華麗なる終章。そして未来へ

中村健蔵
高エネルギー加速器研究機構
素粒子原子核研究所

KEK 12-GeV 陽子シンクロトロン
ーーーその35年の軌跡ーーー
２００６年1月１３日ー１４日

PS実験第３期の素粒子物理

- ニュートリノ振動実験（K2K）
- Ｋ中間子崩壊実験
  - E246: $K^+ \rightarrow \pi^0 \mu^+ \nu$ 崩壊における時間反転対称性の破れの探索
  - E391a: 希な崩壊 $K_L \rightarrow \pi^0 \nu \nu$ の測定

- 第３期の特徴
  - 本格的な国際共同研究
  - ニュートリノ振動実験で世界的な注目
  - ユニークなＫ中間子崩壊実験
  - **PSからJ-PARC (intensity frontier) へ**

本格的国際共同研究

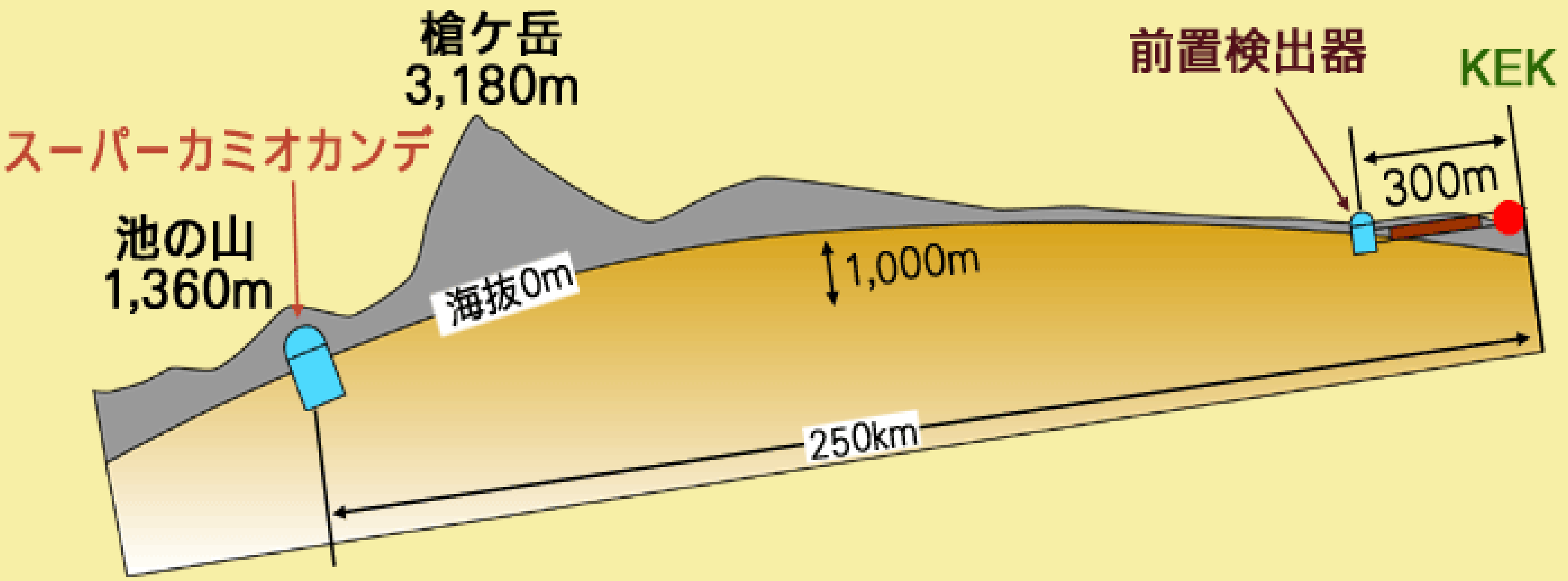
- E246（今里）
  - 日本・ロシア(INR)・カナダ＋α
  - 1992年にKEK-INRのMoU
  - 実験メンバーの過半数が外国人
- K2K
  - K2K-I：日米韓（1995年）
  - K2K-II：日米韓伊仏西露・スイス・カナダ・ポーランド（2002年）
  - 実験メンバーの過半数が外国人
- E391a（稲垣）
  - 当初PACからグループの強化の必要性の指摘
  - 日本・米国（Chicago＋α）・JINR・韓国・台湾


K2K - I


K2K -II
January 9th, 2004

K２K

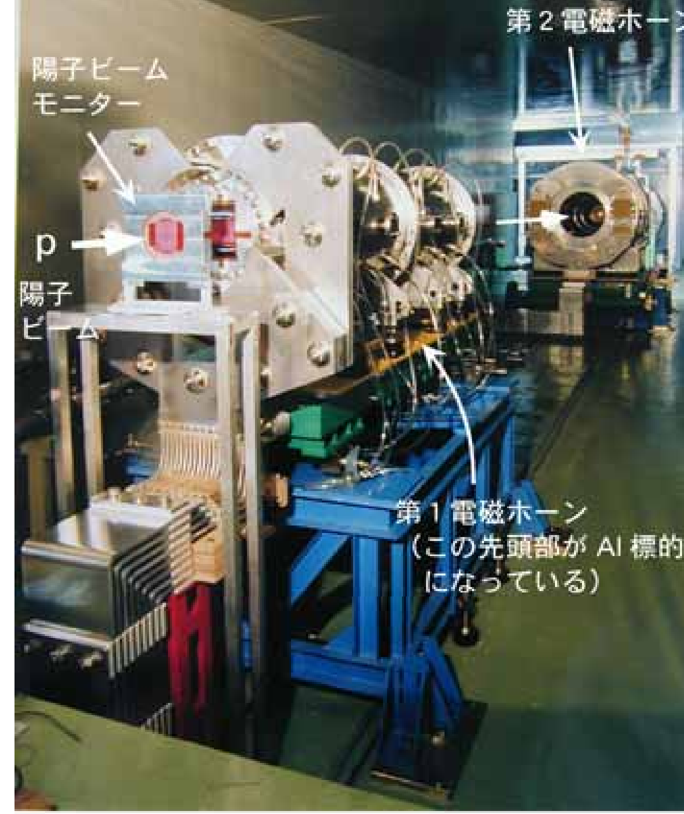

ニュートリノビームの飛行方向と観測装置の配置
スーパーカミオカンデ
(神岡町)
茨城県
北アルプス
高エネルギー
加速器研究機構
(つくば市)
岐阜県
陽子加速器
前置観測装置



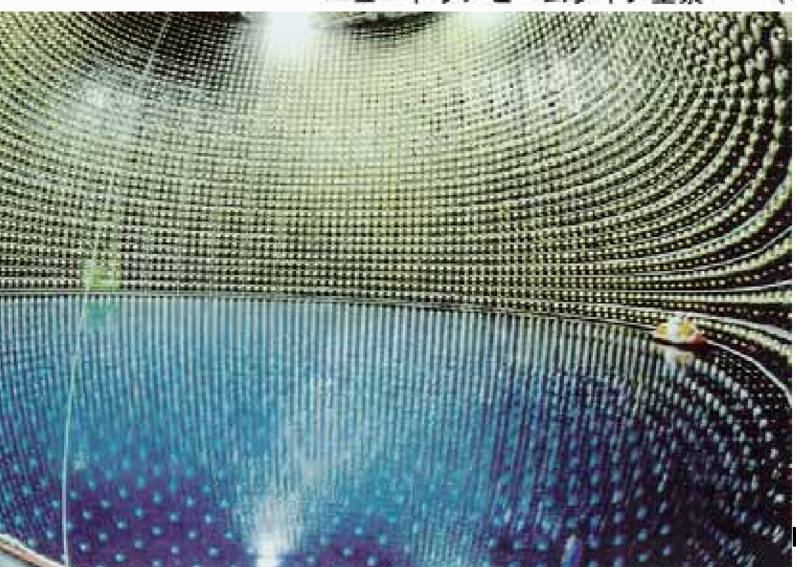
目的: スーパーカミオカンデの発見したニュートリノ振動を、人工ニュートリノを用いて確認

世界初の長基線ニュートリノ振動実験

ニュートリノビームライン全景　　（平成１０年１１月１９日撮影）



ターゲットステーションに設置された
２台の電磁ホーン



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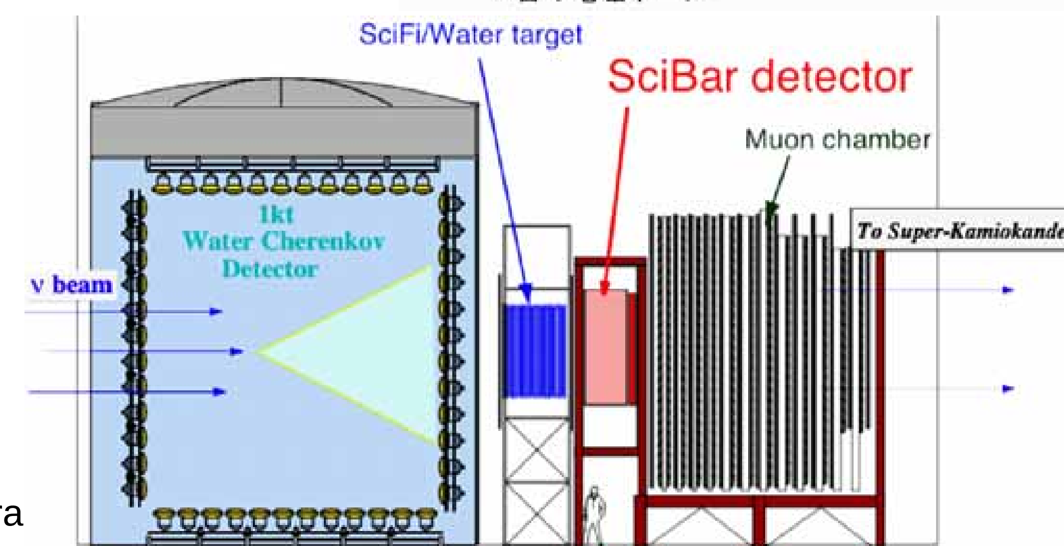
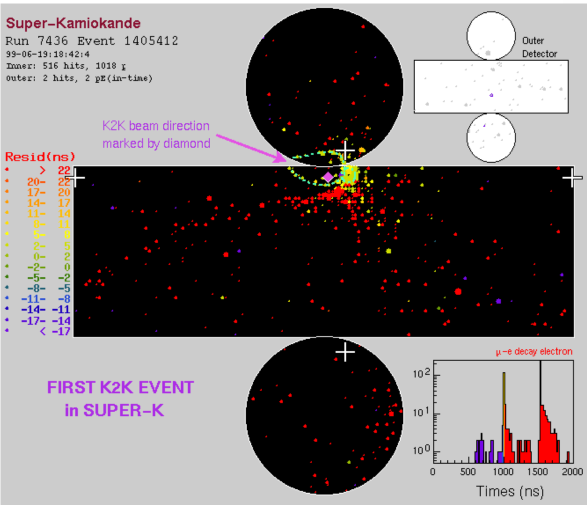
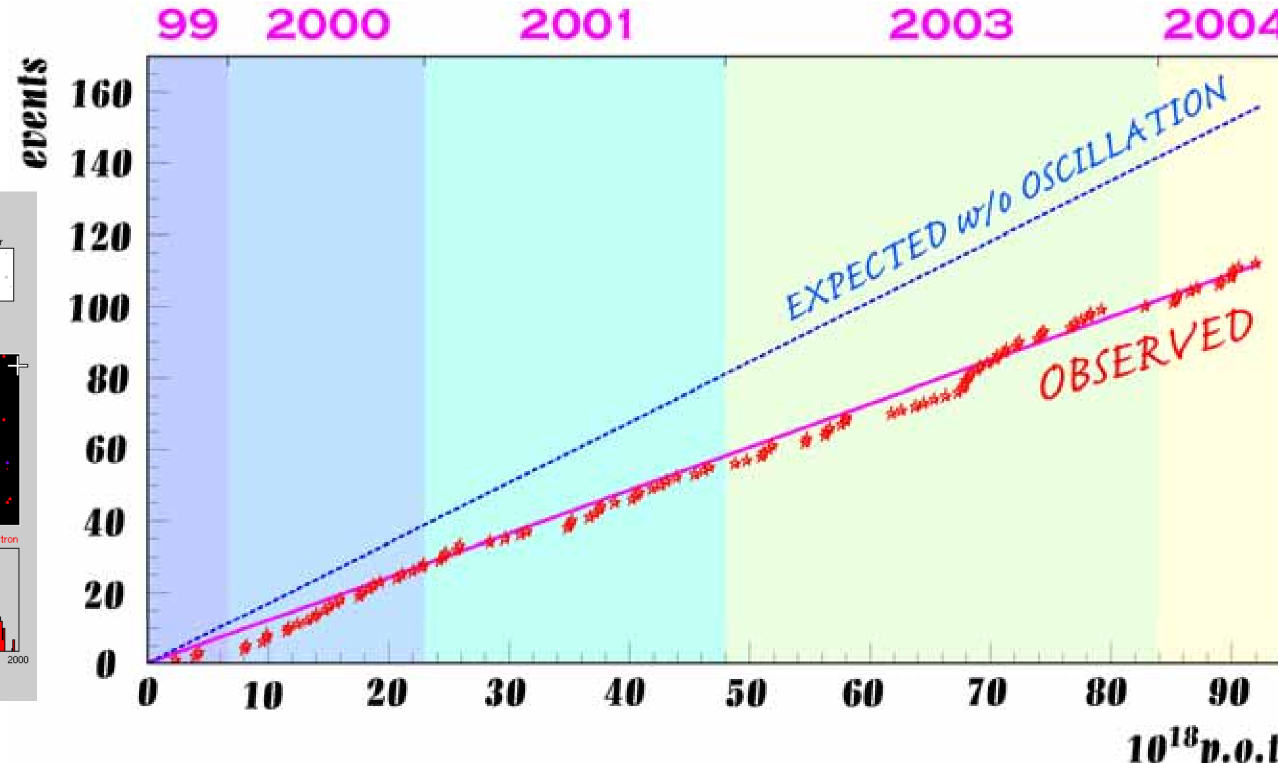


