Rare K decay : status and future output

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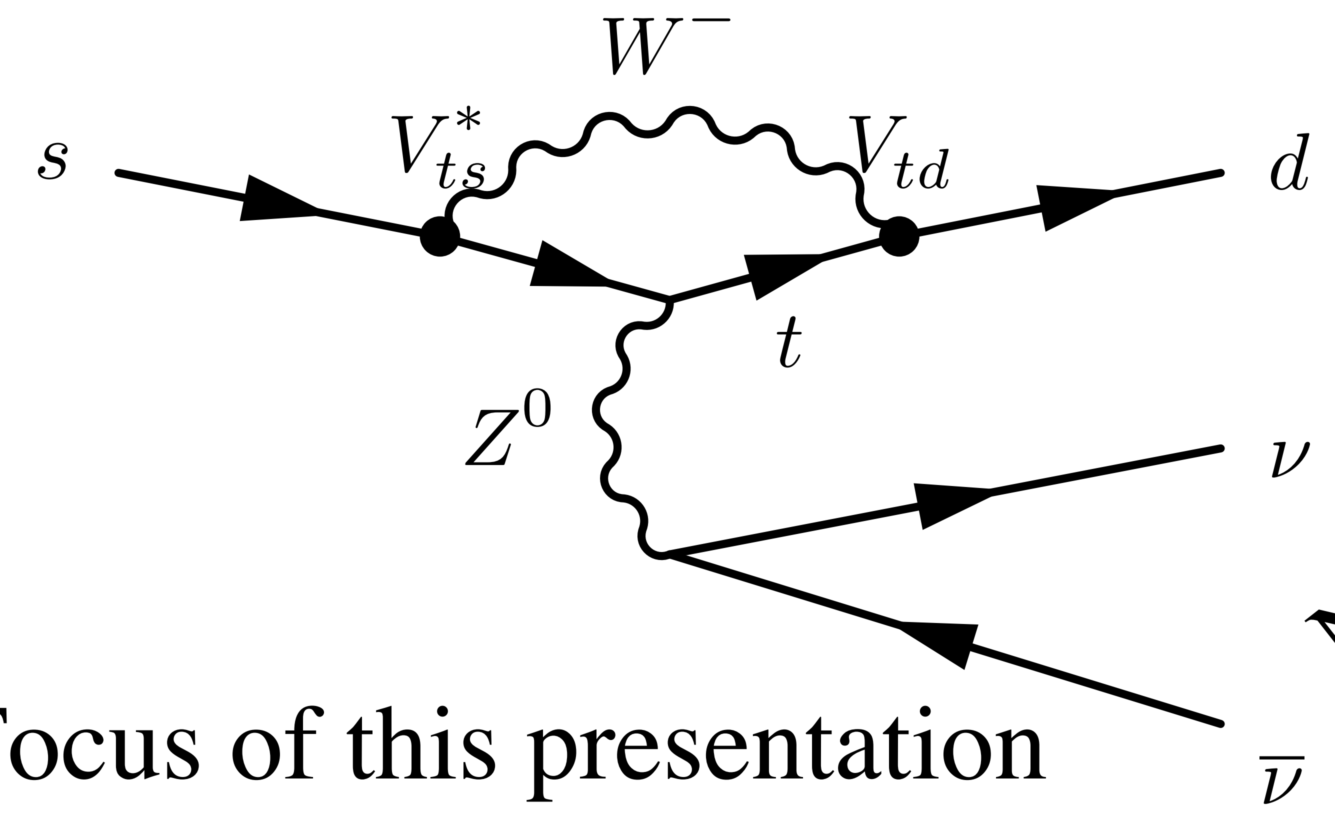
for the KOTO collaboration

2021/11/11 Anomalies 2021

Rare kaon decay observables

$K \to \pi\nu\nu$

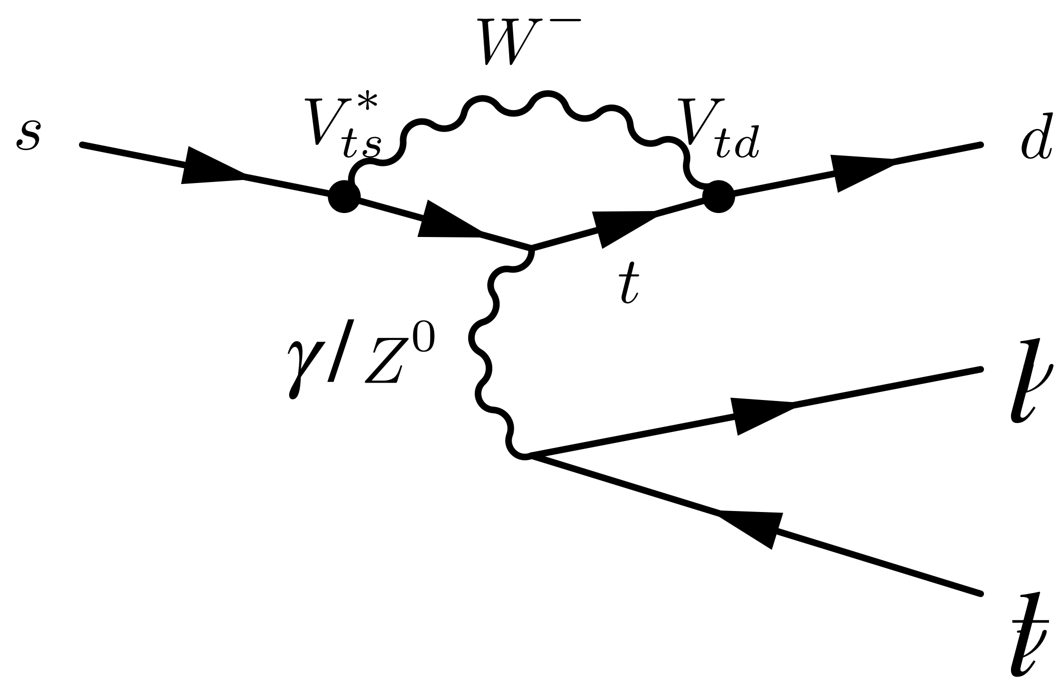


NA62 experiment

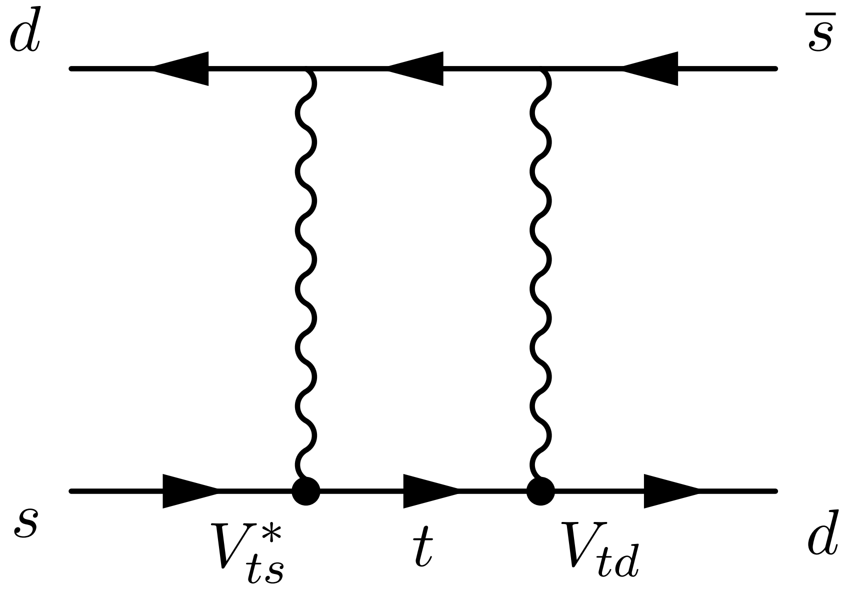
KOTO experiment

Focus of this presentation

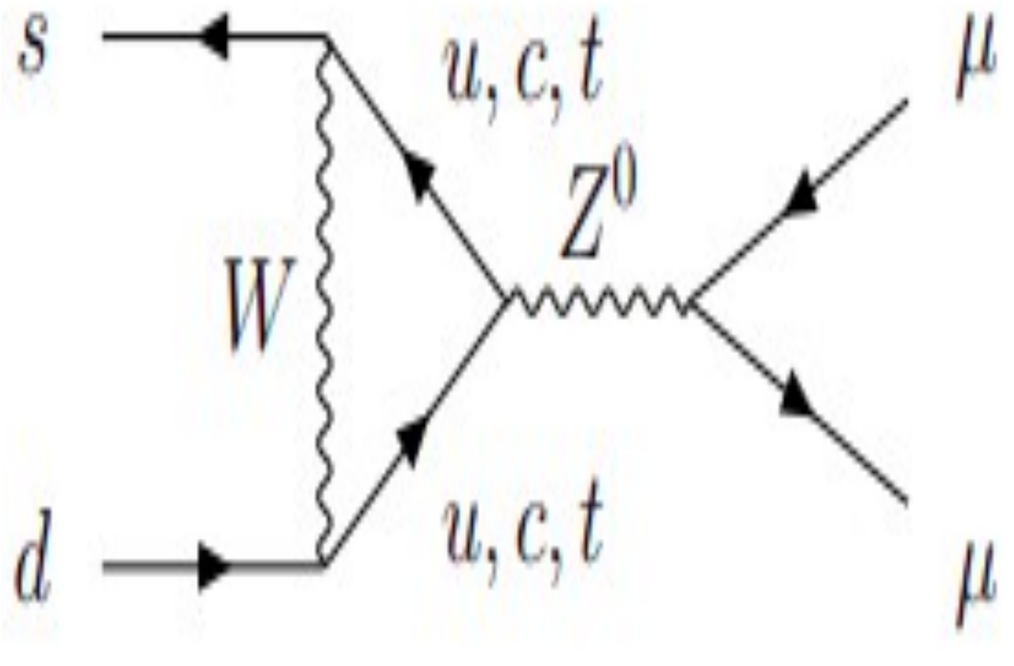
$K \to \pi[ee \text{ or } \mu\mu]$



$\epsilon_K \quad K^0 \leftrightarrows \overline{K}^0$



$K_S \to \mu\mu \text{ or } ee$



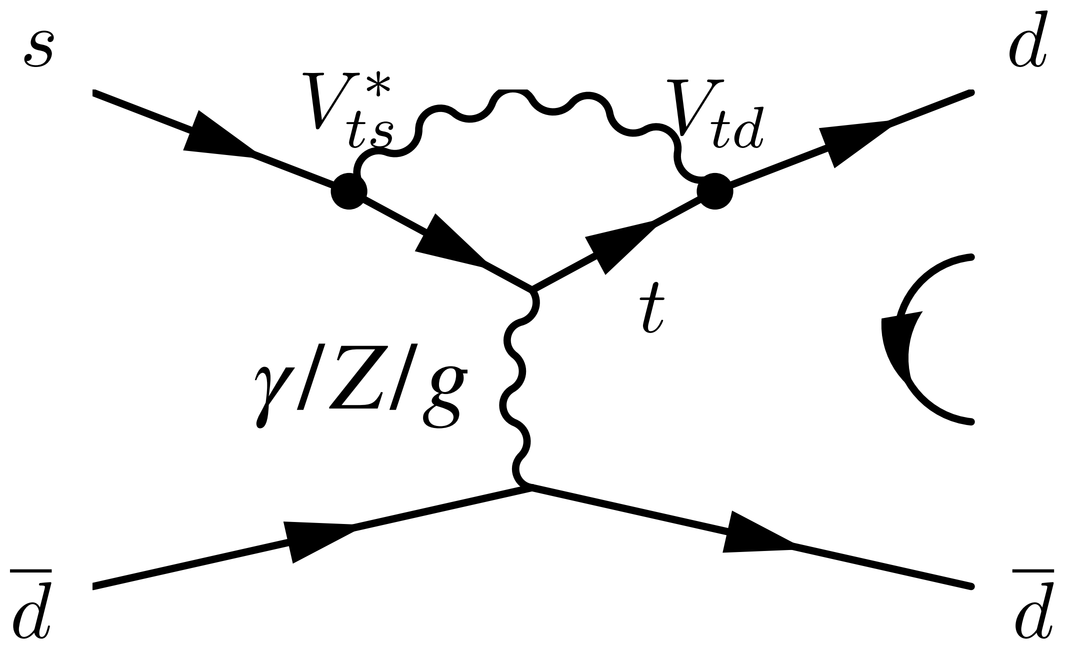
LHCb experiment

$\mathcal{B}_{\mathrm{SM}} = (5.18 \pm 1.5_{\mathrm{LD}} \pm 0.02_{\mathrm{SD}}) \times 10^{-12}$

$\mathcal{B}(K_s \to \mu\mu) < 2.1 \times 10^{-10}$ (90 % CL)

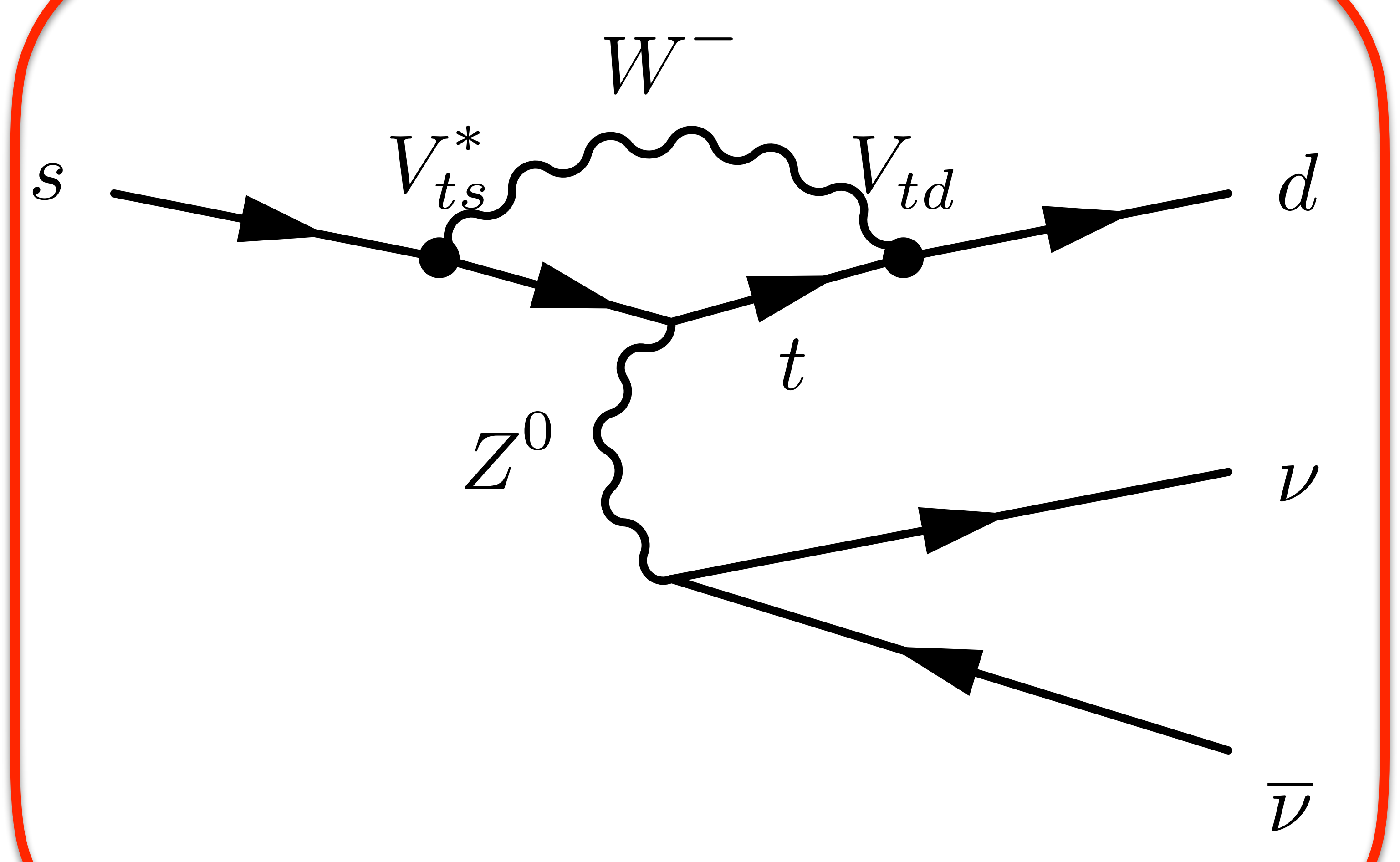
LHCb Collaboration, Phys.Rev.Lett. 125 (2020) 23, 231801

$\epsilon'/\epsilon \quad K \to 2\pi^0$



$K \to \pi\nu\nu$ in SM and Experimental status

	$K_L \to \pi^0\nu\bar{\nu}$	$K^+ \to \pi^+\nu\bar{\nu}$
Calculated BR	$(3.4 \pm 0.6) \times 10^{-11}$	$(8.4 \pm 1.0) \times 10^{-11}$
	Buras et al JHEP11(2015)33	
Theoretical error	Mainly Parameter error from CKM matrix elements	
	$< 2\,\%$	$< 4\,\%$
Quarks in loop	top	top, charm



Precise and Suppressed SM process(BG)
→BSM Physics search(Signal)😀

Correlation between K_L and K^+ in $K \to \pi\nu\nu$

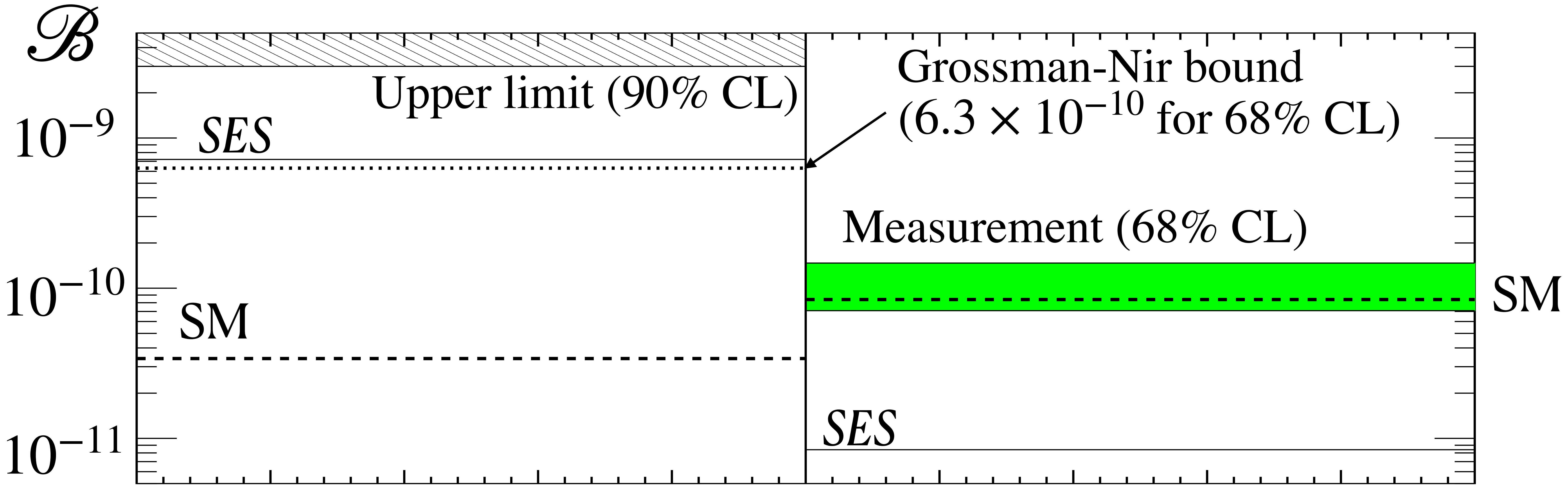
	$K_L \to \pi^0\nu\bar{\nu}$ $\left(K_L \sim (K^0 - \bar{K}^0)/\sqrt{2}\right)$	$K^+ \to \pi^+\nu\bar{\nu}$
Amplitude	$\propto \mathscr{A}_{s\to d} - (\mathscr{A}_{s\to d})^*$	$\propto \mathscr{A}_{s\to d}$
Width	$\propto (\mathrm{Im}\mathscr{A}_{s\to d})^2$	$\propto \lvert\mathscr{A}_{s\to d}\rvert^2$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

Grossman-Nir bound :
(Isospin symmetry in ΔI=1/2 process)

$$\mathscr{B}(K_L) < 4.3 \times \mathscr{B}(K^+)$$

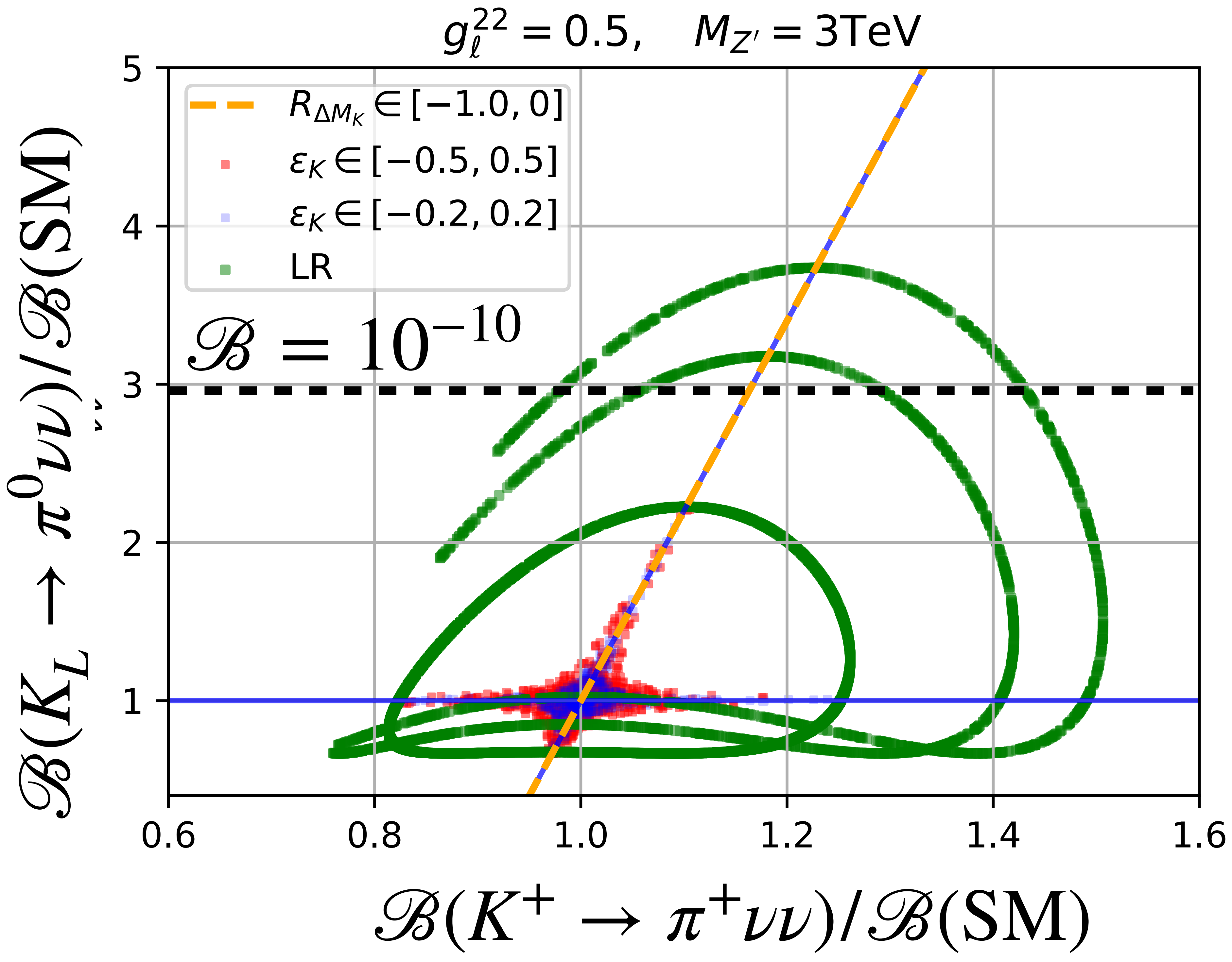
Experimental status on $K \to \pi\nu\nu$

	$K_L \to \pi^0 \nu\bar{\nu}$	$K^+ \to \pi^+ \nu\bar{\nu}$
Experiments	J-PARC KOTO	CERN NA62
Branching ratio	$< 3.0 \times 10^{-9}$ (90 % CL) *PRL* 122, 021802 (2019)	$(10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$ (68 % CL)
Single Event Sensitivity *(SES)*	7.2×10^{-10} *PRL*. 126 (2021) 12, 121801	0.84×10^{-11} *JHEP* 06 (2021) 093



