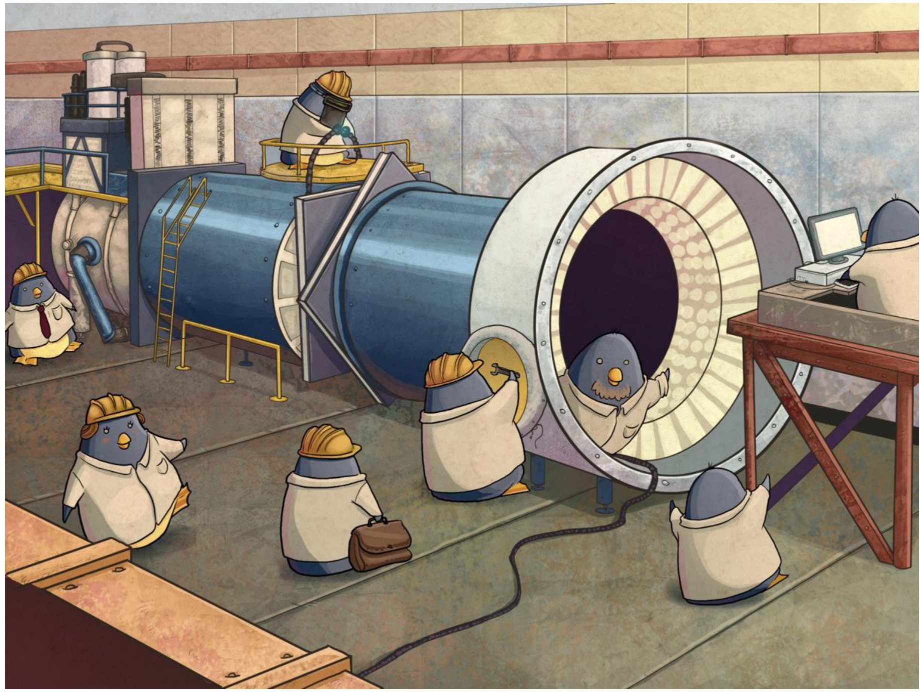
Physics Beyond SM With Kaons at NA62

Jacopo Pinzino



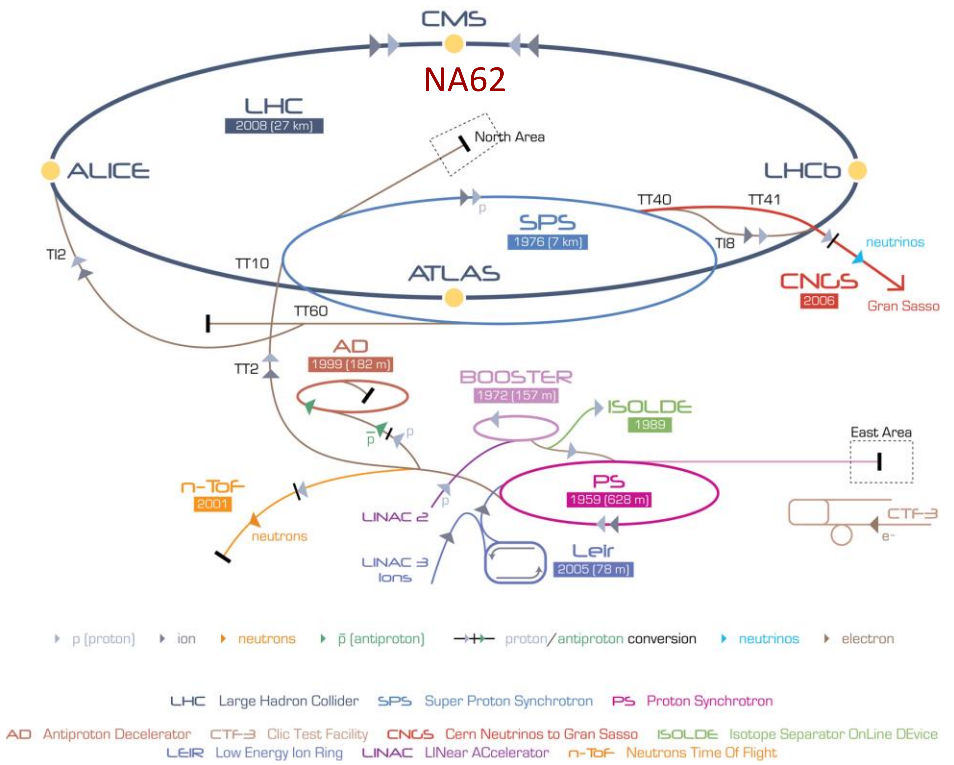
Fellini
Fellowship for Innovation at INFN

H2020 MSCA COFUND
G.A. 754496

INFN Seminars
24/02/21

The NA62 Experiment

- NA62: High precision fixed-target Kaon experiment at CERN SPS
- Main goal: measurement of BR($K^+ \rightarrow \pi^+ \upsilon \bar{\upsilon}$)
- Broader physics program: LFV / LNV in K^+ decays, hidden sector particles searches.

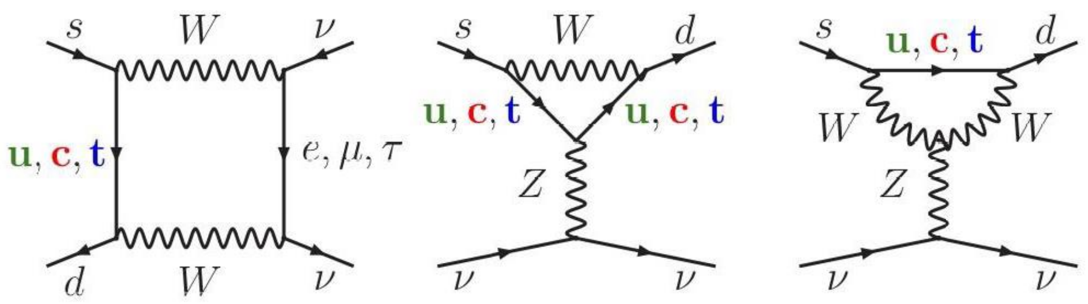


NA62 Timeline

- 2008: NA62 Approval
- 2014: NA62 Pilot Run (partial layout)
- 2015: Commissioning run
- Full detector installation completed in September 2016
- 2016 : First $\pi\nu\nu$ dataset in 2016
- Continuous data-taking until the end of 2018
- data-taking will be resumed in 2021 with improvements

~ 200 participants from: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Torino, TRIUMF, Vancouver UBC

The $K \to \pi\nu\bar{\nu}$ decay



- High sensitivity to New Physics
- FCNC process forbidden at tree level
- Highly CKM suppressed (BR ~ $|V_{ts} x V_{td}|^2$)

- Very clean theoretically: Short distance contribution
- hadronic matrix element extracted from precisely measured BR($K^+ \to \pi^0 e^+ \nu$)
- Precise SM predictions: [Buras et al. JHEP 1511 (2015) 33]

  $BR(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$

  $BR(K_L \to \pi^0\nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$

$BR(B^+ \to \tau^+\nu) = (0.77^{+0.98}_{-0.52}) \times 10^{-4}$

$BR(B \to K\mu^+\mu^-) = (0.99^{+0.40+0.13}_{-0.32-014}) \times 10^{-6}$

$BR(B^- \to \rho^- \eta') = (6.26 \pm 1.70 \pm 0.34) \times 10^{-6}$

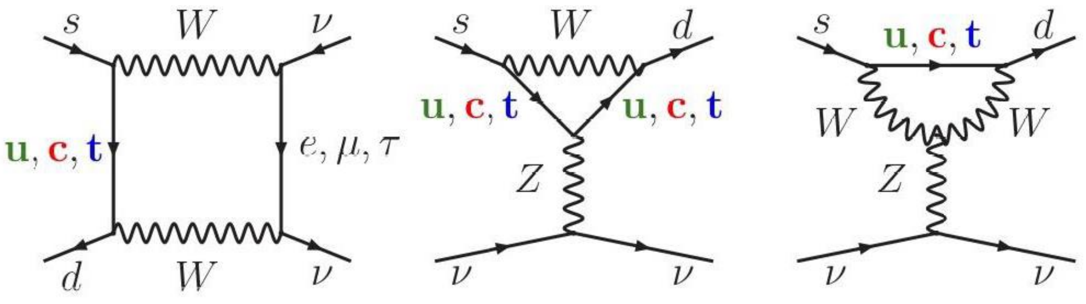
$BR(B_d \to \phi\eta) = (1.18 \pm 0.84 \pm 0.03) \times 10^{-9}$

- Previous Experimental Result:

  $BR(K^+ \to \pi^+\nu\bar{\nu})$(E787/E949) = $(17.3^{+11.5}_{-10.5}) \times 10^{-11}$ [Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)]

  $BR(K_L \to \pi^0\nu\bar{\nu})$(E391a) $< 2.6 \times 10^{-8}$ (90% C.L) [Phys. Rev. D 81, 072004 (2010)]

FCNC



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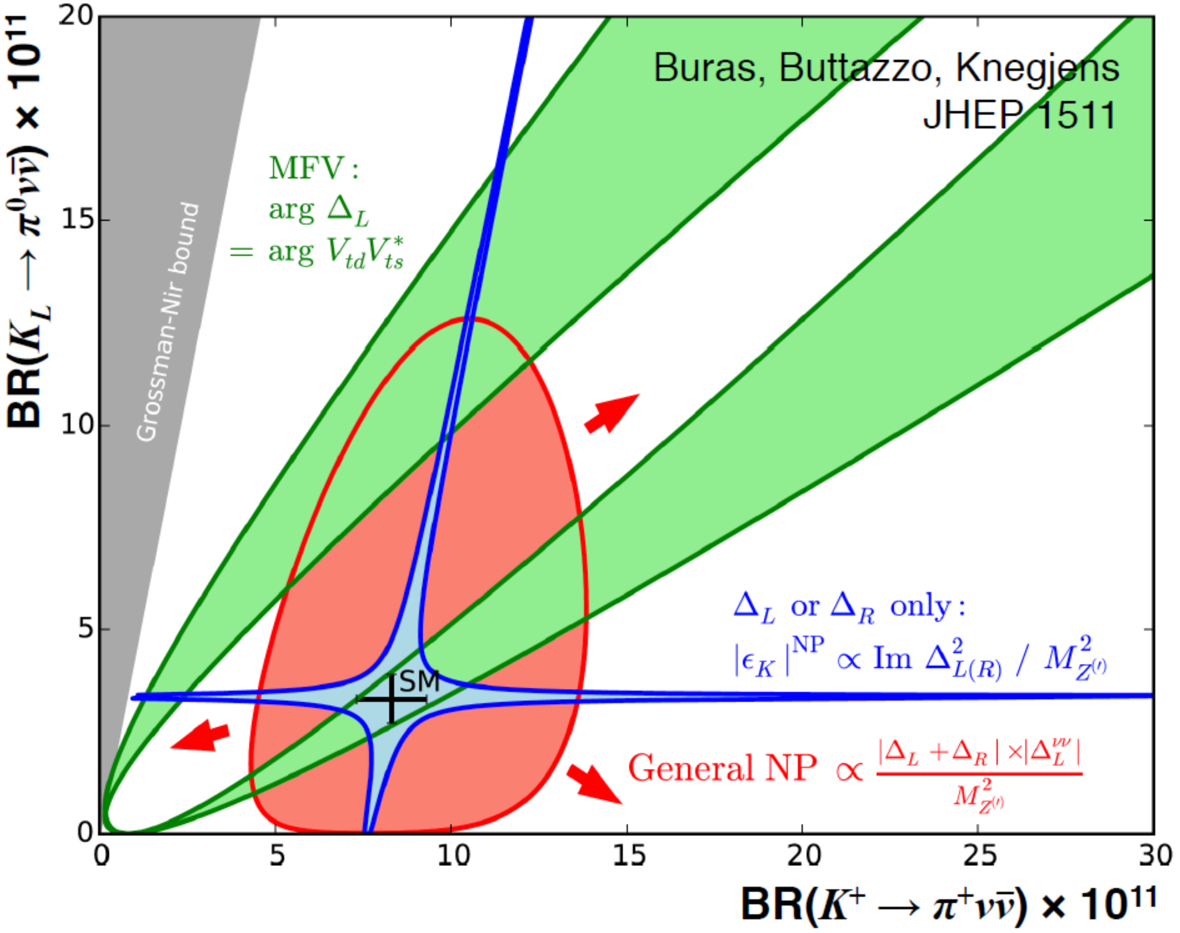
$$H_{eff}^{SM} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_W} \sum_{l=e,\mu,\tau} (V_{cs}^* V_{cd} X^l + V_{ts}^* V_{td} X(x_t))(\bar{s}d)_{V-A}(\bar{\nu}_l \nu_l)_{V-A}$$

- G_F is the Fermi constant,
- α is the electromagnetic coupling constant,
- ϑ_W is the weak mixing angle,
- X^l are functions describing the contribution of the c-quark to the amplitude A_l (with $l = e, \mu, \tau$),
- $X(x_t)$ is function describing the contribution of the t-quark,
- $(\bar{s}d)_{V-A}$ and $(\bar{\nu}_l \nu_l)_{V-A}$ are the quark and lepton neutral weak currents with vector - axial vector structure.

The contribution is proporzional to the square of the loop particles: For example $x_t = m_t^2/M_W^2$

$K \to \pi\upsilon\bar{\upsilon}$ and New Physics

Measurement of charged ($K^+ \to \pi^+\upsilon\bar{\upsilon}$) and neutral ($K_L \to \pi^0\upsilon\bar{\upsilon}$) modes can **discriminate among different NP scenarios**



- Models with CKM-like flavor structure (Models with MFV)
  [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Custodial Randall-Sundrum
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- LFU violation models
  [Isidori et al., Eur. Phys. J. C (2017) 77: 618]
- Leptoquarks
  [S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]
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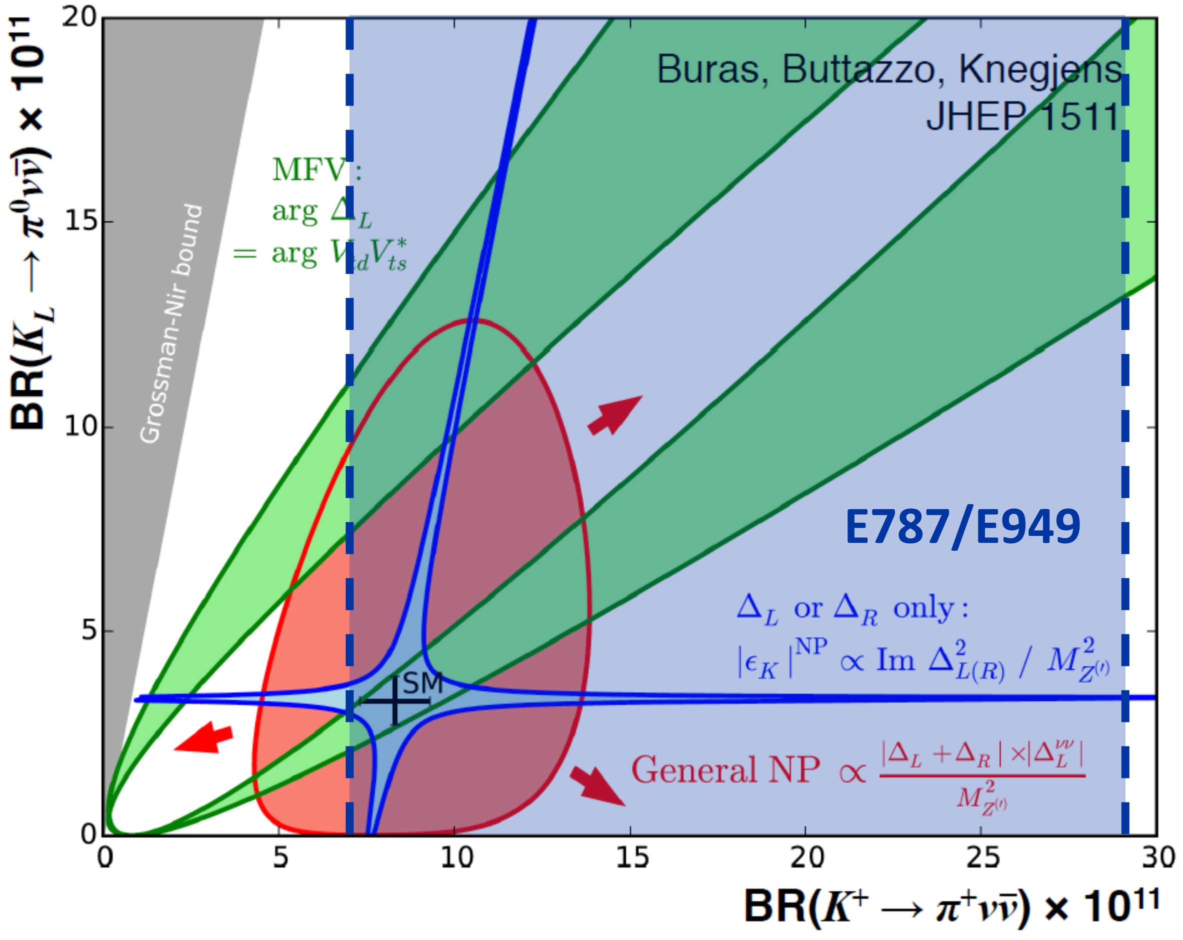

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K → πυῡ and New Physics

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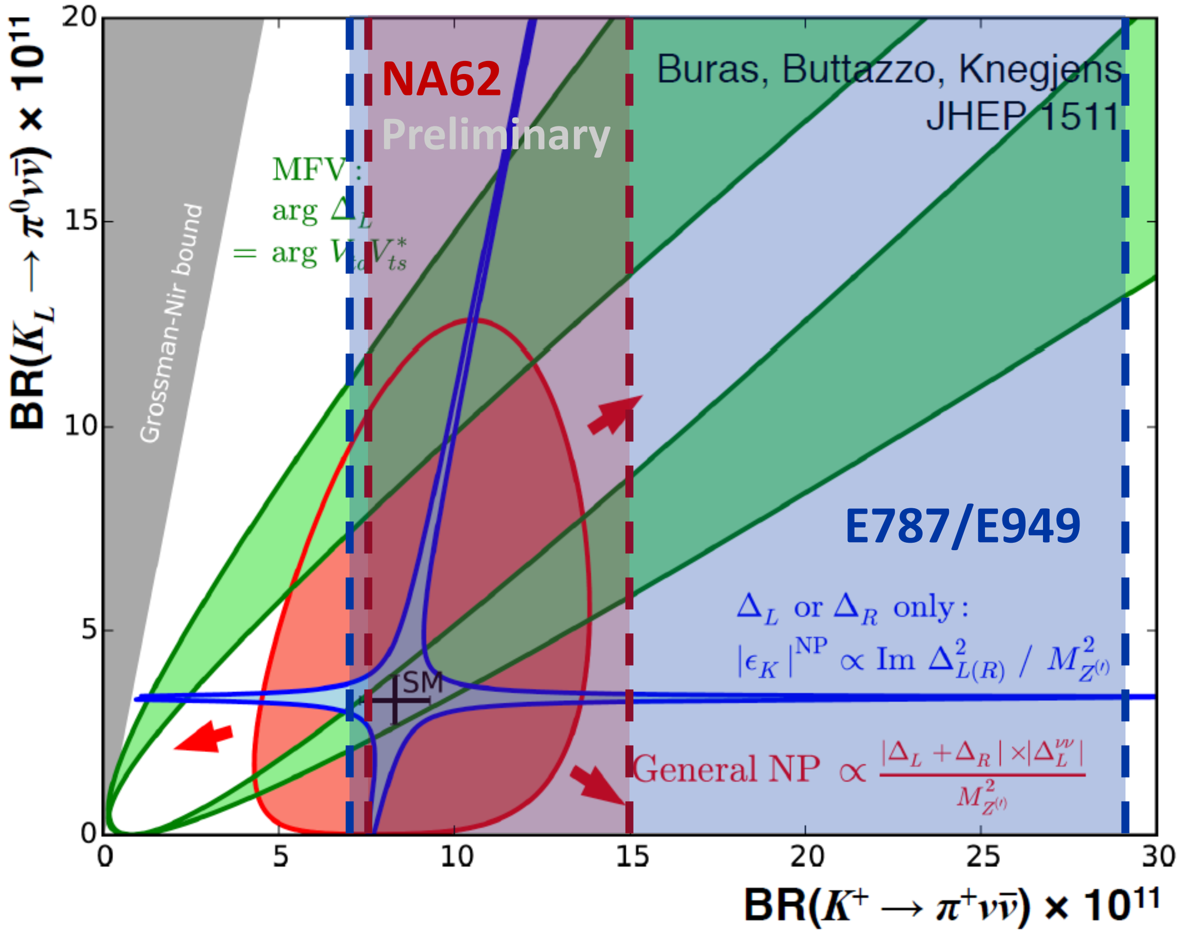

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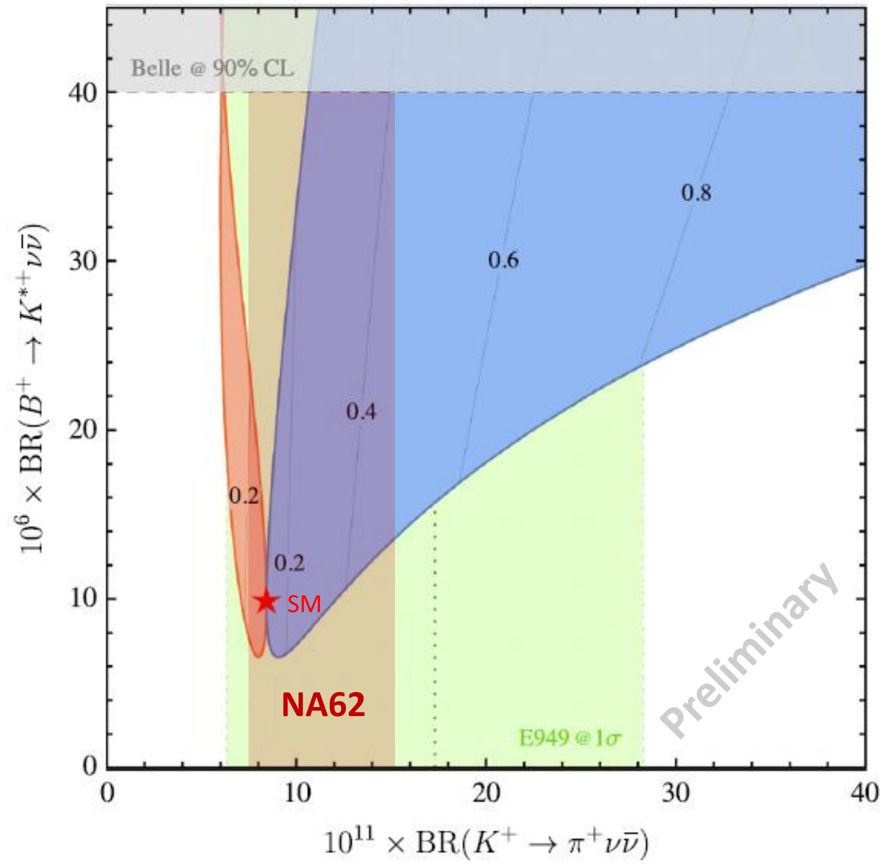
K → πυῡ and the LFU violation

The Measurement of $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$ together with $B^+ \rightarrow K^{*+}\upsilon\bar{\upsilon}$ can **can probe the Lepton-Flavour Universality**

- An interactions responsible for LFU violations can couple mainly to the third generation of left-handed fermions;
- $K \rightarrow \pi\upsilon\bar{\upsilon}$ is the only kaon decays with third-generation leptons (the τ neutrinos) in the final state;
- A deviations from the Standard Model predictions in $K \rightarrow \pi\upsilon\bar{\upsilon}$ branching ratios should be closely correlated to similar effects in $B \rightarrow K^{(*)}\upsilon\bar{\upsilon}$.



EPJ C (2017) 77: 618

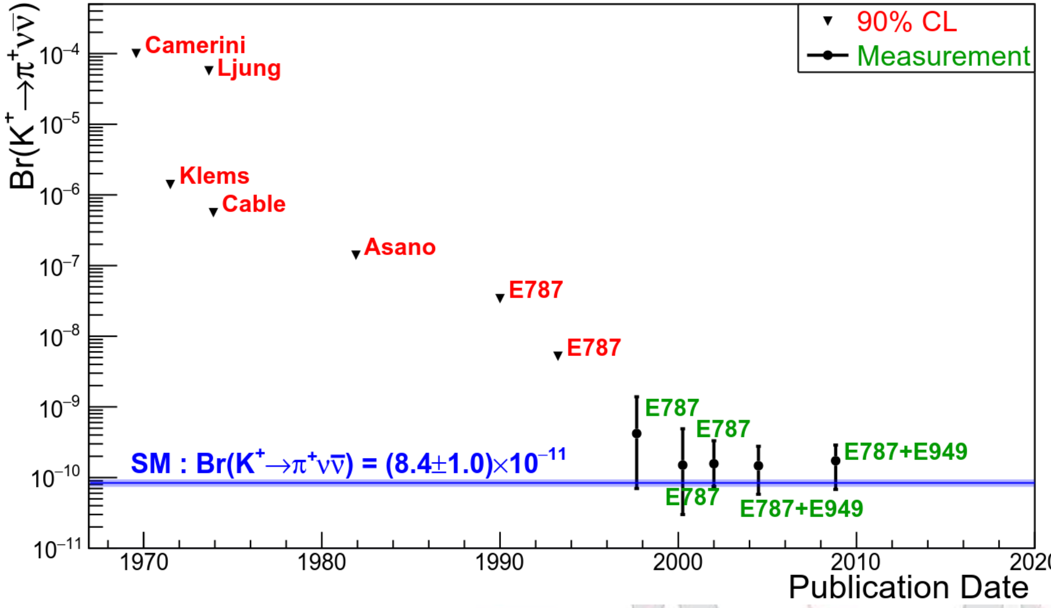
$K \to \pi\nu\bar{\nu}$ Experimental State of the Art

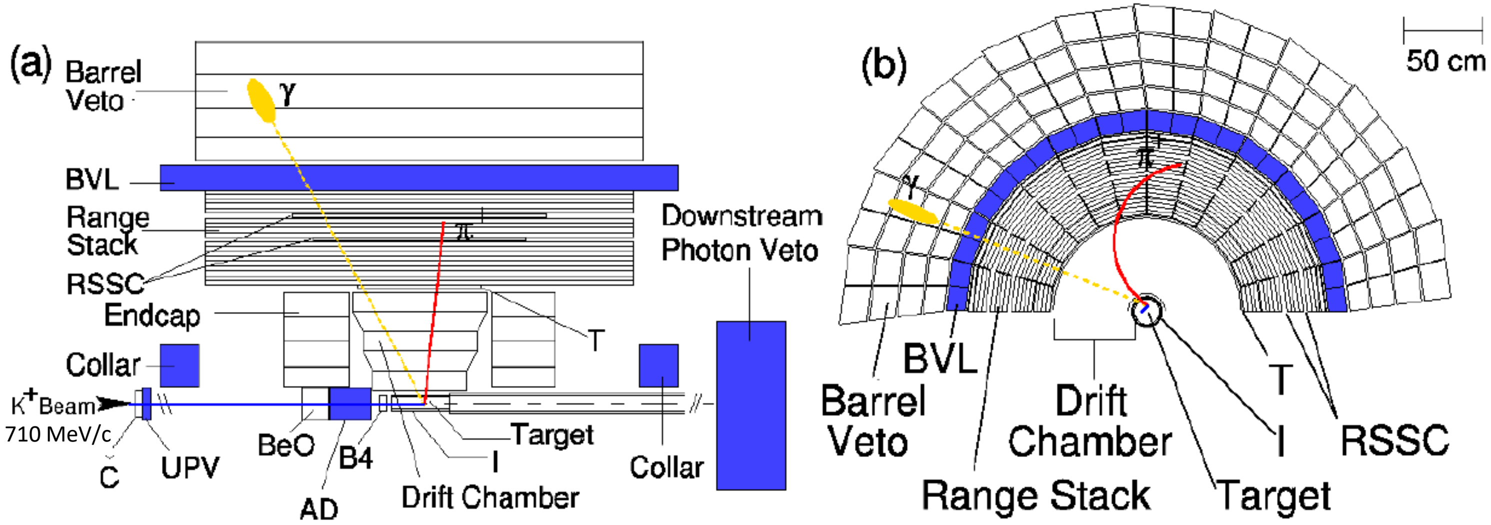
Previous experiments

- <<Kaon decay at rest>> technique
  - Kaon can be efficiently separated from the other beam particles
  - Almost all the kaons decay in the fiducial volume
- E787+E949: K^+ decays: $\sim 3.5\times10^{12}$

  Single Event Sensitivity: $\sim 0.8\cdot10^{-10}$
- $BR(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$

  [Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)]



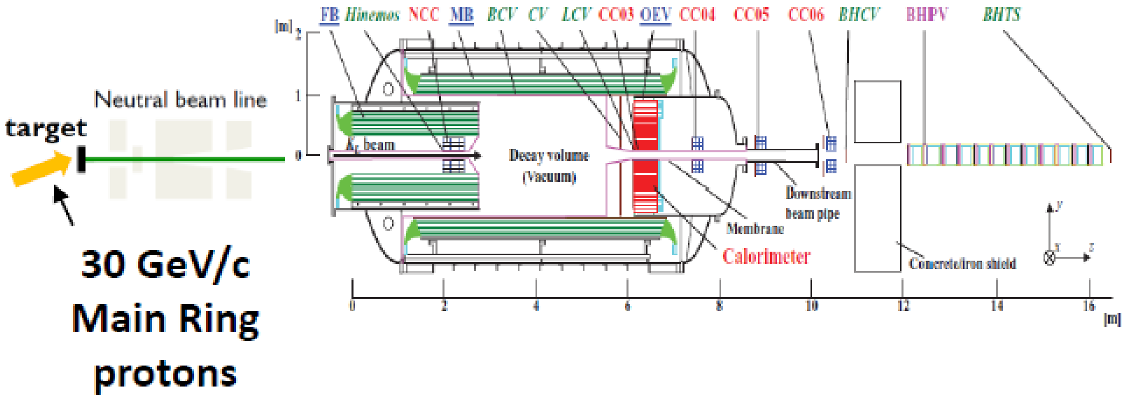


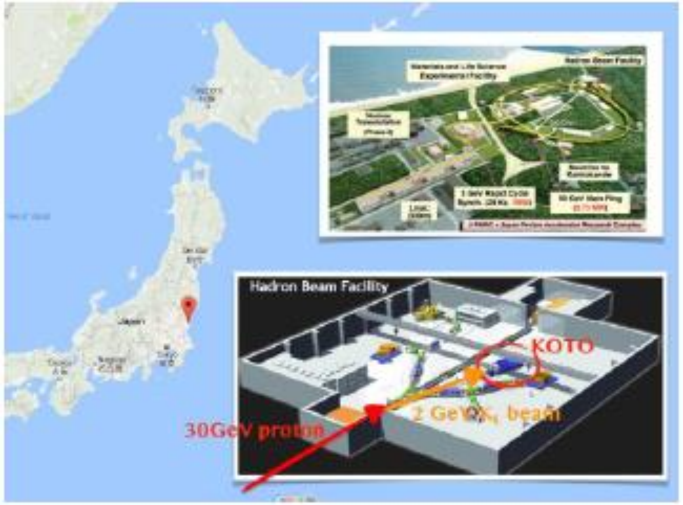
some projects never realised:

- KAMI,
- CKM,
- KOPIO,
- ProjectX.

