Hyper-Kamiokande and proton decay

2024/07/22

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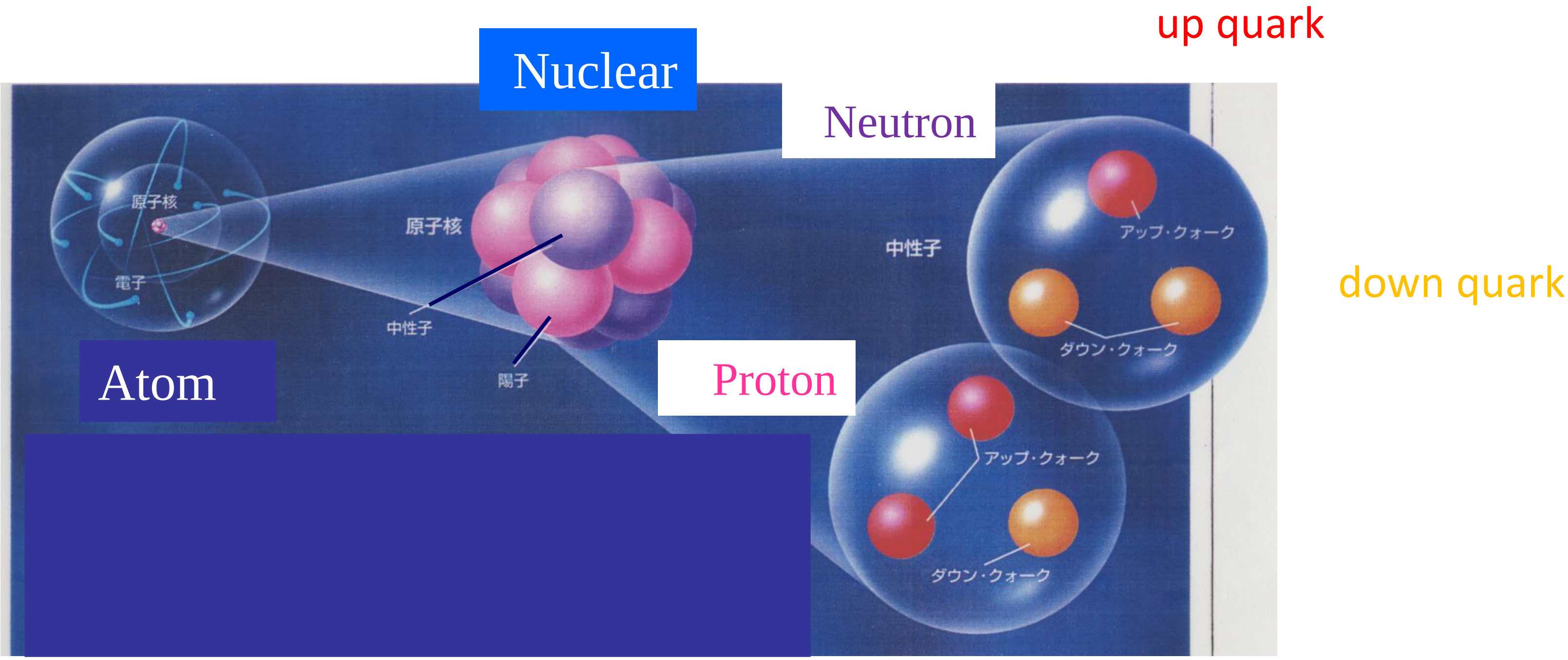
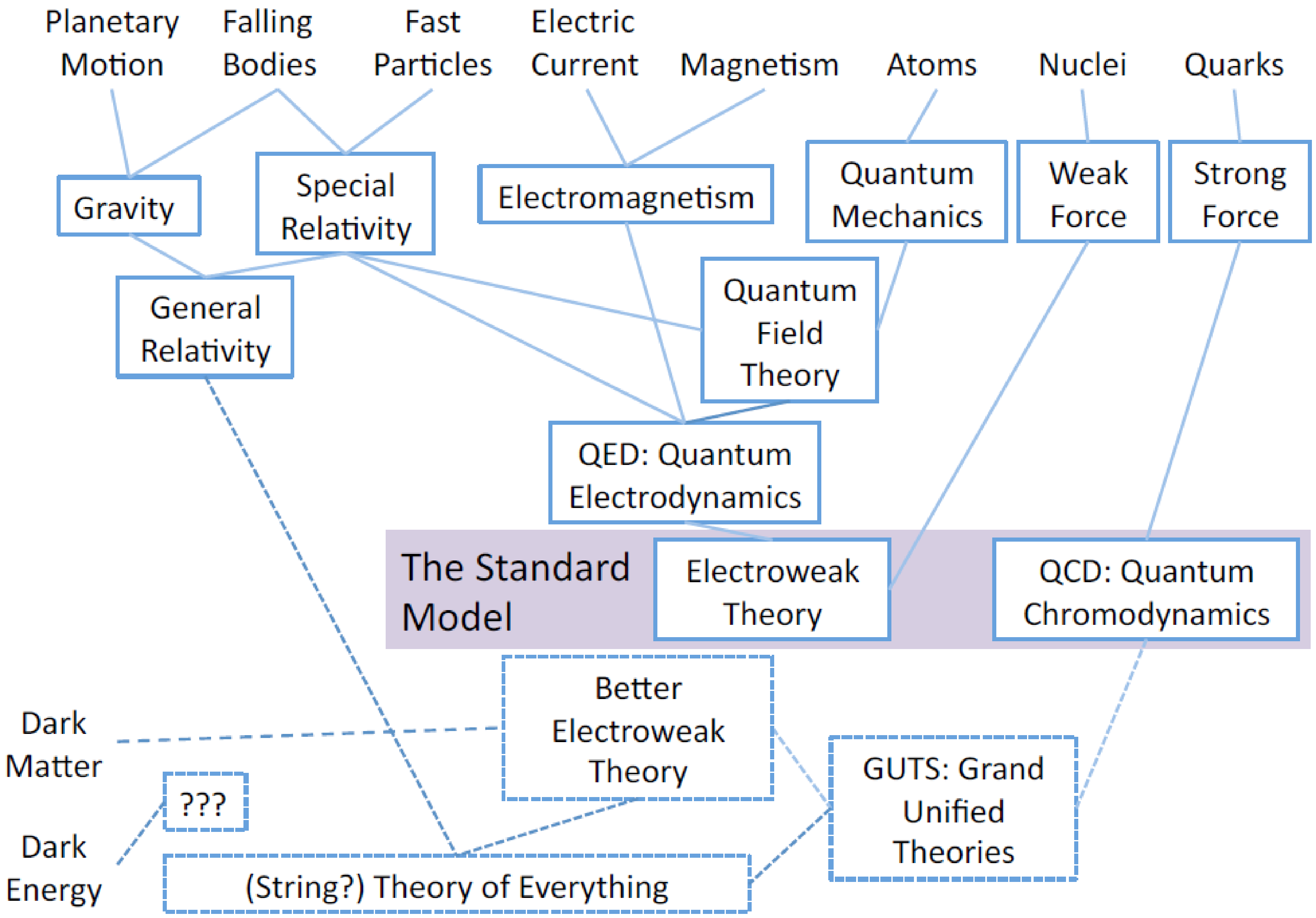
1. Does Proton Decay ?

- Nucleus consists of protons and neutrons.

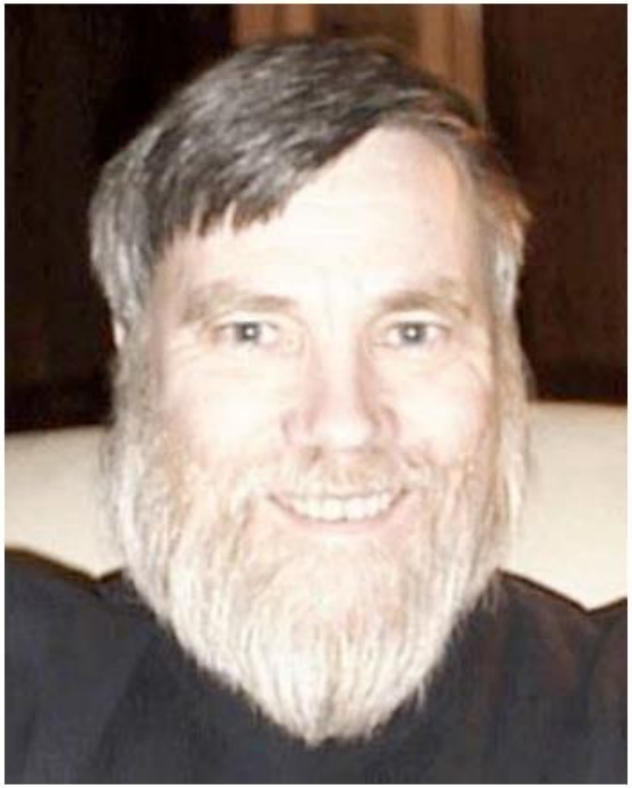

up quark
Nuclear
Neutron
原子核
電子
原子核
中性子
アップ・クォーク
down quark
中性子
ダウン・クォーク
陽子
Atom
Proton
アップ・クォーク
ダウン・クォーク

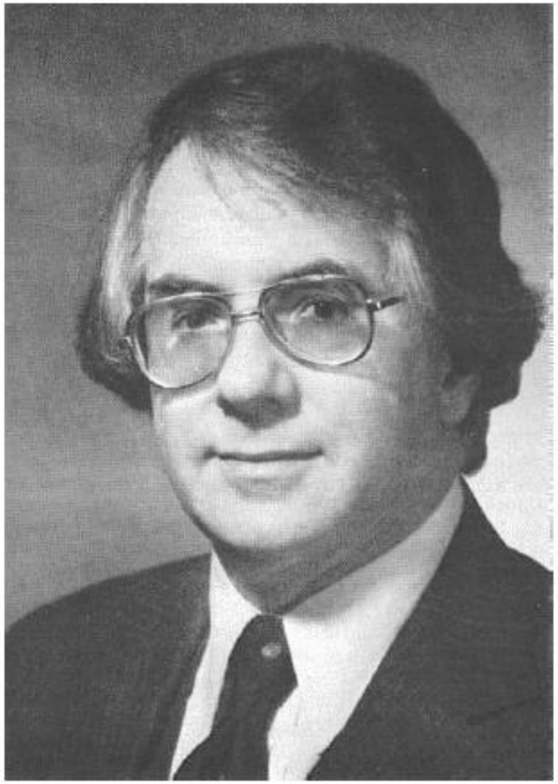
- It is well known that neutron decays spontaneously as β-decay: n → $p+e^-+\overline{\nu_e}$
  - Note that $M_n > M_p$.
- People thought proton is stable because of baryon number conservation.
  - n,p has baryon number 1.
  - We have never observed phenomena with baryon number violation.
  - Proton is the lightest baryon in the world.
  - 1929: Weyl suggests absolute stability of proton
- But is it really true ?

Can we explain everything by a single theory ?


Planetary Motion
Falling Bodies
Fast Particles
Electric Current
Magnetism
Atoms
Nuclei
Quarks
Gravity
Special Relativity
Electromagnetism
Quantum Mechanics
Weak Force
Strong Force
General Relativity
Quantum Field Theory
QED: Quantum Electrodynamics
The Standard Model
Electroweak Theory
QCD: Quantum Chromodynamics
Better Electroweak Theory
GUTS: Grand Unified Theories
Dark Matter
???
Dark Energy
(String?) Theory of Everything

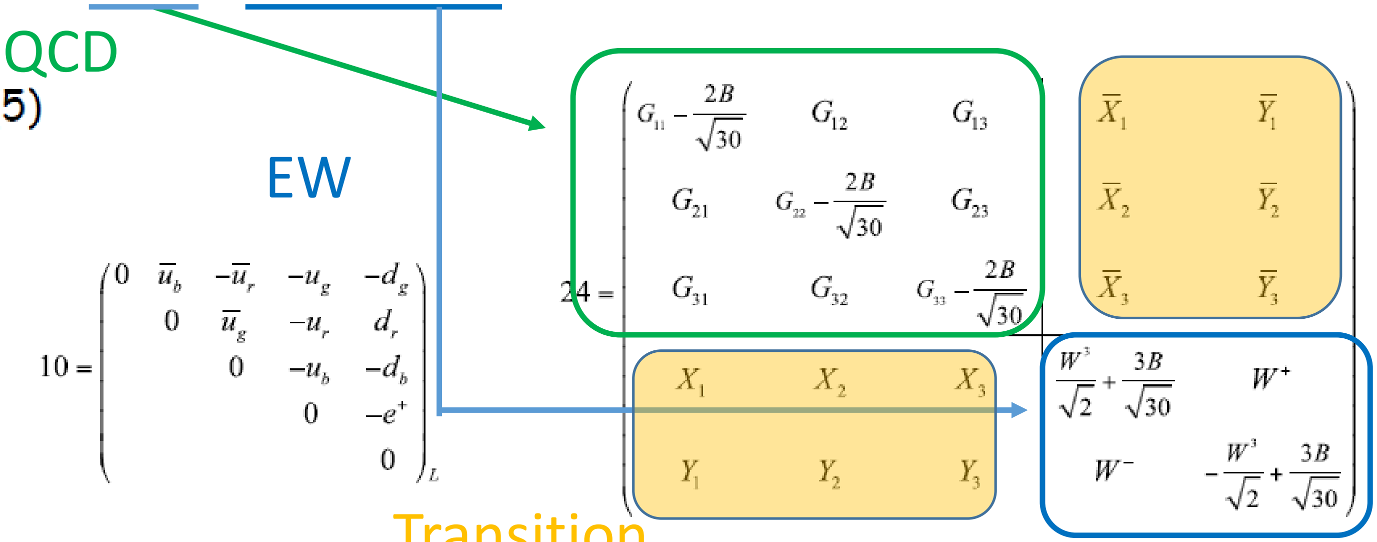
SU(5) by Georgi and Glashow (1974)





Grand Unified Theories

Assume SU(3)⊗SU(2)⊗U(1) is part of a larger symmetry group



E.g. SU(5)

$$\bar{5} = \begin{pmatrix} \bar{d}_g \\ \bar{d}_r \\ \bar{d}_b \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad 10 = \begin{pmatrix} 0 & \bar{u}_b & -\bar{u}_r & -u_g & -d_g \\ & 0 & \bar{u}_g & -u_r & d_r \\ & & 0 & -u_b & -d_b \\ & & & 0 & -e^+ \\ & & & & 0 \end{pmatrix}_L$$

$$24 = \begin{pmatrix} G_{11} - \frac{2B}{\sqrt{30}} & G_{12} & G_{13} & \bar{X}_1 & \bar{Y}_1 \\ G_{21} & G_{22} - \frac{2B}{\sqrt{30}} & G_{23} & \bar{X}_2 & \bar{Y}_2 \\ G_{31} & G_{32} & G_{33} - \frac{2B}{\sqrt{30}} & \bar{X}_3 & \bar{Y}_3 \\ X_1 & X_2 & X_3 & \frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} & W^+ \\ Y_1 & Y_2 & Y_3 & W^- & -\frac{W^3}{\sqrt{2}} + \frac{3B}{\sqrt{30}} \end{pmatrix}$$

Transition between lepton and quark !

generators

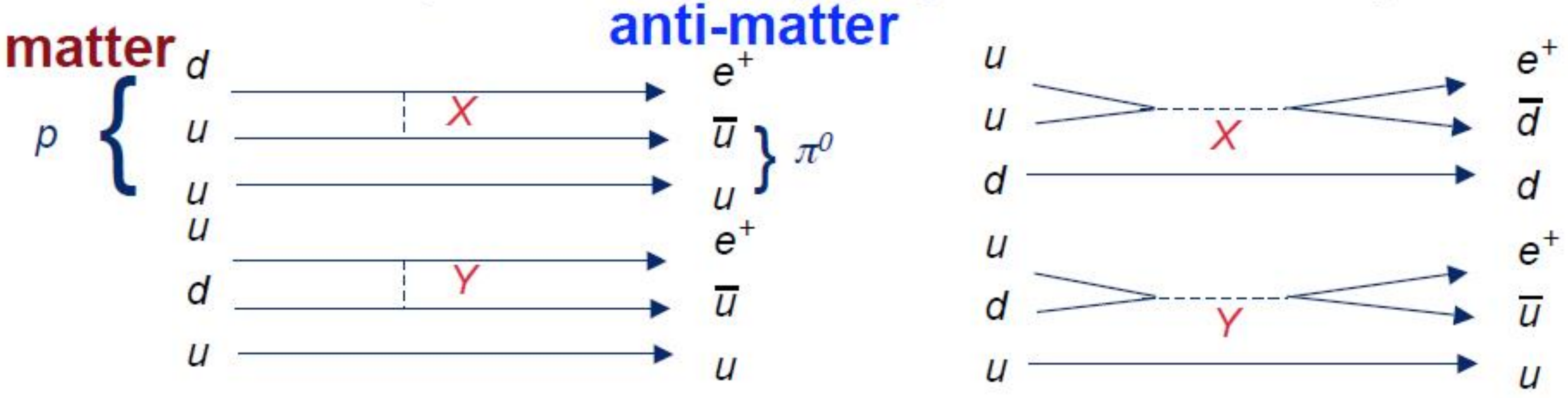
Consequences:

- Single (unified) coupling
- Charge quantization: $Q_d=Q_e/3$, $Q_u=-2Q_d$ ⇒ $Q_p = -Q_e$
- New gauge interactions (X, Y bosons) ⇒ proton decay

Proton Decay in SU(5)
By Georgi and Glashow (1974)

- Decay mechanisms

dominated by the dimension=6 op. gauge boson mediated decays


matter
anti-matter
p
d
u
u
X
e⁺
ū
u
π⁰
u
d
u
Y
e⁺
ū
u
u
u
d
X
e⁺
d̄
d
u
d
u
Y
e⁺
ū
u

($X^{\pm 4/3}$, $Y^{\pm 1/3}$: new gauge bosons)

- Predictions

$$\tau/B\ (p \rightarrow e^{+}\pi^{0}) = 4 \times 10^{29\pm1.7}\ \text{years},\quad B\ (p \rightarrow e^{+}\pi^{0}) \approx 40 \sim 60\ \%$$

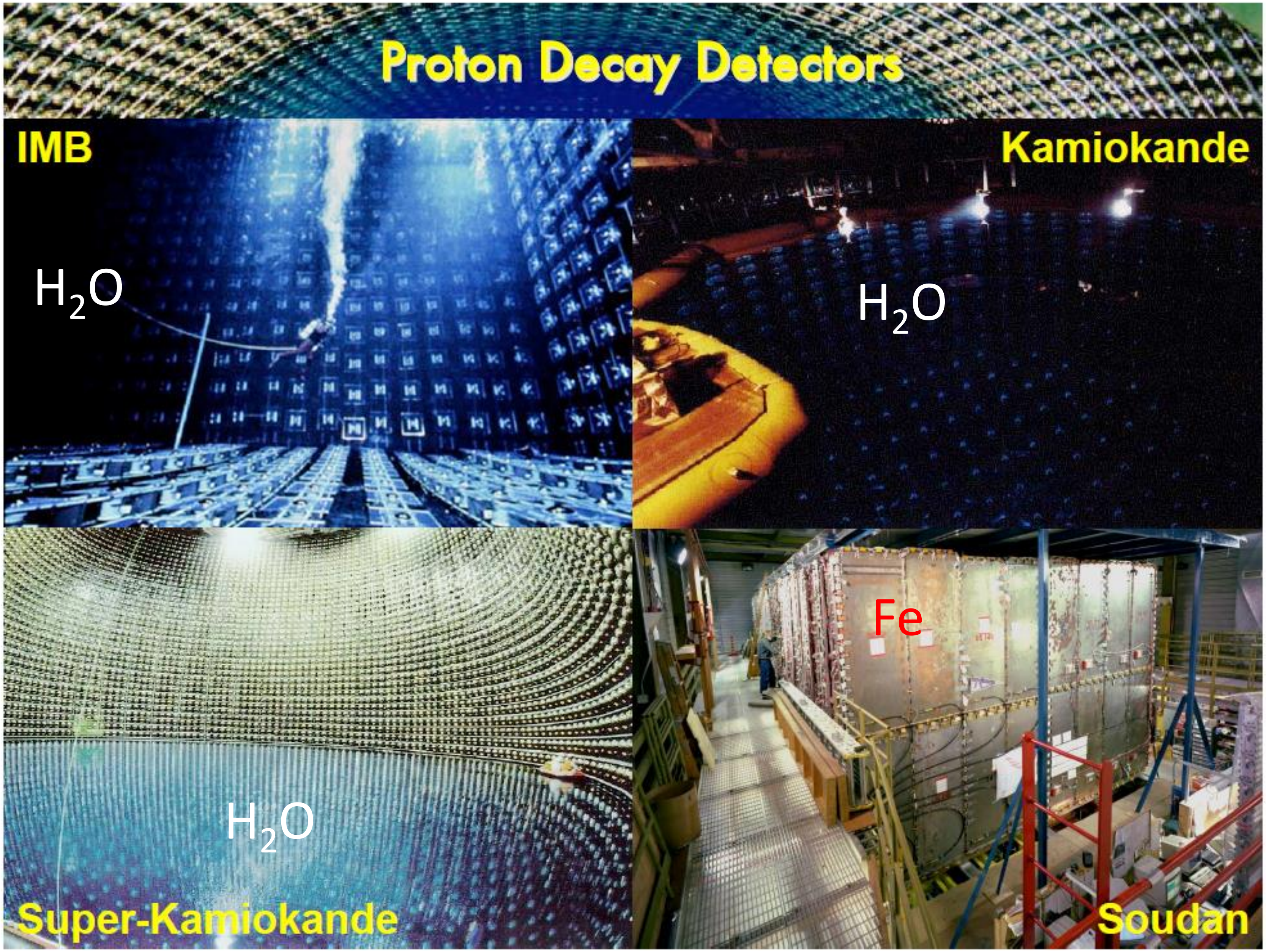
$p \rightarrow e^{+}\pi^{0}$ became the most famous and popular decay mode.

2. How to find proton decay

- Watch a proton for very long time (> 10^{30} years).
  - Age of the universe: ~ 10^{10} years
  - Obviously impossible.

OR

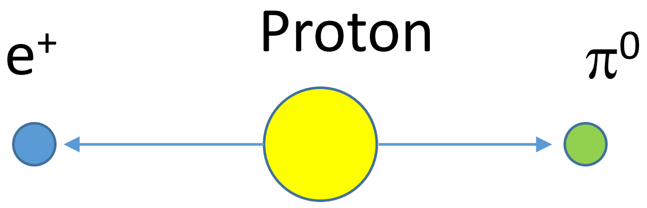
- Watch many protons for (relatively) short time.
  - Lifetime τ: $N(t)=N(t=0)\exp(-t/\tau)$
  - Need huge detector !


Proton Decay Detectors
IMB
Kamiokande
H2O
H2O
Fe
H2O
Super-Kamiokande
Soudan

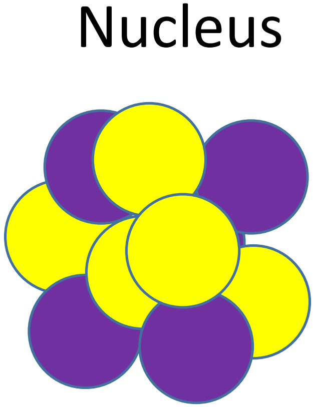
Higher sensitivity in Water Cherenkov Detectors

2. Dominant decay mode: $p \rightarrow e^+\pi^0$

What’s important for $p \rightarrow e^+\pi^0$?



In “free” proton case, e^+ and π^0 emit in back-to-back. Energy corresponding to proton mass is fully used.

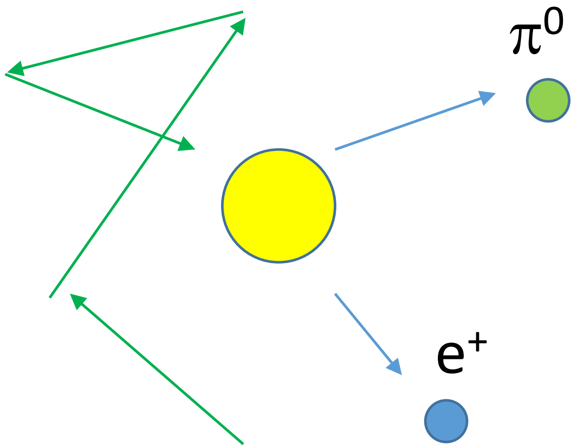


What happens if a bound proton in nucleus decays ?

