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

On behalf of the NA62 collaboration

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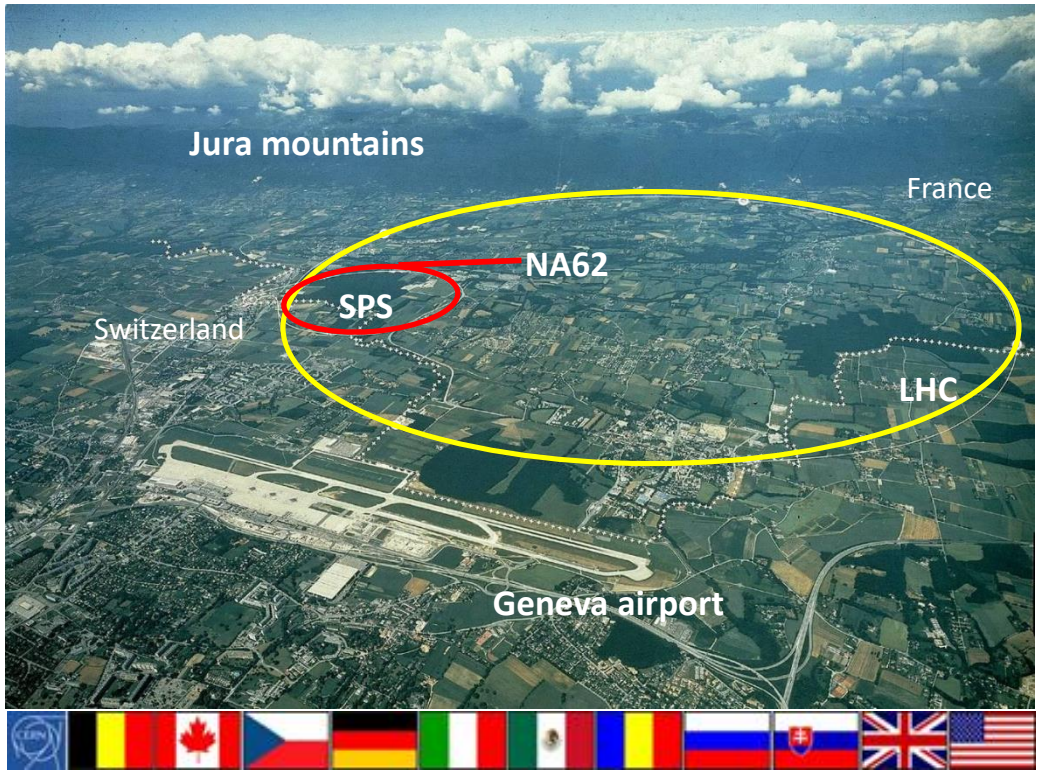
Outline

- The NA62 experiment and detector
- $K^+ \to \pi^+ \nu\bar{\nu}$ 2016 result
- $K^+ \to \pi^+ \nu\bar{\nu}$ 2017 analysis status

The NA62 experiment and detector

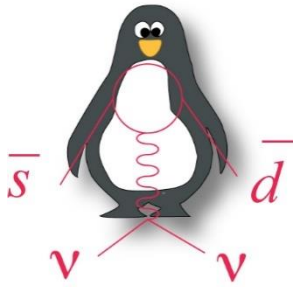
The NA62 Experiment

Fixed target Kaon experiment at CERN SPS

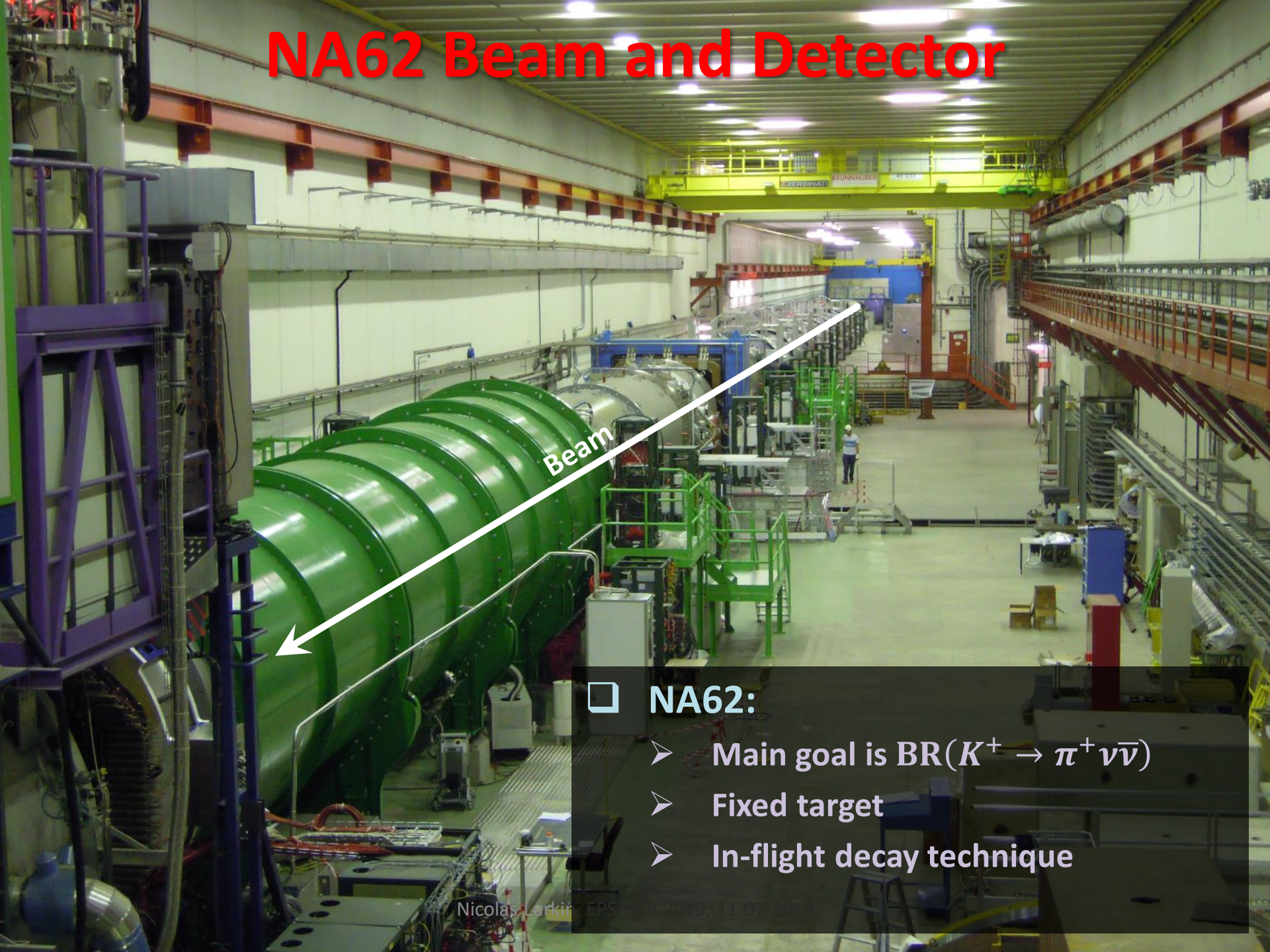


- **2008** • NA62 Approval
- **2009-2014** • Detector R&D and Installation
- **2014** • Pilot Run
- **2015** • Commissioning run
- **2016-2018** • Physics runs
- **2021-2023** • Future runs

