Kaon rare decay experiments

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Flavor Physics in the LHC era

- LHC provides first direct TeV scale physics
- Gauge symmetry : well tested
- Higgs sector : direct observation of Higgs particle at 125GeV !
- *New era started. New physics spectrum is expected.*
- Many ideas for beyond SM ….. need to be distinguished.
- Need to probe flavor structure of BSM models

➢ Flavor physics and indirect searches gain importance.

➢ Esp. SM suppressed processes in B, K, τ, μ will be promising.

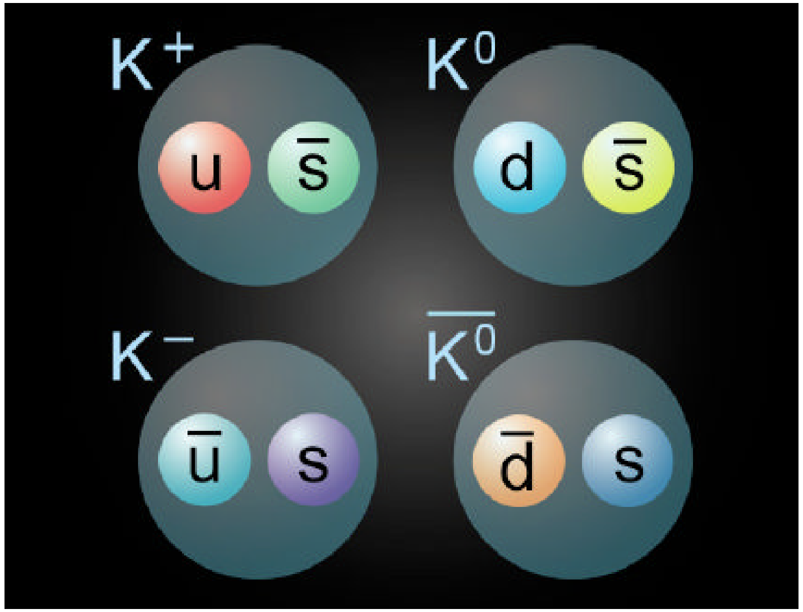
Kaon system

- composite system containing s-quark
- Historically, its decay has brought us key discoveries on particle phys.

Such as ;

- $\tau - \theta$ puzzle → P violation
- Suppression of FCNC
  - GIM mechanism → charm
- CP violation in K decay
  - Kobayashi-Maskawa scheme

  → Three generations of quark



⇒Those are basis of the SM

Kaon rare decay

- SM suppressed process is a promising research ground of BSM
- look for deviations from the SM by precise measurements with high intensity beam.
- Possible to reach higher mass scale

- Topics of this talk : Rare decay $K \rightarrow \pi\nu\nu$
  - Golden mode in Kaon physics
  - FCNC process via loop diagram
- Will concentrate on going or coming experiments
  - $K_L \rightarrow \pi^0\nu\nu$; KOTO (JPARC)
  - $K^+ \rightarrow \pi^+\nu\nu$; NA62 (CERN), ORKA (FNAL)

Decay branching fraction

K^+ DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Leptonic and semileptonic modes			
$e^+ \nu_e$	$(1.584 \pm 0.020) \times 10^{-5}$		247
$\mu^+ \nu_\mu$	(63.55 ± 0.11) %	S=1.2	236
$\pi^0 e^+ \nu_e$	(5.07 ± 0.04) %	S=2.1	228
Called K^+_{e3}.			
$\pi^0 \mu^+ \nu_\mu$	(3.353 ± 0.034) %	S=1.8	215
Called $K^+_{\mu 3}$.			
Hadronic modes			
$\pi^+ \pi^0$	(20.66 ± 0.08) %	S=1.2	205
$\pi^+ \pi^0 \pi^0$	(1.761 ± 0.022) %	S=1.1	133
$\pi^+ \pi^+ \pi^-$	(5.59 ± 0.04) %	S=1.3	125

$\pi^+ \nu \bar{\nu}$ $(1.7 \pm 1.1) \times 10^{-10}$ BNL E787/949 -- 7events

Decay branching fraction (cont.)

K_L^0 DECAY MODES			Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic modes					
$\pi^{\pm} e^{\mp} \nu_e$		[n]	(40.55 ± 0.11) %	S=1.7	229
Called K_{e3}^0.					
$\pi^{\pm} \mu^{\mp} \nu_\mu$		[n]	(27.04 ± 0.07) %	S=1.1	216
Called $K_{\mu 3}^0$.					
Hadronic modes, including Charge conjugation×Parity Violating (*CPV*) modes					
$3\pi^0$			(19.52 ± 0.12) %	S=1.6	139
$\pi^+ \pi^- \pi^0$			(12.54 ± 0.05) %		133
$\pi^+ \pi^-$	*CPV*	[p]	$(1.966 \pm 0.010) \times 10^{-3}$	S=1.5	206
$\pi^0 \pi^0$	*CPV*		$(8.65 \pm 0.06) \times 10^{-4}$	S=1.8	209

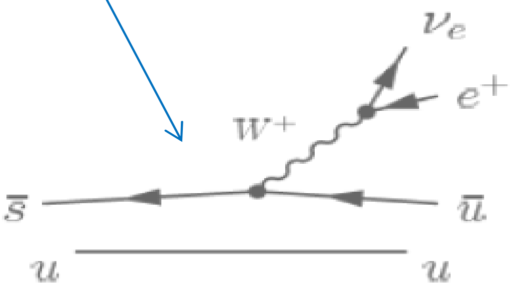
$\pi^0 \nu \bar{\nu}$ $< 2.6 \times 10^{-8}$ 90% C.L. KEK E391a

(SM prediction 2.6×10^{-11})

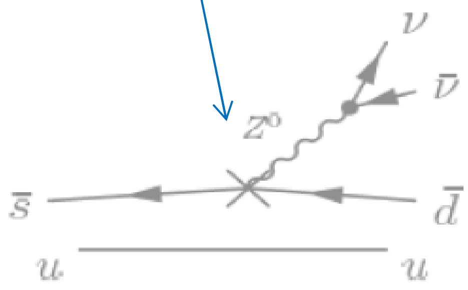
FCNC decay is suppressed

- Weak int. changes flavor of s quark, s→c (CC) but not s→d(NC)

$K^+ \to \mu^+ \nu_\mu$	(63.55 ± 0.11) %
$K^+ \to \pi^0 e^+ \nu_e$	(5.07 ± 0.04) %
Called K^+_{e3}.	
$K^+ \to \pi^0 \mu^+ \nu_\mu$	(3.353 ± 0.034) %
Called $K^+_{\mu 3}$.	



$K^+ \to \pi^+ e^+ e^-$	$(3.00 \pm 0.09) \times 10^{-7}$
$K^+ \to \pi^+ \mu^+ \mu^-$	$(8.1 \pm 1.4) \times 10^{-8}$
$K^+ \to \pi^+ \nu \overline{\nu}$	$(1.7 \pm 1.1) \times 10^{-10}$
$K^+ \to \pi^+ \pi^0 \nu \overline{\nu}$	$< 4.3 \times 10^{-5}$



$K_L \to \pi^\pm e^\mp \nu_e$	(40.55 ± 0.11) %
Called K^0_{e3}.	
$\pi^\pm \mu^\mp \nu_\mu$	(27.04 ± 0.07) %
Called $K^0_{\mu 3}$.	

$\pi^0 \mu^+ \mu^-$	$< 3.8 \times 10^{-10}$
$\pi^0 e^+ e^-$	$< 2.8 \times 10^{-10}$
$\pi^0 \nu \overline{\nu}$	$< 2.6 \times 10^{-8}$
$\pi^0 \pi^0 \nu \overline{\nu}$	$< 8.1 \times 10^{-7}$
$e^\pm \mu^\mp$	$< 4.7 \times 10^{-12}$

Via tree level diagram, yes.

Suppressed in higher order diagrams also.

FCNC by GIM with charm

- Cabibbo **one q doublet w/Cabibbo mixing**

$$q_1 = \begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{pmatrix}$$

$$j_{NC1} \approx \bar{q}_1 \tau_3 q_1 = \bar{u}u - \cos^2\theta_c \bar{d}d - \sin^2\theta_c \bar{s}s - \cos\theta_c \sin\theta_c (\bar{d}s + \bar{s}d)$$

- GIM **added 2nd gen. q doublet**

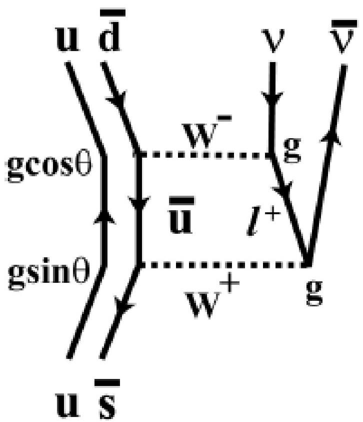
$$q_2 = \begin{pmatrix} c \\ s' \end{pmatrix} = \begin{pmatrix} c \\ d\sin\theta_c - s\cos\theta_c \end{pmatrix}$$

$$j_{NC2} \approx \bar{q}_2 \tau_3 q_2 = \bar{c}c - \sin^2\theta_c \bar{d}d - \cos^2\theta_c \bar{s}s + \cos\theta_c \sin\theta_c (\bar{d}s + \bar{s}d)$$

cancel

Higher order SM

$\pi^+\nu\nu$ ↑ K^+



and

cancels

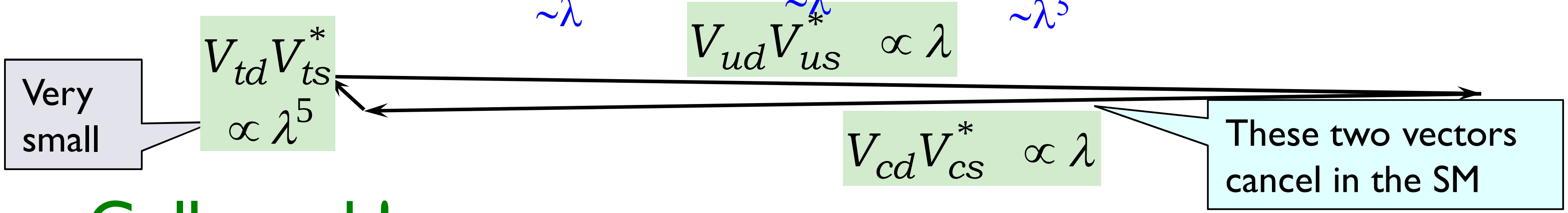
FCNC suppressed

In KM scheme

- unitarity triangle for s → d chain (u,c,t as intermediate states)

$$(s \to d) \propto V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

$\sim\lambda$ $\sim\lambda$ $\sim\lambda^5$



Collapsed !

- However, in general

$$(s \to d) \propto V_{ud} f(m_u) V_{us}^* + V_{cd} f(m_c) V_{cs}^* + V_{td} f(m_t) V_{ts}^*$$

$f(m_a)$: these may depend on a. Lim-Inami (1981) ⟶

$m_u \ll m_c \ll m_t \Rightarrow$ $(s \to d)$ is not exactly zero.

➡ Very sensitive to the higher order contribution.

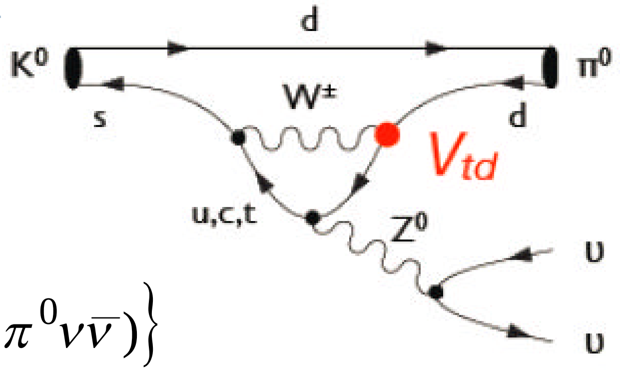
$K \to \pi\nu\bar{\nu}$ decays in the SM

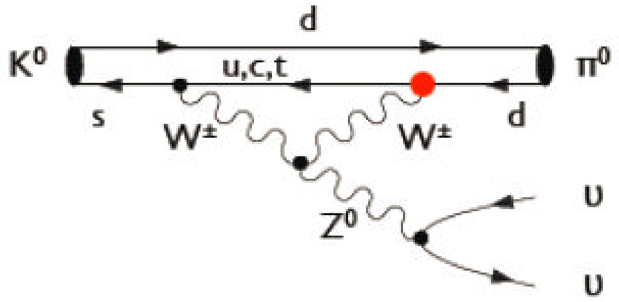
- s → d transition via loop diagram
  - K^0_L : Top quark dominates

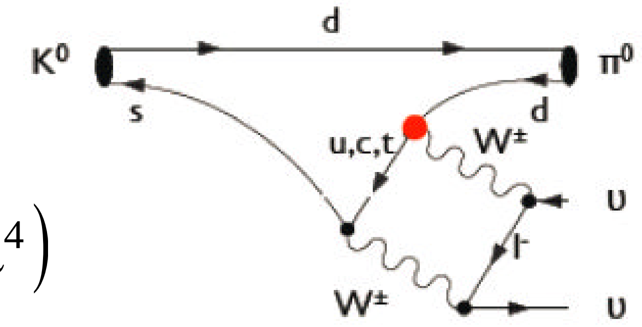
    Superposition of K^0 and $\bar{K}^0$

    $$A(K_L^0 \to \pi^0 \nu\bar{\nu}) \cong \frac{1}{\sqrt{2}}\left\{A(K^0 \to \pi^0 \nu\bar{\nu}) - A(\bar{K}^0 \to \pi^0 \nu\bar{\nu})\right\}$$

    extracts imaginary part of the amplitude
  - K^+ : Both top and charm contribute







$$V_{KM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

… s→c→d real

… s→t→d complex

$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & \lambda^2 A & 1 \end{pmatrix} + o(\lambda^4)$$

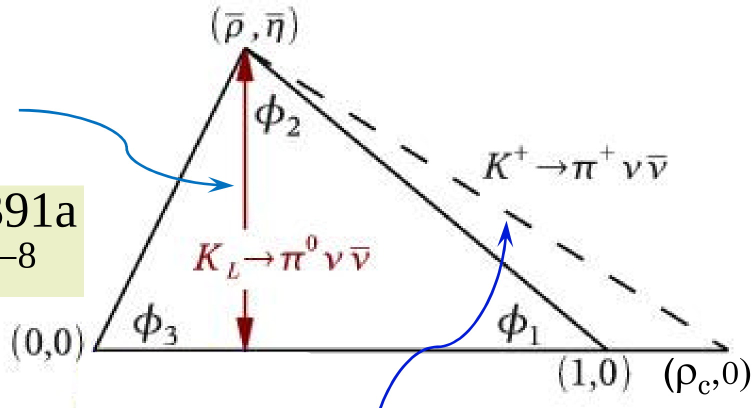
$K \to \pi\nu\bar{\nu}$ decays in the SM (cont.)

$$Br\left(K_L \to \pi^0 \nu\bar{\nu}\right) = \kappa_L \left(\frac{\mathrm{Im}\left(V_{ts}^* V_{td}\right)}{\lambda^5} X_t \right)^2 \quad \propto \bar{\eta}^2$$

$$Br_{SM} = (2.43 \pm 0.39 \pm 0.06) \times 10^{-11}$$

Exp. KEK E391a
$Br < 2.6 \times 10^{-8}$

CP violating



$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \kappa_+ (1 + \Delta_{EM}) \times \left| \frac{V_{ts}^* V_{td}}{\lambda^5} \cdot X_t + \frac{\mathrm{Re}\, V_{cs}^* V_{cd}}{\lambda} \cdot \left(P_c + \delta P_{c,u}\right) \right|^2 \quad \propto \bar{\eta}^2 + (\bar{\rho}_c - \bar{\rho})^2$$

~1.3 charm contribution

$$Br_{SM} = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$$

Exp. BNL E787/949
$Br = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

Hadronic parmeters κ_L, κ_+ are extracted from $K_{\ell 3}$

$(K_L \to \pi^- e^+ \nu_e, K^+ \to \pi^0 e^+ \nu_e$ etc.)

