Rare Kaon Decay Experiments and Future Plan

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(KEK)

Role of Kaon Physics

* To explore New Physics beyond the Standard Model (SM) through the processes
  which are suppressed/prohibited in SM
  and are precisely calculated in SM
  - Aiming to find deviation from SM prediction
  - Possible to reach higher mass scale than direct search.

* To study flavor structure beyond SM
  - Complimentary to other flavor physics programs

Experiments are not so easy…

- Kaon Physics has a long history
  - for ex., discovery of CP violation in $K_L \rightarrow \pi\pi$ 50 years ago

  and many studies had been already done.
- Remaining subjects are
  - rare processes,
  - difficult to define (with missing particles), and/or
  - requiring small systematic uncertainty.

- BUT, we can/should overcome difficulties and exploit the potential of Kaon physics for studying BSM.

Topics in this talk

Experiment @ J-PARC

KOTO

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

Running

E36

Lepton universality in

$R_K \equiv Br(K^+ \to e^+ \nu) / Br(K^+ \to \mu^+ \nu)$

Commissioning

[stopped K^+ decay technique]

Precision level: ~0.25%

Experiment @ CERN

NA62

$K^+ \to \pi^+ \nu\nu$

Commissioning

sensitivity level: $O(10^{-11} \sim 10^{-12})$

*record holder of R_K measurement

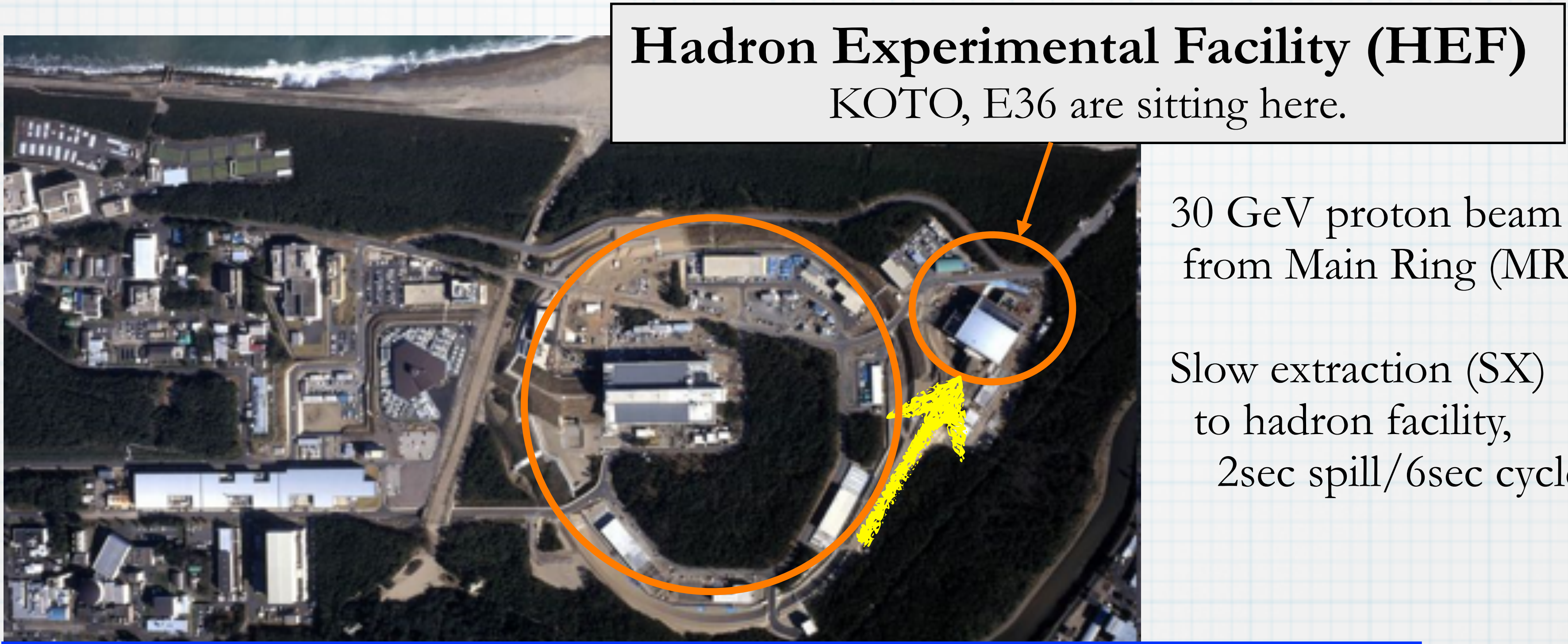
[decay in flight technique]

And, future plan…

(brief and limited)

Before going to each topics, …

J-PARC hadron facility restarted !!



30 GeV proton beam from Main Ring (MR)

Slow extraction (SX) to hadron facility, 2sec spill/6sec cycle

The SX beam had been stopped since the accident on May 23, 2013.

After HEF renovation for safety, we finally restarted the SX beam in April 2015 !!

$K \to \pi \nu \nu$ decay experiments

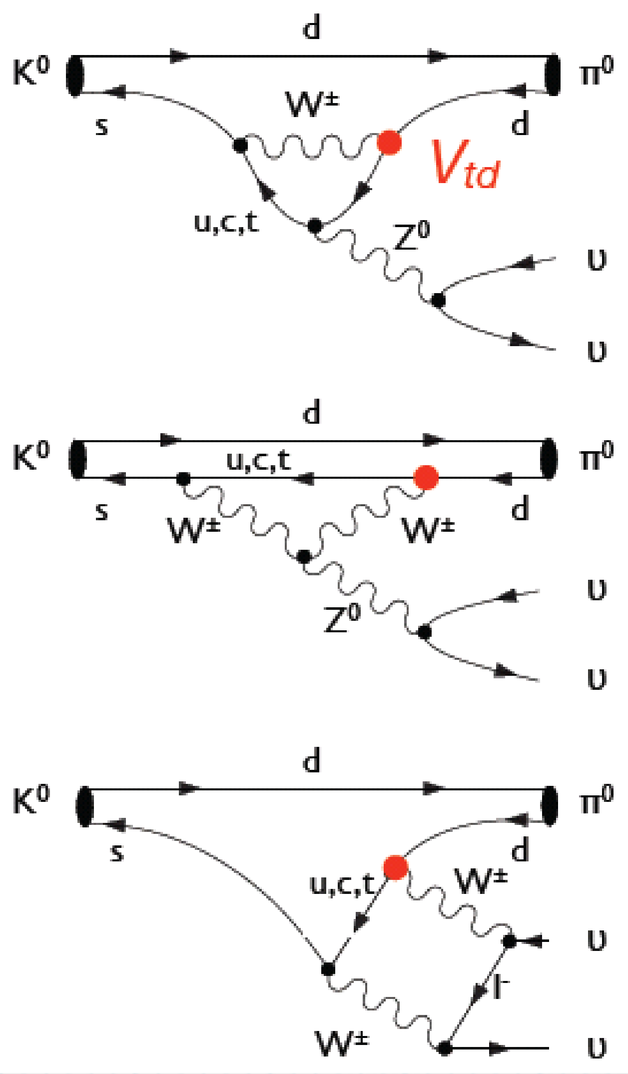
J-PARC KOTO

and

CERN NA62

K→πνν in the Standard Model

* s-d transition via loop diagrams, FCNC process
* $K_L \to \pi^0 \nu\nu$ $Br \propto Im(A_{s\to dZ^*})^2$
  - Top quark dominates
    - K^0-$\overline{K}^0$ superposition extracts imaginary part of the amplitude
    - **CP violating**
* $K^+ \to \pi^+ \nu\nu$ $Br \propto |A_{s\to dZ^*}|^2$
  - Top and charm contribute



K→πνν in the Standard Model

- Theoretically clean: small long distance contribution
- Hadronic parts (κ_L, κ_+) are obtained from measured Br($K^+ \to \pi^0 e^+ \nu$)

$$\mathcal{B}r(K_L \to \pi^0 \bar{\nu}\nu) = \kappa_L \left(\frac{\mathrm{Im}(V_{ts}^* V_{td})}{\lambda^5} X(x_t) \right)^2$$

$$BR_{SM}(K_L \to \pi^0 \nu\nu) = (3.00 \pm 0.31) \times 10^{-11}$$

CKM uncertainties are dominant while intrinsic one ~2%.

Exp: KEK E391a

$$BR < 2.6 \times 10^{-8}$$

Grossman Nir limit:

from measured Br($K^+ \to \pi^+ \nu\nu$)

