The search for new physics with rare kaon decays at the CERN SPS

University of Michigan
25 October 2021

Matthew Moulson, INFN Frascati
for the NA62 Collaboration

Precision physics and rare decays

How can we extend the search for new physics to high effective scales?

Energy frontier Direct search	Intensity frontier Indirect investigation
Create new degrees of freedom in lab Explore spectroscopy of new d.o.f. Λ ~ 1-10 TeV	Evidence of new degrees of freedom as alteration of SM rates Explore symmetry properties of new d.o.f Λ ~ 1-1000 TeV

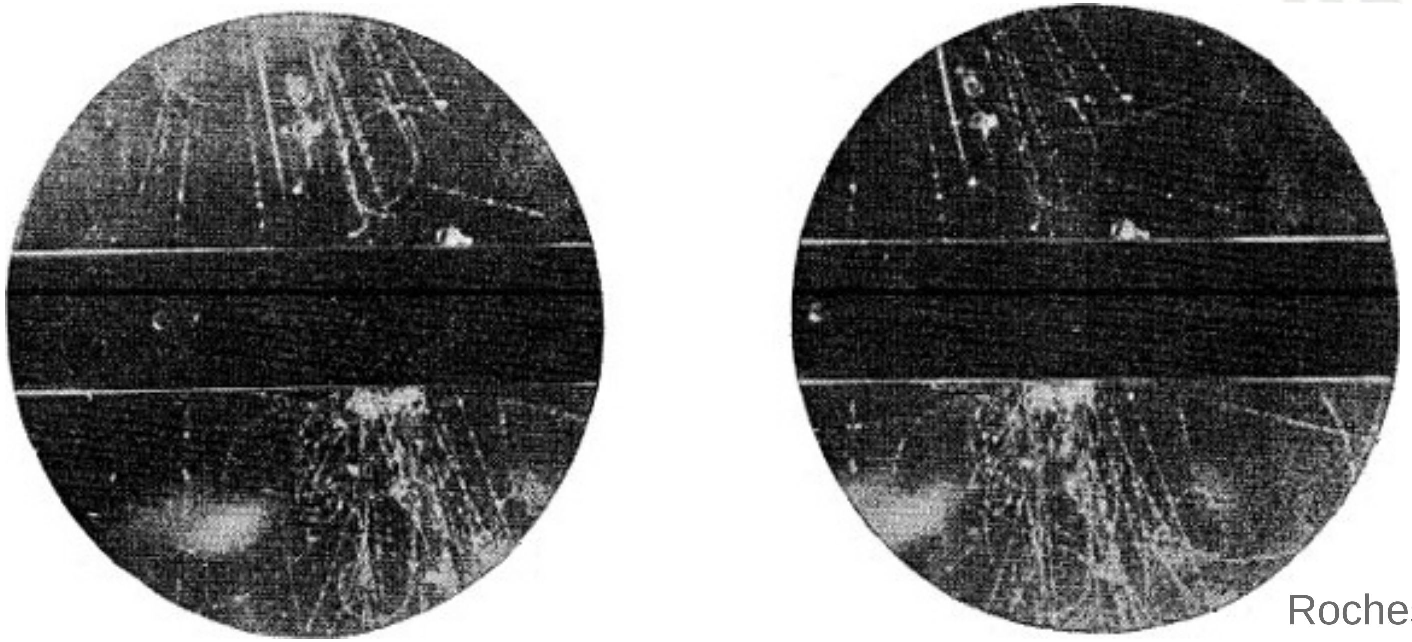
A rare decay is useful as an NP probe if:

- Process is (strongly) suppressed in the SM
- Parameter to be measured precisely calculated in SM
- There are specific predictions for NP contributions

Examples of what may be studied with rare decays:

- Explicit violations of the SM (e.g., lepton flavor violation)
- Tests of fundamental symmetries such as *CP* and *CPT*
- Search for new d.o.f. in the flavor sector, e.g., in FCNC processes
- Strong interaction dynamics at low energy using exclusive processes

What have kaons taught us?



Rochester & Butler
Nature 160 (1947)

- Strangeness, concept of flavor quark model
- τ-θ puzzle: hint of P violation, confirmation of weak $V-A$ structure
- CP violation in mixing of neutral kaons
- Suppression of $K_L \to \mu^+\mu^-$: GIM mechanism and the charm quark
- Direct CP violation in $K \to \pi\pi$ and the CKM paradigm
- Quiet successes of confirmation: conservation of lepton flavor, V_{us}, etc.

Kaons have been fundamental in the development of the SM flavor sector

A history of kaons at the SPS

NA31	1982-1993:	1st generation experiment to measure $\mathrm{Re}\,\varepsilon'/\varepsilon$
NA48	1992-2000:	Next generation measurement of $\mathrm{Re}\,\varepsilon'/\varepsilon$
NA48/1	2000-2002:	Rare K_S decays, e.g., $K_S \to \pi^0 \ell^+ \ell^-$
NA48/2	2003-2007:	Direct CPV in $K^\pm \to \pi^+ \pi^- \pi^\pm$
NA62	2007-2008:	Measurement of $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ with NA48
	2007-2013:	Design, construction, installation
	From 2014:	Measurement of $K^\pm \to \pi^\pm \nu\nu$

Rare kaon decays

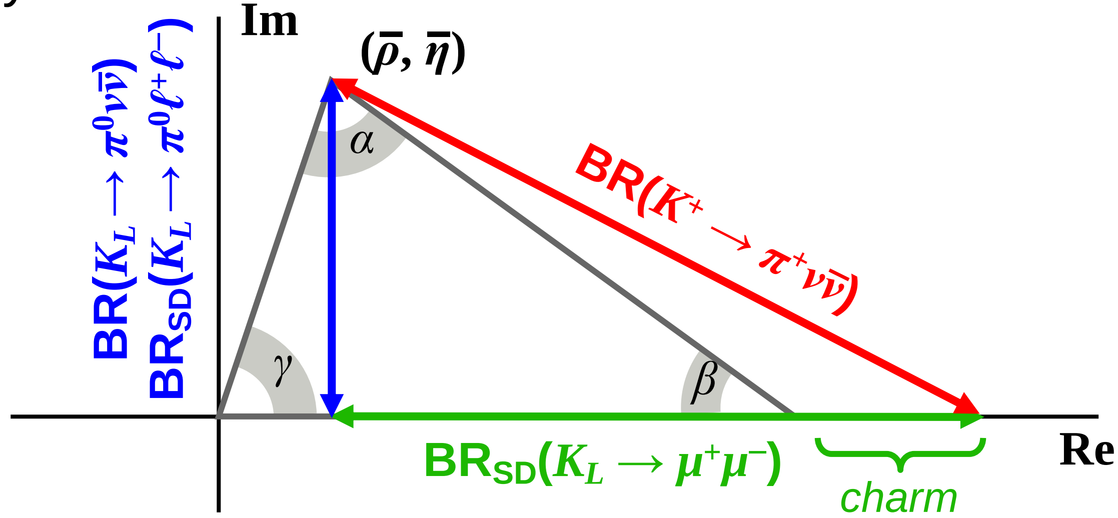
Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 10^{11} (Sep 2019)
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28†
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	1.5 ± 0.3	< 38†
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	< 18.5†
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	< 300†

*Approx. error on LD-subtracted rate excluding parametric contributions   †90% CL

FCNC processes dominated by Z-penguin and box diagrams

Highly suppressed in Standard Model

Rates related to V_{CKM} with minimal non-parametric uncertainty

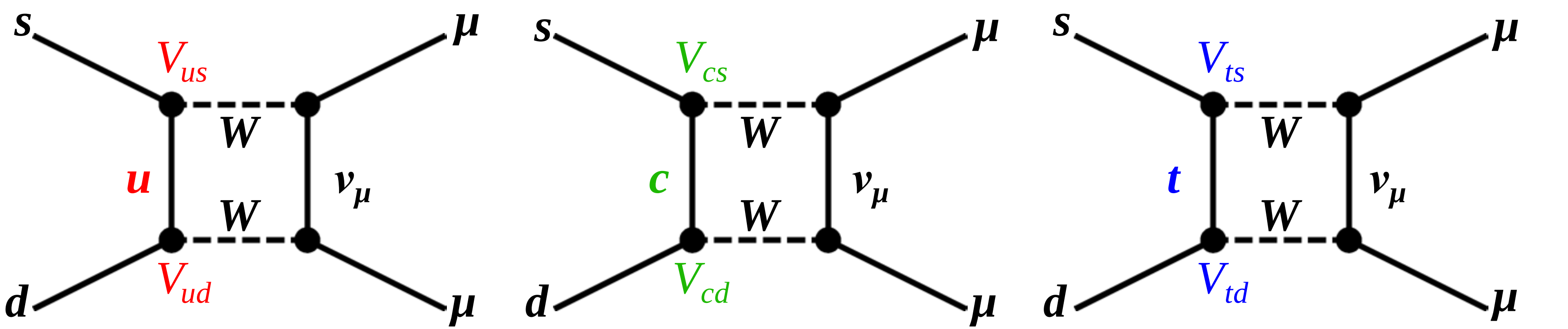


Rare kaon decays

Decay	Γ_{SD}/Γ	Theory err.*	**SM BR × 10^{11}**	Exp. BR × 10^{11} (Sep 2019)
$K_L \to \mu^+\mu^-$	10%	30%	**79 ± 12 (SD)**	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	**3.2 ± 1.0**	< 28†
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	**1.5 ± 0.3**	< 38†
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	**8.4 ± 1.0**	< 18.5†
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	**3.4 ± 0.6**	< 300†

*Approx. error on LD-subtracted rate excluding parametric contributions †90% CL

Rates for FCNC decays are suppressed by GIM mechanism:



$$\mathbf{V^\dagger V = 1} \qquad V_{us}^* V_{ud}\, L(x_u) + V_{cs}^* V_{cd}\, L(x_c) + V_{ts}^* V_{td}\, L(x_t) \approx 0$$

$$x_q = m_q^2/m_W^2$$

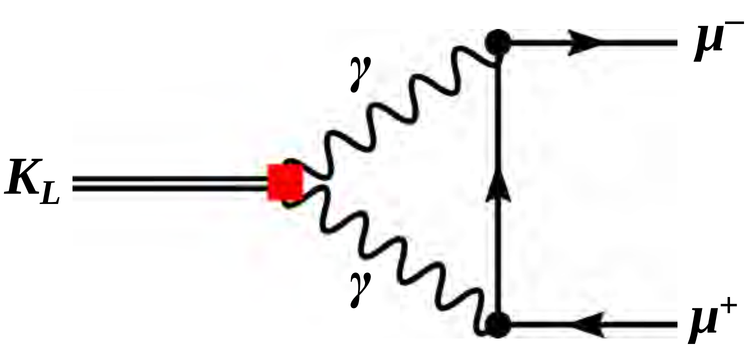
$$L(x_q) \sim x_q \ln x_q \quad (x_q \to 0)$$

Rare kaon decays

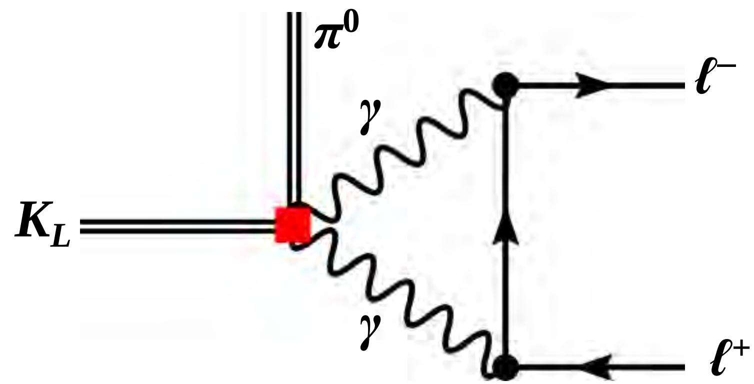
Decay	Γ_{SD}/Γ	Theory err.*	SM BR $\times$ 10^{11}	Exp. BR $\times$ 10^{11} (Sep 2019)
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28†
$K_L \to \pi^0 \mu^+ \mu^-$	30%	15%	1.5 ± 0.3	< 38†
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	< 18.5†
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	< 300†

*Approx. error on LD-subtracted rate excluding parametric contributions †90% CL

No LD contributions from states with intermediate γs for $K \to \pi\nu\bar{\nu}$

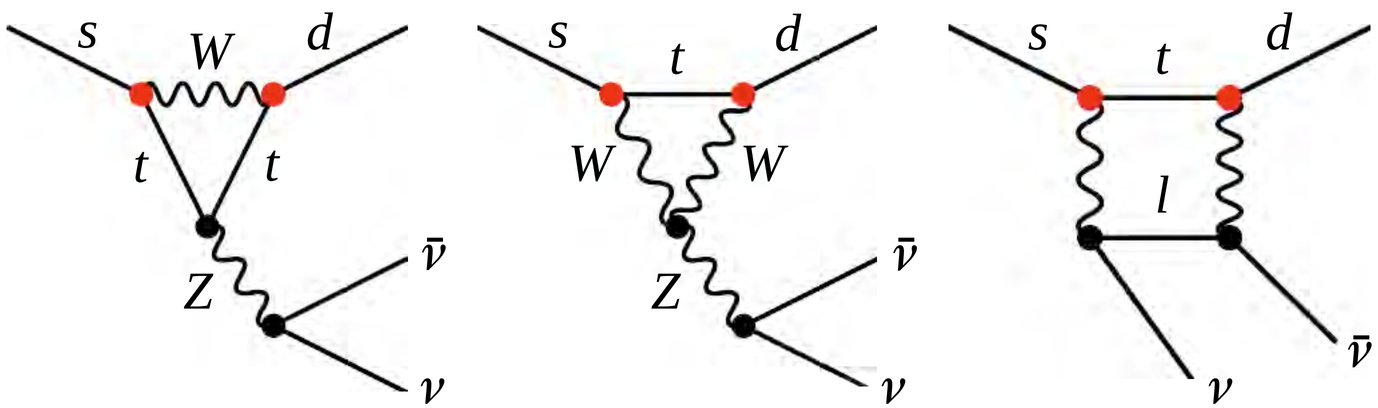


$K_L \to \mu^+\mu^-$



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

$K \to \pi\nu\bar{\nu}$ in the Standard Model

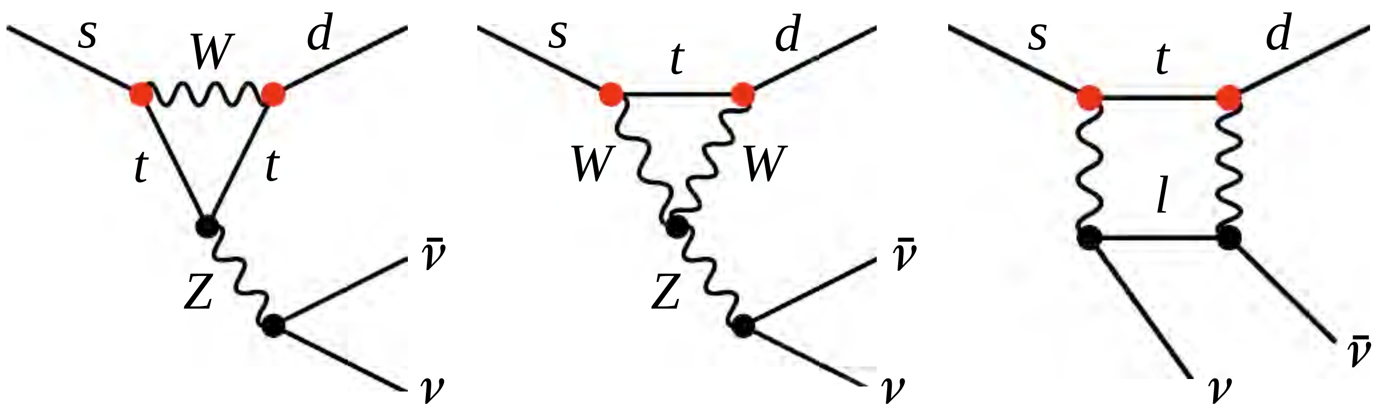


$$\lambda = V_{us}$$
$$\lambda_c = V_{cs}^* V_{cd}$$
$$\lambda_t = V_{ts}^* V_{td}$$
$$x_q \equiv m_q^2/m_W^2$$

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5}X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda}P_c(X)\right)^2\right]$$

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2$$

$K \to \pi\nu\bar{\nu}$ in the Standard Model



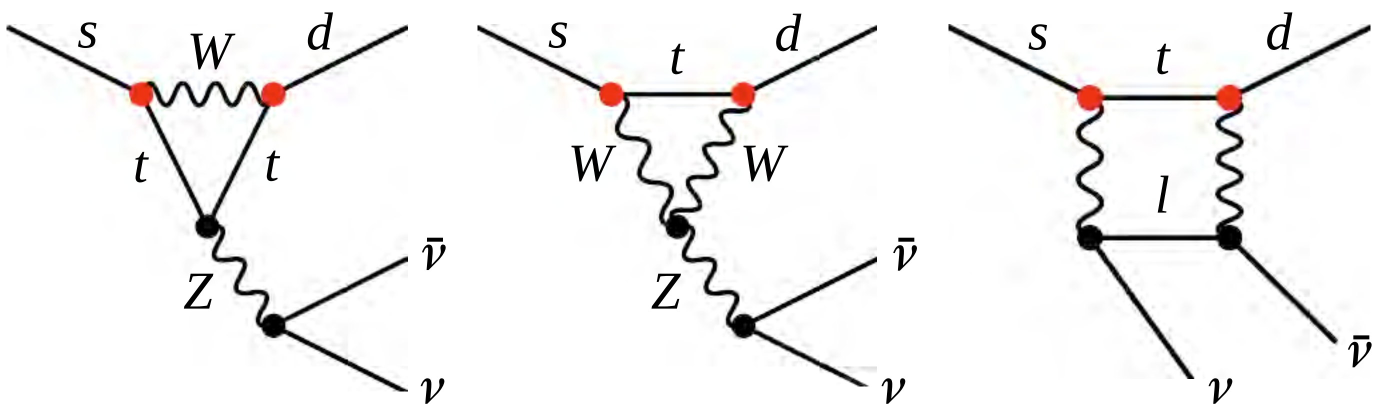
$$\lambda = V_{us}$$
$$\lambda_c = V_{cs}^* V_{cd}$$
$$\lambda_t = V_{ts}^* V_{td}$$
$$x_q \equiv m_q^2 / m_W^2$$

Loop functions favor top contribution

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 \leftarrow \not{CP}$$

$K \to \pi \nu \bar{\nu}$ in the Standard Model



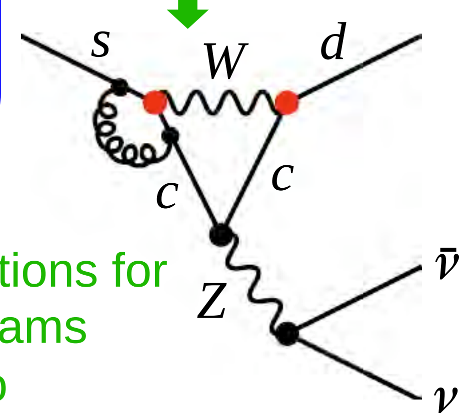
$$\lambda = V_{us}$$
$$\lambda_c = V_{cs}^* V_{cd}$$
$$\lambda_t = V_{ts}^* V_{td}$$
$$x_q \equiv m_q^2 / m_W^2$$

Loop functions favor top contribution

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

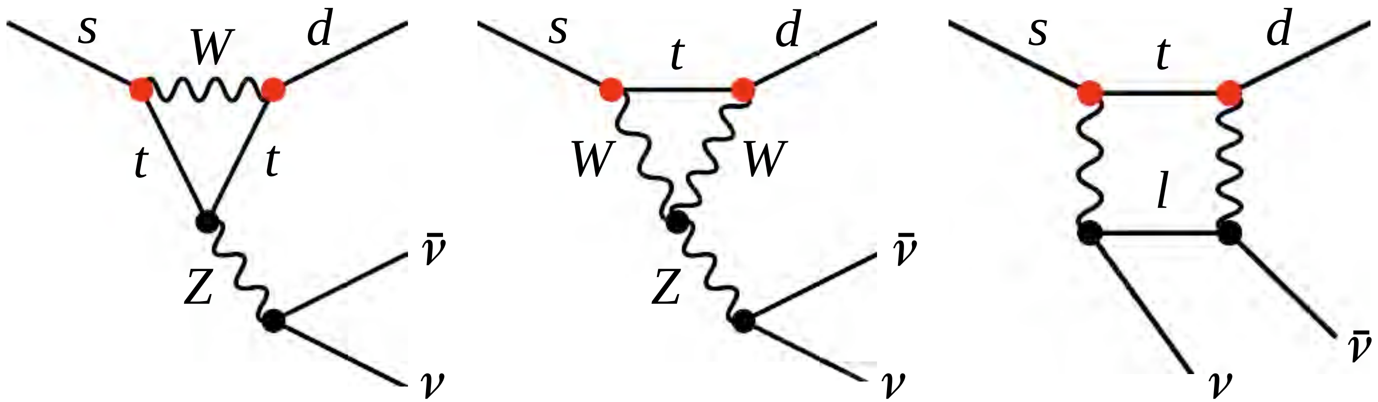
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

← ~~CP~~



QCD corrections for charm diagrams contribute to uncertainty

$K \to \pi\nu\bar{\nu}$ in the Standard Model



$$\lambda = V_{us}$$
$$\lambda_c = V_{cs}^* V_{cd}$$
$$\lambda_t = V_{ts}^* V_{td}$$
$$x_q \equiv m_q^2 / m_W^2$$

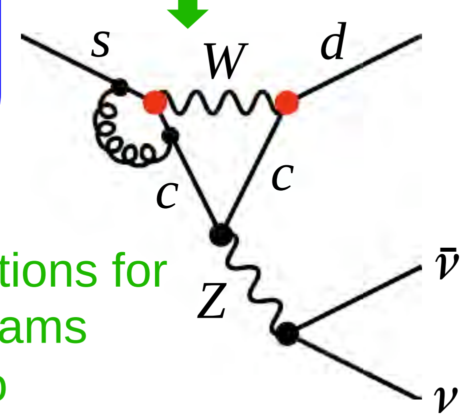
Loop functions favor top contribution

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 \leftarrow \not{CP}$$

$$\kappa_+ = r_{K^+} \frac{3\alpha^2 \mathrm{BR}(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \theta_W} \lambda^8$$

Hadronic matrix element obtained from $\mathrm{BR}(K_{e3})$ via isospin rotation



QCD corrections for charm diagrams contribute to uncertainty

$K \to \pi\nu\bar{\nu}$ and the unitarity triangle

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

Buras et al., JHEP 1511

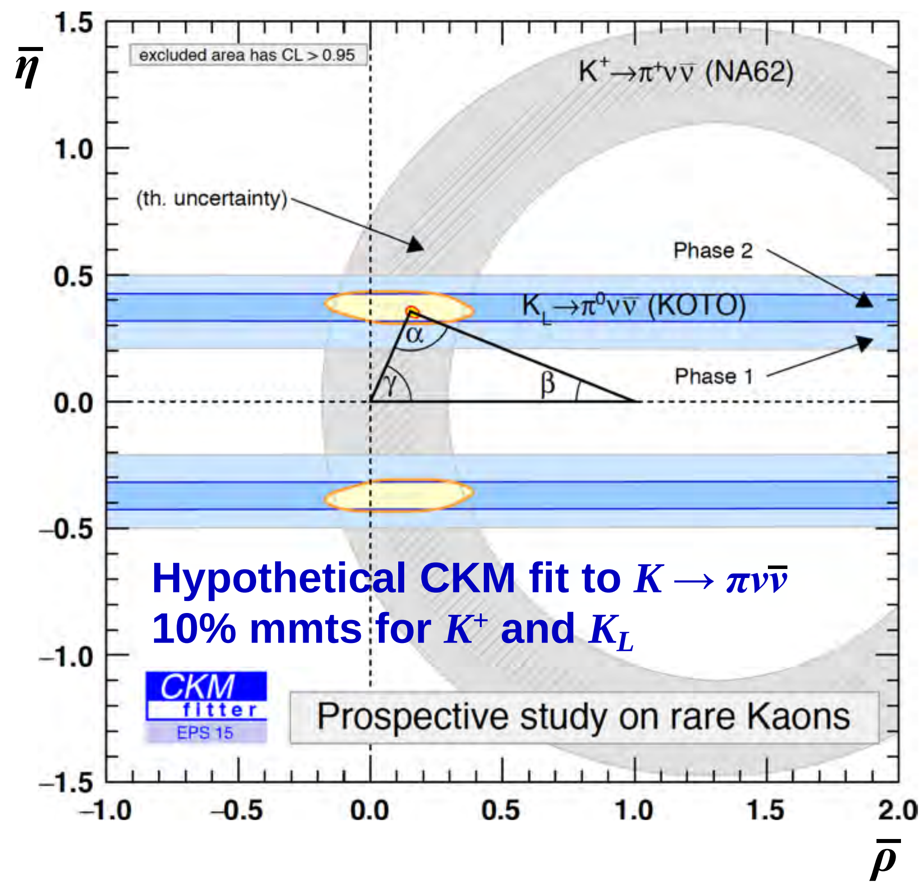
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^2 \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^2 \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^2$$

