BEAUTY 2020 online

Recent results from the NA62 experiment

Elisa Minucci*

on behalf of the NA62 Collaboration

Outline:

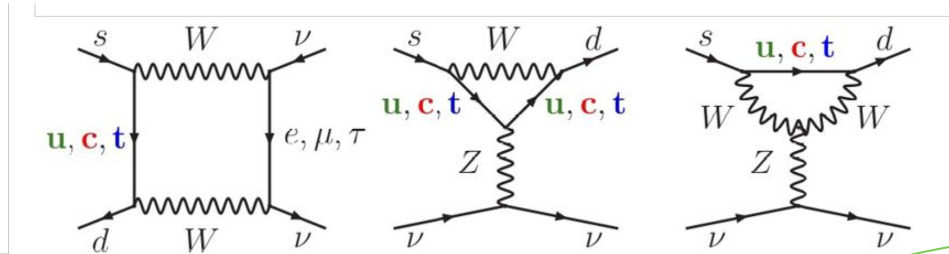
- Introduction
- The NA62 experiment
- $K^+ \rightarrow \pi^+\nu\nu$ analysis
- Other analyses
- Summary & Prospects

European Research Council

* elisa.minucci@cern.ch

$K^+ \to \pi^+ \nu\nu$ in the Standard model

FCNC loop process: s → dνν quark transition



Extremely suppressed by GIM mechanism
&
theoretically well predicted

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = k_+ (1 + \Delta_{EM}) \left[\left(\frac{\Im \lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\Re \lambda_c}{\lambda} (P_c + \delta P_{c,u}) + \frac{\Re \lambda_t}{\lambda^5} X_t \right)^2 \right]$$

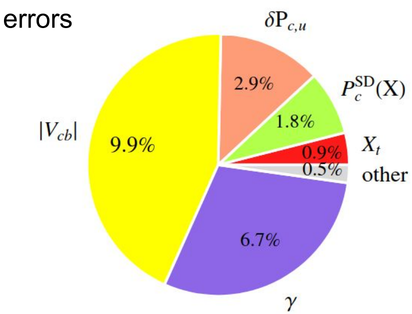
Loops favor top contributions

Hadronic matrix element from Ke3 via isospin rotation

Charm contributes to theory errors

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

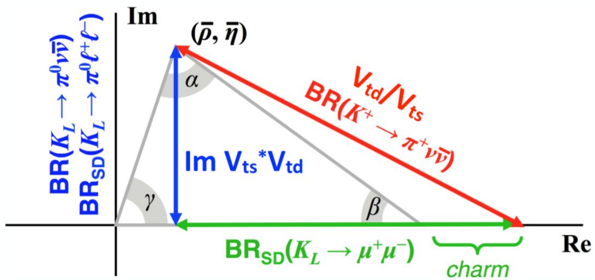
$$Br(K_L \to \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$



[Buras. et. al., JHEP11(2015)033]

$K^+ \to \pi^+ \nu\nu$ and New Physics

Test of SM



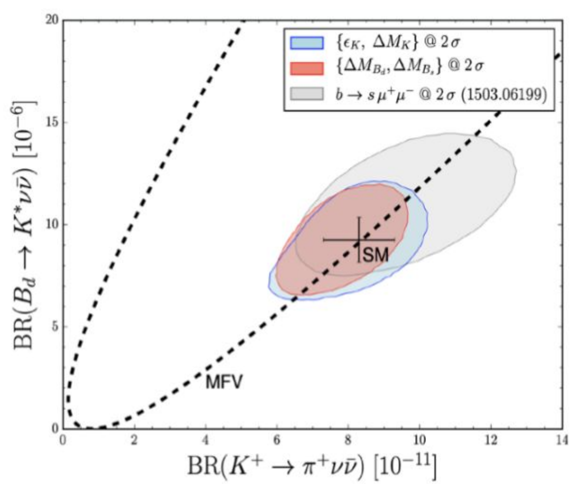
Inputs to the unitary triangle independent from the B-physics

Indirect probes to explore high energy mass scale

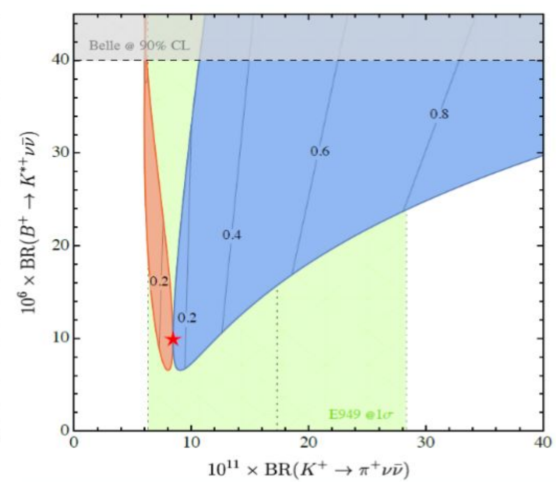
Evidence of New Physics

Custodial Randall-Sundrum [Blake, Buras, Dulin, Gemmler,Gori, JHEP 0903 (2009) 108]
Simplified Z,Z' models [Buras, Buttazzo, Knegjensi, JHEP 1511 (2015) 166]
Littlest Higgs with T-parity [Blake, Buras, Recksiegel, EPJ C76 (2016) no.4 182]
MSSM non MFV [Tonimoto, Yamamoto, PTEP 2016 (2016) no.12 123B02; Blazek et al. Int J Mod Phys A 29 (2014) 1450162; Isidori et al. JHEP 0608 (2006) 064]
LFU violation models [Isidori et al. Eur. Phys J. C (2017) 77]
Leptoquarks [S. Fajfer et al. arXiv:1802.00786v1 (2018)]

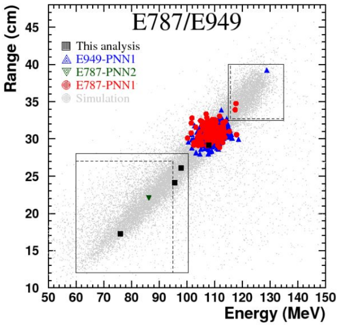
Z' (5 TeV) in constrained MFV



LFU violation



Experimental state of the art



Past experiments:

E787/E949 at BNL
Kaon decay-at-rest technique
(7 candidates)

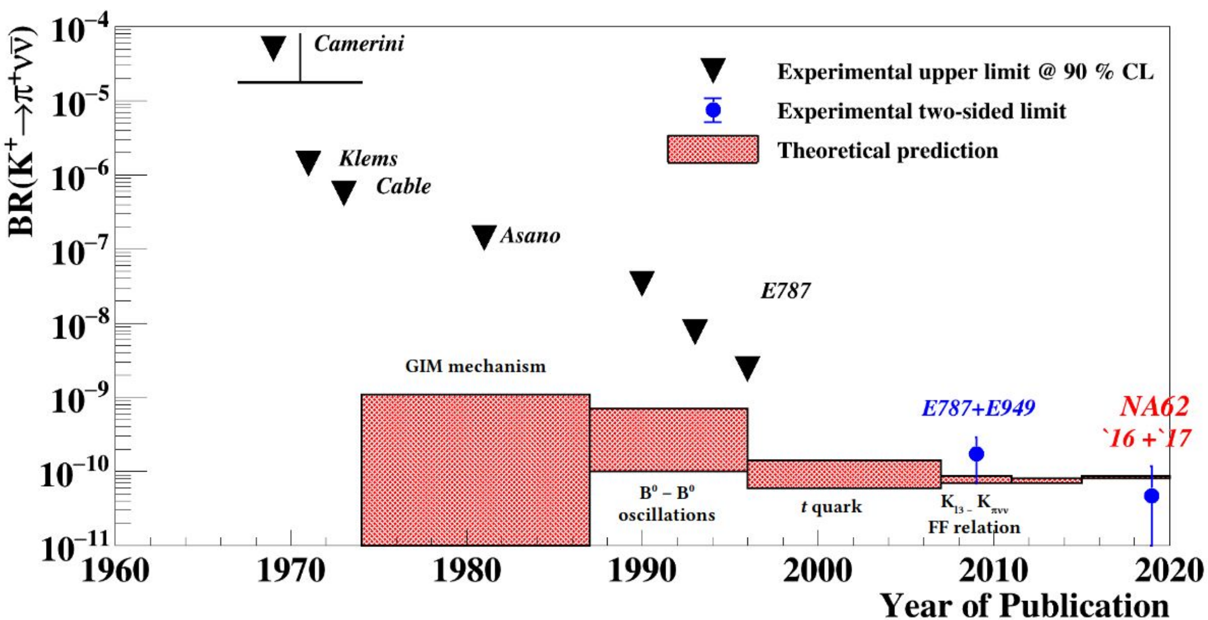
$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

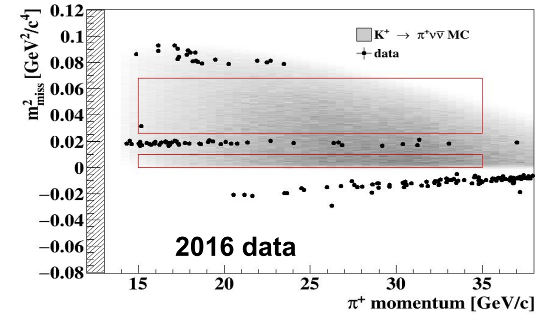
[Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)]