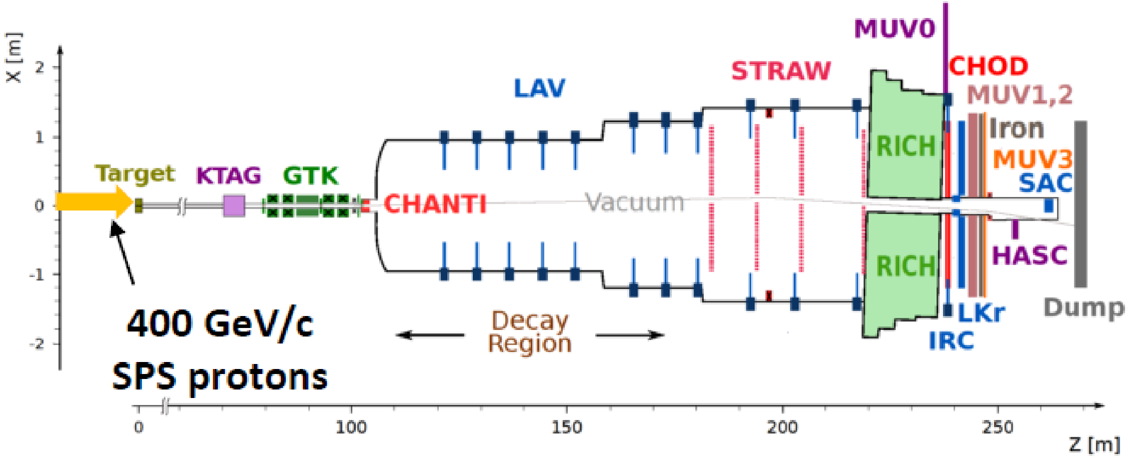
K → πνν̄ Today

- KOTO experiment at JPARC: $K_L \rightarrow \pi^0 \nu\bar{\nu}$





- NA62 experiment at CERN: $K^+ \rightarrow \pi^+ \nu\bar{\nu}$



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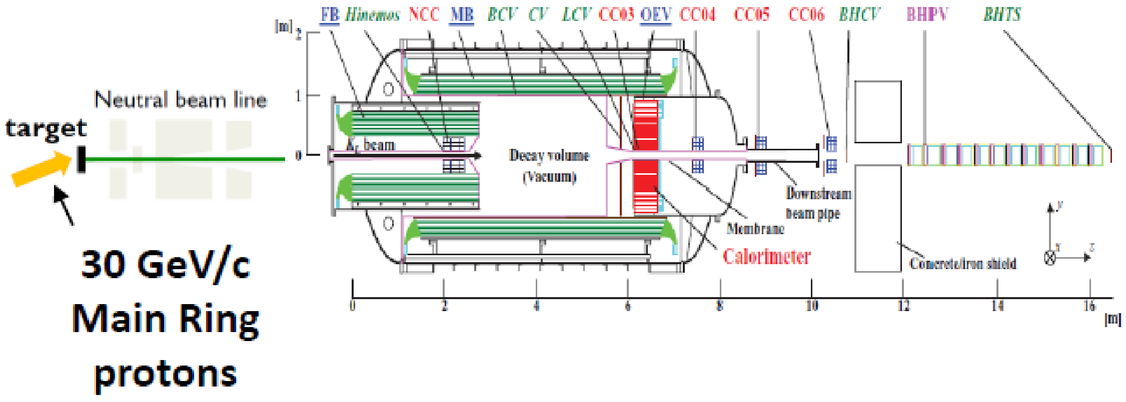

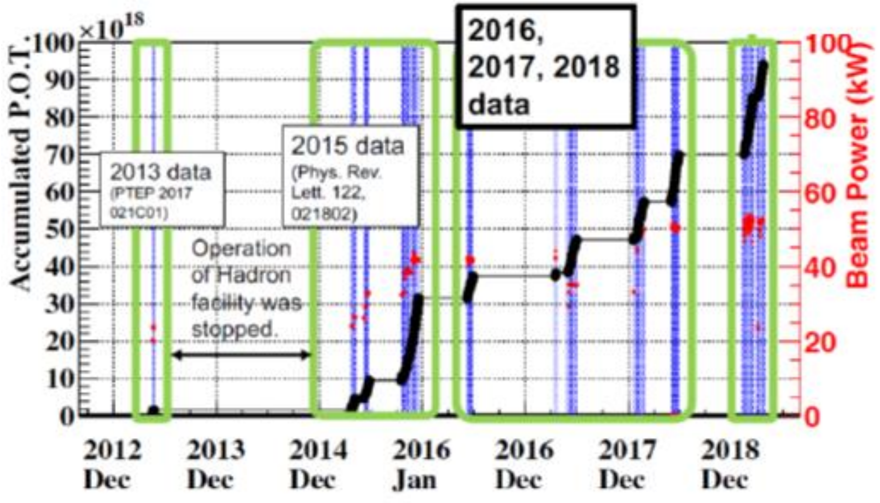

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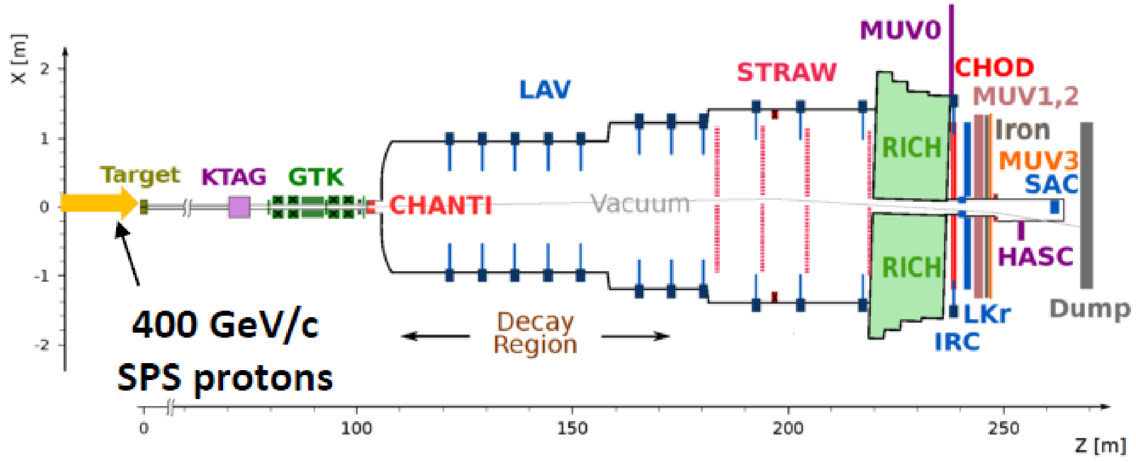
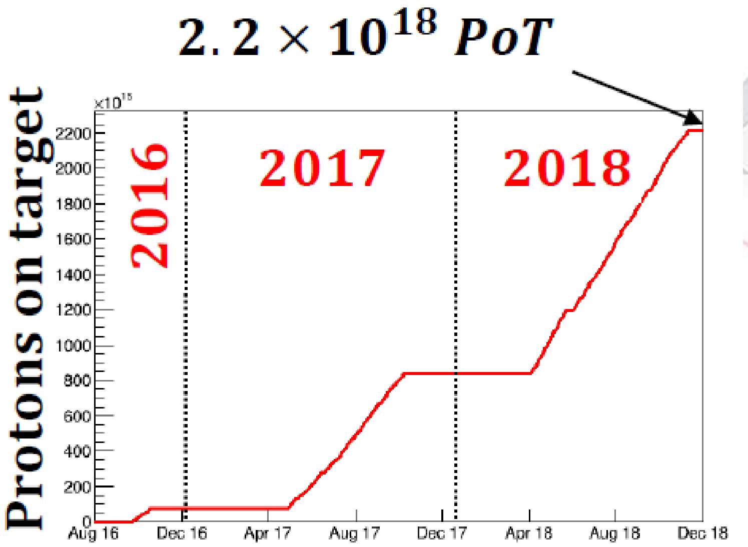
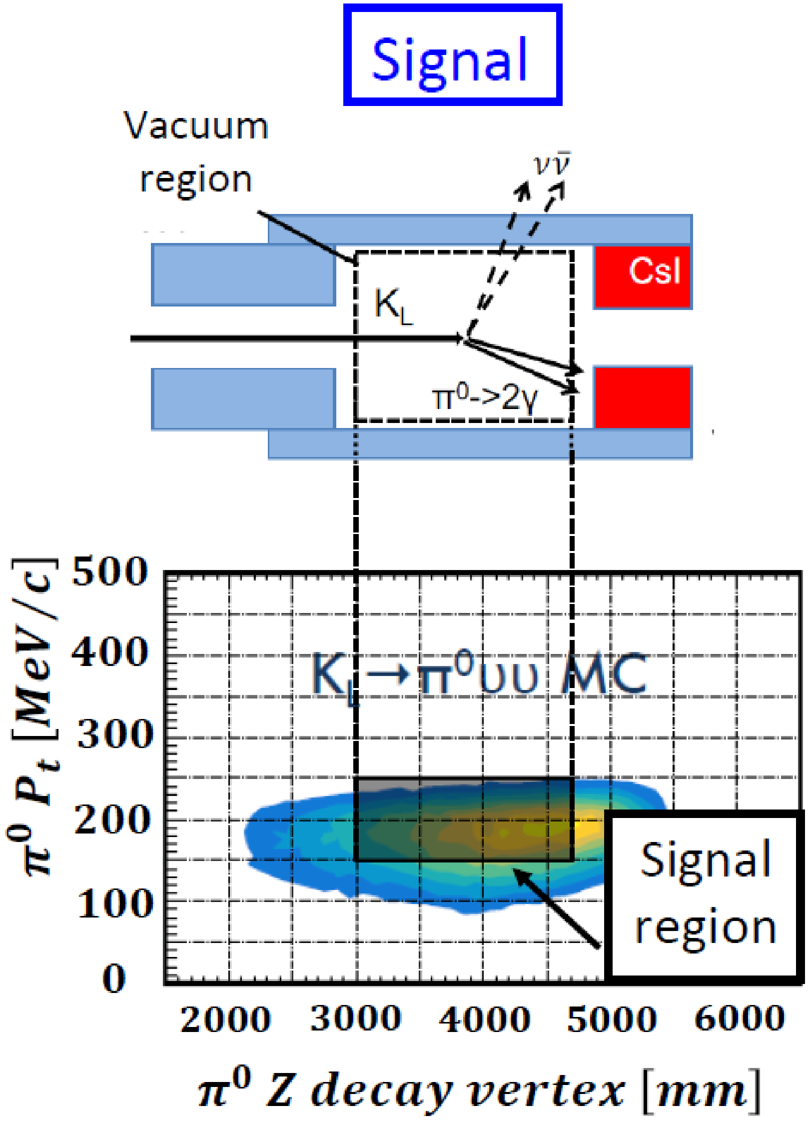




$K \rightarrow \pi^0 \upsilon \bar{\upsilon}$ at KOTO



Hermetic detector and efficient photon detection

Outcome from 2016-17-18 data:

- SES = 6.9 x 10^{-10}
- Total background from data expected = 1.05 ± 0.28
- 0.04 SM signal events expected
- 4 (3) events found in signal region: marginally consistent with the expected background
- K^+ background found: now the largest one
- Dedicated run 2020: estimation of the K^+ background
- Upgrade: New charged veto detector to reduce the K^+ background

$BR(K_L \rightarrow \pi^0 \upsilon \bar{\upsilon})(SM) = (3.4 \pm 0.6) \times 10^{-11}$

$BR(K_L \rightarrow \pi^0 \upsilon \bar{\upsilon})(KOTO) < 3.0 \times 10^{-9}$ (2015 data)

[Phys. Rev. Lett. 122, 021802 (2019)]
[https://indico.cern.ch/event/868940/contributions/3815582/]

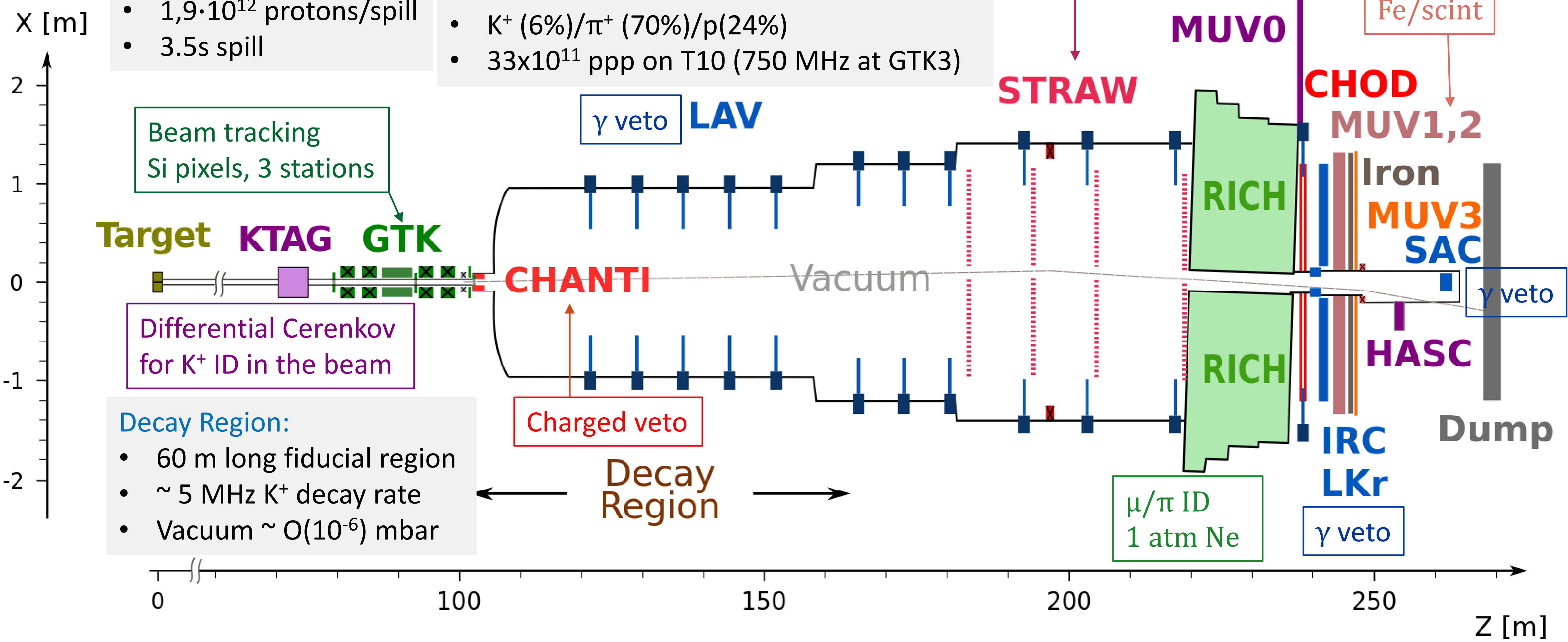
NA62 Layout

SPS Beam:

- 400 GeV/c protons
- 1,9·10^{12} protons/spill
- 3.5s spill

Secondary positive Beam:

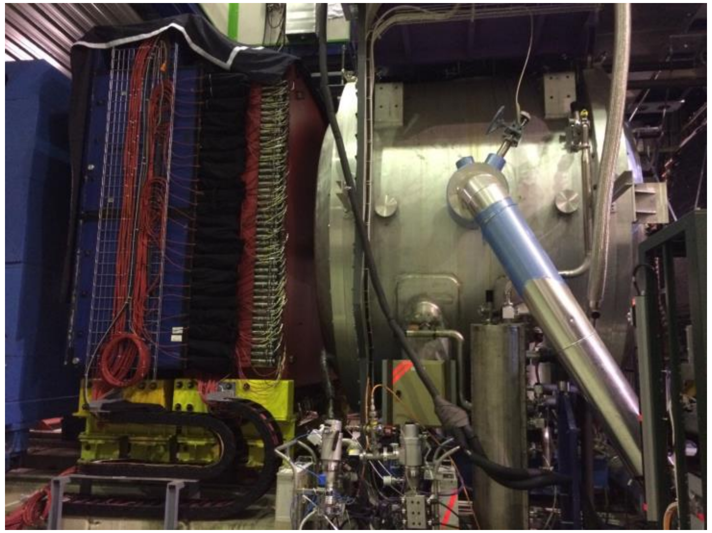
- 75 GeV/c momentum
- 1 % bite 100 mrad divergence (RMS)
- 60x30 mm2 transverse size
- K^+ (6%)/π^+ (70%)/p(24%)
- 33x10^{11} ppp on T10 (750 MHz at GTK3)



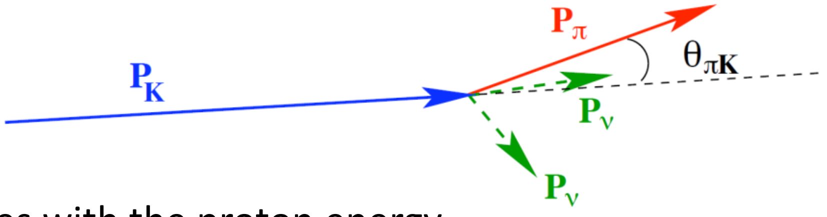
Decay Region:

- 60 m long fiducial region
- ~ 5 MHz K^+ decay rate
- Vacuum ~ O(10^{-6}) mbar

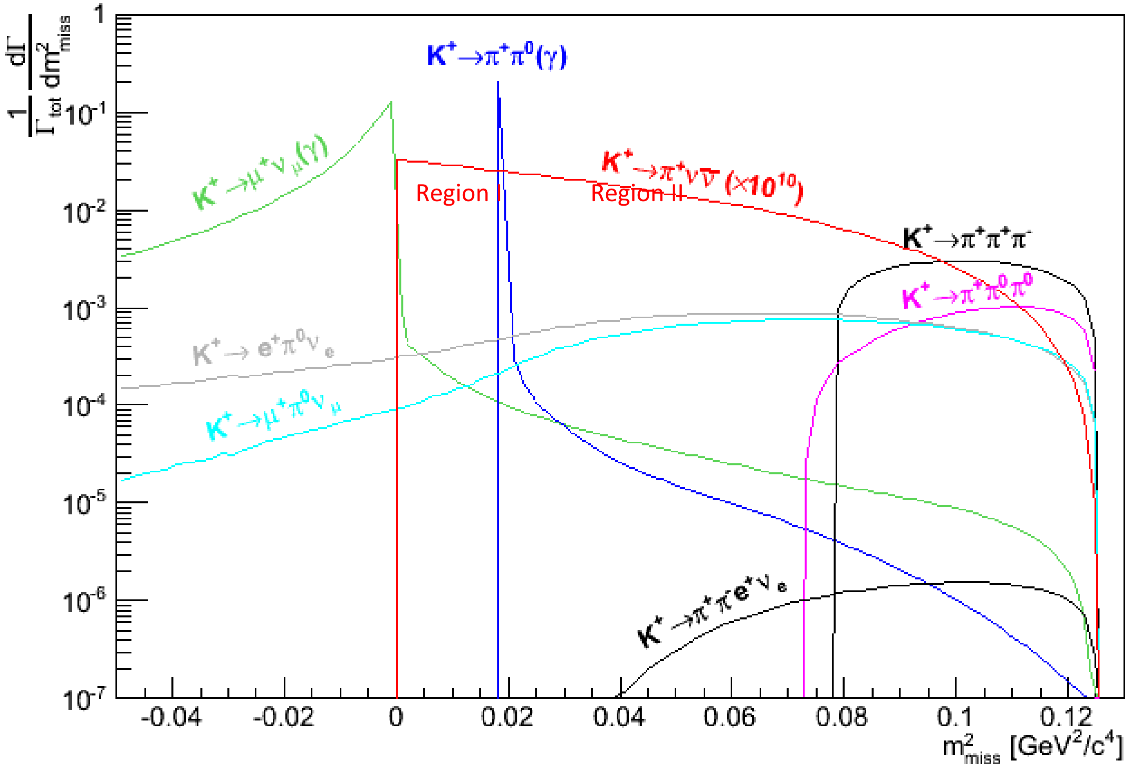
Some photos



Analysis Strategy



- New Decay in flight technique
  - K^+ production cross section increases with the proton energy
  - the detection of photons from background decays is easier at high energy
- Signal: 1 beam track, 1 charged track, nothing else
- Background: K^+ decay modes; beam activity
- Kinematics: $m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$



Key analysis requirements:

- 2 signal regions in m^2_{miss}
- 15 < P_{π^+} < 35 (45 in 2018) GeV/c
- 60 m long decay region

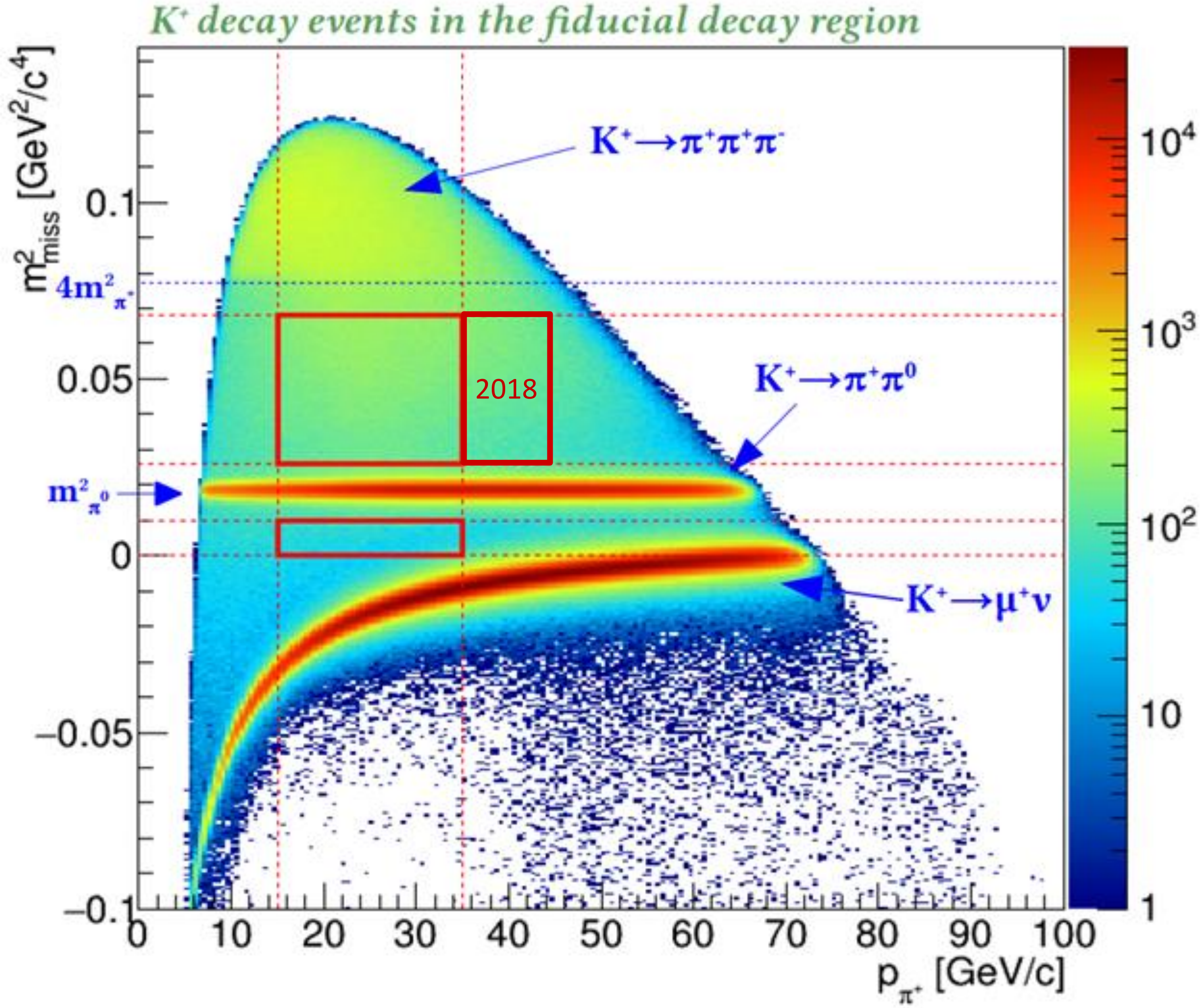
Experimental principles:

1. Precise kinematic reconstruction
2. PID: K upstream, e / μ / π downstream
3. Hermetic γ detection
4. Sub-ns timing

Keystone:

- O (100 ps) Timing between sub-detectors
- O (10^4) background suppression from kinematics
- > 10^7 Muon suppression
- > 10^7 π^0 (from $K^+ \to \pi^+ \pi^0$) suppression
- Signal and background control regions are kept blind throughout he analysis
- 7 categories in 2018 (hardware configurations and momentum)
- use of MVA for particle identification and upstream background rejection

Signal Selection



πνν selection:

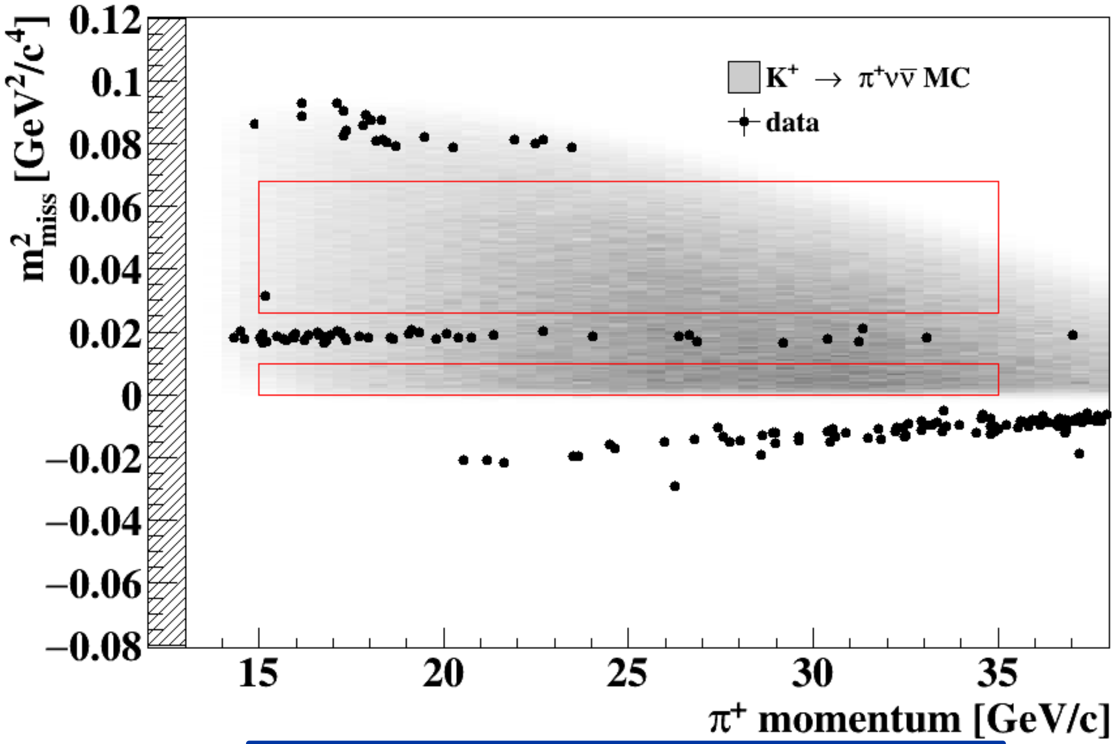
- K^+ Decay Event
- Fiducial Decay Region
- Particle ID: π^+
- Photon rejection
- Multiple charged particle rejection
- Kinematic Selection of the Signal Regions

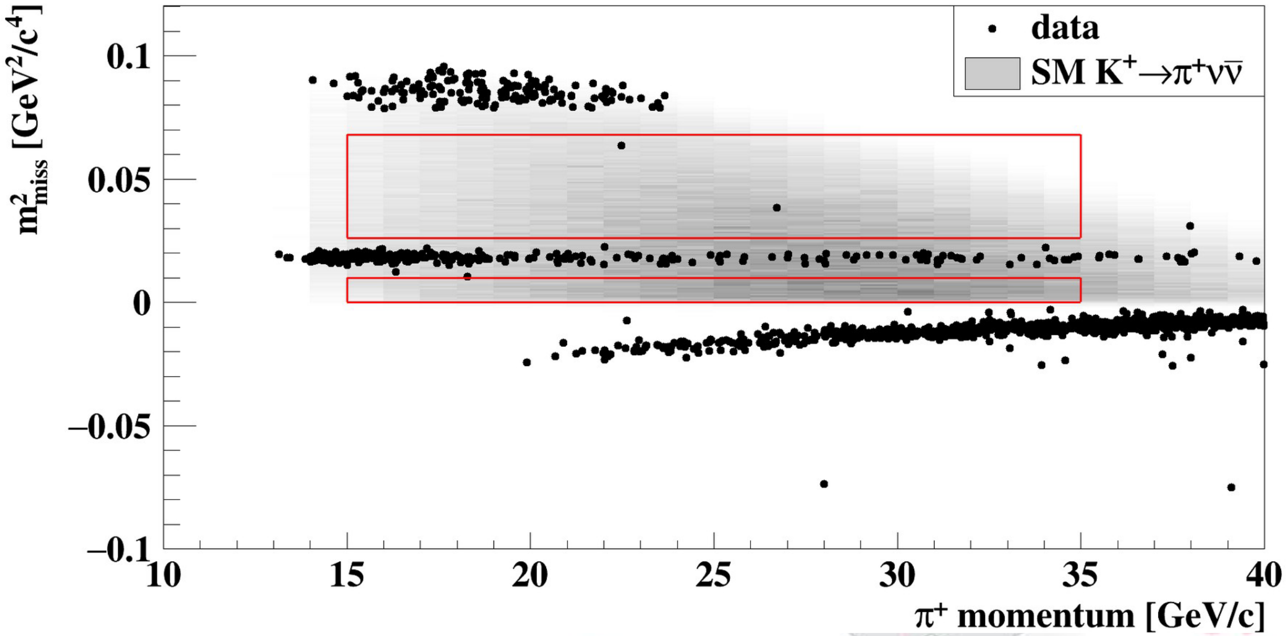
Performance:

- $\geq 10^4$ Kinematic background suppression
- $\geq 10^7$ Muon suppression
- $\geq 10^7$ π^0 (from $K^+ \to \pi^+\pi^0$) suppression
- $O(100\text{ ps})$ timing between sub-detectors

Process	*Branching ratio*
$K^+ \to \pi^+\pi^0(\gamma)$	0.2067
$K^+ \to \mu^+\nu(\gamma)$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^- e^+\nu$	$4.25 \cdot 10^{-5}$

Result of 2016 and 2017 data taking





2016

- 1 events observed
- SES = 3.15×10^{-10}
- Br($K^+ \rightarrow \pi^+\nu\nu$) < 14×10^{-10} @ 90% CL

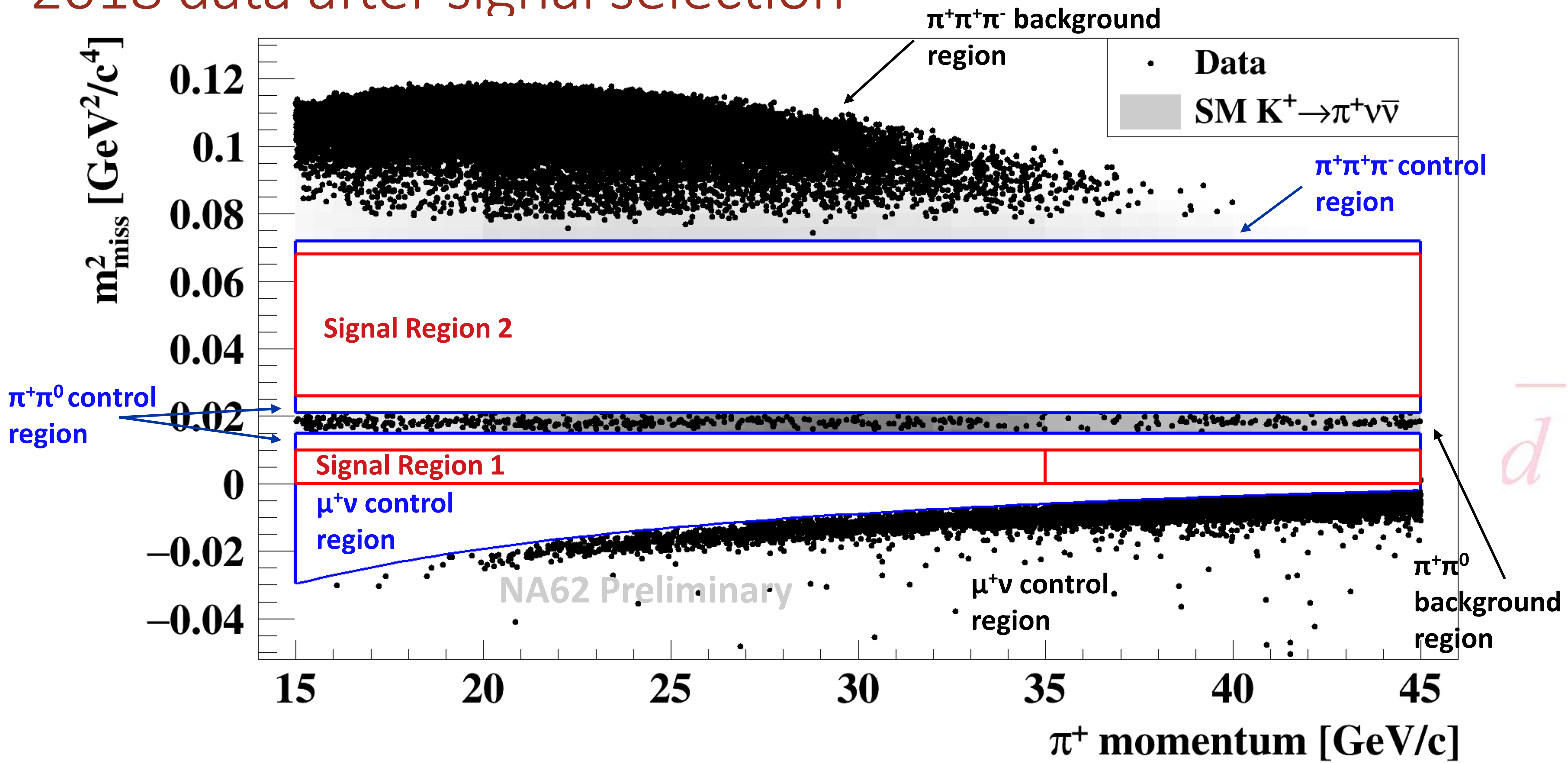
Phys. Lett. B 791 (2019) 156-166

2017

- 2 events observed
- SES = 0.389×10^{-10}
- Br($K^+ \rightarrow \pi^+\nu\nu$) < $1{,}7 \times 10^{-10}$ @ 90% CL

[J. High Energ. Phys. 2020, 42 (2020)]

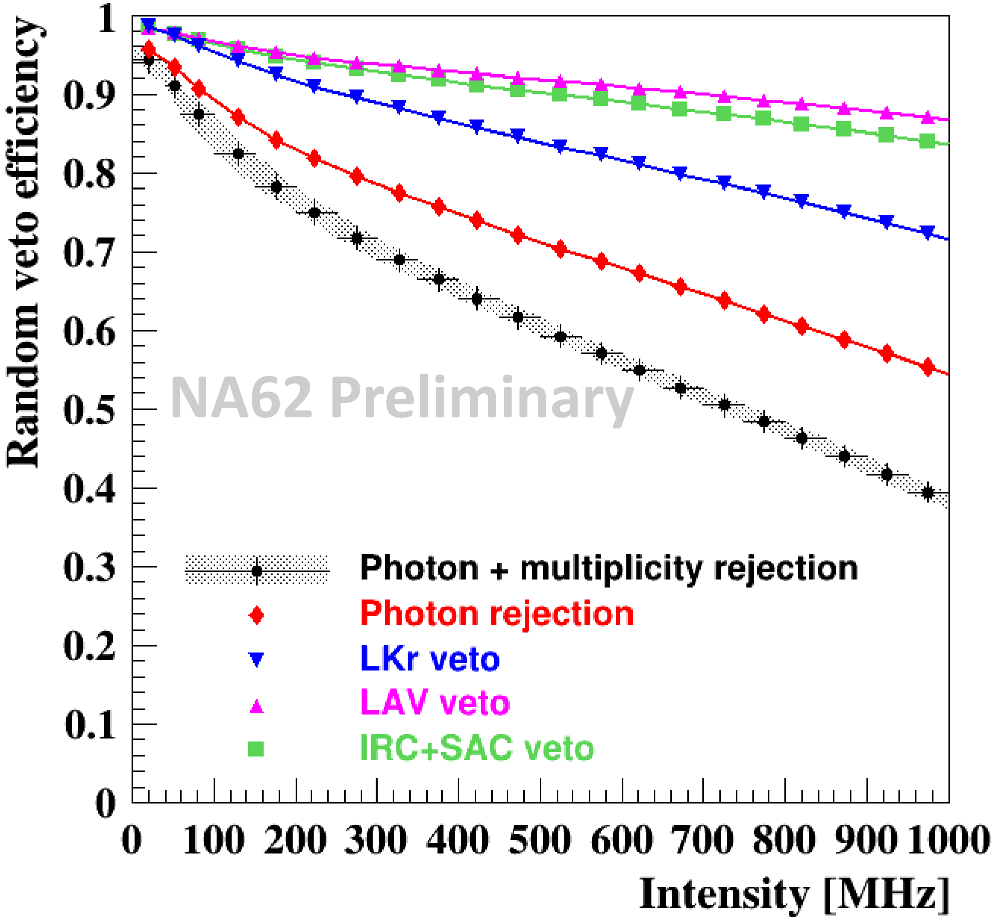
2018 data after signal selection



Single Event Sensitivity (SES)

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

	Error budget S.E.S.
Trigger efficiency	5%
MC acceptance	3.5%
Random Veto	2%
Background(normalization)	0.7%
Instantaneous intensity	0.7%
Total	**6.5%**

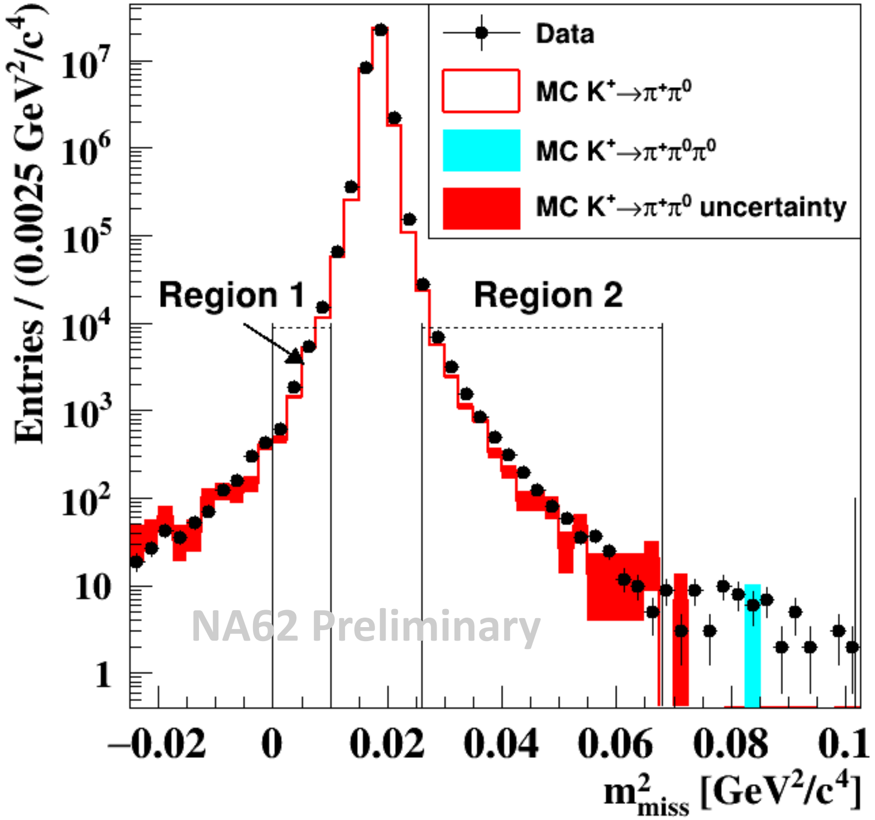


- $K^+ \rightarrow \pi^+\pi^0$ decay used for normalization
- Cancellation of systematic effects (PID, Detector efficiencies, kaon ID and beam related acceptance loss)

$$SES = (1{,}11 \pm 0.07) \cdot 10^{-11}$$

Background from Kaon Decay Estimation

Control $K^+ \to \pi^+\pi^0$ data used to study the tails of the m^2_{miss} distribution



Data in $\pi^+\pi^0$ region after $\pi\nu\nu$ selection (including π^0 rejection)

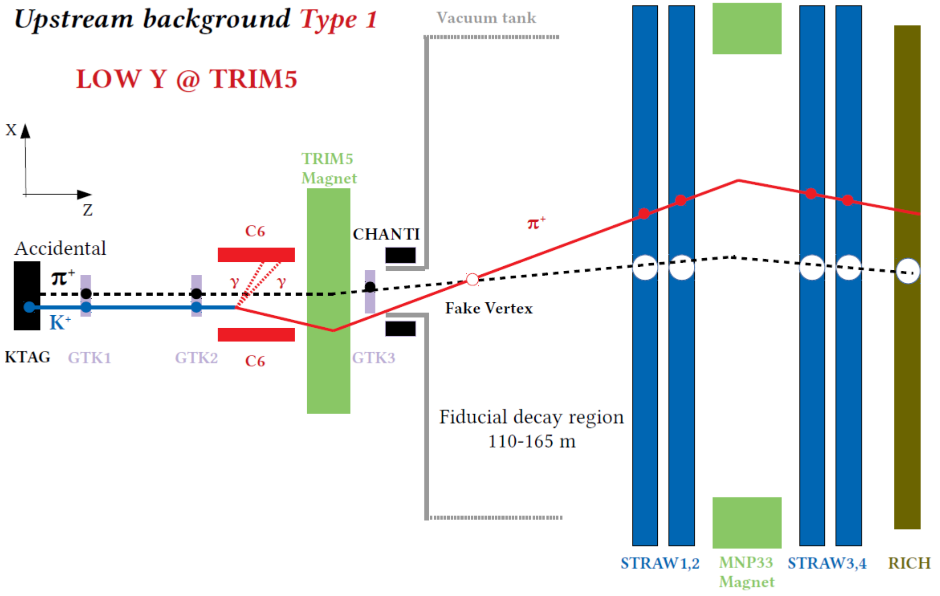
$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) \cdot f_{kin}(region)$$

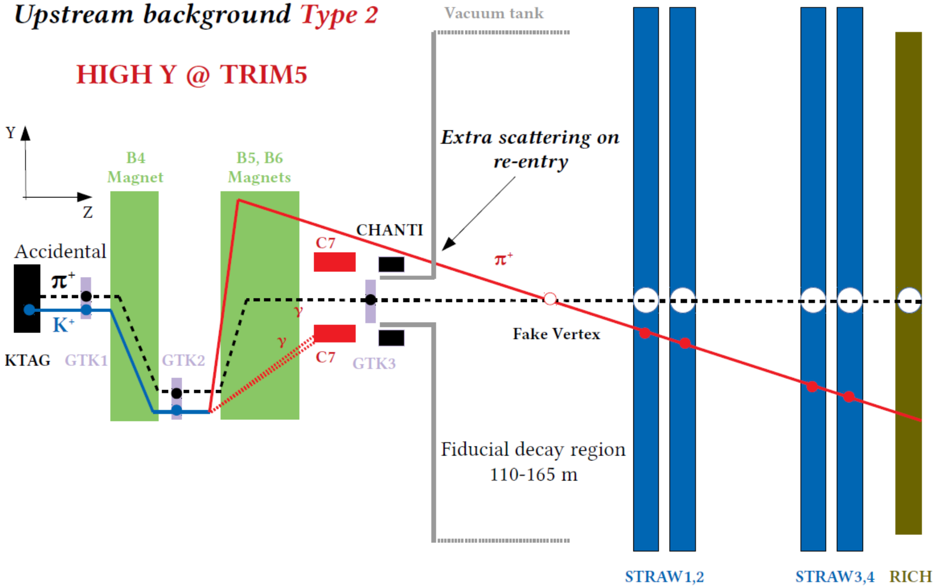
Expected $K^+ \to \pi^+\pi^0$ in signal regions after the $\pi\nu\nu$ selection

Fraction of $\pi^+\pi^0$ in signal region measured on control data

- The same procedure is used for $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^+\pi^-$
- $K^+ \to \pi^+\pi^- e^+\nu_e$ estimation entirely using MC simulations normalized to the S.E.S.

Upstream background

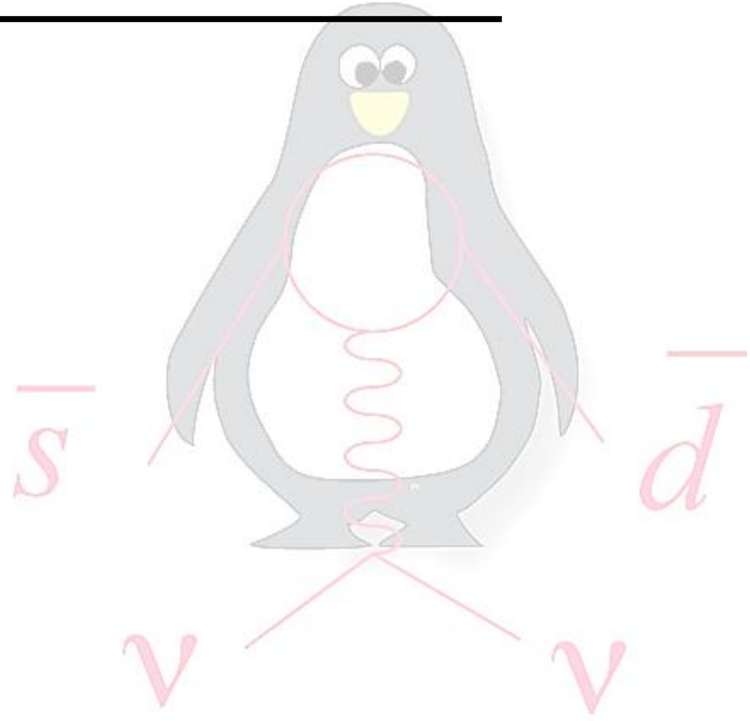




- Pions produced upstream the fiducial volume
  - Early K^+ decay
  - Interaction of beam particles with the beam spectrometer material
- Pions can be associated to an accidental particle of the beam line
- Dangerous if coupled with pion scattering in the first spectrometer chamber
- Kaon-pion association and geometrical cuts effective
- The geometrical origin of those events allow to define samples for backgrounds validation
- Data driven background estimation

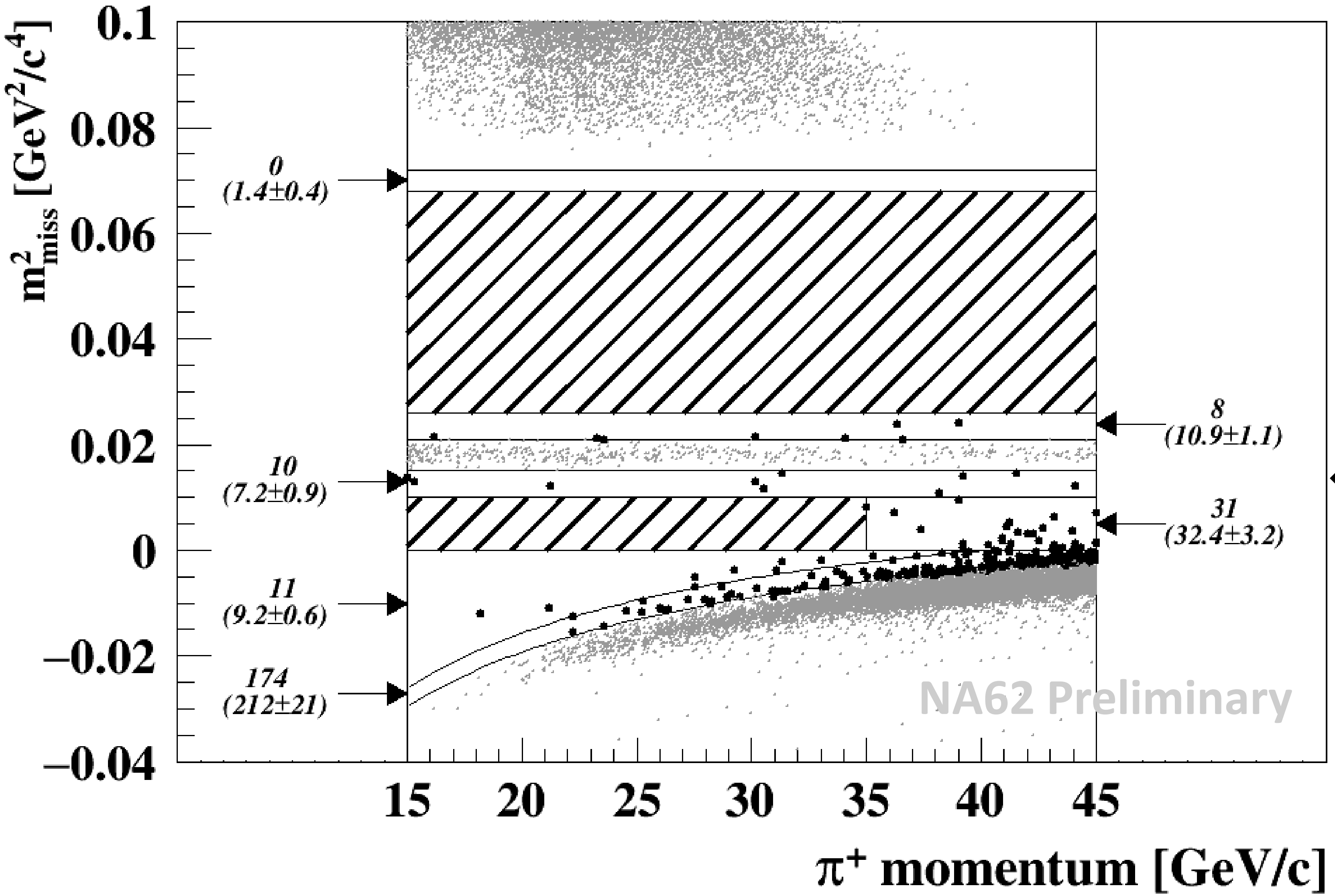
Background summary

Process	Expected events in R1+R2 (2018 data)
$K^+ \to \pi^+ \nu \bar{\nu}$ (SM)	$7.58 \pm 0.40_{syst} \pm 0.75_{ext}$
Total Background	$5.28^{+0.99}_{-0.74}$
$K^+ \to \pi^+ \pi^0 (\gamma)$	0.75 ± 0.04
$K^+ \to \mu^+ \nu_\mu (\gamma)$	0.49 ± 0.05
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	0.50 ± 0.11
$K^+ \to \pi^+ \pi^+ \pi^-$	0.24 ± 0.08
$K^+ \to \pi^+ \gamma\gamma$	< 0,01
$K^+ \to \pi^0 l^+ \nu$	<0,001
Upstream Background	$3.3^{+0.98}_{-0.73}$



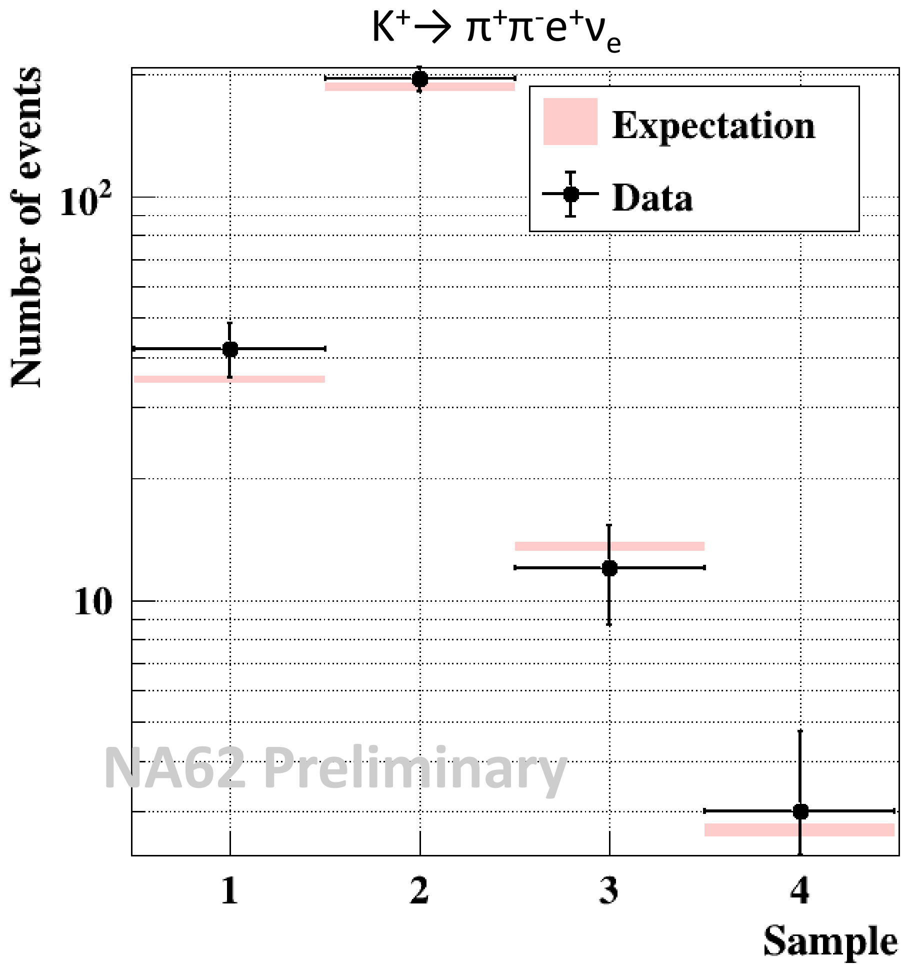
Background expectations validated in control regions using a blind procedure