Dominant uncertainties for SM BRs are from CKM matrix elements

Intrinsic theory uncertainties 1.5-3.5%

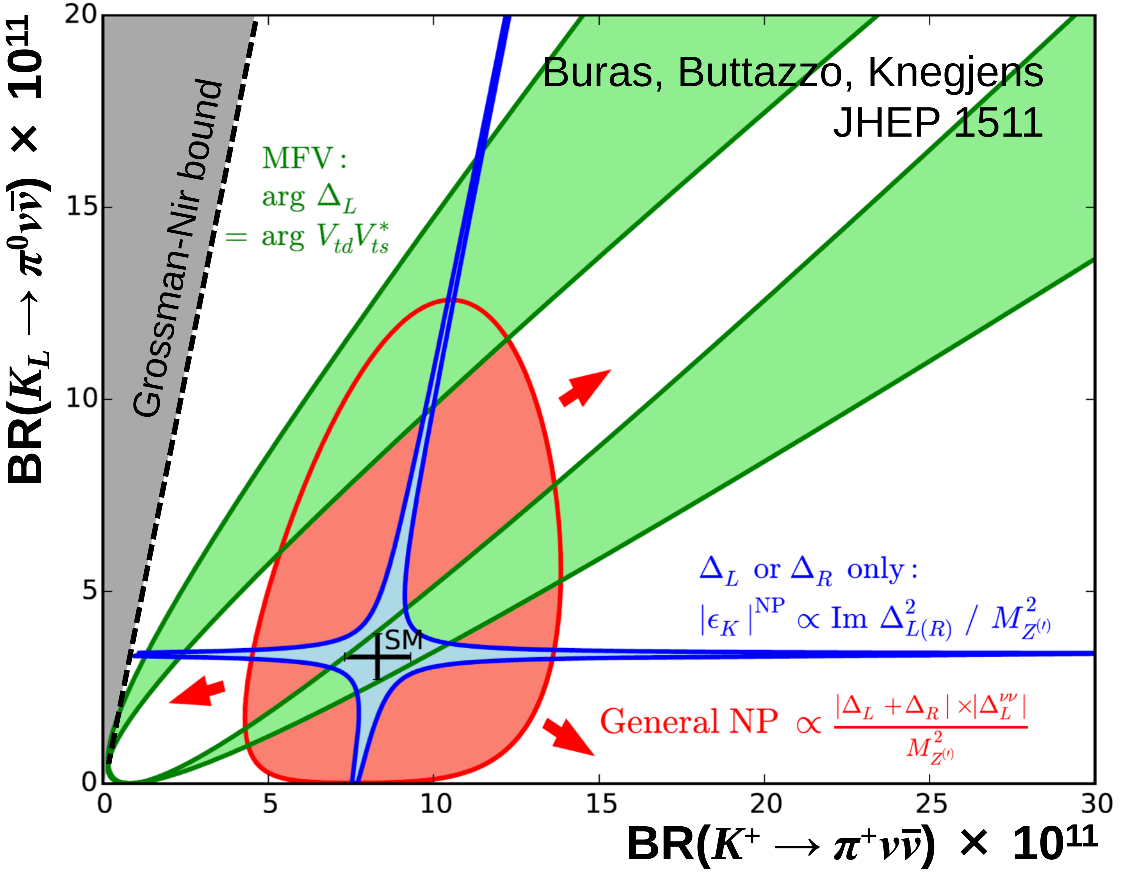
Measuring BRs for both $K^+ \to \pi^+\nu\nu$ and $K_L \to \pi^0\nu\nu$ can determine the CKM unitarity triangle independently from B inputs:

- Over-constrain CKM matrix → reveal NP effects
- Sensitivity complementary to B decays



$K \to \pi\nu\bar{\nu}$ and new physics

New physics affects K^+ and K_L BRs differently
Measurements of both can discriminate among NP scenarios



- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - Z/Z' models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models without above constraints
  - Randall-Sundrum
- **Grossman-Nir bound**

  Model-independent relation

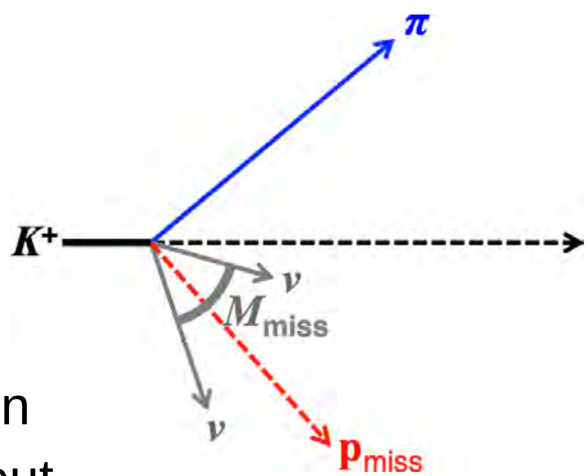
$$\frac{BR(K_L \to \pi^0\nu\bar{\nu})}{BR(K^+ \to \pi^+\nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \leq 1$$

The NA62 experiment at the CERN SPS

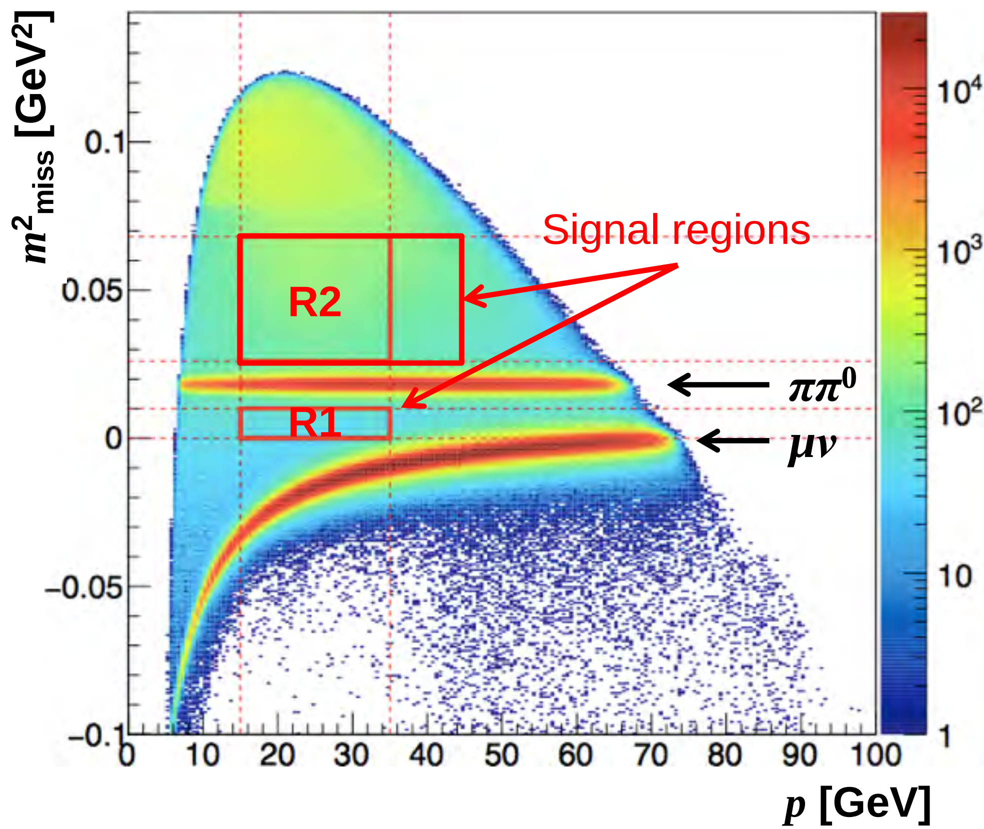
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ with decay in flight

Signal:

BR = (8.4 ± 1.0) × 10^{-11}



- K track in
- π track out
- No other particles in final state
- $M^2_{\text{miss}} = (p_K - p_\pi)^2$



Main backgrounds:

$K^+ \rightarrow \mu^+\nu(\gamma)$	**BR = 63.5%**
$K^+ \rightarrow \pi^+\pi^0(\gamma)$	**BR = 20.7%**

Selection criteria:

- K^+ beam identification
- Single track in final state
- π^+ identification ($\varepsilon_\mu \sim 1 \times 10^{-8}$)
- γ rejection ($\varepsilon_{\pi 0} \sim 3 \times 10^{-8}$)

K12 high-intensity K^+ beamline

Primary SPS proton beam:

- p = 400 GeV protons
- Nominal intensity: 3.3×10^{12} protons/pulse (ppp)
- Typical duty cycle: 4.8 s/16.8 s

  Flat-top: 3 eff. s

High-intensity, unseparated secondary beam

- p = 75 GeV with $\Delta p/p \sim 1\%$

Total rate 750 MHz
- **525 MHz π**
- **170 MHz p**
- **45 MHz K**

Decay volume:

- 60 m long, starting at z = 102 m from target
- 10% of K^+ decay in FV ($\beta\gamma c\tau$ = 560 m)

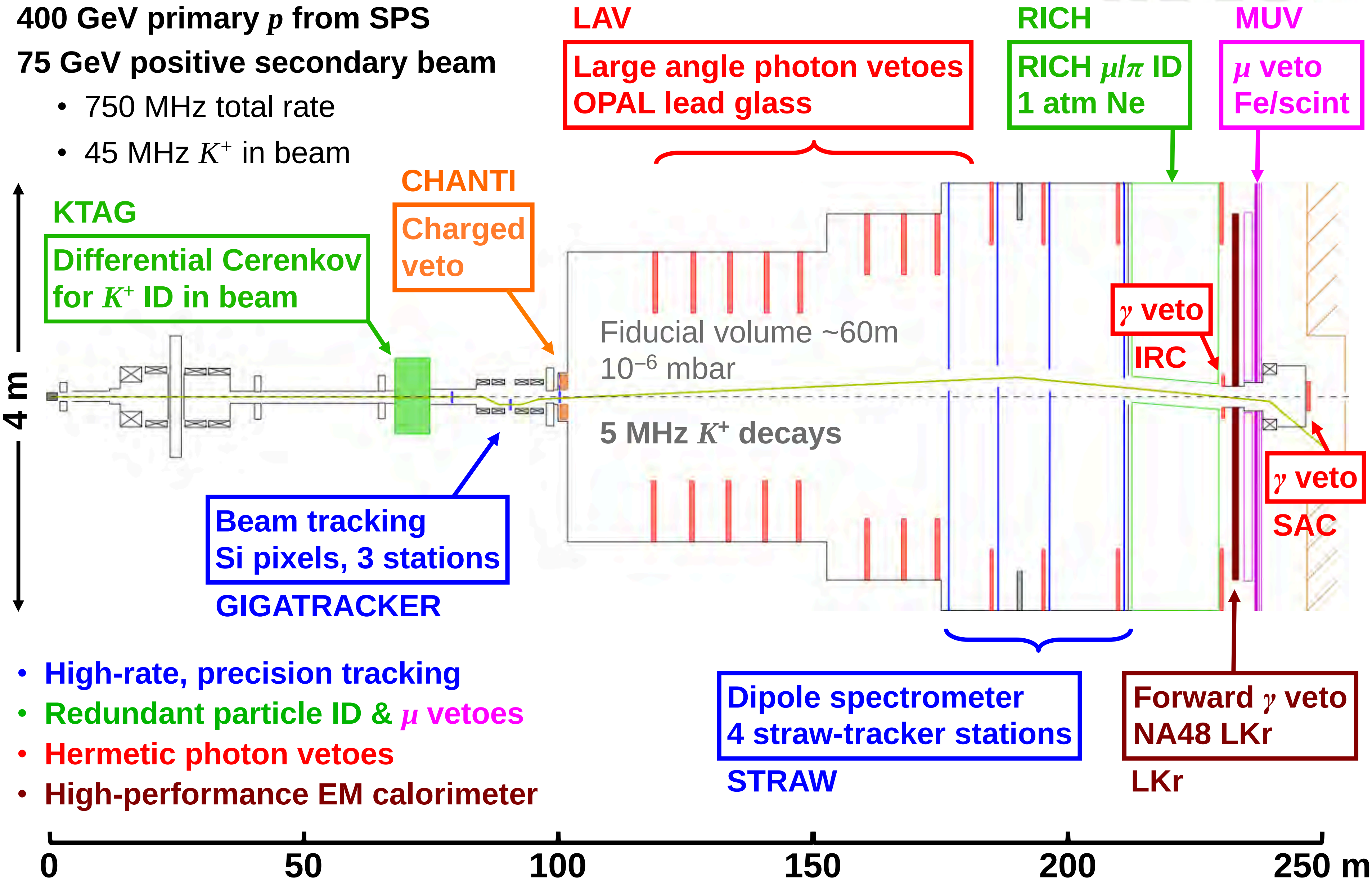
Up to 5×10^{12} K^+ decays/yr

The NA62 experiment at the SPS

400 GeV primary p from SPS

75 GeV positive secondary beam

- 750 MHz total rate
- 45 MHz K^+ in beam

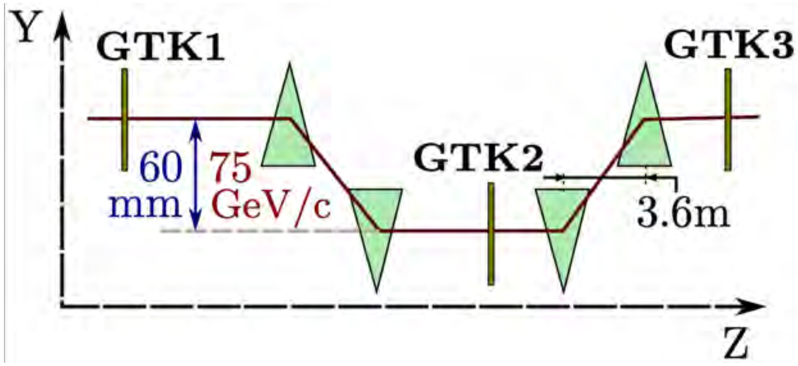


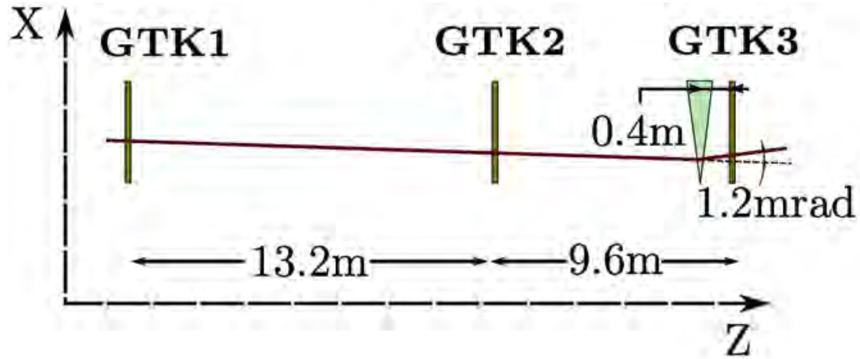
- **High-rate, precision tracking**
- **Redundant particle ID & μ vetoes**
- **Hermetic photon vetoes**
- **High-performance EM calorimeter**

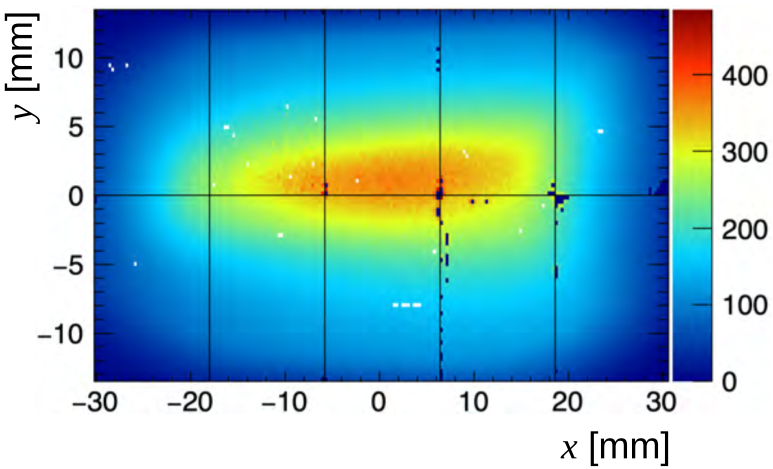
High-rate beam tracking

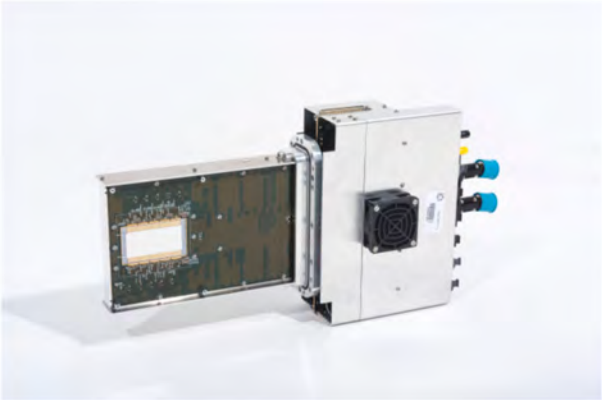
Gigatracker (GTK) beam spectrometer:
3 stations of hybrid silicon pixel detectors installed in beamline achromat

σ_t = 100 ps
σ_p = 0.15 GeV
σ_θ = 16 mrad







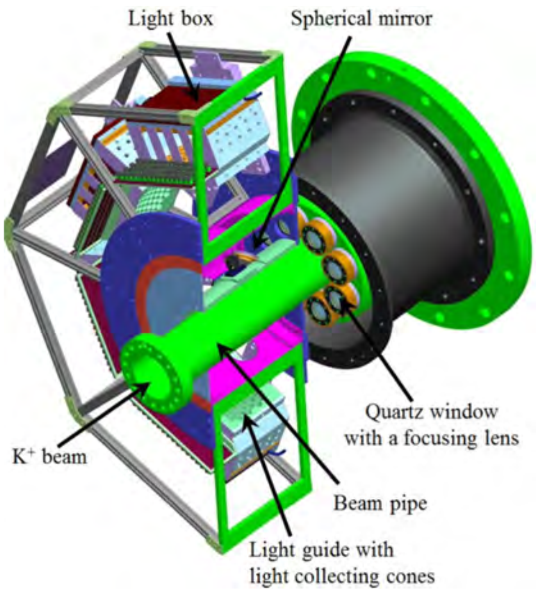


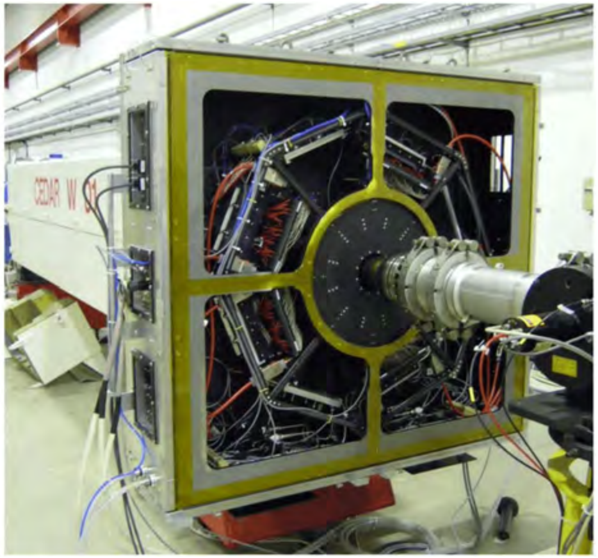
62×27 mm² sensor area
300×300 μm² pixels

Thickness in active area 510 μm:

- Sensor 200 μm + readout chip 100 μm
- Cooling plate 210 μm

Beam particle identification



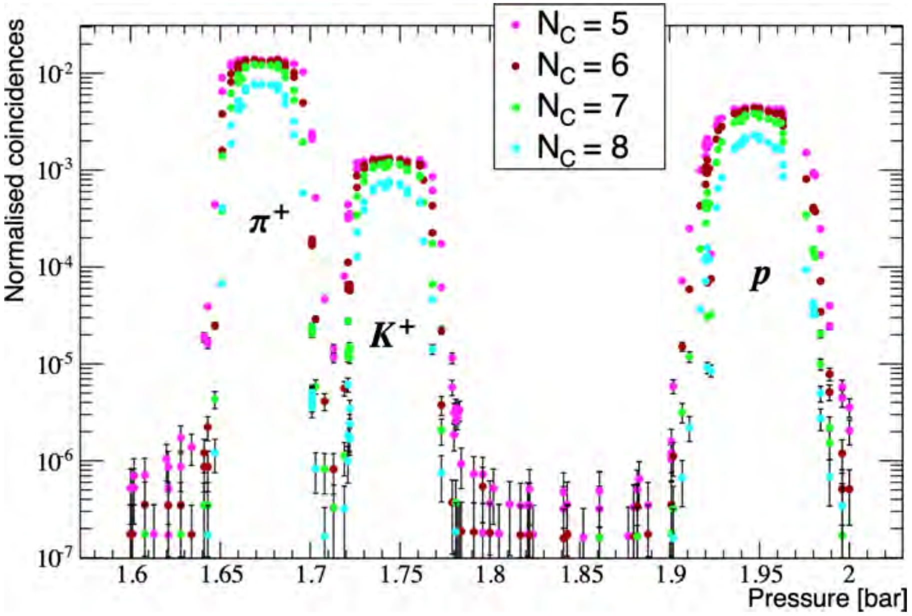


- Must identify 45 MHz of K^+ in 750 MHz beam
- Good time resolution (σ_t < 100 ps) needed to determine event t_0
- **KTAG: Differential Cerenkov detector** based on CEDAR-W with new light collection system

  σ_t = 70 ps

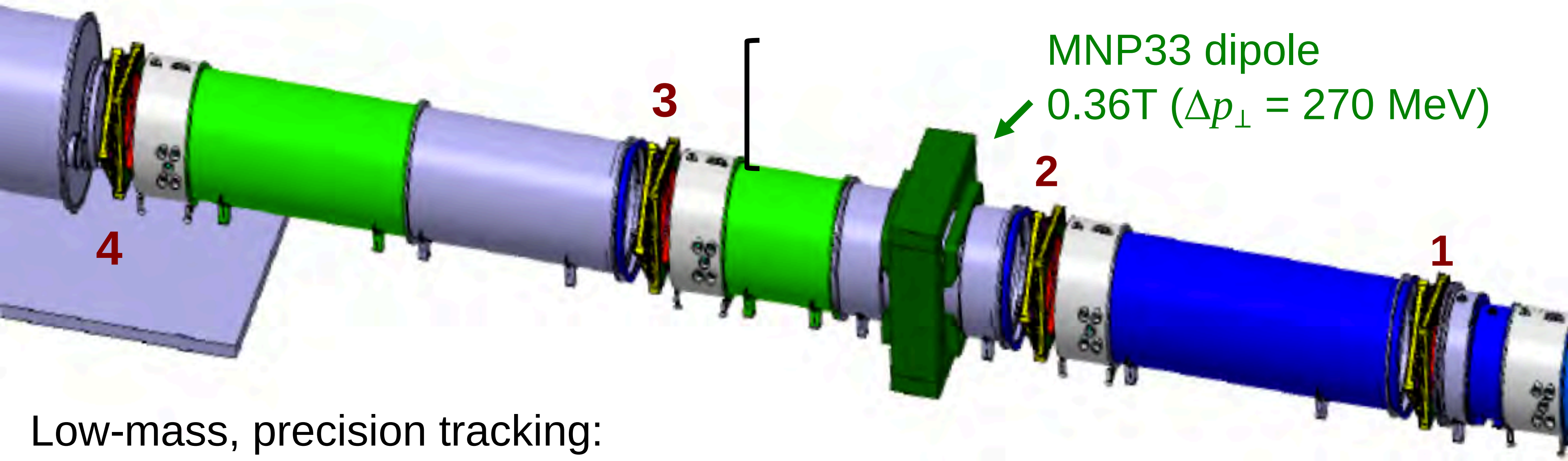
  ε_K > 95% ($N_C \geq 5$)