New physics contributions

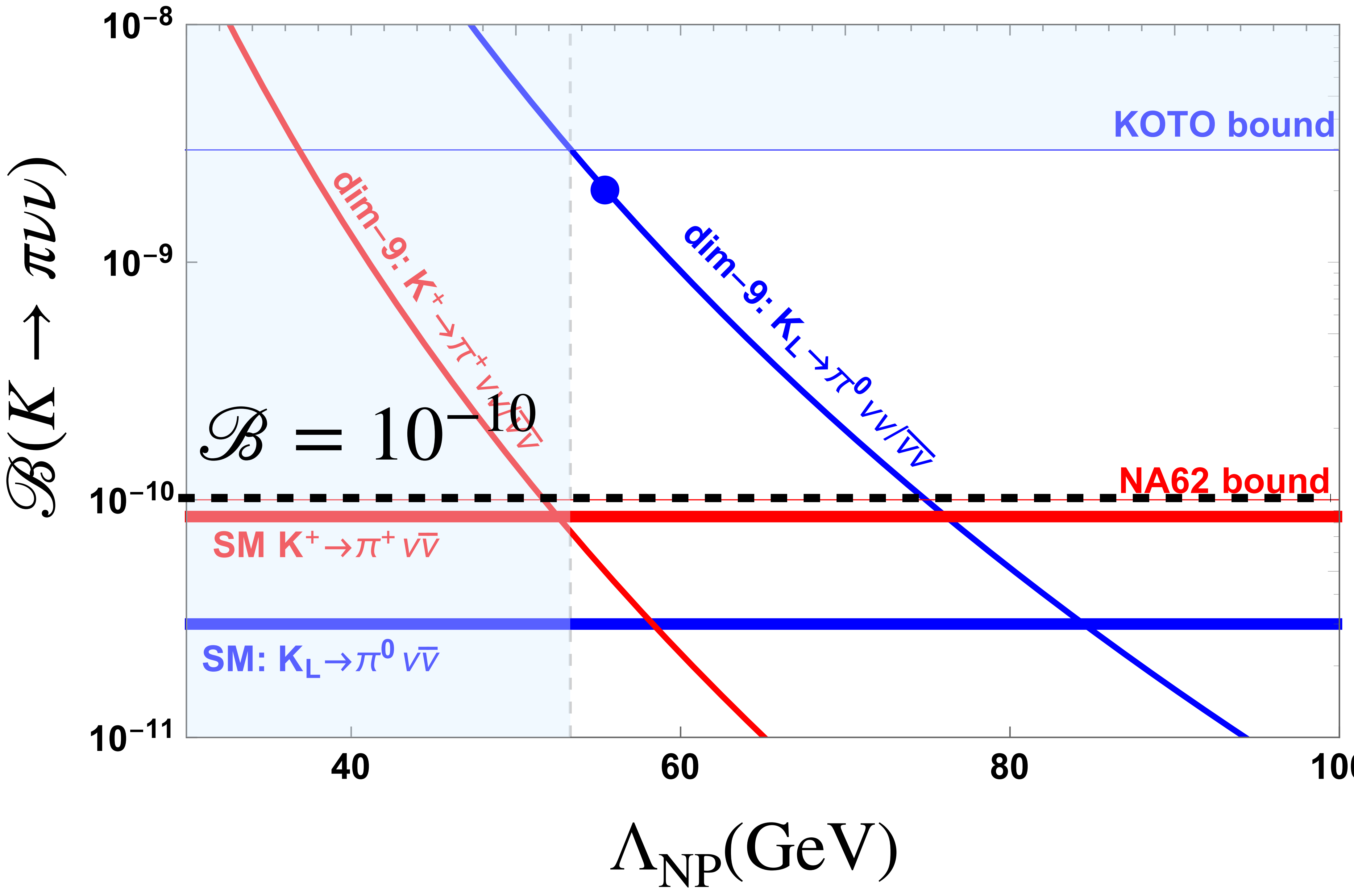
JHEP12(2020)097



Flavor-violating Z' coupling
High energy reach

leptoquark, SUSY, charged Higgs…
dark sector …

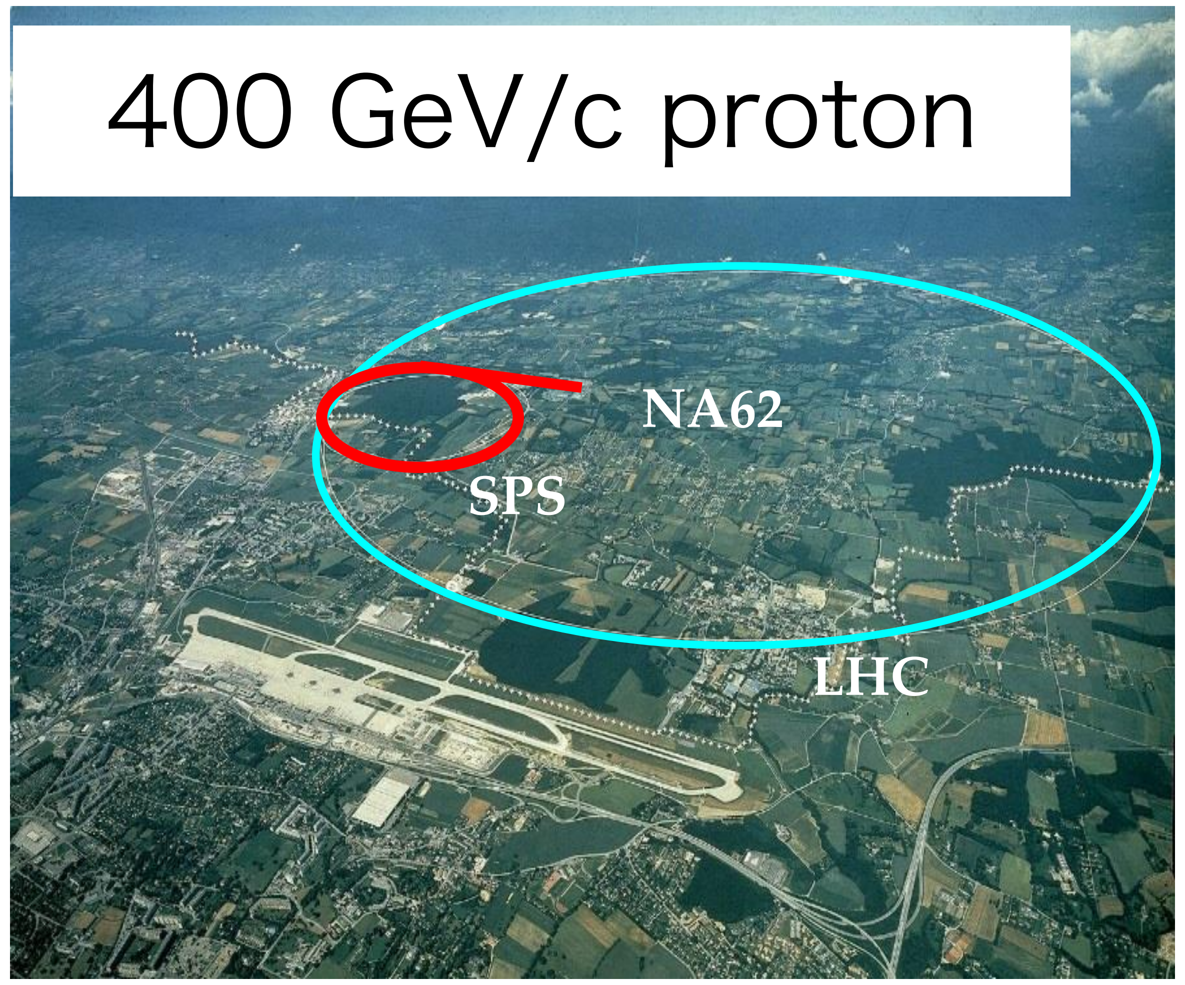
JHEP08(2020)034



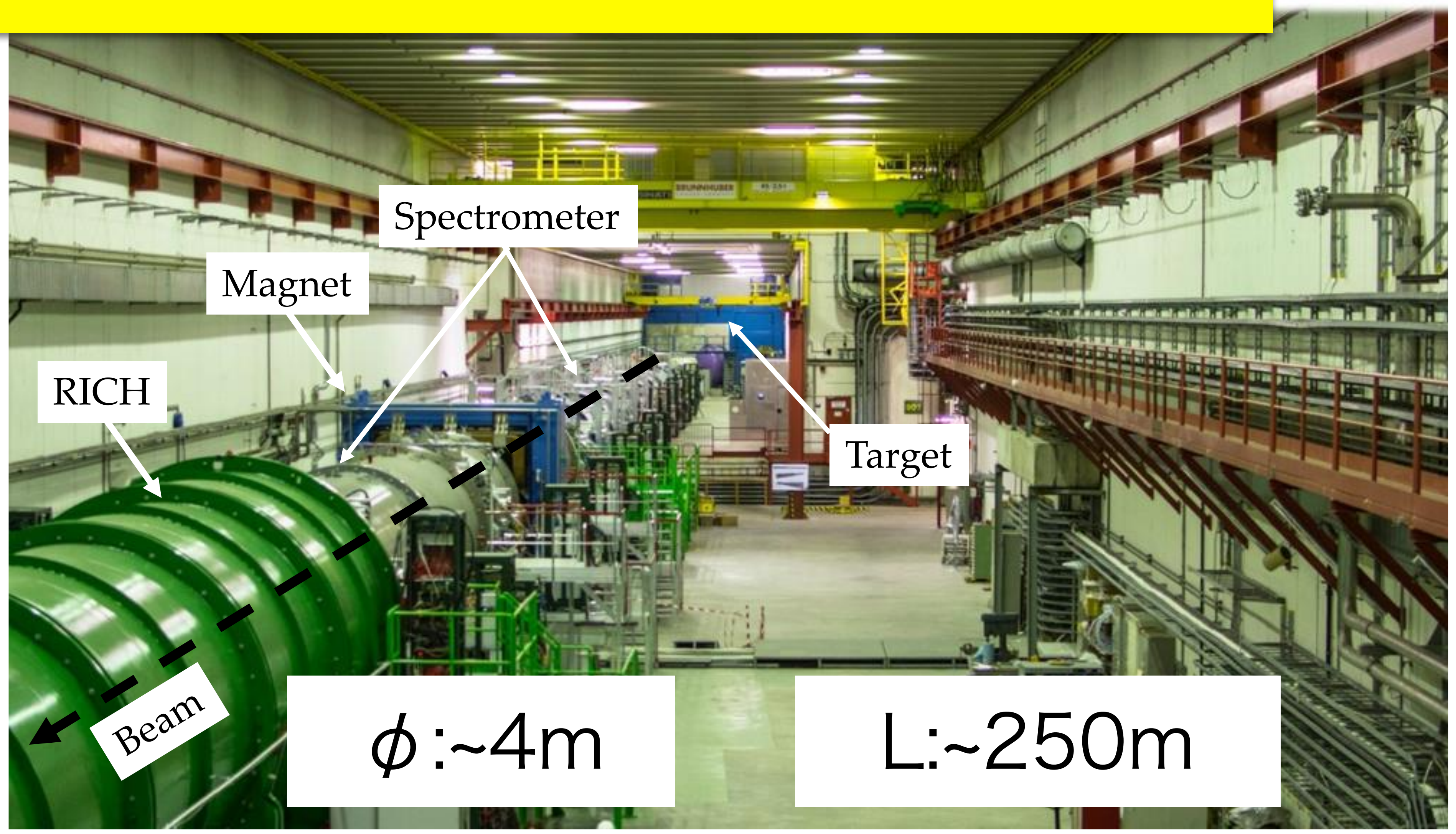
Dim.9 ΔI=3/2 operator

Exotic scenario violating Grossman-Nir bound

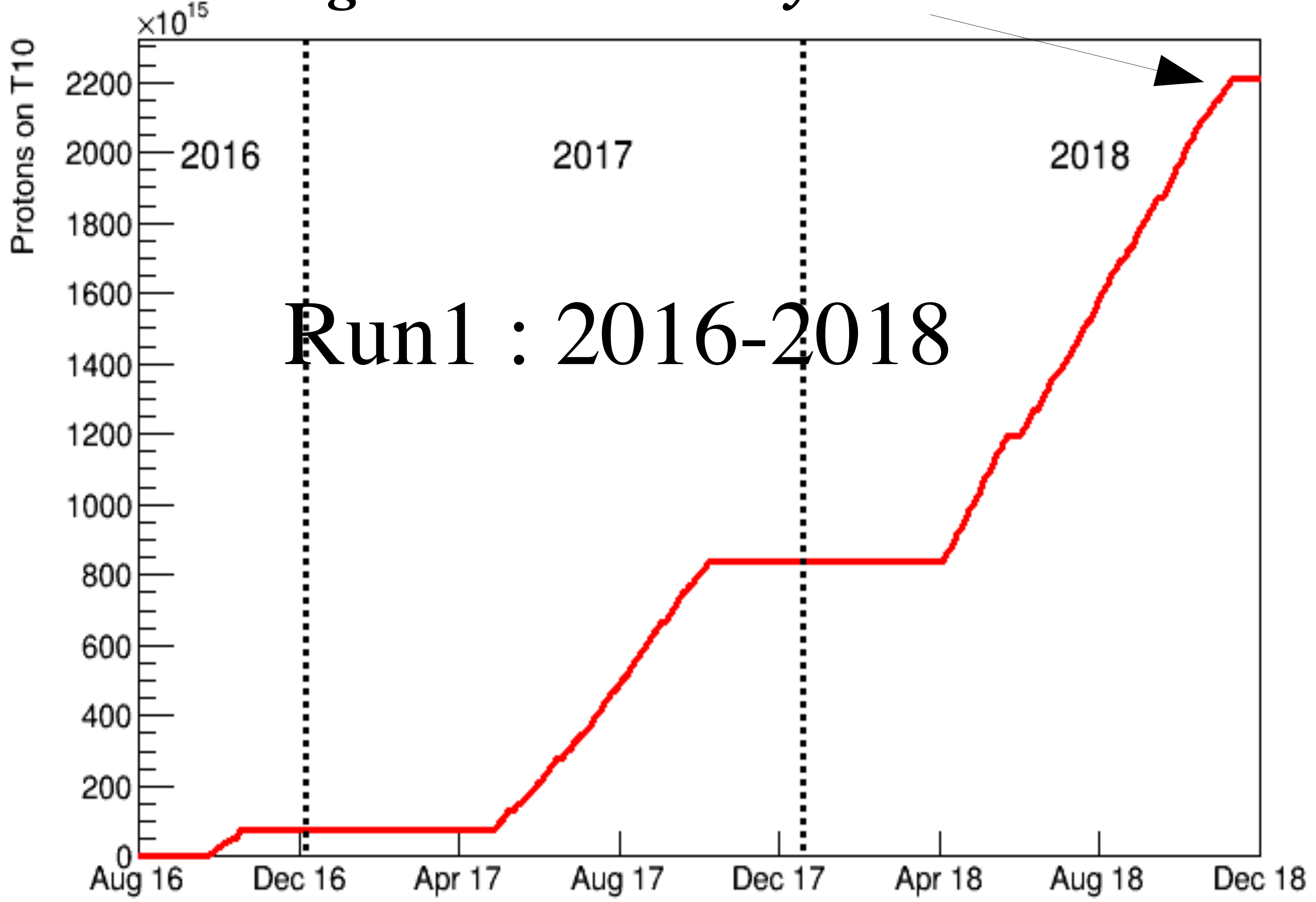
NA62 experiment at CERN



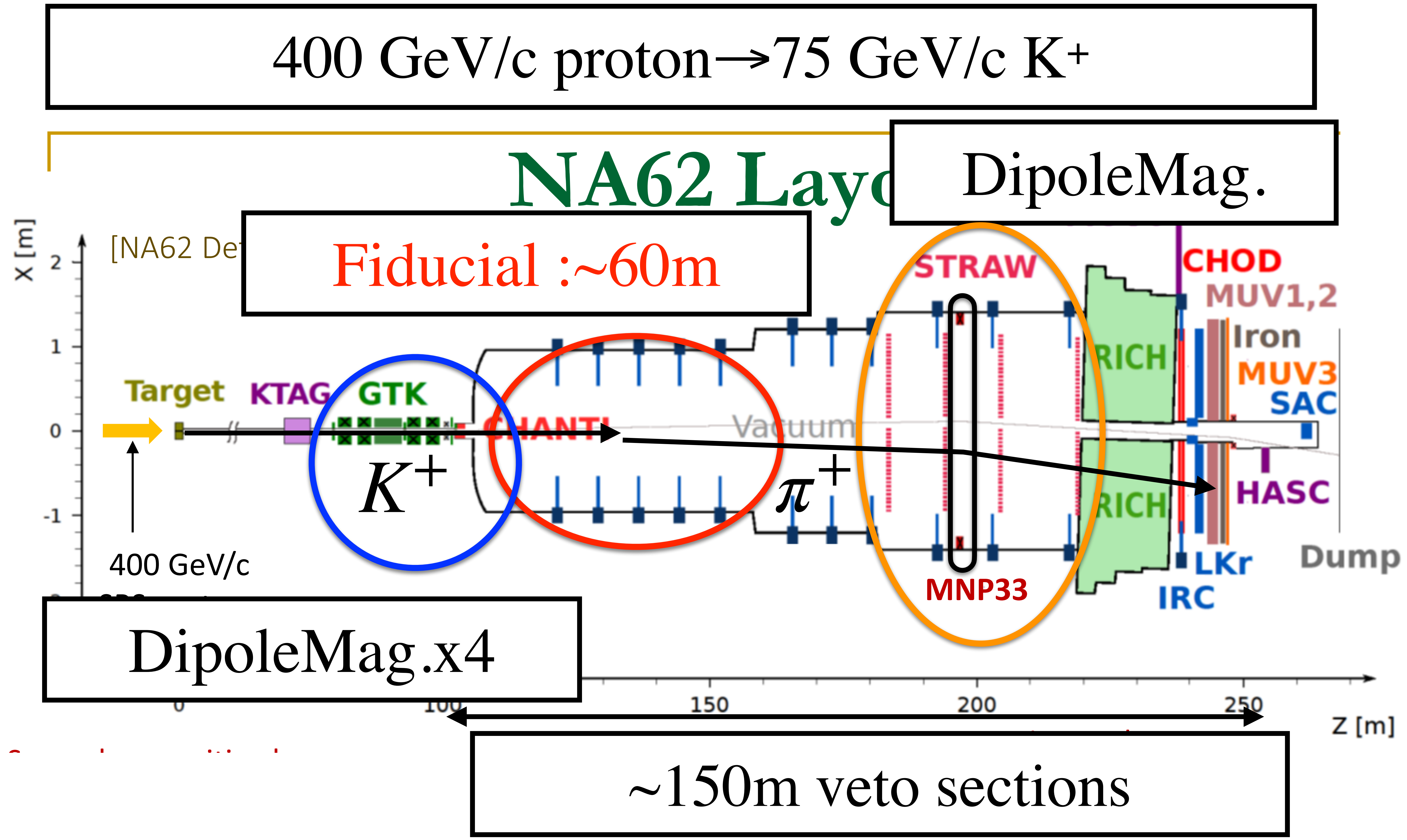
$K^+ \to \pi^+ \nu \bar{\nu} : K^+ \to \pi^+ + \text{nothing}$



Integrated luminosity NA62 Run 1

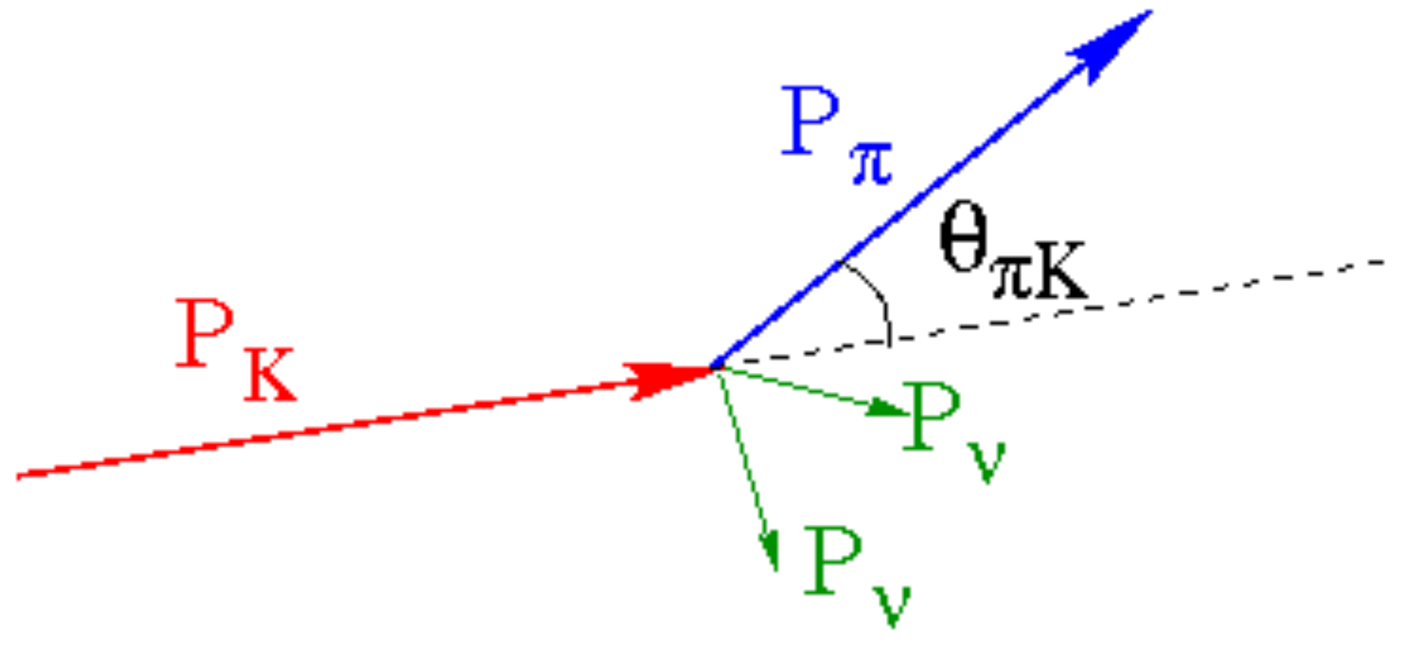


Concept of NA62 detector



mass assumption

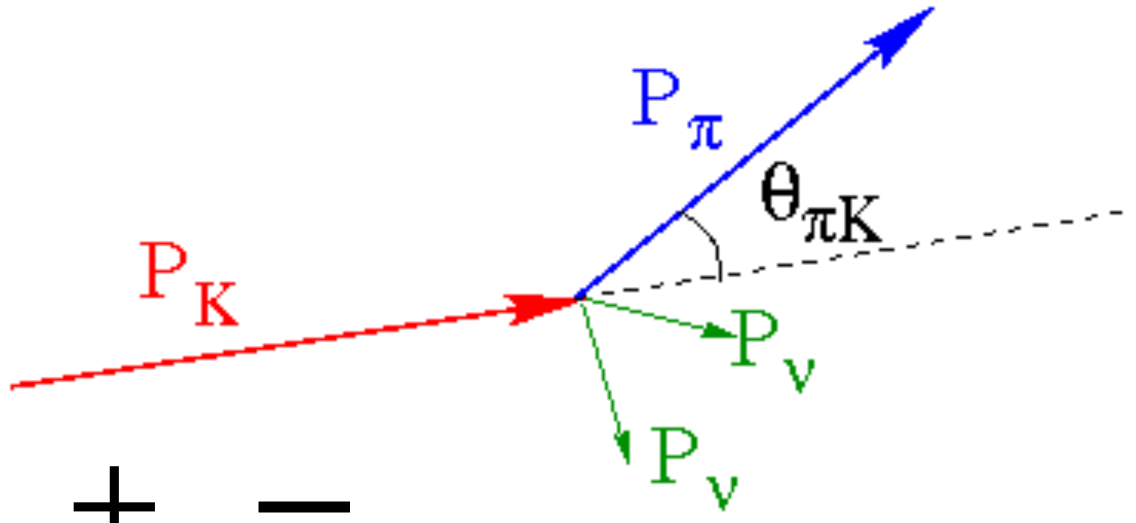
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$



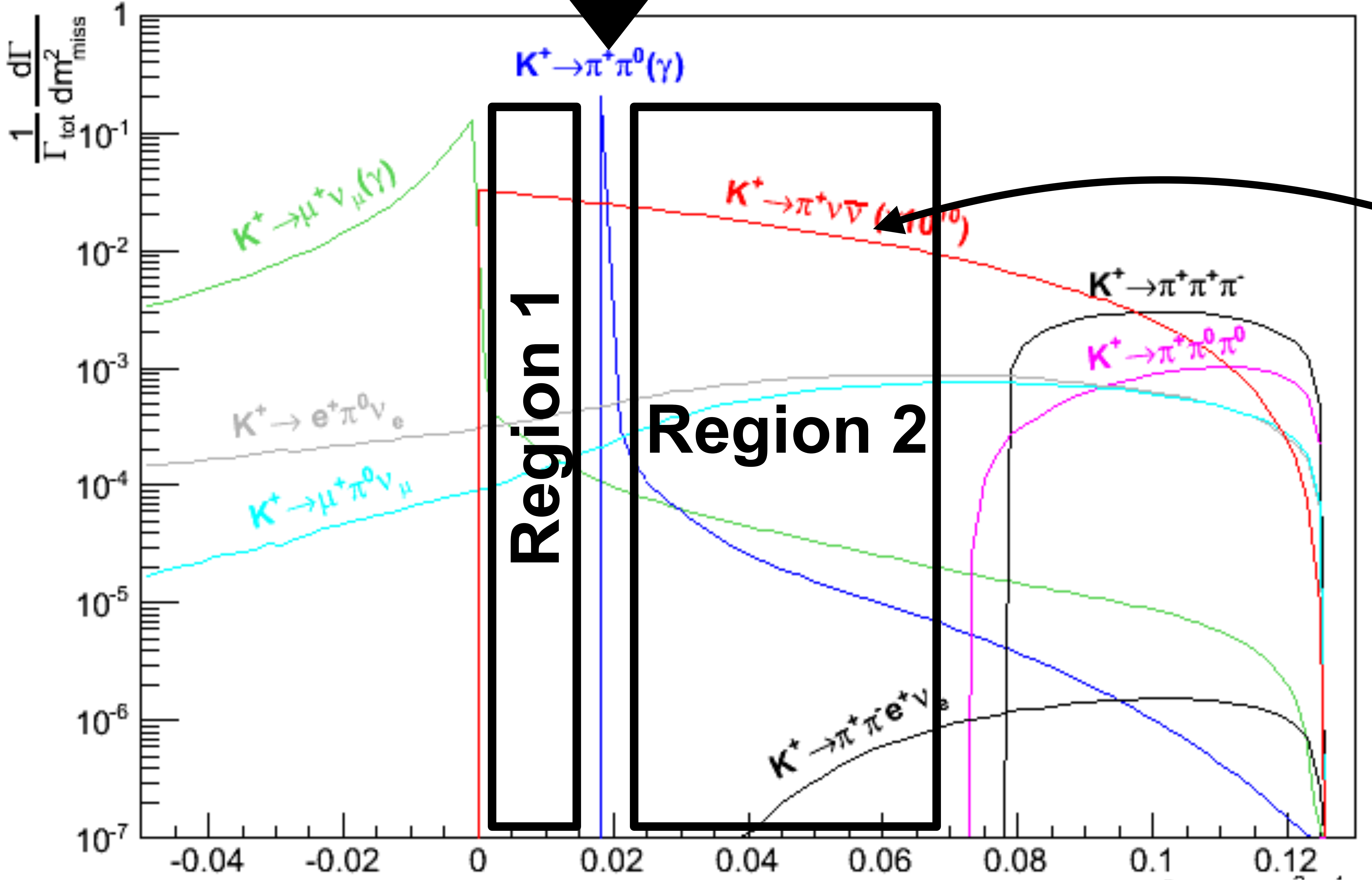
- Decay in flight technique
- High momentum K+(75GeV/c)
- K+ tracking w/ magnetic field → p_K
- π^+ tracking w/ magnetic field → p_π

