Recent results from NA62 experiment at CERN

A.Antonelli for NA62 collaboration

CD2021 - The 10th International Workshop on Chiral Dynamics November 15-19 2021

A general purpose experiment

NA62

Flavour Physics with kaons

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

Main goal:

BR($K^+ \to \pi^+ \nu\nu$)

Search for lepton flavour and number violation, rare and forbidden decays:

$K^+ \to \pi^- e^+ e^+ (\gamma)$

$K^+ \to \pi^- \mu^+ \mu^+ (\gamma)$

$K^+ \to \gamma l^+ \nu$

$K^+ \to \pi^+ \mu^\pm e^\mp (\gamma)$

$K^+ \to \pi^- \mu^+ e^+ (\gamma)$

$\pi^0 \to e^+ e^-$, $\pi^0 \to e^+ e^- e^+ e^-$

$\pi^0 \to \gamma\gamma\gamma$, $\pi^0 \to \gamma\gamma\gamma\gamma$

Hidden sector Physics

Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles:

Heavy neutral Lepton(**H**)
Dark Photon(**A'**), Axion Like Particle (**ALPs**), Dark Scalar (**S**)

In K decays:

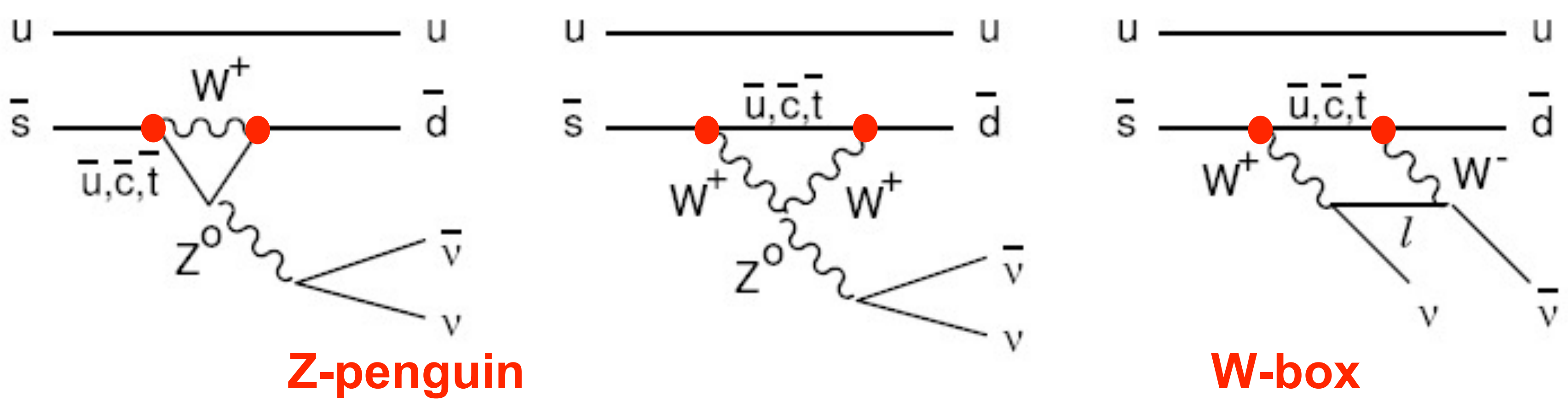
$K^+ \to \mu^+ H$, $K^+ \to e^+ H$

$K^+ \to \pi^+ \pi^0$ with $\pi^0 \to A' \gamma$

K⟶πνν in the Standard Model

Rare decays are a useful mean to search for New Physic complementary to direct search (LHC), exploring higher mass scales : deviation from SM rates is a signal of new degrees of freedom ⟶ Need decays highly suppressed & very well predicted in SM

The **K ⟶ πνν** decay is **FCN neutral current quark transition s⟶dνν**, extremely suppressed in the SM
Forbidden at tree level, dominated by short-distance dynamics (GIM mechanism)



It is characterized by theoretical cleanness in SM prediction: loops and radiative corrections under control, the hadronic matrix elements are obtained from semileptonic decays

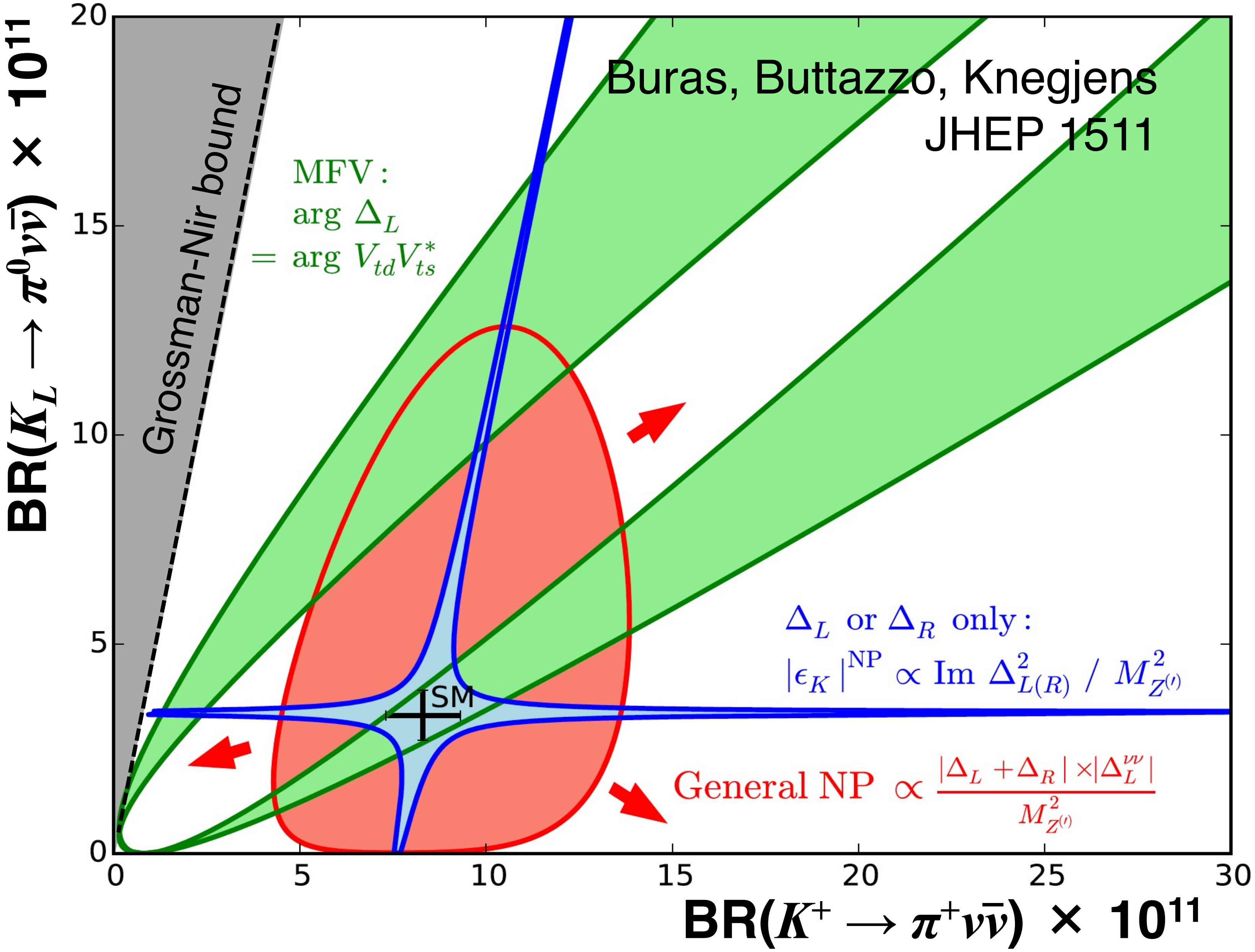
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

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

Main contribution to the errors comes from the uncertainties on the SM input parameters Buras, A.J., Buttazzo, D. et al. JHEP. (2015)033

K → πνν̄ and new physics

New physics affects K^+ and K_L BRs differently
Measurements of both can discriminate among NP scenarios



