BESS実験
―測定器と反陽子流束測定―

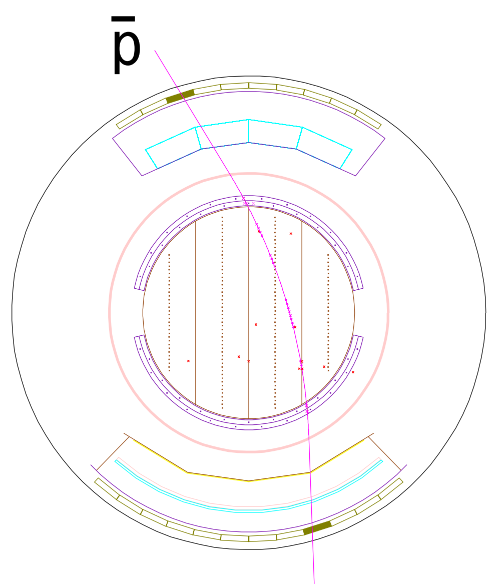
BESS Collaboration

Balloon-borne Experiment with a Superconducting Spectrometer

宇宙線研究所セミナー

東大･理　浅岡陽一

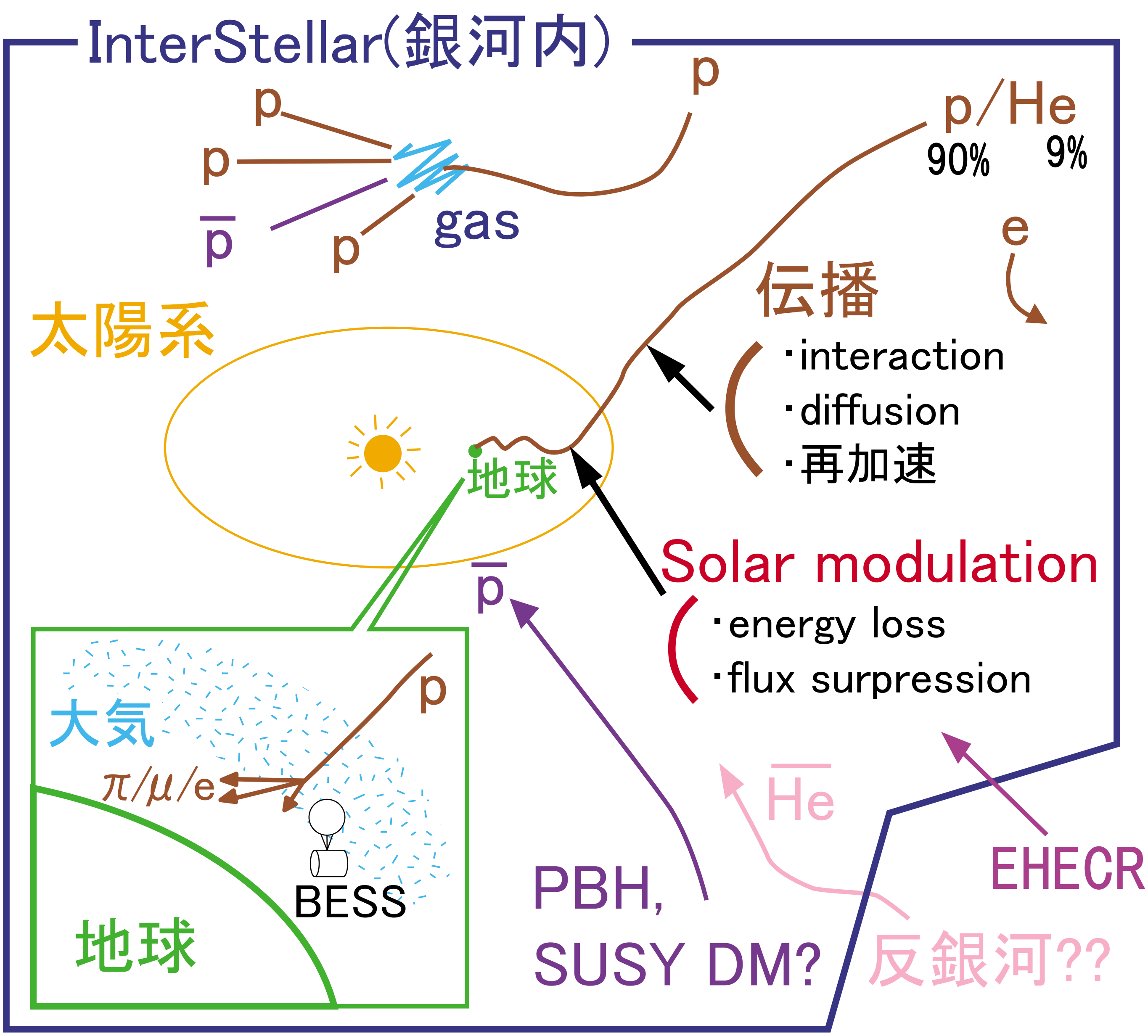
Contents



BESS実験：宇宙における素粒子現象の探求を目的とする気球実験

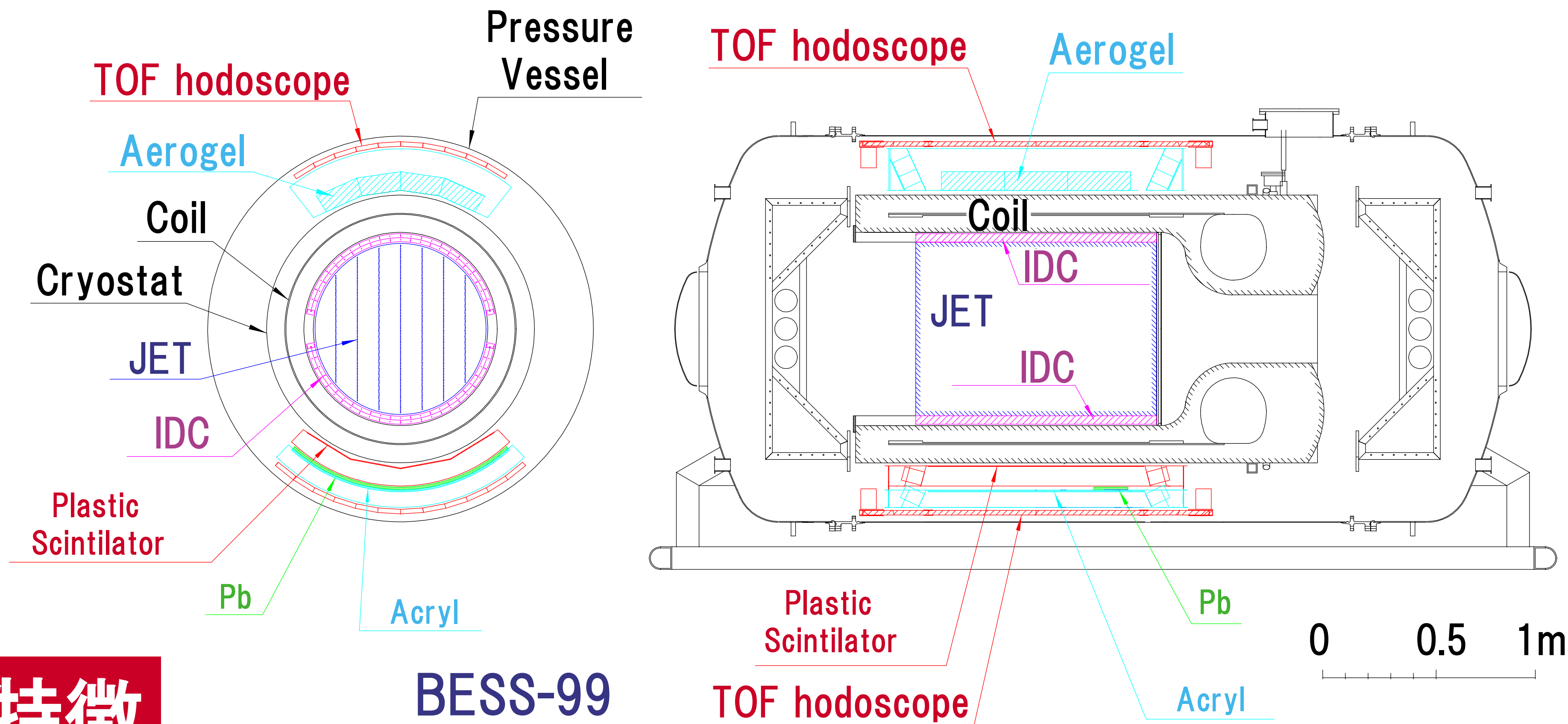
・原始ブラックホール (PBH) の
Hawking radiation による蒸発
・SUSY Dark Matter (neutralino) の対消滅

⇒ 低エネルギー反陽子 (一次起源)



BESS 測定器

TOF ⇒ β
Tracking ⇒ Rigidity = 運動量/電荷

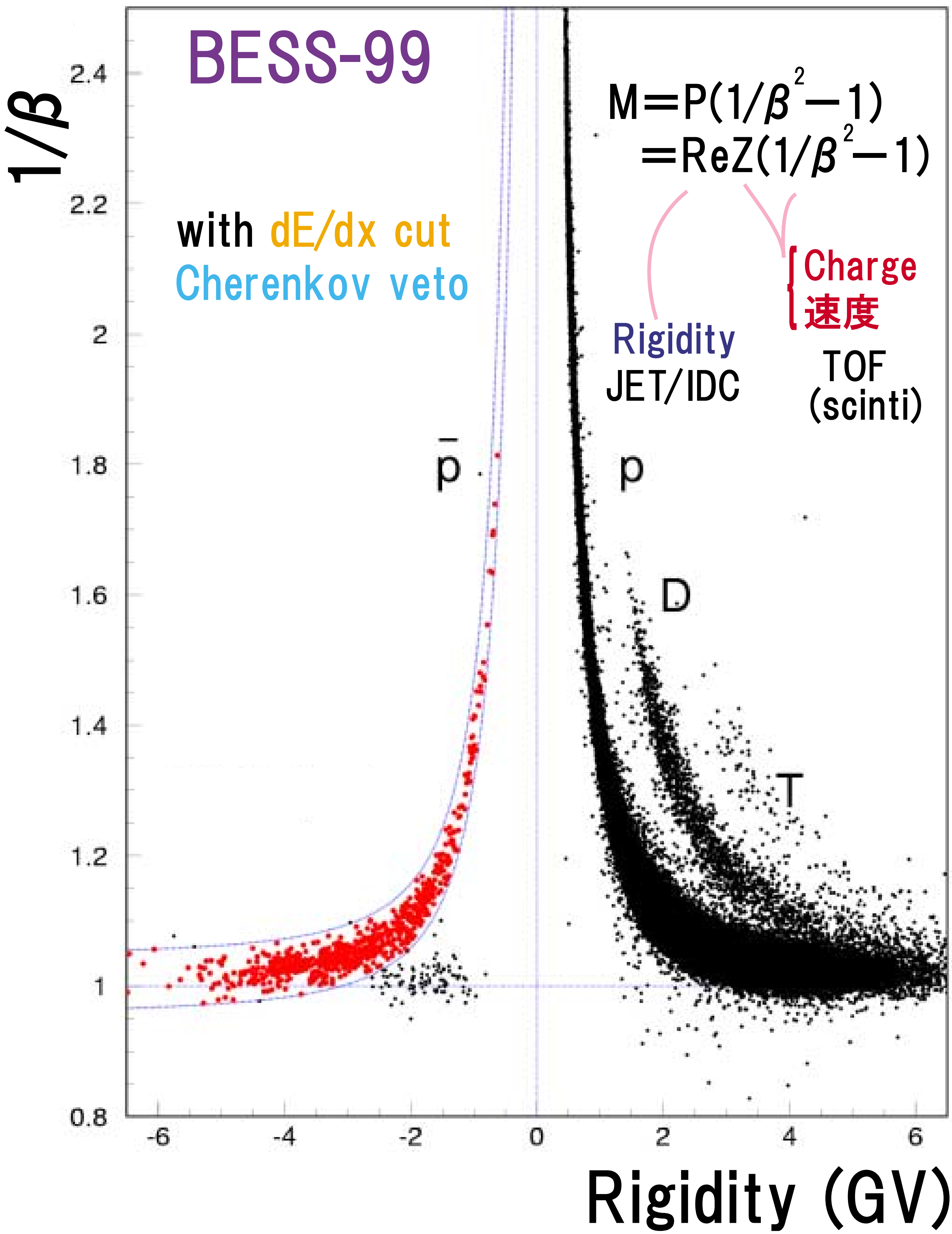


BESS-99

特徴

- 薄肉超伝導ソレノイド ⇒ 大面積・大立体角 ⇔ high statistics
- 強力な粒子識別能力 ⇒ 質量の同定(β・Rigidity)
  dE/dx, Aerogel Cherenkov
- simple な構造 ⇒ 一様な性能 ⇔ low systematics

Particle ID (質量の同定)



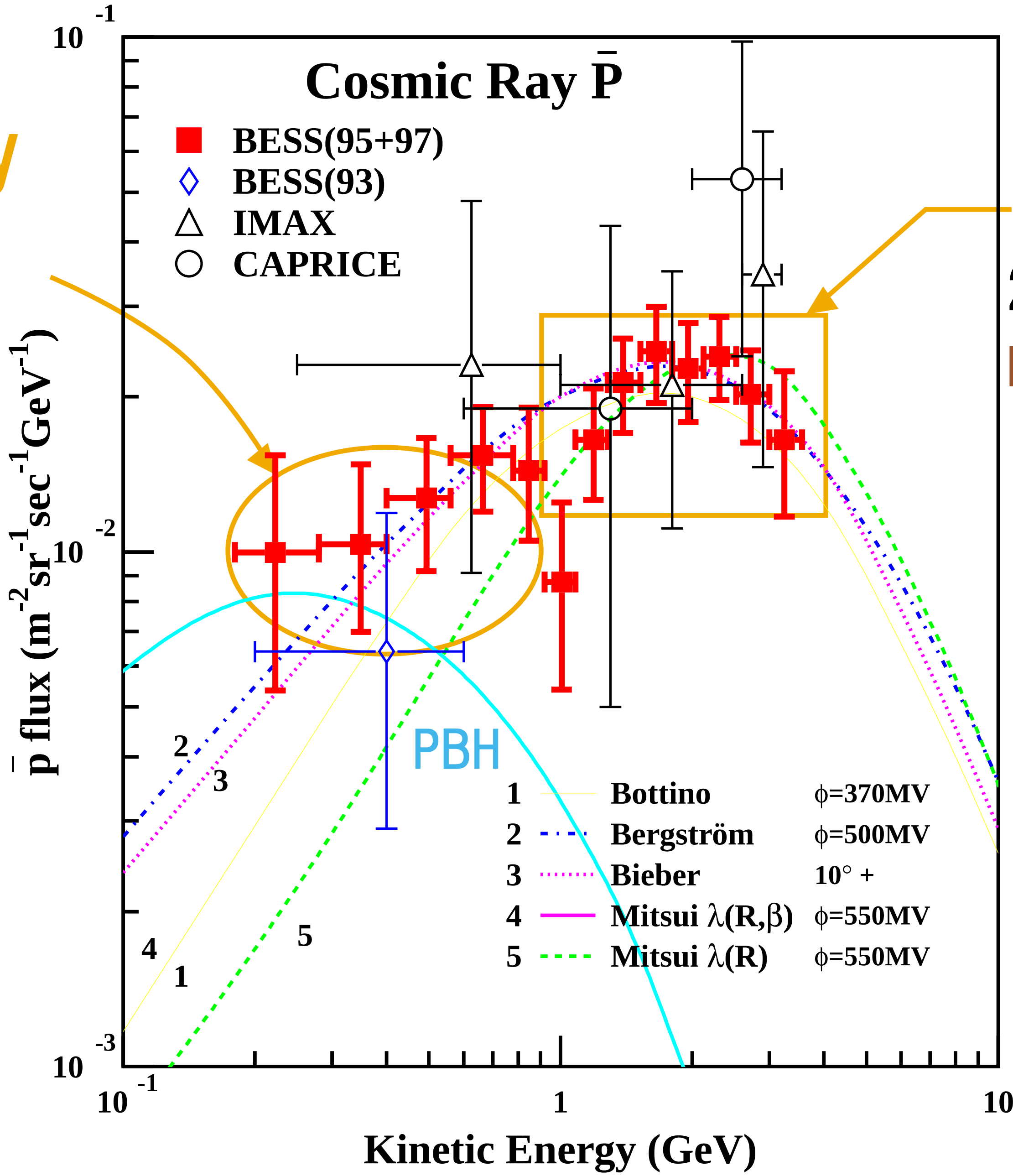
$\bar{P}$ spectrum の測定 @ solar minimum

low energy region

2次起源流束
⇒ 減少
(kinematics)

primary sources
の探索が可能

- PBH蒸発
- SUSY DMの annihilation



peak region

2次起源 dominant

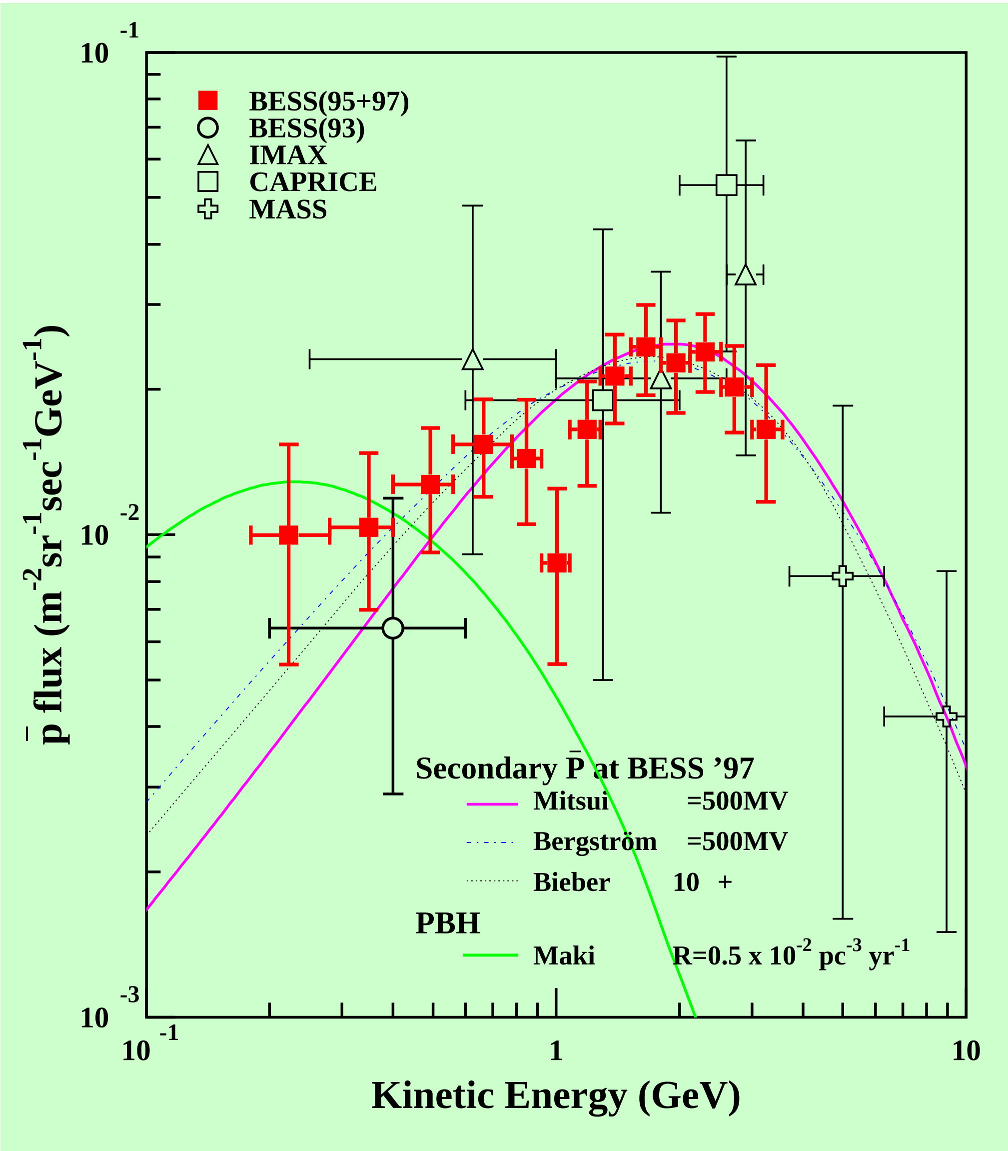
$p+p \longrightarrow p+p+p+\bar{p}$

interstellar gas(rest)

[IS proton flux
$\bar{p}$ flux @ peak
⇒伝播 model の検証

Input, Output
共にBESSで
測定可能

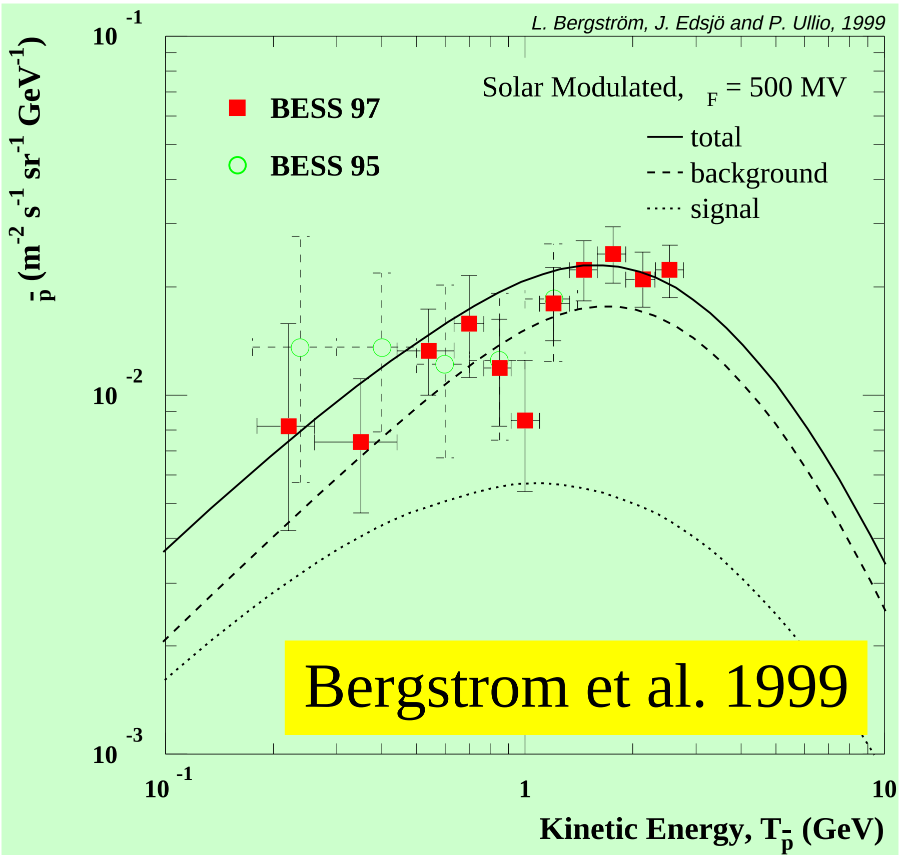
Evaporation of Primordial Black holes

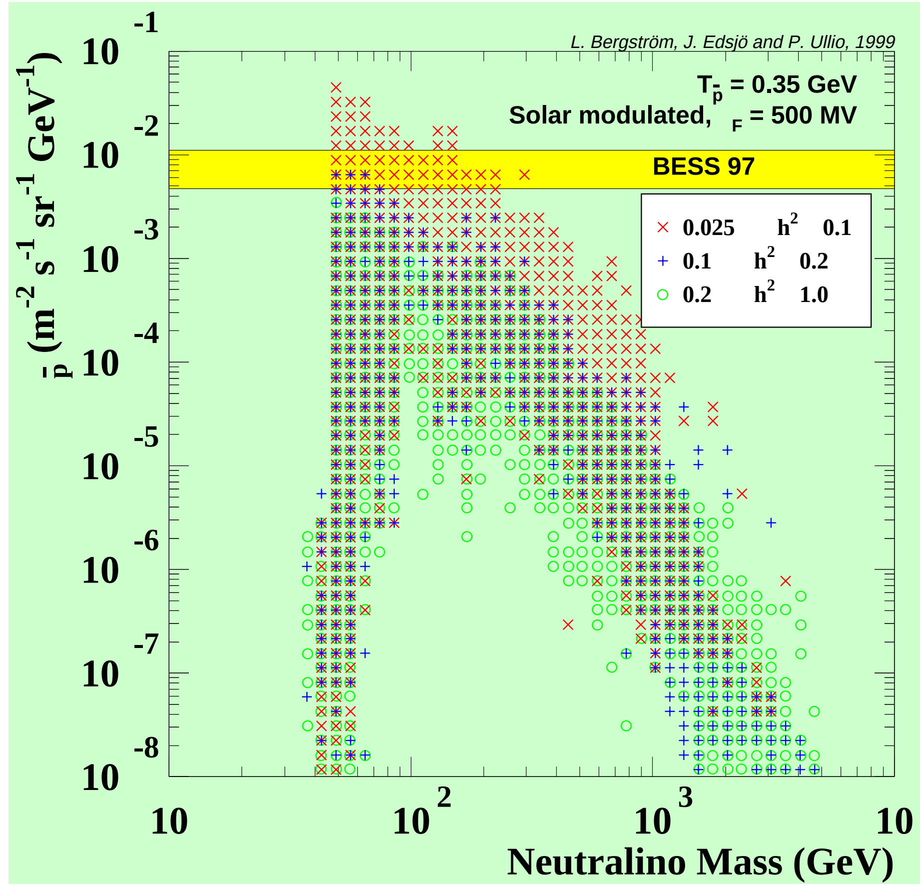


"Black hole explosion ?"
S. W. Hawking, Nature, 1974

- PBHs might be formed by fluctuations in the early Universe.
- $M \sim 5X10^{14}$g now evaporating.
- Distinct spectrum compared to secondary background.
- BESS data limit the evaporation rate
  - Maki et al, 1996.
  - $R < 10^{-2}pc^{-3}yr^{-1}$
  - More stringent than gamma-ray limits.

Indirect search for SUSY Dark matter





- Background is larger at low energies than we expected.
- Difficult to distinguish signal from background by means of spectral shape.

BESS data has limited parameter space for SUSY.

- Bergstrom et al, 1999.
- Bottino et al, 1998.

