Recent results and prospects on rare Kaon decays

Cristina Lazzeroni (University of Birmingham)

MITP Seminar
Open Questions and Future Directions in Flavour Physics

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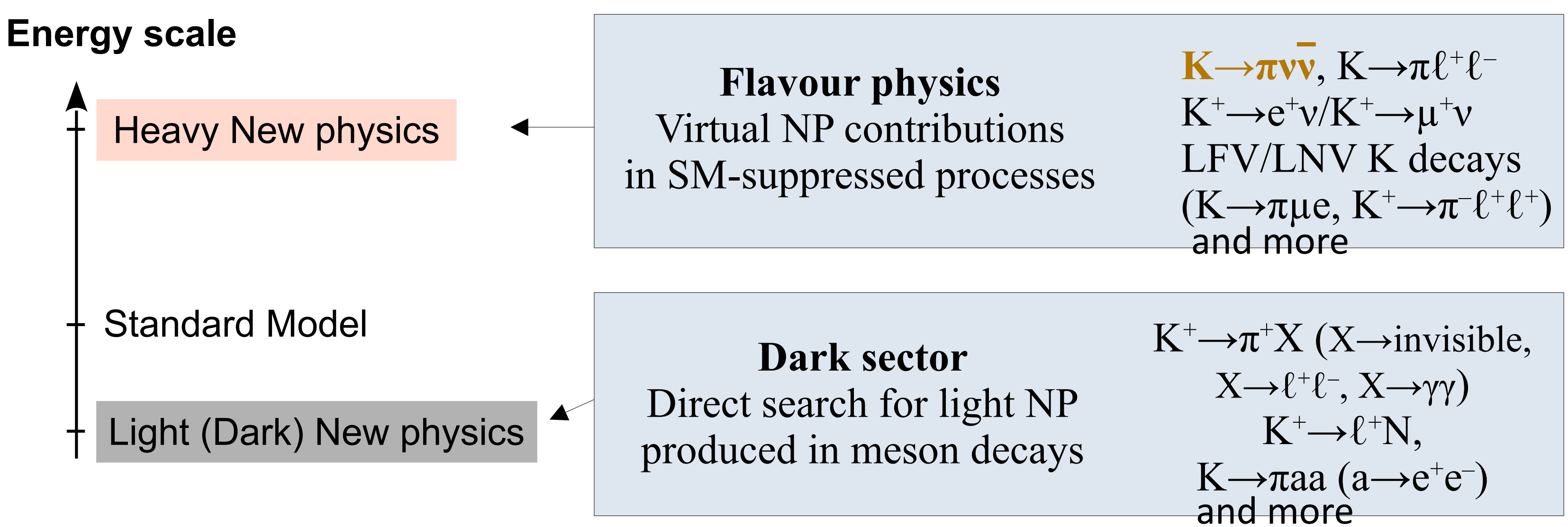
Kaons: flavour physics laboratory@ CERN SPS

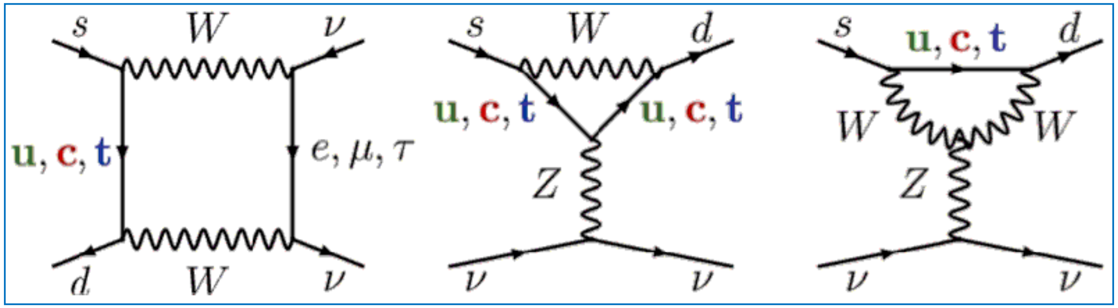
The quintessential precision frontier experiments:
few decay modes, simple final states, large statistics.

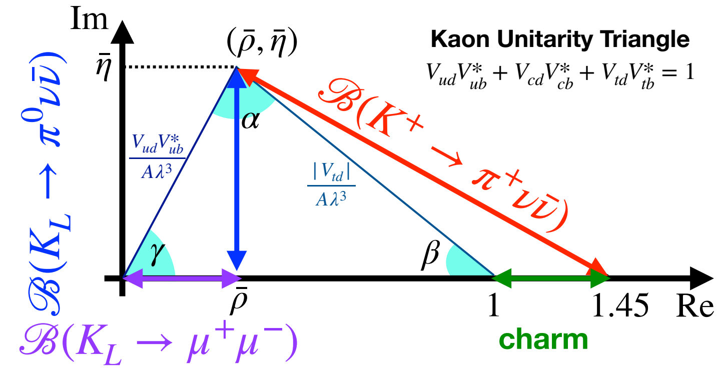
Sensitive probes of new physics:



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

SM: box and penguin diagrams





FCNC process with highest CKM suppression

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

Dominated by short-distance contribution (top quark)
t quark @ NLO QCD + 2-loop EW corrections,
c quark @ NNLO QCD + NLO EW corrections

Hadronic matrix element from BR($K^\pm \to e^\pm \pi^0 \nu$)
"Free" from hadronic uncertainties

SM branching ratios
[JHEP09(2022)148]

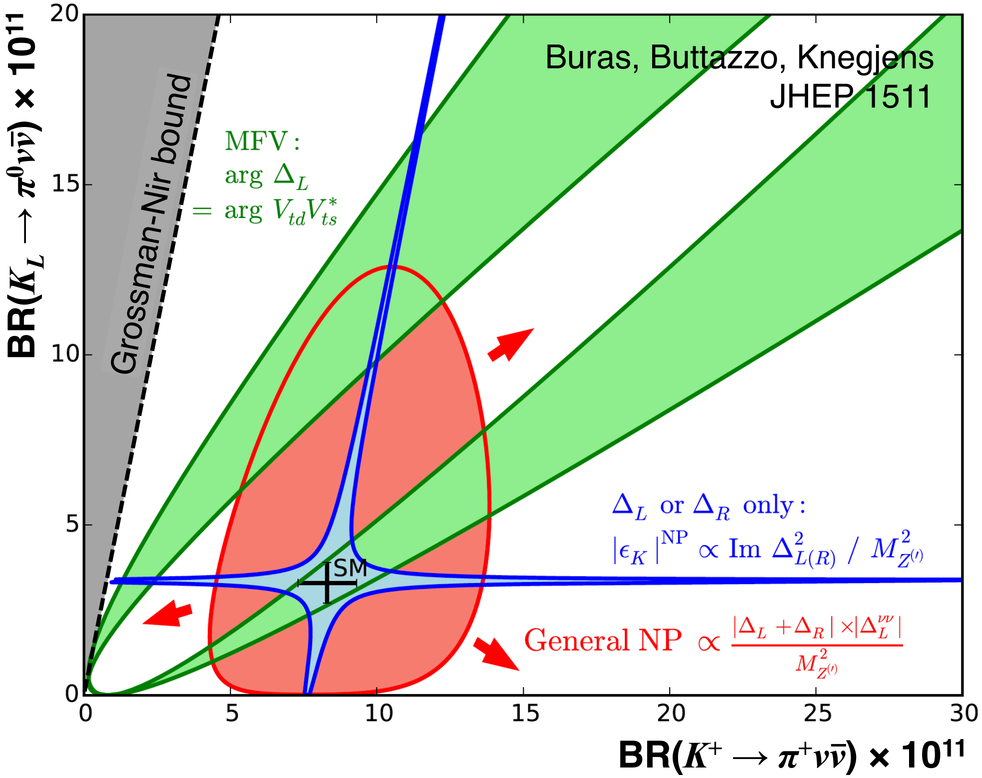
Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\nu$	7.86 ± 0.61
$K^0 \to \pi^0 \nu\nu$	2.68 ± 0.30

Exceptional SM precision
[arxiv:2105.02868]

Sources of uncertainty:
K^+ : SD ~ 2%, LD ~ 3%, Parametric ~ 7%
K^0 : SD ~ 2%, LD ~ 0.8%, Parametric ~ 11%

Before NA62: BNL E787/E949 $Br(K^+ \to \pi^+ \nu\nu) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

Sensitivity to new physics

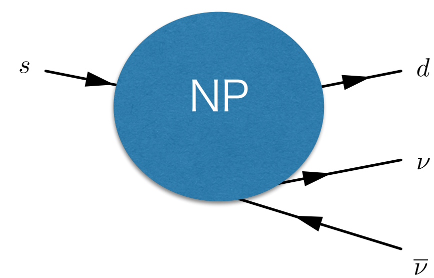


- Models with CKM-like flavor structure
  - –Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - –Z/Z' models with pure LH/RH couplings
  - –Littlest Higgs with T parity
- Models without above constraints
  - –Randall-Sundrum

Grossman-Nir bound

$$\mathscr{B}(K_L \to \pi^0\nu\bar{\nu}) < 4.3\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu})$$

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



Simplified Z,Z' models [JHEP 1511 (2015) 166]
Littlest Higgs with T-parity [EPJ C76 (2016) 182]
Custodial Randall-Sundrum [JHEP 0903 (2009) 108]
MSSM non-MFV [PEPT 2016 123B02, JHEP 0608 (2006) 064
LVF models [Eur Phys J C (2017) 77]

Important to have updated theory scenarios

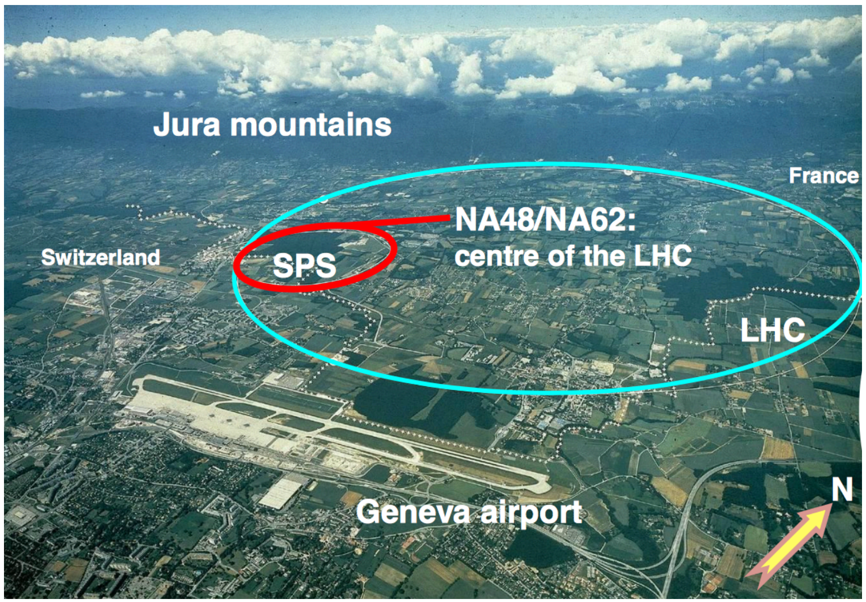
Kaon rare decays

CERN: NA62 (K^+), LHCb (K_S)

JPARC: KOTO, KOTO-II (K_L)

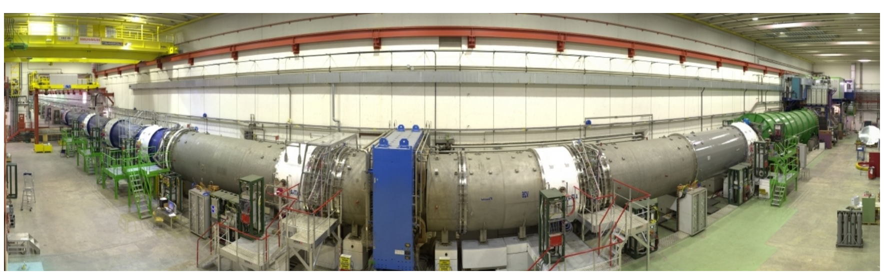
The NA62 experiment

Fixed-target experiment @ CERN North Area
400 GeV proton SPS beam



Main aim: measure $Br(K^+ \to \pi^+ \nu\nu)$ with decay-in-flight technique

Broad physics programme:
- Kaon rare decays
- Searches for LFV/LNV
- Precision measurements
- Exotic searches

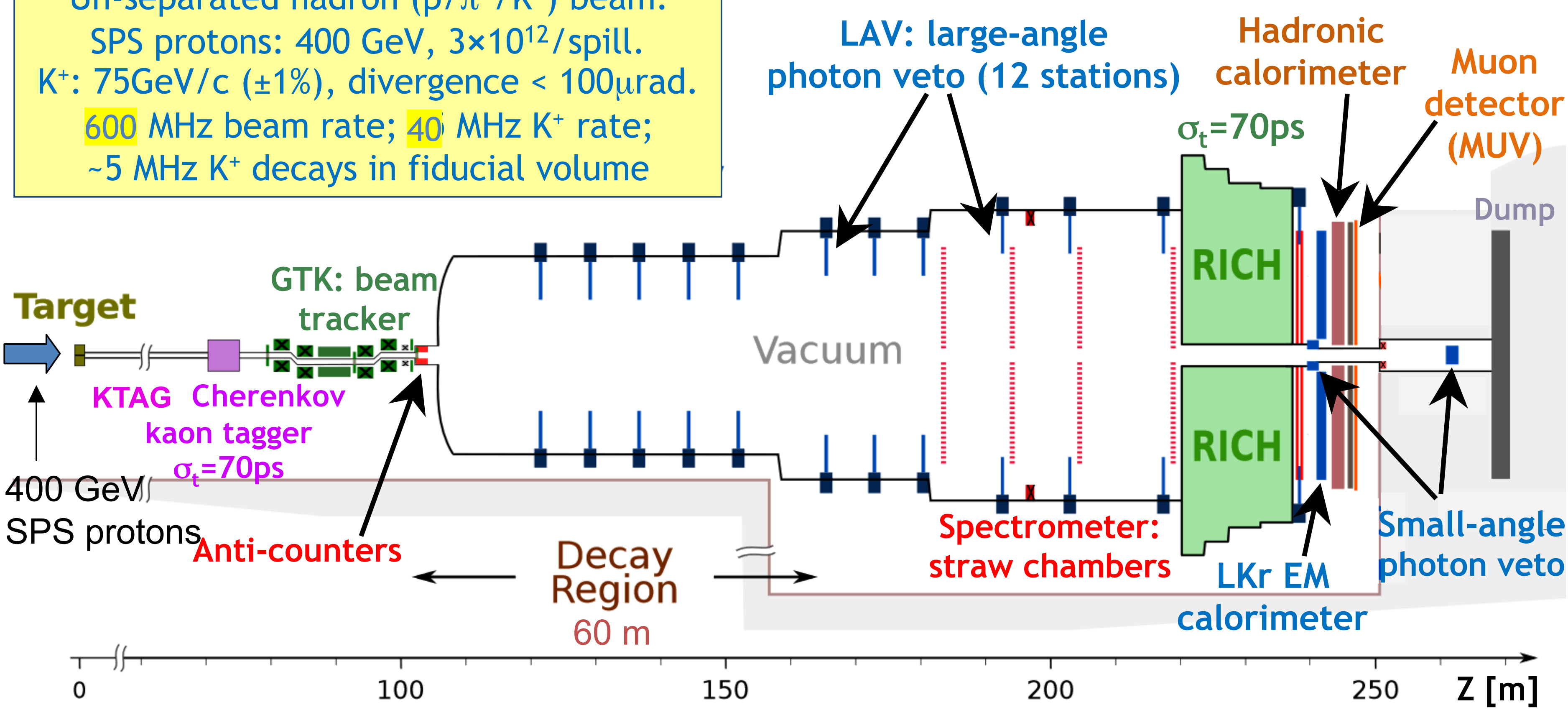


Timeline:
- 2016-2018: Run1 (2.2 10^{18} POT), first observation of $Br(K^+ \to \pi^+ \nu\nu)$
- 2021-LHC Long Shutdown 3: Run2 with improved detector

The NA62 beam and detector

Un-separated hadron (p/π^+/K^+) beam.
SPS protons: 400 GeV, 3×10^{12}/spill.
K^+: 75GeV/c (±1%), divergence < 100μrad.
600 MHz beam rate; 40 MHz K^+ rate;
~5 MHz K^+ decays in fiducial volume

NA62 collaboration, JINST 12 (2017) P05025



Un-separated hadron beam: find K^+
Boosted kaons (75 GeV)

NA62 technique

Tag K^+ and measure momentum.

Identify π^+ and measure momentum.

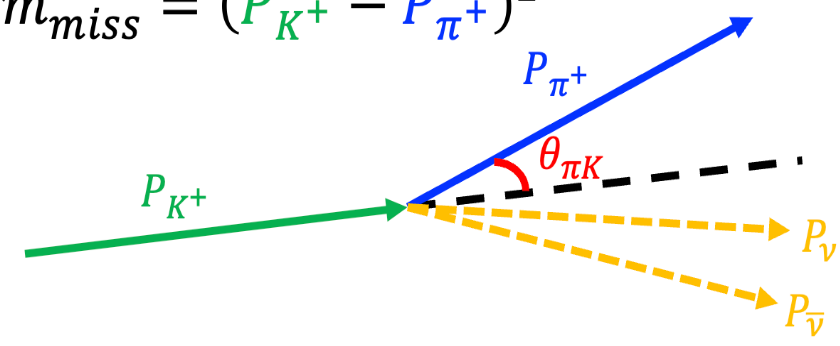
Match K^+ and π^+ in time & form vertex.

- Determine $m^2_{miss} = (P_K - P_\pi)^2$

Reject **any** additional activity.

