CCQE de-excitation γ ray in Super-K

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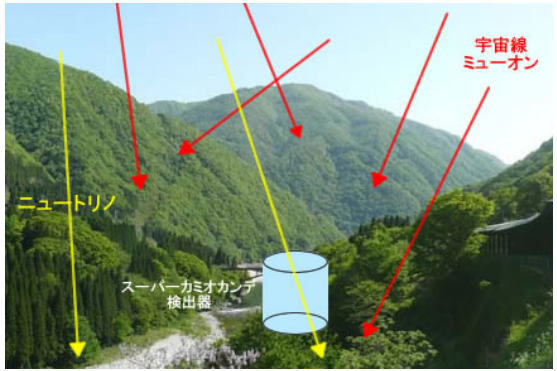
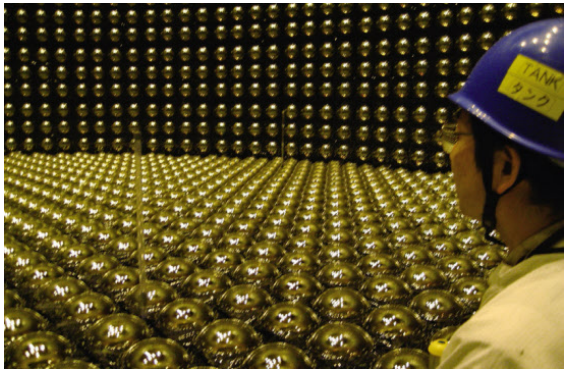
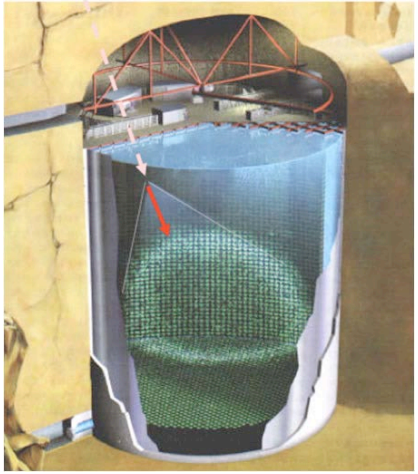
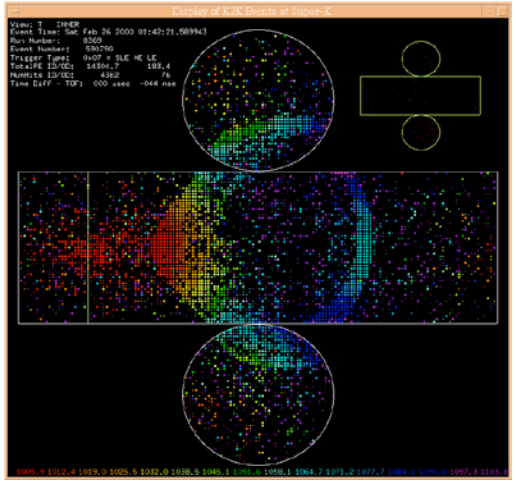
Super-KamiokaNDE





Key word :
1000m Underground
Water Cherenkov Detector
50kton pure water
22.5kton Fiducial Volume
11146 PMTs in Inner Detector



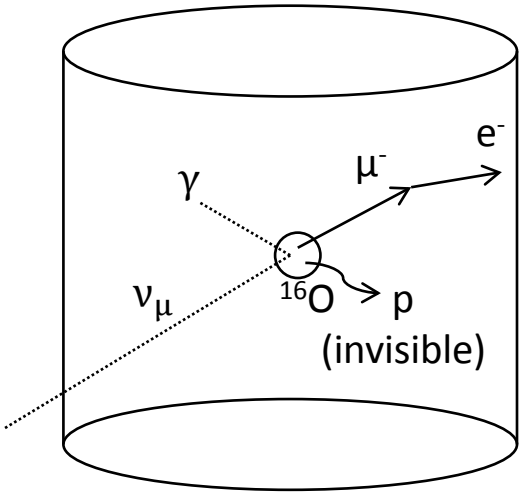


SK phase :
SK-I : 1996~2001
SK-II : 2002~2005
SK-III : 2006~2008
SK-IV : 2008~2018
SK-Gd : Under Work !

