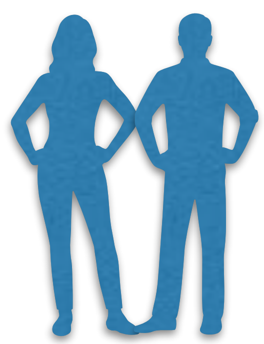
K稀崩壊

南條　創
(大阪大学)

2020.6.4 将来計画委員会勉強会

個性？

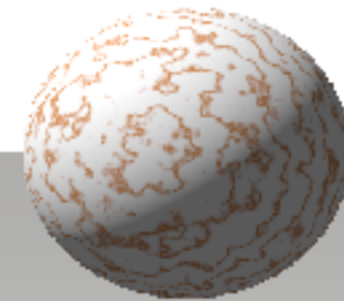
画一的　　個性的　　変？



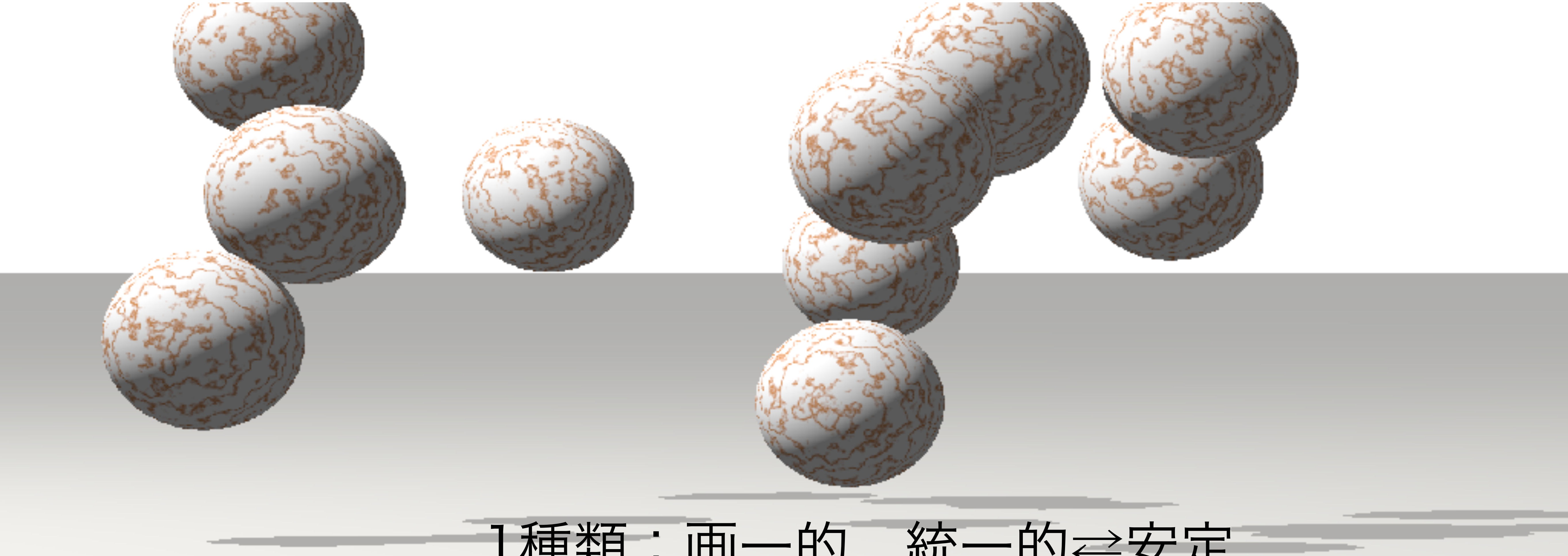
Flavor
Higgs

夢　　妄想

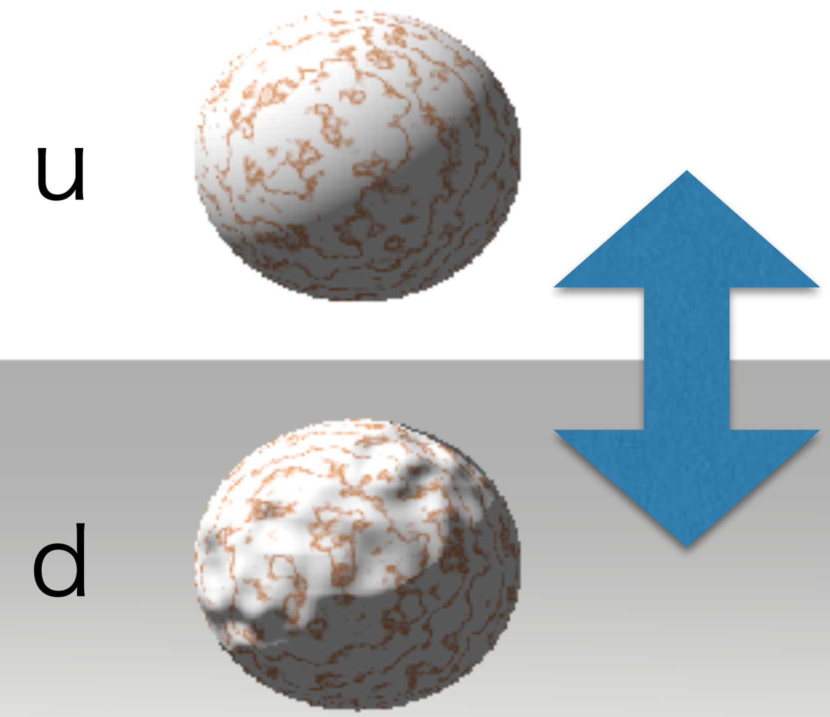
統一的な理解　　実現する力



1種類：画一的、統一的⇄安定



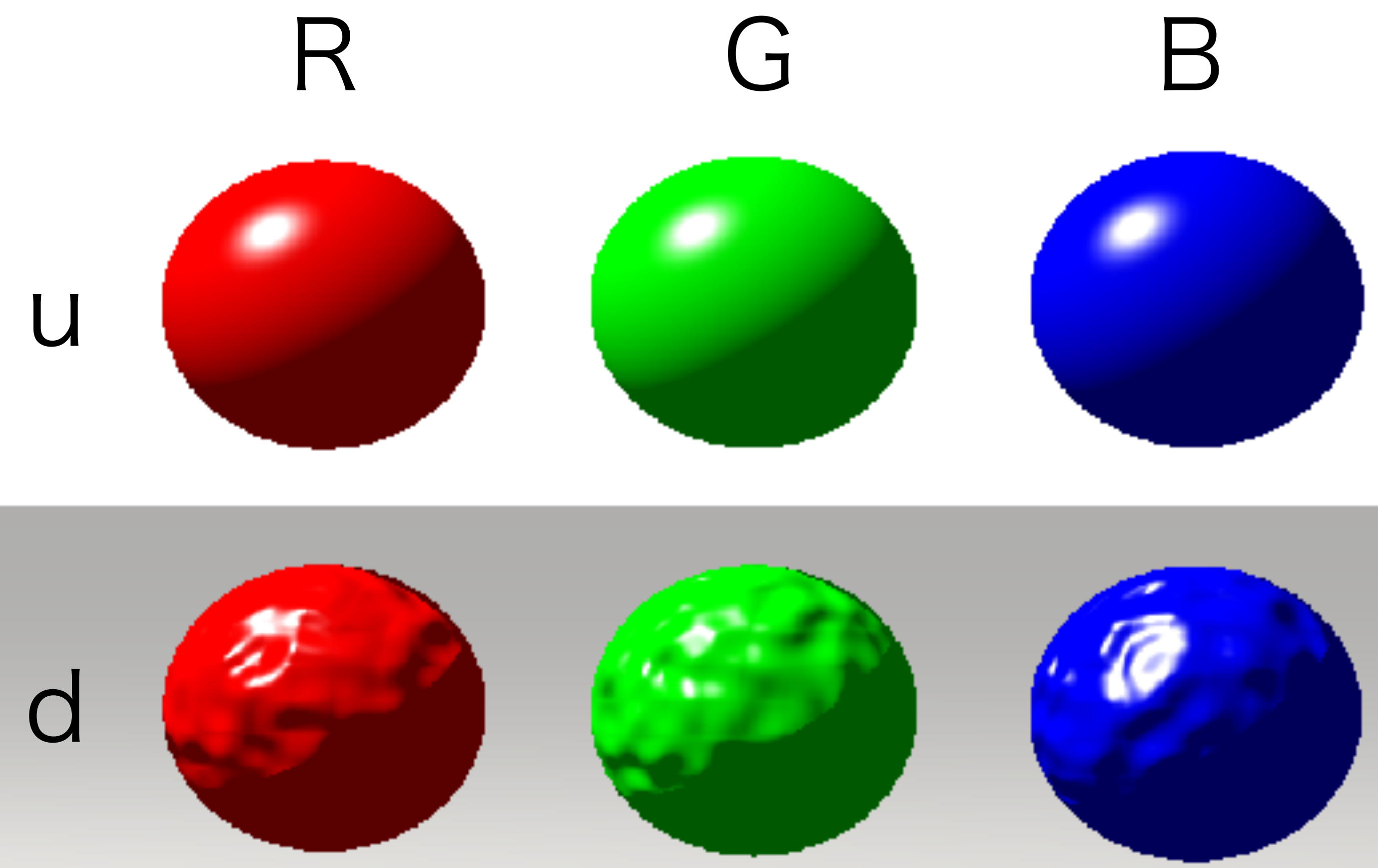
1種類：画一的、統一的⇄安定



昇降演算子$W^{\pm}$

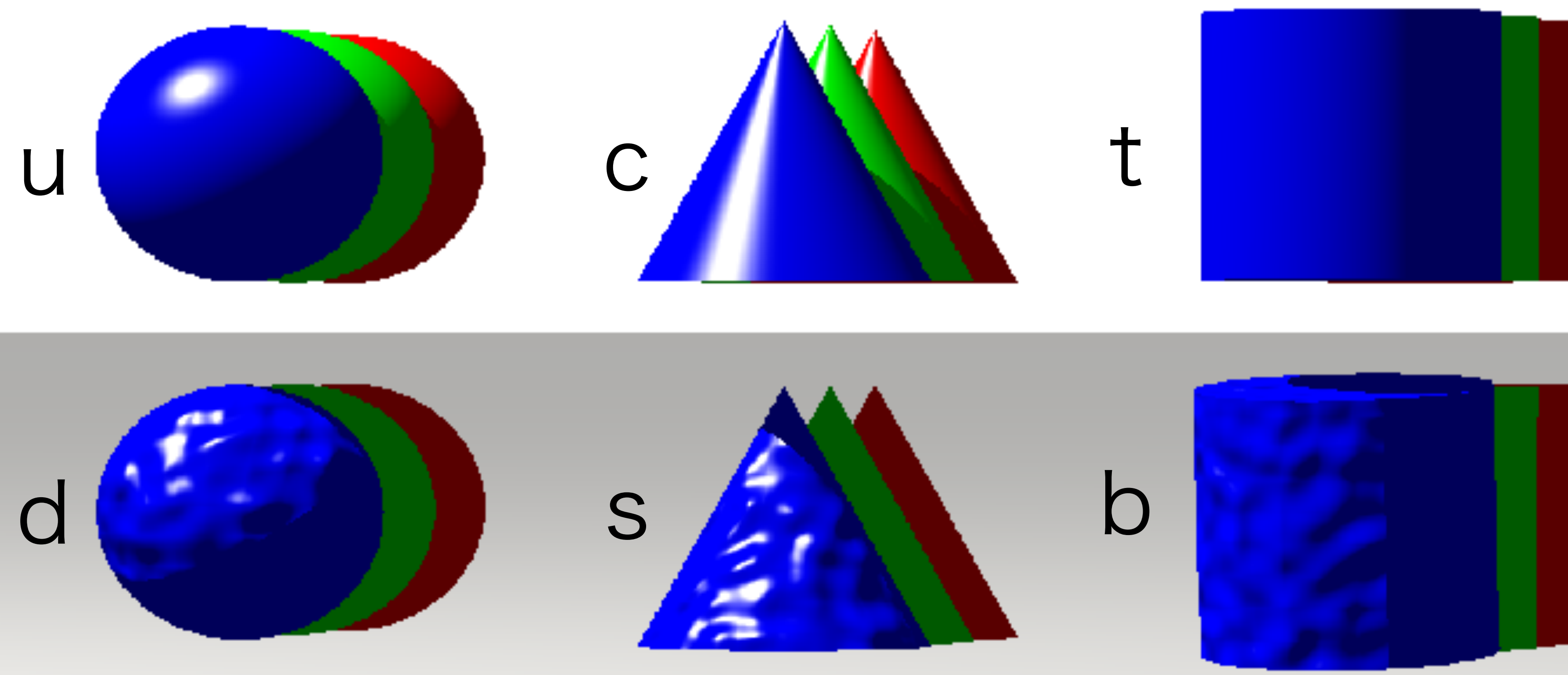
2種類：Spin1/2のような状態

$$s_x, s_y, s_z \rightarrow s^{\pm}, s_z$$



x3種類：カラー

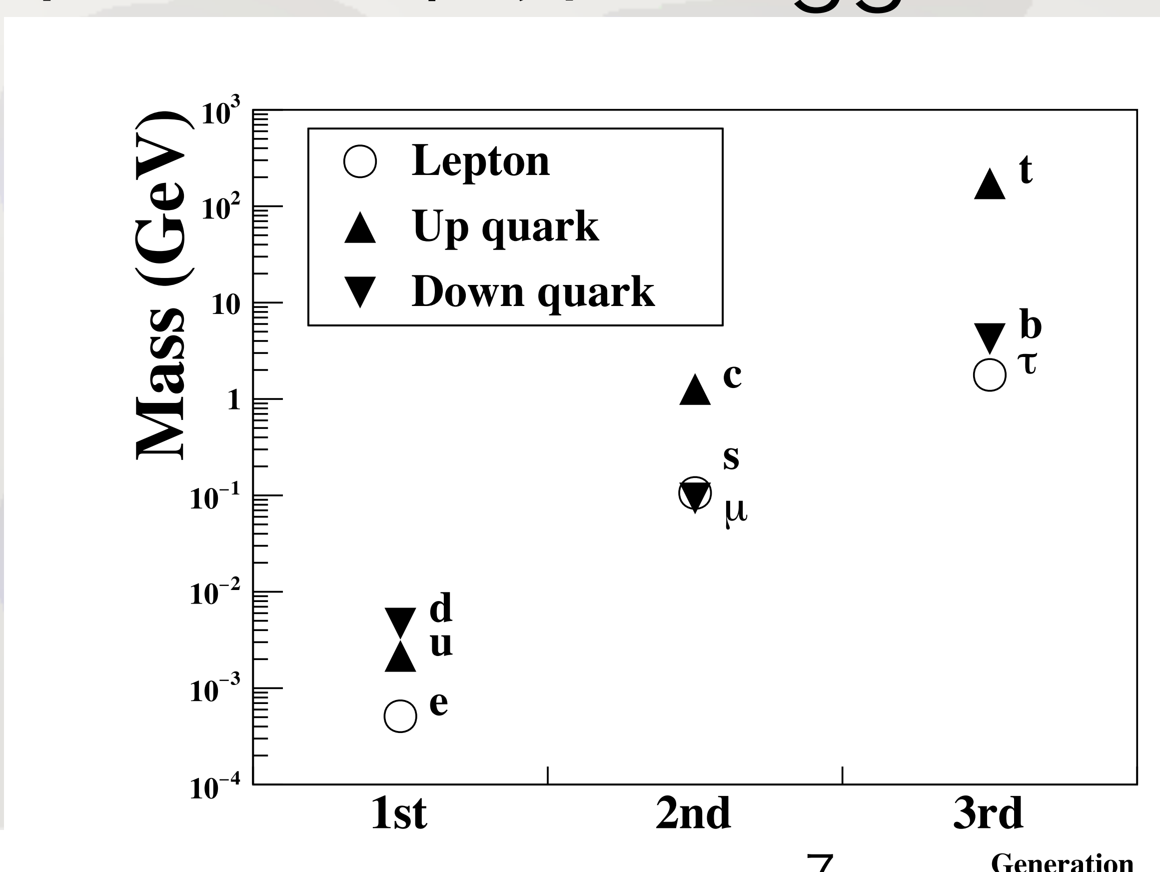
粒子



移り変わり

個性豊かな世界：Higgsが区別

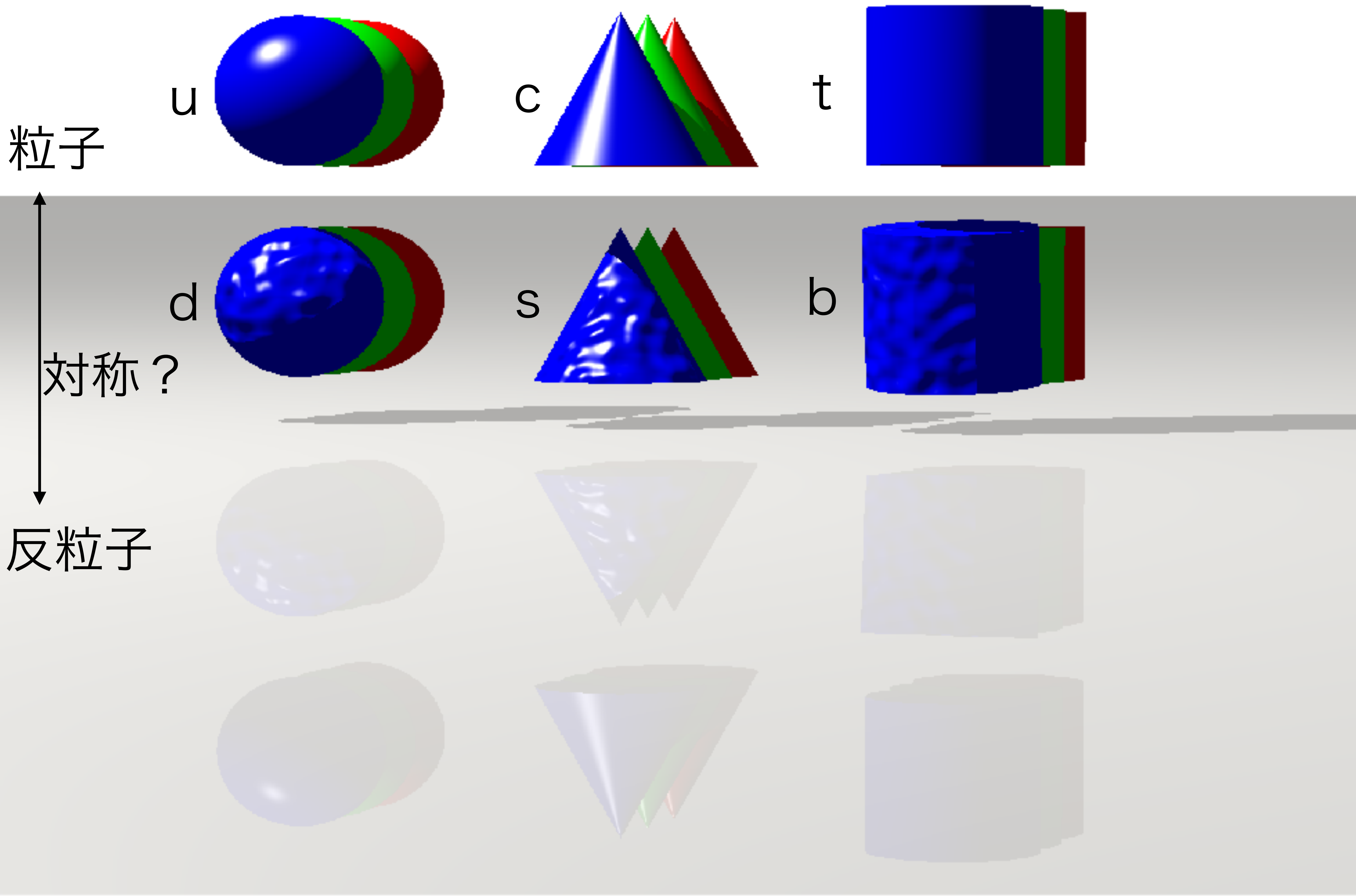
ドラマチック



質量も何桁も違う

個性！

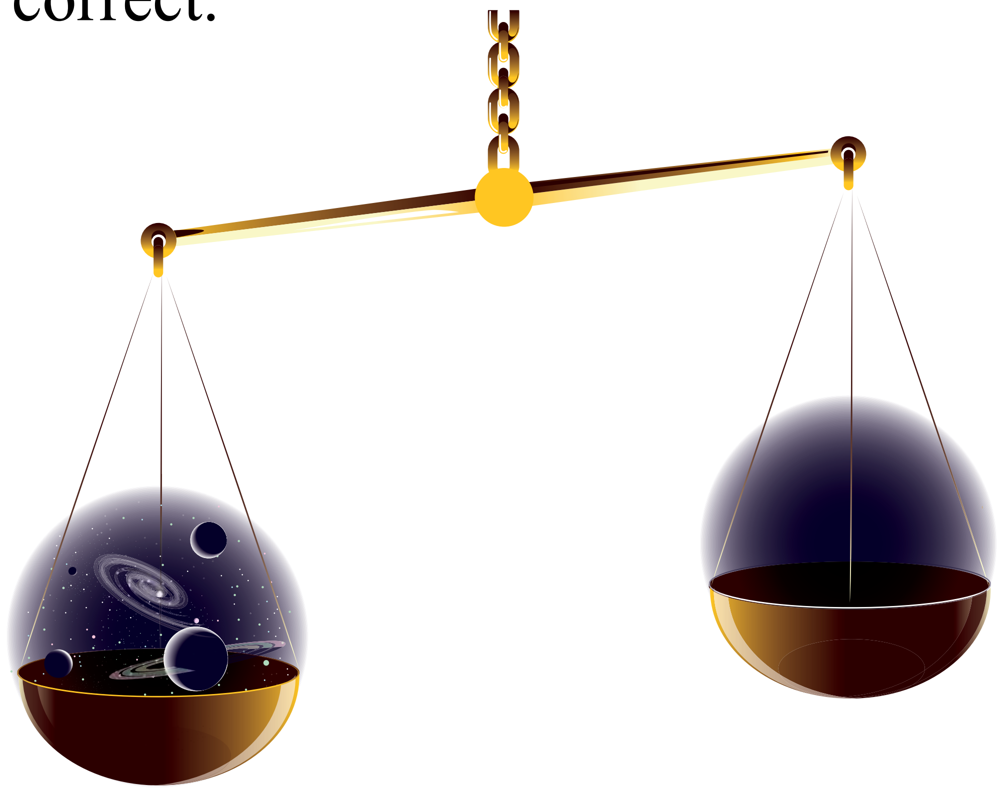
離散的⇄charge?


u
c
t
粒子
d
s
b
対称？
反粒子

Broken Symmetry from Nobel Prize in Physics 2008

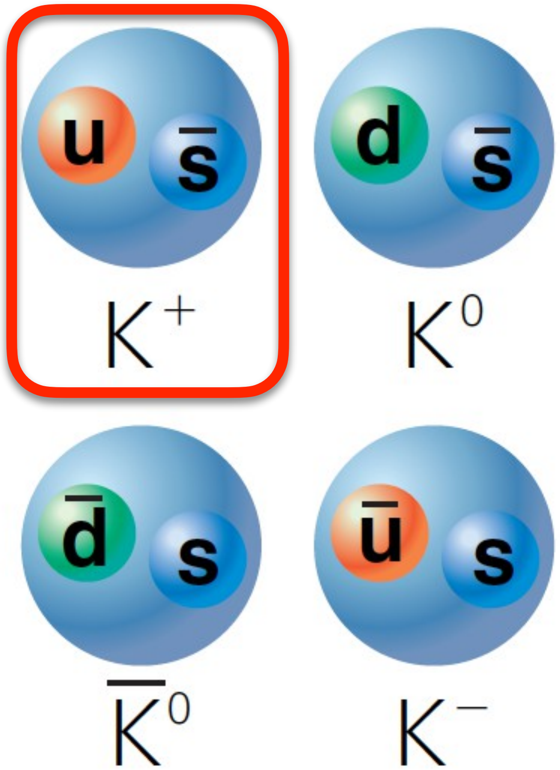
In 1967, Andrei Sakharov [83] (the Nobel Peace Prize 1975) pointed out in a famous work that *CP* violation must be the cause of the asymmetry in the universe. It contains more matter than antimatter. The *CP* violation that the KM Model gives rise to is most probably not enough to explain this phenomenon. To find the origin of this *CP* violation we probably have to go beyond the Standard Model. Such an extension should exist for other reasons as well. It is believed that at higher energies other sectors of particles, so heavy that the present day accelerators have been unable to create them, will augment the model. It is natural that these particles will also cause *CP* violations and in the tumultuous universe just after the Big Bang these particles could have been created. These particles would have been part of the hot early universe and could have influenced it, by an as yet unknown mechanism, to be dominated by matter. Only future research will tell us if this picture is correct.

CPを破る新物理があるはず！



K中間子で探る？

K中間子



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

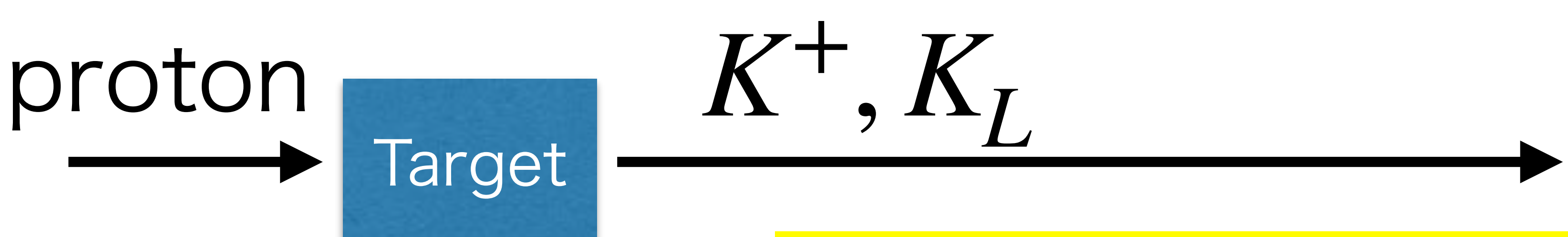
$$K_L \sim \left(\left| K^0 \right\rangle - \left| \overline{K^0} \right\rangle \right) / \sqrt{2}$$

量子重ね合わせ状態

$m(K)$: 0.5 GeV

$\tau(K^+)$: 12 ns ($c\tau \sim 3.7$ m)

$\tau(K_L)$: 51 ns ($c\tau \sim 15$ m)



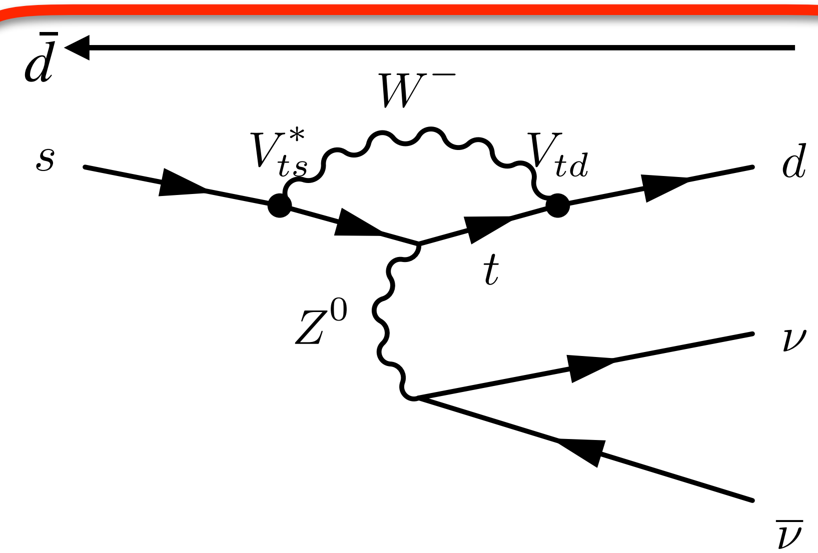
長寿命: 固定票的実験向き

→ ビームラインと検出器

$K \to \pi\nu\nu$ in SM

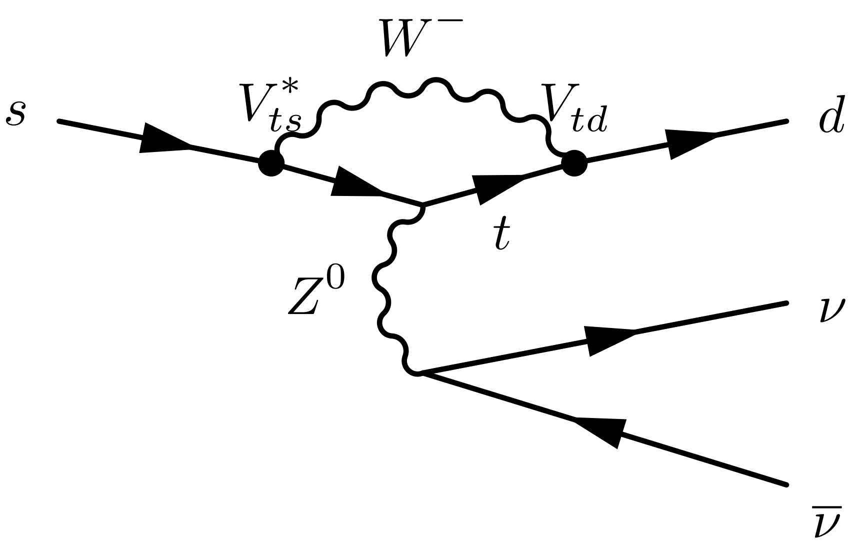
FCNC(中性でフレーバ変化) : GIM, Loopで抑制+CKM

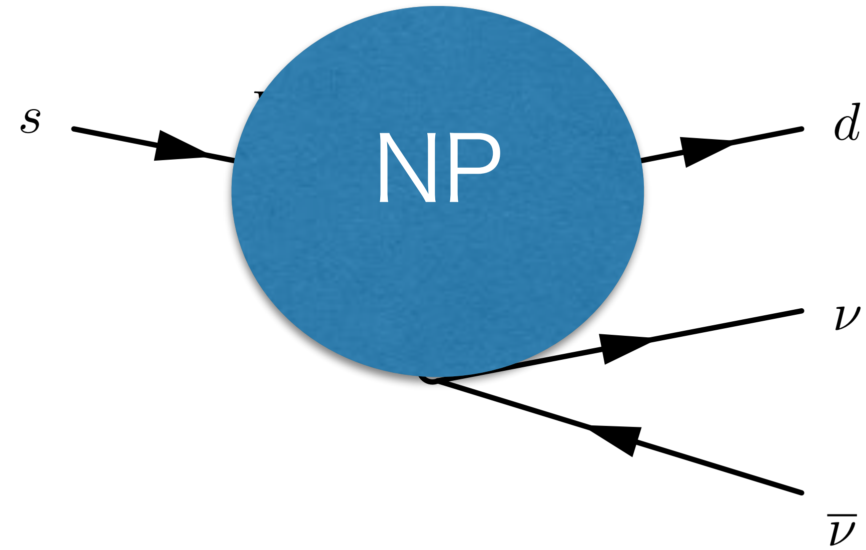
	$K_L \to \pi^0 \nu\overline{\nu}$	$K^+ \to \pi^+ \nu\overline{\nu}$
分岐比 (SM)	$(3.4 \pm 0.6) \times 10^{-11}$	$(8.4 \pm 1.0) \times 10^{-11}$
	Buras et al JHEP11(2015)33	
	CKM行列要素のパラメータ誤差が主要	
理論的不定性	$< 2\ \%$	$< 4\ \%$
ループ中のクォーク	top	top > charm GIM mechanism



標準理論過程(BG):抑制＋精密→新物理探索(Signal)😀

$s \to d$ とCKM行列要素





個性的！

	d	s	b
u	1	λ	λ^3
c	$-\lambda$	1	λ^2
t	λ^3	$-\lambda^2$	1

$\lambda \sim 0.23$

×1/100

$$|V_{ts}^* V_{td}| \sim 5 \times 10^{-4} \ll |V_{tb}^* V_{td}| \sim 10^{-2} < |V_{tb}^* V_{ts}| \sim 4 \times 10^{-2}$$

s→d　　b→d　　b→s

s→d : SM : Flavor transition : Most suppressed

NP : Flavor transition : ?

