Search for Q-ball in Super-Kamiokande

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Introduction

- The Universe has positive baryon number, but the early Universe was baryon symmetric.
  - We need a mechanism to break the baryon symmetry.
- What is dark matter ?

Q-ball can explain these two problems

The properties of Q-balls

- Q-balls are solitons in scalar field which can be stabilized by conservation of a U(1) charge
- aggregates of squark
- Charged Q-ball ： large energy loss, MACRO
- Neutral Q-ball ： can be detected in SK
- Mass M_Q、radius R_Q

$$M_Q = \frac{4\pi\sqrt{2}}{3} M_S Q^{\frac{3}{4}}$$

$$R_Q = \frac{1}{\sqrt{2}} M_s^{-1} Q^{\frac{1}{4}}$$

Q: barion number

M_S: SUSY breaking scale ~1TeV

- Cross section ：

$$\sigma = \pi R_Q^2 = \frac{16\pi^2}{9} M_Q^{-2} Q^2 \approx 6\times10^{-34} Q^{\frac{1}{2}} \left(\frac{1TeV}{M_S}\right)^2 cm^2$$

The interaction of neutral Q-balls

KKST(Kusenko-Kuzmin-Shaposhnikov-Tinyakov) process

- The scalar field has the large expectation value inside Q-balls
  $\longrightarrow$ breaking SU(3) symmetry
- When a Q-ball collides with a nucleon, the nucleon dissociates into three quarks
- The quarks are converted into squarks via gluino exchange and absorbed into a Q-ball
- A Q-ball emits 2 or 3 pions with total energy about 1GeV per nucleon
- Successive events are detected along a single trajectory
- similar to monopole signal

Q + Nucleon $\longrightarrow$ (Q + 1) + pions : Q:barion number

- Energy loss：emitted energy by nucleon absorption

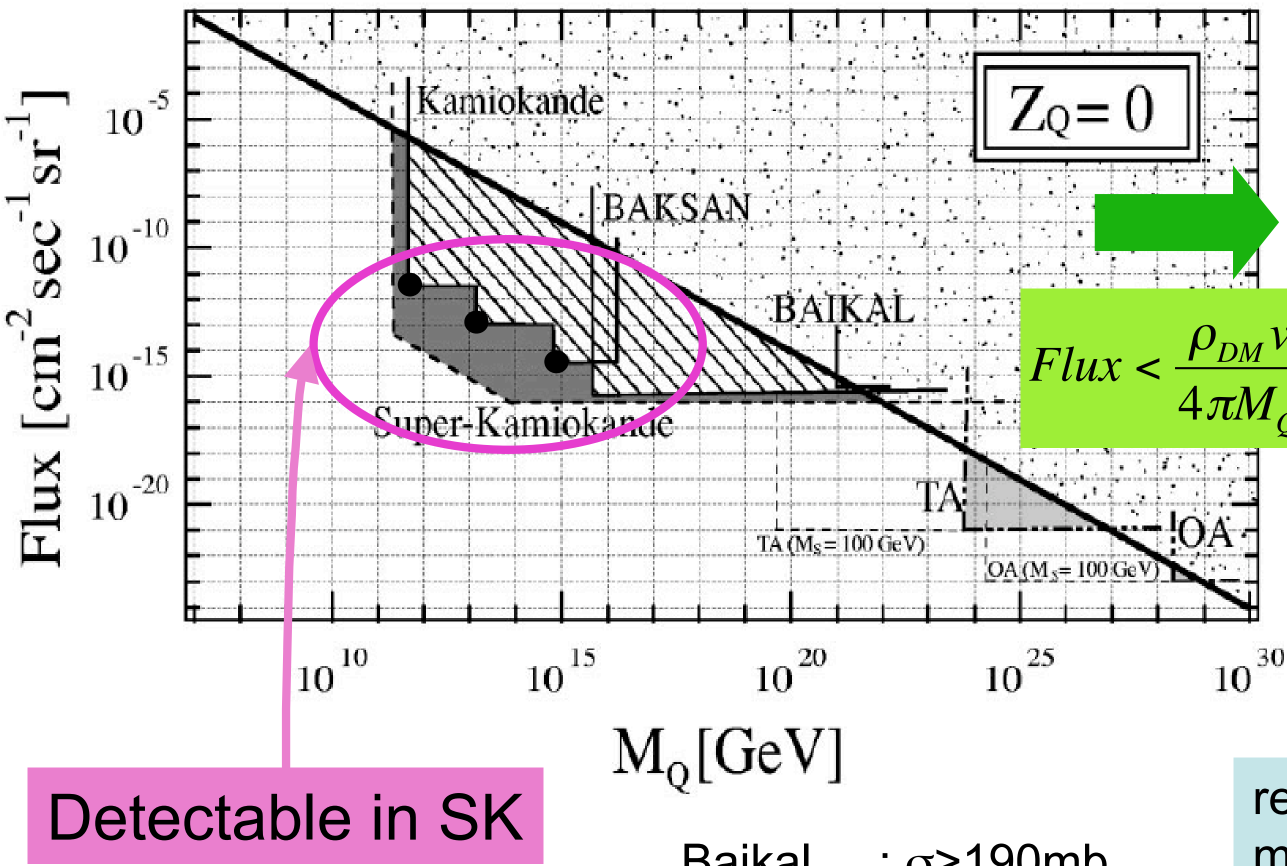
σ =100mb :

$$\frac{dE}{dx} = \frac{1GeV}{\lambda} = \sigma\rho N_A \cdot 1GeV \approx 30\,MeV/cm$$

λ : mean free path

$M_Q \sim 10^{19}$MeV $\longrightarrow$ Energy loss is negligible

Bounds on flux and mass for Q-balls



If Dark Matter of the Galaxy is filled with Q-ball, this area is excluded.

$$Flux < \frac{\rho_{DM} v}{4\pi M_Q} \approx 7.2 \times 10^5 \left(\frac{GeV}{M_Q}\right) cm^{-2} sr^{-1} s^{-1}$$