Signal reconstruction

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



Cut kinematic region of $K^+ \to \pi^+\pi^0$



$m^2_{miss}(\mathrm{GeV}^2/c^4)$

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

$m_{miss} = m_{\nu\bar{\nu}}$

$K^+ \to \pi^+ + \boxed{\pi^0(\to \gamma\gamma)}$

$m_{miss} = m_{\pi^0}$

Br: 21%

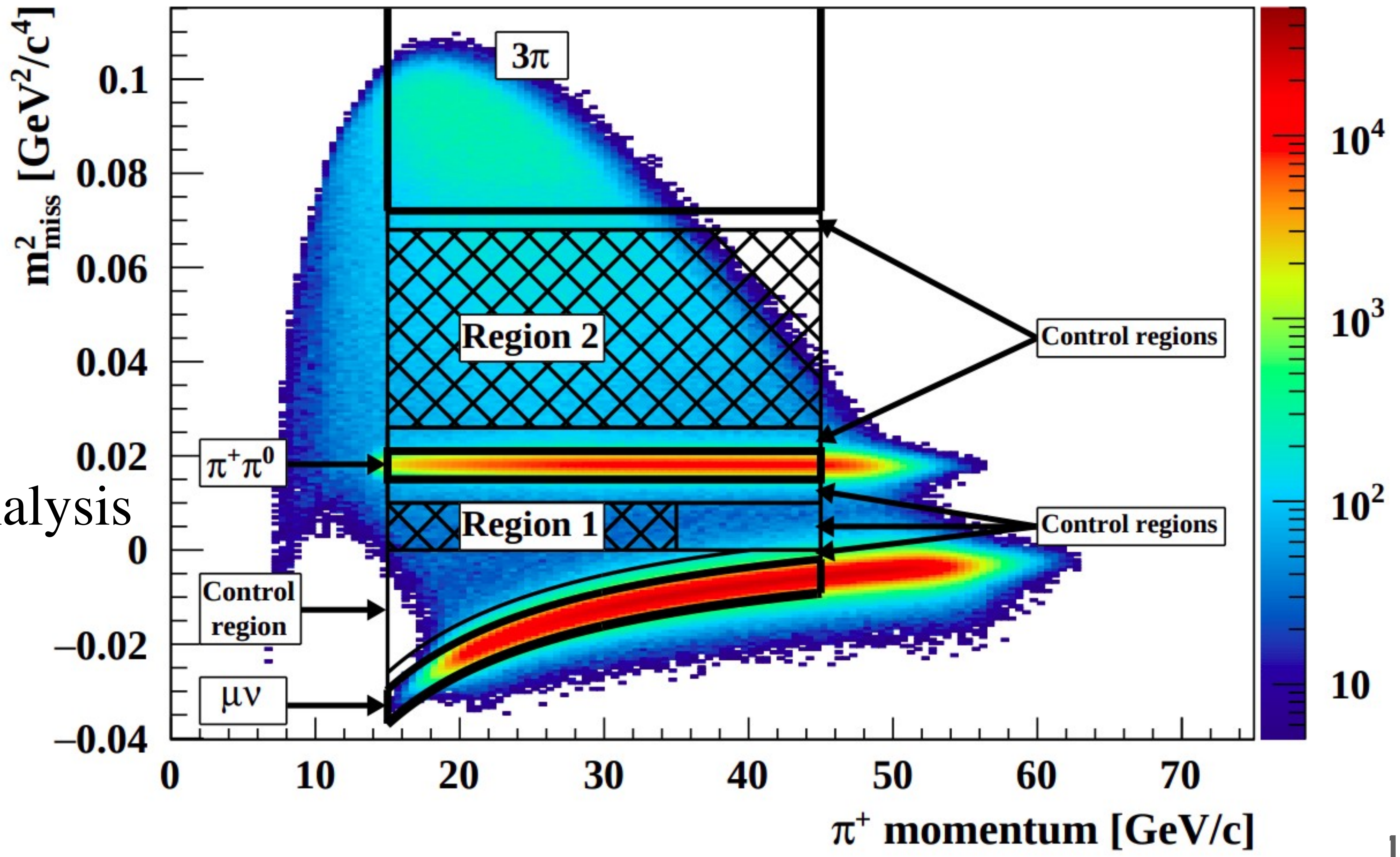
Photo veto

Cut kinematic region

Event selection

K^+, π^+ track
Vertex of K^+ and π^+ tracks
π^+ PID
Photon veto

Two signal regions : Blind analysis
Control regions
around signal regions

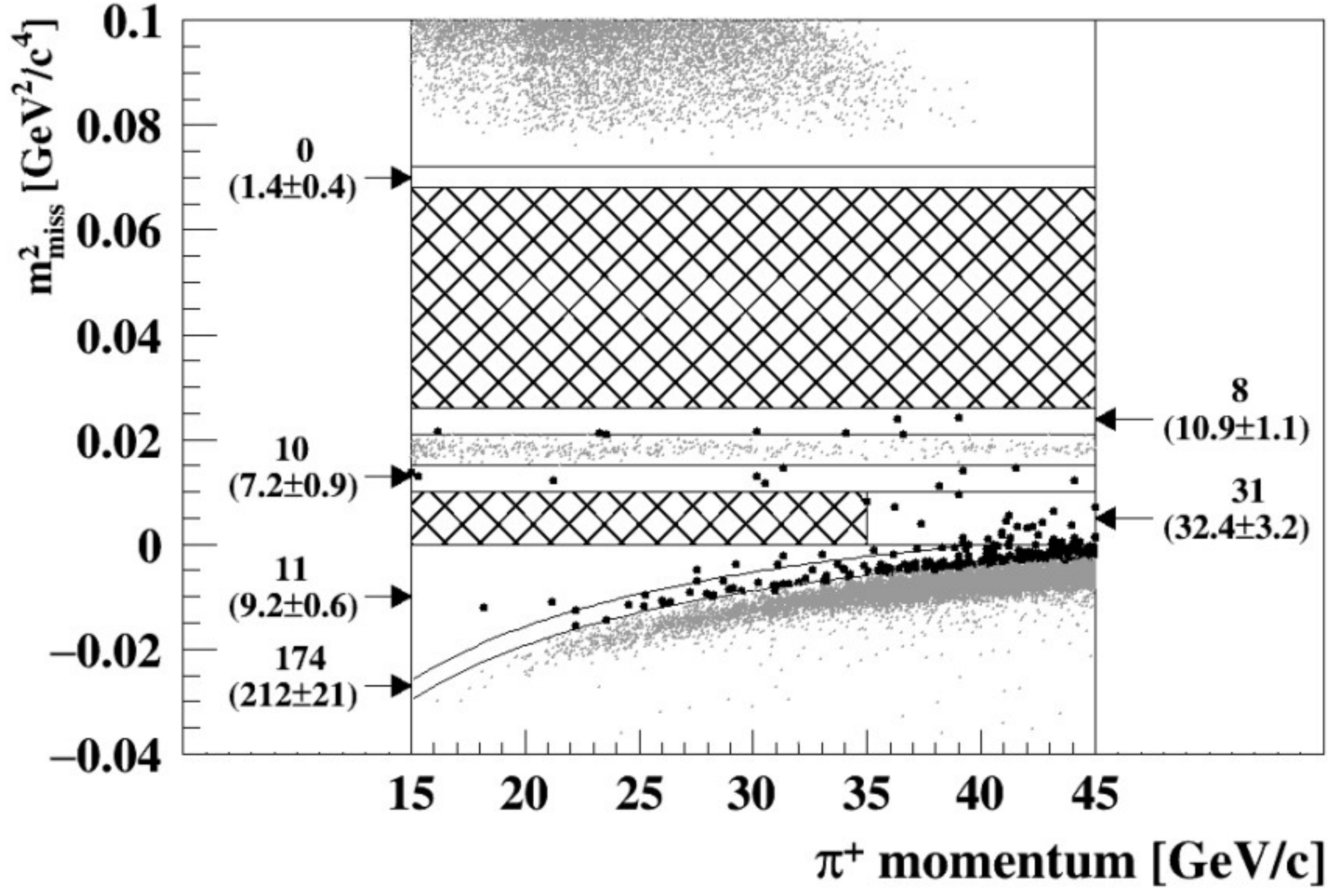


Background estimation of 2018 data

Background estimation

Major decay : data driven (# in signal region / # in control region)

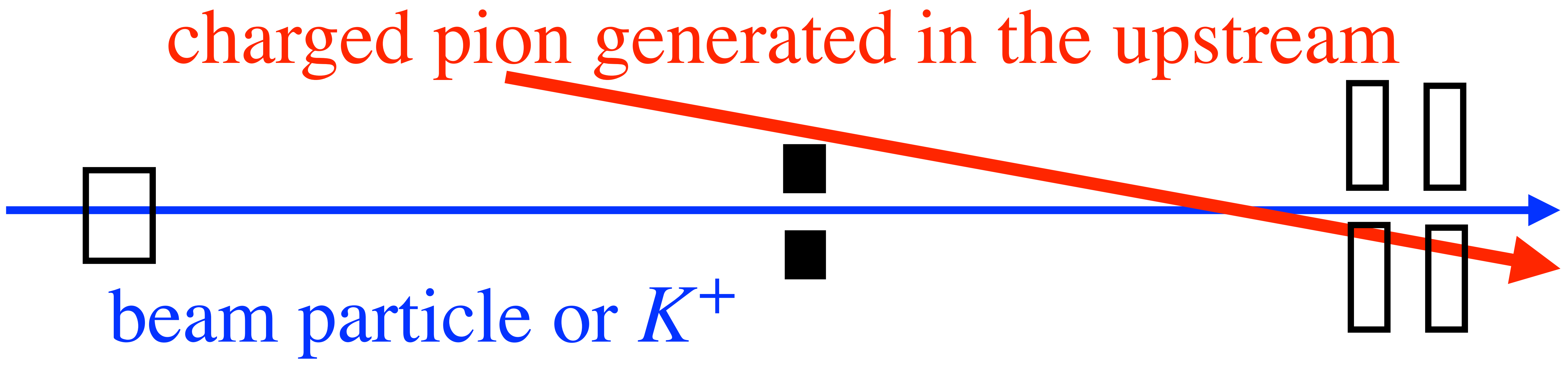
Minor decay : MC



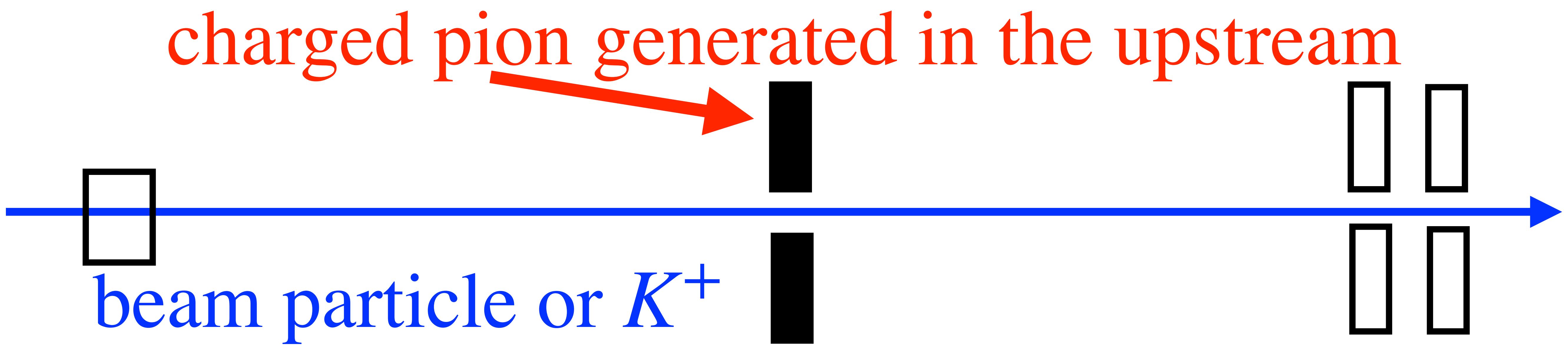
Process	Expected events in R1+R2 (2018 data)
$K^+ \to \pi^+ \nu \bar{\nu}$ (SM)	$7.58 \pm 0.40_{\mathrm{syst}} \pm 0.75_{\mathrm{ext}}$
Total Background	$5.28^{+0.99}_{-0.74}$
$K^+ \to \pi^+ \pi^0 (\gamma)$	0.75 ± 0.04
$K^+ \to \mu^+ \nu_\mu (\gamma)$	0.49 ± 0.05
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	0.50 ± 0.11
$K^+ \to \pi^+ \pi^+ \pi^-$	0.24 ± 0.08
$K^+ \to \pi^+ \gamma \gamma$	< 0.01
$K^+ \to \pi^0 l^+ \nu$	< 0.001
Upstream background	$3.3^{+0.98}_{-0.73}$

Presented by Riccardo Lollini in FPCP2021

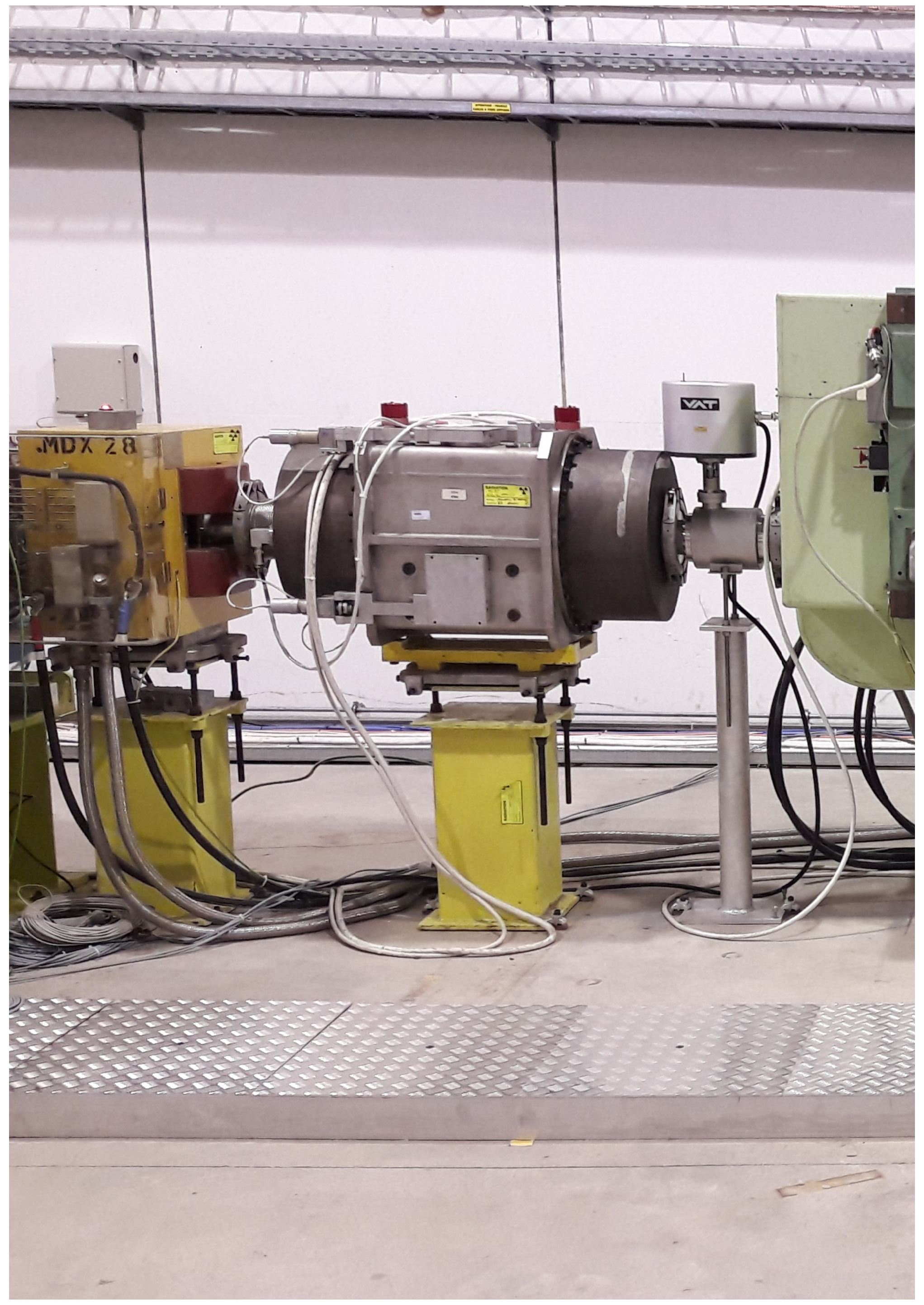
Upstream background



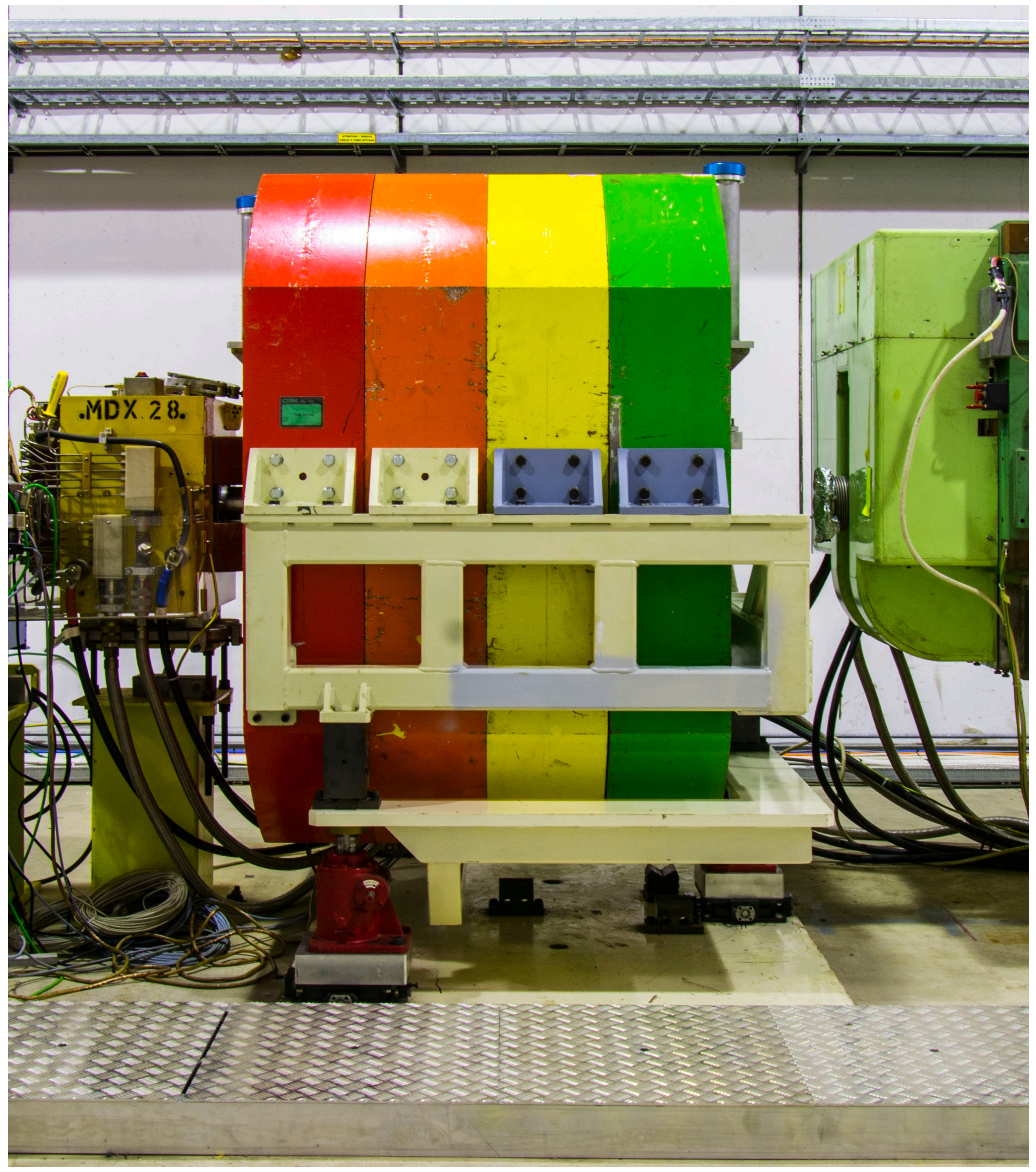
Accidental coincidence / Decay



2016-17

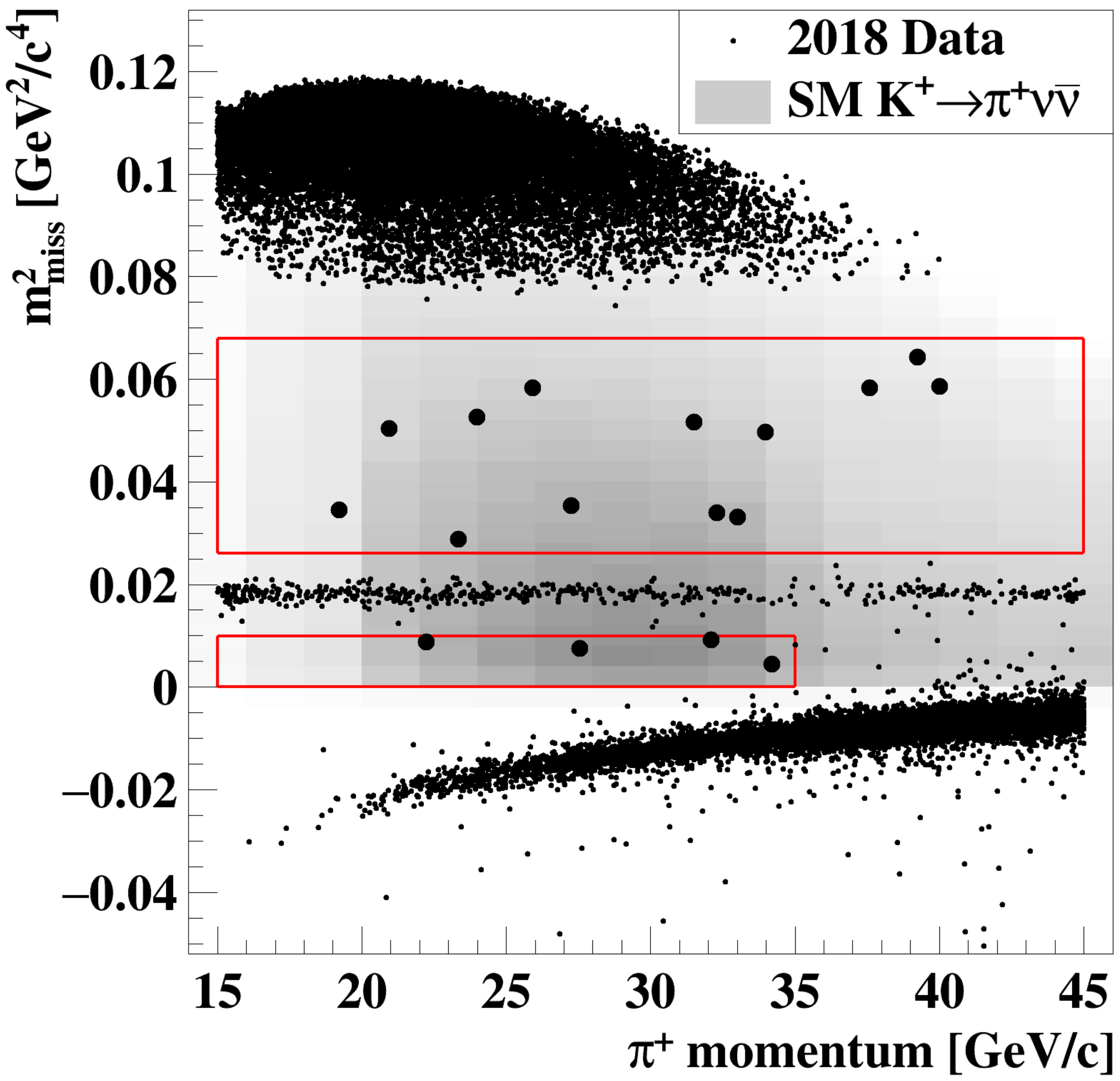


2018-



Collimator to stop such charged pion
New collimator was installed in 2018
NA62 run2 : additional tracker + veto