Decay mode	Branching Ratio [PDG]
$K^+ \to \mu^+ \nu_\mu$	$(63.56 \pm 0.11)\,\%$
$K^+ \to \pi^+ \pi^0$	$(20.67 \pm 0.08)\,\%$
$K^+ \to \pi^+ \pi^+ \pi^-$	$(5.583 \pm 0.024)\,\%$
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	$(4.247 \pm 0.024) \times 10^{-5}$

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



$\mathcal{O}(100)\, ps$ timing between detectors

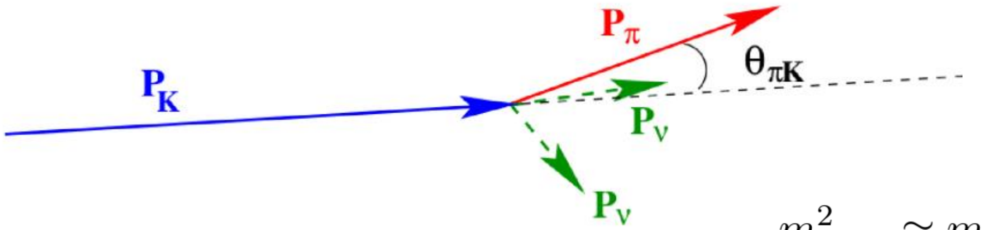
$\mathcal{O}(10^4)$ background suppression from kinematics

$> 10^7$ muon rejection

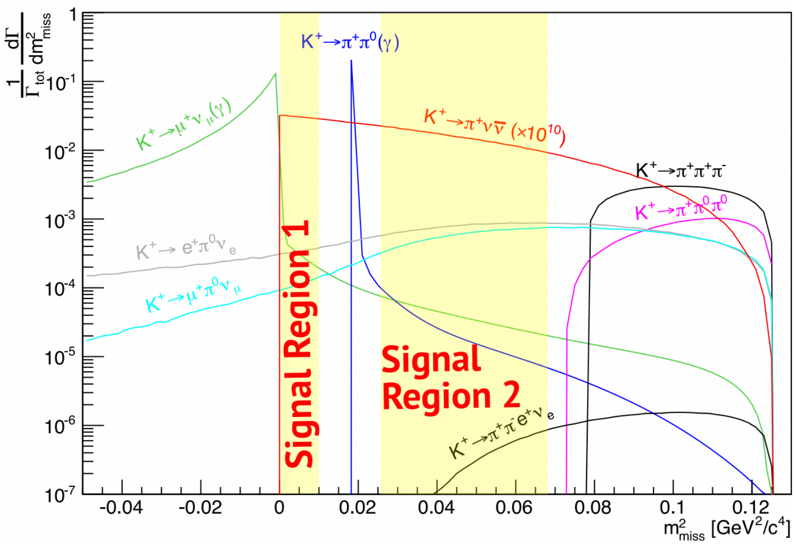
$> 10^7$ rejection of π^0 from $K^+ \to \pi^+ \pi^0$ decays

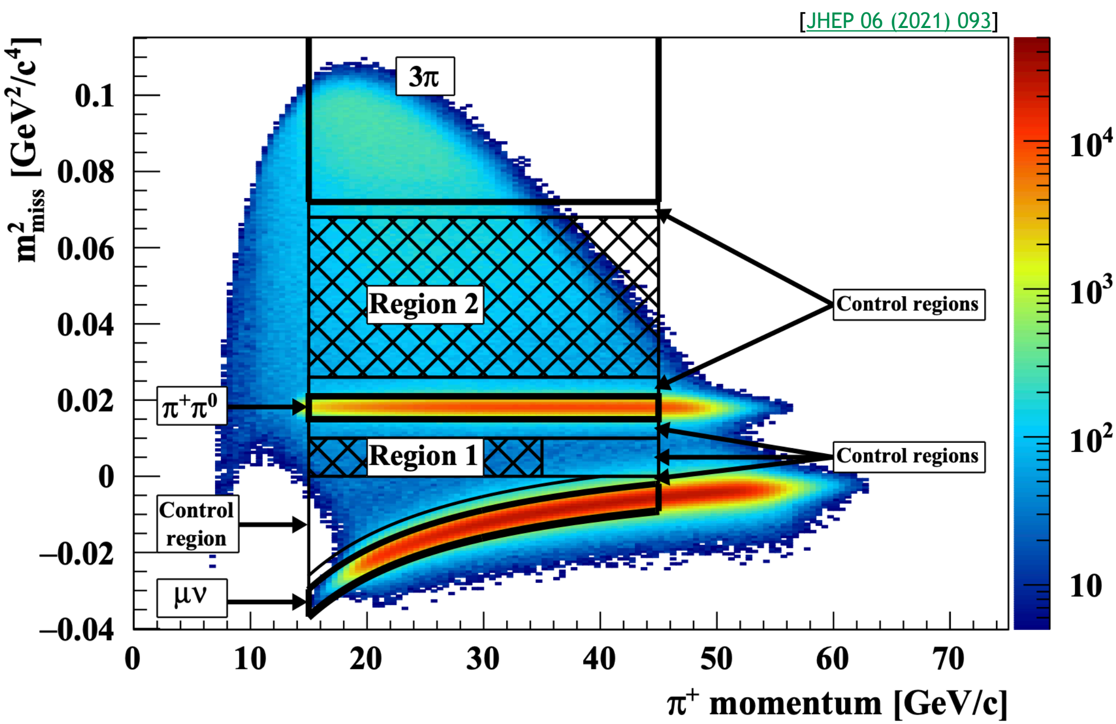
Extreme challenge but… few decay modes, simple final states, large statistics. Maximum use of data for bckg evaluation.

NA62 technique



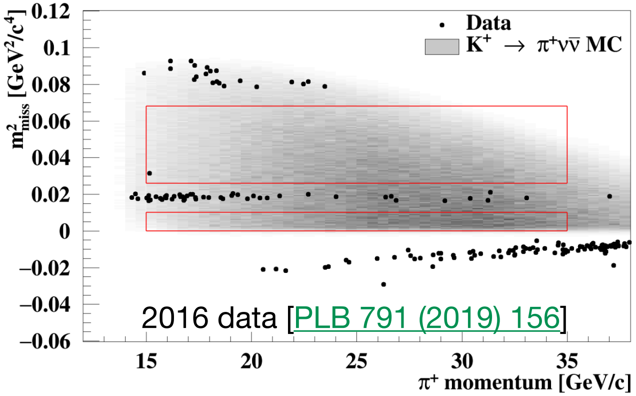
$$m^2_{miss} \approx m^2_K \left(1 - \frac{|p_\pi|}{|p_K|}\right) + m^2_\pi \left(1 - \frac{|p_K|}{|p_\pi|}\right) - |p_K||p_\pi|\theta^2_{\pi K}$$

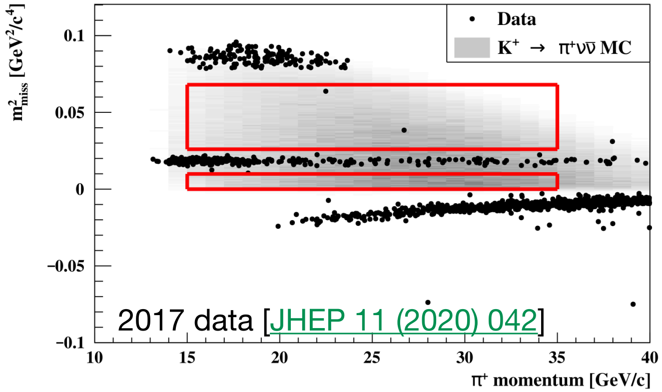


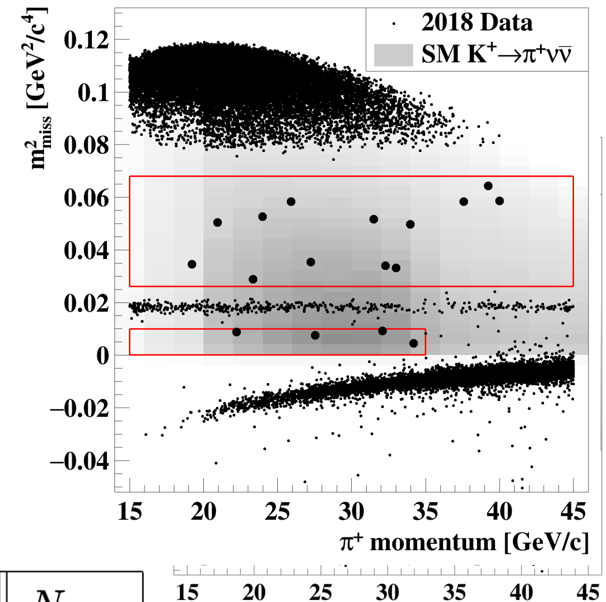


π^+ momentum range: 15—45 GeV/c

Result: 2016+2017+2018 data







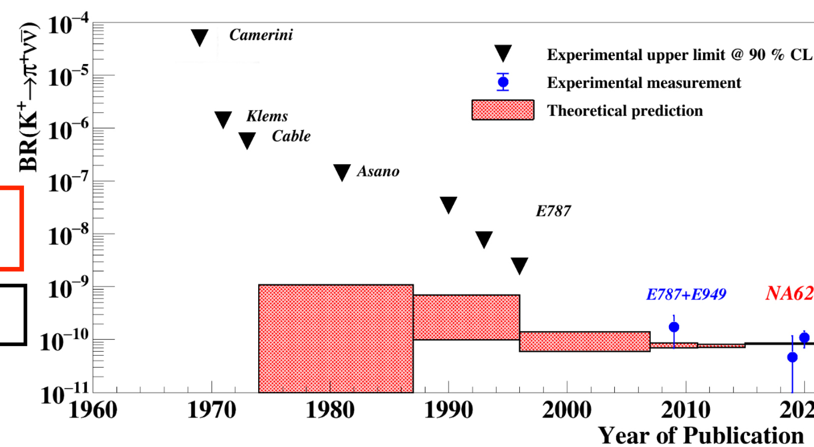
(* $N^{SM,exp}_{\pi\nu\bar{\nu}}$ assumes SM BR from [JHEP 11 (2015) 166])

Data-taking year	[Reference]	N_{bg}	$N^{SM,exp}_{\pi\nu\bar{\nu}}$	N_{obs}
2016	[PLB 791 (2019) 156]	$0.152^{+0.093}_{-0.035}$	0.267 ± 0.020	1
2017	[JHEP 11 (2020) 042]	1.46 ± 0.33	2.16 ± 0.13	2
2018	[JHEP 06 (2021) 093]	$5.42^{+0.99}_{-0.75}$	7.58 ± 0.40	17
2016–18	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$	10.01 ± 0.42	20

$N^{SM,exp}_{\pi\nu\bar{\nu}}$ assumes: $\mathcal{B}^{SM}_{\pi\nu\bar{\nu}} = 8.4\times10^{-11}$

$$\mathscr{B}(K^+ \to \pi^+\nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.4}\Big|_{\text{stat}} \pm 0.9_{\text{syst}}\right) \times 10^{-11} \quad \text{at} \quad 68\,\%\ \text{CL}$$

In background-only hypothesis: $p = 3.4 \times 10^{-4} \Rightarrow$ significance=3.4σ.

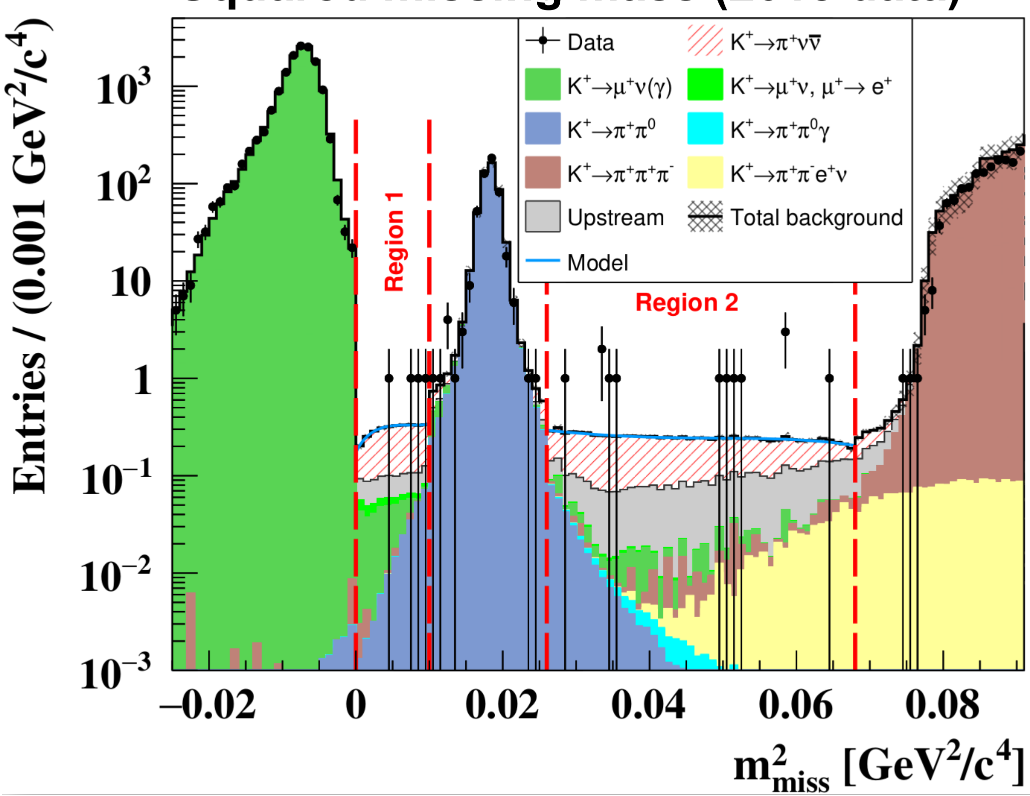


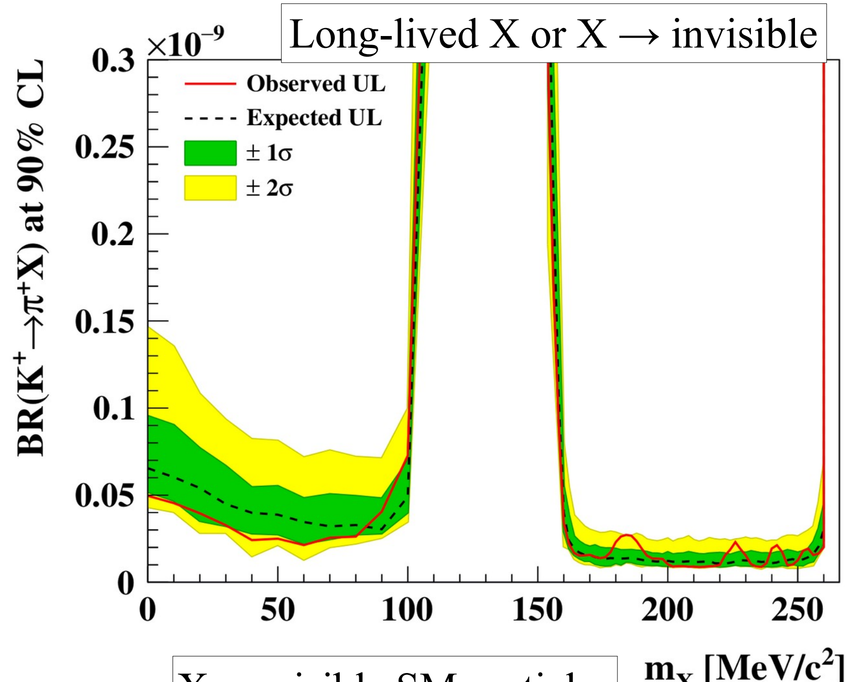
Search for $K^+ \to \pi^+ X_{inv}$

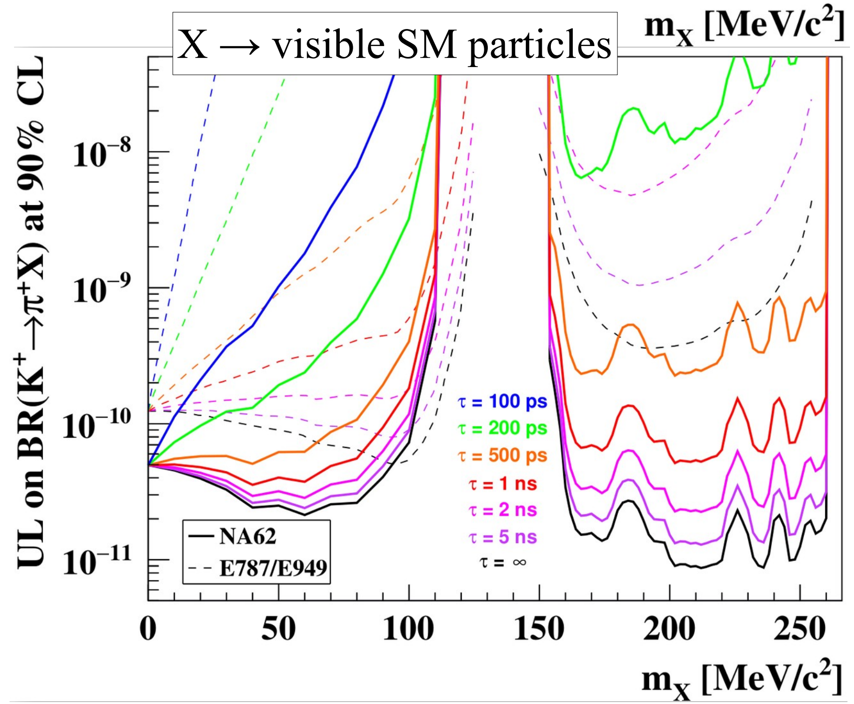
[JHEP 06 (2021) 093]

By-product of $K^+ \to \pi^+ \nu\nu$ analysis
Peak search in **R1** ($0 \leq m_X \leq 110$ MeV/c^2)
and **R2** ($154 \leq m_X \leq 260$ MeV/c^2)
Acceptance scan over m_X and τ_X
Main background: $K^+ \to \pi^+ \nu\nu$

Squared missing mass (2018 data)





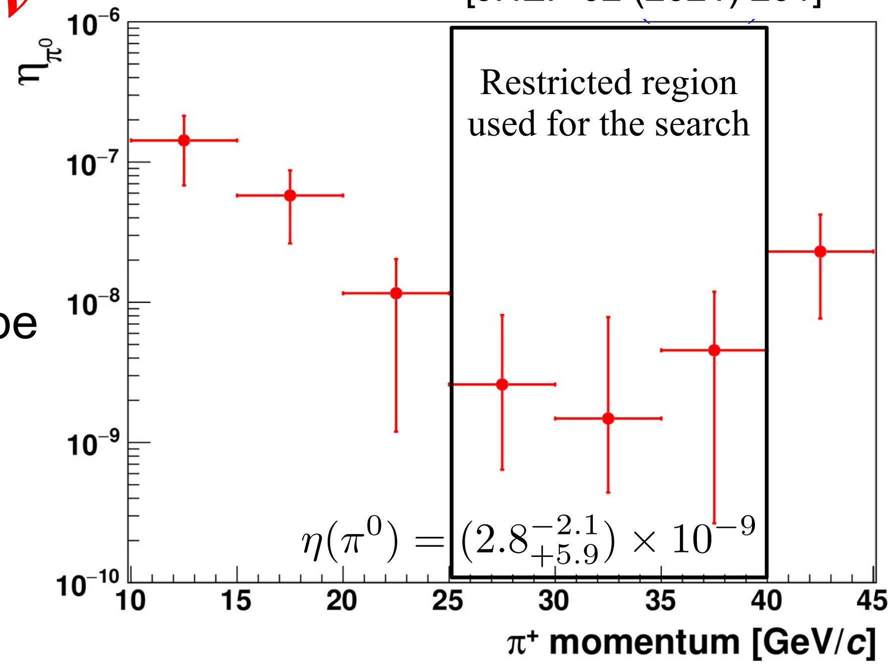


Search for $K^+ \to \pi^+ \pi^0_{inv}$

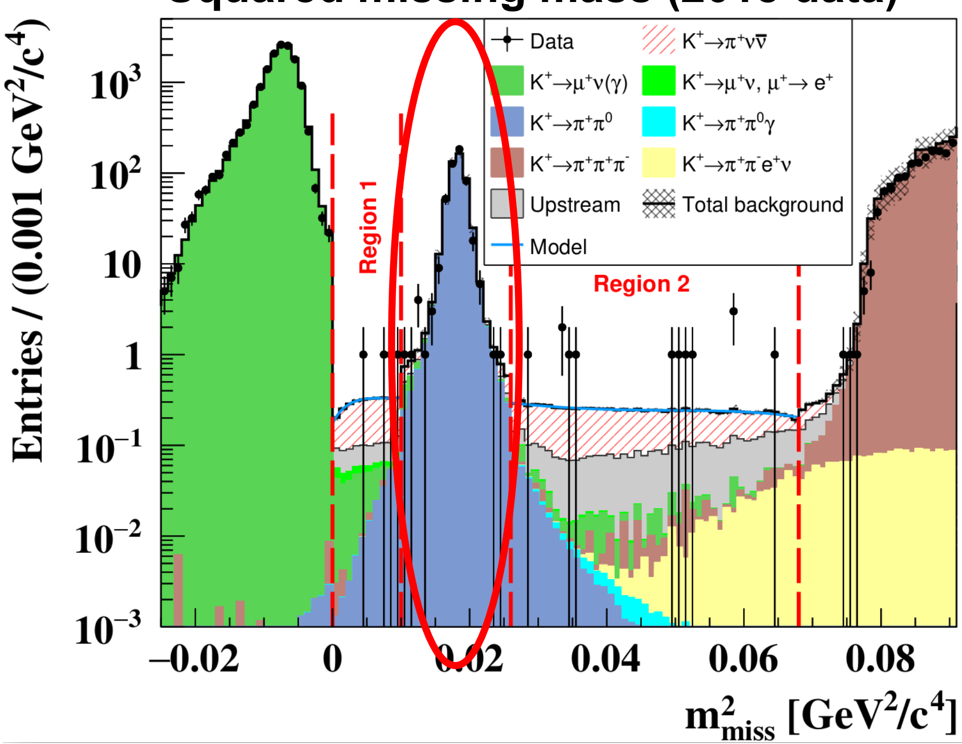
Basic event selection as $\mathbf{K^+ \to \pi^+ \nu\nu}$, but applied to $K^+ \to \pi^+\pi^0$ region on 10% of Run1 data

