

# Kaon 実験

T. Nomura (KEK)

# はじめに

- Beyond SM を狙うことはほぼ必然
  - “標準理論バックグラウンド”との分離が必要
    - 理論的不定性の小さいプロセスを攻める
    - 標準理論では起こらない／抑制されたプロセスを攻める
  - 稀現象を精密に測る
- どこかで何かが見えることは始まりでしかない(おそらく)
  - BSM存在証明→性質理解へ
    - 質量、相互作用、混合、保存則、などなど多種の測定が必要
      - ≡クォーク、レプトンでの歴史をなぞる
      - パラメータが増えたらもっと複雑。幸せかどうかは別として...
  - エネルギーフロンティアと相補的

# Kaon 実験状況

## • 国内

- CP violating rare decay:  $K_L \rightarrow \pi^0 \nu \nu$ 
  - E391a @ KEK  $\rightarrow$  KOTO @ J-PARC
- T violation: polarization in  $K^+ \rightarrow \pi^0 \mu \nu$ 
  - E246 @ KEK  $\rightarrow$  TREK @ J-PARC

検出器準備中

ビームライン建設中  
(フル採択はまだ)

## • 海外

- Lepton universality:  $R_K = K_{e2}/K_{\mu 2}$ 
  - NA62 phase 1 @ CERN
- Rare decay:  $K^+ \rightarrow \pi^+ \nu \nu$ 
  - NA62-II @ CERN
  - P996 @ FNAL

解析中

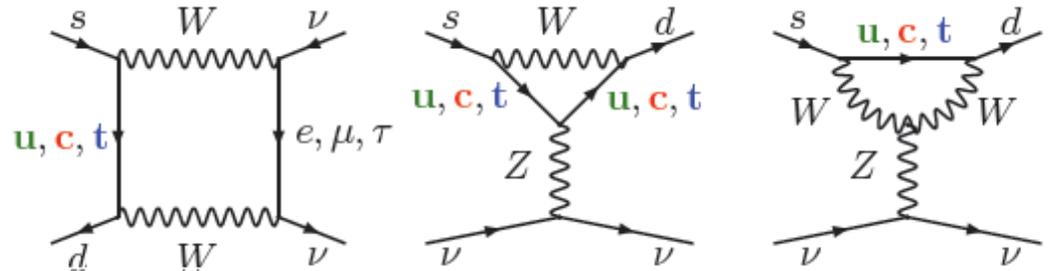
準備中

プロポーザル

Golden modes:  
Rare decay:  $K \rightarrow \pi \nu \nu$

# $K \rightarrow \pi \nu \nu$ in the standard model

- FCNC process
- Loop diagram



– Neutral : CP violating, top loop dominated

$$\text{Br}(K_L \rightarrow \pi^0 \bar{\nu} \nu) = \kappa_L \left( \frac{\text{Im}(V_{ts}^* V_{td})}{\lambda^5} \chi(x_t) \right)^2$$

– Charged: CP conserving, top and charm loop

$$\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}(\gamma)) = \kappa_+ (1 + \Delta_{\text{EM}}) \times \left| \frac{V_{ts}^* V_{td} \chi_t(m_t^2) + \lambda^4 \text{Re} V_{cs}^* V_{cd} (P_c(m_c^2) + \delta P_{c,u})}{\lambda^5} \right|^2$$

○ ハドロン部分の不定性は良く測られた  $\text{Br}(K^+ \rightarrow \pi^0 e^+ \nu)$  で規格化することでキャンセル

# $K \rightarrow \pi \nu \bar{\nu}$ 分岐比

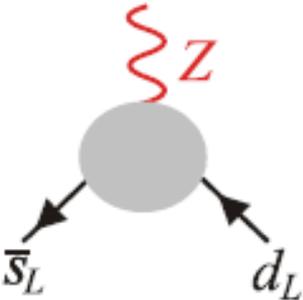
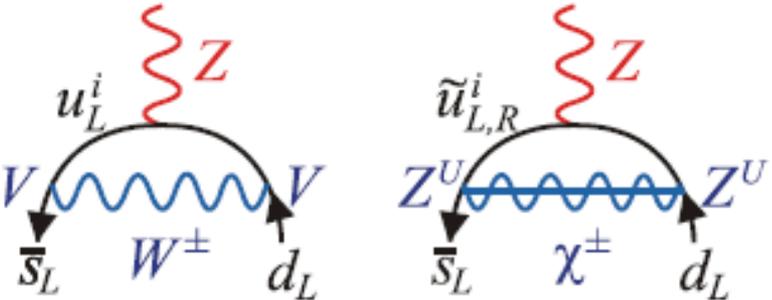
- 理論予測値
  - CKMパラメータの不定性が支配的
  - 理論のintrinsicな不定性は $K^+$ で~5%、 $K_L$ で1~2%と非常に小さい

$\times 10^{-10}$	Theory(SM)	Experiment
$K^+ \rightarrow \pi^+ \nu \bar{\nu} (\gamma)$	$0.85 \pm 0.07^{[1]}$	$1.73_{-1.05}^{+1.15^{[2]}}$
$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$	$0.26 \pm 0.04^{[3]}$	$< 260$ (90% CL) <sup>[4]</sup>

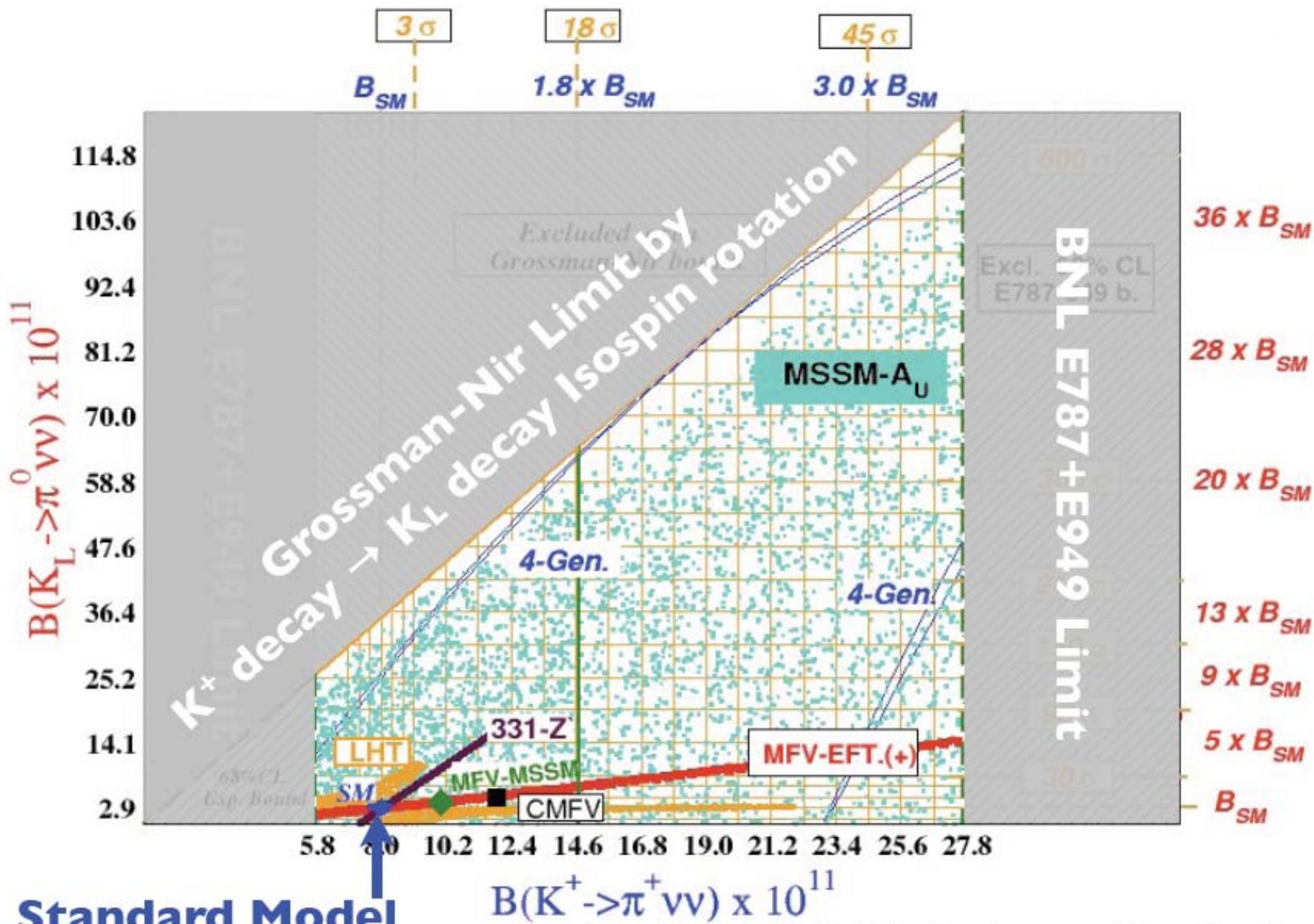
現リミットはSM予測値の3桁上

- [1] J.Brod, M.Gorbahn, PRD78, arXiv:0805.4119
- [2] AGS-E787/E949 PRL101, arXiv:0808.2459
- [3] M. Gorbahn
- [4] KEK-E391a arXiv:0911.4789v1

# $K \rightarrow \pi \nu \nu$ beyond SM

EW Penguin	SM and/or example of SUSY diagram
	

- MFV, MSSM, Little Higgs w/ T parity, ...  
 これまでの実験情報で制限されていないエンハンス領域が広く残っている



# $K_L \rightarrow \pi^0 \nu \nu$ 実験

- J-PARC E14 - Step1  
= KOTO (K0 at TOkai)



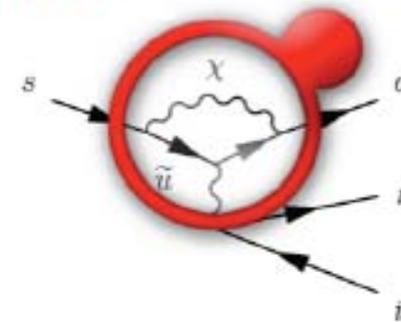
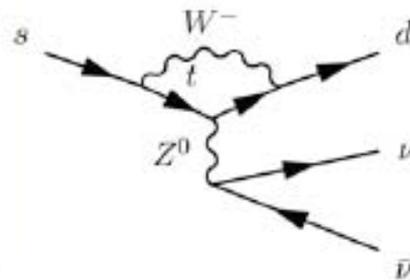
# J-PARCハドロン実験施設において

Full intensity (=300kW)、3 snowmass年のランで  
 $K_L \rightarrow \pi^0 \nu \bar{\nu}$  を数イベント(SM)発見することを狙う実験



## Rare Kaon Decay $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

- direct CP-violating rare decay for Physics beyond the Standard Model



BR

$10^{-5}$

$10^{-6}$

$10^{-7}$

$10^{-8}$

$10^{-9}$

$10^{-10}$

$10^{-11}$

$10^{-12}$

$10^{-13}$

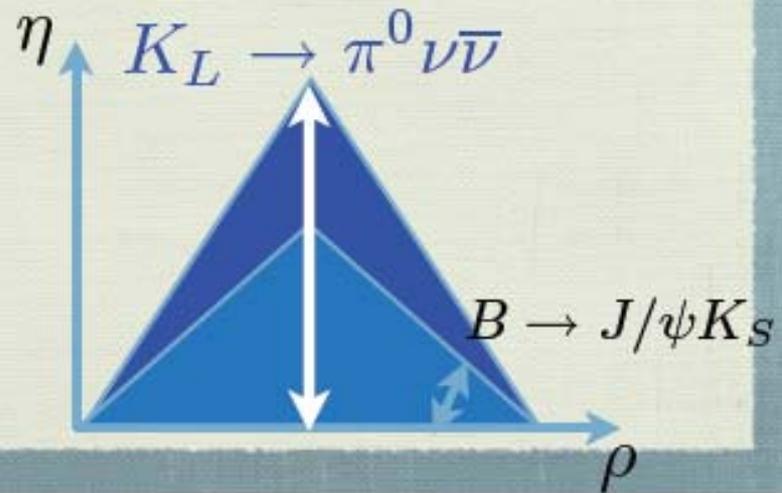
KEK E391a

New Physics

SM  $(2.76 \pm 0.40) \times 10^{-11}$

Step 1

Step 2



# 測定手法

Cartoon for KEK-E391a

$$\underline{K_L} \rightarrow \pi^0 \nu \nu \rightarrow \pi^0 + \text{nothing}$$

1. 2 photon を測定し  
(Csl calorimeter)

他に何も無いことを保証する  
(hermetic veto)

