$K^+ \to \pi^+ \nu\bar{\nu}$ measurement with the NA62 experiment at CERN

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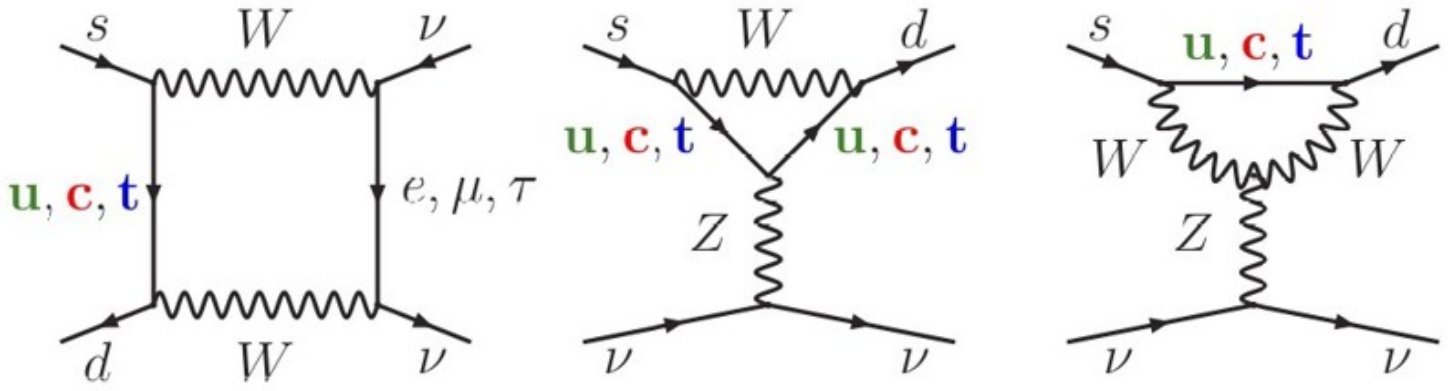
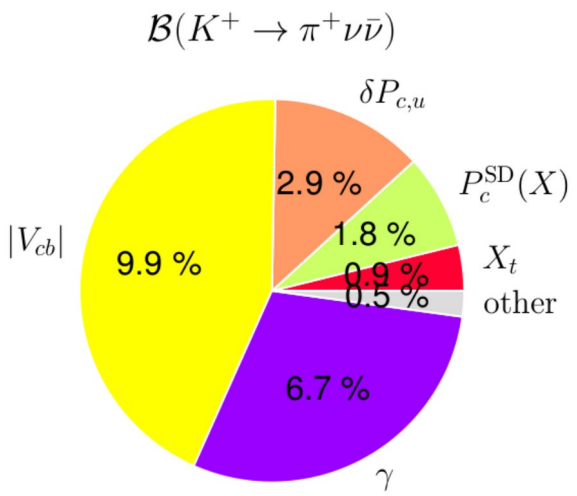
On behalf of the NA62 collaboration
HQL 13th–17th September 2021, Coventry, United Kingdom

The FCNC process K→πνν̄





Parametric uncertainty dominates

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

- FCNC loop processes: s → d coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with K_{l3} decays (per mill precision)
- SM predictions: Buras. et. al., JHEP11(2015)033

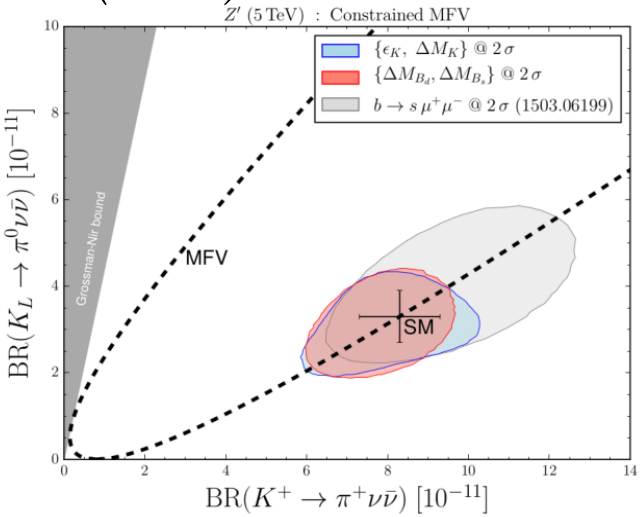
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.03) \times 10^{-10} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (0.84 \pm 0.10) \times 10^{-10}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (0.34 \pm 0.05) \times 10^{-10} \left(\frac{|V_{ub}|}{0.00388}\right)^{2} \left(\frac{|V_{cb}|}{0.0407}\right)^{2} \left(\frac{\sin\gamma}{\sin 73.2^\circ}\right)^{2} = (0.34 \pm 0.06) \times 10^{-10}$$

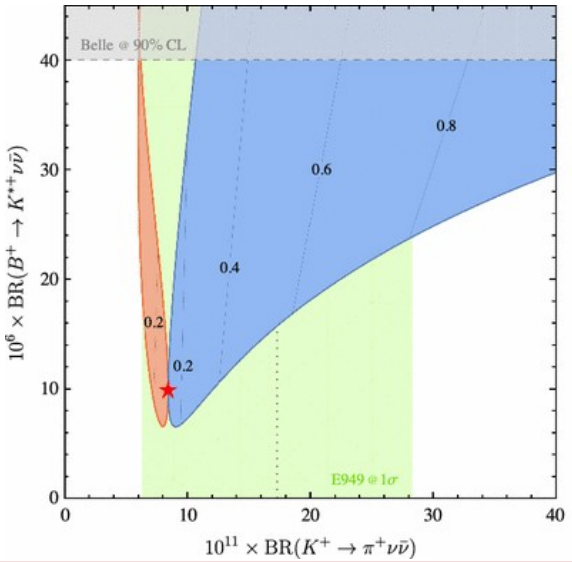
K→πνν̄ beyond the Standard Model

- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM analyses [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],[Isidori et al. JHEP 0608 (2006) 064]
- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- 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)]
- MFV analyses [S. Descotes-Genon, S.Fajfer et. al., PLB 80 (2020) 135769]
- Constraints from existing measurements (correlations model dependent)

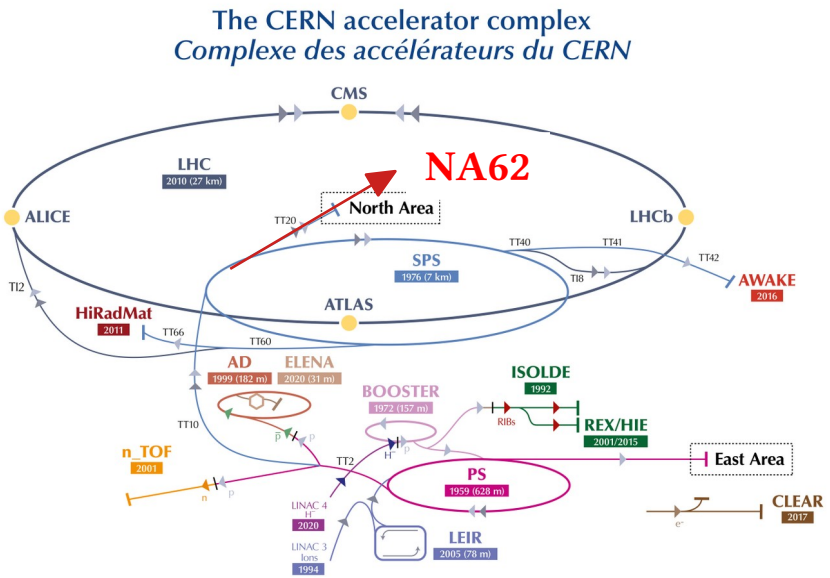
Z'(5 TeV) in Constrained MFV



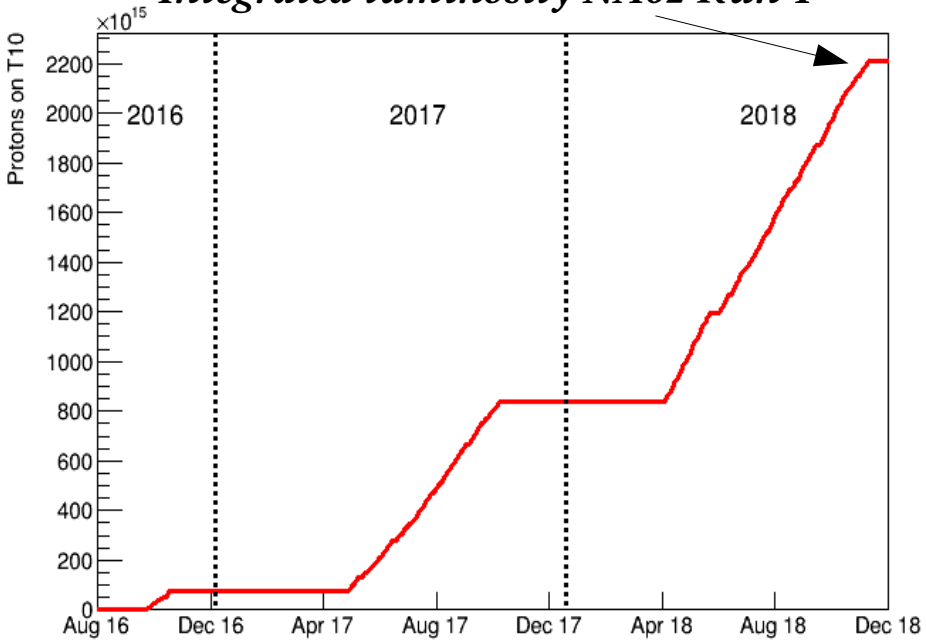
LFU violation



State-of-the-art $K^+ \to \pi^+ \nu\bar{\nu}$ experiments



Integrated luminosity NA62 Run 1



- **Past experiments (E787/E949 @ BNL)**
  - Kaon decay-at-rest technique

    $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

    Phys. Rev. D 79, 092004 (2009)