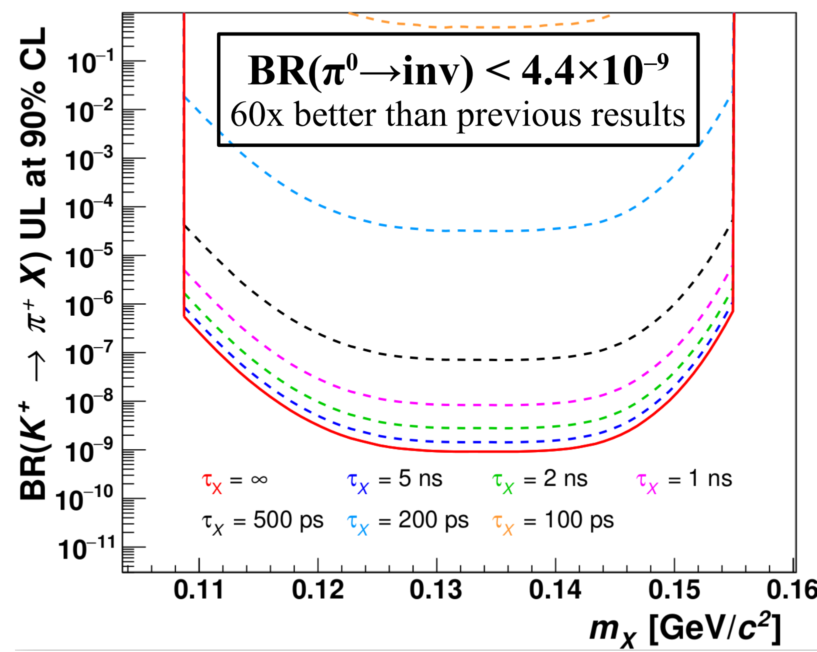
Main $\mathbf{K^+ \to \pi^+\pi^0}$ $(\pi^0 \to \gamma\gamma)$ background estimated from MC with single γ efficiency by tag-and-probe
Expected $\pi^0 \to \gamma\gamma$ events: $\mathbf{10^{+22}_{-8}}$, observed: **12**.
[reaching limits from γ-veto inefficiency]

[JHEP 02 (2021) 201]



Squared missing mass (2018 data)

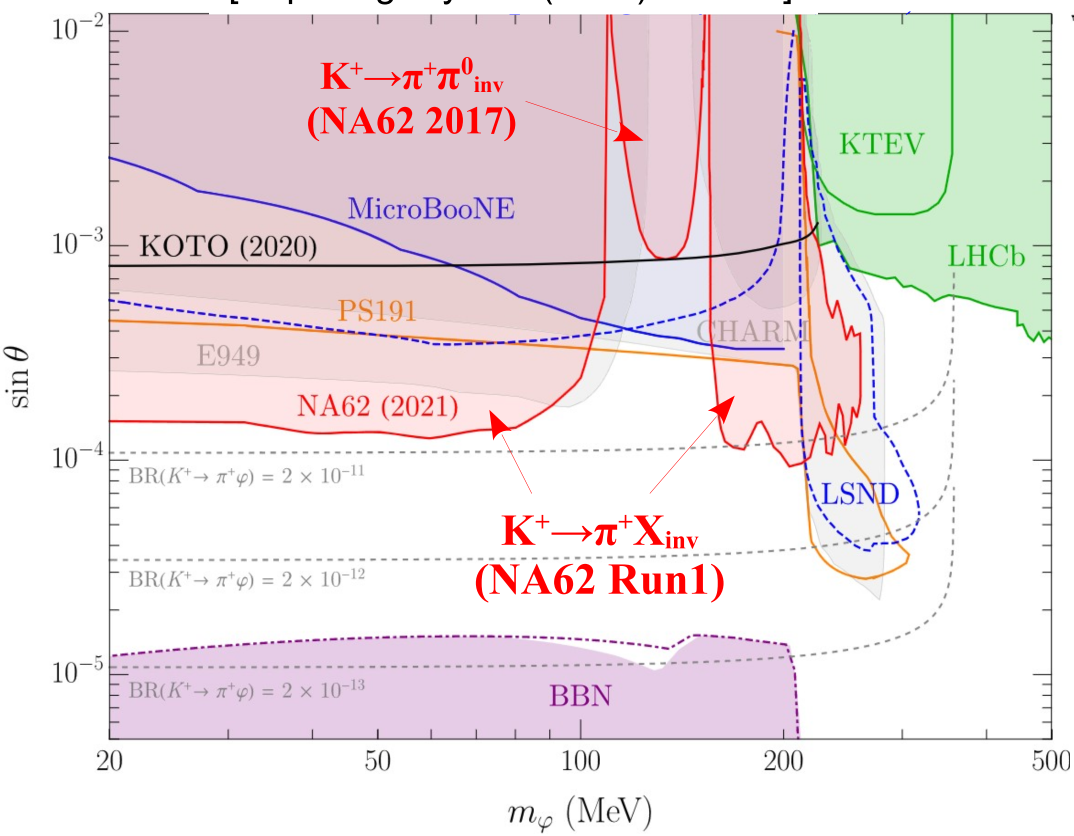




Interpretation of $K^+ \to \pi^+ X$

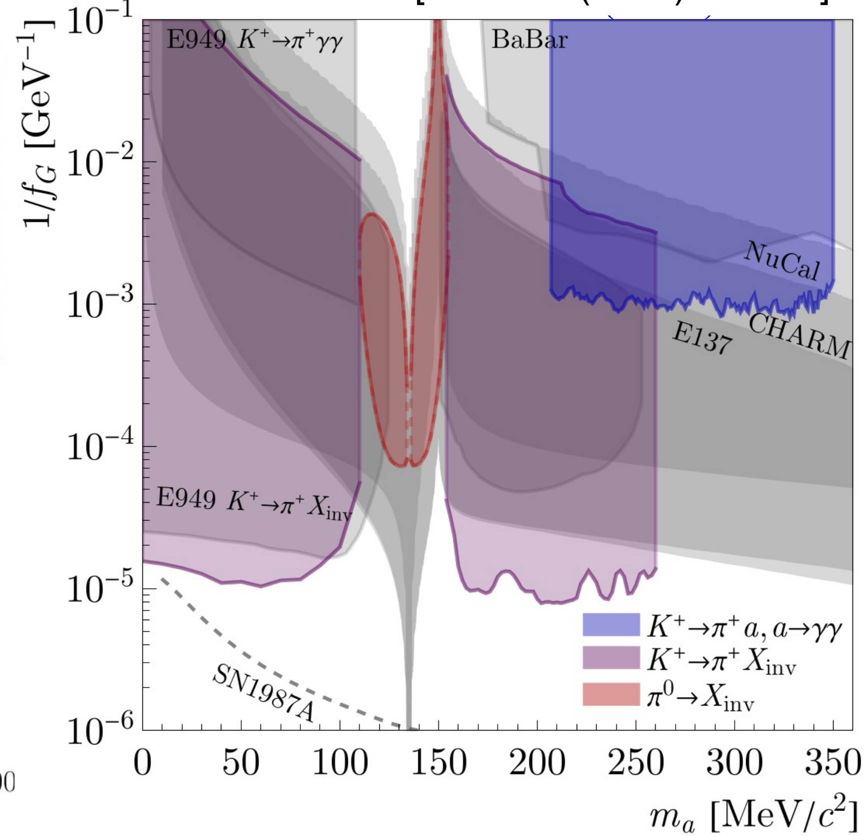
Limits on BRs for $K^+ \to \pi^+ X_{inv}$, $K^+ \to \pi^+\pi^0_{inv}$, $K^+ \to \pi^+ X (X \to \gamma\gamma)$
translate to parameter space for hidden-sector portals

[ReptProgPhys 86 (2023) 016201]



BC4 model, X is a dark scalar

[PLB 850 (2024) 138513]



BC11 model, a is an axion

[BC models within the Physics Beyond Colliders framework]

Upgrading NA62

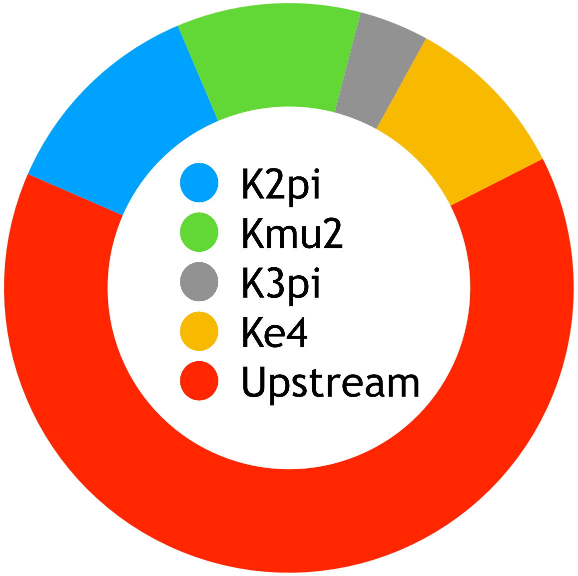
2016—18 analysis proved NA62 technique.

Limitation: tight cuts to reject backgrounds ⇒ reduces signal efficiency.

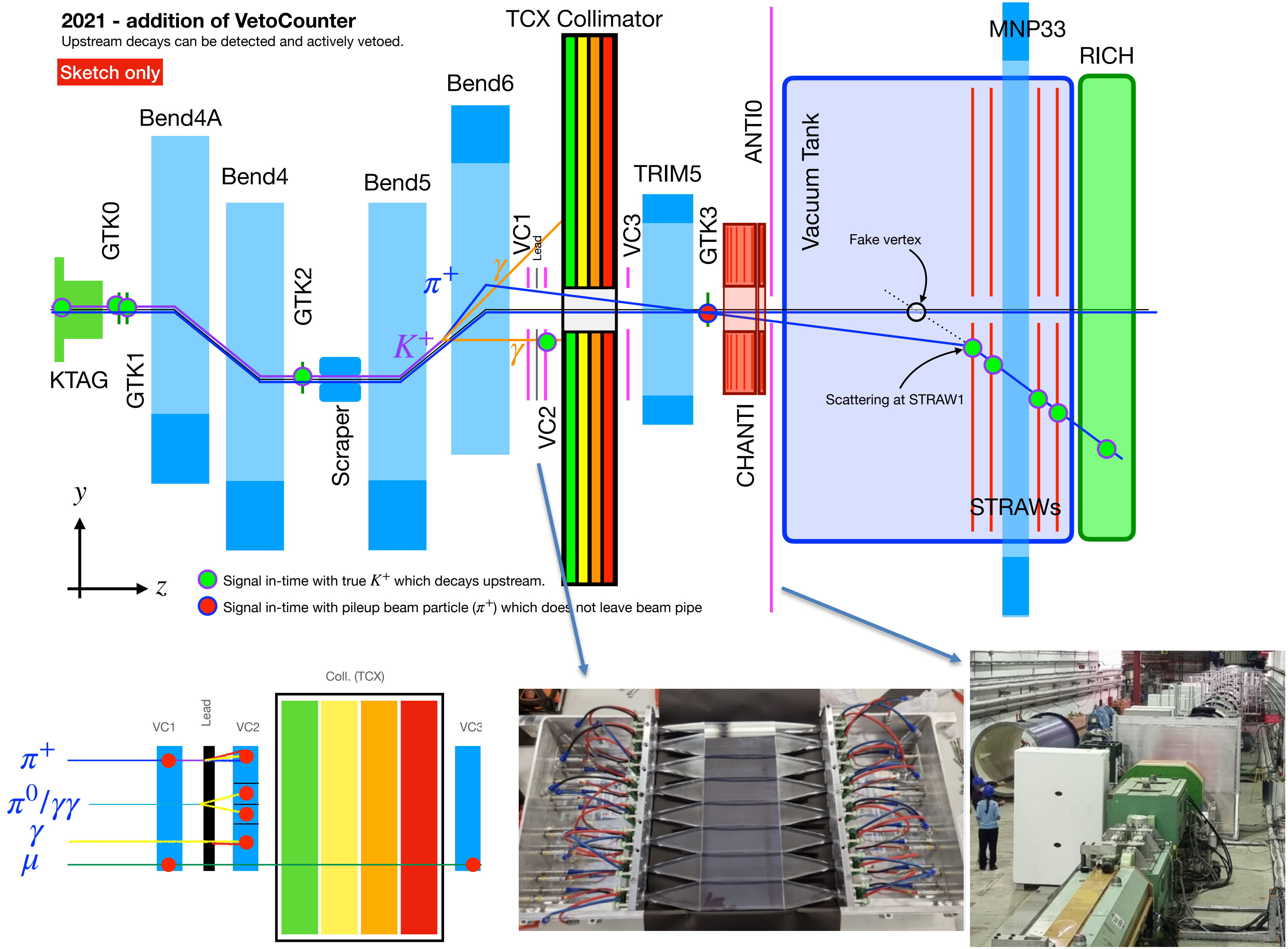
To improve: need new tools to control background.

Background	N(exp) 2018 (S2)
Upstream	$2.76^{+0.90}_{-0.70}$
$K^+ \to \pi^+\pi^0$	0.52 ± 0.05
$K^+ \to \mu^+\nu$	0.45 ± 0.06
$K^+ \to \pi^+\pi^-e^+\nu$	0.41 ± 0.10
$K^+ \to \pi^+\pi^+\pi^-$	0.17 ± 0.08
Total	$4.31^{+0.91}_{-0.72}$

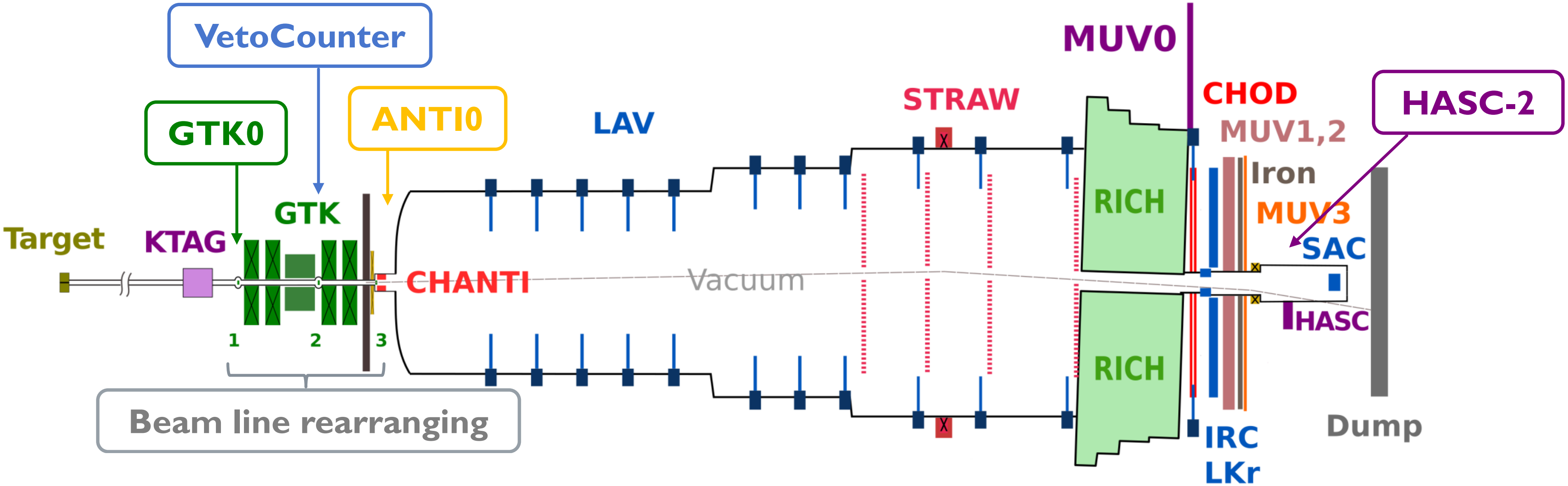
K^+ decays in decay tank



Upstream background


2021 - addition of VetoCounter
Upstream decays can be detected and actively vetoed.
Sketch only
TCX Collimator
MNP33
RICH
Bend6
Bend4A
Bend4
Bend5
TRIM5
ANTI0
Vacuum Tank
GTK0
GTK2
GTK3
VC1
Lead
VC3
VC2
Fake vertex
π^+
γ
K^+
KTAG
GTK1
Scraper
CHANTI
Scattering at STRAW1
STRAWs
y
z
Signal in-time with true K^+ which decays upstream.
Signal in-time with pileup beam particle (π^+) which does not leave beam pipe
Coll. (TCX)
VC1
Lead
VC2
VC3
π^+
$\pi^0/\gamma\gamma$
γ
μ

2021-2022 detector improvements



Additional **GTK** station

Beam line rearranging to swipe away upstream π^+

VetoCounter to detect upstream decays

ANTI0 to veto accidental particles

HASC-2 to further suppress $K^+ \to \pi^+\pi^0$ decays

Intensity increased from 60% to 100% of nominal

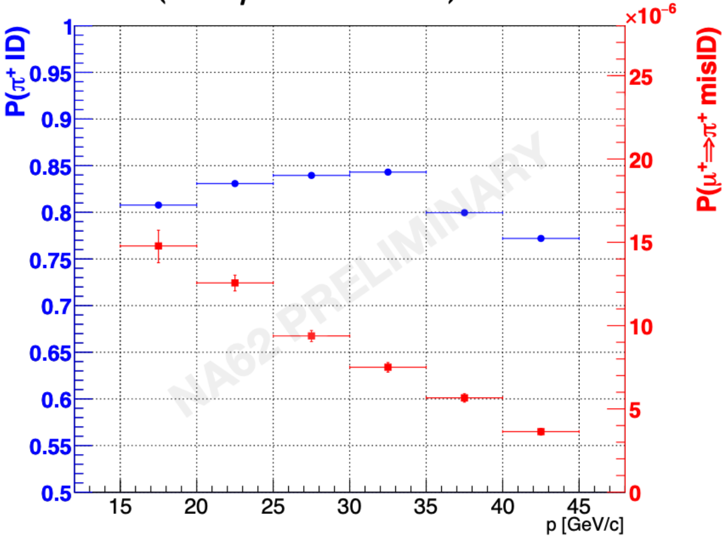
Data taking pushing to the hardware limit of intensity for NA62

