核子崩壊探索の現在と将来

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Contents

1. Introduction

Strong | Weak | EM
(Electroweak)

Grand Unified Theories

The Standard Model has been successful!
… but why so many parameters?

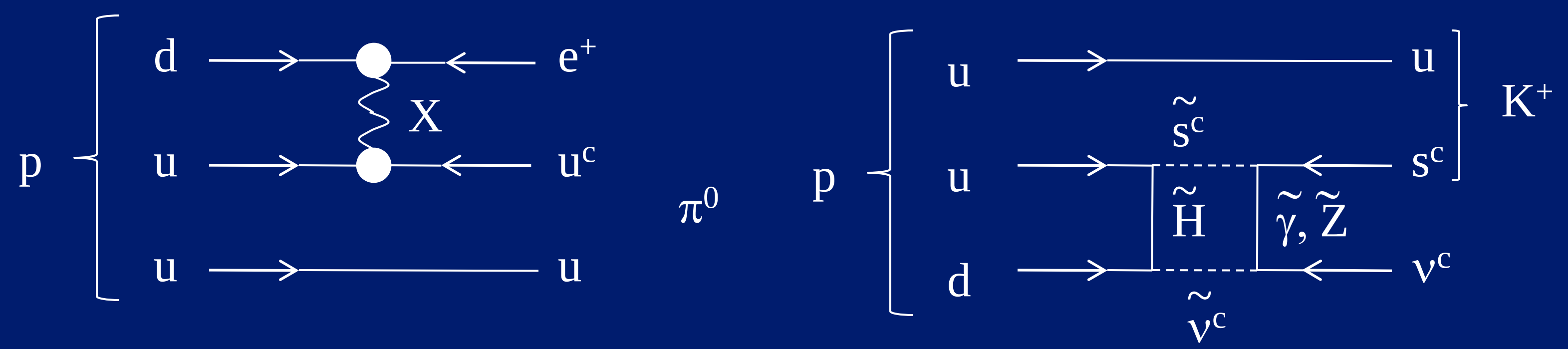
GUTs: attempt to unify Strong and Electroweak interactions.

GUTs scale: ~10^{16} GeV → Cannot be achieved by Accelerators.

Lepton and baryon numbers are not conserved. → Proton decay is permitted !

Nucleon decay experiment is the direct probe for GUTs.

Examples of proton decay



Minimal SU(5) model　　　　SUSY SU(5) model

Proton lifetime predictions

Model	Mode	Prediction (years)
Minimal SU(5)	$P \to e^+\pi^0$	$10^{28.5} \sim 10^{31.5}$ [1]
Minimal SO(10)	$P \to e^+\pi^0$	$10^{30} \sim 10^{40}$ [2]
Minimal SUSY SU(5)	$P \to \bar{\nu}K^+$	$\leq 10^{30}$ [3]
SUGRA SU(5)	$P \to \bar{\nu}K^+$	$10^{32} \sim 10^{34}$ [4]
SUSY SO(10)	$P \to \bar{\nu}K^+$	$10^{32} \sim 10^{34}$ [5]

[1] P. Langacker, Phys. Reports 72, 185 (1981)
[2] D.G. Lee, M.K. Parida, and M. Rani, Phys. Rev. D51, 229 (1995)
[3] H.Maruyama and A. Pierce, Phys. Rev. D65, 55009 (2002)
[4] T. Goto and T. Nihei, Phys. Rev. D59, 115009 (1999)
[5] V. Lucas and S. Ruby, Phys. Rev. D55, 6986 (1997)

核子崩壊観測には巨大な検出器が必要。

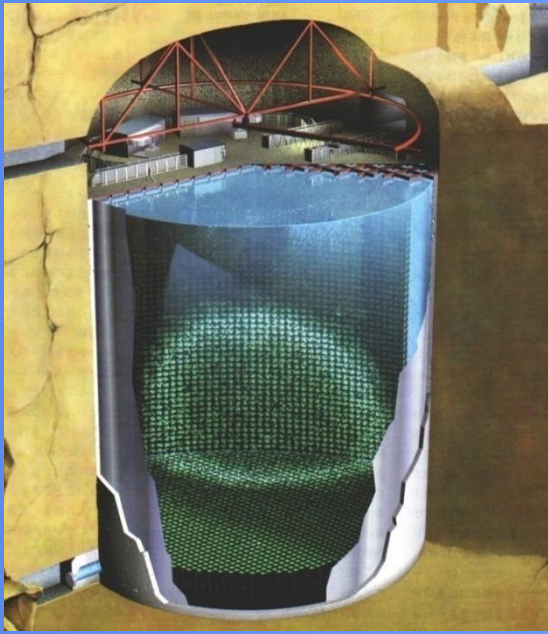
水チェレンコフ検出器は巨大化可能。

- Super-Kamiokandeの場合、
  - Fiducial volume: 22.5 kton
  - => 7 x 10^{33} protons
  - うち、20% のFree proton は核内効果に影響されない。

2. Current status of Nucleon decay search (From recent results from Super-K)

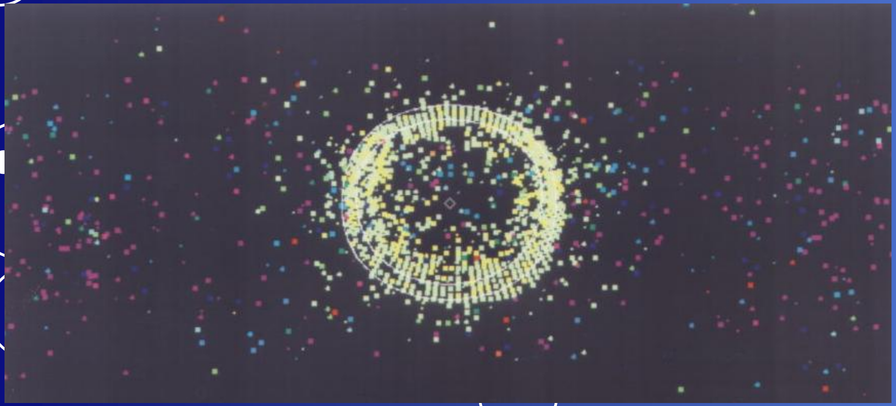
Nucleon Decay Experiment

Super-Kamiokande Detector

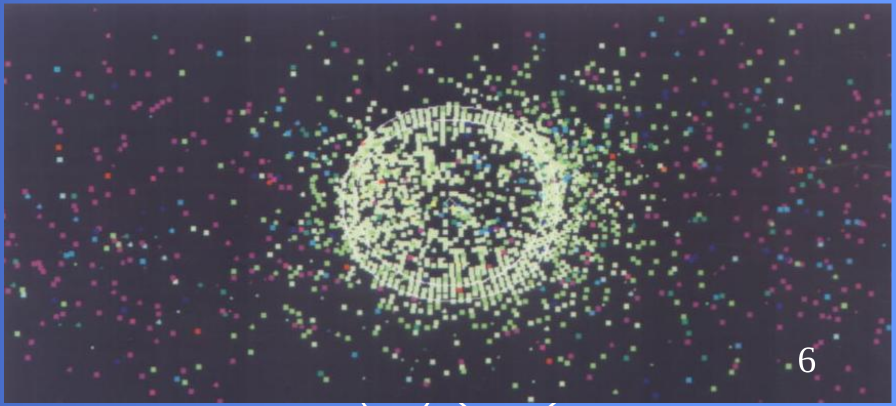


Location: Kamioka mine, Japan. ~1000 m under ground.
Size: 39 m (diameter) x 42 m (height), 50kton water.
Optically separated into inner detector (ID) and outer detector (OD, ~2.5 m layer from tank wall.)
Photo device: 20 inch PMT (ID), 8 inch PMT (OD, veto cosmic rays).
Mom. resolution: 3.0 % for e 1 GeV/c (4.1%: SK-2).
Particle ID: Separate into EM shower type (e-like) and muon type (μ-like) by Cherenkov ring angle and ring pattern.

μ-like ($\mu^{\pm}$)



e-like ($e^{\pm}$, γ)

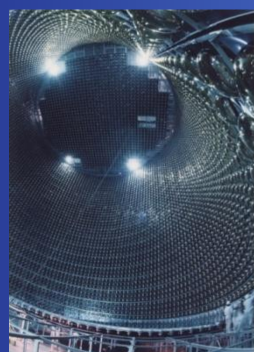


History of Super-Kamiokande

Accident | reconstruction | electronics upgrade

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13

SK-1
Livetime:
- 1489.2 days
Exposure:
- 91.7 kton·yr
Inner PMT: 11146
Photo coverage:
40 %



SK-2
Livetime:
- 798.6 days
Exposure:
- 49.2 kton·yr
Inner PMT:5182
Photo coverage:
19 %

SK-3
Live time:
518 days
Exposure:
31.9kton･yr
ID PMT:11146
Photo coverage:
40 %

SK-4 (~13'Feb)
Live Time:
1417 days
Exposure:
87.3kton･yr

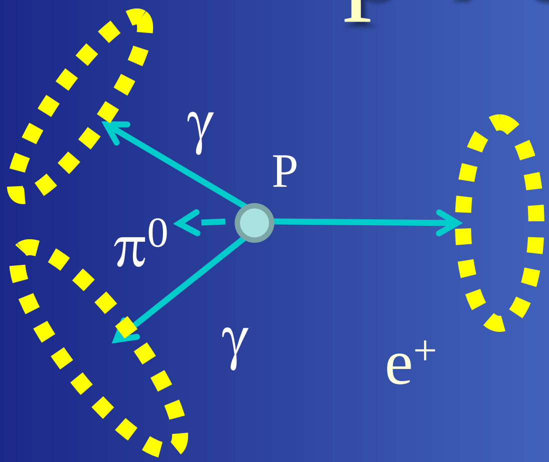
⇨ Same

$e^+\pi^0$ paper 2007: > 8.2×10^{33} years (141kton･year)

νK^+ paper 2005: > 2.3×10^{33} years (92kton･year)

This talk: 260 kton･year exposure in total

$p \rightarrow e^+\pi^0$ mode



Event features;

- e^+ and π^0 are back-to-back (459 MeV/c)
- $\pi^0 \rightarrow 2\ \gamma$s : all particles can be detectable.

➔ Reconstruct proton mass and momentum.

Selection;

- Fully contained, VTX in fiducail volume.
- 2 or 3 ring
- All e-like, w/o decay-e
- $85 < M\pi^0 < 185$ MeV (for 3-ring event) .
- $800 < M_P < 1050$ MeV & $P_{tot} < 250$ MeV/c

Selected by simple cuts !

