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

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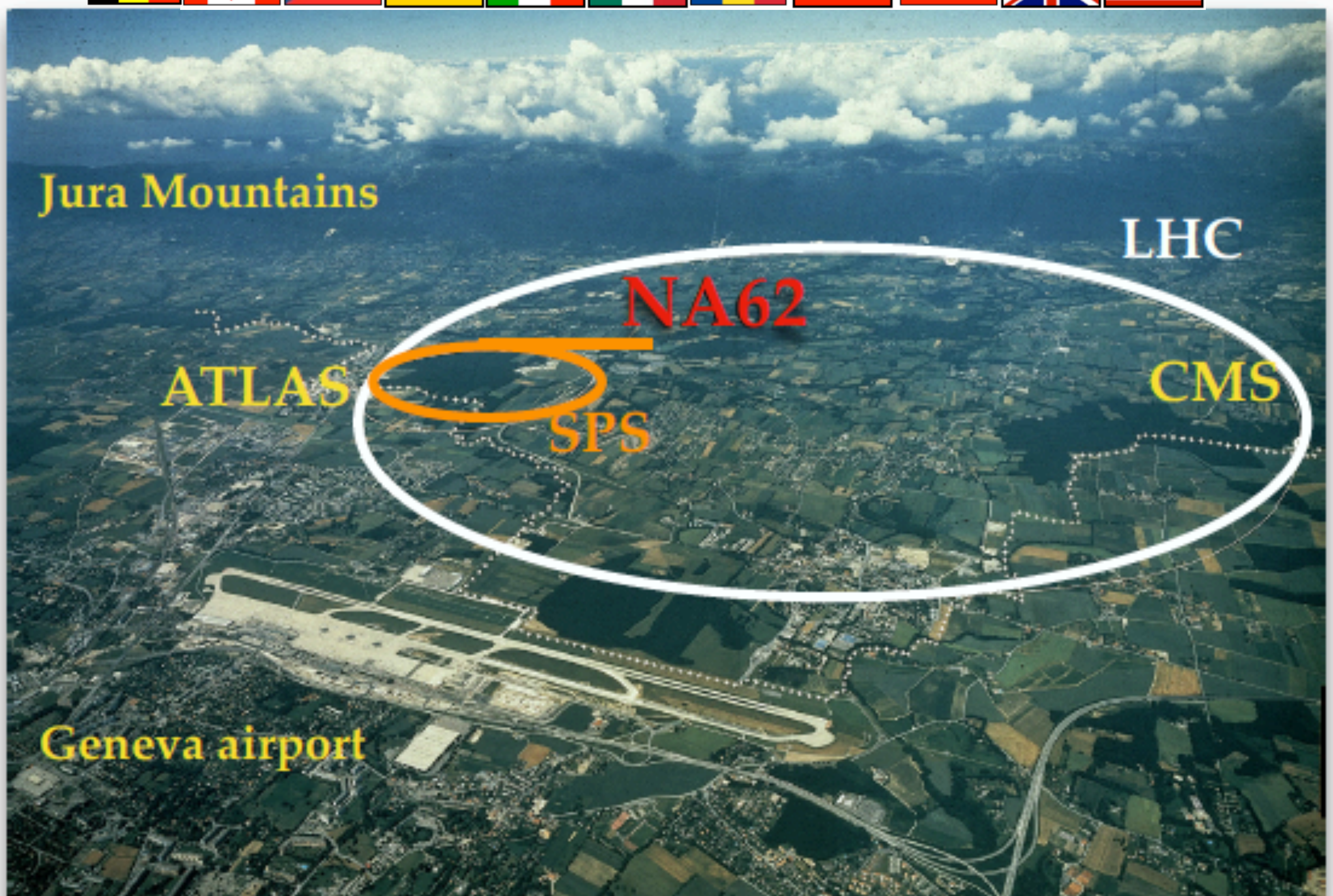
Pittsburg, 4-6 May 2020

NA62 Collaboration

~ 200 participants

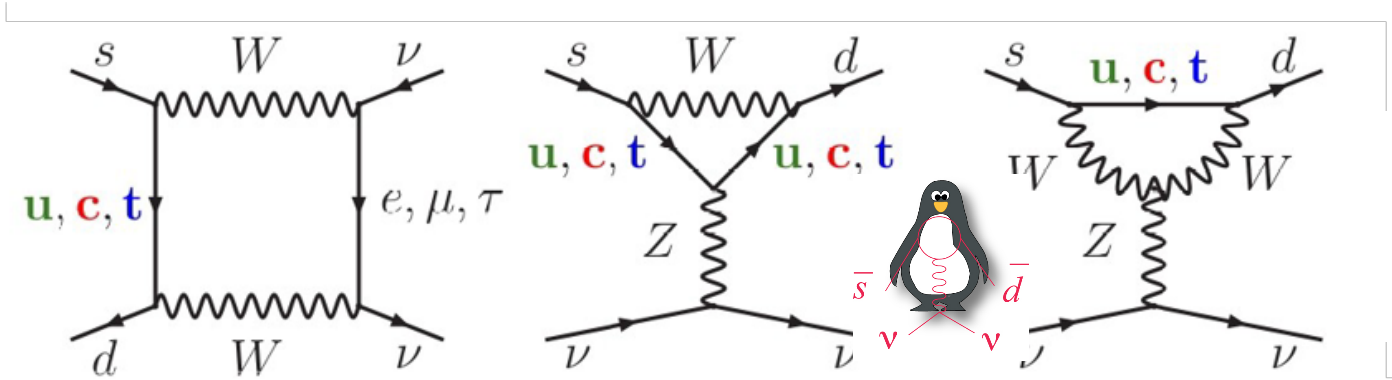
Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax (GMU), Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP) , Rome I, Rome II, San Luis Potosi, TRIUMF, Turin, Vancouver (UBC)



The main aim is the measurement of **BR(K->πνν)**

The physics program is much broader.
Follow the talks by
S. Ghinescu and P.Massarotti

K->πνν in the SM

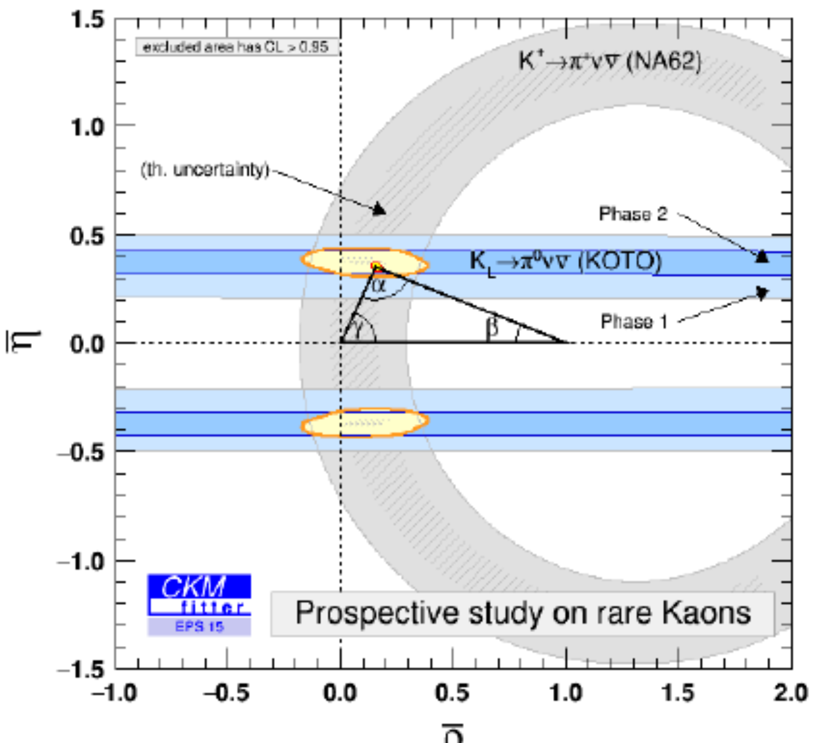


$$A(s \to d\nu\bar{\nu}) \sim$$

$$\sim \frac{m_t^2}{M_W^2}\lambda_t + \frac{m_c^2}{M_W^2}\ln\frac{M_W}{m_c}\lambda_c + \frac{\Lambda_{QCD}^2}{M_W^2}\lambda_u$$

t(68%) *c(29%)* *u(3%)*

Short distance *Long distance*

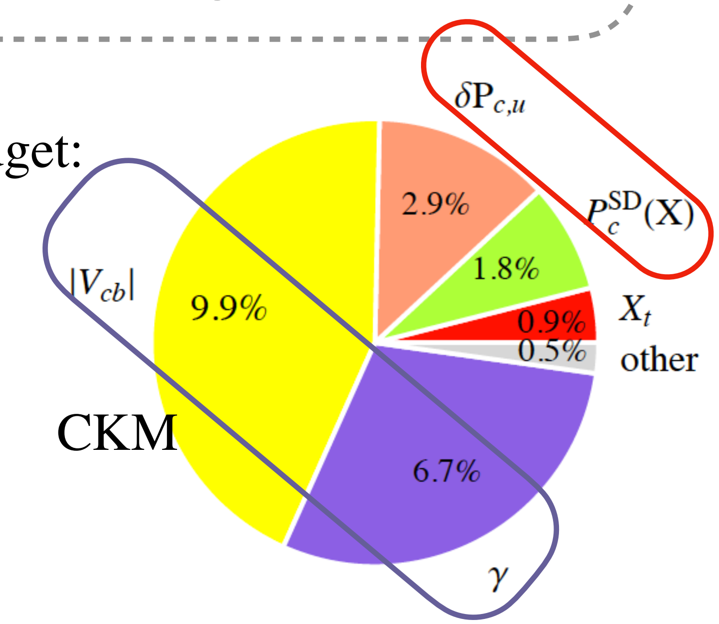


Measuring both $K^+ \to \pi^+ \nu\nu$ and KL $\to \pi^0 \nu\nu$ provides the CKM unitarity triangle independently from measurements in B mesons sector.

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

Buras et al., JHEP11(2015)033

Error budget:



Experimental result before NA62:

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$$

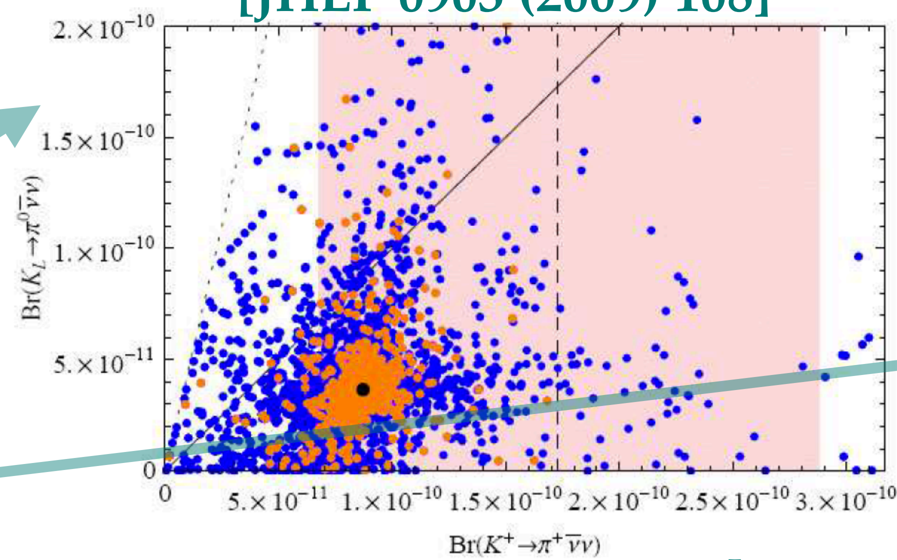
E949, Phys. Rev. D 77, 052003 (2008)
Phys. Rev D 79, 092004 (2009)]

K->πνν for new physics

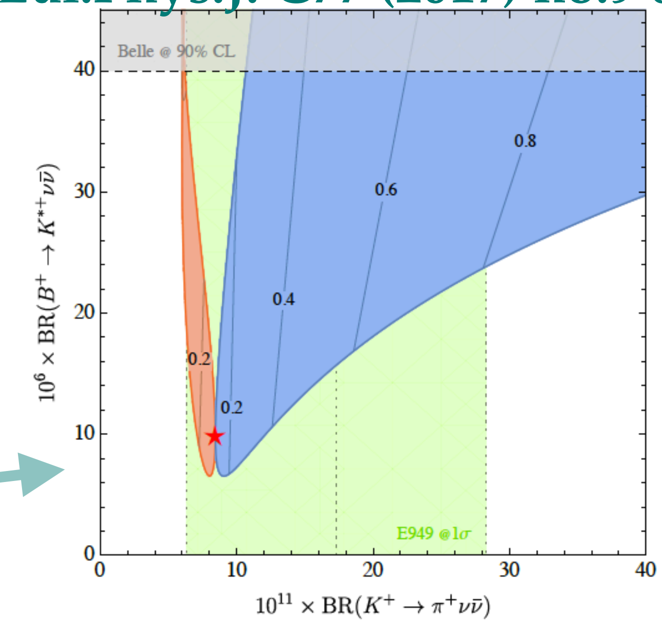
Search for New Physics at the EW scale with sizable coupling to SM particles via indirect effects in loops

- Custodial Randall-Sundrum
  [JHEP 0903 (2009) 108]
- LFU violation models
  [Eur.Phys.J. C77 (2017) no.9 618]
- MSSM scenarios:
  [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]