Theoretical uncertainty is small

Golden modes of K physics

X_t : top quark contribution
$P_c, dP_{c,u}$: charm contribution
(short & long distace)

$K_L \to \pi^0 \nu\nu$ is a CPV process

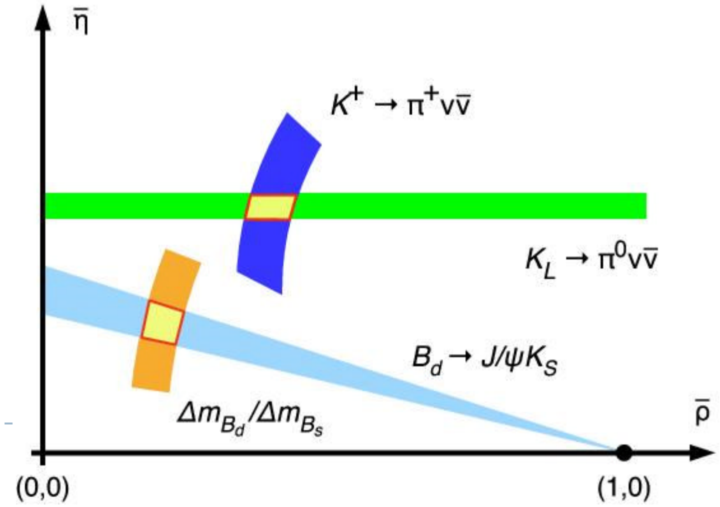
- $\nu\nu$ via Z* CP+, L = 1 to make J = 0
  → final state CP + , but initial state (K_L) CP −

$$A(K_L \to \pi^0 \nu\bar{\nu})$$
$$= \frac{1}{\sqrt{1+\varepsilon^2}}\left[A(K_2 \to \pi^0 \nu\bar{\nu}) + \varepsilon A_1(K_1 \to \pi^0 \nu\bar{\nu})\right]$$
$$= \frac{1}{\sqrt{2(1+\varepsilon^2)}}\left[(1+\varepsilon)A(K^0 \to \pi^0 \nu\bar{\nu}) - (1-\varepsilon)A(\bar{K}^0 \to \pi^0 \nu\bar{\nu})\right]$$
$$\propto V_{td}^* V_{ts} - V_{ts}^* V_{td} \approx 2i\eta$$

Sensitive to CKM matrix element $\mathrm{Im}(V_{td}) = \eta$

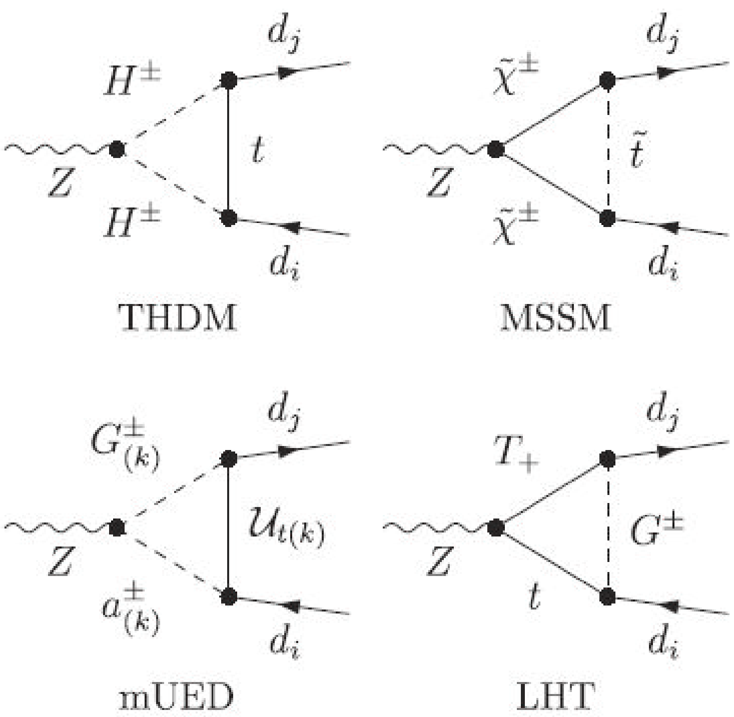
Theoretically clean < 2%

- Measurement is independent from B physics – cross check
- FCNC : suppressed in the SM
- Any new amplitude expected to give large effect



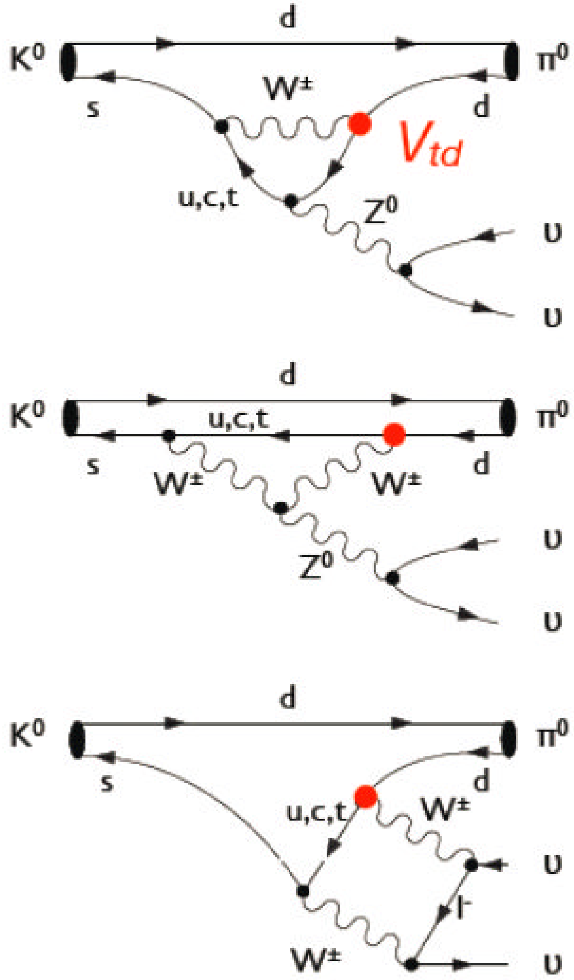
K →πνν : BSM phys. adds extra phase

PHYSICAL REVIEW D 76, 074027 (2007)



THDM: two-HIggs-doublet model
MSSM: minimal-supersymmetric SM
mUED: minimal universal extra dimension
LHT : littlest Higgs model with T parity

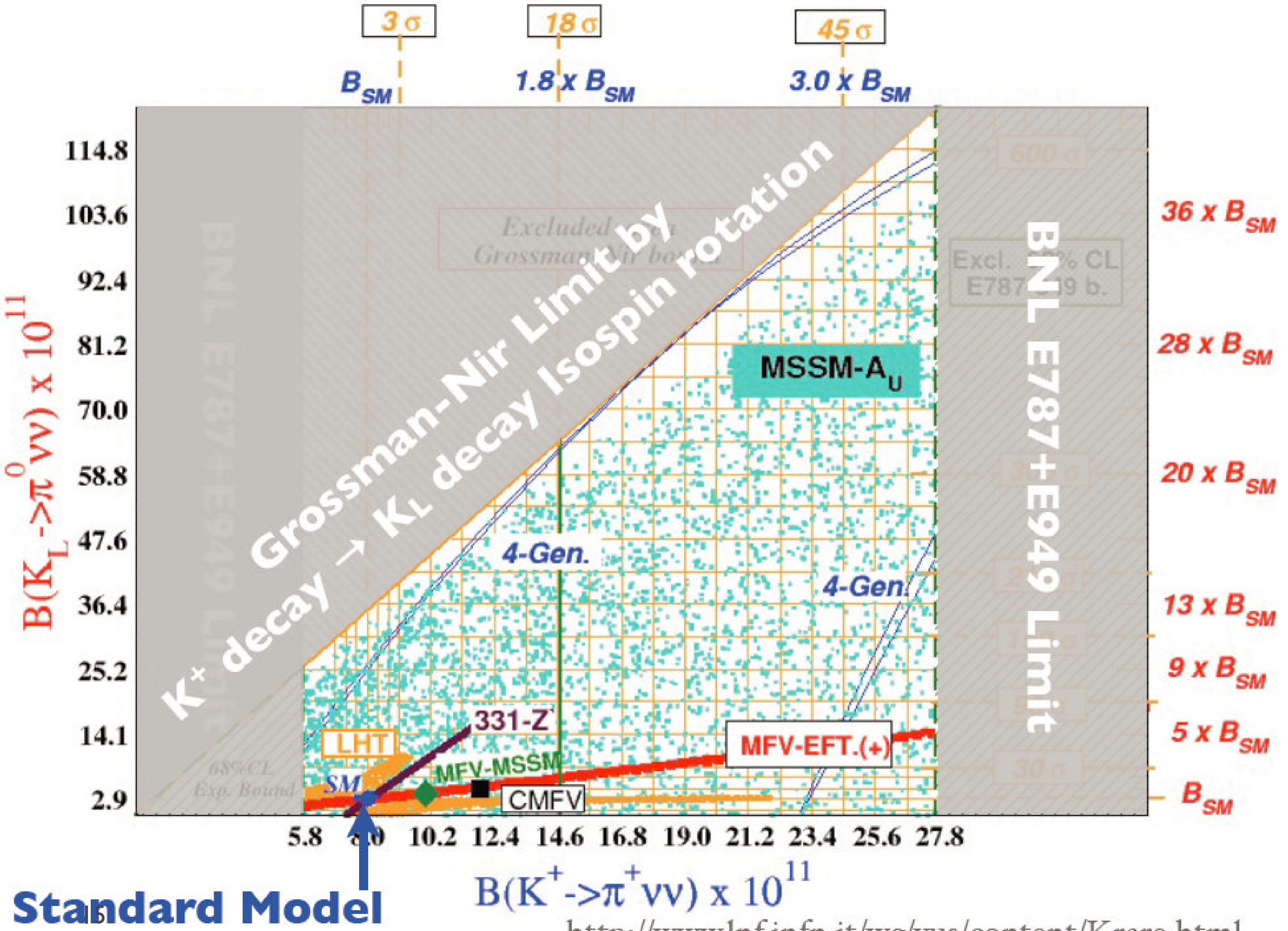
\+



Effect of Physics beyond SM

- Enumeration of BSM candidates … mentioned by Buras et al
  - Little Higgs Model with T-parity
  - RS model based on a warped extra dimension
  - MSSM
  - THDM
  - Extra Z penguin
  - 4-th generation
  - …. and others

- Most of these models give possibility of enhancing $Br(K^+ \to \pi^+ \nu\nu)$ and/or $Br(K^0 \to \pi^0 \nu\nu)$ by factor of 3 to 10 (or more) w.r.t. SM value

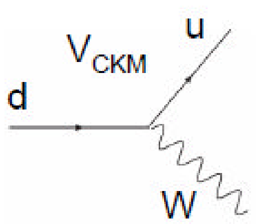


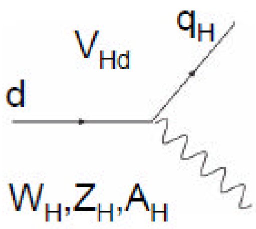
http://www.lnf.infn.it/wg/vus/content/Krare.html

Little Higgs model with T-parity

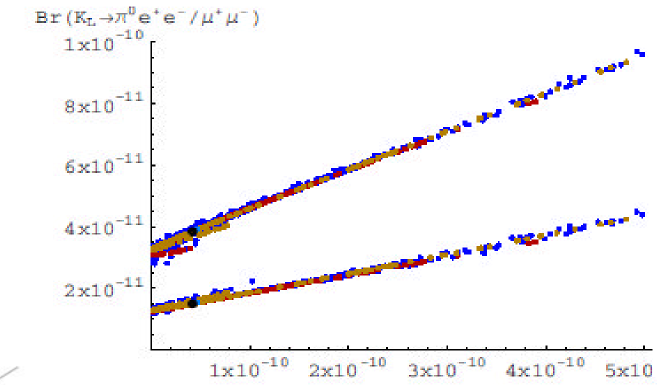
T-parity odd mirror particles are introduced → add new flavor mixing matrix

Calculation by Buras et al.





$Br(K_L \to \pi^0 e^+ e^- / \mu^+ \mu^-)$

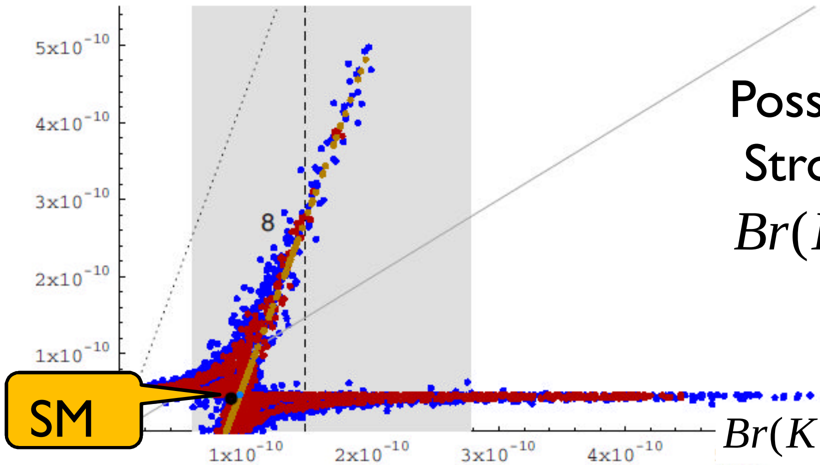


ee

μμ

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

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



$Br(K^+ \to \pi^+ \nu \bar{\nu})$

Possible enhancement of K→πνν signal

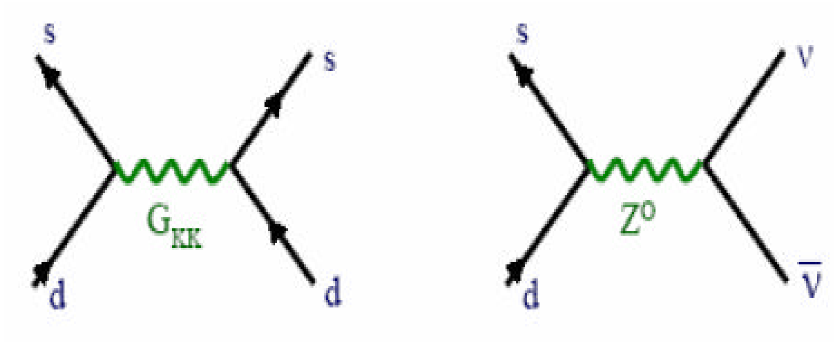
Strong correlation between $K_L \to \pi^0 \nu \bar{\nu}$ and $Br(K_L \to \pi^0 e^+ e^- / \mu^+ \mu^-)$

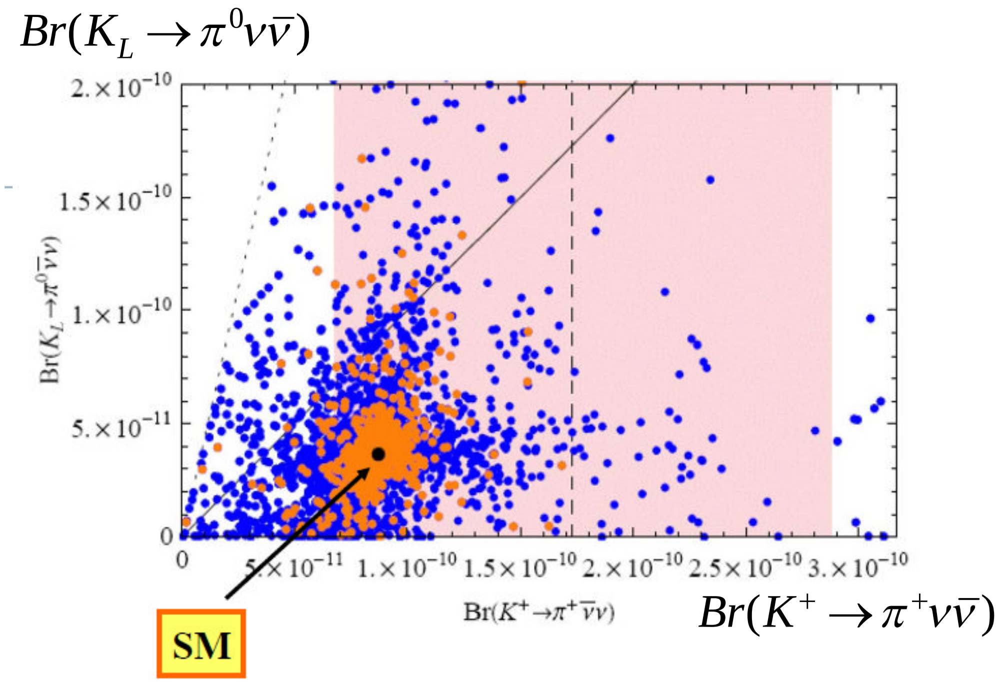
RS model

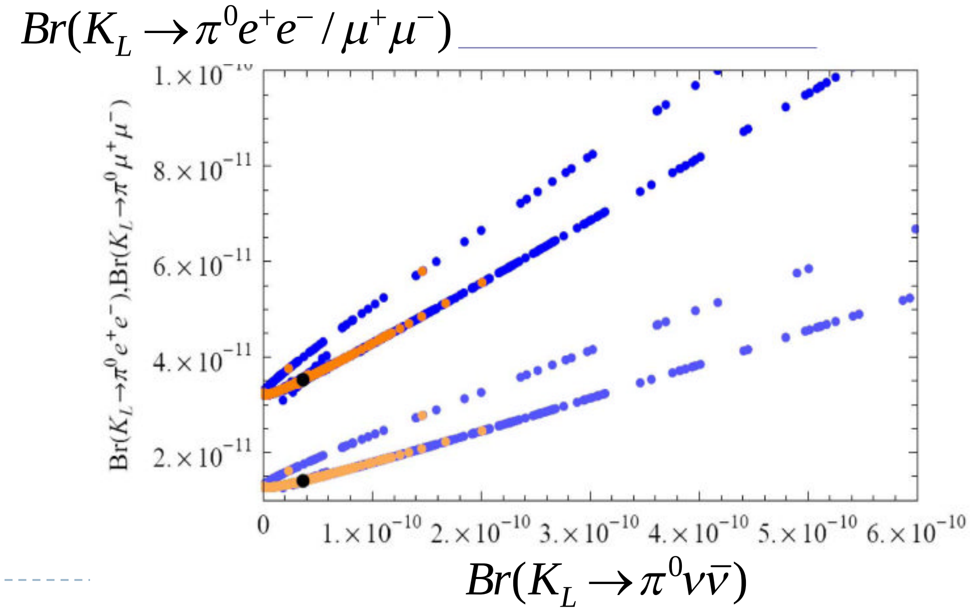
Calculation by Buras et al.