Inefficiencies and uncertainties of proton decay search come from nuclear effect !

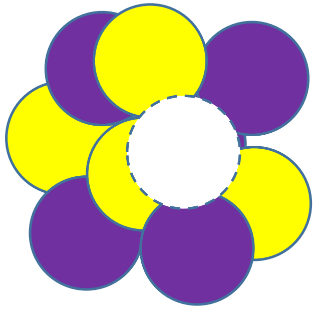
Key 1: Proton never stops in nucleus

- Protons don’t exist locally in nucleus. It is always moving in the nuclear potential (Fermi motion, $p_f \sim 225$ MeV/c).



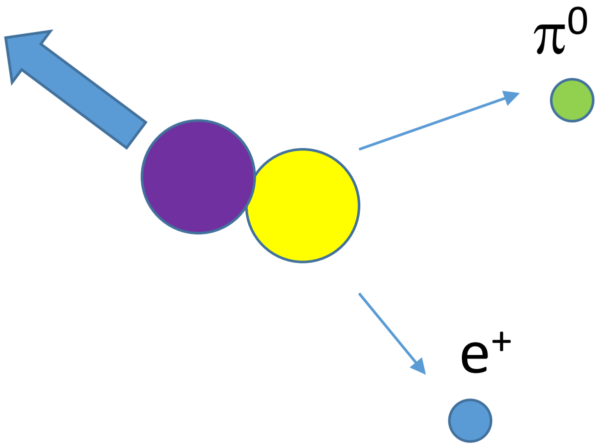
Key 2: Binding energy

- Energy corresponding proton mass should be used for compensating its binding energy (s-state: ~40 MeV, p-state:15 MeV in Oxygen).



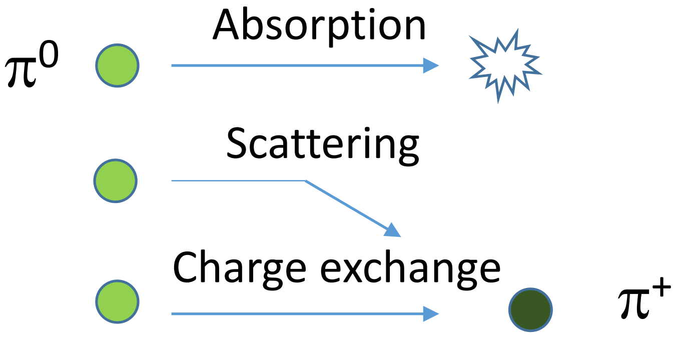
Key 3: Proton strongly binding to other nucleus

- ~ 20% protons are strongly binding to other nucleon which also bring energy when the proton decays (correlated decay)



Key 4: π interacts in nucleus

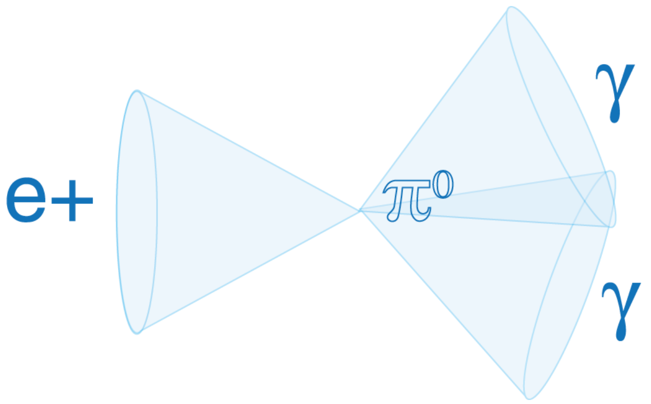
- Mesons (π,K, e.t.c.) in decay products are affected in nuclear interactions before exiting nucleus.


π^0
Absorption
Scattering
Charge exchange
π^+

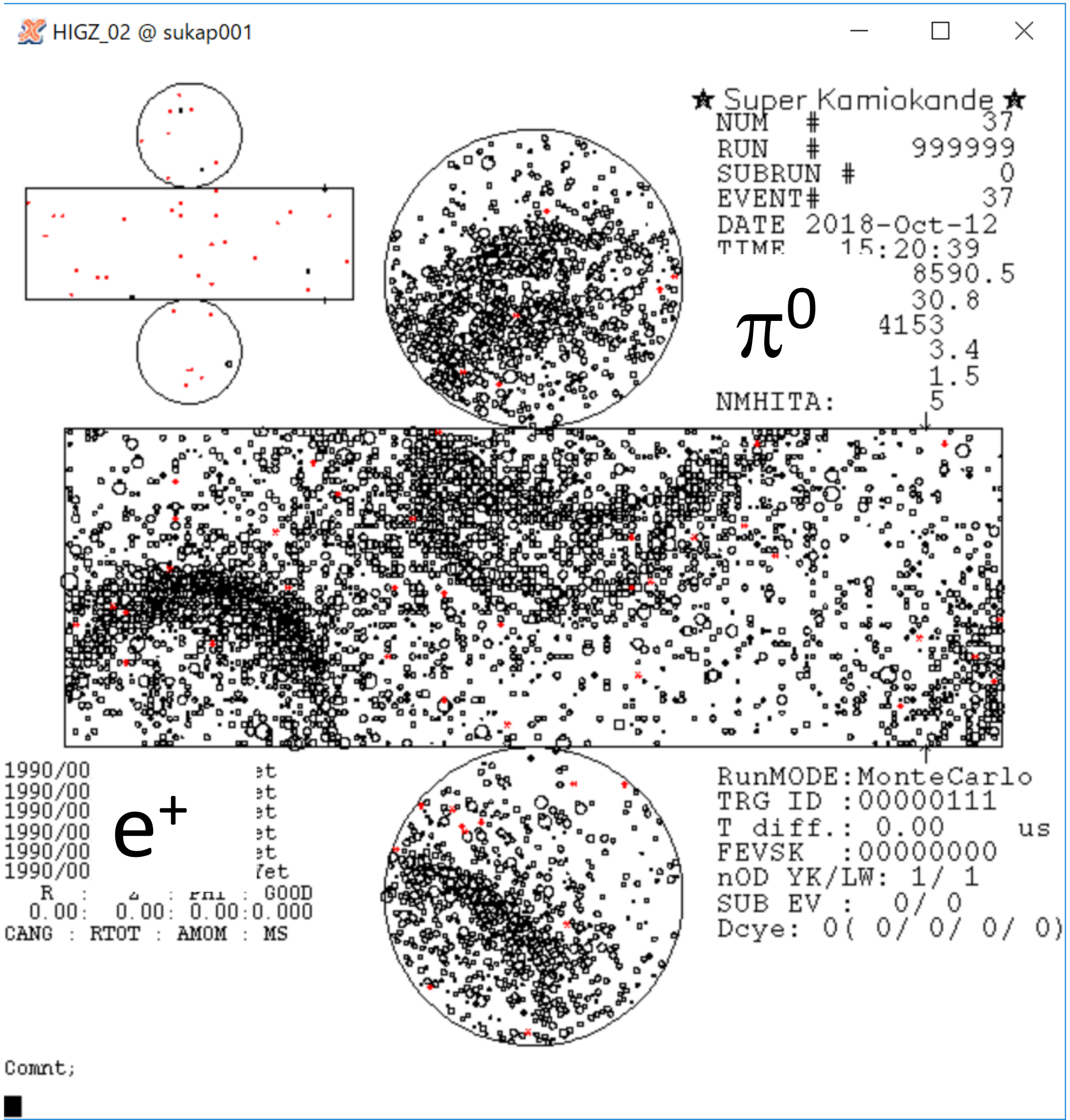
Why water is used for proton decay search ?

- Easy to construct larger detector.
  - ➢ Much cheaper than iron.
  - ➢ You can find large water tank everywhere (common technology).
- High efficiency and low uncertainty.
  - ➢ H_2O has two hydrogens which are not affected by nuclear effect . They are regarded as "free" proton.
    - ✓ Bound proton: ~ 200 MeV/c ~ 0.2c =6×10^7 m/s
    - ✓ velocity of molecular in liquid ~ 10^2 m/s
  - ➢ Free protons contribute high selection efficiency and low uncertainty.

How look like p→$e^+\pi^0$ in SK ?



Three e-like rings should be observed.



```
★ Super Kamiokande ★
NUM    #           37
RUN    #       999999
SUBRUN #            0
EVENT#             37
DATE  2018-Oct-12
TIME    15:20:39
              8590.5
              30.8
           4153
                3.4
                1.5
NMHITA:         5
```

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1990/00          et
1990/00          et
1990/00          et
1990/00          et
1990/00          et
1990/00         Yet
   R  :    Z   : PHI  : GOOD
  0.00:   0.00:  0.00:0.000
CANG  : RTOT  : AMOM  : MS
```

```
RunMODE:MonteCarlo
TRG ID :00000111
T diff.: 0.00      us
FEVSK  :00000000
nOD YK/LW: 1/ 1
SUB EV :  0/ 0
Dcye: 0( 0/ 0/ 0/ 0)
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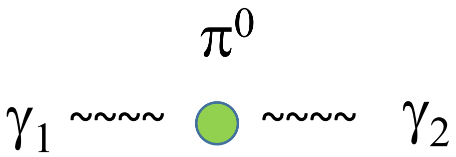
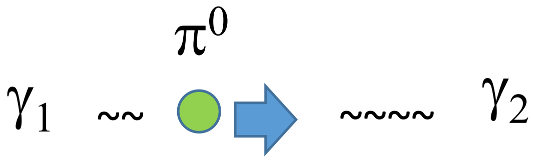
Comnt;
█
```

Stopped π^0 case


π^0
γ_1 ~~~~ ~~~~ γ_2

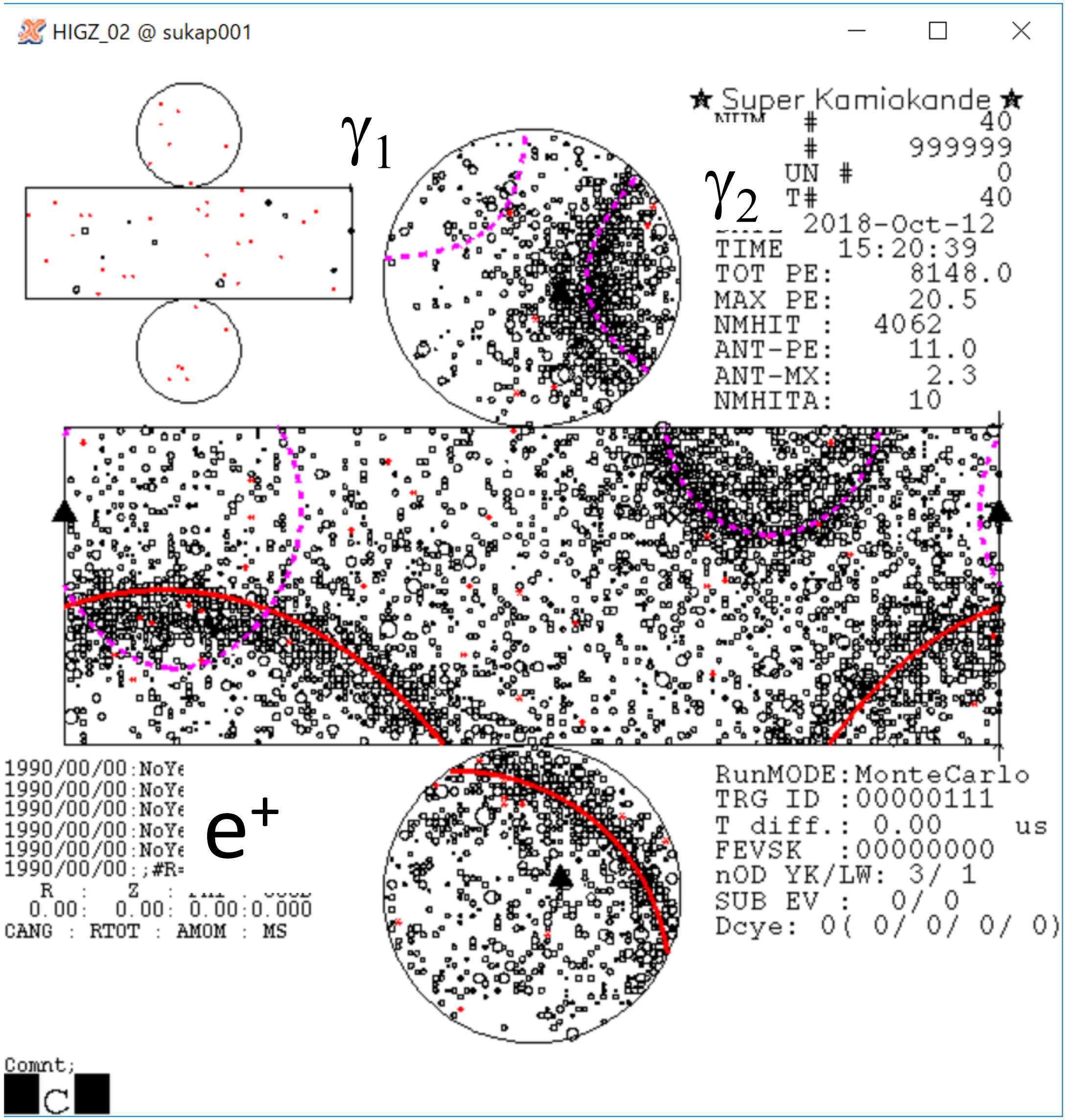
$E_1 = E_2$

If a γ is emitted π^0 direction


π^0
γ_1 ~~ ~~~~ γ_2

$E_1 < E_2$

Sometimes one γ is failed to reconstruct and observed only two rings.


HIGZ_02 @ sukap001
γ_1
γ_2
e^+
Comnt;
C

```
★ Super Kamiokande ★
       #          40
       #      999999
    UN #           0
    T#            40
     2018-Oct-12
TIME     15:20:39
TOT PE:       8148.0
MAX PE:       20.5
NMHIT :    4062
ANT-PE:       11.0
ANT-MX:        2.3
NMHITA:       10
```

```
1990/00/00:NoYe
1990/00/00:NoYe
1990/00/00:NoYe
1990/00/00:NoYe
1990/00/00:NoYe
1990/00/00:;#R=
   R  :   Z  :
  0.00:  0.00:  0.00:0.000
CANG : RTOT : AMOM : MS
```

```
RunMODE:MonteCarlo
TRG ID :00000111
T diff.: 0.00      us
FEVSK  :00000000
nOD YK/LW: 3/ 1
SUB EV :  0/ 0
Dcye: 0( 0/ 0/ 0/ 0)
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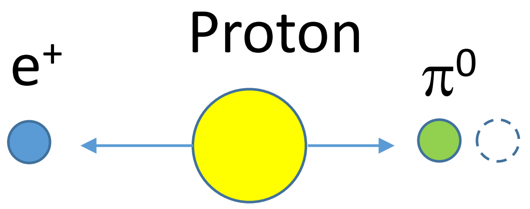
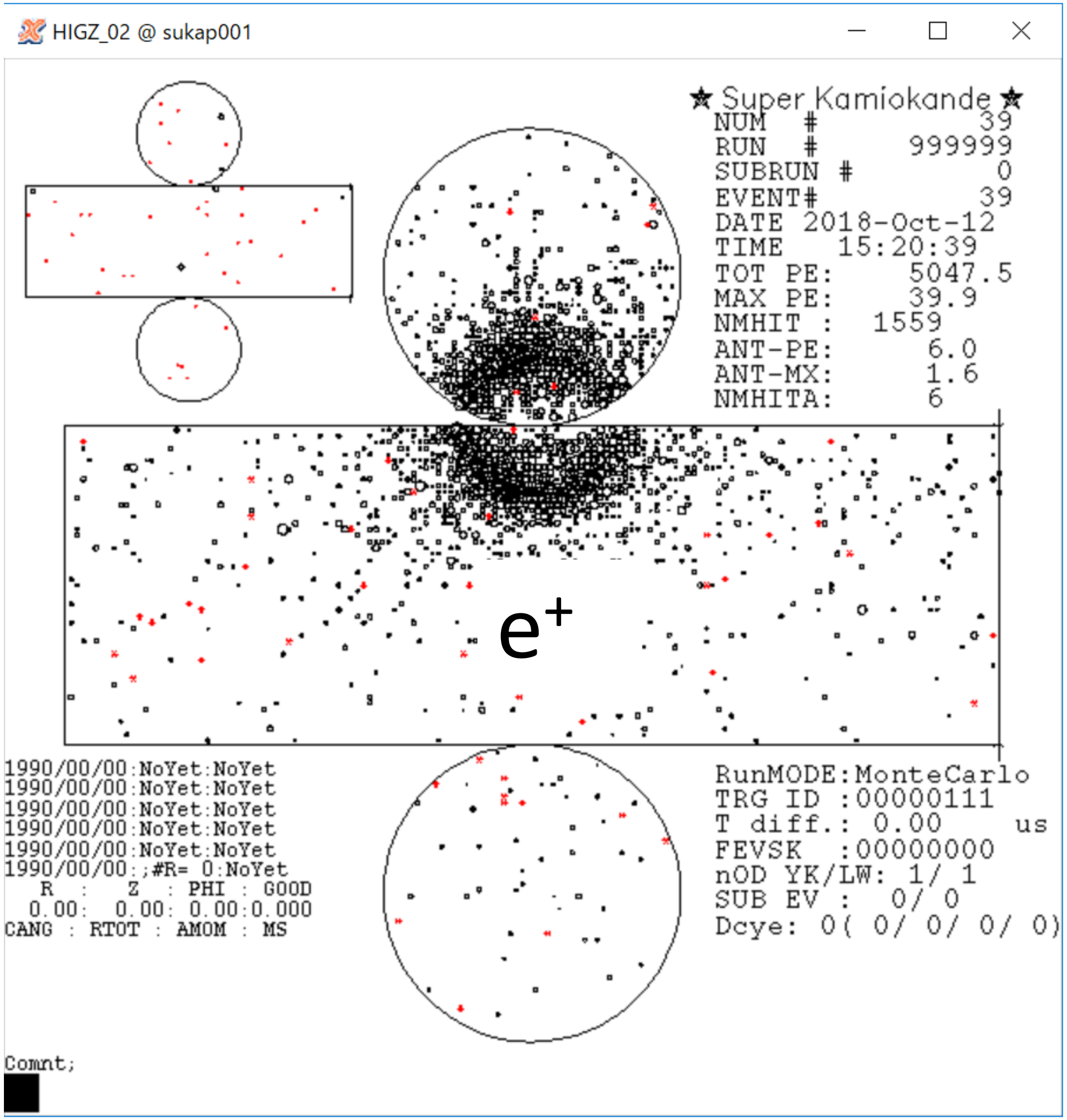


If π^0 is absorbed before exiting nucleus, only e$^+$ is observed (one ring).



```
★ Super Kamiokande ★
NUM    #           39
RUN    #       999999
SUBRUN #            0
EVENT#             39
DATE 2018-Oct-12
TIME     15:20:39
TOT PE:       5047.5
MAX PE:         39.9
NMHIT :     1559
ANT-PE:          6.0
ANT-MX:          1.6
NMHITA:          6
```

```
1990/00/00:NoYet:NoYet
1990/00/00:NoYet:NoYet
1990/00/00:NoYet:NoYet
1990/00/00:NoYet:NoYet
1990/00/00:NoYet:NoYet
1990/00/00:;#R= 0:NoYet
   R  :    Z   : PHI  : GOOD
  0.00:   0.00:  0.00:0.000
CANG : RTOT : AMOM : MS
```

```
RunMODE:MonteCarlo
TRG ID :00000111
T diff.:  0.00      us
FEVSK  :00000000
nOD YK/LW: 1/ 1
SUB EV  :   0/ 0
Dcye:  0( 0/ 0/ 0/ 0)
```