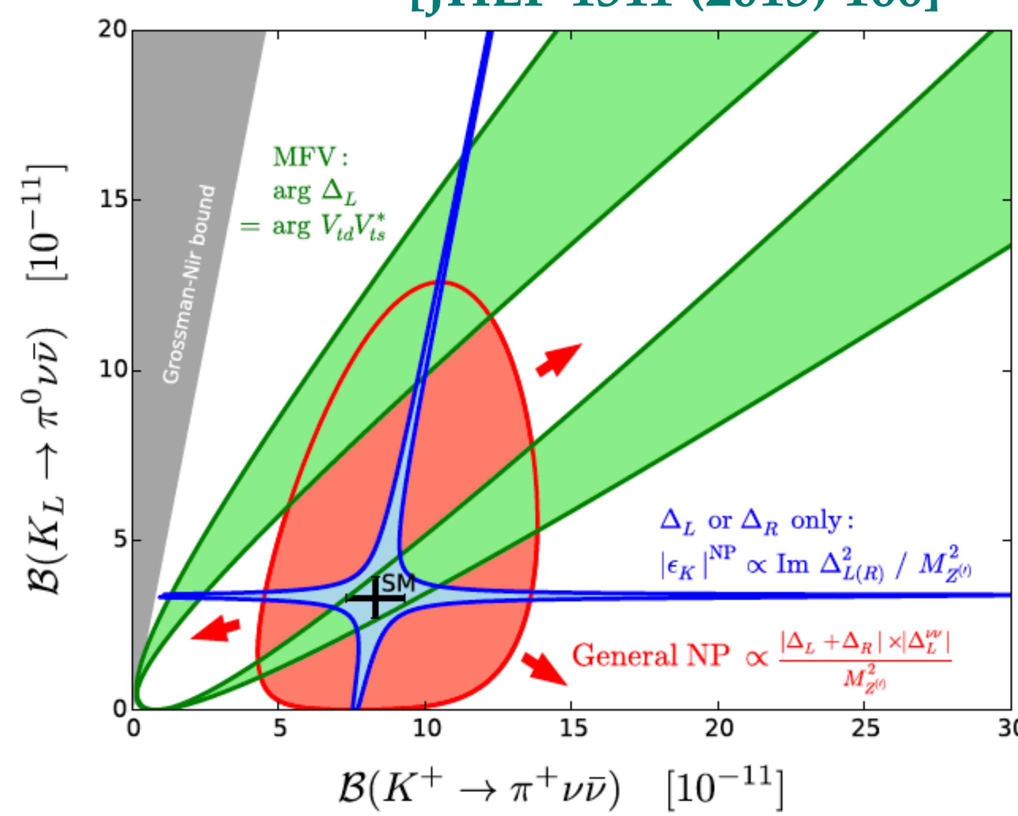
[JHEP 0903 (2009) 108]



[Eur.Phys.J. C77 (2017) no.9 618]

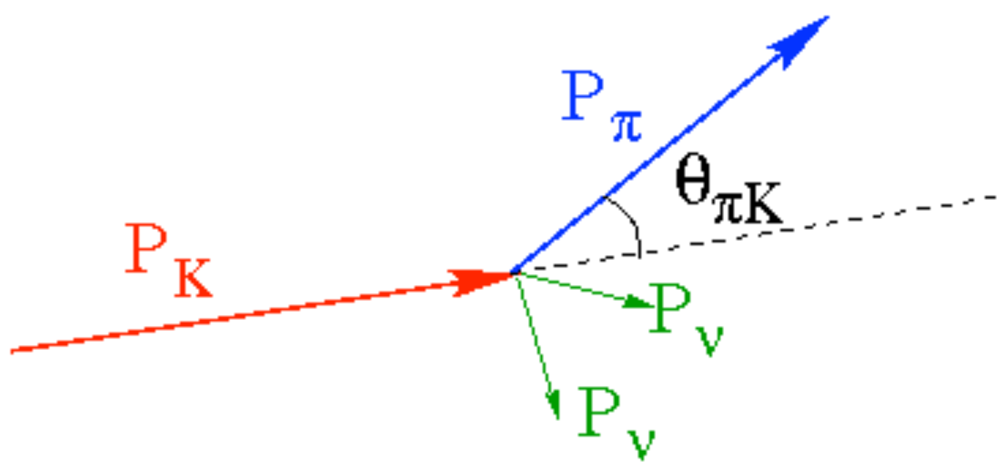


[JHEP 1511 (2015) 166]

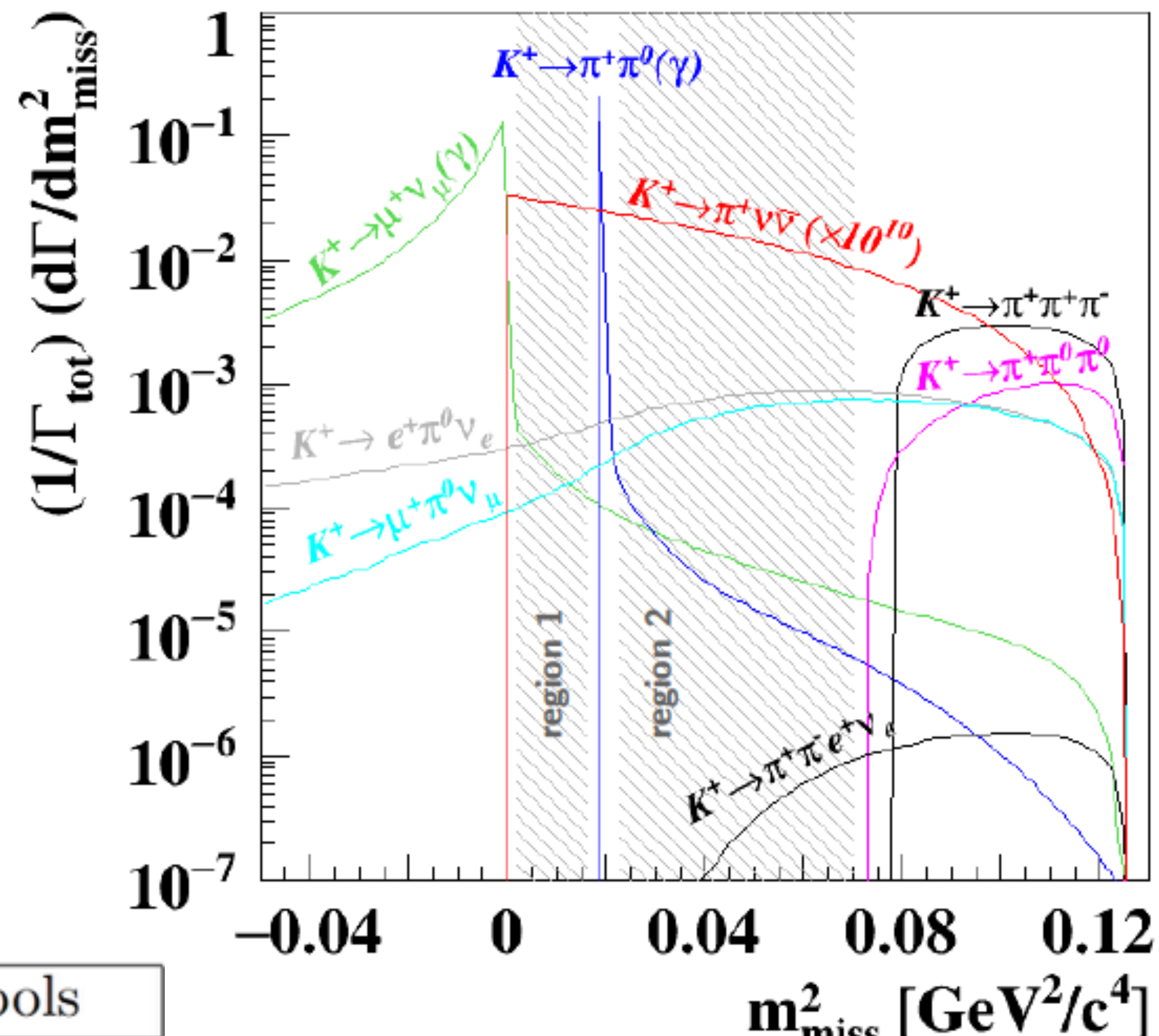


Measurement strategy

Decay in flight technique:



$$m^2_{miss} = (p_K - p_\pi)^2$$



Decay	BR	Main Rejection Tools
$K^+ \to \mu^+\nu_\mu(\gamma)$	63%	μ-ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi-track + kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+\nu_e$	5%	e-ID + γ-veto
$K^+ \to \pi^0\mu^+\nu_\mu$	3%	μ-ID + γ-veto

- very good kinematic reconstruction
- time measurements
- K,π,μ identification
- Hermetic detection of muons
- Hermetic detection of photons

NA62 experiment

JINST 12 P05025 (2017), arxiv:1703.08501

About 20% of K^+ decay inside the fiducial volume

2 years running at high intensity we collected:

- $O(10^{13})$ K^+ decays in fiducial volume

K->πνν at NA62

Same analysis strategy:

☑ **2016 run:**
published result

Phys. Lett. B 791 (2019) 156-166, arXiv.1811.08508

☑ **2017 run:**
result presented
Paper in preparation

☐ **2018 run:**
Analysis ongoing
Preliminary studies in SPSC NA62 status report:
CERN-SPSC-2020-007 ; SPSC-SR-266
https://cds.cern.ch/record/2713499

NA62 apparatus

JINST 12 P05025 (2017), arxiv:1703.08501

LAV: photon veto at large angles lead-glass blocks

STRAW: Downstream tracking

RICH: Ring imaging Cherenkov kinematics and particle ID

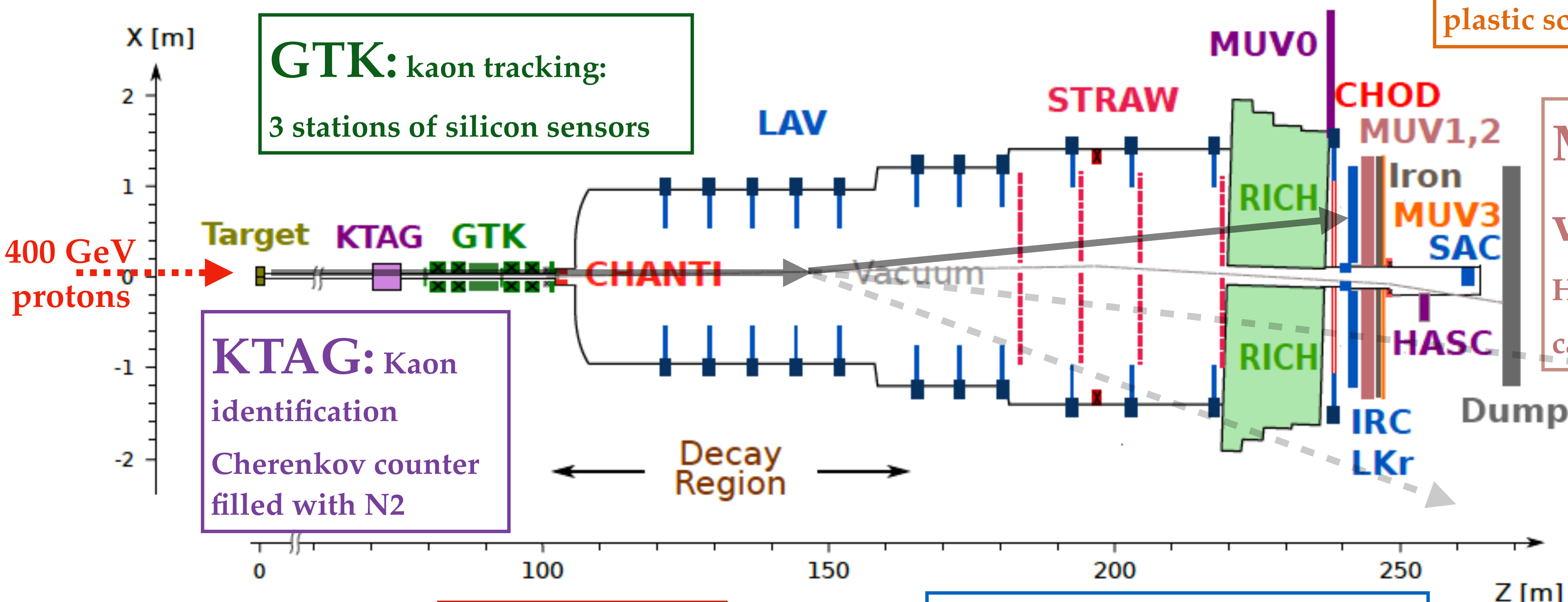
IRC, SAC: lead and scintillator plates Shashlyk configuration