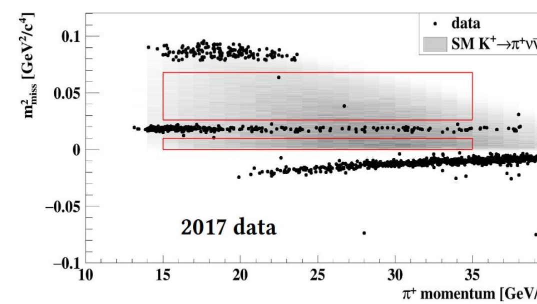
NA62 experiment at CERN SPS
Decay-in-flight technique
2016+2017 data (1+2 observed events)

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.78 \times 10^{-10} @90\% \text{ C.L.}$$

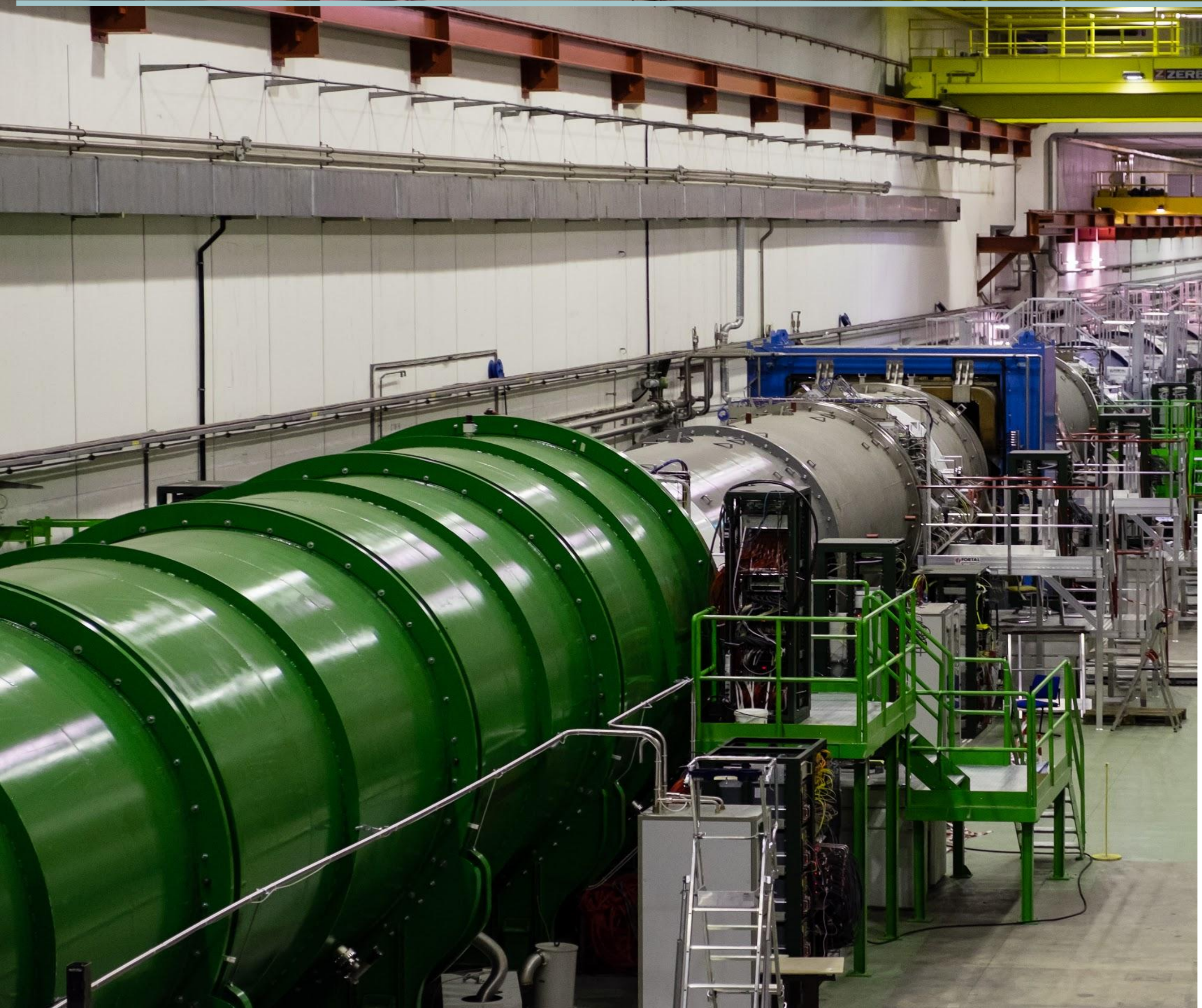
[arXiv:2007.08218 [hep-ex]](submitted to JHEP)

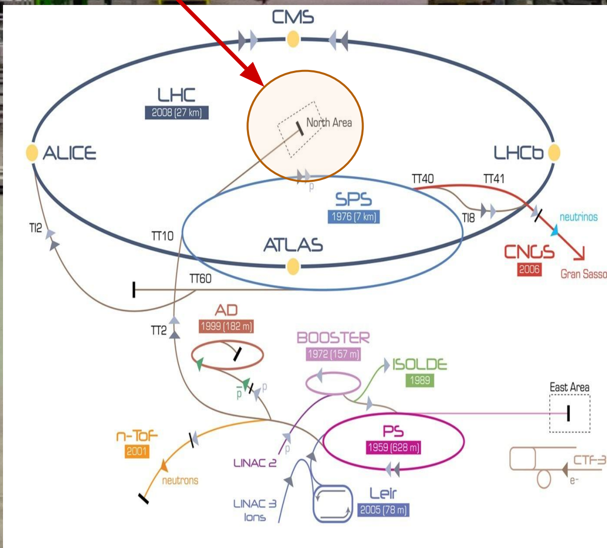




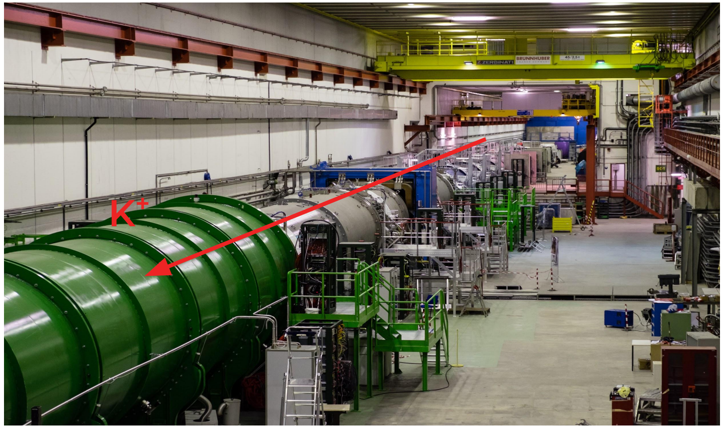


The NA62 experiment at the CERN SPS



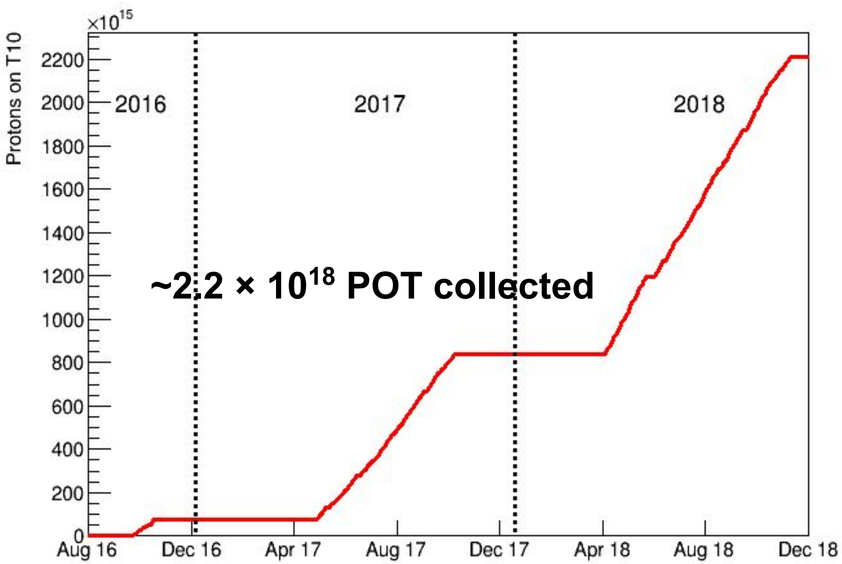


The NA62 experiment at the CERN SPS



Broad physics program

- **Main goal measure $K^+ \to \pi^+ \nu\nu$ branching ratio**
- **Rare and forbidden decays :** LN and LF violation
- **Precision measurements**
- **Exotics searches:** dark photon, heavy neutral leptons, axion-like particles