$$BR < 1.5 \times 10^{-9}$$

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

$$BR_{SM}(K^+ \to \pi^+ \nu\nu) = (9.11 \pm 0.72) \times 10^{-11}$$

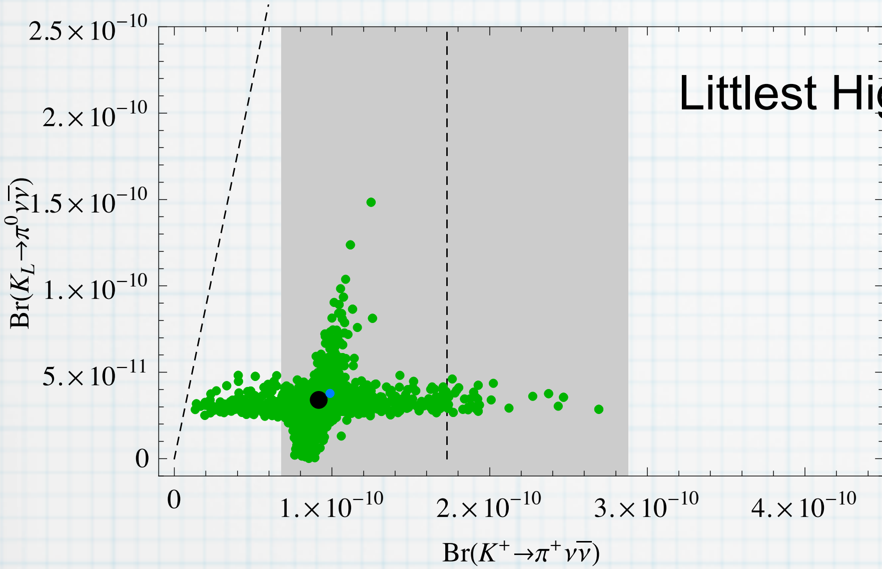
Exp: BNL E787/949

$$BR = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

BR_{SM} are quoted from A.J. Buras, *et al*, arXiv:1503.02693

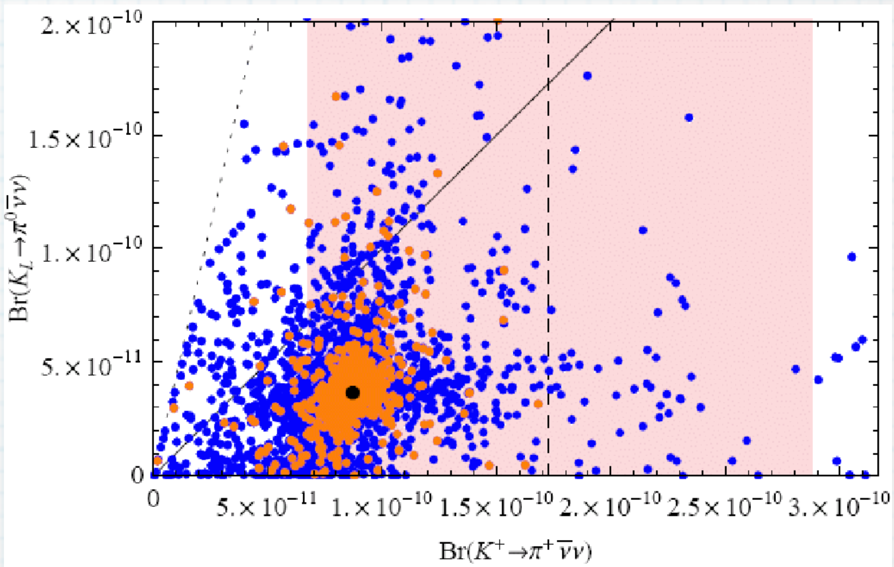
K→πνν beyond the Standard Model

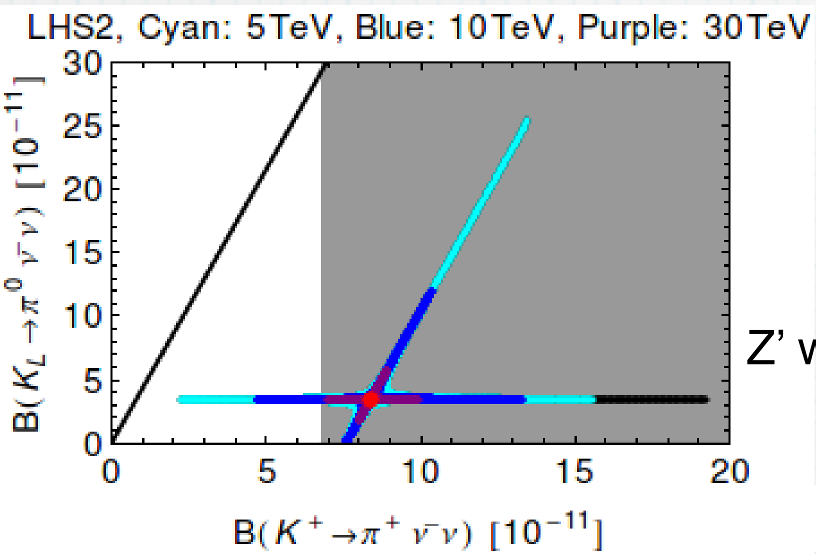
Correlation between Br($K^+ \to \pi^+ \nu\nu$) and Br($K_L \to \pi^0 \nu\nu$)



Littlest Higgs

Randall - Sundrum





Z' with left-handed scenario

Following discussion in PoS KAON13 (2013) 010

J-PARC KOTO

$K_L \rightarrow \pi^0 \nu\nu$ study

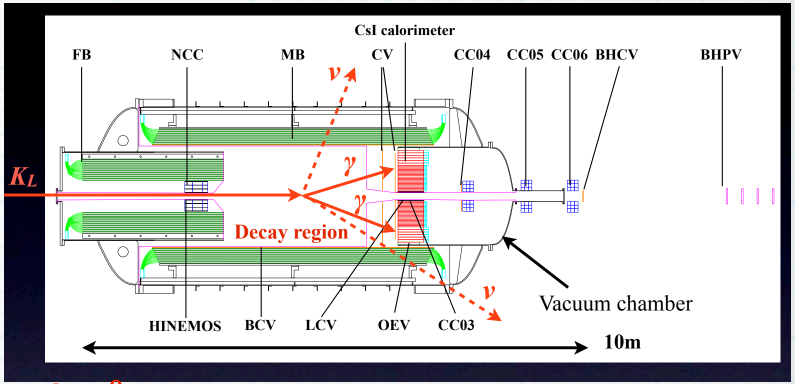
- Goal: a few SM events in 3-4 years run with S/N ratio ~ 2

KOTO

Principle of experiment

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

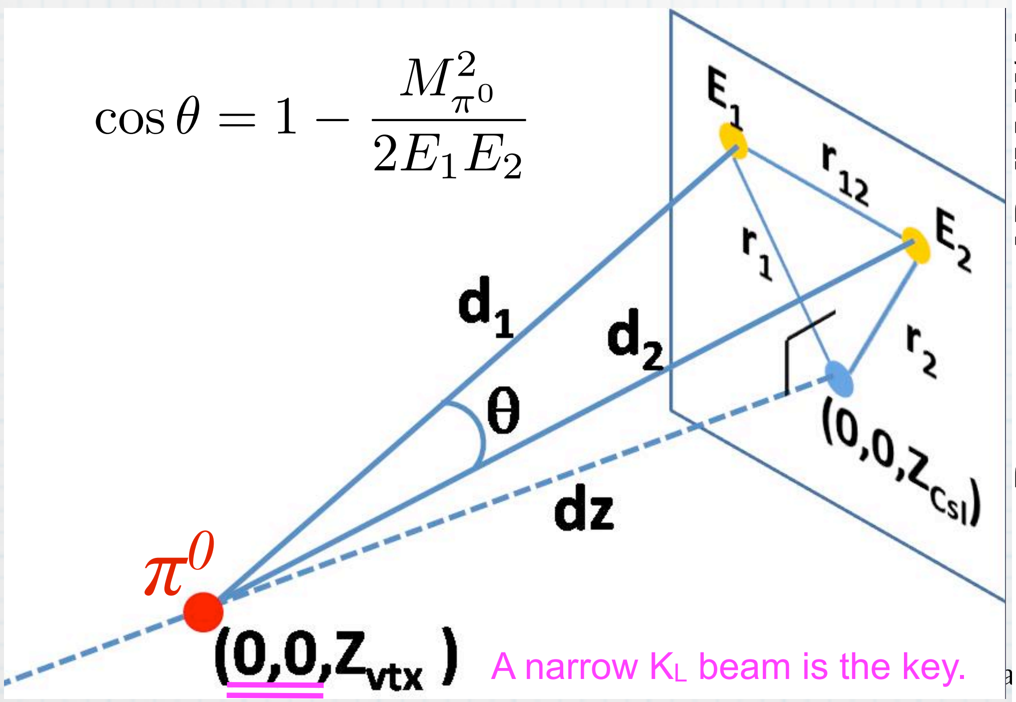
Calorimeter + Hermetic veto detectors



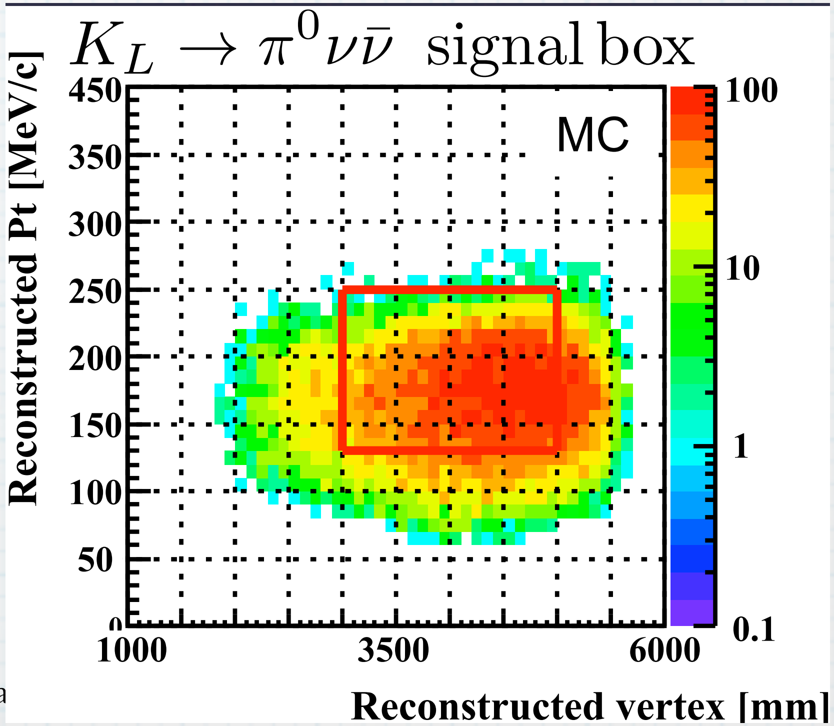
+ kinematic feature (missing P)

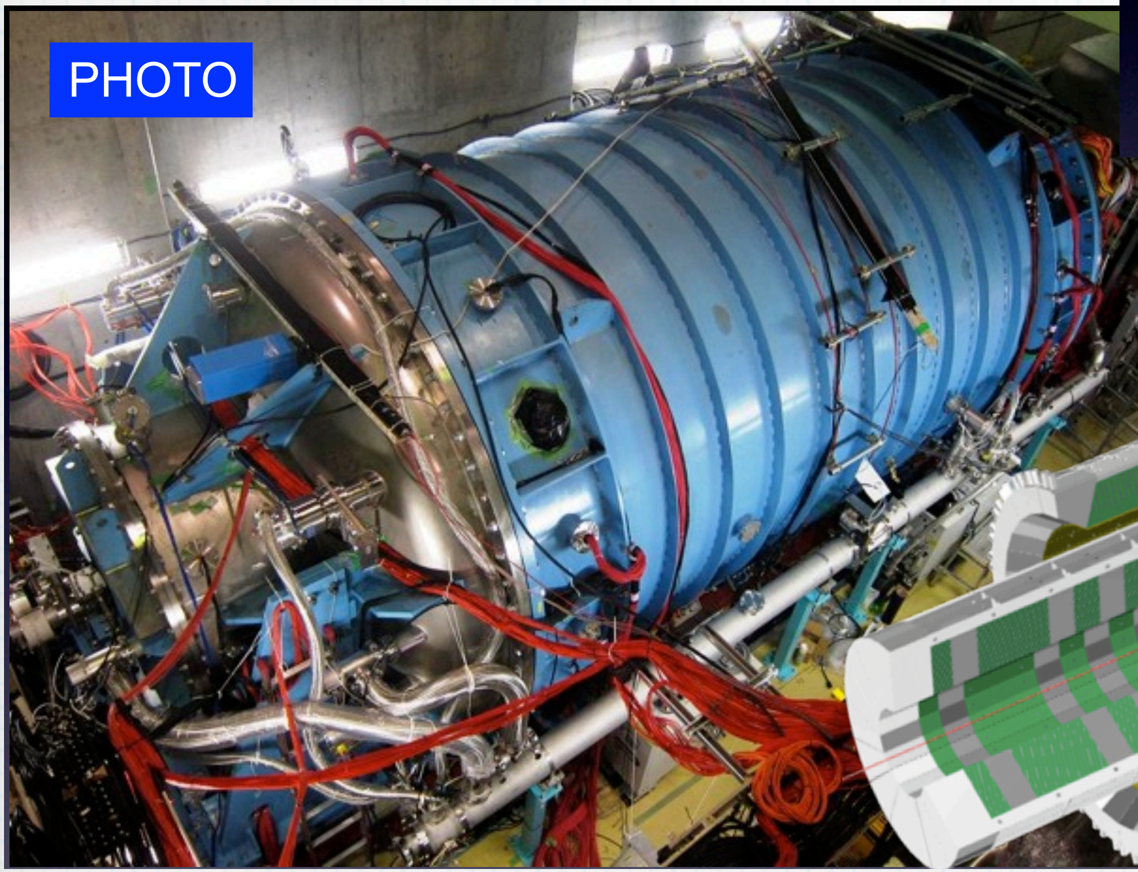
Reconstruct Zvtx and transverse momentum of π^0