- proposed to solve hierarchy problem between Planck / weak scale

➢ KK fermions and bosons
➢ Flavor changing Z coupling

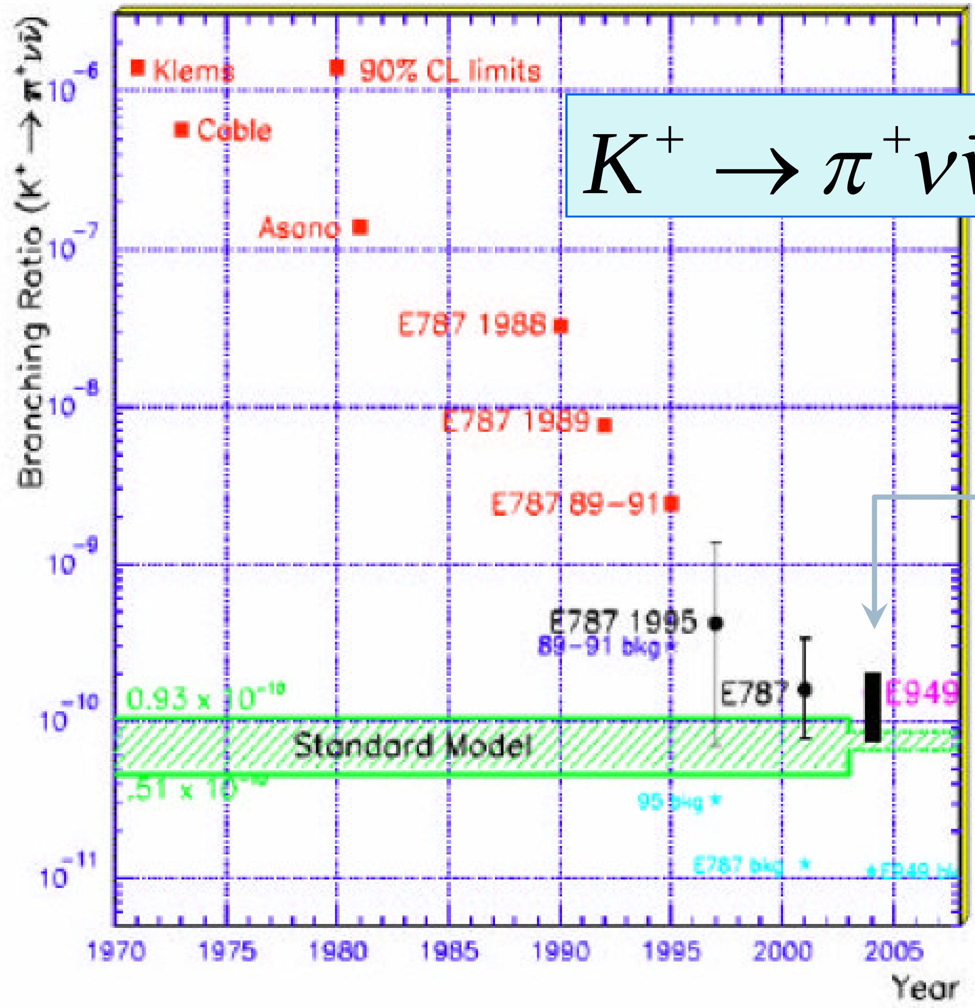






Also strong correlation between
$K_L \to \pi^0 \nu\bar{\nu}$ and $K_L \to \pi^0 e^+e^- / \mu^+\mu^-$

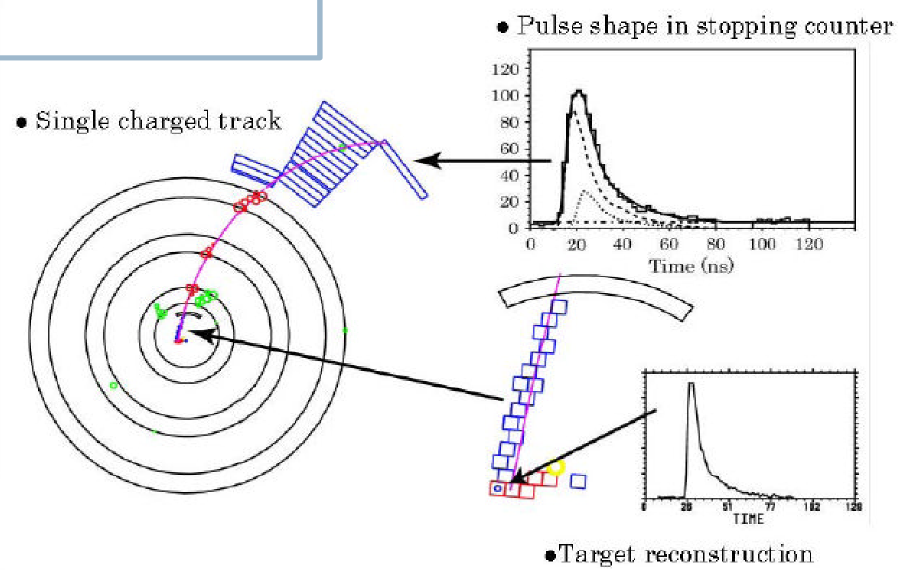
Experiments on K $\rightarrow \pi\nu\bar{\nu}$



$$K^+ \rightarrow \pi^+ \nu\bar{\nu}$$

- E949 observed 7 events

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



Upper limit of $K_L \to \pi^0 \nu\nu$ KEK-PS E391a

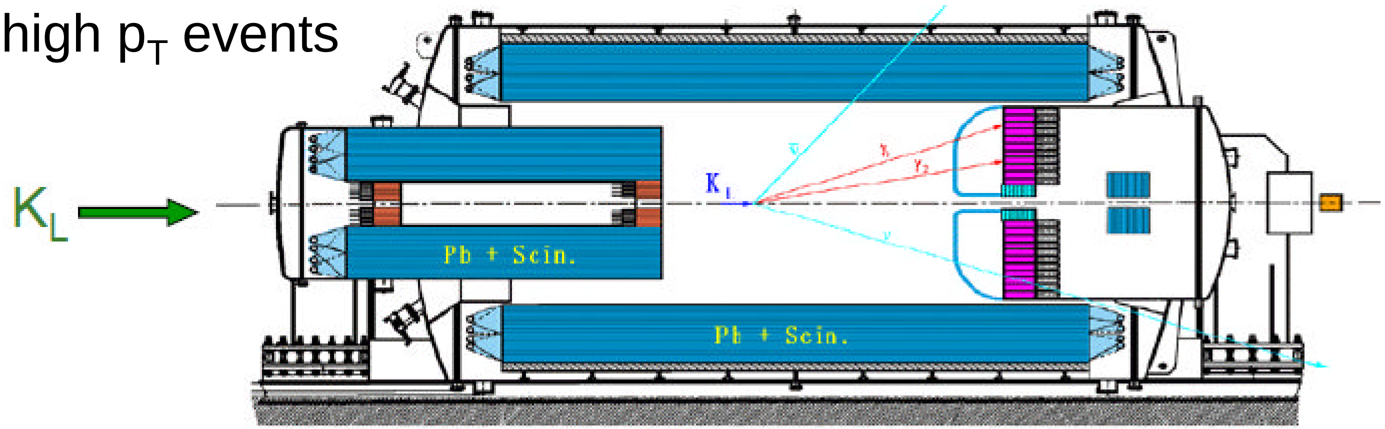
Signature of $K_L \to \pi^0 \nu\nu$ decay : 2γ + nothing

- Detecting nγ (n=1,2,4..) and nothing else → CsI calorimeter and Hermetic veto system with high eff.

  BG source : $K_L \to \pi^0\pi^0$ if 2γ missed (BR ~10^{-3})

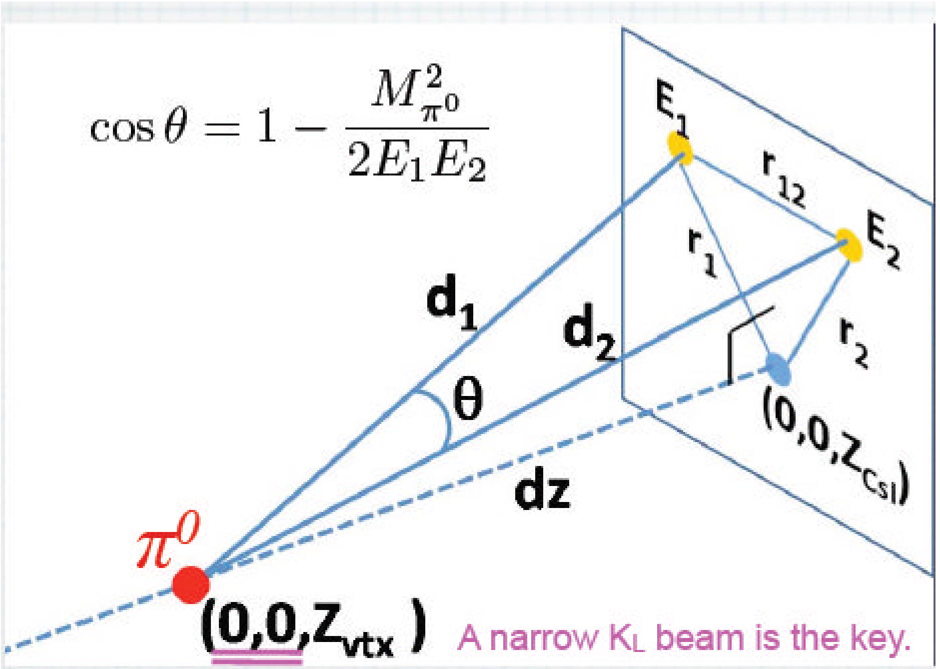
  ↔ $K_L \to \pi^0 \nu\nu$ $BR_{SM} = 2.8 \times 10^{-11}$ reduction of 10^{-8} !!

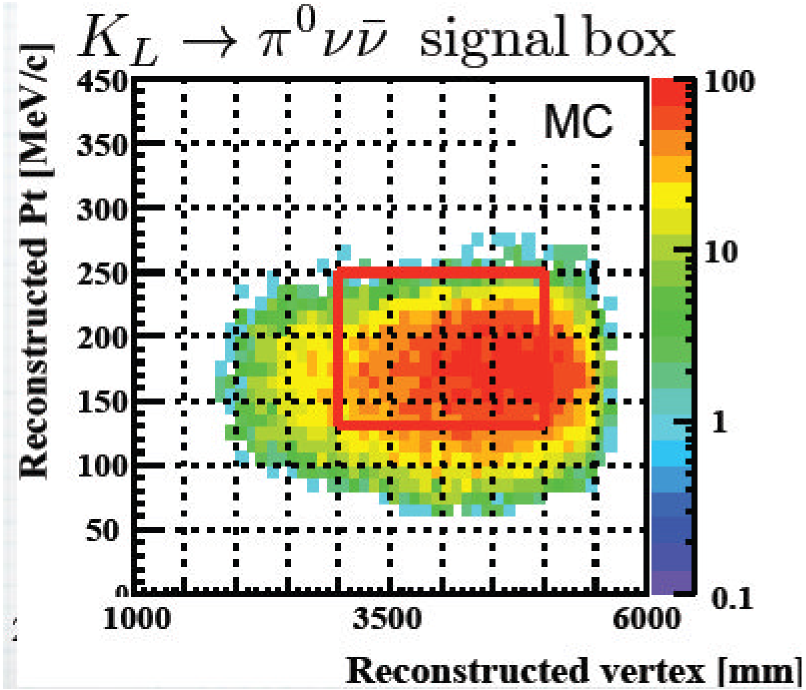
- Pencil beam
  - Reconstruct γ assuming π^0 decays on the beam axis
  - Selecting high p_T events



Kinematics of $K_L \to \pi^0 \nu\nu$

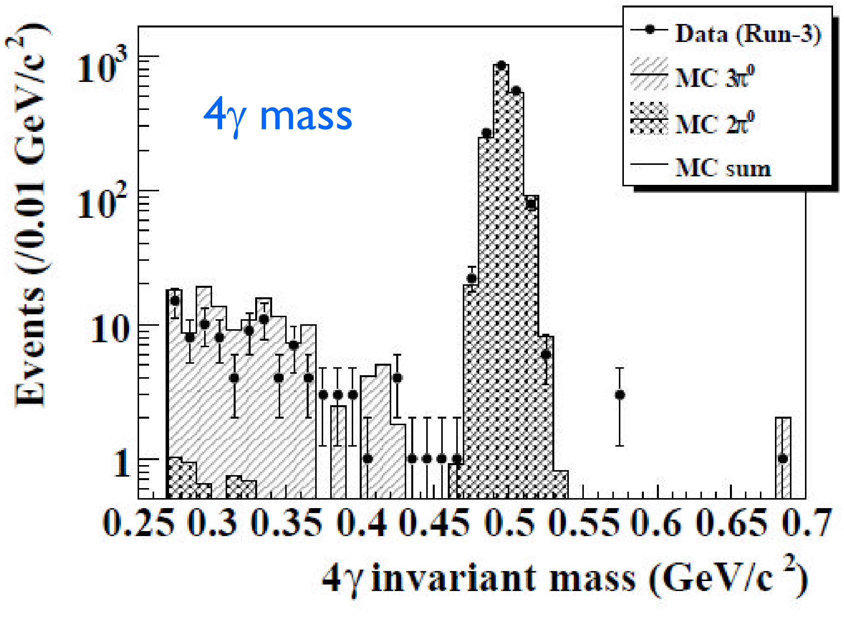
- Signal reconstruction
  - Assume : 2γ come from π^0 on beam axis → calculate Z_{vtx}
  - Calculate P_t of π^0
  - (Z_{vtx}, P_t) defines signal region

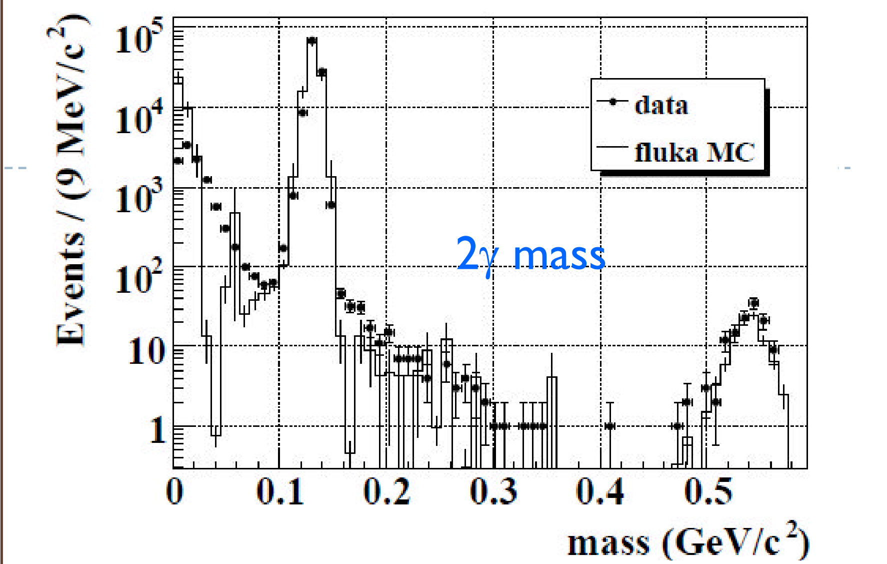


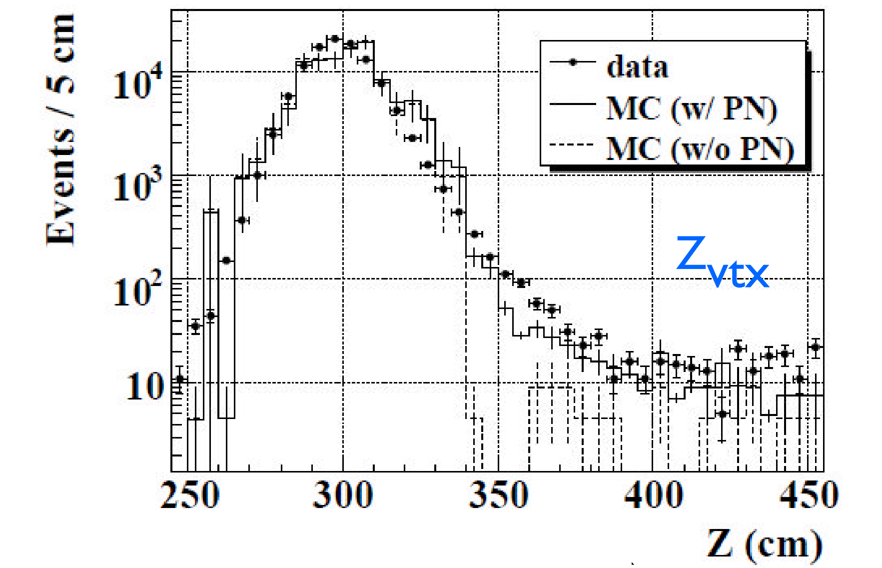


E391a data

- Well calibrated exp.
- π^0, K^0, vtx point, π^0 pt reconstructed







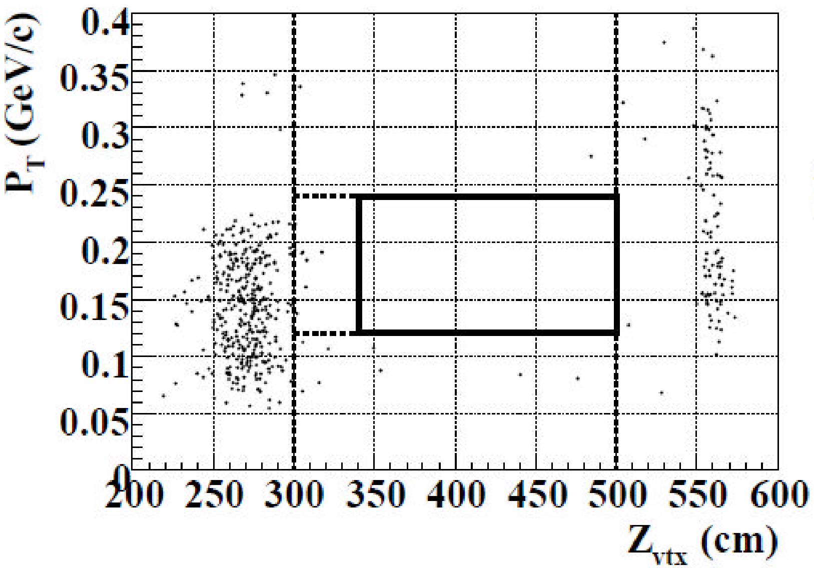
Run with thin Al plate

E391a results (full sample)