CKM-like : Minimum Flavor violation

O(1) : Generic model →High energy

新物理への感度？

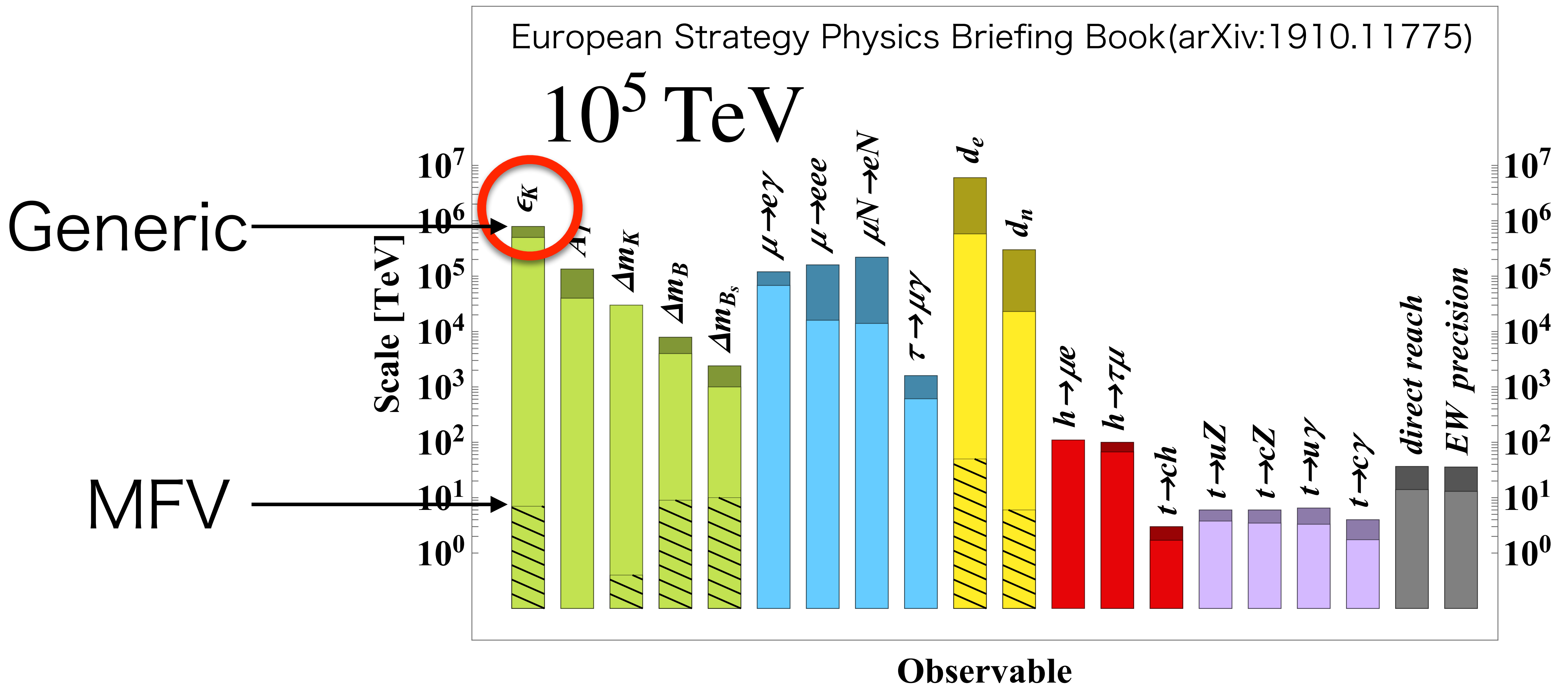


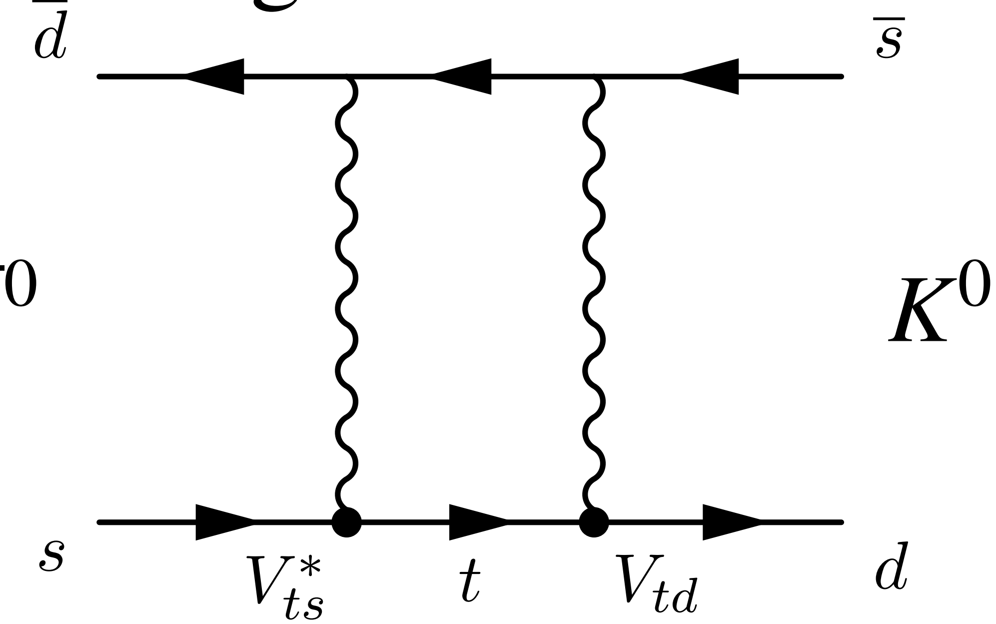
Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and EW precision measurements. The operator coefficients are taken to be either ~ 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS).

Why?

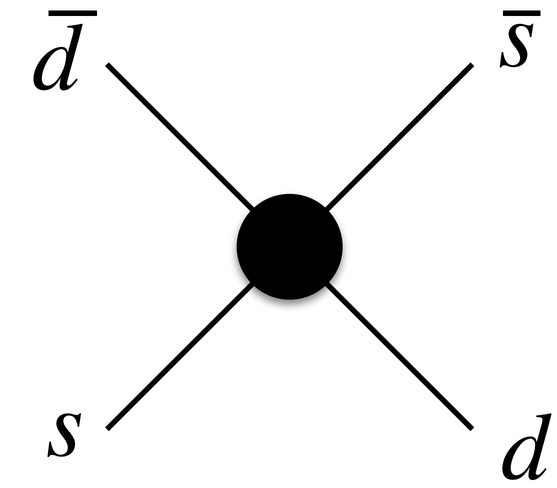
Bona07
Isidori13

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

SM



New Physics



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

$G_F \sim 10^{-5}(\mathrm{GeV}^{-2})$

$m_t \sim 175(\mathrm{GeV})$

Λ	: NPのenergy scale
F_{NP}	: NPのフレーバ遷移(Generic:1)
α_{NP}	: NPのループ構造(Tree:1, Weak Loop: 0.03)

$\mathcal{M}_{NP} > \mathcal{M}_{SM}$であればNP効果が効くだろう→どんなΛ?

Why? (2)

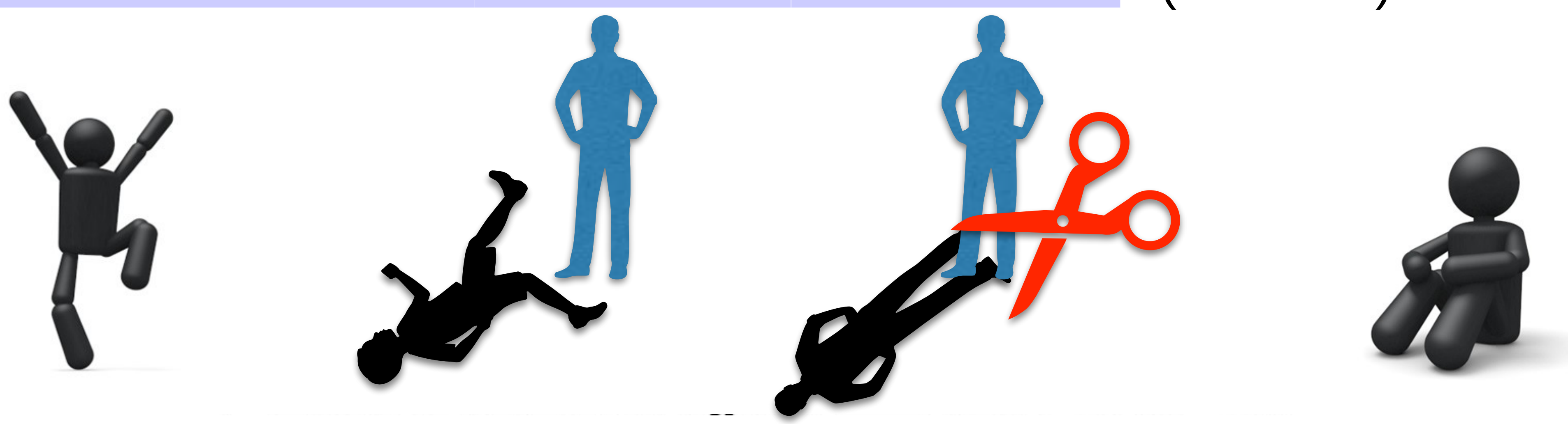
7TeV 2000 1

$$\Lambda < \frac{4\pi}{G_F m_t} \frac{1}{V_{ts}^* V_{td}} \times \sqrt{F_{NP}} \times \alpha_{NP}$$

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

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

(Bona '07)



Generic　　　MFV(SM-like)

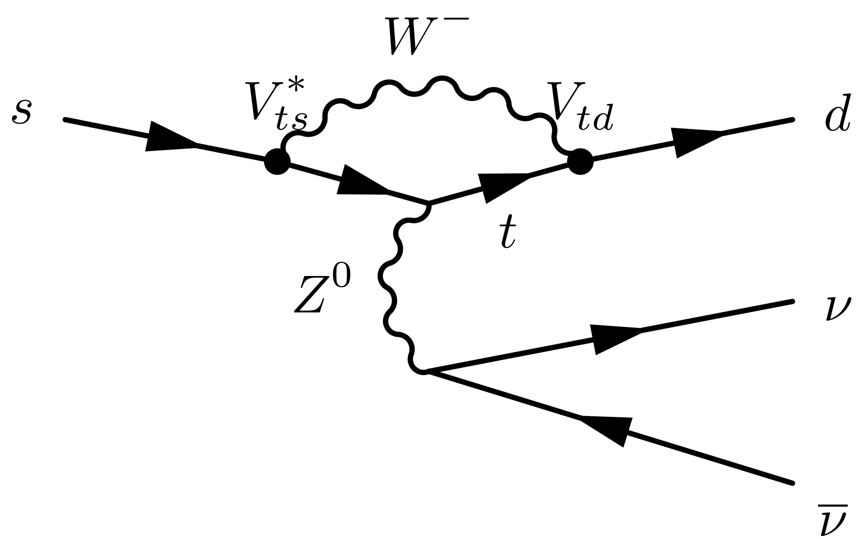
もっと、自由でいいんだよ？

窮屈？

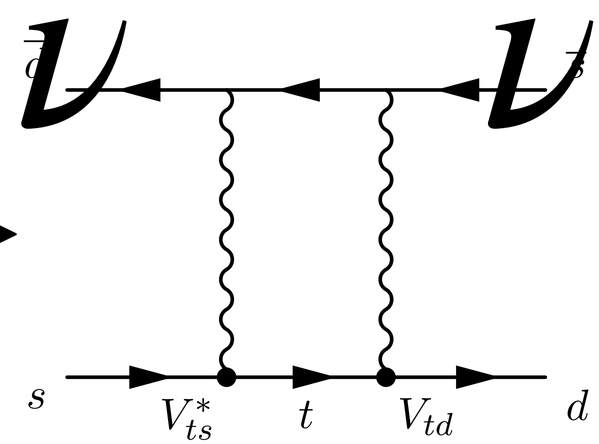
Why? (3)

$K \to \pi\nu\nu$

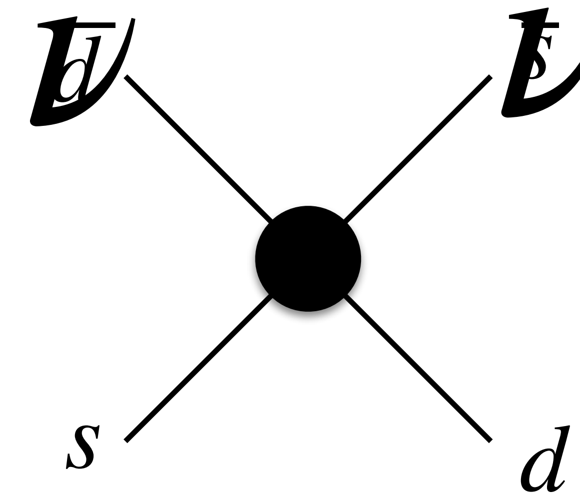
SM



$>$



New Physics



$$\mathscr{M} \sim \frac{G_F^2 m_t^2}{16\pi^2}(V_{ts}^* V_{td}) \times 1 + \frac{F_{NP}}{\Lambda^2}\alpha_{NP}^2$$

$G_F \sim 10^{-5}(\mathrm{GeV}^{-2})$

$m_t \sim 175(\mathrm{GeV})$

Λ	: NPのenergy scale
F_{NP}	: NPのフレーバ遷移(Generic:1)
α_{NP}	: NPのループ構造(Tree:1, Weak Loop: 0.03)

7TeV 50

$$\Lambda < \frac{4\pi}{G_F m_t}\frac{1}{\sqrt{V_{ts}^* V_{td}}}\sqrt{F_{NP}}\alpha_{NP} \sim 4 \cdot 10^2\,\mathrm{TeV}$$

CKM行列は誰が決めた？

PDG

Higgs　　　湯川結合

$$\frac{v}{\sqrt{2}}(\bar{b}'\bar{s}'\bar{d}')_L \begin{pmatrix} \square & \square & \square \\ \square & \square & \square \\ \square & \square & \square \end{pmatrix} \begin{pmatrix} b' \\ s' \\ d' \end{pmatrix}_R$$

$$= \frac{v}{\sqrt{2}}(\bar{b}'\bar{s}'\bar{d}')_L U^{-1} \begin{pmatrix} g_b & & \\ & g_s & \\ & & g_d \end{pmatrix} U \begin{pmatrix} b' \\ s' \\ d' \end{pmatrix}_R$$

$$= \frac{v}{\sqrt{2}} g_b \bar{b}b + \frac{v}{\sqrt{2}} g_s \bar{s}s + \frac{v}{\sqrt{2}} g_d \bar{d}d$$

質量にあたる

Weak固有状態

対角化

Mass固有状態

ユニタリ行列

→ CKM

$$\begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

CKM行列はHiggsのYukawa結合が起源

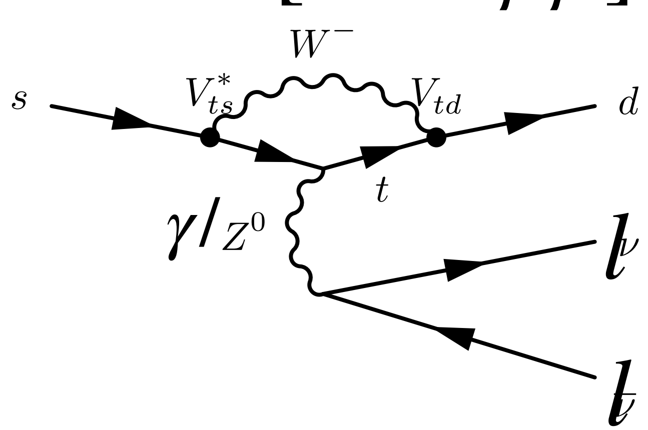
→　Arbitrary?　NPではCKMと違ってもよい？

$s \to d$ Transition

	$K_L \to \pi^0 \nu \bar{\nu}$ $\left(K_L \sim (K^0 - \overline{K^0})/\sqrt{2} \right)$	$K^+ \to \pi^+ \nu \bar{\nu}$
Amplitude	$\propto \mathscr{A}_{s \to d} - (\mathscr{A}_{s \to d})^*$	$\propto \mathscr{A}_{s \to d}$
Width	$\propto (\mathrm{Im}\mathscr{A}_{s \to d})^2$	$\propto \lvert \mathscr{A}_{s \to d} \rvert^2$
CP	CP violating	CP conserving

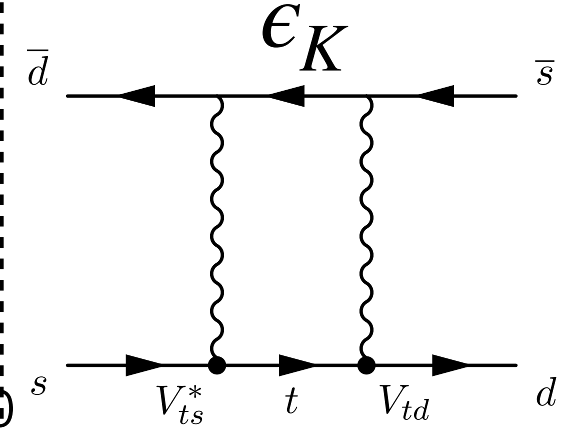
Grossman-Nir bound $\mathscr{B}_{K_L \to \pi^0 \nu \bar{\nu}} < 4.4 \mathscr{B}_{K^+ \to \pi^+ \nu \bar{\nu}}$

$K \to \pi[ee \text{ or } \mu\mu]$

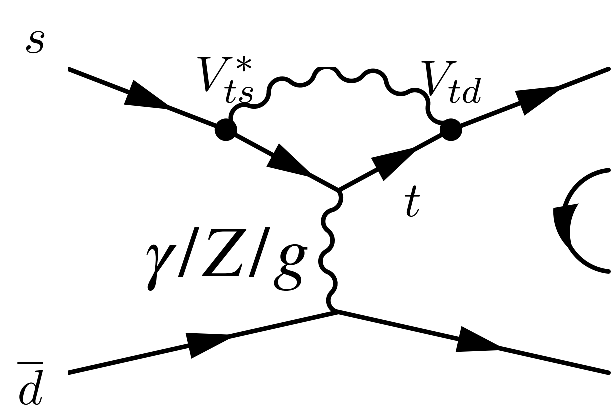


$K_S \to [ee \text{ or } \mu\mu]$ (LHCb)

ϵ_K

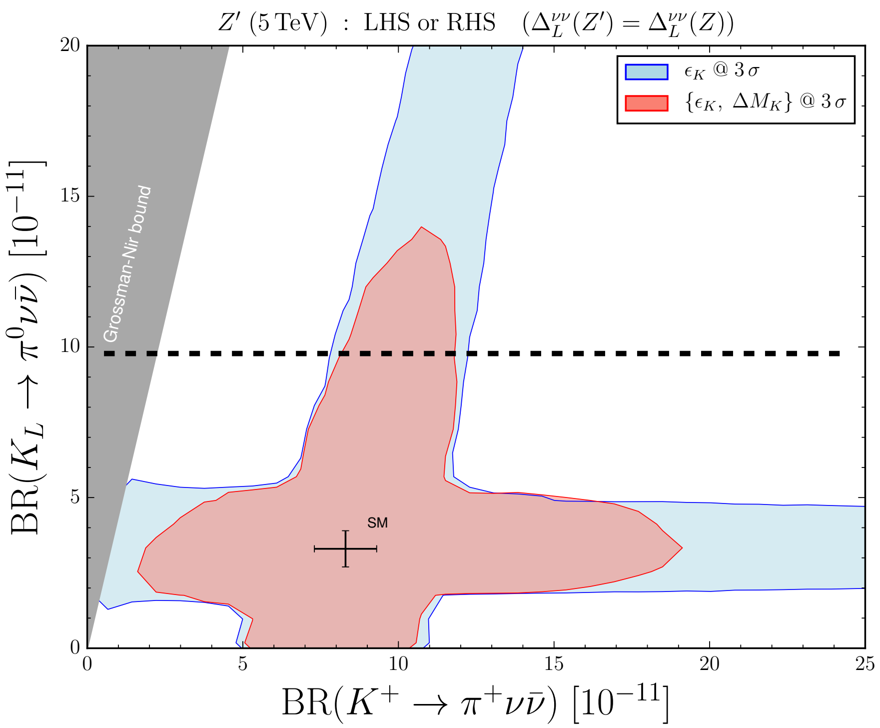


ϵ'/ϵ $K \to 2\pi^0$

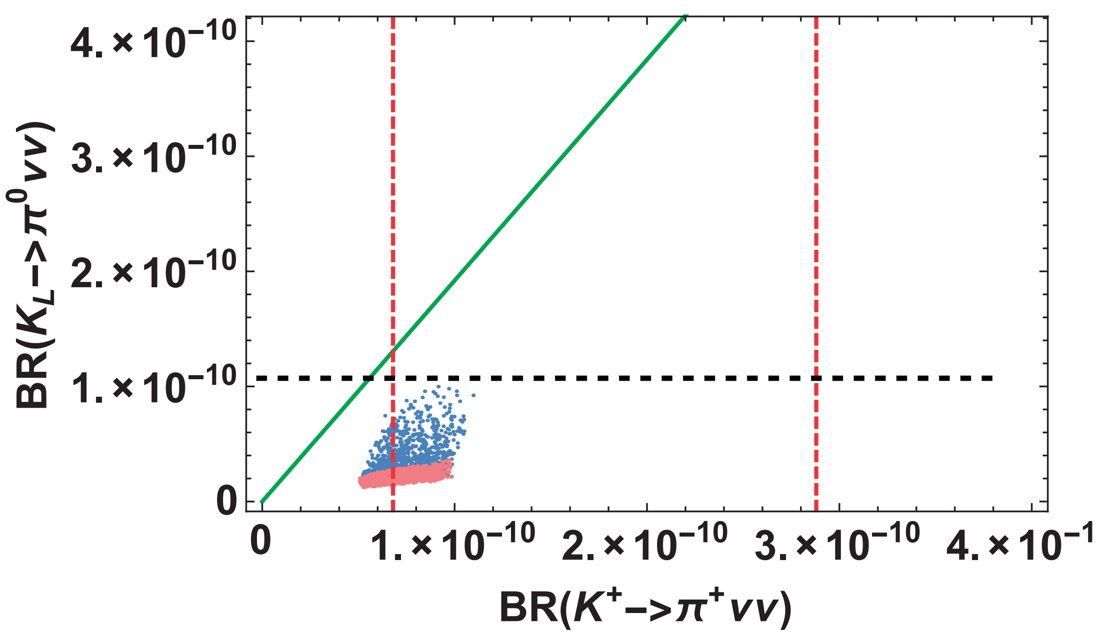


New Physics

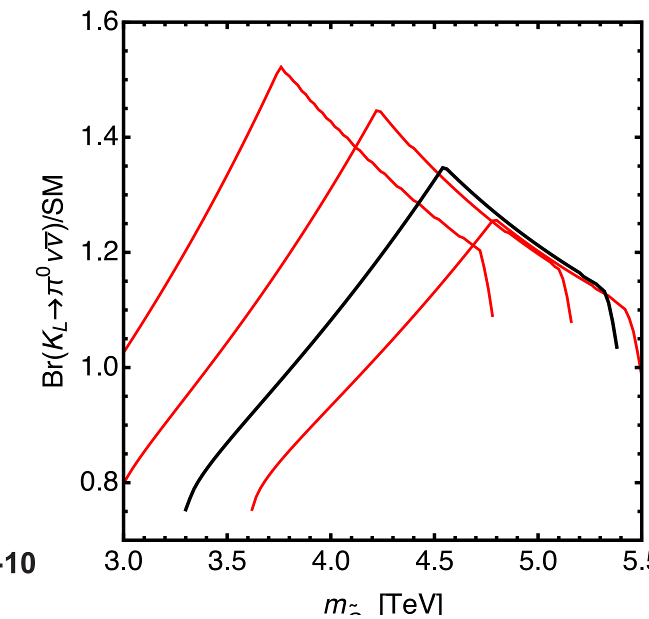
3TeV Z’

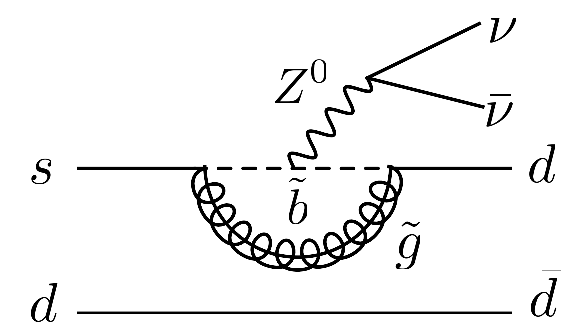


10 TeV scale SUSY



TeV SUSY





A. Buras et al JHEP11(2015)166 Z,Z’

K. Yamamoto et al PTEP(2016)123B02 SUSY

M. Bordon et al EPJC(2017)77:618 LFU

A. Crivellin PRD96(2017) 015023 MSSM

S. Fajfer at al EPJC(2018)78:472 Leptoquark

X. HE et al EPJC(2018)78:472 models

M. Endo et al JHEP04(2018)019 SUSY

C.Chen et al JHEP(2018)145 two Higgs doublet

…

Sizable enhancement is possible

Status of Experimental Search

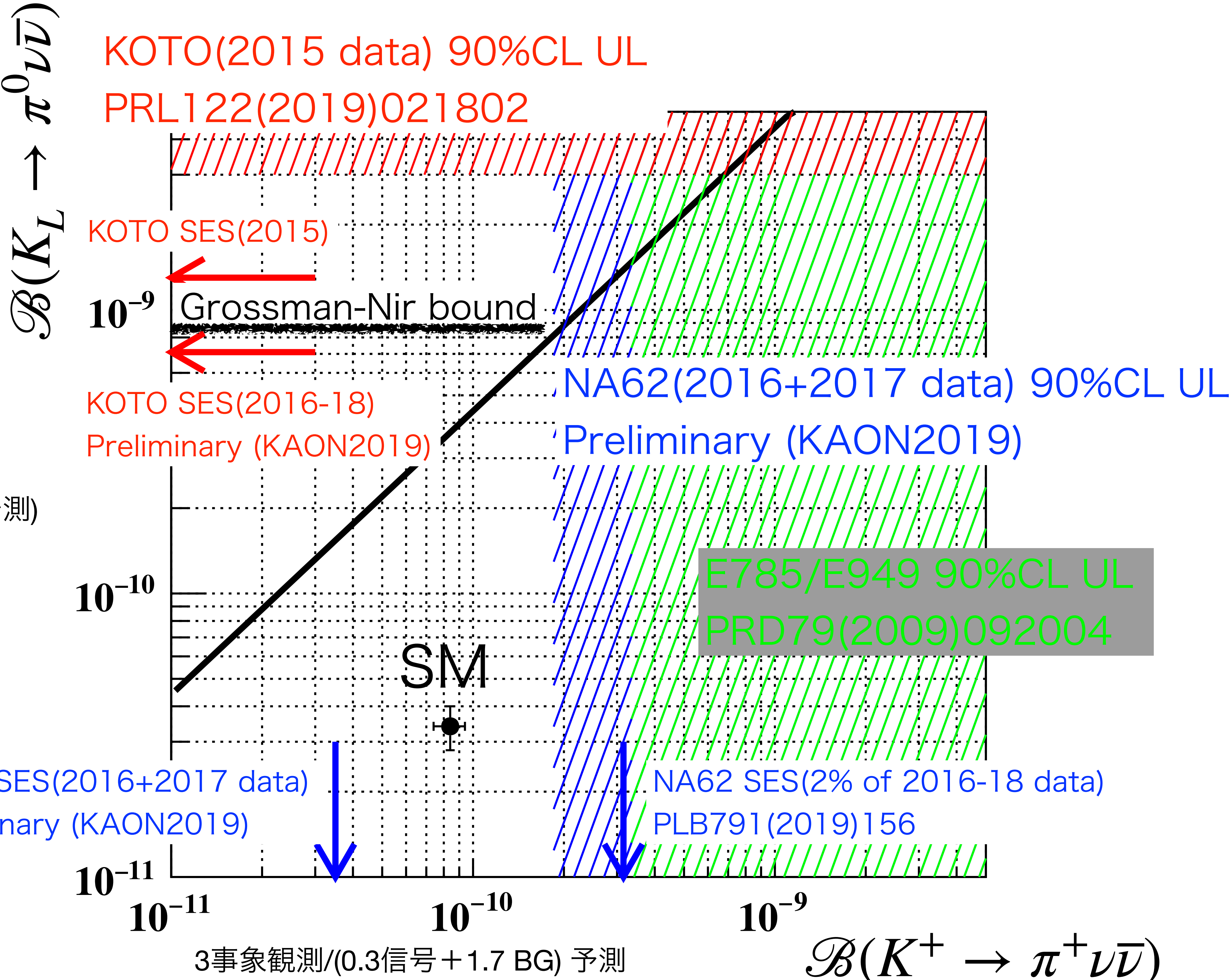
3×10^{-9}

1.3×10^{-9}

4事象観測/(0.34BG予測)