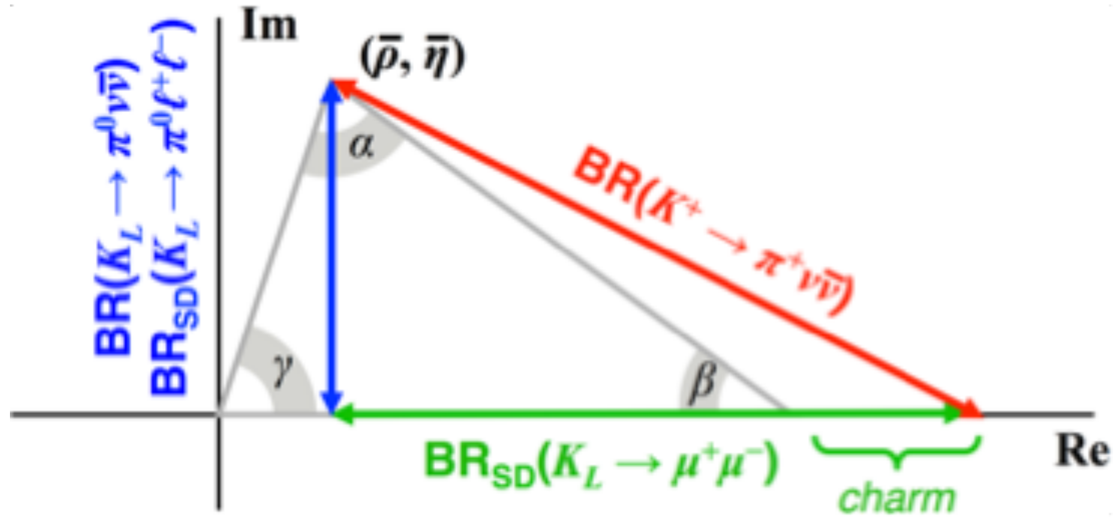
- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - Z/Z' models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models without above constraints
  - Randall-Sundrum
- **Grossman-Nir bound**

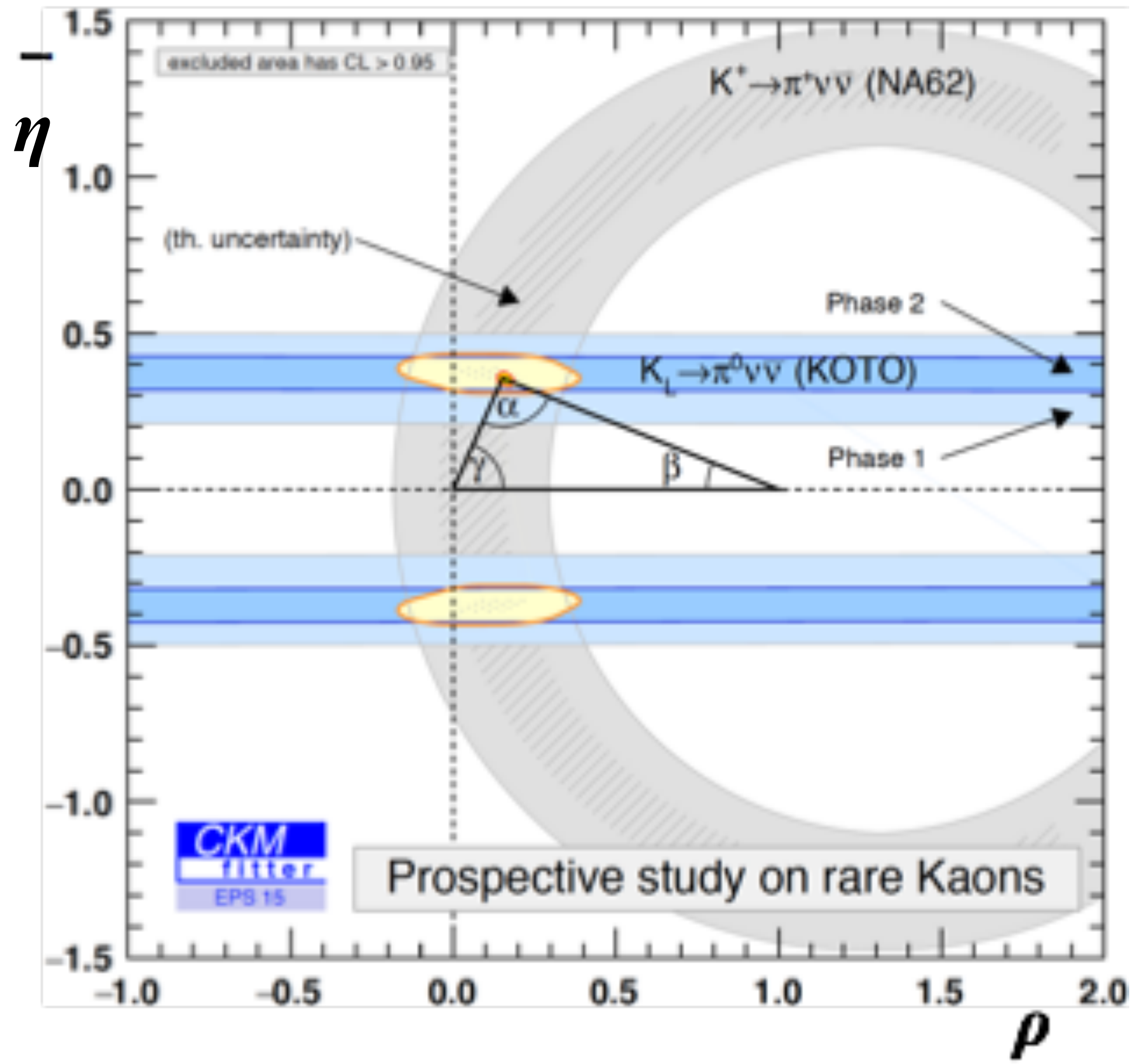
  Model-independent relation

$$\frac{\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})}{\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \leq 1$$

Connection with Flavor Physics

Measurement of BR of charged ($K^+ \to \pi^+ \nu\nu$) and neutral ($K_L \to \pi^0 \nu\nu$) modes can determine the **unitarity triangle** independently from B inputs





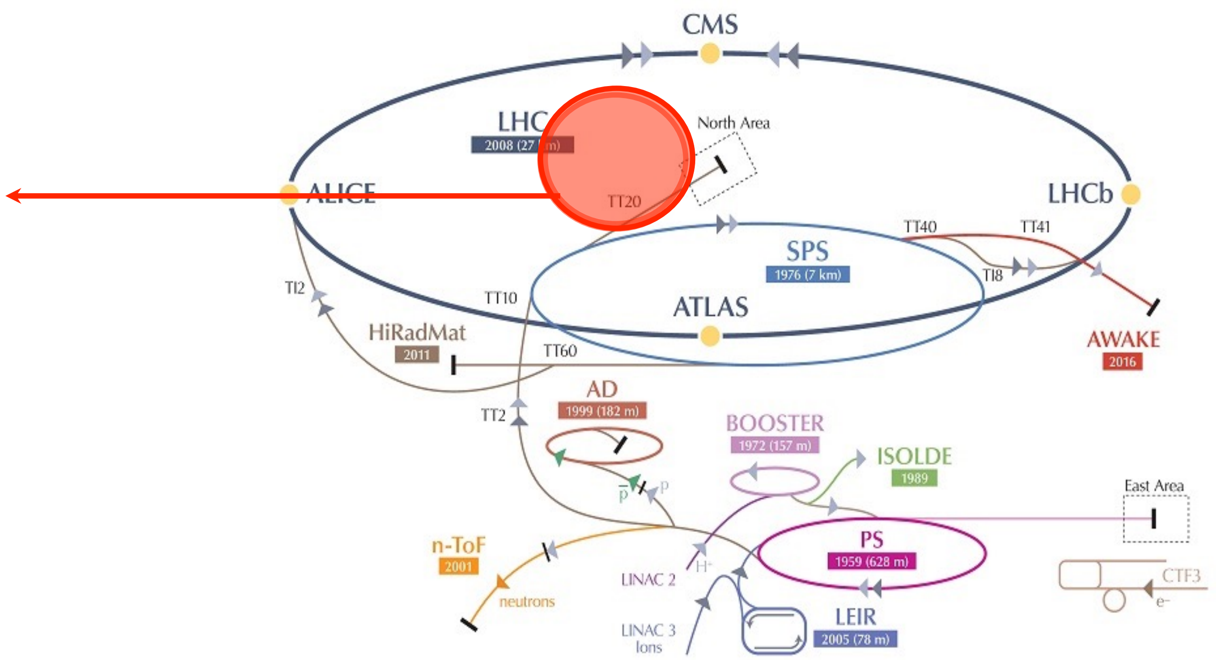
Example of CKM constraints:

- $\mathrm{BR}(K^+ \to \pi^+ \nu\nu)$ to ±10%
- $\mathrm{BR}(K_L \to \pi^0 \nu\nu)$ to 15%