ρ_{DM}=0.3GeV/cm^3,

v ~10^{-3}c

assuming M_S=1TeV

Baikal : σ>190mb、

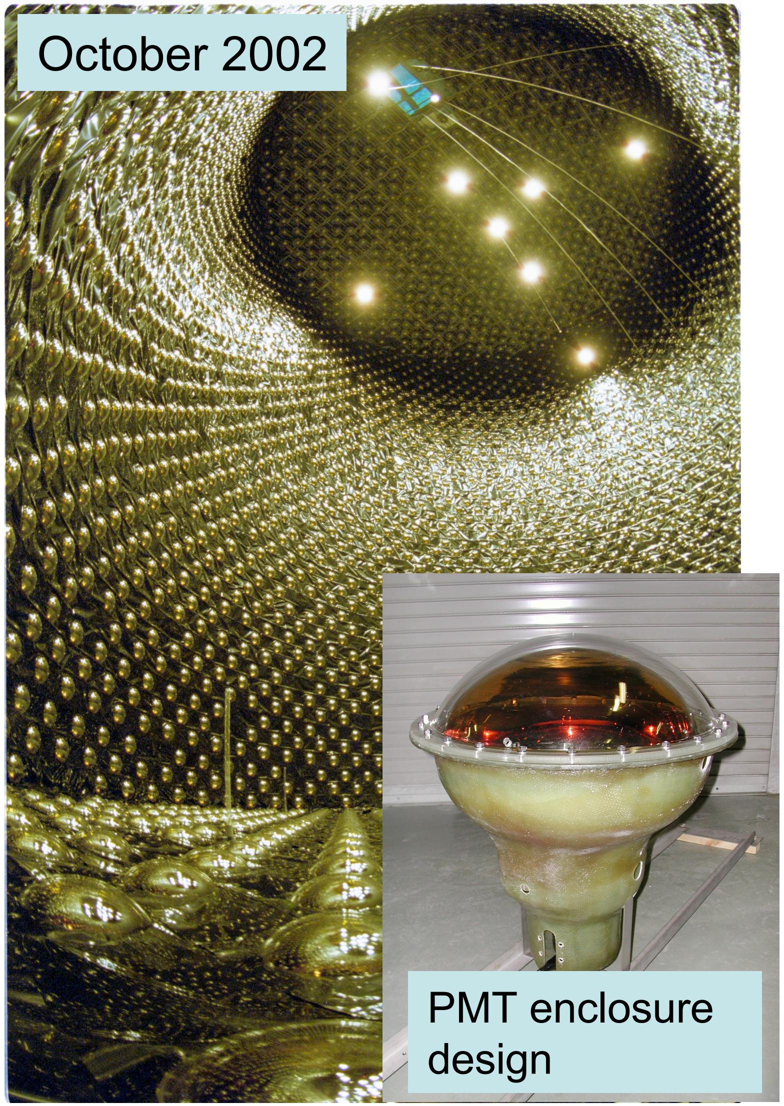
BAKSAN : σ>50mb

Kamiokande : σ>0.1, 1, 10mb

reinterpret the results of monopole search to get Q-ball flux

(J. Arafune et al. Phys. Rev. D 62 (2000) 105013)

Super-Kamiokande



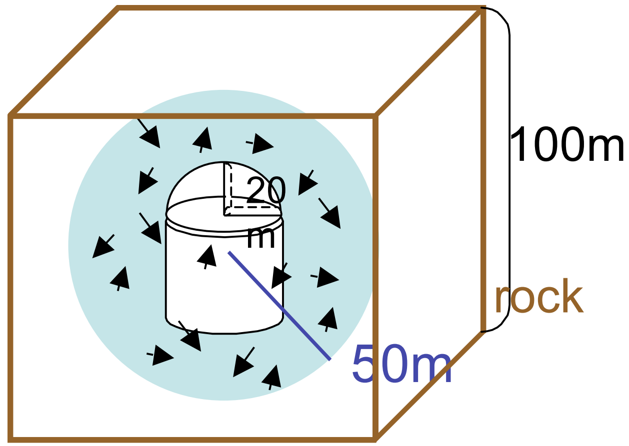
- Cylindrical water Cherenkov detector
- Diameter : 39.3m、Height : 41.4m
- Volume : 50kt (Inner Detector : 32kt,
  Outer Detector : 18kt)

1996/April	SK-I start
2001/July	SK-I finished
2001/Nov.	Accident
2002/Dec.	SK-II started

- The number of PMTs of the Inner Detector : 5,182 (47% SK-I:11,146)
- PMTs are enclosed with cases made of acrylic case and FRP(Fiber Reinforced Plastics) to prevent from breaking PMTs by a shock wave

Q-ball simulation

- generate Q-balls randomly in 50m sphere
- Total charge of emitted pions is equal to that of a collided nucleon
- assuming that the number of emitted pions per nucleon is two or three with equal probability
- not lose energy by collision with a nucleon and collide with next one
- Maximal number of successive events is 20
- Q-ball velocity has some distribution



assuming M_s=1TeV,$v=10^{-3}c$

Cross section (mb)	Mean free path (in water)	Mean interval time	Mass (MeV)	Baryon number
0.1	170m	500μsec	3.8×10^{14}	2.6×10^{10}
1	17m	50μsec	1.2×10^{16}	2.6×10^{12}
10	1.7m	5μsec	3.8×10^{17}	2.6×10^{14}
100	17cm	500nsec	1.2×10^{19}	2.6×10^{16}

The distribution of Q-ball velocity

- If Q-balls are Dark matter, the velocity is assumed to have an approximately Maxwellian distribution with v_{rms}~270km/sec
- Considering the earth goes through this dark mater distribution with the velocity of solar system 220km/sec, one obtain the Q-ball velocity to superpose these two velocities

$$\vec{v} = \vec{v}_m - \vec{v}_e$$

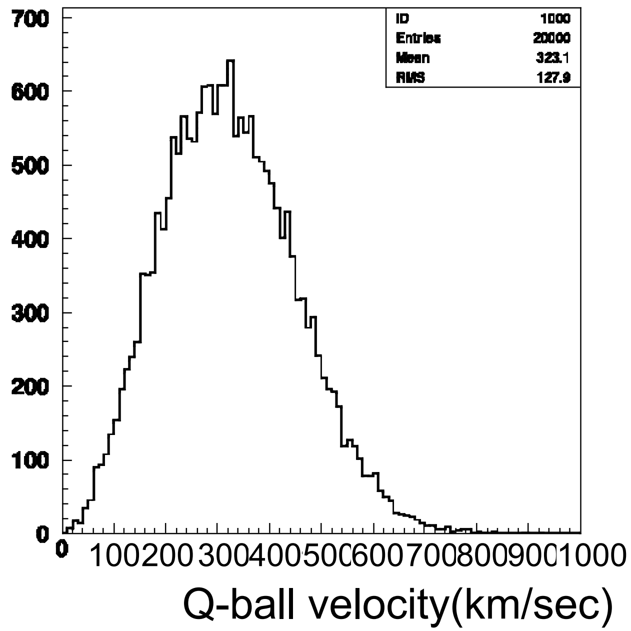
$$v^2 = v_m^2 + v_e^2 - 2v_m v_e \cos\theta$$

