University of Birmingham Particle Physics Seminar

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Latest NA62 results on the search for $K^+ \to \pi^+\nu\bar{\nu}$ and prospects for a neutral pion Dalitz decay measurement

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Outline

- Introduction to NA62
  - History of kaon physics at CERN
  - Physics motivation
  - NA62 beam and detector layout
- The $K^+ \to \pi^+\nu\bar{\nu}$ decay
  - Latest analysis improvements
  - Results from data taken in Run 1
- The $\pi^0 \to e^+e^-\gamma$ decay
  - Theory
  - Experimental status
  - Prospects for a measurement at NA62
- Conclusions and the future of NA62

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   - Prospects for a measurement at NA62
4. Conclusions and the future of NA62

NA62 and kaon physics at CERN

~200 participants, 30 institutes, 14 countries

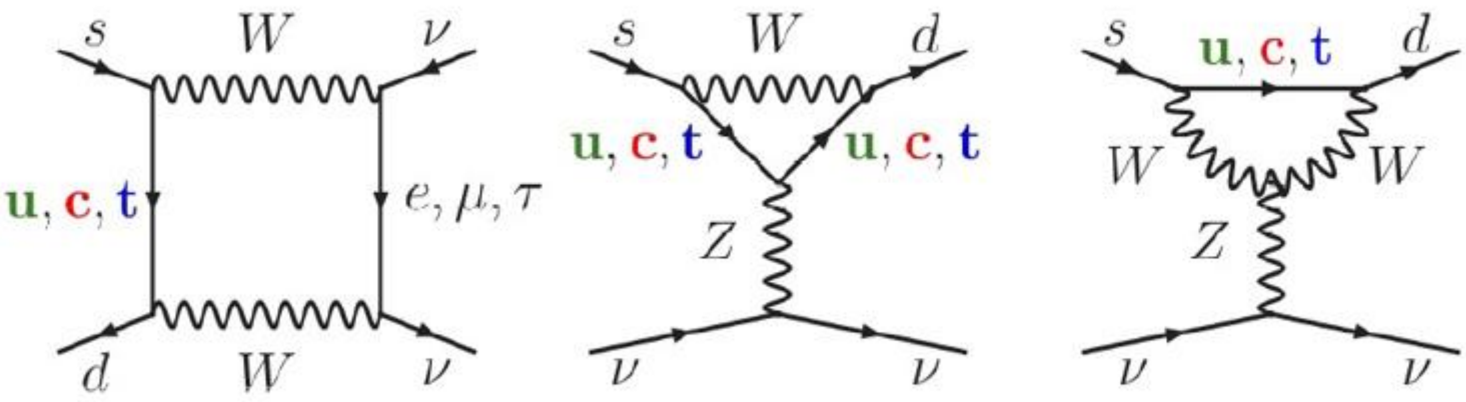
- 1980s — **NA31**: First evidence of direct CPV
- 1997-2001 — **NA48**: Discovery of direct CPV
- 2002 — **NA48/1**: Rare decay studies
- 2003-2004 — **NA48/2**: Precision measurements
- 2007-2008 — **NA62-R_K**: $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$
- 2015-2018 — **NA62 Run 1** (2015-2018)
- 2021-LS3 — **NA62 Run 2** (2021-LS3)

NA62 Run 1 and Run 2 — Main goal: $B(K^+ \to \pi^+\nu\bar{\nu})$ LNV/LFV searches, HNL, precision and rare decay measurements…

- NA31, NA48: K_L/K_S beam
- NA48/1: K_S/hyperon beam
- NA48/2, NA62-R_K: K^+/K^- beam
- NA62 Run 1, NA62 Run 2: K^+ beam

NA62

Physics case: $BR(K^+ \to \pi^+ \nu\bar{\nu})$



The decay is a $\bar{s} \to \bar{d}\nu\bar{\nu}$ transition: flavour changing neutral current process (GIM mechanism) with high CKM suppression. Precise measurement would help constrain the unitarity triangle as well as a variety of new physics models (new sources of flavour violation, lepton flavour non-universality, leptoquark plus more).

It has a theoretically clean prediction (short distance contributions).

Standard model prediction (updated in 2021 which decreased the uncertainty by a factor 2.4 [arXiv:2109.11032]):

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$

The main uncertainty is from the γ CKM parameter knowledge.

$BR(K^+ \to \pi^+ \nu\bar{\nu})$ beyond the SM

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]

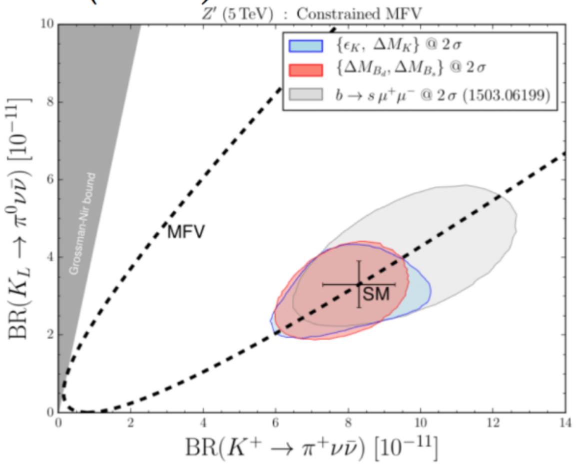
Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, Eur. Phys. J. C76 (2016) 182]

LFU violation models [Isidori et al., Eur. Phys. J. C (2017) 77: 618]

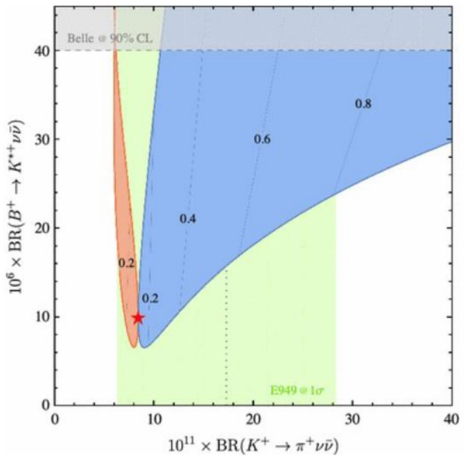
Leptoquarks [S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]

Constraints from existing measurements (correlations model dependent):

Z'(5 TeV) in Constrained MFV



LFU violation



$BR(K^+ \to \pi^+ \nu\bar{\nu})$ experimental status before NA62

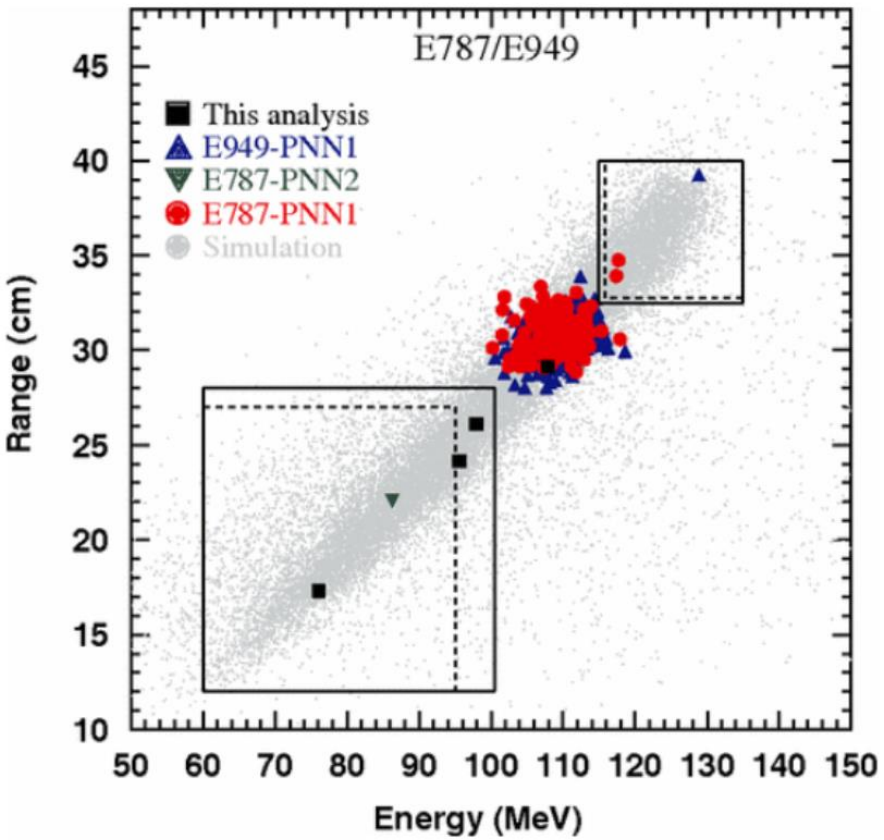
Previous measurements conducted by the BNL E787/E949 experiments [Phys. Rev. D 77, 052003 (2008)] [Phys. Rev. D 79, 092004 (2009)].

They used a decay at rest technique.

Had the sensitivity to observe 1 SM signal event. They observed 7 and used a statistical reweighting procedure to take into account the background.

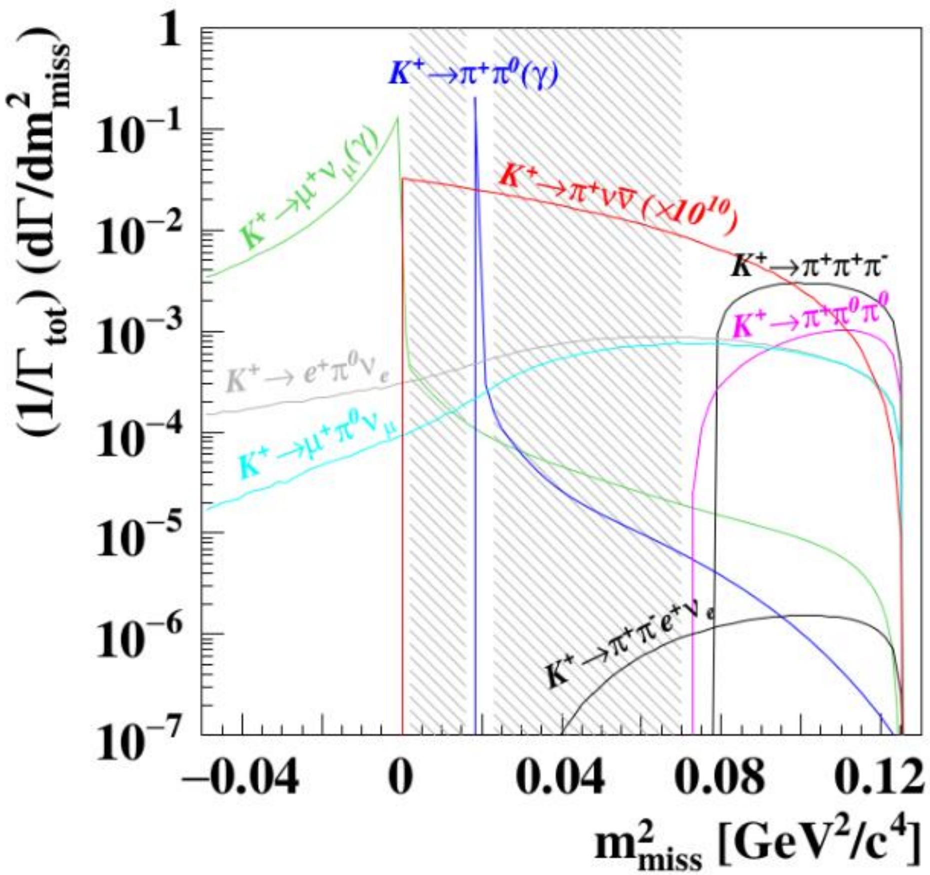
BNL measurement:

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



$BR(K^+ \to \pi^+ \nu\bar{\nu})$ at NA62

Strategy:
- Decay in flight technique ($P_K = 75$ GeV/c).
- Kinematic analysis with $m^2_{miss} = (P_K - P_\pi)^2$ as the main kinematic variable.
- Require:
  - Charged particle identification (K^+ and π^+).
  - Muon and photon rejection.
  - Pion momentum range [15,45] GeV/c.
- Signal and control kinematic regions are blinded during the analysis.



Require:
- Timing resolution O(100ps).
- Kinematic rejection O(10^4) of $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$.
- Muon rejection $> 10^7$ (mainly from $K^+ \to \mu^+\nu$).
- π^0 rejection $> 10^7$ (mainly from $K^+ \to \pi^+\pi^0$ with $\pi^0 \to \gamma\gamma$).

NA62 beam and detector layout

- KTAG (upstream Cherenkov detector) tags kaons in the beam ($\sigma_T \sim 70$ps)
- GTK (silicon pixel spectrometer) tracks the beam
- CHANTI (plastic scintillator) rejects inelastic scattering background
- STRAW (magnetic spectrometer) tracks K^+ decay products
- RICH (downstream Cherenkov detector) provides PID ($\pi^+/\mu^+/e^+$) and timing ($\sigma_T \sim 70$ps)
- LKr (ECAL) provides PID and photon veto
- LAV, IRC and SAC provide additional photon veto to achieve hermetic acceptance (0-50 mrad) of photons
- MUV0 (scintillator) rejects out-of-STRAW-acceptance π^-
- HASC (scintillator) rejects out-of-STRAW-acceptance π^+
- MUV1/2 (scintillators) provide hadronic calorimetry
- MUV3 provides muon detection/veto
- CHOD and NA48-CHOD used for trigger and timing ($\sigma_T \sim 200$ps)

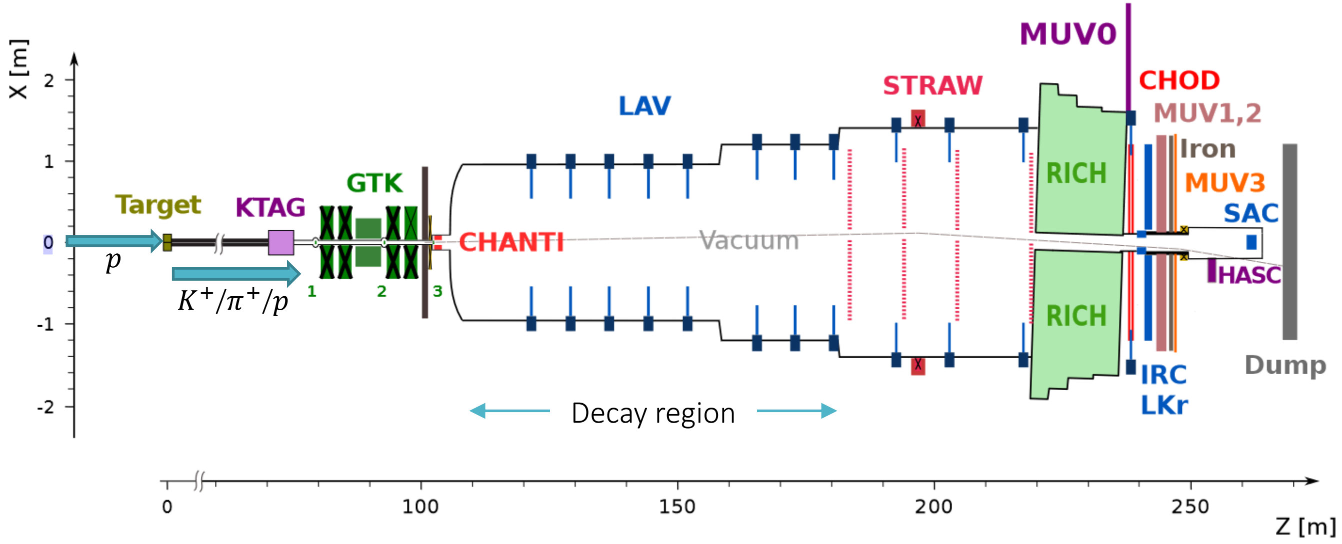
Protons from CERN SPS impinge on beryllium target.

Leads to an unseparated beam consisting of K^+, π^+ and protons entering NA62.

