The NA62 experiment at CERN: recent results and prospects

Evgueni Goudzovski

(University of Birmingham, United Kingdom)

goudzovs@cern.ch

Outline:

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

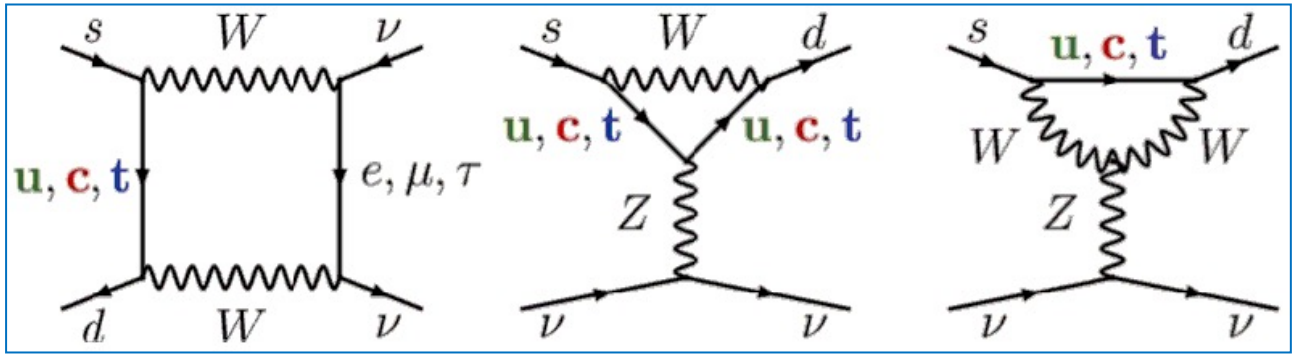
Quarks workshop - New Physics at the Intensity Frontier

7 June 2021

Rare kaon decays and the NA62 experiment

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

SM: Z-penguin and box diagrams



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

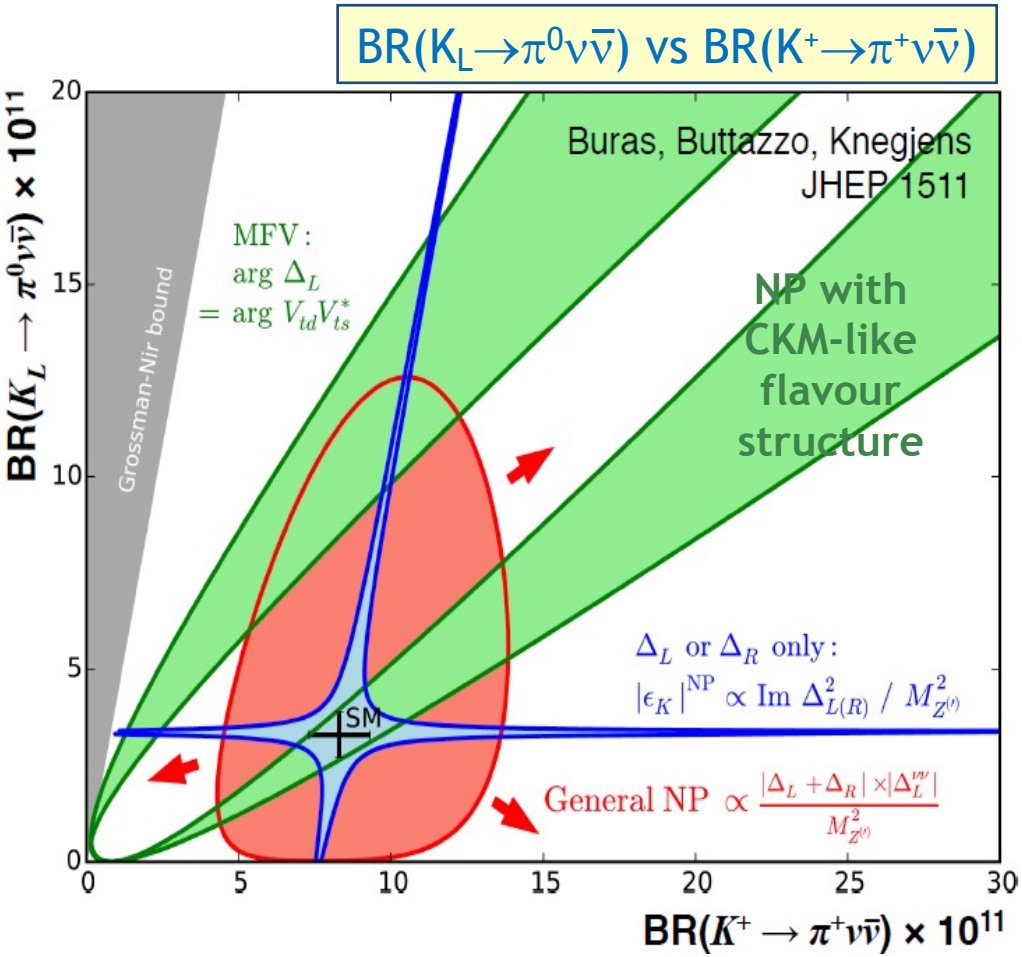
- Maximum CKM suppression: $\sim(m_t/m_W)^2|V^*_{ts}V_{td}|$.
- No long-distance contributions from amplitudes with intermediate photons.
- Hadronic matrix element extracted from measured $BR(K_{e3})$ via isospin rotation.

Mode	Expected BR_{SM}	Experimental status
$K^+ \to \pi^+\nu\nu$	$(8.4\pm1.0)\times10^{-11}$	First evidence 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

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

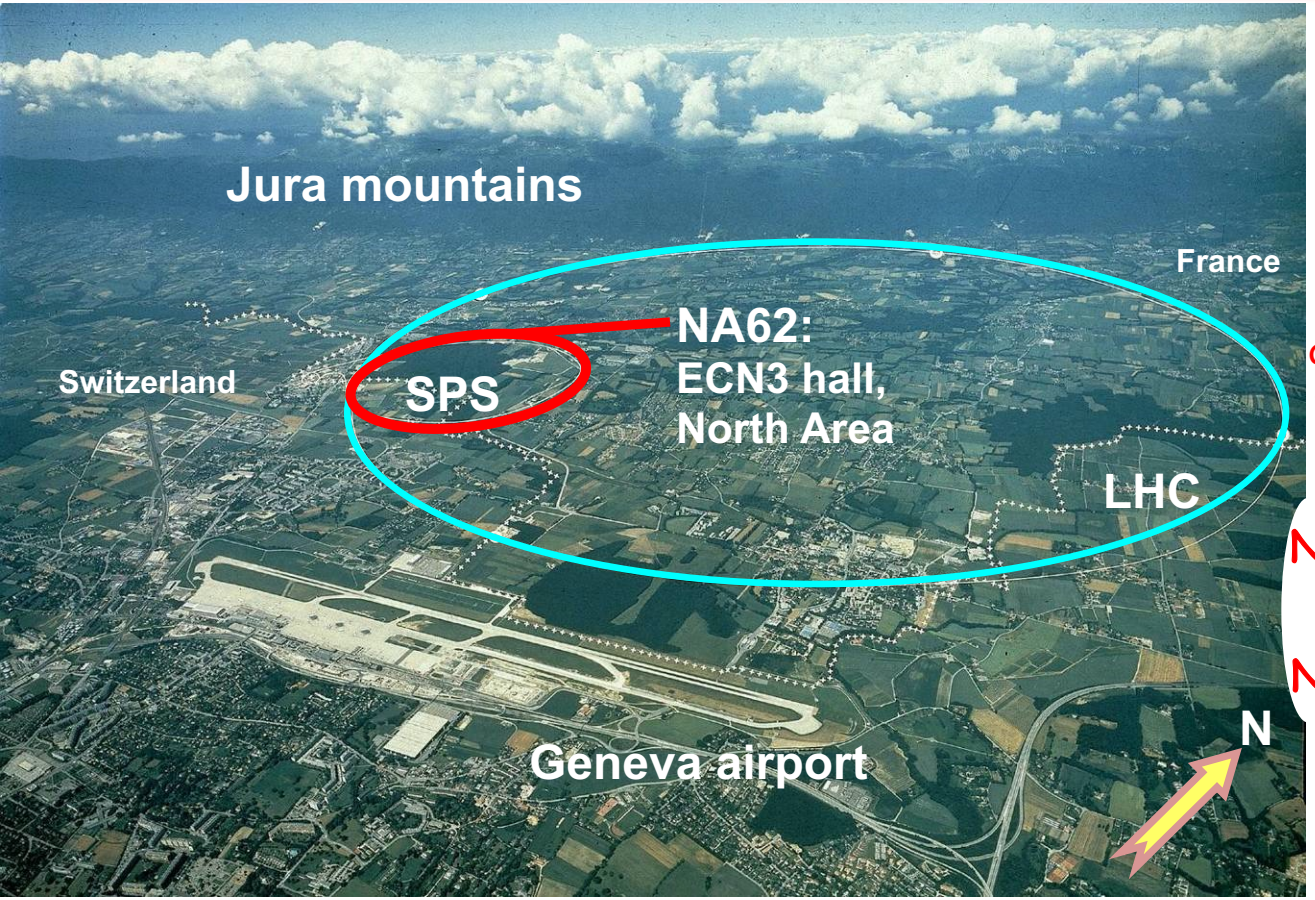
- Correlations between BSM contributions K^+ and K_L BRs. *[JHEP 11 (2015) 166]*
- Need to measure both K^+ and K_L to discriminate among BSM scenarios.
- Correlations with other observables (ε'/ε, ΔM_K, B decays). *[JHEP 12 (2020) 97]*



- **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

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

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: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests
- 2008: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests

NA62

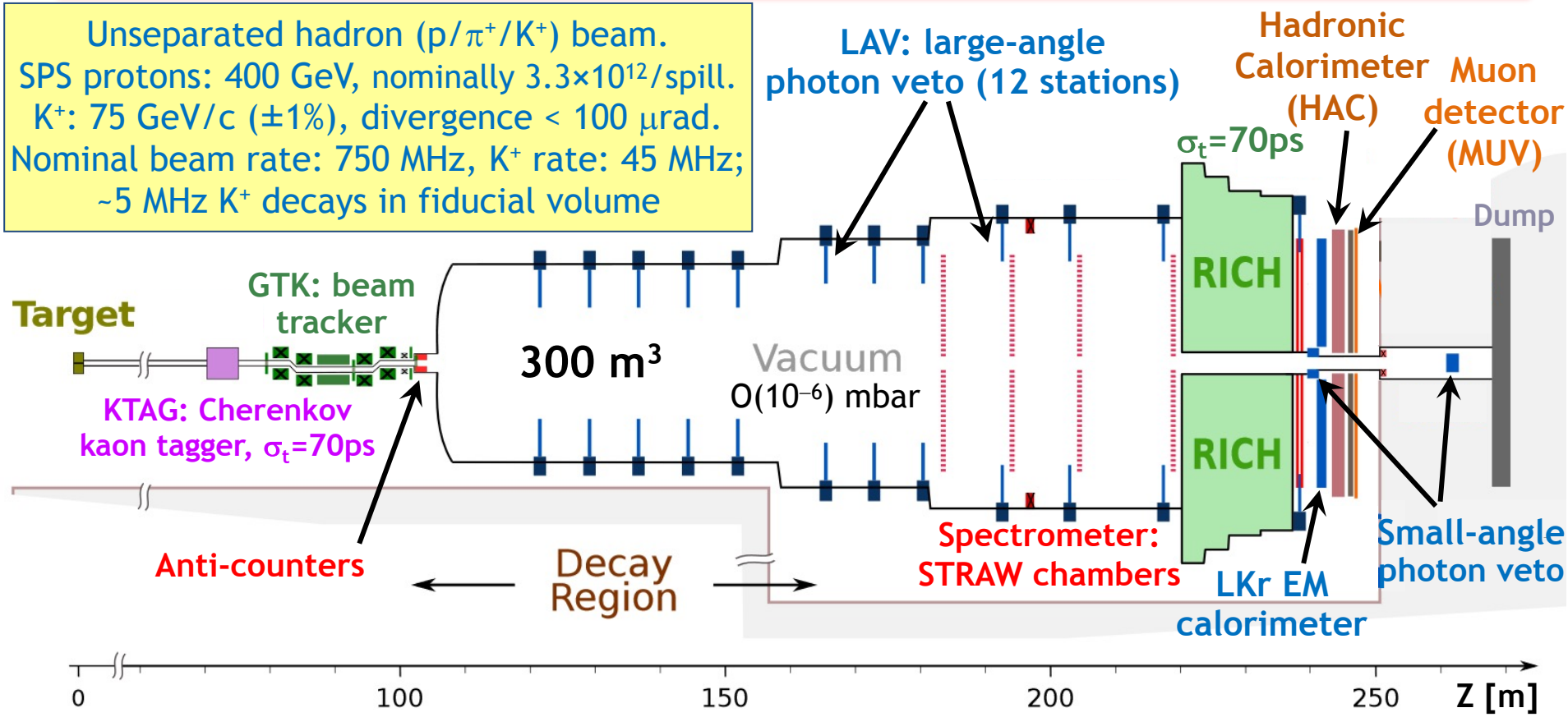
- 2015: commissioning
- 2016-18: physics run 1
- 2021-: physics run 2

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

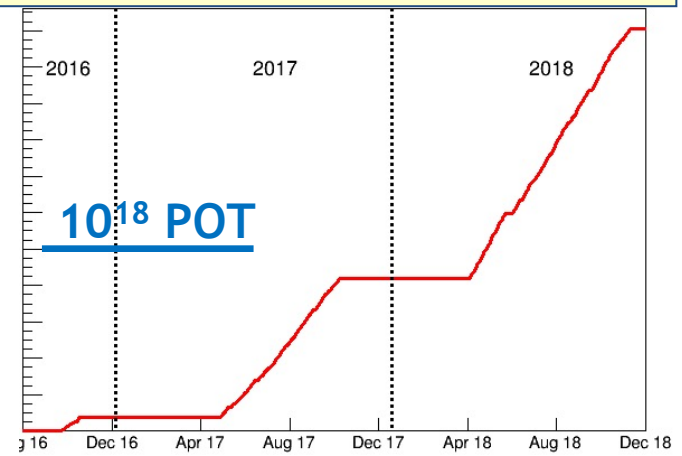
Unseparated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, nominally 3.3×10^{12}/spill.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Nominal beam rate: 750 MHz, K^+ rate: 45 MHz;
~5 MHz K^+ decays in fiducial volume