MC simulations

Proton decay MC <= Efficiency

8 bound protons in O:

- Kinematics of bound proton (Fermi momentum, binding energy)
- Nuclear effects (deexcited nuclear γ, absorption, scattering, charge exchange in nuclear)

are taken into account.

2 free protons: simple two body decay.

Atmospheric ν MC <= **BKG for proton decay**

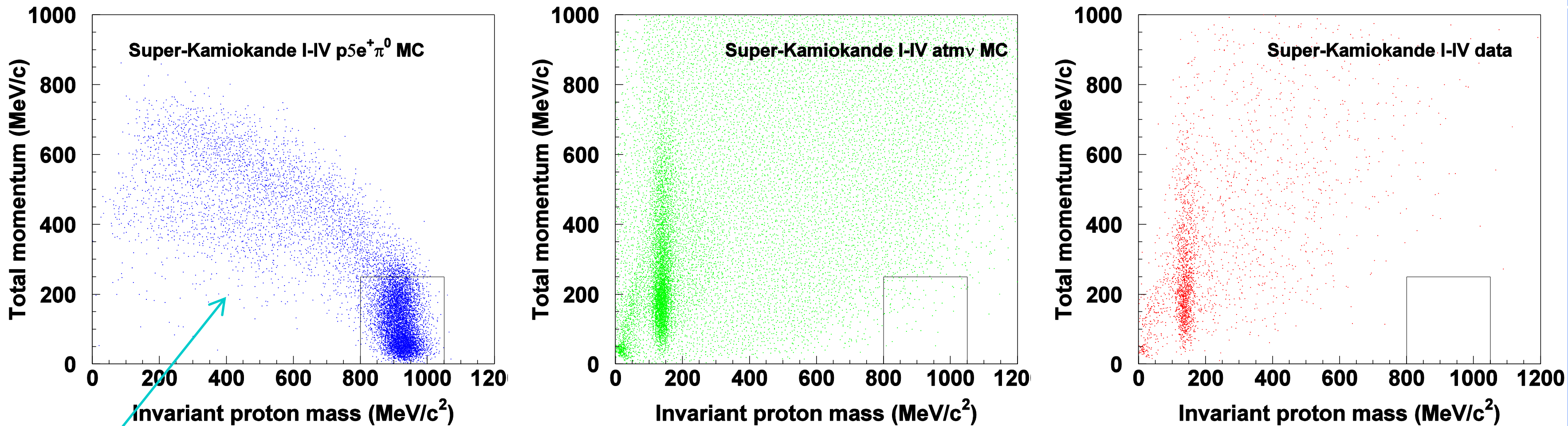
Flux : Primary cosmic rays make ν_μ and ν_e.

M.Honda et .al., Phys.Rev. D**75** 043006(2007)

ν interaction: NEUT Y.Hayato, Nucl.Phys.Proc.Suppl. **112**,171(2002)

M_{tot} vs P_{tot}

Blue: PDK MC **Green: ATMν MC** **Red: Data**



Inefficiency comes from π-interaction in Oxygen.

Dominant BKG: CC1π

$\nu_e p \rightarrow e^+ n \pi^0$

$\nu_e n \rightarrow e^- n \pi^+$ +charge exchange

If n can be tagged, BKG can be reduced.

No candidate observed.

Results of $p \rightarrow e^+\pi^0$

	Exp. (kt・yr)	Eff(%)	BKG	BKG /Mt・yr	Candidate
SK1	91.7	39.2±0.7	0.27	2.9±0.6	0
SK2	49.2	38.5±0.7	0.15	3.0±0.5	0
SK3	31.9	40.1±0.7	0.07	2.3±0.6	0
SK4	87.3	39.5±0.7	0.22	2.5±0.6	0
Total	260.1		0.71		0

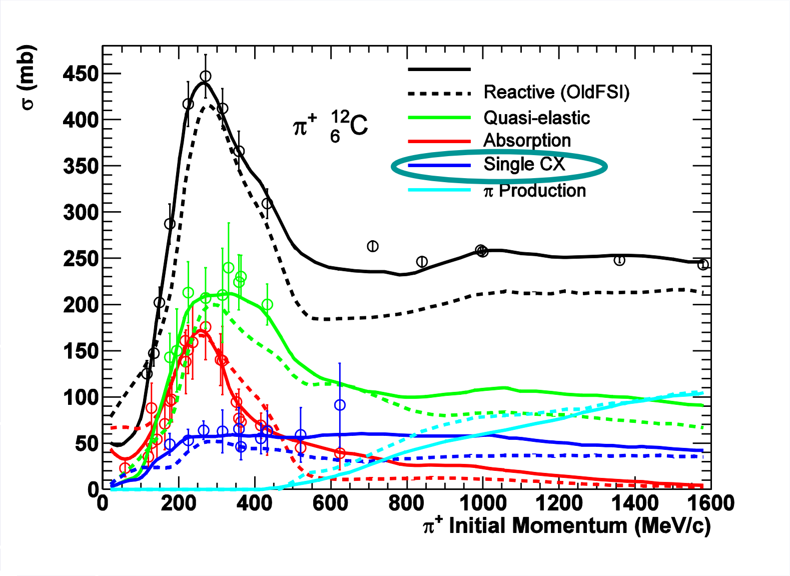
Note 1: In SK2, photo coverage was a half of other periods, but efficiency was almost same.

Lifetime limit (90%C.L,)

$p \rightarrow e^+\pi^0$: >1.4x10^{34} years @ 260kt・year

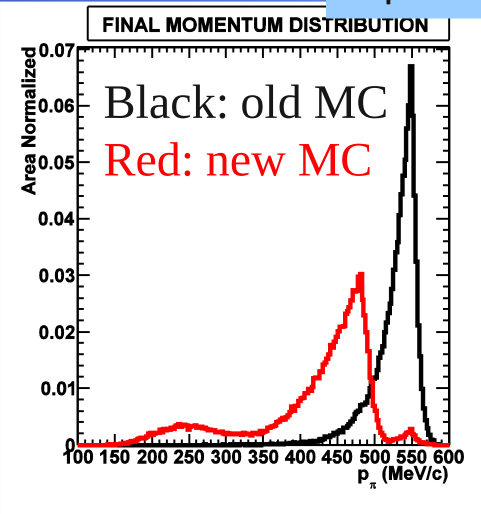
Why efficiencies decreased (45 % → 40 %)
→ Because we have updated π-interaction in Oxygen.

(1) Charge exchange increased to match experimental data.

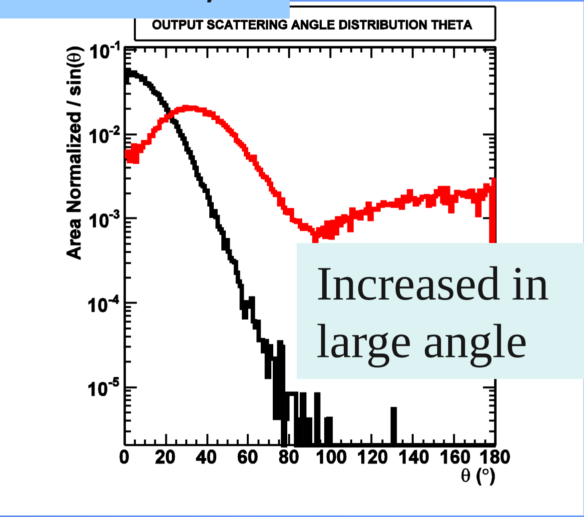


(2) Kinematics of scattered π changed in P > 500 MeV/c

Input: π 550 MeV/c



Final π momentum



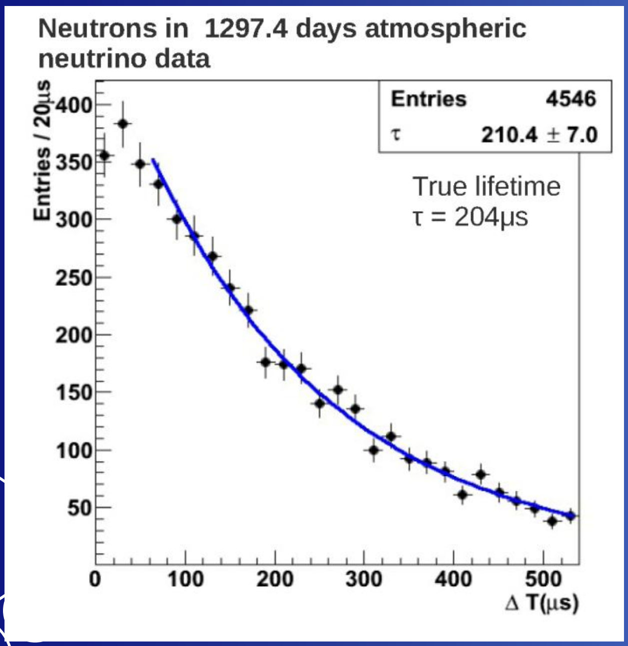
Final π angle (degree)

