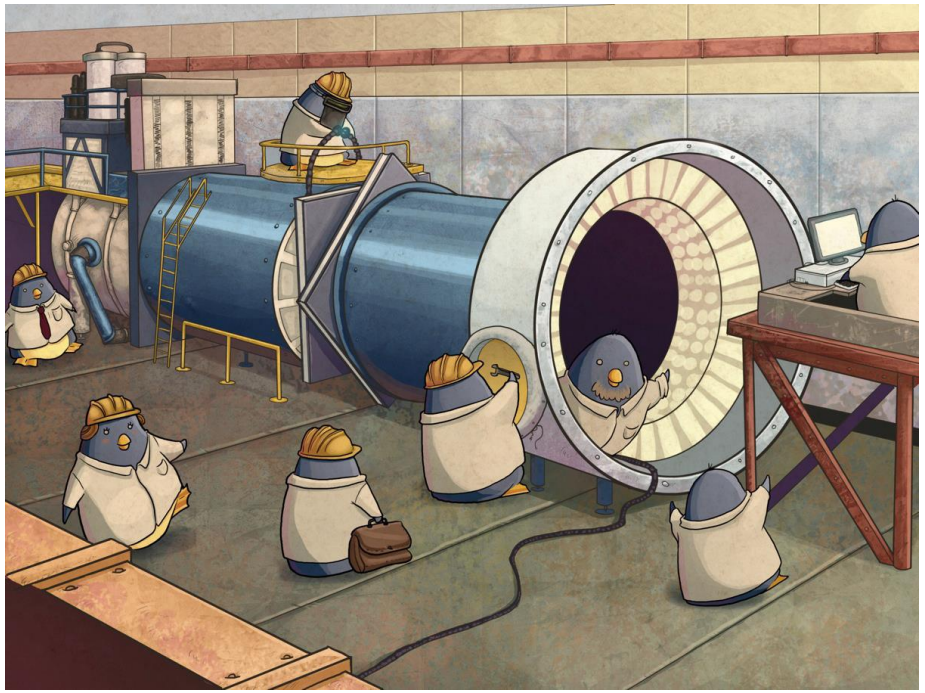
Physics Beyond SM With Kaons From NA62



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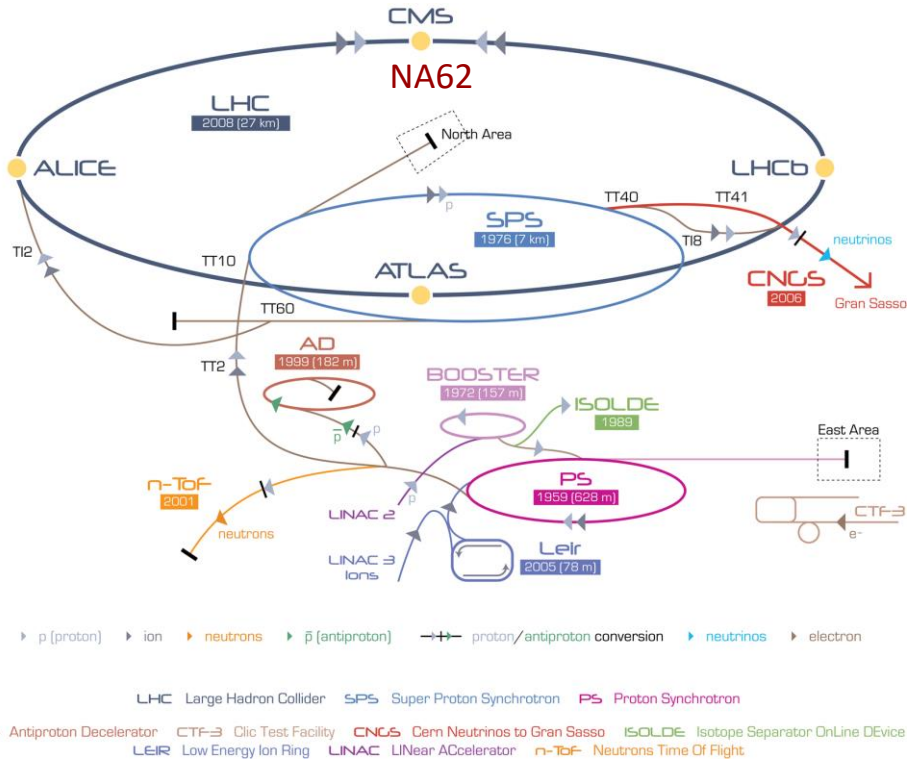
02/07/2019

The NA62 Experiment

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

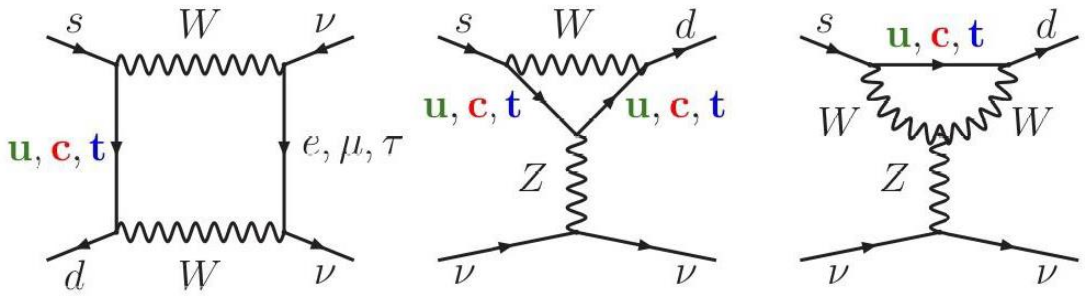


NA62 Timeline

- 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 (This talk)
- Continuous data-taking until the end of 2018

~ 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 ~ $|V_{ts}xV_{td}|^2$)

- Very clean theoretically: Short distance contribution
- hadronic matrix element extracted from precisely measured BR($K^+ \to \pi^0 e^+ \upsilon$)
- SM predictions:

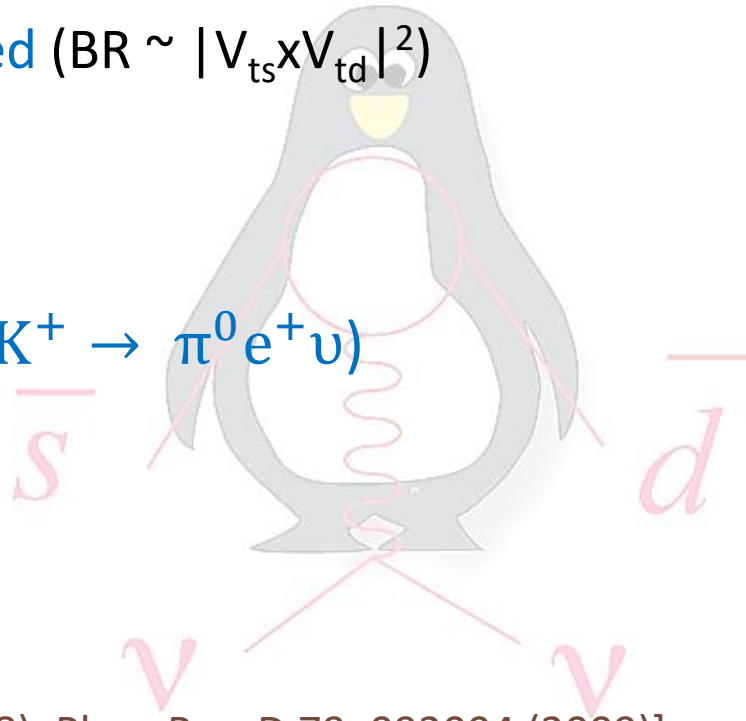
  BR($K^+ \to \pi^+ \upsilon\bar{\upsilon}$) = $(8.4 \pm 1.0) \times 10^{-11}$

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

  [Buras et al. JHEP 1511 (2015) 33]
- Experimental Result:

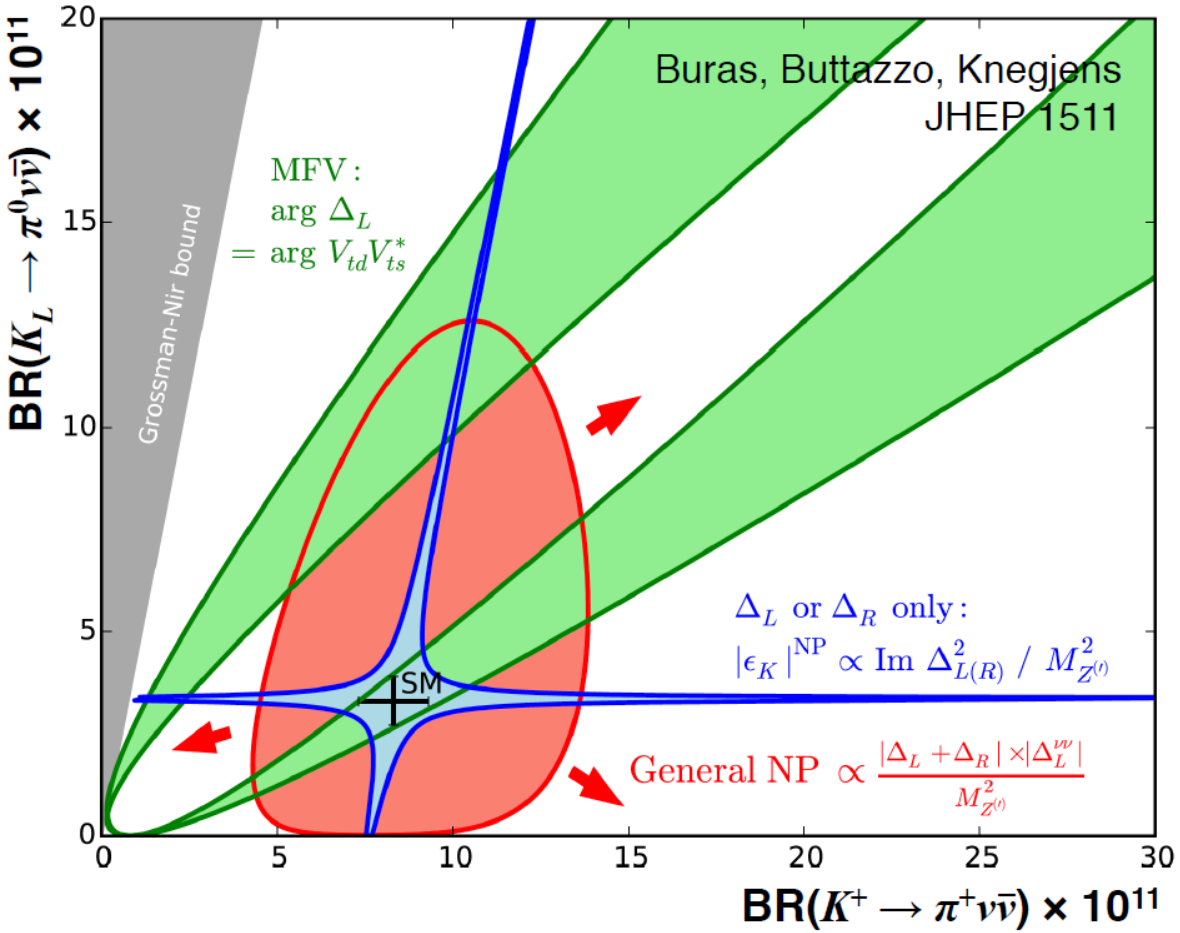
  BR($K^+ \to \pi^+ \upsilon\bar{\upsilon}$) = $(17.3^{+11.5}_{-10.5}) \times 10^{-11}$ [Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)]

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



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

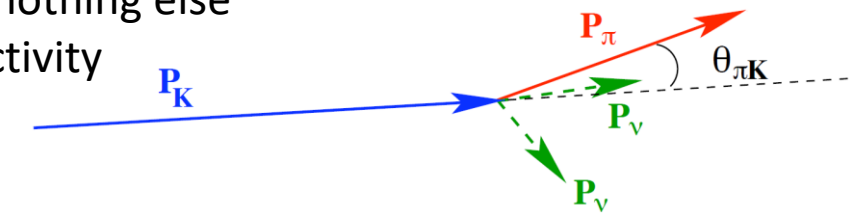
Measurement of charged ($K^+ \to \pi^+\upsilon\bar{\upsilon}$) and neutral ($K_L \to \pi^0\upsilon\bar{\upsilon}$) modes can **discriminate among different NP scenarios**