  $\varepsilon_\pi < 10^{-4}$

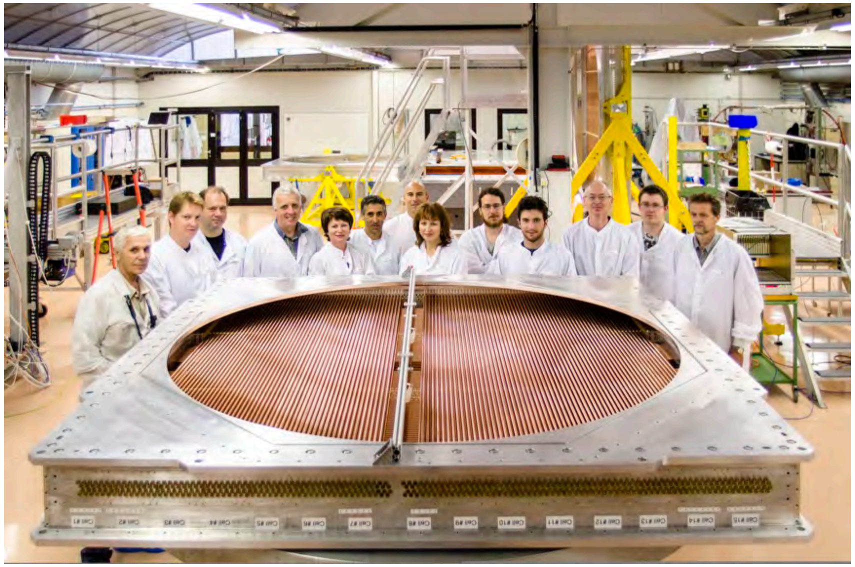


Nominal N_2 gas pressure = 1.75 bar

Precision downstream tracking



Low-mass, precision tracking:
4 straw chambers in vacuum



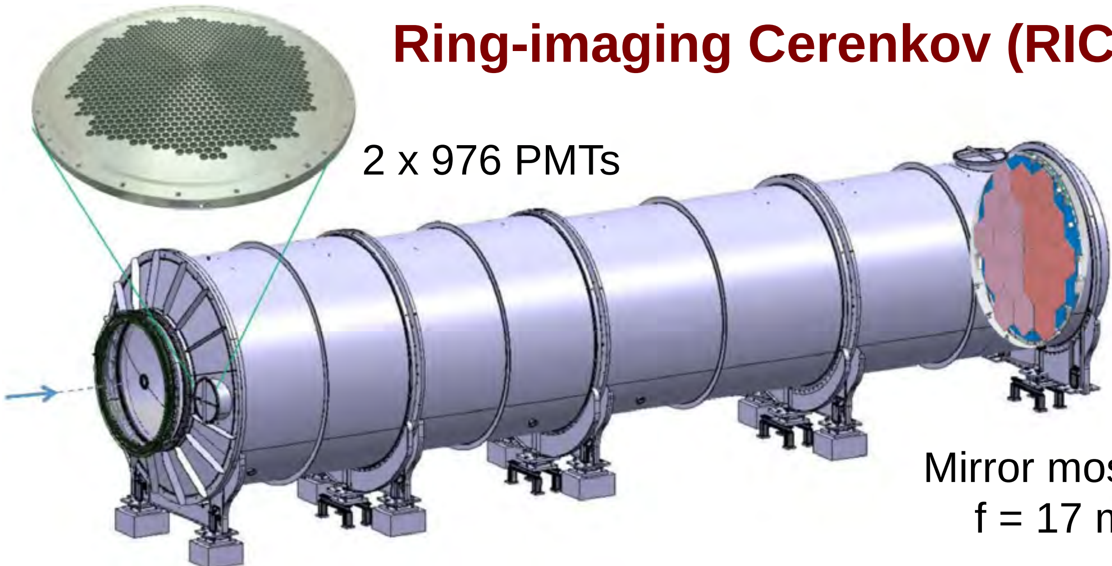
4 views per chamber (xy, uv)
4 staggered layers of straws per view
2.1 m long, 9.6 mm Ø mylar tubes
Central gap in each view for beam
Gas mixture 70% Ar + 30% CO_2
1.8% X_0 total

$\sigma \leq$ 130 µm (1 view)
99% hit eff

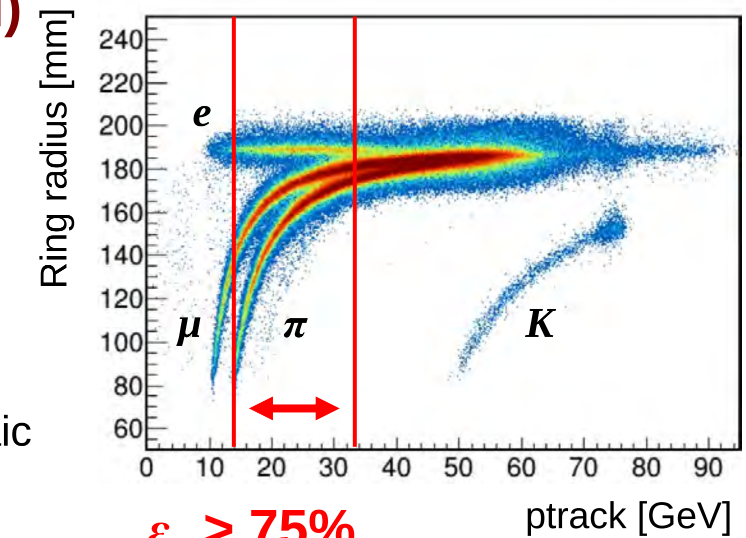
$\boldsymbol{\sigma_p/p}$ ~ 0.3-0.4%
$\boldsymbol{\sigma_\theta}$ ~ 20-60 µrad

Redundant downstream PID

Ring-imaging Cerenkov (RICH)



17-m vessel: Ne at 1 atm
$n - 1 = 6.7 \times 10^{-5}$



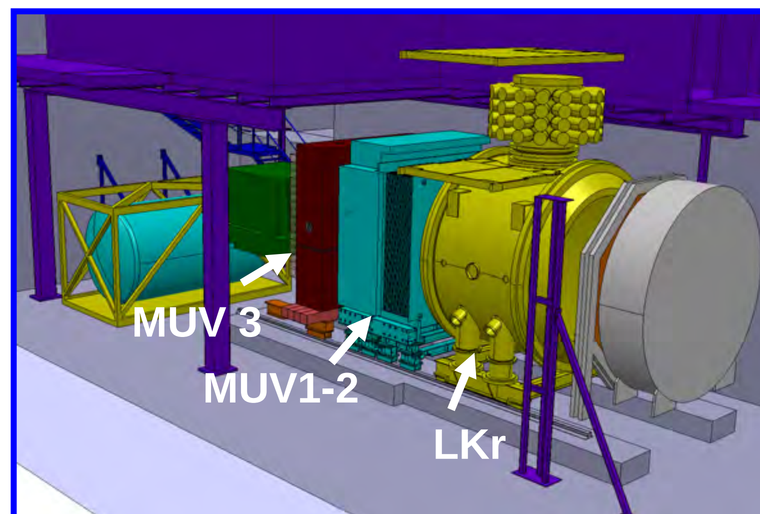
ε_π **> 75%**
ε_μ **~ 10^{-3}**

σ_t **= 100 ps**

Hadronic calorimeters and muon vetoes

MUV1	Iron/scintillator	4.1 λ_{int}
MUV2	Iron/scintillator	3.7 λ_{int}
Muon filter	80 cm iron	4.8 λ_{int}
MUV3	Scintillator tiles	–

Overall μ rejection from LKr + MUV1-2 ~ 10^{-6}
MUV3 provides low-level trigger veto



Hermetic photon veto

Detector	θ [mrad]	Max. $1-\varepsilon$
LAV	8.5 - 50	10^{-4} at 200 MeV
LKr	1 - 8.5	10^{-3} at 1 GeV 10^{-5} at 10 GeV
IRC & SAC	< 1	10^{-4} at 5 GeV

$K^+ \rightarrow \pi^+\pi^0$
BR = 21%

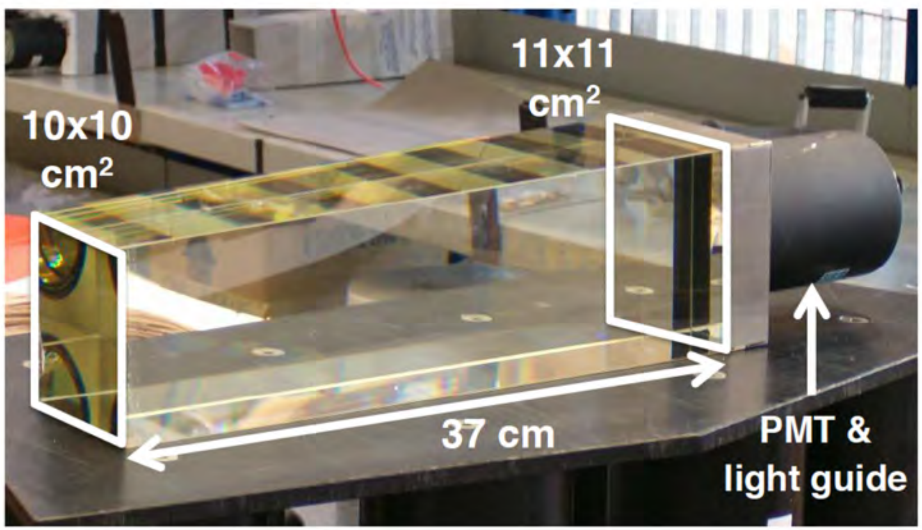
Cut $p_{\pi+}$< 35 GeV gives 2γ with 40 GeV

Rejection from kinematics 10^{-4}

Large-Angle Vetoes (LAV)

12 stations of different size

Energy resolution ~10% at 1 GeV
Time resolution ~ 1 ns
Operation in vacuum 10^{-6} mbar



NA48 liquid krypton calorimeter

Forward veto ($1 < \theta < 8.5$ mrad)
Need $1 - \varepsilon < 10^{-5}$ for $E_\gamma > 5$ GeV

Quasi-homogeneous ionization calorimeter

13248 channels

Readout towers 2x2 cm^2

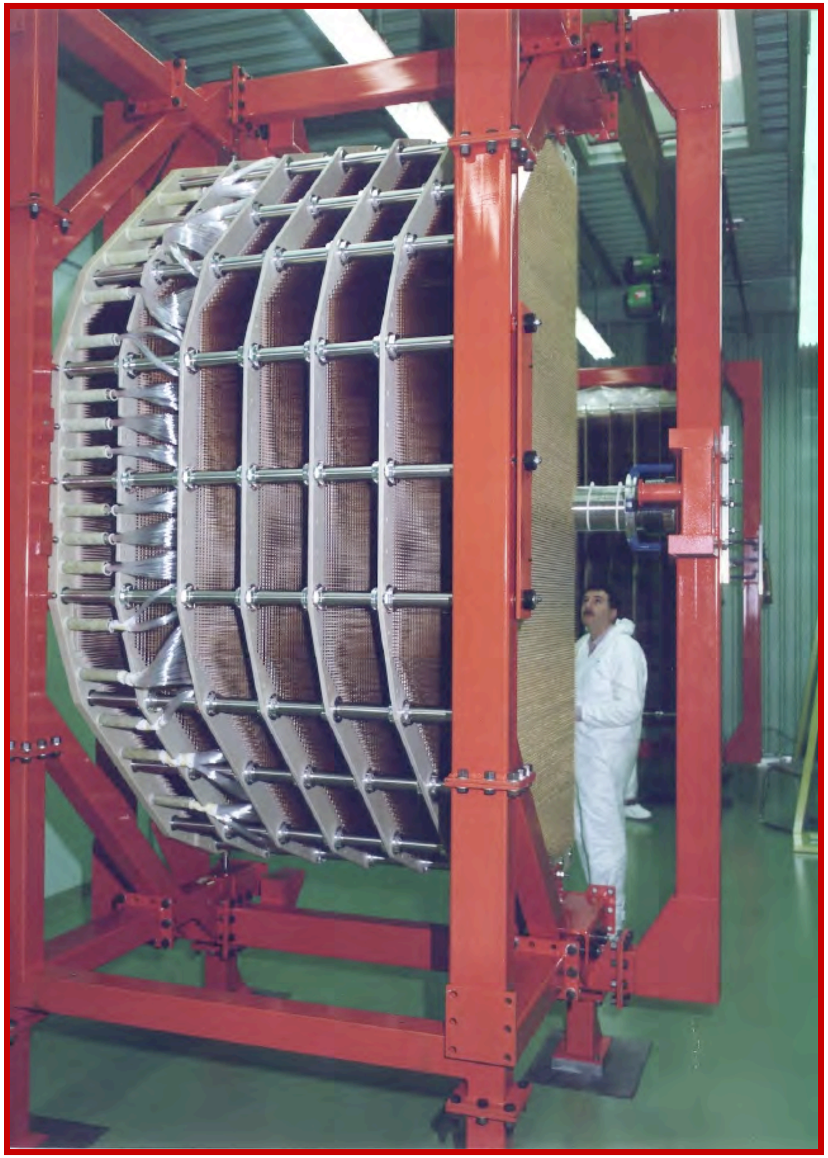
Depth 127 cm = 27 X_0

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\%$$

$$\sigma_x = \sigma_y = \frac{4.2\text{ mm}}{\sqrt{E}} \oplus 0.06\text{ mm}$$

$$\sigma_t = \frac{2.5\text{ ns}}{\sqrt{E}}$$

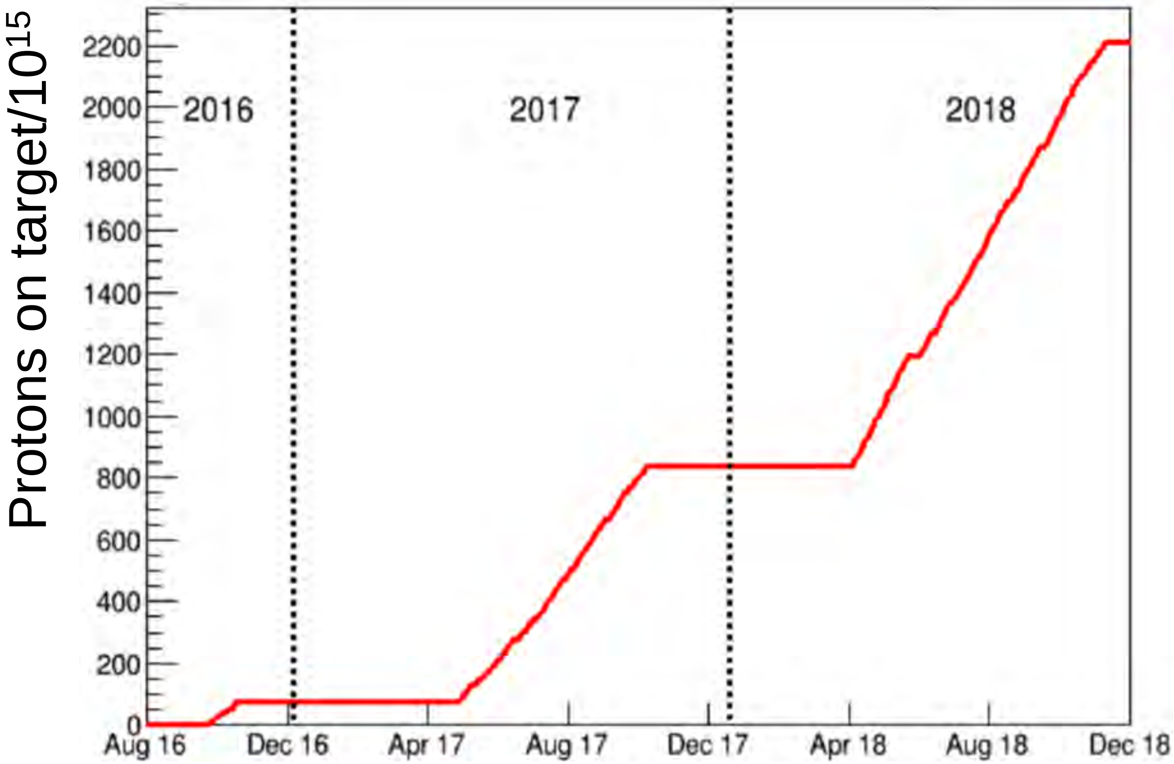
NA62 readout electronics:
14-bit 40 MHz FADCs with large buffers to handle 1 MHz L0 rate



NA62 data taking, 2016-2018

After commissioning in 2014-2015, NA62 Run 1 from 2016-2018 (until LS2)

2.2×10^{18} protons on target in total - three rounds of $K^+ \to \pi^+ \nu\nu$ analysis



2016

40% of nominal intensity
0.12×10^{12} K^+ decays in FV
PLB 791 (2019) 156-166

2017

60% of nominal intensity
1.5×10^{12} K^+ decays in FV
JHEP 11 (2020) 042

2018

60-70% of nominal intensity
2.6×10^{12} K^+ decays in FV
JHEP 06 (2021) 093

Nominal intensity = 3.3×10^{12} pot/3 eff sec

Instantaneous beam intensity can vary by up to a factor of 2

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

PNN trigger: 1 track + missing energy

Level 0

FPGAs in TEL62 acquisition boards

RICH signal (provides time reference)

1-4 CHOD hits, not in opposite quadrants

E(LKr) < 30 GeV and ≤ 1 LKr clusters

No MUV3 hits

Level 1

Fast online reconstruction

K^+ identification from KTAG

≤ 2 LAV hits in time

1 positive track with p < 50 GeV

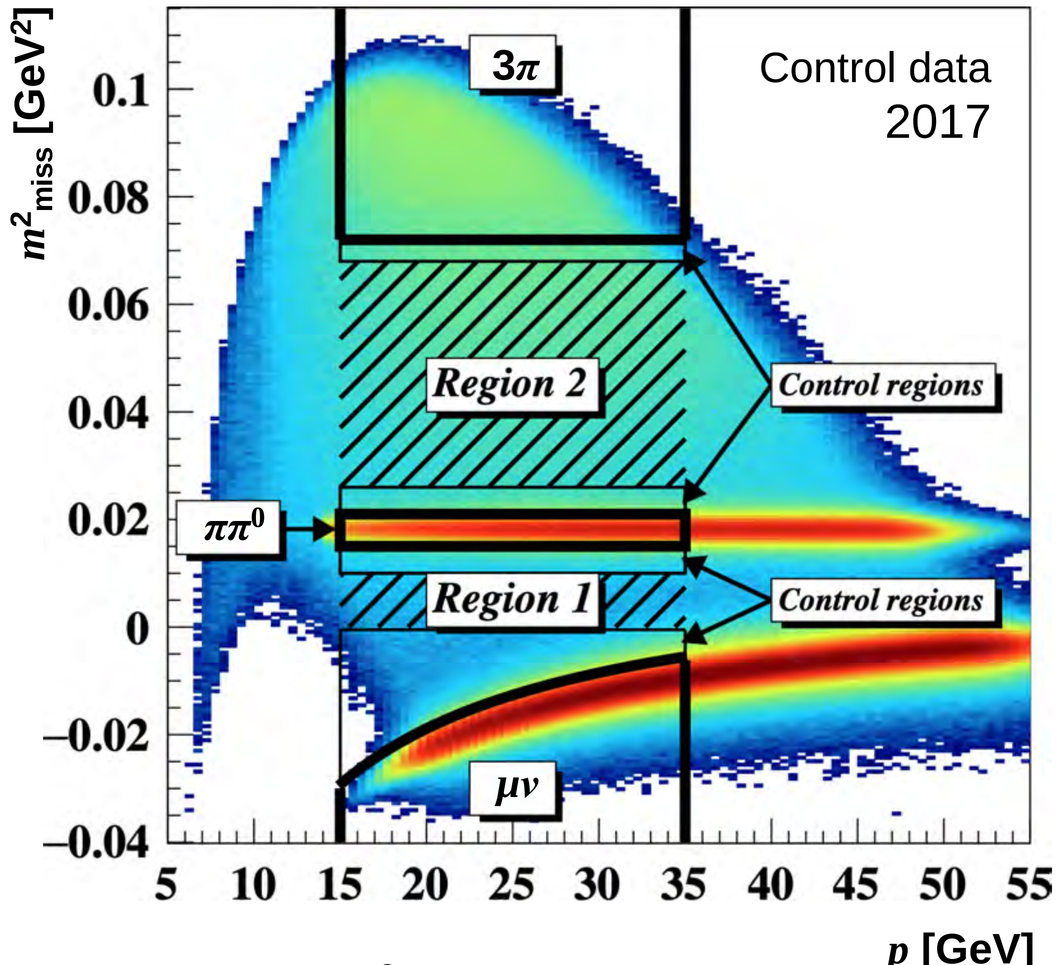
Offline selection:

1. Reconstruct vertex between beam and secondary tracks
2. Kinematic selection
3. π identification/μ rejection (RICH + LKr/MUV1-2 + MUV3)
4. Veto any extra activity (LAV, LKr, IRC-SAC, multiplicity conditions, etc.)

Normalize to $K^+ \to \pi\pi^0(\gamma)$ events collected with minimum-bias trigger

- Similar selection criteria as for $\pi^+\nu\nu$ but no photon veto

$K \to \pi$ vertex selection



$m^2_{\mathrm{miss}} = (P_K - P_\pi)^2$ with m_π hypothesis

$\sigma(m^2_{\mathrm{miss}}) \sim 10^{-3}$ GeV²

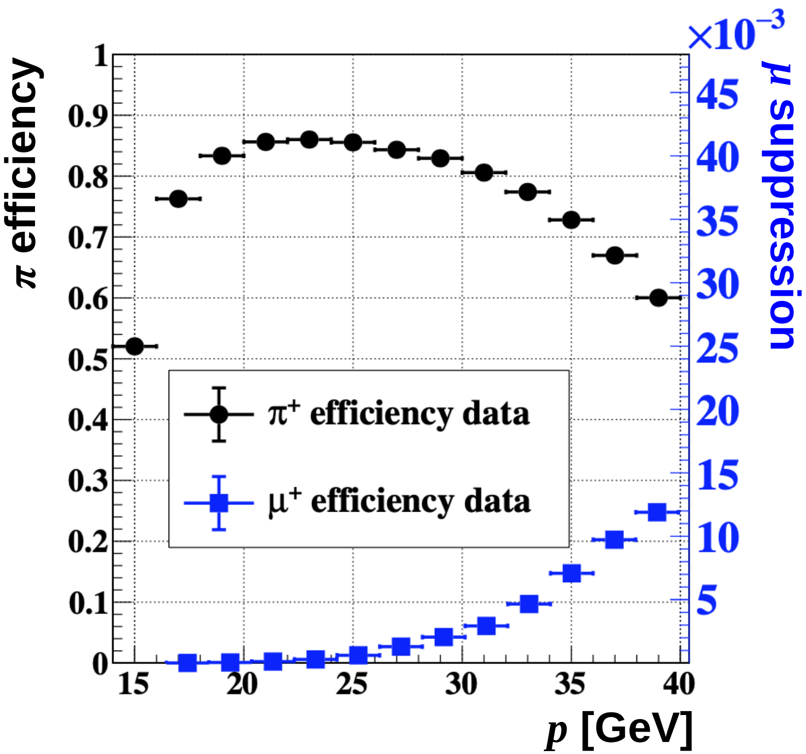
R1: $0 < m^2_{\mathrm{miss}} < 0.10$ GeV² $\quad 15 < p < 35$ GeV

R2: $0.26 < m^2_{\mathrm{miss}} < 0.68$ GeV² $\quad 15 < p < 35$ GeV (45 GeV for 2018)

- Track in GTK in time with KTAG signal
- Single positive track in downstream detectors (straw, RICH)
- Upstream-downstream timing cuts ($\sigma_t \sim 100$ ps)
- Vertex reconstruction:
  - Closest approach < 4 mm
  - 110 m < z_{reco} < 165 m
- Kinematic cuts to define:
  - Signal regions
  - Background control regions
  - Control samples
- Signal and background control regions blinded

π/μ discrimination

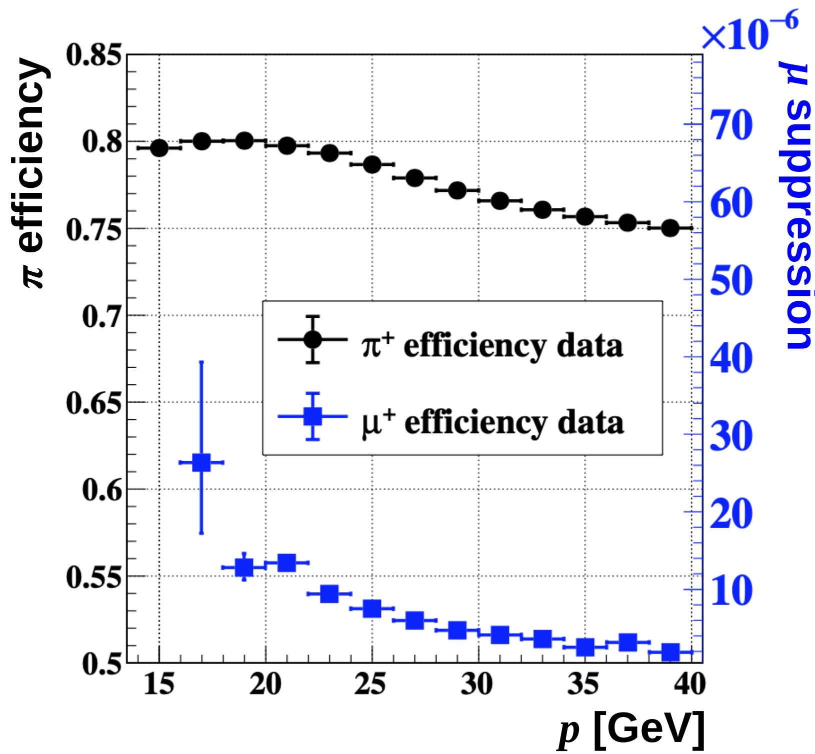
RICH



Track-driven likelihood discriminant:

- Direction from spectrometer track
- Estimate ring radius for μ/π/e
- Obtain likelihood from ring fit
- Additional cuts on m_{track} from free ring fit and straw momentum measurement

Calorimeters and muon vetoes



Veto activity in MUV3

BDT classifier with 13 variables:

- Electromagnetic calorimeter (LKr),
- Hadronic calorimeters (MUV1-2)
- Energy, energy sharing, cluster shape