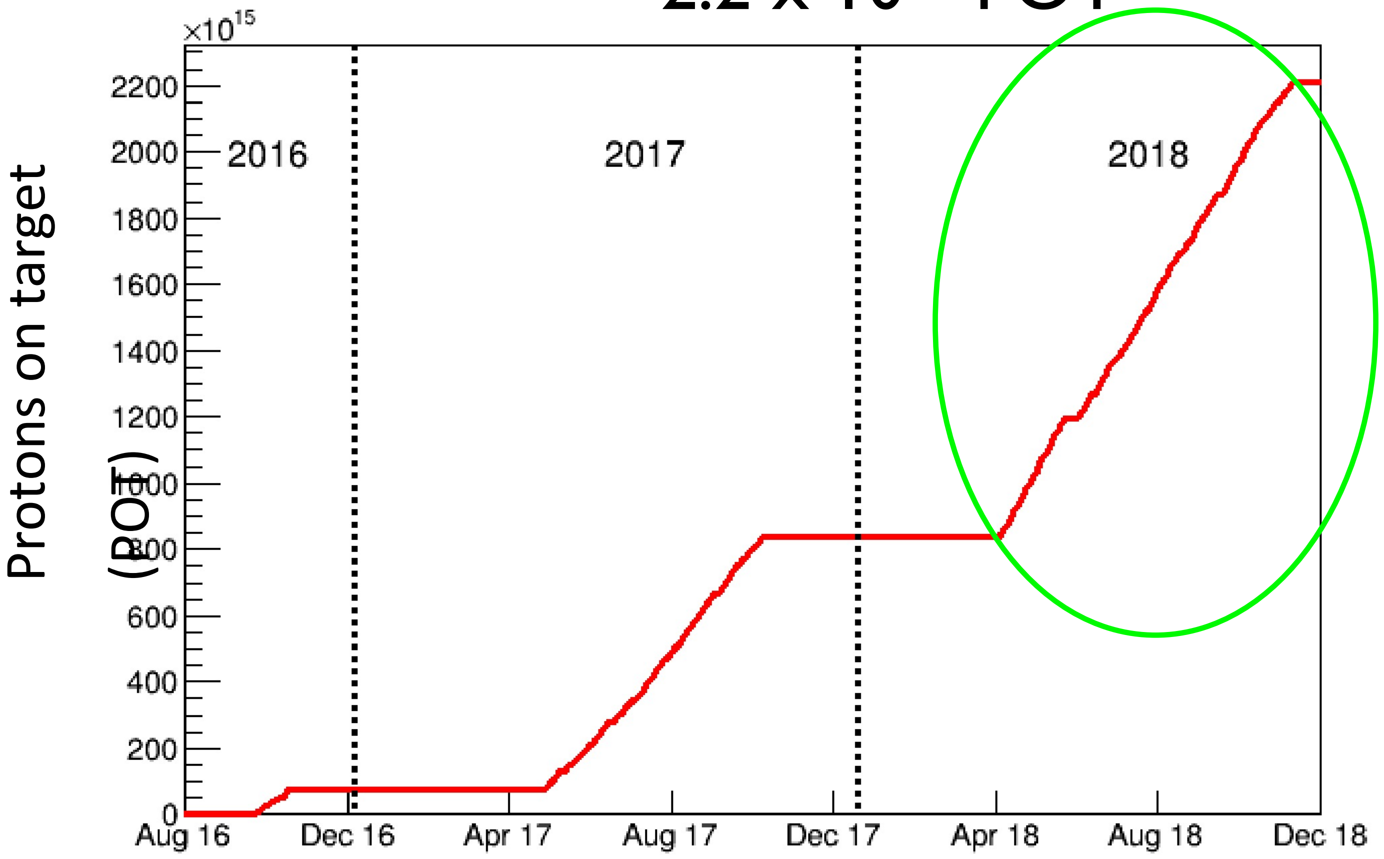
δ(BR)/BR = 10% would lead to **δ**($|V_{td}|$)/$|V_{td}|$ = 7%

- Over-constrain CKM matrix → reveal NP effects
- Sensitivity complementary to B decays

NA62 expertiment @ CERN SPS



2.2 x 10^{18} POT



In the CERN North Area the SpS extraction line provides a secondary charged hadron beam

400 GeV/c **protons** (3 x 10^{12} p/pulse On 40 cm **Be target**

75 GeV/c unseparated secondary hadrons beam **π^+(24%), K^+ (6%), p(70%)** ($\Delta p/p \pm 1\%$)

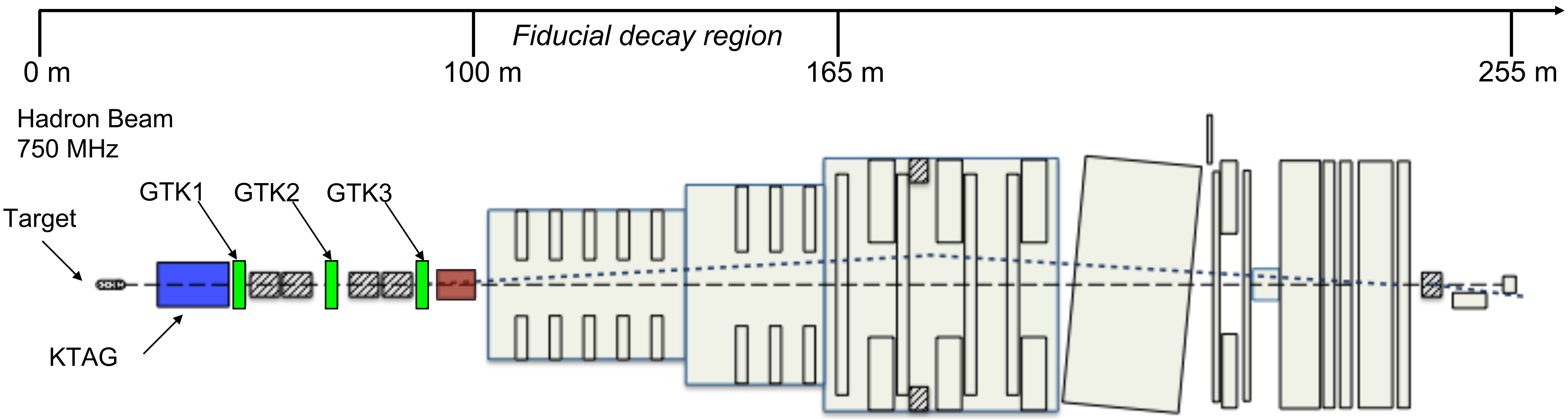
Intensity: 750 MHz (45 MHz K^+).

4.8 x 10^{12} K^+ decays/year, ~ 4 10^{12} K^+ in FV

Run I 2016 -2018:

2016/2017/2018 40%/60%/60-70% nominal intensity

NA62: Beam ID & Tracking

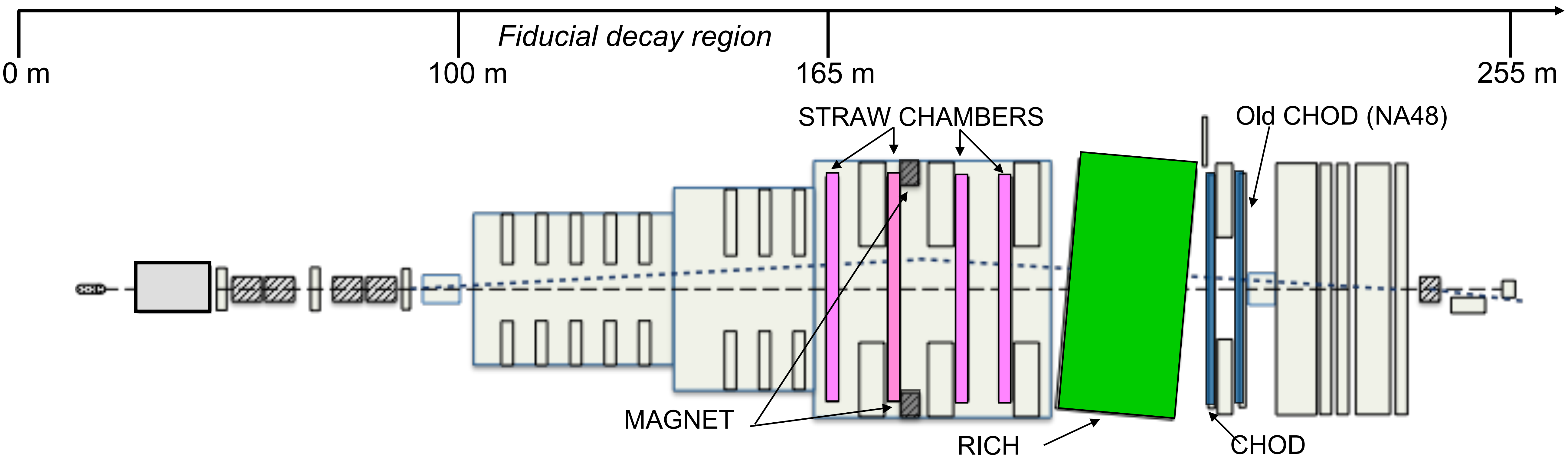


Beam ID & Tracking

KTAG: Differential Čerenkov counter. **σ_t ~70 ps, efficiency > 99%.**

GTK: GigaTracKer Spectrometer. **σ_t ~100 ps, $\sigma_{dx,dy} \approx 0.016$ mrad, $\Delta P/P < 0.4\%$.**