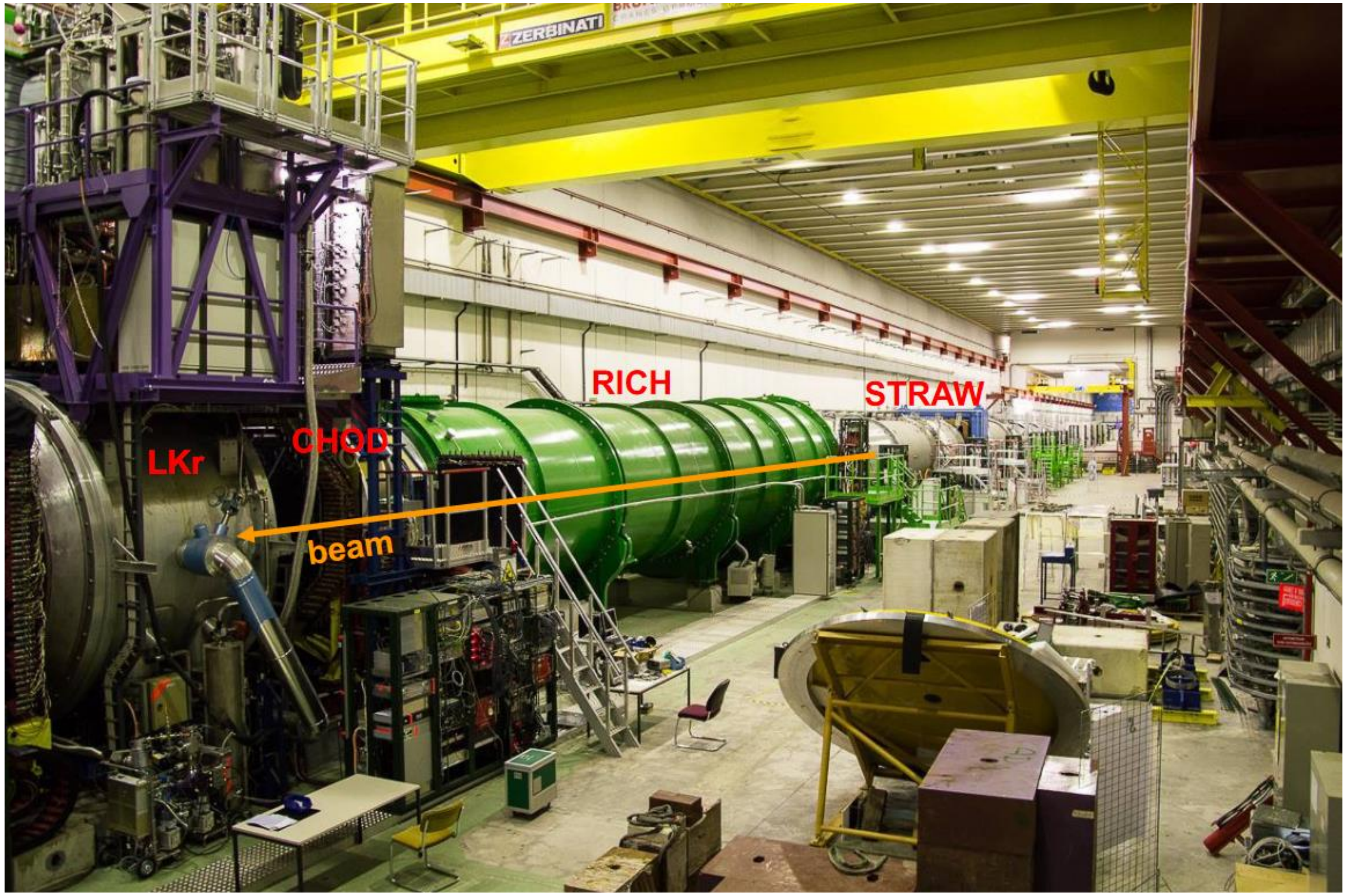
6% of the beam is K^+.

Beam rate ~500 MHz at decay region entrance
$\Rightarrow$ K^+ decay rate ~5 MHz in the decay region.

Beam momentum = 75 GeV/c ($\pm 1\%$)



NA62 beam and detector layout



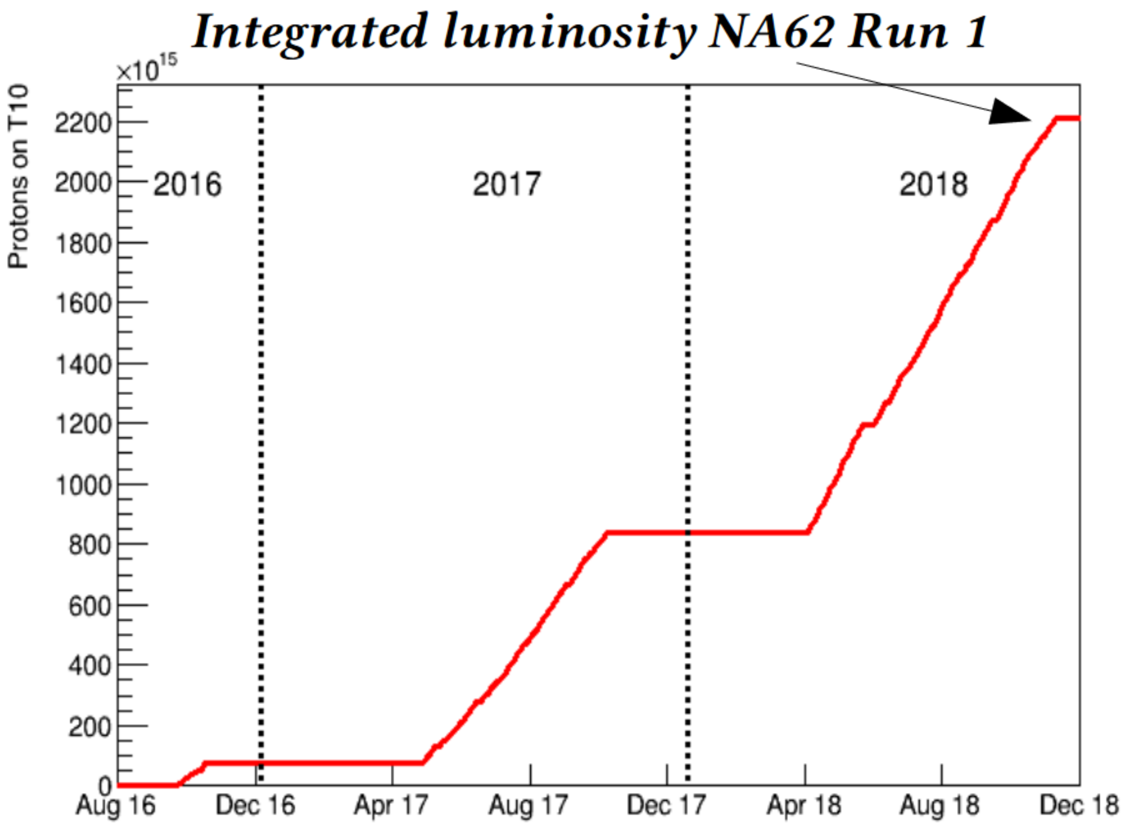
NA62 data taking periods

Run 1 comprises of 3 years of data taking between 2016 and 2018.

- 408 days in total.
- $\sim 6 \times 10^{12}\ K^+$ decays.

Run 2 started in July 2021 and will continue until the start of LS3 (2024).

- Expect to collect $O(10^{13})\ K^+$ decays.



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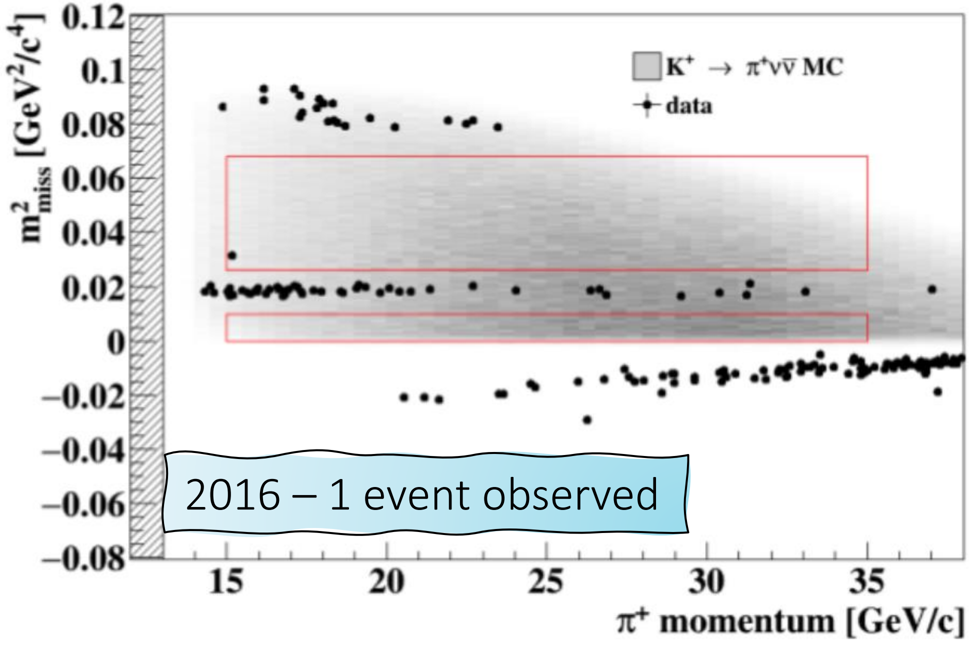
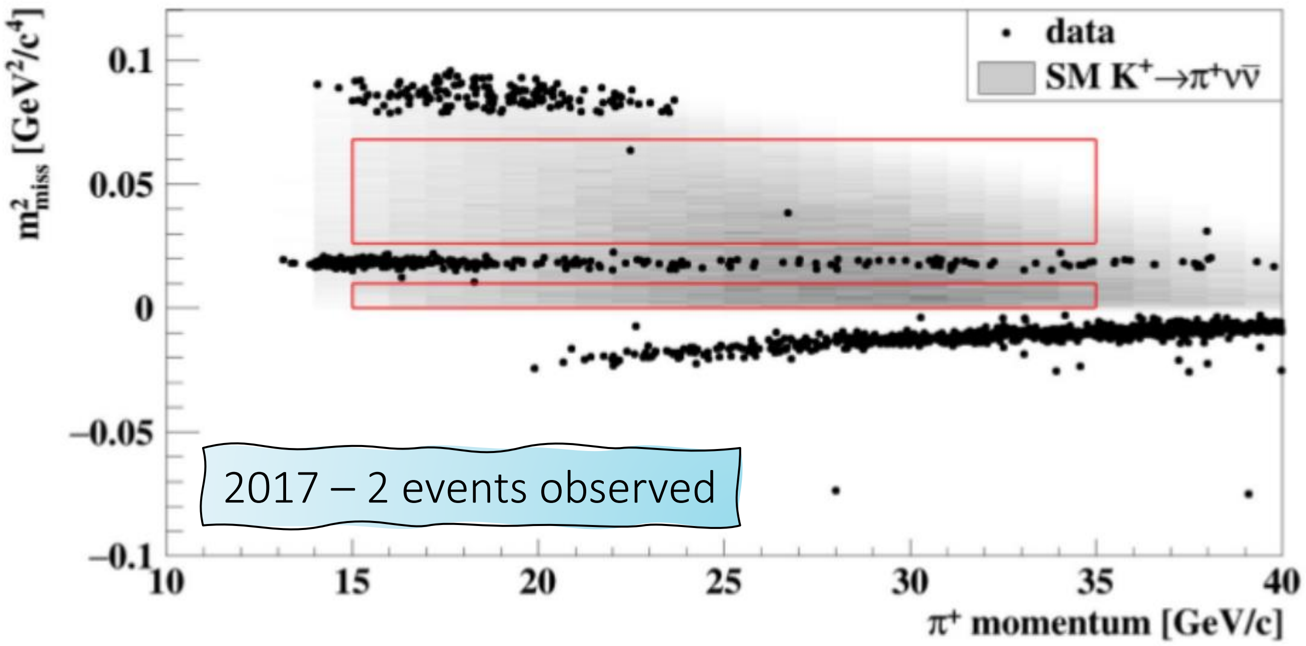
$BR(K^+ \to \pi^+ \nu\bar{\nu})$ 2016/2017 result



2016 – 1 event observed



2017 – 2 events observed

Result from 2016+2017 analysis consistent with background expectation [JHEP 11 (2020) 042]:

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) < 1.78 \times 10^{-10} \text{ @ } 90\% \; CL$$

[JHEP 06 (2021) 093]

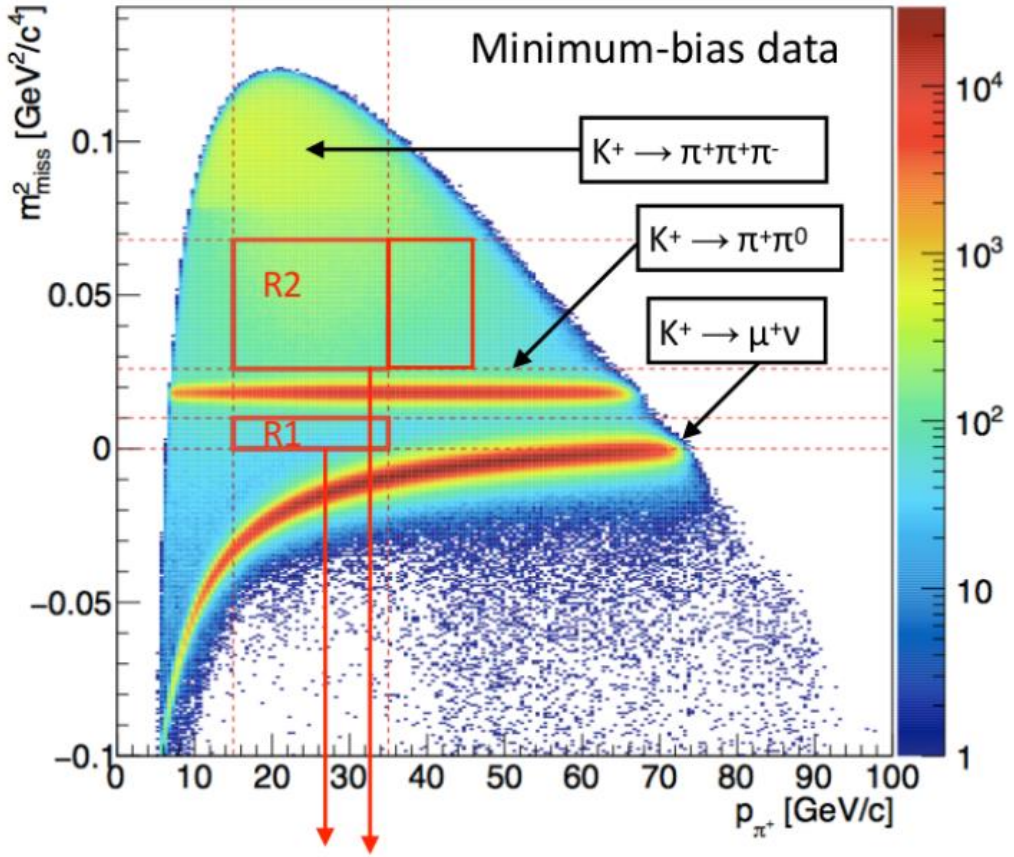
$K^+ \to \pi^+ \nu\bar{\nu}$ selection

$\pi\nu\nu$ trigger:
- L0 (hardware): charged particle present, muon and photon veto.
- L1 (software): K^+ ID, additional photon veto, track reconstruction.