Photon veto efficiency

Evaluate π^0 rejection with $K \to \pi\pi^0$ decays, $0.15 < m^2_{miss} < 0.21$ GeV^2

Single-photon efficiencies from tag-and-probe study:

- Selection and trigger stream same as for $K^+ \to \pi^+\nu\nu$ (1/3 of data set)
- Reconstruct K^+ and one γ from π^0
- Predict location of second γ
- Cuts to eliminate $\pi^+\pi^0\gamma$ events

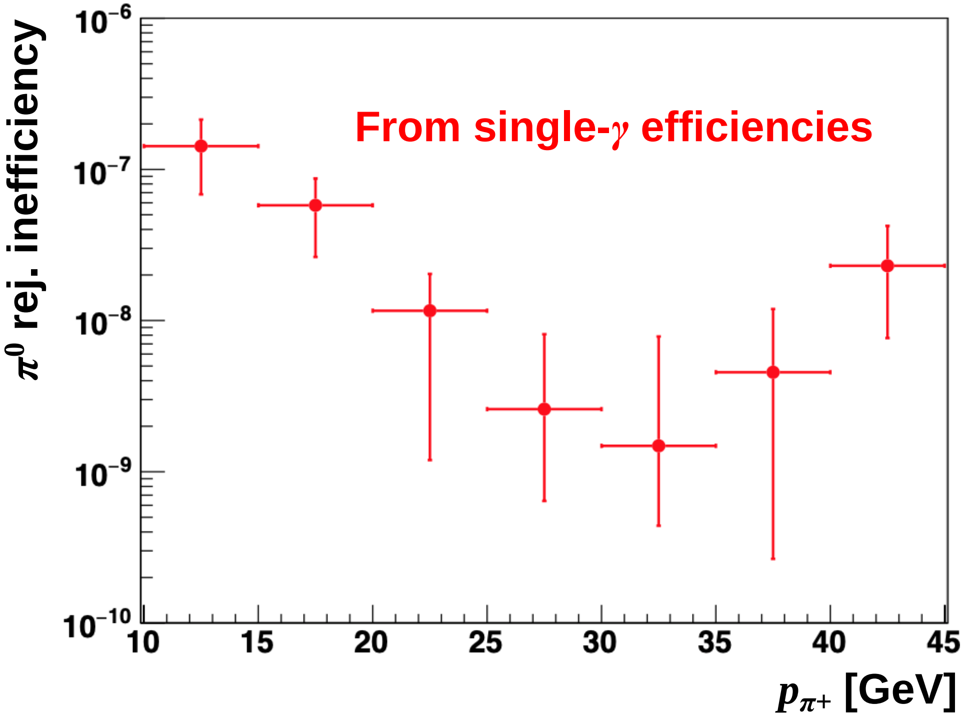
Inefficiency includes γ losses from interaction with material

Obtain correction for method bias by comparing MC results with MC truth

Fold single-particle efficiencies with MC kinematics for $\pi^+\pi^0(\gamma)$

$$\varepsilon_{\pi 0} = 2.7^{+1.5}_{-1.9} \times 10^{-8}$$

15 GeV < $p_{\pi+}$ < 35 GeV



Derive limit on BR($\pi^0 \to$ invisible)

BR < 4.4×10^{-9} (90% CL)

JHEP 02 (2021) 201

Single event sensitivity (SES)

$$\text{SES} = \frac{\text{BR}^{\text{exp}}(K^+ \to \pi\nu\bar{\nu})}{N^{\text{exp}}_{\pi\nu\nu}} = \frac{1}{N^{\text{obs}}_K \, \varepsilon_{\pi\nu\nu}}$$

$N^{\text{exp}}_{\pi\nu\nu}$ Expected (SM) $\pi\nu\nu$ decays

N^{obs}_K Total K^+ flux

$\varepsilon_{\pi\nu\nu}$ Overall acceptance for observing $\pi\nu\nu$

$$= \frac{\text{BR}^{\text{exp}}(K^+ \to \pi^+\pi^0)}{N^{\text{obs}}_{\pi\pi}} \cdot \frac{\varepsilon_{\pi\pi}}{\varepsilon_{\pi\nu\nu}}$$

$N^{\text{obs}}_{\pi\pi}$ Observed $\pi\pi$ decays

$\varepsilon_{\pi\pi}$ Overall acceptance for observing $\pi\pi$

$$\frac{\varepsilon_{\pi\pi}}{\varepsilon_{\pi\nu\nu}} = \frac{\varepsilon^{\text{sel}}_{\pi\pi}}{\varepsilon^{\text{sel}}_{\pi\nu\nu}} \frac{\varepsilon^{\text{RV}}_{\pi\pi}}{\varepsilon^{\text{RV}}_{\pi\nu\nu}} \frac{\varepsilon^{\text{trig}}_{\pi\pi}}{\varepsilon^{\text{trig}}_{\pi\nu\nu}} \cdots$$

Acceptances obtained with MC

Cancellation of systematic effects (e.g., K^+, π^+ selection efficiencies) in ratio

$\varepsilon_{\pi\pi}$ ~ 0.08

$\varepsilon_{\pi\nu\nu}$ ~ 0.03 – 0.06, depending on period

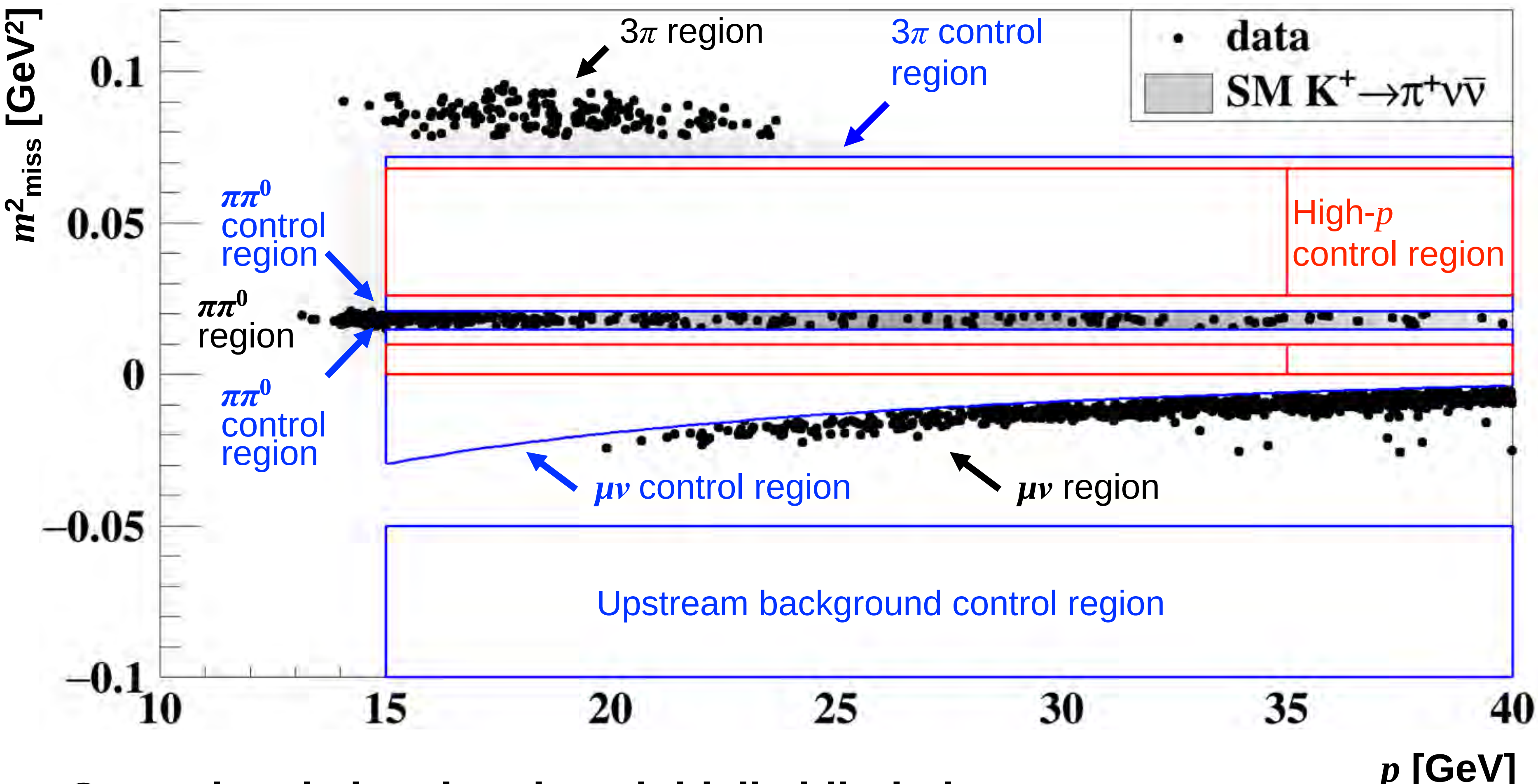
$$\frac{\varepsilon^{\text{trig}}_{\pi\pi}}{\varepsilon^{\text{trig}}_{\pi\nu\nu}} = \frac{\varepsilon^{\text{MinBi}}_{\text{trig}}}{D\,\varepsilon^{\text{PNN}}_{\text{trig}}}$$

$\varepsilon^{\text{MinBi}}$ Minimum bias trigger efficiency ~ 1

D Minimum bias scaledown (400)

ε_{PNN} PNN trigger efficiency ~ 0.9

Data after selection (2017)



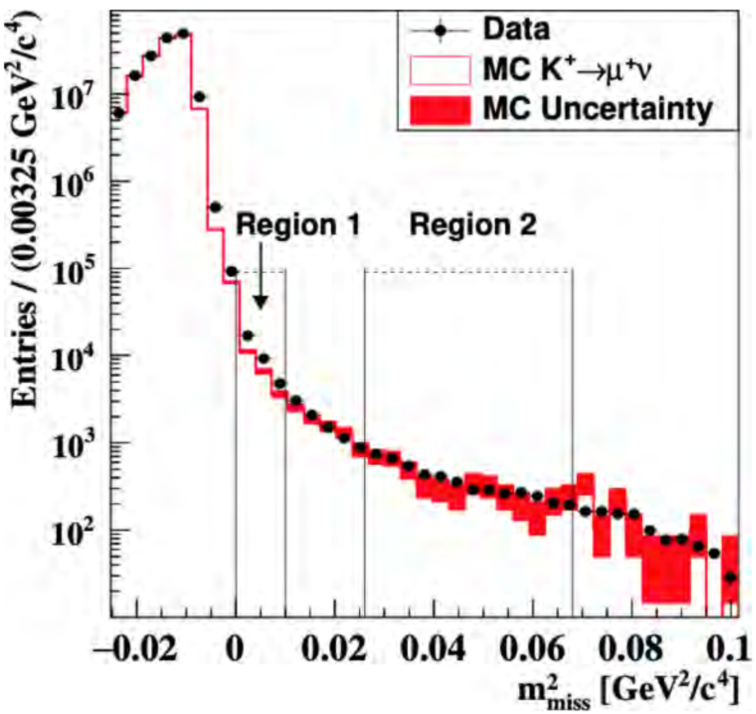
Control and signal regions initially blinded:

Control regions are unblinded to validate background estimates before signal regions are unblinded

Background rejection for $K^+ \to \pi^+\nu\bar{\nu}$

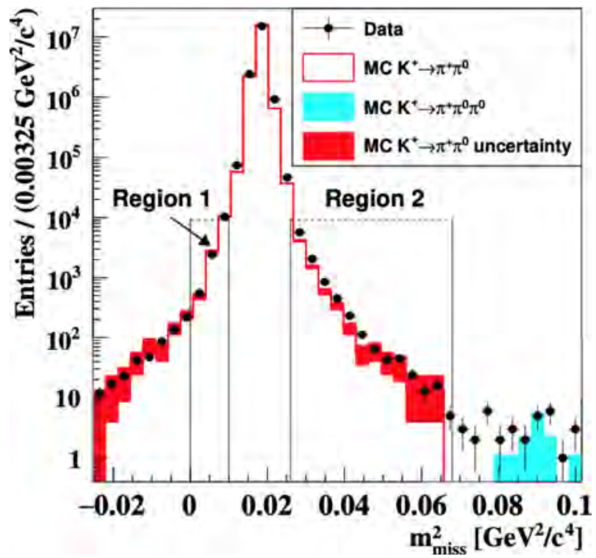
- $\pi^+\pi^0$, $\mu^+\nu$, $\pi^+\pi^-\pi^+$ backgrounds estimated from tails of m^2_{miss} distribution in control samples
- Upstream background estimated by inverting $K^+ \to \pi^+$ matching cuts

$K^+ \to \mu^+\nu$



Control sample: like $\pi^+\nu\nu$ selection but μ instead of π ID required

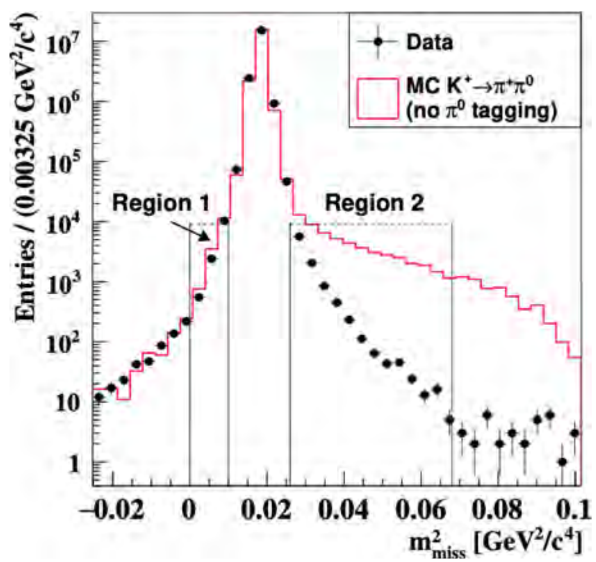
$K^+ \to \pi^+\pi^0$



Control sample:

- Reconstruct π^0
- Impose 2-body kinematics with nominal K^+ momentum

$\varepsilon_{\pi 0}$ **= 1.3 × 10⁻⁸**

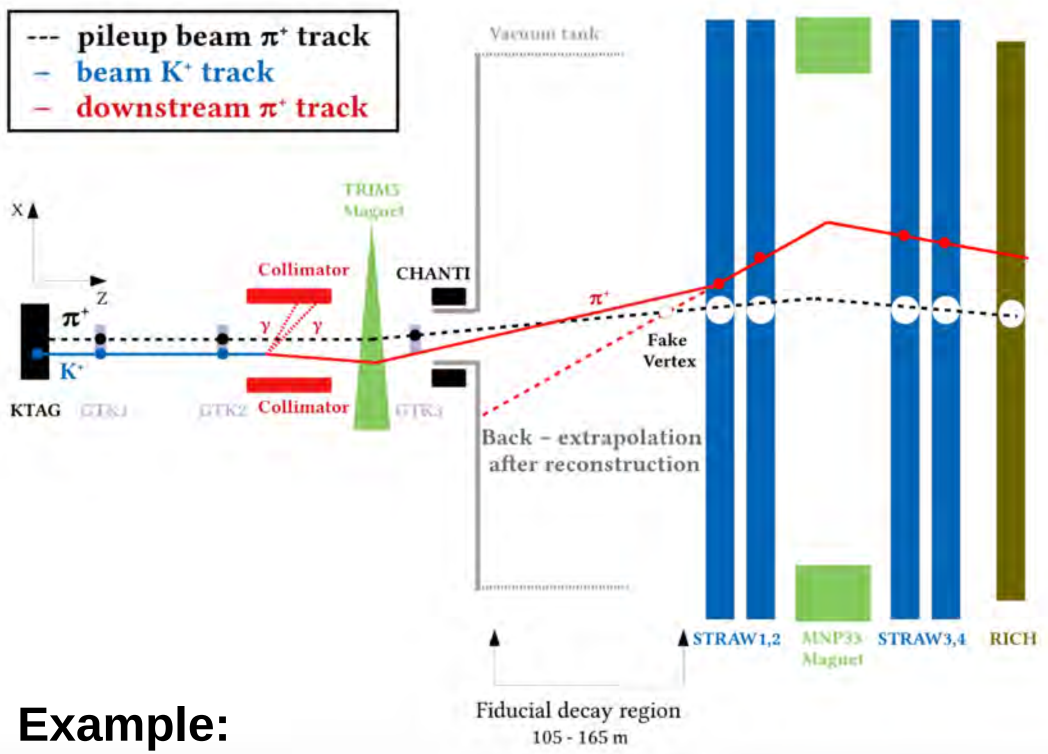


Control sample does not include $K^+ \to \pi^+\pi^0\gamma$!

- Overlaps signal region
- Photon veto more efficient
- Confirm MC with single-γ analysis

Background from upstream activity

Accidental matching of K^+ and π^+ tracks can occur when K^+ decays or beam particle interacts upstream of GTK3

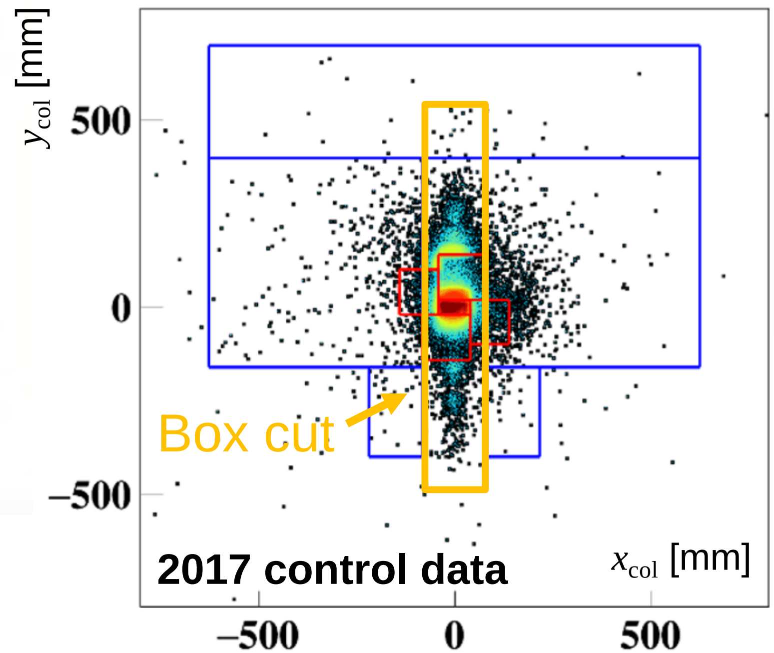


Example:

- K^+ decays between GTK2 and GTK3
- Decay π^+ misreconstructed due to scattering in first straw chamber
- Accidental π^+ leaves track in GTK

Upstream background rejected with cuts on DCA and timing between KTAG-GTK-RICH

Track projection to final collimator with ***inverted*** cuts:

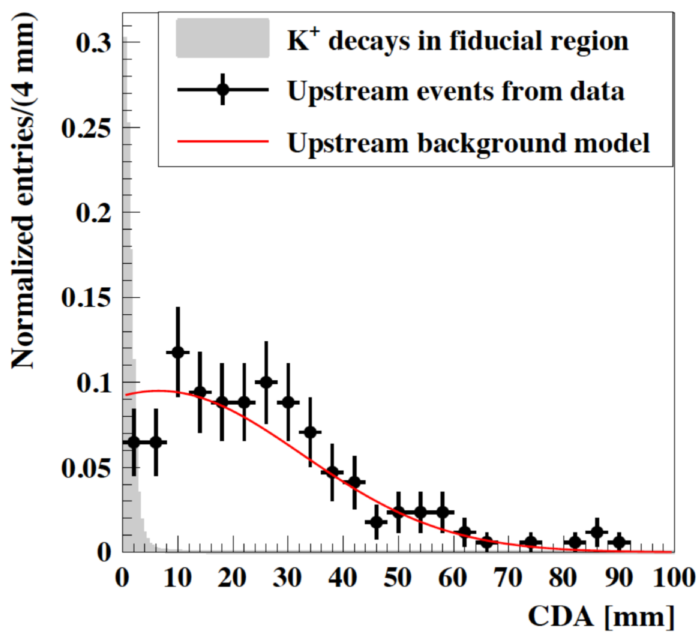


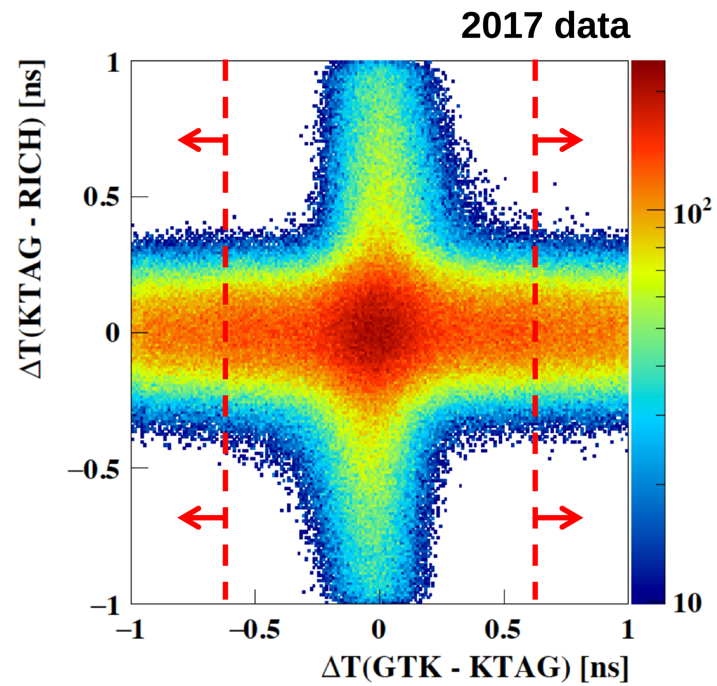
"Box cut" effective but incurs 40% loss of $\pi\nu\nu$ efficiency

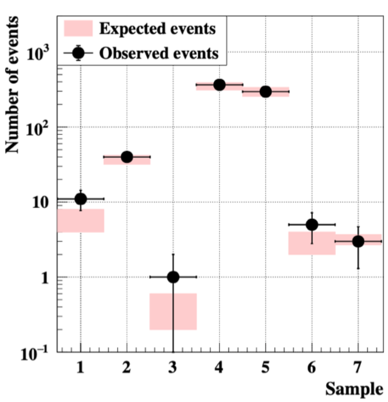
Background from upstream activity

Background model:

MC model validated with control data with Δt (GTK – KTAG) cut inverted



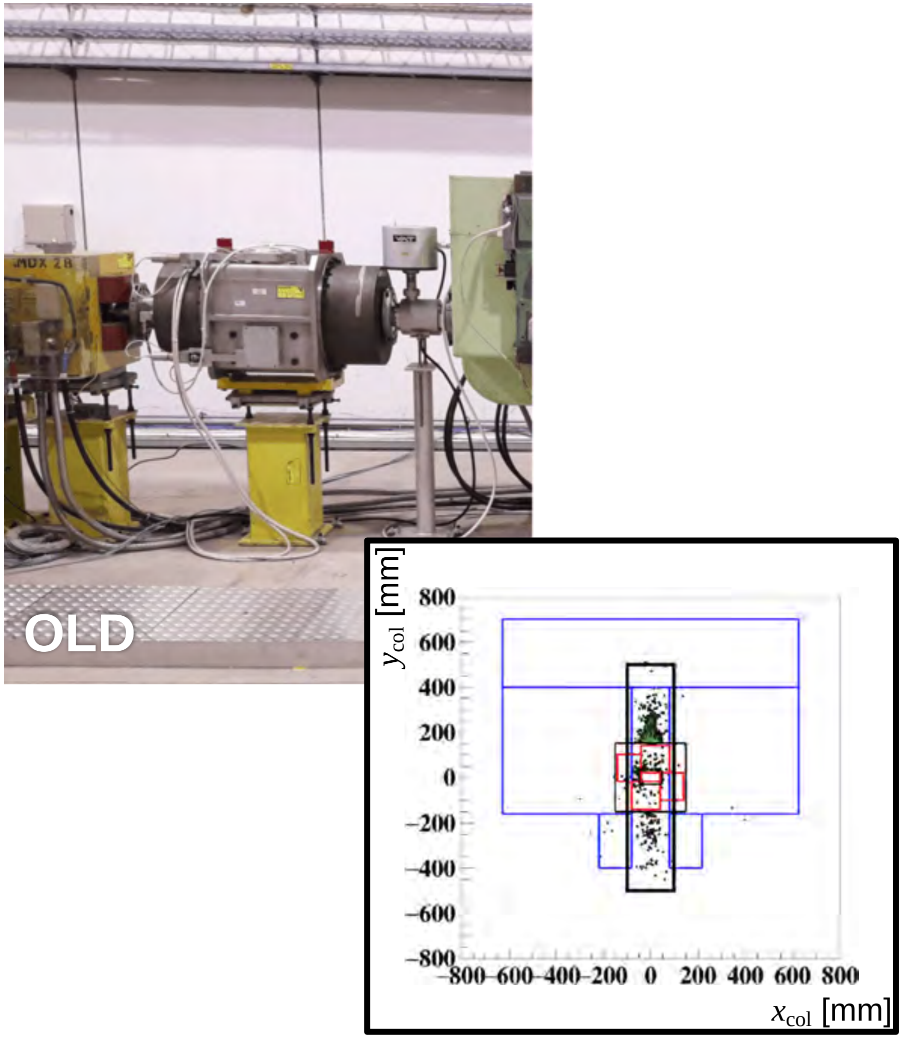


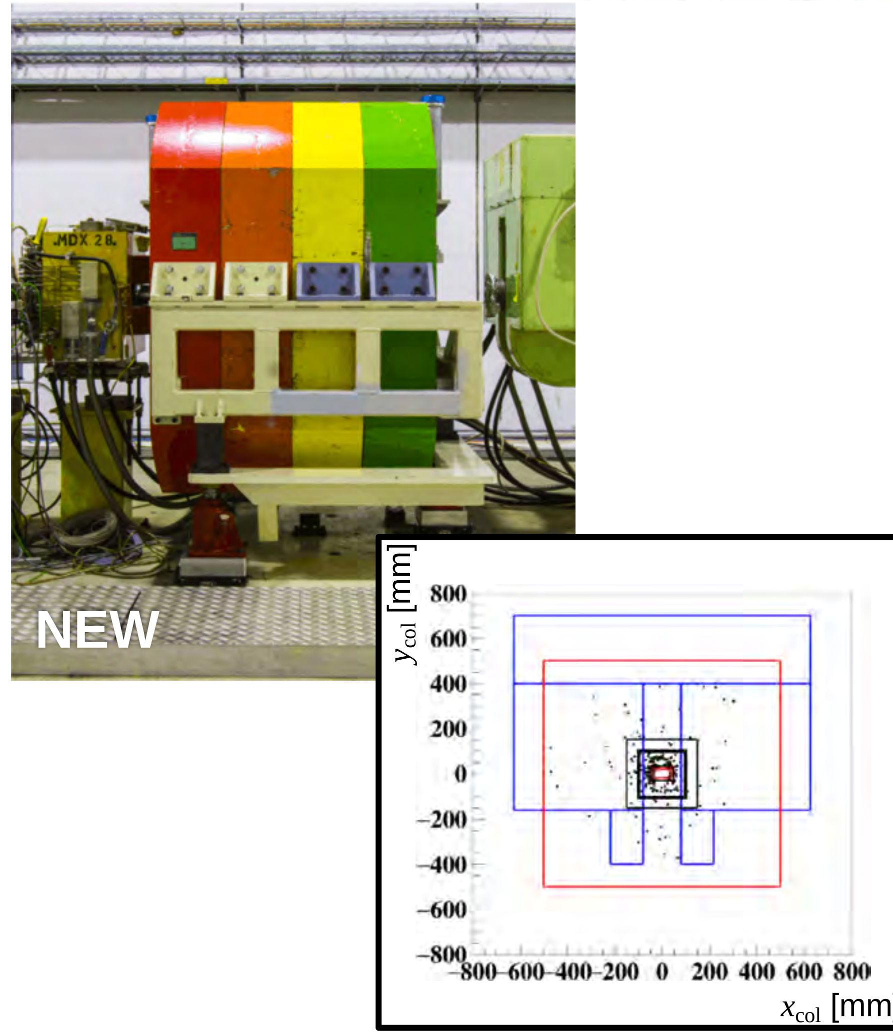


Final estimate of upstream background validated by comparison with 7 different subsamples defined by different inversions of background suppression cuts

- box cuts, GTK veto, near-beam charged veto, m^2_{miss}

New final collimator in 2018





New final collimator installed shortly after start of 2018 run:

“Box cut” eliminated → +60-70% $\pi\nu\nu$ acceptance with S/B unchanged

Expected signal and background

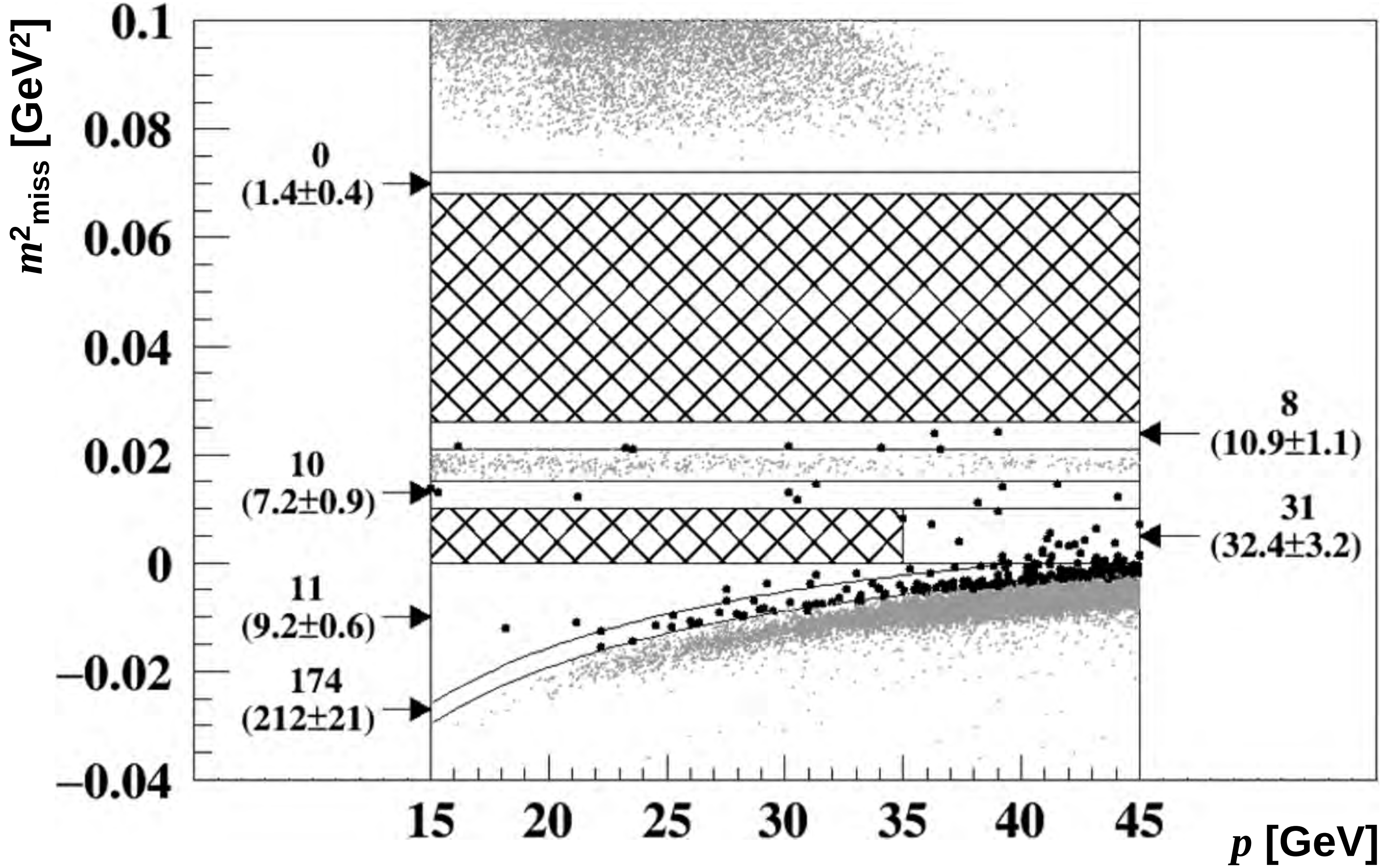
Process	Expected evts 2017 data	Expected evts 2018 data
$K^+ \to \pi^+\nu\nu$ (SM)	$2.16 \pm 0.13 \pm 0.26_{ext}$	$7.58 \pm 0.40 \pm 0.75_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$	0.29 ± 0.04	0.75 ± 0.40
$K^+ \to \mu^+\nu(\gamma)$	0.15 ± 0.04	0.49 ± 0.05
$K^+ \to \pi^+\pi^- e^+\nu$	0.12 ± 0.08	0.50 ± 0.11
$K^+ \to \pi^+\pi^+\pi^-$	0.008 ± 0.008	0.24 ± 0.08
$K^+ \to \pi^+\gamma\gamma$	0.005 ± 0.005	< 0.01
$K^+ \to \pi^0\ell^+\nu$	< 0.001	< 0.001
Upstream background	0.89 ± 0.31	$3.30^{+0.98}_{-0.73}$
Total background	$\mathbf{1.46 \pm 0.33}$	$\mathbf{5.28^{+0.99}_{-0.74}}$

2x acceptance increase from 2016 → 2018:

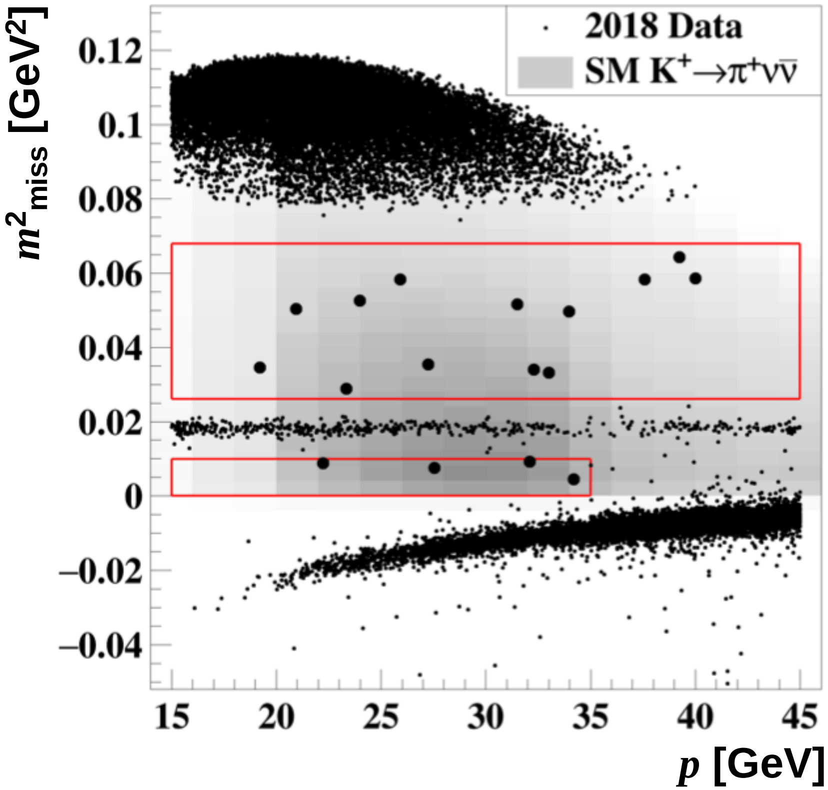
New collimator and other analysis optimizations (p_{max} 35 → 45 GeV for R2)

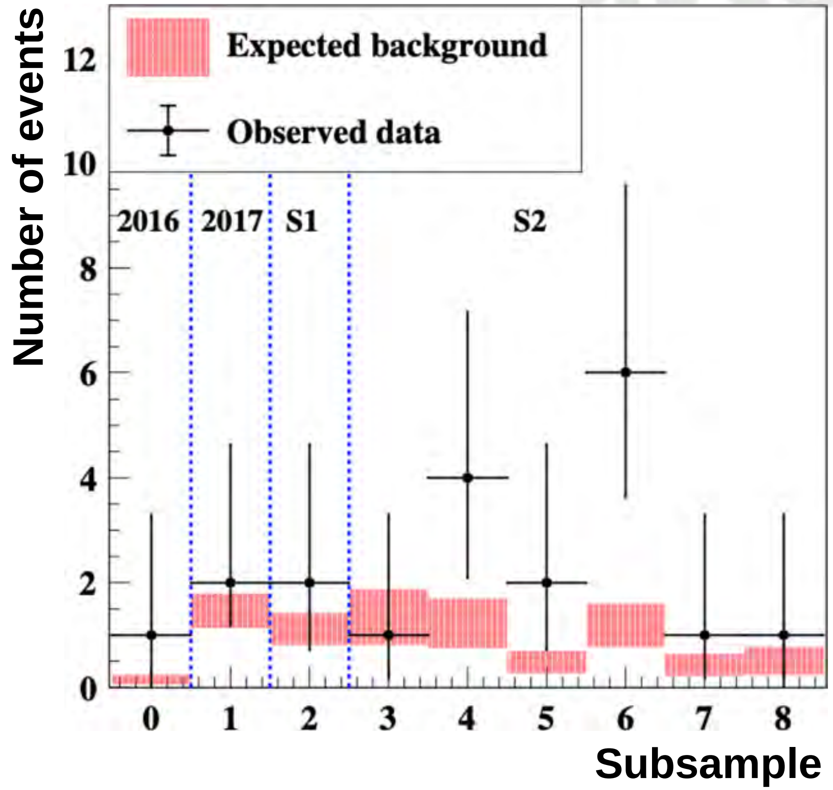
Background validation, 2018 data

Verify good agreement between expected and observed counts in each background control region



Final results: 2016-2018





	2016	2017	2018
Kaon decays in FV	0.12×10^{12}	1.5×10^{12}	2.6×10^{12}
Expected signal	0.26	2.16 ± 0.29	7.58 ± 0.85
Expected background	0.15 ± 0.09	1.46 ± 0.33	$5.28^{+0.99}_{-0.74}$
Observed	**1**	**2**	**17**

NA62 through LS3

Summary of NA62 Run 1 (2016-2018):

- **Expected signal (SM): 10 events**
- **Expected background: 7 events**
- **Total observed: 20 events**
- 3.4σ signal significance
- Most precise measurement to date

$$\mathbf{BR}(K^+ \to \pi^+ \nu\nu) = (10.6\,^{+4.0}_{-3.4\ \mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$$

Plans for NA62 Run 2 (from LS2 to LS3, 2021-2024):

NA62 resumed data taking in July 2021!

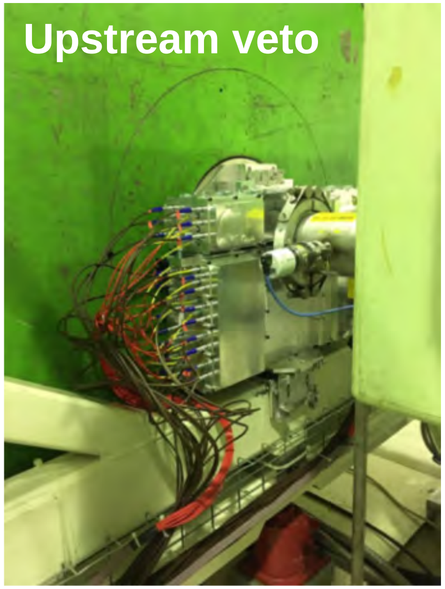
Key modifications to reduce background from upstream decays and interactions:

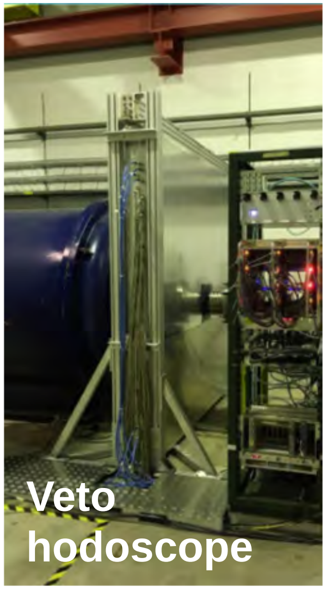
- Rearrangement of beamline elements around GTK achromat
- 4th station added to GTK beam tracker
- New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe

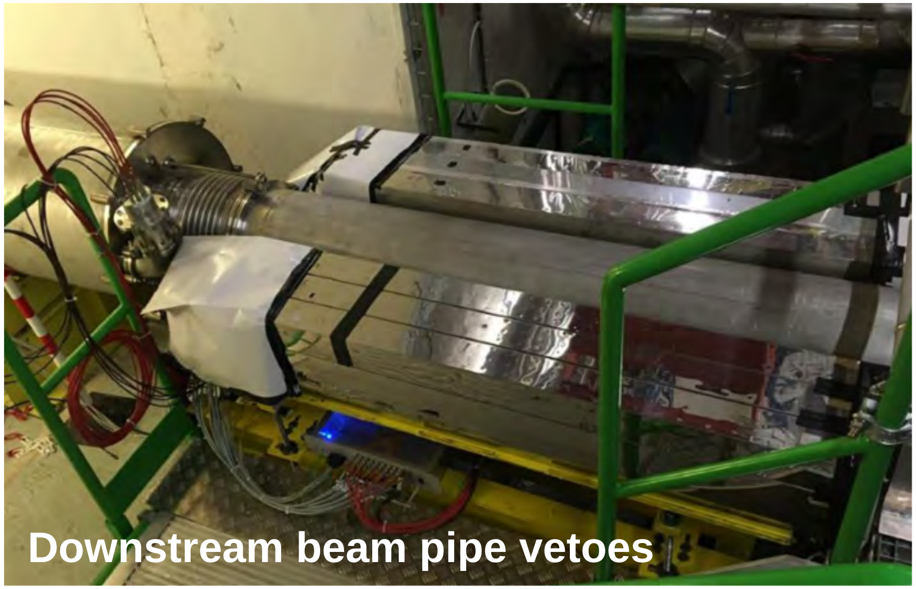
Running at higher beam intensity (70% → 100%)

Expect to measure BR($K^+ \to \pi^+ \nu\nu$) to O(10%) by LS3

NA62 through LS3







NA62 resumed data taking in July 2021!

Key modifications to reduce background from upstream decays and interactions:

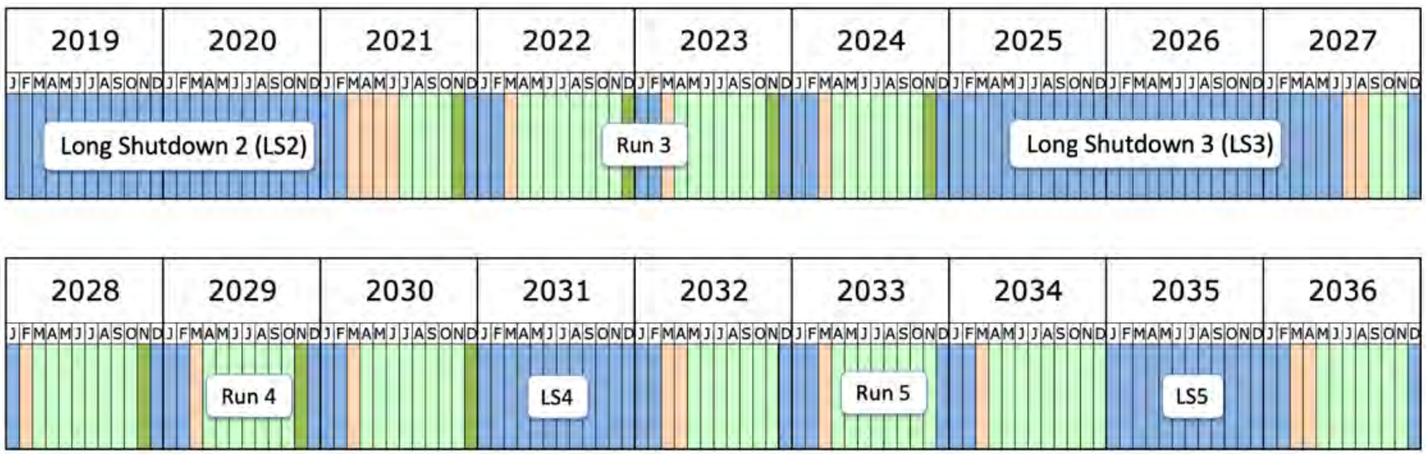
- Rearrangement of beamline elements around GTK achromat
- 4th station added to GTK beam tracker
- New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe

Running at higher beam intensity (70% → 100%)

Expect to measure BR($K^+ \rightarrow \pi^+ \nu\nu$) to O(10%) by LS3

Fixed target runs at the SPS

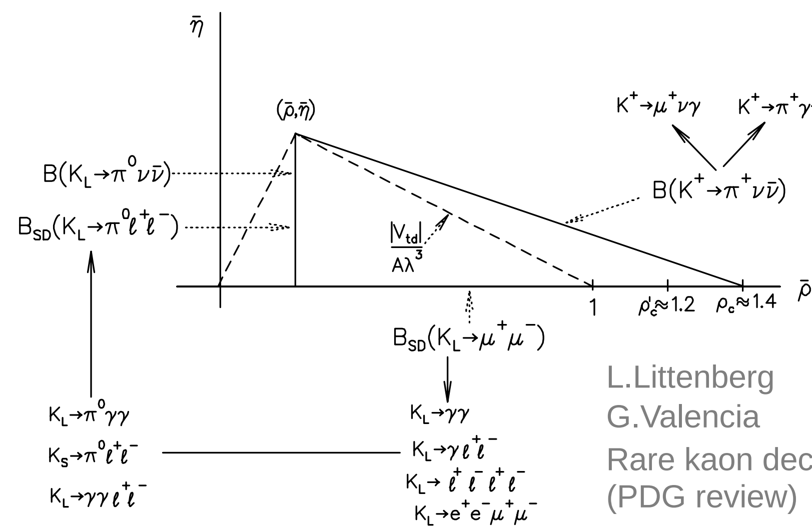
Fixed target runs planned to accompany LHC running through 2036



https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

There is an opportunity at the SPS for an **integrated program** to pin down new physics in kaon decays

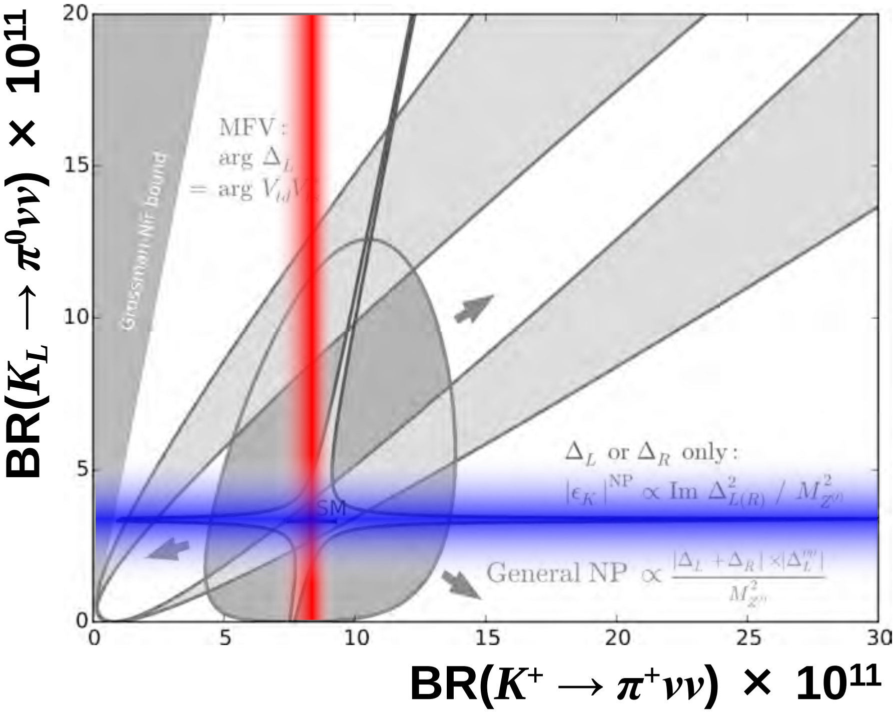
Measurement of all rare kaon decay modes—**charged and neutral**—to give clear insight into the flavor structure of new physics

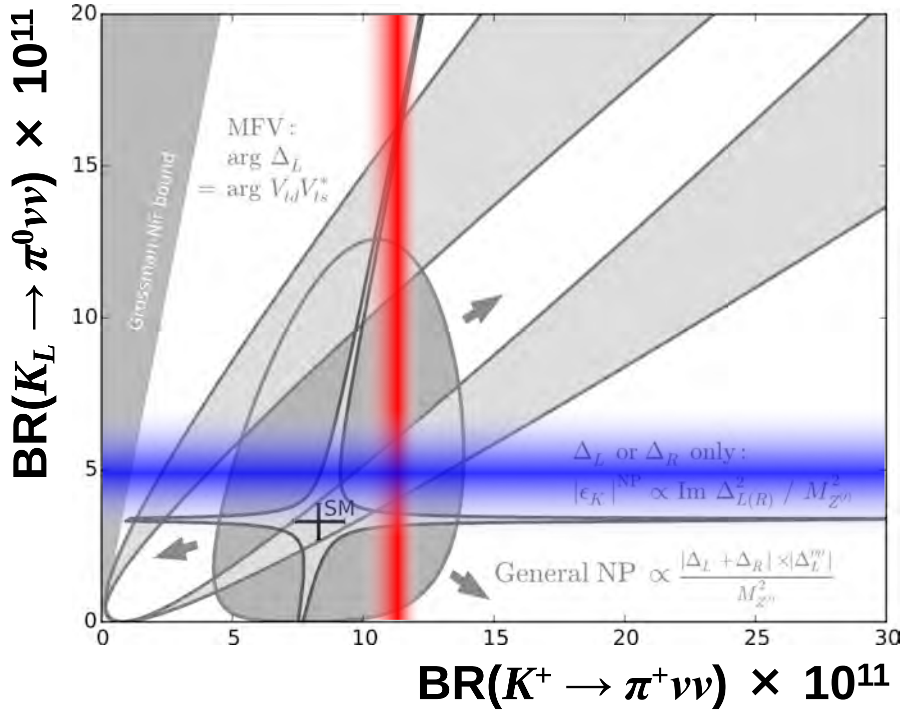


L.Littenberg
G.Valencia
Rare kaon decays
(PDG review)