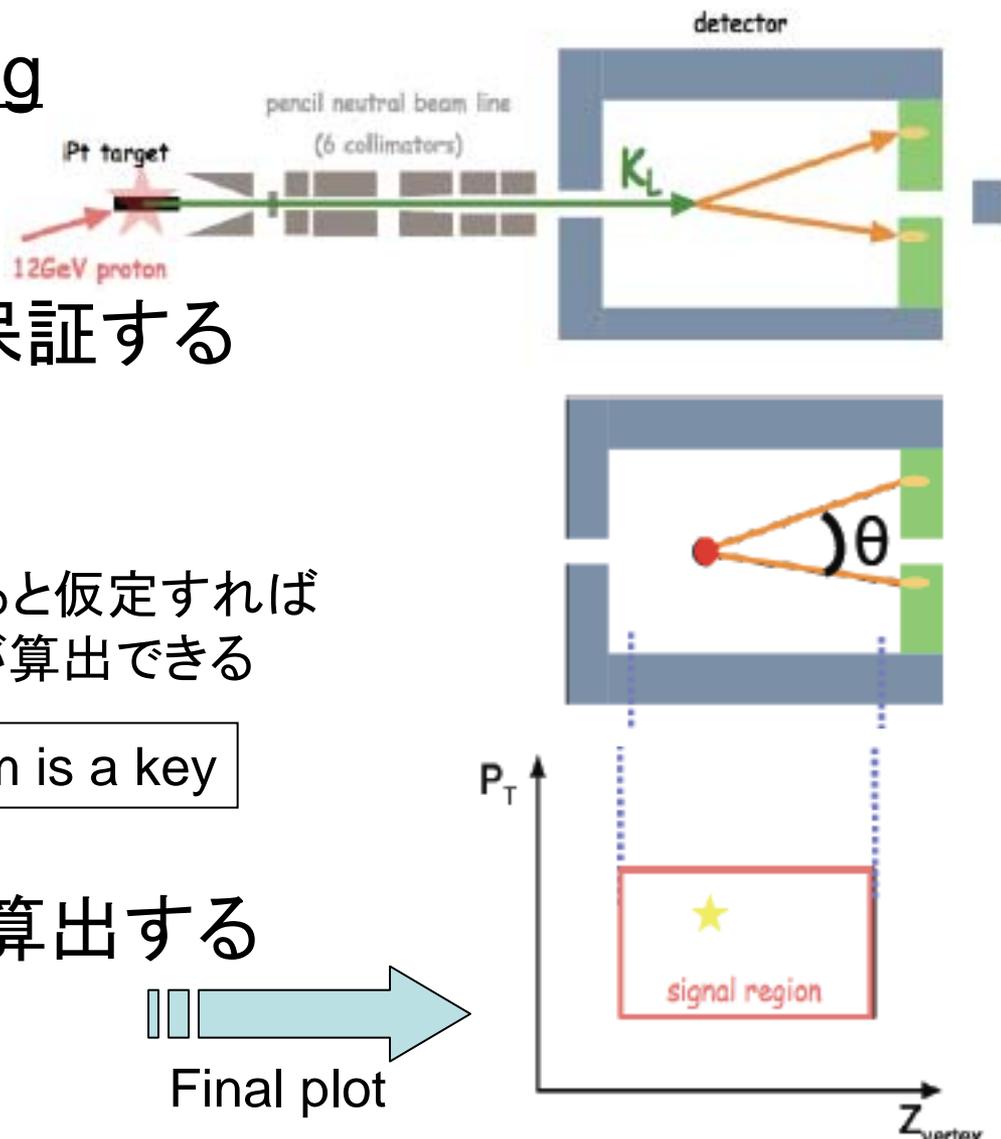
2. 崩壊点を再構成する

崩壊点がビーム軸上にあると仮定すれば  
 $\pi^0$  massの条件から位置が算出できる

narrow  $K_L$  beam is a key

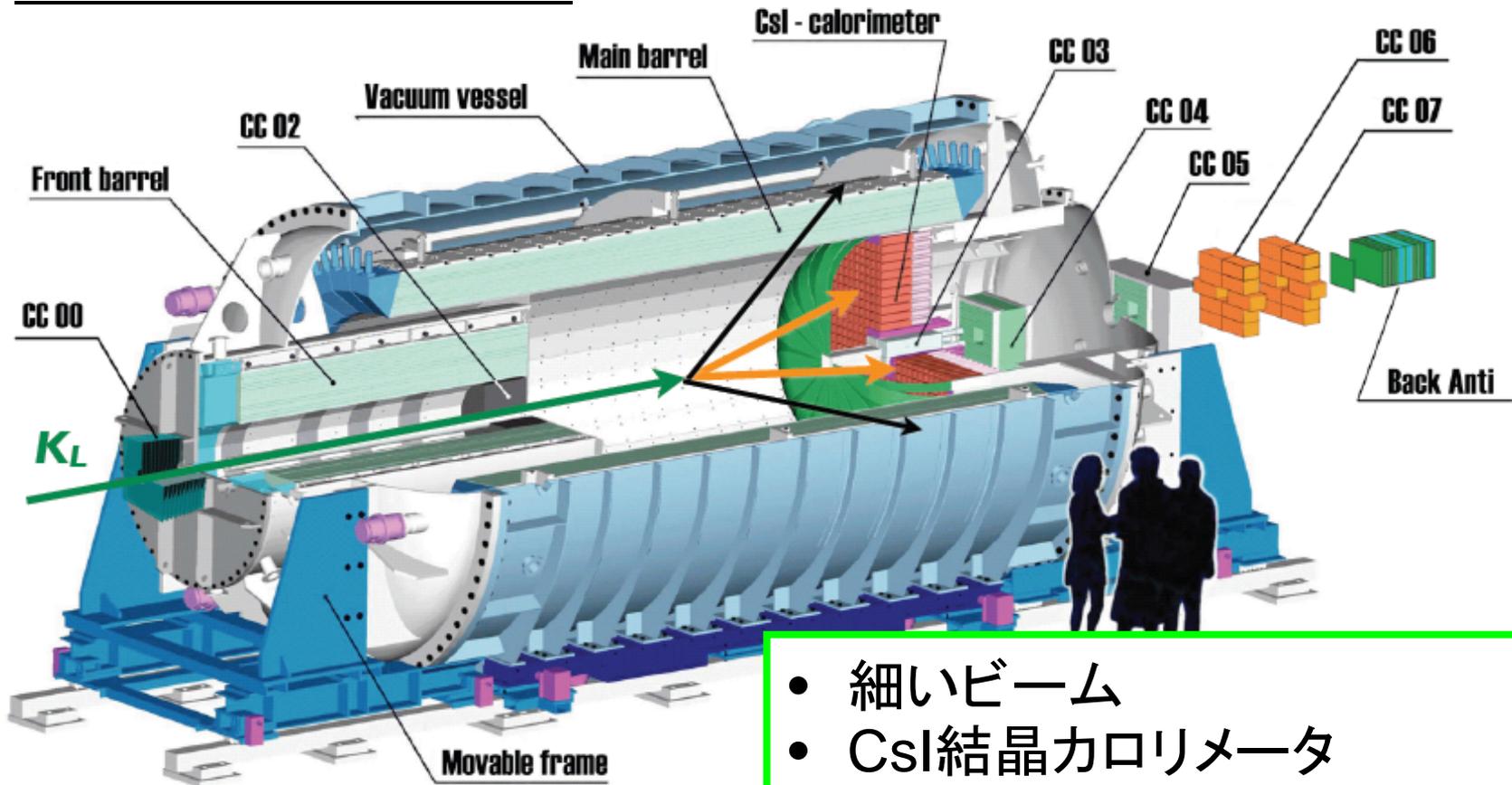
3.  $\pi^0$  横方向運動量を算出する

Final plot



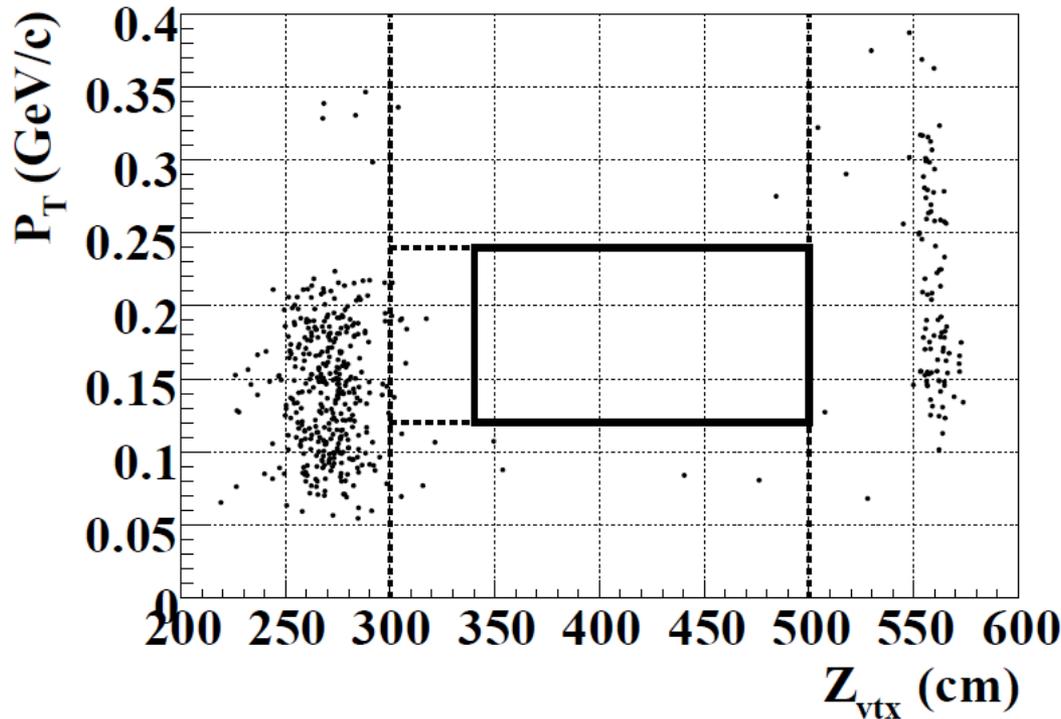
# KEK E391a – パイロット実験 (2004-5)

## KEK-E391a detector



- 細いビーム
- CsI結晶カロリメータ
- $4\pi$ を覆う veto検出器
- 検出器全体を真空中に設置

# KEK E391a – 最終結果



- ゼロイベント  
→ 分岐比上限値
- 信号領域の周りのバックグラウンドはハロー中性子とビーム近くの検出器とのhadronic interactionから来ている

$$\text{Br}(K_L \rightarrow \pi^0 \nu \nu) < 2.6 \times 10^{-8} \text{ (90\%CL)}$$

Phys.Rev.**D81**, 072004 (2010)

KOTOでは  
**beamline、detector**  
共に改善する

# E391a 足跡

- 実験規模 14機関(国内8、海外6)、69名  
full paper (2010) の著者数
- 物理ラン 2004 (Run1)、2005 (Run2、3)
- 結果投稿
  - 2006年: Run1の10%、  
2008年: Run2 full、2010年: Run2+3 full
- D論
  - 実験建設: 佐賀1、KEK総研大(JINR)1
  - $K_L \rightarrow \pi^0 \nu \nu$ : 大阪1、プサン1、京都2、シカゴ2
  - バイプロダクト: シカゴ1、(佐賀1解析中)

# → KOTO @ J-PARC

- 17機関(国内10、海外7)
  - KEK / Kyoto / NDA / Okayama / Osaka / Saga / Yamagata
  - Arizona State / Chicago / Michigan (USA), JINR (Russia), NTU (Taiwan), Chonbuk / Jeju / Kyungpook / Pusan / Seoul (Korea)
- 65名 国内37(内、学生20)、海外28(内、学生8)



# KOTO実験のための増強策

## 感度増強

→  $O(10^{-11})$  sensitivityへ

- ビーム強度
  - 大強度加速器 J-PARC
  - 時間あたりのKL数にして約40倍、崩壊数にして約80倍（生成角度が大きく運動量分布がソフトなため）
- 物理ラン時間
  - E391a Run2+3で2ヶ月→約1年（3 snowmass年）
- 解析の改善
  - カロリメータ用CsIクリスタルの細分化、読み出し回路の増強などによるカット効率の向上

# KOTO実験のための増強策

## バックグラウンド排除

- ビームラインの改善
  - K/中性子比の改善 ← 対中性子バックグラウンド
- 検出器の改善
  - より長いカロリメータによる光子エネルギー測定向上
  - 細分化されたカロリメータによる電磁シャワー識別向上
  - ビーム近傍検出器の増強、位置、サイズの最適化
  - 光子検出器の増強
    - 厚さを増し非検出の確率を抑える ← 対 K崩壊バックグラウンド

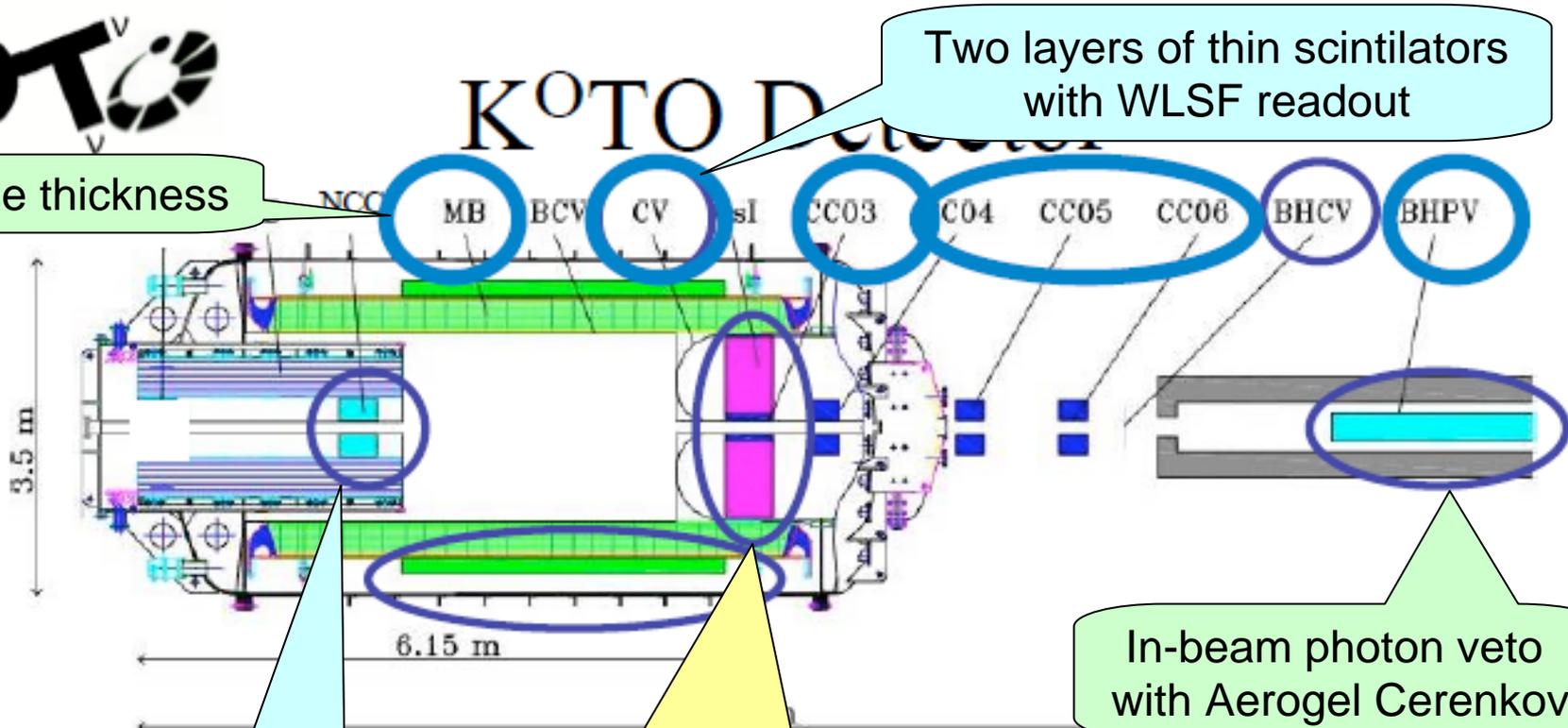
→ S/N比 1~2

K崩壊BGが主、中性子BGは~10%

# 検出器の増強



Increase thickness



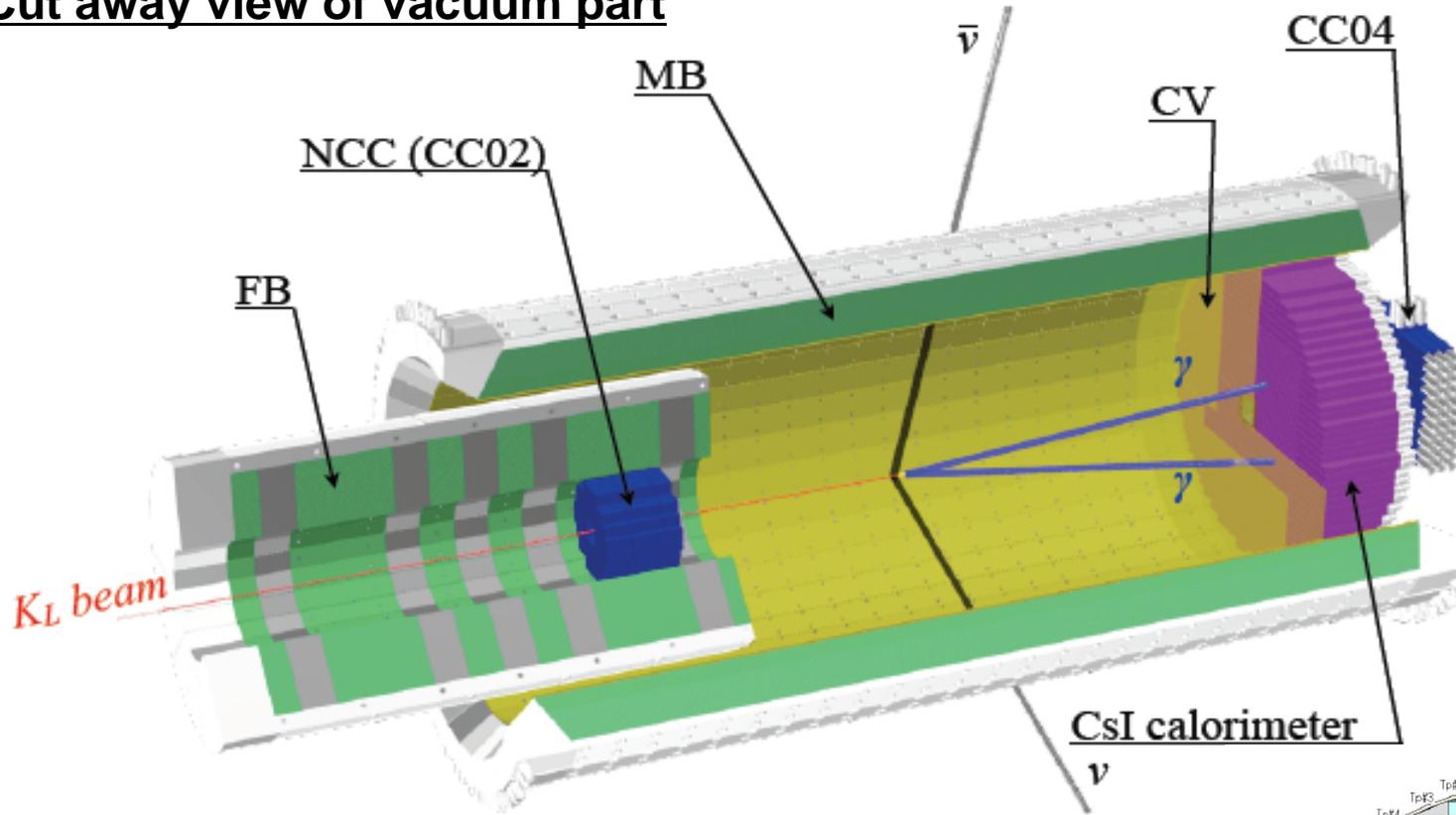
Two layers of thin scintillators with WLSF readout

In-beam photon veto with Aerogel Cerenkov

Pure CsI-based veto and change position

Longer CsI blocks (from KTeV) and finer segmentation  $7\text{cm}^2 \times 30\text{cm} \rightarrow 2.5\text{cm}^2 \times 50\text{cm}$

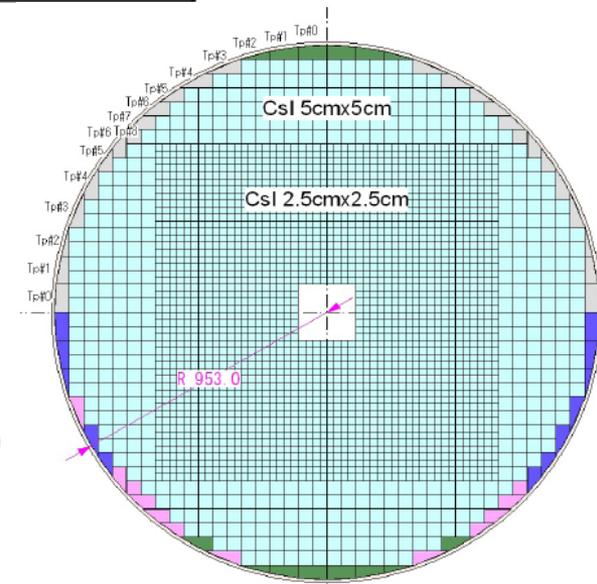
## Cut away view of vacuum part



illustrated by Masuda (Kyoto U)

### Calorimeter upgrade

- 長い結晶 30cm→50cm
- 細分化 7cm→2.5/5cm
- 波形記録 (FADC読み出し)
- CWベースによるHV供給

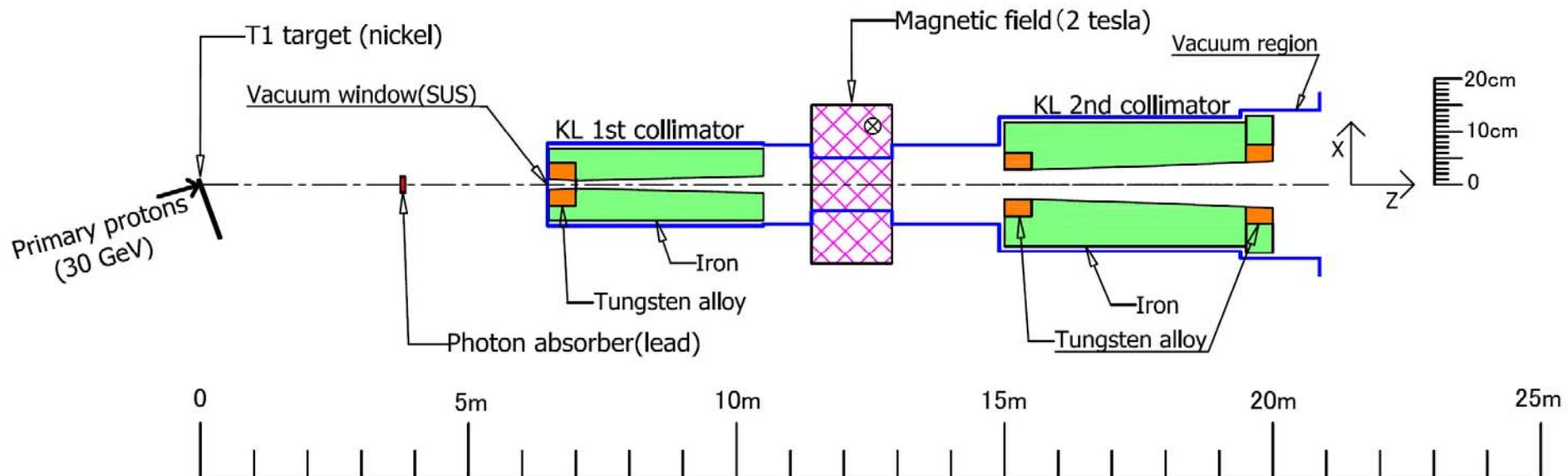


# KOTO実験 現状

- 2009年9月 ビームライン完成
- 2009年10月～2010年2月  
ビームラインサーベイ実験
  - コリメータのアライメント
  - ビームプロファイルの測定
  - KL数の測定 など
- 2010年3月～ Cslカロリメータ建設準備
  - 10月までに建設を完了し、秋のビームタイムからカロリメータのエンジニアリングランへ

# KOTOビームライン

- 生成角(一次陽子の方向とビームラインの角度) 16度
- 中性ビームなのでビームを形作るためにはひたすら精度のよい穴を作る
  - 2台の長いコリメータ 4mものと5mもの
    - ビーム領域周りにはじみ出る粒子(ハロー)を抑えるため  
サイズ、apexの位置、材質を最適化
- 電磁石は荷電粒子掃き出し用の一台のみ