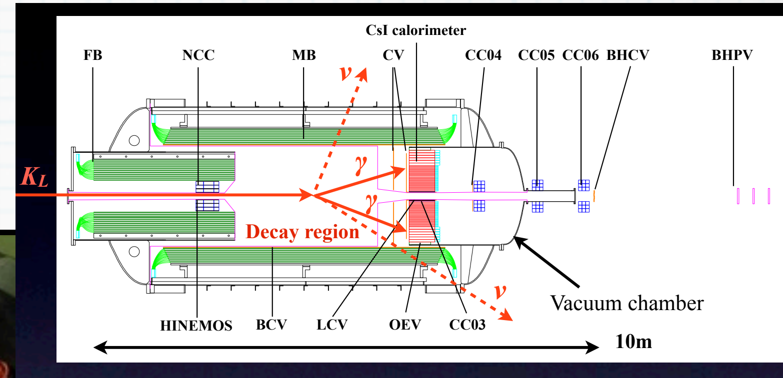
$$\cos\theta = 1 - \frac{M_{\pi^0}^2}{2E_1E_2}$$

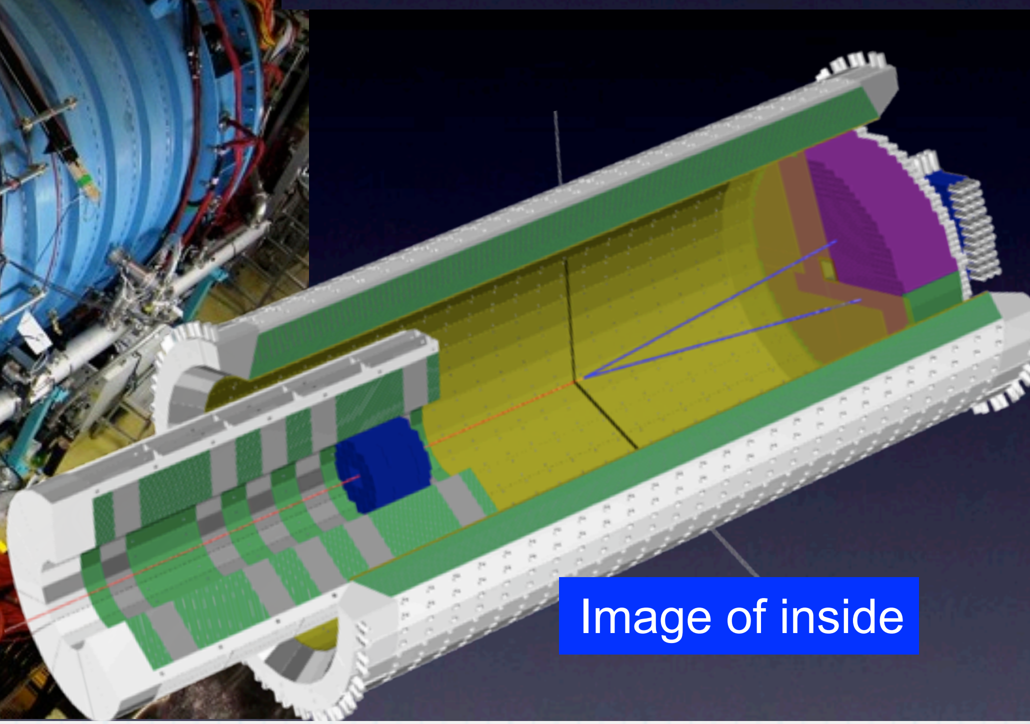


A narrow K_L beam is the key.









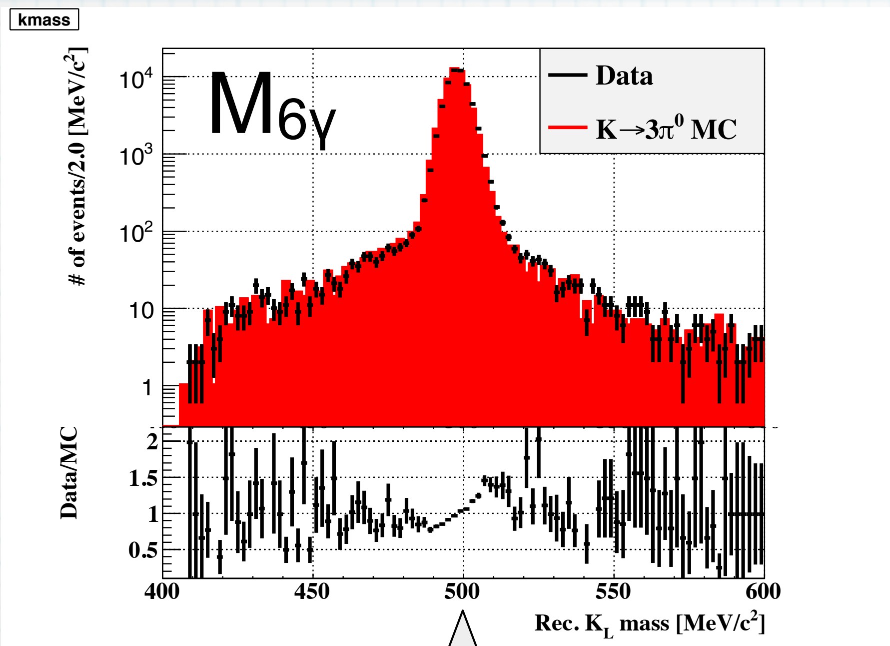
Most of detectors are inside vacuum.

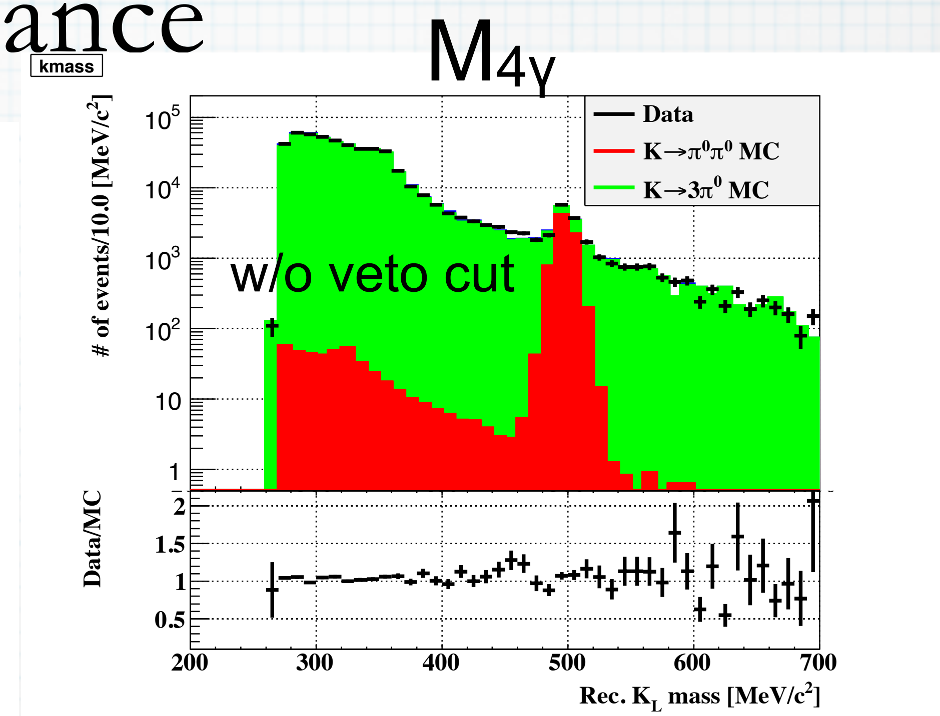
1st physics run in 2013

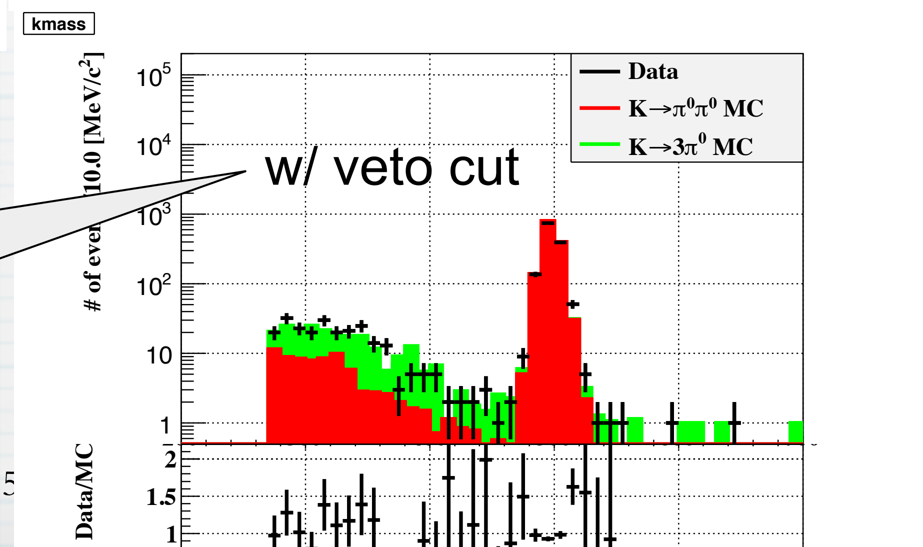
- 1st physics run was done in May 2013.
  - SX beam power was 24 kW.
  - 100 hours of data taking
    (until the accident at HEF happened.)

- Though the data amount was not enough to exceed current upper limit, we learned a lot from it.

Detector performance







Check EM calorimeter

Check veto detectors

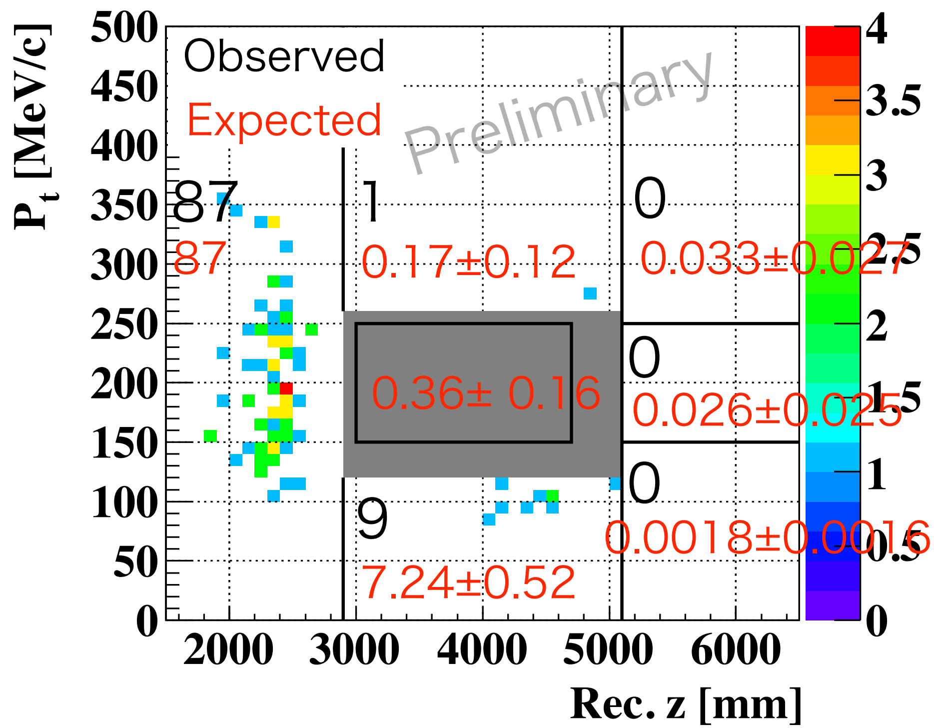
Reconstructed $K_L \to 3\pi^0, 2\pi^0$ (,2γ) events are also used for KL flux calculation

