KOTO実験による
K中間子稀崩壊探索

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

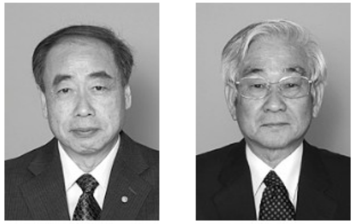
南條　創
(京都大学)

Contents

- Motivation
- KOTO Experiment
- Prospect

Motivation

New Physicsはあるのか？



- 2008 : Kobayashi and Maskawa
  - CP-violation was established.
  - The size is not enough to explain matter dominant universe.
  - New CP-violating particle is expected in higher energy scale.

- 2013 : Englert and Higgs
  - Higgs was discovered but it is far from closing the book.
  - New physics in high energy scale is expected to stabilize Higgs mass.
  - SUSY, little Higgs, Compositeness, Extra Dimension, …?
  - Dark matter?

- New Physicsは存在する。
  - 物質優勢宇宙
  - Dark Matter
  - ...

- どうやって探す？

New Physics Search

- High Energy Frontier ↔ High Intensity Frontier
  - High energy frontier → direct production of heavy particle
  - High intensity frontier → indirect access, high energy reach

    一瞬の高エネルギースケール

    →稀なプロセス

$$\Delta E \times \Delta t \sim \hbar$$

      - 標準理論の抑制
        - GIM, CKM,Helicity...suppression
      - 精密な理論予測
    - Multi-process approach 多方面からフレーバ構造を明らかに
      - Correlation is important.

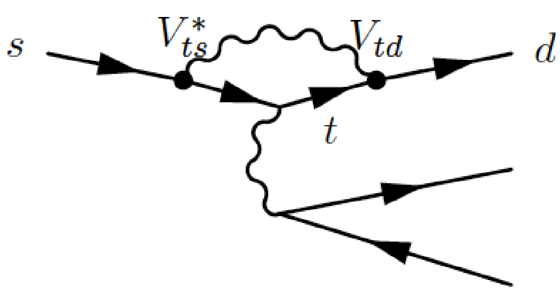
- CP-violation is another guide.

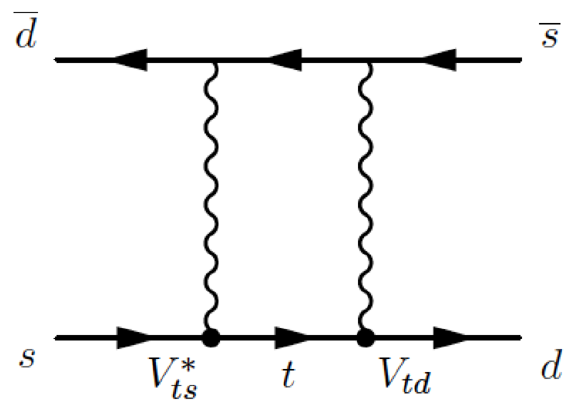
    explanation of matter dominant universe

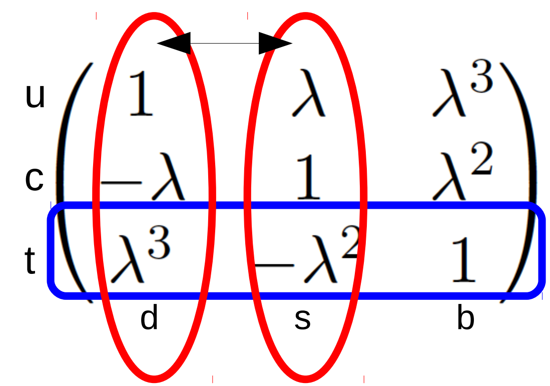
Why Kaon?

Blanke '13

- "Generally most powerful"
  - GIM suppression of u and c quarks
  - Hierarchical structure of CKM for t quark
    - Most suppressed in s → d transition (λ^5)
      - b → d (λ^3) , b → s (λ^2)







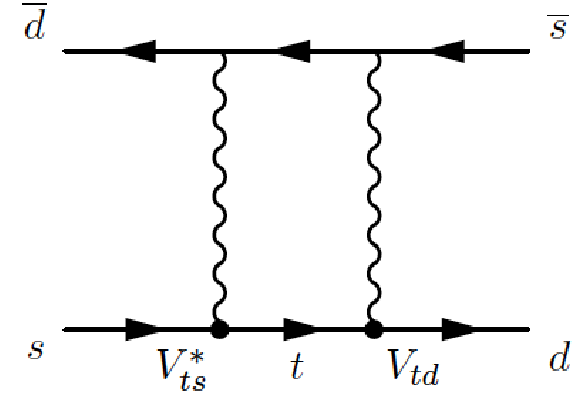
$\lambda \sim 0.23$

$$\underbrace{|V_{ts}^* V_{td}|}_{K\ \text{system}} \sim 5 \cdot 10^{-4} \ll \underbrace{|V_{tb}^* V_{td}|}_{B_d\ \text{system}} \sim 10^{-2} < \underbrace{|V_{tb}^* V_{ts}|}_{B_s\ \text{system}} \sim 4 \cdot 10^{-2},$$

例え$B_{s/d}$ → μμがSM-likeであっても、s → dはNPでエンハンス可能

Bona '07
Ishidori '13

Energy Reach



$K^0 - \overline{K^0}$mixing

$$\mathcal{M}_{\Delta S=2} \sim \frac{G_F^2 m_t^2}{16\pi^2}(V_{ts}^* V_{td})^2 + \frac{F_{NP}}{\Lambda^2}\alpha_{NP}^2$$

Flavor structure

$$\Lambda > \frac{4\pi}{G_F m_t}\frac{1}{|V_{ts}^* V_{td}|}\alpha_{NP}\sqrt{F_{NP}} \sim 7\text{TeV} \times 2000 \times \alpha_{NP}\sqrt{F_{NP}}$$

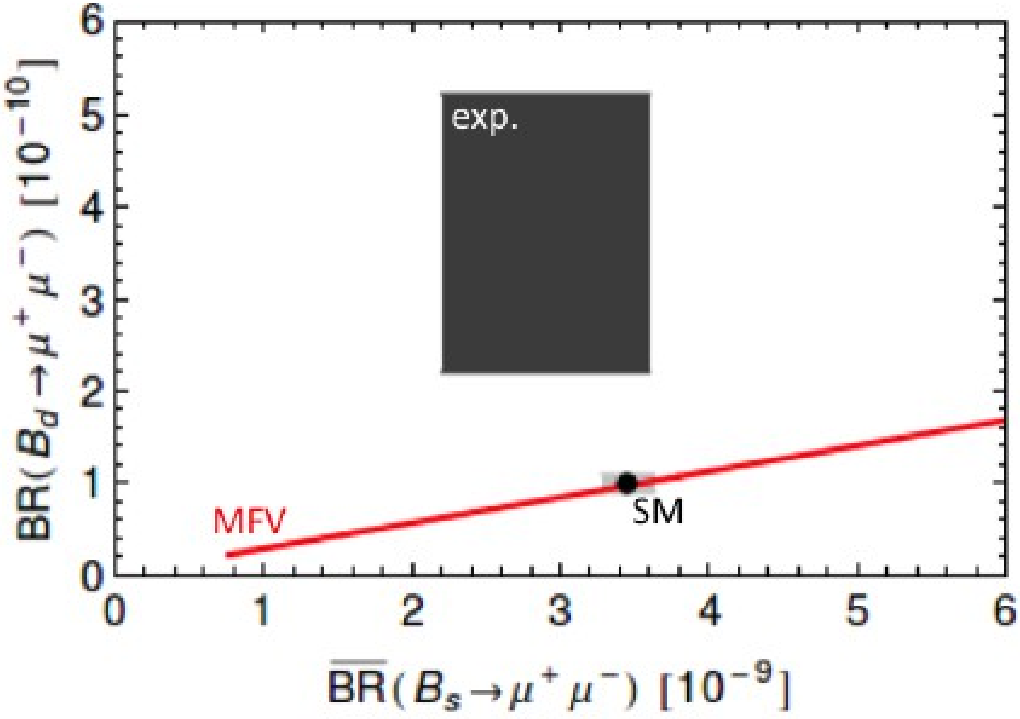
Tree/Strong couple ~1
Loop α_s ~0.1
Loop α_w ~0.03

	MFV	Generic
Tree/Strong couple	5 TeV	24000 TeV
Loop α_s	0.5 TeV	2400 TeV
Loop α_w	0.2 TeV	800 TeV

(Bona '07)

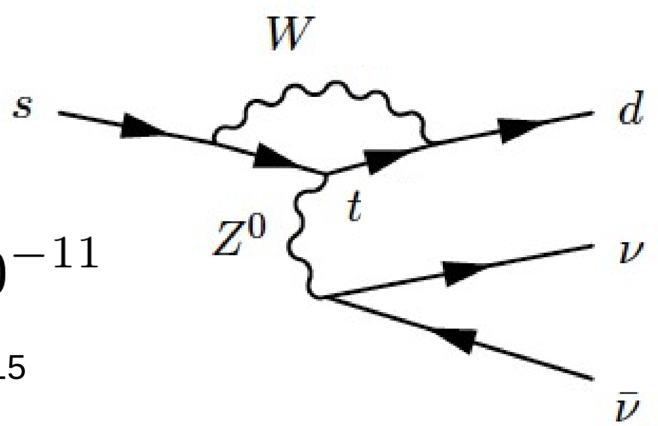
Genericの場合、K sectorが最強 → 10^4 TeVまでのリーチ
なぜまだ見えない？ ↔ Energy scale, Flavor構造
Minimal Flavor Violation likeな場合、Bと強い相関
(NPでもCKMの構造を保持,新しいCPV phaseもない)

- NP > 1 TeV? (ATLAS,CMS)
- Non-MFV like ? (LHCb,CMS)



Buras'13

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



- Rare decay $Br(\mathrm{SM}) = (3.00 \pm 0.30) \times 10^{-11}$
  - Strong suppression from CKM

Buras '15

- Small theoretical uncertainty ~2%
  - High energy scale
  - Hadron matrix element from tree process Ke3/Kmu3

Sensitive to new physics beyond the SM

- CP-violating process $\mathcal{A}(K_L) \propto \mathcal{A}(K^0) - \mathcal{A}(\overline{K_0}) \propto \mathrm{Im}(\mathcal{A}_{s\to d})$
- Related to charged mode $K^+ \to \pi^+ \nu \nu$ $\mathcal{A}(K^+) \propto |\mathcal{A}_{s\to d}|$
  - Grossman-Nir bound :
    - Model-independent inequality w/ iso-spin rotation

$$Br(K_L) < 4.4 \times Br(K^+) \to 1.5 \times 10^{-9} (90\% C.L.)$$

Status

Direct limit
2.6×10^{-8} (KEK E391a)

10^{-8}

Indirect limit
1.5×10^{-9} (Grossman-Nir)

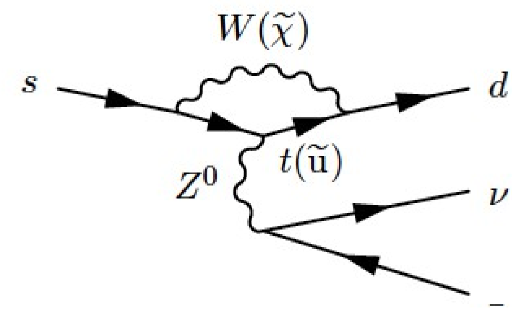
10^{-9}

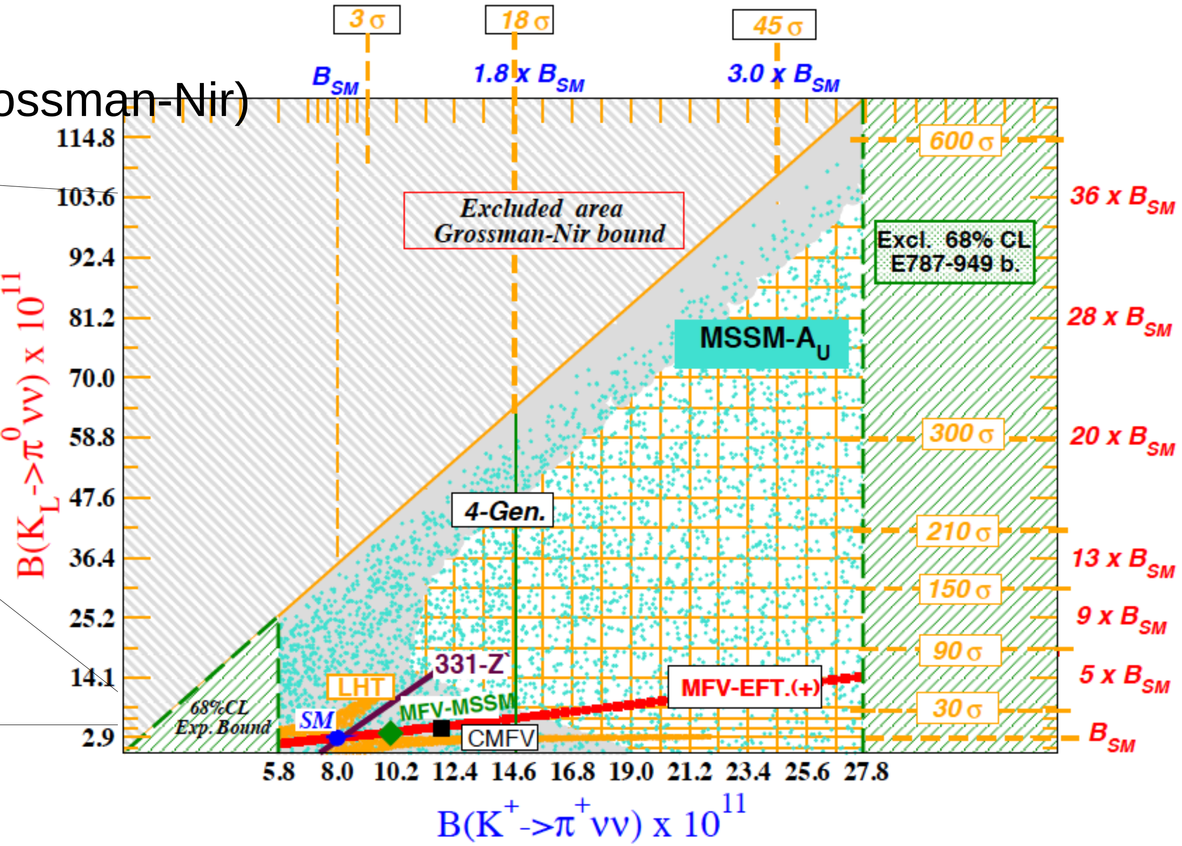
10^{-10}

New Physics?

