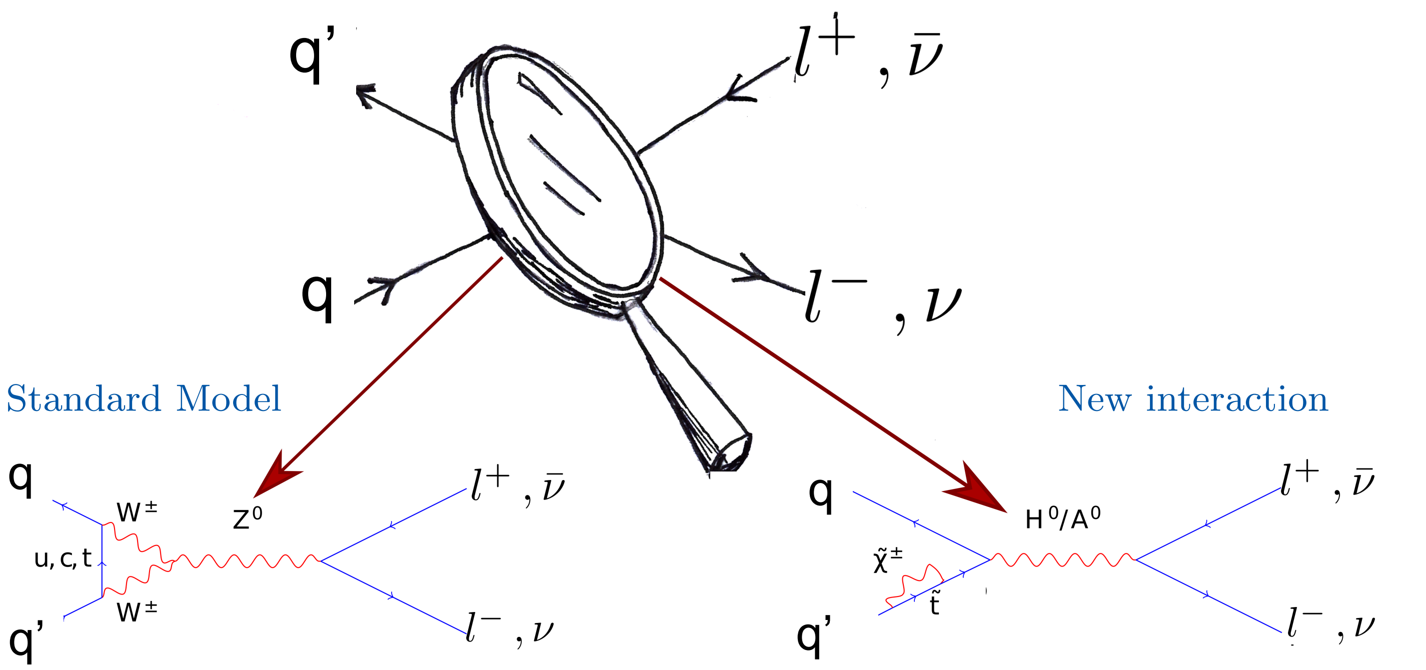
Kaon physics:
Hot topics and future prospects

Prof Cristina Lazzeroni
University of Birmingham
NA62 Spokesperson

Seeking new physics through Flavour



Loops are sensitive to the presence of new physics
Rare processes: new interactions can give major contribution
New interactions can have different symmetries than the SM

Over-constraining new interactions and couplings in the entire quark sector – strange, charm, beauty - is crucial to understand their origin

Seeking new physics through Flavour

Two strategies:

1) Search for deviations with respect to SM predictions

$$\mathcal{O}_{\rm exp} = \mathcal{O}_{\rm SM}\,(1+\delta_{\rm NP})$$

Both exp. and th. must be precise for an effective investigation

Look for observables:

- (highly) sensitive to contributions of beyond-the-SM physics
- ideally mildly sensitive to hadronic corrections
- accessible experimentally

LFU B-anomalies and specific FCNC processes are examples

2) Search for processes forbidden by (accidental) symmetries of the SM

Very clean probes of new physics

LFV and LNV are examples

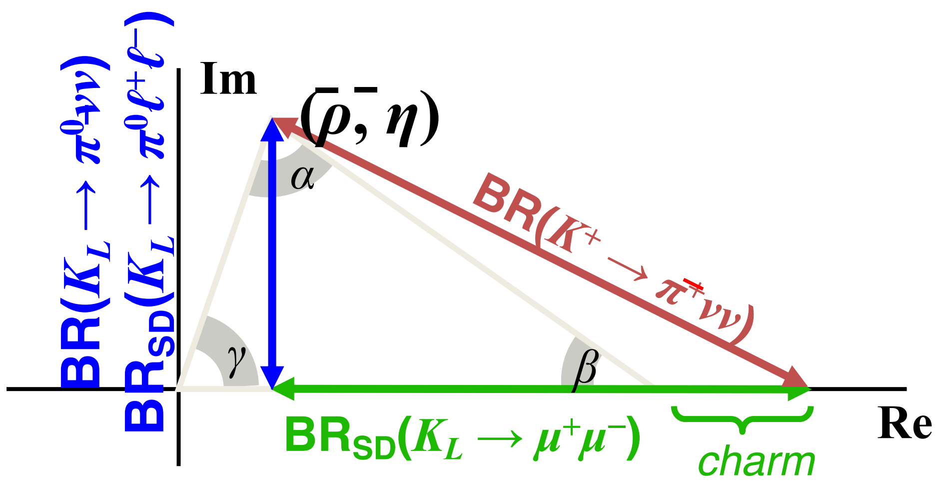
This talk, Kaon physics

Rare Kaon Decays

FCNC dominated by short-distance amplitudes

Decay	Γ_{SD}/Γ	Theory err. (on SD)	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†
$K^+ \to \pi^+ \nu\nu$	90%	4%	8.4 ± 1.0	10.6±5.4
$K_L \to \pi^0 \nu\nu$	>99%	2%	3.4 ± 0.6	< 300†

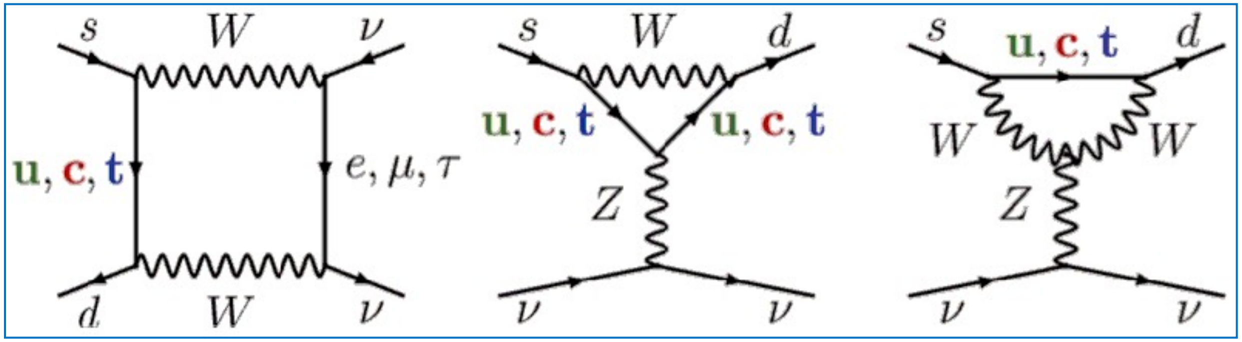
Rates related to CKM matrix elements with minimal non-parametric uncertainty

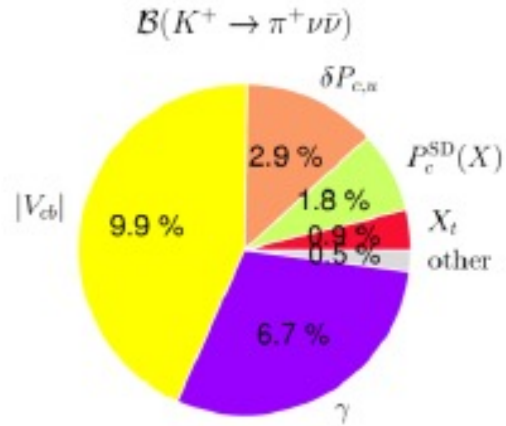


Measuring all charged and neutral rare K decay modes can give clear insight about the new physics flavour structure

The golden channel

SM: box and penguin diagrams





Theoretical error budget
Buras. et. al., JHEP11(2015)033

Ultra-rare decays with
the highest CKM suppression:

$$A \sim (m_t/m_W)^2 |V^*_{ts}V_{td}| \sim \lambda^5$$

Hadronic matrix element related
to a measured quantity $(K^+ \to \pi^0 e^+ \nu)$.

Exceptional SM precision.
Free from hadronic uncertainties.

SM branching ratios
Buras et al., JHEP 1511 (2015) 033

Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\nu(\gamma)$	8.4 ± 1.0
$K_L \to \pi^0 \nu\nu$	3.00 ± 0.31

Unreducible theory error: O(5-3%)

Theoretically clean, almost unexplored.
Sensitive to new physics, and to high-mass scale O(100) TeV

The unitary 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

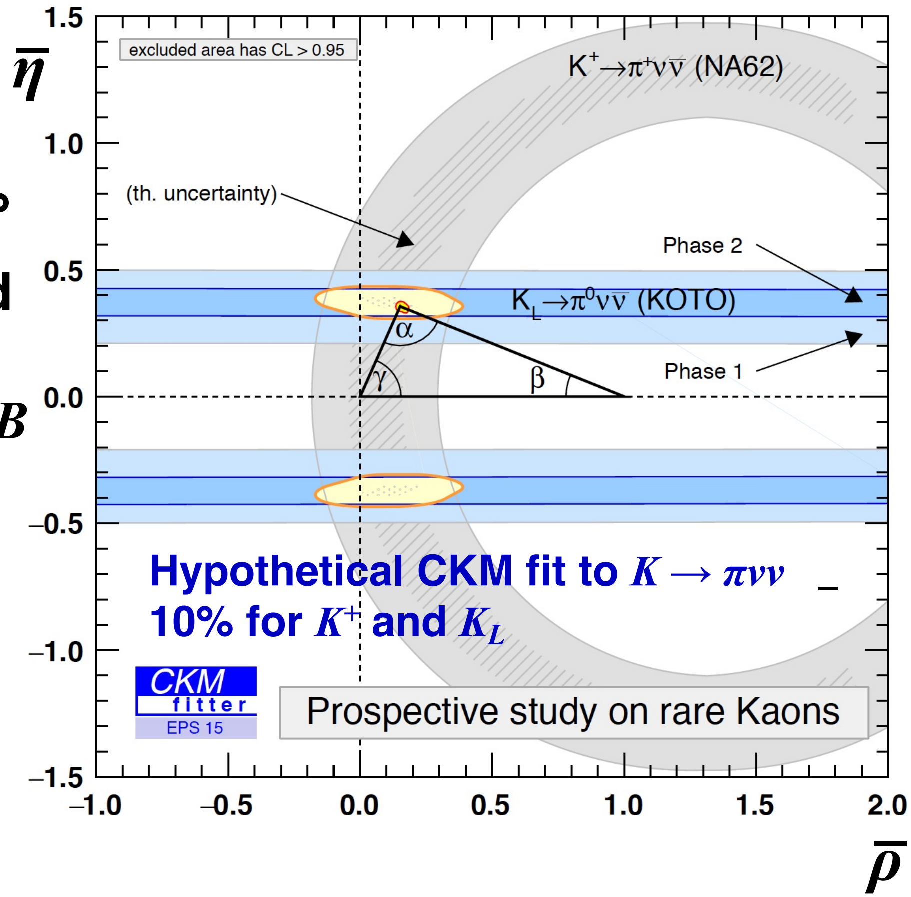
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

Dominant uncertainties for SM BRs are from CKM matrix elements

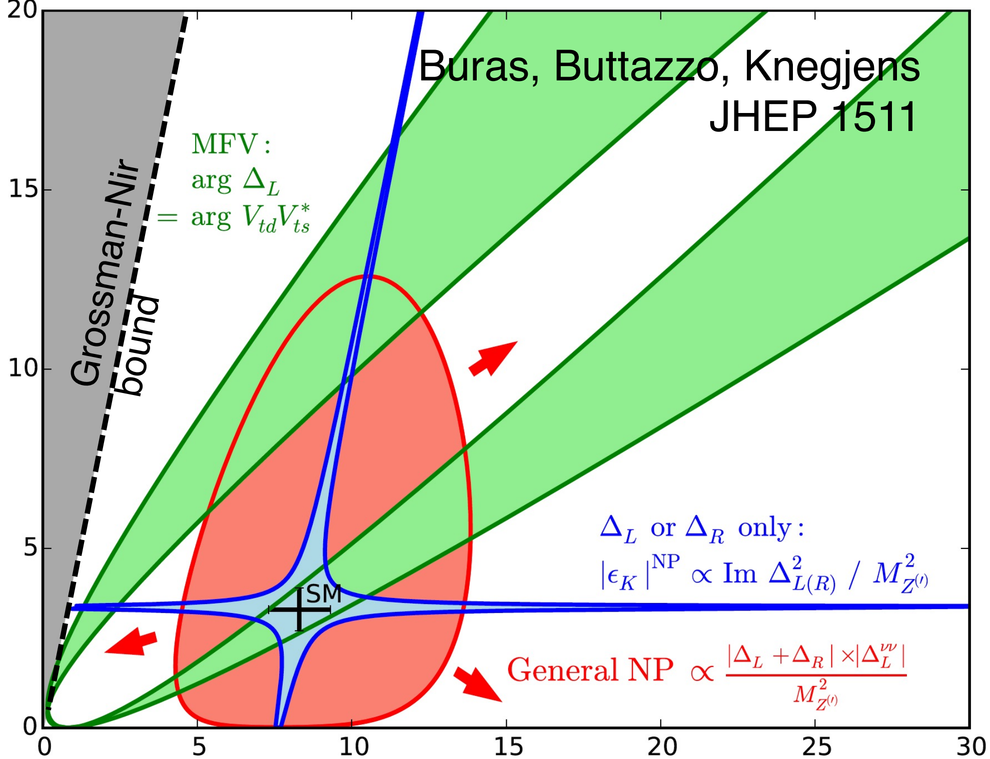
Intrinsic theory uncertainties 1.5-3.5%

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:

- **Sensitivity to O(100) TeV scale**
- Sensitivity complementary to B decays
- To constrain NP, correlations are crucial



$K^+ \to \pi^+ \nu\nu$ and new physics



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

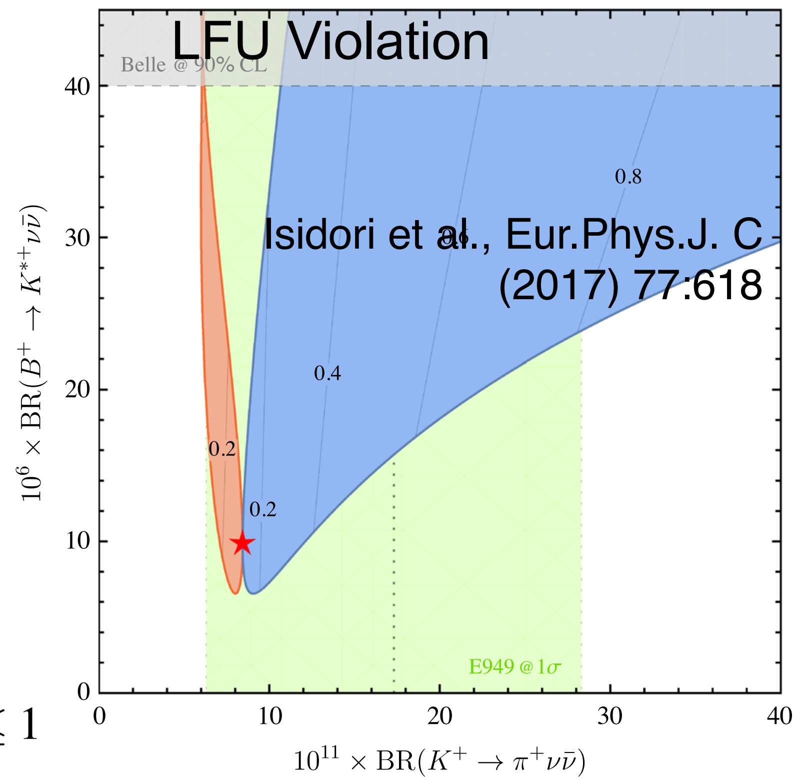
Models without above constraints

Randall-Sundrum

High sensitivity to NP (non-MFV): significant variations wrt SM

New physics affects K^+ and K_L BRs differently

Specific models for effects of NP on $K \to \pi\nu\nu$ BRs are constrained by other kaon measurements, esp. Re ε'/ε, ΔM_K



Grossman-Nir bound

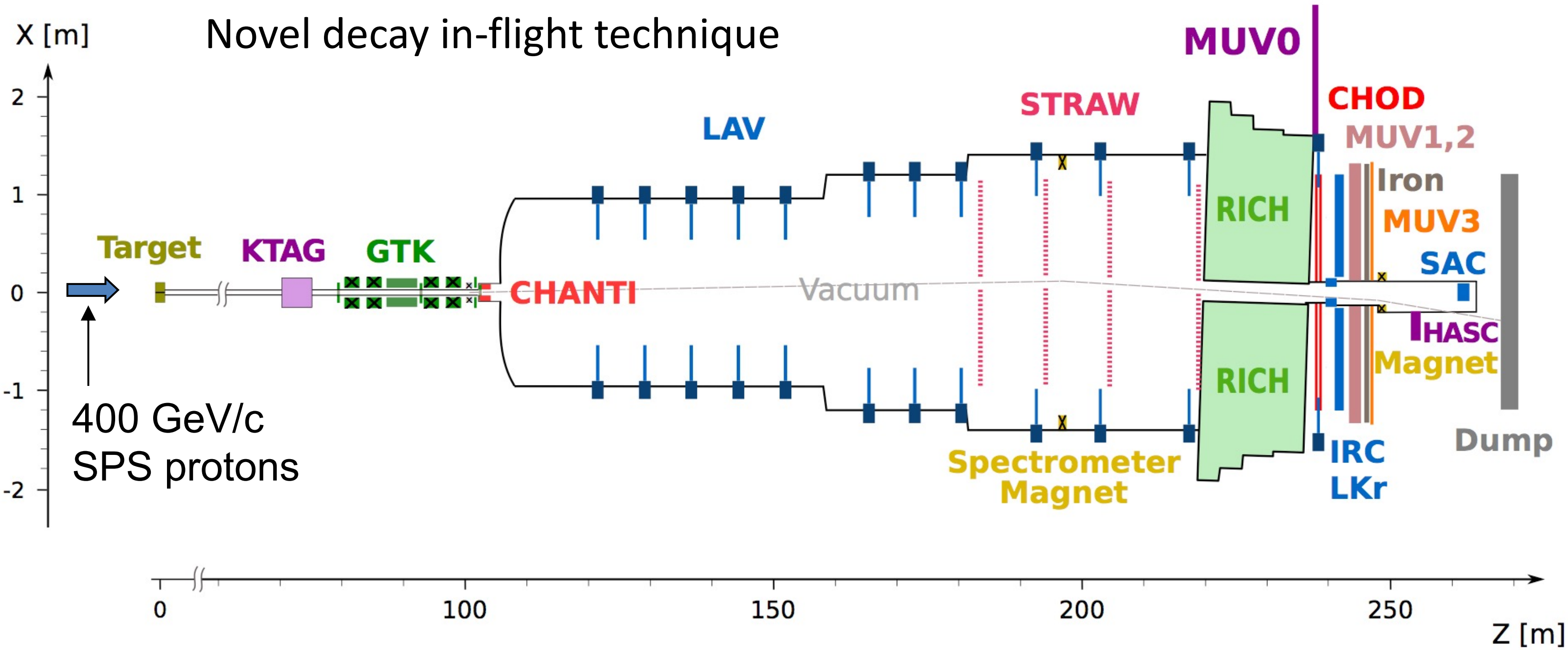
Model-independent relation

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

$K \to \pi\nu\nu$ status and immediate prospects

NA62 beam and detector

Novel decay in-flight technique



SPS Beam:

400 GeV/c protons

2.10^{12} protons/spill

5s spill [3s eff.] / ~16 s

Decay Region:

60 m long fiducial region

~ 5 MHz K^+ decay rate

Vacuum ~ $O(10^{-6})$ mbar

Secondary positive Beam:

75 GeV/c momentum, 1 % bite

100 μrad divergence (RMS)