- 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



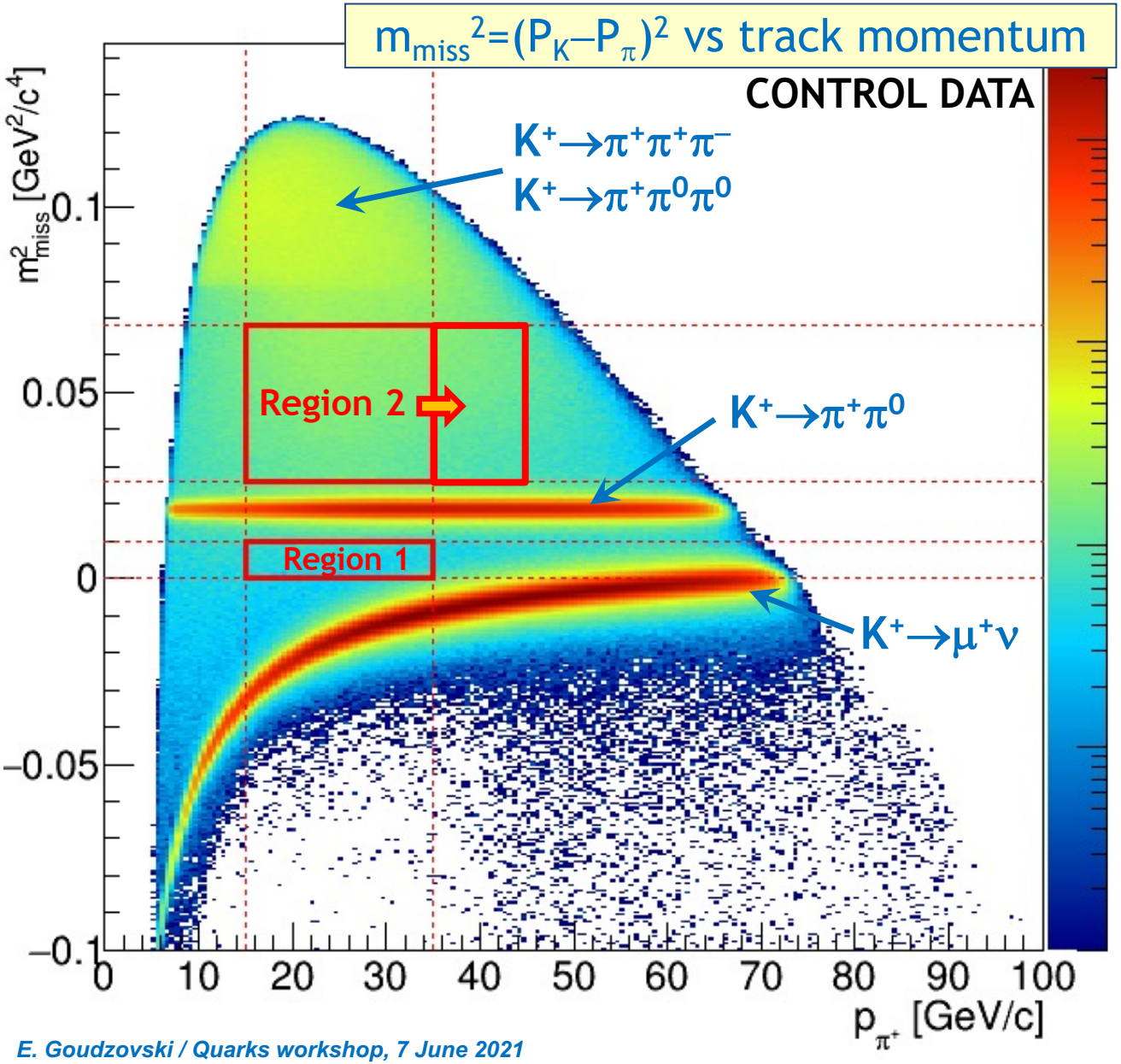
2.2×10^{18} POT collected
(3×10^{16} from 50h in dump mode)

- 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**: beam time starting on **12 July 2021** (**~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: arXiv:2103.15389, to appear in JHEP.*

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}.

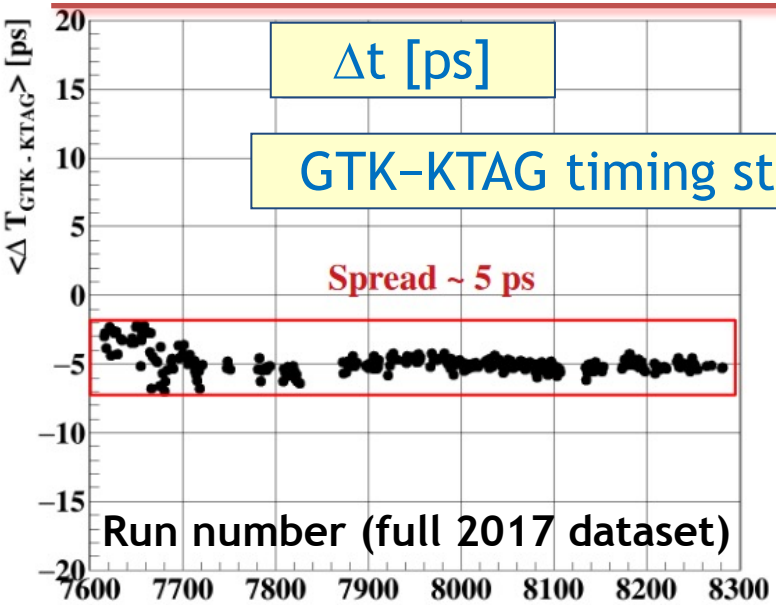
Key parameters: timing, PID

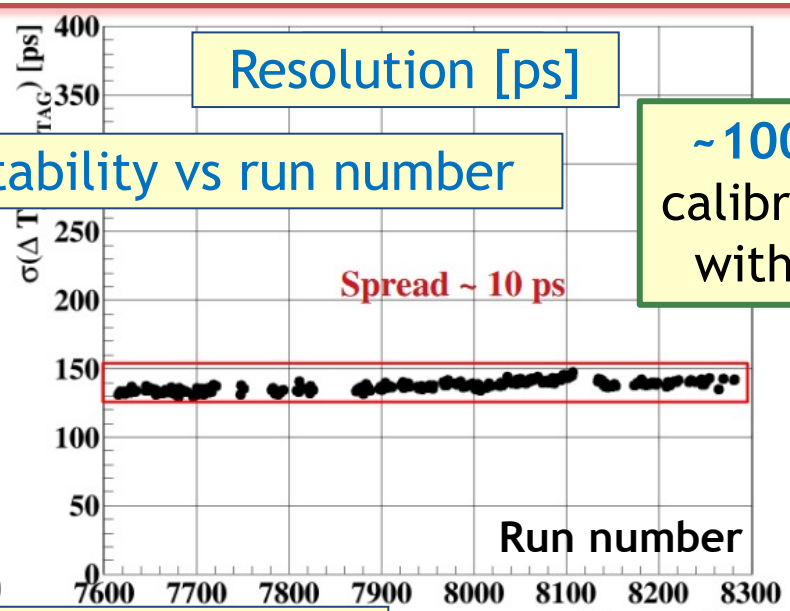
Δt [ps]

Resolution [ps]

GTK–KTAG timing stability vs run number

~100 ps timing, calibrations stable within a few ps

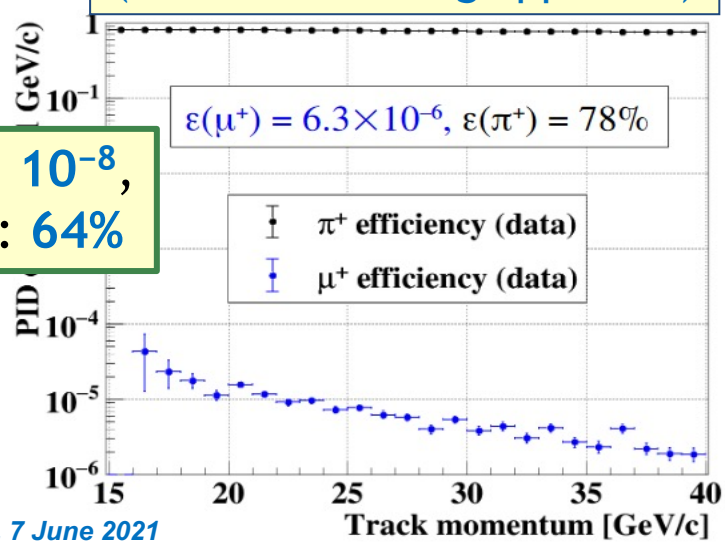


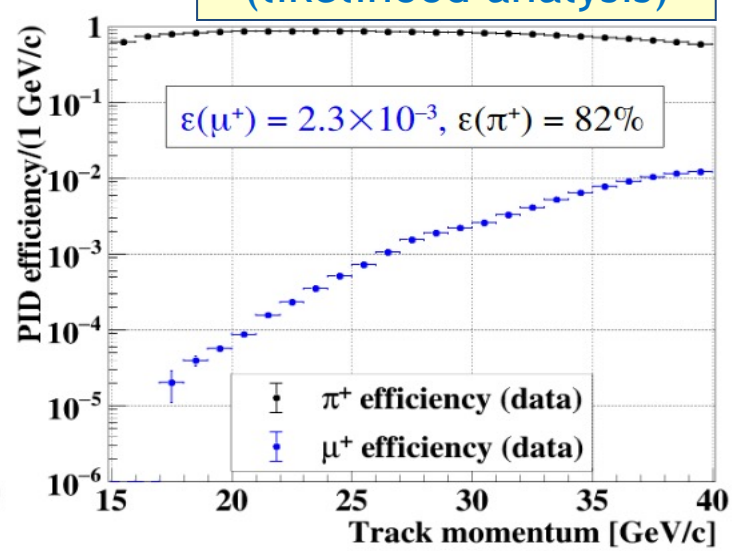


Calorimetric PID (machine learning approach)

RICH PID (likelihood analysis)

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

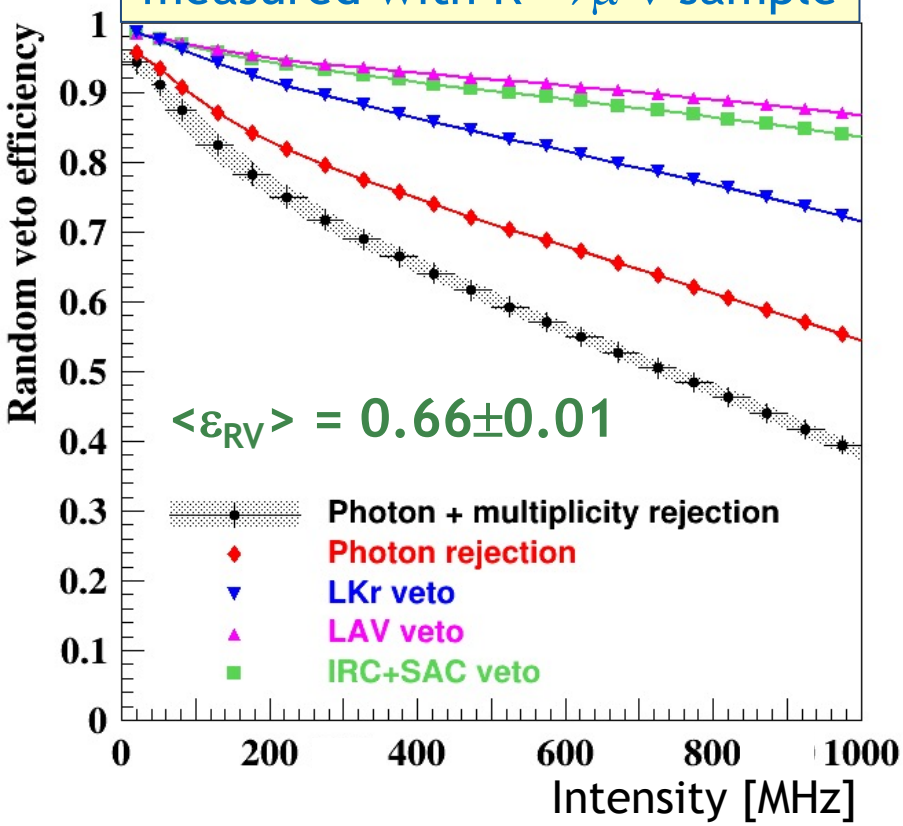




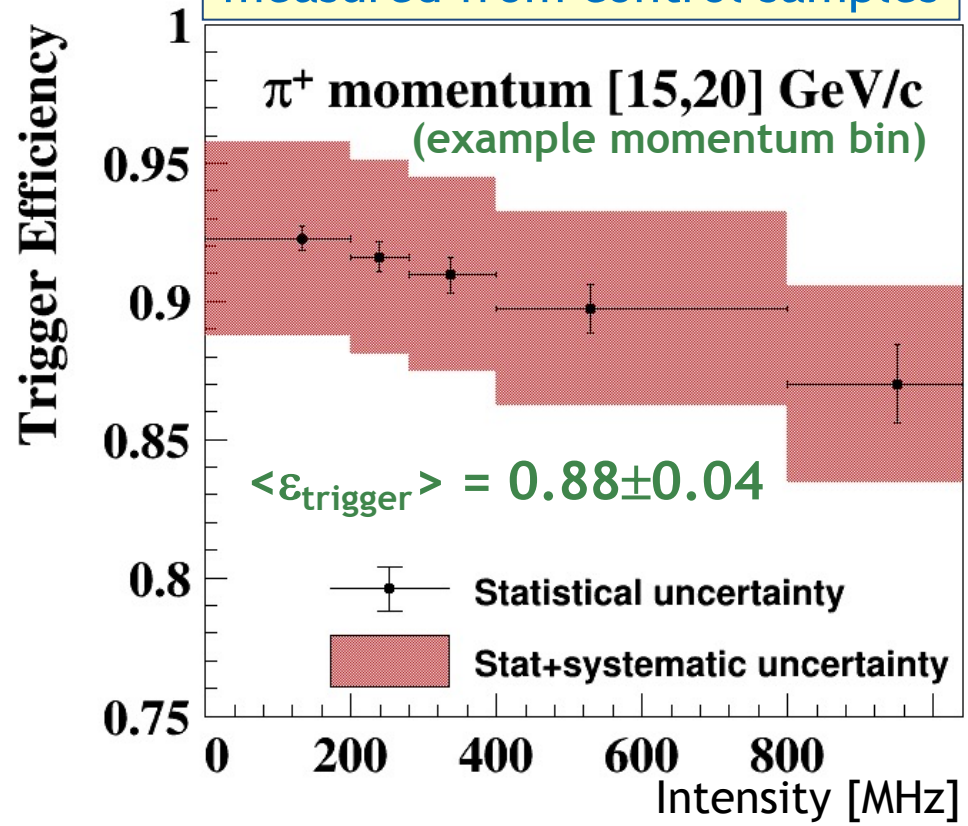
Single event sensitivity (SES)

- Integrated over momentum & intensity, $BR_{SES} = (0.839 \pm 0.053) \times 10^{-11}$.
  (main uncertainties: trigger, acceptance, random veto)
- Expected number of SM events: $N_{\pi\nu\nu} = BR_{SM}/BR_{SES} = 10.01 \pm 0.42_{syst} \pm 1.19_{SM}$.