MUV0, MUV3 plastic scintillators

GTK: kaon tracking: 3 stations of silicon sensors

KTAG: Kaon identification Cherenkov counter filled with N2

Muon veto Hadronic calorimeters

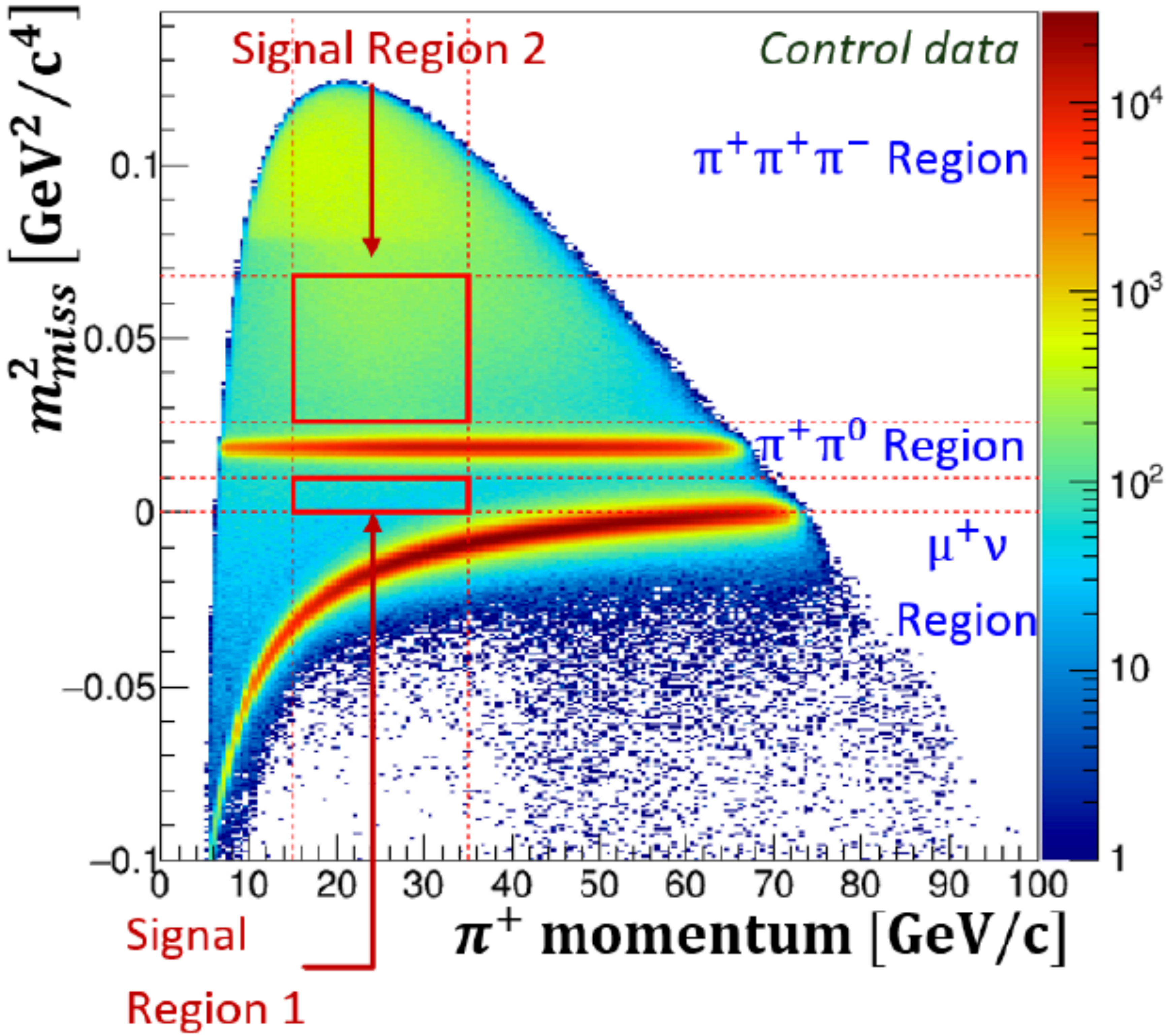


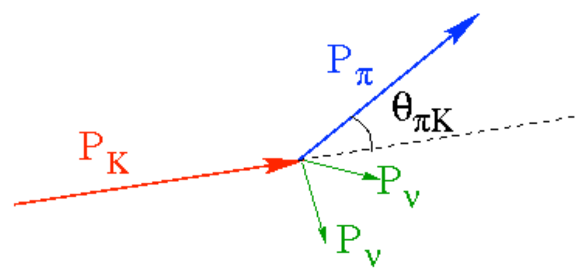
CHOD charged hodoscope

LKr: quasi-homogenous ionization chamber 27X0 deep

Analysis principle

Paper in preparation





- Control data collected with a different trigger
- Data-driven background estimation
- Control regions to validate it
- Normalization to $K \to \pi^+\pi^0$ decay

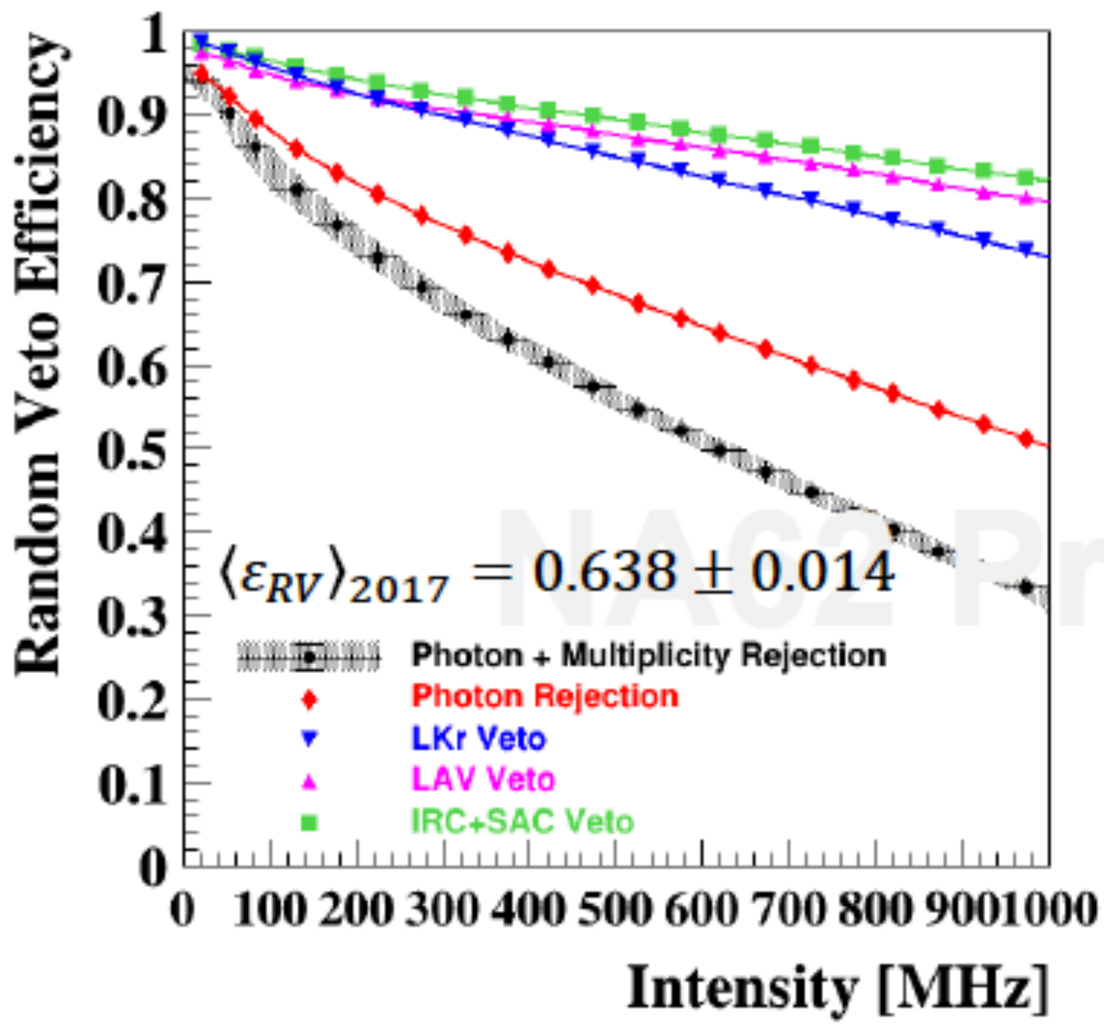
Normalization

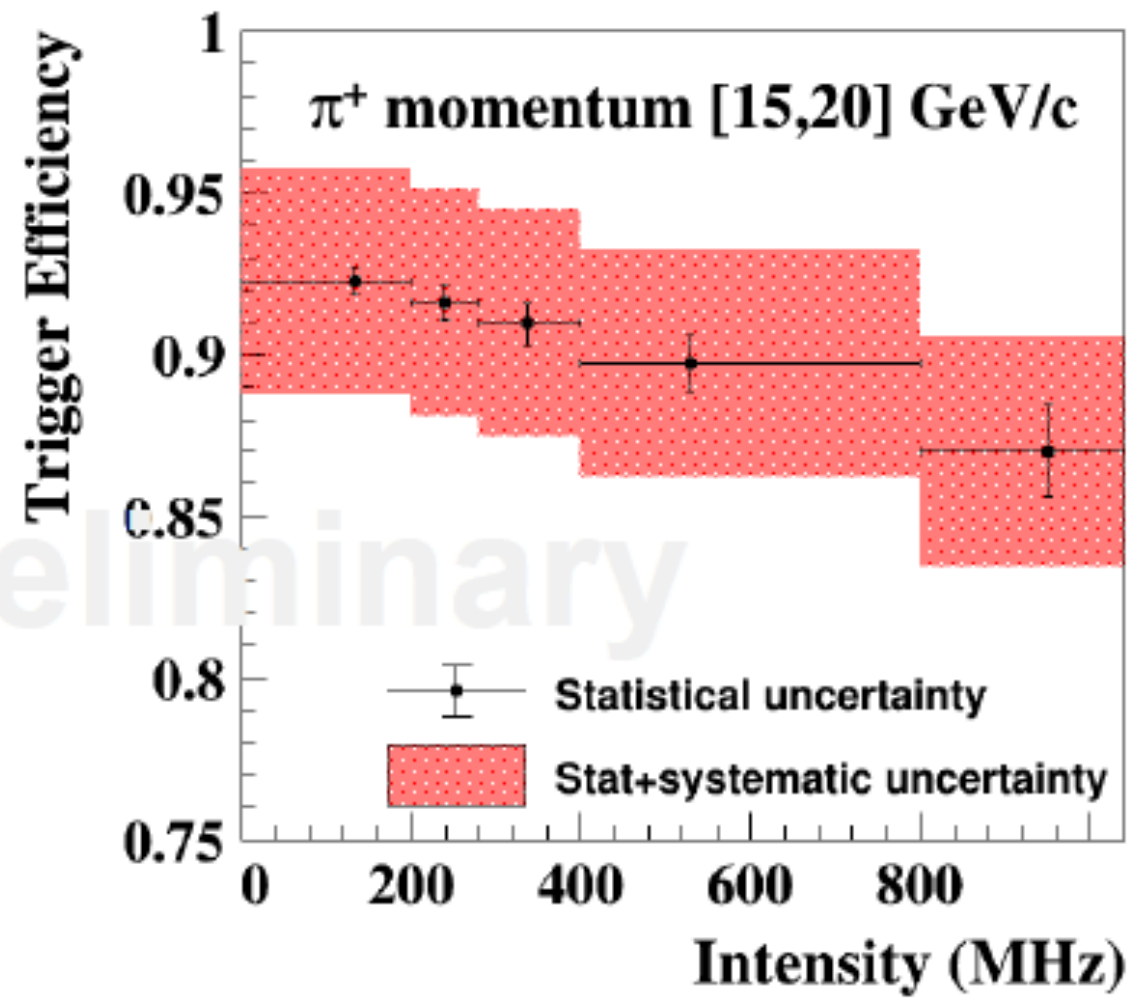
Paper in preparation

Efficiencies not in common with K->π⁺π⁰

$$N_{\pi\nu\nu} = N_{\pi\pi}\epsilon_{trig}\epsilon_{RV}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{BR(\pi\nu\nu)}{BR(\pi\pi)}$$

efficiency and normalization have been computed in bins of pion momentum and intensity





ε(RV), Random Veto efficiency:
signal efficiency due to accidental activity

$$N_{\pi\nu\nu} = 2.16 \pm 0.12 \pm 0.26_{ext}$$

Background from K^+ decays

Paper in preparation

$K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^0$

j: bin in momentum and intensity

$$N^{exp}_{\mu\nu}(region) = \sum_j \left[N(\mu\nu)_j \cdot f_j^{kin}(region)\right]$$

