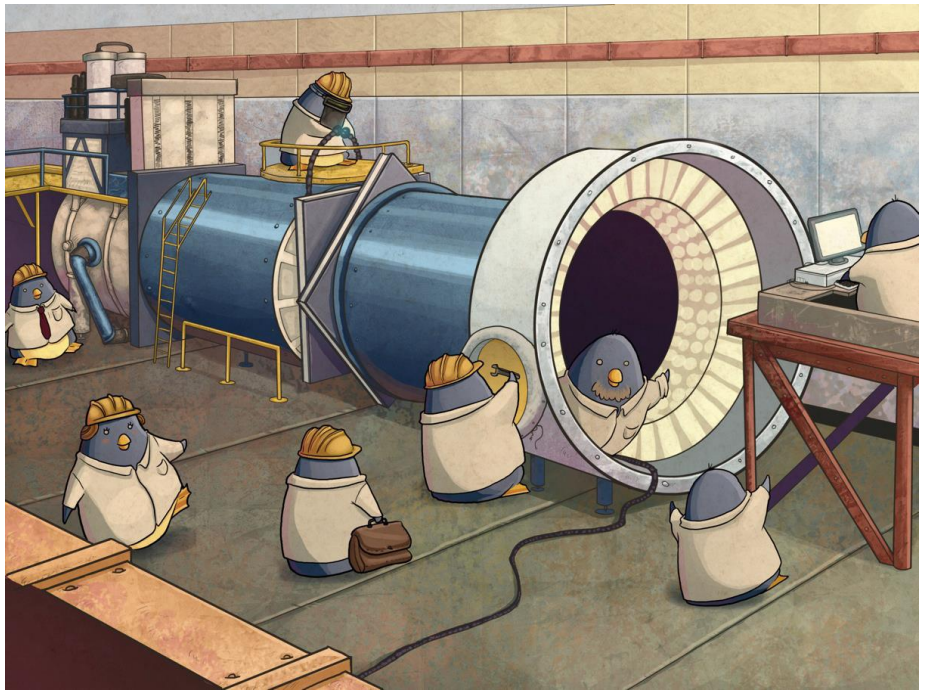
Physics Beyond SM With Kaons at NA62

Jacopo Pinzino

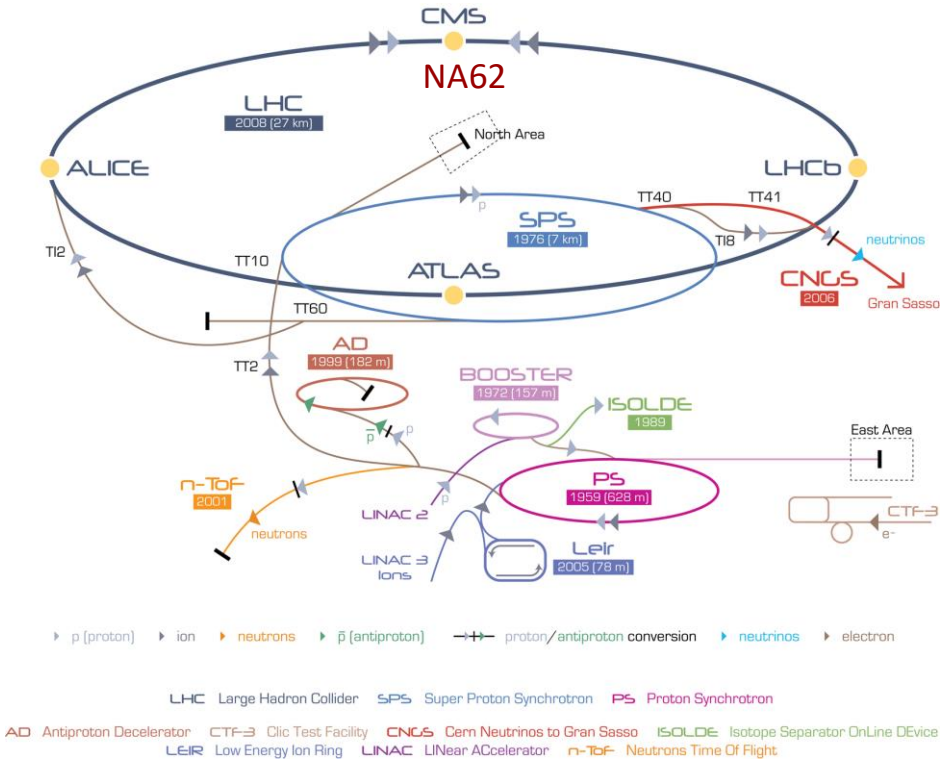


H2020 MSCA COFUND
G.A. 754496

WIN2021
11/06/2021

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.

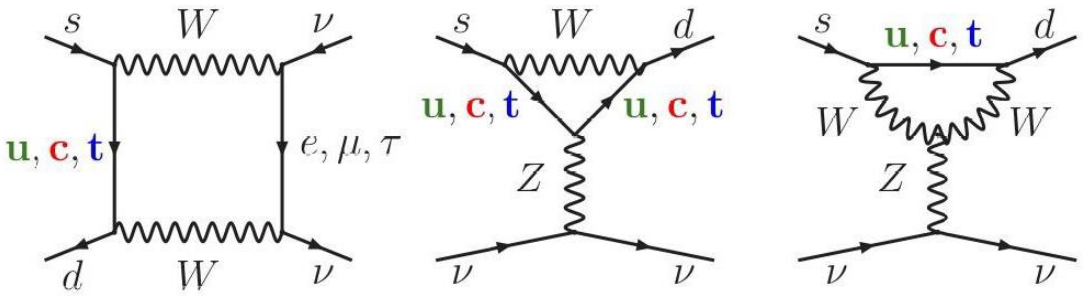


NA62 Timeline

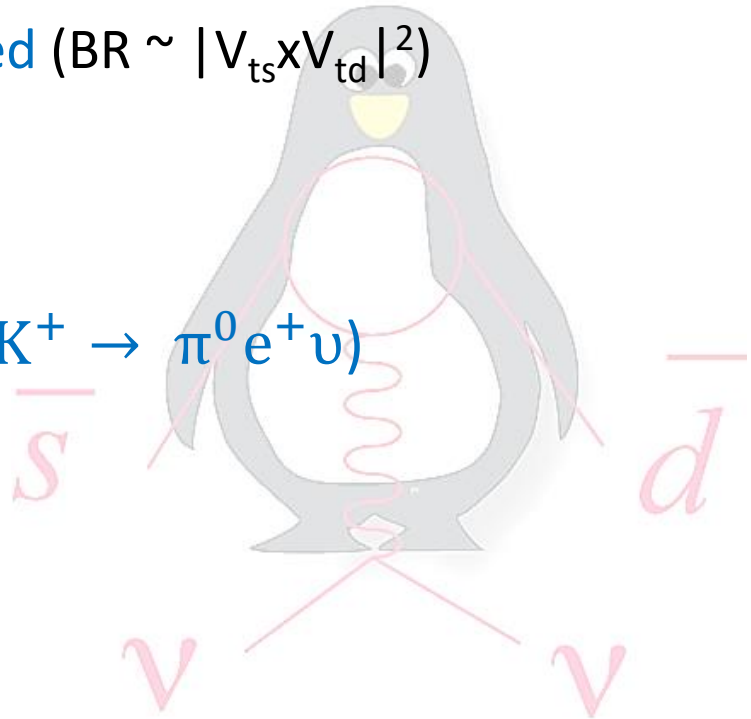
- 2008: NA62 Approval
- 2014: NA62 Pilot Run (partial layout)
- 2015: Commissioning run
- Full detector installation completed in September 2016
- 2016 : First $\pi\nu\nu$ dataset in 2016
- Continuous data-taking until the end of 2018
- data-taking will be resumed in 2021 with improvements

~ 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 $K \to \pi\upsilon\bar{\upsilon}$ 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($K^+ \to \pi^0 e^+ \upsilon$)
- SM predictions:

  BR($K^+ \to \pi^+ \upsilon\bar{\upsilon}$) = $(9.3 \pm 0.8) \times 10^{-11}$

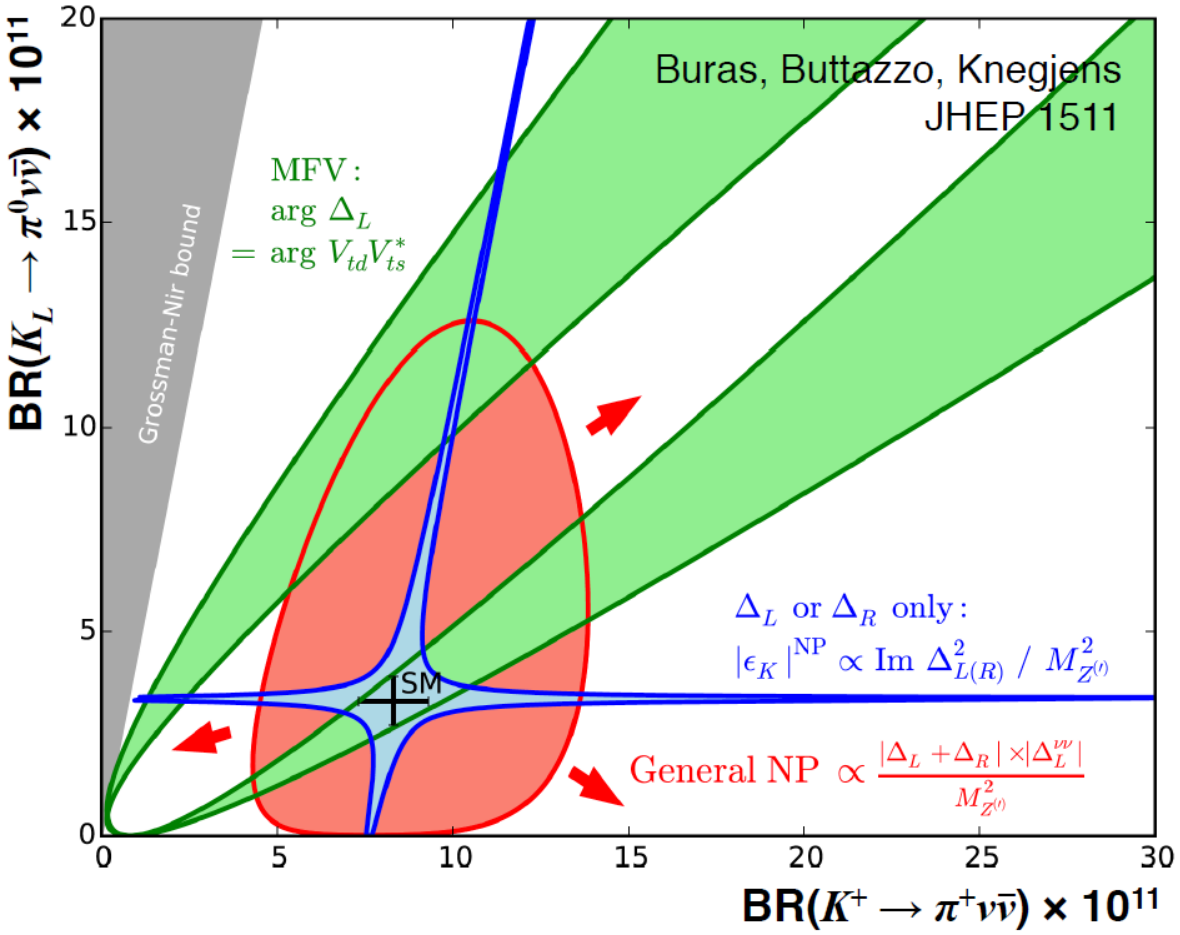
  BR($K_L \to \pi^0 \upsilon\bar{\upsilon}$) = $(3.7 \pm 0.7) \times 10^{-11}$
- Previous Experimental Result:

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

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

$K \to \pi\upsilon\bar{\upsilon}$ 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**



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  [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
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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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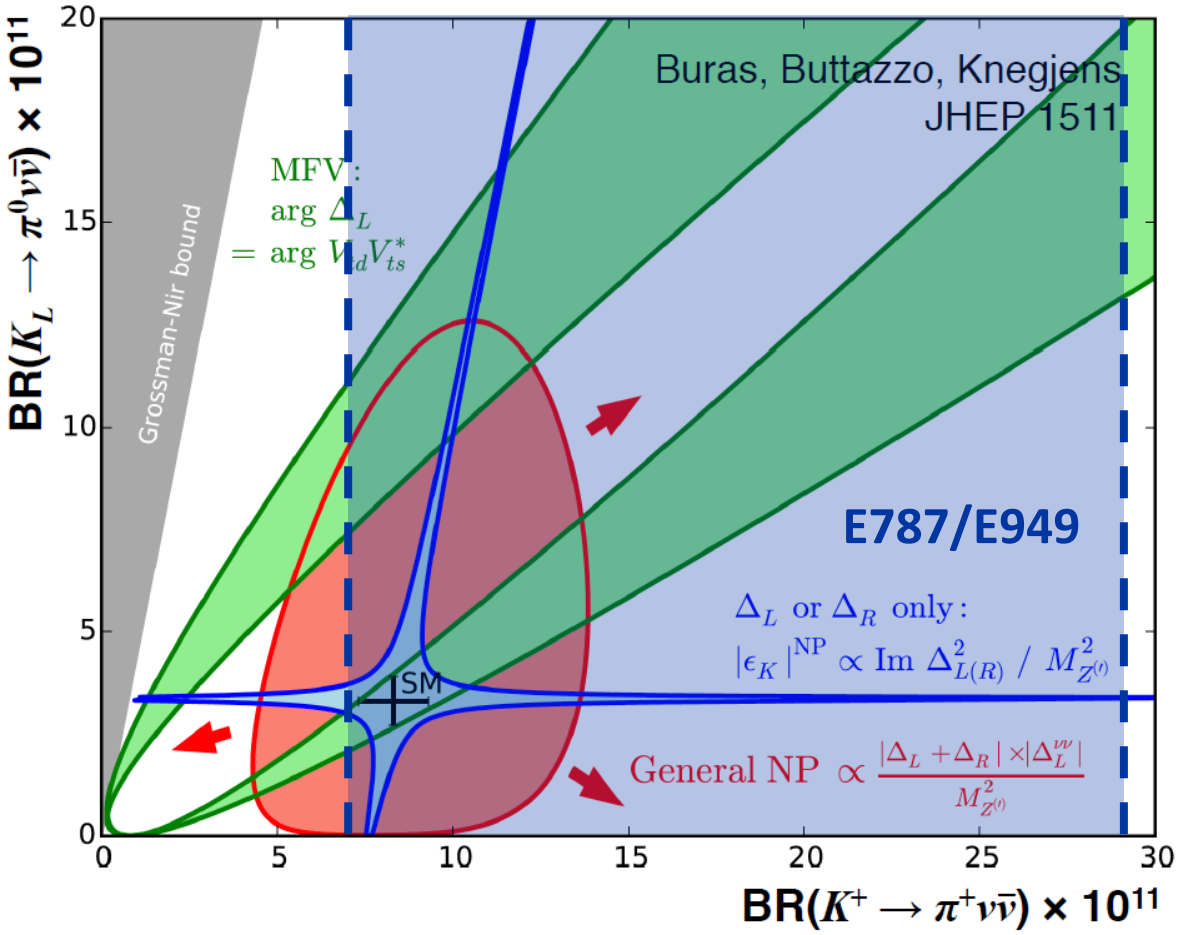

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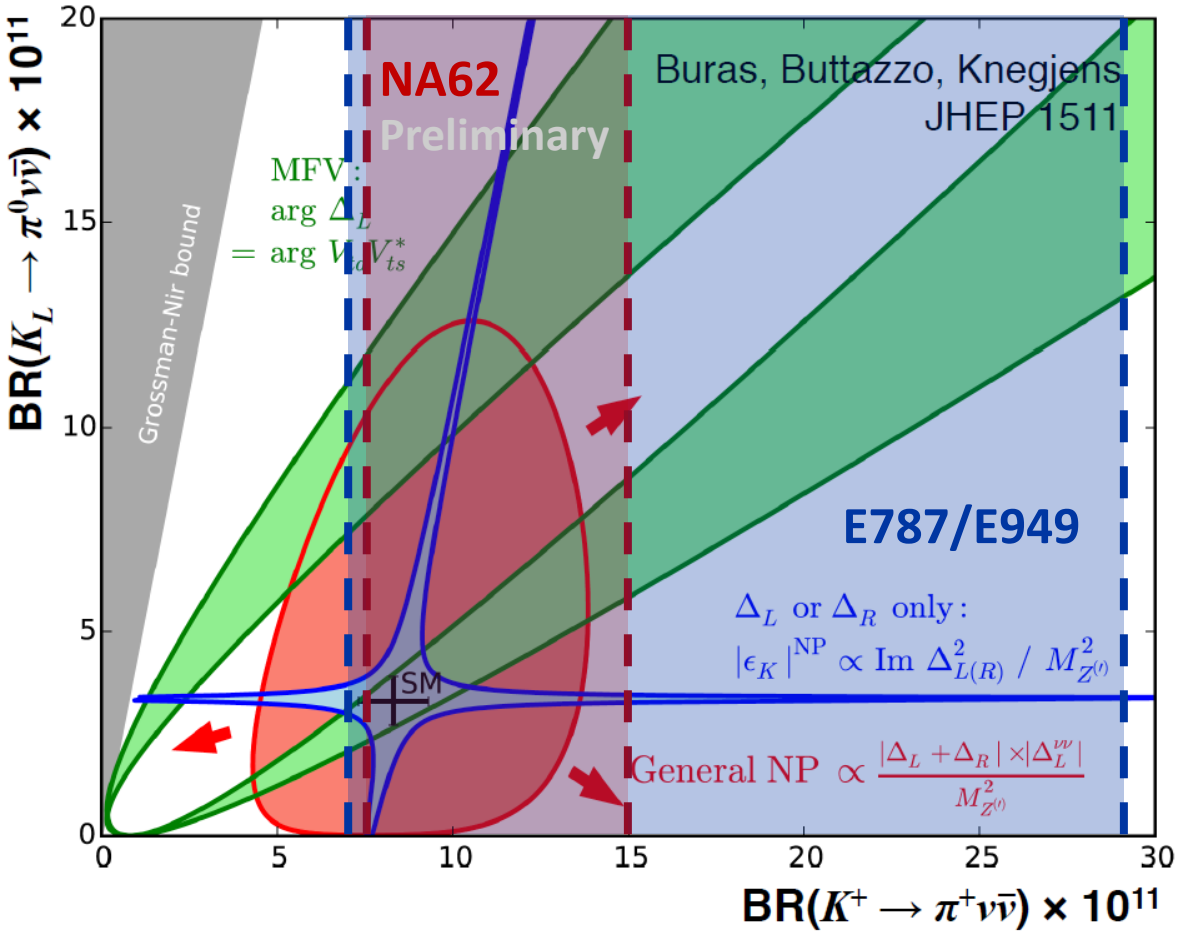