1999年6月19日
第1事象



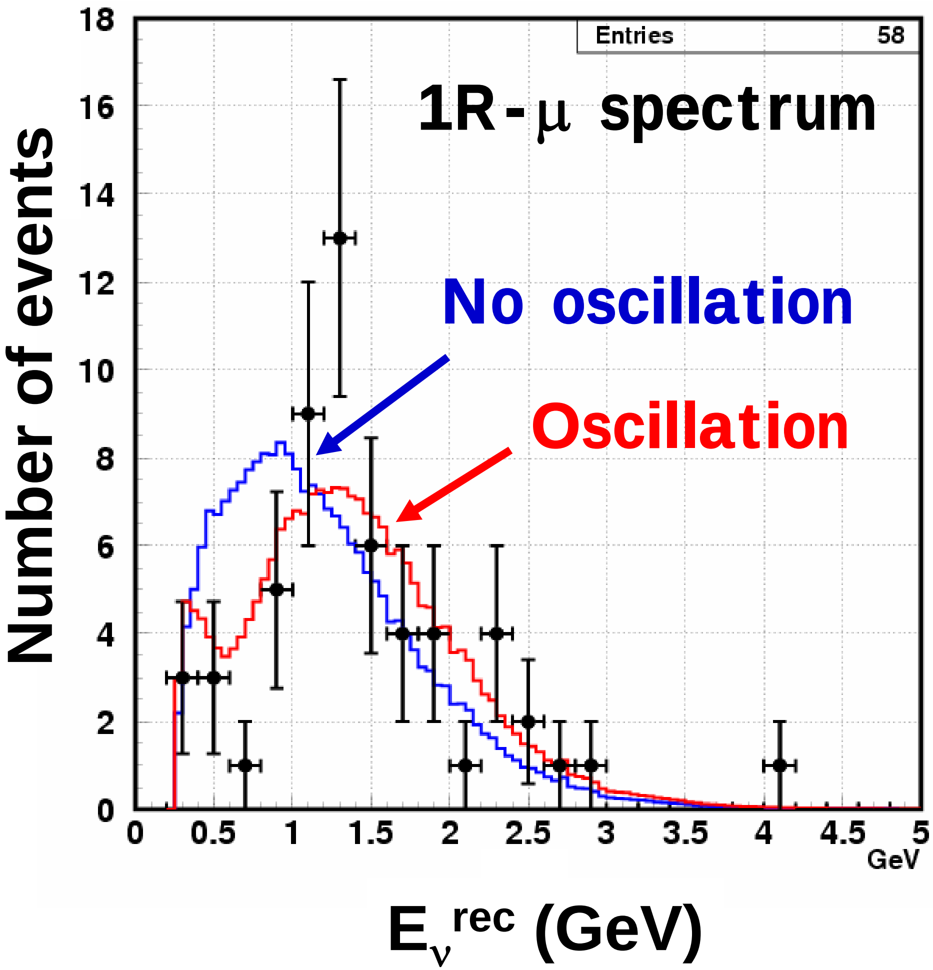


K2K-I+II	N_{sk}^{obs}	N_{sk}^{pred}
FC in 22.5kt	112	155.9
1ring	67	99.0
μ-like	58	90.8
e-like	9	8.2
Multi Ring	45	56.8

K2K events observed in Super-Kamiokande as a function of POT (protons delivered onto the target)

Total POT delivered: 1.049×10^{20}
Used for analysis: 0.922×10^{20}

Spectrum/Oscillation Analysis



Best fit value
(all region)

$\sin^2 2\theta = 1.19 \pm 0.23$

$\Delta m^2 = (2.55 \pm 0.40)\times10^{-3}\mathrm{eV}^2$

(in physical region)

$\sin^2 2\theta = 1.0$

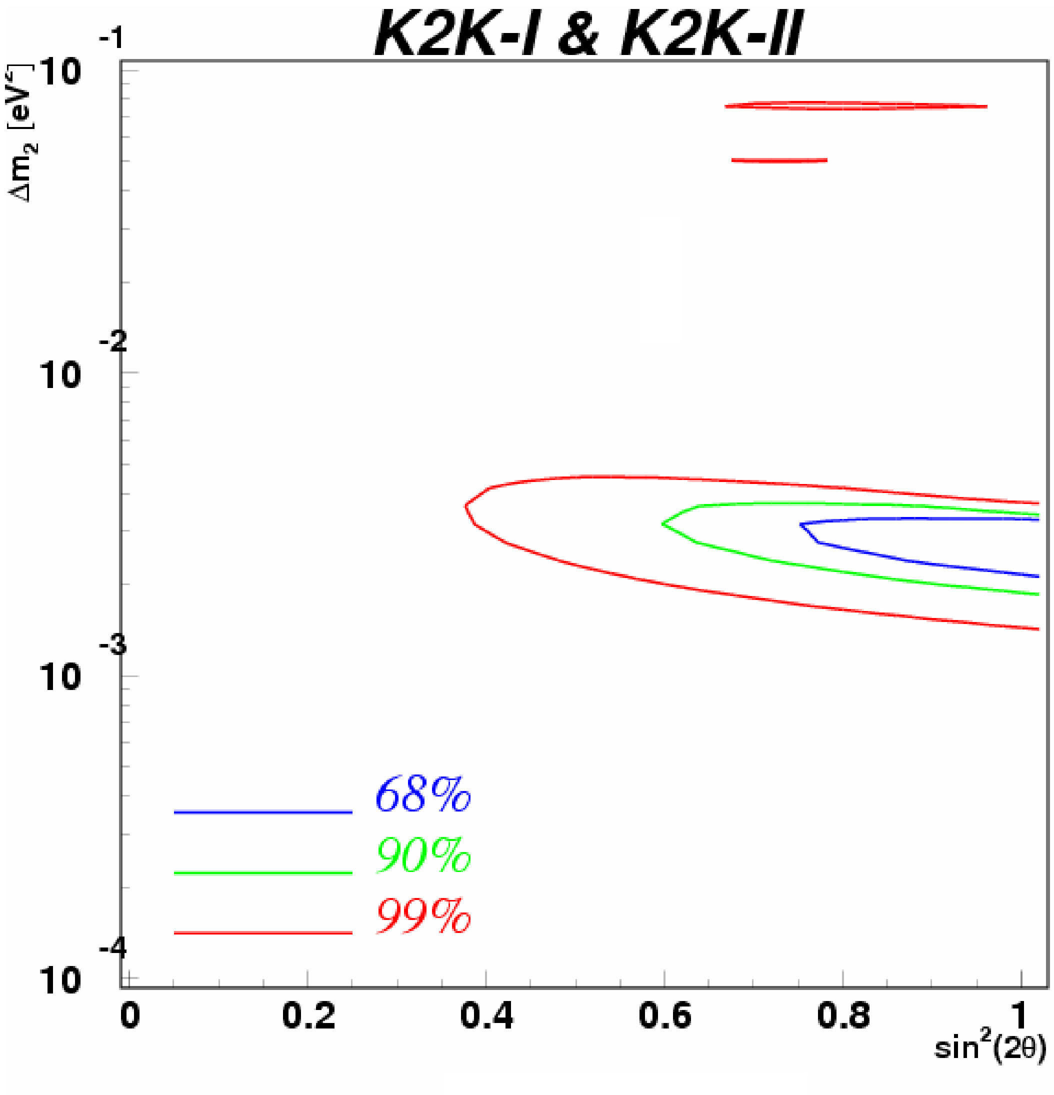
$\Delta m^2 = (2.76 \pm 0.36)\times10^{-3}\mathrm{eV}^2$

No oscillation prob.= 0.003% (4.2σ)
(for best fit in the phys. region)

$1.88\times10^{-3} \le \Delta m^2 \le 3.48\times10^{-3}$ eV^2
(90%CL) @ $\sin^2 2\theta=1$

Confirmed atmospheric neutrino oscillation

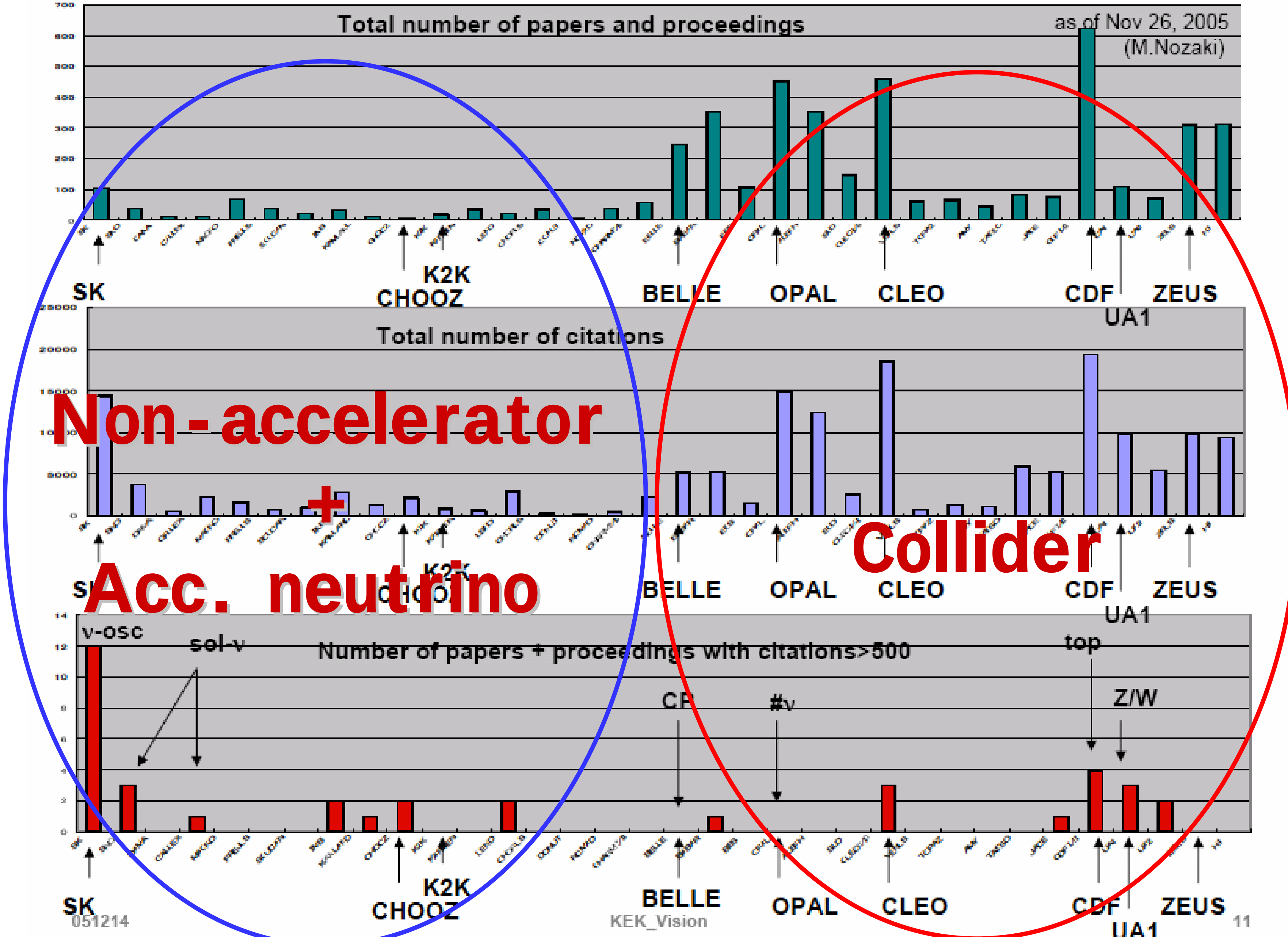
Allowed Parameter Region



Δm^2 (eV^2)

