Proton Decay searches
-- sensitivity, BG and photo-coverage --

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Water as a proton decay detector

- **Source H_2O**
  - 2/10 free proton → no nuclear effect, accurate&high detection efficiency
    → no Fermi motion, good momentum valance
  - 0.54Megaton(Hyper-K) →~2×10^{35} protons

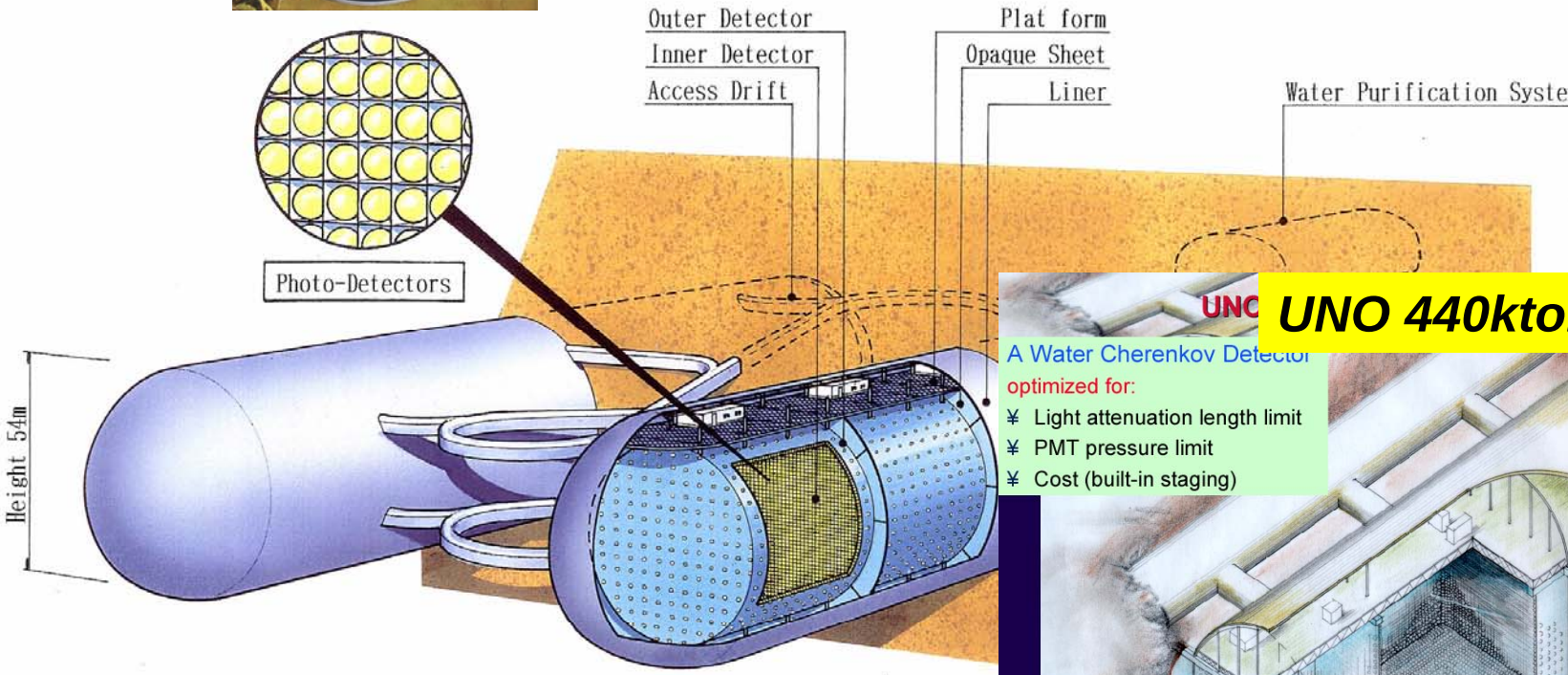
- **Good detector performance**
  - Vertex resolution: 30 cm (1-ring)
    :~20 cm($p \rightarrow e^+\pi^0$)
  - Trigger threshold: 5 MeV electrons
    → trigger ε=100% for most of nucleon decay modes
  - Energy resolution: 3~4% for e, μ
  - Particle ID : 99% 1-ring μ, e
    : ~95% $p \rightarrow e^+\pi^0$,$p \rightarrow \mu^+\pi^0$

These performance is achieved in Super-K-I, 40% photo-coverage.
Question: can we reduce photo-coverage? Keeping the excellent performance?

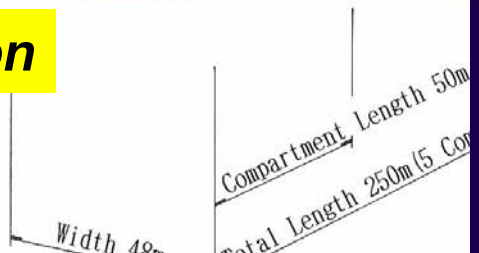
Large water Cherenkov detectors

Super-K 22kton

Simulation was done.
SK-I: 40% coverage
SK-II:19% coverage

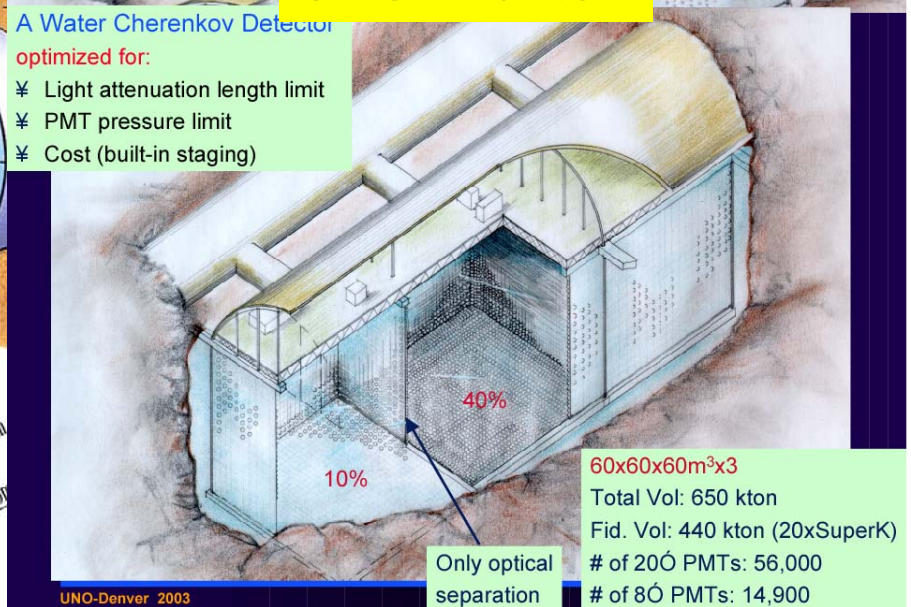


Hyper-K 540kton



UNO 440kton

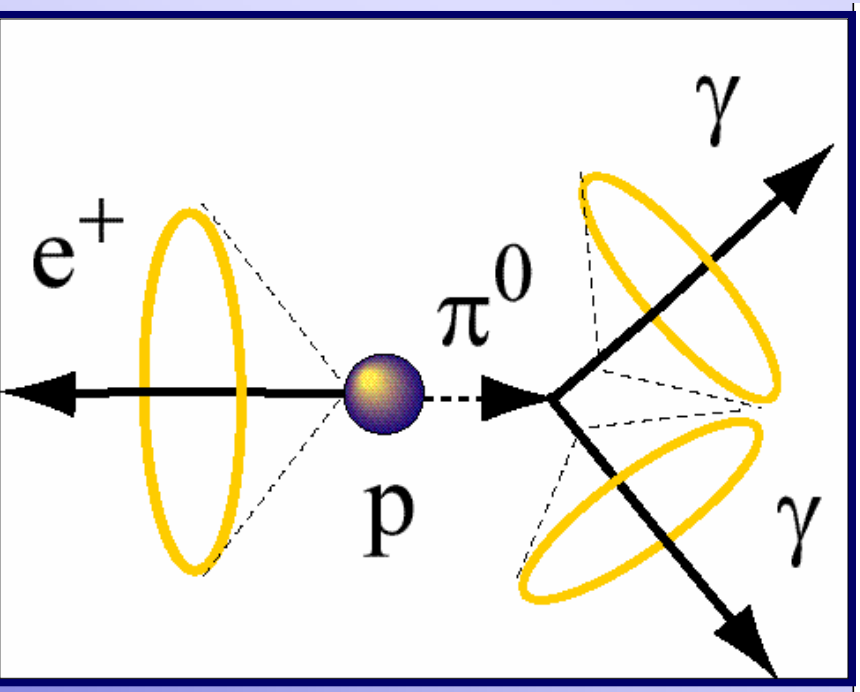
A Water Cherenkov Detector
optimized for:
- ¥ Light attenuation length limit
- ¥ PMT pressure limit
- ¥ Cost (built-in staging)

