Rare kaon decay measurements at NA62

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Outline:

1) Rare kaon decays and the NA62 experiment
2) $K^+ \to \pi^+ \nu\nu$ measurement with NA62 Run 1 dataset
3) Recent results on hidden-sector searches
4) Short-term and long-term plans
5) Summary

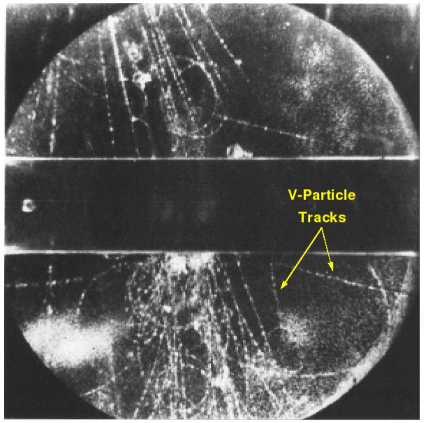
Be.HEP meeting
Brussels, 22 December 2021

Rare kaon decays and the NA62 experiment

Precision frontier: kaon physics

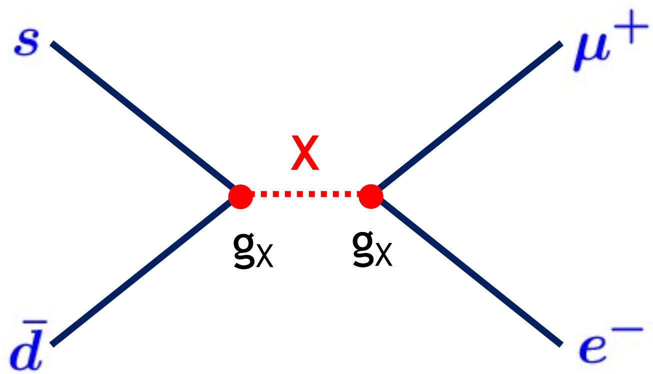
The kaon:

- One of the lightest unstable particles (discovered in 1947); the "**minimal flavour laboratory**".
- High production rates: high statistical precision. Rarest particle decays ever observed, e.g. **$BR(K_L \to e^+e^-) = (9 \pm 5) \times 10^{-12}$**. *(BNL E871 experiment)*



- Essential in establishing the **foundations of particle physics** (quark mixing, CP violation).
- Current focus: searches for **new physics** with rare and forbidden decays.

Example: $K_L \to \mu^+ e^-$



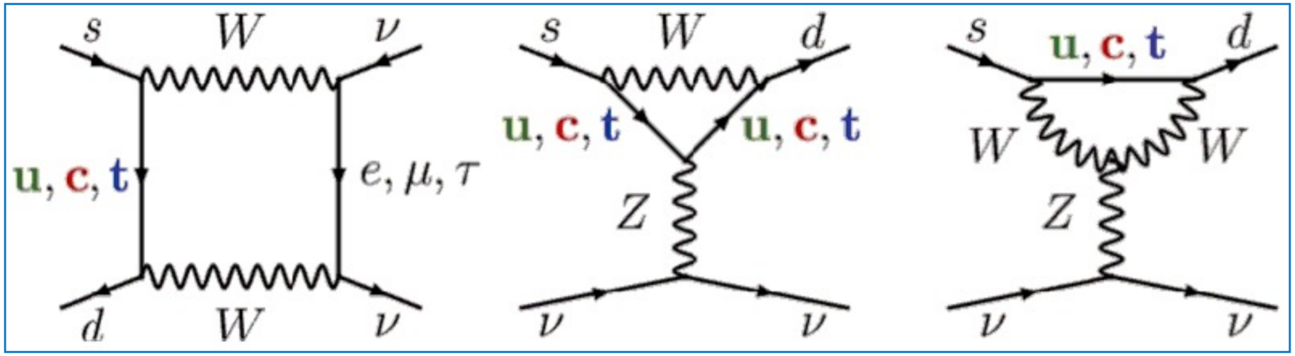
Tree-level process: **Rate** $\sim \left(\frac{g_X}{g_W} \cdot \frac{M_W}{M_X} \right)^4$

For $g_X \approx g_W$ and **decay probability ~ 10^{-12}**,

$$M_X \sim 100 \text{ TeV}$$

$K \to \pi\nu\nu$ 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.

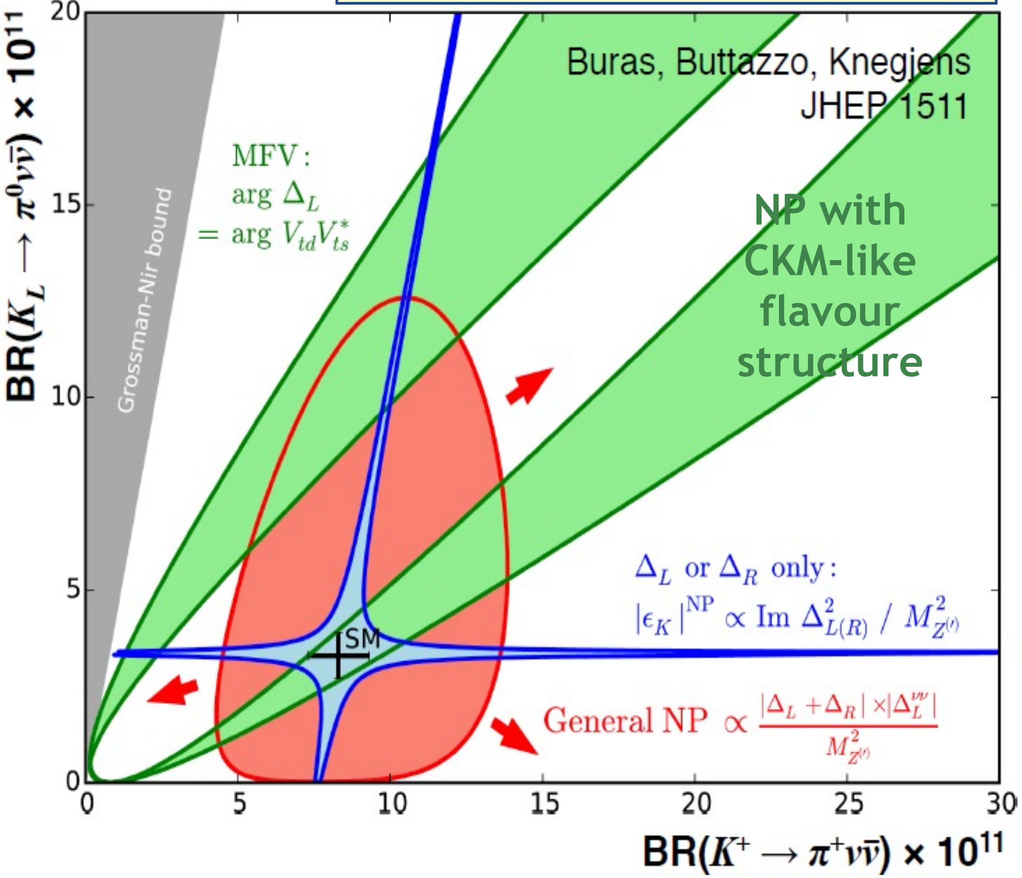
Mode	Expected BR_{SM}	Experimental status
$K^+ \to \pi^+\nu\nu$	$(8.4\pm1.0)\times10^{-11}$	First observation at NA62
$K_L \to \pi^0\nu\nu$	$(3.4\pm0.6)\times10^{-11}$	$BR<300\times10^{-11}$ at 90% CL (KOTO 2015 data)

BR_{SM}: Buras et al., JHEP 1511 (2015) 33; tree-level determination of CKM elements.
SM prediction update: Buras and Venturini, arXiv:2109.11032.

K→πνν and new physics

- Correlations between BSM contributions to K^+ and K_L BRs. *[JHEP 11 (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). *[JHEP 12 (2020) 97]*

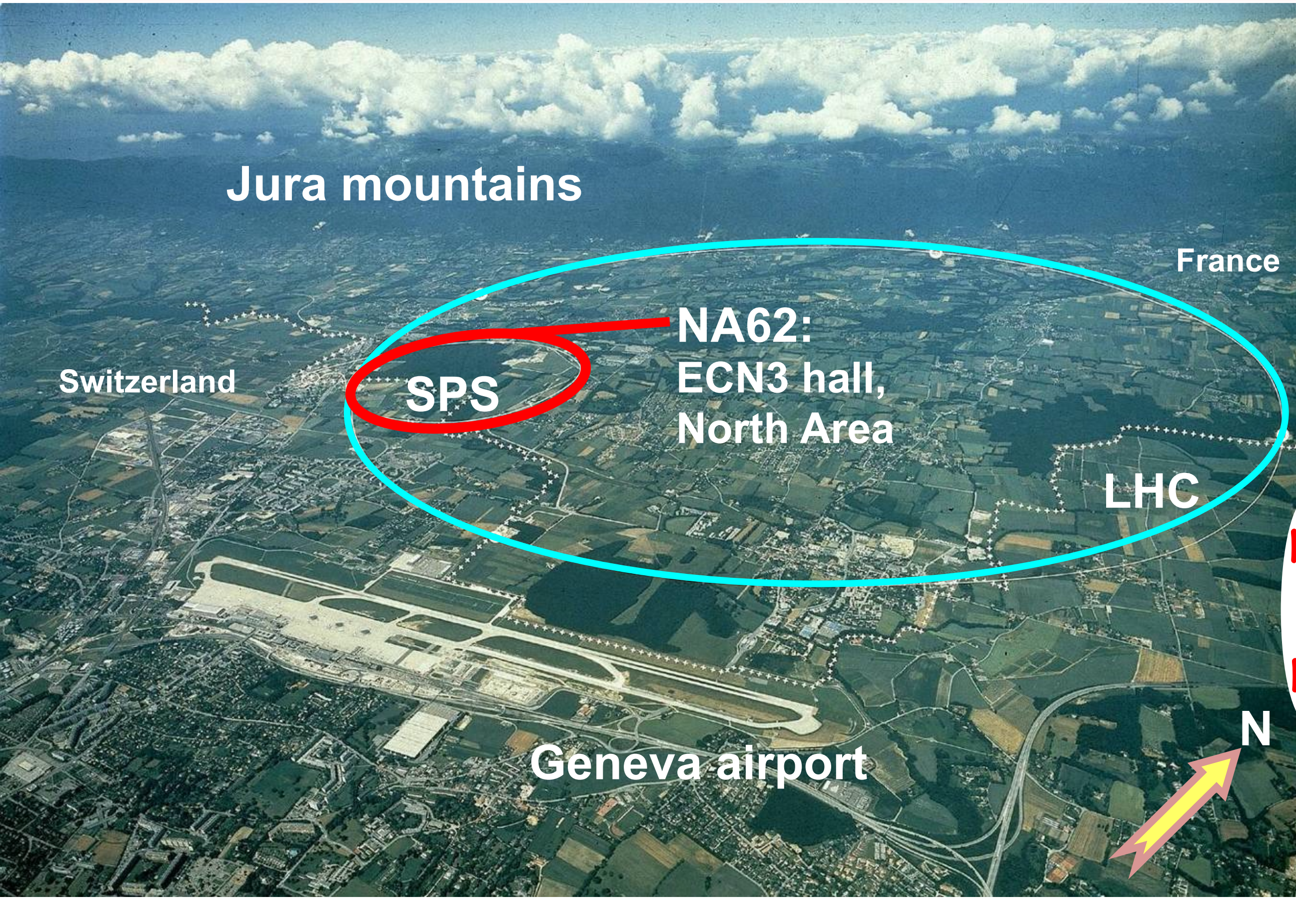
BR($K_L \to \pi^0 \nu\bar{\nu}$) vs BR($K^+ \to \pi^+ \nu\bar{\nu}$)



- **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

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

Kaon experiments 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: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests

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

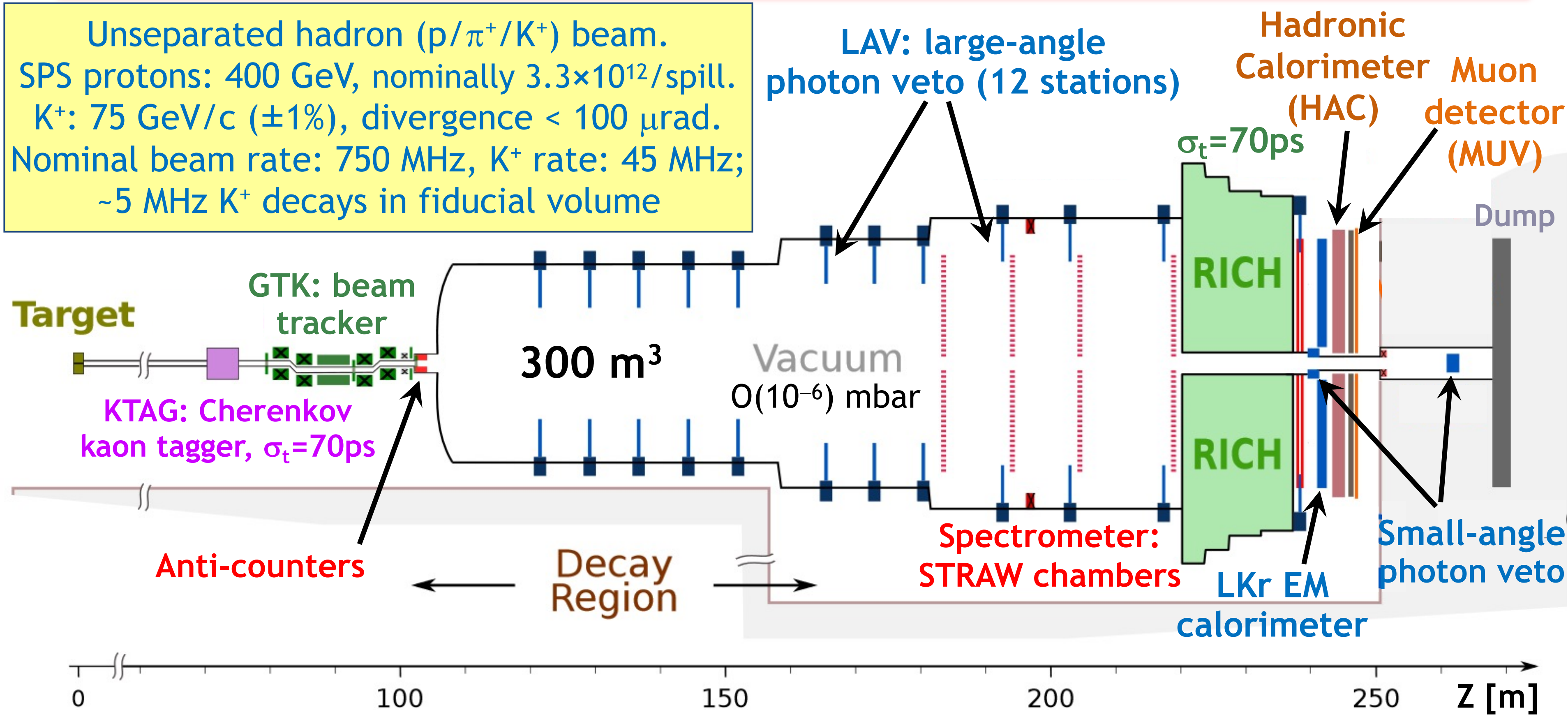
Main NA62 goal: $K^+\rightarrow\pi^+\nu\nu$ measurement to 10% precision with a novel decay-in-flight technique.

Currently ~300 participants from 31 institutions.

NA62 collaboration, JINST 12 (2017) P05025

Beamline & detector

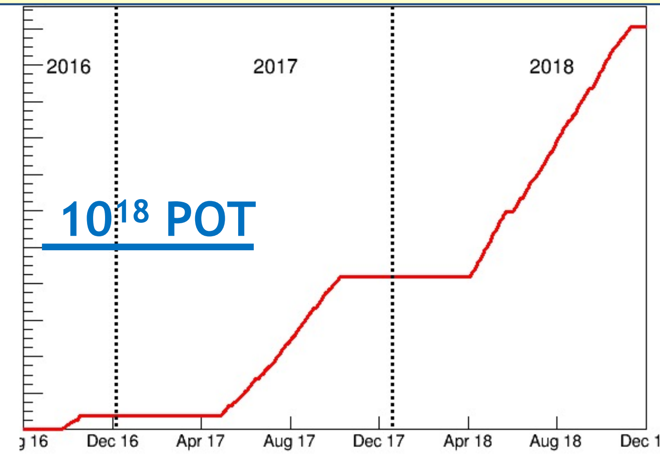
Unseparated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, nominally 3.3×10^{12}/spill.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Nominal beam rate: 750 MHz, K^+ rate: 45 MHz;
~5 MHz K^+ decays in fiducial volume



- 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 $E_{\pi0}$>40 GeV) ~10^{-8}.
- Particle ID (RICH+LKr+HAC+MUV): ~10^{-8} muon suppression.