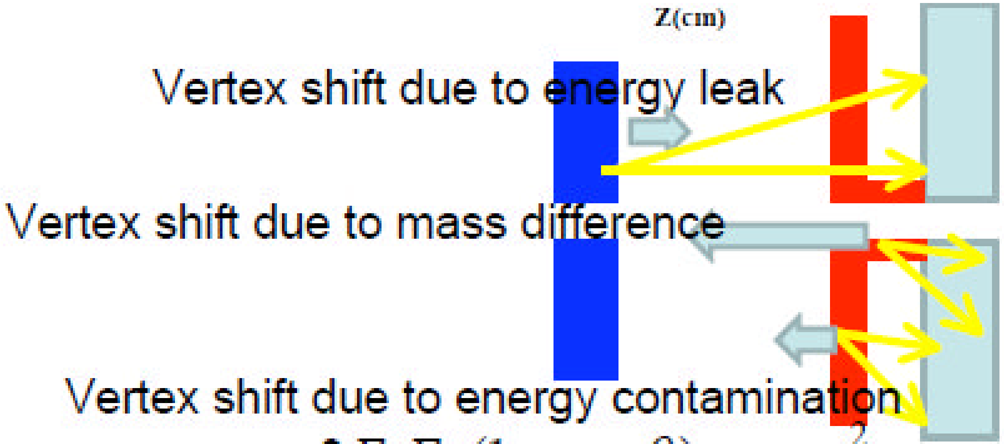
- Z_{vtx} vs $P_T(\pi^0)$ defines good signal box for $\pi^0\nu\nu$
- Single event sensitivity $(1.11 \pm 0.02 \pm 0.10) \times 10^{-8}$
- 0 event remained in the box

➡ Br < 2.6×10^{-8} @90% cl

Morii et al.,
PRD 81, 072004 (2010)



Exp. Data after all cuts

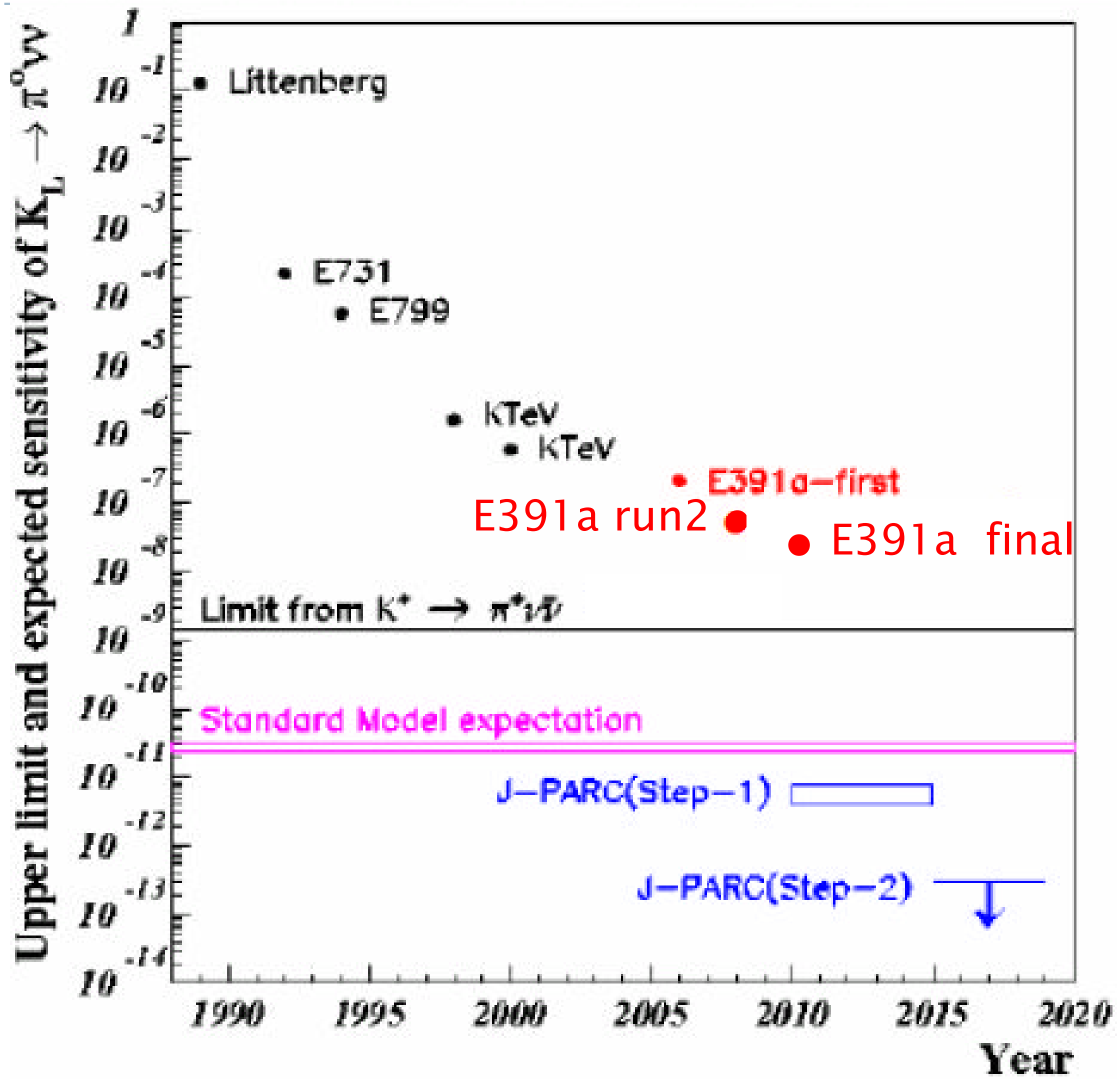


$$2E_1E_2(1-\cos\theta) = m_{\pi 0}^2$$

Probable contamination

Evolution of the upper limit of $K_L \to \pi^0 \nu\nu$

- E391a achieved
  Br < 2.6 x10^{-8}
  - S.E.S ~ 1.1x10^{-8}
  - one order to reach GN limit*



Jparc KL challenges

- step1 : 2x10^{14} pot in 2x10^7 sec
  S.E.S. ~ 8 x 10^{-12}
- step2 : 1.8x10^{21} pot
  S.E.S. ~ 10^{-13}

Grossman–Nir bound

PLB 398 (1997) 163

$$r_{is} \times \frac{\Gamma(K_L \to \pi^0 \nu\bar{\nu})}{\Gamma(K^+ \to \pi^+ \nu\bar{\nu})} = sin^2\theta$$

isospin breaking correction

$$\frac{BR(K_L \to \pi^0 \nu\bar{\nu})}{BR(K^+ \to \pi^+ \nu\bar{\nu})} < \frac{\tau_{K_L}}{\tau_{K^+}} \times \frac{1}{r_{is}} = 4.371... \simeq 4.4$$

$$BR(K_L \to \pi^0 \nu\bar{\nu}) < 4.4 \times UL_{90\%}(K^+ \to \pi^+ \nu\bar{\nu})$$

- Current exp. Bound

$$Br\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = 1.73^{+1.15}_{-1.05} \times 10^{-10} \quad \text{BNL E949}$$

$$< 3.1 \times 10^{-10} \Rightarrow \text{GN limit } 1.4 \times 10^{-9}$$

$$Br\left(K_L^0 \to \pi^0 \nu\bar{\nu}\right) < 2.6 \times 10^{-8} \quad \text{KEK E391a}$$

Morii et al., PRD 81, 072004 (2010)

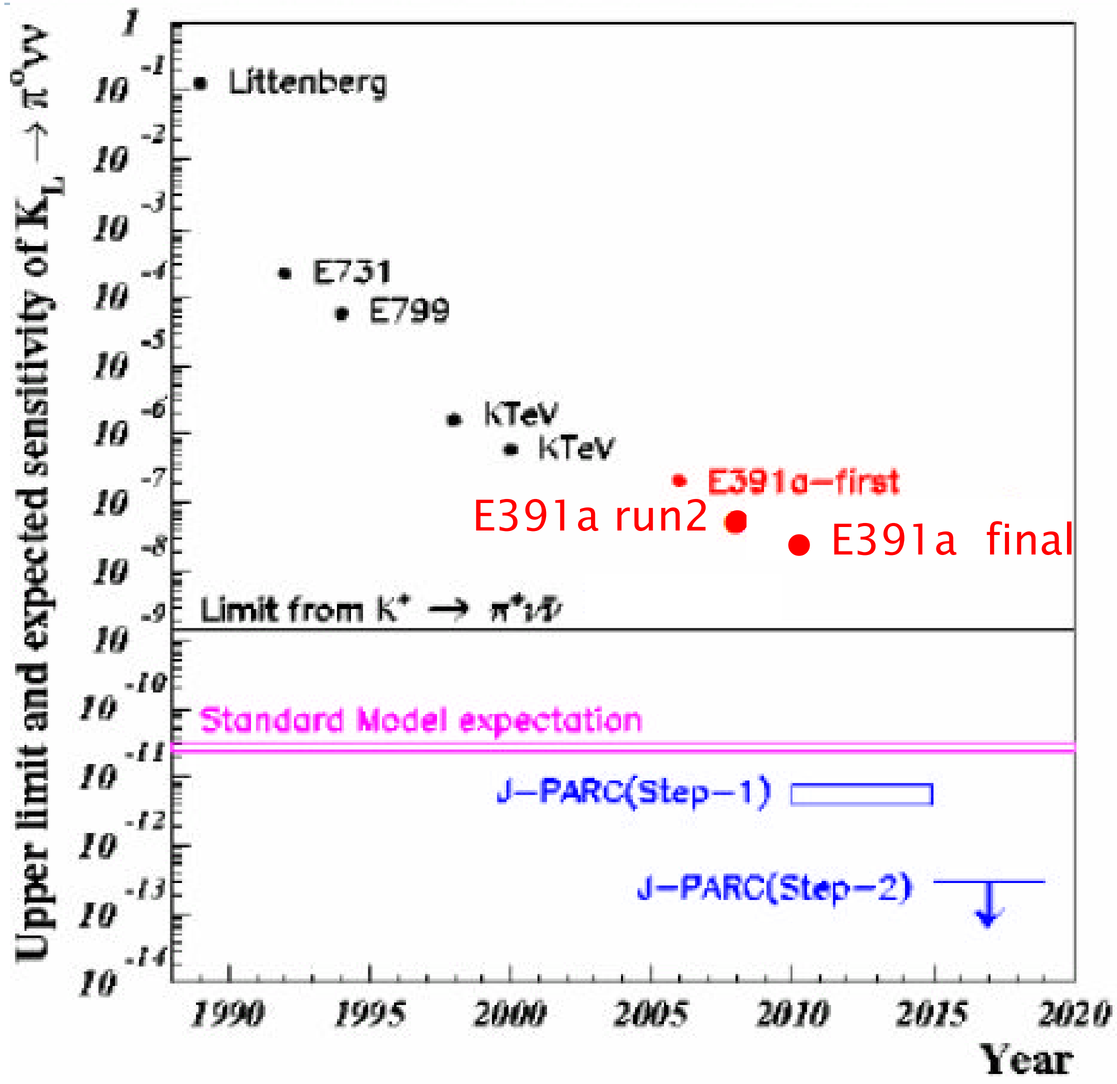
--- current exp. limit is ~20 times larger than GN limit

Evolution of the upper limit of $K_L \rightarrow \pi^0 \nu\nu$

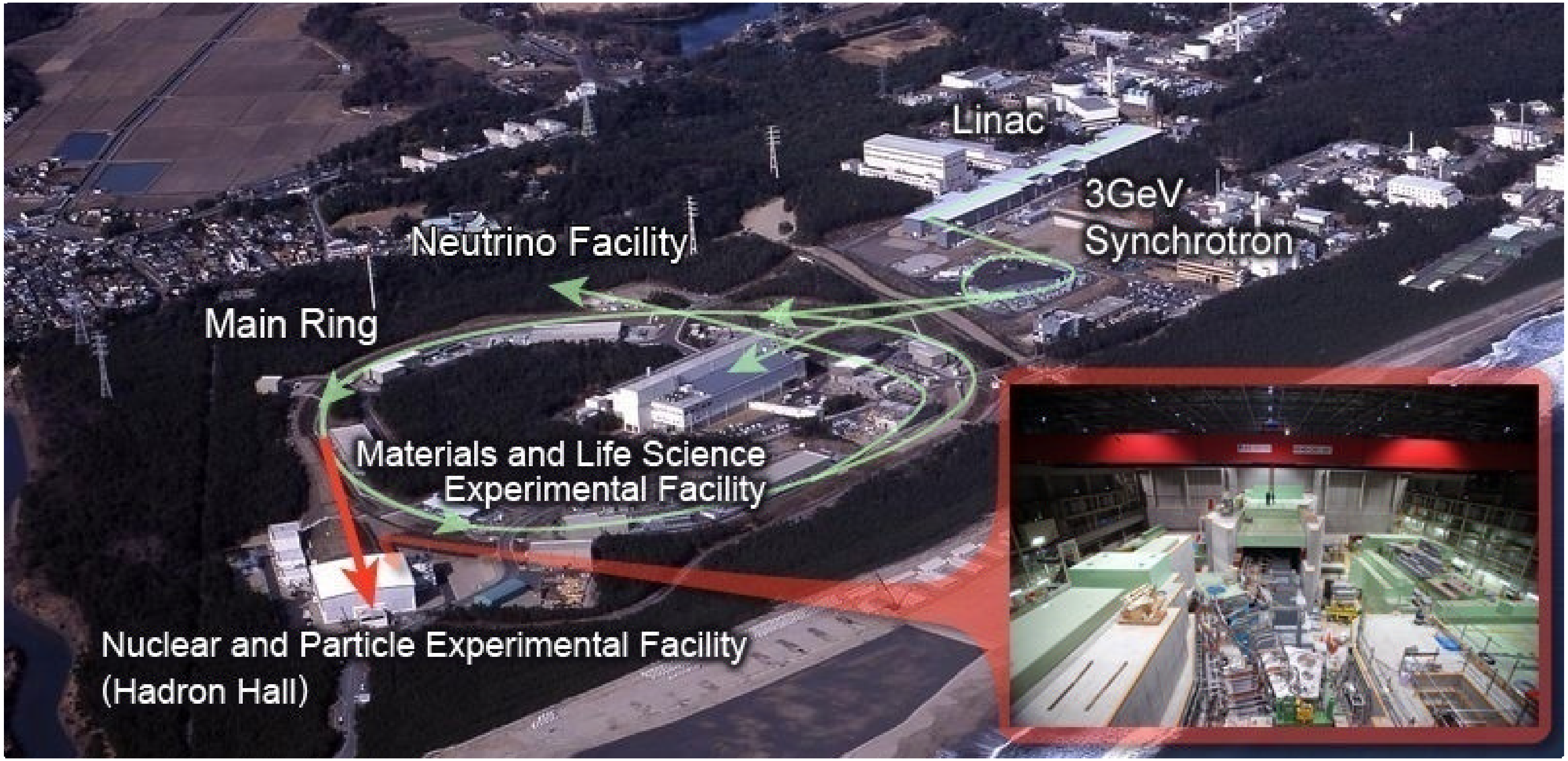
- E391a achieved
  - Br < 2.6 x10^{-8}
  - S.E.S ~ 1.1x10^{-8}
  - one order to reach GN limit

Jparc KL challenges

- step1: 2x10^{14} pot in 2x10^{7} sec
  - S.E.S. ~ 8 x 10^{-12}
- step2 : 1.8x10^{21} pot
  - S.E.S. ~ 10^{-13}

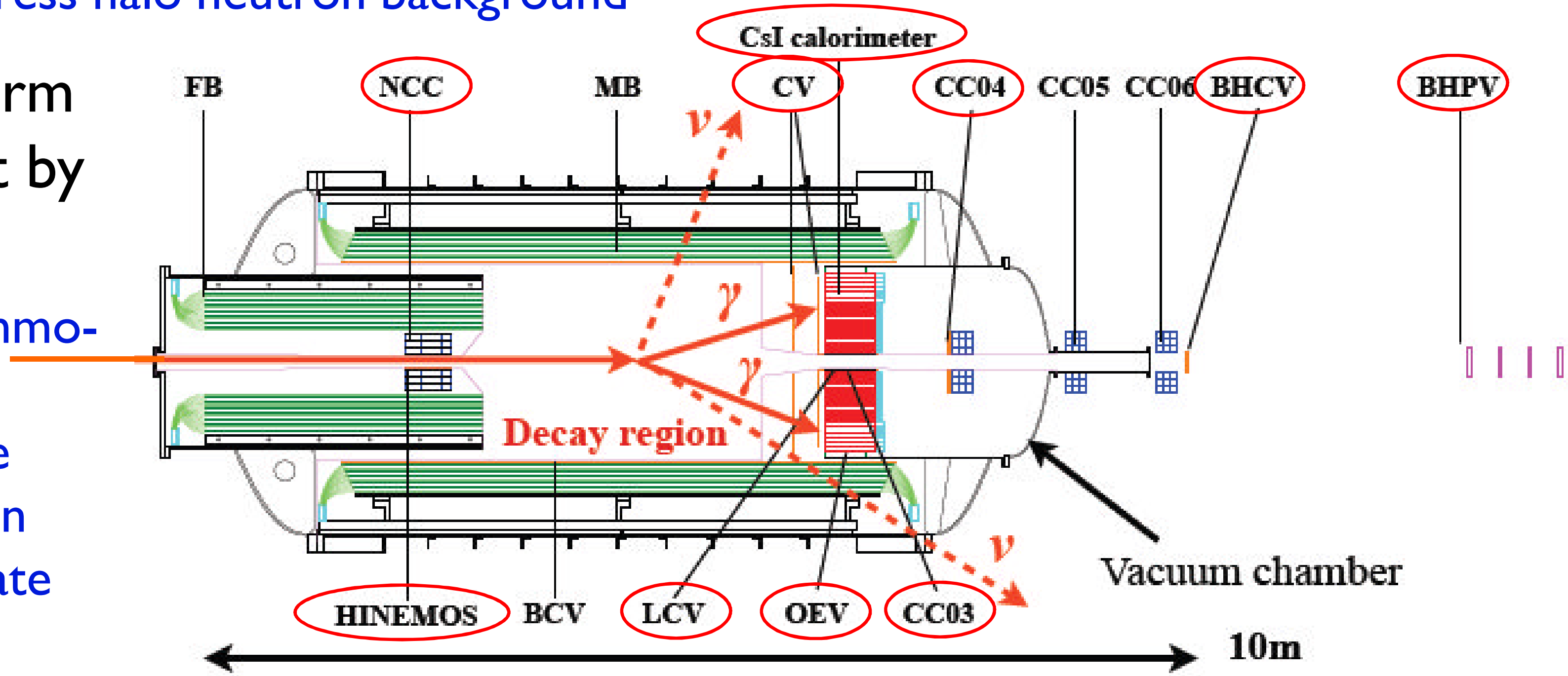


Where is JParc ?