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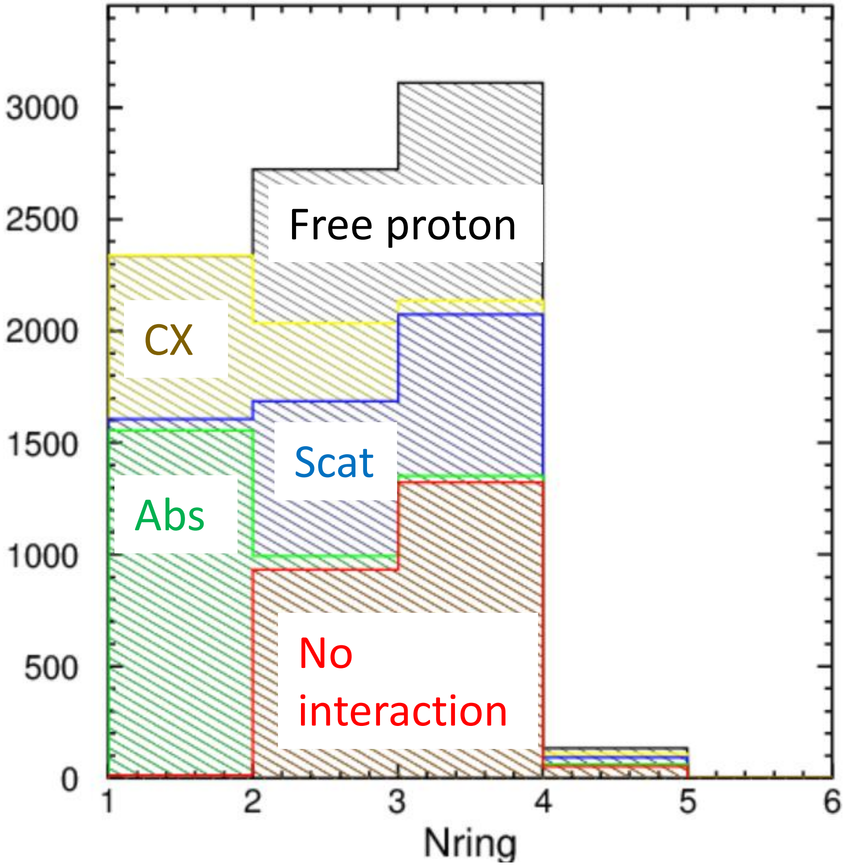
Comnt;
```

Observed number of ring for p→$e^+\pi^0$



Free proton: H in H_2O

No interaction in Nucleus

Abs: π^0 absorption in Nucleus

Scat: scattered

CX: charge exchange

($\pi^0 \rightarrow \pi^{\pm}$, below threshold)

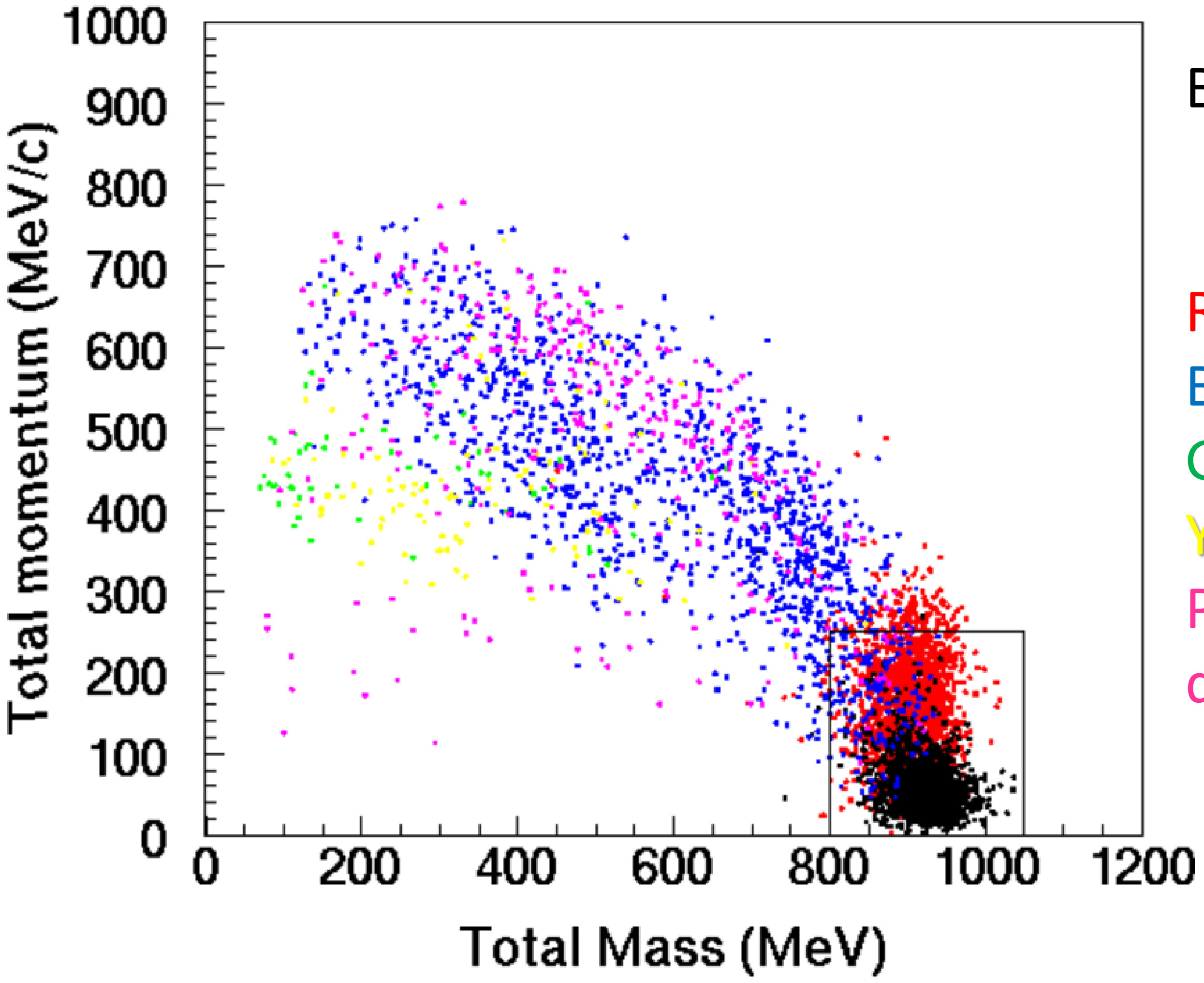
Choose 2 or 3 rings.

Selection criteria for $p \rightarrow e^+\pi^0$

1. Event vertex should be located 1 m inward from the tank wall (fiducial volume cut, 27.2kton).
2. 2 or 3 ring event.
3. All ring should be e-like (Particle IDentification).
4. No Michel electrons.
5. Reconstruct π^0 mass for 3 ring events. It should be $85 < M\pi^0 < 185$ MeV/c^2
6. Reconstruct total mass and momentum should be $800 < M_{tot} < 1050$ MeV/c^2, $P_{tot} < 250$ MeV/c.

Total mass vs Total momentum for p→$e^+\pi^0$

- Selection efficiency ~ 40 %
- Inefficiency is dominated by unavoidable physics processes.



Black: Free proton

Bound proton

Red: No π interaction

Blue: π scatter

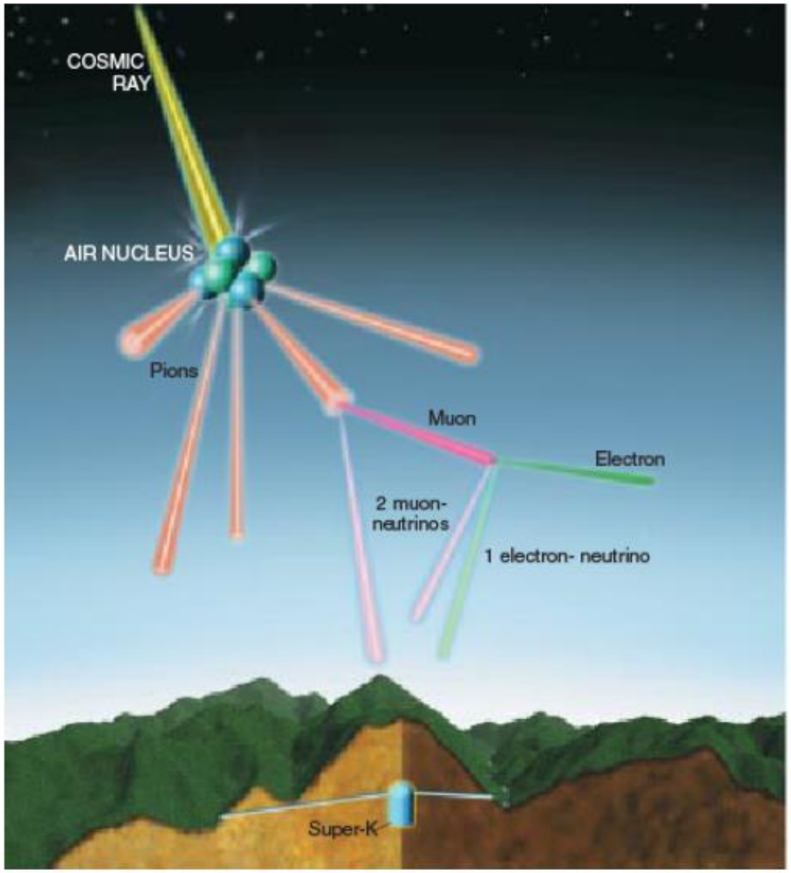
Green: π absorption

Yellow: π CX

Purple: Correlated decay

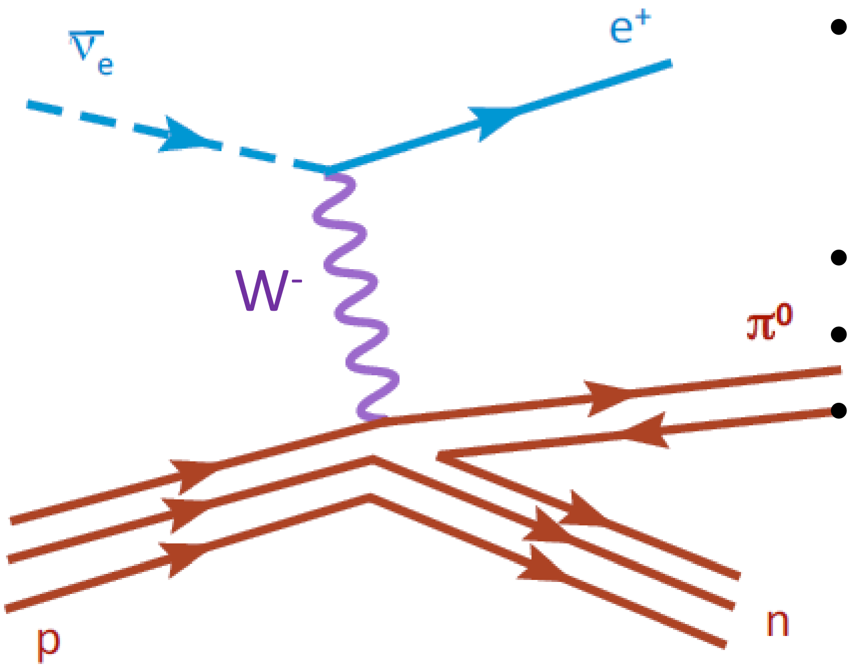
2-2. What's Background events for proton decay searches ?

- Atmospheric neutrino is dominant backgrounds for proton decay searches.
    - ➢ Visible energy ~ 1 GeV.
    - ➢ Solar or SN ν is too low energy.
    - ➢ Cosmic ray μ are rejected by outer detector.


COSMIC RAY
AIR NUCLEUS
Pions
Muon
Electron
2 muon-neutrinos
1 electron- neutrino
Super-K

Typical background for p→$e^+\pi^0$

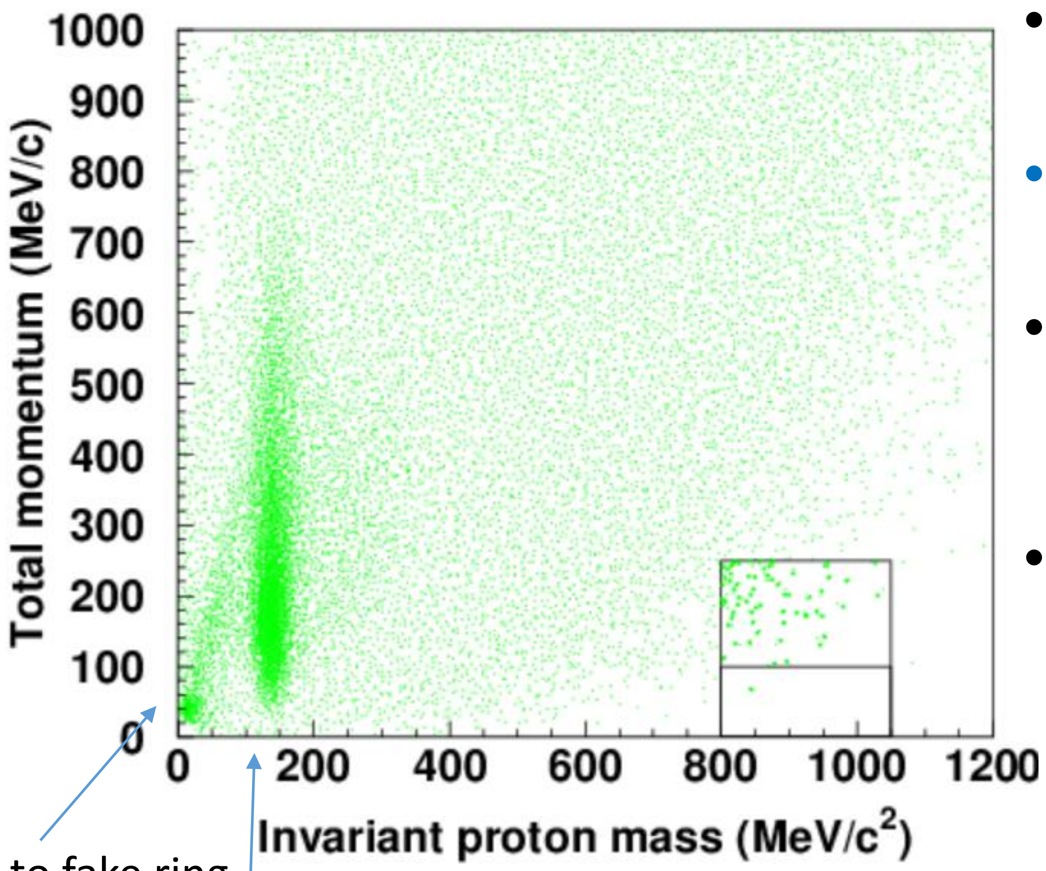
Charged current π^0 production



- Exchange W boson between ν and proton (charged current interaction).
- ν changes to e^+.
- π^0 and neutron are produced.
- Because neutron doesn't emit Chrenkov light, visible particles after the reaction are same as p→$e^+\pi^0$

Total mass vs Total momentum for atmospheric ν background MC

(After all cuts except for total mass and momentum)

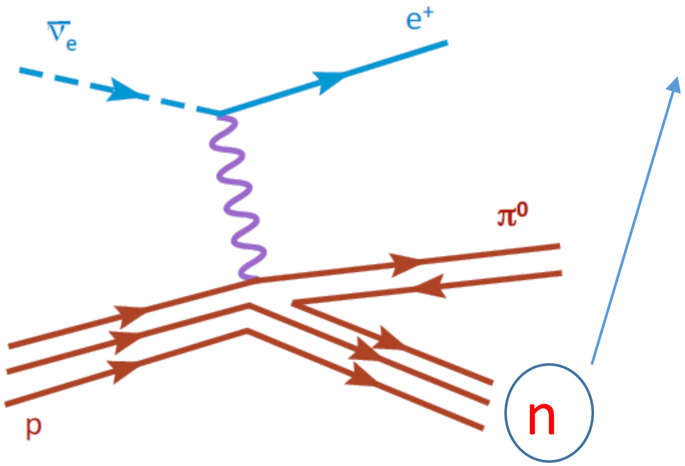


Due to fake ring

π^0 due to 2Re+e is allowed.

- Generate huge atm.n MC, 2000 year of SK!
- Expected BG:
  ~1.3 ev/Mton*yr
- Neutrino events tend to have higher total momentum.
- Almost background free in lower momentum region (<100 MeV/c).
  - ➢ The region corresponds to free proton decay.

Further background reduction

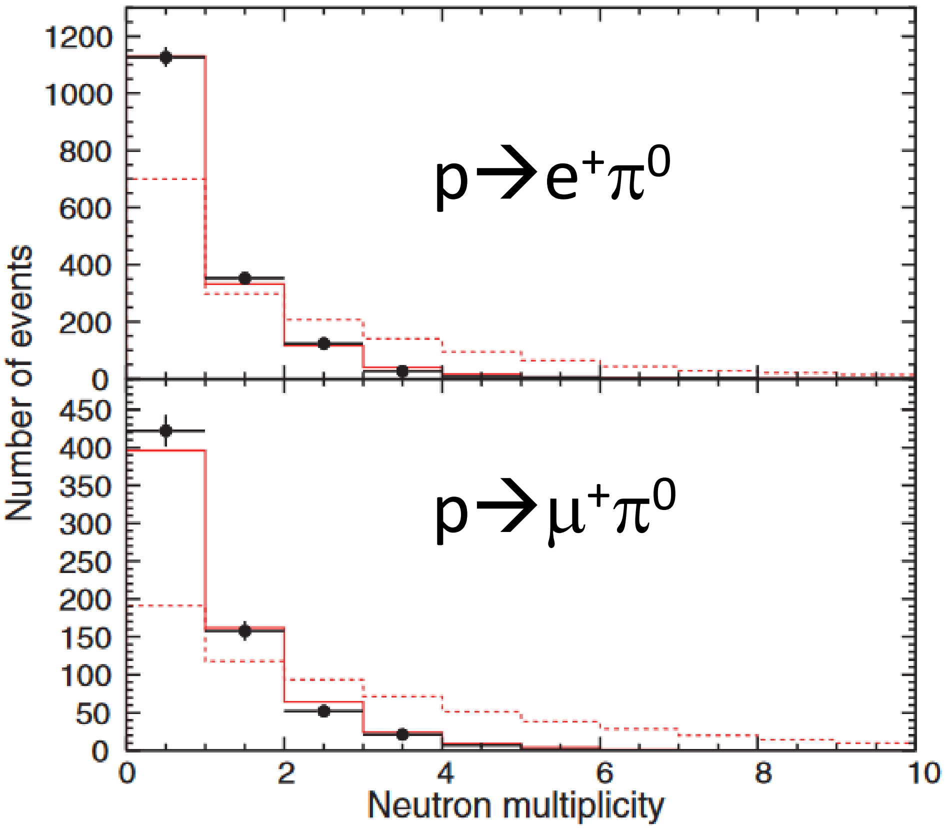


- Neutron doesn’t emit Chrenkov light.
- However, neutron is thermalized in water and finally captured by hydrogen (~200 μs);

  $n + p \rightarrow d + \gamma$ (2.2 MeV)

- If we can detect delayed 2.2 MeV γ ray, we can reduce background more.
- Neutron capture is also important for SN Relic ν and separate ν and ν-bar interactions in atmospheric n oscillation analysis.

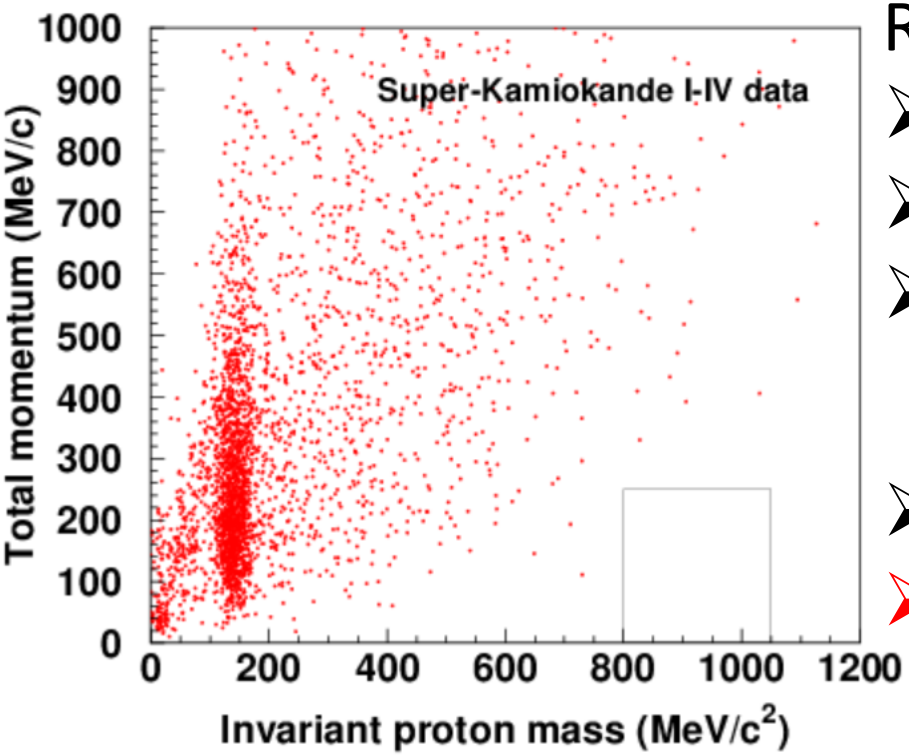
How powerful to reject background



- Sample: out of signal box in M_{tot} vs P_{tot} plot.
  - ➢ Dot: data,
  - ➢ Histogram: Atm.ν MC
    (solid: reconstructed, dash: true)
- ~ 50 % background events are rejected with neutron=0.
- On the other hand, ~ 7.5 % of $p \rightarrow e^+\pi^0$ are accompanied with neutron from deexcitation of nucleus. Neutron tagging reduces a few % in selection efficiency.

2-3. SK result (so far)

- We have not find any evidences of nucleon decays !



Result of $p \rightarrow e^{+}\pi^{0}$

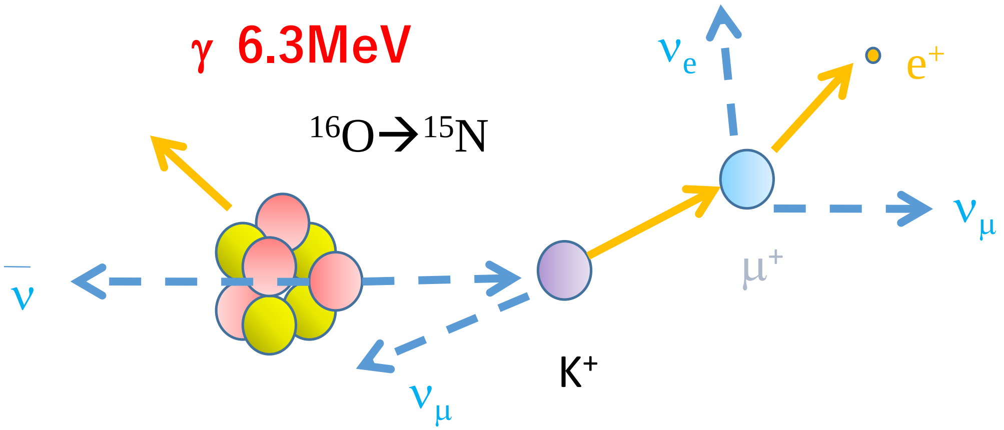
- ➢ Exposure: 450 kton・year
- ➢ Efficiency: 38.6 % (SK-IV)
- ➢ Expected BG: 0.63 events
  - 0.05 evetns in P_{tot} <100MeV/c
  - 0.58 events in 100 ~ 250 MeV/c
- ➢ Observed: 0 event
- ➢ Lower limit of proton life time: > 2.4×10^{34} years

3. SUSY favored decay mode: $p \rightarrow \nu K^+$

3-1 How to find $p \rightarrow \nu K^+$ in Water Cherenkov detector

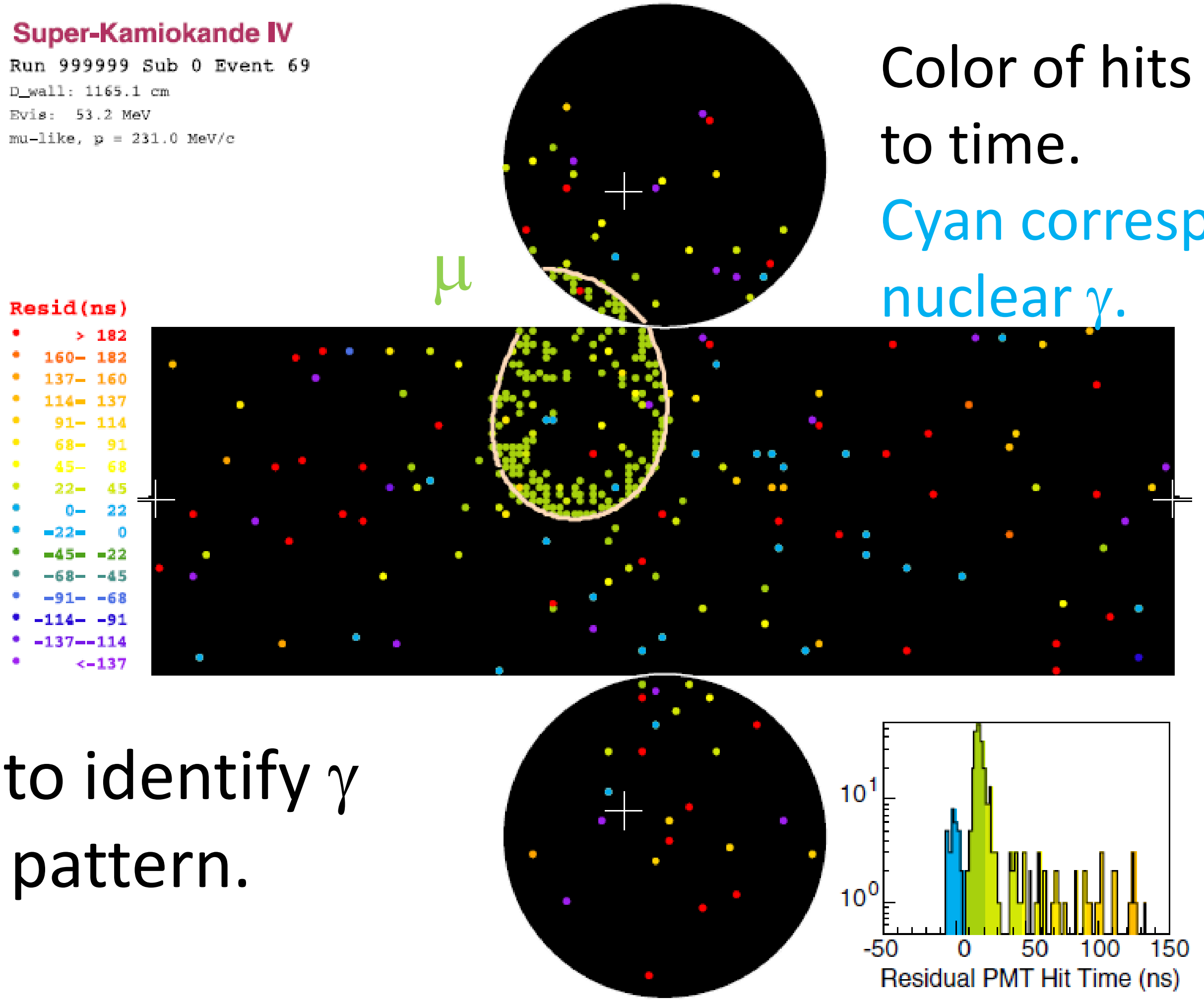
- K^+ has low momentum, most of them stop in water and decay with 12 nsec lifetime.
- Major K^+ decay mode
  - $K^+ \rightarrow \nu\mu^+$: 64 %
  - $K^+ \rightarrow \pi^+\pi^0$: 21 %
- "Stopping K^+" means two body decay products of K^+ should have monochromatic momentum.
  - $K^+ \rightarrow \nu\mu^+$: 236 MeV/c
  - $K^+ \rightarrow \pi^+\pi^0$: 206 MeV/c
- Using this property, Water Cherenkov detector can search for $p \rightarrow \nu K^+$.

3-2. Search for p→νK^+, K^+→$\nu\mu^+$