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



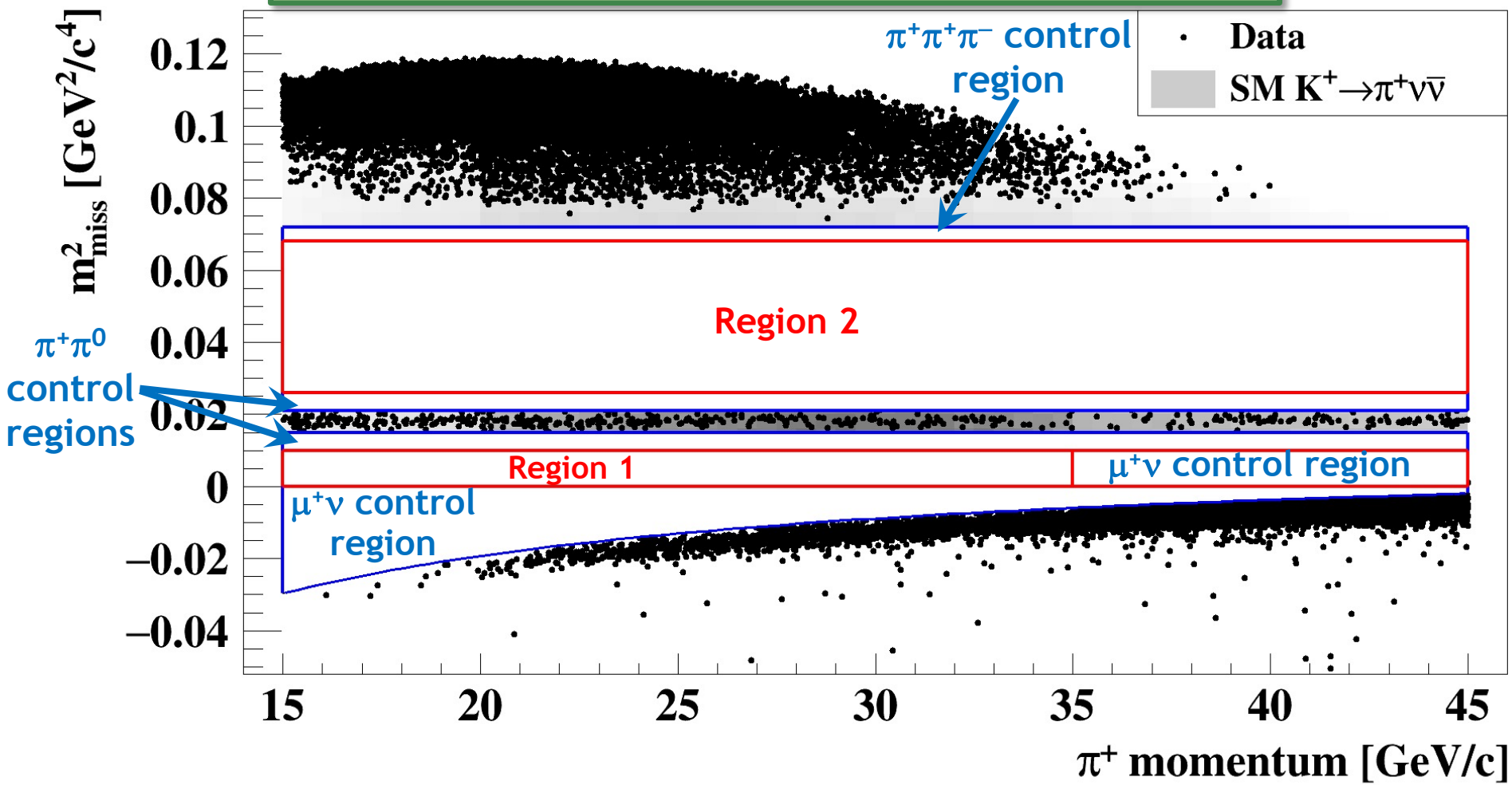
Trigger efficiency $\varepsilon_{trigger}$ measured from control samples



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

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

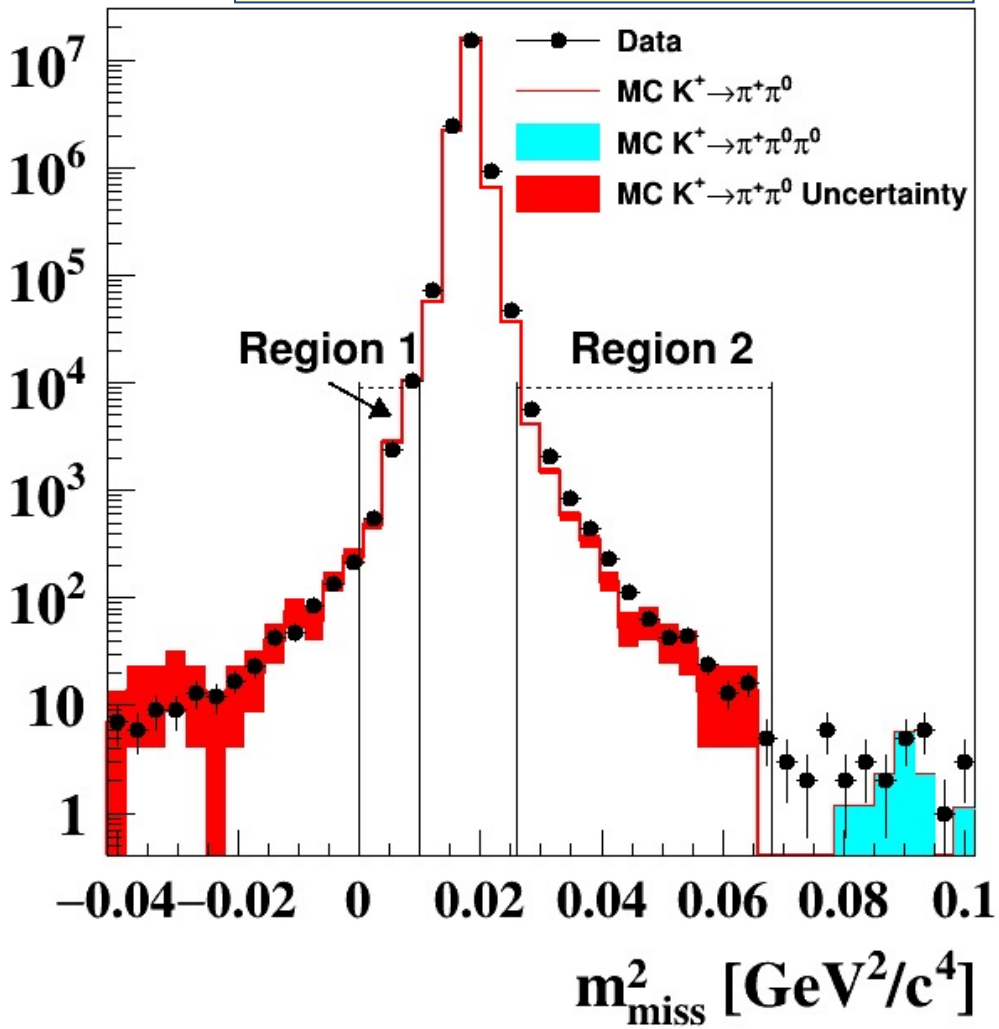
Signal and control regions are blinded



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)

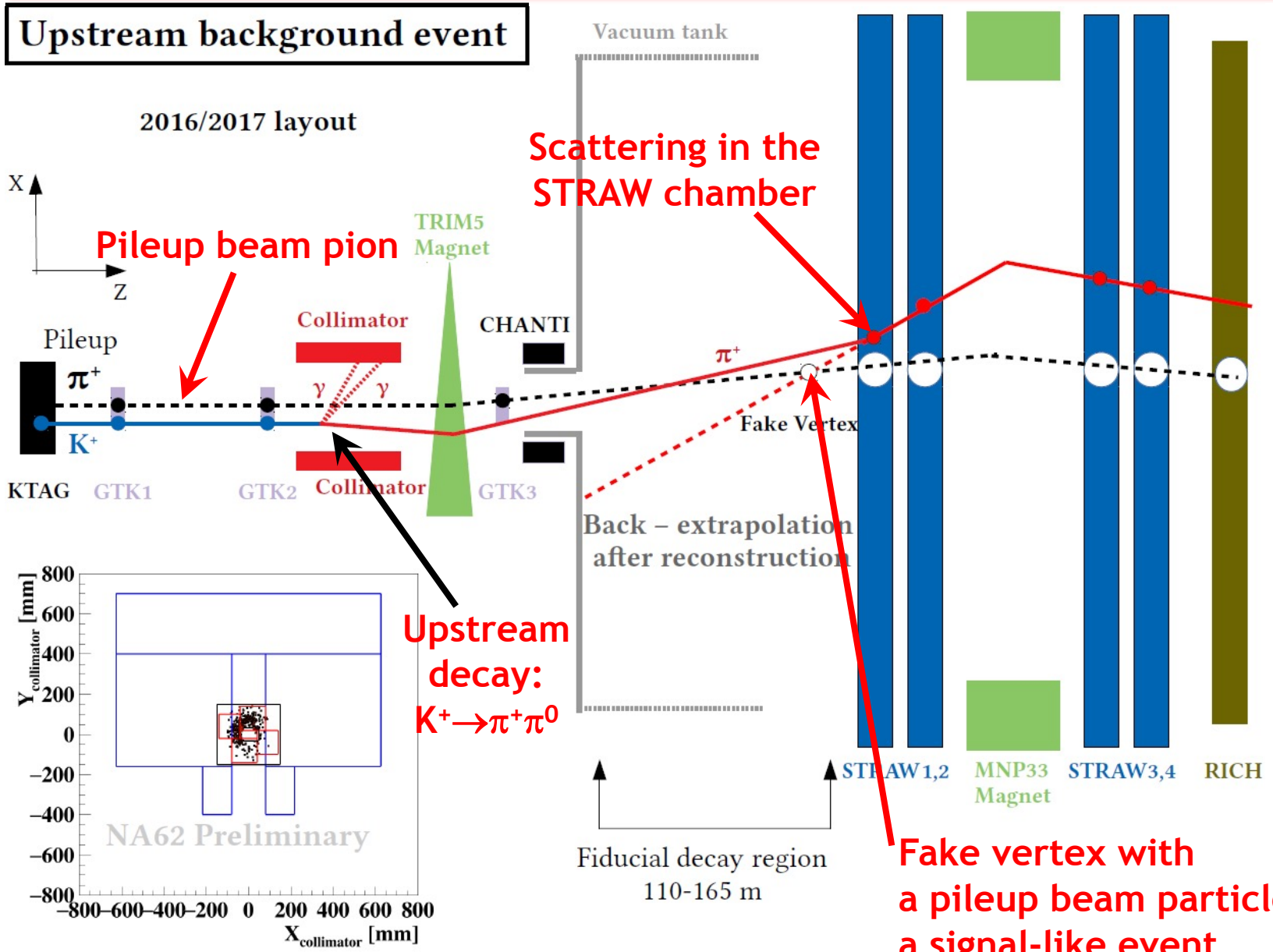
Data events in the $\pi^+\pi^0$ region after the $K_{\pi\nu\nu}$ selection (including π^0 rejection)

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

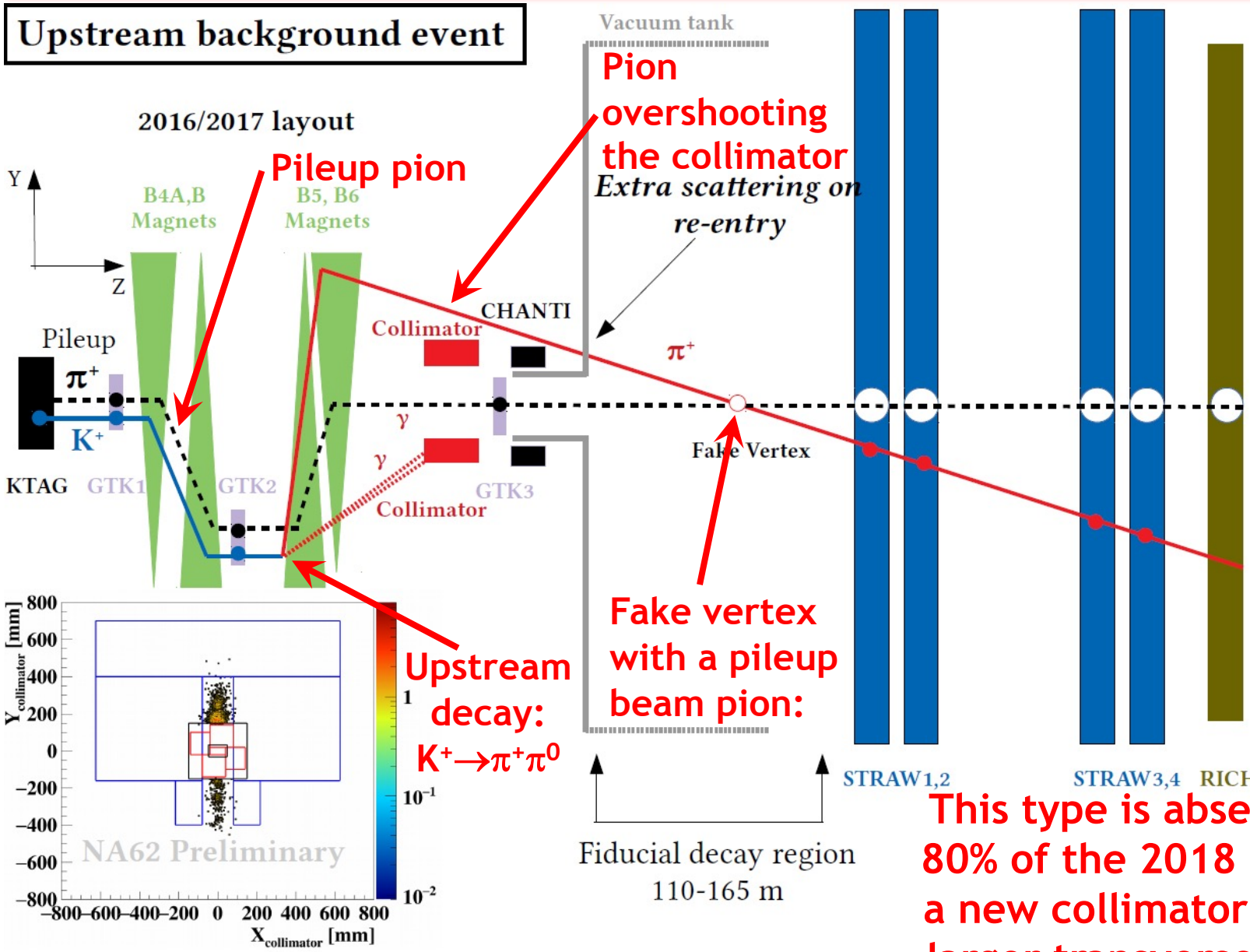
Expected numbers of $K^+\to\pi^+\pi^0$ events in signal regions after $K_{\pi\nu\nu}$ selection