NA62: Secondary ID & Tracking



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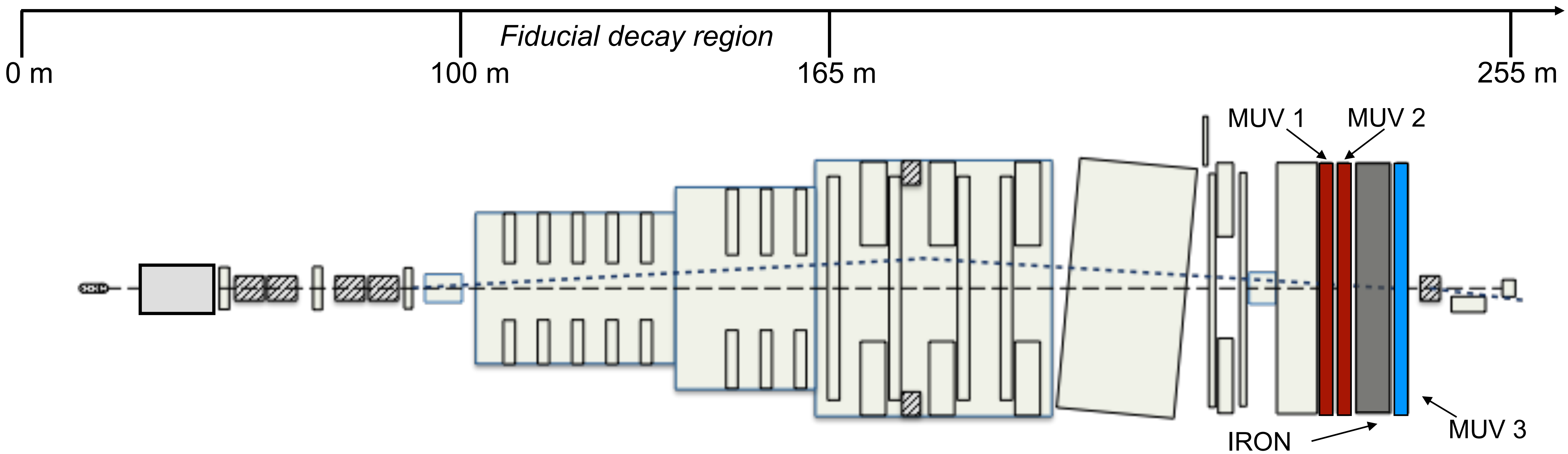
Secondary particle ID & Tracking

STRAW: Spectrometer with STRAW tubes. σ_t ~ 6 ns, $\sigma_{dx,dy}$ ~130 µm, $\sigma p/p$~(0.300+0.005p)% (GeV/c)

RICH: Ring Imaging Cherenkov detector. **µ/π separation ~ 10^{-2}, σ_t of a ring < 100 ps.**

NA62: Muon Veto System



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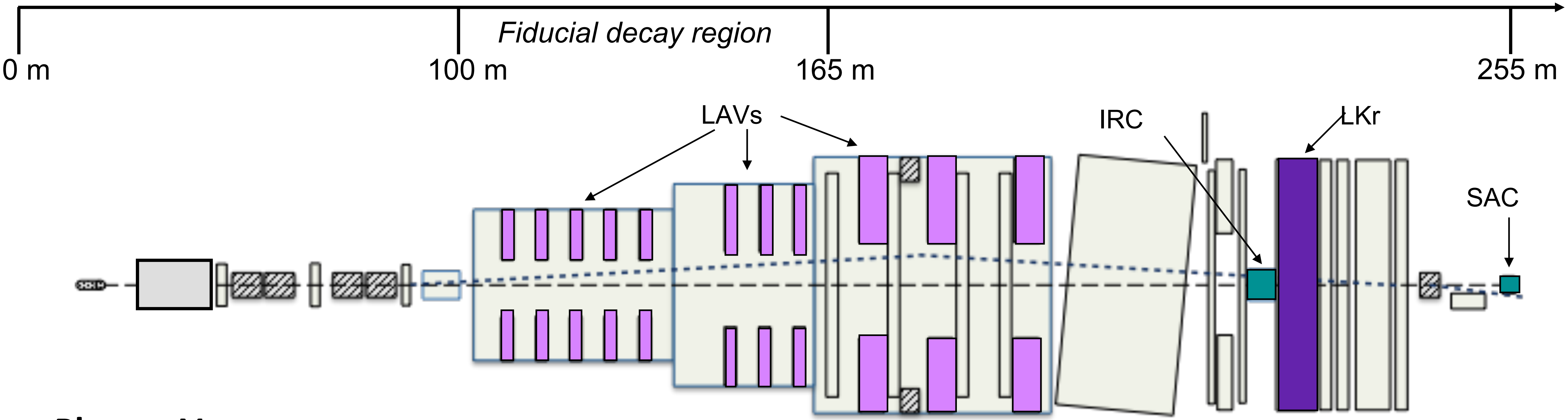
Muon Veto

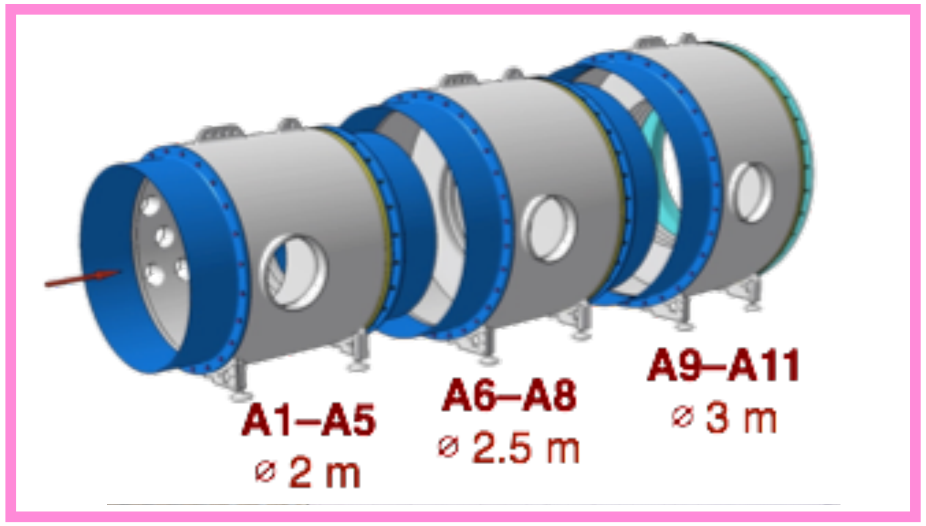
MUV3: Scintillator hodoscope. **σ_t ~500 ps, efficiency ~99.5%.**

MUV1/2: Hadronic calorimeters for the μ/π separation. **Cluster reco at ~20 ns from T_{track}.**

NA62: Photon Veto System



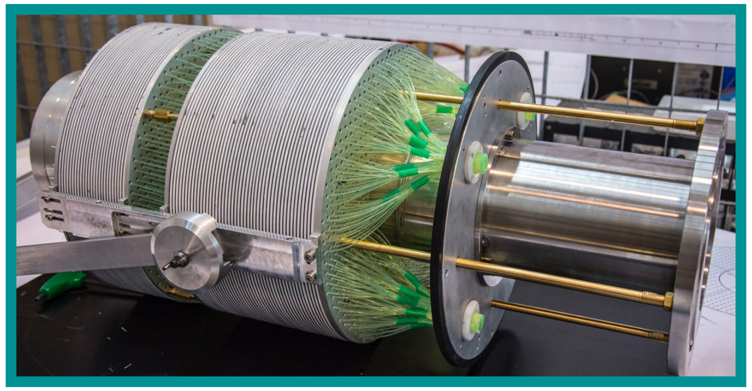
Photon Veto



LKr: NA48 LKr Calorimeter (1 <$\theta\gamma$<8.5 mrad) also for PID. **σ_t~500 ps (E > 3 GeV), σ_t~1 ns (hadronic and MIP clusters), $\sigma_{dx,dy}$ ~1 mm**