60x30 mm^2 transverse size

$K^+(6\%)/\pi^+(70\%)/p(24\%)$

For 33×10^{11} ppp on T10

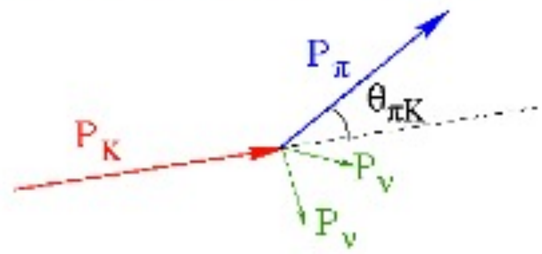
→ 750 MHz at GTK3

Detector and Performances:
JINST 12 (2017) P05025

Data taking periods so far

Decay in flight technique @NA62

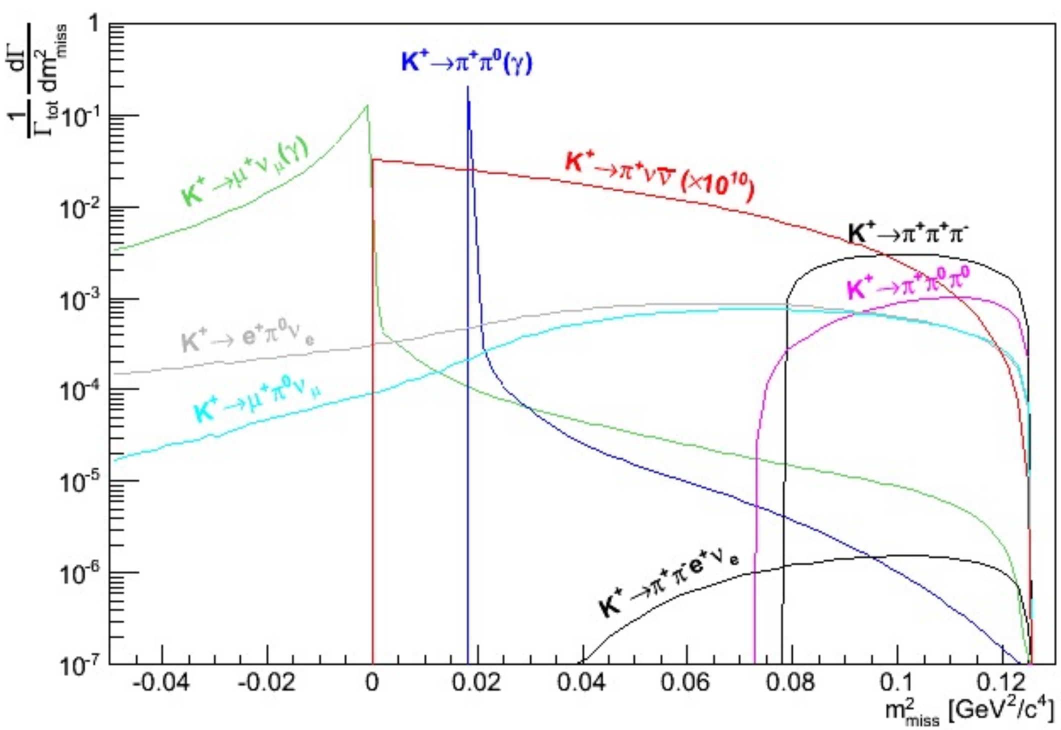
$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$



15 < $P(\pi^+) < P_{max}$ GeV/c
to ensure several tens of GeV
of missing energy

+ Particle ID (calorimeters + Cherenkov + muonID)

Photon veto



Background rejection:

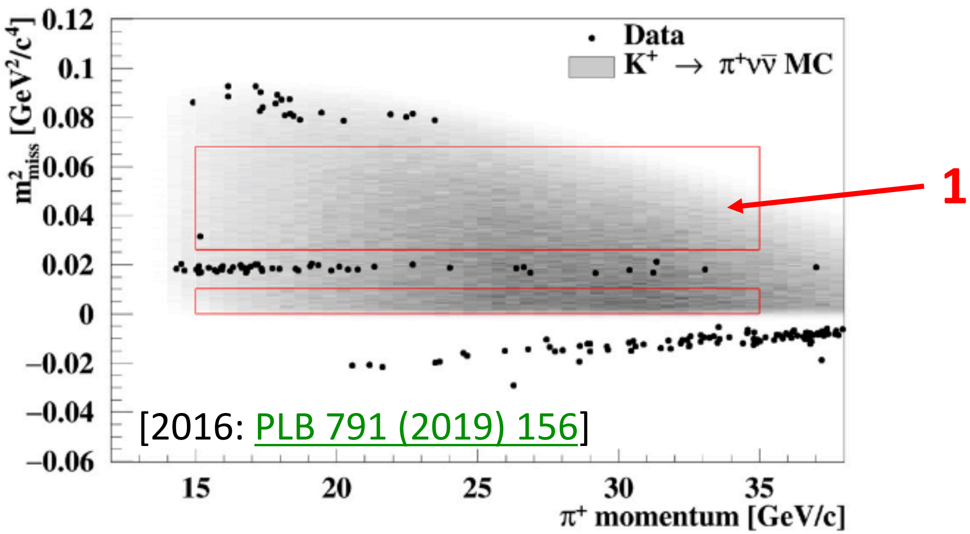
O(100 ps) timing between sub-detectors

O(10^4) background suppression from kinematic conditions

>10^7 muon suppression

>10^7 π^0 suppression (from $K^+ \to \pi^+\pi^0$)

2016 + 2017 data



[2016: PLB 791 (2019) 156]

2016 + 2017 data

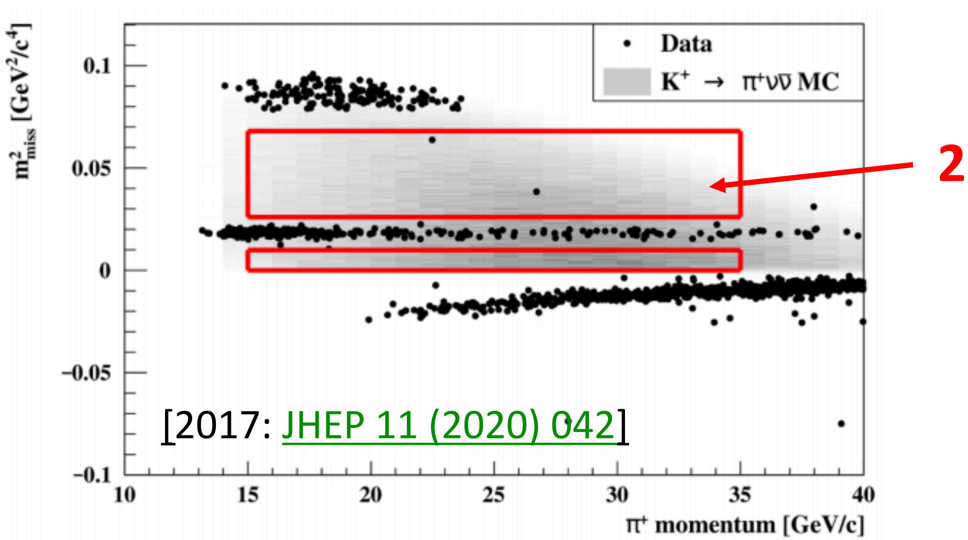
BR($K^+ \to \pi^+ \nu\nu$)

$< 1.78 \times 10^{-10}$ (90%CL)

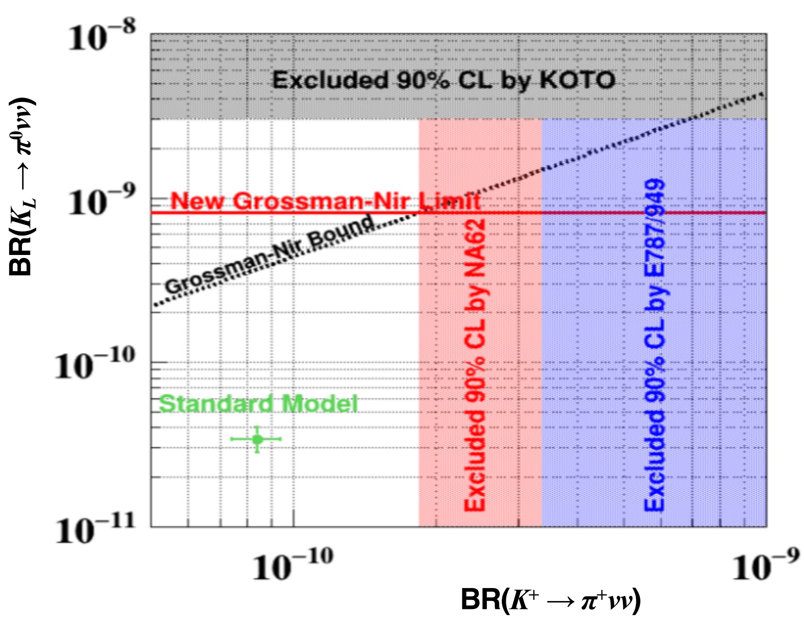
$= 0.48^{+0.72}_{-0.48} \times 10^{-10}$ (68% CL)

Grossman-Nir limit on BR($K_L \to \pi^0 \nu\nu$):

$< 7.8 \times 10^{-10}$ (90%CL)

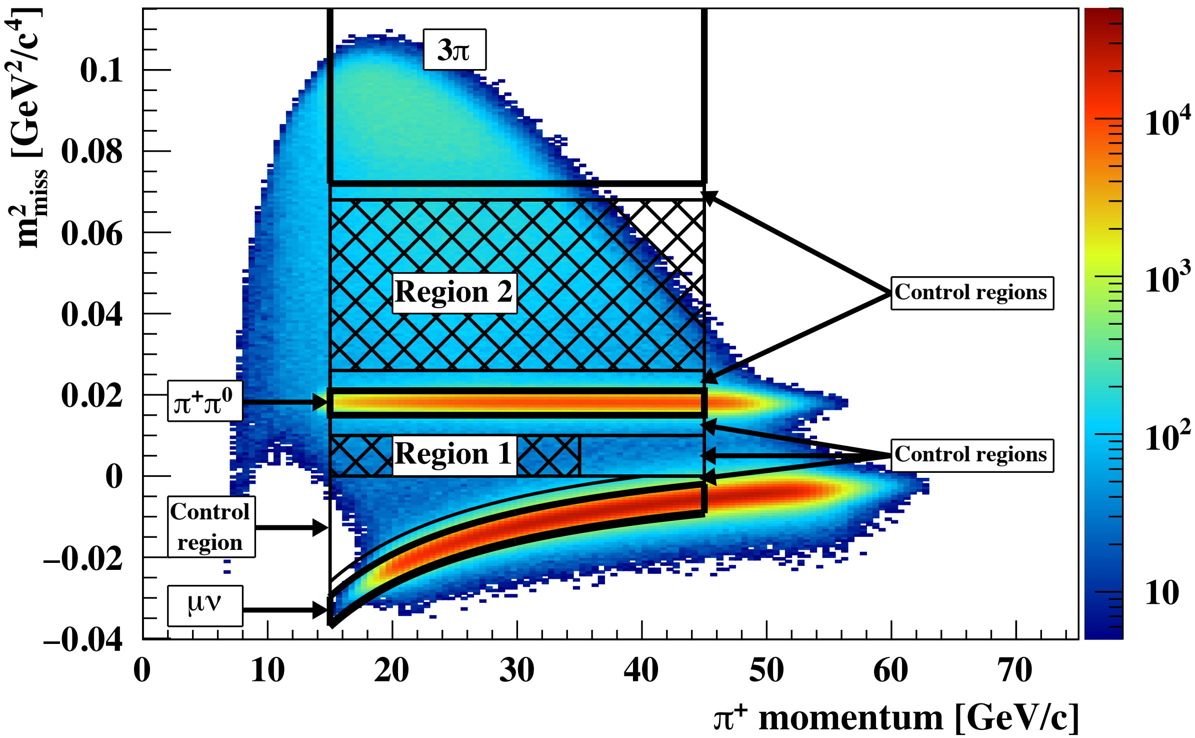


[2017: JHEP 11 (2020) 042]



Signal selection

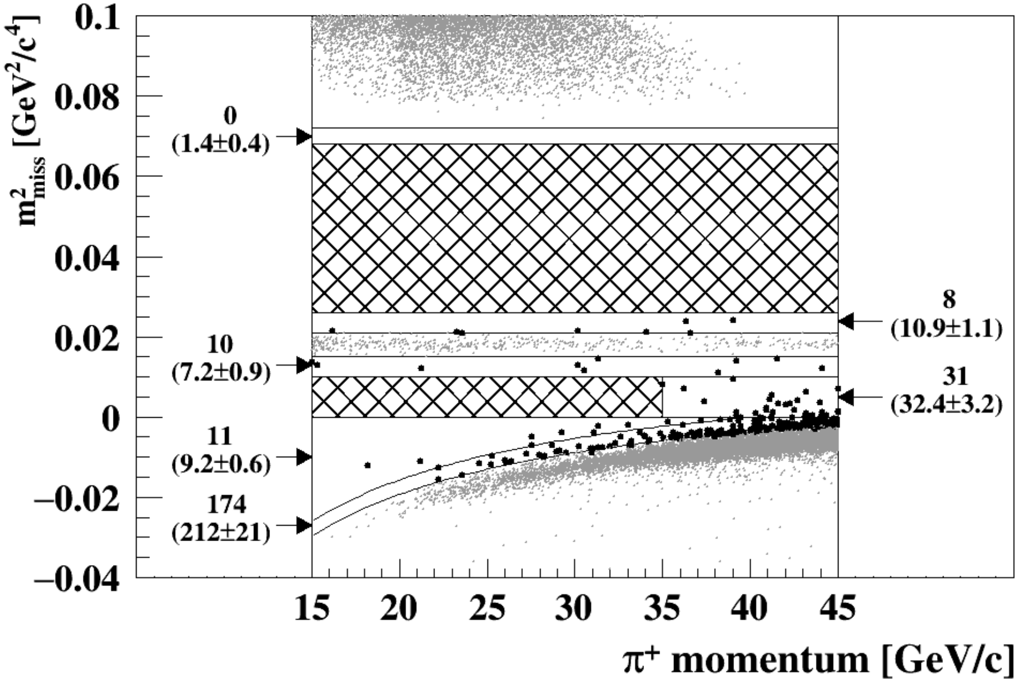
2018 data divided into two subsets, S1 (before, 20%) and S2 (after, 80%) installation of the new final collimator.
S2 divided into six categories corresponding to 5 GeV/c bins of pion momentum in 15–45 GeV/c range.
S1 is separate category integrated over mom due to its small size.
Dedicated selection applied to each category improves signal sensitivity



Control regions are used to validate the background estimates

Improvements led to sizable increase in signal acceptance, while keeping same level of S/B ratio

Background evaluation



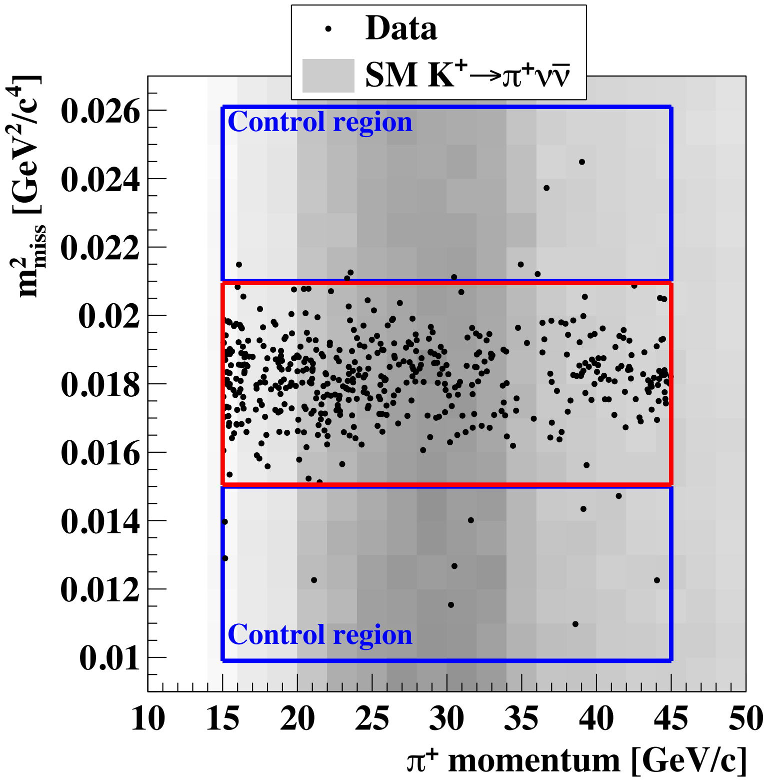
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

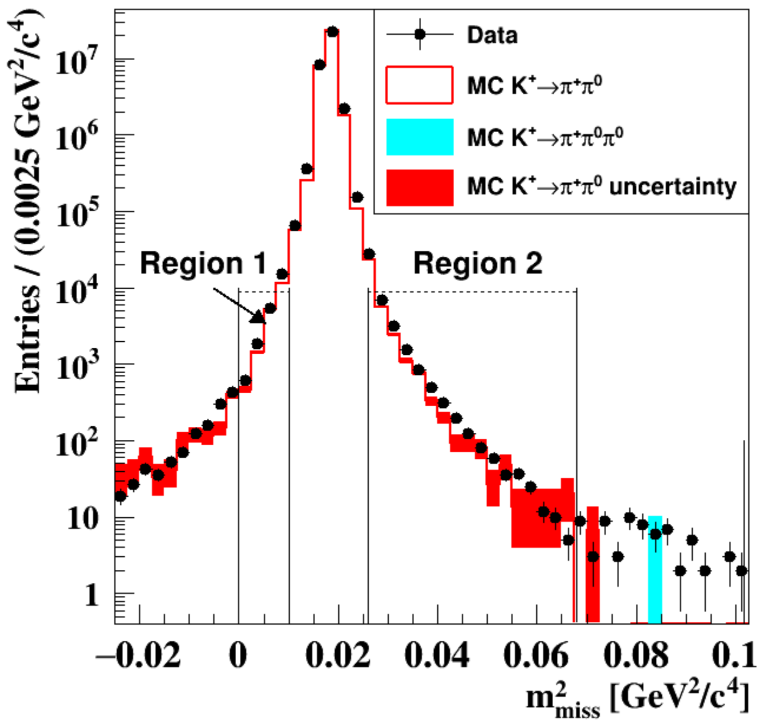
Background from Kaon decays and upstream events evaluated using data and control samples

Good agreement in control regions between expected and observed background events

Background evaluation, e.g $\pi^+\pi^0$

Control data used to study tails of distribution



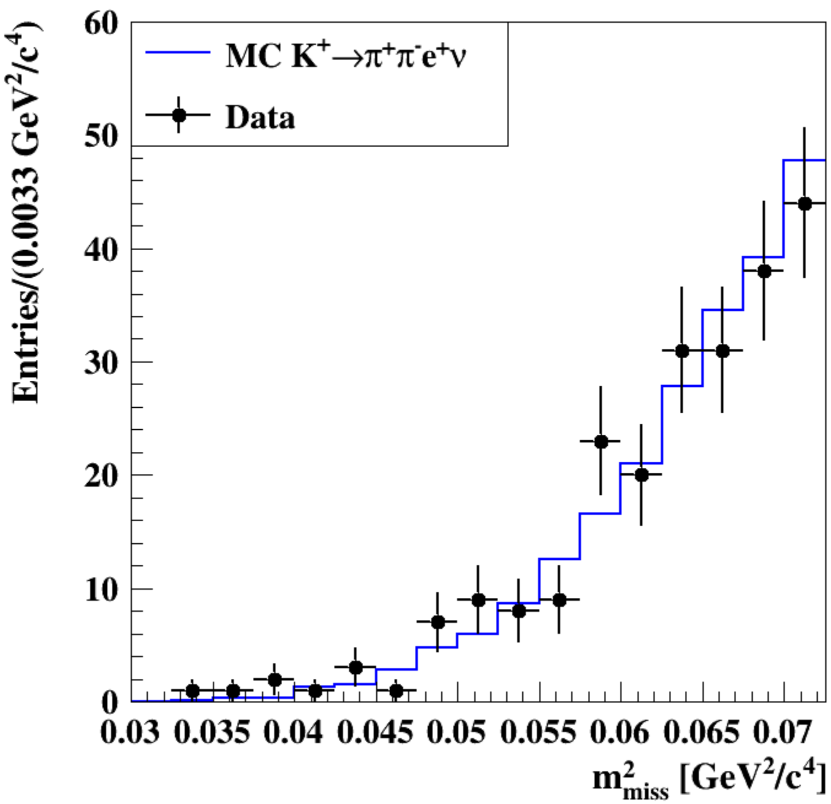


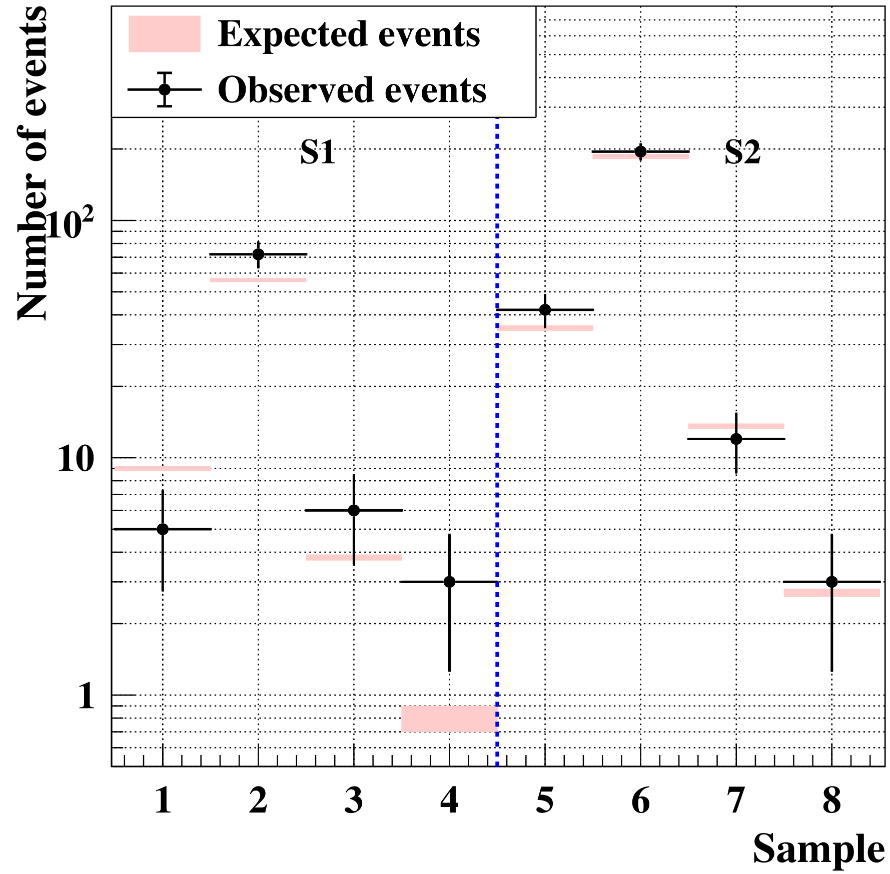
$$N_{\rm decay}^{\rm exp} = N_{\rm bkg} \cdot f_{\rm kin}(\rm region)$$