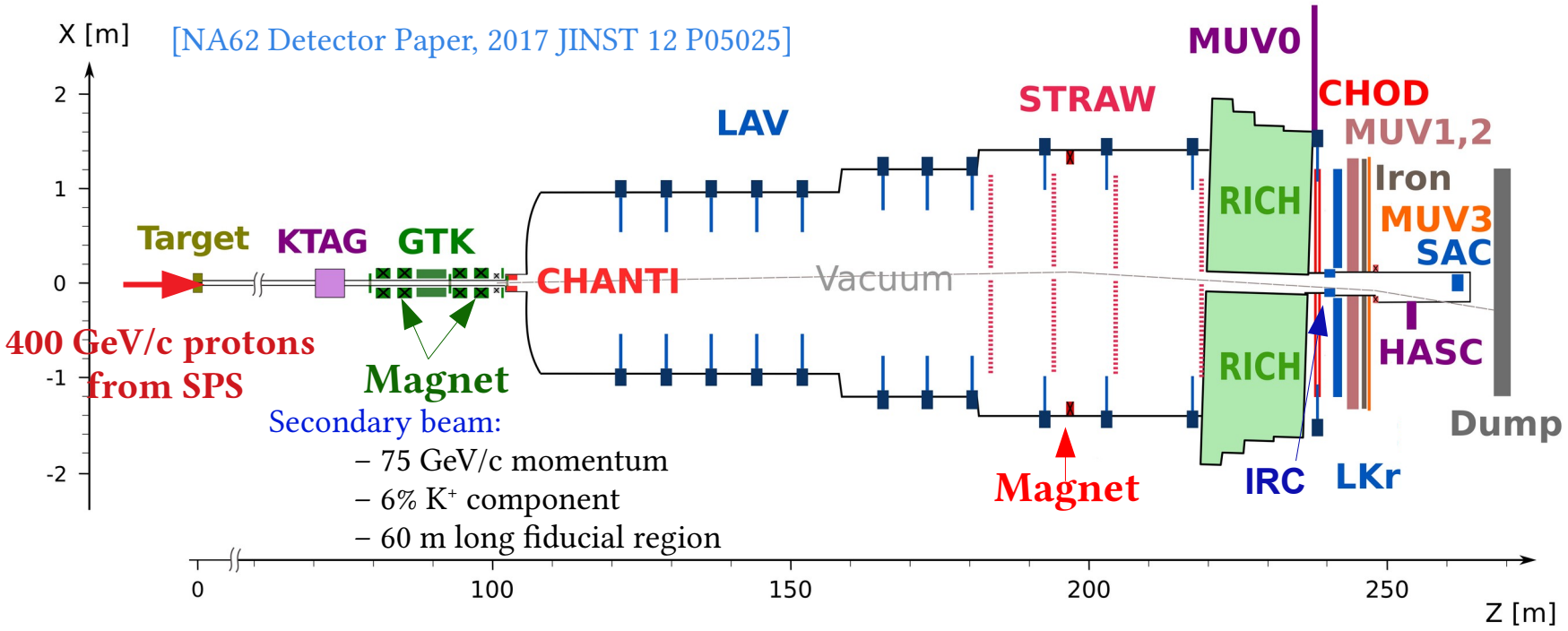
    Phys. Rev. D 77, 052003 (2008)
- **Present state-of-the-art $K^+ \to \pi^+ \nu\nu$ experiments**
  - Kaon decay-in-flight technique
  - NA62 experiment (this talk)

Run 1 statistics

1.9×10^{12} proton per spill on target

~ 2.2×10^{18} POT collected in Run 1

NA62 detector



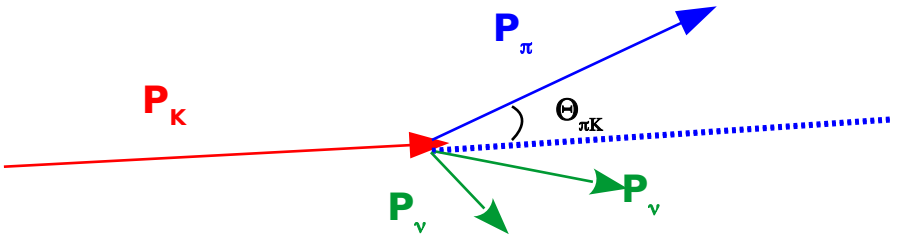
- Upstream detectors (K^+):
  - **KTAG:** Differential Cherenkov counter for K^+ ID
  - **GTK:** Si pixel beam tracker
  - **CHANTI:** Anti-counter for inelastic beam-GTK3 interactions
- Decay Region detectors (π^+):
  - **STRAW:** track momentum spectrometer
  - **CHOD:** Scintillator hodoscopes
  - **LKr/MUV1/MUV2 :** Calorimetric system
  - **RICH:** Cherenkov counter for $\pi/\mu/e$ ID
  - **LAV/SAC/IRC:** Photon veto detectors
  - **MUV3:** Muon veto

Analysis strategy

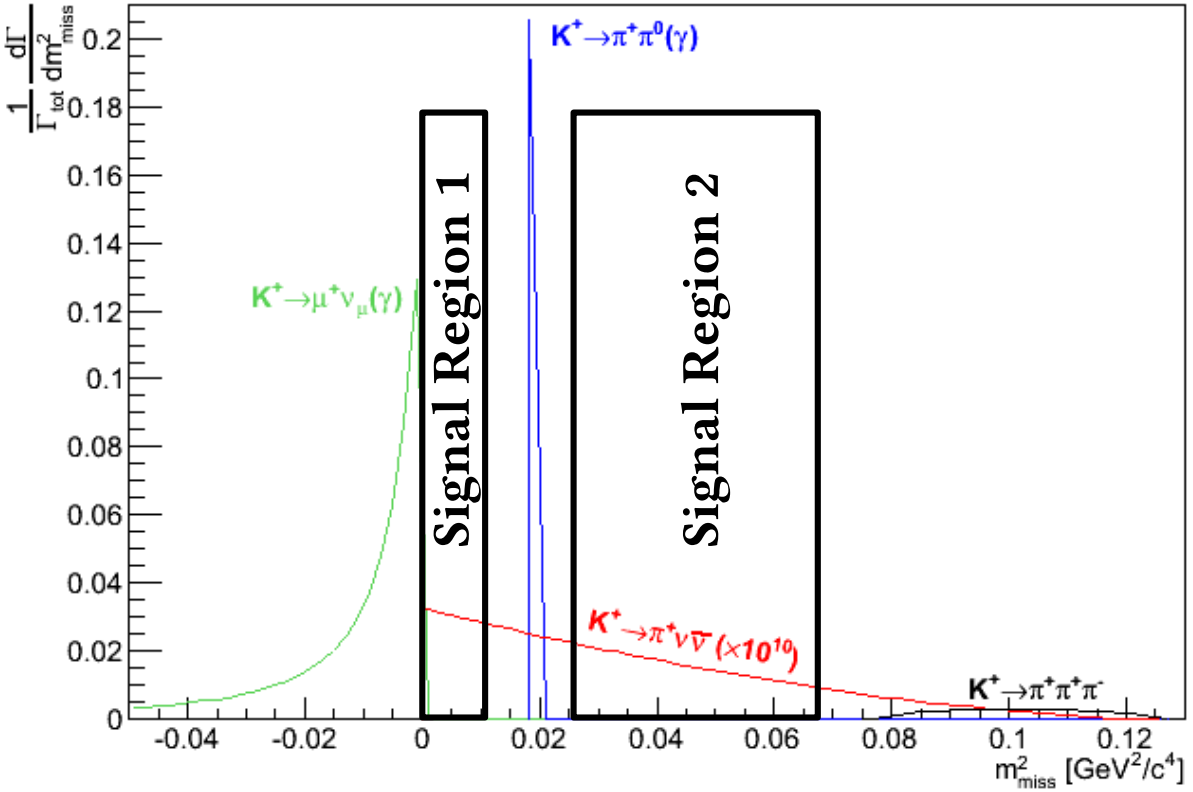
Decay-in-flight technique

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

π^+ mass assumed for the track



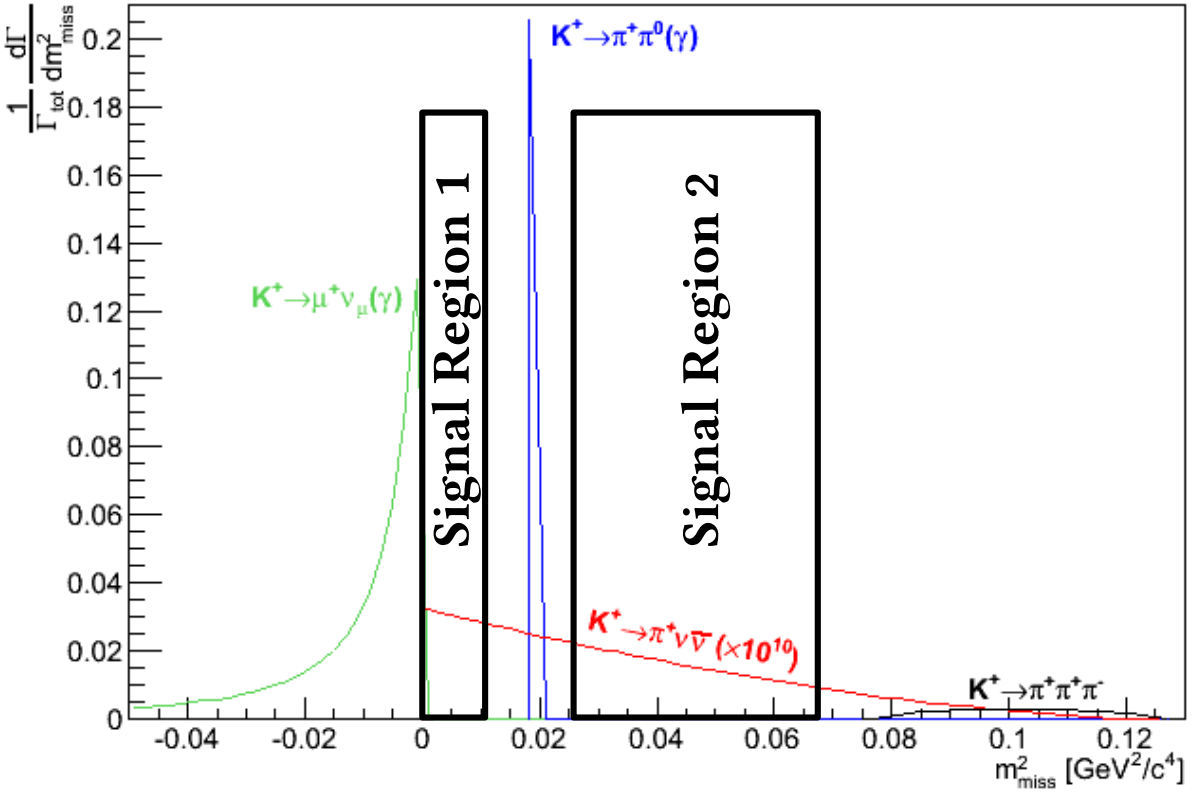
- Muon suppression: > 10^7
- π^0 suppression (from $K^+ \to \pi^+\pi^0$): > 10^7
- Excellent time resolution: O(100ps)
- Kinematic suppression: ~ O(10^4)



Process	Branching ratio
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \mu^+\nu_\mu$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^- e\ \nu_e$	4.3×10^{-5}
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	**8.4×10^{-11}**