（内1事象は誤り）

依然調査中



3事象観測/(0.3信号＋1.7 BG) 予測

1.85×10^{-10}

Prospects

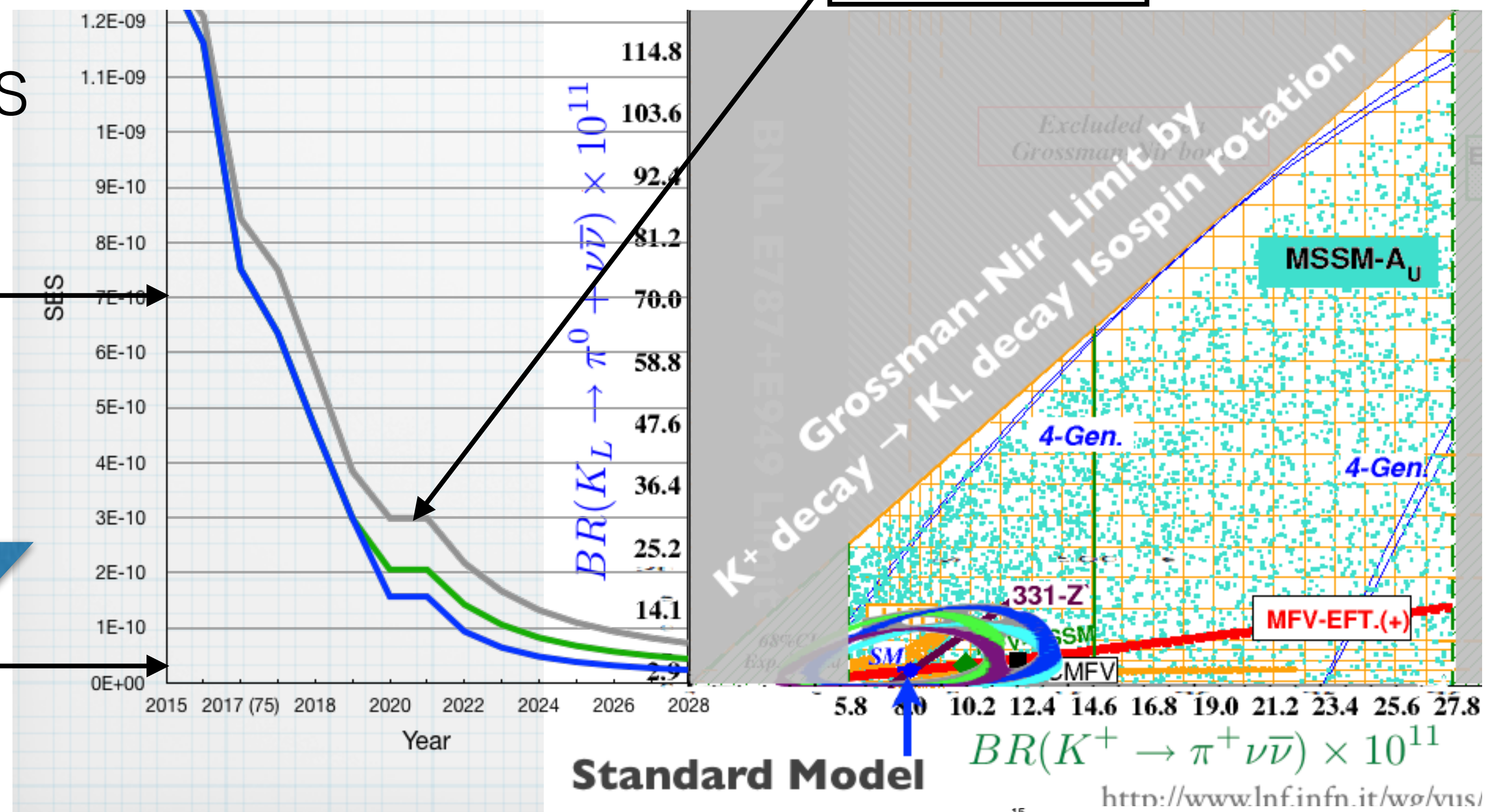
- 2KOTO
  - 高輝度高品質ビーム、背景事象削減

加速器増強

SES

7×10^{-10}

3×10^{-11}

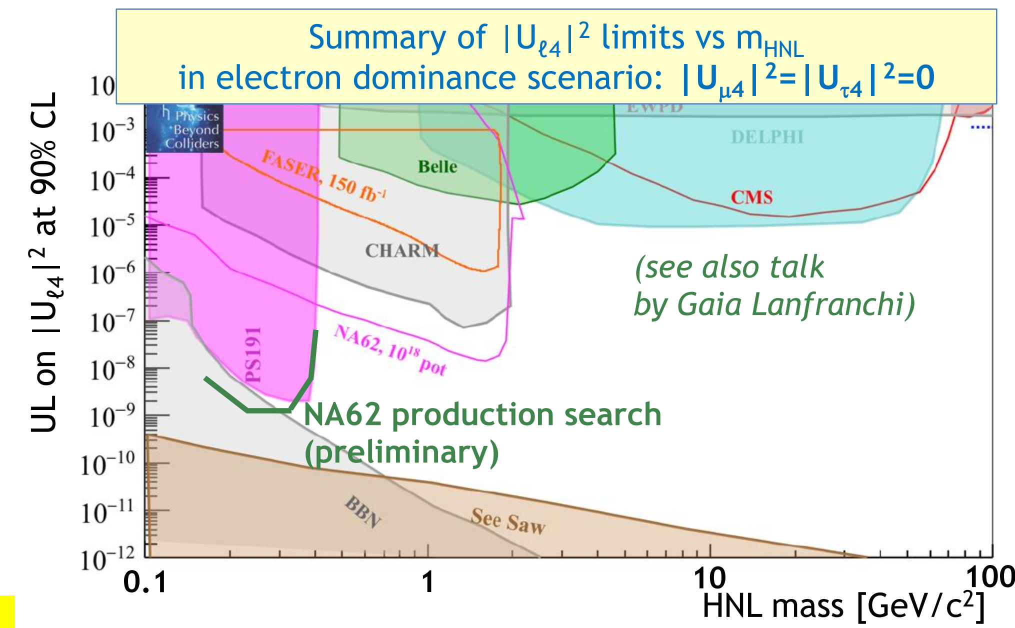


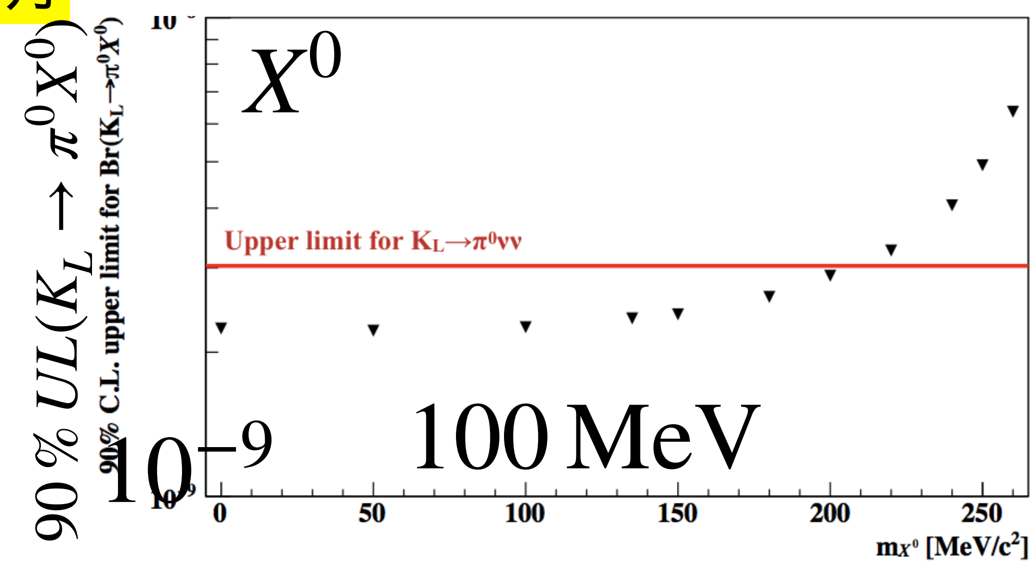
- NA62
  - 2018データの解析
  - 2021-2024 Run
    - 背景事象削減、高輝度ビーム
    - O(10%)での分岐比測定をめざす

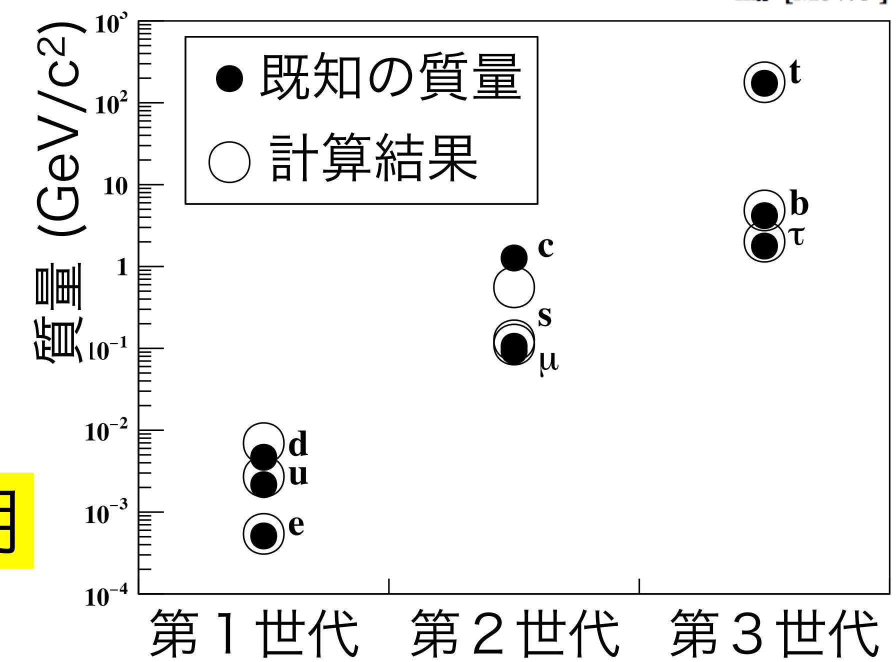
2027?- KLEVER:$K_L \to \pi^0 \nu\nu$

Exotic Search

- NA62 (or NA62++ : Beam dump mode)
  - Heavy Neutral Lepton (Dark Fermion) $K^+ \to e^+N$
  - Axiflavon$K^+ \to \pi^+ a$ StrongCP, 質量の説明
    非常に強い制限
- NA62++ (NA62 with beam dump mode)
  - Dark Scalar/Photon
  - Axion-Like Particle
- KOTO
  - invisible boson X⁰ $(L_\mu - L_\tau)$:$K_L \to \pi^0 X^0$
  - Lorentz violation $K_L \to 3\gamma$
  - Dark Photon $K_L \to \pi^0\pi^0\gamma_D$ 質量の説明
  - Axiflavon?$K_L \to \pi^0 a$ StrongCP, 質量の説明





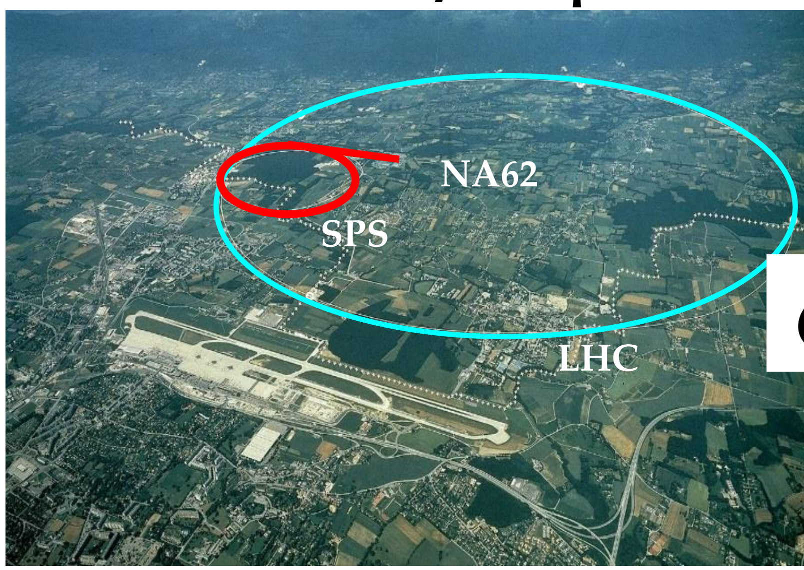


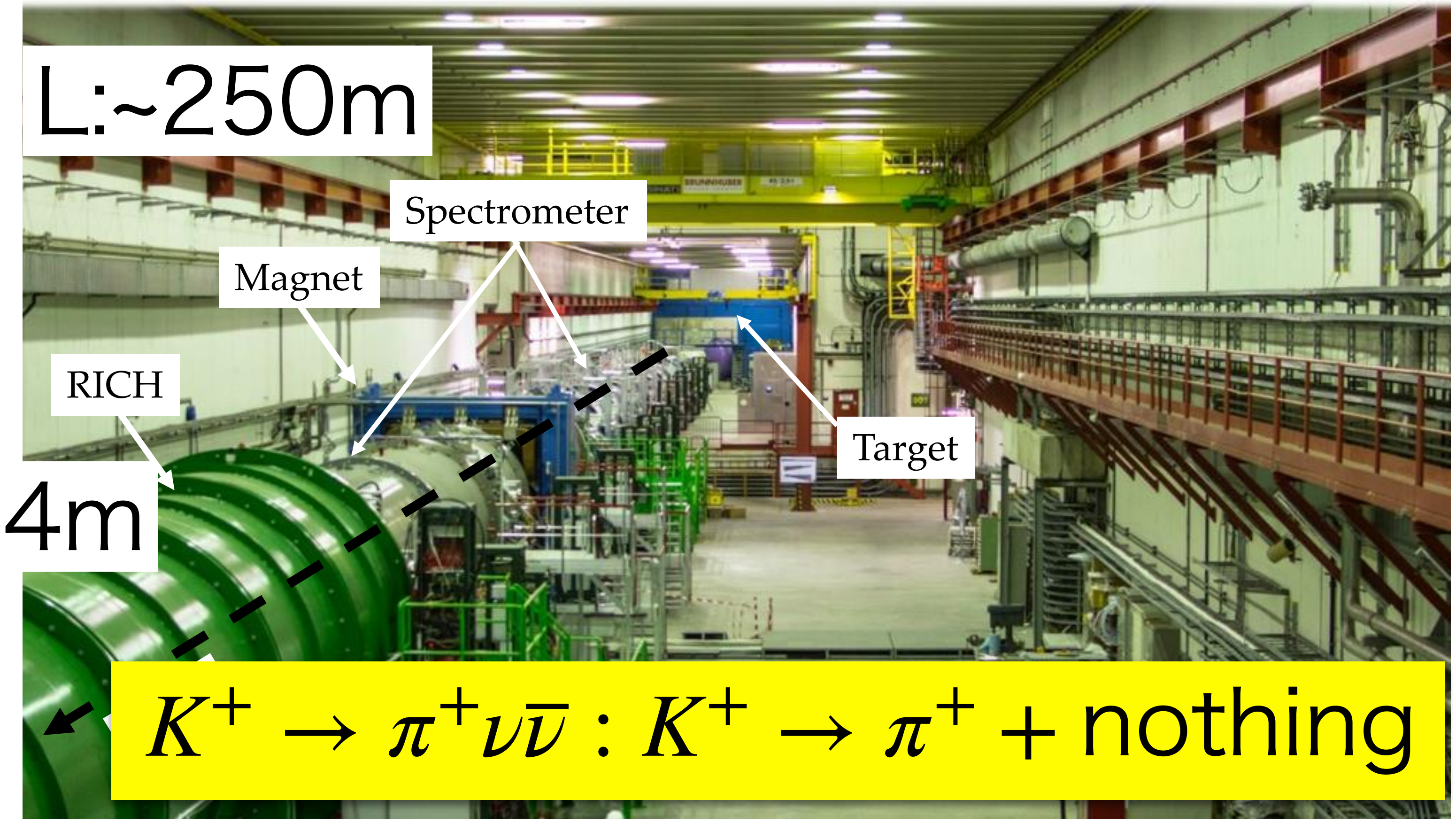
実験： 困難とそれを超えて

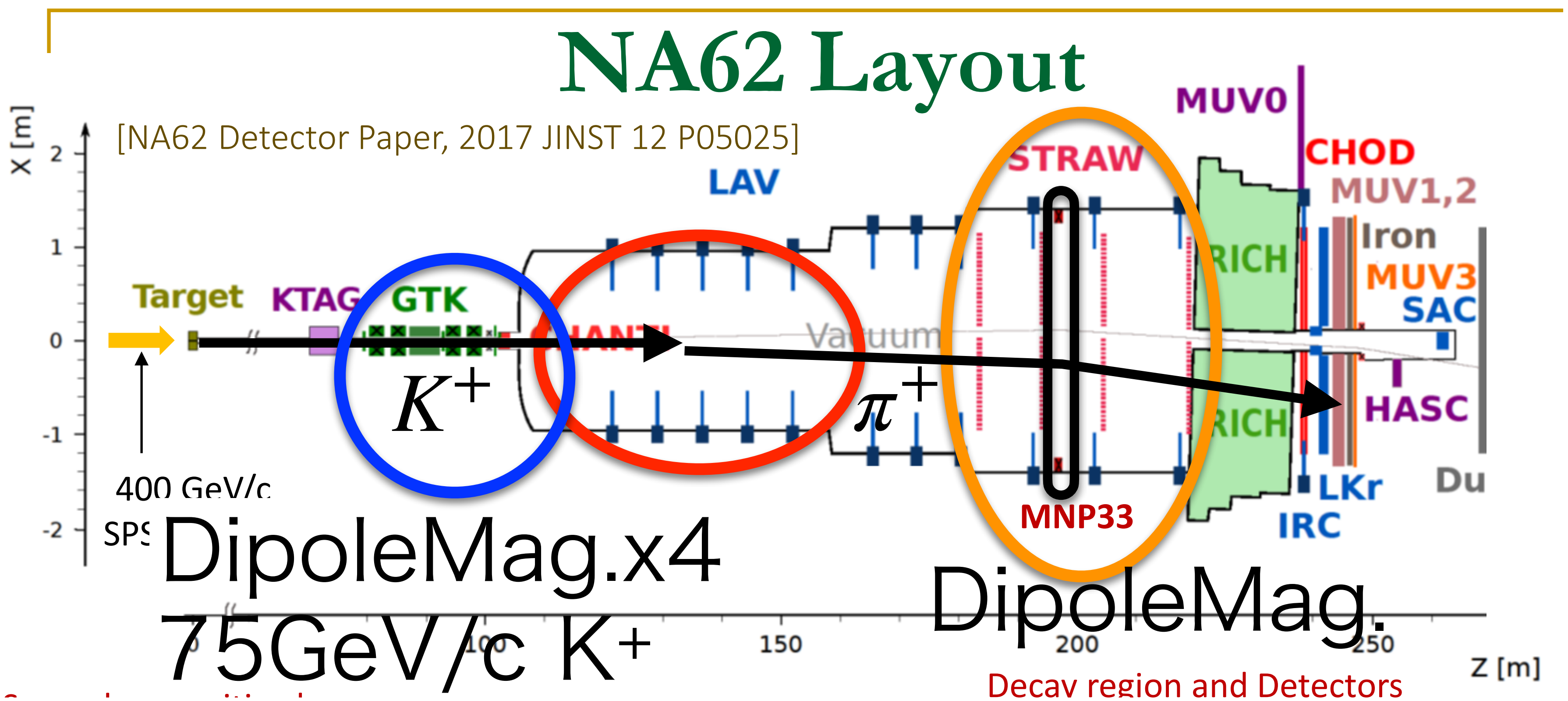
G. Ruggiero (KAON2019)