SM sensitivity
2.4×10^{-11}

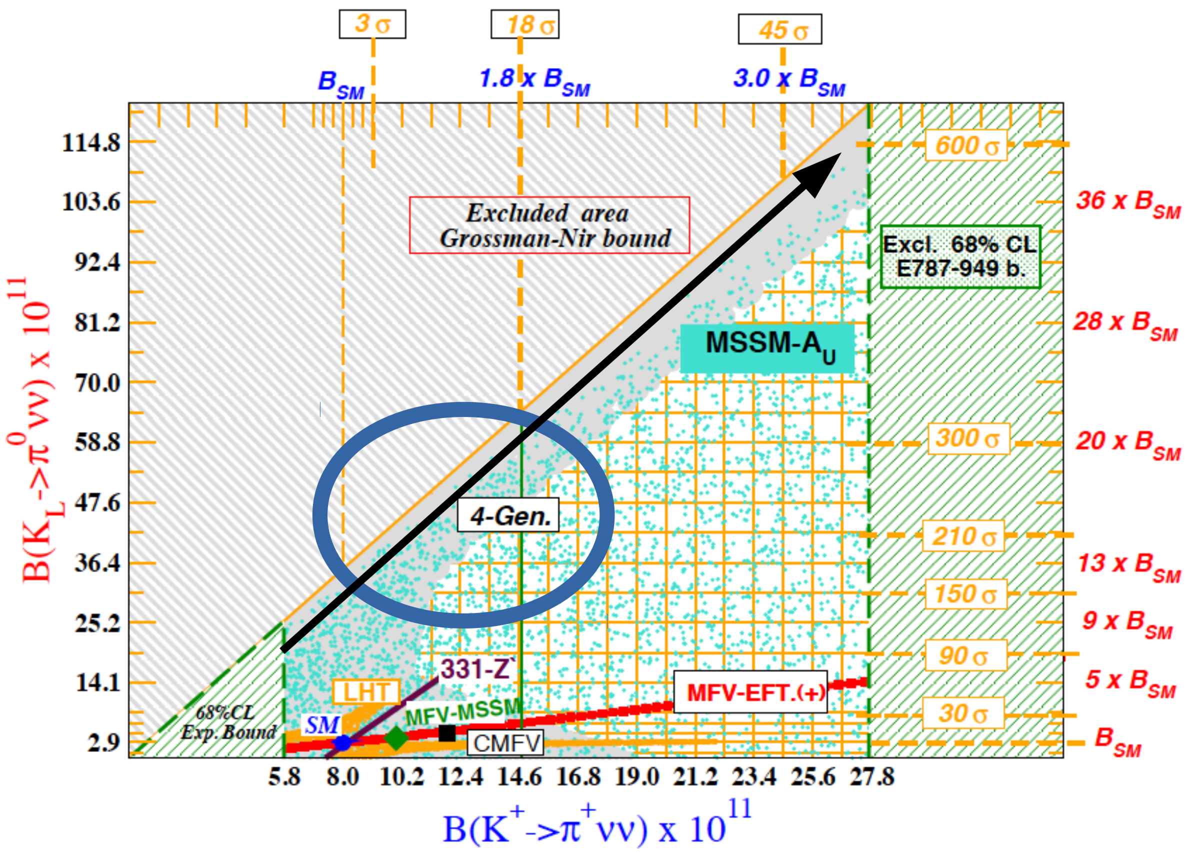
10^{-11}



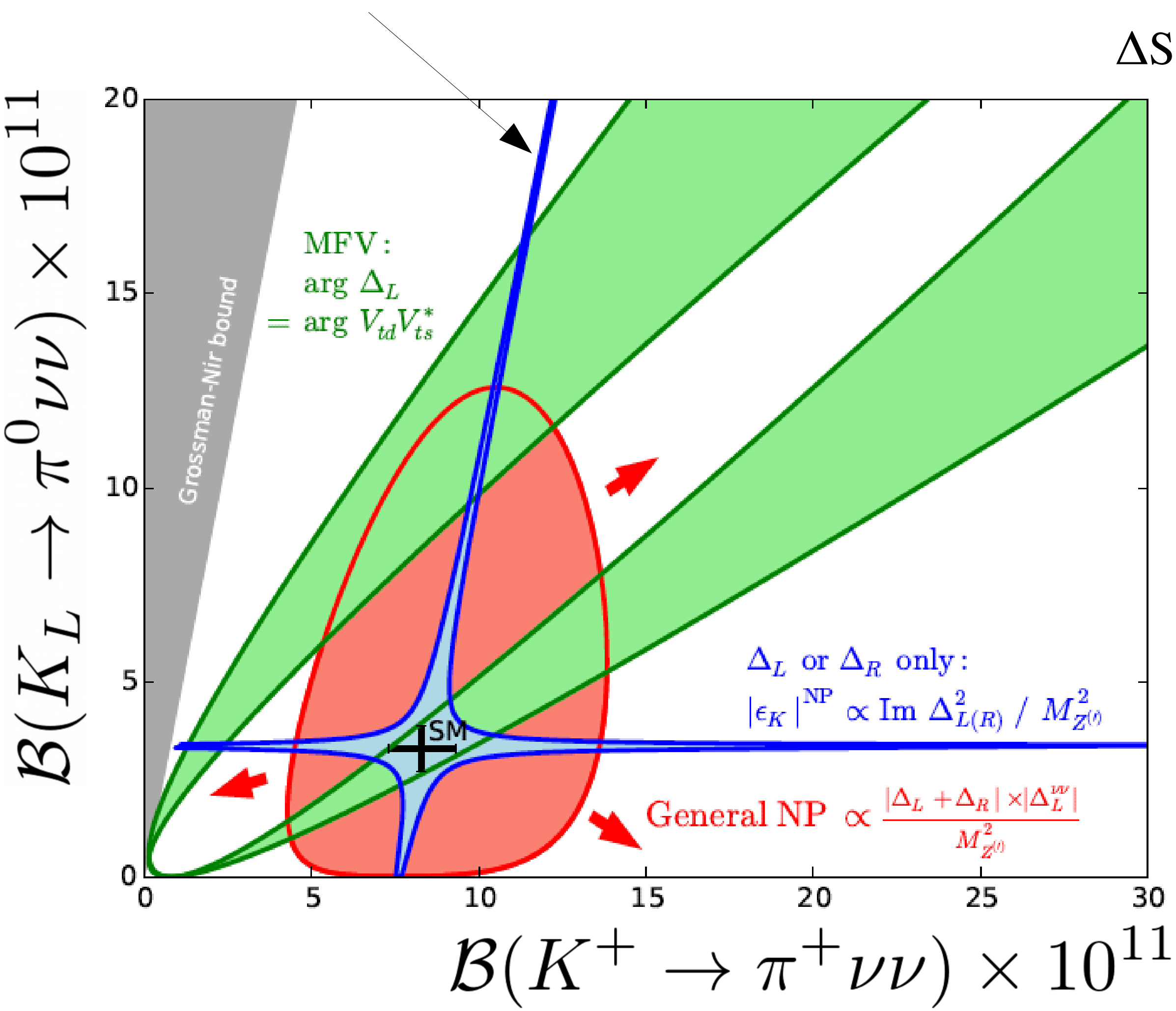


SM extension w/ 4th generation
→ ruled out
Direct search
EW precision test
Higgs mass

Otto '12



ϵ_K from $K^0 - \overline{K^0}$ mixing



ΔS=2とΔS=1のNPによる変化

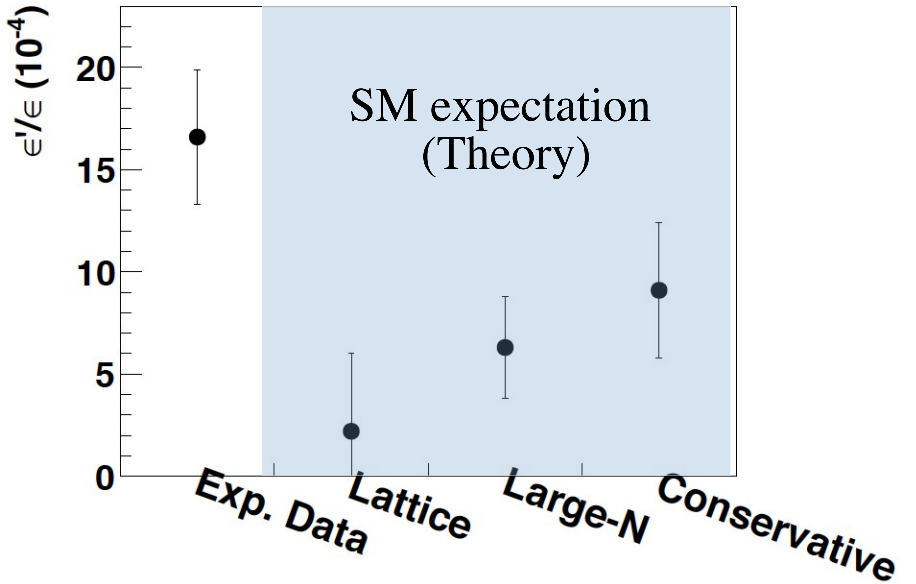
→ 同じnew phaseが支配

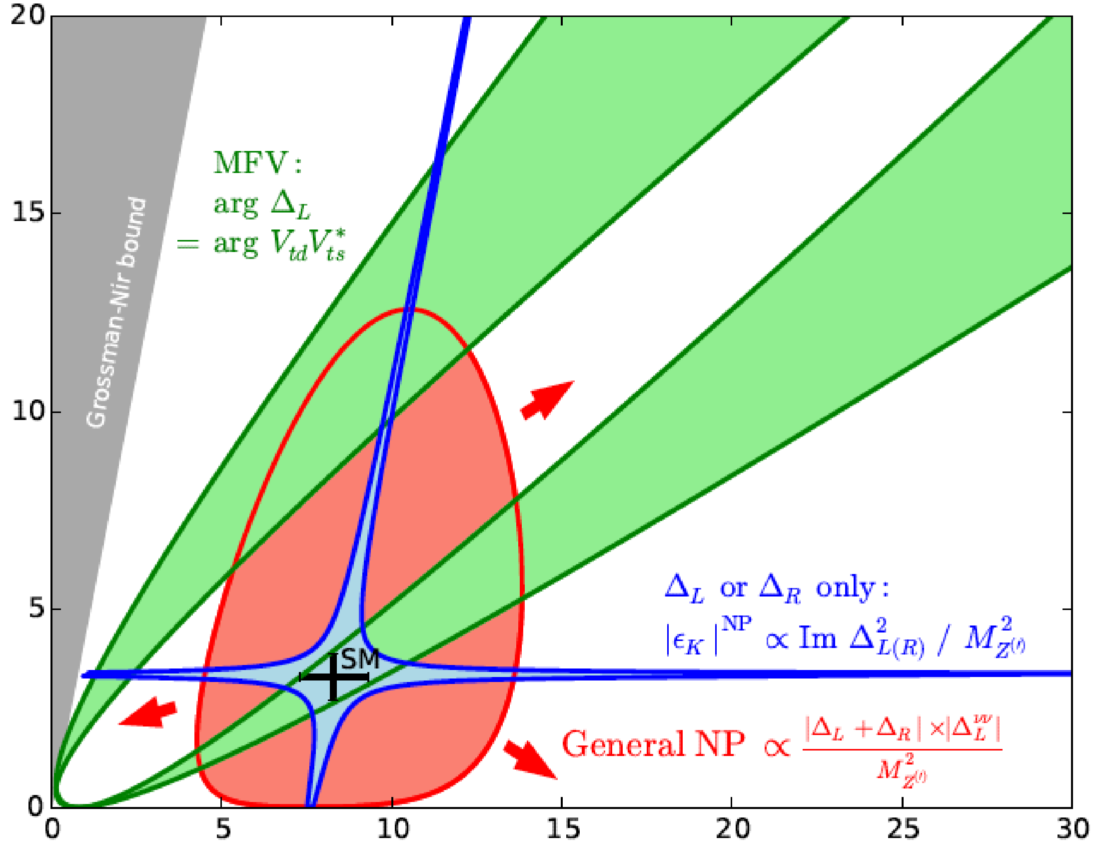
Z'/Z with Left / Right-handed coupling

Littlest Higgs with T-parity

Input from ε'/ε

Direct CPV from KL → ππ
Progress from lattice calculation





$$\mathcal{B}(K^+ \to \pi^+ \nu\nu)(10^{-11})$$

Left and Right-handed coupling still can enhance Br(KL)

$$(\epsilon'/\epsilon)_{\rm Data} > (\epsilon'/\epsilon)_{\rm SM}?$$

MFV
Left or Right-handed coupling

Buras '15

EW penguin contribute to e'/e in negative interference.
Negative correlation btw Br(KL)

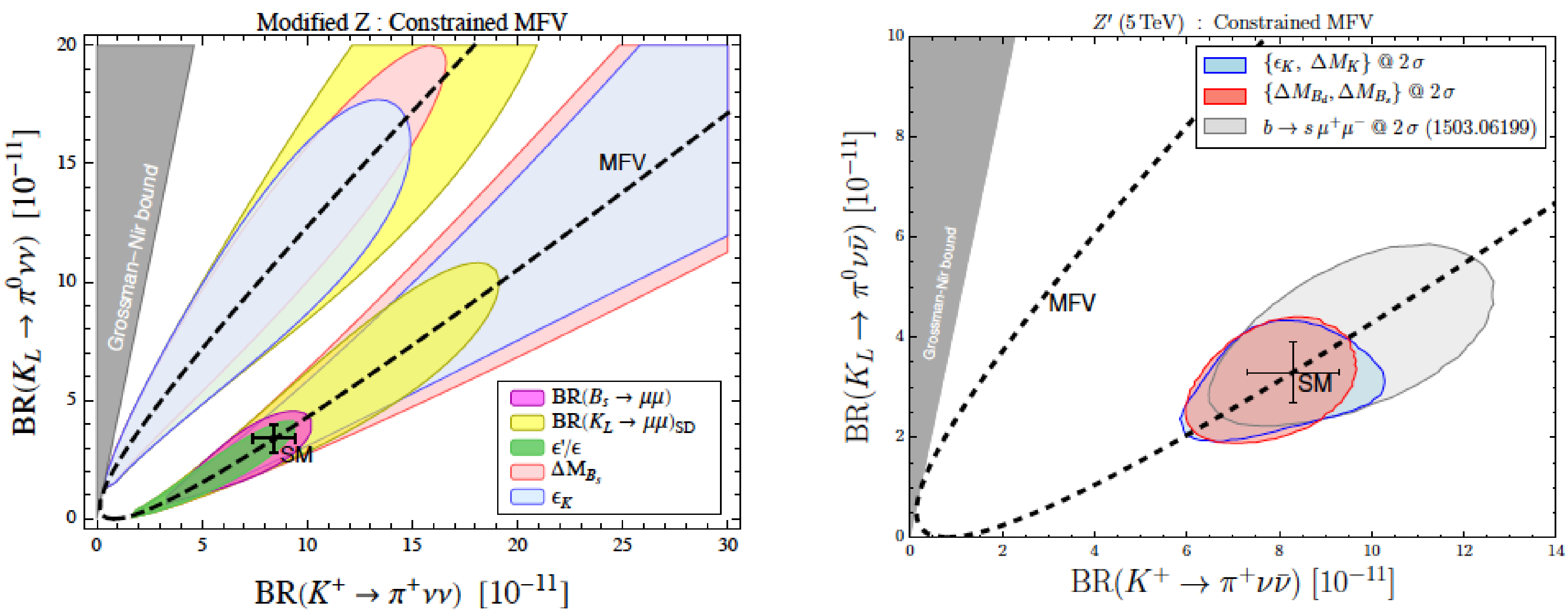


Figure 5: *The 95% C.L. allowed ranges for $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ and $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ in a simplified Z model (left panel) or a 5 TeV Z' model (right panel) obeying CMFV. In the case of the smaller $U(2)^3$ symmetry, the constraints from B processes can be neglected. Note the difference in scale between these plots.*

Buras '15

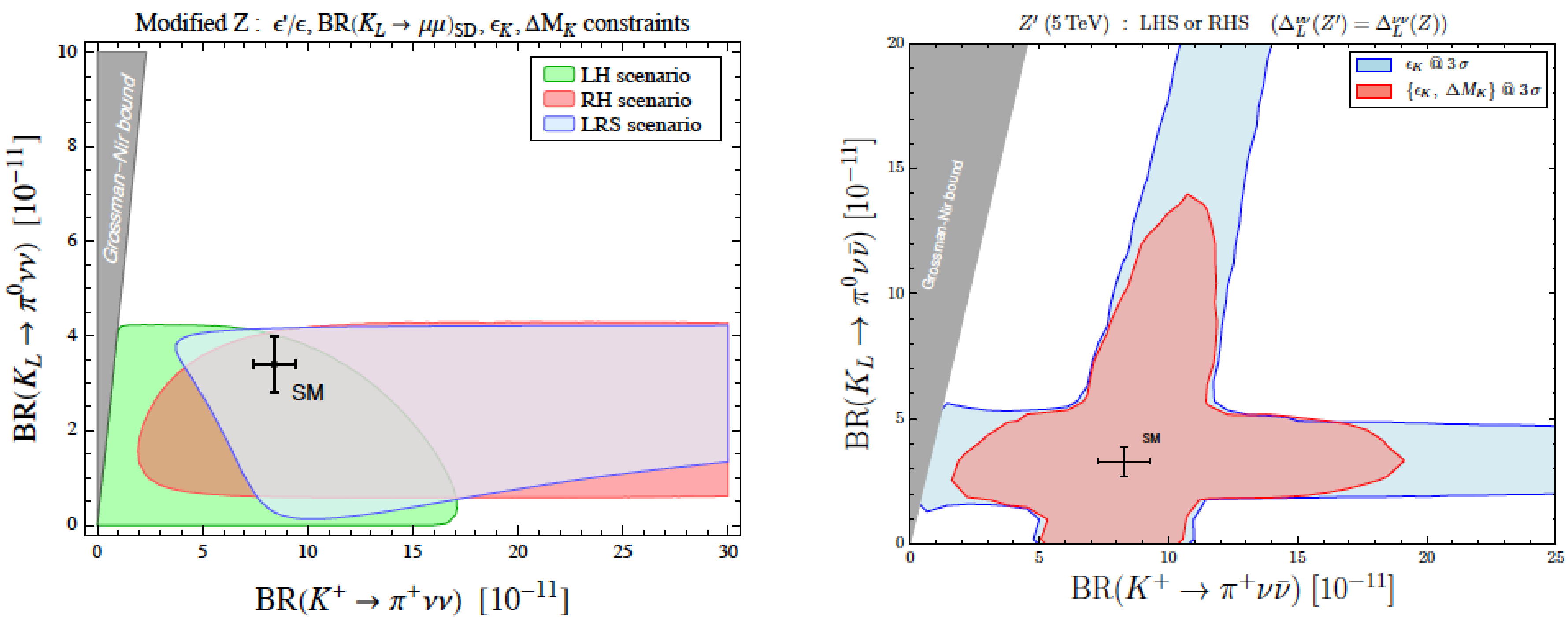


Figure 6: *The allowed ranges for $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ and $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ in a simplified Z model (left) and a 5 TeV Z' model (right) in LH and RH scenarios. The ε_K and ΔM_K constraints are imposed in all cases. In the left-handed plot the ϵ'/ϵ and $K_L \to \mu\mu$ constraints are also imposed.*

Left- and right-handed coupling model can enhance Br(KL)

Buras '15

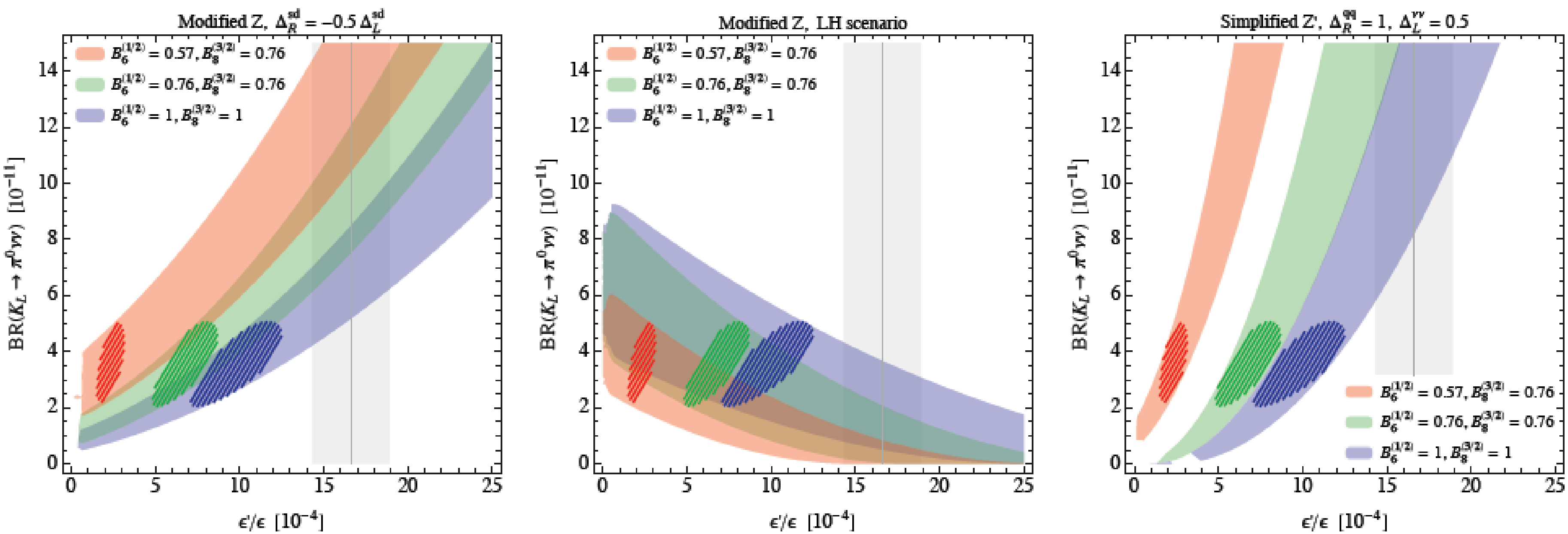
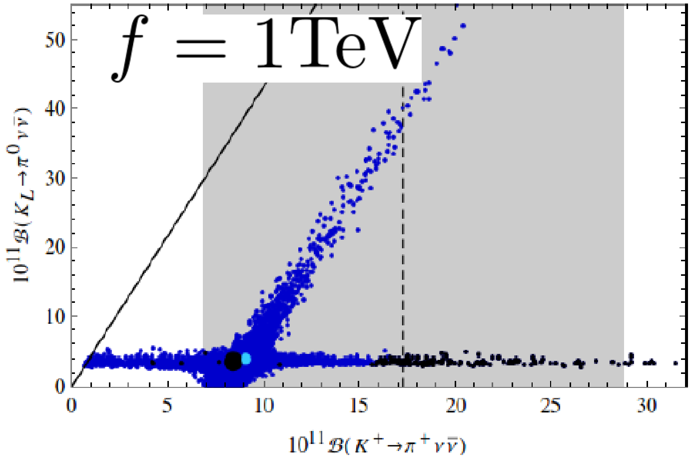