ビームライン完成  
2009年9月

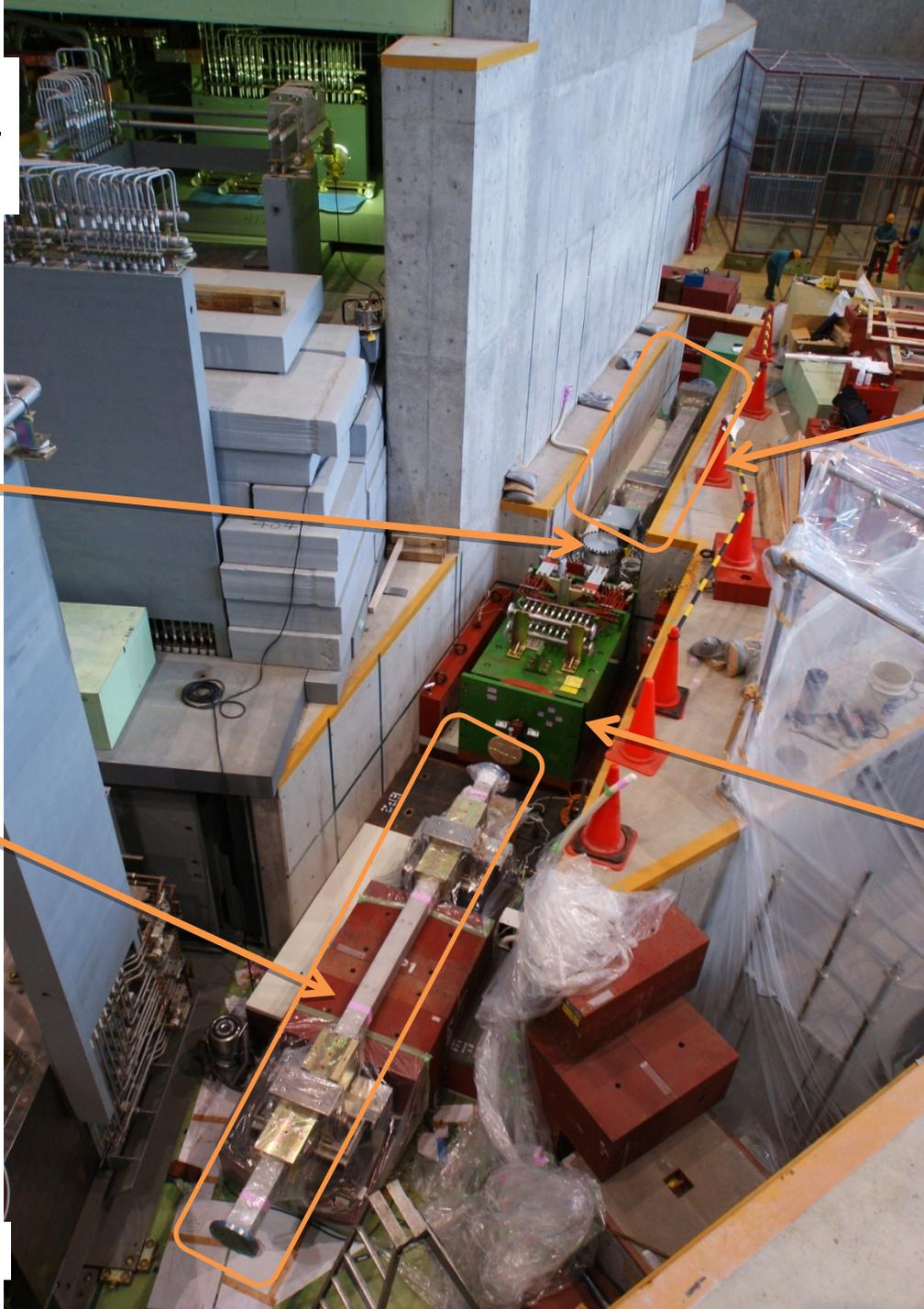
Beam plug

1<sup>st</sup> collimator  
(4m-long)

2<sup>nd</sup> collimator.  
(4.5+0.5m)

Dipole magnet.

Photo on July 11, 2009



Upstream

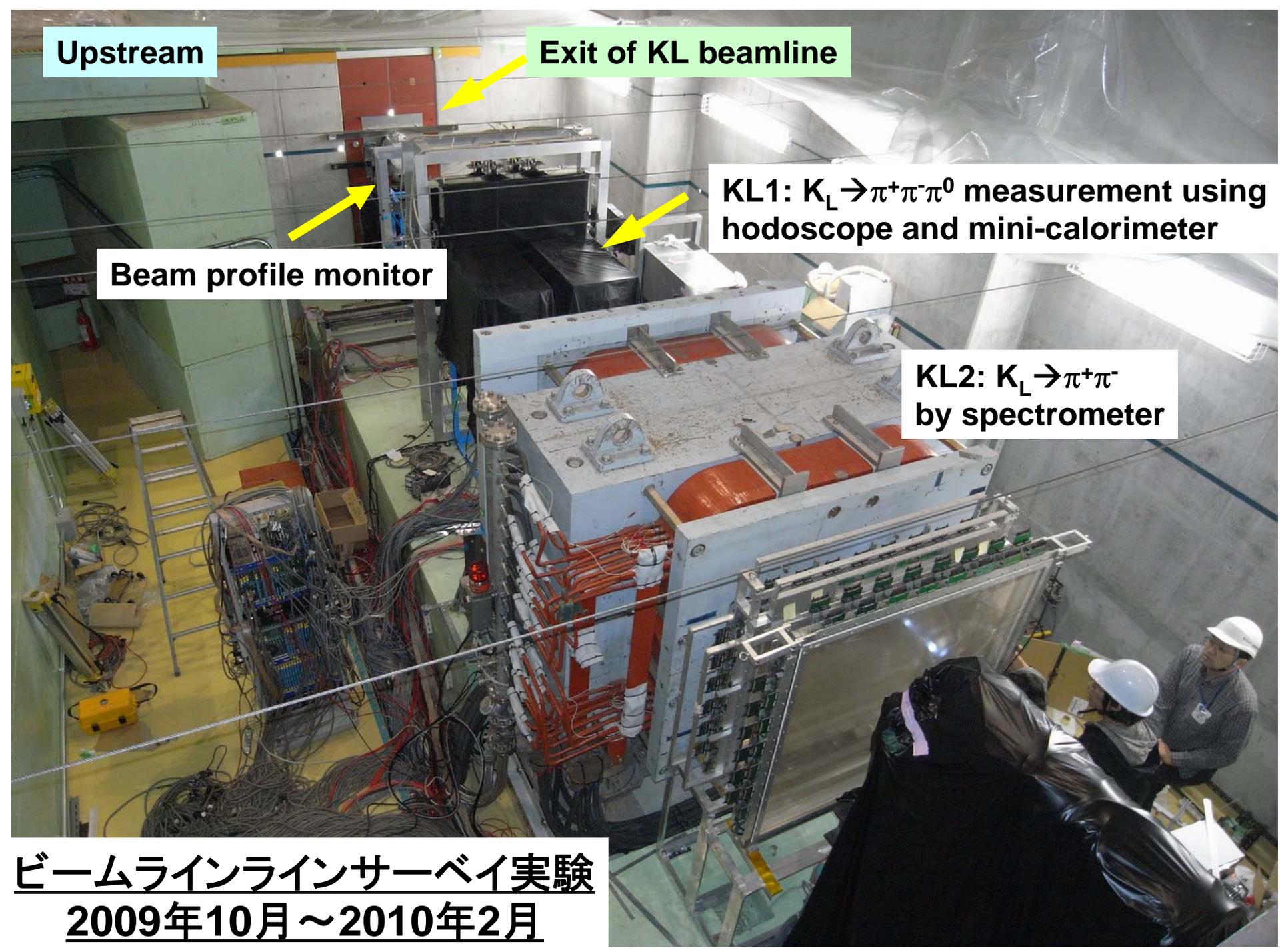
Exit of KL beamline

Beam profile monitor

KL1:  $K_L \rightarrow \pi^+\pi^-\pi^0$  measurement using hodoscope and mini-calorimeter

KL2:  $K_L \rightarrow \pi^+\pi^-$  by spectrometer

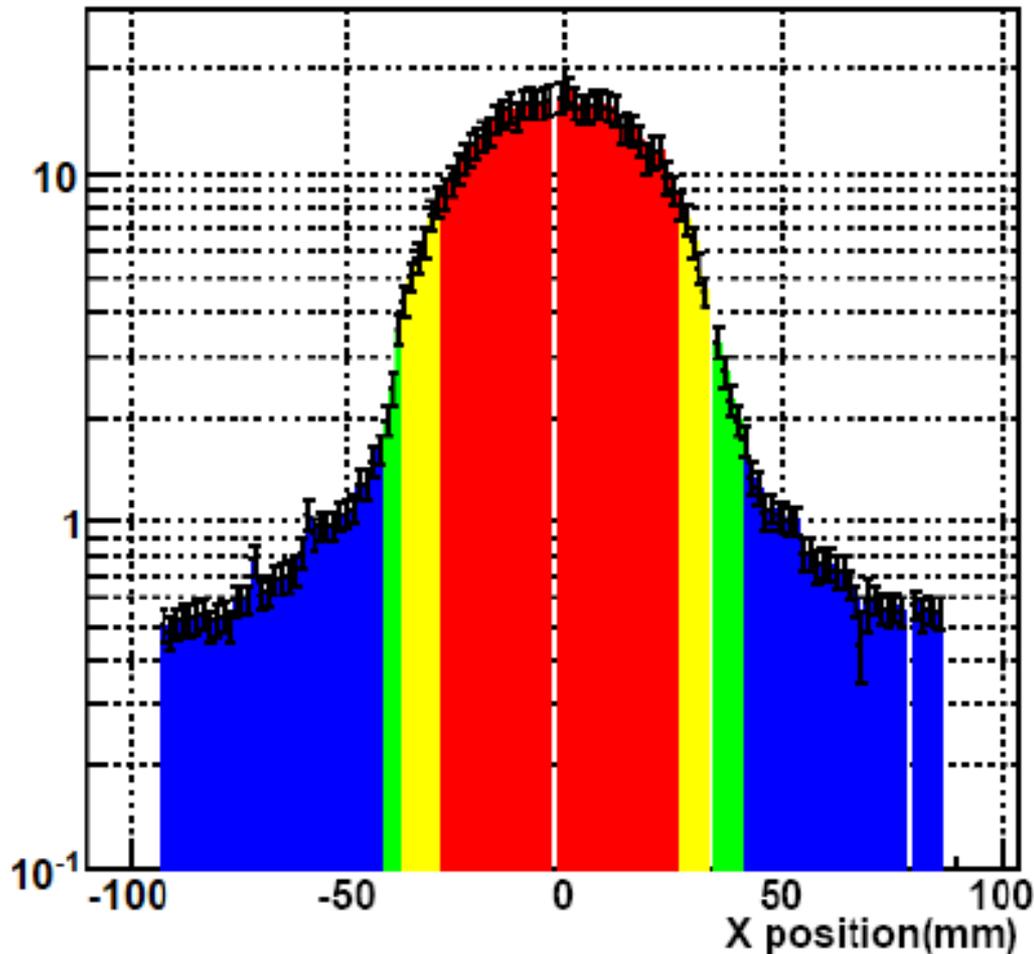
ビームラインラインサーベイ実験  
2009年10月～2010年2月



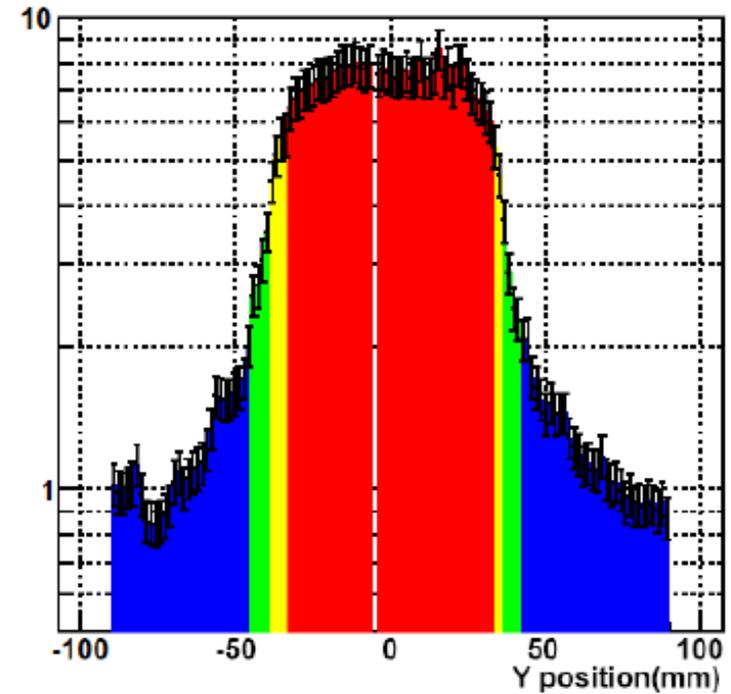
# Collimator Alignment procedure

Adjust collimators' positions/directions by optimizing the beam profile

X-profile

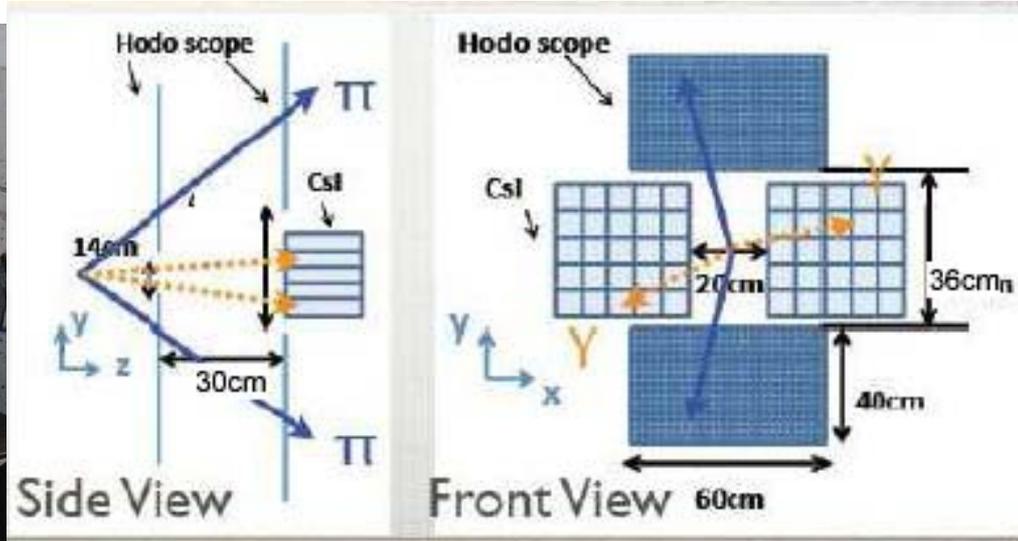
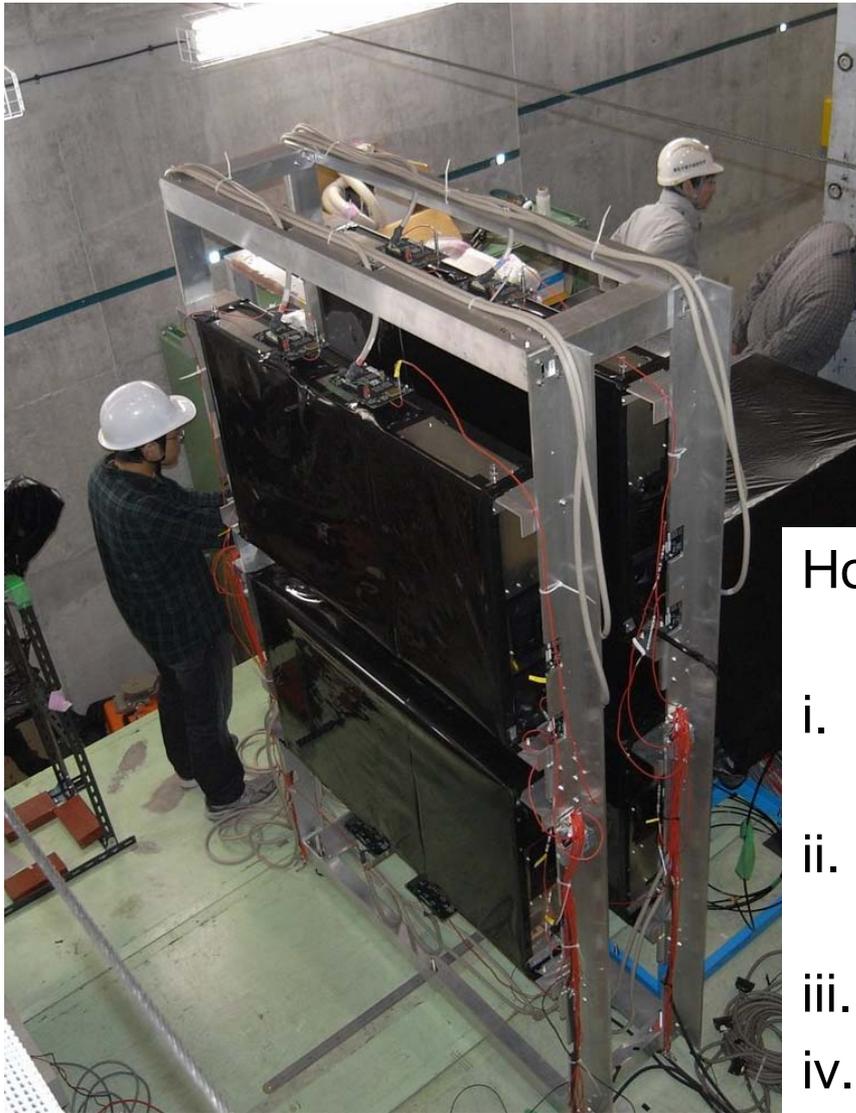


Y-profile



Align both in horizontal and vertical

# $K_L \rightarrow \pi^+ \pi^- \pi^0$ measurement

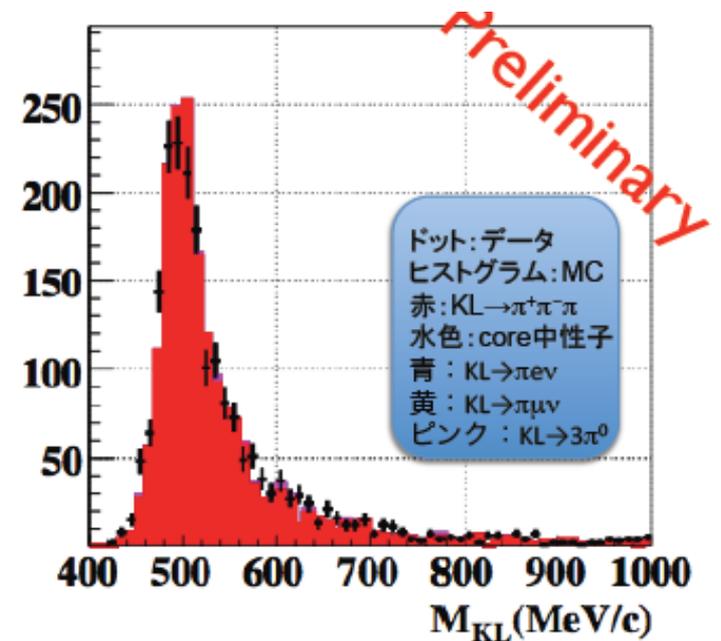
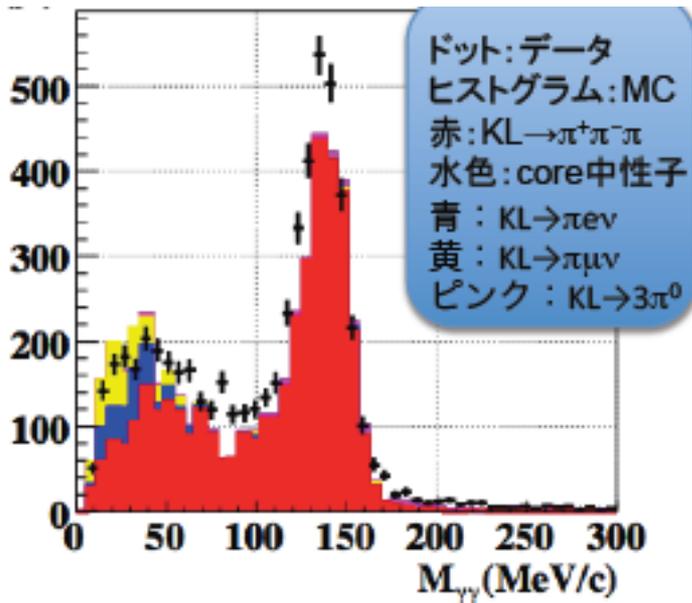