Particle identification performance (2021-22)

Calorimeters

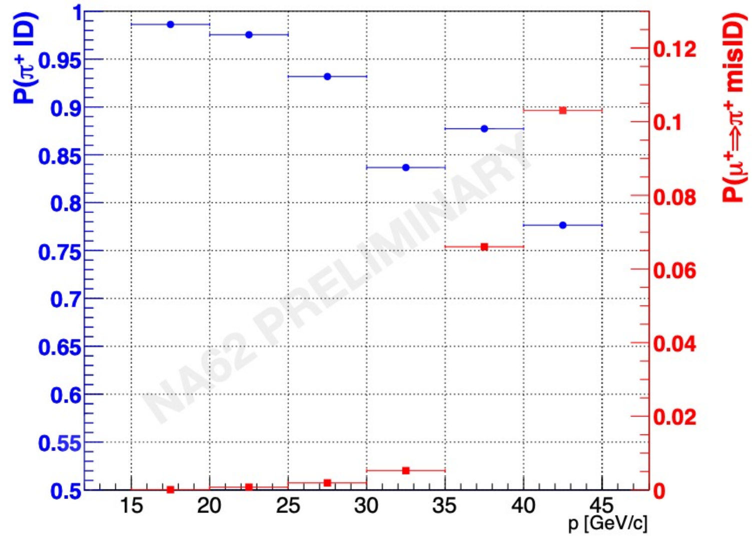
Use BDT classifier for LKr & MUV1,2

+ **MUV3** (fast μ^+ detector)



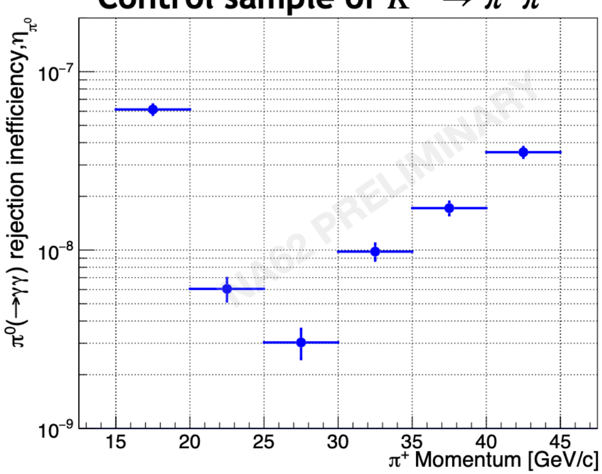
RICH

Designed to distinguish between π^+/μ^+ with $15 - 35$ GeV/c.



Photon veto:

Control sample of $K^+ \to \pi^+\pi^0$



$$\varepsilon(\pi\,\textbf{ID}) = (73.00 \pm 0.01)\,\%$$

$$P(\mu^+\,\textbf{misID as}\,\pi^+) = (1.3 \pm 0.2) \times 10^{-8}$$

$$\eta_{\pi^0} = (1.72 \pm 0.07) \times 10^{-8}$$

Signal sensitivity

Normalisation channel: $K^+ \to \pi^+\pi^0$, momentum range $p \in [15,45]$ GeV/c

Effective number of K^+ decays, N_K:

Number of normalisation events

Downscaling factor of normalisation trigger (generally 400)

$$N_K = \frac{N_{\pi\pi} D_0}{\mathcal{B}_{\pi\pi} A_{\pi\pi}}$$

Branching ratio of $K^+ \to \pi^+\pi^0$ decay

Acceptance of normalisation selection

Single event sensitivity:

(Branching ratio corresponding to expectation of 1 event)

$$\mathcal{B}_{SES} = \frac{1}{N_K \varepsilon_{RV} \varepsilon_{trig} A_{\pi\nu\bar{\nu}}}$$

Random veto efficiency

Trigger efficiency (ratio)

Signal selection acceptance

Number of expected SM events:

(For comparison to previous results use $\mathcal{B}^{SM}_{\pi\nu\bar{\nu}} = 8.4 \times 10^{-11}$ [JHEP 11 (2015) 166], but results are independent of this choice)

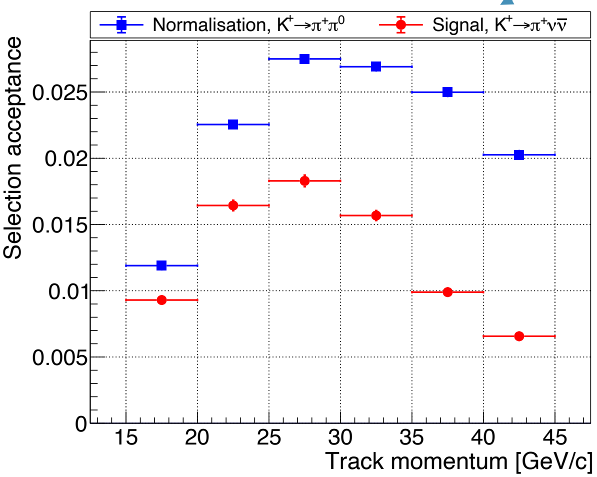
$$N^{SM}_{\pi\nu\bar{\nu}} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}}$$

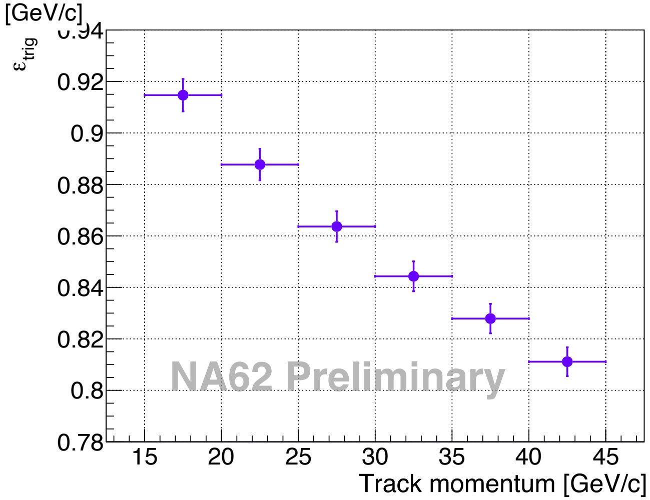
Single-event sensitivity (2021-2022 data)

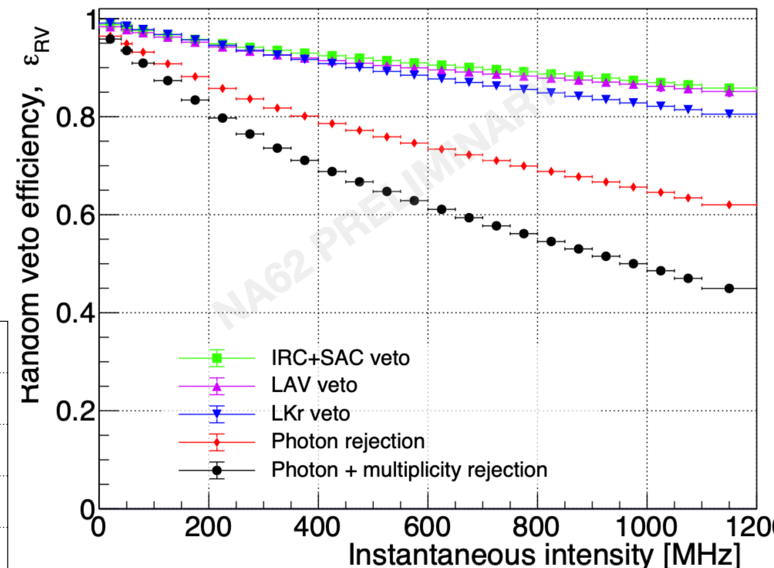
$$N^{SM,exp}_{\pi\nu\nu} = \frac{BR(\pi\nu\nu)_{SM}}{SES} = \frac{BR(\pi\nu\nu)_{SM}}{BR(\pi\pi)} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} (N_{\pi\pi} \times D_0)\, \varepsilon_{trig}\, \varepsilon_{RV}$$

With respect to 2018 analysis:

- Improvements in energy reconstruction
- "Bayesian" K^+-π^+ matching
- Increased signal yield
- More precise ε_{trig} and ε_{RV} evaluation

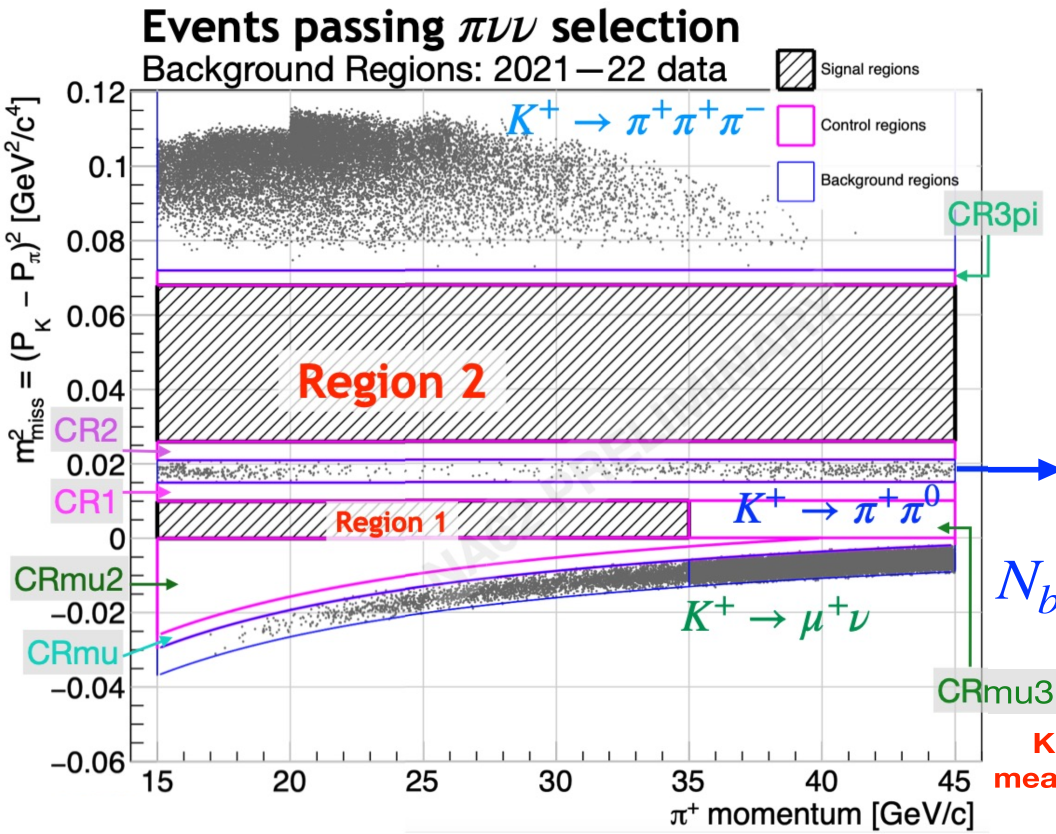






[Random veto (RV): efficiency loss due to beam activity]

Background evaluation (2021-2022 data)



Backgrounds from kinematic misconstruction tails in m^2_{miss}

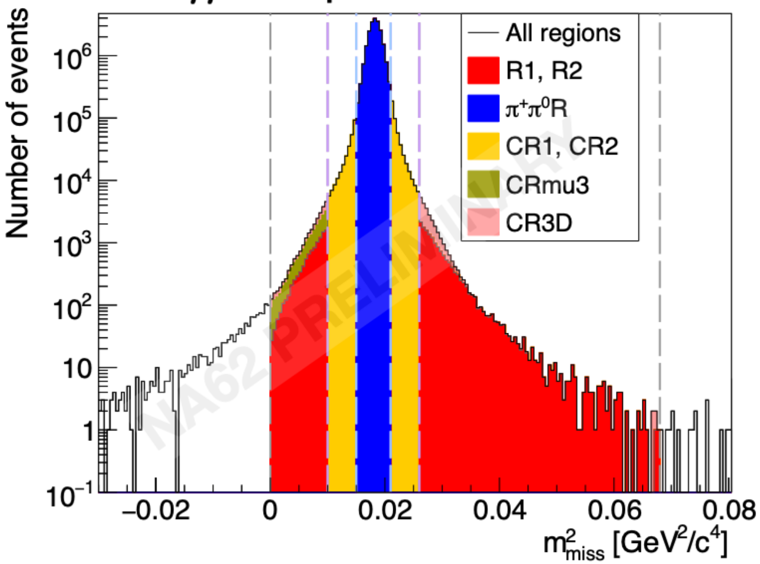
$$N_{bg} = N_{bkgR} \cdot f_{tail} = N_{bkgR} \cdot \frac{N^{CS}_{SR}}{N^{CS}_{bkgR}}$$

- N_{bkgR}: Number of events passing signal selection in background region
- f_{tail}: Kinematic tail fraction: measured in control sample
- N^{CS}_{SR}: Control sample events in Signal Regions
- N^{CS}_{bkgR}: Control sample events in Background Region

Backgrounds: kaon decays (2021-2022 data)

$K^+ \to \pi^+\pi^0(\gamma)$

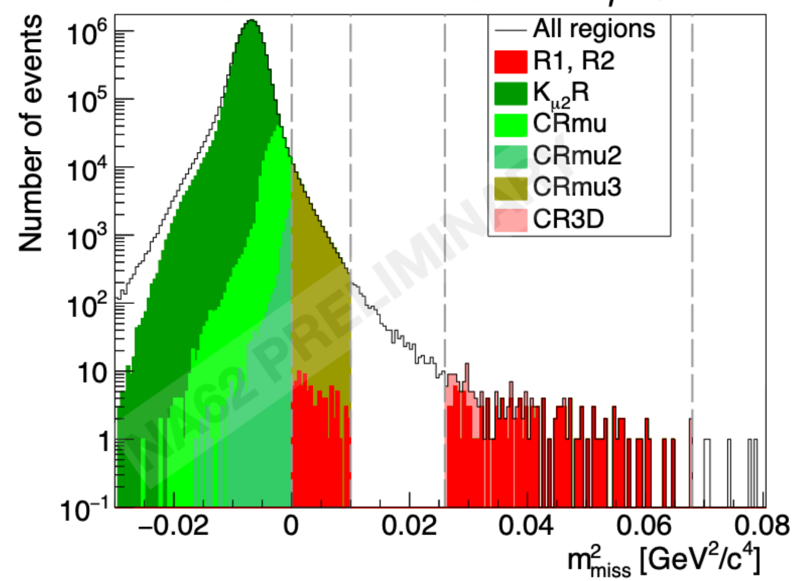
control sample of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ and 2 photons detected in LKr:



$$N_{bg}(K^+ \to \pi^+\pi^0(\gamma)) = 0.83 \pm 0.05$$

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

control sample of $K^+ \to \mu^+\nu$ events with RICH PID=π^+ and Calo PID=μ^+:



- <1% contribution from $K^+ \to \mu^+\nu$ followed by $\mu^+ \to e^+\nu\nu$.

$$N_{bg}(K^+ \to \mu^+\nu) = 0.9 \pm 0.2$$

$K^+ \to \pi^+\pi^0\gamma$: included with "kinematic tails" estimation

$K^+ \to \mu^+\nu\gamma$: not included in "kinematic tails" estimation if γ overlaps μ^+ at LKr (leading to misID as π^+)

- Suppression: based on $(P_K - P_\mu - P_\gamma)^2$ and E_γ with γ = LKr cluster (mis)associated to muon.
  - Necessary for 2021—22 data, since Calorimetric PID degraded at higher intensities.
- Estimation: min. Bias data control sample with signal in MUV3 : $N_{bg}(K^+ \to \mu^+\nu\gamma) = 0.8 \pm 0.4$
- Validation: data sample without $K^+ \to \mu^+\nu\gamma$ veto and PID = "less pion-like" (Calo BDT bins below π^+ bin).

Backgrounds: upstream (2021-2022 data)

$$N_{bg} = \sum_i N_i f_{cda} P_i^{match}$$

N Upstream Reference Sample: signal selection but invert CDA cut (CDA>4mm)

f_{cda} Scaling factor : bad cda —> good cda

P_{match} Probability to pass $K^+ - \pi^+$ matching

Upstream reference sample contains all known upstream mechanisms.

- N provides normalisation.

f_{CDA} **depends only on geometry.**

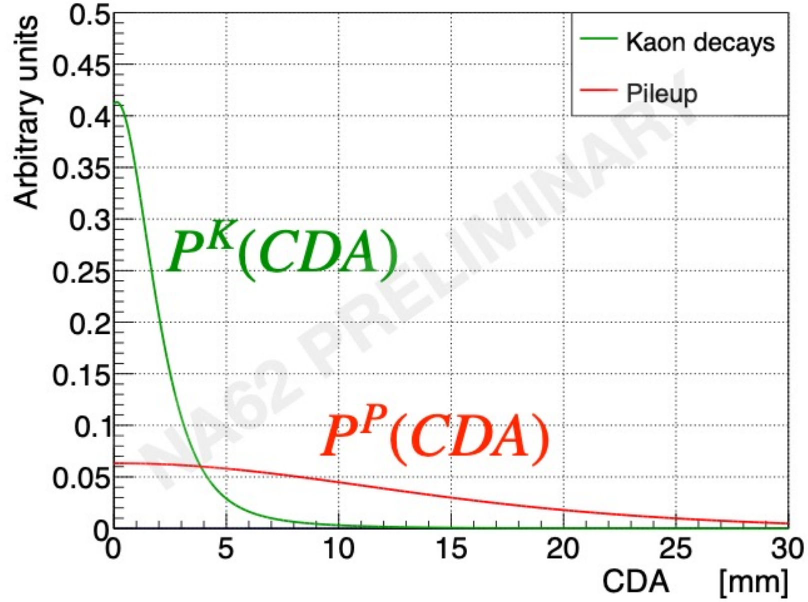
P_{match} **depends on** $(\Delta T_+, N_{GTK})$.