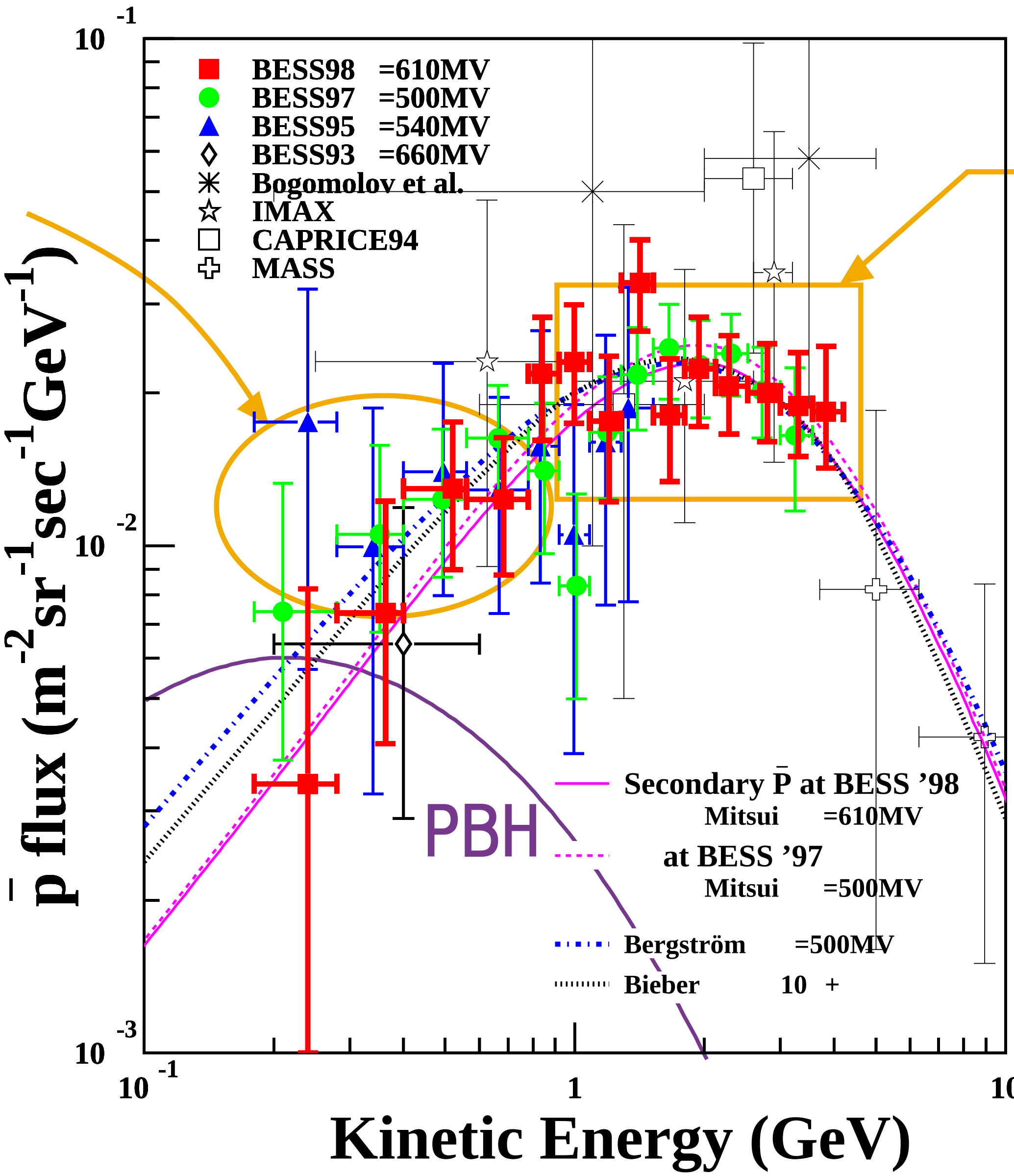
$\bar{P}$ spectrum の測定(93-98)

low energy region

2次起源流束
⇒ 減少
(kinematics)

primary sources
の探索が可能

- PBH蒸発
- SUSY DMの annihilation



peak region

2次起源 dominant

$p+p \rightarrow p+p+p+\bar{p}$

interstellar gas(rest)

[IS proton flux
$\bar{p}$ flux @ peak
⇒伝播 model
の検証

流束の経年変化
⇒ solar modulation
の理解

History

87 Proporsal S. Orito et al.

⋮

92 Ready後帰国(MOU)

93 初 Flight 6 $\bar{p}$

94 2nd Flight 2 $\bar{p}$

95 3rd Flight 43 $\bar{p}$ 折戸研入り

96 気球に穴があいており、となり町との間に落下。
大変な回収の後、2回目のチャンスを待つが時間切れ。

97 4th Flight 415 $\bar{p}$ キャンペーン参加

98 5th Flight 1 season 2回のflightを狙うも、
398 $\bar{p}$ 山火事の影響で時間切れ。

99 気球破裂し、湖に落ちる。1週間でリカバーし、
6th Flight 668 $\bar{p}$ 2回目のチャンスを捉える。

00 7th Flight 2週間以上の天気待ち。打ち上げ時
558 $\bar{p}$ 気球に穴が発見されるがテープで塞ぐ。

- 過去7回地磁気緯度の低いCanada, Lynnlake
  でのFlightに成功した。
- Detectorが原因で予定を遅らせたことはない。
  Balloonの事故にはけっこう遭っている。

Year by Year Improvement of the Detector

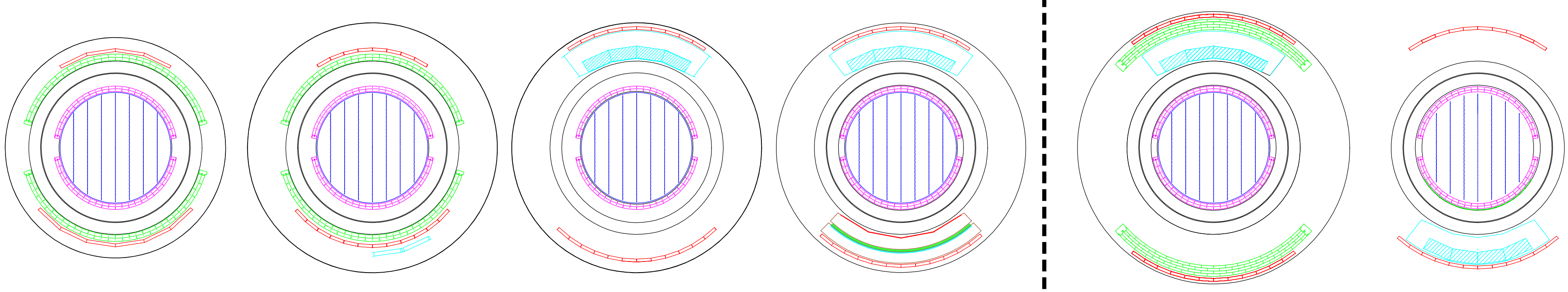
気球実験だからこそ可能！

TOF, JET, Solenoid
のConceptは維持

AMS Technical Flight

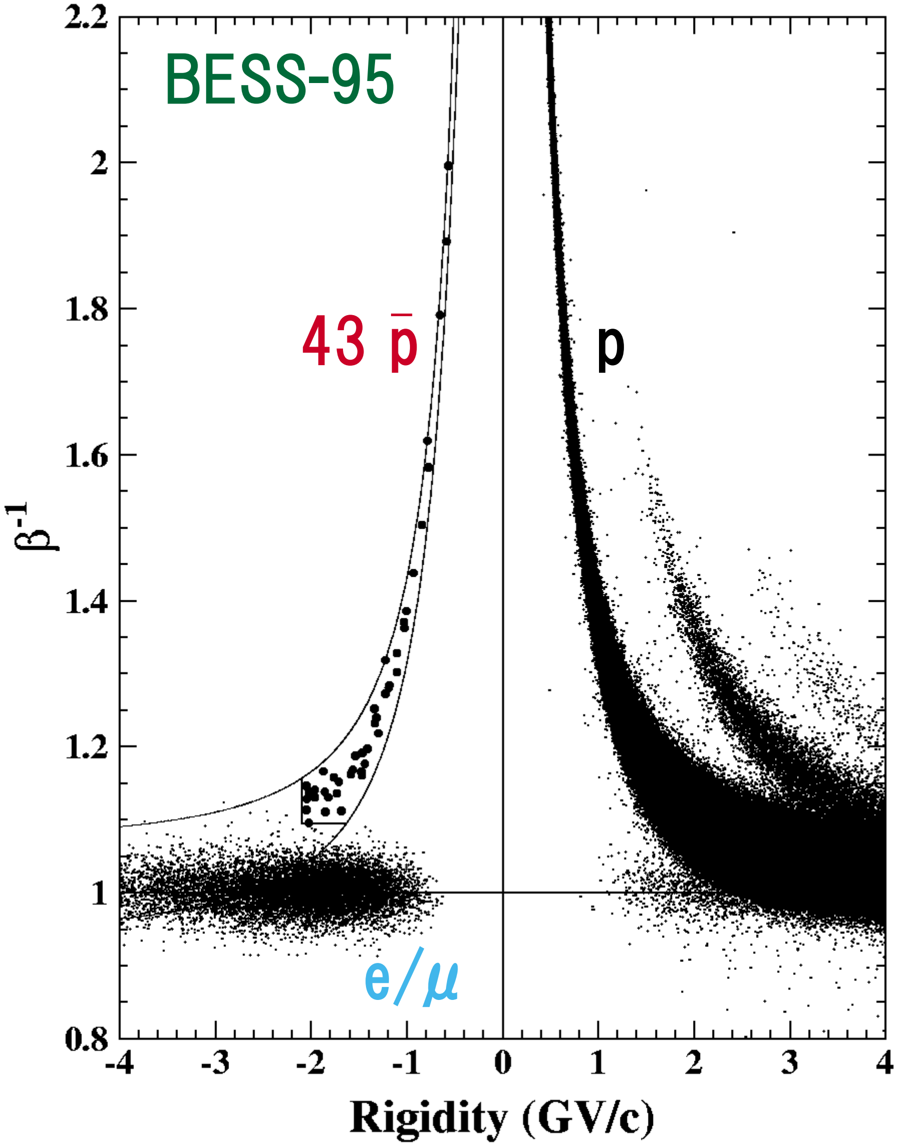
⇒Future

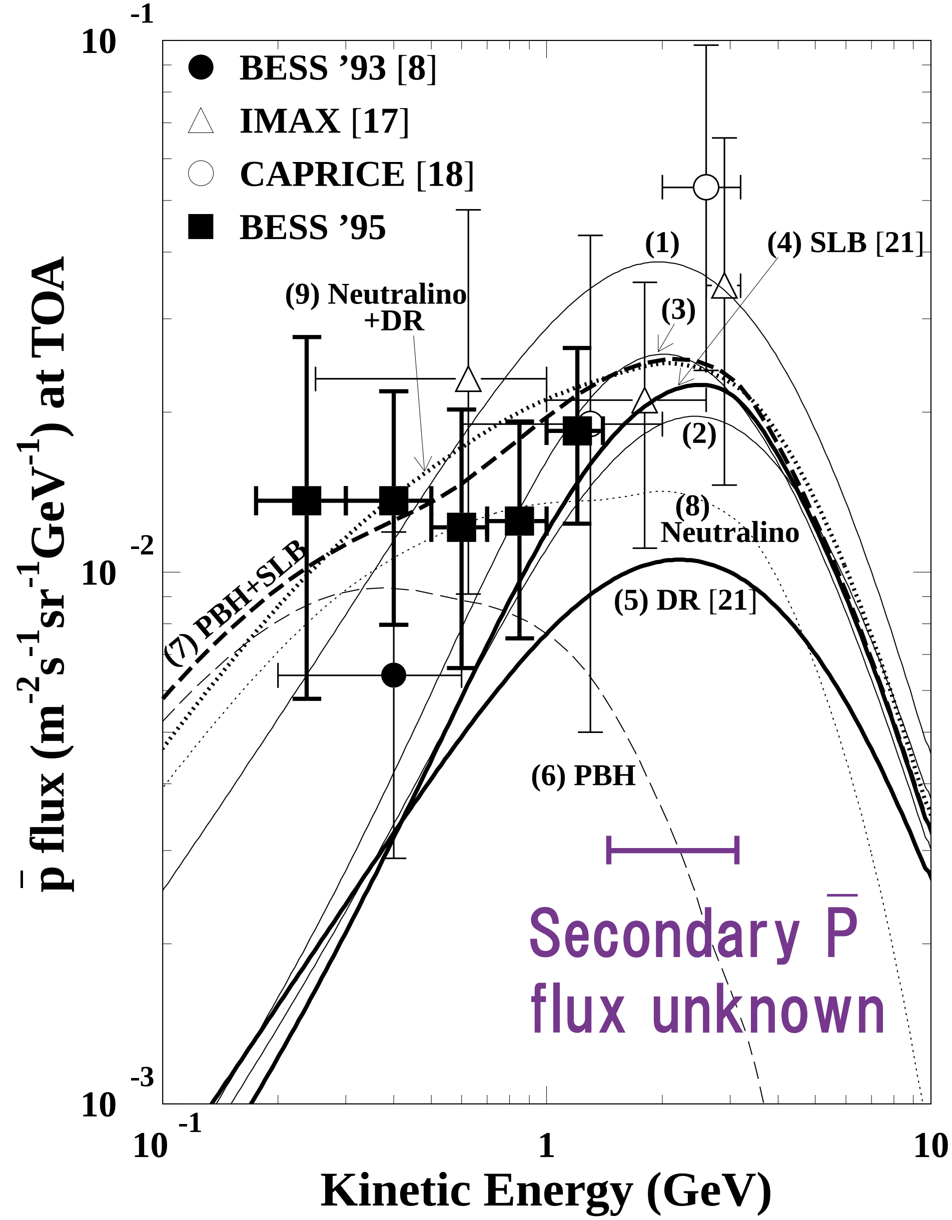
BESS-93,94	BESS-95	BESS-97,98	BESS-99,00	BESS-TeV	BESS-Polar



	Larger Vessel			Larger Vessel	No Vessel
σ_{TOF} =300 ps	σ_{TOF} =110 ps	σ_{TOF} =70 ps Aerogel C 97 n=1.03 $\bar{p}$ 0.2-3.5 GeV 98 n=1.02	Shower Counter $2X_0$ Lead e/μ sep.	New ODC's New JET/IDC's p/He up to 1 TeV	New Mag (ultra thin)
$\bar{p}$ 0.2-0.6 GeV	$\bar{p}$ 0.2-1.4 GeV	$\bar{p}$ 0.2-4.2 GeV	$\bar{p}$ 0.2-4.2 GeV	$\bar{p}$ 0.2-4.2 GeV	$\bar{p}$ 0.1-4.2 GeV
6, 2	43	415, 398	668, 558	⇐ No. of $\bar{p}$'s	

Antiproton Measurement (Before Aerogel)

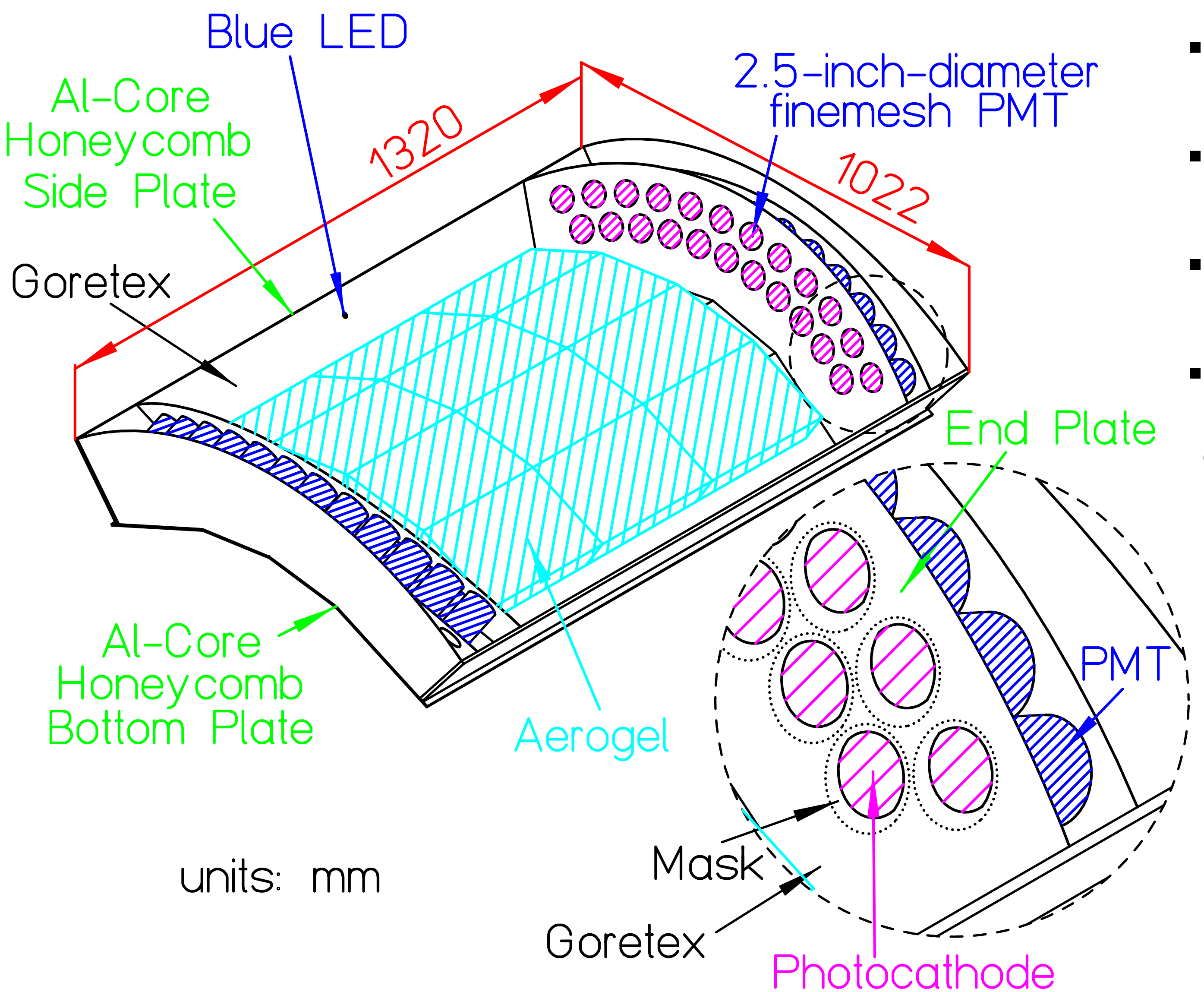




H. Matsunaga et al, PRL, 1998.

Aerogel Cherenkov Counter

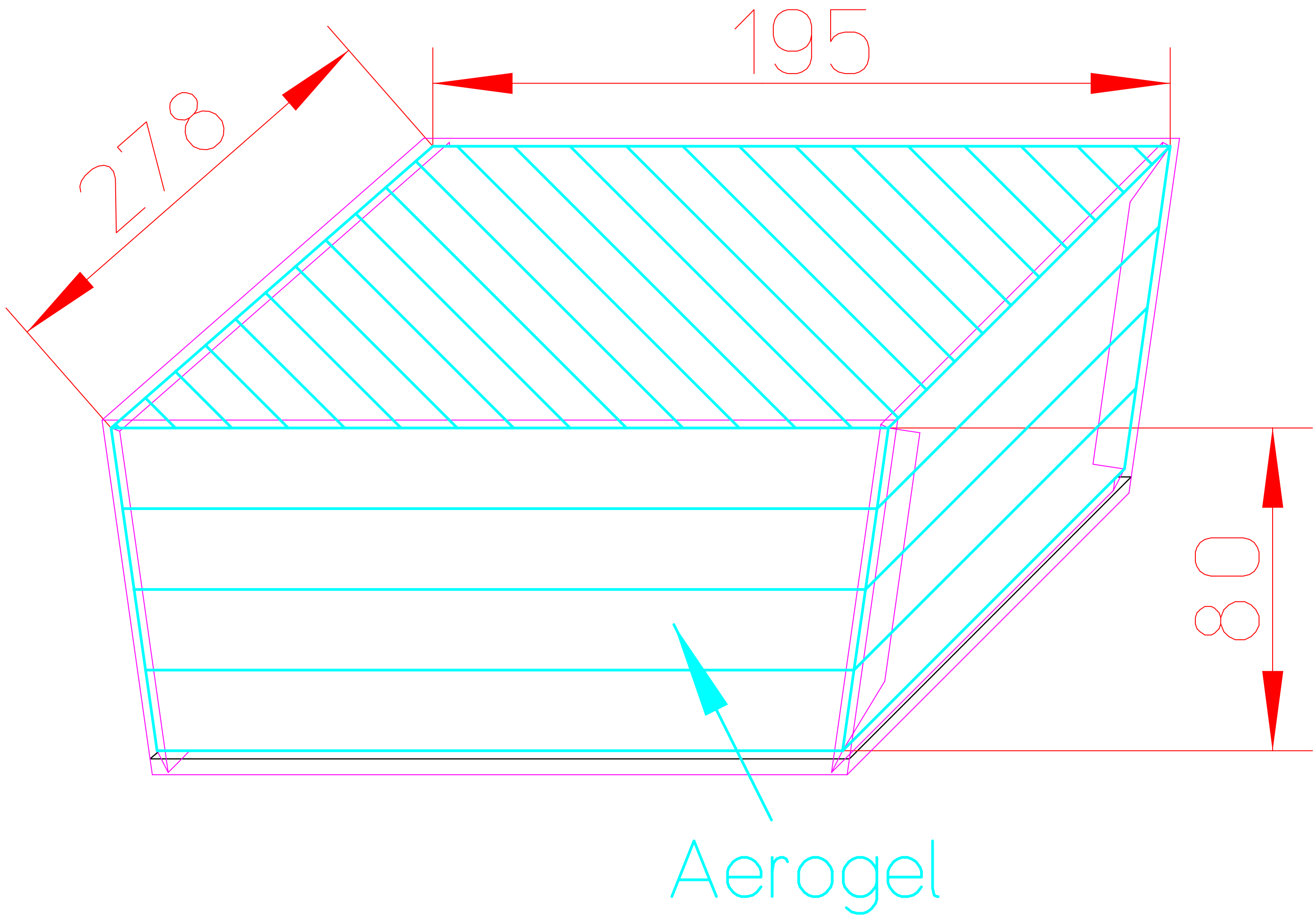
Y.Asaoka et al, NIMA 416 (1998) 236-242



- 大面積大立体角
- PMT稠密配置
- 反射材Goretex
- LEDによるPMT gain calibration

Aerogel

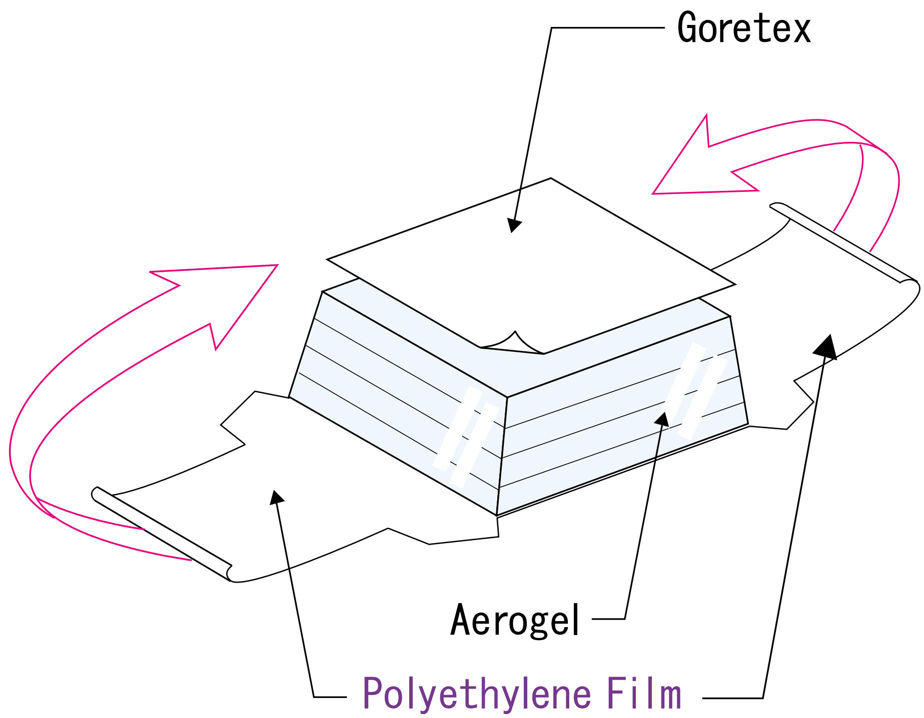
疎水性・透明度に優れる　R&D by KEK(住吉さん他)
非常にfragile ⇔ 振動の多い気球実験でのfeasibility



97　n=1.03　茂利製油
waterjetでcut
98～　n=1.02　KEK(BELLEの協力)
テーパーのついた型
…忘れられないシラザンのにおい

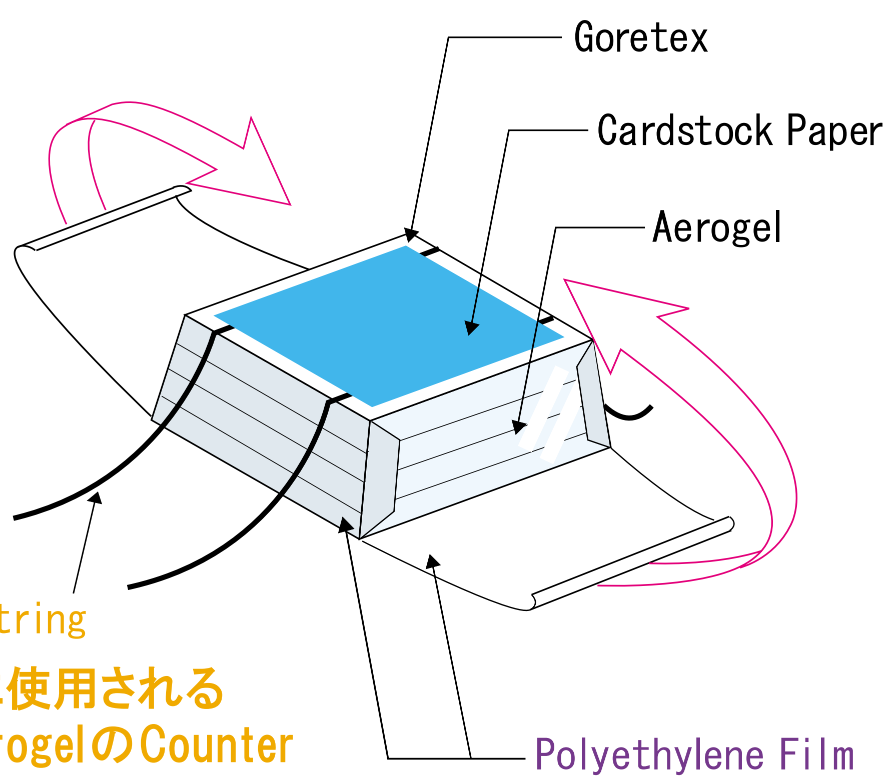
Wrapping of Aerogels

Step1:



紫外光の透過性に優れる

Step2:

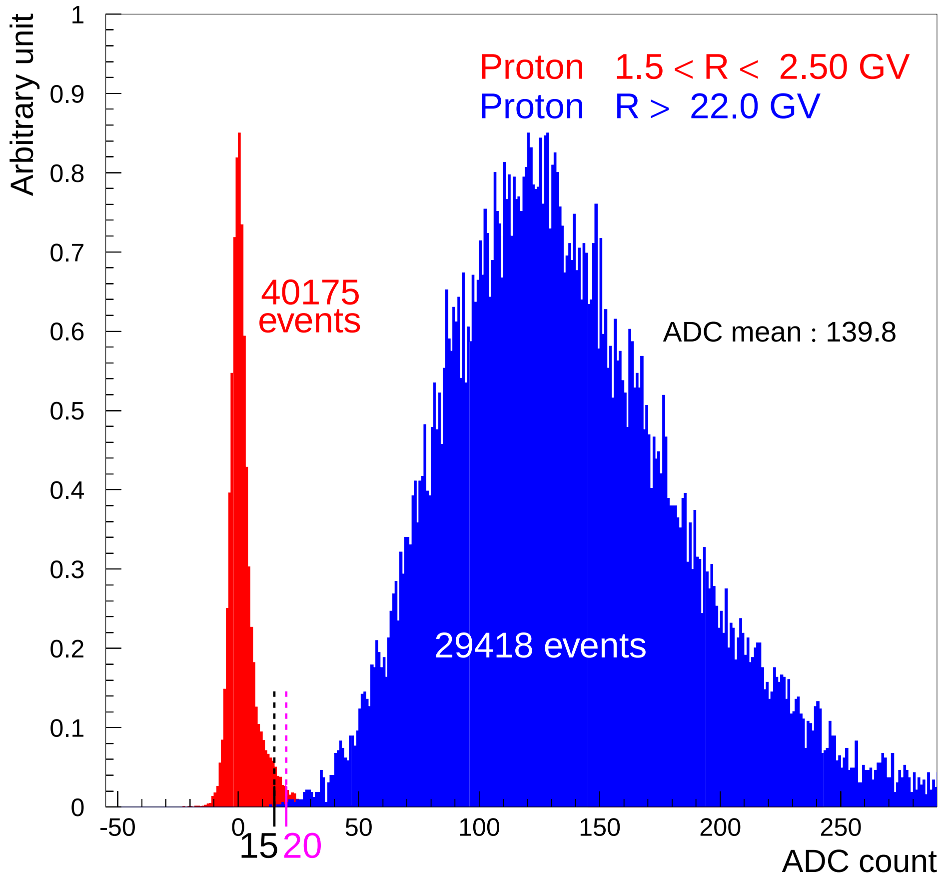


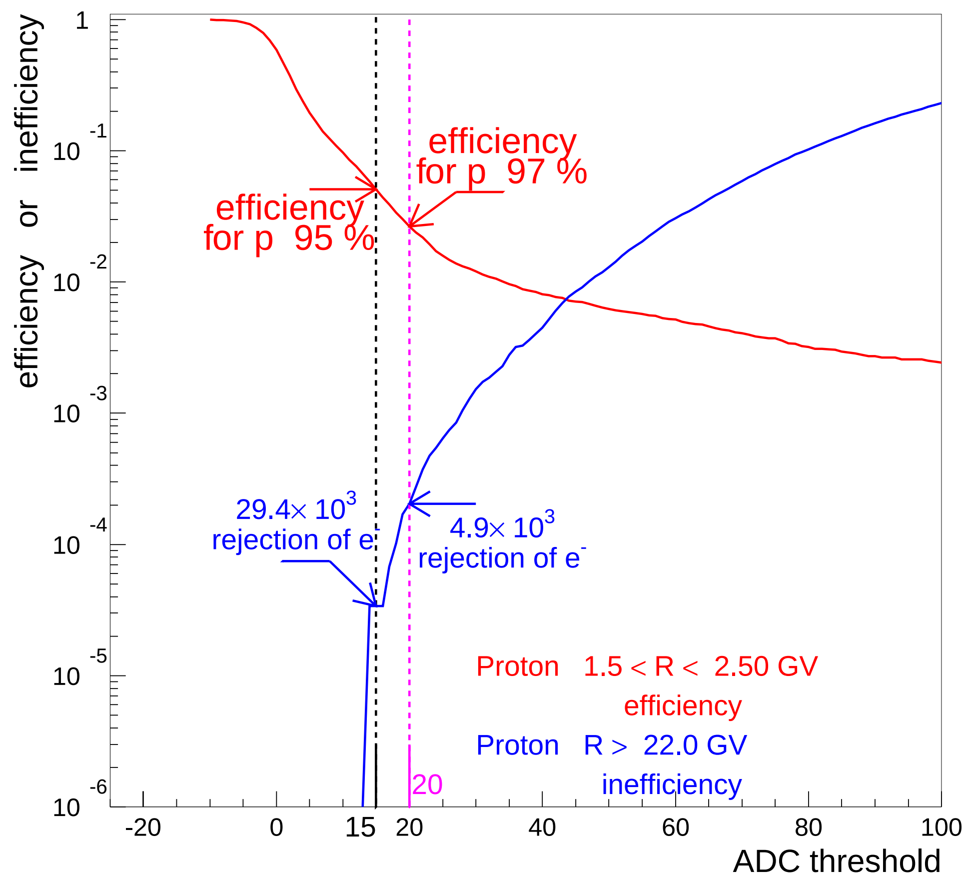
Kevlar String

防弾チョッキなどに使用される
非常に強い糸。AerogelのCounter
への固定に使用する。

Aerogel-97 e/μ Rejection Power

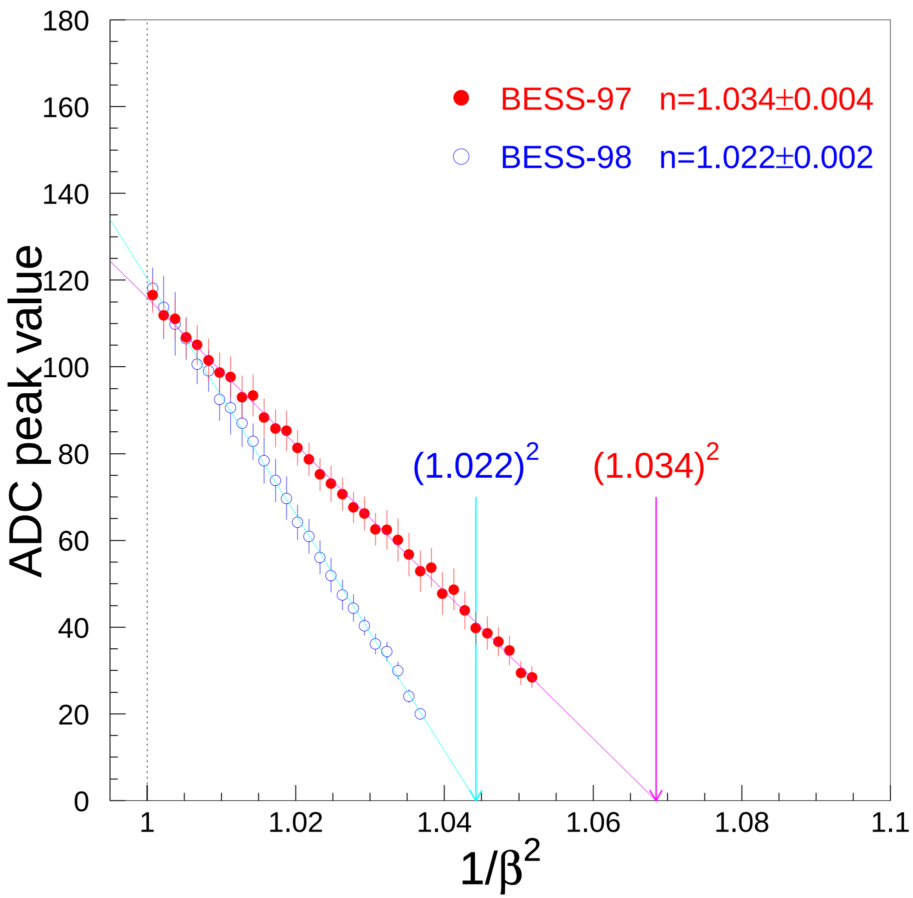
n=1.03

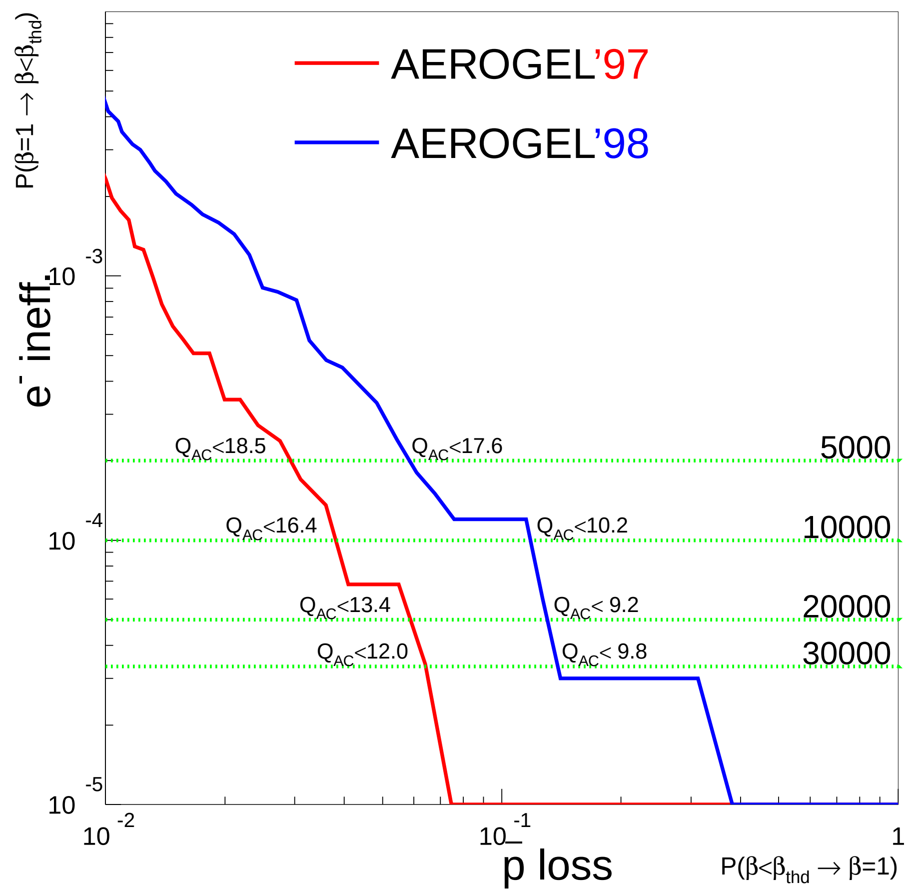




Rejection power was estimated as a function of ADC threshold using high energy proton samples.

Aerogel-97, 98 Comparison

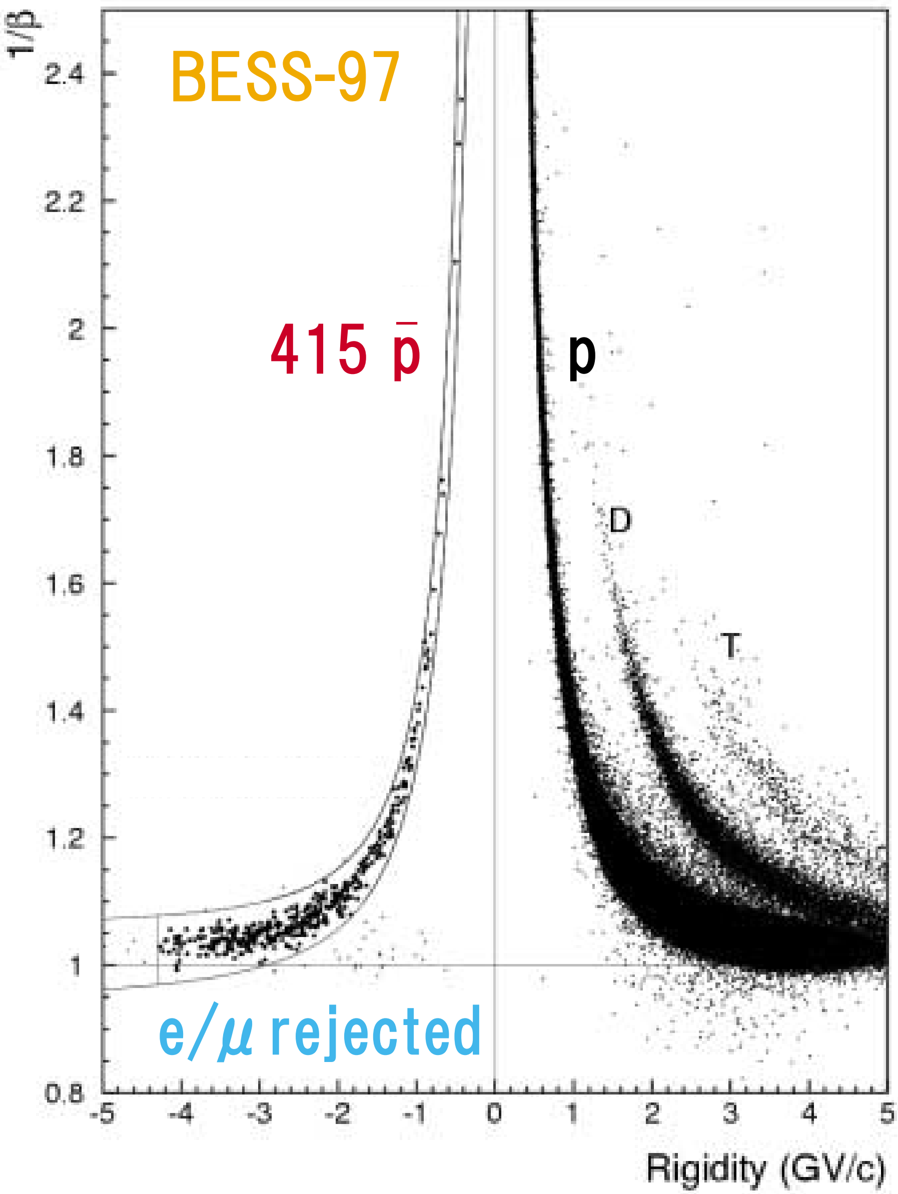




n=1.03 ⇒ n=1.02

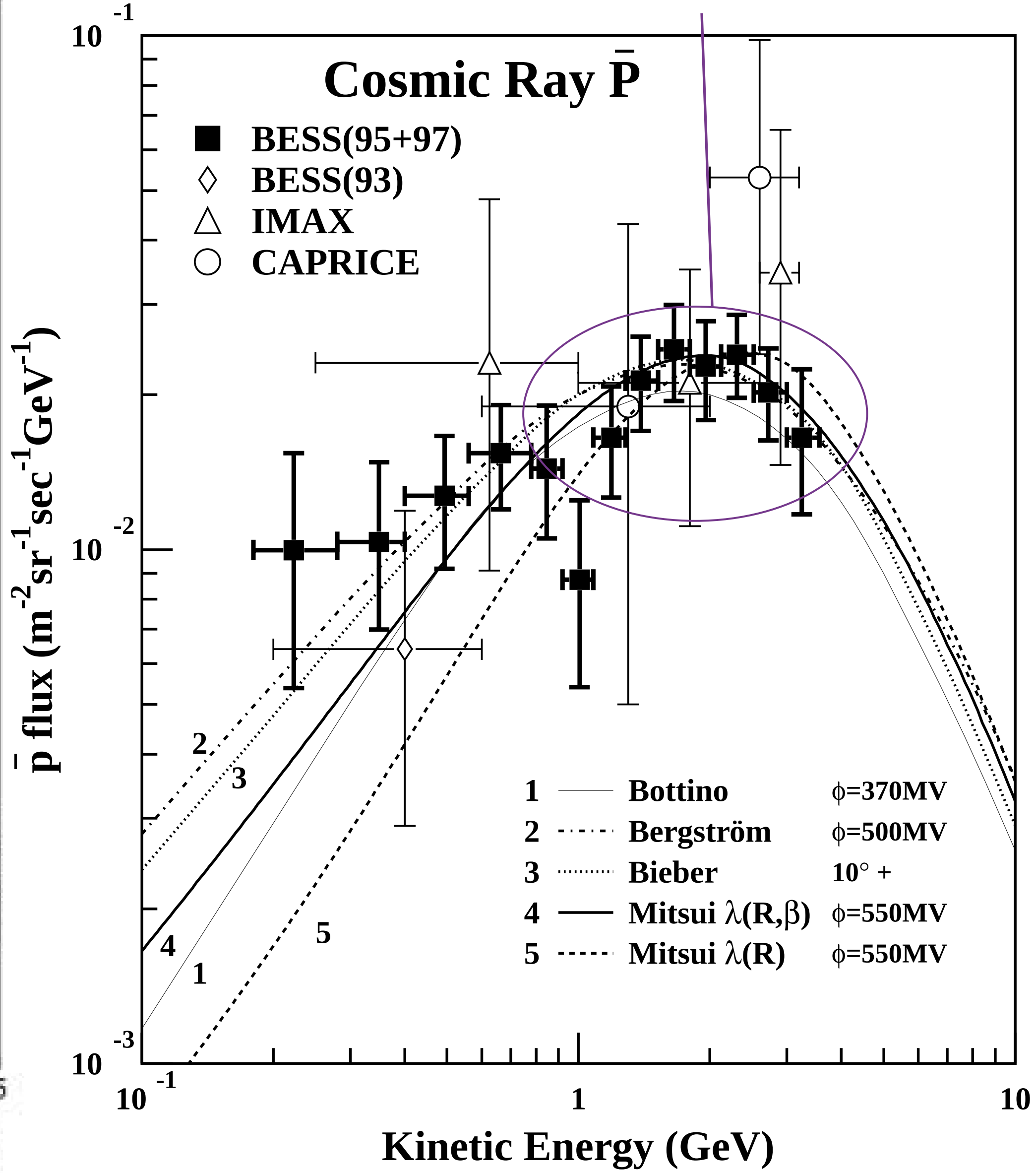
- produced photon: ～66 %
- collected photo electron: ～90 % ⇒ Excellent Transparency

Antiproton Measurement (After Aerogel)



S. Orito et al, PRL, 2000.

Secondary $\bar{P}$ flux determined(±15%)



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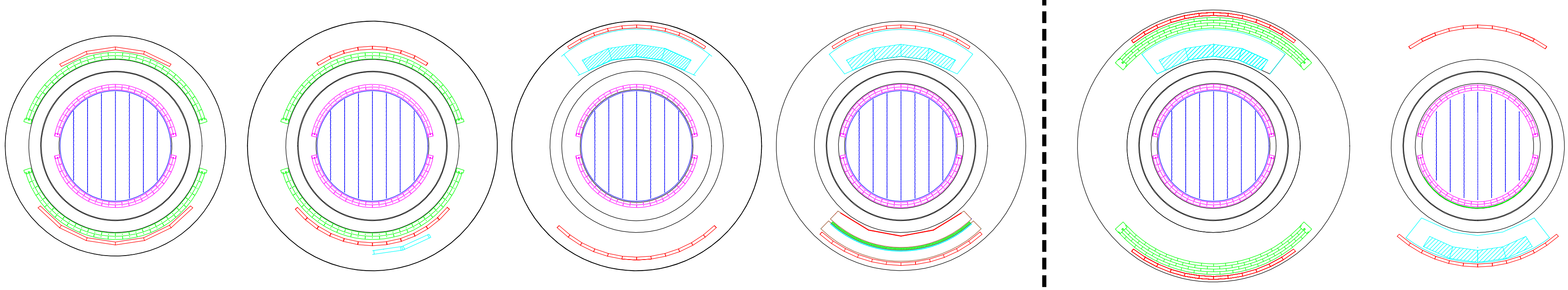

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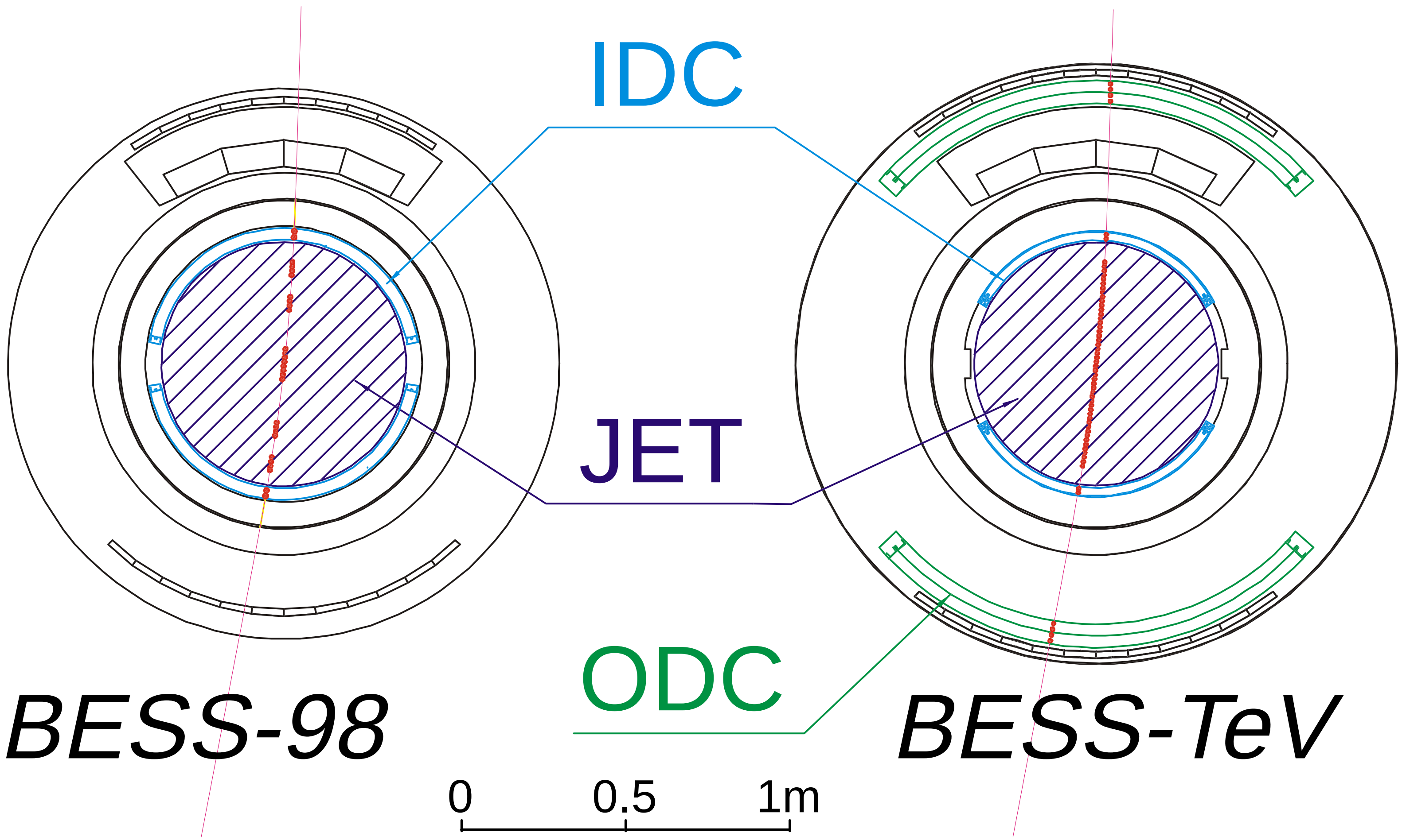
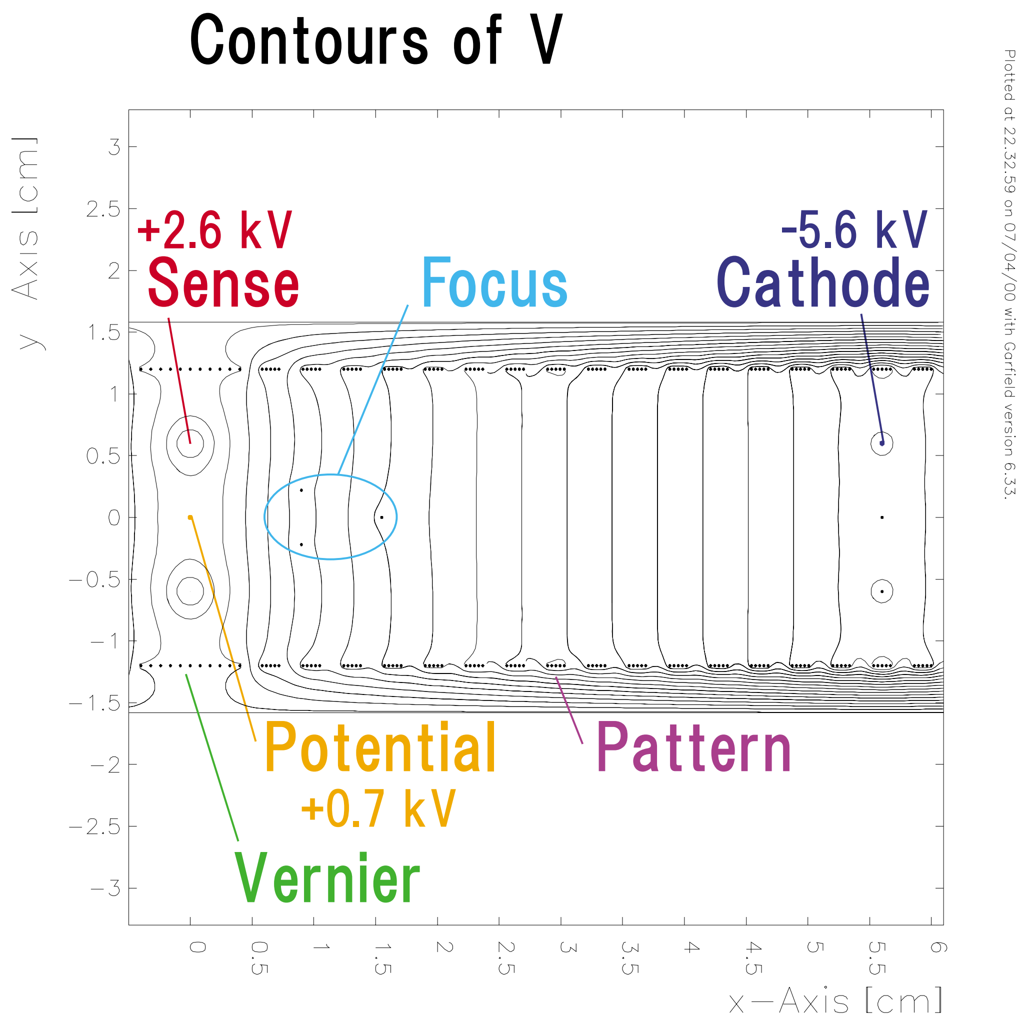
BESS TeV Project

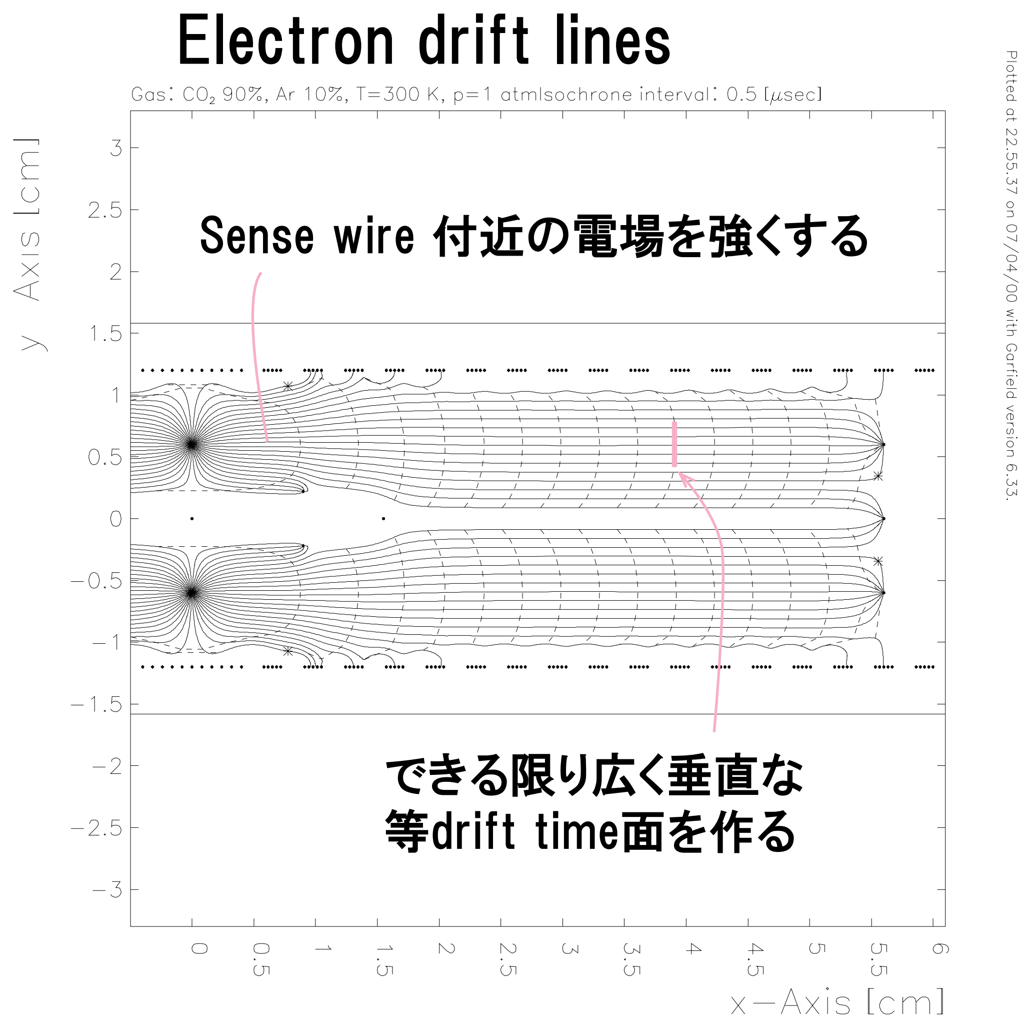


- ODC ⇒ track length X 2
- 位置resolution 向上 (New Chambers)
- 測定点増加 (28→60)

⇒ MDR > 1 TeV (現 200 GeV)
P/He up to 500 GeV
+ lead μ^- up to 500 GeV

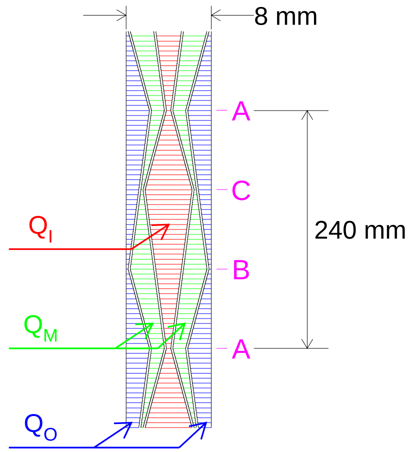
Cell Design using garfield

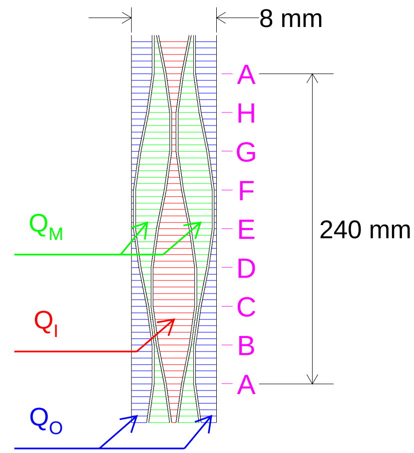


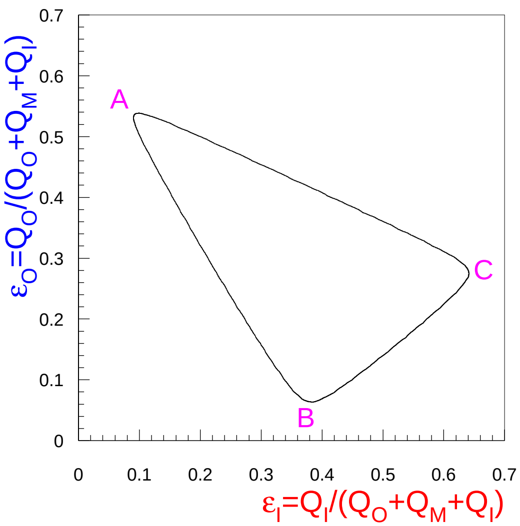


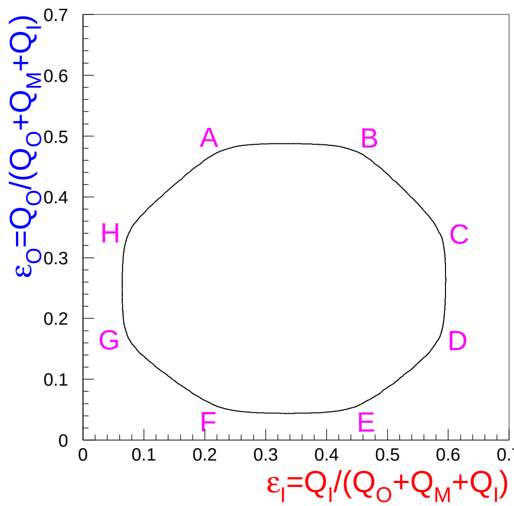
- Garfield によるsignal simulation を用いたoptimization
- 現IDCによるsimulationの妥当性の評価