## Hodoscope + mini-calorimeter (CsI)

- Simple and sure method
- i. 2-track directions by hodoscope  
→ obtain vertex
- ii. 2-photon energies / positions by CsI  
→ calculate  $M(\gamma\gamma)$
- iii. Solve  $p_+$  and  $p_-$  by requiring  $P_T$  balance
- iv. Calculate  $M(\pi^+ \pi^- \pi^0)$

# $K_L \rightarrow \pi^+ \pi^- \pi^0$ measurement

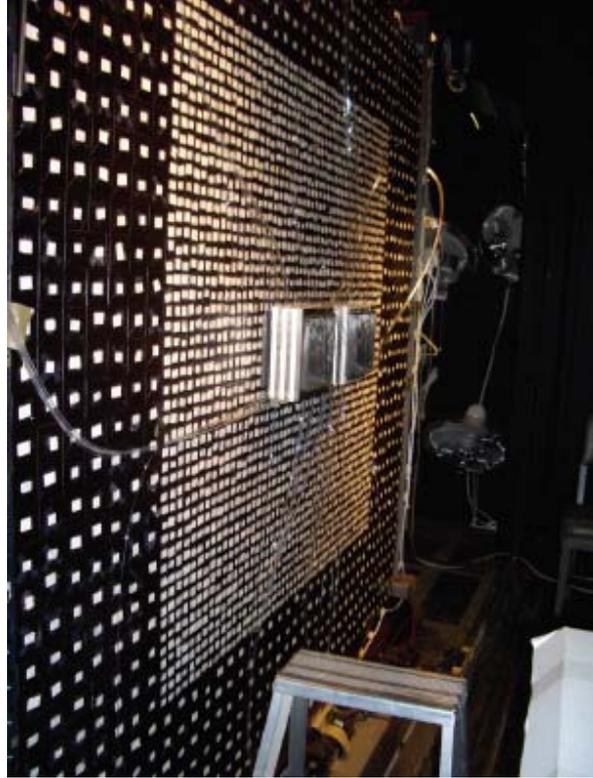
ビーム condition	On spill time(s)	繰り返し周期(s)	標的	ビーム強度 (KW)
デザイン値	0.7	3.3	Ni	300
現在	2.6	6	Ni or Pt	0.5~2.0



プロポーザルで期待していたKL数  
 ←GEANT4ベースのシミュレーション  
 に対し、1.5~2倍の収量が得られた

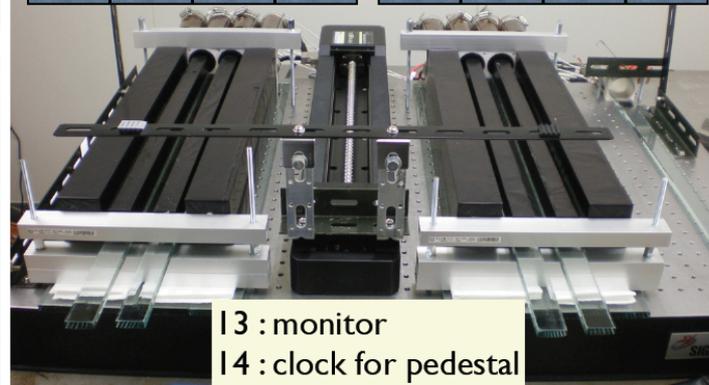
(G3/GFLUKAベースの予測とほぼ同じ。真正FLUKAの予測よりは少ない。)

# New (old KTeV's) CsI crystal



FNAL/USA

Osaka/Japan

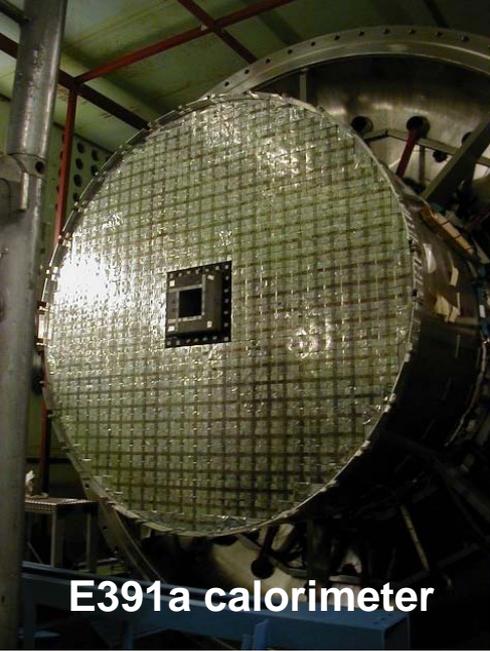


13 : monitor

14 : clock for pedestal

→ 順次、東海へ

# Endcap vessel for calorimeter



E391a calorimeter

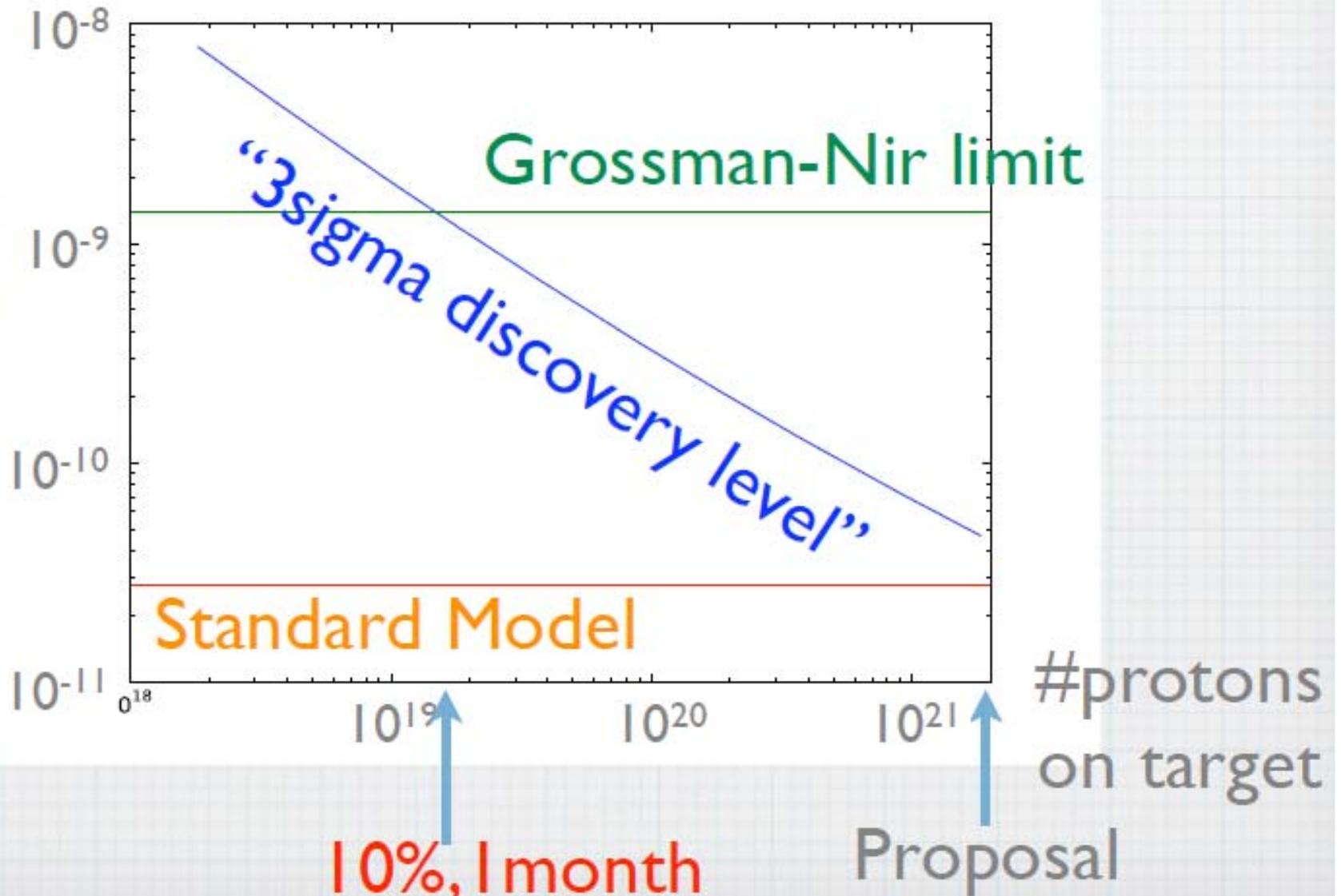
つくば  
東海



# KOTO実験 タイムライン

- 2010年度 カロリメータのエンジニアリングラン
- 2011年度 秋までをめどに  
全検出器のインストール、エンジニアリングラン  
– 新カロリメータ＋増強の一部＋E391a検出器
- 2012年夏のシャットダウンまでに  
**Grossman-Nir limit到達**
  - 物理の第一マイルストーン
  - ビーム強度 $\sim 30\text{kW} \times 1\text{month}$  (net ビーム時間) 相当で達成
    - KL数が期待値よりも多かった分は織り込まれていない

# KOTO sensitivity



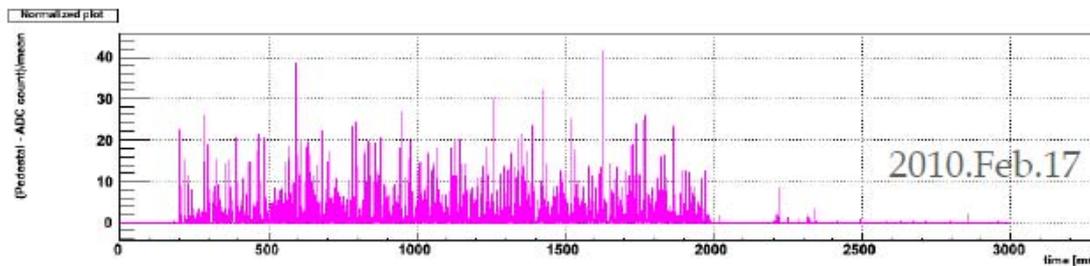
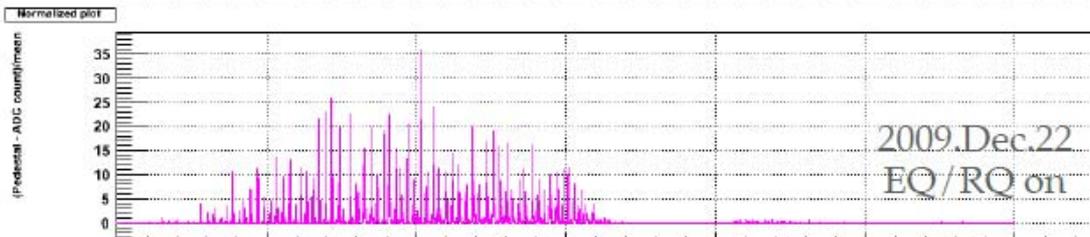
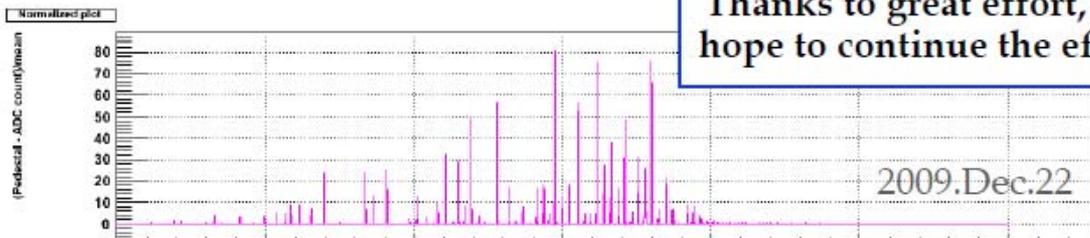
# J-PARC 遅い取り出しビームの (困難な)状況

- 遅い取り出しビームの質と量
  - ビームはDC的でなく、spike状に出ている
    - MR電磁石の大きすぎるリップルに起因する
  - デザイン値 300kW は遠い道のり
    - デザイン値:MRエネルギー、粒子数、繰り返し時間からの算出
    - 実際は取り出しでのビームロスで強度が制限される
      - 加速器機器の放射化、メンテナンスの問題
- 遅い取り出しに割り当てられるビームタイム
  - 加速器運転サイクル数 (予算次第)
  - 速い取り出し=T2K とのビームシェア
    - 現状はT2Kがプライオリティを持つ (J-PARC PAC)

取り出し効率  
現状 98.5%:  
とても優れた  
達成状況だが  
十分ではない

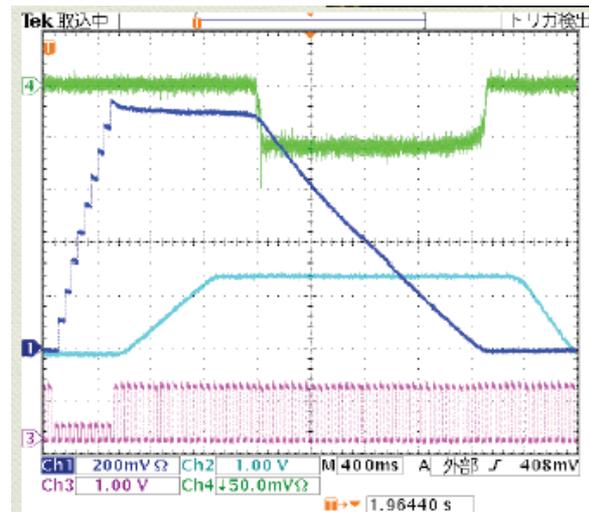
# SX Spill Structure

Thanks to great effort, and hope to continue the effort.



- スパイク構造のビーム
- = 瞬間的なビーム強度が高い
- データ収集のデッドタイム増加
- アクシデンタルヒット率の増加  
(vetoの重要な実験ではよりシビア)

KEKPS in 2005  
to E-hall



# Power upgrade plan of SX (under discussion)

## Power and spill after the summer shutdown

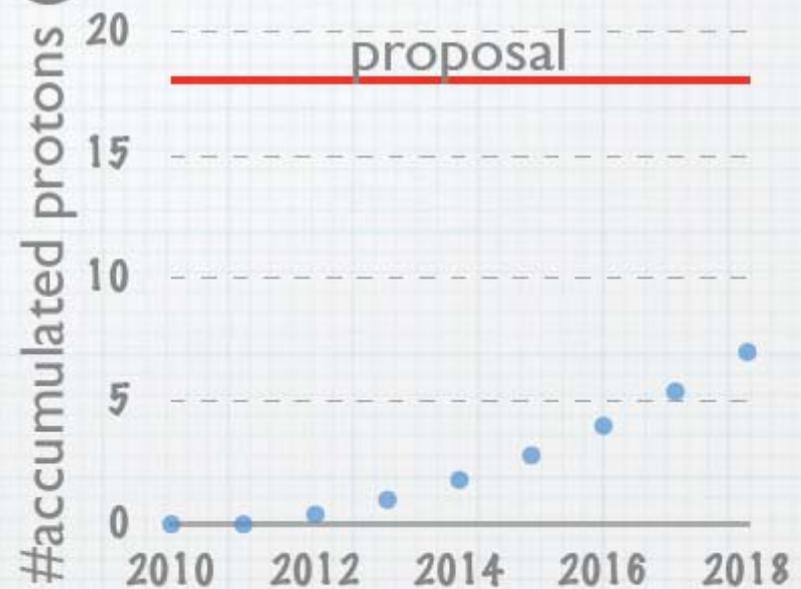
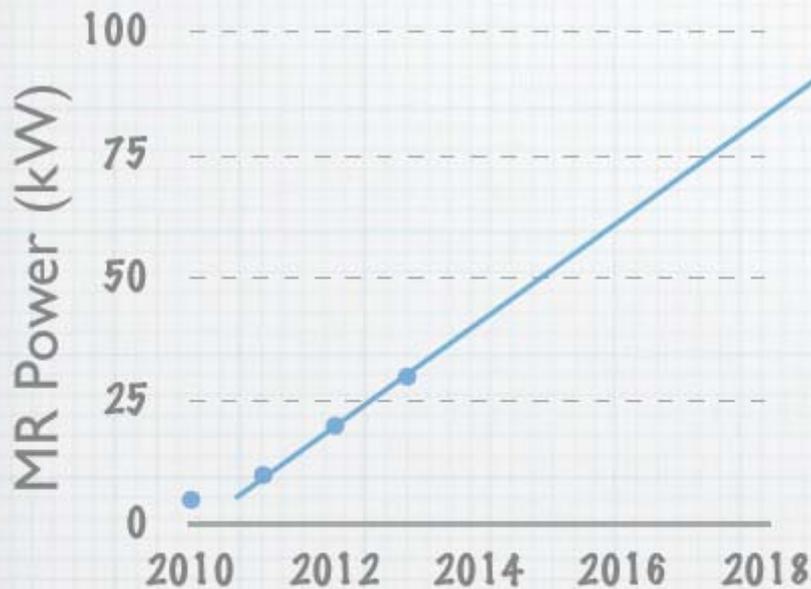
JFY	Beam intensity			Spill structure	
	Key components	Users operation [kW]	Accelerator study [kW]	Key components	Duty [%]
2010	Dynamic bump	5	10	Feedback system Ripple canceller Main magnet PS	15+ $\alpha$
2011	SX collimator	10	20	RQ Power supply	30
2012	Ti chambers Local shields	20	30		> 30
2013		30	> 30		
2014		> 30			

物理学会シンポ「J-PARCの現状と展望」小関氏スライドより

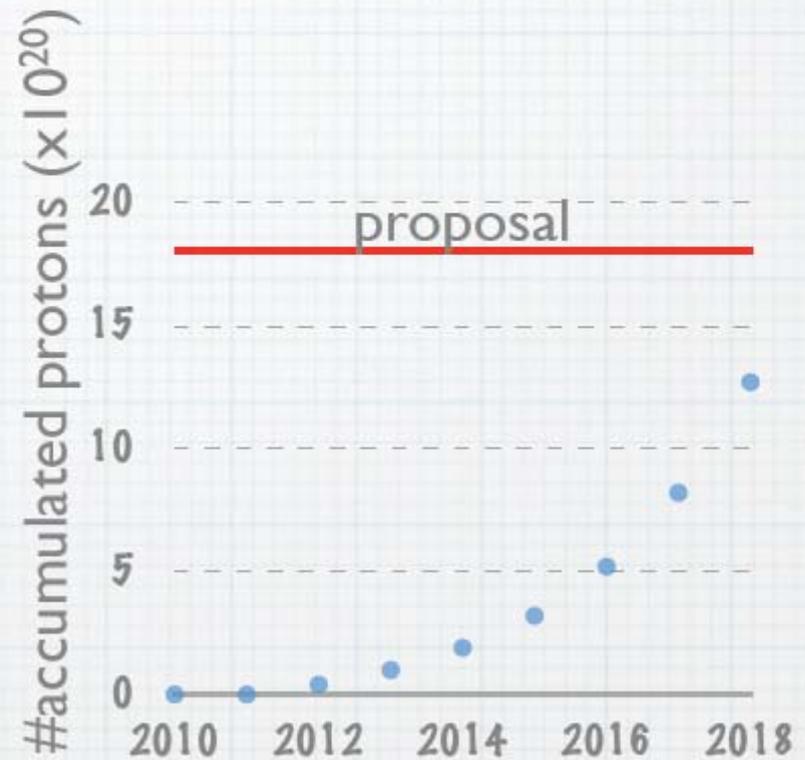
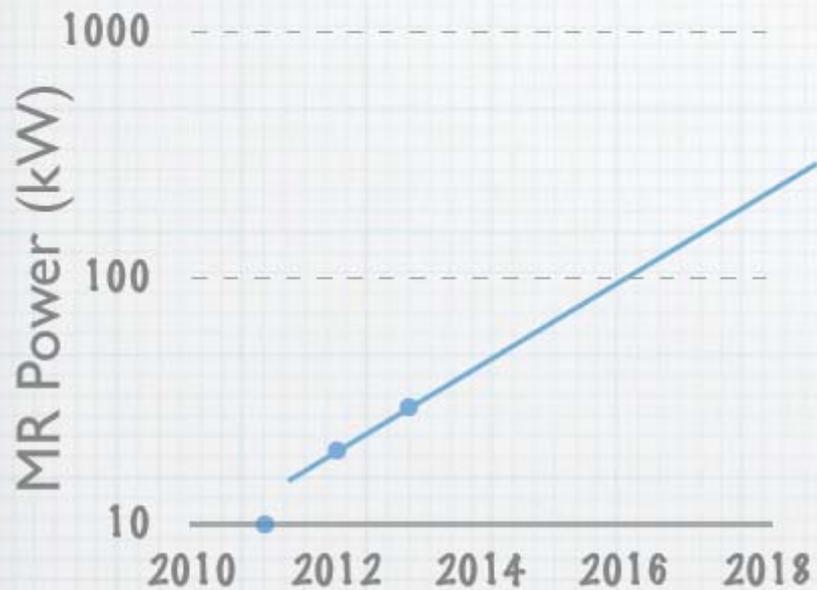
- 30kWまでに3年かかる...
- それ以上はまだ具体案になっていない...