Figure 2: *95% C.L. allowed regions for ε'/ε and $K_L \to \pi^0\nu\bar{\nu}$. Left: model with flavour-changing Z boson couplings $\Delta_R^{sd} = -0.5\Delta_L^{sd}$. Center: modified Z, LH scenario $\Delta_R^{sd} = 0$. Right: 5 TeV Z' with $\Delta_R^{qq} = 1$ and $\Delta_L^{\nu\nu} = 0.5$. The plots are for $B_6 = 1$ (blue), $B_6 = 0.76$ (green), and $B_6 = 0.57$ (red). The hatched regions are the SM predictions at 2σ. The gray band shows the experimental result for ε'/ε.*

Littlest Higgs with T-Parity

Blanke '15

Symmetry breaking scale



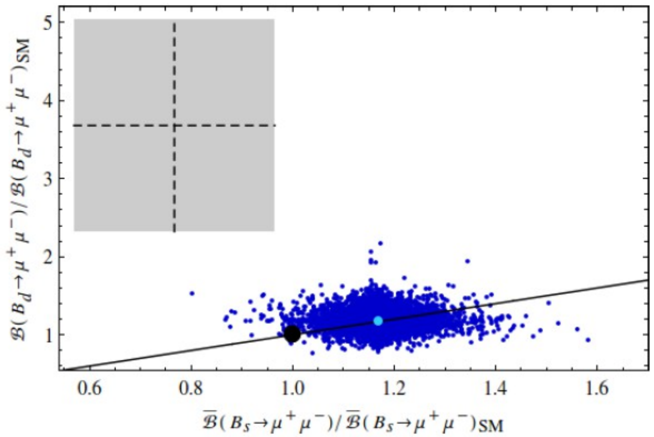


Figure 8: *Correlation between* $\bar{\mathcal{B}}(B_s \to \mu^+\mu^-)$ *and* $\mathcal{B}(B_d \to \mu^+\mu^-)$ *in the LHT model for* $f = 1\,\text{TeV}$. *The large black dot shows the central SM value for our choice of input parameters, and the light blue point shows the contribution from the T-even sector. The experimental* 1σ *ranges are displayed by the grey rectangle [50], and the MFV prediction is indicated by the solid black line.*

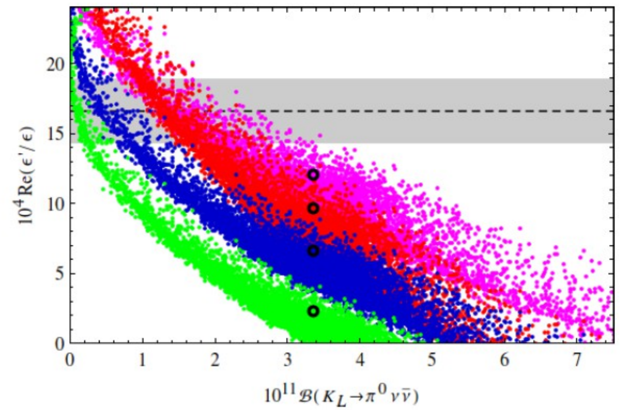


Figure 6: *Correlation between* $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ *and* $\text{Re}(\varepsilon'/\varepsilon)$ *in the LHT model for* $f = 1\,\text{TeV}$ *for different values of* $(B_6^{(1/2)}, B_8^{(3/2)})$: $(1.0, 1.0)$ *(red)*, $(0.76, 0.76)$ *(blue)*, $(0.57, 0.76)$ *(green)*, $(1.0, 0.76)$ *(magenta). The black dots show the corresponding central SM values. The experimental* 1σ *range for* $\text{Re}(\varepsilon'/\varepsilon)$ *is displayed by the grey band [74–77].*

SUSY at 10-50 TeV

Tanimoto, Yamamoto '15

- 10 TeV SUSY → still large enhancement on Br(KL)
- Less correlation btw Br(KL) and ε
  - 50TeV SUSY still have enhancement factor on Br(KL)

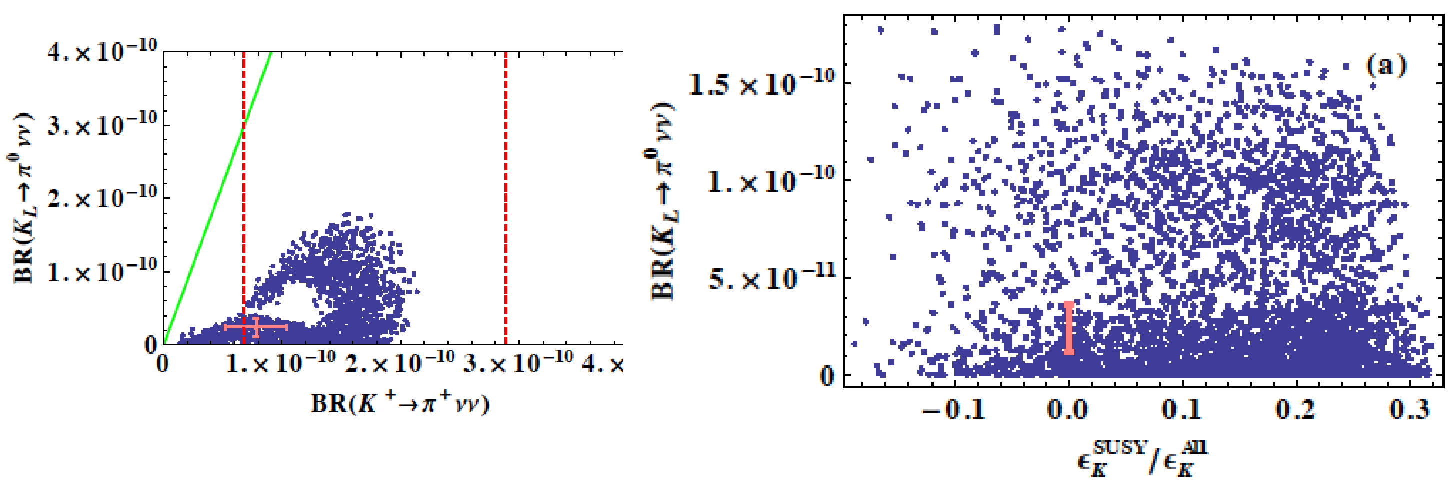


Figure 1: The predicted $BR(K_L \to \pi^0 \nu\bar{\nu})$ versus $BR(K^+ \to \pi^+ \nu\bar{\nu})$
TeV with the mixing angle of $s^u = s^d = 0.1$. The pink cross denotes the SM predictions. The
red dashed lines are the 1σ experimental bounds for $BR(K^+ \to \pi^+ \nu\bar{\nu})$. The green slanting
line shows the Grossman-Nir bound.

Weekly-coupled light Z' with Lμ – Lτ coupling

Fuyuto '14

- Explain g-2 with Mz'<400MeV
  - also relate to B → Kμμ

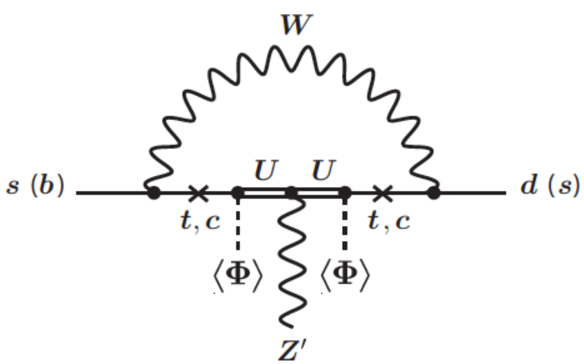
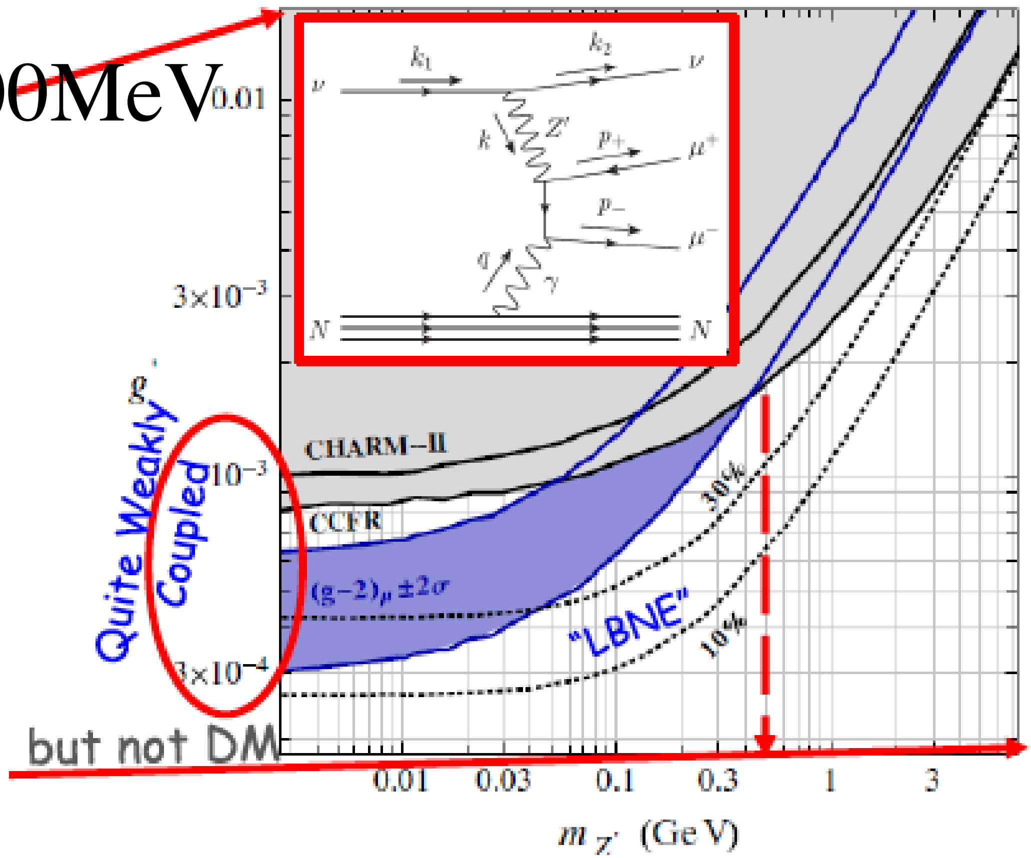


FIG. 1. Effective dsZ' (sbZ') coupling, with Z' coupled to a vector-like U quark that mixes with c, t ("×" flips chirality) and connects with external d-type quarks via a W boson loop.



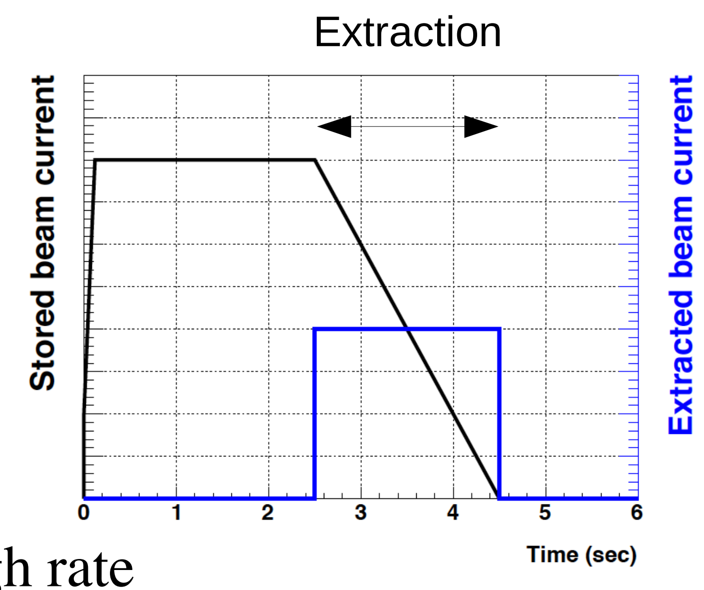
$$K_L \to \pi^0 Z'$$

$$\mathcal{B}(K^+ \to \pi^+ X^0) < 5.6 \times 10^{-8}, \quad (m_{X^0} = m_{\pi^0})$$ from E949 experiment

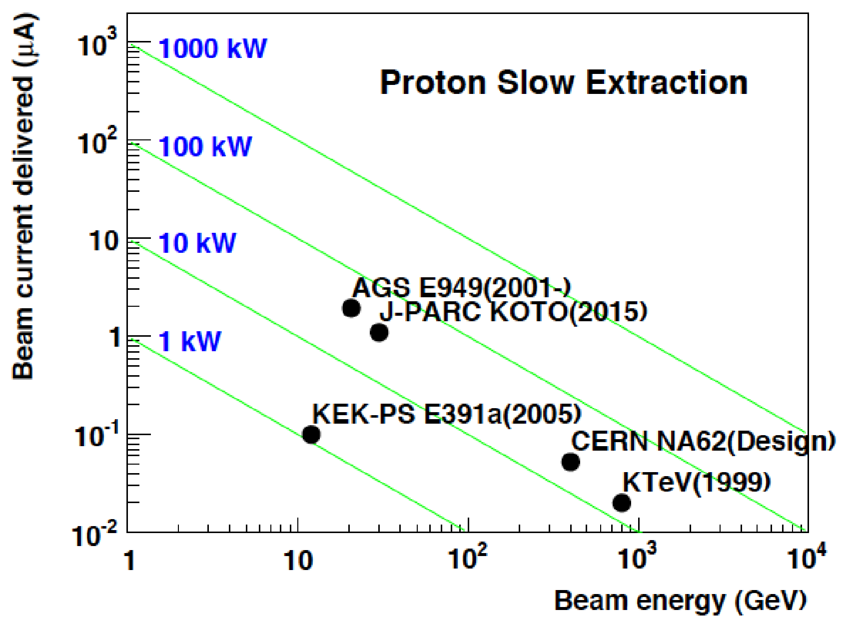
$$Z' \to \nu\nu$$ KOTO already access here.

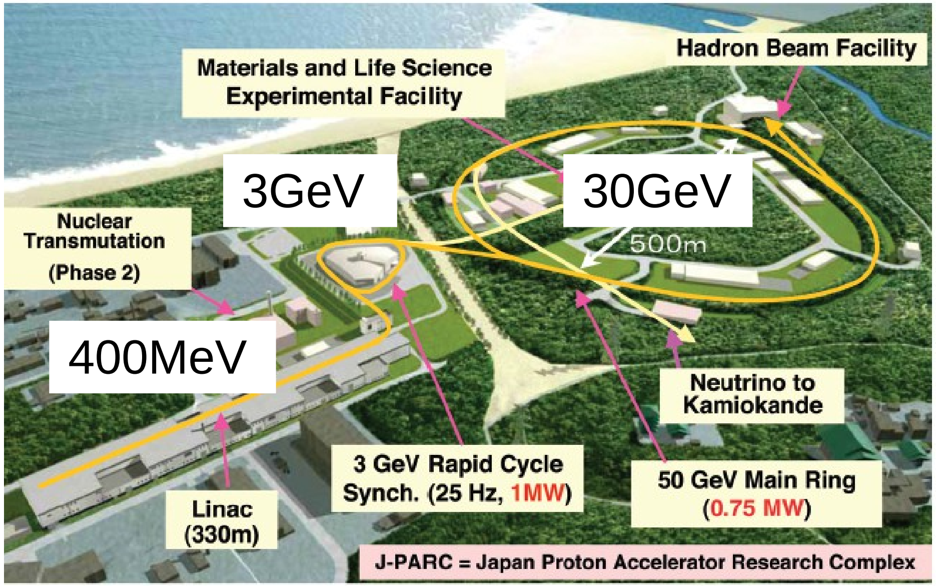
KOTO Experiment

KOTO : K^0 at TOkai



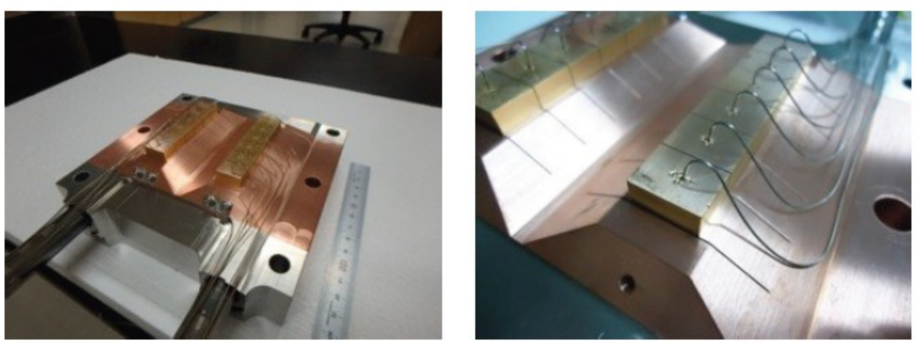
- J-PARC Accelerator
  - High power ↔ Statistics of rare process
  - Slow extraction ↔ Event pile-up due to high rate
    - J-PARC 33kW (June 2015) ~ World-highest class



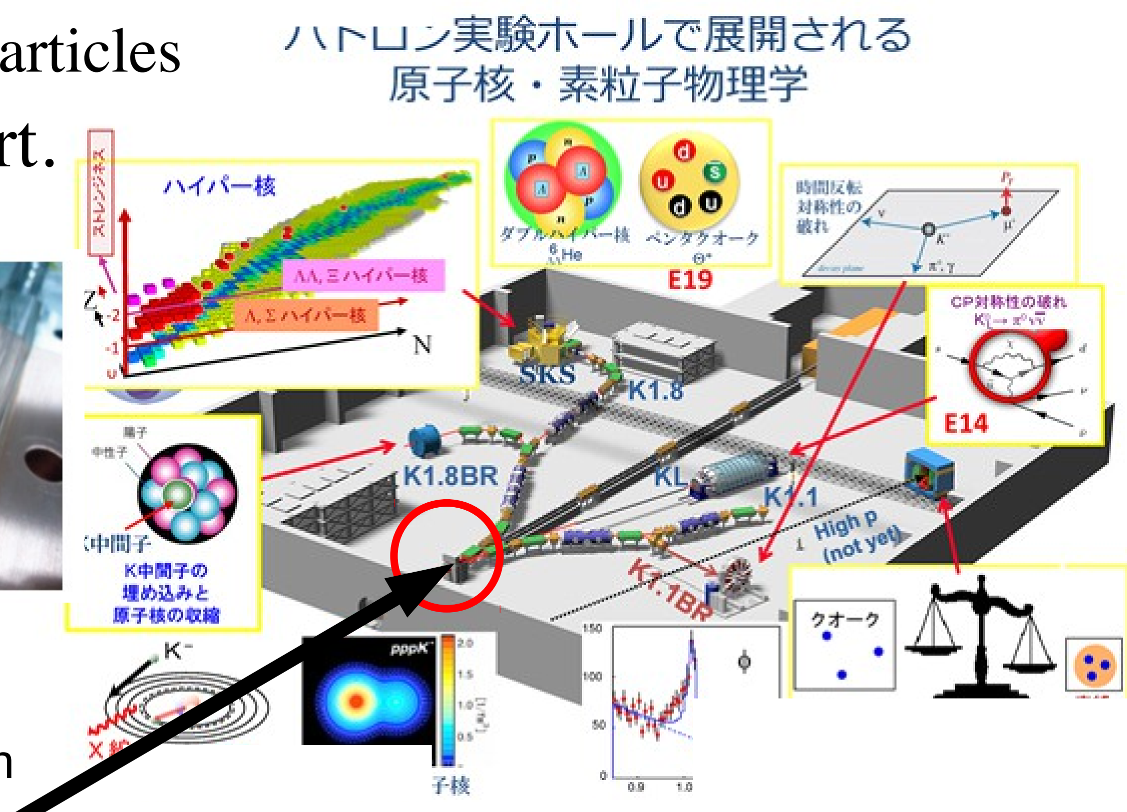


Fixed Target Experiment

- High intensity proton beam+ Primary target
  - High intensity secondary products
- Beam line
  - Transport particles of interest
    - Reduce unwanted particles
  - Long life to transport.