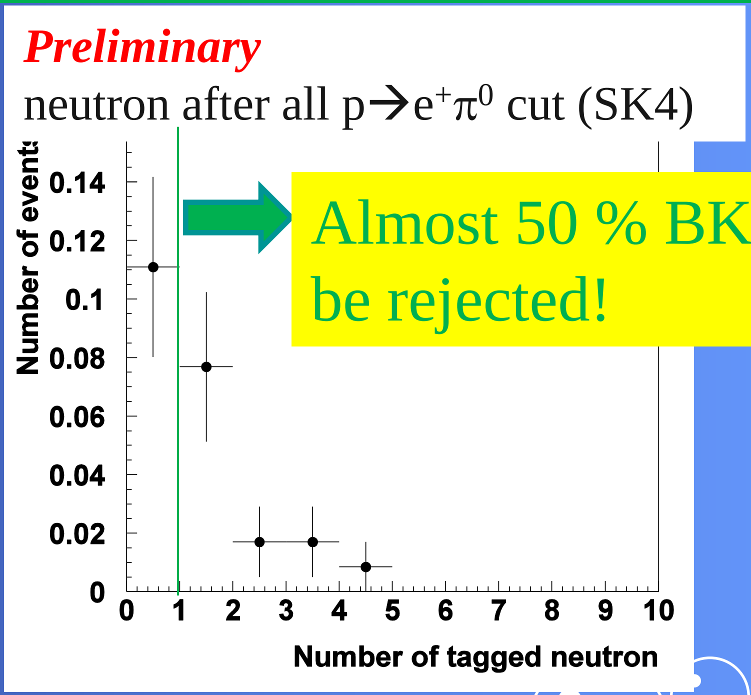
NOTE: Sys.error for π-int → 15 %

On going project: neutron tagging

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

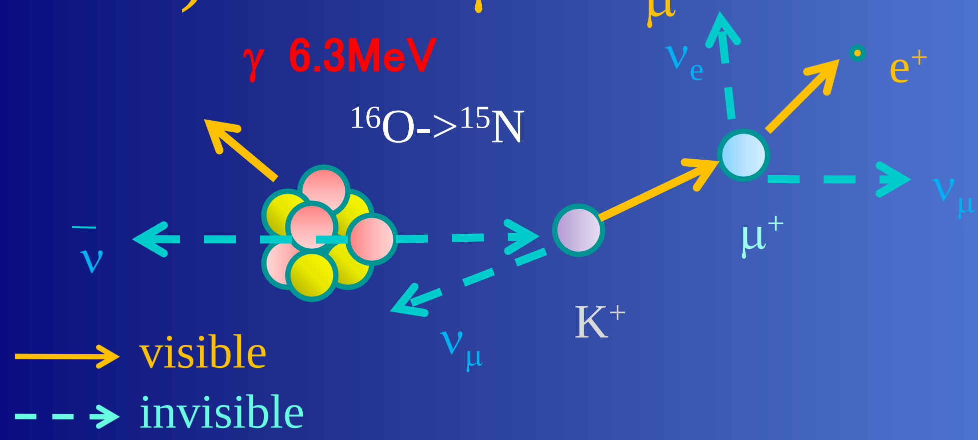
- Search for hit cluster N>7 in 10 ns window after prompt signal.
- Eff. 25 %, BKG 1.4 %.
- MC including neutron capture is under developing.





$p \rightarrow \bar{\nu} + K^+$ mode

A) $K^+ \rightarrow \mu^+ + \nu_\mu$



Event features;

- K^+ is invisible, stops and 2 body decay (P_μ = 236 MeV/c).

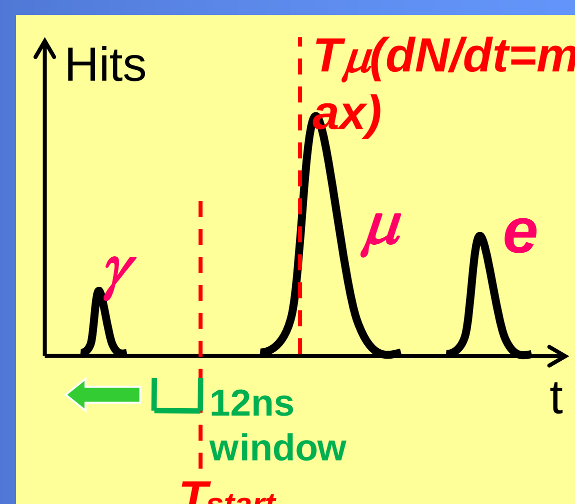
➔ Excess in P_μ.

- Proton in ^{16}O decays and excited nucleus emits 6 MeV γ (Prob. 41%, not clear ring).

=> Tag γ to eliminate BKG.

Selection:

- 1 μ-like ring with decay-e.
- 215 < Pμ < 260 MeV/c
- Search Max hit cluster by sliding time window (12ns width);
  - 8 < Nγ < 60 hits for SK-1,3,4
    4 < Nγ < 30 hits for SK-2
    &
  - $T_\mu - T_\gamma$ < 75 nsec
  - Proton ID liklihood < 0



Recent improvements on BKG rejection

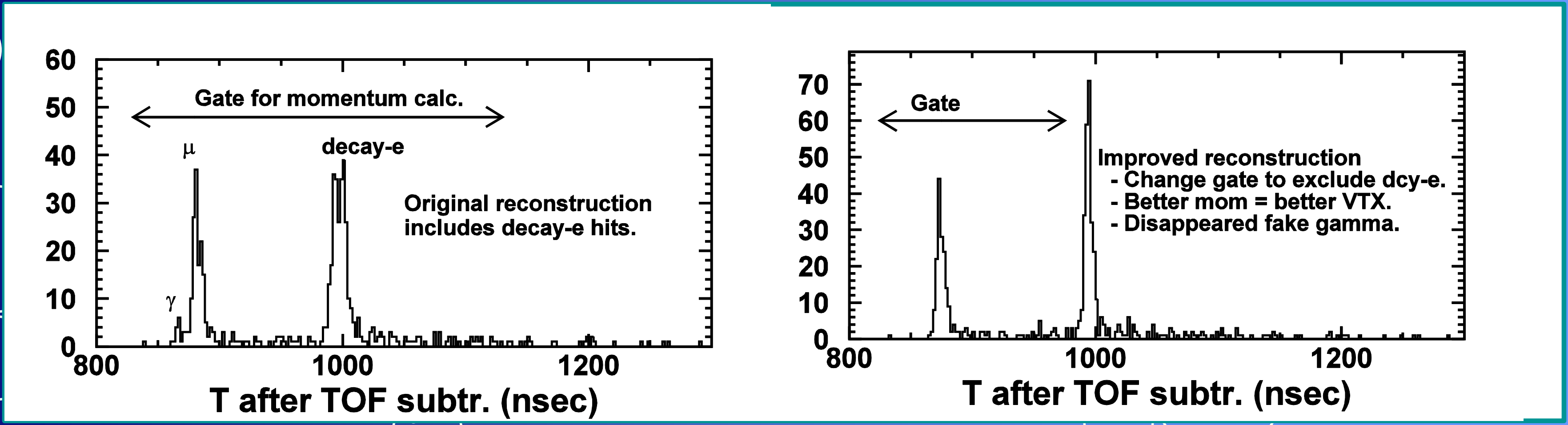
Fix momentum bias for events with decay-e

- Hits in (-50:250nsec) used for momentum.
- If decay-e is closer to μ, Pμ is overestimated

  → generate hit template for VTX fit with larger Pμ

  → VTX is shifted to forward.

  → TOF over-subtracted for backward hits, make mimic γ signal.
- Solution: Time window size is shortened when decay-e is closer to parent μ. BKG is reduced by 30 %.



Results

	Exp. (kton・yr)	Eff(%)	BKG	Data
SK1	91.7	7.9±0.1	0.08	0
SK2	49.2	6.3±0.1	0.14	0
SK3	31.9	7.7±0.1	0.03	0
SK4	87.3	9.1±0.1	0.13	0
Total	260.1		0.38	0

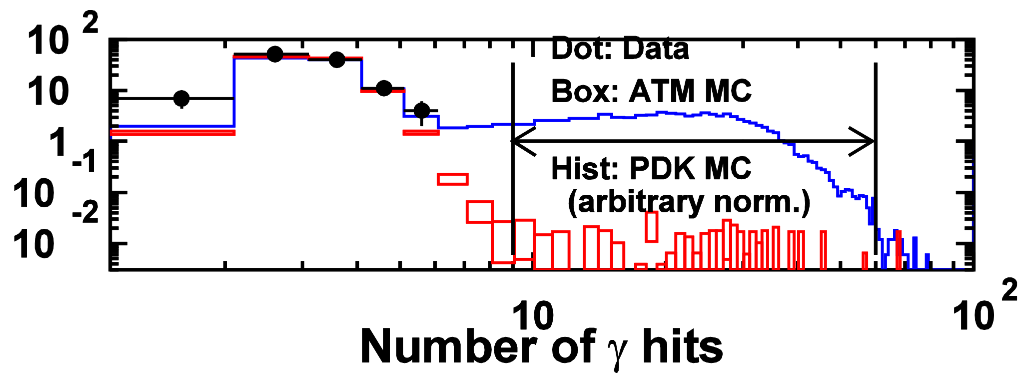
20 % reduced in half PMT density case.

Decay-e tagging efficiency is improved by new electronics.

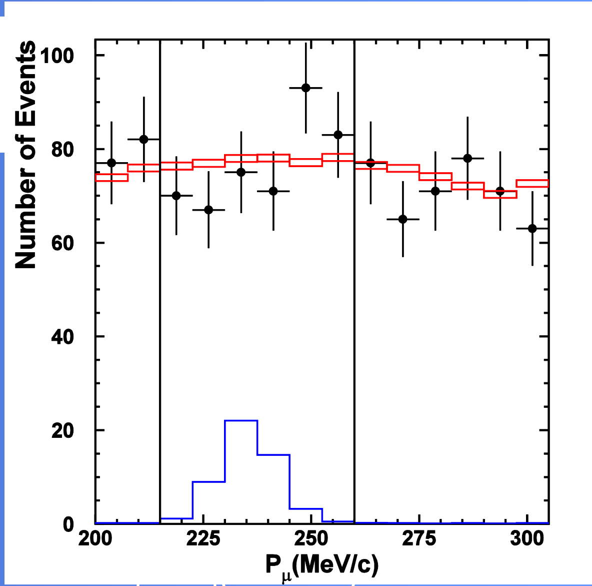
No candidates and no excess in P_μ.

N_γ (except SK2)

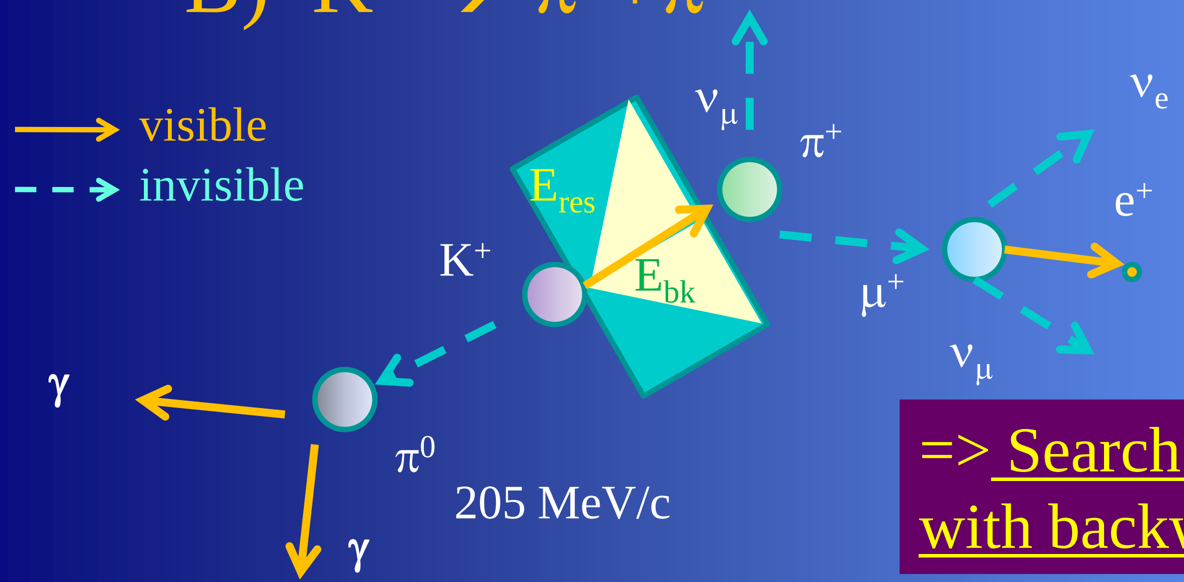
Black: Data
Red: ATM MC
Blue: PDK MC



Black: Data
Red: ATM MC
Blue: PDK MC



B) $K^+ \rightarrow \pi^+ + \pi^0$



Event features;

- Br. 21 %.
- π^0 and π^+ are back-to-back and have 205 MeV/c.
- $P\pi^+$ is just above Č thres. (not clear ring).