# case 1: +10kW/year

\* Assume  $1 \times 10^7$  sec run per year



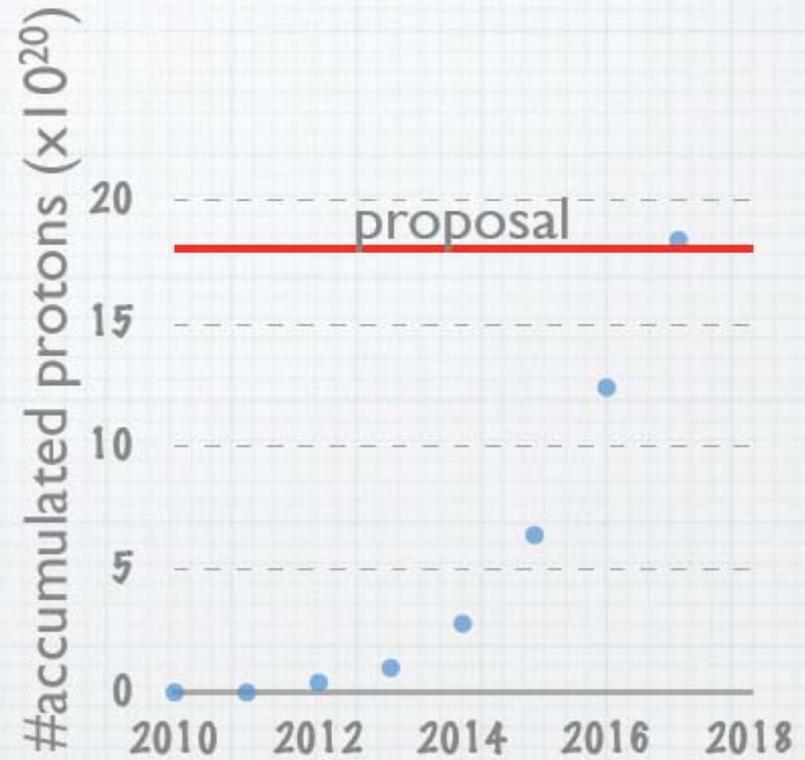
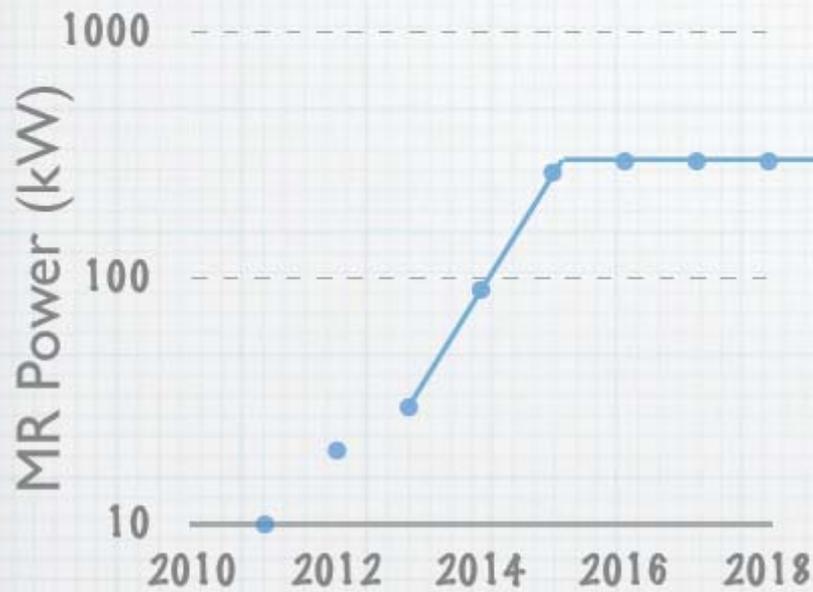
# case 2: x1.5/year



# case 3: "AGS"



# case 4: x3/year



それでも...(いや、だからこそ、か)

# 次期計画

## Step 2 in E14 proposal

生成KL数をかせぐ ← ビームラインは作り直し  
崩壊領域長をかせぐ ← 検出器は作り直し(一部はリサイクルだろうが)

\* targeting angle: 16 → 5deg

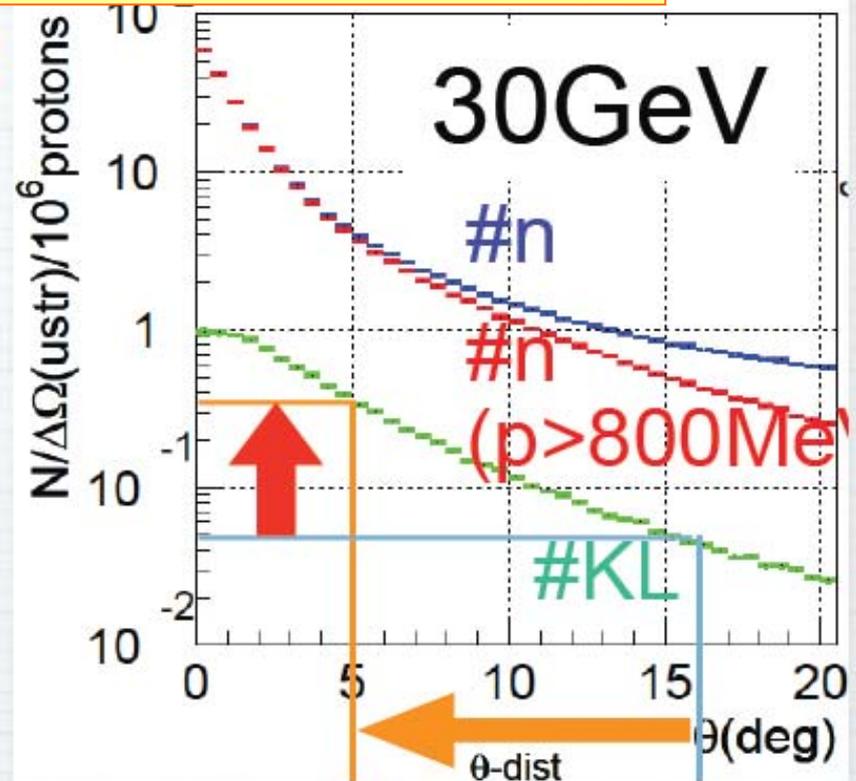
\* longer decay volume:  
2m → 11m

\* calorimeter:  $2m\phi \rightarrow 3m\phi$

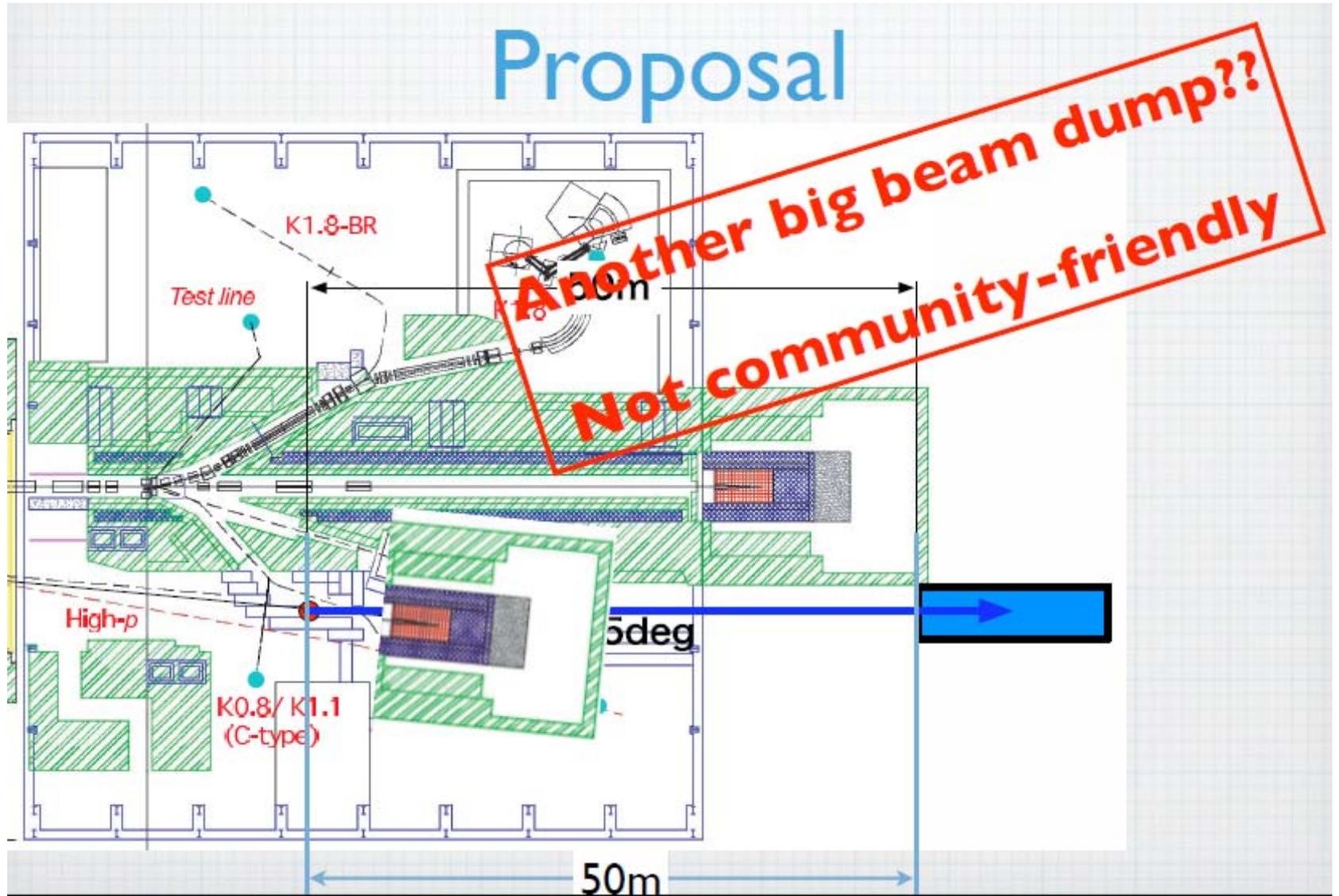
\* 2E14 → 3E14



\* 130 events /  $3 \times 10^7$  sec

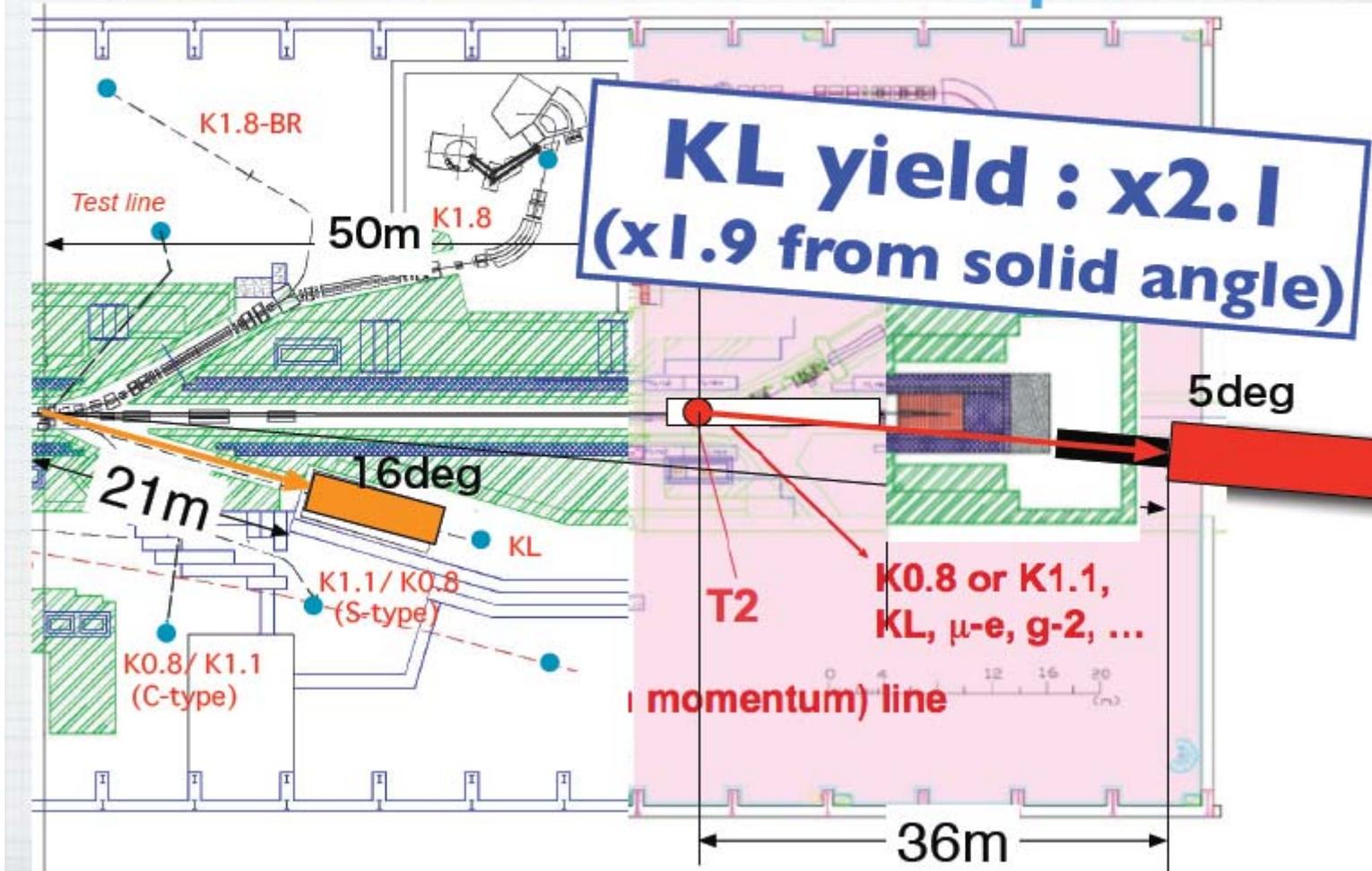


# まだ机上論だが...



さらに机上論だが...

## Behind beam dump



	Step 1	Step 2 in E14 proposal	Step 2 behind dump
#protons/spill	2E+14	3E+14	3E+14
targeting angle	16deg	5deg	5deg
beamline length	21m	50m	36m
beam size	9 $\mu$ str	2 $\mu$ str	3.8 $\mu$ str
#KL/spill	8.1E+06	4.4E+07	2.2E+08
decay length	2m	11m	11m
decay prob.	3.6%	6.0%	6.0%
#SM events	3.5	130	640

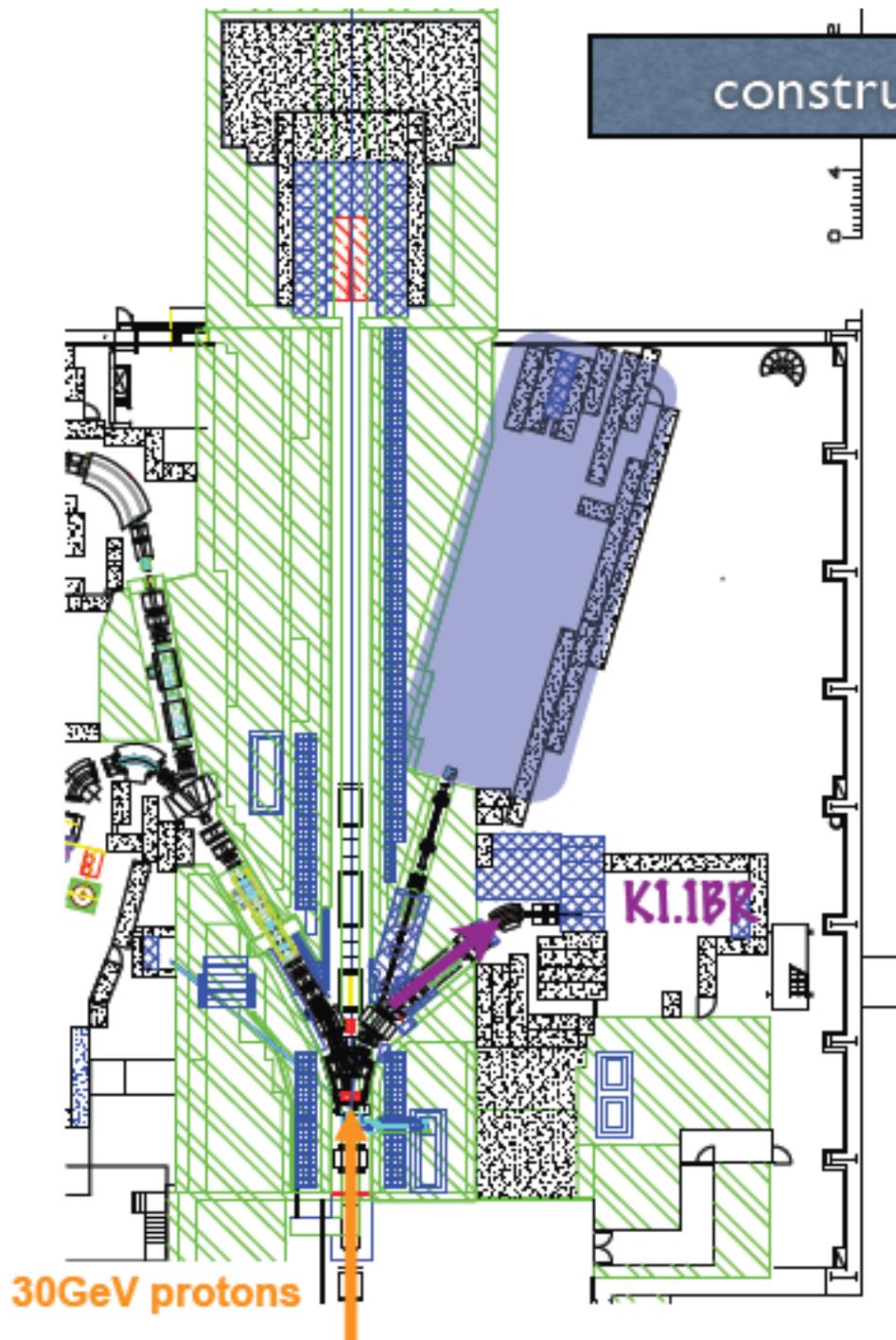
J-PARCで進められているもう一つのKaon実験も簡単に紹介

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

- J-PARC E06 (TREK)



construction to the autumn of 2010



- **K1.1BR line:**

low momentum  $K^\pm$  beam

( $p_{\max} = 0.8 \text{ GeV}/c$ )

20.3m long, single stage

- $\text{Acc} = 4.5 \text{ msr } \% \Delta p/p$  at  $6^\circ$   
c.f.  $\text{Acc}(\text{K1.1}) \sim 2 \text{ msr } \% \Delta p/p$
- $I_{K^\pm} \sim 2.1 \times 10^6/\text{s}$  @ 270 kW
- $\pi^+(\mu^+)/K^+ \sim 0.5$  assuming  $\sigma_\pi/\sigma_K = 600$
- Beam spot :  $d_x \sim d_y \sim 1 \text{ cm} \ll \text{@K5}$

\* K1.1BR will also be used  
as a test beam facility in the early stage.

