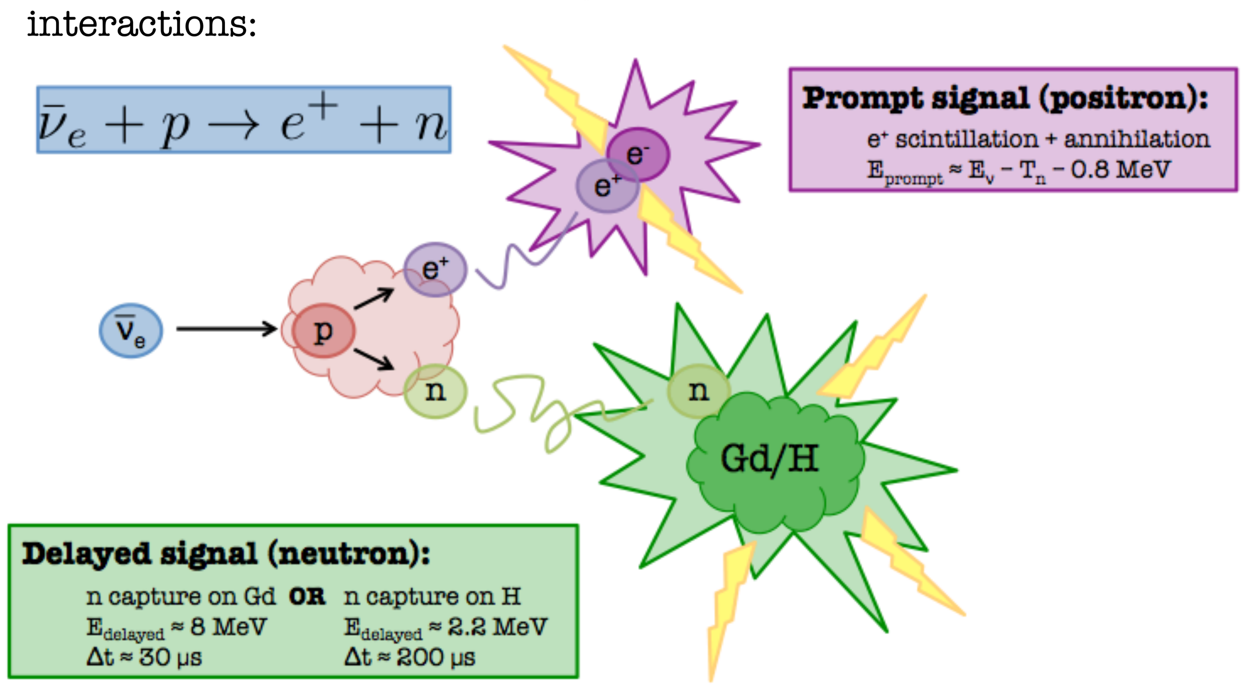
Motivations

Directional information could, in principle, be applied when looking at particular sources such as core-collapse supernovae, when searching for geo-neutrinos, with the possibility to discriminate between crust and mantle, or for nuclear monitoring.



Anti-ν_e detection and selection

Detection: Detection of anti-ν_e through inverse β-decay (IBD) interactions:



Selection: Same selection as for the previous θ_{13} analysis [1]: prompt and delayed energy range together with space and time coincidences cuts. Muon cut, light noise cut and isolation cut are also applied.

Angular distribution

Positron: Assuming the proton target to be at rest, the angular distribution of the positron w.r.t. the incoming anti-ν_e is slightly backward peaked [2]. Nevertheless, since the positron will immediately annihilate with an electron of the medium, one can safely assume the positron vertex to be the anti-ν_e vertex.

Neutron: There is an angular correlation between the anti-ν_e and the initial neutron direction [2]:

$$\cos(\theta_n)_{\max} = \frac{\sqrt{2E_{\bar{\nu}_e}\Delta - (\Delta^2 - m_e^2)}}{E_{\bar{\nu}_e}}$$

where $\Delta = M_n - M_p$

Each elastic scattering changes the neutron direction:

$$\langle \cos(\theta_n) \rangle = \frac{2}{3A}$$

where A is the atomic number of the scattering nucleus.

The neutron directionality is then best preserved for low atomic number nuclei. Since the neutron scatters with a higher probability on H because of larger elastic scattering cross section, the neutron preserves its initial way and by extension the anti-ν_e inital direction.