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

Upstream background: type 1



Upstream background: type 2

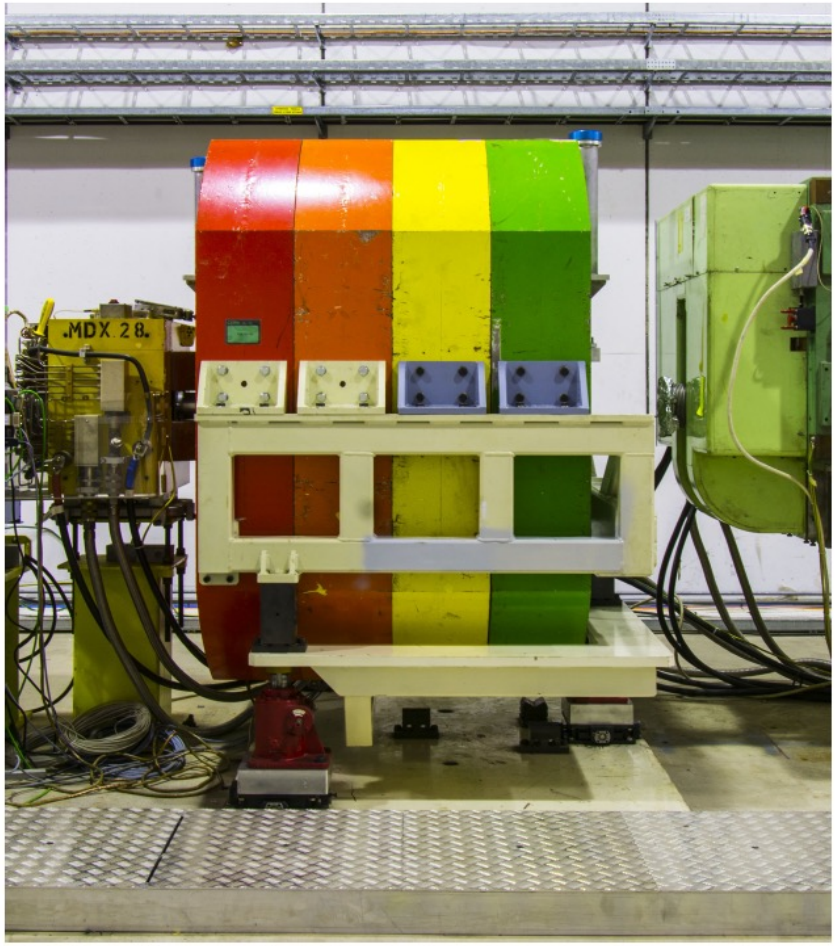


This type is absent in 80% of the 2018 data: a new collimator with larger transverse size

Final collimator replacement

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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
$BR_{SES}\times10^{10}$	**0.54±0.04**	**0.14±0.01**
$N^{exp}_{\pi\nu\bar{\nu}}$	**1.56±0.21**	**6.02±0.82**

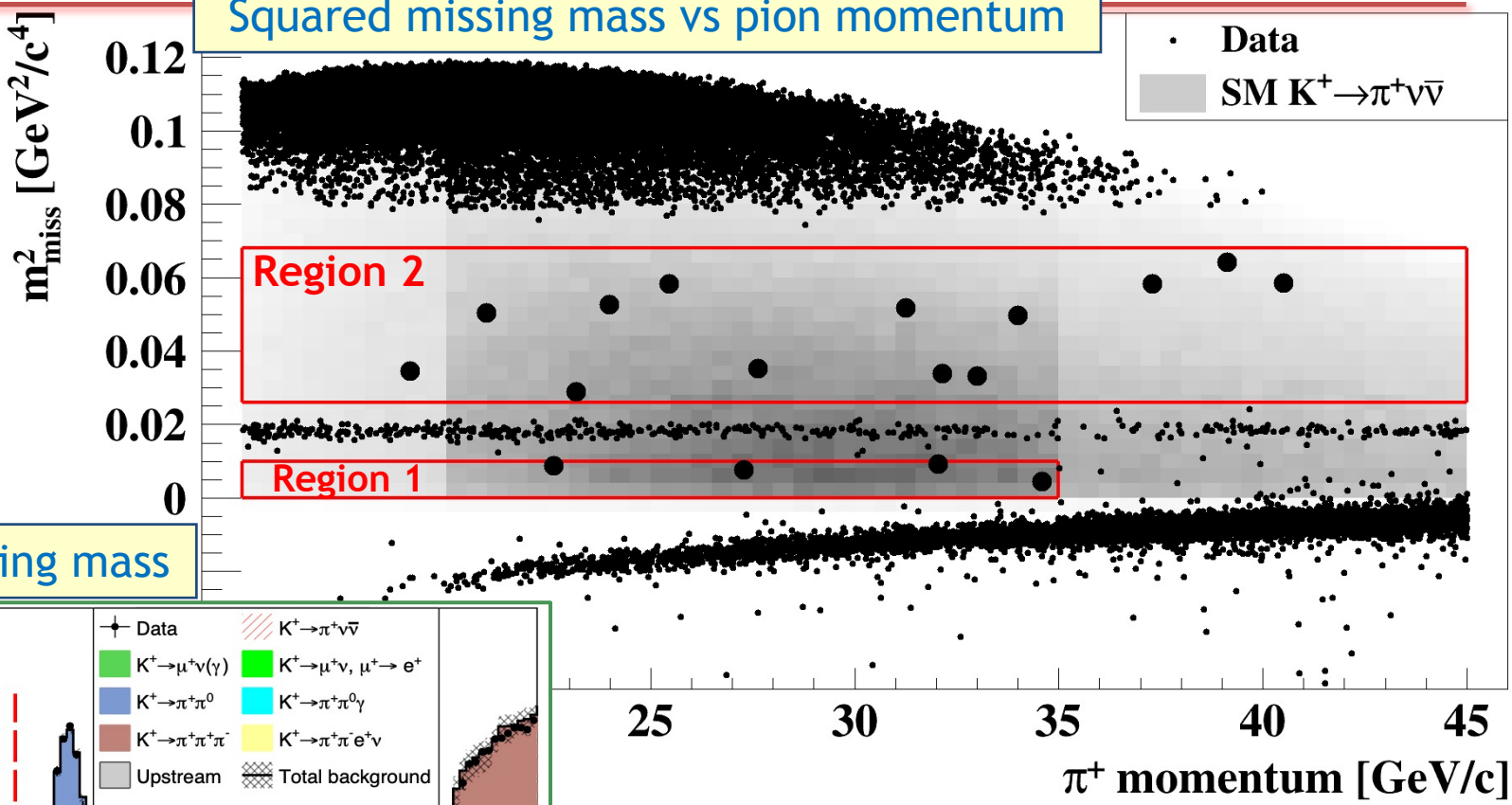
Data-driven background estimates

Dominant background: a data-driven estimate

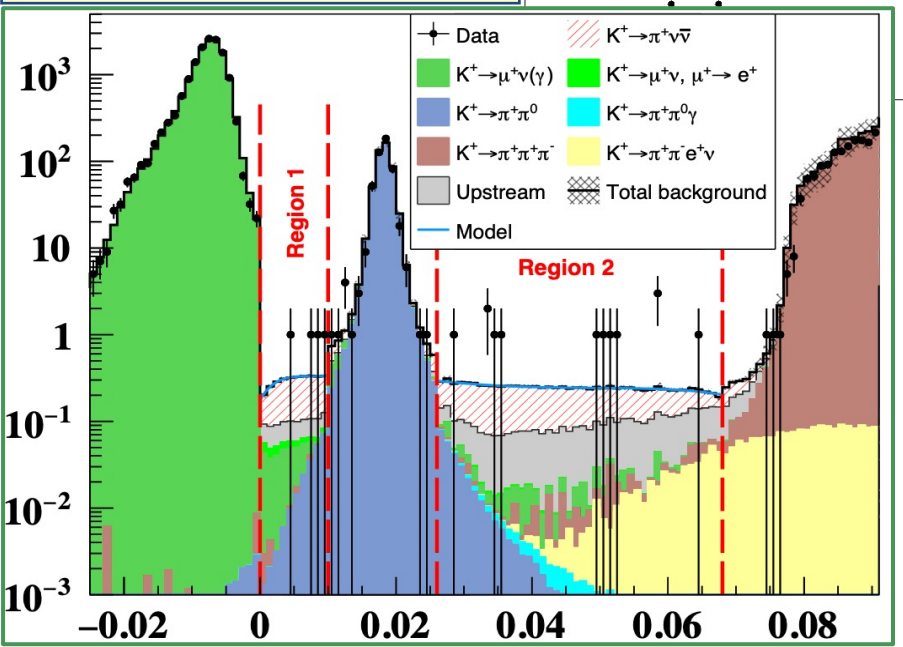
- Most background is **not due to K^+ decays in the vacuum tank**.
- **Improved the beamline layout** and **new upstream veto detectors** to bring Run 2 measurement into a low-background regime.

Opening the box (2018)

Squared missing mass vs pion momentum



Squared missing mass



Full Run 1 data set:

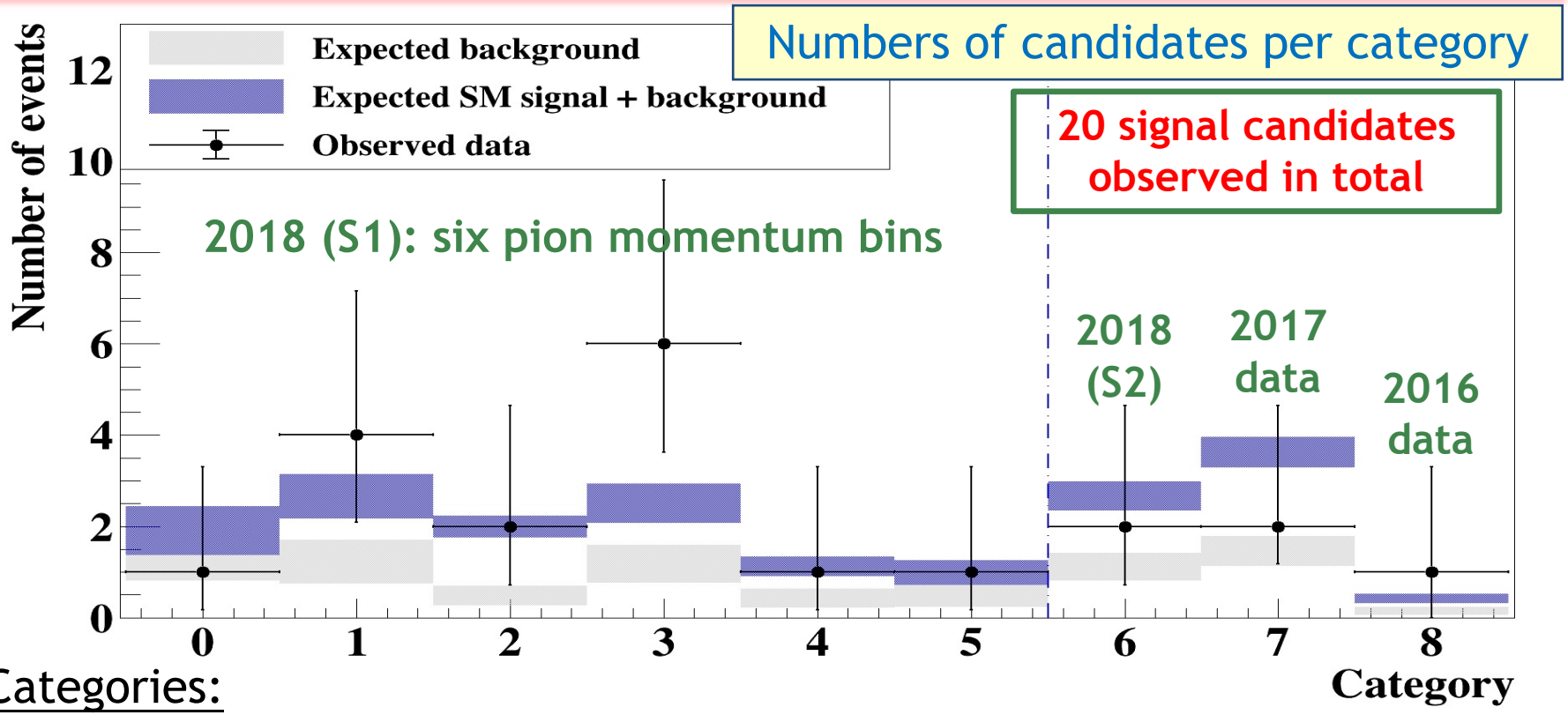
Candidates observed: **20** (**17** in 2018 data)

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

Expected SM events:

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

Result: Run 1 data set



Categories:

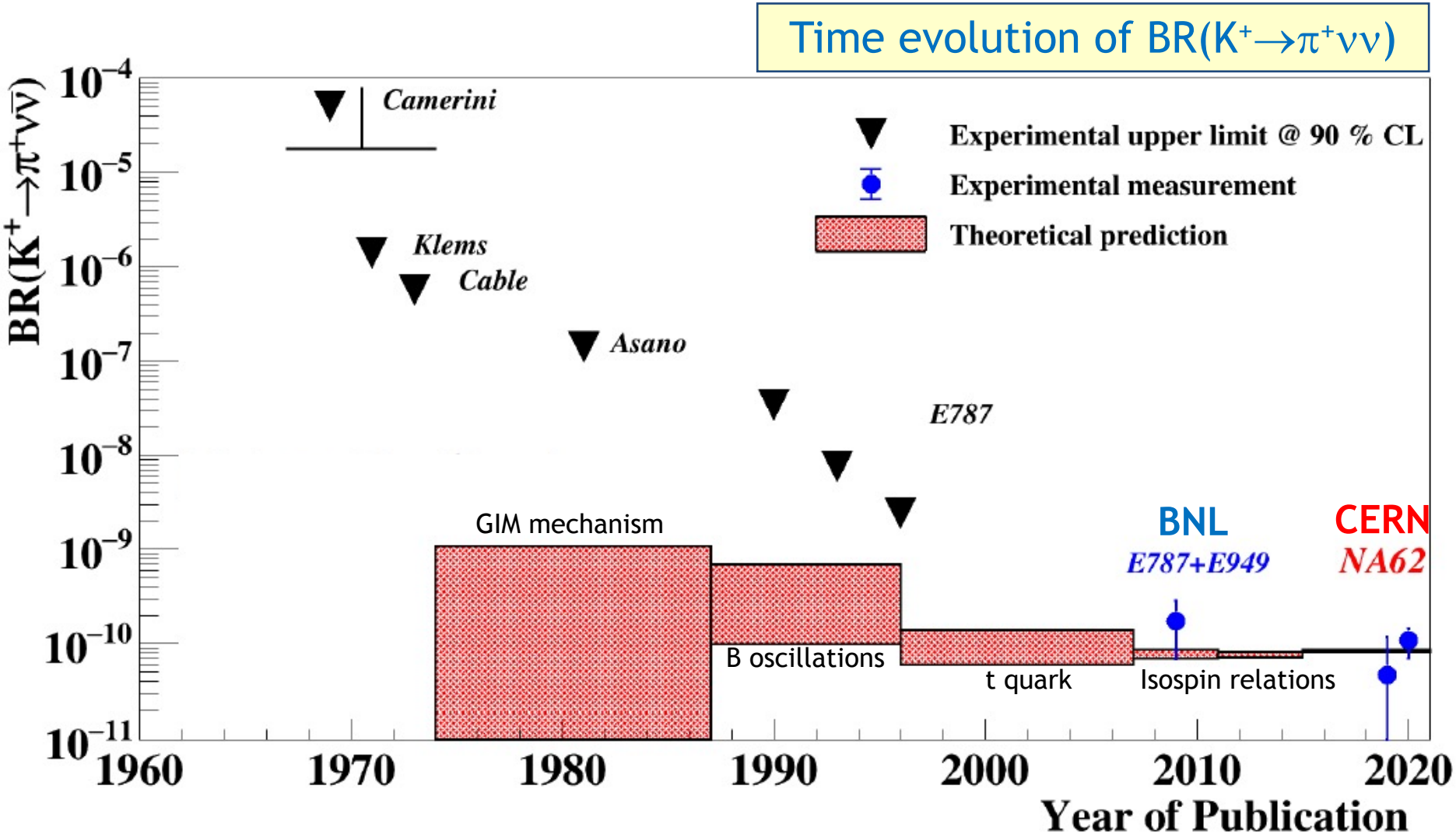
- Main 2018 data set (80%): six pion momentum bins (15–45 GeV/c).
- Early 2018 data sample (old collimator), 2017 and 2016 samples: three separate categories, integrated over pion momentum.

Final result (Run 1 sample):

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

(3.4σ significance)

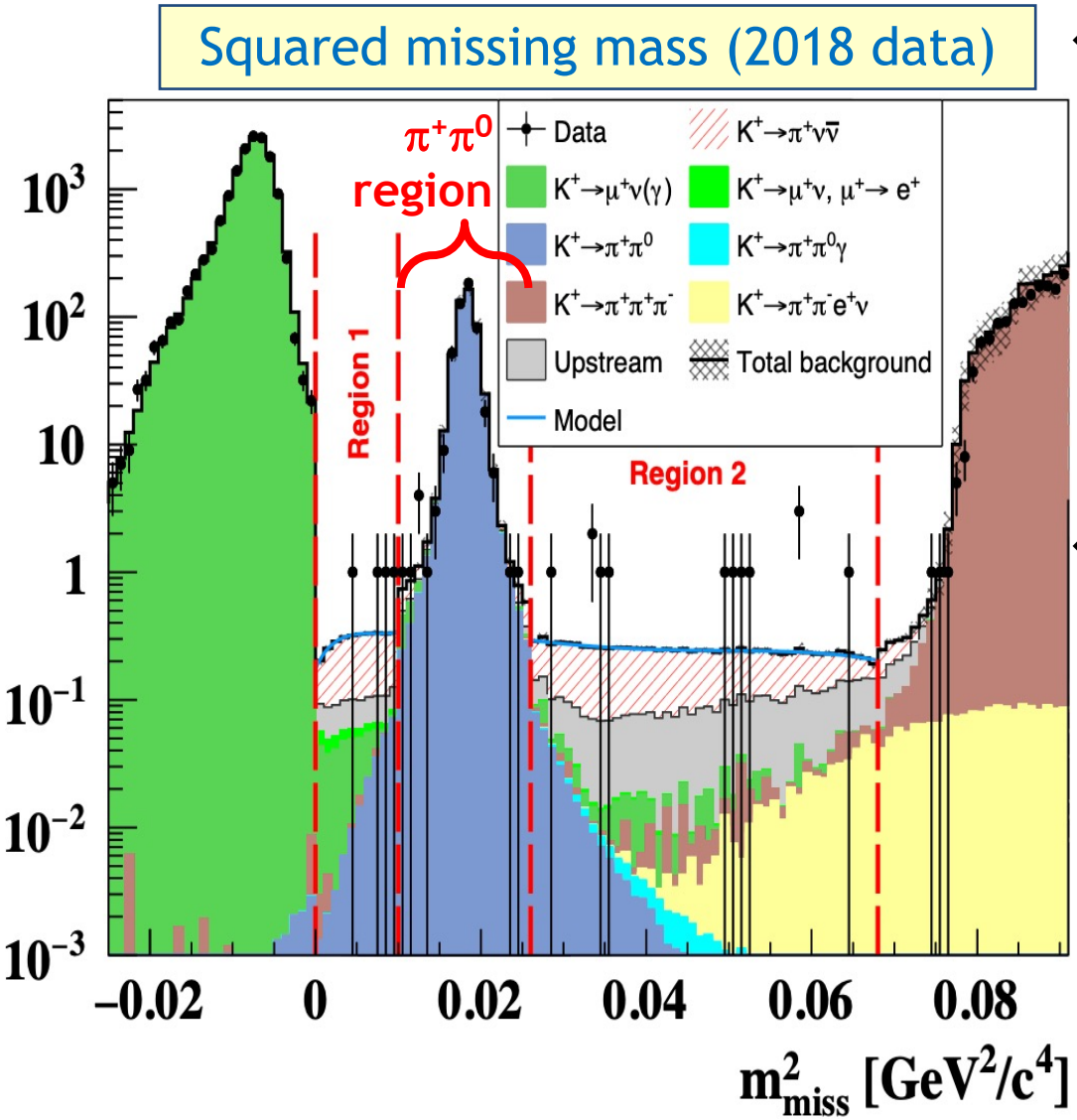
$K^+ \to \pi^+ \nu\nu$: historical perspective



Recent results from hidden-sector searches

- *$K^+ \to \pi^+ X$ (Run 1 data): JHEP 03 (2021) 58; arXiv:2103.15389.*
- *$\pi^0 \to$ invisible (2017 data): JHEP 02 (2021) 201.*
- *Searches for HNL production in $K^+ \to l^+ N$:*
  PLB 807 (2020) 135599; PLB 816 (2021) 136259.
- *Searches for LFV/LNV: PLB797 (2019) 134794; arXiv:2105.06759.*

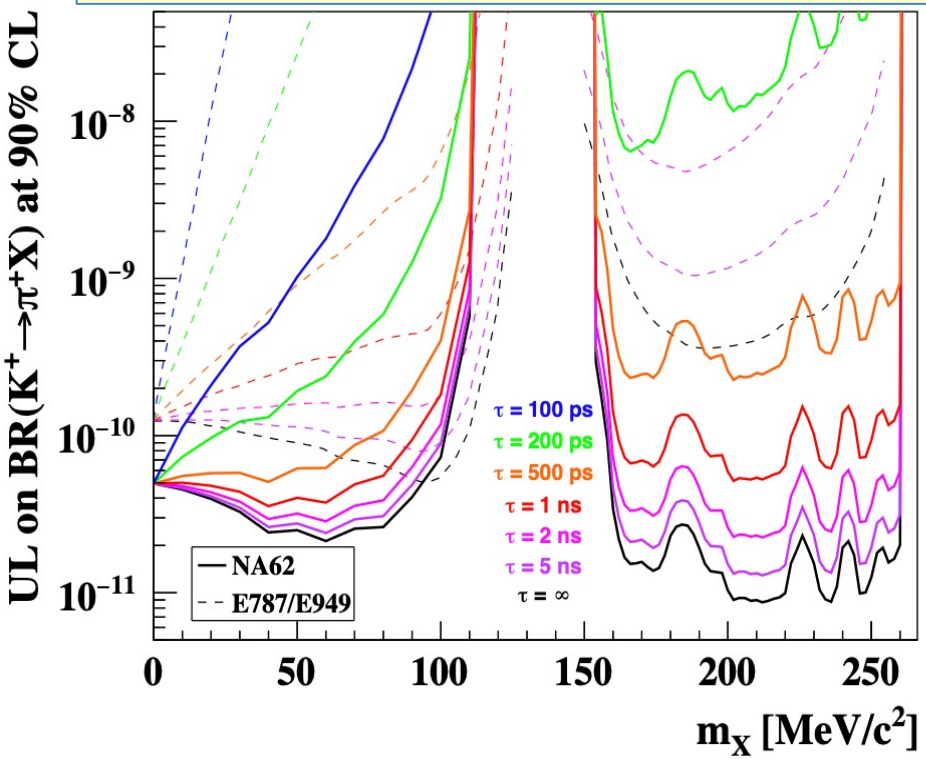
Hidden-sector with $K^+ \to \pi^+ \nu\nu$



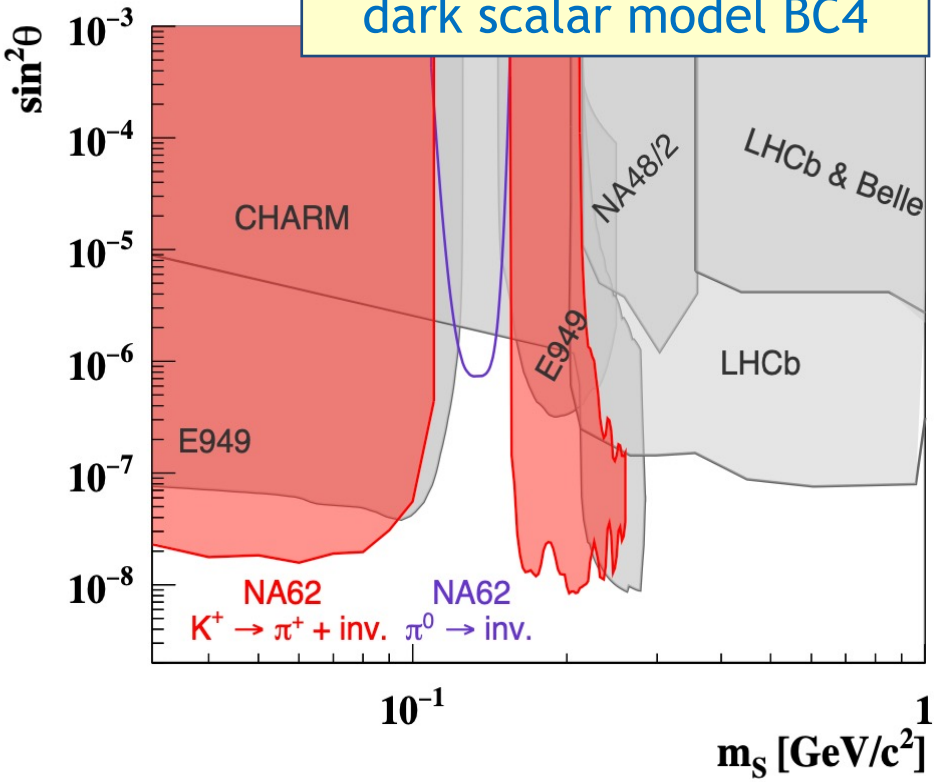
- Signal regions **R1**,**R2**: search for $K^+ \to \pi^+ X$ (X=invisible), $0 \le m_X \le 110$ MeV/c^2 and $154 \le m_X \le 260$ MeV/c^2.
  - ✓ Interpretation: dark scalar, ALP, QCD axion, axiflavon.
  - ✓ Main background: $K^+ \to \pi^+ \nu\nu$.
- The $\pi^+\pi^0$ region: search for $\pi^0 \to$ invisible.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



Interpretation in the PBC dark scalar model BC4



- Mass resolution improved with m_X, and is $\delta m_X \sim 40$ MeV/c² 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 PBC model BC4: dark scalar decaying to visible SM particles only. *[J Phys G47 (2020) 010501]*

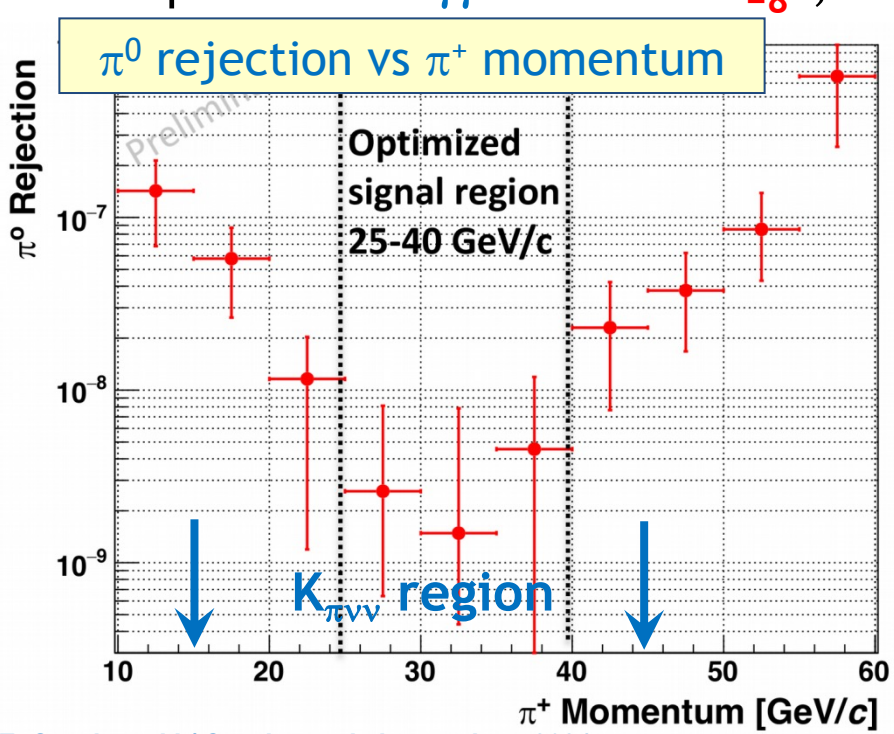
Search for $\pi^0 \to$ invisible (2017 data)