Physics opportunities with kaons

Precision measurements of $K \to \pi\nu\nu$ BRs can provide model-independent tests for new physics at mass scales of up to O(100 TeV)





- $\mathrm{BR}(K^+ \to \pi^+\nu\nu)$ = **$\mathbf{BR_{SM}}$** with δBR = **5%**
- $\mathrm{BR}(K_L \to \pi^0\nu\nu)$ = **$\mathbf{BR_{SM}}$** with δBR = **20%**

- $\mathrm{BR}(K^+ \to \pi^+\nu\nu)$ = **1.33 $\mathbf{BR_{SM}}$** with δBR = **5%**
- $\mathrm{BR}(K_L \to \pi^0\nu\nu)$ = **1.50 $\mathbf{BR_{SM}}$** with δBR = **20%**

Ultra-high-intensity kaon beams

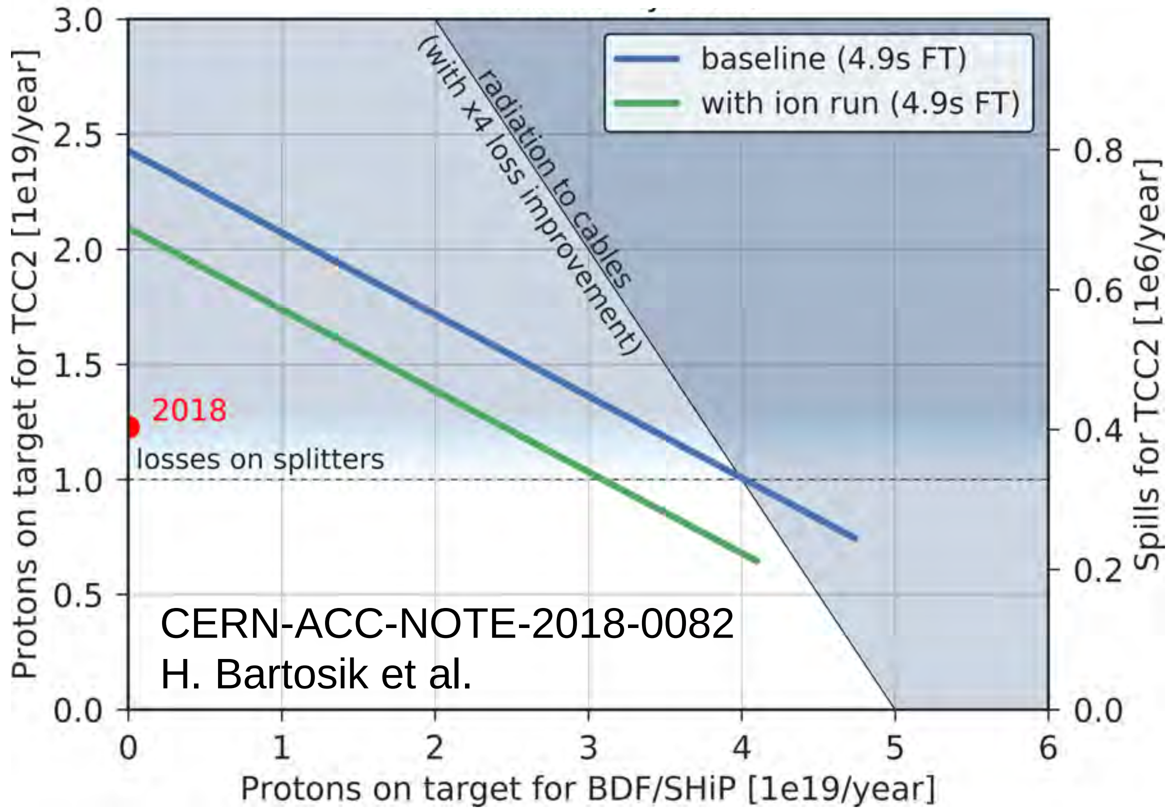
Operational scenarios and limits on the intensity deliverable to the North Area targets were studied in context of the BDF proposal as part of Physics Beyond Colliders

Experiments to measure $K \to \pi\nu\nu$ BRs at the SPS would require:

- $K^+ \to \pi^+\nu\nu$
  6×10^{18} pot/year
  4x increase
- $K_L \to \pi^0\nu\nu$
  1×10^{19} pot/year
  6x increase

increases with respect to present primary intensity

SPS proton sharing (4.9 sec flat top, 80% uptime)



A kaon experiment at 6x present intensity is compatible with a diverse North Area program

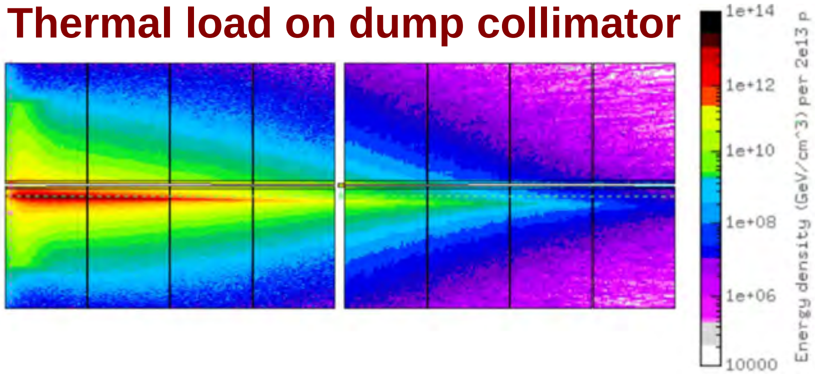
High-intensity proton beam study

Conclusions from PBC Conventional Beams working group

Issue	Approach
Extraction losses	Good results on ZS losses and spill quality from SPS Losses & Activation WG (SLAWG) workshop, 9-11 November 2017: https://indico.cern.ch/event/639766/
Beam loss on T4	Vertical by-pass to increase T4 → T10 transmission to 80%
Equipment protection	Interlock to stop SPS extraction during P0Survey reaction time
Ventilation in ECN3	Preliminary measurements indicate good air containment Comprehensive ventilation system upgrade not needed
ECN3 beam dump	Significantly improved for NA62 Need to better understand current safety margin
T10 target & collimator	Thermal load on T10 too high → Use CNGS-like target? Dump collimator will require modification/additional cooling
Radiation dose at surface above ECN3	8 mrad vertical targeting angle should help to mitigate Preliminary results from FLUKA simulations Proposed target shielding scheme appears to be adequate Mixed mitigation strategy may be needed for forward muons

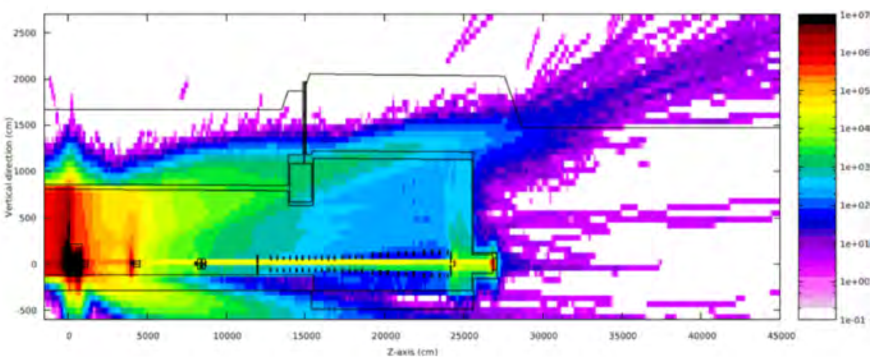
Beam and target simulations

Thermal load on dump collimator



CNGS rod target

Dose rate simulation in ECN3, K_L beam



Thermal simulations of target and TAX dump collimator

- Identified upgrades needed for high-intensity beam
- Target: CNGS-like design: carbon-carbon supports, pressurized air cooling
- TAX: Cooling elements nearer to center of collimator, like for SPS beam dump

Neutral beam and prompt surface dose

- **Neutrons:** Shielding adequate to reduce surface dose; need access shaft airlock
- **Muons:** Additional shielding at target and/or at downstream end of ECN3

Complete evaluation of random veto and trigger rates with full FLUKA beamline simulation for all particles down to 100 MeV

- Random veto rate = 140 MHz

$K^+ \to \pi^+ \nu\nu$ at high-statistics

The NA62 decay-in-flight technique is now well established!

- Background estimates validated by in-depth study with data and MC
- Lessons learned in 2016-2018 will be put in action in 2021-2024

Possible next step:

An experiment at the SPS to measure BR($K^+ \to \pi^+ \nu\nu$) to within ~5%!

Requires 4x increase in intensity → matches present limit with charged secondary beam (after major upgrades)

Basic design of experiment will work at high intensity

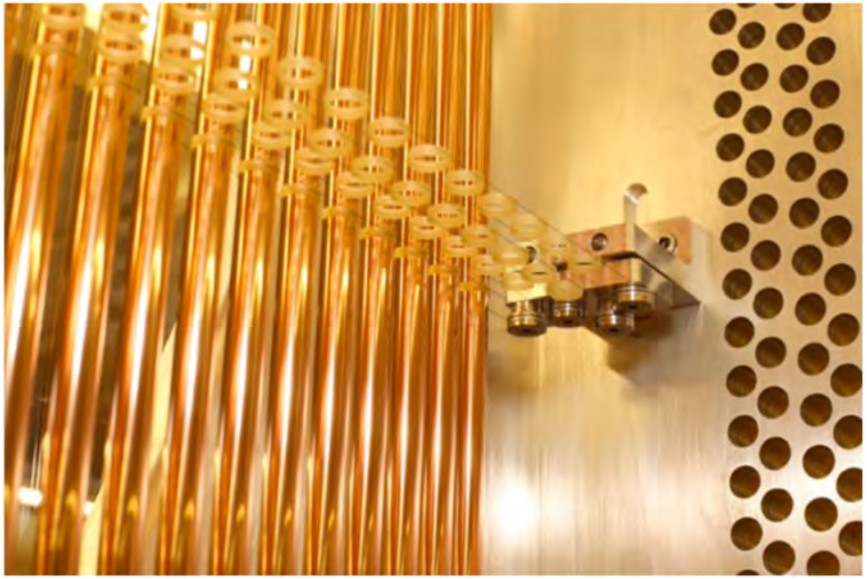
Key challenges:

- Require much improved time resolution to keep random veto rate under control
- Must maintain other key performance specifications at high-rate:
  - Space-time reconstruction, low material budget, single photon efficiencies, control of non-gaussian tails, etc.

Synergies to be explored:

- Challenges often aligned with (sometimes more stringent than) High Luminosity LHC projects and next generation flavor/dark matter experiments

Experimental challenges: STRAW



NA62 straw chambers

- Straw diameter: 9.8 mm
- Hit trailing-time resolution: ~30 ns
- Maximum drift time: ~150 ns
- Mylar straws: 36 wall μm thickness
- Material budget: 1.7% X_0

Straw chambers for 4x intensity

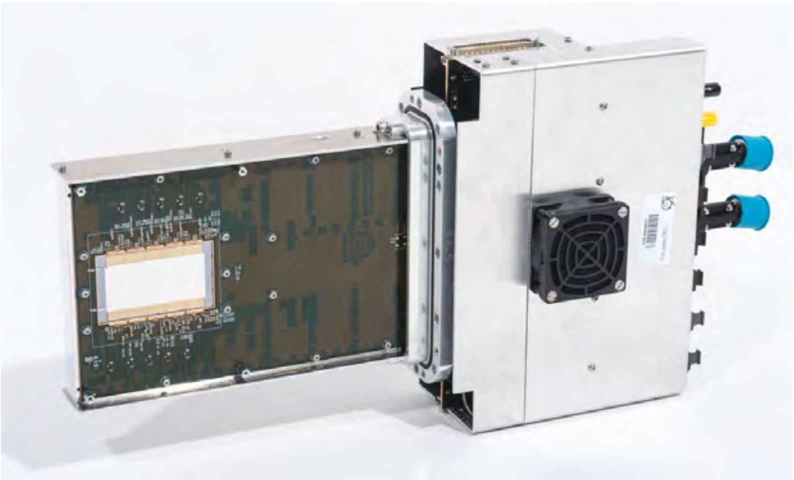
- **Main feature: Straw diameter ~5 mm**
- **Improved trailing-time resolution: ~6 ns (per straw)**
- **Smaller maximum drift time: ~80 ns**
- **Rate capability increased 6-8x**
- Layout: 4 chambers, ~21000 straws
- Decreased straw wall thickness: ~20 μm, with copper and gold plating
- Material budget: 1.4% X_0

Design studies in progress at CERN and Dubna

Experimental challenges: GTK

GTK for 4x intensity

- **Time resolution < 50 ps per plane, no non-gaussian tails!**
- Pixel size: < 300 × 300 μm^2
- Efficiency: > 99% (incl. fill factor)
- Material budget: 0.3-0.5% X_0
- Beam intensity: 3 GHz over ~ 3x6 cm^2
- Maximum local intensity: 8 MHz/mm^2
- Radiation resistance: 2.3x10^{15} n eq/cm^2/yr

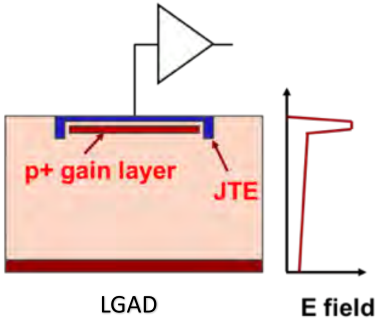


NA62 Gigatracker station

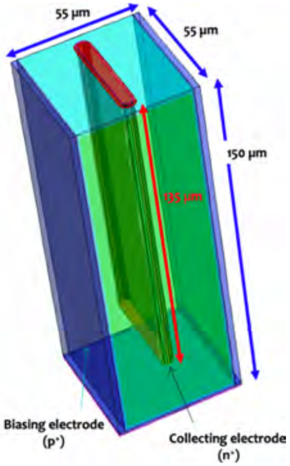
Continue to improve planar sensors while monitoring progress on new technologies

Possible synergies with ongoing development efforts:

LGAD: Low Gain Avalanche Detectors



TimeSPOT: time-stamping 3D sensors

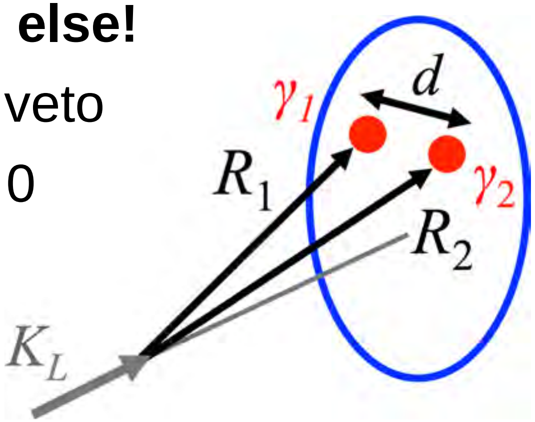


$K_L \to \pi^0 \nu\bar{\nu}$: Experimental issues

Essential signature: 2γ with unbalanced $p_\perp$ + nothing else!

All other K_L decays have ≥ 2 extra γs or ≥ 2 tracks to veto

Exception: $K_L \to \gamma\gamma$, but not a big problem since $p_\perp = 0$



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

$$R_1 \approx R_2 \equiv R = \frac{d\sqrt{E_1E_2}}{m_{\pi^0}}$$

K_L momentum generally is not known

$M(\gamma\gamma) = m(\pi^0)$ is the only sharp kinematic constraint

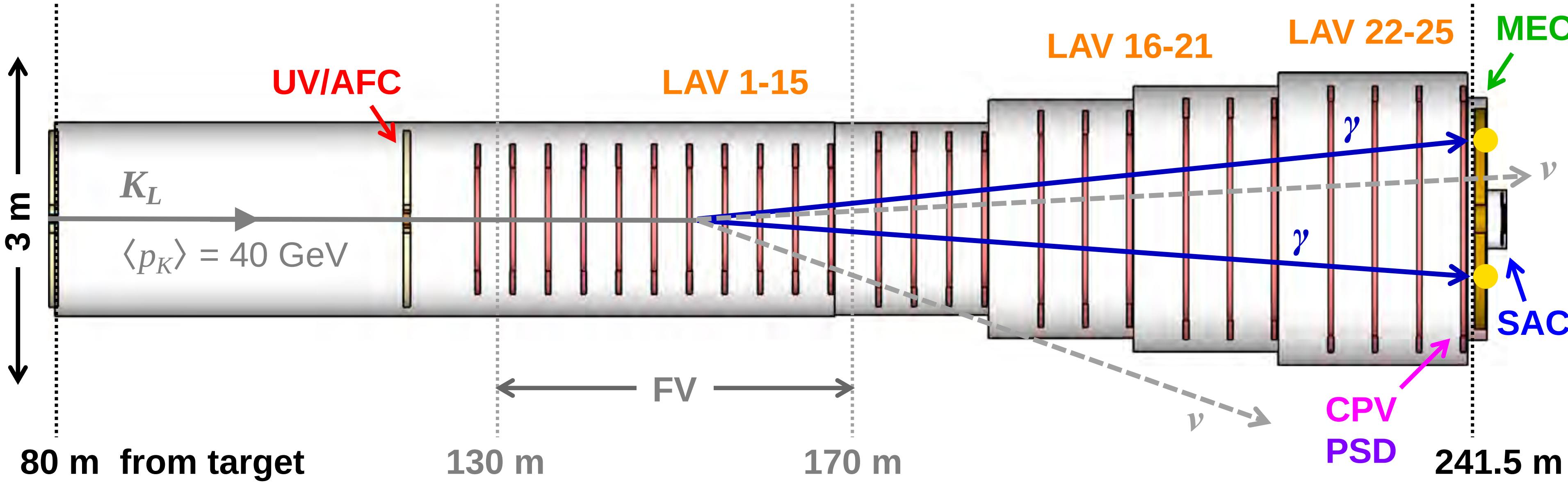
Generally used to reconstruct vertex position

Main backgrounds:

Mode	BR	Methods to suppress/reject
$K_L \to \pi^0\pi^0$	8.64×10^{-4}	γ vetoes, π^0 vertex, $p_\perp$
$K_L \to \pi^0\pi^0\pi^0$	19.52%	γ vetoes, π^0 vertex, $p_\perp$
$K_L \to \pi e\nu(\gamma)$	40.55%	Charged particle vetoes, π ID, γ vetoes
$\Lambda \to \pi^0 n$		Beamline length, $p_\perp$
$n + A \to X\pi^0$		High vacuum decay region

A $K_L \to \pi^0 \nu\bar{\nu}$ experiment at the SPS?

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



KLEVER target sensitivity:
5 years starting Run 4

~ 60 SM $K_L \to \pi^0 \nu\nu$

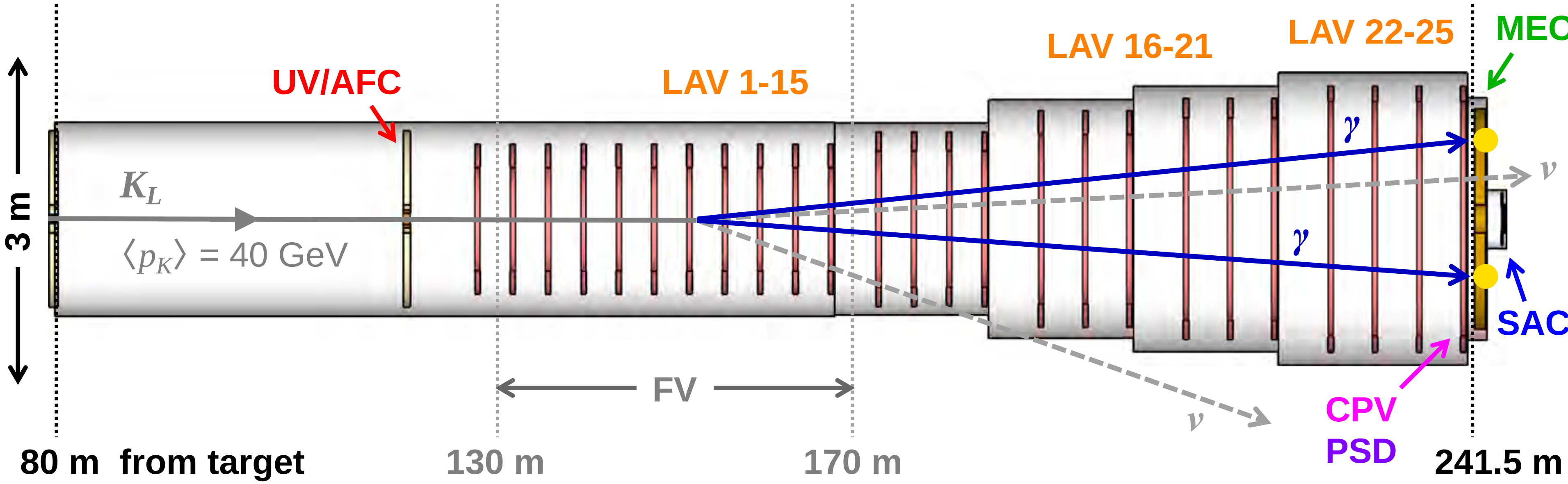
S/B ~ 1

δBR/BR($\pi^0\nu\nu$) ~ 20%

- High-energy experiment: Complementary to KOTO
- Photons from K_L decays boosted forward
  - Makes photon vetoing easier - veto coverage only out to 100 mrad
- Roughly same vacuum tank layout and fiducial volume as NA62

A $K_L \to \pi^0 \nu\bar{\nu}$ experiment at the SPS   *KLEVER*

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



Main detector/veto systems:

UV/AFC	Upstream veto/Active final collimator
LAV1-25	Large-angle vetoes (25 stations)
MEC	Main electromagnetic calorimeter
SAC	Small-angle vetoes
CPV	Charged particle veto
PSD	Pre-shower detector

***KLEVER* target sensitivity:**
5 years starting Run 4

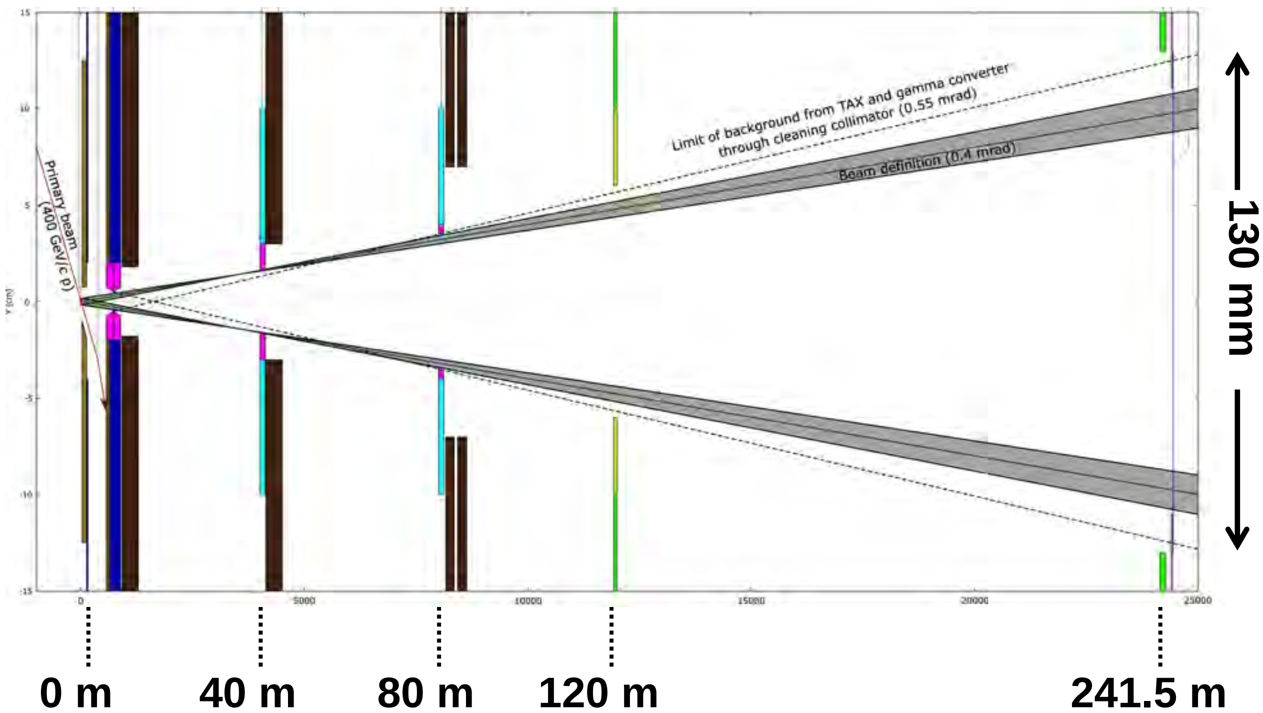
~ 60 SM $K_L \to \pi^0 \nu\nu$
S/B ~ 1

δBR/BR($\pi^0 \nu\nu$) ~ 20%

Neutral beam and beamline

KLEVER

- **400 GeV p on 400 mm Be target**
- **Production angle θ = 8.0 mrad**
- **Solid angle $\Delta\theta$ = 0.4 mrad**
- **2.1 × 10^{-5} K_L/pot in beam**
- **$\langle p(K_L) \rangle$ = 40 GeV**
- Probability for decay inside FV ~ 4%
- Acceptance for $K_L \to \pi^0 \nu\nu$ decays occurring in FV ~ 5%