γ 6.3MeV
$^{16}O \rightarrow ^{15}N$
$\bar{\nu}$
ν_μ
K^+
ν_e
e^+
ν_μ
μ^+

- Visible particle is only μ^+ with Michel electron.
- Search for data excess around 236 MeV/c of μ comparing with atmospheric ν MC.
- After proton decay, 40 % of remaining nucleus emits 6 MeV γ for deexcitation. It is useful to reduce background.

Example of p→νK^+, K^+→$\nu\mu^+$ with γ



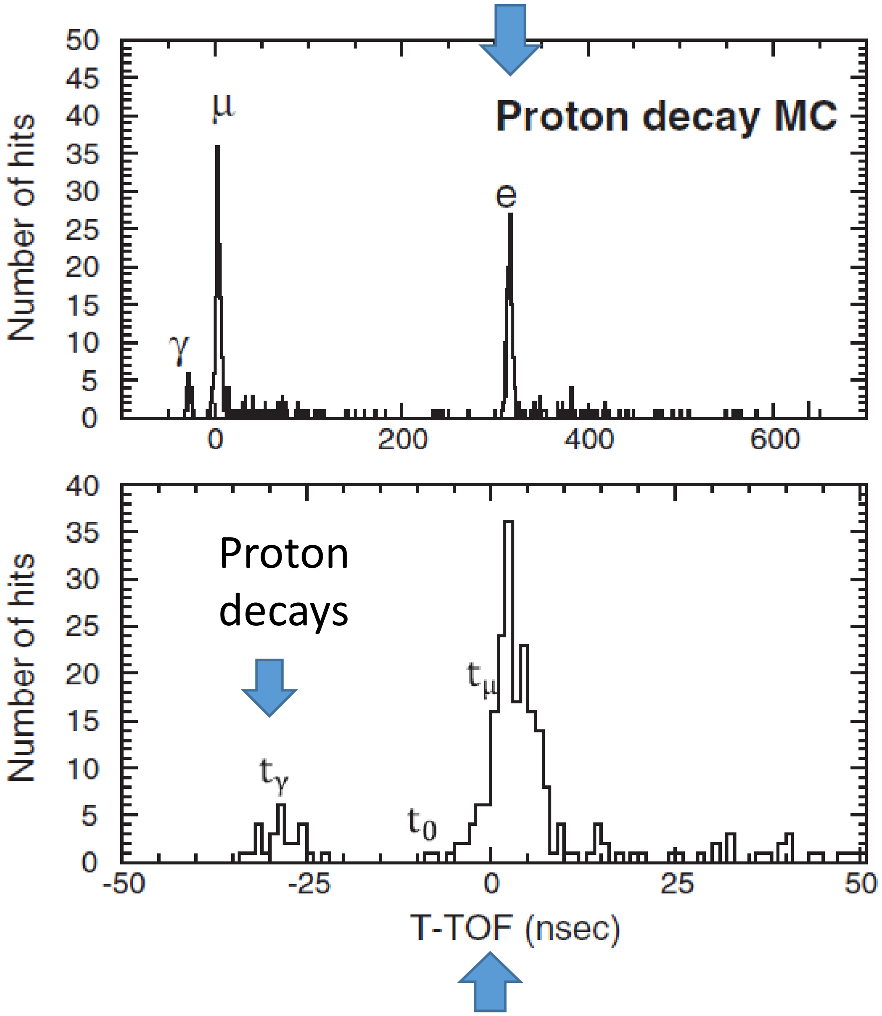
Color of hits corresponds to time.

Cyan corresponds to nuclear γ.

Difficult to identify γ from hit pattern.

Time structure with nuclear γ

μ decays



Proton decays

K⁺ decays

- 3 hit clusters in time should be observed in case of signal.
- The event is triggered by μ hits.
- γ signal is much smaller than μ and easily hidden by tail of μ hits.
- Make 12 nsec time window and slide it toward left from t_0 (end of μ tail) to search for maximum hit cluster.

Selection criteria for $p \rightarrow \nu K^+$, $K^+ \rightarrow \nu \mu^+$

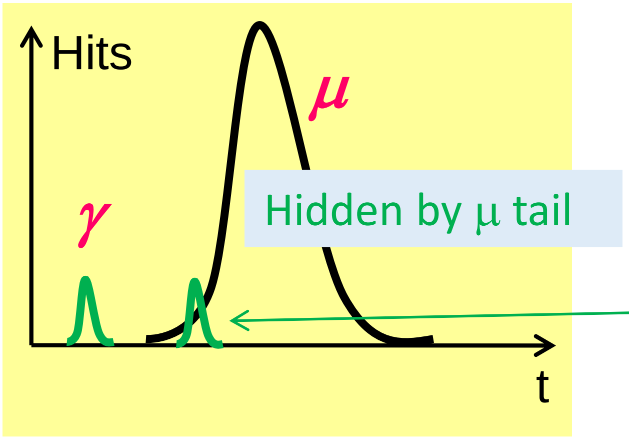
- 1 μ-like ring with Michel electron
- $215 < P\mu < 260$ MeV/c
- Proton rejection cuts
- Search Max hit cluster by sliding time window (12ns width);
  - $4 < N\gamma < 30$ hits
  - $T_\mu - T_\gamma < 75$ nsec

Reduce background by 5×10^{-4} !

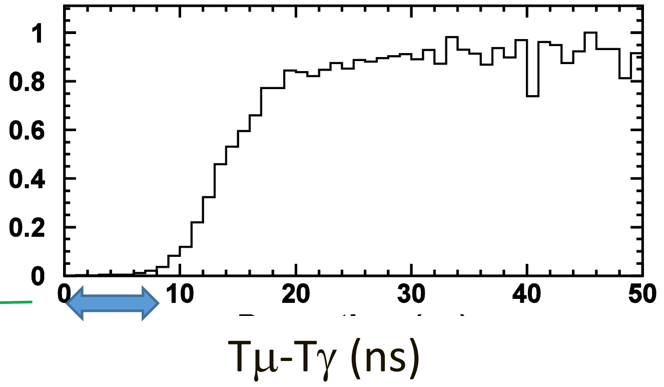
- No neutron
- Selection efficiency = (selected events)/(proton decay in fiducial volume): 9 %
  - $Br(K^+ \rightarrow \nu \mu^+) = 64$ %, only 40 % emits nuclear γ → 26 % even if detector is perfect.

Remark for this analysis

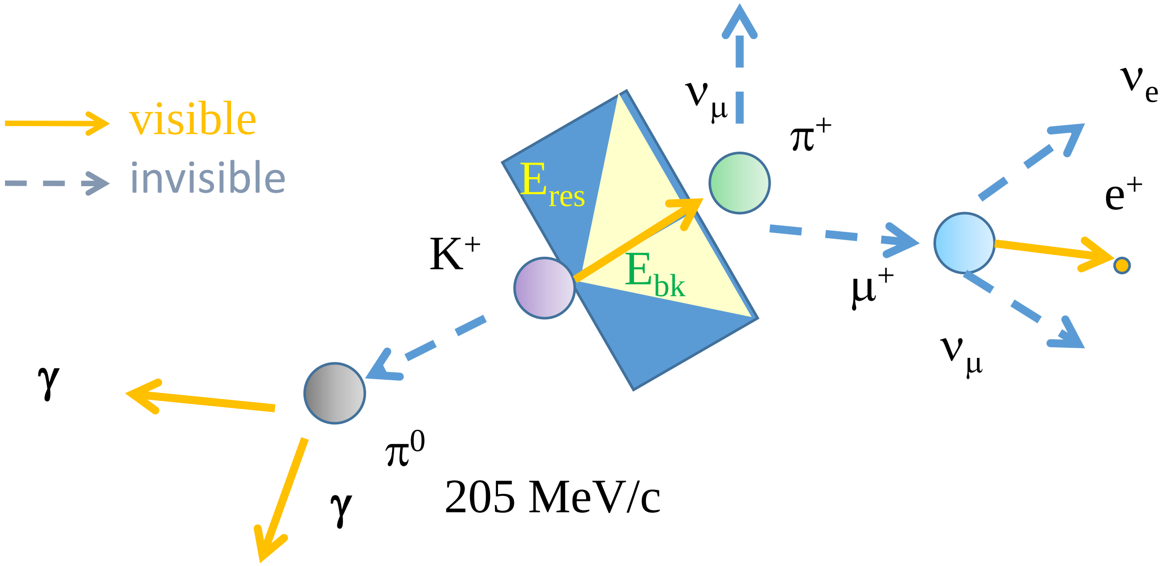
- This analysis is limited by time resolution of PMTs.
  - ➢ If γ is close to μ, γ peak is hidden by μ hits.
  - ➢ Time resolution of SK PMT is 2.2 nsec at 1 photoelectron.
  - ➢ If μ peak becomes sharper, the selection efficiency will be improved.



γ tagging efficiency

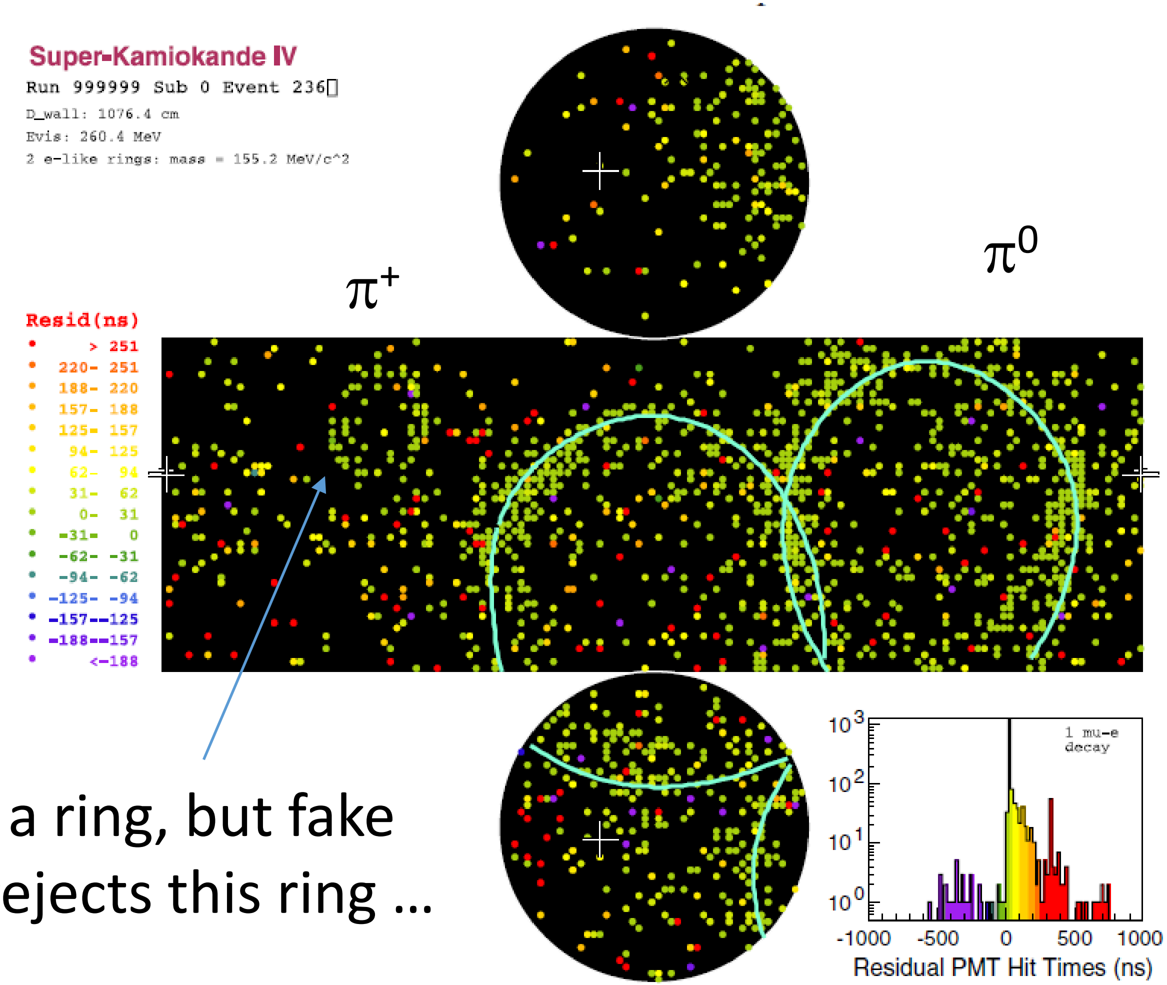


3-3. Search for $p \rightarrow \nu K^+$, $K^+ \rightarrow \pi^+ \pi^0$


visible
invisible
ν_μ
π^+
ν_e
e^+
E_{res}
E_{bk}
K^+
μ^+
ν_μ
γ
π^0
γ
205 MeV/c

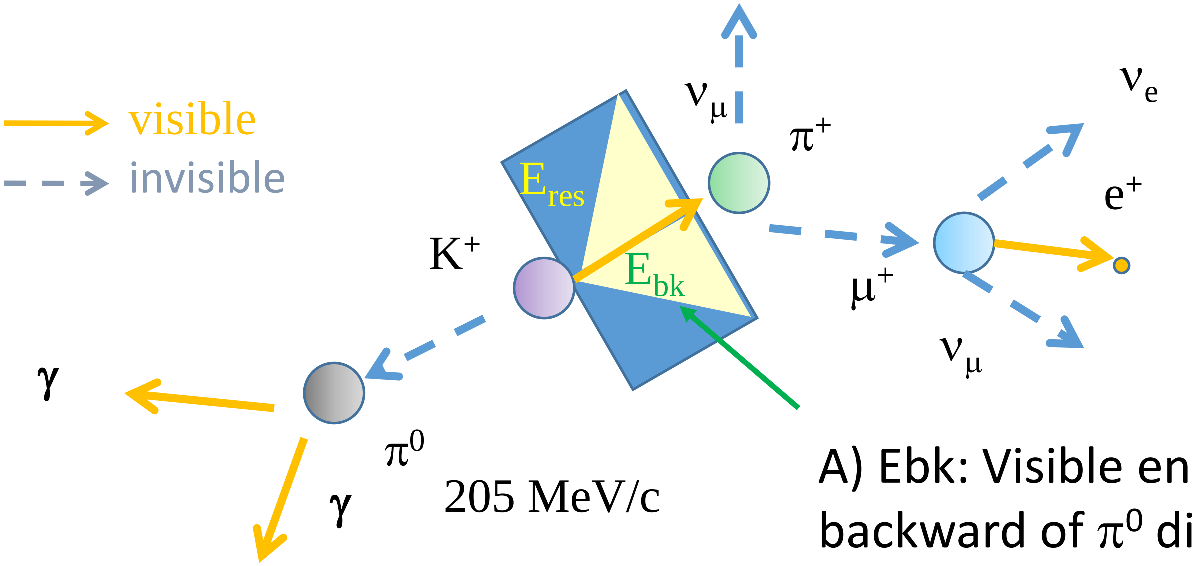
- Both π^+ and π^0 has 205 MeV/c in momentum. This is just above Cherenkov threshold for π^+, thus it is not identified as a ring in most of case.
- π^+ decays into μ (invisible) and ν, μ decays into $e\nu_e\nu_\mu$.
- π^0 decays into 2 γs.
- Search for 206 MeV/c π^0 with Michel electron.

Example of $p \rightarrow \nu K^+$, $K^+ \rightarrow \pi^+ \pi^0$



Look like a ring, but fake ring cut rejects this ring …

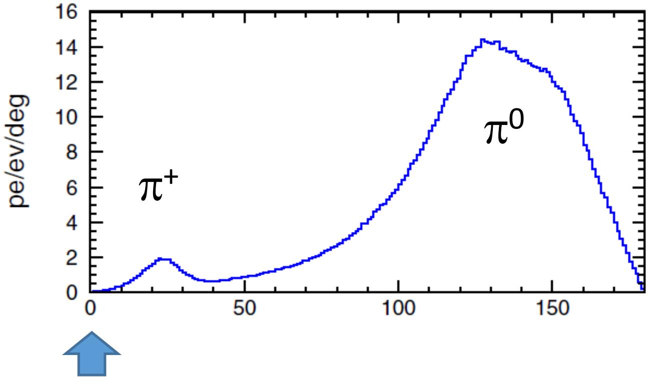
Use π^+ information to select events


visible
invisible
E_{res}
E_{bk}
K^+
ν_μ
π^+
ν_e
e^+
μ^+
ν_μ
γ
π^0
γ
205 MeV/c

A) Ebk: Visible energy sum in backward of π^0 direction (140°-180°)

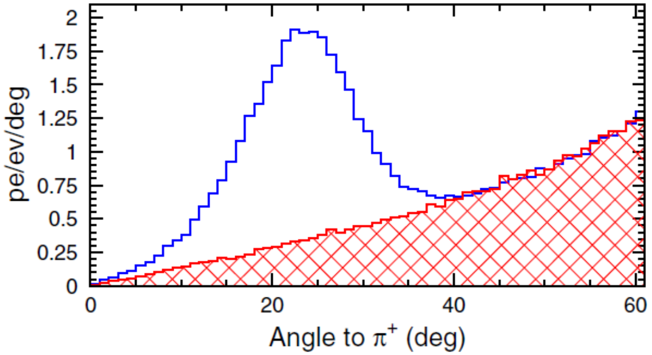
B) Make likelihood for hit pattern.

Charge distribution



π^+ direction

Zoom



Selection criteria for $p \rightarrow \nu K^+$, $K^+ \rightarrow \pi^+ \pi^0$

- 1 or 2 e-like rings with decay-e.
- $85 < M\pi^0 < 185$ MeV.
- $175 < P\pi^0 < 250$ MeV/c.
- E_{bk}: visible energy sum in 140-180 deg. of π^0 dir,
  E_{res}: in 90-140 deg,
  L_{shape}: Likelihood based on charge profile
  $10 < E_{bk} < 50$ MeV
  $E_{res} < 12$ MeV (20 MeV for 1ring)
  $L_{shape} > 2.0$ (3.0 for 1ring)
- No neutrons
- Selection efficiency: 10 % ($Br(K^+ \rightarrow \pi^+ \pi^0)$=21 %)

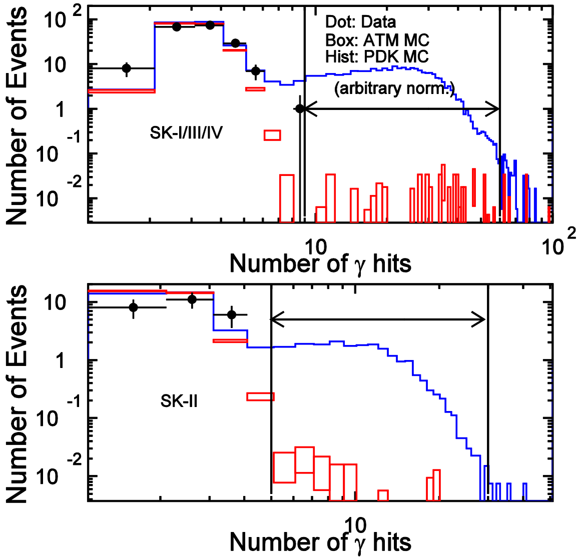
Background for p→νK$^+$

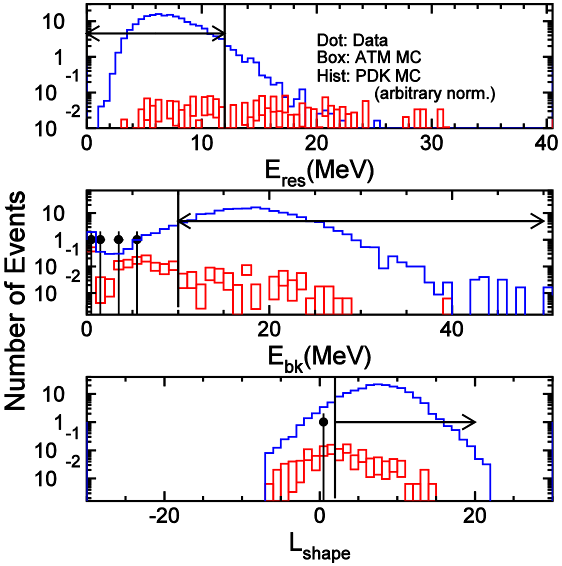
- Dominant background is K$^+$ production by neutrino interactions.
  - $\nu p \rightarrow \nu \Lambda K^+$, $\Lambda \rightarrow p\pi^-$ (BR:64 %, mostly invisible in WCD)
  - Emit nuclear γ as same as the signal.
- It is also rare interaction and we had poor information from very old bubble chamber. Large uncertainty.
- Recently MINERvA measures K$^+$ production. It is very useful information for this analysis.

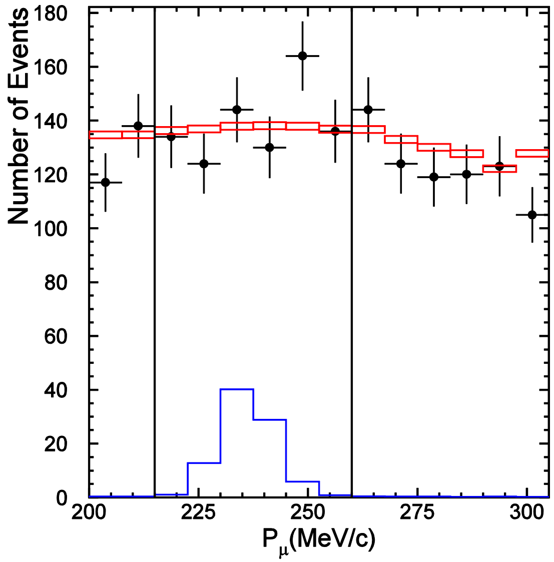
3-4. SK results (So far)

- Exposure: 365 kton・year
- Expected background: 0.3 events for $K^+ \rightarrow \nu\mu$ with nuclear γ, 0.6 events for $K^+ \rightarrow \pi^+\pi^0$.
- No candidates observed and no excess in momentum distribution.
- Lower lifetime limit: > 0.8x10^{34} year

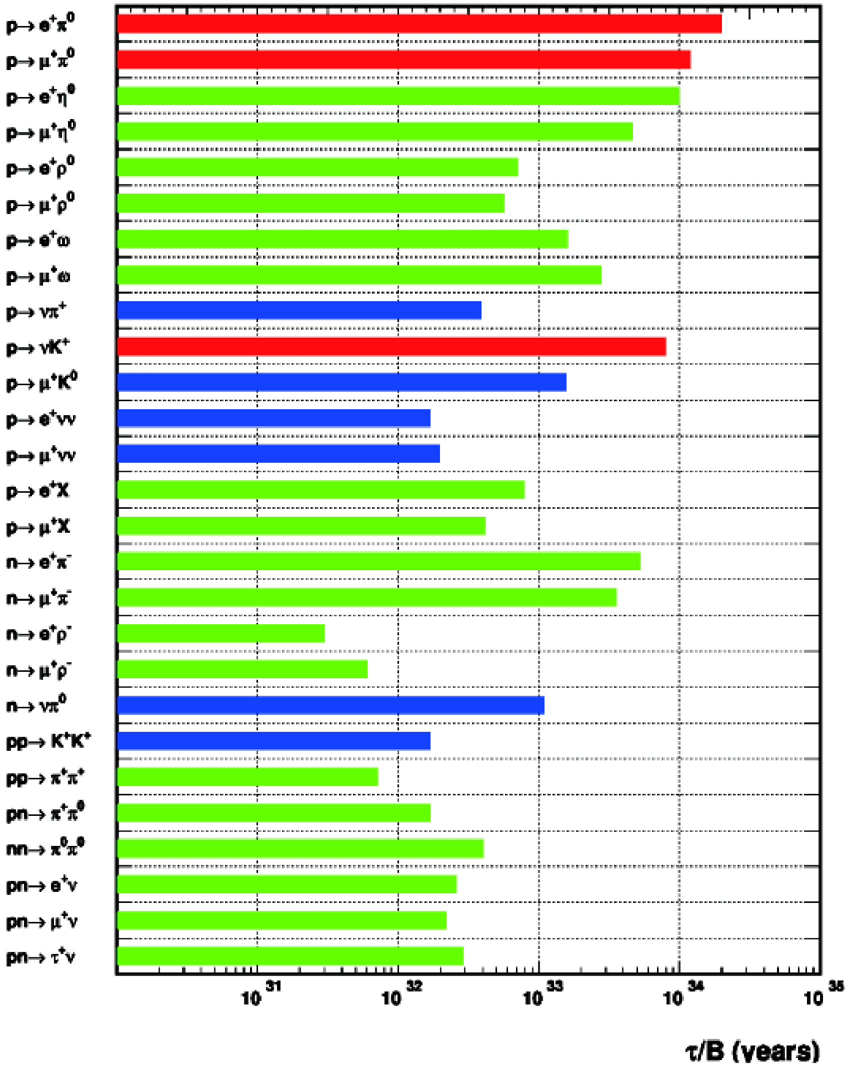
Black: Data
Red: Atm.n MC
Blue: Signal MC