Minimum-bias trigger (used for K^+ flux, efficiencies and background estimation):
- L0 (hardware): charged particle present

$\pi\nu\nu$ selection steps:
- Reconstruction of K^+ and π^+ tracks
- $K^+ - \pi^+$ matching
- Reconstruction of decay vertex
- π^+ ID and μ^+/γ rejection
- Multi-track rejection
- Kinematics (m^2_{miss} vs p_π)

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

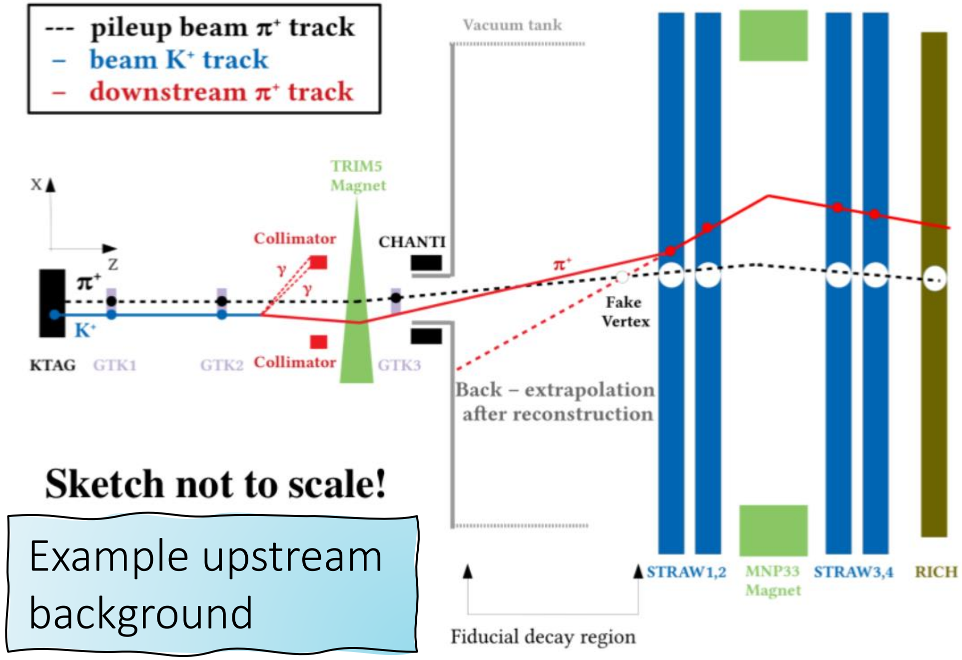


Kinematic cuts to define signal regions R1 and R2

Improvements in 2018 analysis

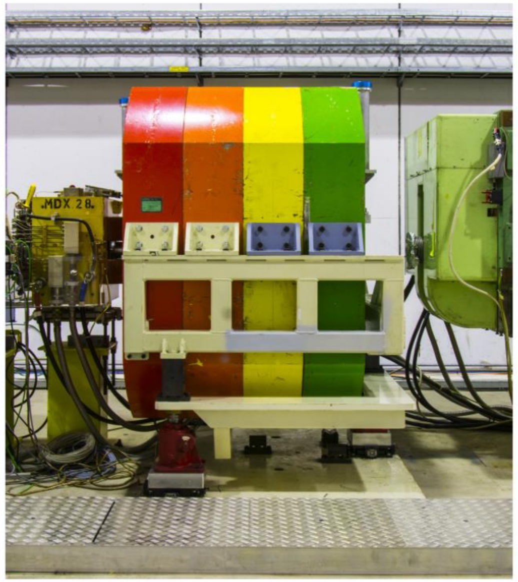
Several improvements were made in the 2018 analysis, with respect to the 2017 one. The aim was to increase the signal efficiency whilst keeping the same signal/background:

- New collimator installed on the beam line to remove background from upstream of the decay volume.
- BDT approach applied for estimation of upstream background (allowed certain geometrical cuts to be relaxed).
- PID conditions optimised in bins of π^+ momentum and BDT used for calorimeter PID.
- Photon rejection optimised by taking into account correlations with Z_{vtx} and π^+ momentum.



Example upstream background

Old collimator



New collimator

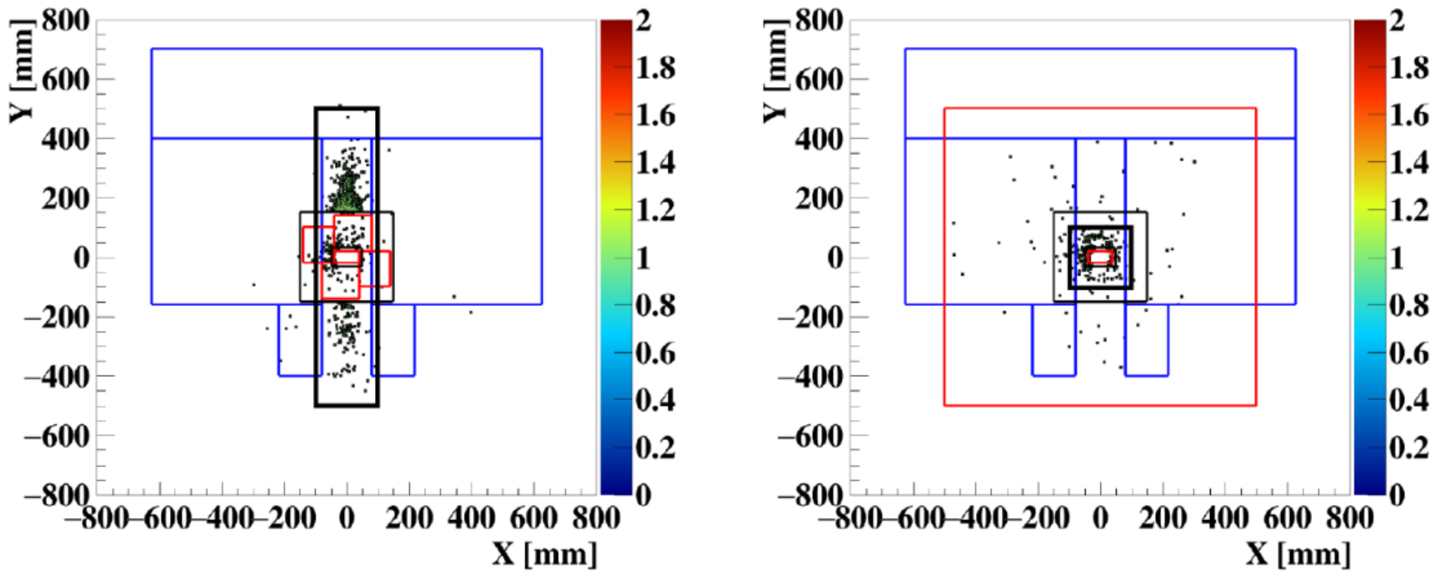
[JHEP 06 (2021) 093]

Improvements in 2018 analysis

Collimator was installed part way through the 2018 run so 2018 sample split into “old-coll” and “new-coll” subsamples

- Different selections used for each subsample.

Track extrapolation to the collimator in sample of upstream events (data):



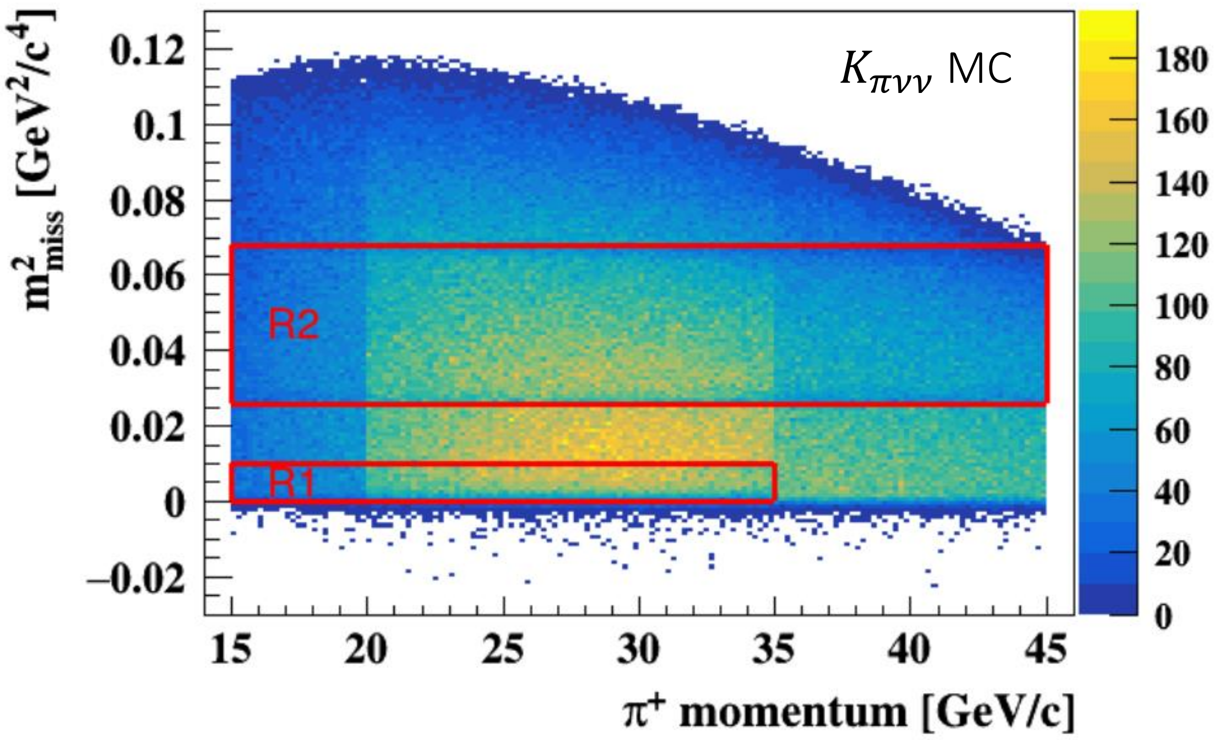
Old collimator

New collimator

Red boxes = collimator coverage.
Blue boxes = last beam line dipole.
Black boxes = cut regions and background validation.

Improvements in 2018 analysis

Final improvement was the enlargement of the second signal region, made possible due to optimised kinematic cuts.



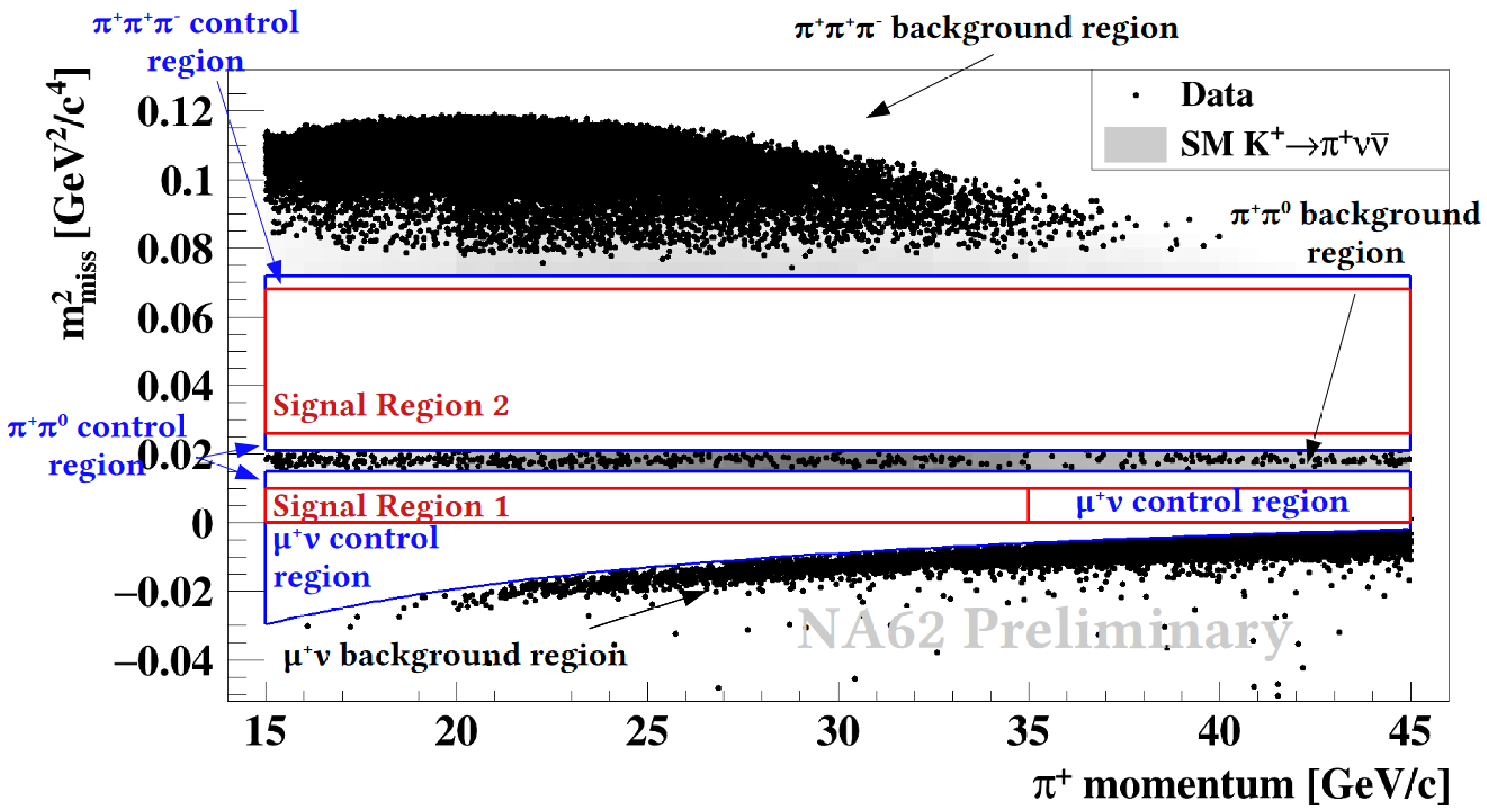
R1/R2 = the two signal regions

In 2016/2017, both signal regions went up to a π^+ momentum of 35 GeV/c.

In 2018, R2 could be increased to 45 GeV/c.

[JHEP 06 (2021) 093]

2018 data after signal selection



Control and signal regions still blinded!

[JHEP 06 (2021) 093]

Single event sensitivity (2018)

The number of expected $K_{\pi\nu\nu}$ events is:

$$N_{\pi\nu\nu}^{exp} = N_{\pi\pi}\epsilon_{trigger}\epsilon_{RV}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{BR(\pi\nu\nu)}{BR(\pi\pi)}$$

where $N_{\pi\pi}$ is the number of $K^+ \to \pi^+\pi^0$ events (normalisation channel), $\epsilon_{trigger}$ and ϵ_{RV} are the trigger and random veto efficiency and $A_{\pi\nu\nu}$ and $A_{\pi\pi}$ are the signal and normalisation acceptances.

Can define the single event sensitivity as:

$$SES = \frac{BR(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}$$

i.e. the branching ratio if one signal event was observed.

	Subset S1	Subset S2
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^2$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^2$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon_{\mathrm{trig}}^{\mathrm{PNN}}$	0.89 ± 0.05	0.89 ± 0.05
ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
$N_{\pi\nu\bar{\nu}}^{\mathrm{exp}}$	$1.56 \pm 0.10 \pm 0.19_{\mathrm{ext}}$	$6.02 \pm 0.39 \pm 0.72_{\mathrm{ext}}$

Total number of expected $K_{\pi\nu\nu}$ events = $7.58 \pm 0.40 \pm 0.75_{ext}$

[JHEP 06 (2021) 093]

Single event sensitivity (2018)

The number of expected $K_{\pi\nu\nu}$ events is:

$$N_{\pi\nu\nu}^{exp} = N_{\pi\pi}\epsilon_{trigger}\epsilon_{RV}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{BR(\pi\nu\nu)}{BR(\pi\pi)}$$

where $N_{\pi\pi}$ is the number of $K^+ \to \pi^+\pi^0$ events (normalisation channel), $\epsilon_{trigger}$ and ϵ_{RV} are the trigger and random veto efficiency and $A_{\pi\nu\nu}$ and $A_{\pi\pi}$ are the signal and normalisation acceptances.

Can define the single event sensitivity as:

$$SES = \frac{BR(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}$$

i.e. the branching ratio if one signal event was observed.