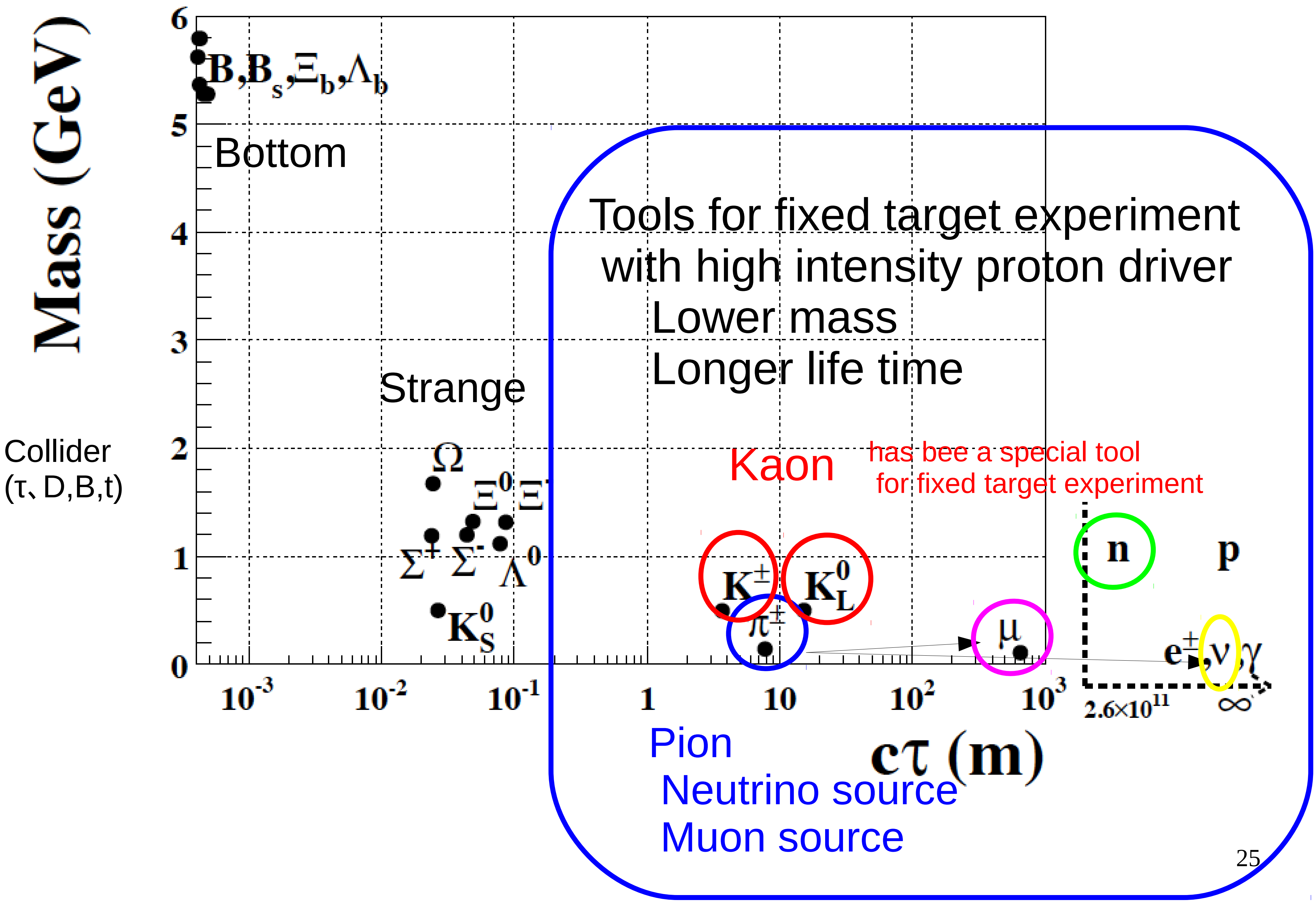


Gold 15mm x 6mm x 66mm

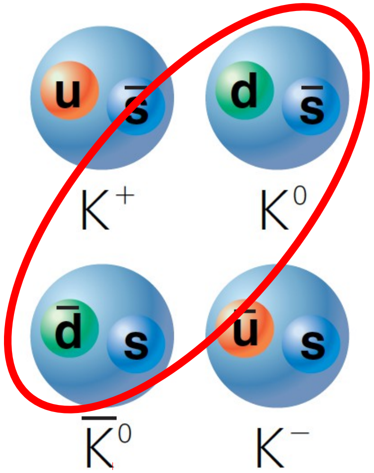


30 GeV proton

Particles mass and life time



Kaon



- Low mass (0.5 GeV)
- Long life time (15m)
- Strangeness

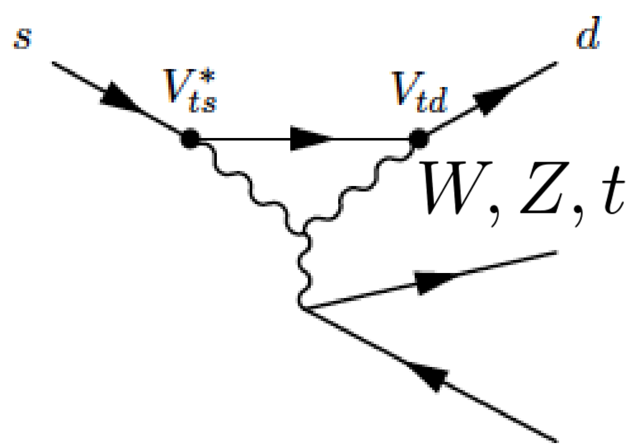
Good for fixed target

$$K_S \sim \left(\left|K^0\right\rangle + \left|\overline{K^0}\right\rangle\right)/\sqrt{2}$$

$$K_L \sim \left(\left|K^0\right\rangle - \left|\overline{K^0}\right\rangle\right)/\sqrt{2}$$

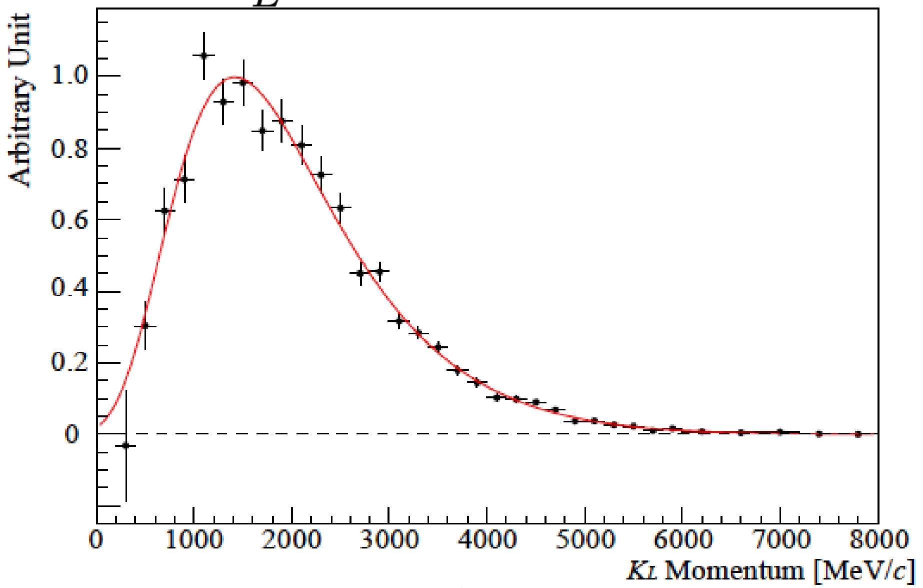
→ Flavor Changing Neutral Current

- s → d transition
  - Flavor changing neutral current (GIM)
  - Strong CKM suppression
- $K_L \rightarrow \pi^0\nu\nu$ (Br $3\mathrm{x}10^{-11}$ in SM)
  - Direct CP-violation



Beam line

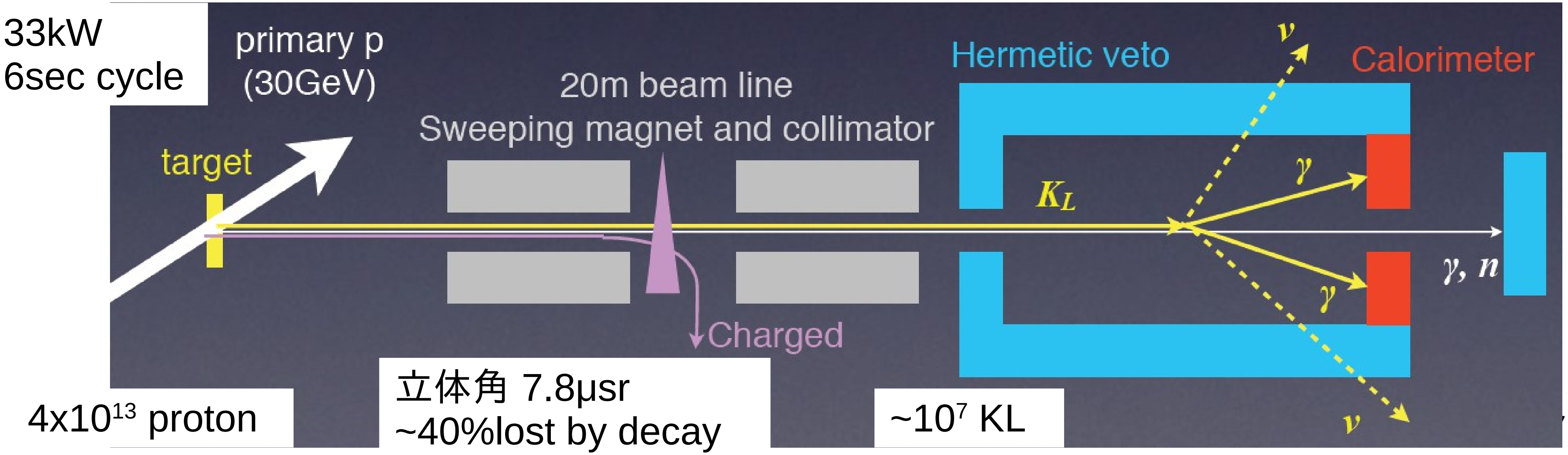
$P_{K_L}^{peak} \sim 1.4\,\mathrm{GeV}/c$

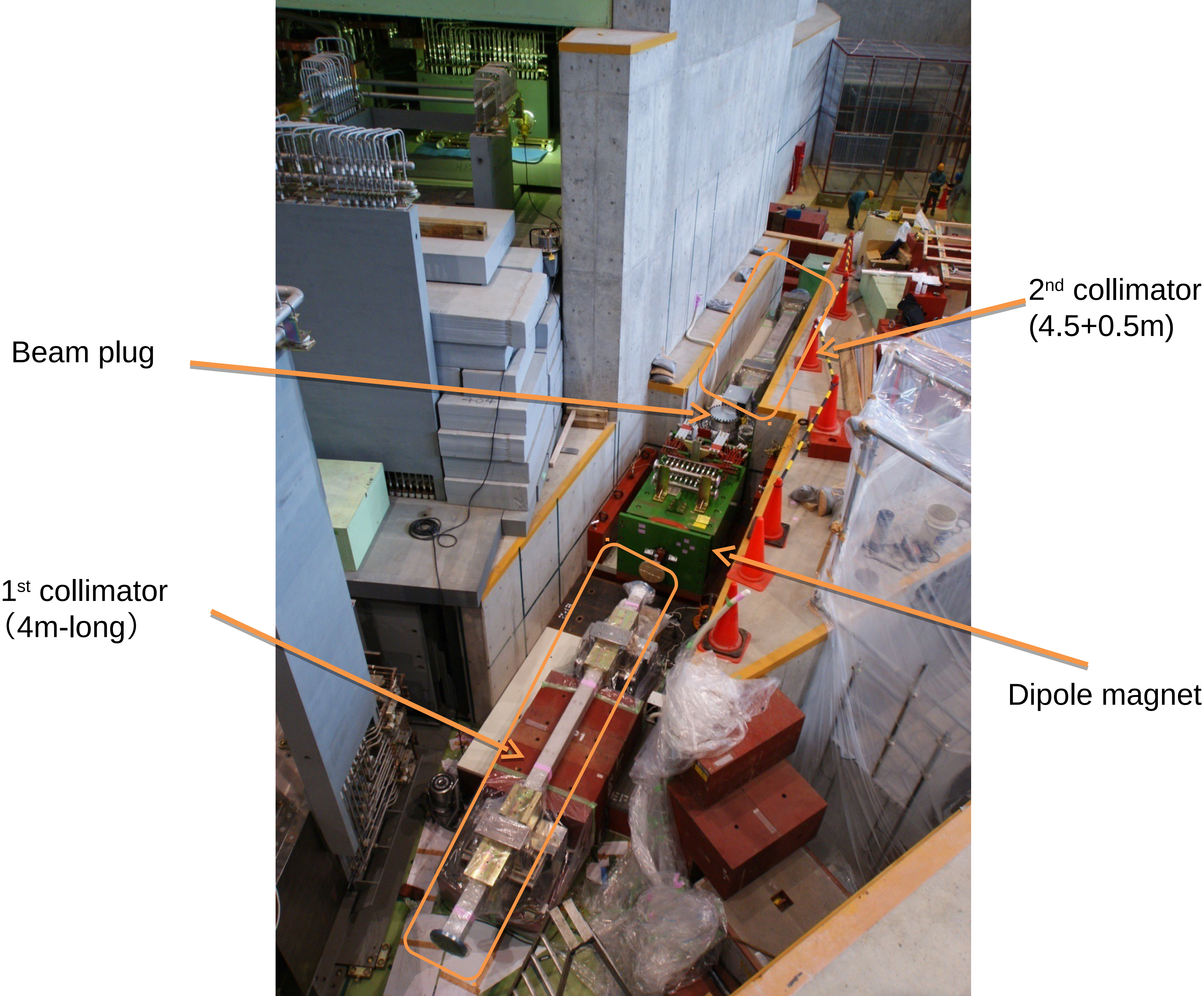


- 金標的 + proton
- KL beam line
  - 電磁石 (charged)
  - 20m長尺 (short-lived)
  - コリメータ (beam halo)

→ 細くシャープな中性ビーム(KL, γ, neutron)

"Pencil Beam"

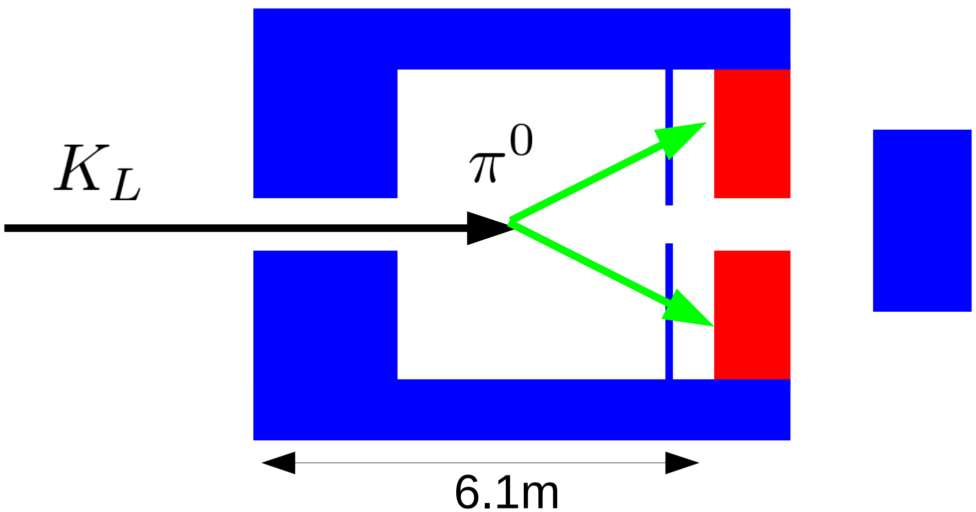




Beam plug
2nd collimator
(4.5+0.5m)
1st collimator
（4m-long）
Dipole magnet

Signal Reconstruction

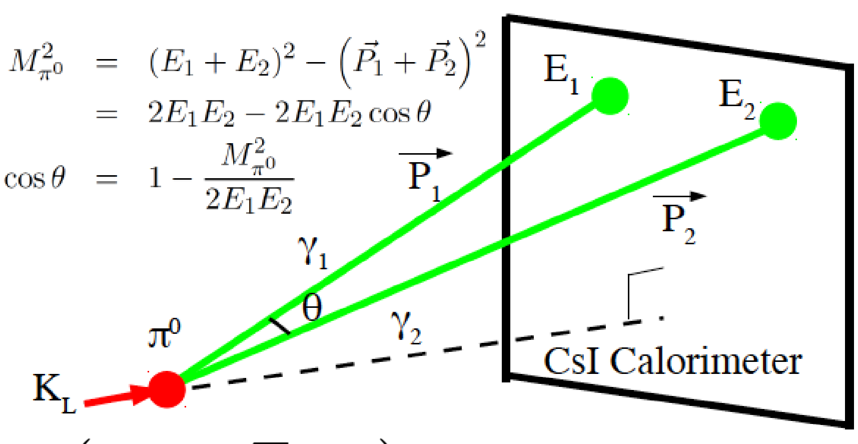
- 2γ+nothing → Calorimeter + Veto detectors
- Beam constraint → "pencil beam"