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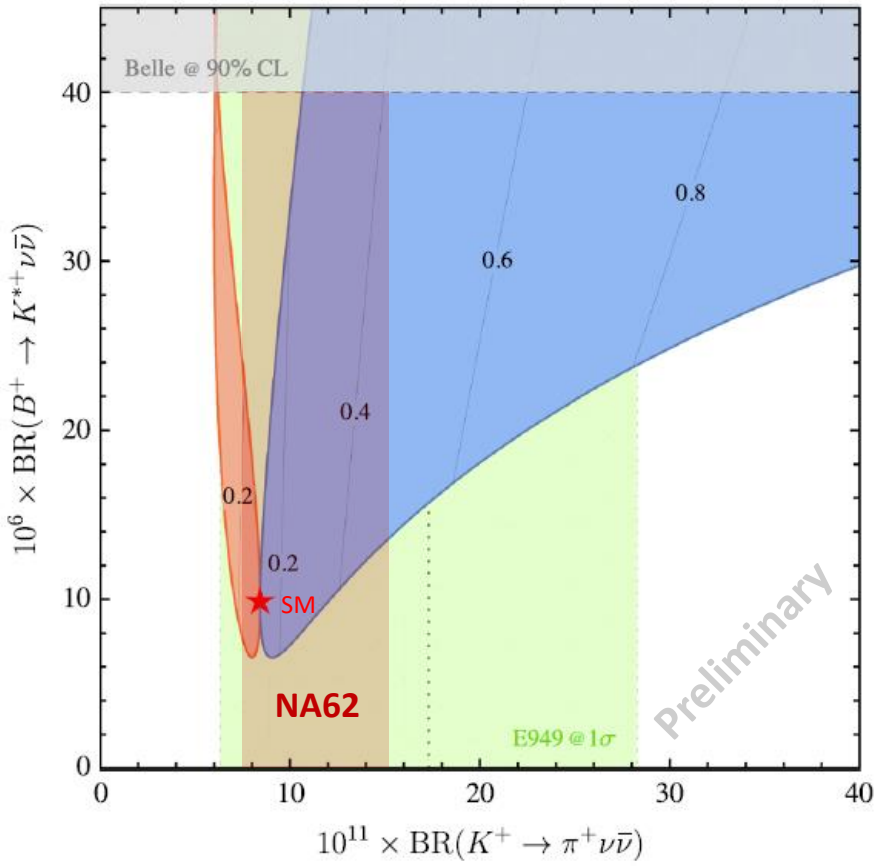
$K \to \pi\upsilon\bar{\upsilon}$ and the LFU violation

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

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

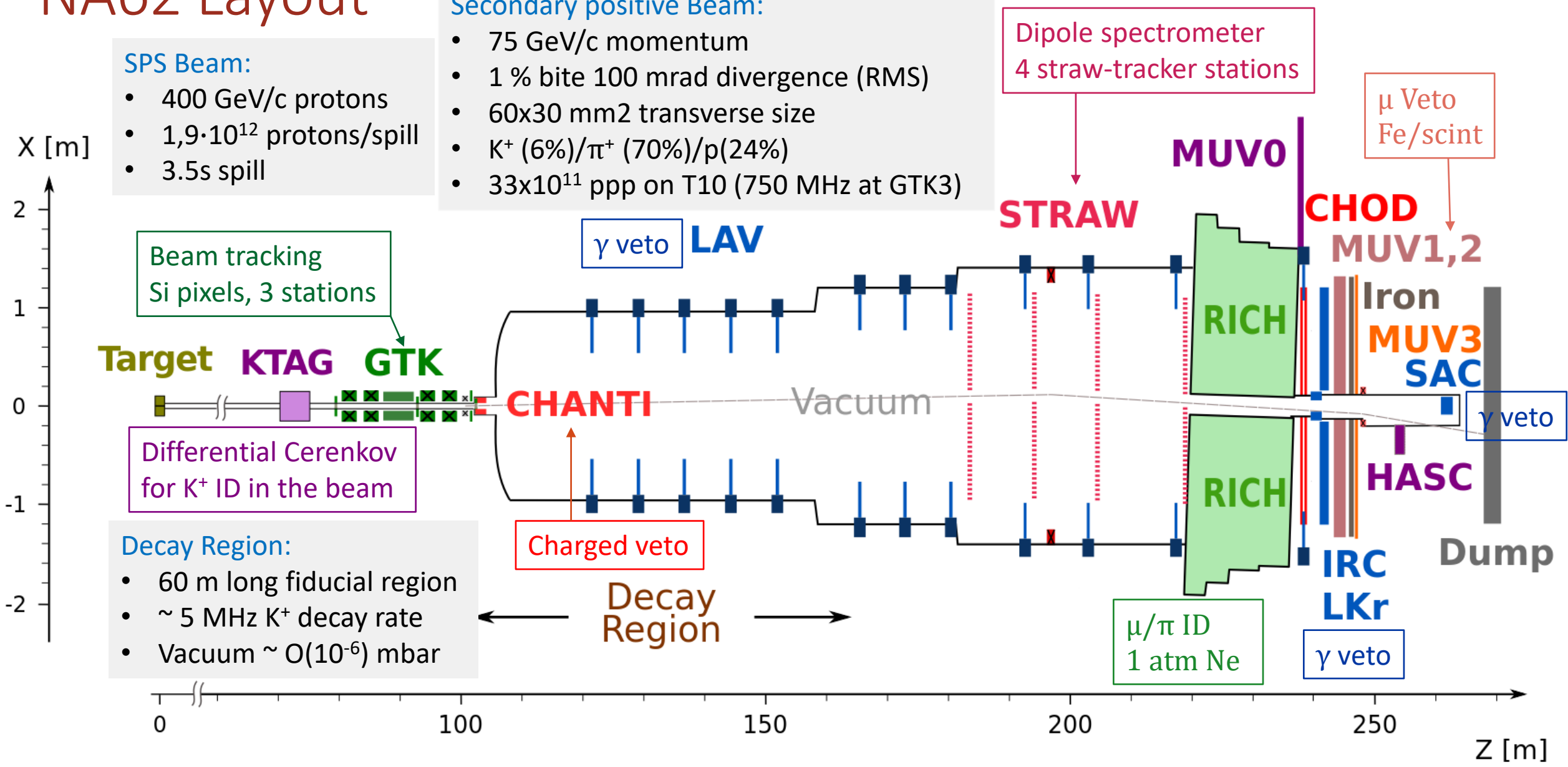


EPJ C (2017) 77: 618

NA62 Layout

SPS Beam:
- 400 GeV/c protons
- $1{,}9 \cdot 10^{12}$ protons/spill
- 3.5s spill

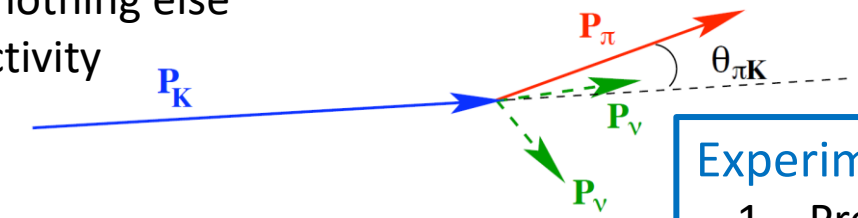
Secondary positive Beam:
- 75 GeV/c momentum
- 1 % bite 100 mrad divergence (RMS)
- 60x30 mm2 transverse size
- K^+ (6%)/π^+ (70%)/p(24%)
- 33×10^{11} ppp on T10 (750 MHz at GTK3)



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

Analysis Strategy

- New Decay in flight technique
- Signal: 1 beam track, 1 charged track, nothing else
- Background: K^+ decay modes; beam activity
- Kinematics: $m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$

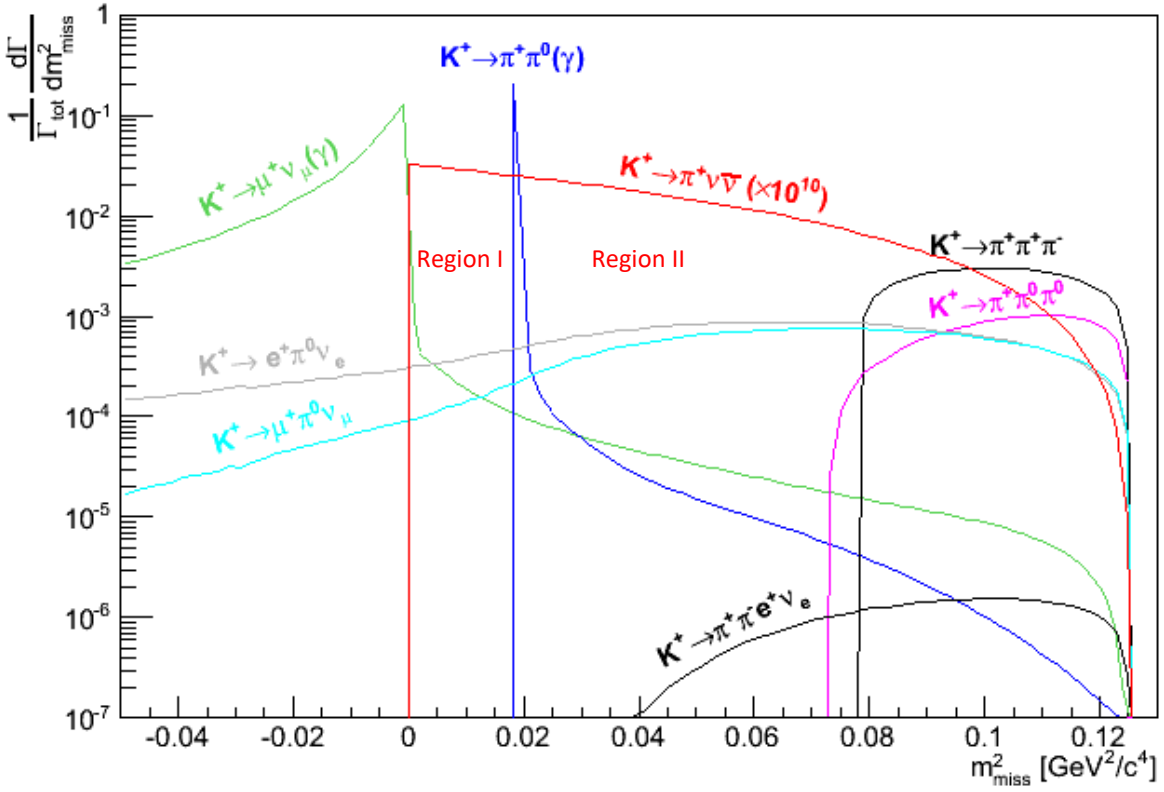


Key analysis requirements:

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

Experimental principles:

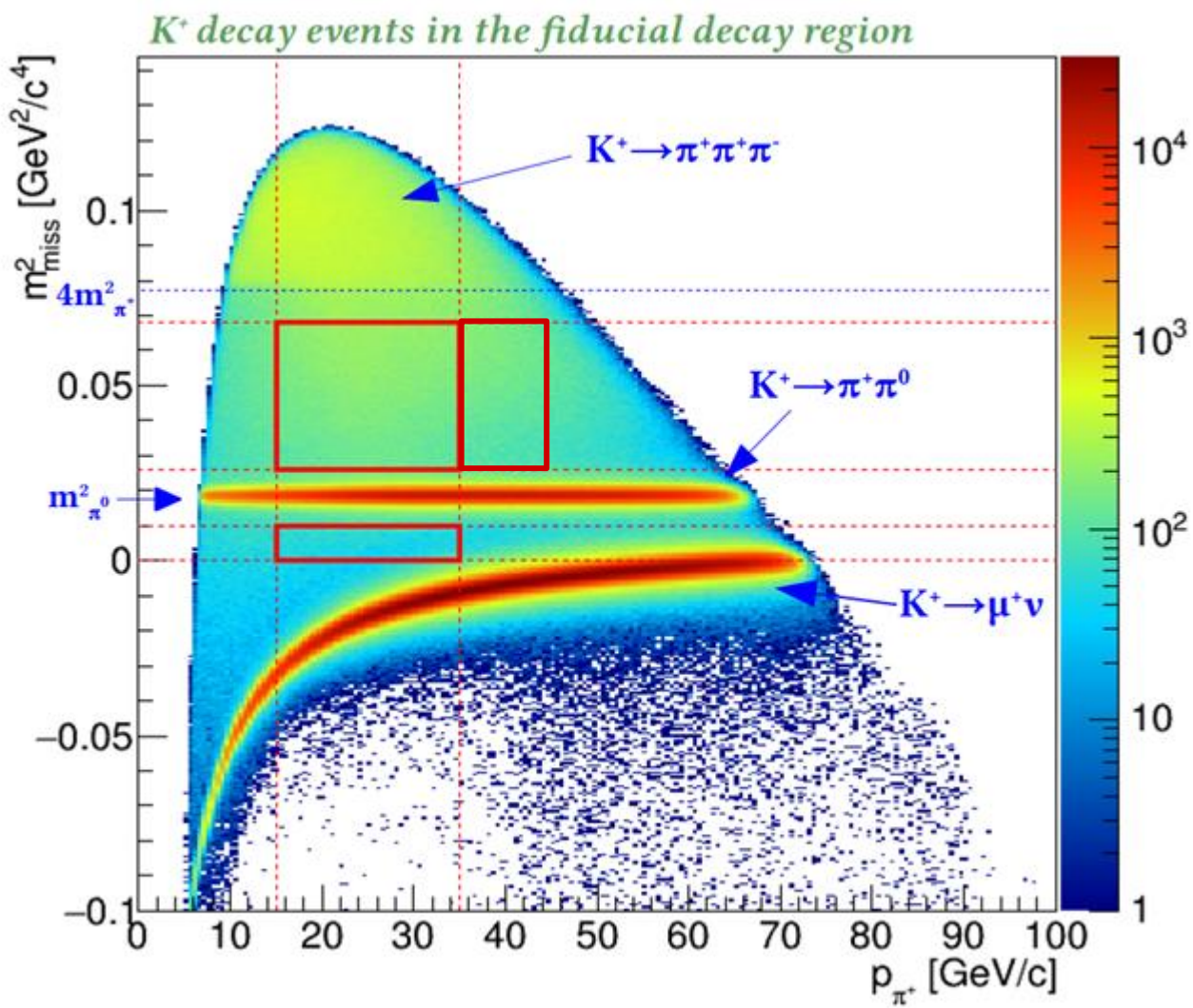
1. Precise kinematic reconstruction
2. PID: K upstream, e / μ / π downstream
3. Hermetic γ detection
4. Sub-ns timing



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 the analysis
- 7 categories (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

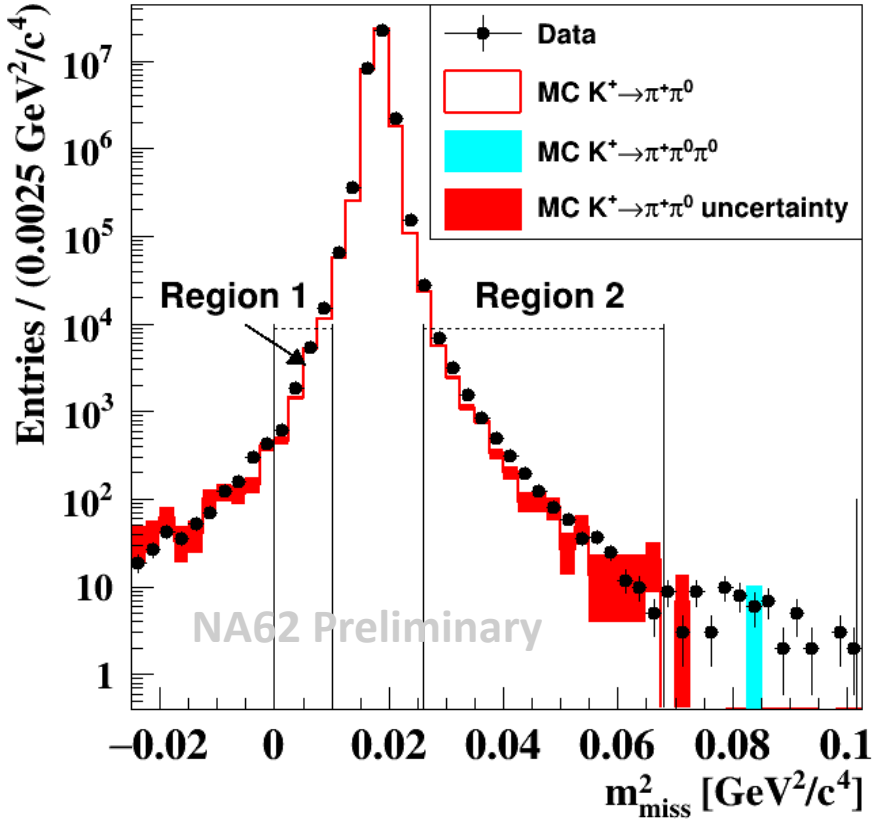
Performance:

- $\geq 10^4$ 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
$K^+ \to \pi^+\pi^-e^+\nu$	$4.25 \cdot 10^{-5}$

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)

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

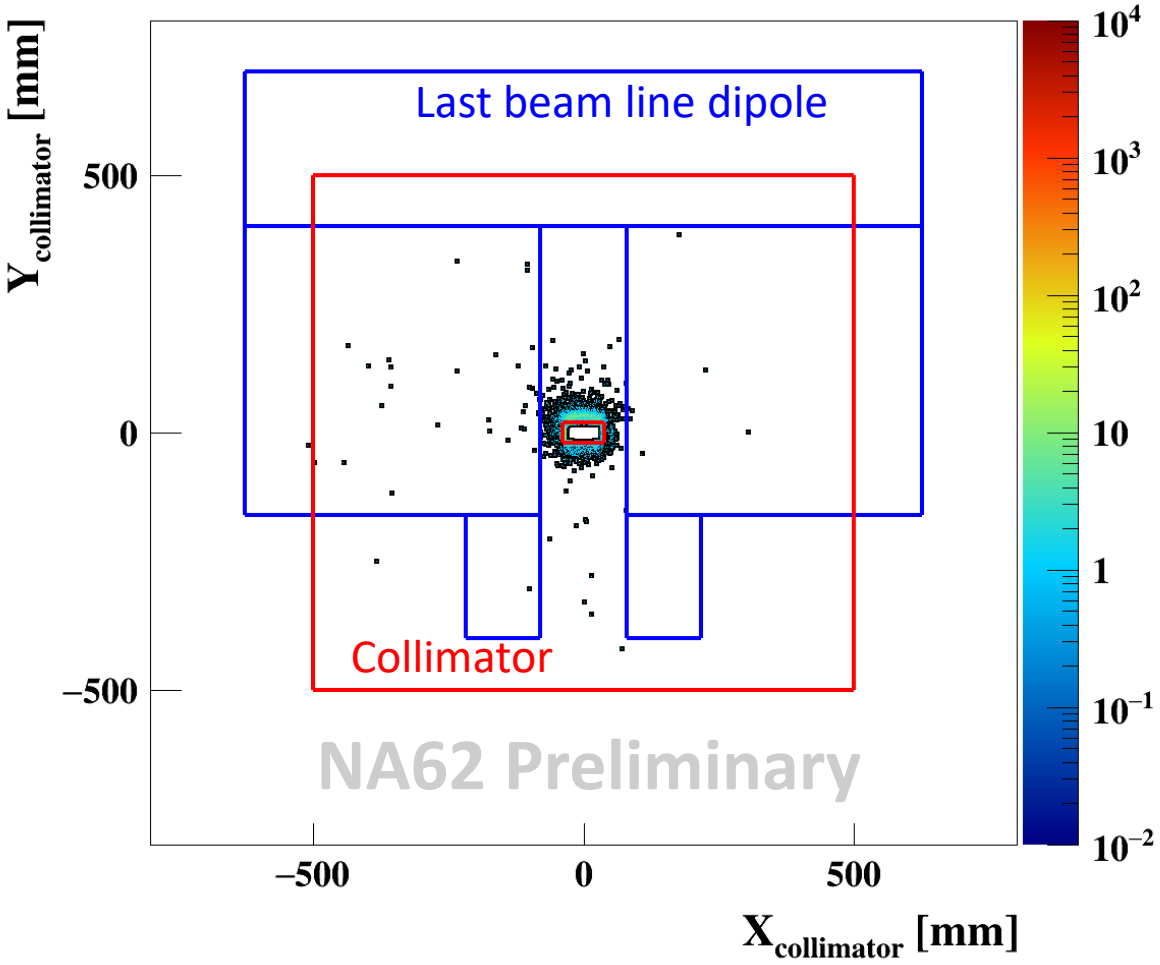
Expected $K^+ \to \pi^+\pi^0$ in signal regions after the $\pi\nu\nu$ selection

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.