Vernier strips









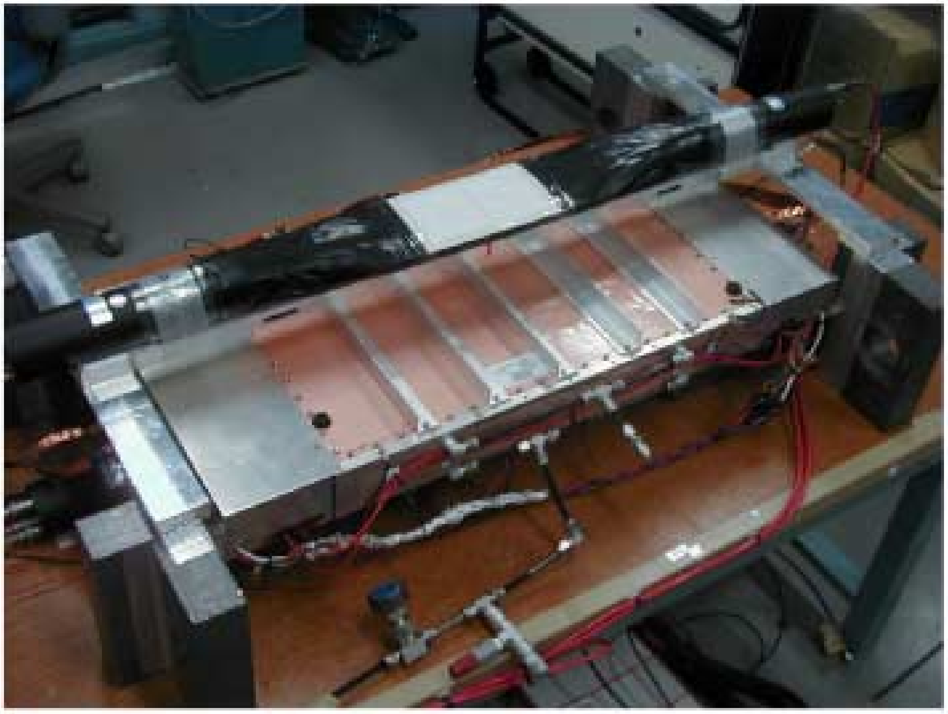
- 各パターンのchargeの比
  ⇒周期的なz座標の測定

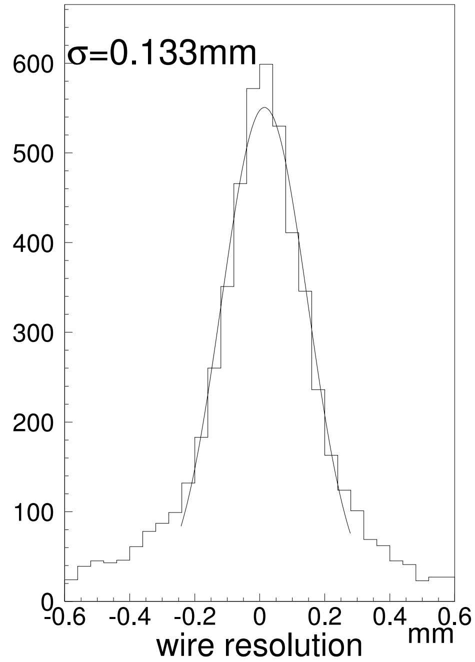
- 3 vernier
  ⇔現IDC: 2 vernier

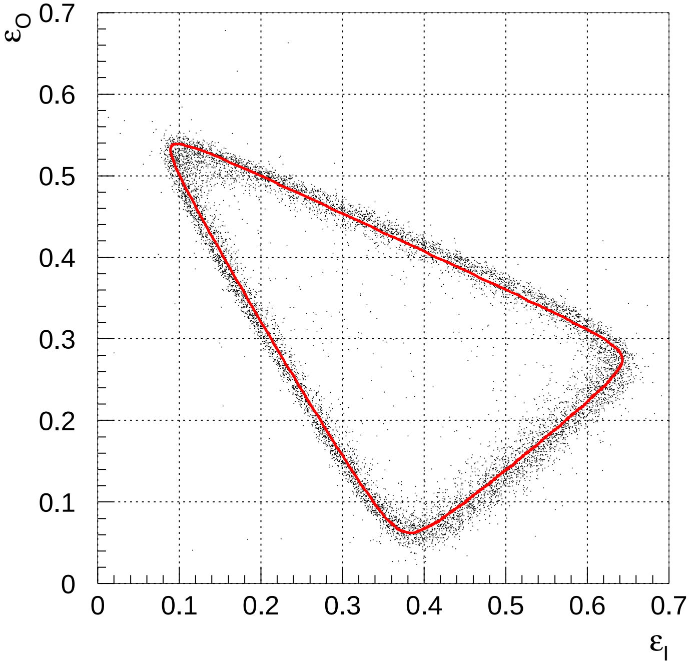
- 周期/位相を変えてz座標を解く

Prototype (R&D)

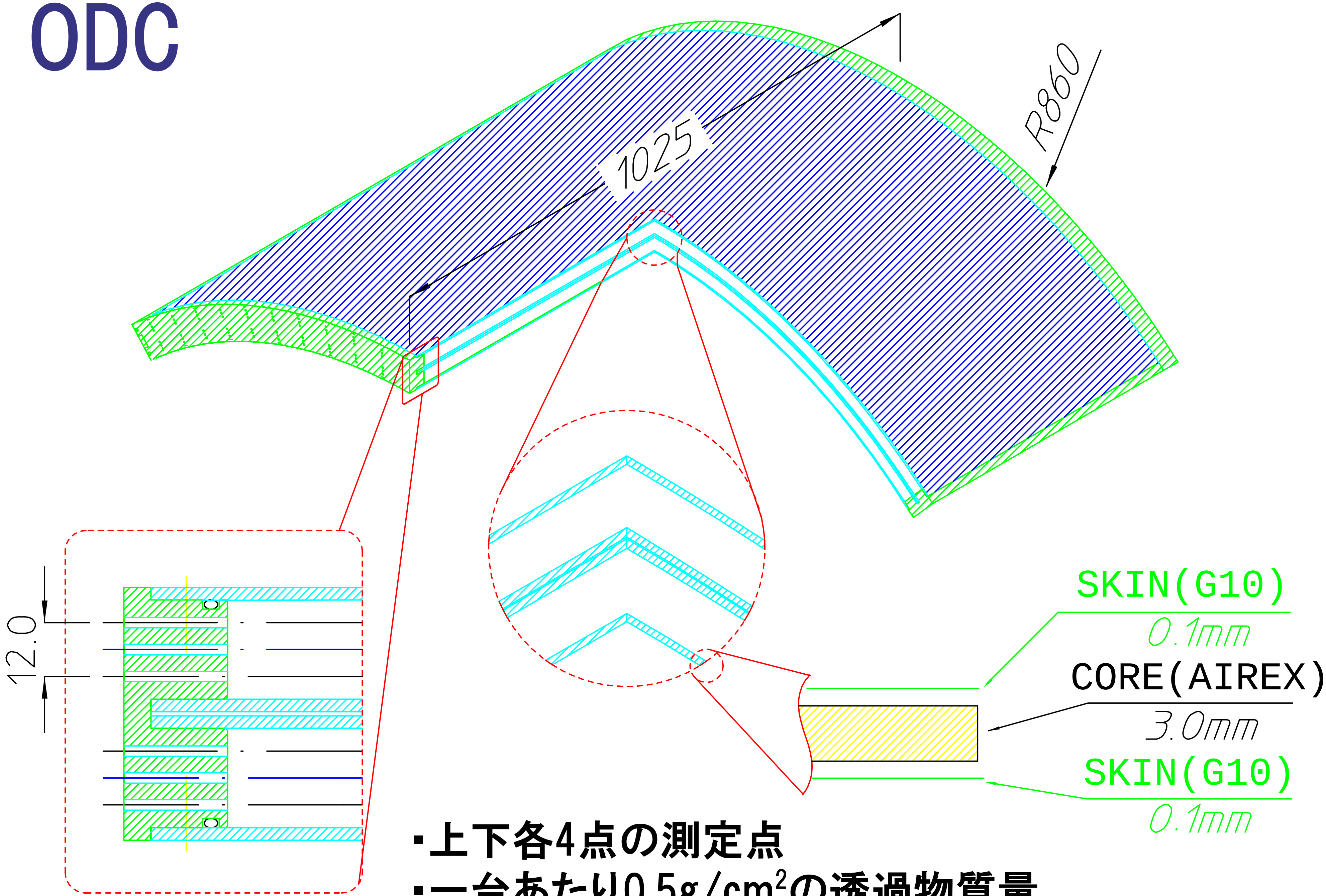
- Performance （cosmi)
  r-ϕ: <150 μm
  z ：～ 1 mm の resolution
- Feasibility
  gas seal/ HVまわり/
  組み立て/ Elec mount/ etc.







ODC

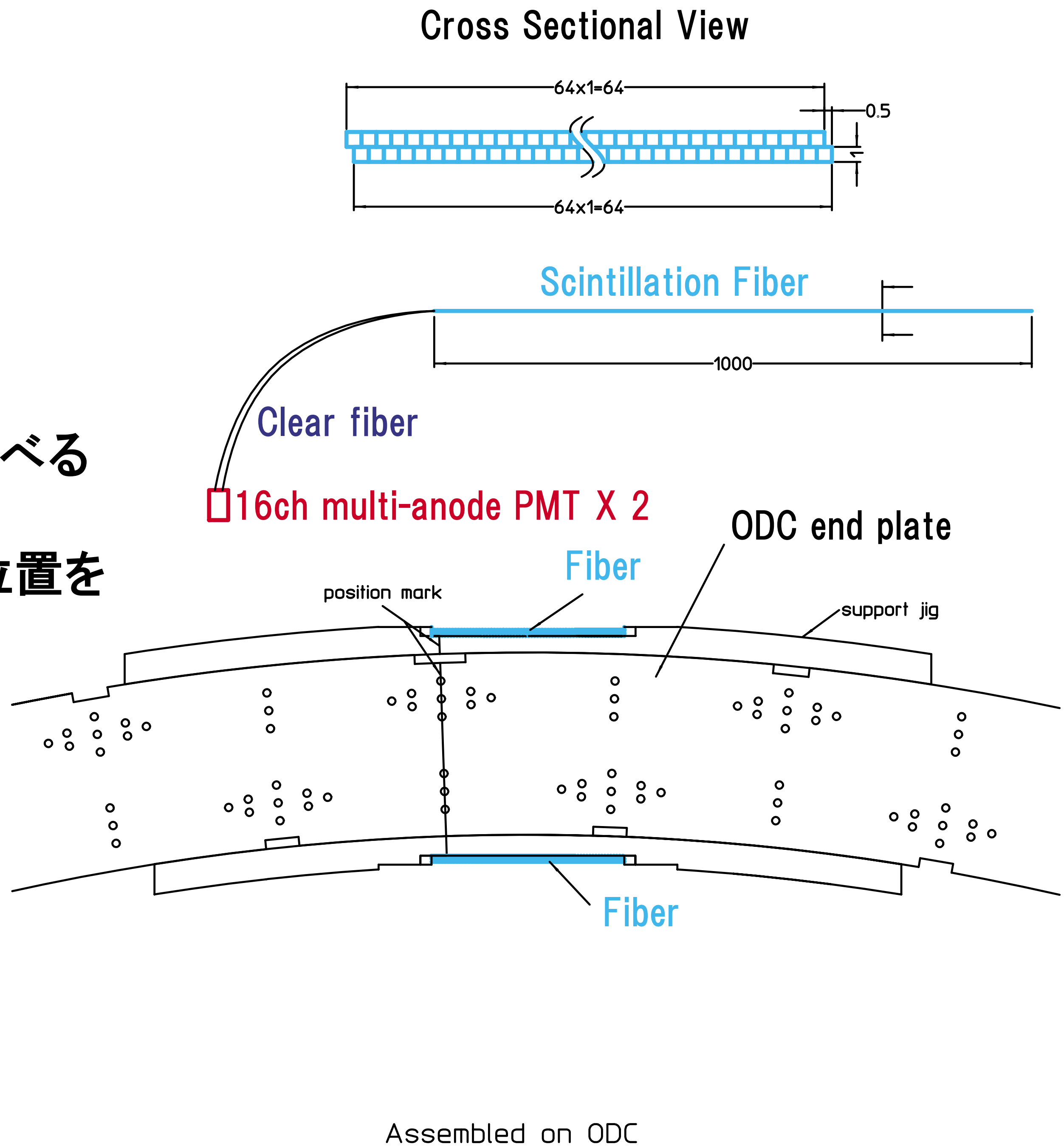


- 上下各4点の測定点
- 一台あたり0.5g/cm^{2}の透過物質量
- CO^2(90 %), Ar(10 %) の混合ガス

Scintillation Fiber

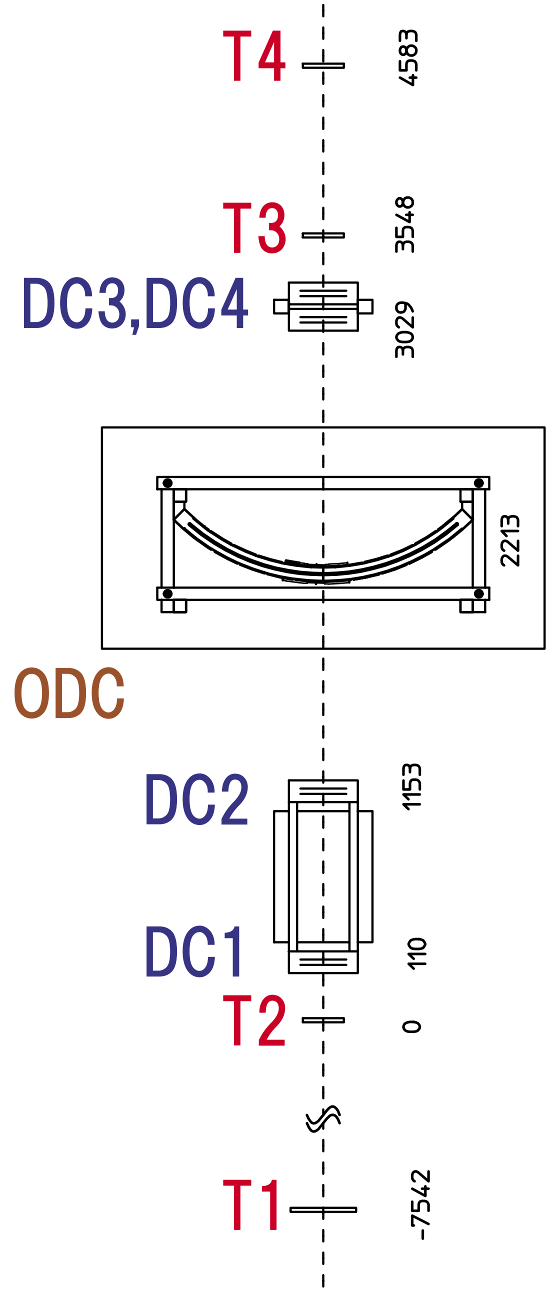
目的:
ODC x-t relation の
absolute calibration
を正確に行なう
⇒ TeV へのカギ

- 64本のfiberを2層並べる
- それぞれのfiberの位置を顕微鏡で測定
- ODC 1 cell の上下に配置
- Trigger に組み込む



ODC Beamtest

@π2 KEK-PS　2000年12月

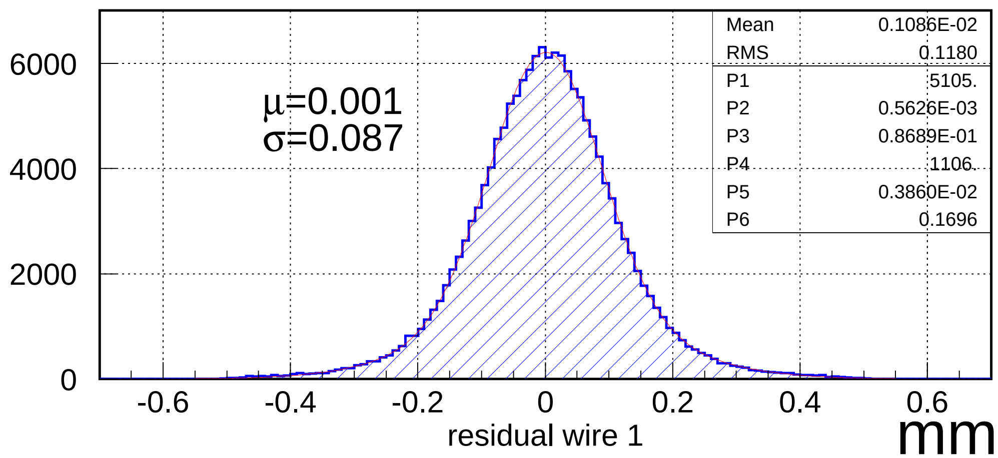


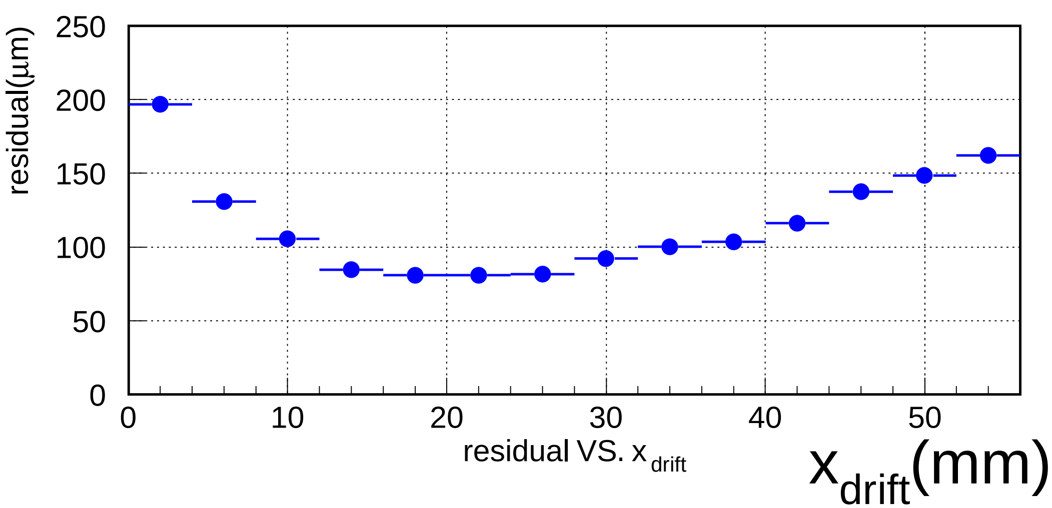
- 完成直後
- 串刺し実験
- 少人数

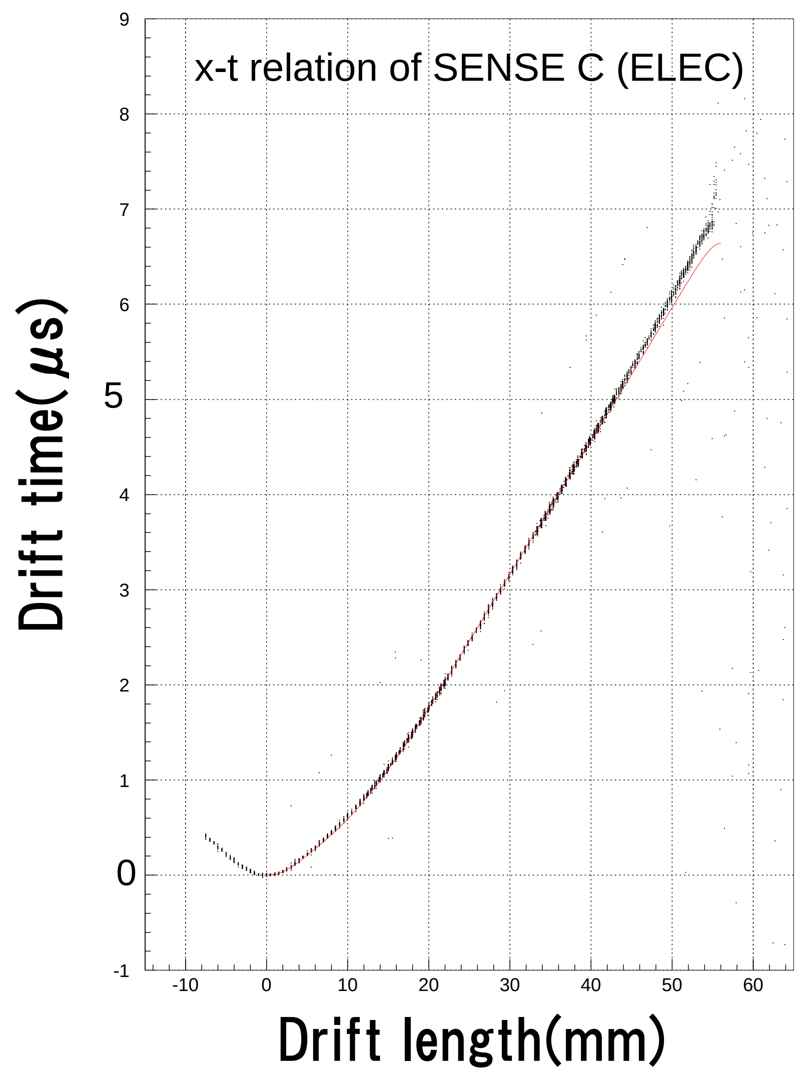
性能評価
- resolution
- X-t relation

ODC Beamtest Results

- X-t relation を Scifi により決定
- near sense ～200 μm
  central region ＜ 100 μm を達成





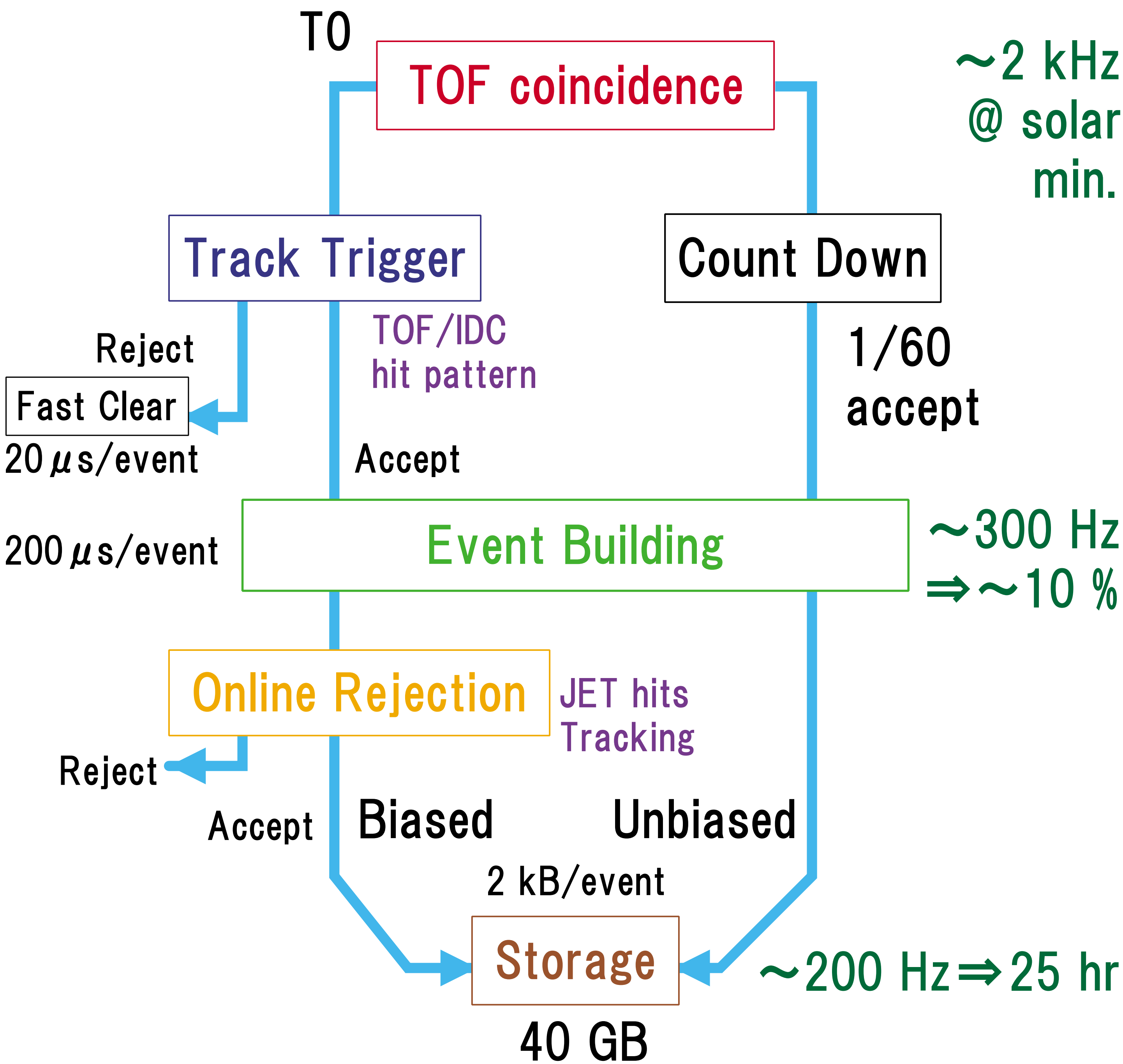


Scifi により決定

Trigger System

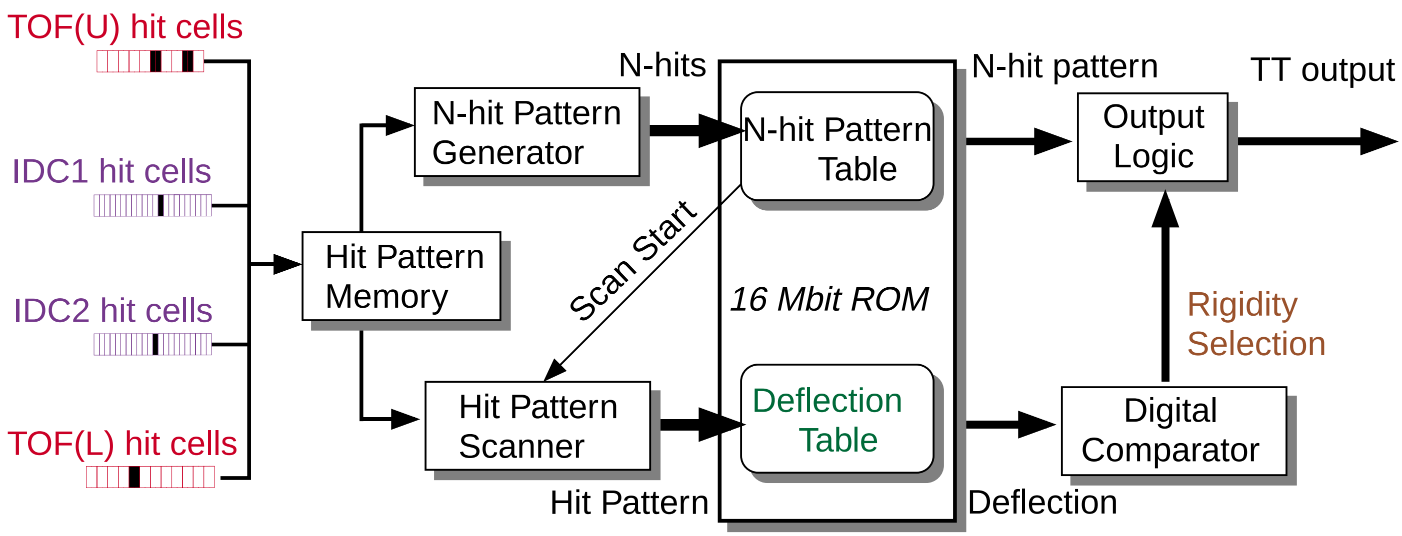
Flight Time, Data Capacity を有効に
利用するために、2つの mode がある.