NA62 Run 1 dataset

Run 1 integrated luminosity



2.2×10^{18} POT collected

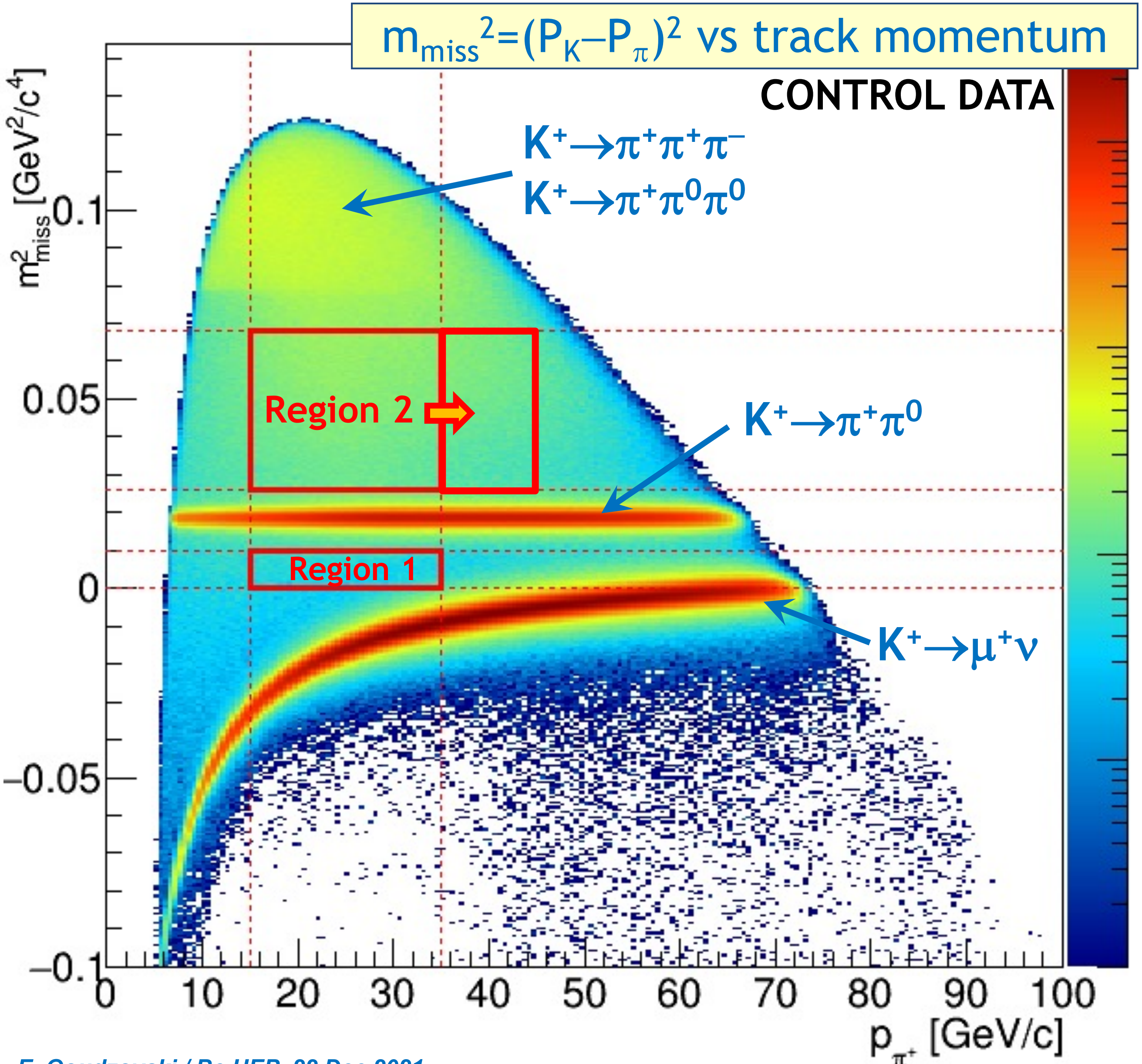
(3×10^{16} from 50h in dump mode)

- Commissioning run **2015**: minimum bias data (~3×10^{10} protons/pulse).
- Physics run **2016** (30 days, ~1.3×10^{12} ppp): 2×10^{11} useful K^+ decays.
- Physics run **2017** (160 days, ~1.9×10^{12} ppp): 2×10^{12} useful K^+ decays.
- Physics run **2018** (217 days, ~2.3×10^{12} ppp): 4×10^{12} useful K^+ decays.
- Run 2 in progress: June 2021 till LS3 (~3×10^{12} ppp).

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

- *The 2016 dataset: PLB 791 (2019) 156.*
- *The 2017 dataset: JHEP 11 (2020) 42.*
- *Full Run 1 data set: JHEP 06 (2021) 93.*

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:

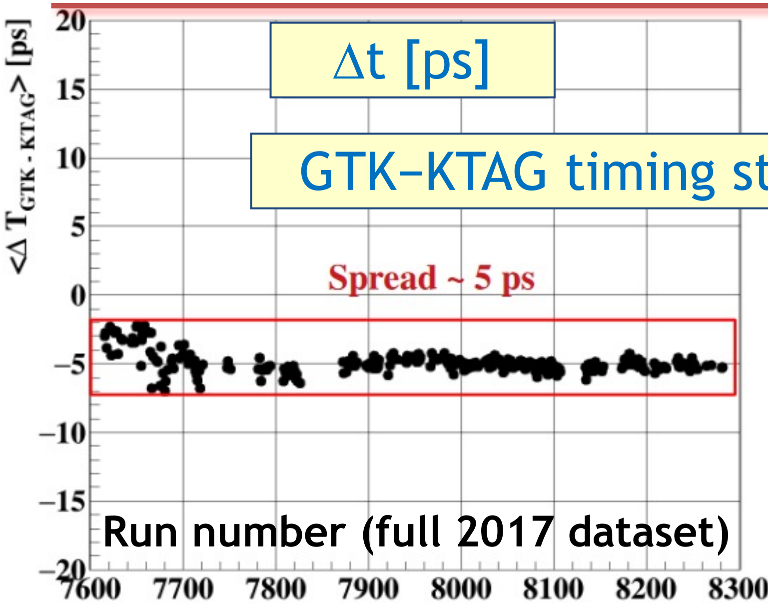
- ✓ PID (calorimeters & Cherenkov detectors): μ suppression 10^{-8}, π efficiency = 64%.
- ✓ Hermetic photon veto: $\pi^0\to\gamma\gamma$ rejection factor = 1.4×10^{-8}.

Key parameters: timing, PID

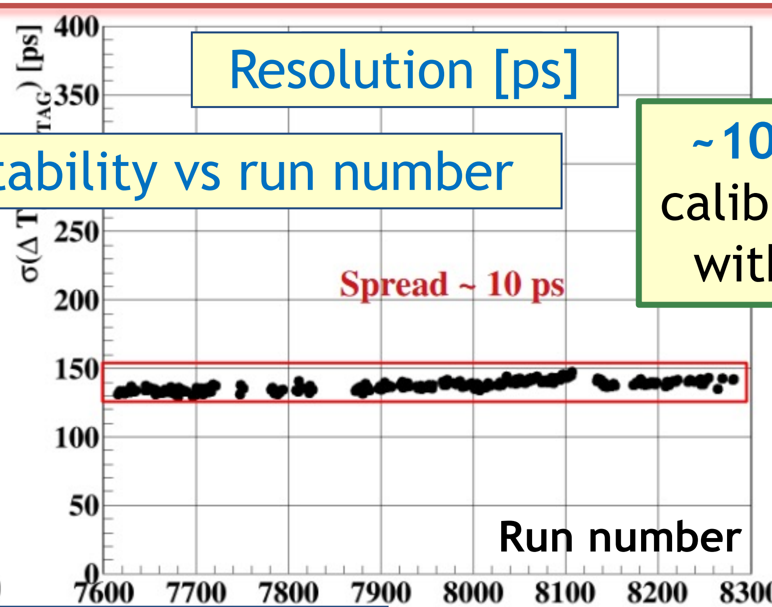
GTK–KTAG timing stability vs run number

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

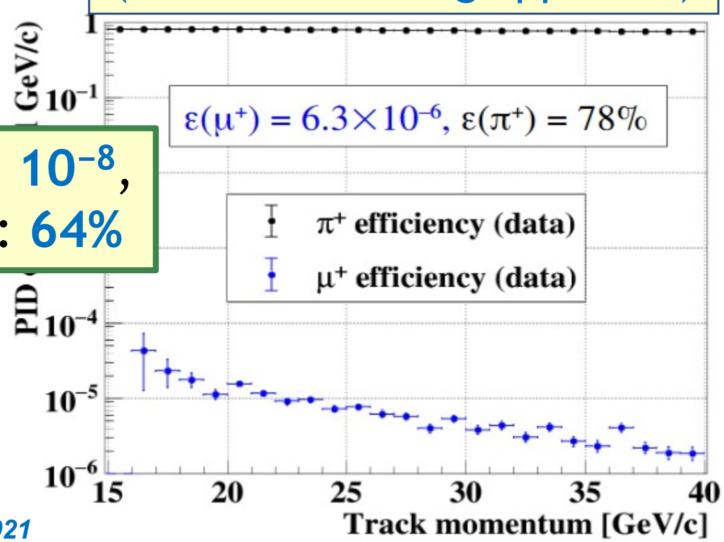
Δt [ps]



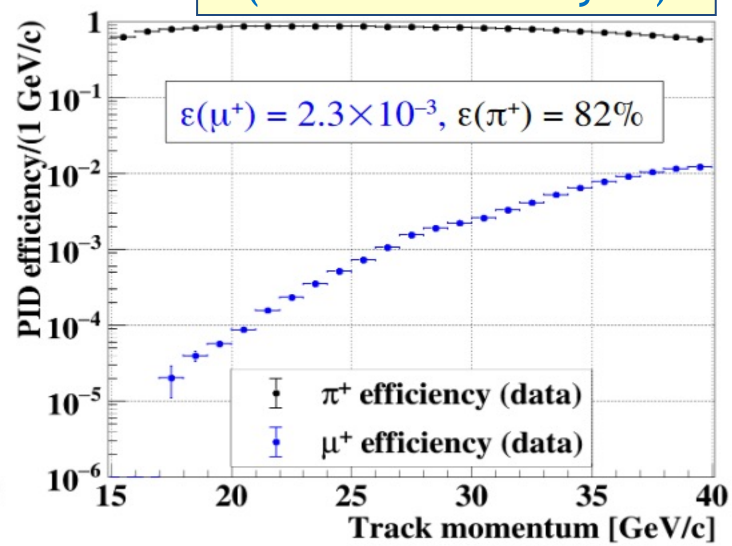
Resolution [ps]



Calorimetric PID
(machine learning approach)



RICH PID
(likelihood analysis)

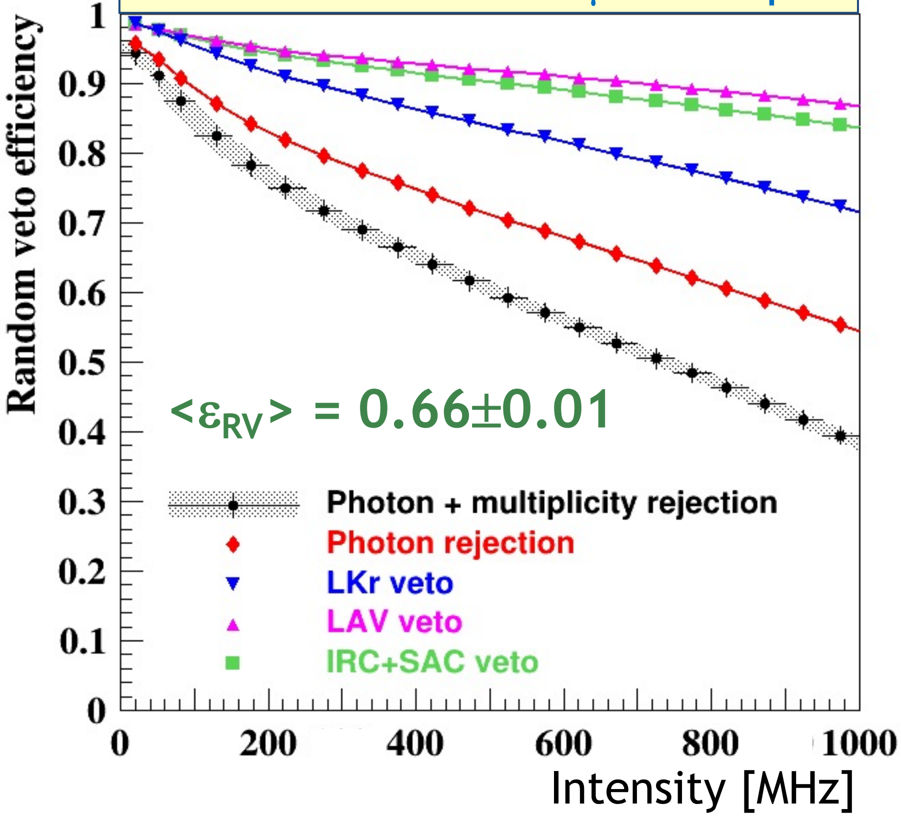


Muon suppression: 10^{-8}, pion ID efficiency: 64%

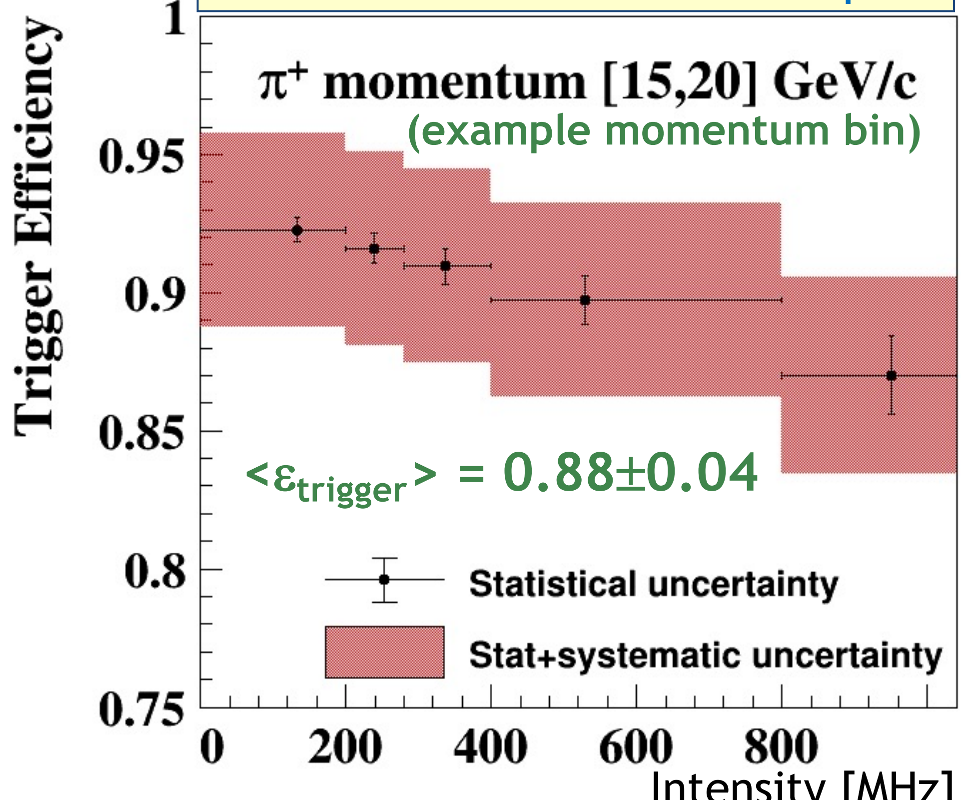
Single event sensitivity (SES)

- For the complete Run 1 dataset, $BR_{SES} = (0.839\pm0.053)\times10^{-11}$.
  (main uncertainties: trigger, acceptance, random veto)
- Expected number of SM events: $N_{\pi\nu\nu} = BR_{SM}/BR_{SES} = 10.01\pm0.42_{syst}\pm1.19_{SM}$.