Atmospheric ν_μ/ $\bar{\nu}_\mu$ CCQE interaction

$$\nu_\mu + {}^{16}_{8}O \rightarrow \mu^- + {}^{15}_{7}N^* + p$$
$$\downarrow \qquad \downarrow$$
$$e^- \qquad \gamma{\sim}6\ MeV$$

$$\nu_\mu + {}^{16}_{8}O \rightarrow \mu^- + {}^{15}_{8}O^* + n$$
$$\downarrow \qquad \downarrow$$
$$e^- \qquad \gamma{\sim}6\ MeV$$



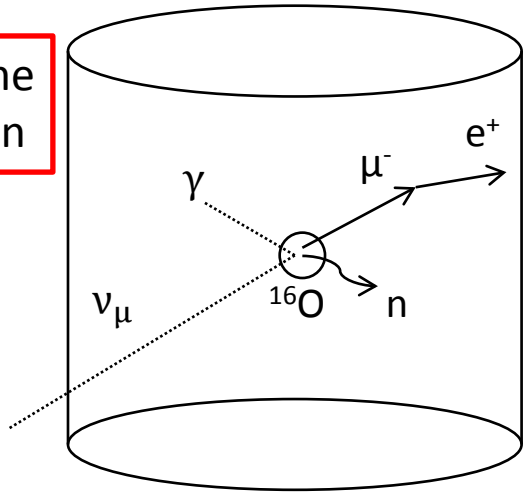
μ and γ at same timing/position

Decay e after ~2.2μs

μ and γ at same timing/position

Decay e after ~2.2μs

n signal after ~200 μs



Br(γ~6 MeV)

Q : Why need Br(γ) ?

A : If μ from CCQE is invisible, 1-Br(γ) of them will leave a decay e in SRN spectrum.
De-excitation γ also caused an uncertainty term in T2K and other analysis.

Q : How much is Br(γ) ?

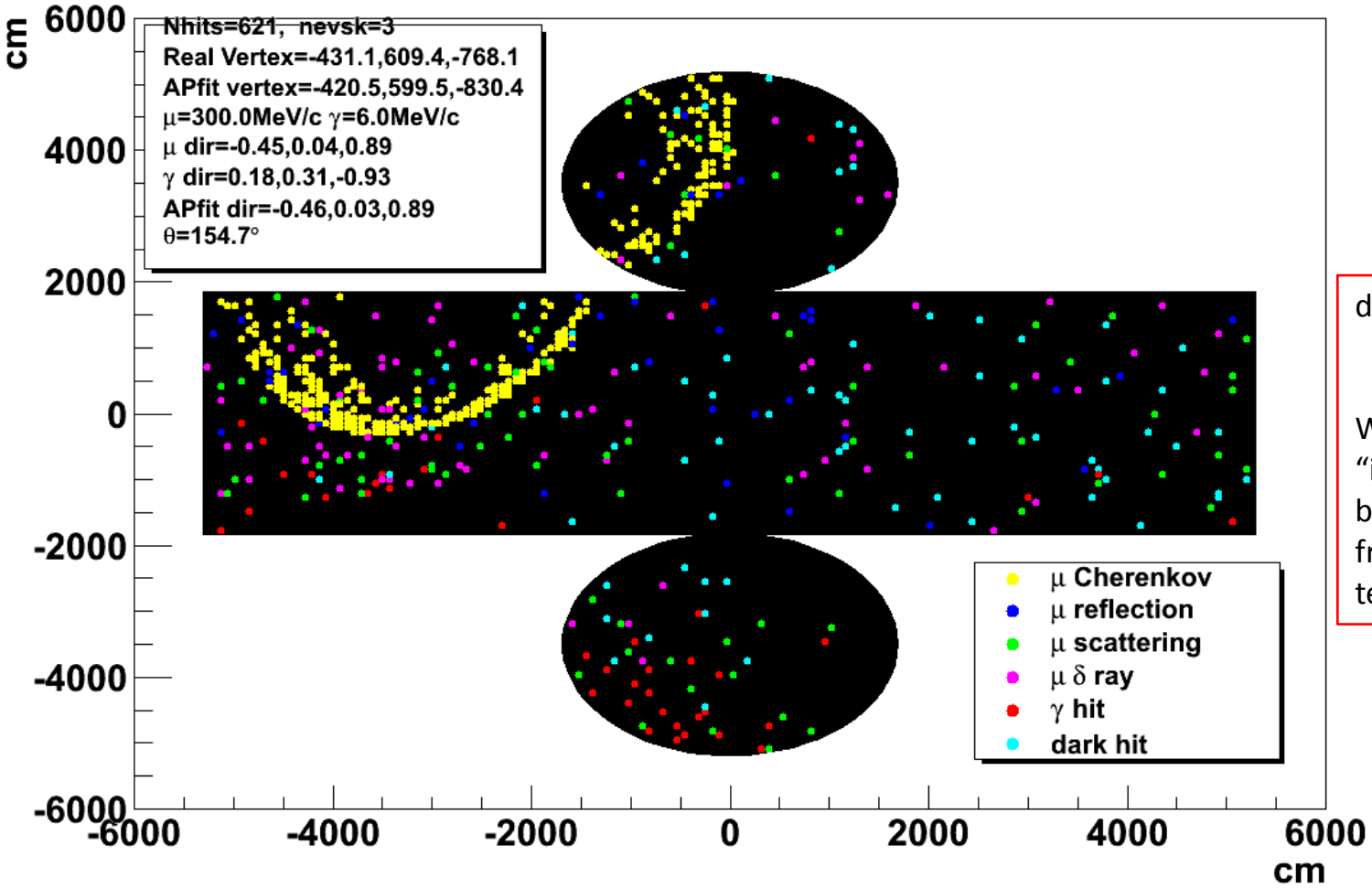
A : Br(γ) = ~40% predicted, but no direct measurement.
(Some indirect measurement by electron/proton beam has been performed)