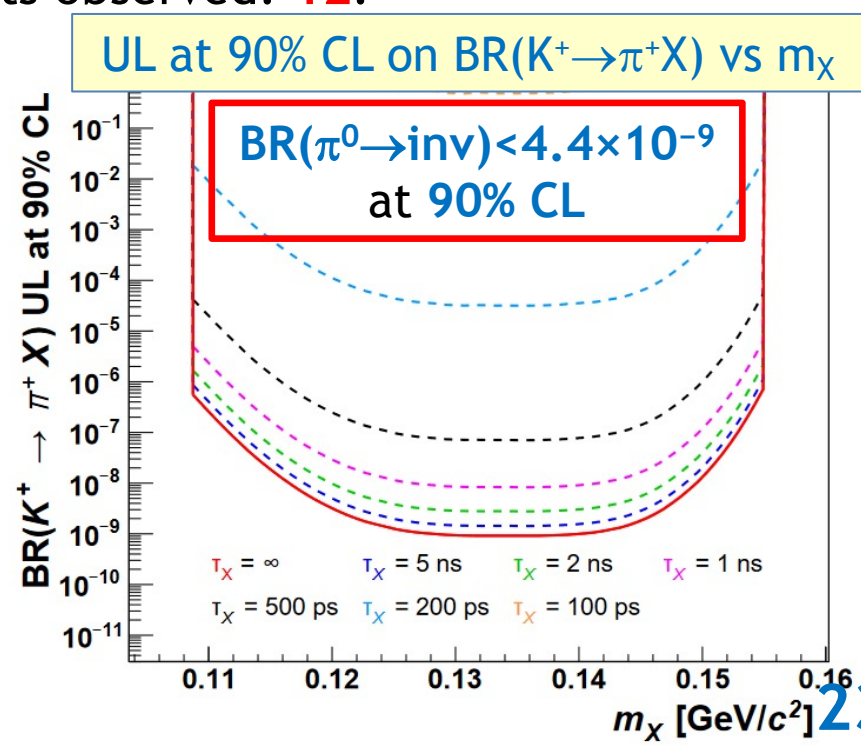
JHEP 02 (2021) 201

- 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.

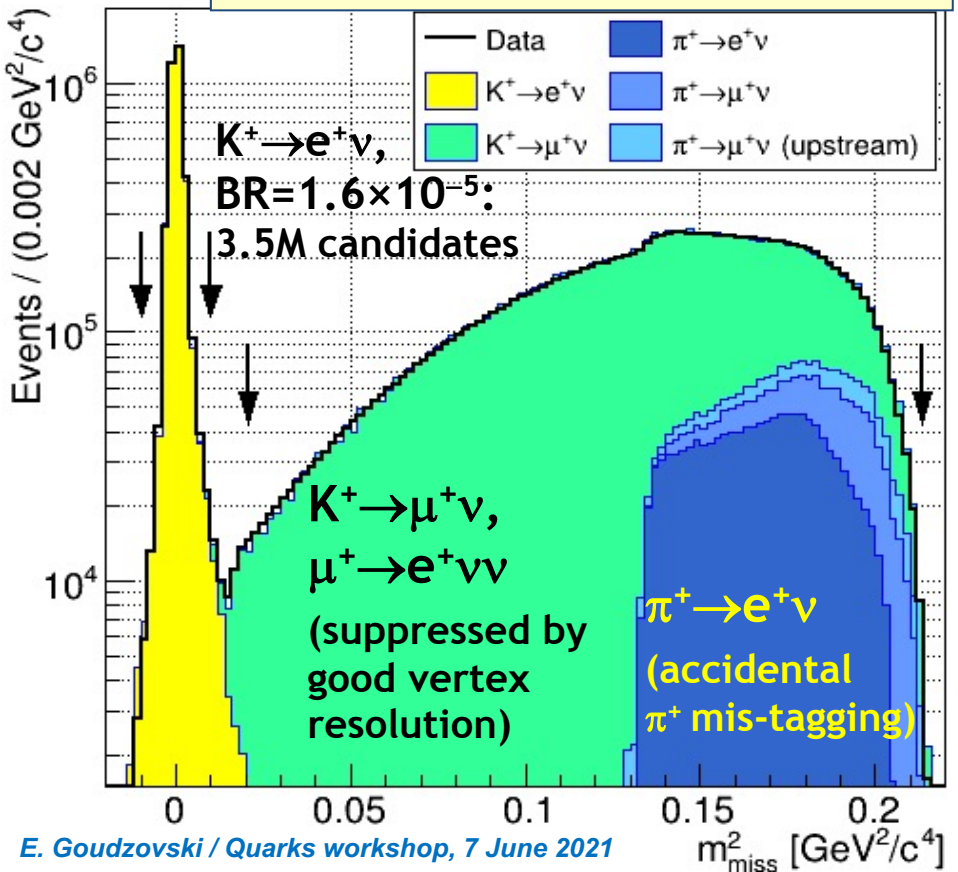




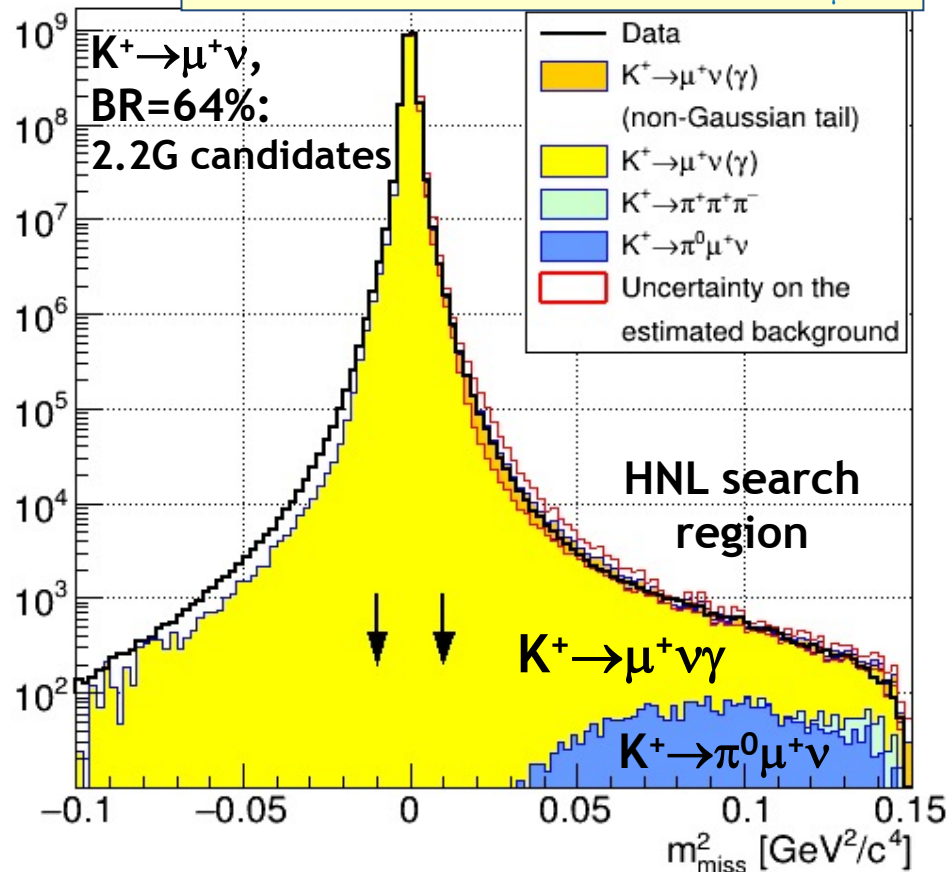
HNL production search: data sample

- 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: $(P_K-P_e)^2$

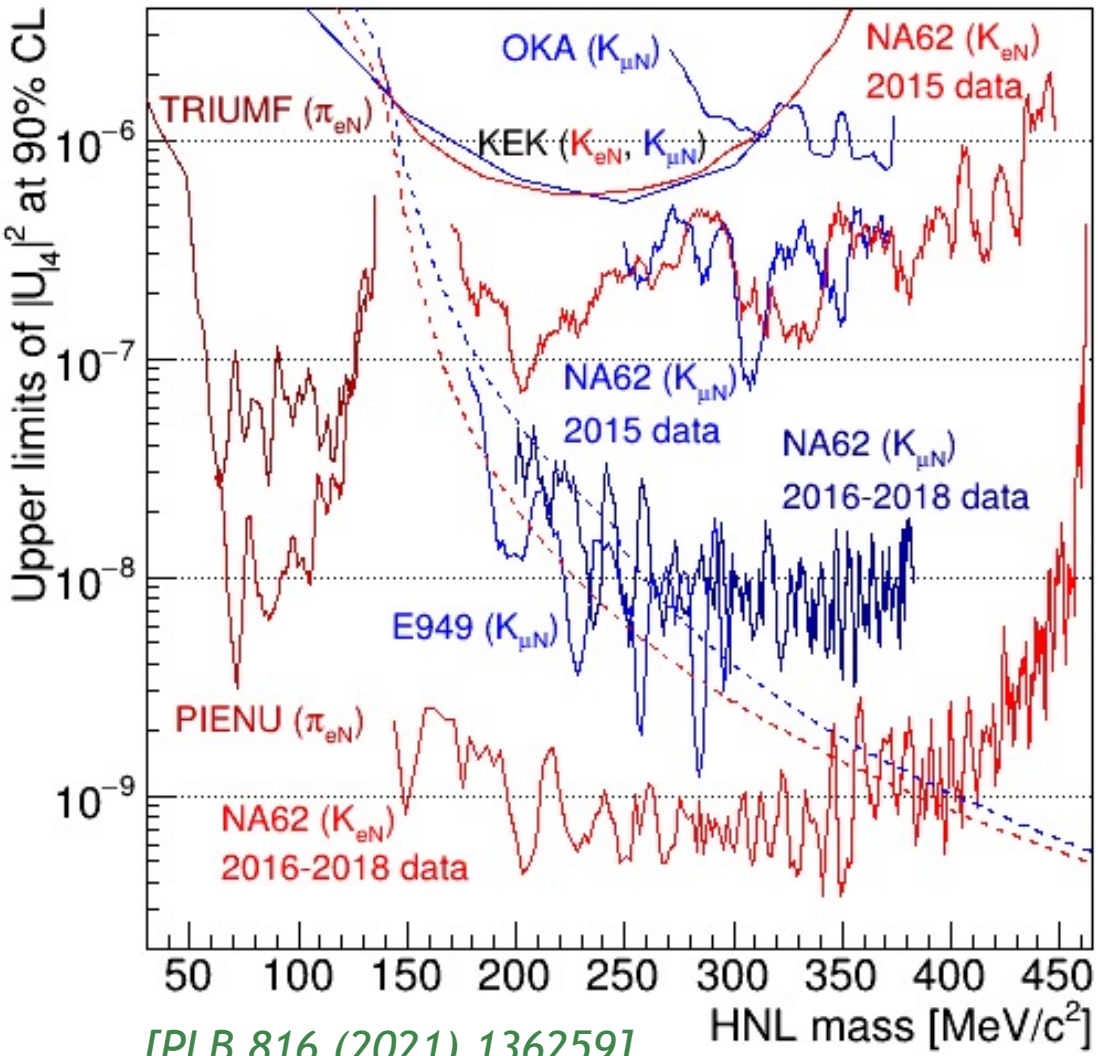


Squared missing mass: $(P_K-P_\mu)^2$



HNL production search: results

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



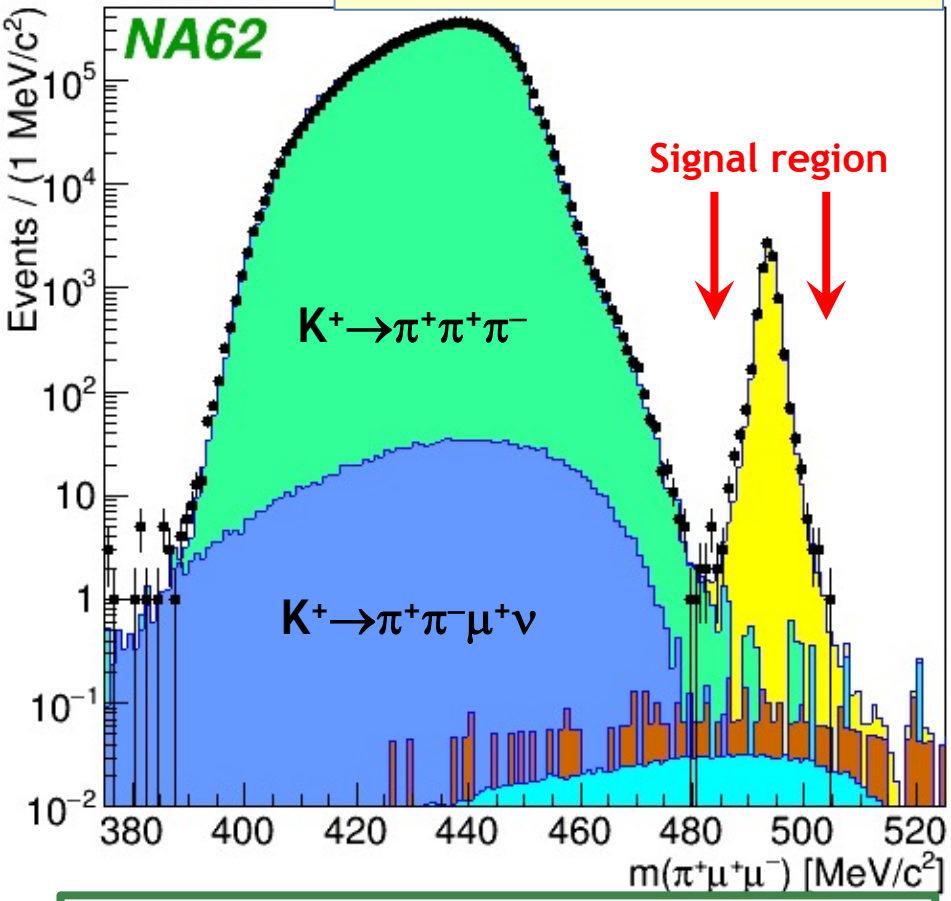
[PLB 816 (2021) 136259]