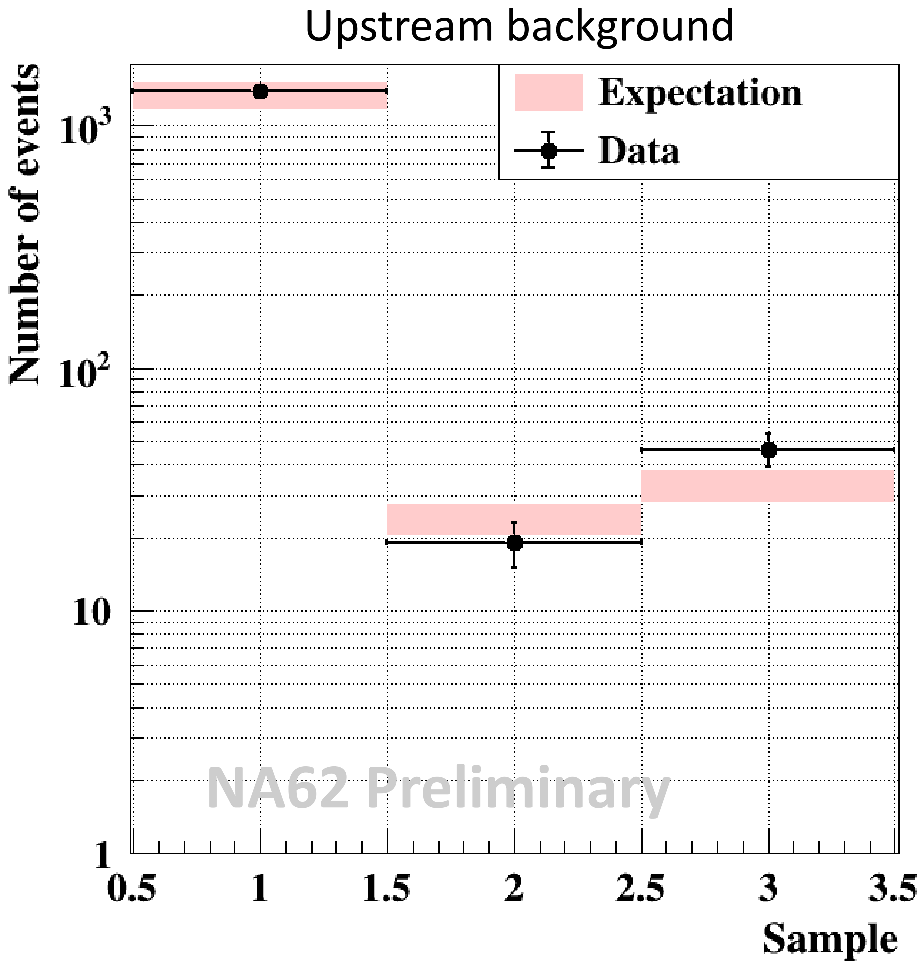
Control regions: main decays



Measured
(expected)

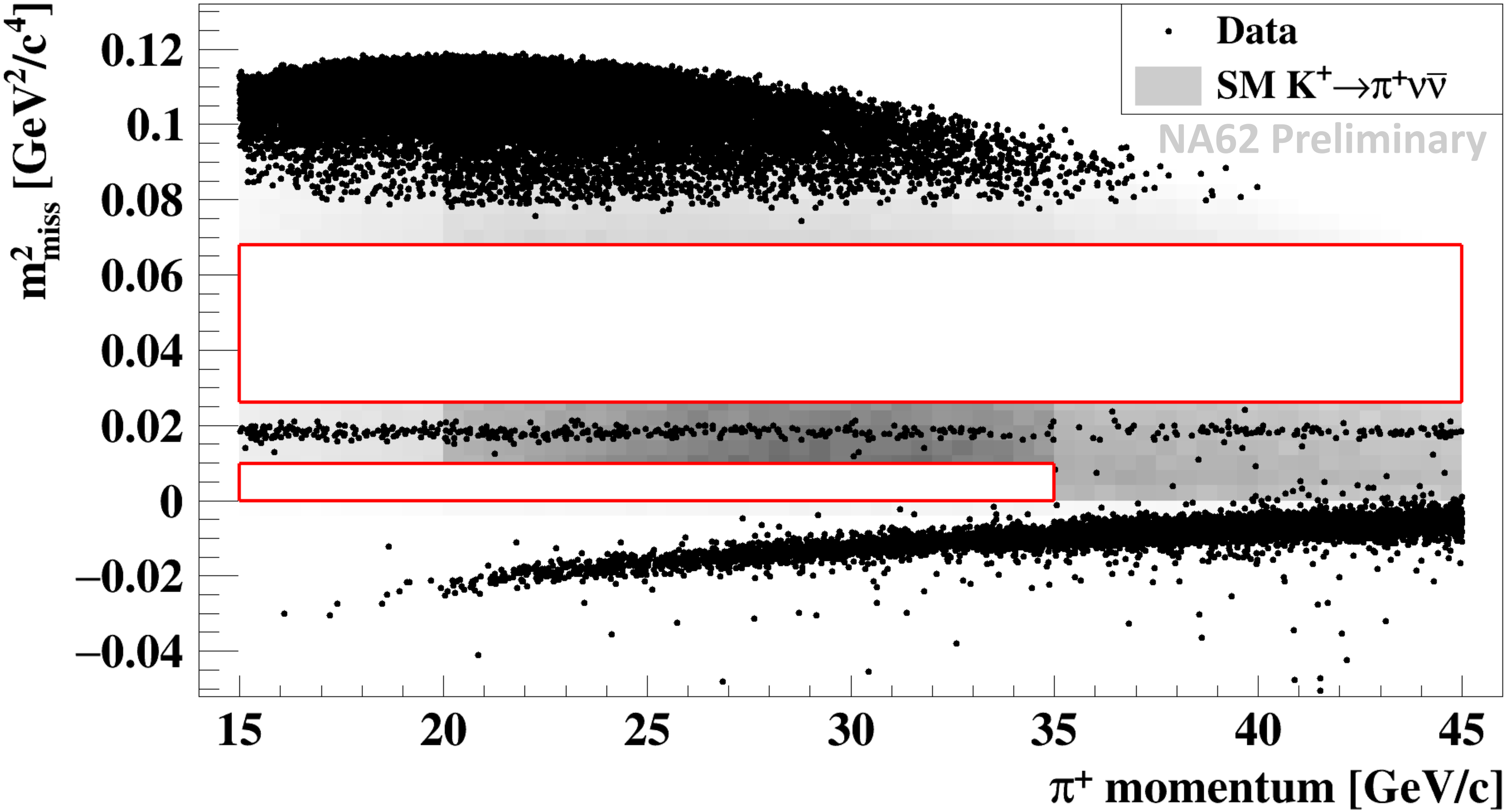
Control regions: $K^+ \rightarrow \pi^+\pi^- e^+\nu_e$ and upstream



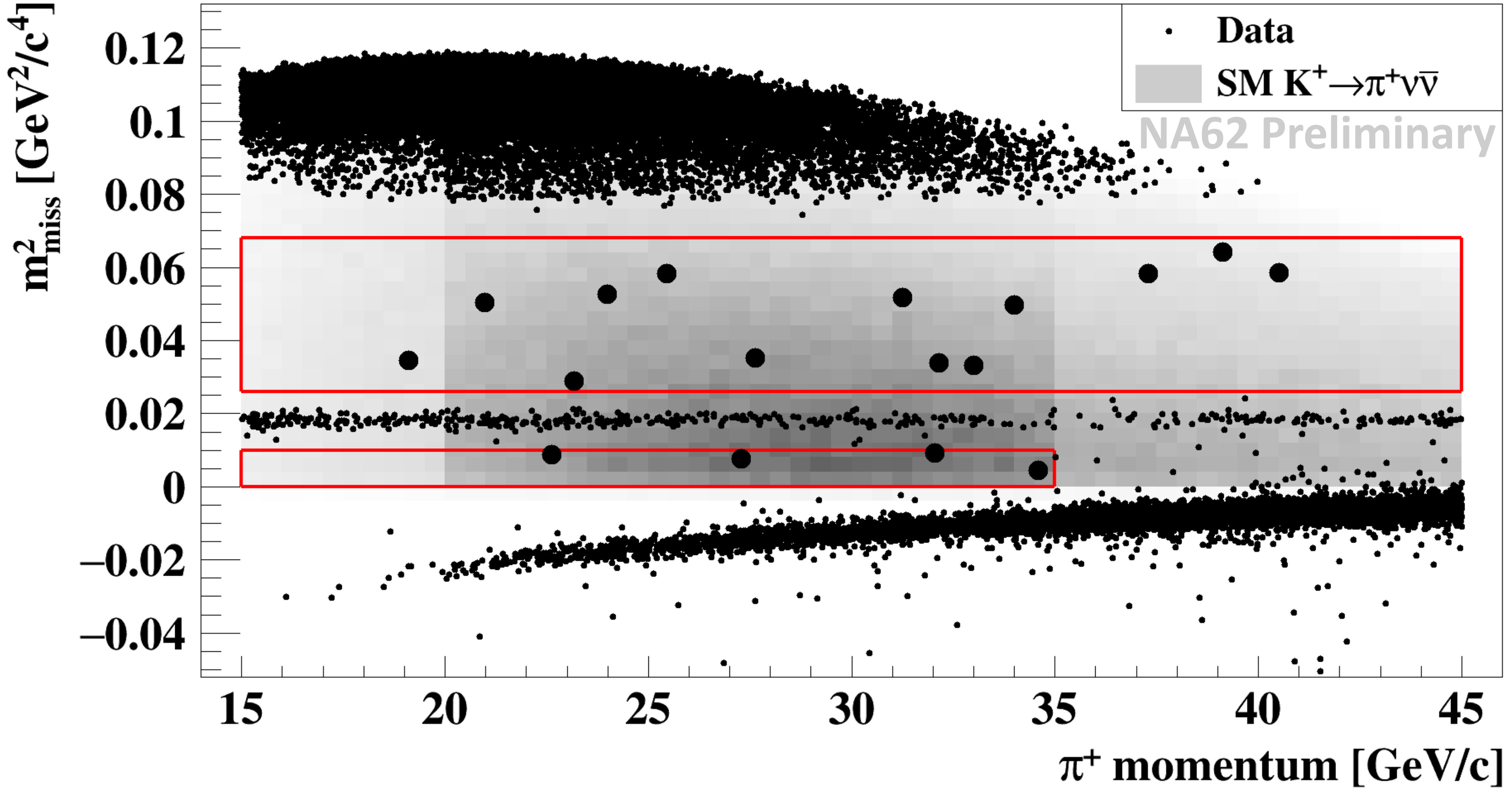


- Data samples defined by inverting signal selection criteria
- The sensitivity of some control samples comparable to the S.E.S.

Before unblinding 2018 data

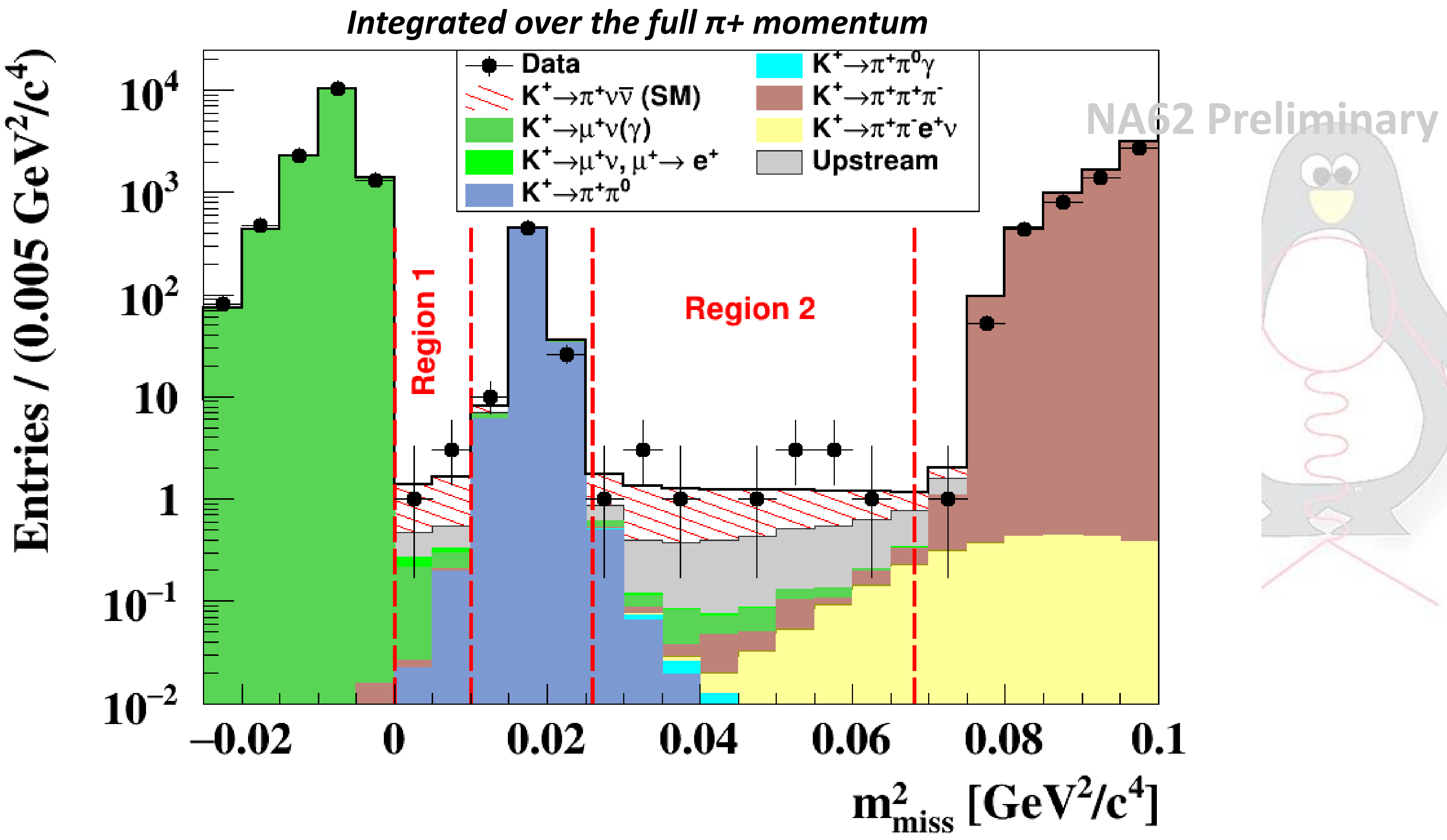


Result

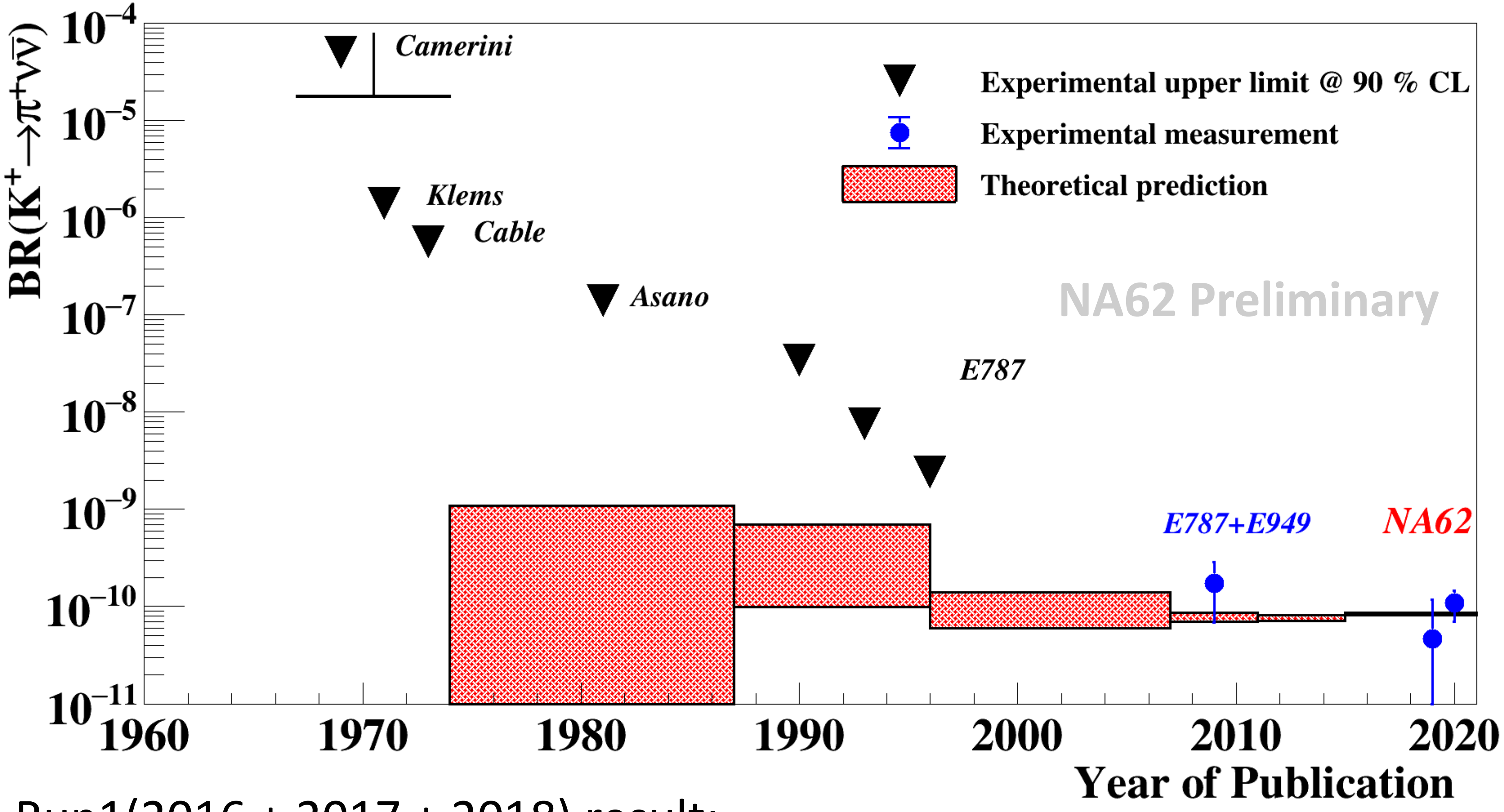


5.3 background + 7.6 SM signal events expected, 17 events observed

m^2_{miss} signal and background in the 2018 data



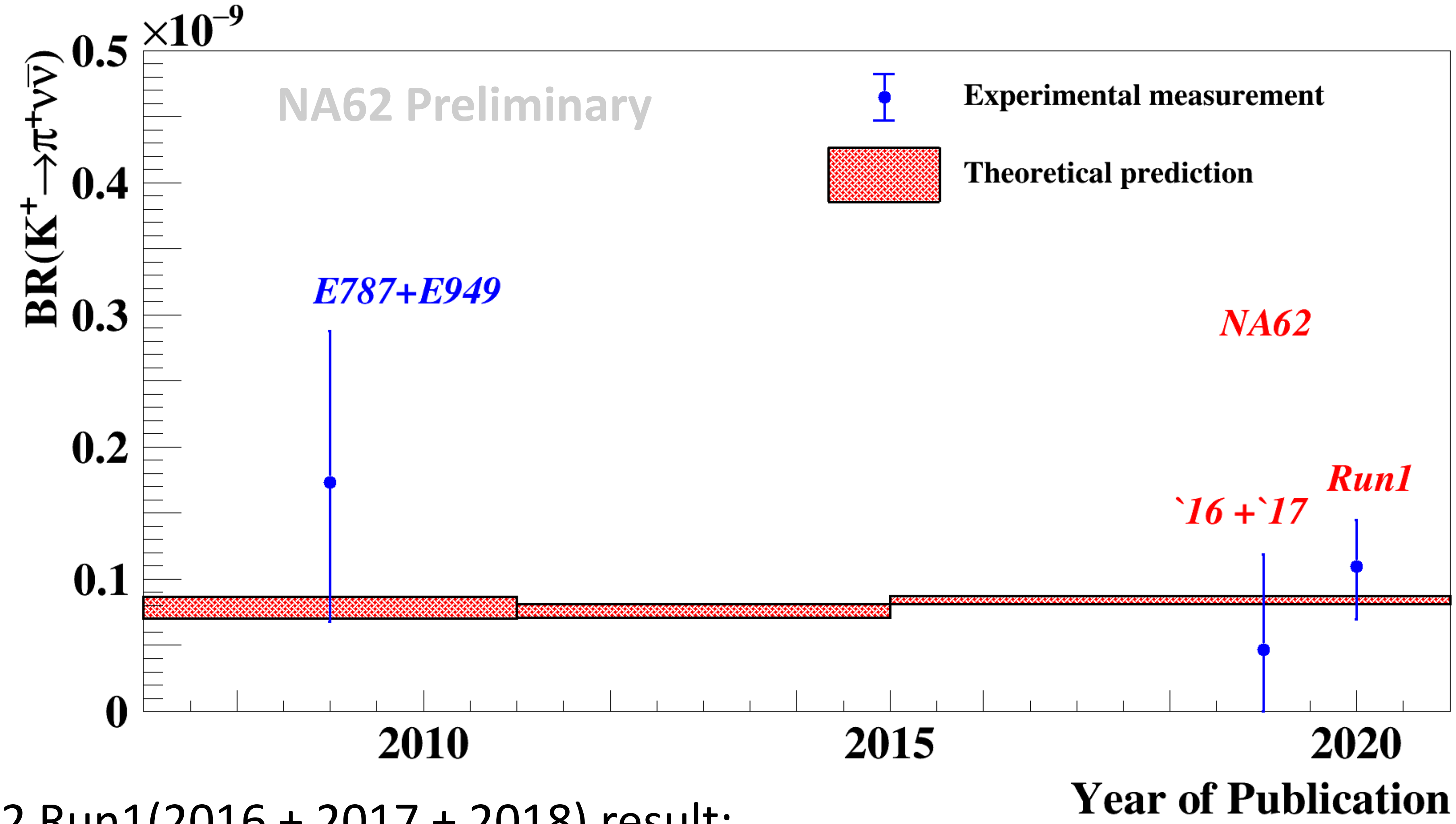
$K \to \pi\upsilon\bar{\upsilon}$ Result and historical context



NA62 Run1(2016 + 2017 + 2018) result:

$$Br(K^+ \to \pi^+ \upsilon\bar{\upsilon}) = (11.0^{+4.0}_{-3.5}{}_{stat} \pm 0.3_{syst}) \cdot 10^{-11} \text{ (3.5σ significance)}$$

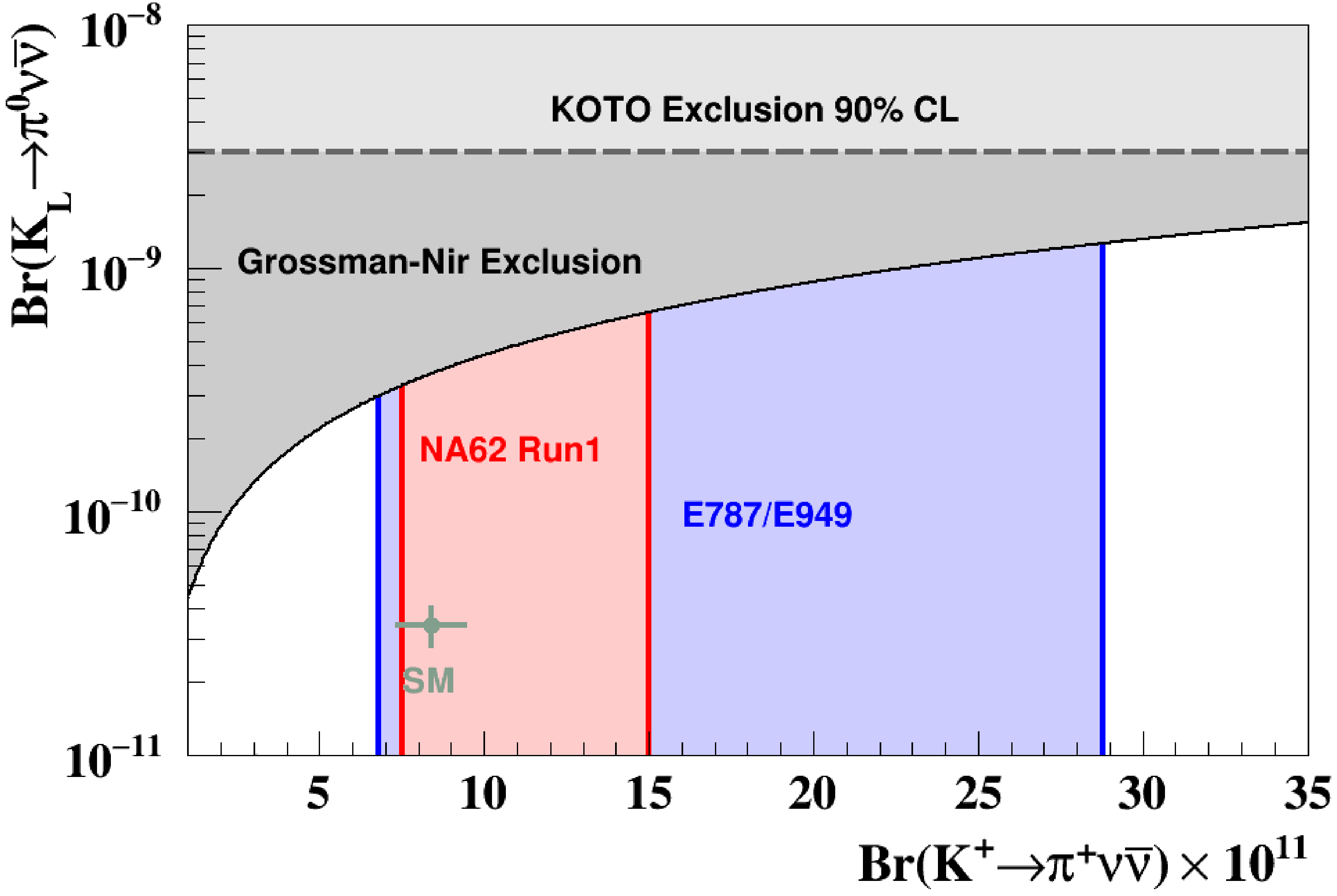
$K \to \pi\nu\bar{\nu}$ Result and historical context



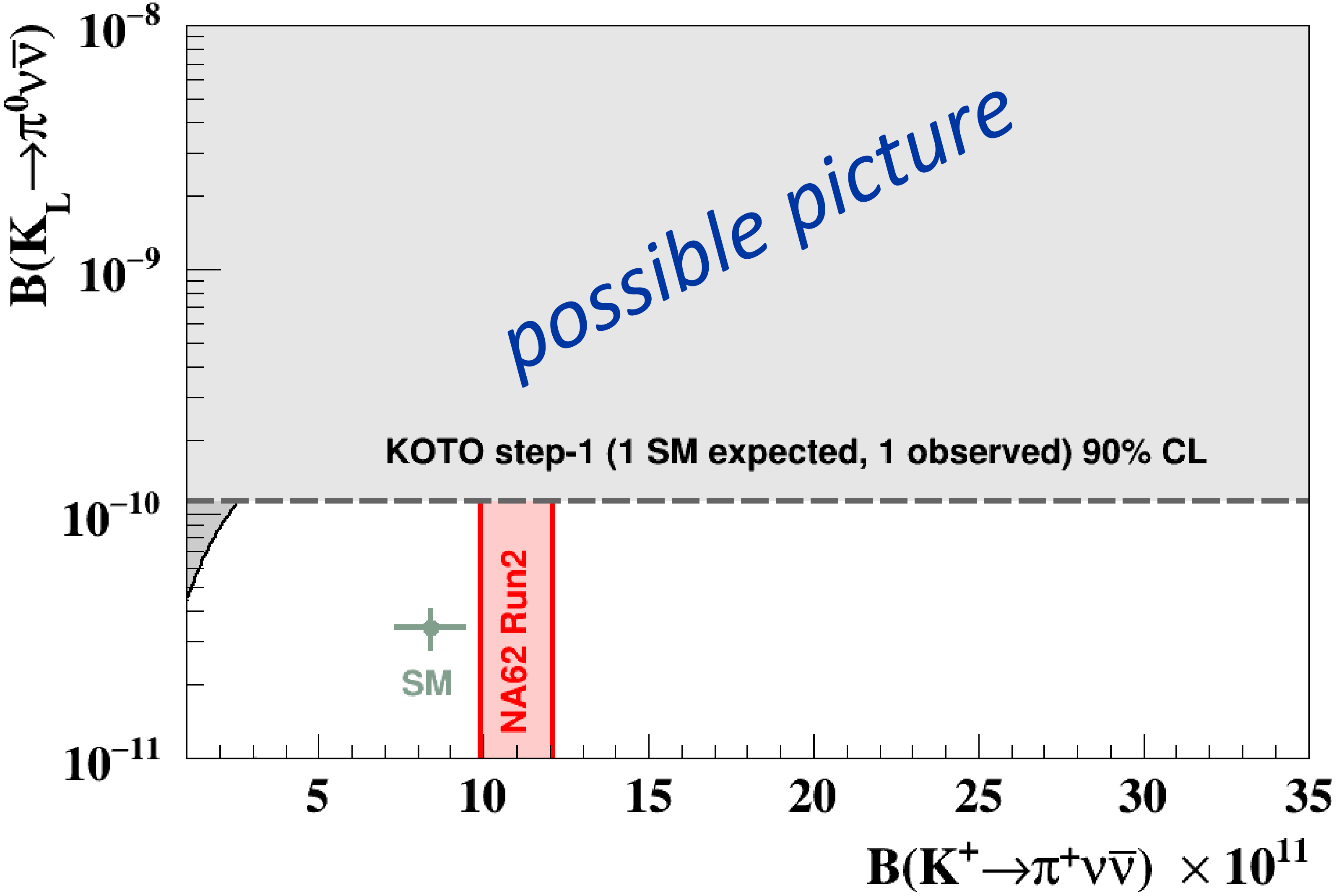
NA62 Run1(2016 + 2017 + 2018) result:

$$Br(K^+ \to \pi^+ \upsilon \bar{\upsilon}) = (11.0^{+4.0}_{-3.5}{}_{stat} \pm 0.3_{syst}) \cdot 10^{-11} \text{ (3.5σ significance)}$$