Q : How to measure Br(γ)? / How to find isotropic ~6MeV γ in a μ event ?

A : 300MeV/c μ has ~500 hits in 1.3μs gate, while 6MeV γ has ~30 hits.
μ vertex/dir is known by reconstruction.
Use simulation to help understand.

SK EVENT DISPLAY

SK Simulation of 300MeV/c μ + 6MeV γ



delta ray basic process:

$$\mu + e \rightarrow \mu + e$$

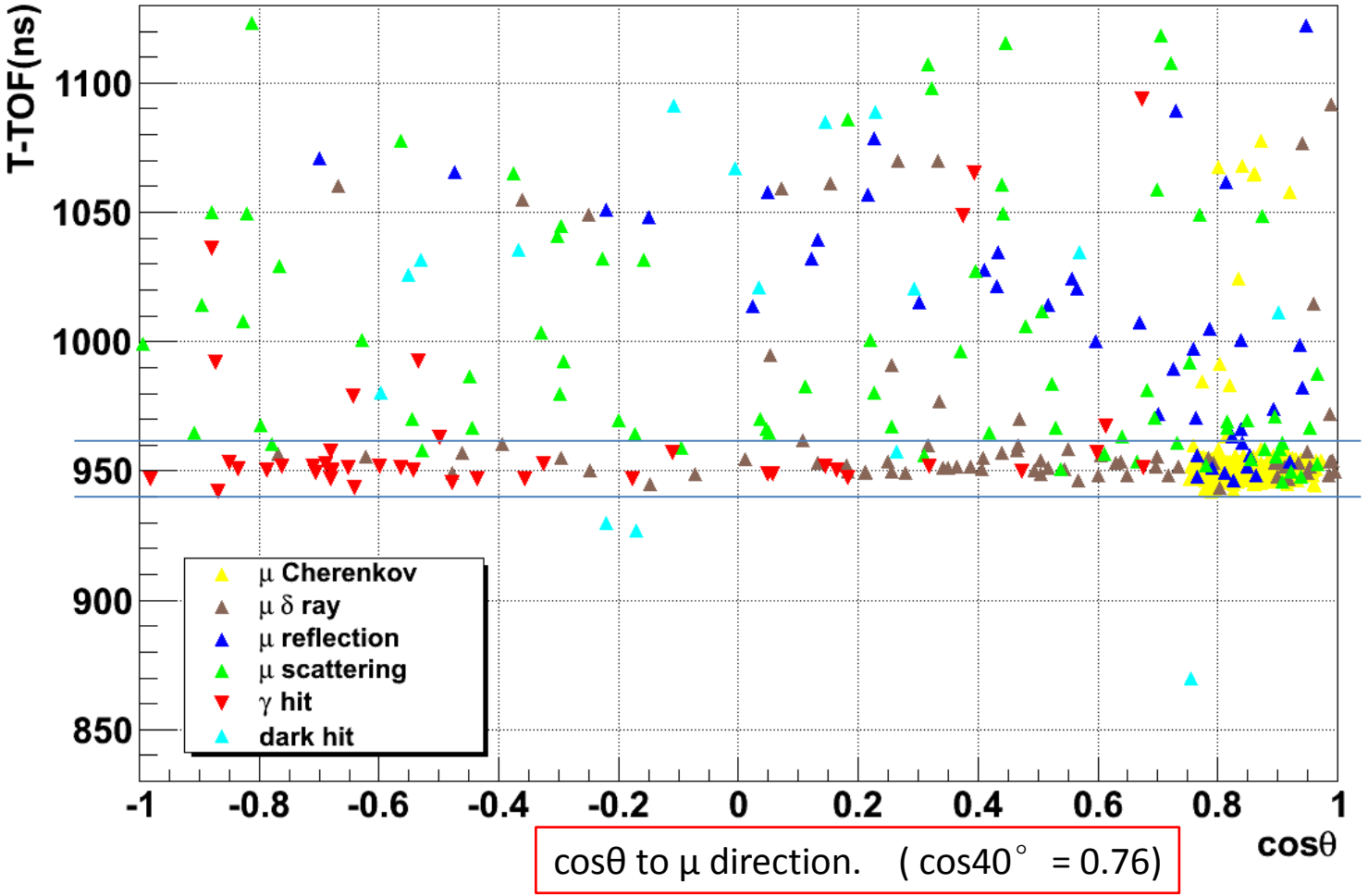
When μ loss energy by "ionization", it is really by scattering electrons from a few eV to a few tens MeV.