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

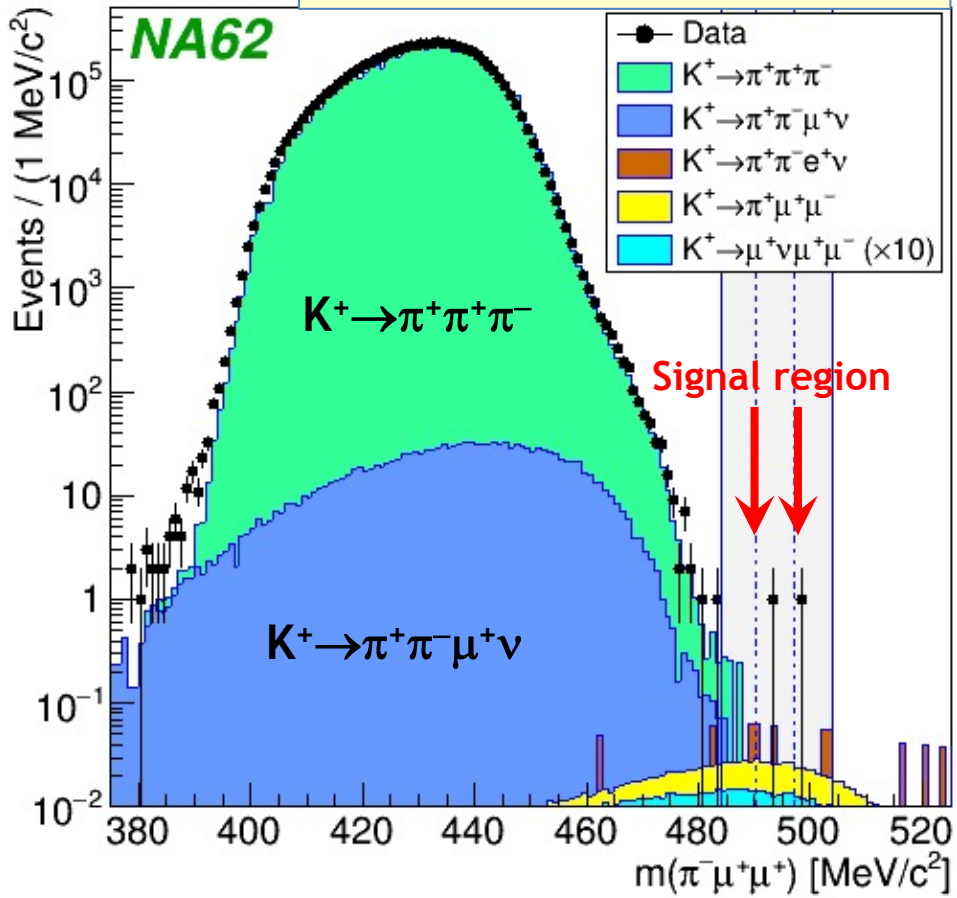
- Full Run 1 dataset analysed.
- Improvement over earlier production searches by up to two orders of magnitude in terms of $|U_{\ell 4}|^2$.
- For $|U_{e4}|^2$, the BBN-allowed range excluded up to **350 MeV**. *[NPB 590 (2000) 562]*
- For $|U_{\mu 4}|^2$, reached BNL-E949 sensitivity, and extended the HNL mass range to **384 MeV**.
- New upper limit at **90%** CL: **$BR(K^+ \to \mu^+ \nu\nu\nu) < 1.0 \times 10^{-6}$**. Similar limits on **$BR(K^+ \to \mu^+ \nu X)$**, with **X=invisible**. *[PRL 124 (2020) 041802]*

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

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



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

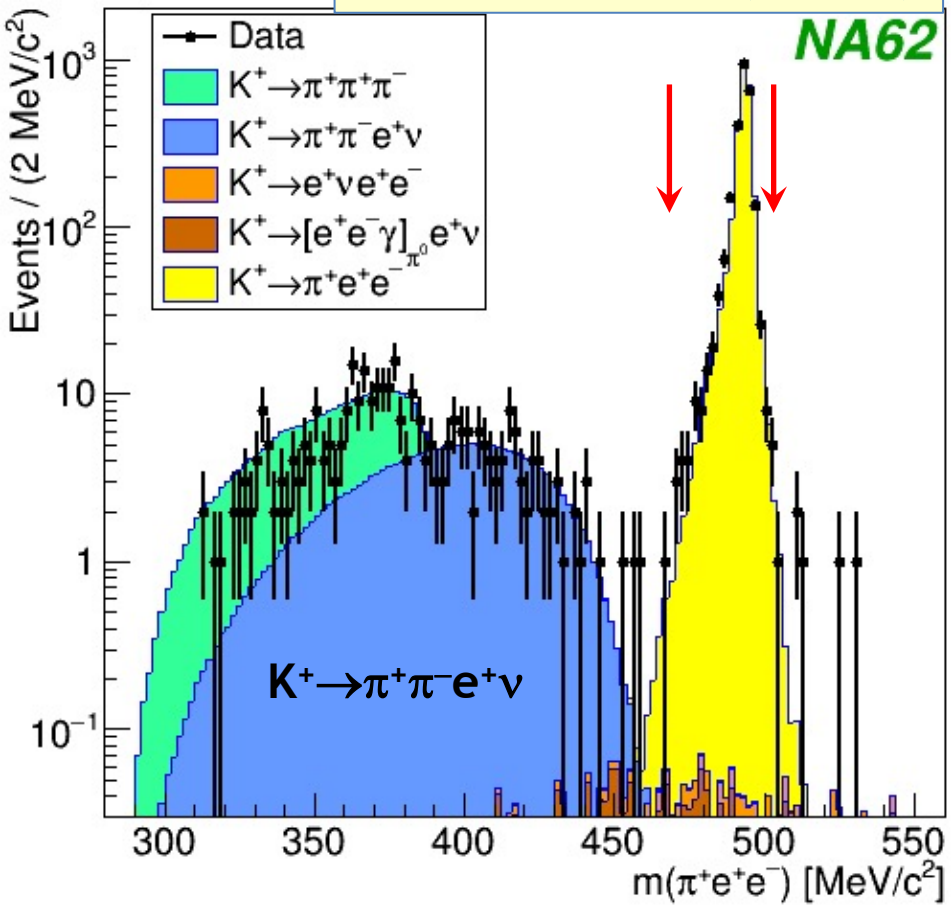


Candidates observed: **8357**
Background: **0.07%**
$BR(K^+ \to \pi^+\mu^+\mu^-) = (0.962 \pm 0.025) \times 10^{-7}$
K^+ decays in FV: **$(7.94 \pm 0.23) \times 10^{11}$**

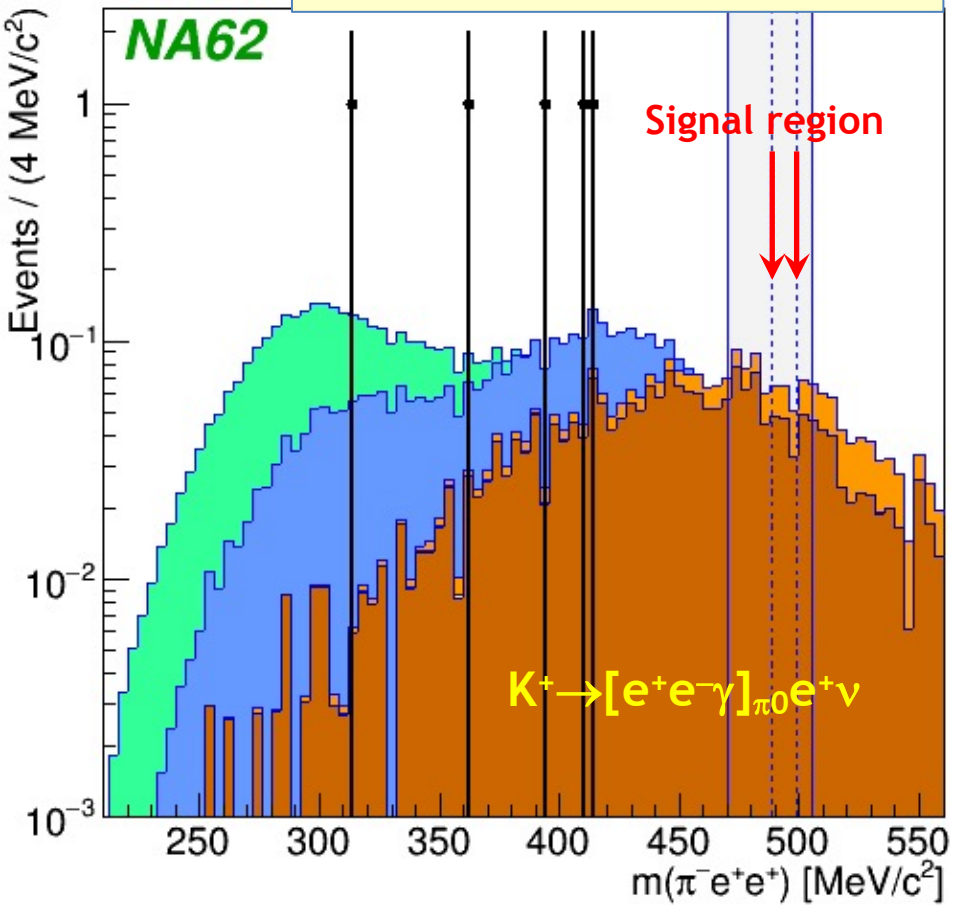
Expected background: **0.91 ± 0.41** evt
Candidates observed: **1**
$BR(K^+ \to \pi^-\mu^+\mu^+) < 4.2 \times 10^{-11}$ at 90% CL
[PLB797 (2019) 134794]

Search for $K^+ \to \pi^- e^+ e^+$ decay (2017)

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



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

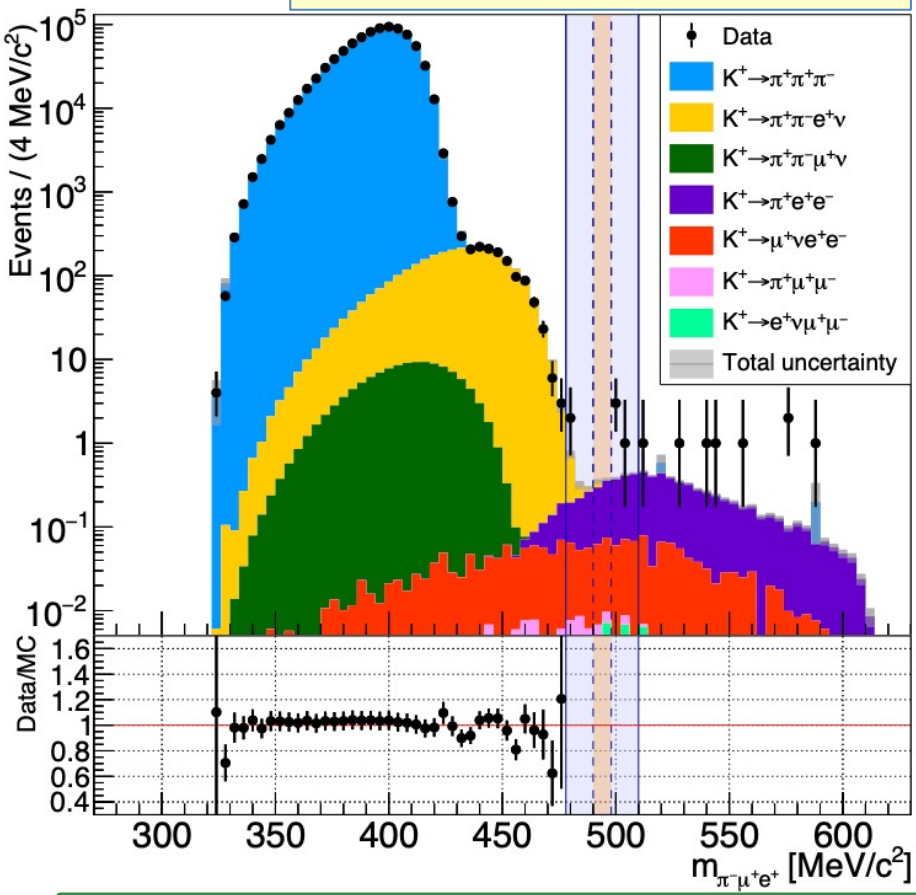


Candidates observed: **2484**
$BR(K^+ \to \pi^+ e^+ e^-) = (3.00 \pm 0.09) \times 10^{-7}$
K^+ decays in FV: **$(2.14 \pm 0.07) \times 10^{11}$**

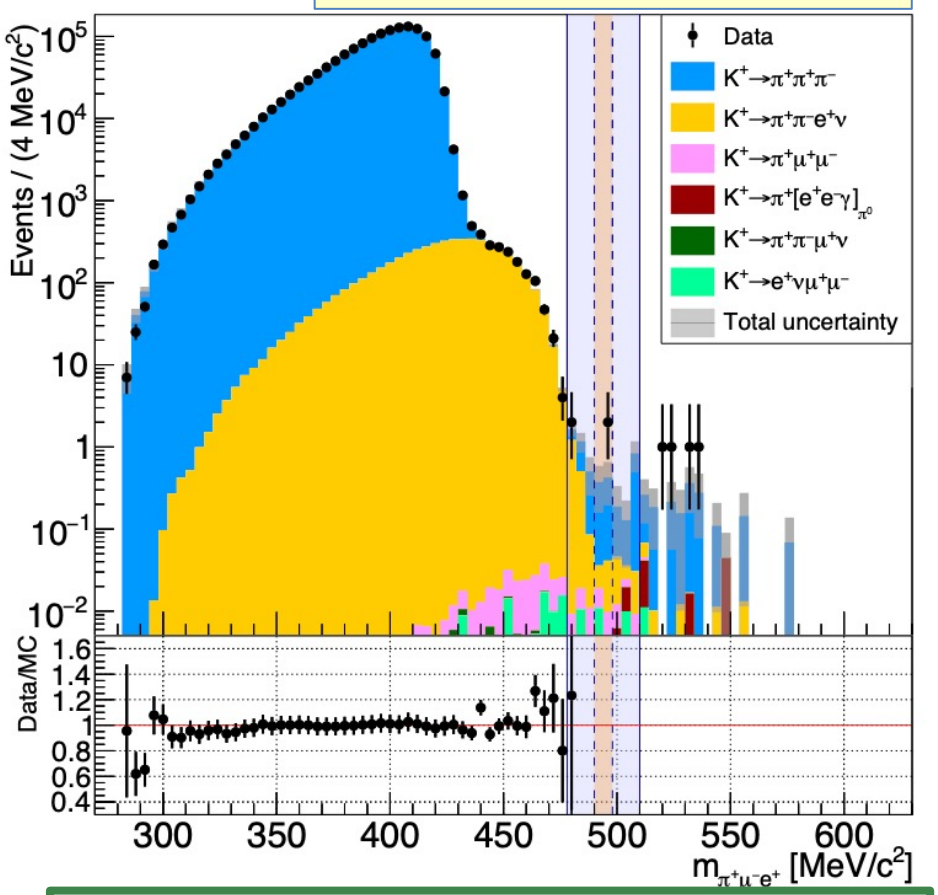
Expected background: **0.16±0.03** evt
Candidates observed: **0**
$BR(K^+ \to \pi^- \mu^+ \mu^+) < 2.2 \times 10^{-10}$ at 90% CL
[PLB797 (2019) 134794]