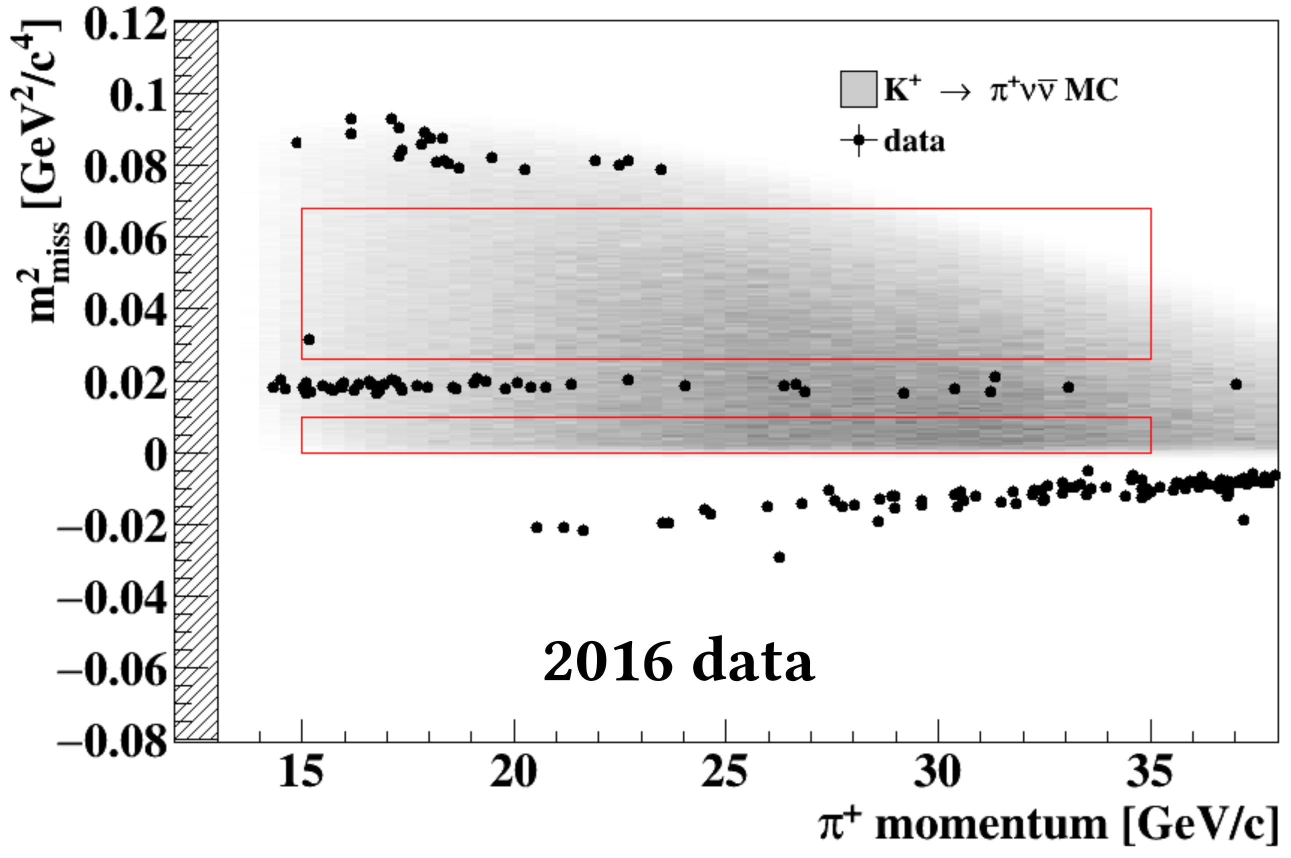
Results of analysis of 2018 data

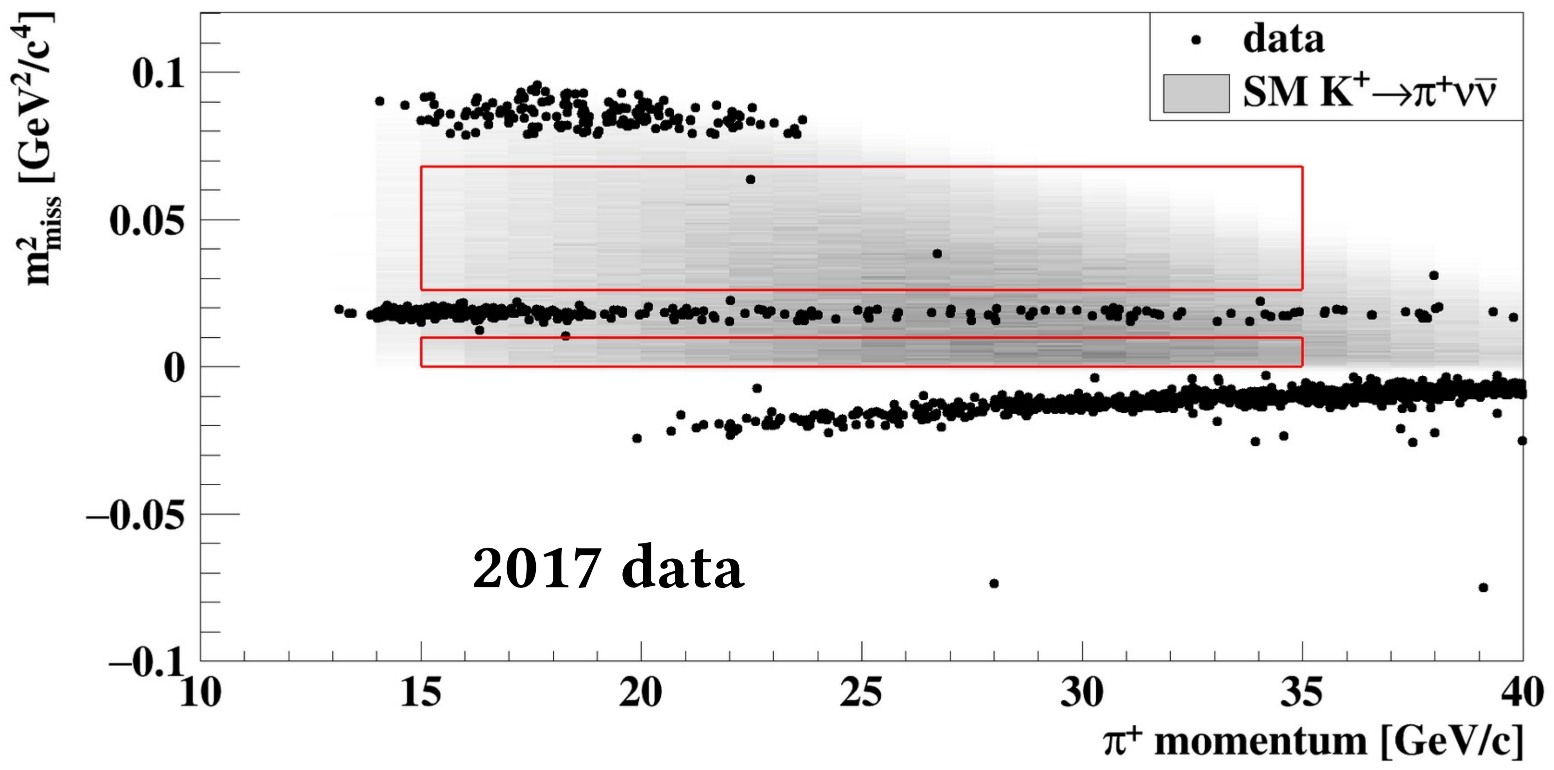


In the signal region
17 events observed,
↔ expected number of events

$$N^{SM}_{\pi^+\nu\nu} = 7.6$$
$$N_{BG} = 5.3$$

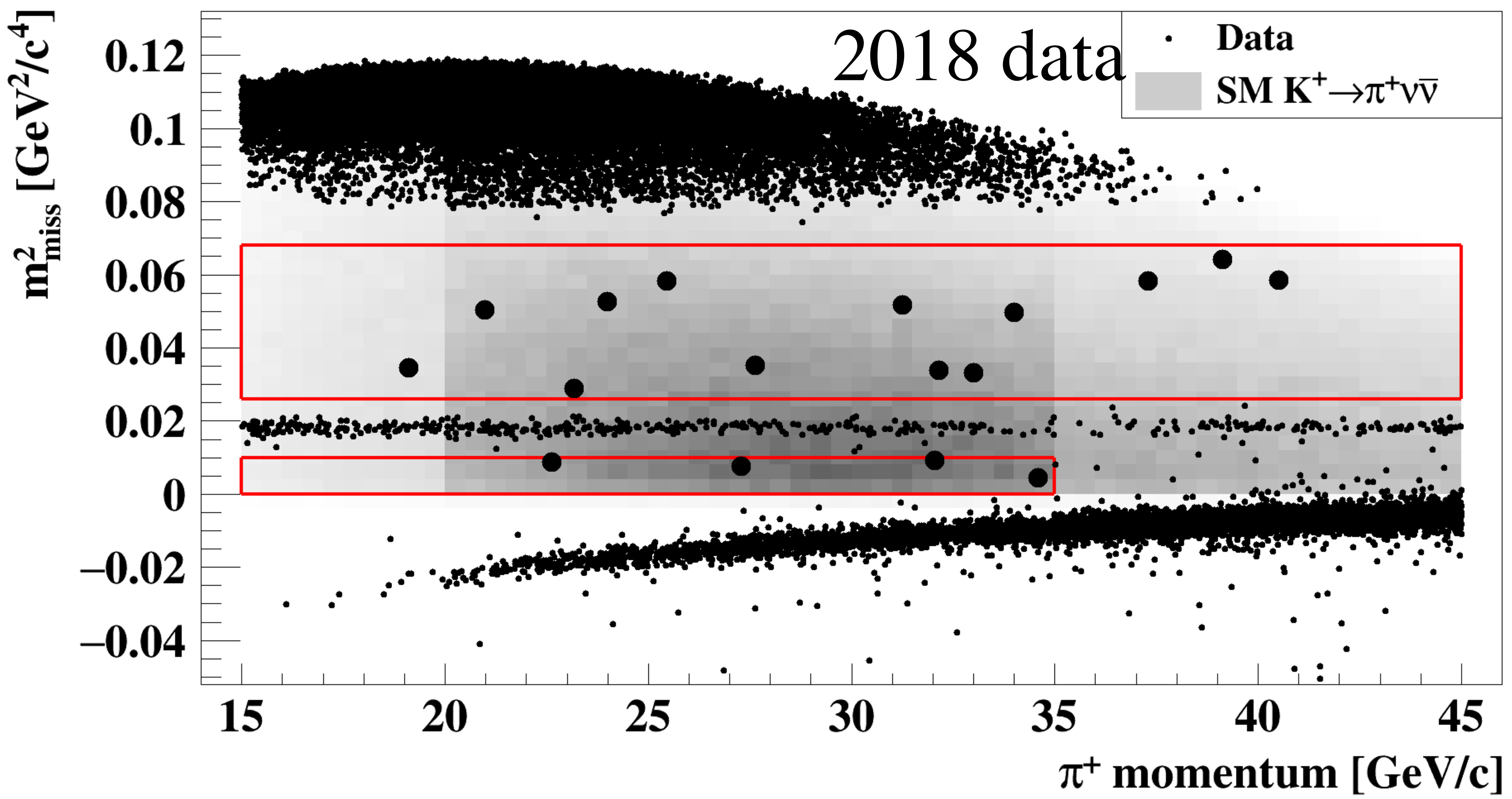
Results of NA62 run1 (2016-2018)





2016 : 1 event observed (*PLB* 791(2019) 156)
2017 : 2 events observed (*JHEP* 11(2020)042)
2018 : 17 events observed
In total 20 events

$$SES = (0.839 \pm 0.053_{\text{syst}}) \times 10^{-11},$$
$$N_{\pi\nu\bar{\nu}}^{\text{exp}} = 10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}},$$
$$N_{\text{background}}^{\text{exp}} = 7.03^{+1.05}_{-0.82}.$$



$\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$ (68 % CL)
Observation with 3.4σ significance
Compatible with SM (8.4×10^{-11})
(*JHEP* 06 (2021) 093)

Prospects

- NA62 run2
  - Started from Aug. 2021, till 2024
  - Measure $\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu})$ at O(10%) precision
    - More events with higher beam intensity
    - Further suppression of the background
- Far future plan
  - Higher beam intensity of SPS is under discussion
    - Factor of 4 more K^+
    - New K_L beam line to search for $K_L \to \pi^0\nu\bar{\nu}$: KLEVER project

KLEVER experiment

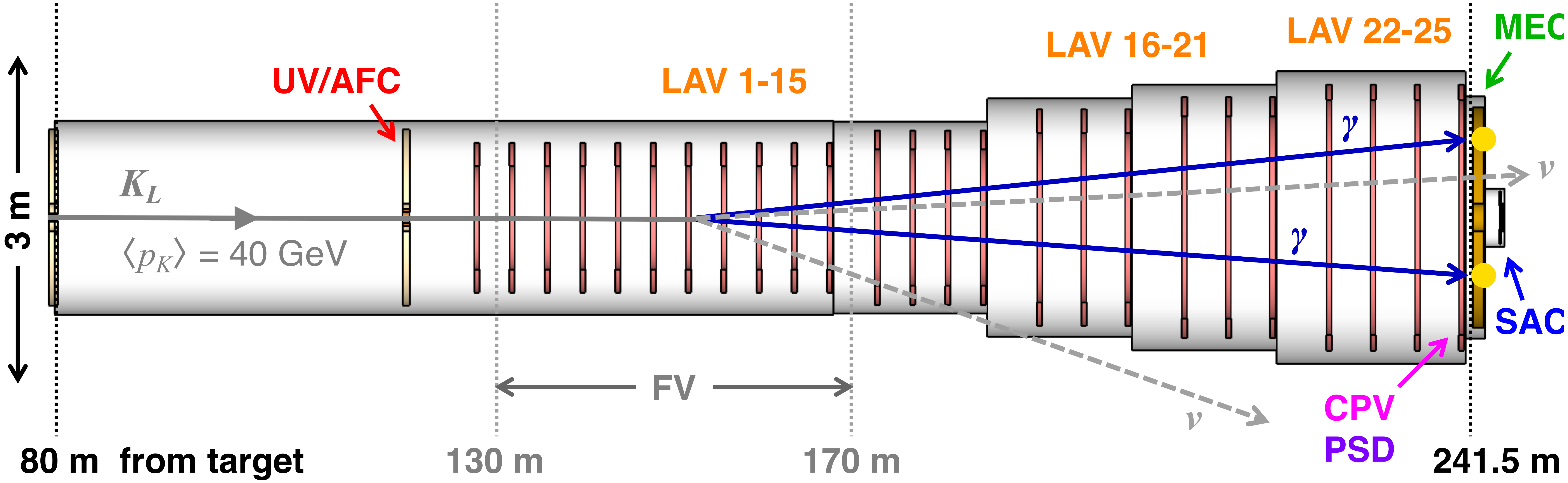
KLEVER target sensitivity:
5 years starting Run 4

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

δBR/BR($\pi^0\nu\nu$) ~ 20%

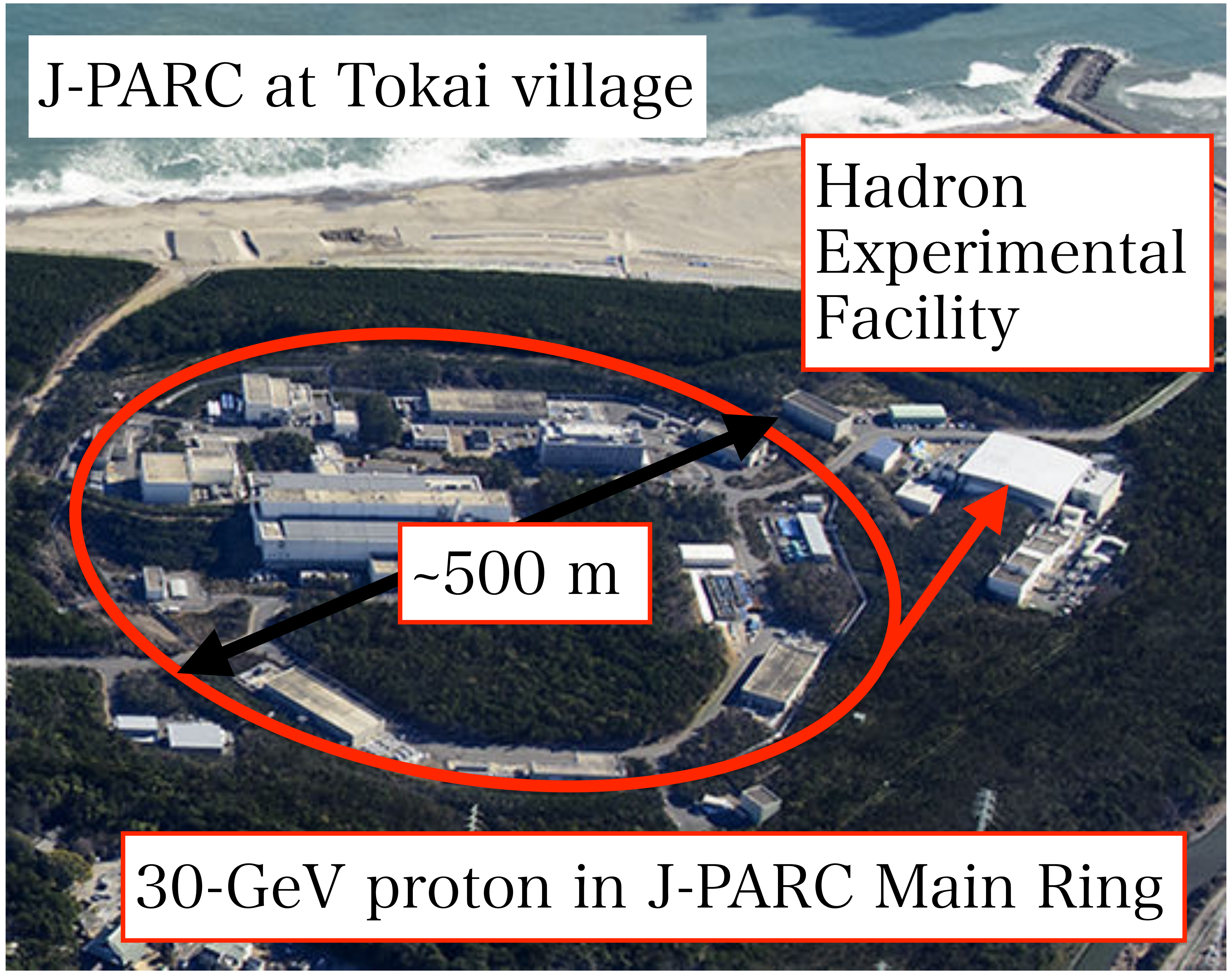
$$< p_{K_L} > \sim 40 \text{ GeV}/c$$

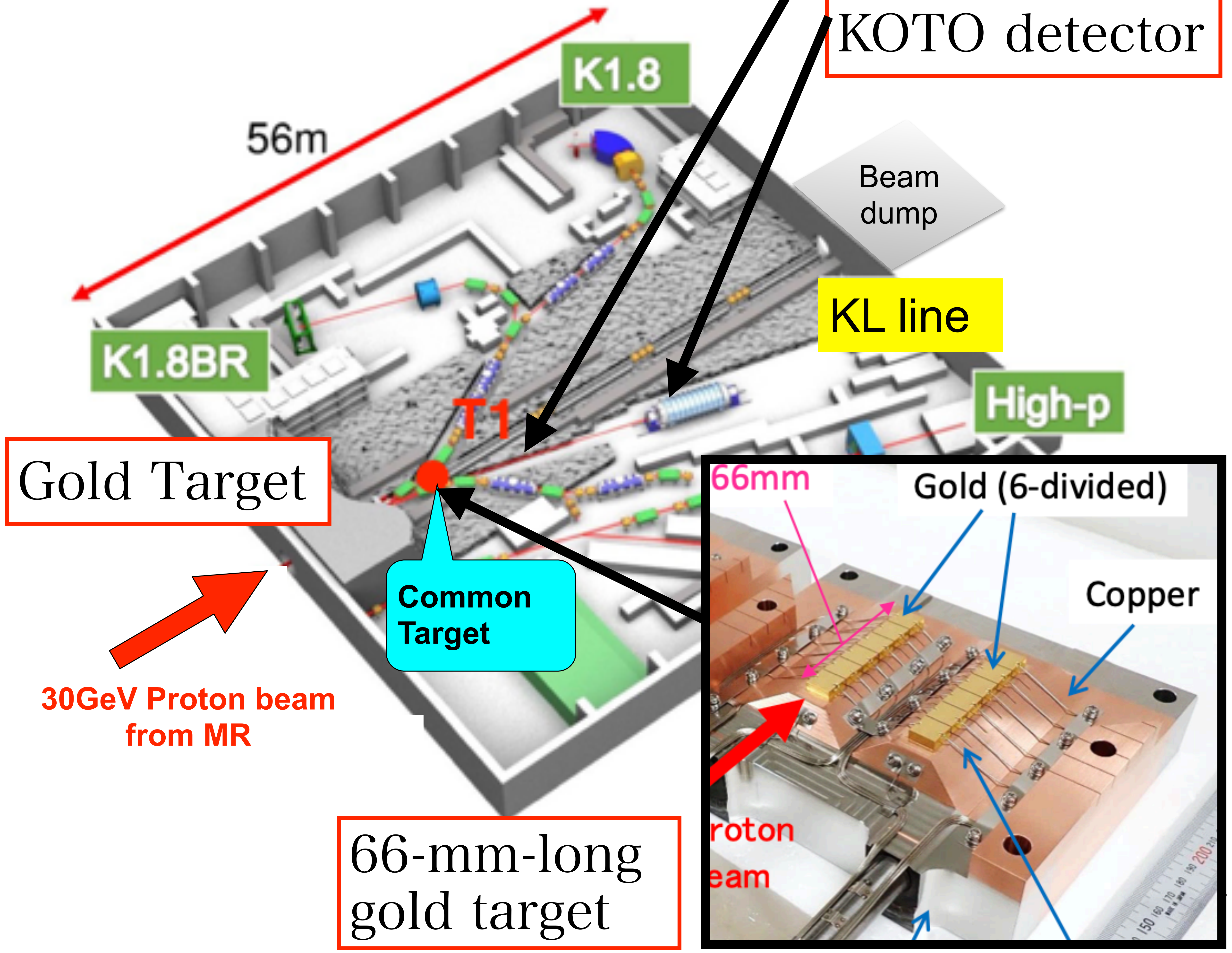
400-GeV SPS proton beam on Be target at z = **0 m**



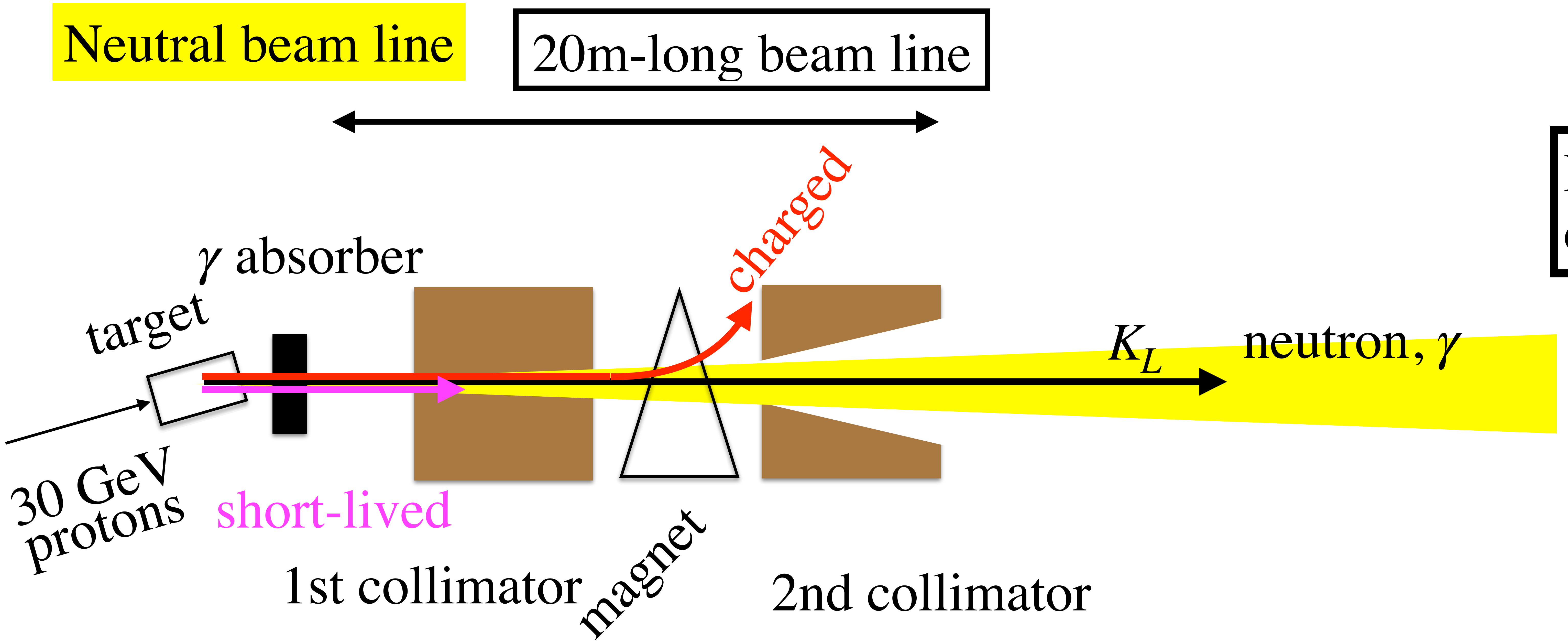
KOTO experiment at J-PARC

KOTO (K0 at Tokai)



