The NA62 experiment at CERN: recent results and prospects

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Outline:

1) Rare kaon decays in the Standard Model and beyond
2) $K^+ \to \pi^+ \nu\nu$ and related measurements with NA62 Run 1 dataset
3) Short-term and long-term plans at CERN
4) KOTO experiment at J-PARC: $K_L \to \pi^0 \nu\nu$ measurement
5) Other recent NA62 results
6) Summary

Particle Physics Seminar
University of Liverpool • 28 October 2020

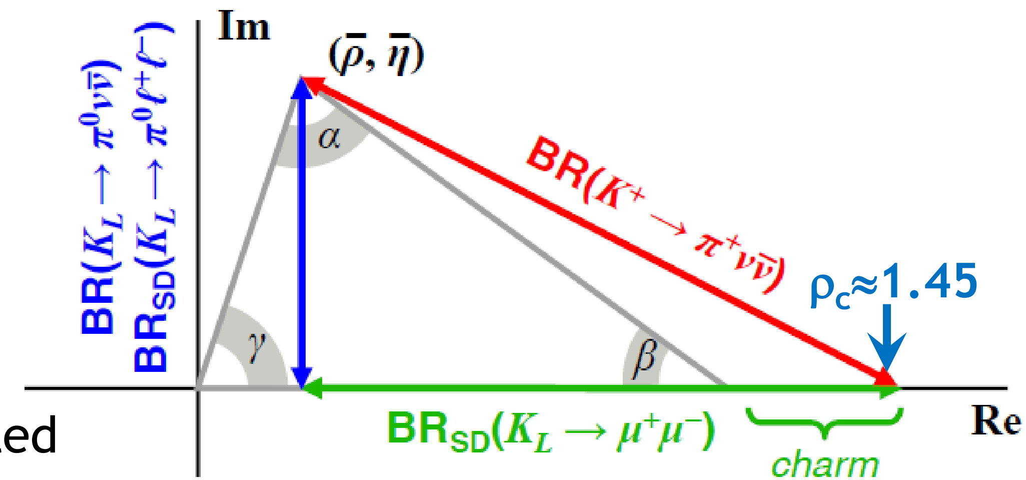
Rare kaon decays: Standard Model and beyond

Introduction: rare kaon decays

Decay	Γ_{SD}/Γ	Theory err.*	SM BR $\times 10^{11}$	Exp. BR $\times 10^{11}$
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28 (@ 90% CL)
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	1.5 ± 0.3	< 38
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	**<17.8** (as of 2019)
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	< 300

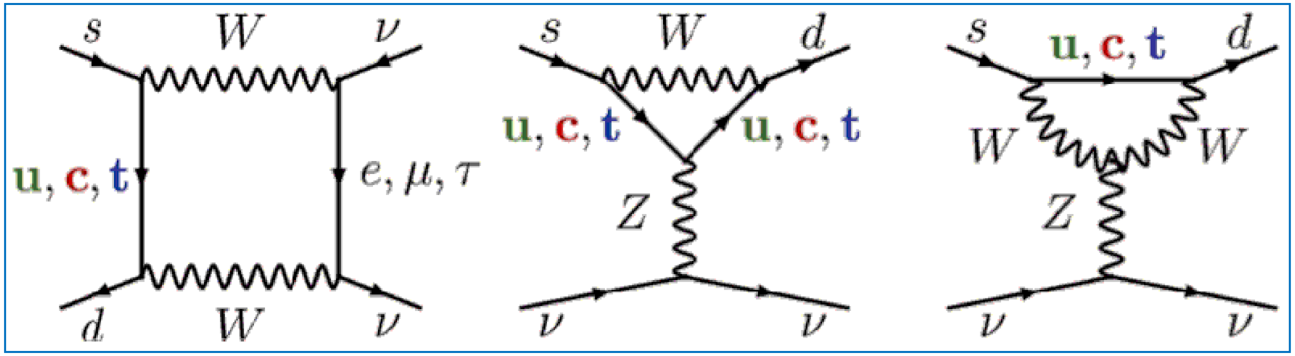
*Approx. error on LD-subtracted rate excluding parametric contributions

- FCNC processes dominated by **Z**-penguin and box diagrams.
- SM rates related to V_{CKM} with minimal non-parametric uncertainties.
- Golden modes $K \to \pi\nu\nu$: uniquely clean theoretically.
- Decays to charged leptons: affected by larger hadronic uncertainties.



$K\to\pi\nu\nu$ in the Standard Model

SM: Z-penguin and box diagrams



"Golden modes": ultra-rare decays, precise SM predictions.

- Maximum CKM suppression: $\sim(m_t/m_W)^2|V^*_{ts}V_{td}|$.
- No long-distance contributions from amplitudes with intermediate photons.
- Hadronic matrix element extracted from measured $BR(K_{e3})$ via isospin rotation.

Mode	Expected BR_{SM}	Experimental status
$K^+\to\pi^+\nu\nu$	$(8.4\pm1.0)\times10^{-11}$	$BR<17.8\times10^{-11}$ at 90% CL (three NA62 candidates, as of 2019)
$K_L\to\pi^0\nu\nu$	$(3.4\pm0.6)\times10^{-11}$	$BR<300\times10^{-11}$ at 90% CL (KOTO 2015 data)

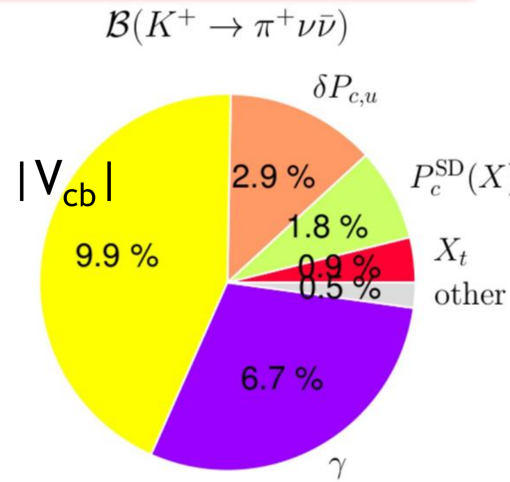
BR_{SM}: Buras et al., JHEP 1511 (2015) 33; tree-level determination of CKM elements

K→πνν and the unitarity triangle

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

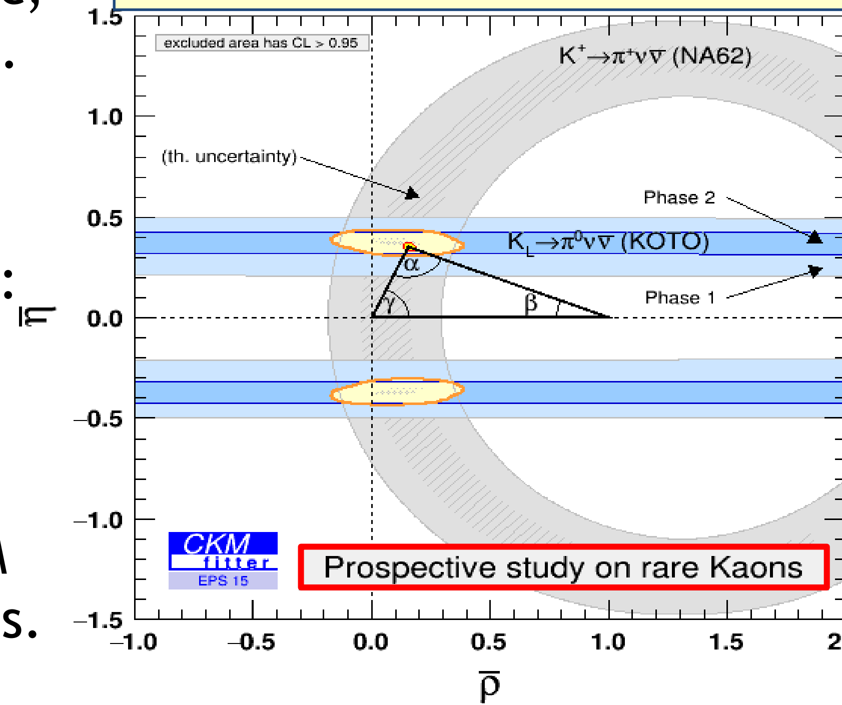
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

Buras et al., JHEP 1511 (2015) 33



- Dominant uncertainties: CKM parametric; intrinsic theory uncertainties are **O(1%)**.
- Work to decrease theory uncertainties *[e.g. Christ et al., PRD 100 (2019) 114506]*.
- Measurements of both **K^+** and **K_L** decays: a clean **sin(2β)** measurement, an independent CKM unitarity test.
- Complementarity to measurements in the **B**-sector. Over-constraining the CKM matrix: reveal the nature of new physics.

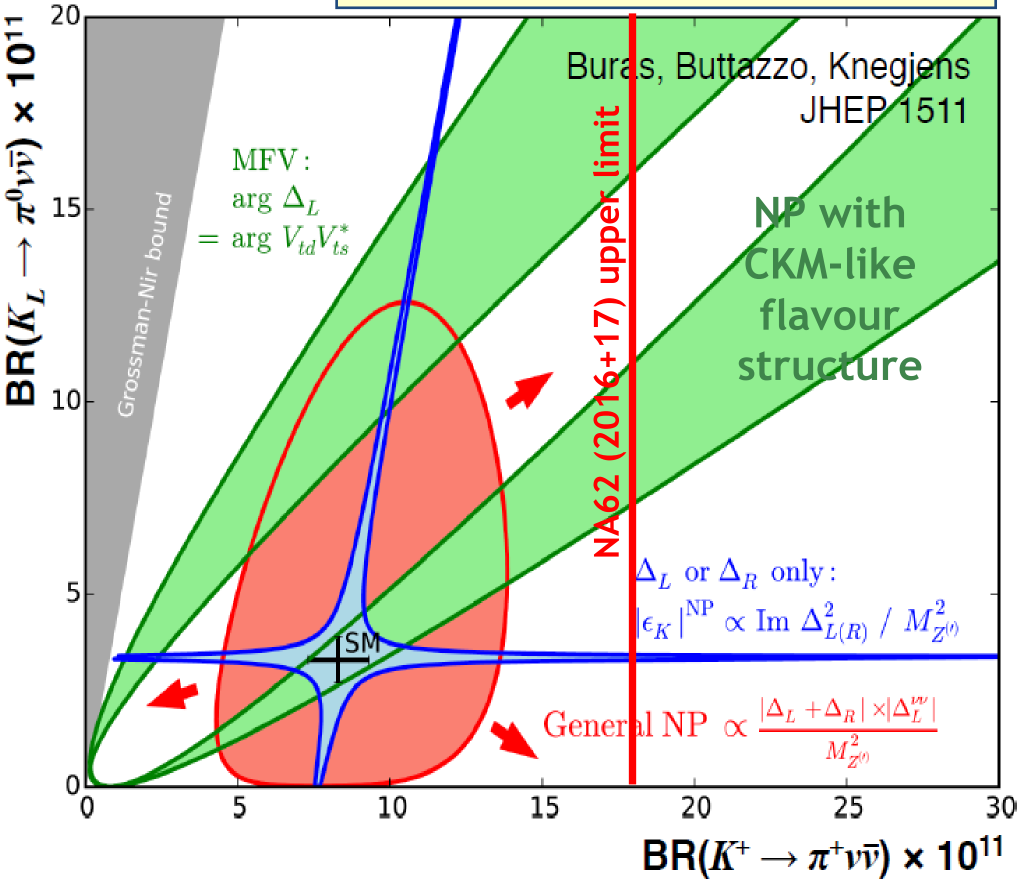
CKM unitarity triangle with kaons



K→πνν and new physics

- Correlations between BSM contributions K^+ and K_L BRs. *[JHEP 1511 (2015) 166]*
- Need to measure both K^+ and K_L to discriminate among BSM scenarios.
- Correlations with other observables (ε'/ε, ΔM_K, B decays). *[arXiv:2006.01138]*

BR($K_L\to\pi^0\nu\bar{\nu}$) vs BR($K^+\to\pi^+\nu\bar{\nu}$)

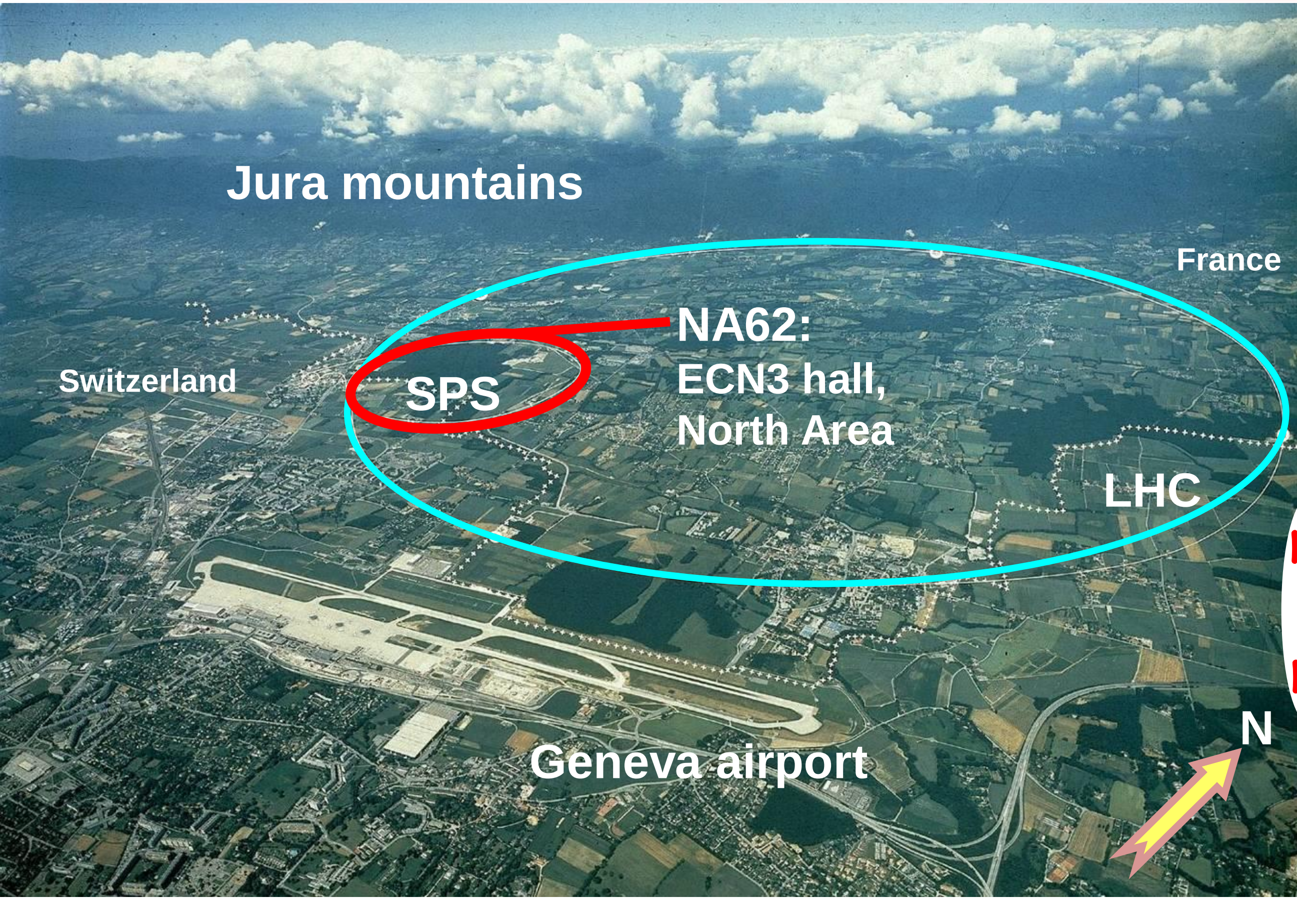


- **Green:** models with CKM-like flavour structure
  - ✓ Models with MFV
- **Blue:** models with new flavour-violating interactions in which LH or RH couplings dominate
  - ✓ Z′ models with pure LH/RH couplings
- **Red:** general NP models without the above constraints
- **The Grossman-Nir bound:** a model-independent relation

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

The NA62 experiment at CERN

Kaon programme at CERN



Earlier: NA31

NA48 discovery of direct CPV
- 1997: ε'/ε: K_L+K_S
- 1998: K_L+K_S
- 1999: K_L+K_S | K_S HI
- 2000: K_L only | K_S HI
- 2001: K_L+K_S | K_S HI

NA48/1
- 2002: K_S/hyperons

NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

NA62 R_K run
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$ | tests

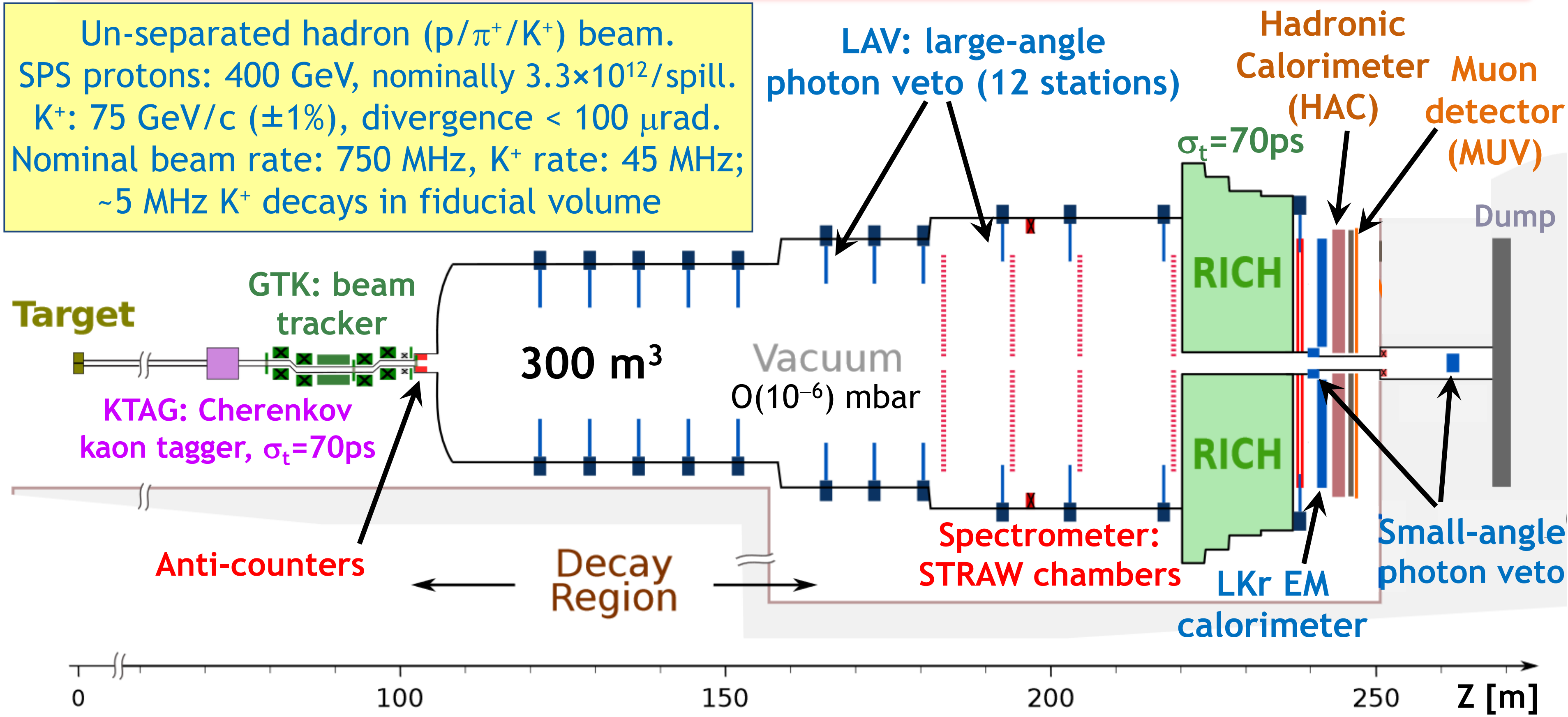
NA62
- 2015: commissioning
- 2016-18: physics run 1
- 2021-: physics run 2

Main NA62 goal: $K^+\to\pi^+\nu\nu$ measurement to 10% precision with a novel decay-in-flight technique.