v : the Q-ball velocity from the earth

v_m : the Q-ball velocity with

Maxwellian distribution

v_e : the velocity of solar system ~220km/sec

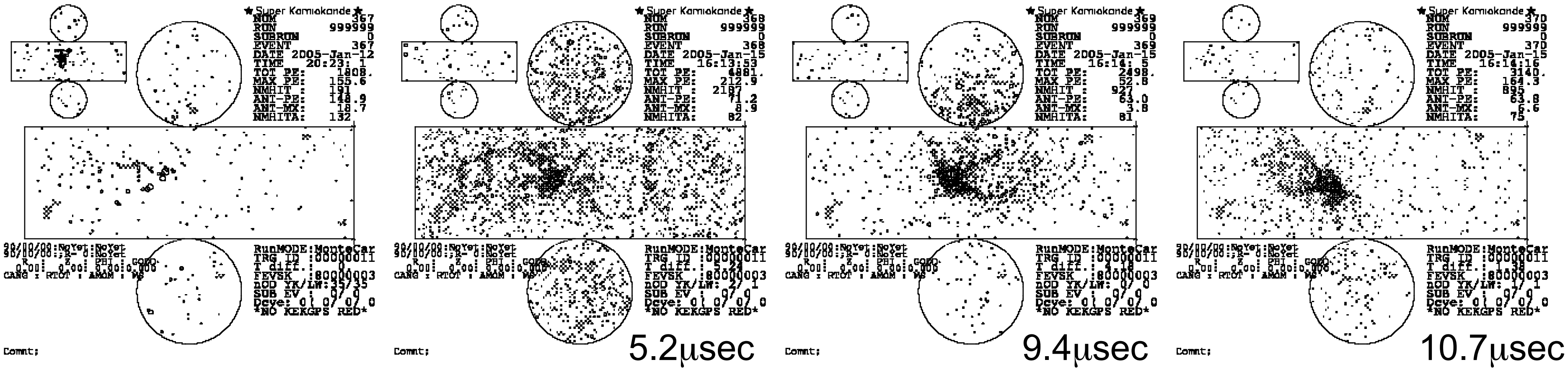


The assumed distribution of Q-ball velocity

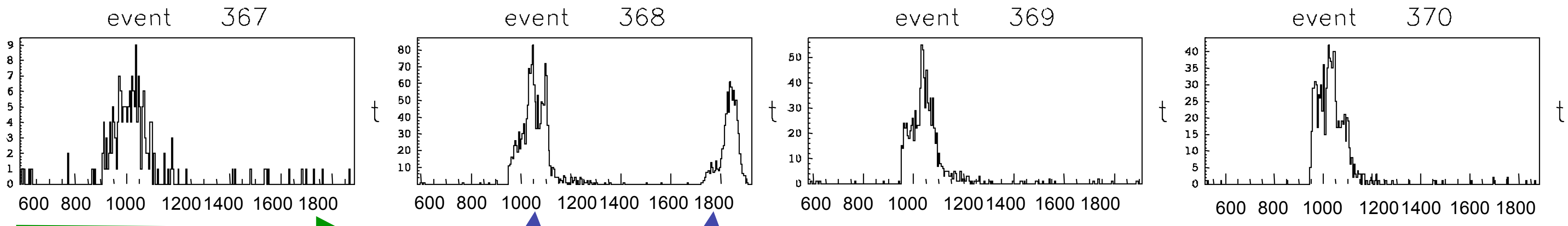
MC:10mb

Sequential events occurred by one Q-ball

1st event | 2nd | 3rd | 4th



hit timing distribution in 1 event

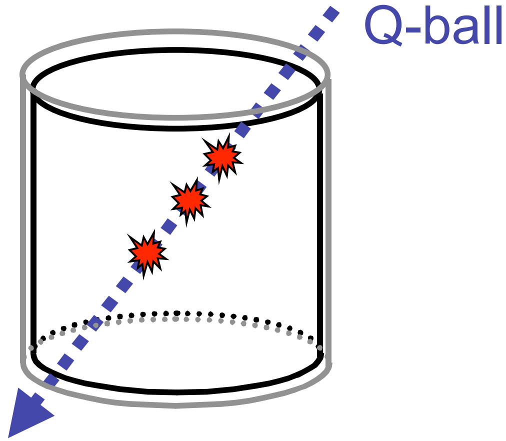


1.3µsec

Two interactions in 1 event

Data reduction

- Data set : SK-II 416.2days
  2003/Jan./21 ~2004/Jun./29
- Sequential events with large charge are regarded as Q-ball events
- Main background event is a coincidence event with cosmic muon



1st reduction

- Charge (Inner Detector) cut
- Need more than two sequential events

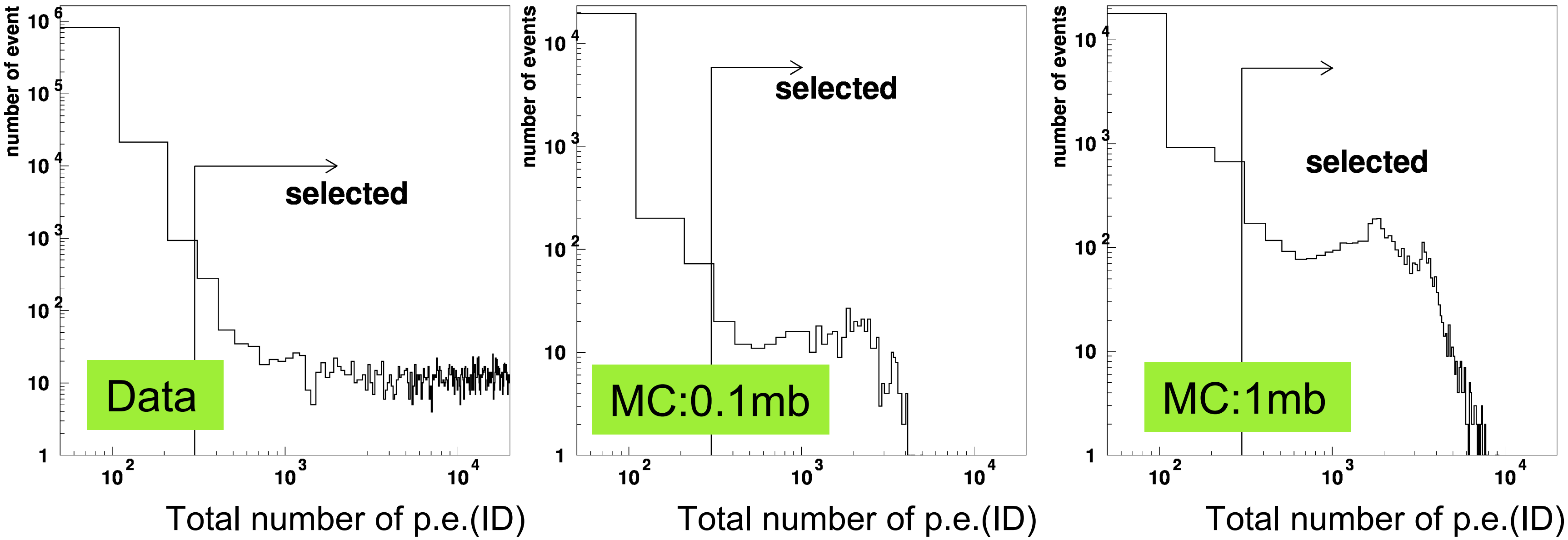
1st event + 2nd,3rd,4th….event

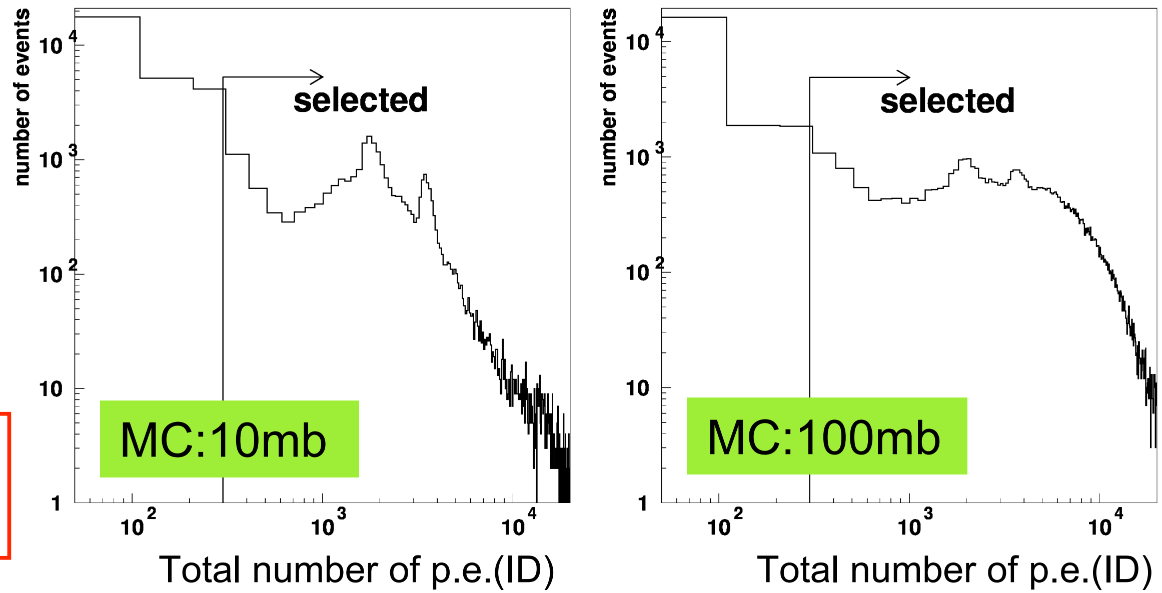
Q>300&
(Q in 300nsec)<10000

100μsec

A chain of events which are occurred by one Q-ball

The distribution of total charge (ID)