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



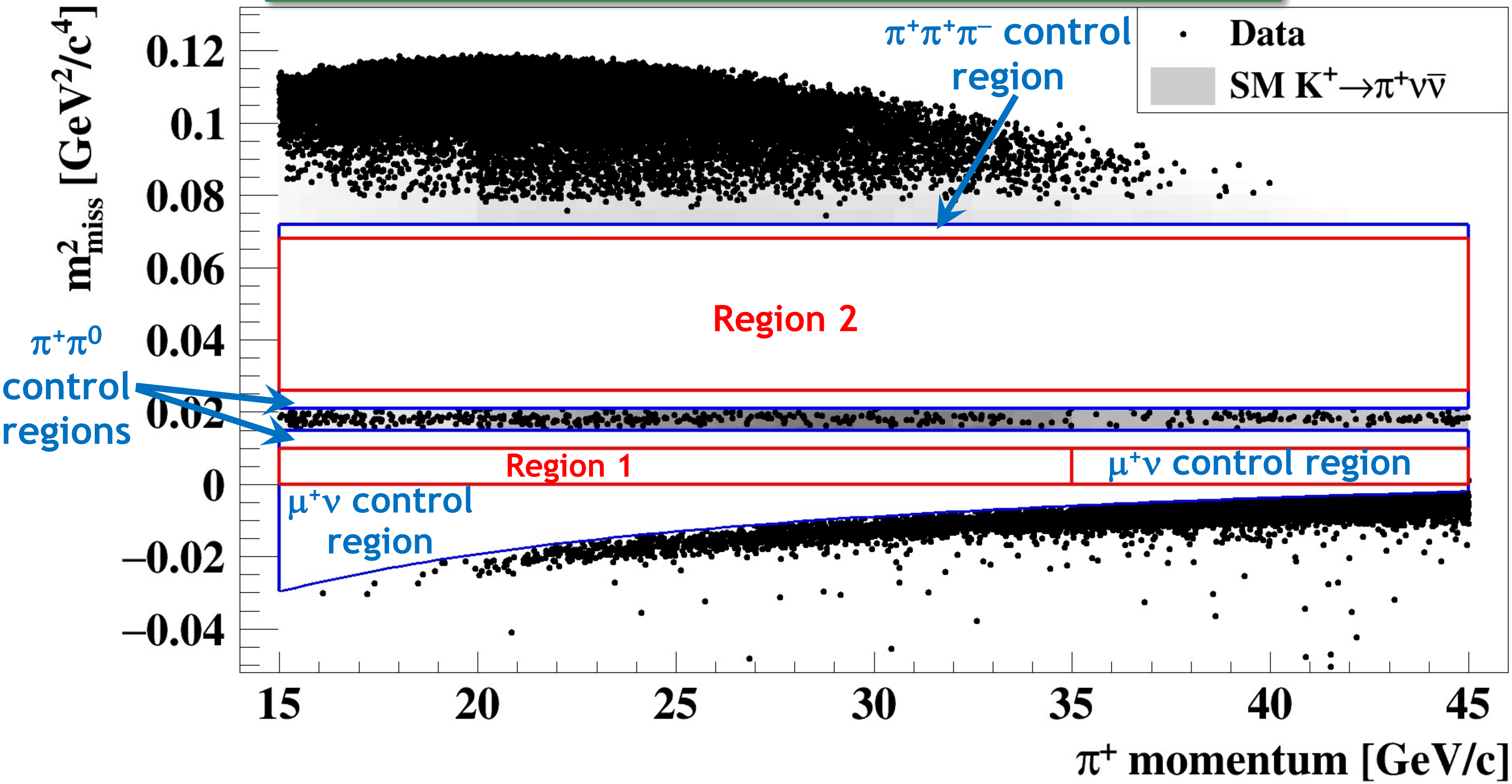
Trigger efficiency $\varepsilon_{trigger}$ measured from control samples



Beam intensity measured from the beam tracker (GTK) time sidebands

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

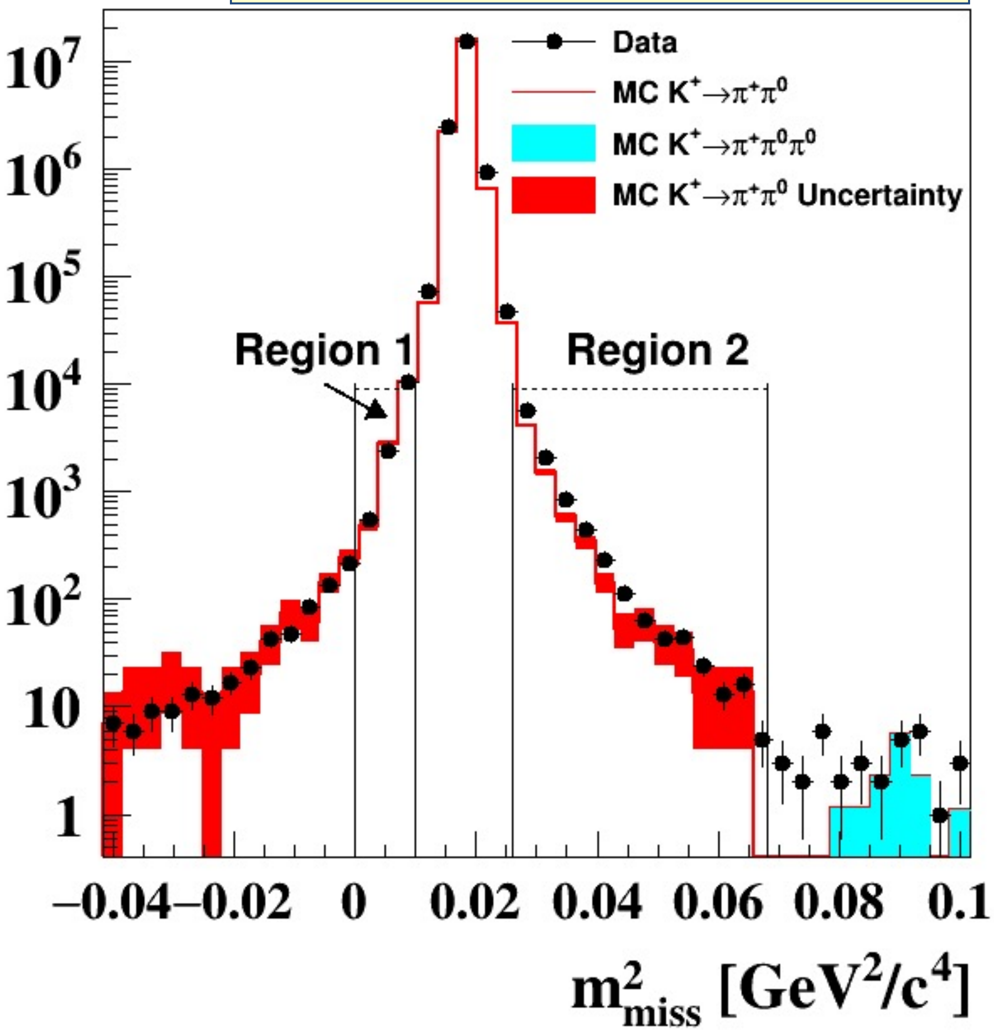
Signal and control regions are blinded



After background evaluation, control regions are opened first, to validate background expectations with the data.

"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)

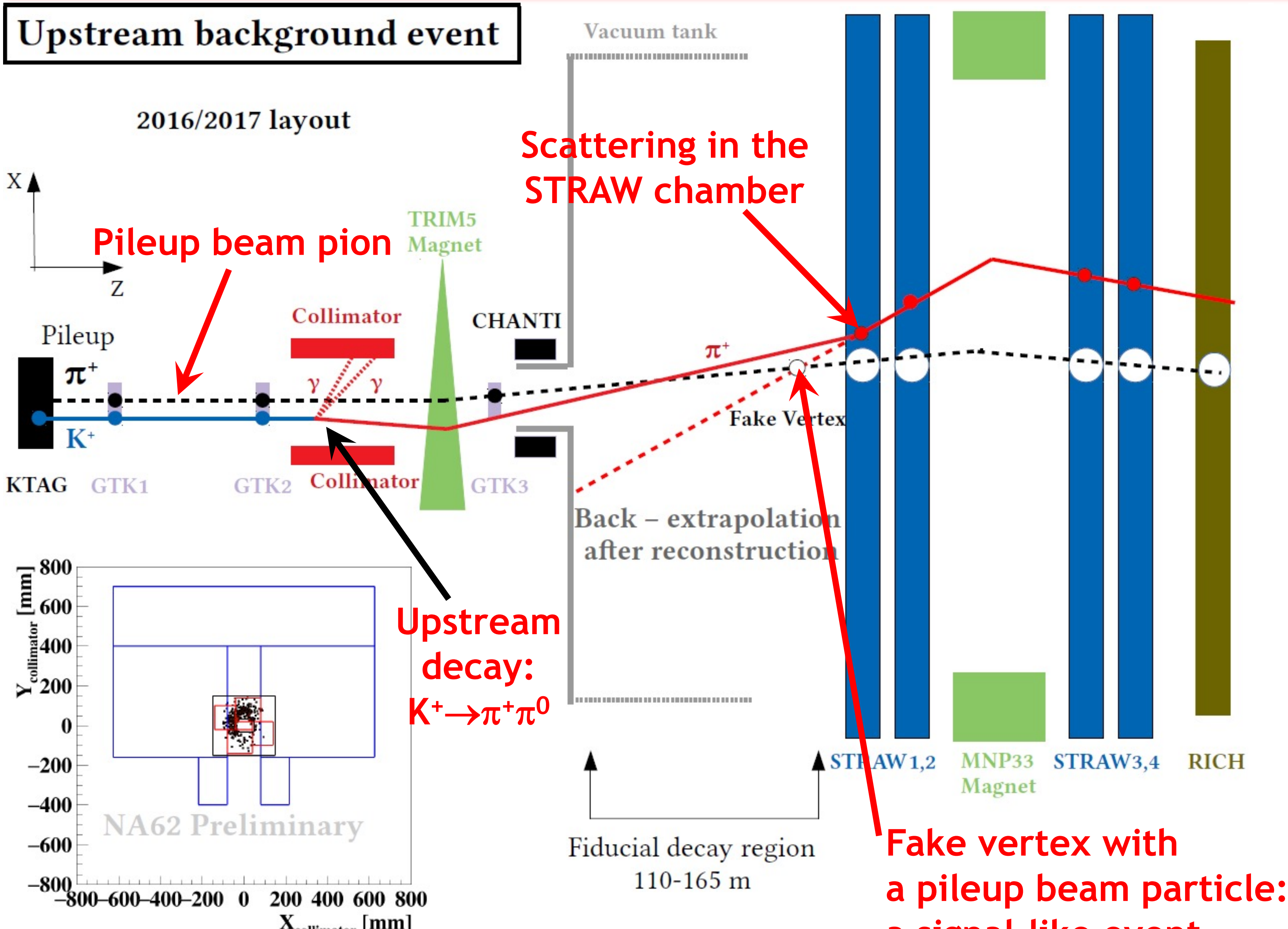
Data events in the $\pi^+\pi^0$ region after the $K_{\pi\nu\nu}$ selection (including π^0 rejection)

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

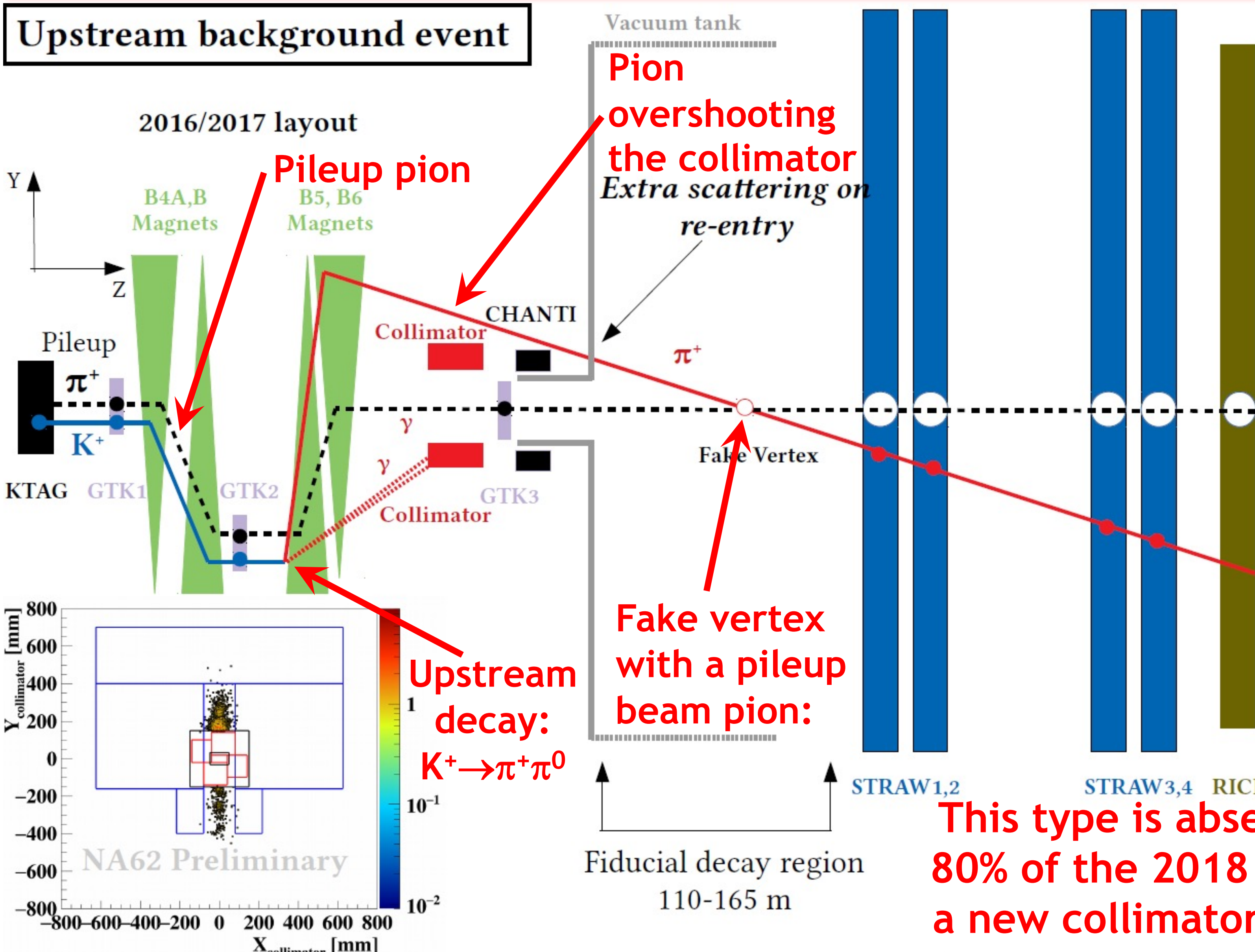
Expected numbers of $K^+\to\pi^+\pi^0$ events in signal regions after $K_{\pi\nu\nu}$ selection

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

Upstream background: type 1



Upstream background: type 2

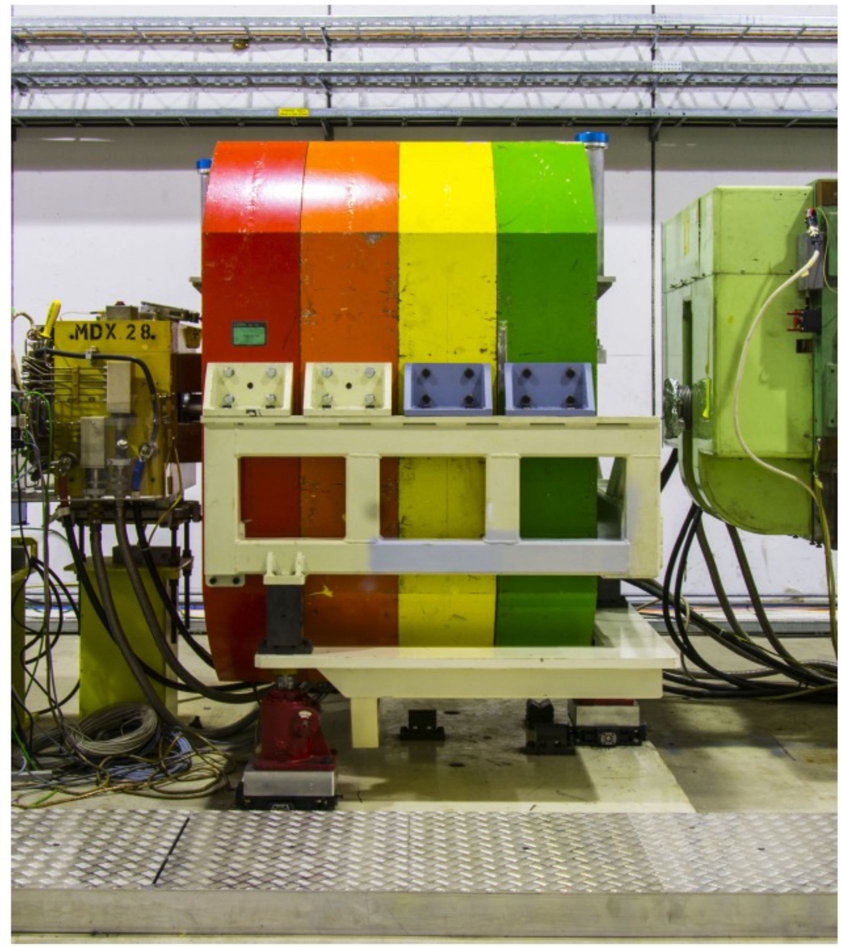


This type is absent in 80% of the 2018 data: a new collimator with larger transverse size

Final collimator replacement

The old collimator

Current collimator (since June 2018)



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

Expected backgrounds (2018 data)

Background	Subset S1 (old collimator)	Subset S2 (new collimator)
$\pi^+\pi^0$	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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
$BR_{SES} \times 10^{10}$	**0.54±0.04**	**0.14±0.01**
$N^{exp}_{\pi\nu\bar{\nu}}$	**1.56±0.21**	**6.02±0.82**