Data driven background evaluation for all kaon decays (except $\pi\,\pi\,e\,\nu$)

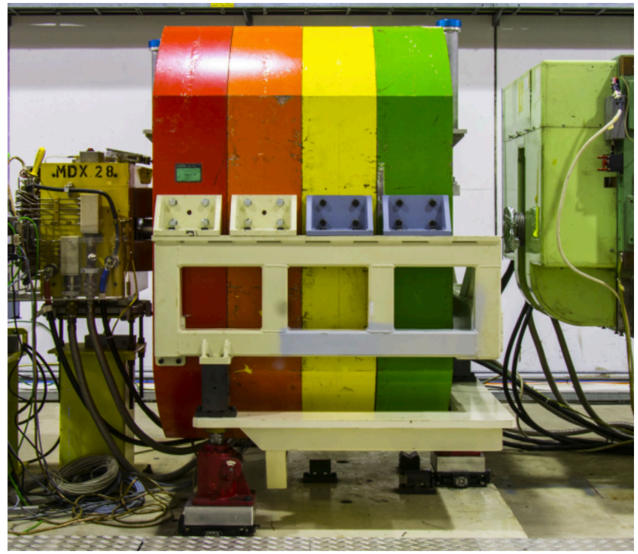
Background evaluation

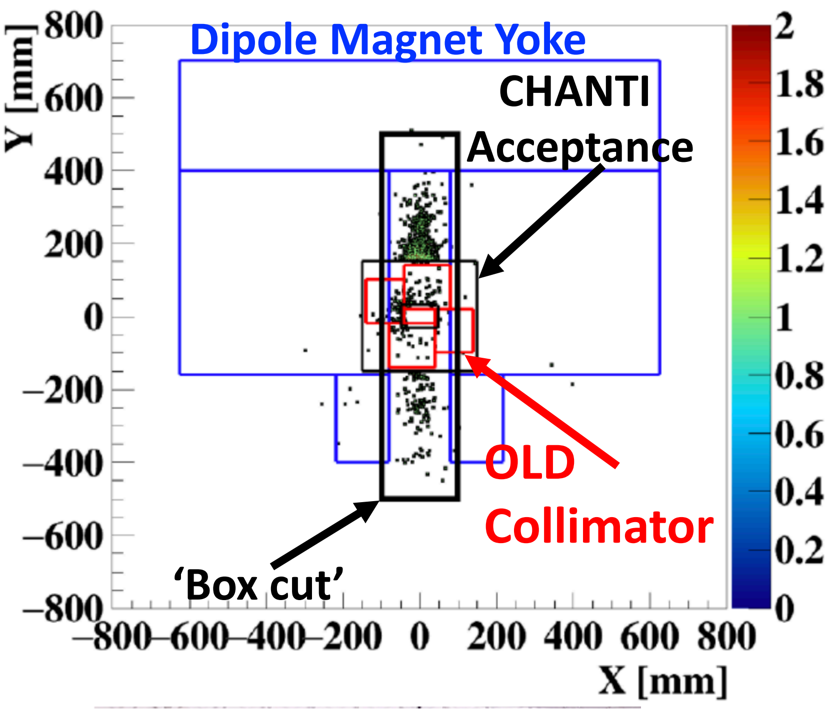
For $\pi\pi e\nu$, validate using samples obtained inverting at least one selection criteria)

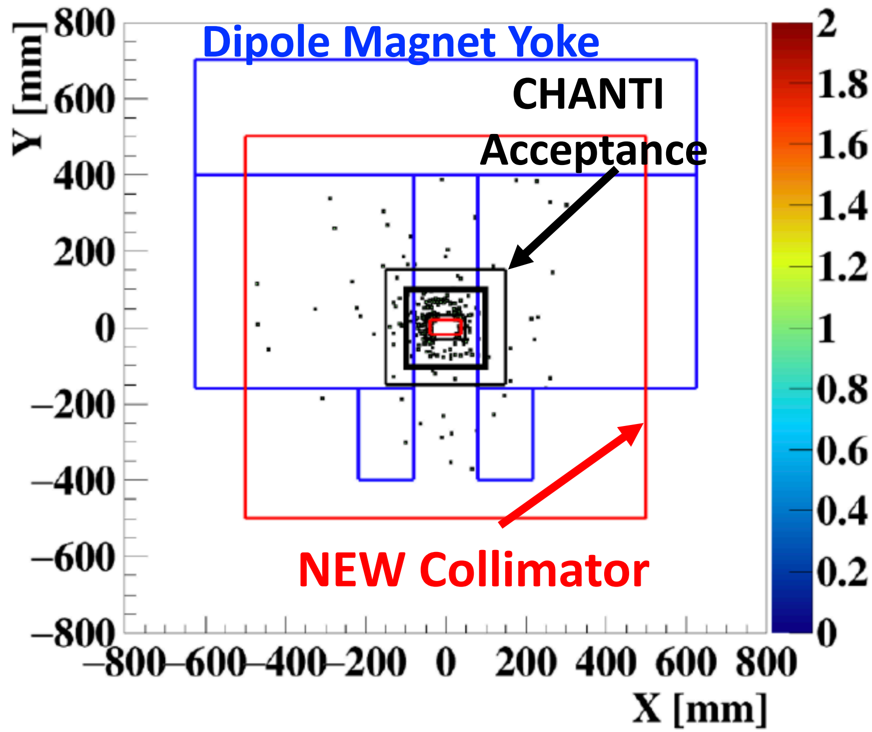




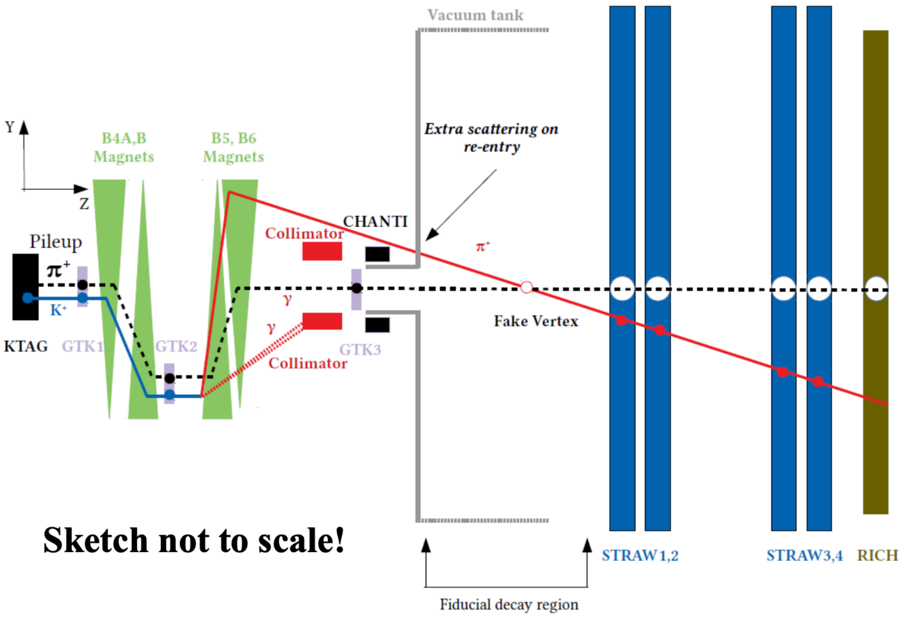
Change in Final Collimator





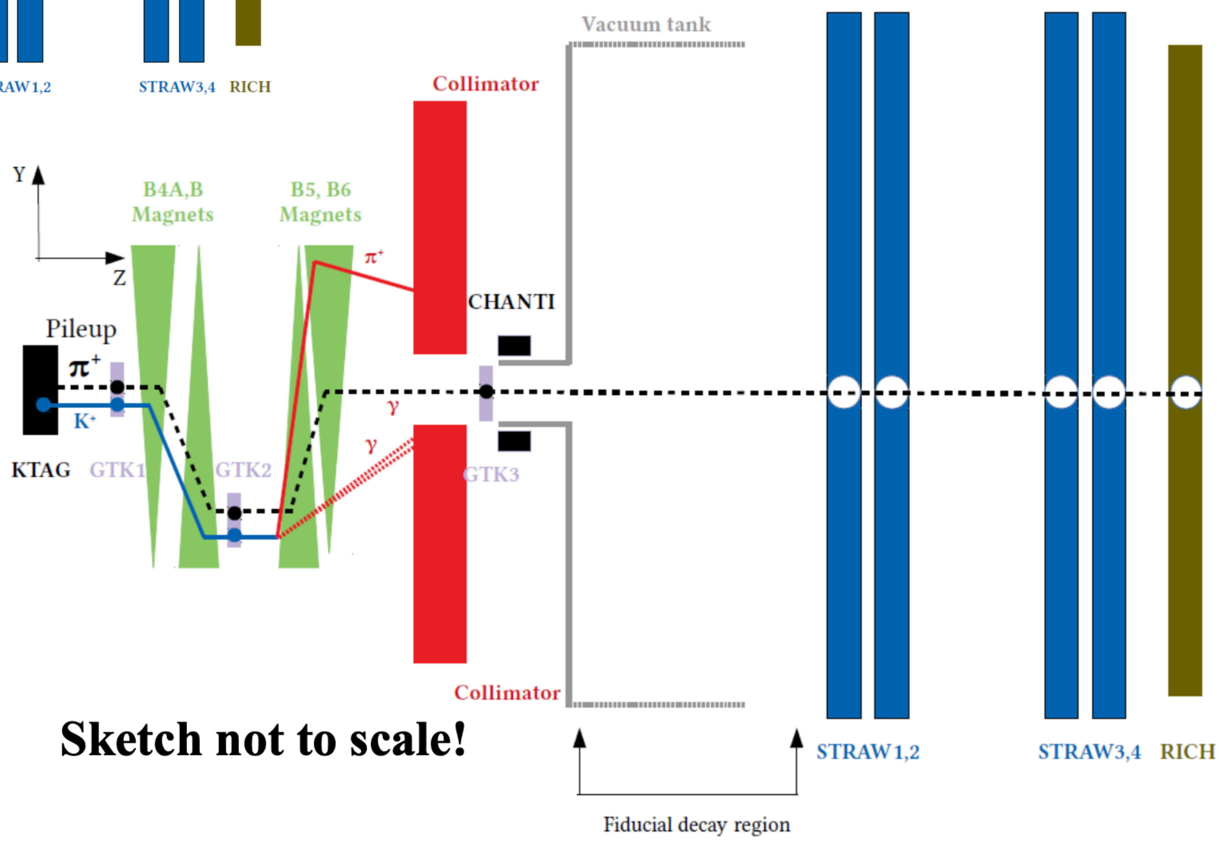


Final Collimator



OLD

Sketch not to scale!



NEW

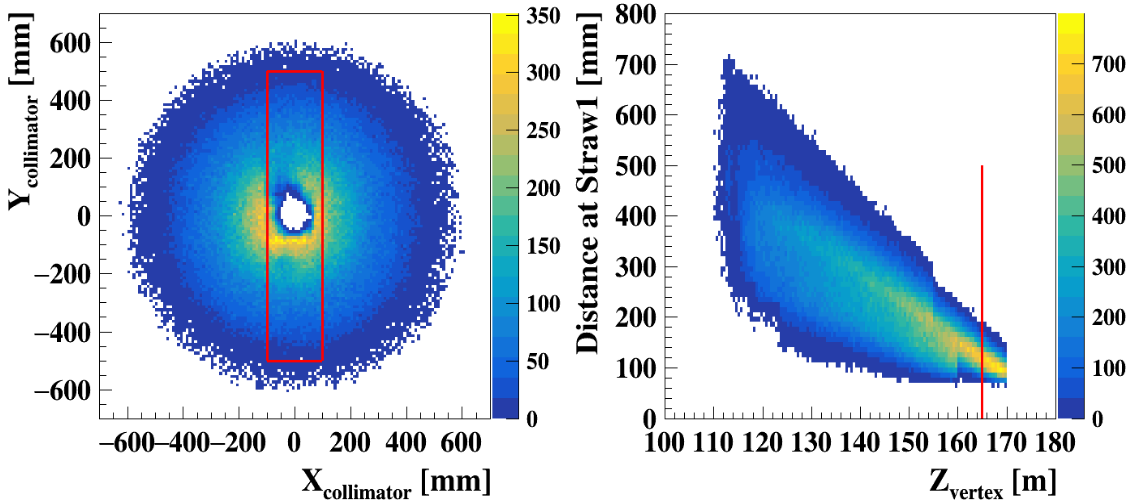
Sketch not to scale!

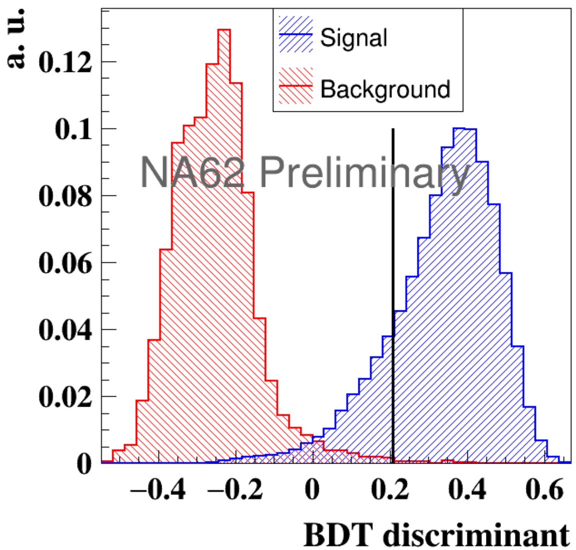
Upstream events rejection

BDT approach possible only after installation of new collimator in 2018
K-pion matching conditions + geometrical variables
Signal training sample: MC simulation
Background training sample: out-of-time data

Both samples normalized to 1

MC $K^+ \to \pi^+ \nu \bar{\nu}$ after cut on BDT discriminant





$\epsilon(sig) \sim 83\%$ @ $\epsilon(bkg) \sim 0.5\%$

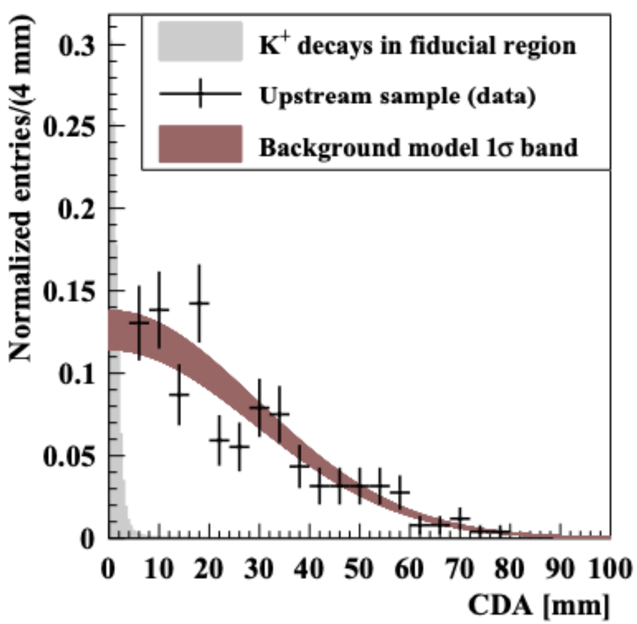
Upstream events rejection

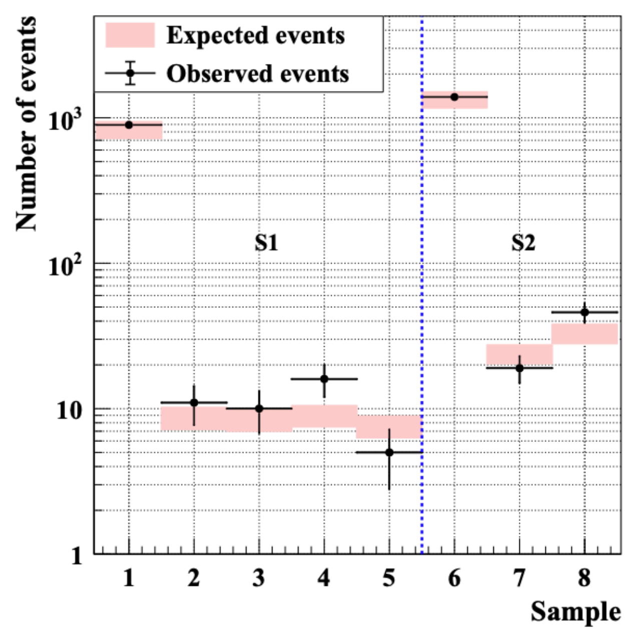
Early decays in upstream region, interaction with material plus beam pileup and scattering in STRAW1

BDT use possible only after installation of new collimator in 2018
K-pion matching conditions + geometrical variables
Signal training sample: MC simulation
Background training sample: out-of-time data

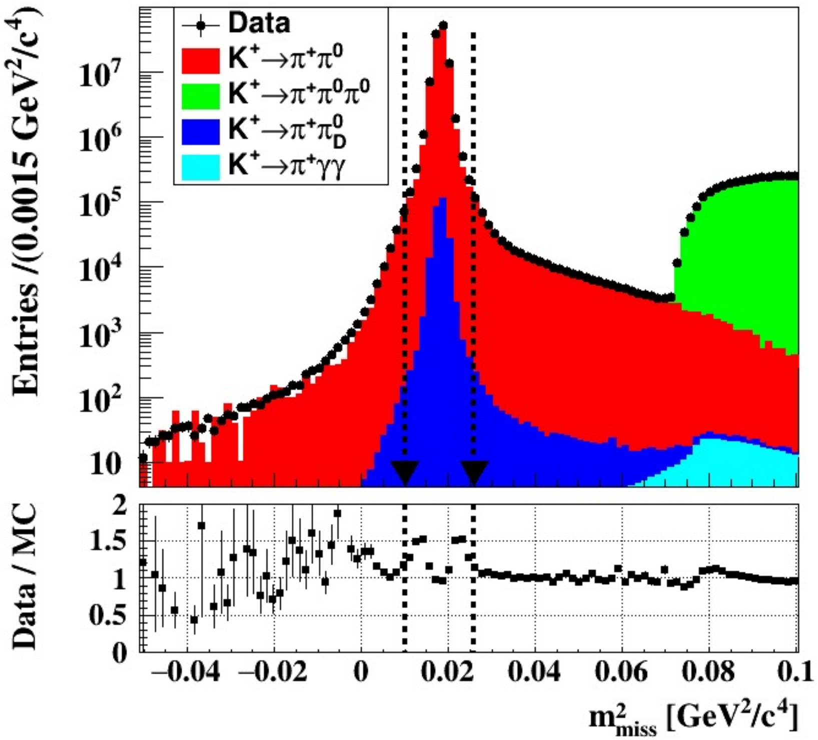
Increase signal acceptance keeping same B/S

Data driven procedure: control sample without time and K-pi matching requirements
Validated using inverted data samples enriched with upstream events



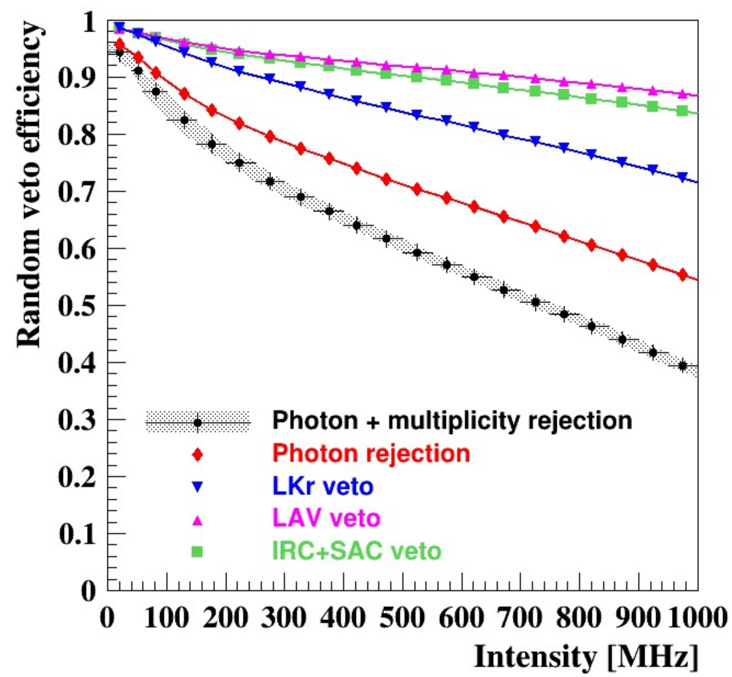


Normalization and Single Event Sensitivity



SES error budget:

Source	Relative uncertainty
trigger efficiency	5%
MC acceptance	3.5%
random veto efficiency	2%
normalization background	0.7%
instantaneous intensity	0.7%
Total	6.5%