$\sin^2 2\theta$

Citation Analysis



将来ビジョン懇談会中間報告より

SPIRES

HEP :: HEPNAMES :: INSTITUTIONS :: CONFERENCES :: EXPERIMENTS :: JOBS :: VIDEOS

Modify your search below.

FIND CN K2K

Browse Author | Format: Standard Cites **Citesummary** LaTeX **72** Papers

Generated on **01/10/06** (mm/dd/yy)
Your result was: **72** [eligible papers = 44 (published or arXiv E-prints)]

Breakdown of search results by citation

	All papers	Published only
Renowned papers(500+ cites):	0	0
Famous papers (250-499 cites) :	1	1
Very well-known papers (100-249) :	1	1
Well-known papers (50-99) :	2	1
Known papers (10-49) :	11	4
Less known papers (1-9) :	20	8
Unknown papers (0) :	9	2
Total eligible papers analyzed:	44	17
Total number of citations:	1156	912
Average citations per paper:	26	54

Current SPIRES Data (Accumulated Citation Number)

CP VIOLATION IN THE RENORMALIZABLE THEORY OF WEAK INTERACTION.
By Makoto Kobayashi, Toshihide Maskawa (Kyoto U.),. 1973.
Published in Prog.Theor.Phys.49:652-657,1973
TOPCITE = 1000+ Cited 4608 times

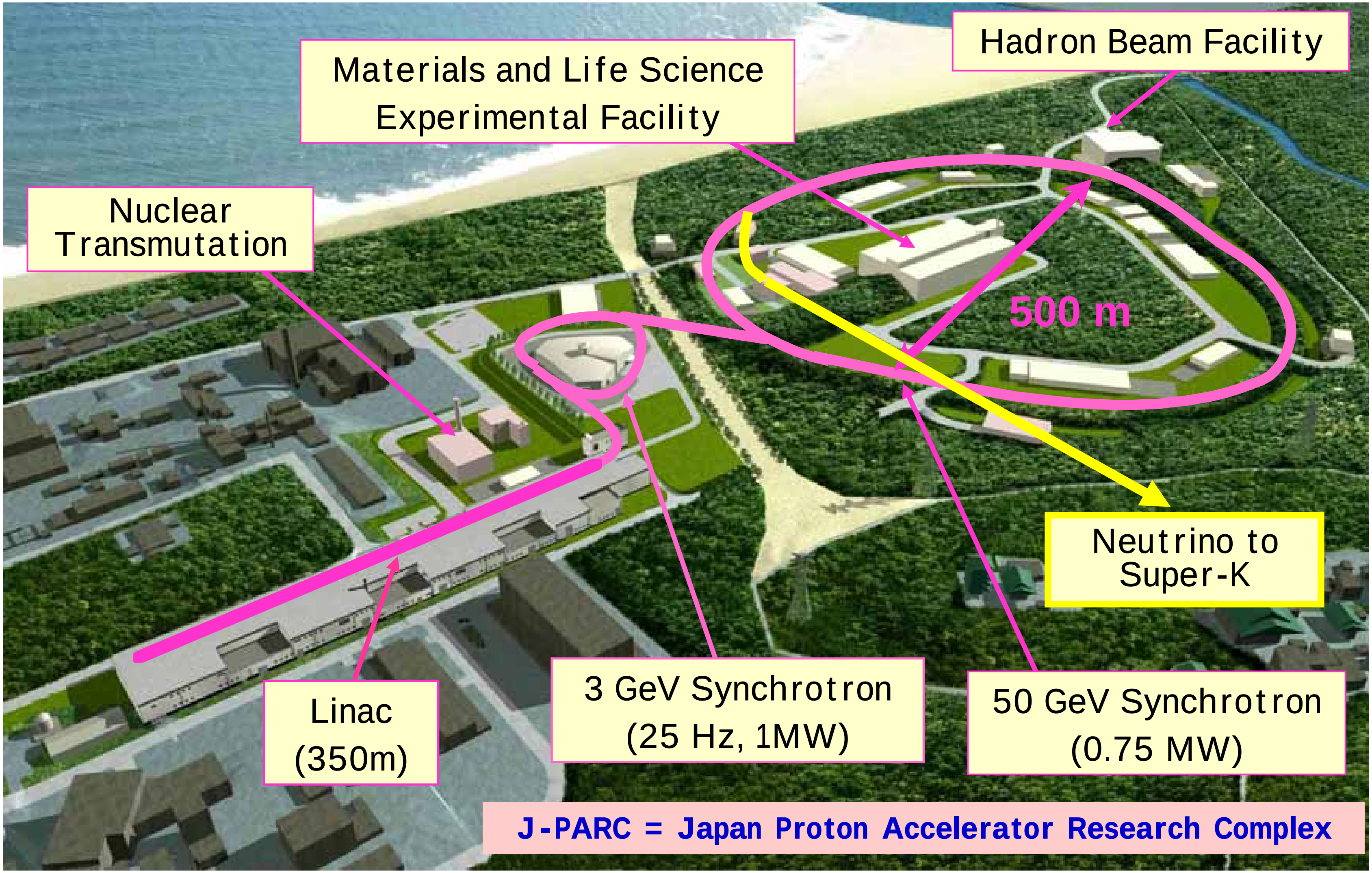
REVIEW OF PARTICLE PHYSICS. PARTICLE DATA GROUP.
By Particle Data Group (K. Hagiwara et al.). 2002.
Published in Phys.Rev.D66:010001,2002
TOPCITE = 1000+ Cited 3258 times

EVIDENCE FOR OSCILLATION OF ATMOSPHERIC NEUTRINOS.
By Super-Kamiokande Collaboration (Y. Fukuda et al.).
Published in Phys.Rev.Lett.81:1562-1567,1998
e-Print Archive: hep-ex/9807003
TOPCITE = 1000+ Cited 2532 times

INDICATIONS OF NEUTRINO OSCILLATION IN A 250 KM LONG BASELINE EXPERIMENT.
By K2K Collaboration (M.H. Ahn et al.). Dec 2002. 5pp.
Published in Phys.Rev.Lett.90:041801,2003
e-Print Archive: hep-ex/0212007
TOPCITE = 250+ Cited 476 times

OBSERVATION OF LARGE CP VIOLATION IN THE NEUTRAL B MESON SYSTEM.
By Belle Collaboration (K. Abe et al.).
Published in Phys.Rev.Lett.87:091802,2001
e-Print Archive: hep-ex/0107061
TOPCITE = 250+ Cited 339 times

12 GeV PSからJ-PARCへ

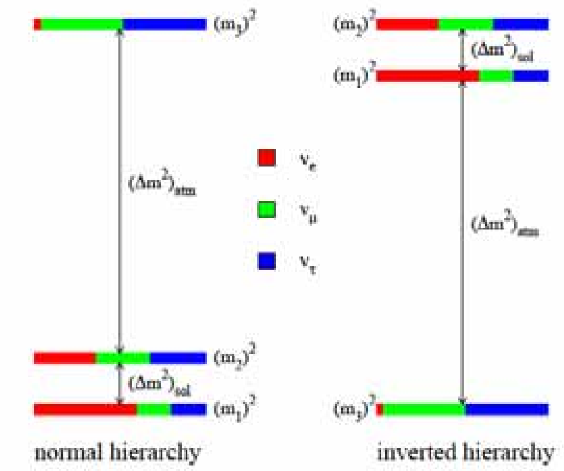


Joint Project between KEK and JAERI

Three unknown parameters

- Neutrino oscillations are sensitive to:
  - 2 mass squared differences
    - $\Delta m_{21}^2 = m_2^2 - m_1^2 = m_{solar}^2$
    - $\Delta m_{32}^2 = m_3^2 - m_2^2 = m_{atm}^2$
    - $(\Delta m_{21}^2 + \Delta m_{32}^2 + \Delta m_{13}^2 = 0)$
    - $\mathrm{Sign}(\Delta m_{31}^2)$ unknown --- mass hierarchy
  - 3 mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
  - 1 CP violating phase in the mixing matrix: δ

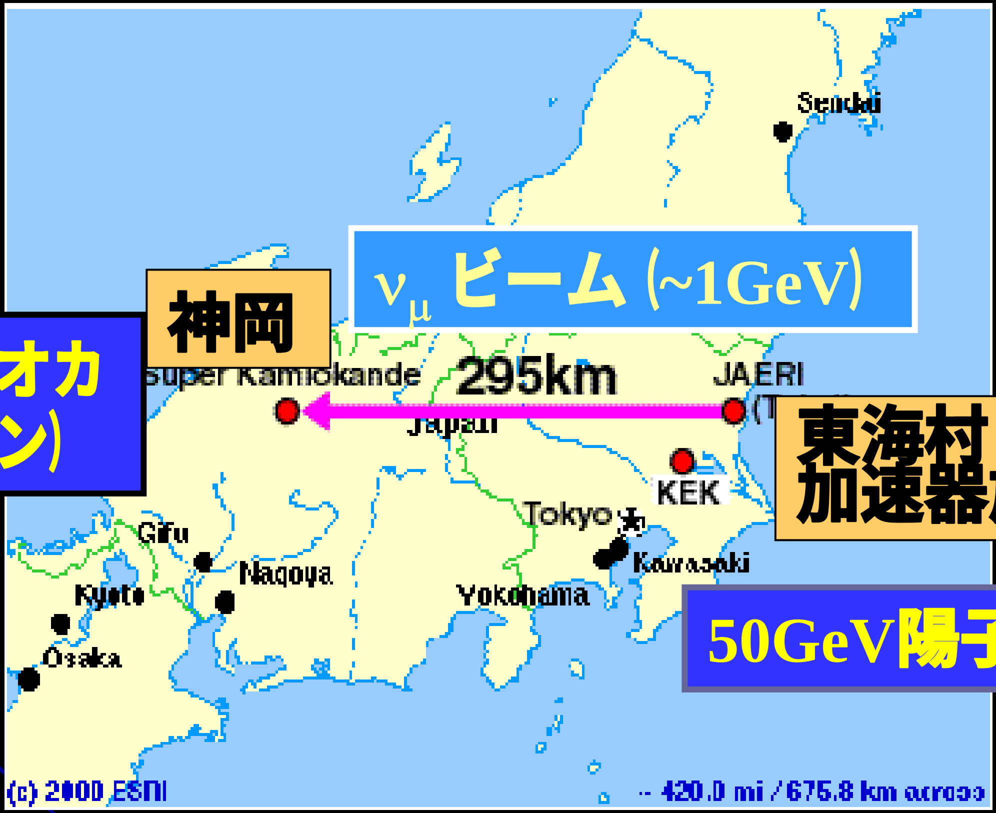
$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & <\mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$