Analysis strategy

- **Analysis improvements in 2018**
  - Analysis performed in 7 separate categories
  - Category definition depends on hardware configurations (S1 and S2) and momentum
  - Selection optimized separately for each category
  - Improved signal efficiency with respect to the 2017 analysis
  - Particle identification and upstream background rejection using MVA



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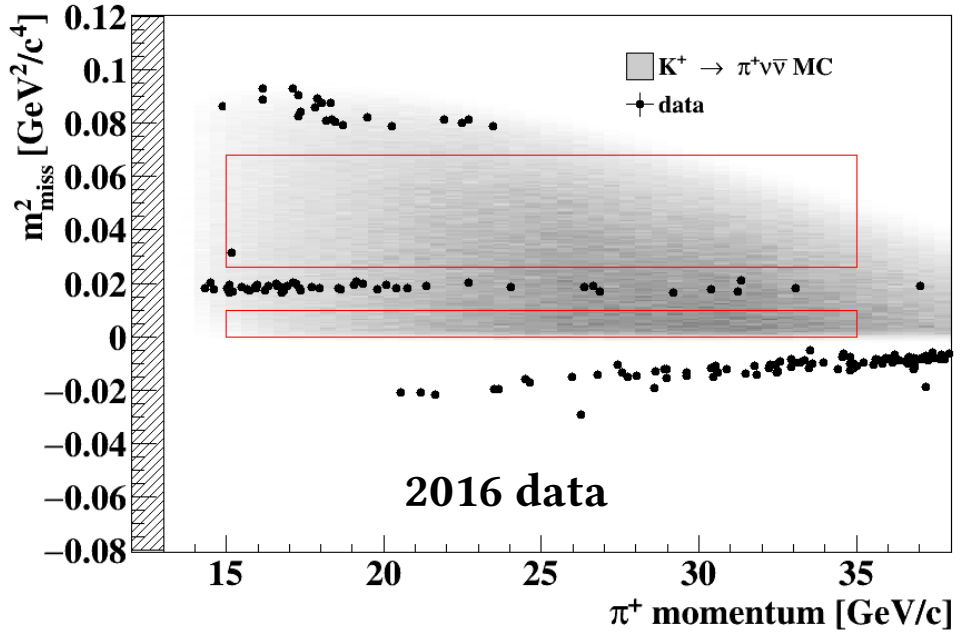
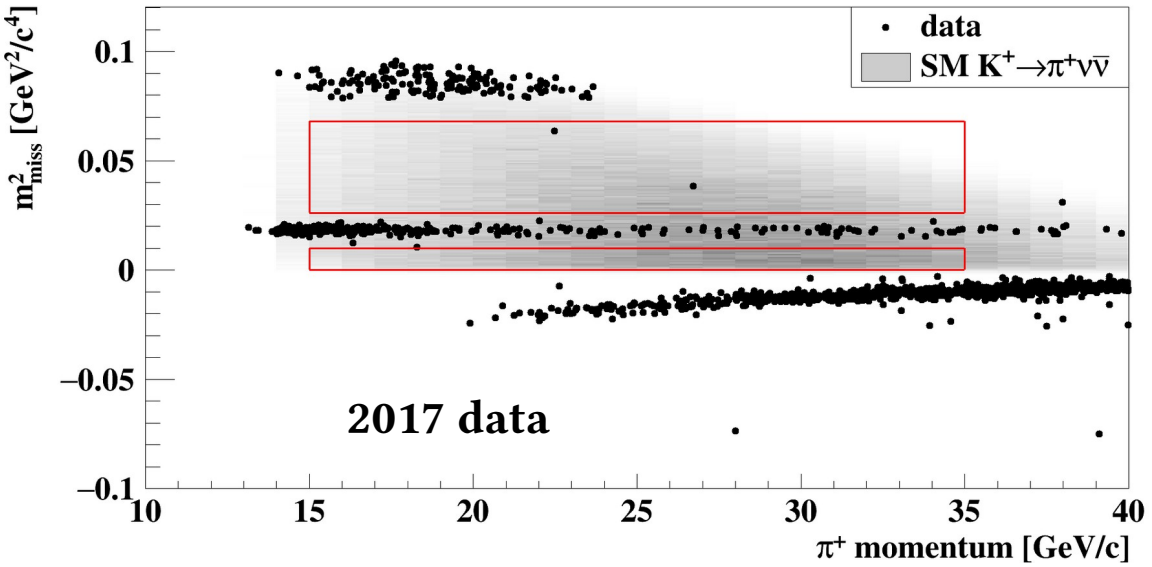
Reminder: 2016 and 2017 data results

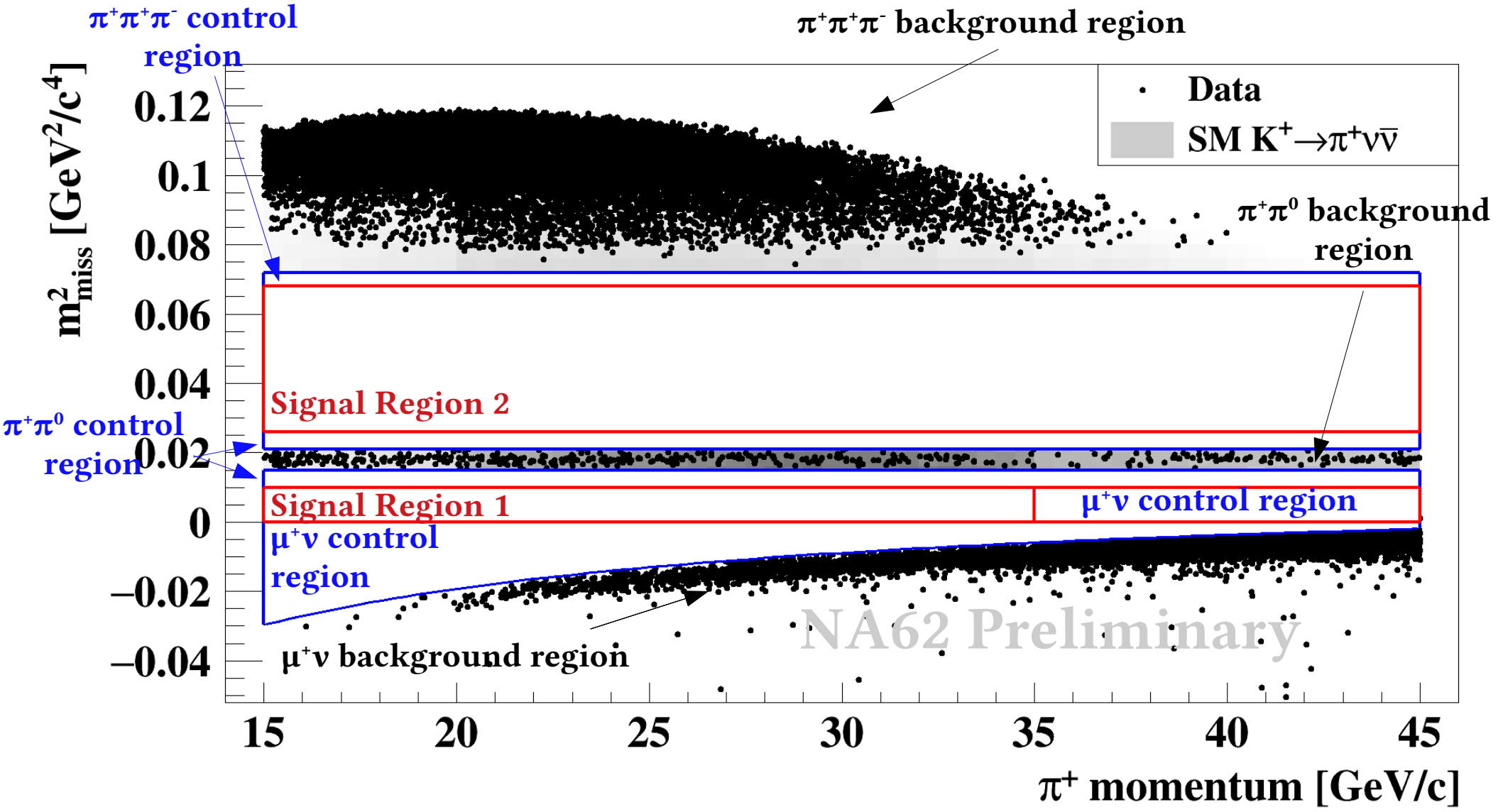




- 1 events observed
- $Br(K^+ \to \pi^+\nu\nu) < 14\times10^{-10}$ @ 90% CL
  Phys. Lett. B 791 (2019) 156-166

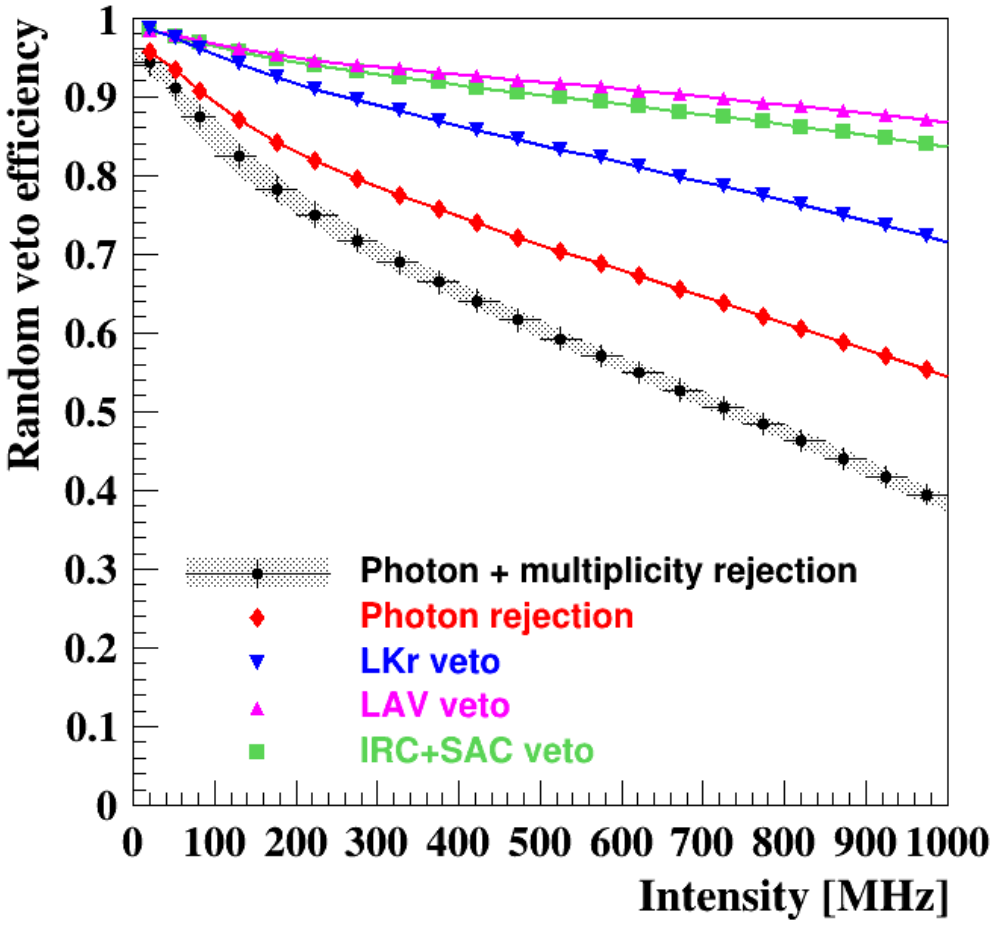
- 2 events observed
- $Br(K^+ \to \pi^+\nu\nu) < 1.78\times10^{-10}$ @ 90% CL
  JHEP 11 (2020) 042