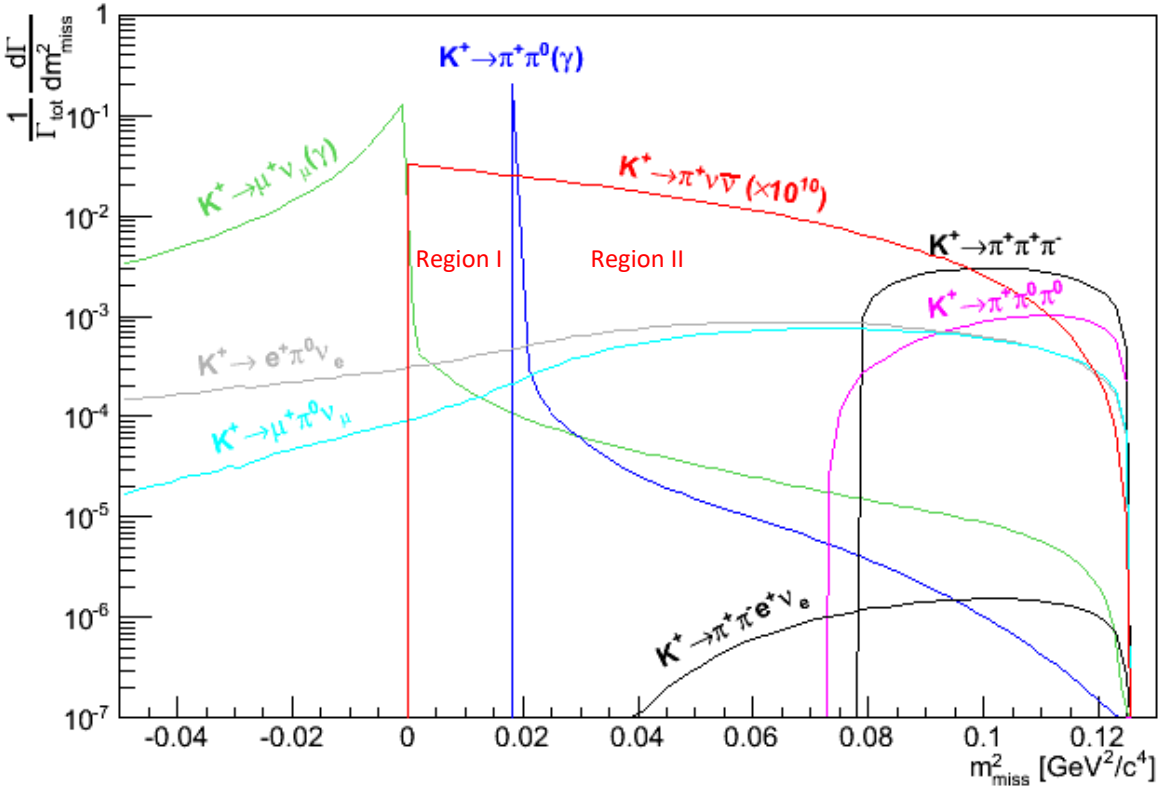


- Models with CKM-like flavor structure:
  - Models with MFV
- Models with new flavour-violating interactions in which either LH or RH currents dominate:
  - *Z*/*Z*′ models with pure LH/RH couplings
  - Little Higgs with *T* parity
- Models without above constraints:
  - Randall-Sundrum

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^+} <35 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

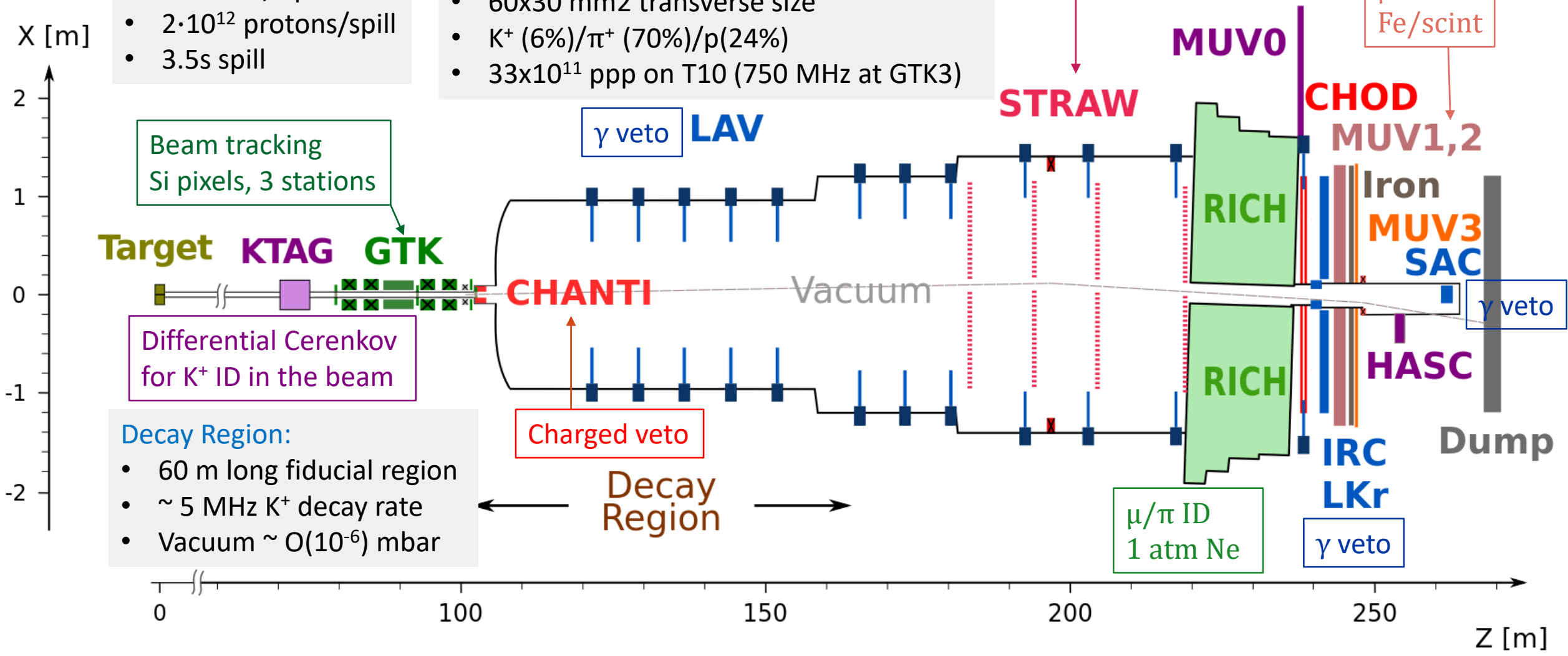
Keystone:

- 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

NA62 Layout

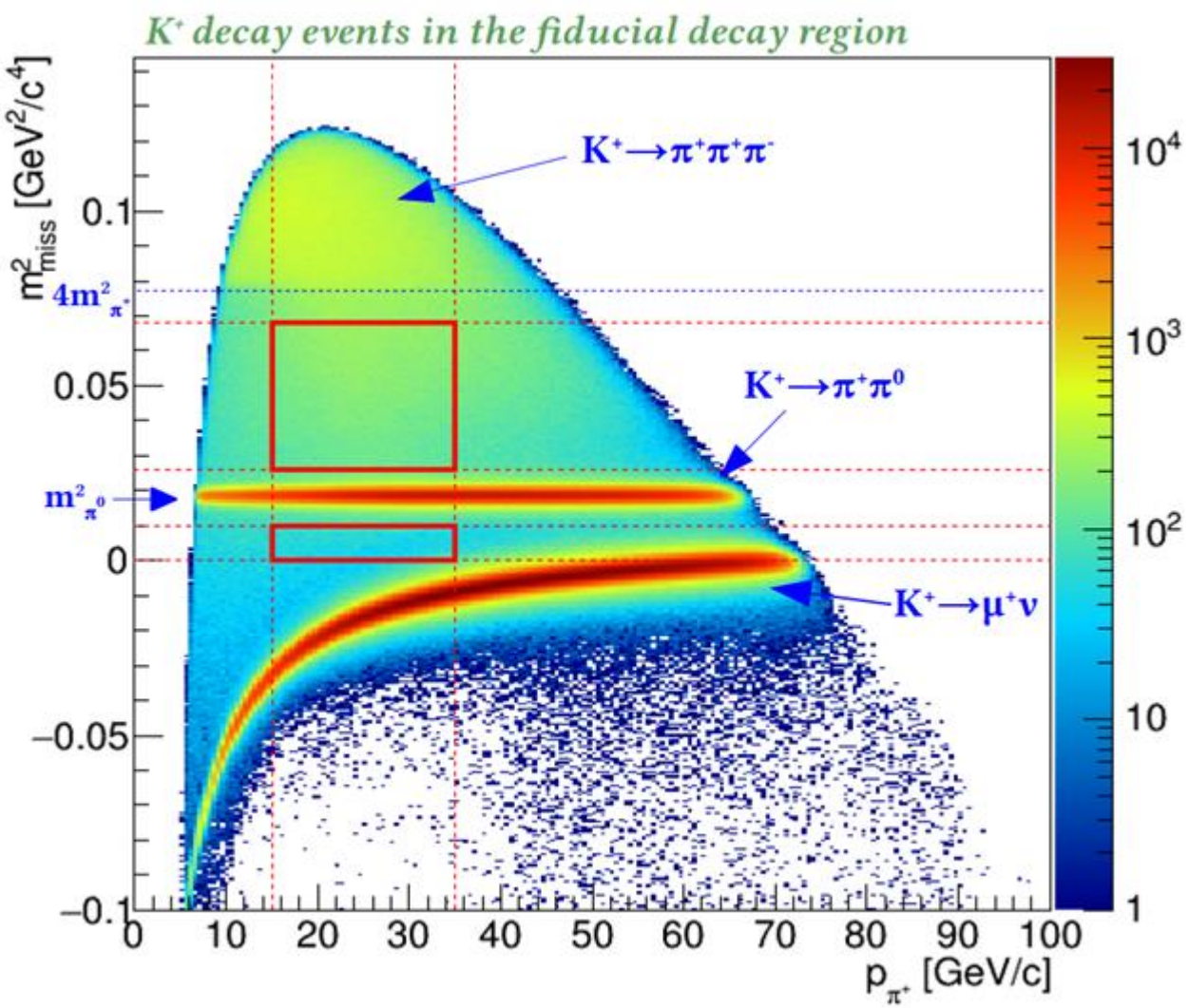
SPS Beam:
- 400 GeV/c protons
- $2 \cdot 10^{12}$ protons/spill
- 3.5s spill

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

Signal Selection



πνν selection:

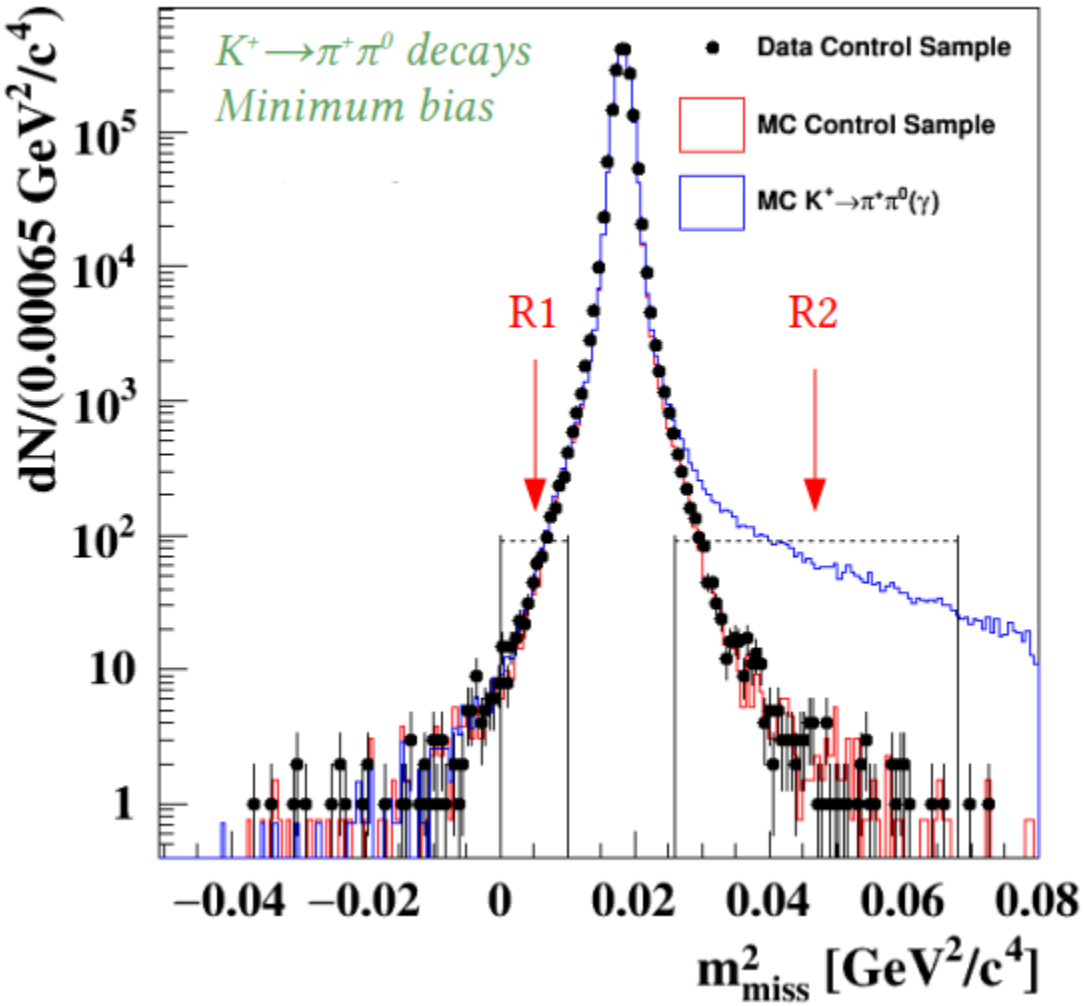
- K^+ Decay Event
- Fiducial Decay Region
- Particle ID: π^+
- Photon rejection
- Multiple charged particle rejection
- Kinematic Selection of the Signal Regions

Performance:

- $\epsilon_{\mu^+} = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
- $\epsilon_{\pi^0} = 3 \cdot 10^{-8}$
- $\sigma(m^2_{miss}) = 1 \cdot 10^{-3}$ GeV² / c⁴
- $\sigma_T \sim O(100\ \text{ps})$

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

Kinematic suppression



Three ways to compute the m^2_{miss}:

- m^2_{miss}(STRAW, GTK)
- m^2_{miss}(RICH, GTK)
- m^2_{miss}(STRAW, Beam)