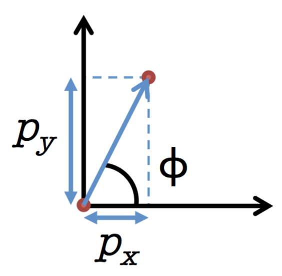
Direction reconstruction method

Each anti-ν_e candidate is composed of a prompt and a delayed signal. From these two vertices, we can build a direction vector for each event:

$$\vec{X}_{\text{Signal}} = \vec{X}_{\text{prompt}} - \vec{X}_{\text{delayed}}$$

The average neutrino wind $\vec{p}$ is defined as the average of normalized direction vectors:

$$\vec{p} = \frac{1}{N}\sum_{i=1}^{N} \frac{\vec{X}^i_{\text{Signal}}}{|\vec{X}^i_{\text{Signal}}|}$$

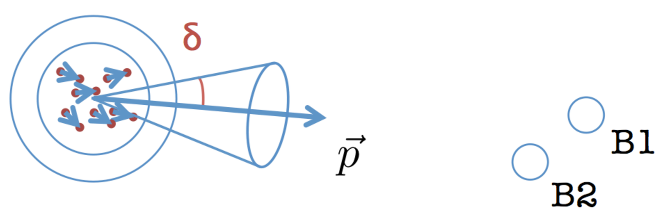


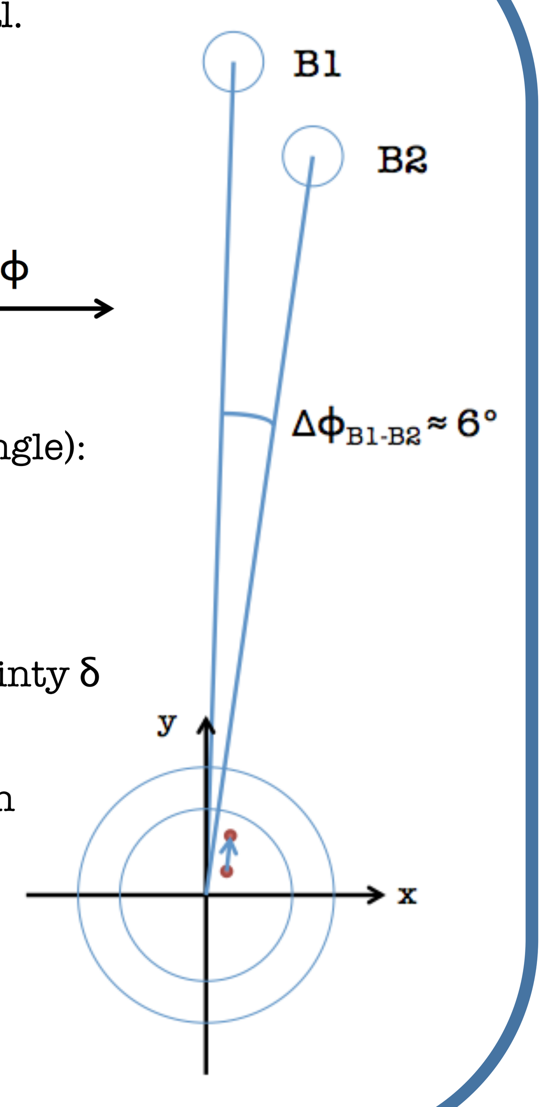
From $\vec{p}$ we can finally deduce ϕ (azimuthal angle) and θ (zenithal angle):