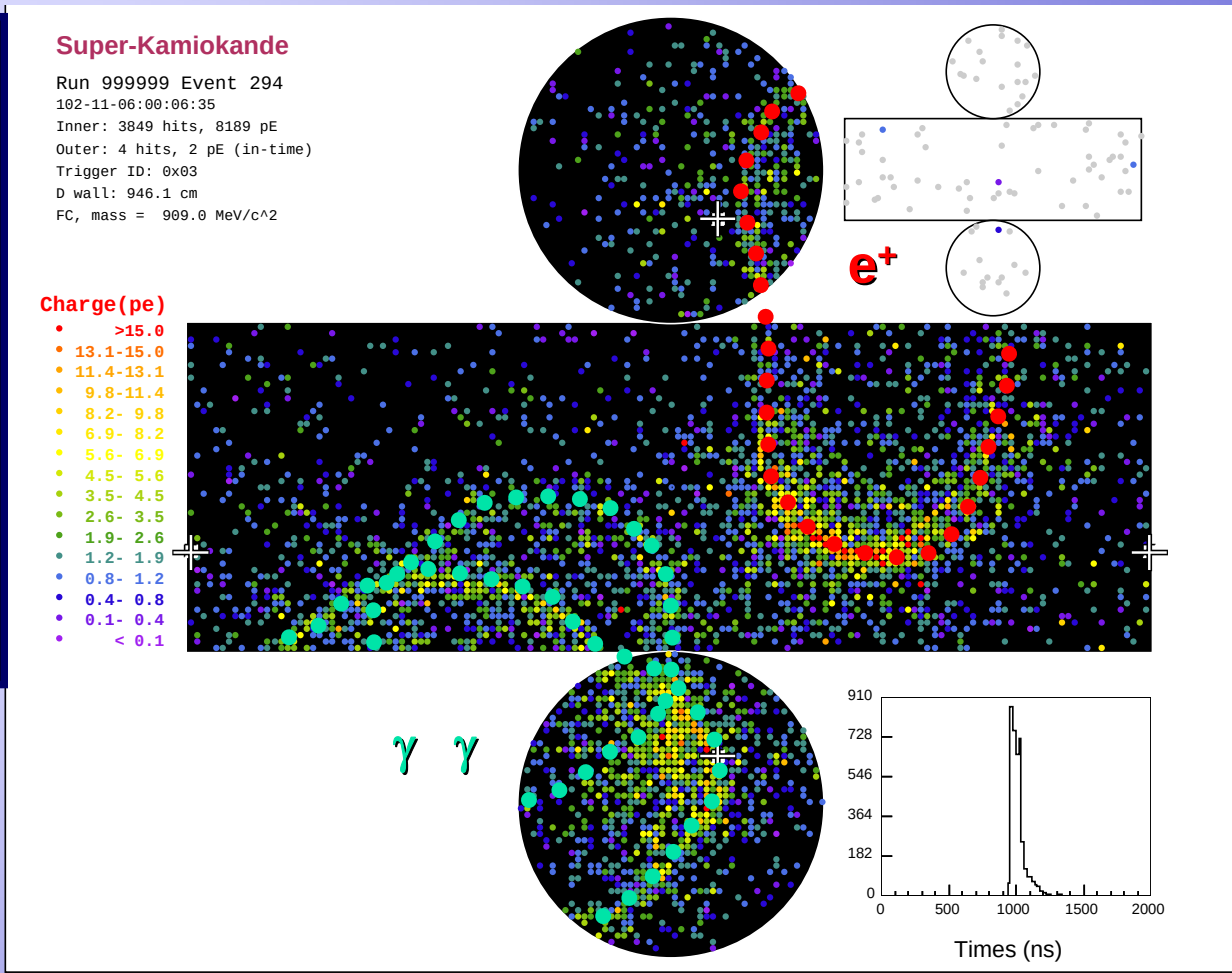


60x60x60m^{3}x3
Total Vol: 650 kton
Fid. Vol: 440 kton (20xSuperK)
# of 20Ó PMTs: 56,000
# of 8Ó PMTs: 14,900

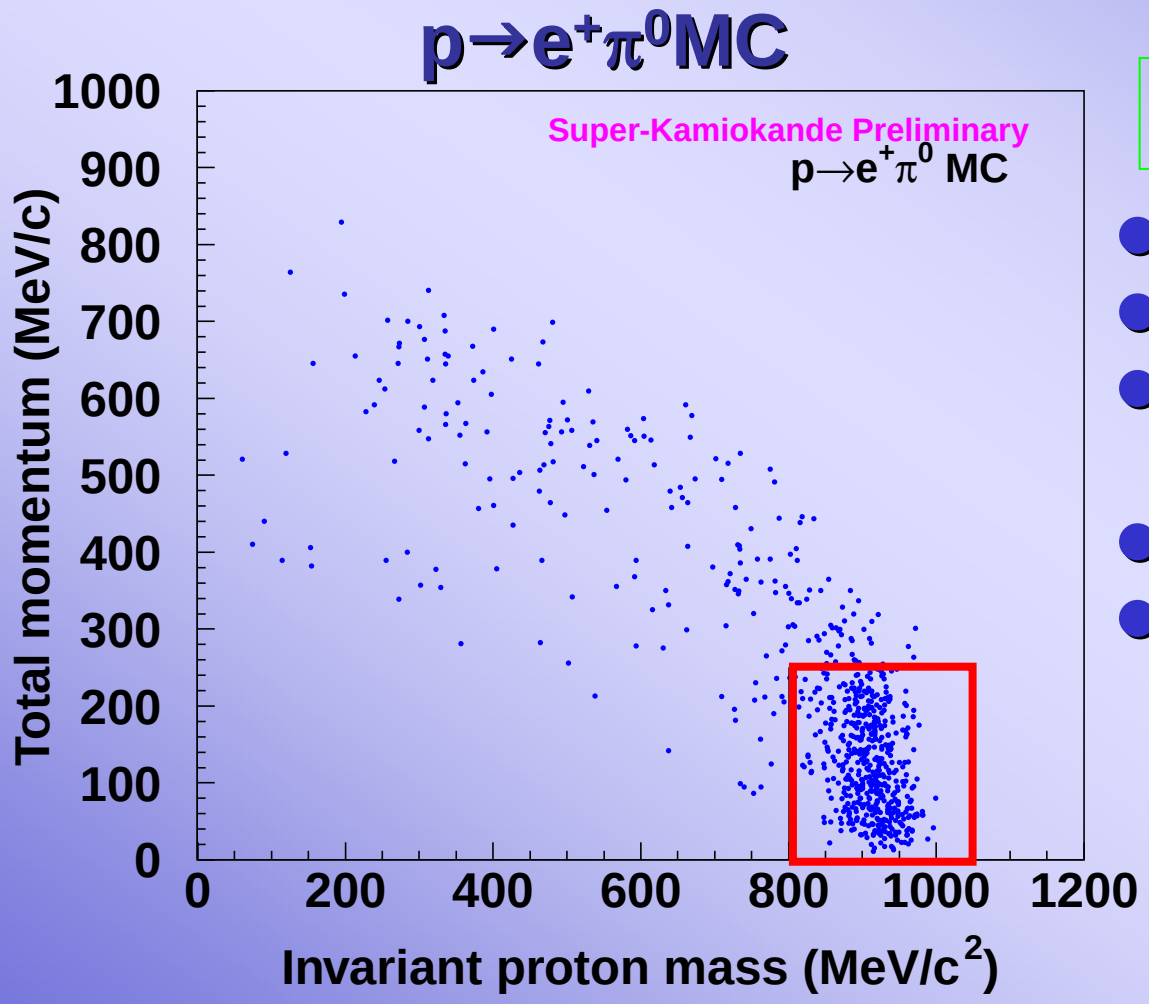
$p \rightarrow e^+\pi^0$ @Super-K

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





$p \rightarrow e^+ \pi^0$ @Super-K



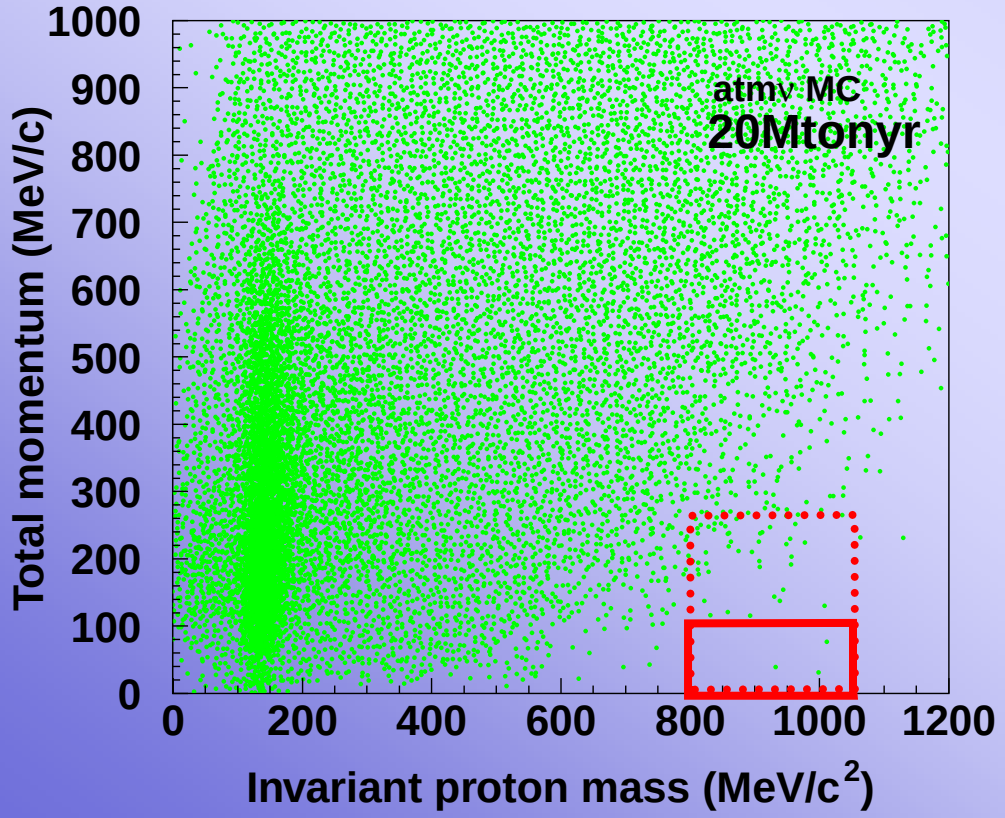
Criteria for $p \rightarrow e^+ \pi^0$

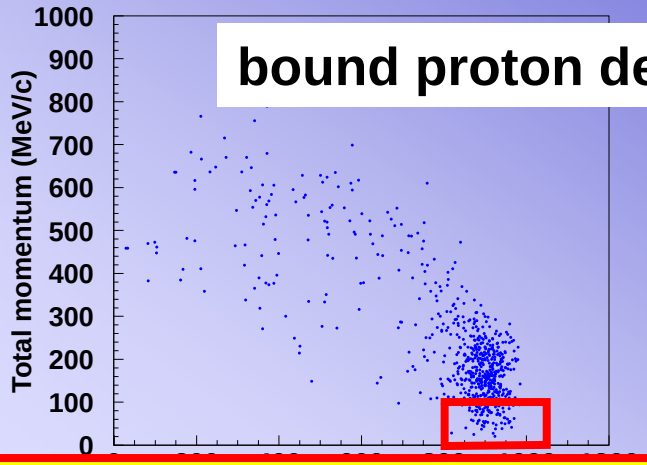
- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 MeV/c^2$ (3-ring)
- No decay electron
- $800 < M_{proton} < 1050$ MeV/c^2
  $P_{total} < 250$ MeV/c