Currently ~300 participants from 31 institutions.

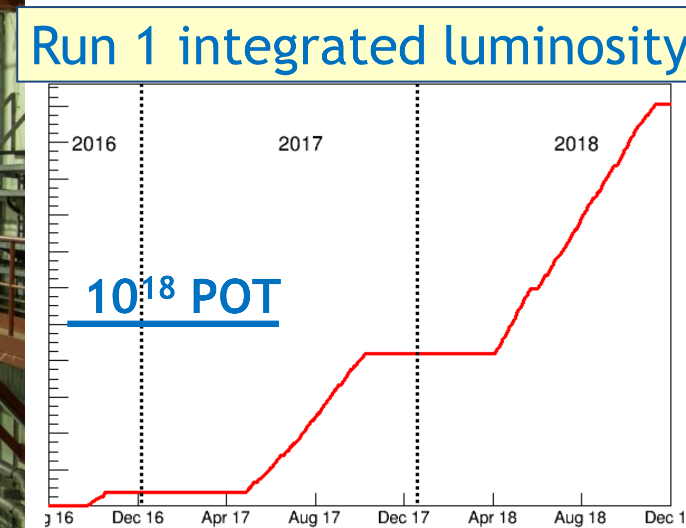
Beamline & detector

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, nominally 3.3×10^{12}/spill.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Nominal beam rate: 750 MHz, K^+ rate: 45 MHz;
~5 MHz K^+ decays in fiducial volume



- Currently, 1 year of operation ≈ 10^{18} protons on target; 4×10^{12} K^+ decays.
- Single event sensitivities for K^+ decays: down to BR~10^{-12}.
- Kinematic rejection factors: 1×10^{-3} for $K^+\to\pi^+\pi^0$, 3×10^{-4} for $K\to\mu^+\nu$.
- Hermetic photon veto: $\pi^0\to\gamma\gamma$ decay suppression (for $E_{\pi 0}$>40 GeV) ~10^{-8}.
- Particle ID (RICH+LKr+HAC+MUV): ~10^{-8} muon suppression.

NA62 status: Run 1 completed



2.2×10^{18} POT collected

- Commissioning run **2015**: minimum bias data (**$\sim3\times10^{10}$** protons/pulse).
- Physics run **2016** (30 days, **$\sim1.3\times10^{12}$ ppp**): **2×10^{11}** useful **K^+** decays.
- Physics run **2017** (160 days, **$\sim1.9\times10^{12}$ ppp**): **2×10^{12}** useful **K^+** decays.
- Physics run **2018** (217 days, **$\sim2.3\times10^{12}$ ppp**): **4×10^{12}** useful **K^+** decays.
- **Run 2** start after the Long Shutdown 2 in **2021** (**$\sim3\times10^{12}$ ppp**).

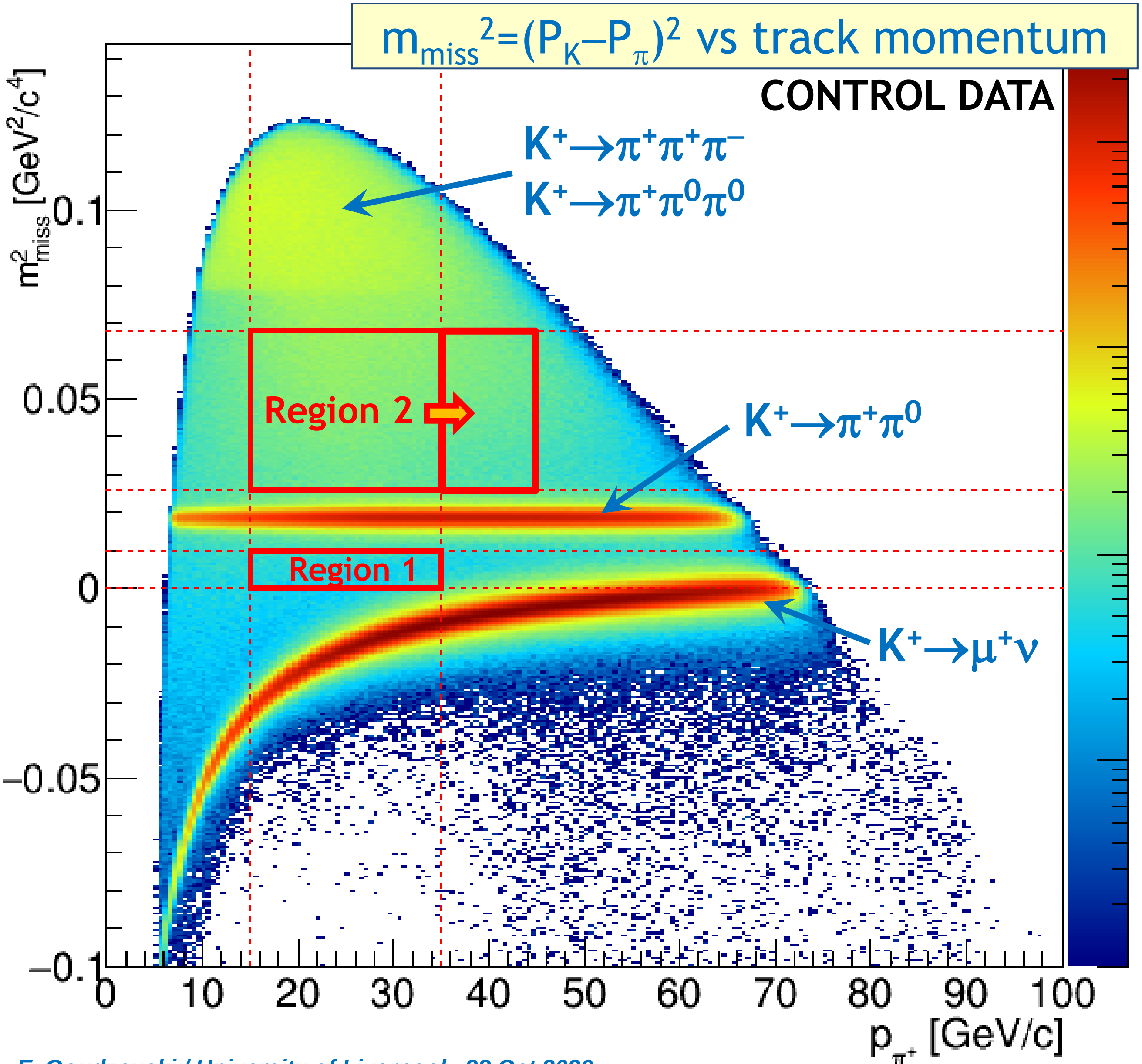
$K^+ \to \pi^+ \nu\nu$ measurement: NA62 Run 1 data set

Analysis of the 2016 data: PLB791 (2019) 156.

Analysis of the 2017 data: arXiv:2007.08218, accepted by JHEP.

Full Run 1 (2016–18) data set: first presented at ICHEP 2020, paper in preparation.

NA62: $K_{\pi\nu\nu}$ signal regions



Main K^+ decay modes (>90% of BR) rejected kinematically.

Resolution on m^2_{miss}: $\sigma=1.0\times10^{-3}$ GeV^4/c^2.

Measured kinematical background suppression:

- ✓ $K^+\to\pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

Further background suppression:

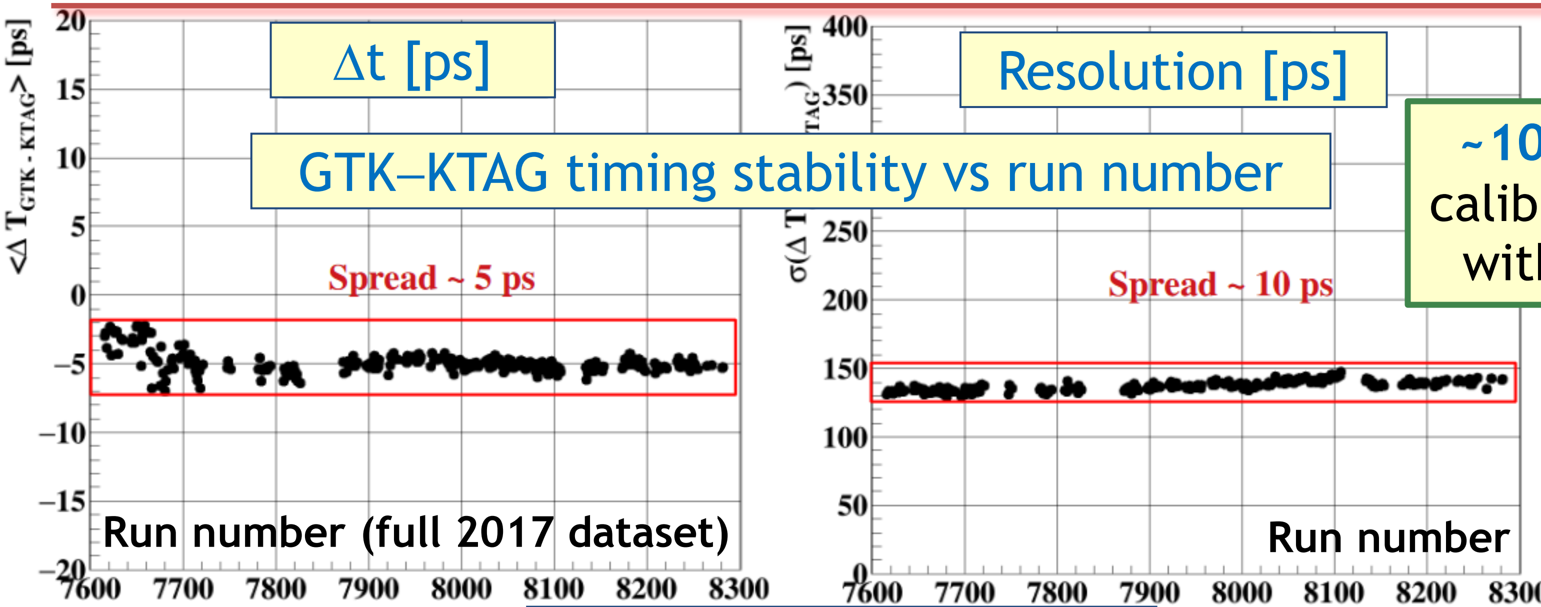
- ✓ PID (calorimeters & Cherenkov detectors): μ suppression 10^{-8}, π efficiency = 64%.
- ✓ Hermetic photon veto: $\pi^0\to\gamma\gamma$ rejection factor = 1.4×10^{-8}.

Key parameters: timing, PID

GTK–KTAG timing stability vs run number

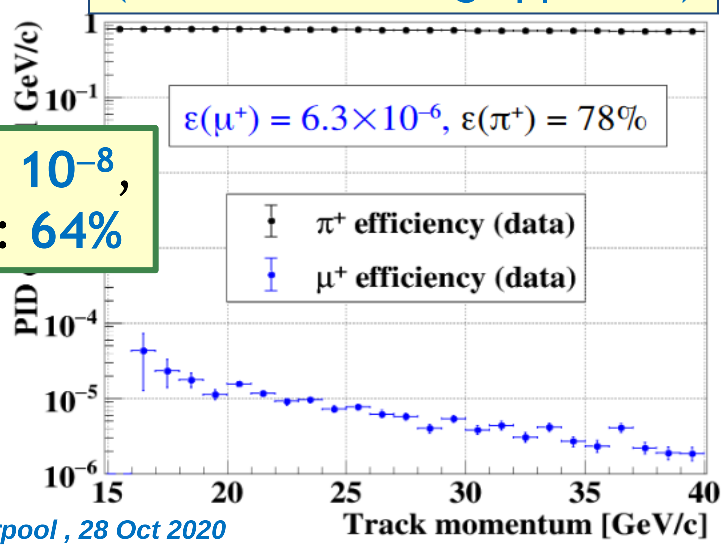
Δt [ps]

Resolution [ps]

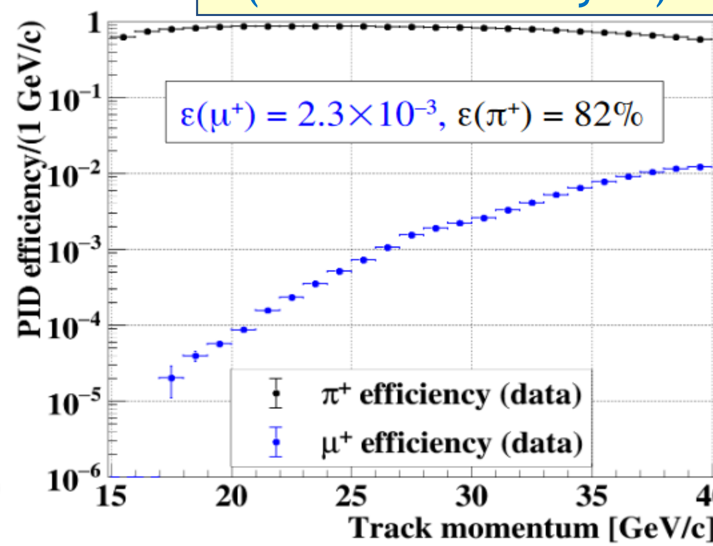


~**100 ps** timing, calibrations stable within a **few ps**

Calorimetric PID (machine learning approach)



RICH PID (likelihood analysis)



Muon suppression: **10^{-8}**, pion ID efficiency: **64%**

Photon veto: see later…

Analysis principle

$$N^{exp}_{\pi\nu\nu} \approx N_{\pi\pi} \epsilon_{trigger} \epsilon_{RV} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \Longrightarrow \text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}}$$

$N^{exp}_{\pi\nu\nu}$: expected number of $K_{\pi\nu\nu}$ events

$Br(\pi\nu\nu)$: Standard Model $K_{\pi\nu\nu}$ branching ratio (central value)

$N_{\pi\pi}$: $K^+\to\pi^+\pi^0$ events selected from the **control data**, without photon + multiplicity rejection, corrected for pre-scaling

ϵ_{RV} : "random veto" $K_{\pi\nu\nu}$ efficiency (photon + multiplicity rejection)

$\epsilon_{trigger}$: trigger efficiency for $K_{\pi\nu\nu}$ events

$A_{\pi\nu\nu}(A_{\pi\pi})$: acceptances from simulations ($A_{\pi\nu\nu}$=6.4% for most data)

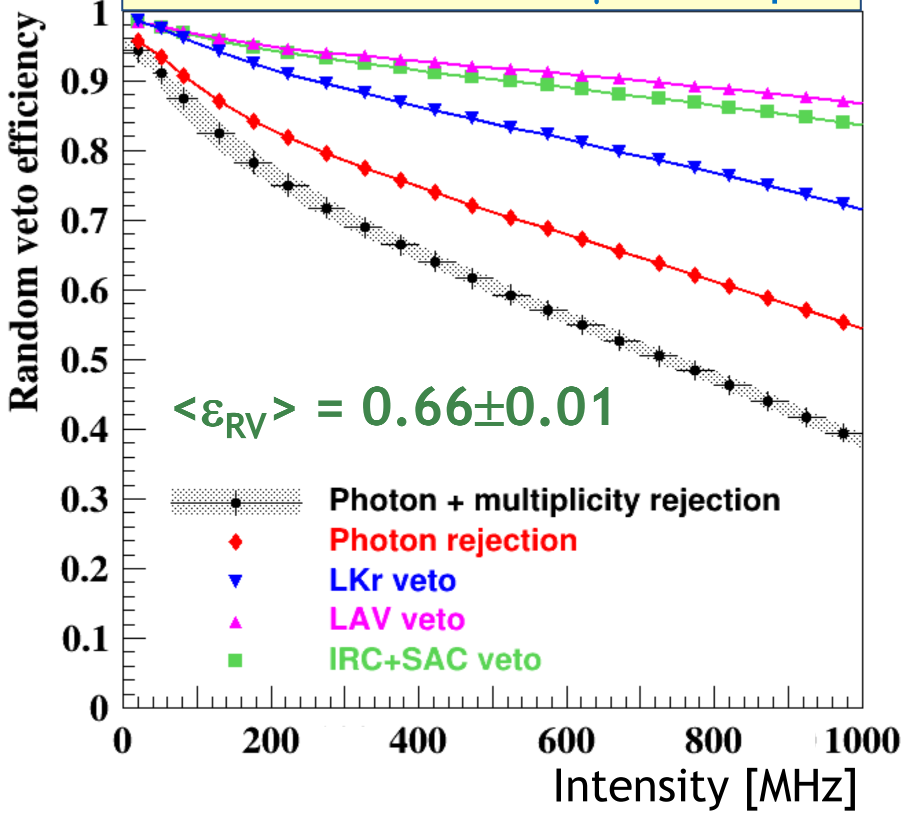
$Br(\pi\pi)$: PDG branching fraction of the $K^+\to\pi^+\pi^0$ decay

Analysis performed in bins of π^+ momentum and instantaneous beam intensity, separately for four data sets.