LAV: Large Angle Veto. 12 stations (8.5 <$\theta\gamma$ <50 mrad). *4 or 5 rings of lead glass crystals read out by PMTs.* *σ_t ~ 1 ns, 10^{-3} to 10^{-5} inefficiency (down to 150 MeV).*

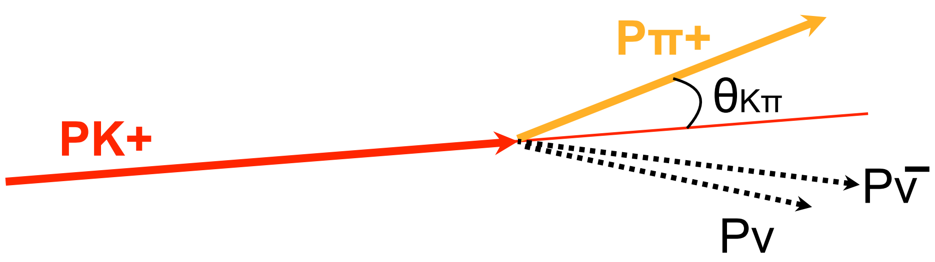
IRC/SAC: Inner Ring Calorimeter and Small Angle Calorimeter ($\theta\gamma$ <1 mrad). Shashlik calorimeters. Lead and plastic scintillator plates. **σ_t < 1 ns, 10^{-4} inefficiency.**



NA62: K → πνν in-flight decay

Design criteria: **high kaon intensity, powerful background suppression**

Kaons with **75 GeV/c** momentum.
Decay in flight technique.
Signal signature: **K^+ track** + **π^+ track**

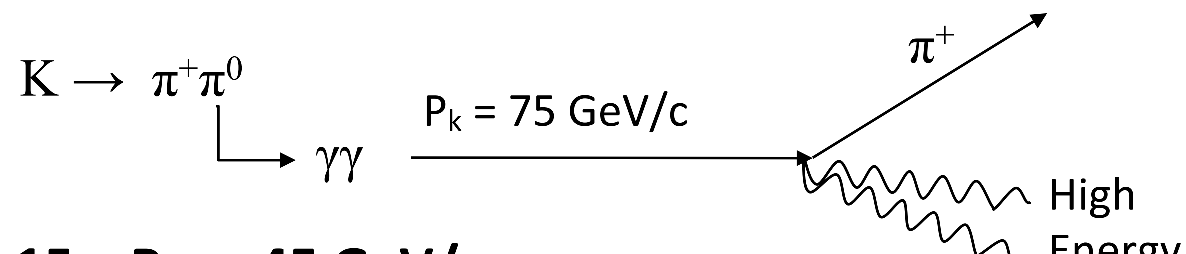


Backgrounds

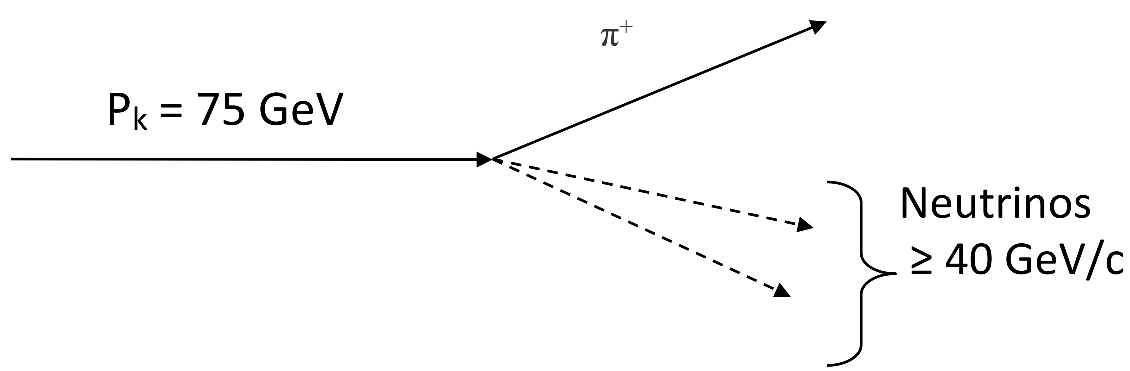
Decay	BR	Main Rejection Tools
$K^+ \to \mu^+\nu_\mu(\gamma)$	63%	μ-ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi-track + kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+\nu_e$	5%	e-ID + γ-veto
$K^+ \to \pi^0\mu^+\nu_\mu$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

Basic ingredients:

- Kinematic suppression: ~O(10^4)
- μ-suppression ($K^+ \to \mu^+\nu$): > 10^7
- π^0-suppression (from $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$): > 10^7
- Timing between sub-detectors: O(100 ps)



15 < $P_{\pi+}$ < 45 GeV/c
(Upper limit guarantees high photon energy)



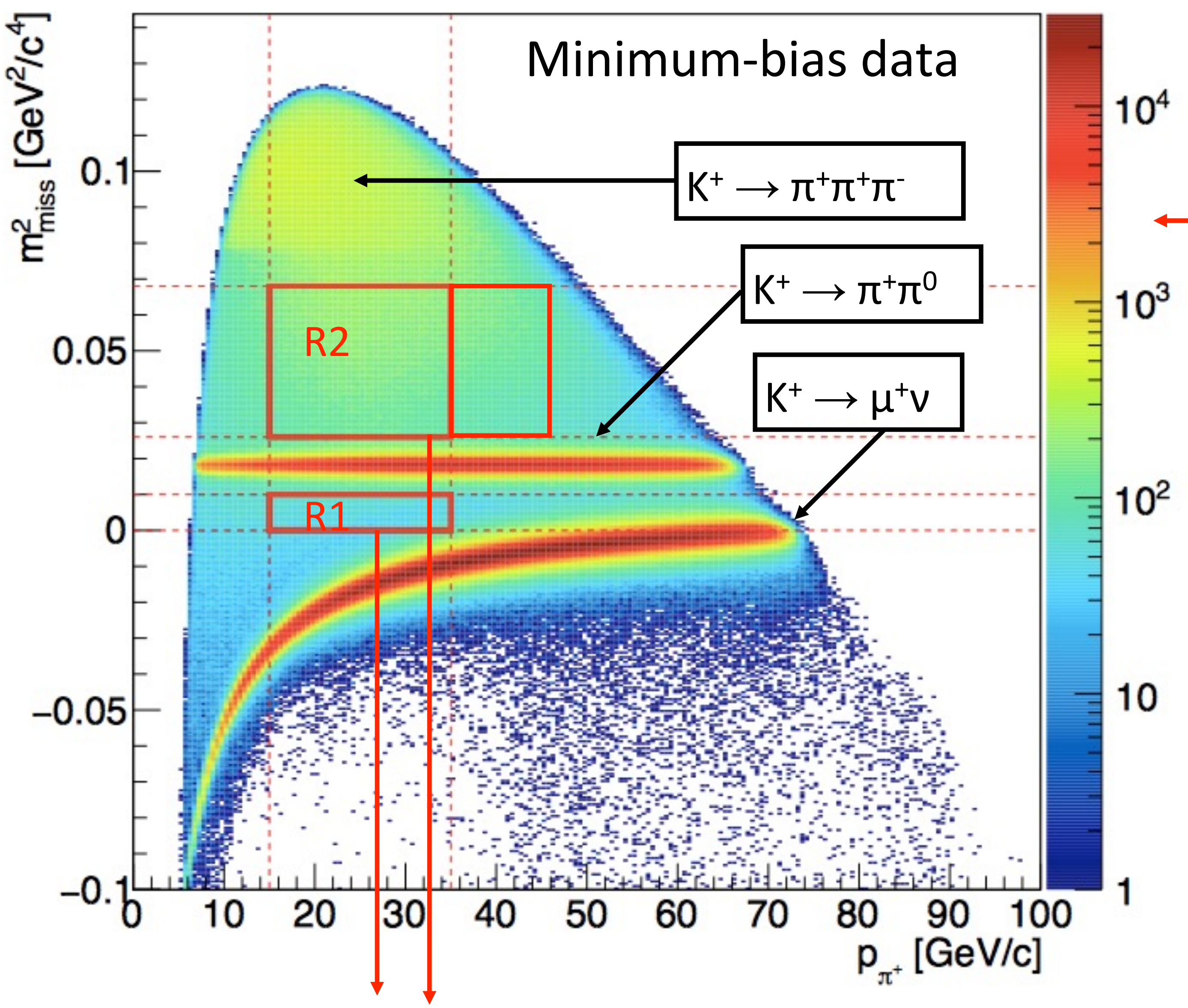
$K^+ \to \pi^+ \nu\nu$ decay selection

Most discriminating variable:

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

2 signal regions, R1,R2 on each side of the $K^+ \to \pi^+\pi^0$ peak (to eliminate 92% of the K^+ width)

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



Kinematic cuts to define signal regions R1 and R2

$\sigma(m^2_{miss}) \sim 10^{-3}$ GeV^2/c^4

- **K^+** : beam particle track in GTK identified as a kaon on KTAG
- **single positive charged particle** in downstream detectors (STRAW, RICH)

Upstream-downstream timing ~100 ps

- **vertex** reconstruction:

CDA < 4mm

110 m < Z_{reco} < 165 m

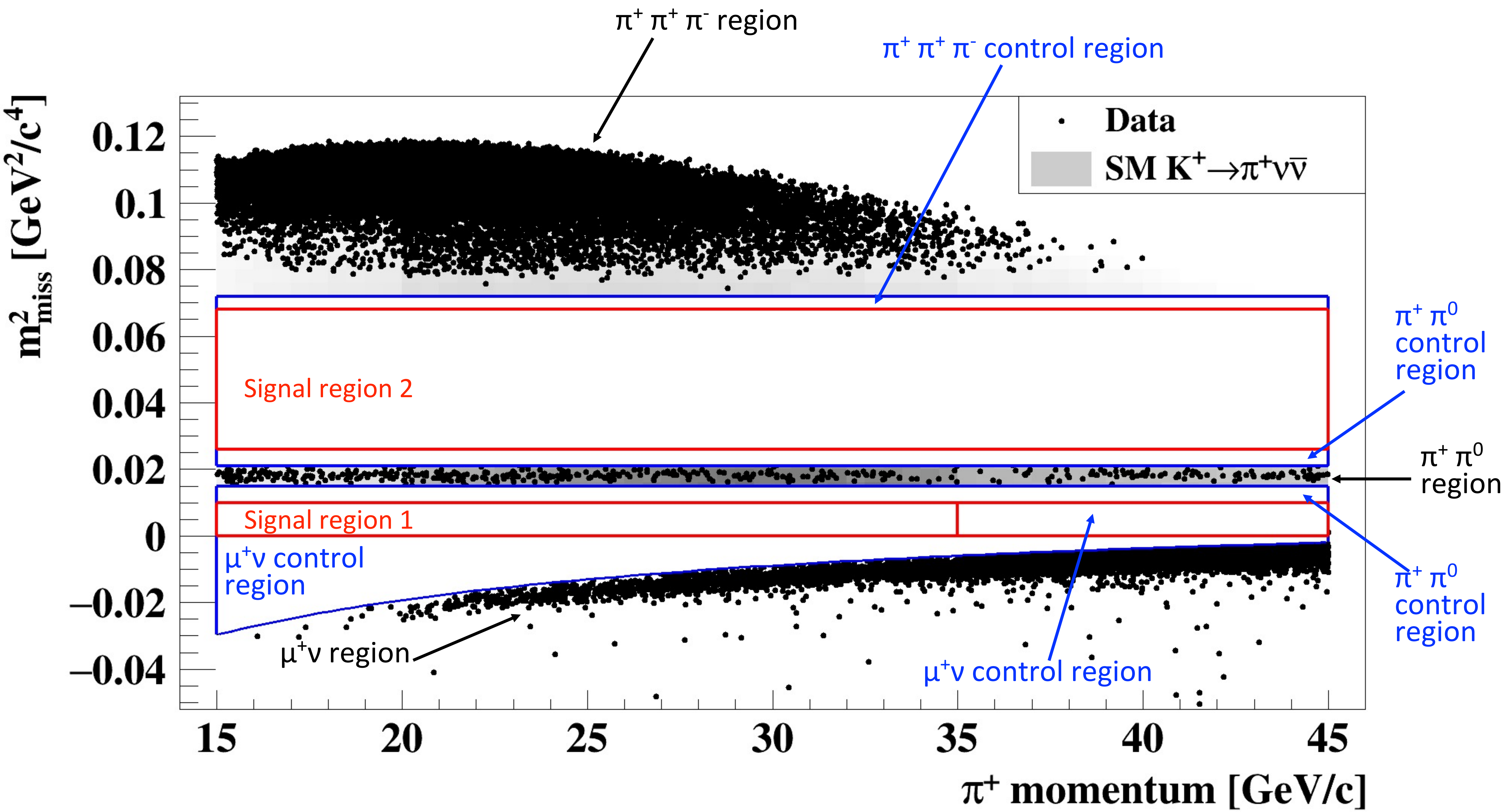
- π^+ identification
- photon rejection
- Multi-track rejection

Particle-ID: $\varepsilon_{\mu+} \sim 10^{-8}$, $\varepsilon_{\pi+} \sim 64\%$

π^0-rejection: $\varepsilon_{\pi 0} \sim 1.4 \cdot 10^{-8}$

(15<P_π<35 GeV)

2018 data after selection



Control regions are blinded to validate background estimation prior to unblind of signal regions

Background from other K^+ decays

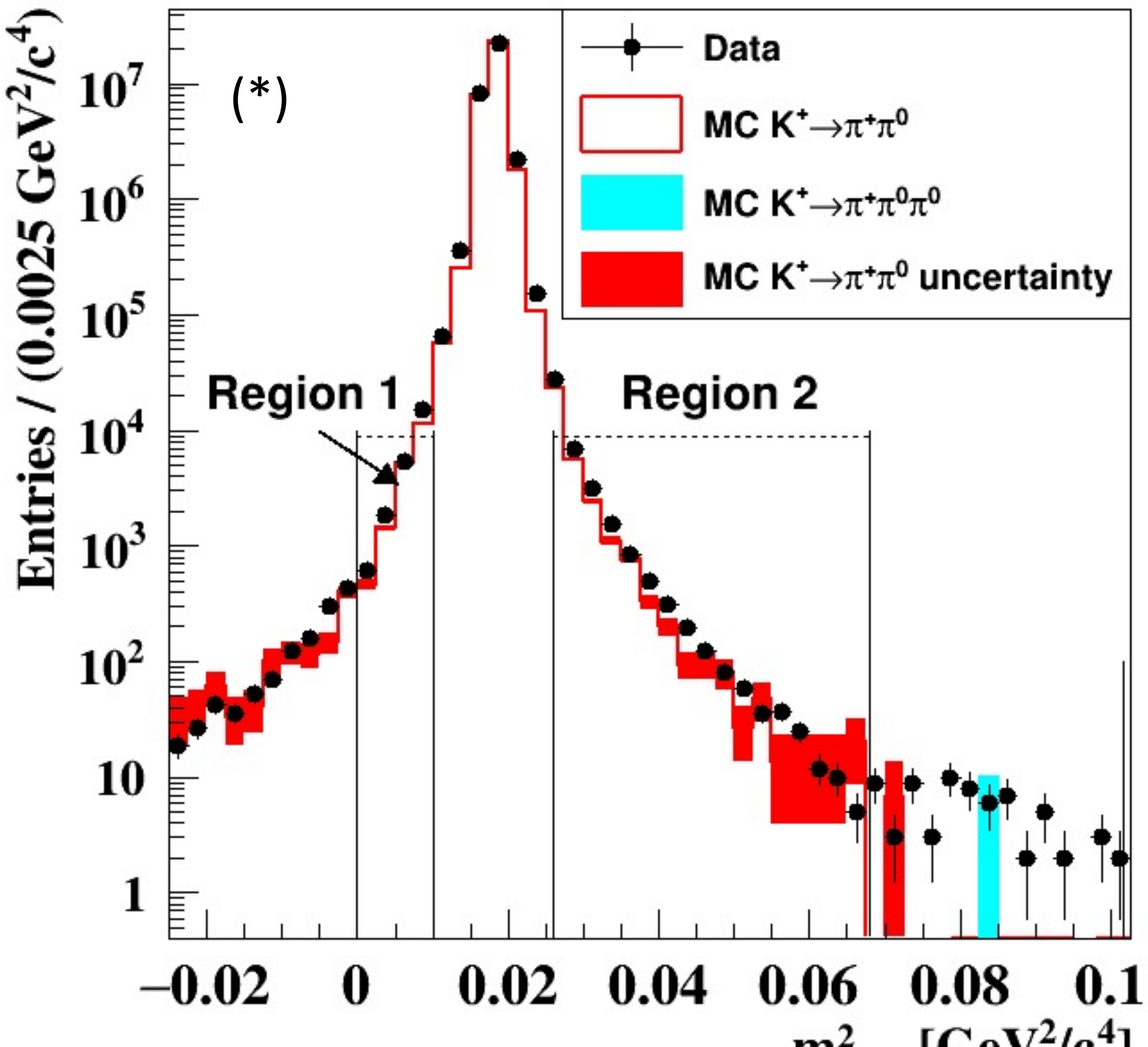
$\pi^+\pi^0$, $\mu^+\nu$, $\pi^+\pi^-\pi^+$ backgrounds in the signal and control region are estimated from tails of m^2_{miss} distribution in control samples