$\varepsilon = 40$ % in SK-I

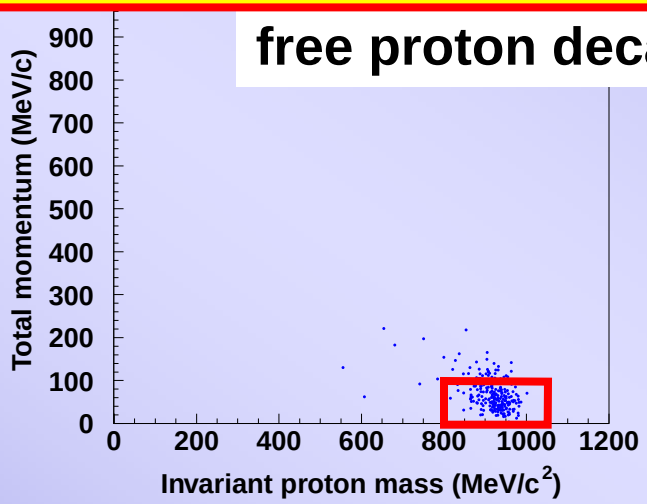
Tight momentum cut for $p \rightarrow e^+ \pi^0$

- P_{tot} < 250 MeV/c,
  BG2.2ev/Mtyr, eff=44%
- P_{tot} < 100 MeV/c,
  BG0.15ev/Mtyr, eff=17.4%

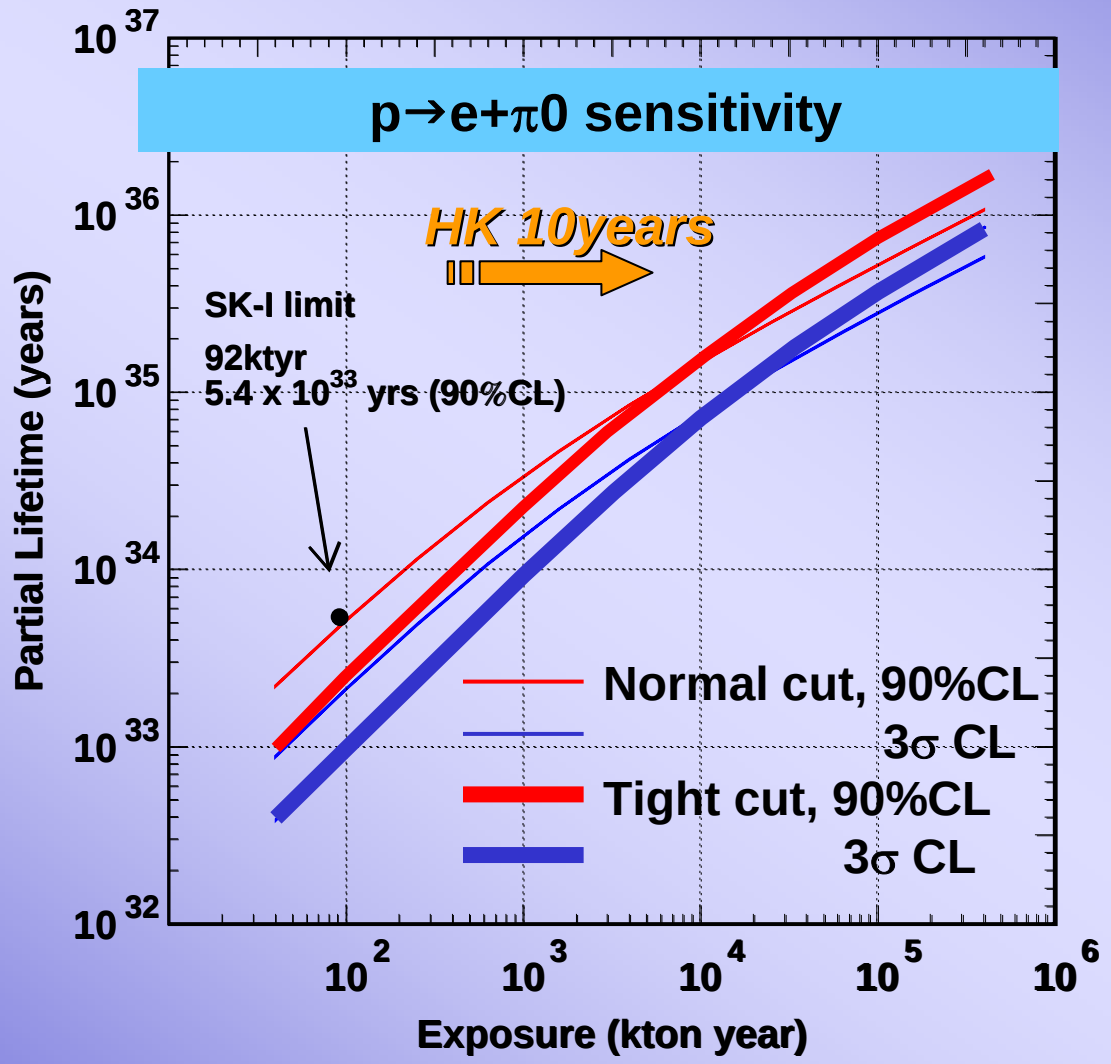




Main target is free proton decays for the tight cut.



Lifetime sensitivity for $p \rightarrow e^+ \pi^0$



Hyper-K 10yrs → ~10^{35} years@90%CL
~4×10^{34} years@3σCL

Reduce photo-sensor cost?

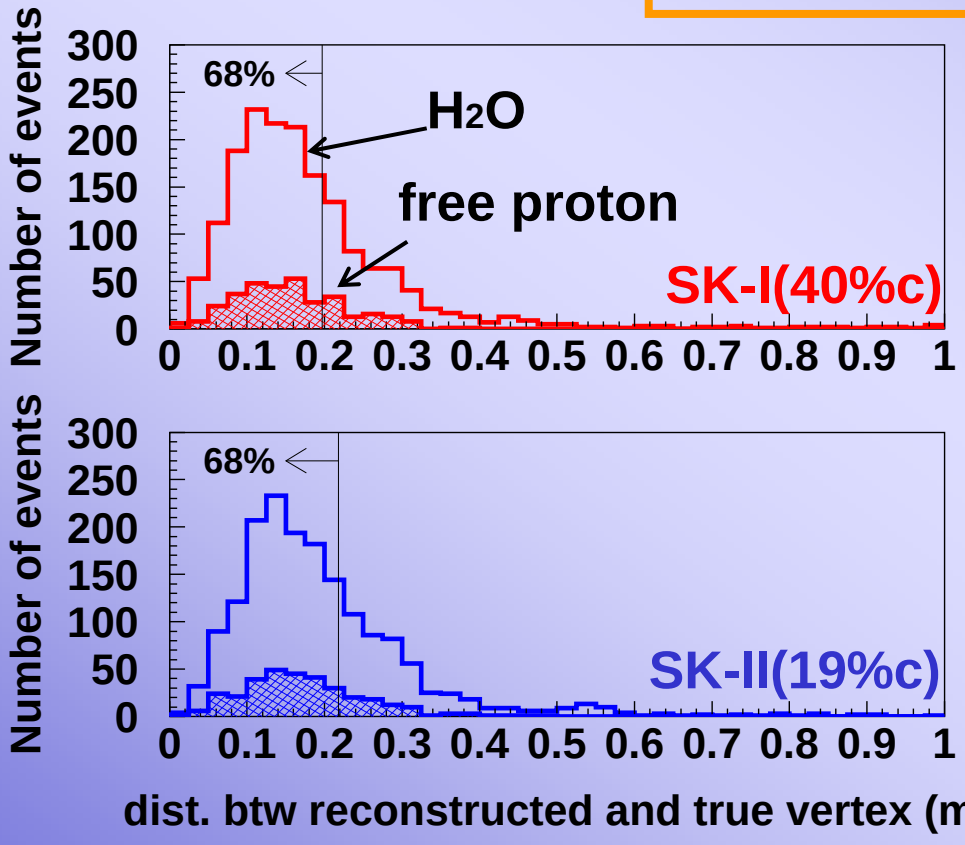
- sensor cost is a significant part of total cost.
  - in case of Hyper-K
    1000$(1/3xSK) x 200,000(40% coverage) = 200M$

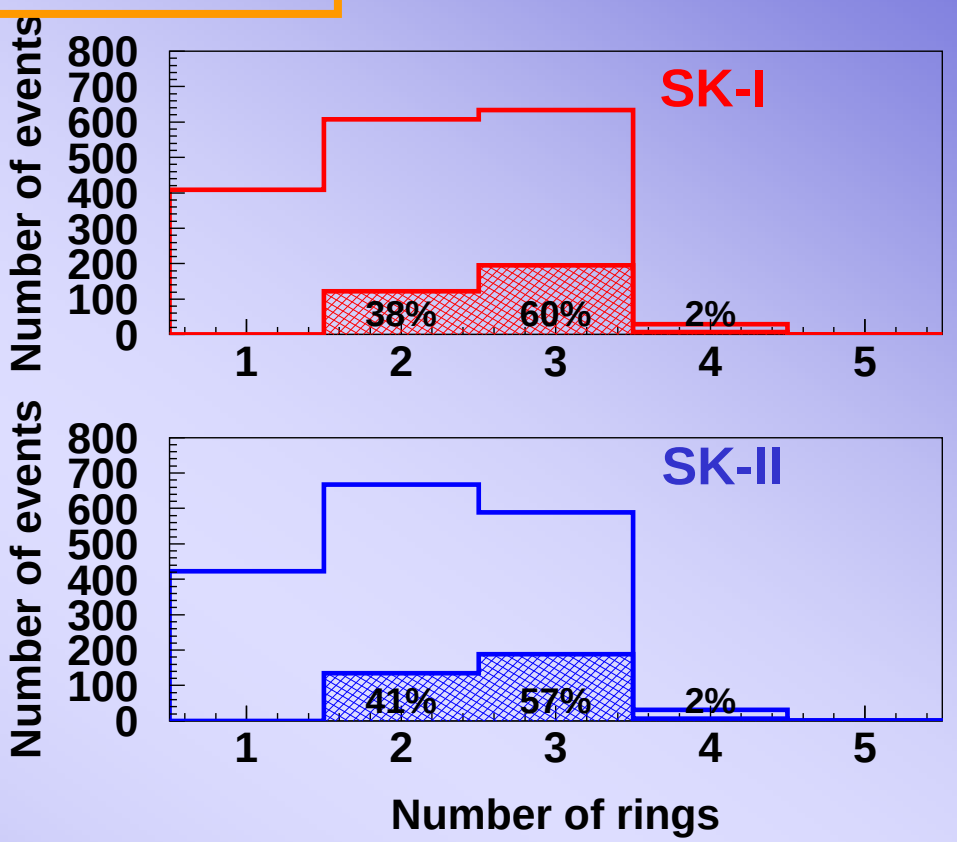
- important to understand minimum requirement of photo-coverage from each physics topics ($p \rightarrow e+\pi 0$ in my talk)