Super-Kの発見以後の加速器ニュートリノ振動実験

- 第１世代：Super-Kの結果の検証
  - K2K
  - MINOS
  - OPERA
- 第２世代：θ_{13}の測定
  - T2K-I
  - (NoνA)
- 第３世代：δの測定、mass hierarchyの決定
  - (T2K-II)
  - (T2KK)
  - (NoνA with proton driver、・・・)

T2K-I



ν_μ ビーム (~1GeV)

神岡

295km

スーパーカミオカンデ　(5万トン)

東海村　大強度陽子加速器施設 (J-PARC)

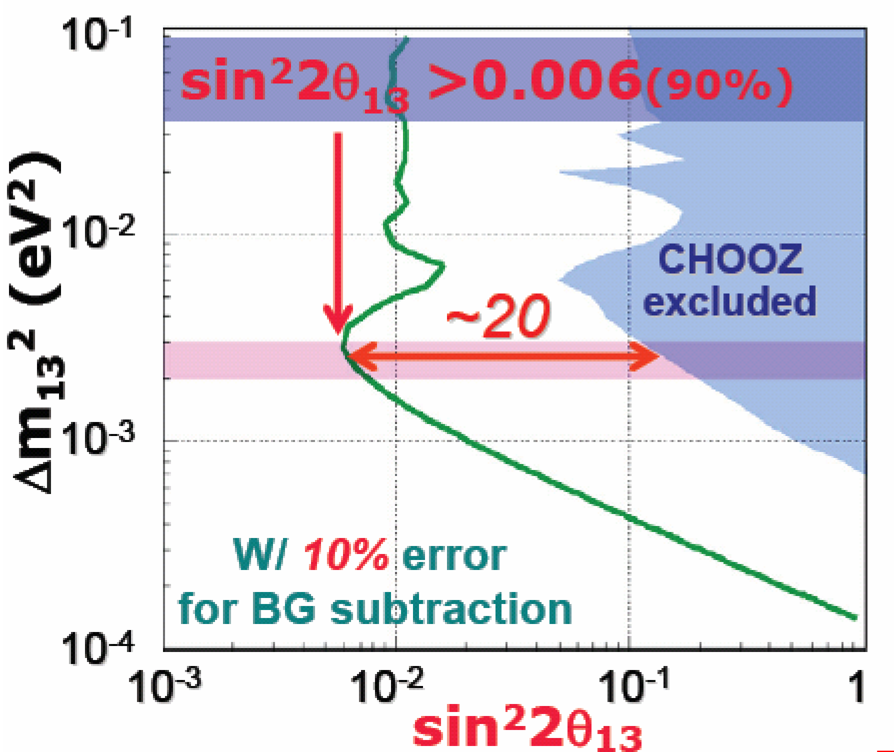
50GeV陽子加速器 (750 kW)

K2K実験の100倍のビーム強度

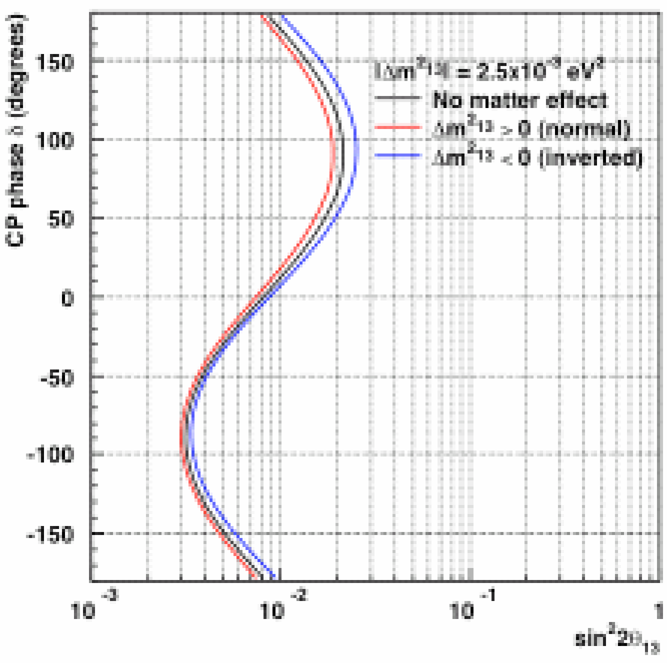
- $\nu_\mu \rightarrow \nu_e$ 振動の発見 (θ_{13}の測定)
- $\nu_\mu \rightarrow \nu_\tau$ 振動パラメーターの精密測定

Sensitivity to θ_{13} as a function of δ for normal and inverted mass hierarchies

- 40 GeV
- 10^{21} POT/yr
- 5 years

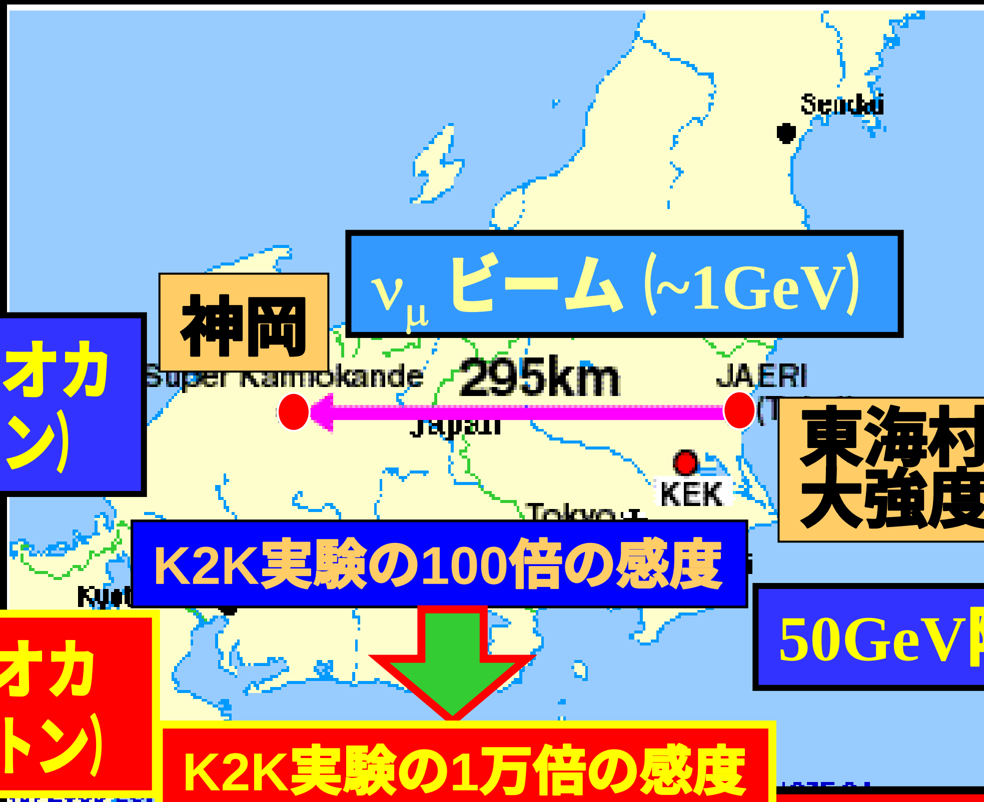


Assuming $\sin^2\theta_{23}=0.5$, $\delta=0$, no matter



Poor sensitivity to sign (Δm_{31}^2)

将来の構想（T2K-II）



ν_μ ビーム (~1GeV)

神岡

295km

東海村
大強度陽子加速器施設

スーパーカミオカンデ　(5万トン)

↓

ハイパーカミオカンデ(100万トン)

K2K実験の100倍の感度

↓

K2K実験の1万倍の感度

50GeV陽子加速器(1MW)

↓

50GeV陽子加速器(5MW)

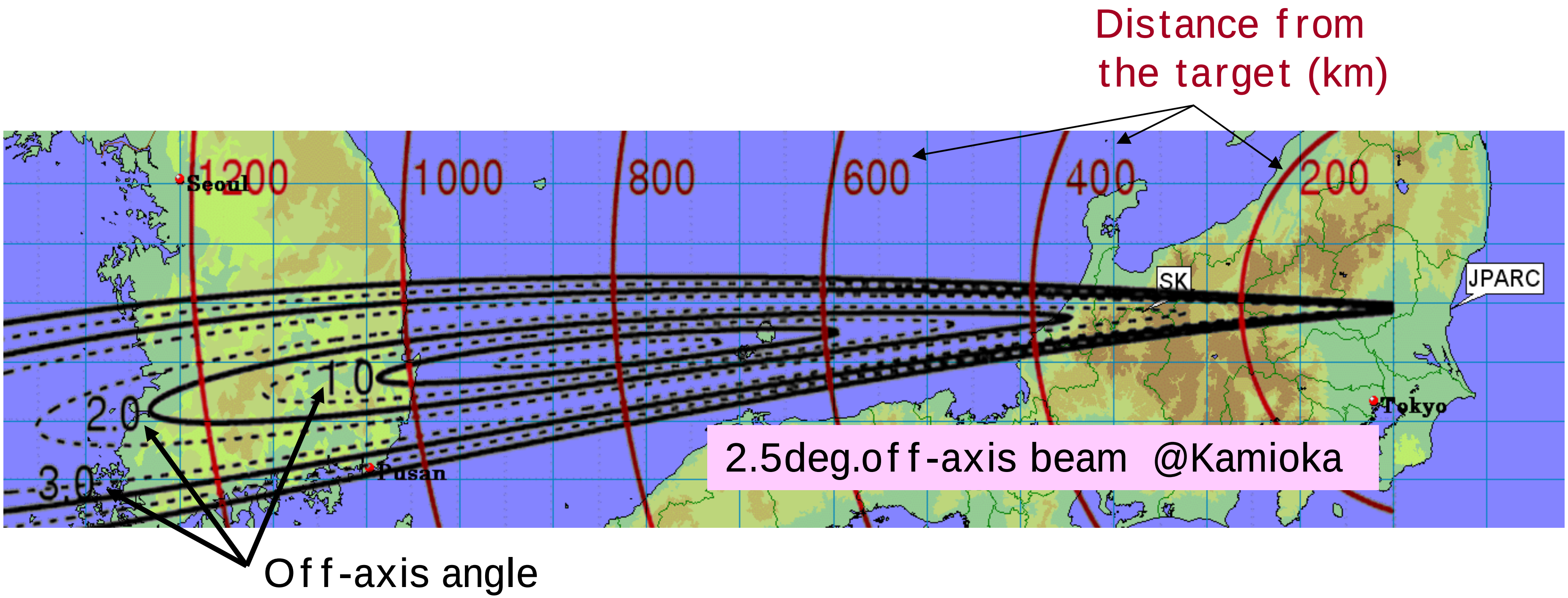
ニュートリノ振動でのCPの破れ ➡ $\nu_\mu \rightarrow \nu_e$ と $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ の差