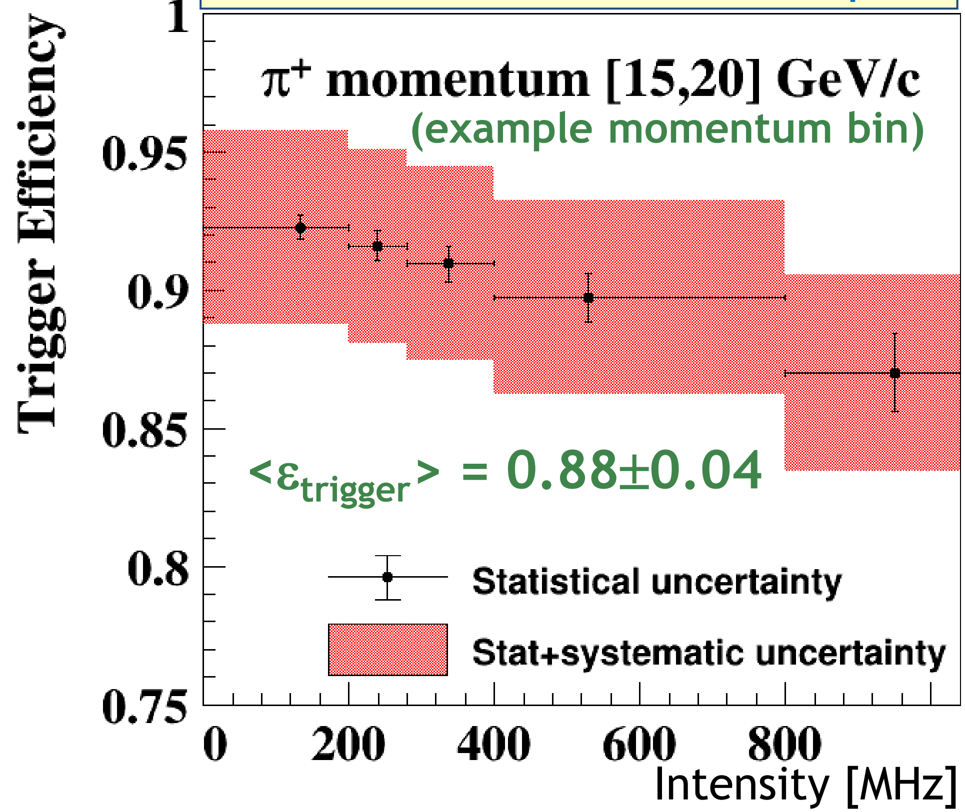
Single event sensitivity

Beam intensity measured event-by-event from beam tracker (GTK) time sidebands

Random veto efficiency ε_{RV} measured with $K^+ \to \mu^+ \nu$ sample



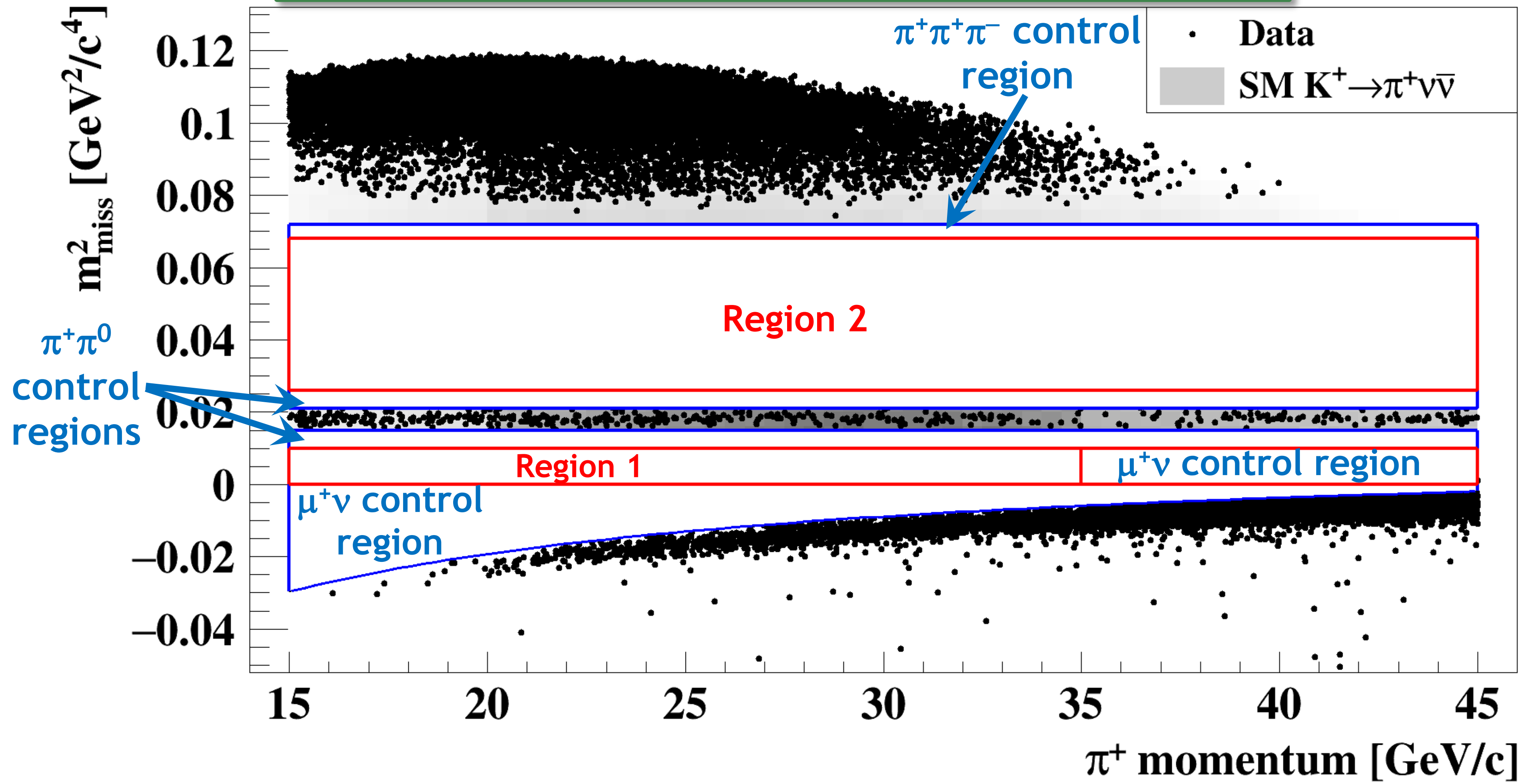
Trigger efficiency $\varepsilon_{trigger}$ measured from control samples



- Integrated over momentum & intensity, $SES_{2018} = (1.11 \pm 0.07) \times 10^{-11}$.
  (main uncertainties: trigger, acceptance, random veto)
- Expected number of SM events: $N_{\pi\nu\nu} = BR_{SM}/SES = 7.58 \pm 0.40_{syst} \pm 0.75_{SM}$.

$K_{\pi\nu\nu}$ data after selection (2018)

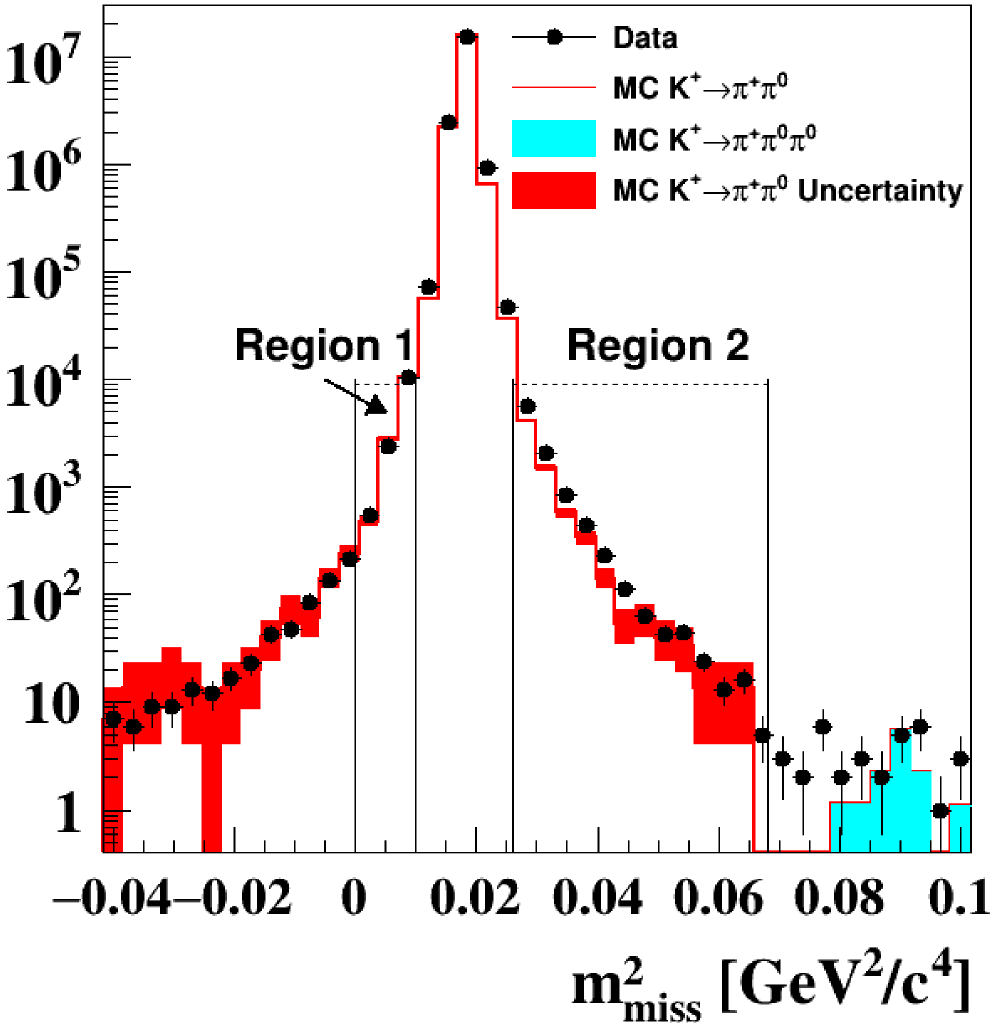
Signal and control regions are blinded



After background evaluation, control regions are opened first, and data are compared with background expectations.

“Conventional” backgrounds

Missing mass spectrum of $\pi^+\pi^0$ events (control data)



The largest background from K^+ decays in the vacuum tank: $K^+\to\pi^+\pi^0$

($K^+\to\mu^+\nu$ is treated similarly)

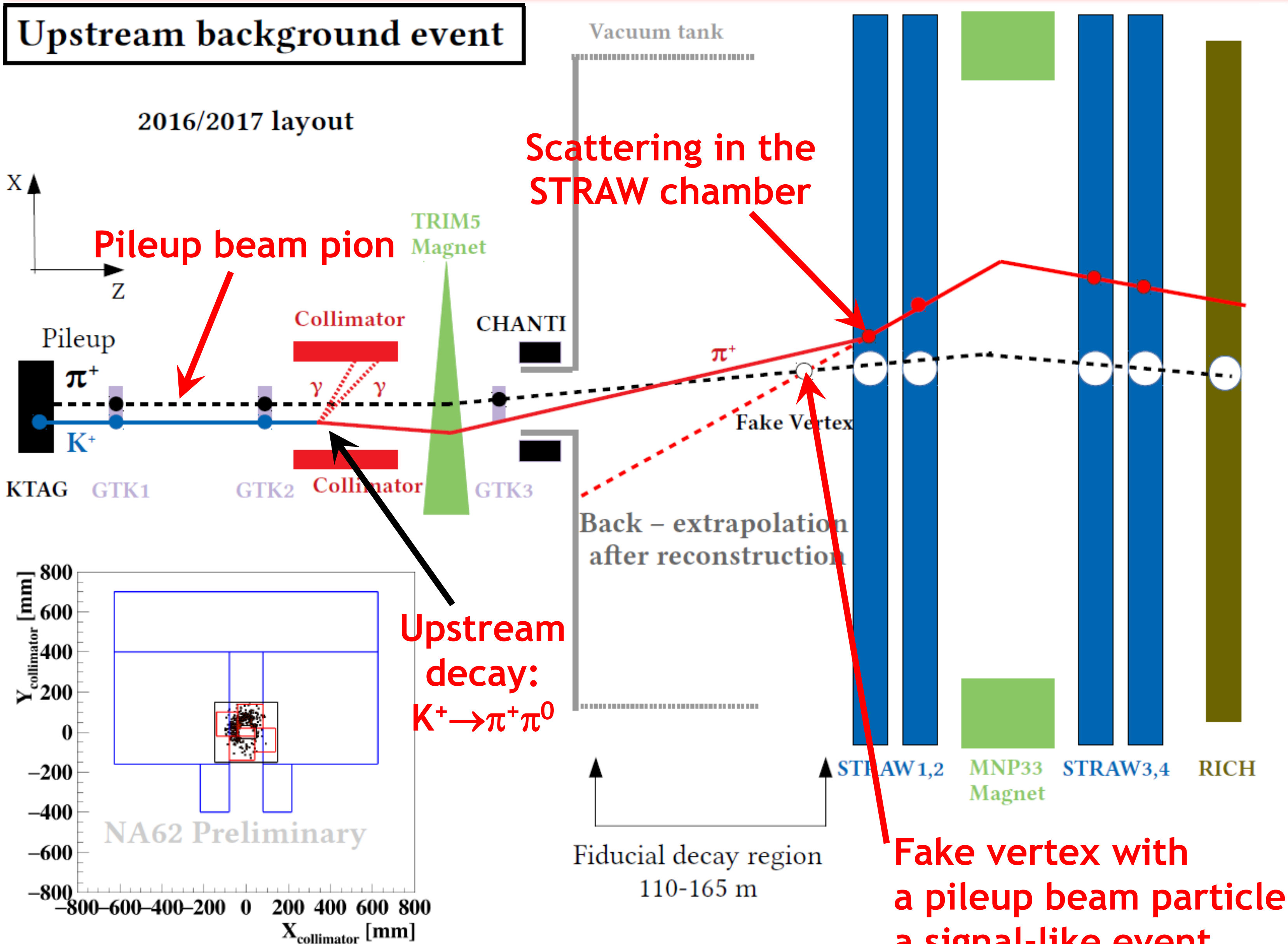
Data events in the $\pi^+\pi^0$ region after the $K_{\pi\nu\nu}$ selection (including π^0 rejection)

$$N_{BKG} = N(\pi^+\pi^0)\, f_{kin}$$

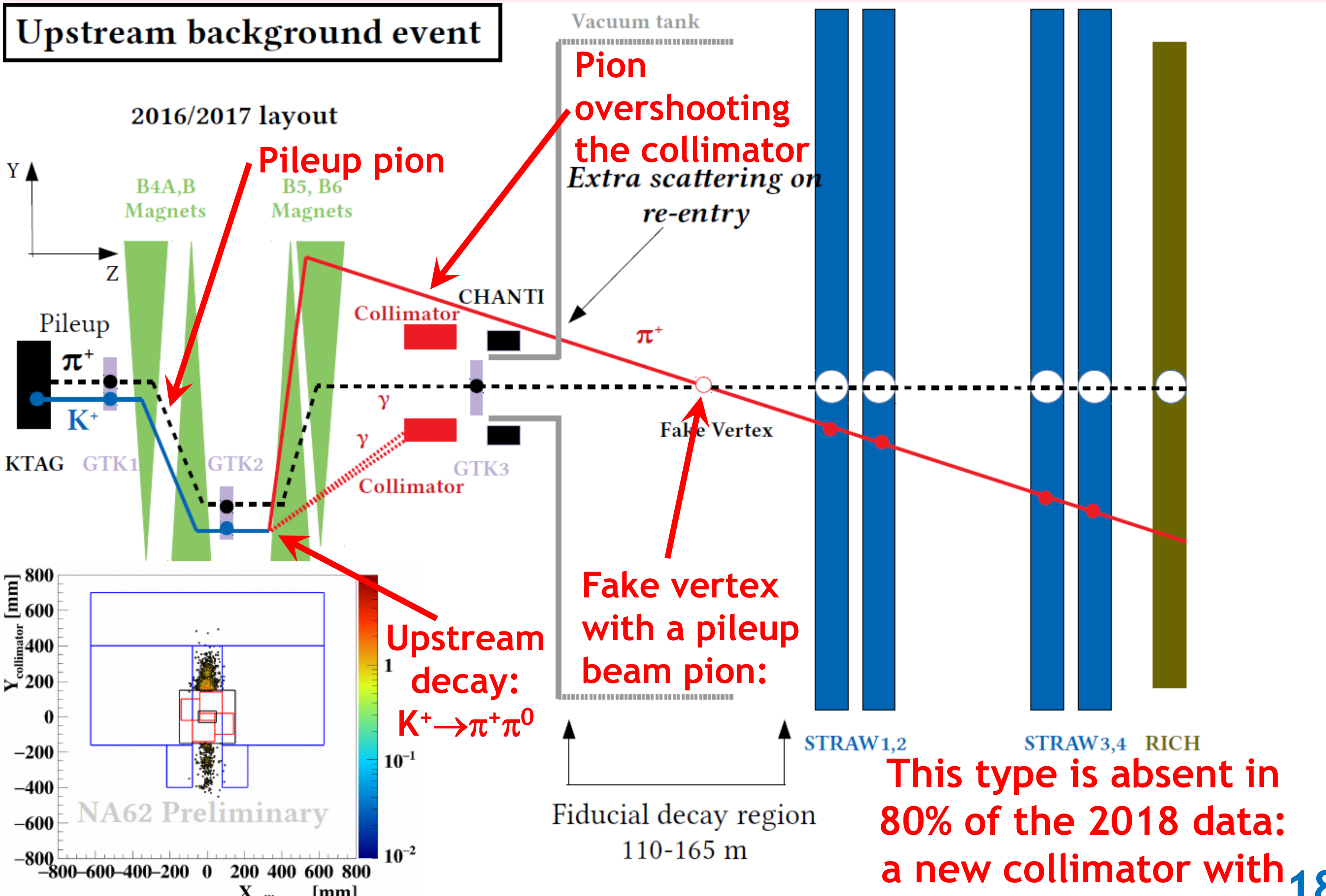
Expected numbers of $K^+\to\pi^+\pi^0$ events in signal regions after $K_{\pi\nu\nu}$ selection

Fraction of $\pi^+\pi^0$ events in signal regions measured from control data

Upstream background: type 1



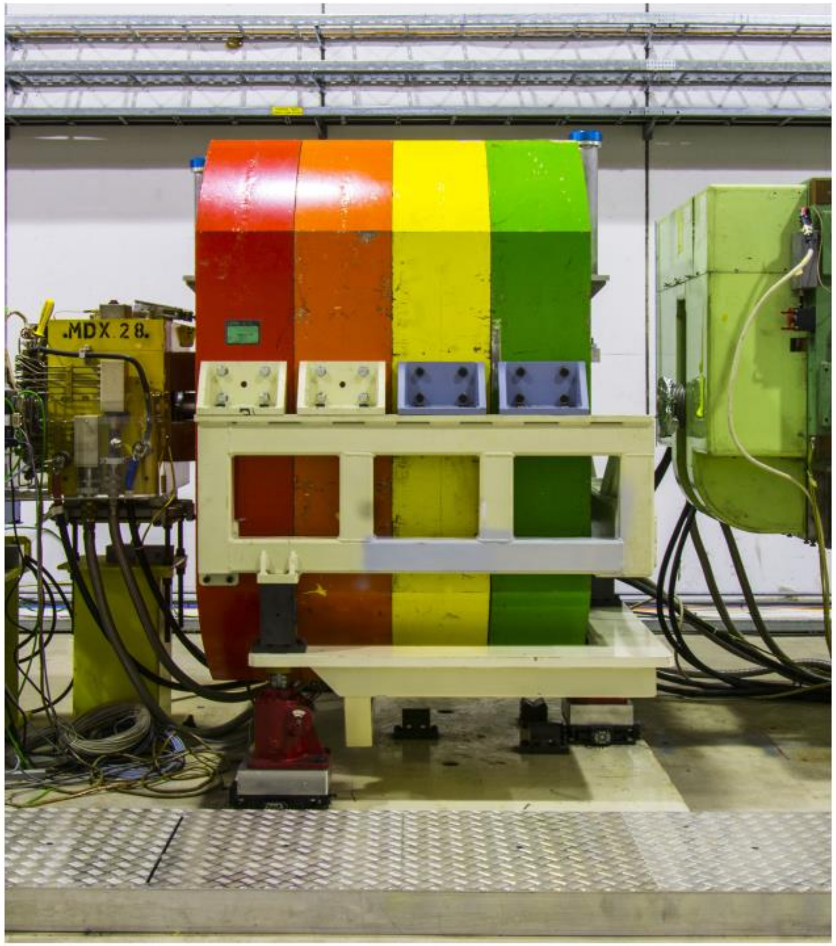
Upstream background: type 2



This type is absent in 80% of the 2018 data: a new collimator with larger transverse size

Final collimator replacement

Old collimator | **New collimator (since June 2018)**



- ❖ The new collimator allows for a looser event selection: signal acceptance $A_{\pi\nu\nu}$ improved from **4.0%** to **6.4%**.