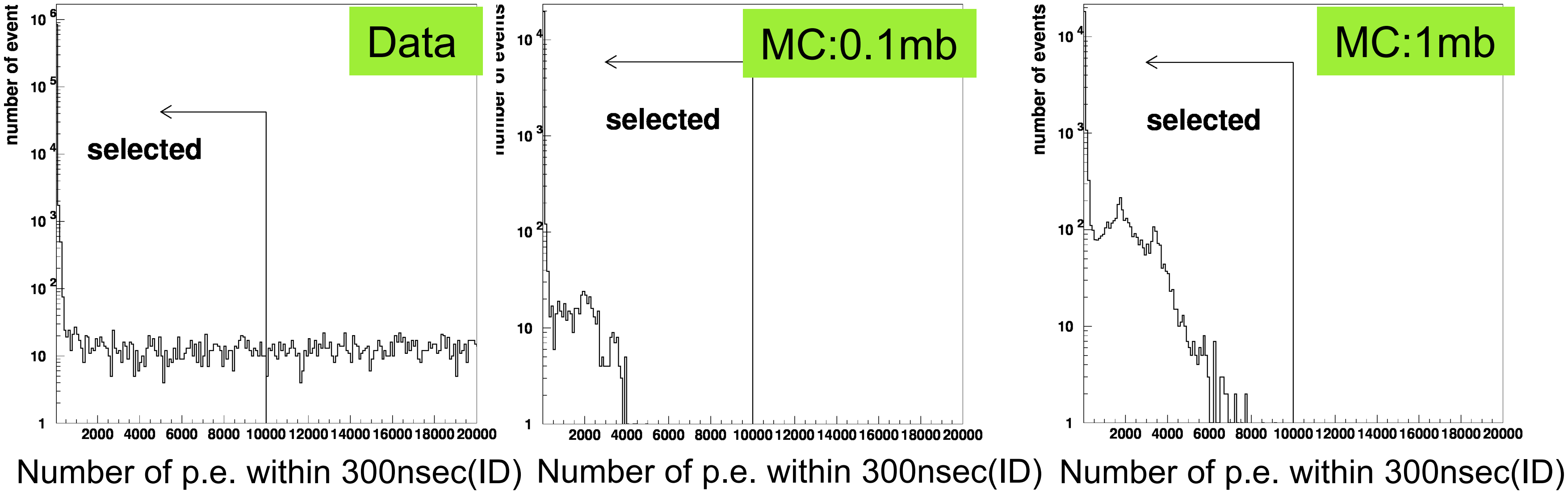


reject low energy events
like decay-e events

- Selection criteria

Total charge(ID)
>300p.e.(about 60MeV)

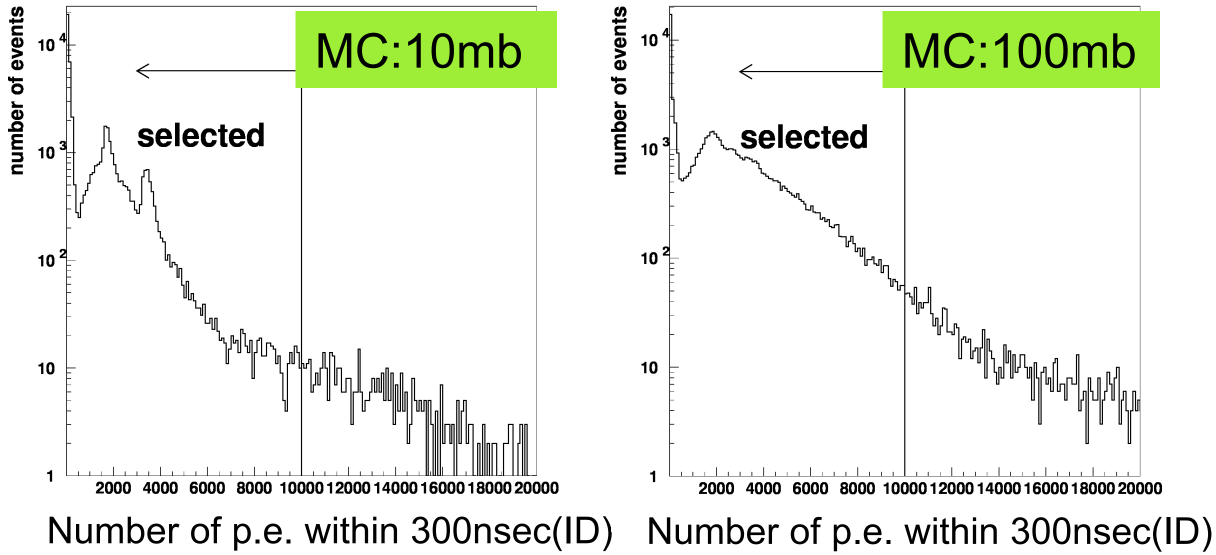
The distribution of charge(ID) within 300nsec time window



reject large charge events like through going muon events

- Selection criteria

charge(ID) within 300nsec <10,000p.e.



2nd reduction

- reject muon and lowE events

① Total charge(ID) vs.number of hit (OD) cut

- reject muon events
  and low energy events
- require large charge(ID)
  & small # of hit (OD)

2nd,3rd,4th….event
1st event + μ + lowE….
μ + μ …
lowE + lowE….

② Noise events cut

- reject continuous electronics noise events
- large charge (ID) & large goodness

1st event + noise+noise…

③ Separated events cut

- one cosmic ray muon event is separately recorded to 2 events

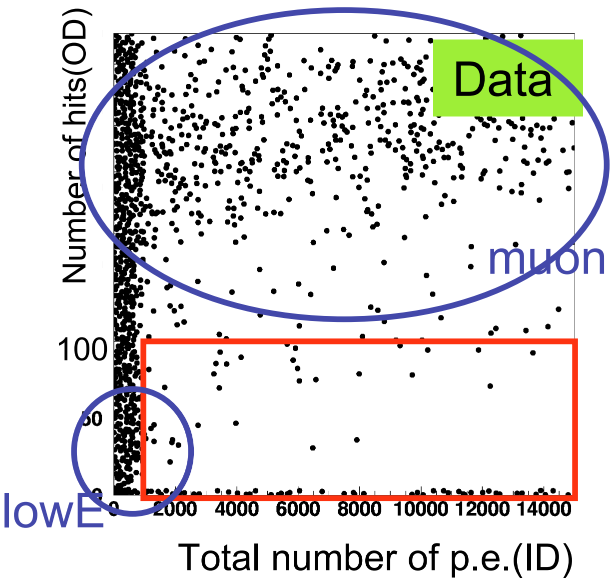
④ Muon events cut

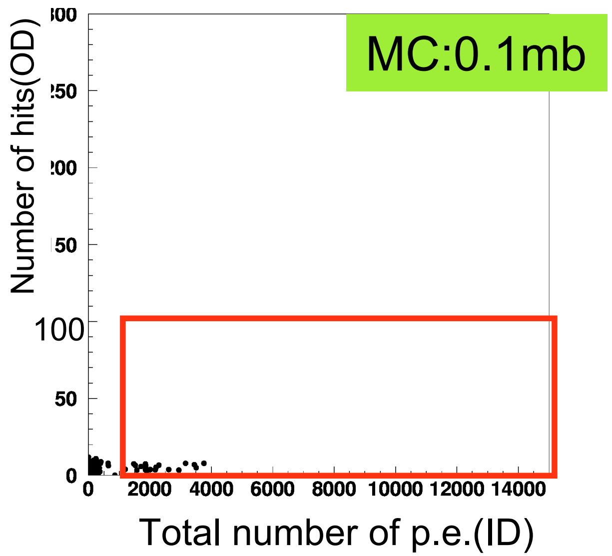
- reject muon events with small # of hit (OD) and lowE events