小さい　　　もっと小さい

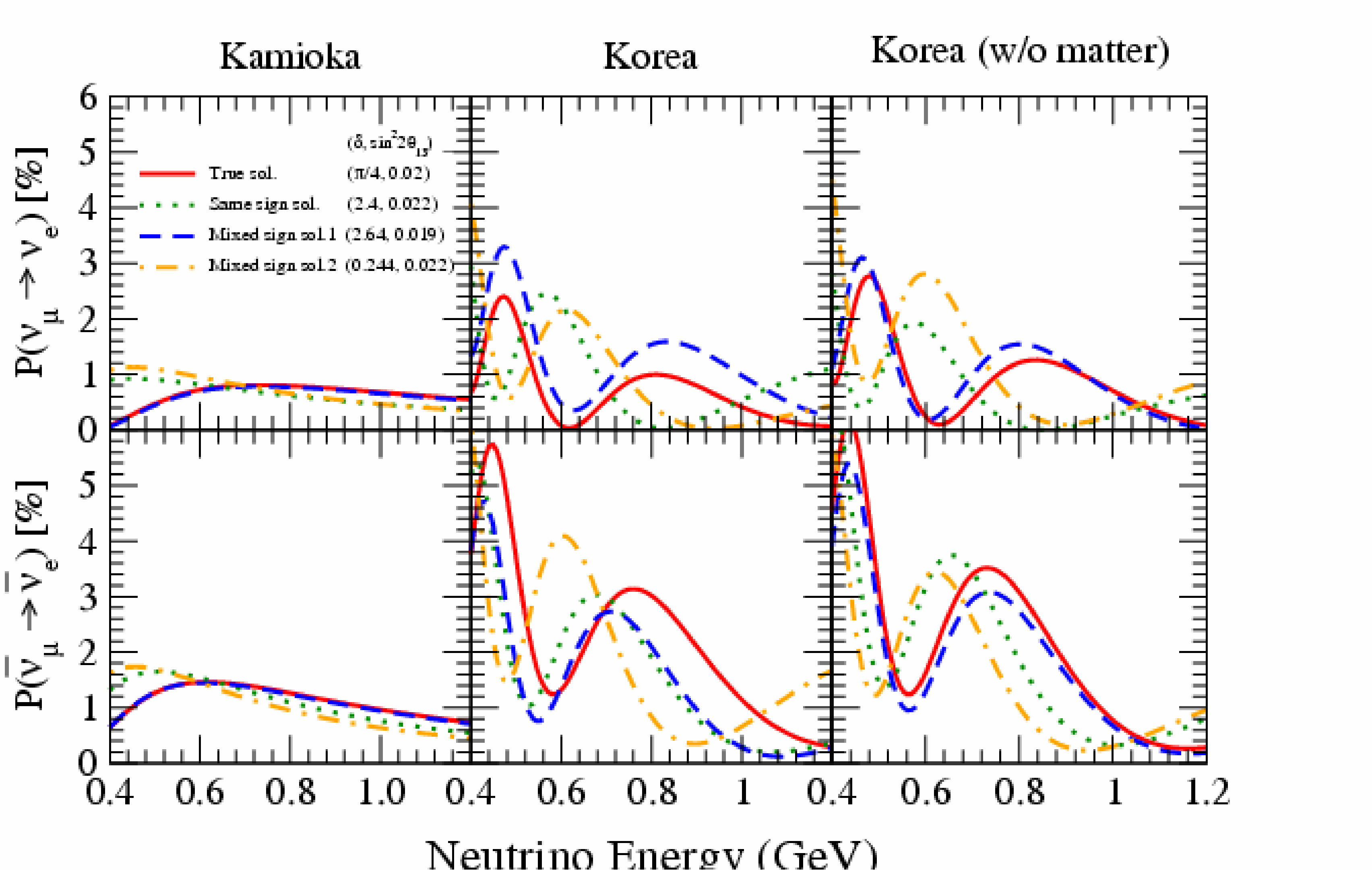
K2K実験の1万倍の感度が必要
更に、$\Delta m_{31}{}^2$の符号を決める必要。

How can T2K measure sign(Δm_{32}^2)?

- Put another detector in Korea (T2KK).
- Can measure θ_{13}, δ, and sign(Δm_{32}^2) simultaneously.
  - Hagiwara, Okamura, Senda
  - Ishitsuka, Kajita, Minakata, Nunokawa



Spectra measured in Korea are different for degenerate solutions



Ishitsuka, Kajita, Minakata, Nunokawa

Sensitivity for 5 detector options - mass hierarchy -

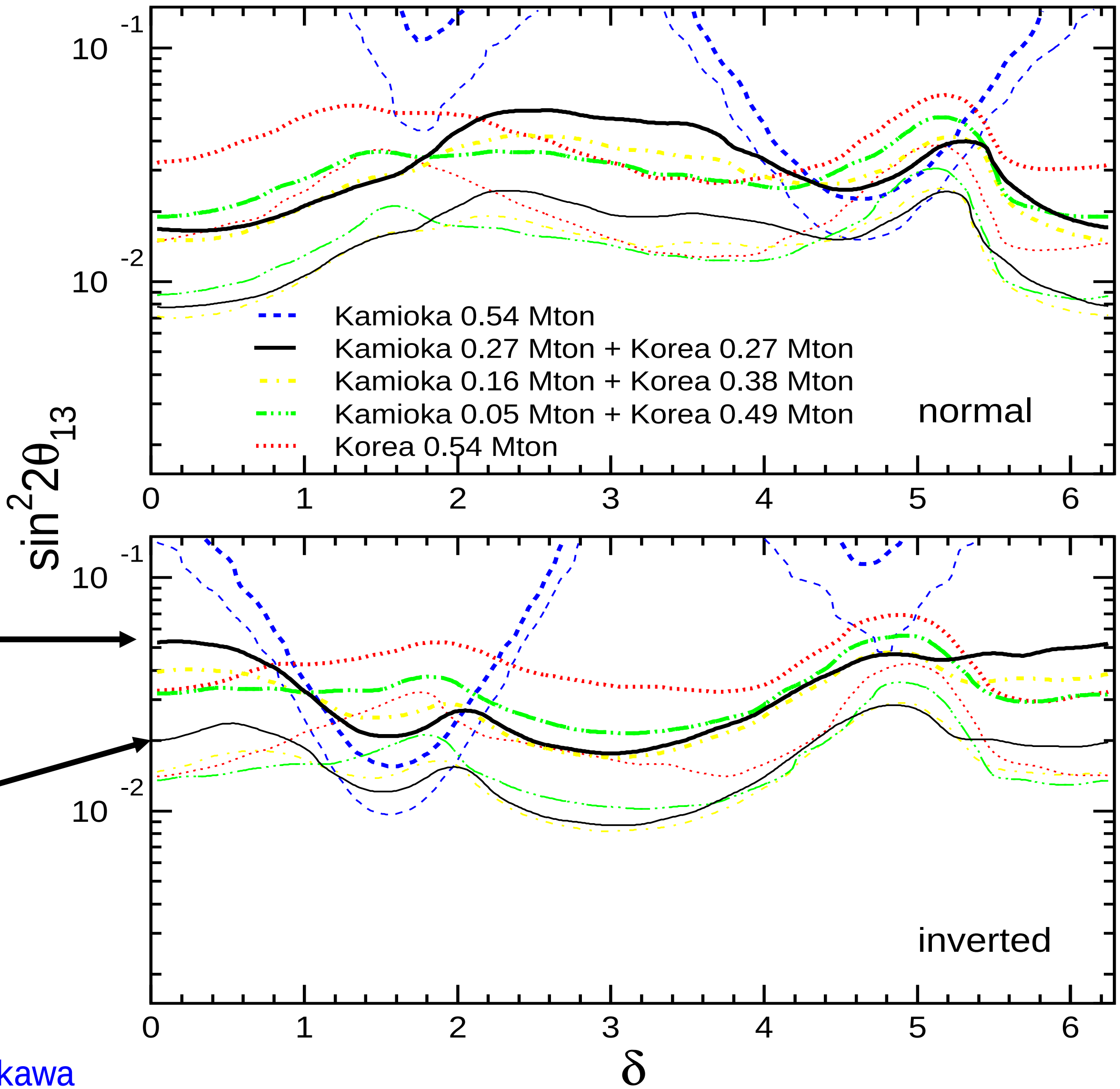
Always assumed:

Kamioka + Korea = 0.54 Mton fid. Mass

4 years neutrino beam + 4 years anti-neutrino beam

3 σ discrimination (thick lines)

2 σ discrimination (thin lines)



Ishitsuka, Kajita, Minakata, Nunokawa

12 GeV PSにおけるK中間子崩壊実験

- 標準模型の検証＋New Physicsの探索
  - Rare (or forbidden) processes
  - Symmetry violation: CP, T
  - → 精密実験
- 第１期（TRISTAN以前）、第２期（TRISTAN以後）にも世界と競う成果。
  - E10（長島）　：$K^+ \to \pi^+ \nu \nu$
  - E137（稲垣）：$K_L \to \mu e$
  - E162（笹尾）：$K_L \to \pi^+ \pi^- e^+ e^-$
  - E195（今里）：$K^+ \to \mu^+ \nu$におけるμ^+偏極の精密測定
- 第３期はKEK-PSが世界の中心の一つとなる。

E10 / RPP '88

$\Gamma(\pi^+ \nu\bar{\nu})/\Gamma_{total}$ Γ_{34}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interactions.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 0.14	90		ASANO	81B	CNTR	+	$T(\pi)$ 116–127 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 0.94	90		[47] CABLE	73	CNTR	+	$T(\pi)$ 60–105 MeV
< 0.56	90		[47] CABLE	73	CNTR	+	$T(\pi)$ 60–127 MeV
<57.0	90	0	[48] LJUNG	73	HLBC	+	
< 1.4	90		[47] KLEMS	71	OSPK	+	$T(\pi)$ 117–127 MeV

[47] KLEMS 71 and CABLE 73 assume π spectrum same as K_{e3} decay. Second CABLE 73 limit combines CABLE 73 and KLEMS 71 data for vector interaction.

[48] LJUNG 73 assumes vector interaction.

E137/ RPP '92

$\Gamma(e^{\pm}\mu^{\mp})/\Gamma_{total}$ Γ_{18}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-10})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
< **0.94**	90	0	AKAGI	91	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 4.3	90		INAGAKI	89	SPEC	In AKAGI 91
< 2.2	90		MATHIAZHA...	89	SPEC	
< 19	90		SCHAFFNER	89	SPEC	
<110	90		COUSINS	88	SPEC	
< 67	90		GREENLEE	88	SPEC	Repl. by SCHAFFNER 89
< 15.7	90		[32] CLARK	71	ASPK	

[32] Possible (but unknown) systematic errors. See note on CLARK 71 $\Gamma(\mu^+\mu^-)/\Gamma(\pi^+\pi^-)$ entry.

BNL E791

E162 / RPP '04

$\Gamma(\pi^+\pi^- e^+ e^-)/\Gamma_{total}$ Γ_{27}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by higher-order electroweak interaction.

VALUE (units 10^{-7})	CL%	EVTS		DOCUMENT ID		TECN	COMMENT
3.11±0.19 OUR AVERAGE							
3.08±0.09±0.18		1125	40	LAI	03C	NA48	
3.2 ±0.6 ±0.4		37		ADAMS	98	KTEV	
4.4 ±1.3 ±0.5		13		TAKEUCHI	98	SPEC	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<4.6	90			NOMURA	97	SPEC	$m_{ee} > 4$ MeV

E195/ RPP '04

K^+ LONGITUDINAL POLARIZATION OF EMITTED μ^+

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
<−0.990	90	[64] AOKI	94	SPEC	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.990	90	IMAZATO	92	SPEC	+	Repl. by AOKI 94
−0.970±0.047		[65] YAMANAKA	86	SPEC	+	
−1.0 ±0.1		[65] CUTTS	69	SPRK	+	
−0.96 ±0.12		[65] COOMBES	57	CNTR	+	

[64] AOKI 94 measures $\xi P_\mu = -0.9996 \pm 0.0030 \pm 0.0048$. The above limit is obtained by summing the statistical and systematic errors in quadrature, normalizing to the physically significant region ($|\xi P_\mu| < 1$) and assuming that ξ=1, its maximum value.

[65] Assumes ξ=1.