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



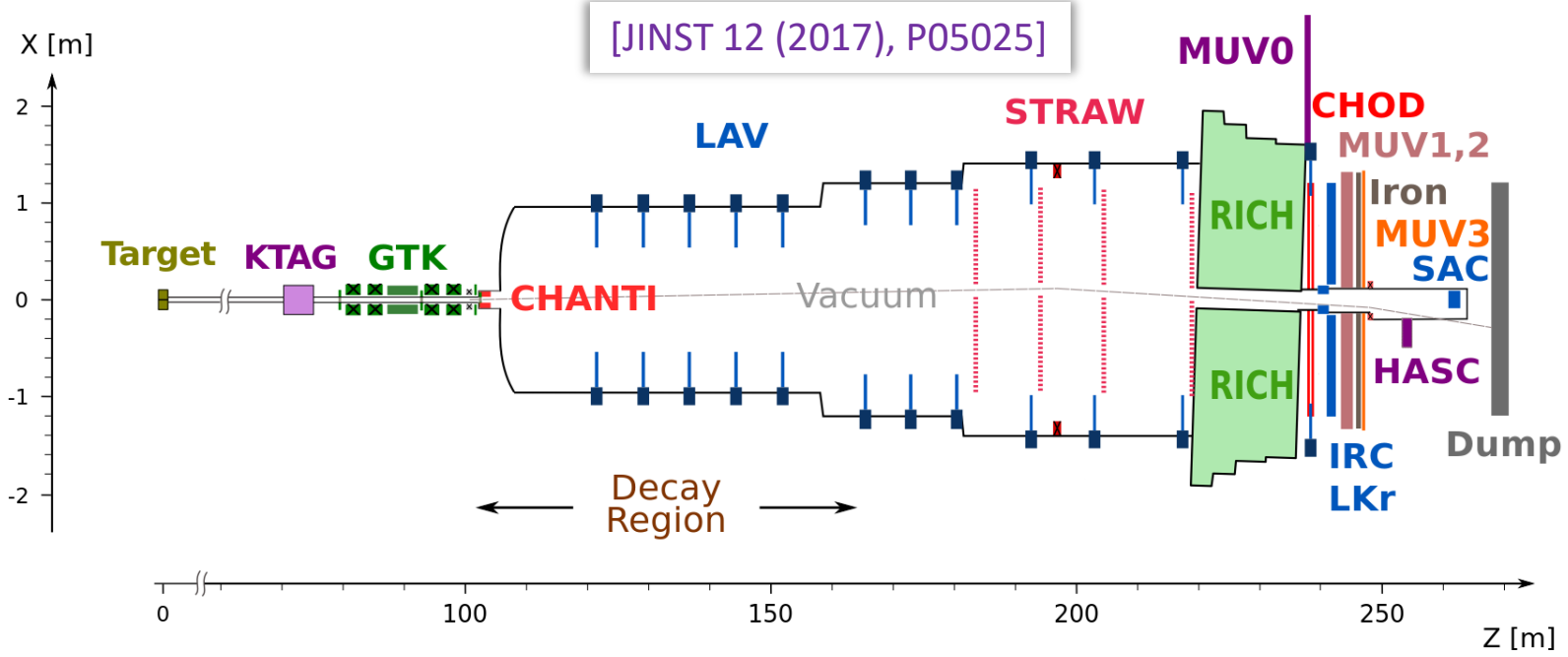
NA62 Beam and Detector



- **NA62:**
  - Main goal is $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$
  - Fixed target
  - In-flight decay technique

NA62 Beam & Detector

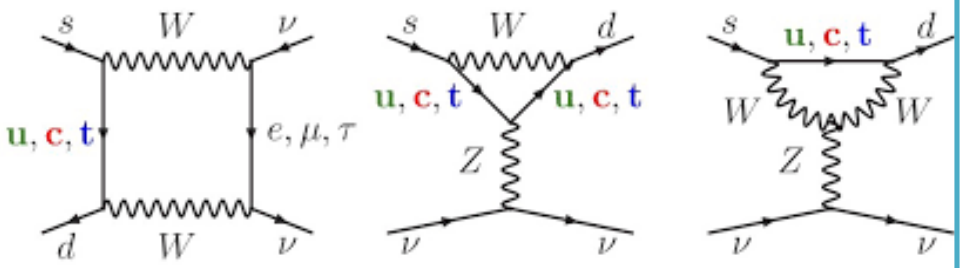
[JINST 12 (2017), P05025]



- SPS Beam:
  - 400 GeV/c protons
  - 2×10^{12} protons/spill
  - 3.5 s spill
- Secondary positive beam
  - 75 GeV/c momentum, 1% bite
  - $100\ \mu$rad divergence (RMS)
  - $60 \times 30\ \mathrm{mm}^2$ transverse size
  - $K^+(6\%)/\pi^+(70\%)/p(24\%)$
  - 33×10^{11} ppp on T10 (750 MHz at GTK3)
- Decay region
  - 60 m long fiducial region
  - ~ 5 MHz K^+ decay rate
  - Vacuum $\sim\mathcal{O}(10^{-6})$ mbar

$K^+ \to \pi^+ \nu\bar{\nu}$ 2016 result

The $K^+ \to \pi^+ \nu\bar{\nu}$ Process



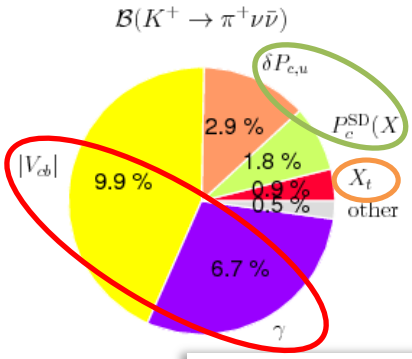
❑ Highly suppressed:

- ➢ FCNC process forbidden at tree level
- ➢ CKM suppression
  ($s \to d$ coupling, $BR \sim |V_{ts}V_{td}|^2$)

❑ Theoretically clean:

- ➢ Dominant short-distance contribution
- ➢ Hadronic matrix element extracted from $BR(K^+ \to \pi^0 e^+ \nu)$

- ➢ Theoretical error budget dominated by CKM parameters



Charm contributions

Top contributions

CKM contributions

[Buras et al., JHEP1511 (2015) 033]

❑ Previous exp. determination:

$BR(K^+ \to \pi^+ \nu\bar{\nu})$
E787/E949 at BNL
$(17.6^{+11.5}_{-10.5}) \times 10^{-11}$

❑ SM Predictions:

$BR(K^+ \to \pi^+ \nu\bar{\nu})$
$(8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{\lvert V_{cb}\rvert}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2°}\right]^{0.74}$
$(8.4 \pm 1.0) \times 10^{-11}$

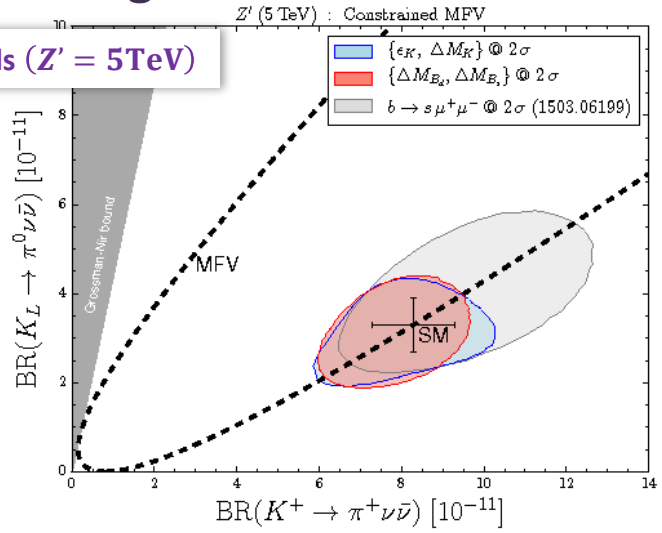
$K^+ \to \pi^+ \nu\bar{\nu}$ in New Physics Scenarios

- Custodial Randall-Sundrum [JHEP 0903 (2009) 108]
- MSSM analyses [JHEP 0608 (2006) 064] [Int.J.Mod.Phys A29 (2014) no.27, 1450162]
- Simplified Z, Z' models [JHEP 1511 (2015) 166]
- Littlest Higgs with T-parity [Eur.Phys.J. C76 (2016) 182]
- LFU violation models [Eur.Phys.J. C77 (2017) no.9 618]

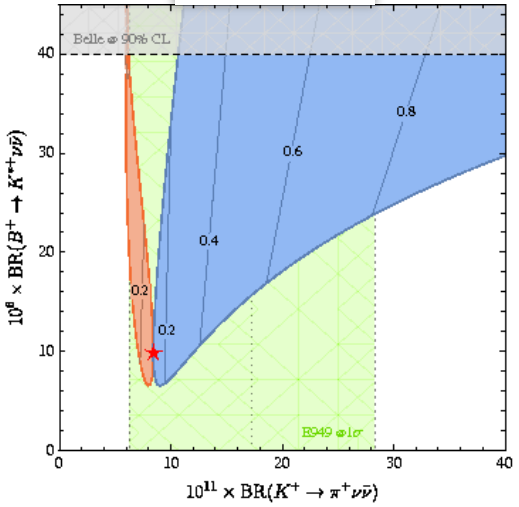
❑ Combine measurement with other channels

- Strong constraints on NP models

Z' models ($Z' = 5$TeV)