→ Protects against mis-reconstruction

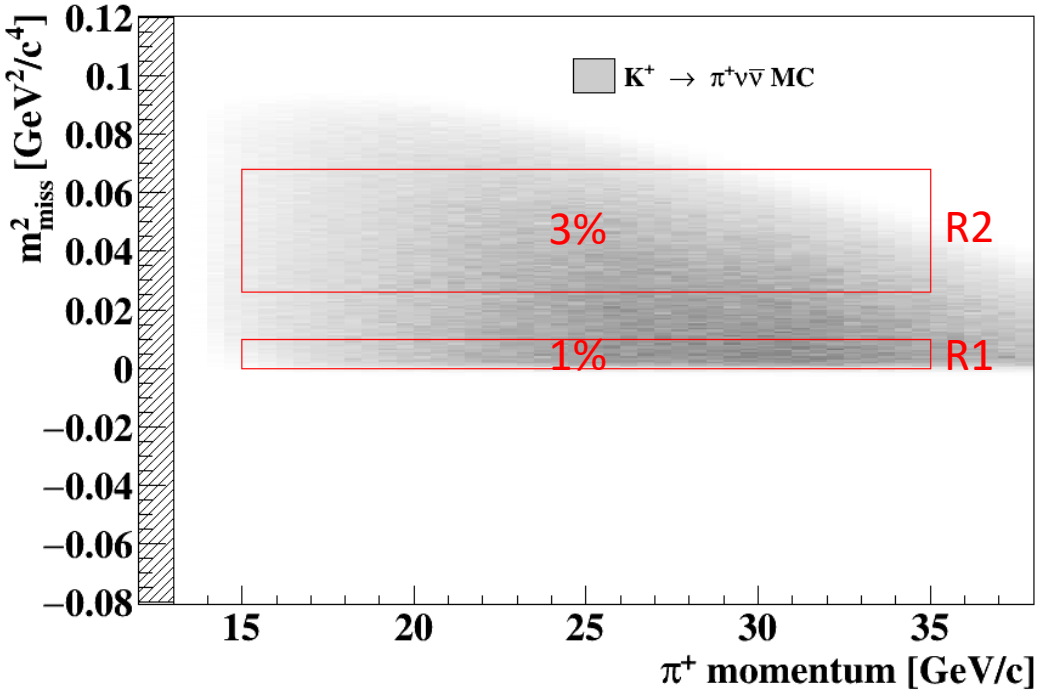
Kinematic suppression:

- Measured using data
- Samples of $K_{\pi\pi}$ and $K_{\mu\nu}$
- Selected using calorimeters

Fraction of Events in signal regions:

- $K^+ \to \pi^+\pi^0 \sim 1 \cdot 10^{-3}$
- $K^+ \to \mu^+\upsilon \sim 3 \cdot 10^{-4}$
- Radiative: $\pi^0 + \gamma \to$ x 30 π^0 rejection in R2

Single Event Sensitivity (SES)



Acceptance $K^+ \to \pi^+\upsilon\bar{\upsilon}$	0.04 ± 0.001
Normalization acceptance ($K^+ \to \pi^+\pi^0$)	0.1
PNN trigger efficiency	0.87± 0.02
Number of K^+ in the fiducial volume	(1.21± 0.02) x 10^{11}

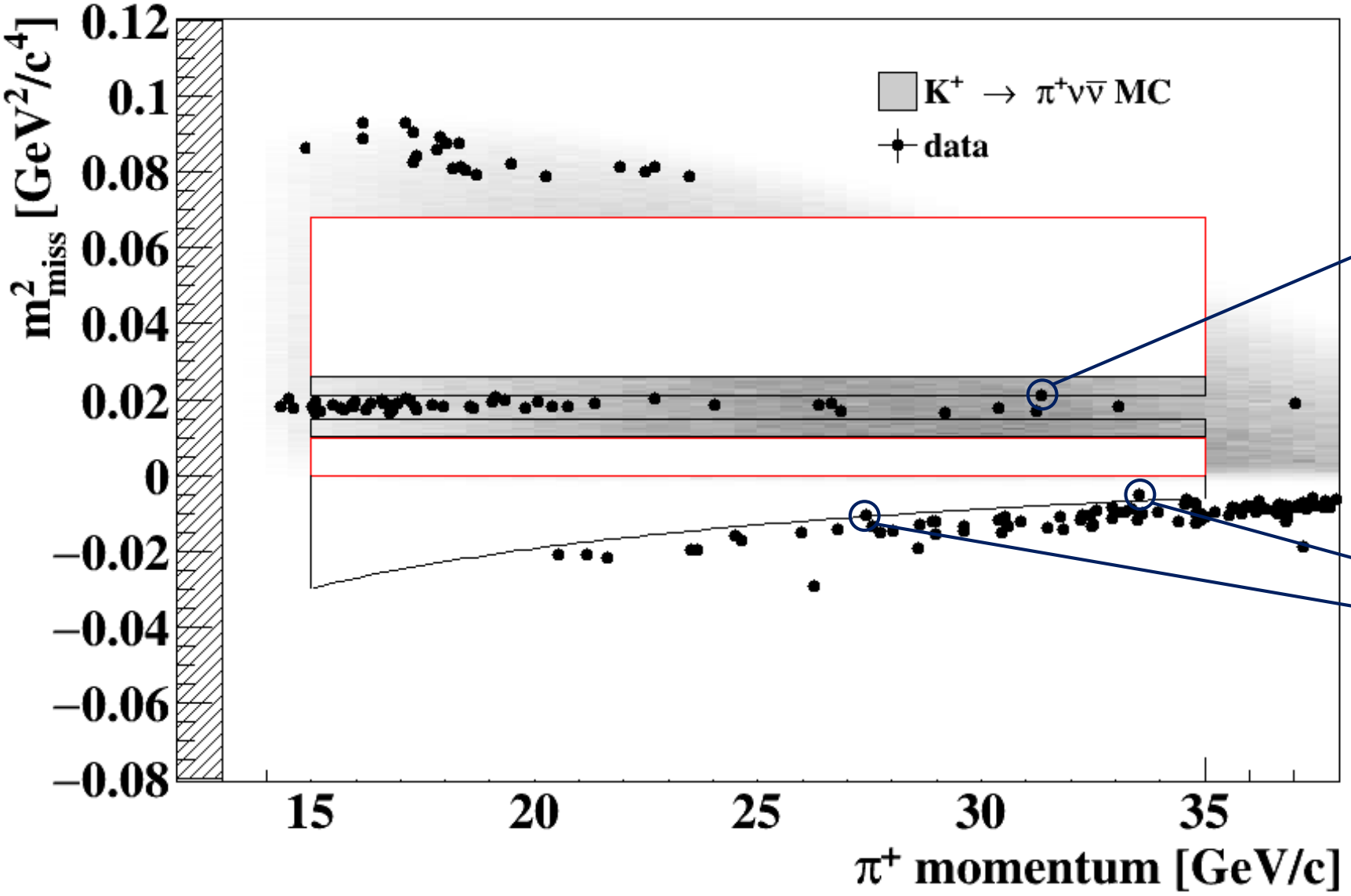
Source	δSES(10^{-10})
Random Veto	±0.17
N_K	±0.05
Trigger efficiency	±0.04
Definition of $\pi^+\pi^0$ region	±0.10
Momentum spectrum	±0.01
Extra activity	±0.09
Simulation of π^+ interactions	±0.02
GTK Pileup simulation	±0.02
Total	±0.24

$$SES = (3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$$

Background summary

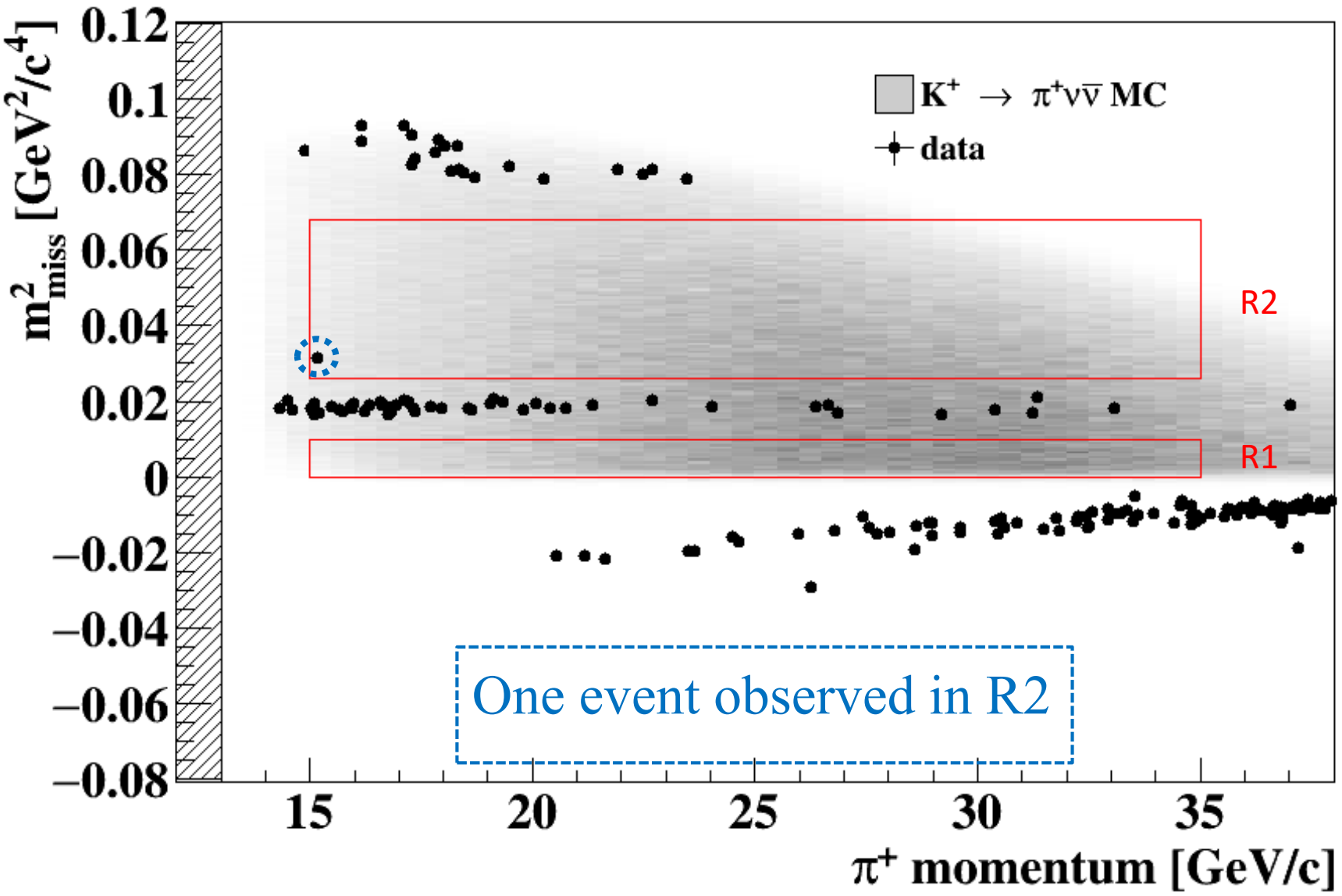
Process	Expected events in R1+R2
$K^+ \to \pi^+ \nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu_\mu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+\pi^- e^+\nu_e$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream Background	$0.050^{+0.090}_{-0.030}\vert_{stat}$

Result



- 1 event observed in $\pi^+\pi^0$ CR2
- 0 events observed in $\pi^+\pi^0$ CR1
- 2 events observed in $\mu^+\upsilon$ CR

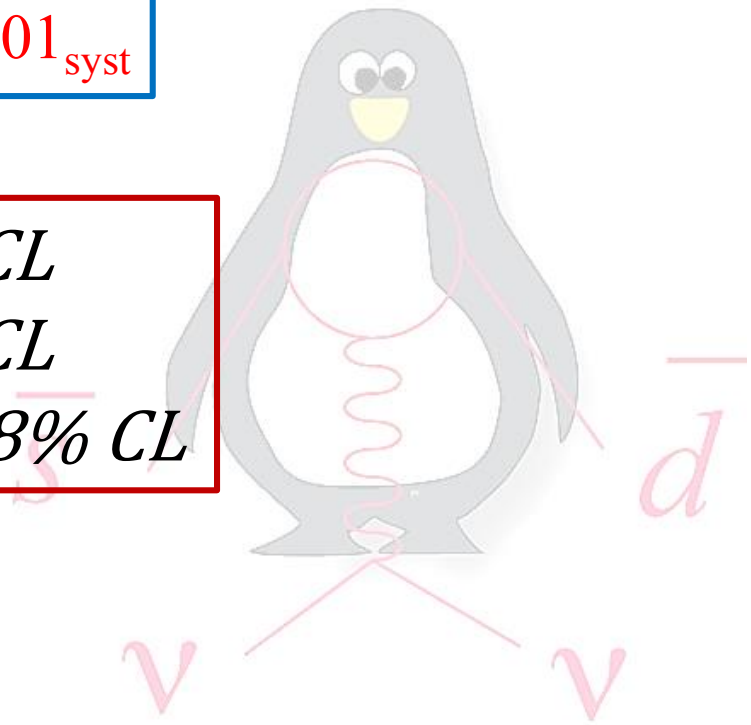
Result


m^2_{miss} [GeV^2/c^4]
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
15
20
25
30
35
π^+ momentum [GeV/c]
$K^+ \to \pi^+\nu\bar{\nu}$ MC
data
R2
R1
One event observed in R2