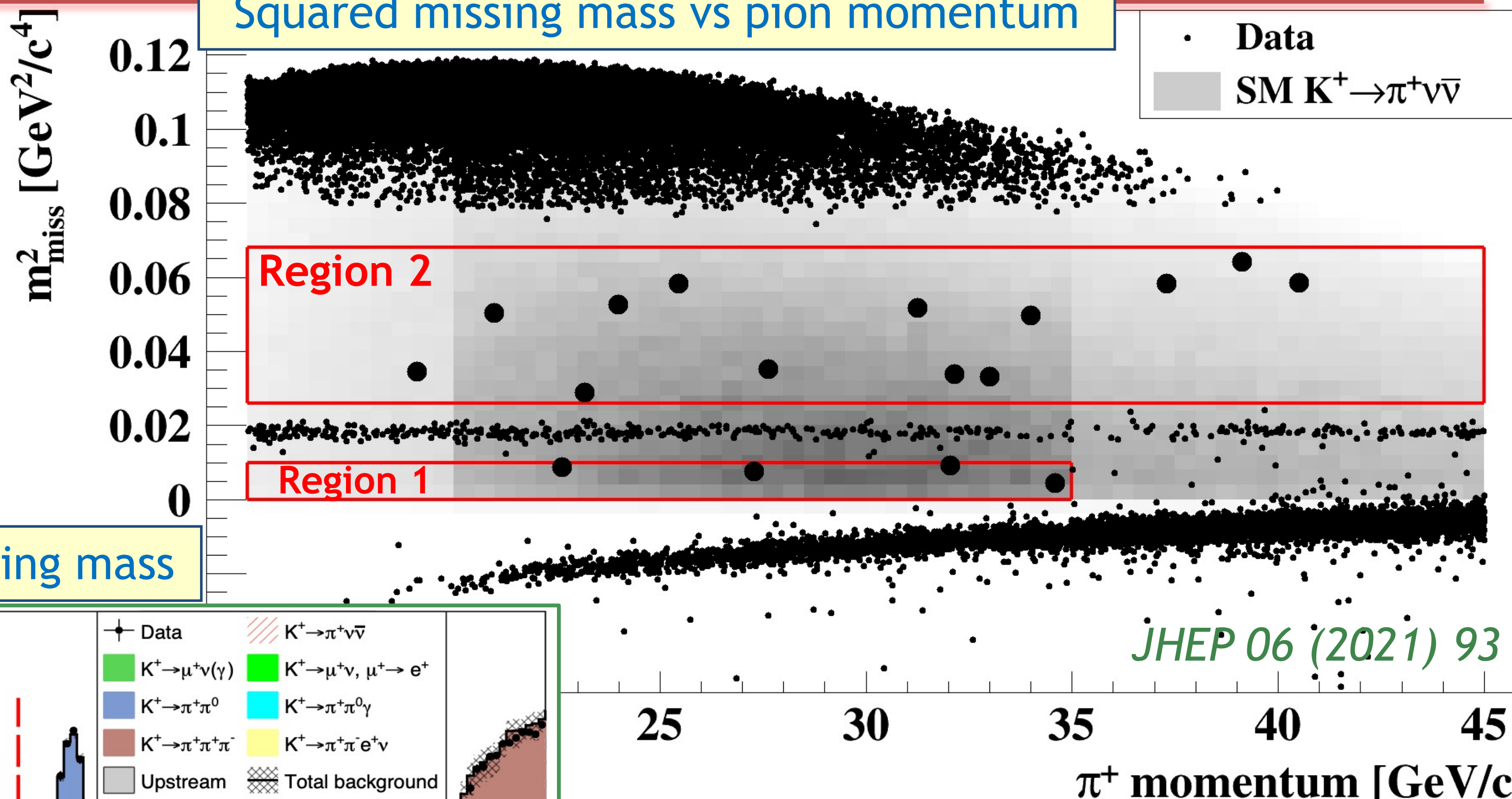
Data-driven background estimates ($\pi^+\pi^0$, $\mu^+\nu$, $\pi^+\pi^+\pi^-$)

Dominant background: a data-driven estimate (Upstream)

- Most background is not due to K^+ decays in the vacuum tank.
- Improved the beamline layout and new upstream veto detectors brings the Run 2 measurement into a low-background regime.

Opening the box (2018)

Squared missing mass vs pion momentum



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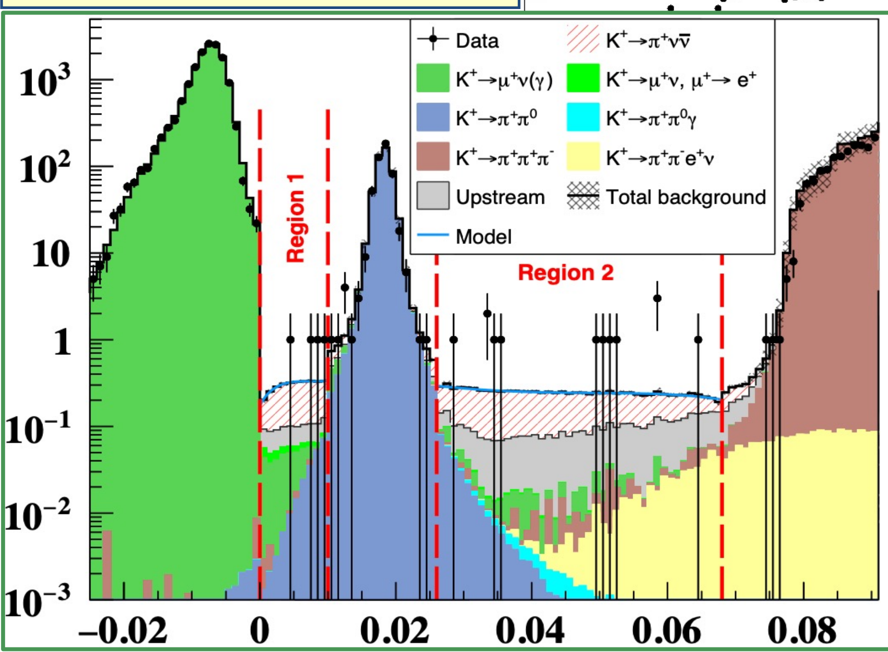
Squared missing mass



Full Run 1 data set:

Candidates observed: **20** (**17** in 2018 data)

Expected background: $7.03^{+1.05}_{-0.82}$

Expected SM events:

$10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

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

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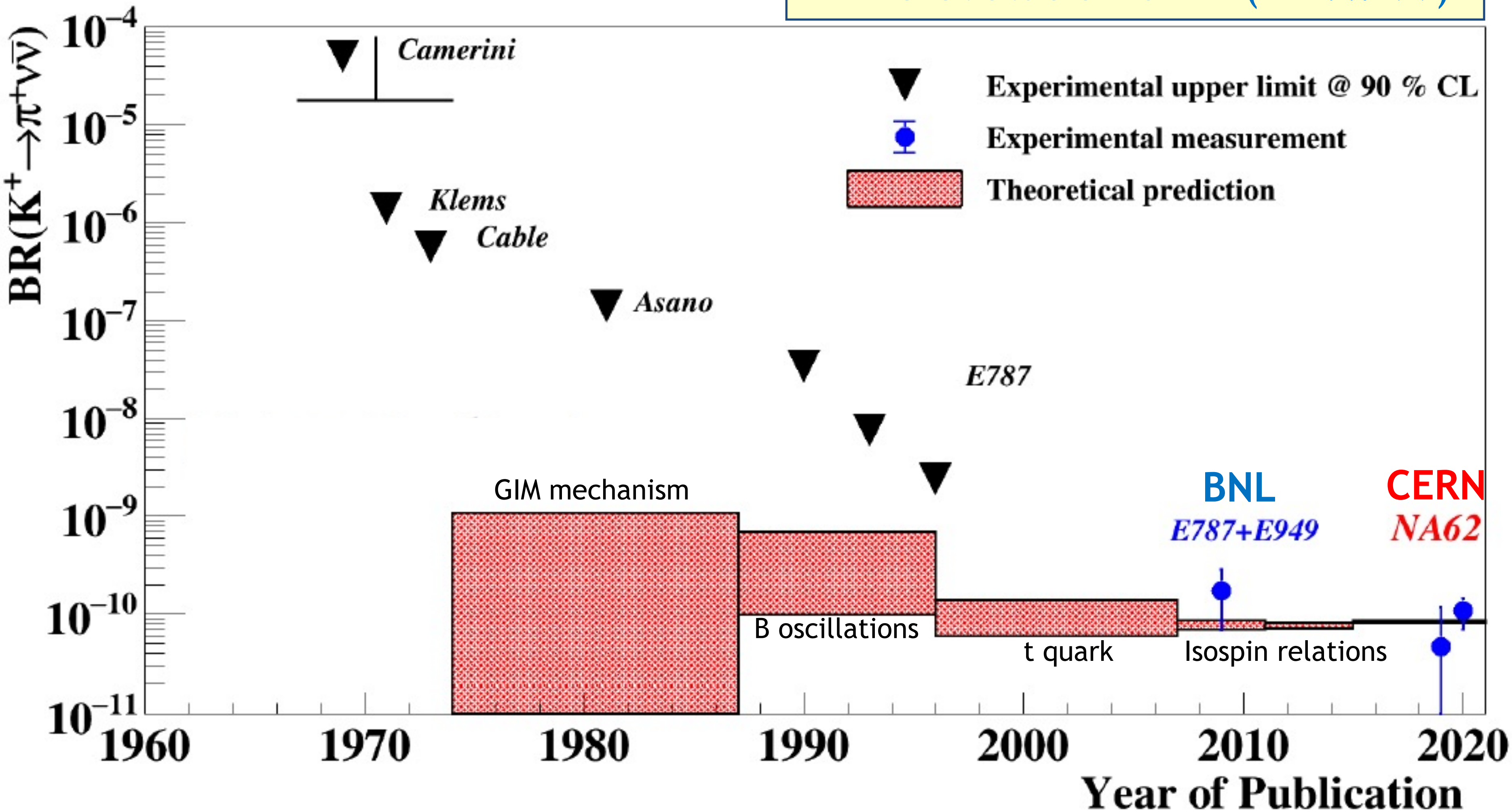
Time evolution of BR($K^+ \to \pi^+ \nu\nu$)



NA62 Run 1: $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$

(**3.4σ** significance)

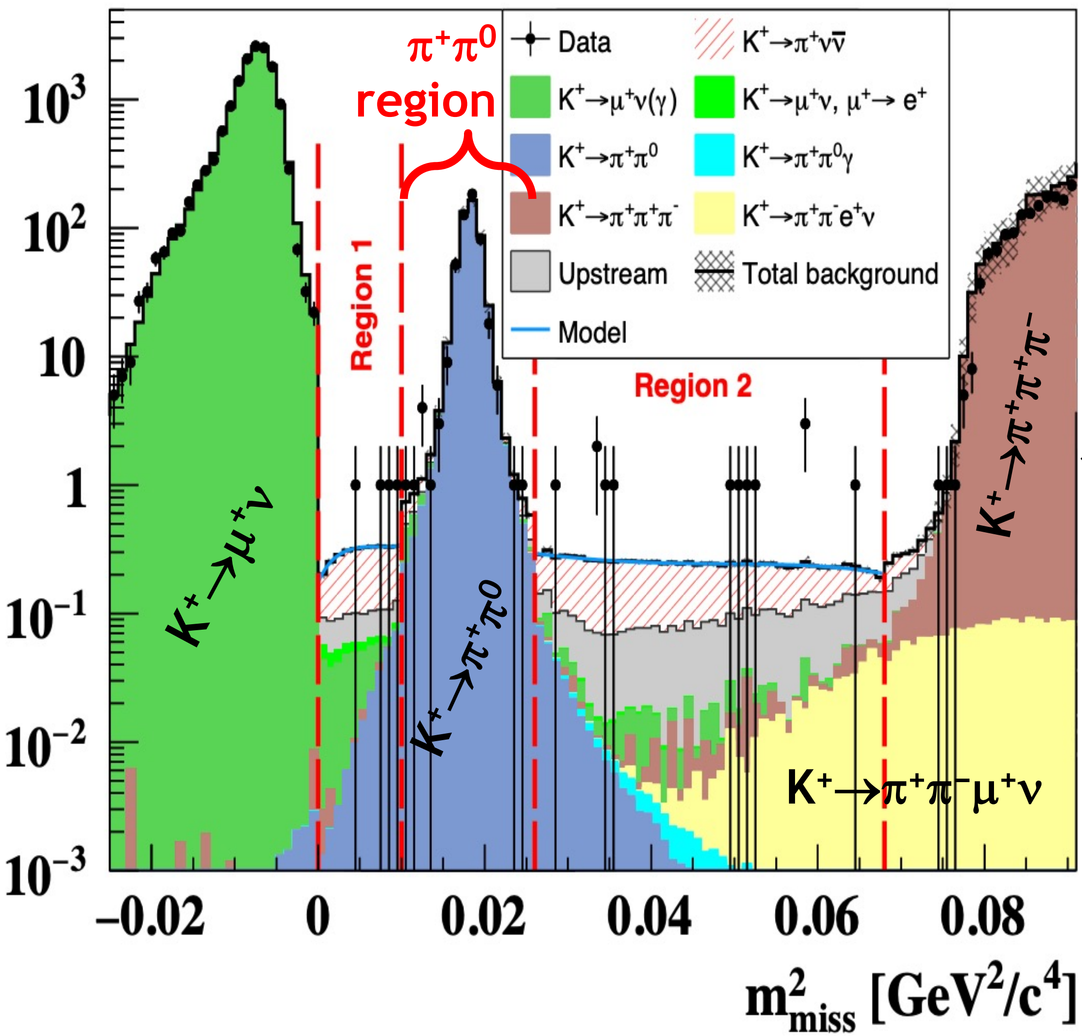
Recent NA62 results

Searches for new physics:

- $K^+ \to \pi^+ X$: JHEP 06 (2021) 93; JHEP 03 (2021) 58.
- $\pi^0 \to$invisible: JHEP 02 (2021) 201.
- HNL production: PLB 807 (2020) 135599; PLB 816 (2021) 136259.
- LFV/LNV: PLB797 (2019) 134794; PRL 127 (2021) 131802; new results.

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

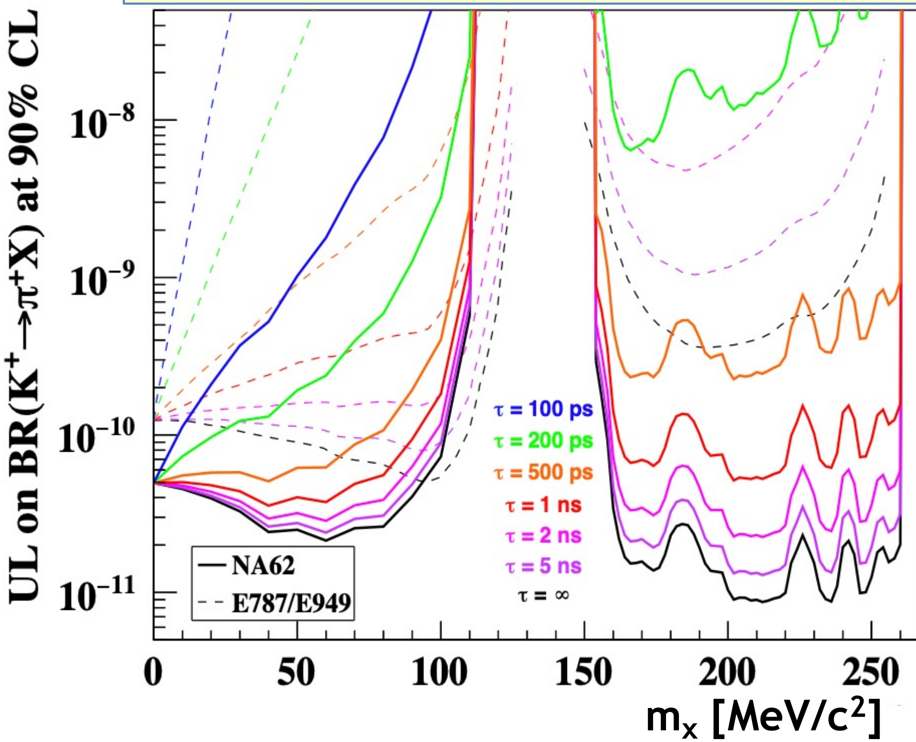
Squared missing mass (2018 data)



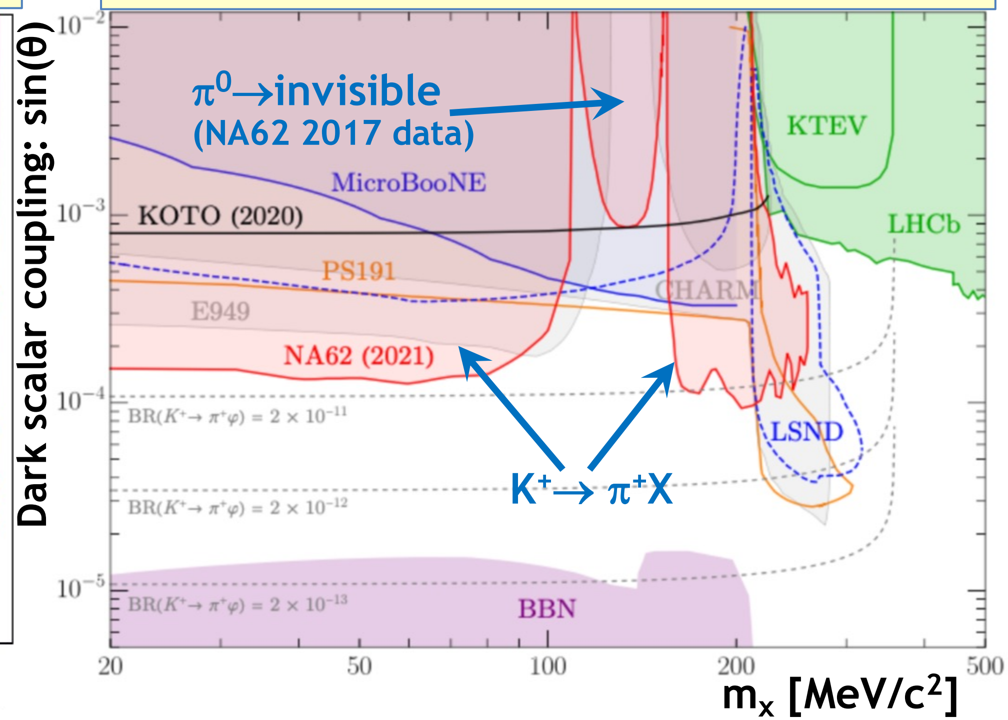
- Signal regions **R1**, **R2**: search for $K^+ \to \pi^+ X$ (X=invisible), $0 \leq m_X \leq 110$ MeV/c^2 and $154 \leq m_X \leq 260$ MeV/c^2.
  - ✓ Interpretation: dark scalar, ALP, QCD axion, axiflavon.
  - ✓ Main background: $K^+ \to \pi^+ \nu\nu$.
- The $\pi^+\pi^0$ region: search for $\pi^0 \to$ **invisible**.
  - ✓ SM rate: $BR(\pi^0 \to \nu\nu) \sim 10^{-24}$.
  - ✓ Observation = BSM physics.
  - ✓ Reduction of $\pi^0 \to \gamma\gamma$ background: optimised π^+ momentum range.
  - ✓ Interpretation as $K^+ \to \pi^+ X$, with m_X between R1 and R2.