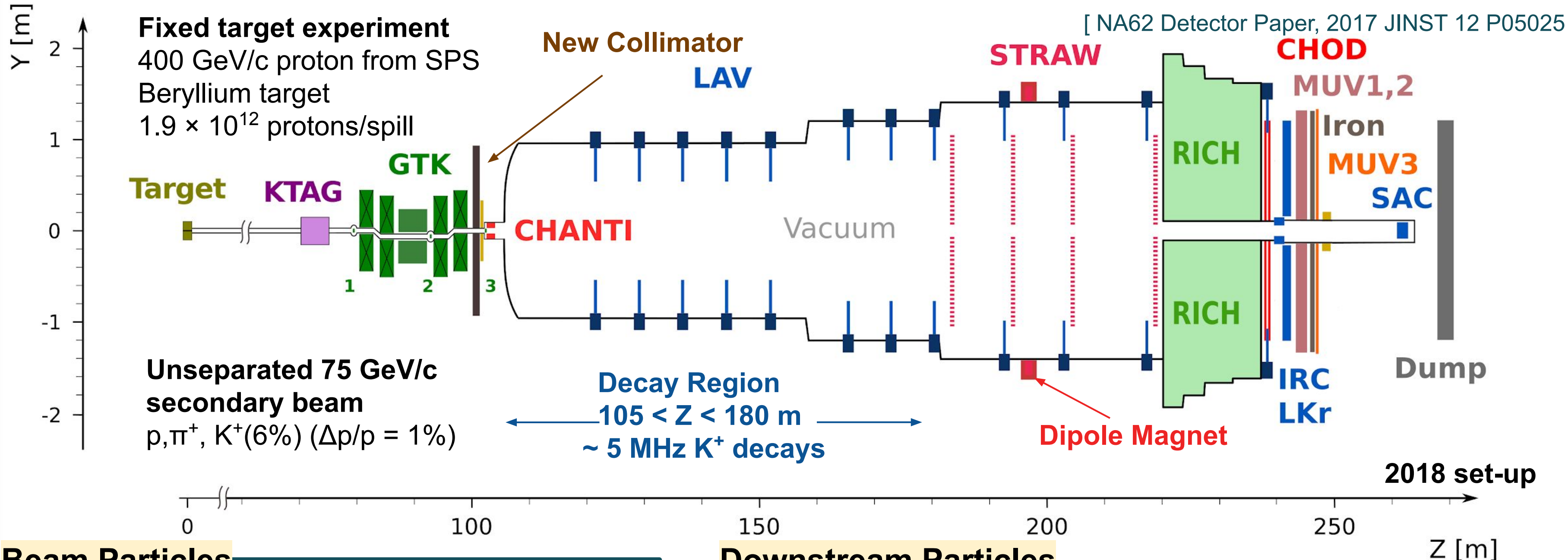


2016: 40% of nominal intensity
~0.12 x 10^{12} K+ decays in fiducial volume

2017: 60% of nominal intensity
~1.15 x 10^{12} K+ decays in fiducial volume

2018: 60%-70%of nominal intensity
~2.6 x 10^{12} K+ decays in fiducial volume

The NA62 Experiment: Kaon decay-in-flight technique



Beam Particles

Tag K^+: KTAG
Cherenkov detector σ_t~70 ps

Beam Tracking: GigaTraKer
hybrid silicon pixels σ_t~200 ps, σ_p~0.2%

CHANTI: Anti-counter for beam- GTK3 inelastics

Downstream Particles

Tracking: STRAW σ_p~0.3%

CHODs: plastic scintillator for fast signal σ_t = 200 ps

π/μ/e ID:
RICH: Ring Imaging Cherenkov detector σ_t = 100 ps
LKr/MUV1/MUV2: Calorimetric system

Photon veto system: LKr/LAV/IRC/SAC

Muon veto: MUV3

$K^+ \rightarrow \pi^+ \nu\nu$: Analysis Strategy

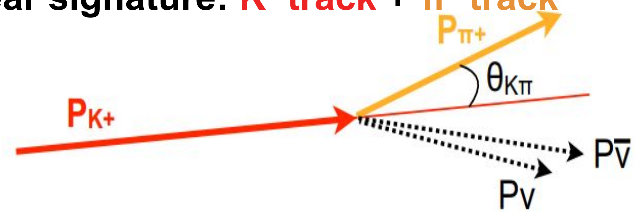
SM Br of $\mathcal{O}(10^{-10})$

High beam intensity

Open kinematics

powerful background suppression up to $\mathcal{O}(10^{11})$

Clear signature: K^+ track + π^+ track

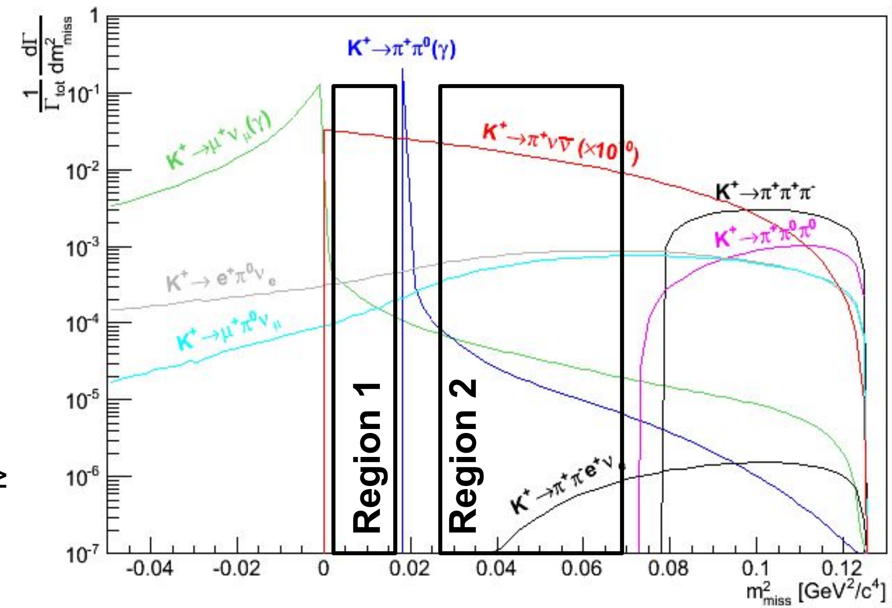


$$m^2_{miss} = (P_K - P_\pi)^2$$

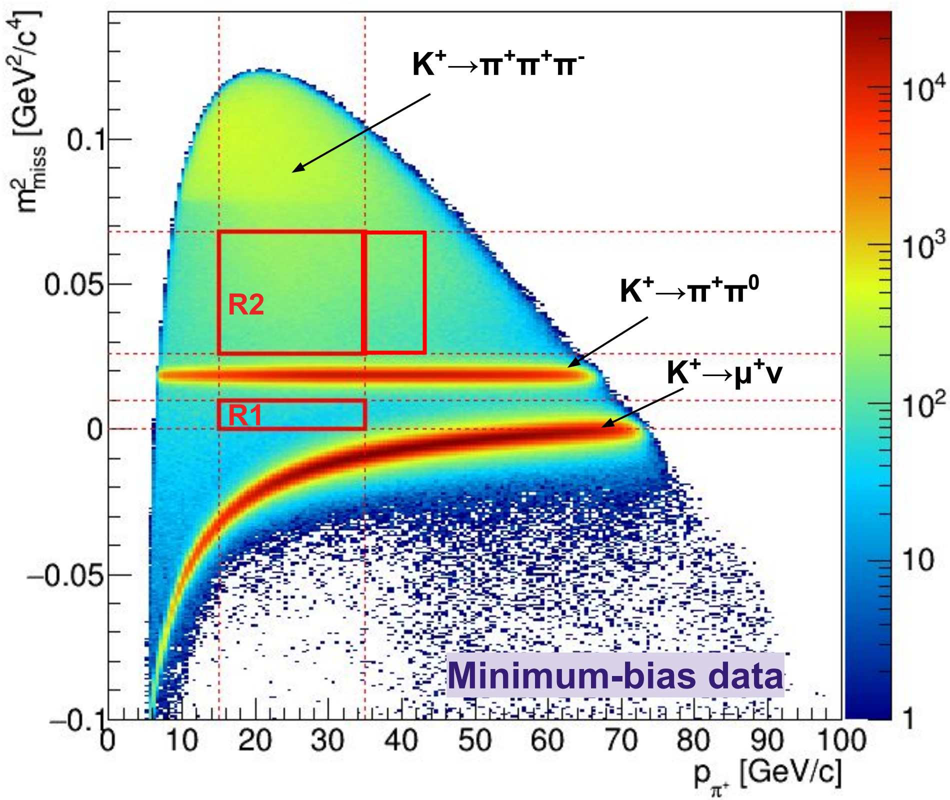
$\sigma_{m2} \sim 10^{-3}$ GeV^2/c^4 at the $K^+ \rightarrow \pi^+\pi^0$ peak

- **high time resolution $\mathcal{O}$(100 ps)**
- **muon suppression > 10^7** ($K^+ \rightarrow \mu^+\nu$)
- **photon suppression > 10^7** ($K^+ \rightarrow \pi^+\pi^0, \pi^0 \rightarrow \gamma\gamma$)
- **kinematic rejection $\mathcal{O}(10^4)$:** accurate m^2_{miss} resolution

- **$15 < P_\pi < 45$ GeV/c**
  - guarantee high photon veto rejection ($P_{\pi 0} \geq 30$ GeV/c)
  - guarantee good π/μ separation



$K^+ \to \pi^+\nu\nu$: 2018 Analysis



Improvements in 2018

Detector:

- New upstream collimator has been installed to reduce upstream background

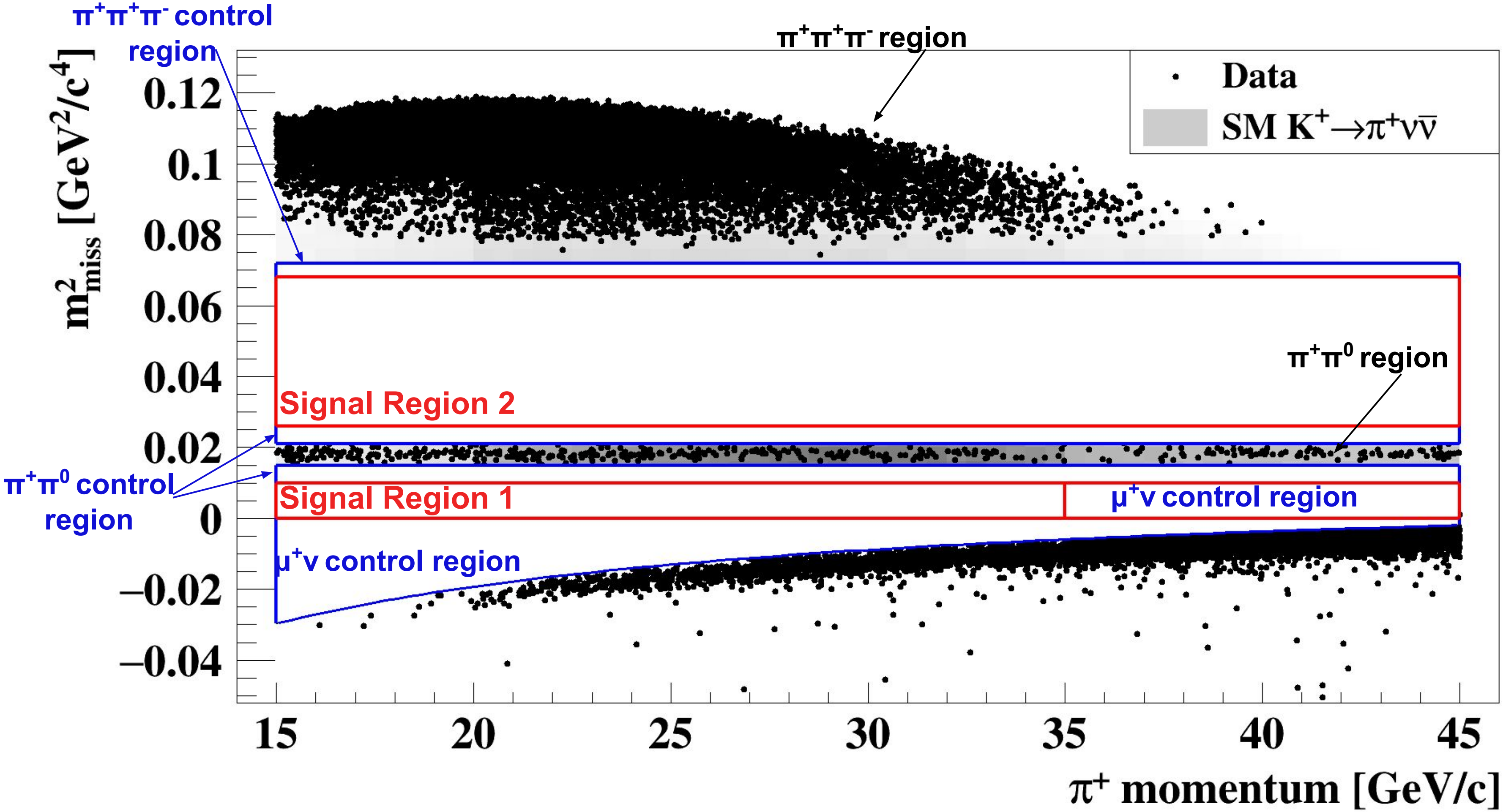
Analysis:

- Analysis performed in 7 separate categories
- Category definition depends on hardware configurations (S1 and S2) and momentum
- Selection optimize separately for each category (π^+ momentum dependent PID, MVA used)

Increase in global signal acceptance: from 3% of 2017 to:

- 4% before upstream collimator installation (20% of data taking)
- 6.4% after upstream collimator installation

2018 data after selection



Single Event Sensitivity

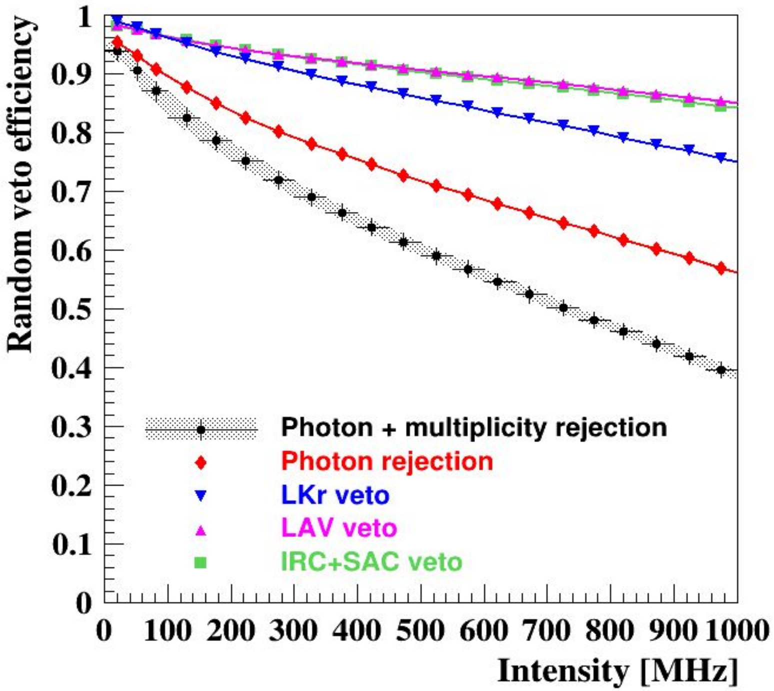
$$S.E.S = \frac{Br(K^+ \to \pi^+ \nu\bar{\nu})}{N_{exp}^{\pi\nu\nu}}$$

$$N_{exp}^{\pi\nu\nu} \simeq N_{\pi^+\pi^0}^{obs} \frac{A_{\pi\nu\nu}}{A_{\pi^+\pi^0}} \frac{Br(K^+ \to \pi^+ \nu\bar{\nu})}{Br(K^+ \to \pi^+ \pi^0)} \epsilon_{trigger} \epsilon_{RV}$$

$K^+ \to \pi^+\pi^0$ normalization channel

Acceptance → Evaluated from MC.
Ratio allows cancellation of systematic effects

Random Veto Efficiency:
losses of signal events because of the accidental presence of photons or/and charged particles



$$N_{exp}^{\pi\nu\nu} = 7.58 \pm 0.40_{syst} \pm 0.75_{ext}$$

$$S.E.S = (1.11 \pm 0.07_{syst}) \times 10^{-11}$$

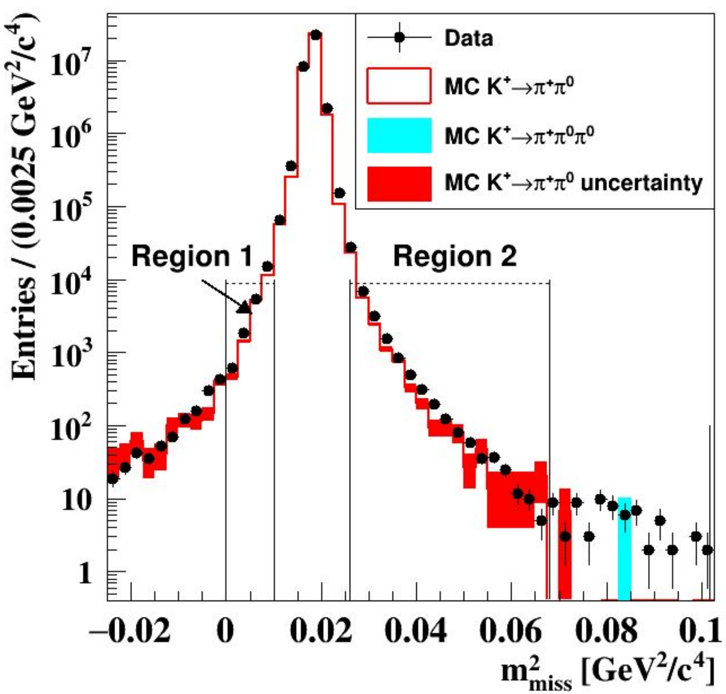
Background from K^+ decays

Exp. $\pi^+\pi^0$ events in control/signal regions after $\pi\nu\nu$ selection

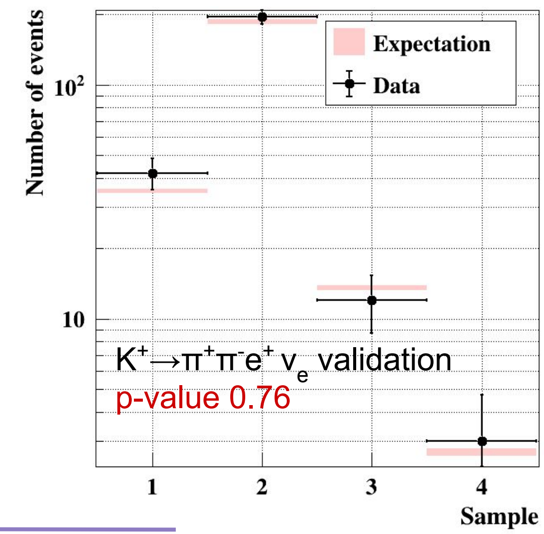
$$\boxed{N^{exp}_{\pi^+\pi^0}(region)} = \boxed{N(\pi^+\pi^0)} \times \boxed{f_{kin}(region)}$$