Background summary (2018)

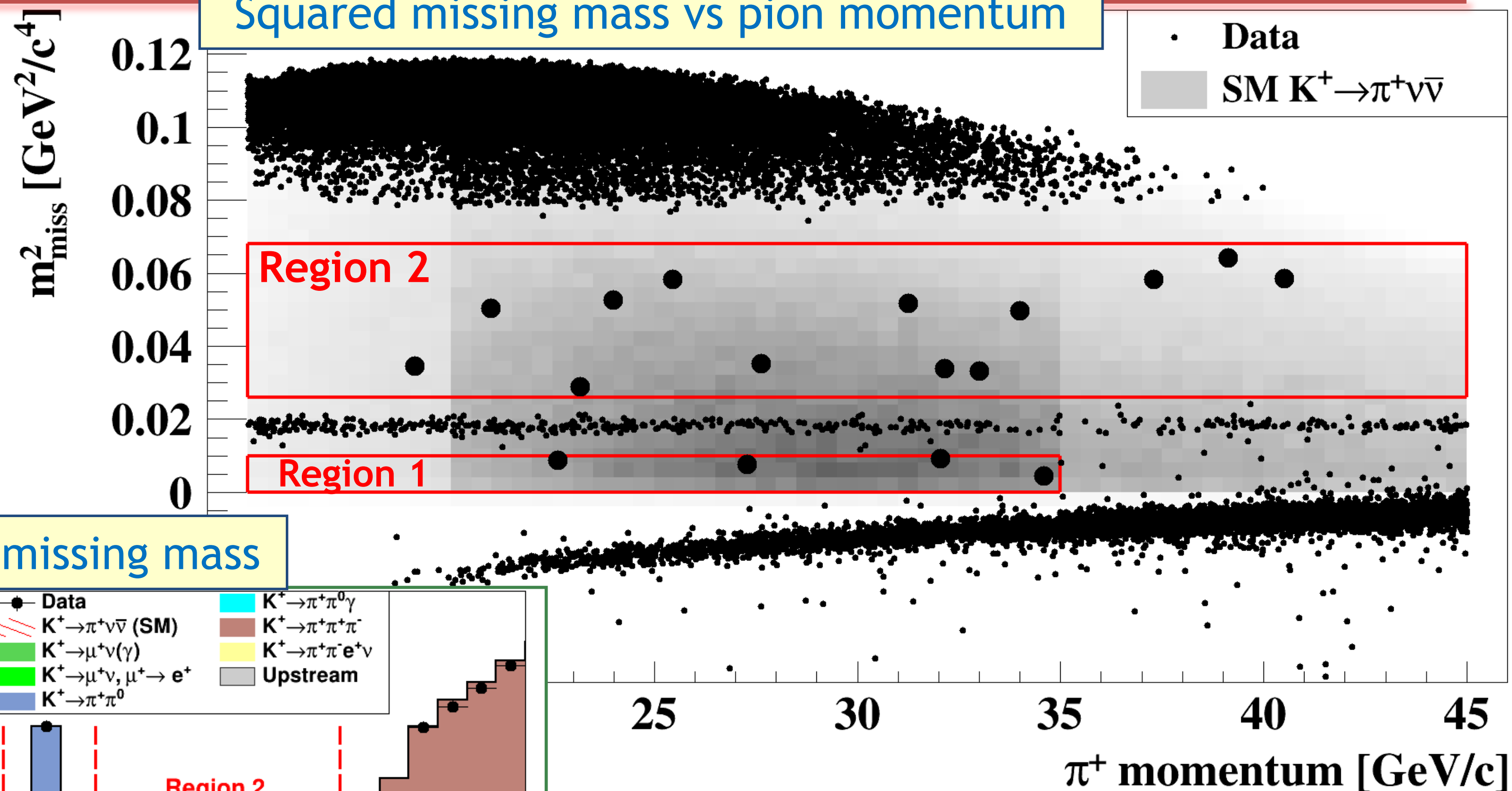
Expected SM signal	**$7.58(40)_{syst}(75)_{ext}$**
$K^+ \to \pi^+\pi^0(\gamma)$ IB	0.75(4)
$K^+ \to \mu^+\nu_\mu(\gamma)$ IB	0.49(5)
$K^+ \to \pi^+\pi^- e^+\nu_e$	0.50(11) (from simulations)
$K^+ \to \pi^+\pi^-\pi^+$	0.24(8)
$K^+ \to \pi^+\gamma\gamma$	< 0.01
$K^+ \to l^+\pi^0\nu_l$	< 0.001
Upstream background	$3.30^{+0.98}_{-0.73}$
Total background	$\mathbf{5.28^{+0.99}_{-0.74}}$

BDT-based estimation

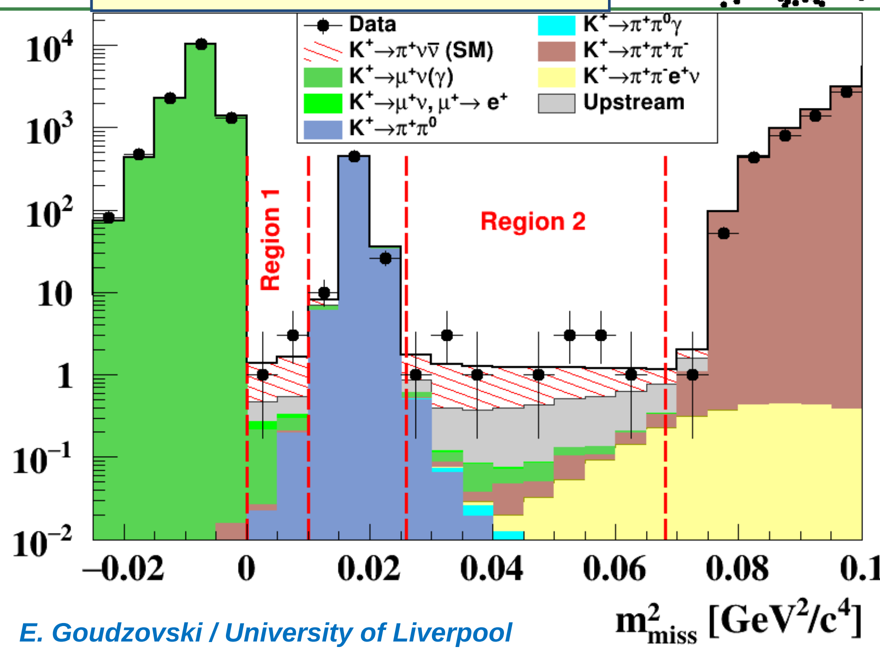
- Most background is still not due to K^+ decays in the vacuum tank!
- Improved the beamline layout and a new upstream veto detector will be used after LS3 to suppress upstream background.
- Contributions from upstream inelastic interactions are under study.

Opening the box (2018)

Squared missing mass vs pion momentum



Squared missing mass



The 2018 data set:

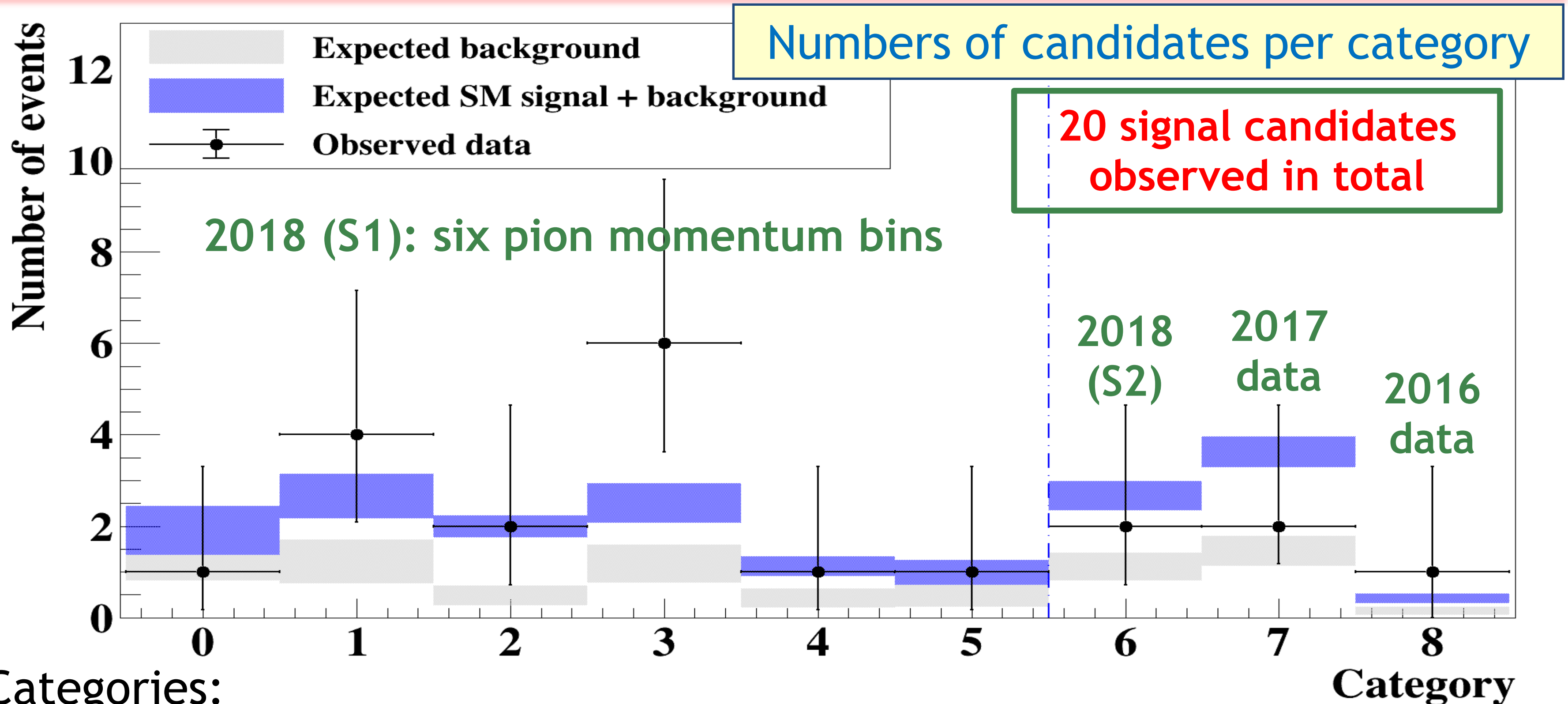
Candidates observed: **17**

Expected background: **5.3±1.0**

Expected SM events: **7.6**

Plus **3** candidates from **2016+17** data

Result: full Run 1 data set



Categories:

- ❖ Main **2018** data set (**80%**): six pion momentum bins (**15–45 GeV/c**).
- ❖ Early **2018** data sample (old collimator), **2017** and **2016** samples: three separate categories, integrated over pion momentum.

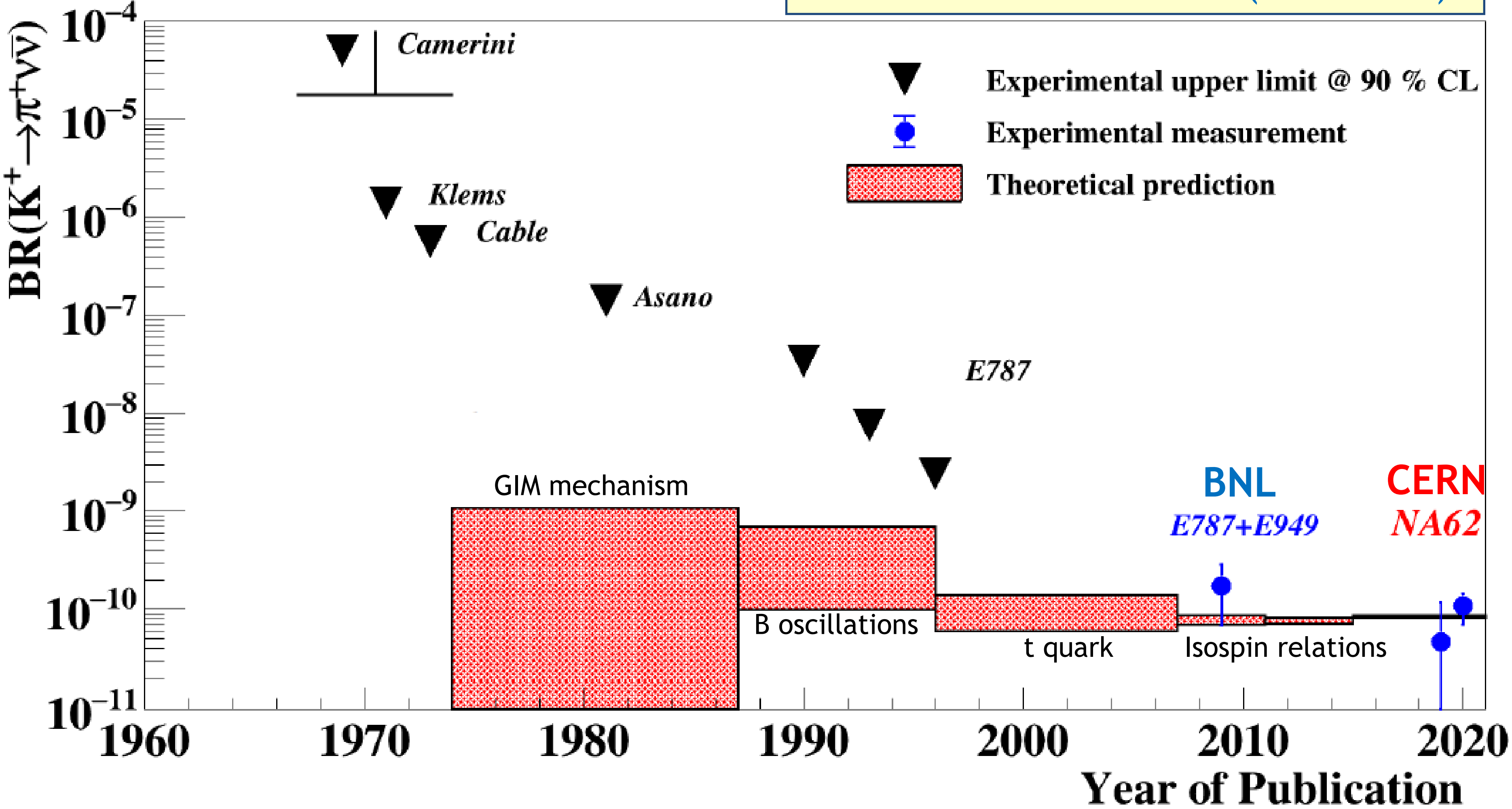
Final result (full Run 1 sample):

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5}{}_{stat.} \pm 0.3_{syst.}) \times 10^{-11}$$

(3.5σ significance)

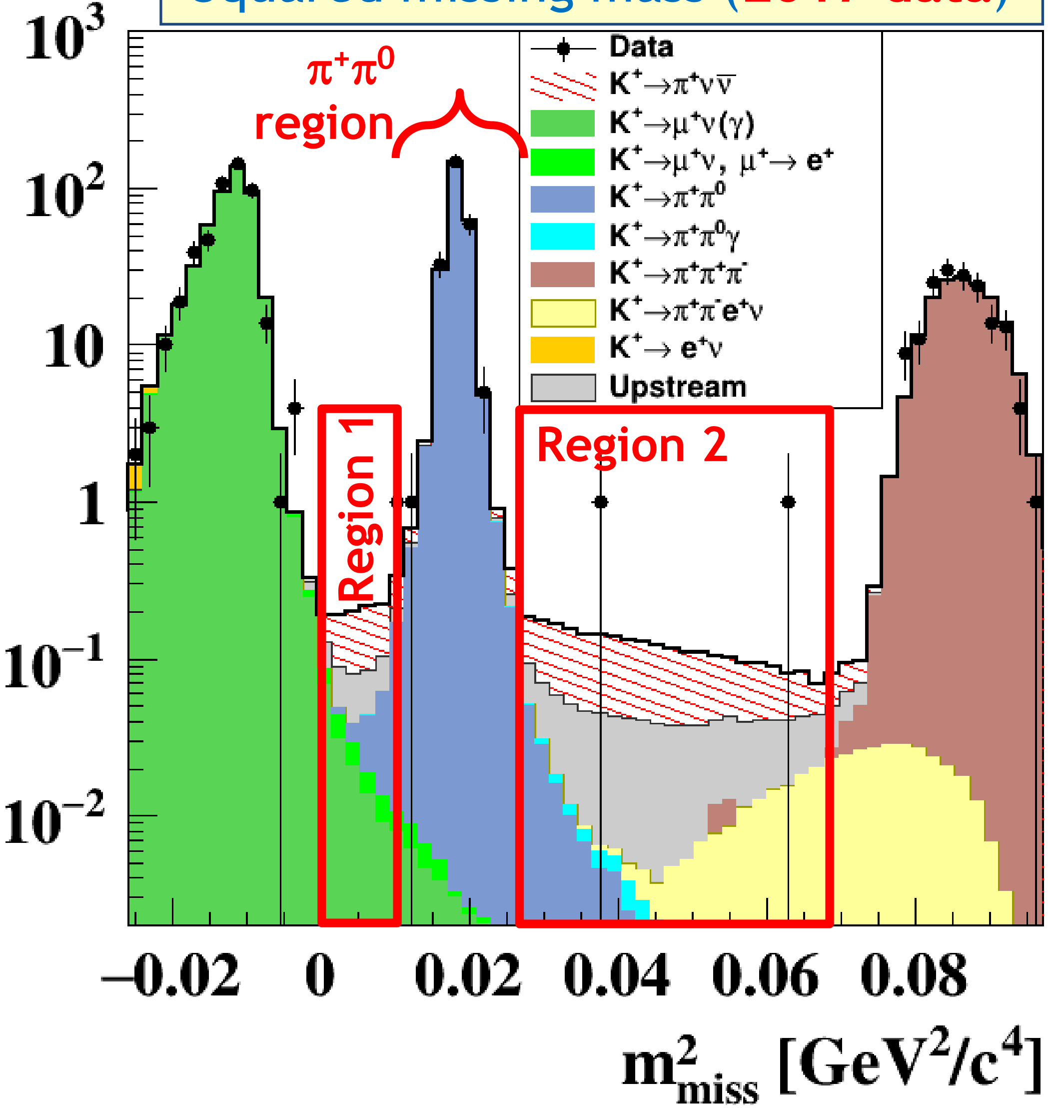
$K^+ \to \pi^+ \nu\nu$: historical perspective