γ[0.18,0.31,-0.93]6.0MeV/c μ[-0.45,0.04,0.89]300.0MeV/c [-431.1cm,609.4cm,-768.1cm]

Simulation

From this Fig :

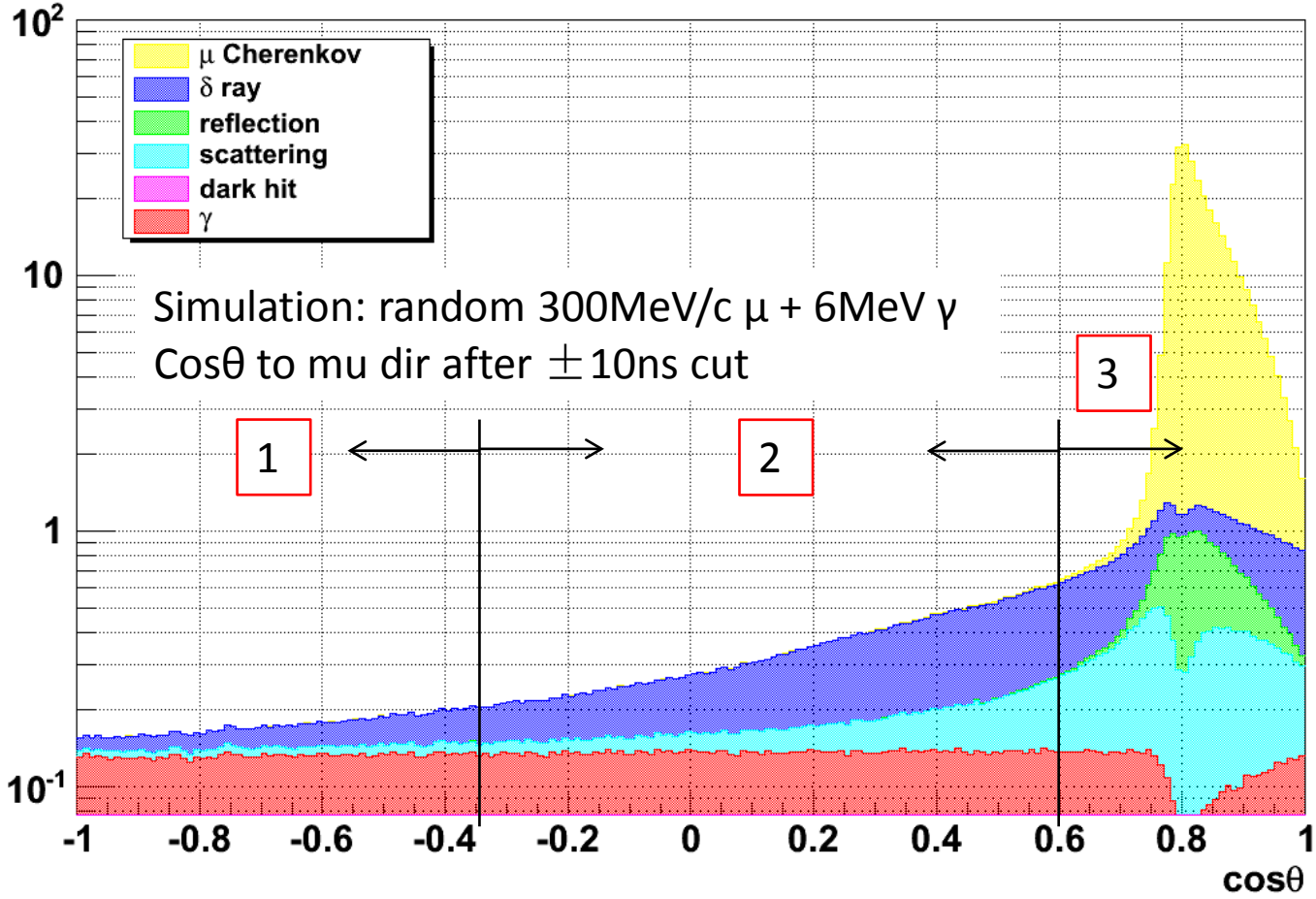
1. Reflected photons can never go to backwards half because they happen on neighbor PMTs.
2. Scattered photons are slow because their travel longer distances.
3. ±10ns T-Tof cut can remove dark/refl/scat