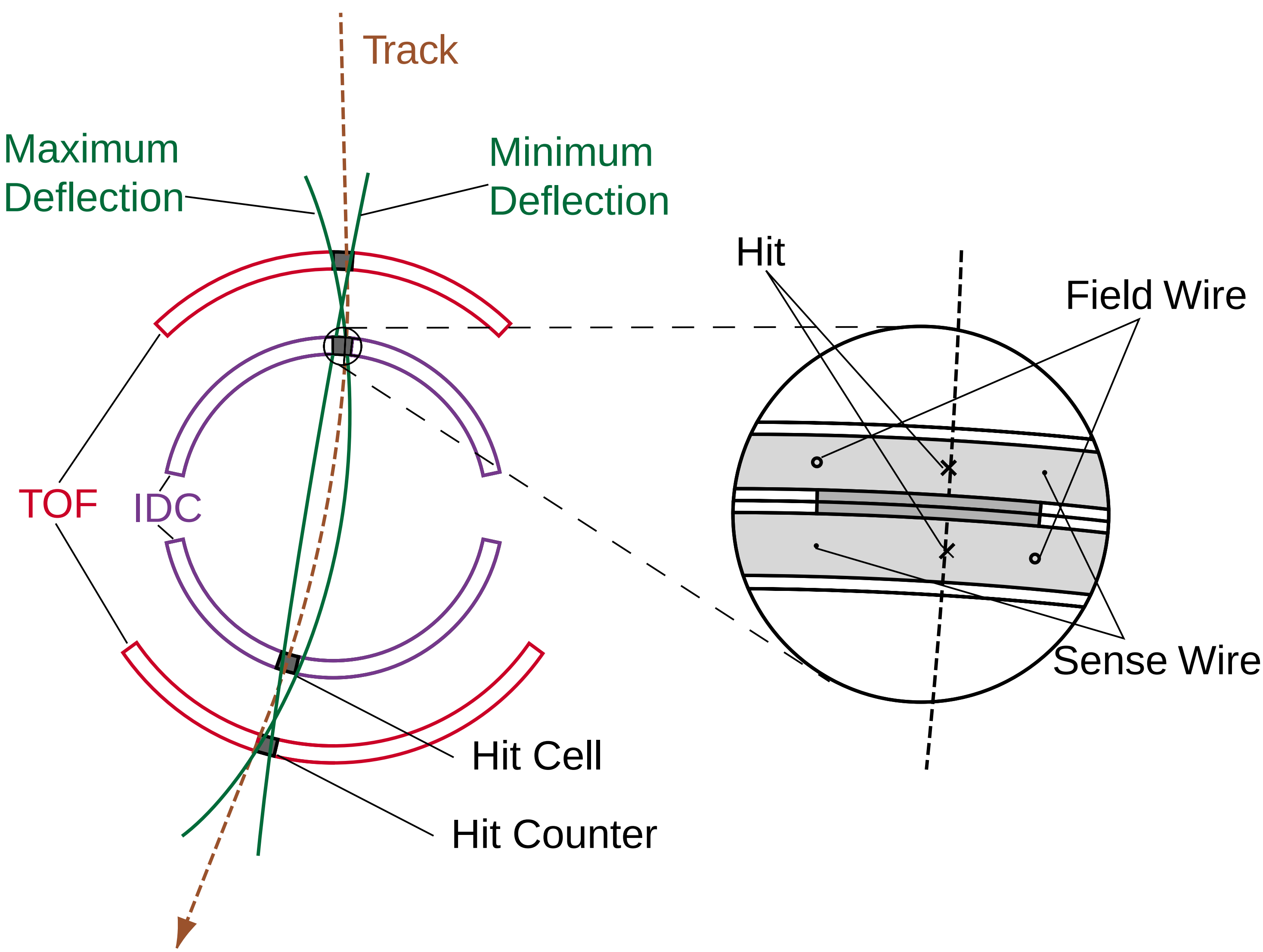
Unbiased … Proton/Junk
Biased … negative charge



Track Trigger

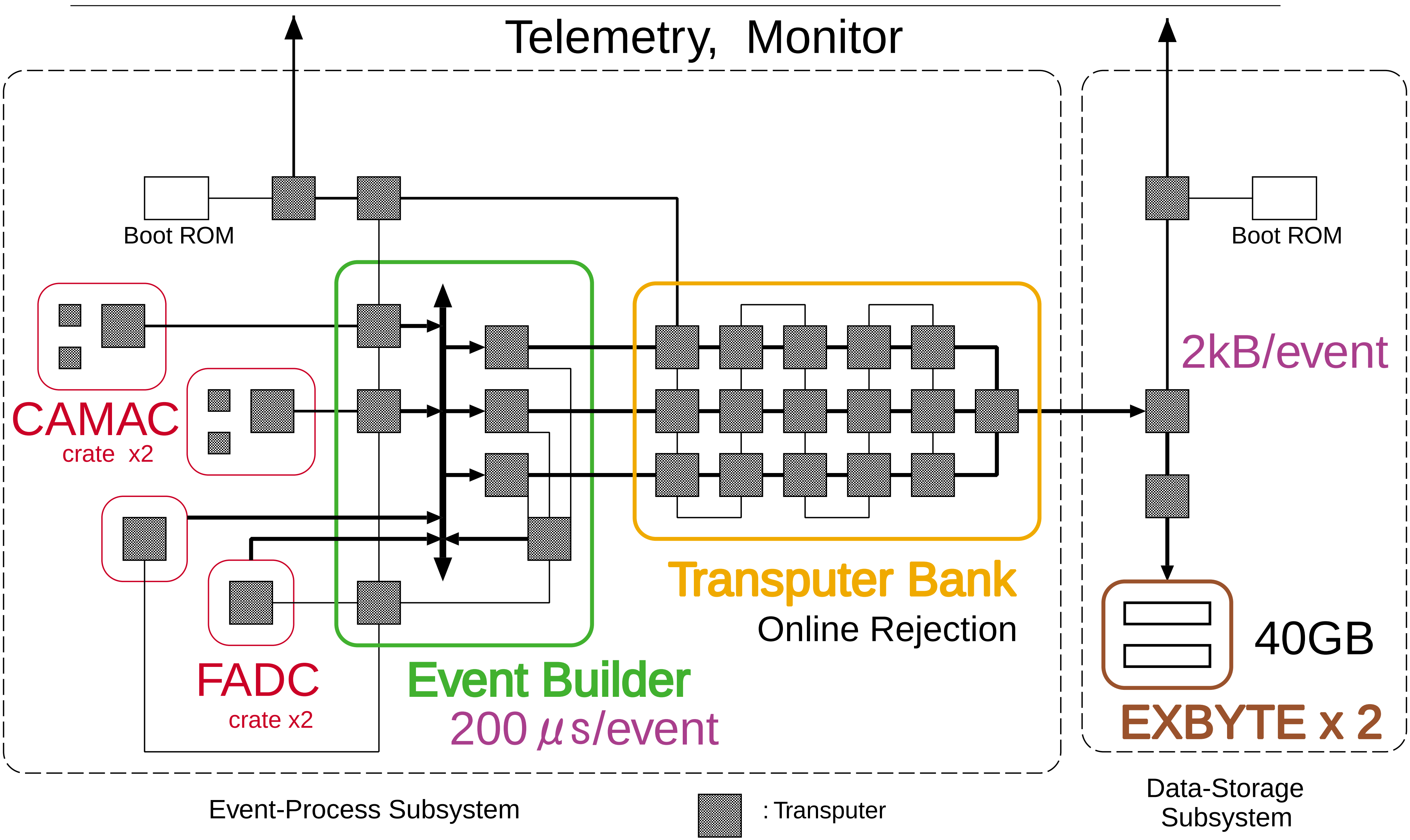
Hit pattern selection / Rough rigidity selection





Data Acquisition

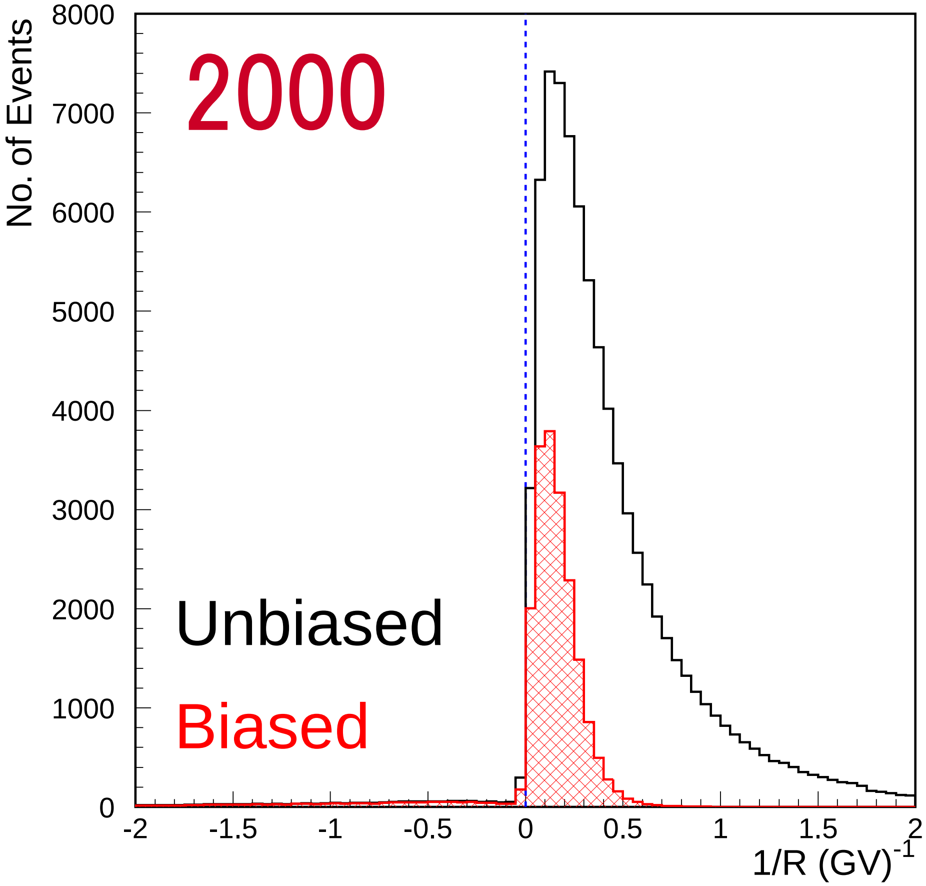
Dead Time Fraction, Data Capacity

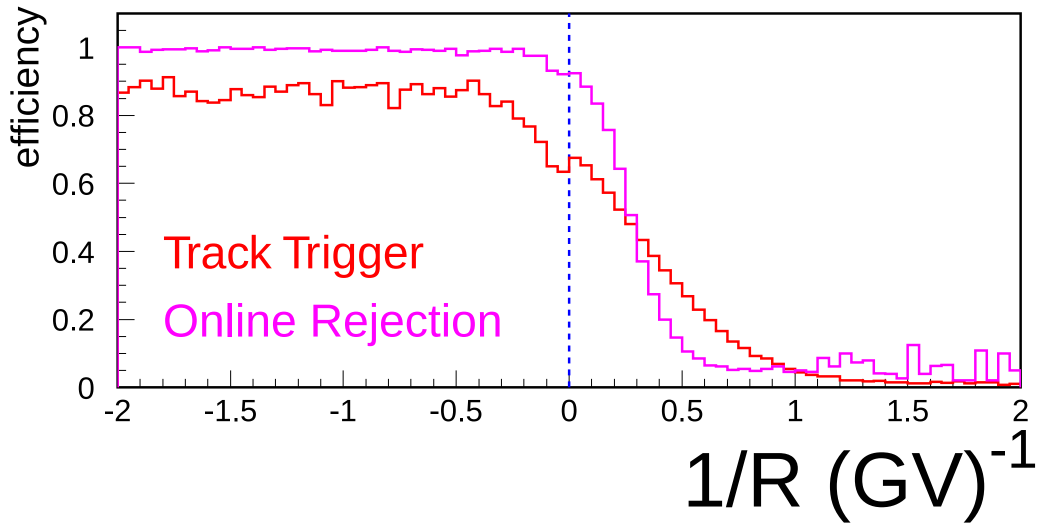


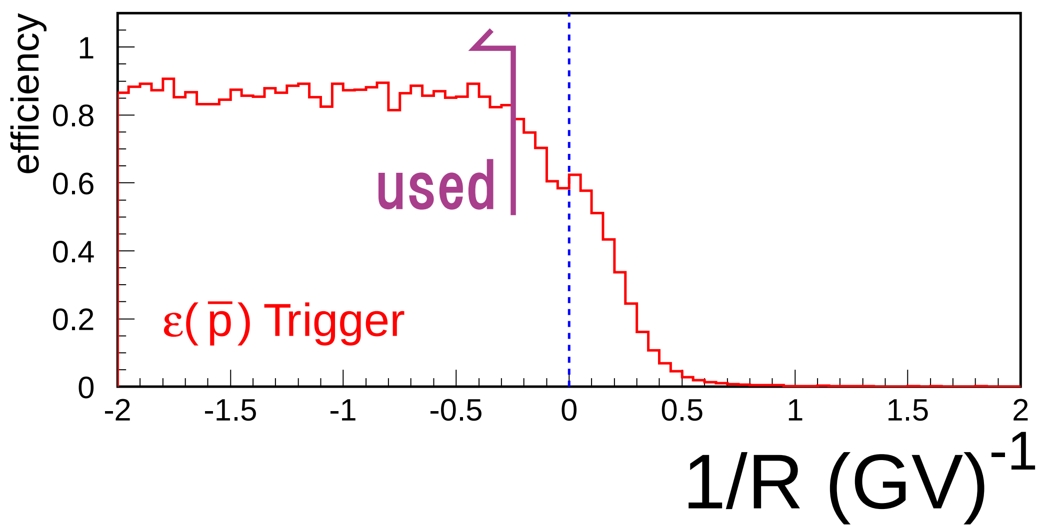
Trigger Mode for Antiproton

- eff. for high energy $\bar{p}$
- rej. of high energy p

⇒ Optimization



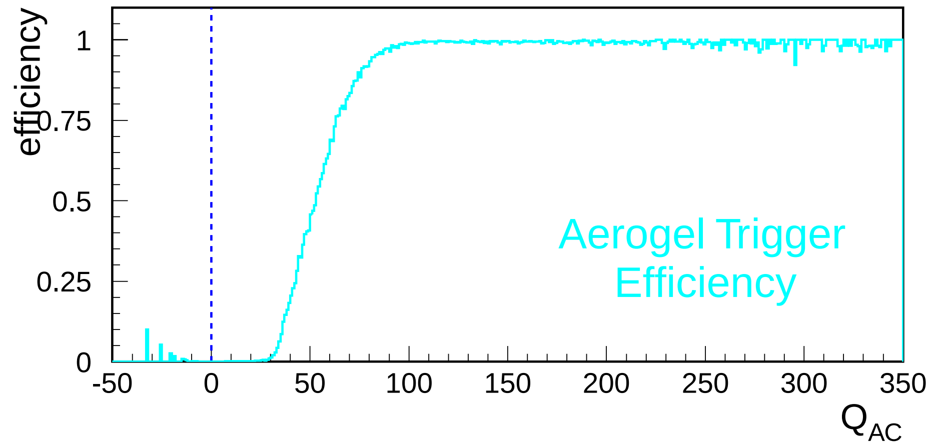


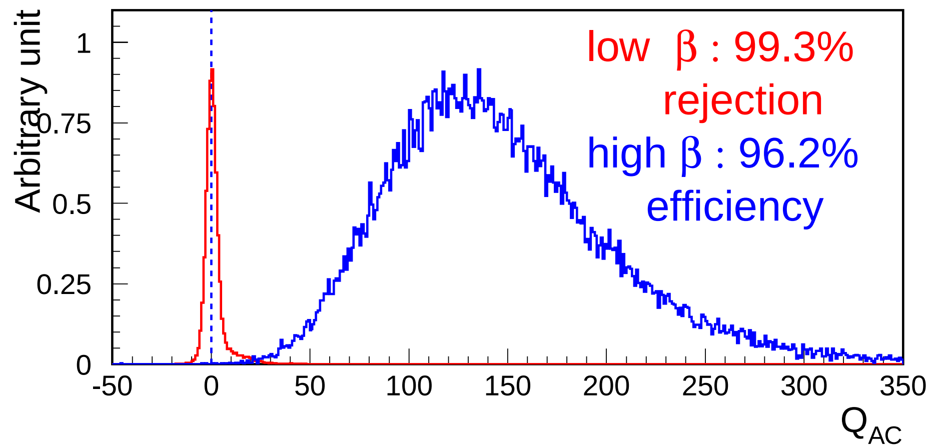


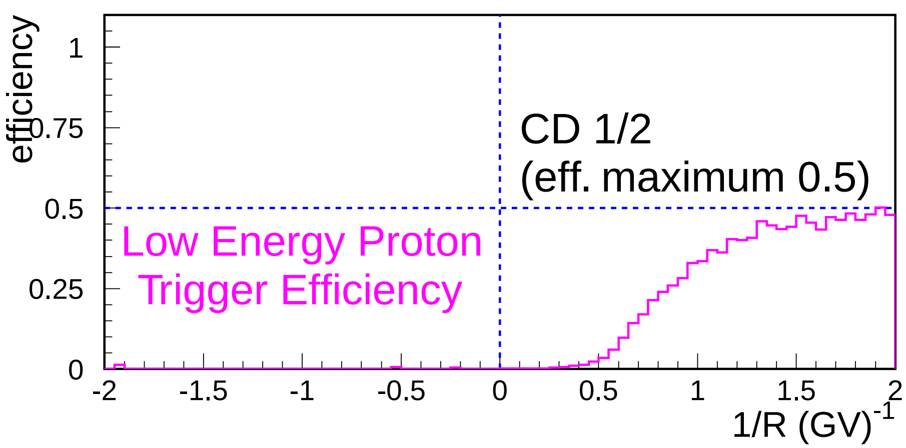
Other Trigger Modes

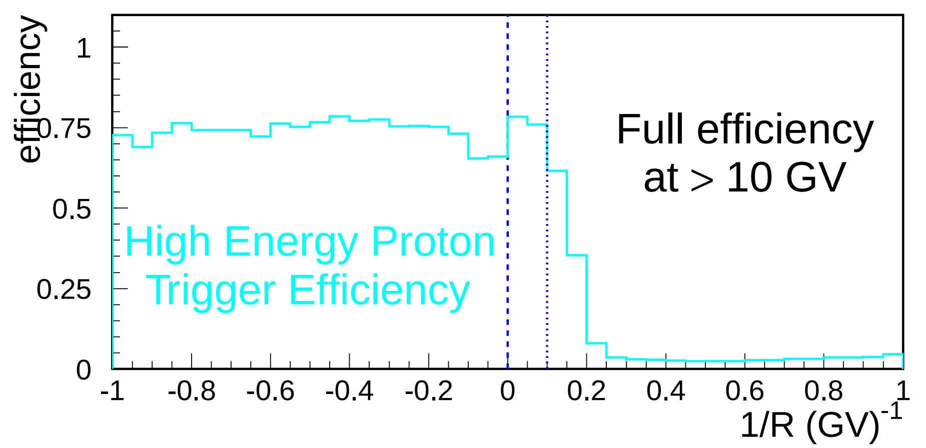
- Aerogel Trigger
  - High energy proton
    Sanuki et al, ApJ, 2000.
  - e/μ
- Low Energy Proton (ascent)
  - atmospheric growth
- High Charge (TOF)

- Filght 時間と Trigger Rate を予測し tune する.
  38/41/40 GB (98/99/00) exabyted.

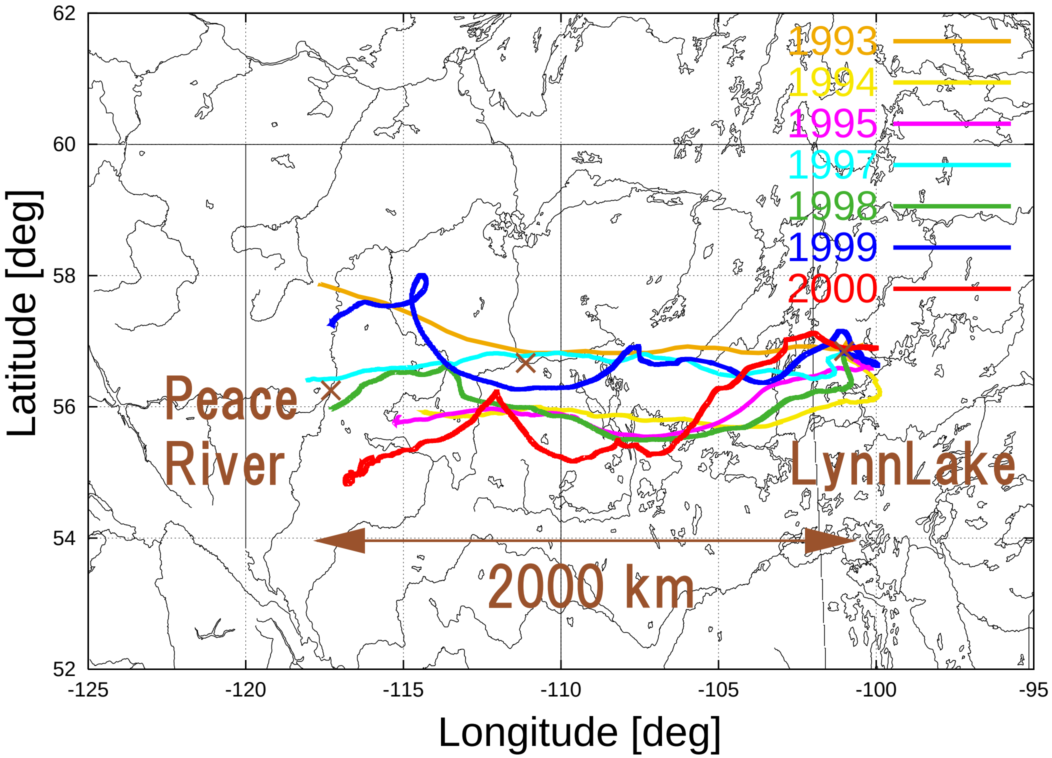


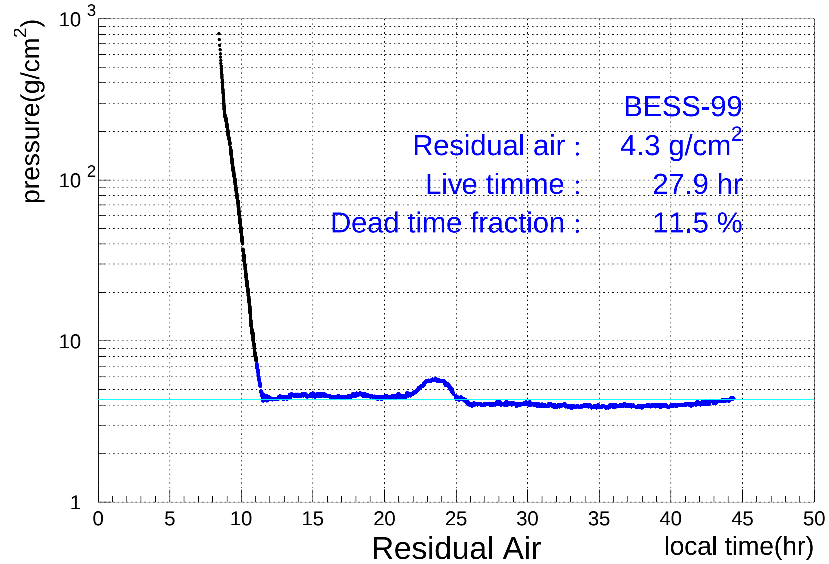


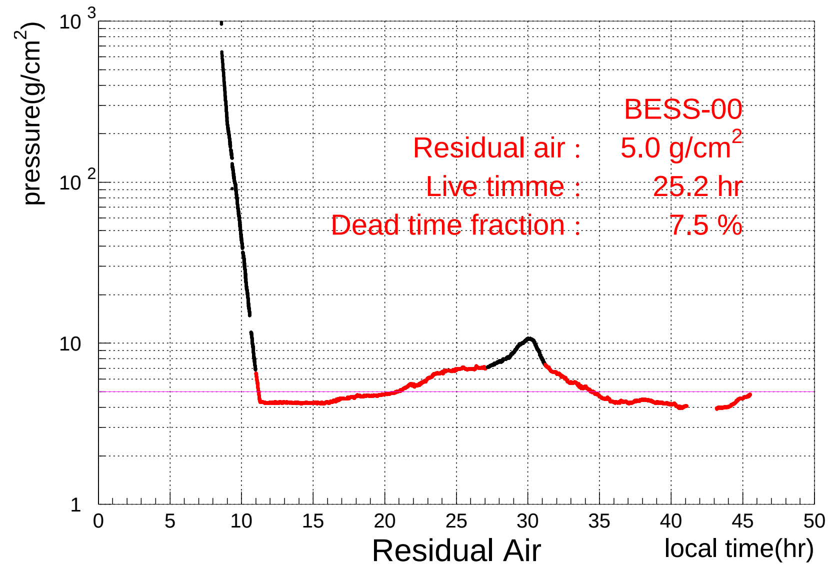




Balloon Flights







- LynnLake, Manitoba, Canada
  low geomagnetic latitude
  (cutoff rigidity 0.3～0.5 GV)
- Floating altitude: 34～39 km

Event Reduction

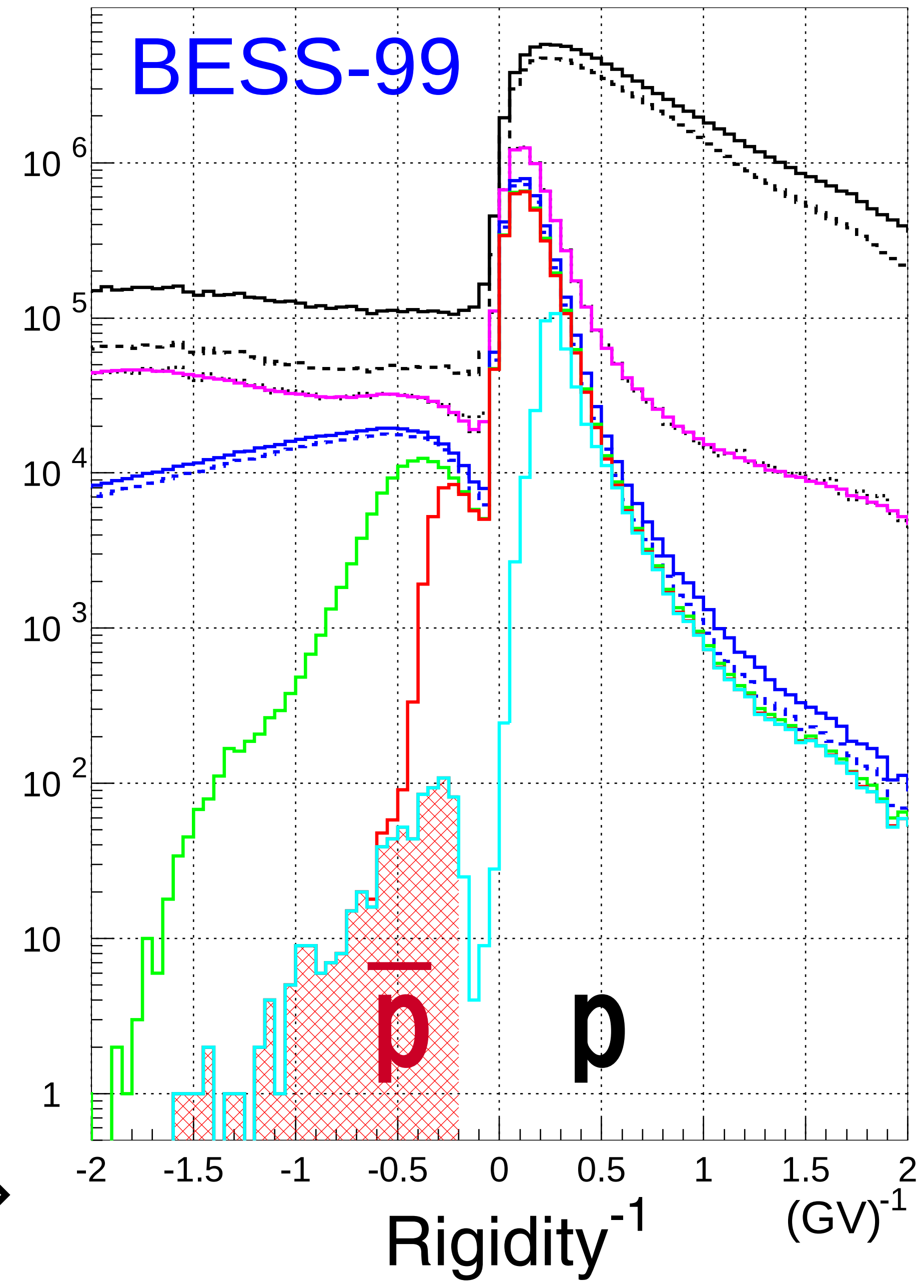
1. first level trigger(TOF coincidence)