KOTO: from May 2013 run

Result of 100 hours run in May 2013

- Summary of
  #BG inside the signal box

BG source	#BG
Hadron interaction events	0.18±0.15
Kaon decay events	0.11±0.04
Upstream events	0.06±0.06
Sum	0.36± 0.16

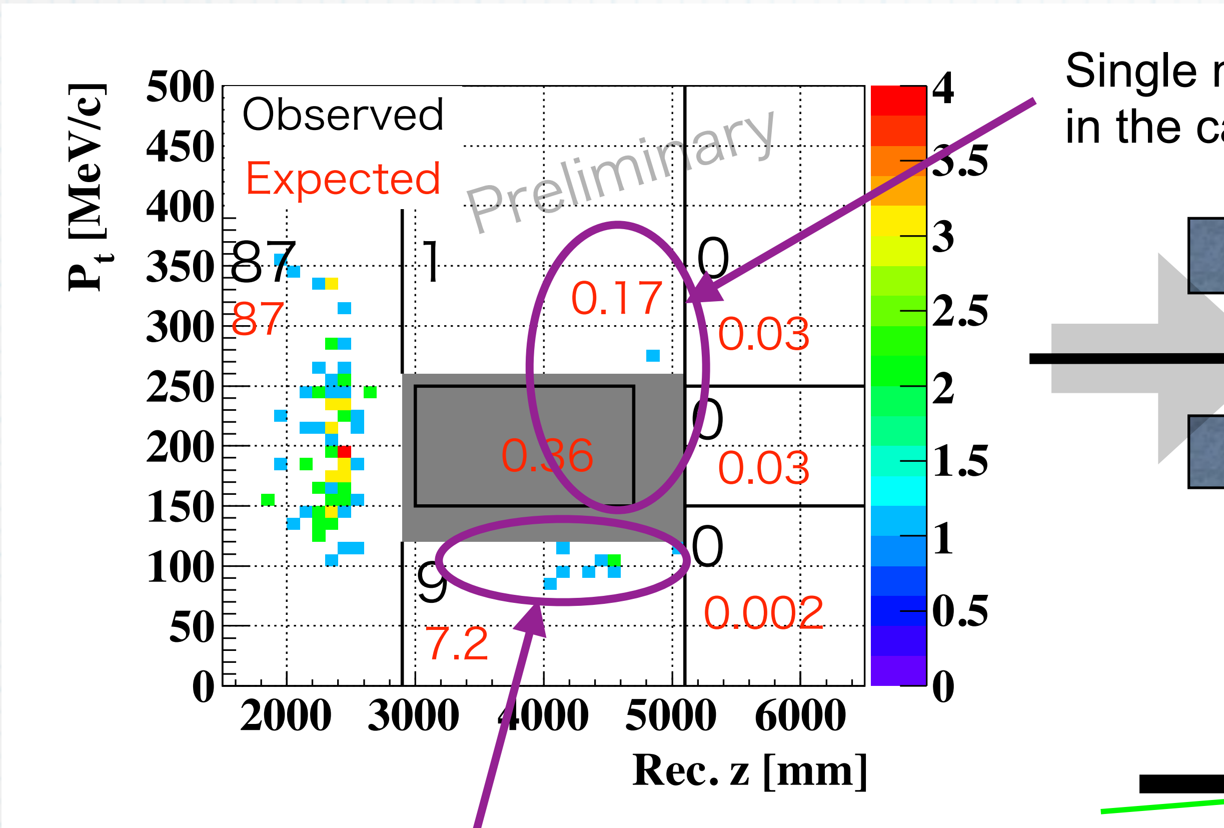


- Sensitivity of the 1st physics run
  $= 1.29\times10^{-8}$
  (cf) S.E.S. of KEK E391a: 1.11×10^{-8}

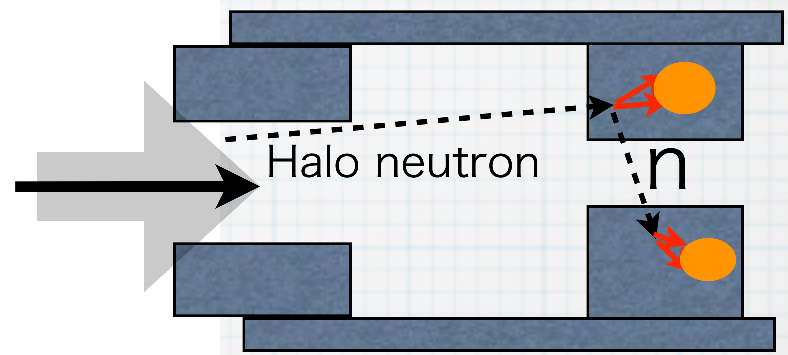
- Observed 1 event in the box (consistent with BG expectation)

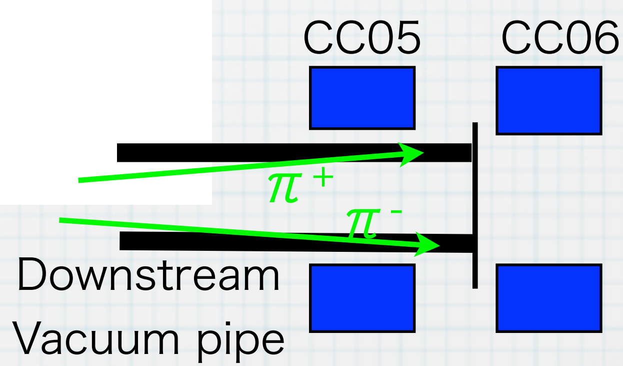
Reported in CKM2014 conference last year

Mechanism of backgrounds



Single neutron makes two clusters in the calorimeter



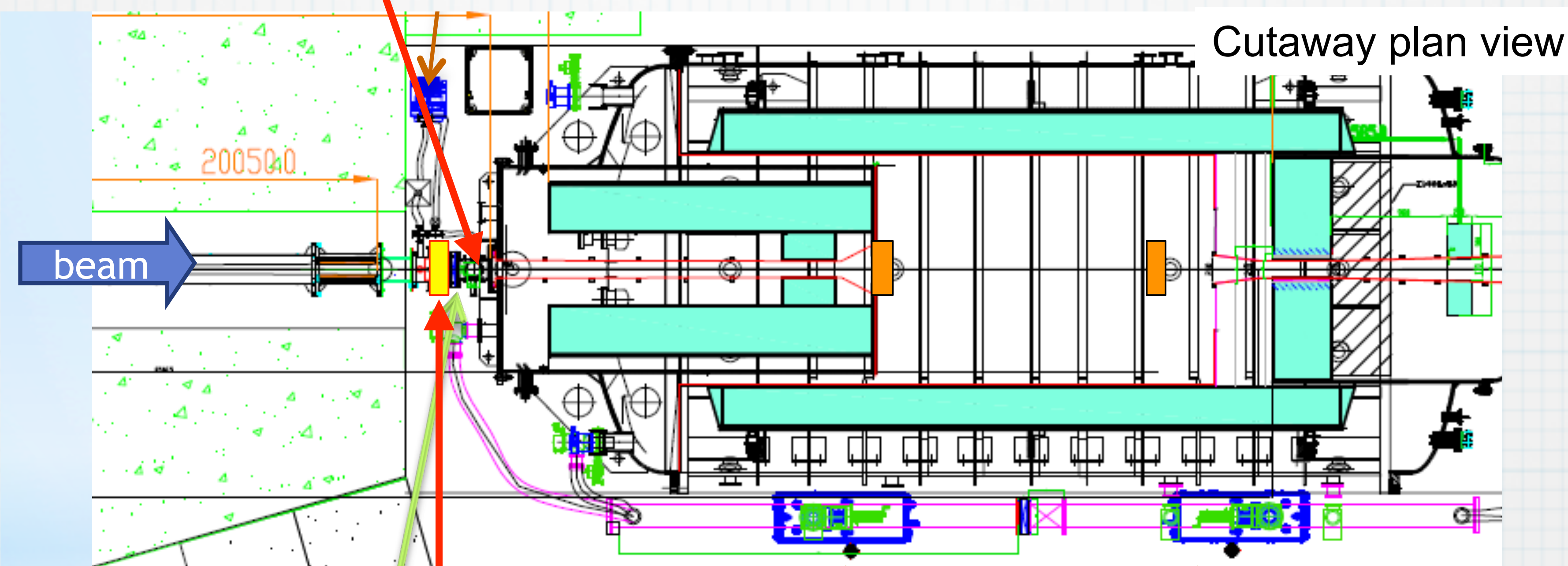


$K_L \to \pi^0\pi^+\pi^-$ with $\pi^+\pi^-$ disappearing due to interaction with the beam pipe

For 2015 run: concerning neutron

Kapton vacuum window
0.125mm ➔ 0.0125mm

➔ to reduce scattering source in the beam



New removable Al target inside the beam

➔ to collect control data for neutrons coming from various places

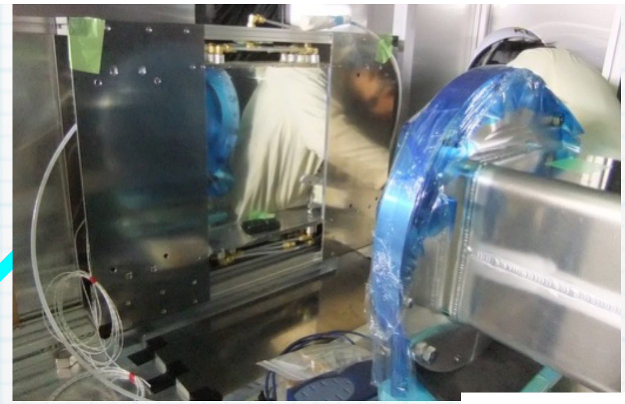
added | existed

KOTO upgrade for 2015 run

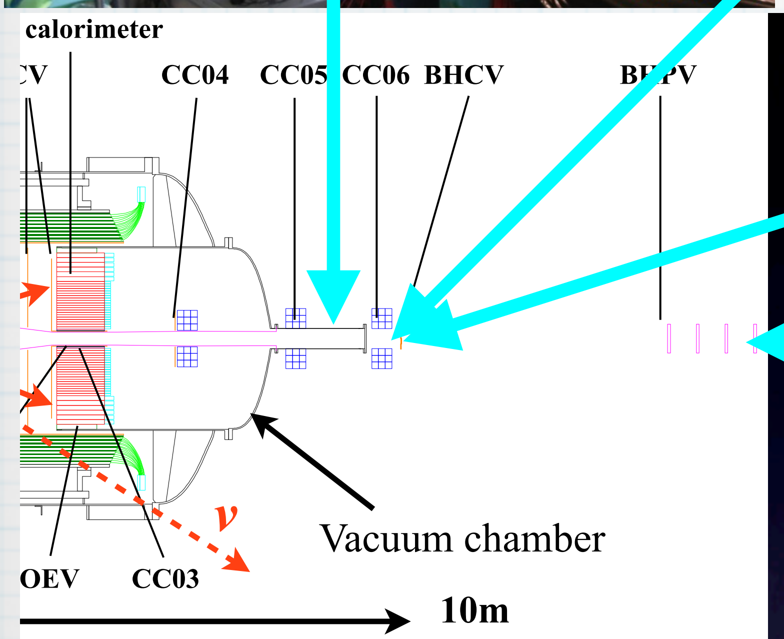
Upgrade downstream detectors

Beam Pipe Charged Veto

New Beam Hole Charged Veto
(Wire chamber with CF_4+C_5H_{12} gas)