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

Fraction of events in $\pi^+\pi^0$ control/signal regions in minimum bias data

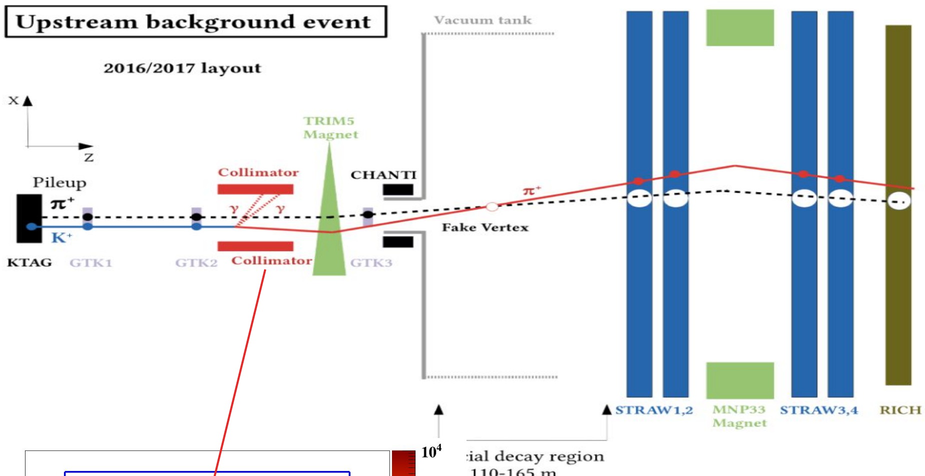


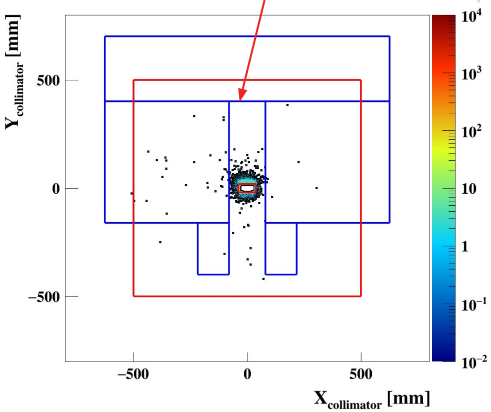
- Same procedure for the $\mathbf{K^+\to\mu^+\nu_\mu}$ and $\mathbf{K^+\to\pi^+\pi^+\pi^-}$ backgrounds
- $\mathbf{K^+\to\pi^+\pi^-e^+\nu_e}$, $\mathbf{K^+\to\pi^0 l^+\nu}$, $\mathbf{K^+\to\pi^+\gamma\gamma}$ are evaluated with simulations normalized to the S.E.S



Upstream Background

Interactions or decays of beam particles upstream of the FV



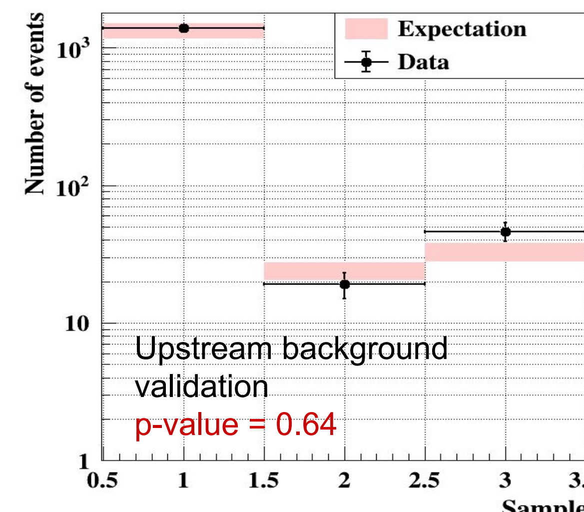


- π^+ is produced and reaches the downstream detectors
- no additional particles associated to the π^+
- a K^+ candidate is reconstructed and matched to a π^+

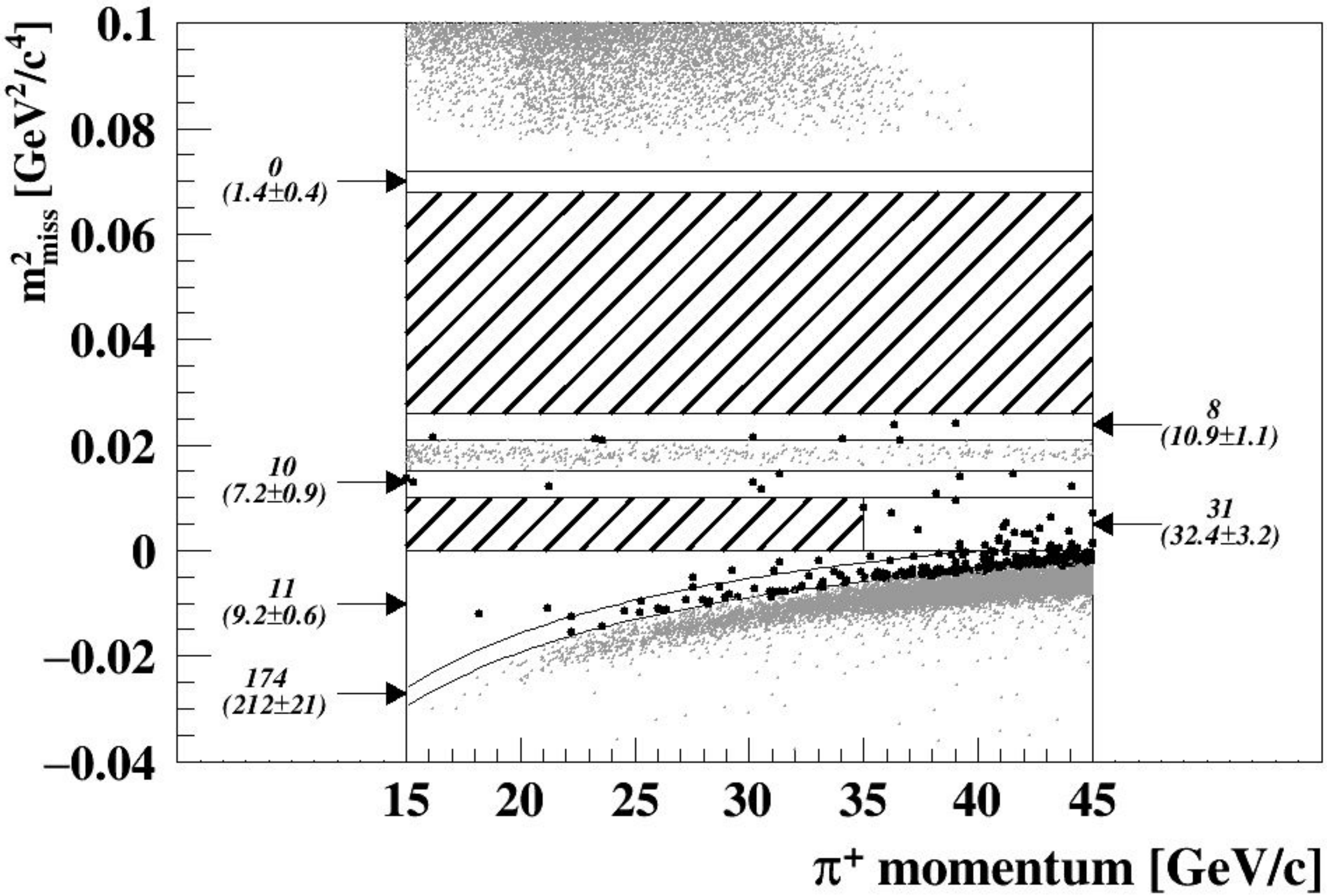
Background evaluation → Data-driven approach