NA62 Experiment at CERN-SPS

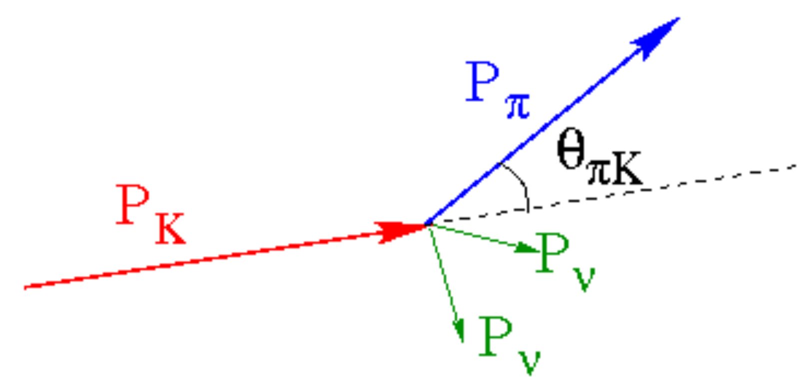
400 GeV/c proton





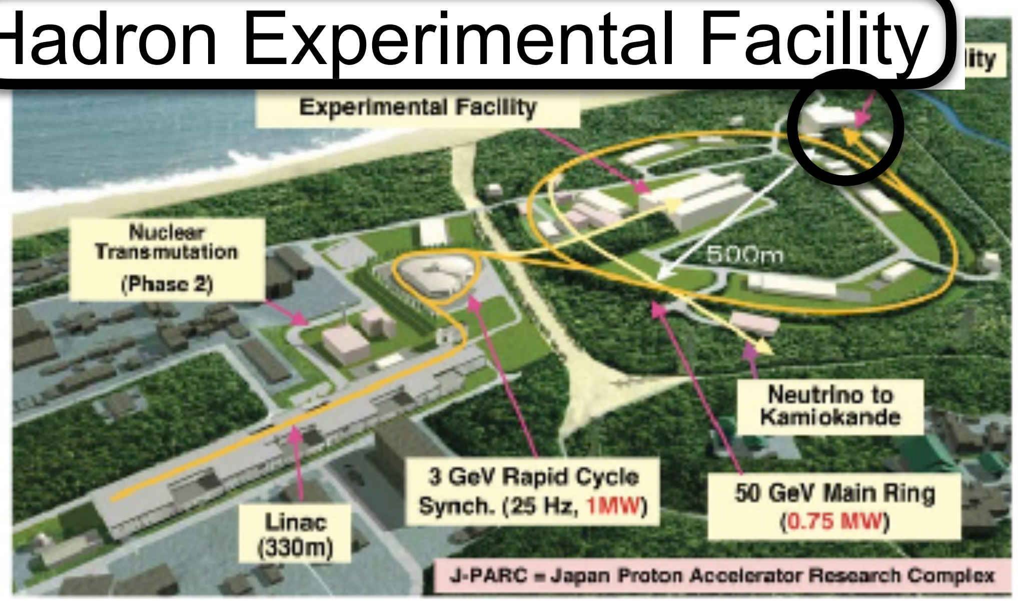


$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$



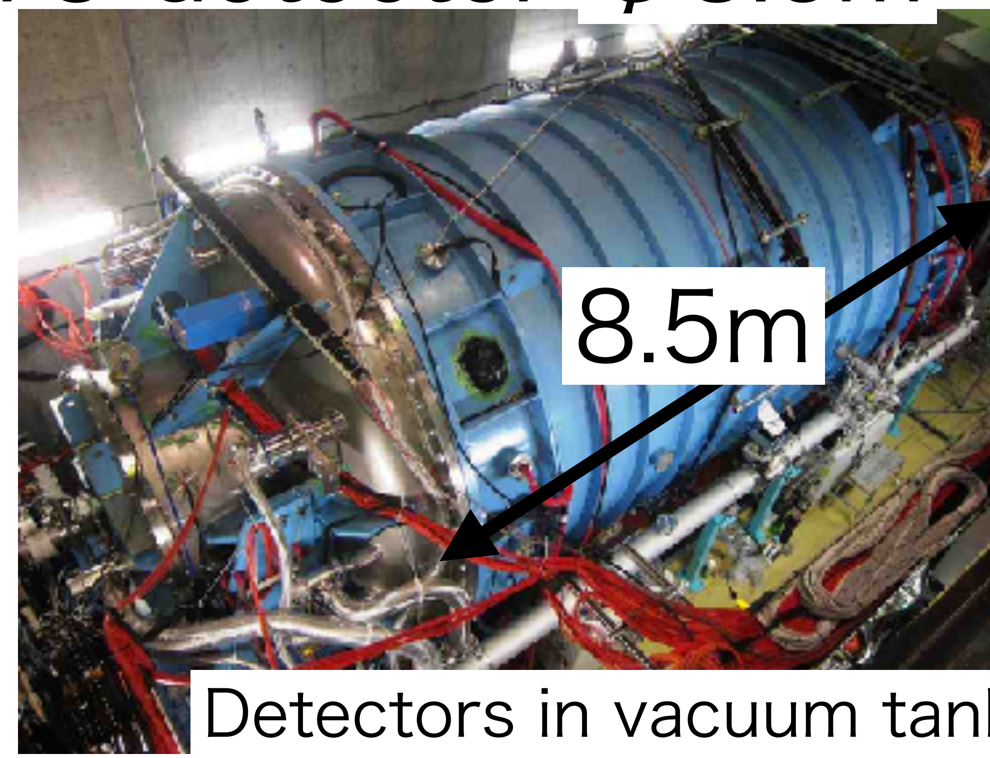
KOTO Experiment at J-PARC-MR

J-PARC MR 30 GeV proton
→Hadron Experimental Facility



30 GeV proton → $p_{K_L}^{\rm peak} \sim 1.5\,({\rm GeV}/c)$

KOTO detector ϕ3.5m

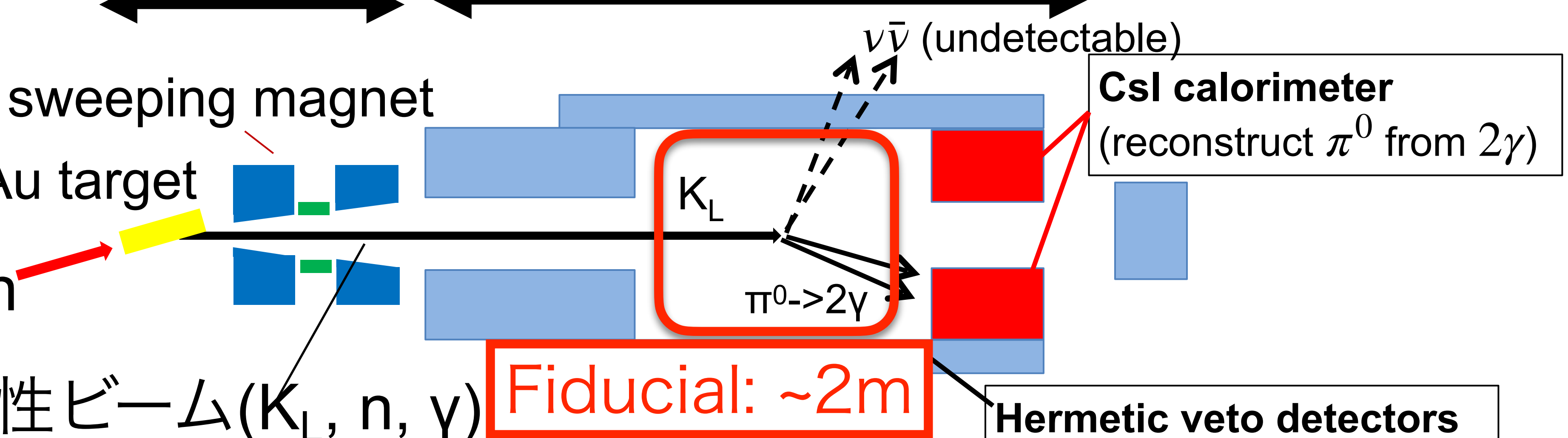


Detectors in vacuum tank

$K_L \to \pi^0 \nu\bar{\nu} : \pi^0(\to \gamma\gamma) +$ nothing

20m-long beam line

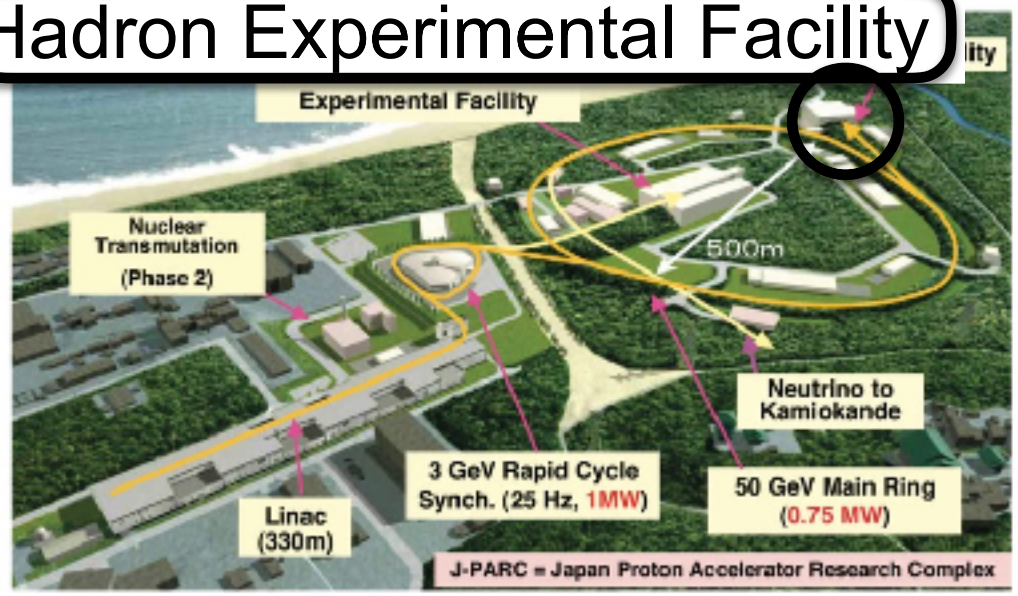
8.5m-long detector in vacuum tank



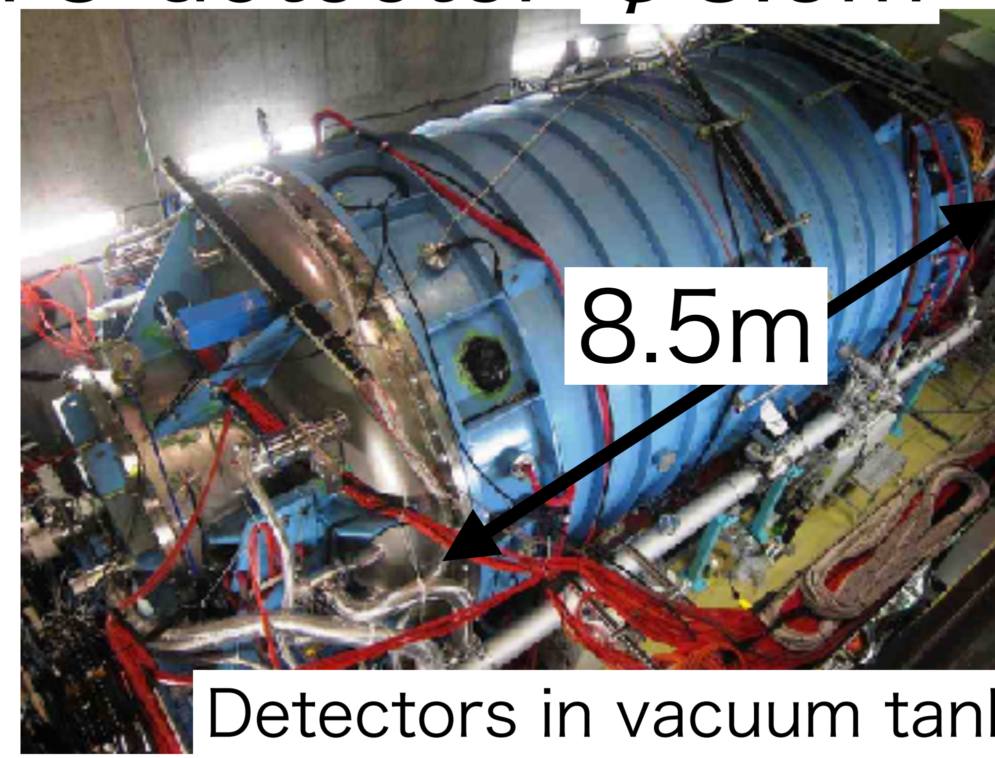
KOTO Experiment at J-PARC-MR

J-PARC MR 30 GeV proton

→Hadron Experimental Facility



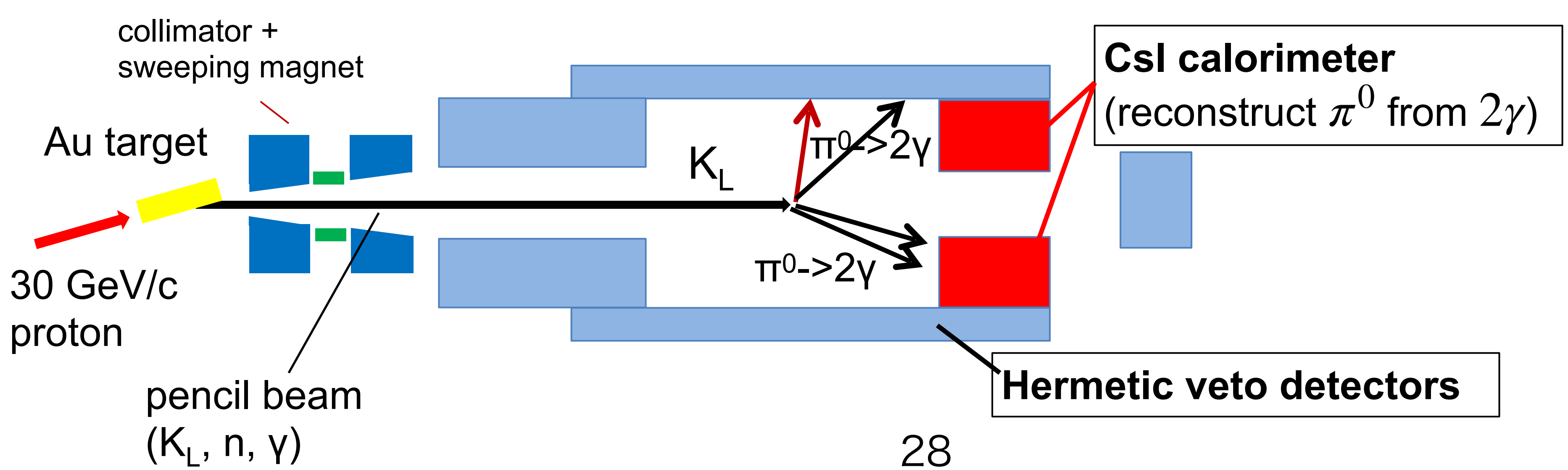
KOTO detector ϕ3.5m



Detectors in vacuum tank

Background to veto

ex.) $K_L \rightarrow 2\pi^0 \rightarrow 4\gamma$



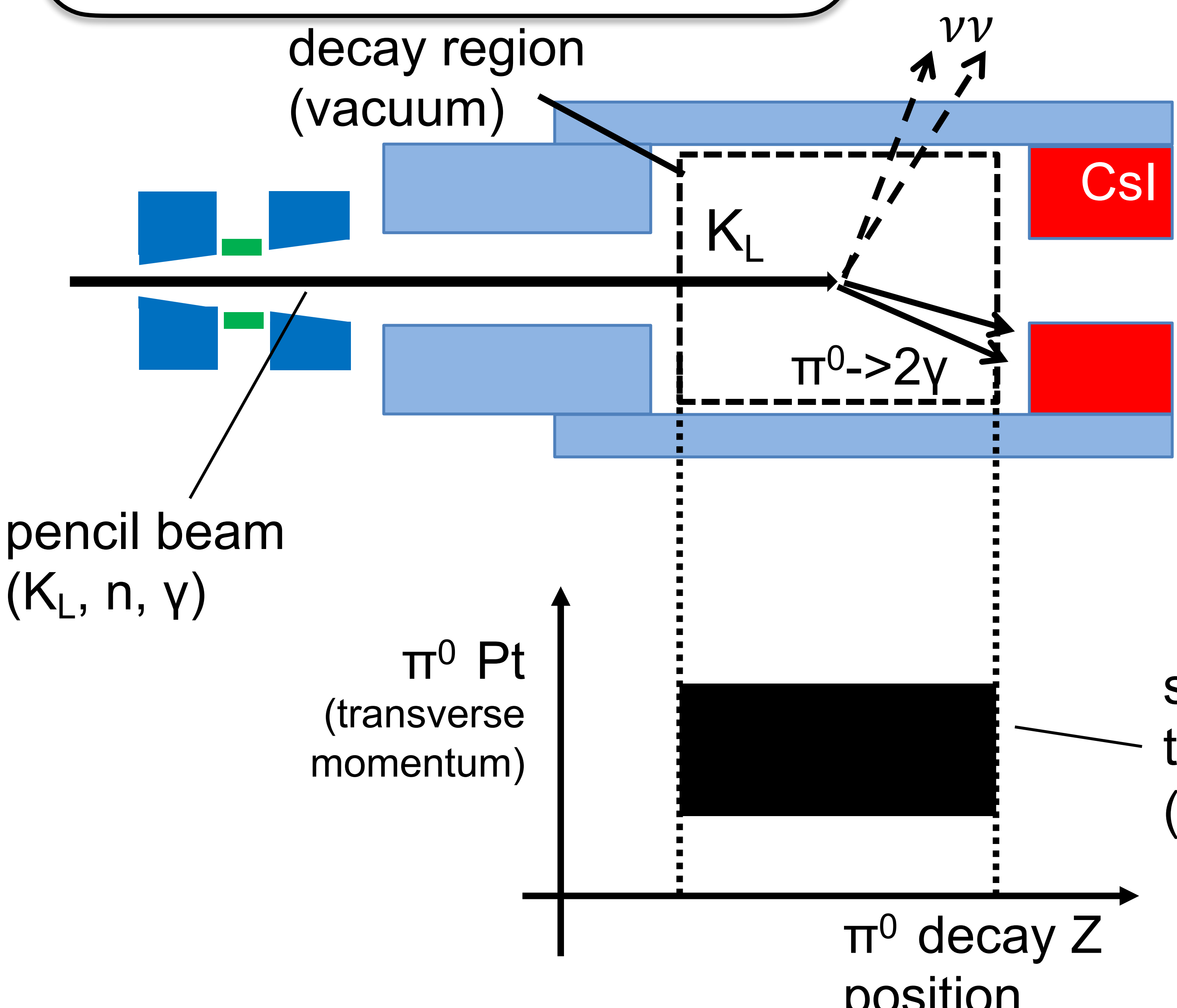
KOTO Signal Reconstruction

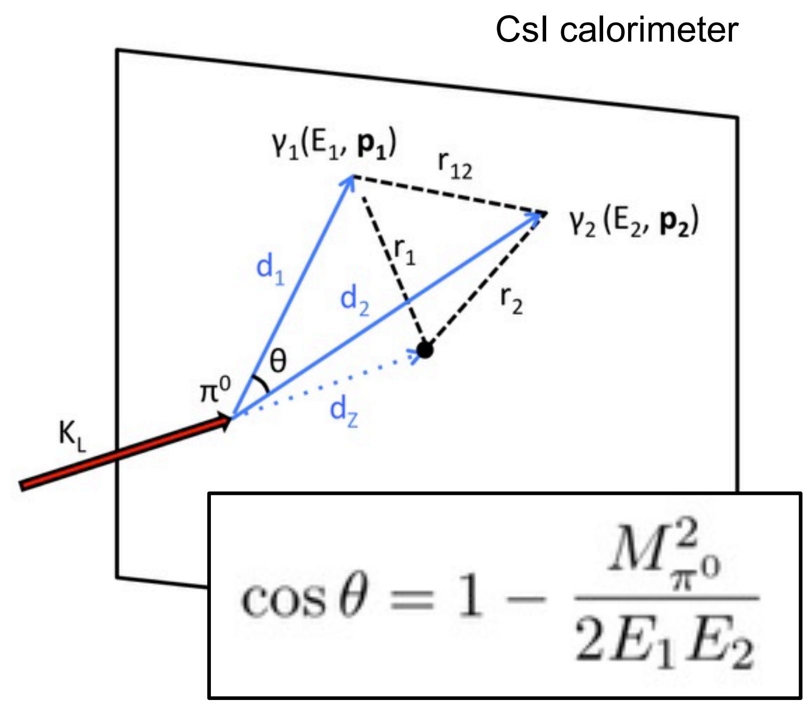
- 2γ in calorimeter
- Assume vertex on axis
- m_{π^0} assumption

→ Full π^0 reconstruction

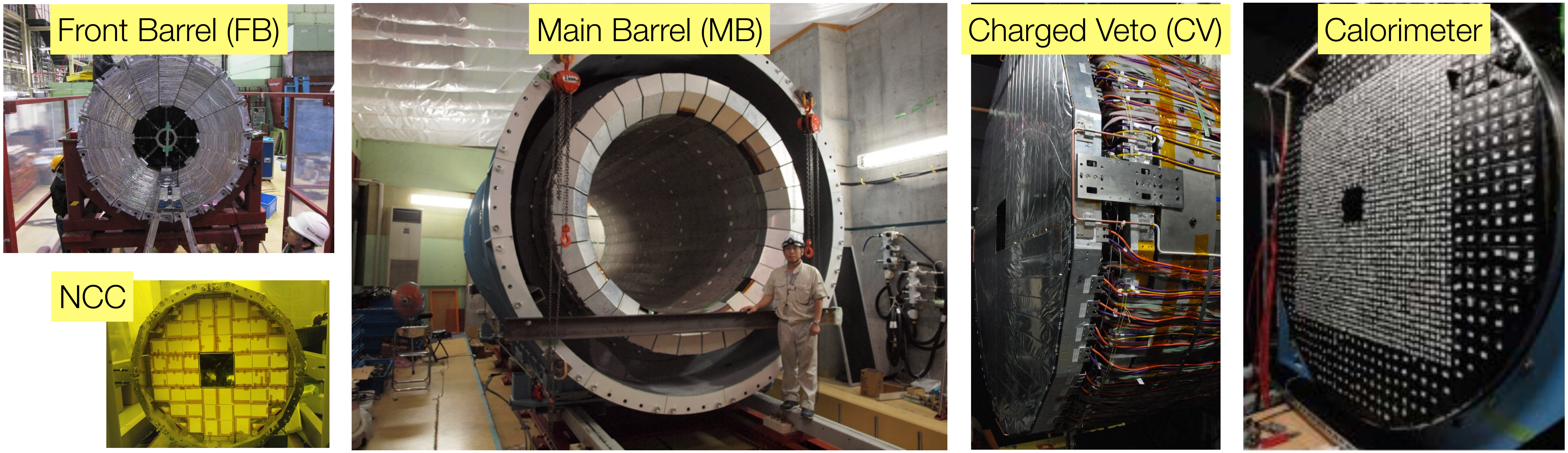
select higher pT

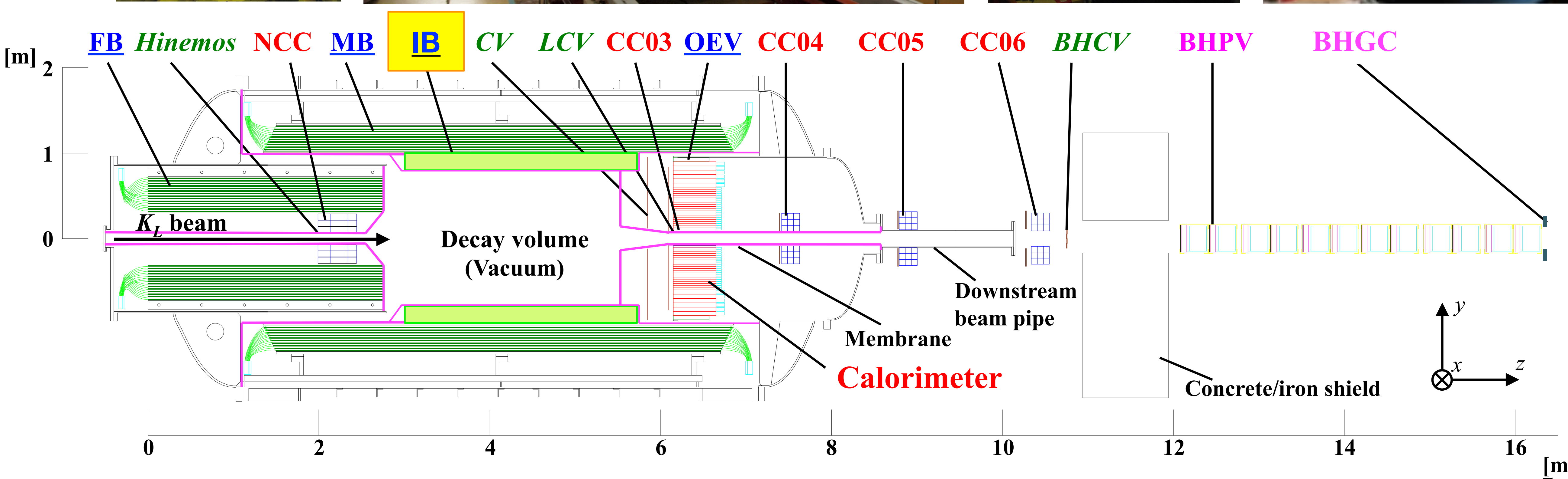
$\leftrightarrow K_L \to 2\gamma, K_L \to \pi^+\pi^-\pi^0$





KOTO Detector





稀崩壊探索、Veto実験の難しい点

- 背景事象　(始状態、終状態ともに中性)
  - 分岐比の大きいもの：シミュレーションが難しい
  - 検出器のinefficiency：10^{-3} ～10^{-4}を議論
- シミュレーション
- 加速器
- 検出器のレート
- 信号事象のアクセプタンス
- などなど
  - ビームライン、データ収集、解析、…

背景事象との戦い$K_L \to \pi^- e^+ \nu$

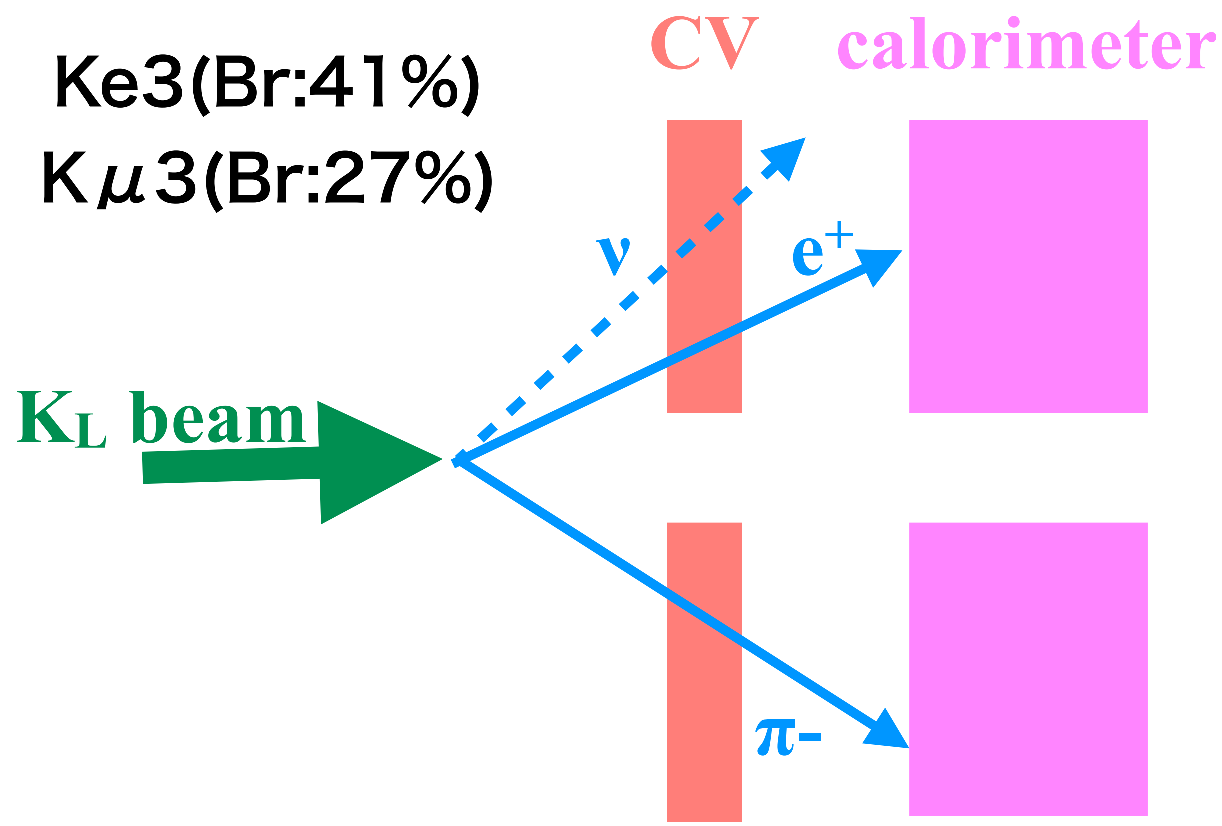
Inefficiency : 10^{-3}/layer

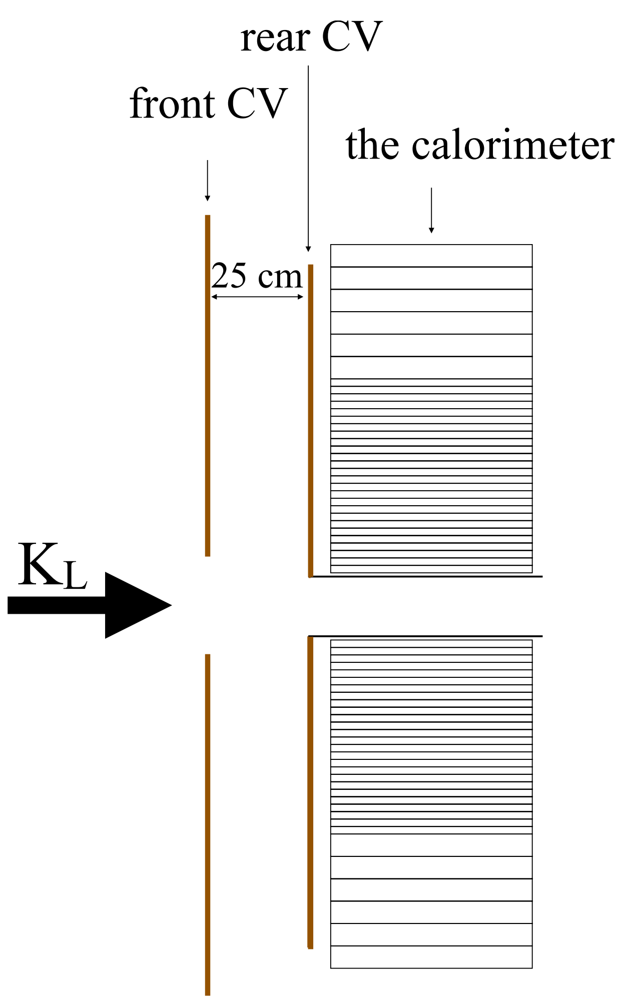
→Background : $O(1) \times (10^{-3})^4 = 10^{-12}$

中性子との相互作用を抑制→薄く！

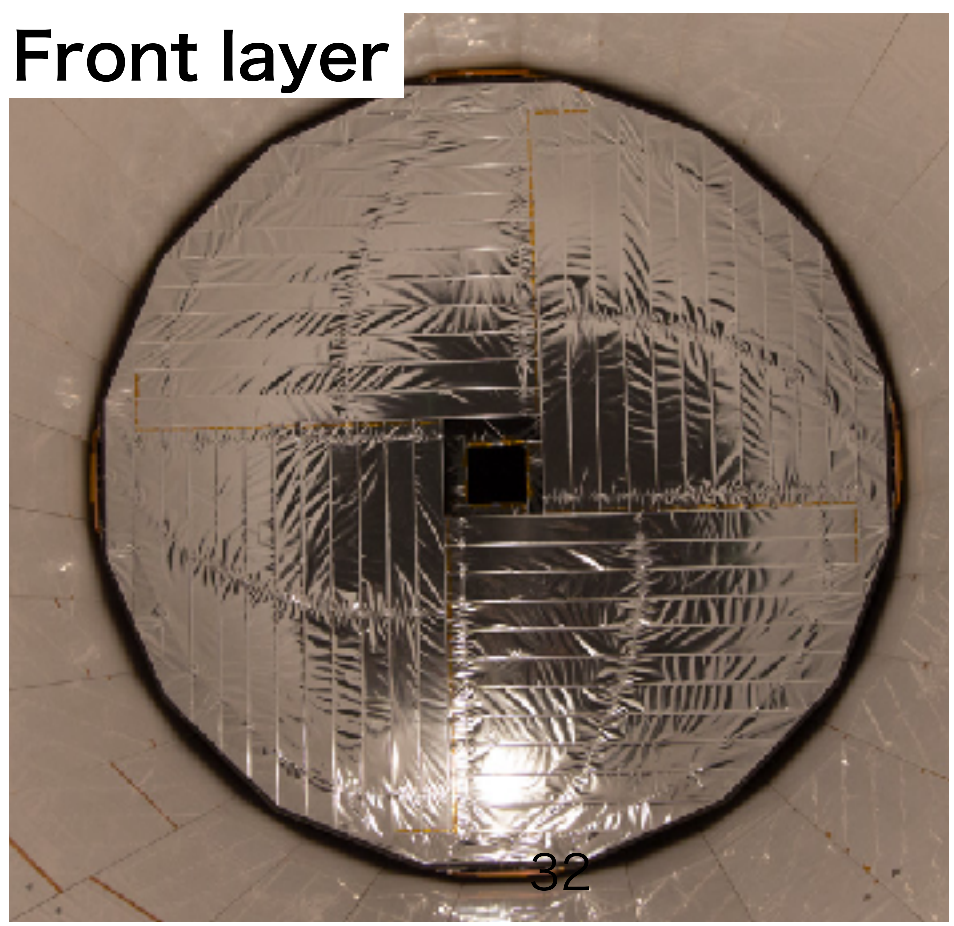
$$n + n \to n + n + \pi^0$$

Ke3(Br:41%)
Kμ3(Br:27%)