$K \to \pi\nu\bar{\nu}$ result and SM



Future (<2025)



NA62 (Run2):

- Hardware improvements

KOTO (step 1):

- Main ring power increase
- Hardware improvements

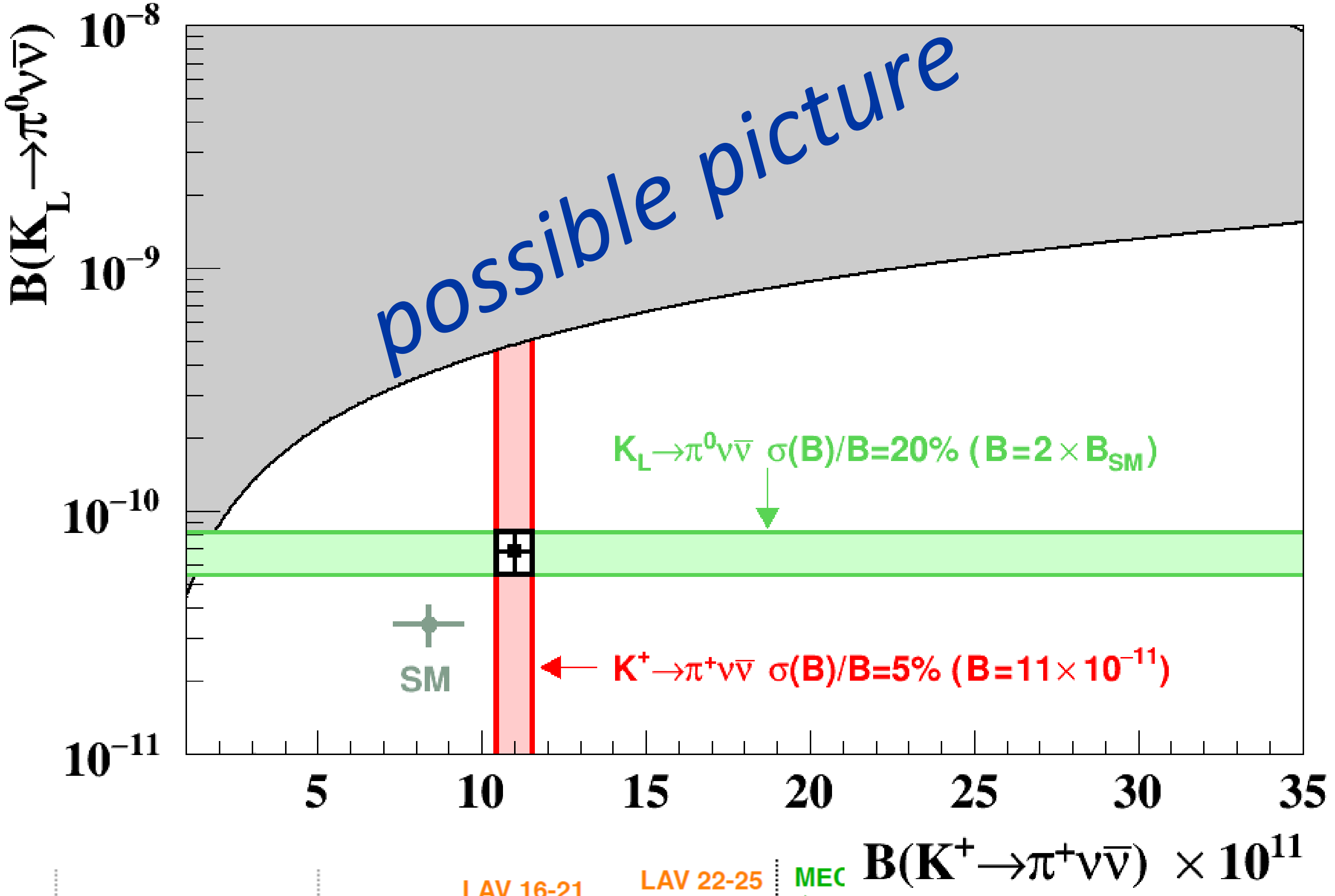
Future (≥2025)

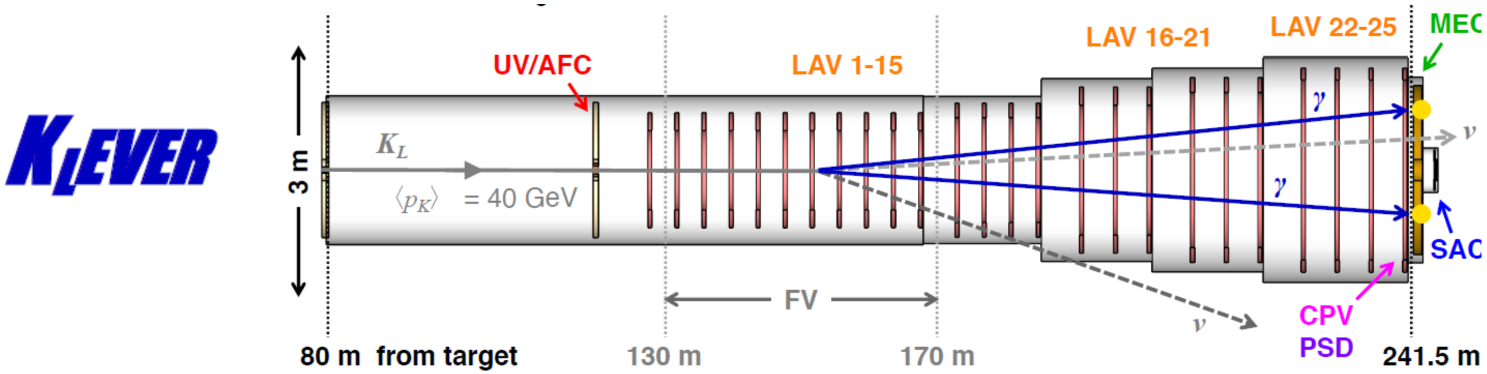
K Facility at CERN:

- K^+/K^0
- NA62-like / KLEVER

KOTO (step 2):

- Hardware upgrade



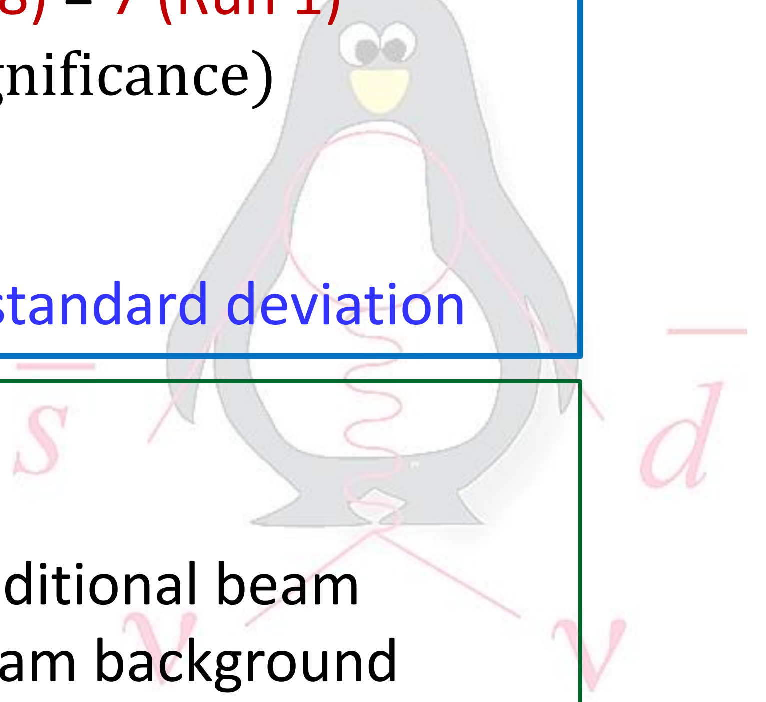


Result summary

Result from the complete Run 1(2016 + 2017 + 2018):

- Observed events: 1 (2016) + 2 (2017) + 17(2018) = 20 (Run 1)
- Expected background ~0.2 (2016) + 1.5 (2017) + 5.3 (2018) = 7 (Run 1)
- $\mathrm{Br}(K^+ \to \pi^+ \upsilon \bar{\upsilon}) = (11.0^{+4.0}_{-3.5}{}_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}}) \cdot 10^{-11}$ (3.5σ significance)
- The most precise measurement of the BR obtained so far

The result is compatible with the SM prediction within one standard deviation

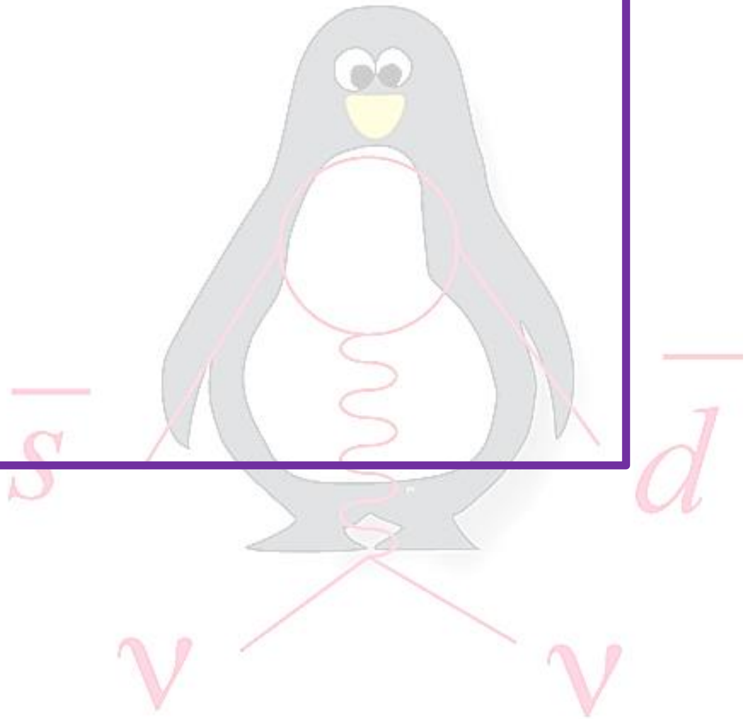


The next Run (2021):

- NA62 will resume data-taking in 2021
- Modifications of the NA62 beam line, installation of an additional beam spectrometer station and a veto counter to reduce upstream background
- New calorimeter downstream of MUV and upstream of the beam dump to further suppress kaon decay background
- More information can be found in the NA62 SPSC addendum

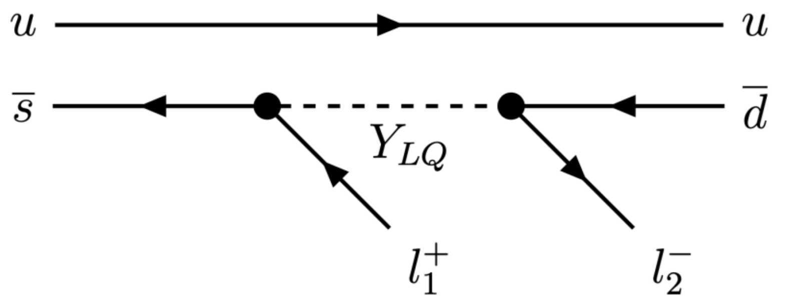
NA62: Broader physics program

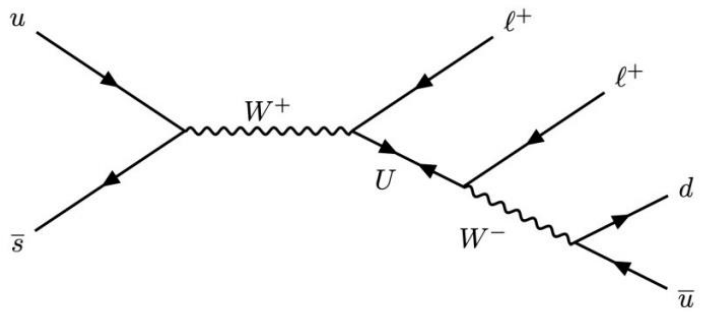
- Rare kaon decays
- LNV/LFV in kaon decays
- Exotic searches:
  - HNL searches [PLB 807 (2020) 135599]
  - Dark Photon [10.1007/JHEP05(2019)182]
  - Axion-like particle

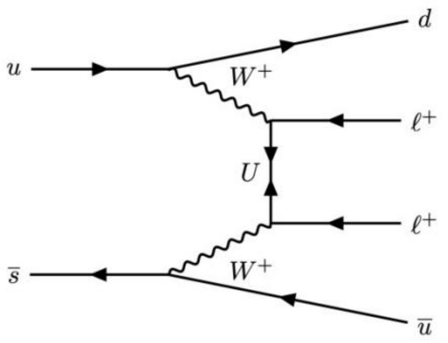


LFV & LNV in Kaon Decays

Violation of LN and LF conservation laws predicted in BSM models (for example via Majorana neutrinos or leptoquark)







Previous experimental results:

- BR($K^+ \to \pi^- e^+ e^+$) < 6.4×10^{-10} @ 90% CL
  [BNL E865 : PRL 85 2877 (2000)]
- BR($K^+ \to \pi^- \mu^+ \mu^+$) < 8.6×10^{-11} @ 90% CL
  [CERN NA48/2 : PL B769 67 (2017)]

LNV/LFV searches in NA62:

- 2017 + 2018 data
- Blind analysis
- Normalization to SM decays ($K^+ \to \pi^+ l^+ l^-$ and $K^+ \to \pi^+ \pi^+ \pi^-$)
- Acceptance:
  - ~5% for $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi e \mu$
  - 10% for $K^+ \to \pi^- \mu^+ \mu^+$
- Main background is due to pion mis-identification and pion decays in flight

LFV & LNV results

Decay	Previous BR upper limit @ 90% CL [PDG]	*NA62* BR upper limit @ 90% CL	
$K^+ \to \pi^-\mu^+\mu^+$	8.6×10^{-11}	$\mathbf{4.2\times10^{-11}}$	Improve by factor **2** with **17 data** [*PLB 797 (2019) 134794*]
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	$\mathbf{2.2\times10^{-10}}$	Improve by factor **3** with **17 data** [*PLB 797 (2019) 134794*]
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	$\mathbf{4.2\times10^{-11}}$	Improve by factor **12** with **17+18 data**
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	$\mathbf{6.6\times10^{-11}}$	Improve by factor **8** with **17+18 data**
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}		Not yet competitive with previous dedicated experiment
$K^+ \to \mu^-\nu e^+e^+$	2.1×10^{-8}		Stay tuned… $SES\sim1\times10^{-10}$ [17 data]
$K^+ \to e^-\nu\mu^+\mu^+$	No previous limit…		Stay tuned… $SES\sim5\times10^{-11}$ [17 data](first search)

Exotic searches example: HNL

A generic possibility of **k** sterile neutrino mass states:

$$\nu_\alpha = \sum_{i=1}^{3+k} U_{\alpha i}\nu_i \quad (\alpha = e, \mu, \tau).$$

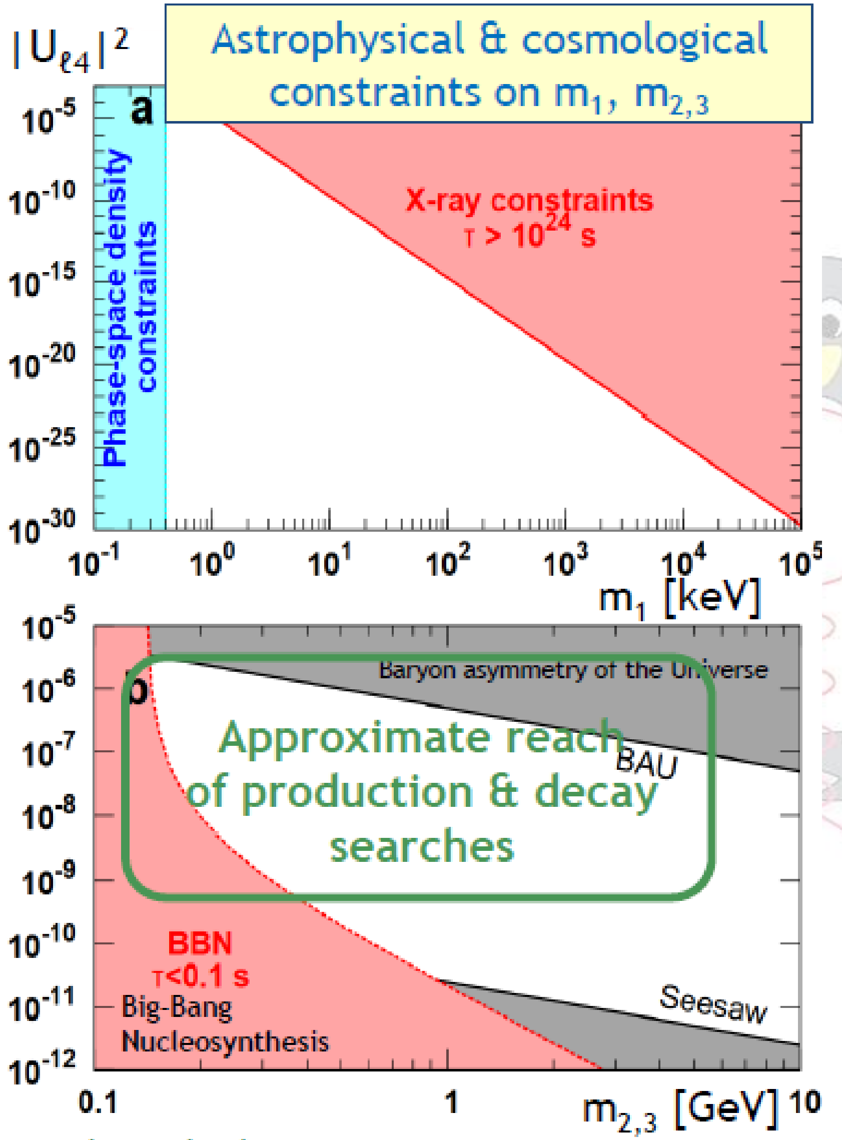
The "neutrino portal" is motivated by its relation to neutrino mass generation.

The νMSM: the most economical theory accounting for ν masses and oscillations, baryogenesis, and dark matter.

[Asaka, Blanchet, Shaposhnikov, PLB 631 (2005) 151]

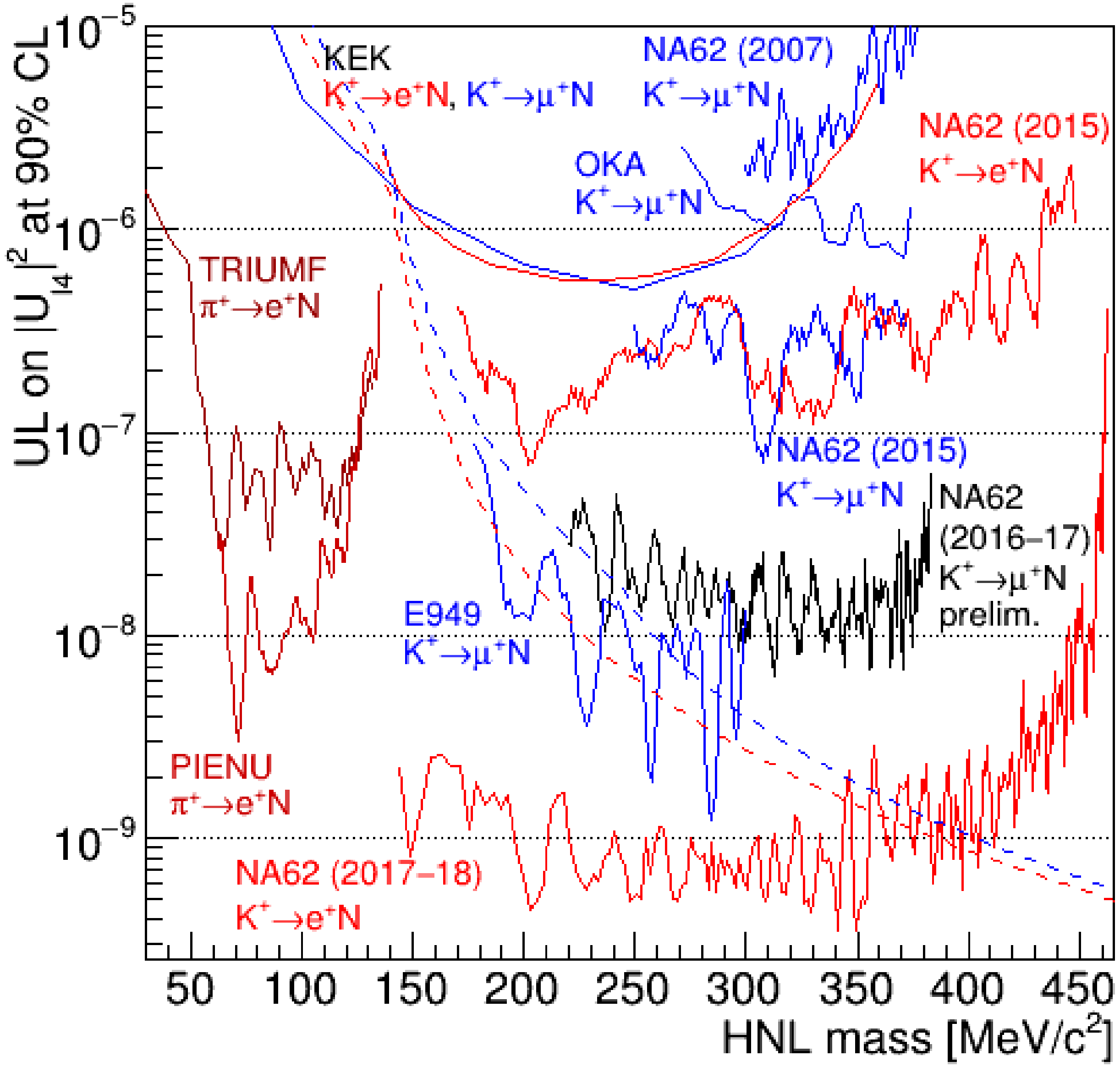
Three Heavy Neutral Leptons (HNLs): **m_1~10 keV** [DM candidate]; **$m_{2,3}$~1 GeV/c^2**.

GeV-scale HNLs can be observed via their **production** and **decay**.



Shaposhnikov, JHEP 0808 (2008) 008
Boyarsky et al., Ann.Rev.Nucl.Part.Sci.59 (2009) 191

HNL summary



- Full 2016 - 18 data set for $|U_{e4}|^2$, ~1/3 of the data set for $|U_{\mu4}|^2$.
- Improvement over earlier production searches by up to two orders of magnitude in terms of $|U_{\ell4}|^2$.
- For $|U_{e4}|^2$, the BBN-allowed range is excluded up to 340 MeV.

[PLB 807 (2020) 135599]

- For $|U_{\mu4}|^2$, the sensitivity approaches the E949 one; the search extends to 383 MeV.

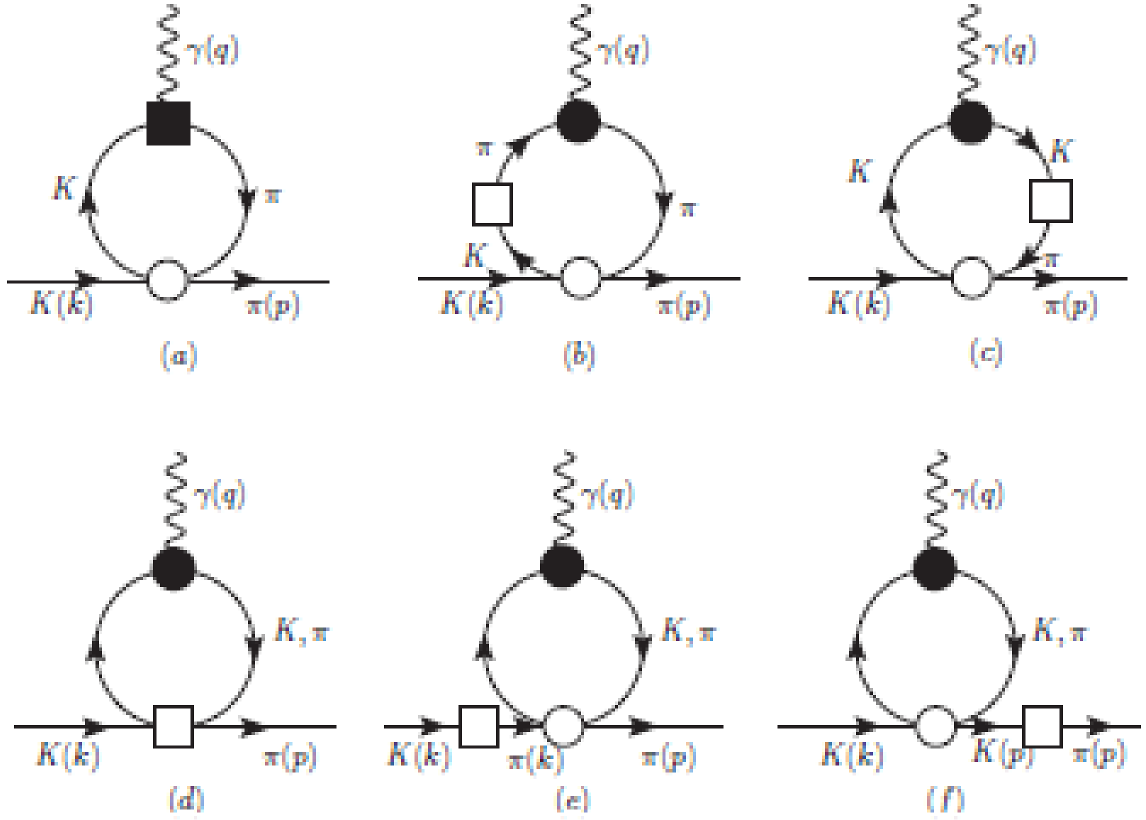
Rare Kaon Decay example: ($K^+ \to \pi^+\mu^+\mu^-$)

FCNC decay described in the scope of ChPT, mediated by one photon exchange $K^+ \to \pi^+ \gamma^*$

[Nucl. Phys. B291 (1987) 692–719], [Phys. Part. Nucl. Lett. 5 (2008) 76–84]

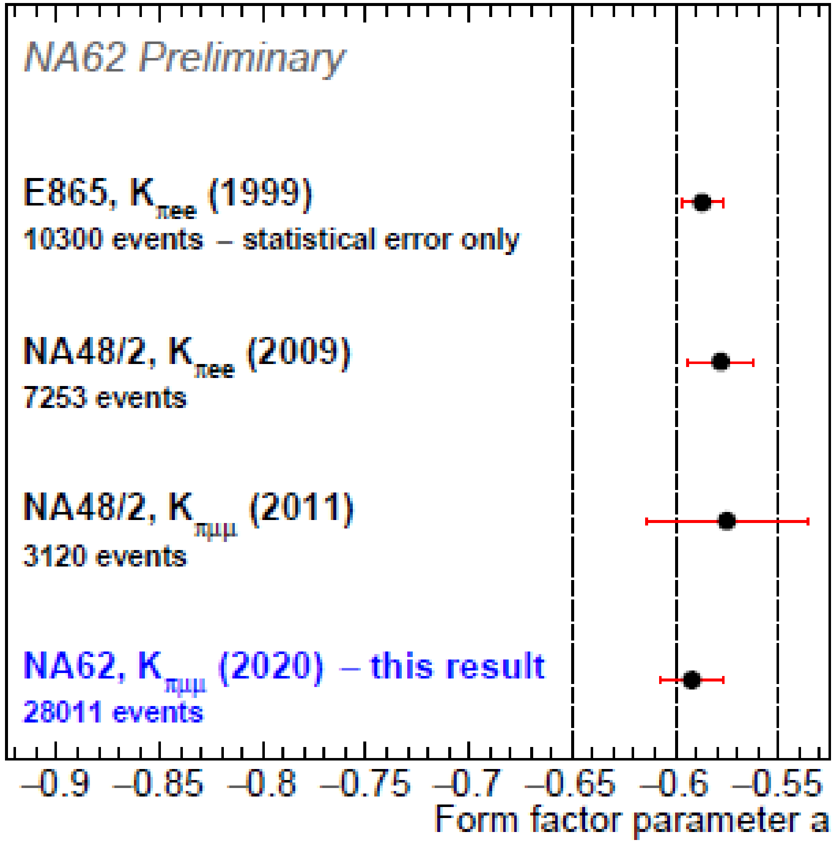
Together with $K^+ \to \pi^+ e^+ e^-$ allow to Test the Lepton Flavour Universality. A precise measurement of these decays could provide an evidence complementary to the B anomaly seen by LHCb.