Projection of the π^+ from the fake vertex to the entrance of the FV

Geometrical distribution used to define analysis cuts



2018 data: Control regions unmasked and validated

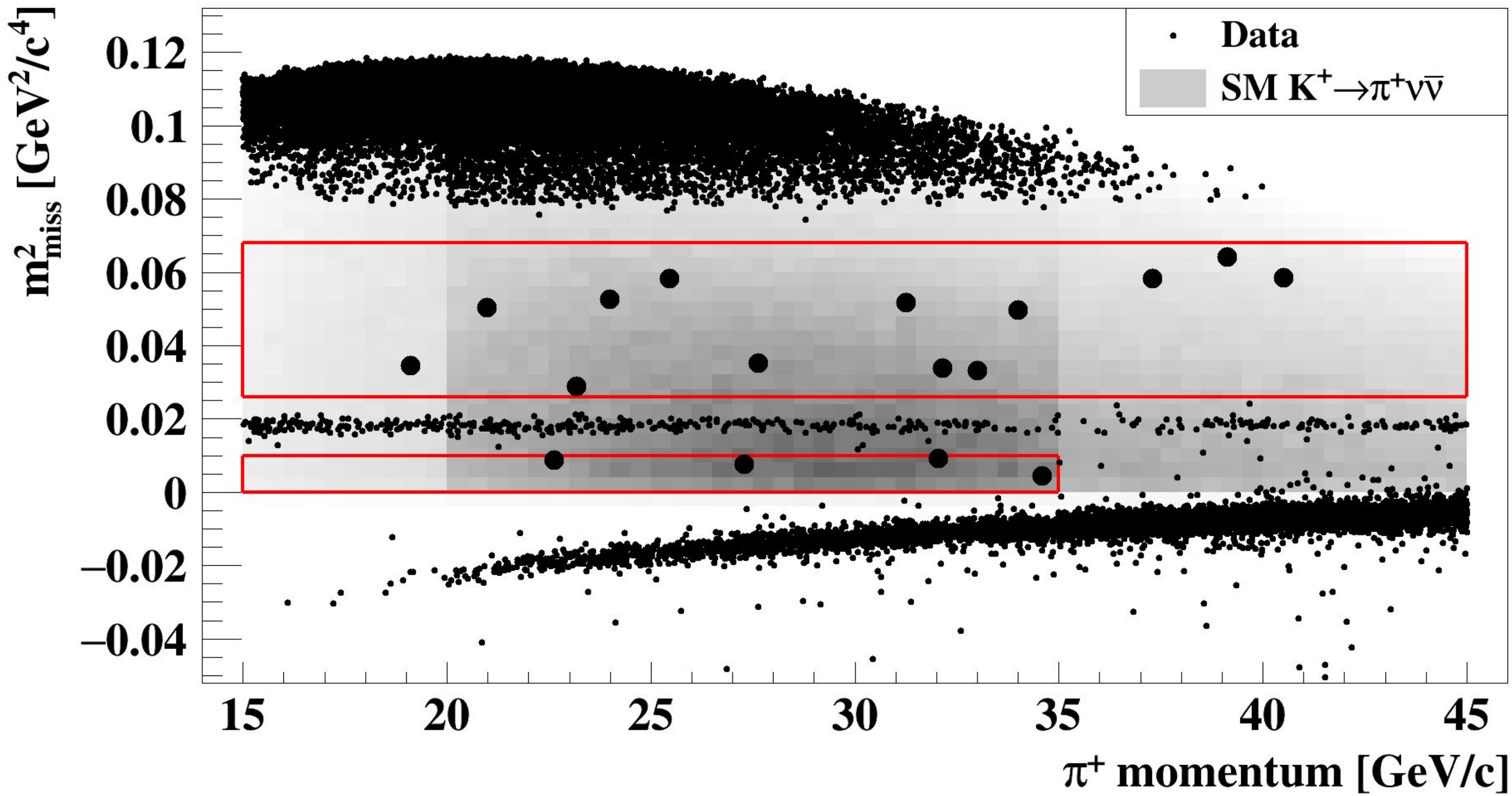


Events observed in all control regions are consistent with expectations

2018 data: Expected events in signal regions

Process	*Expected events (R1+R2)*
$K^+ \to \pi^+ \nu\bar{\nu}$ *(SM)*	$7.58 \pm 0.40_{syst} \pm 0.75_{ext}$
$K^+ \to \pi^+ \pi^0 (\gamma)$	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
$K^+ \to \pi^+ \gamma\gamma$	< 0.1
$K^+ \to \pi^0 l^+ \nu$	< 0.001
Upstream background	$3.30^{+0.98}_{-0.73}$
Total Background	$5.28^{+0.99}_{-0.73}$

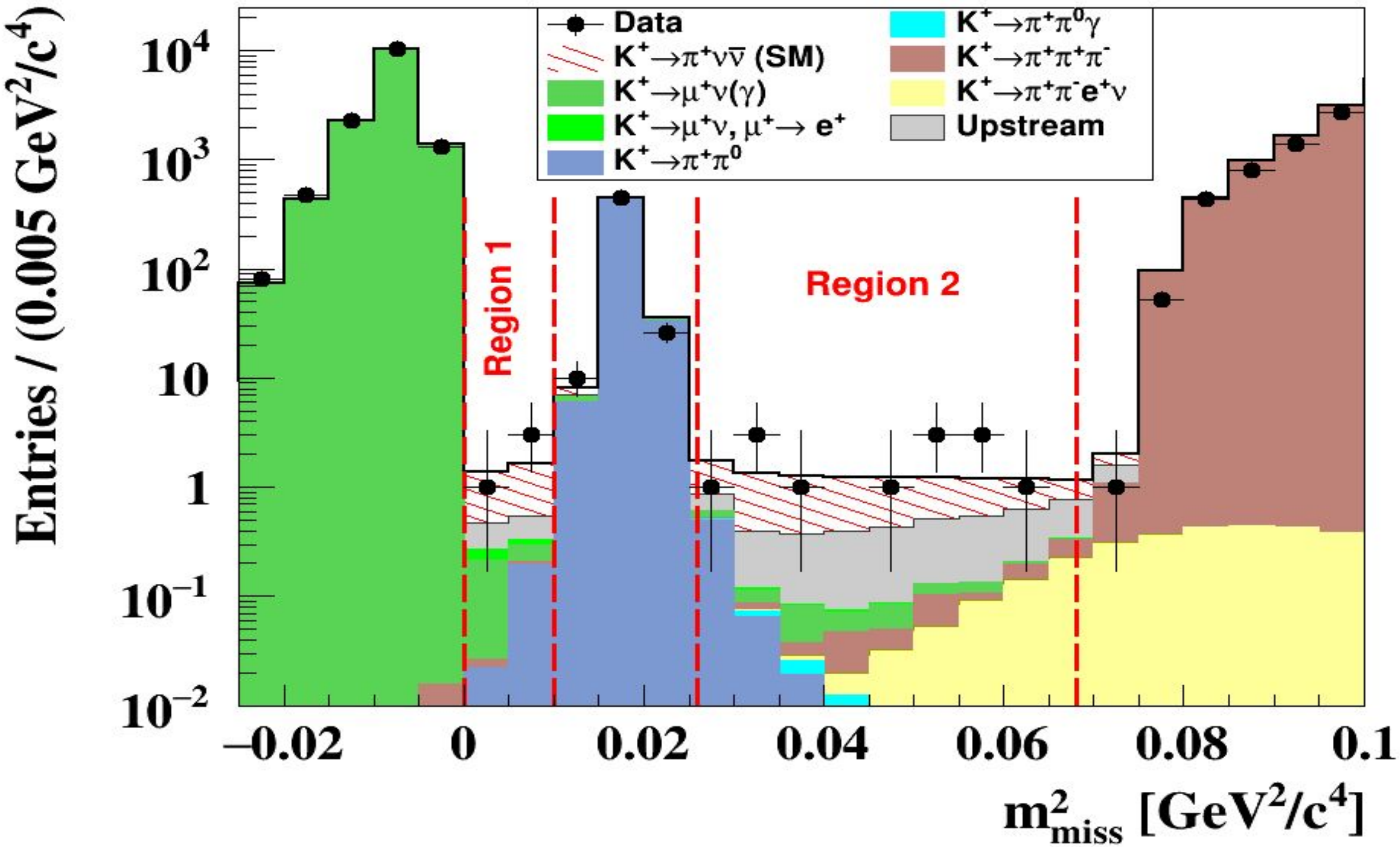
2018 data: Signal regions opened



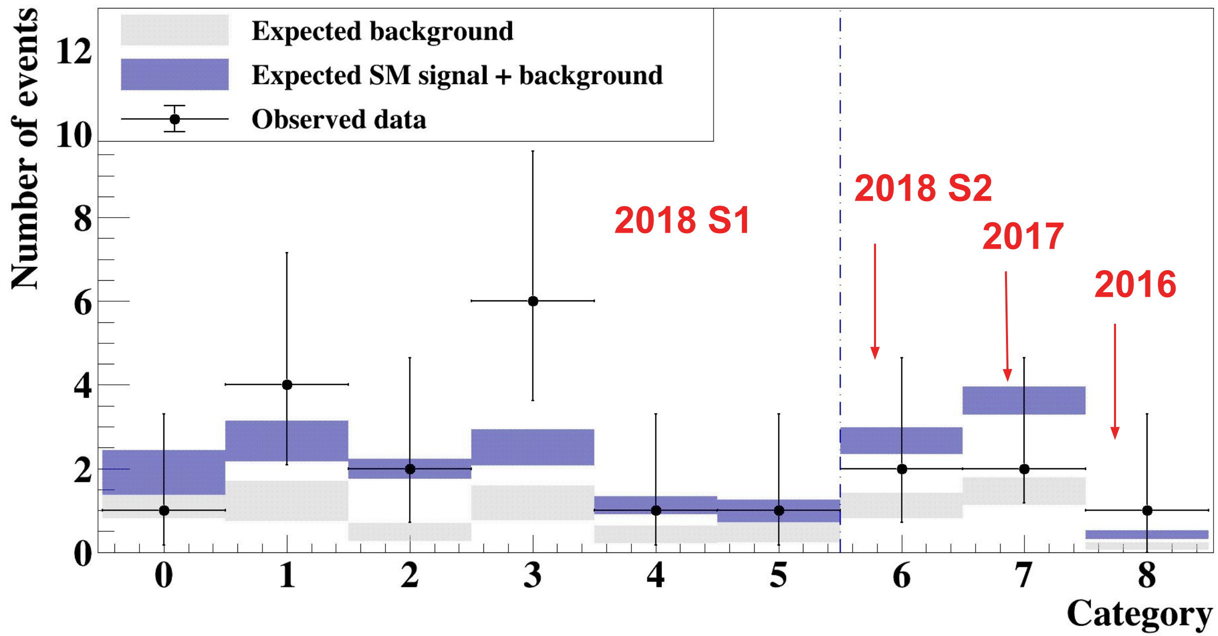
5.3 background + 7.6 SM signal expected events → 17 events observed

2018 data: Signal and background

M^2_{miss} distribution for 2018 data integrated over the full π^+ momentum.