Front layer

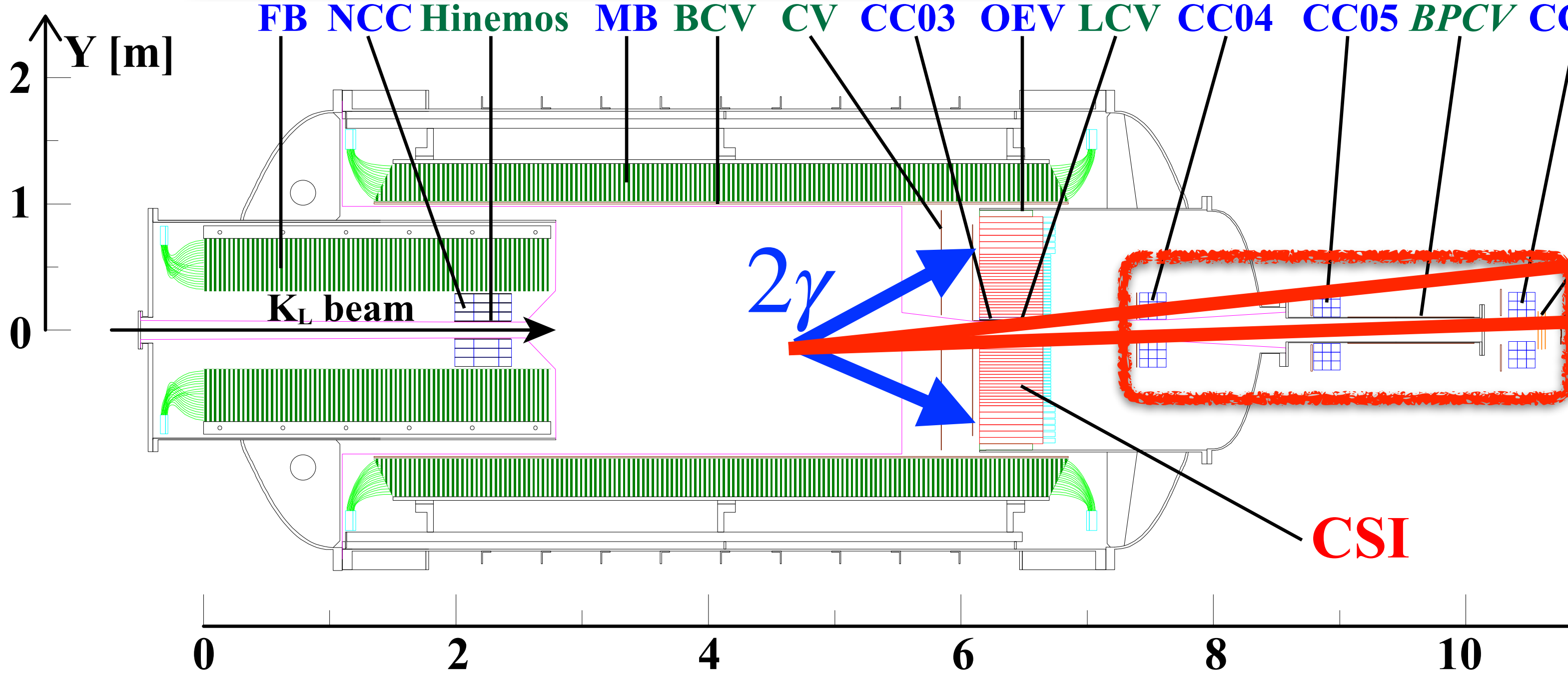


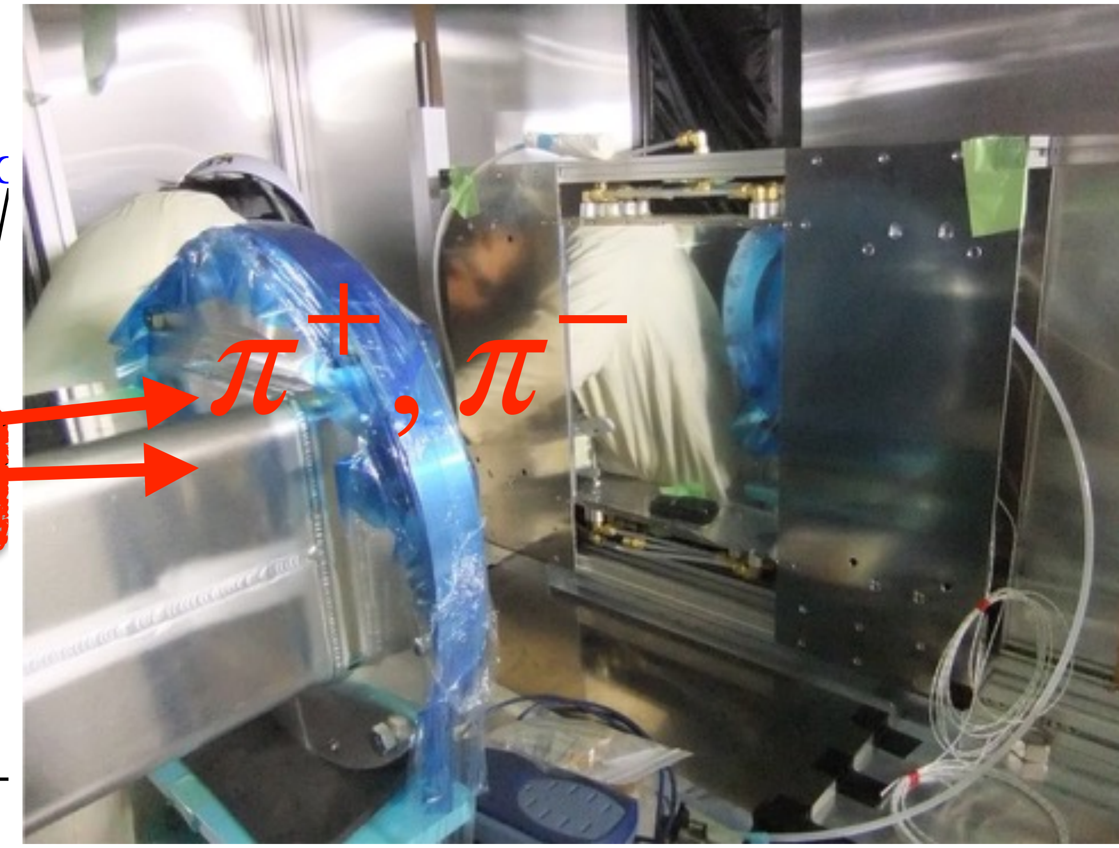
Rear layer

3-mm thick plastic scinti.
1mmφ WLS fiber+MPPC
0.8mm thick CFRP plate

背景事象との戦い$K_L \to \pi^+\pi^-\pi^0$

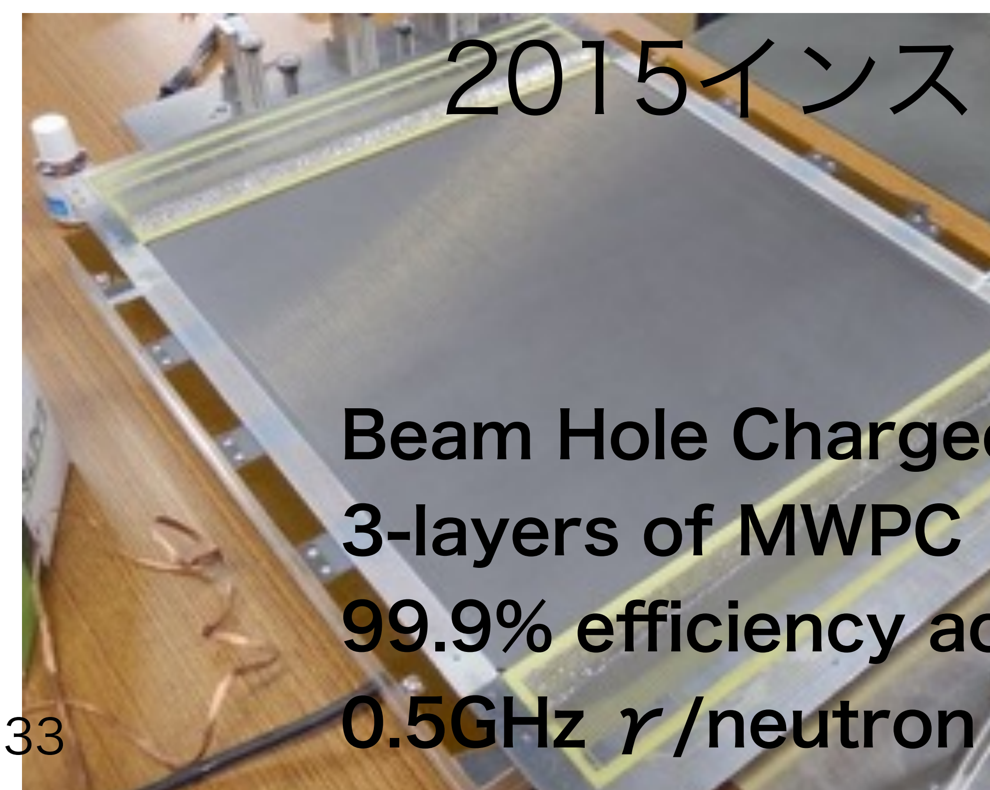
Veto $K_L \to \pi^+\pi^-\pi^0$: $\mathscr{B} = 13\,\%$





2019インストール

DCV(Downstream Charged Veto)
Active Pipe in Vacuum
5mm-thick plastic scintillator



2015インストール

Beam Hole Charged Veto
3-layers of MWPC (thin gap)
99.9% efficiency achieved in
0.5GHz γ/neutron incident

背景事象との戦い$K_L \to 2\pi^0$

$$\mathscr{B} = 10^{-3} \to 10^{-3} \times (10^{-4})^2 = 10^{-11}$$

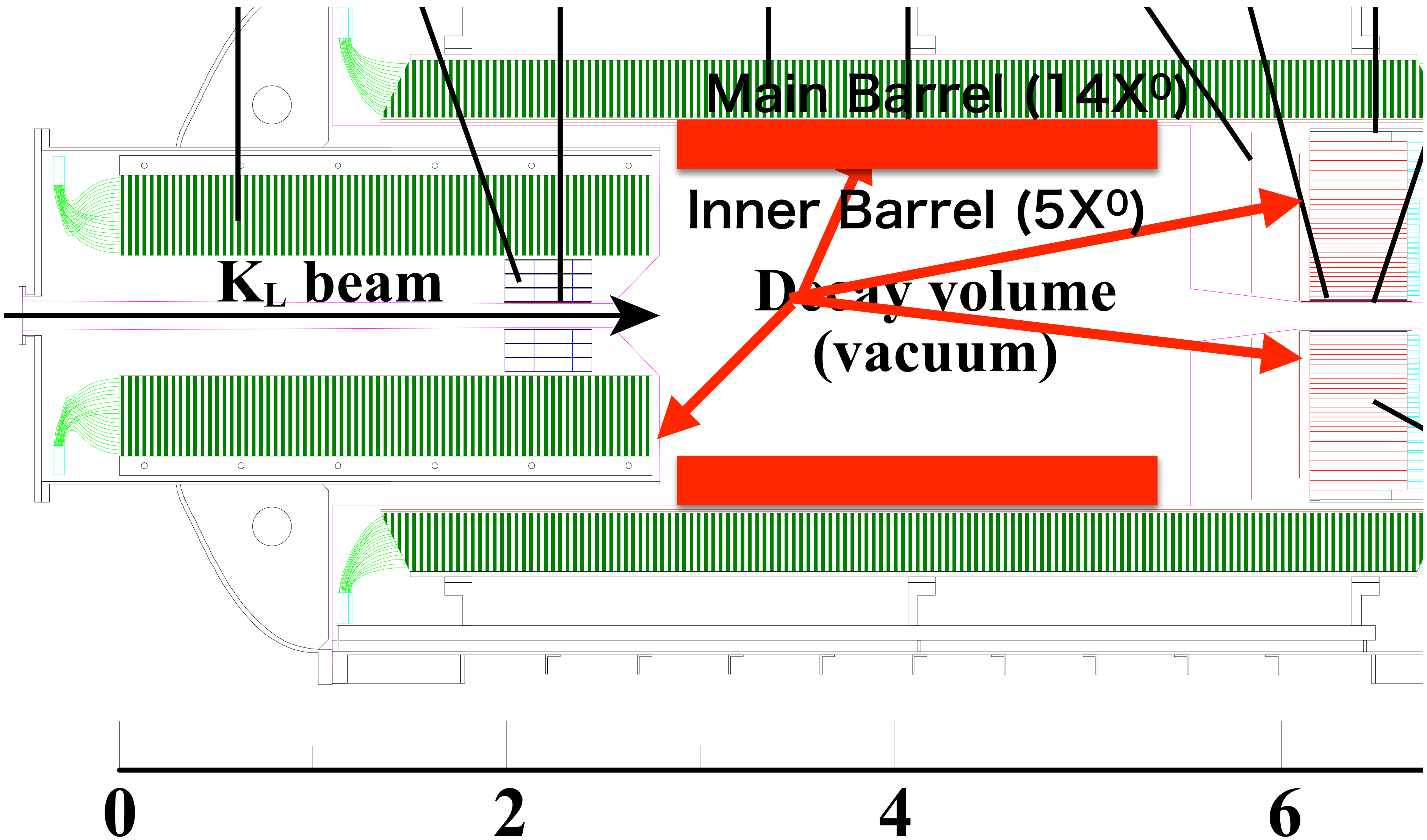
Energy損失：1MeVの検出

Inefficiency

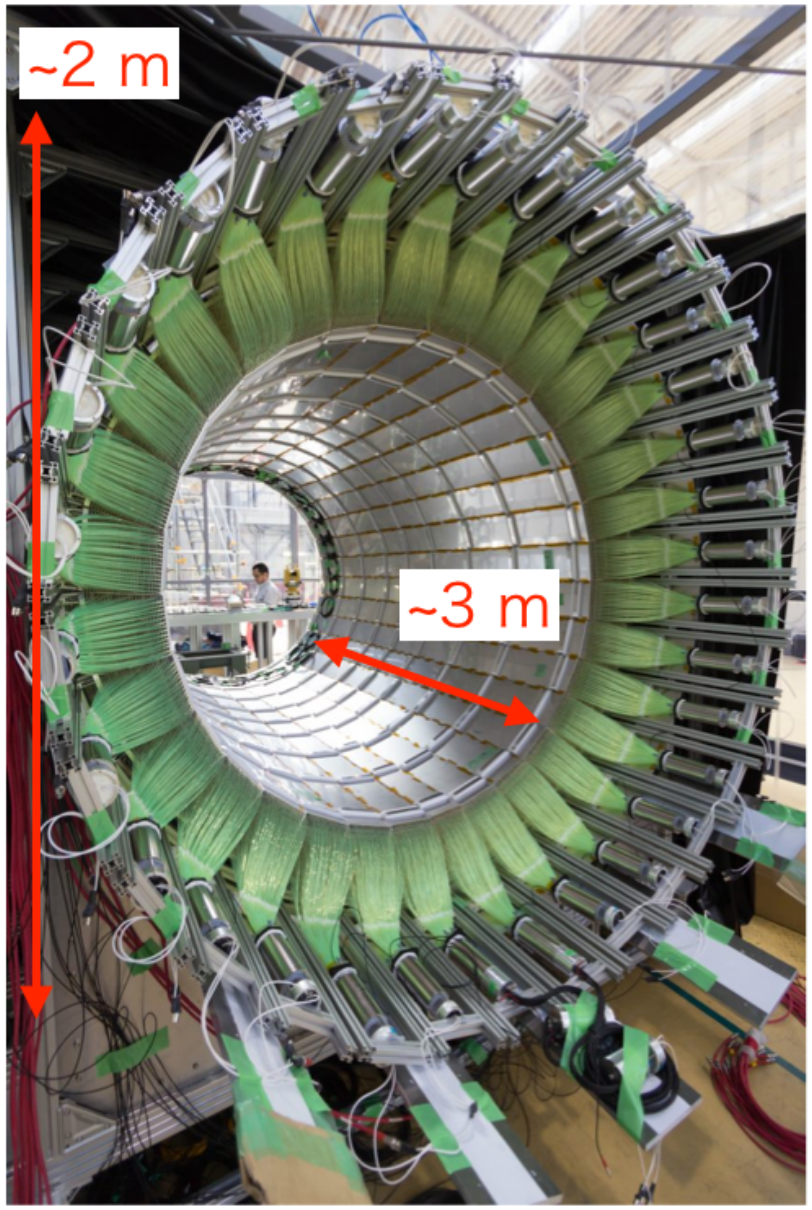
IB (Inner Main Barrel)

5.5m-long lead(1mm)/scinti.(5mm) sandwich ($5X^0$)

Both-end readout with WLS fiber



2016インストール



背景事象との戦い $K_L \to 2\pi^0$

Veto γ escaping in-beam region : 0.5GHz γ/neutron

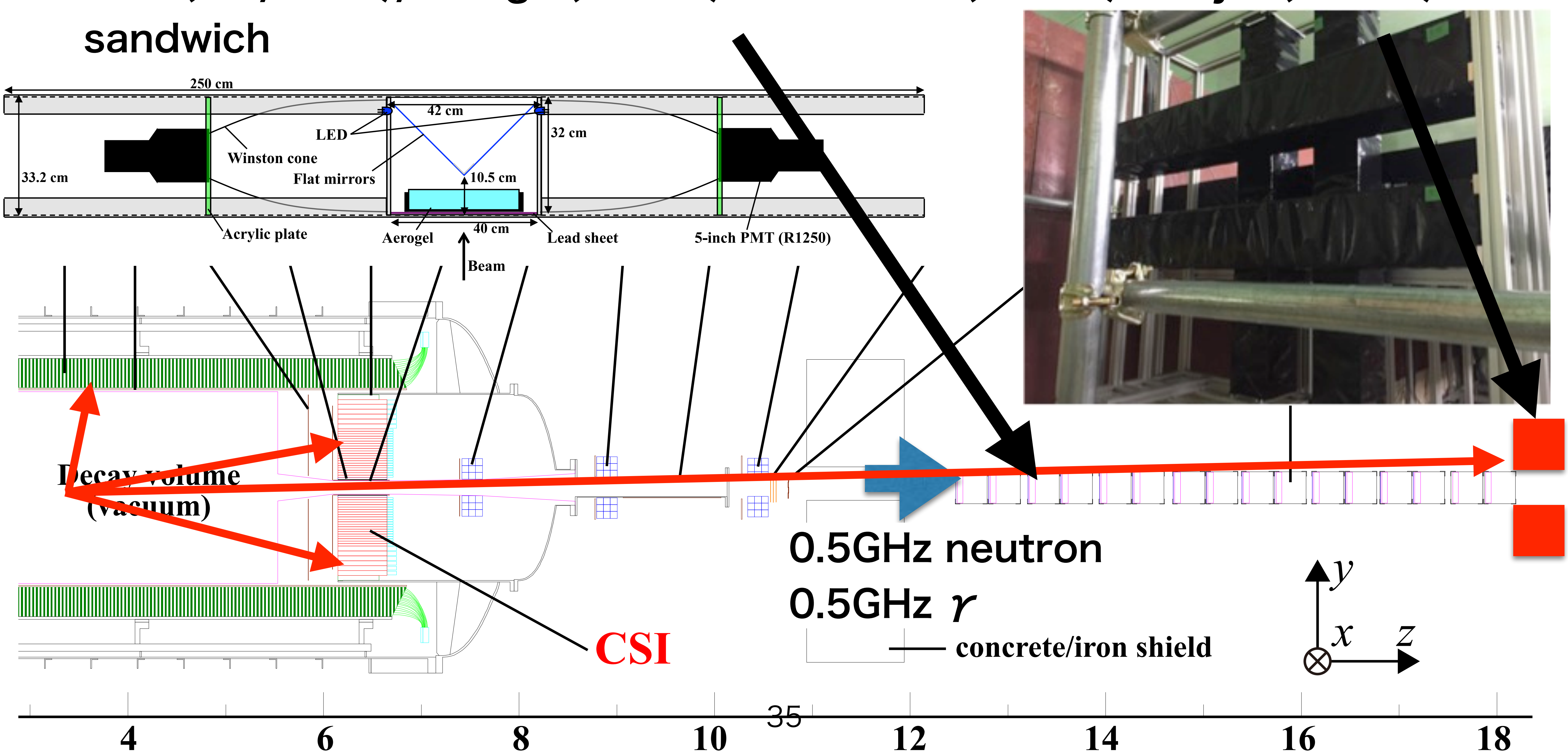
→ Cherenkov radiation → neutron insensitive

BHPV (Beam Hole Photon Veto)

Lead(1.5/3mm)/aerogel(58mm) sandwich

BHGC (Beam Hole Guard Counter)

Lead(10mm)+acrylic(10mm)