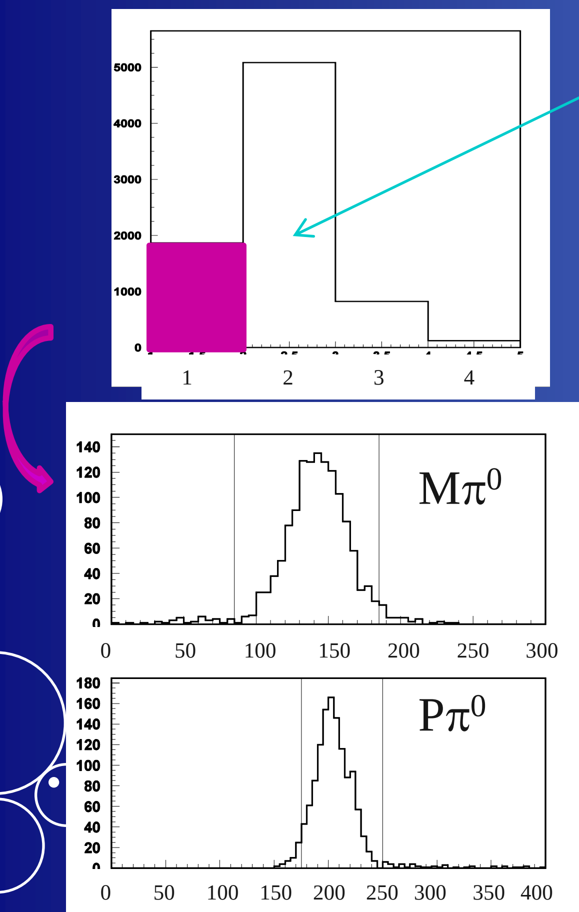
=> Search for monochromatic π^0 with backward activities.

Selection:

- 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 145-180 deg. of π^0 dir,
  E_{res}: in 90-145deg.
  L_{shape}: Likelihood based on charge distribution around π^+ dir.
  $10 < E_{bk} < 50$ MeV
  $E_{res} < 12$ MeV (single ring: 20 MeV)
  $L_{shape} < 2.0$ (single ring: 3.0)

Recent improvement: $p \rightarrow \nu K^+, K^+ \rightarrow \pi^+\pi^0$

of Ring: $K^+ \rightarrow \pi^+\pi^0$



Judge as 1 ring (~20%) if opening angle of 2 γs is small or momentum of one γ is small.

Use "π^0 fitter"

- Make likelihood assuming π^0 and search for missing ring.
- It is used for ν_e appearance analysis of T2K to reduce BKG.

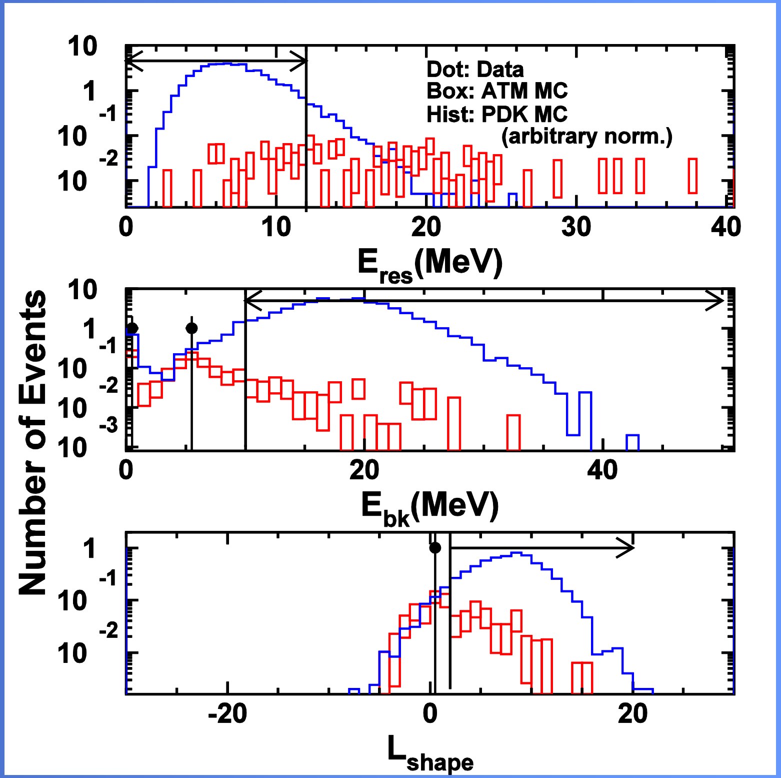
It makes 1 ring sample available for this analysis!

➔ Efficiency increased.

Results

Blue: PDK MC
Red: ATM MC
Black: Data

	Exp. (kton・yr)	Eff(%)	BKG	Data
SK1	91.7	7.8±0.1	0.18	0
SK2	49.2	6.7±0.1	0.17	0
SK3	31.9	7.9±0.1	0.09	0
SK4	87.3	10.0±0.1	0.18	0
Total	260.1		0.61	0



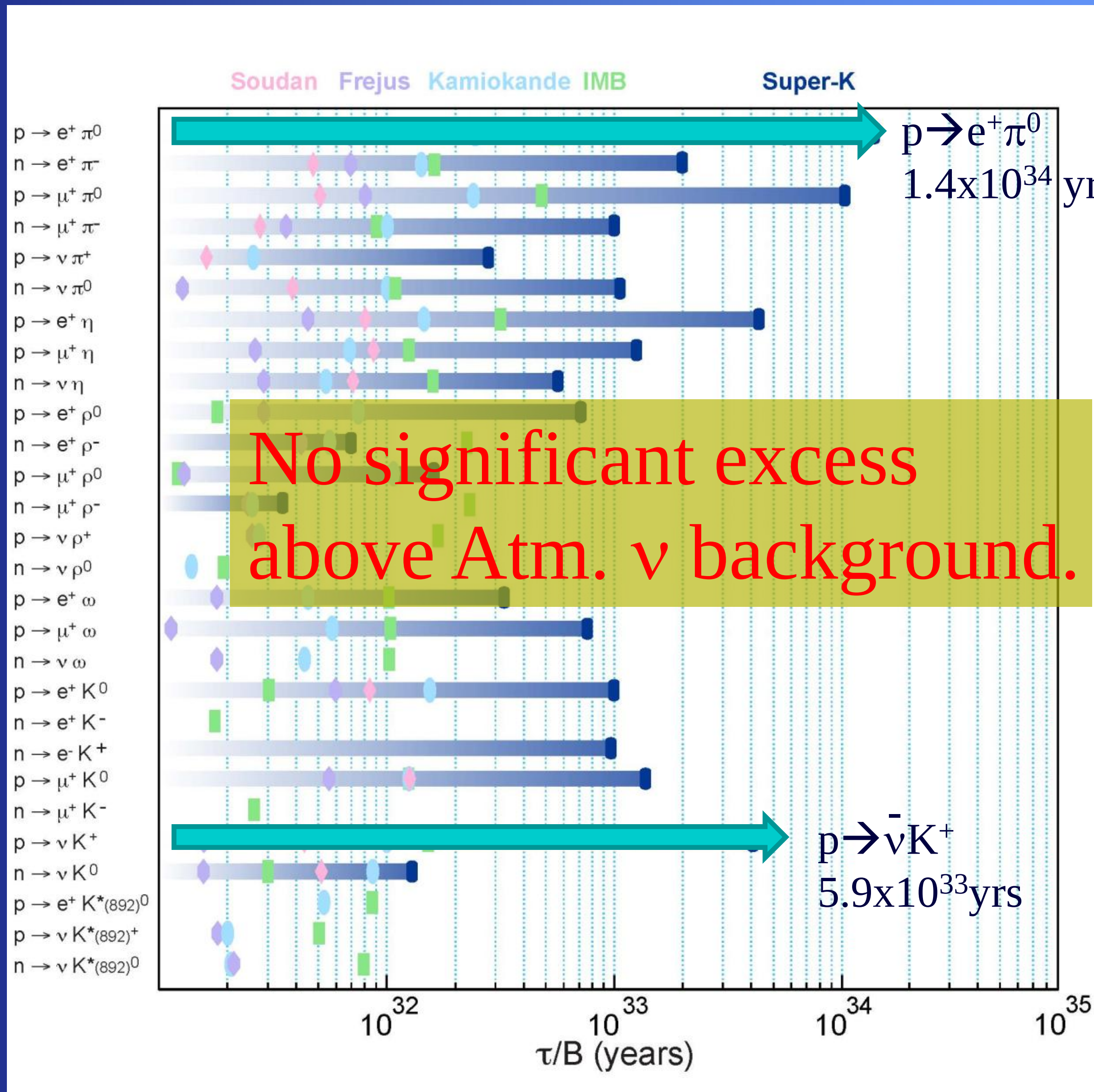
20 % reduced for half PMT density case.

Decay-e tagging efficiency is improved by new electronics.

No candidates.