2018 data after signal selection



Single Event Sensitivity

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

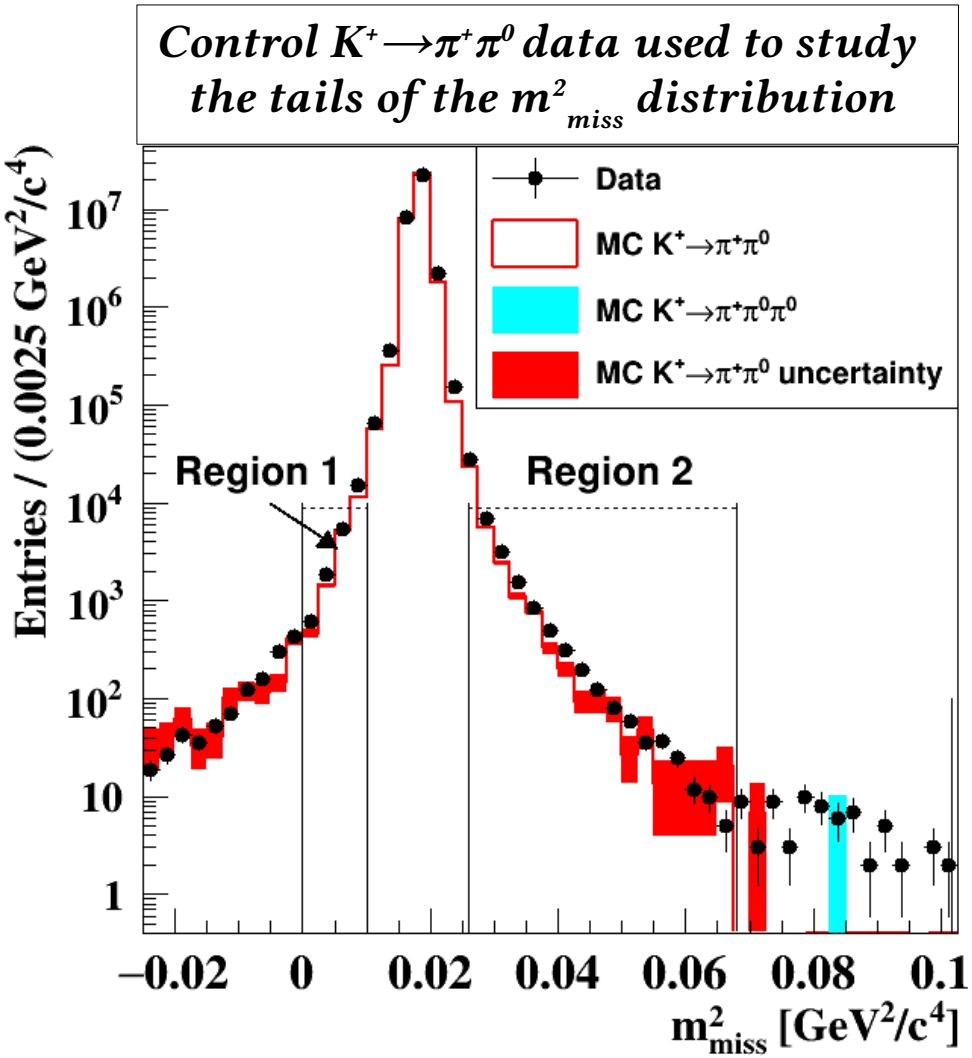


	Error budget S.E.S.
Trigger efficiency	5%
MC acceptance	3.5%
Random Veto	2%
Background(normalization)	0.7%
Instantaneous intensity	0.7%
Total	**6.5%**

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

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

Background from kaon decays



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

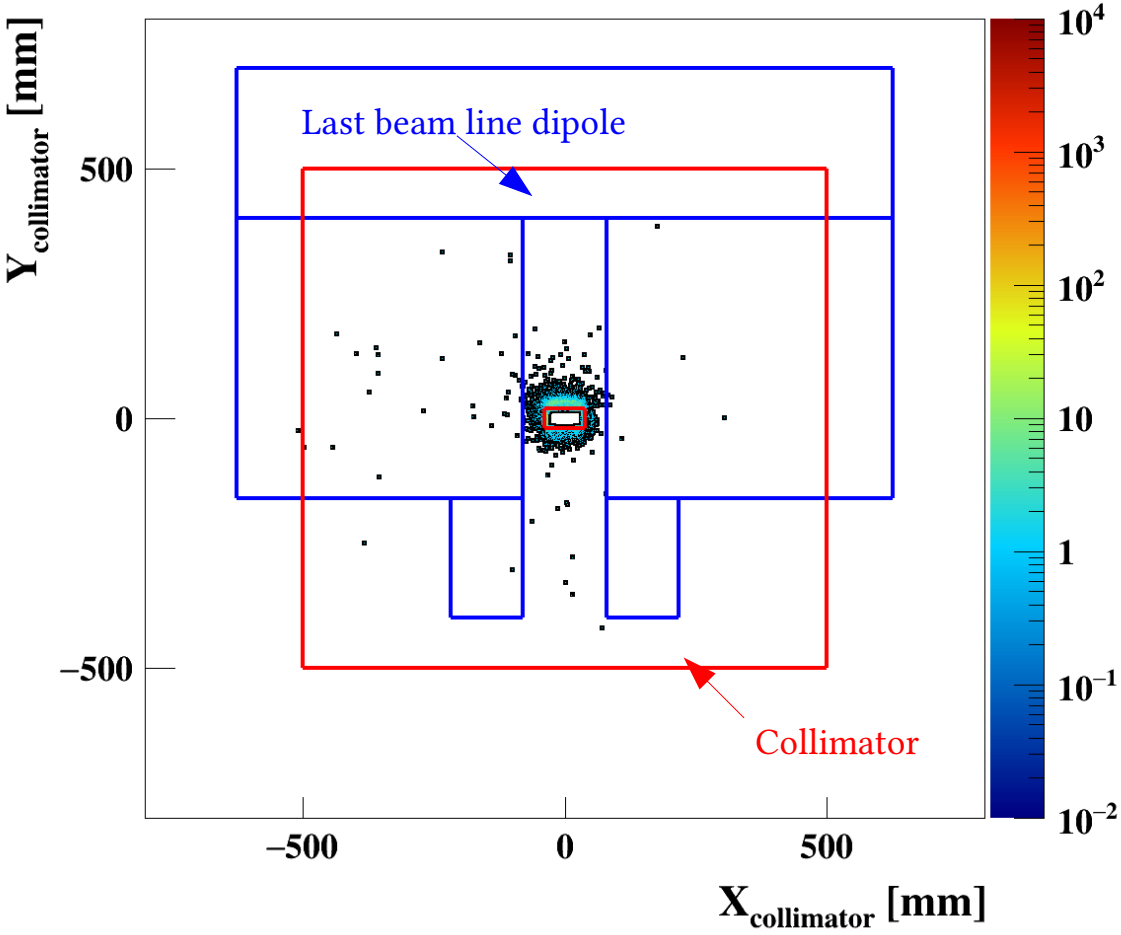
$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) \cdot f_{kin}(region)$$

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

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

Upstream background



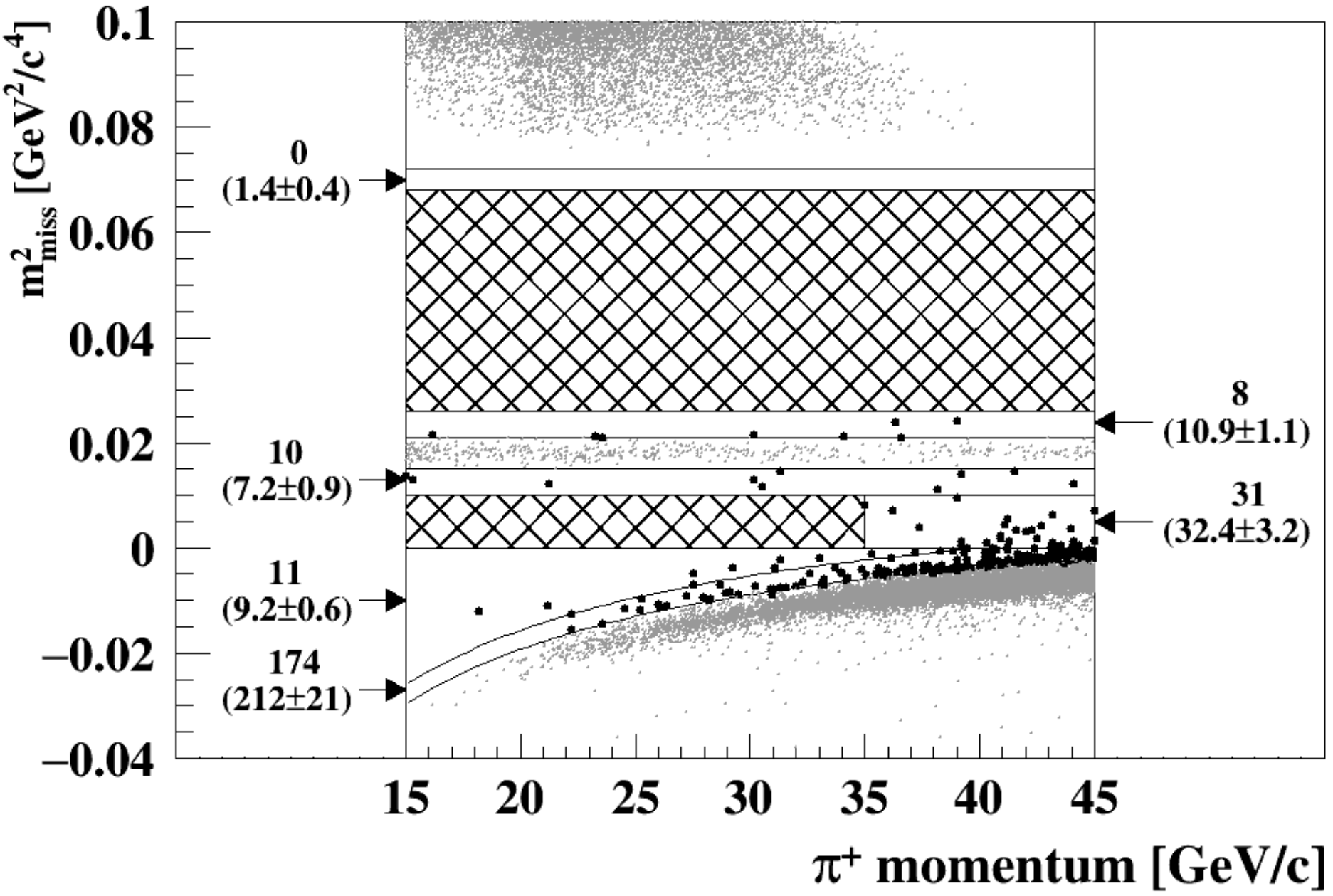
- Pions produced upstream of the fiducial volume (FV)
  - Early K^+ decays (upstream of the FV)
  - Interactions of beam particles with the beam spectrometer material
- Detected pions are associated to an accidental particle from the beam line
- Dangerous if coupled with pion scattering in the first spectrometer chamber
- Kaon-pion association and geometrical cuts effective
- The geometrical origin of those events allows us to define samples for background validation
- Data driven background estimation