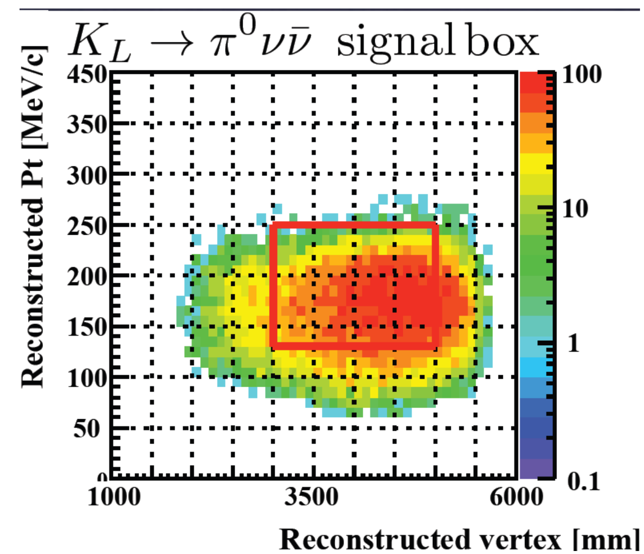
Decay Modes	Branching Fraction
$K_L \to \pi^0 \nu \overline{\nu}$	$(2.4 \pm 0.4) \times 10^{-11}$
$K_L \to \pi^\pm e^\mp \nu$	(40.55 ± 0.11) %
$K_L \to \pi^\pm \mu^\mp \nu$	(27.04 ± 0.07) %
$K_L \to 3\pi^0$	(19.52 ± 0.12) %
$K_L \to \pi^+\pi^-\pi^0$	(12.54 ± 0.05) %
$K_L \to 2\pi^0$	$(8.64 \pm 0.06) \times 10^{-4}$
$K_L \to 2\gamma$	$(5.47 \pm 0.04) \times 10^{-4}$

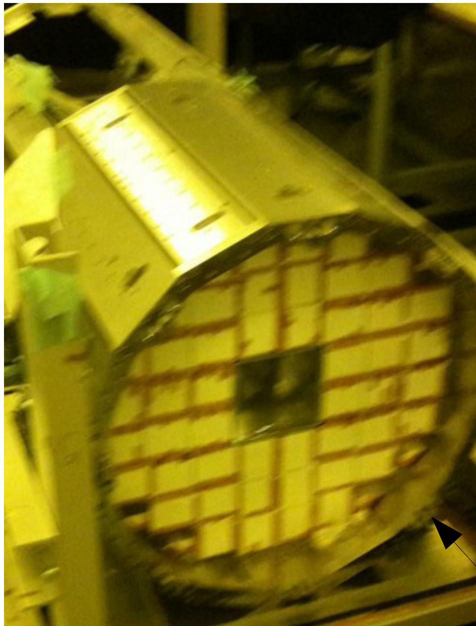
$$M_{\pi^0}^2 = (E_1+E_2)^2 - \left(\vec{P}_1 + \vec{P}_2\right)^2 = 2E_1E_2 - 2E_1E_2\cos\theta$$

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



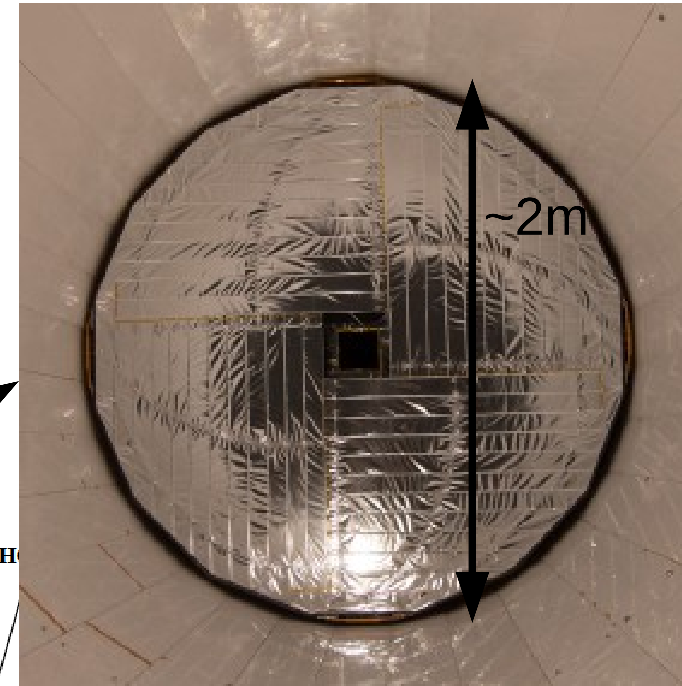
$(0, 0, Z_{vtx})$

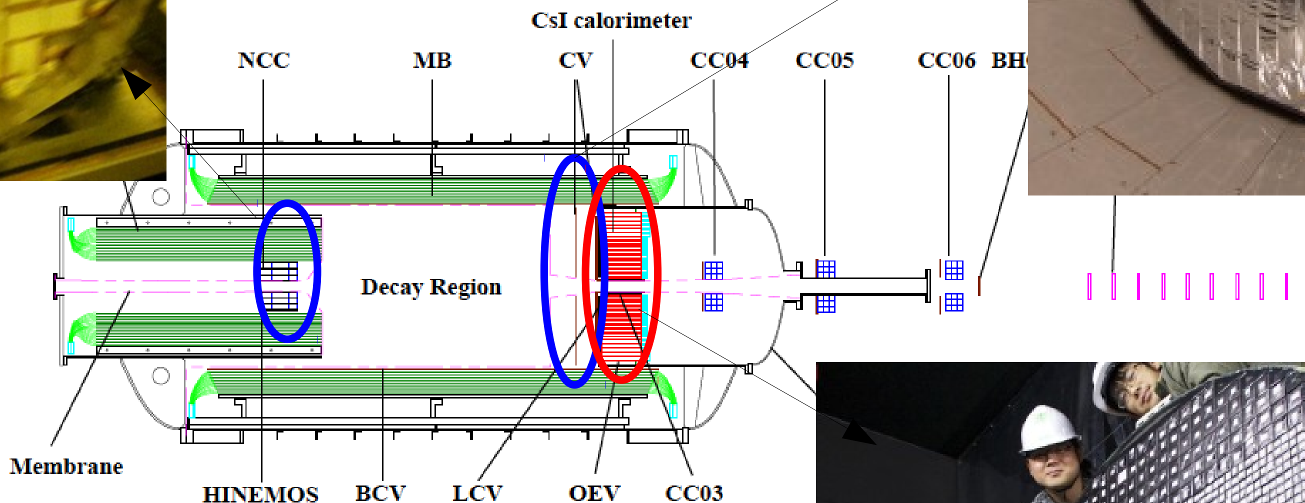


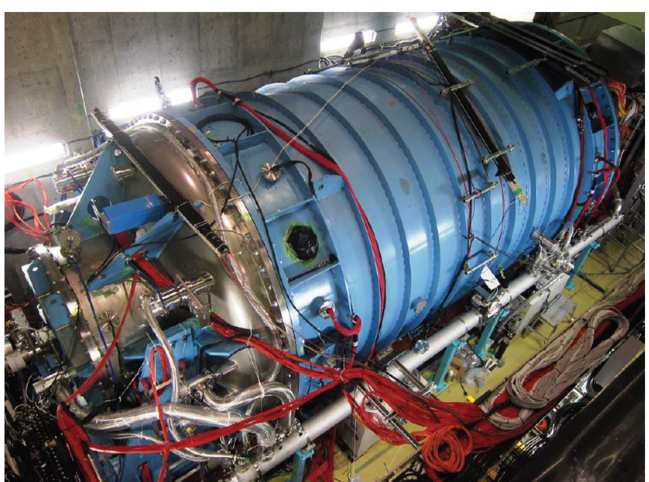


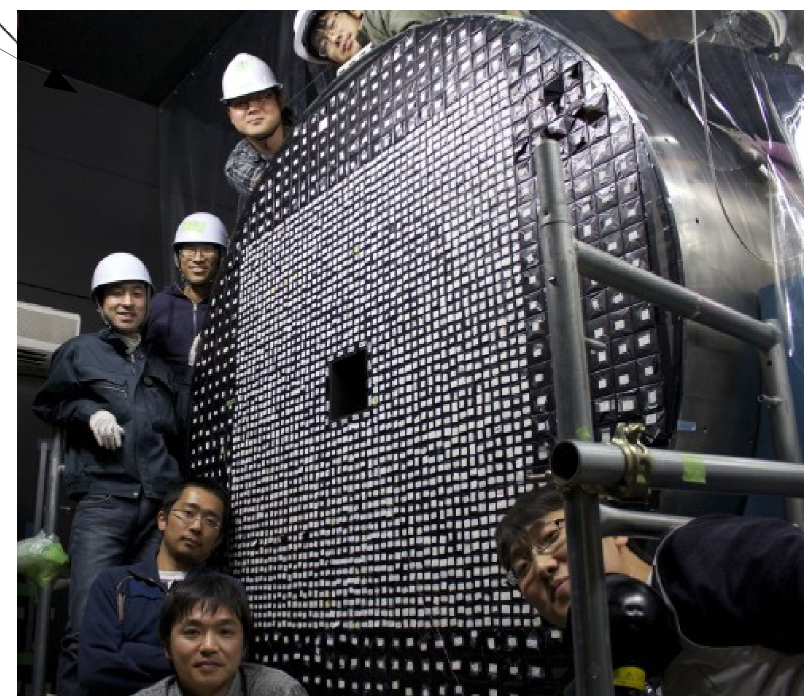
Detector

Veto : γ/charged
$10^{-4} – 10^{-6}$ reduction









History

年度		ビーム (ヶ月)	
2005			
2006	Proposal		
2007			
2008	Beamline construction		
2009			
	Beam measurement	2	
2010	Detector Construction		
		1	大震災
2011			
		1	
2012		1	
	Engineering Run	2	
2013	Physics Run 100hours	0.3	ハドロン事故
2014	Preliminary result Detector upgrade		
2015	Physics Run	2	

1st physics run in 2013

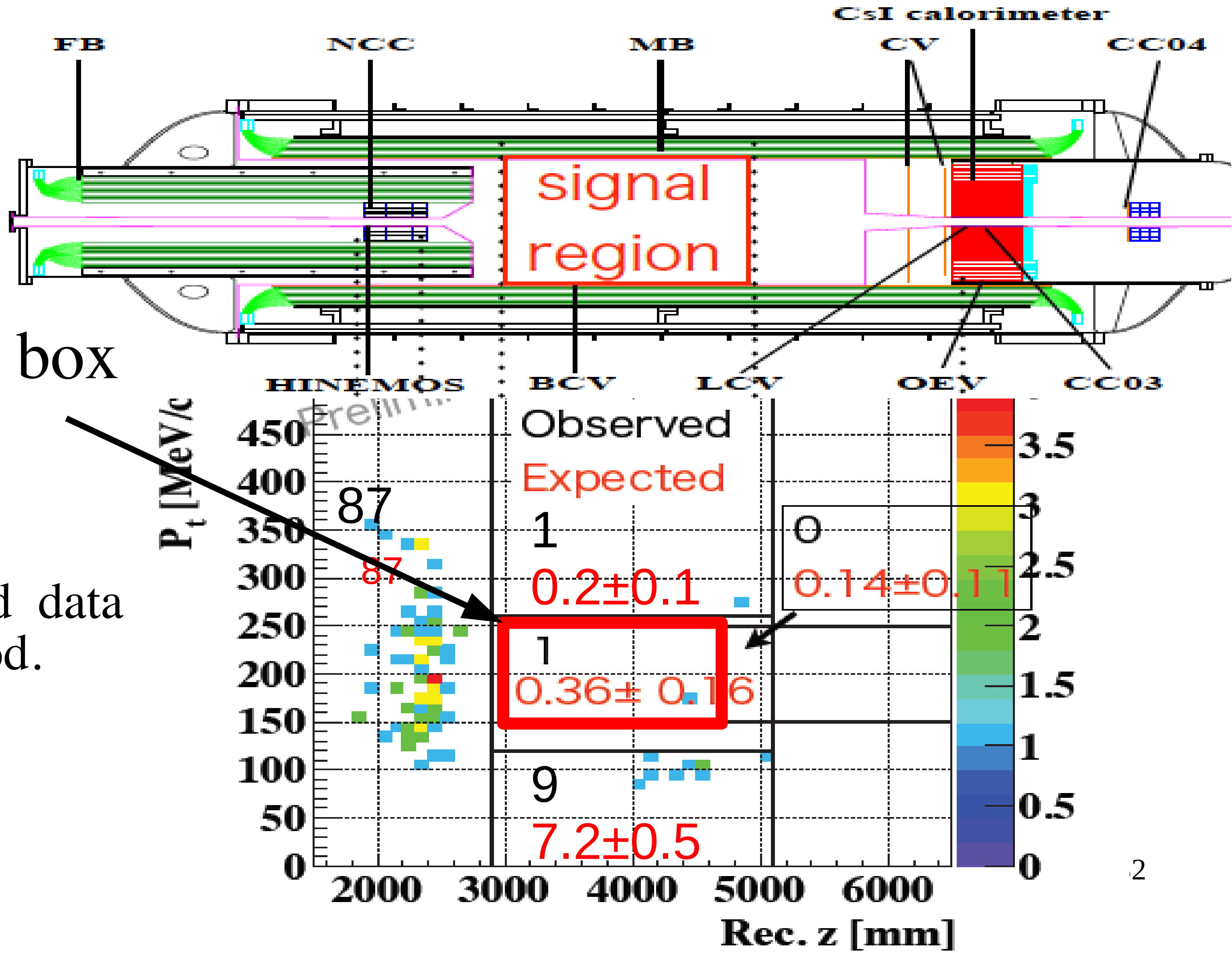
CKM2014

Sensitivity : 1.29×10^{-8} (Preliminary)

~ E391a sensitivity with only 100-hour run

1 event
in the signal box

Number of observed data
→ Well understood.



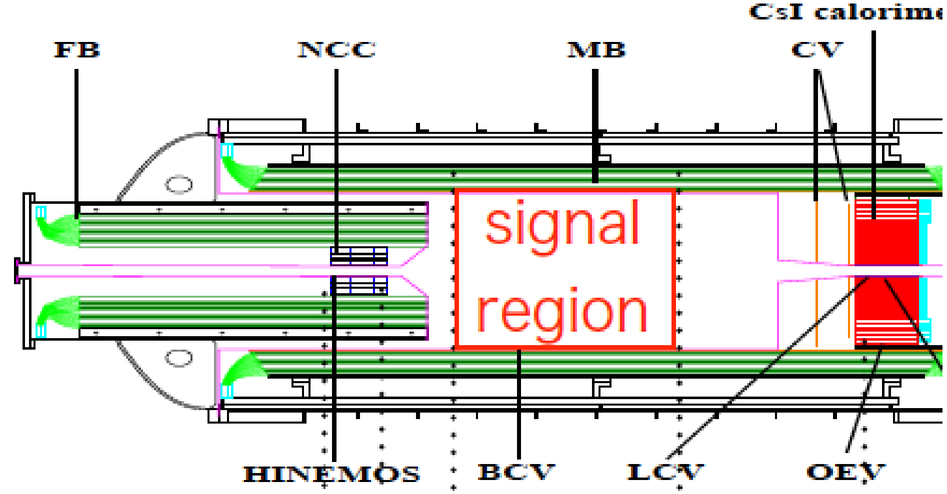
Main background source in E391a

Halo neutron → π^0 at

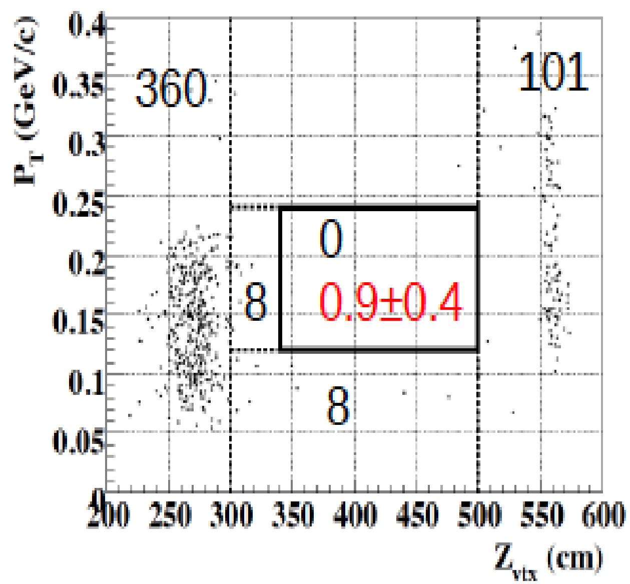
Upstream detector

Downstream detector

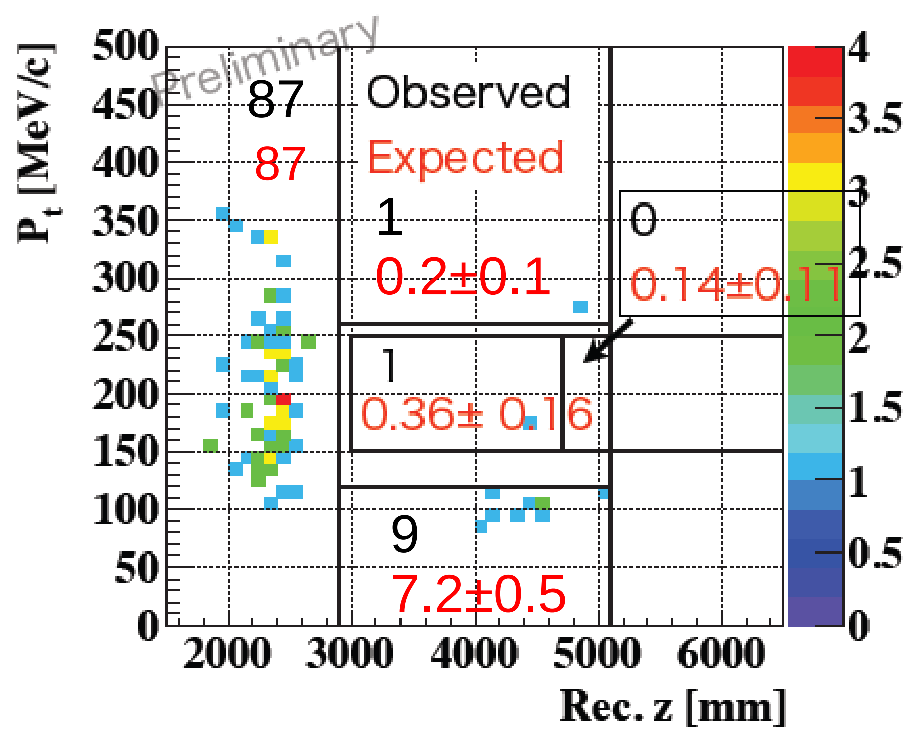
→ Largely reduced.