LFU violation



NA62 Analysis Strategy

Signal and background regions are kept blind throughout the analysis

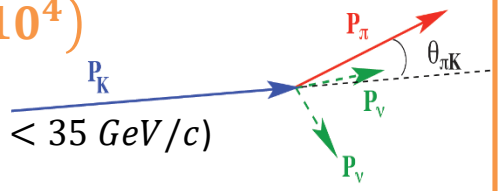
Decay backgrounds	
Decay mode	BR
$\mu^+\nu(\gamma)$	63.5%
$\pi^+\pi^0(\gamma)$	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^+\pi^-e^+\nu$	4.2×10^{-5}
Other backgrounds	
Beam-gas interactions	
Upstream interactions	

Time resolution $\sim \mathcal{O}(100\ \mathrm{ps})$

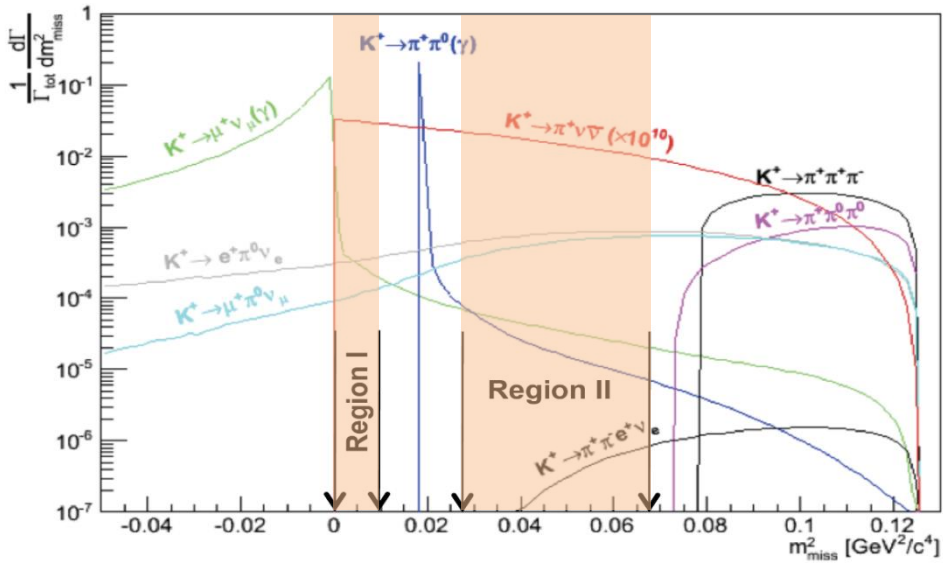
Matching of upstream-downstream activity

Kinematic suppression $\sim \mathcal{O}(10^4)$

- Kaon momentum
- π momentum ($15\ GeV/c < P_\pi < 35\ GeV/c$)



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



PID and high efficiency Veto systems

- Muon suppression $> 10^7$
- π^0 suppression $> 10^7$
- Particle ID (Cherenkov + calorimeters)
- Photon veto

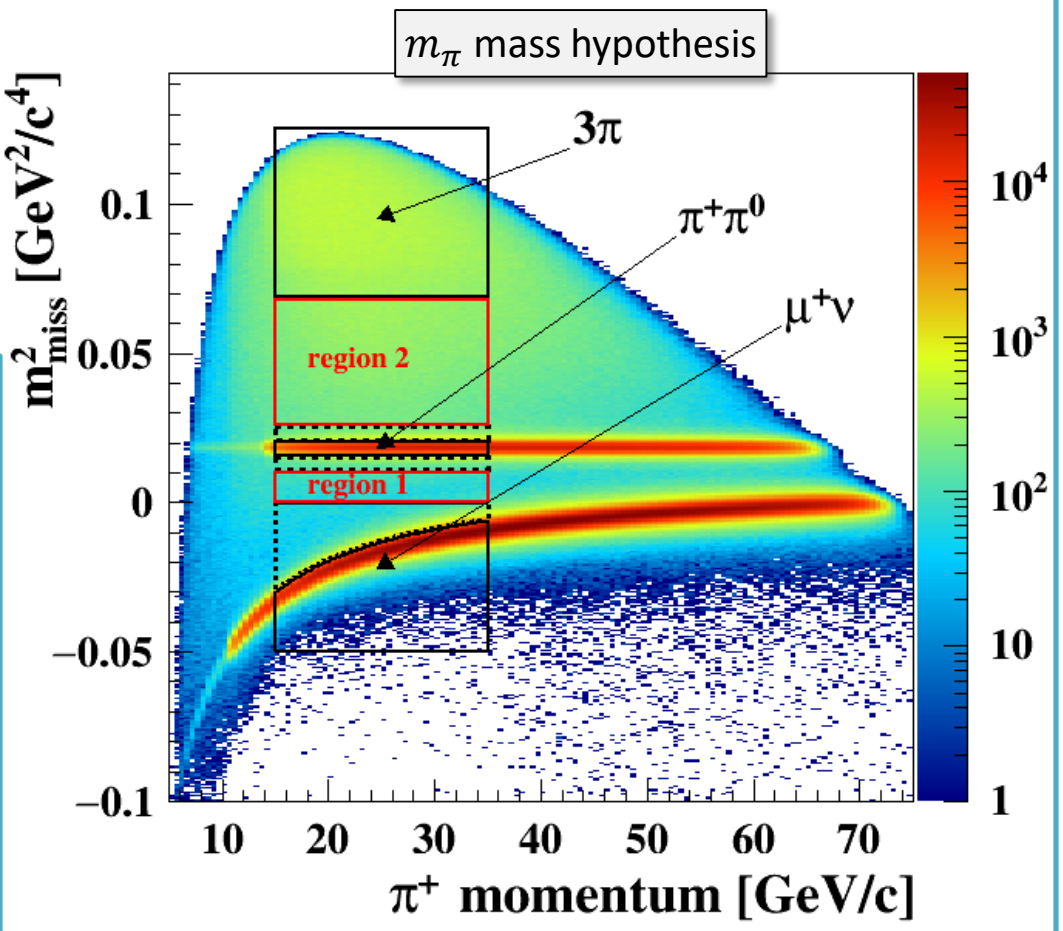
$K^+ \to \pi^+ \nu\bar{\nu}$ Analysis

Selection criteria

- Single track topology
- π^+ identification
- Photon rejection
- Multi-track rejection

Performances

- $\varepsilon_{\mu^+} = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
- $\varepsilon_{\pi^0} = 3 \cdot 10^{-8}$
- $\sigma(m^2_{miss}) = 1 \cdot 10^{-3}\ \mathrm{GeV}^2/c^4$
- $\sigma_t \sim \mathcal{O}(100\ \mathrm{ps})$

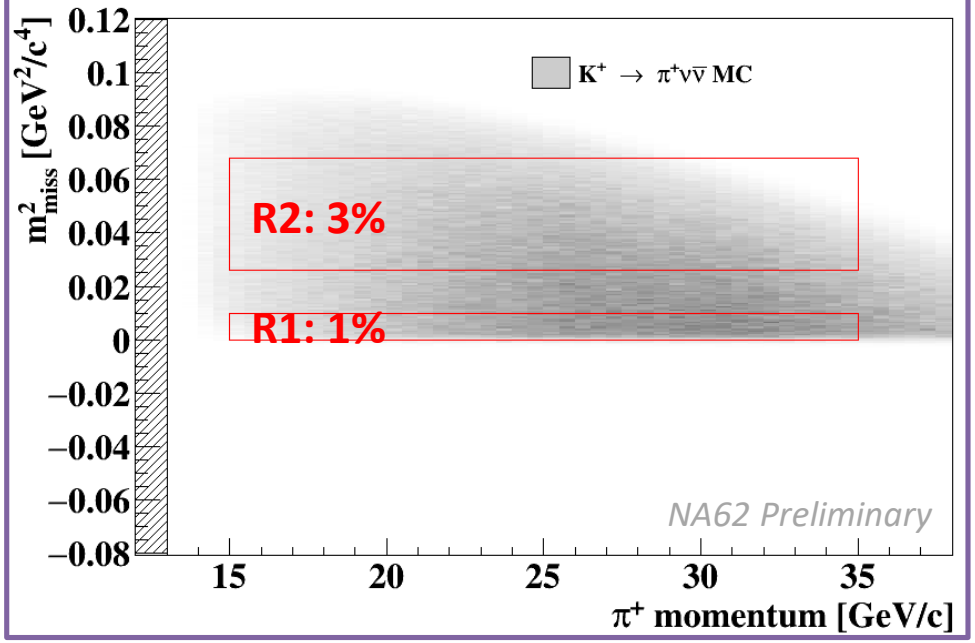


Signal region

- $15 < P_{\pi^+} < 35\mathrm{GeV}/c$
- $\boldsymbol{m^2_{miss}} = (\mathbf{P_K} - \mathbf{P_\pi})^2$ in 3 ways:
  - m^2_{miss}(GTK, STRAW)
  - m^2_{miss}(GTK, RICH)
  - m^2_{miss}(beam, STRAW)