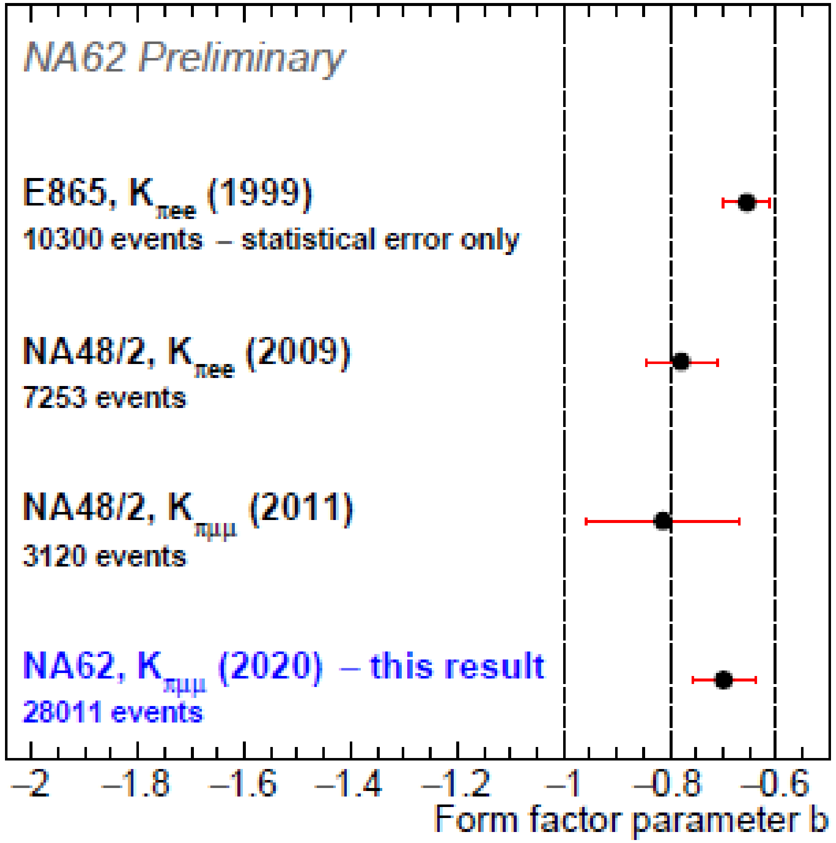
[Phys. Rev. Lett. 122, 191801 (2019)]
[JHEP 02, 049 (2019)]



Preliminary result $K^+ \to \pi^+\mu^+\mu^-$

- $N_K \approx 6.76 \cdot 10^{12}$ using the 2017+2018 data sample
- Preliminary $K_{\pi\mu\mu}$ result consistent with $K_{\pi ee}$ FF parameters → no tension in LFU observed





$$Br(K^+ \to \pi^+\mu^+\mu) = (9.27 \pm 0.11) \cdot 10^{-8}$$

E865, Kee: **[Phys. Rev. Lett. 83 (1999) 4482-4485]**
NA48/2, Kee: **[Phys. Lett. B 677 (2009) 246-254]**
NA48/2, K: **[Phys. Lett. B 697 (2011) 107-115]**

LFU Fellini project

I have started recently a FELLINI project that aims to measure precisely (enhancing the precision by a factor 5) the form factor parameters a and b, by collecting O(200k) candidates of $K^+ \to \pi^+ \mu^+ \mu^-$ and $K^+ \to \pi^+ e^+ e^-$ decays.

Current limitations:

- Statistic error: during the 2016-2018 run there was a trigger downscaling conditions that limited the collected statistic;
- Systematics error:
  - The main source of systematic error is due to the tracks' reconstruction algorithm (optimized for one track events, mis-reconstruction due to accidental hits);
  - A secondary source of error is due to the trigger inefficiency: STRAW tracker high level trigger and charged hodoscope hardware trigger.

$$a^{\mu\mu}_{NA62} = -0.564 \pm 0.034_{stat} \pm 0.024_{syst} \pm 0.001_{ext} = -0.564 \pm 0.042$$

$$b^{\mu\mu}_{NA62} = -0.797 \pm 0.118_{stat} \pm 0.114_{syst} \pm 0.003_{ext} = -0.797 \pm 0.164$$

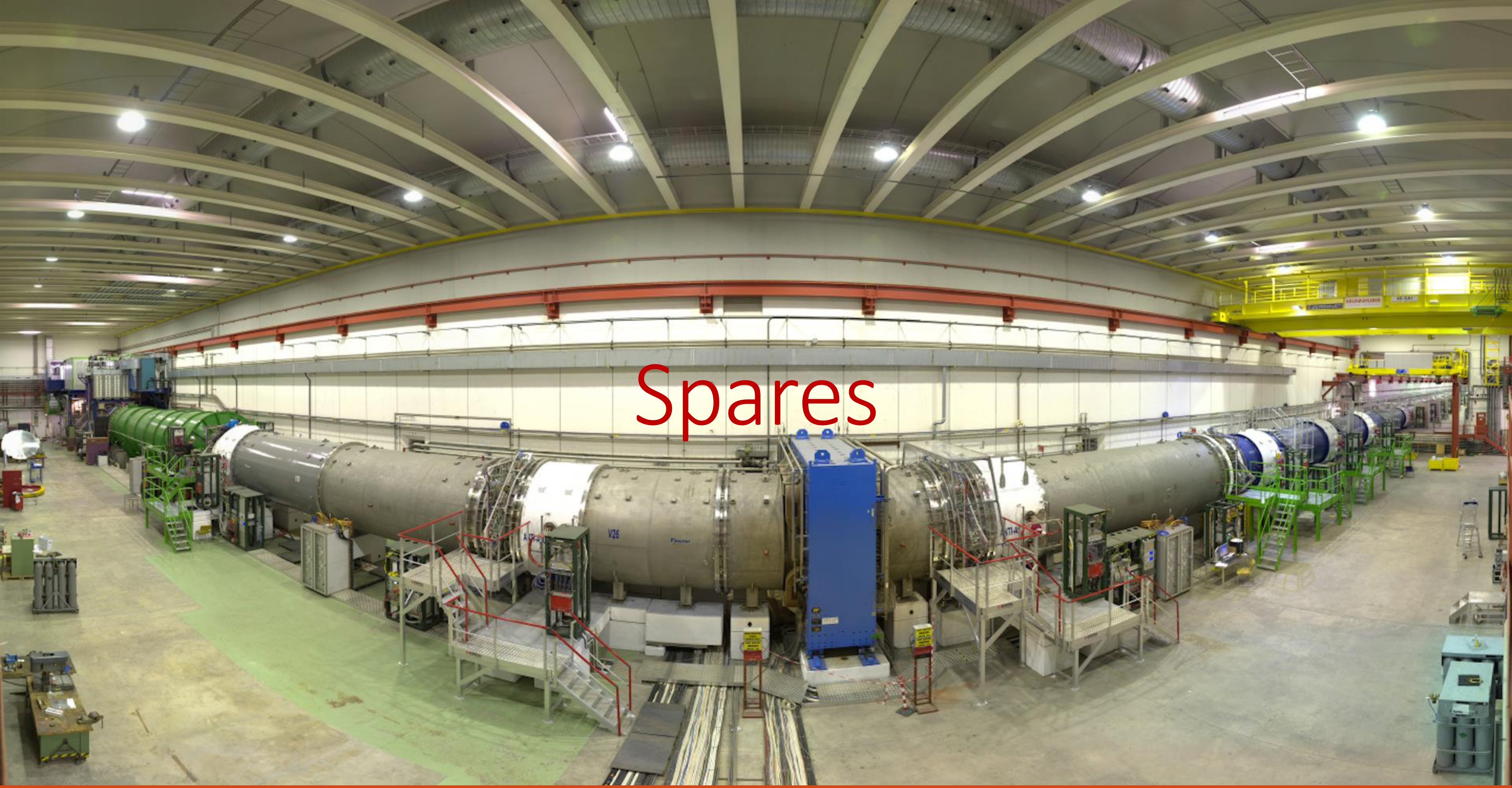
Conclusion

$K^+ \rightarrow \pi^+\upsilon\bar{\upsilon}$:

- Result from the complete Run 1(2016 + 2017 + 2018) compatible with the SM prediction within one standard deviation
- $Br(K^+ \rightarrow \pi^+\upsilon\bar{\upsilon}) = (11.0^{+4.0}_{-3.5}{}_{stat} \pm 0.3_{syst}) \cdot 10^{-11}$ (3.5σ significance)
- The most precise measurement of the BR obtained so far

- Upper limit improved for LFV and LNV channels ($K^+ \rightarrow \pi^- l^+ l^+$ and $K^+ \rightarrow \pi e \mu$)
- $|U_{\mu 4}|^2$ and $|U_{e4}|^2$ limit improved for the HNL
- Preliminary $K_{\pi\mu\mu}$ result consistent with $K_{\pi ee}$ FF parameters

Spares



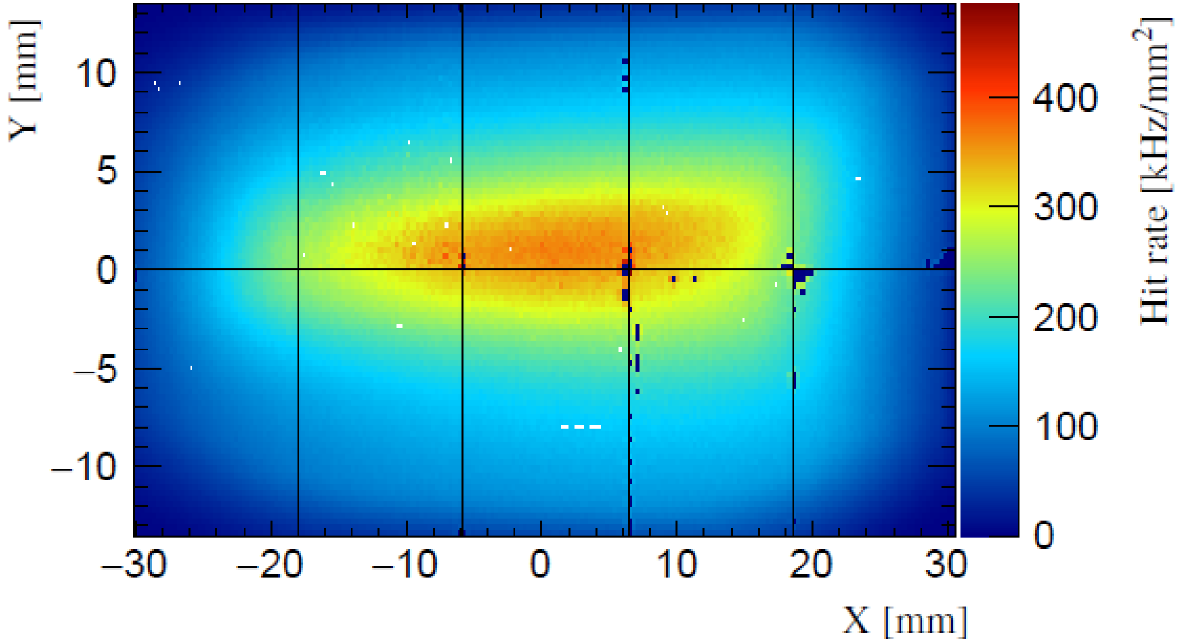
GigaTracker (GTK)

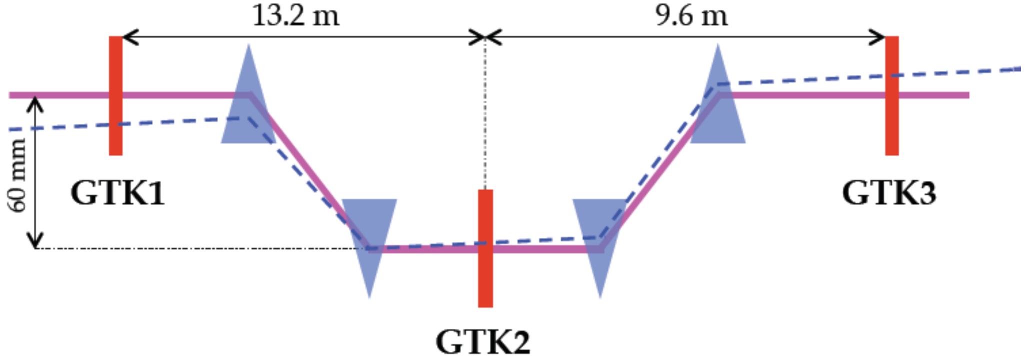
Beam Conditions:

- Overall Rate 750 MHz
- In beam centre 140 KHz/pixel

Precision:

- Hit Time resolution < 200 ps
- Direction resolution = 16 μrad
- Momentum resolution = 0.2%

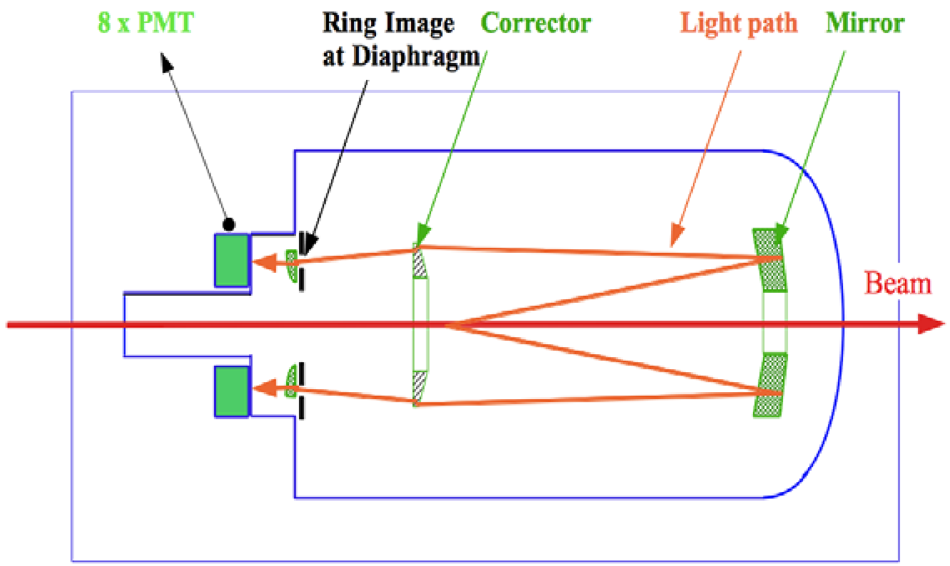




Overview

- 18000 pixel/station (200 x 90)
- 300 x 300 μm^2
- Thicknes = 500 μm (< 0.5% X_0)
- Total area = 62.8 x 27 mm^2

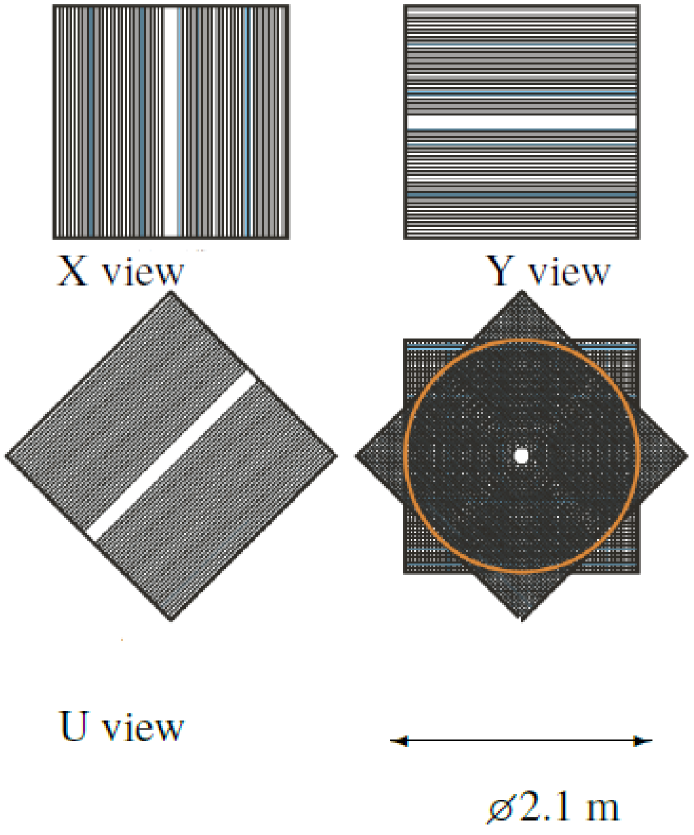
KTAG

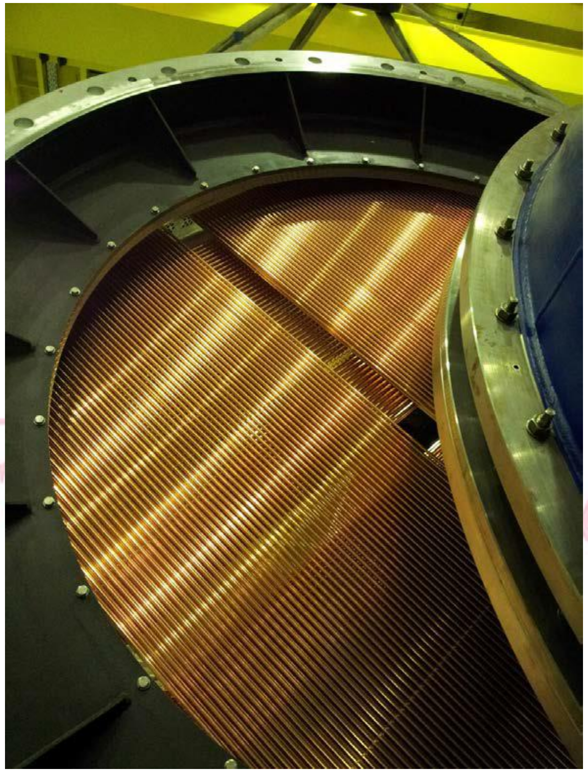


- Filled with nitrogen (N2) at 1.75 bar at room temperature
- total of 3.5 x 10^{-2} X_0 of material
- Can be filled with H_2 (7 x 10^{-3} X_0)
- Time resolution = 70 ps

Straw Tracker

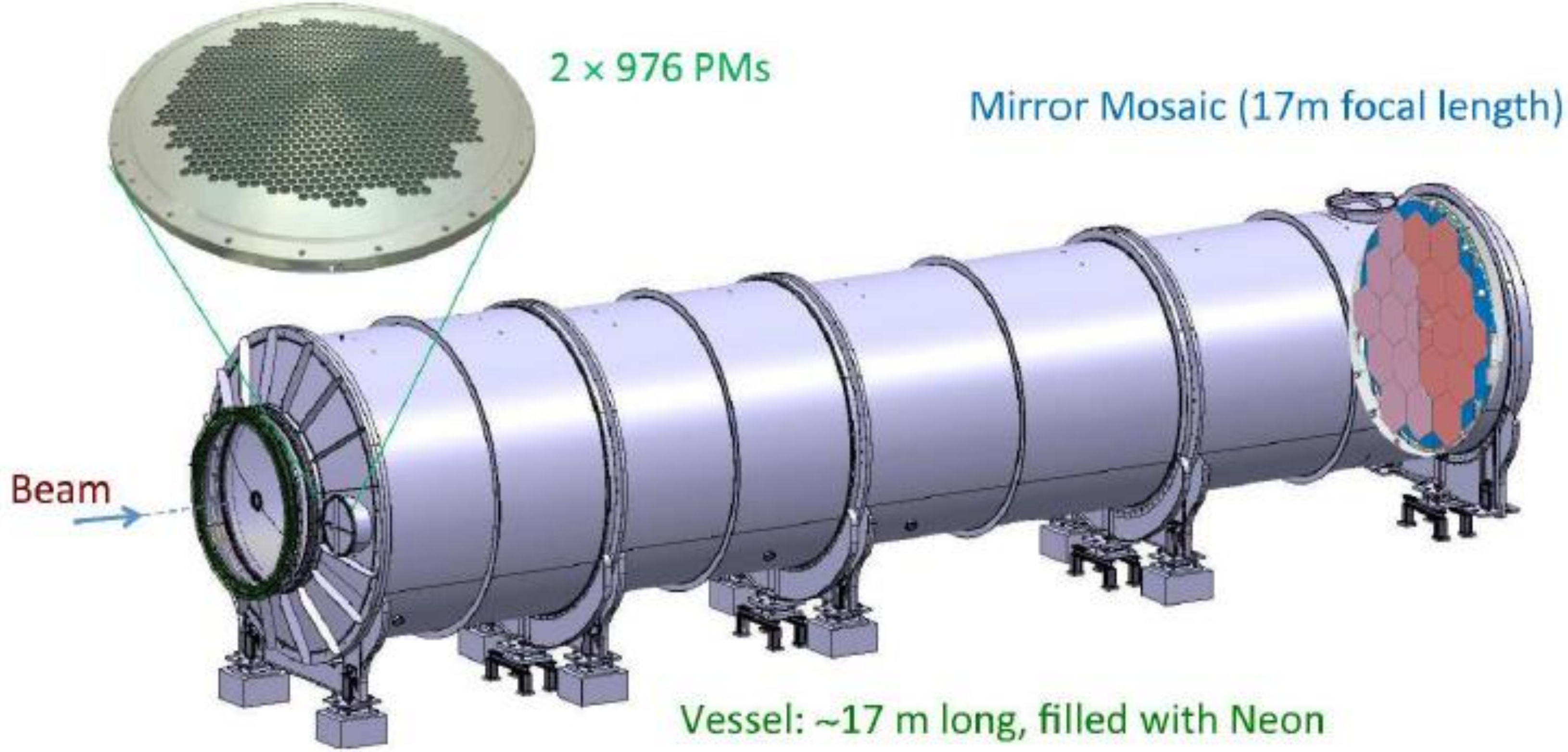
- Ultra-thin Straws installed in Vacuum
- 4 Chambers each measures 4 coordinates (views)
- High accuracy (130µm per View)
- High efficiency
- Straws: 2.1m long and ϕi =9.8mm;
- Straw Material: 50 nm Cu + 20 nm Au on 36 µm of Mylar
- Total 7168 Straws (4x4x4x112)
- Gas: Ar/CO2 (70/30)
- Material Budget of the Spectrometer: 1.8% of X0





RICH

- 17.5 m long
- 4.2 m wide
- 18 hexagonal mirrors
- Neon at about 990 mbar
- Time resolution < 100 ps

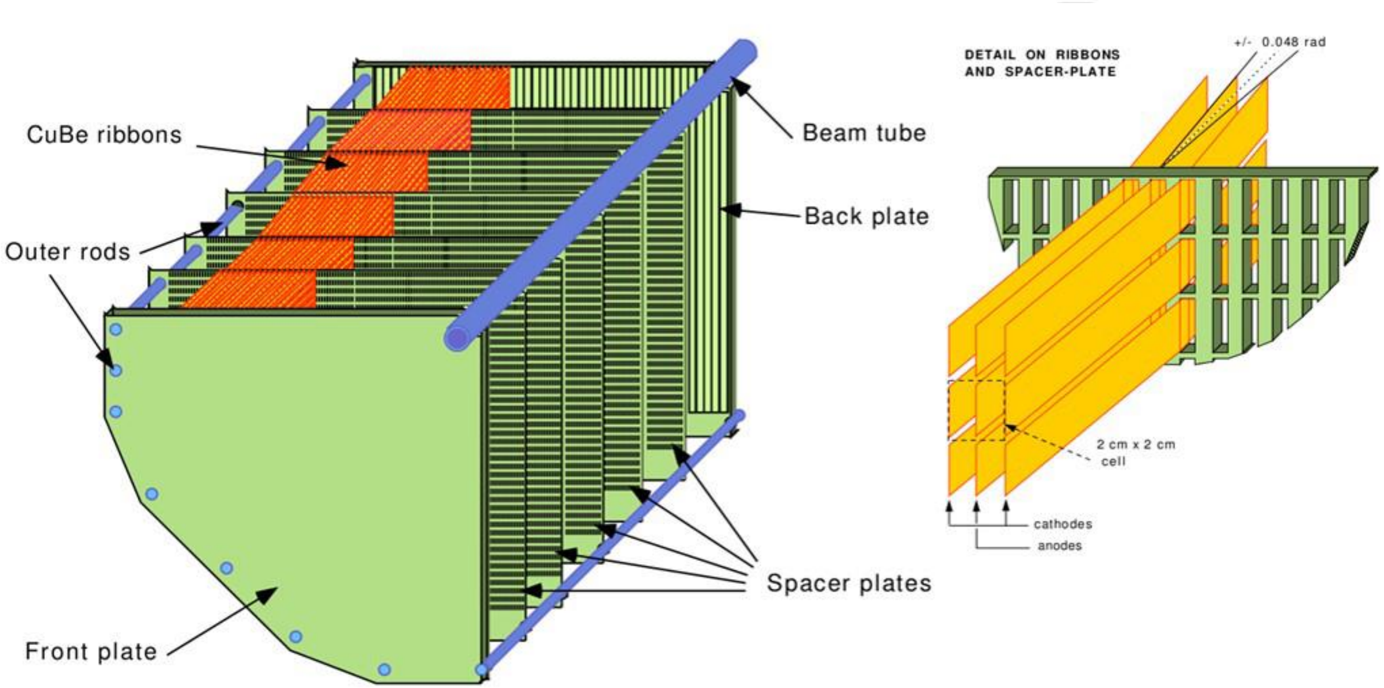


Large-angle veto system (LAV)

- 12 stations
- Full geometric coverage from 8.5 to 50 mrad
- In only 0.2% of $K^+ \rightarrow \pi^+ \pi^0$, decayed in the fiducial region, one photon is outside acceptance
- Inefficiency < 10^{-4}

Liquid Krypton Calorimeter

- quasi-homogeneous calorimeter
- filled with about 9000 litres of liquid krypton at 120 K
- 127 cm depth (27 X_0)
- 13248 longitudinal cells with a cross section of about 2 x 2 cm^2