$p \rightarrow \bar{\nu} K^+$ Combined lifetime limit (90% CL):
$> 5.9 \times 10^{33}$ yrs @260 ktont・yr

Summary of the current search results

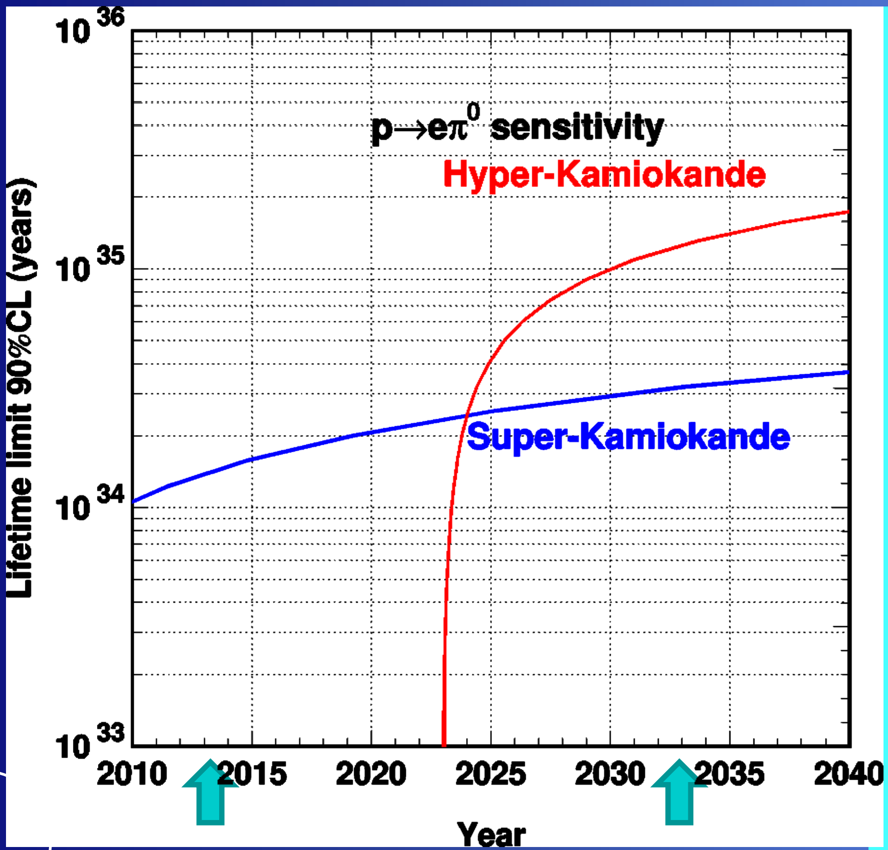


$p \rightarrow e^+\pi^0$
$1.4\text{x}10^{34}$ yrs

No significant excess above Atm. ν background.

$p \rightarrow \bar{\nu}K^+$
$5.9\text{x}10^{33}$yrs

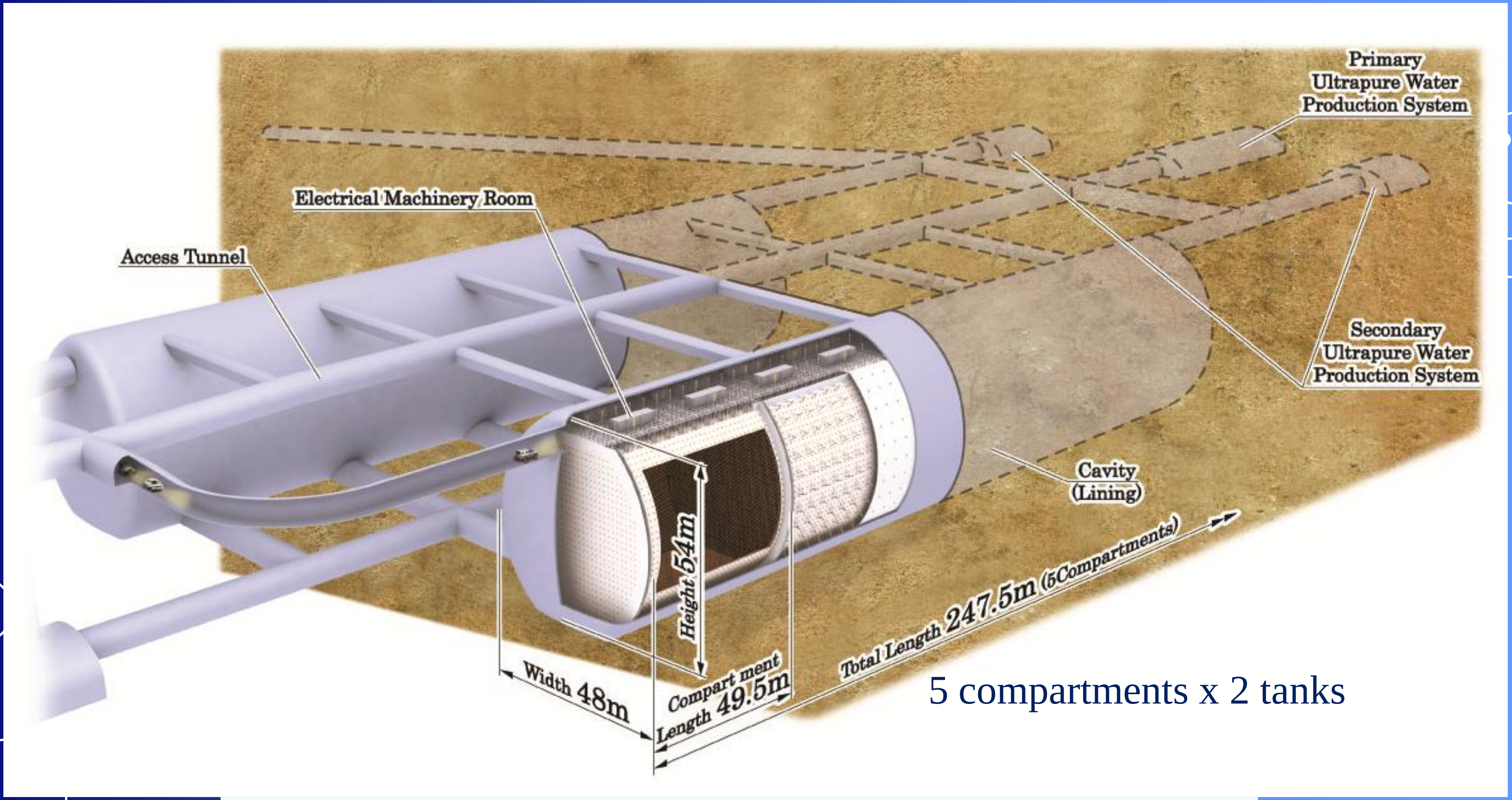
3. Future prospects



- Even if SK continue to run 20 years more, the sensitivity can reach just only ~2 times more longer life time.
- Obviously we need larger detector (1 Megaton class) if we want to explore one order longer lifetime.

Let's build Hyper-Kamiokande!