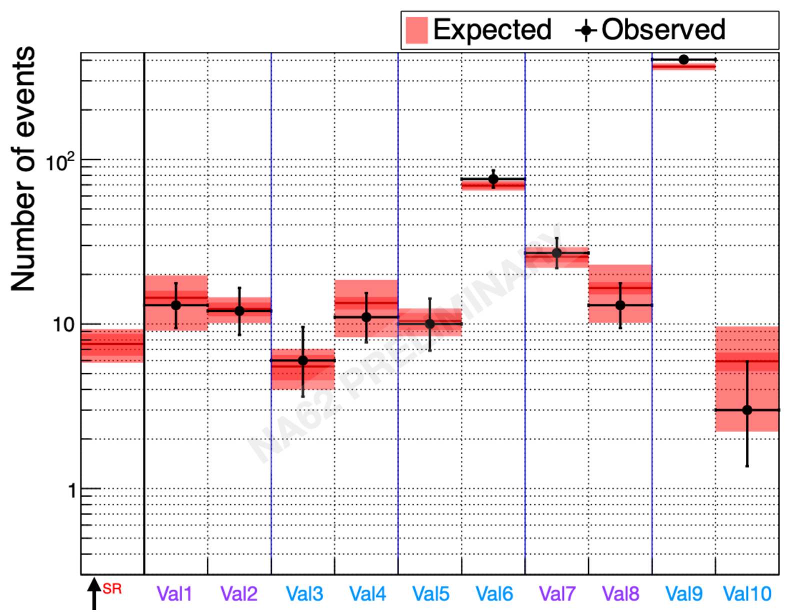
(Time matching, intensity/pileup estimator)

Invert & loosen upstream vetos to enrich with different mechanisms:

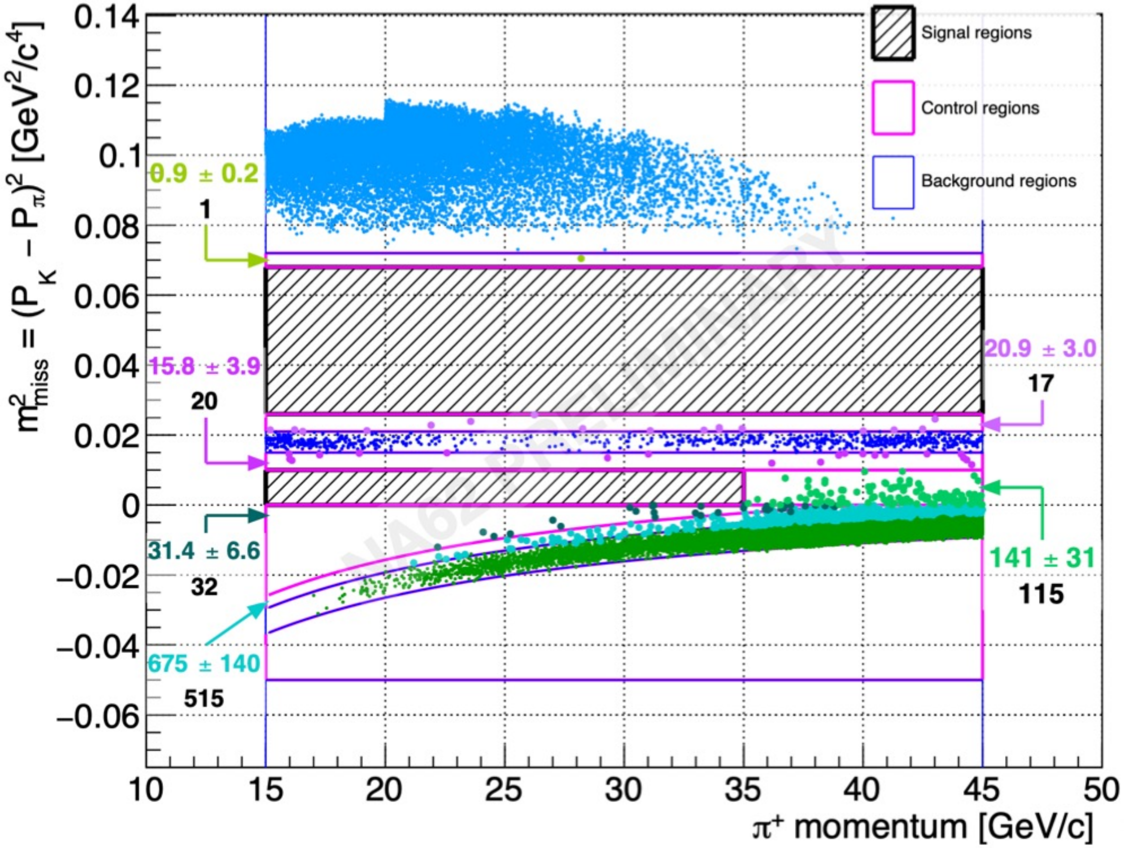
- Interaction-enriched: Val1,2,7,8
- Accidental-enriched: Val3,4,5,6,9,10
- **All independent.**

$$N_{bg}(\text{Upstream}) = 7.4^{+2.1}_{-1.8}$$





Background evaluation (2021-22 data)

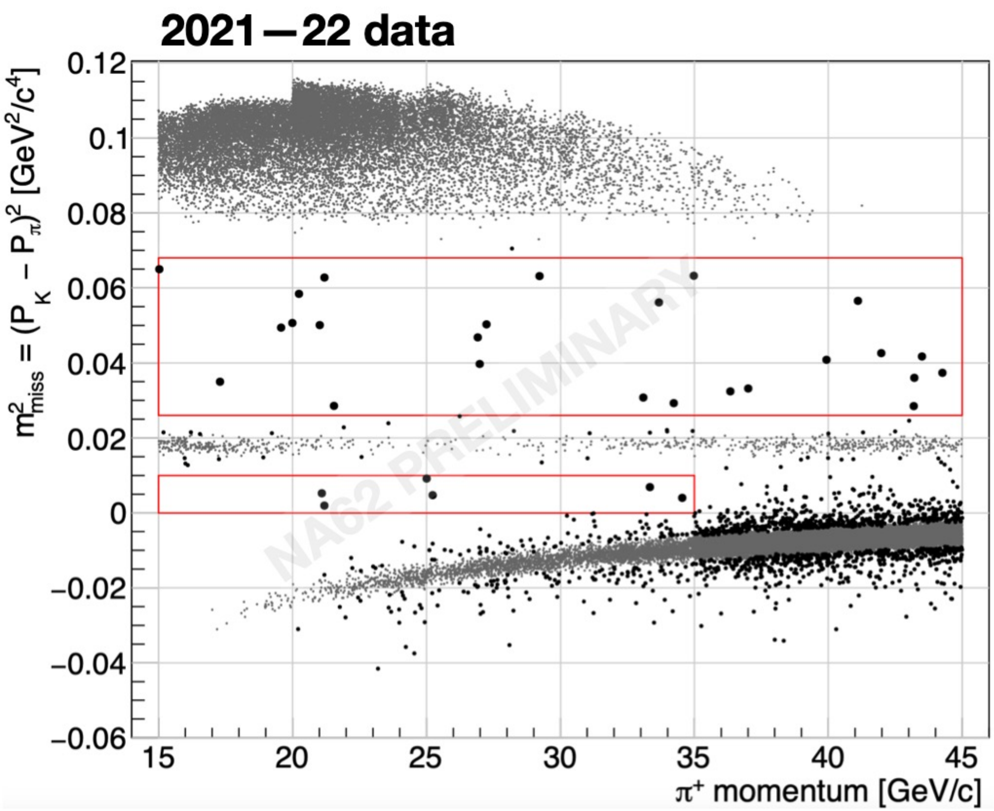


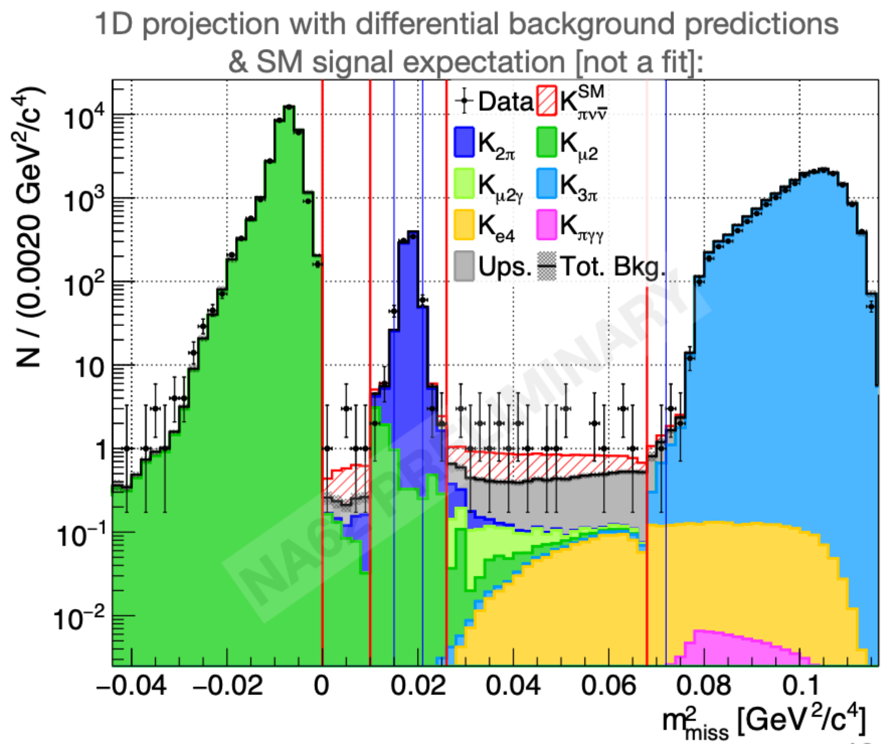
$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \pi^+\pi^0$	0.76 ± 0.04
$K^+ \to \pi^+\pi^0\gamma$	0.07 ± 0.01
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \mu^+\nu$	0.87 ± 0.19
$K^+ \to \mu^+\nu\gamma$	0.82 ± 0.43
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89^{+0.34}_{-0.28}$
$K^+ \to \pi^0\ell^+\nu$	< 0.001
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$

Sensitivity for BR $\sim \sqrt{S+B}/S = 0.5$

- **Similar but improved with respect to 2018 analysis for same amount of data.**

Signal regions (2021-22 data)





Expected SM signal: $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

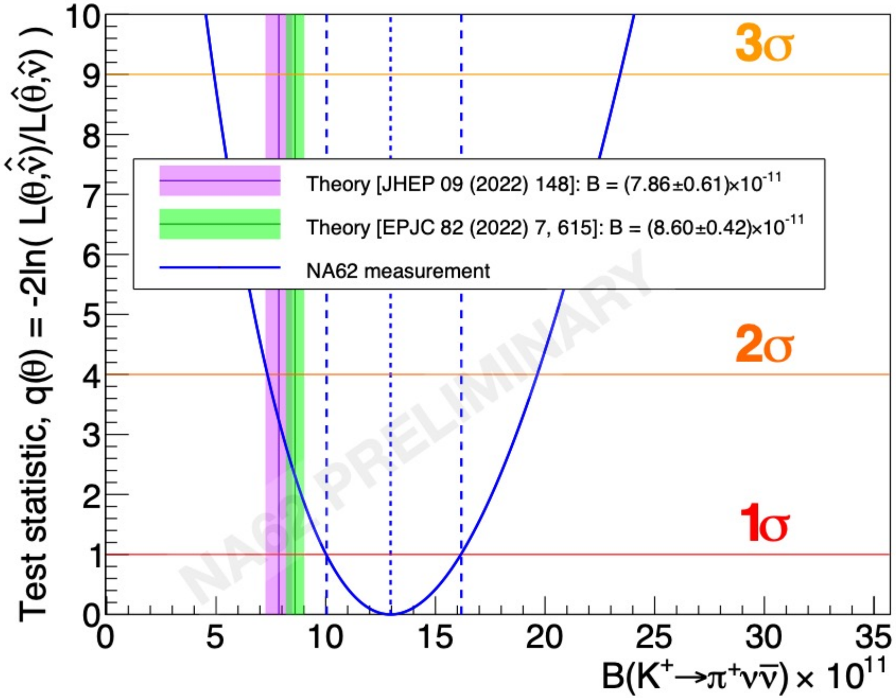
Expected background: $N_{bg} = 11.0^{+2.1}_{-1.9}$

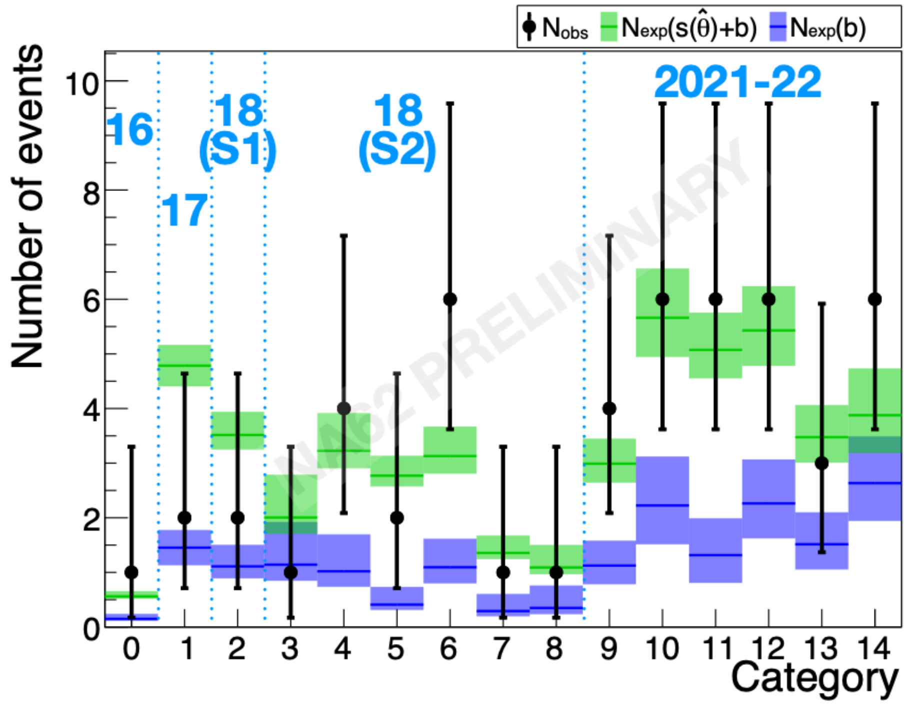
Observed: $N_{obs} = 31$

$$\mathcal{B}_{21-22}(K^+ \to \pi^+\nu\bar{\nu}) = \left(16.0^{+5.0}_{-4.5}\right)\times 10^{-11} = \left(16.0\ \left(^{+4.8}_{-4.2}\right)_{stat}\ \left(^{+1.4}_{-1.3}\right)_{syst}\right)\times 10^{-11}$$

Combining NA62 results: 2016-22

Integrating 2016—22 data: $N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$





Background-only hypothesis p-value = 2×10^{-7} $\Rightarrow$ **significance** $Z > 5$

$$\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-2.9})\times 10^{-11}$$

$$\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0\ (^{+3.0}_{-2.7})_{stat}\ (^{+1.3}_{-1.2})_{syst})\times 10^{-11}$$

$K^+ \to \pi^+ \nu\nu$ result in context

BNL E787/E949 experiment
[Phys.Rev.D 79 (2009) 092004]

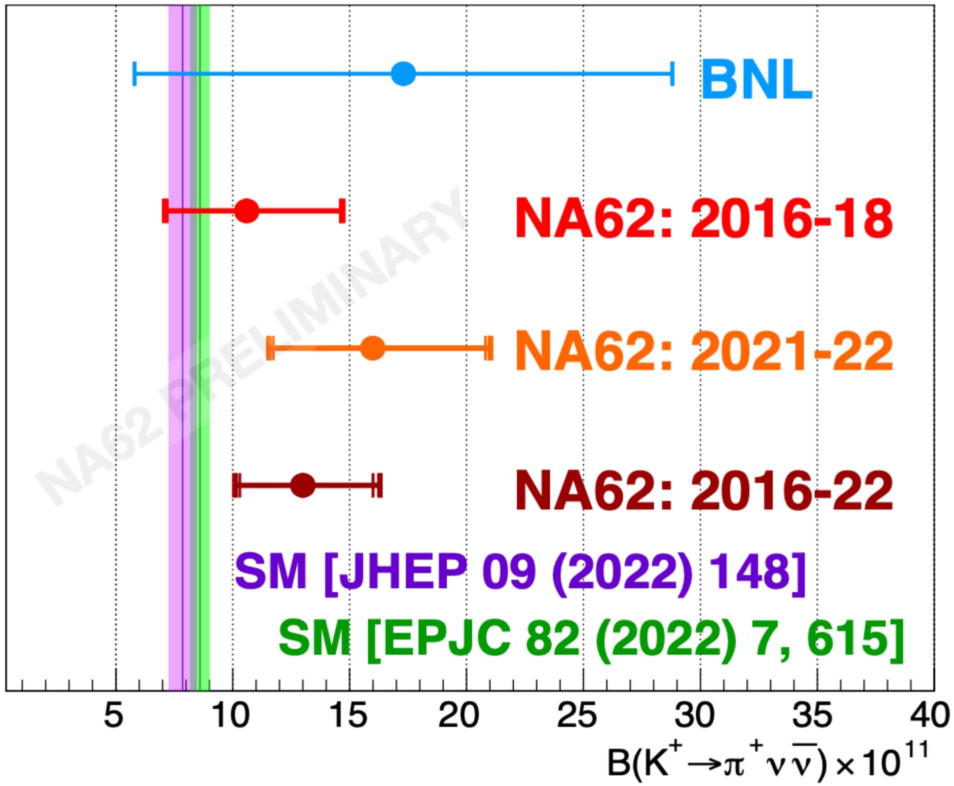
$$\mathcal{B}^{16-18}_{\pi\nu\bar{\nu}} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

$$\mathcal{B}^{21-22}_{\pi\nu\bar{\nu}} = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11}$$

$$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

New: NA62 result from 2021-22 data
[CERN EP Seminar 24/9/24, paper in preparation]



NA62 results are consistent
Central value moved up

Fractional uncertainty decreased:
40% to 25%

Rarest decay process ever measured !