2. second level trigger
   hit pattern & rigidity selection

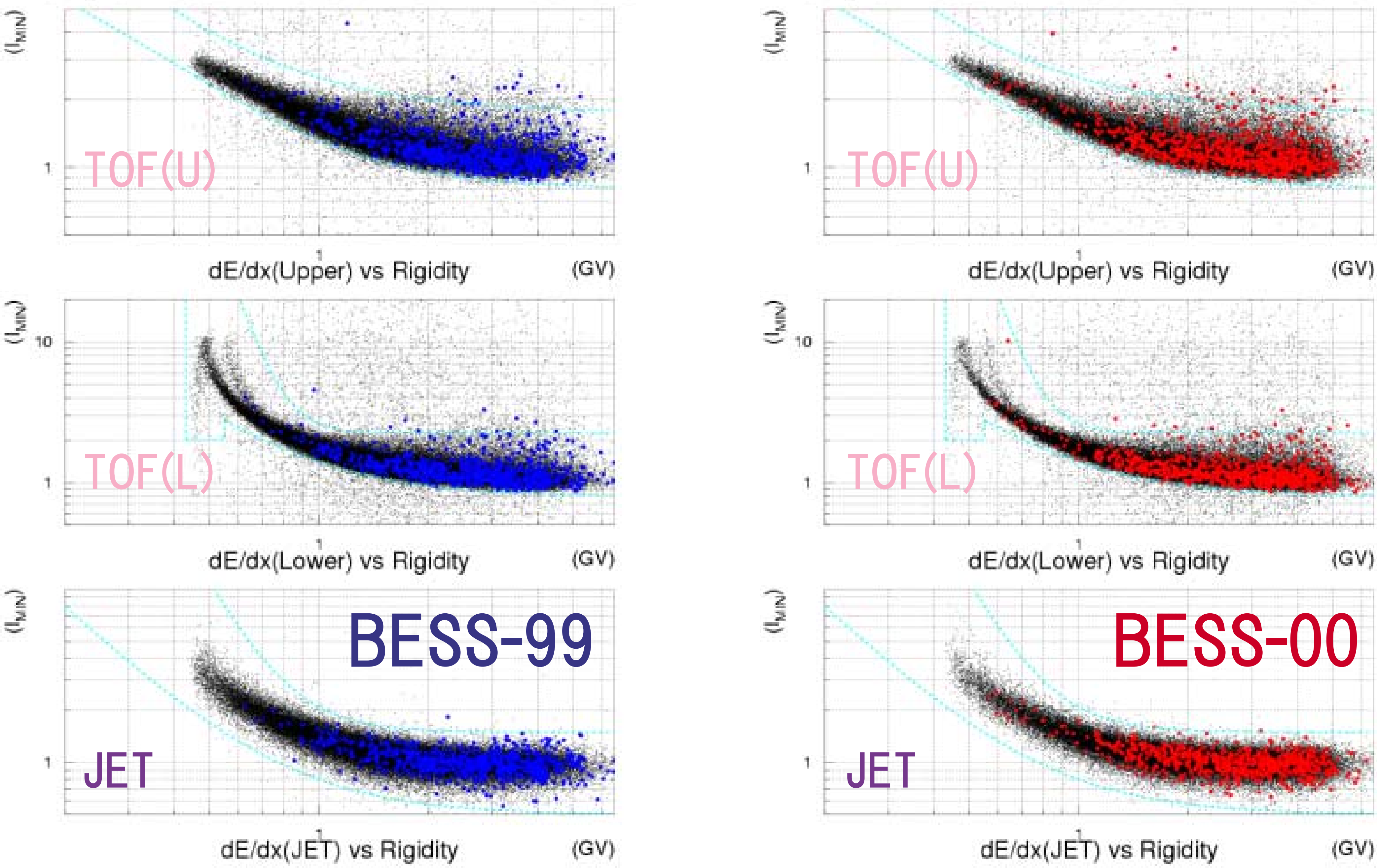
3. fiducial volume cut
4. single particle selection
5. track quailty cut

6. dE/dx cut
7. mass cut
8. aerogel Cherenkov veto

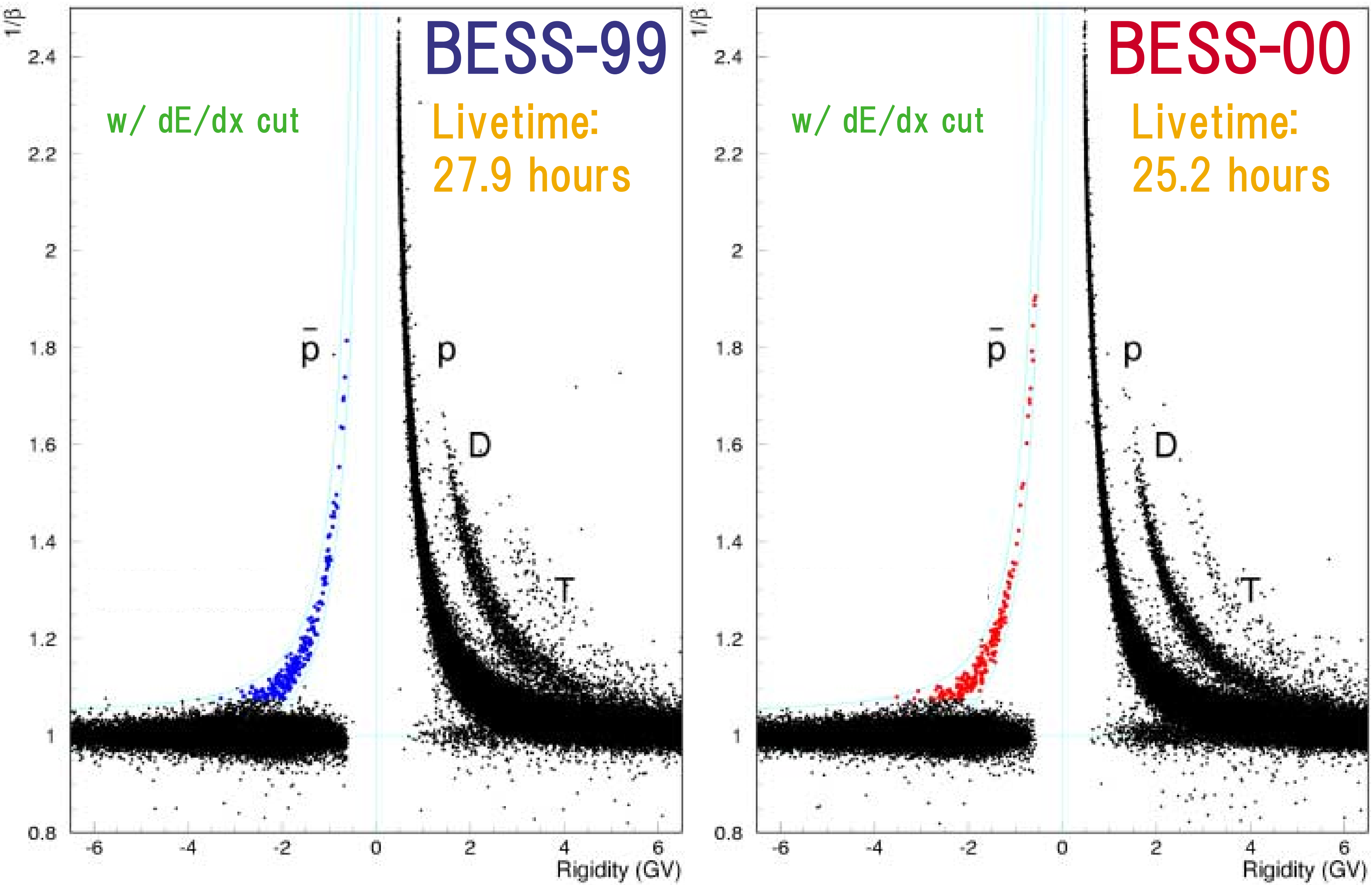
Rigidity = 運動量/電荷 ⇒



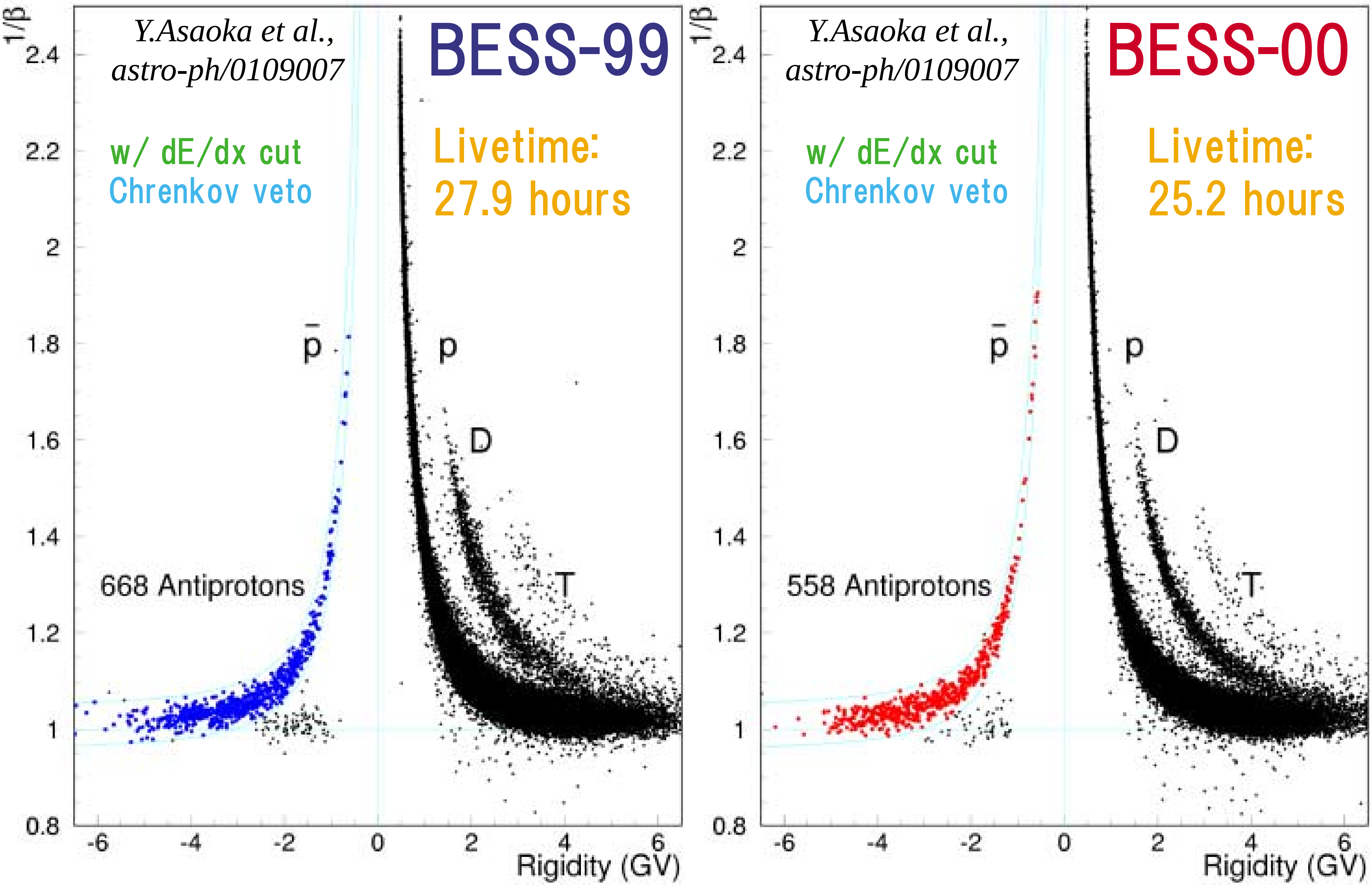
dE/dx band cuts



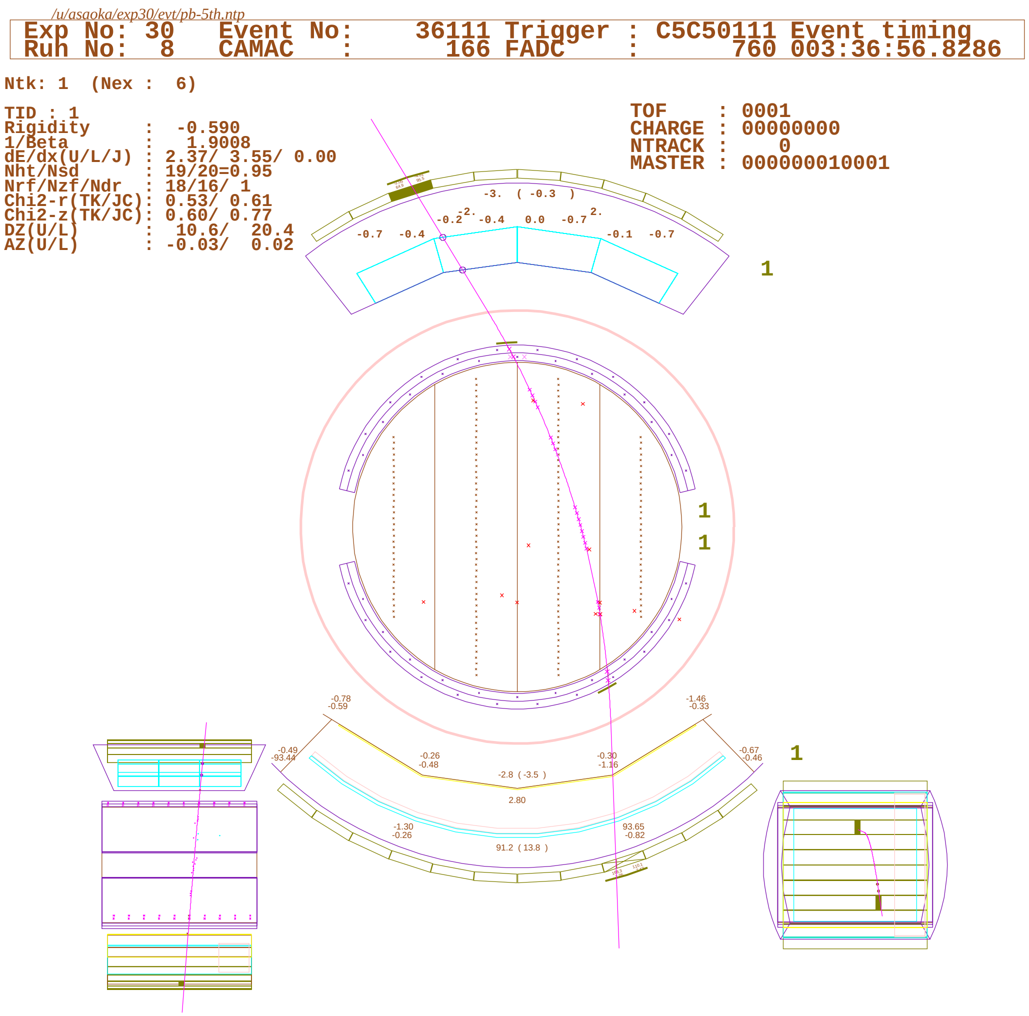
Antiproton Identification Plots

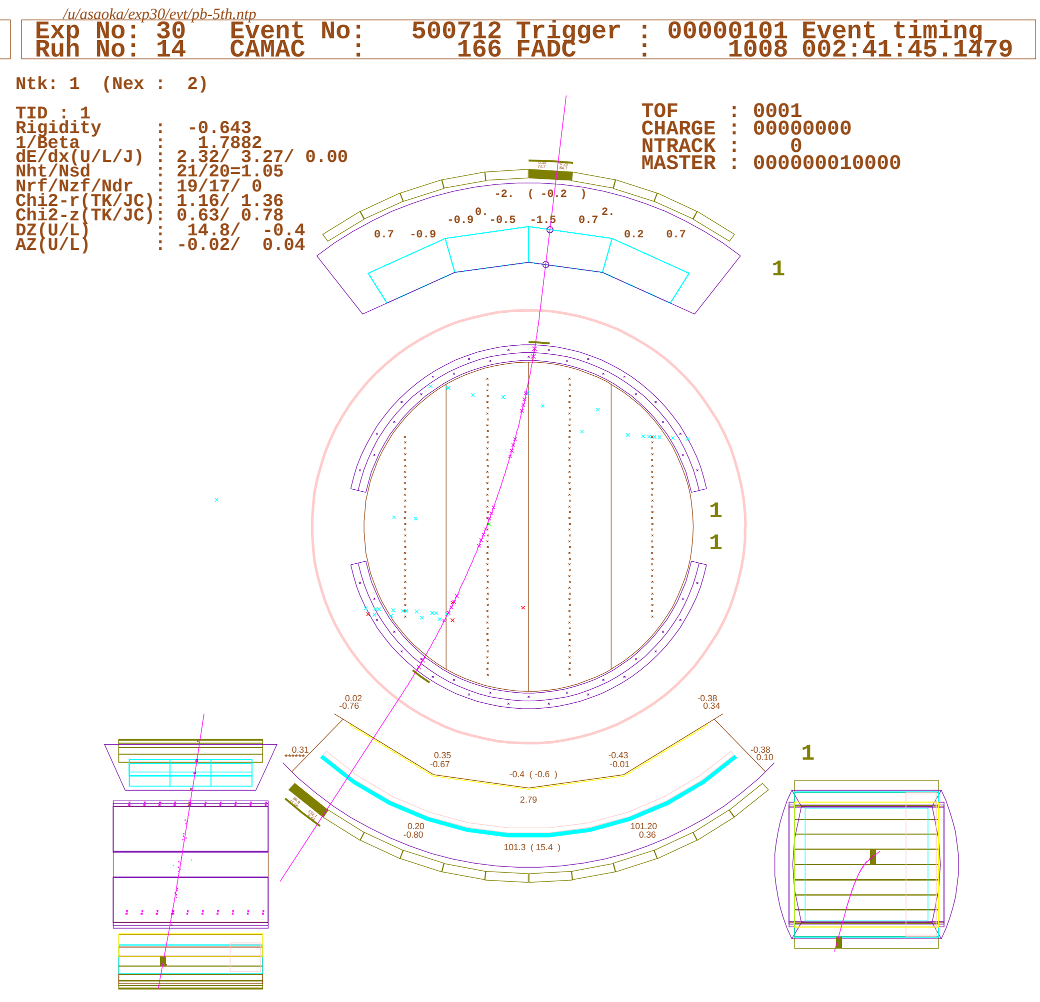


Antiproton Identification Plots



Event Display





Examples for BESS-00 Low Energy $\bar{p}$ events

Absolute Flux Calculation

$$N(\bar{p}) = N_{obs} - N_{e/\mu} - N_{atmos}$$

$$J(\bar{p})dE = \frac{N(\bar{p})}{S\Omega\varepsilon t}$$

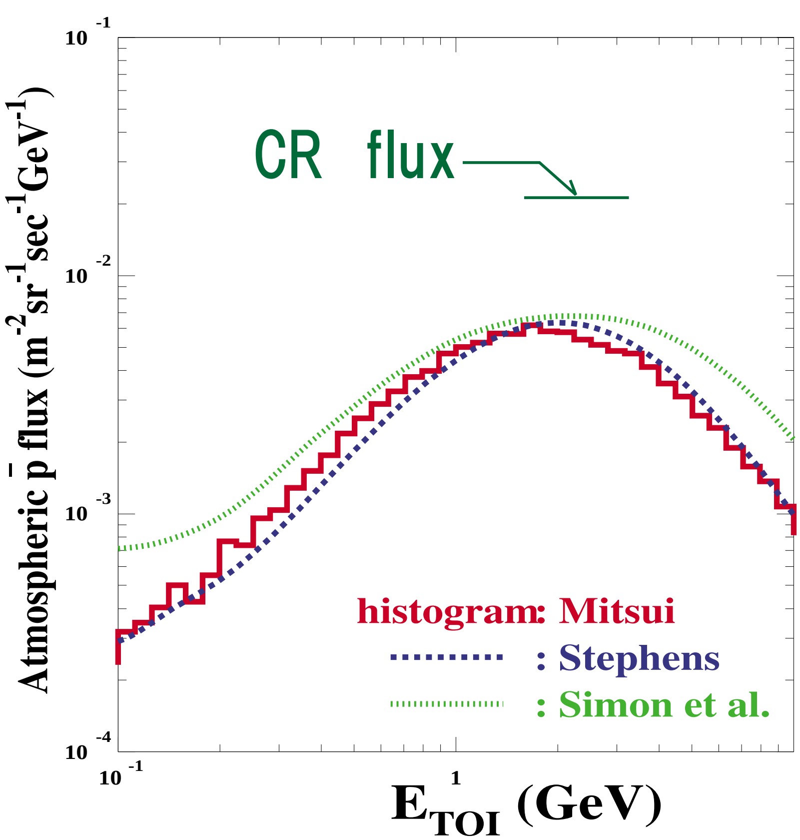
Backgrounds

1. e/μ contamination
   - Contamination < 5% (max. @ 4GeV)
   - Aerogel rejection factor: ～4000

2. Atmospheric $\bar{p}$ subtraction
   - Subtraction < 25±7%(syst.) (max. @ 2GeV)
   - Calculations

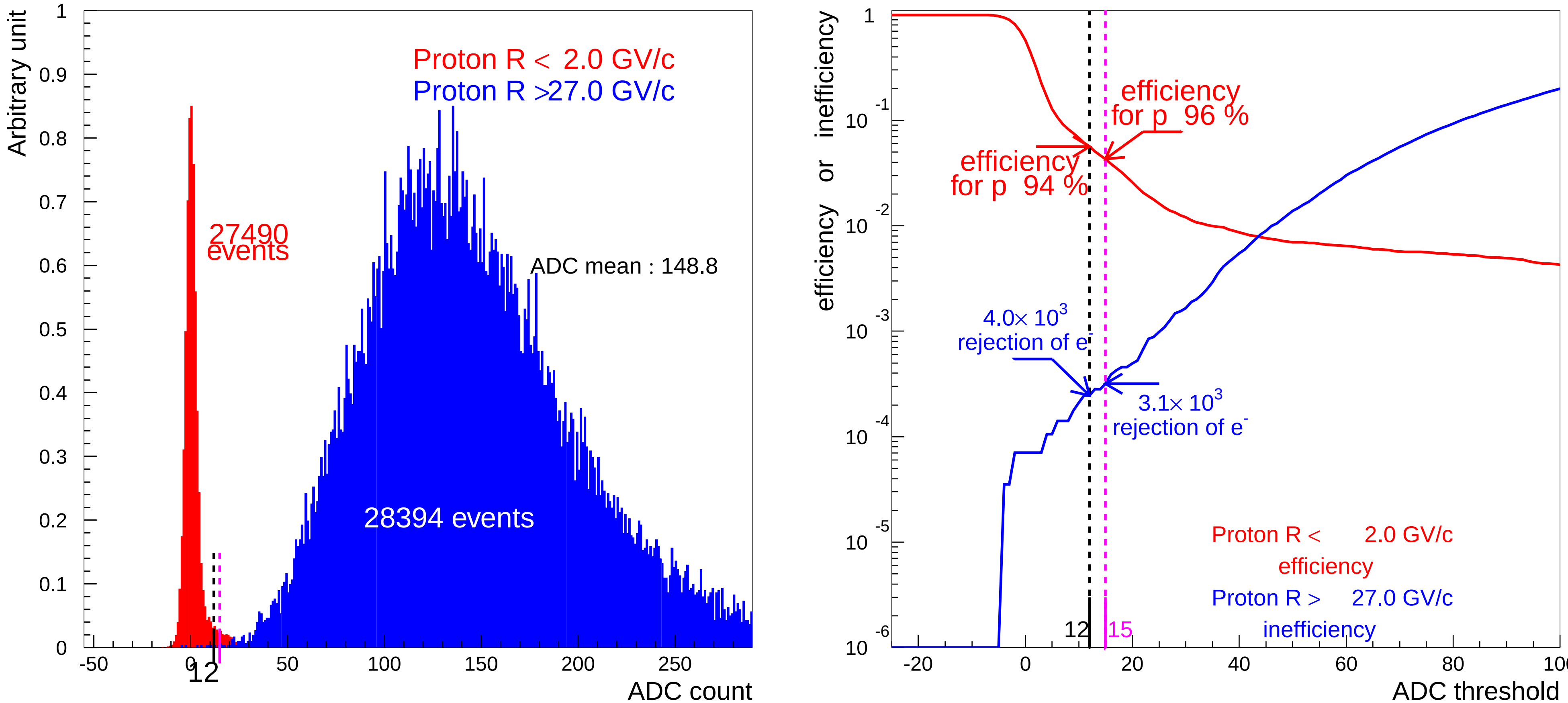
(Mitsui, Pfeifer et al, S.A.Stephens)

山頂高度での
大気反陽子測定
⇒モデルの検証



Aerogel e/μ Rejection Power

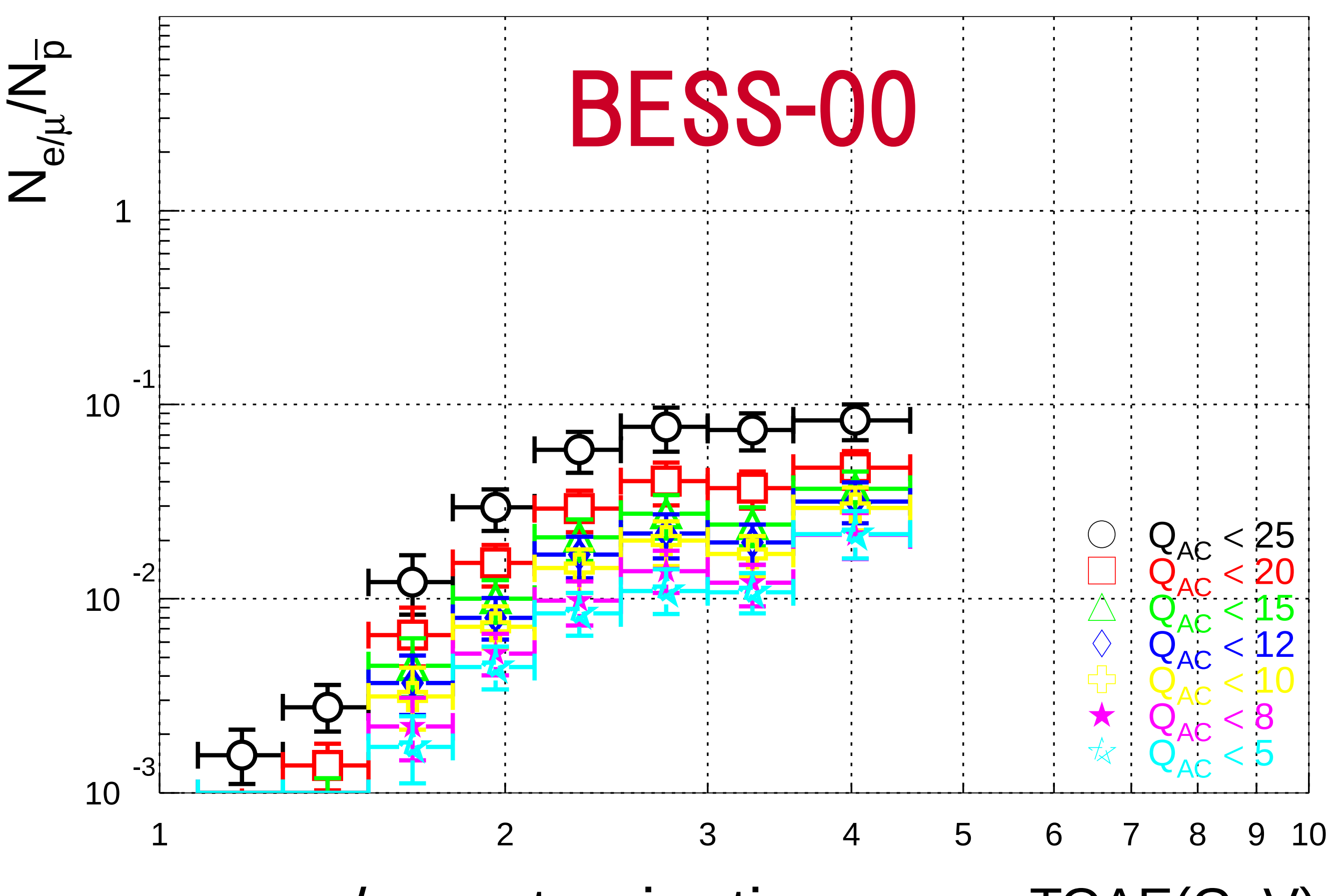
BESS-00



Rejection power estimated as a function of ADC threshold using high energy proton samples.

Estimation of e/μ Contamination

1) No. of e/μ in the mass band were counted.
2) Rejection factor was obtained for a given ADC threshold.
3) No. of e/μ contamination in the $\bar{p}$ candidates were calculated



e/μ contamination

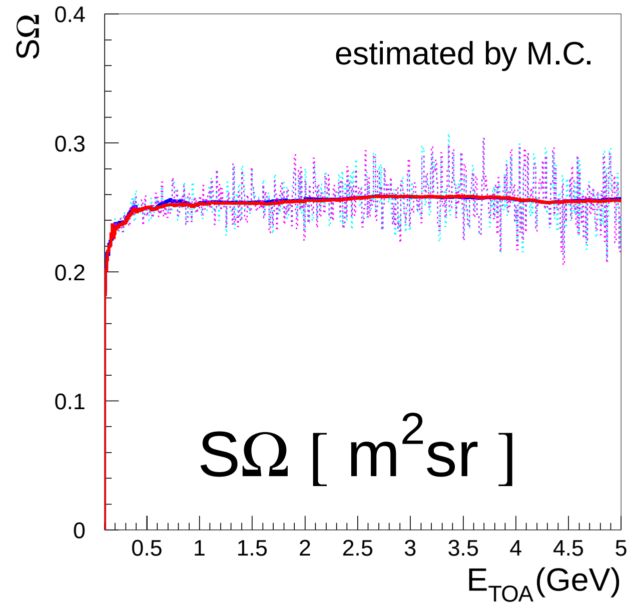
⇒ e/μ contamination was kept below 5% when applying Q_{AC} < 12.