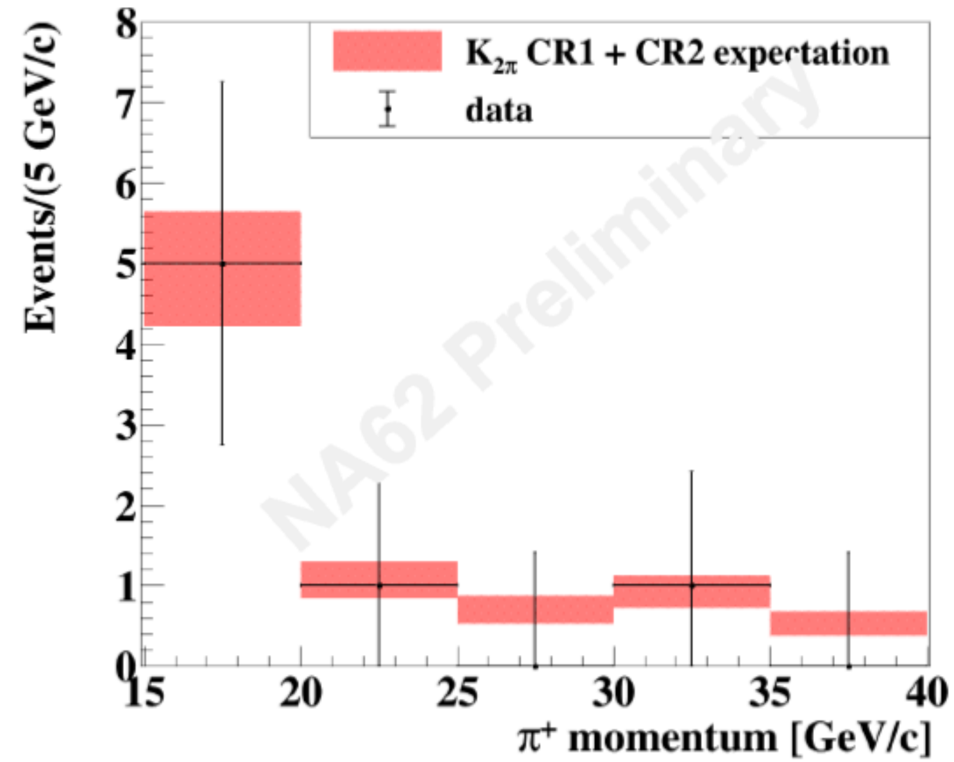
Nexp in the Signal (control) region

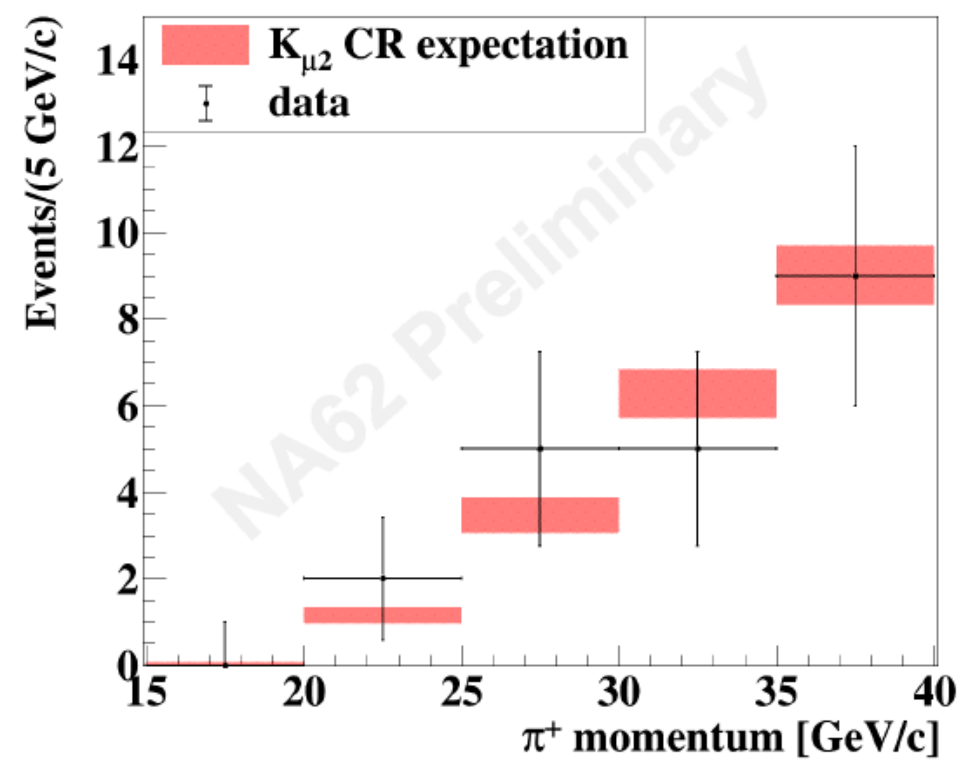
Sample selected on background region with πνν trigger data to get the shape

Fraction of events in the signal (control) region, measured in control data

$$N^{exp}_{\pi\pi}(region) = \sum_j \left[N(\pi^+\pi^0)_j \cdot f_j^{kin}(region)\right]$$

Validation in control regions

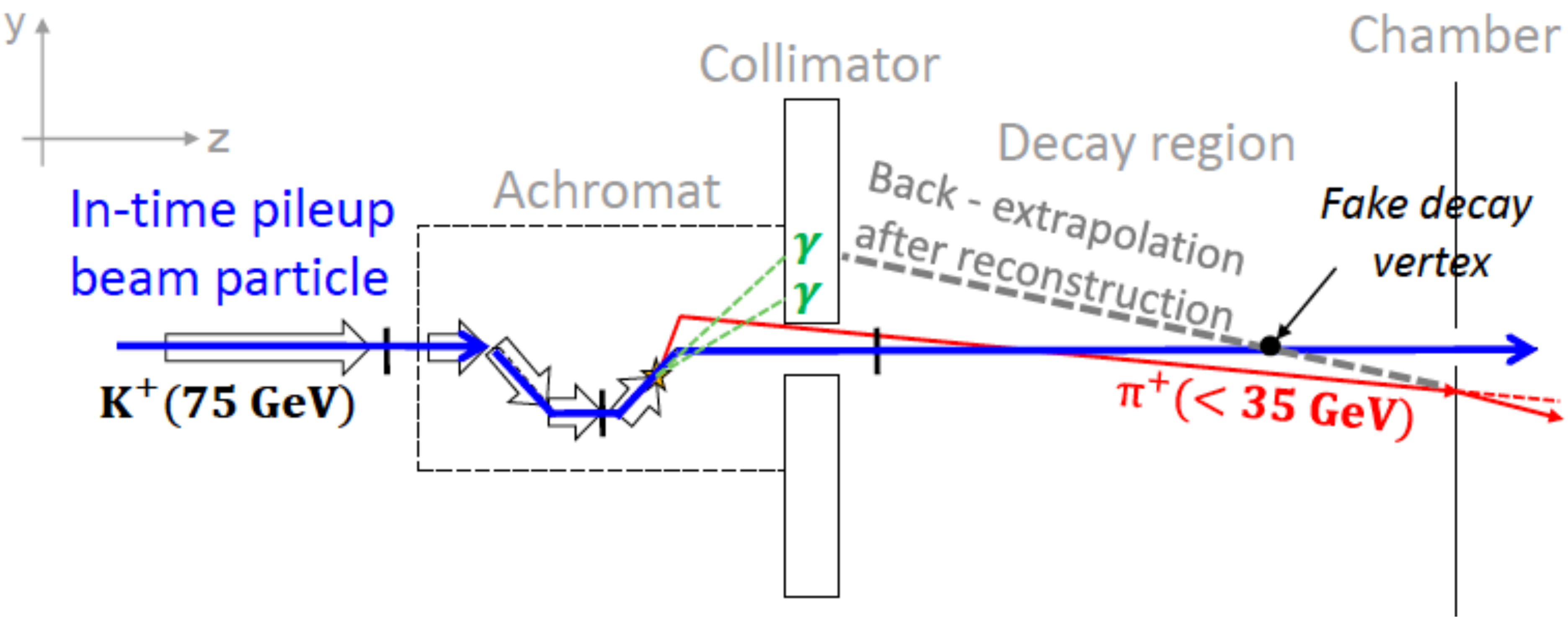




Upstream background

Paper in preparation

Not only Kaon decays in decay region:



- K^+ decays/interacts in the achromat
- Secondary π^+ downstream
- Beam elements block additional particles
- π^+ scattering in straw chamber 1

Count events on data with inverted $K-\pi$ matching

- Pileup beam particle tagged as K+

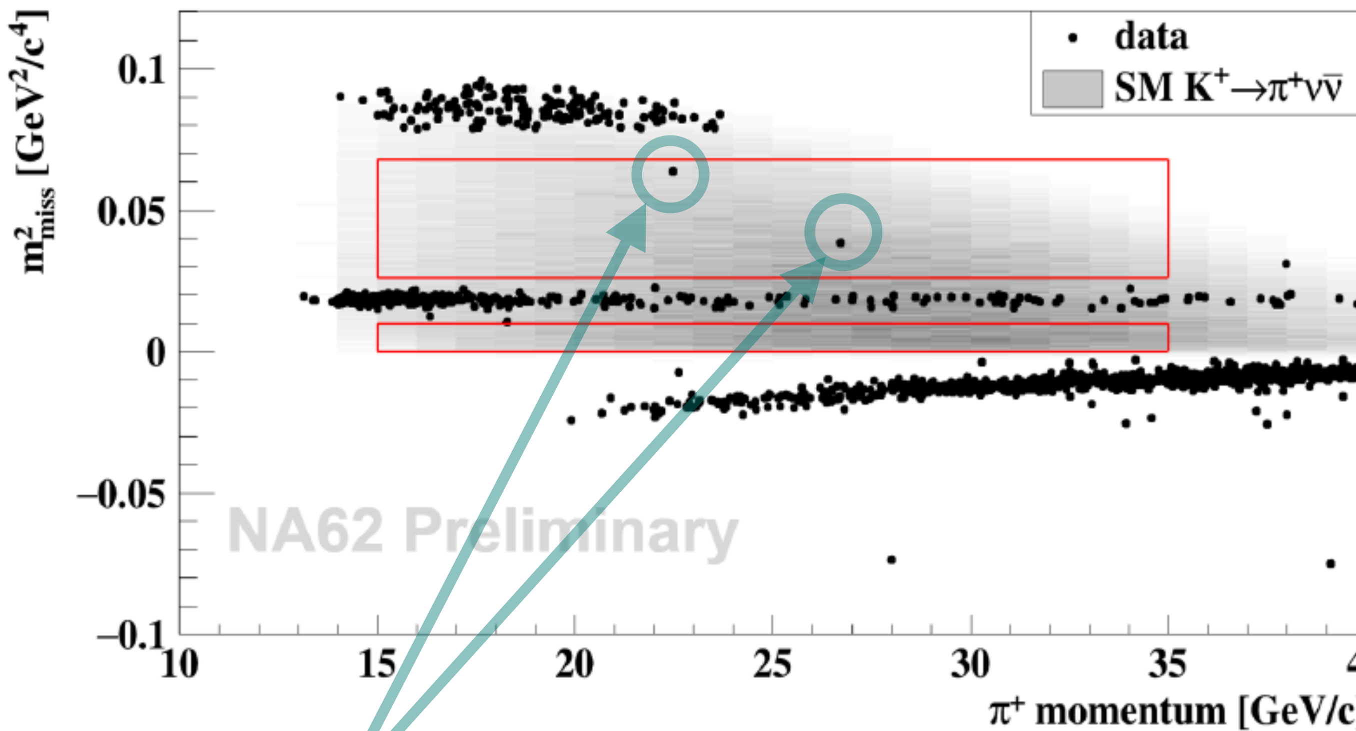
Estimate the probability to occur from data/simulation

Summary of expected Sig and Bkg

Paper in preparation

Process	Expected events
$K^+ \to \pi^+\nu\bar{\nu}$	$2.16 \pm 0.12_{syst} \pm 0.26_{ex}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.29 \pm 0.03_{stat} \pm 0.03_{sy}$
$K^+ \to \mu^+\nu_\mu(\gamma)$ IB	$0.11 \pm 0.02_{stat} \pm 0.03_{sy}$
$K^+ \to \mu^+\nu_\mu\ (\mu^+ \to e^+decay)$	$0.04 \pm 0.02_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$0.12 \pm 0.05_{stat} \pm 0.03_{sy}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.02 \pm 0.02_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l\ (l = e^+, \mu^+)$	negligible
Upstream background	$0.9 \pm 0.2_{stat} \pm 0.2_{syst}$
Total background	$1.5 \pm 0.2_{stat} \pm 0.2_{syst}$

$$N_{\pi\nu\nu} = 2.16 \pm 0.12 \pm 0.26_{ext}$$



2 events observed, both in Region 2

2017 dataset

Result from analysis of 2016 dataset:

Phys. Lett. B 791, 156 (2019)

$N^{exp}_{\pi\nu\nu}(\mathrm{SM}) = 0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$

Total background $0.152^{+0.092}_{-0.033}|_{stat} \pm 0.013_{syst}$

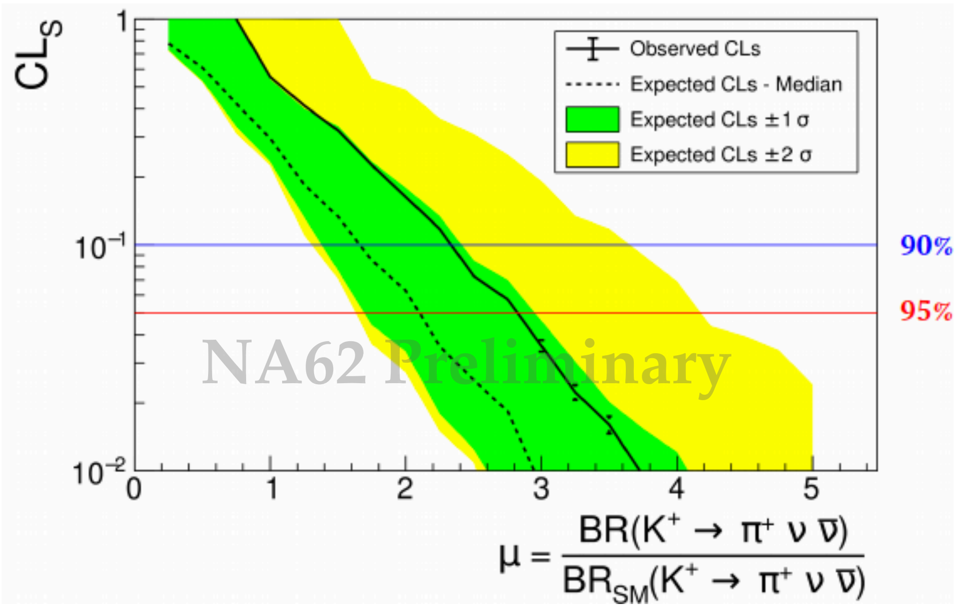
1 event observed

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

Results with 2016 and 2017 data

Paper in preparation

2016 and 2017:

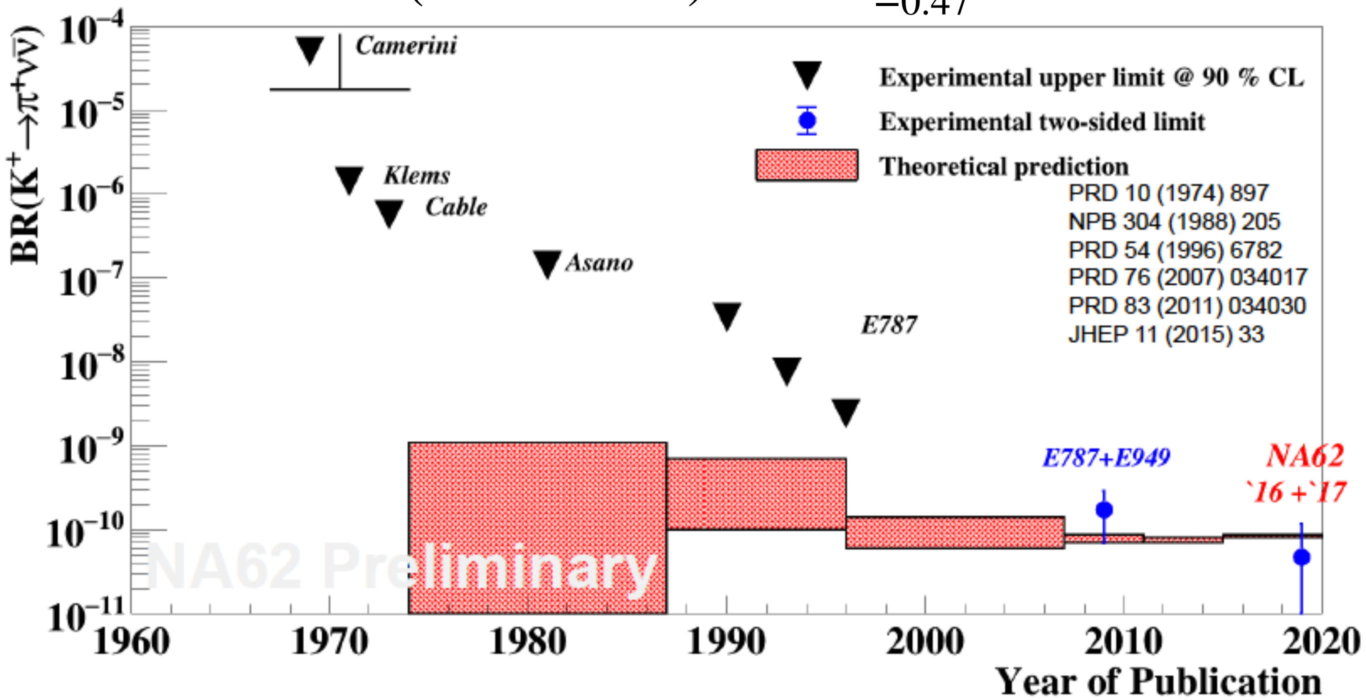


$$BR_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (0.84 \pm 0.10) \times 10^{-10}$$

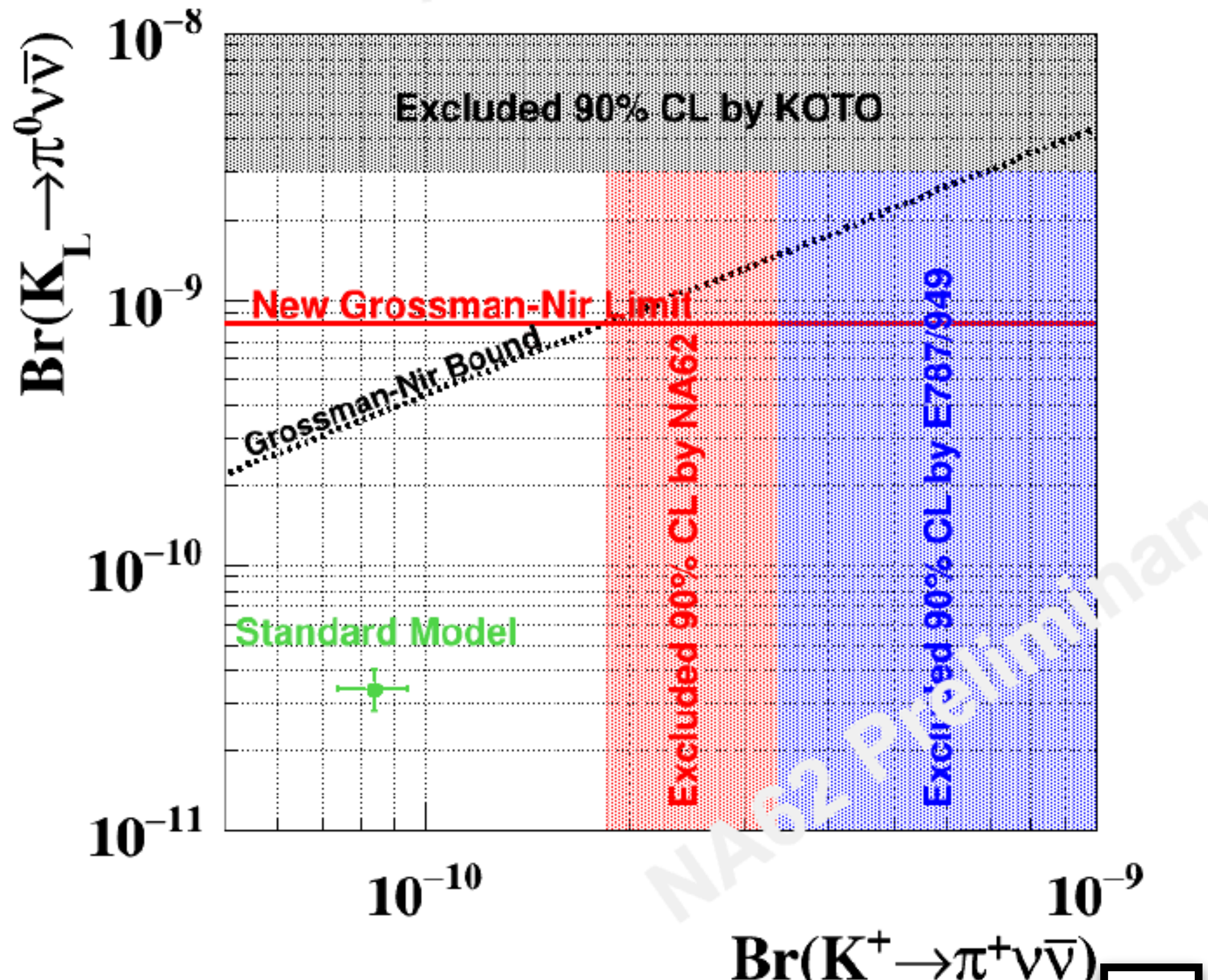
Observed UL at 90% CL:

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) < 1.85 \times 10^{-10}$$

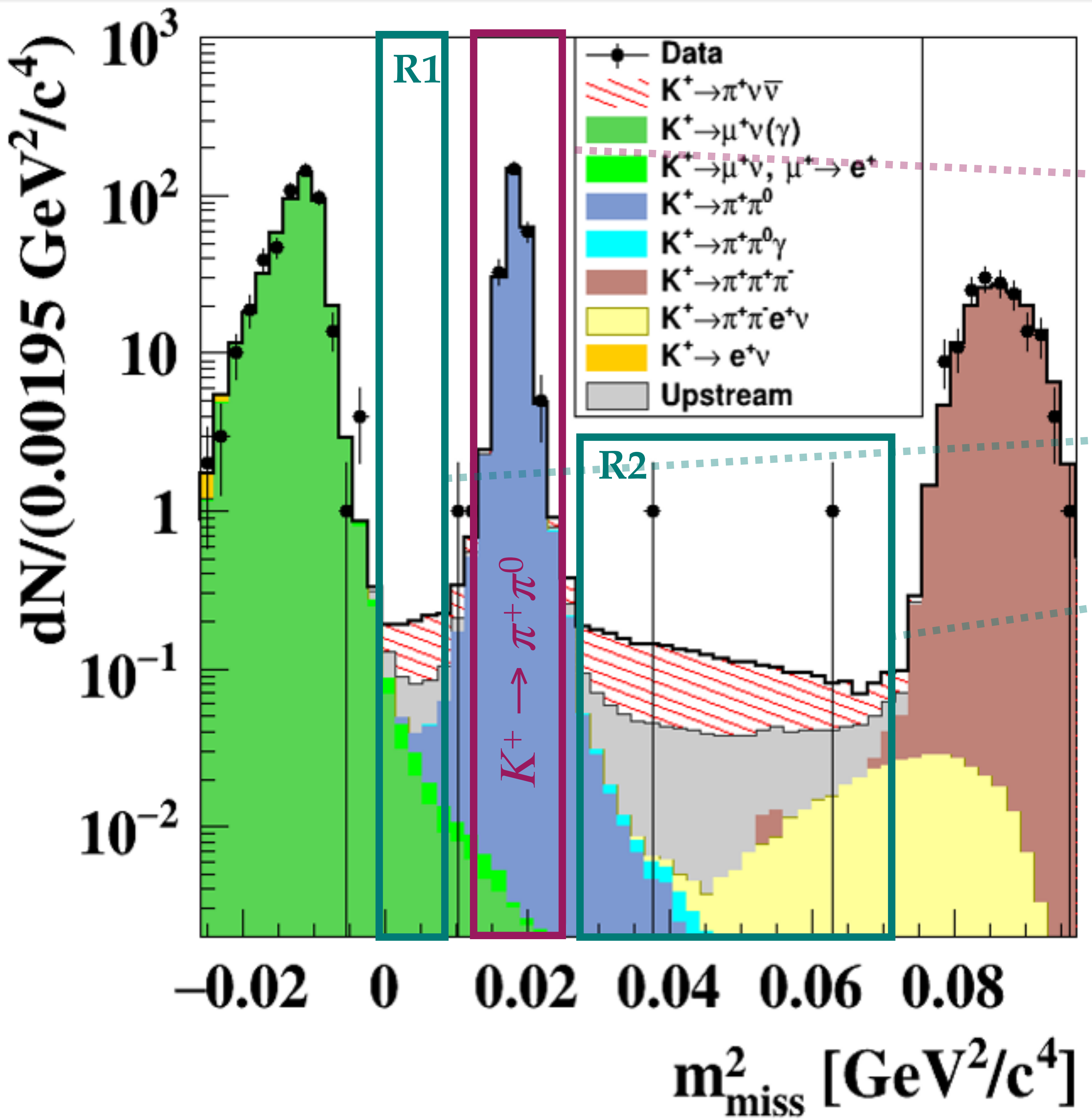
$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = 0.47^{0.72}_{-0.47} \times 10^{-10}$$



Grossman-Nir bound



Exotics with $K^+ \to \pi^+ + \text{inv}$



Search for $K^+ \to \pi^+\pi^0$, π^0 -> **inv**

NEW

Search for $K^+ \to \pi^+$**X**, X invisible

hidden sector searches

$K^+ \rightarrow \pi^+\pi^0$, π^0 -> inv

Paper in preparation

CERN-SPSC-2020-007 ; SPSC-SR-266

- π^0 -> νν is not forbidden because of neutrino non-zero masses, but in the SM: BR(π^0 -> νν) ~ O(10^{-24}), so any observation ==> **BSM physics**
- The present experimental limit is 2.7 10^{-7} at 90% C.L., from BNL experiments

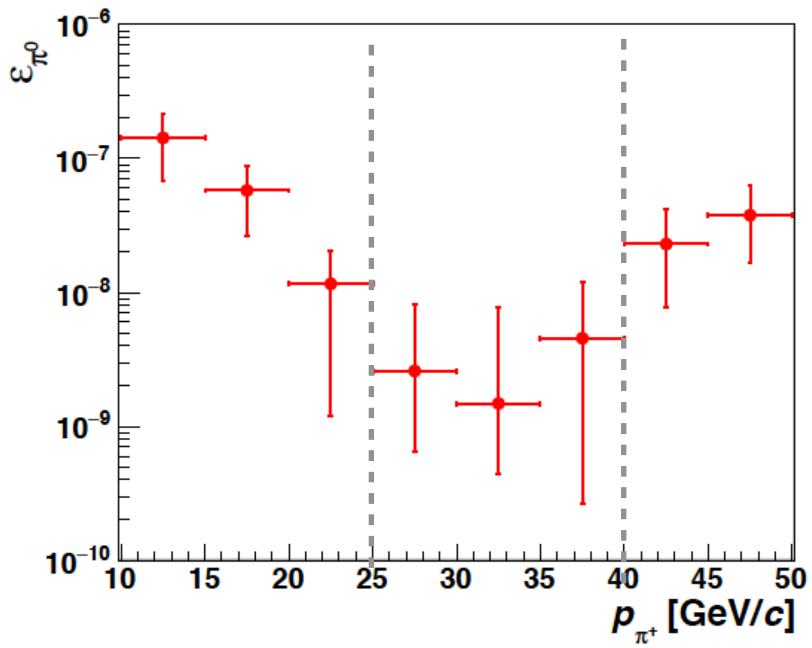
The hermetic photon veto in NA62, essential for πνν analysis, allows for the search in the Kaon decay

$$K^+ \to \pi^+\pi^0(\gamma), \quad \pi^0 \to \text{invisible}$$

Analysis strategy:

$$\mathrm{BR}(\pi^0 \to \text{invisible}) = \mathrm{BR}(\pi^0 \to \gamma\gamma) \times \frac{N_s}{N_{\pi^0} \times \epsilon_{sel} \times \epsilon_{trig}}$$