E391a Final (5month)
S.E.S : 1.11×10^{-8}

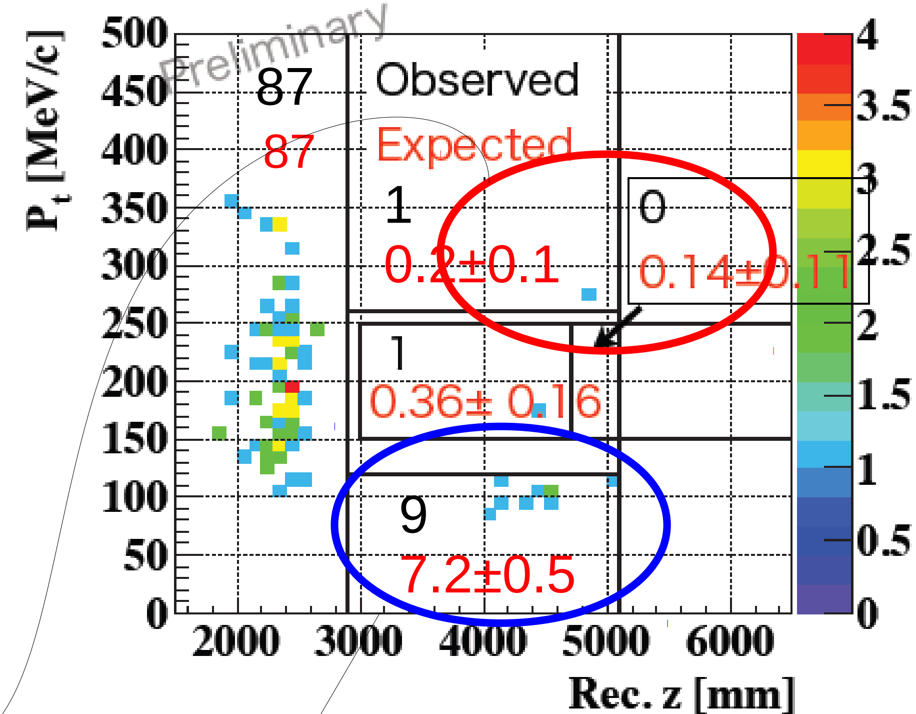


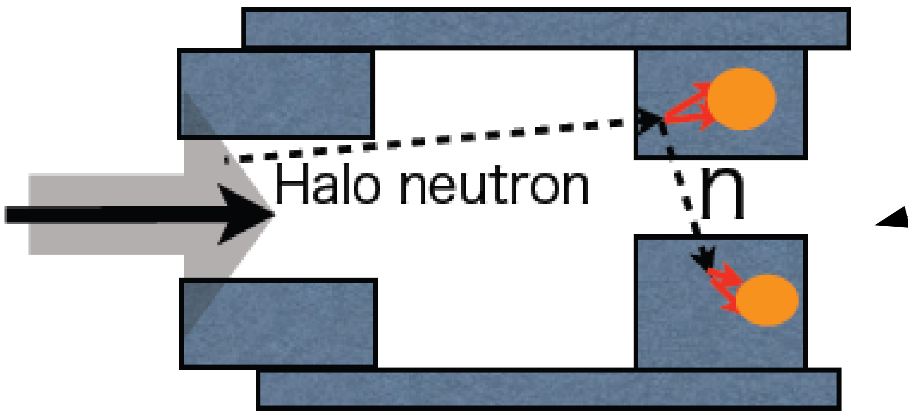
KOTO 1st Physics run(4days)
S.E.S : 1.29×10^{-8}

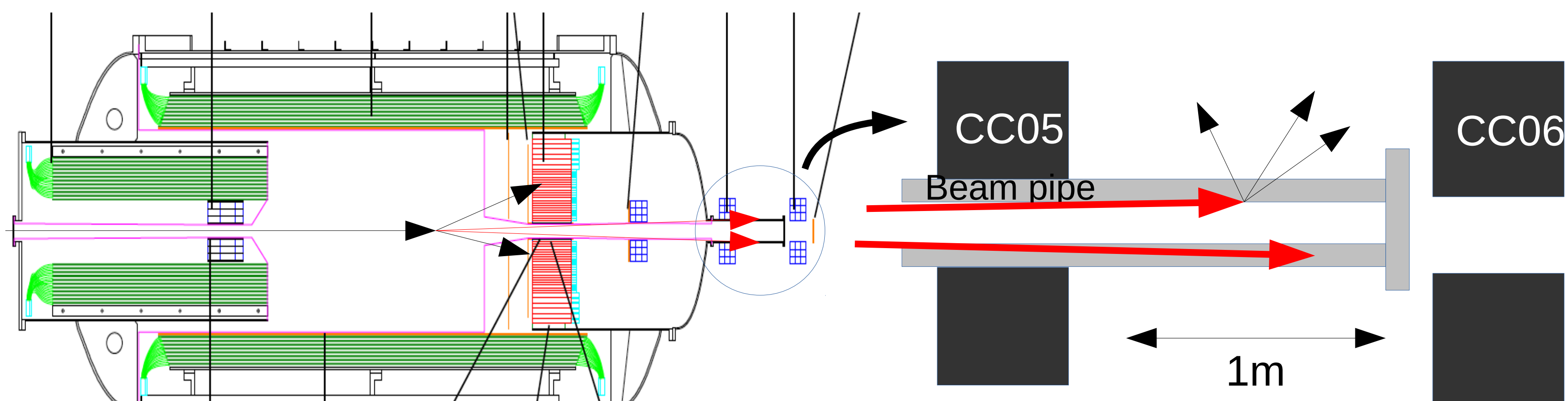


Background source in KOTO

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

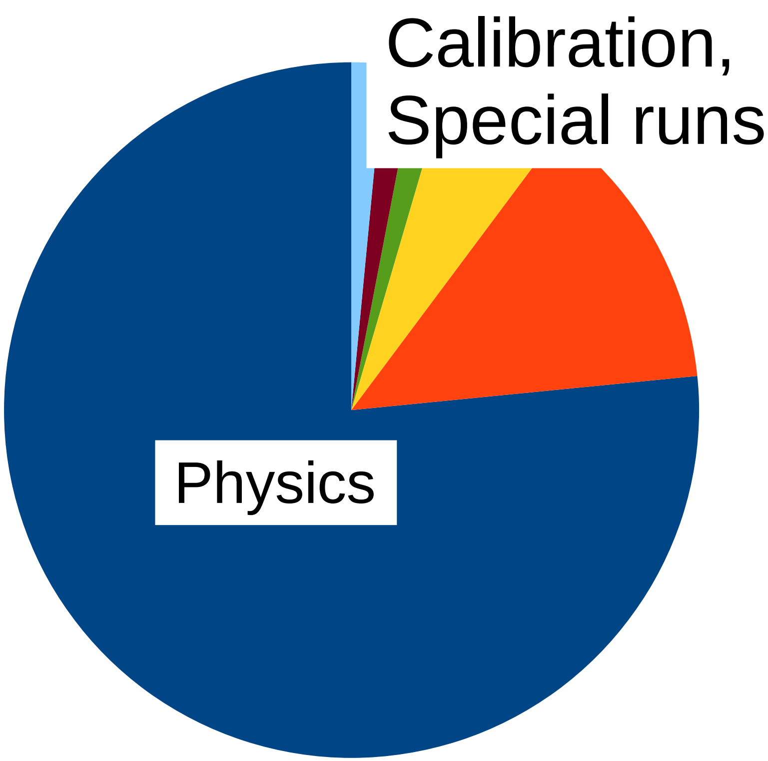


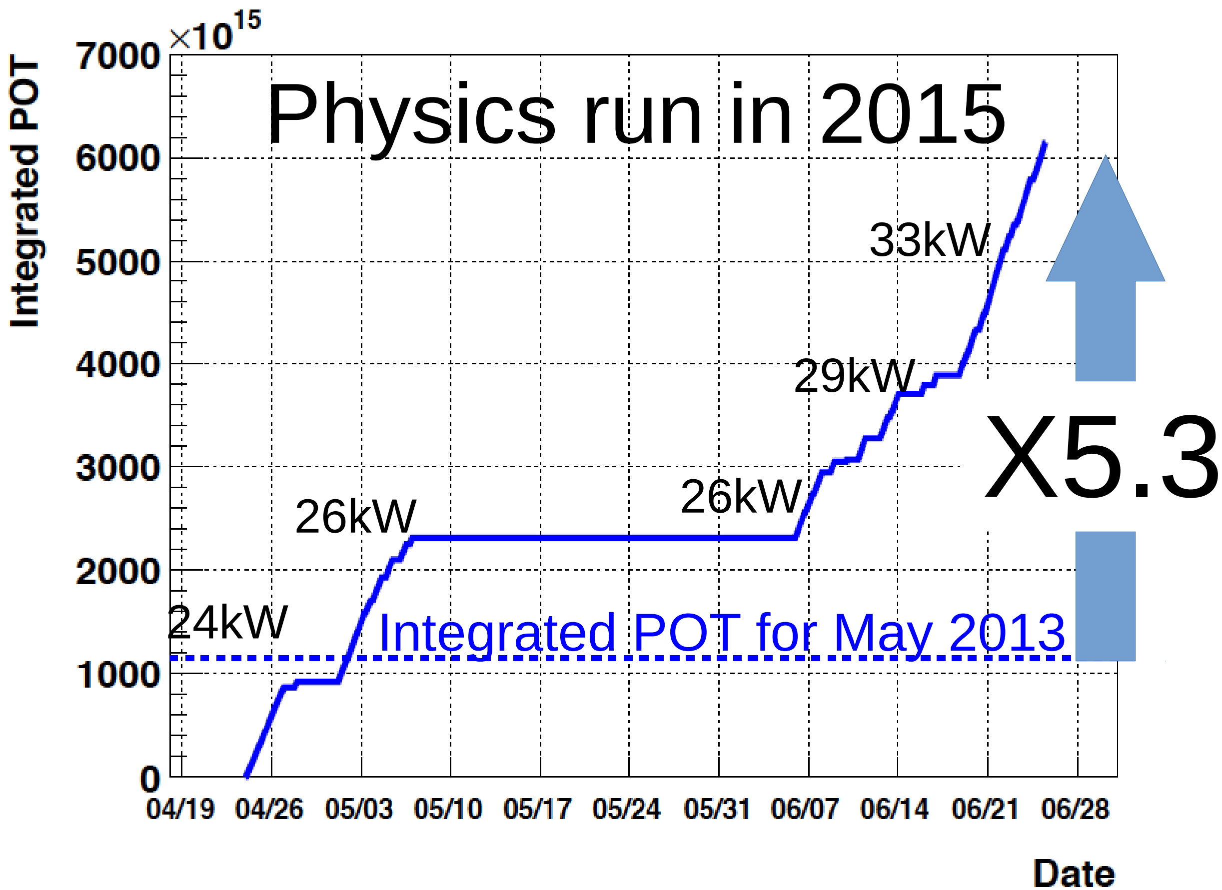




Run in April-June 2015

- Physics run
  - 5.3 times higher POT ↔ run in May 2013
- Calibration and special runs

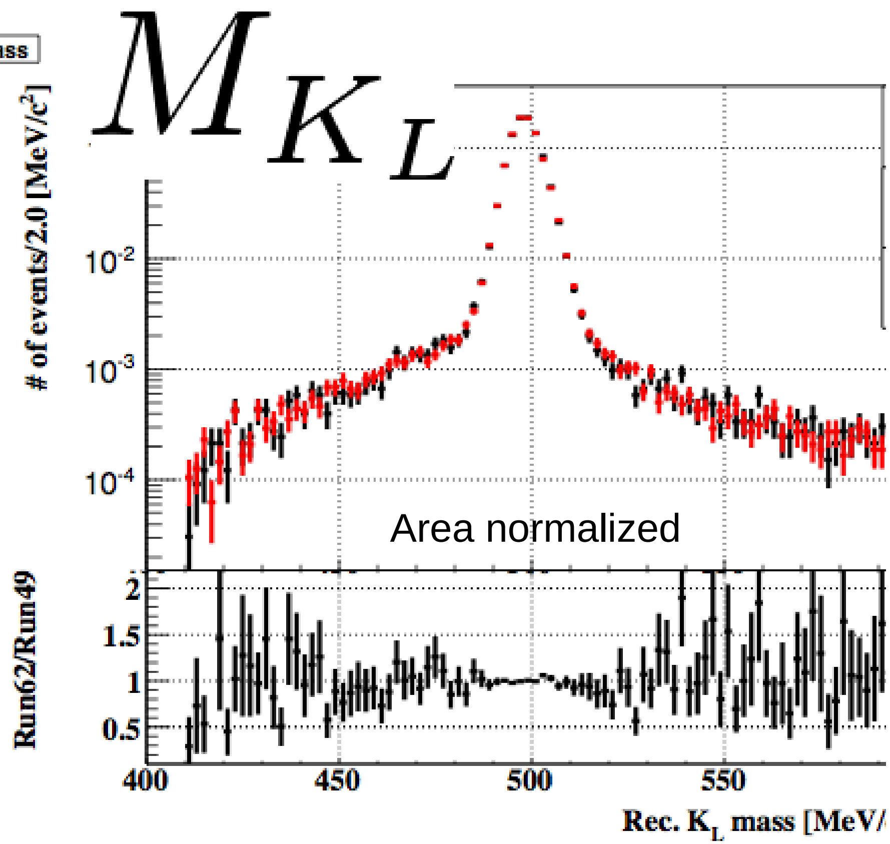


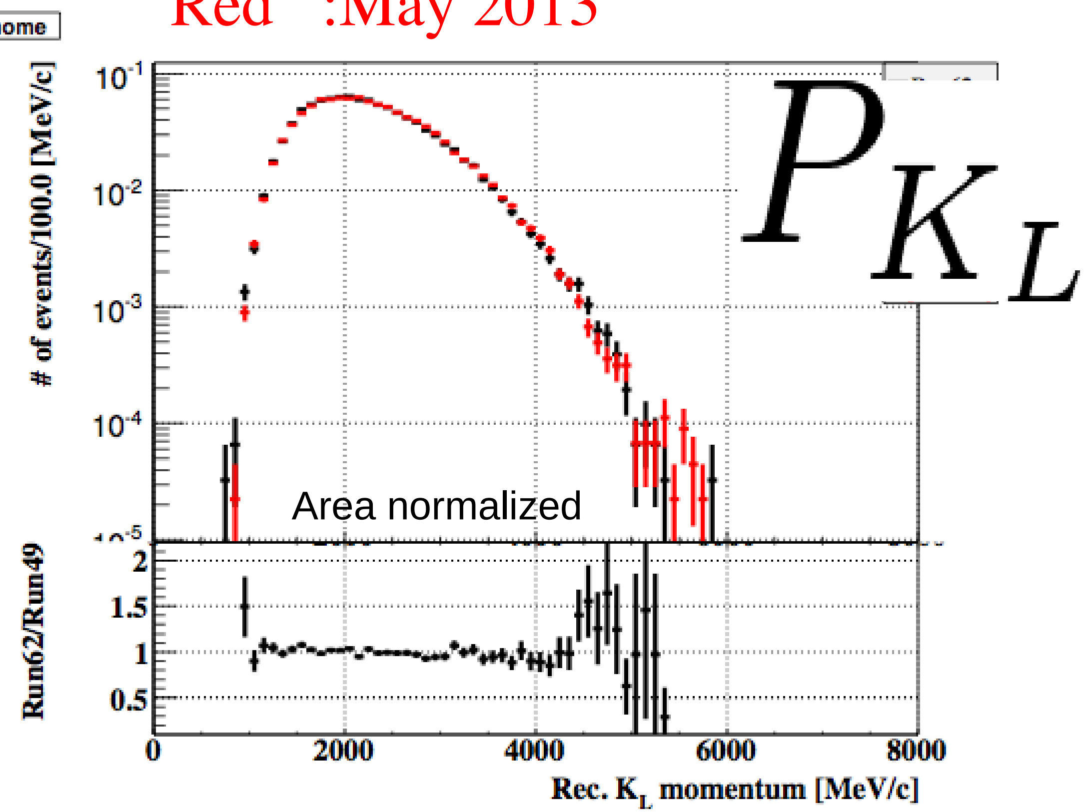


Check with $3\pi^0$ sample

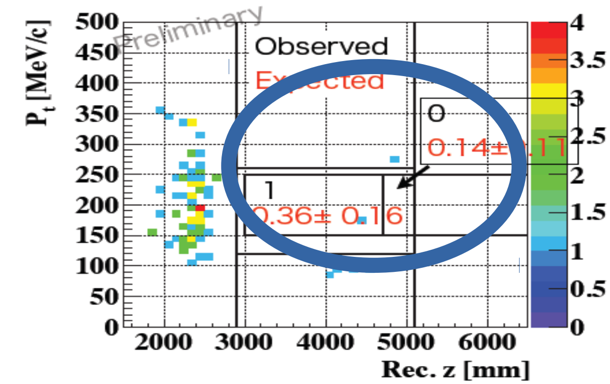
- Calorimeter and KL properties consistent with the run in May 2013.
- More detailed calibration is on-going
- Study to suppress background