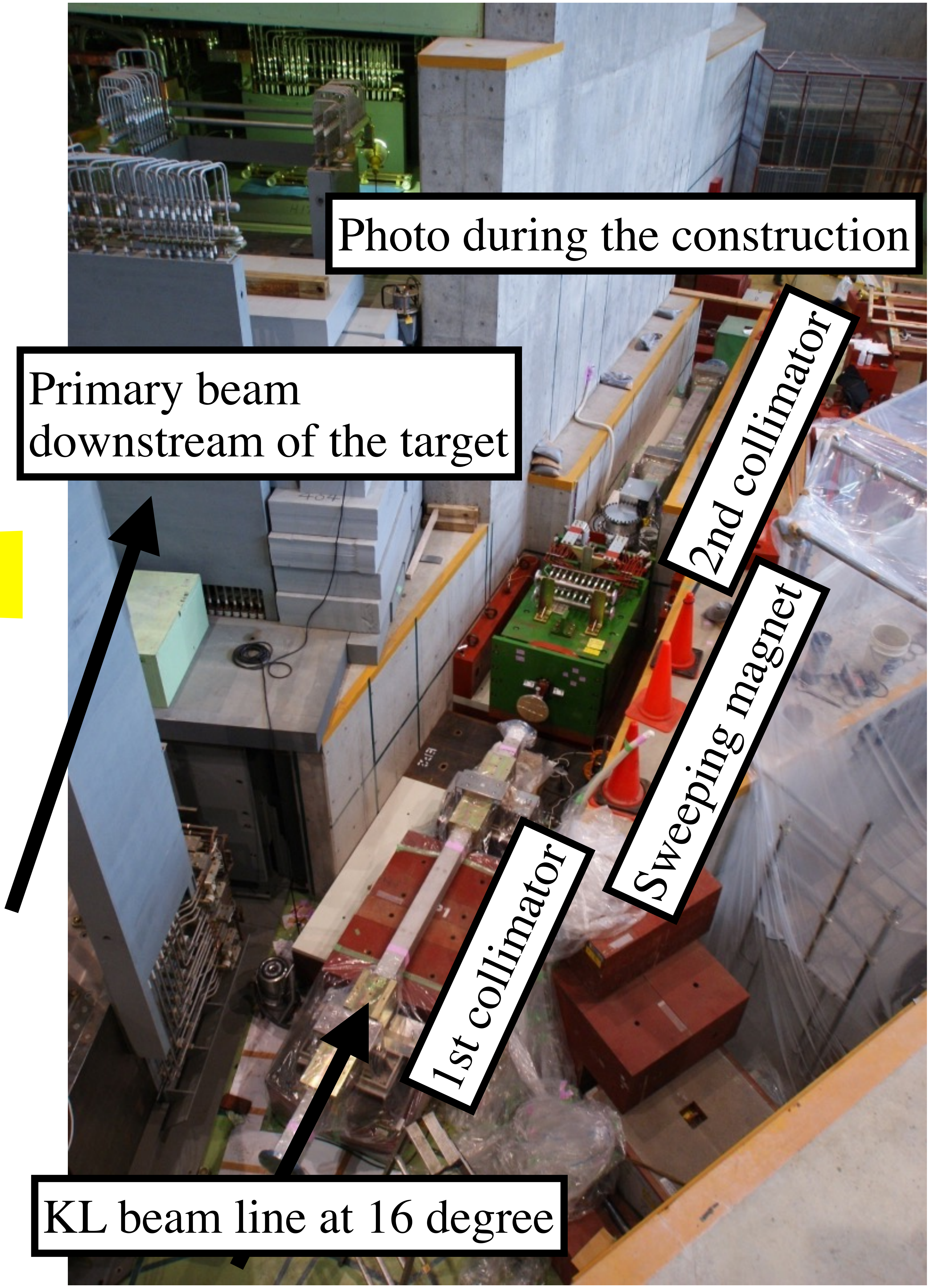


KL beam line

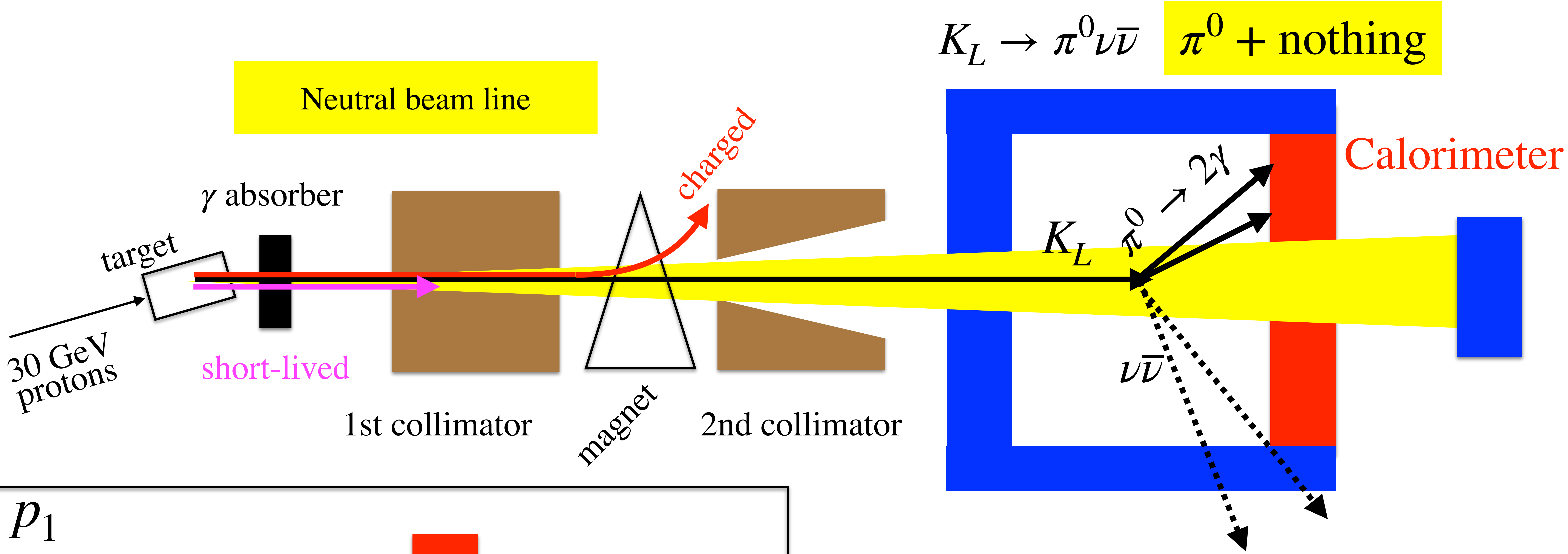


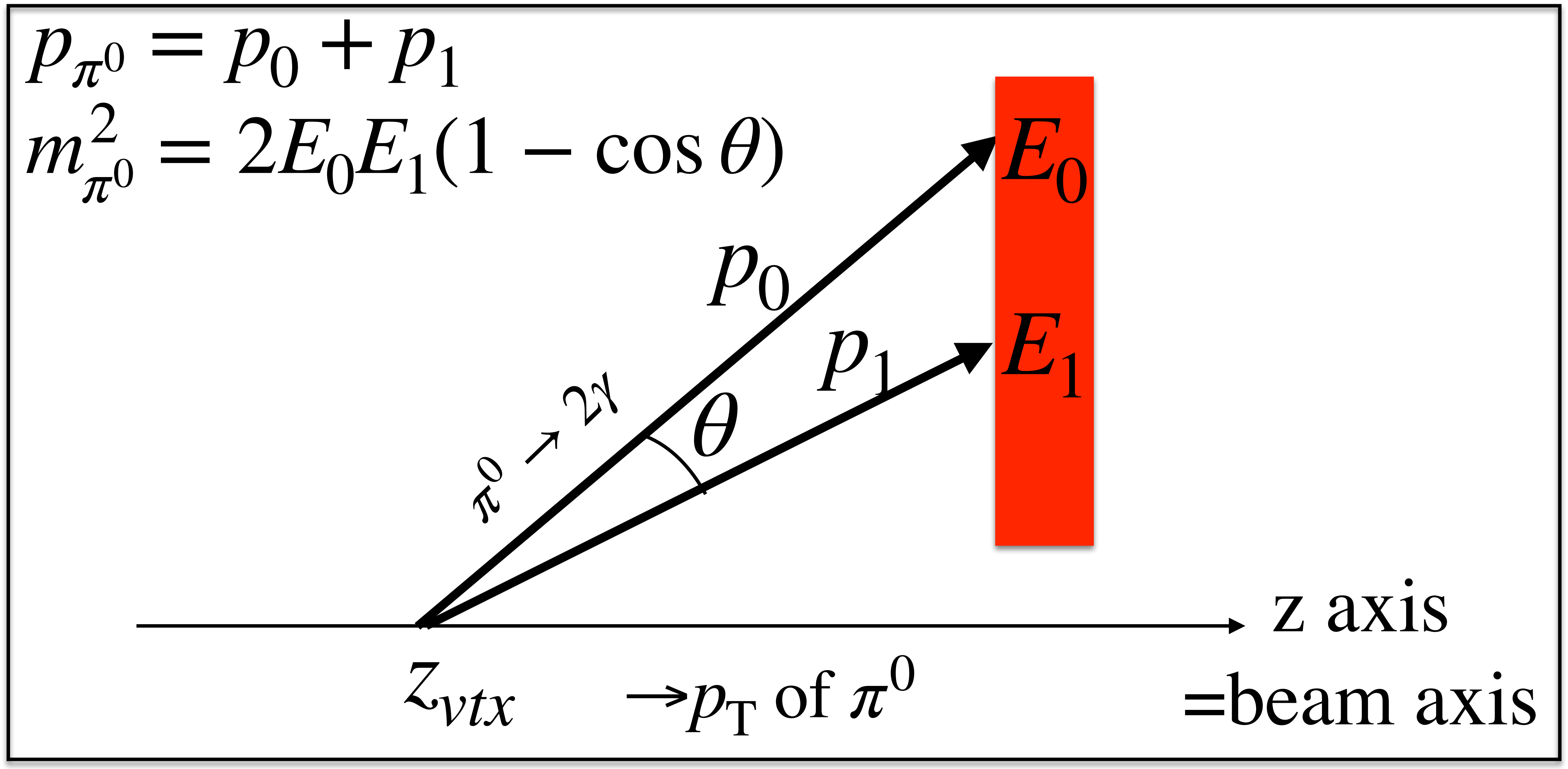
Short-lived particles decay out.
Charged particles are swept out.

Narrow neutral beam (K_L, neutron, γ)



Signal reconstruction





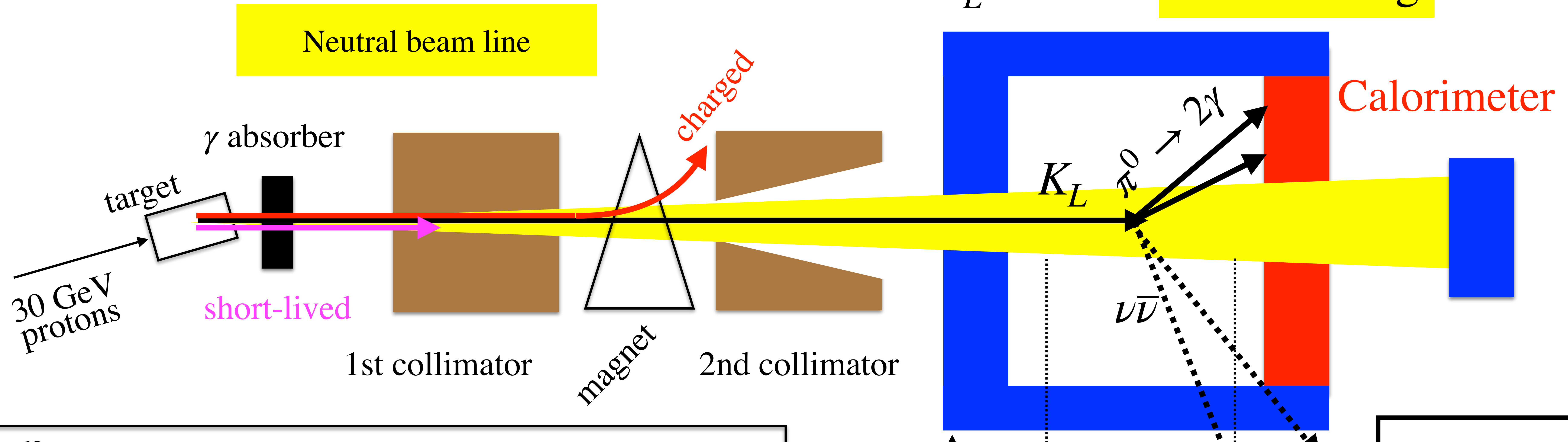
Assume the vertex on beam axis

⇕

Narrow beam

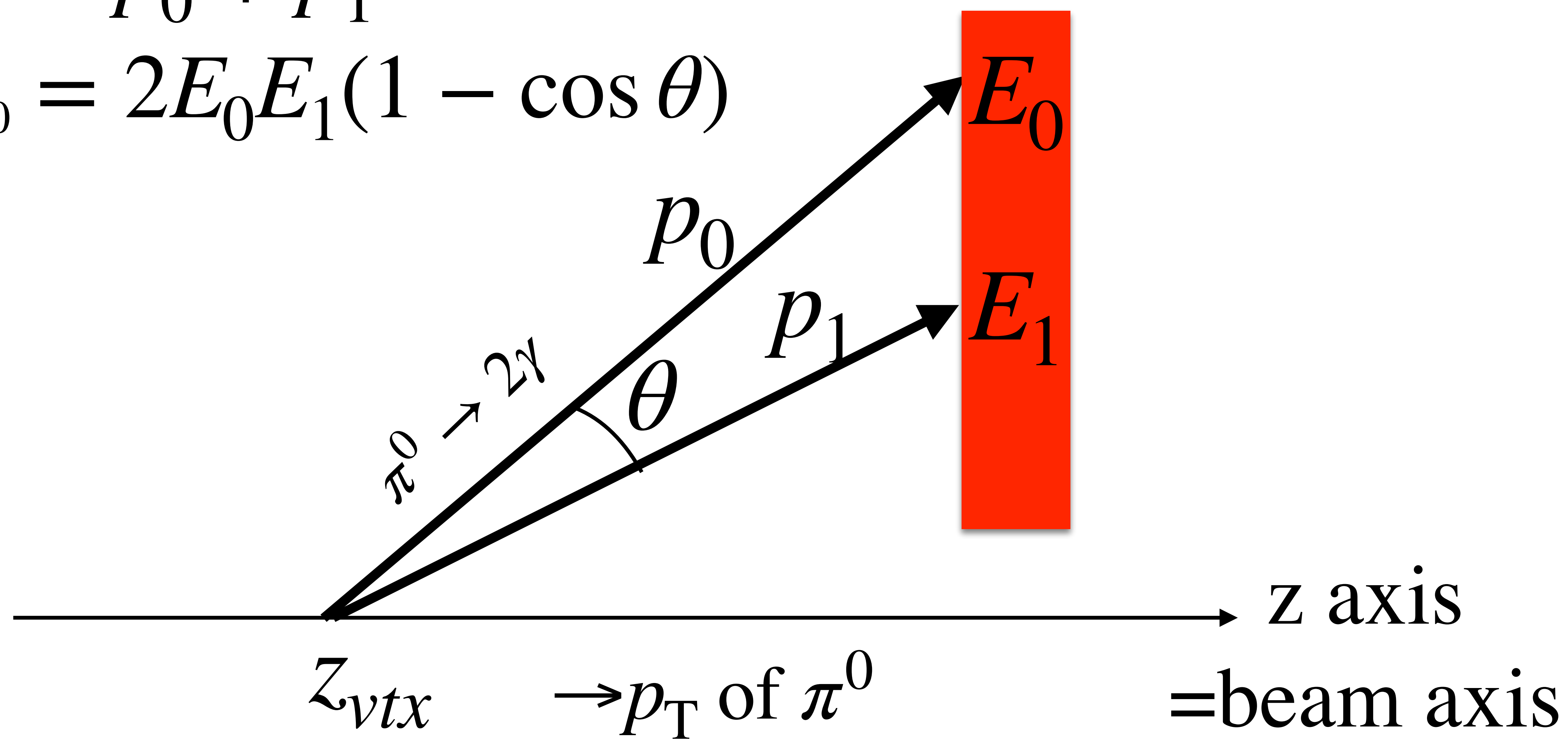
Signal reconstruction

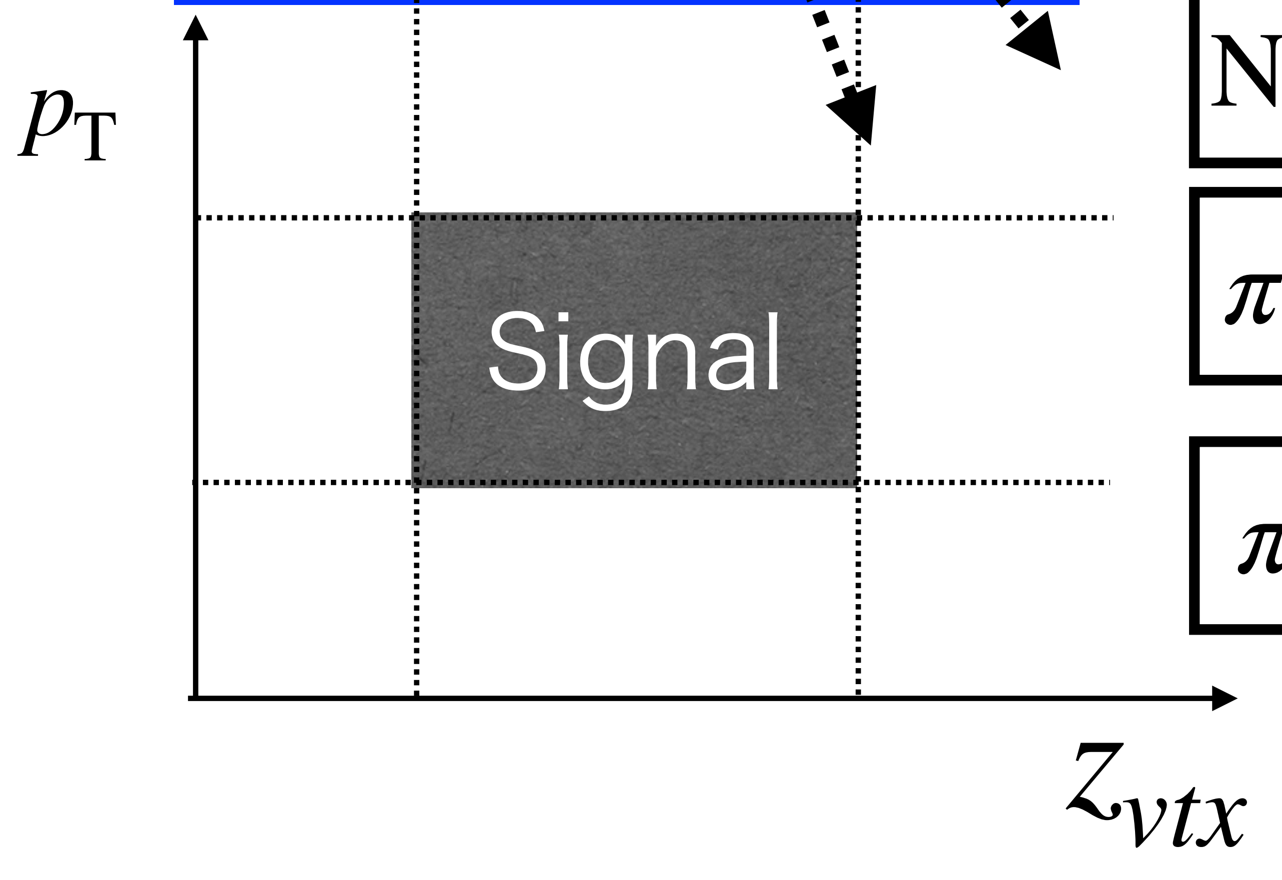
$K_L \to \pi^0 \nu \bar{\nu}$ **π^0 + nothing**



$p_{\pi^0} = p_0 + p_1$

$m^2_{\pi^0} = 2E_0E_1(1 - \cos\theta)$





Narrow beam

π^0 reconstruction from 2γ

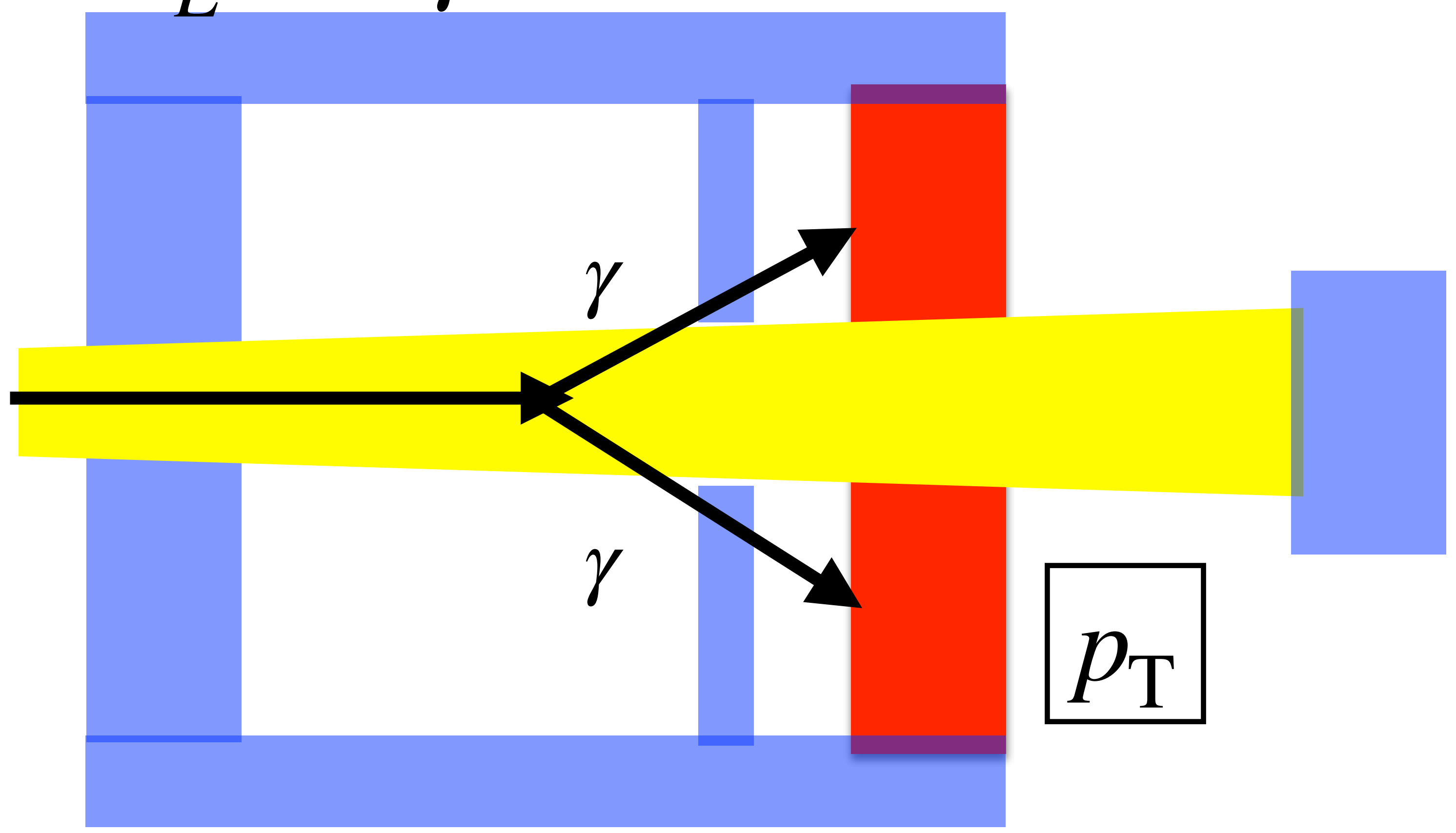
π^0 P_T due to missing $\nu\bar{\nu}$

blind analysis

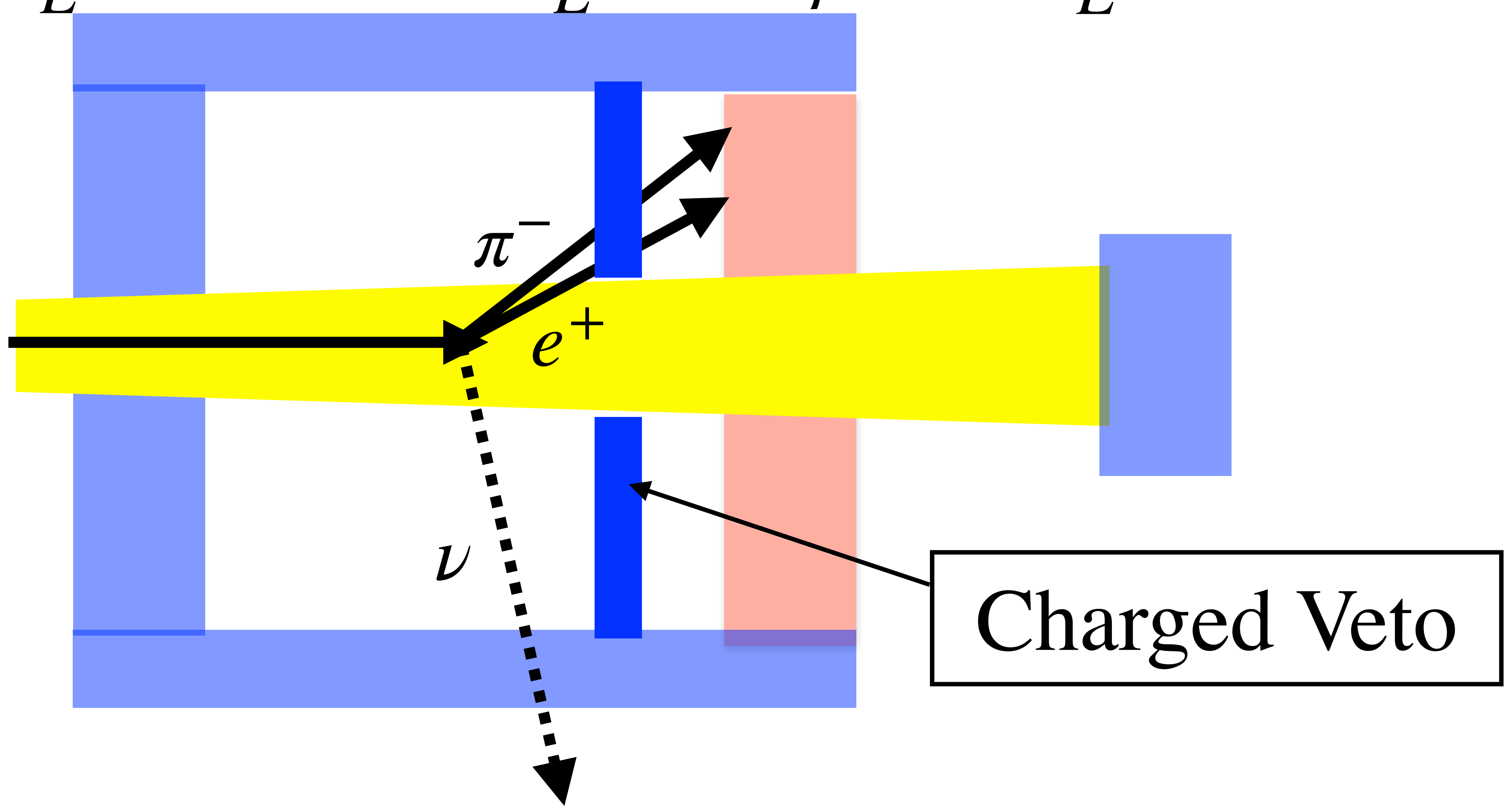
Background from K_L decay

Two observable particles in the final state

$K_L \to 2\gamma$

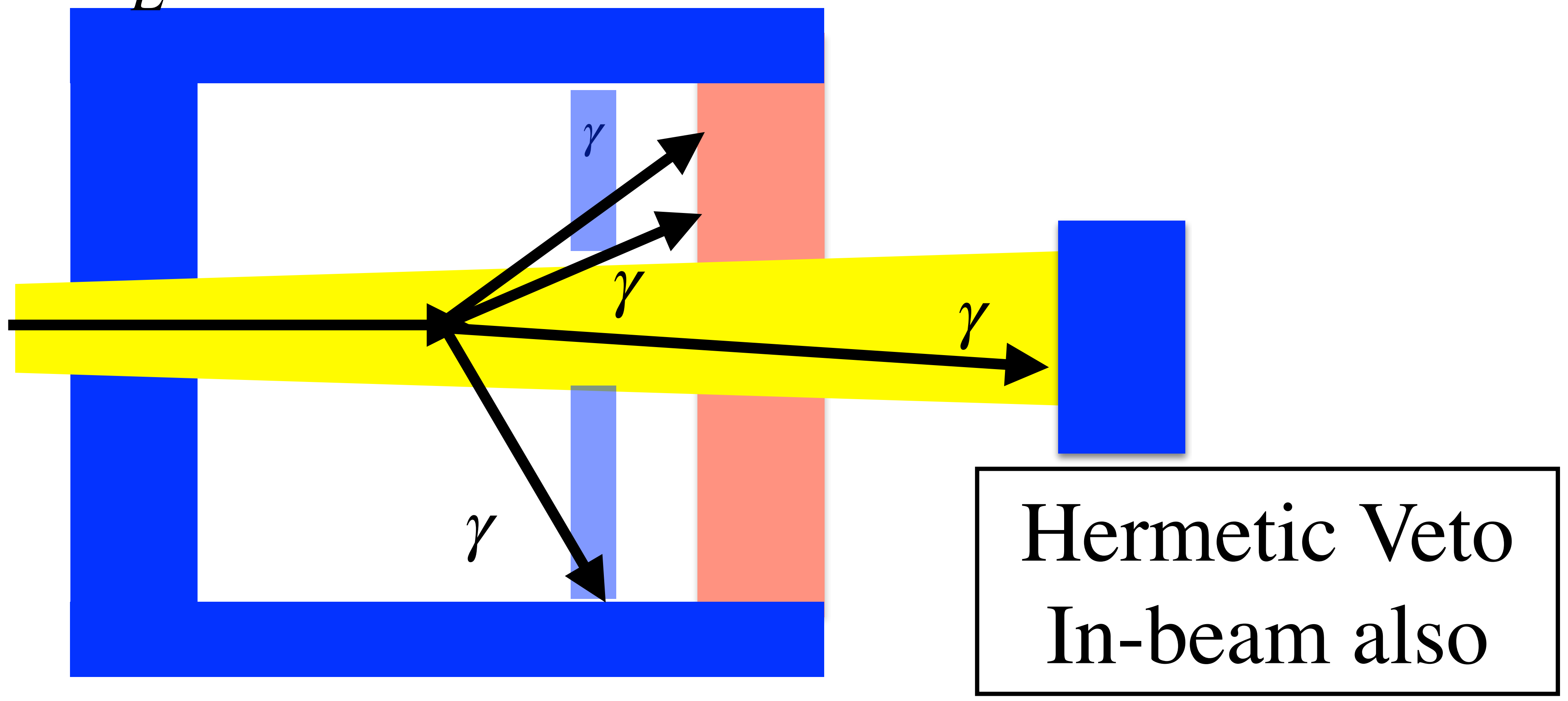


$K_L \to \pi^\pm e^\mp \nu$ / $K_L \to \pi^\pm \mu^\mp \nu$ / $K_L \to \pi^+ \pi^-$