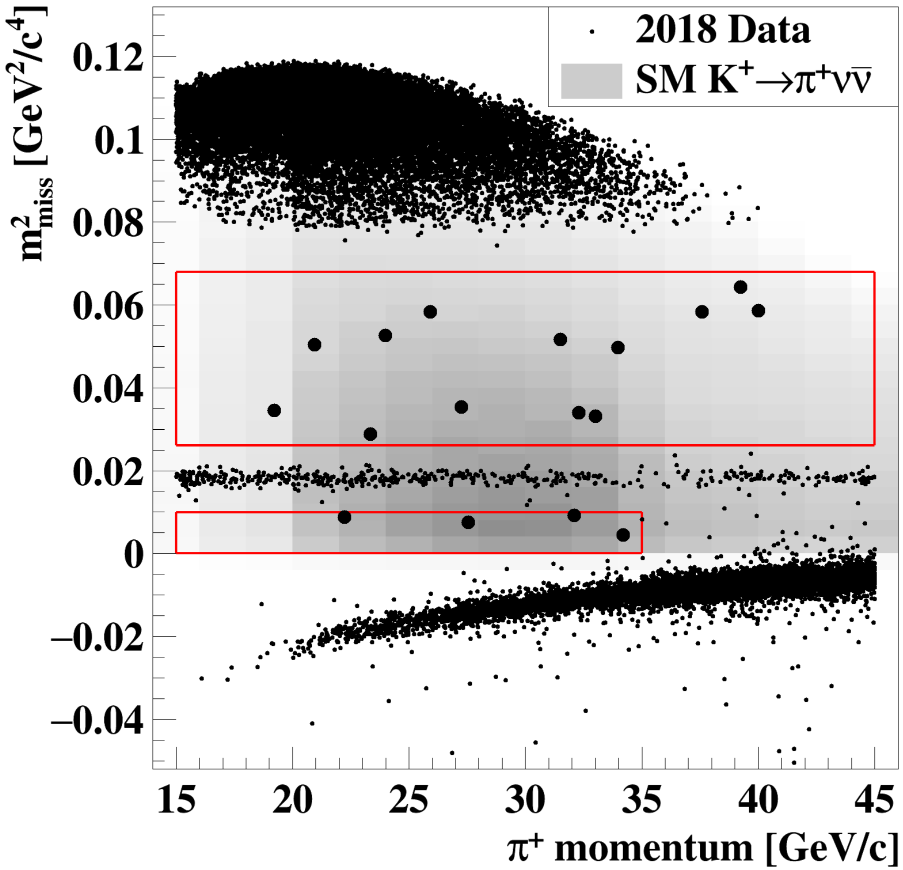
$$N^{exp}_{\pi\nu\nu} \approx N_{\pi\pi} \cdot \epsilon_{trigger} \cdot \epsilon_{RV} \cdot \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \cdot \frac{Br(\pi\nu\nu)}{Br(\pi\pi)}$$

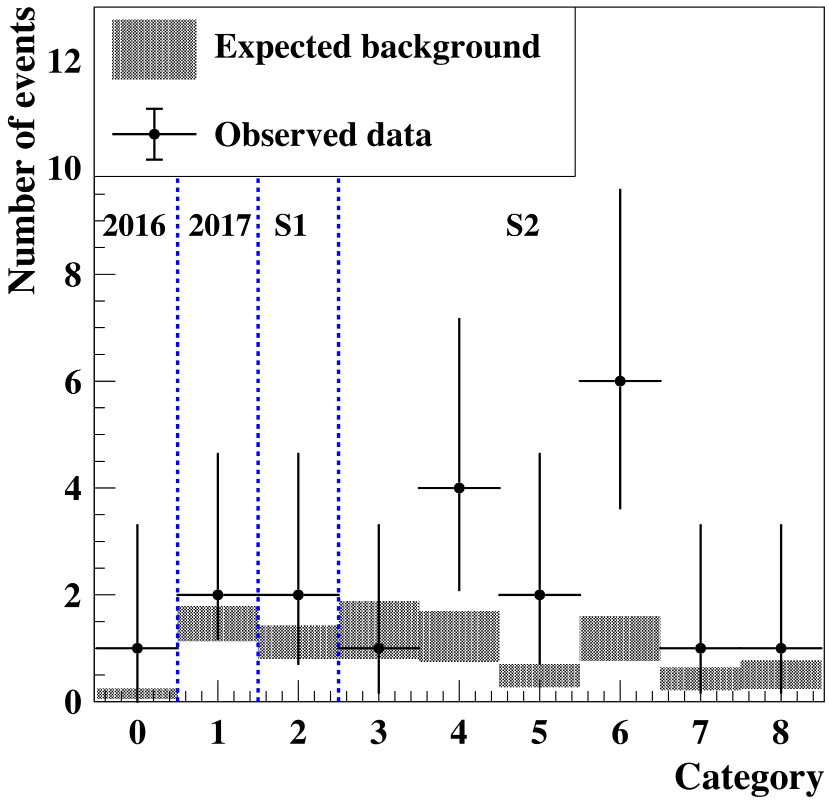
$A_{\pi\nu\nu}($ S1 $) \simeq 4.0\%$, $A_{\pi\nu\nu}($ S2 $) \simeq 6.4\%$

$$\text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}} = (1.11 \pm 0.07_{syst.}) \times 10^{-11}$$

Result: 2016+2017+2018 data

[JHEP 06 (2021) 093]





$$SES = (0.839 \pm 0.053_{sys}) \times 10^{-11}$$

$$N_{obs}(2016 + 2017 + 2018) = 20$$

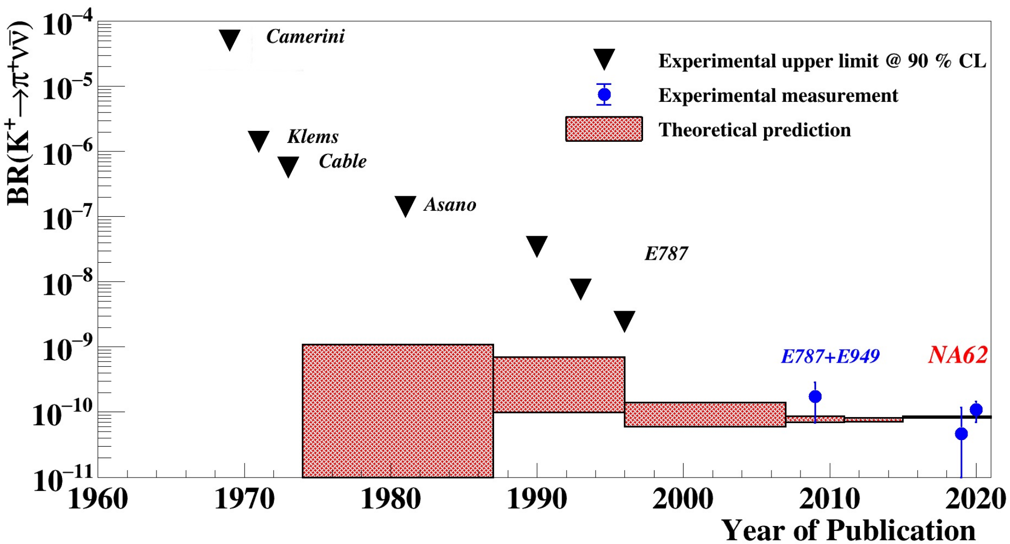
$$N^{exp}_{\pi\nu\nu} = 10.01 \pm 0.42_{sys} \pm 1.19_{ext}$$

$$N^{exp}_{background} = 7.03^{+1.05}_{-0.82}$$

$$Br(K^+ \to \pi^+\nu\nu) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{sys}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

3.4σ significance

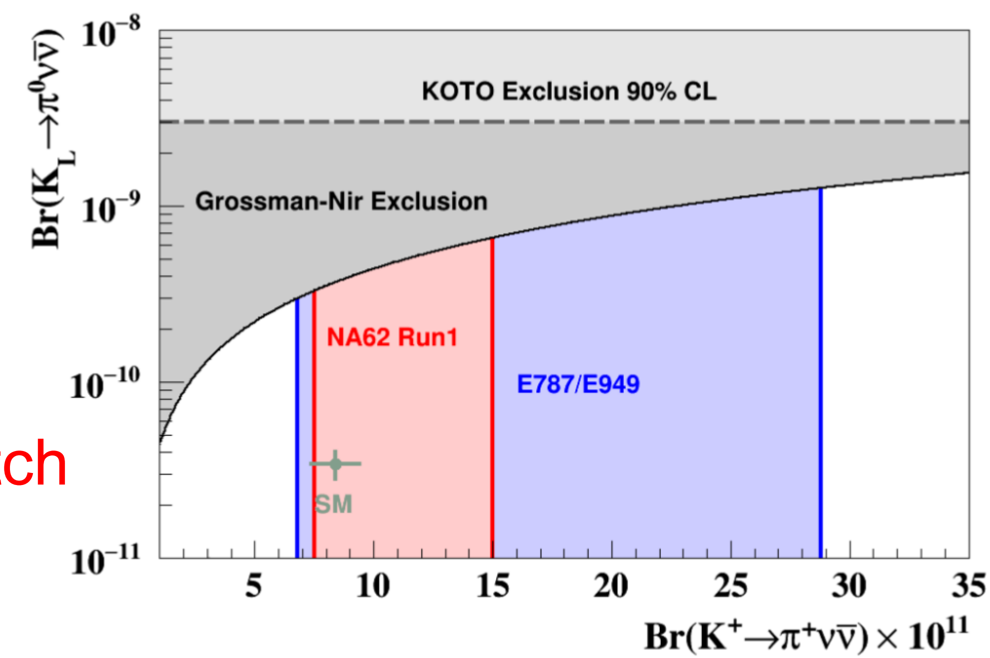
Implications of $K^+ \to \pi^+ \nu\nu$



Most precise determination of the decay rate to date

Provides strongest evidence so far (3.4 σ) for its existence

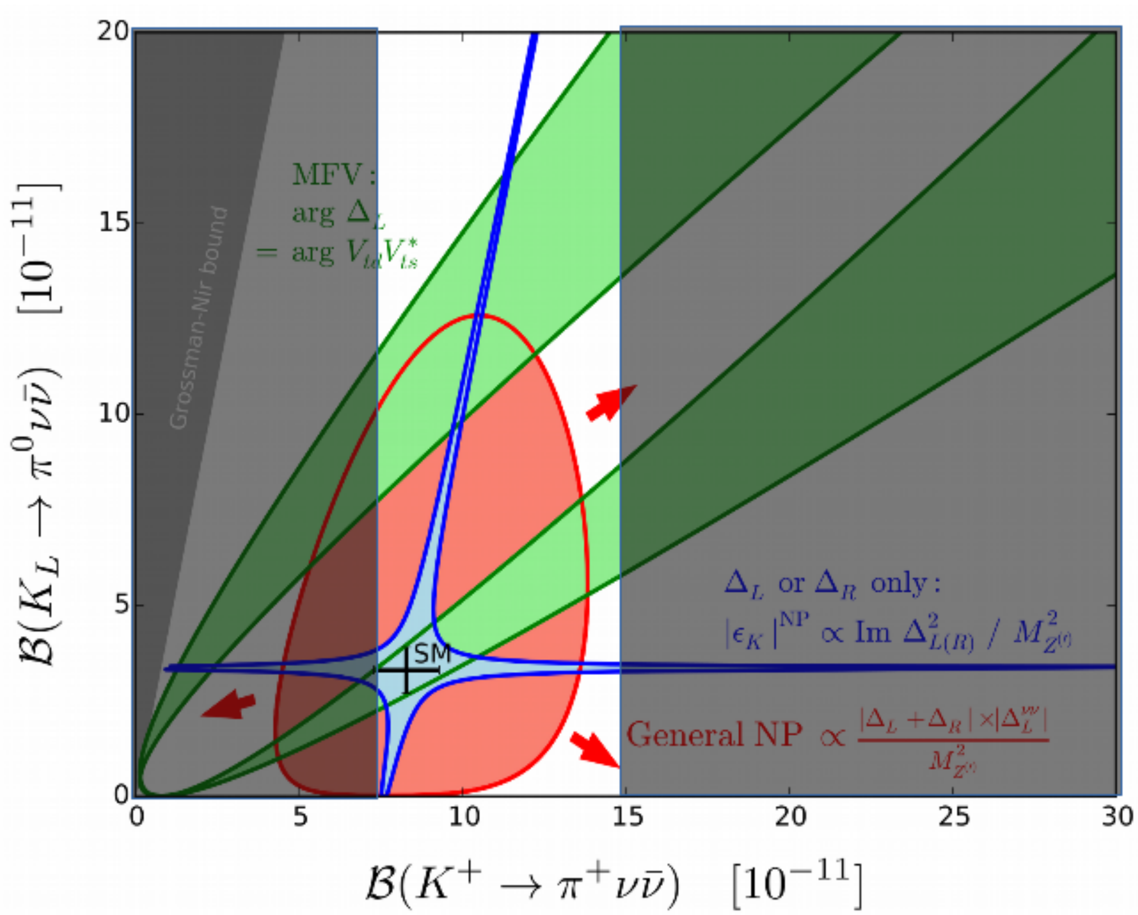
Part of parameter space already ruled out



Next target: at least x3 improved precision to match theoretical uncertainty by LS3

$K^+ \to \pi^+ \nu\nu$ Run1 result

NA62 Run1(2016 + 2017 + 2018) result:



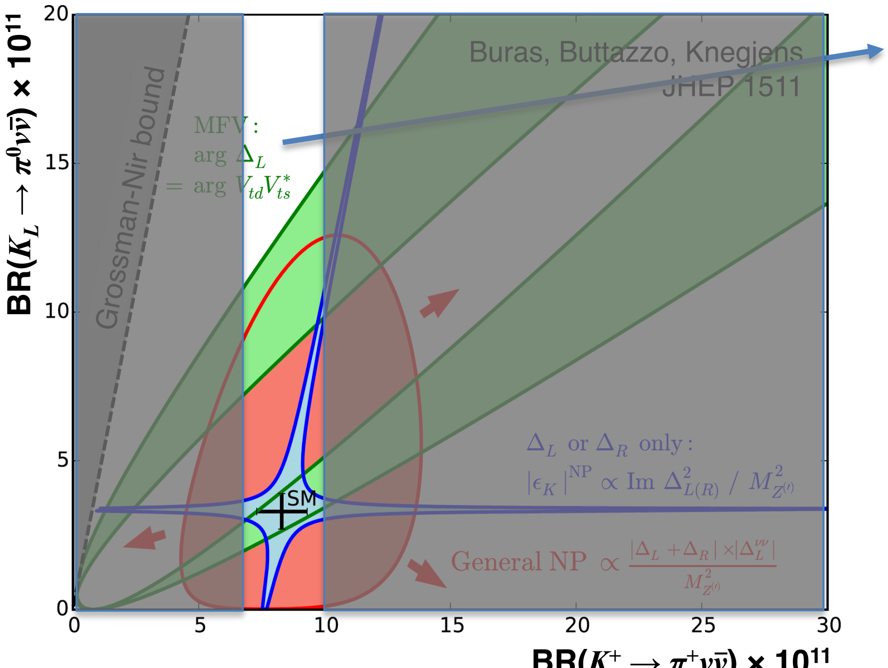
Large values with respect to SM expectation start to be excluded

High precision measurement needed

$K^+ \rightarrow \pi^+ \nu\nu$ Run2

Reach O(10%) precision on the $K \rightarrow \pi \nu \nu$ measurement

Run2 allows NA62 to perform a measurement of the branching ratio of the ultra-rare kaon decay $K^+ \rightarrow \pi^+ \nu\nu$ with significantly improved accuracy, to substantially increase its sensitivity on several rare and forbidden kaon decays, and to reach unprecedented sensitivity in the investigation of several Standard Model (SM) extensions involving feebly interacting long-lived particles.



NA62@LS3

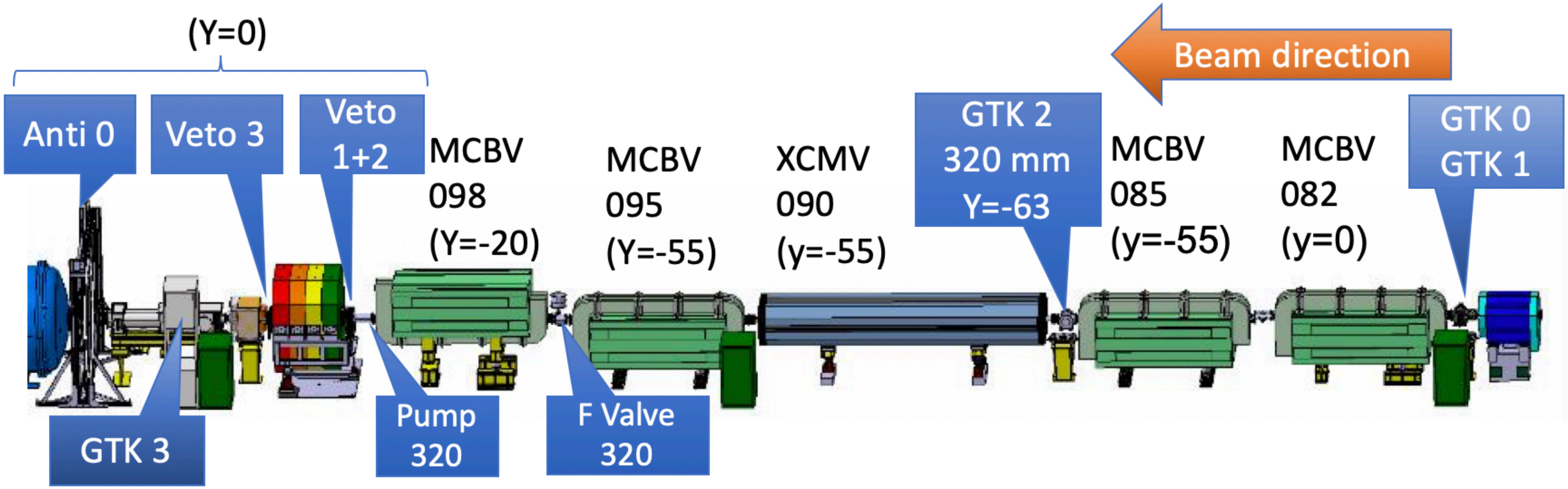
O(10%) precision

Constrain New Physics models

Detector additions

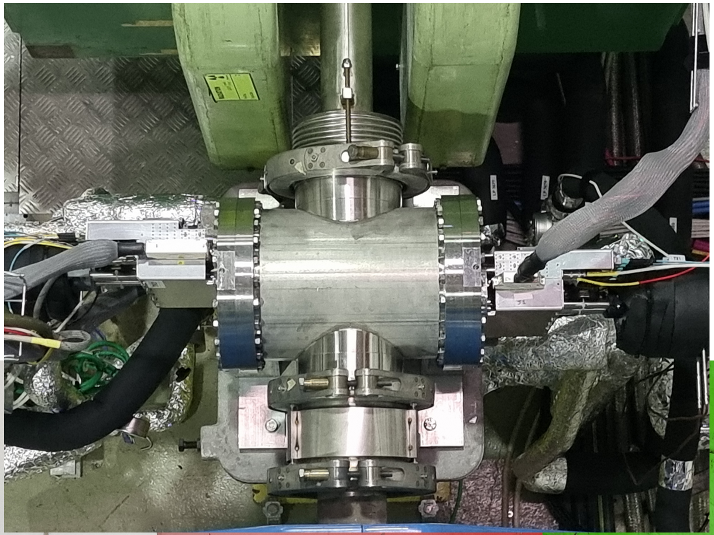
Optimized achromat for background reduction in $K^+ \rightarrow \pi^+ \nu \nu$ analysis, with addition of 4th GTK station (GKT0, next to GTK1), VETO counter before/after last collimator, 2nd HASC module

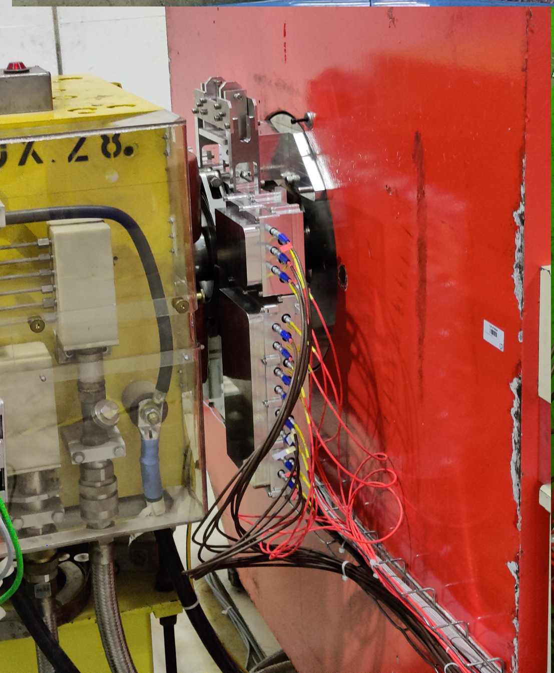
For muon background reduction in dump mode and trigger use, new ANTI0 hodoscope