Time evolution of BR($K^+ \to \pi^+ \nu\nu$)



Hidden-sector physics with $K^+ \to \pi^+ \nu\nu$

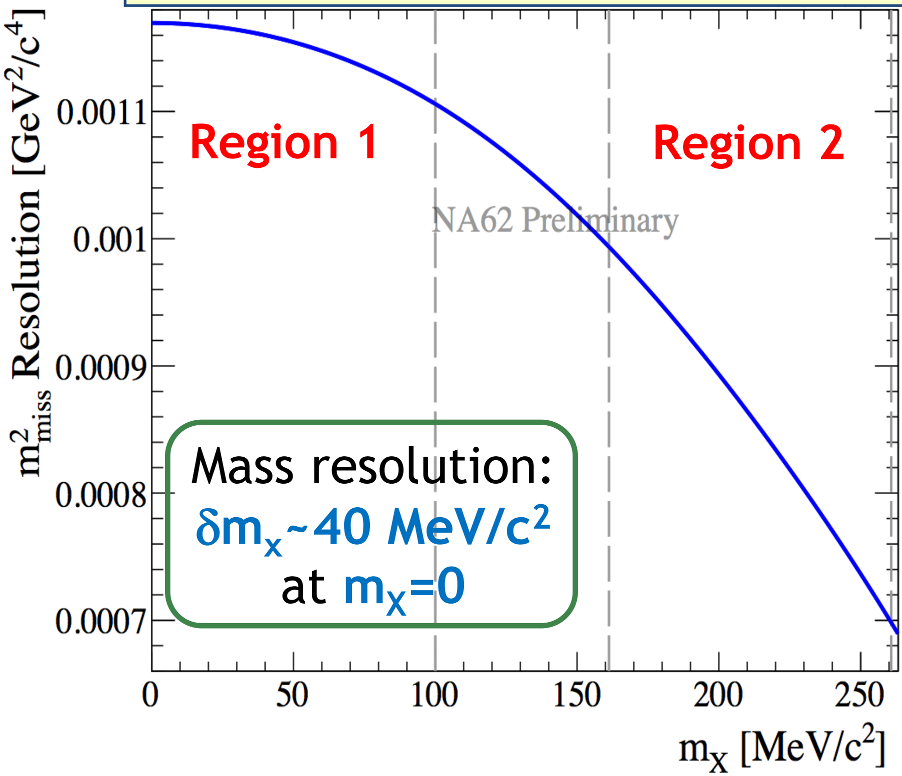
Squared missing mass (**2017 data**)



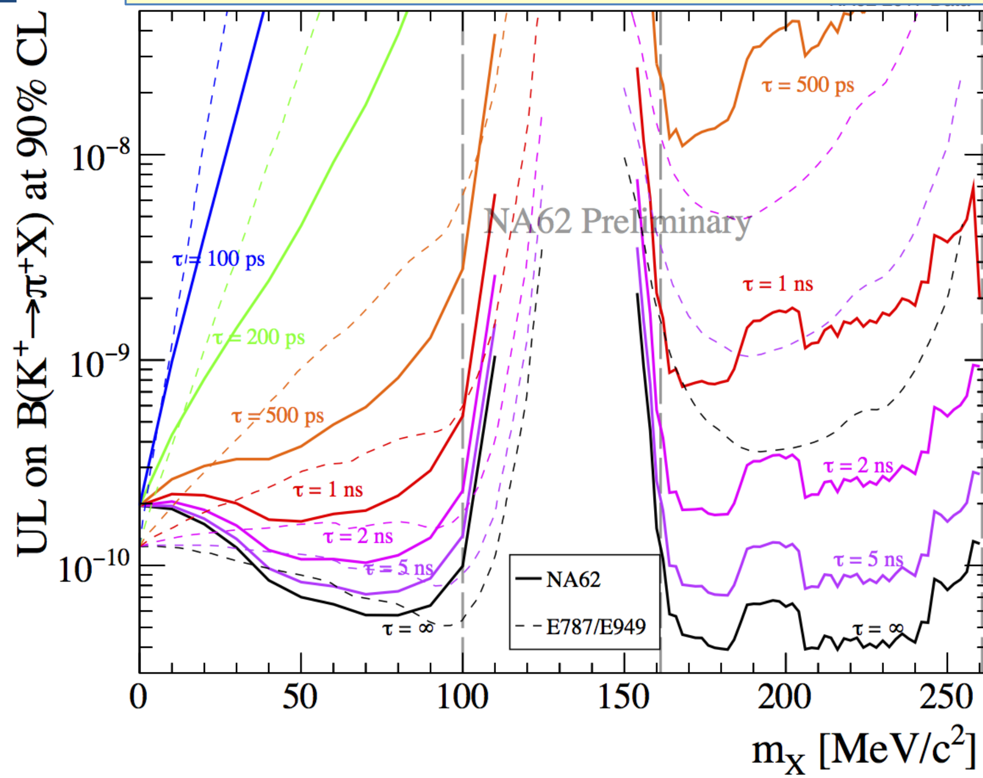
- Signal regions **R1**,**R2**: search for $K^+ \to \pi^+ X$ (X=invisible), $0 \le m_X \le 100$ MeV/c^2 and $160 \le m_X \le 260$ MeV/c^2.
  - ✓ Interpretation: dark scalar, ALP, QCD axion, axiflavon.
  - ✓ Main background: $K^+ \to \pi^+ \nu\nu$.
- The $\pi^+\pi^0$ region: search for **$\pi^0 \to$invisible**.
  - ✓ SM rate: $BR(\pi^0 \to \nu\nu) \sim 10^{-24}$.
  - ✓ Observation = BSM physics.
  - ✓ Reduction of $\pi^0 \to \gamma\gamma$ background: optimized π^+ momentum range.
  - ✓ Extension: $K^+ \to \pi^+ X$, with m_X between R1 and R2.

Search for $K^+ \to \pi^+ X$ (2017 data)

Squared missing mass resolution



UL at 90% CL on BR($K^+ \to \pi^+ X$) vs m_X



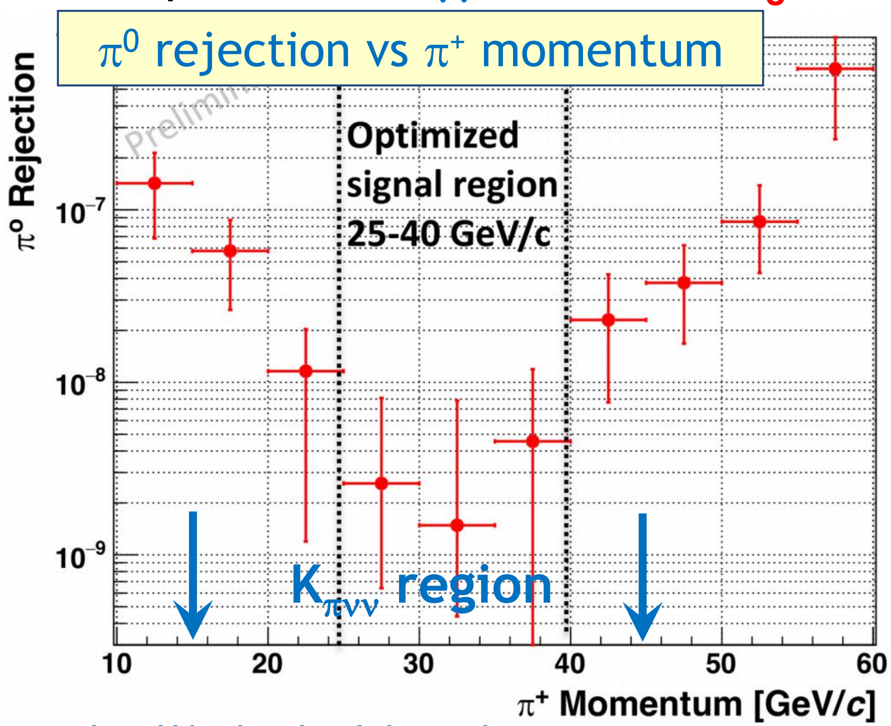
- ❖ Two candidates in **2017** data, consistent with background: no signal.
- ❖ Upper limits of **BR($K^+ \to \pi^+ X$)**, depending on **X** mass and lifetime.
- ❖ Region 2: order of magnitude improvement on BNL E949 *[PRD79 (2009) 092004]*
- ❖ Not limited by background: significant improvements soon.

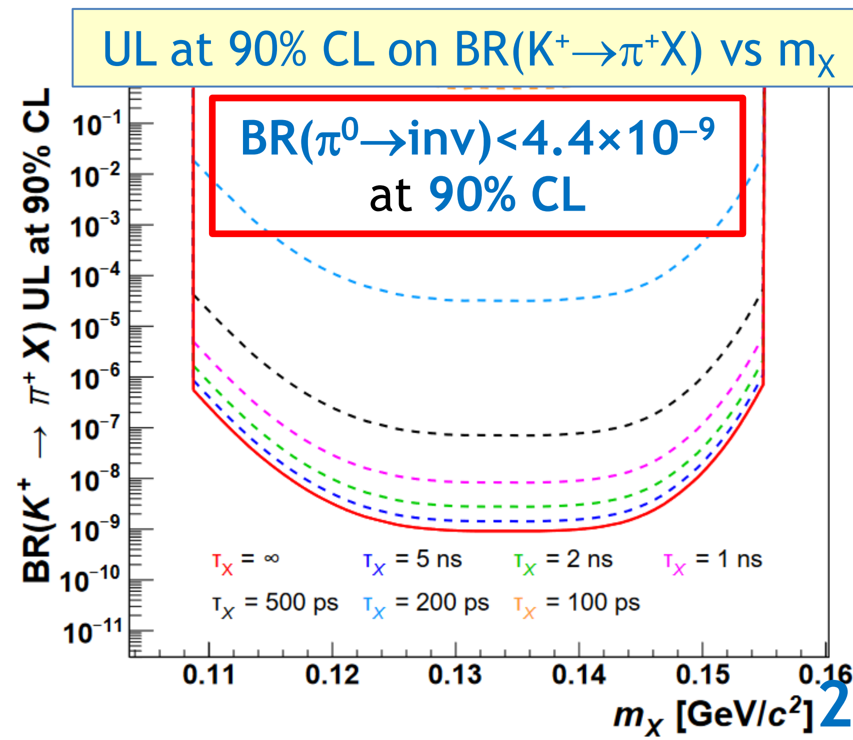
Search for $\pi^0 \to$invisible (2017 data)

- Rejection of ($K^+ \to \pi^+\pi^0(\gamma)$, $\pi^0 \to \gamma\gamma$) decays: *[arXiv:2010.07644]*
  simulation based on single-photon efficiency measured with $K^+ \to \pi^+\pi^0$ decays.
- Rejection of $\pi^0 \to \gamma\gamma$ decays for $K^+ \to \pi^+\nu\nu$ analysis: $\varepsilon \approx 2\times10^{-8}$.
- For $\pi^0 \to$invisible search ($25<p_\pi<40$ GeV/c): $\varepsilon = (2.8^{+5.0}_{-2.1})\times10^{-9}$

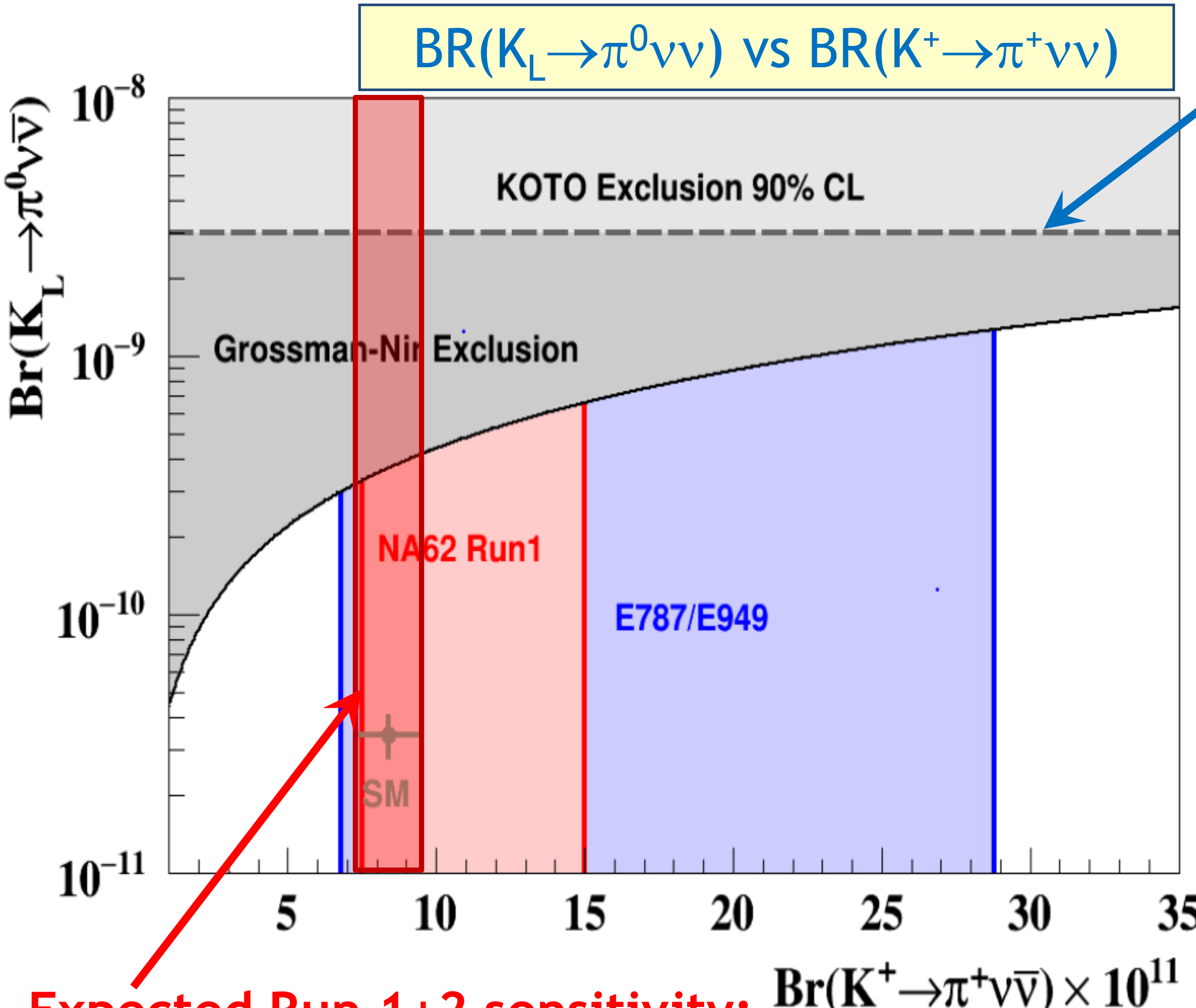
Search for $\pi^0 \to$invisible: (1/3 of the 2017 data set).

- $K_{\pi\nu\nu}$ trigger and selection used, with $0.015<m^2_{miss}<0.021$ GeV^2/c^4.
- Expected $\pi^0 \to \gamma\gamma$ events: 10^{+22}_{-8}, events observed: 12.





Short-term plans: NA62 Run 2



Expected Run 1+2 sensitivity:
$\delta BR/BR \approx 10\%$

KOTO result with 2015 data:
$BR(K_L \to \pi^0 \nu\nu) < 3.0 \times 10^{-9}$

PRL 122 (2019) 021802

NA62 Run 2 (2021–24):

- Higher beam intensity.
- Optimized beamline, new veto detectors: reduced upstream background, higher acceptance.
- Fourth kaon beam tracker station added.
- Collect ~100 SM candidates in total.

Long-term plans: $K^+ \to \pi^+ \nu\nu$ at CERN

- The $K^+ \to \pi^+ \nu\nu$ decay in-flight technique is firmly established, and is expected to reach an O(10%) measurement by 2024.
- A possible next step after LS3 (in ~2027): a $K^+ \to \pi^+ \nu\nu$ experiment with ×4 beam intensity (present SPS limit), aiming at ~5% precision.
  - ✓ Challenge: O(10ps) time resolution for key detectors to keep random veto under control, while maintaining other performances.

New pixel beam tracker (GTK):

time resolution: <50 ps per plane;
pixel size: <300×300 μm^2;
efficiency: >99% per plane (incl.fill factor);
material budget : 0.3–0.5% X_0;
beam Intensity: 3 GHz on 30×60 mm^2;
peak intensity: 8.0 MHz/mm^2.