$|(\xi$ PARAMETER)×(μ LONGITUDINAL POLARIZATION)$|$

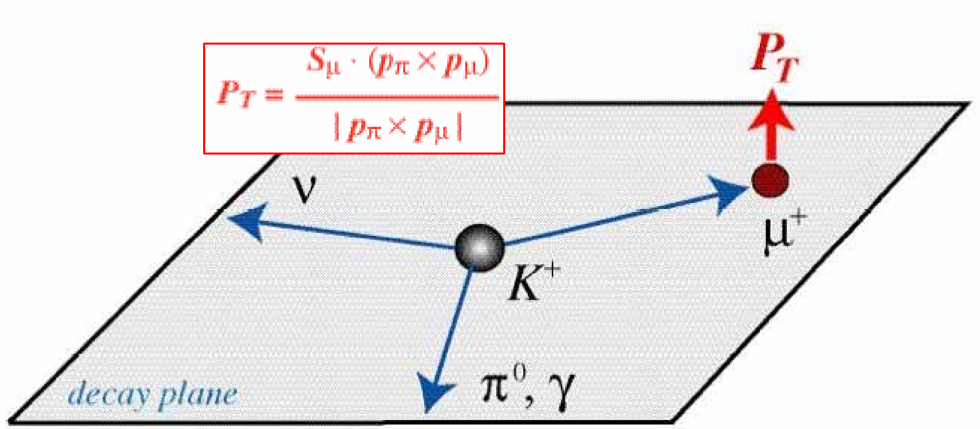
($V-A$) theory predicts $\xi = 1$, longitudinal polarization = 1.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.0027±0.0079±0.0030		BELTRAMI	87	CNTR		SIN, π decay in flight
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.0013±0.0030±0.0053		[35] IMAZATO	92	SPEC	+	$K^+ \to \mu^+ \nu_\mu$
0.975 ±0.015		AKHMANOV	68	EMUL		140 kG
0.975 ±0.030	66k	GUREVICH	64	EMUL		See AKHMANOV 68
0.903 ±0.027		[36] ALI-ZADE	61	EMUL	+	27 kG
0.93 ±0.06	8354	PLANO	60	HBC	+	8.8 kG
0.97 ±0.05	9k	BARDON	59	CNTR		Bromoform target

[35] The corresponding 90% confidence limit from IMAZATO 92 is $|\xi P_\mu| > 0.990$. This measurement is of K^+ decay, not π^+ decay, so we do not include it in an average, nor do we yet set up a separate data block for K results.

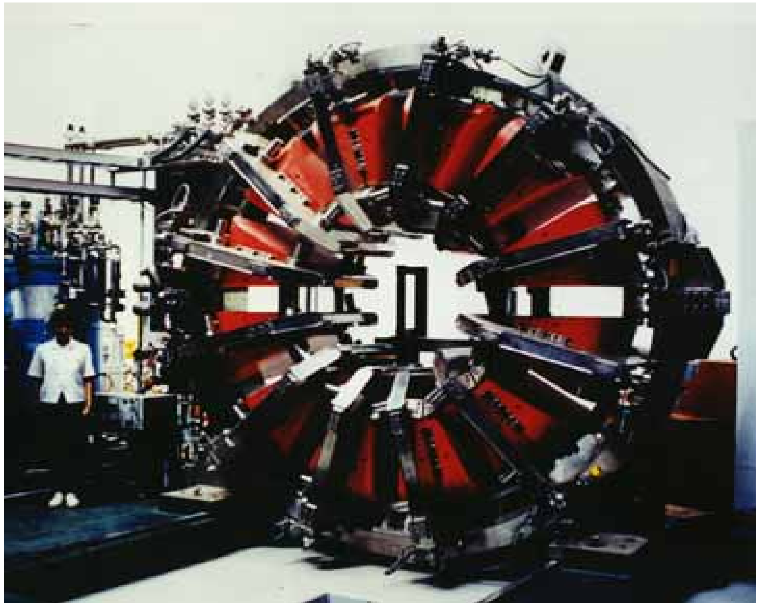
T violation in $K^+ \rightarrow \pi^0 \mu^+ \nu$

measurement of muon transverse polarization



E246 experiment

- North counter hall
- K5 stopped K^+ beam
- SC Toroidal Spectrometer
- Beam time of 650 shifts



- T-odd correlation
- small final state interactions

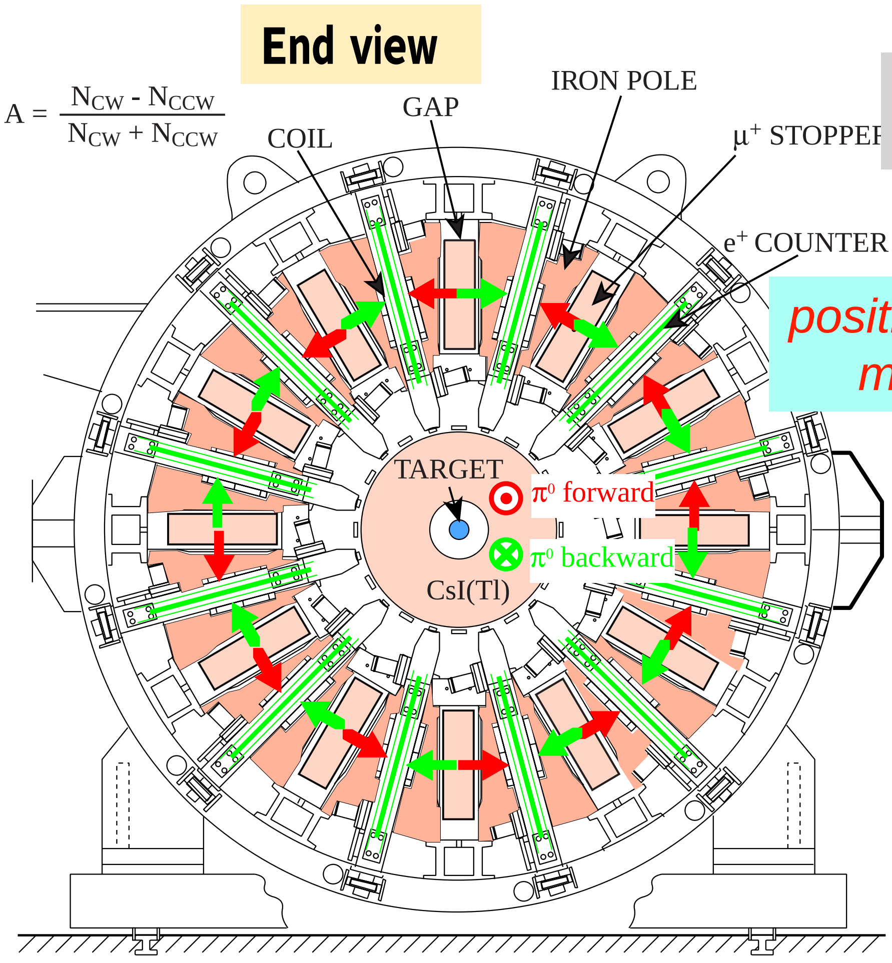
$P_T \neq 0$ ⇒ T violation

(CPT theorem) ⇒ CP violation

- **P_T (Standard Model) ~ 10^{-7}**
- **P_T (Final State Interaction) ~ 10^{-6}**
- ***P_T is a sensitive probe of non-SM CP violation***

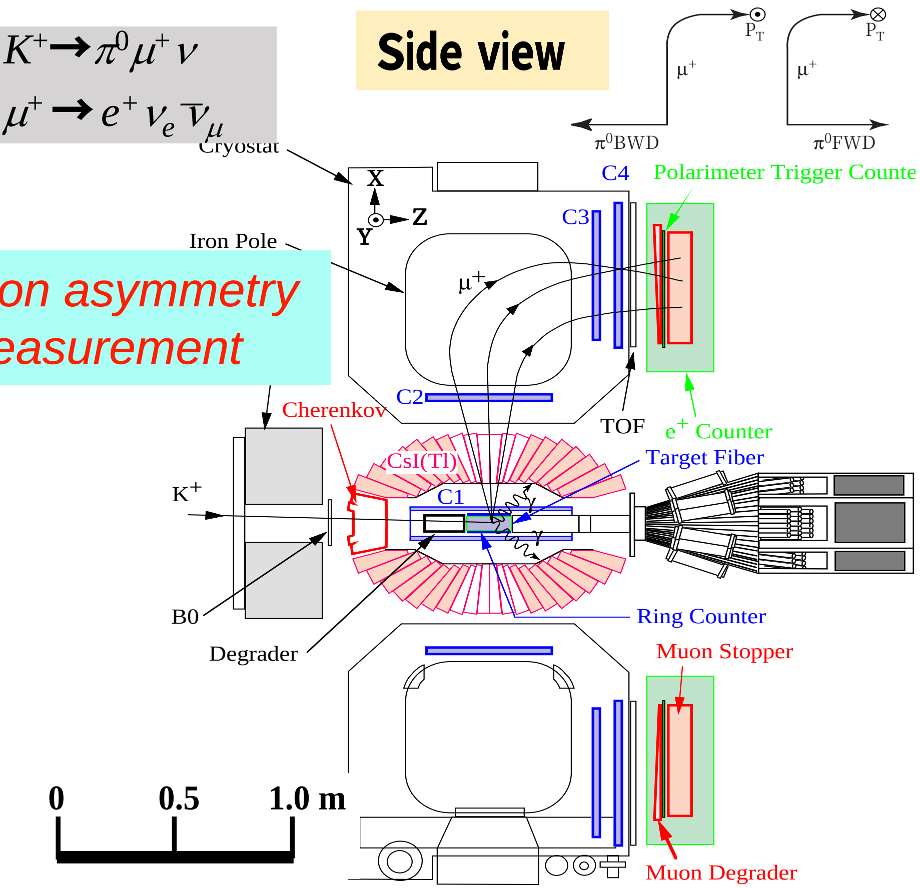
E246 setup and results

$$A = \frac{N_{CW} - N_{CCW}}{N_{CW} + N_{CCW}}$$



$$K^+ \rightarrow \pi^0 \mu^+ \nu$$
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

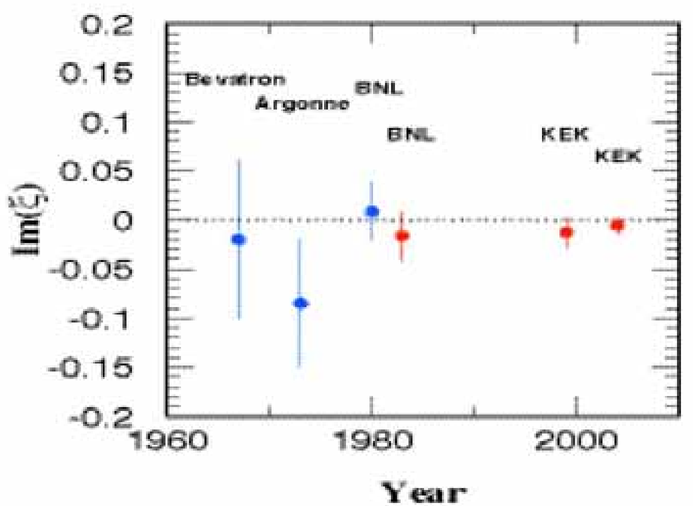
positron asymmetry measurement



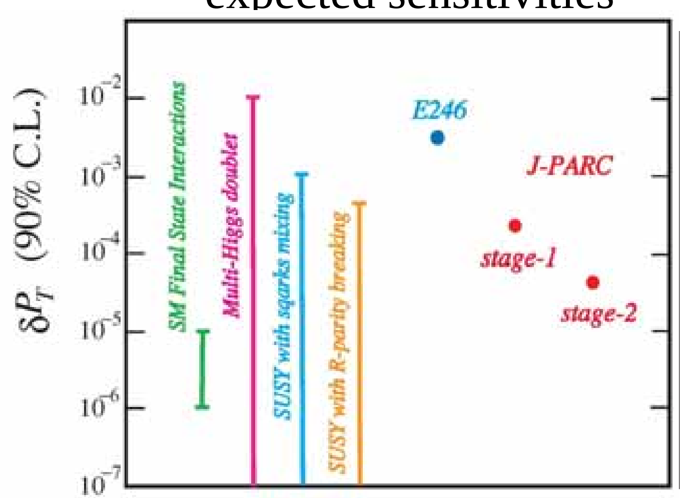
- P_T = - 0.0017 ± 0.0023 (*stat*) ± 0.0011(*syst*) ($|P_T| < 0.0050$: 90% *C.L.*)
- Imξ = - 0.0053 ± 0.0071 (*stat*) ± 0.0036 (*syst*) ($|\mathrm{Im}\xi| < 0.016$: 90% *C.L.*)