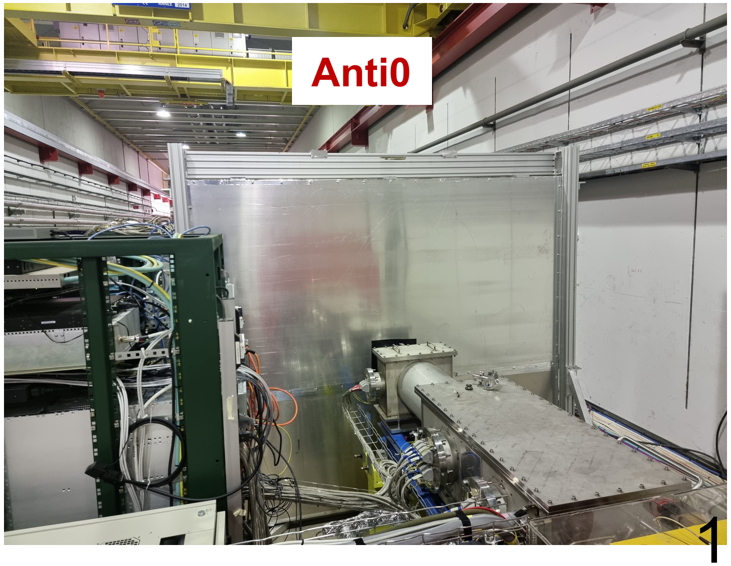


New detector installed and commissioned

One major goal reached

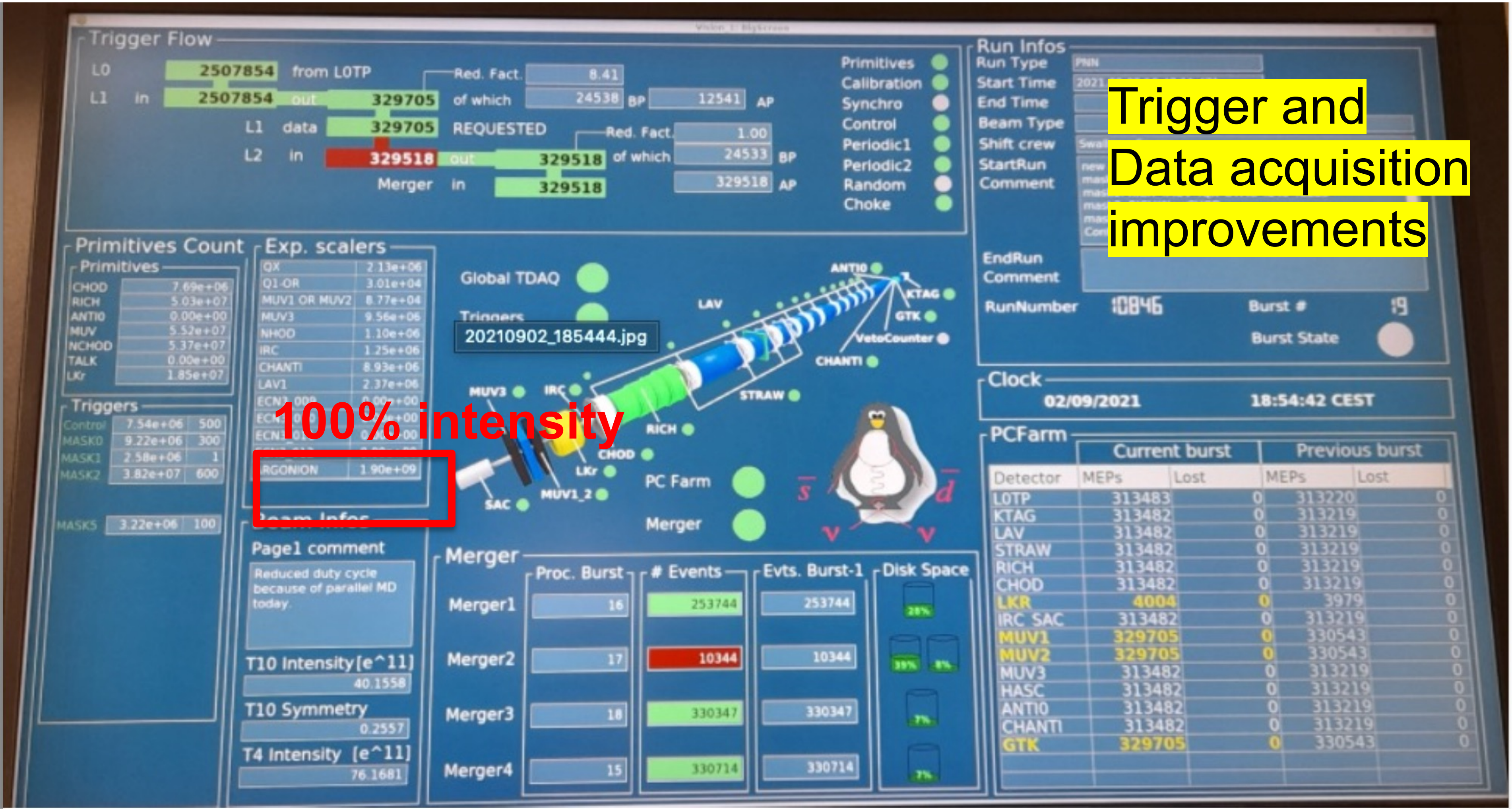




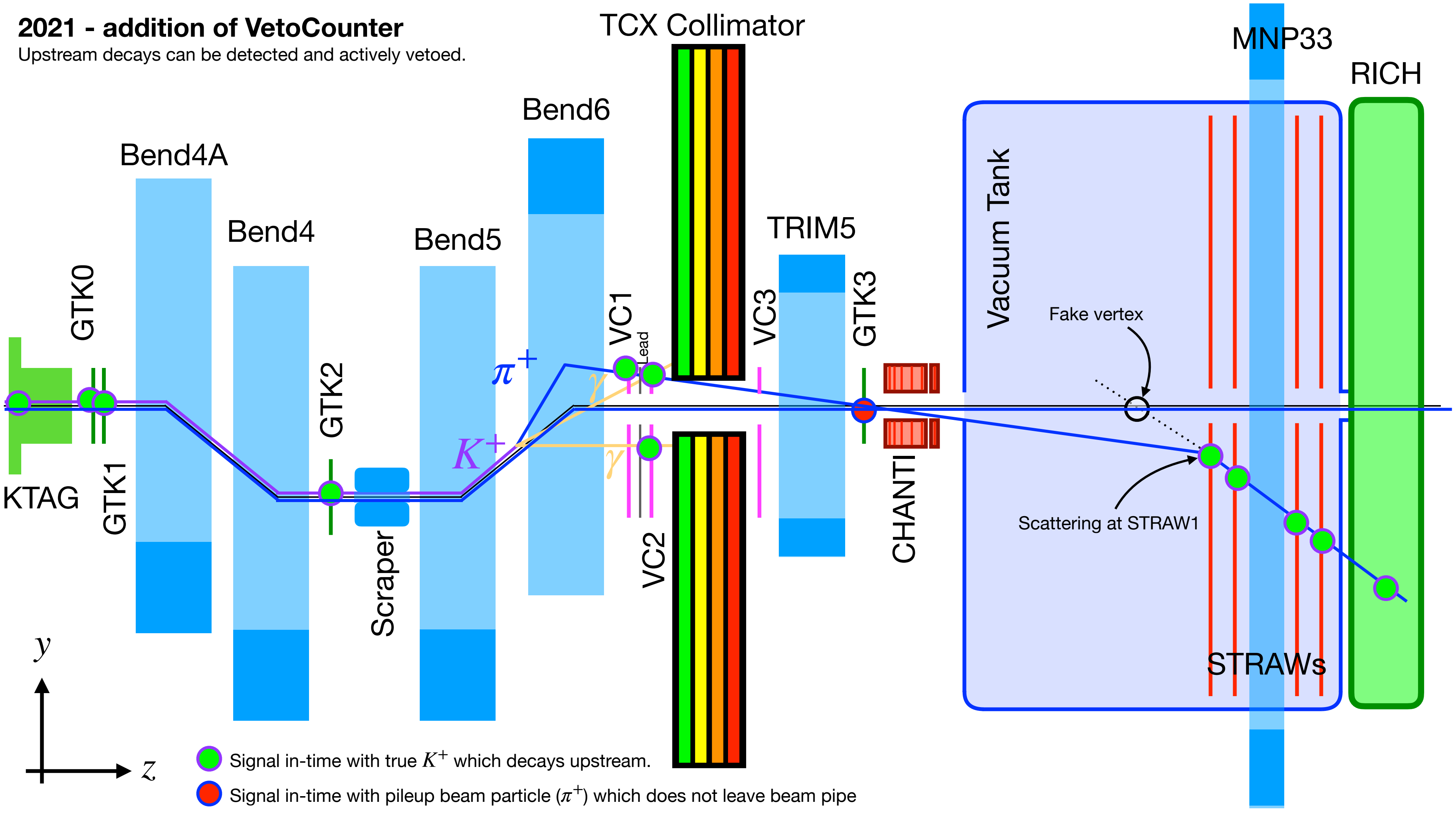


Data taking at nominal intensity

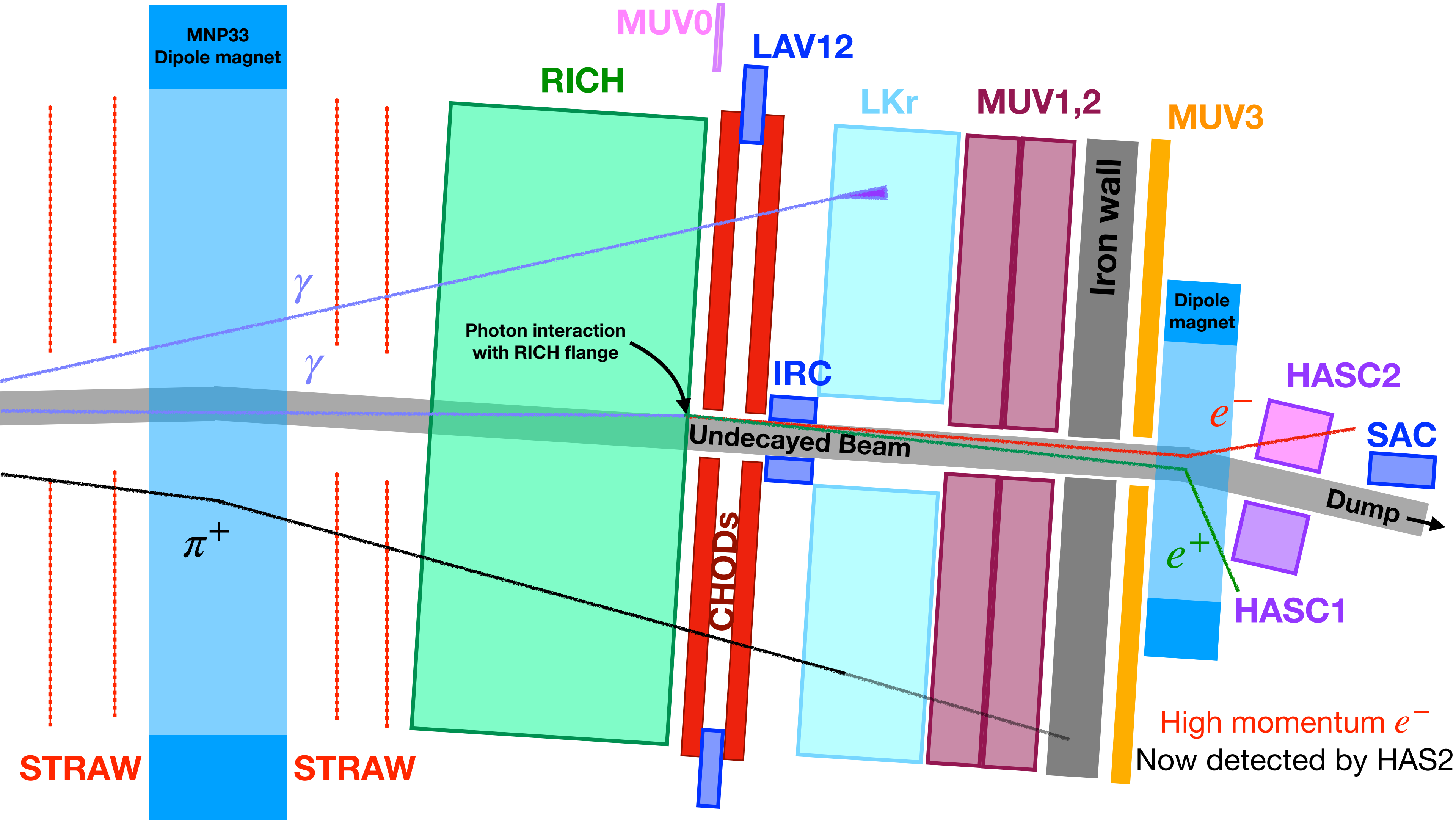
Another major goal reached



Background reduction: VetoCounter

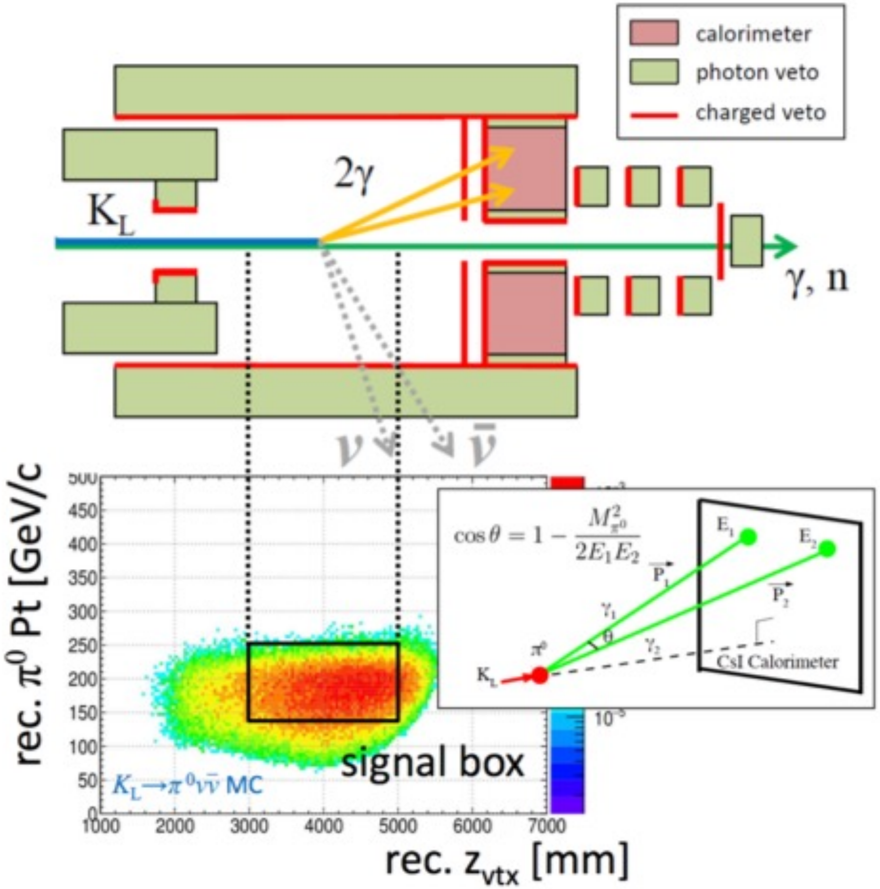


Background reduction: HASC2



The KOTO experiment

- $K_L \to \pi^0 \nu \bar{\nu}$ event signatures:
  - two γs and nothing extra.
  - veto system is crucial!

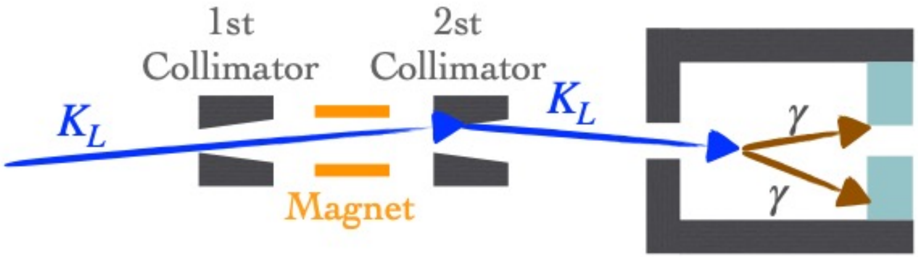


- Event reconstructed by assuming m_{π^0}.
- Signal region is defined in 2-D plane of
  - π^0 decay vertex (rec. Z_{vtx})
  - π^0 transverse momentum (rec. π^0 Pt)

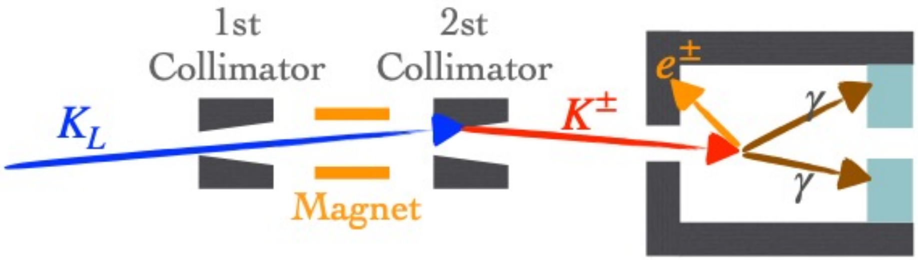
The KOTO experiment

New BG Sources

Beam halo K_L BG ($K_L \to \gamma\gamma$)



K± BG ($K^\pm \to \pi^0 e^\pm \nu$)



BG Table
of 2016-2018 data

source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07 [a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25 [a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
total		1.22 ± 0.26

[a] Background sources studied after looking inside the blind region.

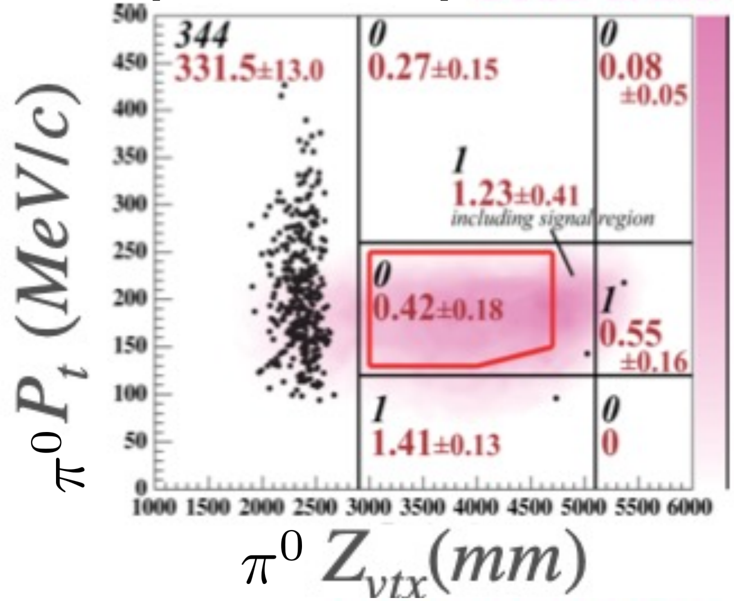
KOTO: $K^0 \to \pi^0 \nu \bar{\nu}$

2015 data: [PRL.122.021802]
0.42 predicted background
S.E.S. = 1.30 x 10^{-9}
No events observed

$$BR(K_L \to \pi^0 \nu\nu) < 3.0 \times 10^{-9} \text{ at } 90\% \text{ CL}$$

(current best limit)

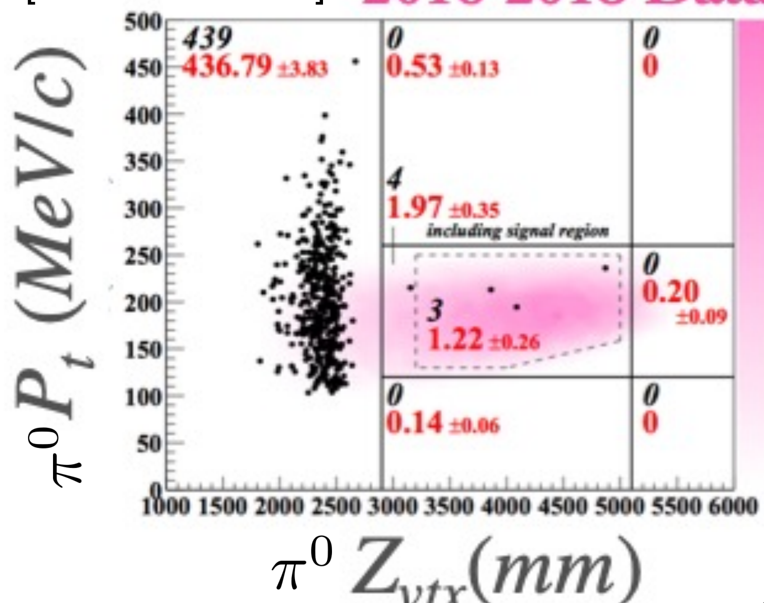
[PRL.122.021802] 2015 Data



2016-2018 data: [PRL.126.121801]
A better S.E.S. = 7.20 x 10^{-10}
3 events appeared,
with 1.22 background events
(1.22 includes newly-found backgrounds)

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

[PRL.126.121801] 2016-2018 Data

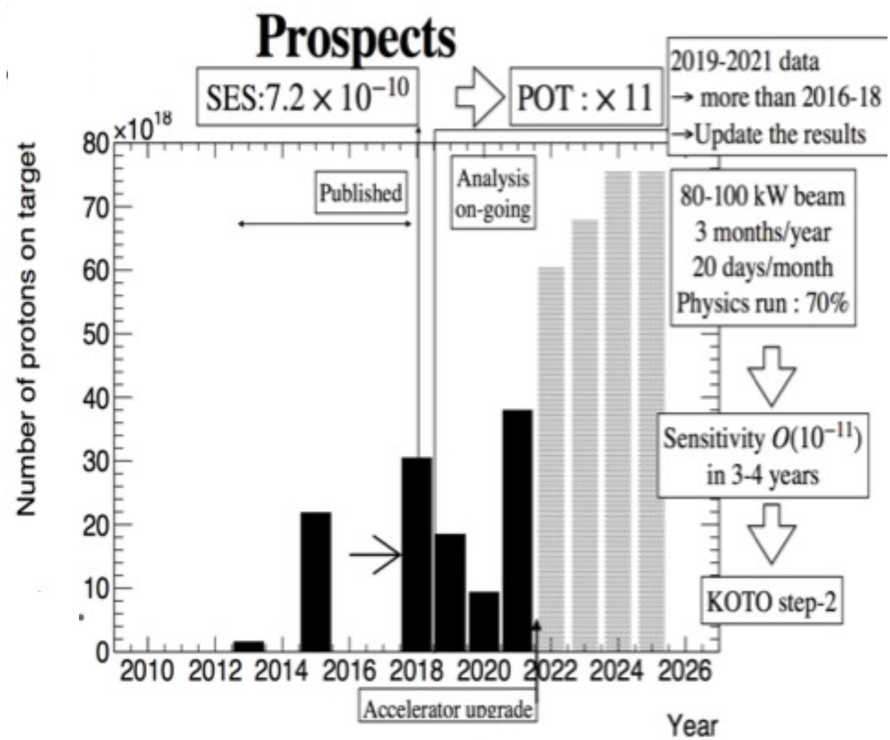


KOTO: Prospects $K^0 \to \pi^0 \nu \bar{\nu}$

2021-2022 shutdown:
J-PARC main ring power supply upgrade:
Beam power 64kW → 80-100 kW

KOTO DAQ upgrade: event throughput x4
Will be able to collect $K_L \to \pi^0 e^+ e^-$
[J.Phys.Conf.Ser 1526.012026]

2022-2025:
KOTO will collect x 11 more data
Projected S.E.S. ~ O(10^{-11}) by 2026