A current NA62 GTK station

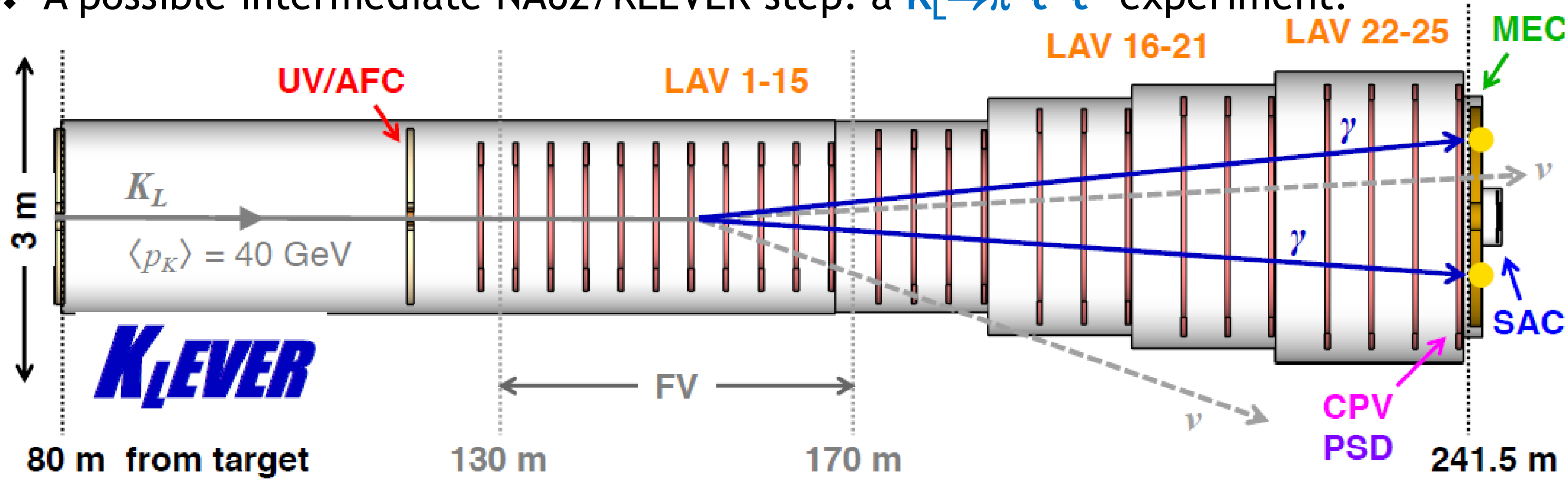
New STRAW spectrometer:

operation in vacuum;
straw length/diameter: 2.2 m/5 mm;
trailing time resolution: ~6 ns per straw;
maximum drift time: ~80 ns;
layout: ~21000 straws (4 chambers);
material budget: 1.5%X_0.

A current NA62 STRAW chamber

Long-term plans: $K_L \to \pi^0 \nu\nu$ at CERN

- **KLEVER**: a high-energy experiment (10^{19} pot/year) complementary to KOTO.
- Photons from K_L decays boosted forward: veto coverage only up to **100 mrad**.
- Vacuum tank layout and fiducial volume similar to NA62.
- A possible intermediate NA62/KLEVER step: a $K_L \to \pi^0 \ell^+ \ell^-$ experiment.



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

Target sensitivity:

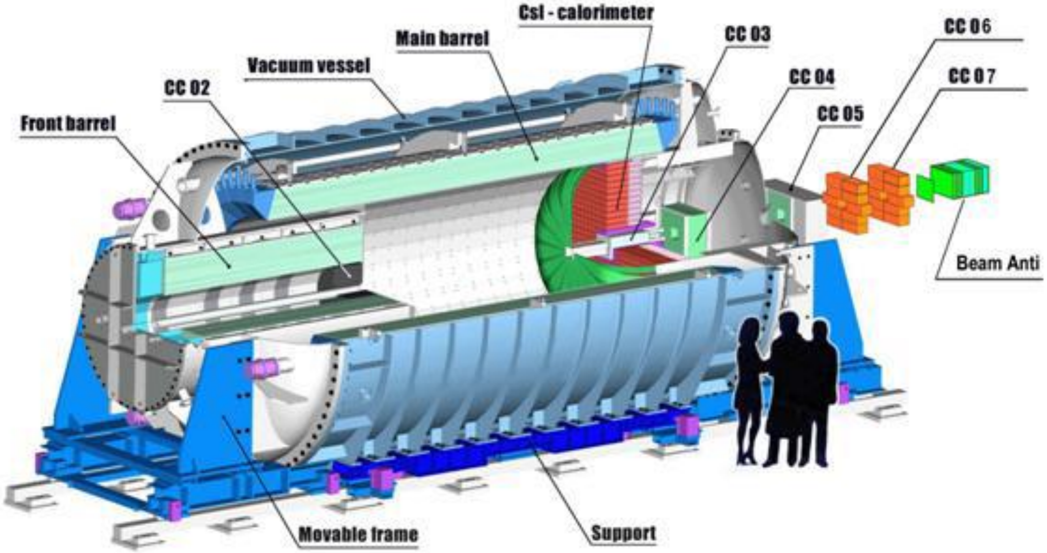
60 SM $K_L \to \pi^0 \nu\nu$ events with **S/B~1** in **5** years of running;

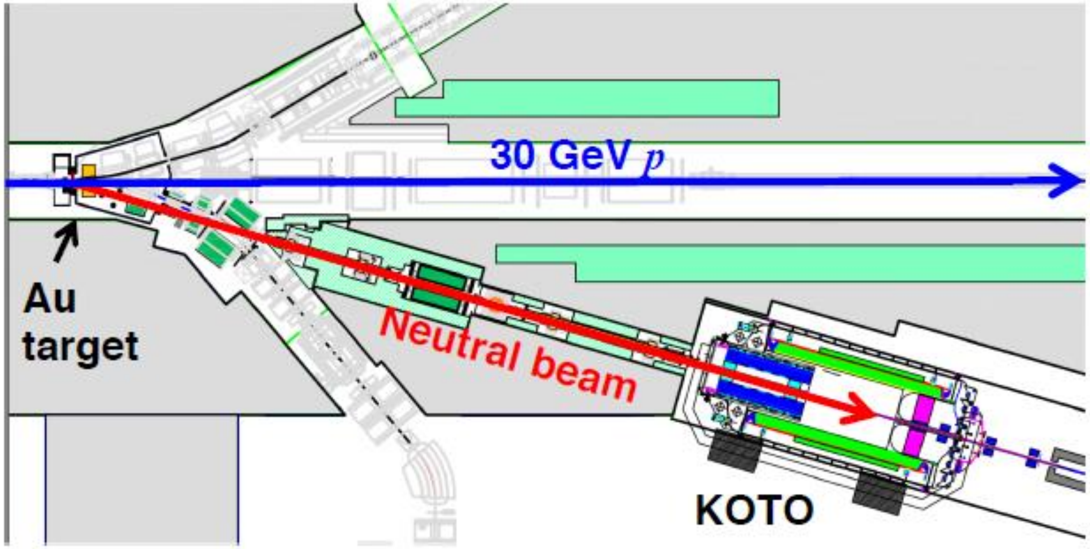
$\delta BR(K_L \to \pi^0 \nu\nu)/BR(K_L \to \pi^0 \nu\nu) \sim 20\%$.

The KOTO experiment at J-PARC

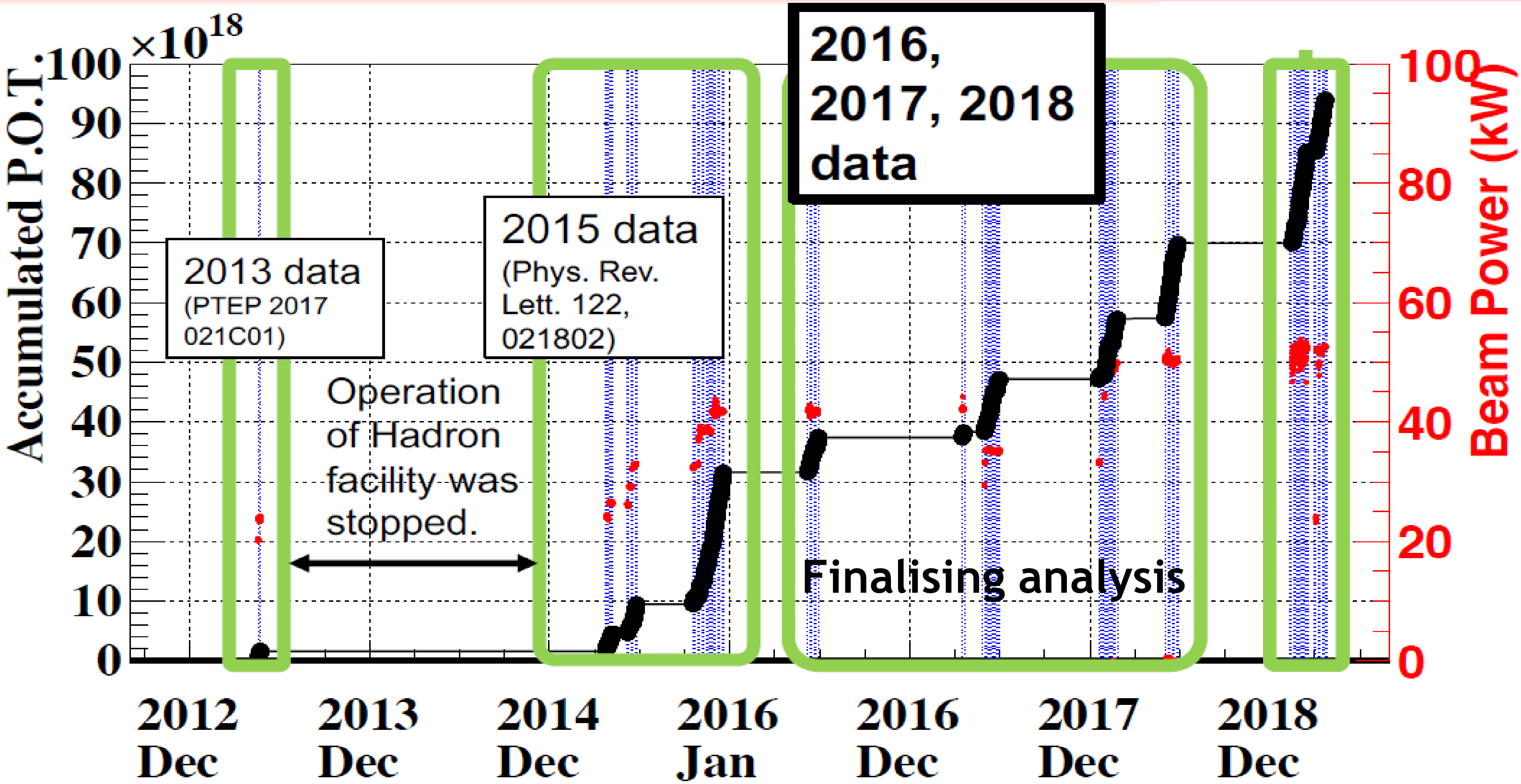
KOTO at J-PARC: $K_L \to \pi^0 \nu\nu$

- Primary beam: **30 GeV** protons; **50 kW = 5.5×10^{13} p/5.2 s** (in 2019).
- Neutral "pencil" beam (at **16°**): **$\langle p(K_L)\rangle$ = 2.1 GeV**, with **50%** in the **(0.7–2.4) GeV** range.
- Beam composition: K_L, neutrons, photons.
- Fiducial decay region length: **3 m**.
- CsI calorimeter + hermetic photon veto.





KOTO status



2015 run

- Reached **40 kW** beam power, 3×10^{19} POT collected.
- Final 2015 result: $BR(K_L \to \pi^0 \nu\nu) < 3.0\times10^{-9}$ at **90%** CL.
  PRL 122 (2019) 021802

2016–2018 runs

- Reached **50 kW** beam power, 4×10^{19} POT collected.
- Preliminary results reported in 2019/20.

2019 run

- Analysis in progress.

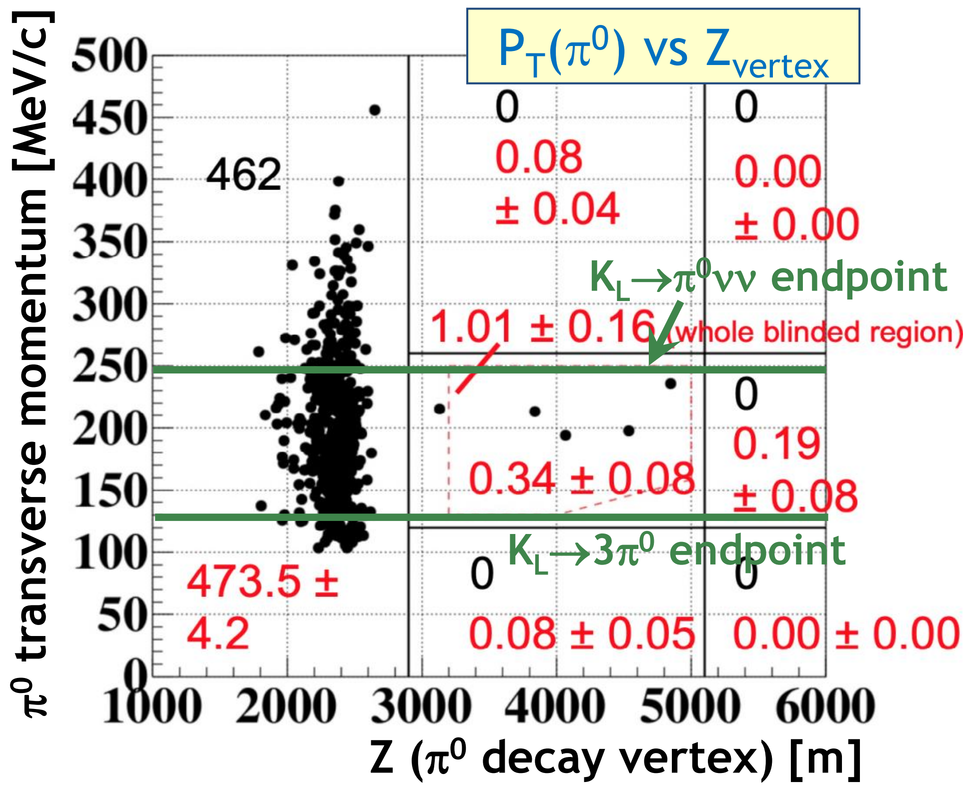
KOTO: 2016–18 data

Preliminary results (N.Shimizu at ICHEP 2020)

Single-event sensitivity:
$BR_{SES}=71\times10^{-11}$ ($=20\times BR_{SM}$)

Main backgrounds:

source		#BG (90% C.L.)	#BG (68% C.L.)
K+/-	$K^{\pm}\to\pi^0\pi^{\pm}$	0.09±0.09	0.09±0.09
	$K^{\pm}\to\pi^0 e^{\pm}\nu$	0.90±0.27	0.90±0.27
	$K^{\pm}\to\pi^0\mu^{\pm}\nu$	<0.21	<0.12
Neutron	Upstream π^0	0.001±0.001	0.001±0.001
	Hadron cluster	0.02 ±0.00	0.02 ±0.00
	CV-pi0	<0.10	<0.05
	CV-eta	0.03±0.01	0.03±0.01
Total	central value	1.05±0.28	1.05±0.28



After a blind analysis, **four candidate events** in the signal region.

- One event demonstrated to be background (timing in a veto counter).
- Background estimate (revised): **1.05±0.28** events, mainly from $K^{\pm}$ decays.
- The result on $BR(K_L\to\pi^0\nu\nu)$ is to be reported soon.

Short-term plans: KOTO step-1

Signal: need **20** times more (flux × acceptance) to **reach SM sensitivity**.

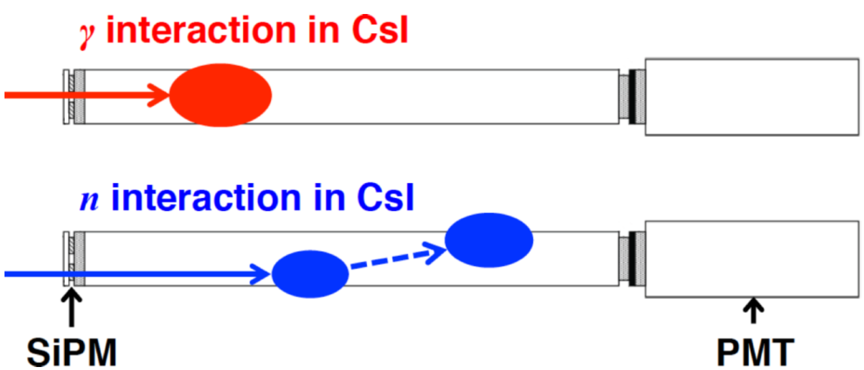
- ✓ Increase the beam power (**50→100 kW**) gradually by **2024**.
- ✓ 8–16 months of additional running planned in **2020–2024**.

Background: need **~10** times improvement in background rejection to obtain **S/B ≈ 1**, assuming SM signal rate.

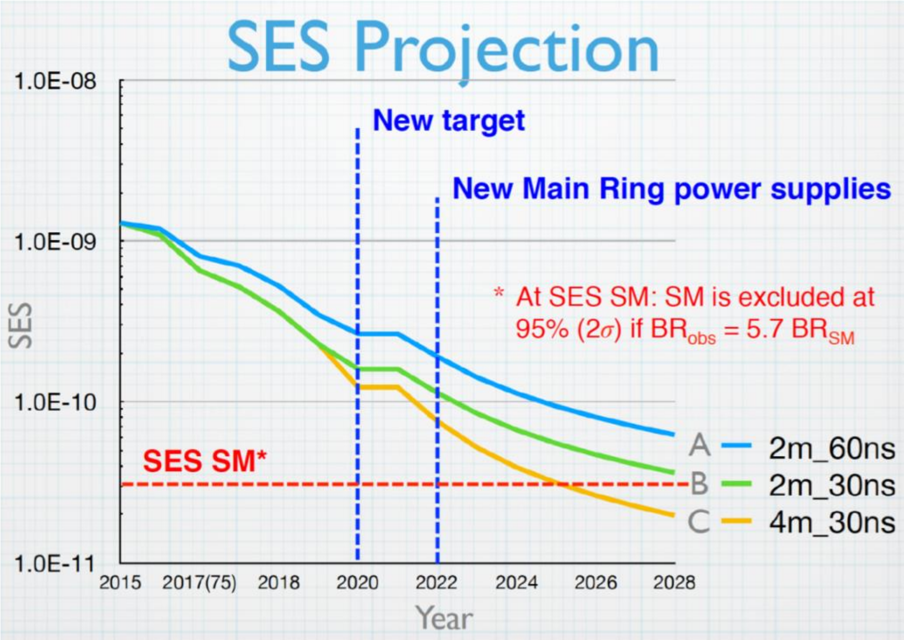
- ✓ Continuing programme of incremental detector upgrades.