Linac
3GeV Synchrotron
Neutrino Facility
Main Ring
Materials and Life Science Experimental Facility
Nuclear and Particle Experimental Facility (Hadron Hall)

Detector upgrade E391a→KOTO

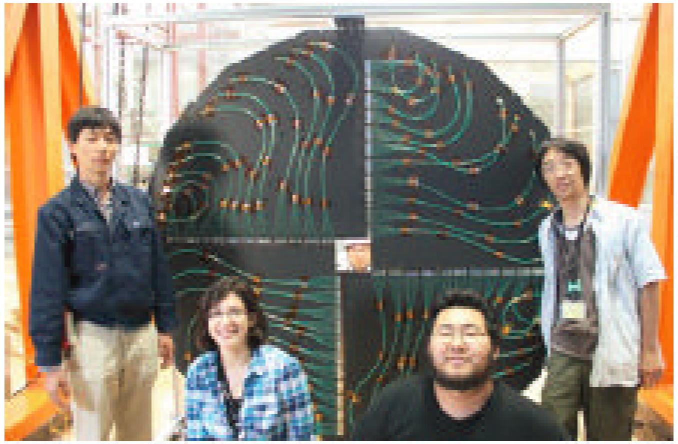
- CsI calorimeter with KTeV crystal
  - Longer 30cm →50cm (27X_0), Finer granularity 7x7 → 2.5x2.5cm^2
  - ⇒ Better energy and positional resolution
- New Veto and beam hole counters
  - CC with CsI crystal, Charged Veto with thinner scintillator
  - ⇒ Suppress halo neutron background
- Waveform readout by FADC
  - ⇒Accommodate double pulse in high rate

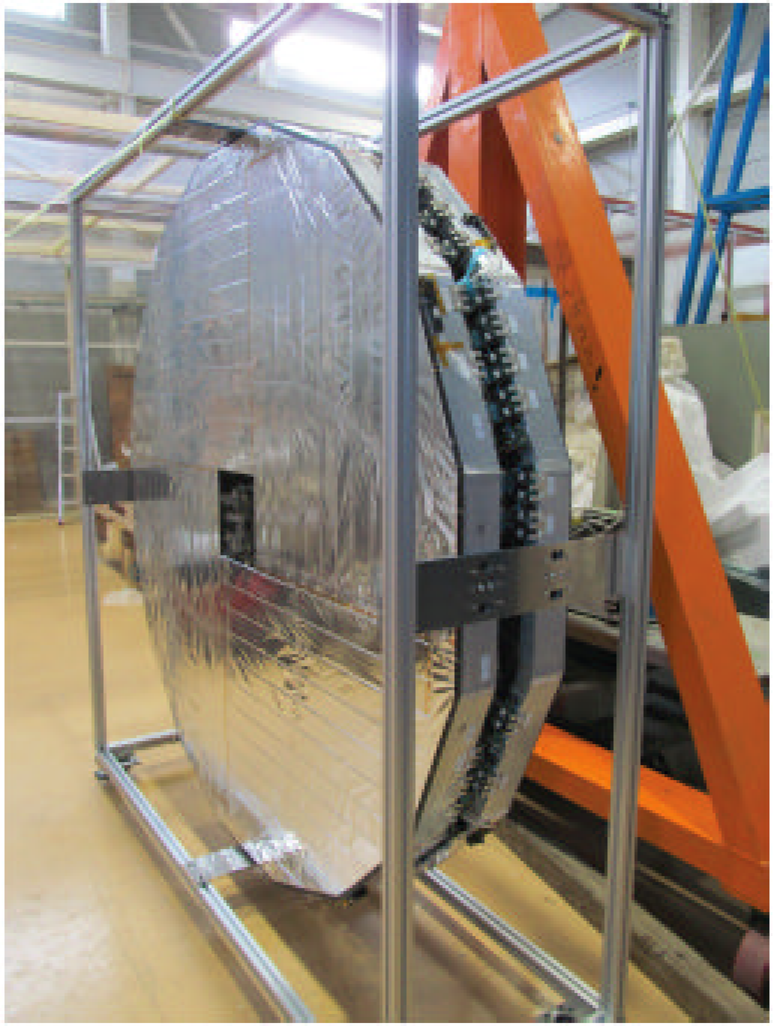


CsI calorimeter

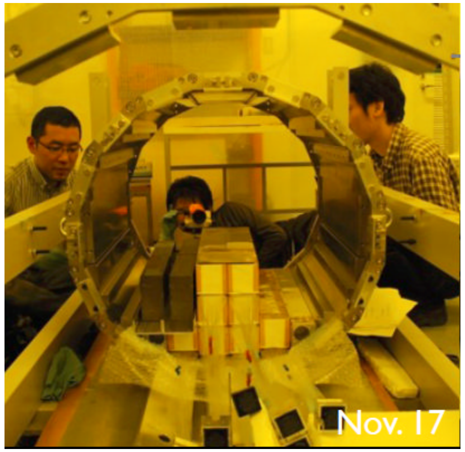
Main Barrel Veto

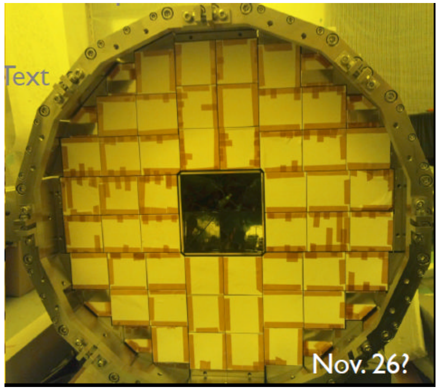
Charged Veto in front of CsI





Upstream veto counters

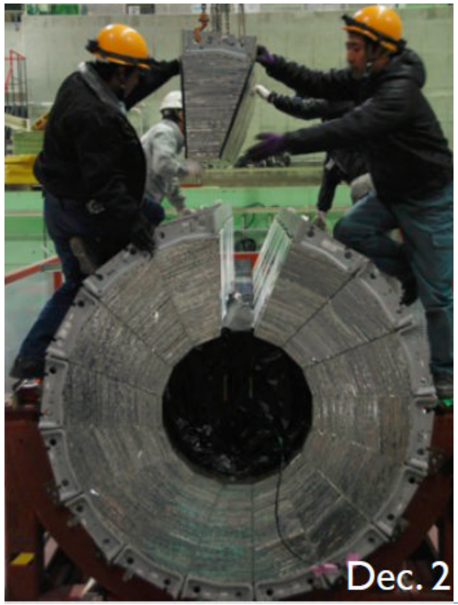




Neutron Collar Counter (NCC)
newly constructed

Placed inside the FB
FB+NCC slid into MB
↓

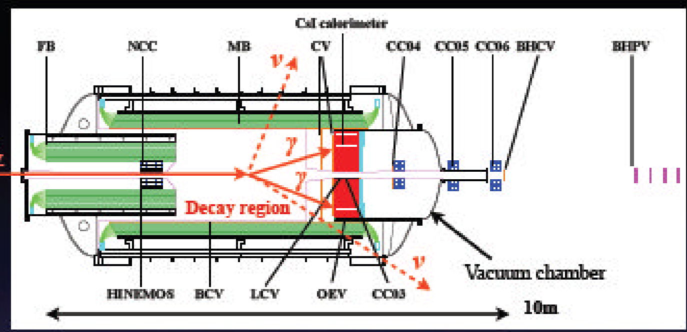
Front Barrel (FB)
From E391a
re-assembled →

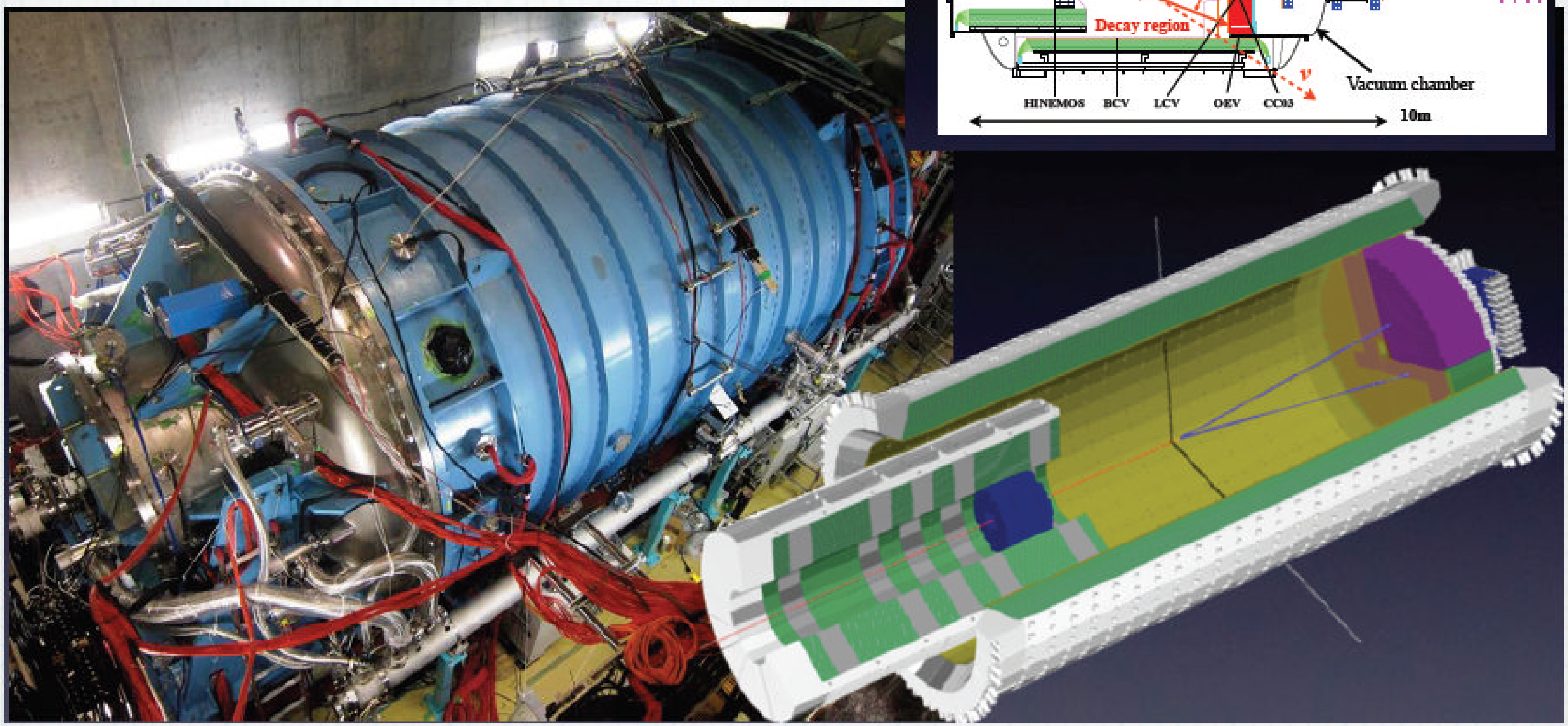


Vacuum vessel

Nomura, PIC 2013

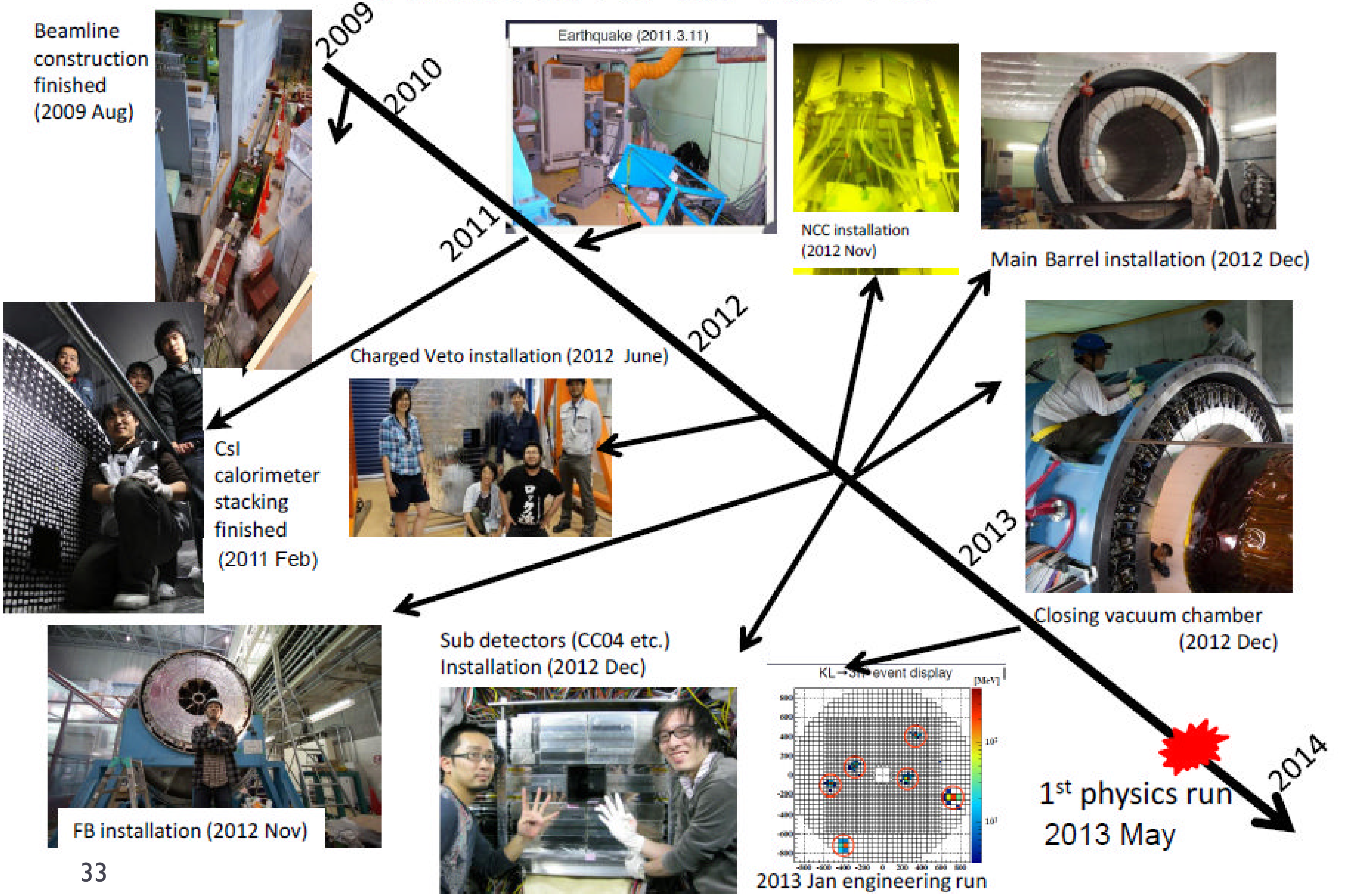
~10^{-5} Pa for decay region
~0.1 Pa for detector region