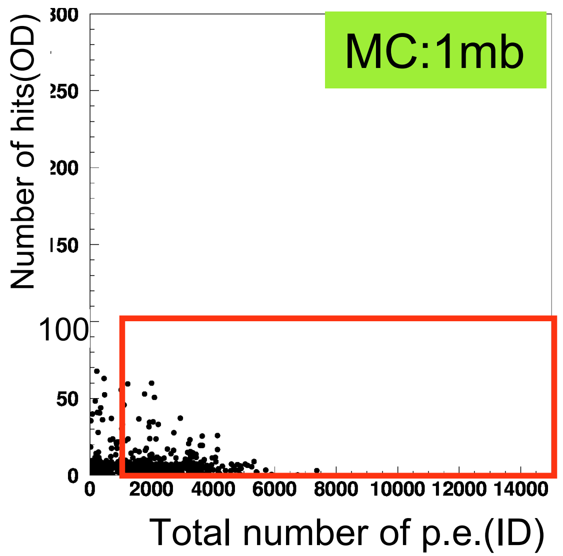
1st event + μ + lowE
μ + μ

① Number of hit (OD) vs.total charge(ID) after the 2nd event

reject muon and lowE events

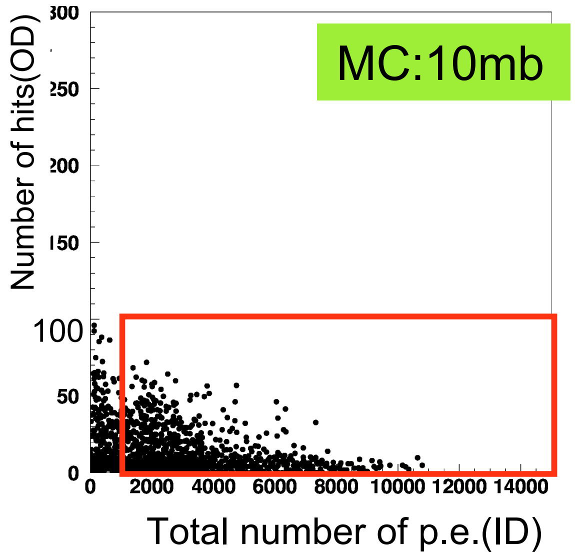


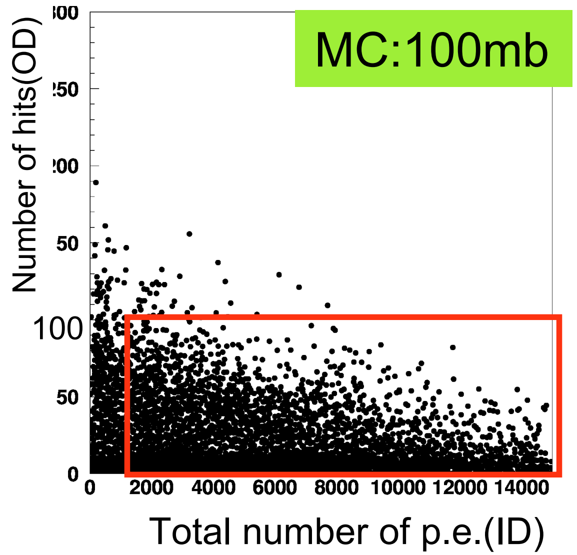




- Selection criteria

Total charge(ID)>1,000p.e.
&
Number of hit (OD)＜100

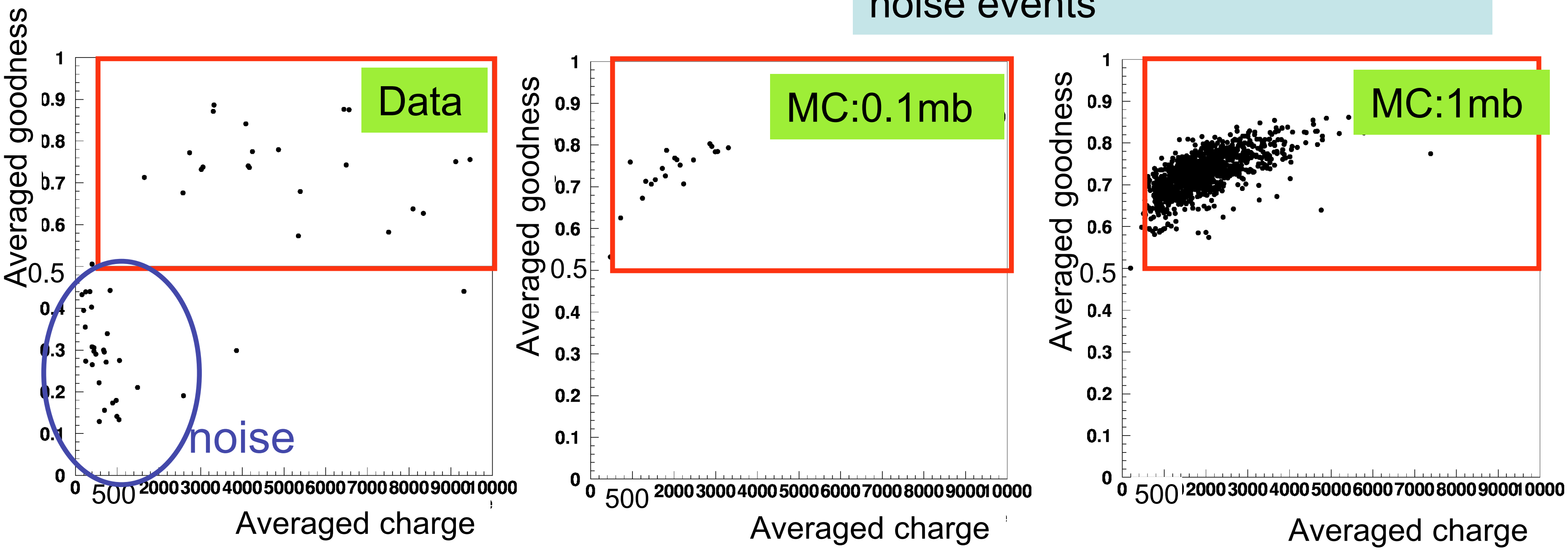




If at least one event meets these criteria after 2nd event, the chain of events which the event is contained is selected.