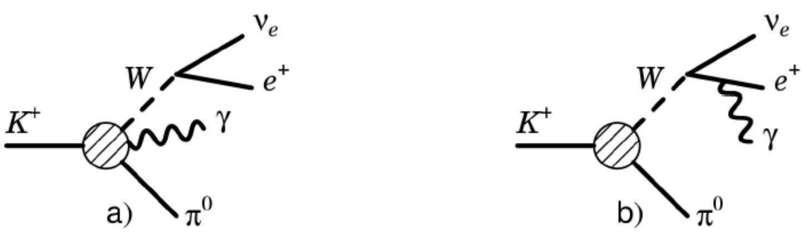
Highlights of other K^+ analyses

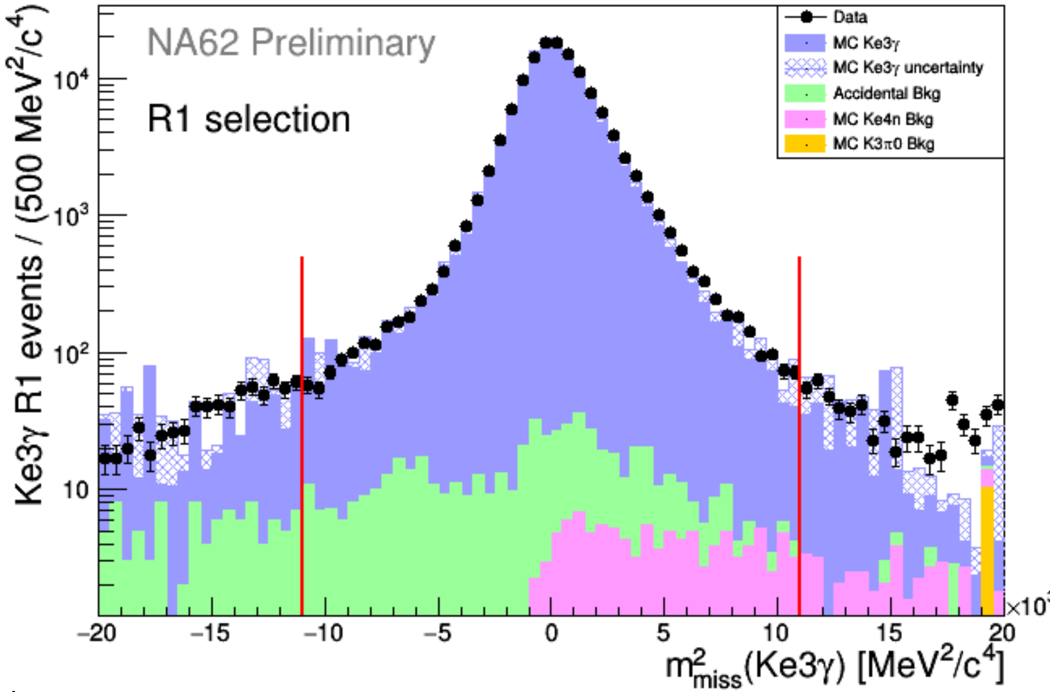
NA62 $K^+ \to \pi^0 e^+ \nu\gamma$

[PoS EPS-HEP2021 553]

Test of ChiPT with $K^+ \to \pi^0 e^+ \nu\gamma$

DE (a) + IB (b) + INT





2017 and 2018 data

$$R_j = \frac{\mathcal{B}(Ke3\gamma^j)}{\mathcal{B}(Ke3)} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \mid E_\gamma^j, \theta_{e,\gamma}^j)}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma))}$$

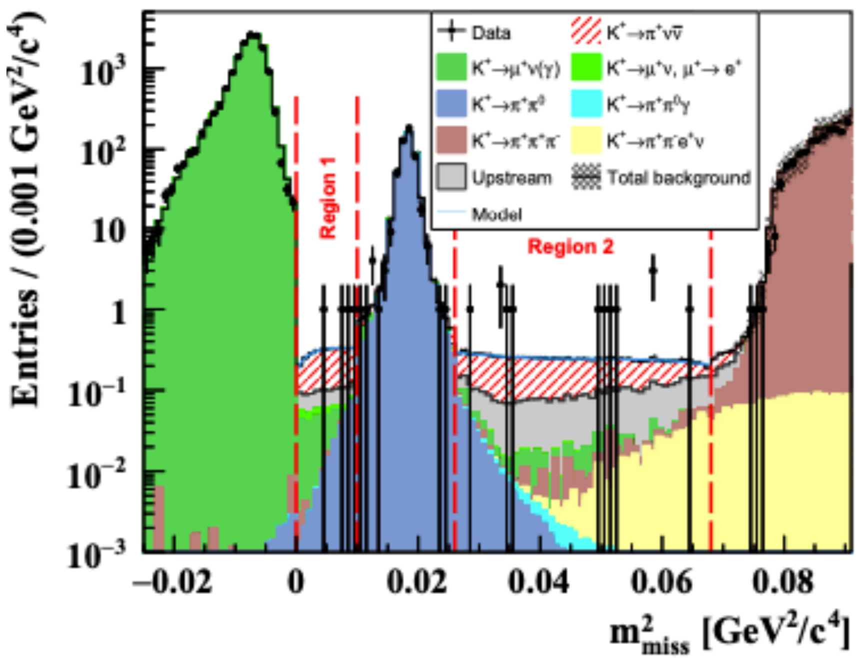
	E_γ^i	$\theta_{e\gamma}^i$	ChPT $O(p^6)$	NA62 (preliminary)
$R_1 \times 10^2$	$E_\gamma > 10$ MeV	$\theta_{e\gamma} > 10°$	1.804 ± 0.021	$1.684 \pm 0.005 \pm 0.010$
$R_2 \times 10^2$	$E_\gamma > 30$ MeV	$\theta_{e\gamma} > 20°$	0.640 ± 0.008	$0.599 \pm 0.003 \pm 0.005$
$R_3 \times 10^2$	$E_\gamma > 10$ MeV	$0.6 < \cos\theta_{e\gamma} < 0.9$	0.559 ± 0.006	$0.523 \pm 0.003 \pm 0.003$

Search for $K^+ \to \pi^+ X$

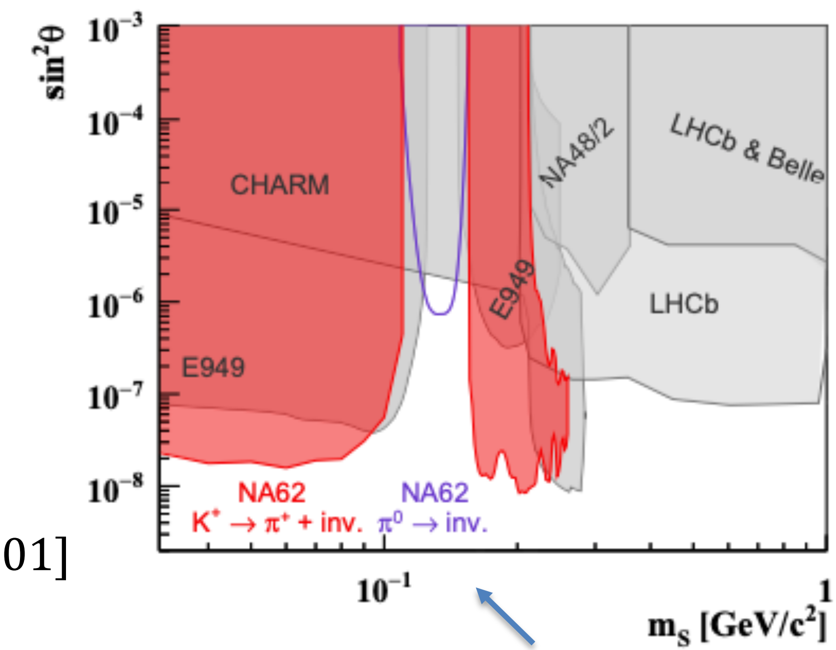
[arXiv:2103.15389]

Perform peak search considering $K^+ \to \pi^+ \nu\nu$ **as SM background**
Improvement on previous limit by factor ~4

Search for X scalar or pseudo-scalar



Dark Scalar, production and decay driven by mixing with Higgs boson

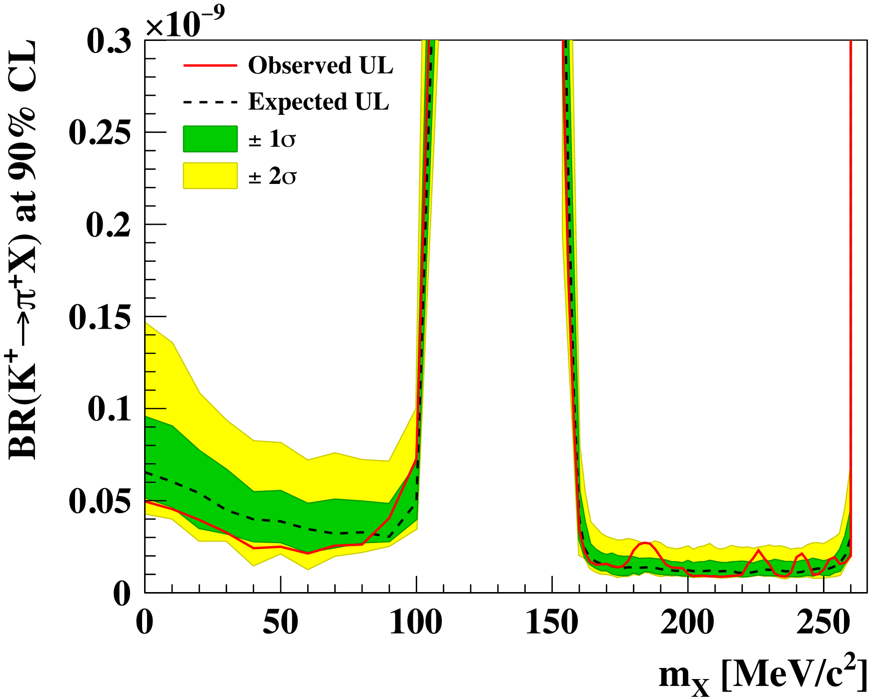


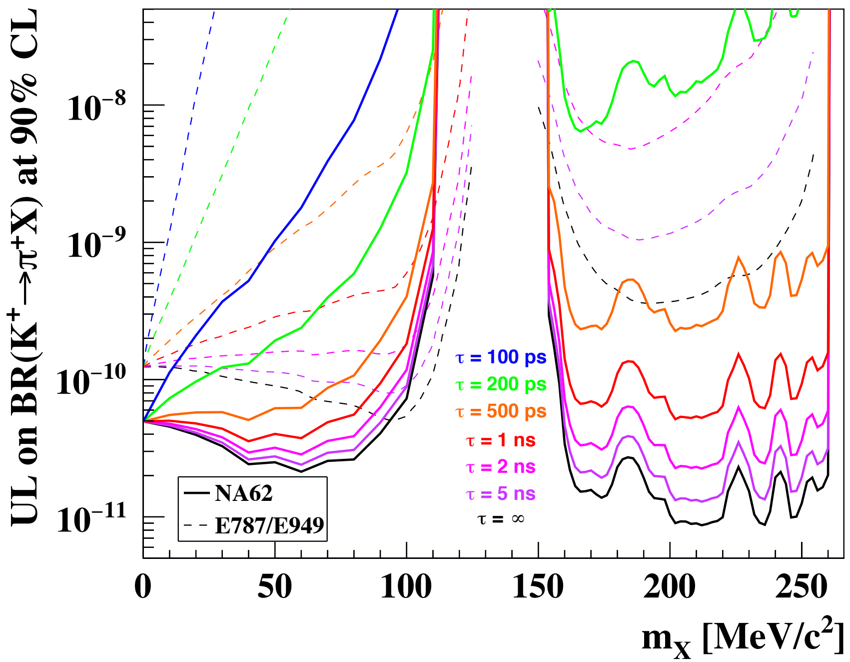
Also published: π^0 to invisibles [JEHP 02 (2021) 201] and π^+X 2017 data [JHEP 03 (2021) 058]

Assuming X decays only to visible SM particles, with lifetime inversely proportional to the mixing parameter

Search for $K^+ \to \pi^+ X$

Perform peak search considering $K^+ \to \pi^+ \nu\nu$ **as SM background**





Stable or invisibly decaying

Decaying to visible SM particle

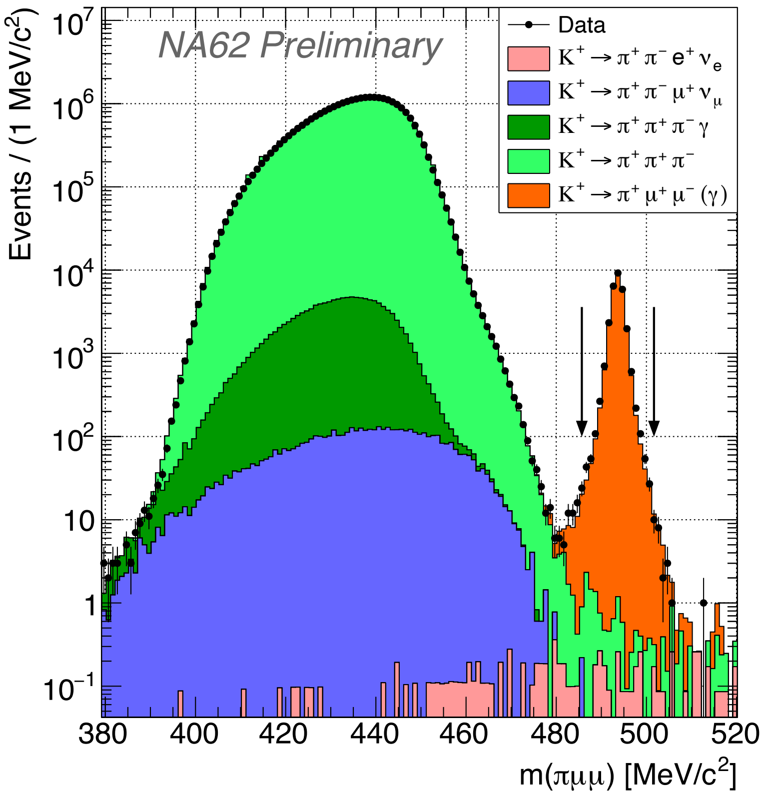
Improvement on previous limit by factor ~4

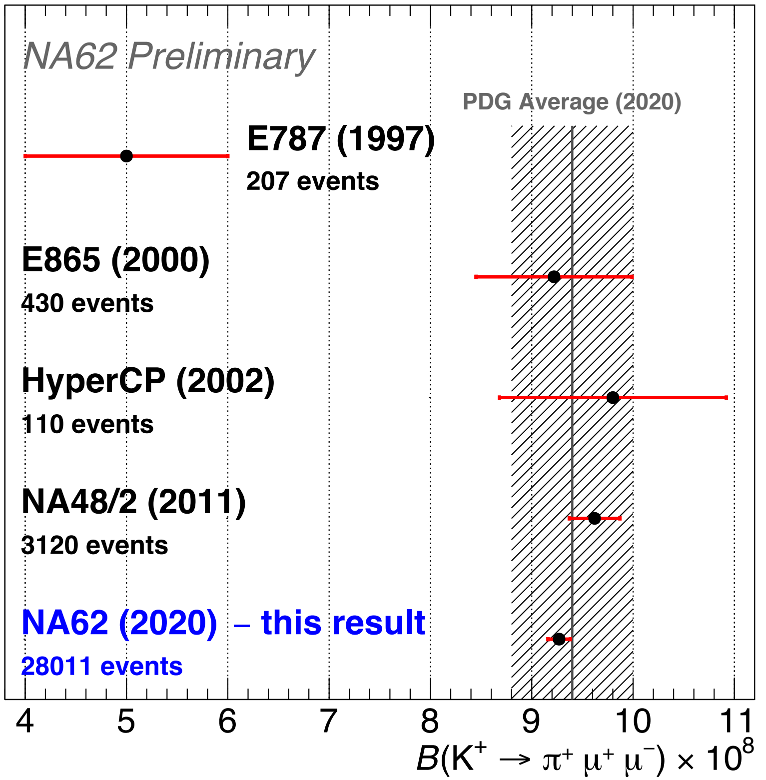
Sensitivity to X with shorter lifetimes substantially improved by extension of FV in S2 sample

$K^+ \rightarrow \pi^+\mu^+\mu^-$ decays

FCNC decay, sensitive to new physics

Measurement based on 2.8 10^4 candidates from Run1





$$a_+ = -0.592 \pm 0.015$$
$$b_+ = -0.669 \pm 0.058$$
FF

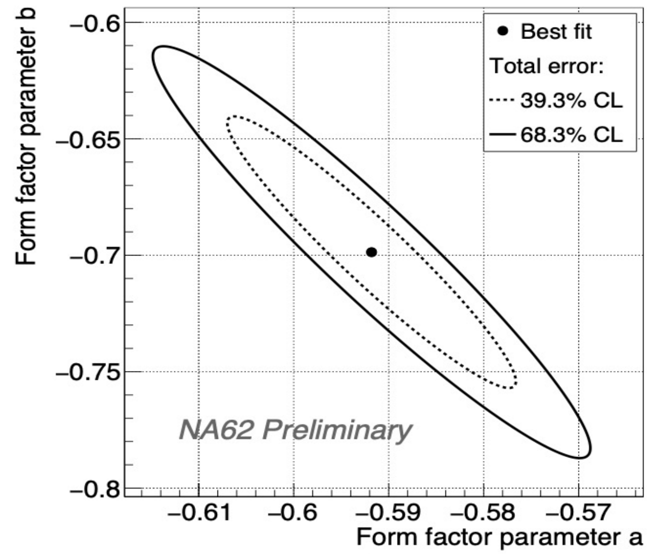
$$\mathcal{B}(K^+ \to \pi^+\mu^+\mu^-) = (9.27 \pm 0.11) \times 10^{-8}$$

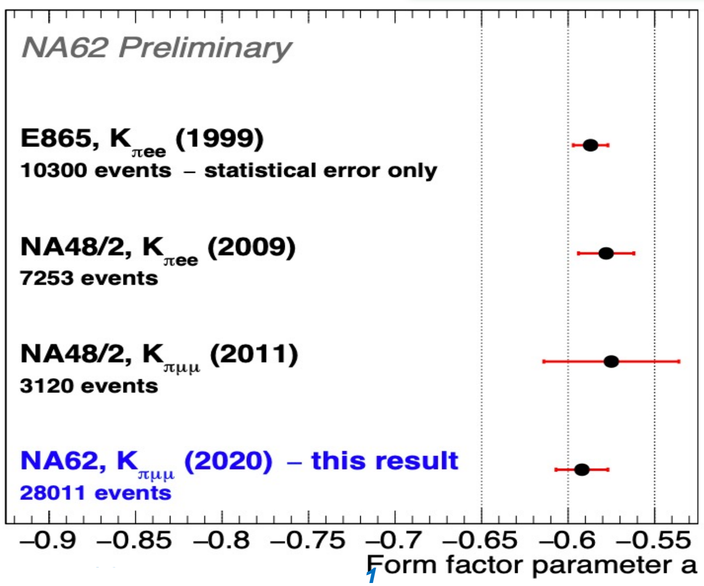
Presented at ICHEP2020. Paper in preparation.

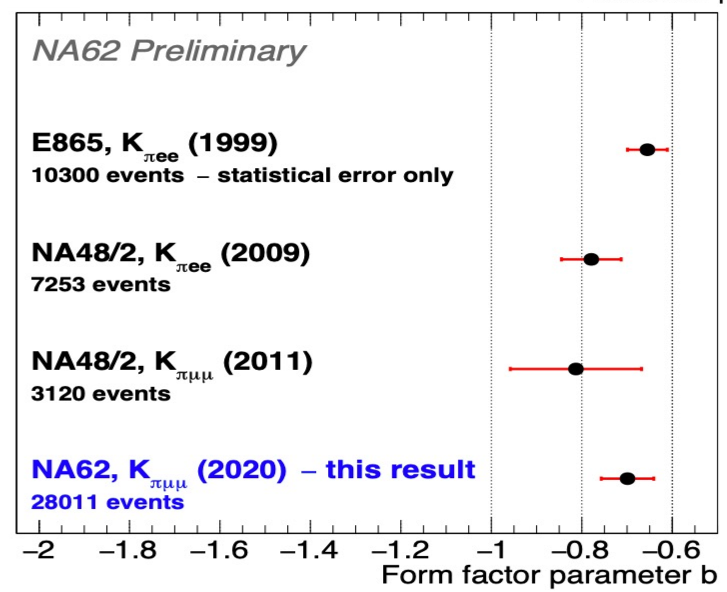
Revised, more stringent trigger for di-muon and di-elect in 2021

$K^+ \rightarrow \pi^+\mu^+\mu^-$ decays

	a	b	$\mathcal{B}_{\pi\mu\mu} \times 10^8$
Best fit	-0.592	-0.699	9.27
Errors	δa	δb	$\delta\mathcal{B}_{\pi\mu\mu} \times 10^8$
Statistical	0.013	0.046	0.07
Systematic			
Reconstruction efficiency	0.005	0.026	0.06
Beam & pileup simulation	0.005	0.024	0.05
Trigger efficiency	0.001	0.005	0.04
Background	0.000	0.001	0.01
Total systematic	0.007	0.035	0.08
External			
PDG error on $\mathcal{B}(K_{3\pi})$	0.001	0.003	0.04
Total	0.015	0.058	0.11



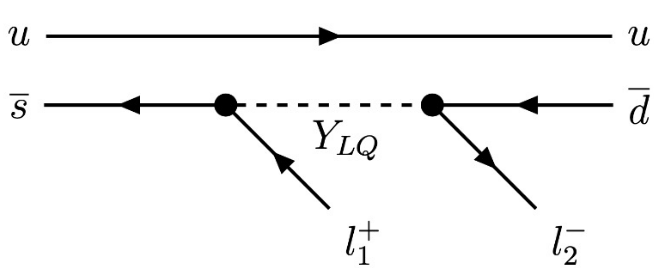




Paper in preparation.