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

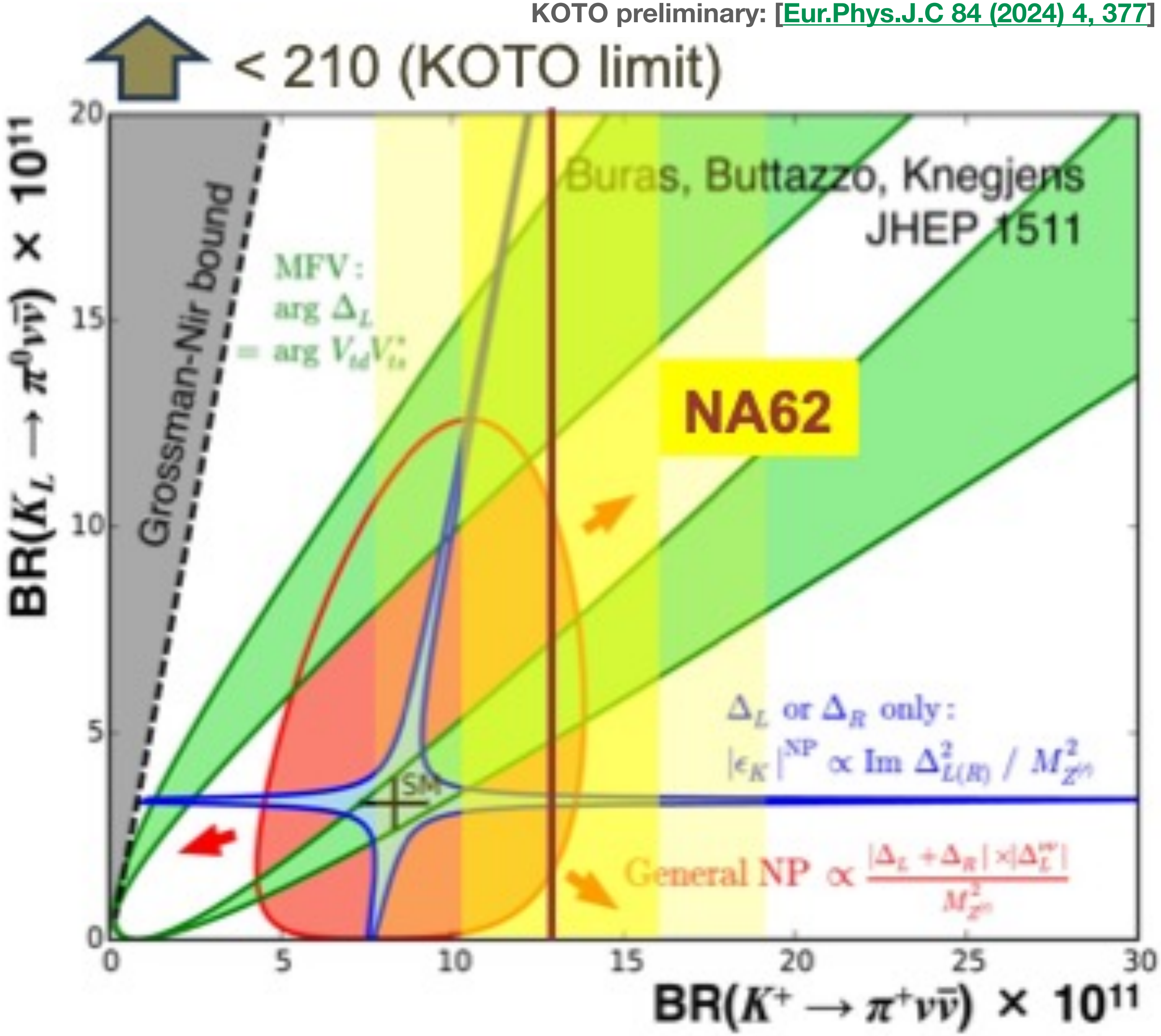
Part of parameter space already ruled out

Fractional uncertainty: 25%
Still consistent with SM

Need full NA62 data-set
to clarify SM tension

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

KOTO preliminary: [Eur.Phys.J.C 84 (2024) 4, 377]



2σ range : [7.4 — 19.7] $\times 10^{-11}$

$$\mathscr{B}^{16-22}_{\pi\nu\bar{\nu}} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

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

Kaon decays induced by scalar or tensor BSM operators

$$\mathrm{BR}(K \to \pi\nu\overset{(-)}{\nu}) = \mathrm{BR}_{\mathrm{SM}}(K \to \pi\nu\bar{\nu}) + \sum_{i\leq=j}^{3} \mathrm{BR}_{\mathrm{LNV}}(K \to \pi\nu_i\nu_j)$$

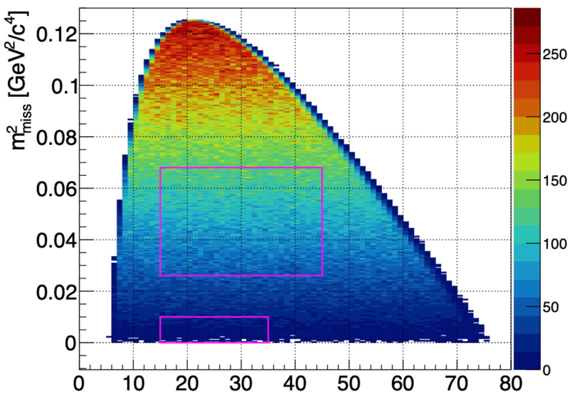
$$\mathscr{B}(K^+ \to \pi^+\nu\hat{\nu}) = J_V^{K^+} f_V^{K^+} + J_S^{K^+} f_S^{K^+} + J_T^{K^+} f_T^{K^+}$$

$$\mathscr{B}(K_L \to \pi^+\nu\hat{\nu}) = J_V^{K_L} f_V^{K_L} + J_S^{K_L} f_S^{K_L} + J_T^{K^+} f_T^{K_L}$$

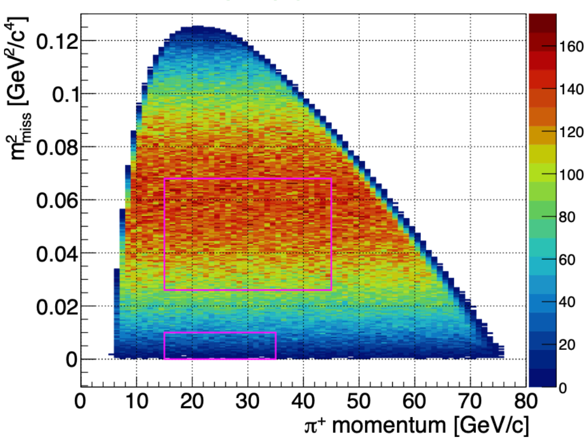
J=current,
f Wilson coeff

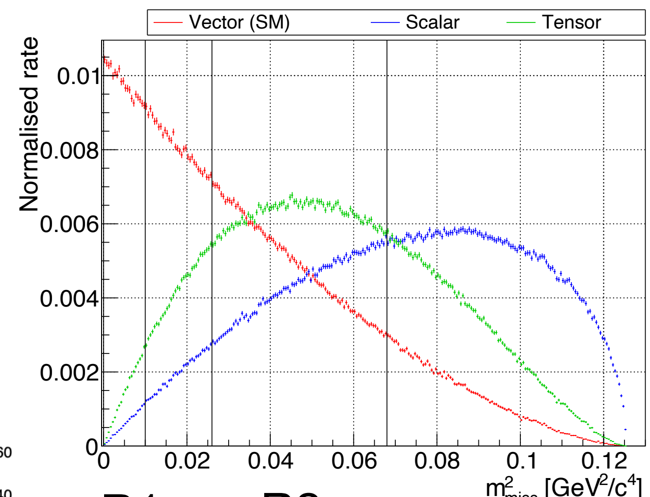
[JHEP 12 (2020)186,
arXiv:2405.06742,
Eur. Phys. J. C (2024) 84: 680]

Scalar



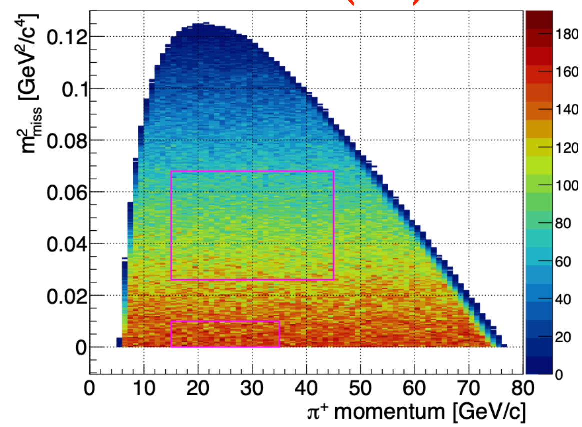
Tensor





R1 R2

Vector (SM)



Probing 3-generation BSM

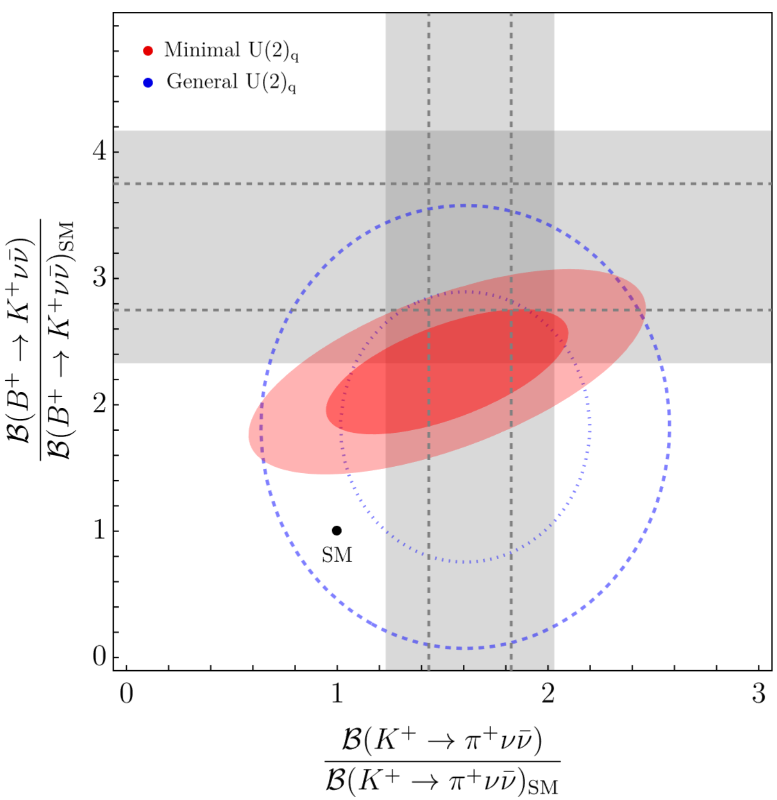
[Allwicher, Bordone, Isidori, Piazza, Stanzione, doi.org/10.48550/arXiv.2410.21444]

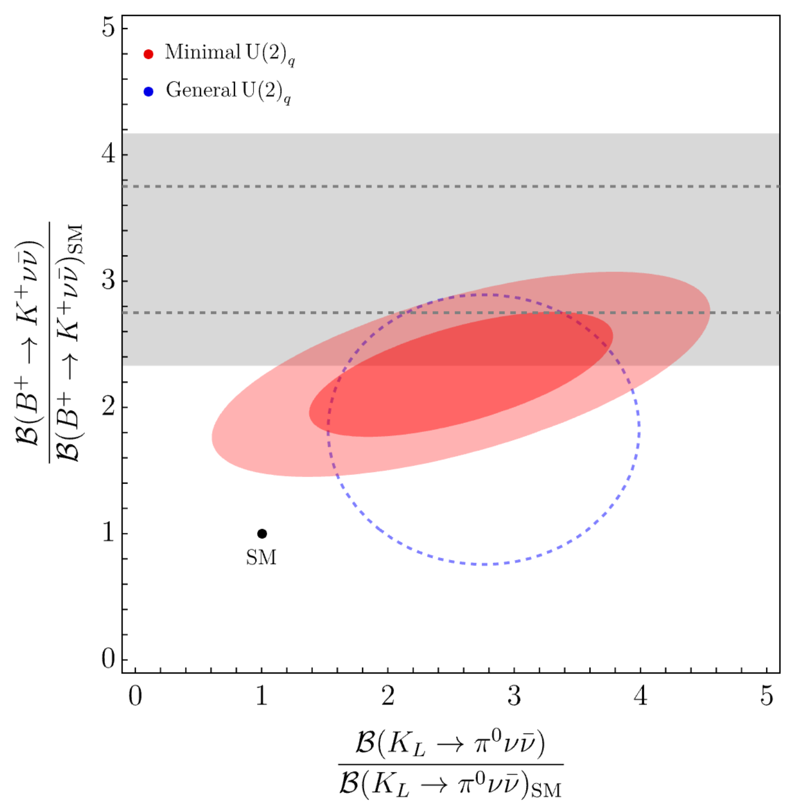
EFT with dimension-six semileptonic operators built in terms of SM fields.
Minimally-broken $U(2)^5$ flavor symmetry acting on the lightest two SM families.
Reduce the number of relevant operators to 5

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})^{\rm SM} = (8.09 \pm 0.63) \times 10^{-11}$$
$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})^{\rm SM} = (2.58 \pm 0.30) \times 10^{-11}$$

(for comparison)

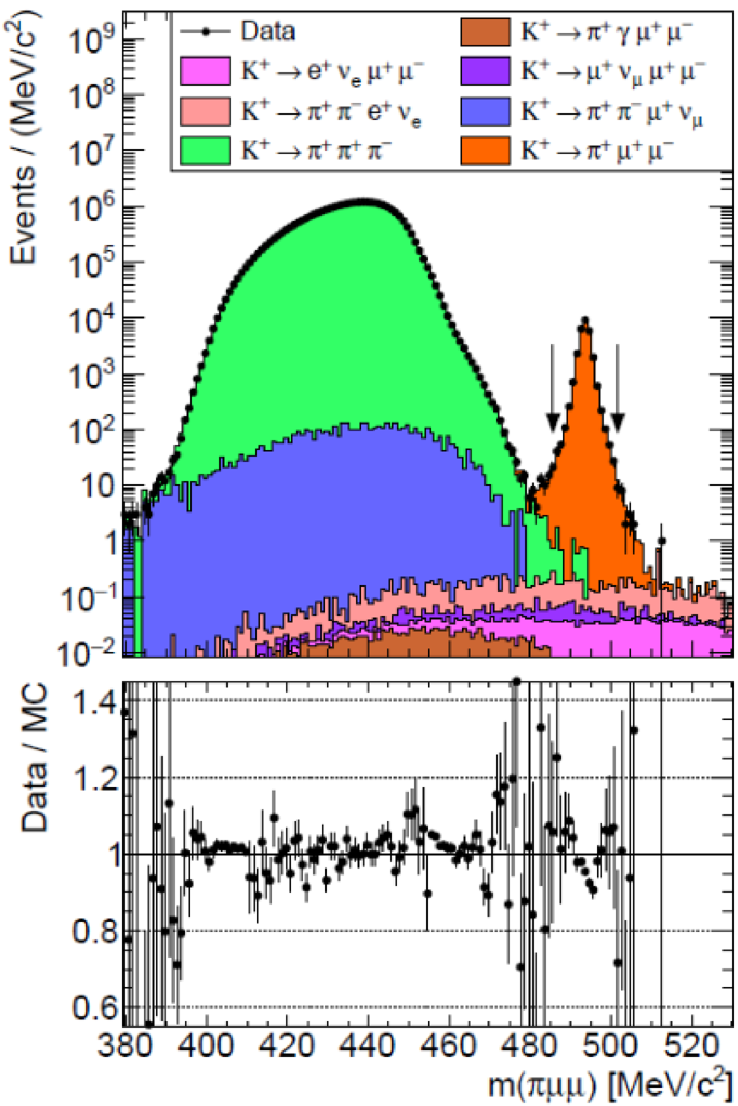
$$B(K^+ \to \pi^+ \nu\nu) = (12.3 \pm 3.2) \times 10^{-11} \qquad B(K_L \to \pi^0 \nu\nu) = (6.7 \pm 2.2) \times 10^{-11}$$

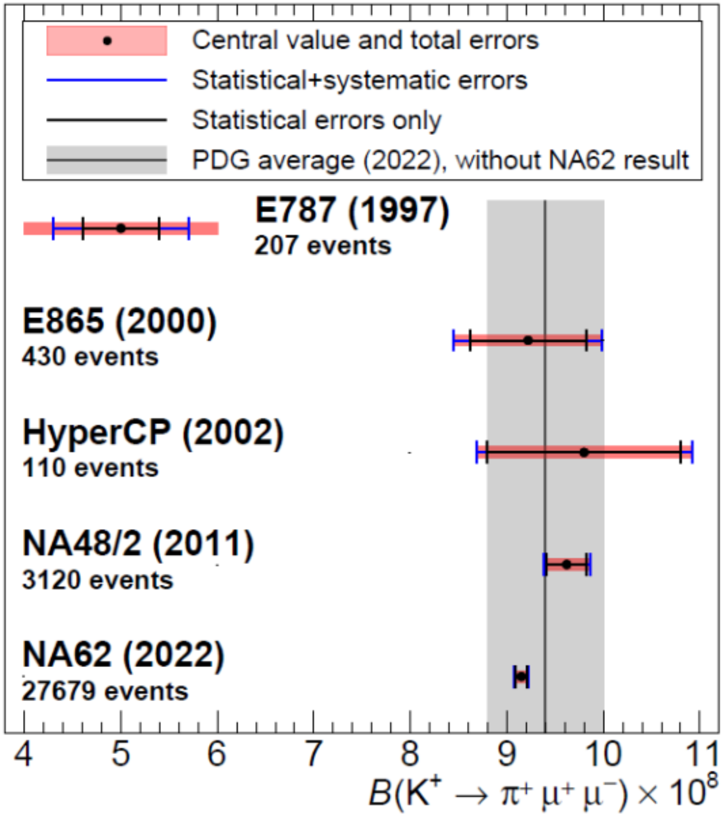




NA62: $K^+ \to \pi^+\mu^+\mu^-$ [doi:10.1007/JHEP11(2022)011]

FCNC decay, long-distance mediated by photon exchange
Together with electron channel tests LFU





$$\boldsymbol{BR(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08)\times 10^{-8}}$$

$$A_{\mathrm{FB}} = \frac{\mathcal{N}(\cos\theta_{K\mu} > 0) - \mathcal{N}(\cos\theta_{K\mu} < 0)}{\mathcal{N}(\cos\theta_{K\mu} > 0) + \mathcal{N}(\cos\theta_{K\mu} < 0)}$$

$\theta_{K\mu}$ between K and μ− in the μμ rest frame

$$A_{FB} = (0.0 \pm 0.7)\times 10^{-2} \text{ @ 68\% CL}$$

NA62: $K^+ \to \pi^+ \mu^+ \mu^-$

$$W(z) = G_F M_K^2 (a + bz) + W^{\pi\pi}(z)$$

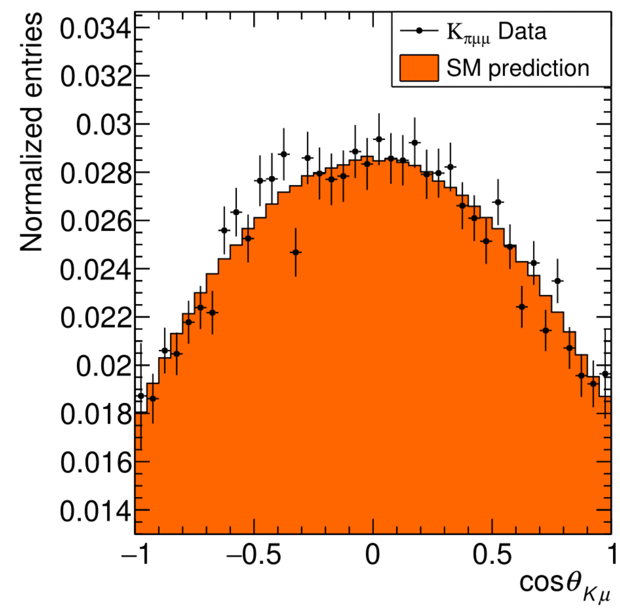
$$z = m(\mu^+\mu^-)^2 / M_K^2$$

Measurement	$K_{\pi\mu\mu}$ candidates	$\mathcal{B}_{\pi\mu\mu} \times 10^8$
E787 [8]	207	$5.0 \pm 0.4_{\rm stat} \pm 0.7_{\rm syst} \pm 0.6_{\rm ext} = 5.0 \pm 1.0$
E865 [9]	430	$9.22 \pm 0.60_{\rm stat} \pm 0.49_{\rm syst} = 9.22 \pm 0.77$
HyperCP [10]	110	$9.8 \pm 1.0_{\rm stat} \pm 0.5_{\rm syst} = 9.8 \pm 1.1$
NA48/2 [11]	3120	$9.62 \pm 0.21_{\rm stat} \pm 0.11_{\rm syst} \pm 0.07_{\rm ext} = 9.62 \pm 0.25$
NA62, this result	27679	$9.15 \pm 0.06_{\rm stat} \pm 0.03_{\rm syst} \pm 0.04_{\rm ext} = 9.15 \pm 0.08$

Table 2. Comparison with the previous measurements of the $K_{\pi\mu\mu}$ branching fraction.