- SK-II (19% coverage ←→ SK-I 40%) is a good opportunity to investigate physics sensitivity with reduced photo-coverage
  - well tuned SK-II detector simulation
  - fitters (vertex,ring#,particle ID,momentum…) are also well tuned and calibrated.
  - reliable study is possible.

(1)vertex fitter and (2)ring fitter

p→e+π0 Monte Carlo



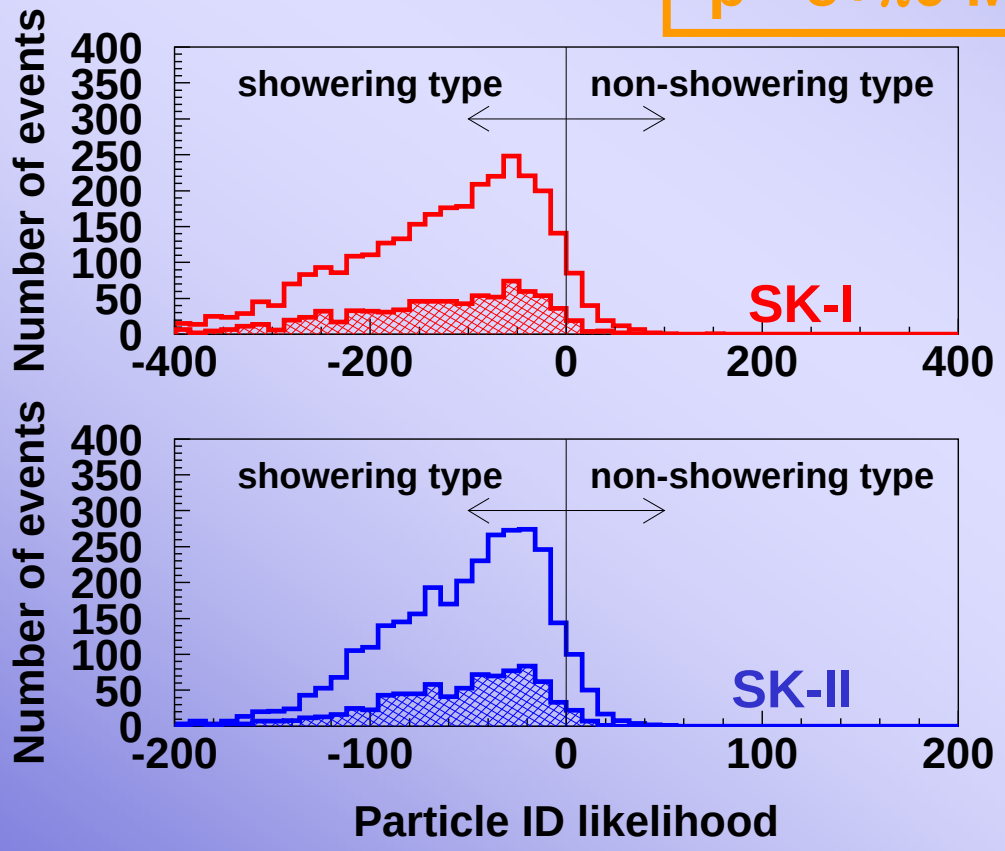


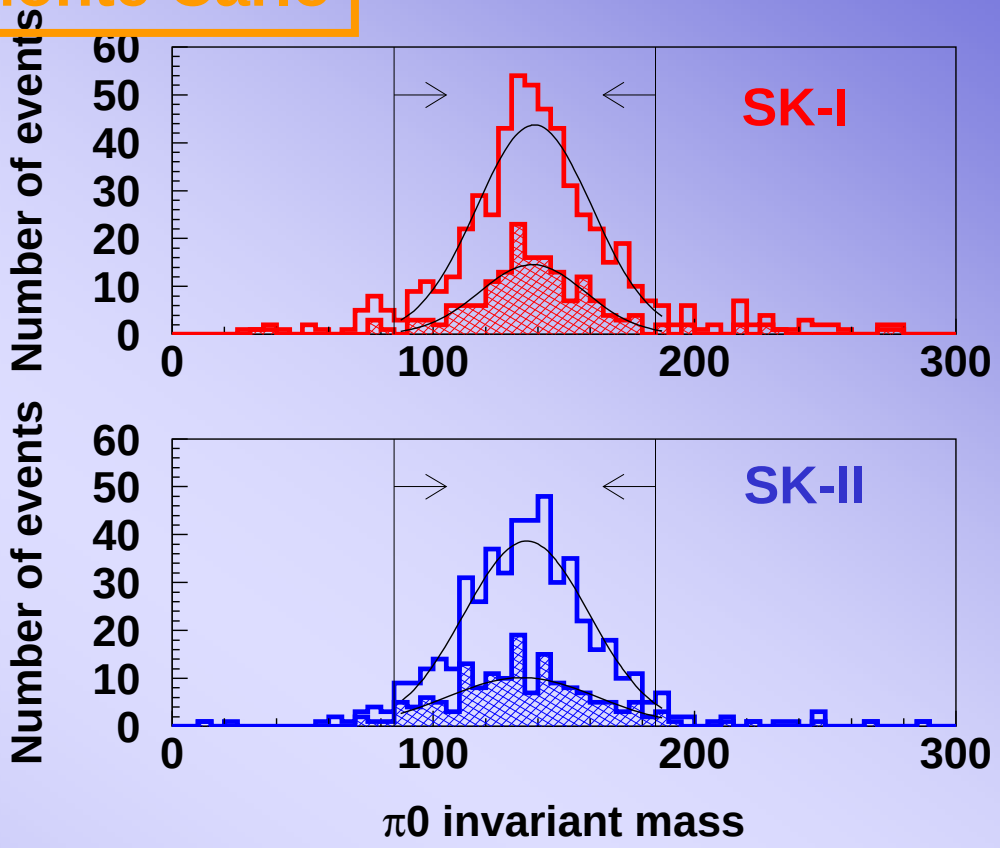
19.7cm(68%) → 21.8cm(68%)
Almost same performance