September 4-7, 2013 T. Nomura (KEK), PIC 2013 - IHEP, Beijing 17

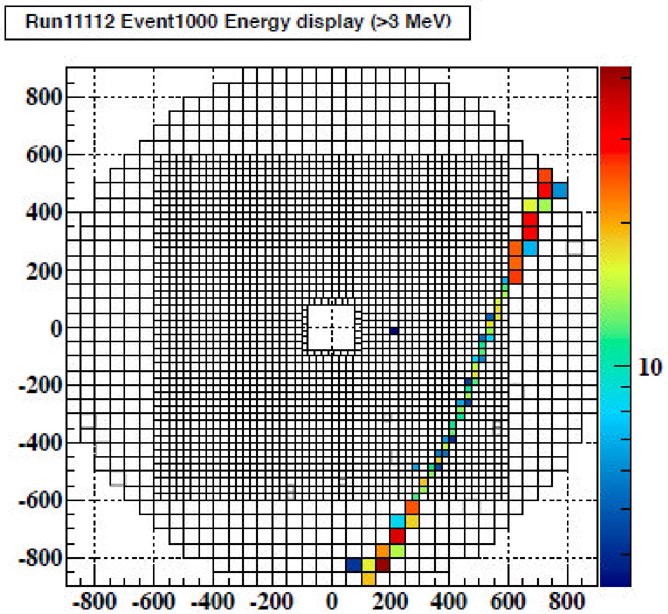
Timeline of KOTO

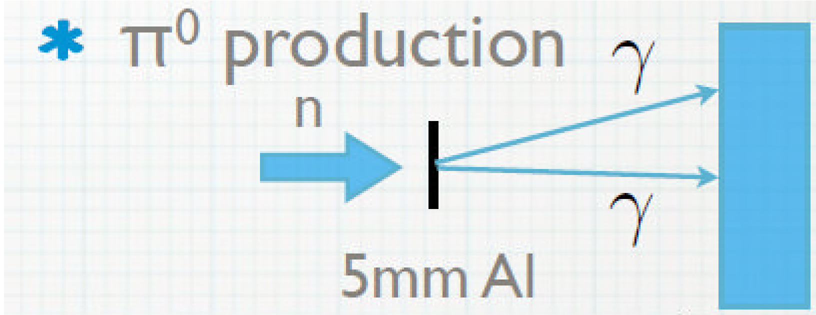


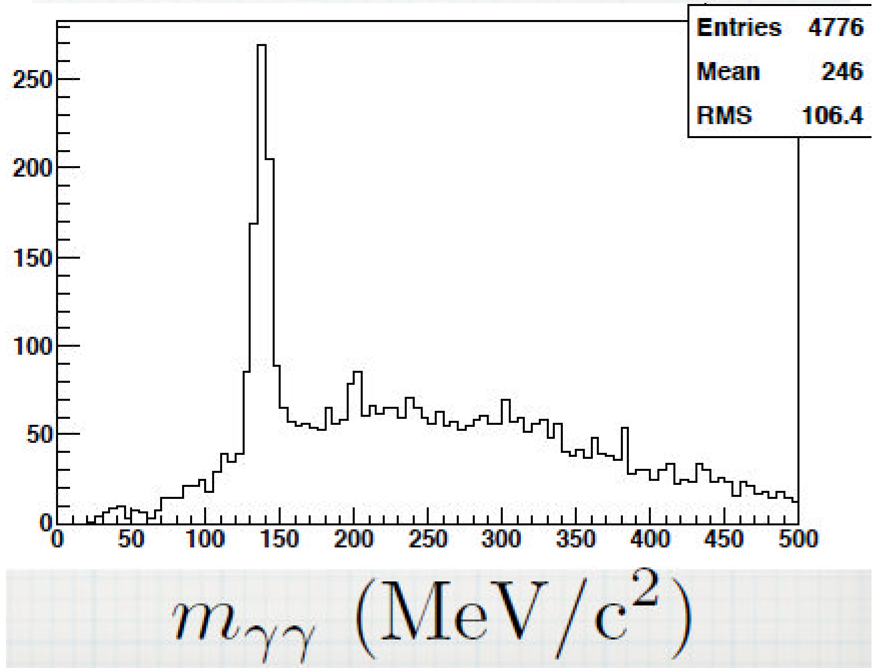
calibration signal at the engineering run

Neutral beam

Cosmic μ

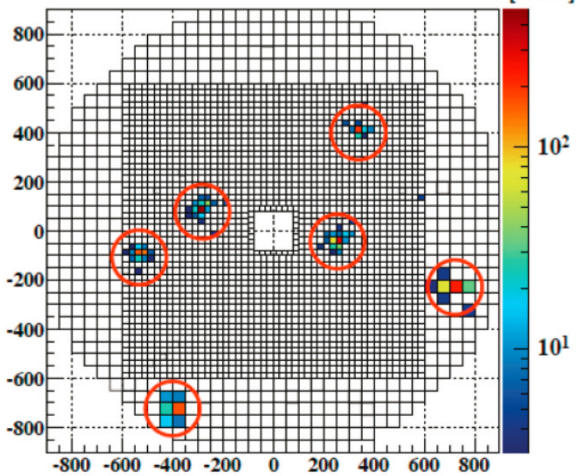




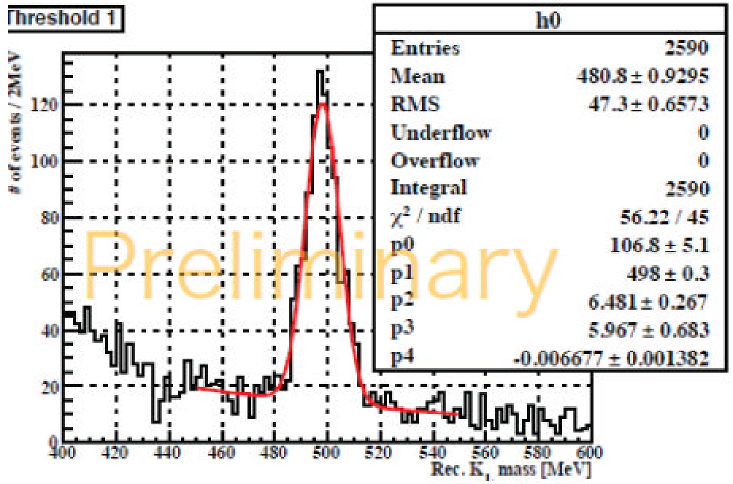


calibration signal at the engineering run

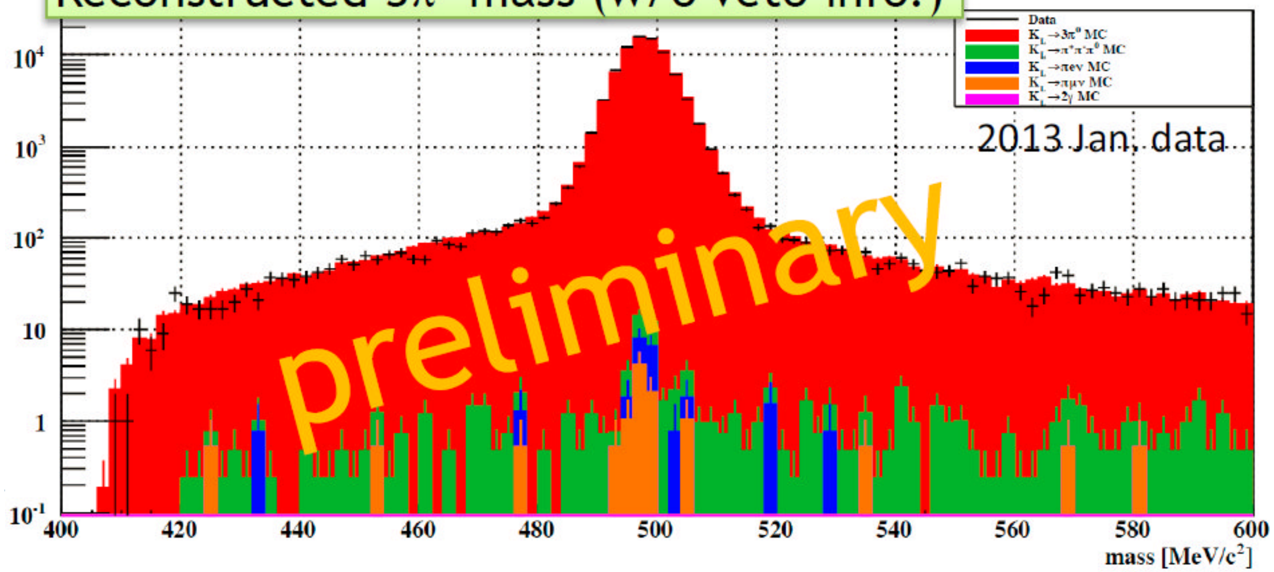
KL→3π^0 event display



Rec. 2π^0 mass distribution

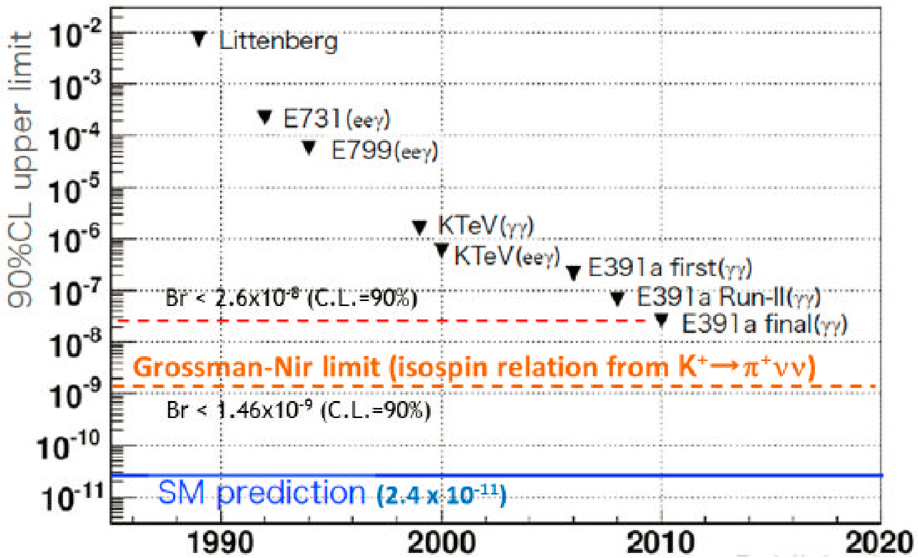


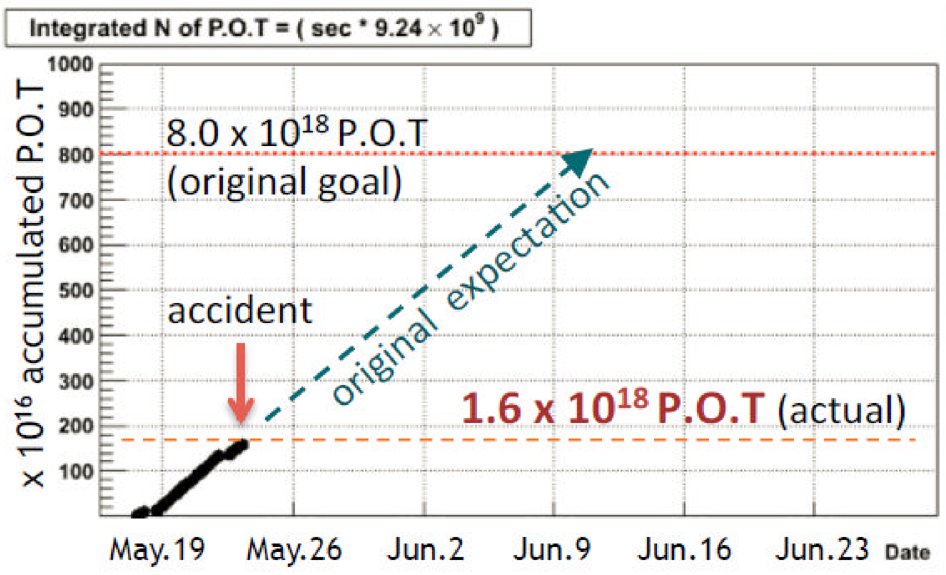
Reconstructed 3π^0 mass (w/o veto info.)



1st Physics run

- Scheduled in May – June 2013 (25kW)
- Expected to reach the Grossman-Nir limit
- BUT… a radiation accident on May 23 at hadron hall terminated the run at ~1/5 of planned statistics (already equivalent to E391a).
- Analysis of these data is on going.





KOTO milestone

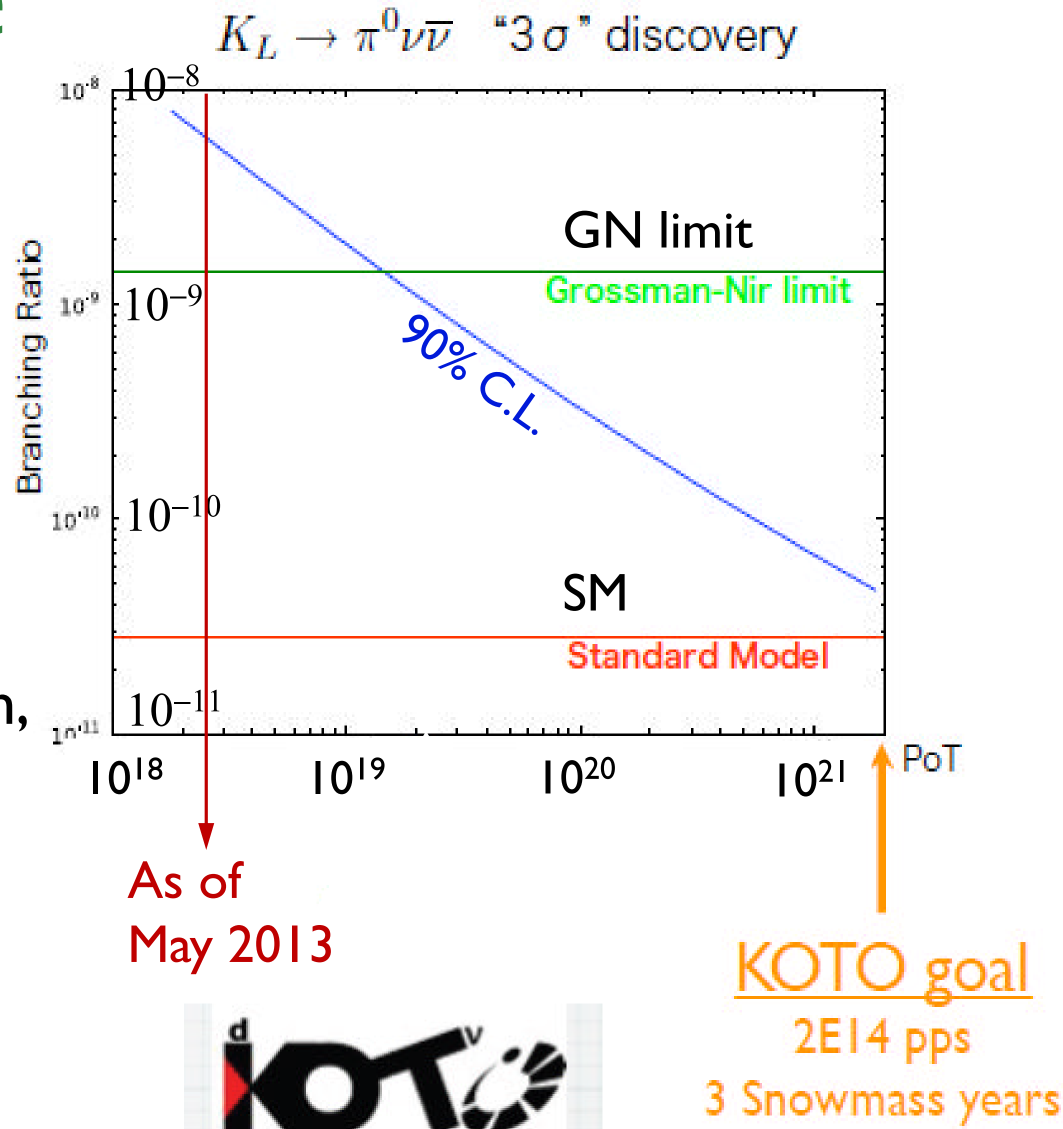
- Dec. 2012 : Engineering run with full detector
- May 2013 : Physics run! … till the acccident

Reinforce safety measures

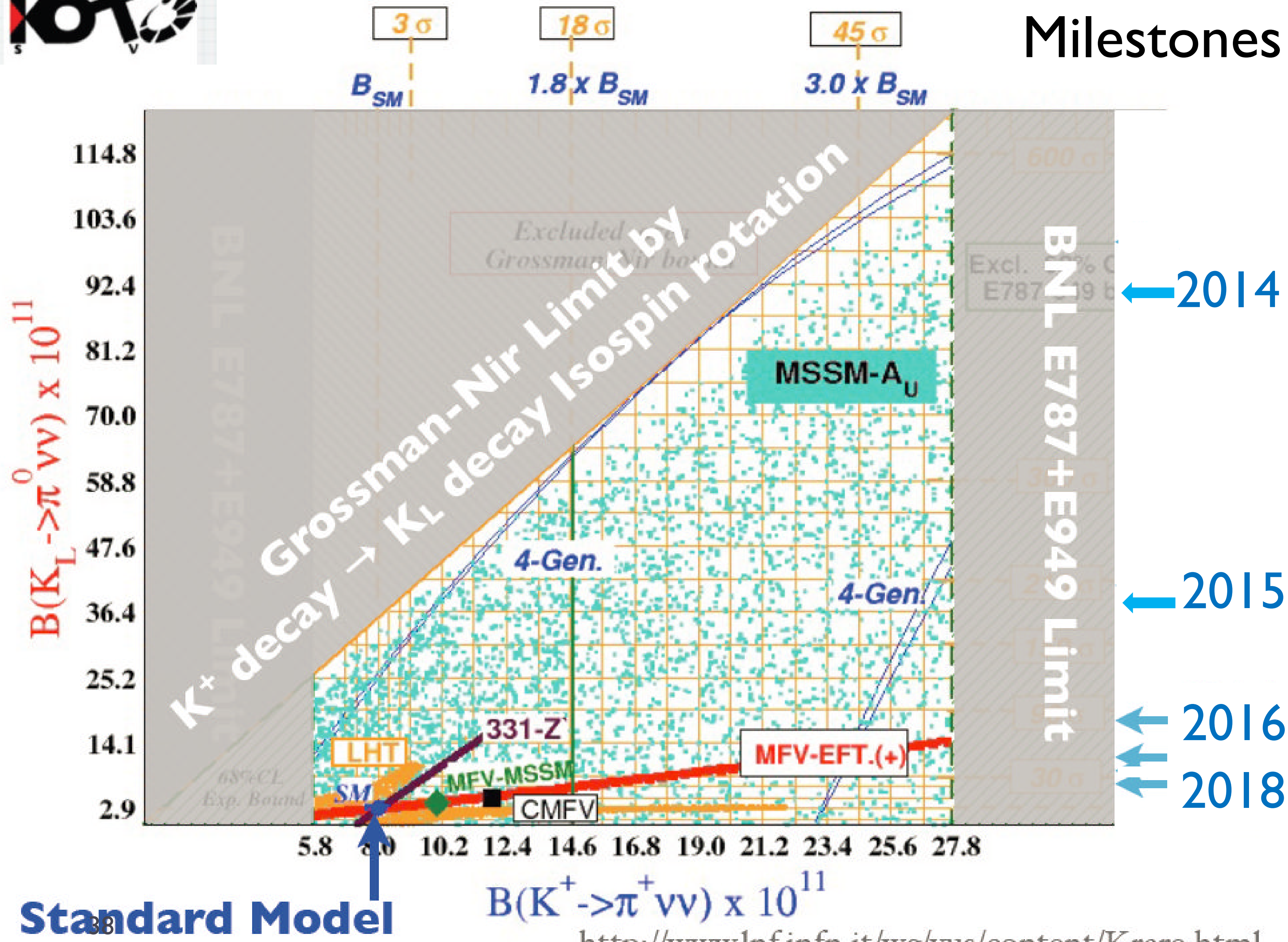
- Autumn or winter 2014 : Hope to restart physics run, and cross the GN limit.