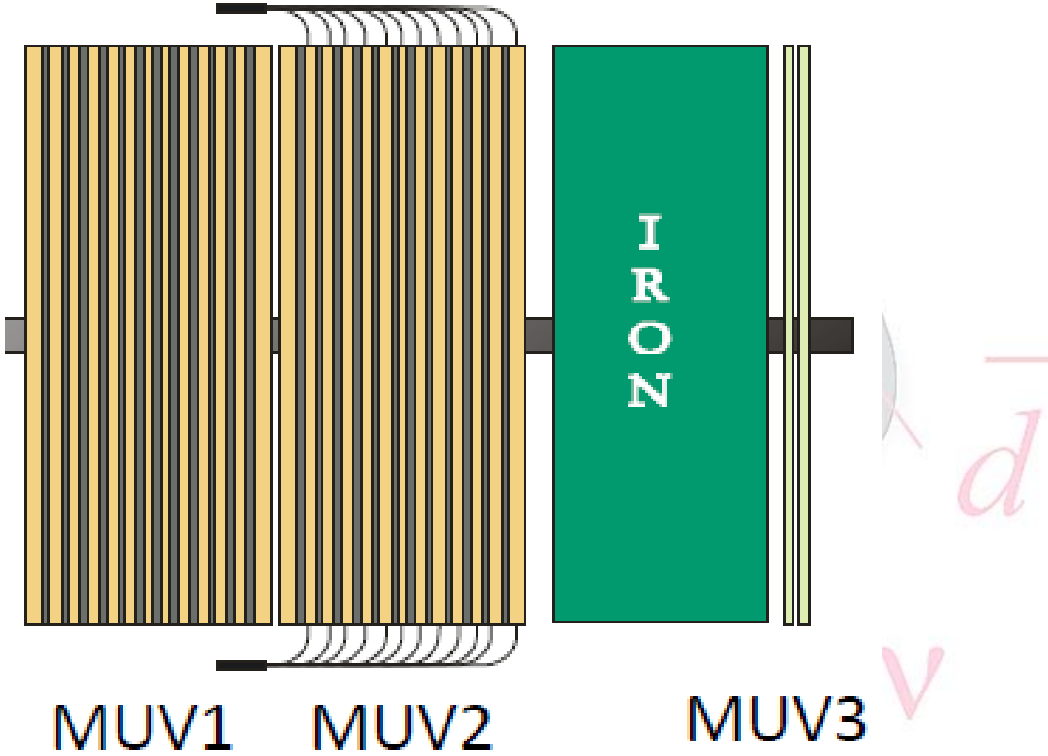
Muon Veto

MUV 1 + 2

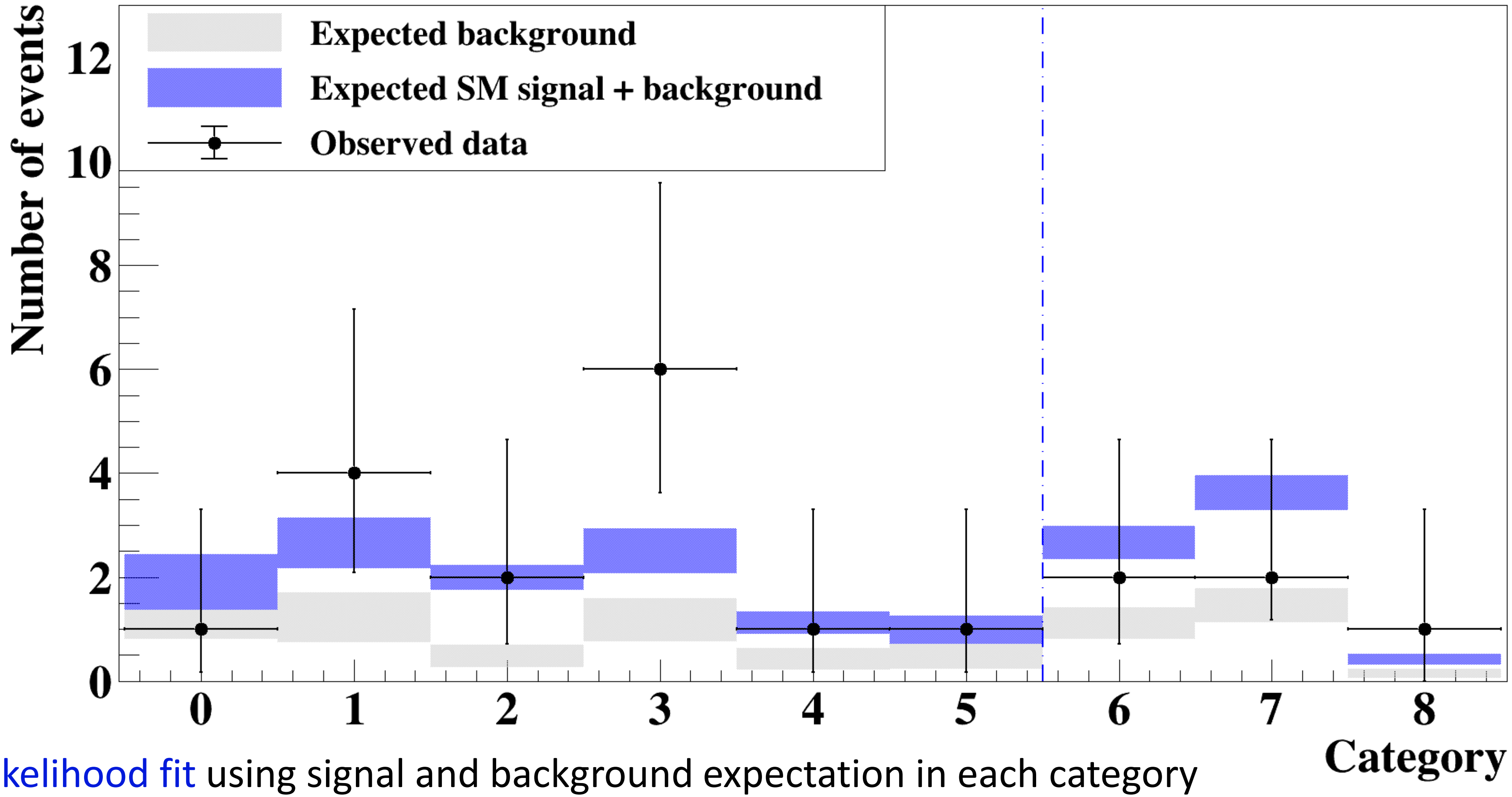
- iron/scintillator sandwich
- 24(MUV1) and 22(MUV2) detection layers
- Alternating horizontal and vertical scintillator strips

MUV3

- After 80 cm of iron
- Fast muon trigger
- Tiles scintillators + PMT

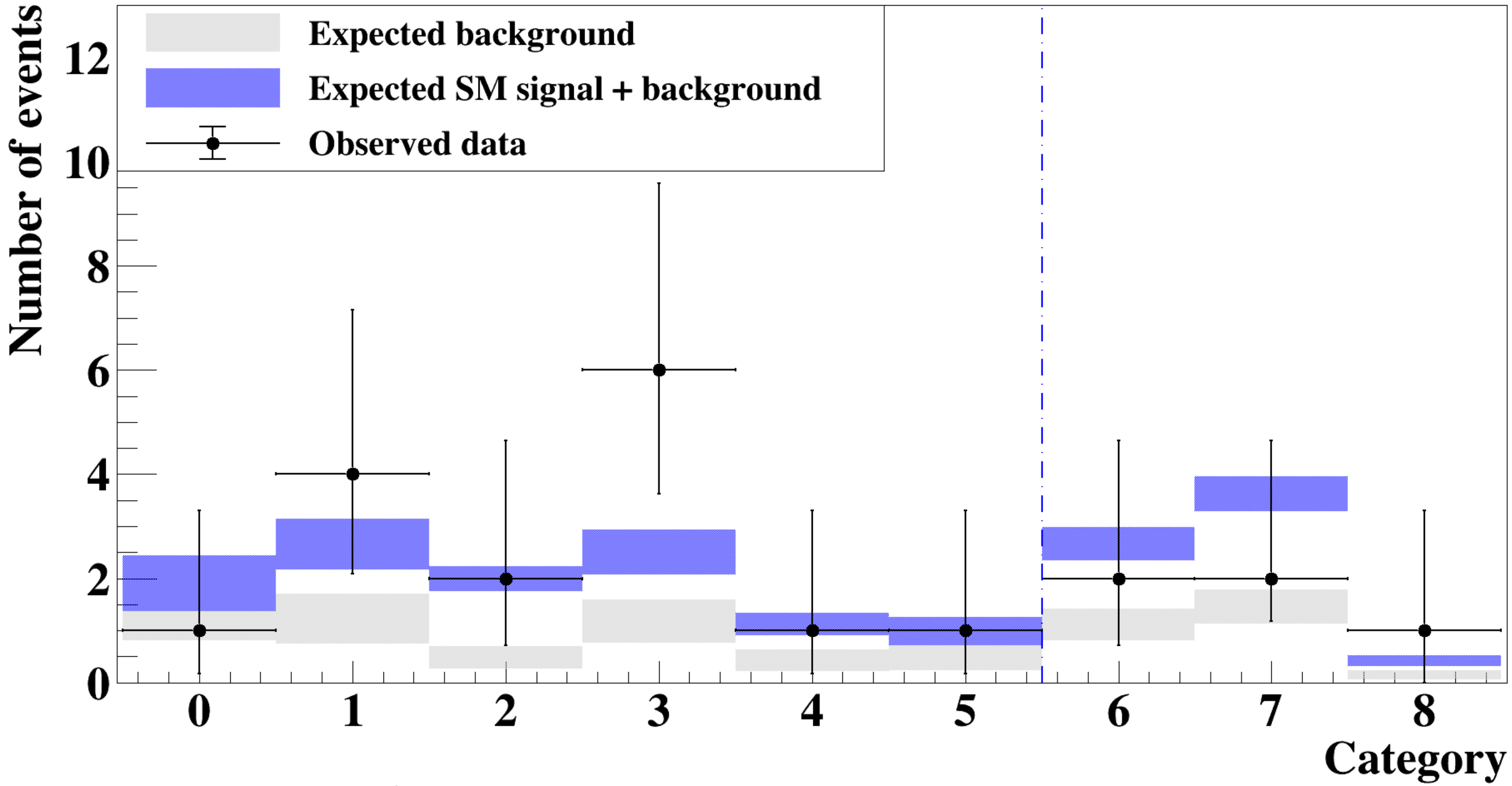


Result



- Maximum likelihood fit using signal and background expectation in each category
- Two samples with different hardware configurations in 2018:
  - 2018_S1 ~80% of the 2018 dataset, 5 GeV/c wide bins from 15-45 GeV/c
  - 2018_S2 ~ 20% of the 2018 dataset, integrated over momentum
  - 2016 and 2017 datasets, integrated over momentum added as separate categories

Result

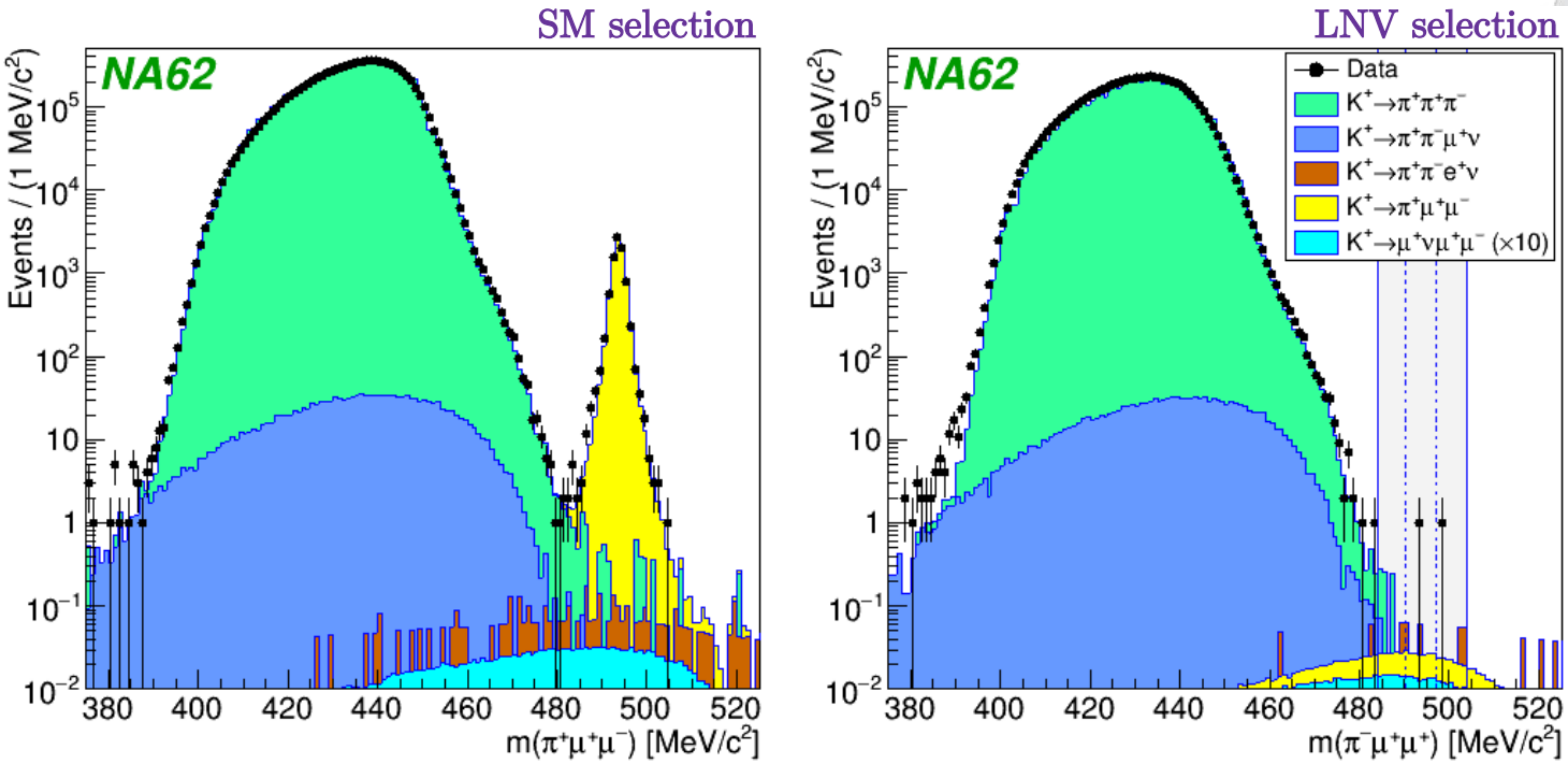


NA62 Run1(2016 + 2017 + 2018) result:

$$Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (11.0^{+4.0}_{-3.5}{}_{stat} \pm 0.3_{syst}) \cdot 10^{-11} \text{ (3.5σ significance)}$$

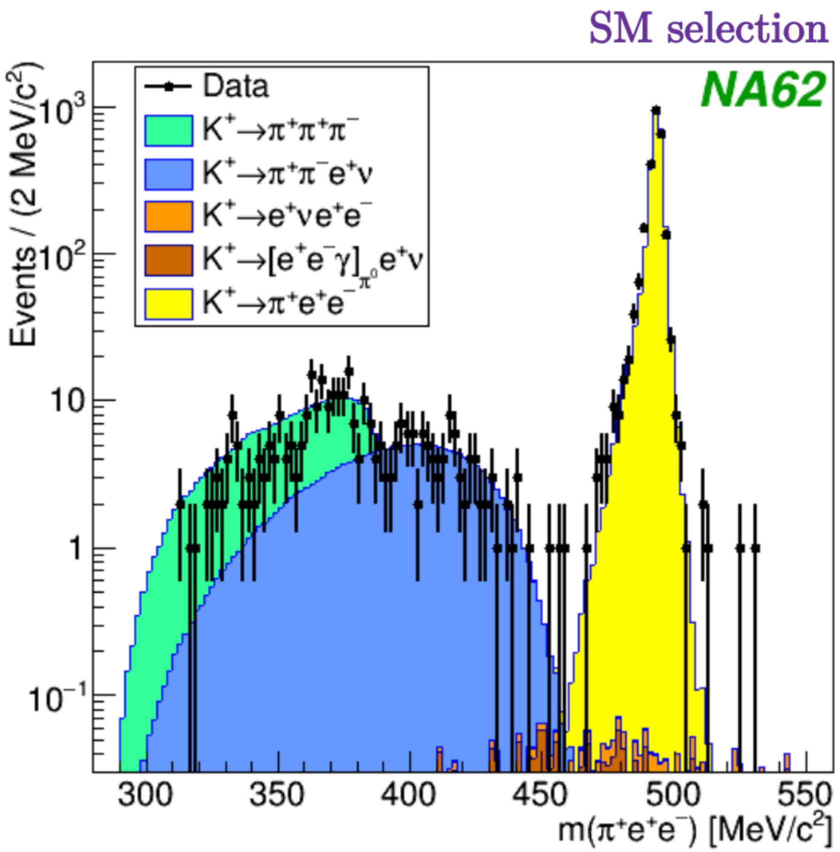
$K^+ \to \pi^- \mu^+ \mu^+$

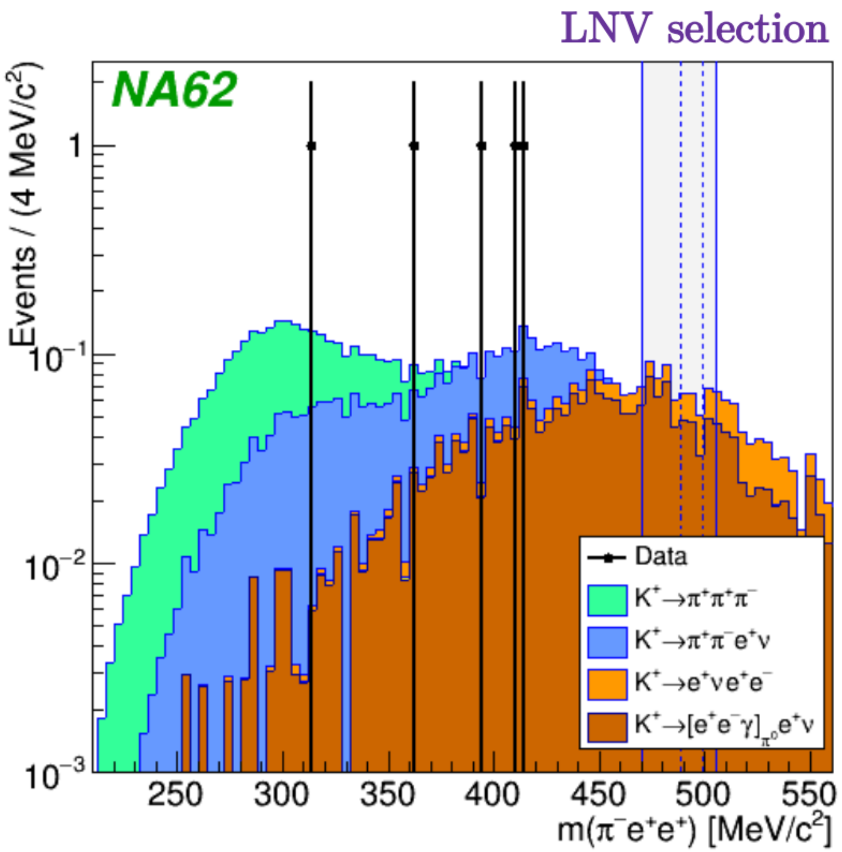
- Expected background in the blinded region: 0.91 ± 0.41
- One candidate observed in the signal region
- $BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \cdot 10^{-11}$ @ *90% CL*



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

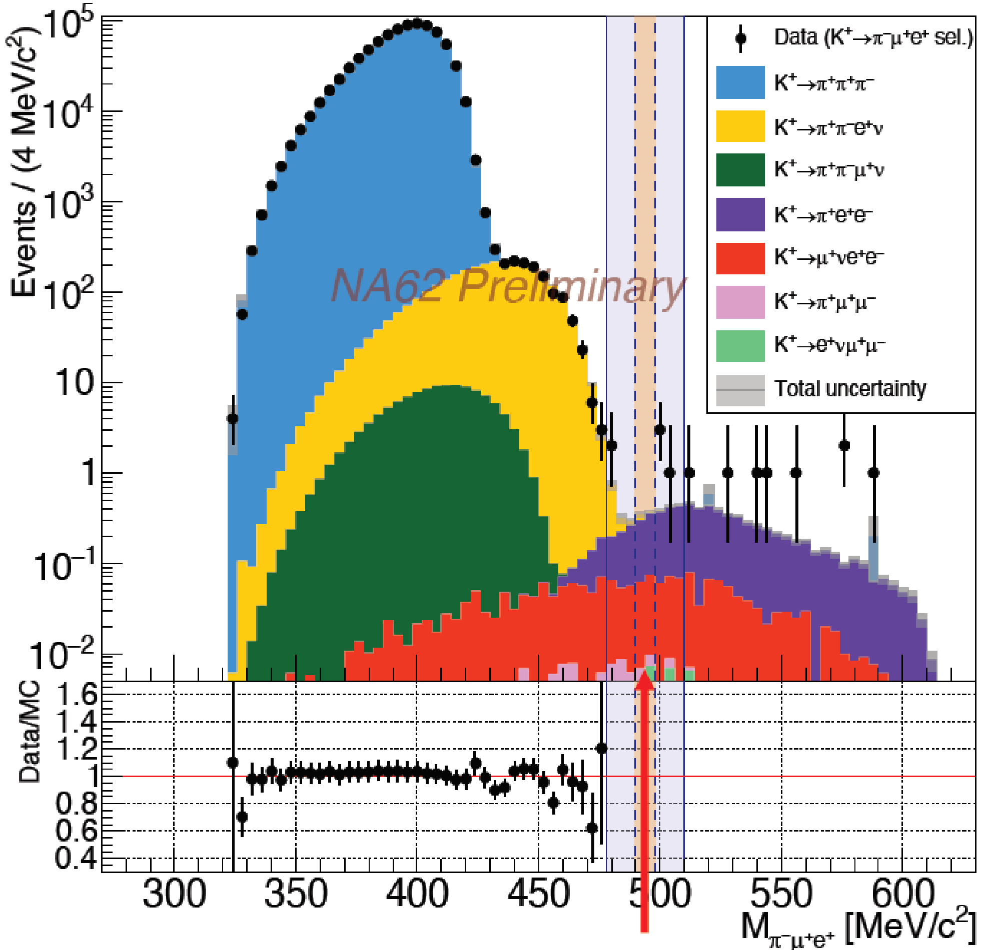
- Expected background in the blinded region: 0.16 ± 0.03
- No candidate observed in the signal region
- $BR(K^+ \to \pi^- e^+ e^+) < 2.2 \cdot 10^{-10}$ @ *90% CL*





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

$BR(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11}$ @ 90% CL

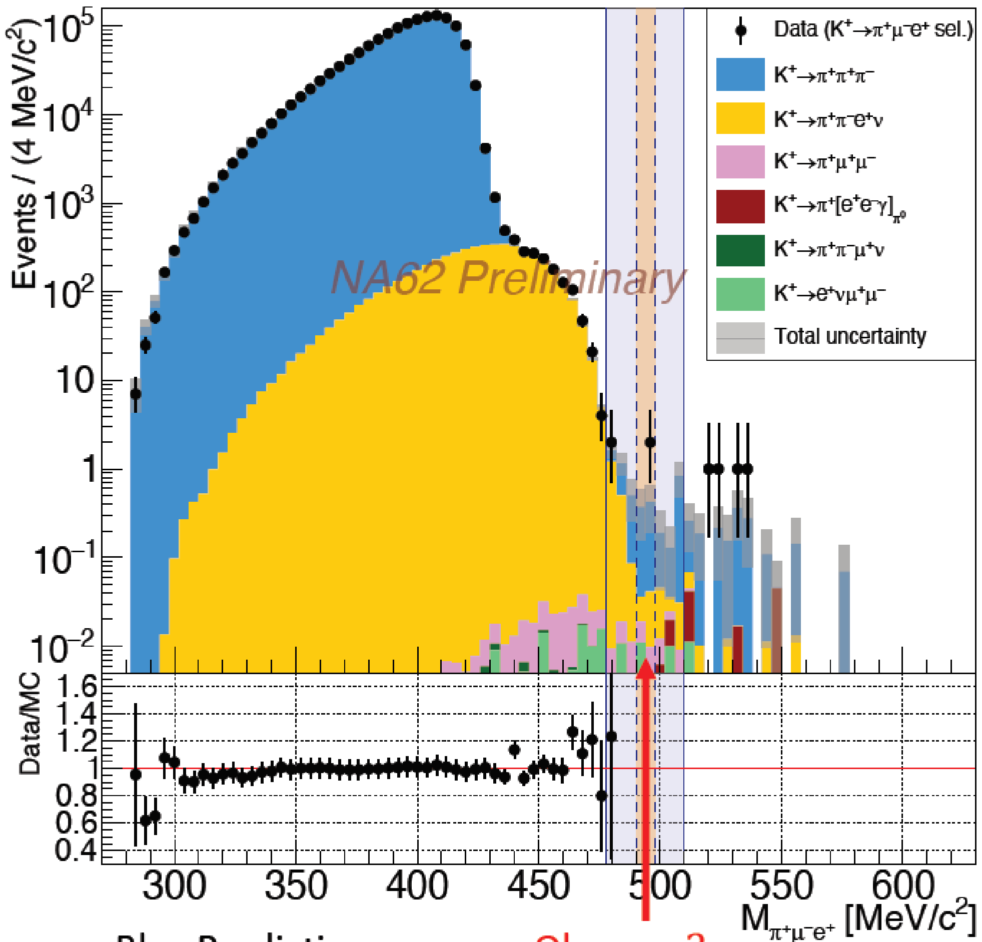


Bkg. Prediction:

$N_{SR}^{tot} = 1.06 \pm 0.20$

Observe 0 events in SR

$BR(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11}$ @ 90% CL



Bkg. Prediction:

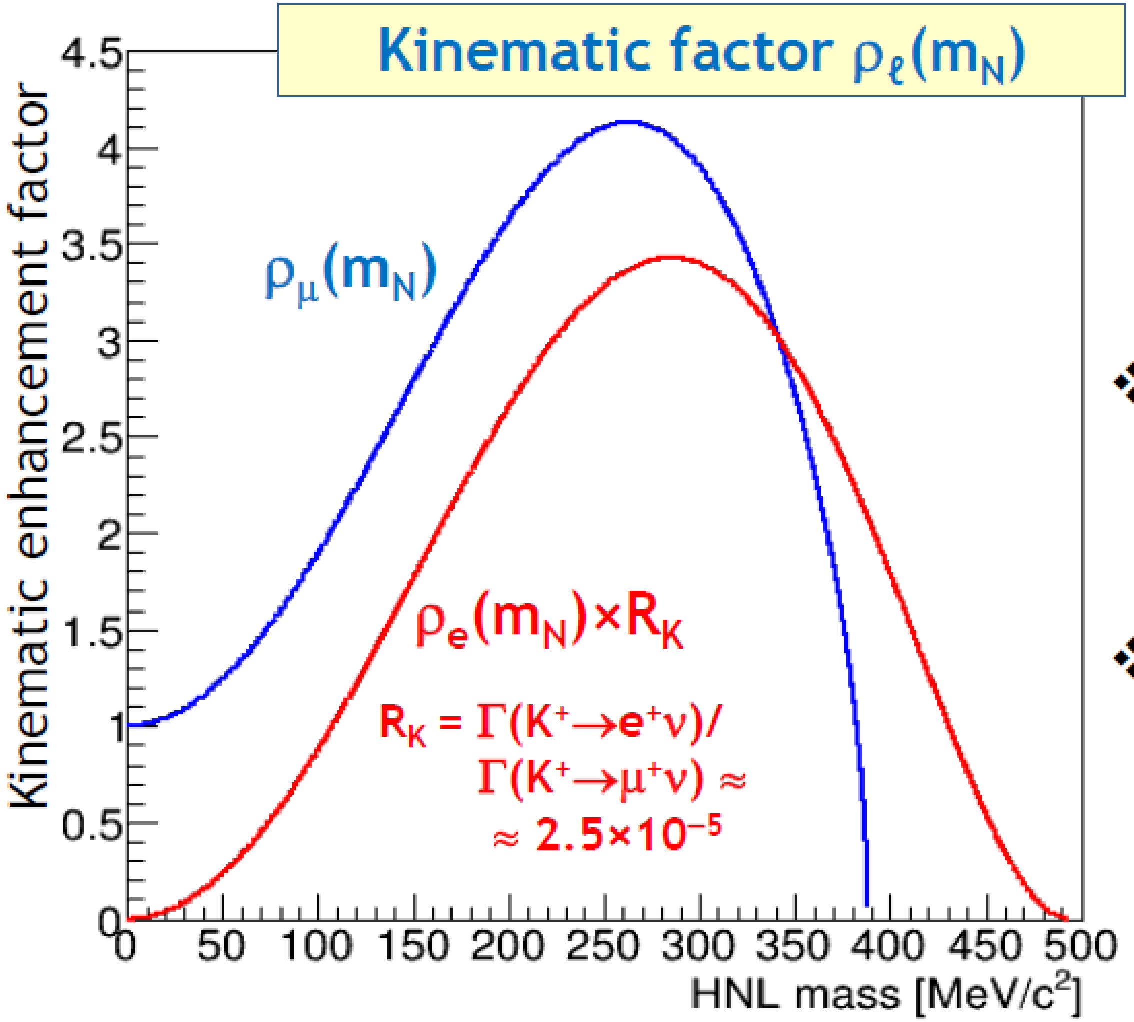
$N_{SR}^{tot} = 0.92 \pm 0.34$

Observe 2 events in SR

HNL production in K^+ decay

$$BR(P^+ \to \ell^+ N) = \underbrace{BR(P^+ \to \ell^+ \nu) \times \rho_\ell(m_N)}_{O(1)} \times |U_{\ell 4}|^2$$

R. Shrock, PLB96 (1980) 159



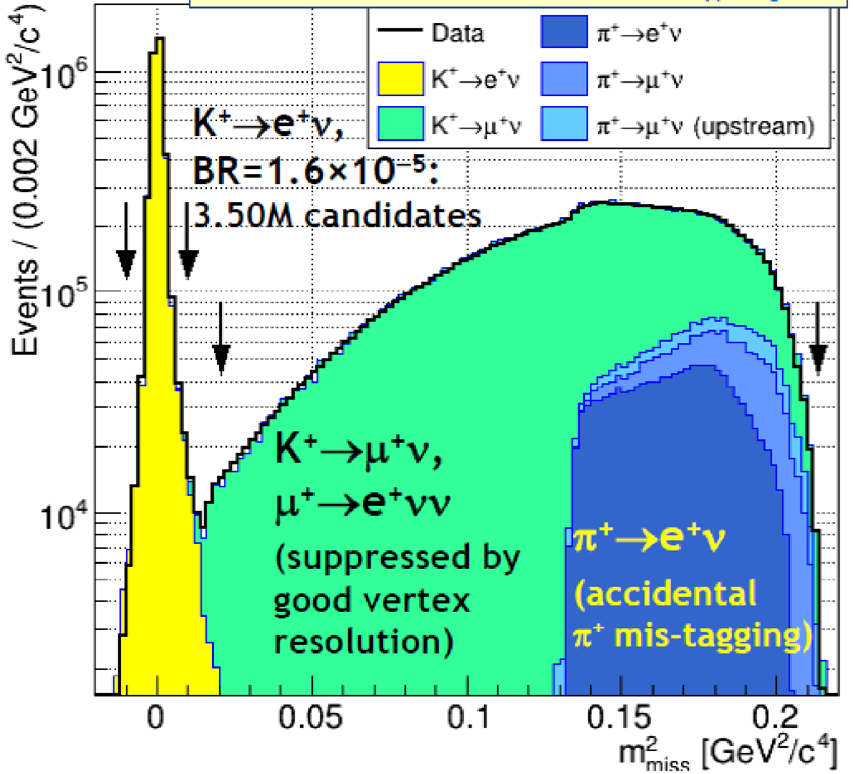
$K^+ \to \ell^+ N$

- HNL production is enhanced kinematically wrt SM decays (except near kinematic endpoints).
- Factor ~10^5 enhancement in the $K^+ \to e^+ N$ case: helicity suppression is relaxed.