$K^+ \to \pi^+ \nu\bar{\nu}$ Single Event Sensitivity

- **Signal acceptance: 4%**
- **Normalisation**
  - $K^+ \to \pi^+\pi^0$ from control trigger
  - Acceptance: 10%
  - Number of kaon decays in the fiducial volume:
    $N_K = 1.21(4) \times 10^{11}$



Uncertainties

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

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

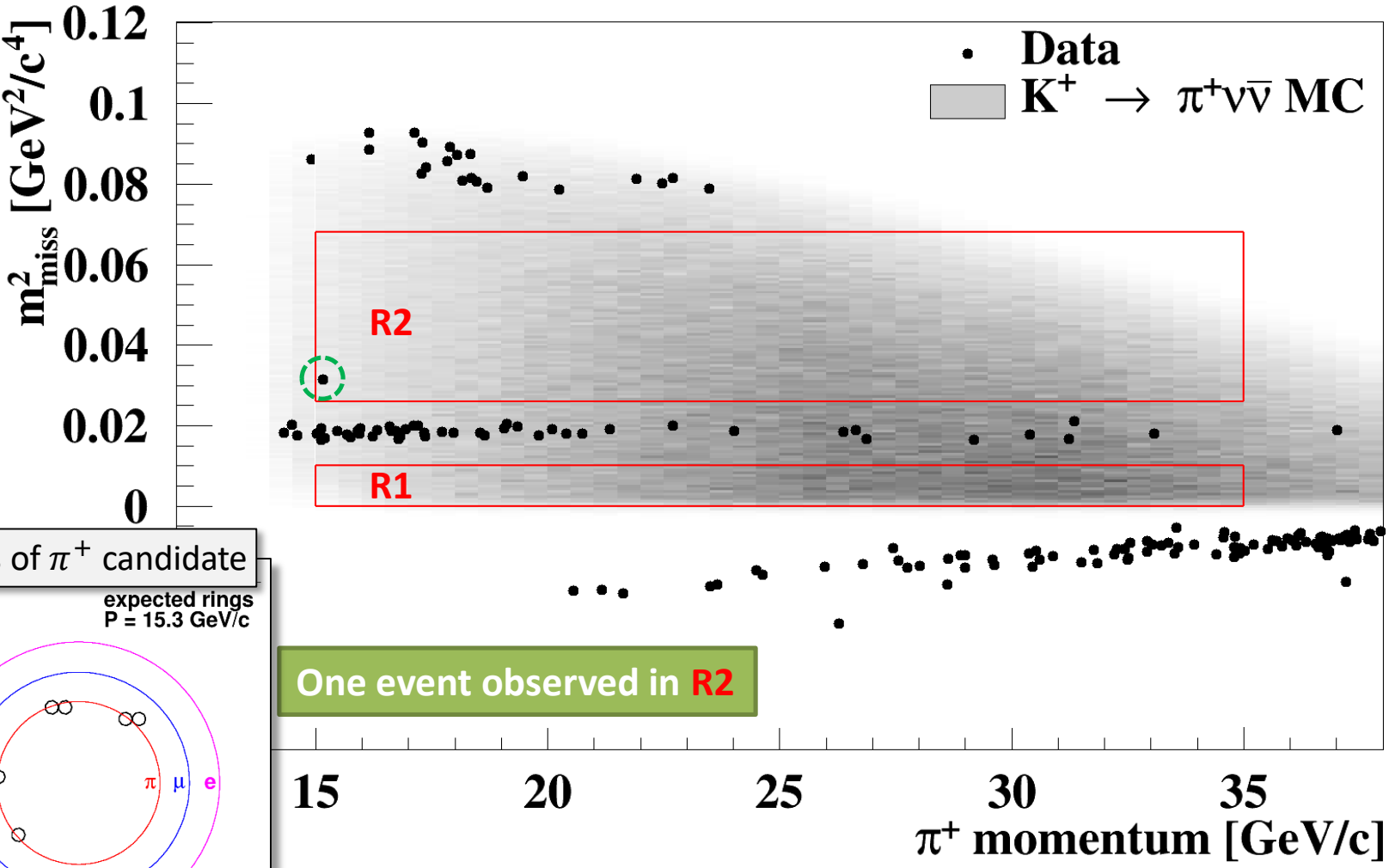
$K^+ \to \pi^+ \nu\bar{\nu}$ Background Summary

- $K^+ \to \pi^+\pi^0(\gamma)$ (Data driven)
  - Control region: 1 observed
    $1.46 \pm 0.16_{\text{stat}} \pm 0.06_{\text{syst}}$ expected
- $K^+ \to \mu^+\nu_\mu(\gamma)$ (Data driven)
  - Control region: 2 observed
    $1.02 \pm 0.16_{\text{stat}} \pm 0.31_{\text{syst}}$ expected
- $K^+ \to \pi^+\pi^- e^+\nu_e$ (MC)
  - 600M MC decays
  - Good agreement across 5 validation samples

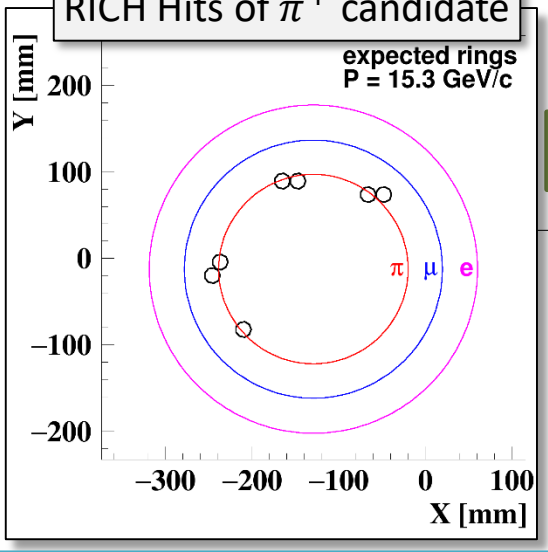
Process	Expected events (R1+R2)
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{\text{stat}} \pm 0.020_{\text{syst}} \pm 0.032_{\text{ext}}$
Total Background	$0.152^{+0.092}_{-0.033}\big\vert_{\text{stat}} \pm 0.013_{\text{syst}}$
$K^+ \to \pi^+\pi^0(\gamma)$	$0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}}$
$K^+ \to \mu^+\nu(\gamma)$	$0.020 \pm 0.003_{\text{stat}} \pm 0.006_{\text{syst}}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{\text{stat}} \pm 0.002_{\text{syst}}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.013^{+0.017}_{-0.012}\big\vert_{\text{stat}} \pm 0.009_{\text{syst}}$
$K^+ \to \pi^0\ell^+\nu$ $(\ell = \mu, e)$	< 0.001
$K^+ \to \pi^+\gamma\gamma$	< 0.002
Upstream background	$0.050^{+0.090}_{-0.030}\big\vert_{\text{stat}}$

- **Upstream background (accidental and interactions)**
  - Data driven
  - Geometrical and Kaon-pion matching cuts effective
  - Addition of a copper block in the beam line in 2017
  - Installation of a new final collimator in 2018