$$SES = (1.11 \pm 0.07) \cdot 10^{-11}$$

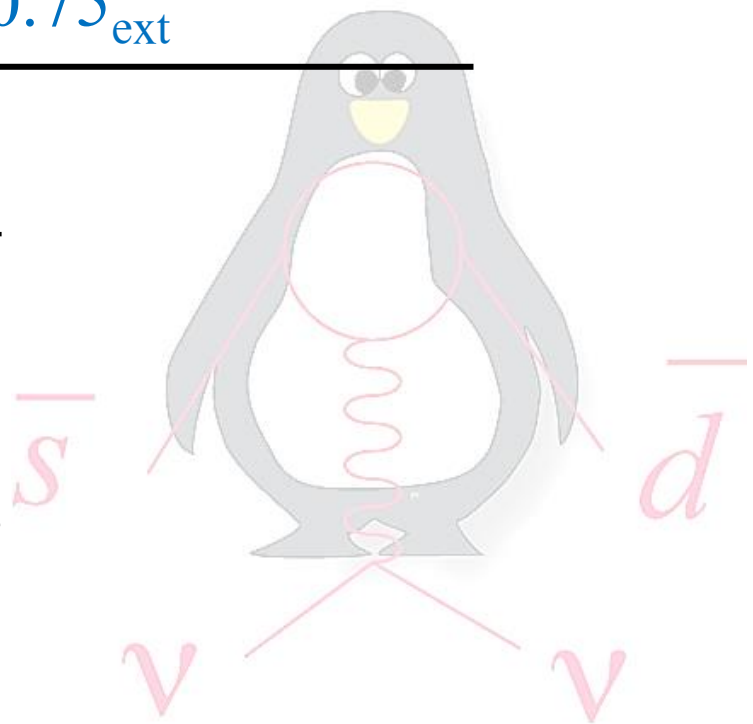
Upstream background



- 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

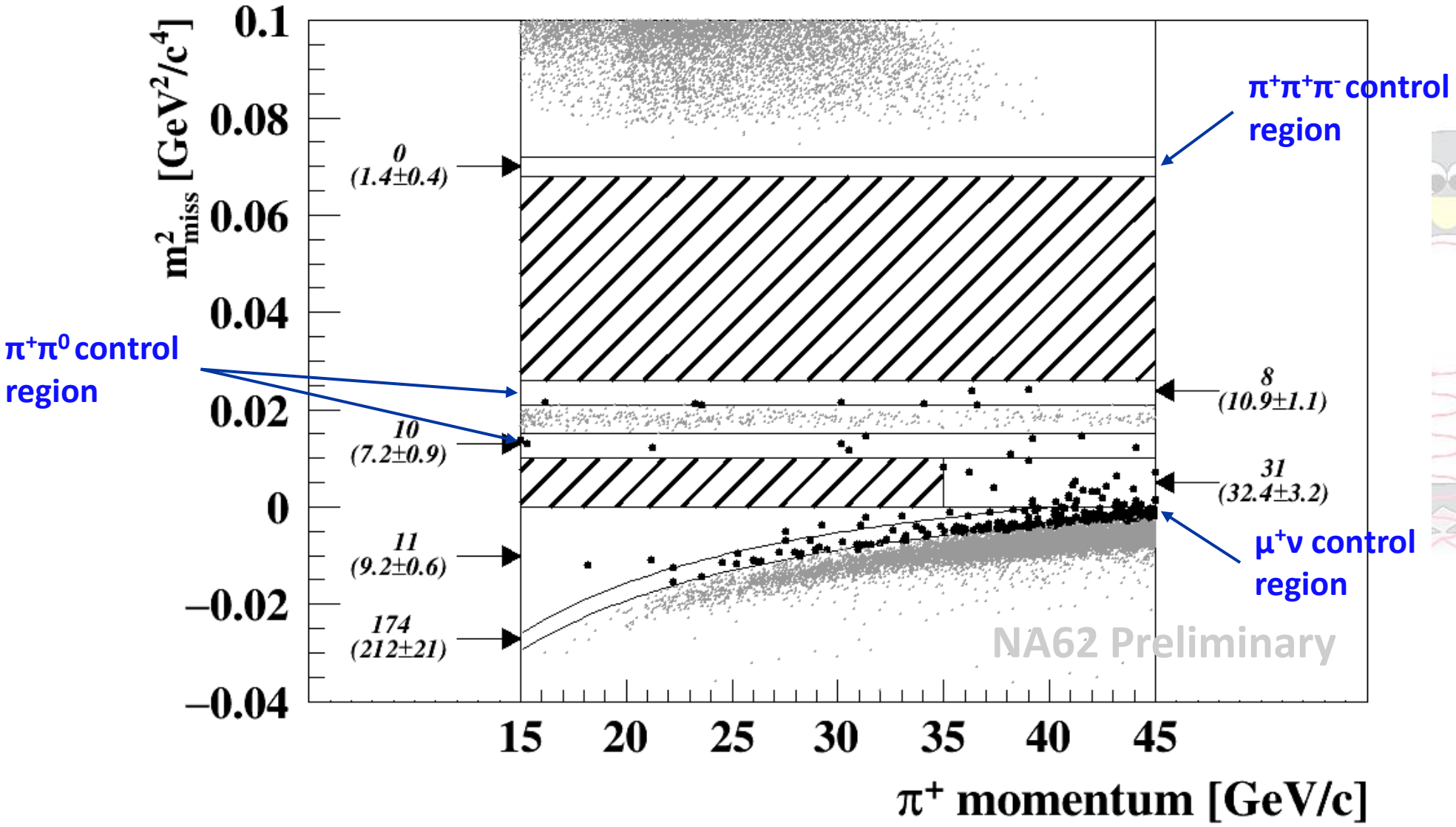
Expected events

Process	Expected events in R1+R2 (2018 data)
$K^+ \to \pi^+ \upsilon \bar{\upsilon}$ (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	$3.3^{+0.98}_{-0.73}$