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

Expected number of **$K \to \pi^+\pi^0$** events in signal/control regions after πνν selection

Events in $\pi^+\pi^0$ region after πνν selection (including π^0 rejection)

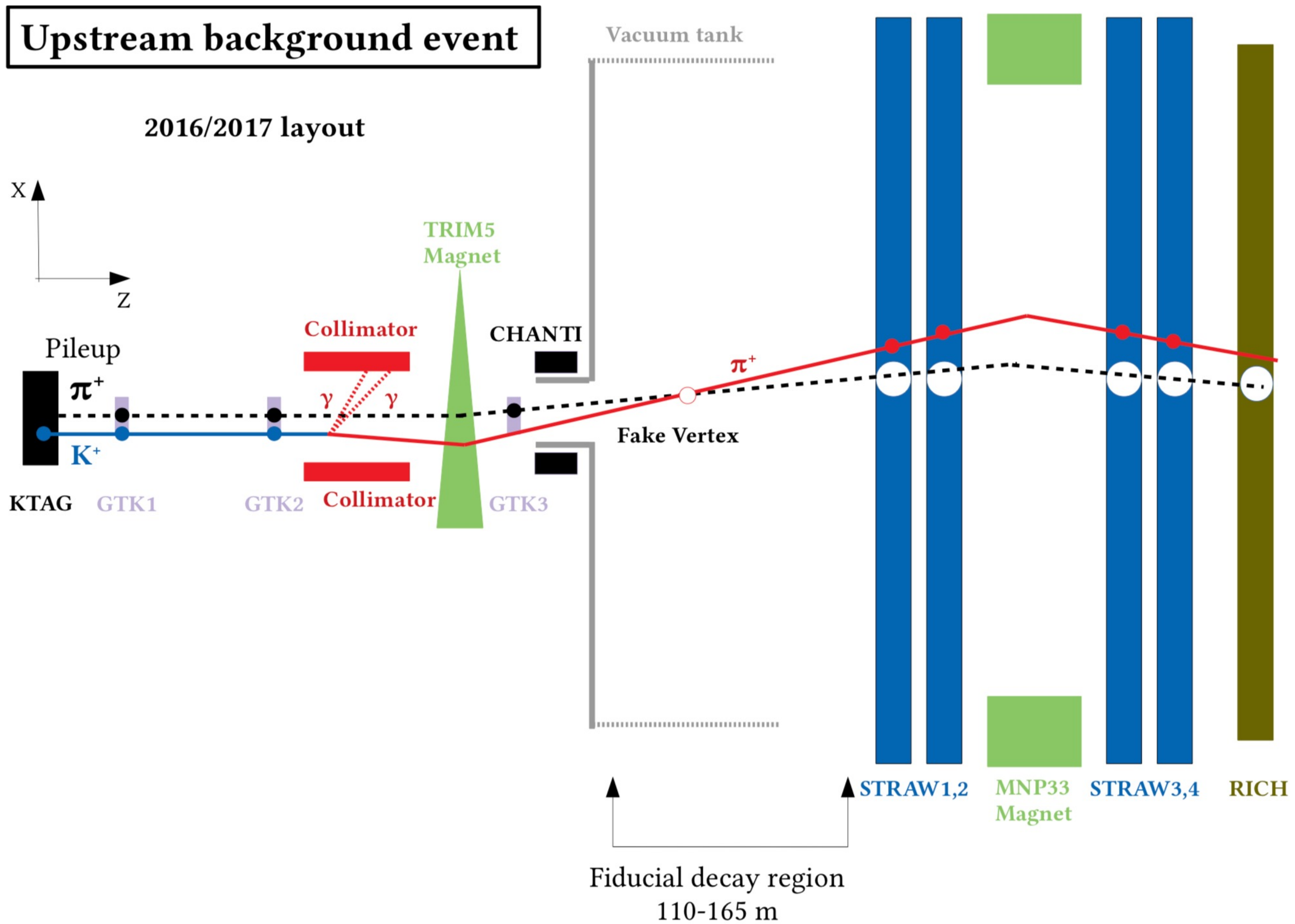
Fraction of $\pi^+\pi^0$ in signal/control regions measured with minimum bias data (*)



- Same procedure for **$K^+ \to \mu^+\nu(\gamma)$** and **$K^+ \to \pi^+\pi^+\pi^-$** backgrounds where particle identification, γ and multiplicity rejection are proved to be independent from the cuts on m^2_{miss}
- For **$K^+ \to \pi^+\pi^- e^+\nu$** a different method is used: estimation using MC simulation (validated using minimum-bias samples) normalized to the SES

Upstream background

K^+ may decay upstream the fiducial volume (with 2 photons lost in the collimator)

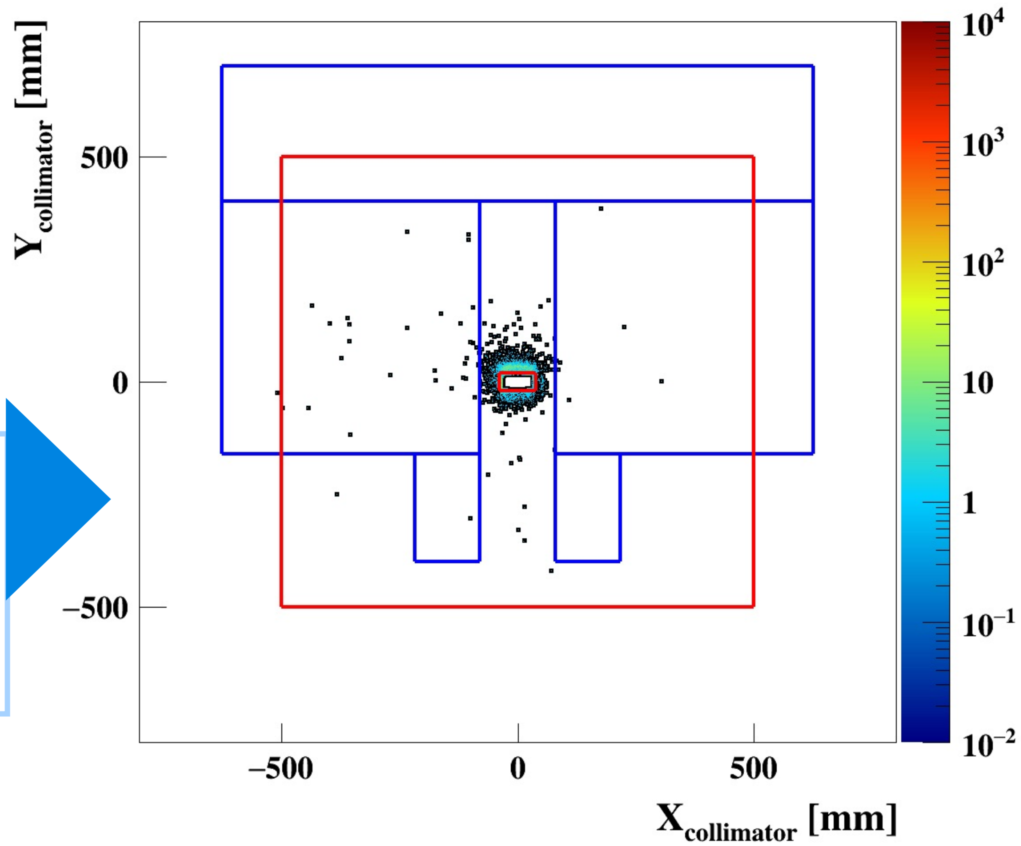


π^+ from decay can be matched with a beam π^+ (misidentify as a K^+): producing a fake vertex in FV