Black :April-May 2015
Red :May 2013

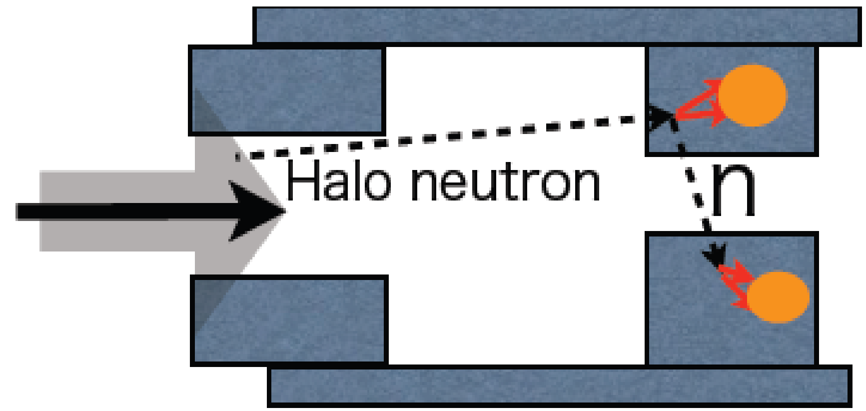




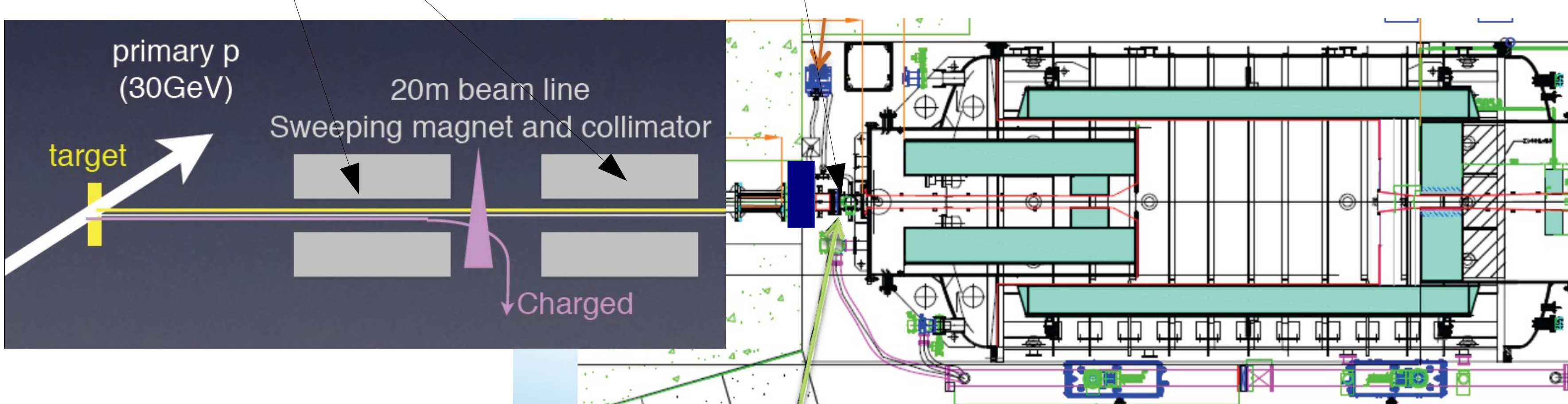
To suppress halo neutron



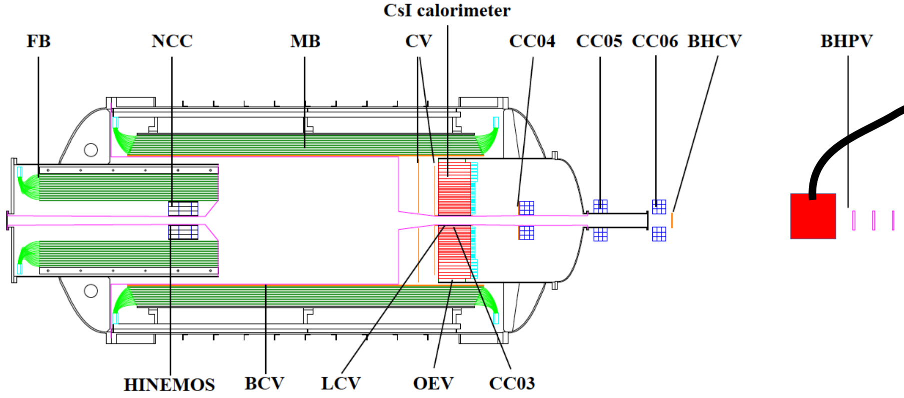
- Upstream beam window
  - Kapton 125um → 12.5um
  - Reduce neutron scattering
- Re-alined collimator
  - Reduce neutron scattering on the collimator inner surface

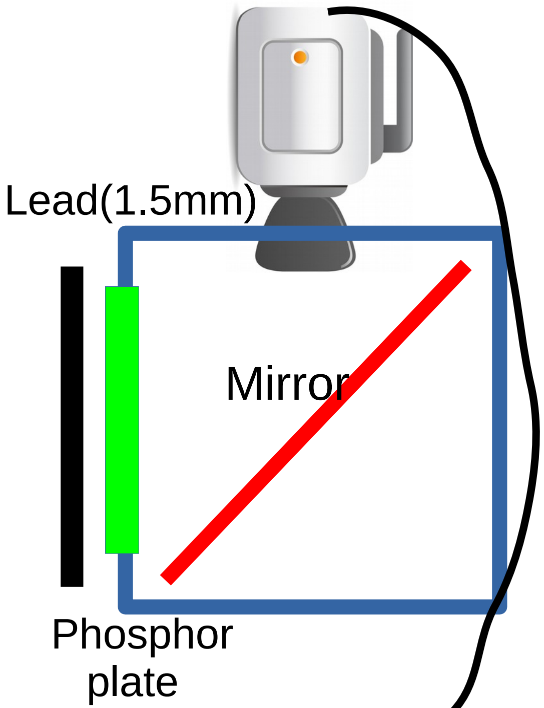


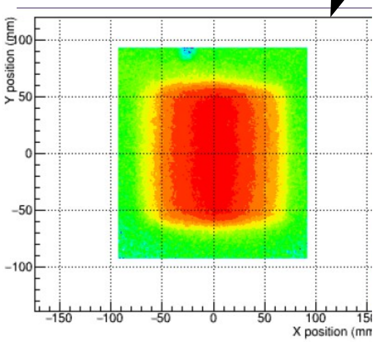
Hadron interaction events



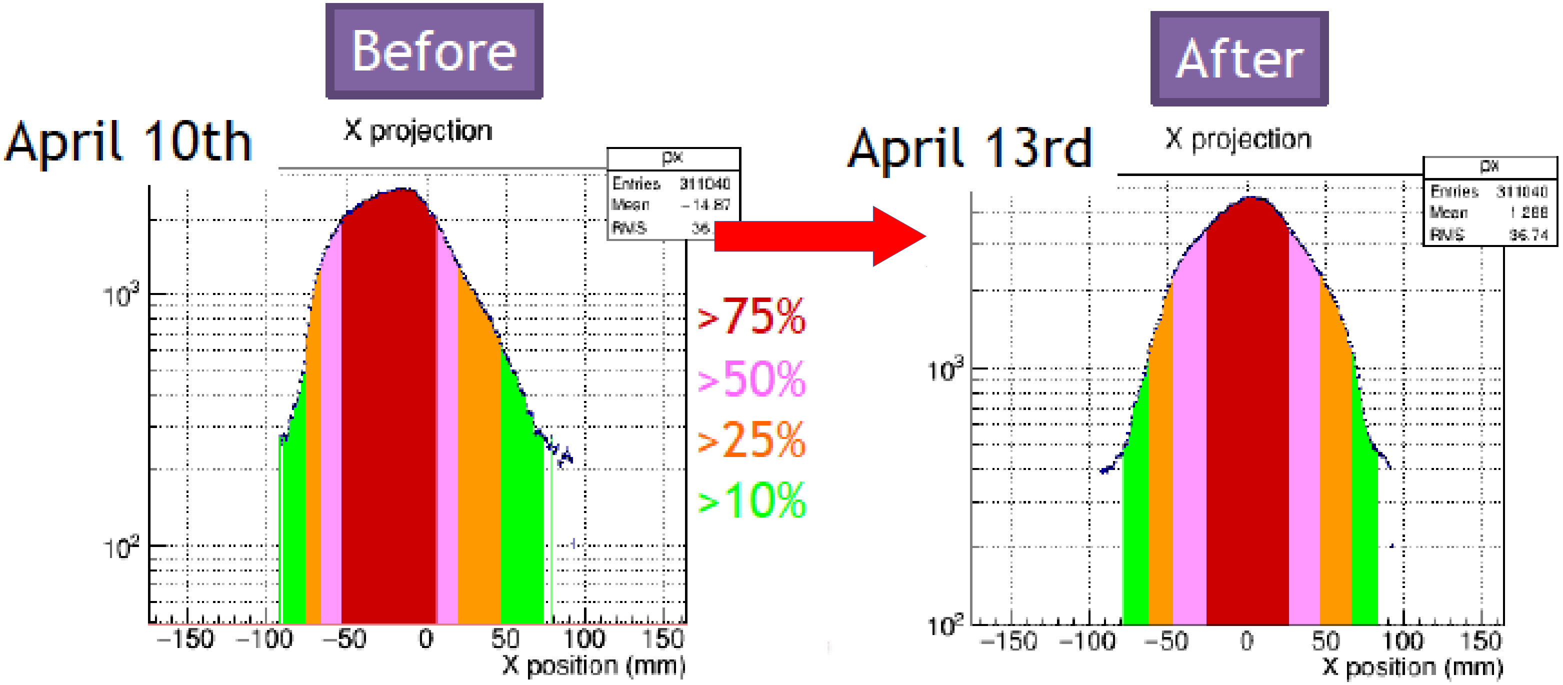
Collimator alignment with new beam profile monitor



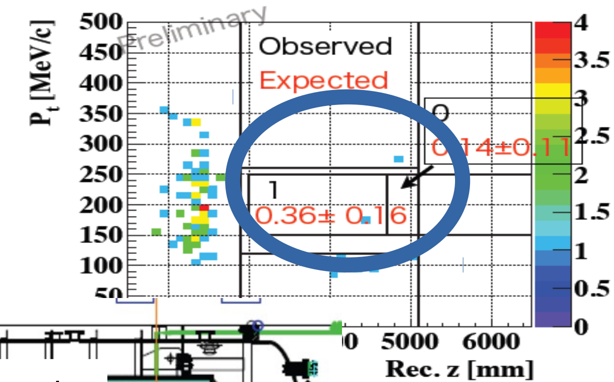


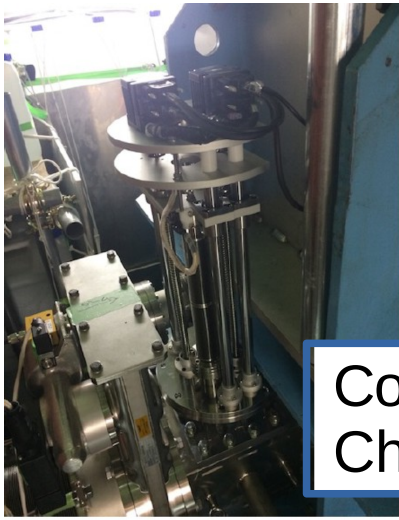


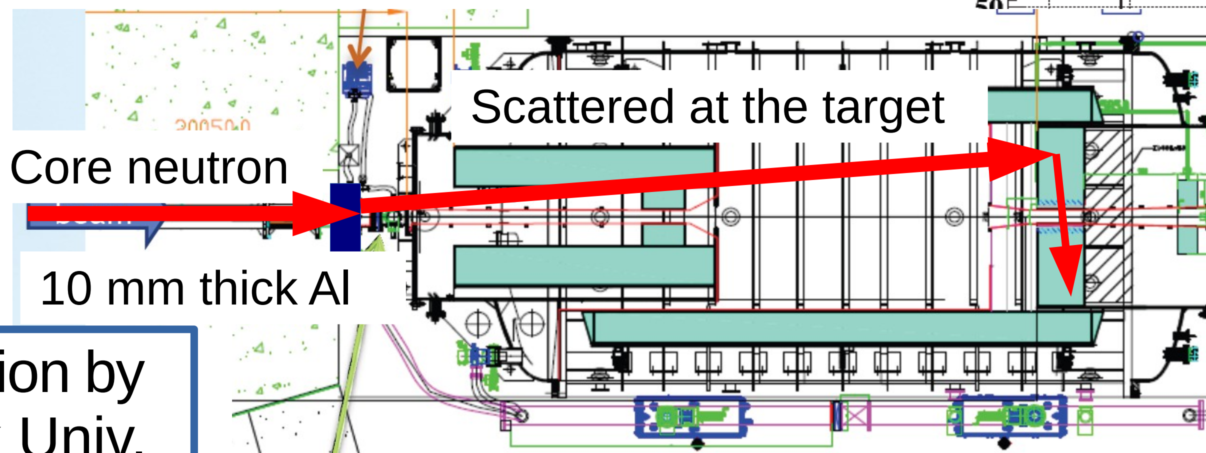
Re-alined collimators



To understand hadron interaction events



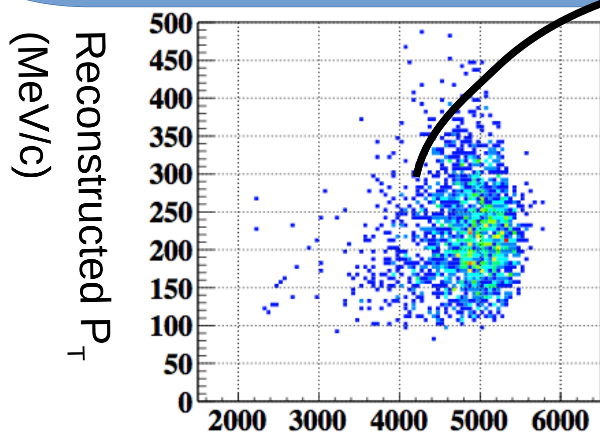


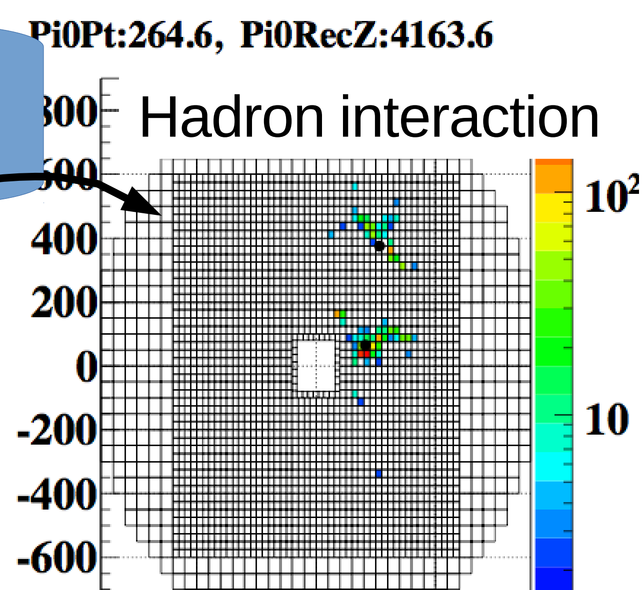


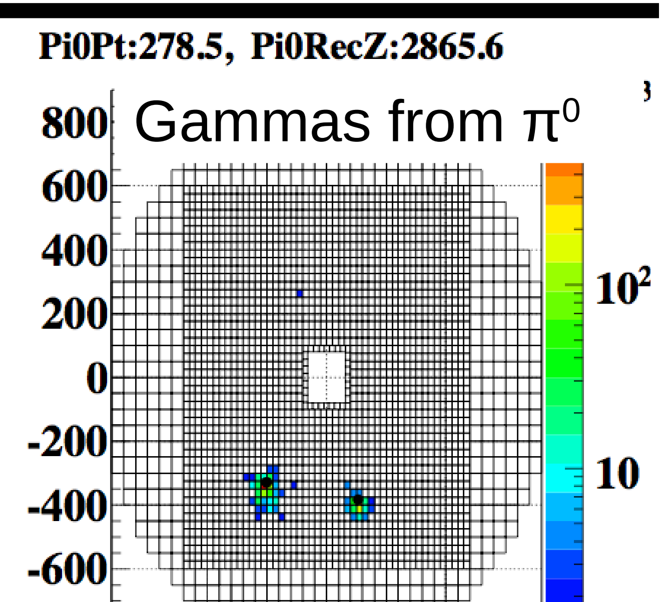
Contribution by Chonbuk Univ.

* Removed in physics run

Took Al-target data 70 hours
> 15 times higher statics
than May 2013

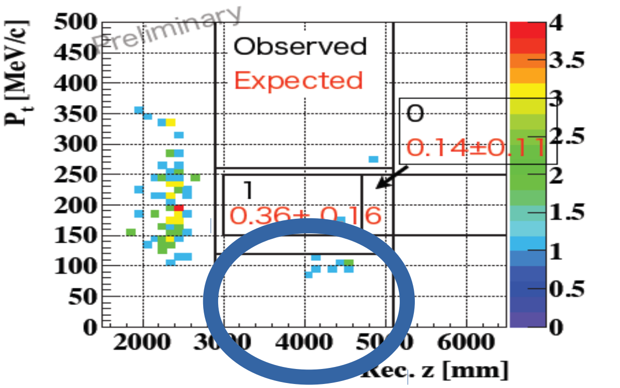


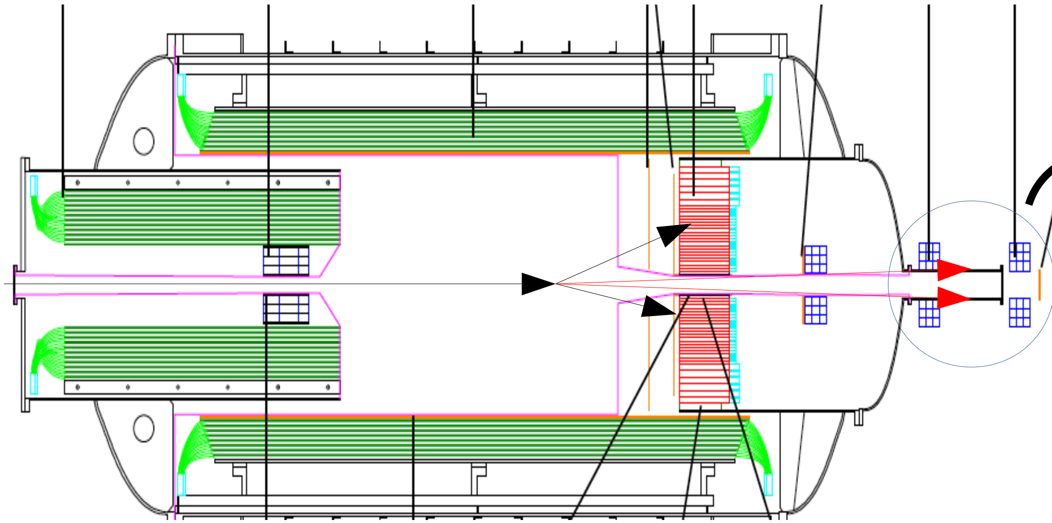


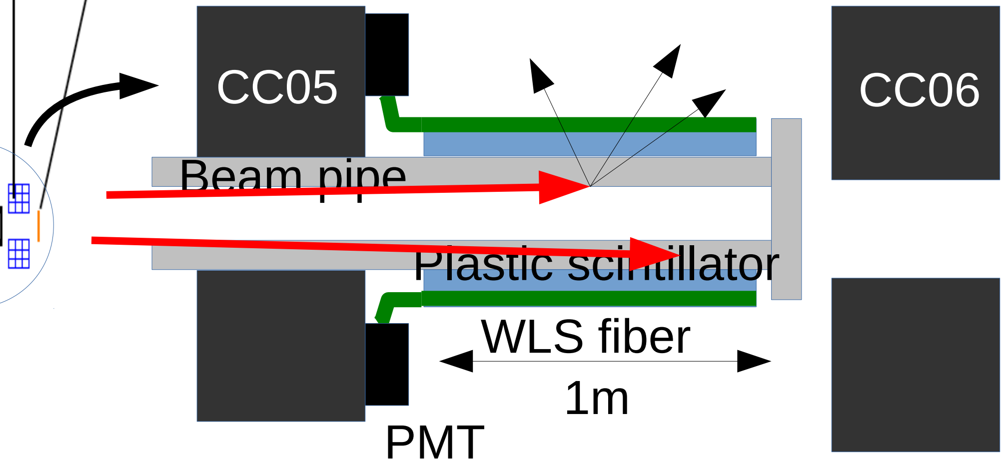


Developing BG reduction with cluster shape

To suppress low P_T events







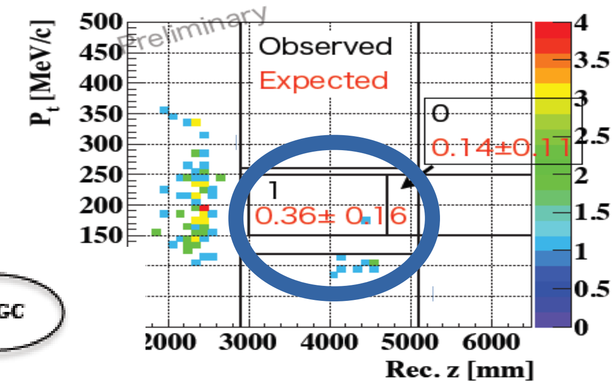
- Beam pipe (5mm t)