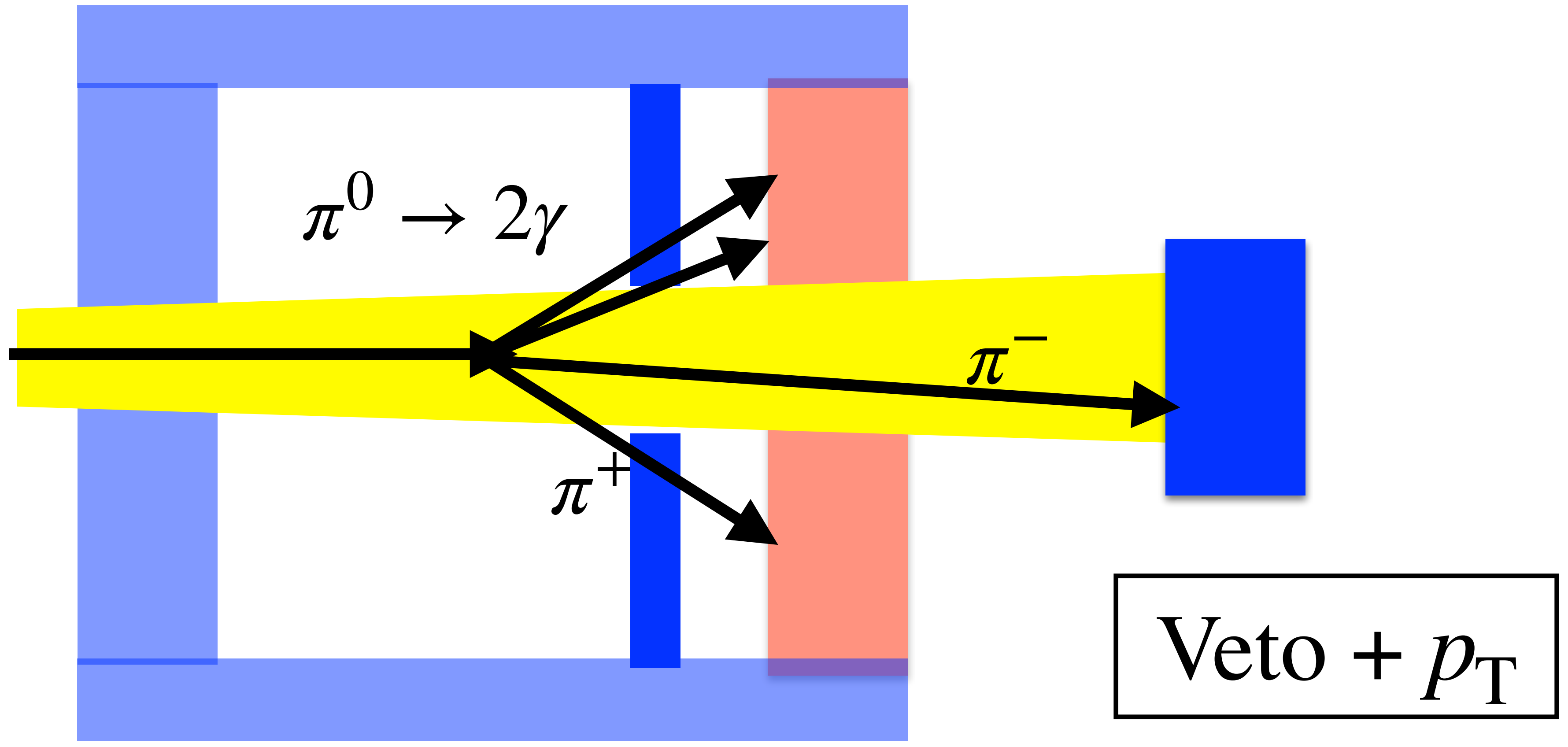


Extra particles for veto

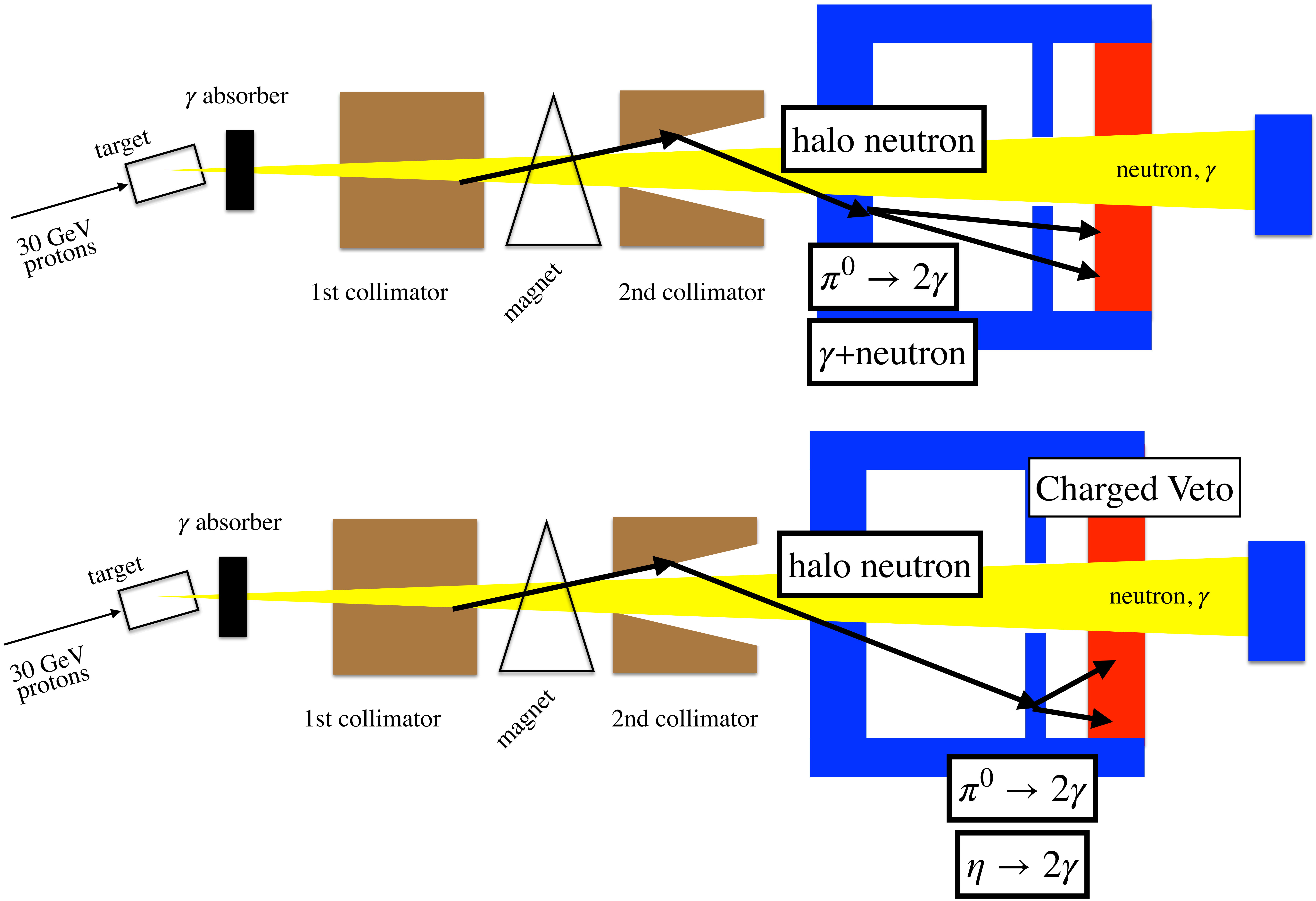
$K_L \to 2\pi^0$



$K_L \to \pi^+ \pi^- \pi^0$

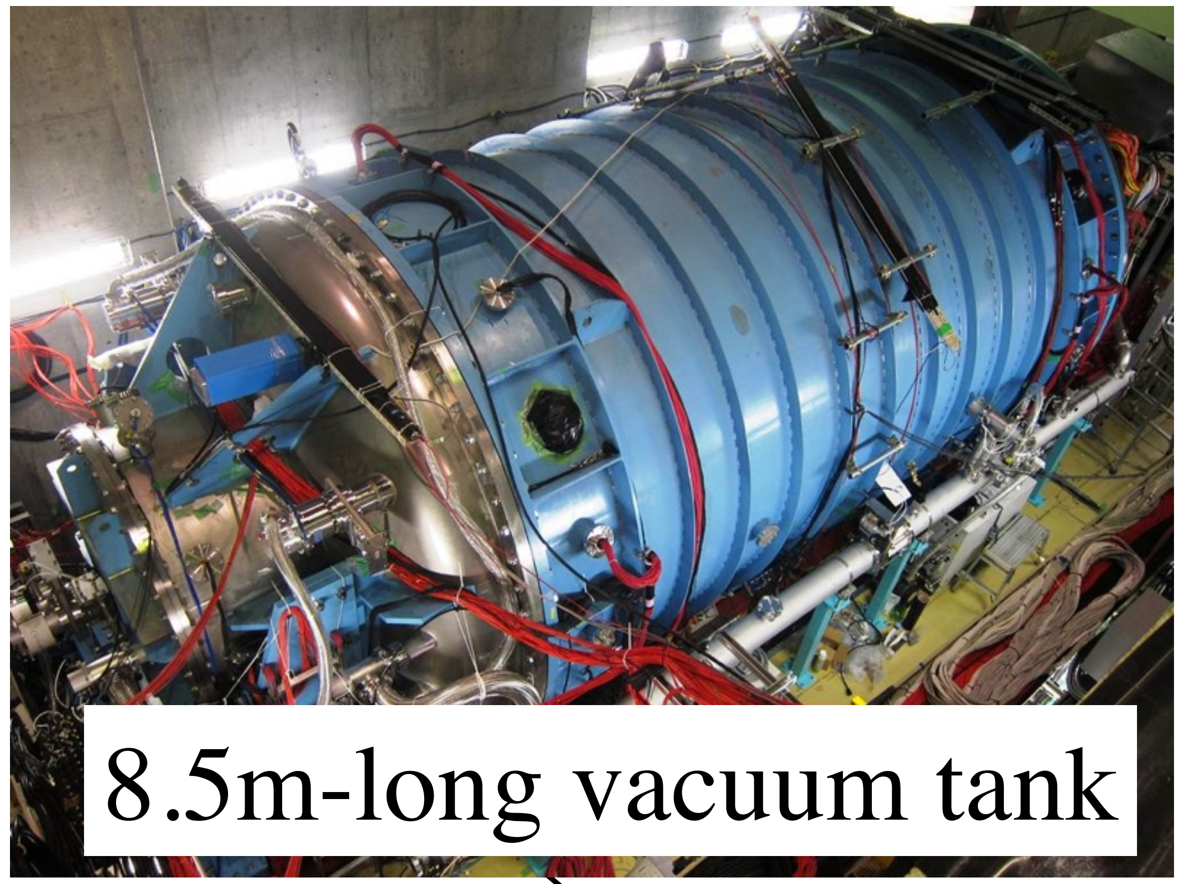


Background from π^0/η production from neutron

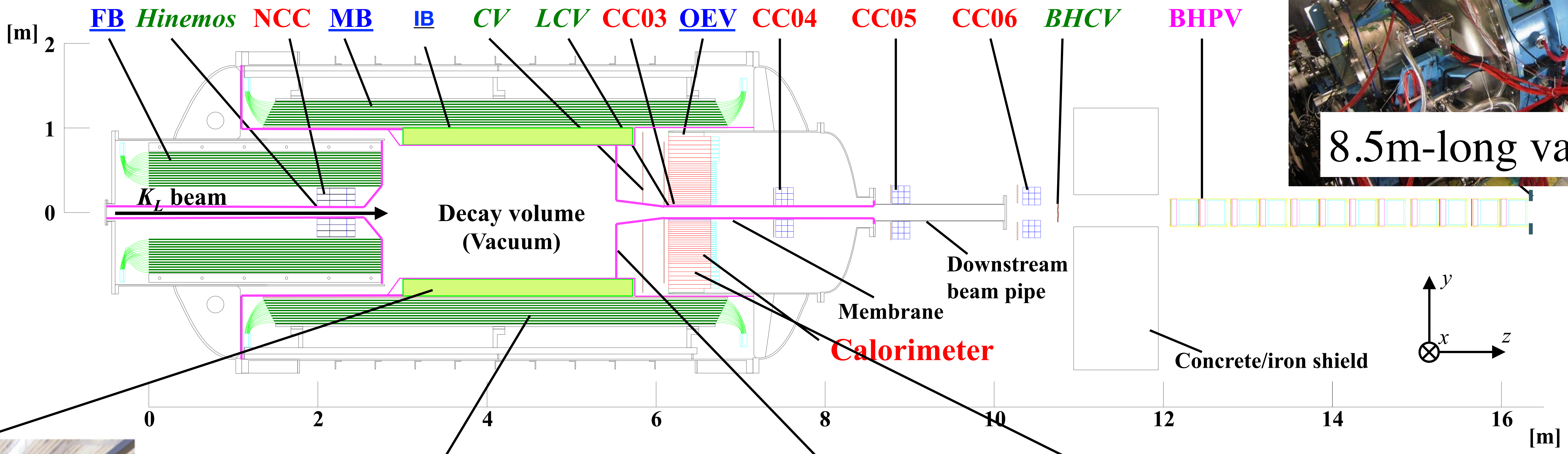


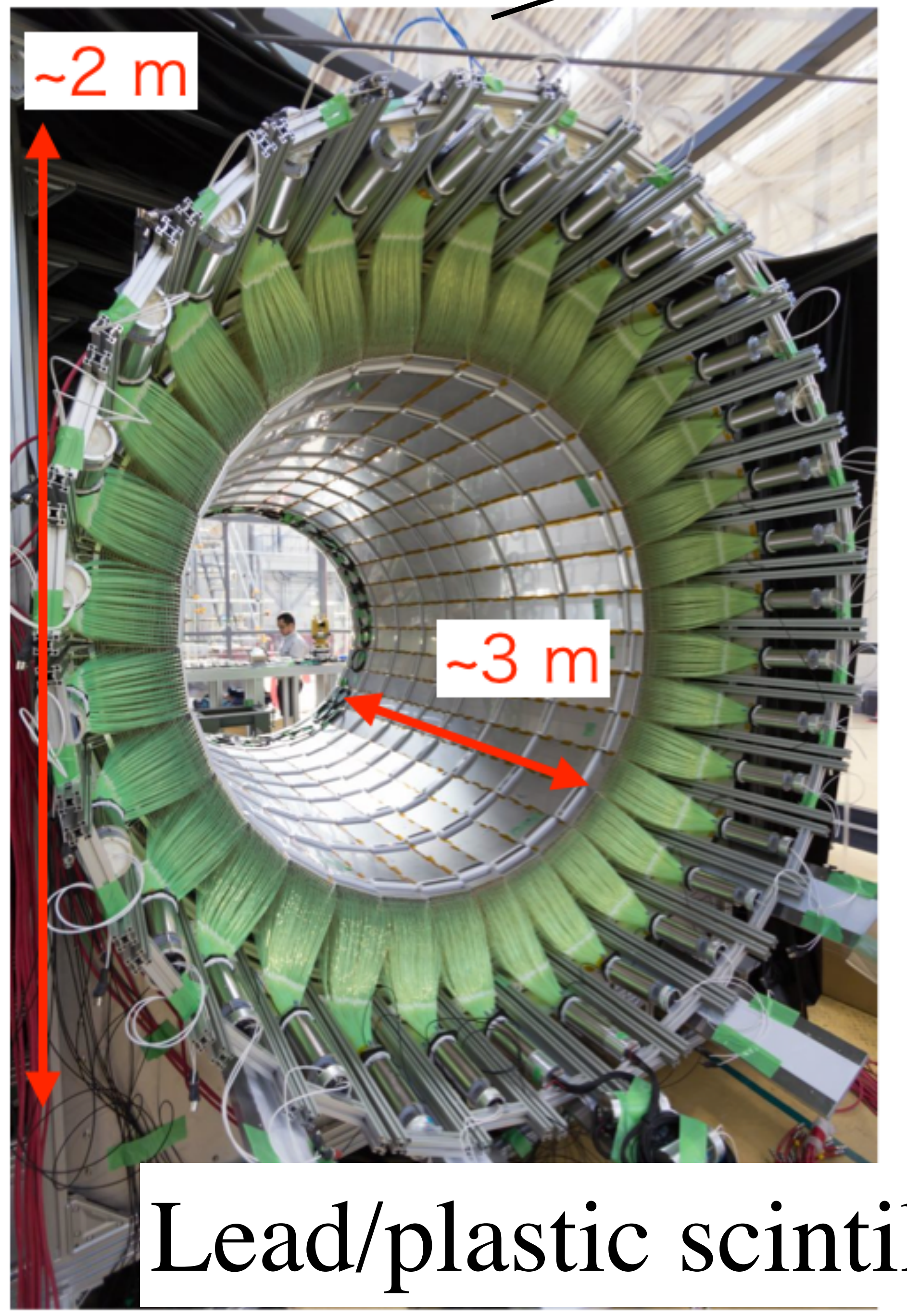
- Less detector material
- Detector material away from beam
- Detector position away from signal reigon

KOTO detector

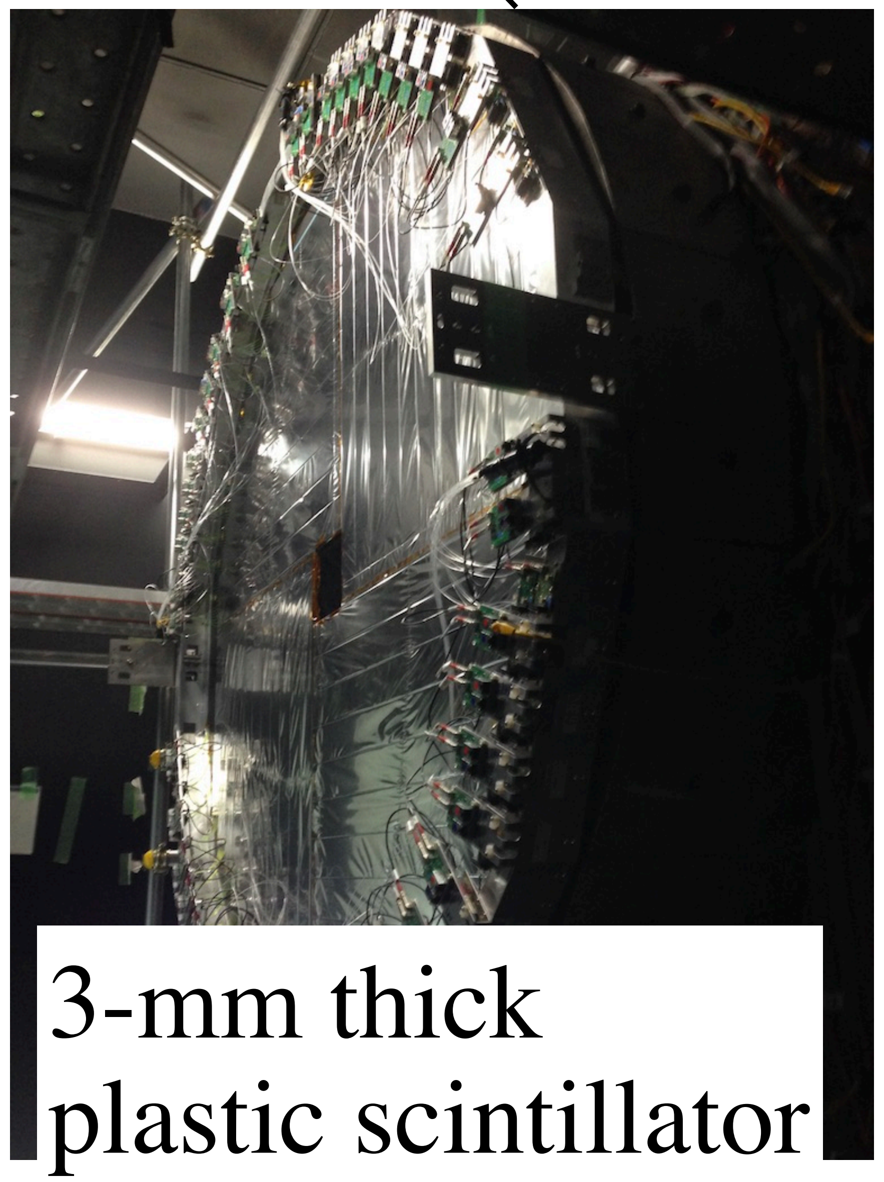


8.5m-long vacuum tank

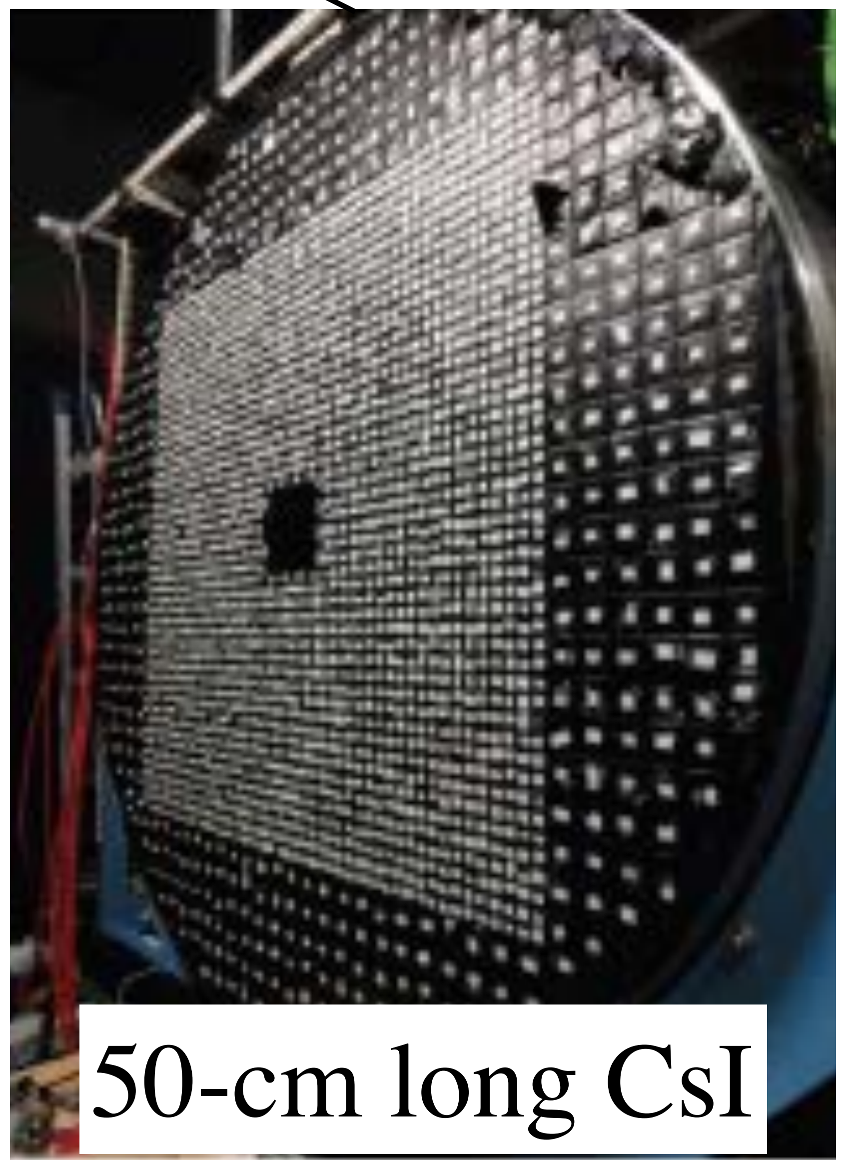




Lead/plastic scintillator sandwich counter



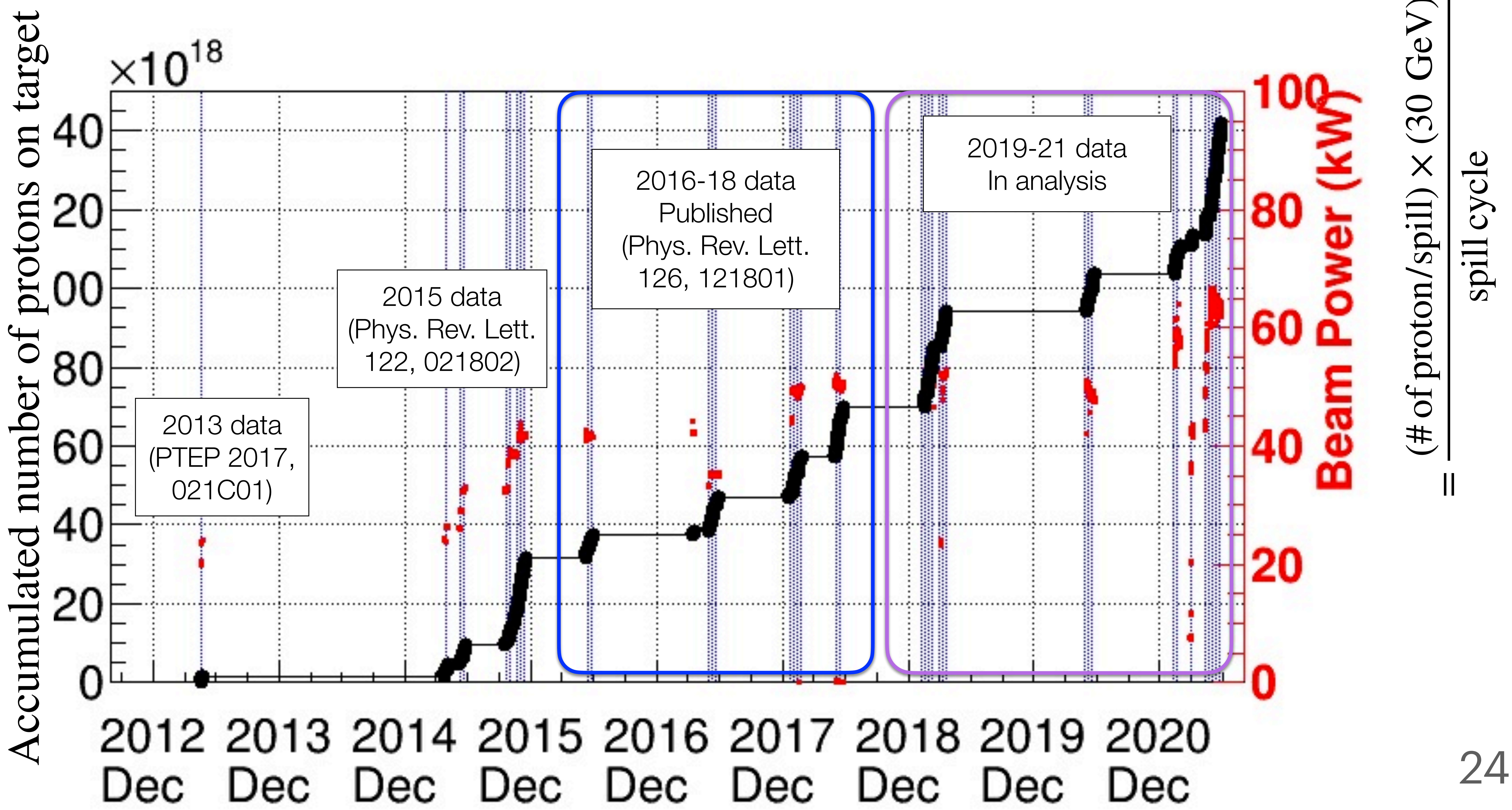
3-mm thick
plastic scintillator



50-cm long CsI

Diameter ~1.9 m
50-cm long CsI crystals
Cross section
  2.5 cm × 2.5 cm
  5 cm × 5 cm