Search for $K^+ \to \pi^+ X$ (Run 1 data)

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



Dark scalar searches below the K mass

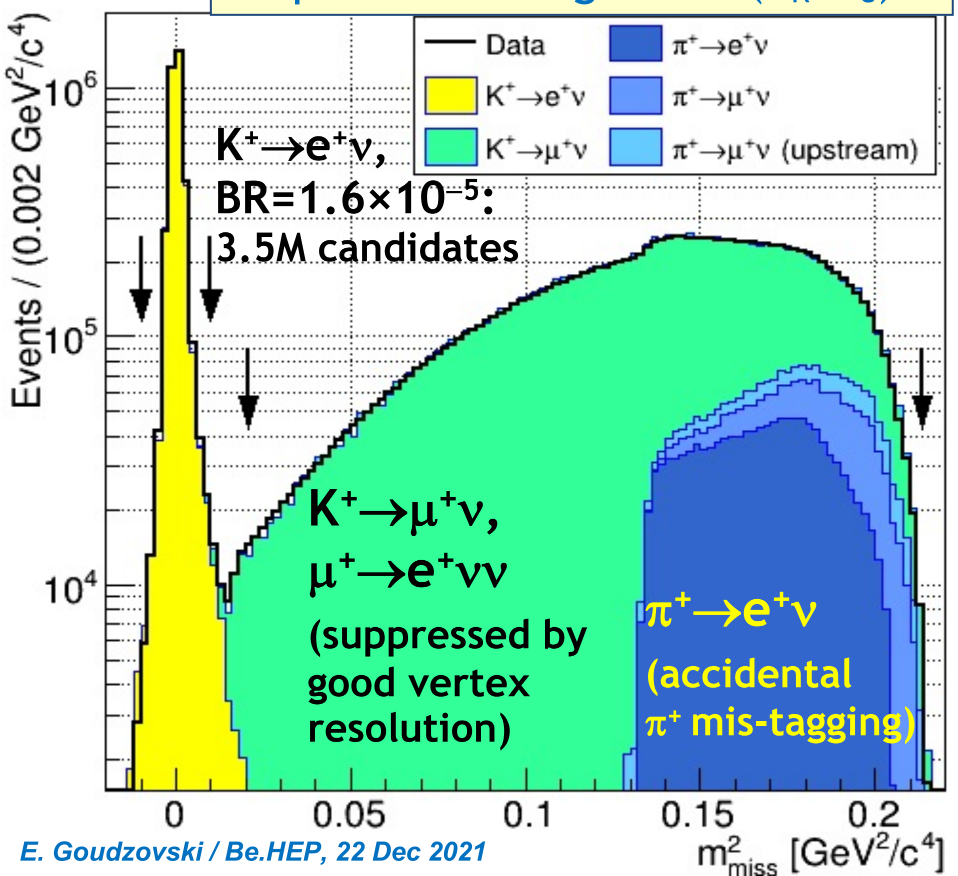


- Mass resolution improves with m_X and is δm_X~40 MeV/c^2 at m_X=0.
- Upper limits of $BR(K^+ \to \pi^+ X)$ established depending on X mass and lifetime.
- Improvement on BNL-E949 over most of m_X range. *[PRD79 (2009) 092004]*
- Interpretation within the minimal dark scalar model (decays to visible SM particles only). *[PBC Model BC4, EPJ C81 (2021) 1015]*
- Note the **KOTO** result based on 2016−18 data. *[PRL125 (2021) 021801]*

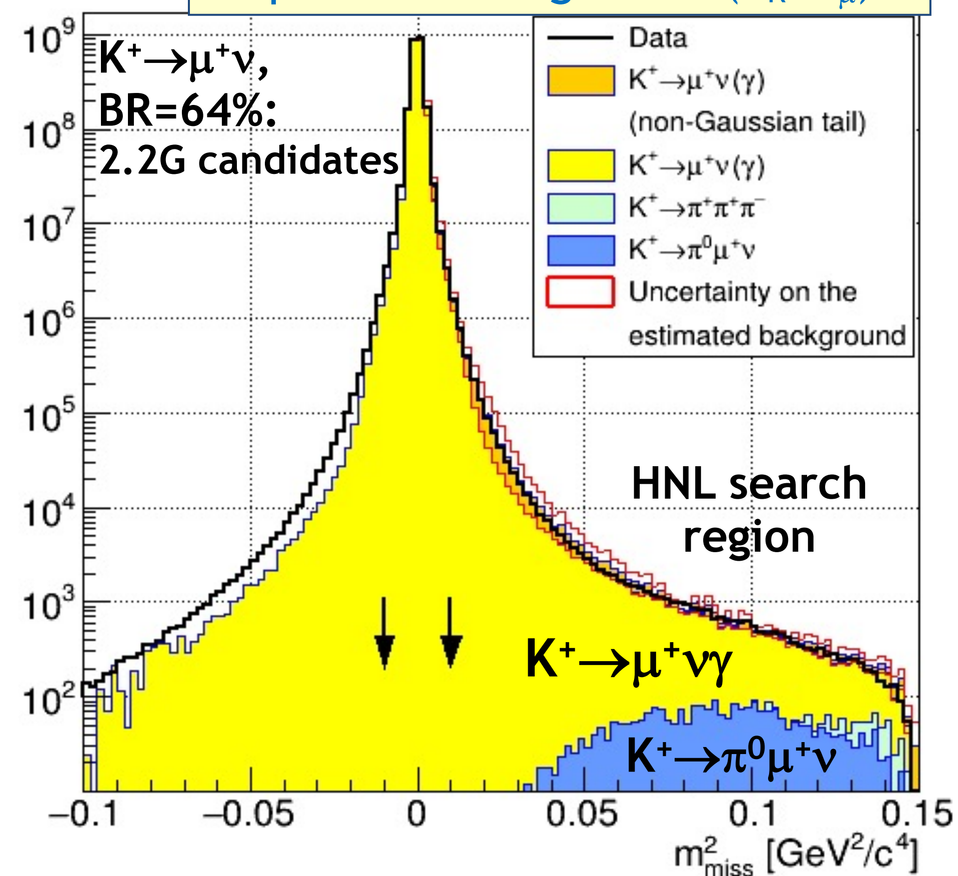
HNL production search: data sample

- 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: $(P_K-P_e)^2$

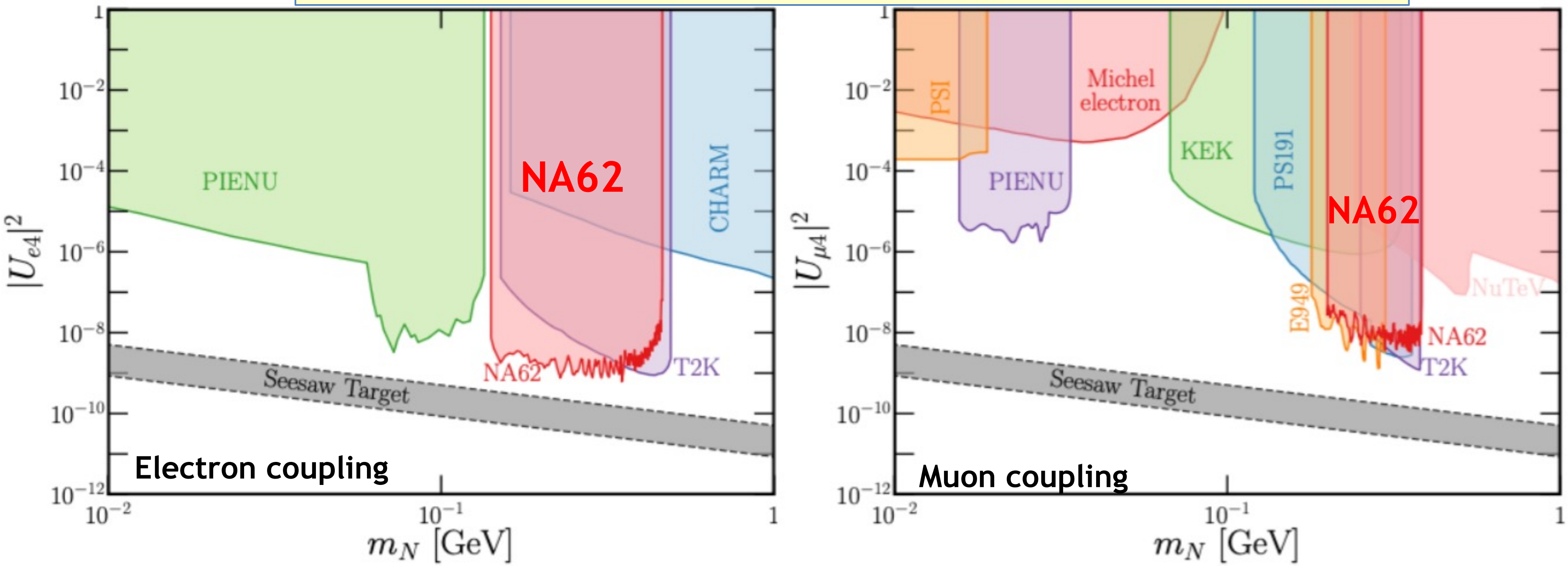


Squared missing mass: $(P_K-P_\mu)^2$



HNL production search: results

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

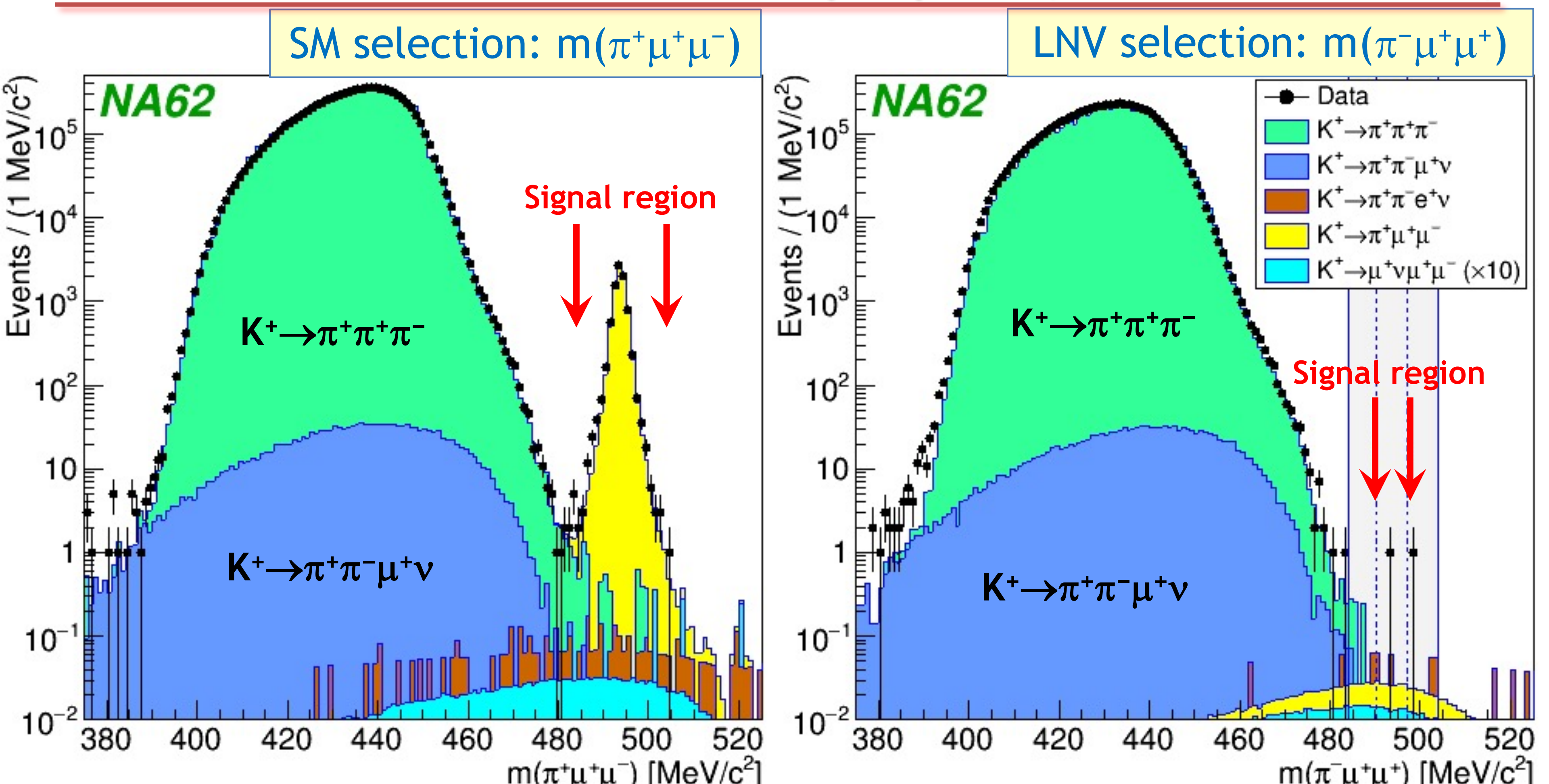


- For $|U_{e4}|^2$, complementary to search for $\pi^+ \to e^+ N$ at PIENU.
- For $|U_{\mu 4}|^2$, complementary to search for $K^+ \to \mu^+ N$ at BNL-E949.
- In both cases, complementary to HNL decay searches at T2K.

- NA62 also set an upper limit at **90%** CL: **$BR(K^+ \to \mu^+ \nu\nu\nu) < 1.0 \times 10^{-6}$**, and similar limits on **$BR(K^+ \to \mu^+ \nu X)$**, with **X=invisible**.