$K^+ \to \pi^+ \nu\bar{\nu}$ Results



RICH Hits of π^+ candidate



One event observed in R2

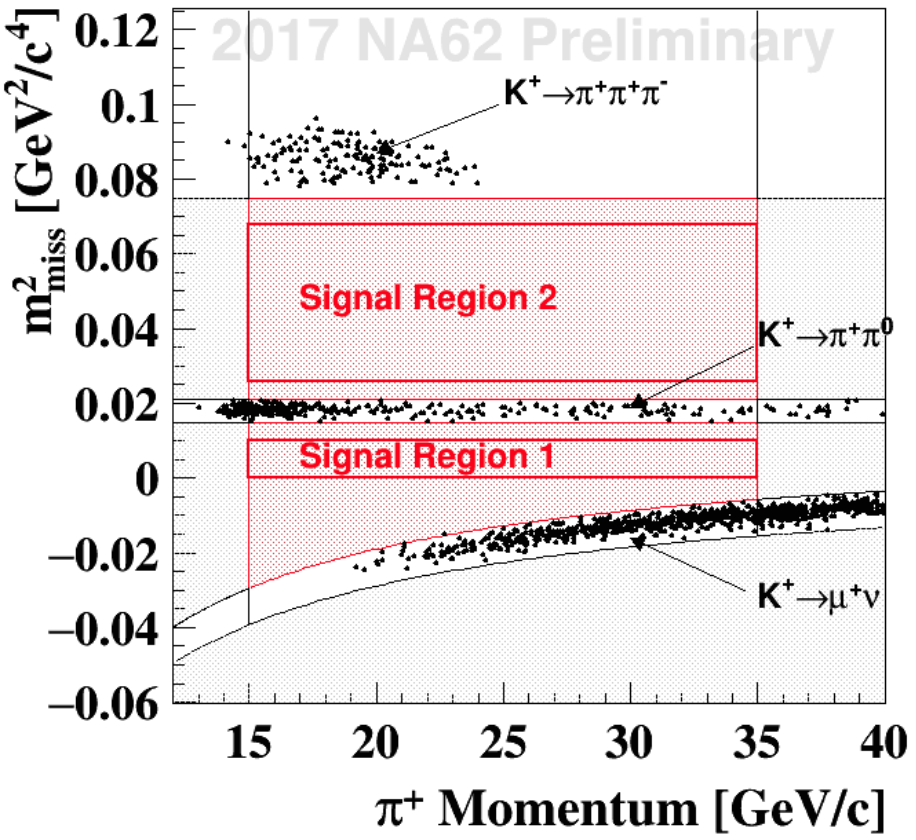
$BR(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL

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

$K^+ \to \pi^+ \nu\bar{\nu}$ 2017 analysis status

$K^+ \to \pi^+ \nu\bar{\nu}$ 2017 update

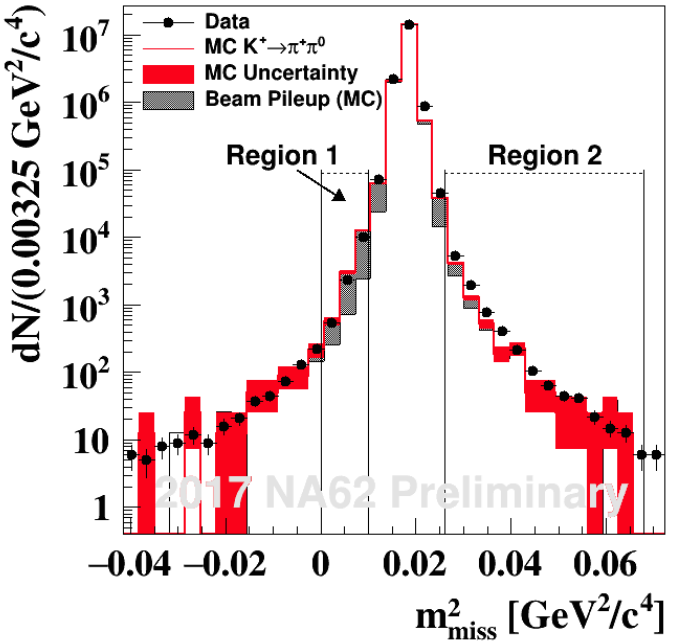
- **Higher beam intensity**
- **2016-like selection**
  - Comparable performances
  - Better pileup treatment in IRC/SAC
  - Improved LKr reconstruction
  - 40% better π^0 rejection (does not depend on intensity)
  - Slightly improved usage of RICH variables
    No effect from intensity on π efficiency and μ rejection.



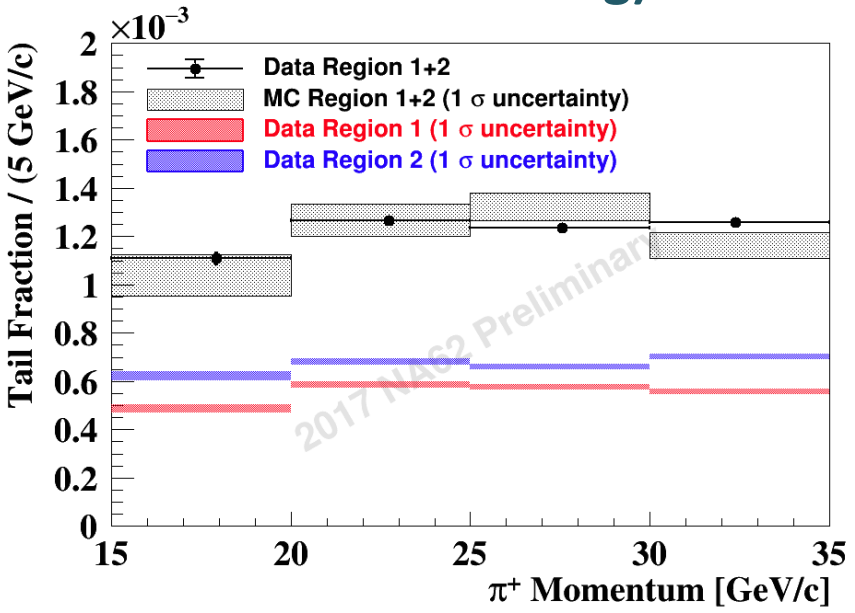
- **Expectations**
  - $N_K = 1.3(1) \times 10^{12}$ ($\sim 10 \times 2016$) from $\pi^+\pi^0$
  - $SES = (0.34 \pm 0.04) \times 10^{-10}$ (scales linearly with intensity)
  - Expected SM $K^+ \to \pi^+\nu\bar{\nu}$ events: 2.5 ± 0.4

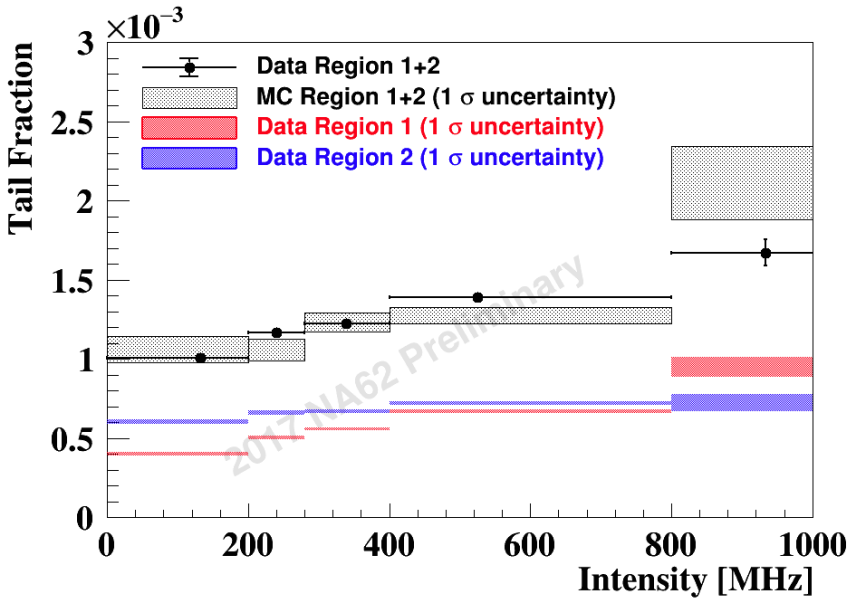
Background $K^+ \to \pi^+\pi^0(\gamma)$

- Selected with π^0 tagging with 2 γ in LKr
- Data-MC agreement over 5 orders of magnitude
- Tail fraction: fraction of events entering Region 1 or Region 2
- Radiative photon has $\times 30$ reduction



- Slight dependence on intensity (due to $K^+ - \pi^+$ matching)