3. Summary of SK results



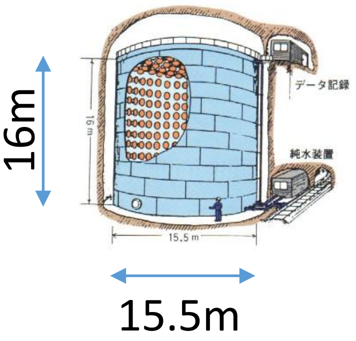
- Most of modes have been investigated with > 0.3 Mton・year exposure (red and green in the left figure).
- Super-Kamiokande can cover large number of decay modes.
- Many of them are the most stringent limits on nucleon lifetime.
- We observed some candidates, but still consistent with expected backgrounds and no evidence of nucleon decay has been observed.

Future prospects

- Still no evidence has been found. Major decay modes are explored up to around 10^{34} years.
- Proton lives longer, ~10^{35} years ?
  - Run SK 10 times more (~200 years)? → Impossible.
- Absolutely, we need larger detector !

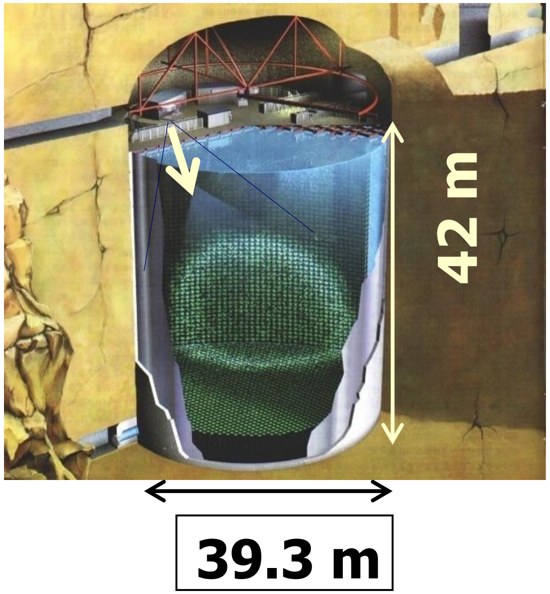
4. Hyper-Kamiokande project

SN Neutrino


16m
データ記録
純水装置
16 m
15.5 m
15.5m

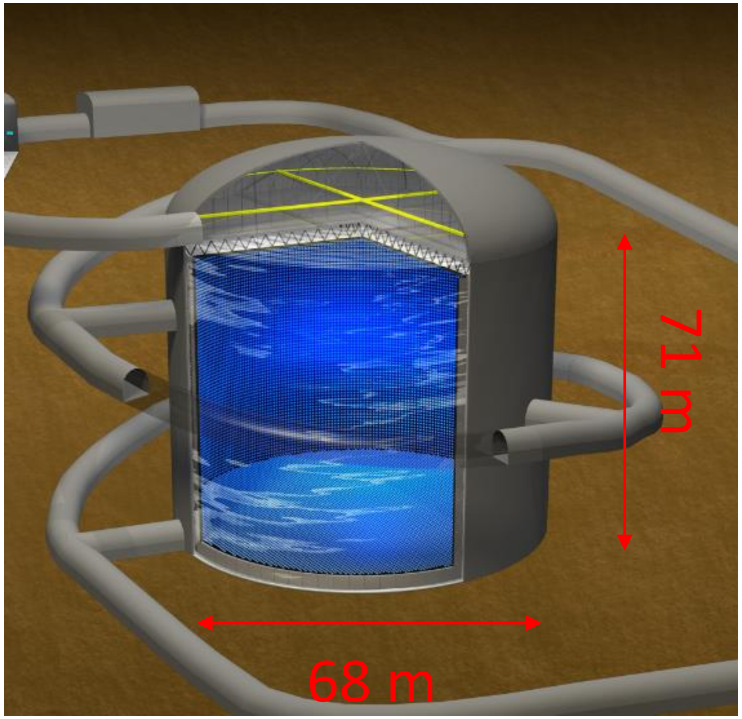
Kamiokande
3kton

Neutrino oscillation



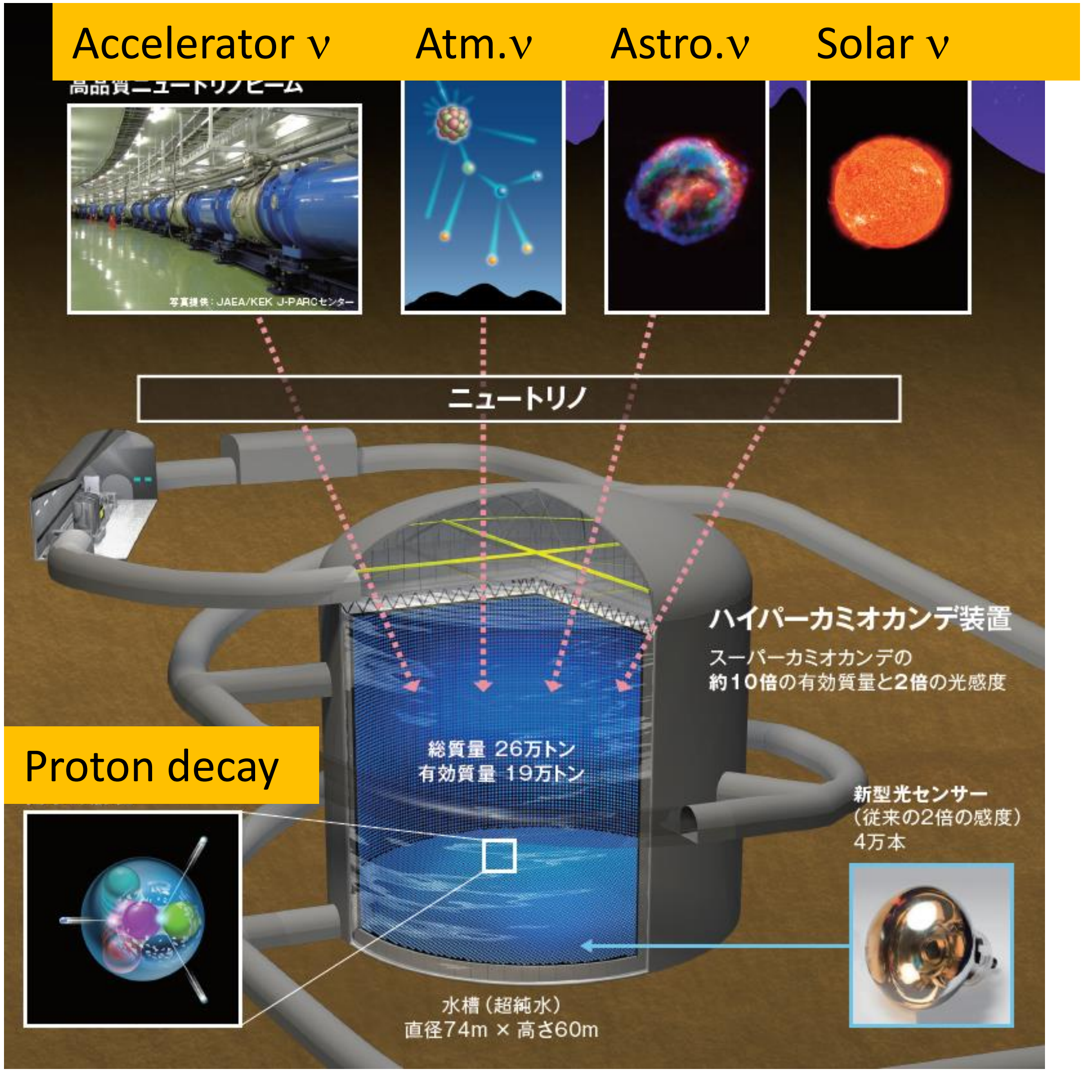
Super-Kamiokande
50kton

Proton decay ?



Hyper-Kamiokande
260kton

Hyper-K is multi-purpose detector



Accelerator ν Atm.ν Astro.ν Solar ν

Proton decay

高品質ニュートリノビーム
写真提供：JAEA/KEK J-PARCセンター
ニュートリノ
ハイパーカミオカンデ装置
スーパーカミオカンデの
約10倍の有効質量と2倍の光感度
総質量 26万トン
有効質量 19万トン
新型光センサー
（従来の2倍の感度）
4万本
水槽（超純水）
直径74m × 高さ60m

HYPER-K COLLABORATION

22 countries, 105 institutes, ~630 people as of March 2025, and growing

Collaborating Institutes

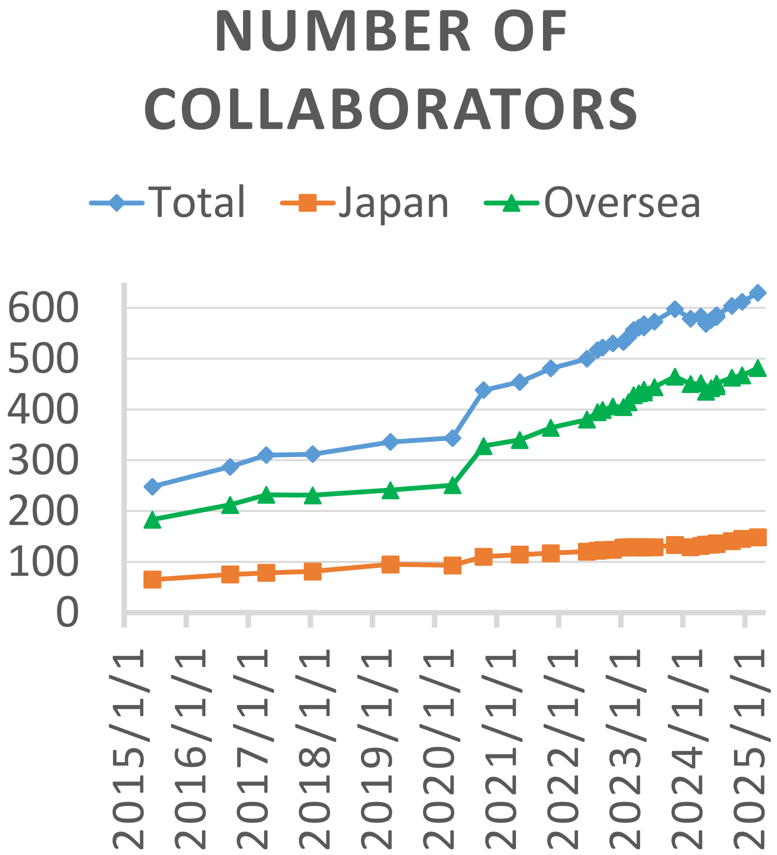
Europe	363 members
Armenia	3
Czech	9
France	58
Germany	1
Greece	4
Italy	50
Poland	46
Russia	26
Spain	48
Sweden	5
Switzerland	15
Ukraine	2
UK	96

Asia	180 members
India	11
Korea	21
Japan	148

Oceania	9 members
Australia	9

Americas	69 members
Brazil	3
Canada	45
Mexico	11
USA	10

Africa	10 members
Morocco	10

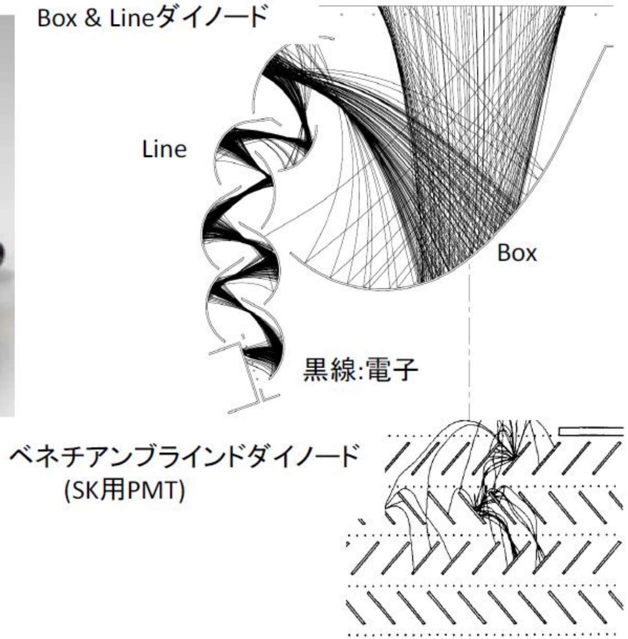


I hope Vietnam joins soon.

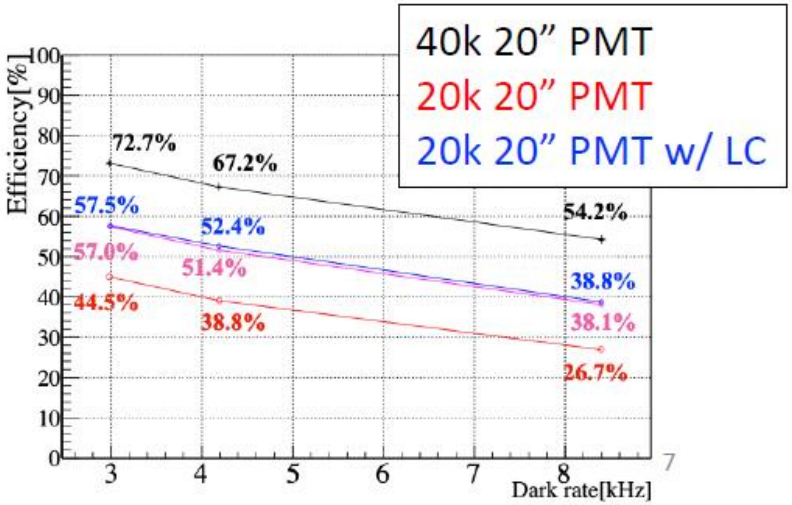
Enhance proton decay search with HK

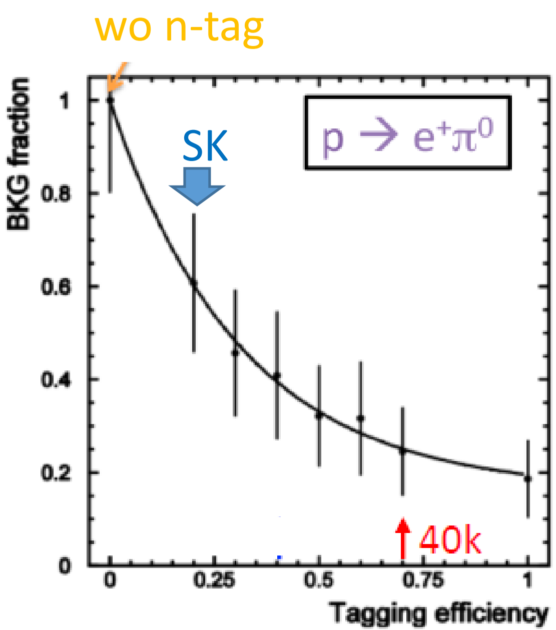
- Fiducial volume: 22.5kton (SK) → 190kton (HK)
- New photo sensor: Box&Line PMT
  - 2 times better photon counting performance
  - a half time resolution

Box&Line PMT


Box & Lineダイノード
Line
Box
黒線:電子
ベネチアンブラインドダイノード
(SK用PMT)

Better photon counting contributes neutron tagging



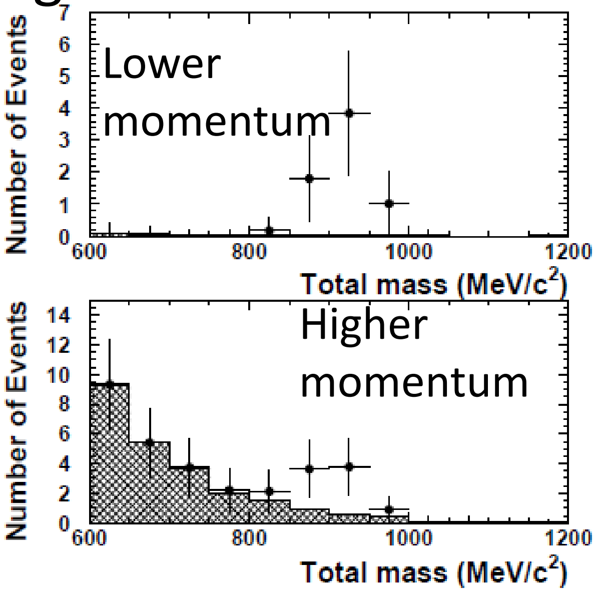


- Neutron tagging efficiency study with several detector set up.
- Efficiency depends on dark rate.
- Achive ~ 70% in the current baseline design (black) with ~ 4kHz dark rate.

- p→e+p0 background reduction vs. Neutron tagging efficiency
- Background of HK becomes a half of SK !

Sensitivity for p→$e^+\pi^0$

Expected signal after 10 years run assuming the current lifetime limit

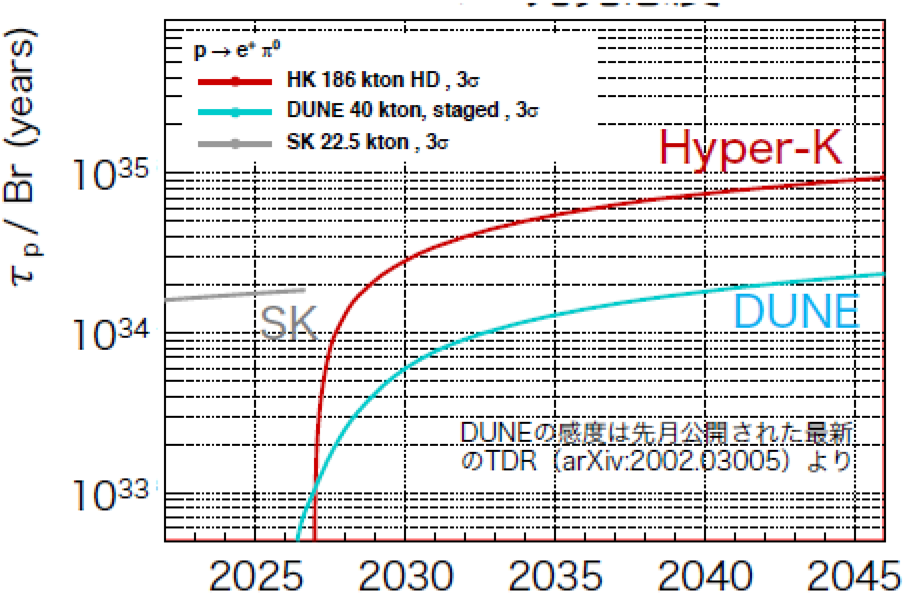


$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20

(SK: 0.18)

(SK: 1.1)

3σ discovery potential

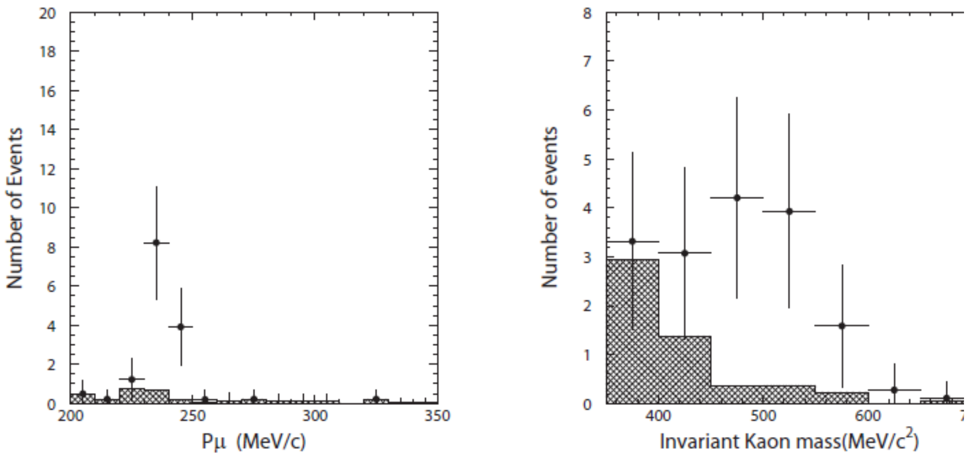


DUNEの感度は先月公開された最新のTDR（arXiv:2002.03005）より

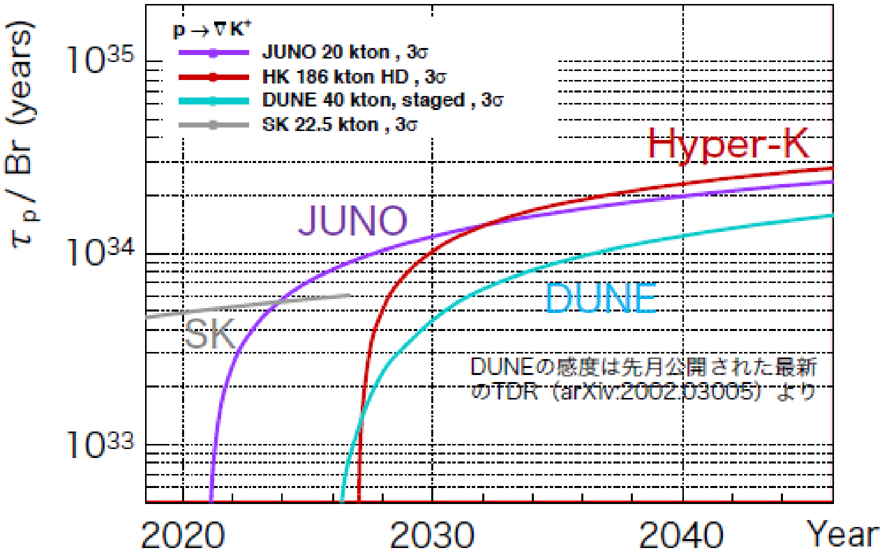
Reach to 10^{35} years !

Sensitivity for p→νK$^+$

Expected signal after 10 years run assuming the current lifetime limit



3σ discovery potential



DUNEの感度は先月公開された最新のTDR（arXiv:2002.03005）より

Prompt γ		$\pi^+\pi^0$		p_μ Spectrum		
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]	σ_{fit} [%]
12.7 ± 2.4	0.9 ± 0.2	10.8 ± 1.1	0.7 ± 0.2	31.0	1916.0	8.0

Better sensitivity than other detectors !.

What are still unknown in ν oscillation?

Unknow parameter

CP phase

$c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- θ_{12} = 33.6° ± 1.0° Solar ν, KamLAND
- θ_{23} = 45° ± 6° (90%CL) Atm. ν, Acc. ν

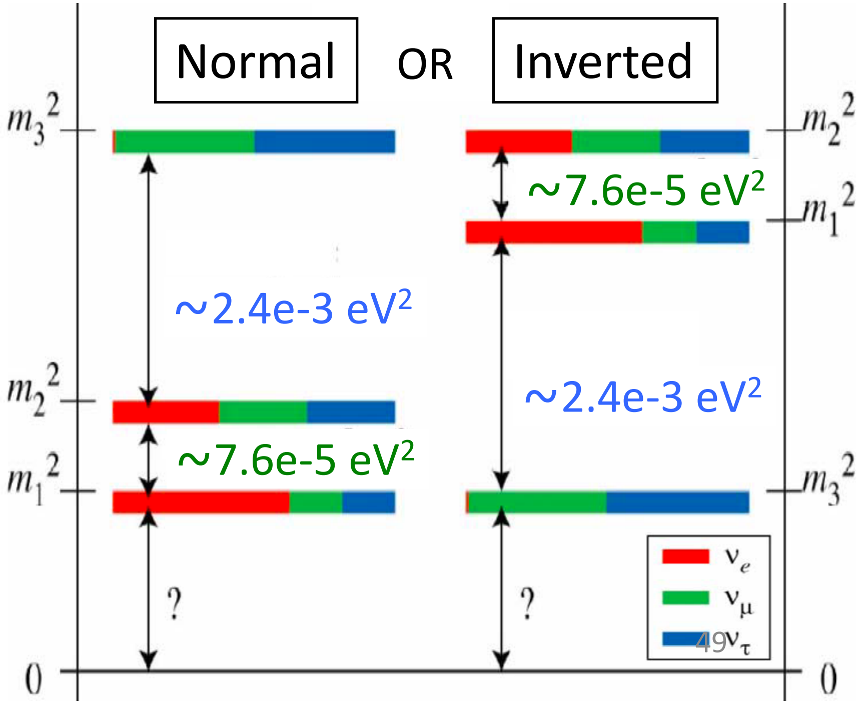
θ_{23} : How close to 45° ?
Octant? (<45°, >45° ?)

- θ_{13} = 9.1° ± 0.6° Rector, Acc. ν

Indication of $\theta_{13} \neq 0$ by T2K
PRL107, 041801 (2011)

Later precise measurements by reactor ν experiments

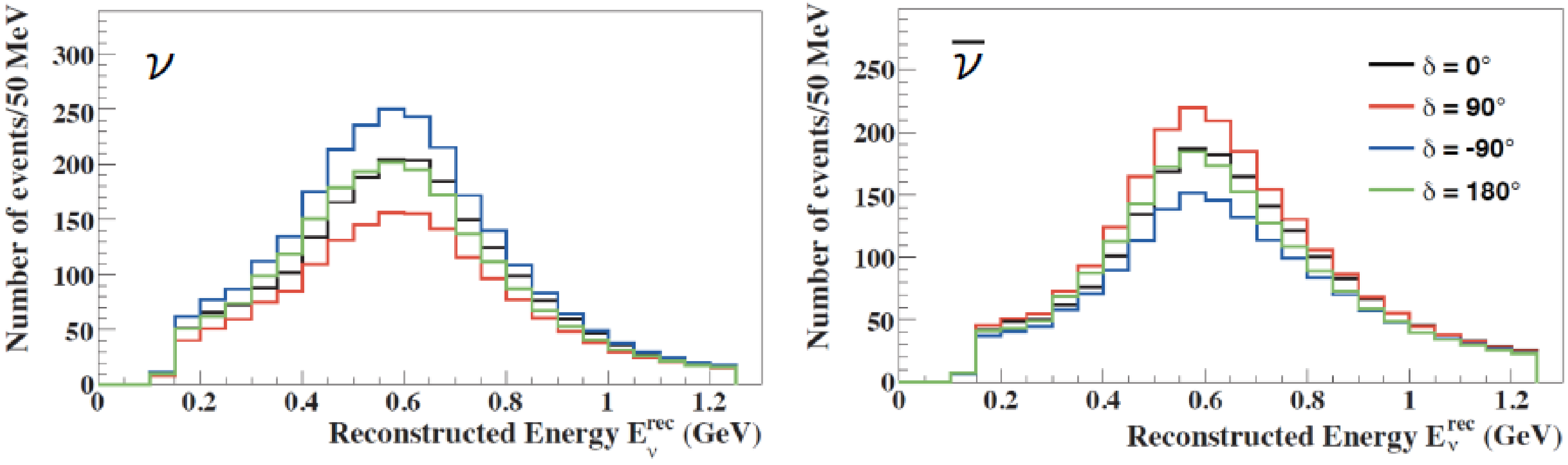
Mass hierarchy


Normal
OR
Inverted
m_3^2
m_2^2
m_1^2
~2.4e-3 eV²
~7.6e-5 eV²
?
0
m_2^2
m_1^2
m_3^2
~7.6e-5 eV²
~2.4e-3 eV²
?
0
ν_e
ν_μ
ν_τ

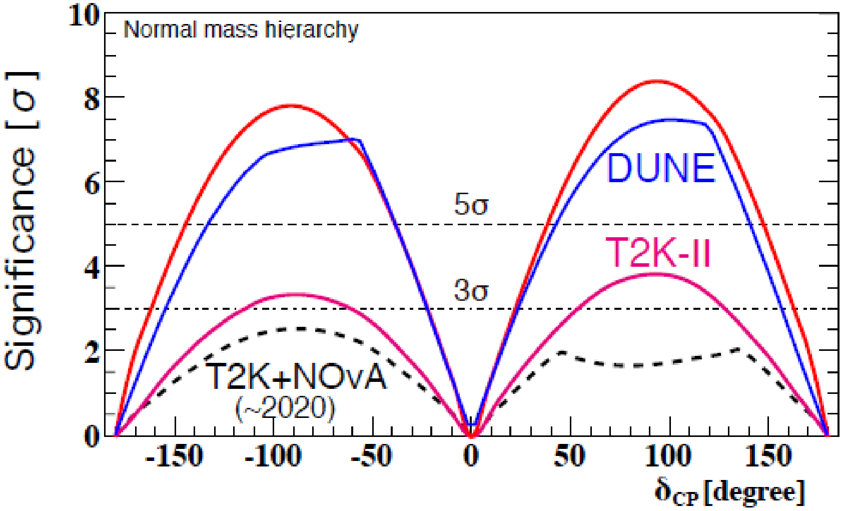
Effects of unknown parameters on ν oscillation are small ➔ Need statistics = larger detector !

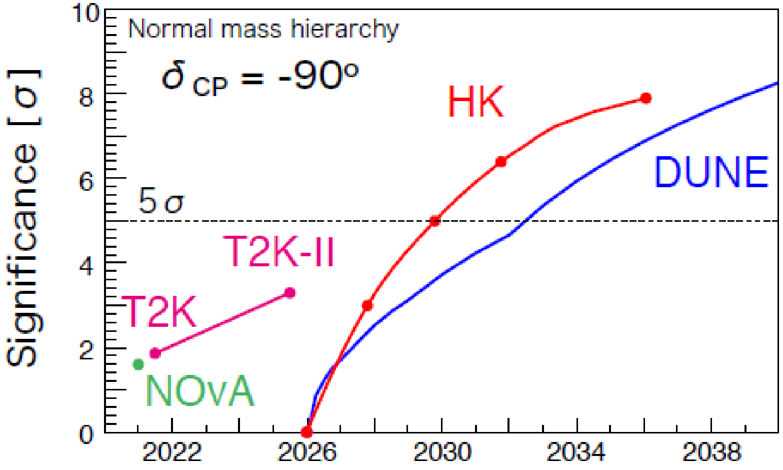
- ν beam experiments: Can study CP phase by comparing ν ν-bar oscillation.

Expected ν_e spectrum at HK (assuming 1.3 MW x 10 years)



Sensitivity of CP violation