Total expected background

	2018 data
Expected SM signal	**$7.58(40)_{syst}(75)_{ext}$**
$K^+ \longrightarrow \pi^+\pi^0(\gamma)$	0.75(5)
$K^+ \longrightarrow \mu^+\nu(\gamma)$	0.64(9)
$K^+ \longrightarrow \pi^+\pi^-e^+\nu$	0.51(10)
$K^+ \longrightarrow \pi^+\pi^+\pi^-$	0.22(8)
$K^+ \longrightarrow \pi^+\gamma\gamma$	< 0.01
$K^+ \longrightarrow \pi^0 l^+\nu$	< 0.001
Upstream	$3.30^{+0.98}_{-0.73}$
Total background	**$5.42^{+0.99}_{-0.75}$**

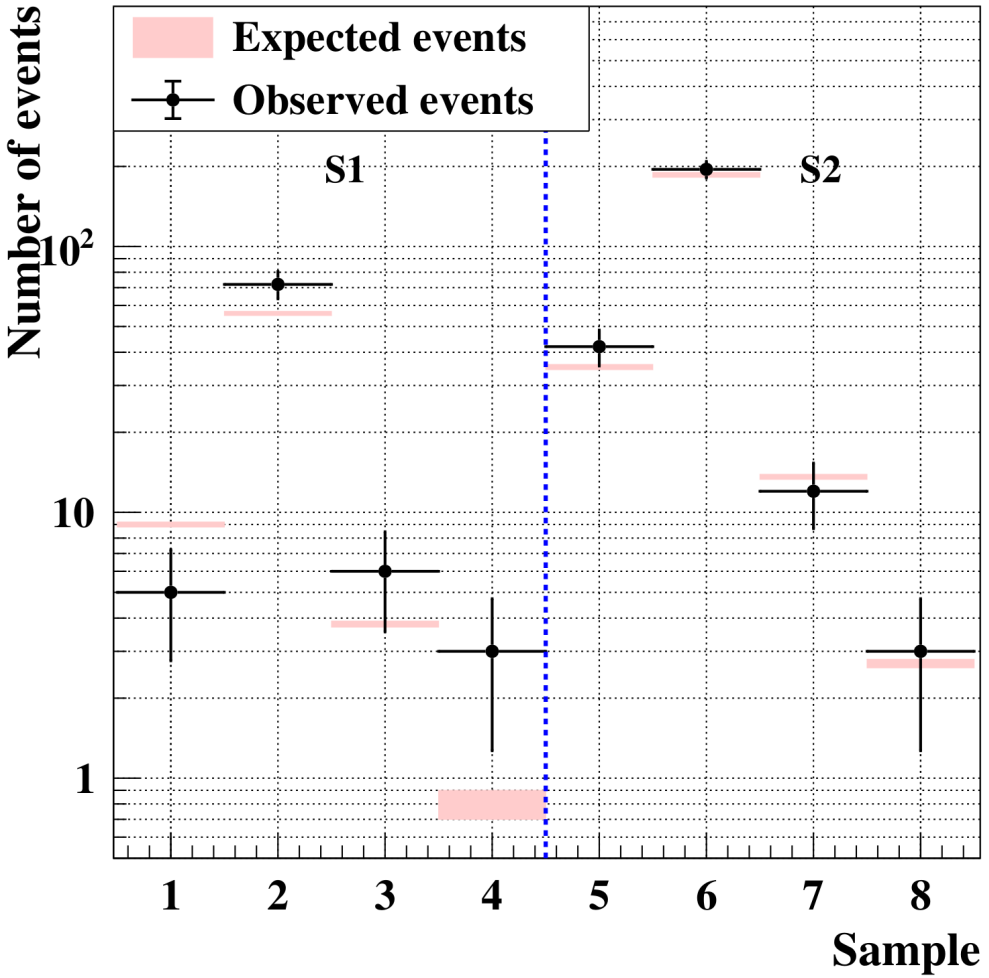
- Background expectations validated in control regions using a blind procedure