T violation in the J-PARC era

History of $K_{\mu 3}$ P_T



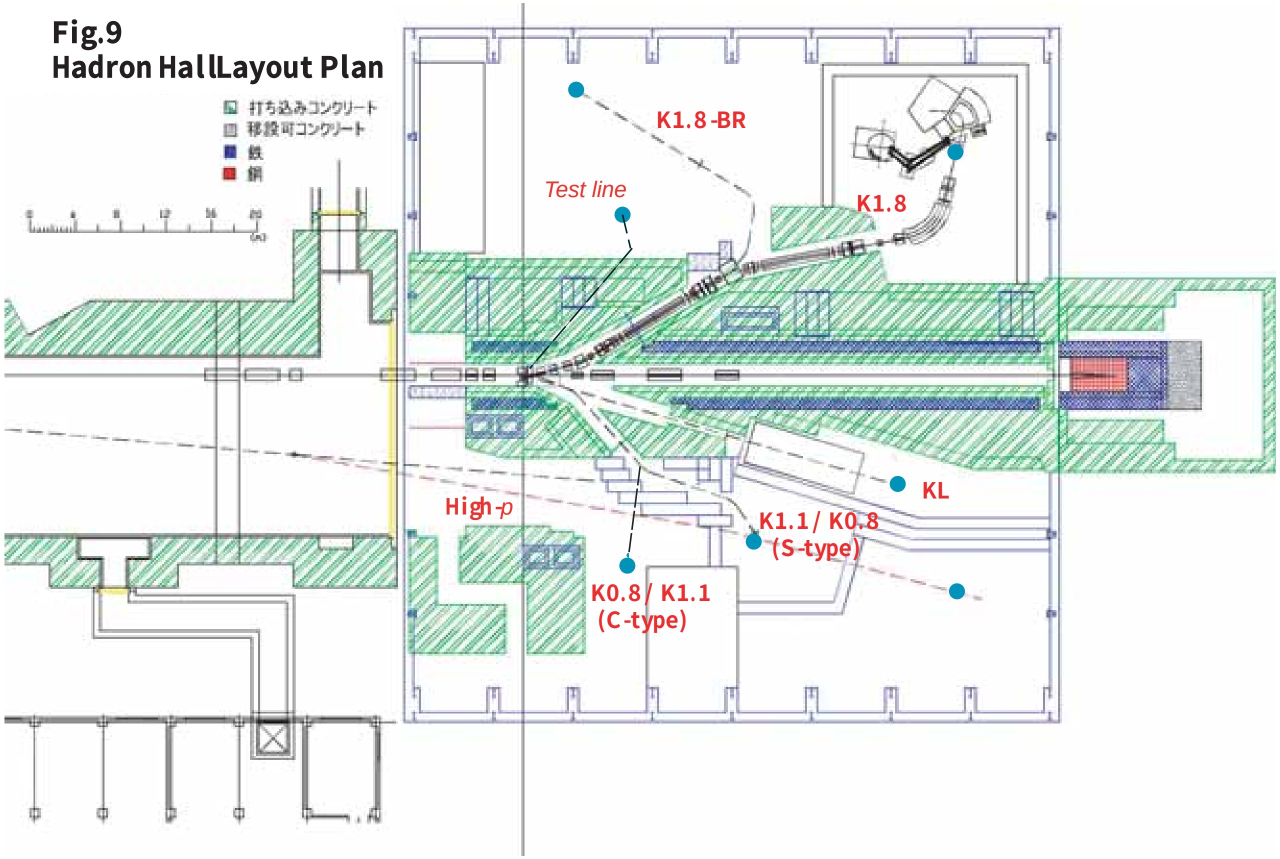
Model-allowed regions and expected sensitivities



Motivation for J-PARC experiments

- **Sensitivity reaches the allowed regions of several new physics models**
- **P_T is sensitive to scalar interactions of the type (flavor off-diagonal) different from EDM and *g*-2, and not measurable at LHC, and tensor interactions**
  [W.-F. Chang and J.Ng hep-ph/0512334]
- **E246 was statistical-error limited**
  - *No problem at all to improve the error*
  - *Further suppression of systematic errors is also possible with an upgraded detector*
- **P_T ($K \rightarrow \gamma\mu\nu$) can be also measured which is complementary to $P_T(K_{\mu 3})$ with pseudo-scalar interactions**
  [M.Kobayashi *et al*. Prog.Theo.Phys. 55 (1996)]

Possible secondary lines in Phase 1



- only small experimental area in Phase 1 (60m^{W}x 56m^{L}) with one primary line and a production target

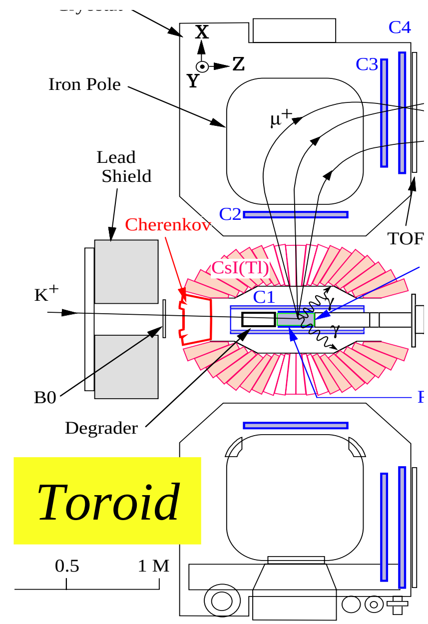
J-PARC experiment

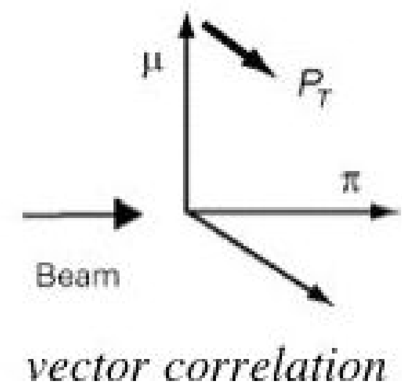
First stage in Phase-1

E246 upgraded detector

- Addition of a new tracking element
- Finer segmentation of target fiber
- Improvement of CsI(Tl) readout
- Active polarimeter
- New magnet for muon field
- Precise alignment

$\delta P_T \sim 1.2 \times 10^{-4}$ @10^6/s K^+ & 10^7 s

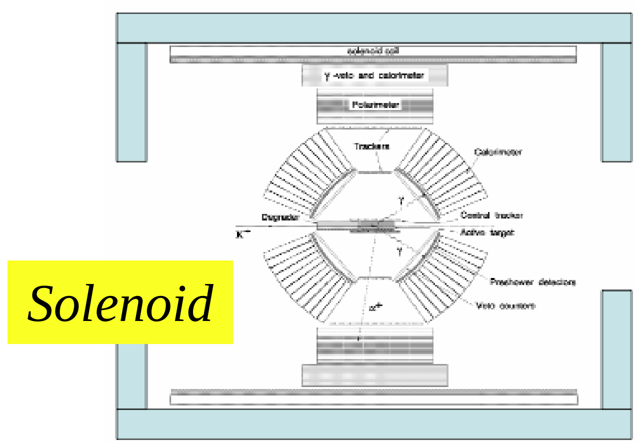


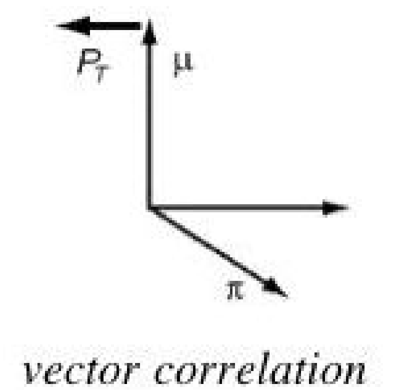


Second stage

New detector with larger Acceptance

$\delta P_T \sim 4 \times 10^{-5}$ ($K_{\mu 3}$)
$\delta P_T \sim 7 \times 10^{-5}$ ($K_{\mu\nu\gamma}$)
@10^6/s K^+ & 10^7 s



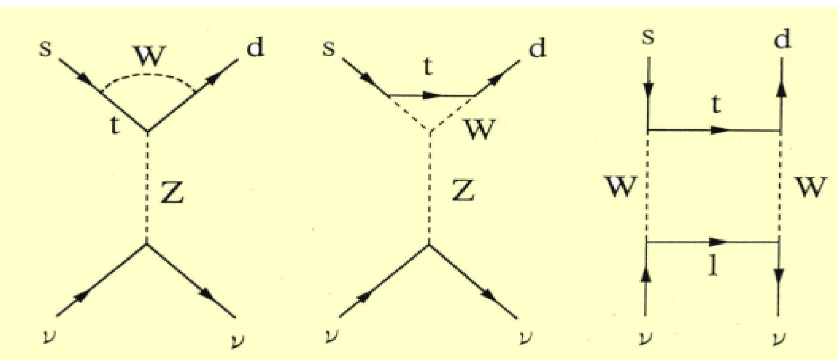


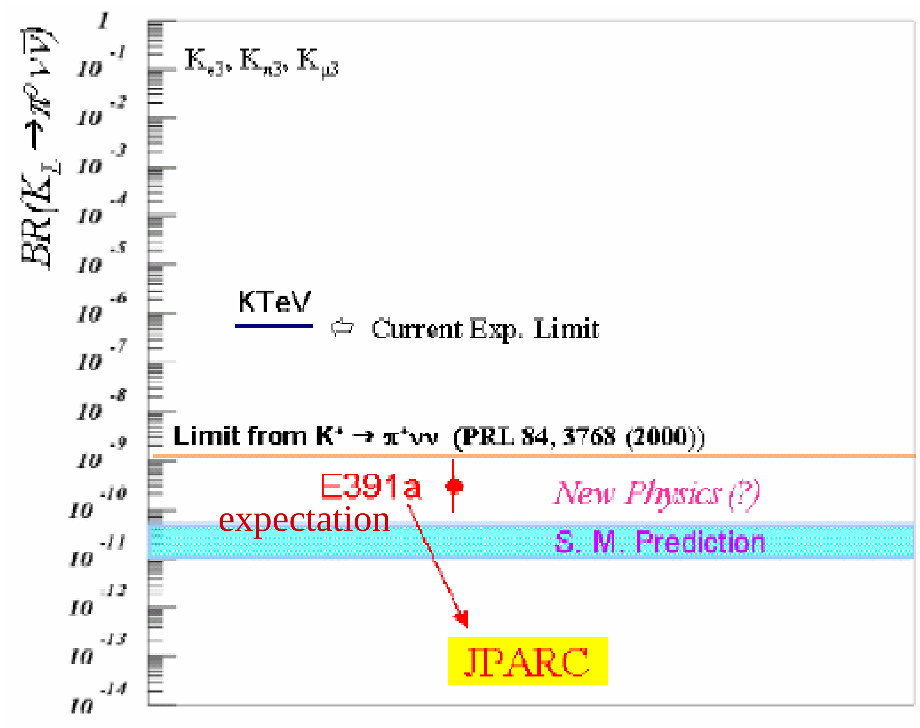
Precise measurement of Br($K_L \to \pi^0 \nu\bar{\nu}$)

E391a at KEK-PS and extension at J-PARC

$K_L \to \pi^0 \nu\bar{\nu}$ physics

- Flavor Changing Neutral Current
- Direct CP violation ($\Delta s = 1$)



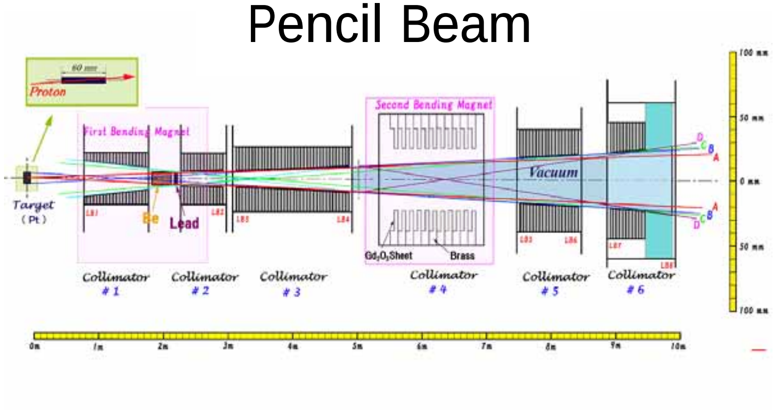


- Clean measurement of Im(V_{td})
- Most clear test for the standard model
- Clue for the new physics