	SES error budget
Trigger efficiency	5%
MC acceptance	3.5%
Random veto	2%
Background (normalisation)	0.7%
Instantaneous intensity	0.7%
Total	6.5%

By design, some systematics cancel: PID, detector inefficiencies, kaon ID, beam related acceptance losses

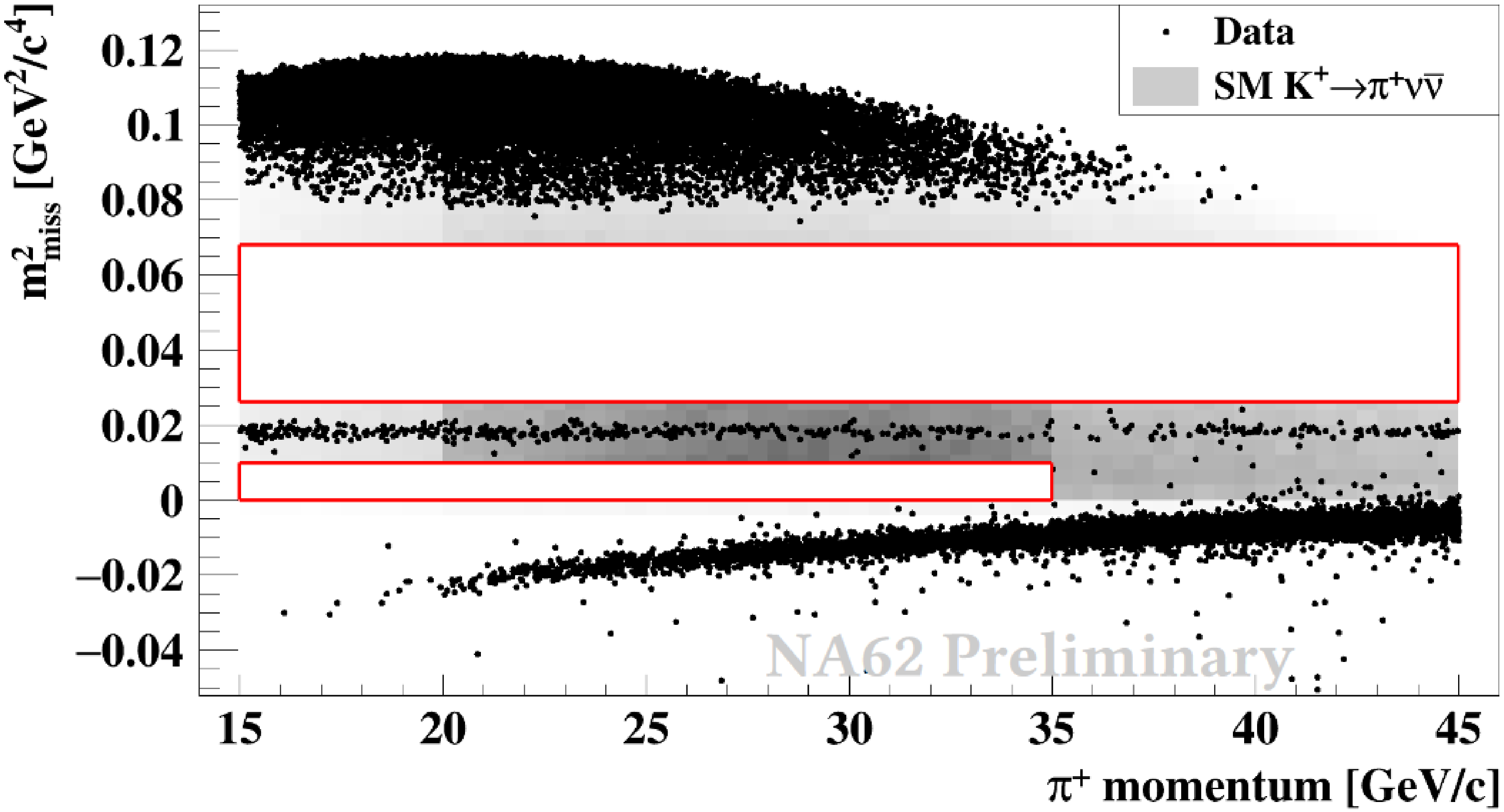
Total expected background (2018)

Background	2018 data
$K^+ \to \pi^+\pi^0$	0.75(4)
$K^+ \to \mu^+\nu$	0.49(5)
$K^+ \to \pi^+\pi^-e^+\nu$	0.50(11)
$K^+ \to \pi^+\pi^+\pi^-$	0.24(8)
$K^+ \to \pi^+\gamma\gamma$	<0.01
$K^+ \to \pi^0 l^+\nu$	<0.001
Upstream	$3.30^{+0.98}_{-0.73}$
Total	$5.28^{+0.99}_{-0.74}$

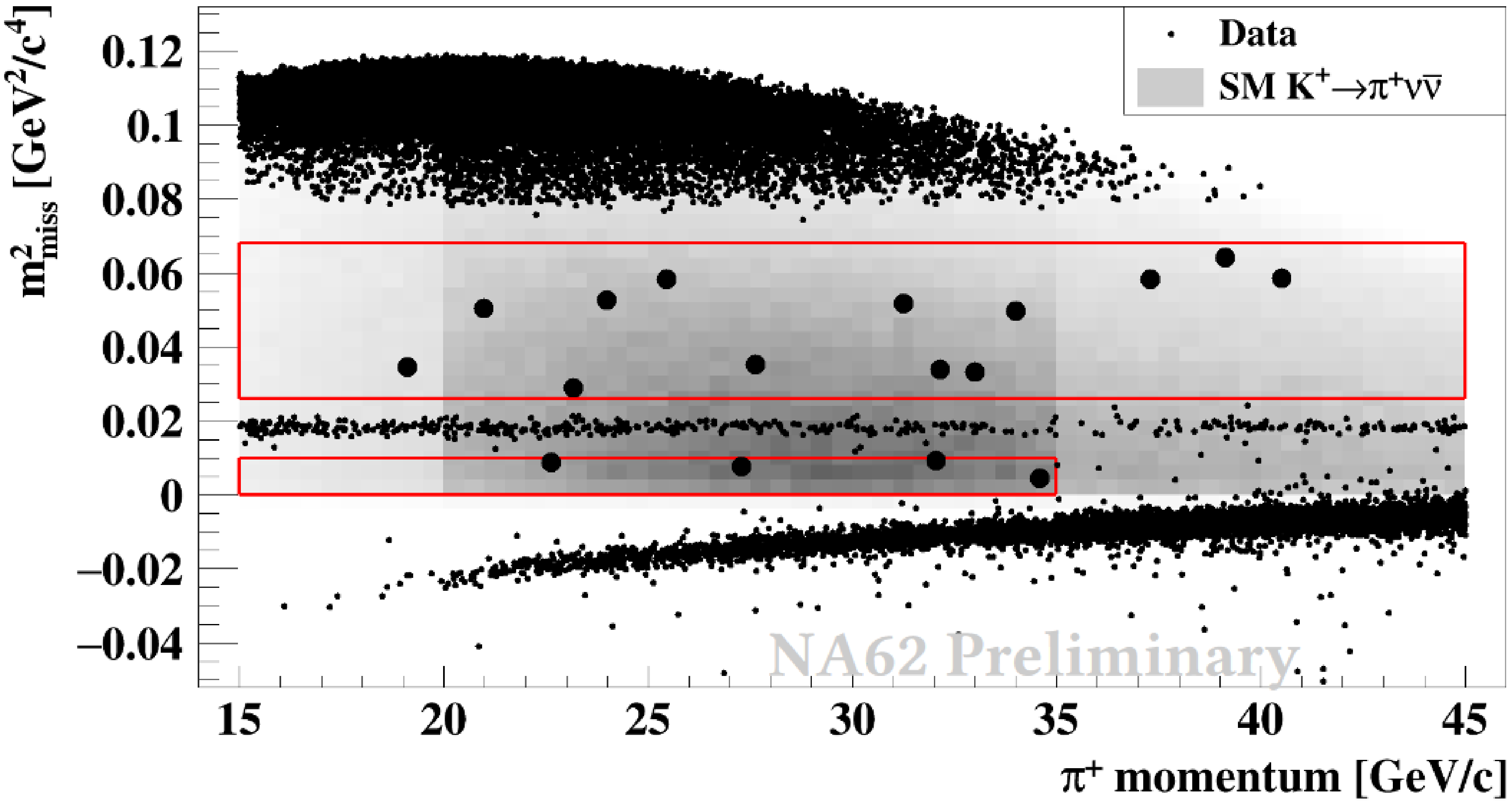
Background expectations validated in control regions using a blind procedure.

Expected SM signal = $7.58 \pm 0.40_{syst} \pm 0.75_{ext}$

2018 data before unblinding



2018 data after unblinding



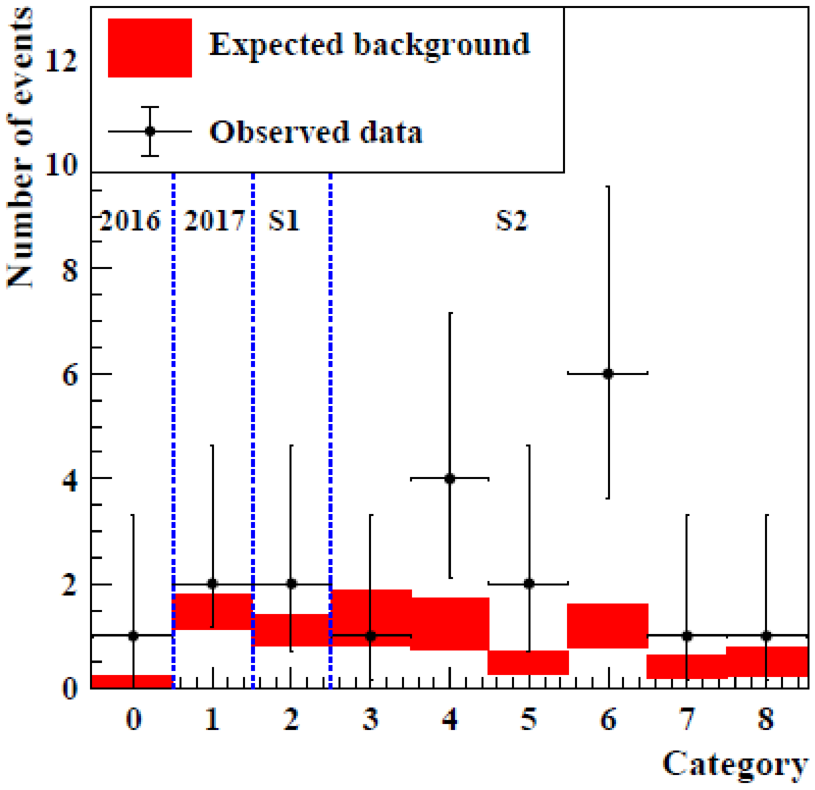
17 events observed!

Run 1 results

Maximum likelihood fit conducted using signal and background expectation in sub-samples based on different hardware configurations.

The sub-samples (categories):

- 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.

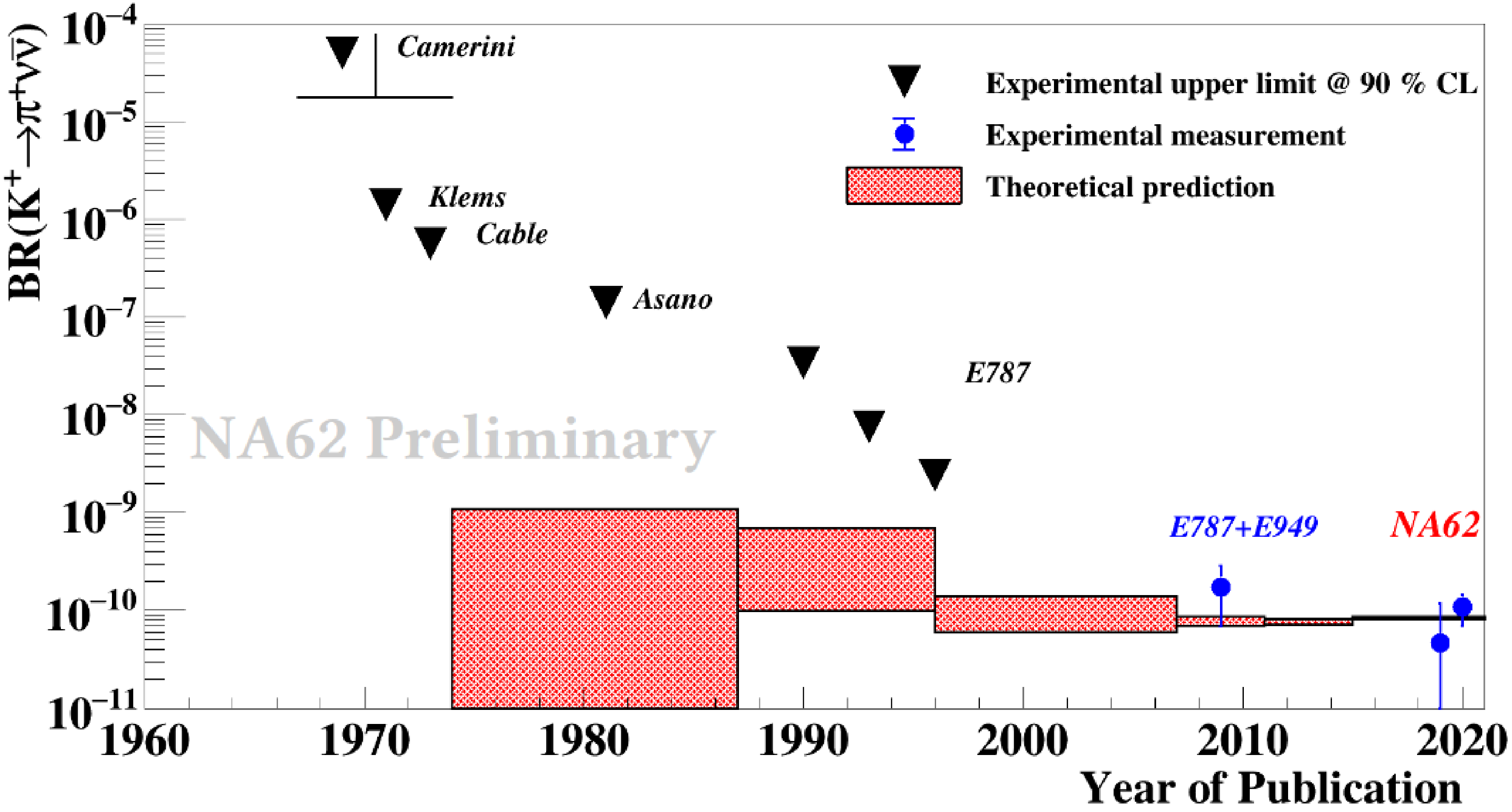


NA62 Run 1 (2016+2017+2018) result (68% CL):

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.4}{}_{stat} \pm 0.9_{syst}\right) \times 10^{-11}$ (3.4σ significance and within 1σ of SM)

[JHEP 06 (2021) 093]

Comparison with world data



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The π^0 Dalitz decay

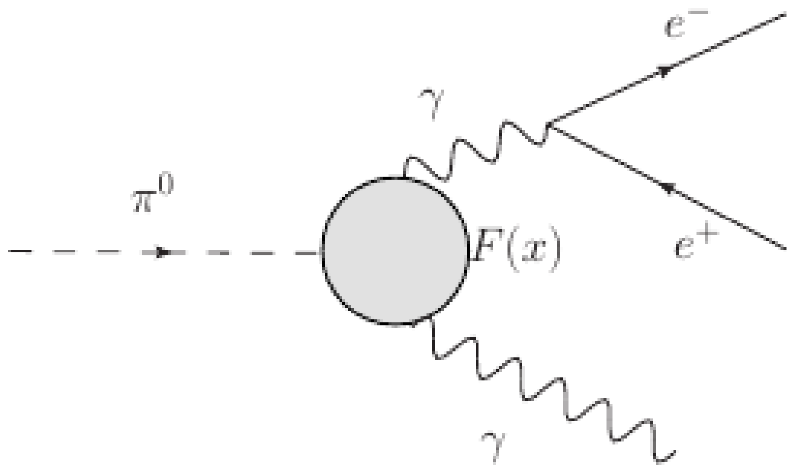
- In 1951 at the University of Birmingham, the π^0 Dalitz (π_D^0) decay was hypothesised by Richard Dalitz.