Efficiency(74% for 2-3rings) doesn't change
Fraction of 3ring slightly decrease

(3)Particle ID and (4)π0 mass

p→e+π0 Monte Carlo



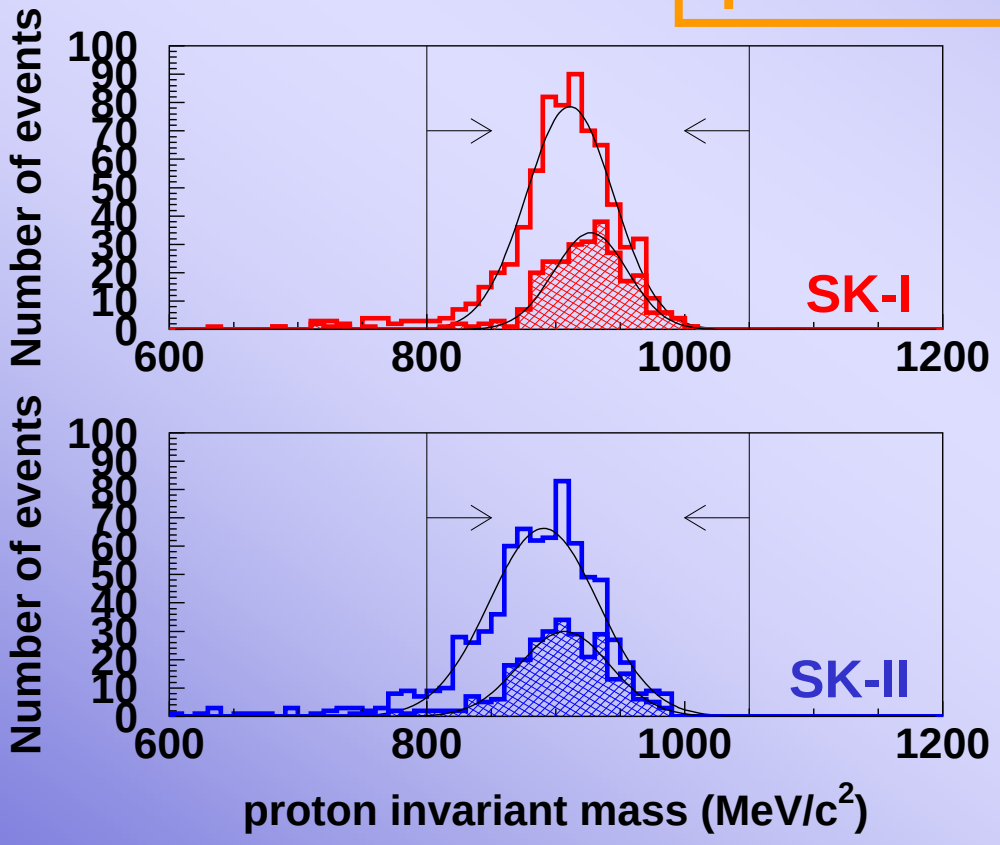


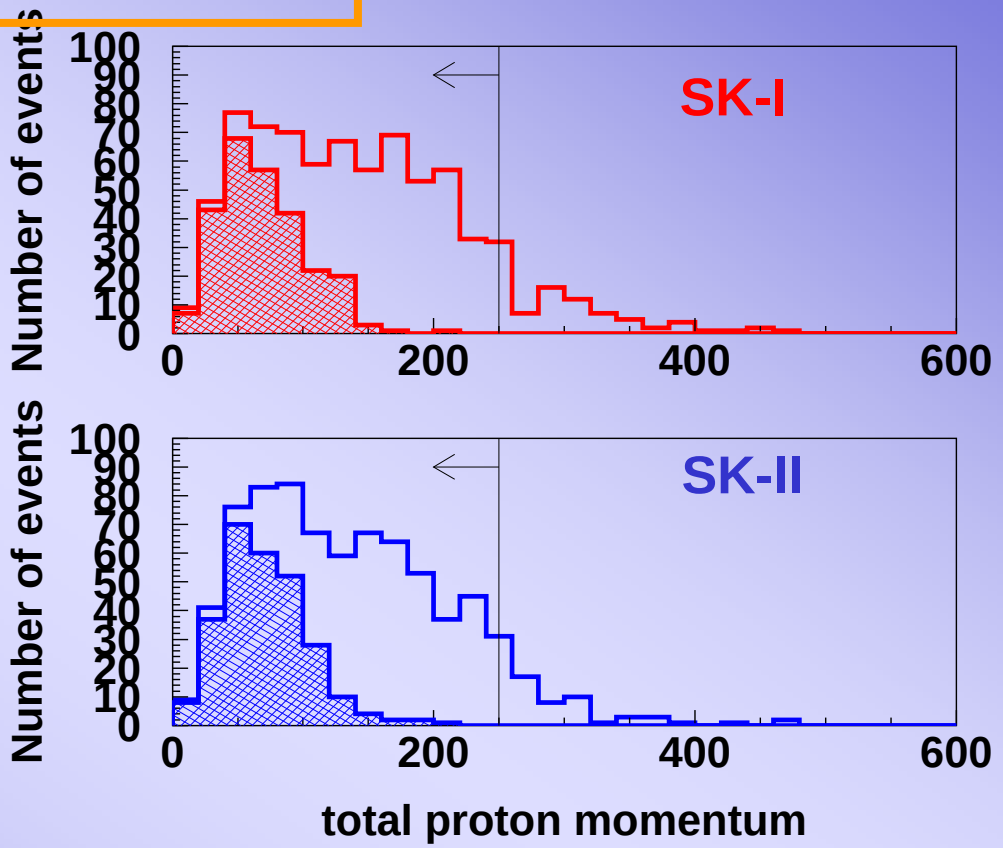
PID performance; 94-95%
96% for free proton decay

π0 mass resolution;
22.1MeV → 24.0MeV
free proton 20.2MeV → 28.5MeV

(5)Proton mass and (6)proton momentum

p→e+π0 Monte Carlo





proton mass resolution;

33.8MeV→42.3

free proton 28.5MeV→35.2

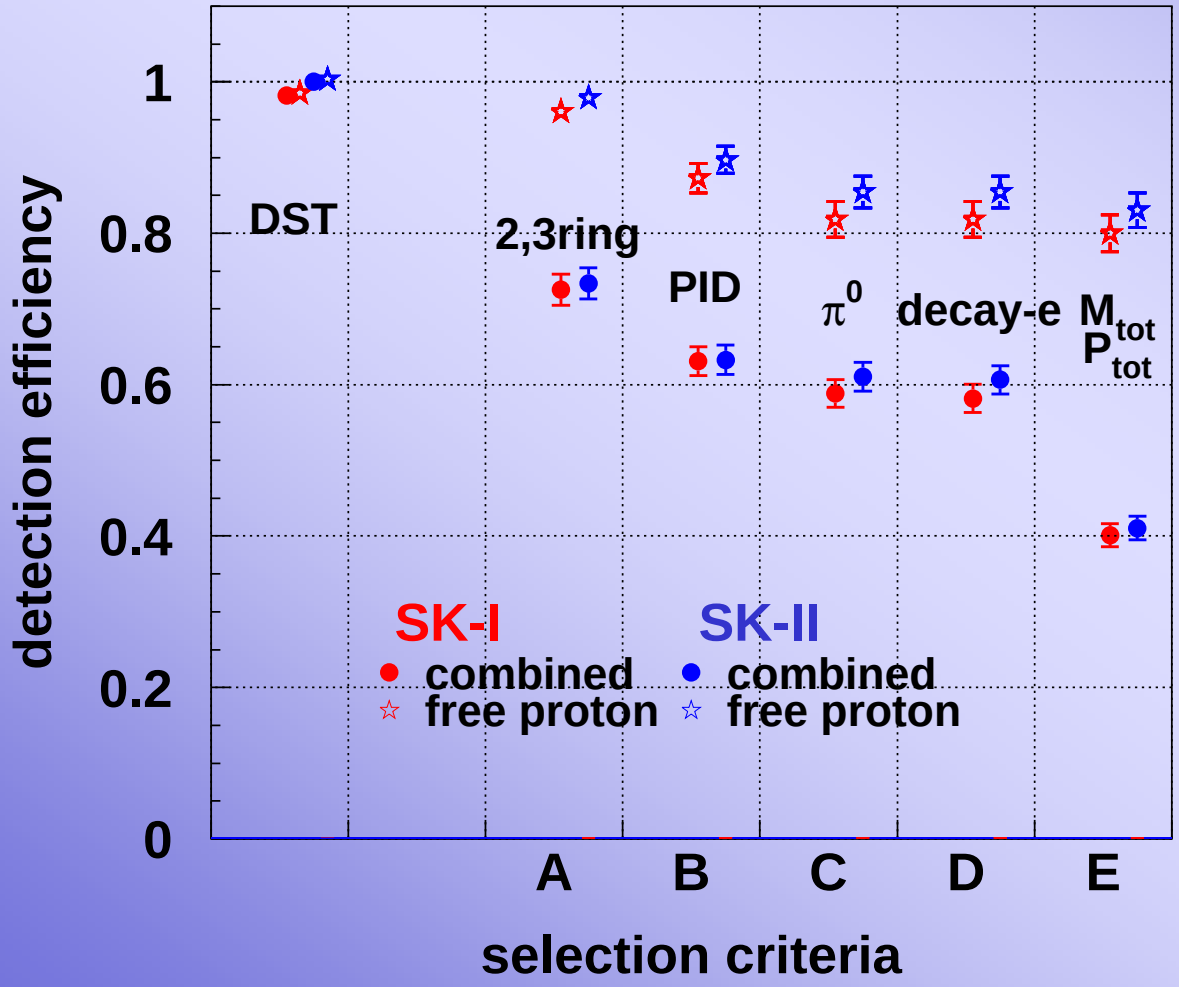
proton mom. resolution;