- **4 collimation stages** to minimize neutron halo, including beam scattered from absorber
- **Photon absorber** in dump collimator

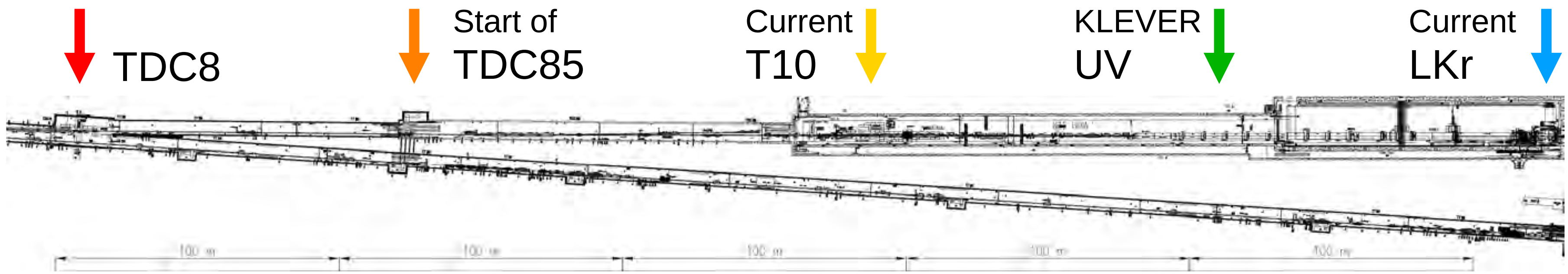
NB: Choice of higher production angle under study to decrease rate of $\Lambda \to n\pi^0$ decays in detector:

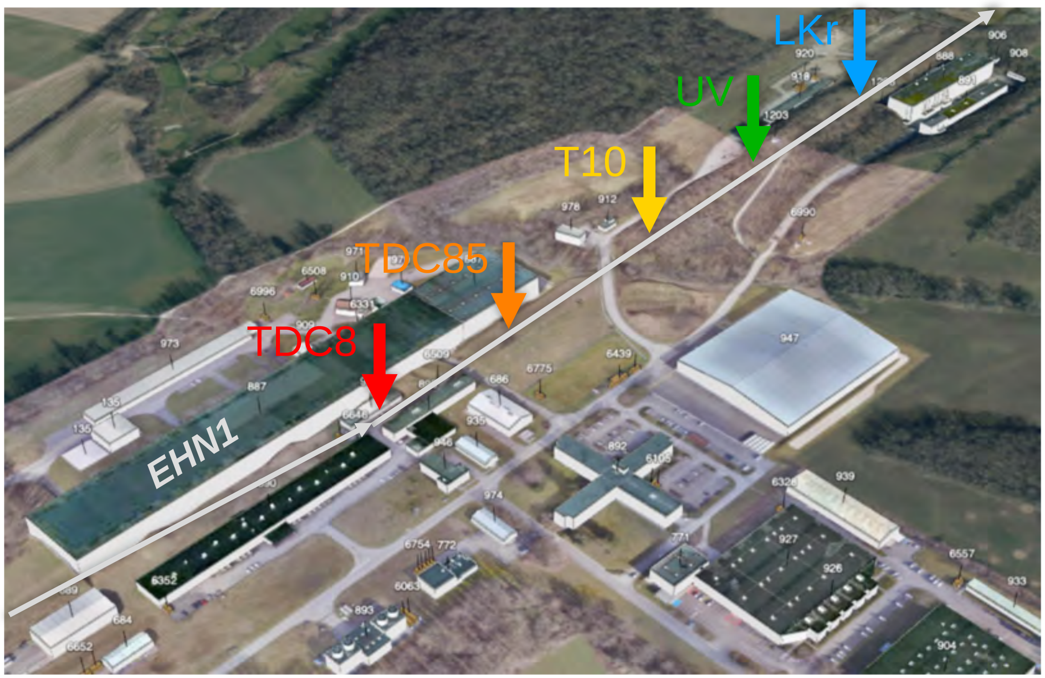
Possible changes to beamline configuration and experimental layout

Long beamline to suppress $\Lambda \to n\pi^0$ K_LEVER

Maintain θ = 8 mrad and increase length of beamline

E.g.: Move T10 from TCC8 to start of TDC85 (120 m → 270 m from T10 to UV)





- Maintain K_L momentum
  - Fewer design changes for KLEVER
- Preserve K_L flux per solid angle
  - Still lose 2x in K_L flux due to tighter beam collimation
- Infrastructure work needed
- RP issues for area downstream of TDC85 to be investigated
- **Alternatively, ECN3 extension would solve problem**

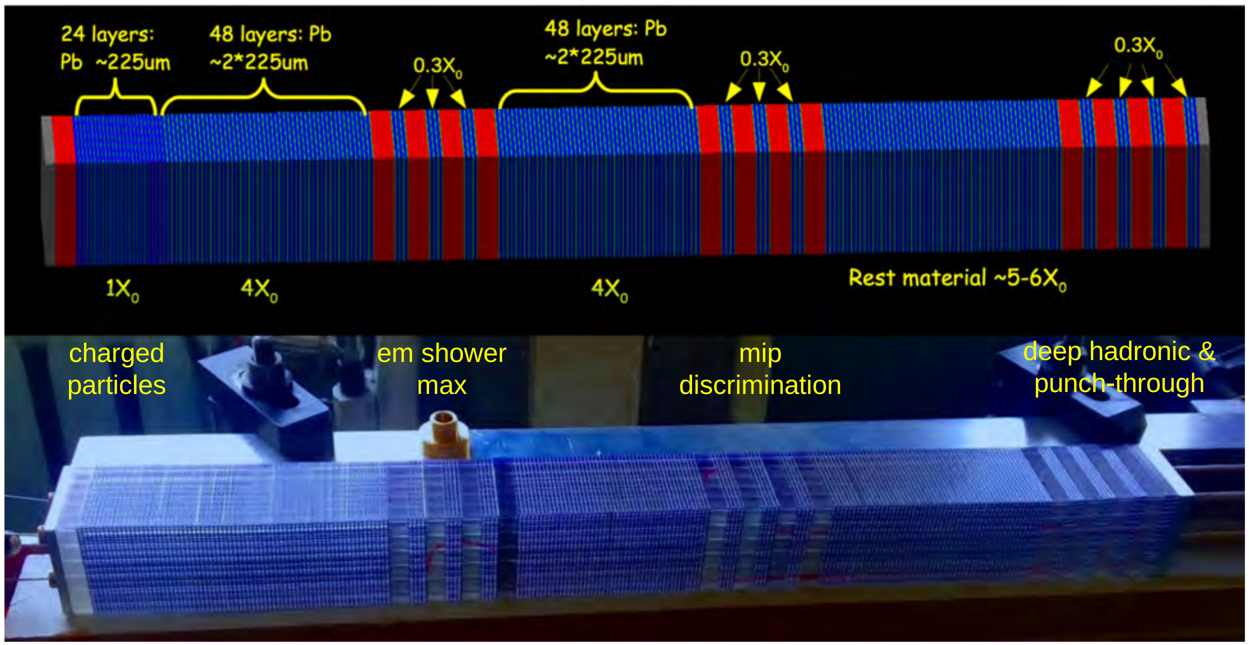
Shashlyk calorimeter with spy tiles

KLEVER

Requirements for main electromagnetic calorimeter (MEC):

Excellent efficiency, time resolution ~ 100ps, good 2-cluster separation

LKr calorimeter from NA62:
Photon detection efficiency probably adequate
Time resolution ~ 500 ps for π^0 with $E_{\gamma\gamma}$ > 20 GeV → requires improvement



Main electromagnetic calorimeter (MEC):

Fine-sampling shashlyk based on PANDA forward EM calorimeter produced at Protvino

0.275 mm Pb + 1.5 mm scintillator

PANDA/KOPIO prototypes:

$\boldsymbol{\sigma_E/\sqrt{E}}$ **~ 3%** $/\sqrt{E}$ (GeV)

$\boldsymbol{\sigma_t}$ **~ 72 ps** $/\sqrt{E}$ (GeV)

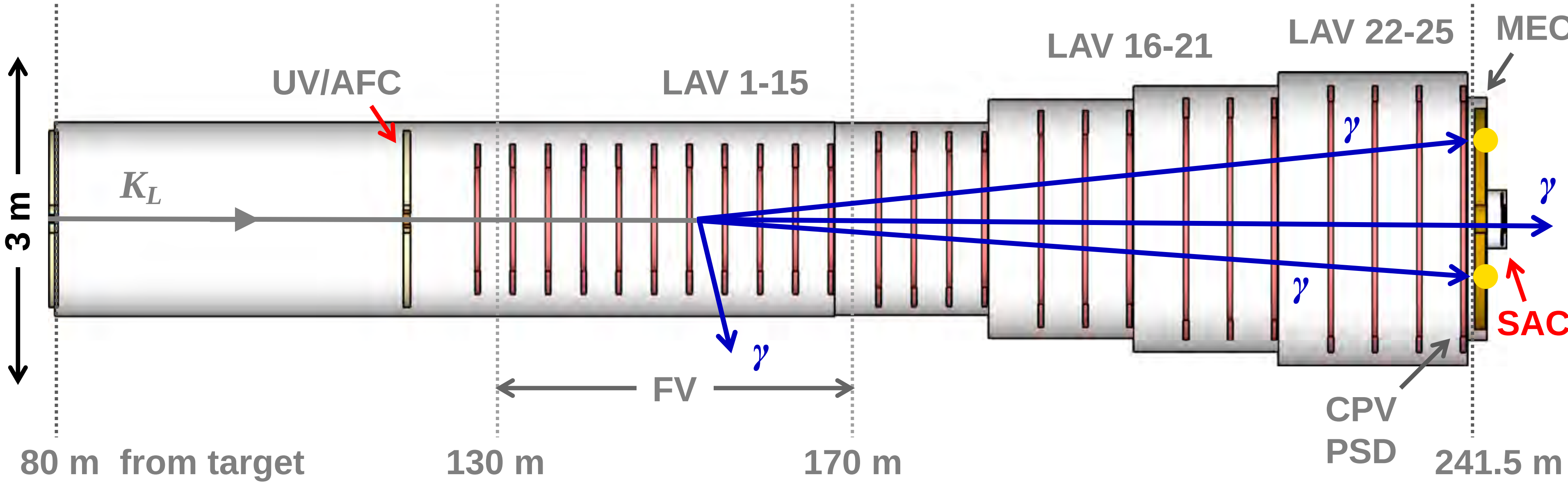
$\boldsymbol{\sigma_x}$ **~ 13 mm** $/\sqrt{E}$ (GeV)

Longitudinal shower information from spy tiles

- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers

Small-angle photon veto

KLEVER



Small-angle photon calorimeter system (SAC)

- Rejects high-energy γs from $K_L \to \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 430 MHz of beam neutrons

Beam comp.	Rate (MHz)	Req. $1 - \varepsilon$
γ, E > 5 GeV	**50**	**10^{-2}**
γ, E > 30 GeV	**2.5**	**10^{-4}**
n	**430**	**–**

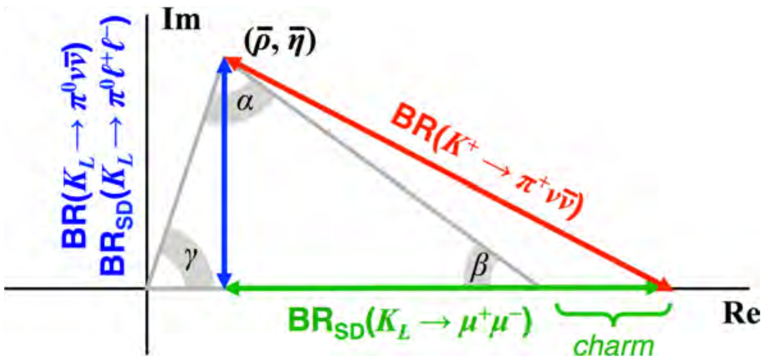
Possible solutions:

- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber to exploit enhancement of photon conversion by coherent interaction with lattice
- Compact Cerenkov calorimeter with oriented crystals

What about $K_L \to \pi^0 \ell^+ \ell^-$?

$K_L \to \pi^0 \ell^+ \ell^-$ vs $K \to \pi \nu \nu$:

- Somewhat larger theoretical uncertainties from long-distance physics
  - SD CPV amplitude: γ/Z exchange
  - LD CPC amplitude from 2γ exchange
  - LD indirect CPV amplitude: $K_L \to K_S$
- $K_L \to \pi^0 \ell^+ \ell^-$ can be used to explore helicity suppression in FCNC decays

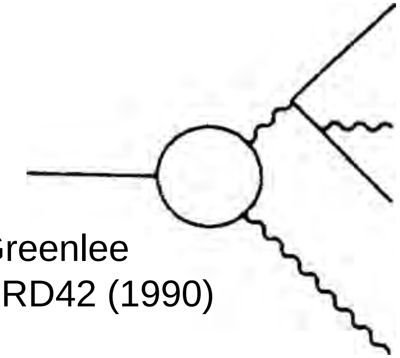


$K_L \to \pi^0 \ell^+ \ell^-$ CPV amplitude constrains UT in same way as BR($K_L \to \pi^0 \nu \nu$)

Experimental status:

BR($K_L \to \pi^0 e^+ e^-$) < 28 × 10^{-11} Phys. Rev. Lett. 93 (2004) 021805

BR($K_L \to \pi^0 \mu^+ \mu^-$) < 38 × 10^{-11} Phys. Rev. Lett. 84 (2000) 5279–5282



Greenlee
PRD42 (1990)

Main background: $K_L \to \ell^+ \ell^- \gamma\gamma$

- Like $K_L \to \ell^+ \ell^- \gamma$ with hard bremsstrahlung

BR($K_L \to e^+ e^- \gamma\gamma$) = (6.0 ± 0.3) × 10^{-7} $E_\gamma^* > 5$ MeV

BR($K_L \to \mu^+ \mu^- \gamma\gamma$) = 10$^{+8}_{-6}$ × 10^{-9} $m_{\gamma\gamma} > 1$ MeV

Integrated program with K^+ and K_L beams

Availability of high-intensity K^+ and K_L beams at the SPS:
Important physics measurements at boundary of NA62 and KLEVER!

Example: Experiment for rare K_L decays with charged particles

- K_L beamline, as in KLEVER
- Tracking and PID for secondary particles, as in NA62

Physics objectives:

- $K_L \rightarrow \pi^0 \ell^+ \ell^-$
  Excellent π^0 mass resolution – look for signal peak over Greenlee background
- Lepton-flavor violation in K_L decays
- Radiative K_L decays and precision measurements
- K_L decays to exotic particles

Will provide valuable information to characterize neutral beam

- Example: Measurement of K_L, n, and Λ fluxes and halo
- Experience from KOTO and studies for KLEVER show this to be critical!

Just getting started!

Summary and outlook

$K \to \pi\nu\nu$ and other rare kaon decays are uniquely sensitive indirect probes for new physics at high mass scales

Need precision measurements of both rare K^+ and K_L decays!

During Run 1 (2016-2018), NA62 observed **20 candidate $K^+ \to \pi^+\nu\nu$** events with **10 expected signal** events and **7 expected background** events

$$\mathrm{BR}(K^+ \to \pi^+\nu\nu) = (10.6\,^{+4.0}_{-3.4\,\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$$

NA62 will improve on current knowledge of BR($K^+ \to \pi^+\nu\nu$) in short term, ultimately reaching O(10%) precision

Next generation rare kaon experiments with high-intensity beams and cutting-edge detectors will provide a powerful tool to search for physics beyond the Standard Model

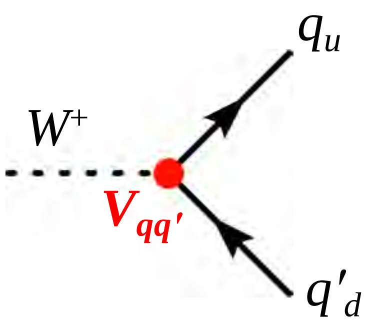
An integrated program of K^+ and K_L experiments is taking shape at CERN

Additional information

Matthew Moulson, INFN Frascati
for the NA62 Collaboration

The CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



V is unitary: $\mathbf{V}^\dagger\mathbf{V} = \mathbf{1}$

$$\sum_i V_{ij}V^*_{ik} = \sum_i V_{ji}V^*_{ki} = \delta_{jk}$$

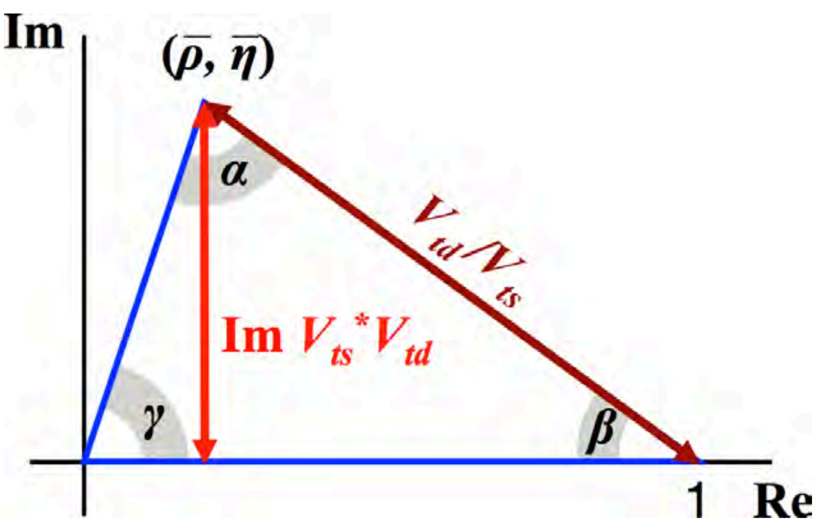
B unitarity triangle

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

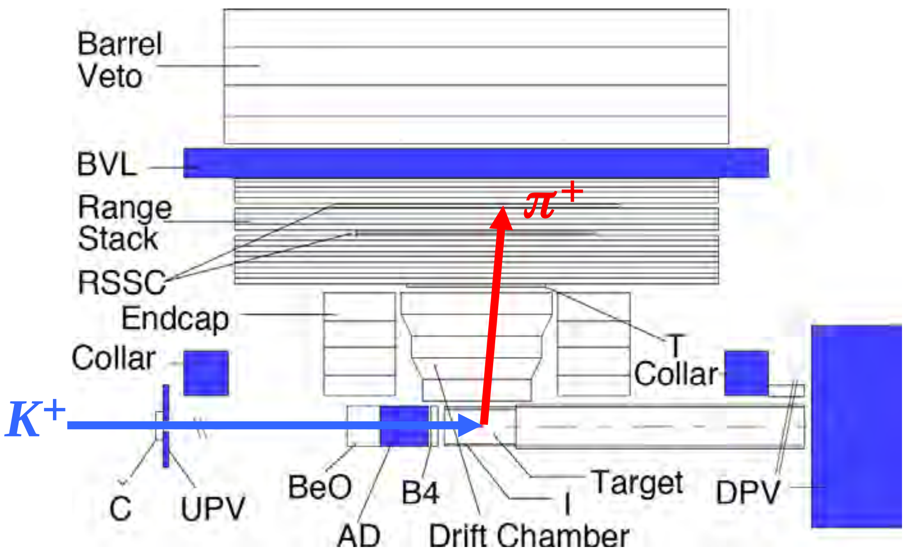
K unitarity triangle

$$V_{ud}V^*_{us} + V_{cd}V^*_{cs} + V_{td}V^*_{ts} = 0$$

Observable	Measurement
$K^+ \to \pi^+\nu\bar{\nu}$	$\lvert V^*_{ts}V_{td}$
$K_L \to \pi^0\nu\bar{\nu}$	$\mathrm{Im}\, V^*_{ts}V_{td} \propto \eta$
$B_d \to J/\psi K_S$	$\sin 2\beta$
$\frac{\Delta m_{B_d}}{\Delta m_{B_s}} = \frac{B_d - \bar{B}_d}{B_s - \bar{B}_s}$	$\lvert V_{td}/V_{ts}$

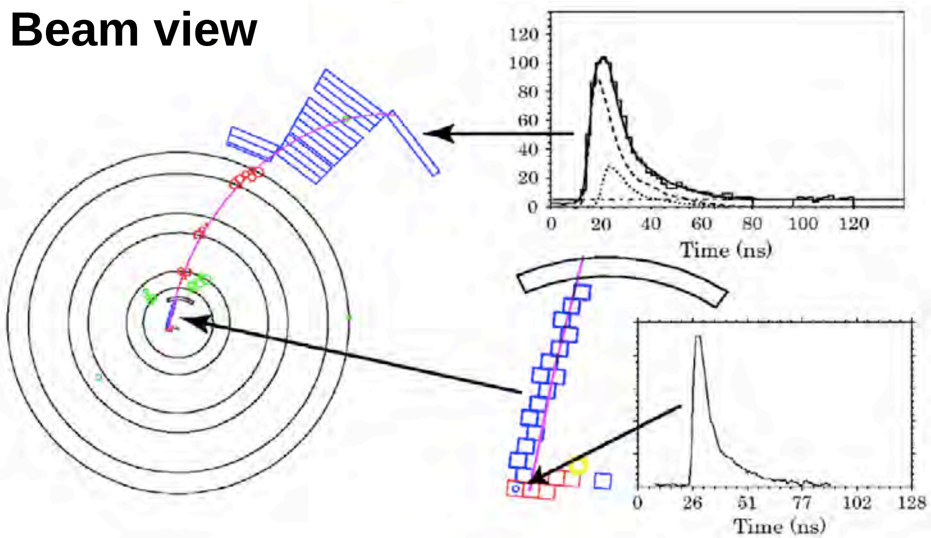


State of the art: BNL 787/949



Side view

Beam view



700 MeV K^+ beam stopped in active **scintillating-fiber target**

Drift chamber (B = 1T) to measure π^+

Range stack:

19 layers of 1.9-cm thick scintillator

- Measures E and R for π^+
- Waveform digitizers record π-μ-e decay chain

4π photon vetoes

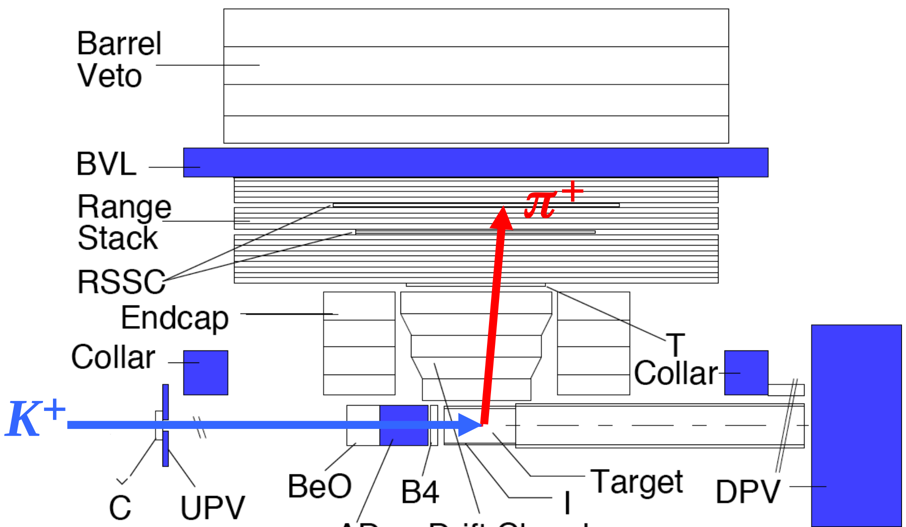
Main 787 running from 1995-1998

Upgraded to 949 in 2001:

Expected 10 events in 60 week run

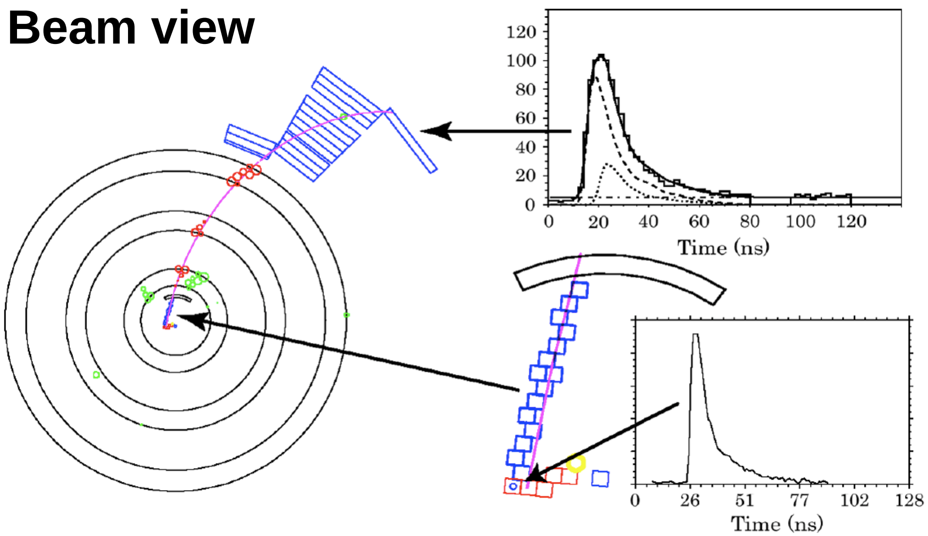
Canceled in 2002 after 12 weeks!