Control regions: $K^+ \to \pi^+\pi^0$, $\mu^+\nu_\mu$ and $\pi^+\pi^+\pi^-$

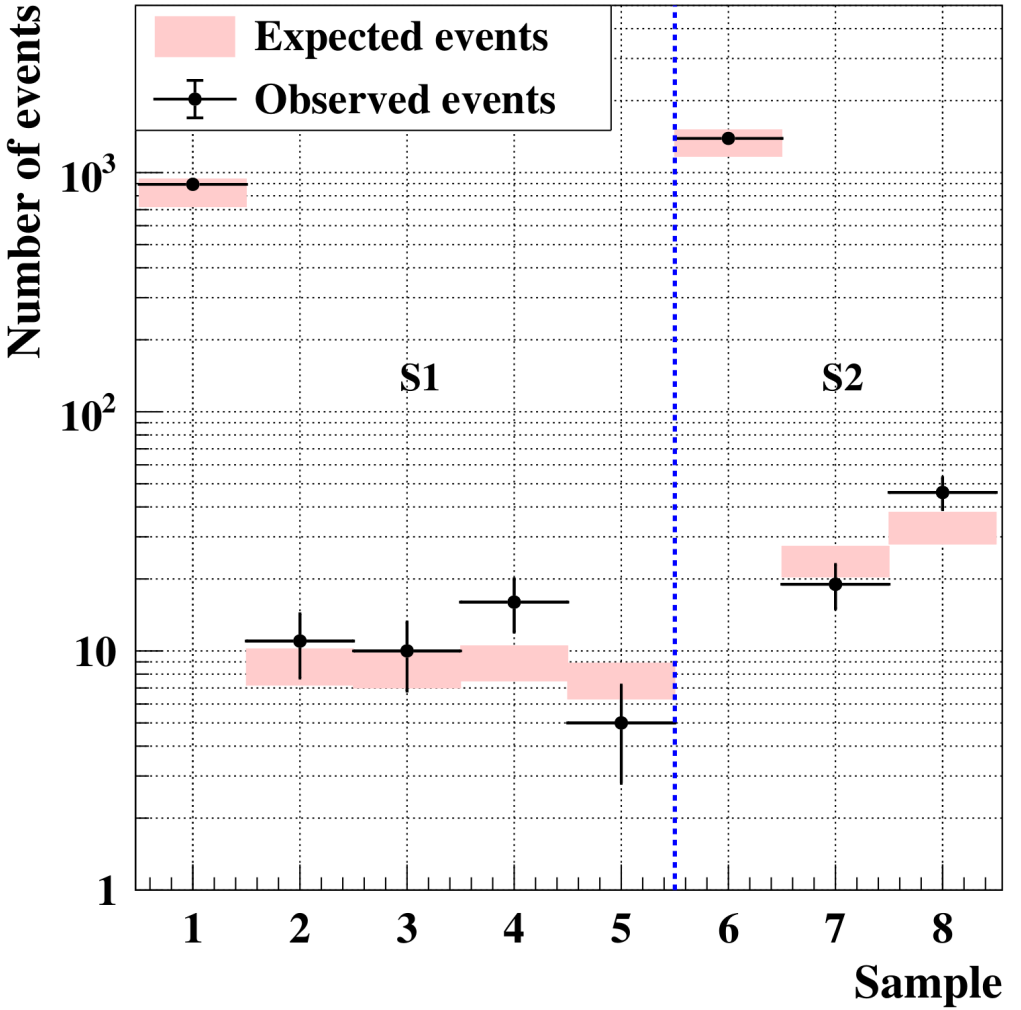


Control regions: $K^+ \to \pi^+\pi^-e^+\nu_e$ and upstream

$K^+ \to \pi^+\pi^-e^+\nu_e$ control samples

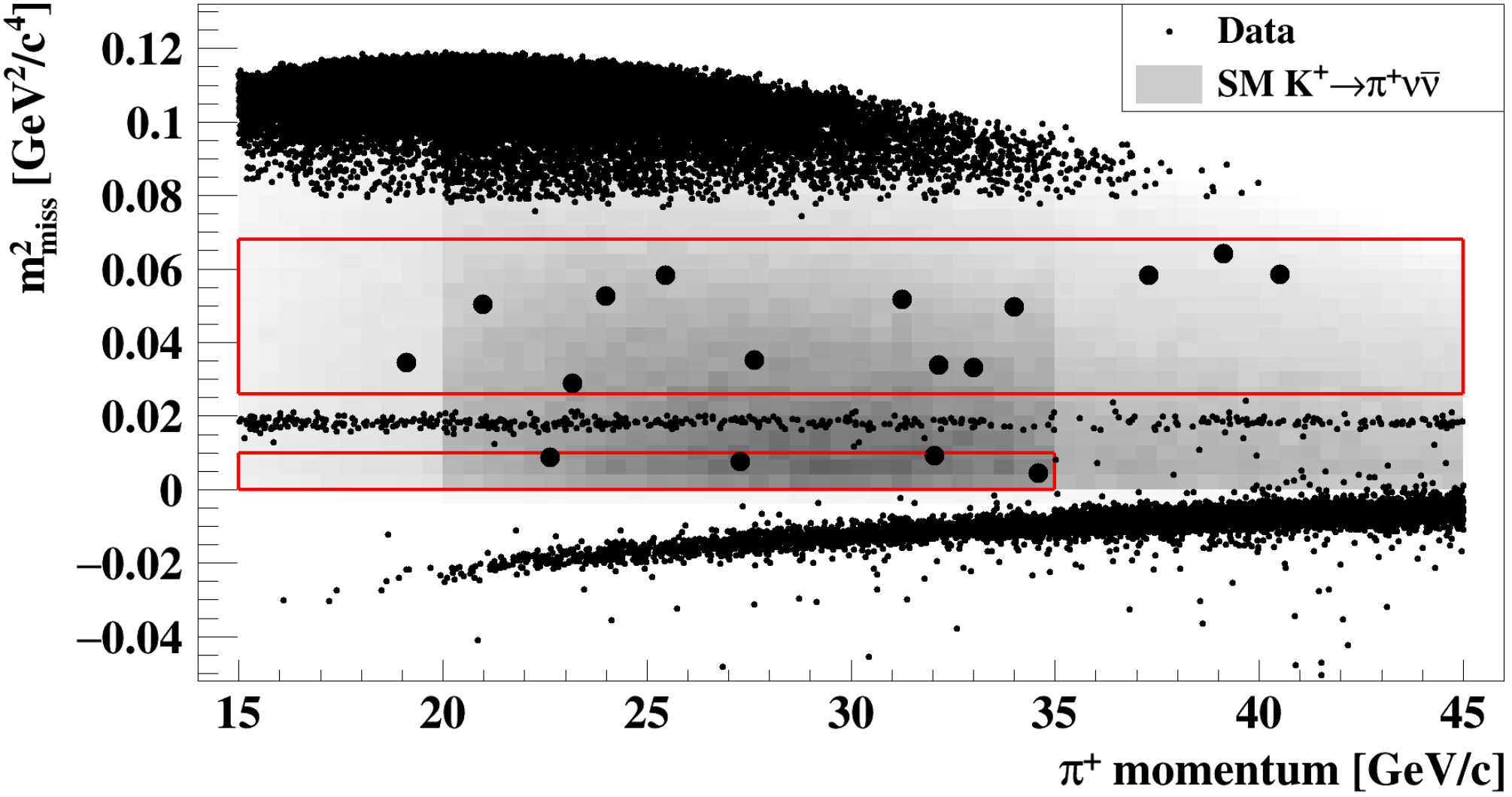


Upstream background control samples



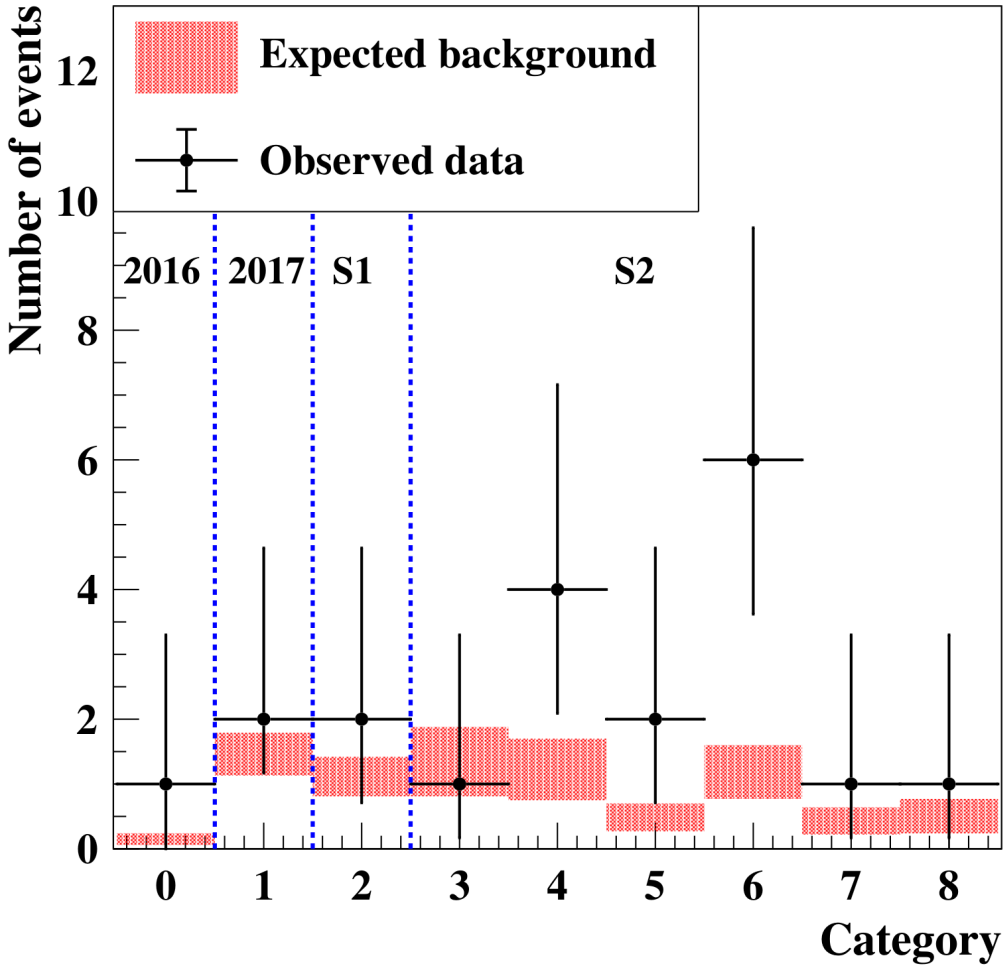
- Data samples defined by inverting signal selection criteria
- The sensitivity of some control samples comparable to the S.E.S.

Opening the box in the 2018 data



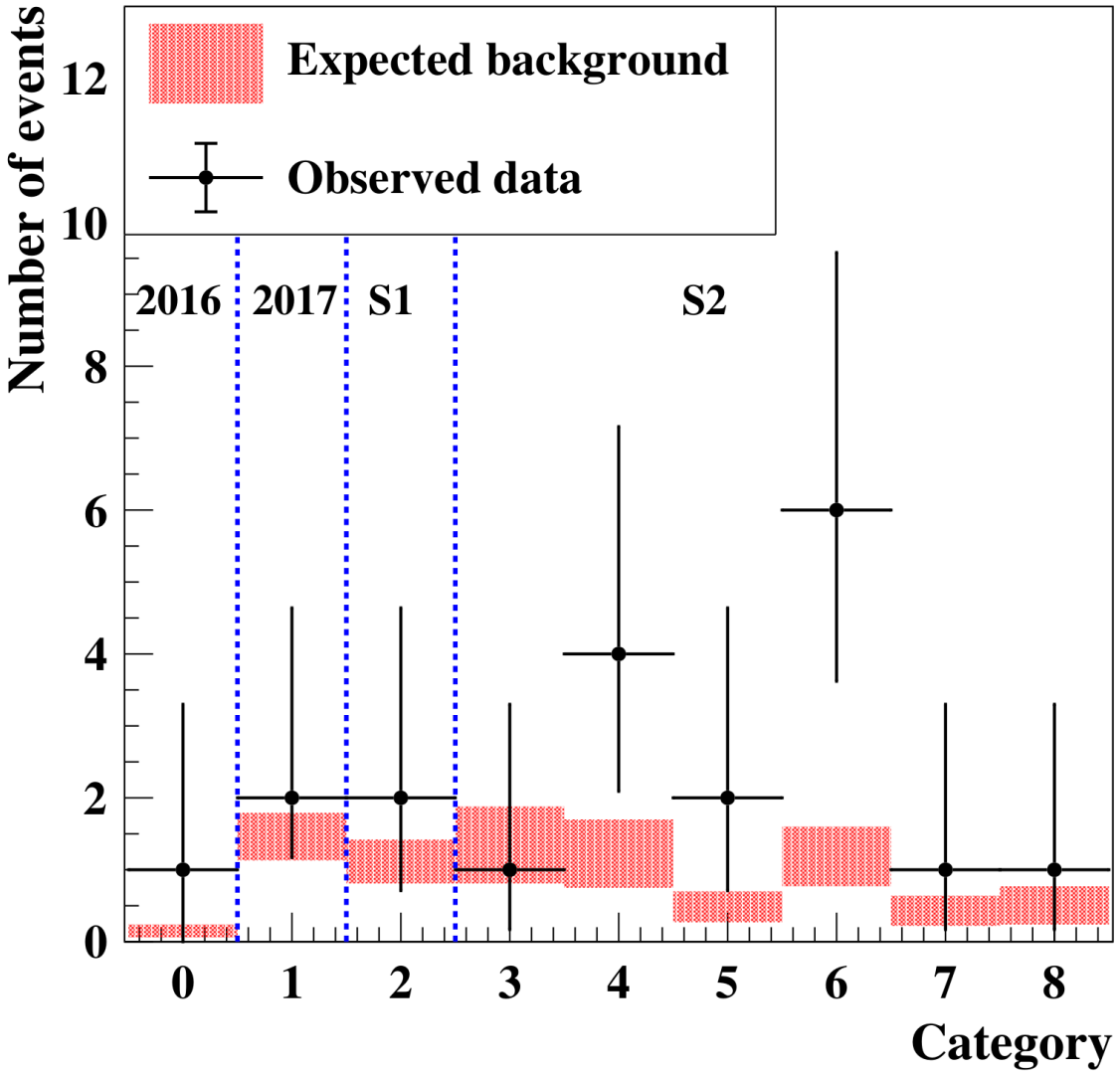
5.4 background + 7.6 SM signal events expected, 17 events observed