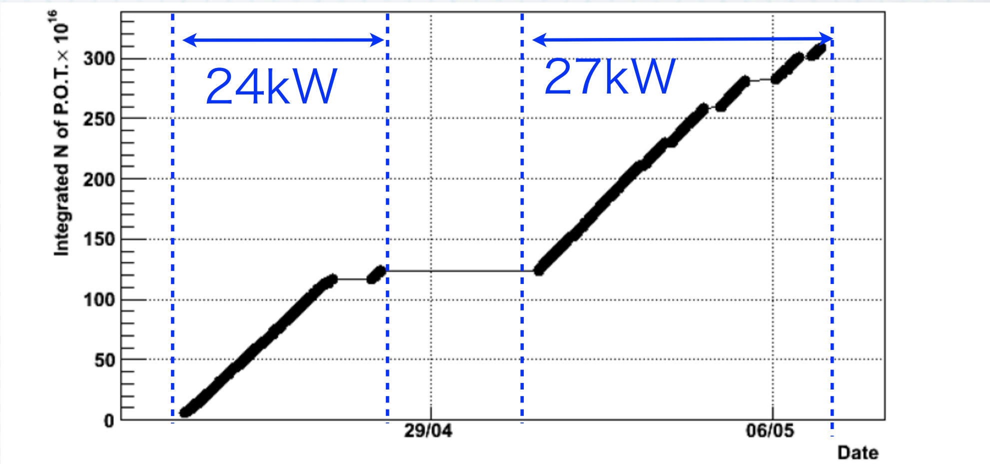
Beam Profile Monitor
(fluorescent plate+CCD+IIT)



Additional Beam Hole Photon Veto modules
and near-by-beam detector most downstream

KOTO status and plan in 2015

- Upgrade to reduce backgrounds were done during 2-year beam break.
- KOTO restarted physics run in this April.
  - About twice of May 2013 data has been collected. (Analysis is ongoing.)
- Will run more in June and fall
  - Target sensitivity in 2015 will be $O(10^{-9})$ ~ Grossman Nir limit.



We collected 3.09×10^{18} p.o.t (167hours)
(We used 1.42×10^{18} p.o.t for analysis of previous run data.)

5

CERN NA62

$K^+ \to \pi^+ \nu\nu$ measurement

- Aims to collect O(100) events in 2 years of data
  $\Rightarrow$ ~10% precision for $Br(K^+ \to \pi^+ \nu\nu)$
- Decay in flight technique

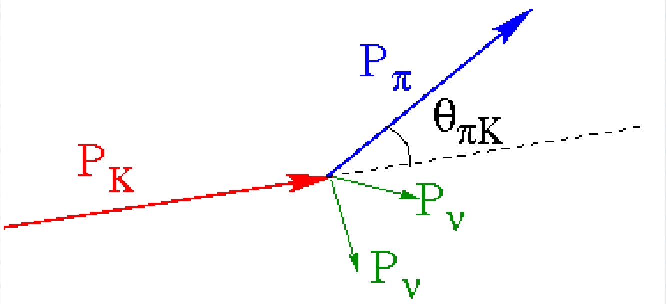
Figures are quoted from the slides by
G. Ruggiero @CERN EP seminar, March 10, 2015

Signal and background

* $K^+ \rightarrow \pi^+ \nu\nu$ signature
  - Kaon ID for incoming charged particle
  - Pion ID for outgoing charged particle
  - No other activities

K⁺ major decay modes		[rejection method]
$K^+ \rightarrow \mu^+ \nu$	63.6%	←π/μ separation
$K^+ \rightarrow \pi^+ \pi^0$	20.7%	←extra γ
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	5.6%	←extra charged particle
$K^+ \rightarrow \pi^0 e^+ \nu$	5.1%	←π/e separation, extra γ
$K^+ \rightarrow \pi^0 \mu^+ \nu$	3.4%	←π/μ separation, extra γ
$K^+ \rightarrow \pi^+ \pi^0 \pi^0$	1.8%	←extra γ

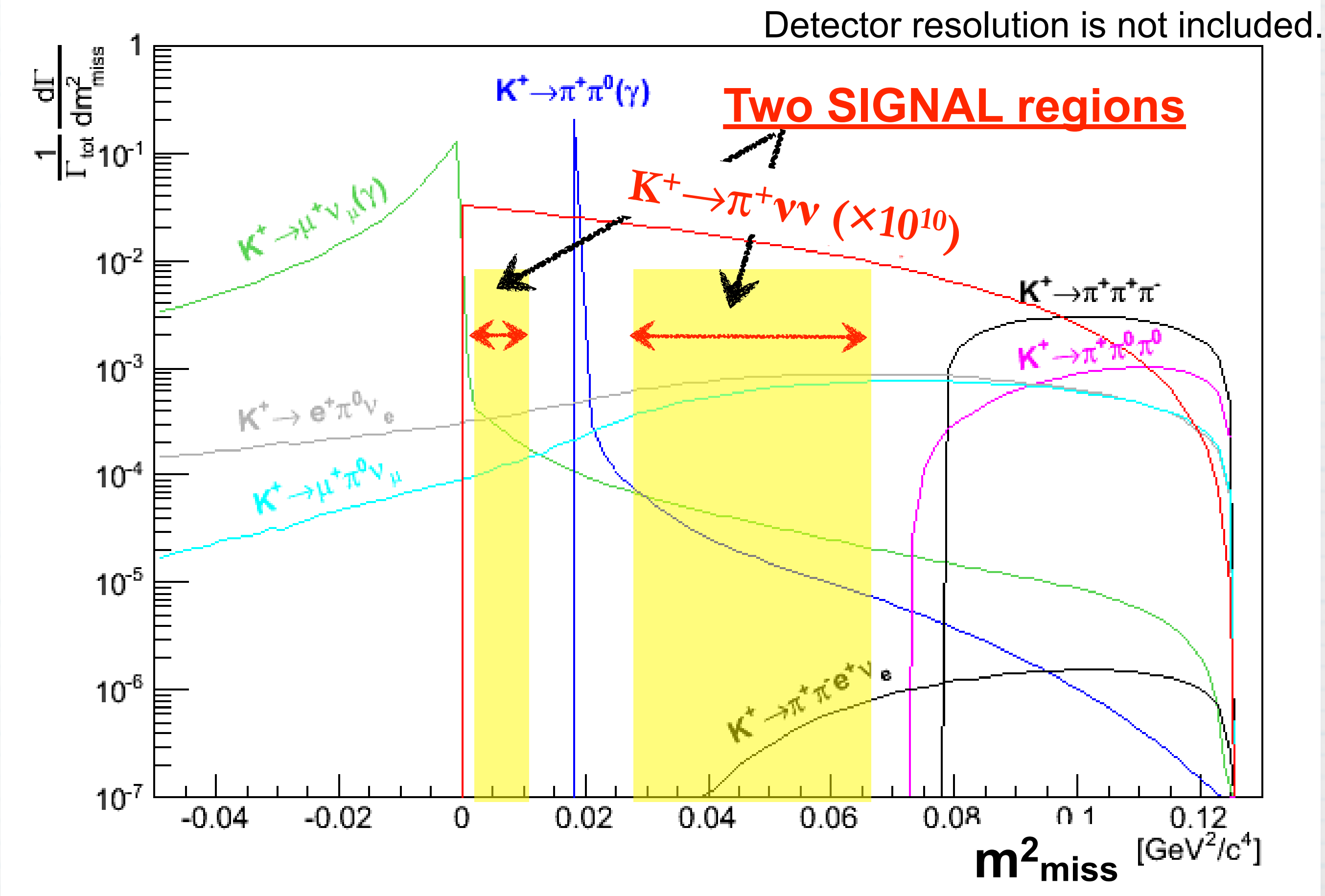
Signal and background



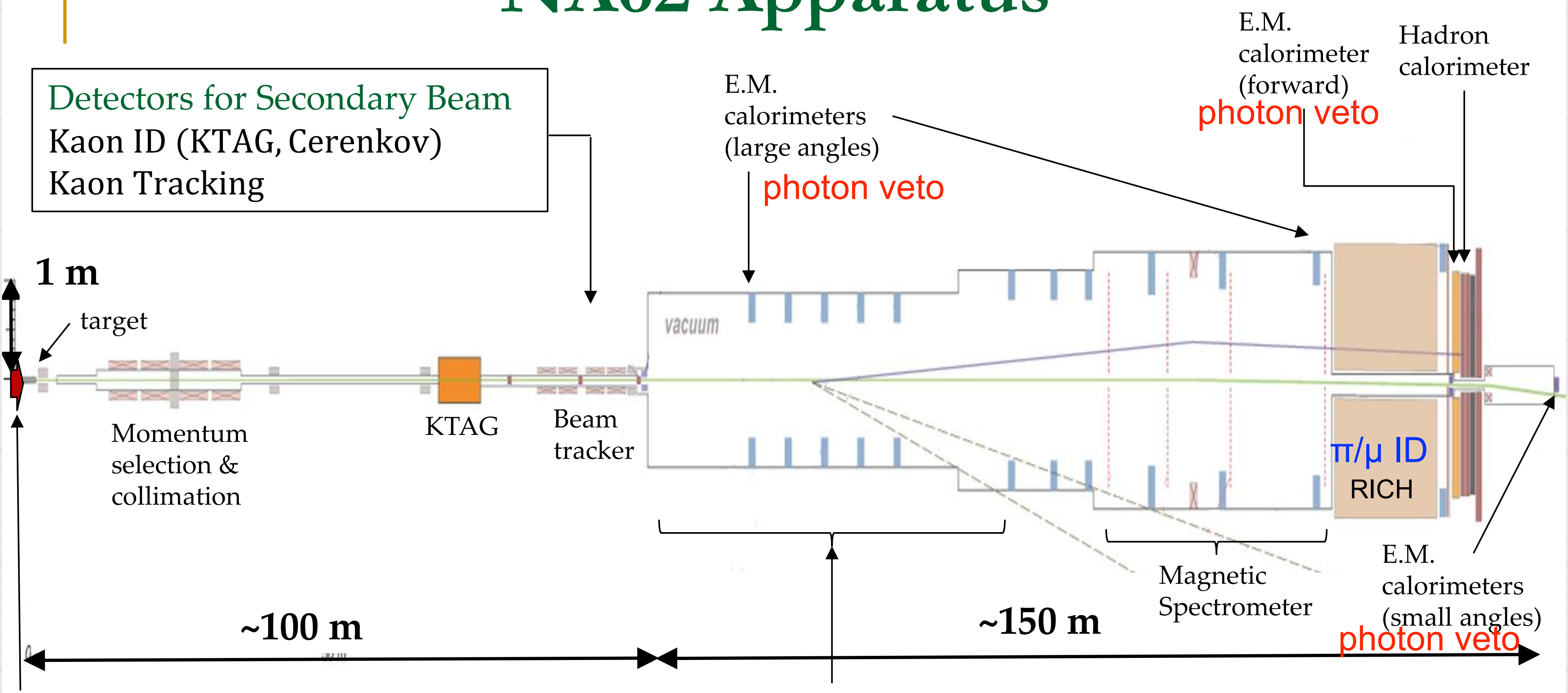
- BG suppression by kinematic constraint
  - Kinematic variable: $m^2_{miss}=(P_K-P_\pi)^2$