Result: 2016+2017+2018 data



2018 S1: 80% of 2018 data after the installation of the new collimator
5 GeV/c π^+ momentum bins

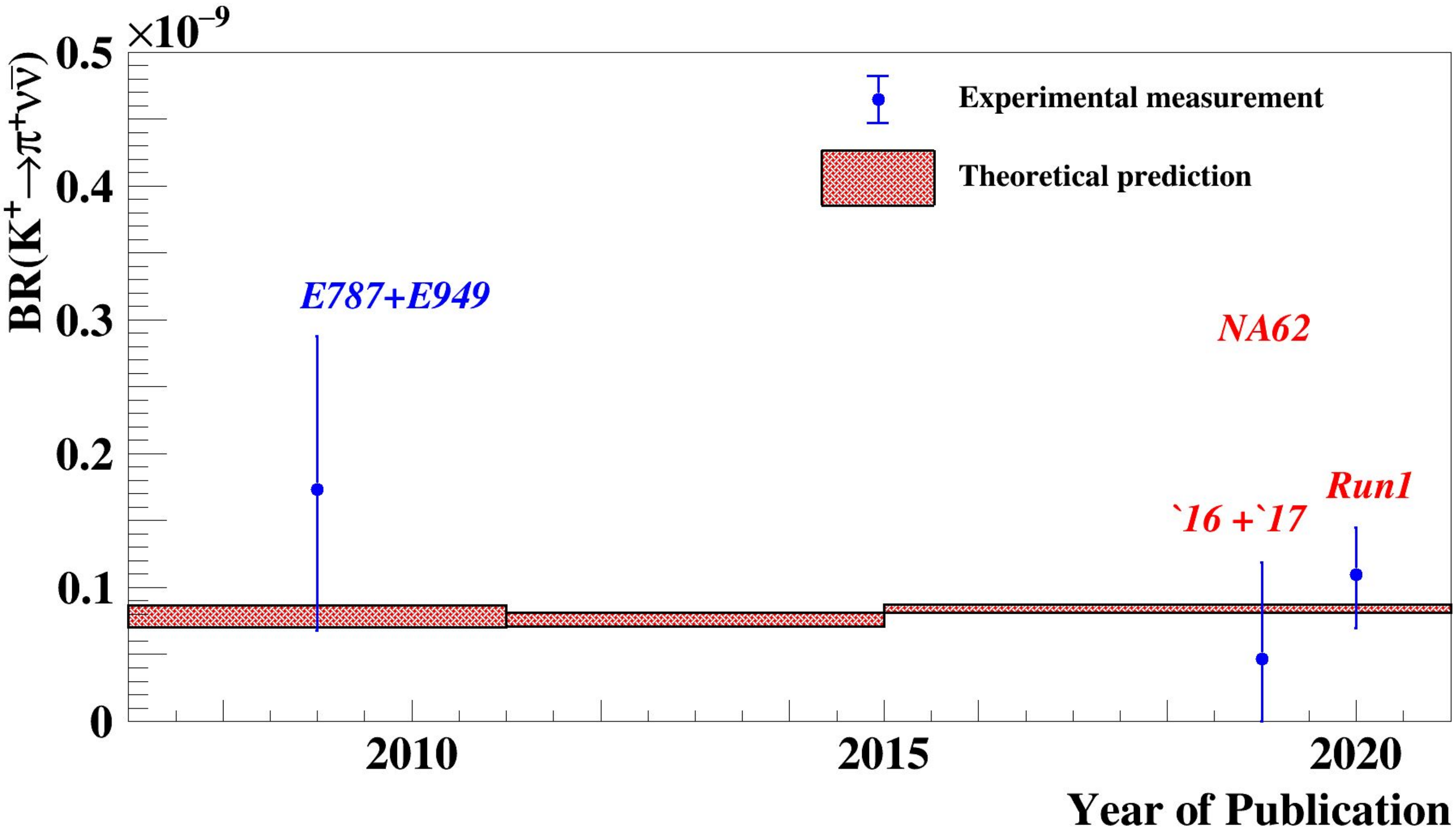
2018 S2: 20% of 2018 data before the installation of the new collimator integrated over full π^+ momentum range

Run 1(2016+2017+2018 data) preliminary result

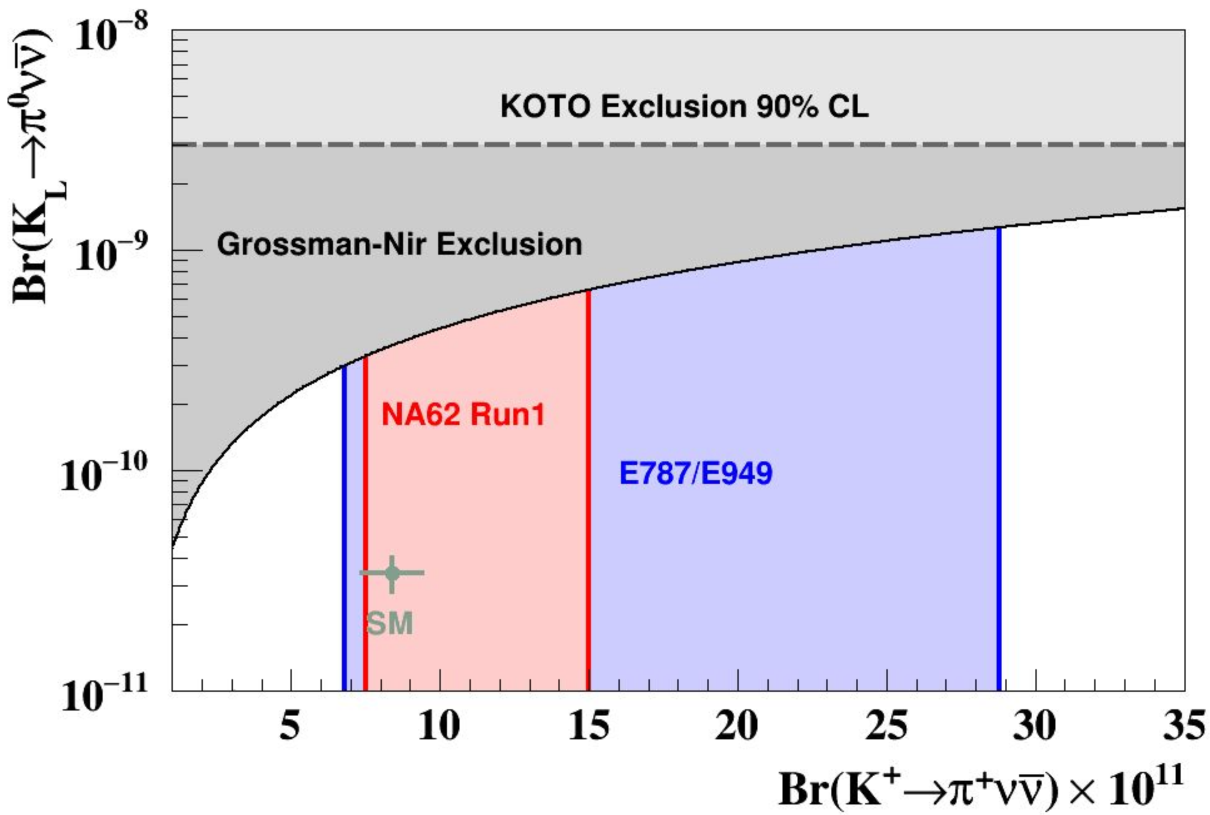
$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5 stat} \pm 0.3_{syst}) \times 10^{-11} (3.5\sigma\ significance)$$

Maximum Likelihood Fit using signal and background expectation in each category

$K^+ \rightarrow \pi^+ \nu\nu$: Historical context



K → πνν: Grossman-Nir limit



$K^+ \rightarrow \pi^+\mu^+\mu^-$: Form Factors and Branching Ratio

FCNC decay described in the scope of ChPT, mediated by $K^+ \rightarrow \pi^+\gamma^*$
Together with $K^+ \rightarrow \pi^+e^+e^- \rightarrow$ Test of LFU

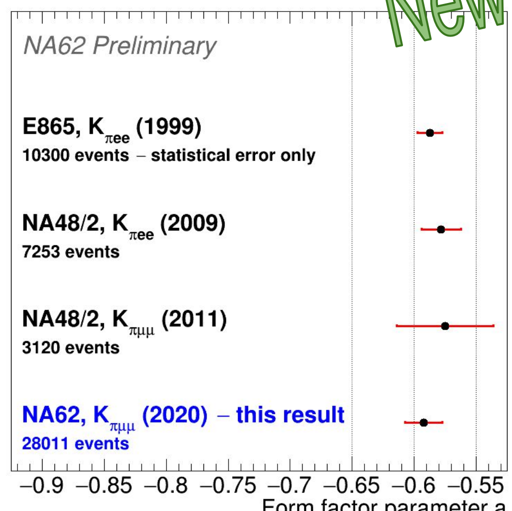
FFs
NLO ChPT

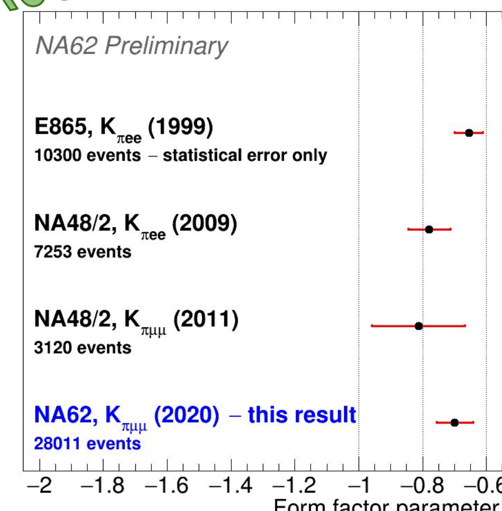
K3π loop term

$$d\Gamma/dxdz \propto G_F M^2_K (a+bz)+|W^{\pi\pi}(z)|^2,$$
$$z=m(\mu^+\mu^-)^2/M^2_K$$