Revised, more stringent trigger for di-muon and di-elect in 2021

Lepton Number and Lepton Flavour Violation



[Phys Rev Lett 127 (2021) 131802]

Background sources:

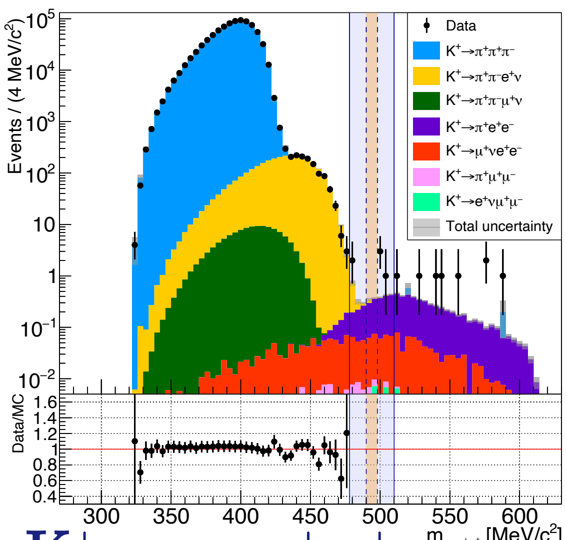
Mid-ID $\pi^{\pm} \Rightarrow e^{\pm}$ $e^{\pm} \Rightarrow \pi^{\pm}$

$\pi^{\pm} \Rightarrow \mu^{\pm}$ $e^{\pm} \Rightarrow \mu^{\pm}$

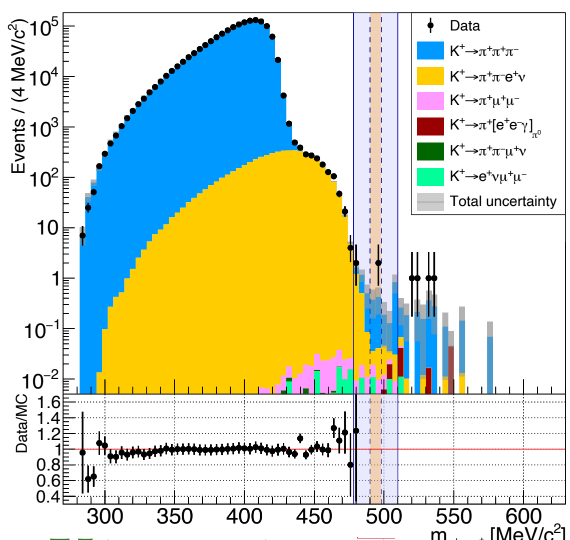
pion decays in flight

E.g. $K^+ \to \pi^{\pm}\mu^{\mp}e^+$ decays ($\Delta L = 2$ if π^- + $\Delta L_e = 1$ and $\Delta L_\mu = 1$) mediated by a leptoquark

[JHEP 12 (2019) 089], [NPB 176 (1980) 135]



$K^+ \to \pi^- \mu^+ e^+$



$K^+ \to \pi^+ \mu^- e^+$

2017 and 2018 data

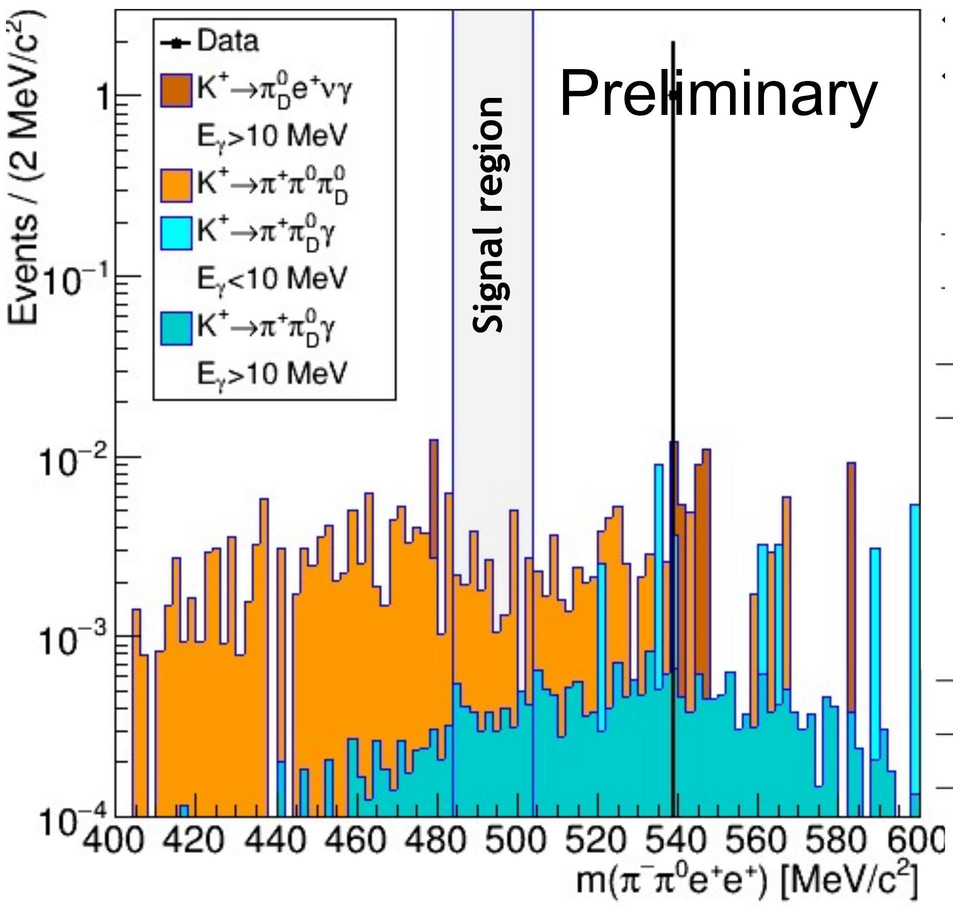
Blind analyses

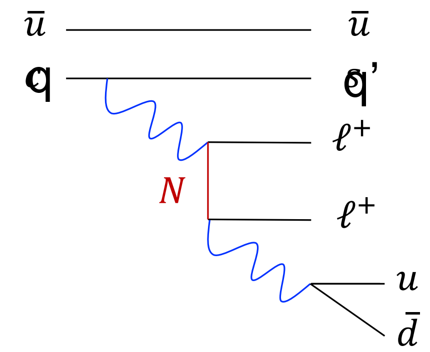
$$
\begin{aligned}
\mathcal{B}(K^+ \to \pi^- e^+ e^+) &< 5.3 \times 10^{-11}, \\
\mathcal{B}(K^+ \to \pi^- \pi^0 e^+ e^+) &< 8.5 \times 10^{-10}, \\
\mathcal{B}(K^+ \to \pi^- \mu^+ \mu^+) &< 4.2 \times 10^{-11}, \\
\mathcal{B}(K^+ \to \pi^- \mu^+ e^+) &< 4.2 \times 10^{-11}, \\
\mathcal{B}(K^+ \to \pi^+ \mu^- e^+) &< 6.6 \times 10^{-11}, \\
\mathcal{B}(\pi^0 \to \mu^- e^+) &< 3.2 \times 10^{-10}.
\end{aligned}
$$

LNV/LFV:

$$
\begin{aligned}
\mathcal{B}(K^+ \to \pi^- \mu^+ e^+) &< 4.2 \times 10^{-11} \\
\mathcal{B}(K^+ \to \pi^+ \mu^- e^+) &< 6.6 \times 10^{-11}
\end{aligned}
$$

NA62: LNV $K^+ \to \pi^-\pi^0 e^+ e^+$





Mode	Control region	Signal region
$K^+ \to \pi^+\pi^0\pi^0_D$	0.16 ± 0.01	0.019
$K^+ \to \pi^+\pi^0_D\gamma$	0.06 ± 0.01	0.004
$K^+ \to \pi^0_D e^+\nu\gamma$	0.05 ± 0.02	–
$K^+ \to \pi^+\pi^0 e^+ e^-$	0.01	0.001
Pileup	0.20 ± 0.20	0.020 ± 0.020
Total	0.48 ± 0.20	0.044 ± 0.020
Data	1	0

Expected background: **0.044±0.020** evt
Candidates observed: **0**
BR($K^+ \to \pi^-\pi^0 e^+ e^+$)<$8.5\times10^{-10}$ at 90% CL

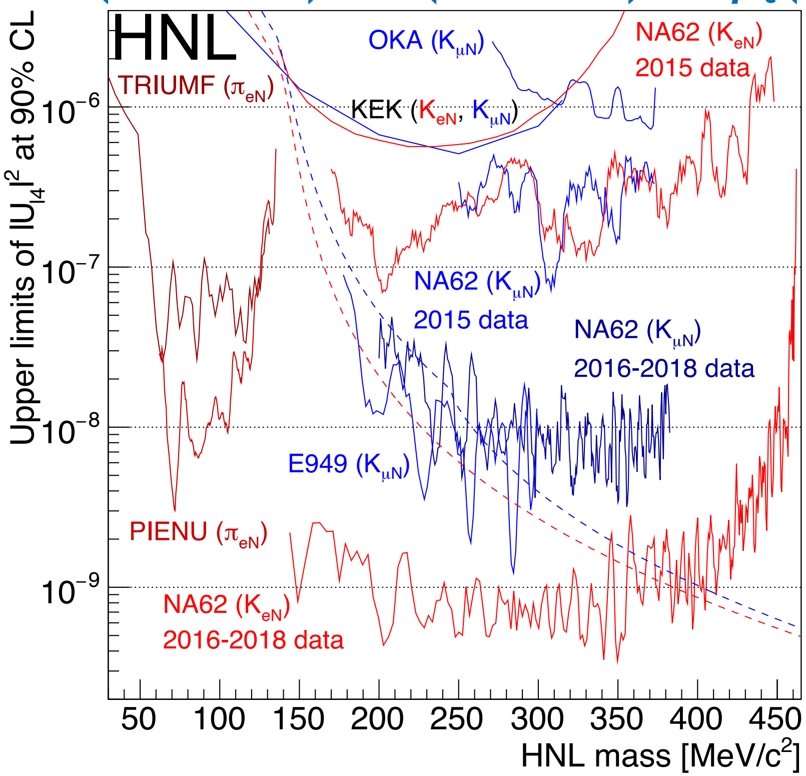
First search for this mode
Paper in preparation

Heavy Neutral Leptons, LNV/LFV searches

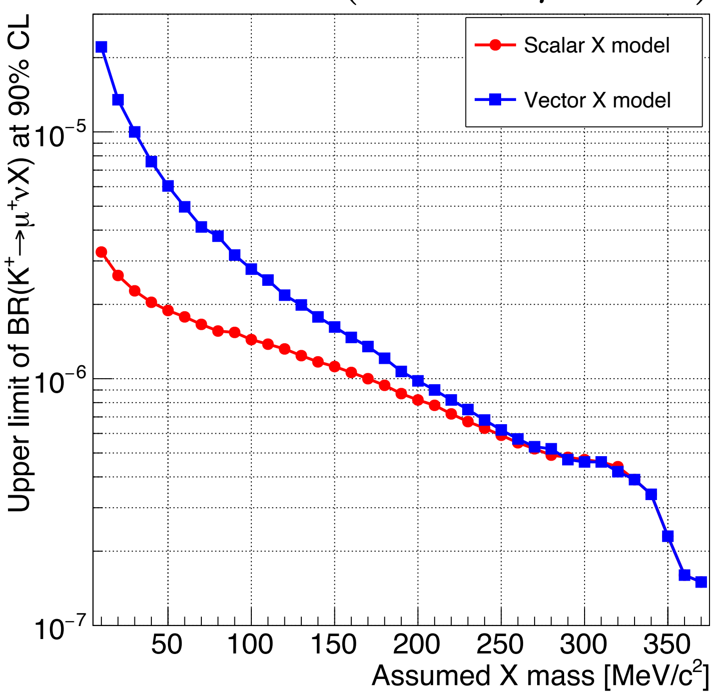
Full 2016-2018 data set

Signal: excess of data events over estimated background

$\Gamma(P^+ \to \ell^+ N) = \Gamma(P^+ \to \ell^+ \nu) \times \rho_\ell(m_N) \times |U_{\ell 4}|^2$



$\mathcal{B}(K^+ \to \mu^+ \nu X)$



$$\mathcal{B}(K^+ \to \mu^+ \nu \nu \bar{\nu}) < 1.0 \times 10^{-6} \quad \text{at } 90\% \text{ CL}$$

Phys. Lett. B 816 (2021) 136259
Phys. Lett. B 807 (2020) 135599

Lepton Universality

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

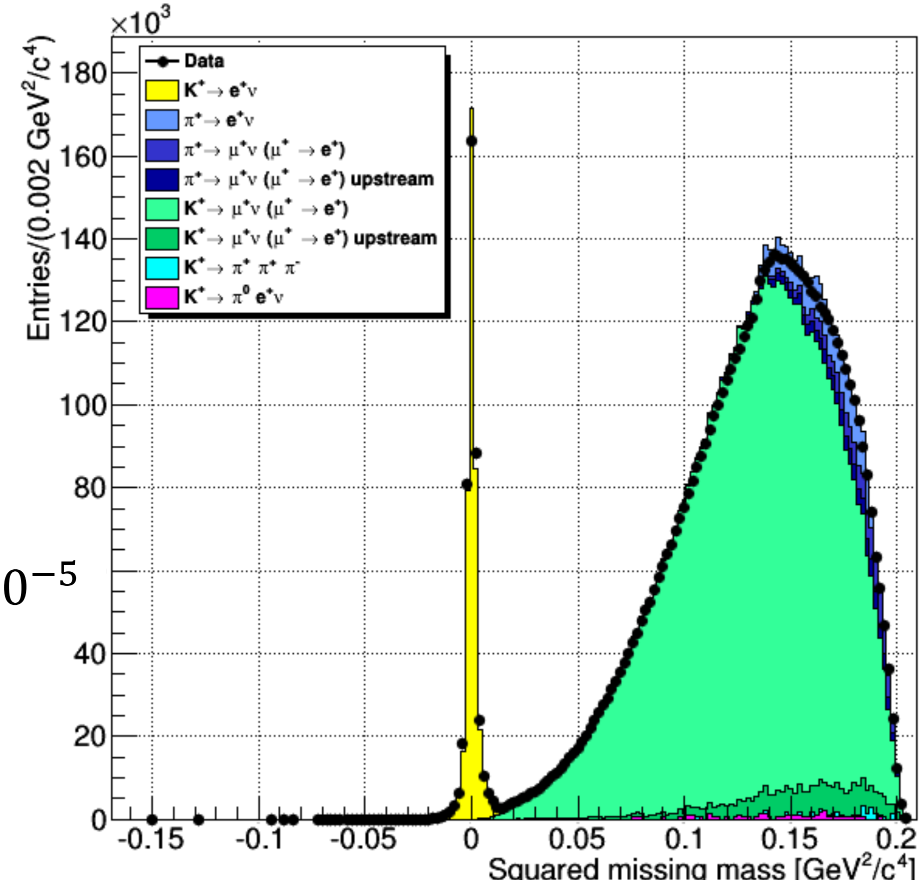
SM: $R_K = (2.477 \pm 0.001) \times 10^{-5}$

[PRL 99 (2007) 231801]

Exp. status (2007 NA62)

$R_K = \left(2.488 \pm 0.007_{stat} \pm 0.007_{syst}\right) \times 10^{-5}$

[PLB 719 (2013) 326]

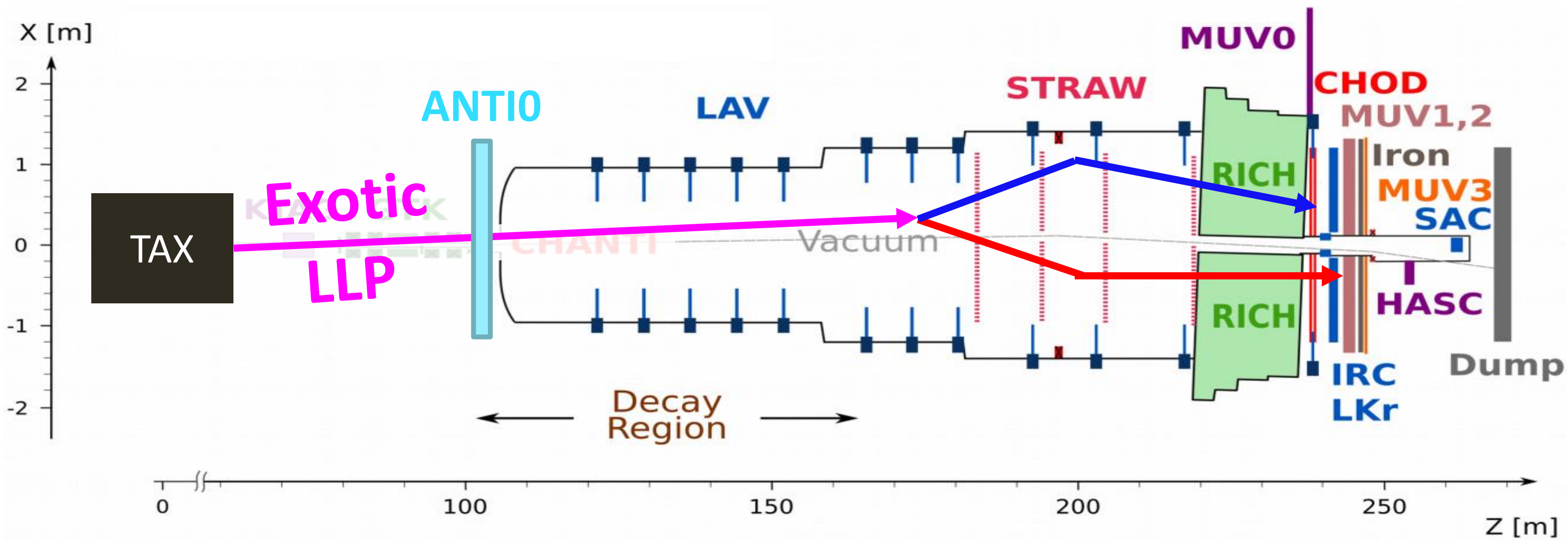


NA62 present: novel method using muon decays for normalization.

Collected sample several times larger than 2007 sample.

No systematic uncertainties that limited 2007 measurement.

NA62 in dump mode



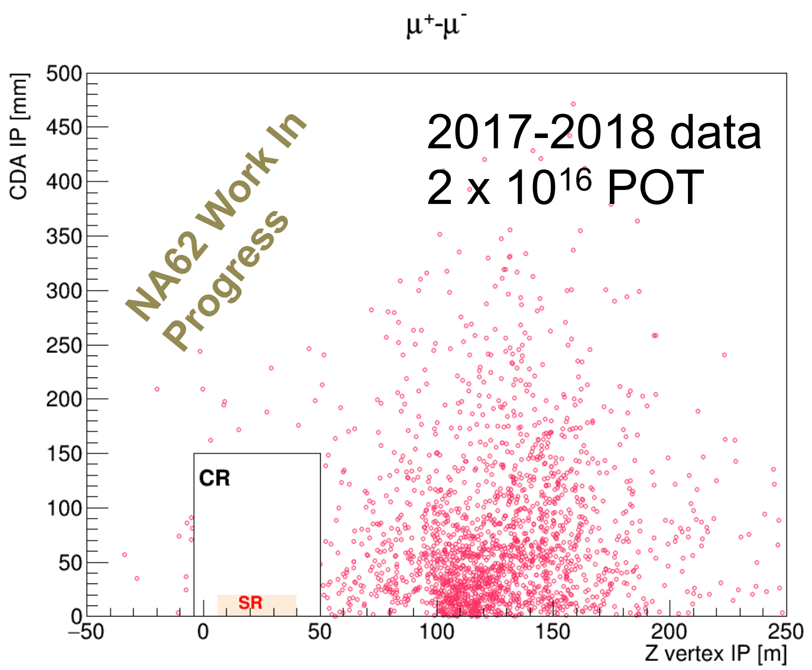
Long decay volume and detector characteristics/performances: suitable to search for feebly-interacting long-lived particles

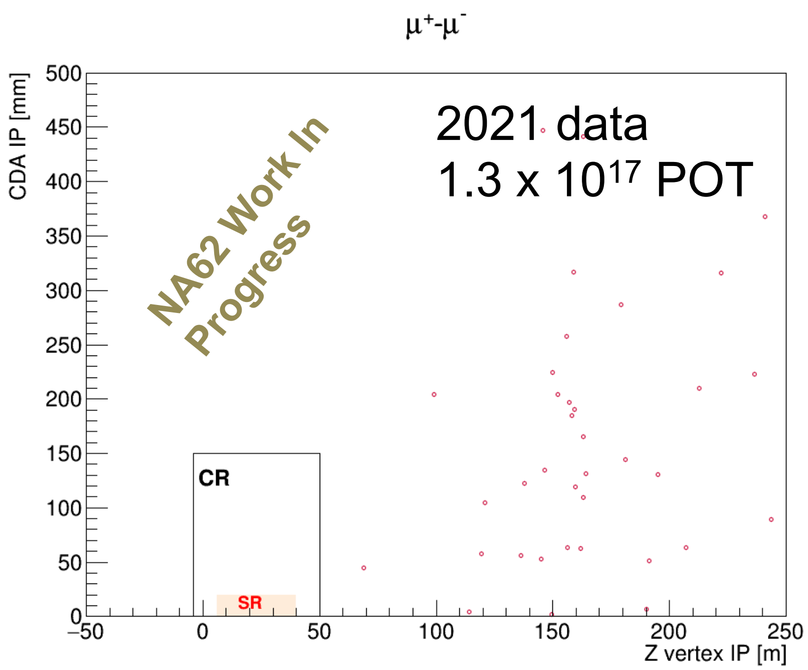
Extend Dark Particle mass range > M(K) (D, B associated production)

Dump mode is most sensitive to forward processes, complimentary to off-axis experiments

NA62 in dump mode

Anti0 Hodoscope with scintillator tiles instruments the entrance of decay volume. Trigger improved. **Aim for 10^{18} POT by LS3.**
Beam line magnet tuning for increased muon sweeping, ~x4 reduction of single muon rate
About 10 days of dump mode taken in 2021, at 150-180% nominal.
Collected about 1.3 x10^{17} POT. Data analysis started.