Results



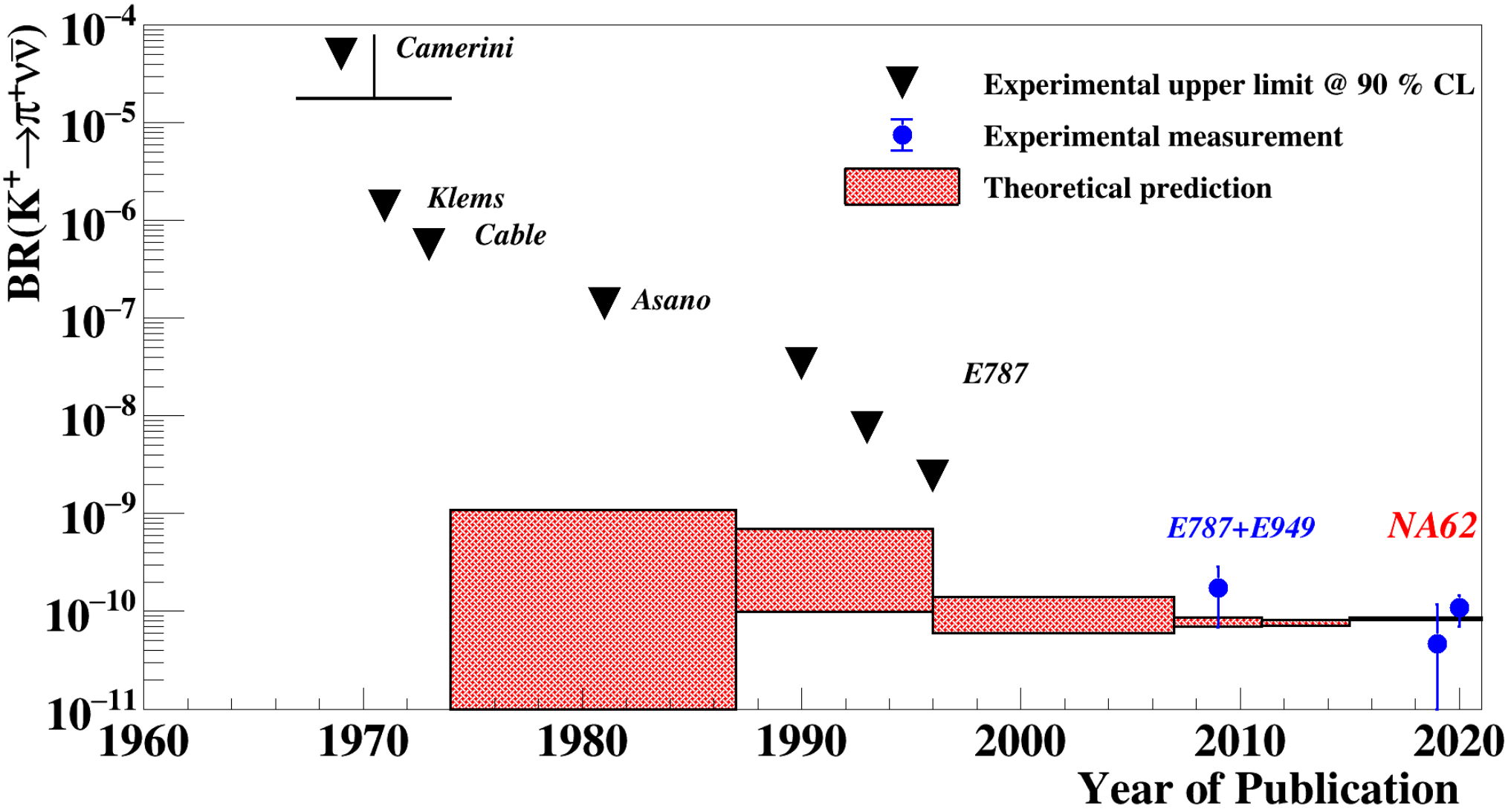
- Maximum likelihood fit using signal and background expectation in each category
- Two samples with different hardware configurations in 2018
  - 2018_S1 ~ 20% of the 2018 dataset, integrated over momentum
  - 2018_S2 ~ 80% of the 2018 dataset, 5 GeV/c wide bins from 15-45 GeV/c
  - 2016 and 2017 datasets,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

Results



- **NA62 Run1(2016 + 2017 + 2018) result [JHEP 06 (2021) 093]:**
  - $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4 stat.} \pm 0.9_{syst.}) \times 10^{-11}$ (3.4σ significance)

$K^+ \to \pi^+ \nu\nu$ decay: Historical context



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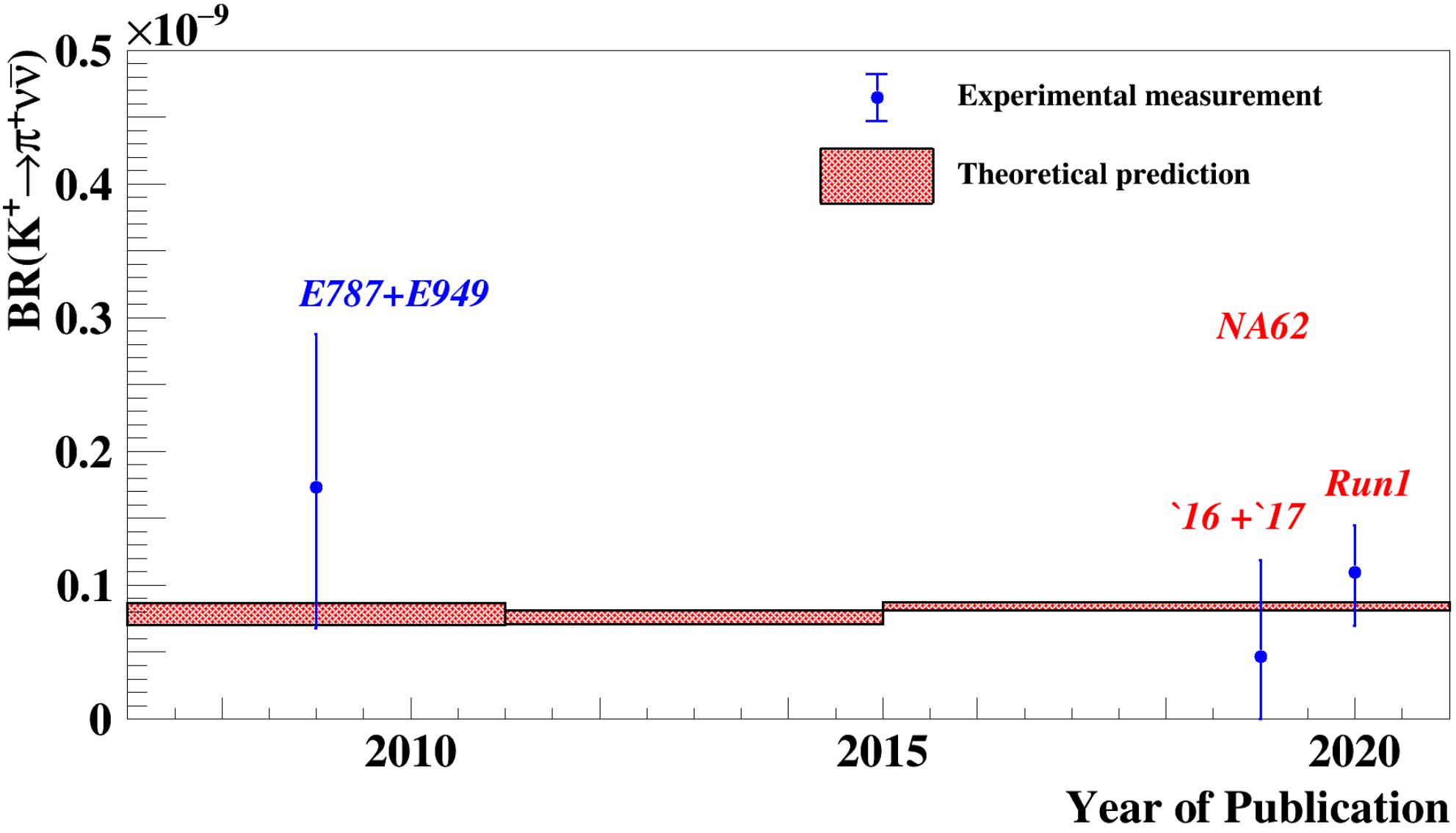
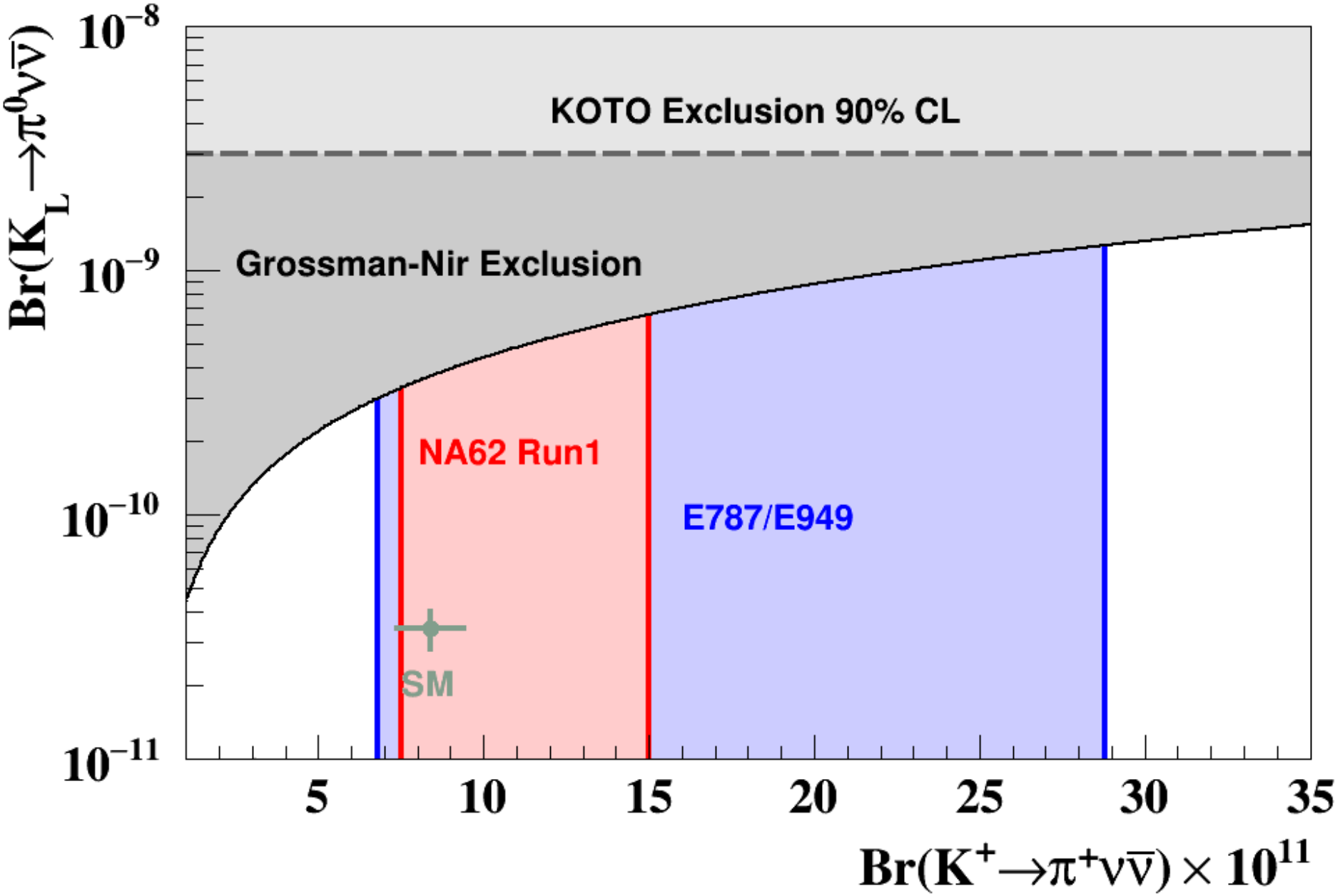
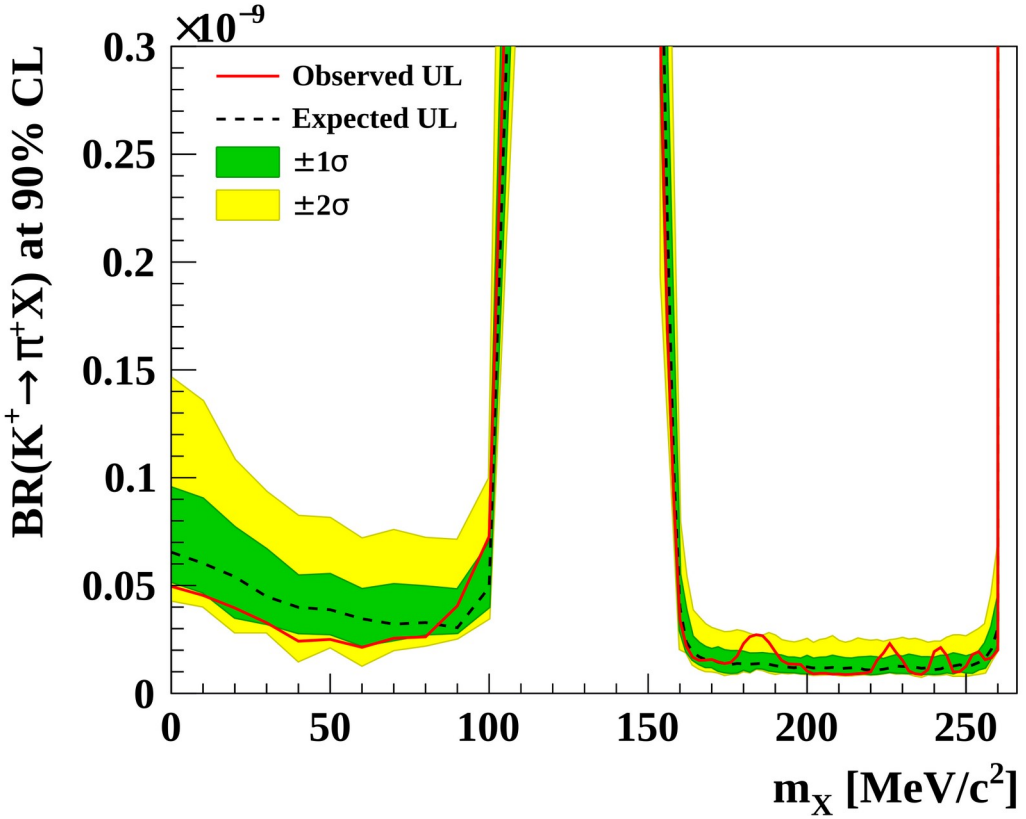
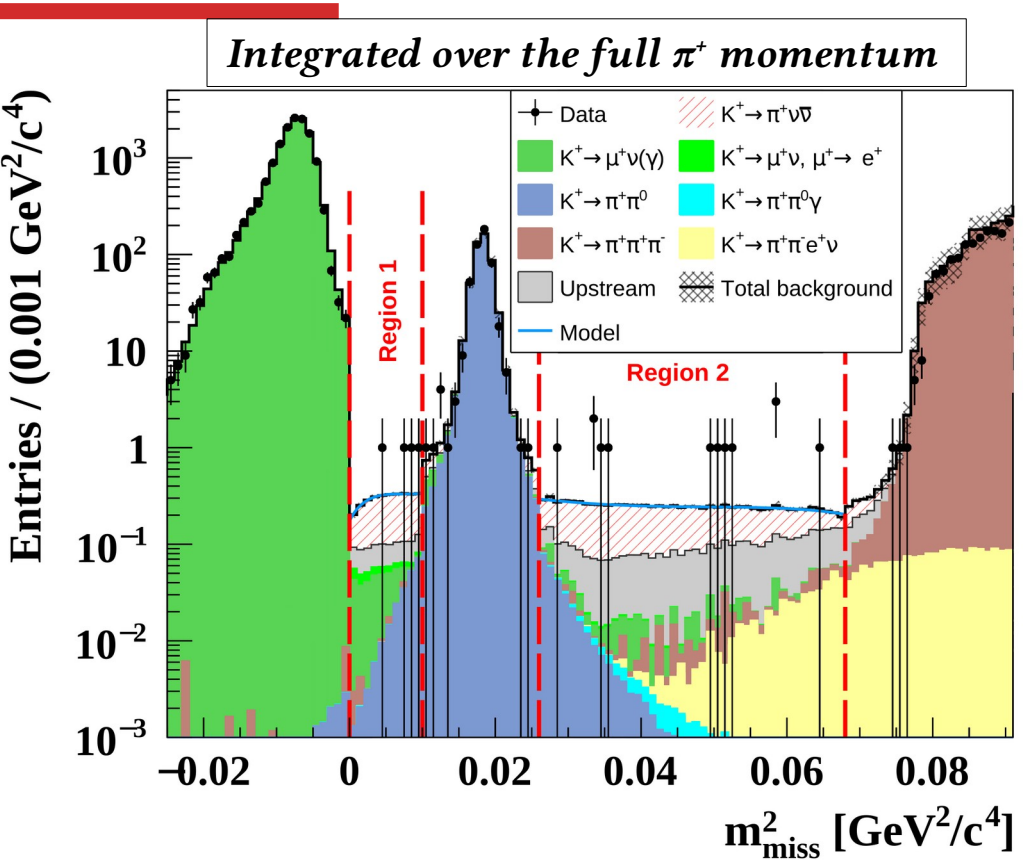