Example:

Dual side readout for CsI calorimeter modules installed at end of 2018 run



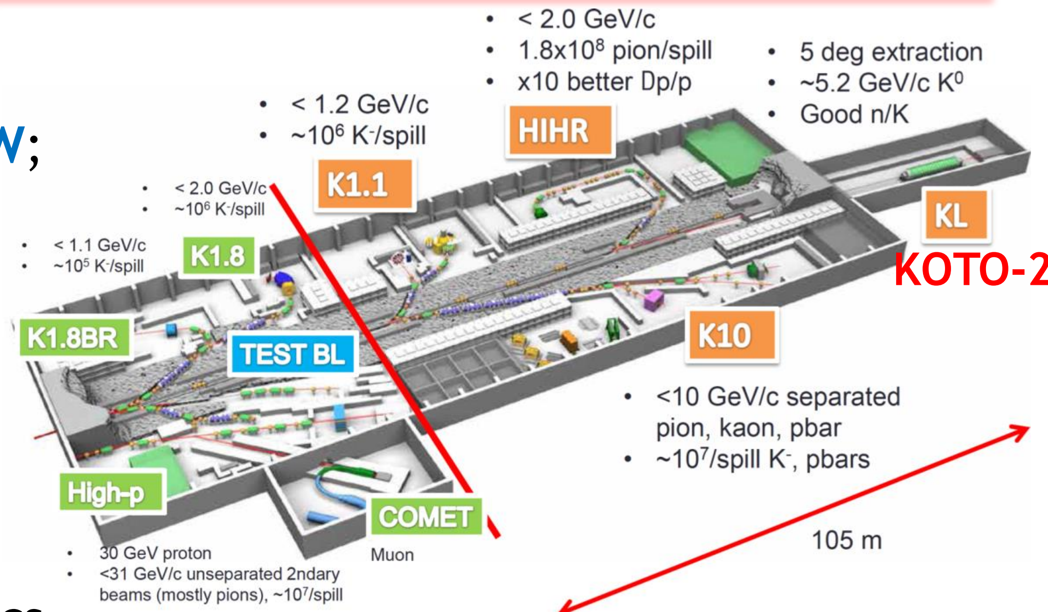
Resolve γ/n interaction depth by reading light from front CsI face with a SiPM



Long-term plans: KOTO step-2

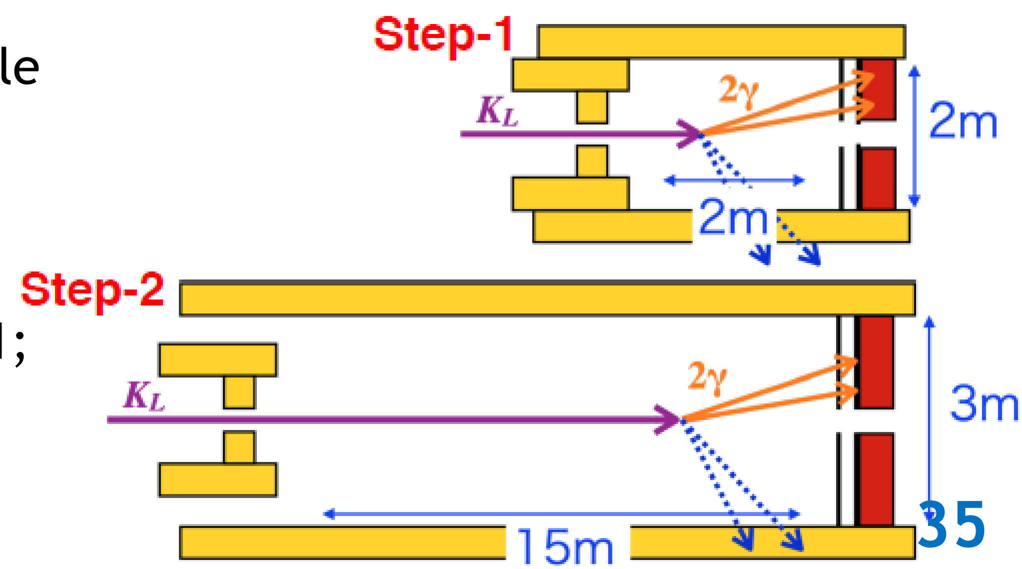
To reach O(100) signal events:

- proton beam power above **100 kW**;
- new neutral beamline at **5°** with **<p(K_L)> = 5.2 GeV/c**;
- larger fiducial decay volume;
- complete rebuild of the detector.



Hadron hall extension required:

- a joint project with nuclear physics community;
- on the list of KEK future large-scale projects, with medium priority.



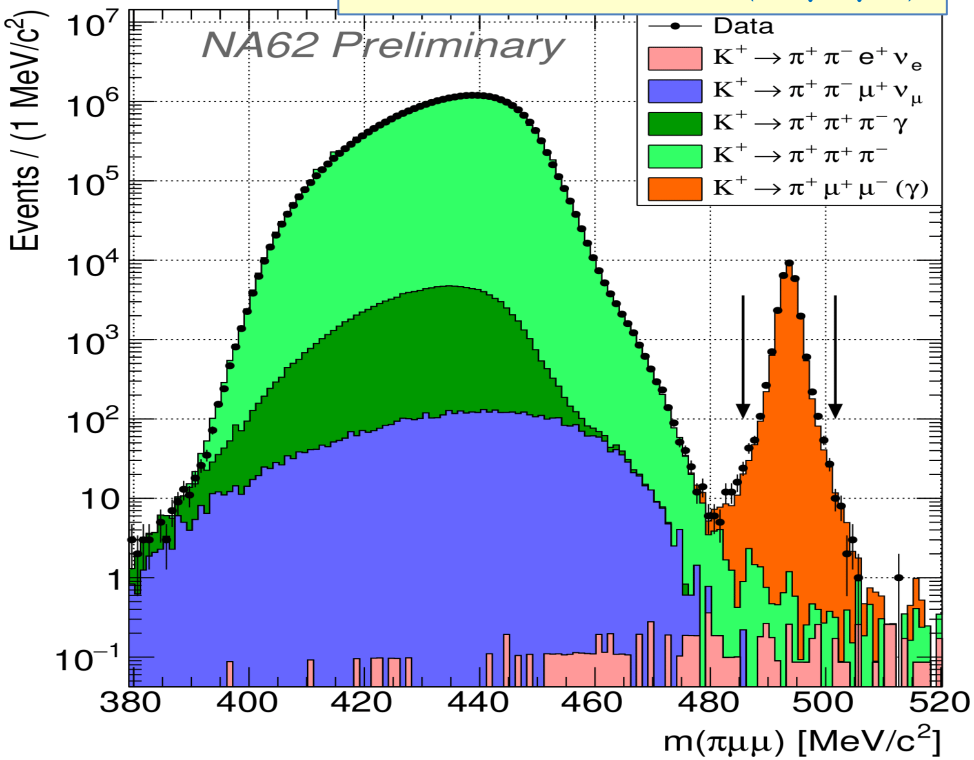
Expected sensitivity:

- signal acceptance: **5×** KOTO step-1;
- 60 SM events with **S/B~1** at **100 kW** beam power (**3×10⁷ s**).

Recent NA62 results beyond the flagship analysis

$K^+ \to \pi^+\mu^+\mu^-$ measurement (Run 1)

SM selection: $m(\pi^+\mu^+\mu^-)$



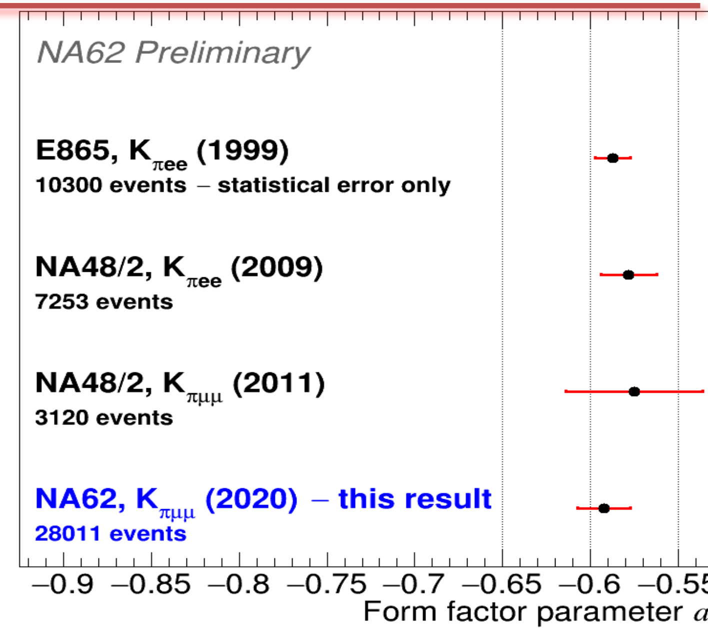
28011 candidates (**~0.05%** background): **~10** times the world sample.

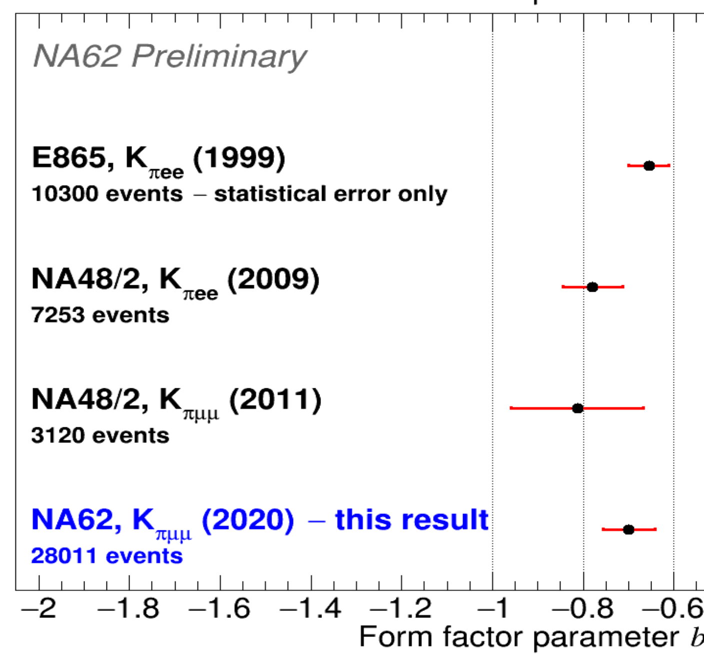
Preliminary result:

$BR(K^+ \to \pi^+\mu^+\mu^-)$=

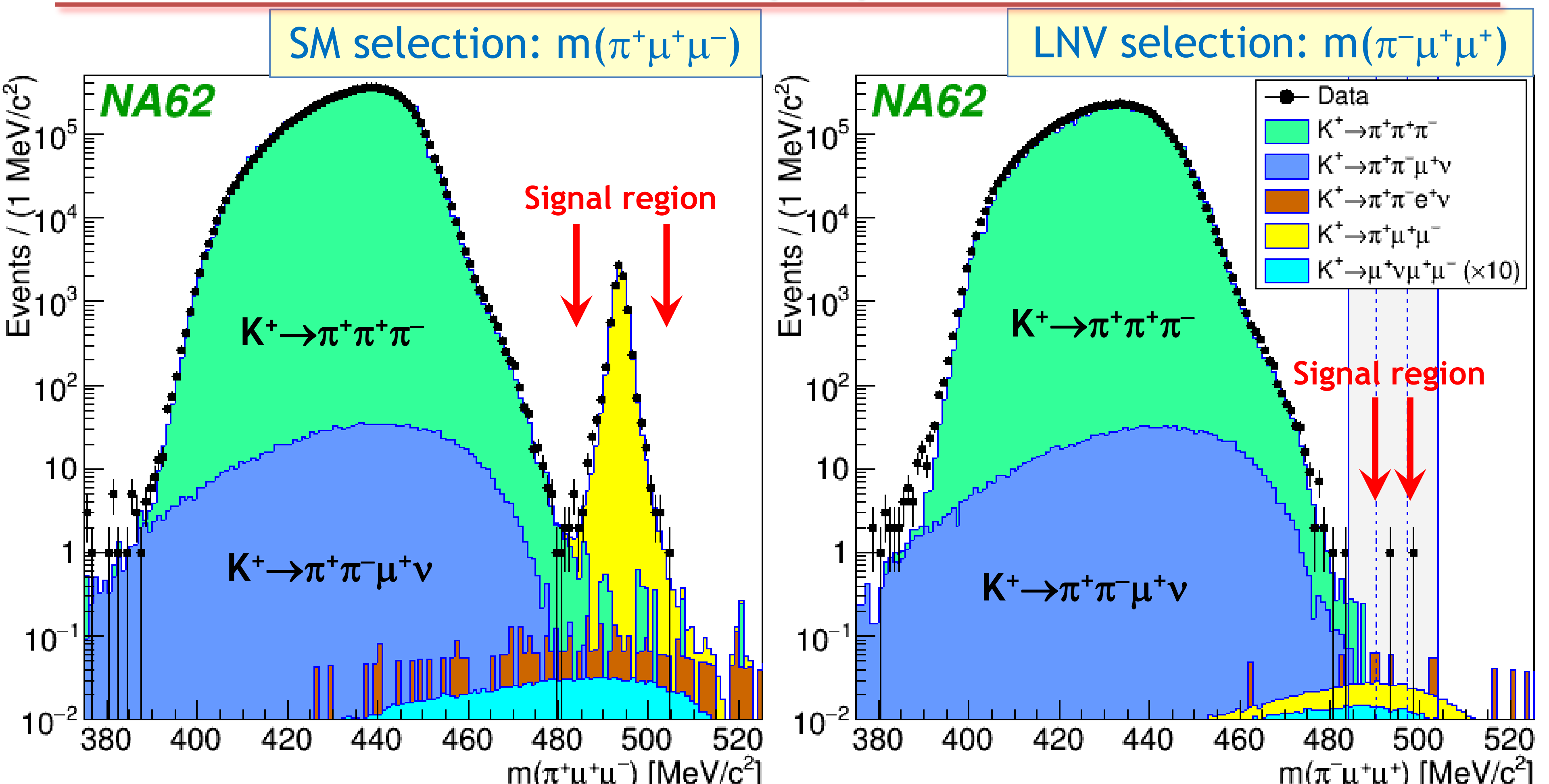
$(9.27 \pm 0.07_{stat} \pm 0.08_{syst} \pm 0.04_{ext}) \times 10^{-9}$.

LU test: **$K \to \pi\mu\mu$** vs **$K \to \pi ee$** FF parameters.





Search for $K^+ \to \pi^- \mu^+ \mu^+$ decay (2007)

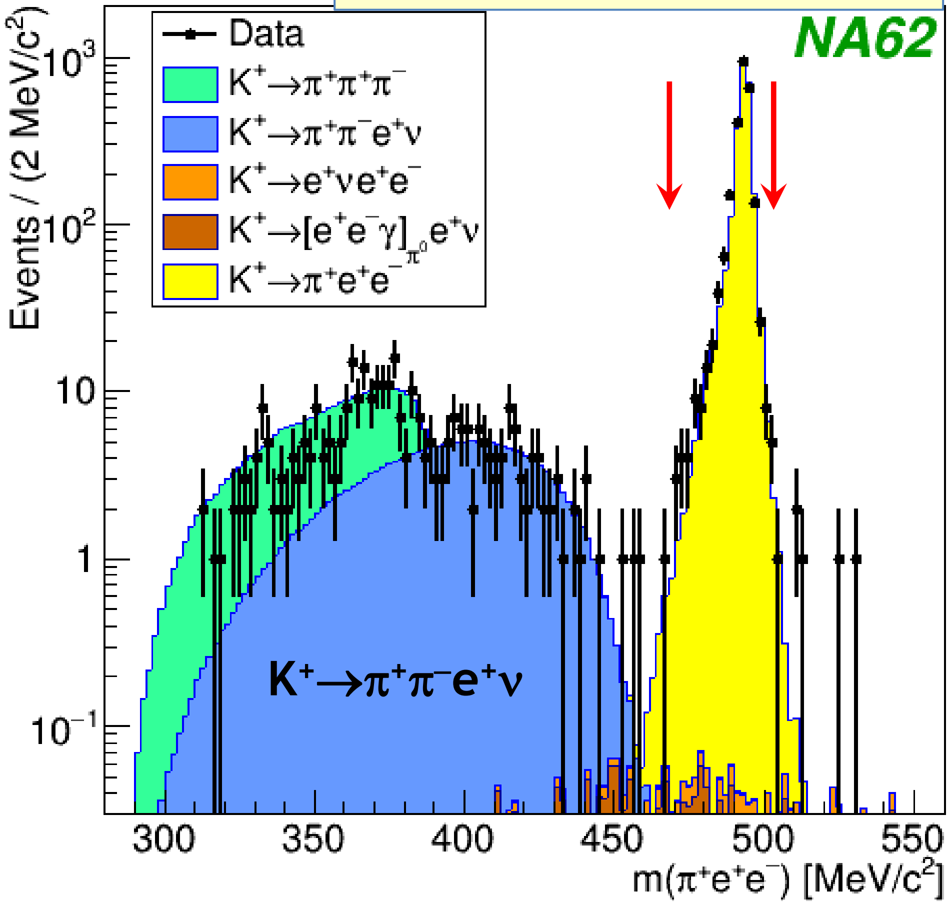


Candidates observed: **8357**
Background: **0.07%**
$BR(K^+ \to \pi^+ \mu^+ \mu^-) = (0.962 \pm 0.025) \times 10^{-7}$
K^+ decays in FV: **$(7.94 \pm 0.23) \times 10^{11}$**

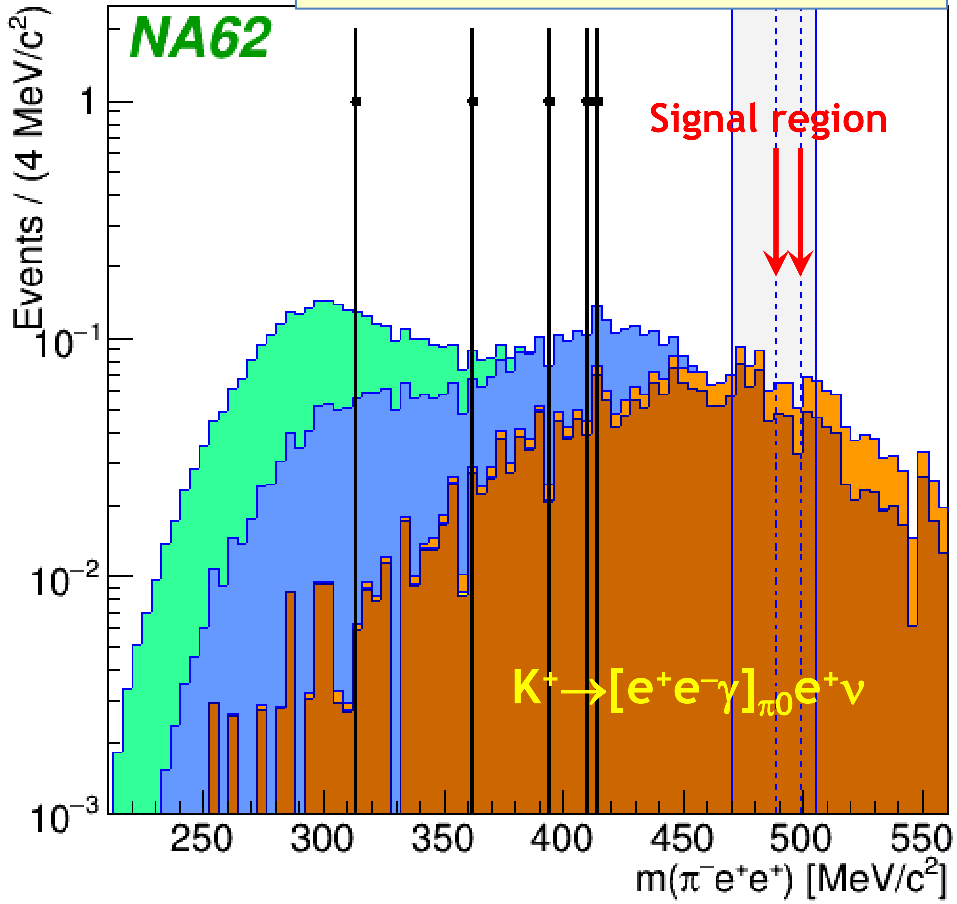
Expected background: **0.91 ± 0.41** evt
Candidates observed: **1**
$BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ at 90% CL
[PLB797 (2019) 134794]