177MeV(68%)→171

free proton 81MeV(68%)→83

Efficiency in each step

p→e+π0 Monte Carlo



Detection eff. =

(40.1+-1.5)% -- SK-I

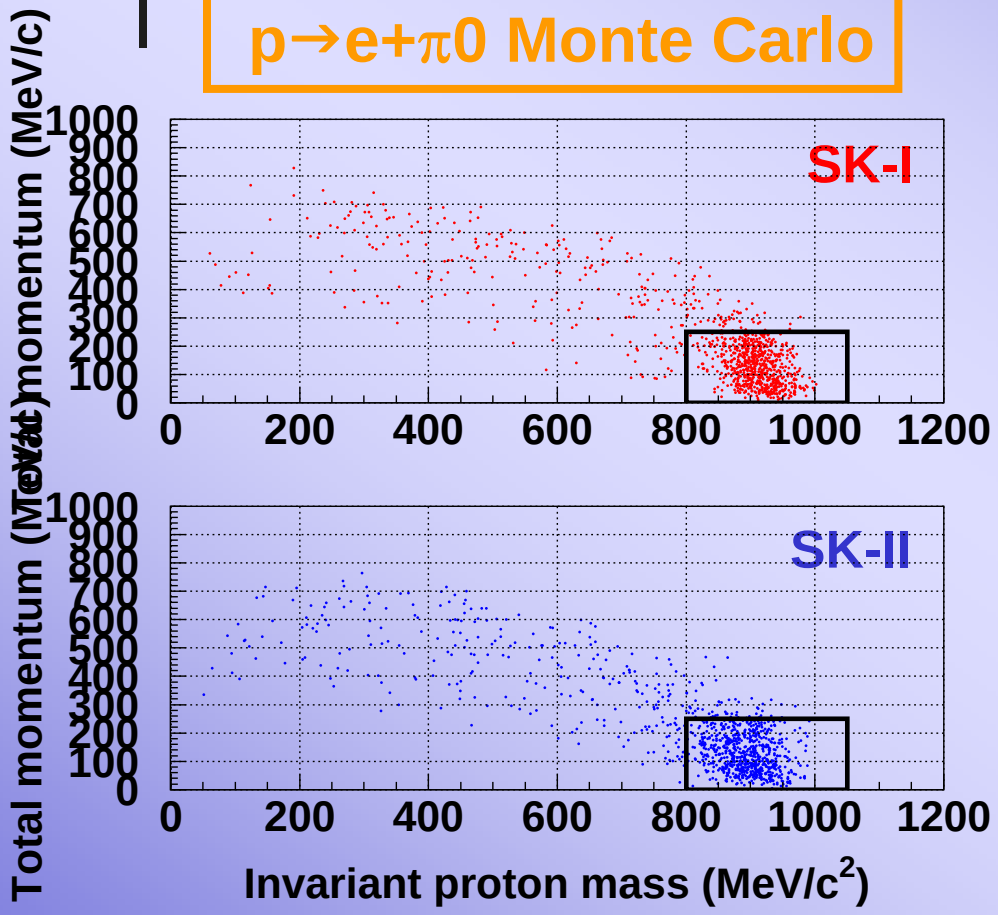
(41.1+-1.5)% -- SK-II

Same efficiency within 1% level

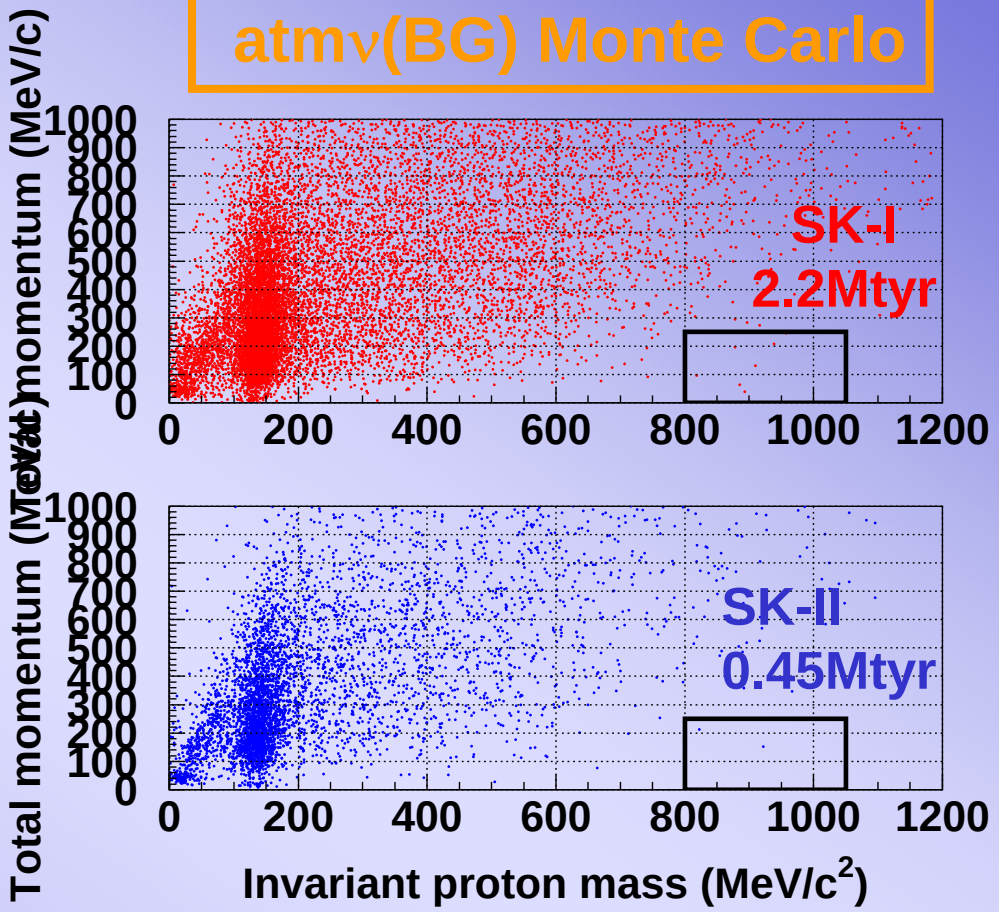
Slightly worse resolution of π0 and proton mass

Proton mass vs momentum

p→e+π0 Monte Carlo



atmν(BG) Monte Carlo



(40.1+-1.5)%→(41.1+-1.5)%

8ev/2.2Mtonyr→2ev/0.45Mtonyr
~10+-7ev/2.2Mtyr
Same BG level within 70%

Conclusion

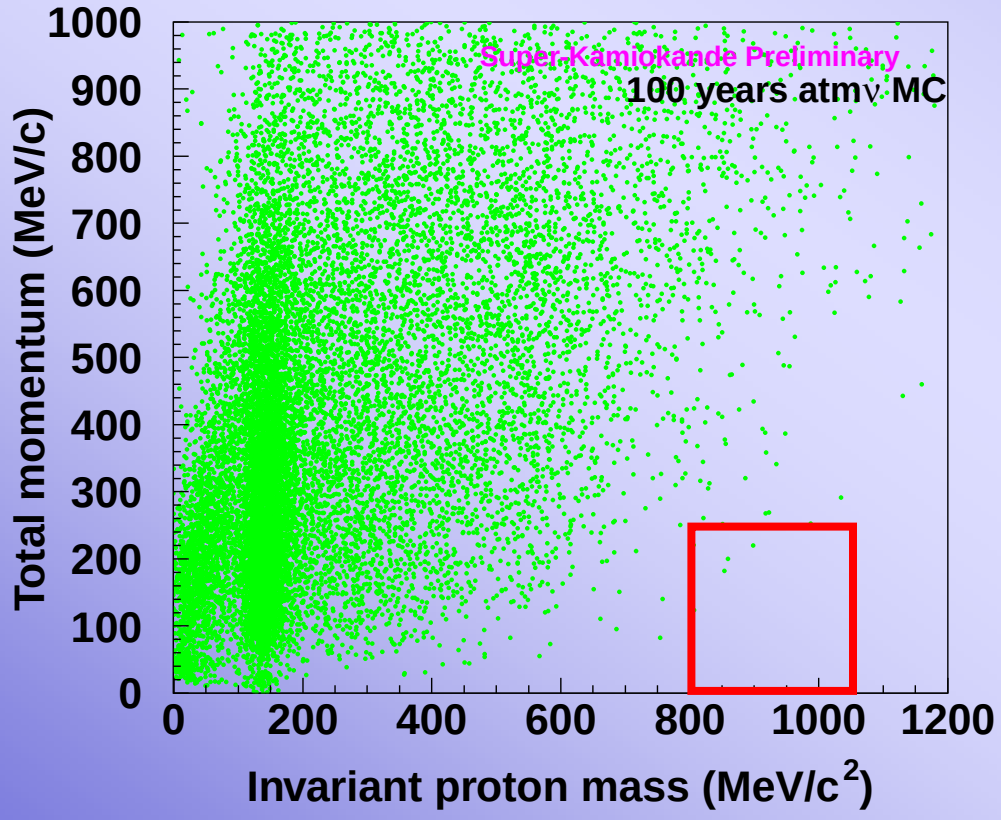
- Water Cherenkov detector is a excellent detector for $p \rightarrow e^+\pi^0$ searches.

- detailed comparison btw 40% and 20% coverage
  - same $p \rightarrow e^+\pi^0$ efficiency even with 20% coverage
  - slightly worse mass resolution
  - 10% coverage maybe acceptable
  - need further studies on other decay modes, like $p \rightarrow \nu + K^+$, $e^+ + K^0$, ...