背景事象との戦いneutron→π^0/η

Hit detectors →π^0/η production→2γ

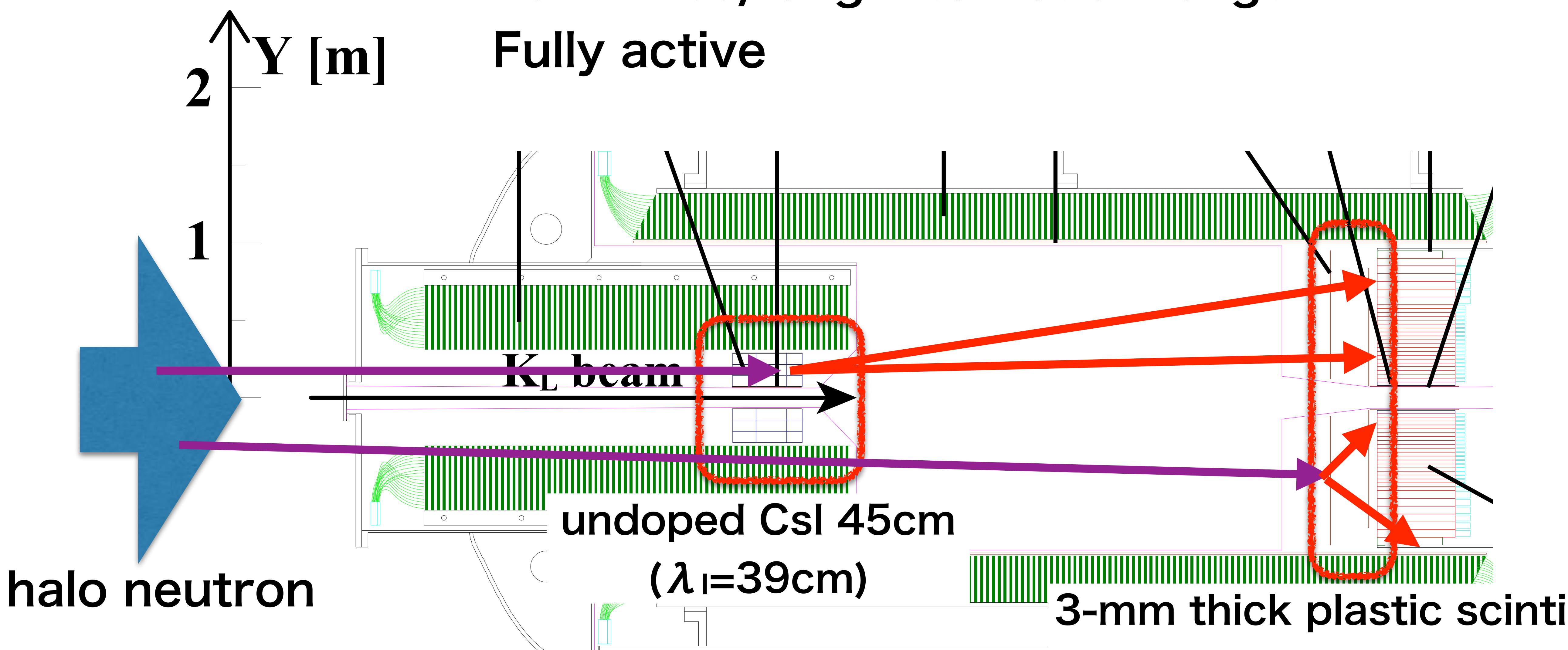
Collimated beam

Away from beam in R

Away from signal region in Z

Low-mass/long interaction length

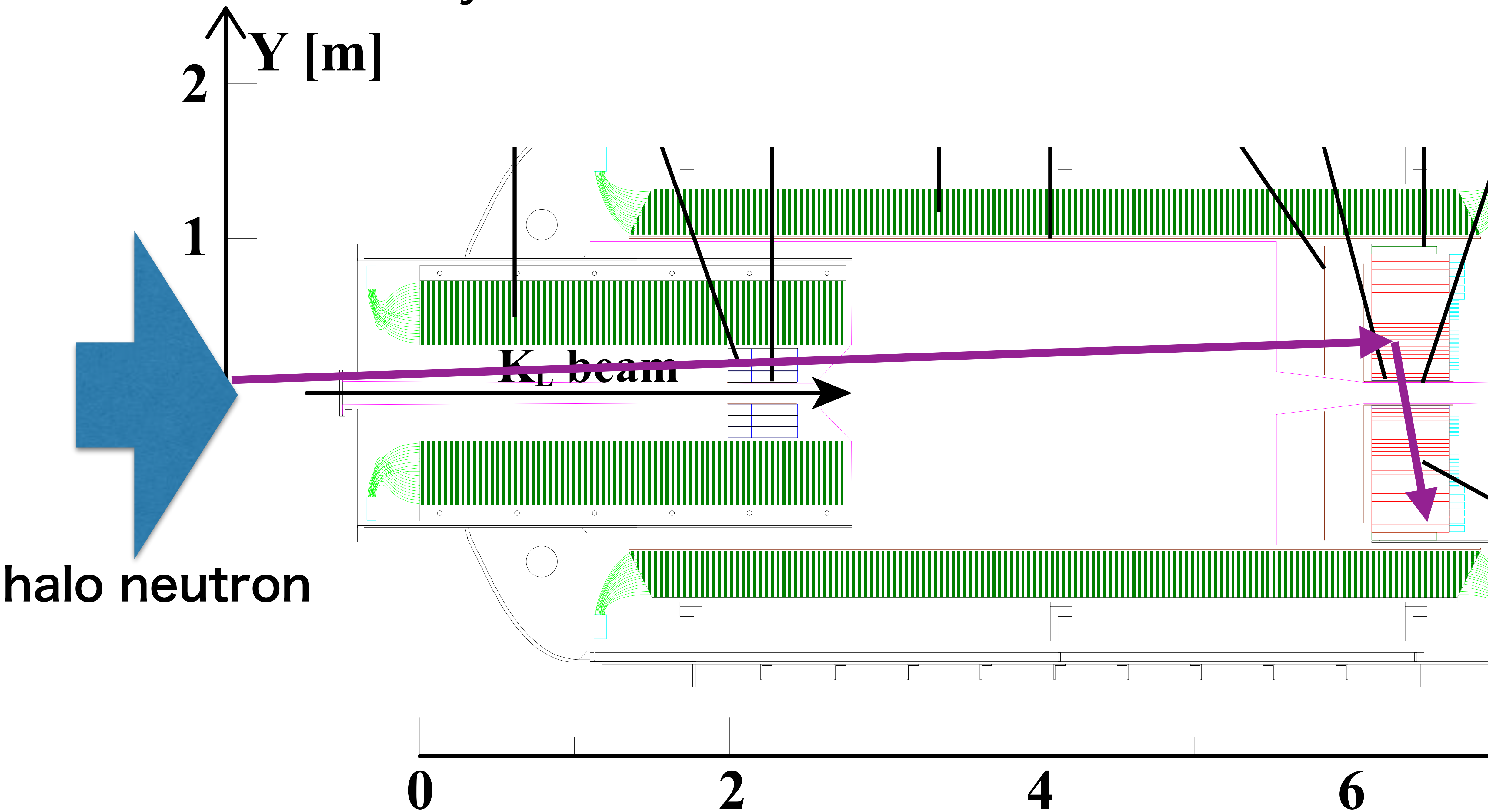
Fully active



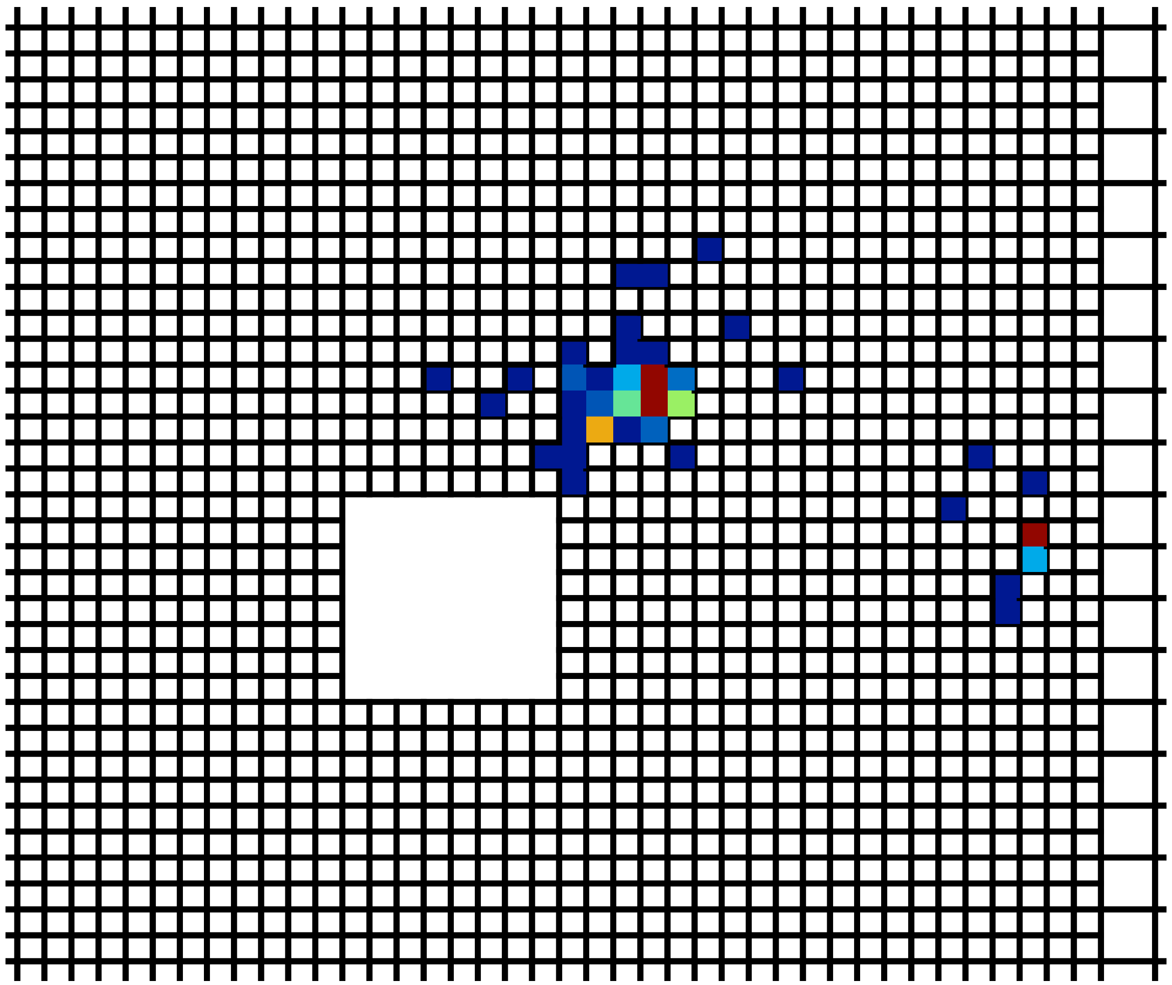
背景事象との戦いneutron→2 hits

Single neutron hit CSI calorimeter directory

secondary neutron -> another cluster



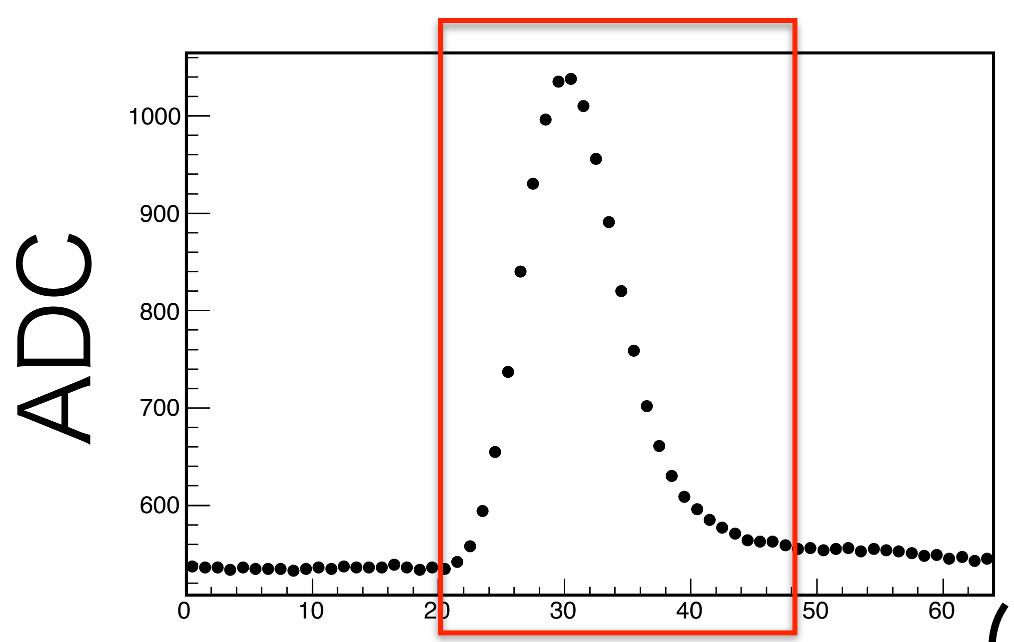
背景事象との戦いneutron→2 hits



n/γ discrimination

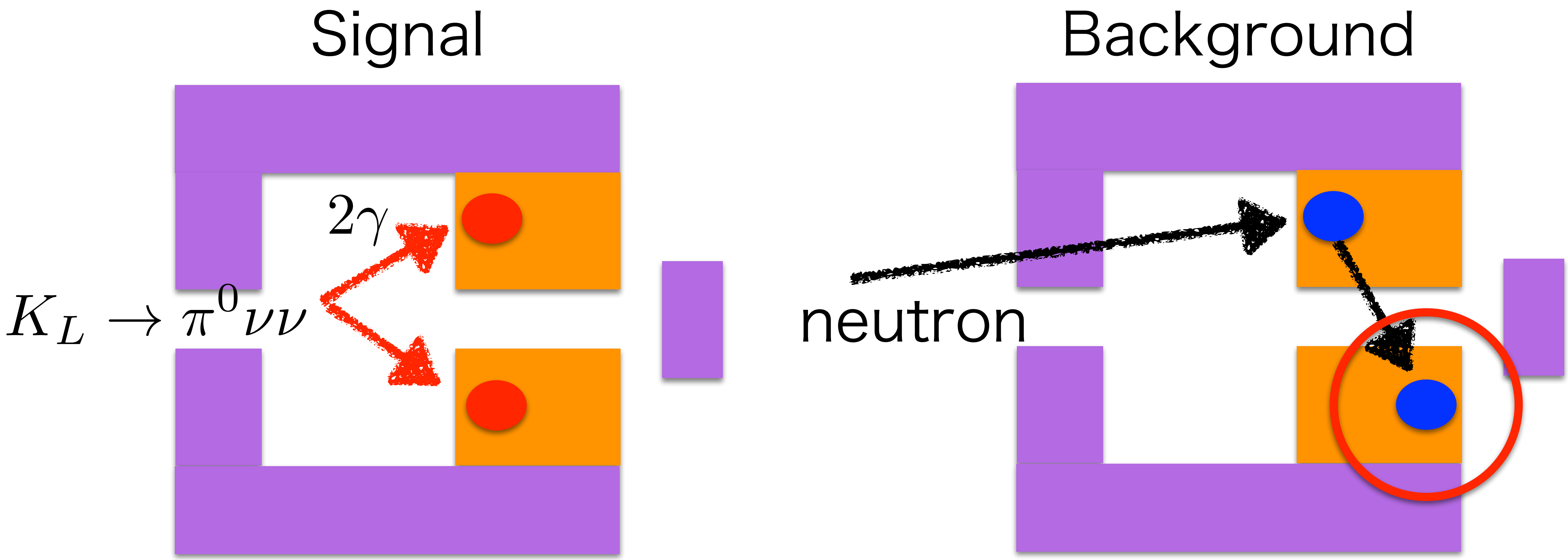
Cluster形状 ~ 10^{-5}

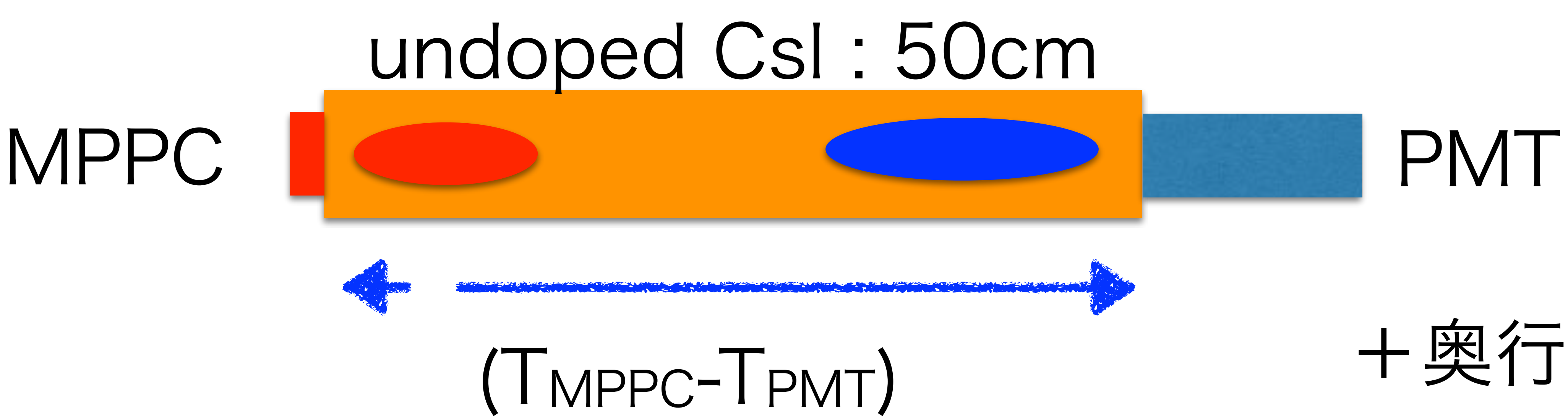
波形弁別 ~ 10^{-1}



(clock=8ns)

背景事象との戦いneutron→2 hits





gamma < neutron background

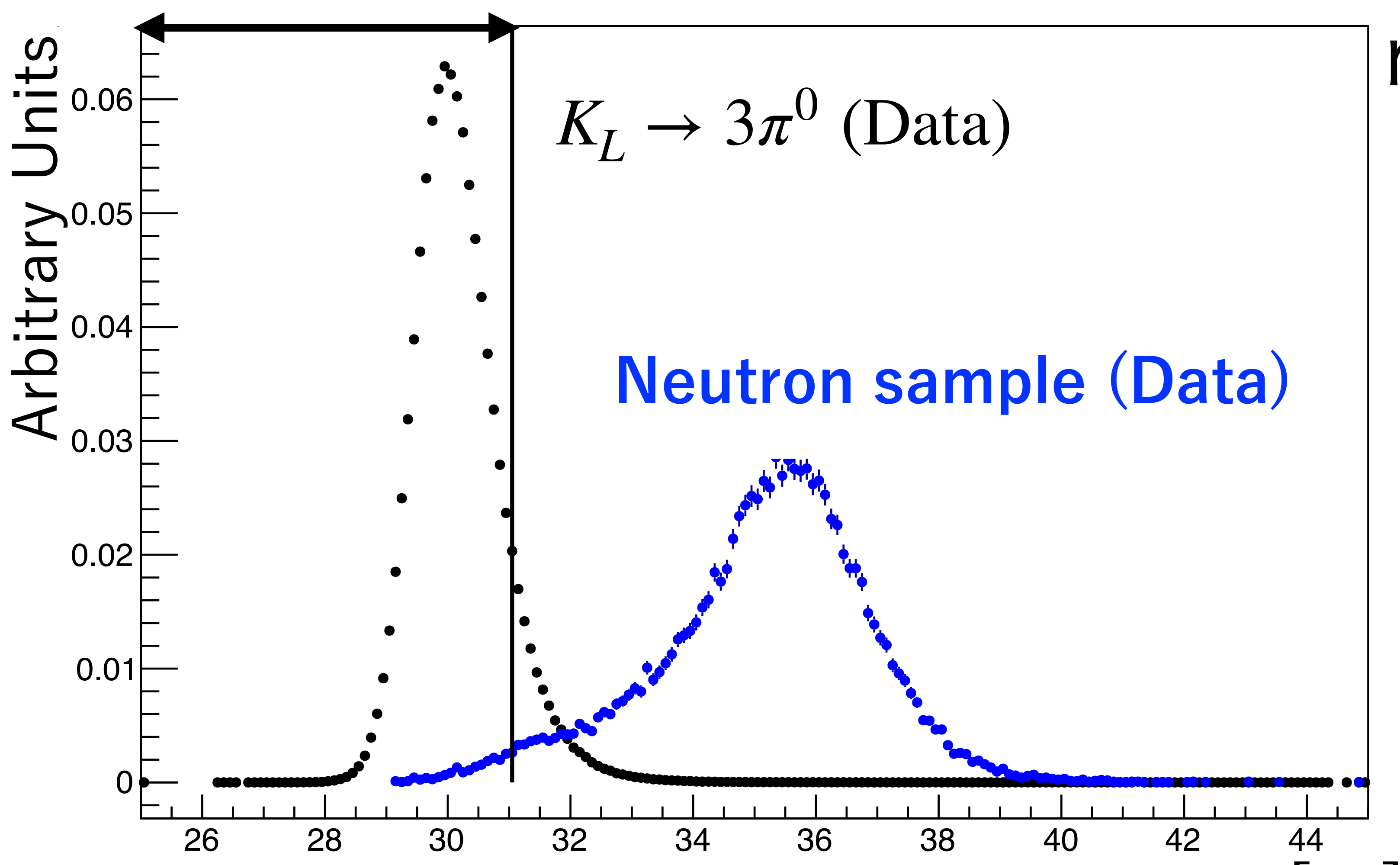
＋奥行き方向の位置
4次元カロリメータ

Upgrade Work in 2019

CsI結晶に4000個のMPPCを接着

背景事象との戦いneutron→2 hits

- 実際のビームで得た性能
  - 信号事象90%選択、背景事象2%に削減



Osugi

$$\Delta T = T_{MPPC} - T_{PMT}$$

n/γ discrimination

Cluster形状 $\sim 10^{-5}$

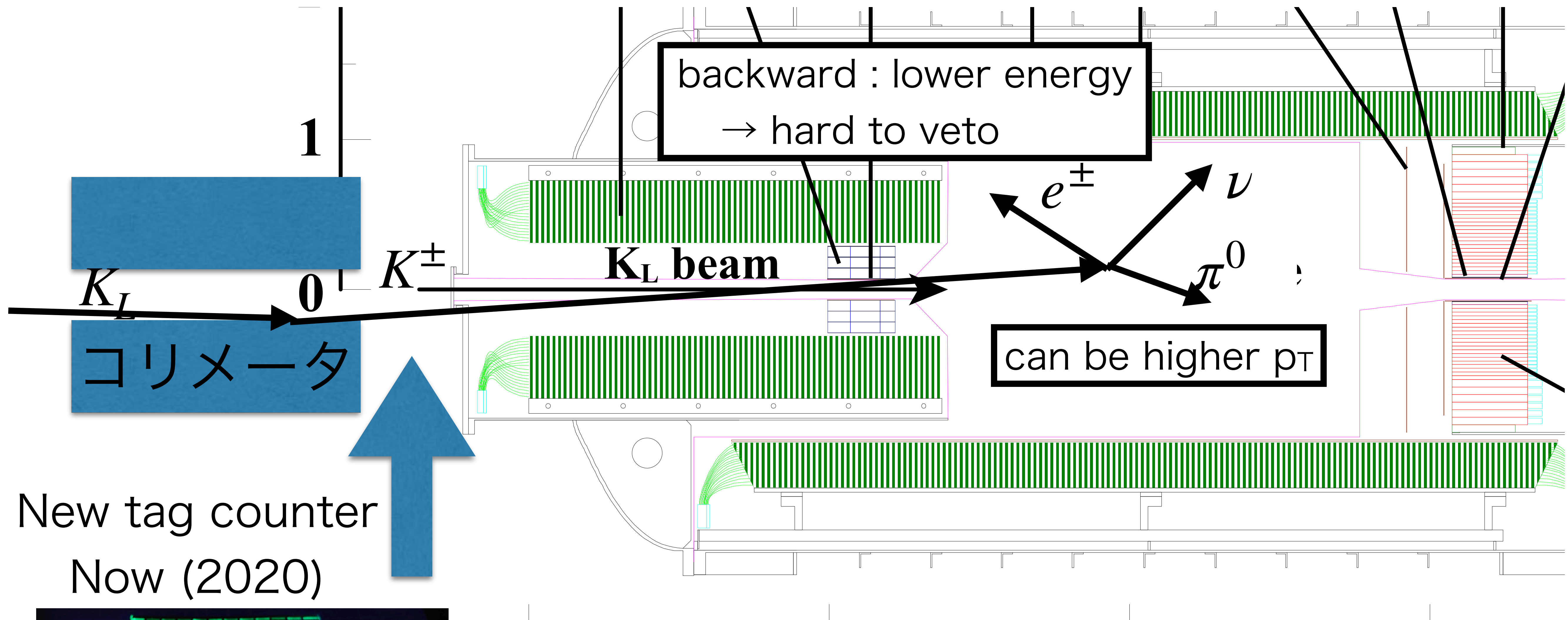
波形弁別 $\sim 10^{-1}$

両読み0.02

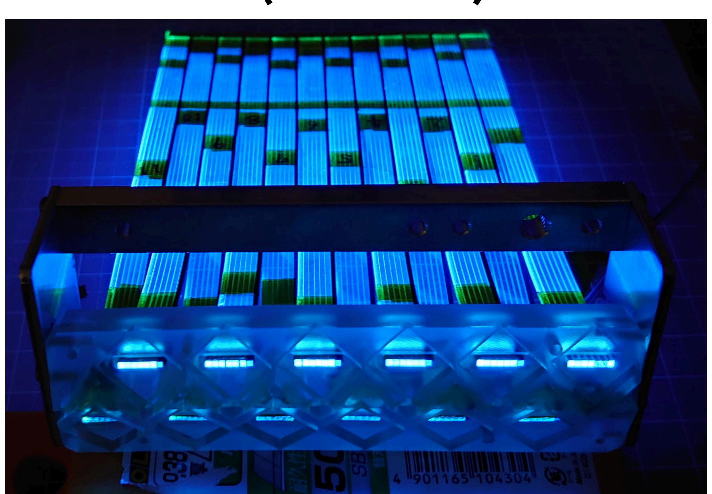
$N/S \sim 0.5$

背景事象との戦い$K_L \to K^+ \to \pi^0 e^+ \nu$

$\mathscr{B} = 5.1\,\%$



Now (2020)



Shimizu, Kotera

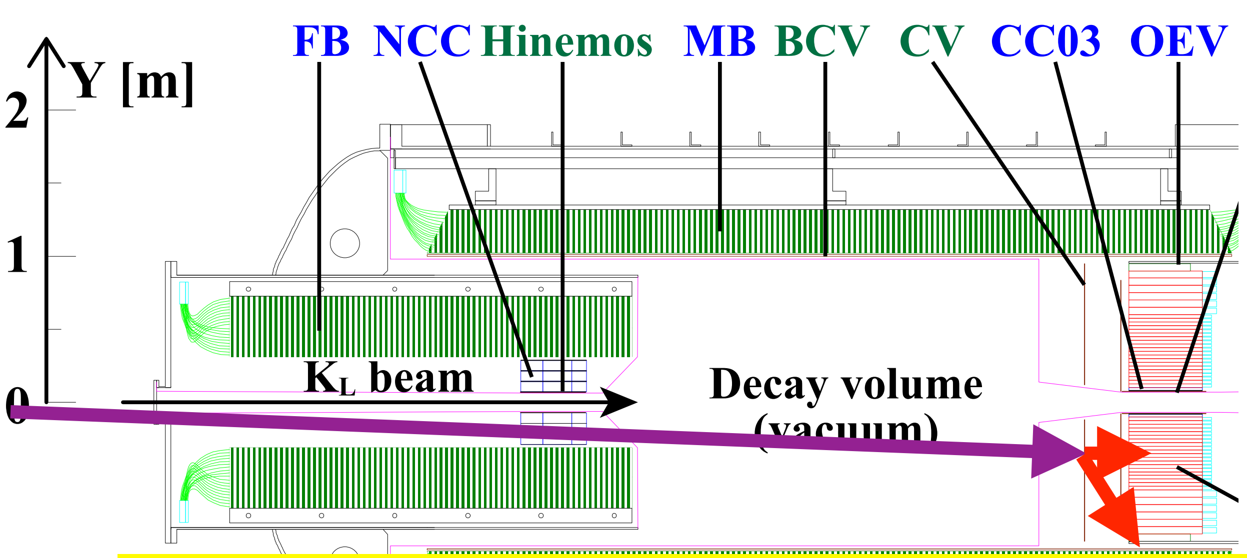
$N_{K^+} \sim 10^{-6} N_{K_L}$?→主要背景事象

→ 超低物質量真空中荷電粒子Vetoの開発

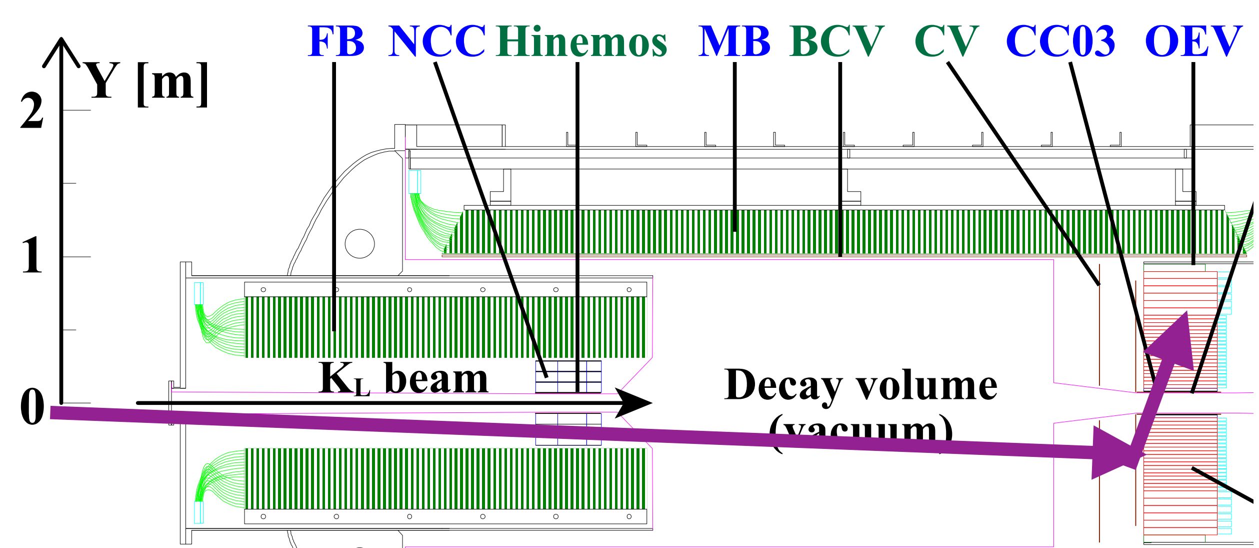
シミュレーション

- O(1)の分岐比のモード
- 10^{-9}の分岐比感度まで作る
  - 10^6 daysかかる=>1000 CPUでも3年ほど…
    - $K_L \to 2\pi^0(\mathscr{B} = 10^{-3})$：1000CPUなら1日
- 背景事象になりそうなphase spaceに特化
- Fast simulation (shower simulationをしない)

グーグルのTPU(Tensor Processing Unit)のような専用ハードで解決できんかな？



π^0/η生成に特化したsimulation



neutron→2 hitsに気づかない

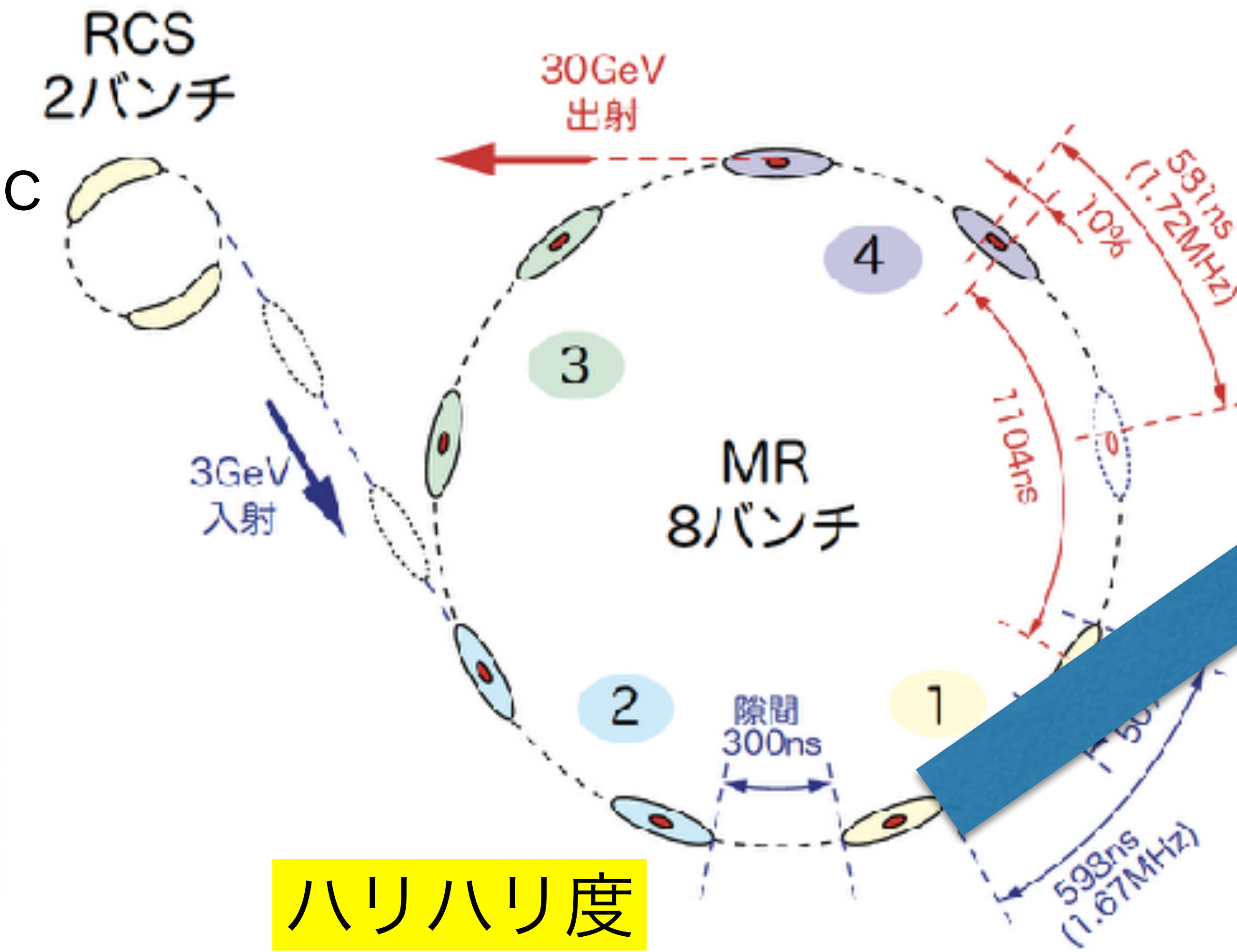
遅い取り出し

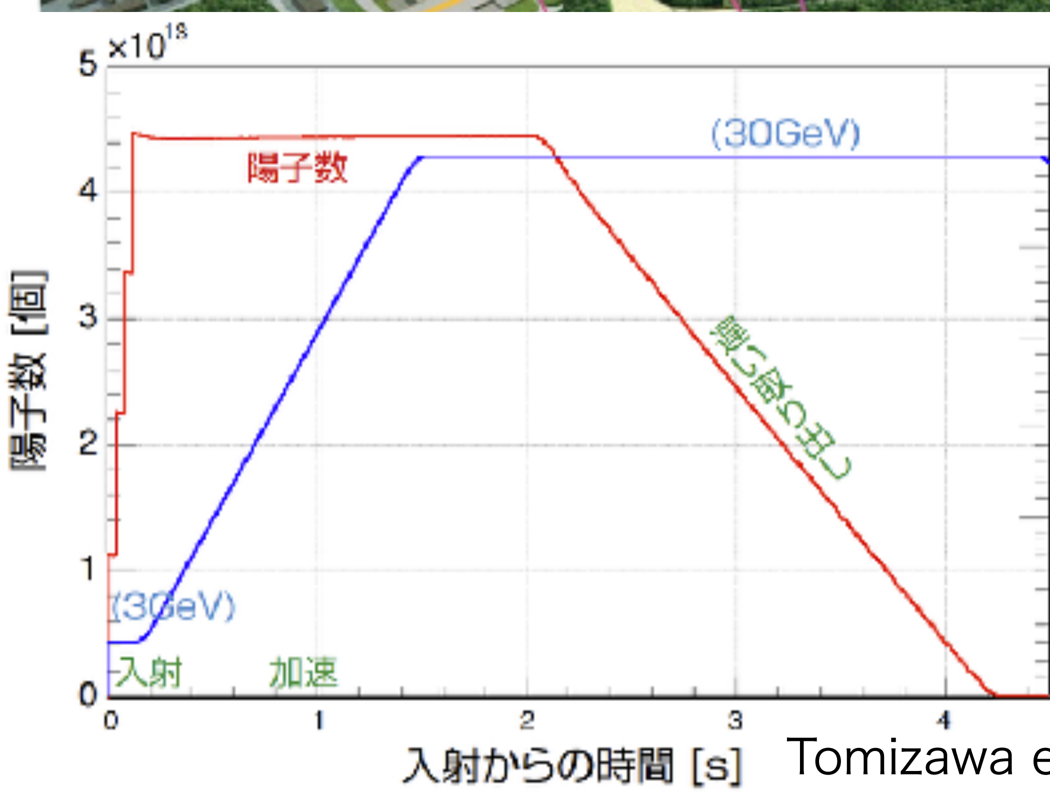
51kW

$Power \propto N_p^{ring}/T_{cycle}$ 5.2sec

$Rate \propto N_p^{ring}/T_{spill}$ 2sec

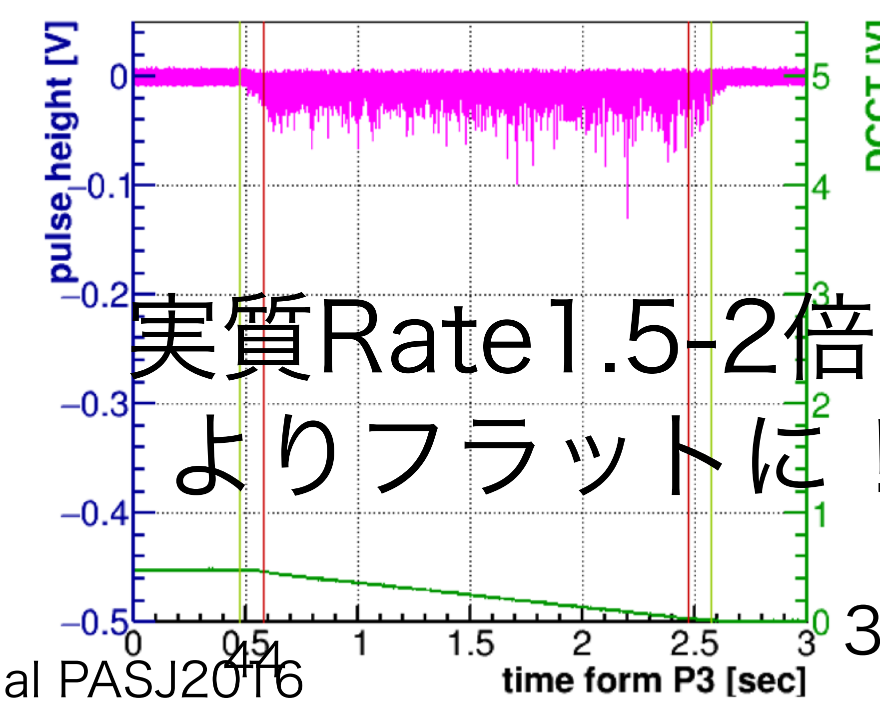
5.5×10^{13}pronts/2sec



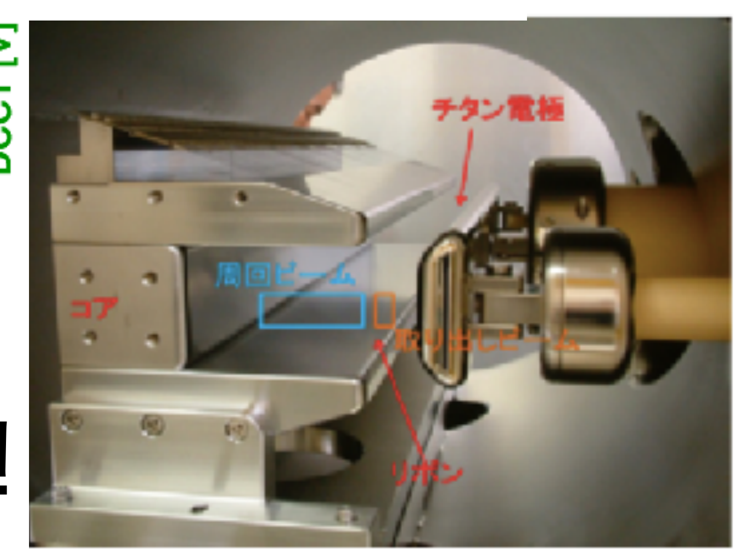


Tomizawa et al PASJ2016

ハリハリ度

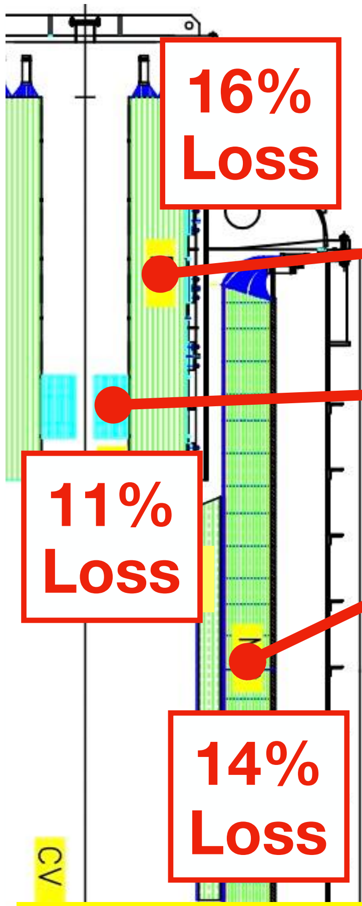


実質Rate1.5-2倍
よりフラットに！

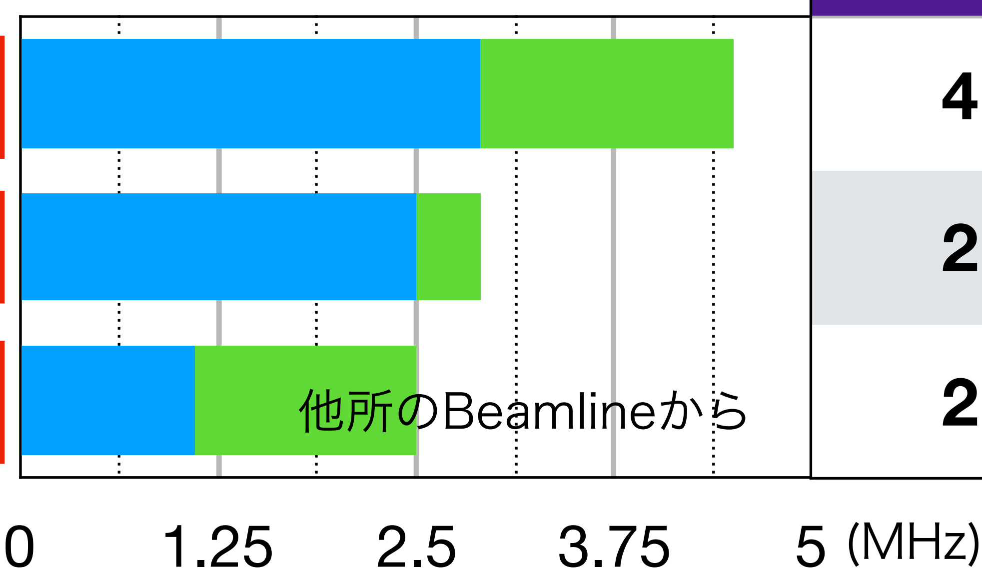


30um厚リボン:ビームロス

検出器のレート



偶発事象レートR [MHz]