Search for $K^+ \to \pi^- e^+ e^+$ decay (2007)

SM selection: $m(\pi^+ e^+ e^-)$



LNV selection: $m(\pi^- e^+ e^+)$



Candidates observed: **2484**

BR($K^+ \to \pi^+ e^+ e^-$) = $(3.00 \pm 0.09) \times 10^{-7}$

K^+ decays in FV: **$(2.14 \pm 0.07) \times 10^{11}$**

Expected background: **0.16 ± 0.03** evt

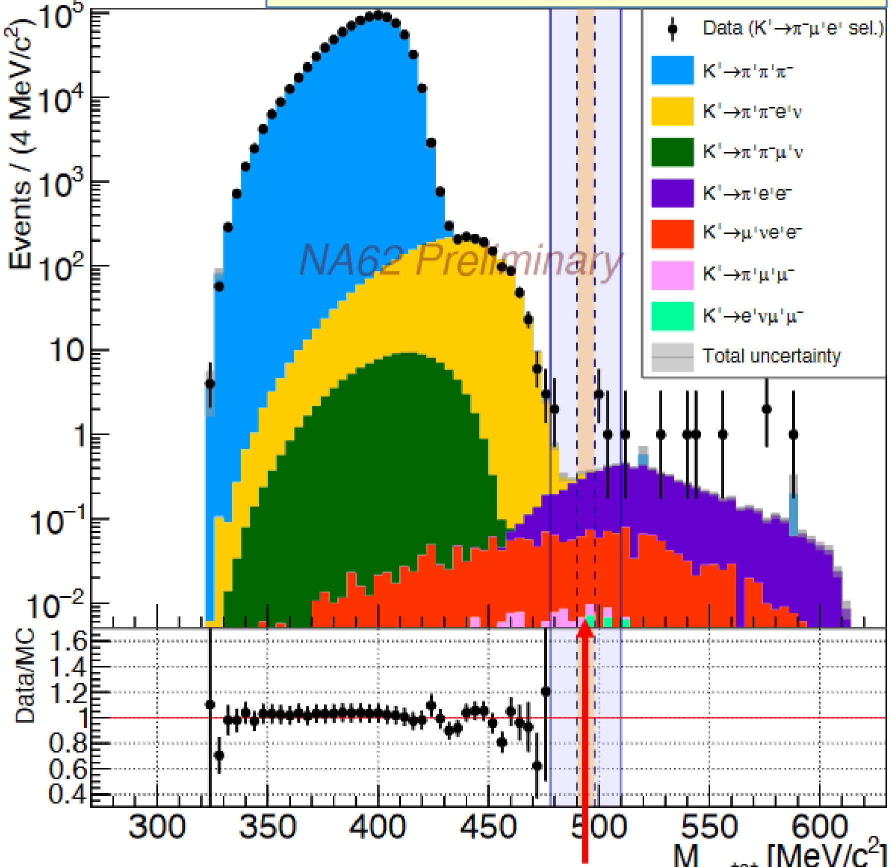
Candidates observed: **0**

BR($K^+ \to \pi^- \mu^+ \mu^+$)<$2.2 \times 10^{-10}$ at 90% CL

[PLB797 (2019) 134794]

Search for $K^+ \to \pi\mu e$ decays (Run 1)

LNV decay: $m(\pi^- \mu^+ e^+)$

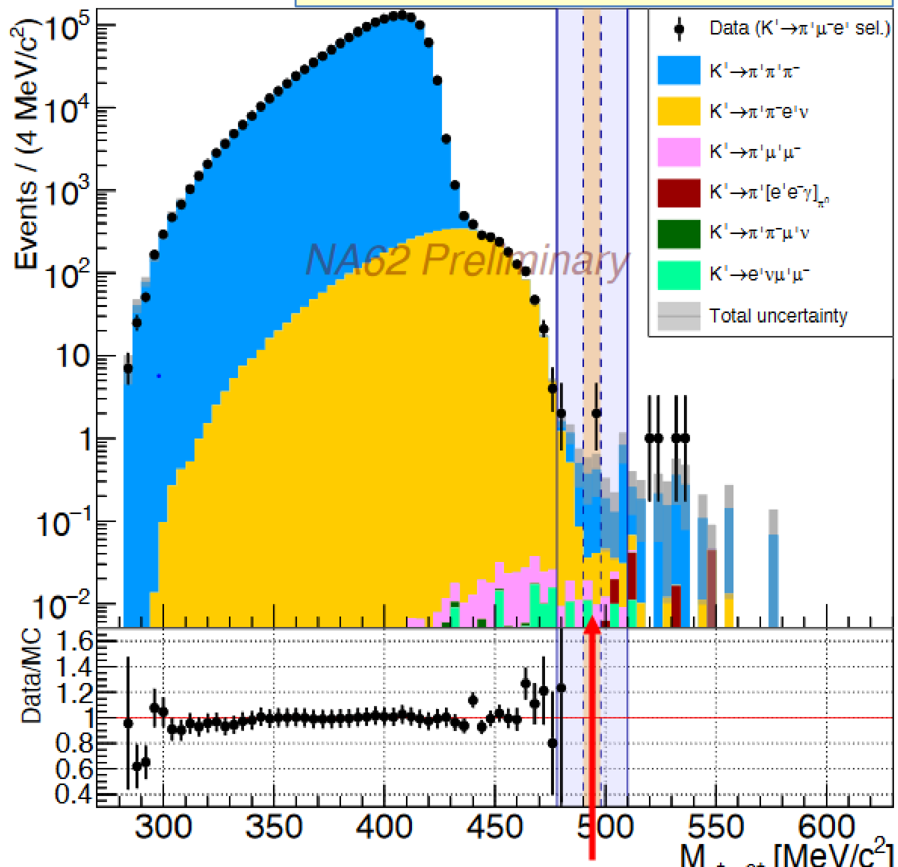


Bkg. Prediction:
$N_{SR}^{tot} = 1.06 \pm 0.20$

Observe 0 events in SR

Preliminary result (ICHEP 2020):
$BR(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11}$ at 90% CL

LFV decay: $m(\pi^+ \mu^- e^+)$



Bkg. Prediction:
$N_{SR}^{tot} = 0.92 \pm 0.34$

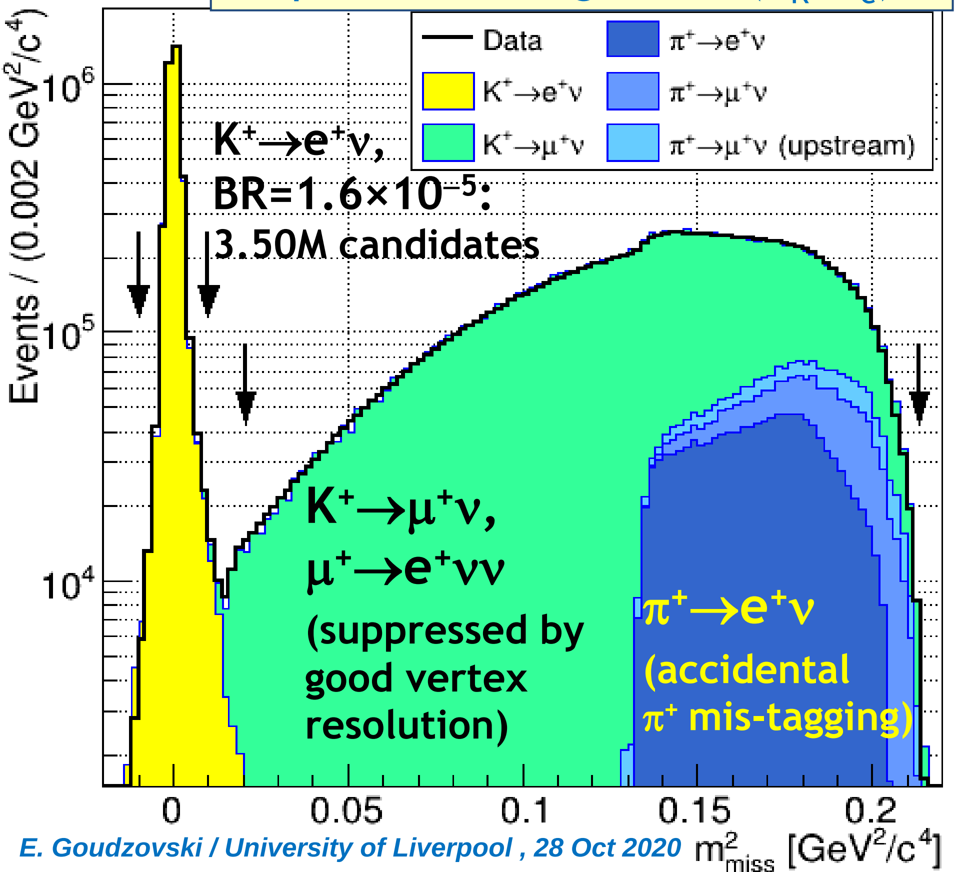
Observe 2 events in SR

Preliminary result (ICHEP 2020):
$BR(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11}$ at 90% CL

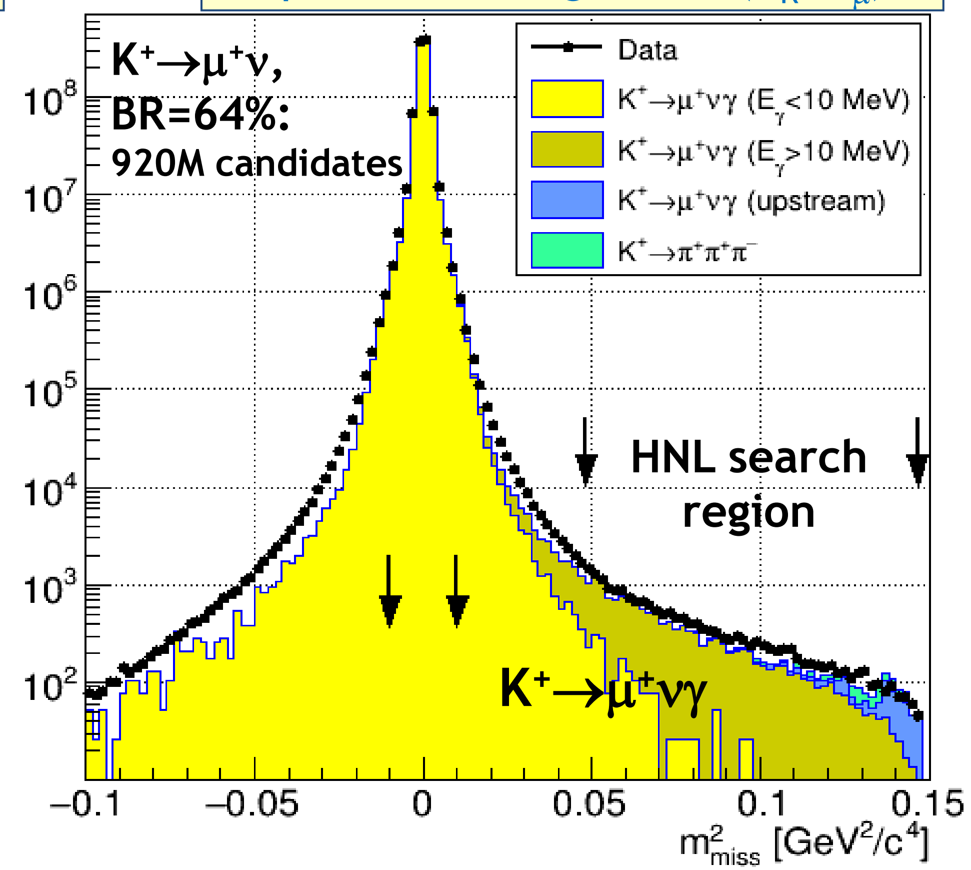
HNL production search: data sample

- Triggers used: $K_{\pi\nu\nu}$ for $K^+ \to e^+N$; Control/400 for $K^+ \to \mu^+N$.
- Numbers of K^+ decays in fiducial volume: $N_K=(3.52\pm0.02)\times10^{12}$ in positron case; $N_K=(4.29\pm0.02)\times10^9$ in muon case.
- Squared missing mass: $m^2_{miss}=(P_K-P_\ell)^2$, using STRAW and GTK trackers.
- HNL production signal: **a spike above continuous missing mass spectrum**.

Squared missing mass: $(P_K-P_e)^2$



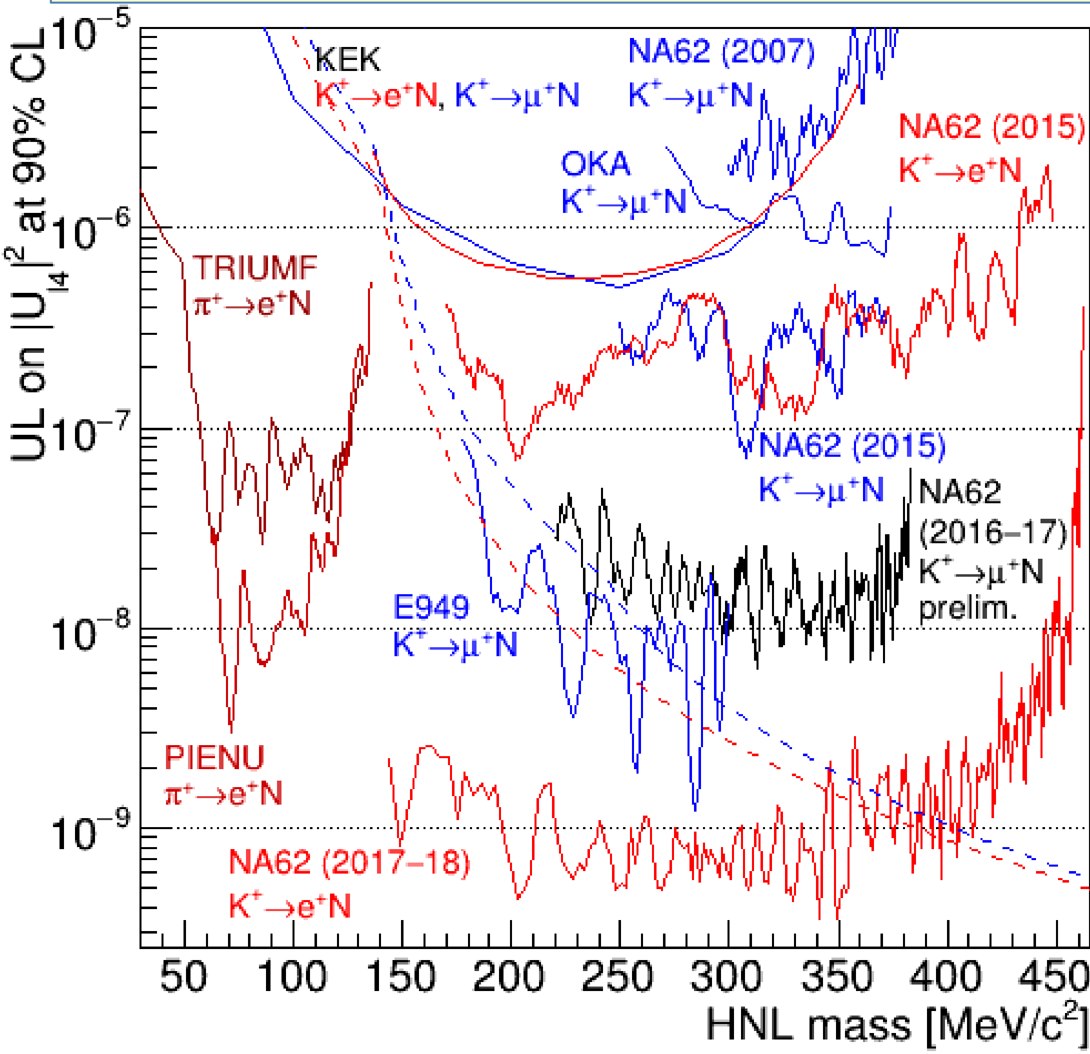
Squared missing mass: $(P_K-P_\mu)^2$



HNL production search: results

PLB807 (2020) 135599

$|U_{\ell 4}|^2$ limits vs m_{HNL} from production searches



$K^+ \to \ell^+ N$

- Full 2016–18 data set for $|U_{e4}|^2$, ~1/3 of the data set for $|U_{\mu 4}|^2$.
- Improvement over earlier production searches by up to two orders of magnitude in terms of $|U_{\ell 4}|^2$.
- For $|U_{e4}|^2$, the BBN-allowed range is excluded up to **340 MeV**.
- For $|U_{\mu 4}|^2$, sensitivity approaches the E949 one; the search extends to **383 MeV**.

Summary

- Rare **K** decays: unique new-physics probes up to **O(100 TeV)** mass scale.
- **NA62 Run 1** in **2016–18**: exposure to 6×10^{12} K^+ decays in flight.
- Many new results; most importantly, first evidence for the $K^+\to\pi^+\nu\nu$ decay: **20** candidates,

$$Br(K^+ \to \pi^+\nu\bar{\nu}) = (11.0^{+4.0}_{-3.5}{}_{stat.} \pm 0.3_{syst.}) \times 10^{-11}$$

[preliminary]

- Short-term plans for $K\to\pi\nu\nu$ decays:
  - ✓ NA62 to reach **O(10%)** precision on $BR(K^+\to\pi^+\nu\nu)$ by **2024** with an established decay in flight technique;
  - ✓ KOTO is making significant progress in background reduction, aiming to reach SM sensitivity to $BR(K_L\to\pi^0\nu\nu)$ by **2024**.
- Next-generation kaon experiments:
  - ✓ High-intensity kaon beam facility at CERN: **O(5%)** precision on $BR(K^+\to\pi^+\nu\nu)$ followed by a K_L experiment;
  - ✓ KOTO step-2 at J-PARC: plans to measure $BR(K_L\to\pi^0\nu\nu)$;
  - ✓ detector technology: synergies with future collider & flavour experiments.