# 海外情勢

$$K^+ \rightarrow \pi^+ \nu \nu$$

- CERN NA62-II
- FNAL P996

# Techniques for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

## “Stopped”

- Work in Kaon frame
- High Kaon purity  
(Electro-Magneto-static Separators)
- Compact Detectors

## “In-Flight”

- Decays in vacuum (no scattering, no interactions)
- RF separated or Unseparated beams
- Extended decay regions

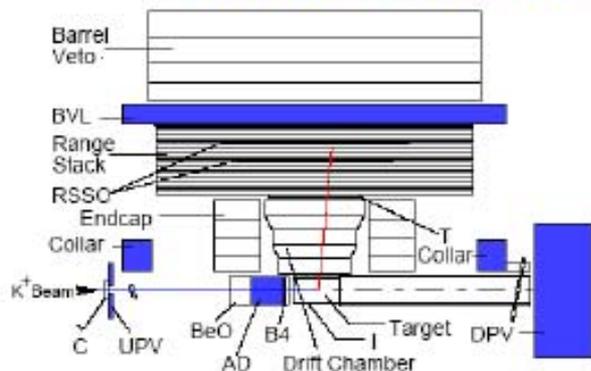
Exp	Machine	Meas. or UL 90% CL	Notes
	Argonne	$< 5.7 \times 10^{-5}$	Stopped; HL Bubble Chamber
	Bevatron	$< 5.6 \times 10^{-7}$	Stopped; Spark Chambers
	KEK	$< 1.4 \times 10^{-7}$	Stopped; $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
E787	AGS	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$	Stopped
E949	AGS	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	Stopped; PPN1+PPN2
NA62	SPS		In-Flight; Unseparated
P996	FNAL		Stopped; Tevatron as stretcher ring?

現在値 @BNL

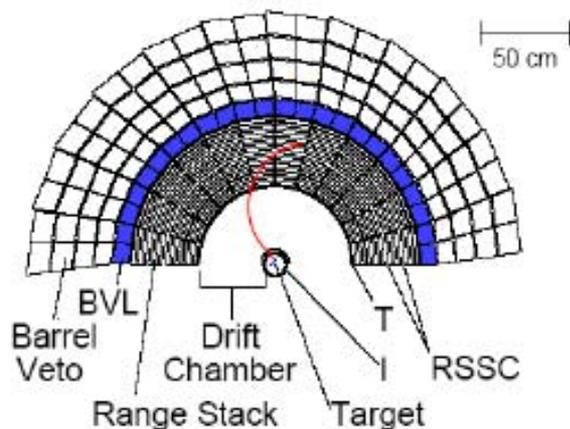
Next @ CERN

# E787/E949 Technique

“The entire AGS beam of  $65 \times 10^{12}$  (Tp/ spill) at a momentum of 21.5 GeV/c was delivered to the E949  $K^+$  production target”



- Duty Factor: 2.2 s / 5.4 s ~ 40%
- 1 int. length Pt target
- Before separators: 500  $\pi$  : 500 p : 1 K
- After separators: Purity  $K:\pi \sim 3-4 : 1$
- Incoming 710 MeV/c  $K^+$  identified by Č and slowed down by BeO and Active Degradator
- ~27%  $K^+$  stopped in the target (1.6 MHz)
- 1 T solenoid



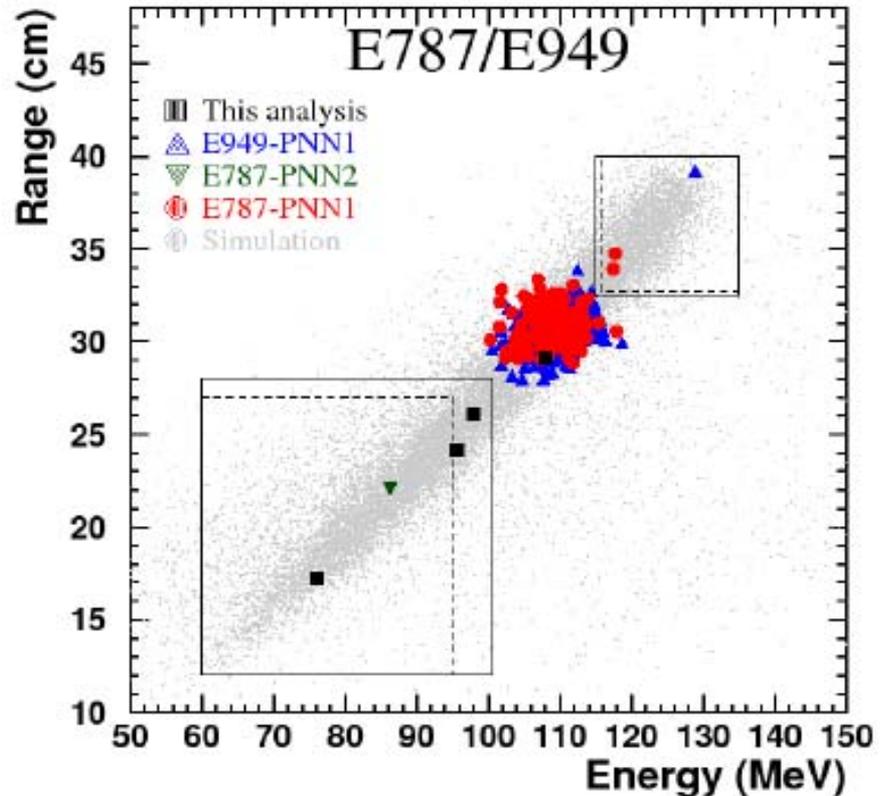
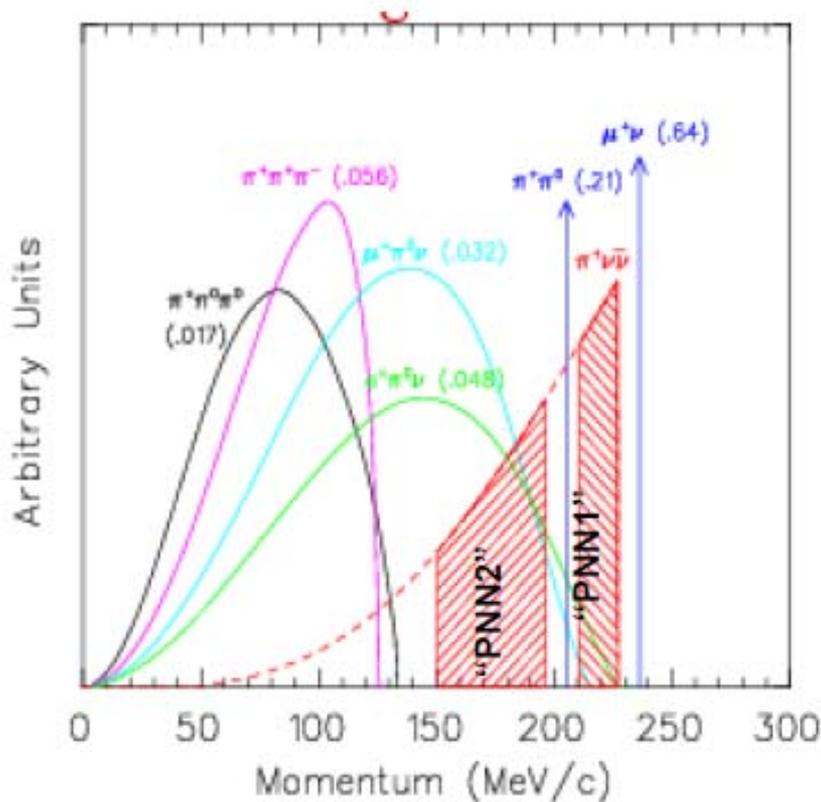
$K^+$ : Č x B4 x Target

$\pi^+$ : Delayed Coincidence  
Range  
Energy  
Momentum  
 $\pi^+ \rightarrow \mu^+ \rightarrow e^+$

# E787/E949: Final Result

arXiv:0903.0030v1

PRD79:092004,2009



$$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$



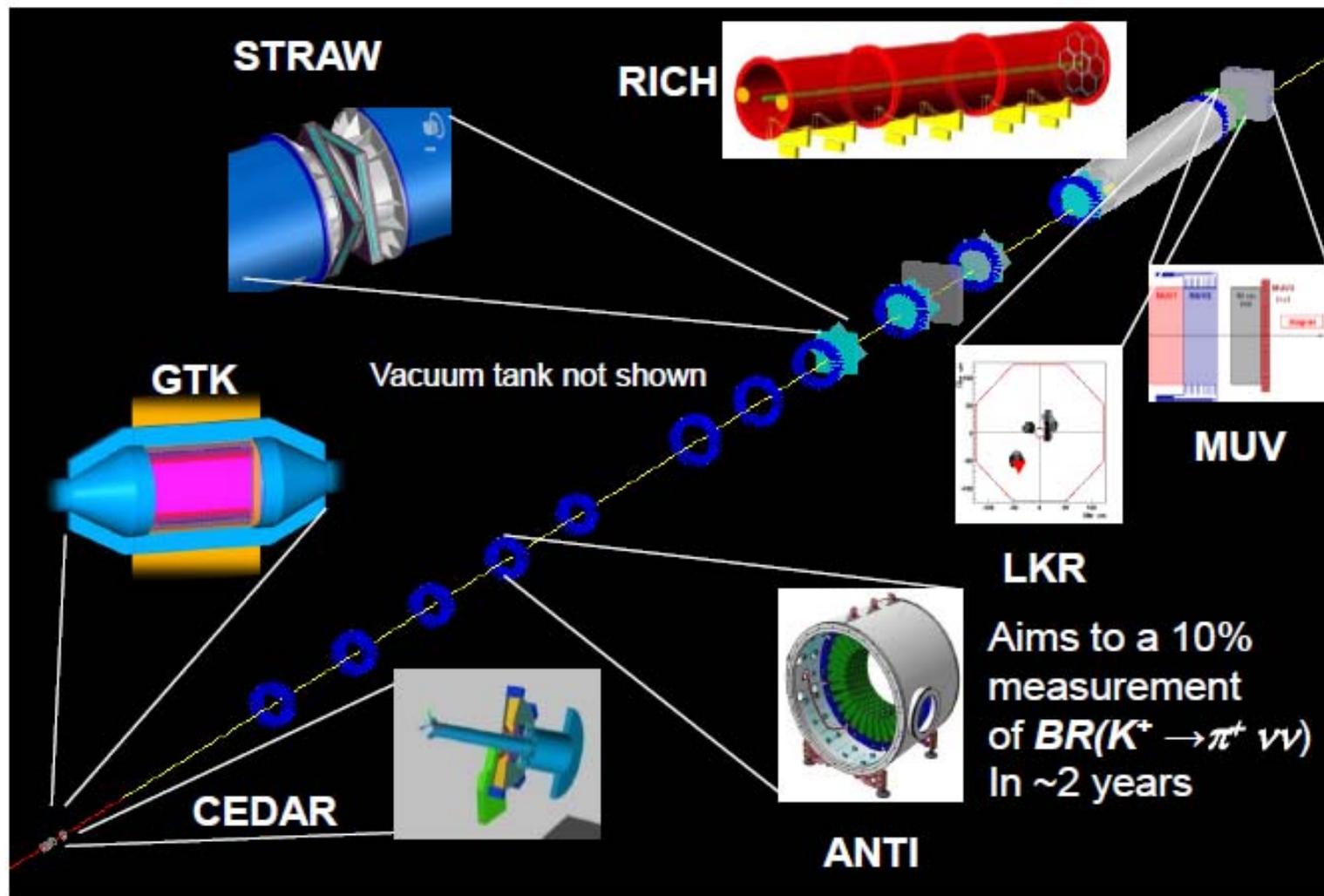
<b>NA48</b> discovery of direct CPV	1997: $\epsilon'/\epsilon: K_L+K_S$
	1998: $K_L+K_S$
	1999: $K_L+K_S$   $K_S$ HI
	2000: $K_L$ only   $K_S$ HI
	2001: $K_L+K_S$   $K_S$ HI
<b>NA48/1</b>	2002: $K_S$ /hyperons
<b>NA48/2</b>	2003: $K^+/K^-$
	2004: $K^+/K^-$



**NA62 phase I:** Bern ITP, Birmingham, CERN, Dubna, Fairfax, Ferrara, Florence, Frascati, IHEP Protvino, INR Moscow, Louvain, Mainz, Merced, Naples, Perugia, Pisa, Rome I, Rome II, Saclay, San Luis Potosí, SLAC, Sofia, TRIUMF, Turin

<b>NA62</b> (phase I)	2007: $K_{e2}^+/K_{\mu2}^+$
	2008: $K_{e2}^+/K_{\mu2}^+$
<b>NA62</b> (phase II)	2007–2012: design & construction
	2013–2015: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ data taking

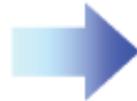
# $K^+$ Decays in flight: NA62



# NA62 guidance principles

O(100)  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  events,  $\sim 10\%$  background @BR(SM) =  $8 \times 10^{-11}$

N(K decays)  $\sim 10^{13}$   
Acceptance = 10%

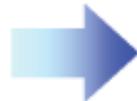


Kinematical rejection



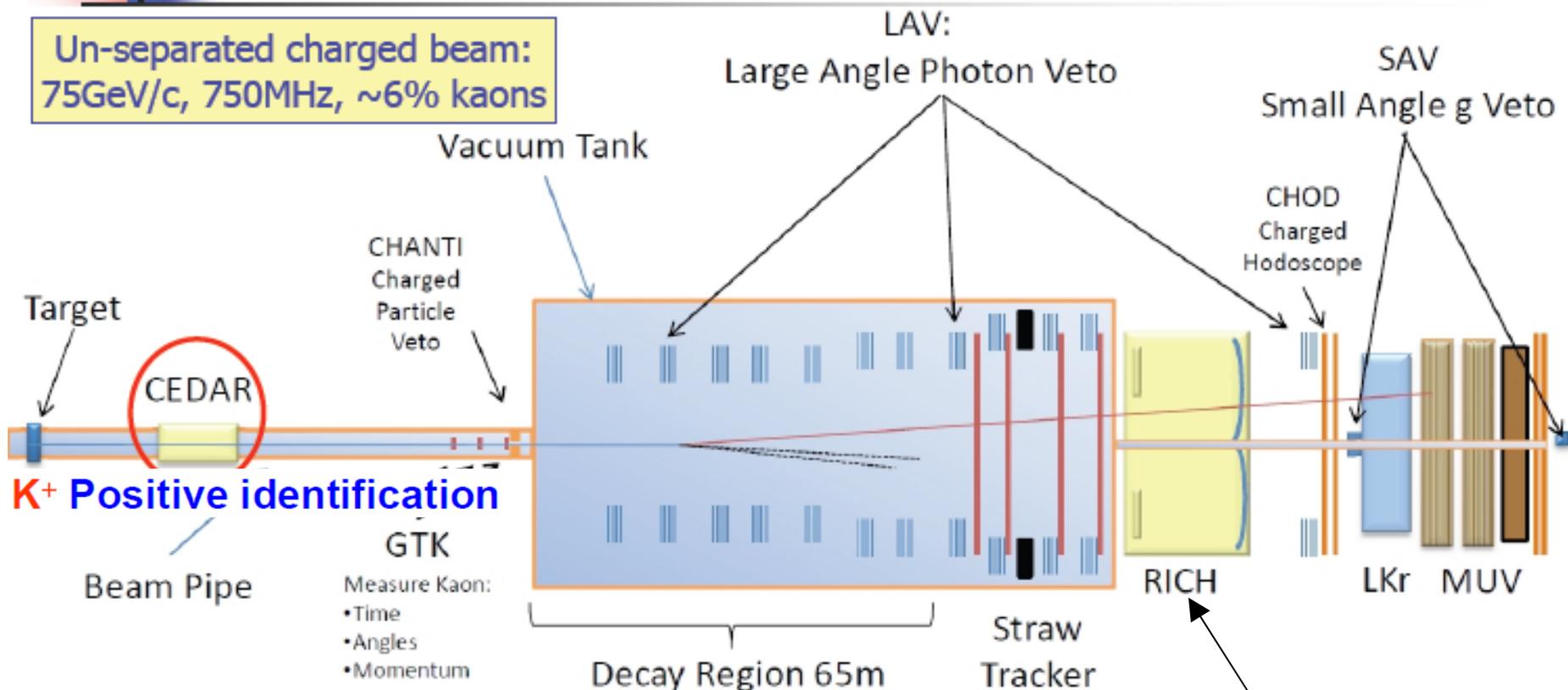
Single track signature:  $m_{\text{miss}}^2 = (P_K - P_\pi)^2$

Particle ID and veto  
in addition to kinematical rejection



- Kaon decay in flight technique;
- 400 GeV proton beam from SPS;
- Unseparated high energy  $K^+$  beam ( $P_K = 75 \text{ GeV}/c$ );
- Kaon momentum: beam tracker;
- Pion momentum: spectrometer;
- Charged track veto: spectrometer;
- Photon veto: calorimeters;
- Beam kaon identification: CEDAR;
- $\pi/\mu/e$  separation: RICH;

# NA62 (phase II) layout



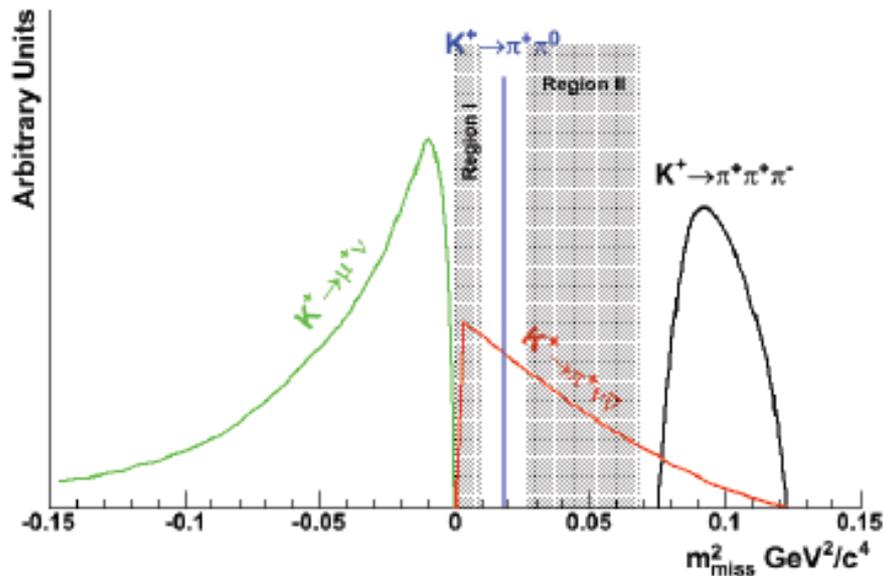
$\pi/\mu$  separation

$\pi/e$  separation (E/P)

- Record  $K^+$  decay SES of  $\sim 10^{-12}$ ;
- Hermetic veto & redundant measurements;
- R&D finishing, subdetectors construction has started.
- Approved by the CERN research board in December 2008.