cosθ to μ direction. (cos40° = 0.76)

Build Likelihood from Hit Map

300MeV/c μ and 6MeV γ



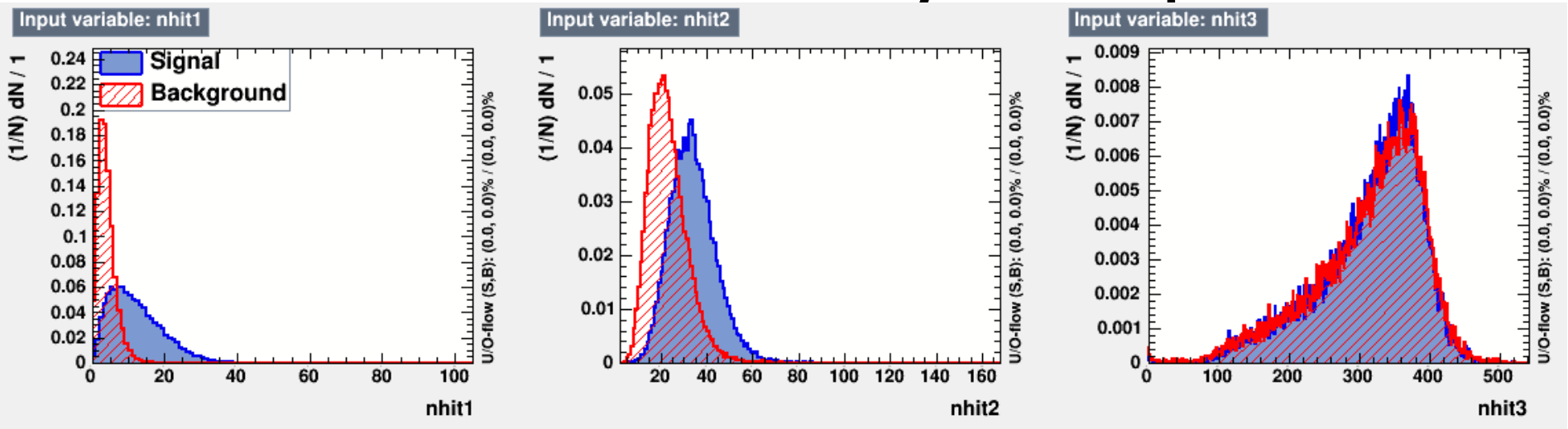
Hits in (T0-10ns, T0+10ns) can be separated into 3 categories:

1. $-1 < \cos\theta < -0.34$
Mainly γ hits, with a little delta ray hits

2. $-0.34 < \cos\theta < 0.6$
Mainly delta ray hits, with a little possible γ hits

3. $0.6 < \cos\theta < 1$
Mainly μ Cherenkov hits, with a little delta ray hits or a little possible γ hits

How to classify w/o γ



300MeV/c μ simulation, BG means no γ events, SG is generated with uniform 6MeV/c γ