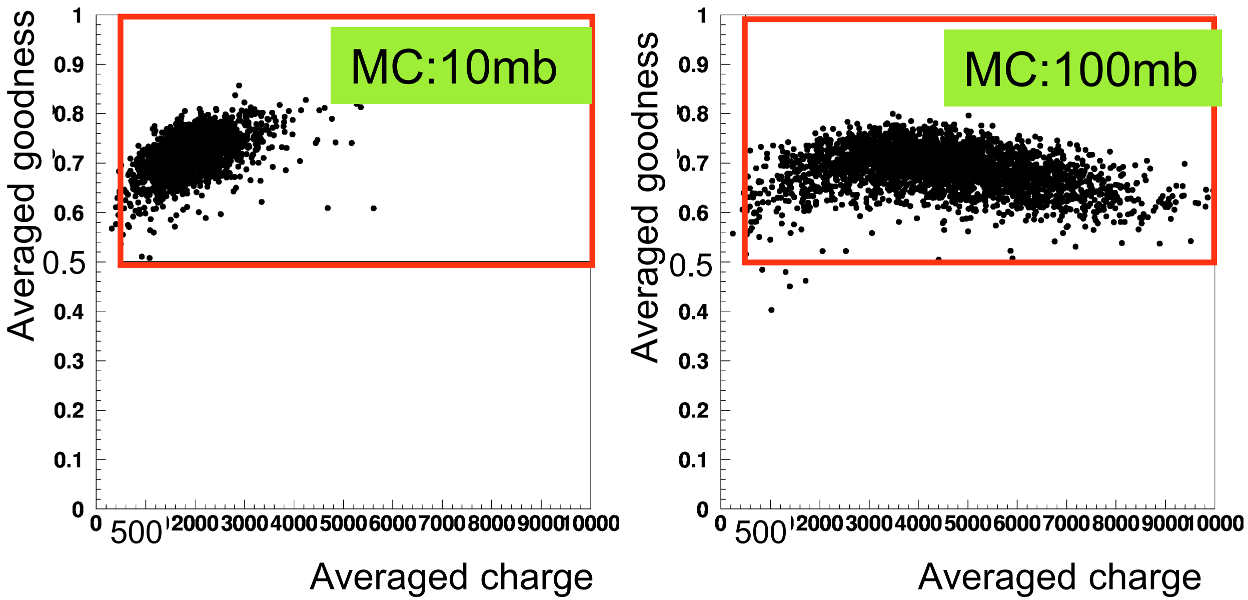
② Noise event cut

reject the continuous electronics noise events



- Selection criteria

averaged goodness of
a chain of events > 0.5
&
averaged charge(ID) of
a chain of events > 500p.e.



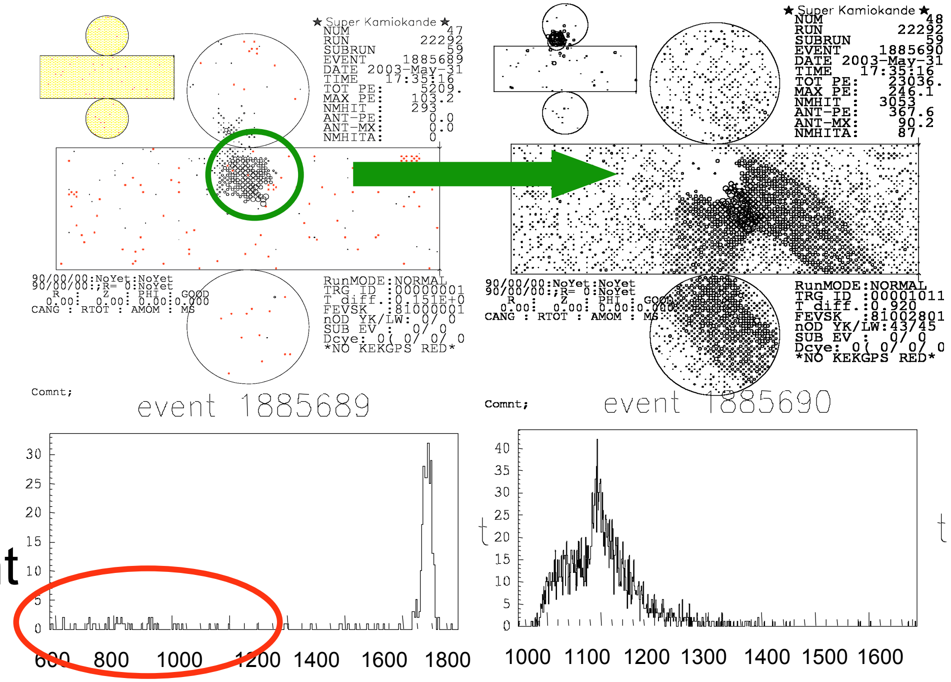
③ Separated events cut

- One cosmic ray muon event is separately recorded to 2 events
- Reject

  Number of events in a chain of events＝ 2

  &

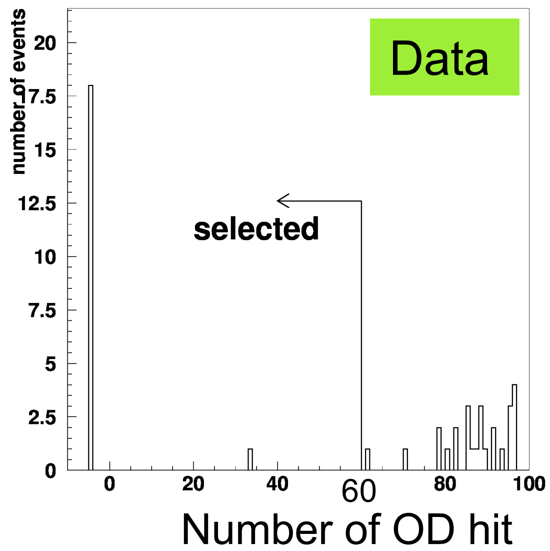
  number of hit (OD) of the 2nd event ＞６０