Upgrade barrel Veto

- In 3-4 years : reach to SM sensitivity



Milestones



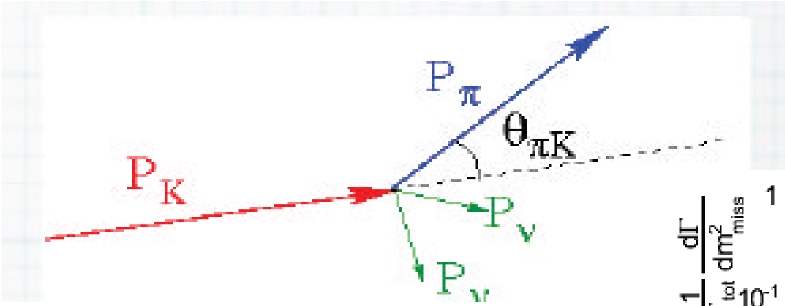
http://www.lnf.infn.it/wg/vus/content/Krare.html

$K^+ \to \pi^+ \nu \bar{\nu}$ measurement to come

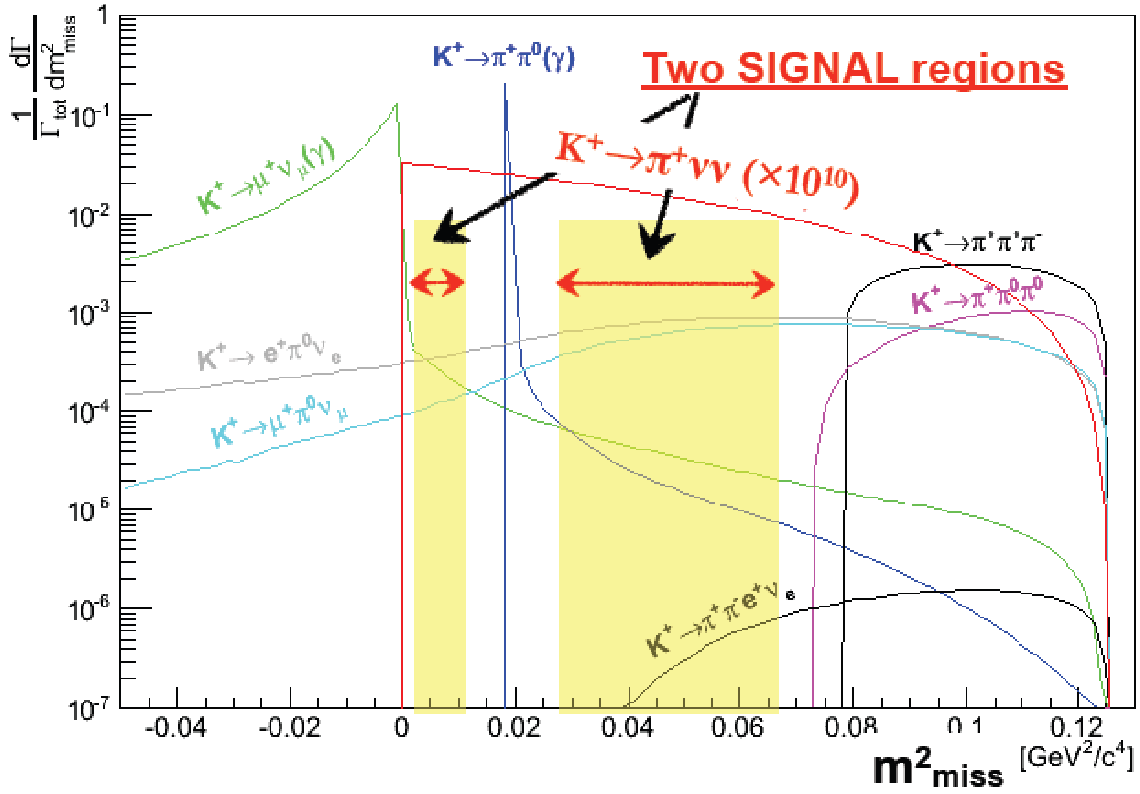
- NA62 (CERN)
  - "Decay in flight" experiment
  - Aims to collect ~100events
  - CERN NA31 → NA48 → NA62

    (neutral K ε'/ε rare decays → K^+ rare decays)
  - Construction & engineering run
- ORKA (FNAL)
  - Stopped K^+ experiment using FNAL main injector
  - Aims to collect ~1000events
  - BNL E787 → E949(record holder) →FNAL ORKA
  - Scientific approval / R&D on going

NA62 kinematics and BG



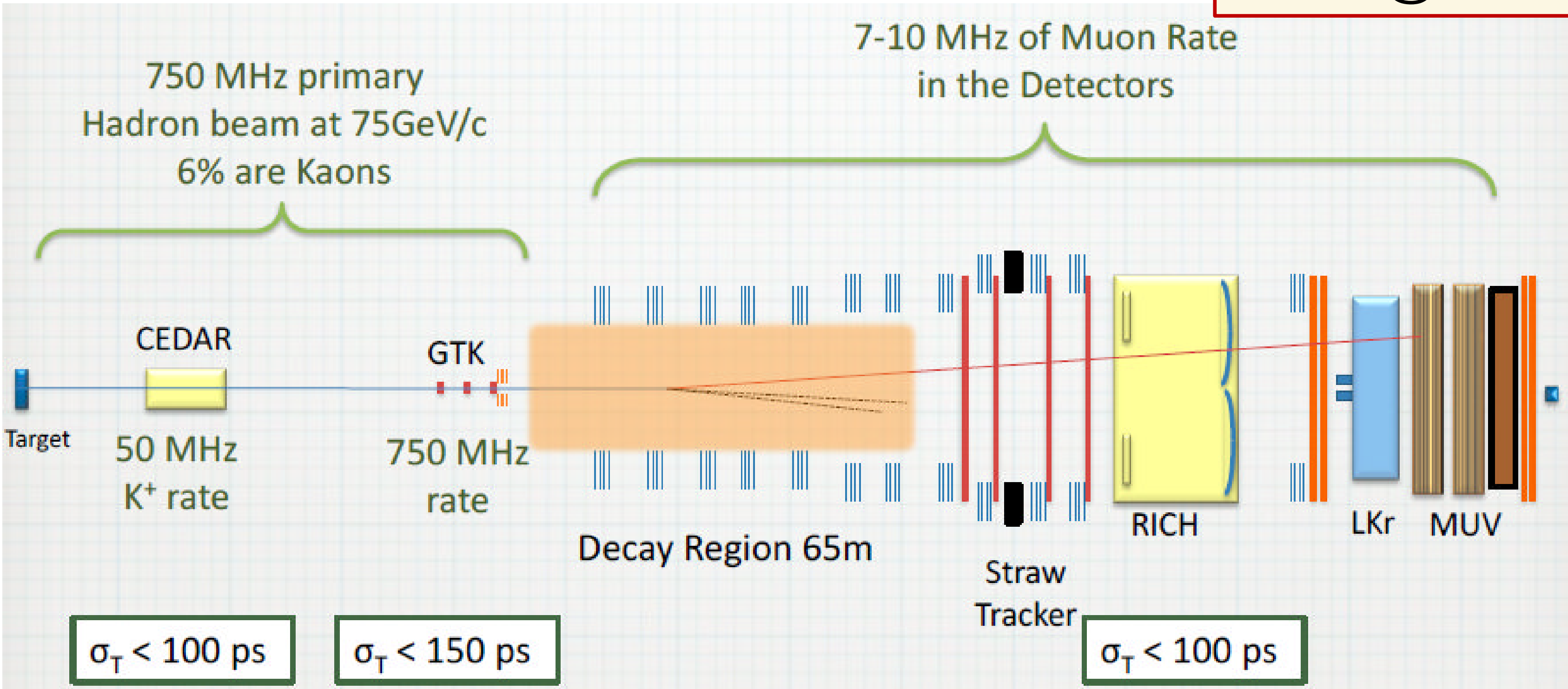
- Decay in flight
- K^+ in, π^+ out, nothing else, missing P
  - Missing mass measurement
  - Good tracking
  - Particle ID of K , π
- Photon veto to suppress $\pi^+\pi^0$

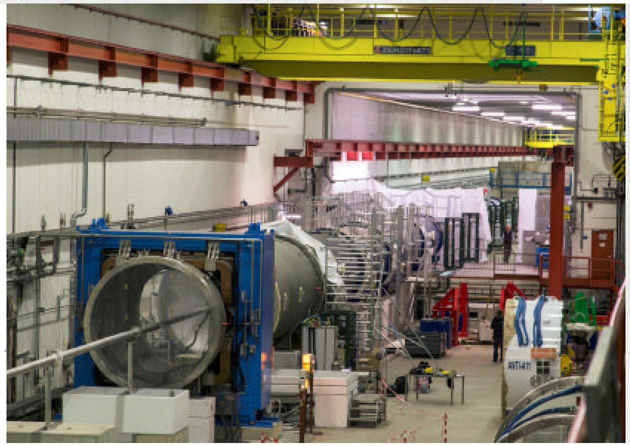


G. Ruggiero, Kaon 2013

NA62 detector

F. Harn @ Kaon 13

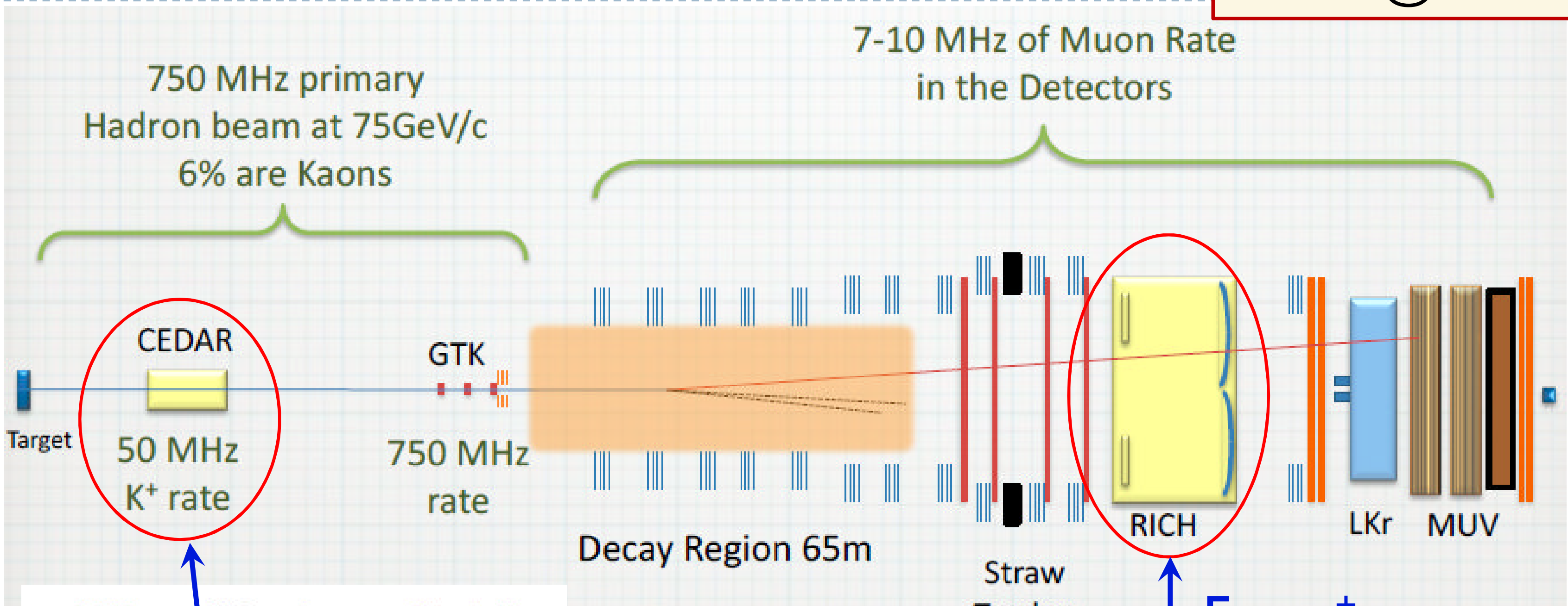




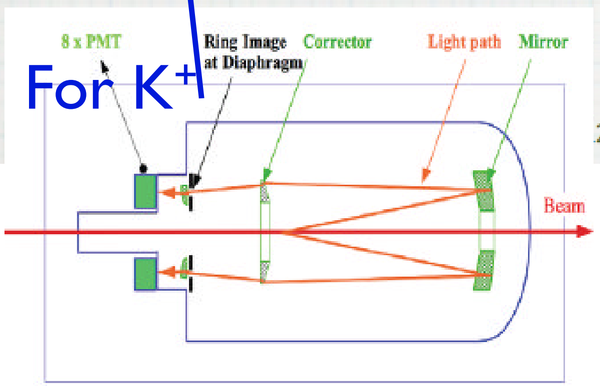
⇒ 4.5×10^{12} K^+ decays/year
in fiducial region