# Kinematics and backgrounds

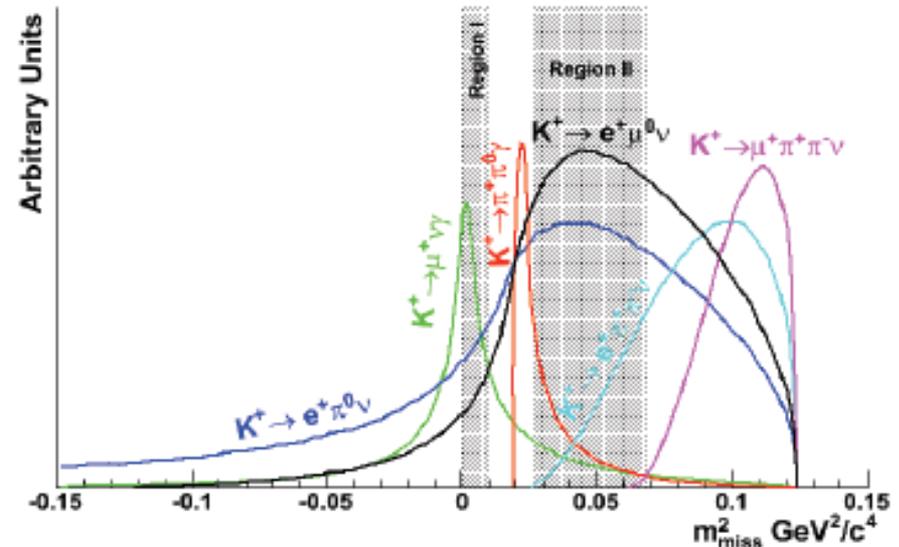
Kinematically constrained



92% of total background

- ▶ Allows us to define a signal region
- ▶  $K^+ \rightarrow \pi^+ \pi^0$  forces us to split it into two parts (Region I and Region II)

NOT kinematically constrained



8% of total background

- ▶ Span across the signal region
- ▶ Rejection relies on vetoes/PID

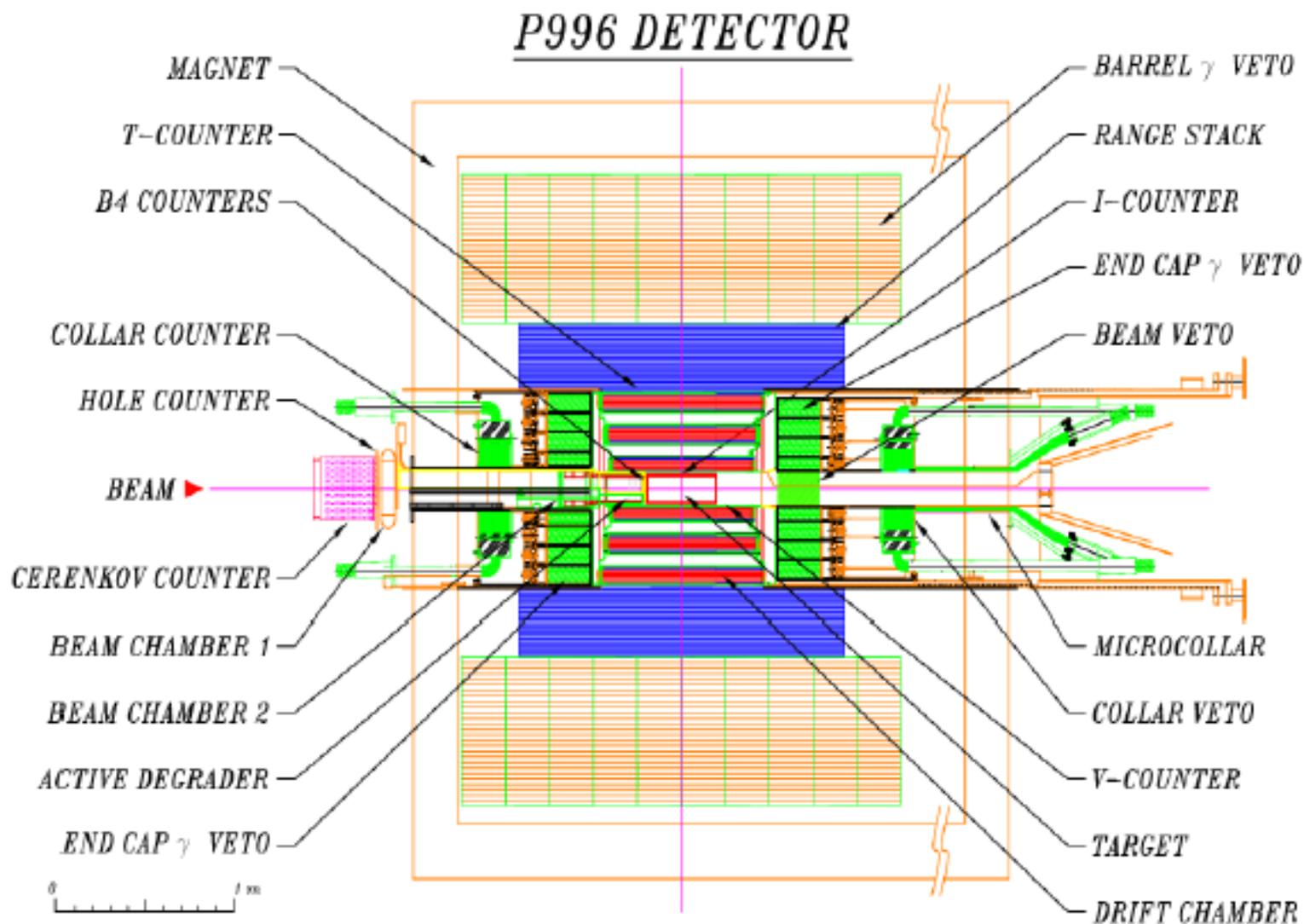
# NA62 Sensitivity

Decay Mode	Events
Signal: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ SM [flux = $4.8 \times 10^{12}$ decay/year]	55 evt/year
$K^+ \rightarrow \pi^+ \pi^0$ [ $\eta_{\pi^0} = 2 \times 10^{-8}$ ( $3.5 \times 10^{-8}$ ) ]	4.3% (7.5%)
$K^+ \rightarrow \mu^+ \nu$	2.2%
$K^+ \rightarrow e^+ \pi^+ \pi^- \nu$	$\leq 3\%$
Other 3 – track decays	$\leq 1.5\%$
$K^+ \rightarrow \pi^+ \pi^0 \gamma$	~2%
$K^+ \rightarrow \mu^+ \nu \gamma$	~0.7%
$K^+ \rightarrow e^+ (\mu^+) \pi^0 \nu$ , others	negligible
Expected background	$\leq 13.5\%$ ( $\leq 17\%$ )

Definition of “year” and running efficiencies based on NA48 experience:  
 ~100 days/year; 60% overall efficiency

# P996 Detector

Use existing (CDF or CLEO) solenoid

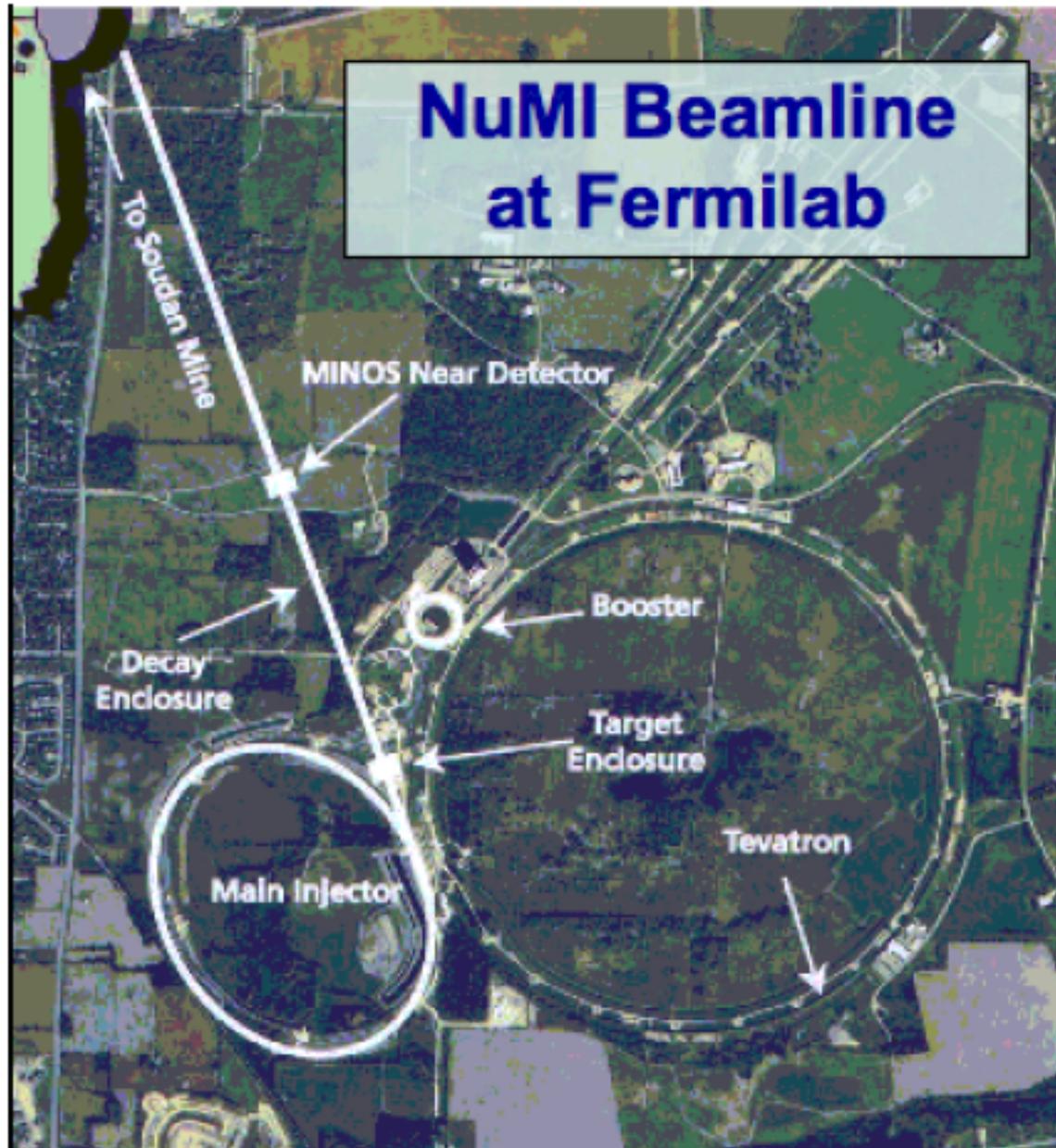


## Rate of Incident Kaons

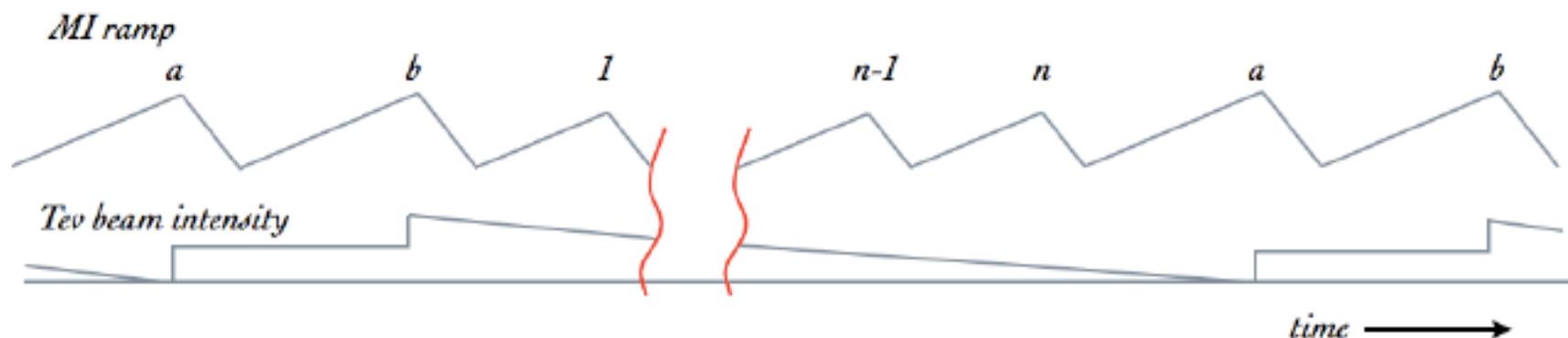
The expected rate of kaons incident on P996:

$$\begin{aligned}
 N_K(\text{P996})/\text{spill} &= N_K(\text{E949})/\text{spill} \times R_{\text{surv}} \times R_{\text{proton}} \times R_{K/p} \\
 &= 12.8 \times 10^6 \times 1.1048 \times 1.48 \times (6.8 \pm 1.7) \\
 &= (142 \pm 36) \times 10^6.
 \end{aligned}$$

- ▶  $R_{\text{surv}} = 1.1048$ , the relative rate of survival of 550 MeV/c kaons in the 13.74m P996  $K^+$  beamline compared to 710 MeV/c  $K^+$  in the 19.6m E949 beamline,
- ▶  $R_{\text{proton}} = (96 \times 10^{12}) / (65 \times 10^{12})$  protons per spill,
- ▶  $R_{K/p} = 6.8 \pm 1.7$ , the relative production rate of  $K^+$  into the P996 and E949 kaon beamline acceptance as determined from MARS-LAQSGM simulation.



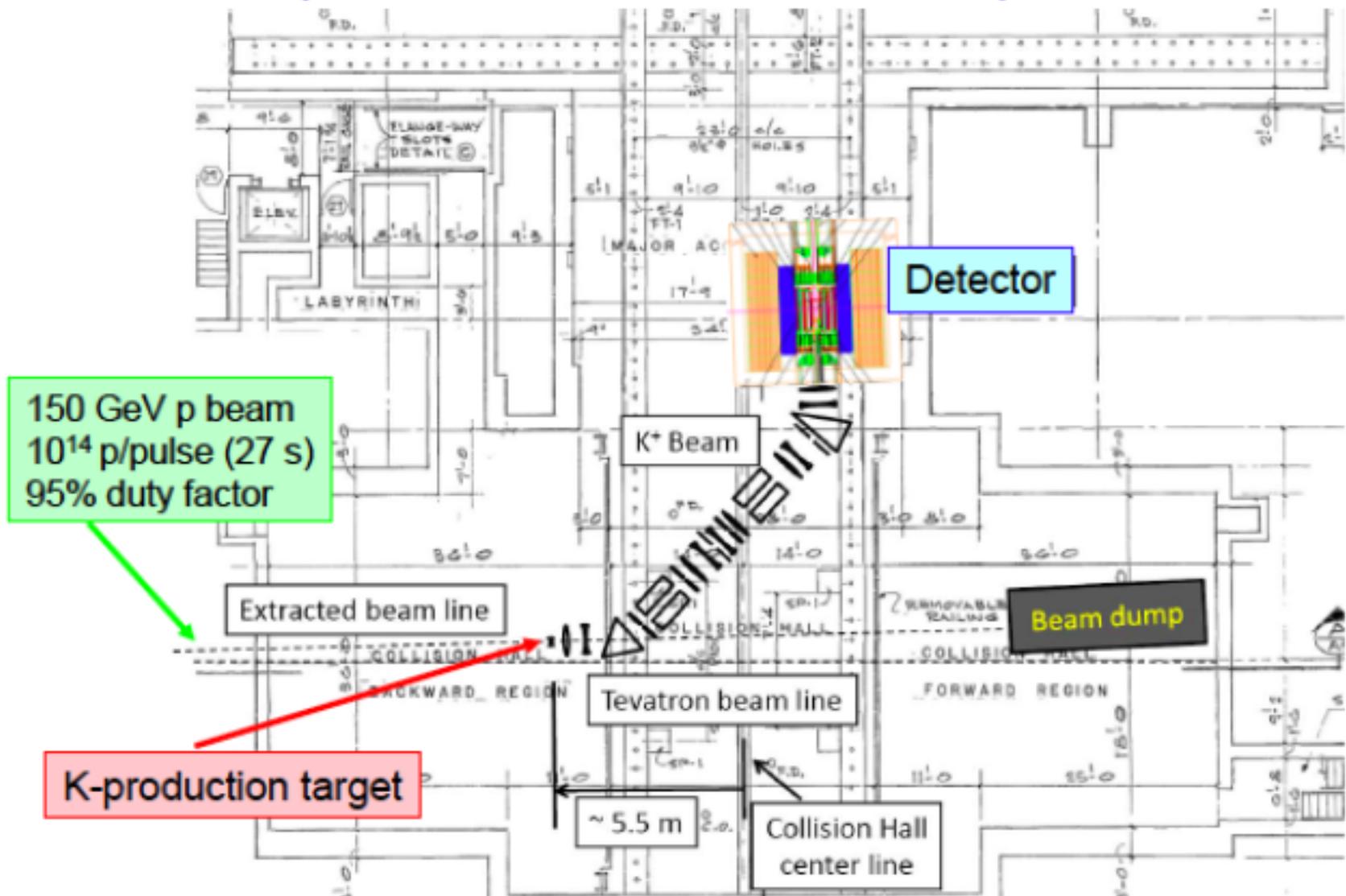
## The Tevatron as a “Stretcher”