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

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



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



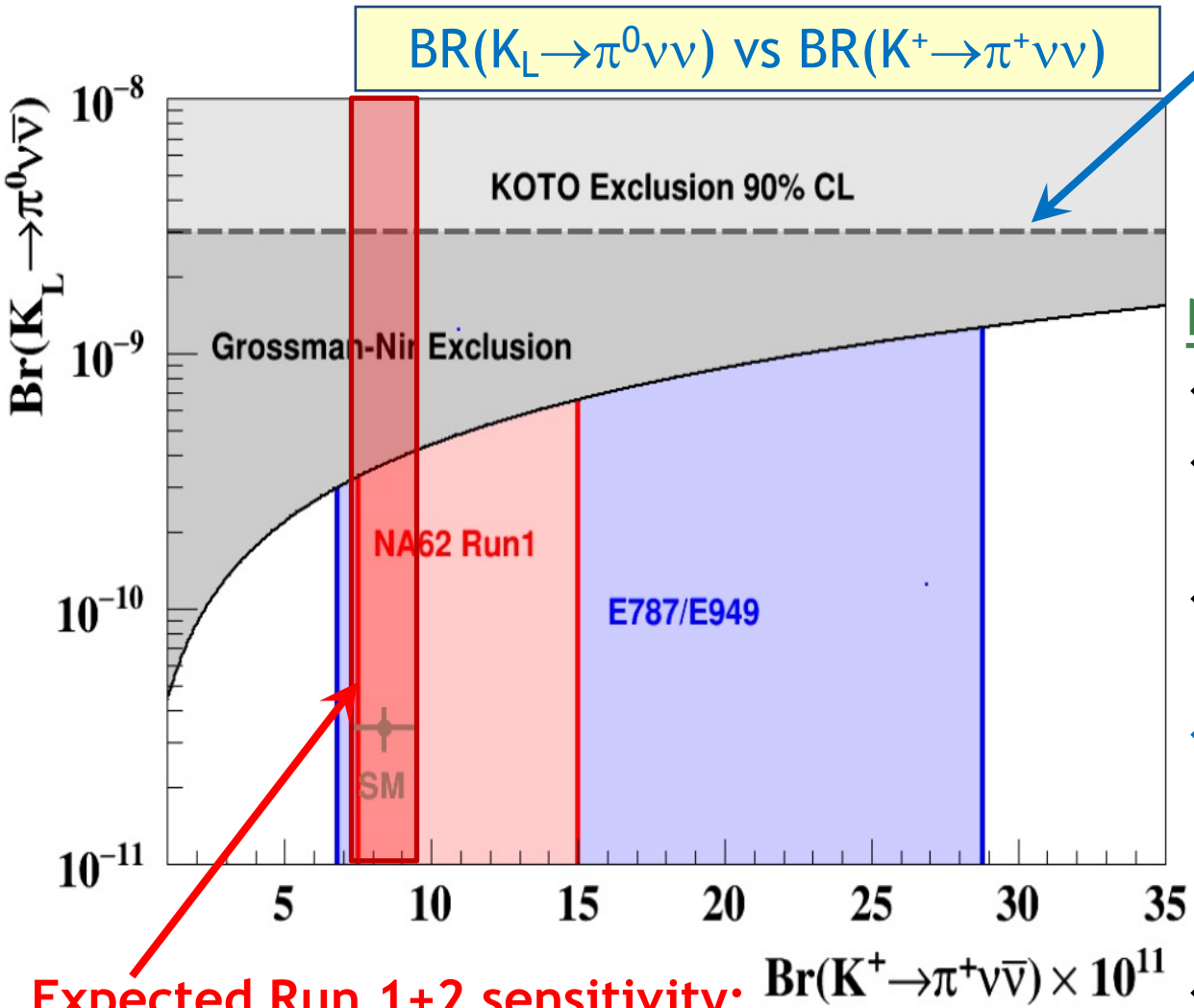
K^+ decays in FV: $(1.33\pm0.02)\times10^{12}$
Expected background: 1.07 ± 0.20 evt
Candidates observed: 0
$BR(K^+\to\pi^-\mu^+e^+)<4.2\times10^{-11}$ at 90% CL

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

[arXiv:2105.06759]

Future plans

Short-term plans: NA62 Run 2



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

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

NA62 Run 2 (2021–24):

- 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 (in ~2028): 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.

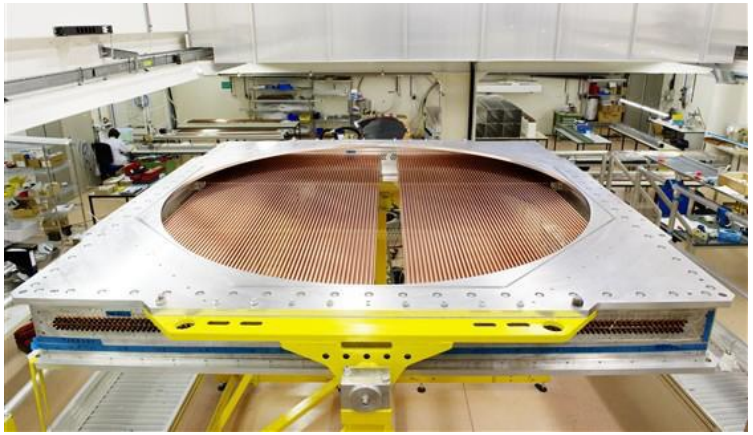
New pixel beam tracker (GTK):

time resolution: <50 ps per plane;
pixel size: <300×300 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:

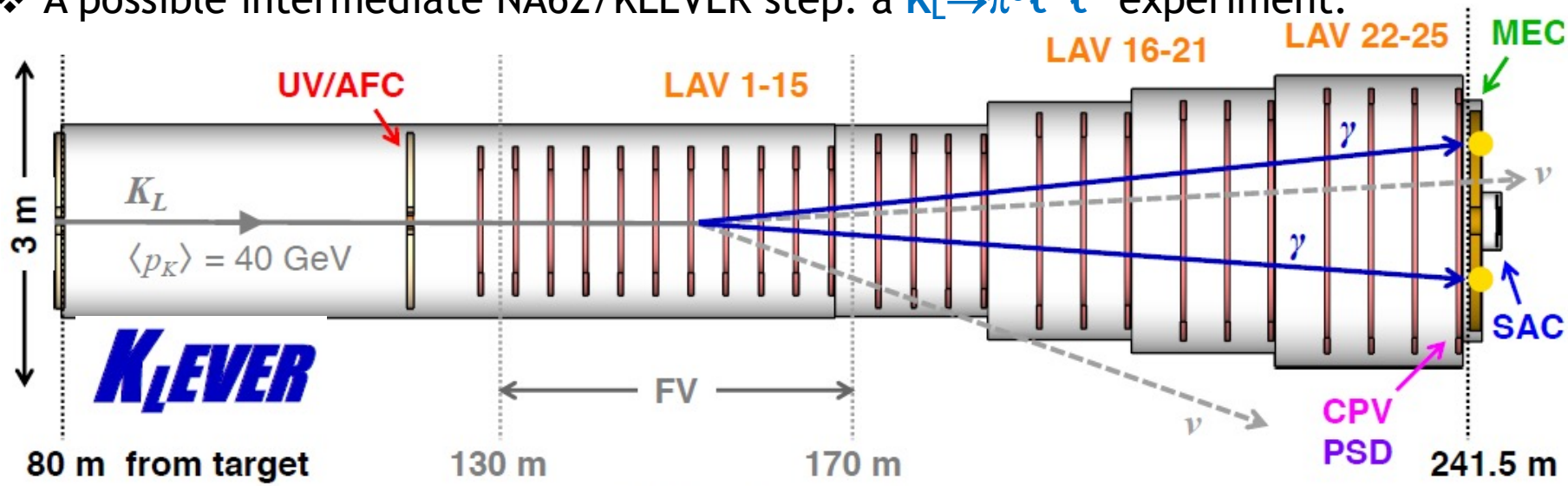
operation in vacuum;
straw length/diameter: 2.2 m/5 mm;
trailing time resolution: ~6 ns per straw;
maximum drift time: ~80 ns;
layout: ~21000 straws (4 chambers);
material budget: 1.5%X_0.



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;

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

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,

$$\mathrm{BR}(K^+\to\pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}})\times10^{-11}$$

[arXiv:2103.15389]

- Searches on hidden-sector mediator production and other BSM physics in kaon decays:
  - ✓ extension of the $K^+\to\pi^+\nu\nu$ analysis: searches for $K^+\to\pi^+X$ and $\pi^0\to$inv;
  - ✓ dedicated searches for $K^+\to\ell^+N$ and $K^+\to\mu^+\nu X$ decays;
  - ✓ dedicated searches for LNV/LFV kaon decays;
  - ✓ other analyses are in progress.
- Future of kaon experiments at CERN:
  - ✓ aiming to O(10%) precision on BR($K^+\to\pi^+\nu\nu$) by 2024;
  - ✓ planning to collect 10^{18} POT in dump mode by 2024;
  - ✓ 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.

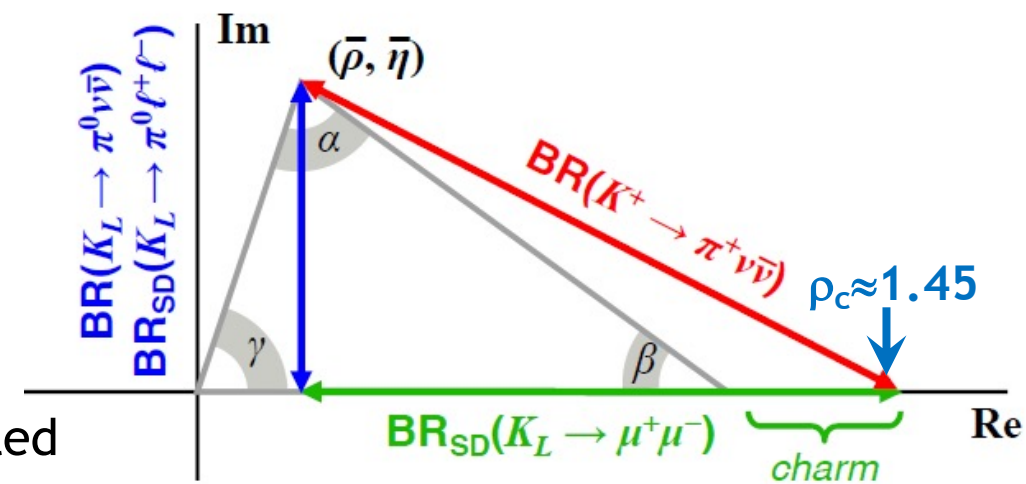
Spares

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 $K \to \pi\nu\nu$: uniquely clean theoretically.
- Decays to charged leptons: affected by larger hadronic uncertainties.

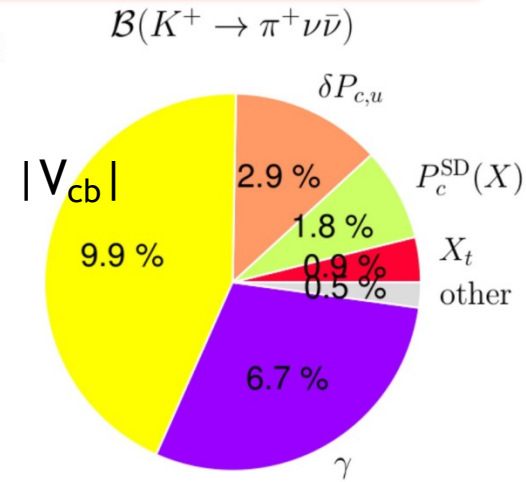


K→πνν and the unitarity triangle

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

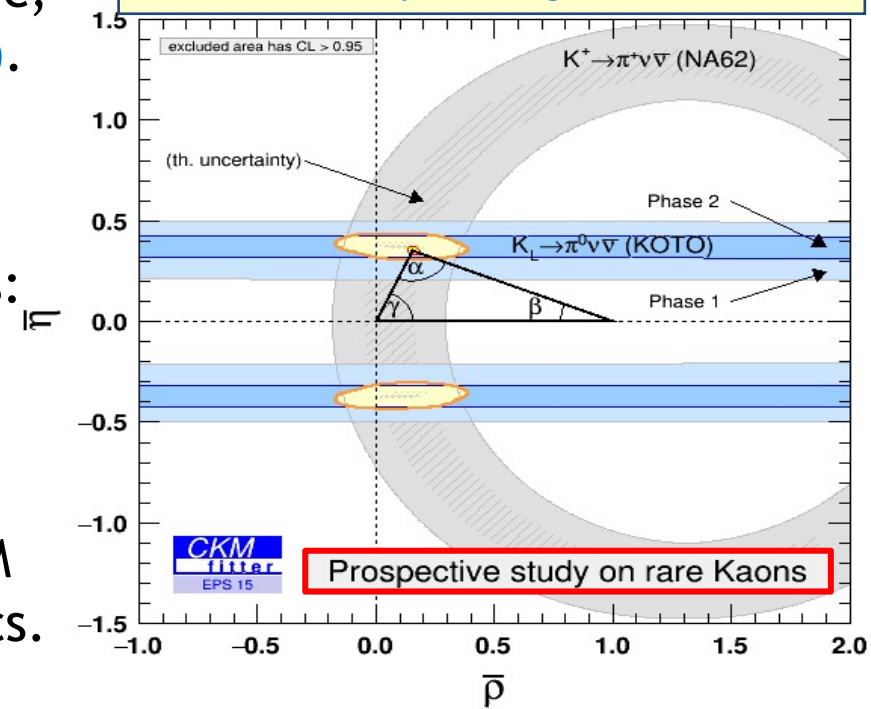
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^{2} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2} \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^{2}$$

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)

$N_{\pi\pi}$: $K^+ \to \pi^+\pi^0$ 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.