- Instead of decaying to two real photons (most common way), one photon is virtual and produces an electron-positron pair:
$$\pi^0 \rightarrow e^+e^-\gamma$$

- The decay rate depends on the electromagnetic transition form factor $F(x)$, given by QCD in the SM. A form factor describes the underlying physics of the interaction by providing the momentum dependence of the matrix element. It can be measured by comparing the point-like ($p-l$) QED calculation to the rate observed in real life.

$$\frac{d\Gamma}{dq^2} = \left.\frac{d\Gamma}{dq^2}\right|_{p-l} \left|\mathcal{F}\left(q^2\right)\right|^2$$

q=four-momentum transfer



Decay	PDG branching ratio (%)
$\pi^0 \rightarrow \gamma\gamma$	98.823 ± 0.034
$\pi^0 \rightarrow e^+e^-\gamma$	1.174 ± 0.035
$\pi^0 \rightarrow e^+e^-e^+e^-$	$(3.34 \pm 0.16) \times 10^{-5}$
$\pi^0 \rightarrow e^+e^-$	$(6.46 \pm 0.33) \times 10^{-8}$

The π^0 Dalitz decay

- Convenient to introduce two kinematic variables (M_{ee} is the e^+e^- invariant mass; p are four momenta):

$$x = \left(\frac{M_{ee}}{m_{\pi^0}}\right)^2 = \frac{(p_{e^+} + p_{e^-})^2}{m_{\pi^0}^2}, \quad y = \frac{2p_{\pi^0} \cdot (p_{e^+} - p_{e^-})}{m_{\pi^0}^2 (1-x)}$$

- The leading order decay rate is then given by:

$$\frac{d^2\Gamma^{LO}(\pi_D^0)}{dxdy} = \Gamma(\pi^0 \to \gamma\gamma) \frac{\alpha}{4\pi} \frac{(1-x)^3}{x} \left(1 + y^2 + \frac{r^2}{x}\right) |\mathcal{F}(x)|^2$$

- But what about next-to-leading order? Require radiative corrections, leading to a correction δ to the LO term:

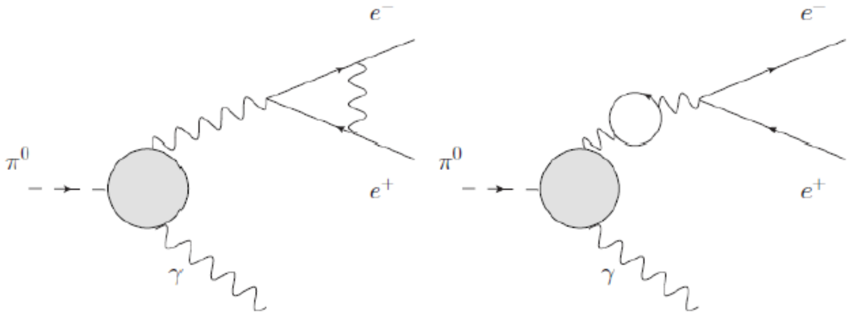
$$\frac{d^2\Gamma(\pi_D^0)}{dxdy} = \frac{d^2\Gamma^{LO}(\pi_D^0)}{dxdy} (1 + \delta(x,y))$$

- Three sources of radiative corrections have been investigated thus far: virtual, one-photon-irreducible and bremsstrahlung. The radiative correction function δ can be split into components depending on their origin:

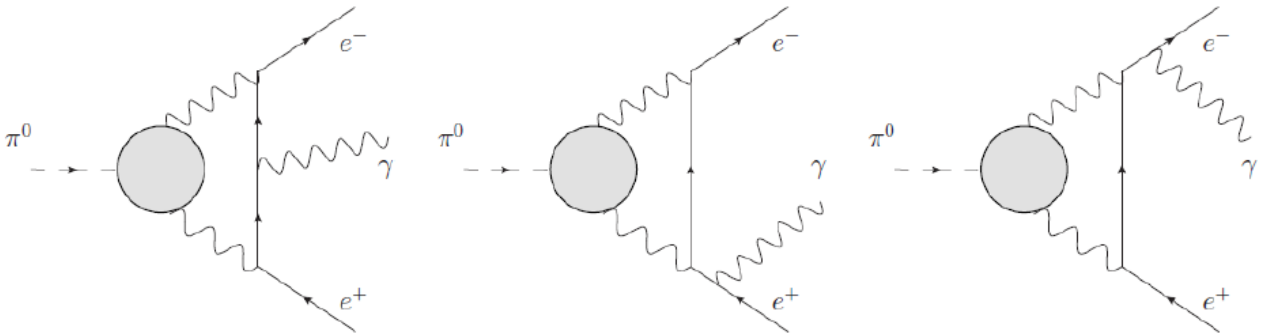
$$\delta = \delta^{virt} + \delta^{1\gamma IR} + \delta^{BS}$$

Types of radiative correction

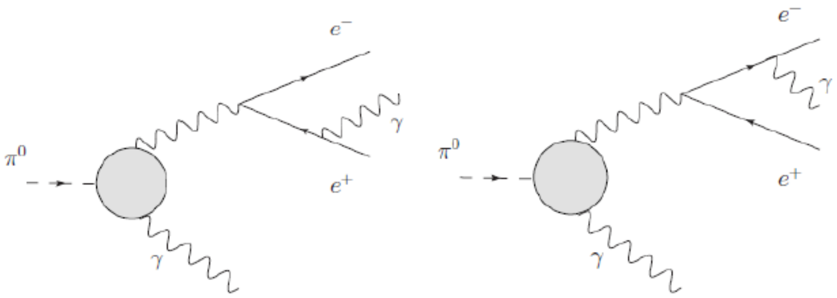
Virtual



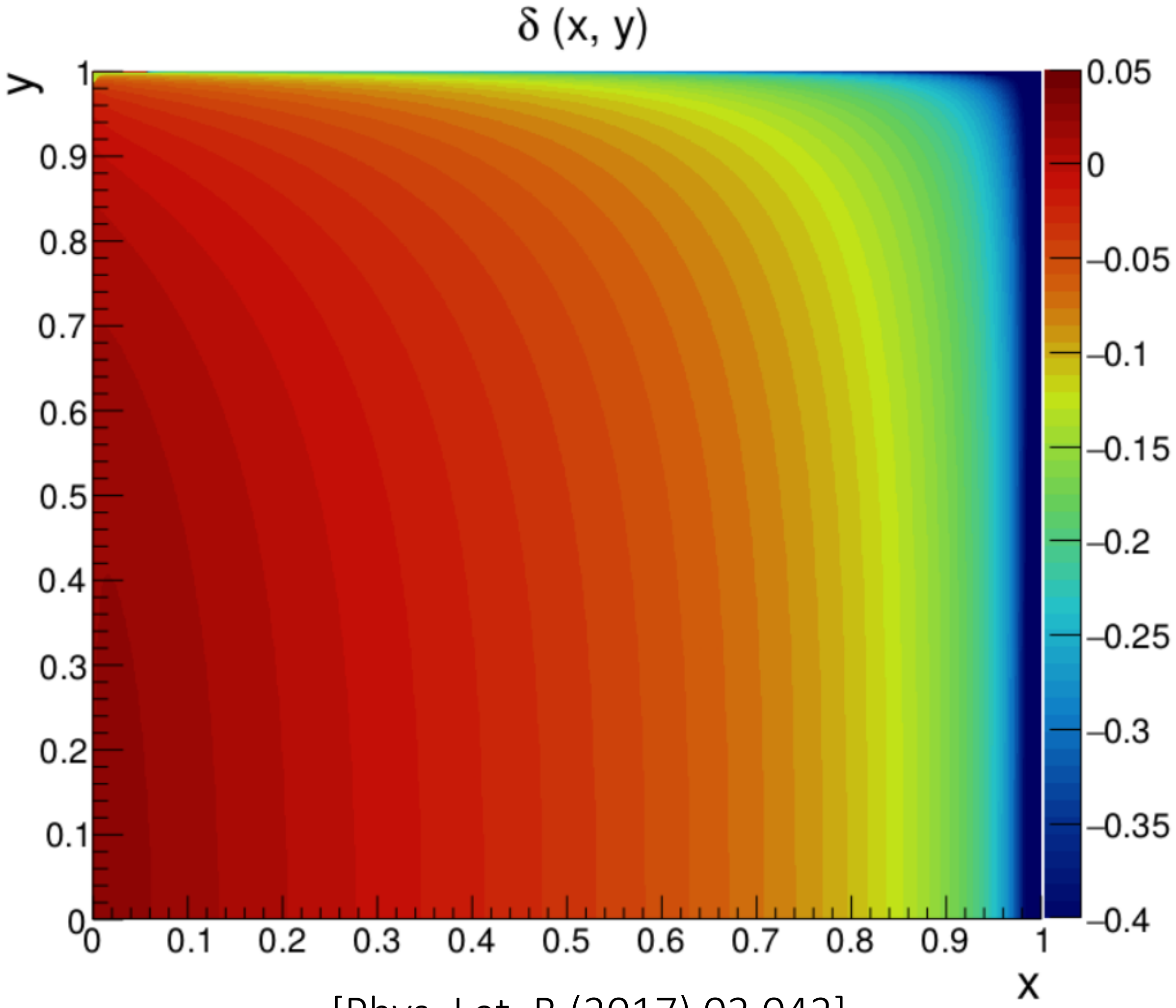
One-photon irreducible



Bremsstrahlung



Size of the radiative corrections

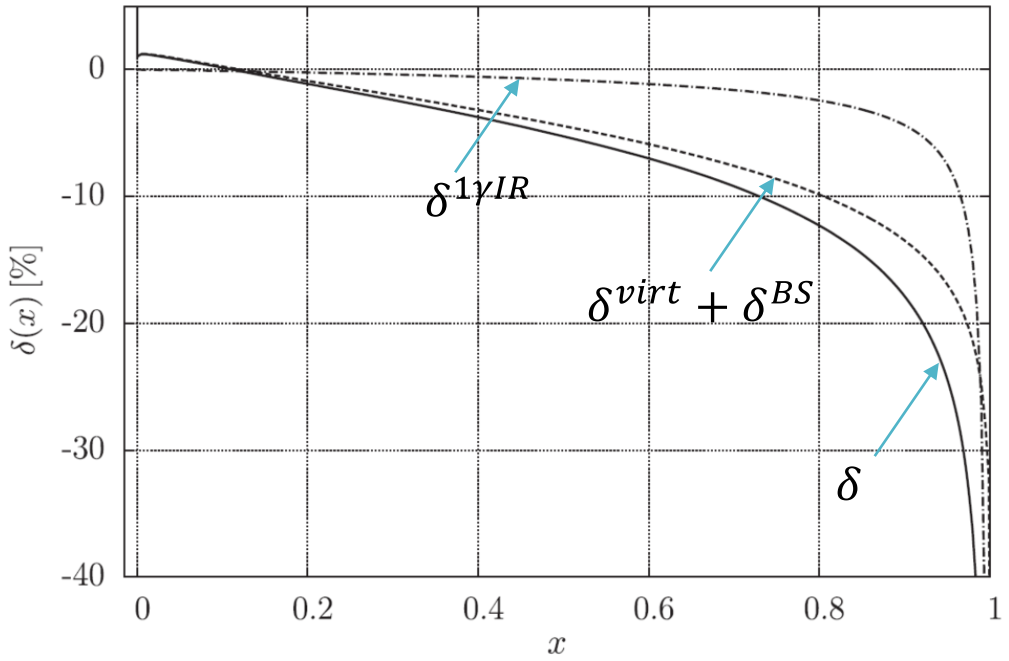


[Phys. Let. B (2017) 02 042]

At the extremes of the x and y distributions, the radiative corrections can alter the LO decay rate by up to 40%.

Hence very important to account for correctly!

Size of the radiative corrections



The virtual and bremsstrahlung calculations were completed in the 1970s.

But the one-photon-irreducible component was not included until 2015 (motivated by a new precision π_D^0 form factor measurement at NA62) [Phys. Rev. D 92, 054027] [J. Phys. Let. B. (2017) 02042].

The new radiative corrections led to a new SM $B(\pi_D^0)$ with a 0.05% relative uncertainty:

$$B(\pi_D^0)_{SM} = (1.1836 \pm 0.0006)\%$$

This is very precise compared to the current PDG value that has a 3% relative uncertainty:

$$B(\pi_D^0)_{PDG} = (1.174 \pm 0.035)\%$$

Most recent $B(\pi_D^0)$ measurement

There has actually been a more precise measurement of $B(\pi_D^0)$ but it is excluded from the PDG average.

It was published by the KTeV collaboration in 2019 [Phys. Rev. D 100, 032003], based on data taken in 1999:

$$B(\pi_D^0)_{KTeV} = (1.1559 \pm 0.0116)\ \%$$

This measurement has a 1% uncertainty and is 2.4σ from the SM calculation.

It was excluded from the PDG average because the measurement was done in the kinematic range $M_{ee} > 15$ MeV/c and then extrapolated to the full M_{ee} range using the radiative corrections published in 1972 that excluded the one-photon irreducible component (and no error on this extrapolation was accounted for).

Interestingly, using the NA62 Monte Carlo decay generators that include the full radiative corrections, we can correct the KTeV result (this only corrects the extrapolation, not any MC acceptance effects):

$$B(\pi_D^0)_{KTeV,\,full\,rad\,corr} = (1.1749 \pm 0.0118)\ \%$$

which is within 1σ of the SM calculation.

Motivation for a new $B(\pi^0_D)$ measurement

Lots of motivations!

- Since the most recent theoretical advances of the SM $B(\pi^0_D)$ calculation, there has not been an experimental branching ratio measurement that includes the most recent radiative corrections.

- It is used as normalisation for several rare π^0 decay measurements:
  - Dominates uncertainty on $B(\pi^0 \to e^+e^-e^+e^-)$
  - Largest source of uncertainty on $B(\pi^0 \to e^+e^-)$

- It is also starting to limit measurements in the rare kaon sector:
  - $K^+ \to \pi^+e^+e^-$
  - $K^\pm \to \pi^\pm\pi^0e^+e^-$
  - $K_{L,S} \to \pi^+\pi^-e^+e^-$

Can NA62 produce a new, precise, measurement of $B(\pi^0_D)$ that includes all radiative corrections?

$B(\pi_D^0)$ analysis strategy at NA62

Best decay chain to use at NA62: $K^+ \to \pi^+\pi^0$ (~20% BR) with $\pi^0 \to e^+e^-\gamma$ (~1% BR).

The π_D^0 decay is not rare meaning statistics shouldn't be a problem! Hence want to reduce systematics as much as possible.

- Normalise the measurement using $K^+ \to \pi^+\pi^0$ with $\pi^0 \to anything$. The signal selection can thus be a stricter version of the normalisation selection, leading to systematics cancellation.
- Use as few detectors as possible in the analysis.
- Use the minimum-bias trigger (requires a signal in the NA48-CHOD, akin to the presence of a charged particle; has a downscaling of 400 in Run 1).

Notation used in the following slides:

$\epsilon = \frac{N_{\pi_D^0}}{N_\pi^0}$ = ratio between the number of π_D^0 events (signal) and the number of π^0 events (normalisation).

$B(\pi_D^0)$ analysis strategy at NA62

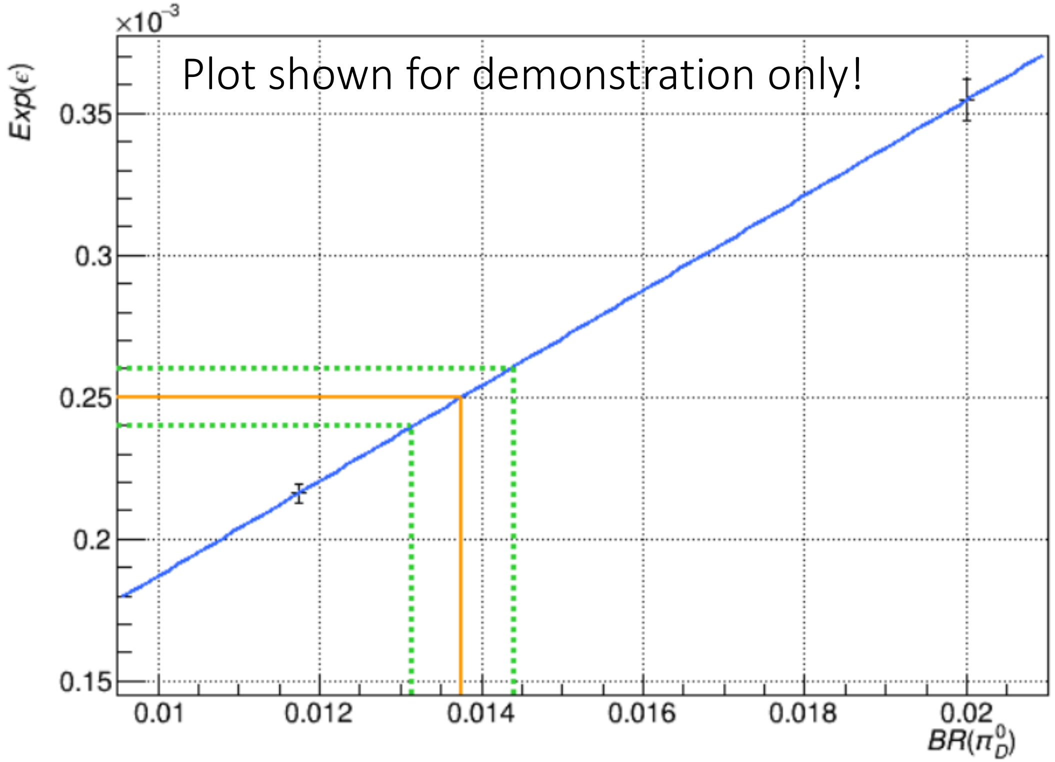
- To actually do the measurement, vary $B(\pi_D^0)$ in the MC and calculate the expected value of ϵ given some value of $B(\pi_D^0)$:

$$Exp(\epsilon) = \frac{N_{\pi_D^0}}{N_{\pi^0}}$$

- Plot $Exp(\epsilon)$ against $B(\pi_D^0)$ and perform a linear fit.
- Using the fit, find the measured $B(\pi_D^0)$ given the measured value of ϵ from data, as shown by the solid line on the plot:

$$\epsilon^{data} = \frac{N_{\pi_D^0}^{data}}{N_{\pi^0}^{data}}$$

- Statistical error on the measured ϵ is converted to a statistical error on $B(\pi_D^0)$.