The main background is $K^+ \rightarrow \pi^+\pi^0$, π^0->γγ with undetected photons



Using a counting experiment approach in the region: 25<p<40 GeV and m^2_{miss} in [0.012,0.021] GeV2/c4

$$\mathrm{BR}(\pi^0 \to \text{invisible}) \leq 4.4 \times 10^{-9} \quad \text{at 90\% C.L.}$$

An improvement by a factor 60 wrt the previous experimental result

$K^+ \to \pi^+ X$, X invisible

Paper in preparation

NEW

Motivation: feebly interacting new particle foreseen in several models

Dark scalar: mixing with the Higgs

$$\mathcal{L}_{\rm scalar} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} - (\mu S + \lambda S^2) H^\dagger H$$

$$\mu = \sin\theta \quad \lambda = 0$$

JHEP05(2010)010, JHEP02(2014)123

Pseudo-scalar

Axion-like particles (ALPs) JHEP 03 (2015) 171

QCD axion, Axiflavon (m~0)

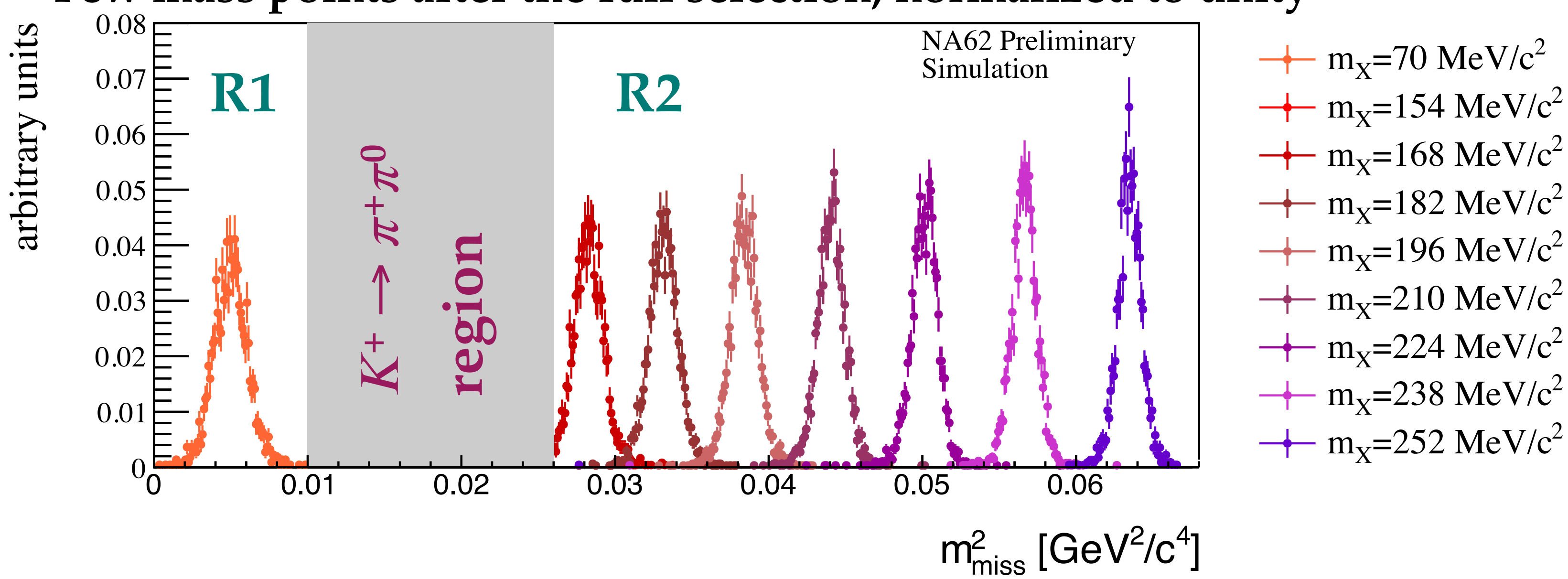
Phys. Rev. D16 (1977) 1791–1797.

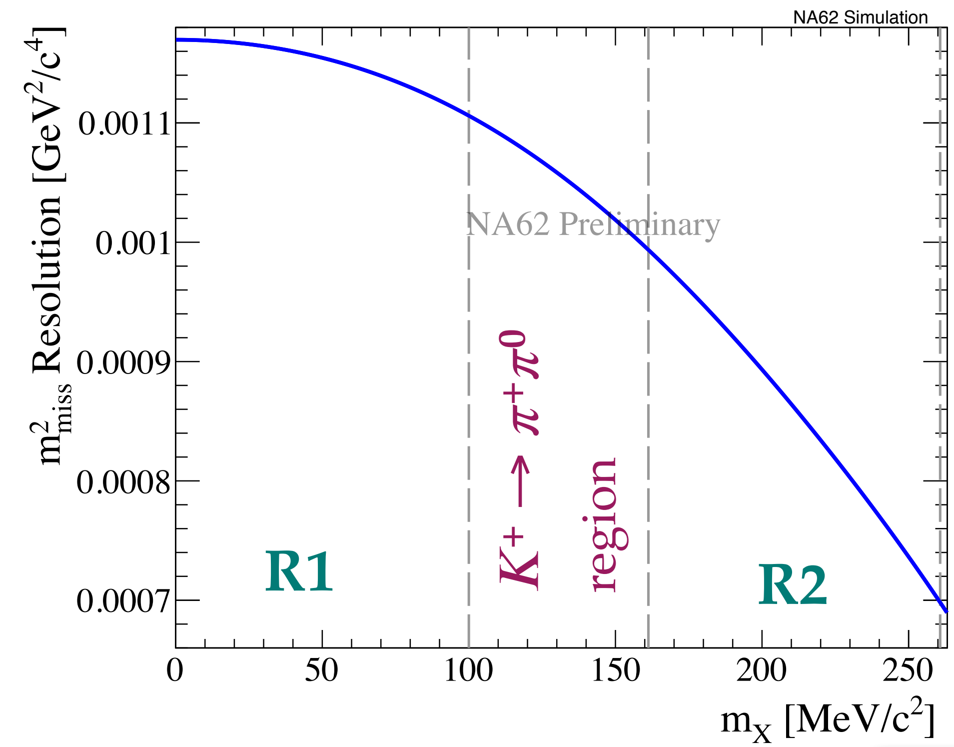
Phys. Rev. D 95, 095009 (2017)
arxiv:1612.05492

Analysis strategy:

Use exactly the same selection, normalization and background evaluation of $\pi\nu\nu$ analysis
Generate signal with two body decay for 200 mass hypotheses to compute acceptance

Few mass points after the full selection, normalized to unity





$K^+ \to \pi^+ X$, X invisible

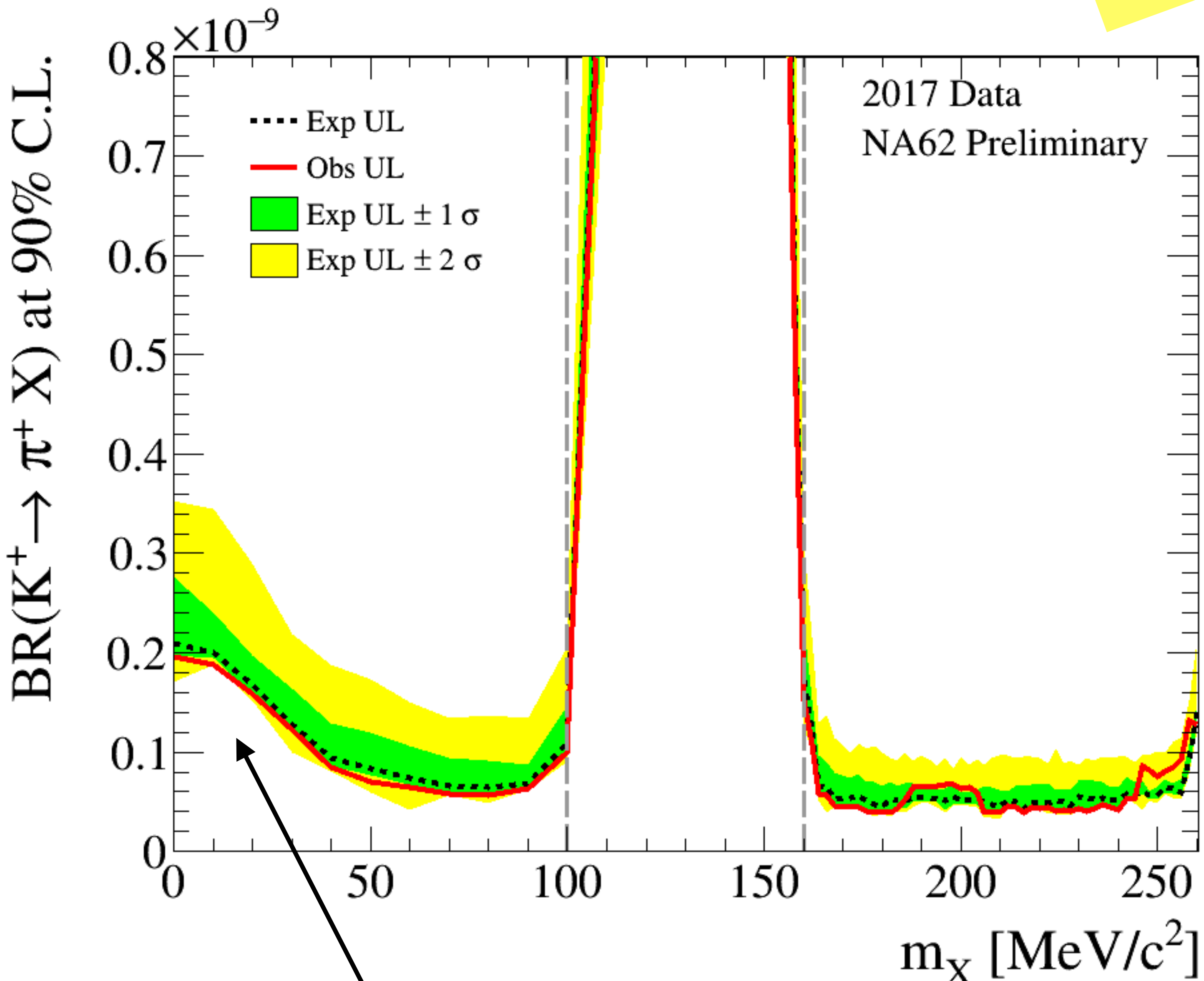
Paper in preparation

NEW

Bump hunting in m^2_{miss}

No deviation from the SM have been observed, so: *setting upper limit*

- Shape analysis on m^2_{miss}
- Fully frequentist approach
- Profiled likelihood test statistic



Background model

- **shape:** Parameterized with polynomial functions in R1 and R2
- **Bkg yield** from πνν analysis, including K->πνν from simulation and with SM BR

Signal model

- **shape**: Gaussian
- **Ns** from efficiency and normalization obtained in bins of p and intensity, as in πνν analysis

Sensitivity degrades at small m_X because of resolution.
In particular, for axion models, half of the signal is cut away

$K^+ \to \pi^+ X$, with X decaying

Paper in preparation

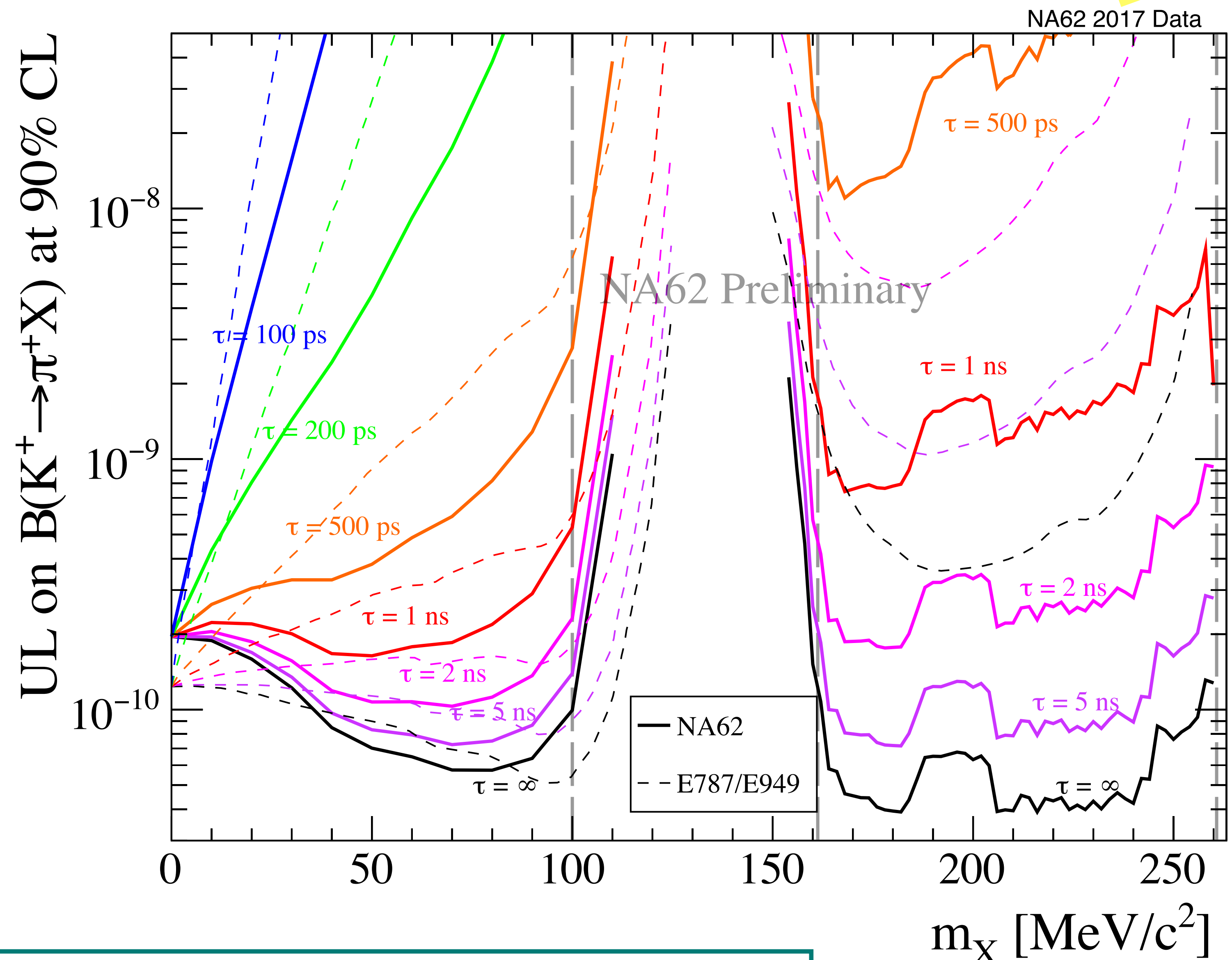
NEW

If X decays to visible SM particles

Probability that X does not decay within the NA62 apparatus:

$$P = e^{-\left(\frac{\Delta L}{\beta\gamma c\tau}\right)}$$

Comparison with BNL result
A. V. Artamonov *et al.* (E949 Collaboration)
Phys. Rev. D 79, 092004



Small improvement for mX in 40-80 MeV
Improved of ~1 order of magnitude in Region2

Prospects with 2018 data: Improvements are expected from a dedicated analysis exploiting the two-body kinematics, and extending the signal regions, especially at low masses

Conclusions

- With 2016 and 2017 data the upper limit at 90% CL

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) < 1.85 \times 10^{-10}$$ Preliminary

- 2018 data analysis is ongoing

Preliminary

Papers in preparation

- The same analysis principle with 2017 dataset has been exploited to search for exotic physics:

$$\mathrm{BR}(\pi^0 \to \text{invisible}) \leq 4.4 \times 10^{-9}$$ at 90% CL Preliminary

NEW

$BR(K^+ \to \pi^+ X) < (0.5 - 2) \cdot 10^{-10}$ at 90% CL for m_X in [0,100] MeV

$BR(K^+ \to \pi^+ X) < (0.4 - 1.4) \cdot 10^{-10}$ at 90% CL for m_X in [160,260] MeV

Preliminary

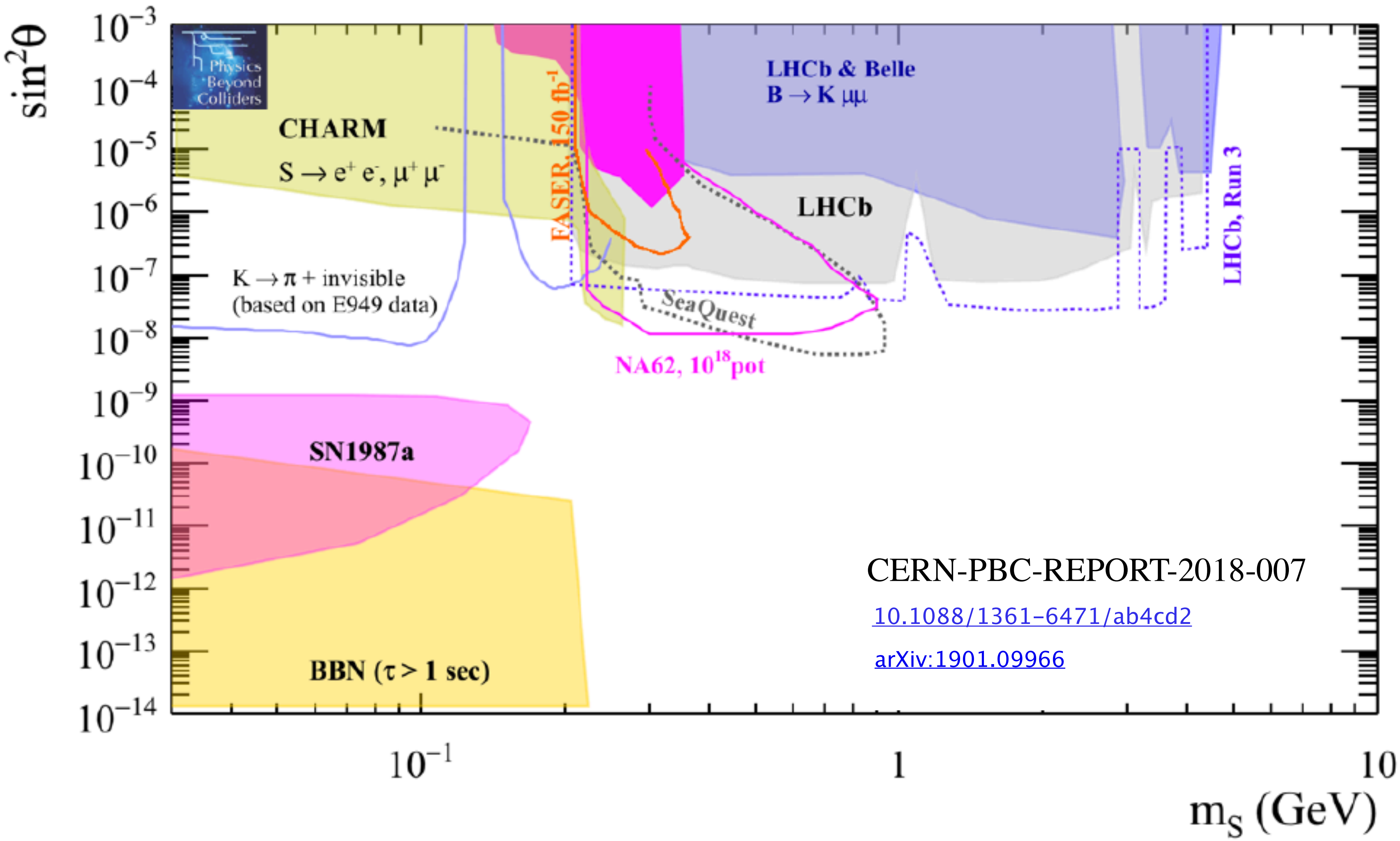
- 2018 data analysis is ongoing

Stay tuned and safe!

Thank you

Spares

Dark scalar, Higgs mixing



$$\mathrm{BR}(K^+ \to \pi^+ X) = f \times \frac{2|p_X|}{m_X} \times \sin^2\theta$$

F. Bezrukov, D. Gorbunov, JHEP05(2010)010

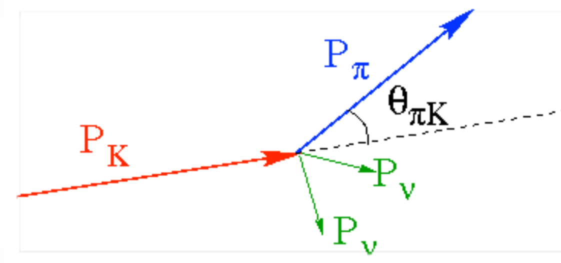
Jackson D. Clarke, Robert Foot and Raymond R. Volkas, JHEP02(2014)123

NA62 apparatus

JINST 12 P05025 (2017), arxiv:1703.08501

- very good kinematic reconstruction
- Precise time measurements

$$m^2_{miss} = (p_K - p_\pi)^2$$



33×10^{11} ppp on T10 (750 MHz at GTK3)
Secondary beam: 75 GeV/c momentum
K^+ (6%)/π^+ (70%)/p(24%)

FV: Fiducial decay volume

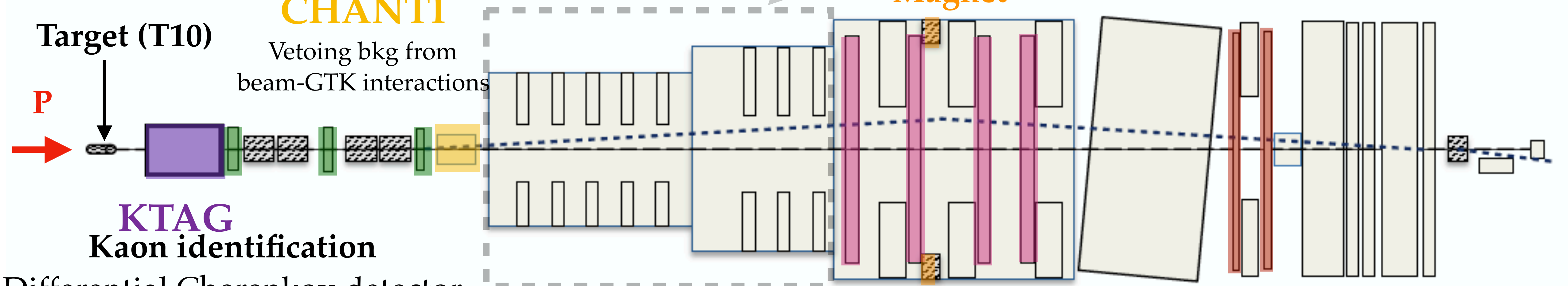
CHOD
Charged Hodoscope, plastic scintillator

Magnet

Target (T10)

CHANTI
Vetoing bkg from beam-GTK interactions

P



KTAG
Kaon identification
Differential Cherenkov detector
$\sigma(t) = 70$ ps

0 | 100 m | 160 m

GTK
Kaon tracking
Si pixel, 3 stations
$\sigma(t) = 200$ ps, $\sigma(p)/p = 0.2\%$

120 m **tube in vacuum**
(500 m³ at 10^{-6} mbar)

STRAW
Downstream tracking: Dipole spectrometer
4 straw-tracker stations
$\sigma(p)/p = 0.3\%$

- ☑ **Time resolution ~ 100 ps**
- ☑ **$\sigma(m^2_{miss}) = 10^{-3}$ GeV²/c⁴**

NA62 apparatus

JINST 12 P05025 (2017), arxiv:1703.08501

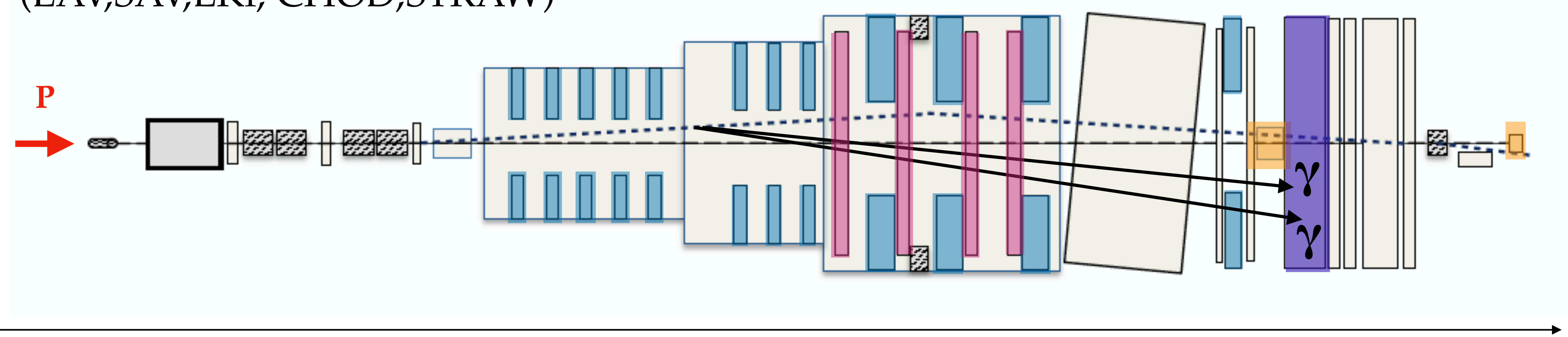
background rejection: $K^+ \rightarrow \pi^+\pi^0$

Hermetic photon veto system
(LAV,SAV,LKr)

Multiplicity rejection
(LAV,SAV,LKr, CHOD,STRAW)

Large Angle Veto (LAV)
12 stations (lead glass blocks)
Covering angles $8.5 < \theta < 50$ mrad

CHOD
Charged Hodoscope,
plastic scintillator



LKr calorimeter

Photon detection

Covering angles $1 < \theta < 8.5$ mrad

Small Angle Veto (SAV)
IRC: Inner Ring Calorimeter
Small Angle Calorimeter
Covering angles <1 mrad