HK 10 years



- In 60 % region in δ_{CP}, we can discovery δ_{CP} with 5σ.
- If = δ_{CP} ± 90 degree, we can discover it within 5 years.

Atmospheric ν : $\nu_\mu \rightarrow \nu_e$ enhancement by matter effect

ν_e oscillation due to non-zero θ_{13} provides atm. nu. observation to investigate mass hierarch effect

$\nu_\mu \rightarrow \nu_e$ osc. probability in matter:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}^M \sin^2\left(\frac{1.27\Delta m^2_{31,M} L}{E}\right)$$

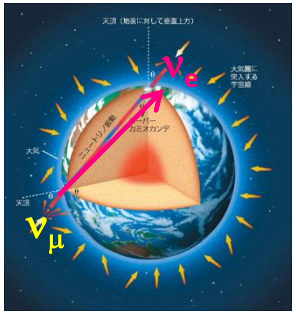
$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - A_{CC}/\Delta m^2_{31}\right) + \sin^2 2\theta_{13}}$$

$\sin^2\theta_{13,M}$ has resonance feature when

$$A_{CC} \sim \Delta m^2_{31} \cos 2\theta_{13} \qquad (A_{CC} = 2\sqrt{2}G_F N_e E)$$

$\nu_\mu \rightarrow \nu_e$ resonance in multi-GeV region

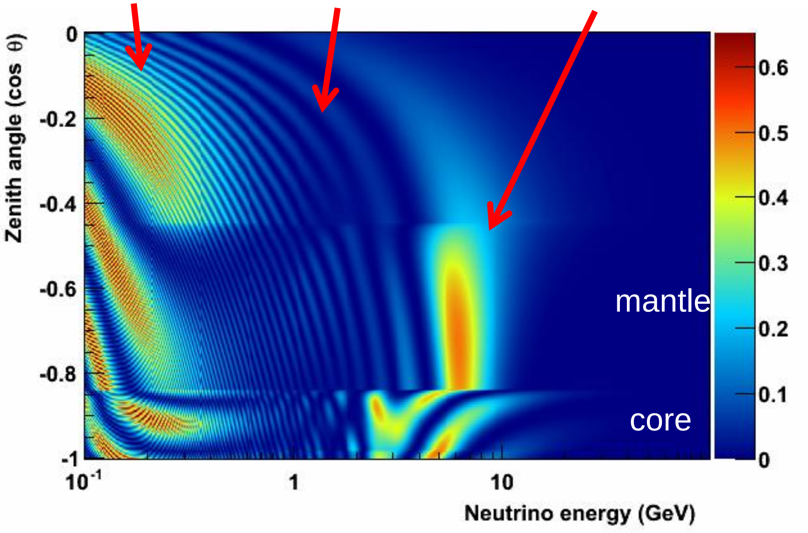
P($\nu_\mu \rightarrow \nu_e$) of earth-throughgoing ν :



solar term effect

Interference

Resonance due to non-zero θ_{13}



Occurrence of resonance feature depends on neutrino type and mass ordering:

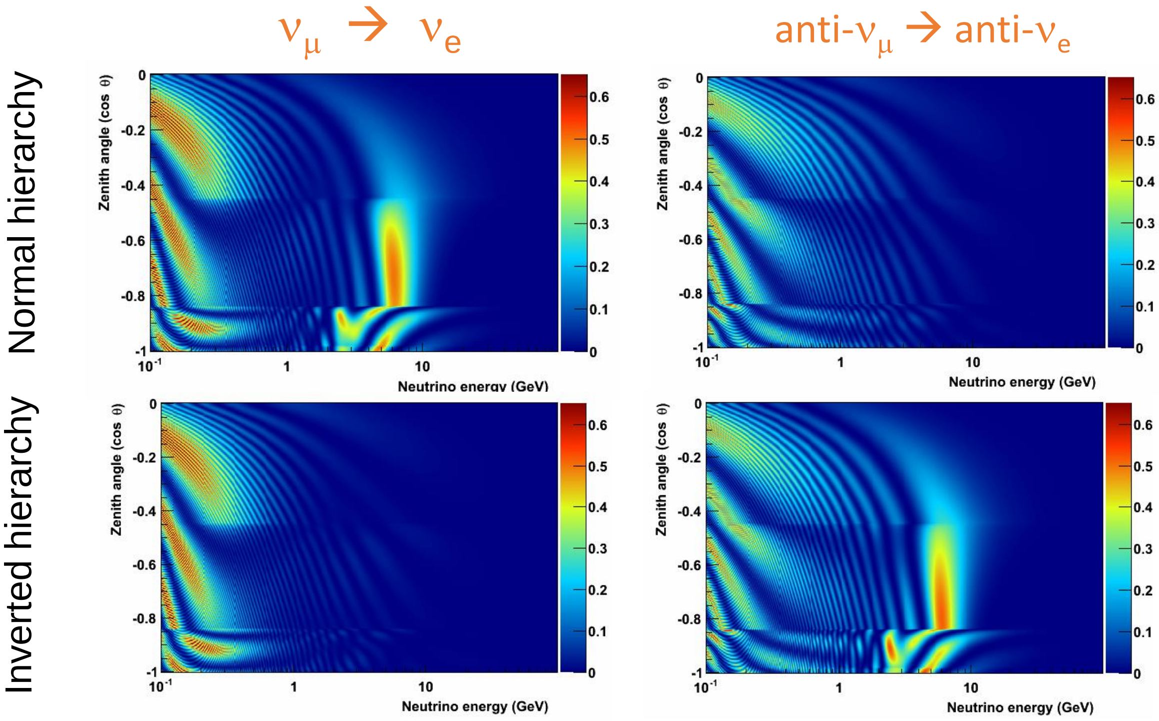
$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - {A_{CC}}\big/{\Delta m^2_{31}}\right) + \sin^2 2\theta_{13}}$$

In case of Inverted hierarchy:

$$\Delta m^2 \rightarrow -\Delta m^2$$

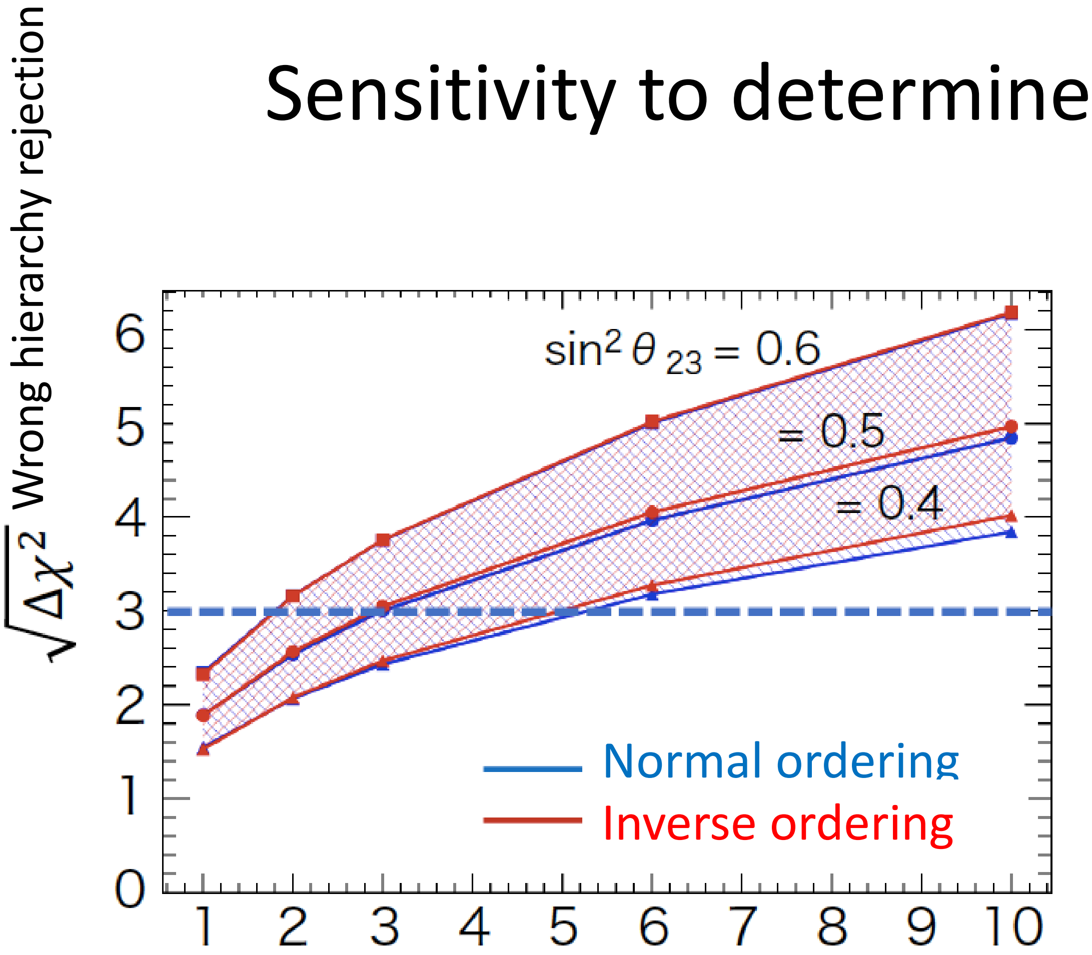
In case of anti neutrino :

$$A_{CC} \rightarrow -A_{CC}$$



Possible to determine mass ordering !

Sensitivity to determine mass ordering



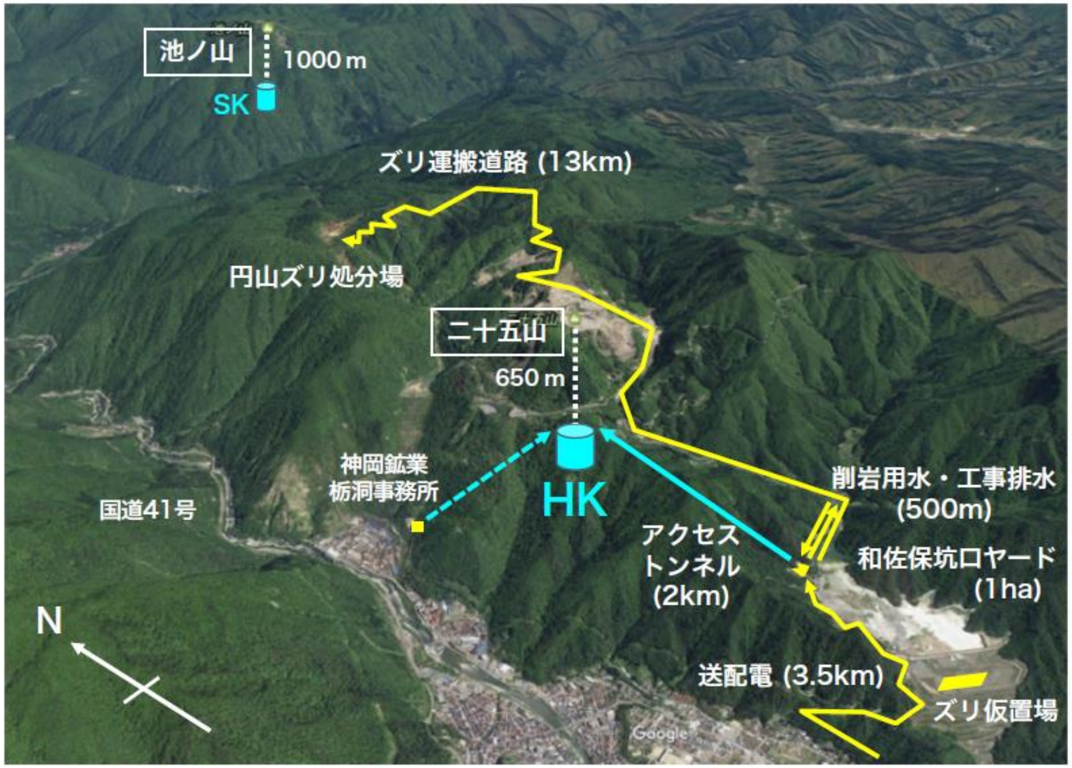
Beam ν: sensitive to δCP, but weak in mass hierarchy.

Atm. ν: large uncertainty from δCP.

➔Combining both analysis gives good sensitivity to mass ordering.

3σ determine within 2 ~ 5 years !

Construction of HyperK is on-going !


池ノ山
1000 m
SK
ズリ運搬道路 (13km)
円山ズリ処分場
二十五山
650 m
神岡鉱業
栃洞事務所
HK
国道41号
削岩用水・工事排水
(500m)
アクセス
トンネル
(2km)
和佐保坑口ヤード
(1ha)
N
送配電 (3.5km)
ズリ仮置場
Google

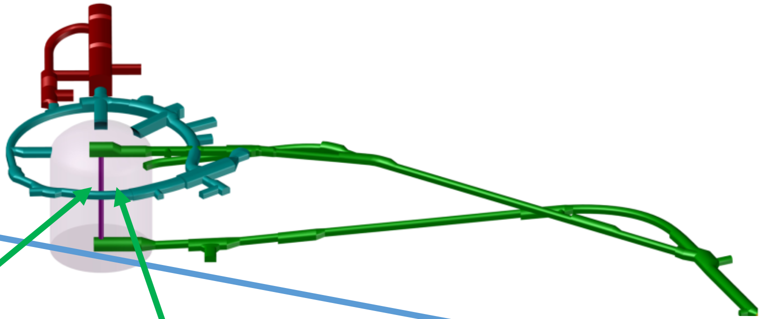
Making entrance yard for tunnel.

2021 May

ハイパーカミオカンデ 着工記念式典
Hyper-Kamiokande Groundbreaking Ceremony
京大学
ICRR
宇宙線

2022 June

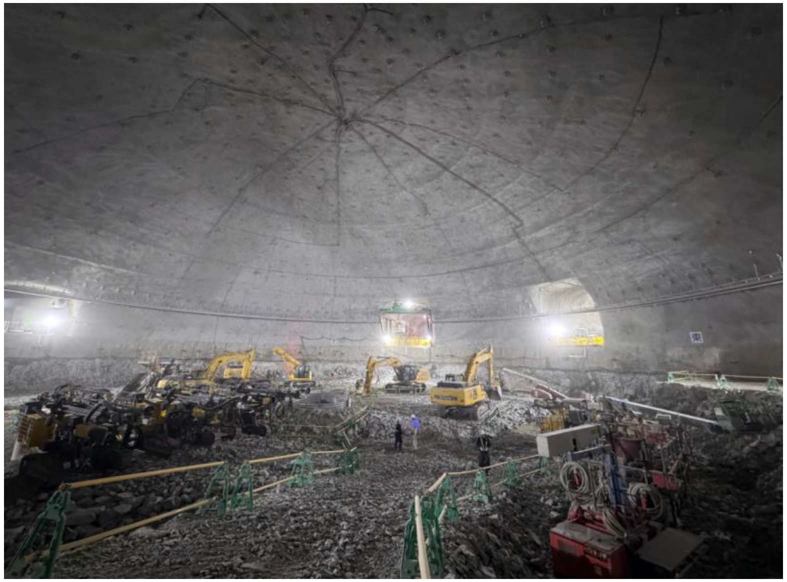
2023 Ocr



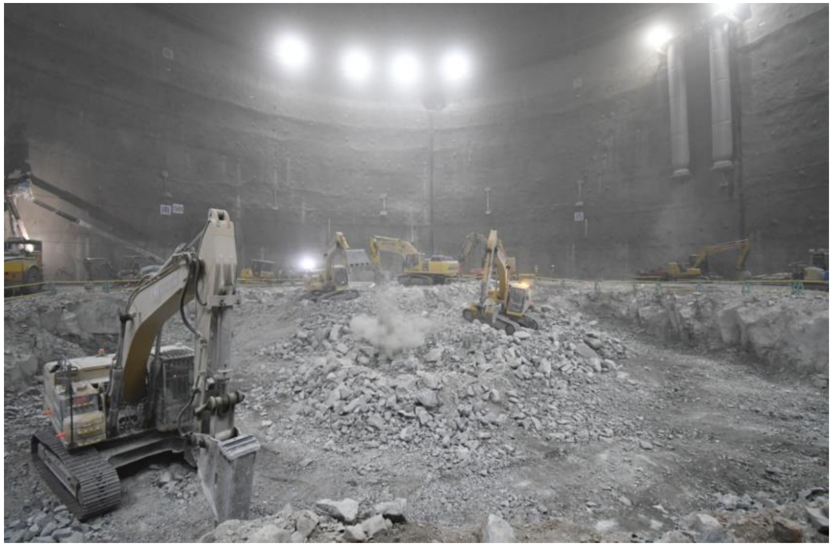
Entrance of tunnel

Center of tank at top

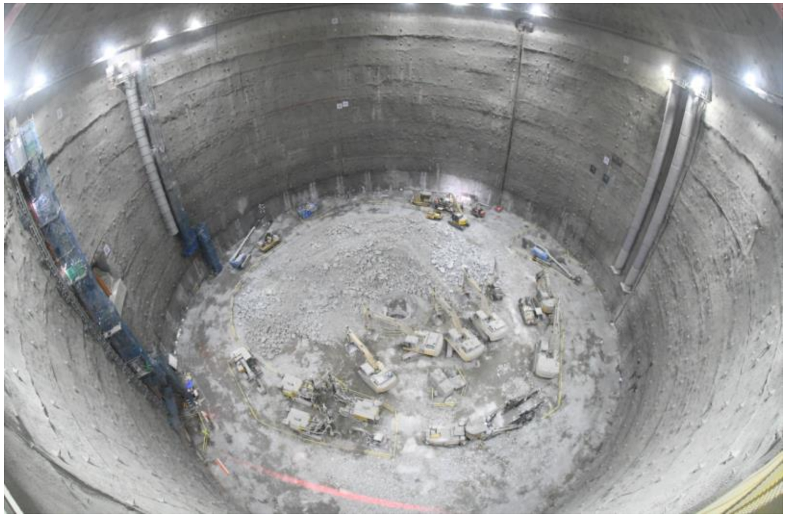
2024 Feb



2024 June



2024 Aug



2025 Aor

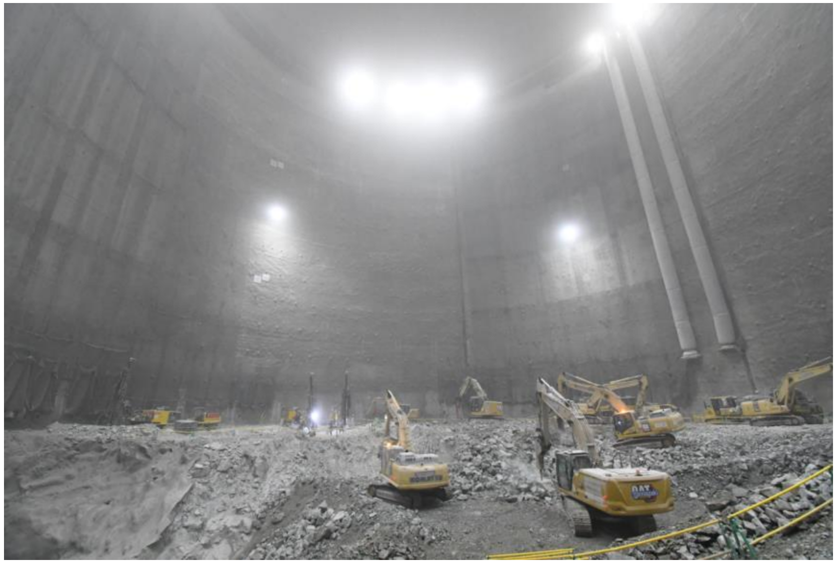


Photo: End of June, 2025

Excavation is almost finished !

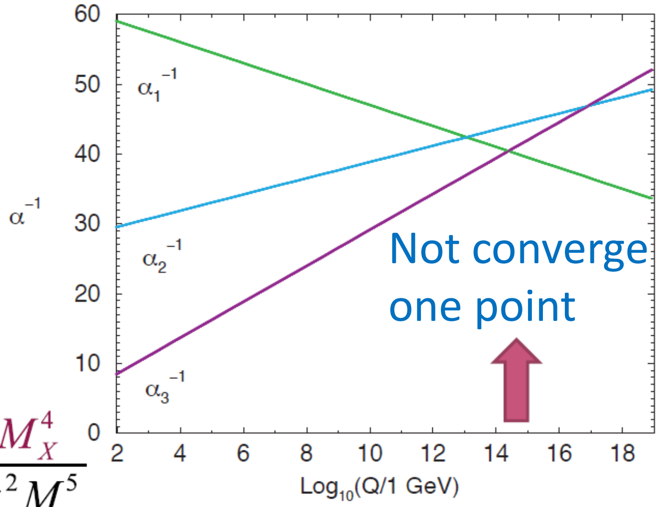
- ➔ Start construction of stainless tank in this summer.
- ➔ PMT assembly will start end of 2026.
- ➔ HK operation will start in 2028.

4. Summary

- Proton decay is a key phenomena of Grand Unified Theories beyond the Standard Model.
- Super-Kamiokande is the leading detector to hunt proton decays and have searched for it for more than 20 years.
- However, no evidence has been observed and the current proton lifetime limits are around 10^{34} years.
- It may be around the corner ! Hope three times lucky (3度目の正直 in Japanese） in Hyper-Kamiokande.
- HK also can determine remaining ν oscillation parameters .

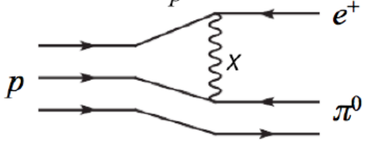
Backup

Gauge Coupling Unification



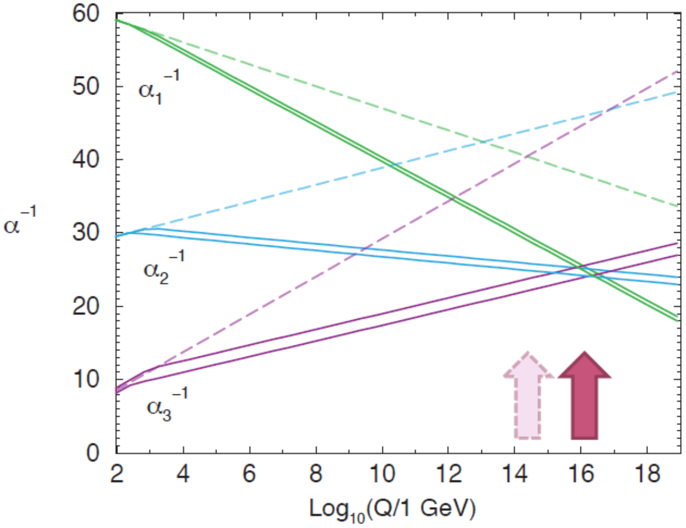
Not converge at one point

$$\tau \approx \frac{M_X^4}{\alpha^2 M_p^5}$$



$\tau(e^+\pi^0) = 4.5\times10^{29\pm1.7}$ *years* (predic

Problems solved by SUSY ...



Unification scale pushed up...

$\tau(e^+\pi^0) \approx 10^{35-38}$ years

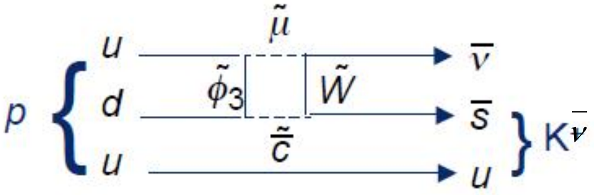
SUSY GUTs

- Unification scale higher than non-SUSY-GUTs ($M_x \sim 2 \times 10^{16}$ GeV)

  suppression of gauge boson mediated decay

$$\tau/B\,(p \rightarrow e^+\pi^0) \approx \left(M_X/2\mathrm{x}10^{16}\mathrm{GeV}\right)^4 \mathrm{x}\ 10^{36\pm1}\ \mathrm{years}$$

dominated by the D=5 op. (color Higgs triplet, q=1/3) mediated decays



$M_3 \sim 3 \times 10^{16}$ GeV, $M_{susy} \sim 1$ TeV

$$\tau/B\,(p \rightarrow K^+\bar{\nu}) \approx \left(0.003/\beta_H\right)^2 \left(M_{\tilde{q}}/1\mathrm{TeV}\right)^2 \left(M_3/10^{16}\mathrm{GeV}\right)^2 \left(2/\tan\beta\right)^2 \cdots$$

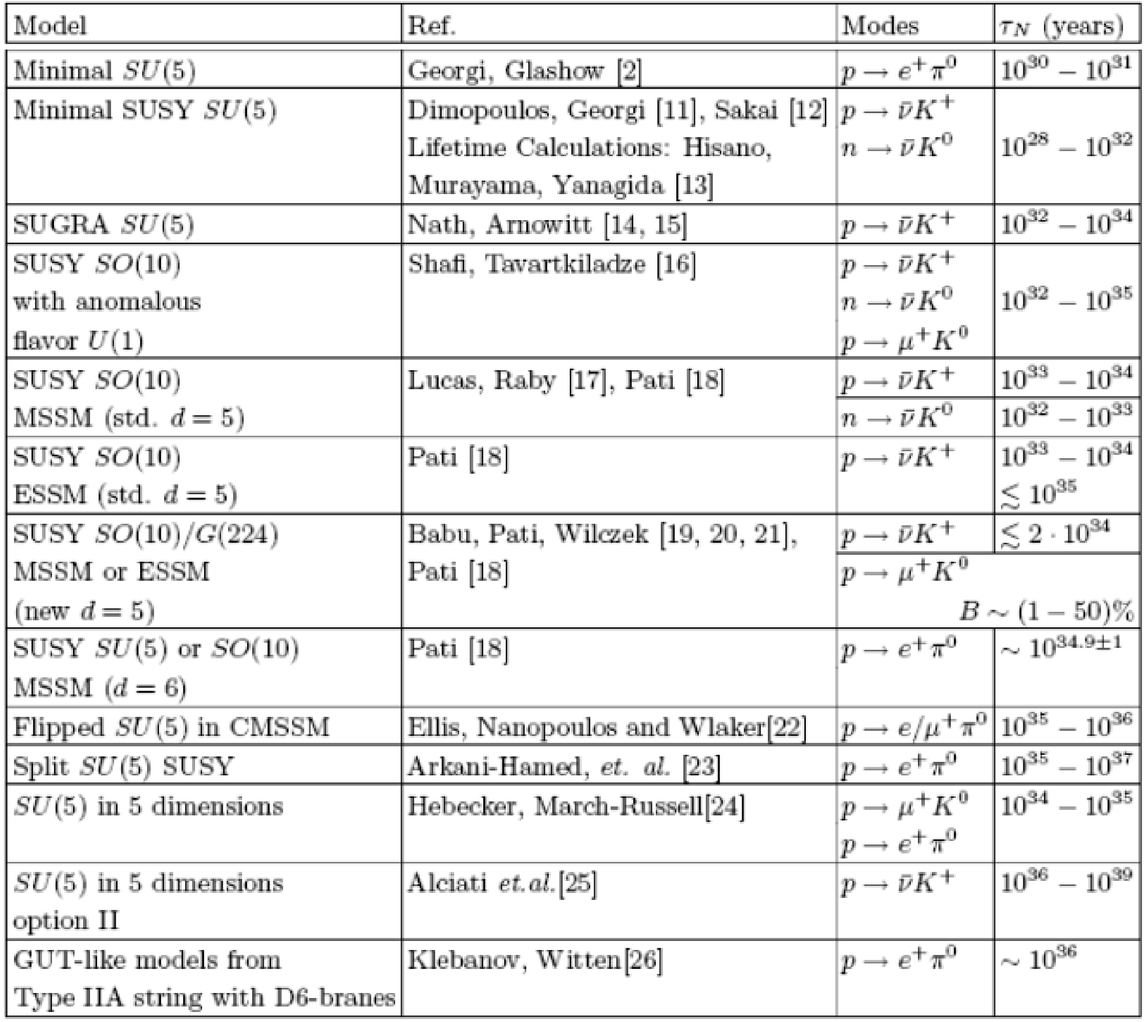
$$\mathrm{x}9\mathrm{x}10^{31}\ \mathrm{years}$$

(β_H : hadronic matrix element in GeV^3)

⇒ highly model dependent

p→ $\bar{\nu}$ K$^+$ is regarded as dominant mode in SUSY-GUTs.