supplements

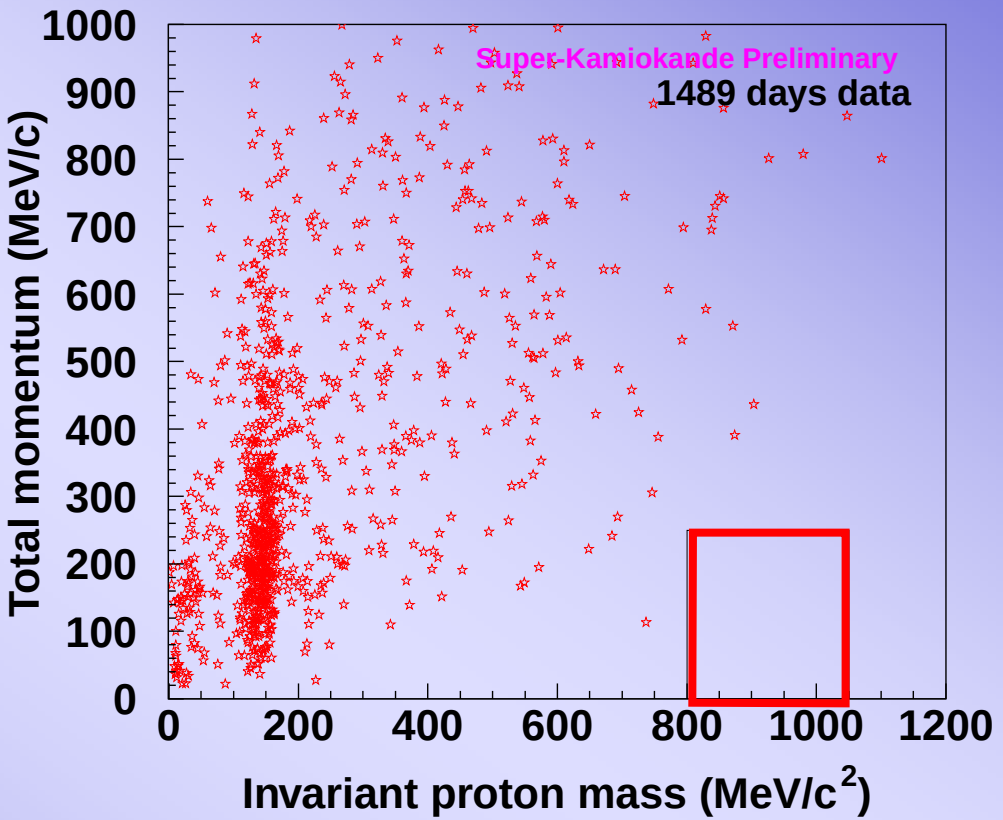
$p \rightarrow e^+ \pi^0$ @Super-K-I

AtmνBG MC



0.3 exp'd BG

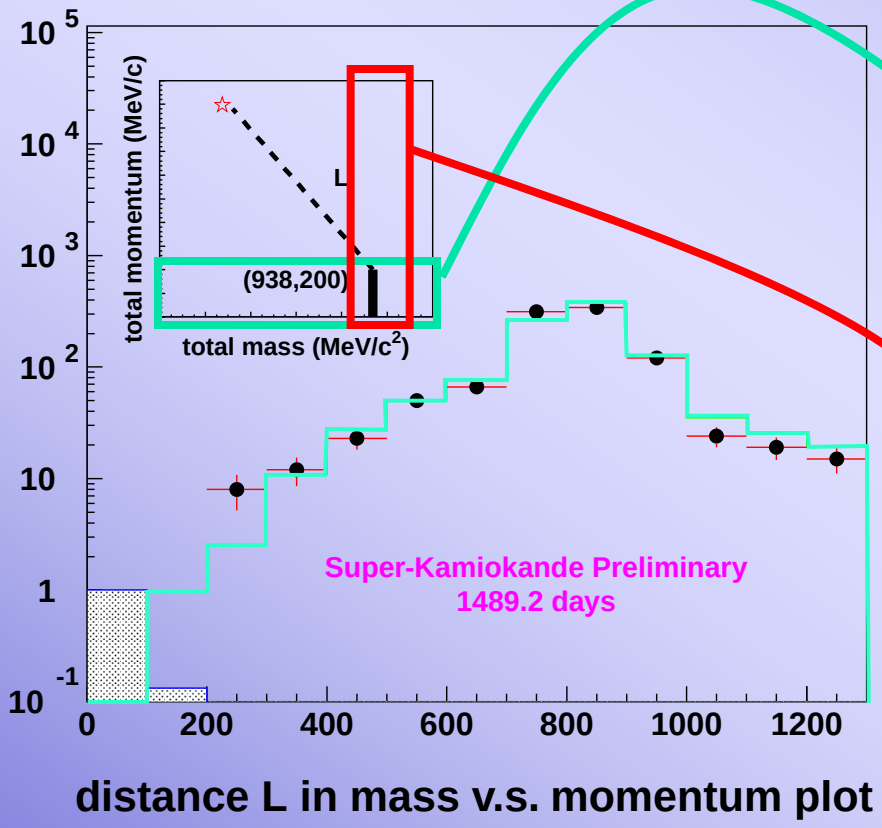
data



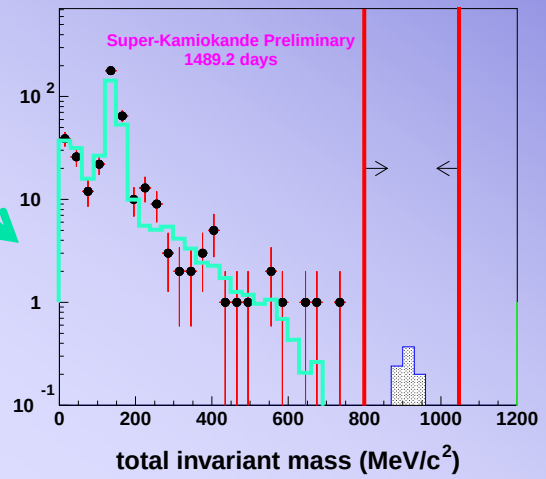
0 candidate

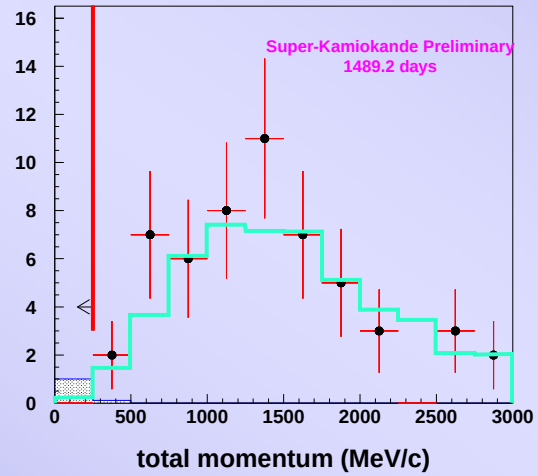
$\tau_p/B(p \rightarrow e^+ \pi^0) > 5.4 \times 10^{33}$ years (90% CL)

Comparison of data and MC in $p \rightarrow e^+ \pi^0$ search



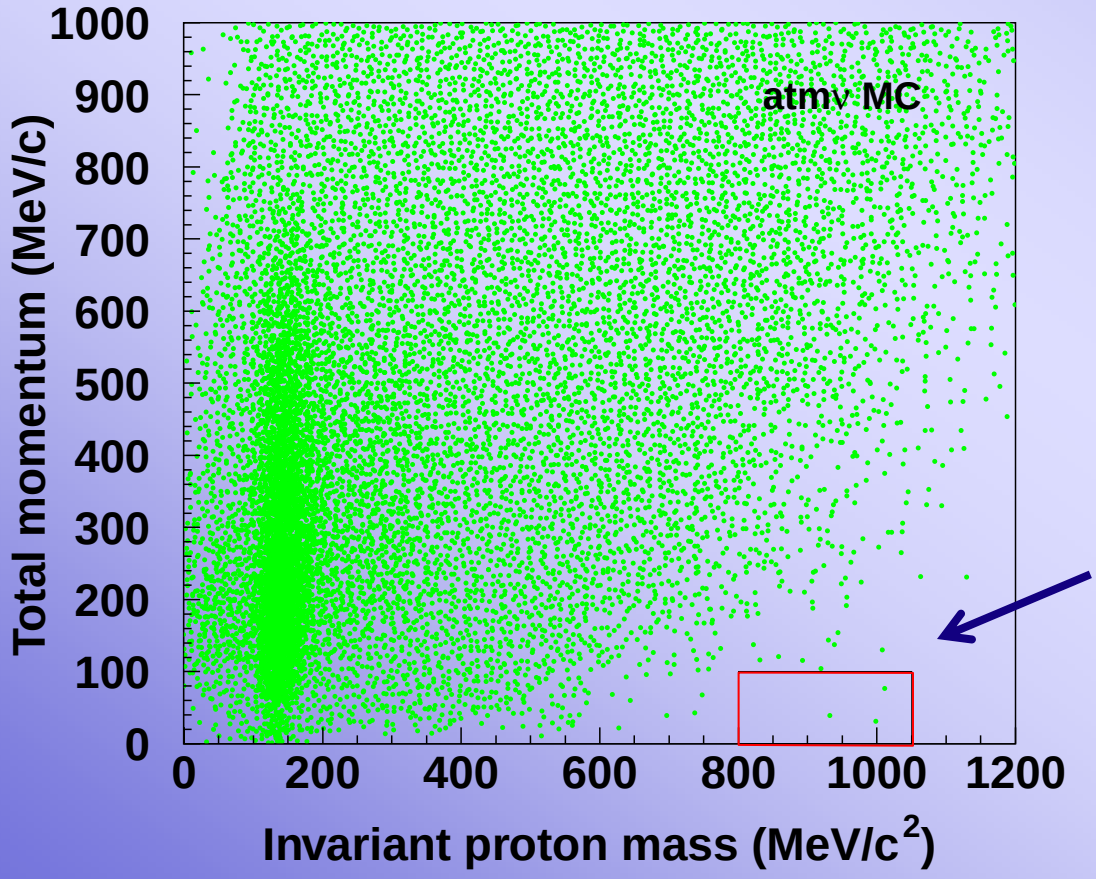
distance L in mass v.s. momentum plot





Backgrounds for $p \rightarrow e^+ \pi^0$ search (2)

Tight momentum cut to reduce BG



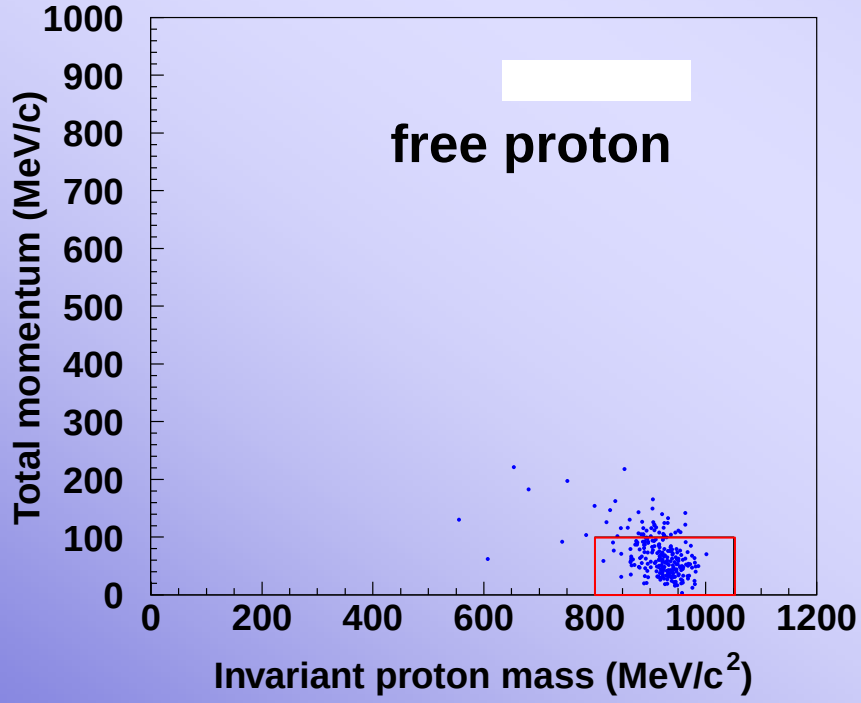
- P_{tot} < 250 MeV/c
- P_{tot} < 100 MeV/c

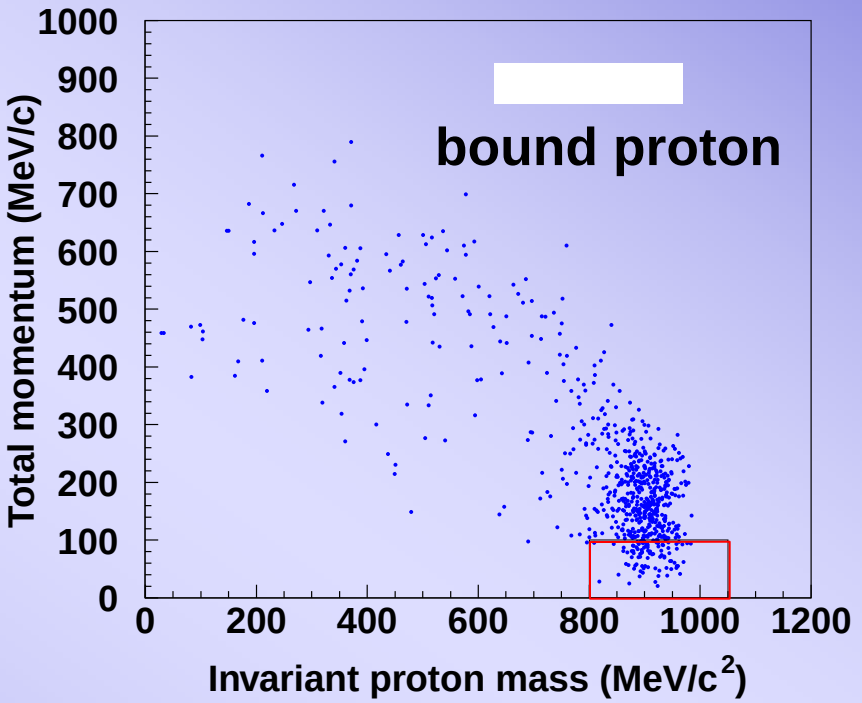
BG events in signal box
3 events/20 Mton・yr