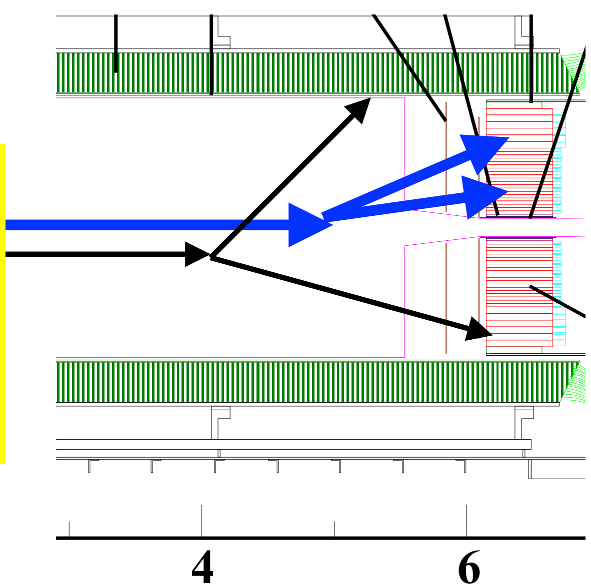
R [MHz]	w [ns]	L [%]
4.5	40	16
2.9	40	11
2.5	60	14

2019 Run(by Shiraishi)

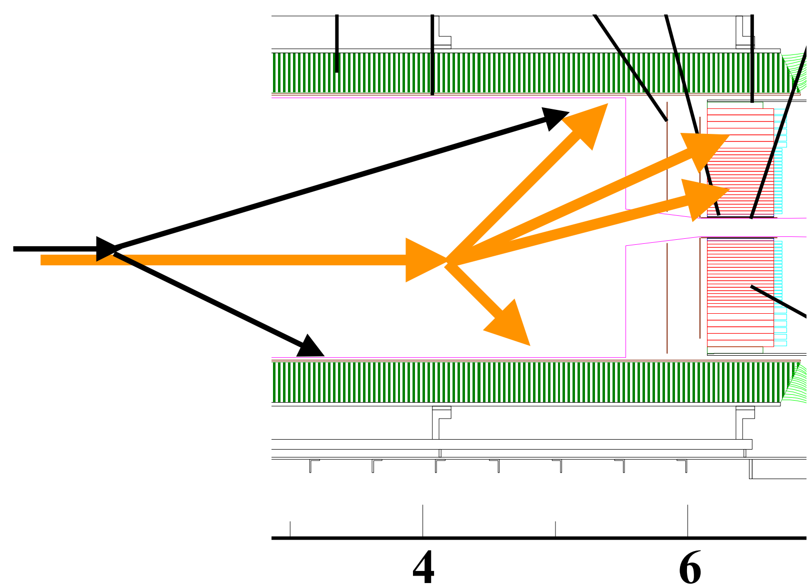
ビーム強度
ハリハリ度
他所から

↓

加速器増強
シールド

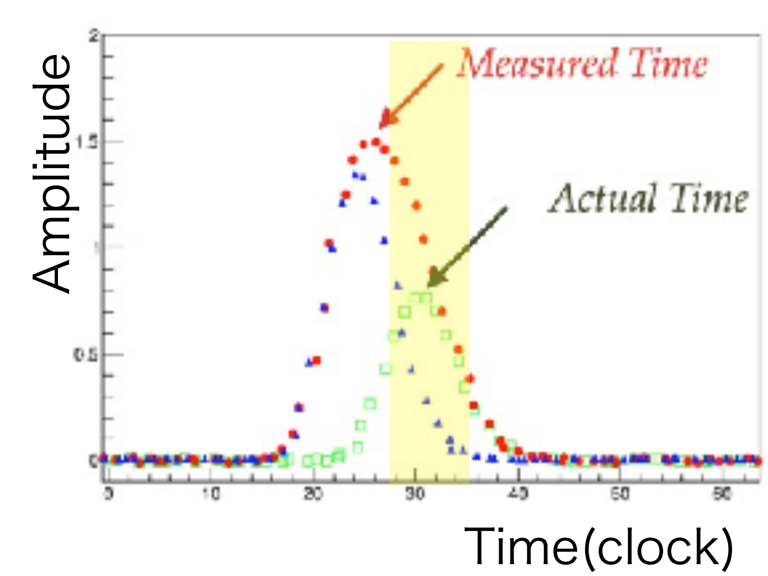


別のKLの崩壊で
信号をveto 😢



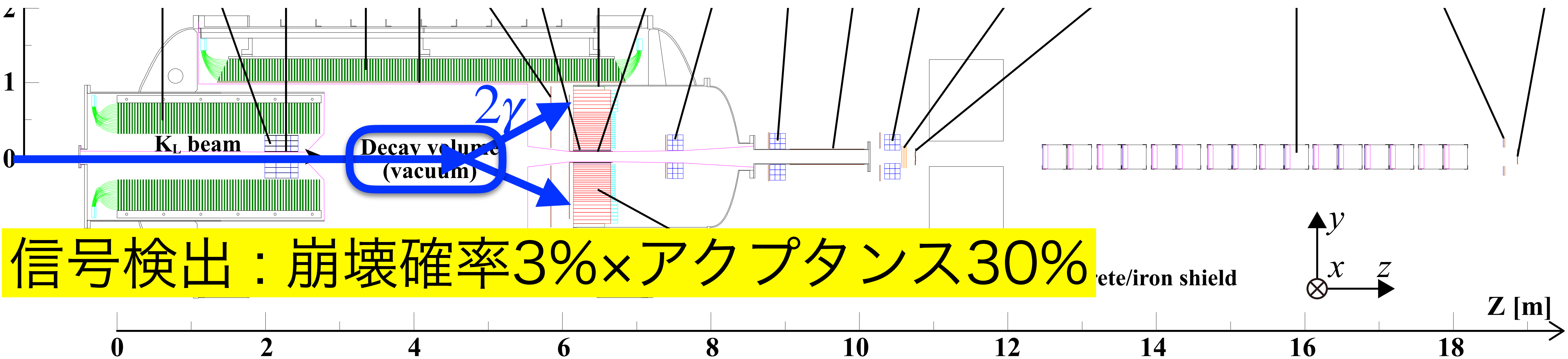
別のKLの崩壊で
背景事象をvetoできない 😢

example of overlapped waveform

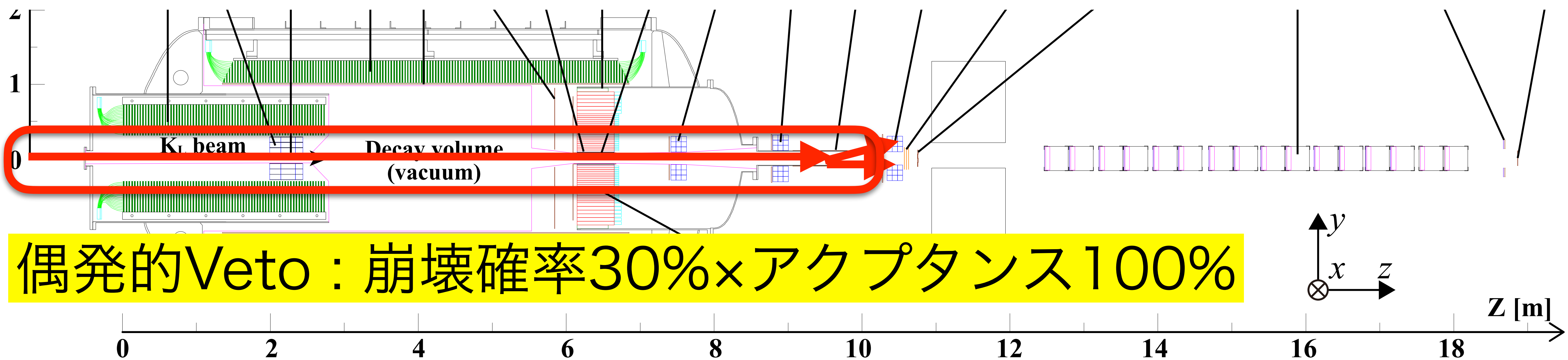


single channel rate→分割すれば解決

信号事象アクセプタンス



信号検出：崩壊確率3%×アクセプタンス30%

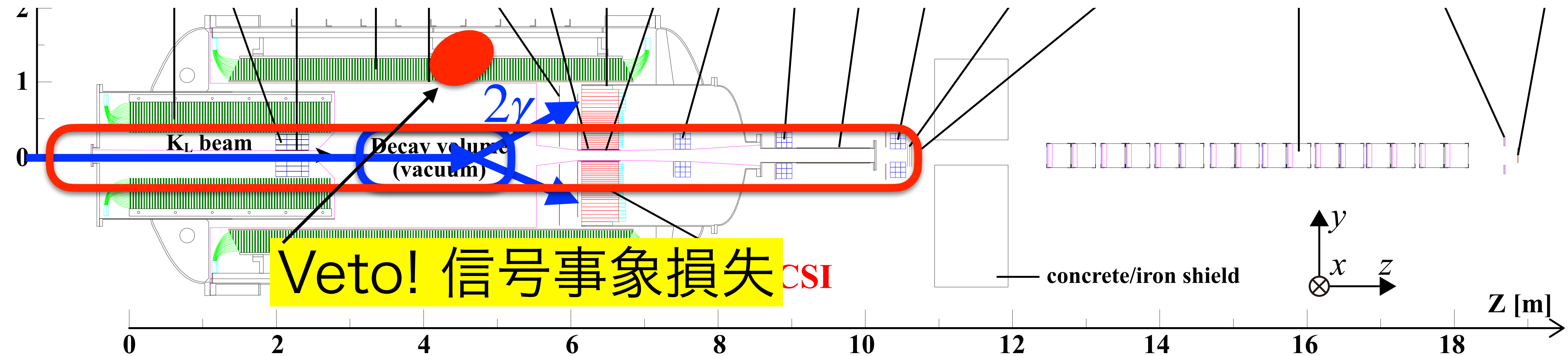


偶発的Veto：崩壊確率30%×アクセプタンス100%

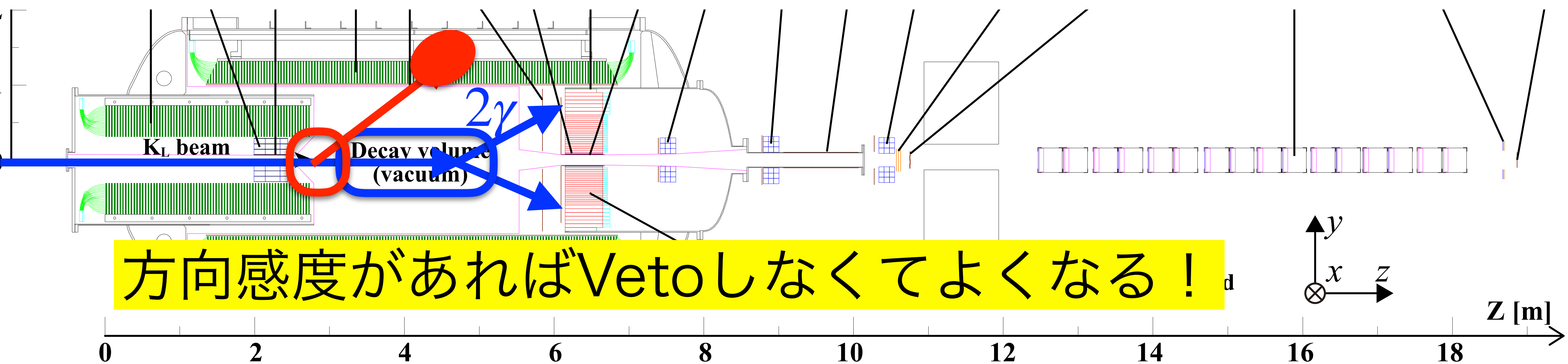
信号事象の数: 信号×(1-偶発的Veto確率)

beam強度のBottle neck

γ 線方向感度？



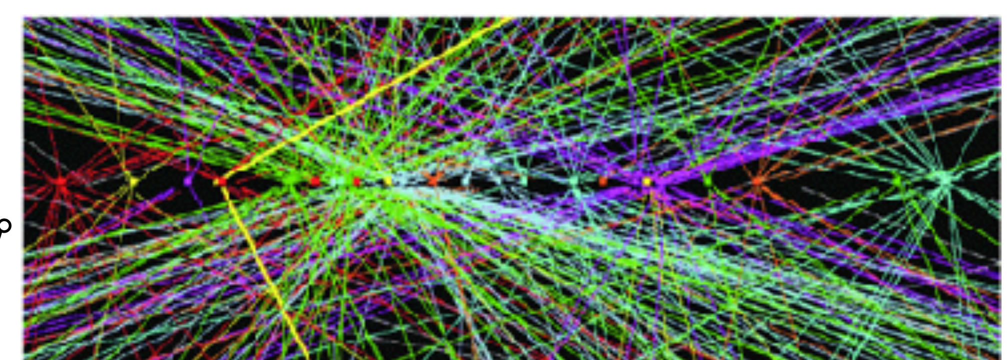
Veto! 信号事象損失



方向感度があればVetoしなくてよくなる！

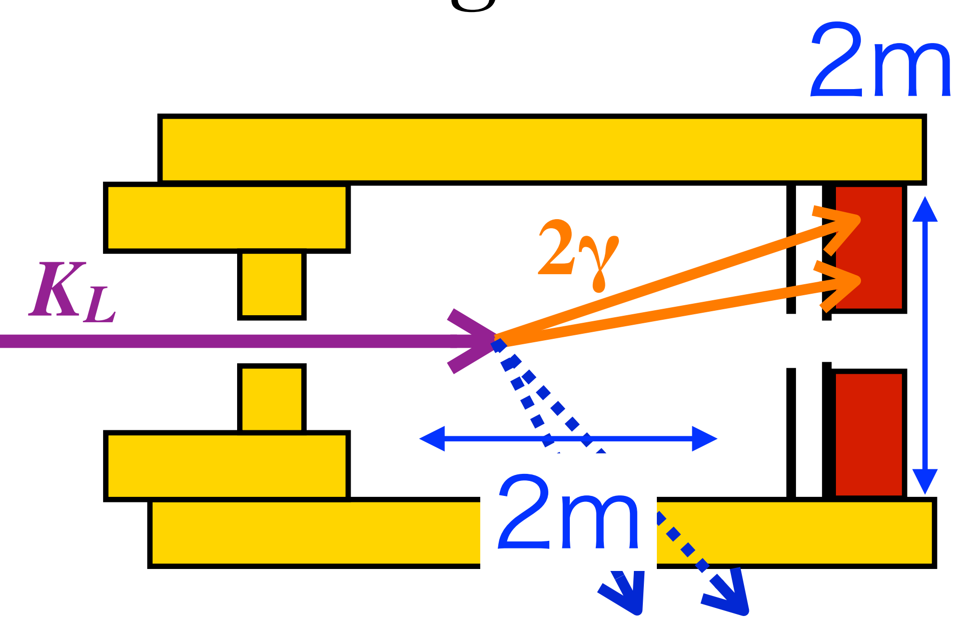
具体化？

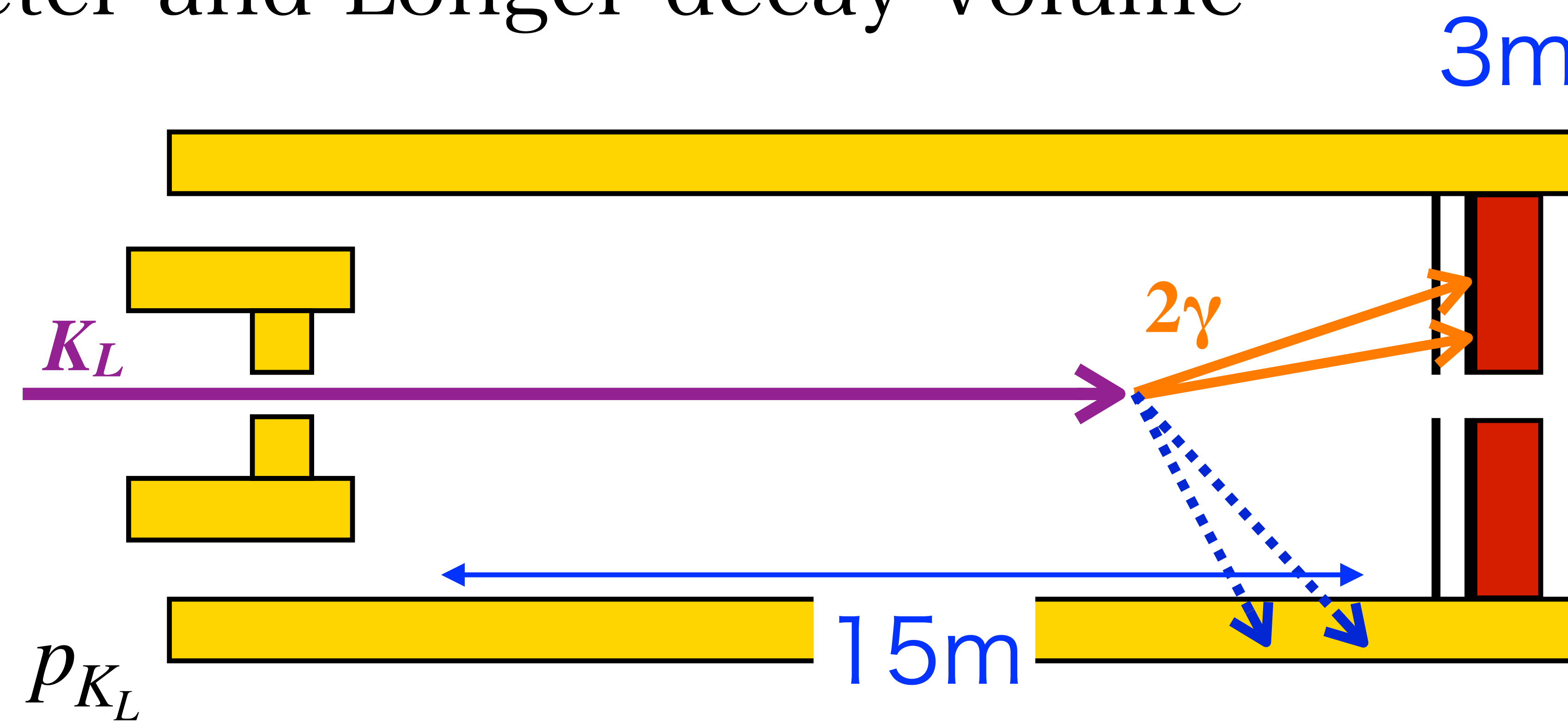
LHCの
パイルアップ

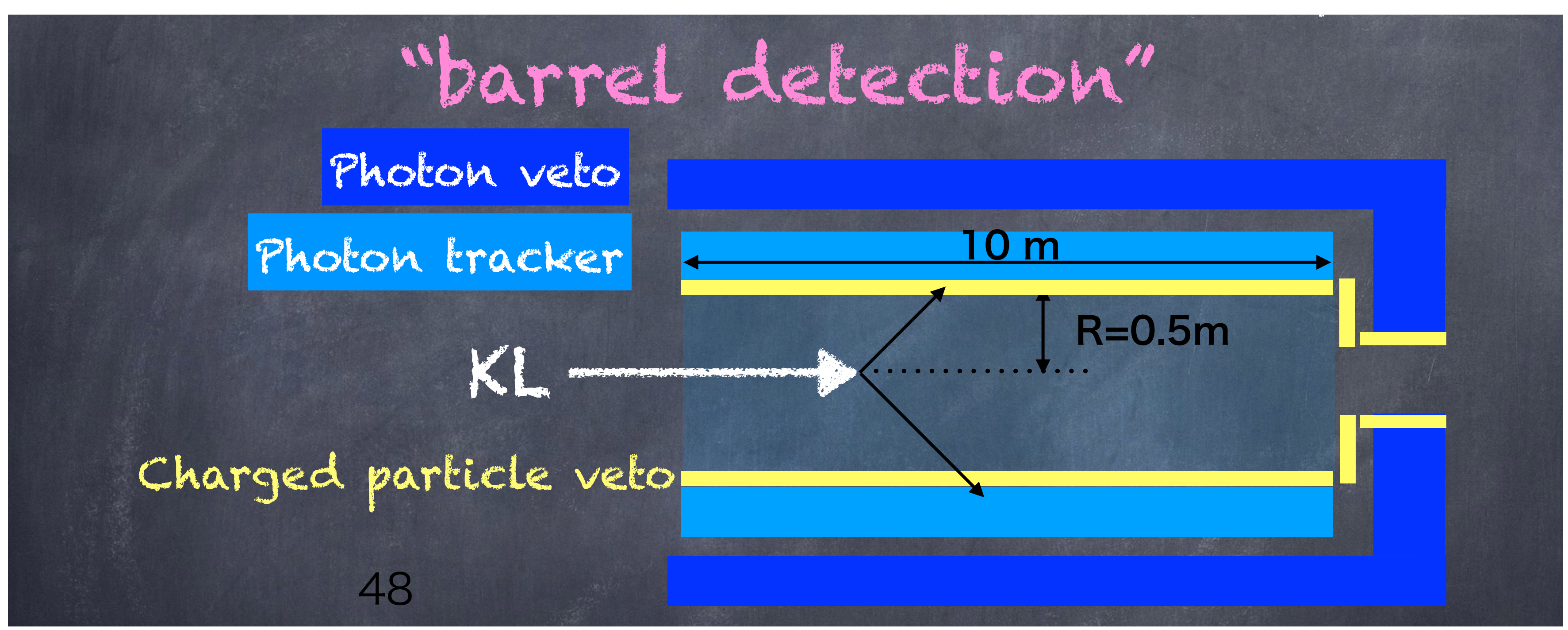


Beyond

- Large calorimeter and Longer decay volume







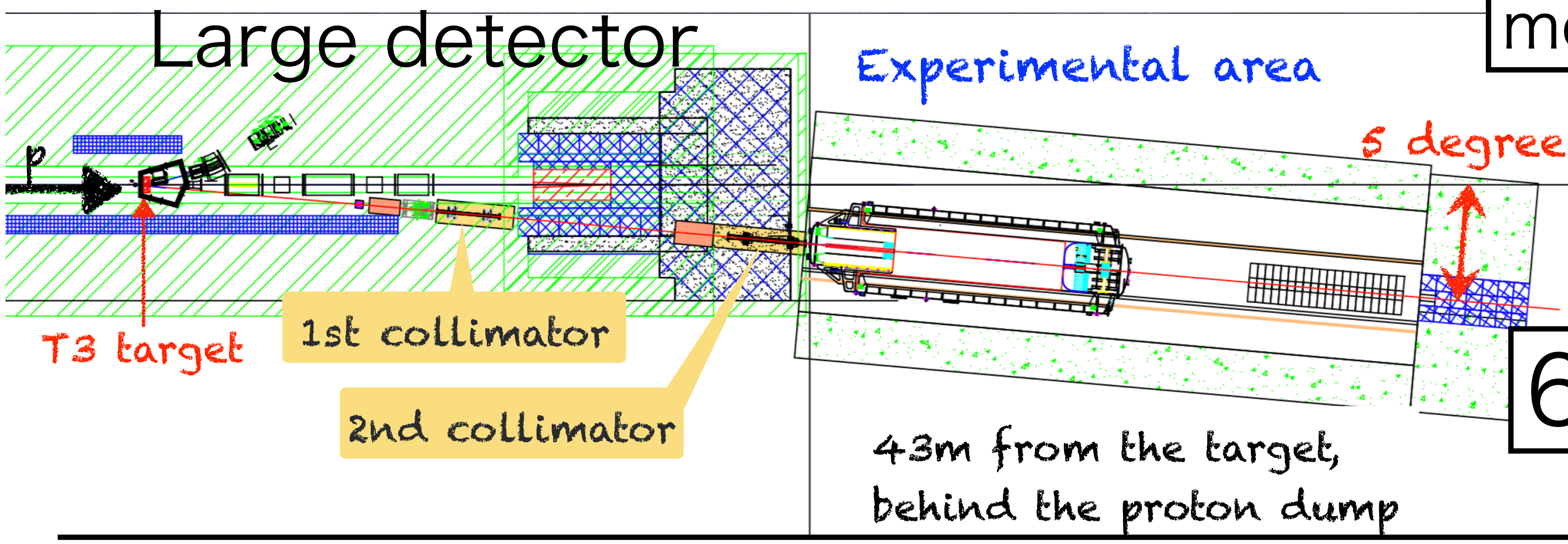
Future Plan : Rare Kaon Decay Experiments

T. Nomura KAON2019

KOTO Step2 $K_L \to \pi^0 \nu \overline{\nu}$

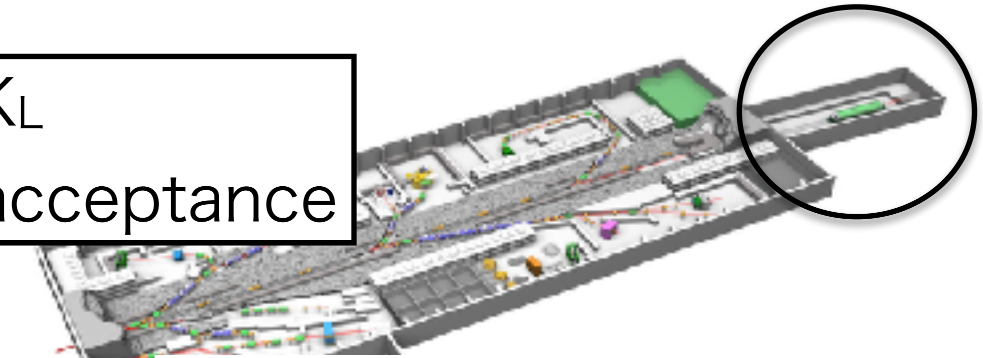
New beam line w/ 5 deg. extraction

Large detector



more K_L

more acceptance



Extension of hall

60 SM events w/ S/N~1

KLEVER

K_L Experiment for VEry Rare events

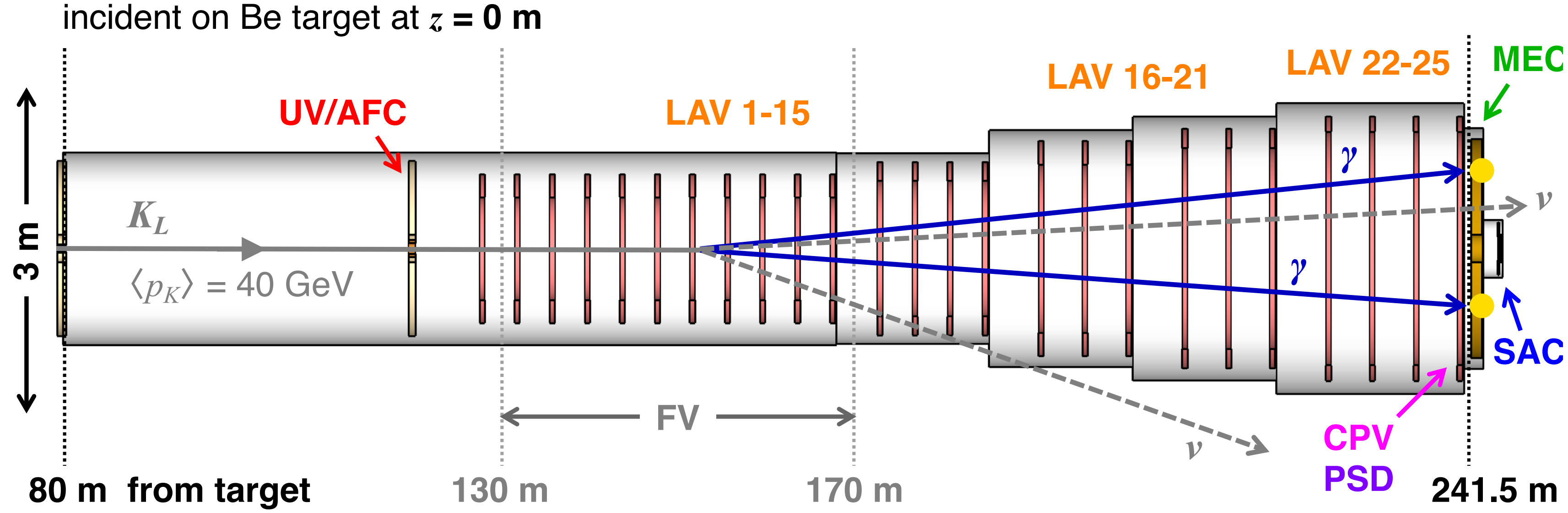
KLEVER target sensitivity:
5 years starting Run 4