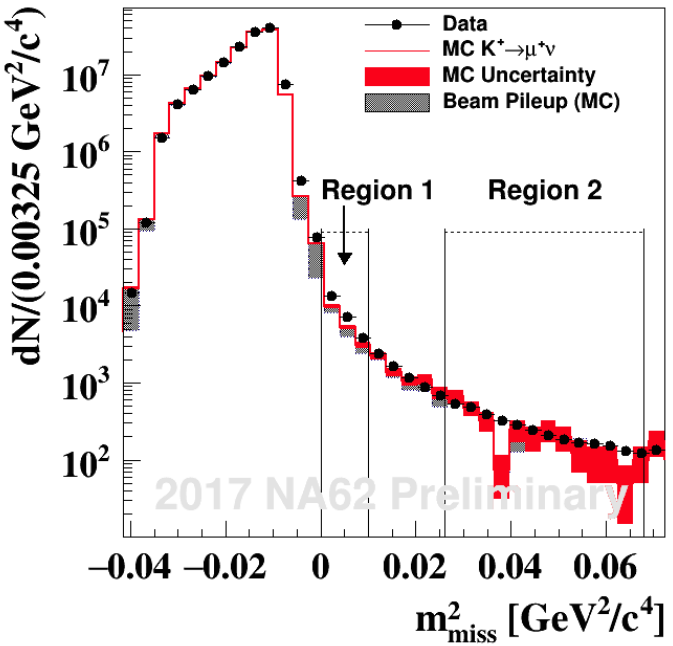




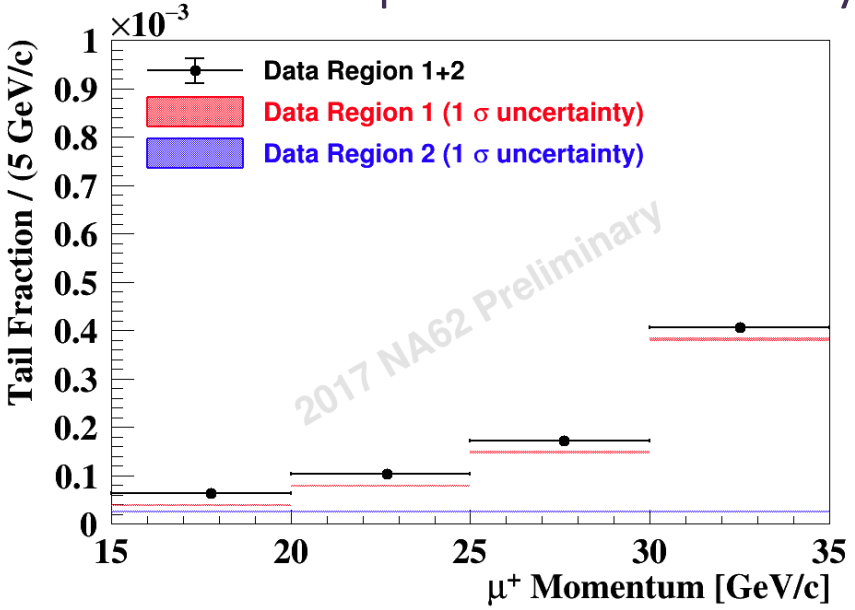
HI

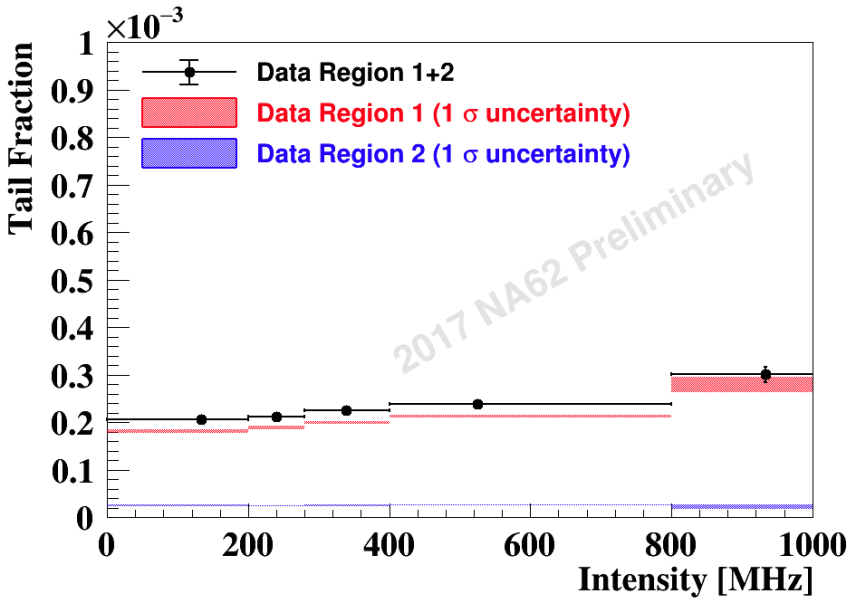
Background $K^+ \to \mu^+\nu(\gamma)$

- Selected tagging μ^+ in MUV3
- Good Data-MC agreement
- Tail fraction: fraction of events entering Region 1 or Region 2
- Rejection at 10^{-5} in Region 2 (including radiative tail)