Result

- 1 observed Events
- SES = $(3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$
- Expected Background = $0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

$$BR(K^+ \to \pi^+ \upsilon\bar{\upsilon}) < 14 \cdot 10^{-10} \text{ @ } 95\% \text{ CL}$$
$$BR(K^+ \to \pi^+ \upsilon\bar{\upsilon}) < 11 \cdot 10^{-10} \text{ @ } 90\% \text{ CL}$$
$$BR(K^+ \to \pi^+ \upsilon\bar{\upsilon}) = 2.8^{+4.4}_{-2.3} \cdot 10^{-10} \text{ @ } 68\% \text{ CL}$$



For comparison:

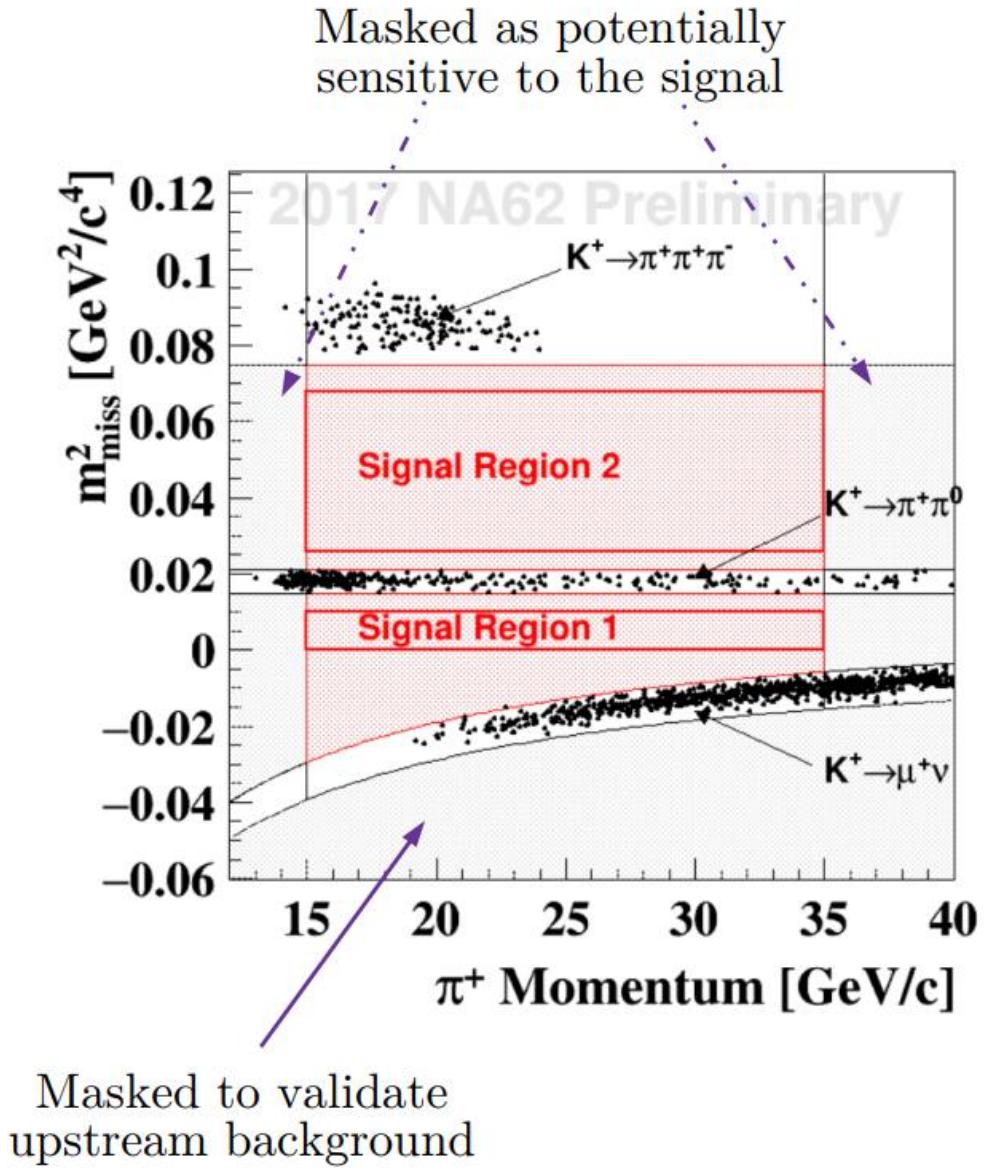
- SM prediction: $BR(K^+ \to \pi^+ \upsilon\bar{\upsilon})_{SM} = (0.84 \pm 0.10) \times 10^{-10}$
- BNL E949/E787 (Kaon decays at rest): $BR(K^+ \to \pi^+ \upsilon\bar{\upsilon})_{exp} = 1.73^{+1.15}_{-1.05} \cdot 10^{-10}$

2017 Data: Selection and SES

- 2016-like selection
- Comparable to the 2016 analysis performances
  - Better treatment of pileup in IRC and SAC
  - 40% lower π^0 rejection inefficiency compared to 2016: $(1.4 \pm 0.1) \times 10^{-8}$
  - Slightly improved usage of RICH variables

NA62 Preliminary

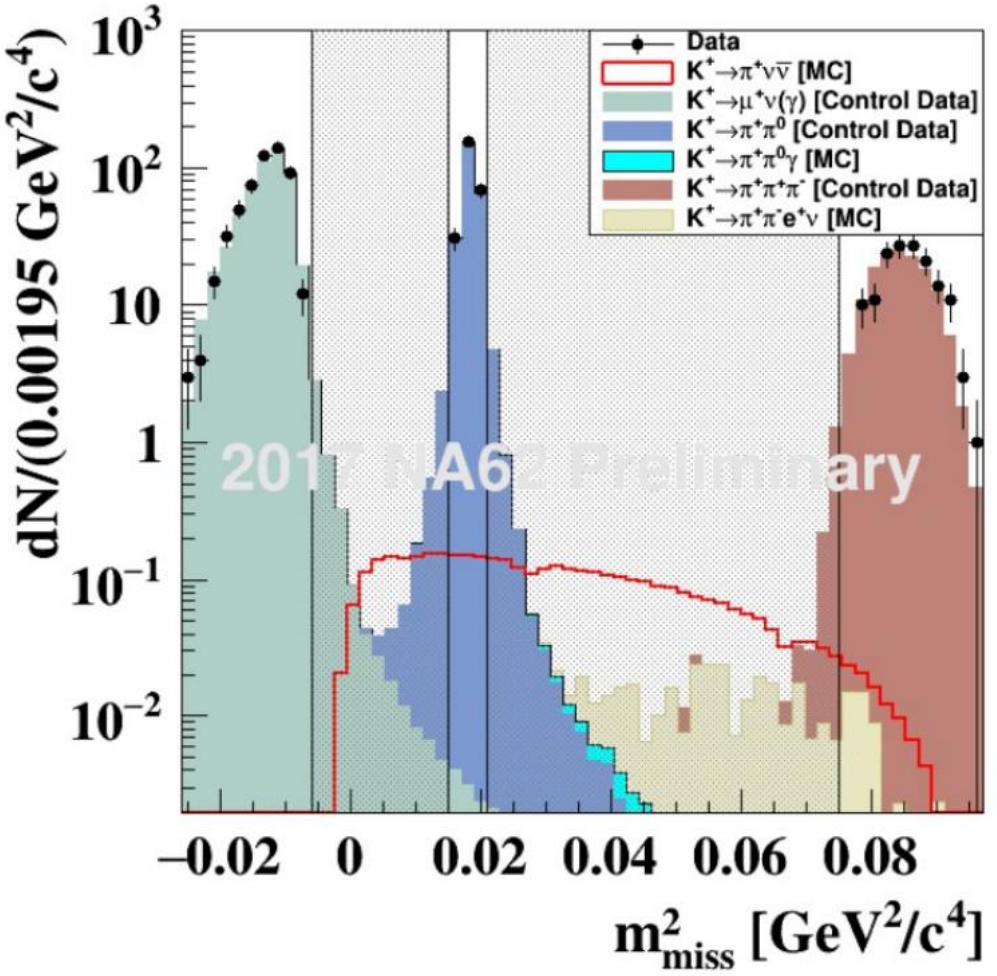
N_K	$(13 \pm 1) \times 10^{11}$
SES	$(0.34 \pm 0.04) \times 10^{-10}$
Expected SM $K^+ \to \pi^+ \nu\bar{\nu}$	2.5 ± 0.4



2017 Data: backgrounds

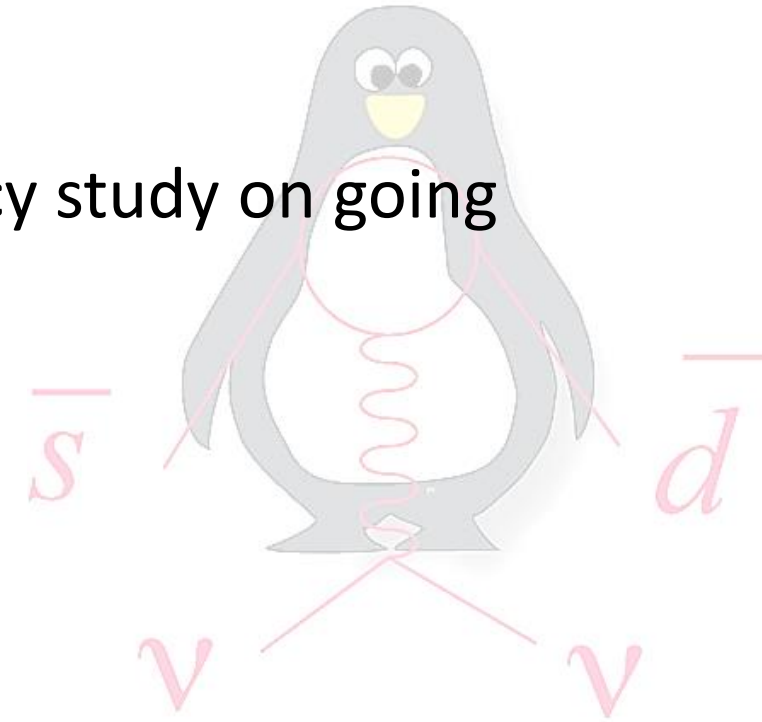
- 2017 data allows detailed comparison between data and background models
- Good agreement between m_{miss} model and data confirms validity of estimated background from kaon decays

Process	Expected events in signal regions
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.35 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.16 \pm 0.01_{stat} \pm 0.05_{syst}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.22 \pm 0.08_{stat}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.015 \pm 0.008_{stat} \pm 0.015_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l$	$0.012 \pm 0.012_{syst}$
Upstream Background	Analysis on–going



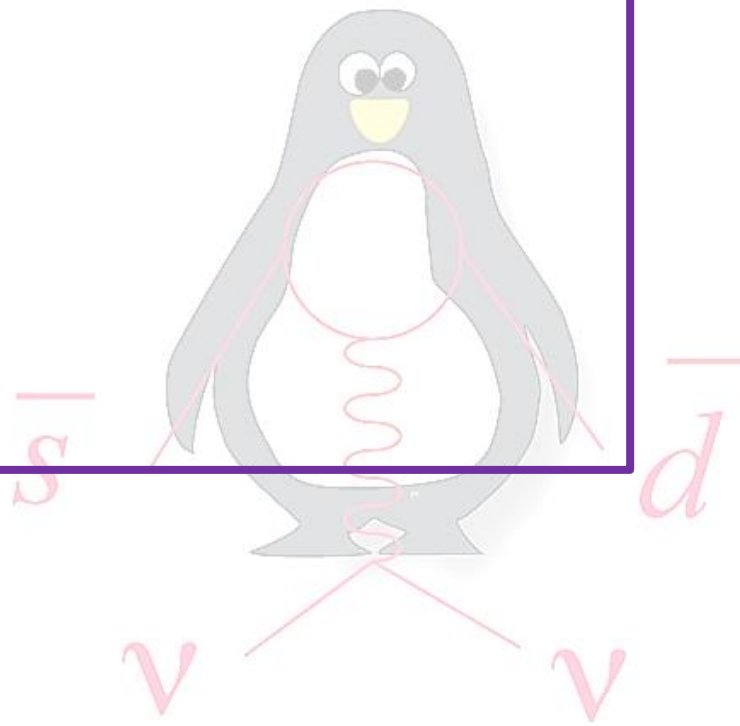
Prospects

- 2017 data analysis is on going:
  - SES is 10 times better than for 2016
  - Upstream background estimation on going
  - Background rejection and reconstruction efficiency study on going
  - Expected about 2.5 events
- 2018 to be analysed



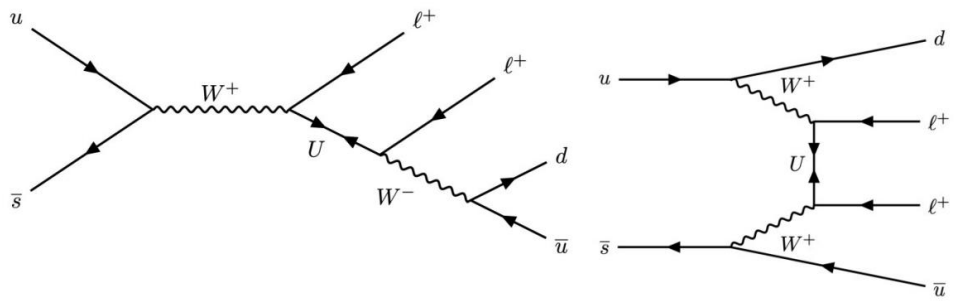
NA62: Broader physics program

- Rare kaon decays
- LNV/LFV in kaon decays [this talk]
- Exotic searches [Monica Pepe talk]:
  - HNL searches
  - Dark Photon
  - Axion-like particle