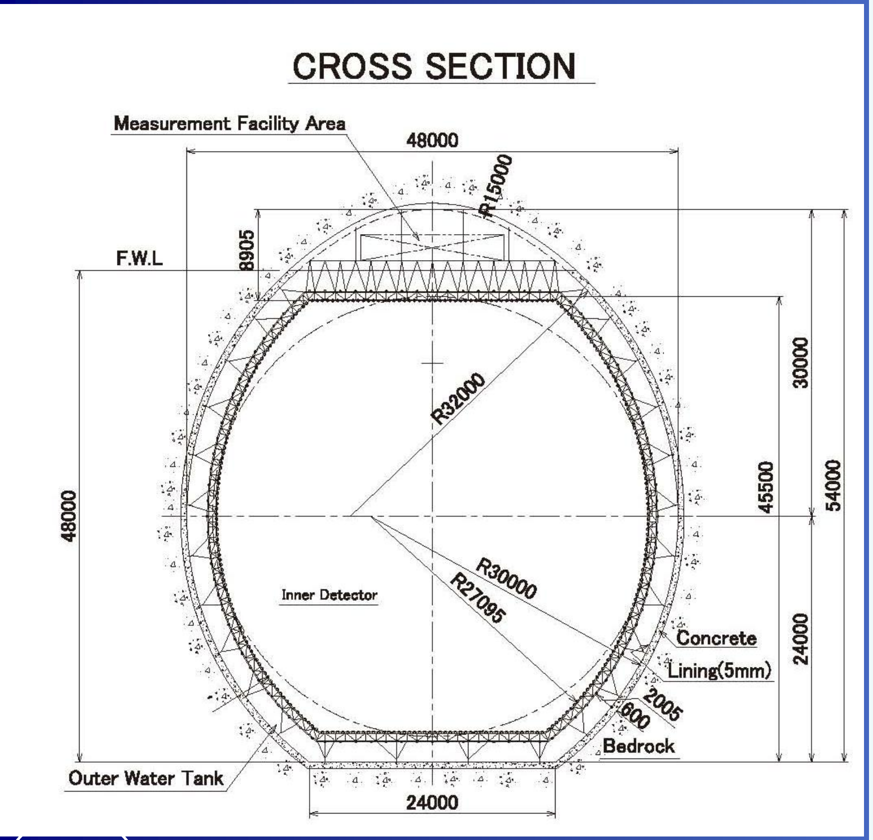
Hyper-Kamiokande



5 compartments x 2 tanks

1 Mega ton Water Chrenkov Detector

Base design



- Total Volume: 0.99 Mton
- Inner Volume: 0.74 Mton
- Fiducial volume: 0.56 Mton

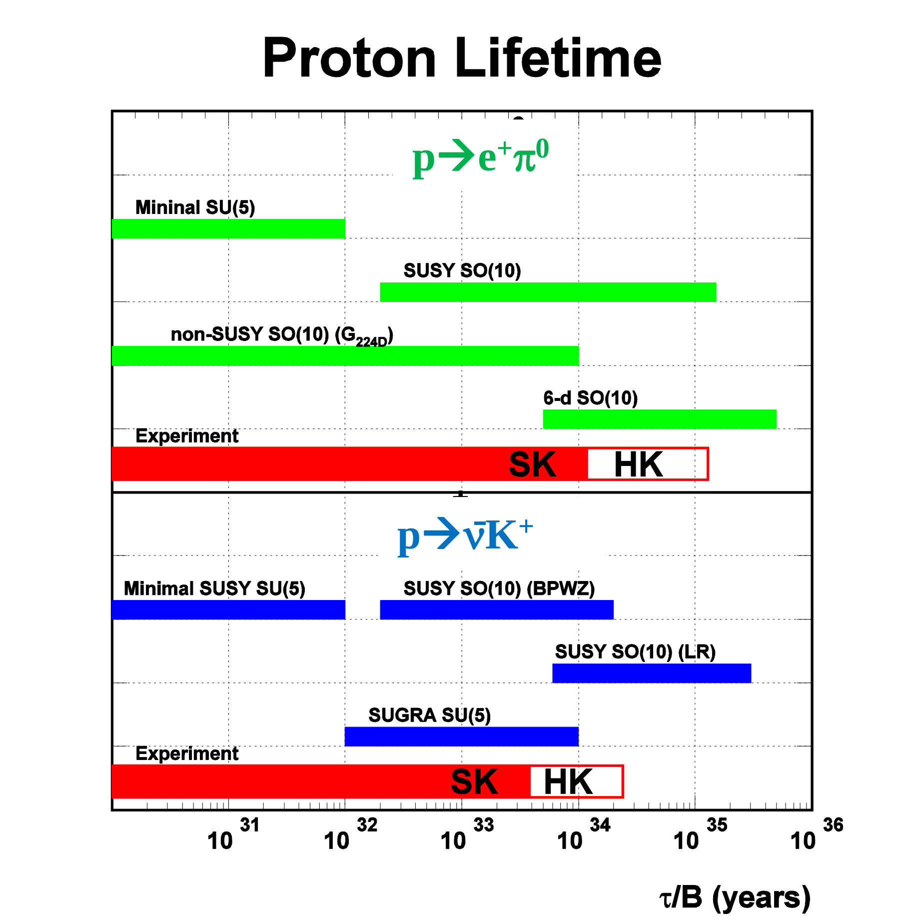
  (0.056 Mton x 10 compartments)
- Outer volume: 0.2 Mton
- Photo-sensors:

  99,000 20 inch PMT (ID)

  (20 % photo coverage)

  25,000 8 inch PMT (OD)

Hyper-K for Nucleon Decay



- Sensitivity (90%CL) with HK 10 years run;
  $e^+\pi^0$: 1.3x10^{35} year
  $\bar{\nu}K^+$: 2.5x10^{34} year
- 3σ discovery potential
  $e^+\pi^0$: 5.6x10 ^{34} years
  $\bar{\nu}K^+$: 1.2x10^{34} year

(with base design)

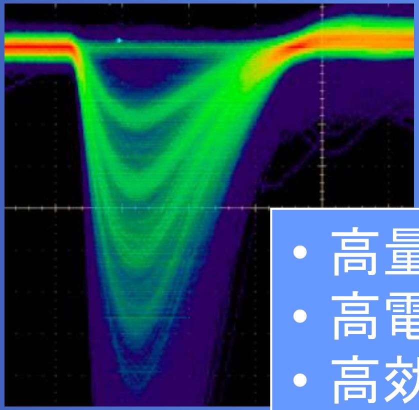
Letter of Intent: Hyper-Kaiokande Experiment
arXiv:1109.3262 [hep-ex]

R&D status toward Hyper-K

新型光センサーの開発

- ハイパーカミオカンデ用光センサー：複数の候補
  - [既存] 50cm径 Super-K PMT
  - [開発中] 50cm径 高効率改良型PMT
  - [開発中] 50cm径 高効率ハイブリッド光検出器（HPD）

20cm径 HPD Prototype



- 高量子効率
- ダイノード改良
- 開発リスク小

- 高量子効率
- 高電界光電子加速＋半導体
- 高効率1pe検出、高時間分解能
- 構造単純化による製造コスト減

より「安価」かつ「高性能」

新型光センサーの開発（つづき）

- 「20cm径HPD」と「50cm径高量子効率PMT」を製作

  神岡地下で水チェレンコフ検出器に取り付けて性能・実証試験

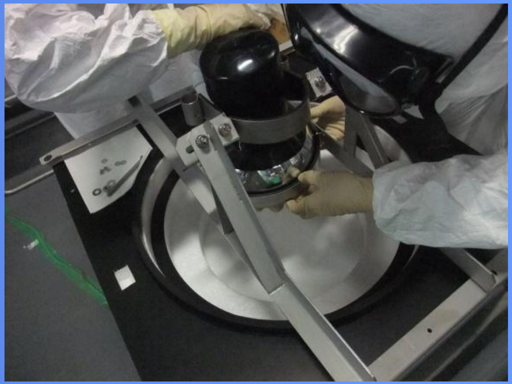
  – 取り付け前に、センサーとしての基本性能の測定、および水中での使用に関する安全性（水漏れ・漏電等がないか）の確認
  – ケーブル接続部が水中なので、防水接続方法の確立

  → 200トン水チェレンコフ検出器への取り付けを7月に開始

低電圧線
（HVおよび
AD bias電圧
のコントロール）

HPDケーブルの防水接続

タンク内でケーブル接続



HPDを支持金具に取付

学生が中心となってアクティブに活動

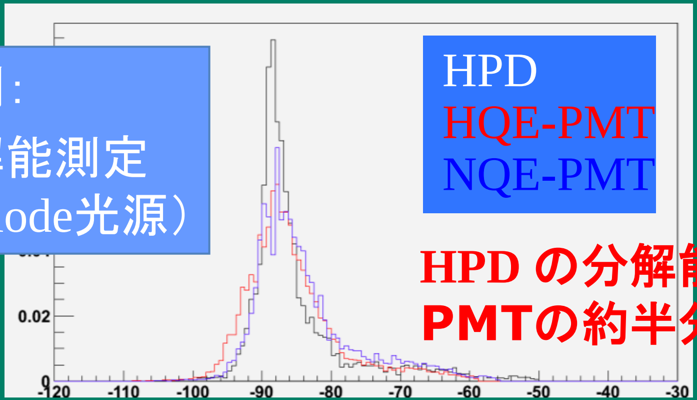
新型光センサーの開発（つづき）

今月中旬に全センサー取付完了

– HPD 8本 + 高量子効率PMT 5本（+ Super-K PMT 227本）

→ 200トン検出器完成、実験開始！

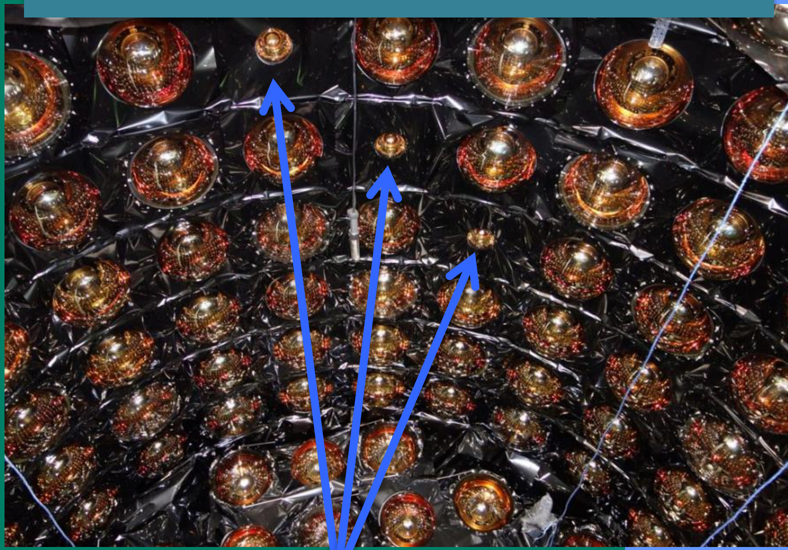
試験の例：
時間分解能測定
（Laser Diode光源）



HPD の分解能は PMTの約半分！

HPD/PMT hit timing relative to LD flash timing (ns)

200トン水チェレンコフ検出器

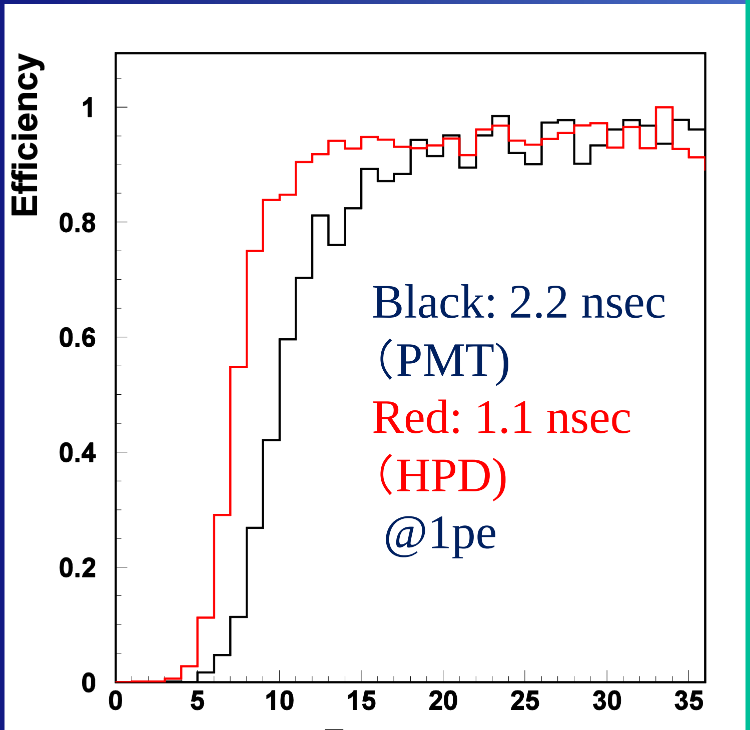


20cm径HPD

- 50cm径HPDおよび改良型PMTのプロトタイプを今年製造
- 2015年に最終候補光センサーを200本程度製造し、Hyper-Kプロトタイプタンクで2年ほどかけて試験