Avoid regions of

- $m^2_{miss} \lesssim 0$ ($K^+\rightarrow\mu^+\underline{\nu}$)
- $m^2_{miss} \sim m_\pi^2$ ($K^+\rightarrow\pi^+\underline{\pi^0}$)
- $m^2_{miss} > (2m_\pi)^2$ ($K^+\rightarrow\pi^+\underline{\pi\pi}$)



NA62 Apparatus



SPS proton
400 GeV
10^{12} p/s

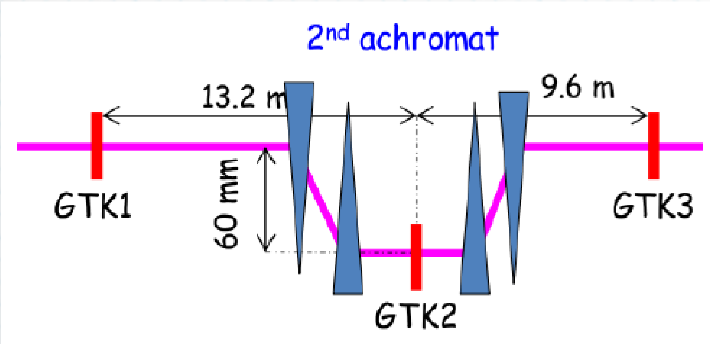
Secondary Beam
$p = 75$ GeV/c
$\Delta p/p \sim 1\%$
X,Y Divergence < 100 μrad
$K(6\%), \pi(70\%), p(23\%)$
750 MHz
Beam size: 6.0 × 2.7 cm²

Kaon Decay
~5 MHz
$4.5 \times 10^{12}/year$
60 m length
10^{-6} mbar vacuum

Detectors for decay products
Charged particle tracking
Charged particle Time Stamping
Photon detection
Charged particle ID
Pion and muon identification

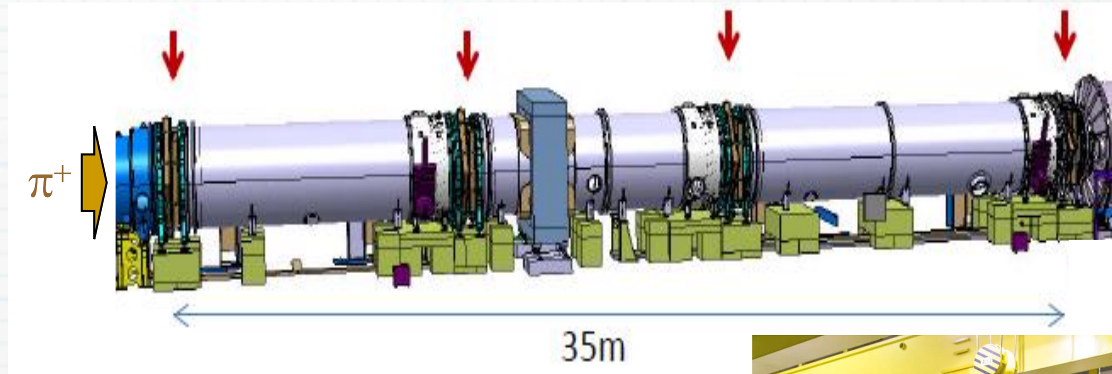
Key detectors

Beam tracker : measure P_K



"Gigatracker"
3 planes of Si pixel detectors

Secondary tracker : measure P_π



magnetic spectrometer
with 4 stations of
straw chambers in vacuum

RICH :π/μ separation

17m, Ne 1atm radiator, 10^{-2} μ rejection

RICH Vessel

RICH Mirrors

RICH PMs

2014 pilot run

Done in Oct.-Dec. 2014
with 5~20% of nominal beam intensity

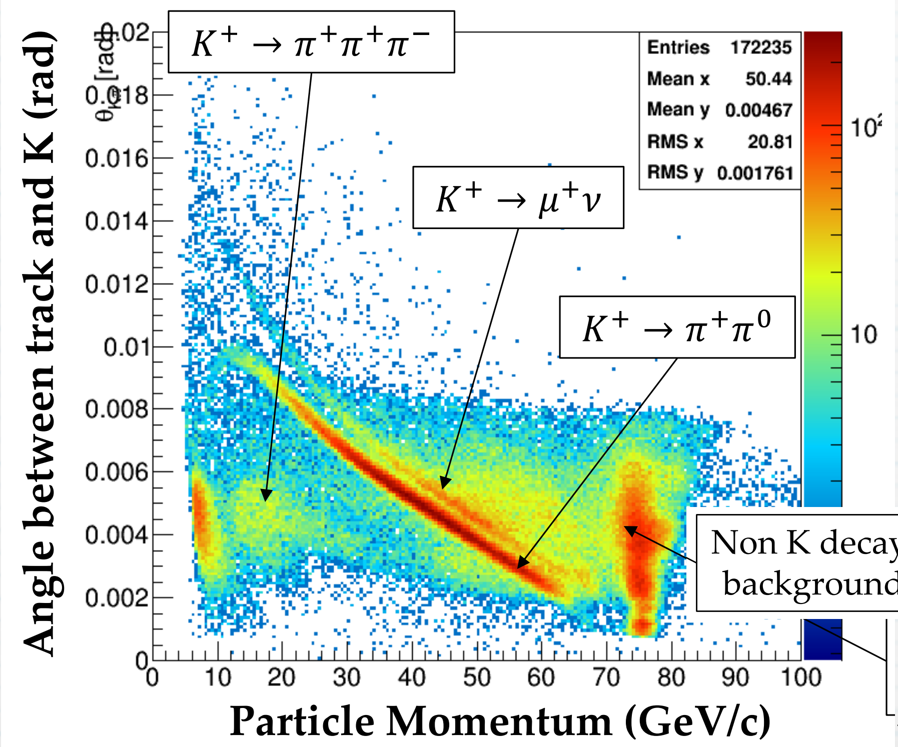
- Detector commissioning (with almost all detectors installed)
- Data quality studies with loose trigger condition

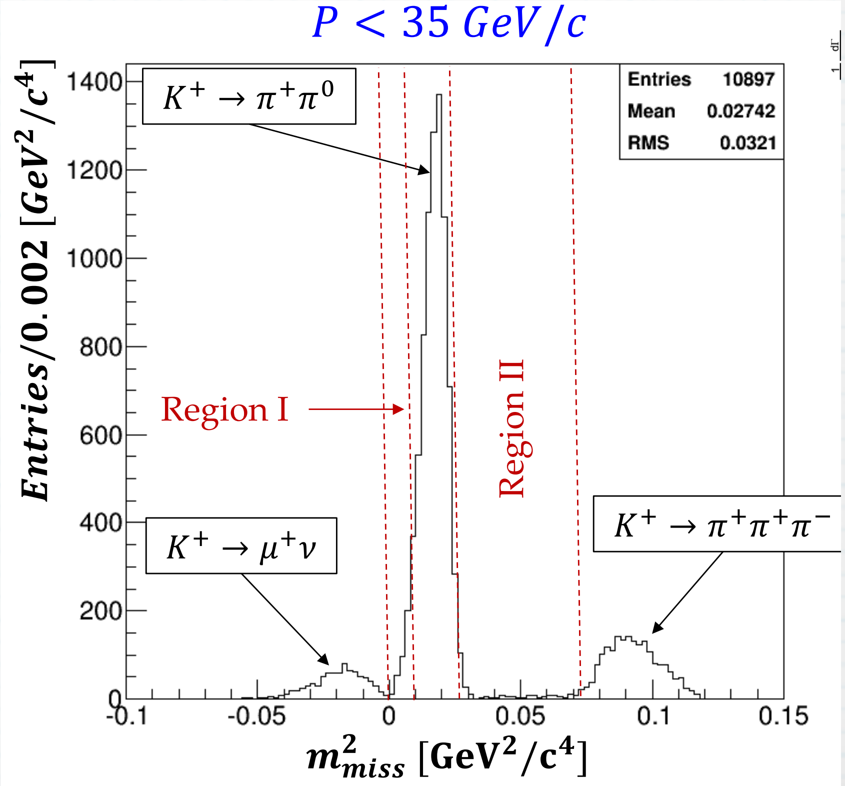
$\theta_{K\pi}$ vs P_{π}

- Events with only 1 track
- Only online μ veto applied

$M^2_{miss}=(P_K-P_\pi)^2$

- GTK not used
- Photon veto not applied





Status and plan in 2015

* Almost all the detectors have been installed.
* Pilot run was done in 2014 (October - December)
  with lower intensity
  - Good data quality at first look
  - Reprocessing with the complete detector calibrations and reconstructions is on going.

* 2015 run is scheduled from beginning of July to mid November

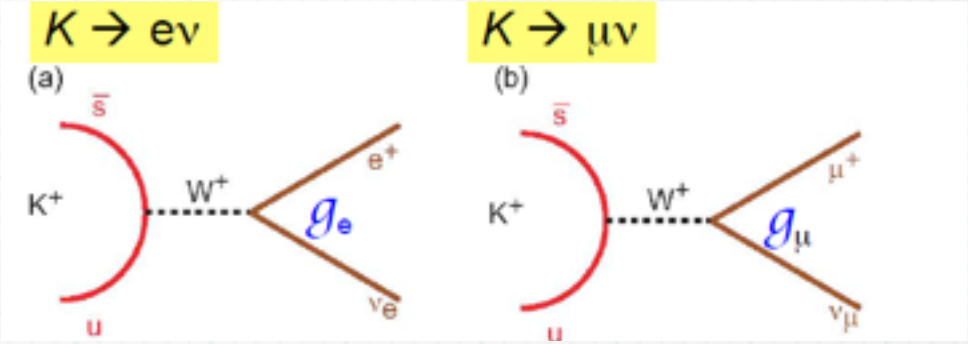
J-PARC E36:
Lepton universality in K^+ decay

- Measure $R_K = Br(K^+ \to e^+\nu)/Br(K^+ \to \mu^+\nu)$ with accuracy of $\Delta R_K/R_K = 0.25\%$
- Stopped Kaon decay technique

Lepton universality in K_{l2} decay

* Precise measurement of decay width ratio

$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$



$$\Gamma(K_{l2}) = g_l^2\,(G^2/8\pi)\, f_K^2 m_K m_l^2 \{1-(m_l^2/m_K^2)\}^2$$

$$g_e = g_\mu\ ?$$

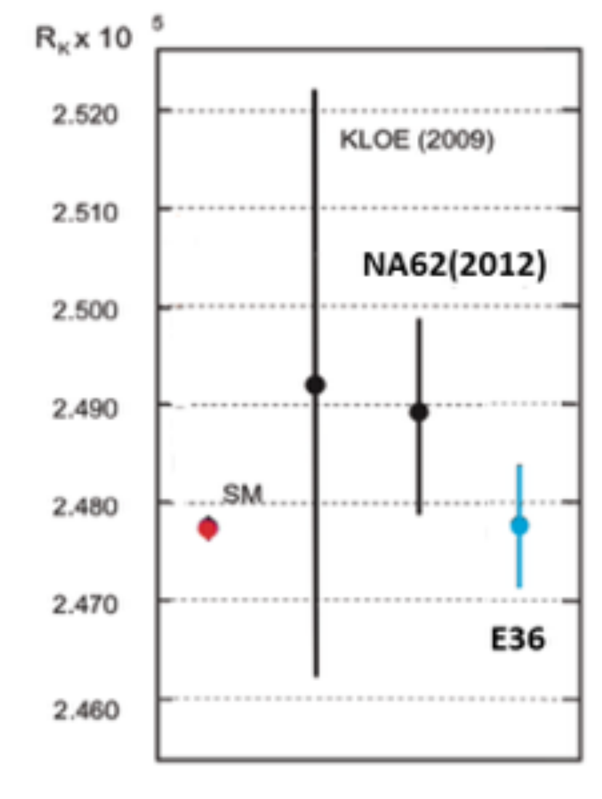
* In the ratio of the $\Gamma(K_{e2})$ to the $\Gamma(K_{\mu2})$, the hadronic form factors are cancel out, and R_K^{SM} is highly precise.

$$R_K^{SM} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta_r)$$

$R_K^{SM}=(2.477\pm0.001)\times10^{-5}$
$\Rightarrow \Delta R_K/R_K \sim 0.04\%$

* Some New Physics model calculate $O(10^{-3})$ deviation from SM.