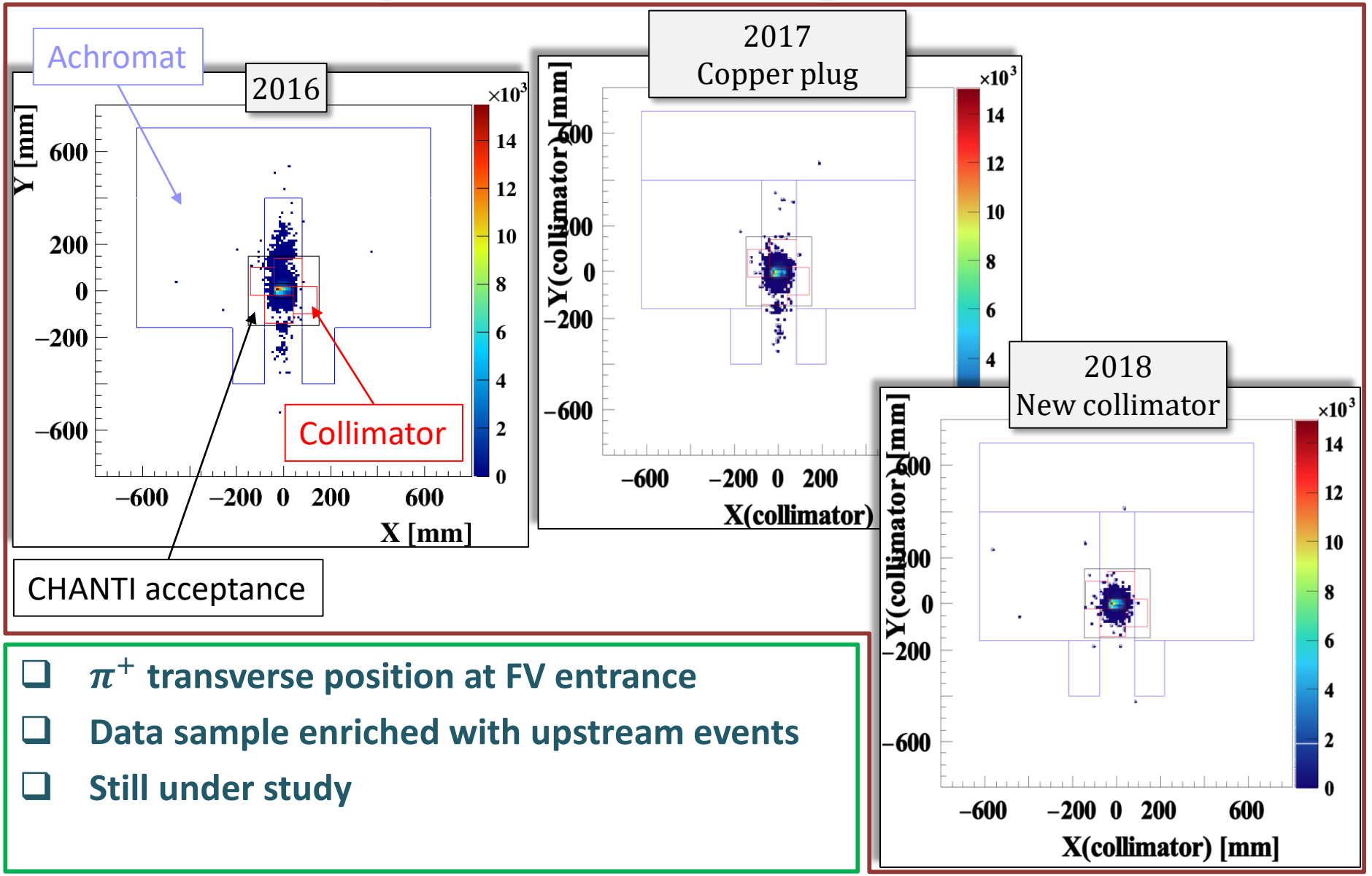


- Dominated by kinematics
  - Little dependence on intensity





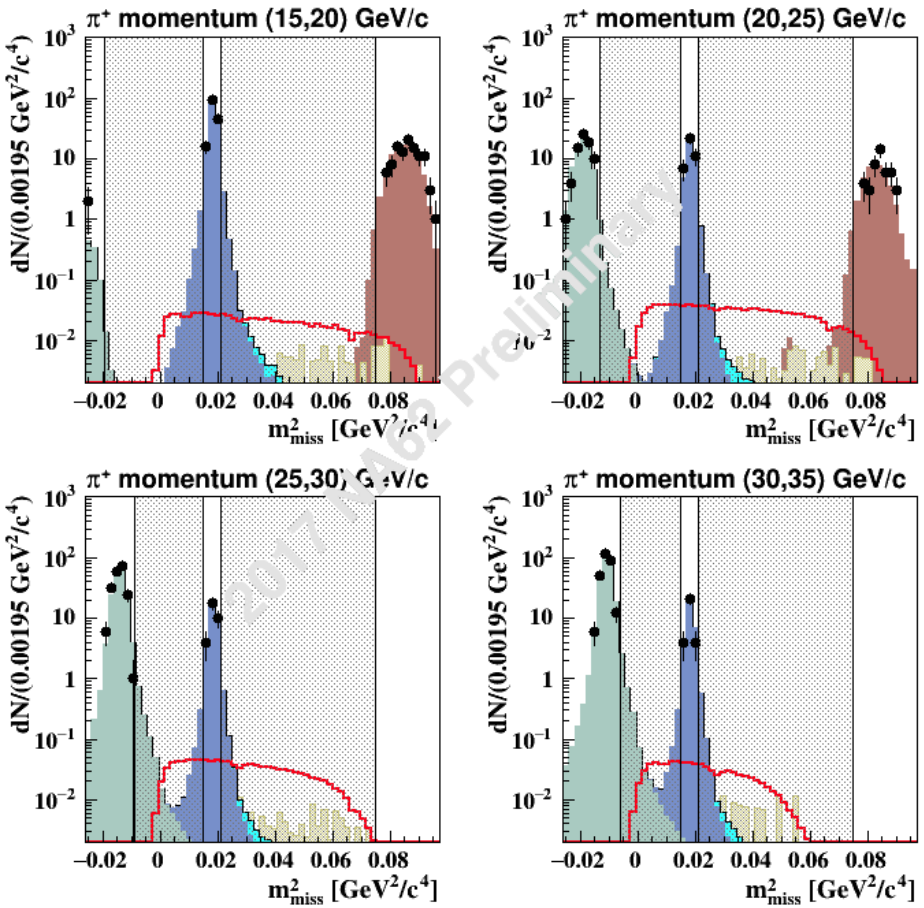
Upstream background



- π^+ transverse position at FV entrance
- Data sample enriched with upstream events
- Still under study

$K^+ \to \pi^+ \nu\bar{\nu}$ 2017 update

❑ Preliminary background estimates



Process	Expected events
$K^+ \to \pi^+\pi^0(\gamma)$	$0.35 \pm 0.02_{\text{stat}} \pm 0.03_{\text{syst}}$
$K^+ \to \mu^+\nu(\gamma)$	$0.16 \pm 0.01_{\text{stat}} \pm 0.05_{\text{syst}}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.22 \pm 0.08_{\text{stat}}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.015 \pm 0.008_{\text{stat}} \pm 0.015_{\text{syst}}$
$K^+ \to \pi^0 \ell^+ \nu$ $(\ell = \mu, e)$	$0.012 \pm 0.012_{\text{syst}}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{\text{syst}}$
Upstream Bckg.	Ongoing

❑ Detailed comparison of data and background models

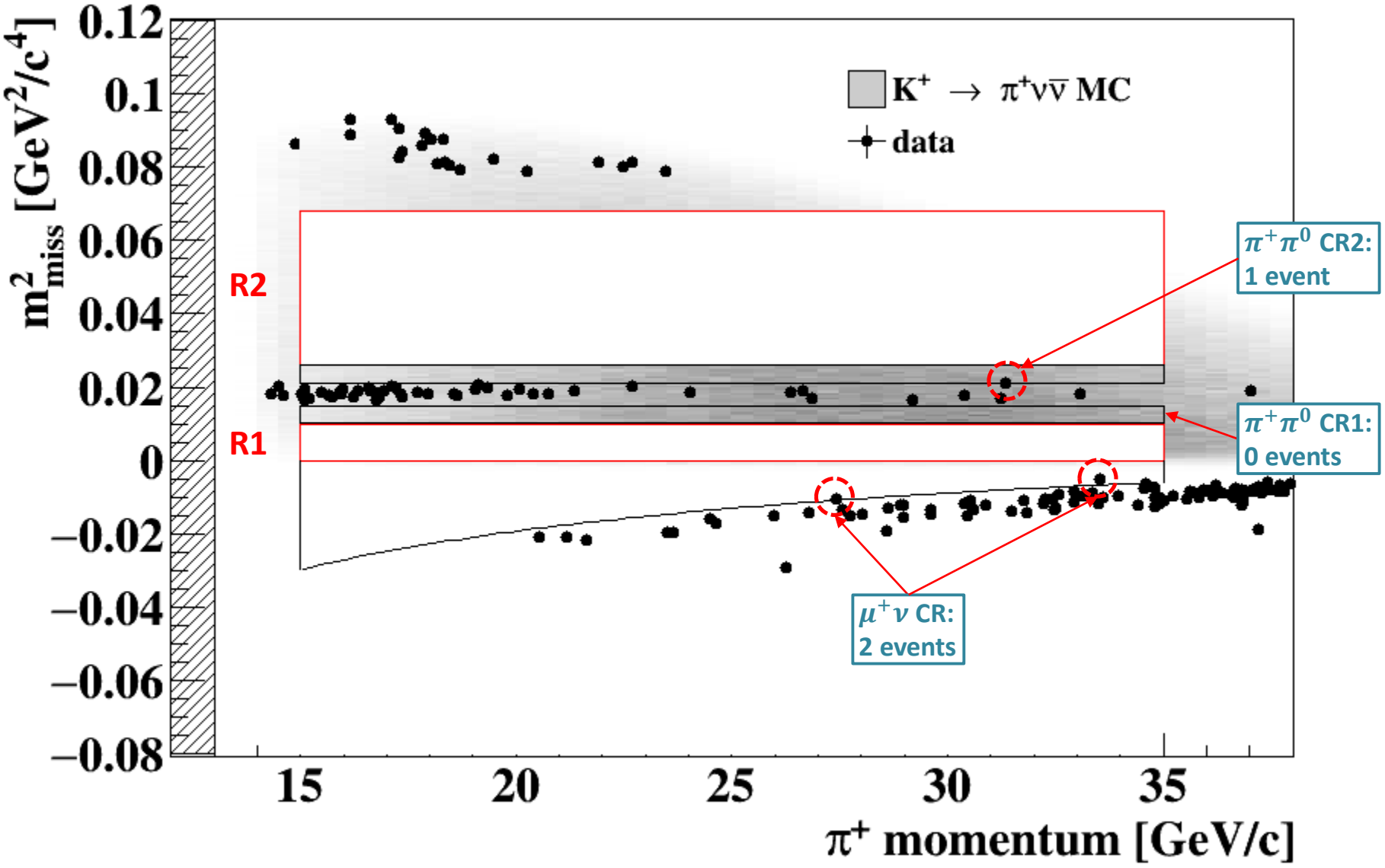
- Shape depends on P_{π^+} and signal region
- Background distributions normalised separately to background regions. Signal normalised to expected SM events .
- Remarkable agreement

Conclusions

- **One event observed in Region 2 in 2016**
- **The result is compatible with the Standard Model**
  - $BR(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL
  - **Published in** [Phys. Lett. B 791 (2019) 156-166]
- **Decay-in-flight technique is working!**