KOTO Data Accumulation

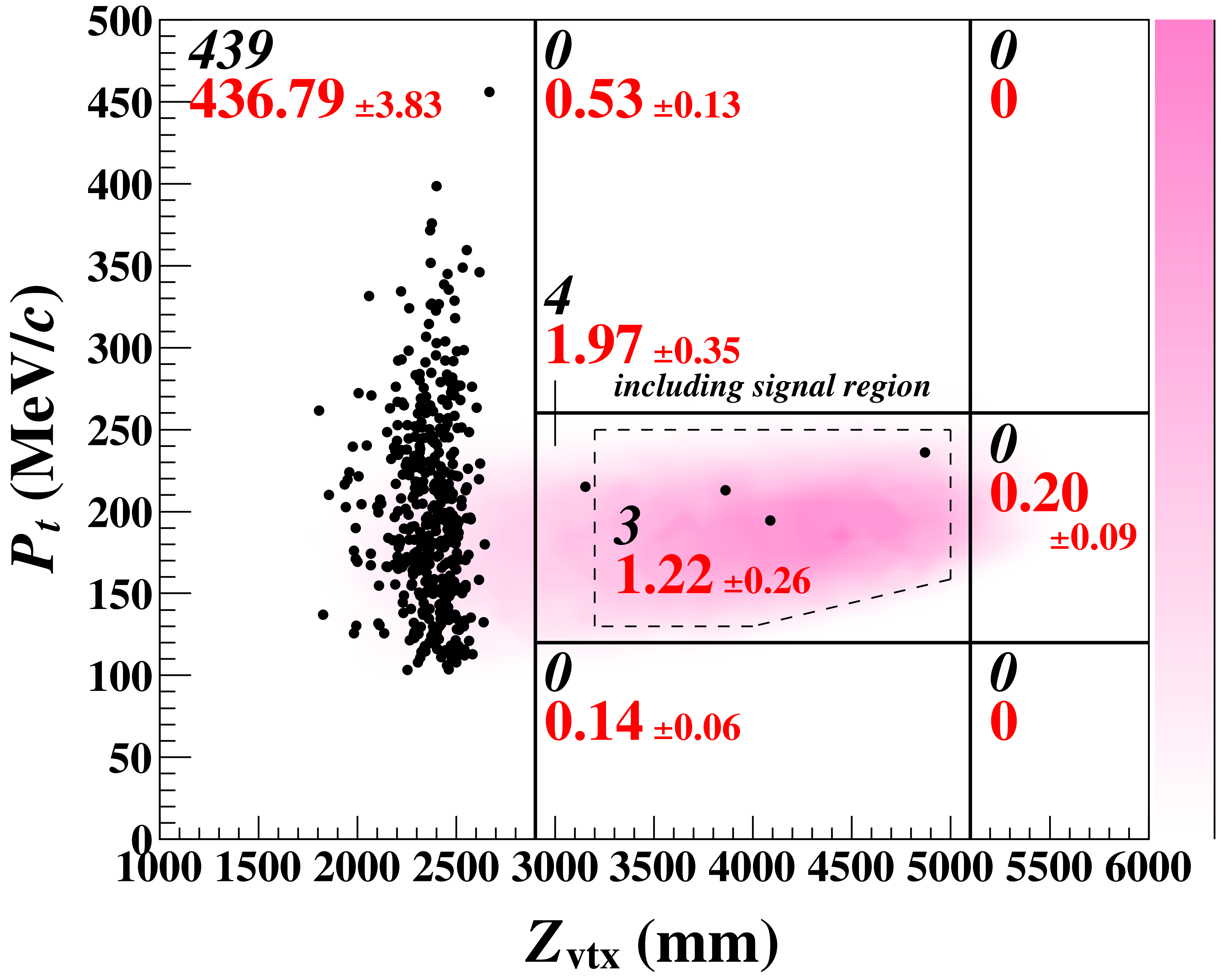


Analysis of 2016-18 data

Results of 2016-18 analysis

Phys.Rev.Lett.126(121801)(2021)

3 events observed
SES=$(7.20 \pm 0.05_{stat.} \pm 0.66_{syst.}) \times 10^{-10}$
$\mathscr{B}(K_L \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}$ (90 % CL)

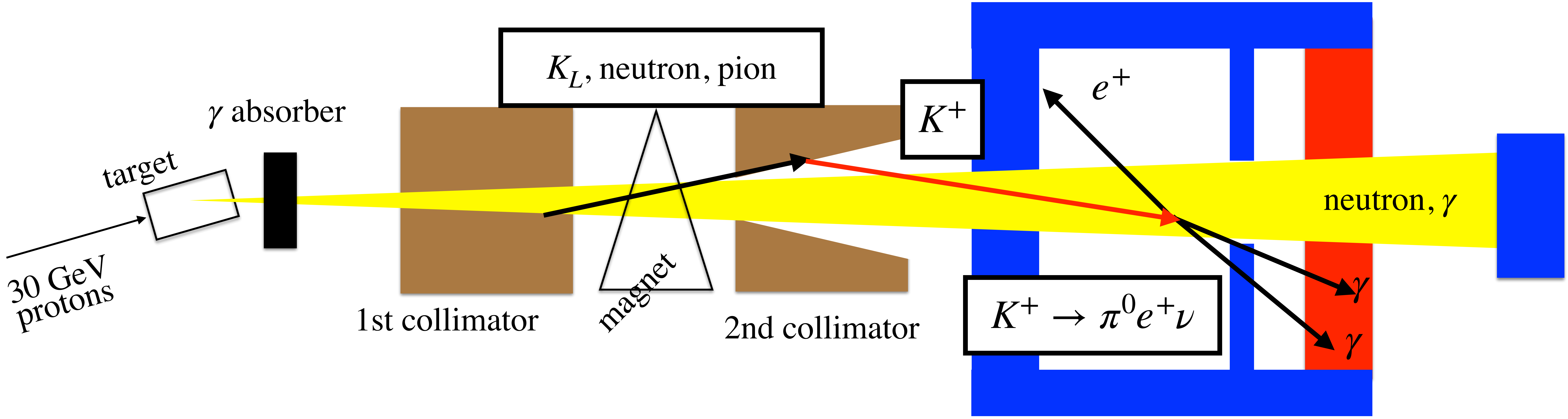


No events in the surrounding regions
except for the upstream region

- New background sources were found
- # of observed events is consistent to # of backgrounds

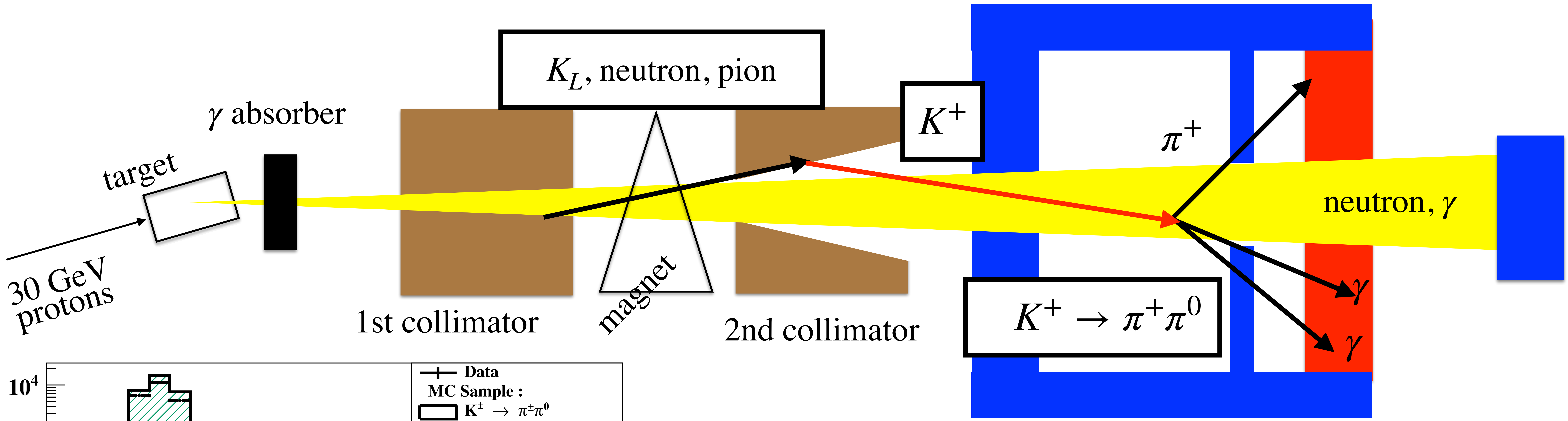
$K^{\pm}$ decay	: 0.87 ± 0.25
Halo $K_L \to 2\gamma$	: 0.26 ± 0.07
Others	: 0.09
Total	: 1.22 ± 0.26

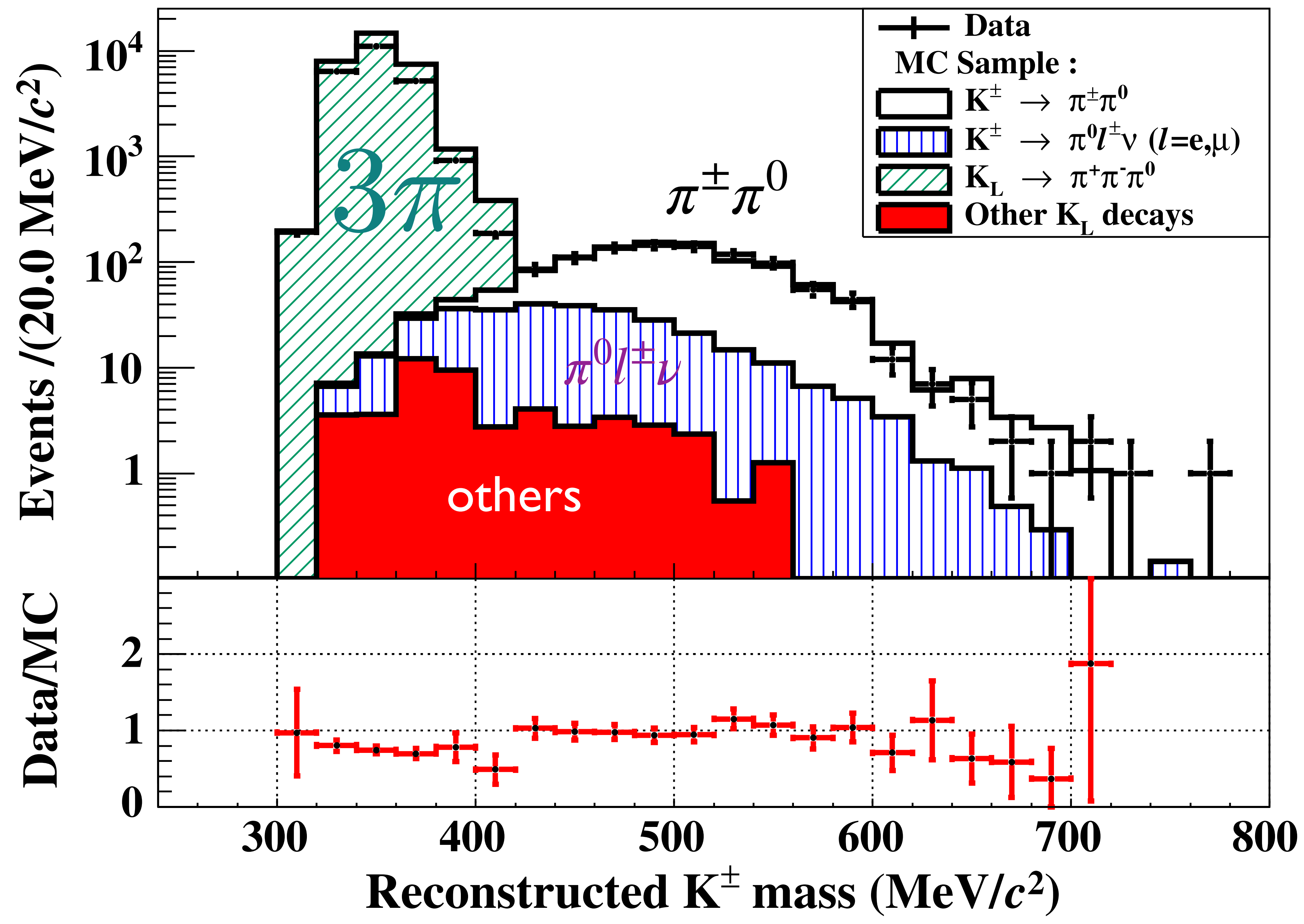
Charged kaon background



$K^{\pm}$ generated in the 2nd collimator due to hadronic interaction
$\mathscr{B}(K^{\pm} \to \pi^0 e^{\pm} \nu) = 5\,\%$
Backward-going $e^{\pm}$ → low energy → missed due to the detector inefficiency
π^0 kinematics is similar to the signal

Charged kaon flux measurement with $K^{\pm} \to \pi^{\pm}\pi^{0}$





Triggering $K^{\pm} \to \pi^{\pm}\pi^{0}$ in June 2020

3 clusters in CSI && Hit in Charged Veto detector

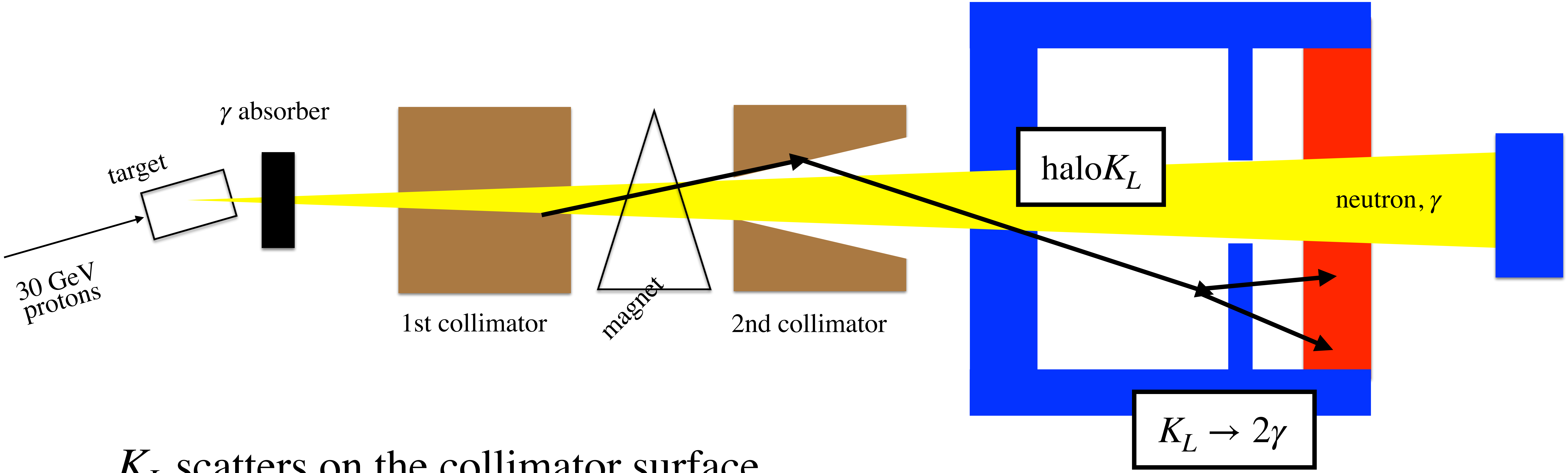
Matching between a Charge Veto hit and one CSI cluster

Reconstruct π^0 from 2 γ

Reconstruct $\pi^{\pm}$ with p_T balance → $K^{\pm}$ reconstruction

847 $K^{\pm} \to \pi^{\pm}\pi^{0}$ events → $K^{\pm}/K_L = 2.6 \times 10^{-5}$

Halo $K_L \to 2\gamma$ background

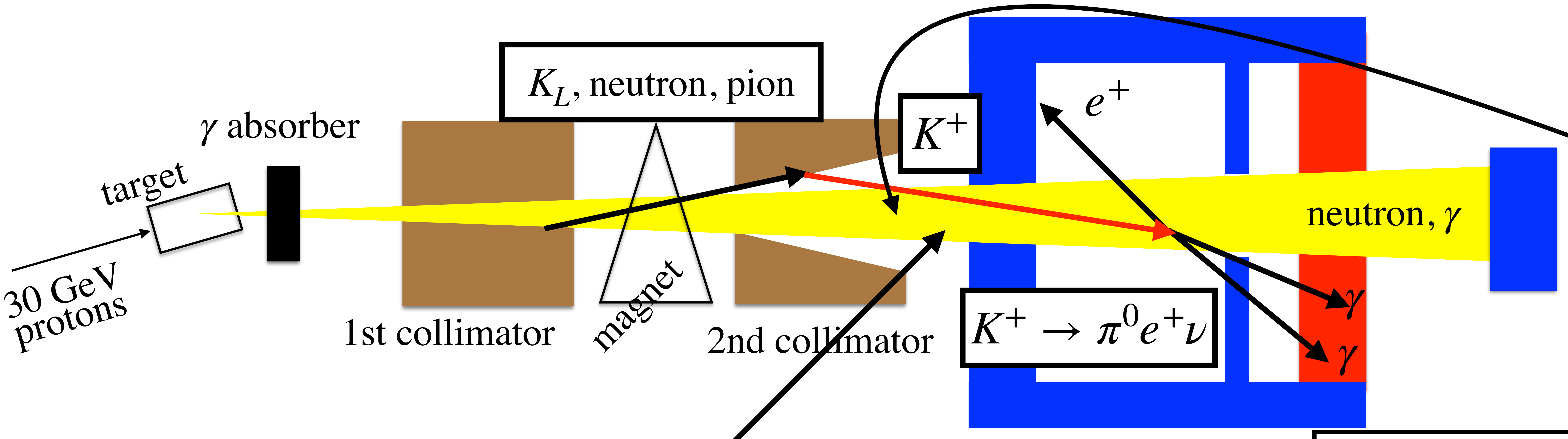


K_L scatters on the collimator surface
Off-axis π^0 decay
$\to$ fake large p_T due to vertex assumption on the beam axis
Two photons and nothing else

Halo K_L flux was evaluated and number of background is evaluated.

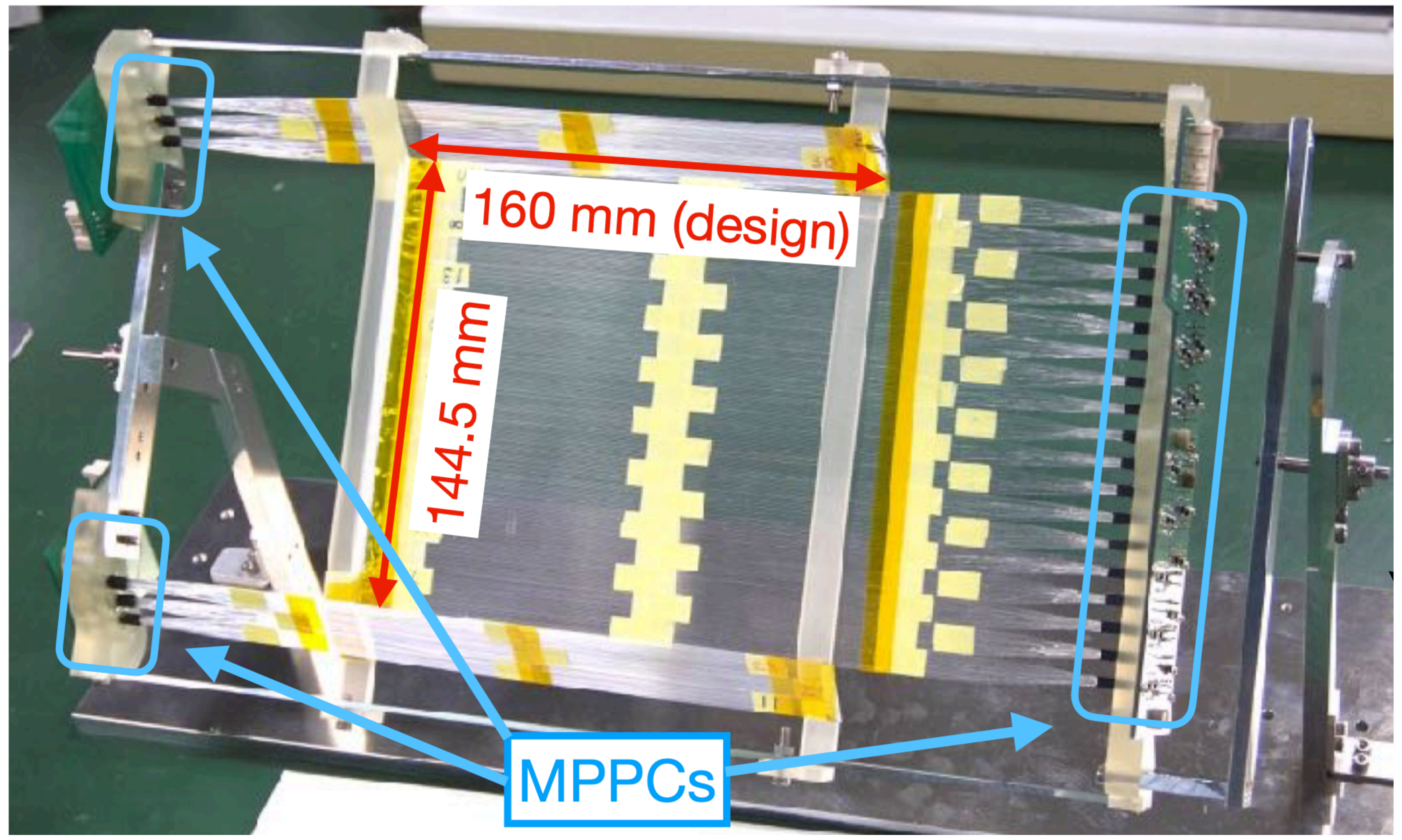
Future prospects

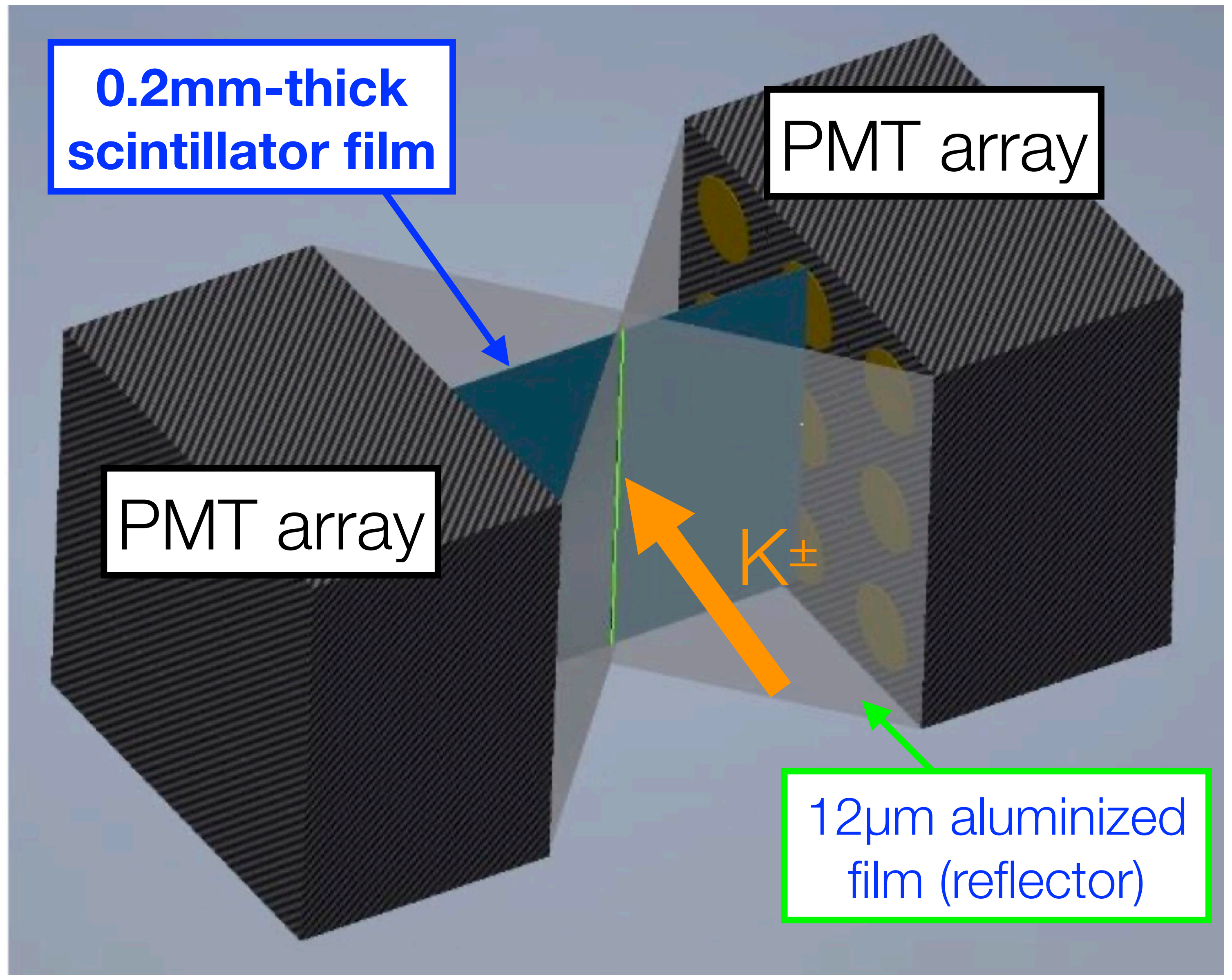
Reduction of $K^{\pm}$ backgrounds toward the next analysis