Lepton Number Violation

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

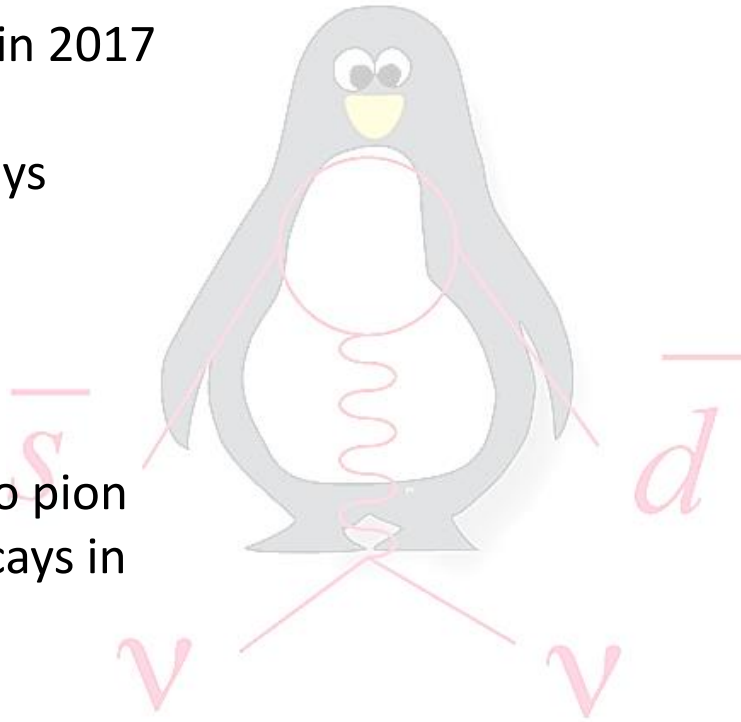


Previous experimental results:

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

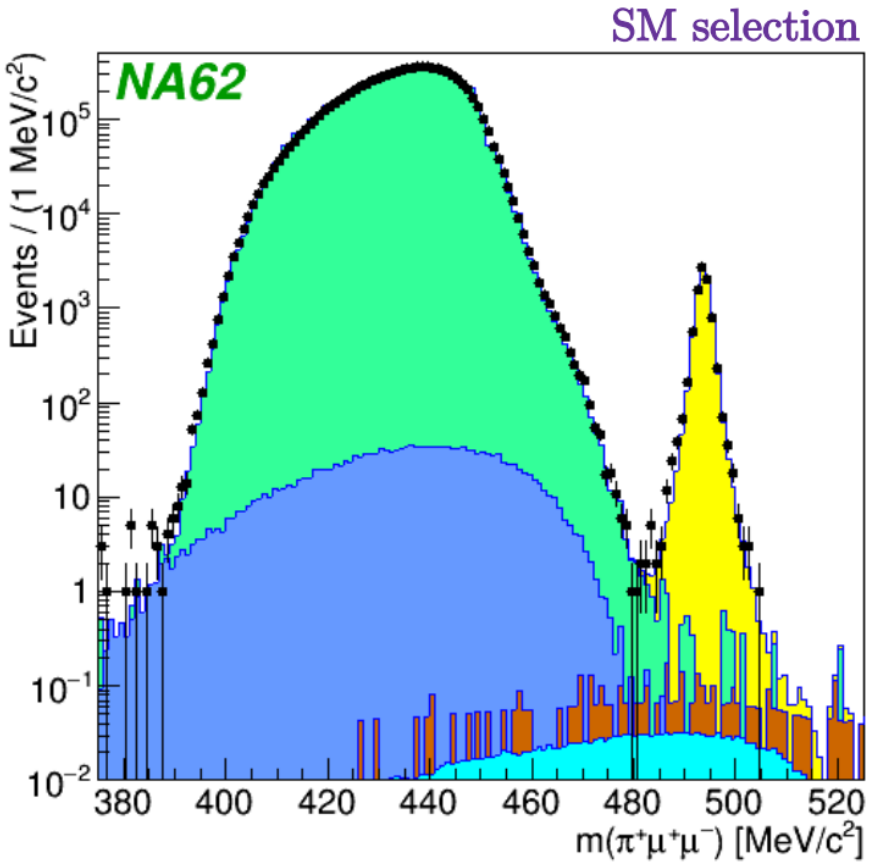
LNV searches in NA62:

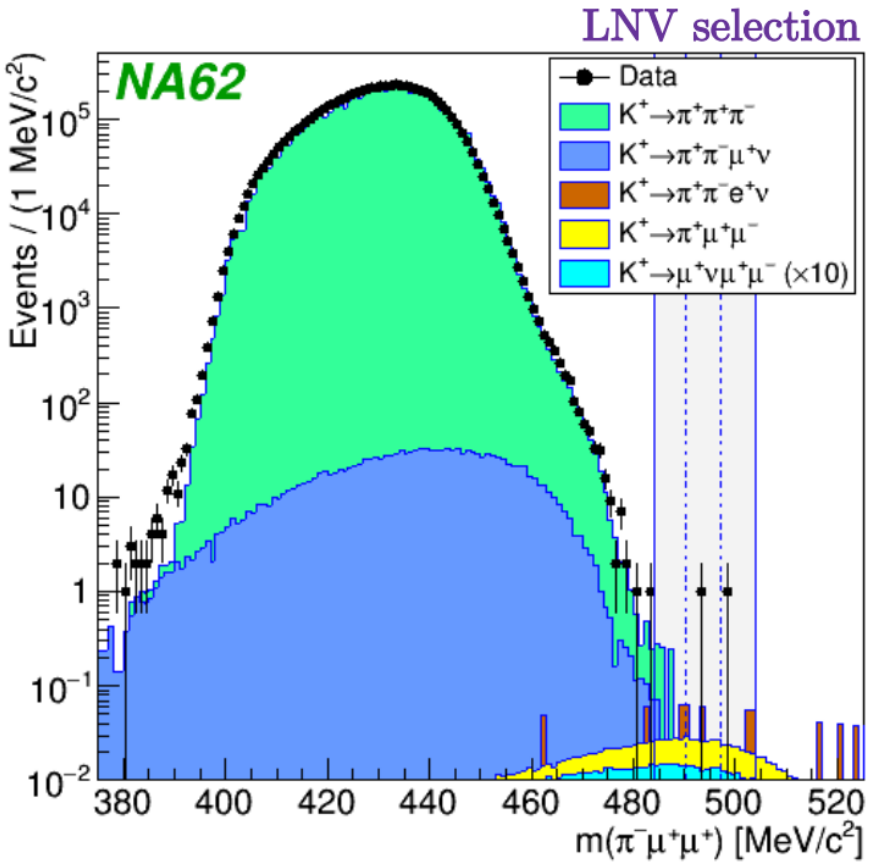
- ~3 months of data taking in 2017
- Blind analysis
- Normalization to SM decays ($K^+ \to \pi^+ l^+ l^-$)
- Acceptance:
  - 5% for $K^+ \to \pi^- e^+ e^+$
  - 10% for $K^+ \to \pi^- \mu^+ \mu^+$
- Main background is due to pion mis-identification and decays in flight