[PLB 807 (2020) 135599; PLB 816 (2021) 136259]

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



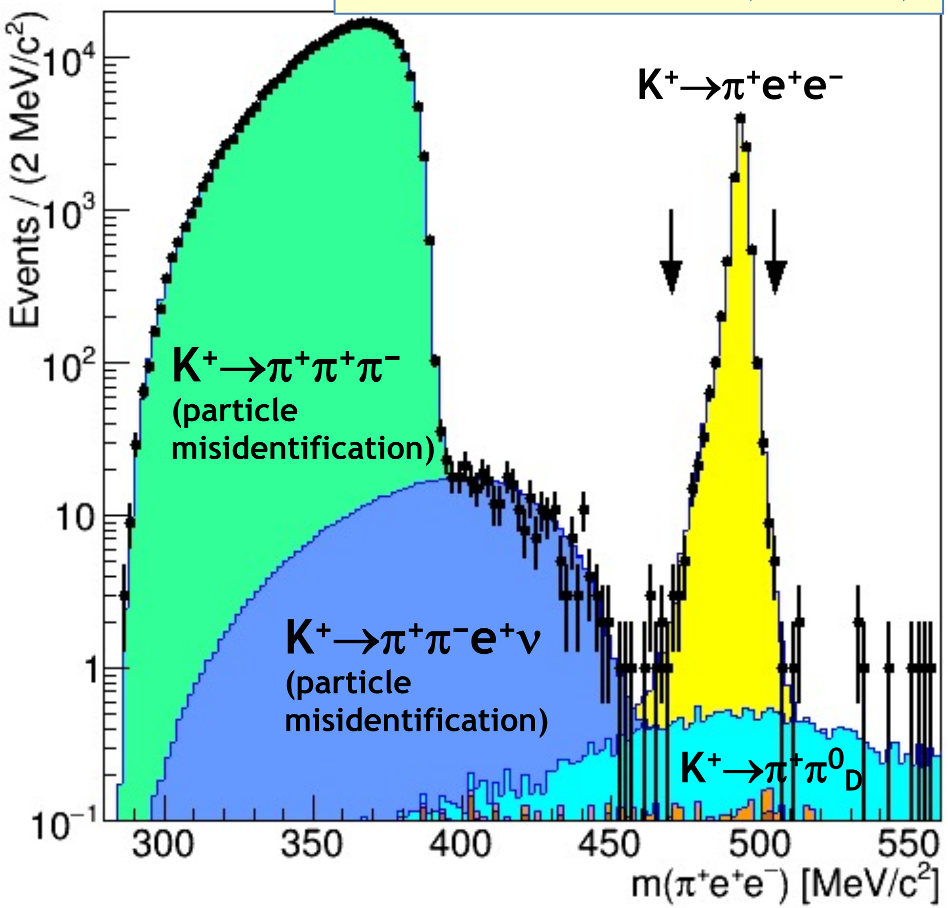
Candidates observed: **8357**
Background: **0.07%**
$BR(K^+ \to \pi^+ \mu^+ \mu^-) = (0.962 \pm 0.025) \times 10^{-7}$
K^+ decays in FV: **$(7.94 \pm 0.23) \times 10^{11}$**

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

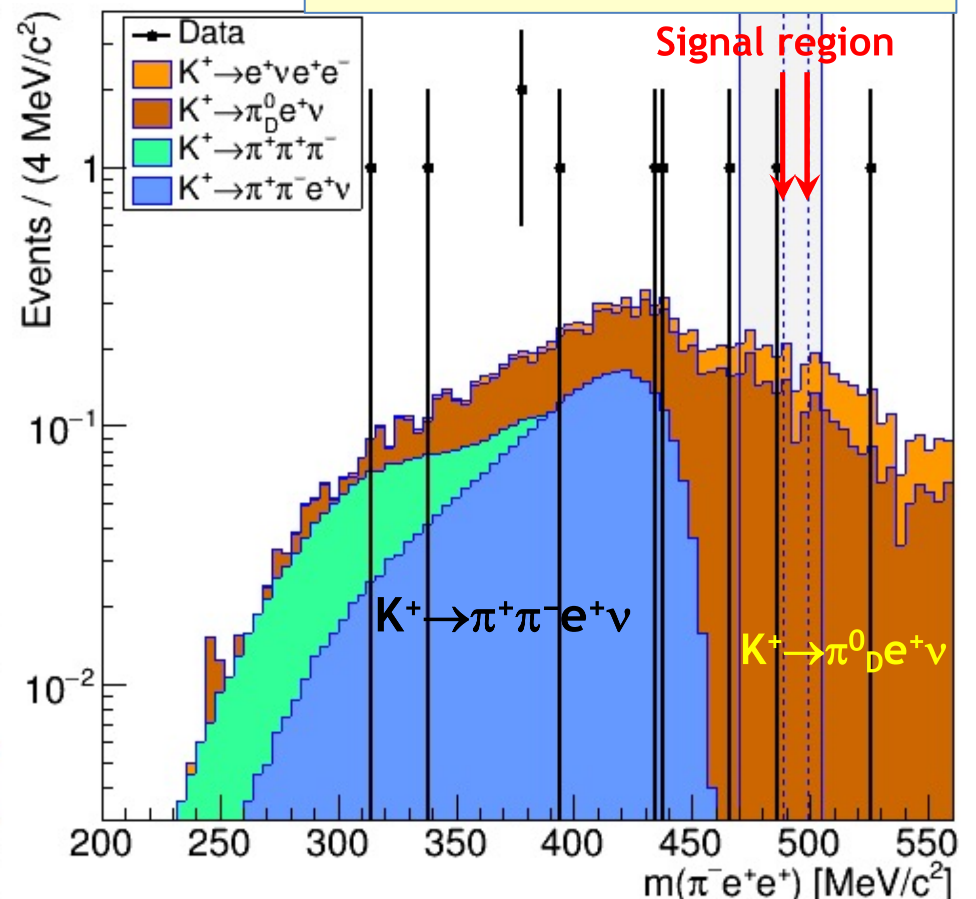
[PLB797 (2019) 134794]

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

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



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



Candidates observed: 11041

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

K^+ decays in FV: $(1.015 \pm 0.032) \times 10^{12}$

Expected background: 0.43 ± 0.09 evt

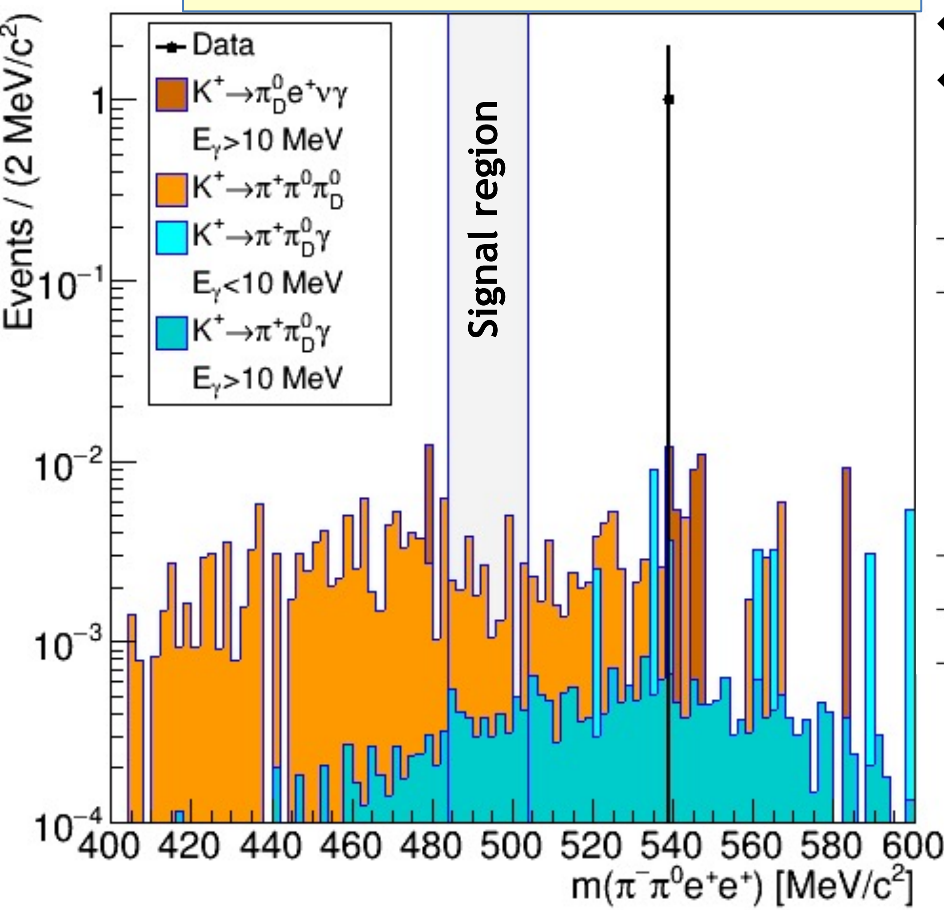
Candidates observed: 0

$BR(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ at 90% CL

(to be published in 2022)

Search for $K^+ \to \pi^- \pi^0 e^+ e^+$ (Run 1)

LNV selection: $m(\pi^- \pi^0 e^+ e^+)$



- Normalisation to the SM decay $K^+ \to \pi^+ e^+ e^-$.
- The neutral pion is reconstructed in the LKr calorimeter via $\pi^0 \to \gamma\gamma$ decay.

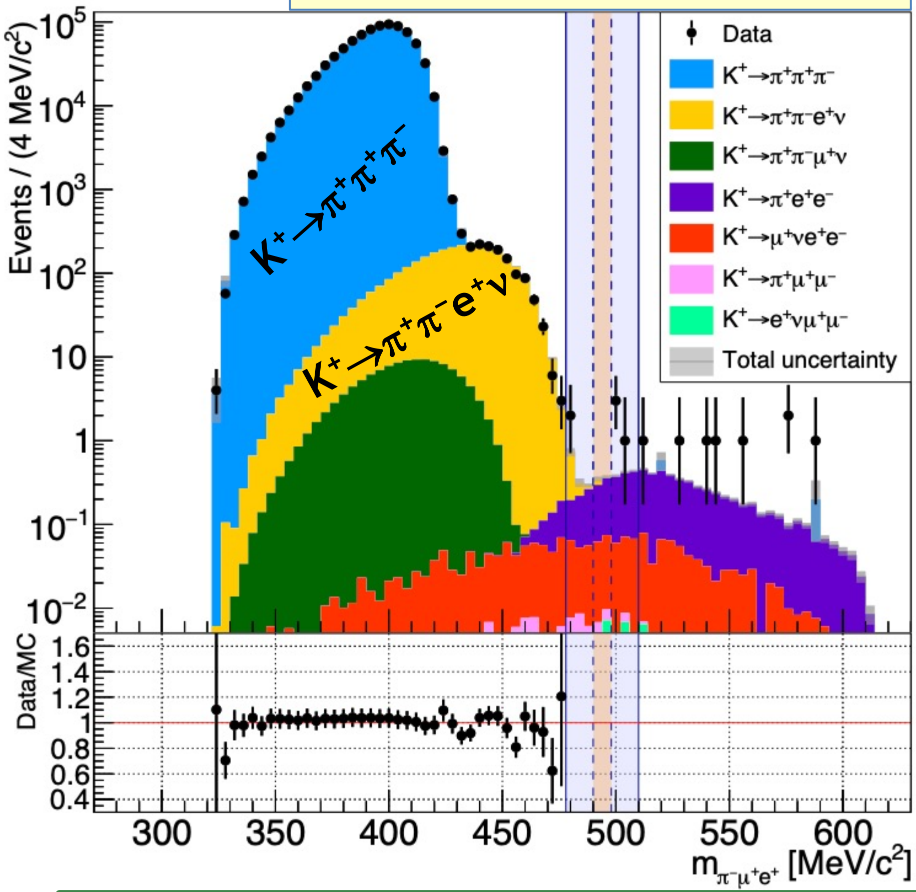
Mode	Control region	Signal region
$K^+ \to \pi^+\pi^0\pi^0_D$	0.16 ± 0.01	0.019
$K^+ \to \pi^+\pi^0_D\gamma$	0.06 ± 0.01	0.004
$K^+ \to \pi^0_D e^+\nu\gamma$	0.05 ± 0.02	–
$K^+ \to \pi^+\pi^0 e^+ e^-$	0.01	0.001
Pileup	0.20 ± 0.20	0.020 ± 0.020
Total	0.48 ± 0.20	0.044 ± 0.020
Data	1	0

Expected background: 0.044±0.020 evt
Candidates observed: 0
$BR(K^+ \to \pi^- \pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ at 90% CL
First search for this mode.

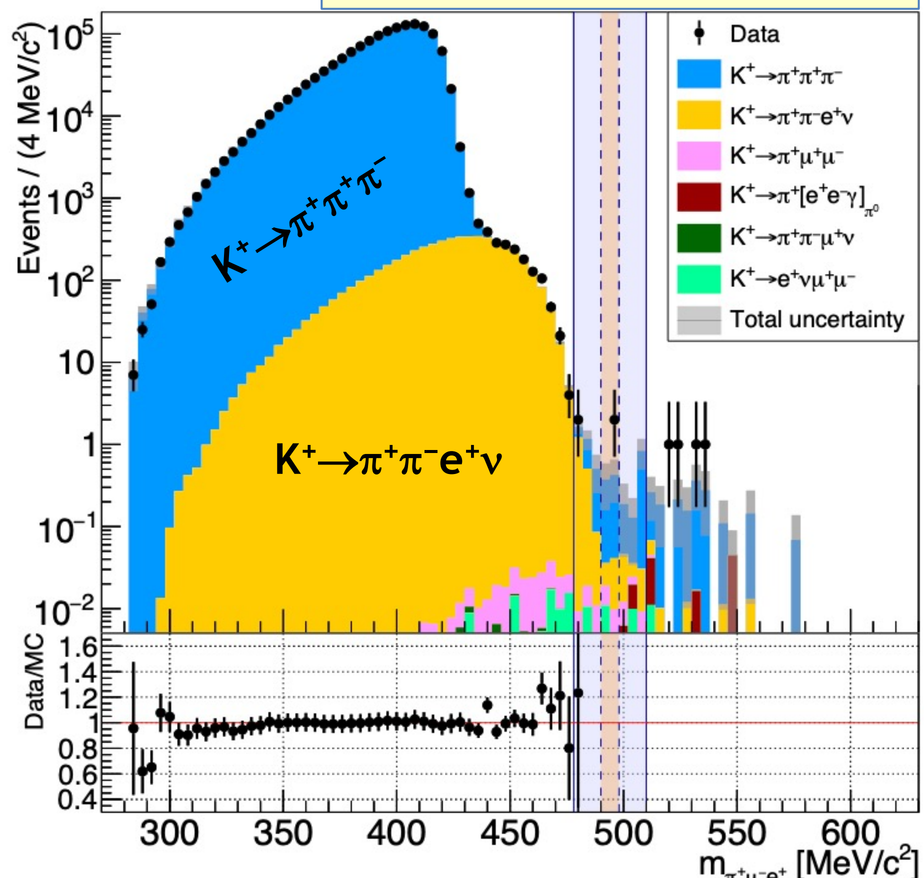
(to be published in 2022)

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

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



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



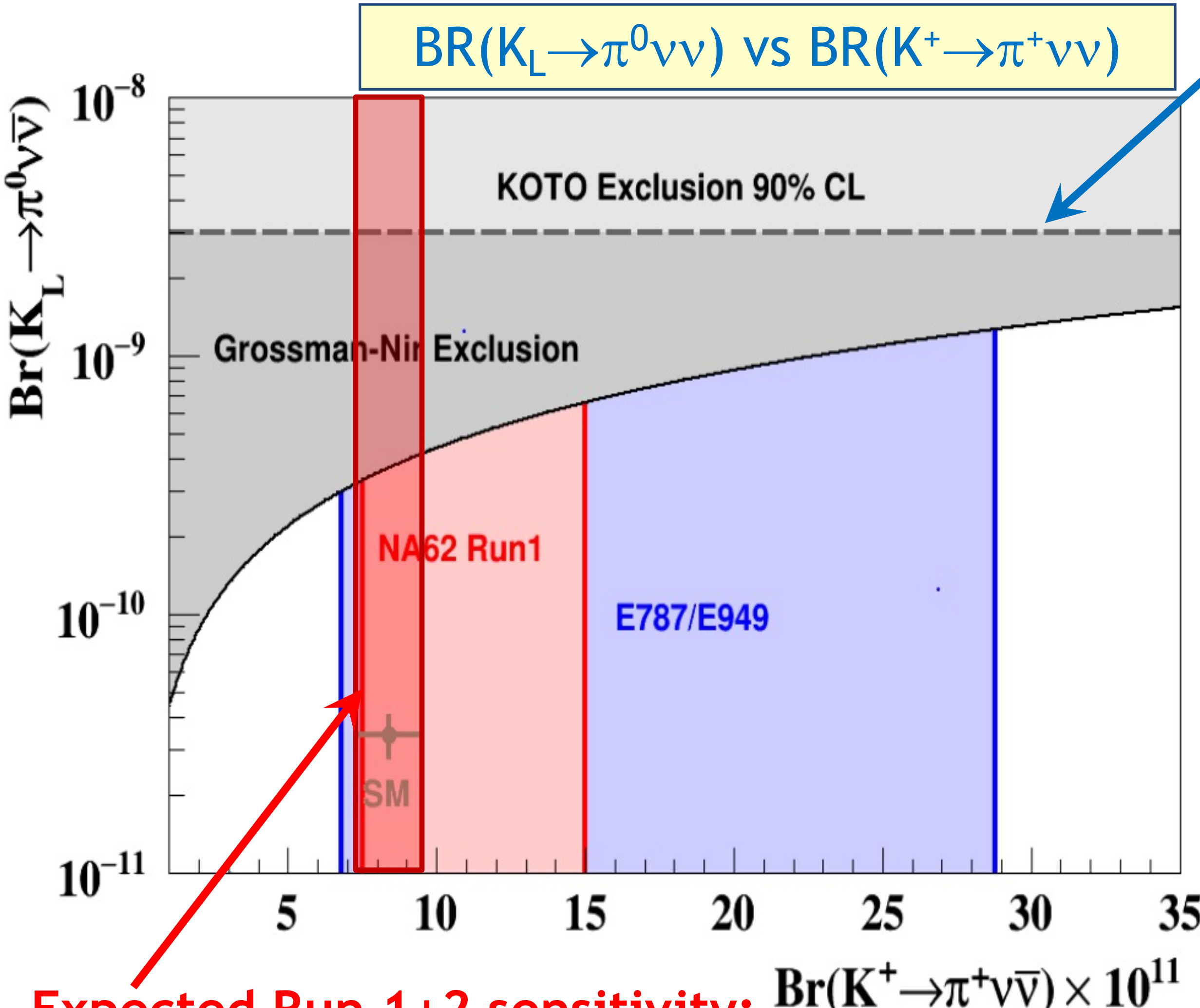
K^+ decays in FV: $(1.33\pm0.02)\times10^{12}$
Expected background: 1.07 ± 0.20 evt
Candidates observed: 0
$BR(K^+\to\pi^-\mu^+e^+)<4.2\times10^{-11}$ at 90% CL

Expected background: 0.92 ± 0.34 evt
Candidates observed: 2
$BR(K^+\to\pi^+\mu^-e^+)<6.6\times10^{-11}$ at 90% CL
$BR(\pi^0\to\mu^-e^+)<3.2\times10^{-10}$ at 90% CL

[PRL 127 (2021) 131802]

Future plans

Short-term plans: NA62 Run 2



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

KOTO limit (2015 data):
BR($K_L \to \pi^0 \nu\nu$)<3.0×10^{-9}
PRL122 (2019) 021802
2016–18 data also published:
PRL126 (2021) 121801

NA62 Run 2 (2021–):

- Higher beam intensity.
- Optimised beamline, new veto detectors.
- Fourth kaon beam tracker station.
- $K^+ \to \pi^+ \nu\nu$ measurement in low-background, high-acceptance regime, at **O(10%)** precision.
- Collection of **10^{18}** POT in up to **90 days** in **beam dump mode**.