Installation of additional magnet planned in 2023 $\to \times 1/10$

0.5-mm-square scintillating fibers installed in 2021 $\to \times 1/20$



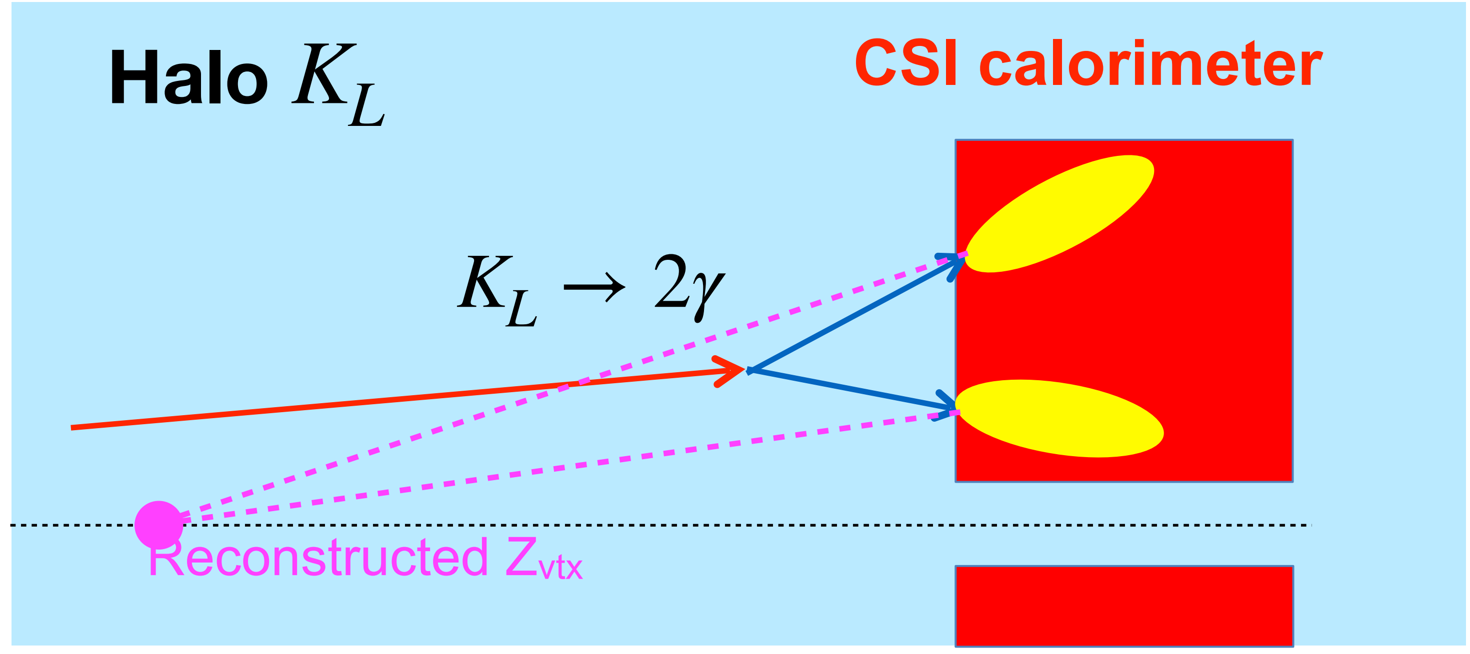


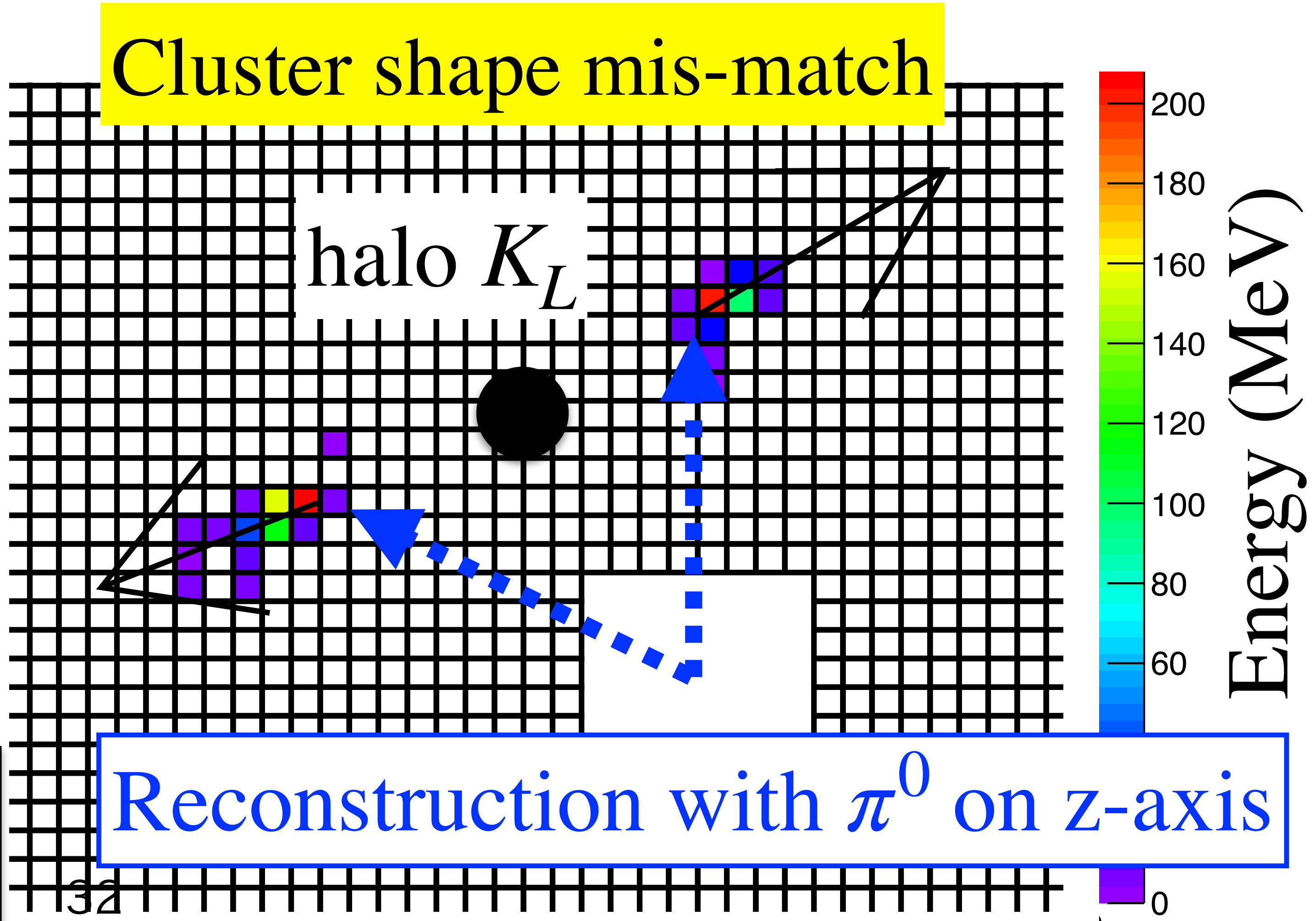
Upgrade with 0.2-mm-thick scintillator planned in 2022 $\to \times 1/100$

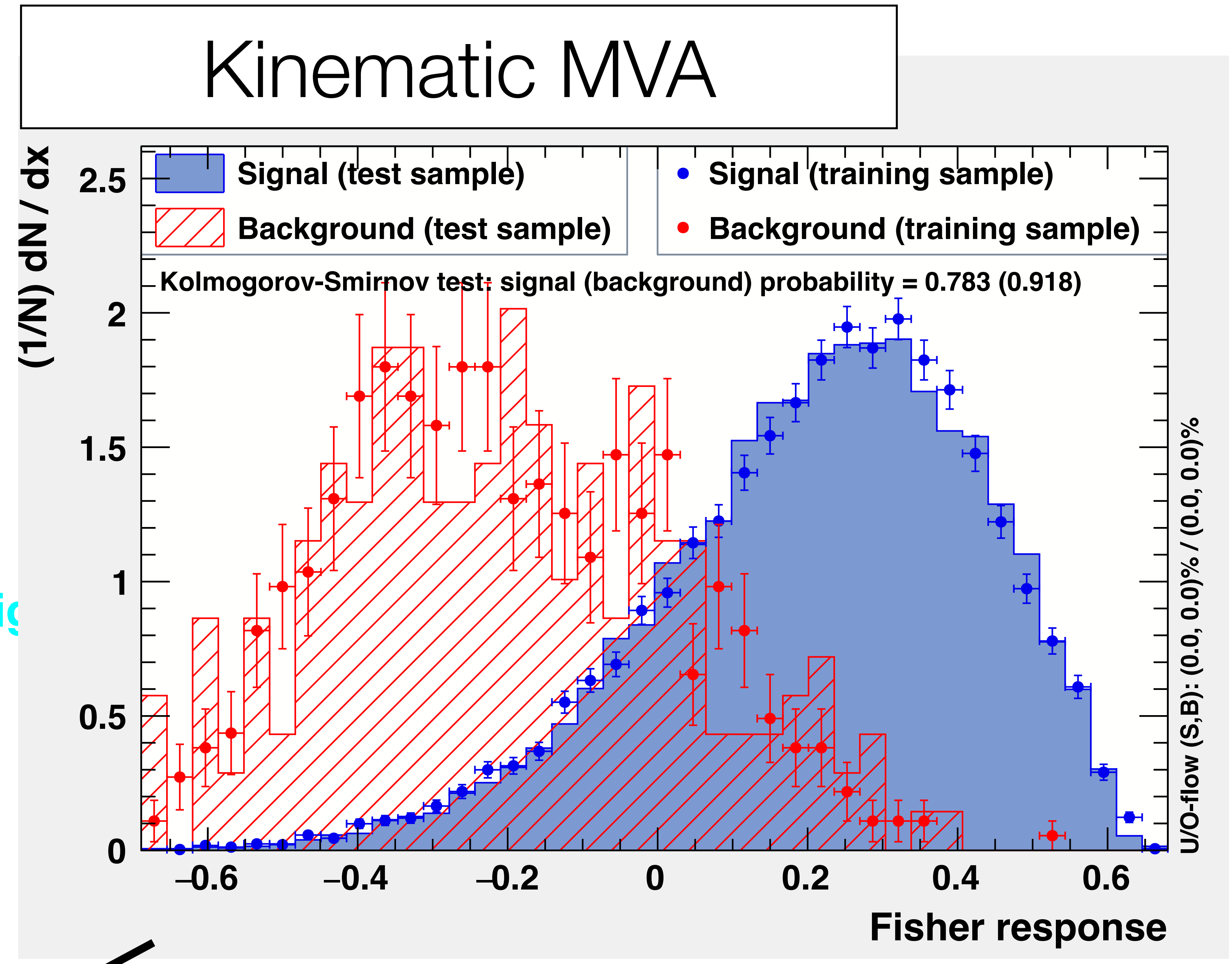
Expected reduction $\times 1/1000$ in total

0.02 events in SM sensitivity

Reduction of halo $K_L \to 2\gamma$ background

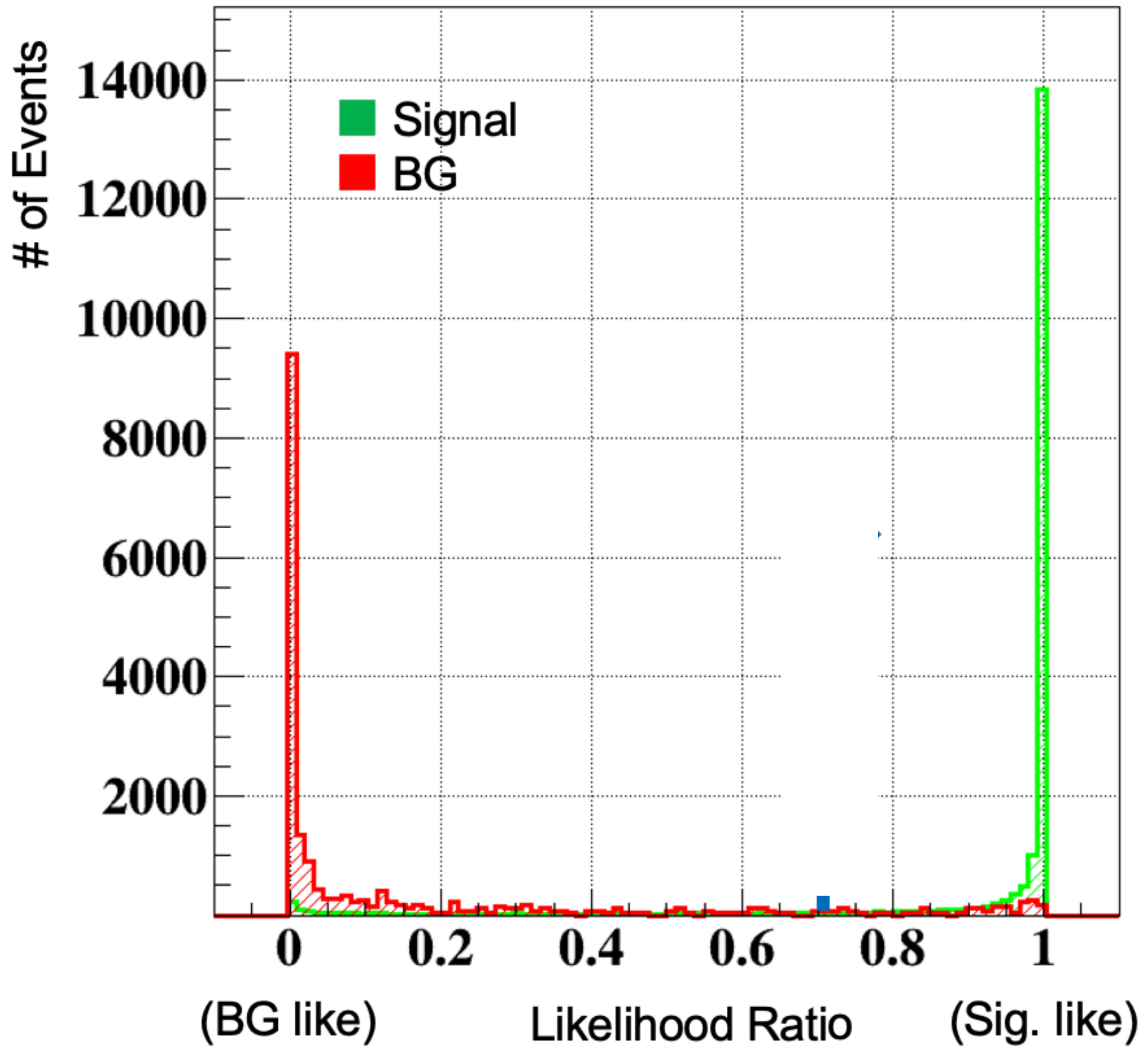






Likelihood Ratio for cluster shape

$$\frac{\mathscr{L}(\pi^0 \text{ on z-axis})}{\mathscr{L}(\pi^0 \text{ on z-axis}) + \mathscr{L}(K_L \text{ on COE-axis})}$$



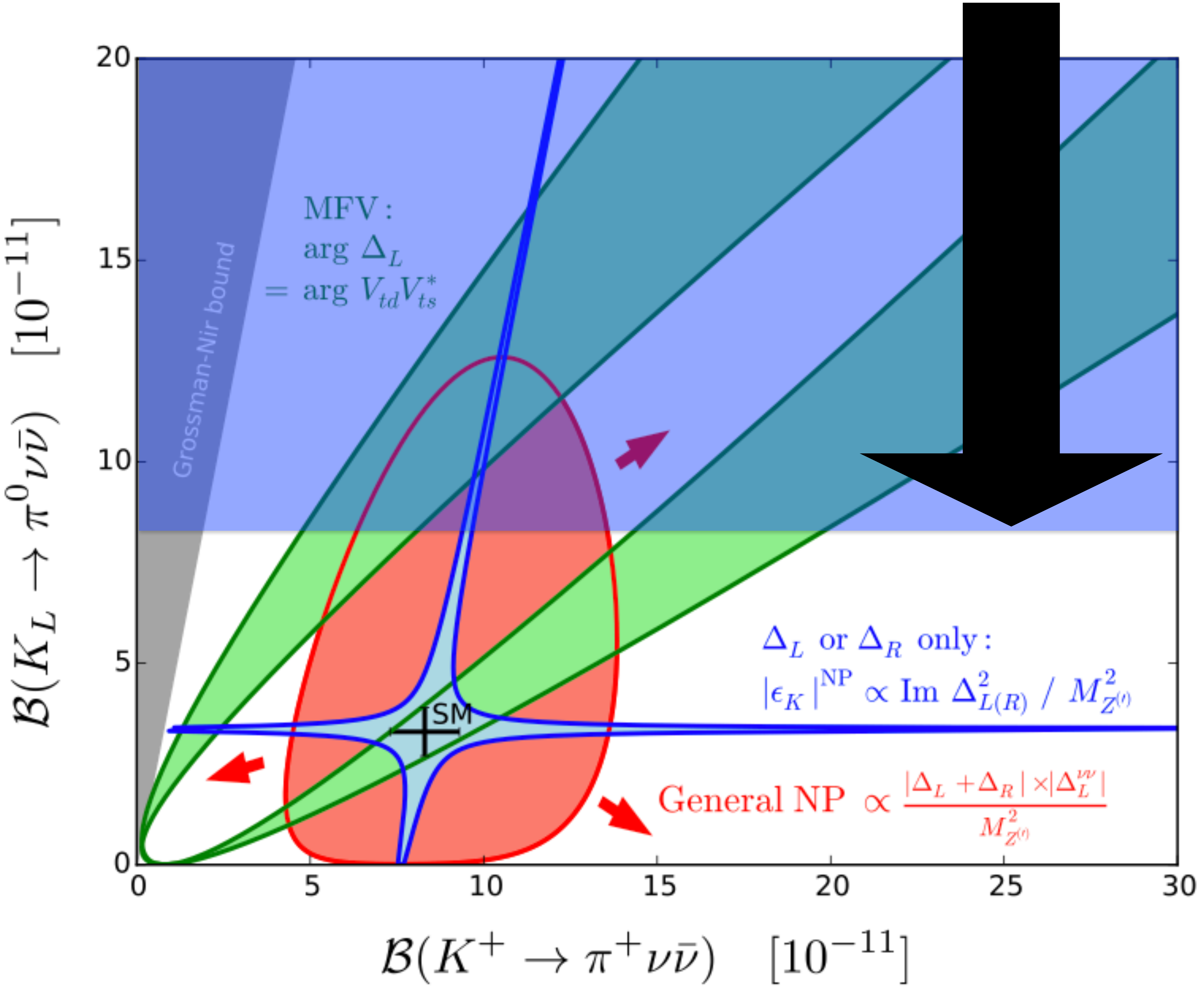
Reduce it by a factor of 16 so far with 90% signal efficiency

➡ 0.4 events in SM sensitivity

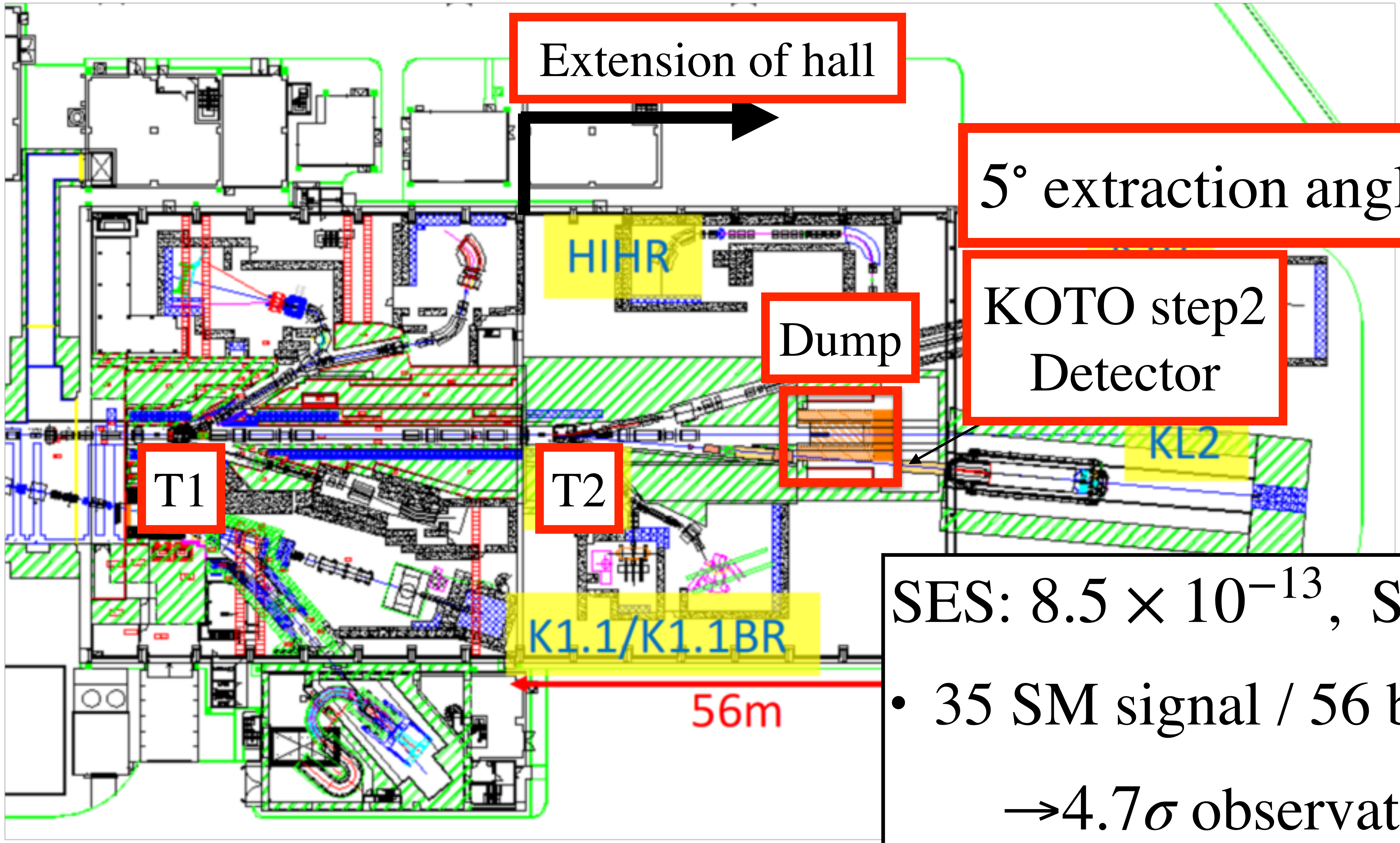
More reduction is under study

Prospects

KOTO will reach $O(10^{-11})$ sensitivity



KOTO step-2 with extension of hadron experimental facility

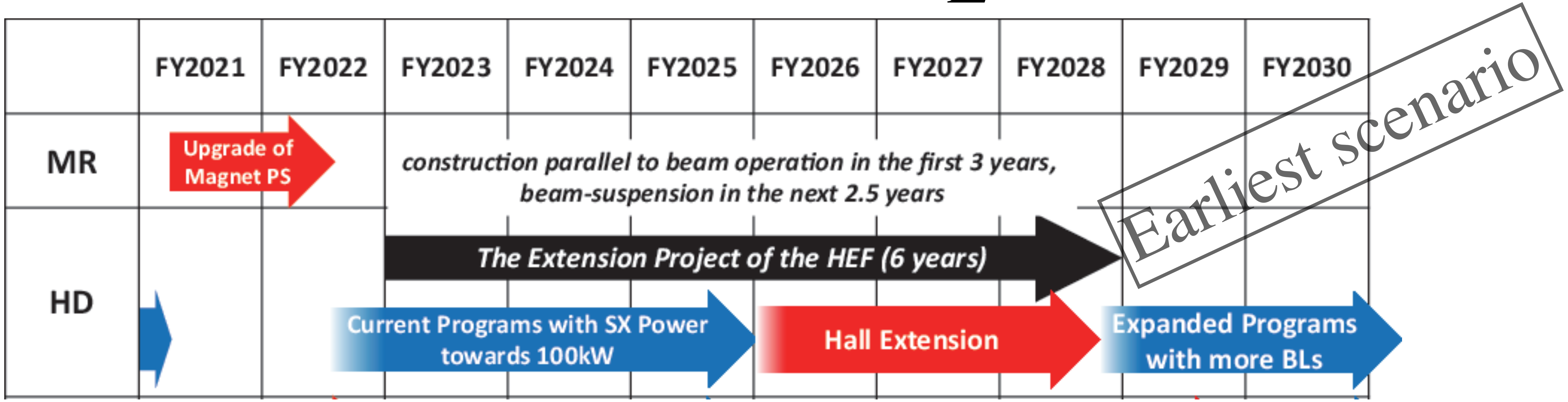


Higher momentum & higher intensity K_L

SES: 8.5×10^{-13}, S/B=0.63

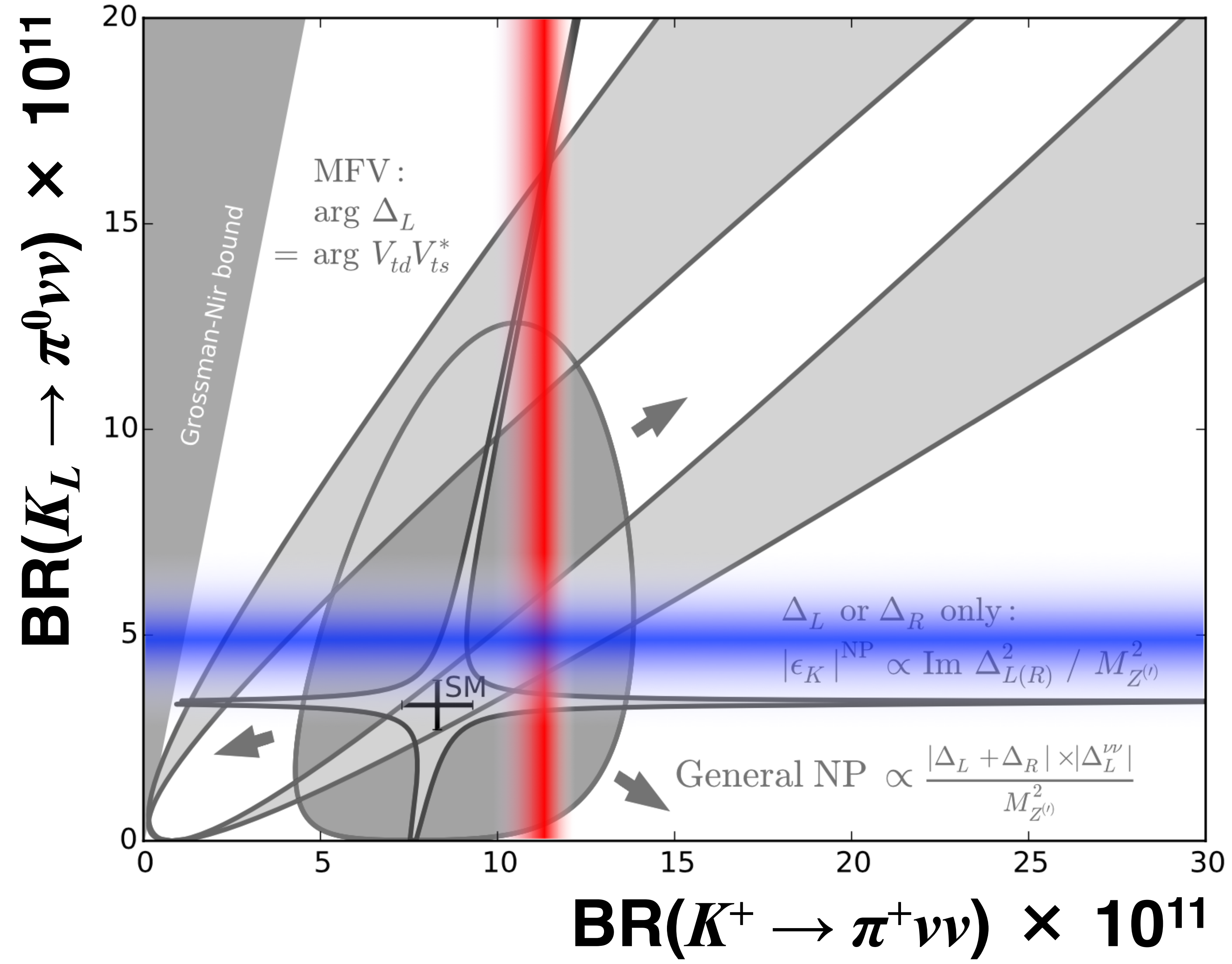
- 35 SM signal / 56 background events
  $\rightarrow 4.7\sigma$ observation
- $\Delta\mathscr{B}/\mathscr{B} = 27\,\%$ $\rightarrow$ CKM parameter : $\Delta\eta/\eta = 14\,\%$
- 44% deviation from SM→90%-CL indication of NP

Time line for $K_L \to \pi^0 \nu \bar{\nu}$



$SES : O(10^{-11})$

$SES : O(10^{-13})$



KOTO step-1 → KOTO step-2

CERN KLEVER

Summary

- Rare kaon decay : sensitive to new physics
- World-wide efforts
- $K^+ \to \pi^+ \nu \overline{\nu}$
  - NA62 experiment at CERN
    - run1 (2016-18) $\mathscr{B}(K^+ \to \pi^+ \nu \overline{\nu}) = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$ (68 % CL)
    - run2 : 2021-2026 : O(10%) measurement
- $K_L \to \pi^0 \nu \overline{\nu}$
  - KOTO experiment at J-PARC
    - $\mathscr{B}(K_L \to \pi^0 \nu \overline{\nu}) < 3 \times 10^{-9}$ (90 % CL)
    - will reach SES of O(10^{-11})
  - KLEVER (CERN) and KOTO step-2 : aiming at 30-60 SM events observation