Measurement	Signal candidates	a_+	b_+	$\rho(a_+, b_+)$
E865, $K_{\pi ee}$ [14]	10300	-0.587 ± 0.010	-0.655 ± 0.044	—
NA48/2, $K_{\pi ee}$ [15]	7253	-0.578 ± 0.016	-0.779 ± 0.066	-0.913
NA48/2, $K_{\pi\mu\mu}$ [11]	3120	-0.575 ± 0.039	-0.813 ± 0.145	-0.976
NA62, $K_{\pi\mu\mu}$, this result	27679	-0.575 ± 0.013	-0.722 ± 0.043	-0.972

Table 3. Comparison with the previous measurements of the $K^\pm \to \pi^\pm \ell^+ \ell^-$ form factor parameters. The E865 $K_{\pi ee}$ measurement [14] does not provide the systematic uncertainties, nor the correlation coefficient of the form factor parameters.



A lot more data available, and coming.

Uncertainties are stat-related

Also, electron channel to come

	δa_+	δb_+	$\delta\mathcal{B}_{\pi\mu\mu} \times 10^8$	$\delta A_{\rm FB} \times 10^2$
Statistical uncertainty	0.012	0.040	0.06	0.7
Trigger efficiency	0.002	0.008	0.02	0.1
Reconstruction and particle identification	0.002	0.007	0.02	0.1
Size of the simulated $K_{\pi\mu\mu}$ sample	0.002	0.007	0.01	0.1
Beam and accidental activity simulation	0.001	0.002	0.01	—
Background	0.001	0.001	—	—
Total systematic uncertainty	0.003	0.013	0.03	0.2
$K_{3\pi}$ branching fraction	0.001	0.003	0.04	—
$K_{\pi\mu\mu}$ radiative corrections	0.003	0.009	0.01	0.2
Parameters α_+ and β_+	0.001	0.006	—	—
Total external uncertainty	0.003	0.011	0.04	0.2
Total uncertainty	**0.013**	**0.043**	**0.08**	**0.7**

Table 1. Summary of uncertainties.

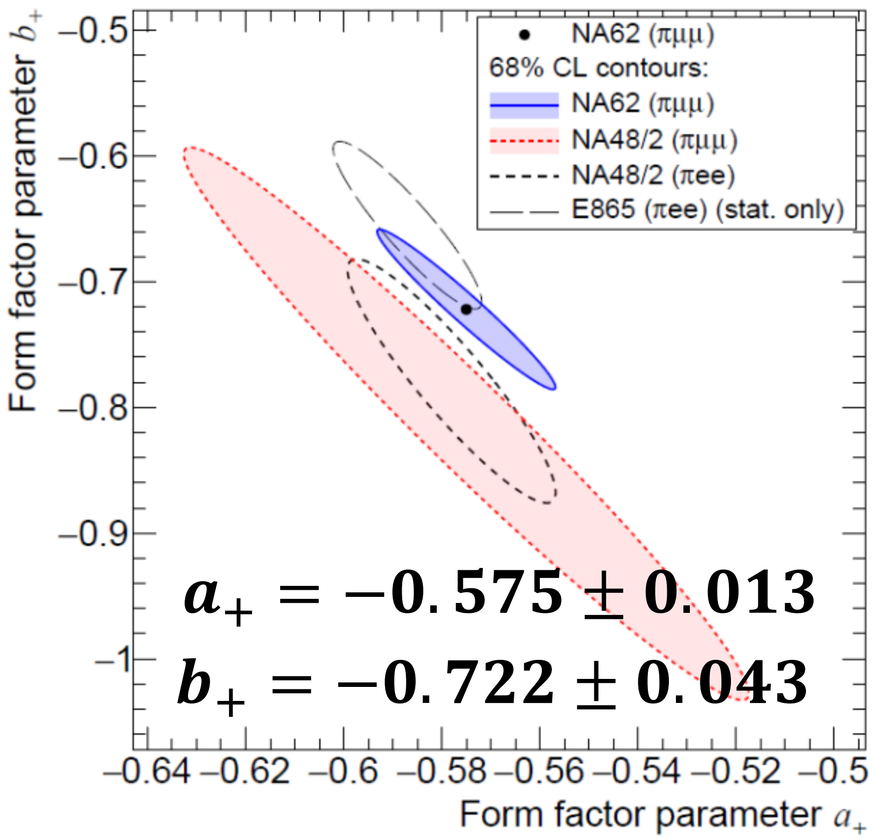
NA62: $K^+ \to \pi^+ \mu^+ \mu^-$

$$W(z) = G_F M_K^2 (a + bz) + W^{\pi\pi}(z)$$

$$z = m(\mu^+\mu^-)^2 / M_K^2$$

[JHEP09(2022)148]

$$a_+^{\mu\mu} - a_+^{ee} = -\sqrt{2}\,\mathrm{Re}\left[V_{td}V_{ts}^*(C_9^\mu - C_9^e)\right]$$



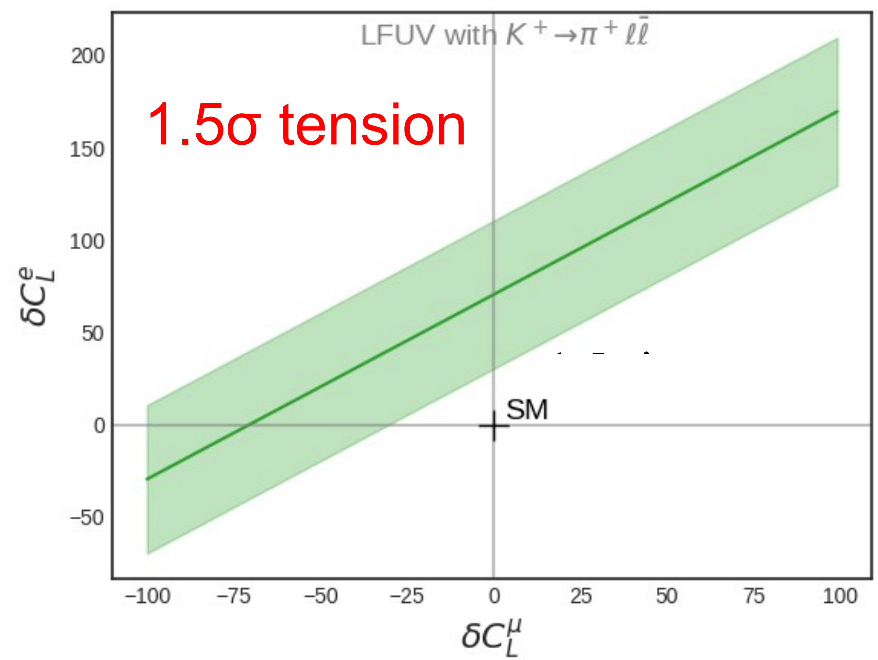
$$a_+ = -0.575 \pm 0.013$$

$$b_+ = -0.722 \pm 0.043$$

[doi:10.1007/JHEP11(2022)011]

Sensitive to LFUV in SD contributions

[PRD93 (2016) 074038]



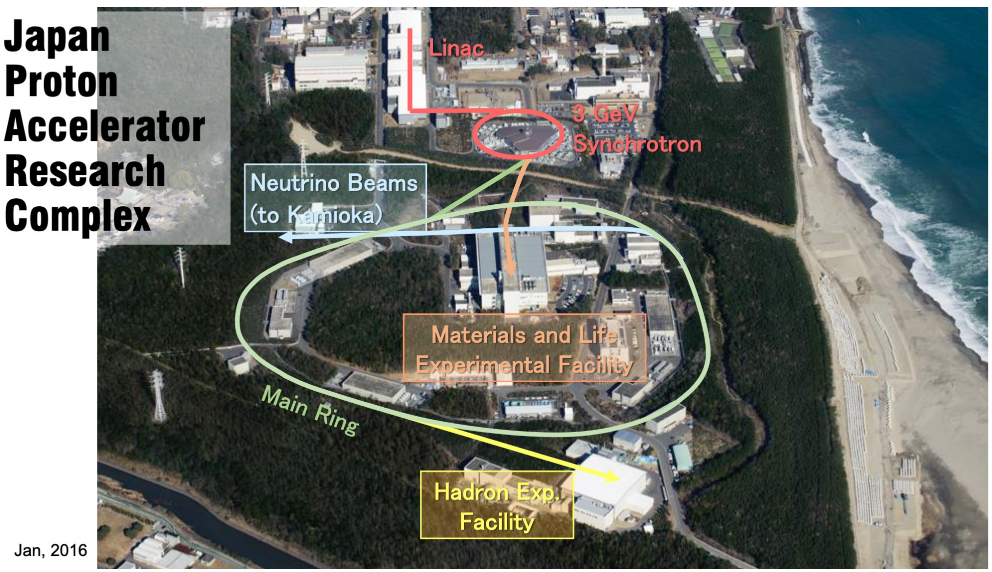
Kaons at JPARC

KEK, NDA, Osaka, Yamagata,
Jeonbuk, Korea, Pusan, NTU, Chicago

30 GeV proton from Main Ring of J-PARC

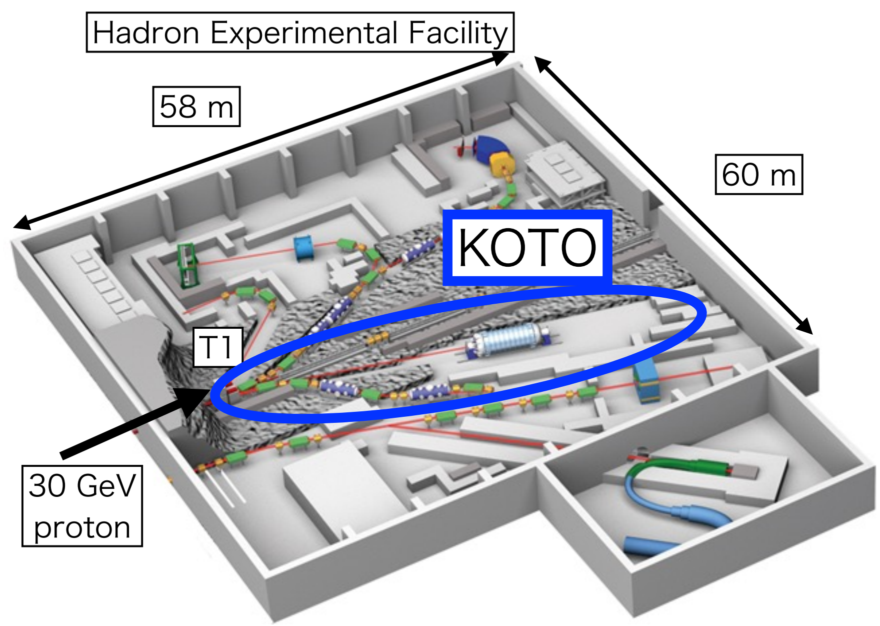
Slow extraction : 2-s spill / 4.2-s cycle

Beam power : 82 kW as of June 2024



Jan, 2016

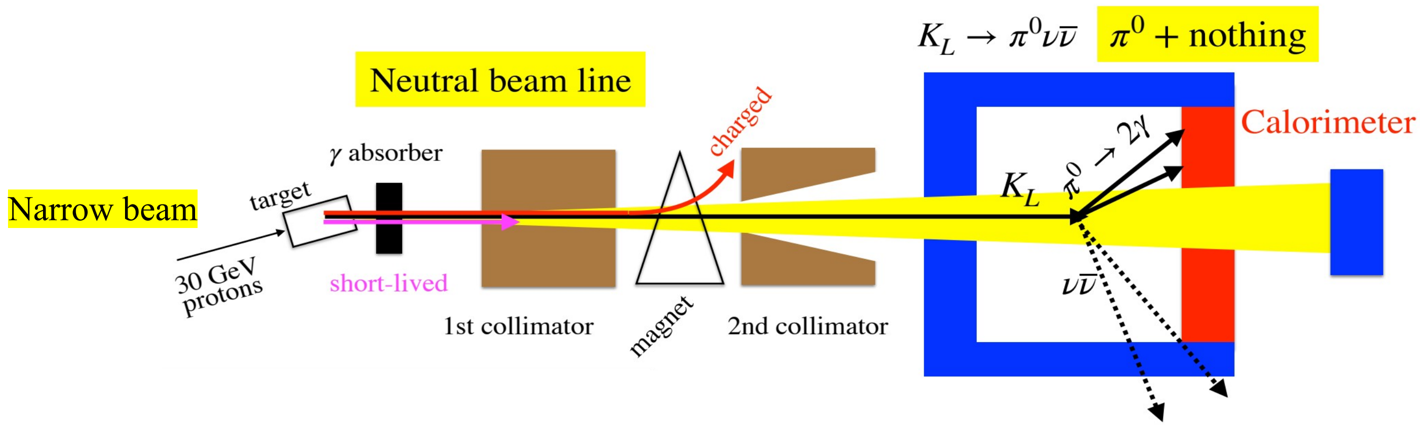
- T1 target at Hadron experimental facility
- Beam extraction angle : 16°
- 20-m beamline + KOTO Detector



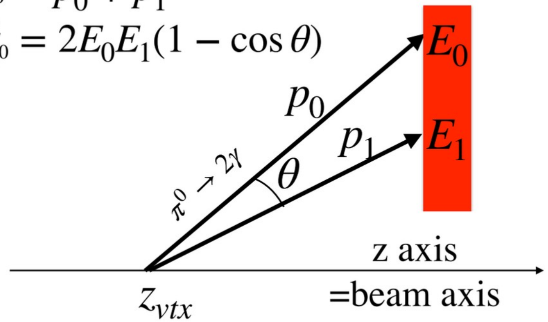
KOTO concept

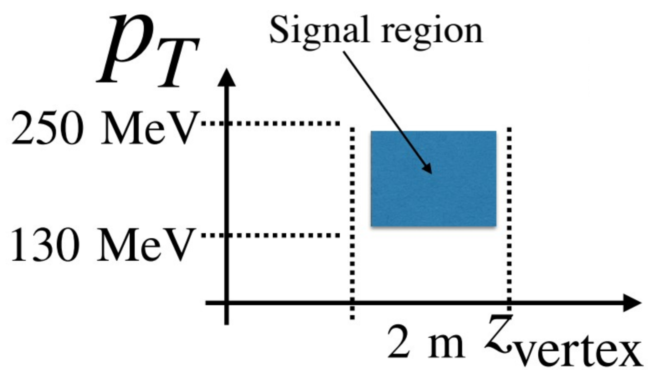
Key points of KOTO experiment:

1) K_L pencil beam, only K_L direction known
   → only PT information can be used (to reject $K_L \to \gamma\gamma$)
2) Z_{vtx} reconstructed assuming 2 clusters from π^0 decay
3) Charged and photon vetoes to reject background



$p_{\pi^0} = p_0 + p_1$
$m_{\pi^0}^2 = 2E_0E_1(1 - \cos\theta)$





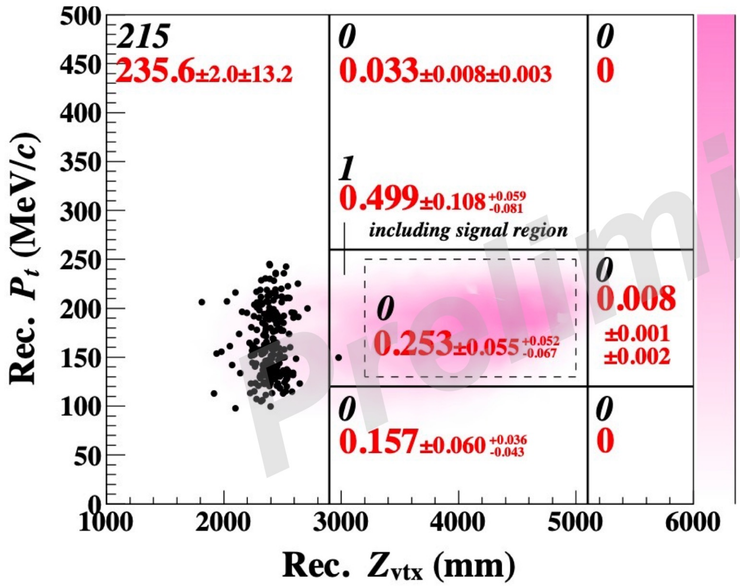
KOTO result of 2021 data analysis

KEK, NDA, Osaka, Yamagata,
Jeonbuk, Korea, Pusan, NTU, Chicago

Final PT vs Z plot

Black: observed
Red: expected BG
Contour: signal MC

Single Event Sensitivity = $(9.26 \pm 0.03_{stat} \pm 0.75_{syst}) \times 10^{-10}$



$N_{observed} = 0$

$BR(K_L \to \pi^0 \nu\bar{\nu}) < 2.1 \times 10^{-9}$ (90% C.L.)

We will submit the paper on this result soon.

List of the backgrounds

Source	Estimated value
Upstream π^0	$0.060 \pm 0.046\ (stat.) \pm 0.007\ (syst.)$
$K_L \to 2\pi^0$	$0.059 \pm 0.022\ (stat.)\ ^{+0.051}_{-0.060}\ (syst.)$
$K^\pm$	$0.042 \pm 0.014\ (stat.)\ ^{+0.004}_{-0.029}\ (syst.)$
Scattered and halo K_L ($K_L \to 2\gamma$)	$0.045 \pm 0.010\ (stat.) \pm 0.006\ (syst.)$
Hadron cluster BG	$0.024 \pm 0.004\ (stat.) \pm 0.006\ (syst.)$
η production in CV	$0.023 \pm 0.010\ (stat.) \pm 0.005\ (syst.)$
Sum	$0.253 \pm 0.055\ (stat.)\ ^{+0.052}_{-0.067}\ (syst.)$

Related to photo-nuclear interaction

MC statistics

Statistics of the control data for inefficiency evaluation

Preliminary

34

Obtained the world best limit.