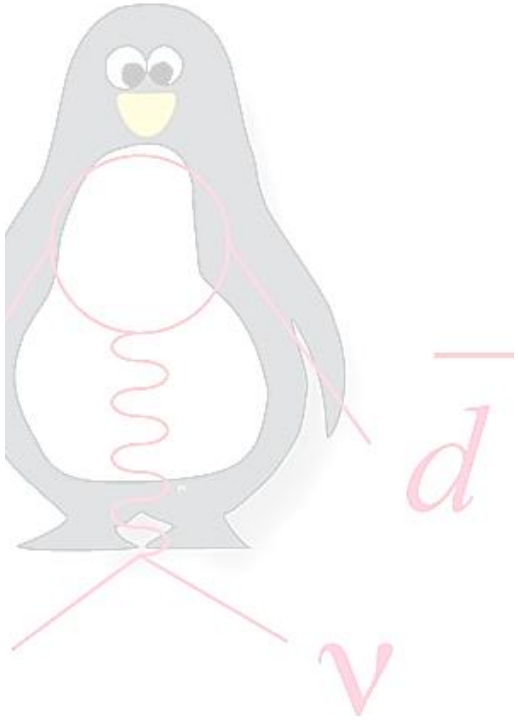


$K^+ \to \pi^- \mu^+ \mu^+$

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

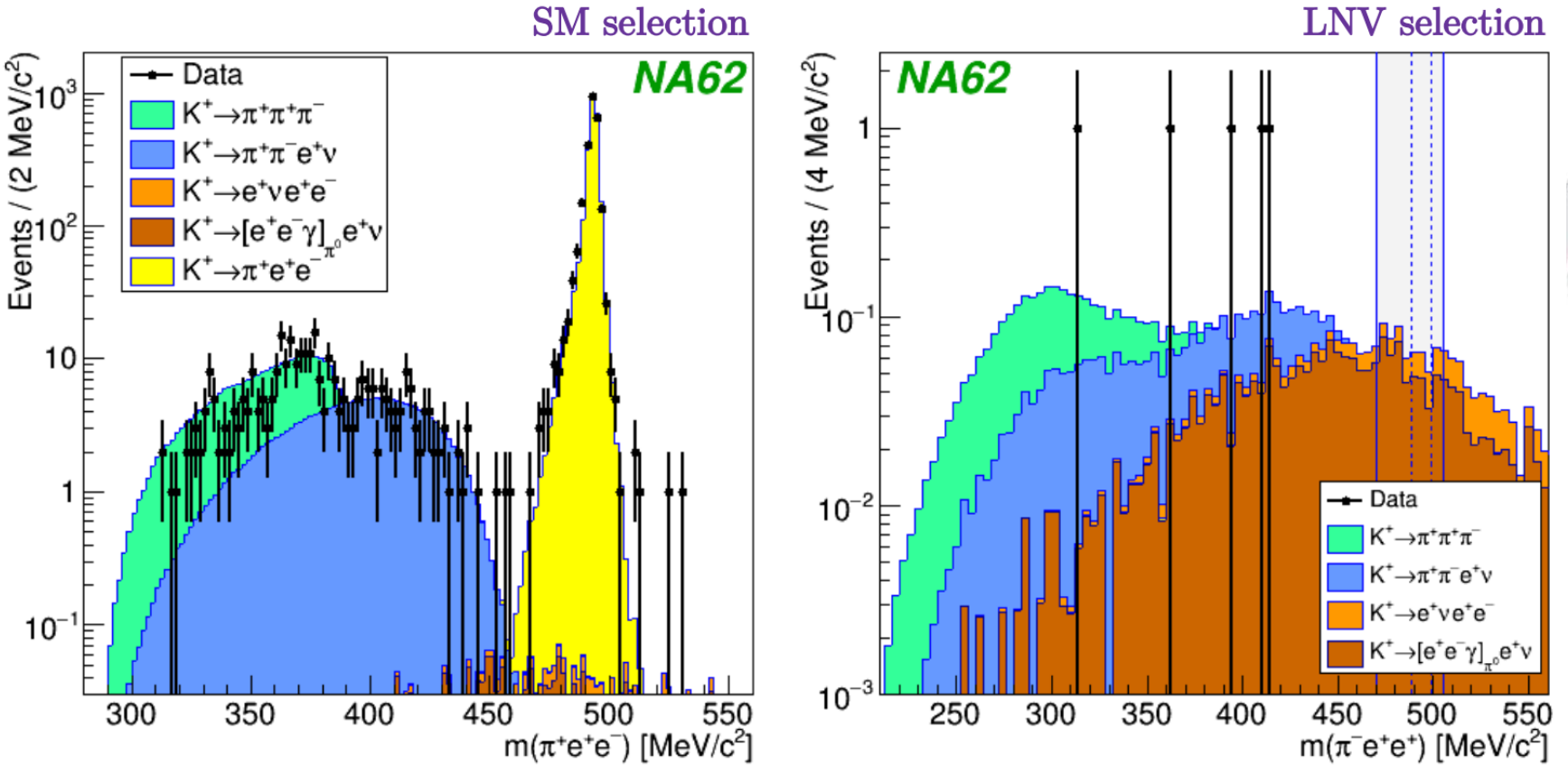


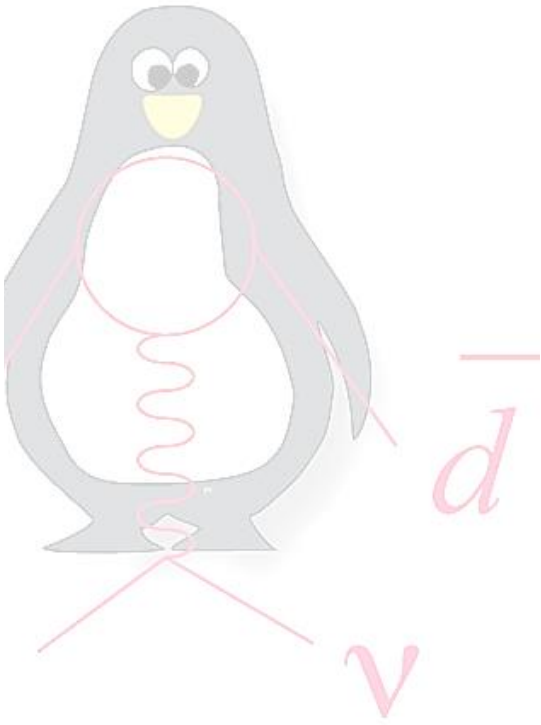




$K^+ \to \pi^- e^+ e^+$

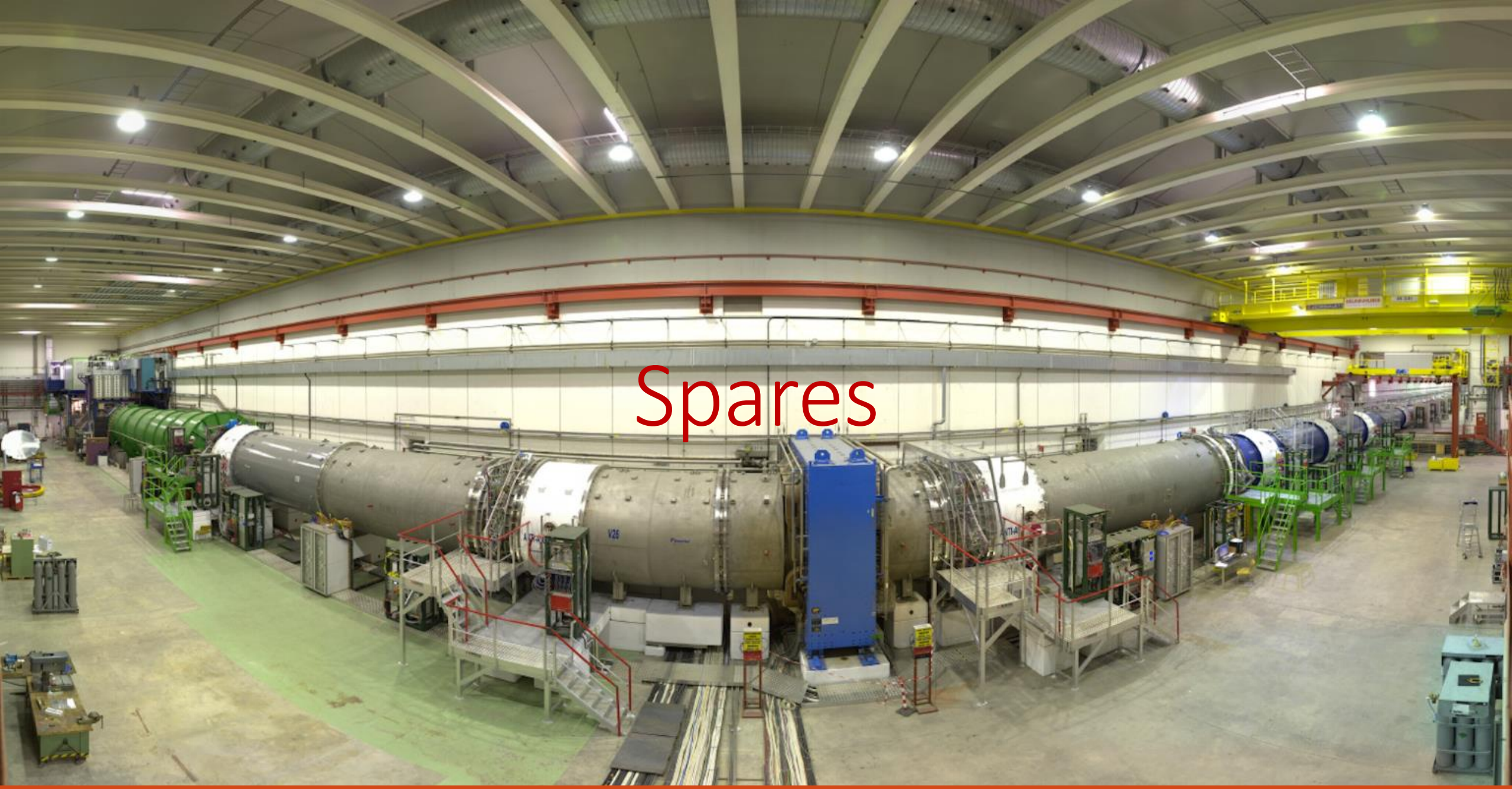
- Expected background in the blinded region: 0.16 ± 0.03
- No candidate observed in the signal region
- $\mathrm{BR}(K^+ \to \pi^- e^+ e^+) < 2.2 \cdot 10^{-10}$ @ *90% CL*





Conclusion

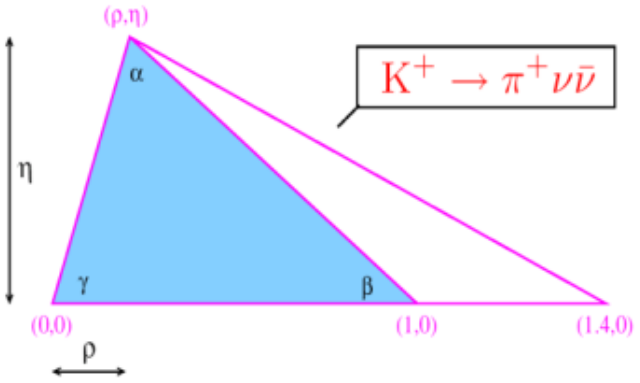
- $K^+ \to \pi^+ \nu\bar{\nu}$: analysis of 2016 data finished and published
  - The novel decay-in-flight technique is established [Phys. Lett. B 791 (2019) 156]
- $K^+ \to \pi^+ \nu\bar{\nu}$: analysis of 2017 data on going
  - Results expected in 2019
- LNV $K^+ \to \pi^- l^+ l^+$: new result from the analysis of 3 months of 2017 data taking [arXiv:1905.07770 submitted to Phys. Lett. B]
  - about 3 times more data to analyse


Spares

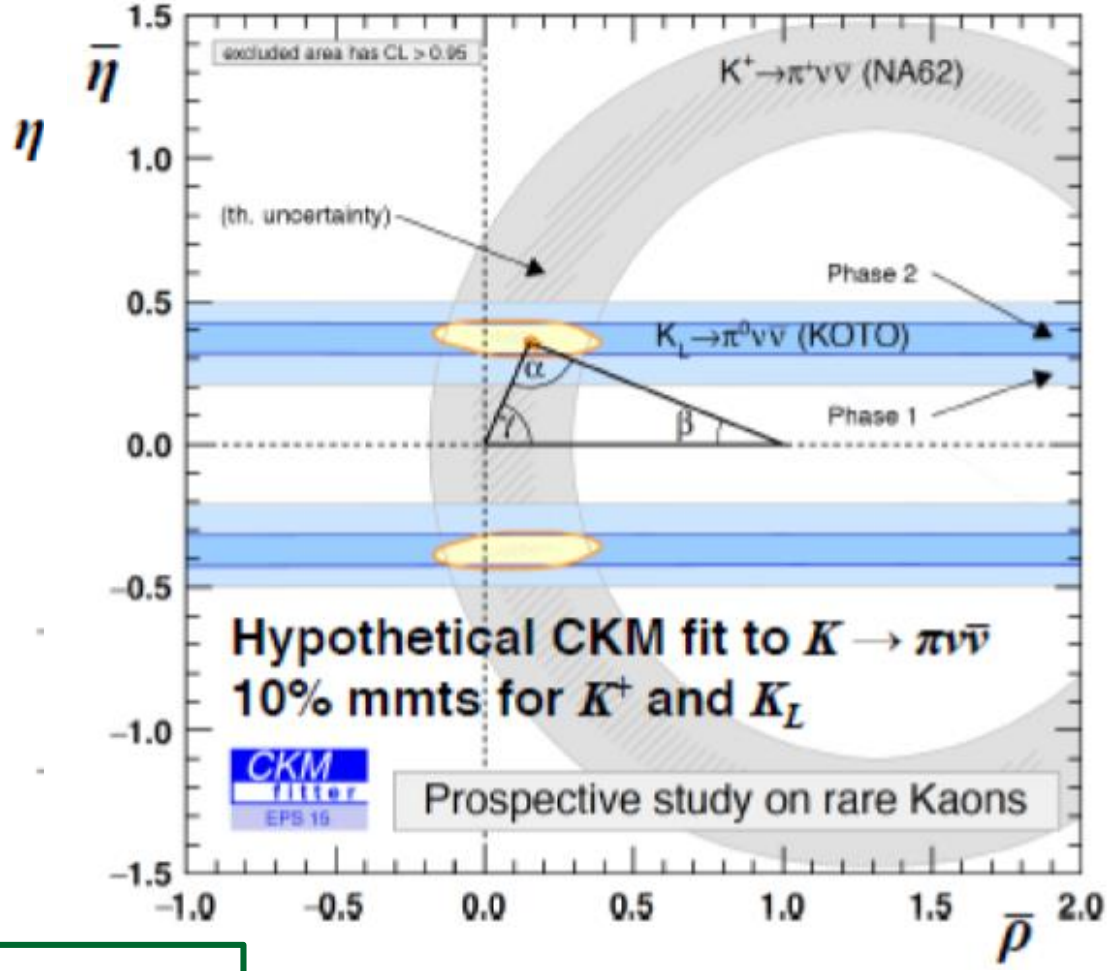
backgrounds : $K^+ \to \pi^+\pi^- e^+\nu_e$ (K_{e4})

$K_L \to \pi^0\nu\bar{\nu}$

$K_L \to \pi^0 e^+ e^-$ { $K_S \to \pi^0 e^+ e^-$, $K_L \to \pi^0\gamma\gamma$, $K_L \to ee\gamma\gamma$ }



$K_L \to \mu^+\mu^-$ { $K_L \to \gamma\gamma$, $K_L \to e^+e^-\gamma$, $K_L \to e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$ }



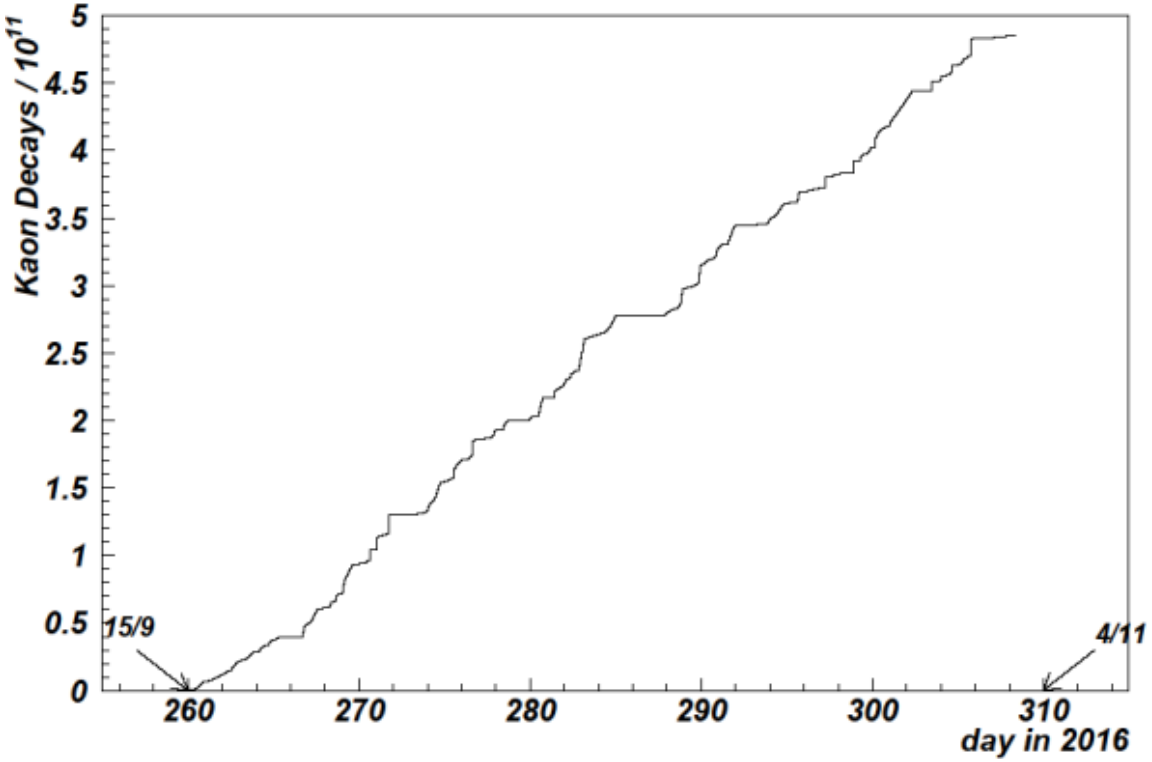
- K physics alone can fully constrain the CKM unitarity triangle
- Comparison with B physics can provide description of NP flavour dynamics

NA62 “Luminosity”

2016 Run

$13 \cdot 10^{11}$ ppp on target (40% normal)