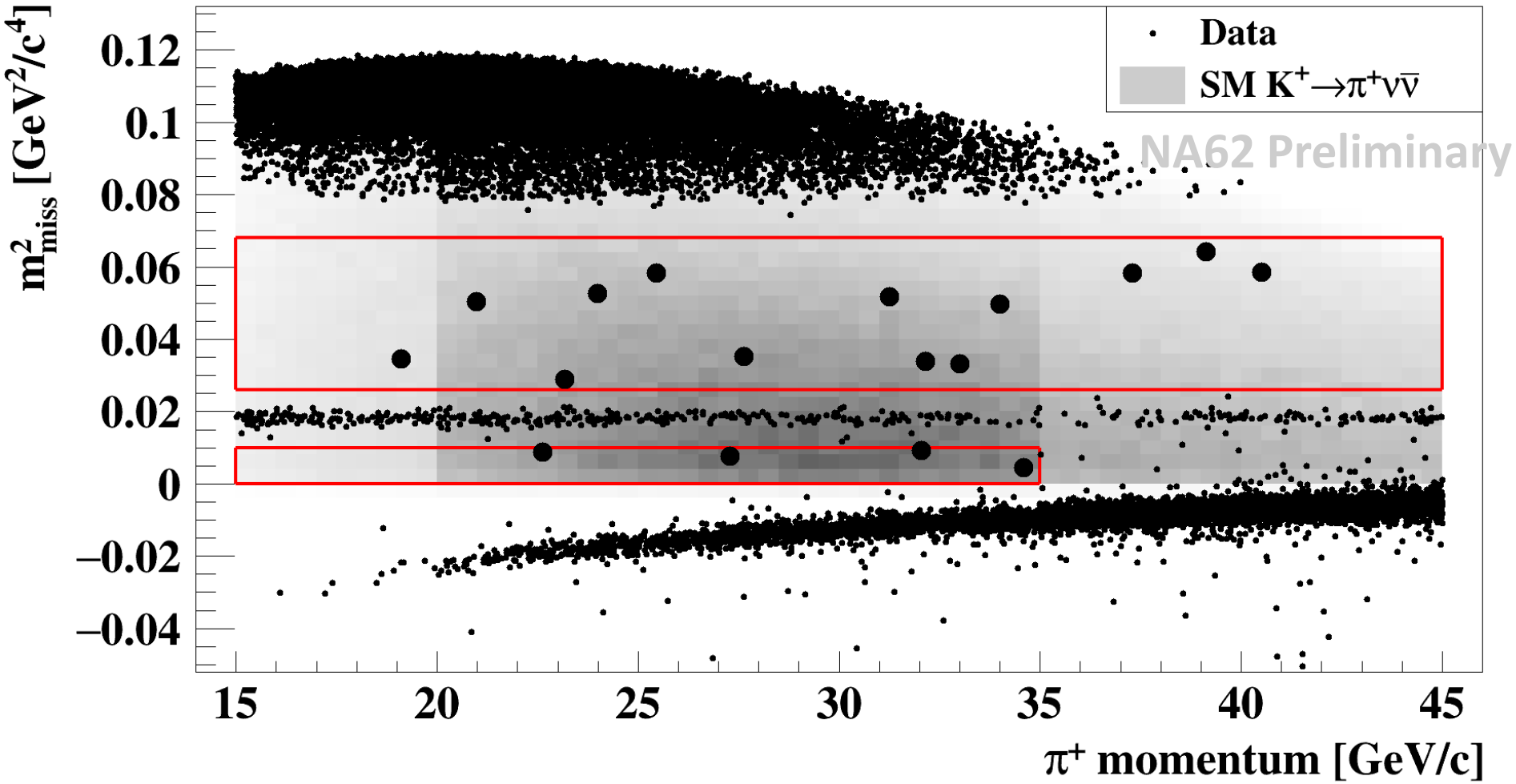


Background expectations validated in control regions using a blind procedure

Control regions: main decays



Result

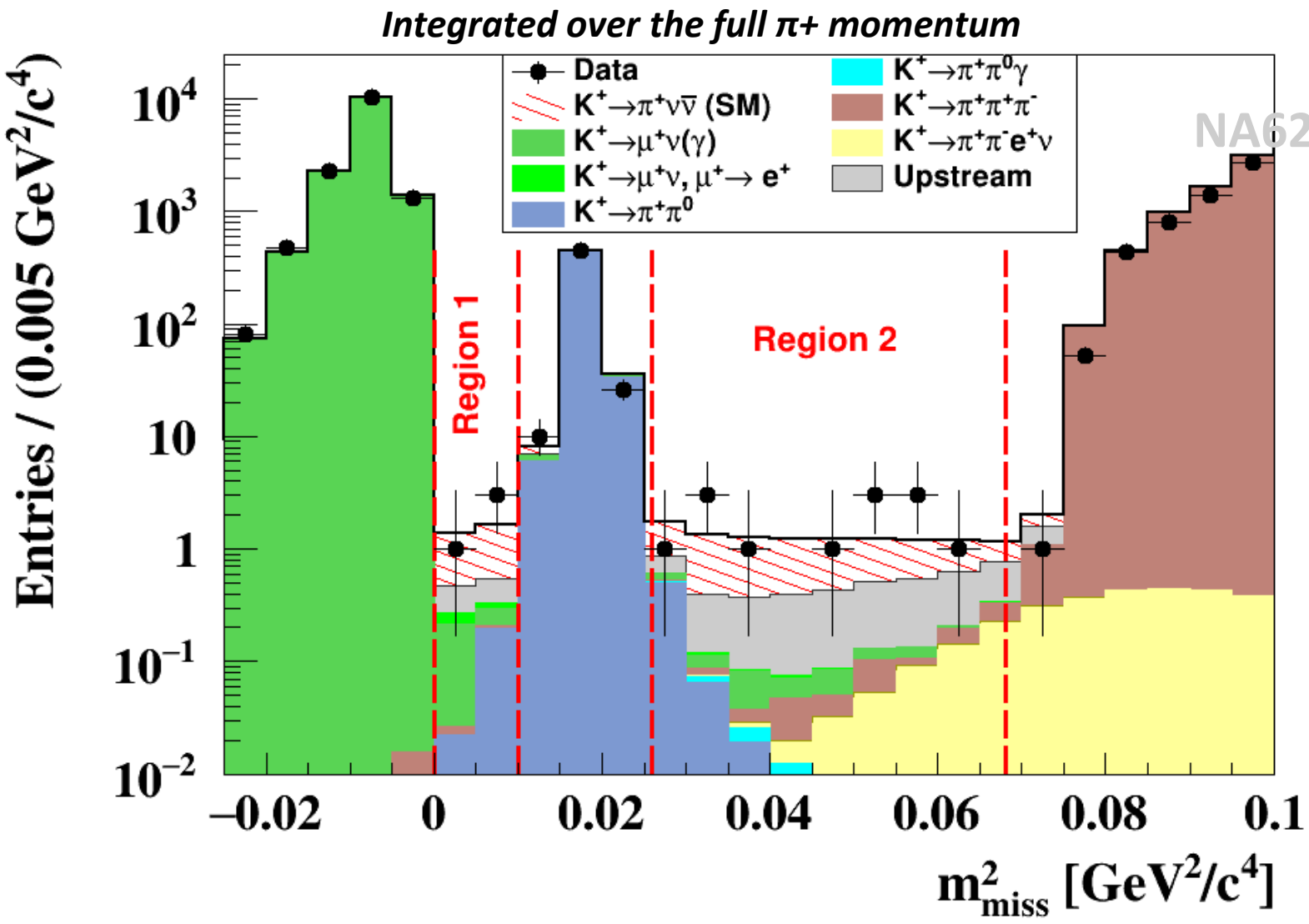


5.3 background + 7.6 SM signal events expected, 17 events observed

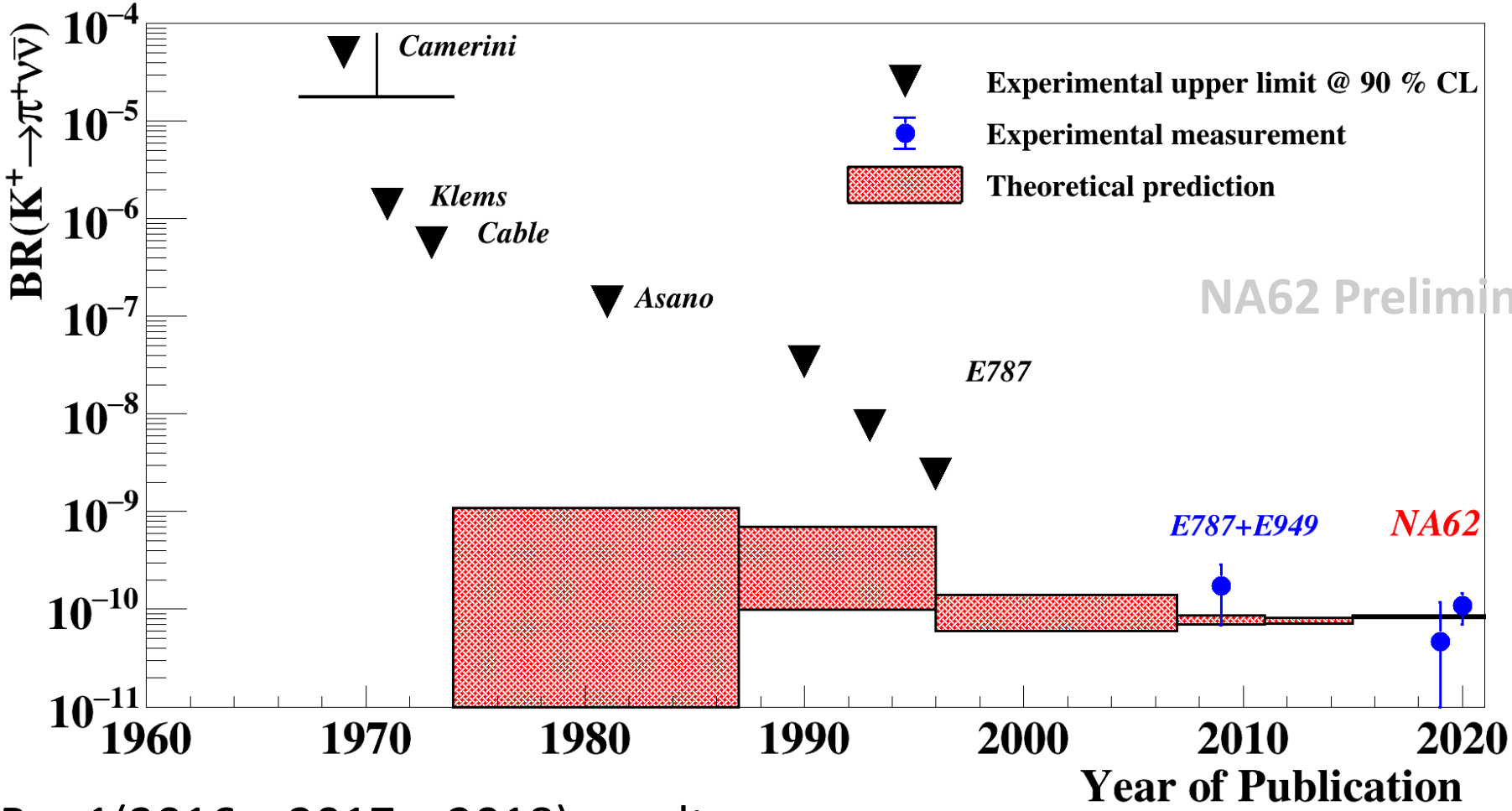
1 event observed with 2016 data [Phys. Lett. B 791 (2019) 156-166]

2 events observed with 2017 data [J. High Energ. Phys. 2020, 42]

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



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



NA62 Run1(2016 + 2017 + 2018) result:

$$\mathrm{Br}(K^+ \to \pi^+\upsilon\bar{\upsilon}) = (10.6^{+4.0}_{-3.4\,\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \cdot 10^{-11} \text{ (3.4σ significance)}$$

[arXiv:2103.15389 [hep-ex]](accepted by JHEP)

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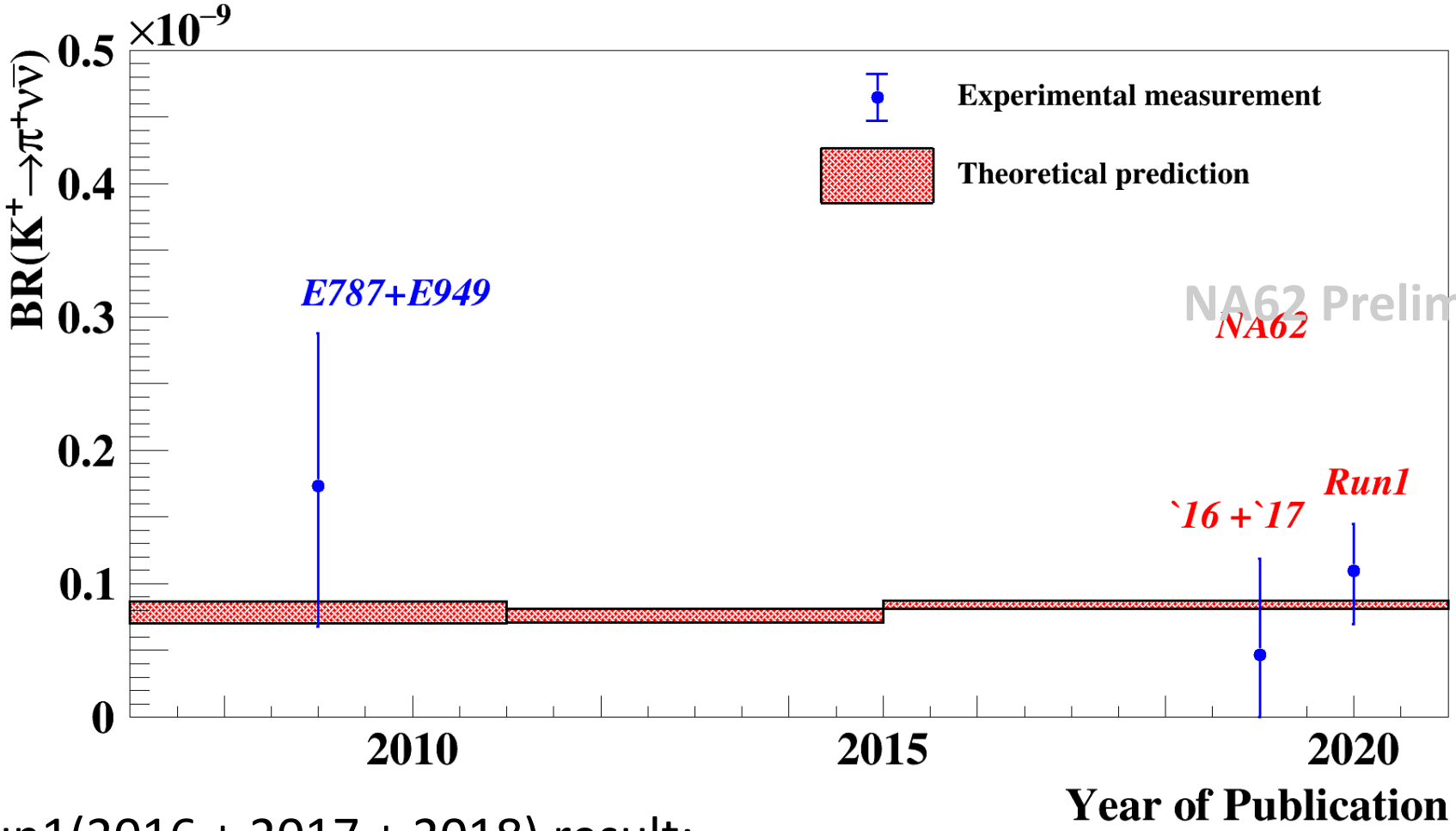