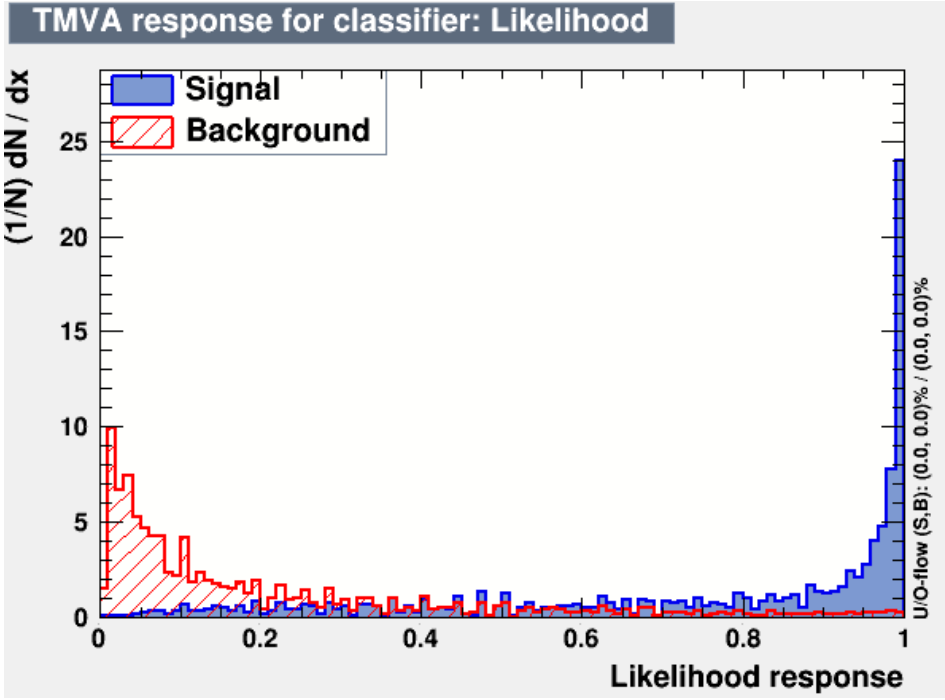
nhit1 : hits number in $-1 < \cos\theta < -0.34$

nhit2 : hits number in $-0.34 < \cos\theta < 0.6$

nhit3 : hits number in $0.6 < \cos\theta < 1$

Use 1 and 2 to make likelihood (3 is too similar)

300MeV/c μ w/o γ



How to calculate Br(γ)

Signal : CCQE with γ
BG : CCQE without γ
Eff : Cut Efficiency when cut at max significance

Br(γ) = $N_s/(N_s + N_b)$

We can observe N_{total} , but don't know N_s and N_b

$$\begin{cases} N_s + N_b = N_{total} \\ N_s \times Eff_s + N_b \times Eff_b = N'_{total} \end{cases}$$

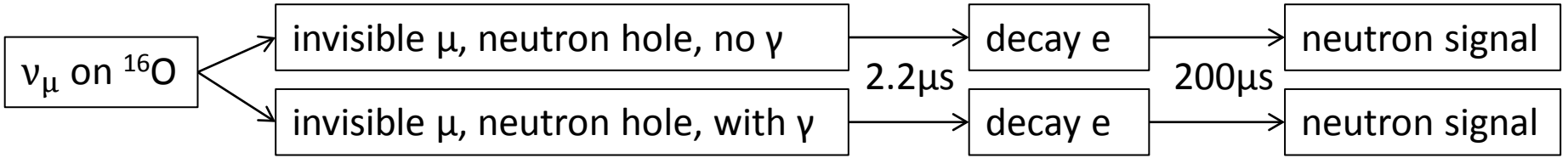
Summary & Future

1. Introduced how to measured Br(γ) of ν_μ CCQE de-excitation γ

2. Paper writing & Real data analysis in future

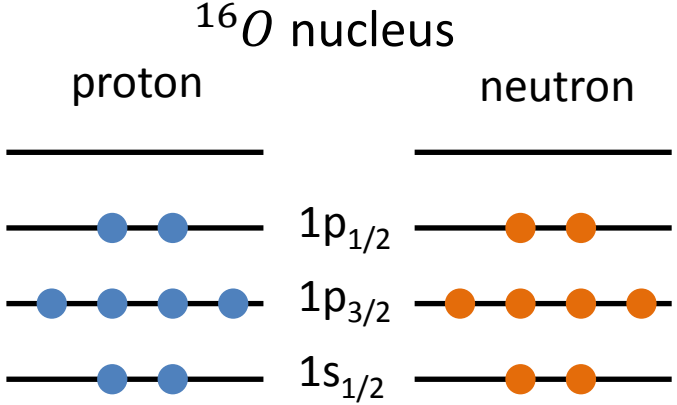
3. In this talk, I only did 6MeV γ simulation, but in real case it should be a mix of 6.18 MeV, 6.32 MeV, 9.93MeV or even secondary γ.

4. With coincident search of γ and decay e, a sample of de-excitation γ can be made. And Br(γ) measurement may be better in SK-Gd.



Backup

Oxygen de-excitation γ



de-excitation occurs when $1p_{3/2}$ or $1s_{1/2}$ is knock out.