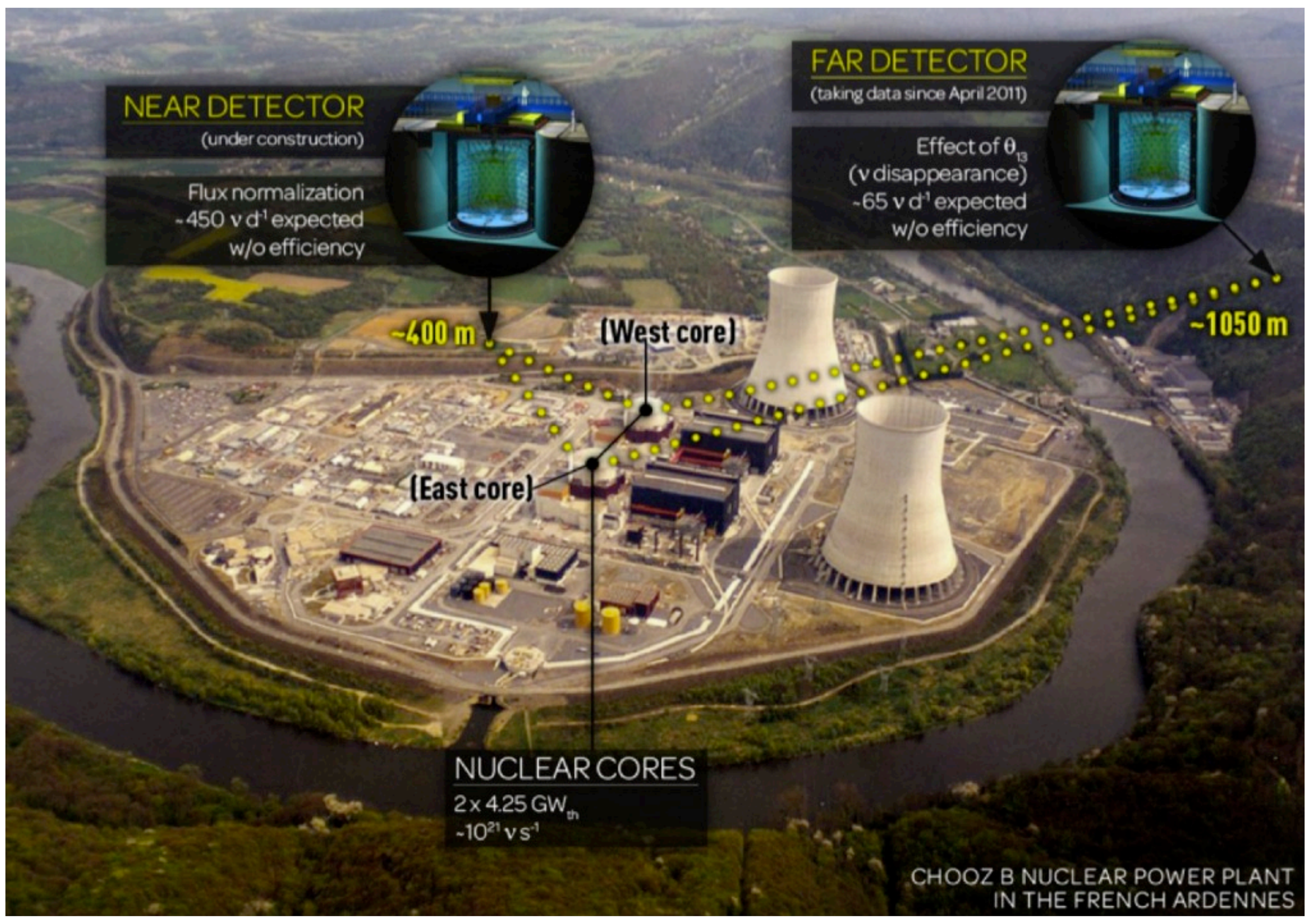
$$\phi = \text{Arctan}\left(\frac{p_y}{p_x}\right) \qquad \theta = \text{Arctan}\left(\frac{p_z}{\sqrt{p_x^2 + p_y^2}}\right)$$

In this analysis, we used the way Chooz did to compute the uncertainty δ on the measured angles [3]:

« An uncertainty on the measurement of the neutrino direction can be given as the cone around $\vec{p}$ which contains 68 % of the integral of the $\vec{p}$ distribution. »