$B(\pi^0_D)$ analysis selection

Normalisation ($K^+ \rightarrow \pi^+\pi^0_{everything}$) selection:

- Reconstruction of exactly one π^+ track that crosses the beam axis within the decay volume
- $K^+ - \pi^+$ time matched
- π^+ ID and μ^+ rejection
- Kinematics ($m^2_{miss} = (P_K - P_\pi)^2$; also defines signal region)

≡

Signal ($K^+ \rightarrow \pi^+\pi^0_D$) selection:

- Reconstruction of exactly one π^+ track that crosses the beam axis within the decay volume
- $K^+ - \pi^+$ time matched
- π^+ ID and μ^+ rejection
- Kinematics ($m^2_{miss} = (P_K - P_\pi)^2$; also defines signal region)
- Decay vertex has three tracks, one of which is the π^+ found in the normalisation selection
- Other two tracks:
  - $e^\pm$ ID
  - Separated at STRAW (to remove γ that undergo conversion in the STRAW gas)
  - In-time with the π^+ track

N.B. No reconstruction of the photon is carried out in an attempt to reduce the number of detectors used in the analysis.

Pileup treatment

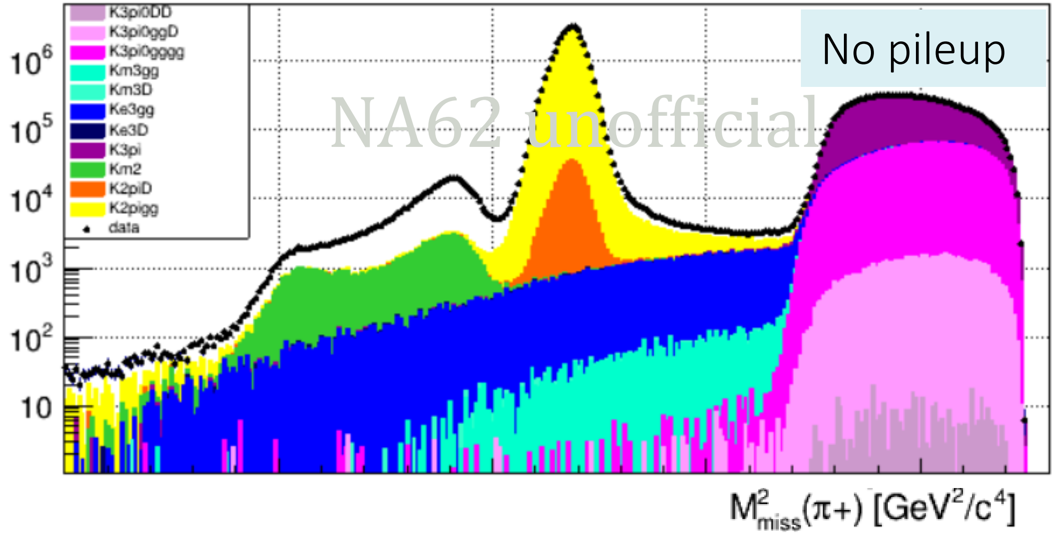
Due to the high intensity nature of NA62 and the (relatively, compared to other measurements conducted) large branching ratio we're trying to measure, pileup plays a very important role in the analysis.

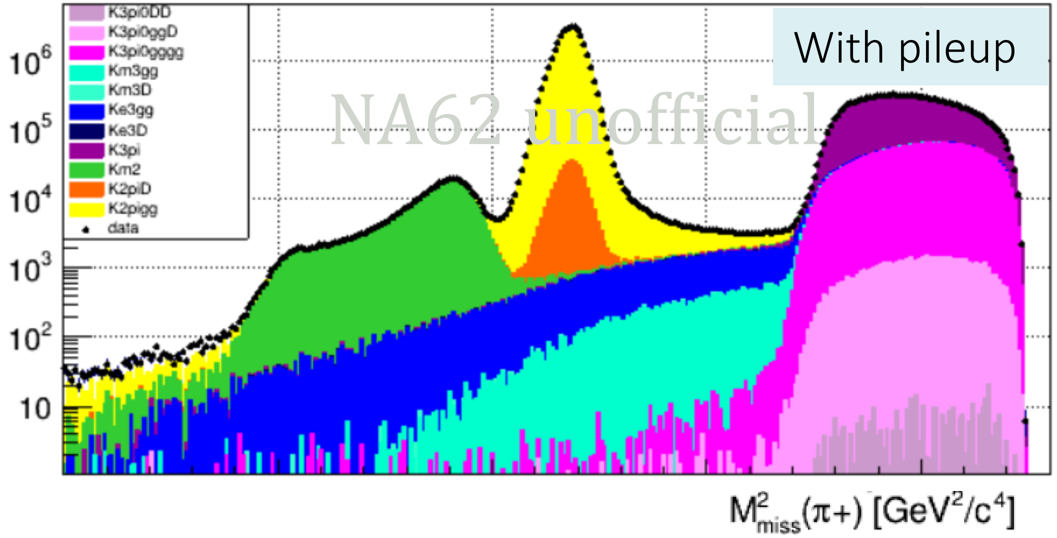
Without any pileup treatment, find very poor data/MC agreement.

To properly simulate pileup, inject randomly chosen MC events from a difference MC sample at the reconstruction stage. This sample contains a beam that is not forced to decay (hence includes decays, inelastic scattering, kaons that pass straight through…).

This provides a much better pileup simulation than the traditional approach of injecting hits into the detectors.

Plots produced using normalisation selection





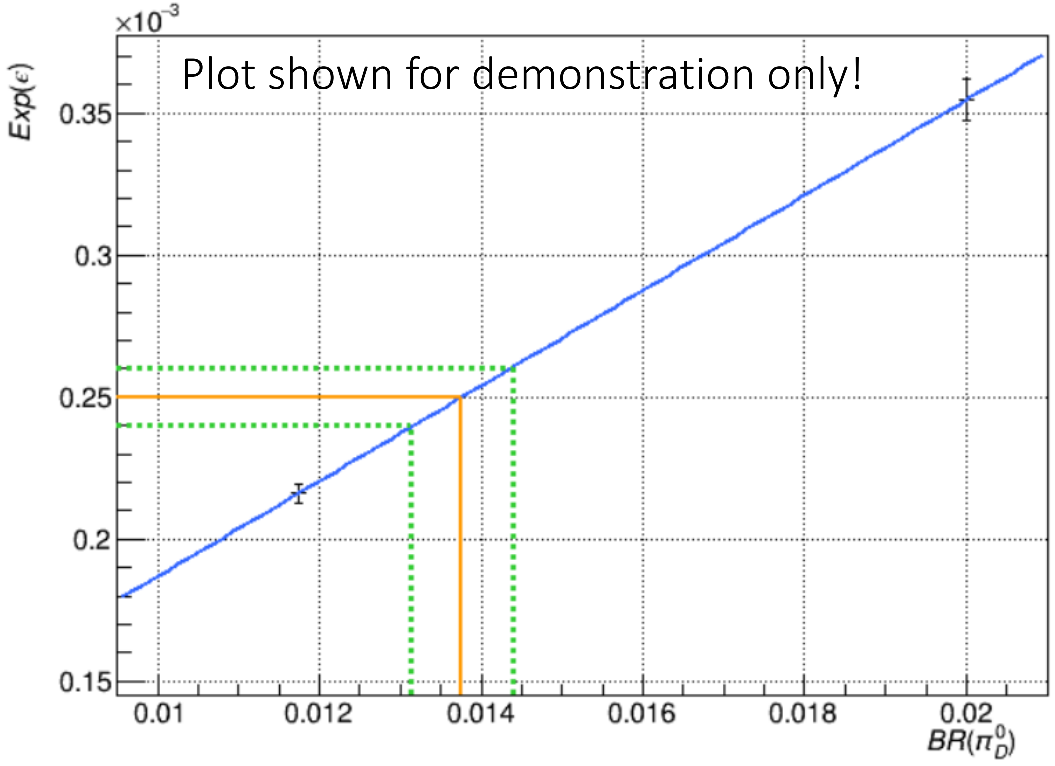
MC samples

For the $B(\pi_D^0)$ measurement, we need (at least) two data points in order to perform the linear fit. Let's stick with only two for now…

What value for $B(\pi_D^0)$ should be used for each point?

- Want to minimise the distance between the points so that the linear approximation holds.
- Want to minimise extrapolation.

Hence, have one point at the PDG $B(\pi_D^0)$. Where is best for the second point?

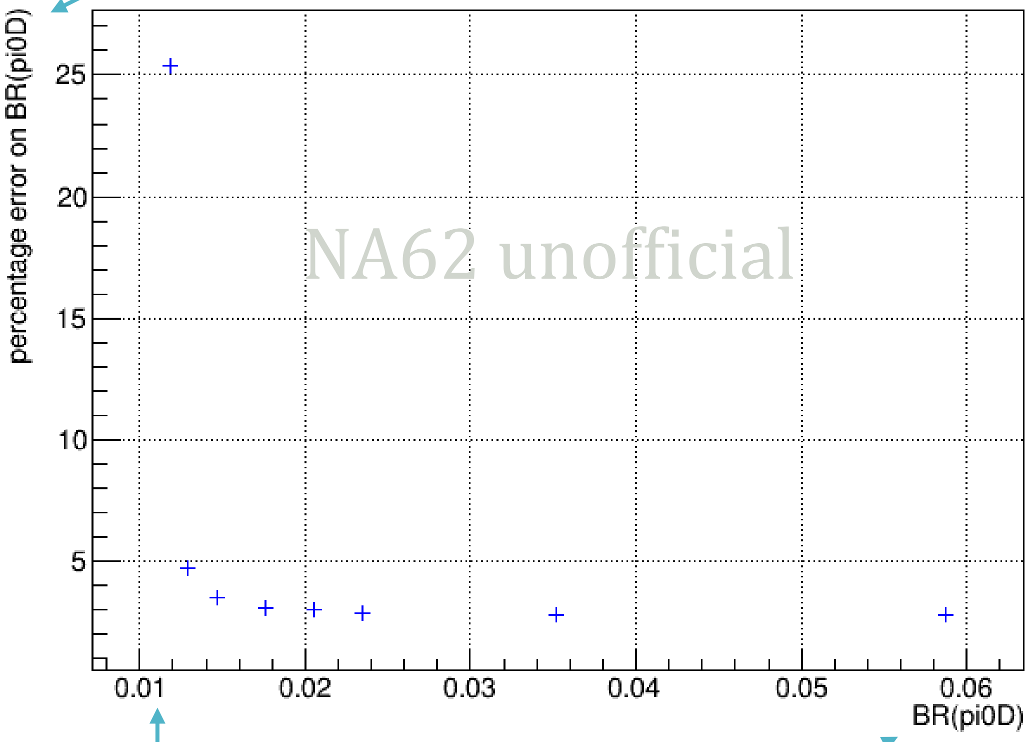


MC samples

With one point at the PDG $B(\pi_D^0)$. Where is best for the second point?

- Can estimate the $B(\pi_D^0)$ and its uncertainty for different positions by scaling the $N_{\pi_D^0}$ observed.
- Systematic error on $B(\pi_D^0)$ from the fit uncertainties stops reducing once we reach $B(\pi_D^0) \sim 0.02$ (approx. twice the PDG value).
- To keep in-line with the linear approximation, use 0.02 as the second data point.

Systematic error on $BR(\pi_D^0)$ from the fit uncertainties

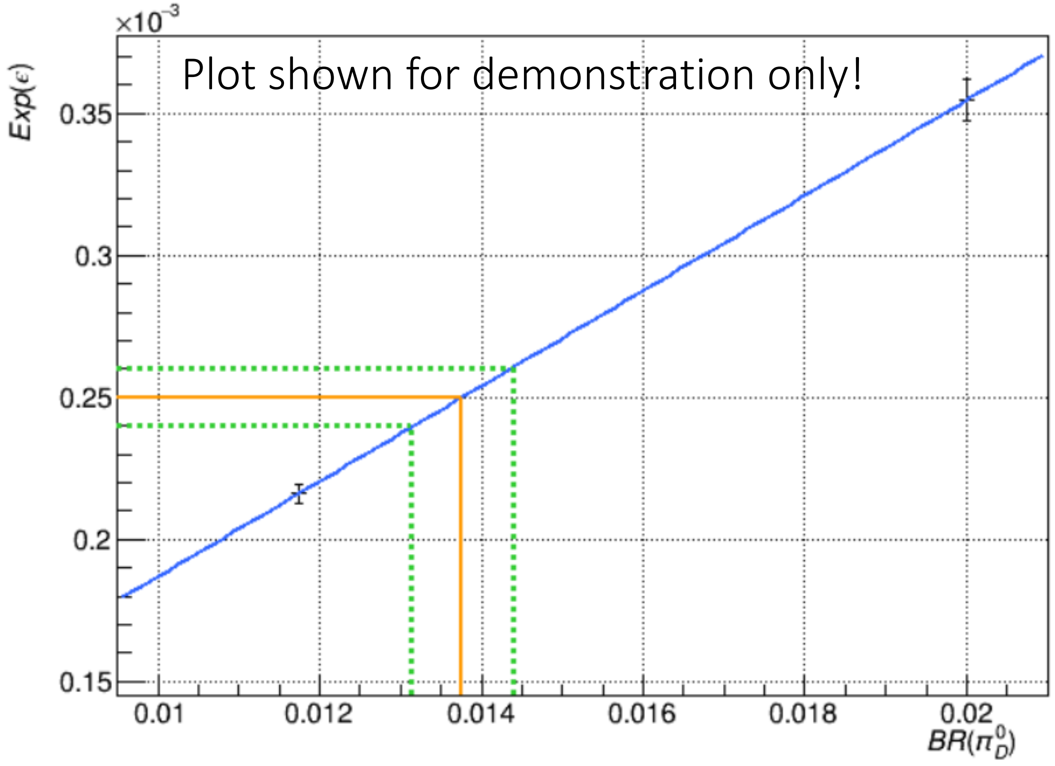


PDG value

Position of second data point

MC samples

- The MC sample used is a combination of the 6 main K^+ decay modes (with $\pi^0_{\gamma\gamma}$ and π^0_D too) (more details on this in back-up).
- With this MC sample, only ~0.2% of the events will be $K^+ \to \pi^+\pi^0_D$ decays due to suppression by the branching ratio.
- Also have suppression by the signal acceptance.
- This means that to obtain a 1% statistical error on a single data point, we require 1 billion MC events
  - With the current NA62 MC samples, we have 800M already available.
  - Leads to a systematic uncertainty on $B(\pi^0_D)$ from the fit of $\sim 1\%$.



Expected statistical and systematic errors

Statistical error from data on $B(\pi^0_D)$ is expected to be sub-dominant

- With 10^{12} K^+ decays in Run 1, expect $O(10^5)$ π^0_D decays in the final signal sample $\Rightarrow$ σ_{stat}~0.3%.

Systematic errors expected to be dominant

- Assuming 1 billion MC events are available, the systematic error from the fit uncertainties is expected to be $\sim 1\%$.
- This analysis is also unusual in that the signal and normalisation decays have different numbers of charged particles in the final state. The track reconstruction efficiency (three tracks vs. one track) is thus expected to play a vital role. Initial studies suggest a systematic error of $\sim 0.5\%$.
- Also $e^{\pm}$ PID, trigger… (expected to be less than that above but studies in progress)

A $B(\pi^0_D)$ measurement at NA62 should hence be able to improve on the 3% PDG precision.