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$K \to \pi\upsilon\bar{\upsilon}$ summary

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)
- $\mathrm{Br}(K^+ \to \pi^+\upsilon\bar{\upsilon}) = (10.6^{+4.0}_{-3.4\,\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \cdot 10^{-11}$ (3.4σ significance)
- The most precise measurement of the BR obtained so far

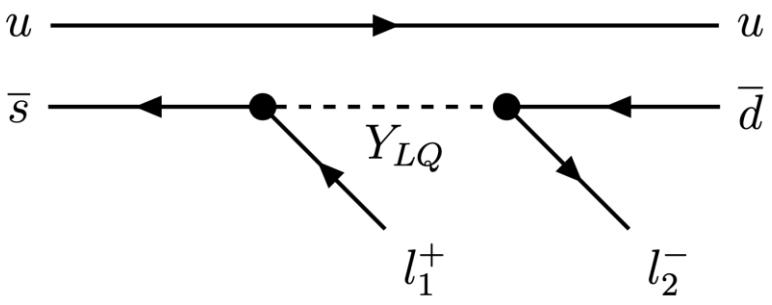
The result is compatible with the SM prediction within one standard deviation

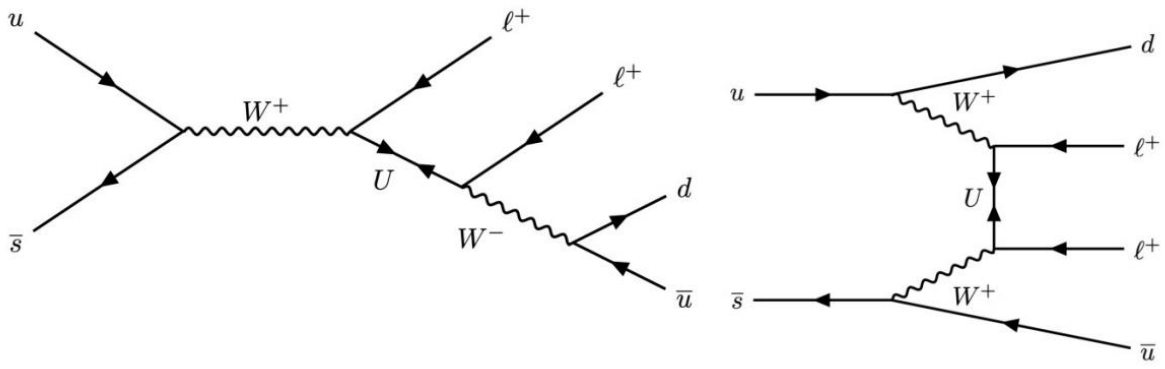
The next Run (2021):

- 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

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:

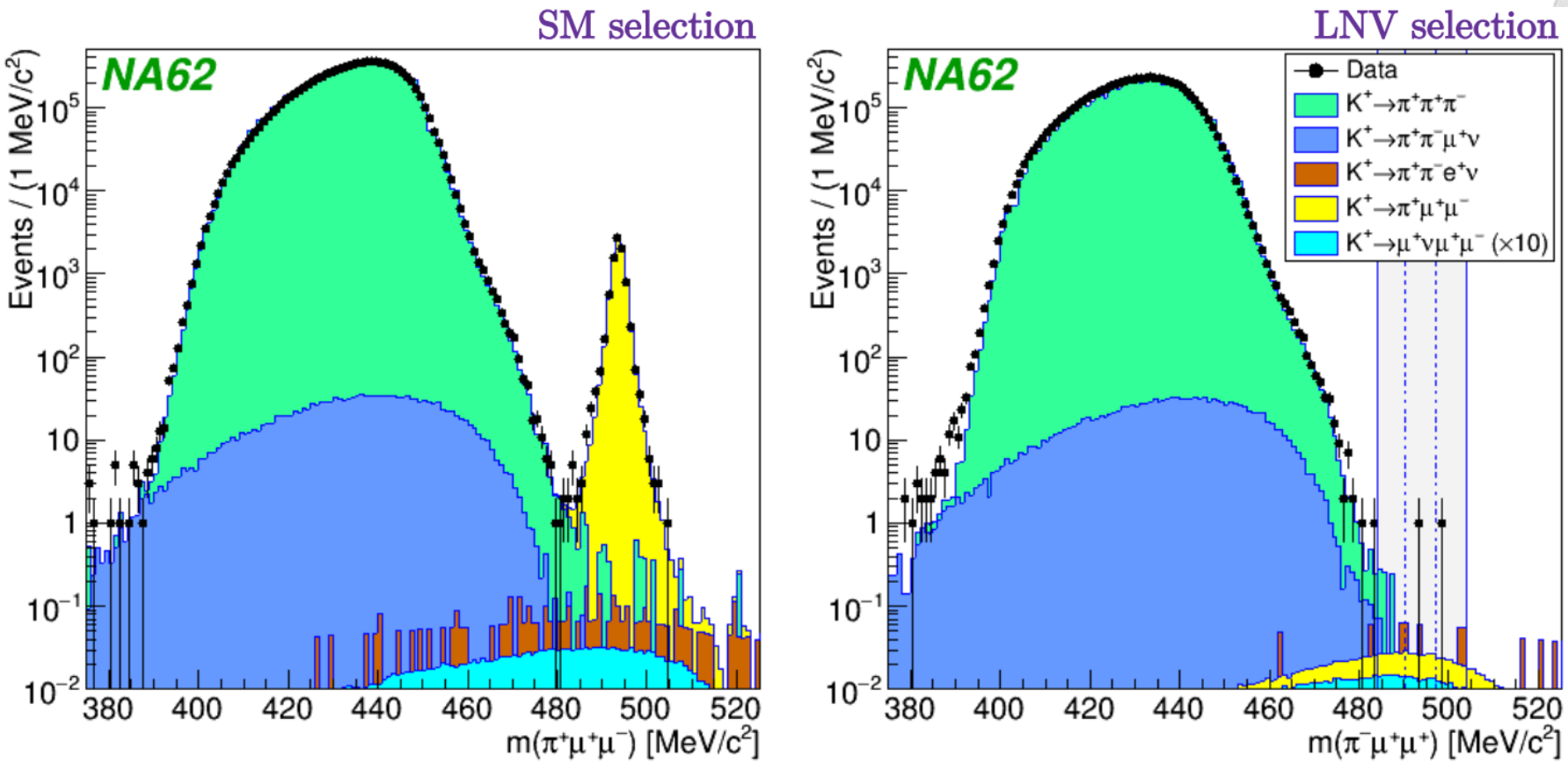
- BR($K^+ \to \pi^- e^+ e^+$) < 6.4×10^{-10} @ 90% CL
  [BNL E865 : PRL 85 2877 (2000)]
- BR($K^+ \to \pi^- \mu^+ \mu^+$) < 8.6×10^{-11} @ 90% CL
  [CERN NA48/2 : PL B769 67 (2017)]