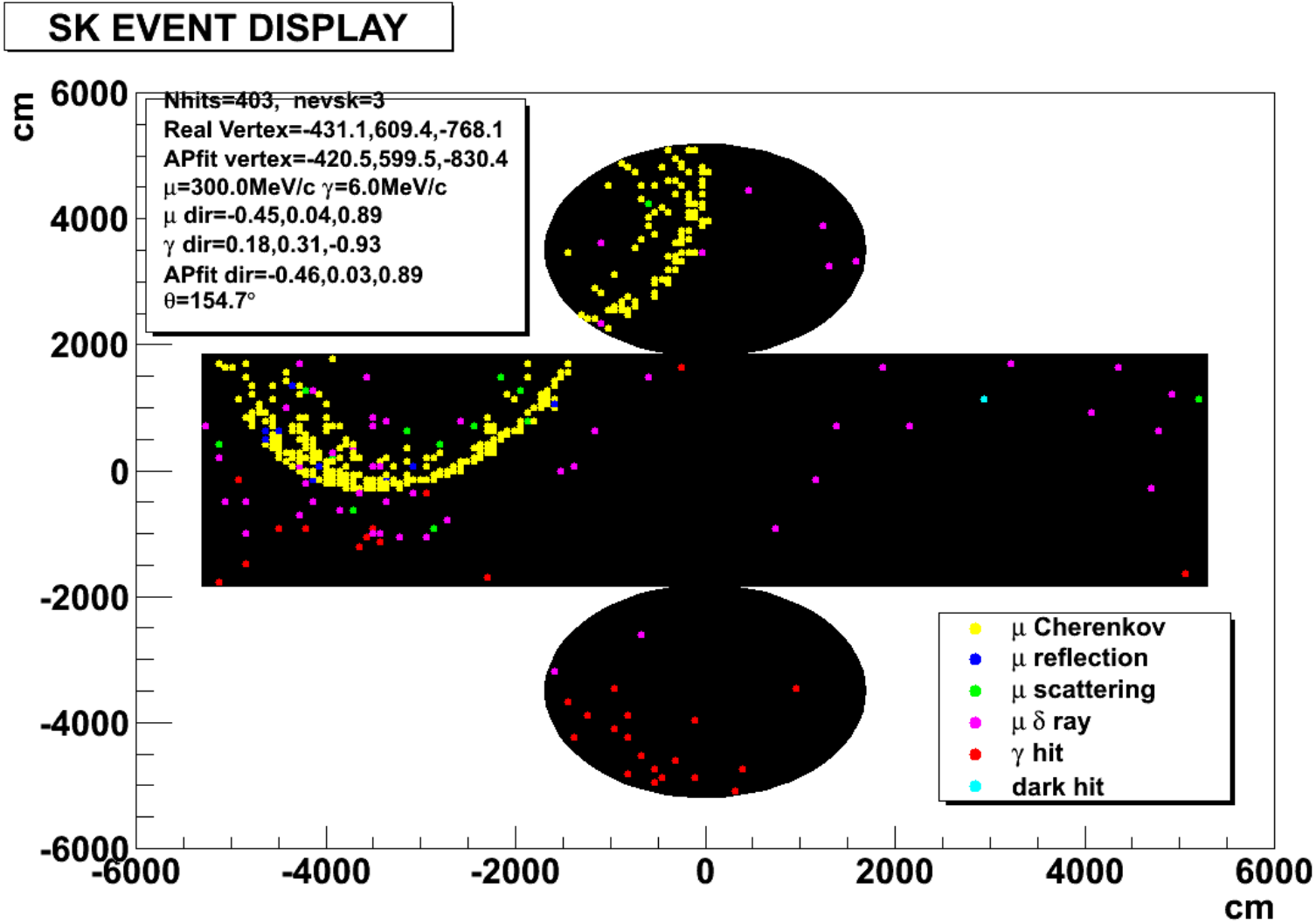
($1p_{1/2}$ case is stable)

PHYSICAL REVIEW D 90, 072012 (2014)