～0.15 events/Mton・yr

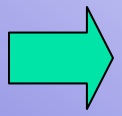
Analysis for discovery of $p \rightarrow e^+ \pi^0$

Tight momentum cut
⇒ target is mainly free protons
efficiency=17.4%, 0.15BG/Mtyr





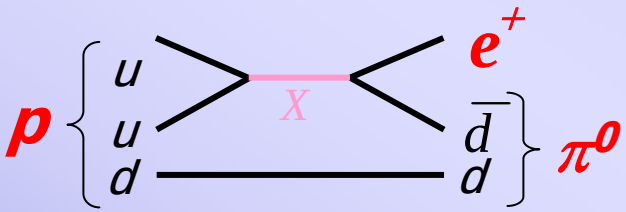
No Fermi momentum
No binding energy
No nuclear effect



Small systematic uncertainty of effici
High detection efficiency
Perfectly known proton mass and moment

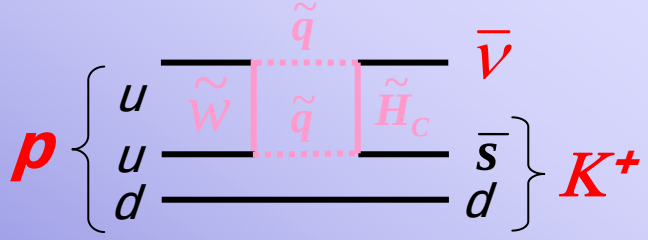
Lifetime prediction

- **Dimension=6 (2 fermion – 2 fermion)**

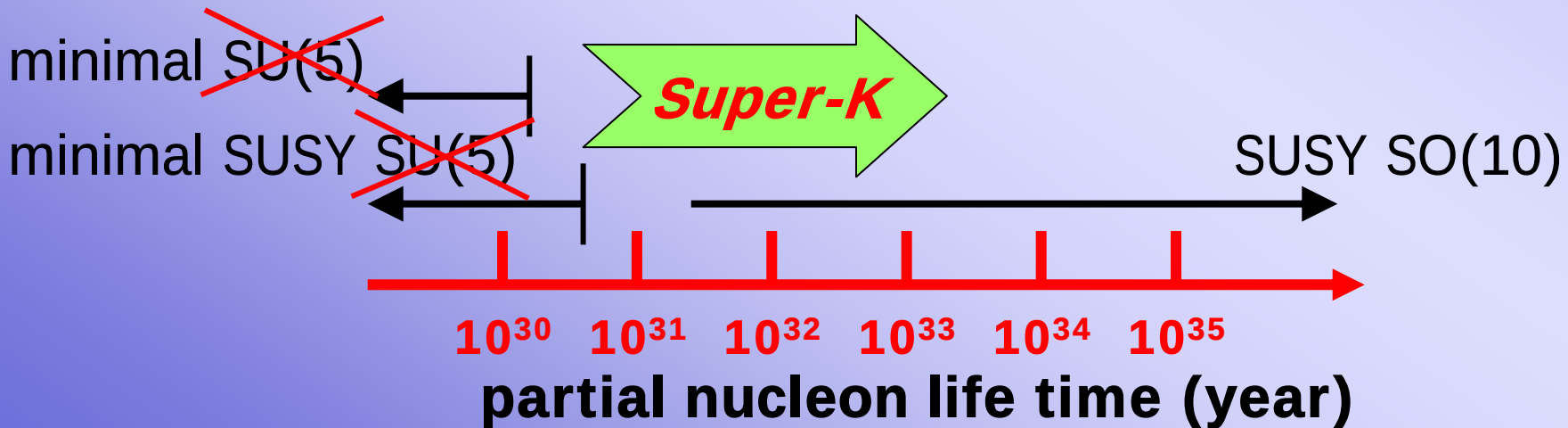


$$\Gamma = \frac{g^4 m_p^5}{M_X^4} \qquad :\tau(p \to e^+ \pi^0) = 10^{\sim 35?}\ years$$

- **Dimension=5 (2 fermion - 2 sfermion)**

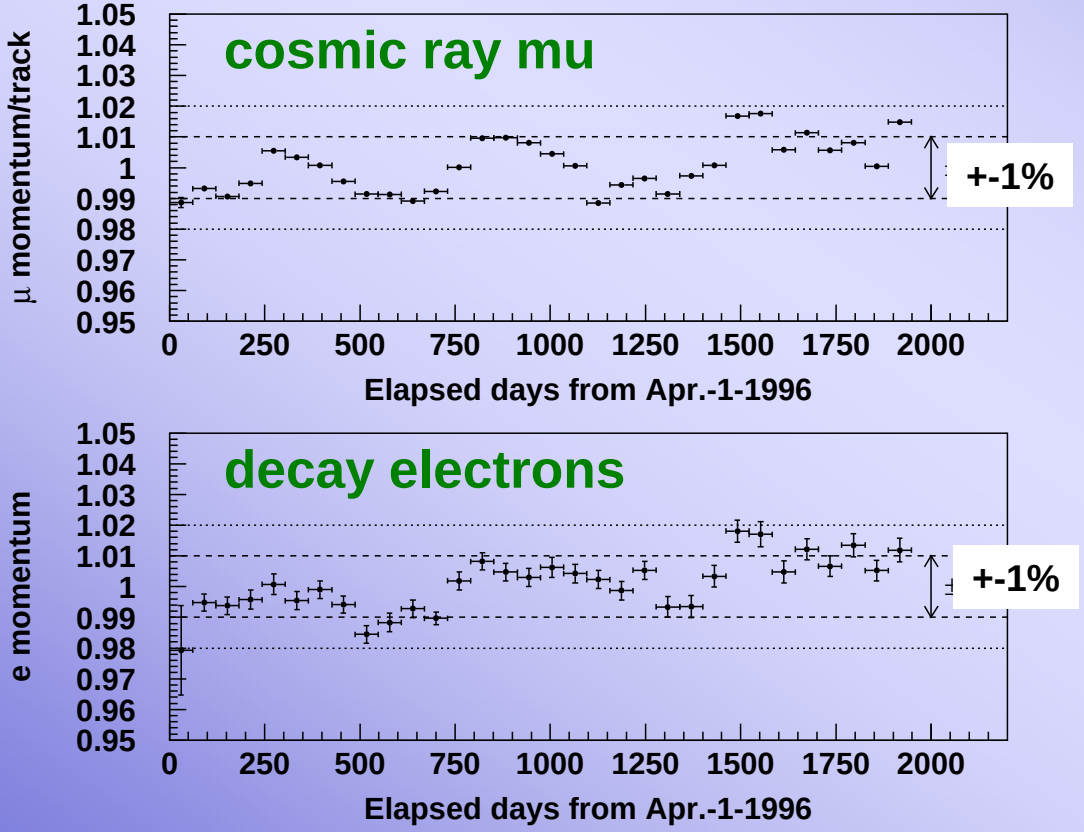


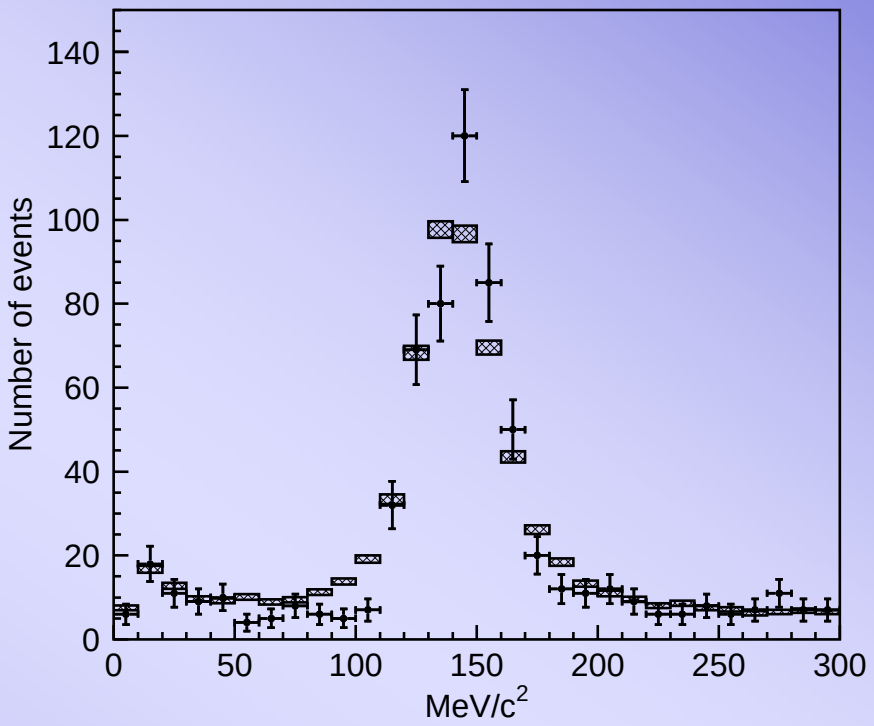
$$\Gamma = \frac{h^4 m_p^5}{M_{Hc}^2 M_X^2} \qquad :\tau(p \to \nu K^+) = 10^{29\sim 39?}\ years$$



energy reconstruction

Full Super-K-I period





Corrected for light attenuation length in water
Time variation of E scale ~ 0.9%

E scale difference < 1.8%
(decaye, pi0, cosmic mu)

energy scale uncertainty of neutrino detection < 2.0%