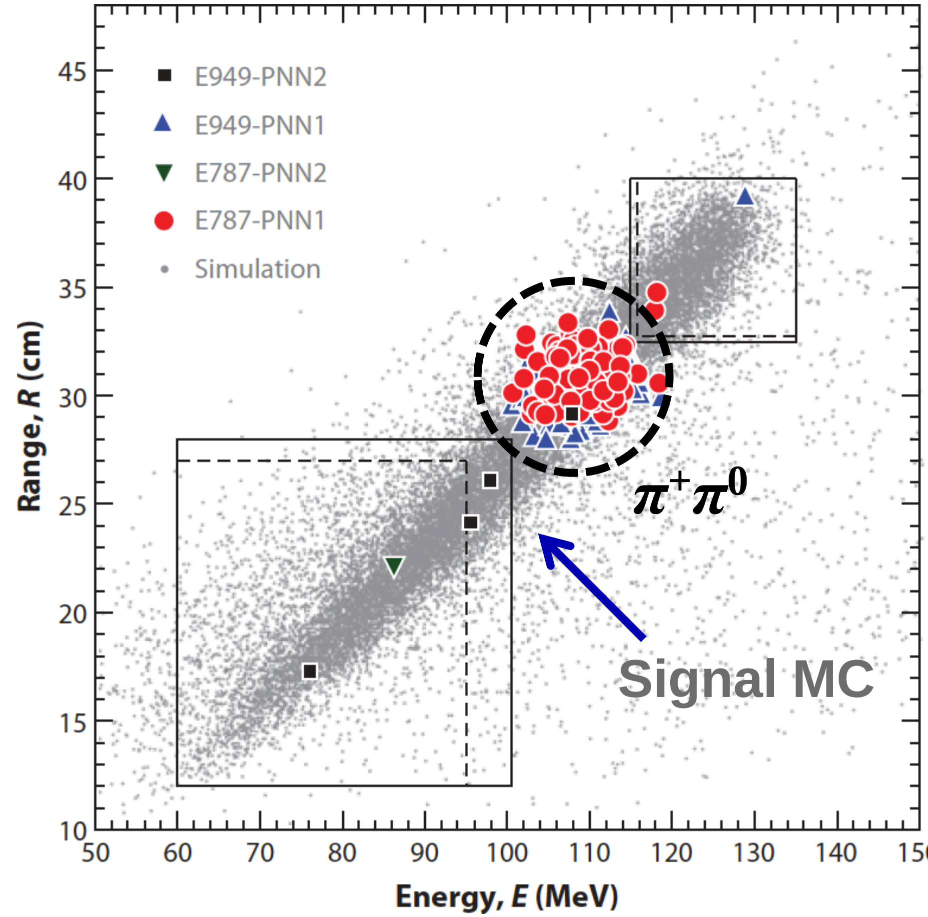
State of the art: BNL 787/949



Side view

Beam view



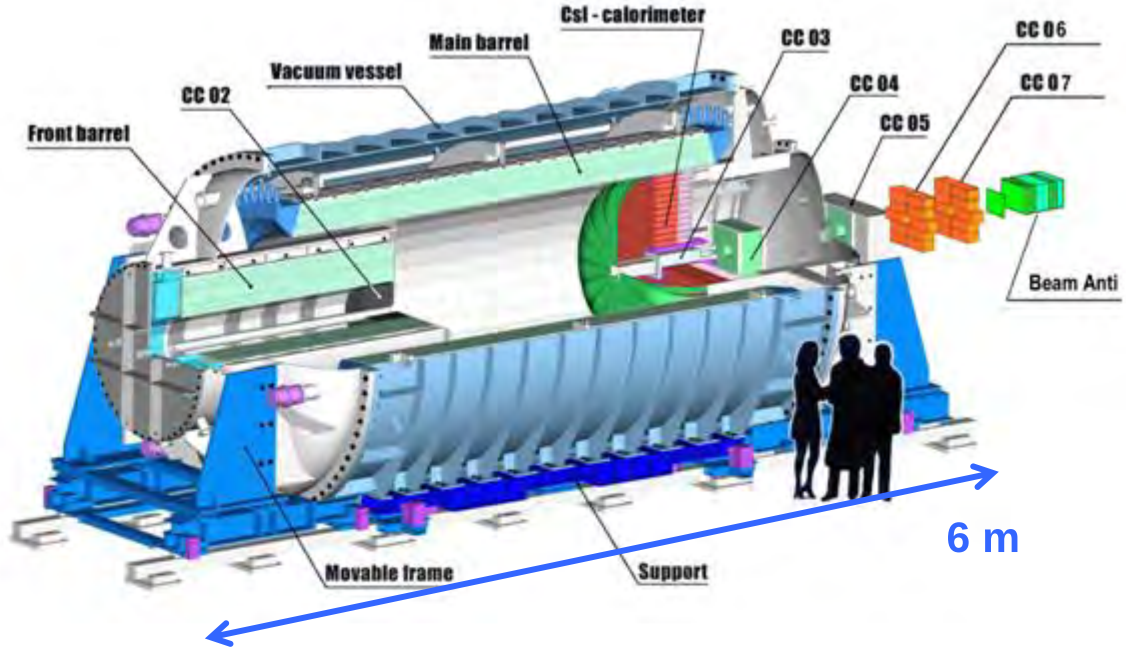


7 candidate $K^+ \rightarrow \pi^+\nu\nu$ events

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

$2\times$ BR$_{SM}$ but entirely consistent

$K_L \to \pi^0 \nu\bar{\nu}$ at J-PARC



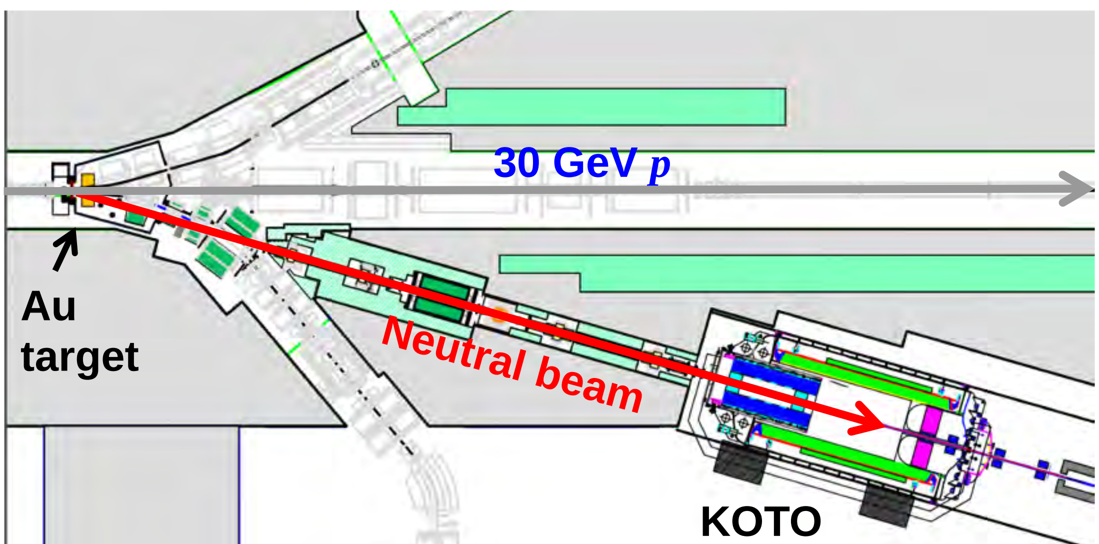
Primary beam: 30 GeV *p*

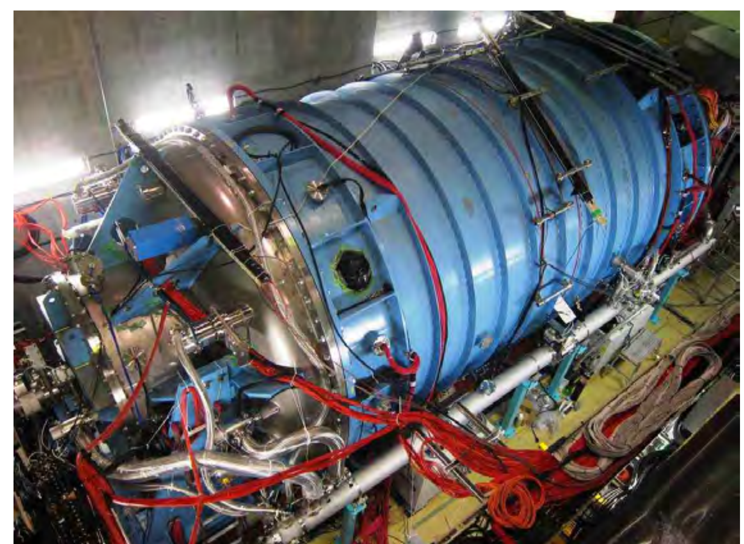
50 kW=5.5 × 10^{13} p/5.2 s (2019)

Neutral beam (16°)

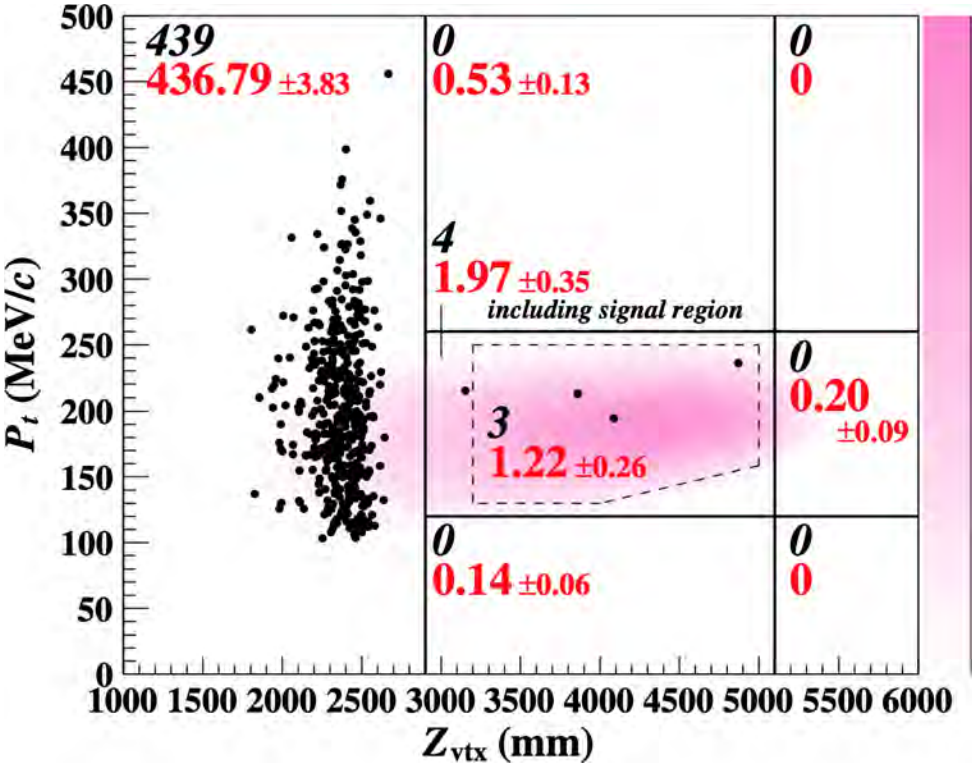
$\langle p(K_L)\rangle$ = 2.1 GeV

- 50% of K_L have 0.7-2.4 GeV
- 8 μsr "pencil" beam





Final result: 2016-2018 data



Expected backgrounds

Source	Expected (68%CL)
$K_L \to \pi^0\pi^0\pi^0$	0.01 ± 0.01
$K_L \to \gamma\gamma$ halo	**0.26 ± 0.07**
Other K_L decays	0.005 ± 0.005
$K^\pm_{e3} + K^\pm_{\mu3} + K^\pm_{\pi2}$	**0.87 ± 0.25**
n interaction in CsI	0.017 ± 0.002
η from n in CV	0.03 ± 0.01
π^0 from upstream int.	0.03 ± 0.03
Total	**1.22 ± 0.26**

* Newly evaluated source since KAON 2019

BR($K_L \to \pi^0\nu\nu$) < 4.9 × 10^{-9} (90%CL)

30.5 × 10^{19} pot

SES = (7.20 ± 0.05_{stat} ± 0.66_{syst}) × 10^{-10}

0.04 signal + 1.22 background events expected

3 events in signal box

K_L flux from $K_L \to 2\pi^0$ = 6.8 × 10^{12}

$\pi^0\nu\nu$ acceptance from MC:

Decay in FV: 3.3%

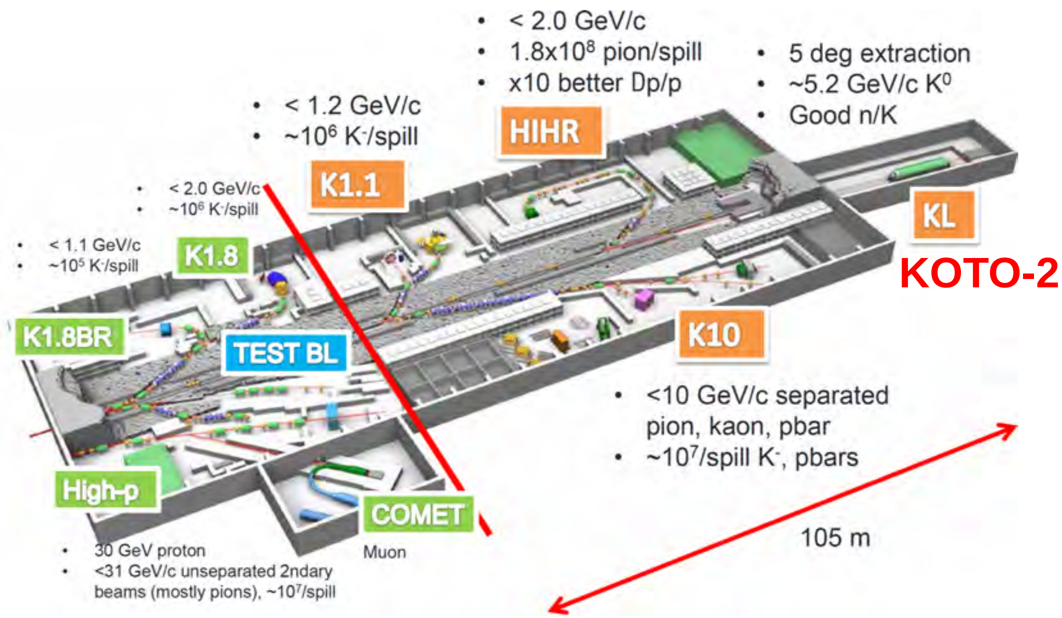
Overall acceptance: 0.6%

PRL 126 (2021) 121801

KOTO long-term plans: Step-2

- **Plan outlined in 2006 proposal to upgrade to O(100) SM event sensitivity over the long term**
- **Now beginning design work for a new experiment to achieve this sensitivity**

- Increase beam power to > 100 kW
- New neutral beamline at 5°
  $\langle p(K_L) \rangle$ = 5.2 GeV
- Increase FV from 2 m to 12 m
  Complete rebuild of detector
- **Requires hadron-hall extension**

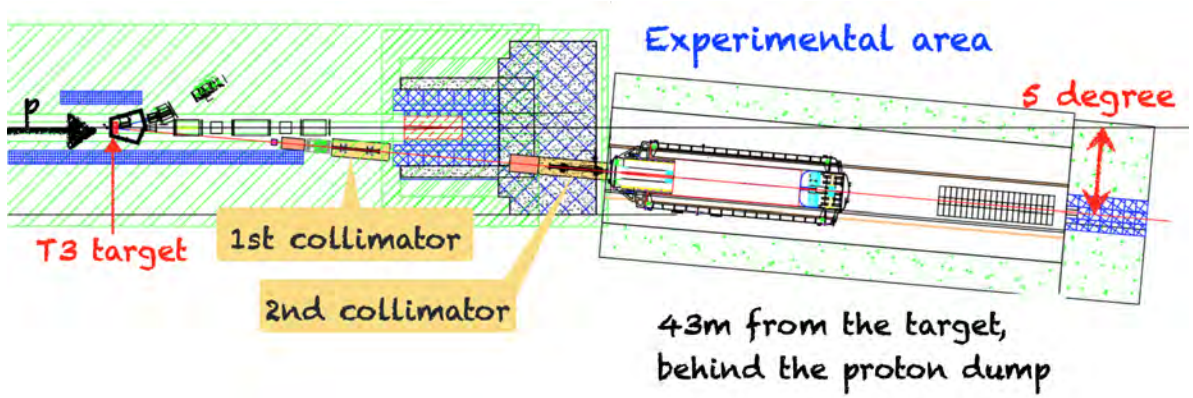


- Hadron-hall extension is a joint project with nuclear physics community
  KOTO Step-2 is a flagship project
- Described in KEK Road Map 2021 for research strategy 2022-2027
- Focused review conducted in Aug 2021, with KOTO providing Step-2 input

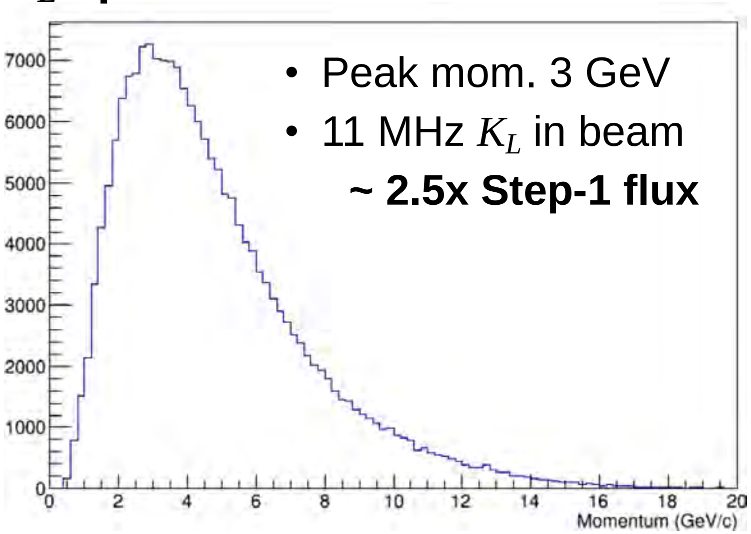
KOTO Step-2 detector

Step-2 beamline setup in hadron-hall extension

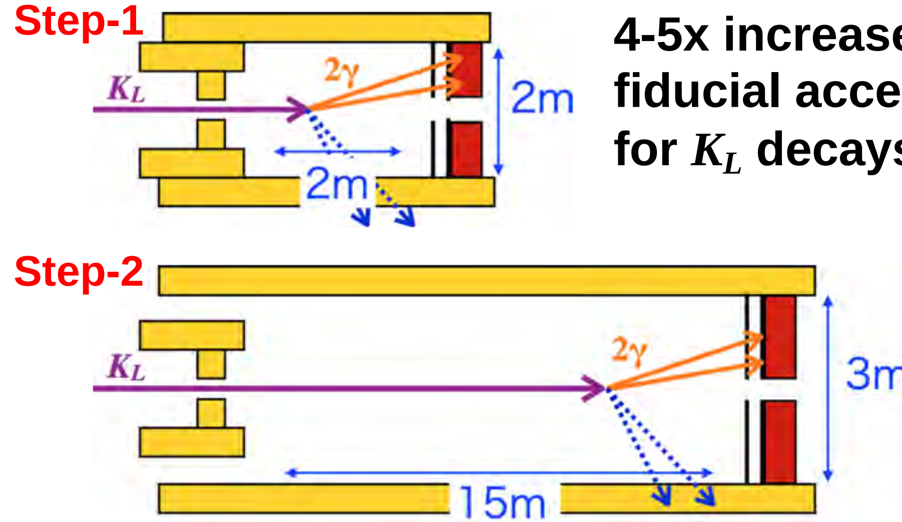
- Smaller angle (16˚ → 5 ˚)
- Longer beamline (20 → 43 m)
- 2 collimators



K_L spectrum at beam exit



- Peak mom. 3 GeV
- 11 MHz K_L in beam
  ~ 2.5x Step-1 flux



4-5x increased fiducial acceptance for K_L decays

New sensitivity studies for smaller beam angle & larger detector:
~ 60 SM evts with S/B ~ 1 at 100 kW beam power (3×10^7 s)

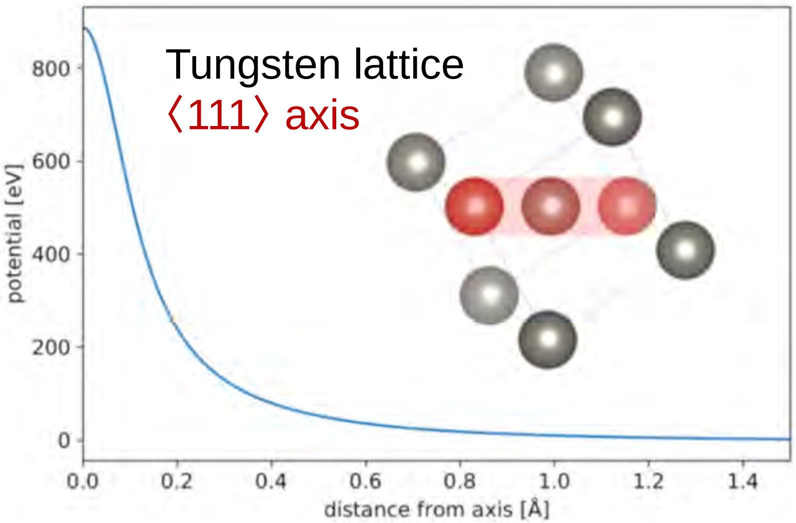
Coherent effects in crystals

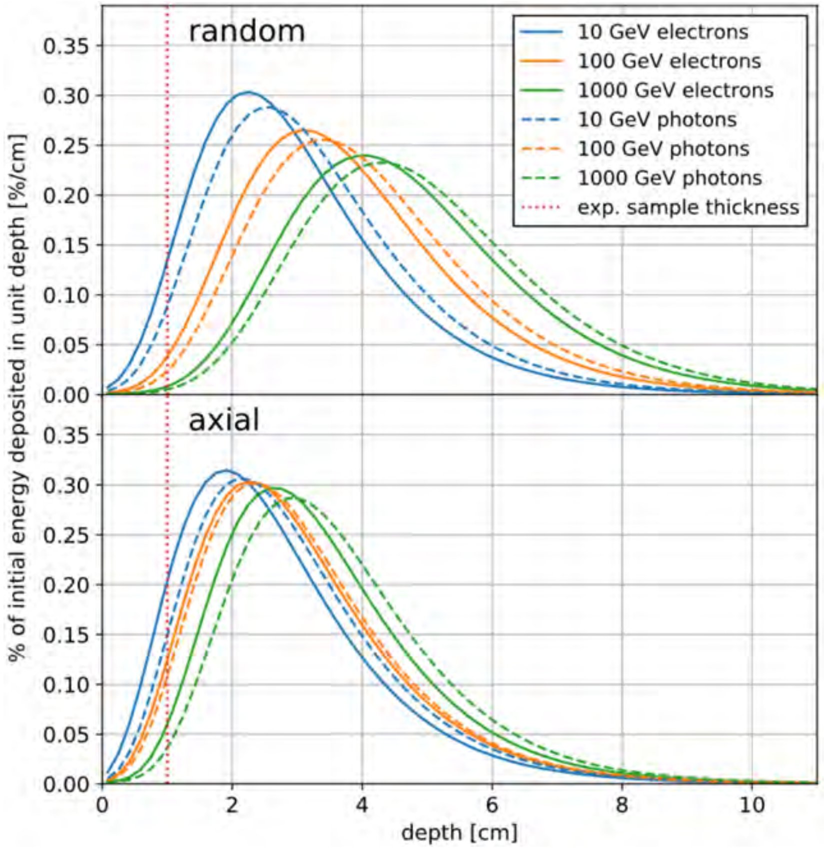
30 mm tungsten ($9X_0$) beam photon absorber

- reduces γ flux in beam 1000x:
- scatters ~35% of K_L in beam

Can it be made thinner?

Exploit coherent effects in crystals!





Coherent superposition of Coulomb fields

Electric field ε approx. const. ~ 10^{10}-10^{12} V/cm

Effective field $\varepsilon' = \gamma_{\text{eff}}$ ($\gamma_{\text{eff}} = E/m_e c$)

For $\varepsilon' \sim \varepsilon_0 = 2\pi m^2 c^3/eh$ virtual pairs disassociate

- Early initiation of EM showers
- Minimize fluctuations of deposited energy vs depth

Pair production enhanced by coherent effects at small θ_γ and high E_γ