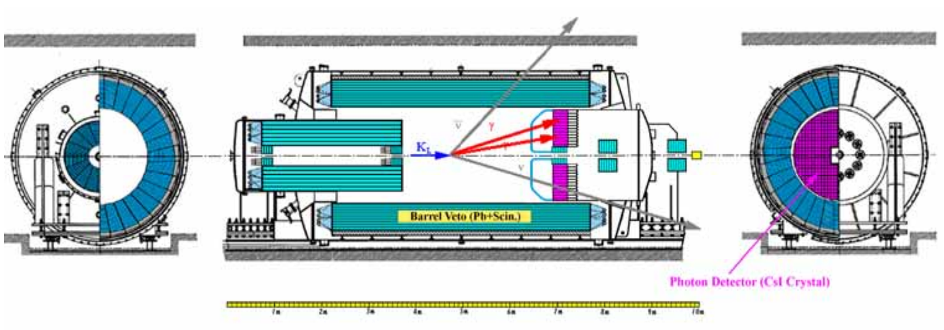
Method

- **Pencil beam**
- **Detector with complete veto system**
  - **4π coverage with thick calorimeter**
  - **Wide acceptance**
  - **Double decay chamber**
  - **Operation in high vacuum**
- **High P_T selection**
- **Step by step approach**
  - **KEK-PS E391a**
  - **J-PARC**

Pencil Beam



Detector system



Run Summary of E391a

We established several techniques

Pencil beam, high vacuum, large size calorimeters, calibrations, *etc*

Three runs since 2004

Run-1: Feb.-June 2004, 200 shifts

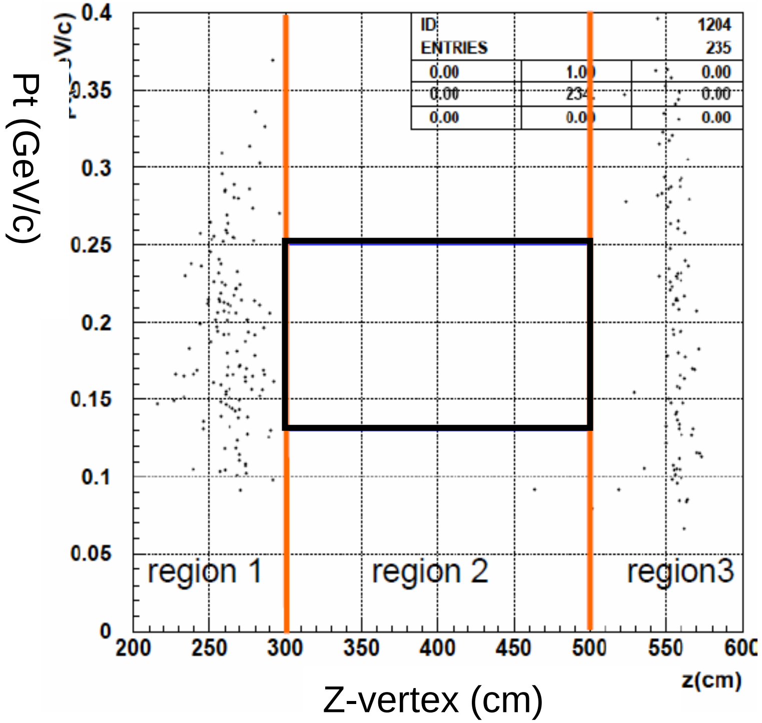
Run-2: Jan.-April 2005, 120 shifts

Run-3: Nov.-Dec 2005, 100 shifts

Promising figure is seen in a preliminary analysis using a few % sample.

Expect to improve the present limit by 2-3 orders of magnitude, which is a good stand point for J-PARC experiment.

Final plot using Run-2 one week data



Extension to J-PARC

Two step approach

Step-1: A-line, T0-target (share with K+ beam user), and detector modifications

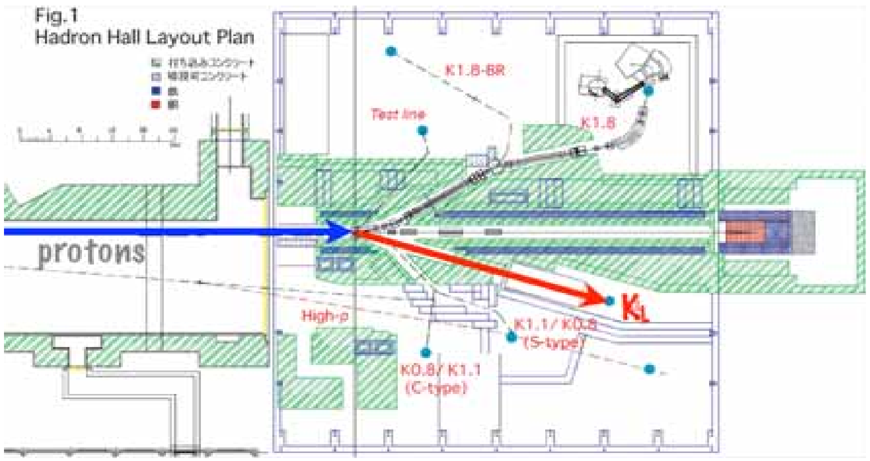
10 SM events

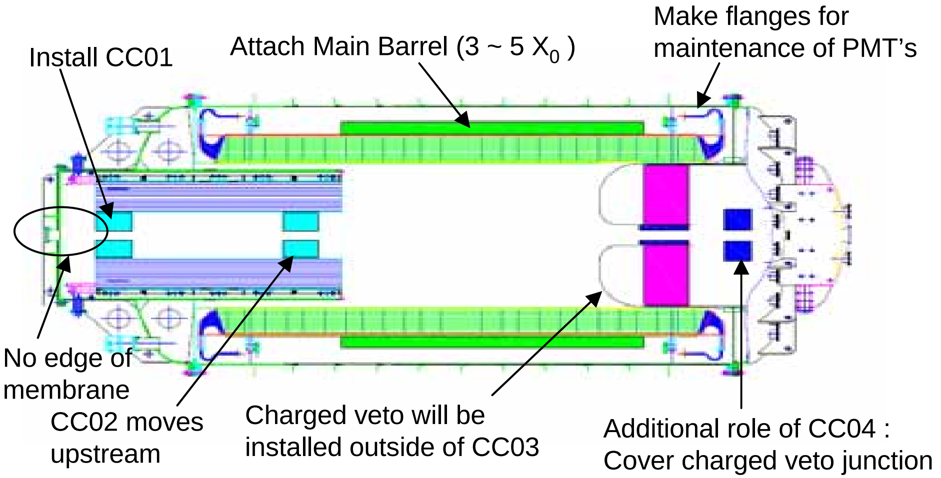
"*Discovery*"

Step-2: B-line (dedicated) and brand new detector

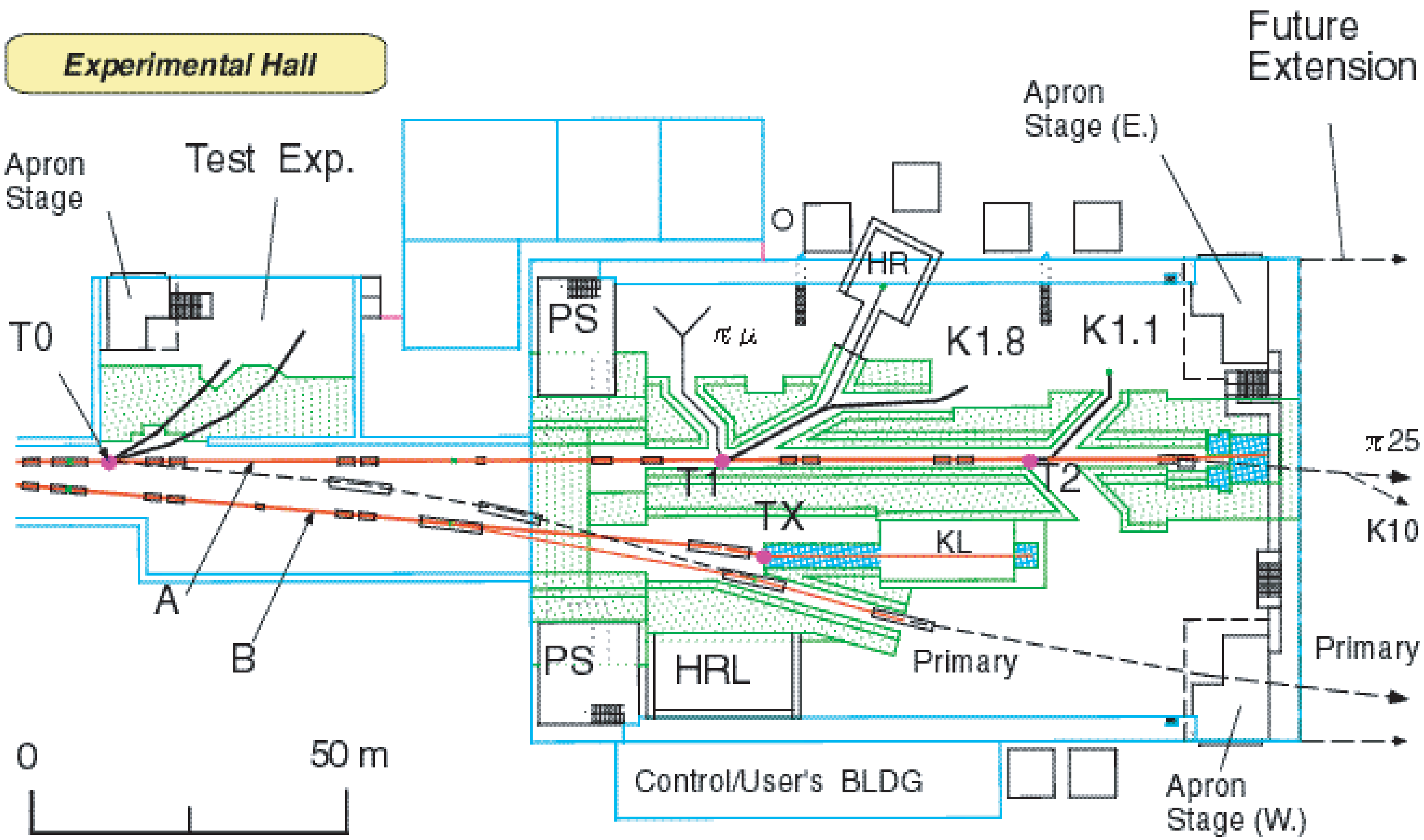
>100 SM events

"*Measurement*"





Phase-2 Hall



- Hall size = 60m (W) x 100 m (L)
- More than 2 target stations
- Test beam facility

各時代のPS（素粒子実験の立場から）

- 第１期（1977-1984）
  - PSはKEKの高エネルギーの表看板であったが、世界の注目を浴びることはなかった。
  - しかし、多くの人材を育成し、日本の高エネルギーの発展の基礎を築いた。
- 第２期（1985-1998）
  - 高エネルギーの主力が抜け、PSでは大型実験が可能となった。
  - K中間子崩壊実験がTRISTANの陰で世界に通用する実力を養成した時代。
  - （中高エネルギー核物理の台頭。）
- 第３期（1999-2005）
  - PS/K2KがKEKB/BELLEとともにKEKを代表する2大プロジェクトとして世界をリードした。
  - K中間子崩壊実験は、世界の中心の一つとなった。
  - （核物理はハイパー核、ハドロン物理で世界をリードする成果）
- PS加速器
  - 全期間を通じ、ビーム強度に不満はあったが、安定した運転とビーム供給は特筆される。ユーザーには使いやすいマシンであった。
- J-PARC
  - PSの成果を受け継ぎ、更に発展を見込む。
  - しかし、当初は忍耐を要するであろう。いかに短時間で軌道に乗せるかが問題。