Aim to reach SM sensitivity by 2027

Rare kaon decays after 2030

Unfortunately, HIKE (high-intensity kaons) at CERN was not approved

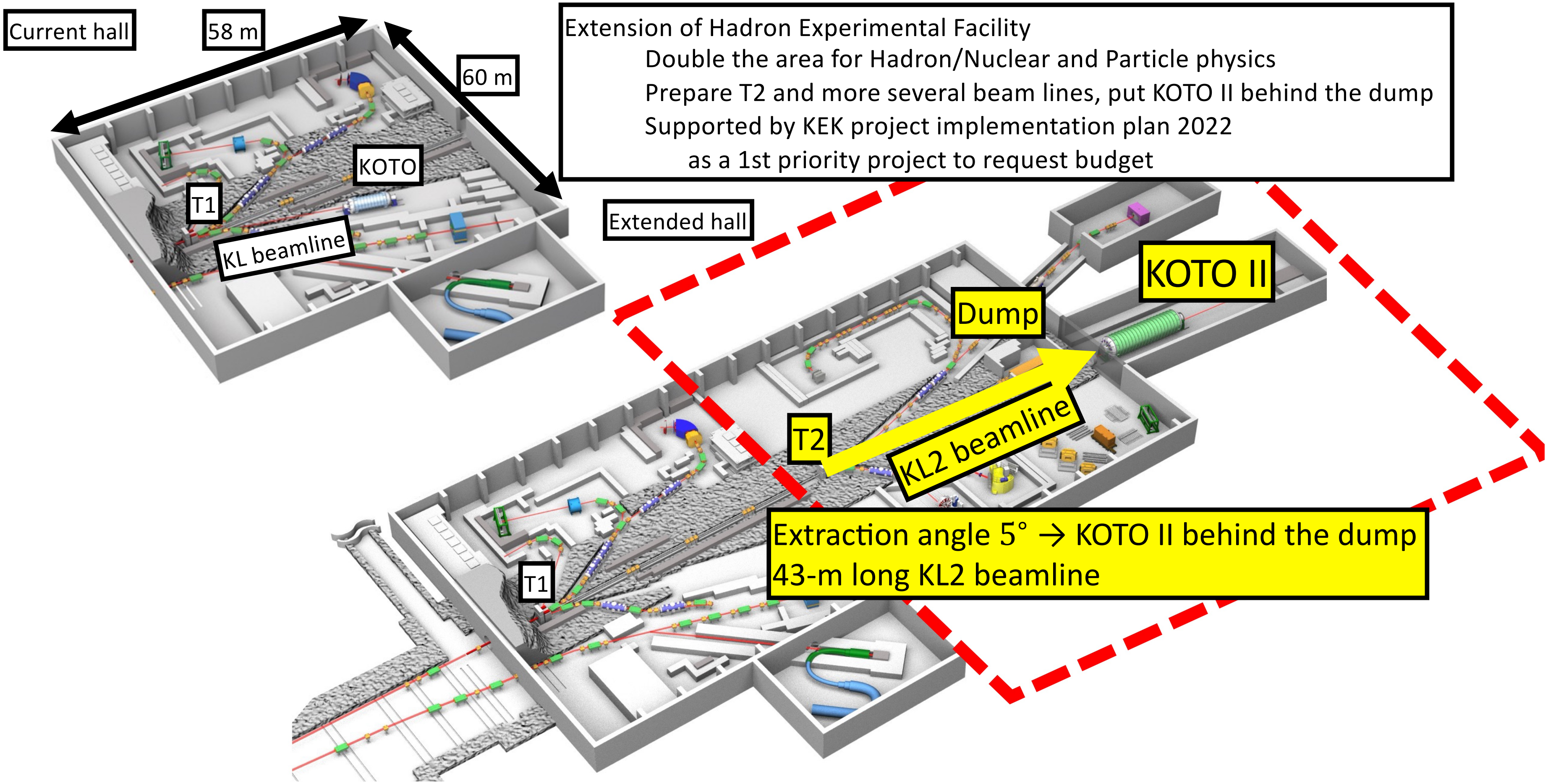
CERN: LHCb (K_S)

JPARC: KOTO-II (K_L)

KOTO-II and Extension of J-PARC hadron hall

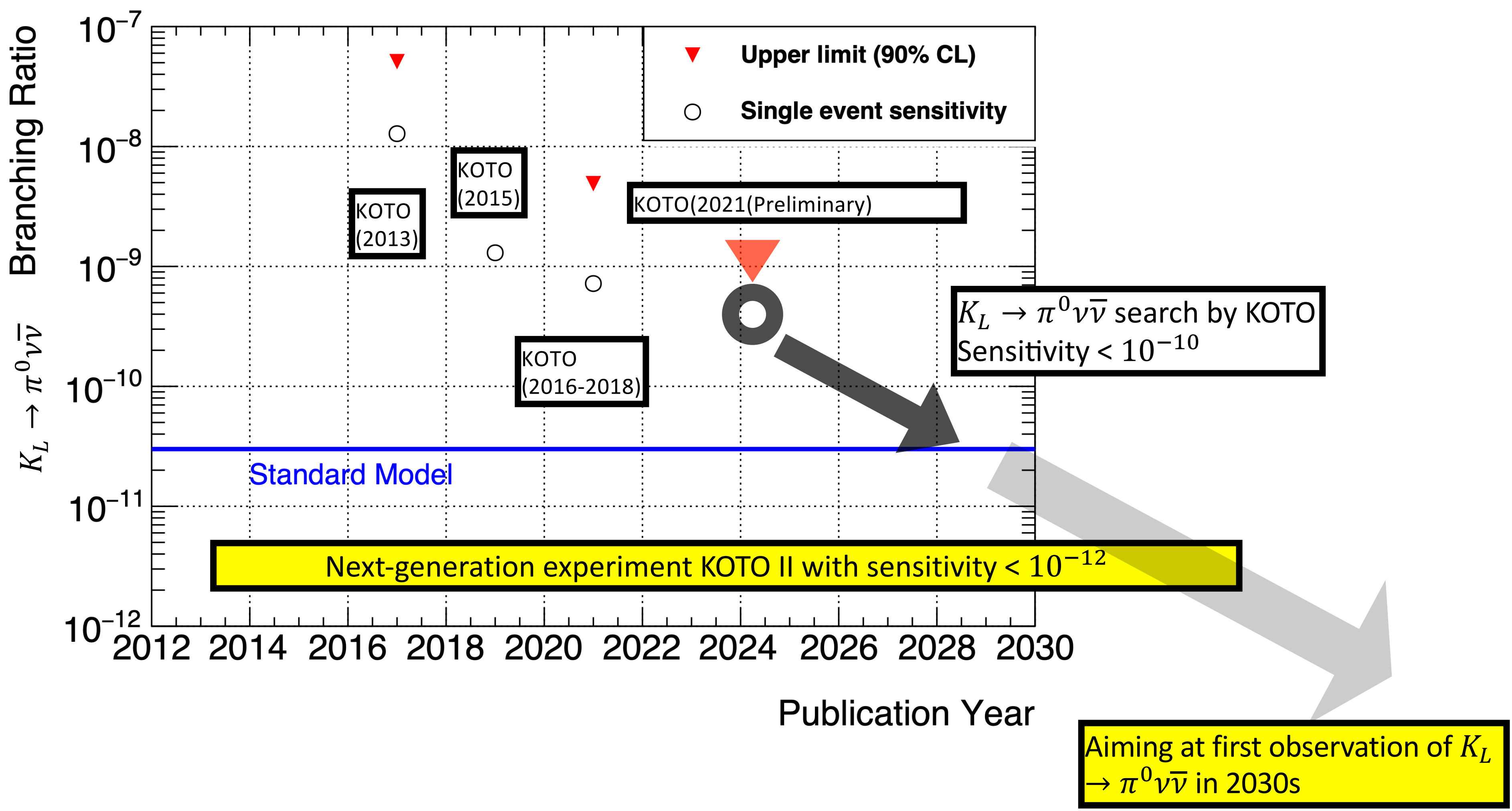
Extension of Hadron Experimental Facility

- Double the area for Hadron/Nuclear and Particle physics
- Prepare T2 and more several beam lines, put KOTO II behind the dump
- Supported by KEK project implementation plan 2022
  - as a 1st priority project to request budget



Prospects for $K^0 \to \pi^0 \nu\nu$

KEK, NDA, Osaka, Yamagata,
Jeonbuk, Korea, Pusan, NTU, Chicago



Aim to collect O(50) with B/S=1 events in 2030s

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

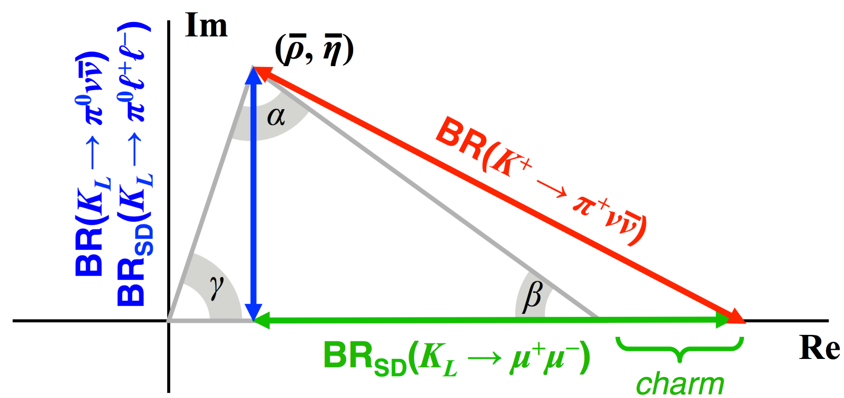
Contributions from long-distance physics

- 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, measure $|a_S|$
  - 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, give unique access to SD BSM effects in the photon coupling via the tau loop

[arXiv:hep-ph/0404127,arXiv:hpe-ph/0404136, arXiv:hep-ph/0606081]
[arXiv:0705.2025, arXiv:1812.00735, arXiv:1906.03046, https://indico.cern.ch/event/1196830/]

$K_L \to \pi^0 \ell^+ \ell^-$ CPV amplitude constrains UT η



$$\mathcal{B}(K_L \to \pi^0 e^+ e^-) = 3.54^{+0.98}_{-0.85} \left(1.56^{+0.62}_{-0.49}\right) \times 10^{-11}$$
$$\mathcal{B}(K_L \to \pi^0 \mu^+ \mu^-) = 1.41^{+0.28}_{-0.26} \left(0.95^{+0.22}_{-0.21}\right) \times 10^{-11}$$

(2 sets of values corresponding to constructive (destructive) interference btw direct and indirect CP-violating contributions)

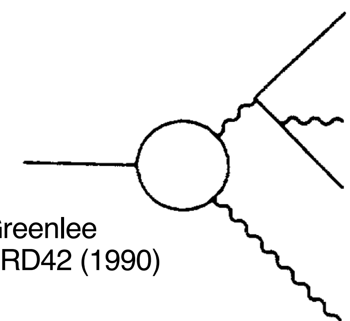
Experimental bounds from KTeV:

BR($K_L \to \pi^0 e^+ e^-$) < 28 × 10^{-11}
BR($K_L \to \pi^0 \mu^+ \mu^-$) < 38 × 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

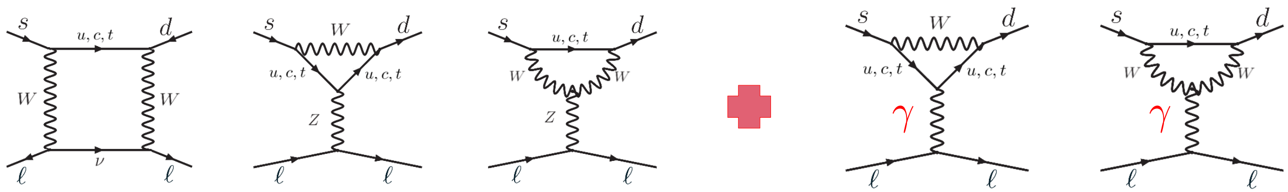


Greenlee PRD42 (1990)

BR($K_L \to e^+ e^- \gamma\gamma$) = (6.0 ± 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

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

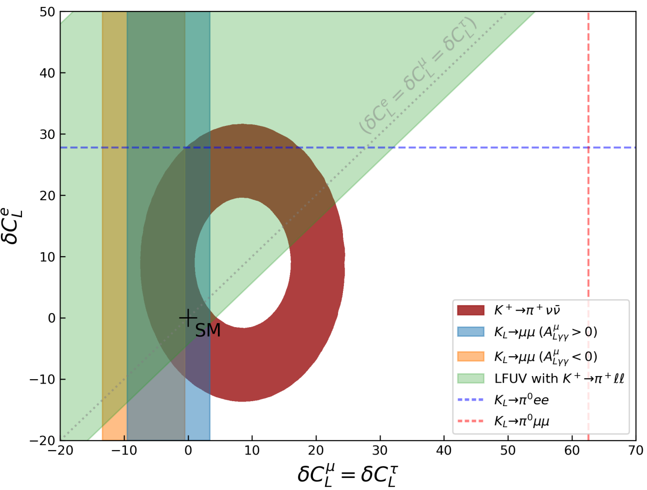
[D'Ambrosio, Iyer, Mahmoudi, Neshatpour
2206.14748, 2311.04878, 2404.03643]



Access to photon coupling

Can be used to explore helicity suppression in FCNC decays, give unique access to SD BSM effects in γ coupling via τ loop

Lepton Flavour Universality Violation:

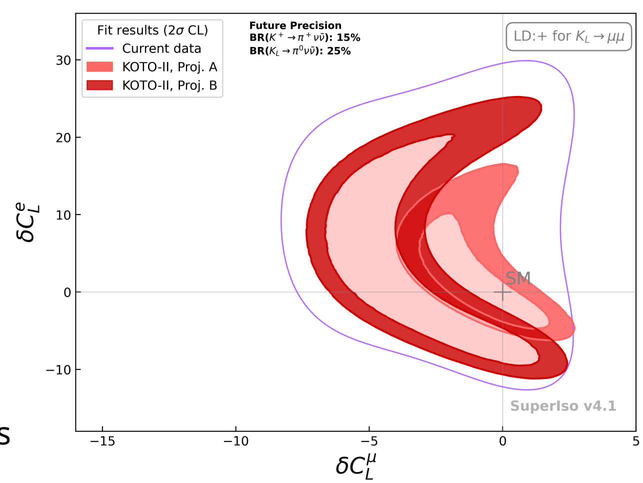


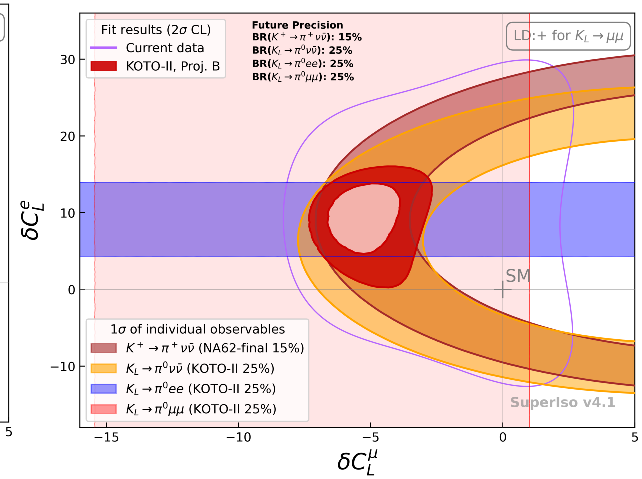
Bounds from individual observables:

Coloured regions: 68% CL measurements
Dashed lines: 90% upper limits

We assume NP contributions of the charged and neutral leptons related to each other by the $SU(2)_L$ gauge symmetry and we work in the chiral basis

$$\delta C_L^\ell \equiv \delta C_9^\ell = -\delta C_{10}^\ell \qquad \delta C_L^e \neq \delta C_L^\mu = \delta C_L^\tau$$





Projection A
Observables already measured are kept, others assumed at their SM values, all with target precision of KOTO-II

Projection B
All measurements give current best-fit point with target precision of KOTO-II

Summary

Kaon physics: sensitive probe to both “heavy” and “light” new physics

Heavy New Physics probed via flavour physics observables
Light New Physics probed via production searches in K decays

NA62 new result on 2016-22 data:

$$\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11} = \left(13.0 \left({}^{+3.0}_{-2.7}\right)_{\mathrm{stat}} \left[{}^{+1.3}_{-1.2}\right]_{\mathrm{syst}}\right) \times 10^{-11}$$

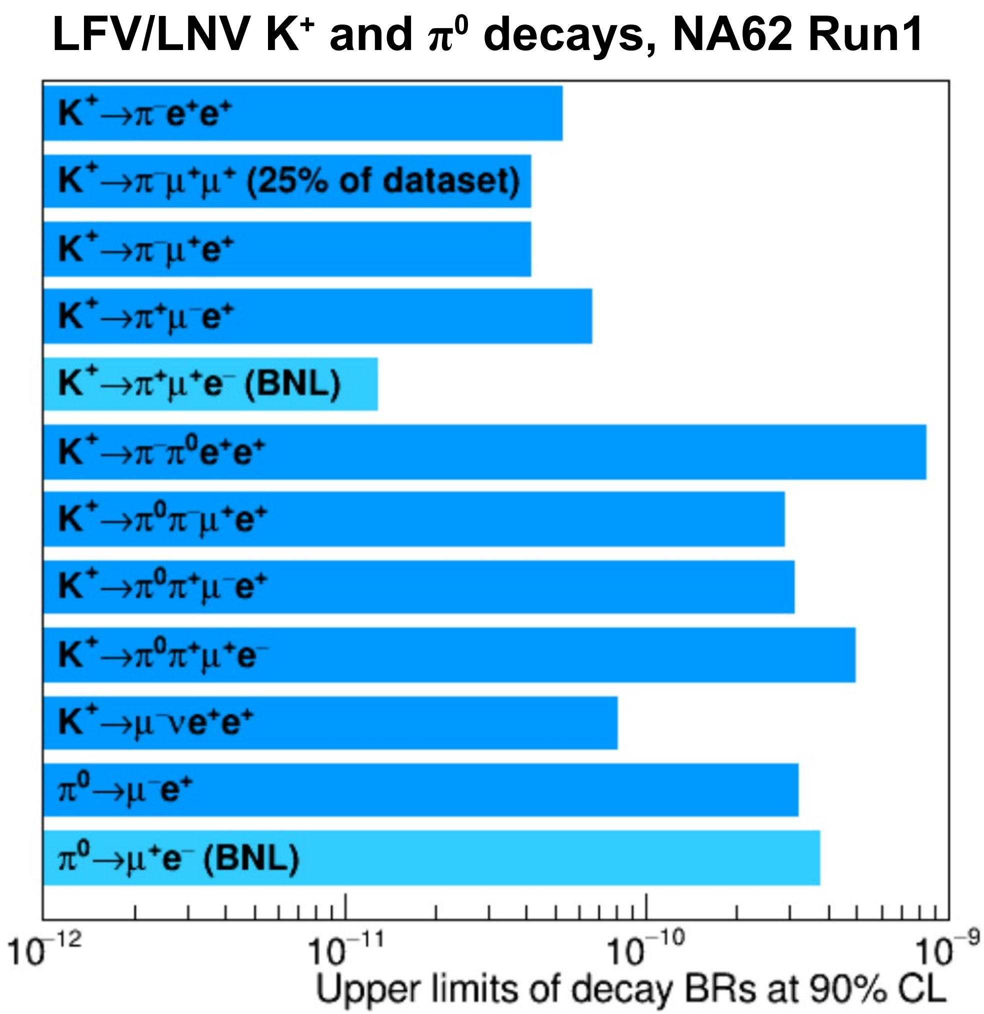
First observation of this decay (significance > 5 σ)
Rarest particle decay ever observed !
NA62 will continue to take data until LS3: large stat will also more investigations

KOTO-II, the successor to KOTO, aims at first observation of
$K_L \to \pi^0 \nu\nu$ by 2030s.

Increasingly important to combine K^+ and K_L measurements, and with other flavour measurements

Additional material

Other LFV / LNV results



NA62: UL on BRs of LNV/LFV K^+ and π^0 decays ~ $O(10^{-9}$-$10^{-11})$