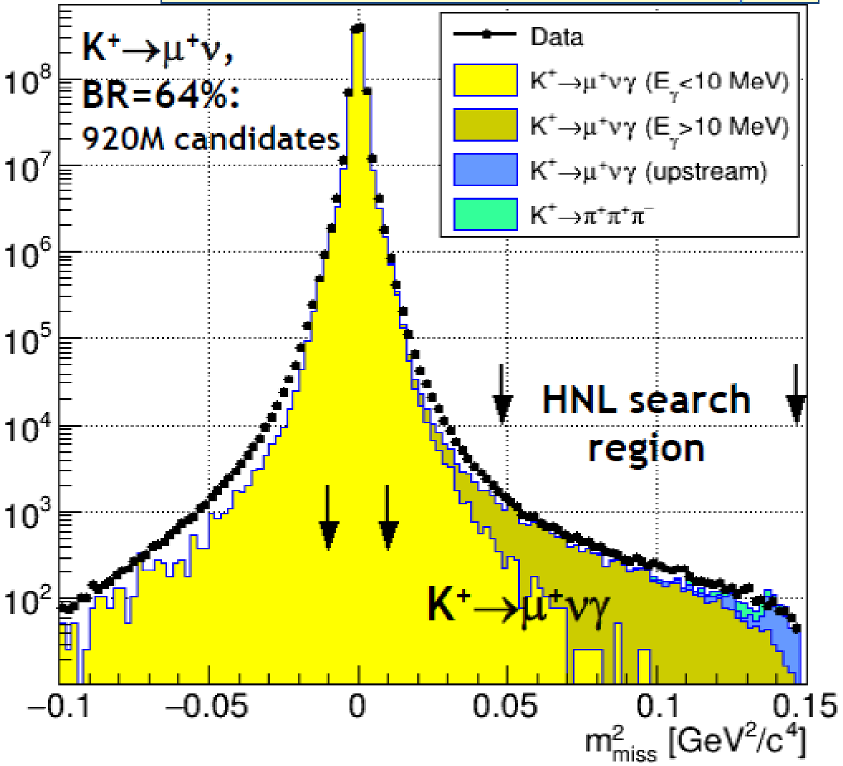
Data Sample

- Number of K^+ in fiducial volume:
  - $(3.52 \pm 0.02) \cdot 10^{12}$ positron case
  - $(4.29 \pm 0.02) \cdot 10^{9}$ muon case
- A spike in the continuous m_{miss} spectrum is a HNL production signal

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

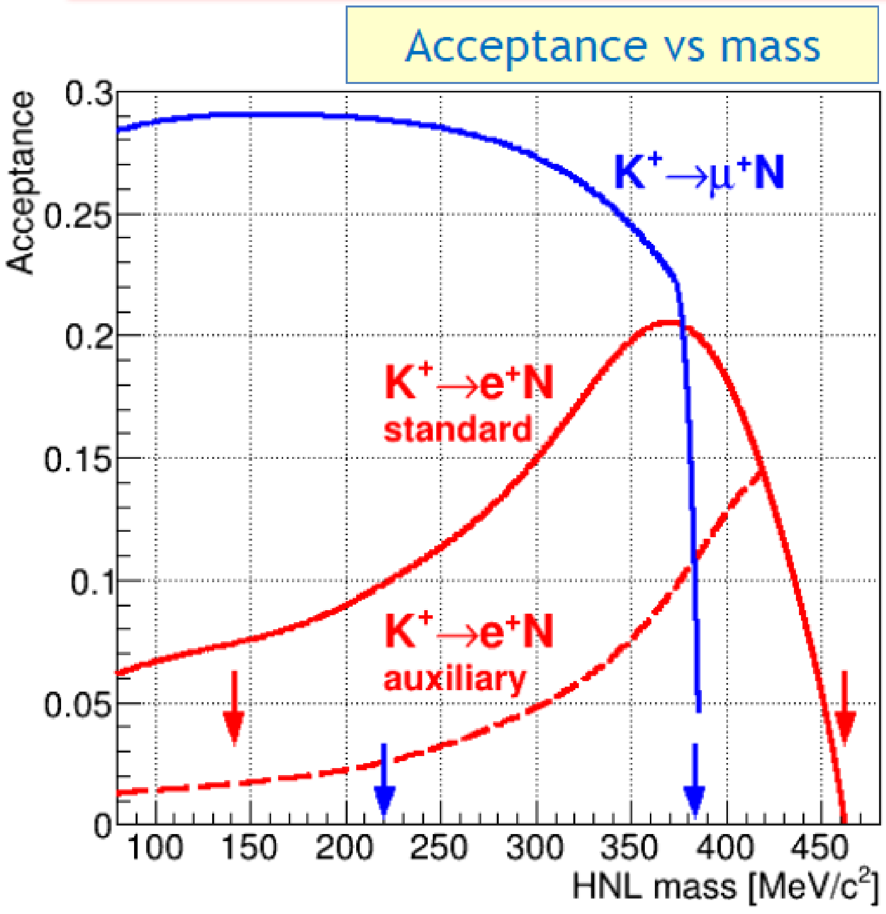


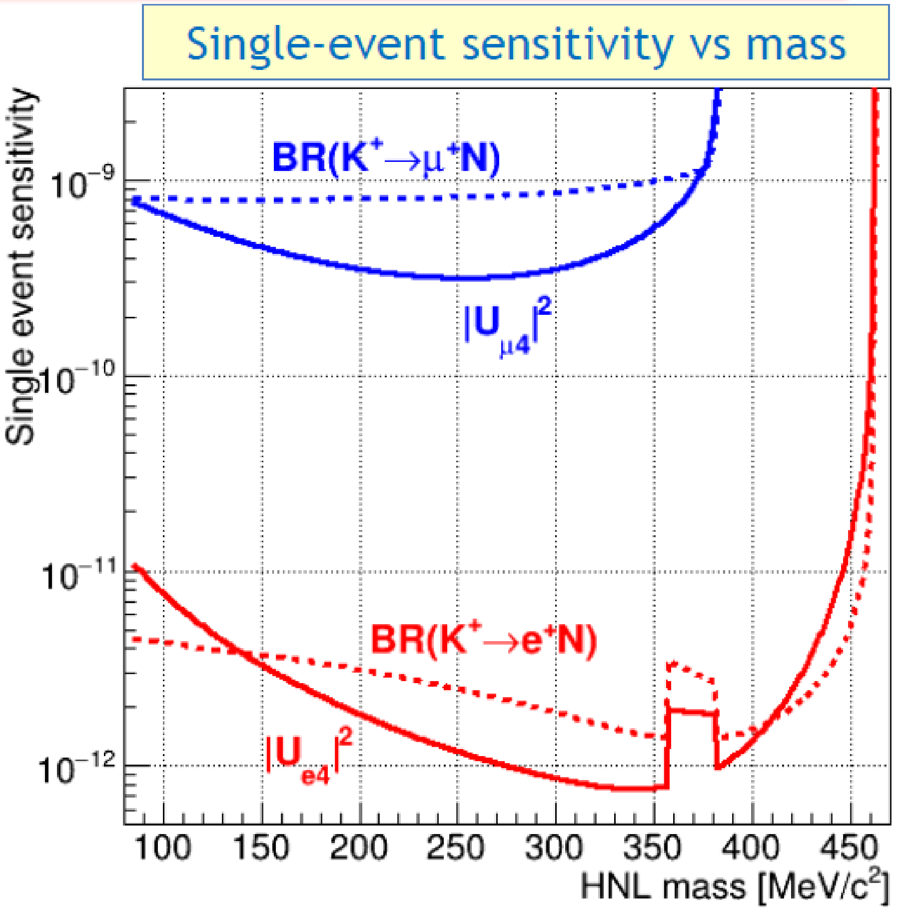
Squared missing mass: $(P_K - P_\mu)^2$



Acceptance & single event sensitivity

- Standard K_{e2} selection: $p_e < 30$ GeV/c
- Auxiliary K_{e2} selection: $p_e < 20$ GeV/c

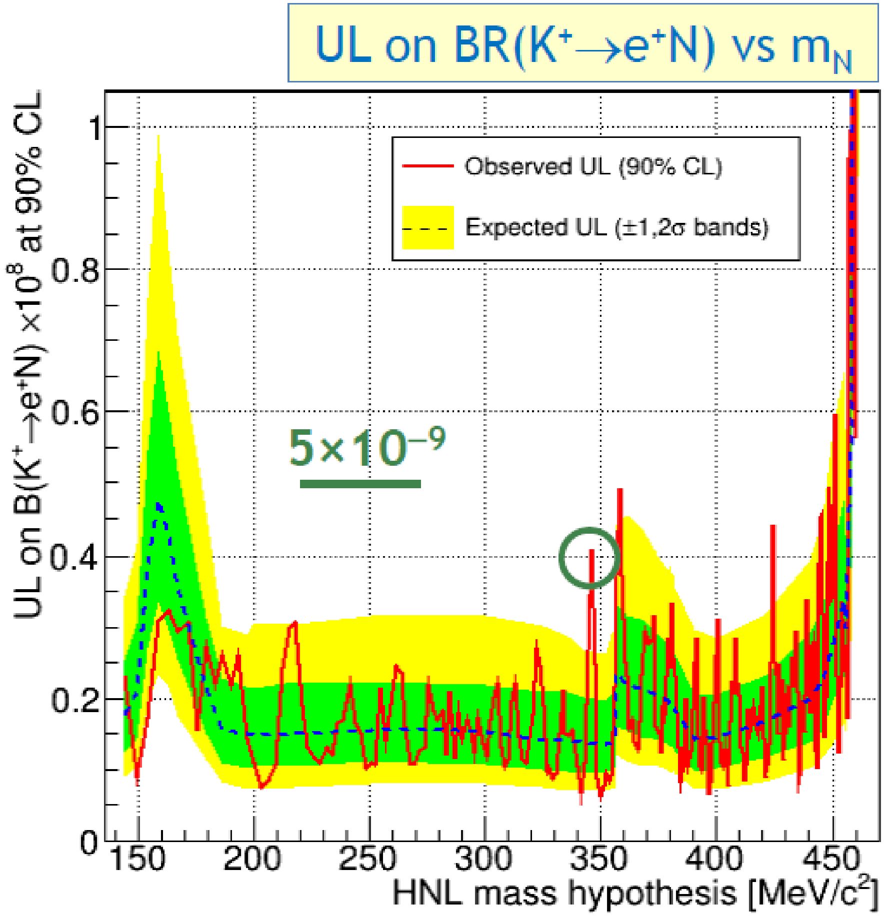


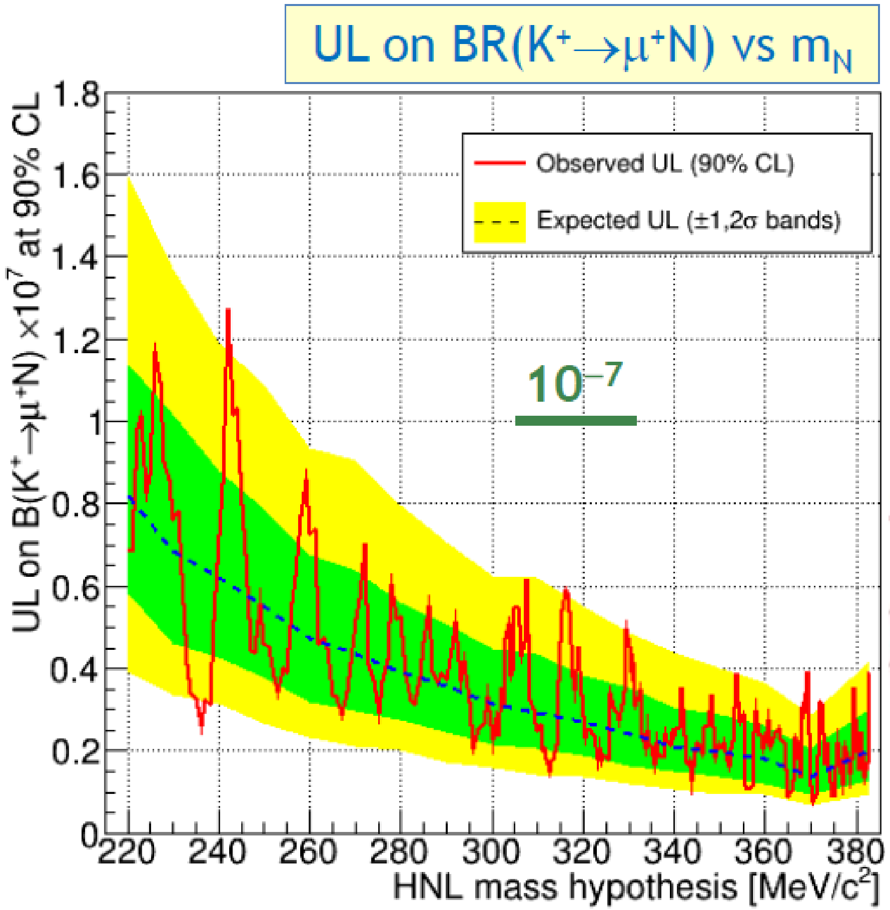


Definitions: $BR_{SES} = 1/(N_K A)$, $|U_{\ell 4}|^2_{SES} = BR_{SES} / [BR(K^+ \to l^+ \upsilon)\, \rho_\ell(m_N)]$.

Upper limits on BR ($K^+ \rightarrow l^+N$)

- 90% CL
- Upper Limit vs HNL mass hypothesis

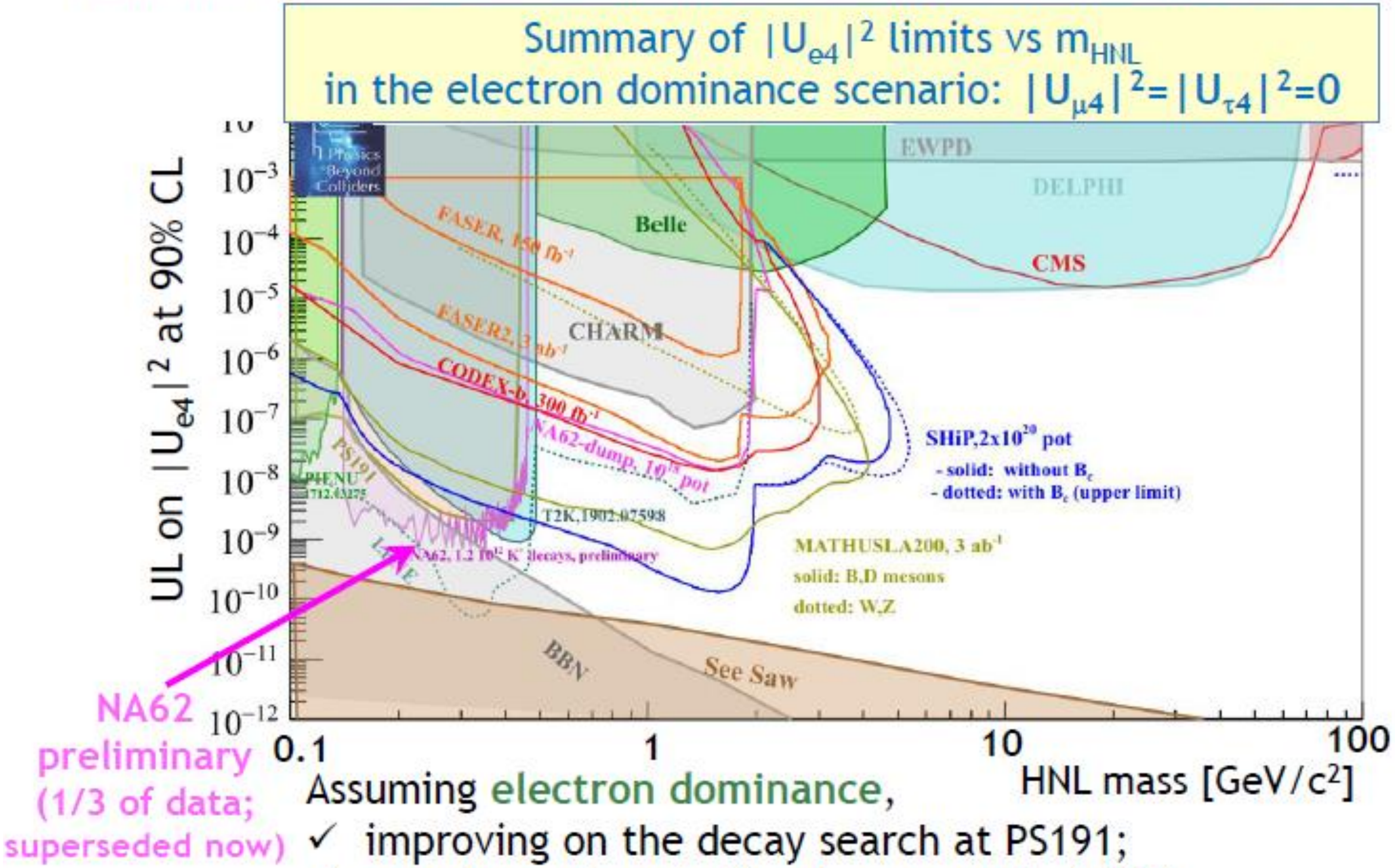




- In the e^+ case, maximum local significance of 3.6 for m_N=346 MeV/c^2.
- Accounting for look-elsewhere effect, global significance = 2.2

HNL Comparison to decay searches

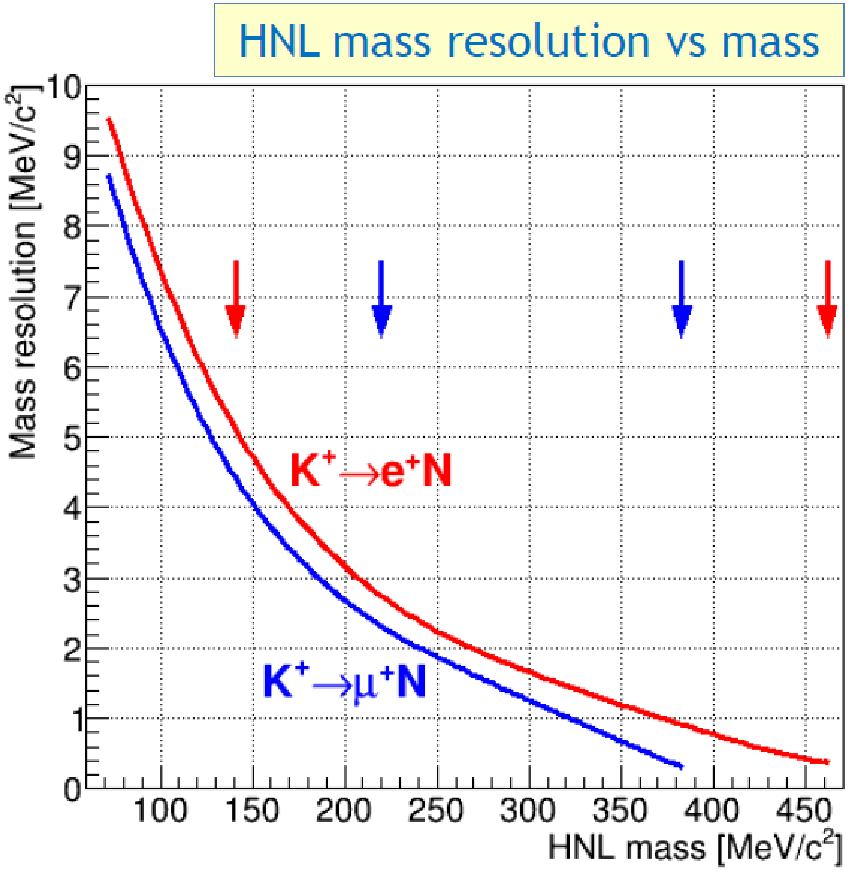
(CERN-PBC-REPORT-2018-007; update: Gaia Lanfranchi, PBC meeting, 6 Nov 2019)

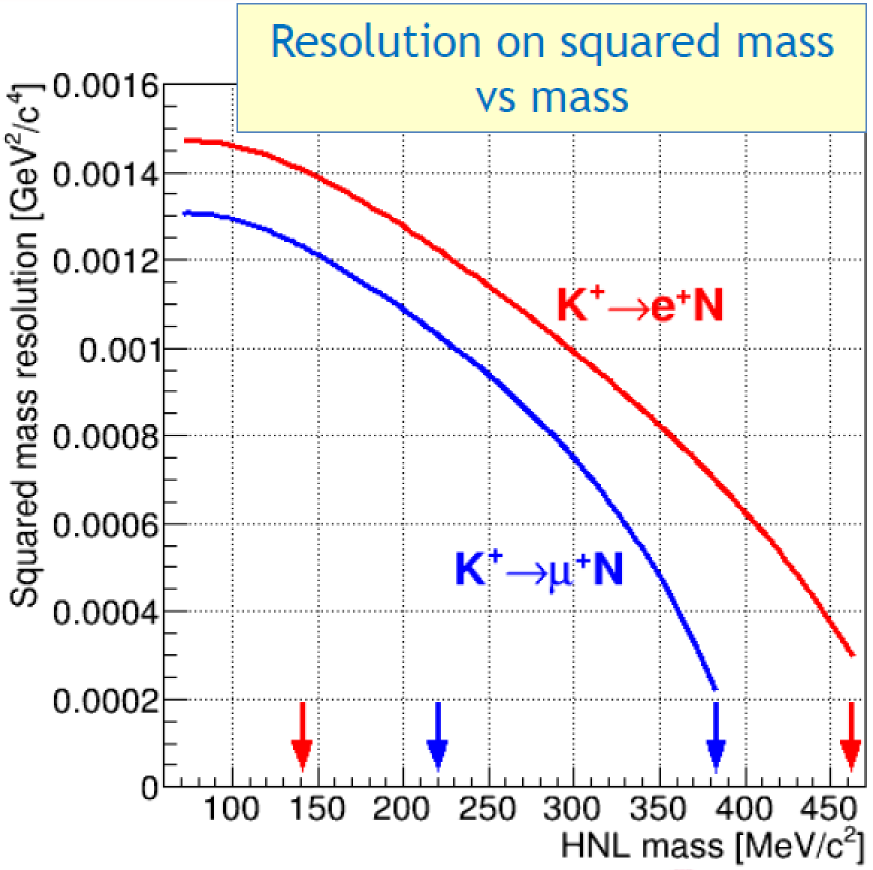


Assuming **electron dominance**,

- ✓ improving on the decay search at PS191;
- ✓ complementary to the decay search at T2K;
- ✓ BBN-allowed range is excluded up to $m_N \approx 340$ MeV/c².

HNL Comparison to decay searches

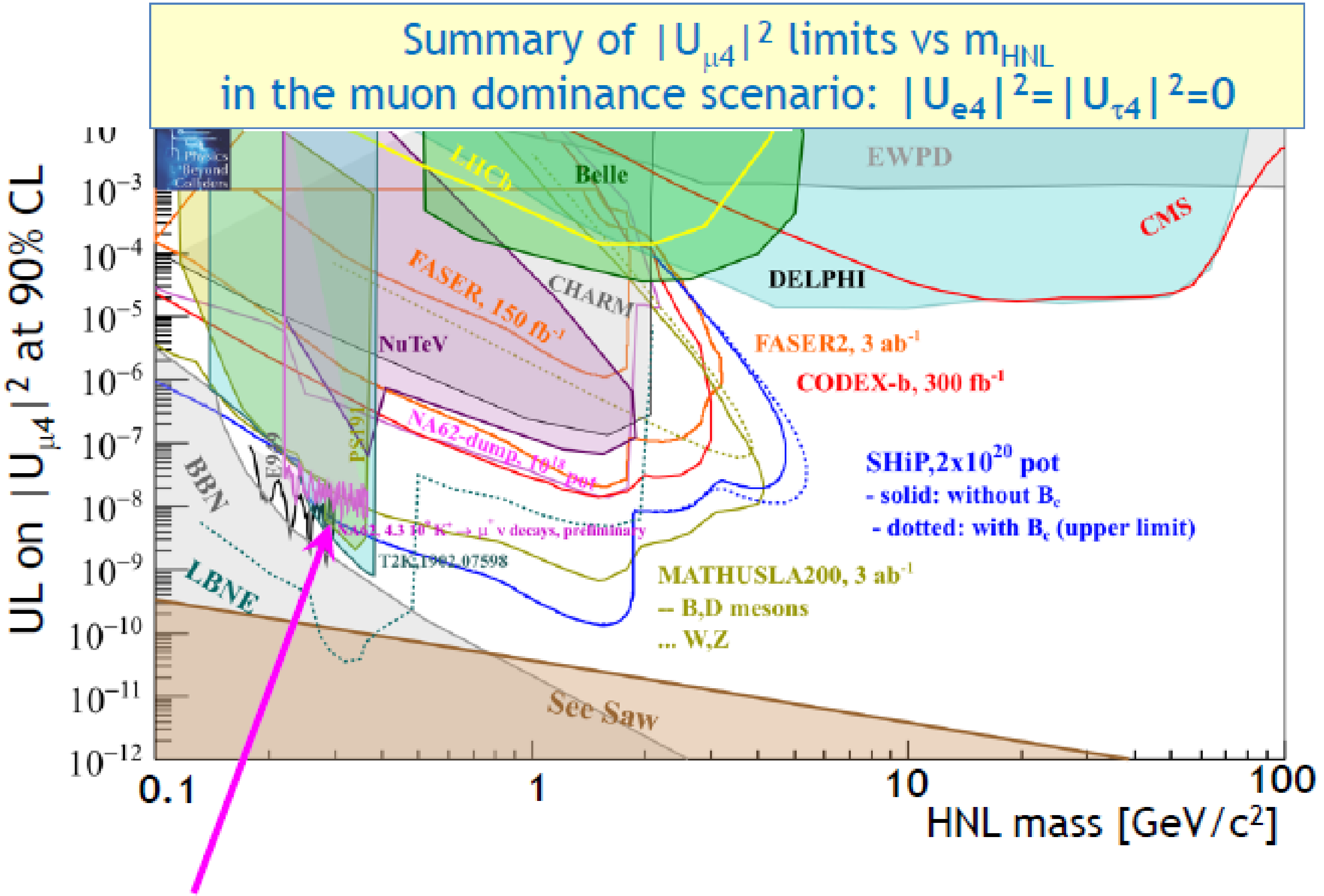




Selection for each HNL mass hypothesis (m_{HNL}) includes a "mass window" condition: $|m-m_{HNL}|<1.5\sigma_m$

HNL Comparison to decay searches

(CERN-PBC-REPORT-2018-007; update: Gaia Lanfranchi, PBC meeting, 6 Nov 2019)



NA62 preliminary: approaching the E949 (production) and T2K (decay) limits

References (ICHEP 2020)

- Radoslav Marchevski: New result on the search for the K+ to pi+ nunu decay at the NA62 experiment at CERN (pdf slides)
- Evgueni Goudzovski: Search for heavy neutral lepton production at the NA62 experiment (pdf slides)
- Lubos Bician: New measurement of the K+ to pi+ mu+ mu- decay at NA62 (pdf slides)
- Joel Swallow: Searches for lepton flavour and lepton number violation in K+ decays (pdf slides)