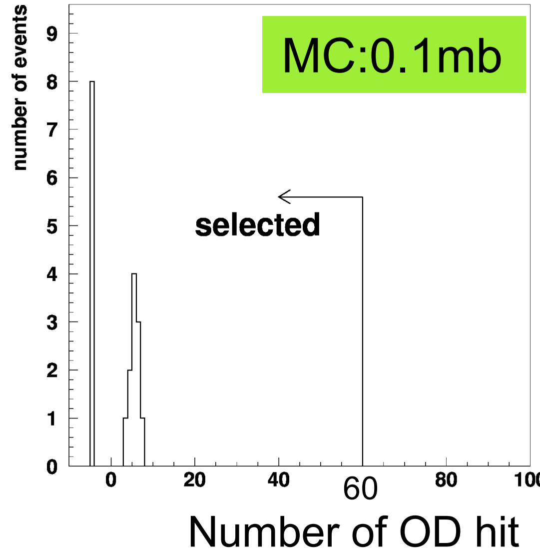


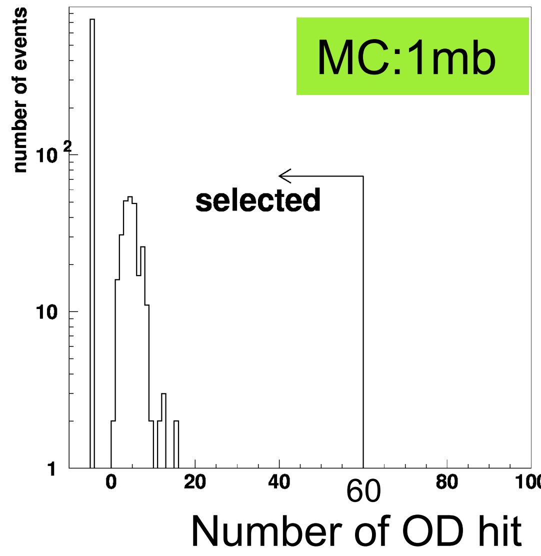
Triggered by
low energy event

Number of hit (OD)
of the 2nd event

reject the separated events

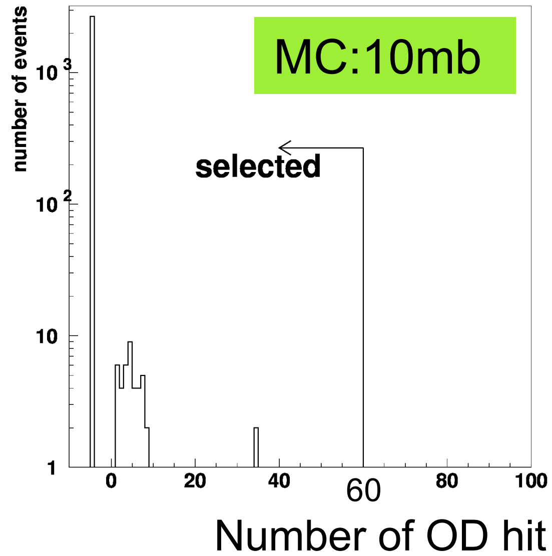


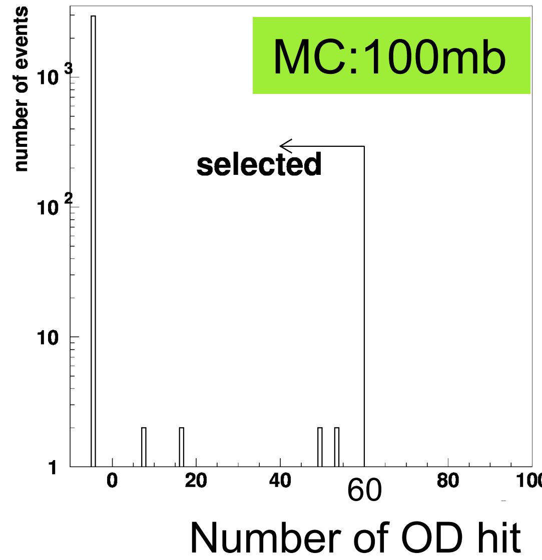




- reject
Number of events
 in a chain of events =2
&
Nhit(OD) of the 2nd event>60

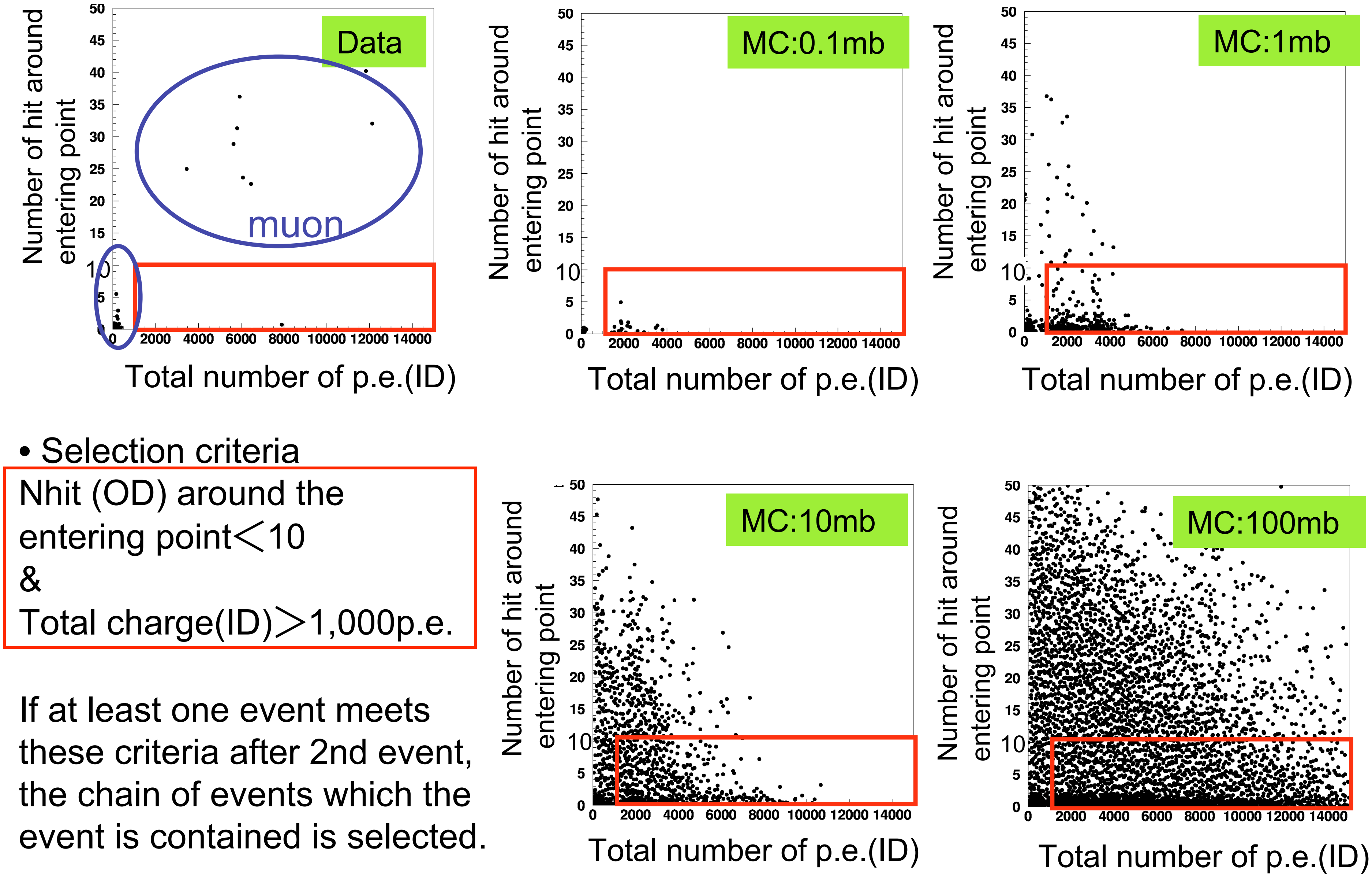
- select
Number of events >2





④ Muon event cut

reject muon events with small nhit (OD)



- Selection criteria

Nhit (OD) around the entering point＜10
&
Total charge(ID)＞1,000p.e.

If at least one event meets these criteria after 2nd event, the chain of events which the event is contained is selected.

Reduction summary

Data

reduction	Data
1st cut	1,679,400
total charge(ID)vs. nhit (OD)cut	77
noise event cut	45
separated events cut	19
muon event cut	1

One chain of events is observed

contains 2 events

during 416.2 days of live time
(2003/Jan/21~2004/Jun/29)

MC

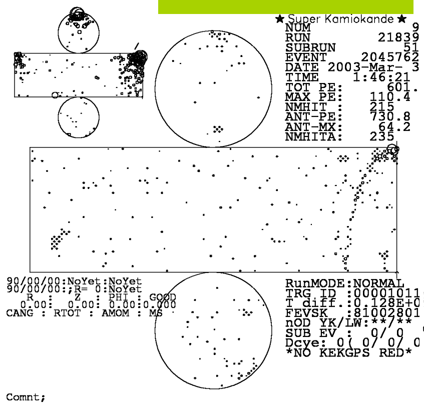
reduction	MC : 0.1mb	MC : 1mb	MC : 10mb	MC : 100mb
generated events	20,000	20,000	20,000	20,000
1st reduction	158(0.8%)	1488(7.4%)	2863(14%)	3184(16%)
total charge(ID)vs.nhit(OD)cut	20(13%)	1013(68%)	2744(96%)	2970(93%)
noise event cut	19(95%)	1011(100%)	2734(100%)	2962(100%)
separated events cut	19(100%)	1011(100%)	2734(100%)	2961(100%)
muon event cut	19(100%)	995(98%)	2720(99%)	2918(99%)
Total reduction efficiency	0.095%	4.98%	13.6%	14.6%

obtain the Q-ball flux upper limits using the efficiencies

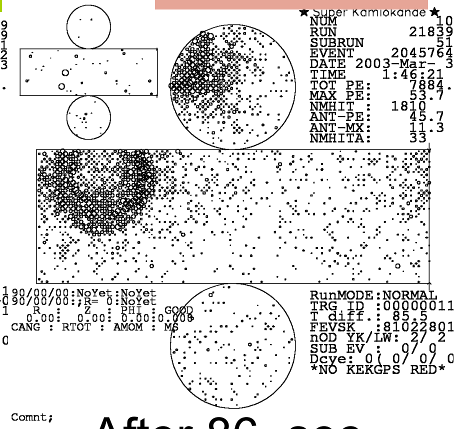
Q-ball ?