Test: HPD time resolution with SK4 setup

Efficiency curve of γ tagging

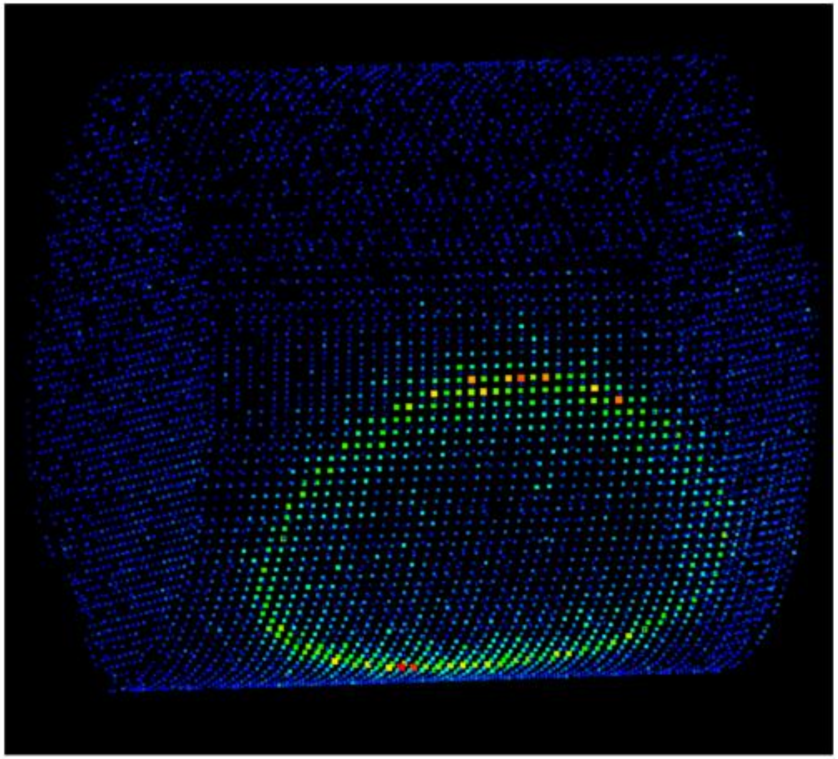


Tμ –Tγ (nsec)
~ K^+ decay time

- γ tagging efficiency close to μ is increased. K^+ decay ~exp(-12ns/t).
- Selection efficiency of p→νK^+γ:
  9.1 % → 13.1 %
  (44% increased)
- Background rate:
  1.5 → 1.0 evts/Mt･yr
  (33% decreased)

➔ Even though half density of sensor, performance of HK with HPD may be better than SK !

Software development



•Simulation: Based on GEANT4

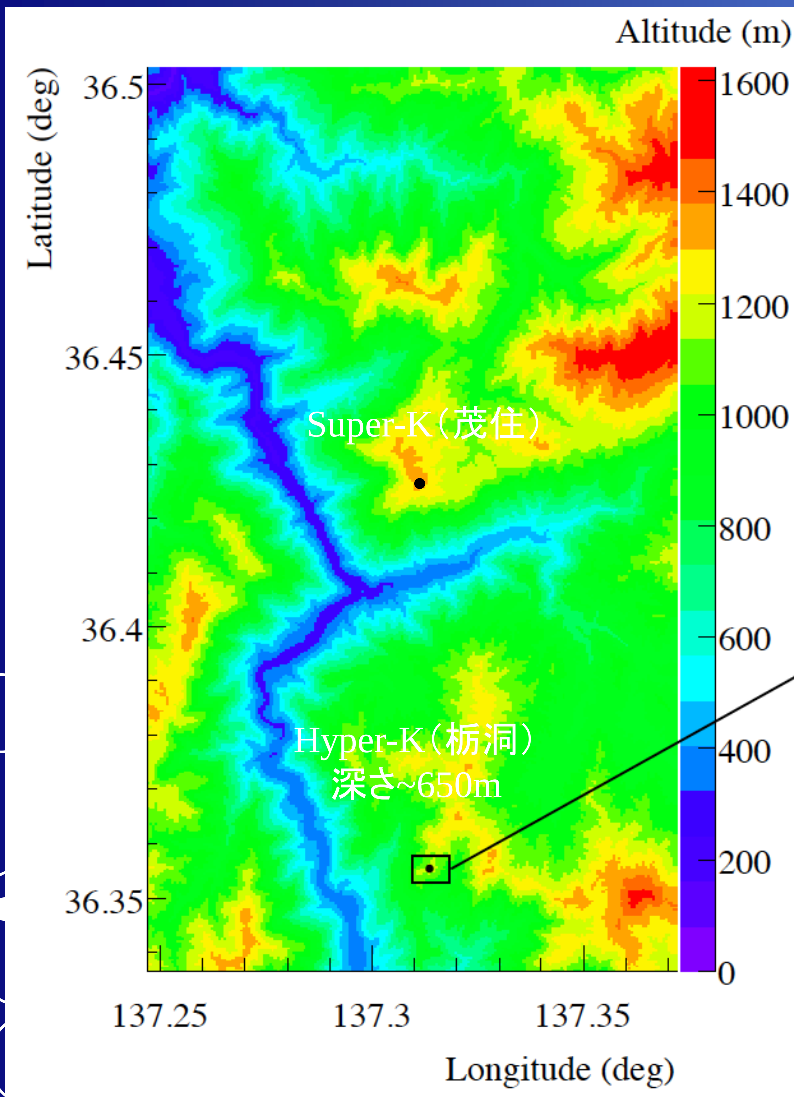
- Make SK geometry and compare with one used in SK.
- Real HK geometry egg shape) installed.

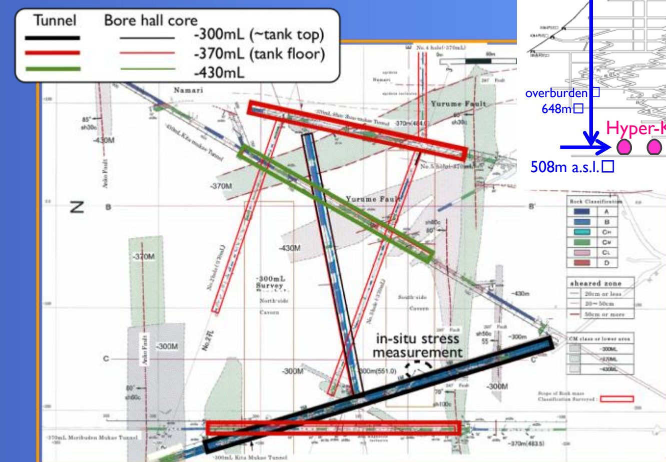
•Reconstruction tool based on likelihood method

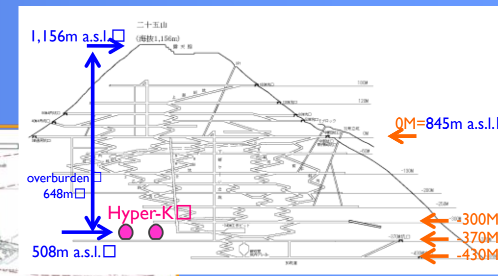
- Originally developing for SK, but also can be used for HK.
- Interface between HK simulation was made.
- Under tuning for HK.

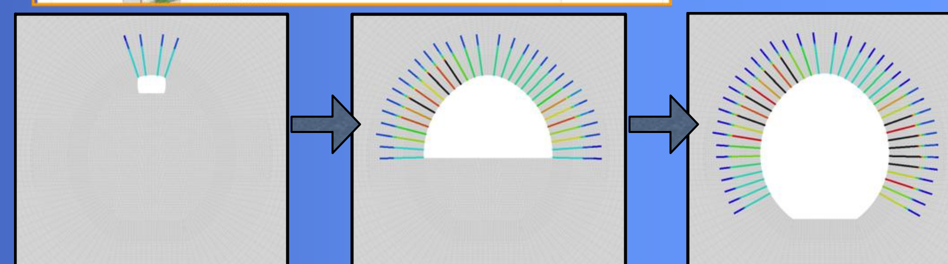
Optimize detector parameters (sensor, detector length)
➔ Start soon!

地質調査・空洞設計









- 技術設計書を作成中
  - 候補地（栃洞）周辺のボーリング、地質分布調査、岩盤応力測定
  - 詳細空洞解析（岩盤等級分布、岩盤塑性変形、PSアンカー強度・摩擦力を考慮）
- Super-K site（茂住）の可能性の再検討
  - 掘削コスト、宇宙線バックグラウンド、鉱業活動と切り分け、既存実験への影響（振動）等の検討

4. Summary

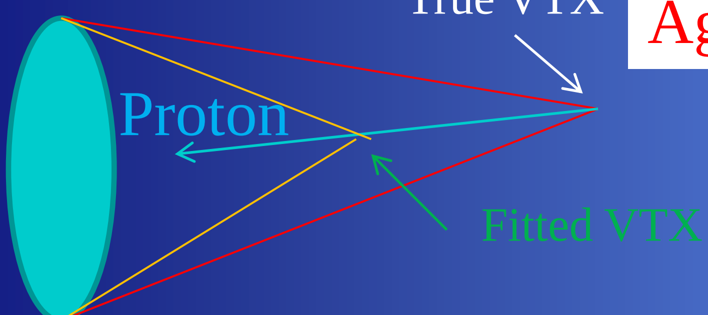
- Current exposure of Super-K: 260kt・years.
- Nucleon decay signal has not been found yet.
- Proton life time limit: 1.4×10^{34} years for $e^+\pi^0$, 5.9×10^{33} years for νK^+.
- To explore one order longer life time, larger detector is needed.
- Hyper-K sensitivity (base design): 1.3×10^{35} years for $e^+\pi^0$, 2.5×10^{34} years for νK^+.
- Various R&D are running toward Hyper-K construction.

Backup

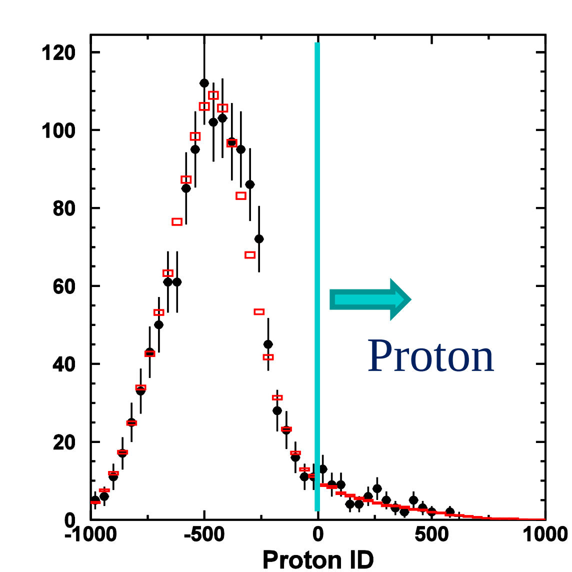
Recent improvements on BKG rejection (2)

Proton ID

- Dominant BKG is CCQE with high mom. recoiled proton and invisible μ, the proton is identified as μ-ring.
  → VTX is shifted to forward to adjust C-ang.
  → TOF over-subtracted for backward hits, make mimic γ signal.
- Proton and muon ring can be separated using likelihood function based on opening angle and hit pattern.



Black: Data
Red: ATM ν MC
Agree well.