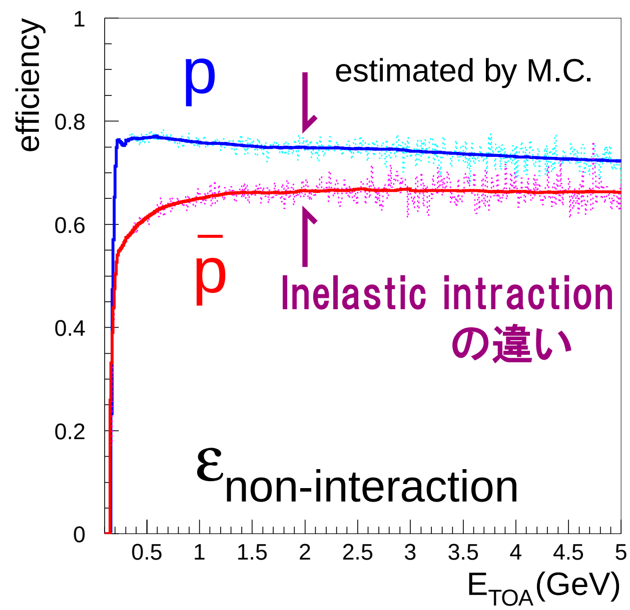
Corrections

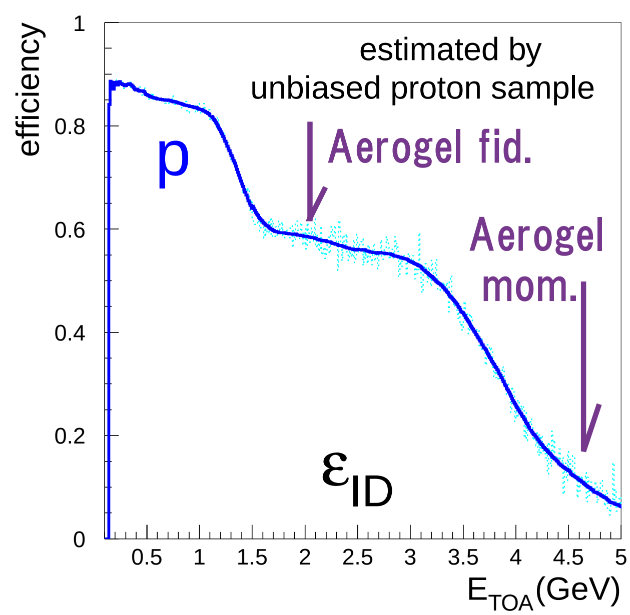
$$J(\bar{p})dE = \frac{N(\bar{p})}{S\Omega\varepsilon t}$$

1. Exposure Factor ($S\Omega t$)
   1). Live time (t):
      - 1MHz clock, directly measured
      - dead time fraction ～10 %
   2). $S\Omega$: M.C. simulation
      - simple geometry

2. Detection Efficiencies (ε)
   1). Interaction losses
      M.C. simulation
      calibrated by $\bar{p}$ beam
      @ KEK-PS K2 in 1999
      ±15% ⇒ ±5% (syst.)
   2). Event Selection
      - unbiased proton sample
      - high efficiencies



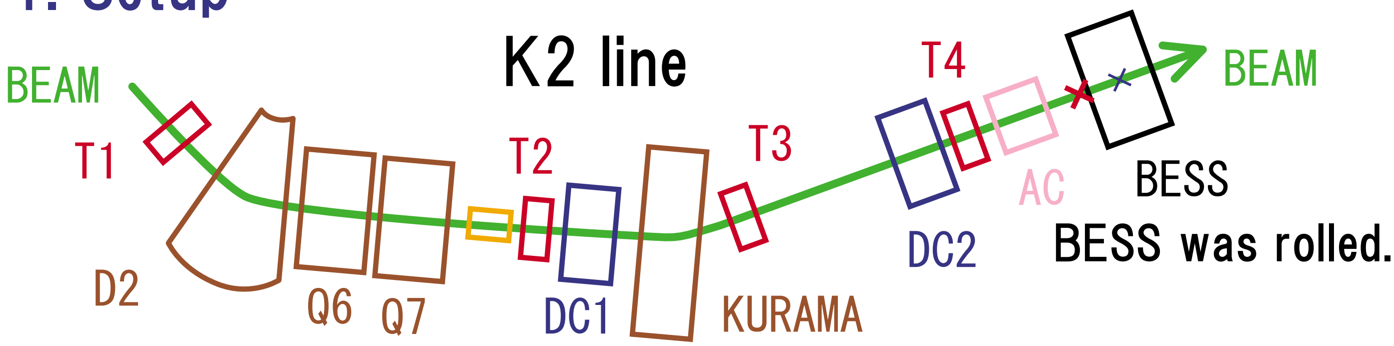




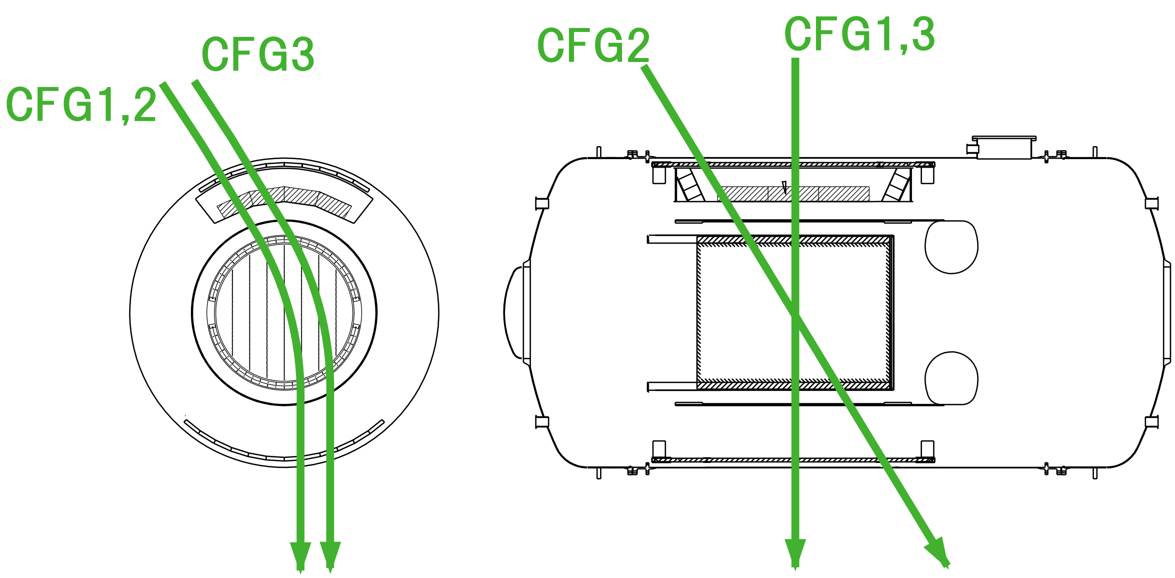
BESS detector beam test @ KEK

using low E antiproton and proton beam

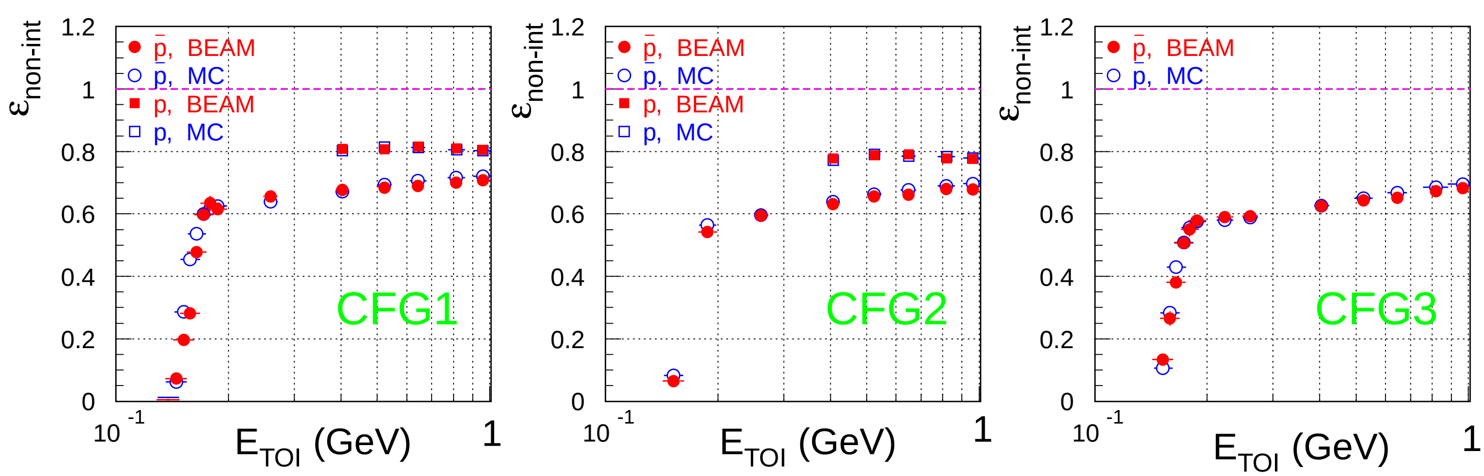
1. Setup



2. Beam incidence



3. Direct measurement of the detection efficiencies



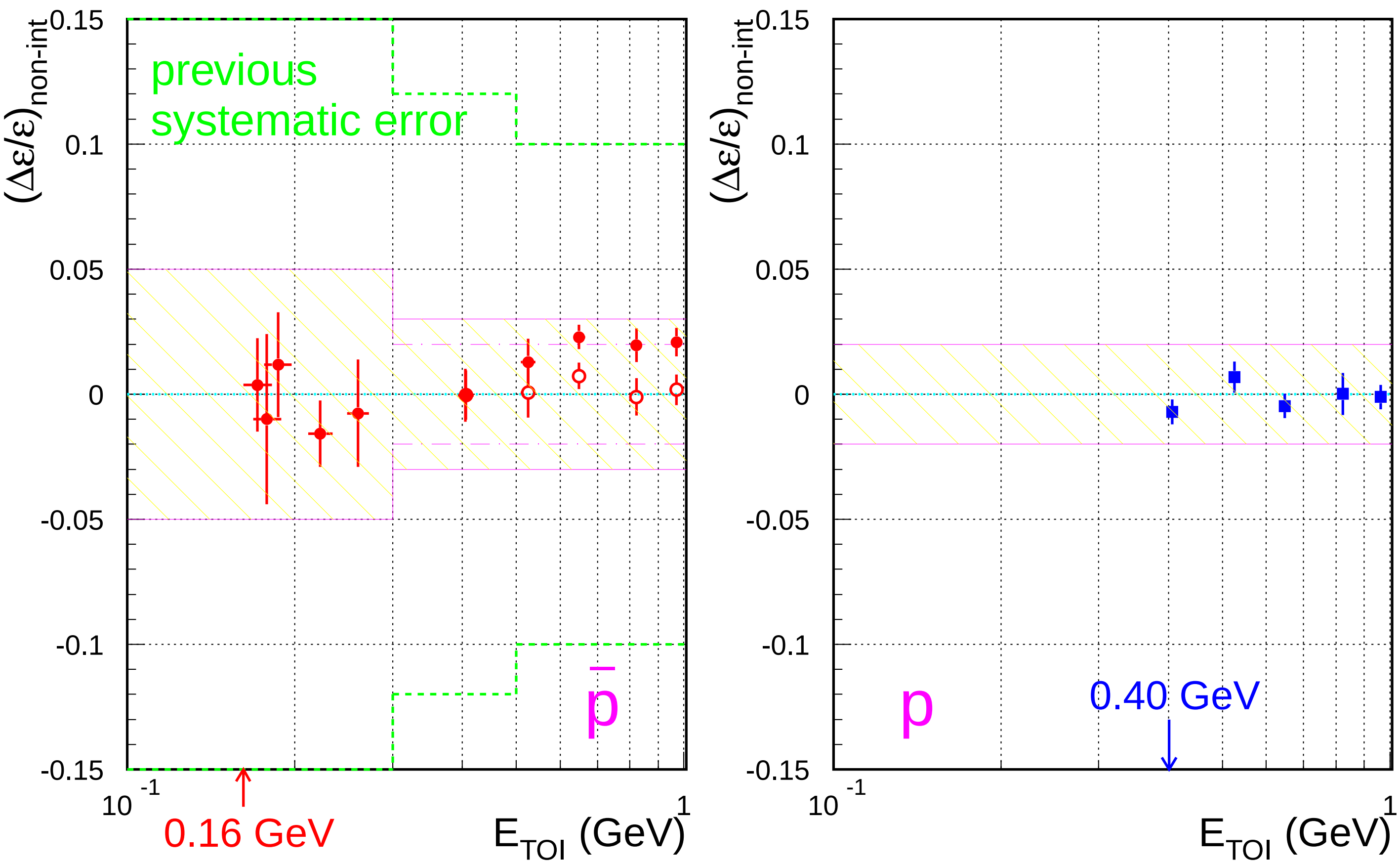
Systematic Uncertainty of the Detection Efficiencies

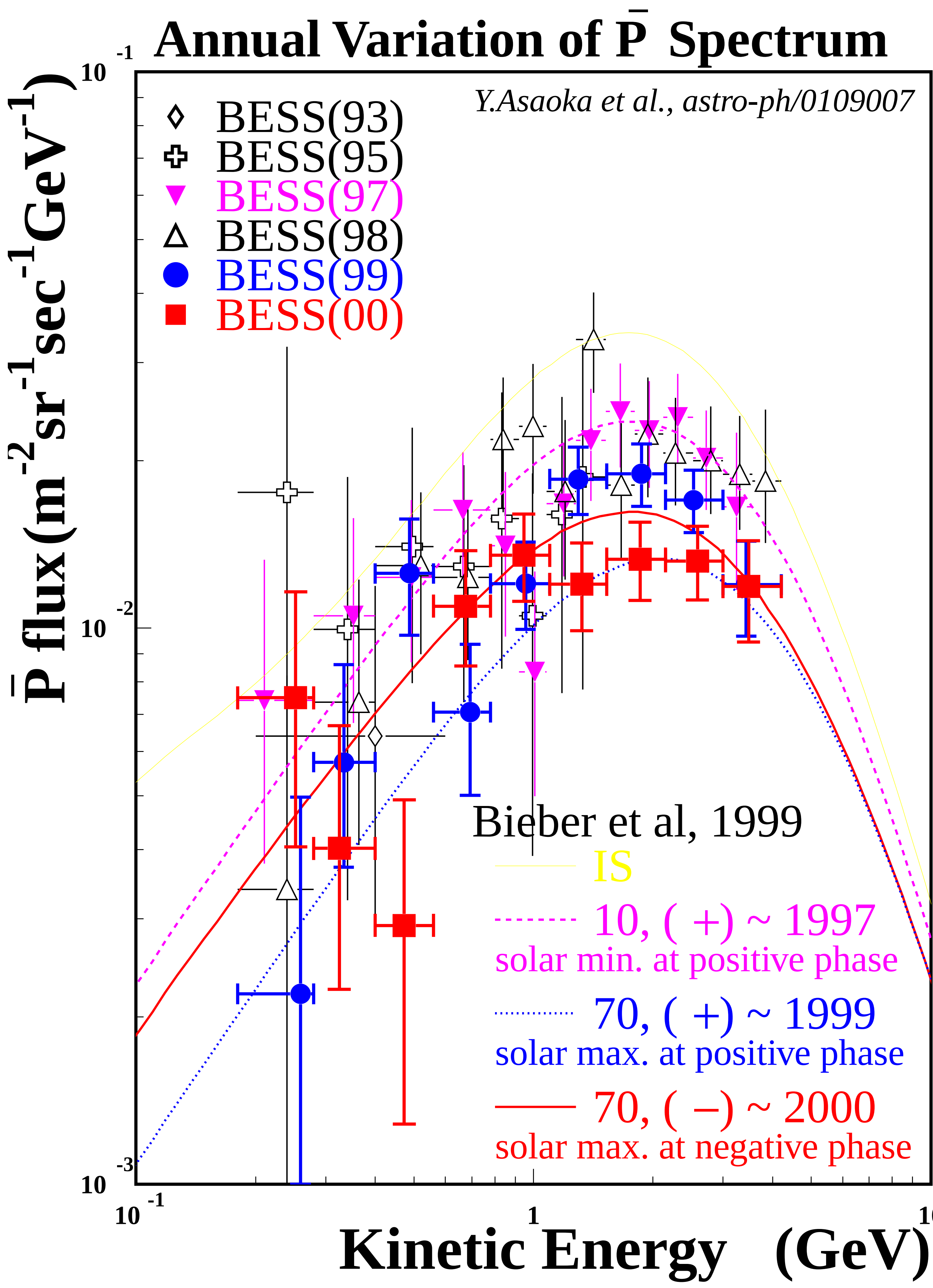
Y.Asaoka et al, physics/0105003, submitted to NIMA

1). The systematic errors of the beam test itself were estimated to be within ±1%.

2). BESS M.C. simulation was verified by comparing with beam test data.
(hadronic interaction/material/detector response)

3). The relative systematic error of the detection efficiencies are kept within 5%.

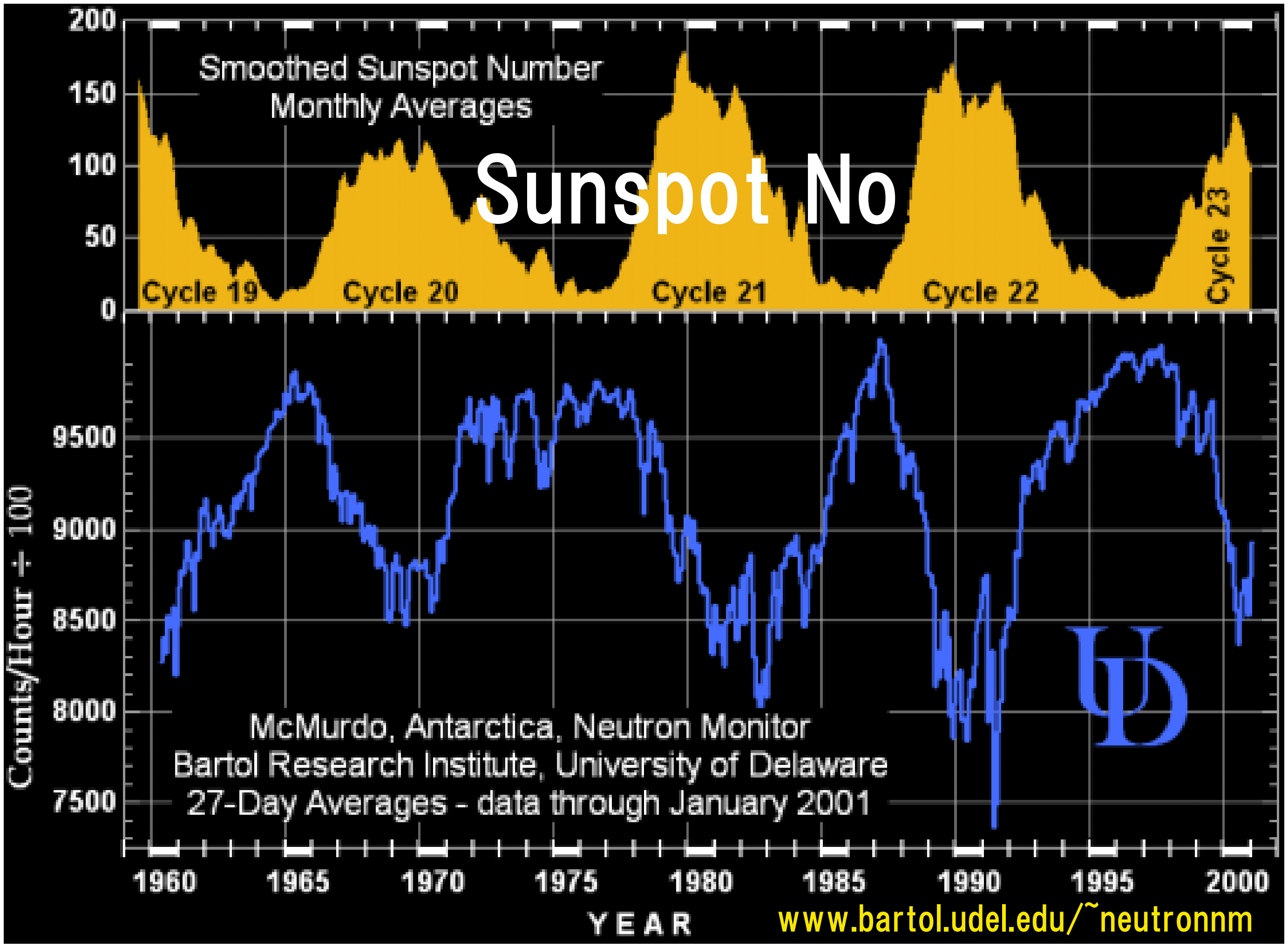




Annual Variation of P̄ Spectrum
Y.Asaoka et al., astro-ph/0109007
BESS(93)
BESS(95)
BESS(97)
BESS(98)
BESS(99)
BESS(00)
Bieber et al, 1999
IS
10, (+) ~ 1997
solar min. at positive phase
70, (+) ~ 1999
solar max. at positive phase
70, (–) ~ 2000
solar max. at negative phase
$\bar{P}$ flux $(m^{-2}sr^{-1}sec^{-1}GeV^{-1})$
10^{-1}
10^{-2}
10^{-3}
1
10
Kinetic Energy (GeV)

Solar Modulation

Positive Polarity | Negative Polarity | Positive Polarity | Negative Polarity



1960 1990

Neutron intensity

The process by which expanding solar wind modifies the energy spectrum of cosmic rays.

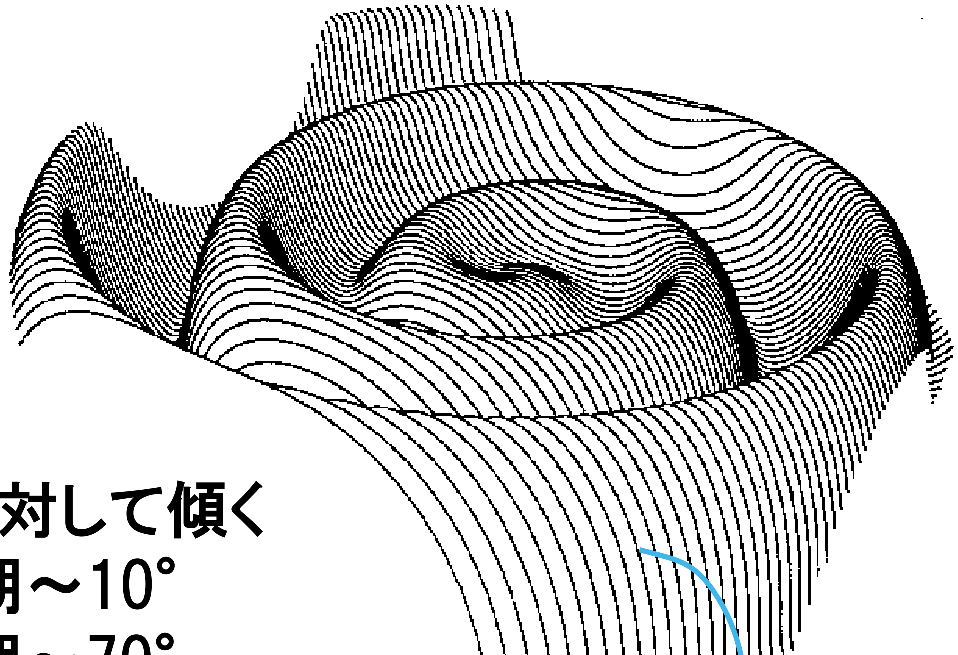
11-year cycle

Sun's magnetic field polarity reverses at each solar maximum.

22-year cycle

Charge Sign Dependence?

Sun's field

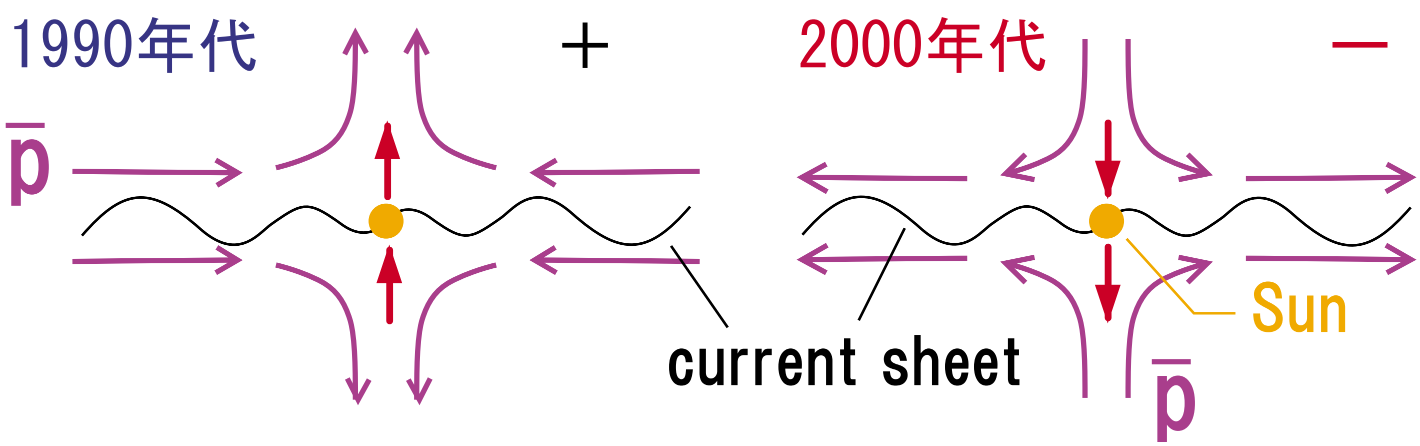


- 太陽磁場：pole に対して傾く
  太陽活動極小期～10°
  極大期～70°
- 太陽磁場は太陽風のplasma中に固定
- 太陽風の radial flow(～400km/s)
- 25日周期の太陽の自転

⇒ wavy inclined current sheet

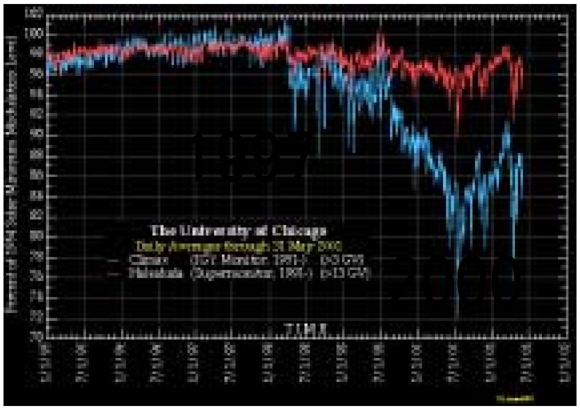
Drift in/out along current sheet

gradient and curvature drift

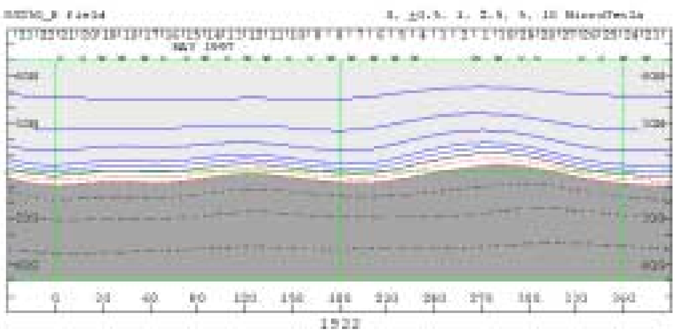


driftの向き ⇔ 粒子の電荷/太陽磁場のpolarity

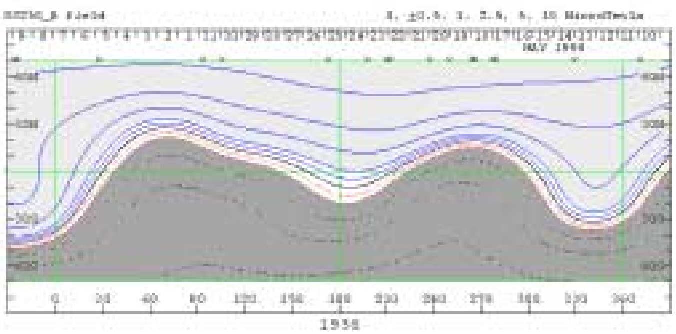
Current Sheet Tilt Angle



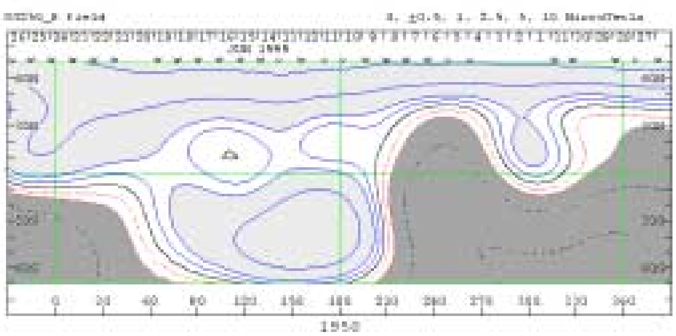
Current sheet tilt angle governs the level of solar modulation.