Outline

Introduction to NA62

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

The $\pi^0 \to e^+e^-\gamma$ decay

Conclusions and the future of NA62

- History of kaon physics at CERN
- Physics motivation
- NA62 beam and detector layout

- Latest analysis improvements
- Results from data taken in Run 1

- Theory
- Experimental status
- Prospects for a measurement at NA62

Conclusions

NA62 has collected 6×10^{12} K^+ decays in flight during Run 1, with multiple world leading analyses taking place.

Summary of this talk:

- 20 $K^+ \to \pi^+ \nu\bar{\nu}$ candidates observed in Run 1, corresponding to a signal significance of 3.5σ [JHEP 06 (2021) 093].
- A $B(\pi^0_D)$ measurement at NA62 should be able to incorporate the most up-to-date radiative corrections as well as improve on the current PDG average.

Large variety of other measurements have been/are being conducted at NA62:

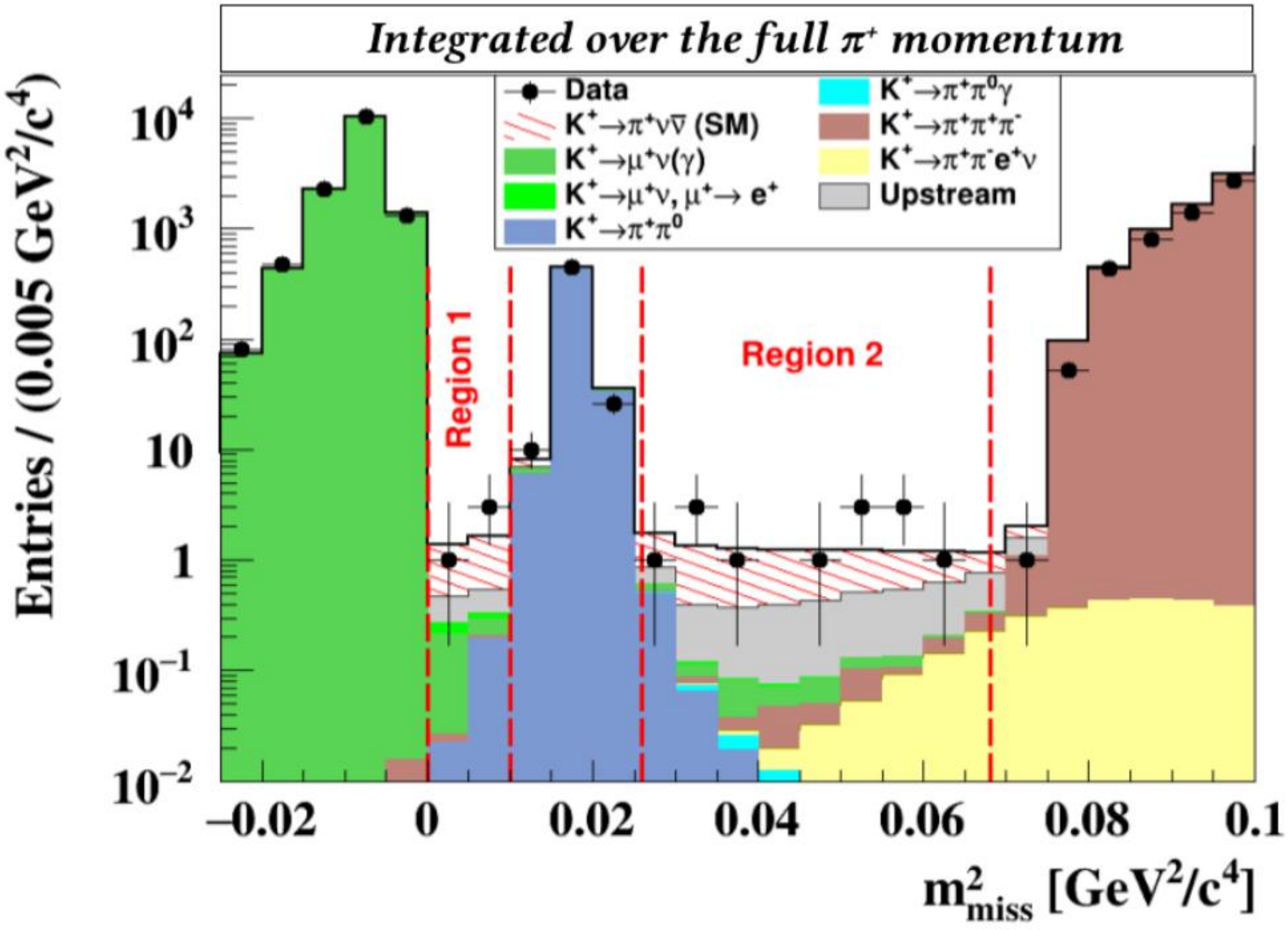
- Rare decay and precision measurements (e.g. $K^+ \to \pi^+\mu^+\mu^-$ [ICHEP 2020 proceedings]).
- Exotic searches of e.g. HNL in $K^+ \to l^+ N$ [PLB 807 (2020) 135599, PLB 816 (2021) 136259].
- Searches for forbidden decays e.g. LFV and LNV [Phys. Rev. Lett. 127, 131802 (2021)].

NA62 Run 2 started in July 2021 and will continue until LS3. Improvements relative to Run 1:

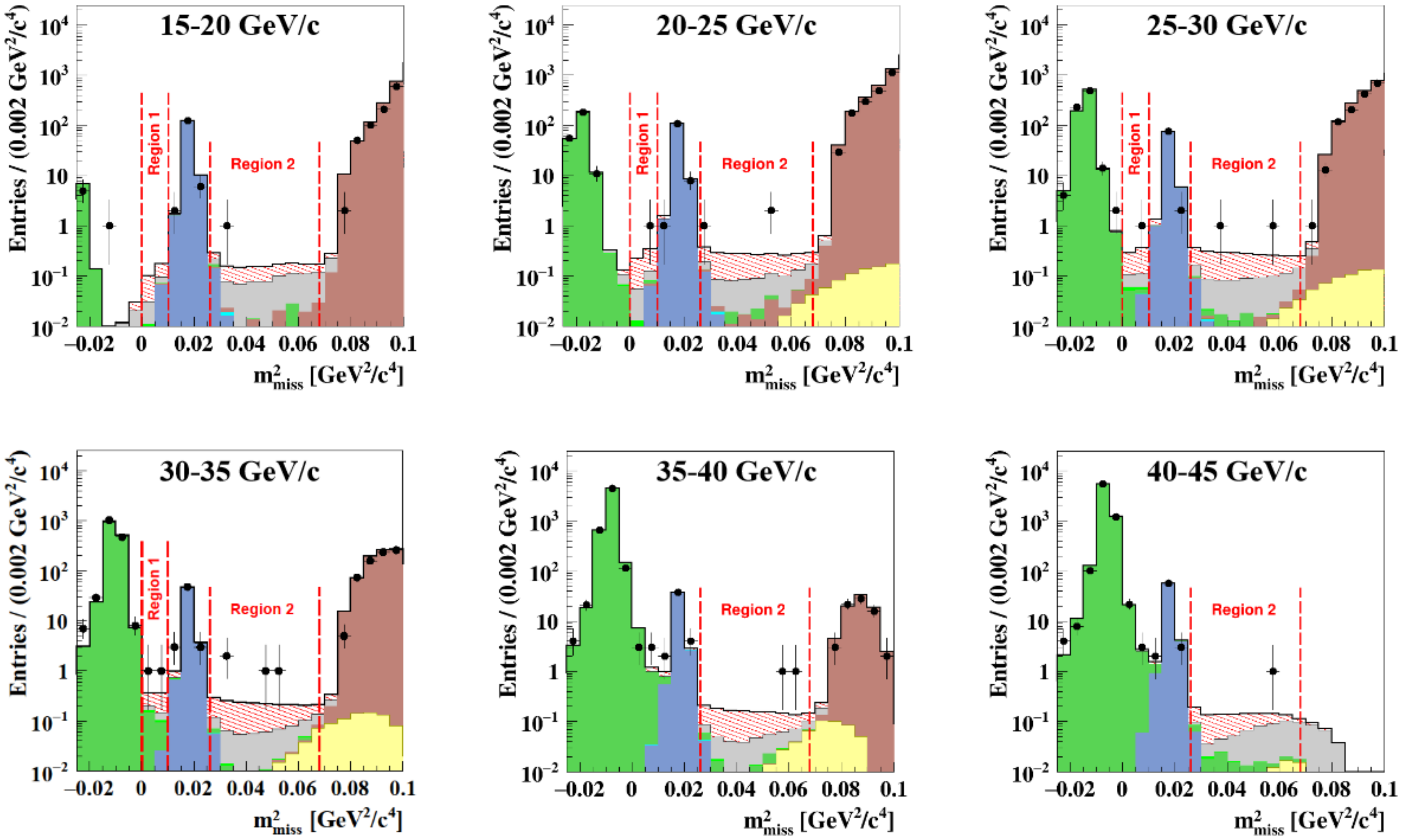
- Higher intensity (70% -> 100%).
- 4th GTK station added.
- Three new veto counters placed upstream or downstream of decay region.

Back-up

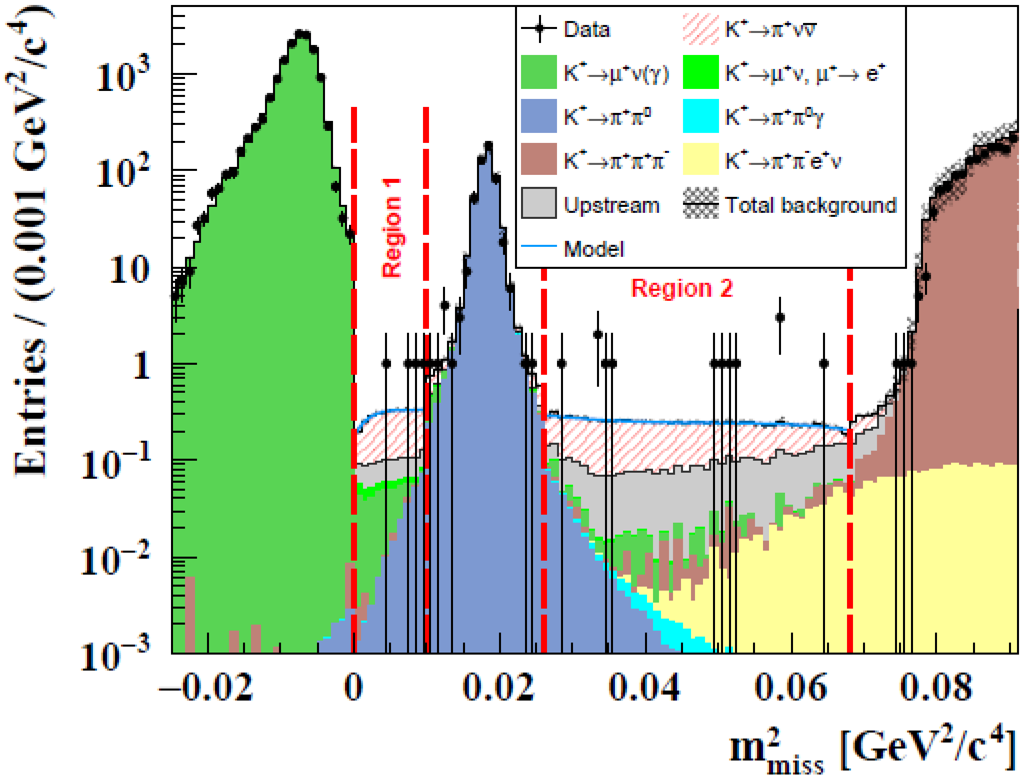
$K^+ \to \pi^+ \nu\bar{\nu}$ opened signal regions