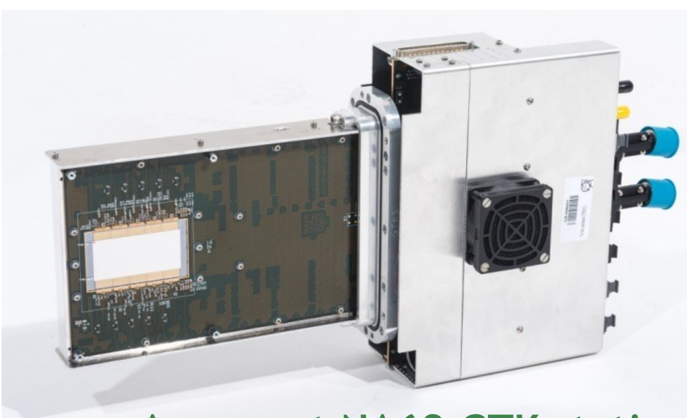
Long-term plans: $K^+ \to \pi^+ \nu\nu$ at CERN

A possible next step after LS3: an in-flight $K^+ \to \pi^+ \nu\nu$ experiment at ×4 beam intensity (present SPS limit), aiming at ~5% precision.

✓ Challenge: 20–40 ps time resolution for key detectors to keep random veto under control, while maintaining other performances.

New pixel beam tracker (GTK):

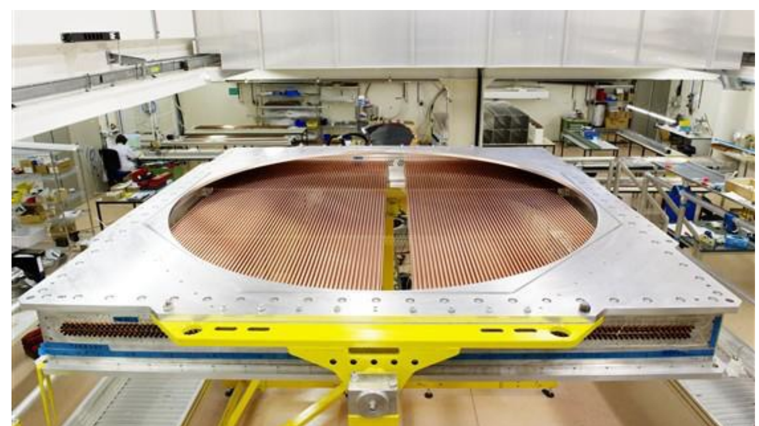
time resolution: <50 ps per plane;
pixel size: <300×300 μm²;
efficiency: >99% per plane (incl.fill factor);
material budget : 0.3–0.5% X_0;
beam intensity: 3 GHz on 30×60 mm²;
peak intensity: 8.0 MHz/mm².



A current NA62 GTK station

New STRAW spectrometer:

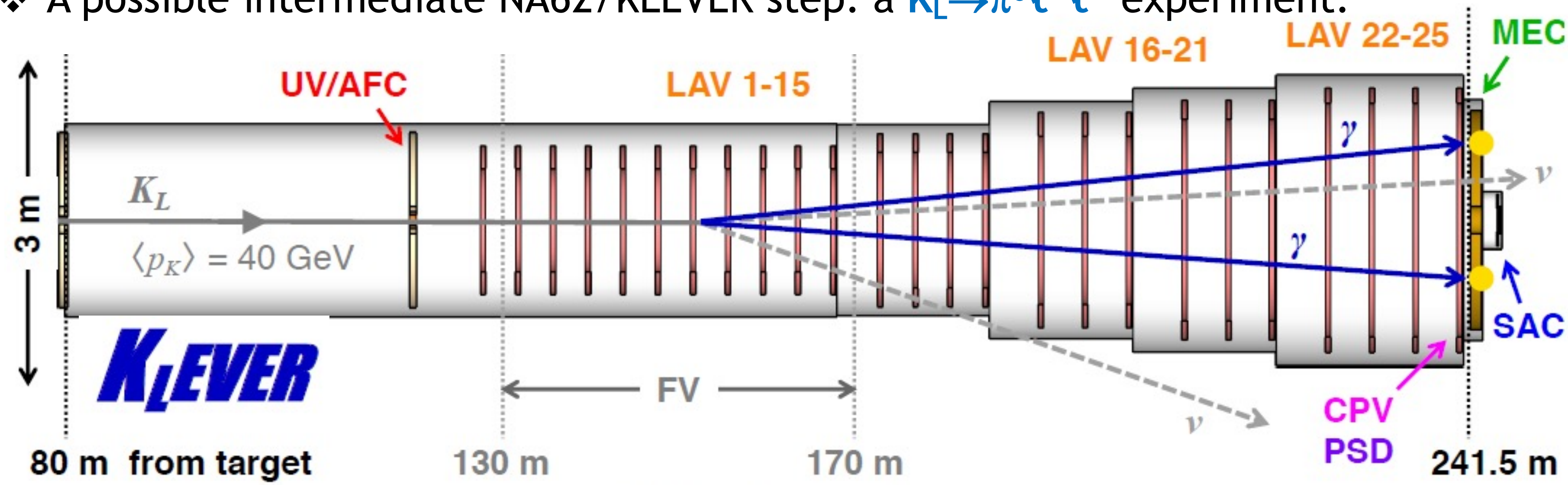
operation in vacuum;
straw length/diameter: 2.2 m/5 mm;
trailing time resolution: ~6 ns per straw;
maximum drift time: ~80 ns;
layout: ~21000 straws (4 chambers);
material budget: 1.5%X_0.



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;

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

Summary

- NA62 Run 1 in 2016–18: 2.2×10^{18} POT; 6×10^{12} K^+ decays in flight.

- First evidence for the $K^+\to\pi^+\nu\nu$ decay: from 20 candidates,

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

[JHEP 06 (2021) 93]

- Searches on hidden-sector mediator production and other BSM physics in kaon decays:
  - ✓ dark scalar/ALP production: searches for $K^+\to\pi^+X$ and $\pi^0\to$inv;
  - ✓ HNL production: searches for $K^+\to\ell^+N$ and $K^+\to\mu^+\nu X$ decays;
  - ✓ a comprehensive programme for LNV/LFV kaon decays.

- Future kaon experiments at CERN:
  - ✓ NA62 Run 2 is in progress;
  - ✓ aiming to O(10%) precision on BR($K^+\to\pi^+\nu\nu$) by 2025;
  - ✓ planning to collect 10^{18} POT in dump mode by 2025;
  - ✓ in the long term, a high-intensity kaon beam facility at CERN, including O(5%) precision on BR($K^+\to\pi^+\nu\nu$) and a K_L experiment.

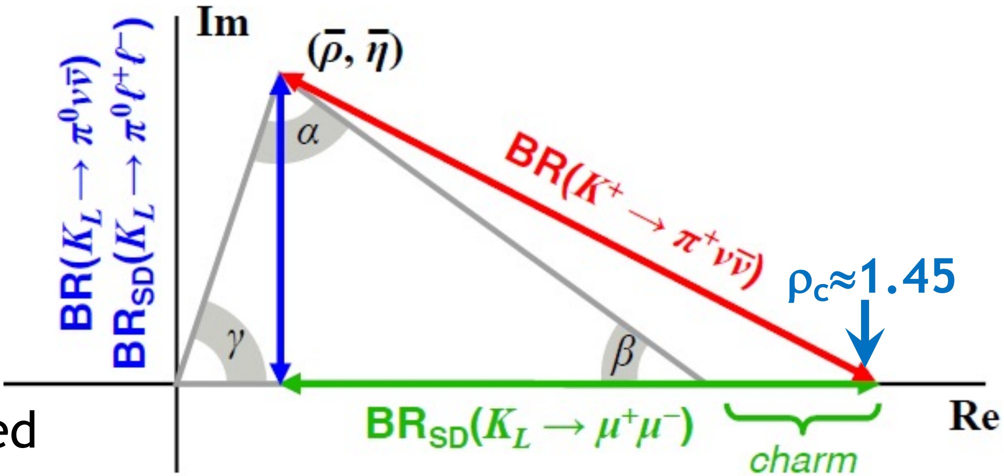
Spares

Rare kaon decays

Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 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→πνν**: uniquely clean theoretically.
- Decays to charged leptons: affected by larger hadronic uncertainties.

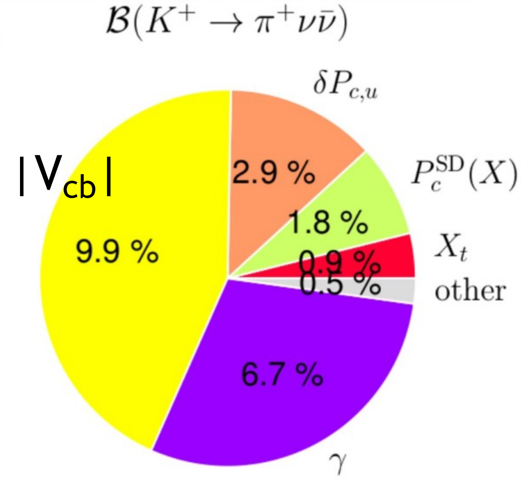


K→πνν and the unitarity triangle

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

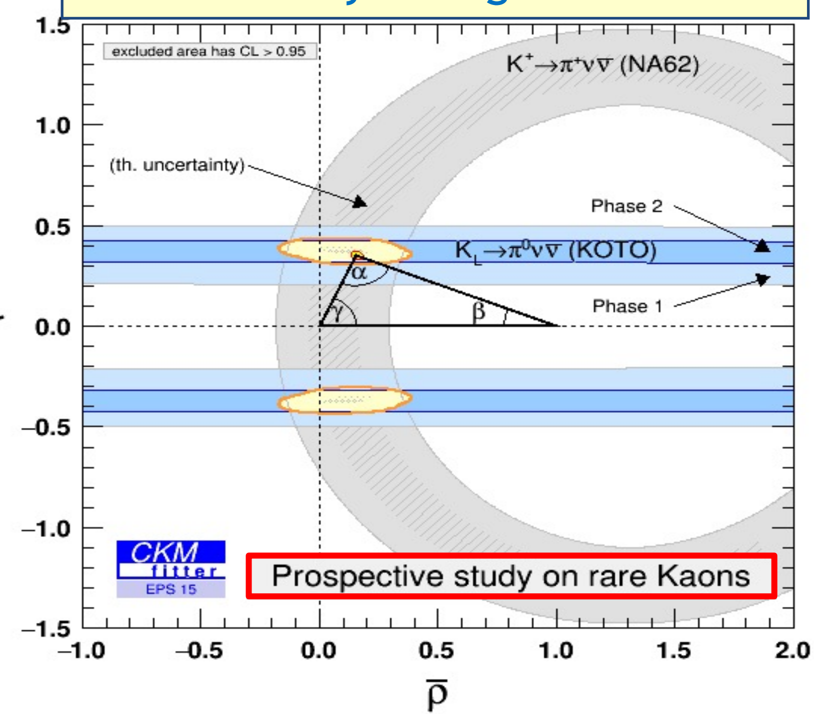
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^2 \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^2 \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^2$$

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



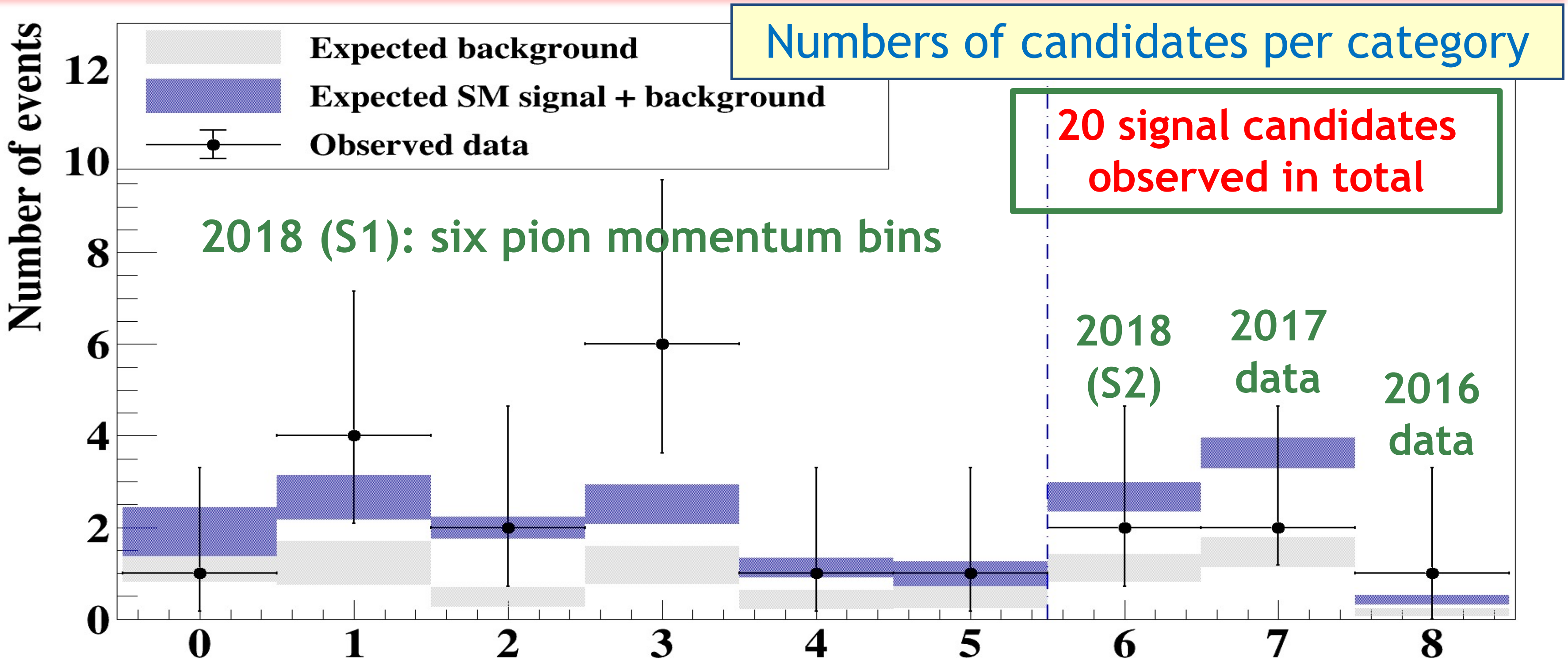
Analysis principle

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

- $N^{exp}_{\pi\nu\nu}$: expected number of $K_{\pi\nu\nu}$ events
- $Br(\pi\nu\nu)$: Standard Model $K_{\pi\nu\nu}$ branching ratio (central value)
- $N_{\pi\pi}$: $K^+\rightarrow\pi^+\pi^0$ 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 $K^+\rightarrow\pi^+\pi^0$ decay

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

Result: Run 1 data set



<u>Categories:</u>

❖ 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.