Analysis:
Precise 3-tracks vertex reconstruction + PID based on LKr + MUV3
FF parameters a and b extracted from fit of z spectrum
Normalization: $K^+\rightarrow\pi^+\pi^+\pi^- \rightarrow N_K \sim 6.76 \times 10^{12}$
Signal: $N(\pi^+\mu^+\mu^-) = 28011$ (9× NA48/2)
Expected background: < 0.1%

New Results



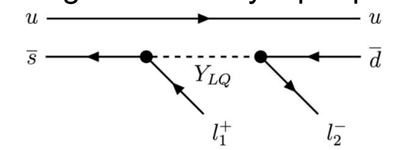


Model-dependent
$Br(K^+ \rightarrow \pi^+\mu^+\mu^-) = (9.27 \pm 0.11)\times 10^{-8}$
PDG: $Br(K^+ \rightarrow \pi^+\mu^+\mu^-) = (9.4 \pm 0.6)\times 10^{-8}$

LNV & LFV at NA62: $K^+ \rightarrow \pi^\pm \mu^\mp e^+$

Interesting to search for New Physics effects, exploring high mass scale

E.g mediated by leptoquark



Experimental strategy: precise three tracks vertex reconstruction + particle ID (LKr+MUV3)

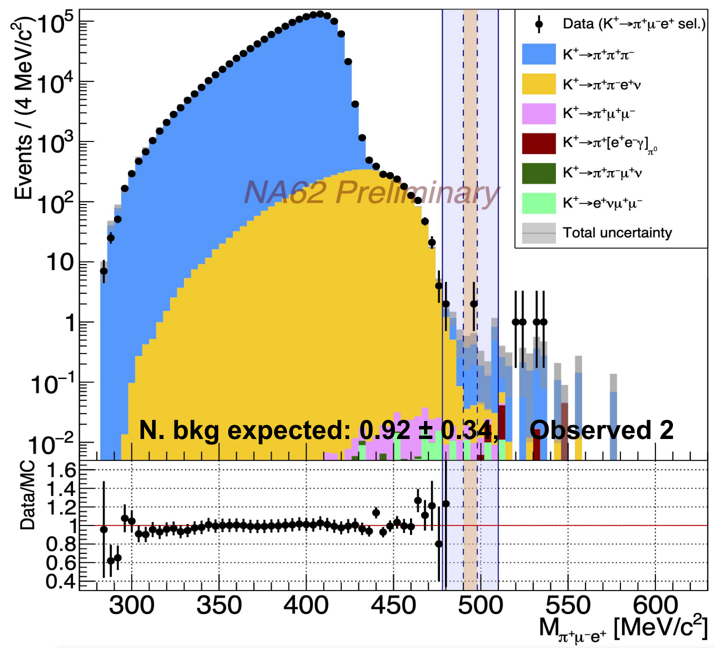
Background: mis-ID $e^\pm \leftrightarrow \pi^\pm$(data-driven), $\pi^\pm$ decay in flight

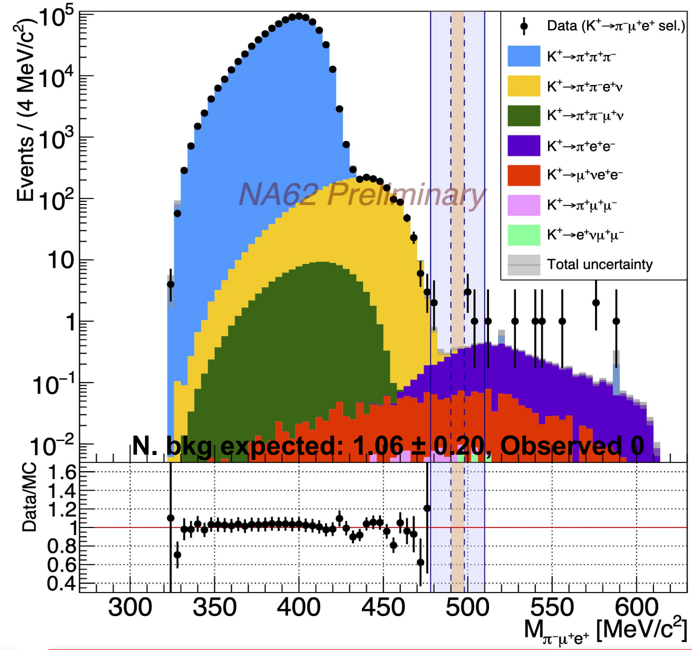
Normalization: $K^+ \rightarrow \pi^+\pi^+\pi^-$

2017+2018 Data:

1.32×10^{12} K^+ decays in FV

New Results



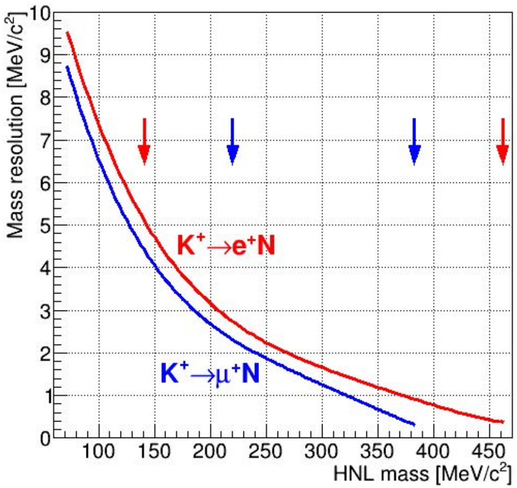


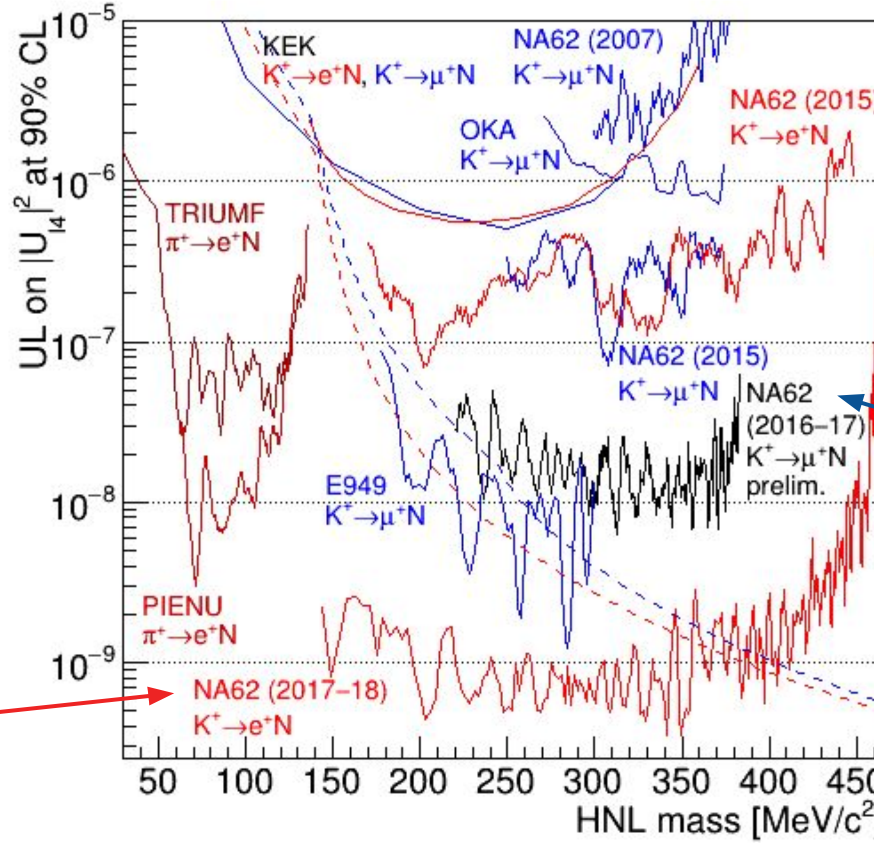
$Br(K^+ \rightarrow \pi^+\mu^-e^+) < 6.6 \times 10^{-11}$ @ 90% C.L

$Br(K^+ \rightarrow \pi^-\mu^+e^+) < 4.2 \times 10^{-11}$ @ 90% C.L

Heavy Neutral Lepton

HNL production: $K^+ \to \mu^+ N$, $K^+ \to e^+ N$
Peak search above continuous missing mass spectrum: $m^2_{miss} = (P_K - P_l)^2$





New Results
⅓ data sample

Final results
PLB 708 (2020) 135599

Summary & Prospects

- **$K^+ \to \pi^+ \nu\nu$** NA62 results from Run1(2016+2017+2018)
  - 20(1+2+17) events observed with total expected background ~7
  - **most precise measurement so far**

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5 stat} \pm 0.3_{syst}) \times 10^{-11}$$

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

- **New results from analyses on rare and forbidden kaon decays as well as on exotic searches have been shown**

Towards 2021

- NA62 will resume data taking in 2021
- Upgrade of the experiment setup. Installation of:
  - additional beam spectrometer station
  - upstream veto counter to reduce upstream background
  - new calorimeter downstream of MUV and upstream of the beam dump to further suppress kaon decay background

Thanks