Many Other GUTs Beyond This Simple Story



Model	Ref.	Modes	τ_N (years)
Minimal $SU(5)$	Georgi, Glashow [2]	$p \to e^+\pi^0$	$10^{30} - 10^{31}$
Minimal SUSY $SU(5)$	Dimopoulos, Georgi [11], Sakai [12] Lifetime Calculations: Hisano, Murayama, Yanagida [13]	$p \to \bar{\nu} K^+$ $n \to \bar{\nu} K^0$	$10^{28} - 10^{32}$
SUGRA $SU(5)$	Nath, Arnowitt [14, 15]	$p \to \bar{\nu} K^+$	$10^{32} - 10^{34}$
SUSY $SO(10)$ with anomalous flavor $U(1)$	Shafi, Tavartkiladze [16]	$p \to \bar{\nu} K^+$ $n \to \bar{\nu} K^0$ $p \to \mu^+ K^0$	$10^{32} - 10^{35}$
SUSY $SO(10)$ MSSM (std. $d = 5$)	Lucas, Raby [17], Pati [18]	$p \to \bar{\nu} K^+$ $n \to \bar{\nu} K^0$	$10^{33} - 10^{34}$ $10^{32} - 10^{33}$
SUSY $SO(10)$ ESSM (std. $d = 5$)	Pati [18]	$p \to \bar{\nu} K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d = 5$)	Babu, Pati, Wilczek [19, 20, 21], Pati [18]	$p \to \bar{\nu} K^+$ $p \to \mu^+ K^0$	$\lesssim 2 \cdot 10^{34}$ $B \sim (1 - 50)\%$
SUSY $SU(5)$ or $SO(10)$ MSSM ($d = 6$)	Pati [18]	$p \to e^+\pi^0$	$\sim 10^{34.9 \pm 1}$
Flipped $SU(5)$ in CMSSM	Ellis, Nanopoulos and Wlaker[22]	$p \to e/\mu^+\pi^0$	$10^{35} - 10^{36}$
Split $SU(5)$ SUSY	Arkani-Hamed, *et. al.* [23]	$p \to e^+\pi^0$	$10^{35} - 10^{37}$
$SU(5)$ in 5 dimensions	Hebecker, March-Russell[24]	$p \to \mu^+ K^0$ $p \to e^+\pi^0$	$10^{34} - 10^{35}$
$SU(5)$ in 5 dimensions option II	Alciati *et.al.*[25]	$p \to \bar{\nu} K^+$	$10^{36} - 10^{39}$
GUT-like models from Type IIA string with D6-branes	Klebanov, Witten[26]	$p \to e^+\pi^0$	$\sim 10^{36}$

TABLE I: Summary of the expected nucleon lifetime in different theoretical models.

A. Bueno et al. hep-ph/0701101

Uncertainties in the predictions:

Nuclear matrix elements updated w. lQCD, still:
x10 uncertainty in lifetime

SUSY masses: ~ x100 uncertainty in lifetime

Proton life time:
$10^{30} \sim 10^{35}$ years

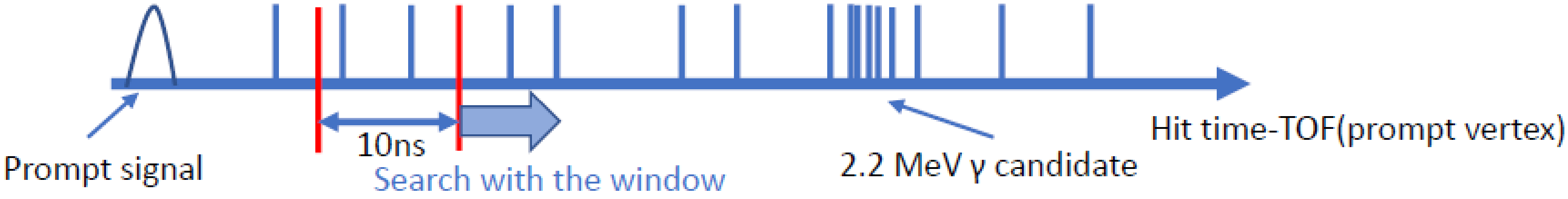
Modes beyond $e^+\pi^0$, $K^+\nu$

and other antilepton + meson decays

$p \to \mu^- \pi^+ K^+$	$B + L$
$n \to \bar{n}$	$\Delta \mathrm{B} = 2$, TeV < scale < GUT
$pp \to K^+ K^+$	$\lambda''_{\mathrm{uds}} < 10^{-8}$
$p \to e^- \pi^+ \pi^+ \nu\ \nu$	6 dimensions
$n \to \nu\ \nu\ \nu$	invisible
$p \to e^+\ \gamma$	radiative

there is plenty to keep us busy …

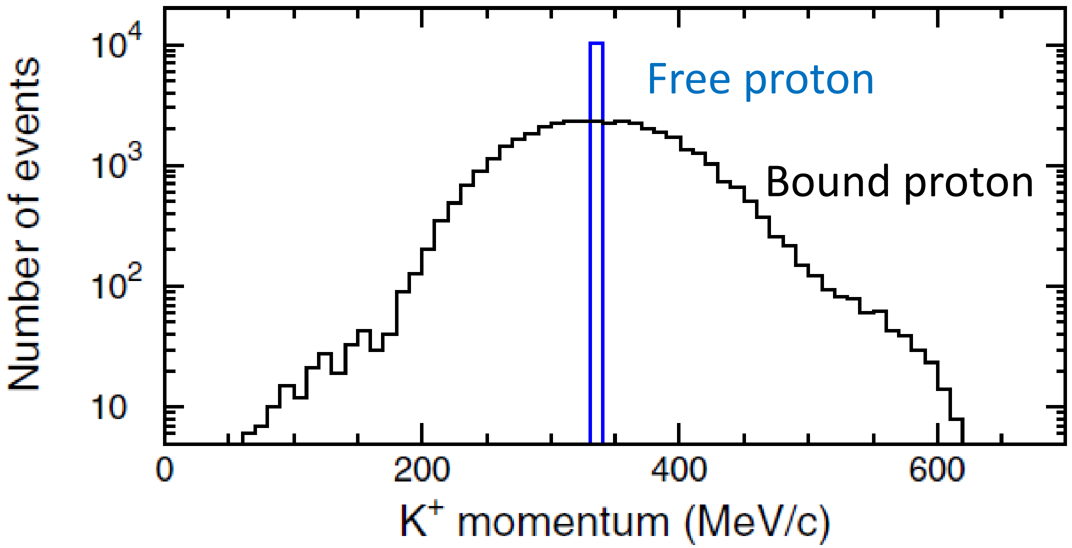
How to find 2.2 MeV γ


Prompt signal
10ns
Search with the window
2.2 MeV γ candidate
Hit time-TOF(prompt vertex)

- After Time-of-Flight subtraction, search for 7 hits in 10 nsec time window. → candidates of γ.
- Make 16 variables related to space and time information of each hits (RMS of phi, theta, hit time, e.t.c.)
- Put them into Neural Network to judge γ or not.
- Neutron tagging efficiency: 21 % (mis-tagging: 1.8 %)

3. p $\rightarrow \nu K^+$ search

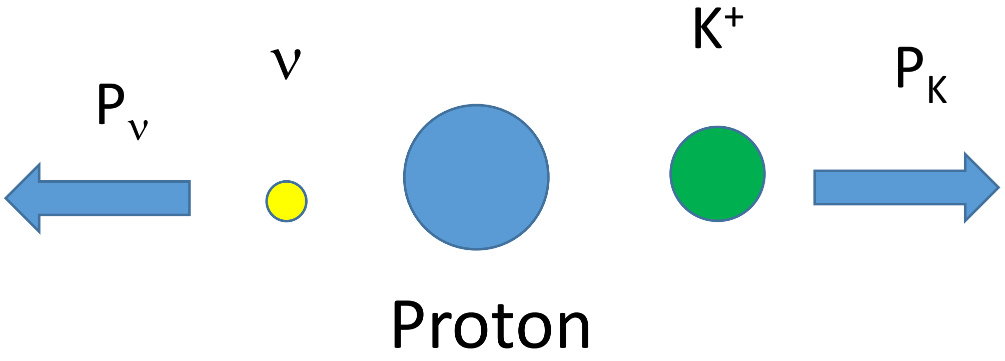
Difficulty of p→νK$^+$



- K$^+$ mass: 494 MeV, relatively heavy.
- Cherenkov threshold: 560 MeV/c.
- Most of K$^+$ can not emit Cherenkov light.

Q. Calculate momentum of K$^+$ from free proton decay.

Hint: proton mass: 938 MeV, "free" means proton momentum=0.


P_ν
ν
K^+
P_K
Proton

Conservation of momentum: $P_\nu = P_K$

Conservation of energy: $M_P = \sqrt{M_K^2 + P_K^2} + P_\nu$

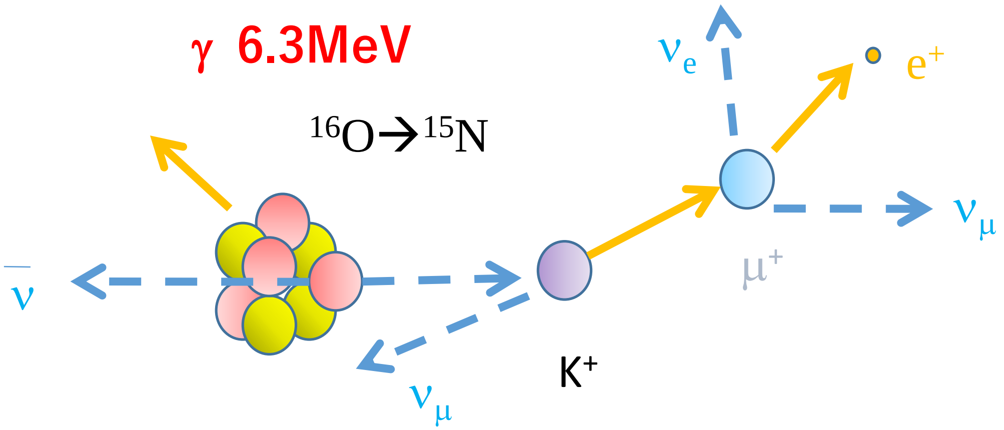
Proton Electron Neutrino

$$P_K = \frac{M_P^2 - M_K^2}{2M_P}$$

3-1 How to find $p \rightarrow \nu K^+$ in Water Cherenkov detector

- K^+ has low momentum, most of them stop in water and decay with 12 nsec lifetime.
- Major K^+ decay mode
  - $K^+ \rightarrow \nu\mu^+$: 64 %
  - $K^+ \rightarrow \pi^+\pi^0$: 21 %
- "Stopping K^+" means two body decay products of K^+ should have monochromatic momentum as seen in the previous question !
  - $K^+ \rightarrow \nu\mu^+$: 236 MeV/c
  - $K^+ \rightarrow \pi^+\pi^0$: 206 MeV/c
- Using this property, Water Cherenkov detector can search for $p \rightarrow \nu K^+$.

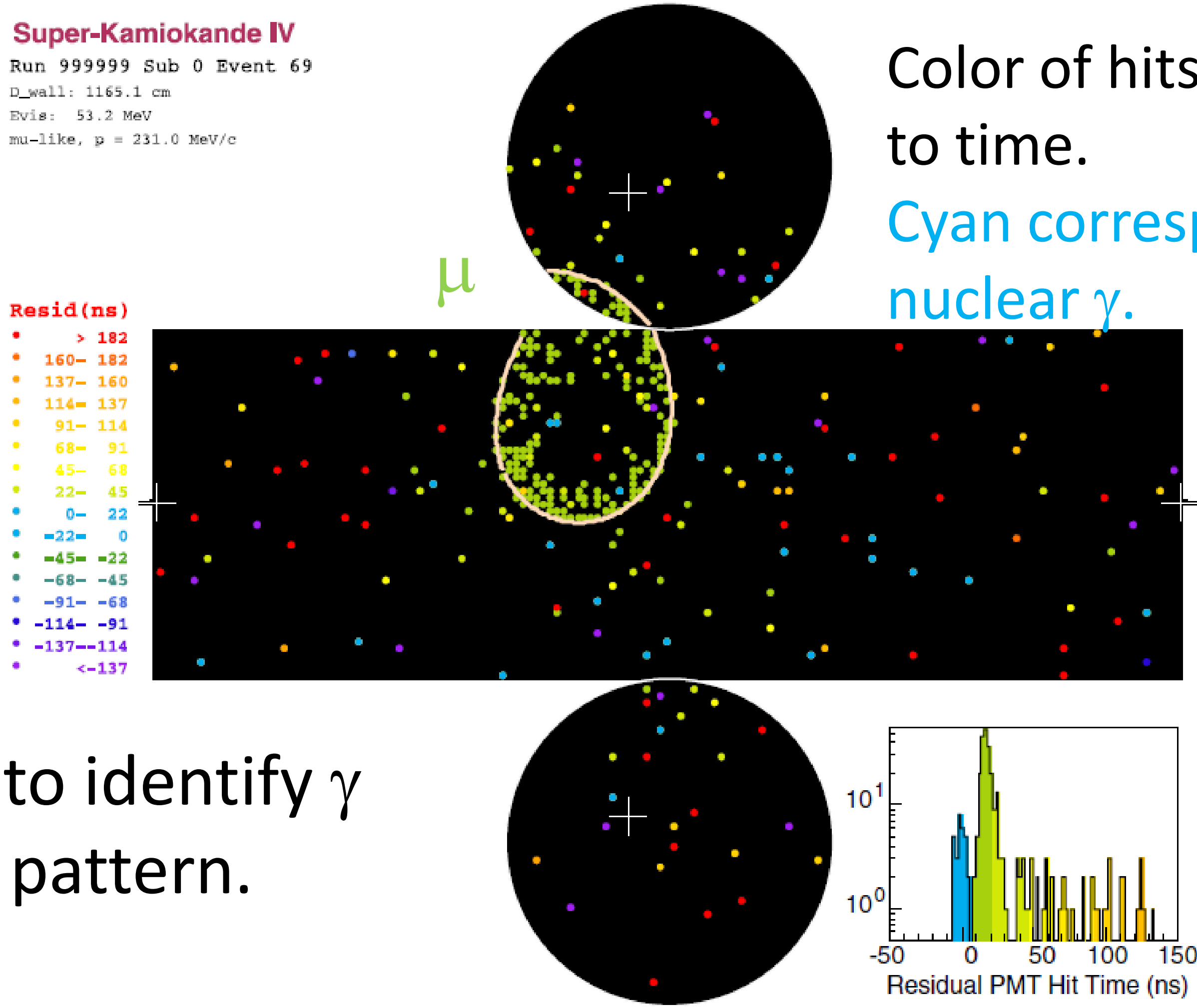
3-2. Search for p→νK^+, K^+→$\nu\mu^+$



γ 6.3MeV
$^{16}O \rightarrow {}^{15}N$
ν_e
e^+
ν_μ
μ^+
$\bar{\nu}$
ν_μ
K^+

- Visible particle is only μ^+ with Michel electron.
- Search for data excess around 236 MeV/c of μ comparing with atmospheric ν MC.
- After proton decay, 40 % of remaining nucleus emits 6 MeV γ for deexcitation. It is useful to reduce background.