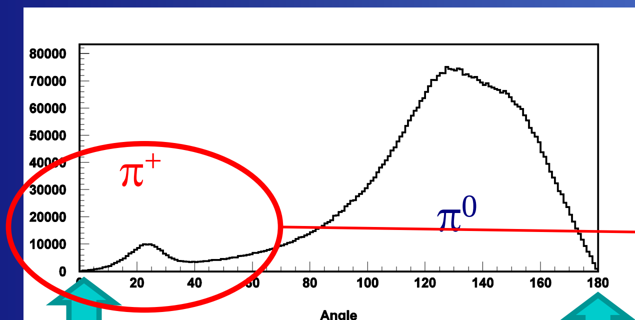


260 <Pμ<400 MeV

BKG is reduced to ~50 %.

Recent improvement(2): p→νK$^+$,K$^+$→π$^+$π^0

Charge distribution in angle

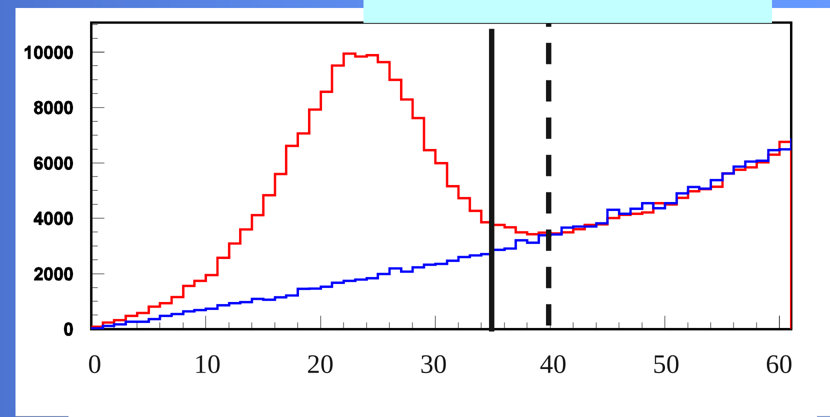


zoom

Opposite of π^0 dir = π^+ dir

π^0 dir

Red: PDK MC
Blue: BKG



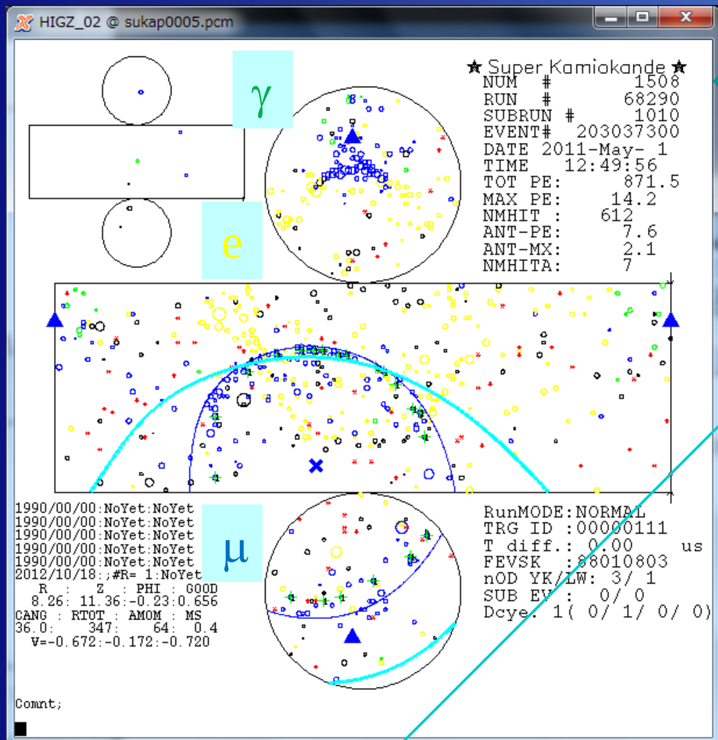
Conventional method: Use corrected charge sum in <40° →Ebk

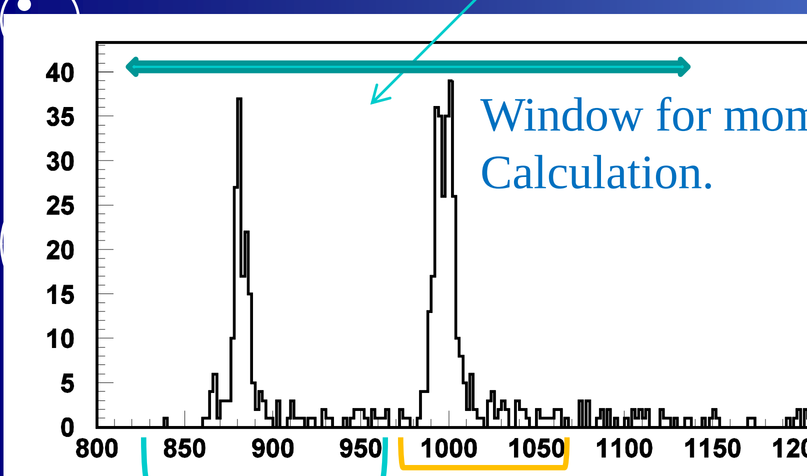
New method: 1. Define Ebk by charge sum in < 35°

2. Make expected charge distribution for signal and BKG, and compare observed charge by likelihood. → Compare shape of dist.

$$L_{shape} = \sqrt{-\log(\prod_{\theta=0}^{40^\circ} \Pr ob(q_{obs}, q_{\exp}^{sig})} - \sqrt{-\log(\prod_{\theta=0}^{40^\circ} \Pr ob(q_{obs}, q_{\exp}^{BKG})}$$

Candidate event ➔ seems mis-fitted event





- Candidate event in the last SK meeting.

Original VTX: (805.3,-184.5,1135.8)

Pμ = 239.0 MeV/c

➔ Decay-e is so close to μ (115 nsec).

➔ In momentum calculation, hits in (-50:+250 nsec) &70° cone are used. So this Pμ includes decay-e hits and overestimated.

➔ Also VTX shifted in forward to adjust larger C-ang from overestimated Pμ. Make fake prompt γ

Separate μ and e by time and fit individually.

VTX (922.0,-221.0,1301.4)

Pμ = 199.9 MeV/c

2-2 Probability as a signal

- $p \rightarrow \nu K^+$, $K^+(stop) \rightarrow \nu\mu^+$ then P_μ =236 MeV/c.
- If the candidate is the signal, true P_μ should be 236 MeV/c, but reconstructed as 239 MeV/c with this kinematics.
- How much probability does it happen ?

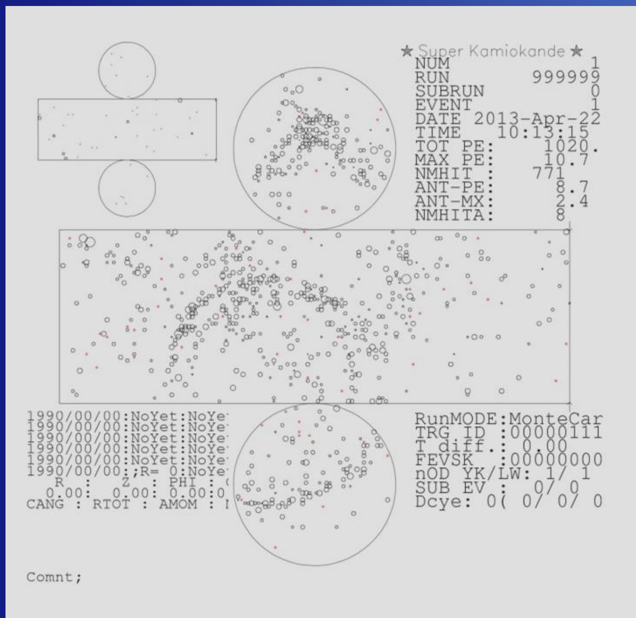
➔ Make MC to simulate the candidate kinematics.

Set up

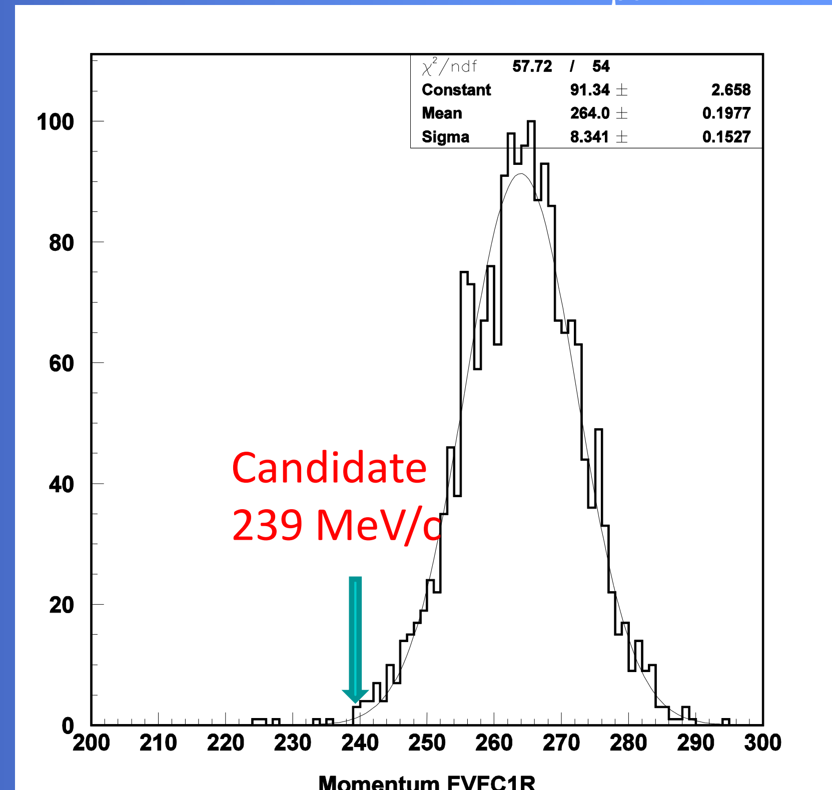
- Use VTX and direction, and time difference of μ, e, γ from individual fit results.
- Set Pμ=236 MeV/c

➔ Apply reconstruction to see momentum distribution.

Generated event
: 2000 evts



Reconstructed P_μ



Reconstructed P_μ is shifted (mean: 264 MeV/c) due to decay-e.
It is very hard to reproduce the candidate momentum by the signal event.

There are 3 events in 239-240 MeV/c bin.

→ 0.15 ±0.09 %

→ < 0.33 % @ 95 % C.L.