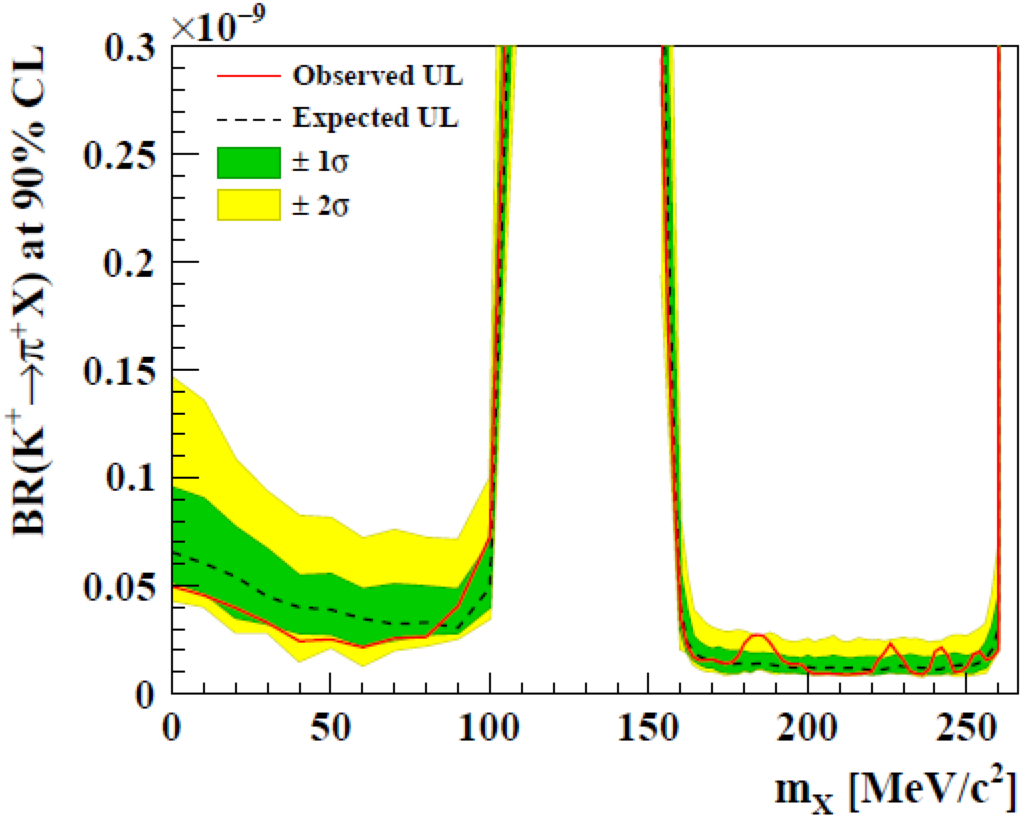


$K^+ \to \pi^+ \nu \bar{\nu}$ opened signal regions



$K^+ \to \pi^+ \nu\bar{\nu}$ re-interpreted as $K^+ \to \pi^+ X$

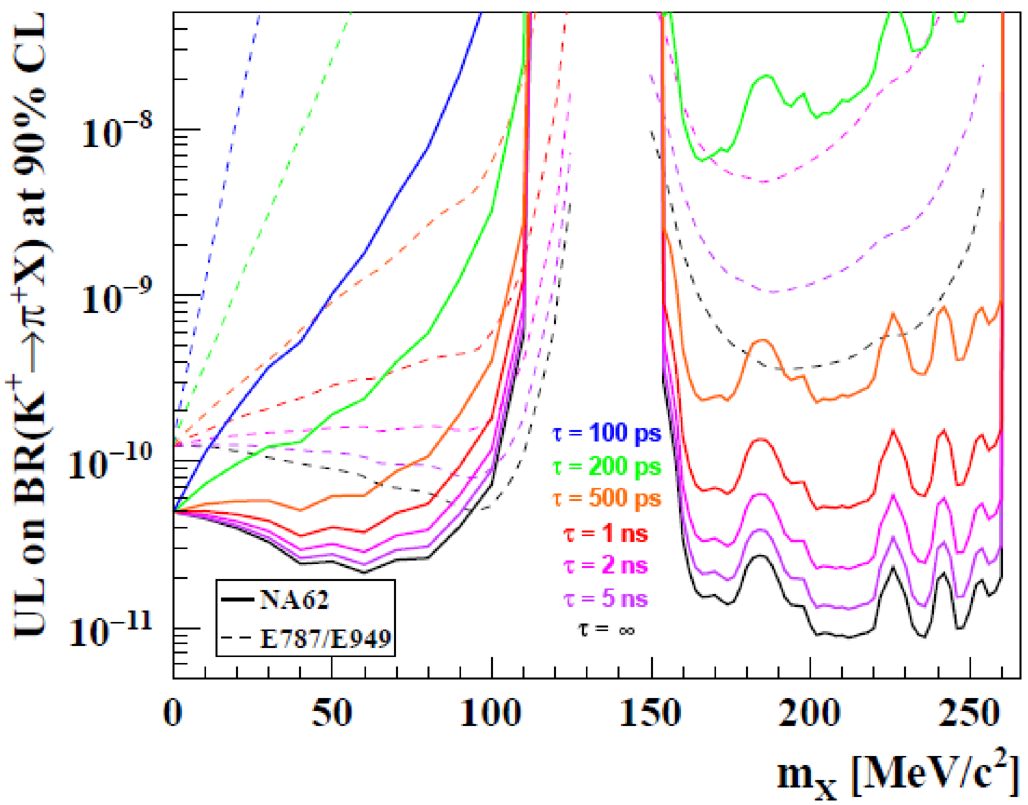


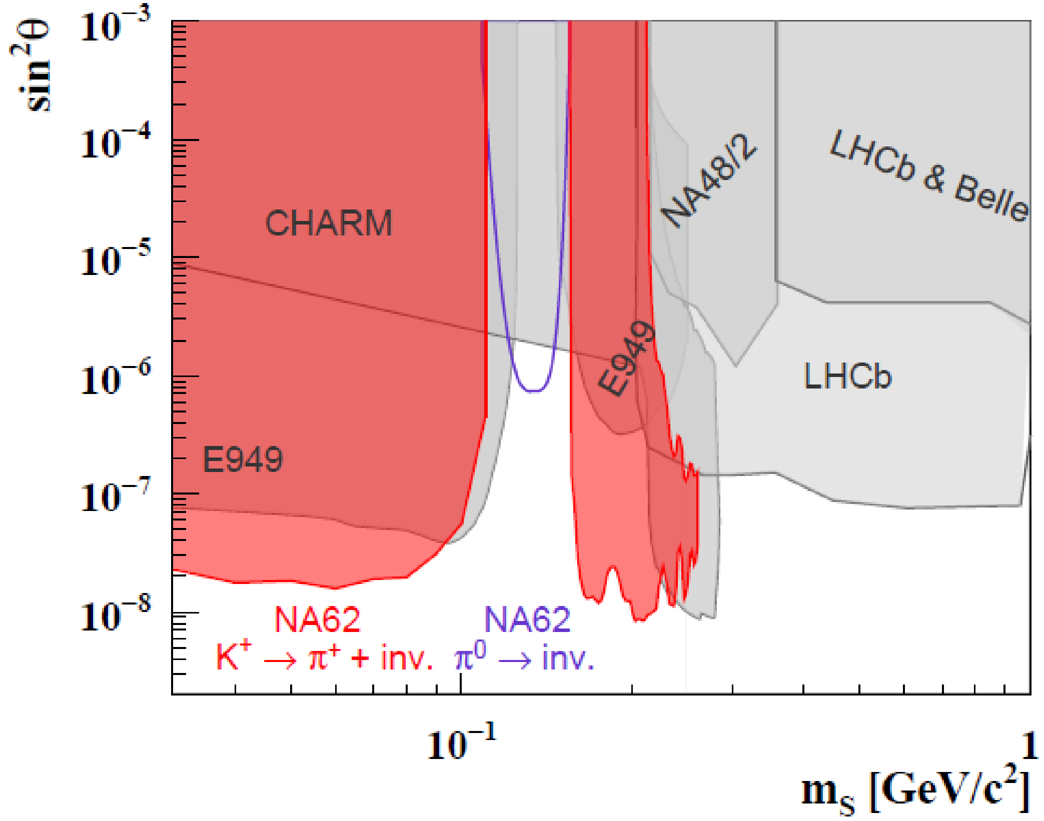


Peak search performed, looking for peak at m_X^2.

[JHEP 06 (2021) 093]

$K^+ \to \pi^+ \nu\bar{\nu}$ re-interpreted as $K^+ \to \pi^+ X$

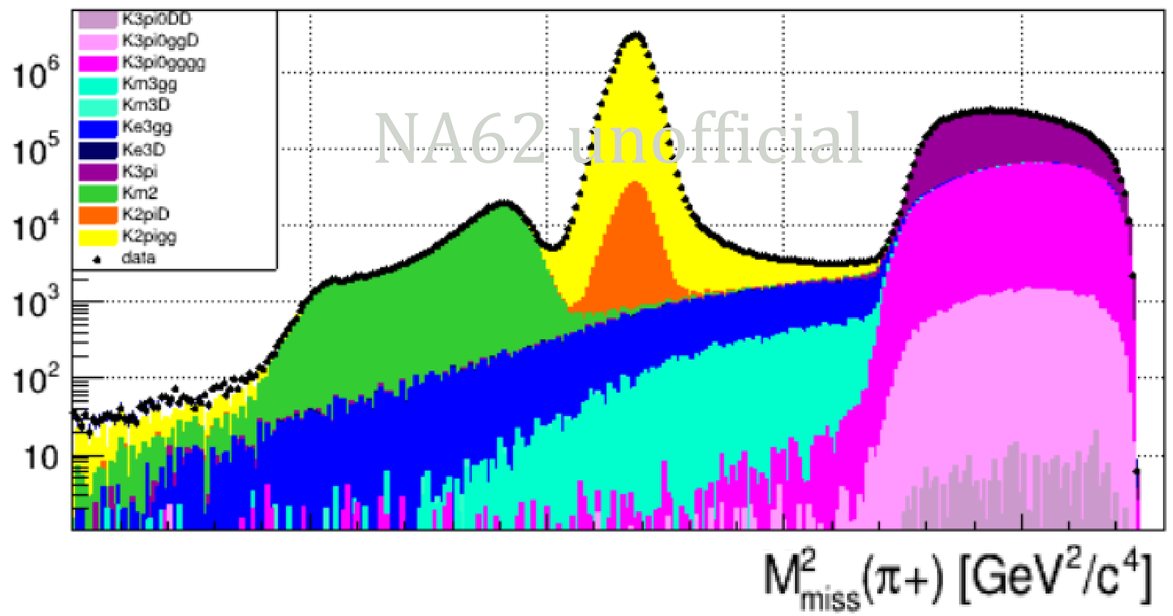




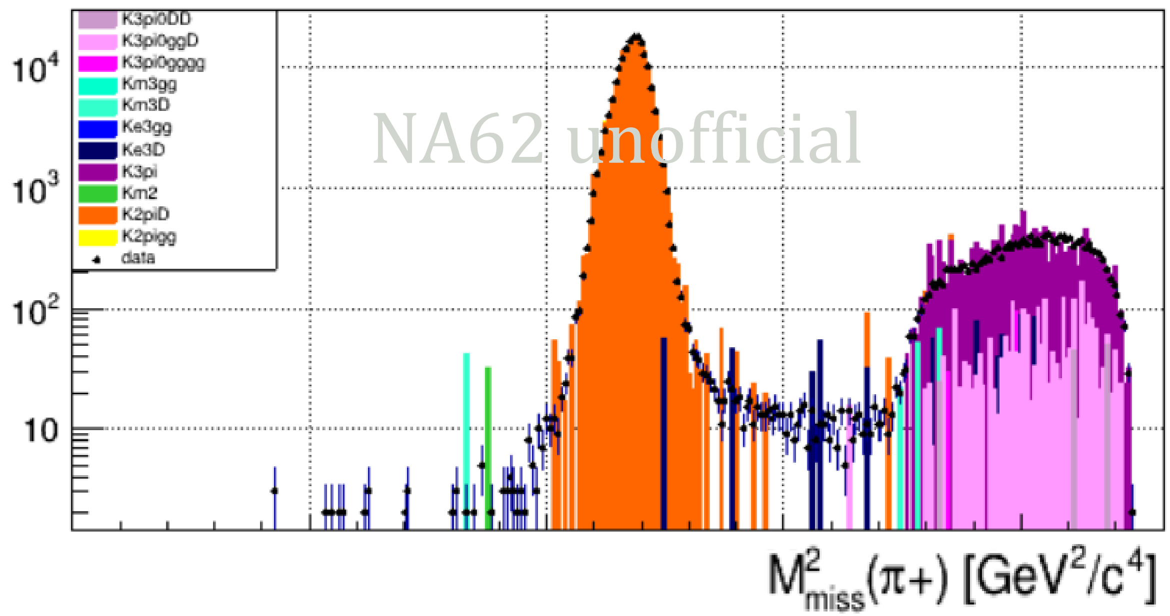
Interpretation if X is a dark-sector scalar, S, which mixes with the Higgs boson according to the mixing parameter $\sin^2\theta$.

π_D^0 analysis signal regions

Normalisation

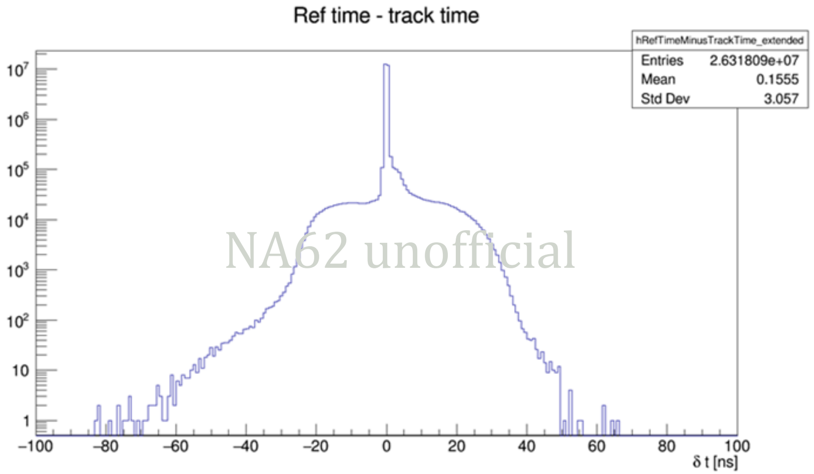


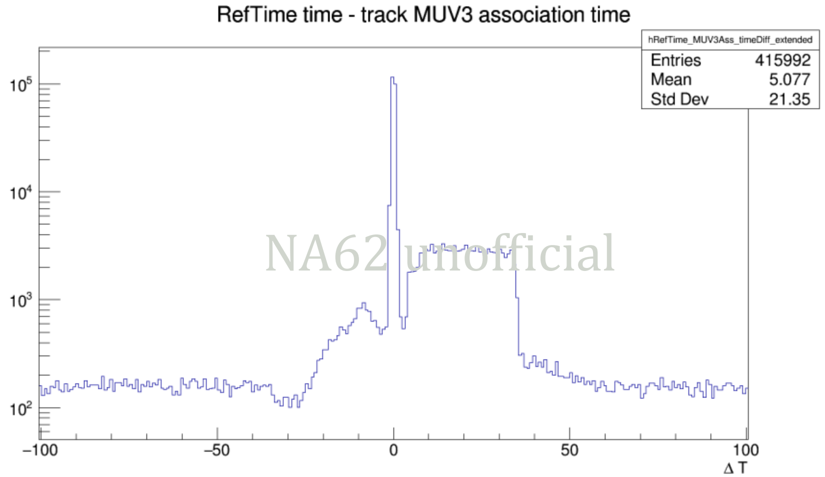
Signal



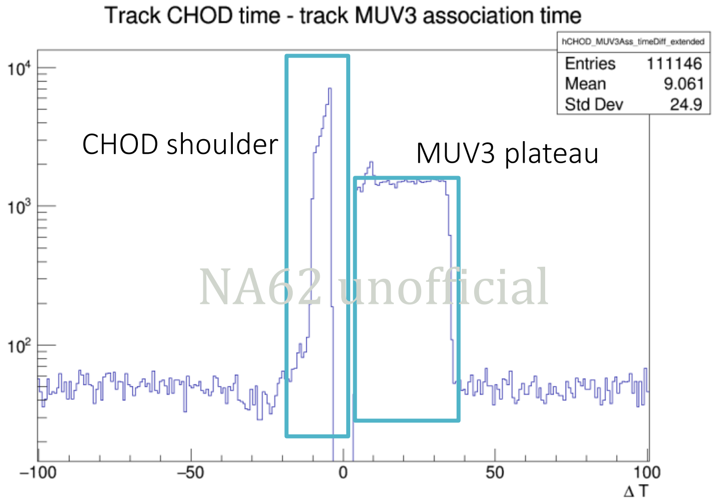
WIP: figures produced with ~40% of total MC available

Pileup effects





Altered π^0 selections used to produce these plots.



Both features caused by detector deadtime, causing the selected track to be associated with a hit at an earlier time. Without simulation of this pileup effect, find very poor data/MC agreement.

MC samples in π_D^0 analysis

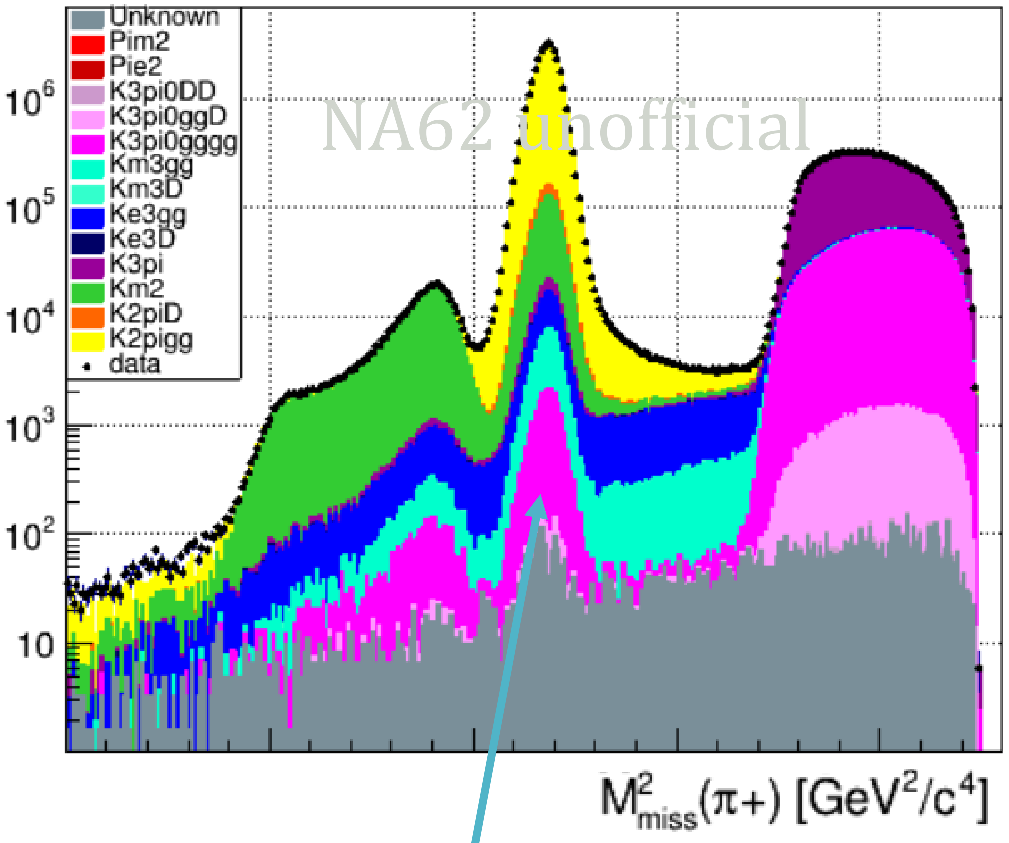
How much MC is required and what type of MC is required?

Traditionally in NA62, one MC sample contains one decay mode, the analysis is run on that one decay mode and then multiple MC samples are combined by normalising them with respect to each other using the acceptances and branching ratios.

However, the normalisation (π^0) and signal (π_D^0) decays are included in the MC sample used to inject pileup at the reconstruction stage (they have to be to obtain a proper simulation).

- This means that there are normalisation/signal decays present in non-signal MC samples (e.g. π_D^0 events pass the selection in a $K^+ \to \mu^+\nu$ sample), leading to a large over-estimate in the acceptance, making it impossible to correctly normalise each MC sample correctly with respect to each other after running the analysis.

Plot produced using normalisation selection



Normalisation decays present in other MC samples.

MC samples in π_D^0 analysis

Hence need to combine all the MC samples required into a single sample, in the correct proportions (based on BR). This is equivalent to normalising before we run the analysis, rather than after.

- However, this has the negative side-effect of limiting the statistical precision.
- This mixture of MC samples will be referred to as "mixed MC".
- Colour in histograms now represents the true decay mode that was selected (rather than the sample type) and there are no problems with normalisation.