NA62 K^+ in, π^+ out PID

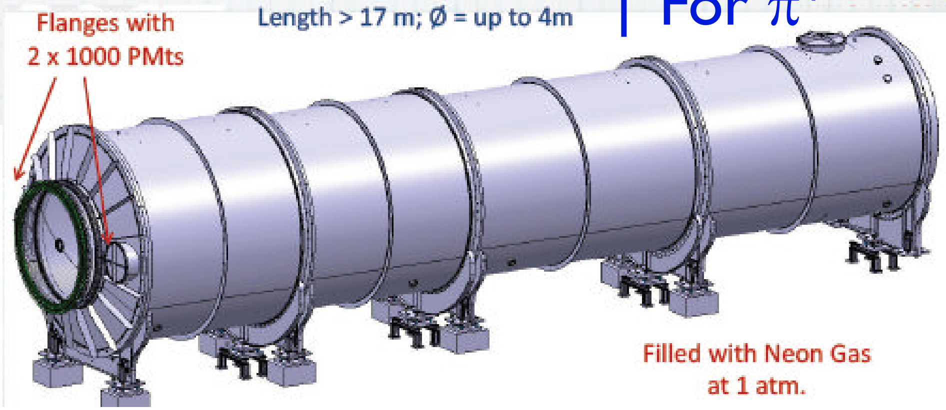
F. Harn @ Kaon 13



For K^+

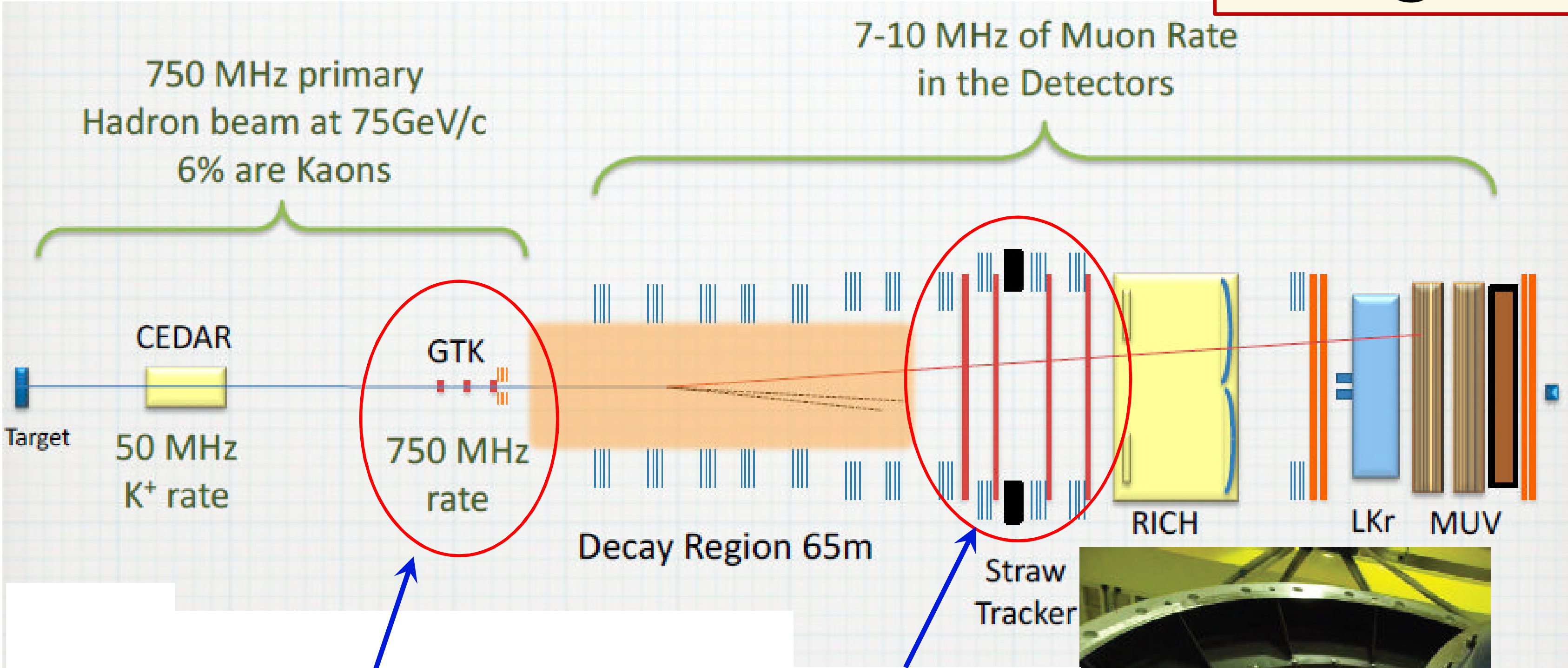


For π^+



NA62 detector   Trackers

F. Harn @ Kaon 13

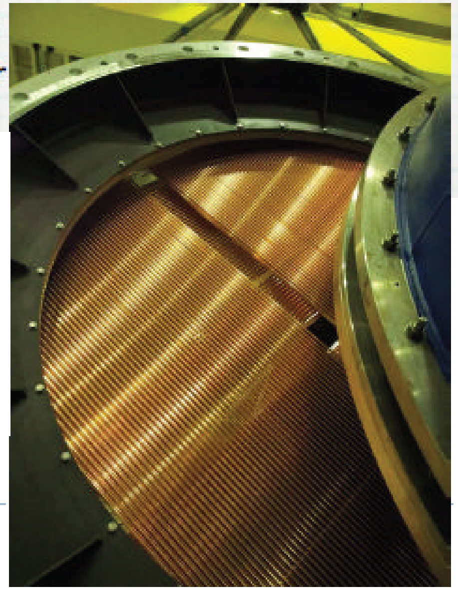


For π^+

Thin Si pixel detectors
$\Delta\theta \sim 0.016$ mrad.
$\Delta t \sim 200$ps

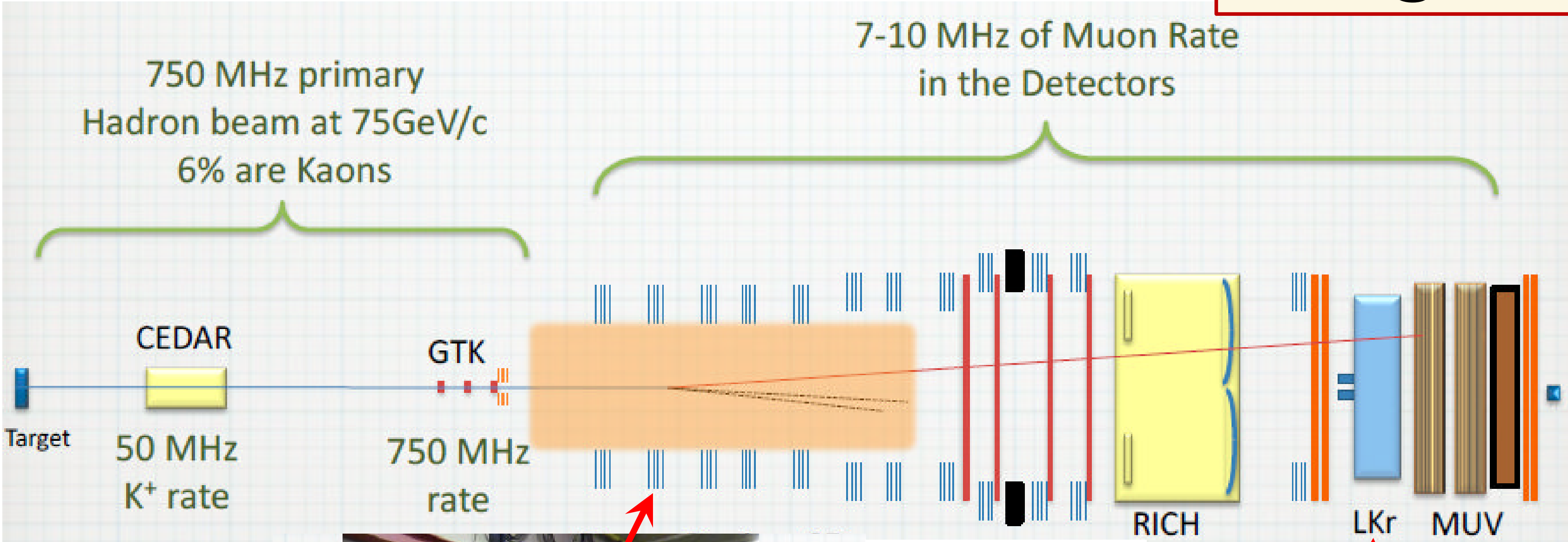
For π^+

Straw tubes
$\Delta x \sim 140\mu m$



NA62 detector Veto counters

F. Harn @ Kaon 13

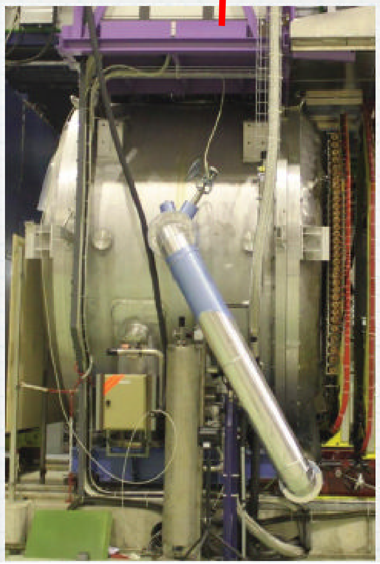


Large angle photons

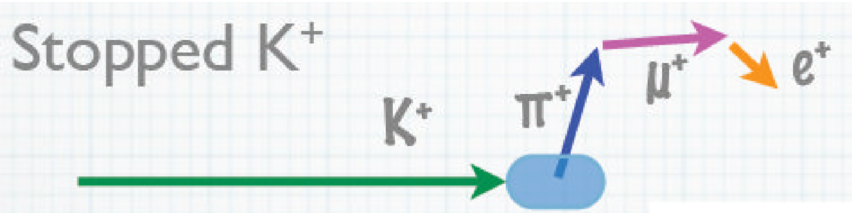
Lead glass from OPAL

Small angle photons

Liquid Kr calorimeter from NA48

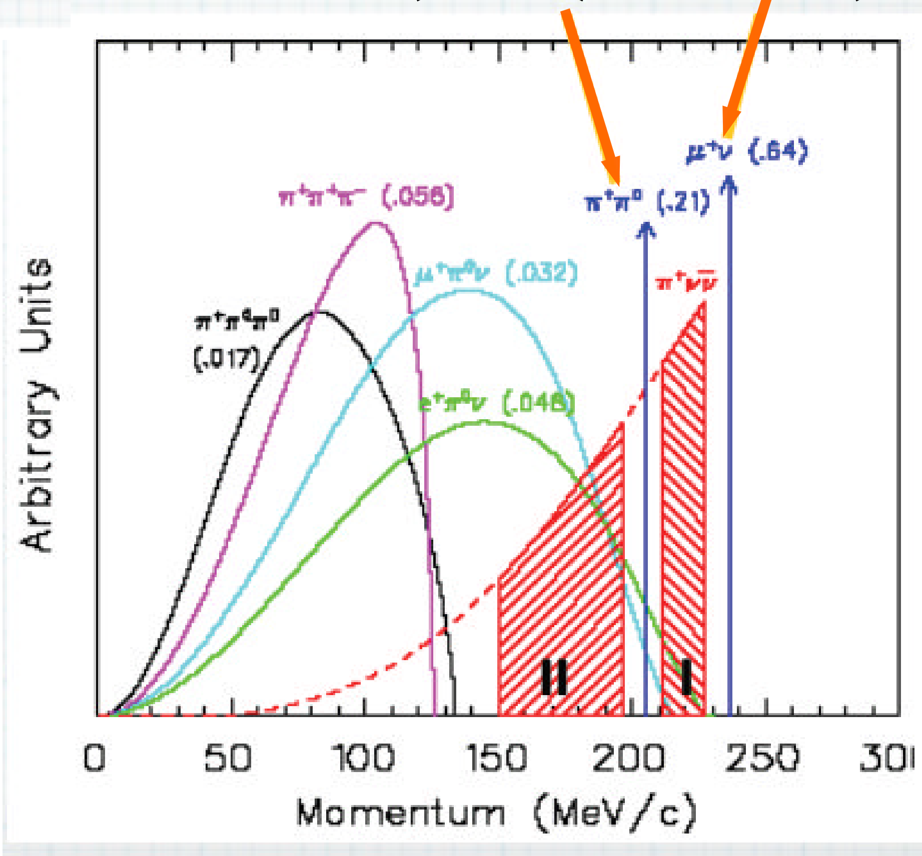


ORKA kinematics and BG



Avoid these peaks

$K^+ \rightarrow \pi^+\pi^0$ **(Br=21%)** $K^+ \rightarrow \mu^+\nu$ **(Br=64%)**



Needs

π^+ momentum measure-ment

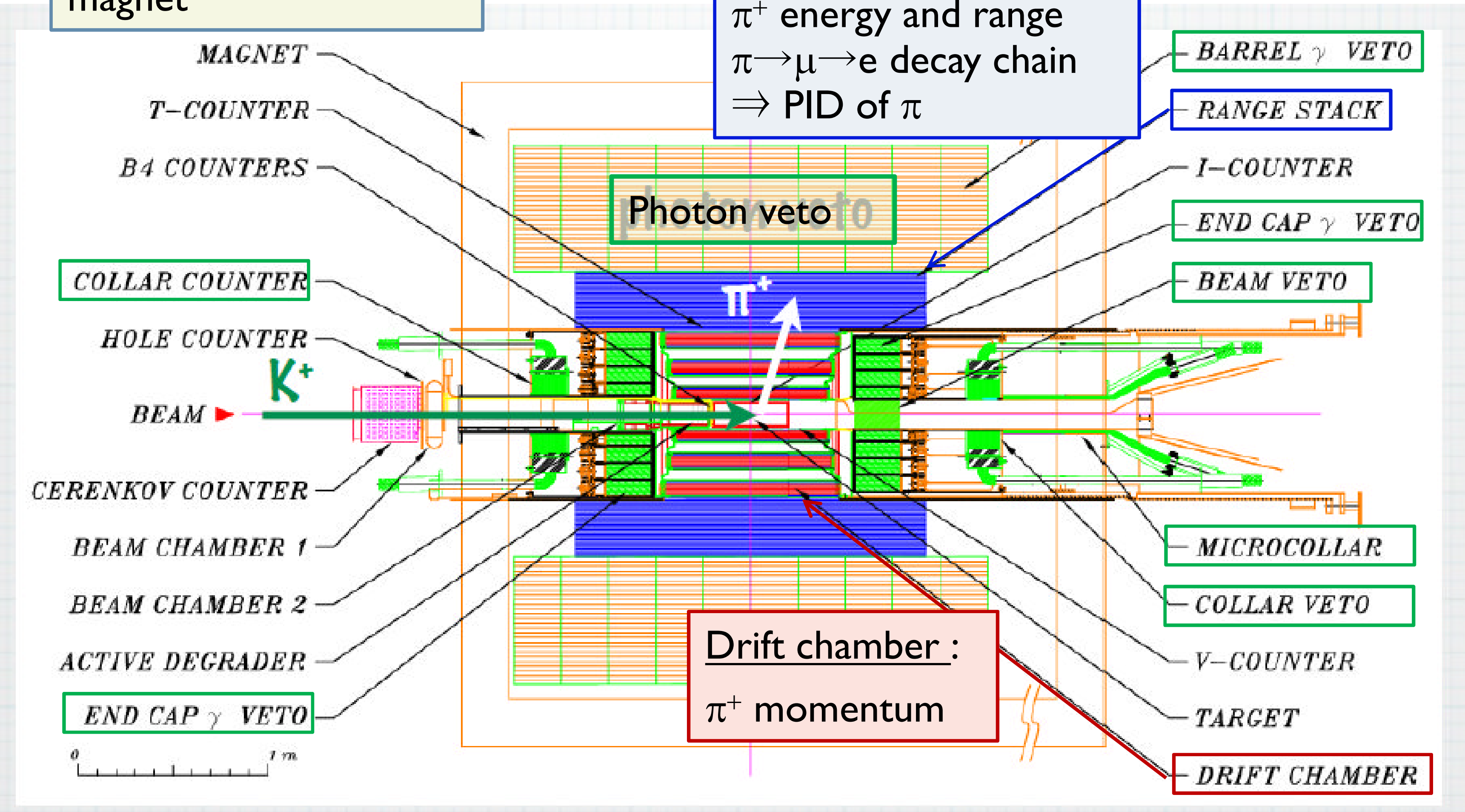
PID via range, energy, decay chain

hermetic photon veto

Established technique in BNL E787/949

ORKA detector

Plans to sit inside CDF magnet

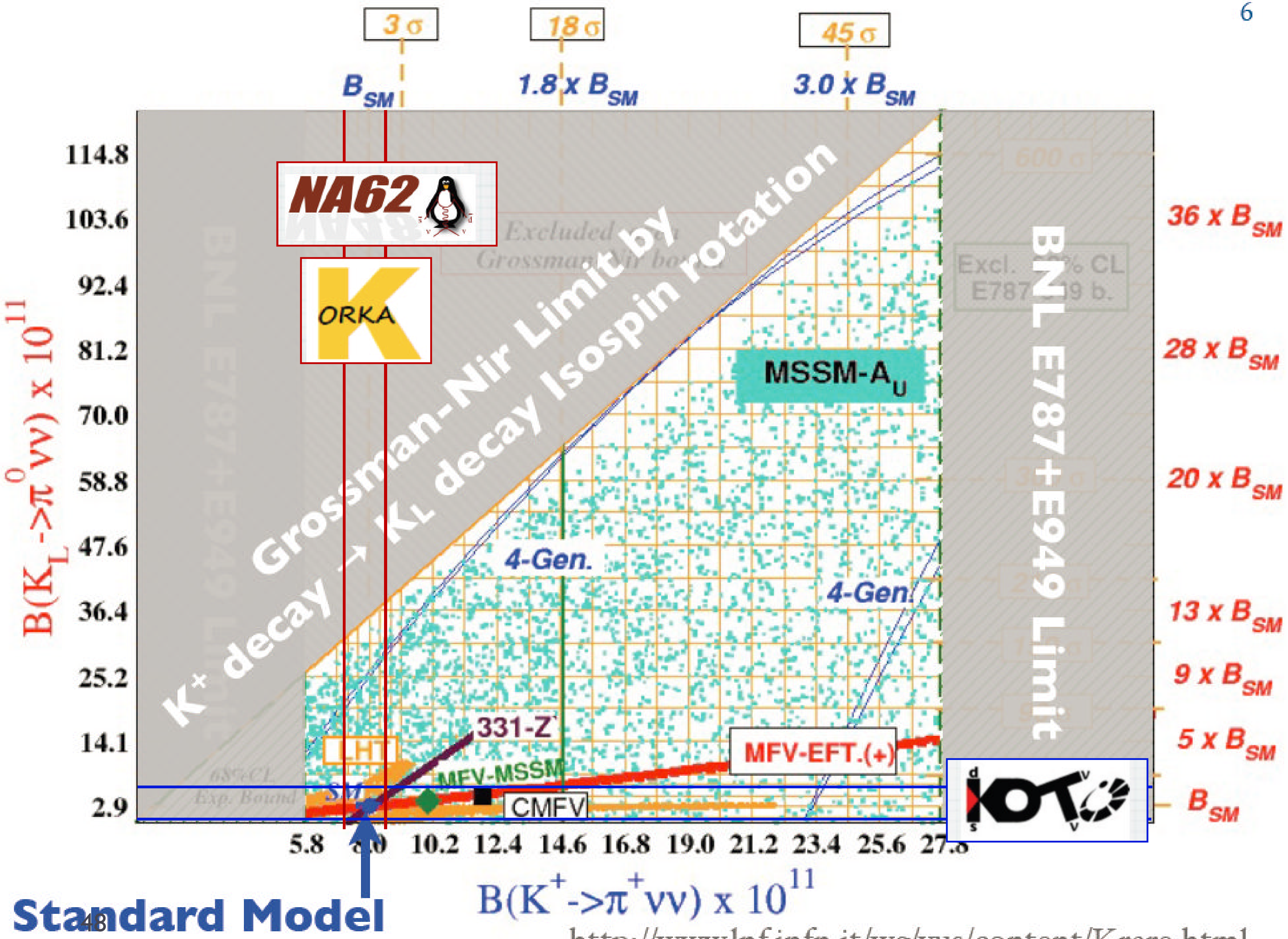


ORKA

Sensitivity

- 210 SM events/year with FNAL main injector
- Improvements over BNL E949
  - K beam flux ×10 (improvement of 2ry beam line)
  - Acceptance ×11 (PID, DAQ,…)
- 5% measurement in 5 years
  - Statistic + systematic

- Detector R&D on going
  - Leadglass+scint. Cal
  - GEM tracker



http://www.lnf.infn.it/wg/vus/content/Krare.html

Summary

- BSM physics should be studied in the various approach, and rare Kaon decay is a promising research target.
- $K \to \pi\nu\nu$ rare decay experiment has made progress with step by step approach. That will reach the immediate milestone (GN bound) in a year.
- Precision data on the $K \to \pi\nu\nu$ process for a serious test of the SM will be available in 4 ~ 5 years.
  - $K_L \to \pi^0\nu\nu$ by KOTO (JPARC)
  - $K^+ \to \pi^+\nu\nu$ by NA62 (CERN), ORKA (FNAL)

감사합니다

Thank you