Experimental status of R_K



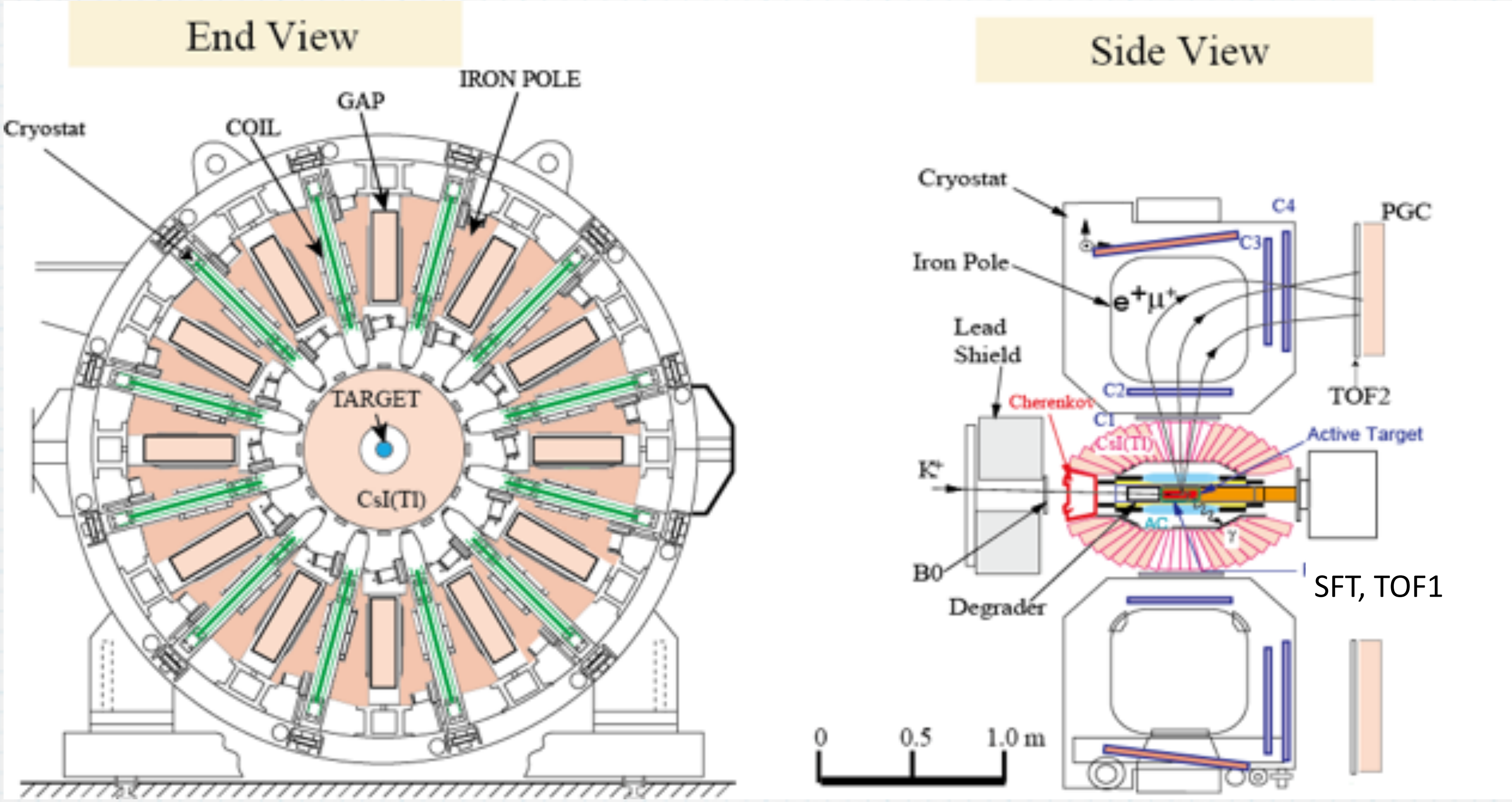
- KLOE @ DAΦNE (in-flight decay) (2009)
  $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$
- NA62 @ CERN-SPS (in-flight decay) (2013)
  $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$

⇒ World average (2013)

$R_K = (2.488 \pm 0.009) \times 10^{-5}$, $\delta R_K/R_K = 0.4\%$

These experiment utilized K^+ decay in flight.

- J-PARC E36 characteristics :
  - Stopped K^+ experiment: different systematic properties
    2 body decay has a monochromatic charged particle.
  - Goal: $\delta R_K / R_K = \pm 0.2\%$ (stat) $\pm 0.15\%$ (syst) [0.25% total]



Reasonable upgrade of KEK-PS E246 with the Toroidal spctrometer

Stopped K method

- K1.1BR beamline
- K^+ stopping target

Momentum measurement

- MWPC (C2, C3, C4)
- C1 GEM
- Spiral Fiber Tracker(SFT)

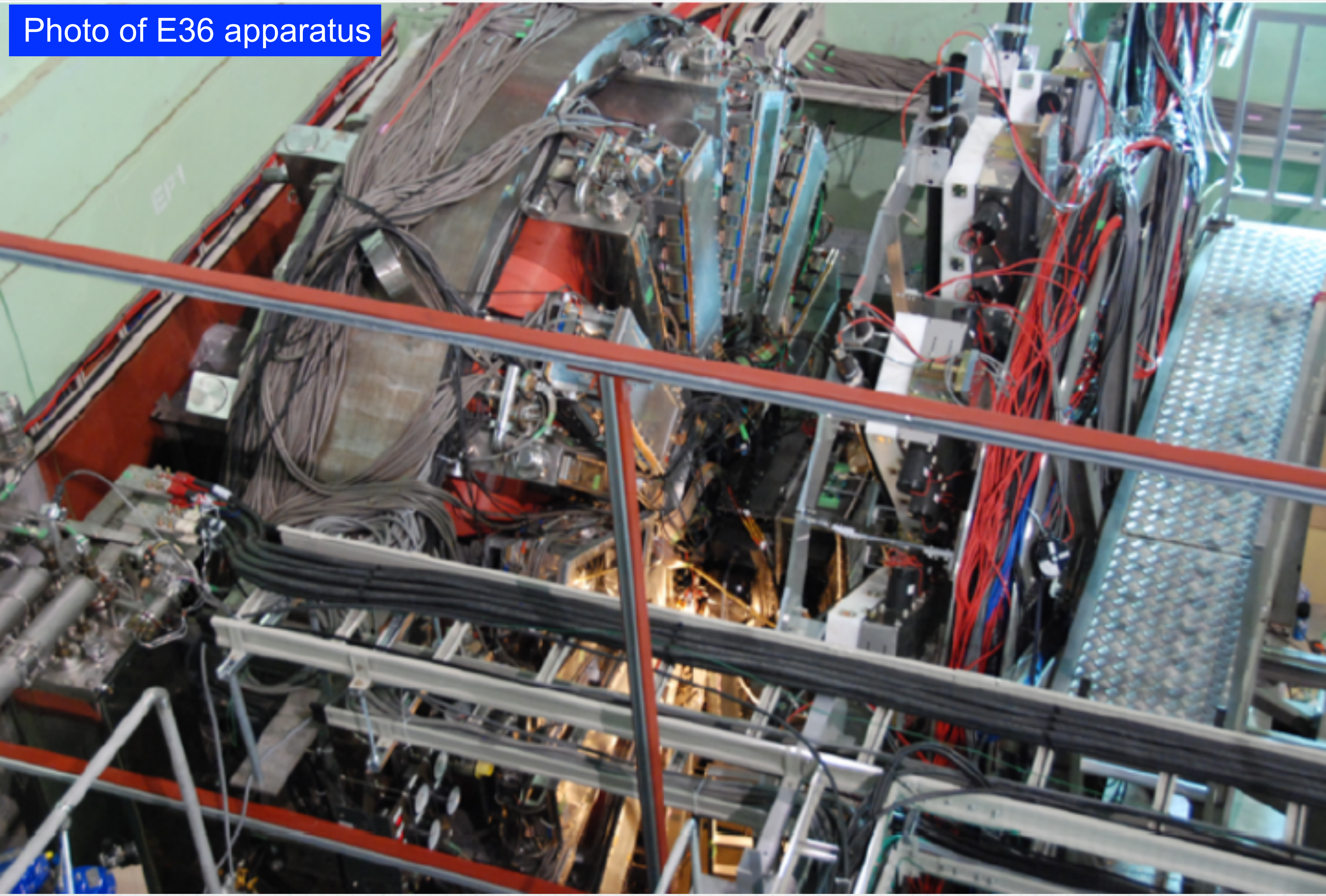
PID

- TOF
- Aerogel Cherenkov (AC)
- Pb glass counter (PGC)

Gamma ray

- CsI(Tl)