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

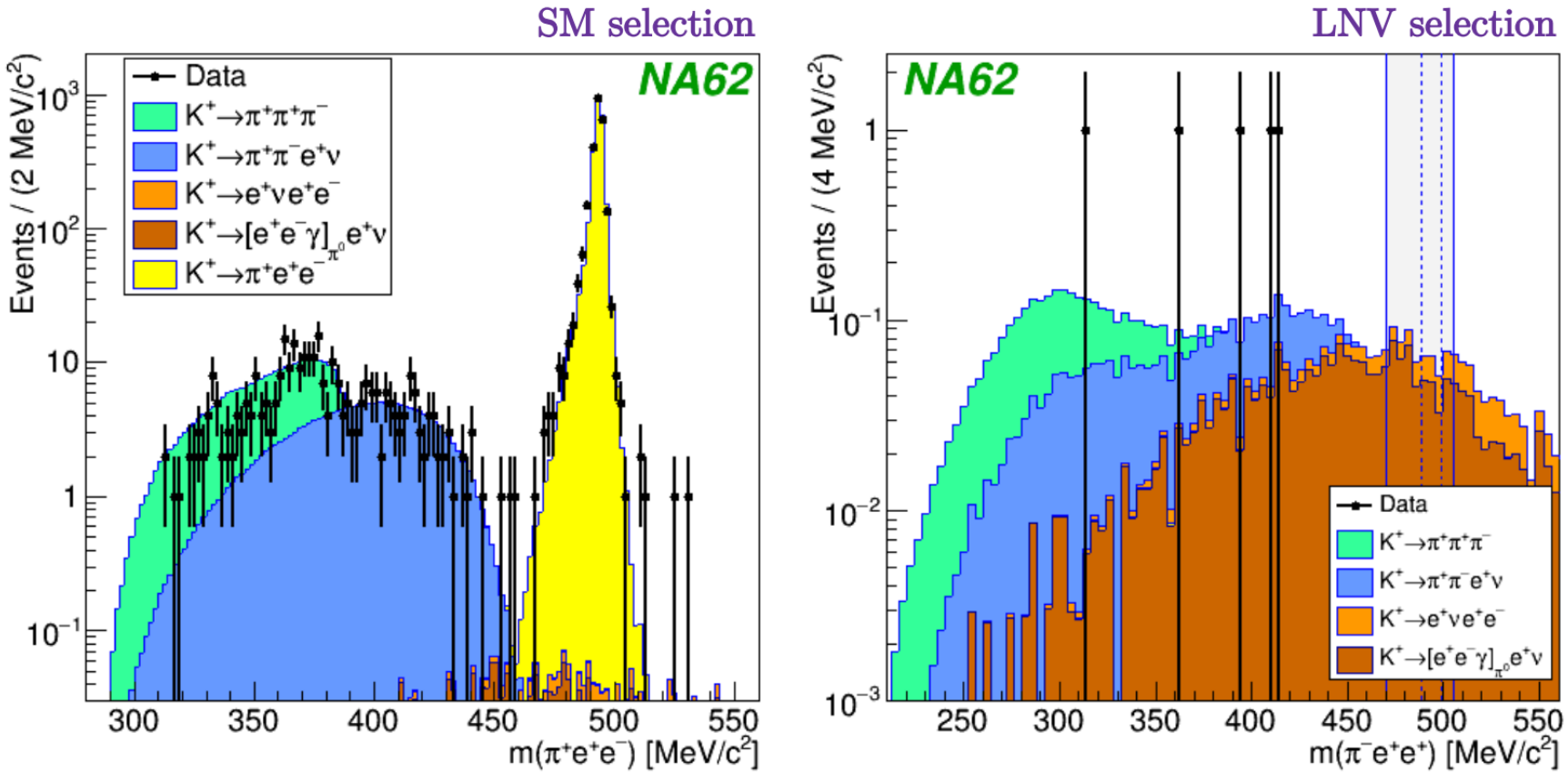
$K^+ \to \pi^- \mu^+ \mu^+$

- 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*



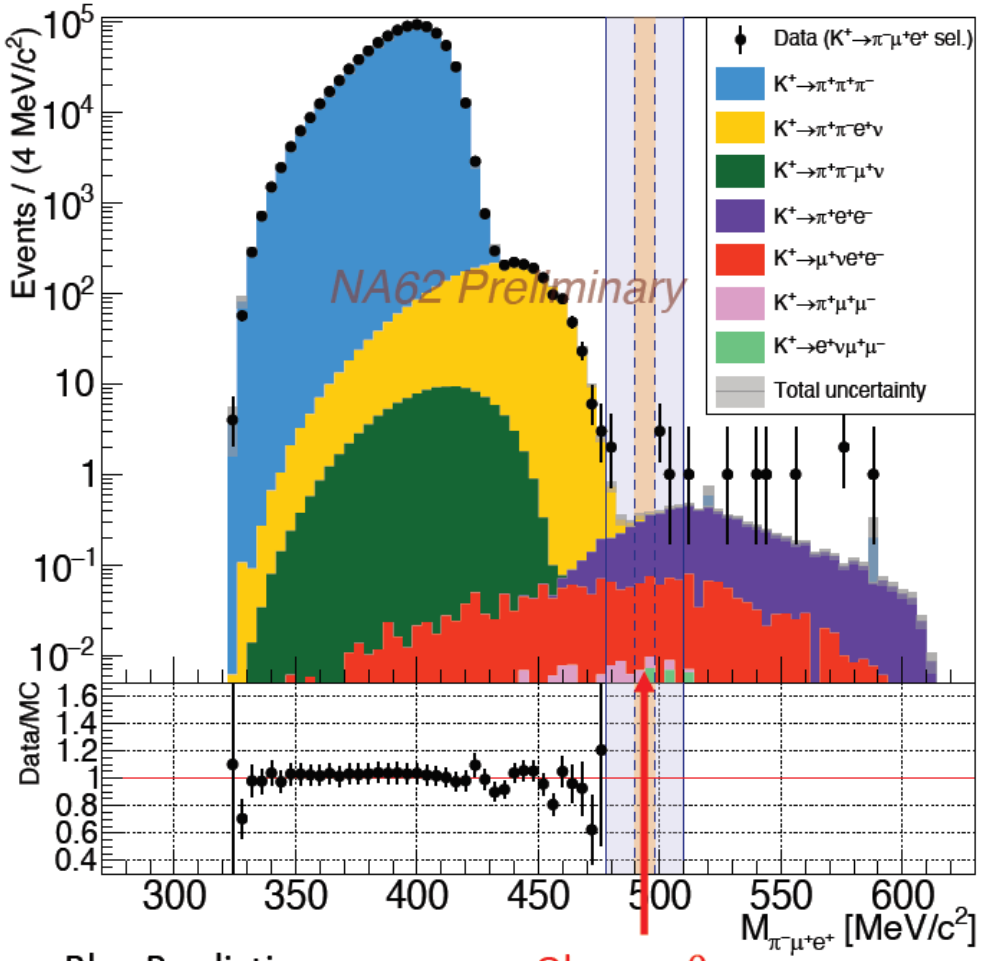
$K^+ \to \pi^- e^+ e^+$

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



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

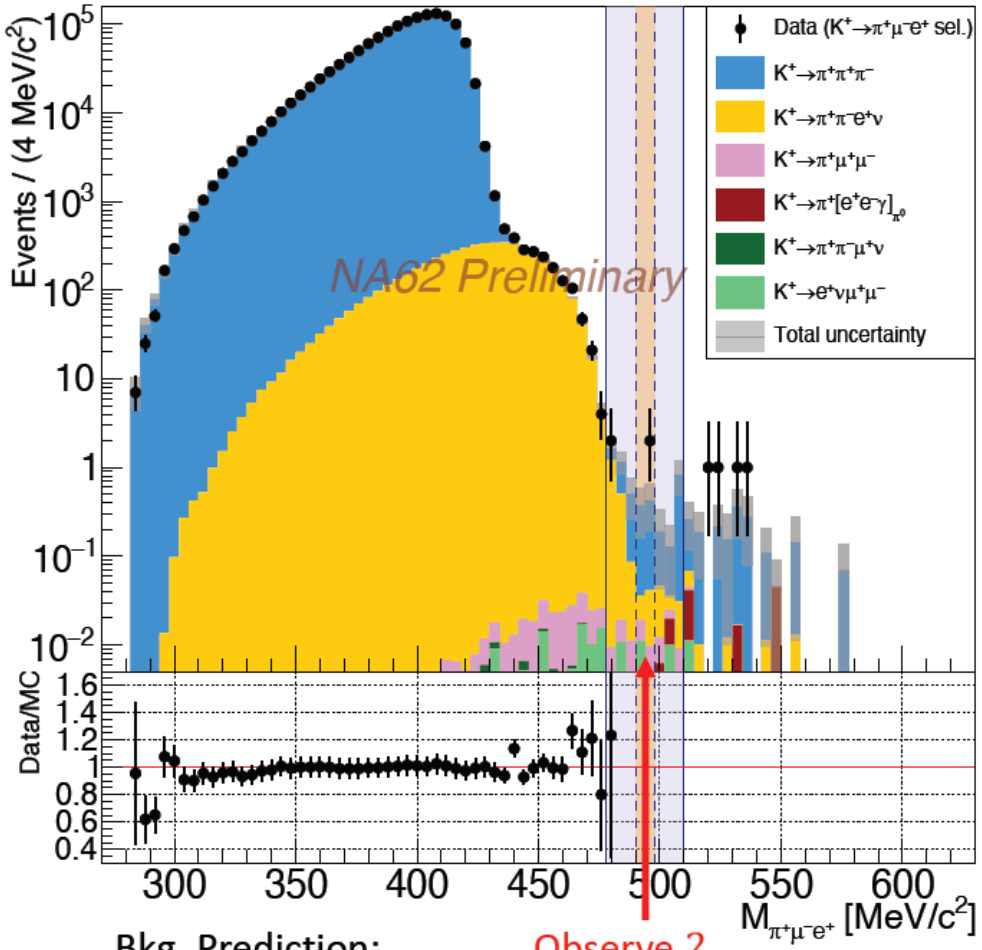
$$BR(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11} \text{ @ } 90\% \ CL$$



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

Observe 0 events in SR

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



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

Observe 2 events in SR

Conclusion LFV & LNV

Decay	Previous *BR* upper limit @ 90% CL [PDG]	*NA62 BR* upper limit @ 90% CL	
$K^+ \to \pi^- \mu^+ \mu^+$	$8.6 \cdot 10^{-11}$	$4.2 \cdot 10^{-11}$	Improve by a factor **2** with **2017** data [*PLB 797 (2019) 134794*]
$K^+ \to \pi^- e^+ e^+$	$6.4 \cdot 10^{-10}$	$2.2 \cdot 10^{-10}$	Improve by a factor **3** with **2017** data [*PLB 797 (2019) 134794*]
$K^+ \to \pi^- \mu^+ e^+$	$5.0 \cdot 10^{-10}$	$4.2 \cdot 10^{-11}$	Improve by a factor **12** with **2017+2018** data [*arXiv:2105.06759*]
$K^+ \to \pi^+ \mu^- e^+$	$5.2 \cdot 10^{-10}$	$6.6 \cdot 10^{-11}$	Improve by a factor **8** with **2017+2018** data [*arXiv:2105.06759*]
$K^+ \to \pi^+ \mu^+ e^-$	$1.3 \cdot 10^{-11}$		Not yer competitive with previous dedicated experiment
$K^+ \to \mu^- \upsilon e^+ e^+$	$2.1 \cdot 10^{-8}$		Stay tuned… SES~1×10^{-10} [2017 data]
$K^+ \to e^- \upsilon \mu^+ \mu^+$	No previous limit		Stay tuned… SES~5×10^{-11} [2017 data]
$\pi^0 \to \mu^- e^+$	$3.4 \cdot 10^{-9}$	$3.2 \cdot 10^{-10}$	Improve by a factor **11** with **2017+2018** data [*arXiv:2105.06759*]