Gd-analysis

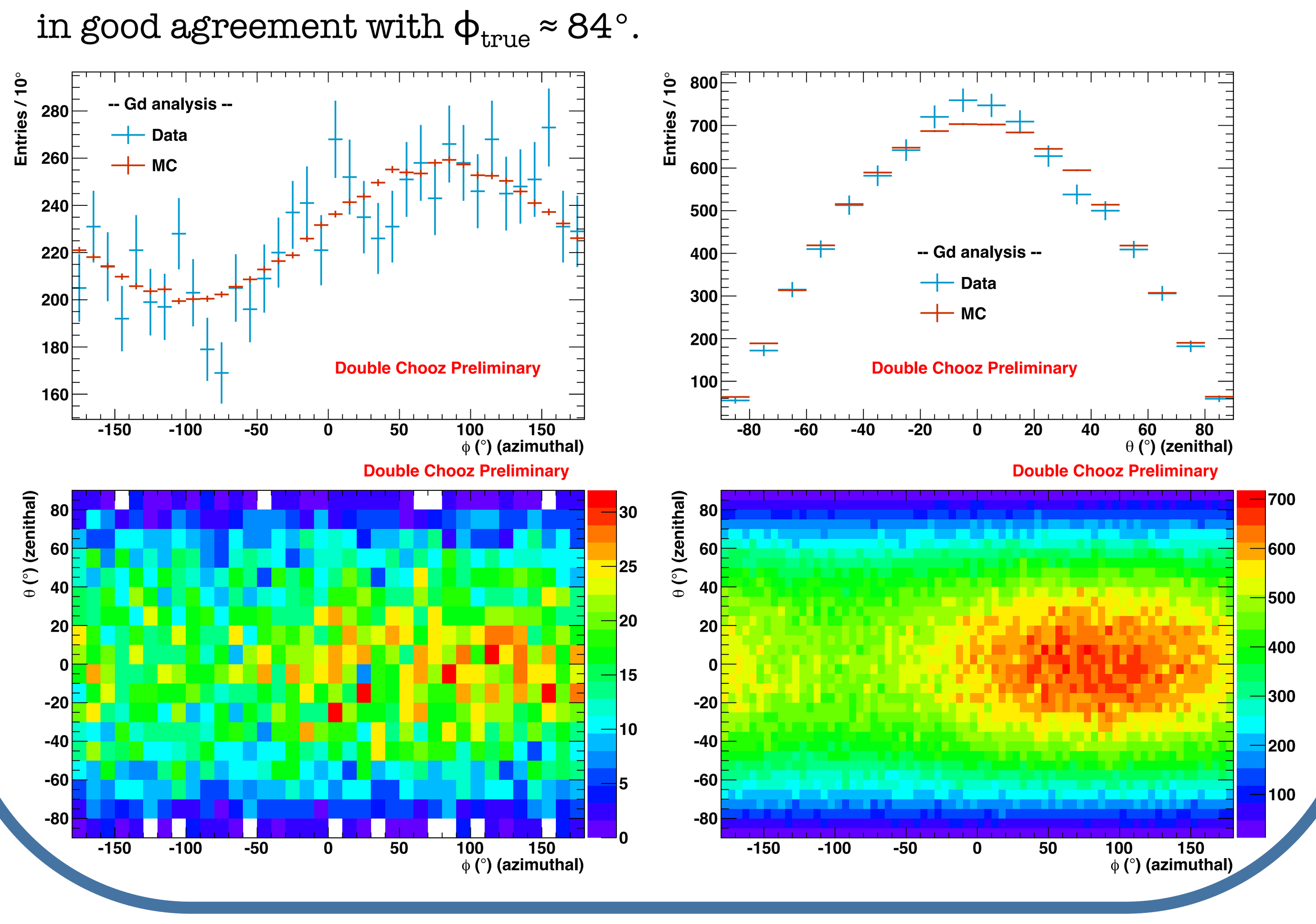
With the selection of the 8246 anti-ν_e candidates with neutron capture on Gd, we can proceed to the calculation of the ϕ and θ angles. The $\vec{p}$ vector coordinates are obtained from the mean value of the normalised p_x, p_y and p_z distributions:

$\vec{p}$ = (0.0055, 0.0585, -0.0049),

which leads to the determination of the angles:

ϕ = 84.6° θ = -4.7° δ = 9.4°,

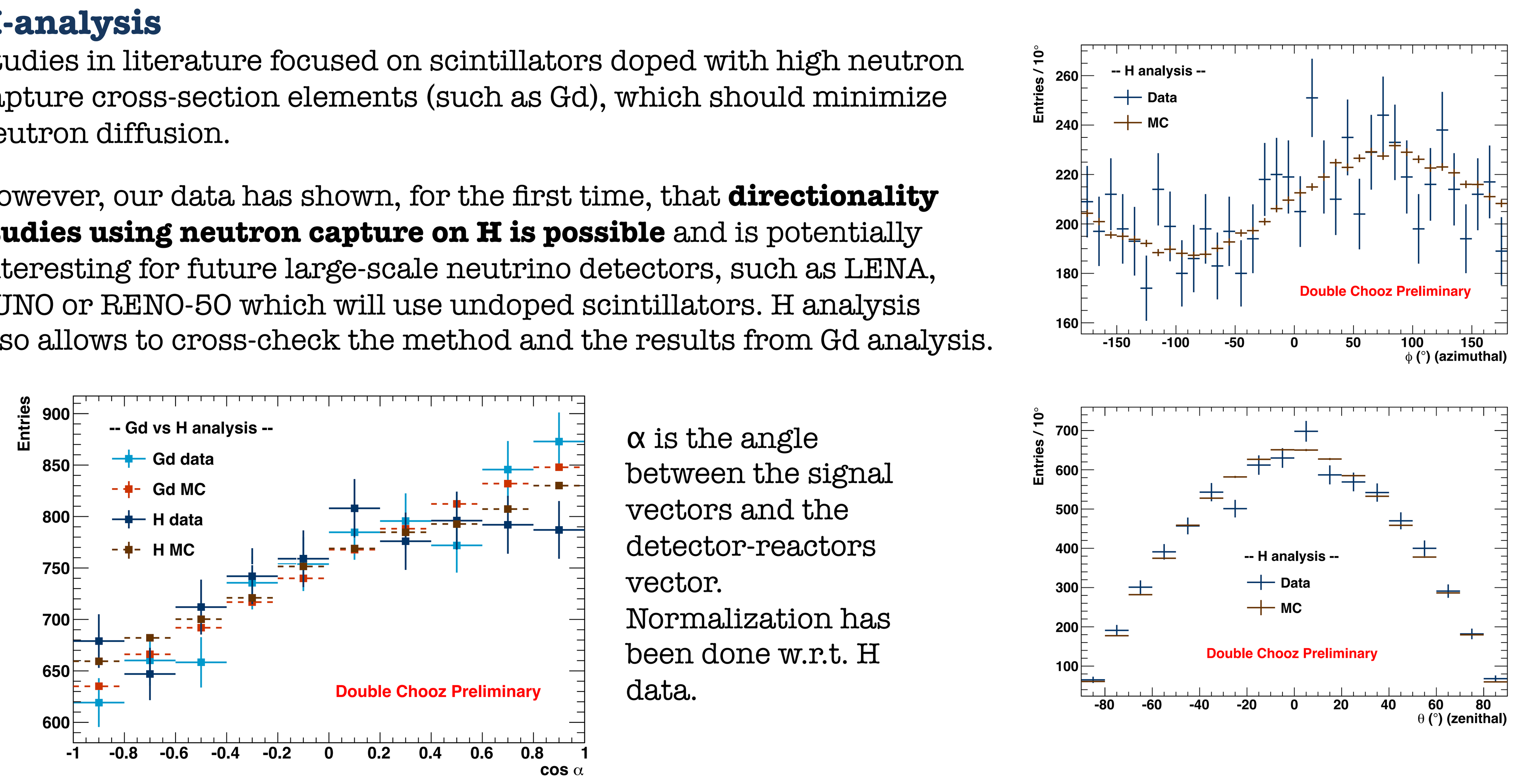
in good agreement with $\phi_{\text{true}} \approx 84°$.



H-analysis

Studies in literature focused on scintillators doped with high neutron capture cross-section elements (such as Gd), which should minimize neutron diffusion.

However, our data has shown, for the first time, that **directionality studies using neutron capture on H is possible** and is potentially interesting for future large-scale neutrino detectors, such as LENA, JUNO or RENO-50 which will use undoped scintillators. H analysis also allows to cross-check the method and the results from Gd analysis.



α is the angle between the signal vectors and the detector-reactors vector. Normalization has been done w.r.t. H data.

Double Chooz first results on CBS: The Big Bang Theory S05E11

References

[1] Y. Abe et al. "Reactor anti-ν_e disappearance in the Double Chooz experiment". Phys.Rev., D**86**:052008, 2012.

[2] P. Vogel and J.F. Beacom. "Angular distribution of neutron inverse beta decay, anti-ν_e + p → e⁺ + n". Phys.Rev., D**60**:053003, 1999.

[3] M. Apollonio et al. "Determination of neutrino incoming direction in the CHOOZ experiment and its application to supernova explosion location by scintillator detectors". Phys.Rev., D**61**:012001, 2000.