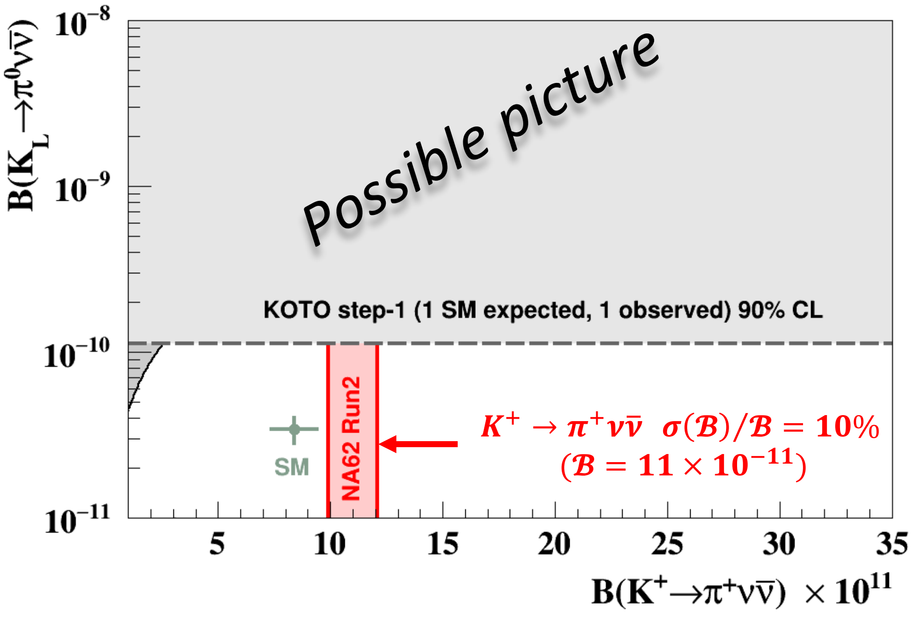
O(200) background rejection

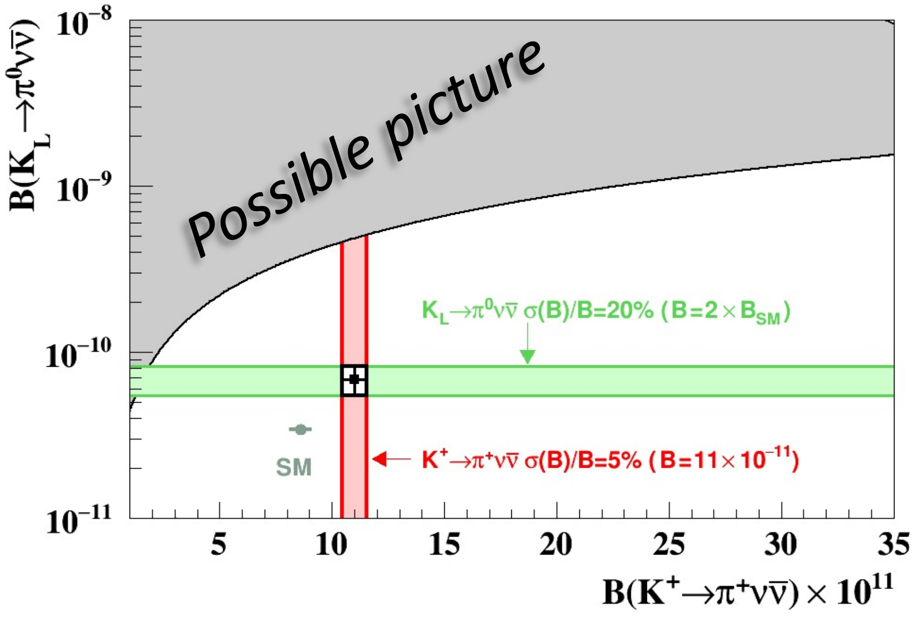
Beyond LS3 (>2025)

Clear opportunity in the Kaon sector

Going beyond 10% measurement on $K^+ \to \pi^+ \nu\nu$

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





Approach ultimate theory error, possibility to find clear evidence of deviation from SM

High-Intensity Kaon Experiments (HIKE) at the SPS

EU Strategy deliberation document: **CERN-ESU-014.** "Rare kaon decays at CERN" mentioned: "**Other essential activities for particle physics**"

Broad programme with multiple phases, K^+ + K_L beams and dump mode.

Exceptional sensitivity to discovery new physics:

Rare K decays, precision measurements , exotic particles in K/dump

FCNC in K are complementary to B in testing LFUV with comparable sensitivity

HIKE Timeline:

Modification of Target and TAX to stand 6 x NA62 nominal intensity by 2028

Step 1 after LS3: K^+

Reach ultimate theory error $K^+ \rightarrow \pi^+ \nu\nu$ decays, +other K^+ physics, + dump.

Step 2: switch to K_L mode

Transition: K_L rare decays with tracking & PID. Periodic dump mode.

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

Integrated programme with multiple phases: common upgrades for intensity and detectors between projects, more flexibility on schedule, synergies with HL-LHC

$K^+ \rightarrow \pi^+ \nu\nu$ at high intensity

An experiment at the SPS NA-ECN3 to measure BR($K^+ \rightarrow \pi^+ \nu\nu$) to within ~5%

Requires at least 4-6 x increase in intensity

Basic design of experiment will work at high intensity

Key points:

- 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 for detectors with collider projects and other rare processes experiments:

- Challenges often broadly aligned with High Luminosity LHC projects and next generation rare processes/ flavor/ dark matter experiments

K^+ and K_L beams

Availability of high-intensity K^+ and K_L beams at the SPS NA-ECN3: Unique facility, clear physics case

Important physics measurements also at boundary btw the two

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
- **10^{13} K_L decays in fiducial volume /year @ 10^{19} POT/year**

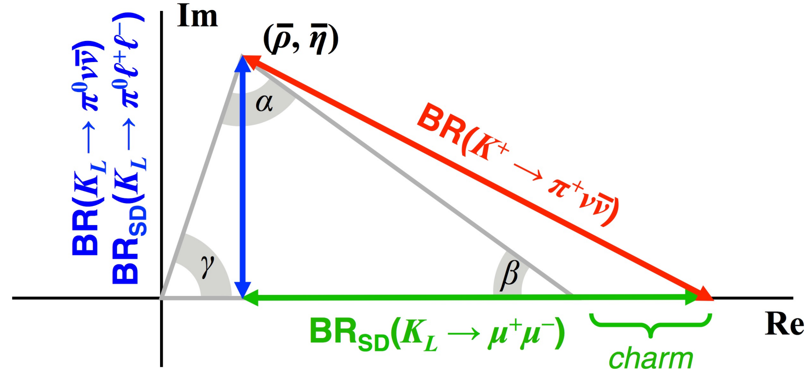
Physics objectives:

- $\boldsymbol{K_L \to \pi^0 \ell^+ \ell^-}$
  Excellent π^0 mass resolution – look for signal peak over Greenlee bckg
- 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

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



$K_L \to \pi^0 \ell^+ \ell^-$ 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: $K_L \to K_S$
- $K_S \to \pi^0 \ell^+ \ell^-$ will help reducing theoretical uncertainties
  - measured NA48/1 with limited statistics
  - planned by LHCb Upgrade
- $K_L \to \pi^0 \ell^+ \ell^-$ 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:

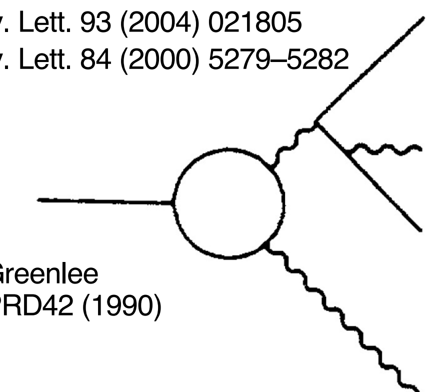
$BR(K_L \to \pi^0 e^+ e^-) < 28 \times 10^{-11}$

$BR(K_L \to \pi^0 \mu^+ \mu^-) < 38 \times 10^{-11}$

Phys. Rev. Lett. 93 (2004) 021805
Phys. Rev. Lett. 84 (2000) 5279–5282

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

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



Greenlee
PRD42 (1990)

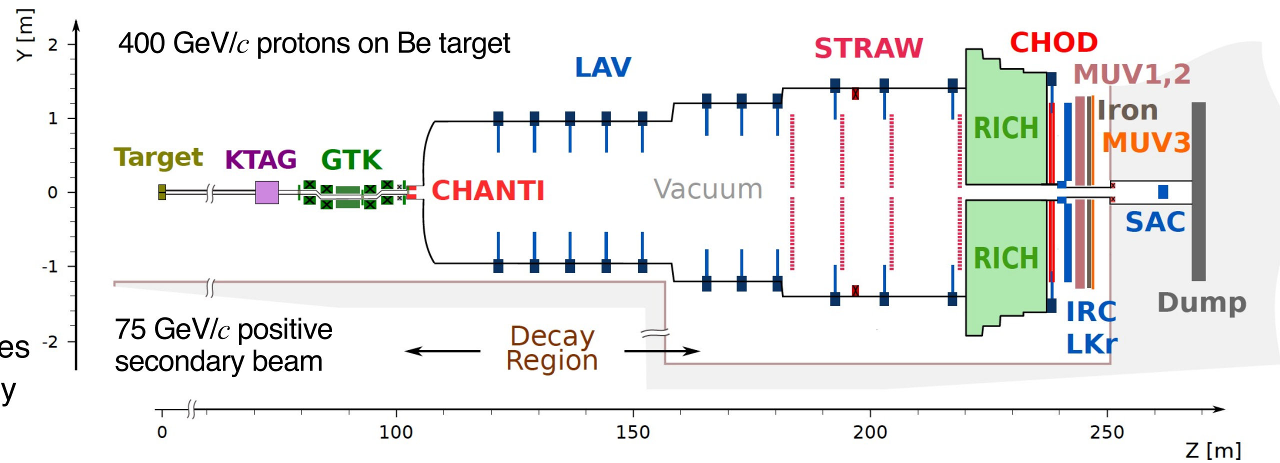
$BR(K_L \to e^+ e^- \gamma\gamma) = (6.0 \pm 0.3) \times 10^{-7}$ $\quad E_\gamma^* > 5$ MeV

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

High-rate beam 1.3--2 10^{13} protons on target over ~3 sec effective spill
Unseparated secondary hadron beam
<50ps time resolution (similar to HL-LHC)

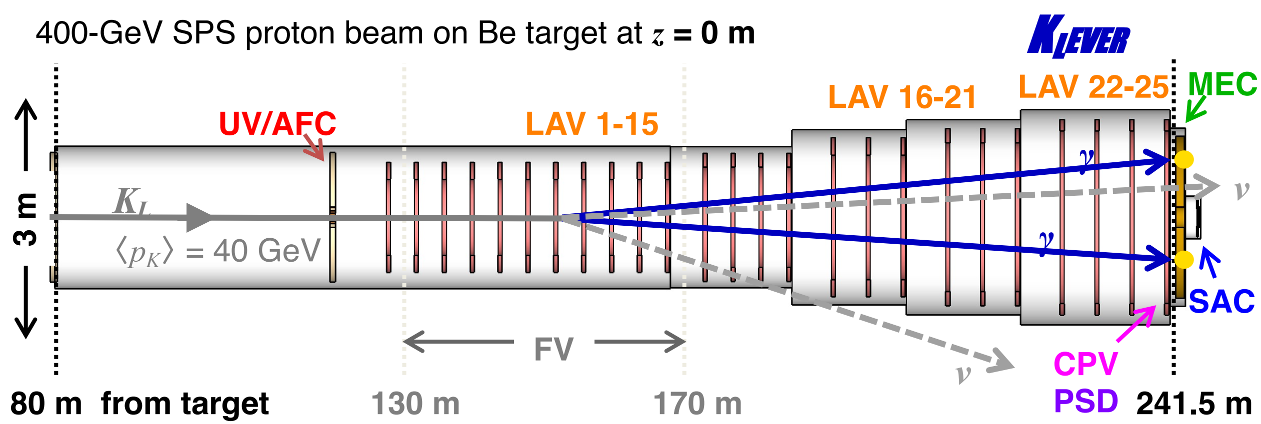
K^+ phase

- Essential K^+ ID, momentum, space and time – 200 MHz of K^+
- High-rate, precision tracking of pion
- Minimize material
- Highly efficient PID and muon vetoes
- Highly efficient and hermetic photon vetoes
- High-performance EM calorimeter (energy resolution, linearity, time, granularity)



K_L phase

- 2γ with unbalanced p_T + nothing else
- K_L momentum generally not known
- Background rejection from Λ and neutrons, and dominant K decays
- Background rejection mainly by vetoes



Efficient, large-coverage vetoes
Determination of angle of incident photons
PID for neutron rejection

10^{13} K_L decays in FV /year @ 10^{19} POT/year

Extending ECN3 by 150 m would eliminate Λ background

LoI in preparation.

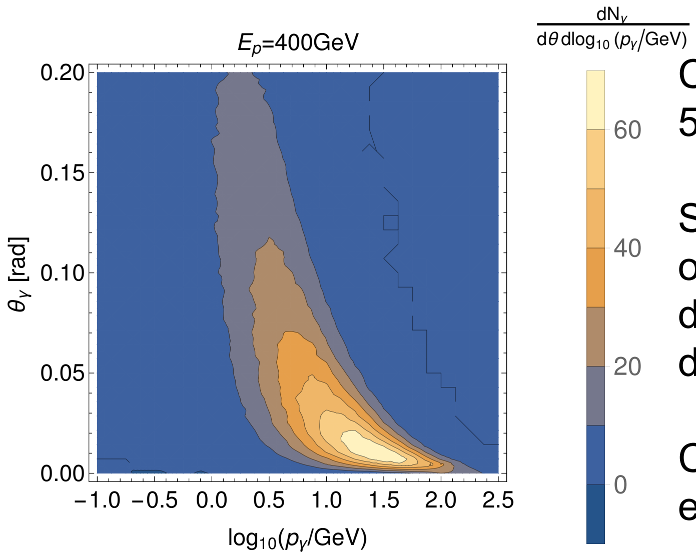
Feebly interacting particles (dump phase)

Physics goals for operation in dump mode after 2025:

- **Search for visible decays feebly-interacting new-physics particles**
- **x10 statistics improvement expected with respect to 2021-2023 data taking**
- If no signal and negligible background → x10 sensitivity improvement

Dump mode is most sensitive to forward processes, complimentary to off-axis experiments

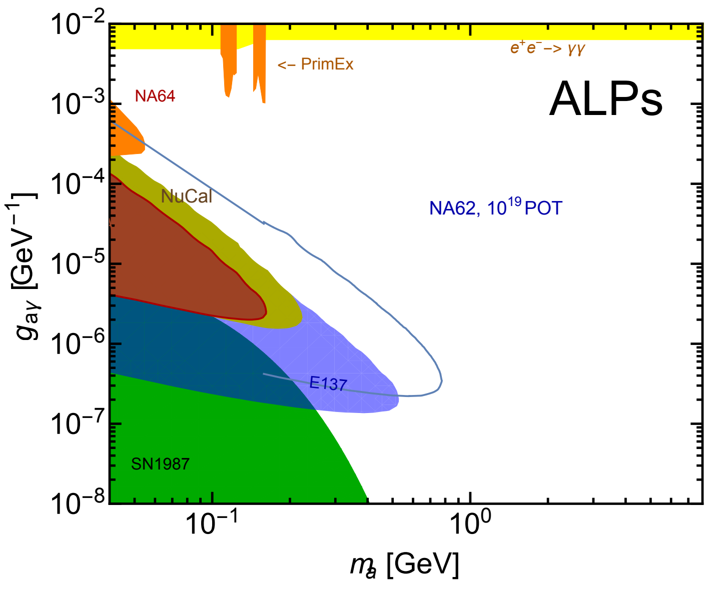
Distribution of photons from neutral pion decays in TAX (Primakov production). ALPs go approximately in the same direction



Can capture distribution up to 5 mrad

Sensitivity to lifetime depends on production-detector distance and length of detector (few ns)

Complimentary to other experiments

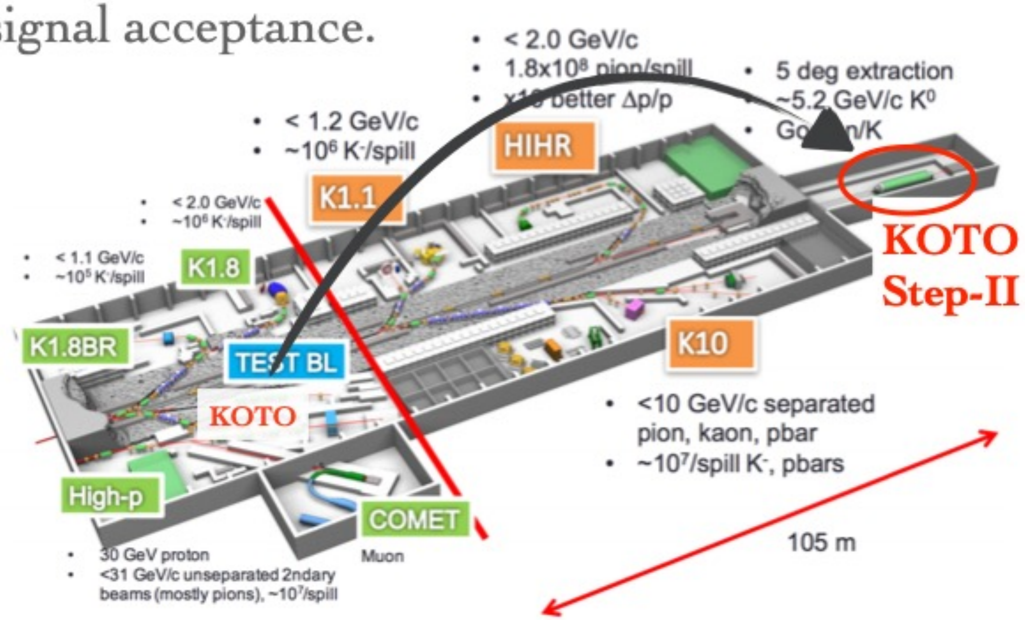


The KOTO-II experiment

[arXiv:2110.04462v1]

KOTO Step-II aims to measure $K_L \to \pi^0 \nu \bar{\nu}$ with SES of O(10^{-13}), based on:

- Higher J-PARC accelerator beam power.
- New beamline with the richer KL yields.
- Larger detector for the better signal acceptance.



But, it will take 6 years
to extend the Hadron hall.

Expect KOTO Step-II to have $K_L \to \pi^0 \nu \bar{\nu}$ 35 SM events,
with 56 BG events.

The KOTO-II experiment

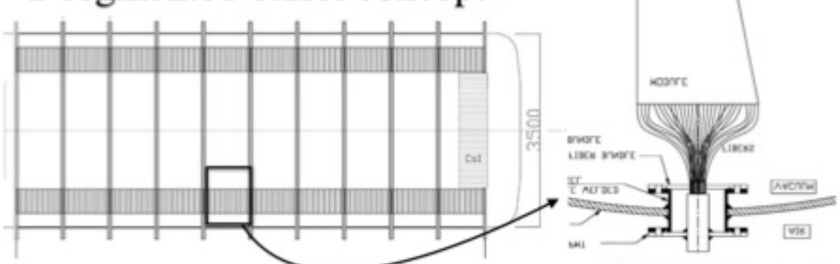
Detector

KOTO STEP-II

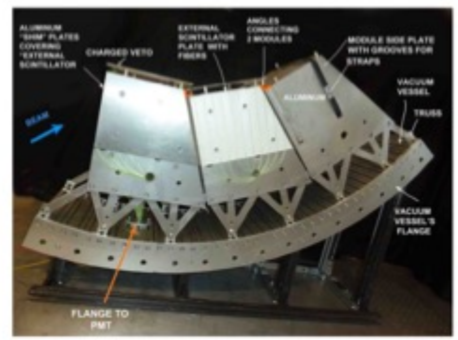
[arXiv:2110.04462v1]

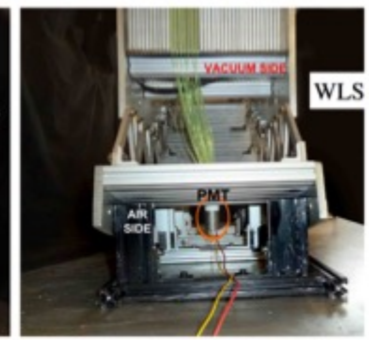
- Calorimeter Diameter: 2m → 3m; Fiducial region: 2m → 12m
- Z-segmented barrel veto to improve position & timing resolution.
  - The barrel veto is at the R&D stage.

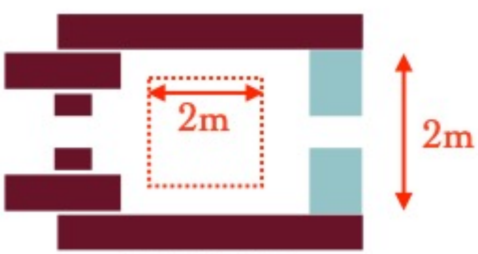
z-segmented barrel concept



PMT outside vacuum







KOTO

KOTO Step-II

Summary

Rare kaon processes are an excellent portal to explore physics beyond the Standard Model.
Specific channels benefit from high suppression, precise SM theoretical prediction, excellent sensitivity to new physics and particular experimental handles.
A global picture is needed to pin down new physics:
many precision measurements and precise theory, and study patterns and correlations of new physics models.

Kaon Physics is a portal to explore physics beyond the SM.
Excellent sensitivity to rare kaon decays, LF/LN violation processes and Lepton Universality tests. Program to search for feebly interacting particles.

Many present results.
Plans for longer term high-intensity kaon beam experiments.