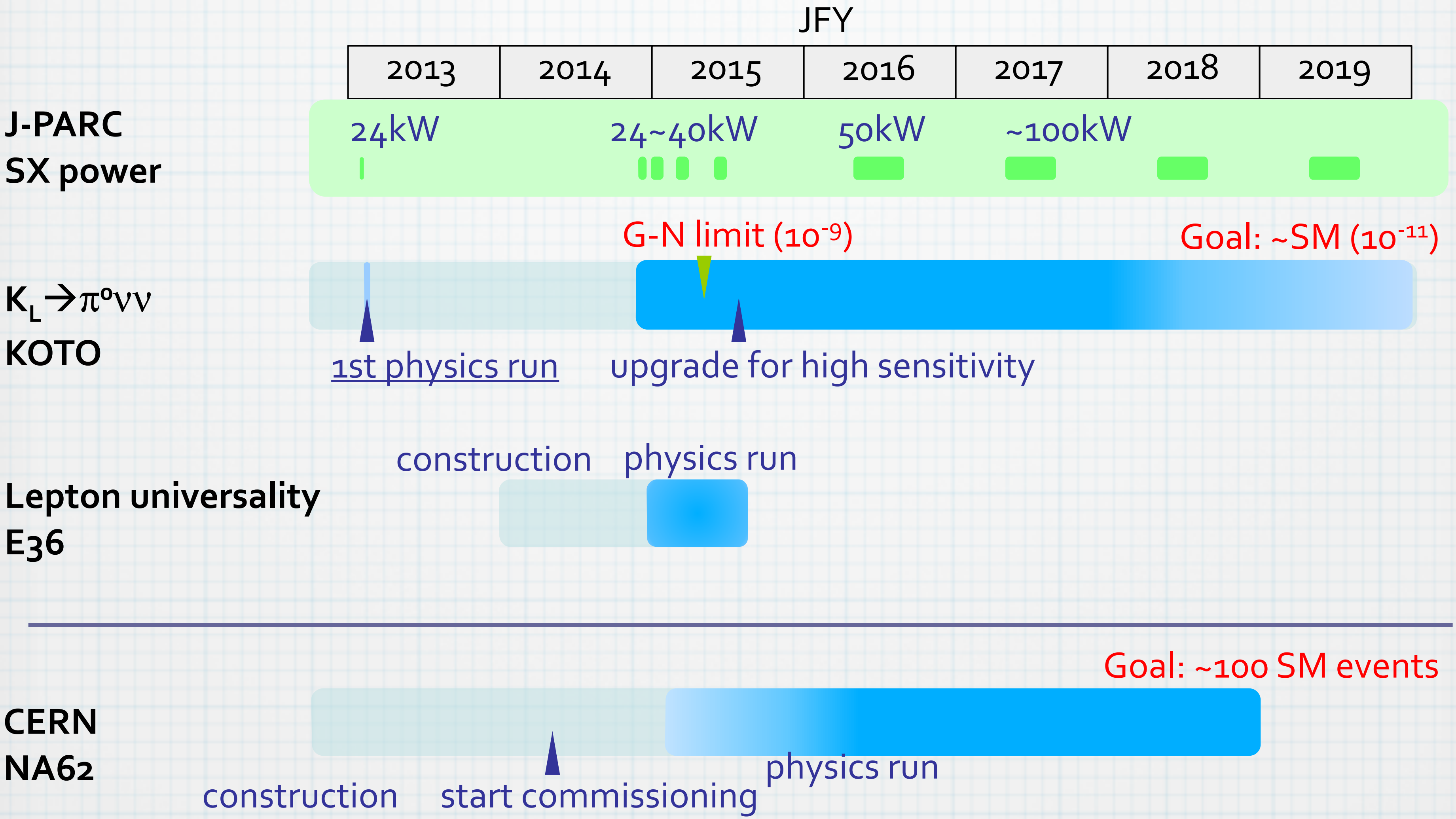
Photo of E36 apparatus



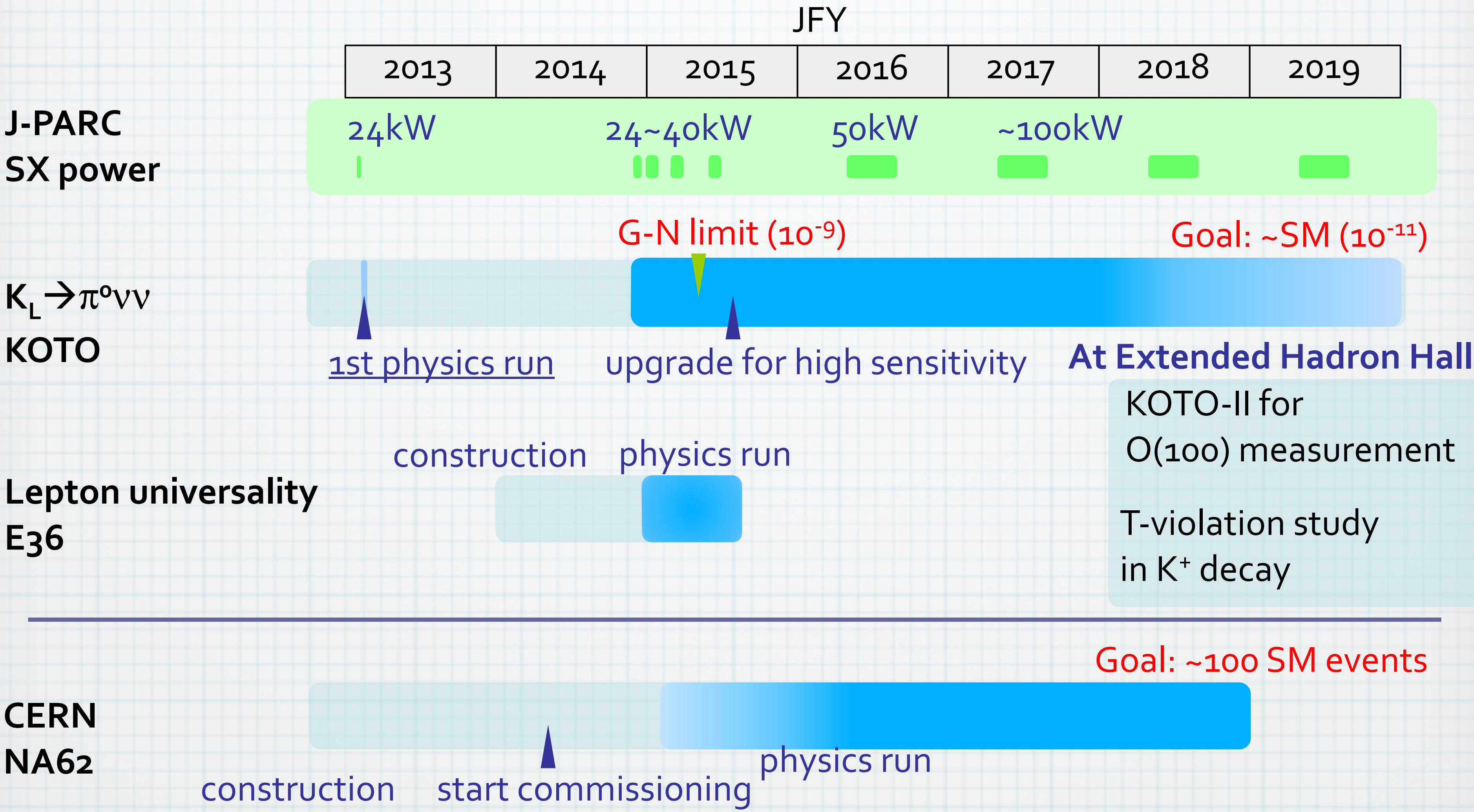
E36 status and plan in 2015

* The E36 detector, the toroidal magnet and its cryogenics have been installed at K1.1BR area.
* Commissioning with full magnetic field started in the April beam time.
* Next steps are
  * June : continue commissioning and then start physics runs
  * In fall : do physics runs
* (After the fall run, the E36 apparatus will be dismantled for the construction of other new beam lines.)

Scope in time domain

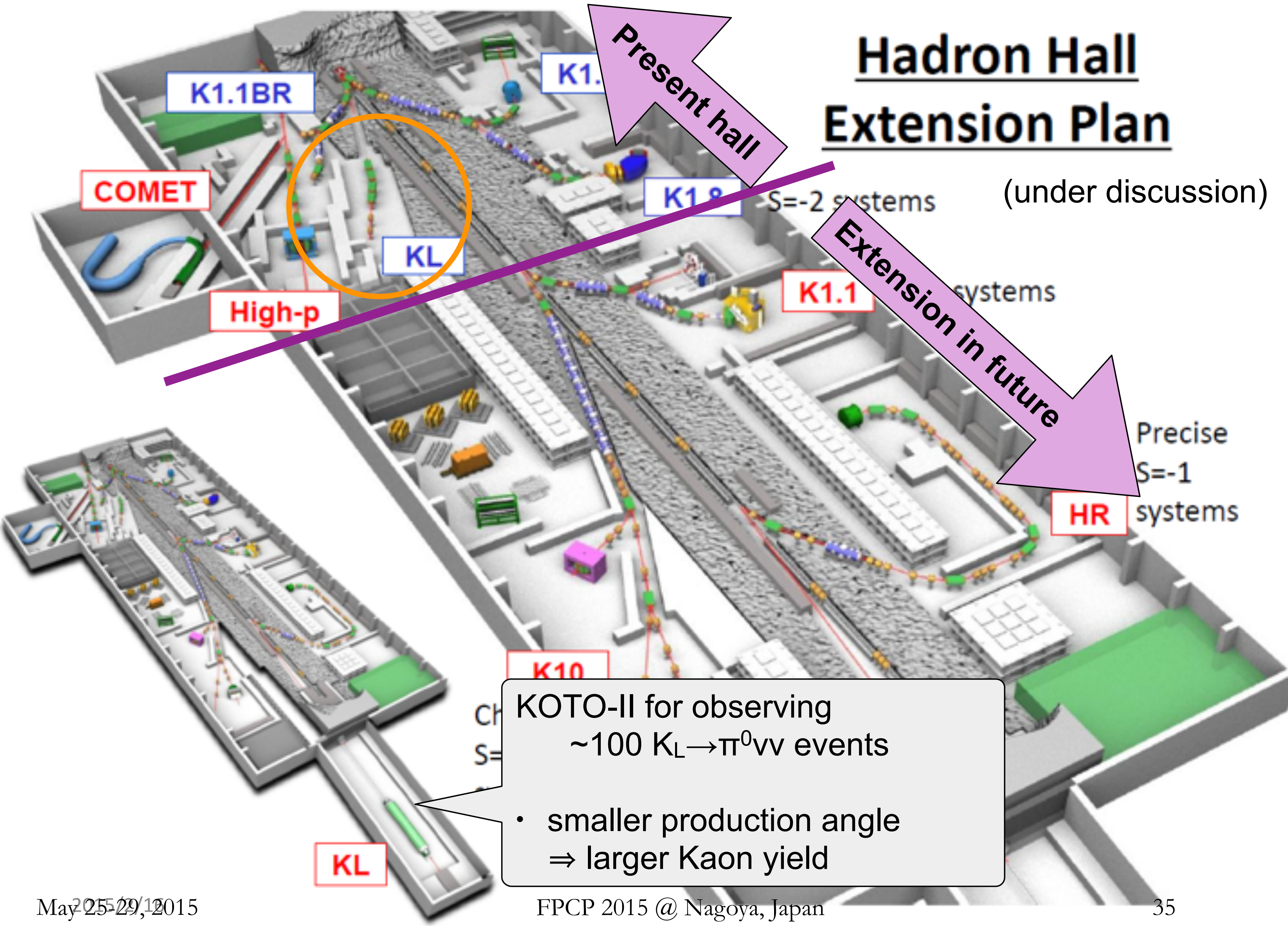


Scope in time domain, further



Hadron Hall Extension Plan

(under discussion)



KOTO-II for observing
~100 $K_L \rightarrow \pi^0 \nu\nu$ events

- smaller production angle
⇒ larger Kaon yield

Summary

* Kaon rare decay study is one of the important approaches to new physics beyond SM.
* Now, three kaon experiments in Japan and Europe are running or almost ready to run.
  - J-PARC KOTO ($K_L \to \pi^0 \nu\nu$) restarted physics run in April 2015 and will continue data taking.
  - CERN NA62 ($K^+ \to \pi^+ \nu\nu$) started commissioning in 2014 and will proceed to physics run.
  - J-PARC E36 (Lepton flavor universality in K_{l2} decays) started commissioning and will complete physics run in this year.

* Look forward to interesting results coming !!