Cosmic ray μ + atmospheric ν ?

1st event



2nd event



After 86μsec

Estimate the experimental value to be coincident the 1st event with atmospheric ν in 100μsec during 416.2days live time

- event rate of atmospheric ν : 11.4 events/day (all volume)
- event rate of the 1st event :0.34 events/sec

$$11.4 events/day \times 416.2 days \times 0.34 events/sec \times 100 \mu sec = 0.16 events$$

the expected value ＝ 0.16events

The probability to observe more than 1event ＝ 15%

We can considered that one residual chain of events is an accidental coincidence event between cosmic ray μ and atmospheric ν

Flux upper limit

Flux upper limit $\boxed{F < \frac{N_0}{\varepsilon S_{eff} \Omega T}}$

Effective aperture : $S_{eff}\Omega = \varepsilon \cdot \pi r^2 \cdot 4\pi = \varepsilon \cdot \pi 50^2 \cdot 4\pi (m^2 sr)$

ε: detection efficiency (from MC reduction)

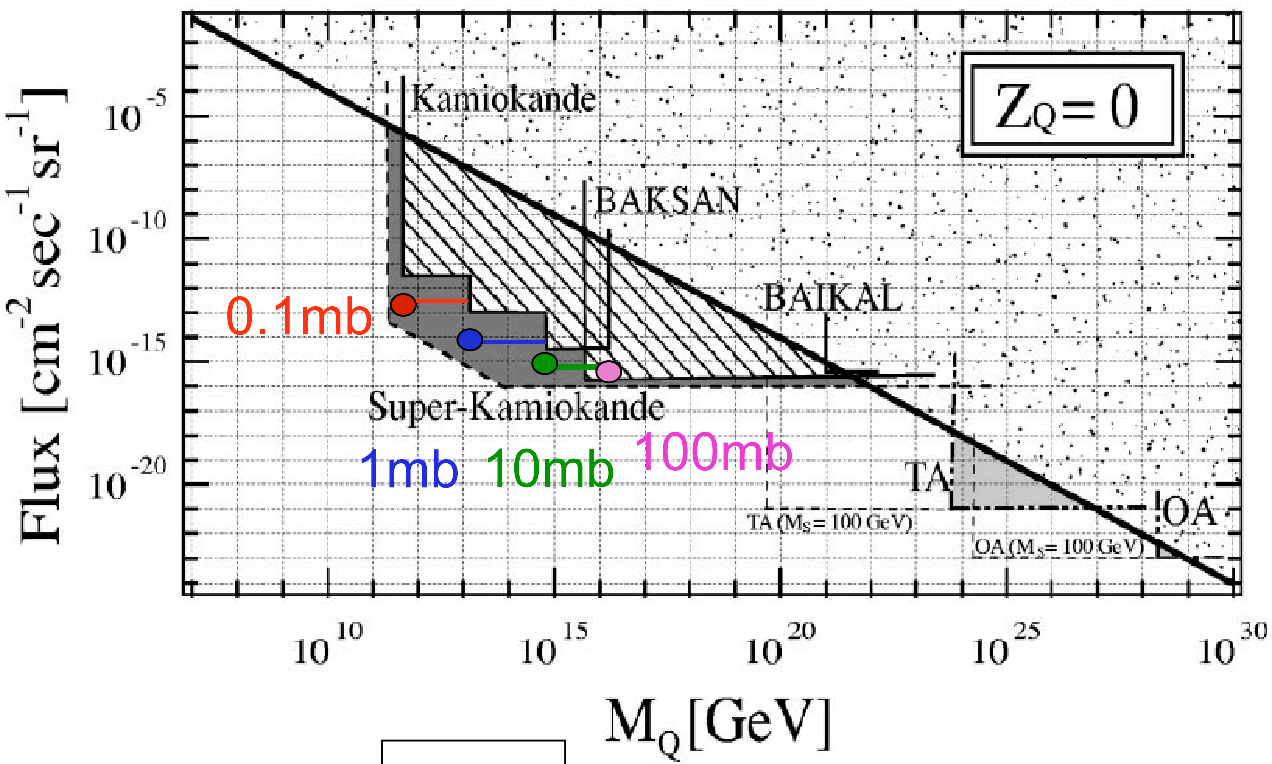
T : live time 416.2days

N_0 = 3.9 (90%C.L.)
: expected value if we can find one observed event

cross section	detection efficiency	effective aperture (cm^2sr)	Flux upper limit ($cm^2sr^{-1}sec^{-1}$)
0.1mb	0.095%	9.4×10^5	1.2×10^{-13}
1mb	4.98%	4.9×10^7	2.2×10^{-15}
10mb	13.6%	1.3×10^8	8.1×10^{-16}
100mb	14.6%	1.4×10^8	7.5×10^{-16}

Comparison with other experiments

preliminary



SK-II

	SK-II		
$\sigma : 0.1mb$	$F < 1.2 \times 10^{-13} (cm^2 sr^{-1} sec^{-1})$	x0.04	$F < 3 \times 10^{-12}$(Kamiokande)
$\sigma : 1mb$	$F < 2.2 \times 10^{-15} (cm^2 sr^{-1} sec^{-1})$	x0.07	$F < 3 \times 10^{-14}$(Kamiokande)
$\sigma : 10mb$	$F < 8.1 \times 10^{-16} (cm^2 sr^{-1} sec^{-1})$	x0.27	$F < 3 \times 10^{-15}$(Kamiokande)
$\sigma : 100mb$	$F < 7.5 \times 10^{-16} (cm^2 sr^{-1} sec^{-1})$	x2.5	$F < 3 \times 10^{-16}$(BAKSAN)

Summary

- Search for Q-balls has been carried out during SK-II 416.2 days(2003/Jan/21~2004/Jun/29) of live time.

- One Q-ball candidate has been observed, but it can be regarded to be an accidental coincidence between cosmic ray muon and atmospheric neutrino.

- The upper limits on Q-ball flux are calculated

  σ =0.1mb : $F<1.2\times10^{-13}(cm^{2}sr^{-1}sec^{-1})$

  σ =1mb : $F<2.2\times10^{-15}(cm^{2}sr^{-1}sec^{-1})$

  σ =10mb : $F<8.1\times10^{-16}(cm^{2}sr^{-1}sec^{-1})$

  σ=100mb : $F<7.5\times10^{-16}(cm^{2}sr^{-1}sec^{-1})$

- We can obtain more stringent flux limits than those of Kamiokande by about 3~25 times