Grossman-Nir limit



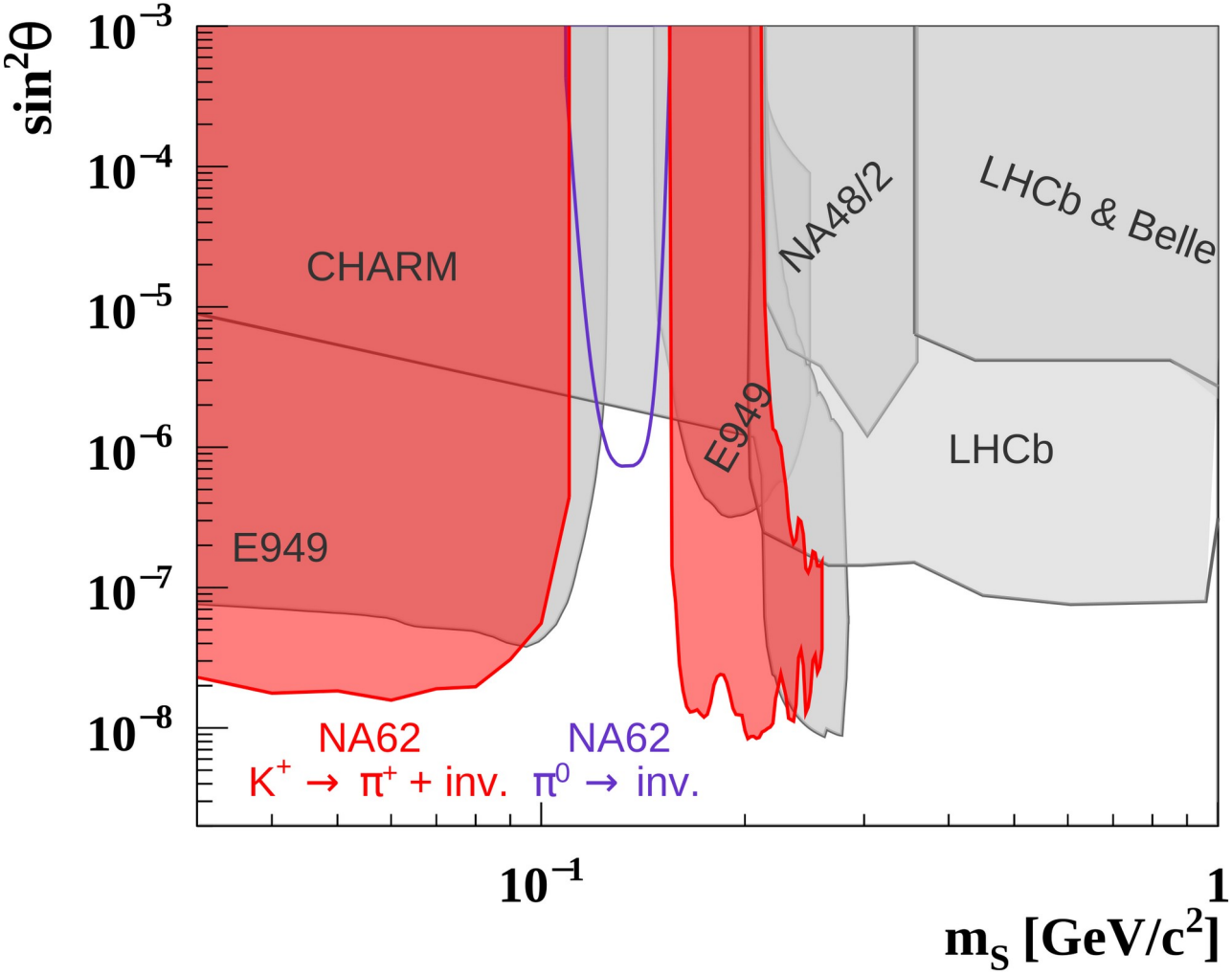
Search for $K^+ \to \pi^+ X$(invisible)





- Search for X particle production in $K^+ \to \pi^+ X$ decays
- Technique: peak searching using the m^2_{miss} observable for m_X in the 0-260 MeV/c^2 range
- Background shapes taken from the $K^+ \to \pi^+ \nu\nu$ analysis including the shape of the SM $K^+ \to \pi^+ \nu\nu$ process itself
- **90% Upper limits on BR($K^+ \to \pi^+ X$) in (10^{-11} – 10^{-10}) range [JHEP 06 (2021) 093]**

Search for $K^+ \to \pi^+ X$(invisible)



- Exclusion limits for a dark-sector scalar X particle mixing with the Higgs
  - ★ BC4 model [J. Phys. G 47 (2020) 010501]

Summary and conclusions

- NA62 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)
  - $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4 stat.} \pm 0.9_{syst.}) \times 10^{-11}$ (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
- Search for $K^+ \to \pi^+ X$(invisible): 90% CL upper limits in the range 10^{-11} – 10^{-10}

- NA62 Run 2 just started with important hardware improvements to further suppress background
  - 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 reject background from kaon decays