☑ $\varepsilon(\pi^0) = 3\ 10^{-8}$

NA62 apparatus

JINST 12 P05025 (2017), arxiv:1703.08501

background rejection: $K \rightarrow \mu^+ \nu$

Particle identification:
To separate π/μ/e

The RICH is used also to obtain
an independent p momentum measurement

RICH
Ring Imaging
Cherenkov detector

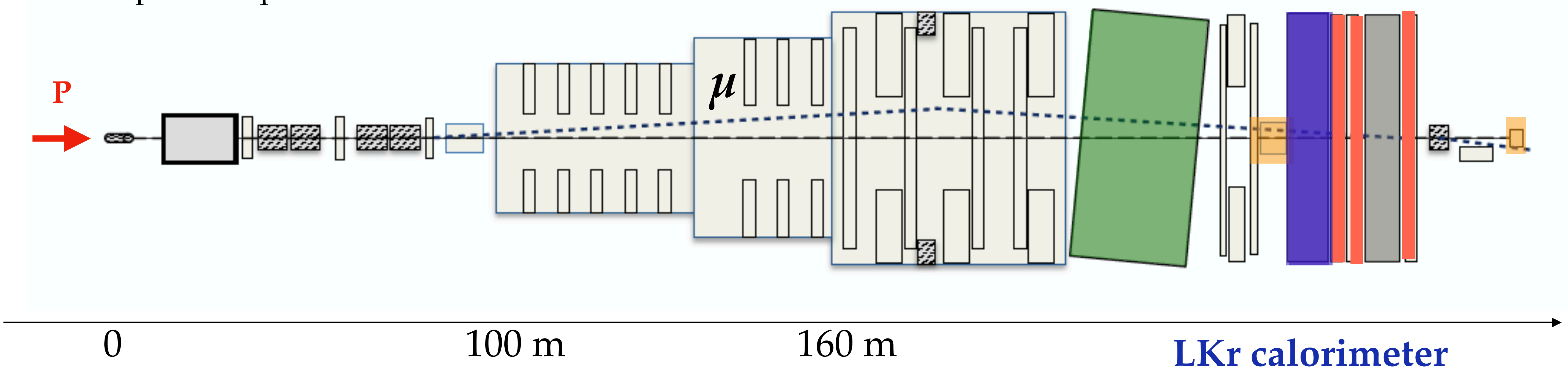
Neon 1 Atm
π/μ/e separation

MUV
Muon veto system

MUV1 & MUV2:
Hadronic calorimeters for
the μ/π separation

MUV3: Efficient fast Muon Veto
used in the hardware trigger level.

Iron



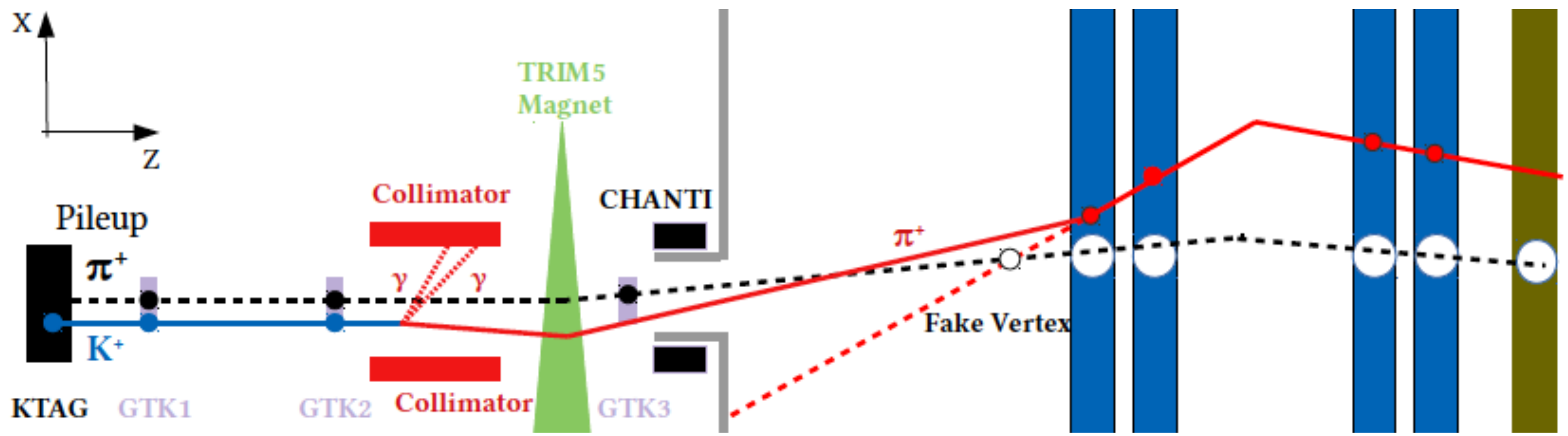
LKr calorimeter
Photon detection

Multivariate analysis
with MUV1, MUV2 and LKr info

2 algorithm for the RICH variables

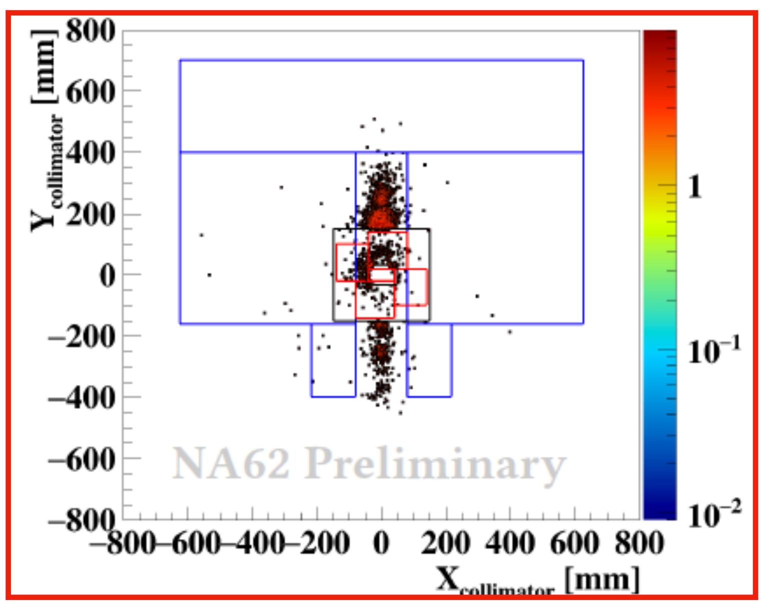
☑ $\varepsilon(\mu^+) = 10^{-8}$ $\varepsilon(\pi^+) = 64\%$

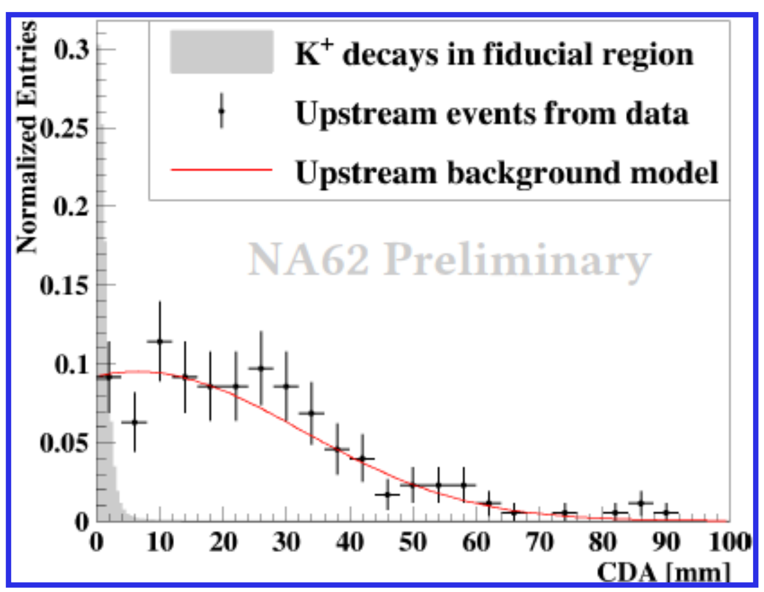
Upstream background

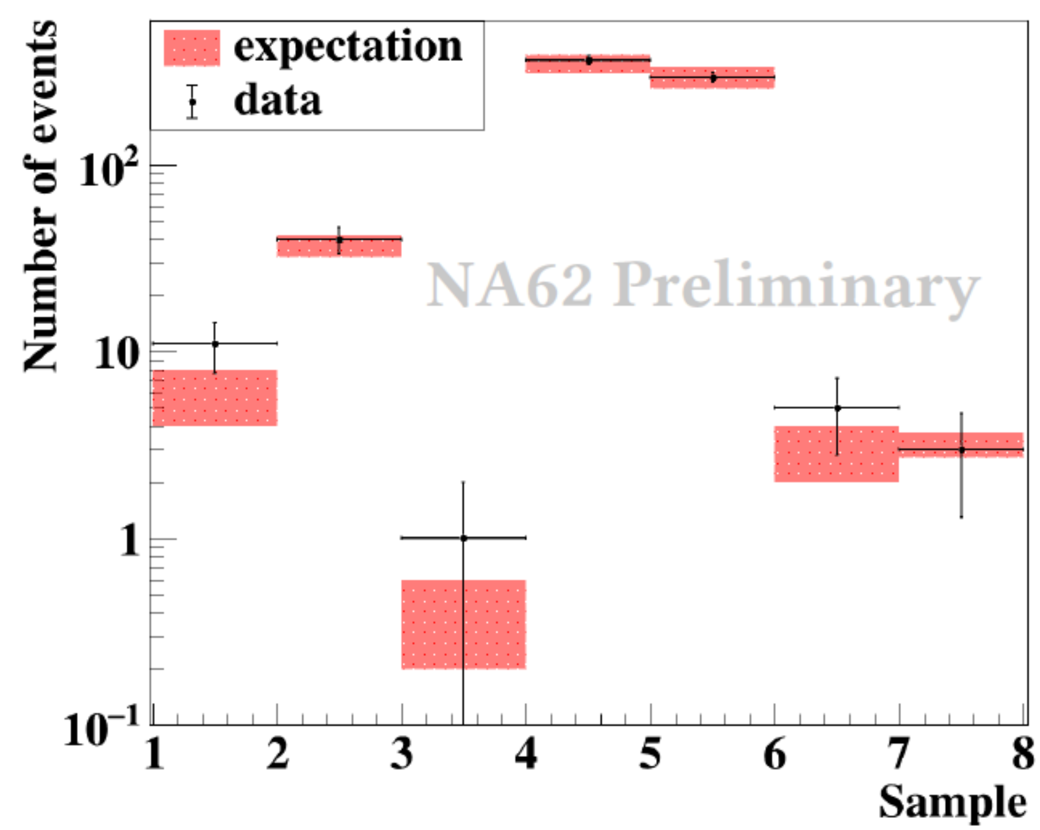


$$N^{bg}_{upstream} = N^{upstream}_{\pi^+} \cdot P^{reco}_{pileup} \cdot P^{matching}_{K-\pi}$$

Upstream enriched sample

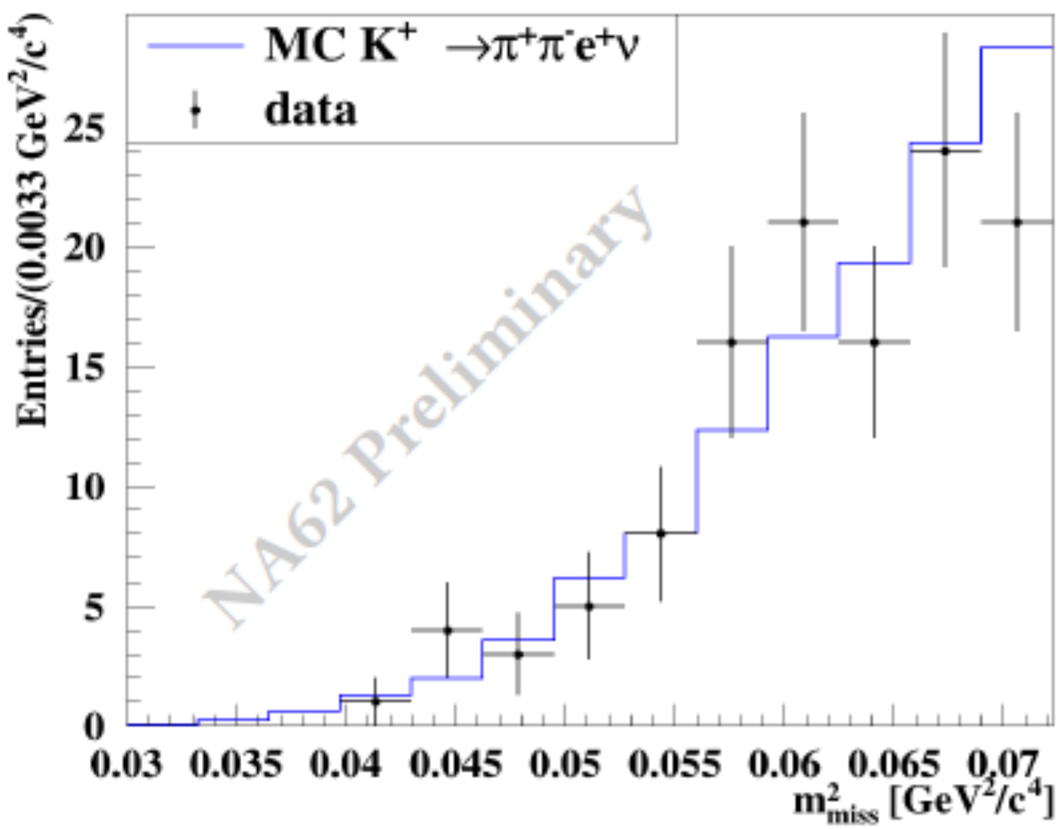






Bkg: $K^+ \to \pi^+\pi^-e^+\nu$

MC simulation validated using data



Validation in the control region