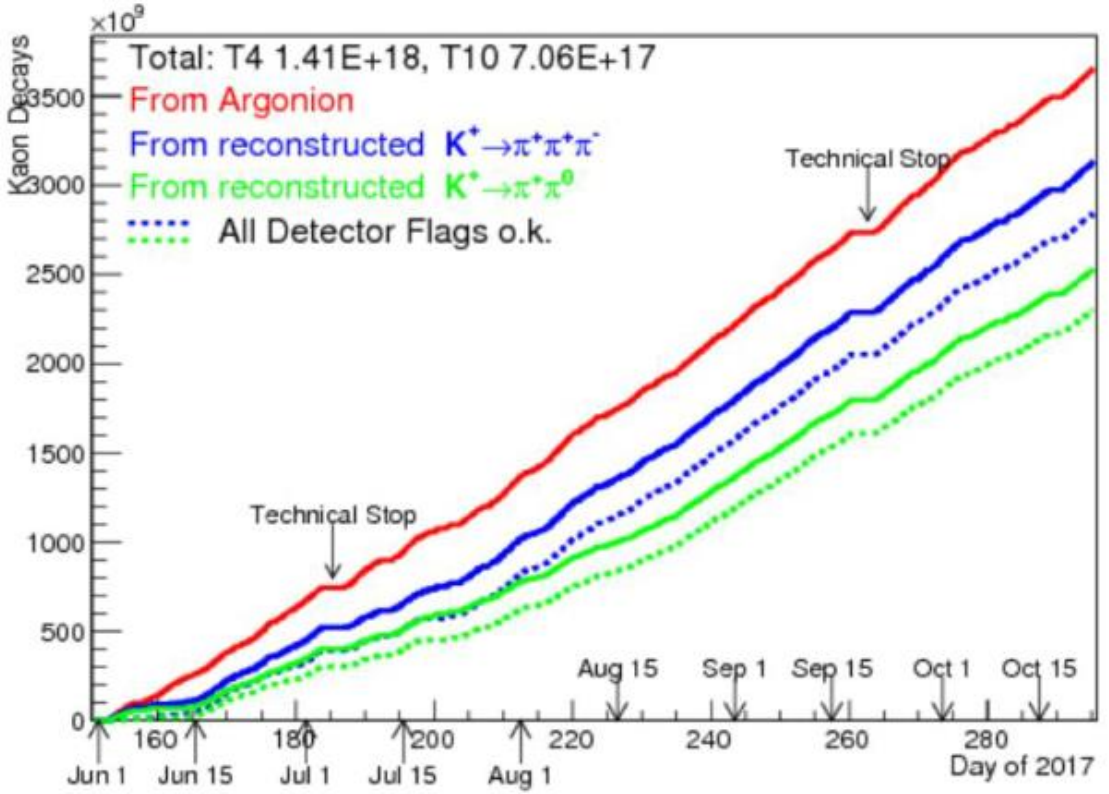
$\sim 1 \cdot 10^{11}$ K^+ decays useful for $\pi^+ \upsilon \bar{\upsilon}$



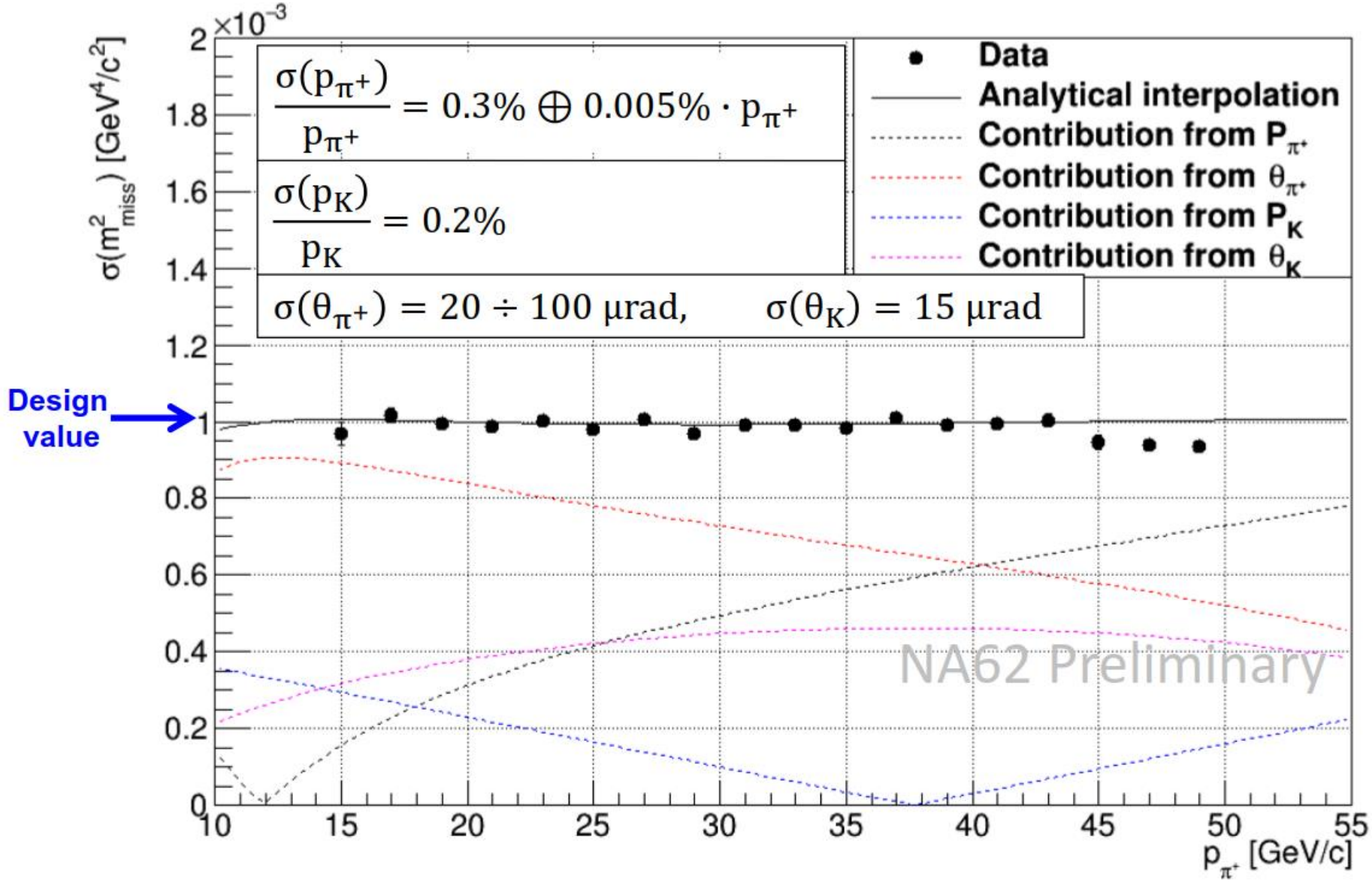
2017 Run

$20 \cdot 10^{11}$ ppp on target (60% normal)

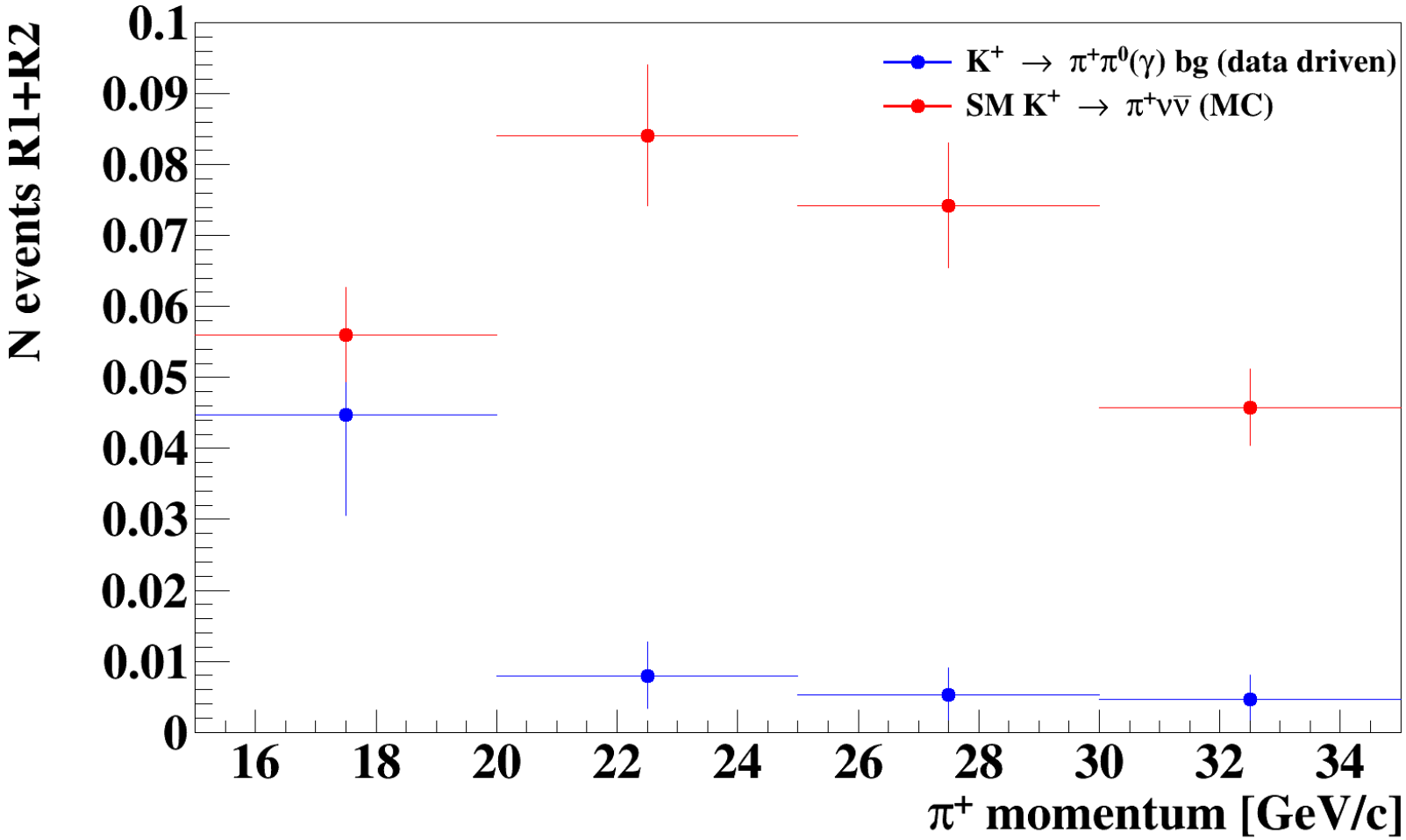
$> 3 \cdot 10^{12}$ K^+ decays collected



Kinematic Resolution



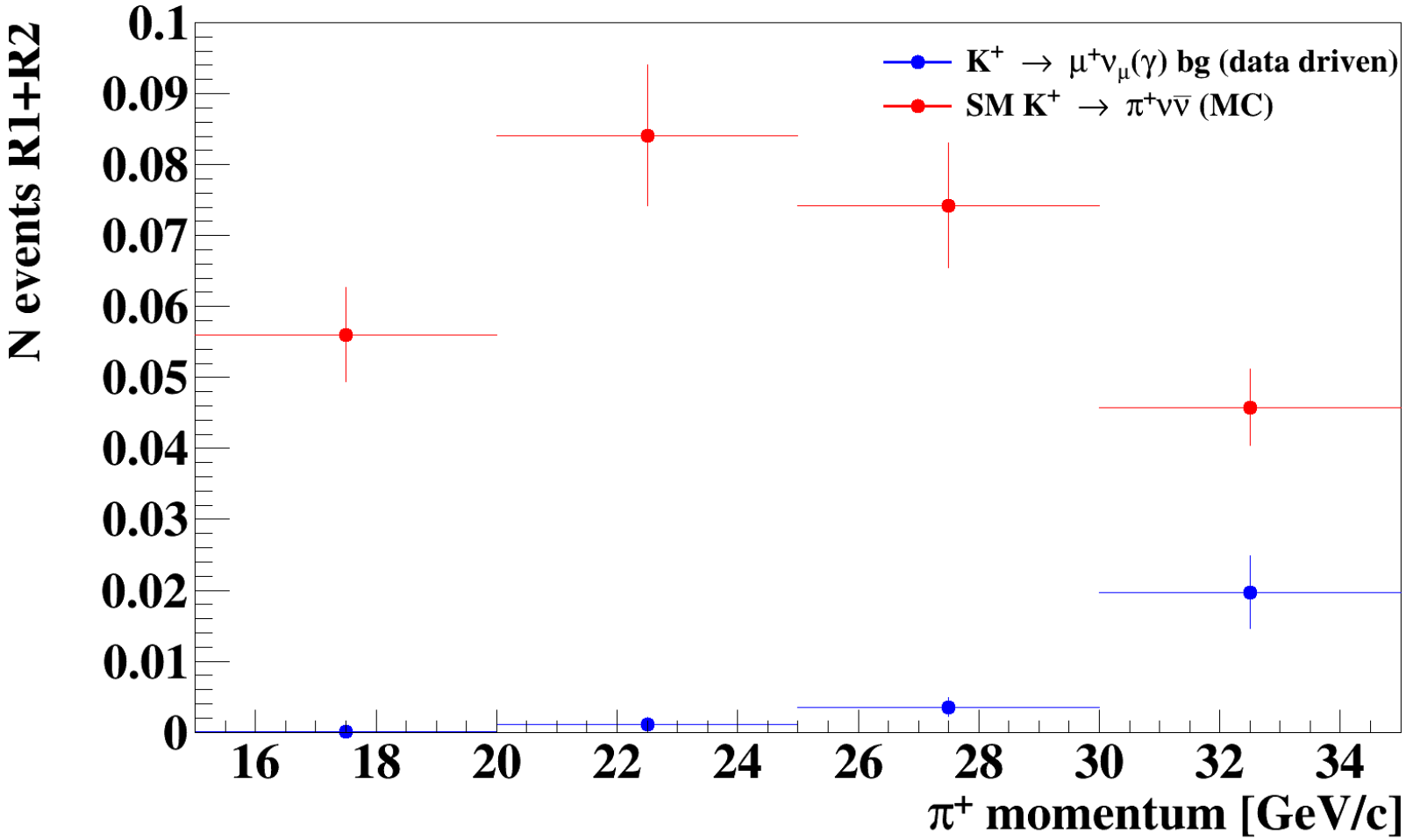
backgrounds : $K^+ \to \pi^+\pi^0(\gamma)$



- Data driven background estimation
- Control region validation: 1 event observed (1.5 expected)

$$N^{bg}_{\pi\pi(\gamma)} = 0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}}$$