### Operating scenario

- ▶  $n$  pulses to NuMI beam (1.33 s ramp to 120 GeV) for  $NO\nu A$  + 2 pulses to Tevatron (1.67 s ramp to 150 GeV);  $n \approx 18$ .
- ▶ Provides  $P996 \ 96 \times 10^{12}$  protons with a 27.3 s cycle and 94% duty factor
- ▶ If NuMI beam is off, higher intensity to P996 is possible.
- ▶ Main Injector could directly feed P996, at a lower duty factor, for detector commissioning
- ▶ P996 could also be a “day one” user of Project-X

# P996 sited in CDF hall



## Preliminary Total Project Cost Estimate (FY10 \$M)

Description	Total Cost	60% contingency	Total with contingency
<b>Total Project Cost</b>	<b>33.3</b>	<b>20.0</b>	<b>53.3</b>
Accelerator and Beams	7.5	4.5	12.0
Detector	22.4	13.4	35.8
Project Management	2.7	1.6	4.4
Other Project Cost	0.7	0.4	1.1

- ▶ Based on E949 experience and Fermilab FY99 fixed target operations.
- ▶ Includes use of an existing solenoid.
- ▶ Improved cost estimate in progress

# $K_{e2}/K_{\mu2}$ ratio

- CERN NA62
- KLOE

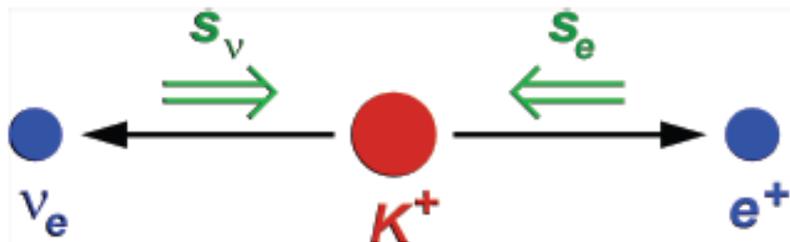
# $R_K = K_{e2}/K_{\mu2}$ in the SM

Observable sensitive to lepton flavour violation and its SM expectation:

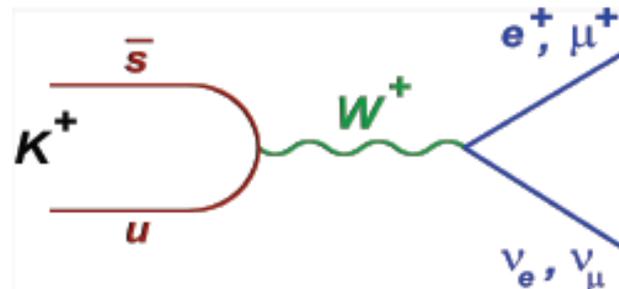
$$R_K = \frac{\Gamma(K^\pm \rightarrow e^\pm \nu)}{\Gamma(K^\pm \rightarrow \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left( \frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \cdot (1 + \delta R_K^{\text{rad. corr.}})$$

(similarly,  $R_\pi$  in the pion sector)

Helicity suppression:  $f \sim 10^{-5}$



Radiative correction (few %) due to  $K^+ \rightarrow e^+ \nu_\gamma$  (IB) process, by definition included into  $R_K$



- **SM prediction:** excellent sub-permille accuracy due to cancellation of hadronic uncertainties.
- Measurements of  $R_K$  and  $R_\pi$  have long been considered as tests of lepton universality.
- **Recently understood:** helicity suppression of  $R_K$  might enhance sensitivity to non-SM effects to an experimentally accessible level.

$$R_K^{\text{SM}} = (2.477 \pm 0.001) \times 10^{-5}$$

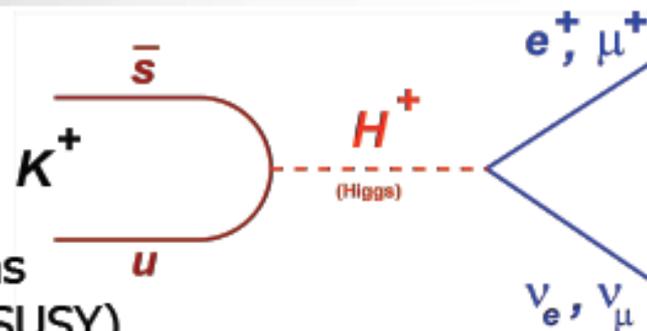
$$R_\pi^{\text{SM}} = (12.352 \pm 0.001) \times 10^{-5}$$

Phys. Lett. 99 (2007) 231801

# Leptonic meson decays: $P^+ \rightarrow l^+ \nu$

SM contribution is helicity suppressed:

$$\Gamma(P^+ \rightarrow l^+ \nu) = \frac{G_F^2 M_P M_l^2}{8\pi} \left(1 - \frac{M_l^2}{M_P^2}\right)^2 f_P^2 |V_{qq'}|^2$$



Sizeable tree level charged Higgs ( $H^\pm$ ) contributions in **models with two Higgs doublets (2HDM including SUSY)**

PRD48 (1993) 2342; Prog.Theor.Phys. 111 (2004) 295

(numerical examples for  $M_H = 500 \text{ GeV}/c^2$ ,  $\tan\beta = 40$ )

$\pi^+ \rightarrow l\nu$	$\Delta\Gamma/\Gamma_{\text{SM}} \approx -2(m_\pi/m_H)^2 m_d/(m_u+m_d) \tan^2\beta \approx 2 \times 10^{-4}$
$K^+ \rightarrow l\nu$	$\Delta\Gamma/\Gamma_{\text{SM}} \approx -2(m_K/m_H)^2 \tan^2\beta \approx 0.3\%$
$D_s^+ \rightarrow l\nu$	$\Delta\Gamma/\Gamma_{\text{SM}} \approx -2(m_D/m_H)^2 (m_s/m_c) \tan^2\beta \approx 0.4\%$
$B^+ \rightarrow l\nu$	$\Delta\Gamma/\Gamma_{\text{SM}} \approx -2(m_B/m_H)^2 \tan^2\beta \approx 30\%$

$R = \text{Br}(K \rightarrow \mu\nu) / \text{Br}(K_{e3})$   
 $(\delta R/R)_{\text{exp}} = 1.0\%$ ,  
 challenging  
 by not hopeless

PRL100 (2008) 241802

$$f_{D_s}^{(\text{QCD})} = (241 \pm 3) \text{ MeV}$$

$$f_{D_s}^{(\text{exp})} = (277 \pm 9) \text{ MeV}$$

$\sim 4\sigma$  discrepancy + new data:  
 PRD79 (2009) 052001

BaBar, Belle:  $\text{Br}_{\text{exp}}(B \rightarrow \tau\nu) = (1.42 \pm 0.43) \times 10^{-4}$   
 Standard Model:  $\text{Br}_{\text{SM}}(B \rightarrow \tau\nu) = (1.33 \pm 0.23) \times 10^{-4}$

(SM uncertainties:  $\delta f_B/f_B = 10\%$ ,  $\delta |V_{ub}|^2/|V_{ub}|^2 = 13\%$ )

Obstructed by hadronic uncertainties

# $R_K = K_{e2}/K_{\mu2}$ beyond the SM

## 2HDM – tree level (including SUSY)

$K_{12}$  can proceed via exchange of charged Higgs  $H^\pm$  instead of  $W^\pm$

→ Does not affect the ratio  $R_K$

## 2HDM – one-loop level

Dominant contribution to  $\Delta R_K$ :  $H^\pm$  mediated LFV (rather than LFC) with emission of  $\nu_\tau$

→  $R_K$  enhancement can be experimentally accessible

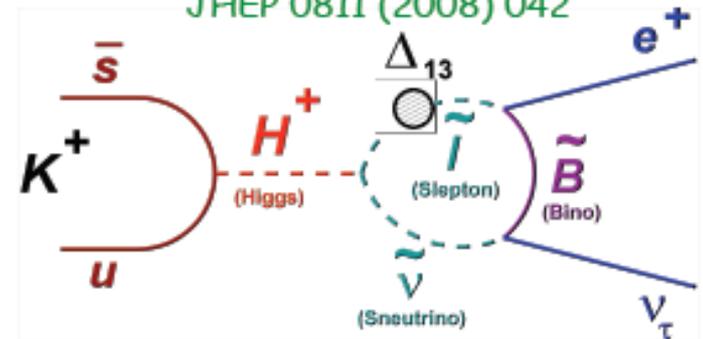
$$R_K^{\text{LFV}} \approx R_K^{\text{SM}} \left[ 1 + \left( \frac{m_K^4}{M_{H^\pm}^4} \right) \left( \frac{m_\tau^2}{M_e^2} \right) |\Delta_{13}|^2 \tan^6 \beta \right]$$

Up to ~1% effect in large (but not extreme)  $\tan\beta$  regime with a massive  $H^\pm$

Example:

( $\Delta_{13} = 5 \times 10^{-4}$ ,  $\tan\beta = 40$ ,  $M_{H^\pm} = 500 \text{ GeV}/c^2$ )  
lead to  $R_K^{\text{MSSM}} = R_K^{\text{SM}}(1 + 0.013)$ .

PRD 74 (2006) 011701,  
JHEP 0811 (2008) 042



Analogous SUSY effect in pion decay is suppressed by a factor  $(M_\pi/M_K)^4 \approx 6 \times 10^{-3}$   
(see also PRD76 (007) 095017)

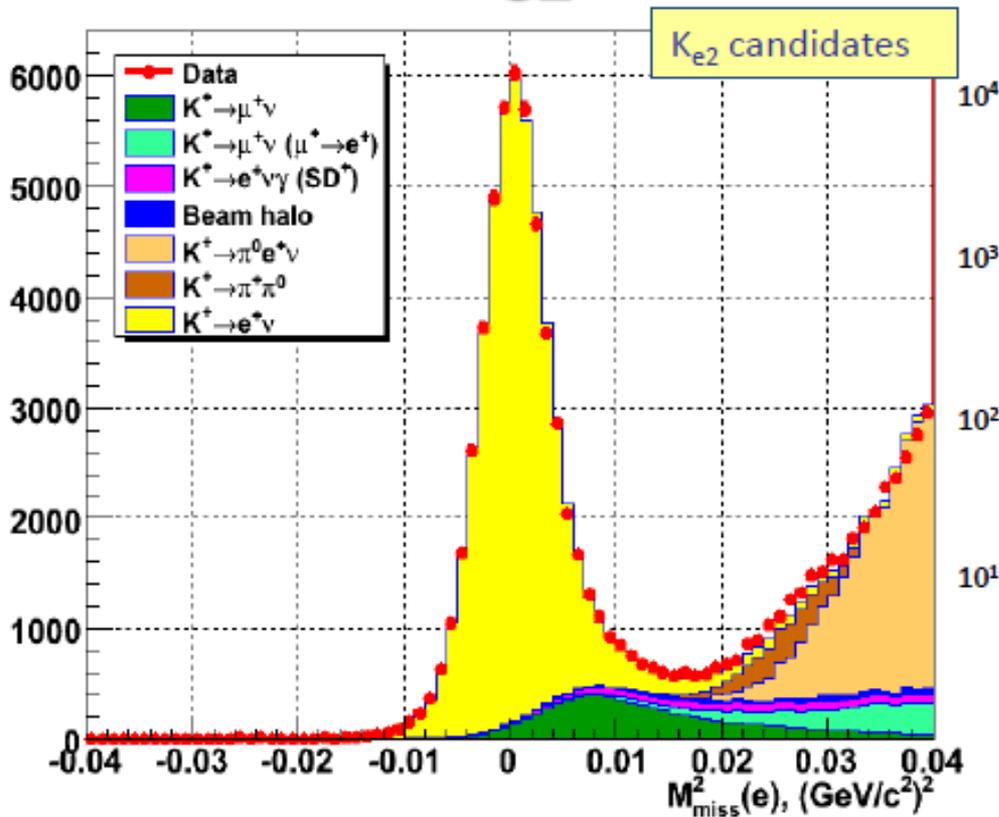
Large effects in B decays due to  $(M_B/M_K)^4 \sim 10^4$ :

$B_{\mu\nu}/B_{\tau\nu} \rightarrow \sim 50\%$  enhancement;

$B_{e\nu}/B_{\tau\nu} \rightarrow$  enhanced by ~one order of magnitude.

Out of reach:  $\text{Br}^{\text{SM}}(B_{e\nu}) \approx 10^{-11}$

# $K_{e2}$ : 40% of data set



51,089  $K^+ \rightarrow e^+ \nu$  candidates,  
99.2% electron ID efficiency,

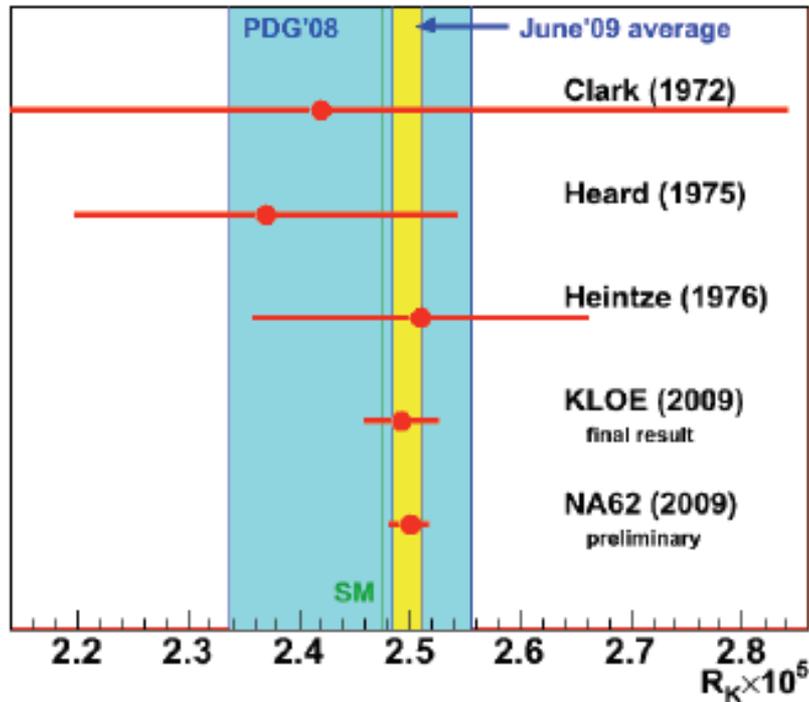
Backgrounds:

Source	B/(S+B)
$K_{\mu 2}$	$(6.28 \pm 0.17)\%$
$K_{\mu 2} (\mu \rightarrow e)$	$(0.23 \pm 0.01)\%$
$K_{e 2 \gamma} (SD^+)$	$(1.02 \pm 0.15)\%$
Beam halo	$(0.45 \pm 0.04)\%$
$K_{e 3}$	0.03%
$K_{2\pi}$	0.03%
<b>Total</b>	<b><math>(8.03 \pm 0.23)\%</math></b>

$$R_K = (2.500 \pm 0.012_{\text{stat}} \pm 0.011_{\text{syst}}) \times 10^{-5}$$

$$R_K = (2.500 \pm 0.016) \times 10^{-5}$$

# $R_K$ : sensitivity to new physics

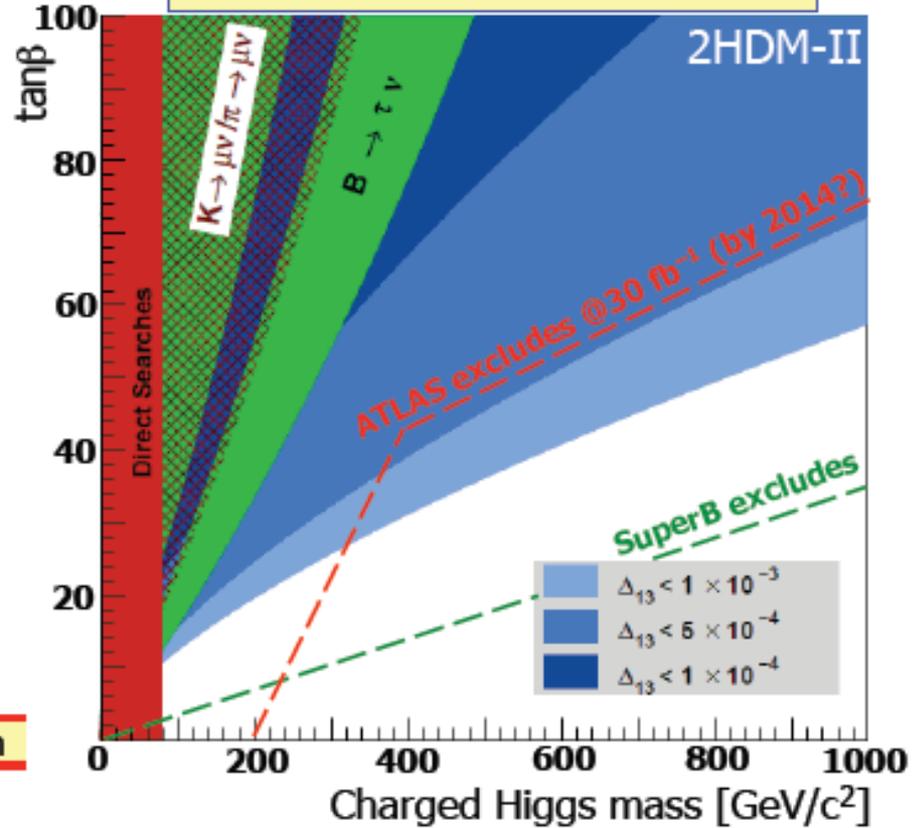


World average	$\delta R_K \times 10^5$	Precision
March 2009	$2.467 \pm 0.024$	0.97%
June 2009	$2.498 \pm 0.014$	0.56%

$R_K$  measurements are currently in agreement with the SM expectation at  $\sim 1.5\sigma$ .

Any significant enhancement with respect to the SM would be evidence of new physics.

$(M_{H^\pm}, \tan\beta)$  95% exclusion limits



For non-tiny values of the LFV slepton mixing  $\Delta_{13}$ , sensitivity to  $H^\pm$  in  $R_K = K_{e2}/K_{\mu 2}$  is better than in  $B \rightarrow \tau \nu$

# まとめ？

- J-PARCでのKaon実験は準備進行中である
    - $K_L \rightarrow \pi^0 \nu \nu$  実験 (E14/KOTO) : Stage 2
    - T violation in  $K^+ \rightarrow \pi^0 \mu^+ \nu$  (E06/TREK) : Stage 1
  - 海外でもKaon実験がメニューに載って進んでいる
    - Ke2/ $K_{\mu 2}$  ratio,  $K^+ \rightarrow \pi^+ \nu \nu$  実験 (CERN NA62, FNAL P996)
- ← これらは実は「リサイクル」ベースの実験
- デザインゴールに到達するためには今後5年レベルで実験が続けられる
  - その先は大掛かりな増強が必要となる  
(が、今のところ具体案の段階には至っていない)