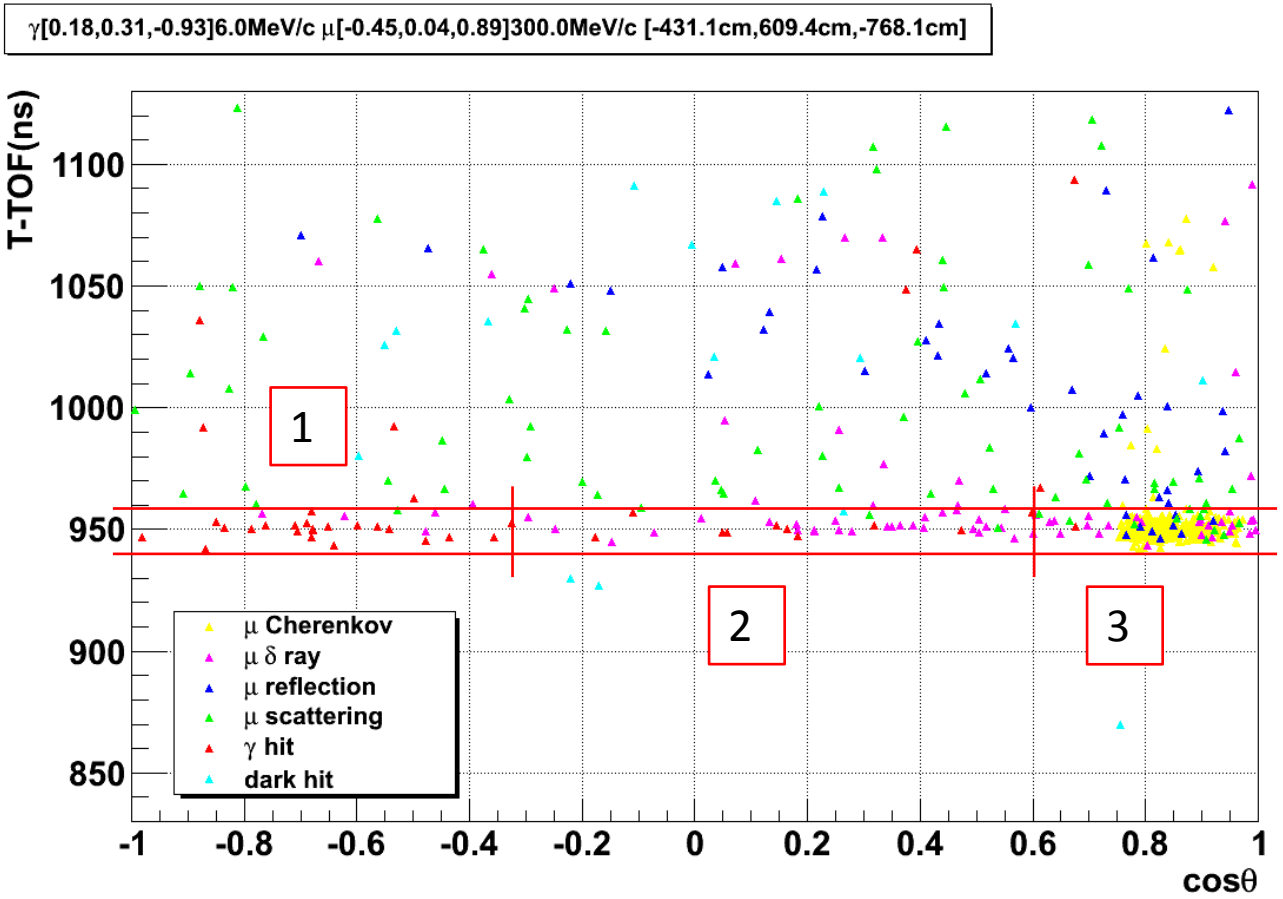
	$1p_{1/2}$	$1p_{3/2}$	$1s_{1/2}$
Spectroscopic factors	0.632	0.703	0.422
γ-ray branching ratios:			
> 6 MeV from p hole	0%	91.8%	14.7%
> 6 MeV from n hole	0%	86.9%	14.7%
3–6 MeV from either	0%	0%	27.8%

SF is from calculation, branching ratio of each state Is from electron/proton beam experiment.

Br(γ>6MeV) = 4/16 * 0.703 * 91.8% + 4/16 * 0.703 * 86.9% + 2/16 * 0.422 * 14.7% + 2/16 * 0.422 * 14.7% = 33%


SK EVENT DISPLAY
Nhits=403, nevsk=3
Real Vertex=-431.1,609.4,-768.1
APfit vertex=-420.5,599.5,-830.4
μ=300.0MeV/c γ=6.0MeV/c
μ dir=-0.45,0.04,0.89
γ dir=0.18,0.31,-0.93
APfit dir=-0.46,0.03,0.89
θ=154.7°
μ Cherenkov
μ reflection
μ scattering
μ δ ray
γ hit
dark hit
cm
6000
4000
2000
0
-2000
-4000
-6000
-6000
-4000
-2000
0
2000
4000
6000
cm

How to classify w/o γ



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