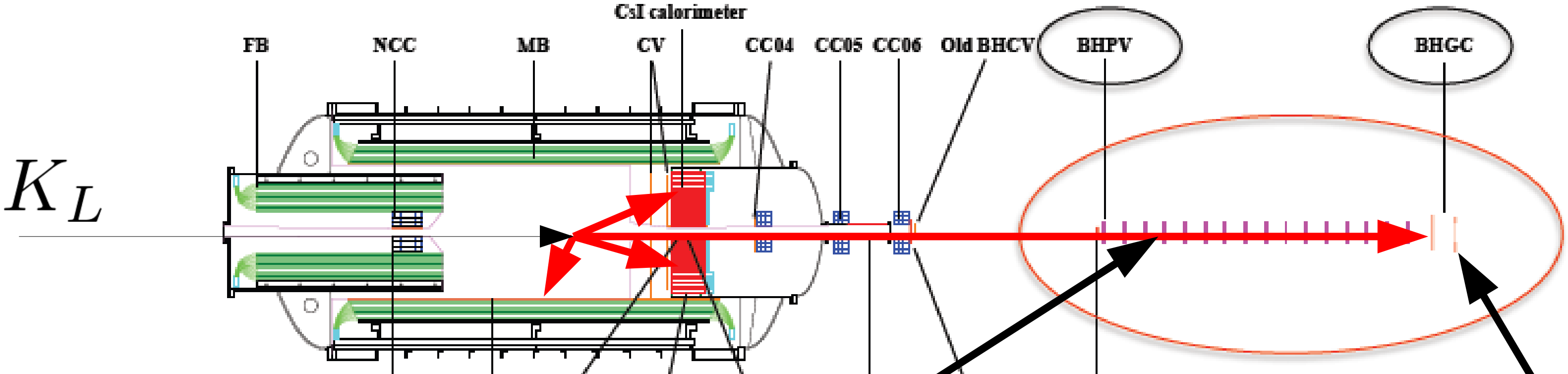
  SUS → Aluminum

- Installed Beam Pipe Charged Veto
  - Plastic scintillator 5-mm thick
  - Wavelength shifting fiber readout

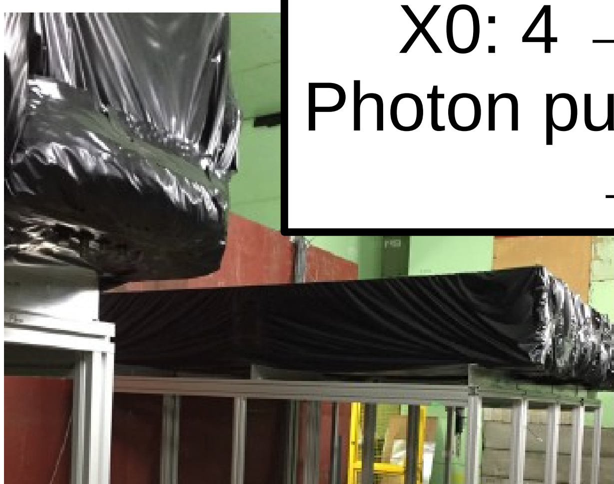
~1/60 reduction expected

To suppress $K_L \rightarrow 2\pi^0$



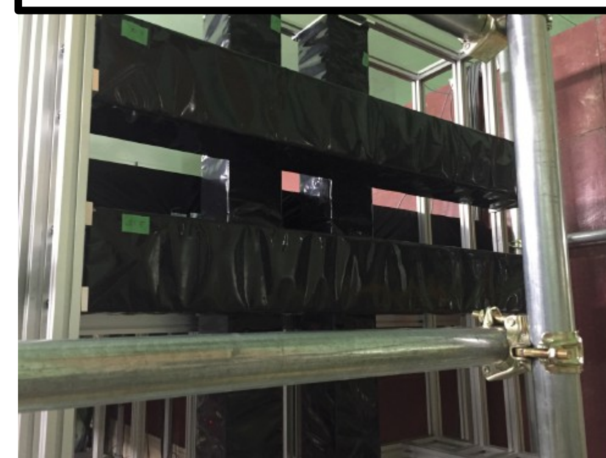


Added modules
X0: 4 → 6.2
Photon punch-through inefficiency
→ 1/5



In-beam photon veto
Lead and Aerogel
Cherenkov detector

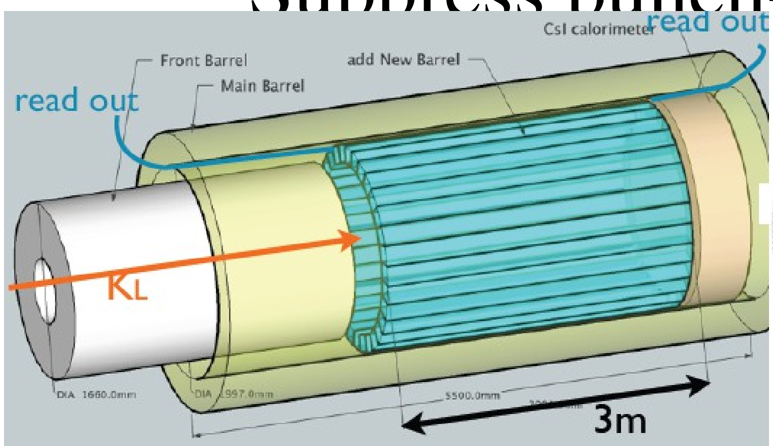
Lead and Acrylic
Cherenkov detector

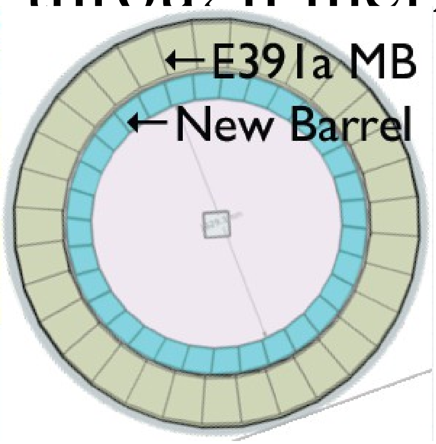


Prospect

To suppress $K_L \rightarrow 2\pi^0$ more

- Install inner barrel detector in winter 2015
- Add 5 X0 to 13.5 X0 of current Main Barrel
  - Suppress punch-through inefficiency by 1/50.

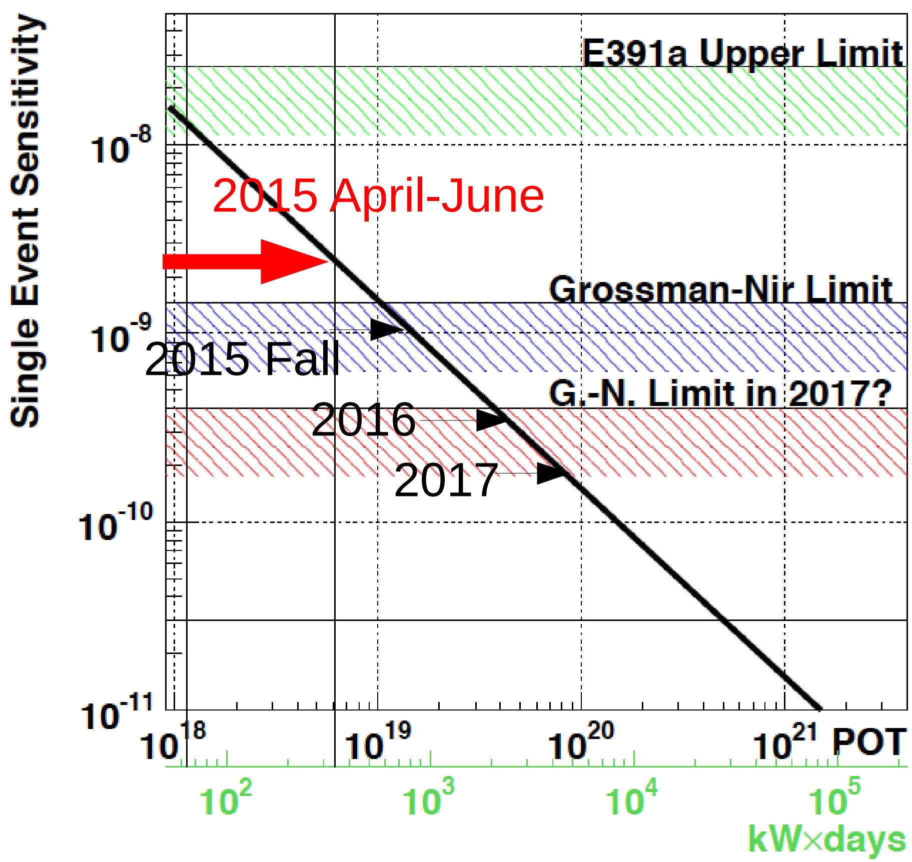


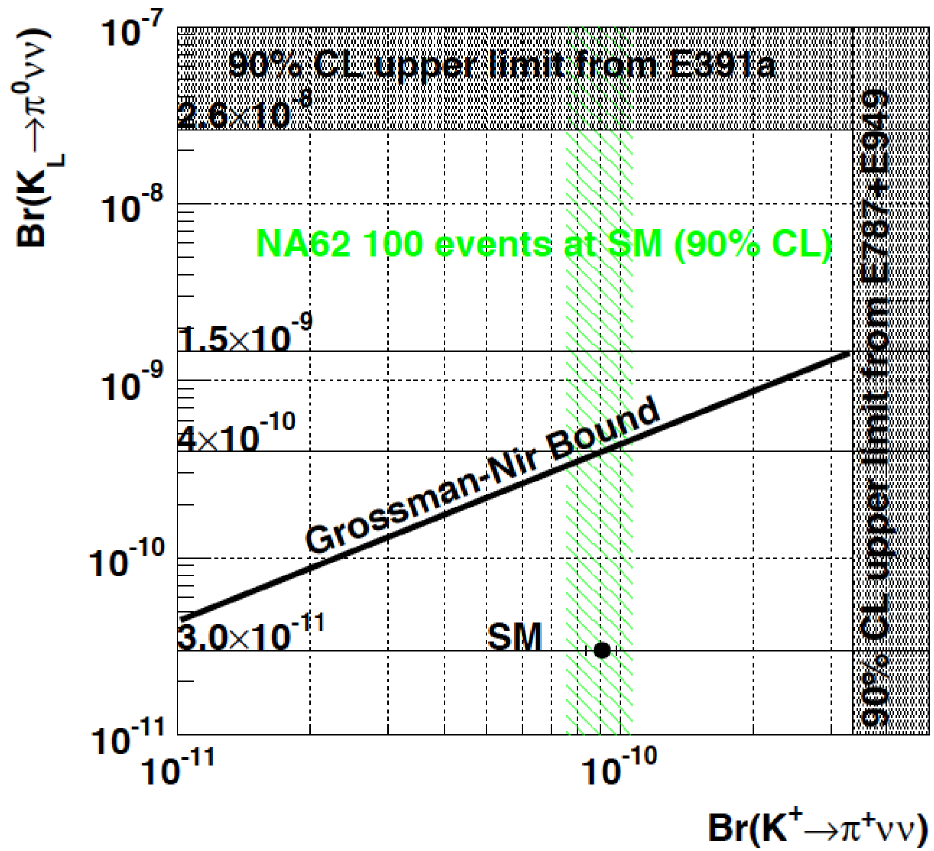


Gluing fiber to scintillator was mostly finished.
Module assembly will start soon.
Will install it in this winter
+ Maintenance for existing broken channels in vacuum

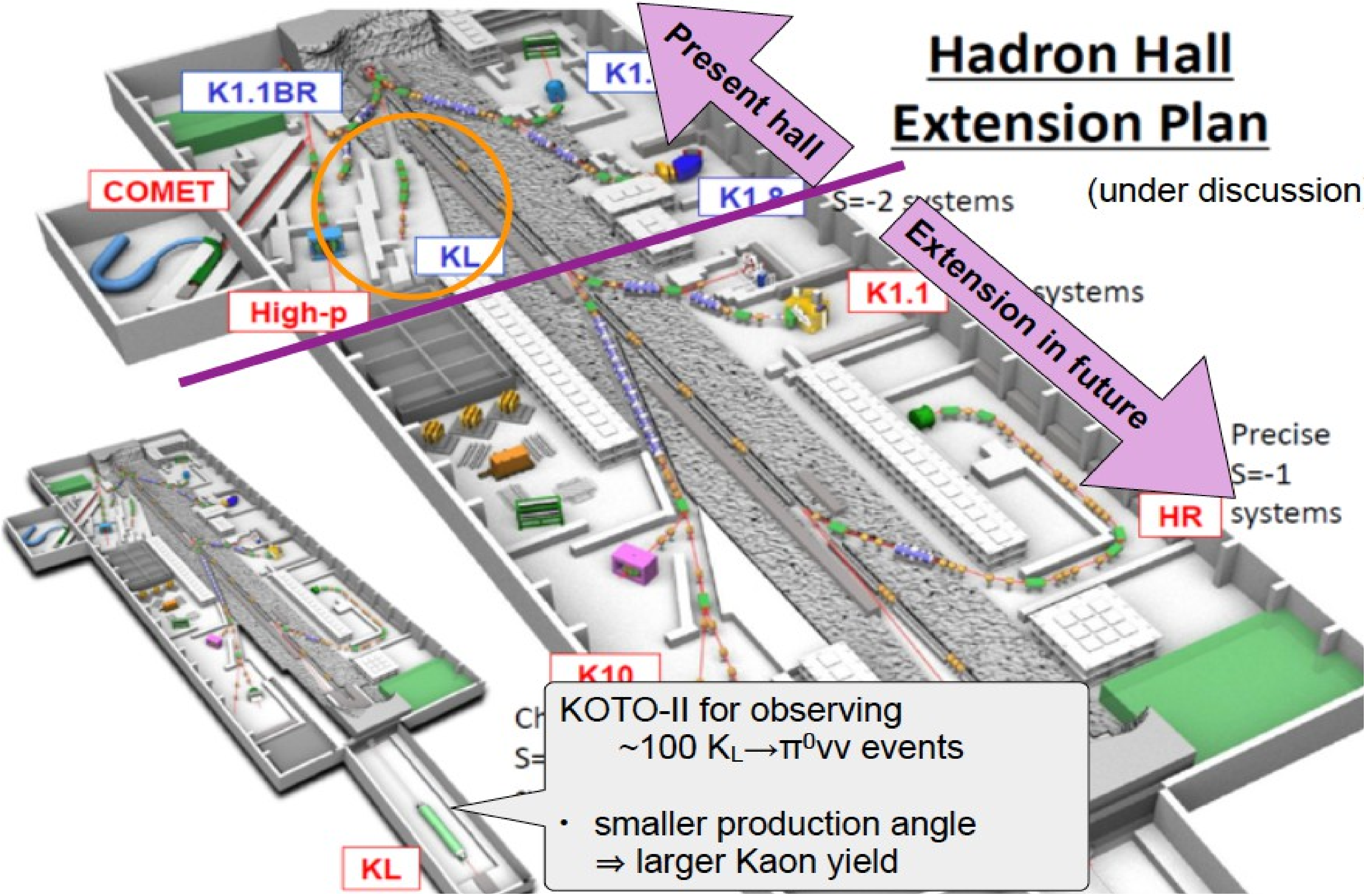
Plan

- NA62 will take 100 events toward 2017 for $K^+ \to \pi^+ \nu\nu$
  - Push Grossman-Nir limit down.
- We will overcome our background and improve our sensitivity





Long term plan



Summary

New physics scenario

- MFV or non-MFV?
  - MFV like
    - $Br(K_L \to \pi^0 \nu\nu) \leftrightarrow \varepsilon'/\varepsilon >$ SM? will suppress Br(KL) enhancement
    - Strong correlation pattern from ε_K
  - Non-MFV with only left or right-handed coupling
    - Similar to MFV
  - Non-MFV with left and right-handed coupling
    - Z' model , generic SUSY, .. → will still enhance Br(KL) largely
    - NP in 5 TeV still enhance Br(KL) largely
- SM extension with 4 generation

  → ruled out
- Littlest Higgs with T-parity

  → under pressure from $B \to \mu\mu$
- KOTO already have discovery potential for light Z' with $\sim\pi^0$ mass

KOTO

- 1st Physics run in 2013
  - Sensitivity ~ current limit with only 100 hours data
  - New background mechanism → neutron
- Restarted in 2015
  - already took 5.3 times larger statistics
  - Data to study neutron background
  - Calibration and study to suppress neutron background
- Prospects
  - Will overcome neutron background
  - Will search $O(10^{-11})$ area for Br(KL) ~2018
  - Continue to KOTO Step2 in enlarged Hadron Experimental Facility