Example of $p \rightarrow \nu K^+$, $K^+ \rightarrow \nu \mu^+$ with γ

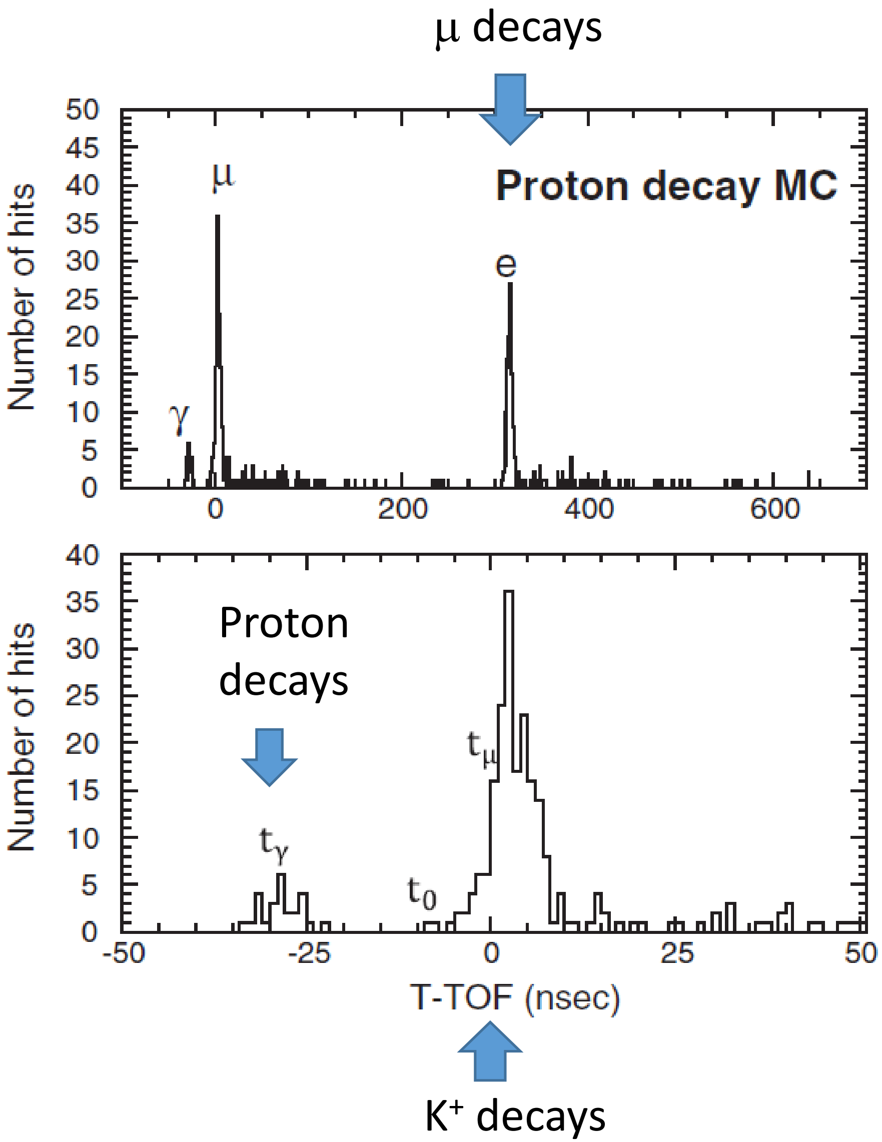


Color of hits corresponds to time.

Cyan corresponds to nuclear γ.

Difficult to identify γ from hit pattern.

Time structure with nuclear γ



μ decays

Proton decays

K^+ decays

- 3 hit clusters in time should be observed in case of signal.
- The event is triggered by μ hits.
- γ signal is much smaller than μ and easily hidden by tail of μ hits.
- Make 12 nsec time window and slide it toward left from t_0 (end of μ tail) to search for maximum hit cluster.

Selection criteria for $p \rightarrow \nu K^+$, $K^+ \rightarrow \nu \mu^+$

- 1 μ-like ring with Michel electron
- $215 < P\mu < 260$ MeV/c
- Proton rejection cuts
- Search Max hit cluster by sliding time window (12ns width);
  - $4 < N\gamma < 30$ hits
  - $T_\mu - T_\gamma < 75$ nsec

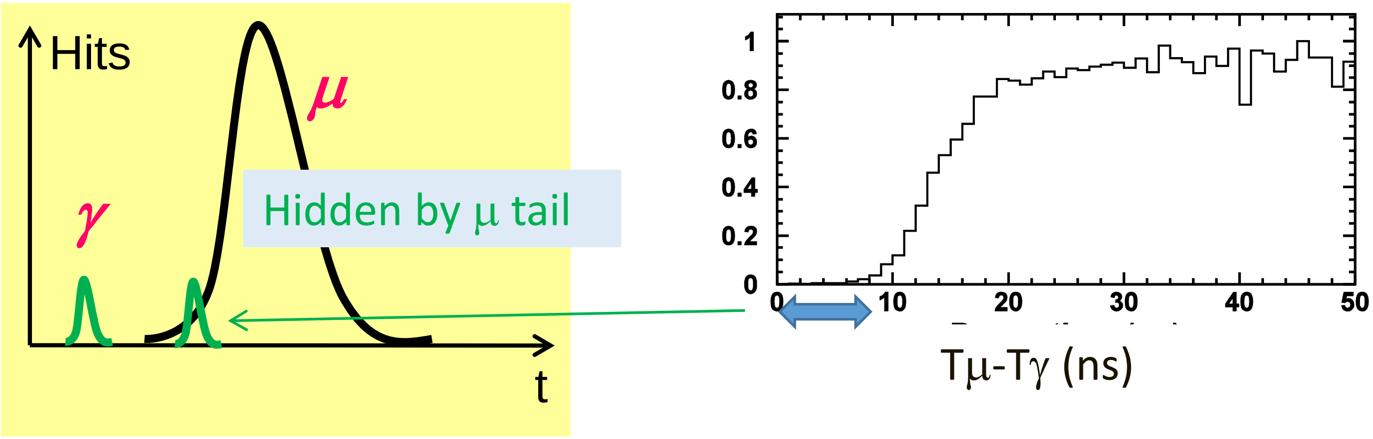
Reduce background by 5×10^{-4} !

- No neutron
- Selection efficiency = (selected events)/(proton decay in fiducial volume): 9 %
  - $Br(K^+ \rightarrow \nu \mu^+) = 64$ %, only 40 % emits nuclear γ → 26 % even if detector is perfect.

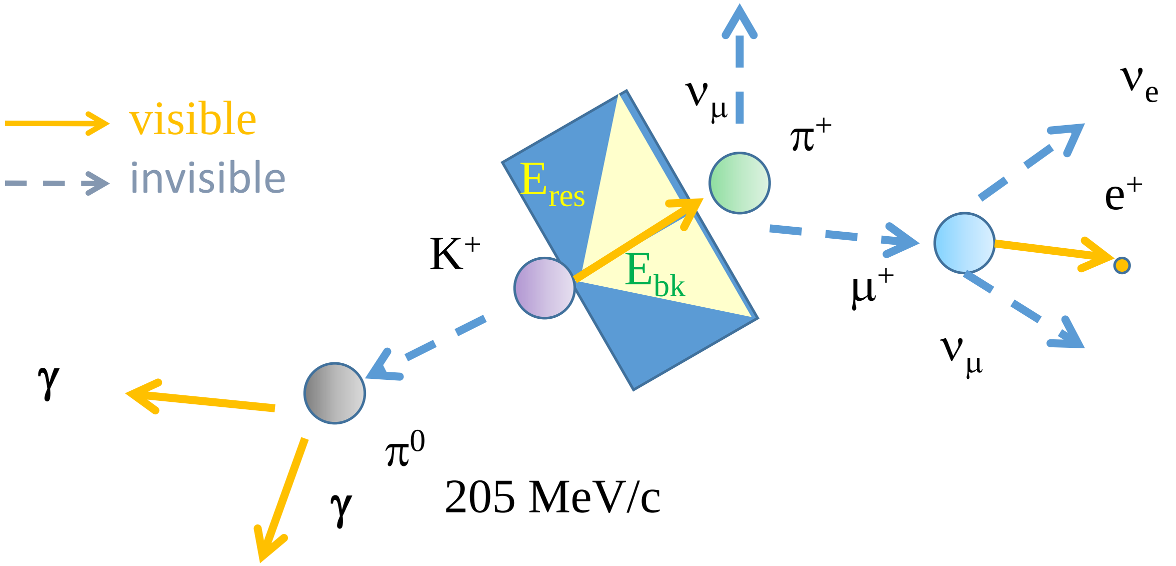
Remark for this analysis

- This analysis is limited by time resolution of PMTs.
  - ➢ If γ is close to μ, γ peak is hidden by μ hits.
  - ➢ Time resolution of SK PMT is 2.2 nsec at 1 photoelectron.
  - ➢ If μ peak becomes sharper, the selection efficiency will be improved.

γ tagging efficiency

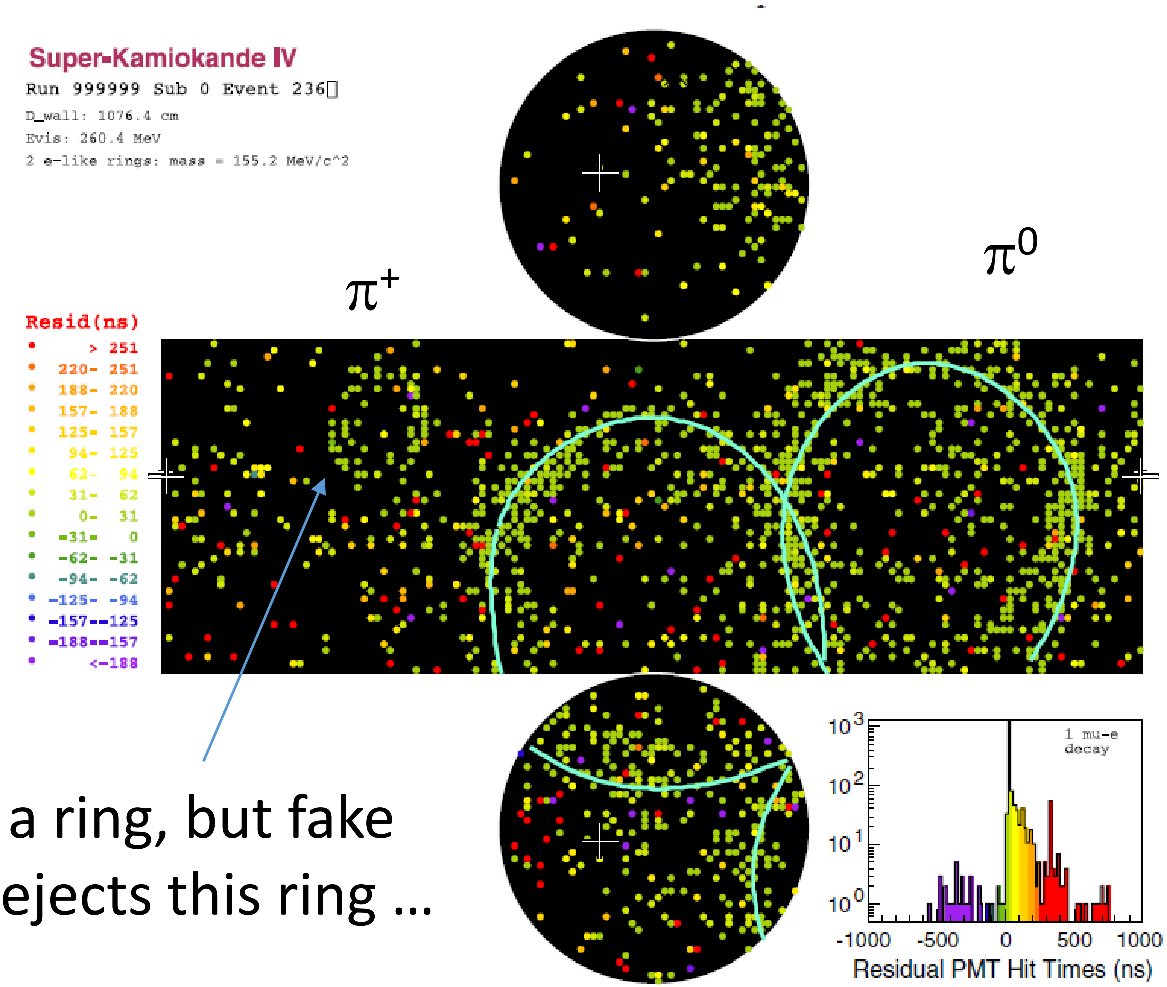


3-3. Search for $p \rightarrow \nu K^+$, $K^+ \rightarrow \pi^+ \pi^0$


visible
invisible
ν_μ
π^+
ν_e
E_{res}
e^+
K^+
E_{bk}
μ^+
ν_μ
γ
π^0
γ
205 MeV/c

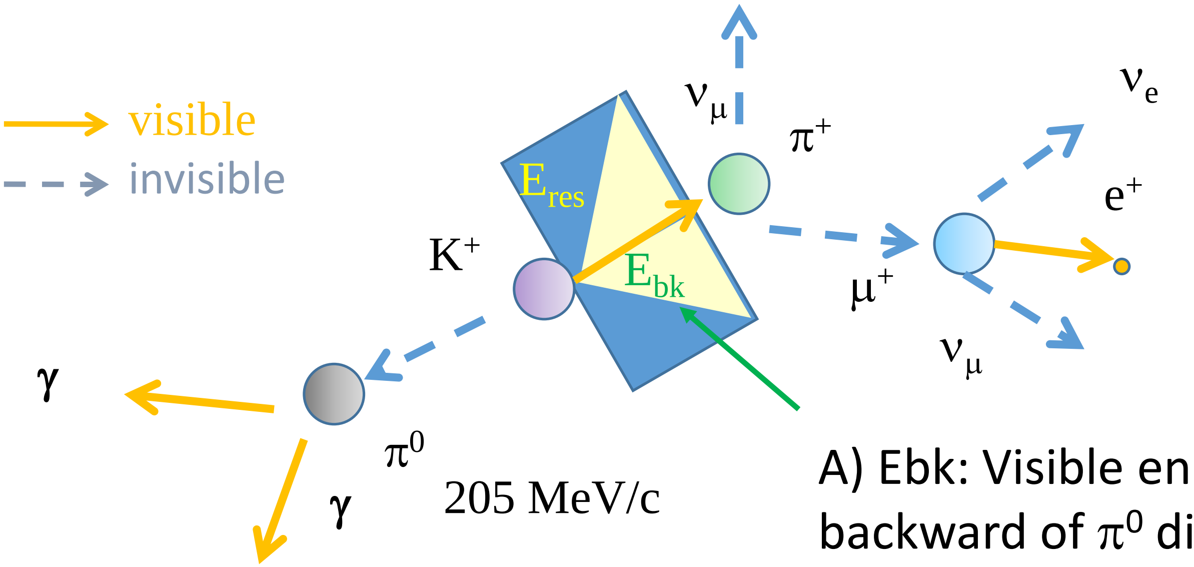
- Both π^+ and π^0 has 205 MeV/c in momentum. This is just above Cherenkov threshold for π^+, thus it is not identified as a ring in most of case.
- π^+ decays into μ (invisible) and ν, μ decays into $e\nu_e\nu_\mu$.
- π^0 decays into 2 γs.
- Search for 206 MeV/c π^0 with Michel electron.

Example of $p \rightarrow \nu K^{+}$, $K^{+} \rightarrow \pi^{+}\pi^{0}$



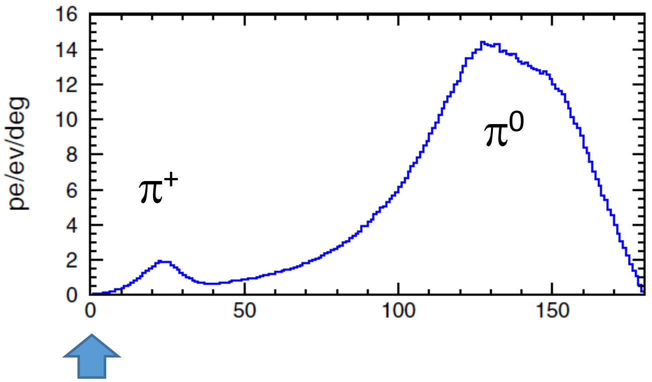
Look like a ring, but fake ring cut rejects this ring …

Use π^+ information to select events


visible
invisible
ν_μ
π^+
ν_e
e^+
E_{res}
K^+
E_{bk}
μ^+
ν_μ
γ
π^0
γ
205 MeV/c

A) Ebk: Visible energy sum in backward of π^0 direction (140°-180°)

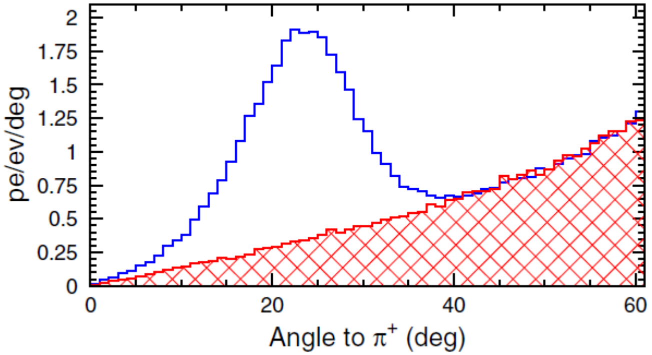
Charge distribution



π^+ direction

Zoom

B) Make likelihood for hit pattern.



Selection criteria for $p \rightarrow \nu K^+$, $K^+ \rightarrow \pi^+\pi^0$

- 1 or 2 e-like rings with decay-e.
- $85 < M\pi^0 < 185$ MeV.
- $175 < P\pi^0 < 250$ MeV/c.
- E_{bk}: visible energy sum in 140-180 deg. of π^0 dir,

  E_{res}: in 90-140 deg,

  L_{shape}: Likelihood based on charge profile

  $10 < E_{bk} < 50$ MeV

  $E_{res} < 12$ MeV (20 MeV for 1ring)

  $L_{shape} > 2.0$ (3.0 for 1ring)
- No neutrons
- Selection efficiency: 10 % ($Br(K^+ \rightarrow \pi^+\pi^0)=21$ %)

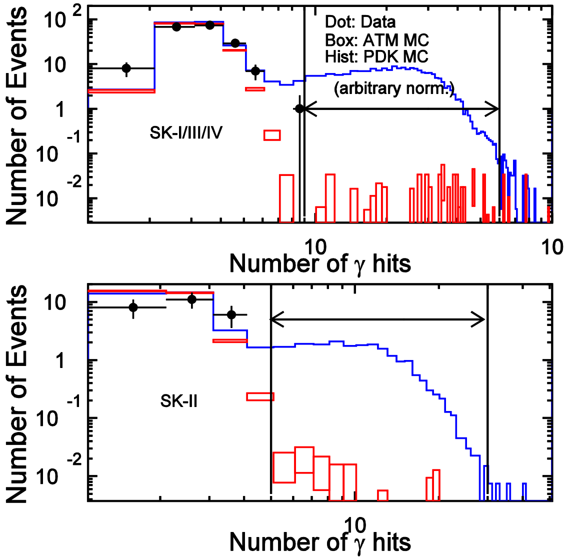
Background for $p \rightarrow \nu K^+$

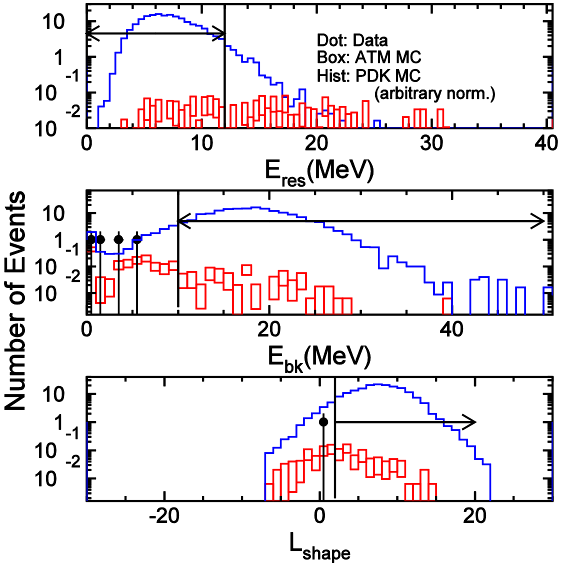
- Dominant background is K^+ production by neutrino interactions.
  - ➢ $\nu p \rightarrow \nu \Lambda K^+$, $\Lambda \rightarrow p\pi^-$ (BR:64 %, mostly invisible in WCD)
  - ➢ Emit nuclear γ as same as the signal.
- It is also rare interaction and we had poor information from very old bubble chamber. Large uncertainty.
- Recently MINERvA measures K^+ production. It is very useful information for this analysis.

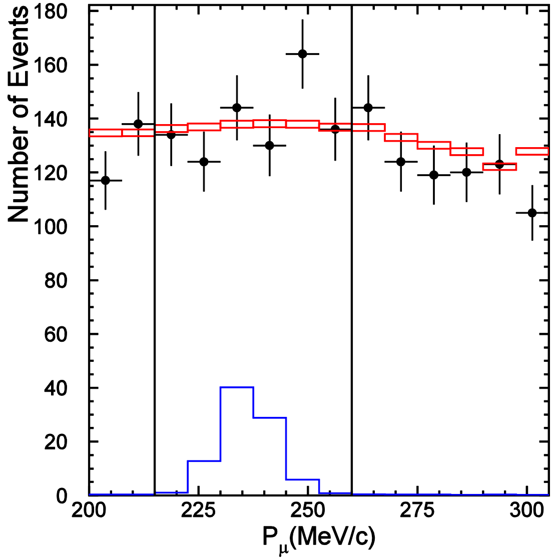
3-4. SK results (So far)

- Exposure: 365 kton・year
- Expected background: 0.3 events for $K^+ \rightarrow \nu\mu$ with nuclear γ, 0.6 events for $K^+ \rightarrow \pi^+\pi^0$.
- No candidates observed and no excess in momentum distribution.
- Lower lifetime limit: > 0.8×10^{34} year

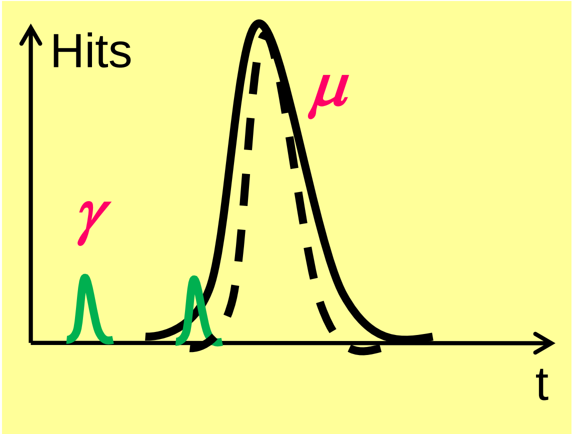
Black: Data
Red: Atm.n MC
Blue: Signal MC





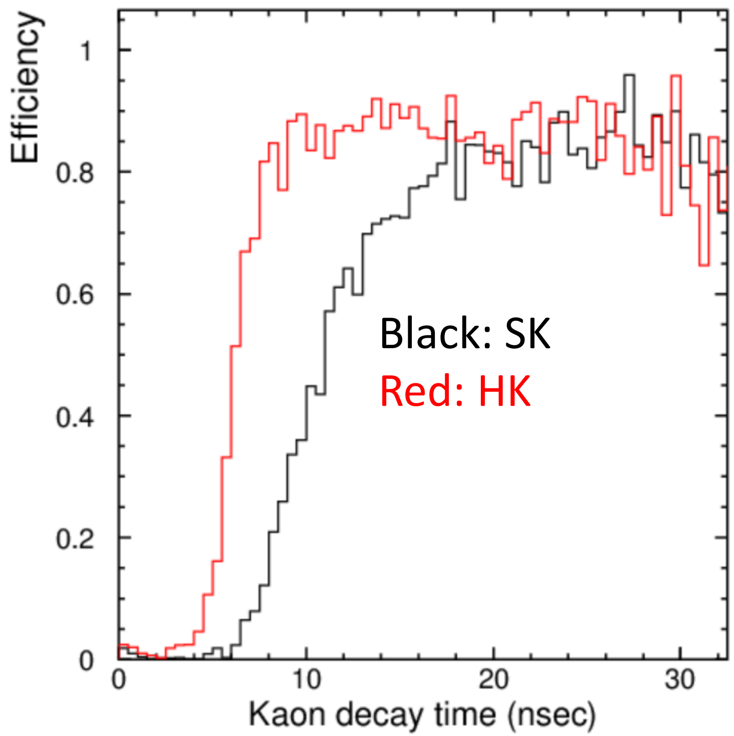


Faster PMT response improves nuclear γ tagging in $p \rightarrow \nu K^+$



- Time resolution: 2.2nsec (SK) →1.1 nsec (HK).
- Sharper time distribution of μ → γ close to μ cab be identified !

γ tagging efficiency



(Better photon counting also contributes improvement)