60 SM $K_L \to \pi^0 \nu\nu$
$S/B \sim 1$

$\delta BR/BR(\pi^0 \nu\nu) \sim 20\%$

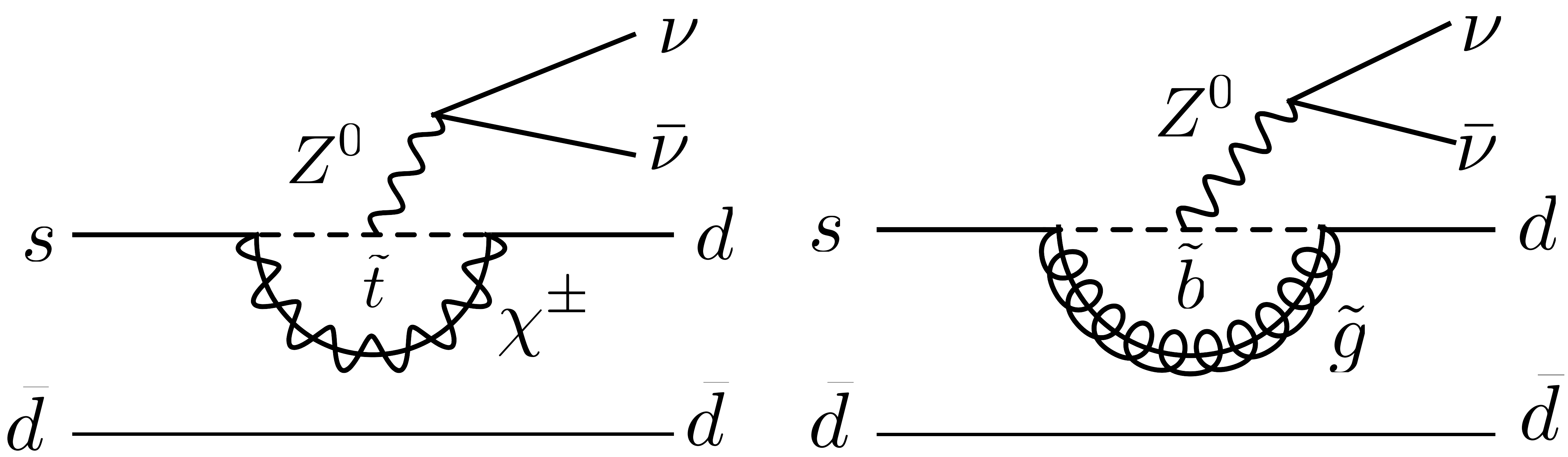
M .Moulson KAON2019

400-GeV SPS proton beam (2×10^{13} pot/16.8 s)
incident on Be target at z = **0 m**

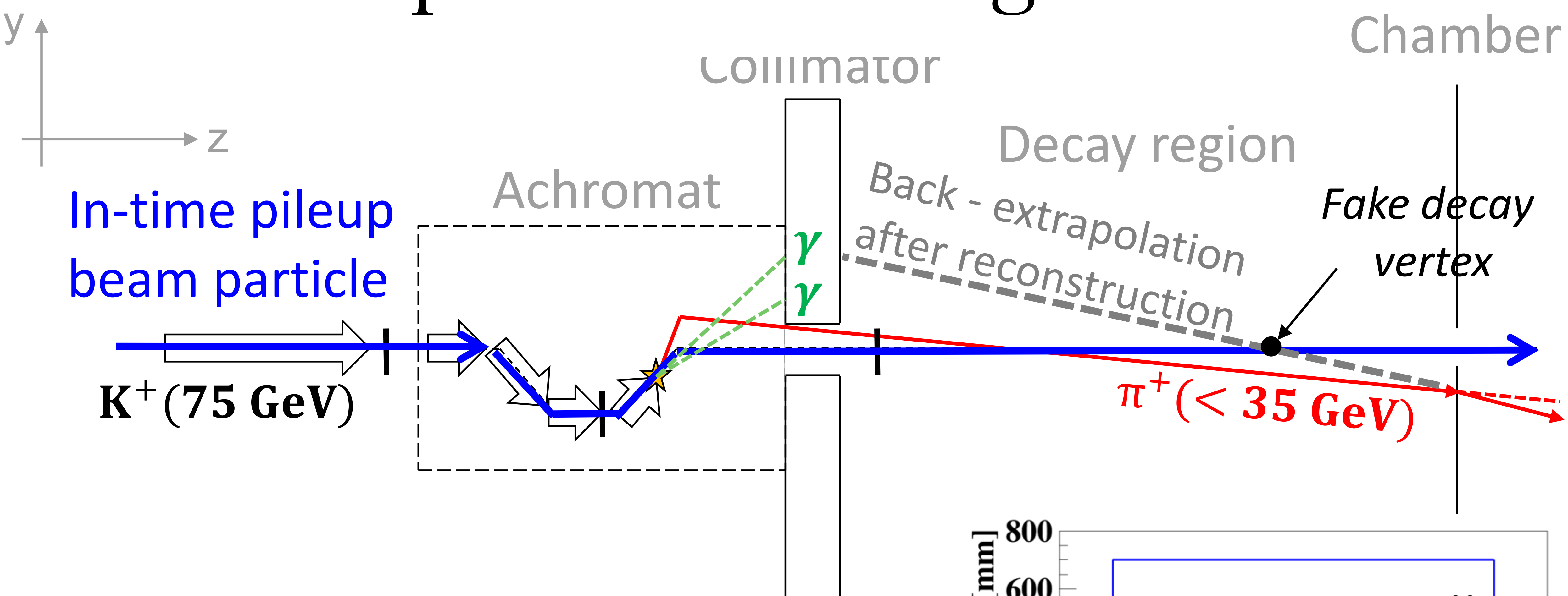


おしまい

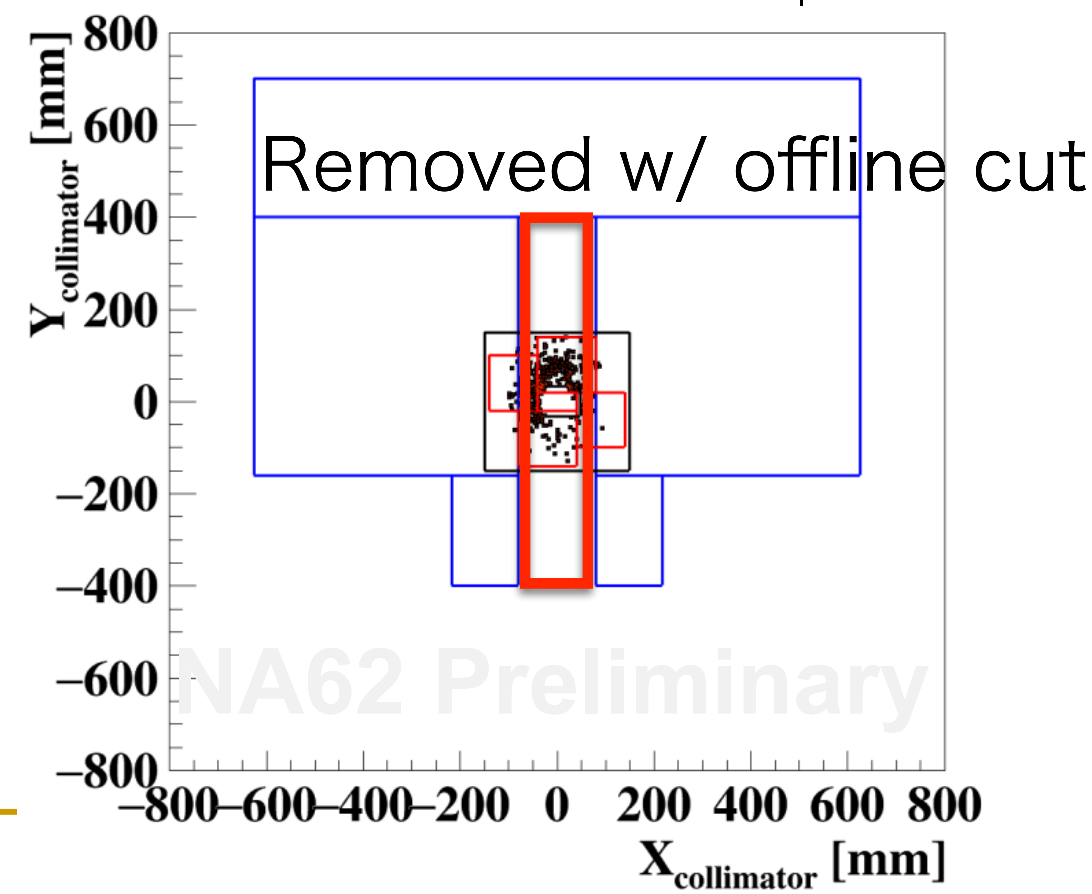
- 日欧ともにs→dのフレーバプロジェクト
  - 米からはどちらにも参加
  - Exoticな方向性もある
- もっと自由なのかも
- 夢を現実へ
  - 実験→予期せぬこともおこる
  - 比較的短いサイクルで開発→物理
- KOTO実験
  - 現行から将来計画まで見据えて良いタイミング
  - 参加してみようという方、熱望しています！


ν
Z^0
$\bar{\nu}$
s
d
$\tilde{t}$
$\chi^{\pm}$
$\bar{d}$
$\bar{d}$
ν
Z^0
$\bar{\nu}$
s
d
$\tilde{b}$
$\tilde{g}$
$\bar{d}$
$\bar{d}$

NA62 upstream background



- K^+ decays/interacts in the achromat
- Secondary π^+ downstream
- Beam elements block additional particles
- π^+ scattering in straw chamber 1
- Pileup beam particle tagged as K^+

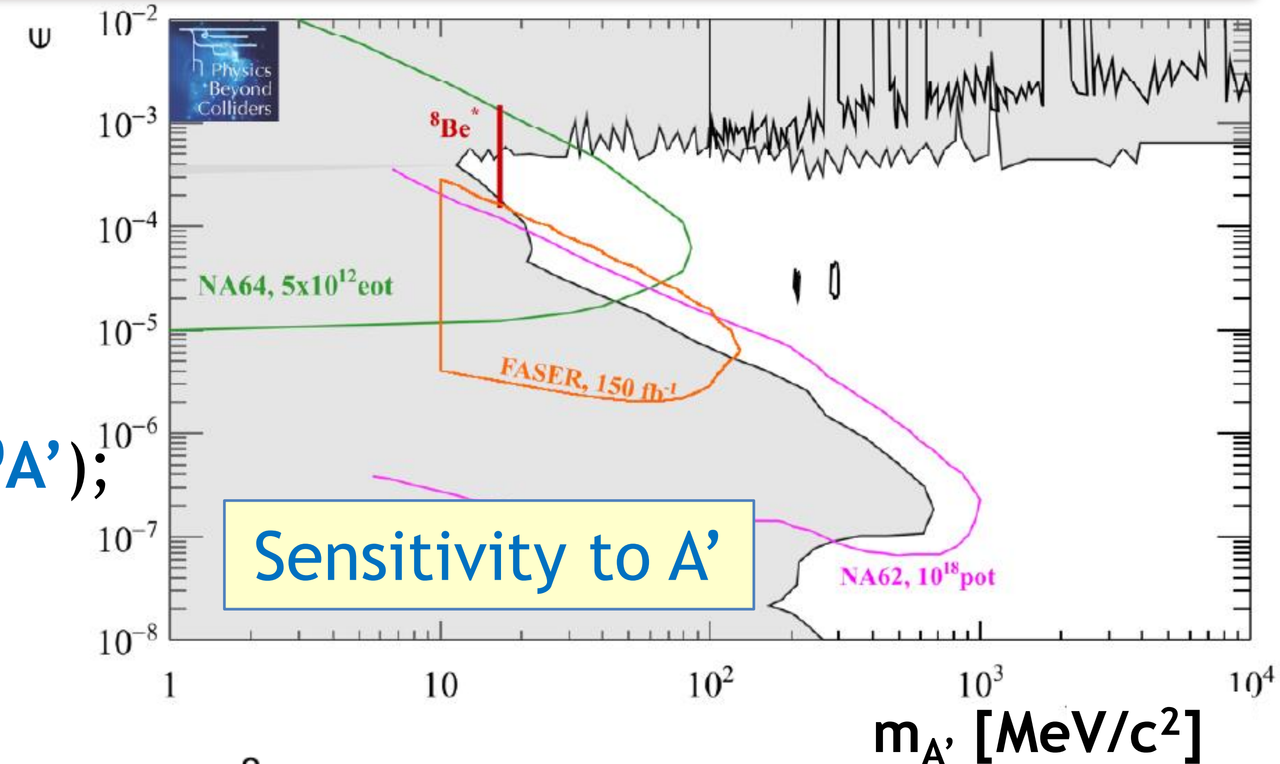


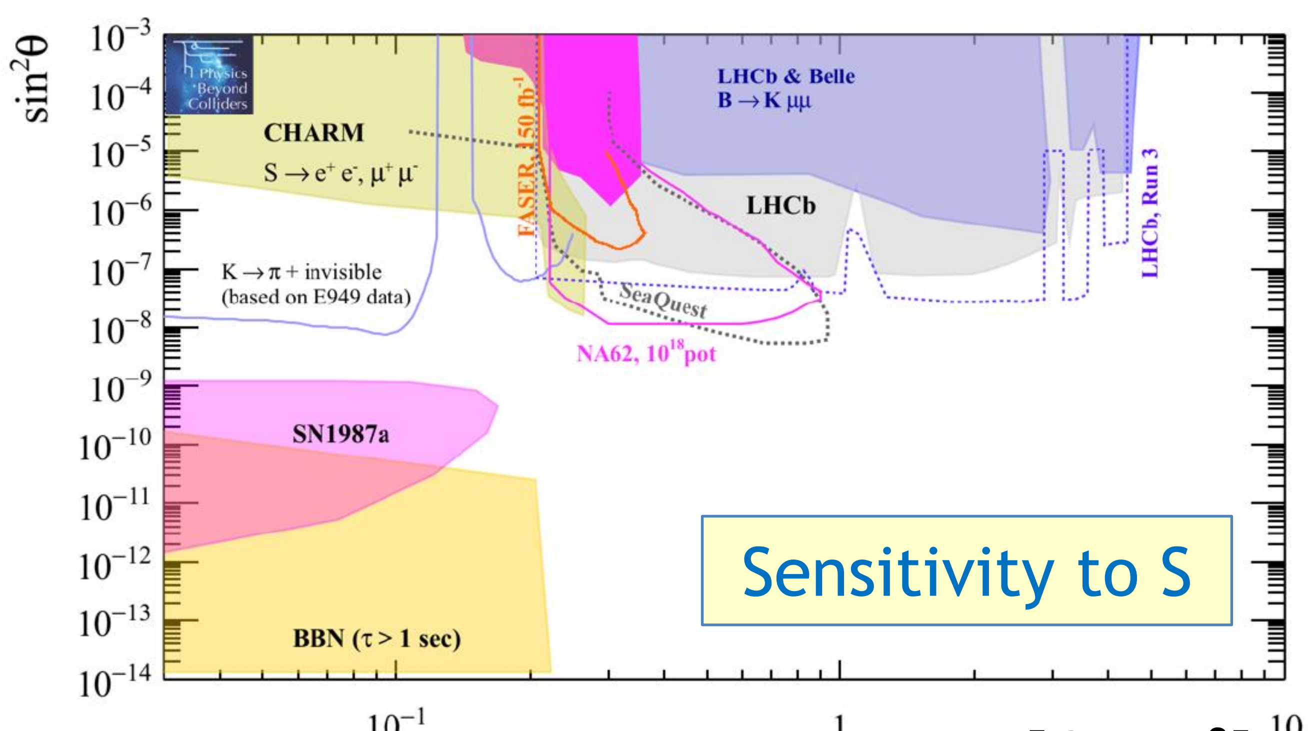
Beam dump operation: prospects

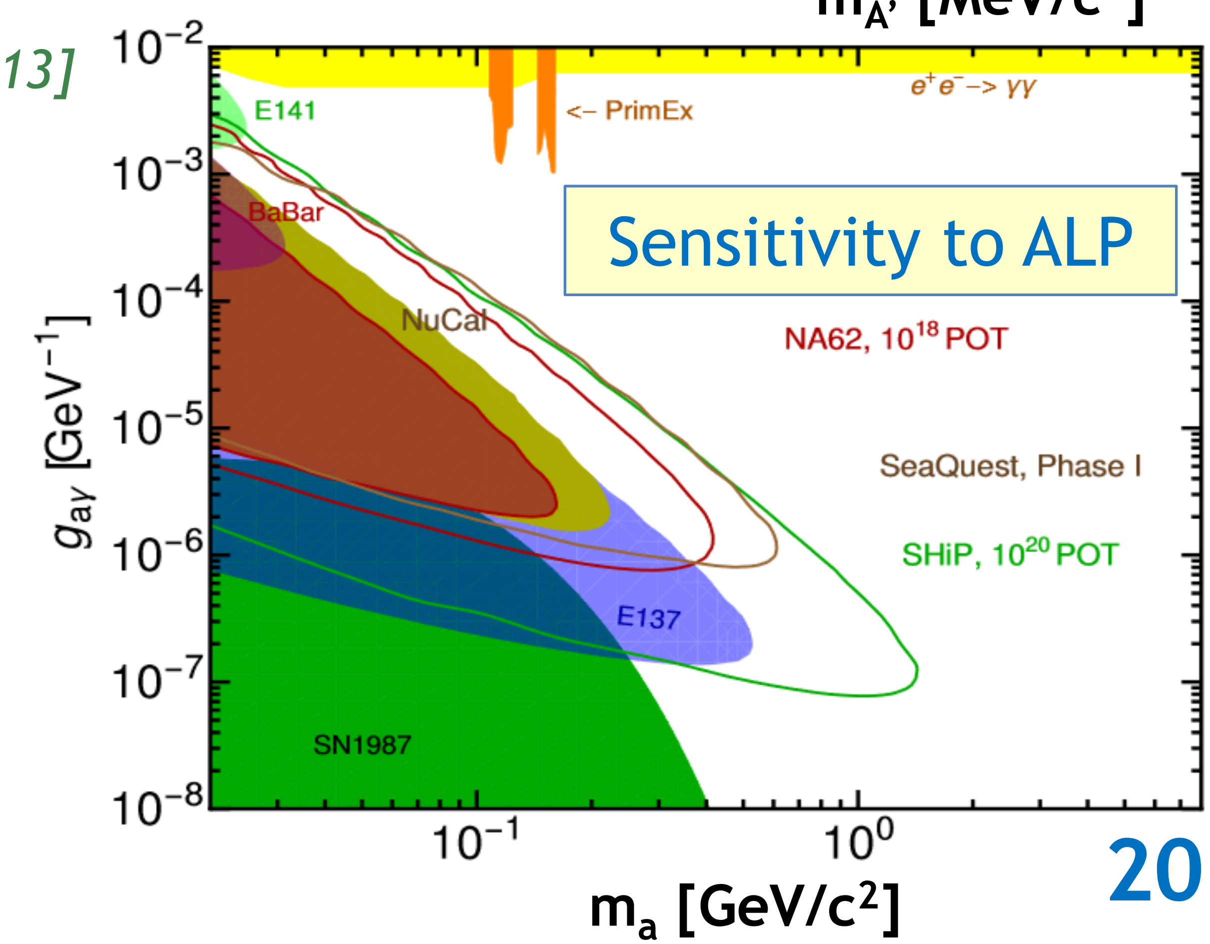
Dark scalar S:
production in K→πS and B→KS decays;
decays via $S\to\ell^+\ell^-$ and $S\to\pi^+\pi^-$.

Dark photon A':
production in light meson decays
(including $\pi^0\to\gamma A'$, $\eta\to\gamma A'$, $\rho\to\pi^0 A'$, $\omega\to\pi^0 A'$);
decays mainly via $A'\to\ell^+\ell^-$.

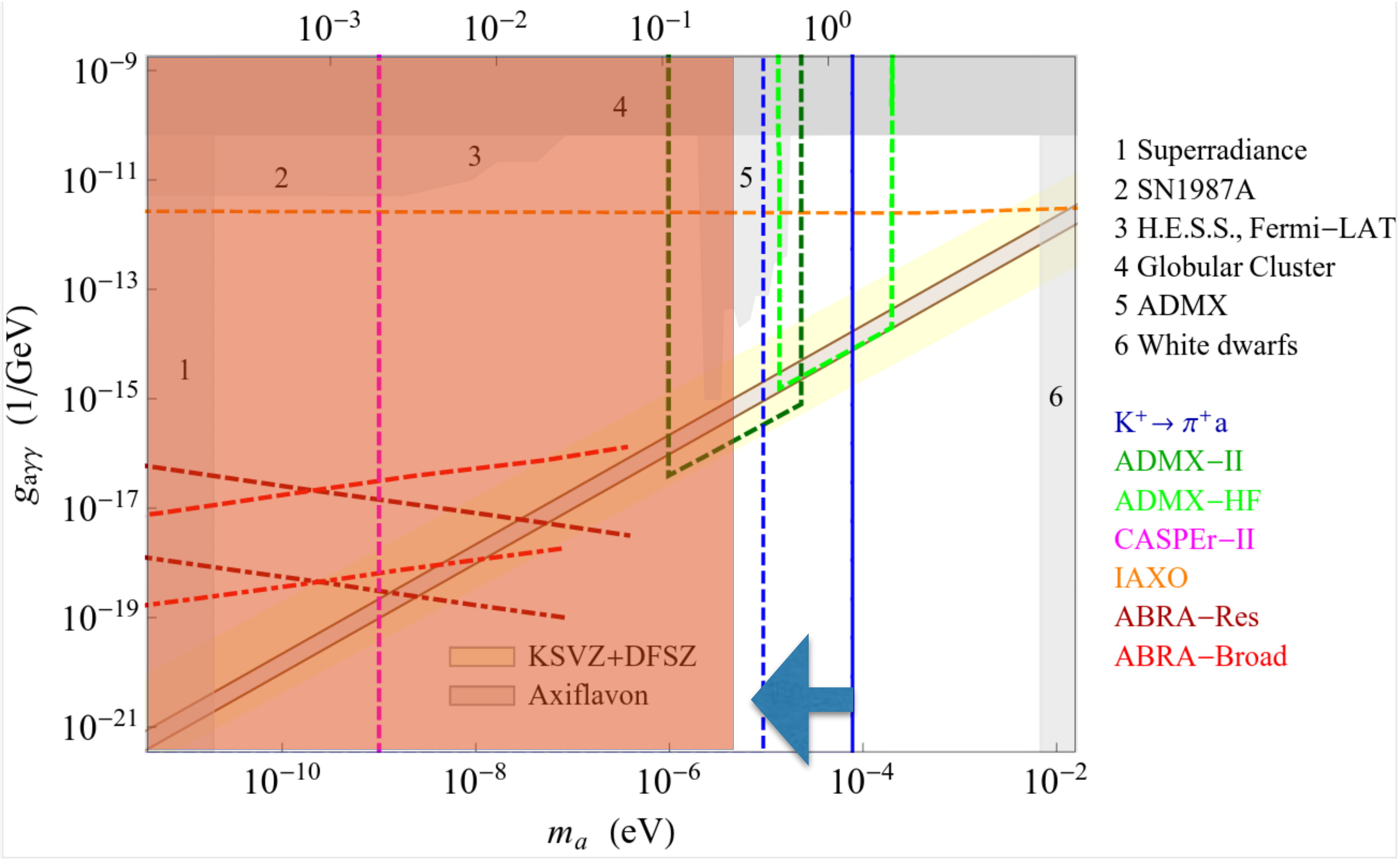
Axion-like particle (ALP):
Primakoff effect production; $a\to\gamma\gamma$ decay.
[Döbrich et al., JHEP 1602 (2016) 018; 1905 (2019) 213]







Axiflavon Constraints



$$10^7\,\text{GeV} \lesssim f_a \lesssim 10^{12}\,\text{GeV} \xrightarrow{\text{flavor}} f_a \approx (10^{11} - 10^{12})\,\text{GeV}$$

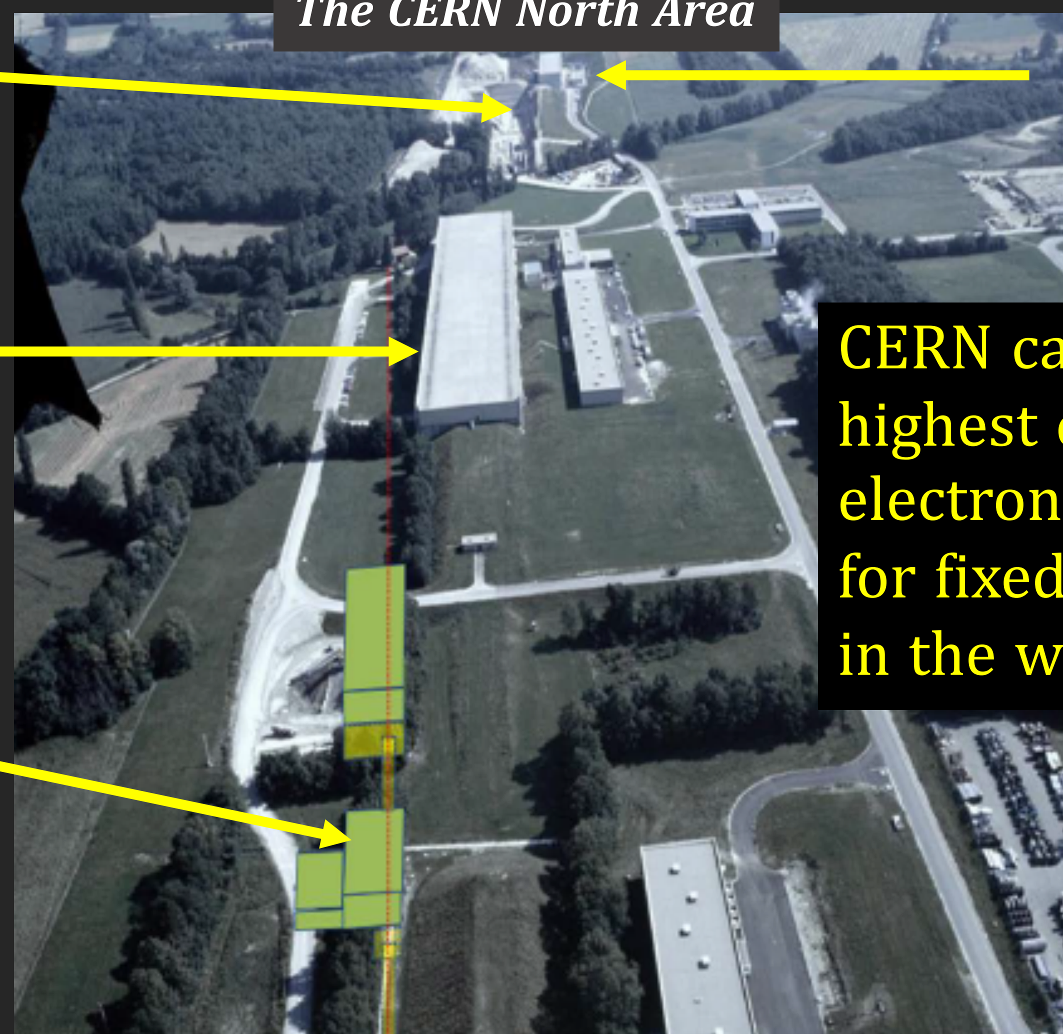
Beam dump/fixed target: Opportunities @ CERN

NA62-dump @ K12
400 GeV p beam
up to 2x10^{18} pot/year

NA64^{++}(e) @ H4
(100 GeV e- beam
up to 5x10^{12} eot/year)
ESPP submission #9

SHiP @ BDF
400 GeV p
up to 4x10^{19} pot/year
ESPP submissions #12 and #129

The CERN North Area



NA64^{++} (μ) @ M2
100-160 GeV muons,
up to 10^{13} μ/year

CERN can provide the highest energy proton-, electron- and muon- beams for fixed target/beam experiments in the world.

A possible "Hidden Sector Campus" (HSC)

G. Lanfranchi

13