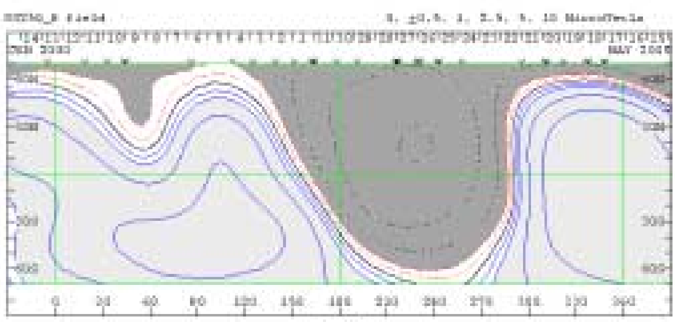
1997 May
Quiet Sun
Tilt angle ~ 10°



1998 May
Moderate Activity
Tilt angle ~ 30°



1999 May-June
High Solar Activity



2000 May-June
High Solar Activity
Polarity has Reversed!

quake.stanford.edu/~wso/coronal.html

Current Evidence of Charge Sign Dependence

general consensus:
太陽活動極大期では
drift effect が無視できる

existing evidence:
極性反転の前後で
最も大きな変化

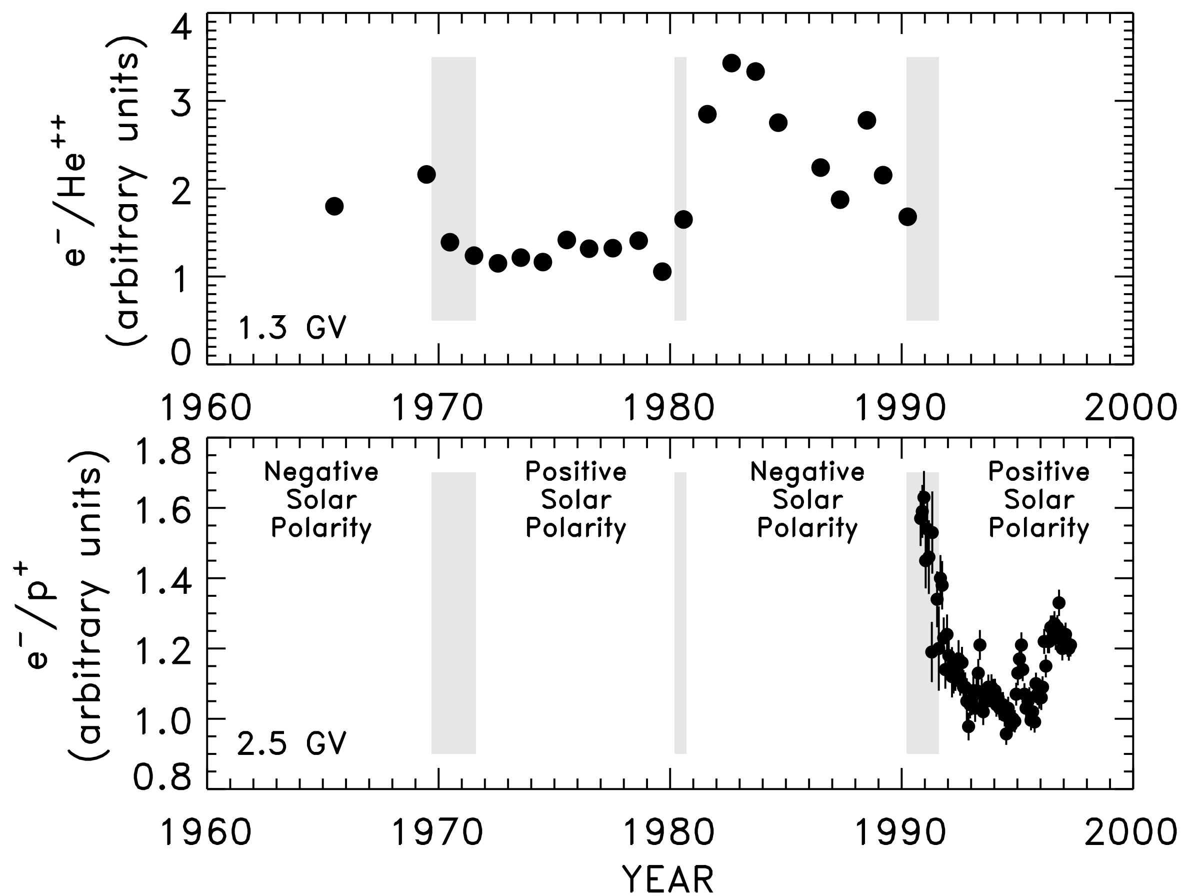
極性反転の前後での観測

- e^-/He, e^-/p ratio
  ⋯ $M_e \ll M_{He,p}$
- $\bar{P}/P$ ratio (1999 & 2000)
  ⇒ ideal probe

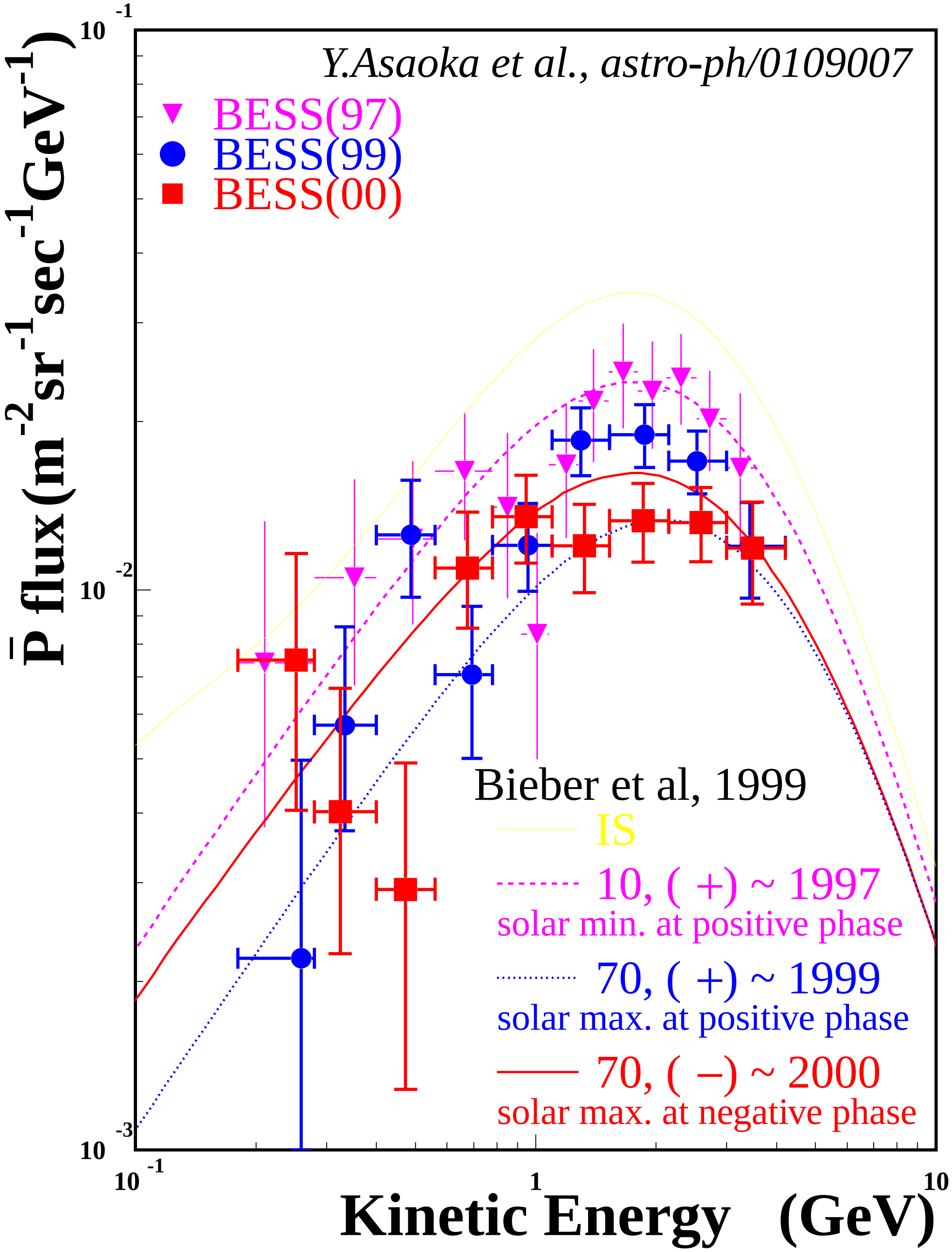
Bieber et al, PRL, 1999.

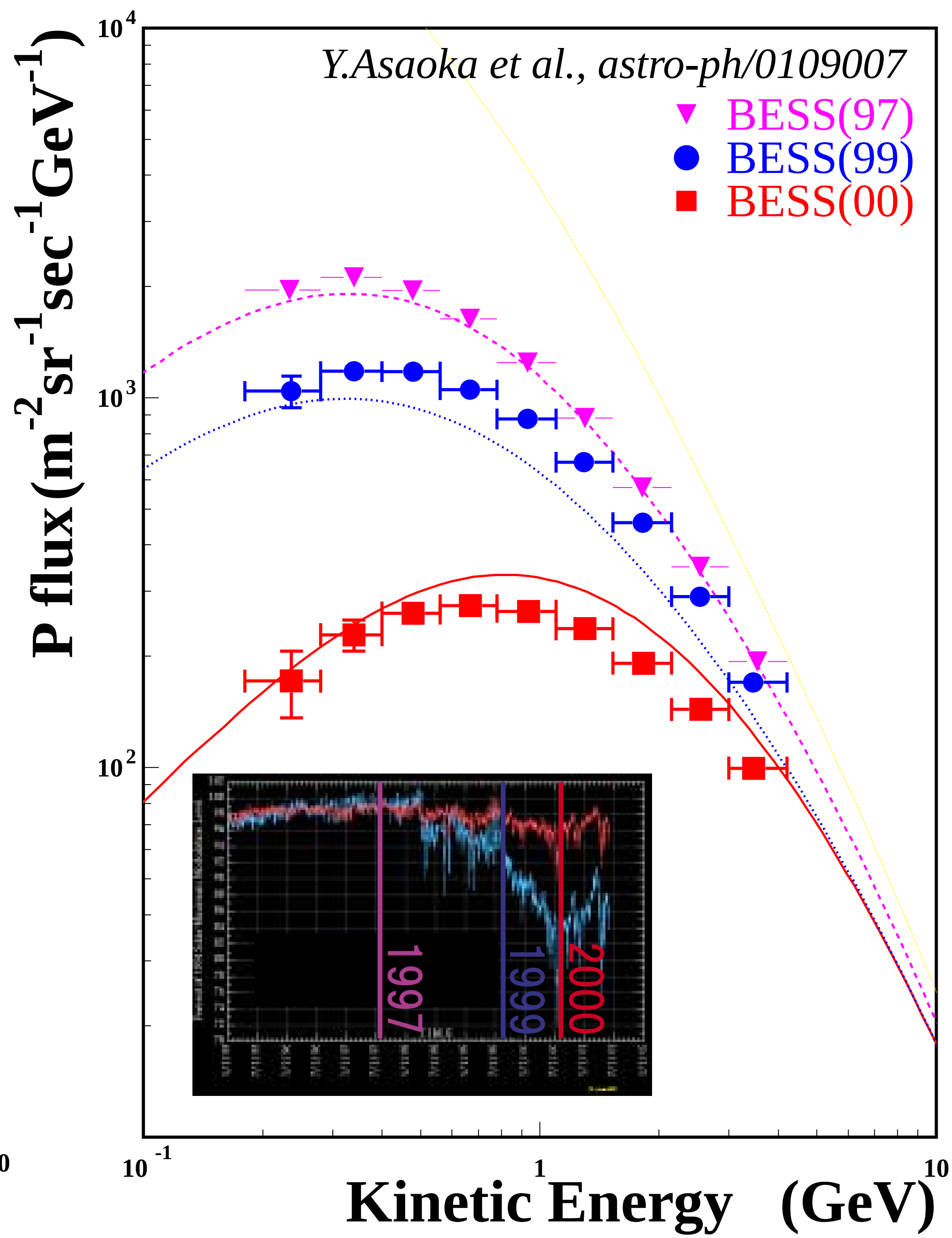
e^-/He: Balloon
e^-/p : Ulysses

Bieber et al, 1999.

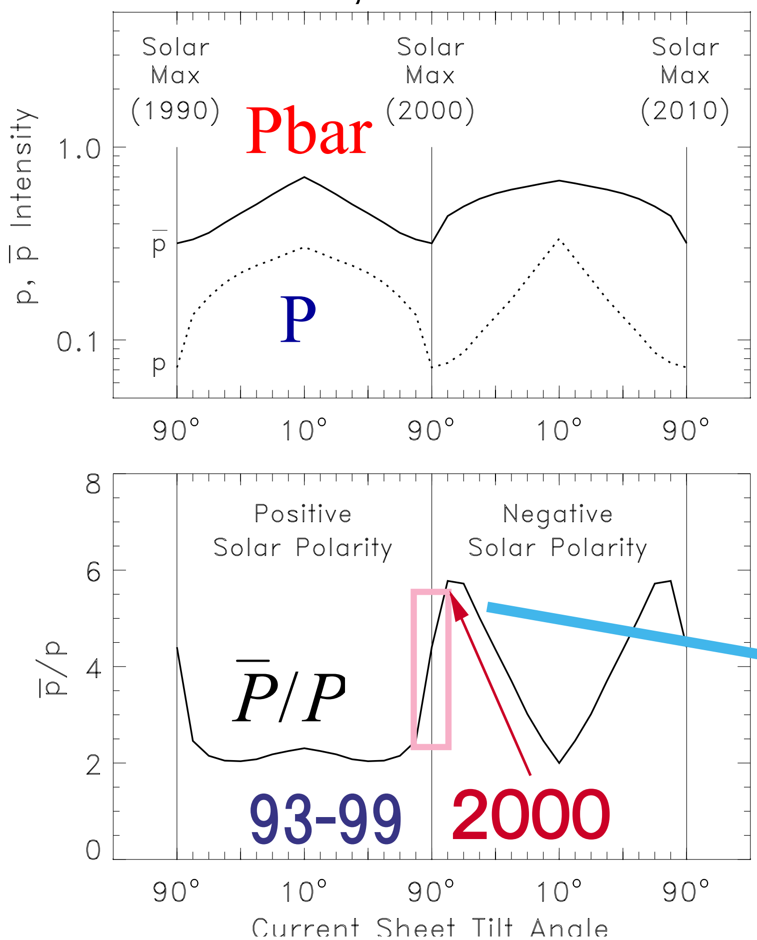


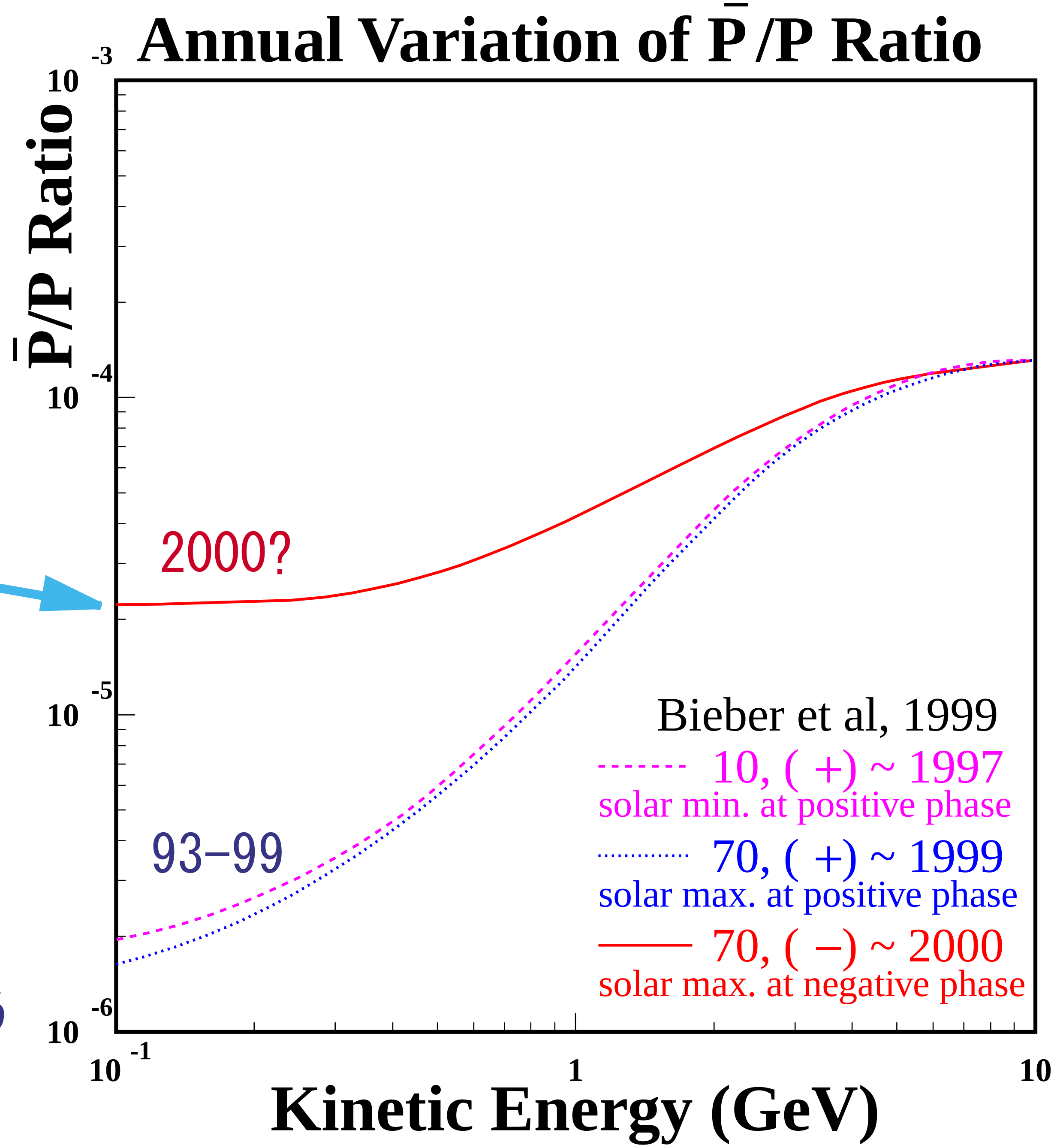
$\bar{P}$ and P spectrum following the solar field reversal





$\bar{P}$/P ratio following the solar field reversal





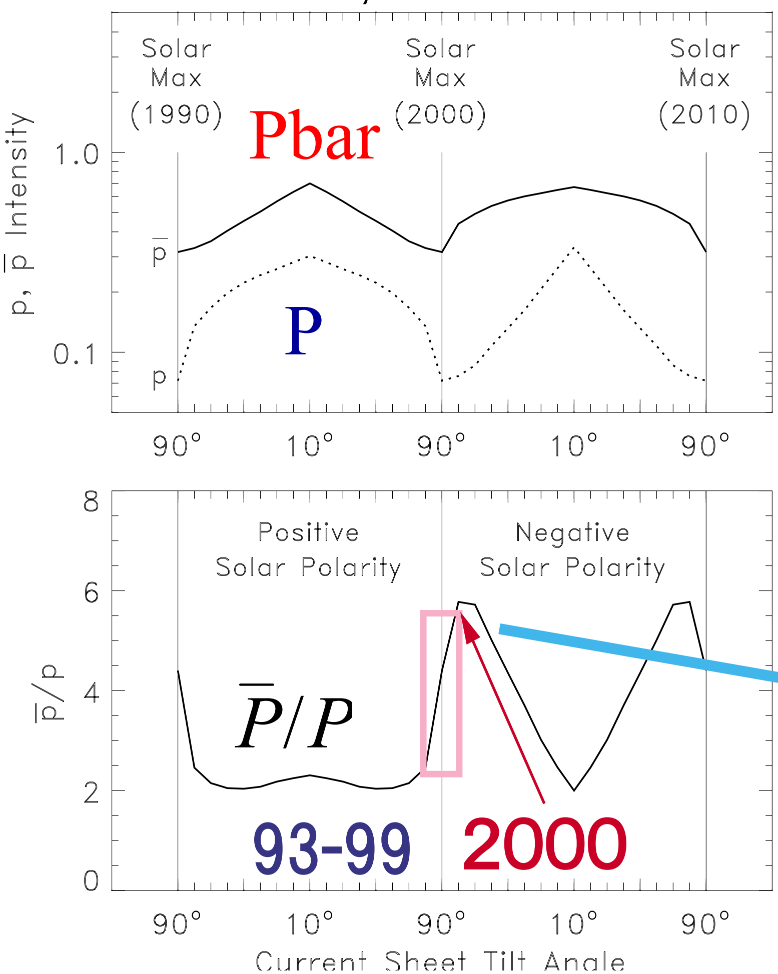
- IS spectrum の違い
- Charge sign の違い

polarity (+) ⇒打ち消しあう

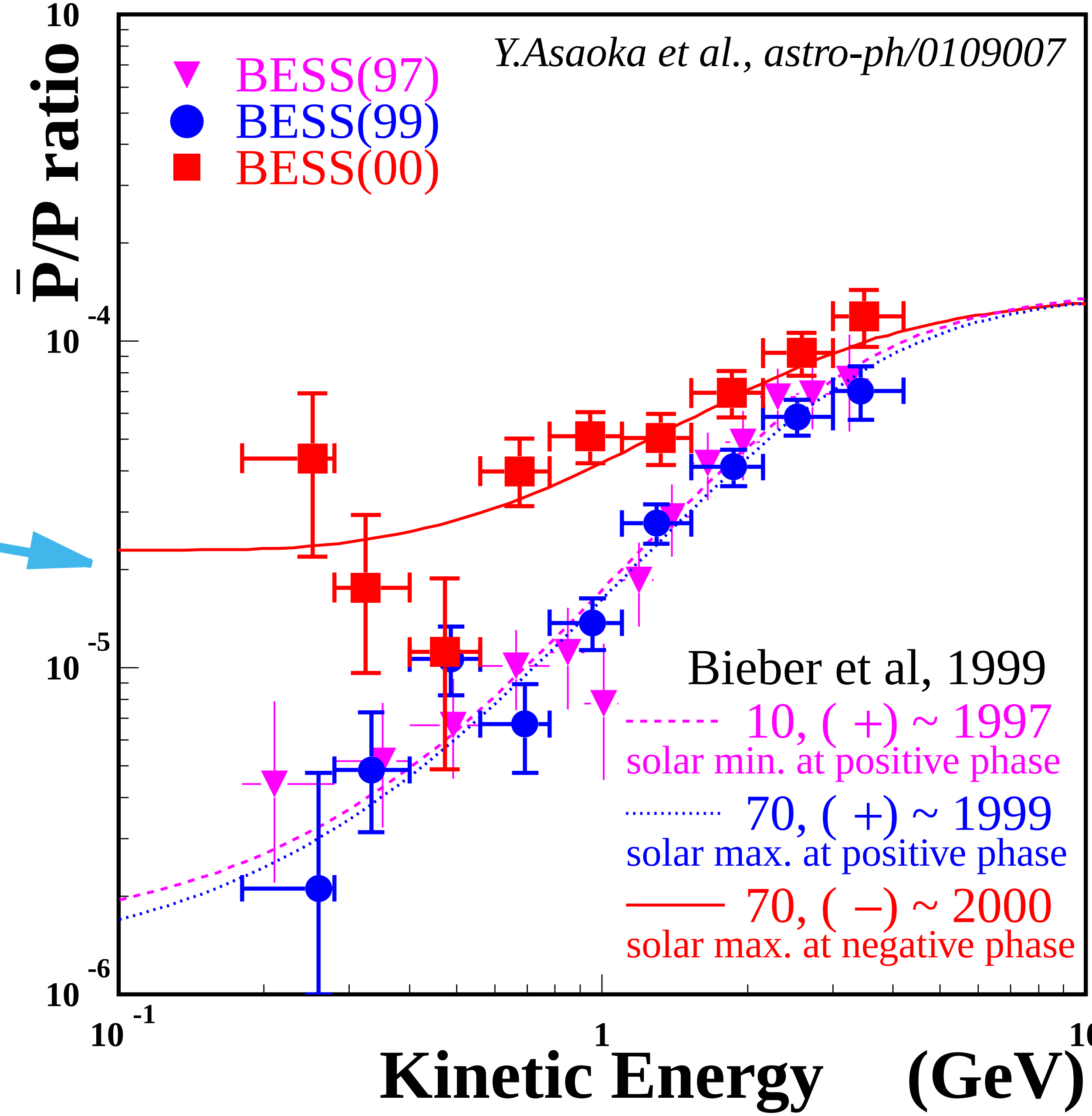
(—) ⇒強めあう

$\bar{P}$/P ratio following the solar field reversal

Bieber et al, 1999



Annual Variation of $\bar{P}$/P Ratio



- IS spectrum の違い
- Charge sign の違い

polarity (+) ⇒打ち消しあう

(—) ⇒強めあう

Summary

BESSによる反陽子絶対流束の測定

1993 ～ 1994:

質量の同定による positive な検出

1995 ～ 1997:

太陽活動極小期における観測

- Energy Spectrum の測定
- 二次起源反陽子流束の peak を捉える.
  - ⇒宇宙線伝播モデル
- 一次起源成分の流束に制限を与える.
  - ⇔低エネルギー領域での若干の過剰
  - 一次起源成分の寄与の可能性残る.

1998 ～ 2000:

太陽活動極大期までの流束の経年変化

- Suns's polarity の反転の前後での測定
- 反陽子・陽子比の急激な上昇を捉える.
  - ⇒ Charge sign dependence

Future:

BESS-Polar (南極周回飛翔)

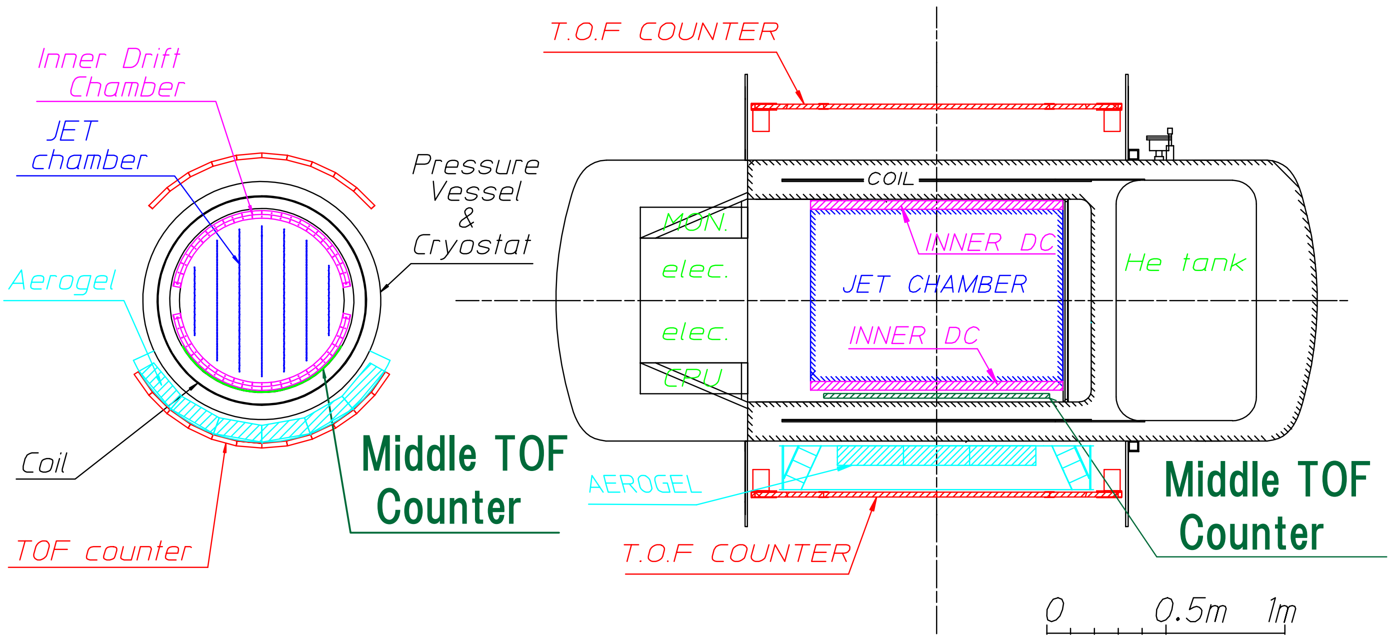
- 一次起源流束の有無に決着.

BESS Polar

AMSとも相補的な物理

No Vessel, New Mag (ultra thin)

$\bar{p}$ 0.1-4.2 GeV by Middle TOF



2003-2004, 2006?