<u>**Final result (Run 1 sample):**</u>

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

(**3.4σ** significance)

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

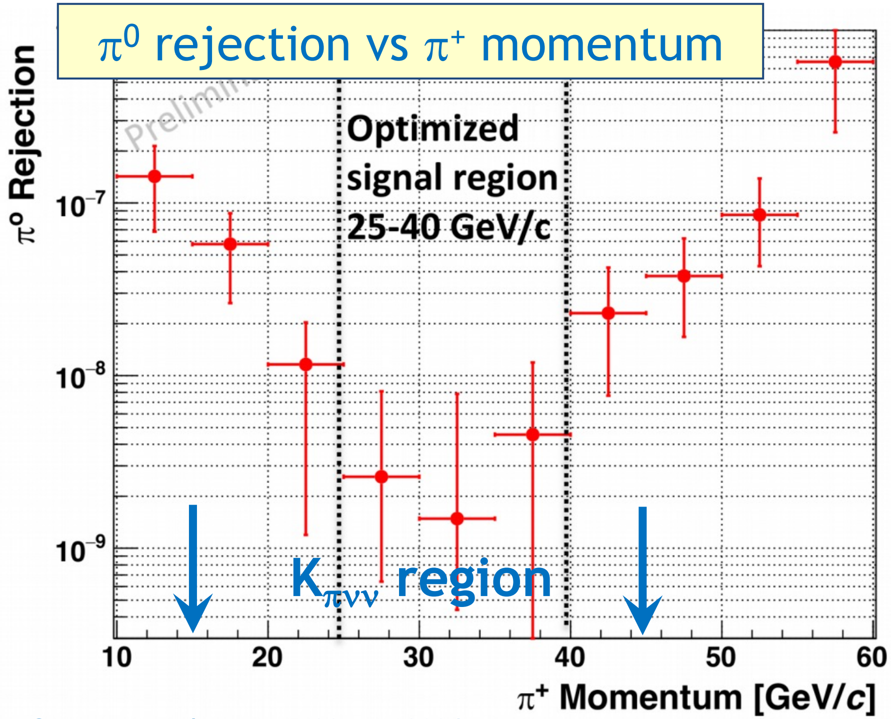
JHEP 02 (2021) 201

- Rejection of ($K^+ \to \pi^+\pi^0(\gamma)$, $\pi^0 \to \gamma\gamma$) decays: 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: $\varepsilon \approx 10^{-8}$.
- For $\pi^0 \to$invisible search ($25<p_\pi<40$ GeV/c): $\varepsilon = (2.8^{+5.0}_{-2.1})\times 10^{-9}$

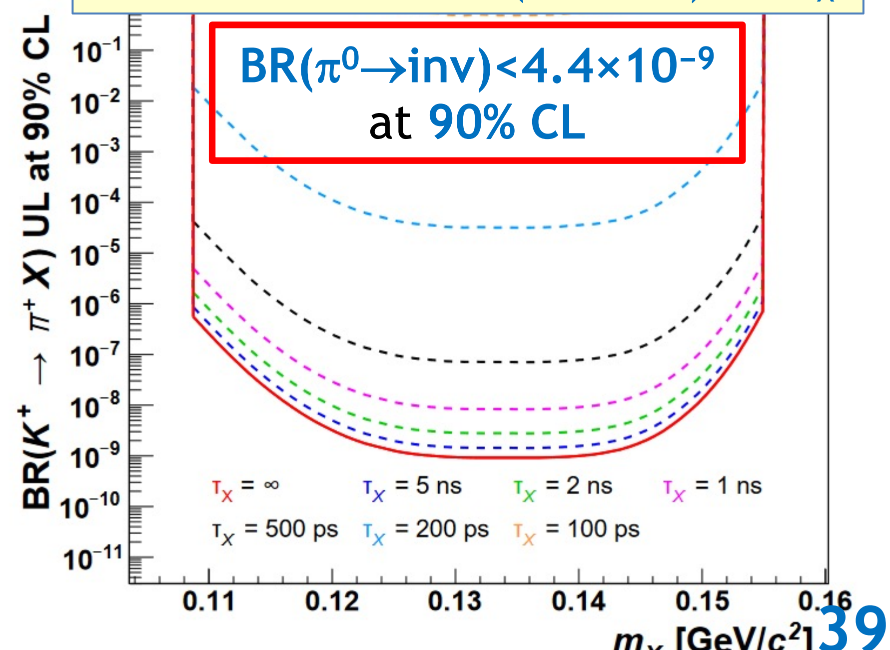
Search for $\pi^0 \to$invisible: (1/3 of the 2017 data set).

- $K_{\pi\nu\nu}$ 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.

π^0 rejection vs π^+ momentum

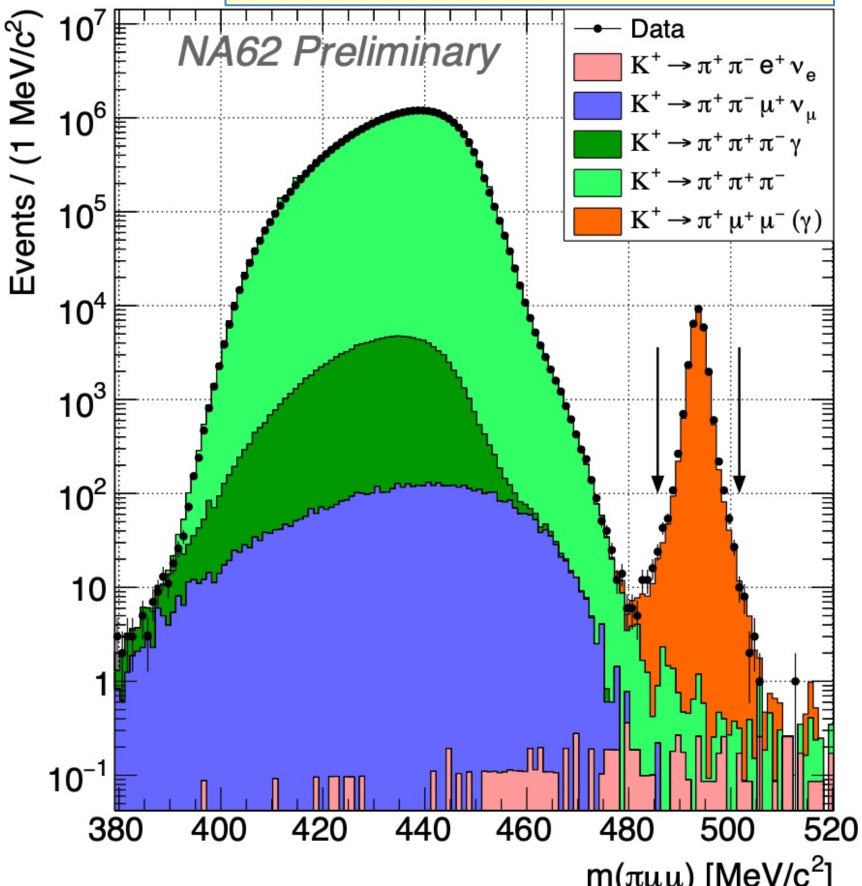


UL at 90% CL on BR($K^+ \to \pi^+X$) vs m_X

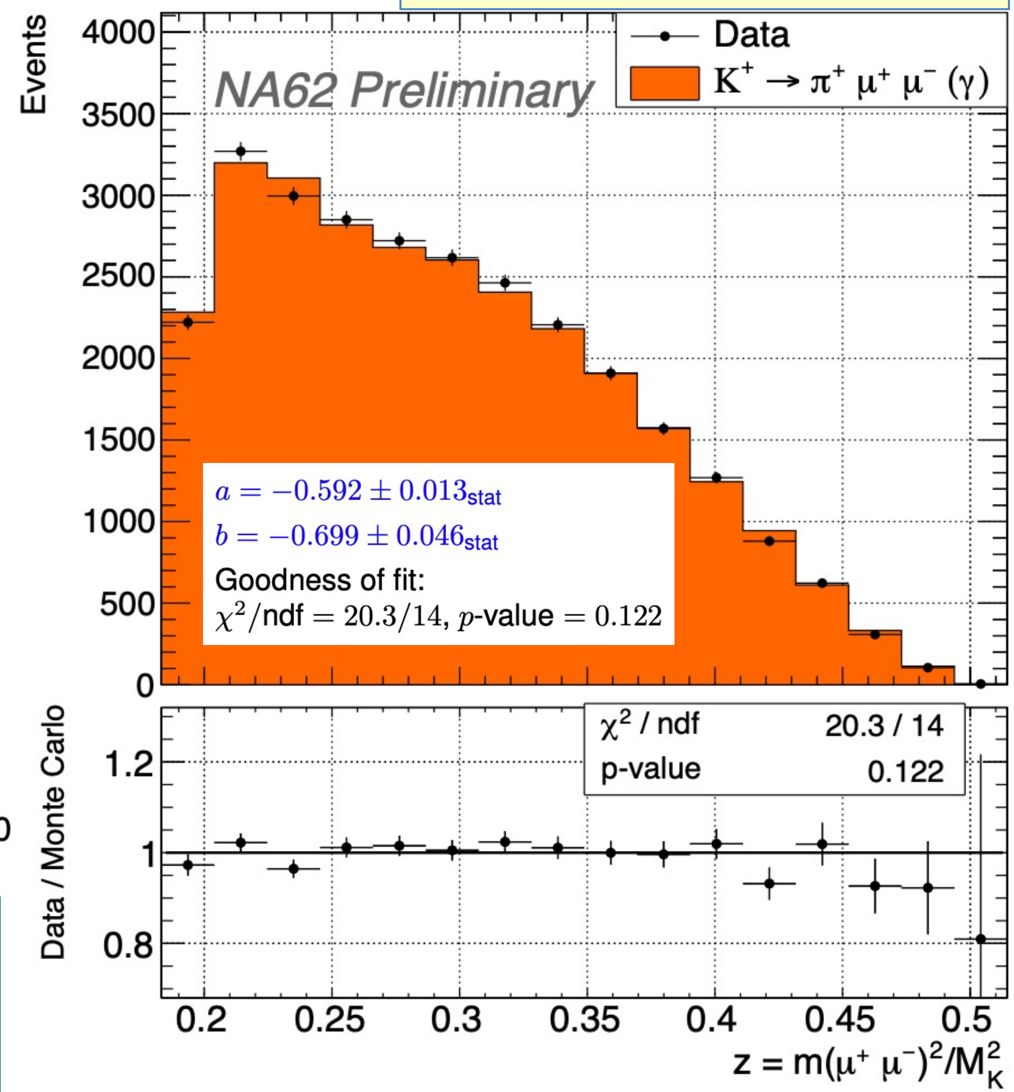


$K^+ \to \pi^+\mu^+\mu^-$ measurement (1)

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



Fit to the form factor

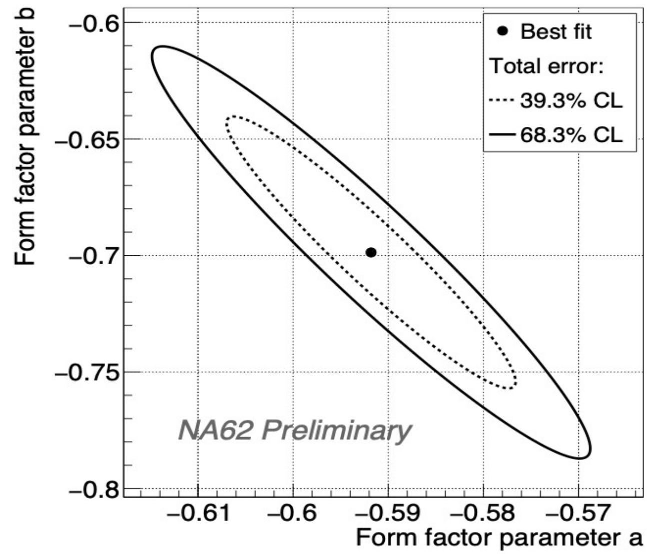


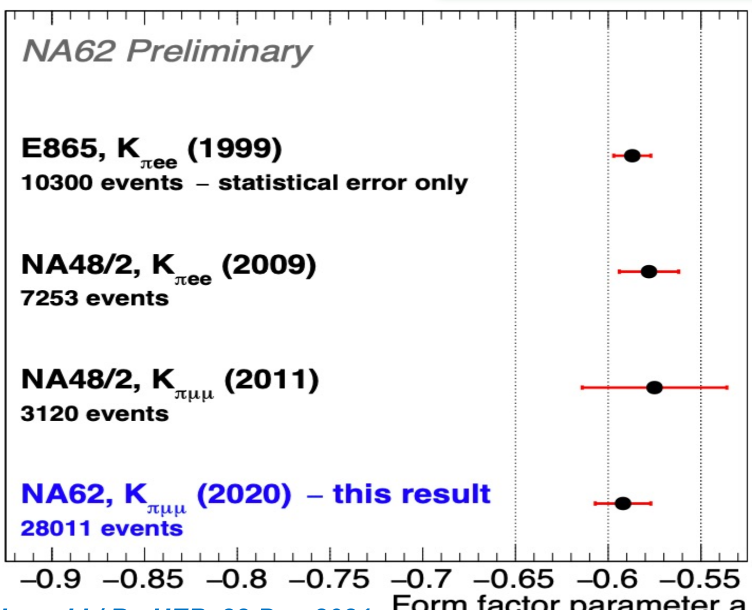
The complete Run 1 sample used.
Candidates observed: **28011**.
Ten times larger samples wrt NA48/2.
Expected bkg: **12.5±12.5** events.

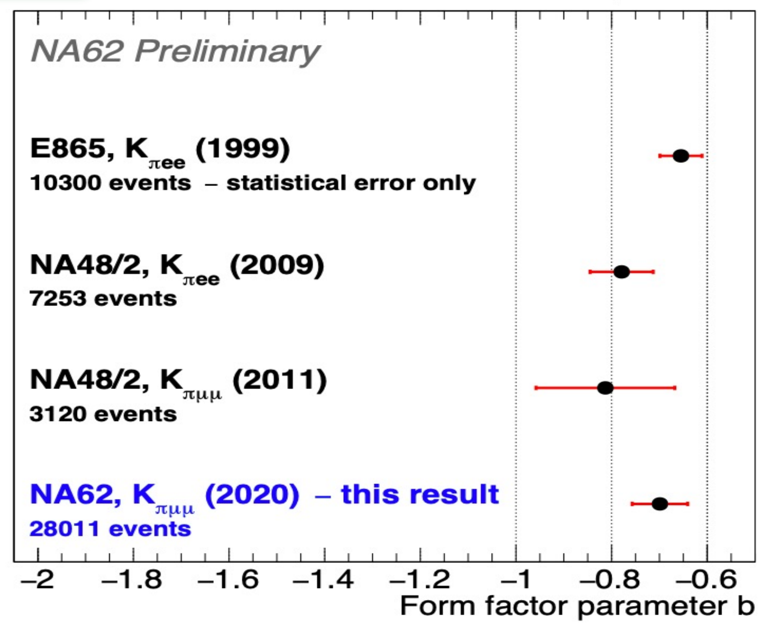
$K^+ \to \pi^+\mu^+\mu^-$ measurement (2)

Form-factor parameters and model-dependent BR measurement:

	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







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

Measurement performed in three kinematic regions:

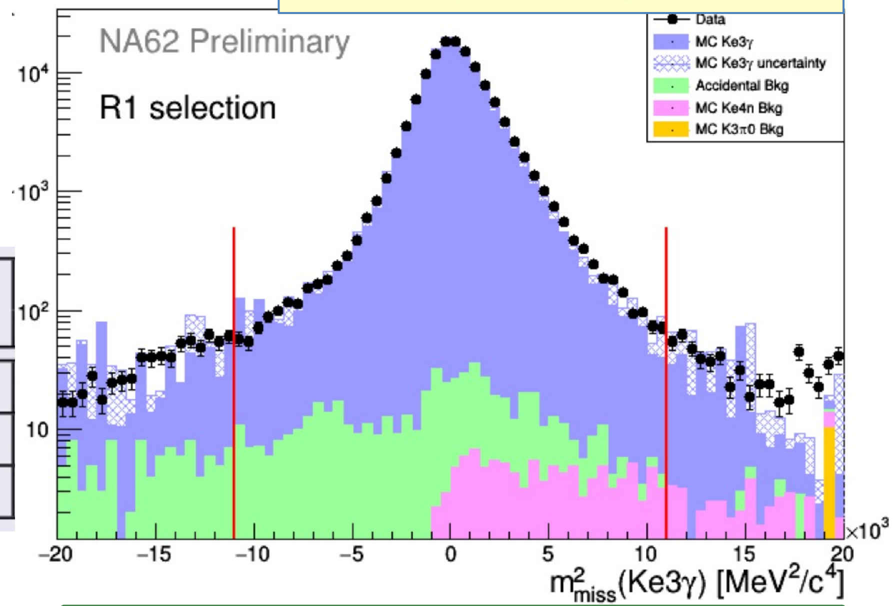
$$R_j = \frac{\mathcal{B}(Ke3\gamma^j)}{\mathcal{B}(Ke3)} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu \gamma \mid E_\gamma^j, \theta_{e,\gamma}^j)}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu (\gamma))}$$

	E_γ cut (*)	$\theta_{e,\gamma}$ cut (*)
$R_1\ (\times 10^2)$	$E_\gamma > 10\ MeV$	$\theta_{e,\gamma} > 10^\circ$
$R_2\ (\times 10^2)$	$E_\gamma > 30\ MeV$	$\theta_{e,\gamma} > 20^\circ$
$R_3\ (\times 10^2)$	$E_\gamma > 10\ MeV$	$0.6 < \cos\theta_{e,\gamma} < 0.9$

T-odd observable ξ
(in the kaon rest frame):

$$\xi = \frac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{m_K^3}\ ;\ A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

Missing mass spectrum



Candidates observed: **130k**
(for R_1: $E_\gamma > 10$ MeV, $\theta_{e\gamma} > 10^o$).
Background contamination: **0.5%**.

	$O(p^6)$ ChPT	ISTRA+	OKA	**NA62 preliminary**
$R_1\ (\times 10^2)$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.684 \pm 0.005 \pm 0.010$
$R_2\ (\times 10^2)$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.599 \pm 0.003 \pm 0.005$
$R_3\ (\times 10^2)$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.523 \pm 0.003 \pm 0.003$

NA62 asymmetry measurements:

	R_1 selection	R_2 selection	R_3 selection
$A_\xi\ (\times 10^2)$	$-0.1 \pm 0.3_{stat} \pm 0.2_{MC}$	$-0.3 \pm 0.4_{stat} \pm 0.3_{MC}$	$-0.9 \pm 0.5_{stat} \pm 0.4_{MC}$