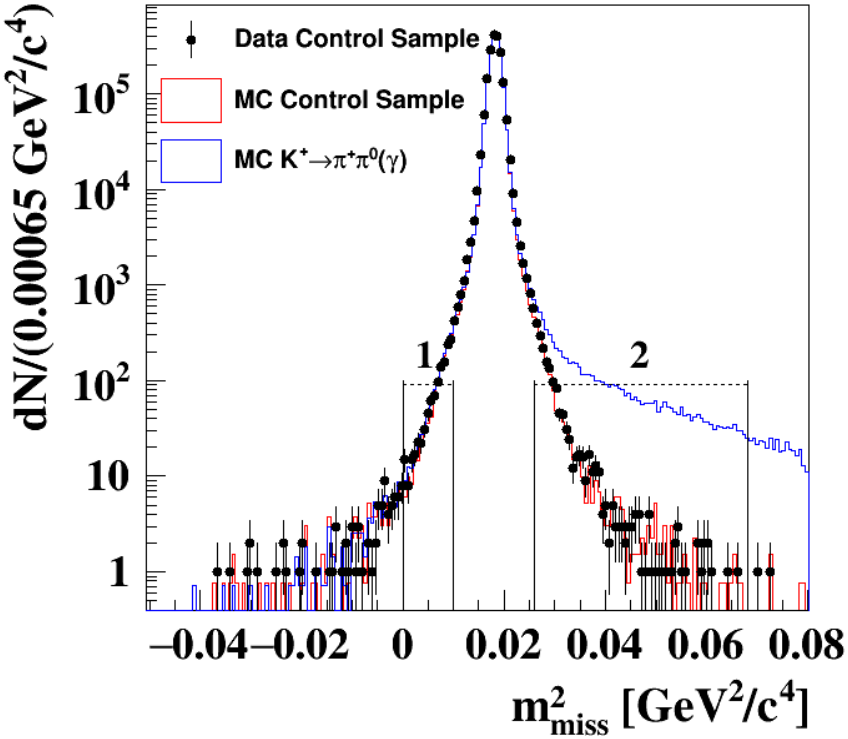
- **Analysis of 2017 data is ongoing.**
  - Analysis largely similar to 2016
  - Expect about a factor 10 of improvement (from statistics)
  - Signal-over-background ratio does not degrade with intensity
  - Detailed background study

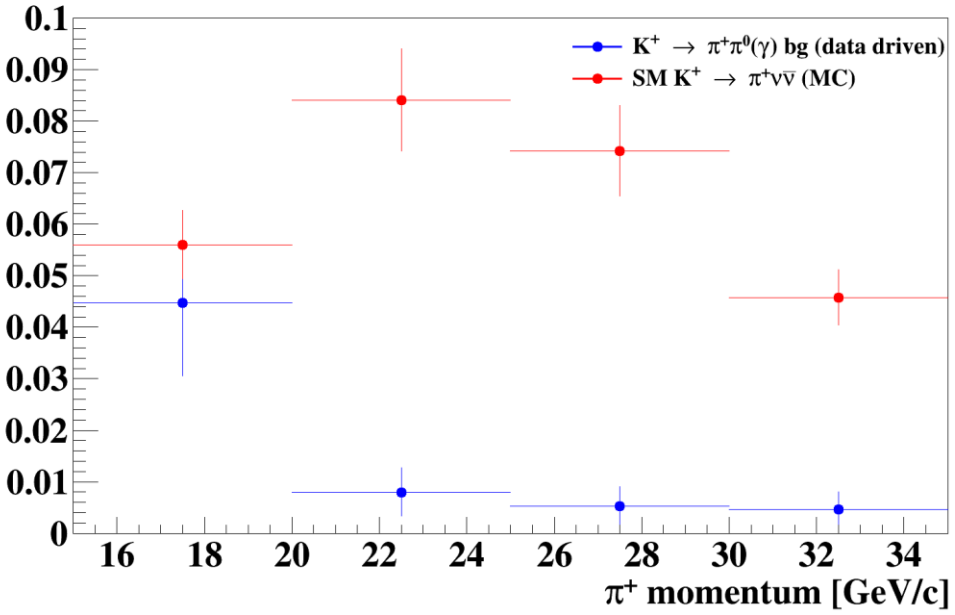
$K^+ \to \pi^+ \nu\bar{\nu}$ Background validation



Background $K^+ \to \pi^+\pi^0(\gamma)$

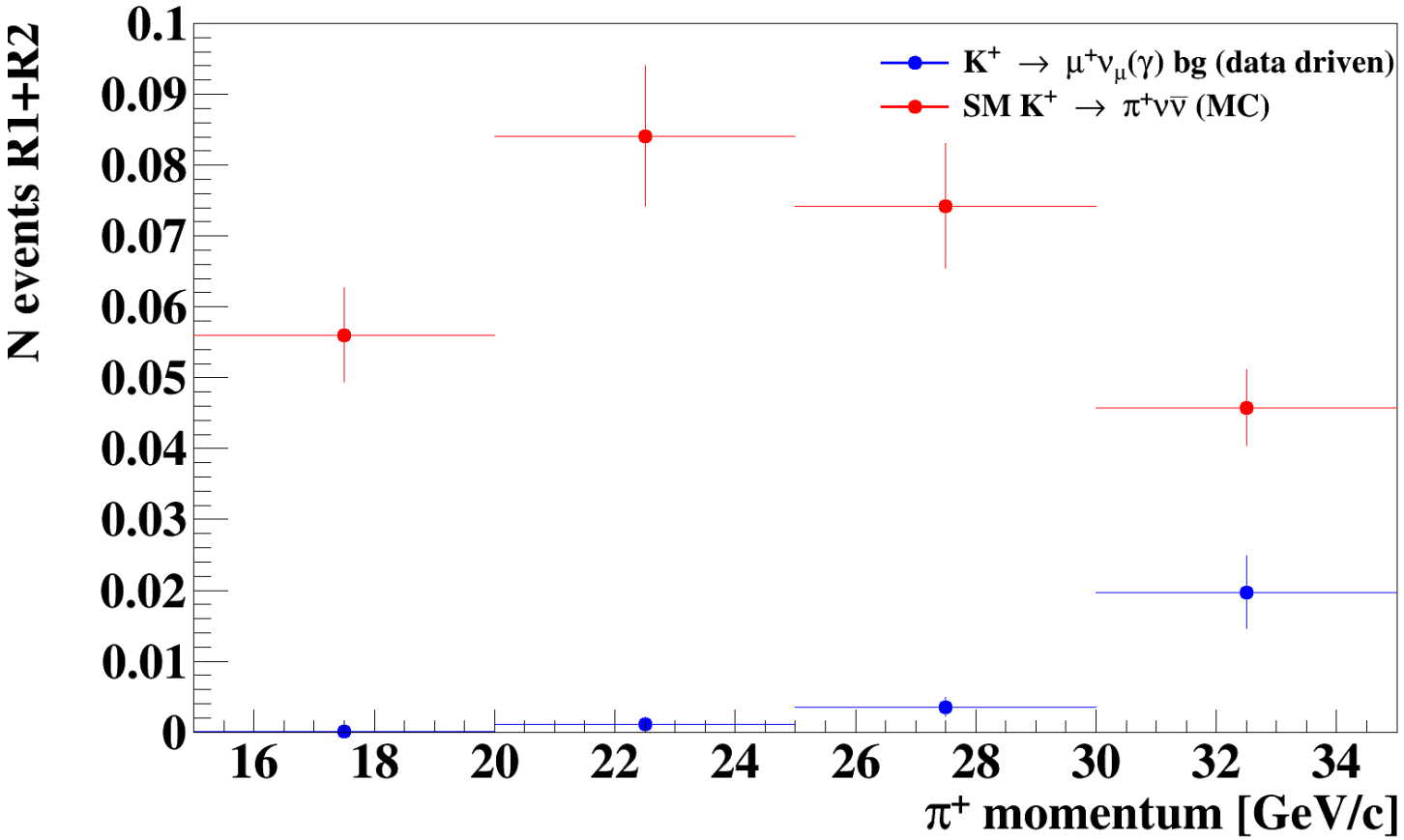
- **Data driven background estimation**
  - $N_{\pi\pi}^{CR1,2} = 1.46 \pm 0.16_{\text{stat}} \pm 0.06_{\text{syst}}$
  - $N_{\pi\pi}^{R1,2} = 0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}}$





Background $K^+ \to \mu^+\nu(\gamma)$

- **Data driven background estimation**
  - $N_{\mu\nu}^{R1,2} = 0.020 \pm 0.003_{\text{stat}} \pm 0.006_{\text{syst}}$



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

MC estimation

- 6×10^8 simulated decays, good agreement across 5 validation $K^+ \to \pi^+\pi^-e^+\nu$ enriched samples (invert multiplicity criteria)
- $N_{\pi\pi e\nu}^{R1,2} = 0.013^{+0.017}_{-0.012}|_{\text{stat}} \pm 0.009_{\text{syst}}$