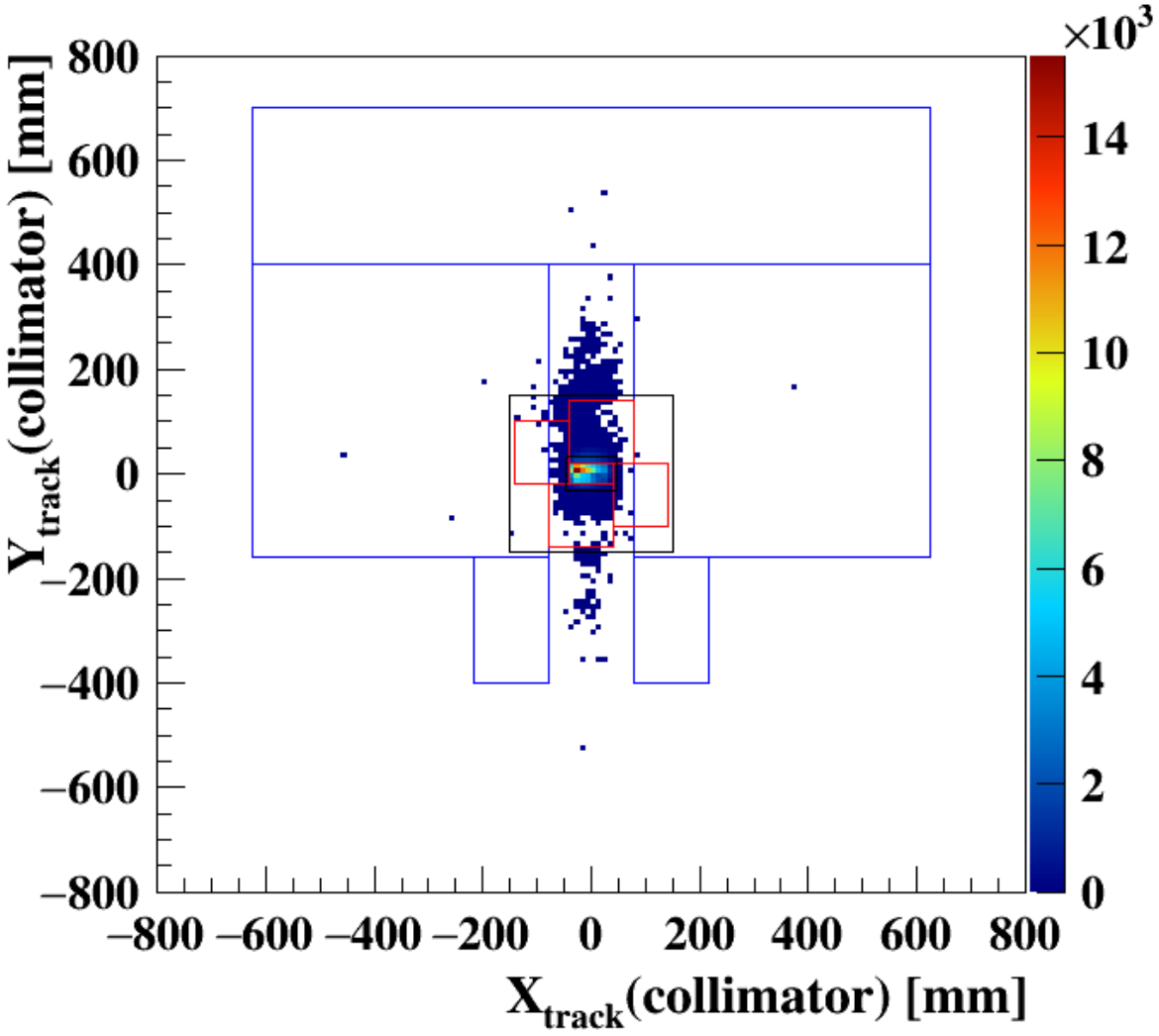
backgrounds : $K^+ \to \mu^+\nu_\mu(\gamma)$



- Data driven background estimation
- Control region validation: 2 event observed (1.1 expected)

$$N^{bg}_{\mu^+\nu_\mu(\gamma)} = 0.020 \pm 0.003_{stat} \pm 0.003_{syst}$$

Upstream background



- Accidental particles from the beam line
- Pions from interactions with beam spectrometer material
- Kaon-pion matching and geometrical cuts effective
- Data driven estimation

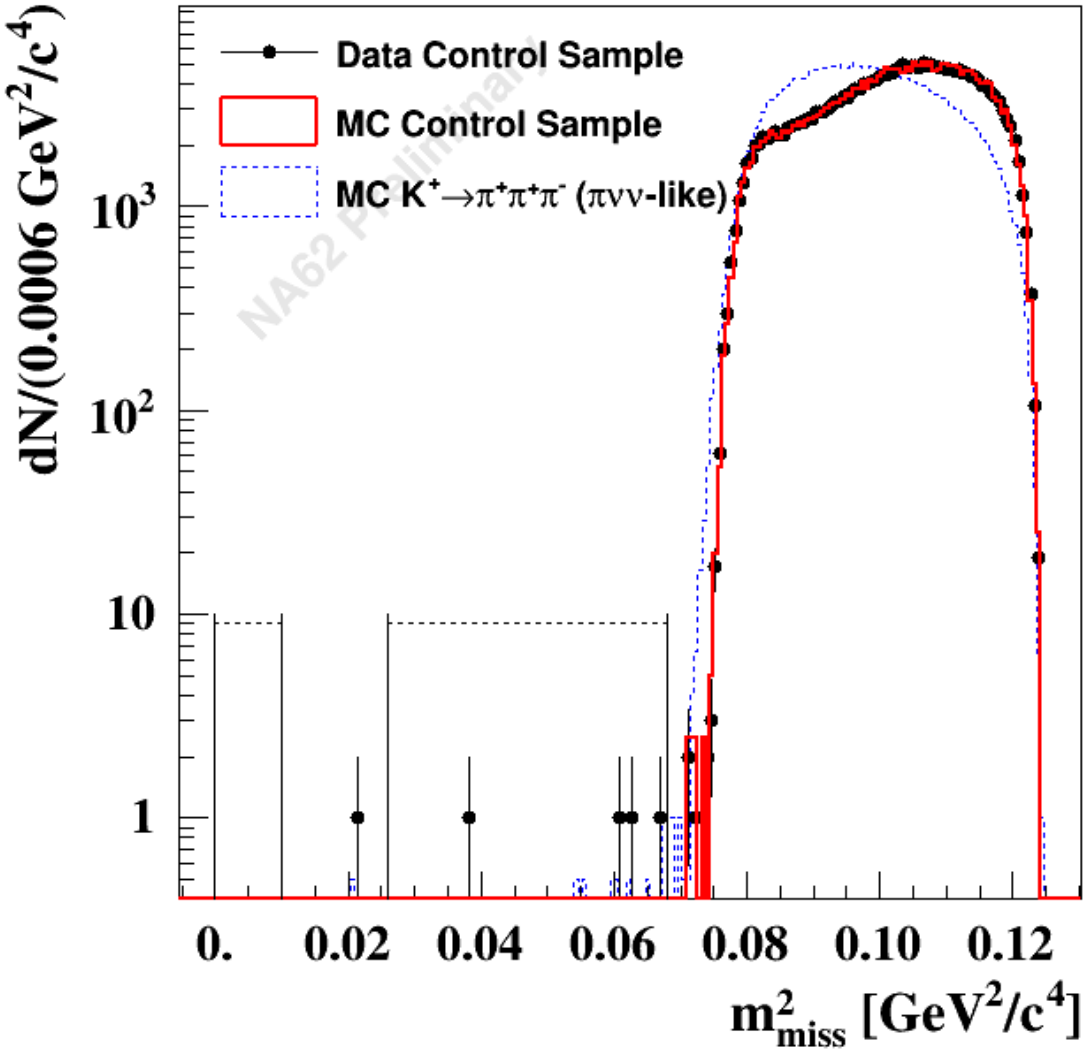
$$N^{bg}_{\text{upstream}} = 0.050^{+0.090}_{-0.030}$$

backgrounds : $K^+ \to \pi^+\pi^+\pi^-$

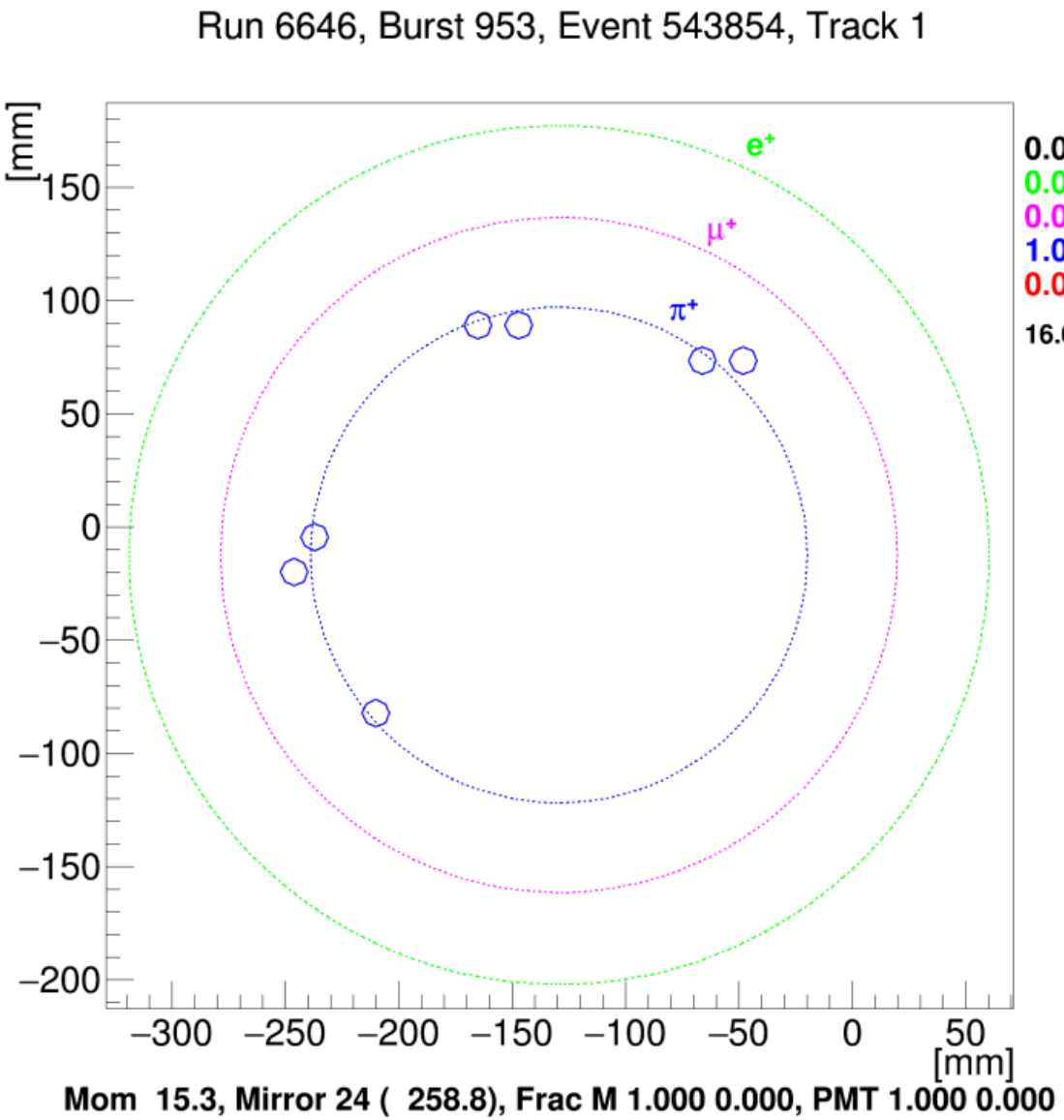
$$N_{\pi\pi\pi}^{exp} = N(\pi^+\pi^+\pi^-) \cdot f^{kin}(R2)$$

- $N(\pi^+\pi^+\pi^-)$: Event in $\pi^+\pi^+\pi^-$ region after $\pi^+\nu\nu$ selection
- f_{kin} measured on a $\pi^+\pi^+\pi^-$ control sample selected tagging the $\pi^+\pi^-$ pair
- Kinematic rejection factor corrected for biases induced by the control sample selection using MC
- $f_{kin}(R2) \leq 10^{-4}$

$$N_{\pi^+\pi^+\pi^-}^{bg} = 0.002 \pm 0.001_{stat} \pm 0.002_{syst}$$



Result: RICH ring for the observed event



Likelihood value under different mass hypothesis

NA62 Physics beside $K^+ \to \pi^+ \nu \bar{\nu}$

- Standard kaon physics:
  - ChPT studies: $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+e^-$, $K^+ \to \pi^+\ell^+\ell^-$
- Searches for lepton-flavor or -number violating decays
  - $K^+ \to \pi^+\mu^\pm e^\mp$, $K^+ \to \pi^-\mu^+e^+$, $K^+ \to \pi^-\ell^+\ell^+$
- Heavy neutral lepton production searches
  - $K^+ \to l^+ \nu_h$ (analysis with 2015 data published in Phys.Lett. B778 (2018) 137-145)
  - ν_h from upstream K, D decays with $\nu_h \to \pi\ell$
- Searches for long-lived dark sector particles
  - Dark photon γ' produced in π/ρ decays in target, with $\gamma' \to \ell^+\ell^-$
  - Axion-like particle A^0 produced in target/beam dump, with $A^0 \to \gamma\gamma$
- π^0 decays rare and forbidden/LFV, dark photon production:
  - $\pi^0 \to$ invisible, $\pi^0 \to 3/4\gamma$, $\pi^0 \to ee, eee$, $\pi^0 \to \mu e$, $\pi^0 \to \gamma'\gamma$