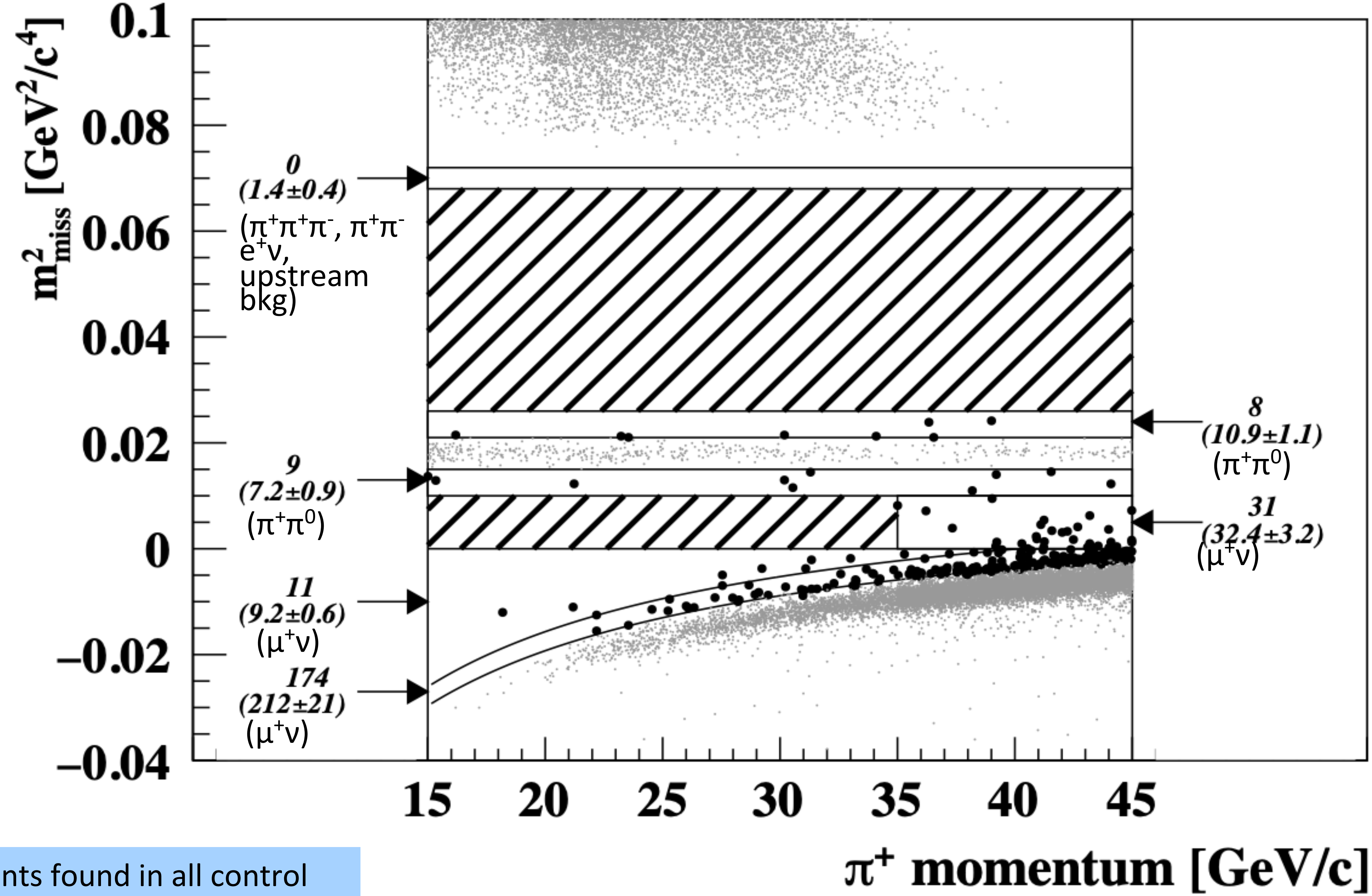
- Geometrical distribution of upstream events is used to define analysis cuts and background estimation in the selected signal sample

- Sample enriched in upstream background is obtained by reversing K^+- π^+ matching cuts (CDA, Δt)
- Data driven background estimation

π^+ from upstream background projected from the fake vertex backward at the collimator



Control regions unmasked and validated



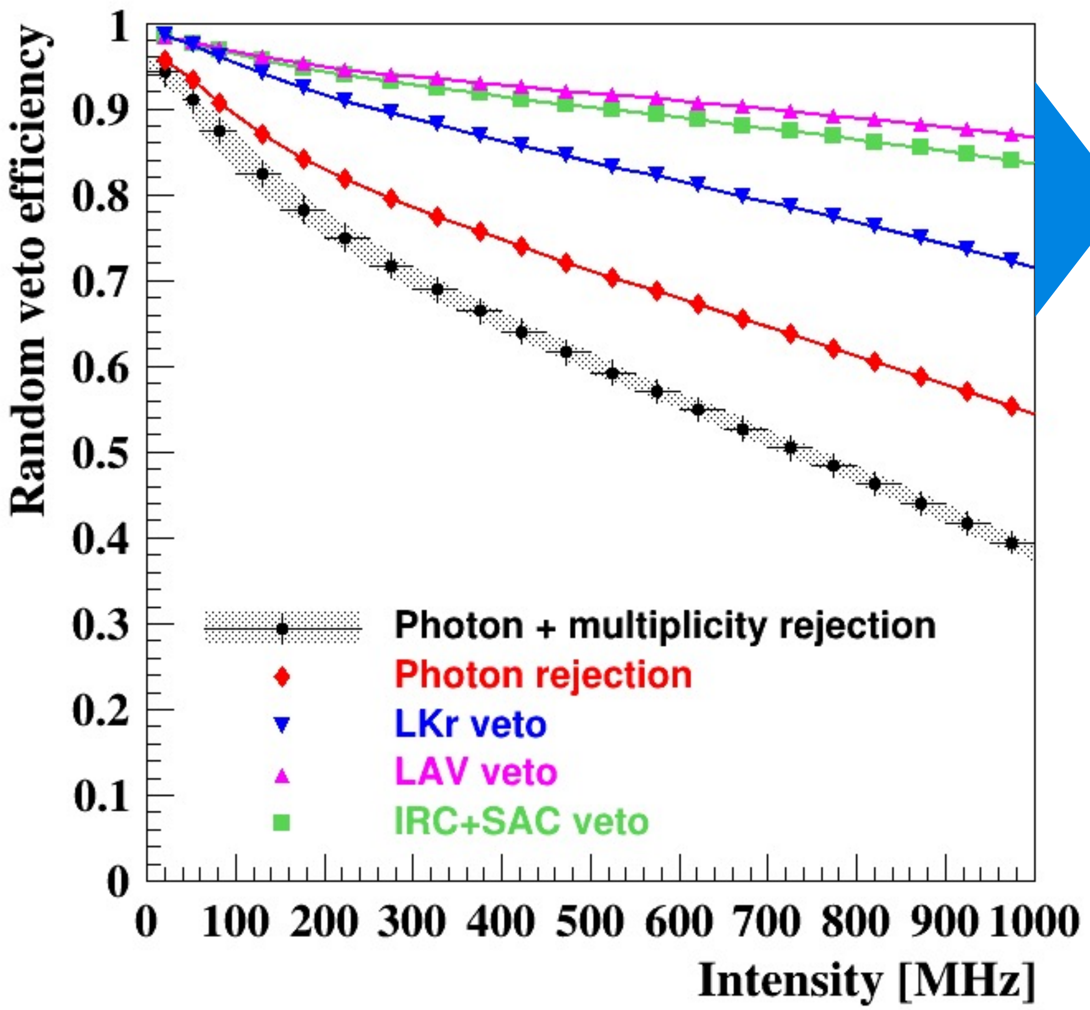
Events found in all control regions are consistent with expectations

Single event sensitivity (SES)

$$SES = \frac{BR(K^+ \to \pi^+ \nu\bar{\nu})}{N^{exp}_{\pi\nu\nu}}$$

$$N^{exp}_{\pi\nu\nu} \simeq N^{obs}_{\pi^+\pi^0} \cdot \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \cdot \frac{BR(K^+ \to \pi^+\pi^0)}{BR(K^+ \to \pi^+\nu\bar{\nu})} \cdot \varepsilon_{trigger} \cdot \varepsilon_{RV}$$

- $K^+ \to \pi^+\pi^0$ decay used for normalization
- Acceptances obtained with MC. Use of the ratio allows cancellation of systematic effects



Random Veto: signal efficiency losses due to accidental coincidence in the veto detectors (estimated with $K^+ \to \mu^+\nu$ data sample for which no γ-signals are expected)

Error source	Budget on SES error
Trigger efficiency	5%
MC acceptance	3.5%
Random Veto	2%
Bkg (normalization)	0.7%
Instantaneous intensity	0.7%

$$N^{exp}_{\pi\nu\nu} = \mathbf{7.58} \pm 0.40_{syst} \pm 0.75_{ext}$$ (SM)

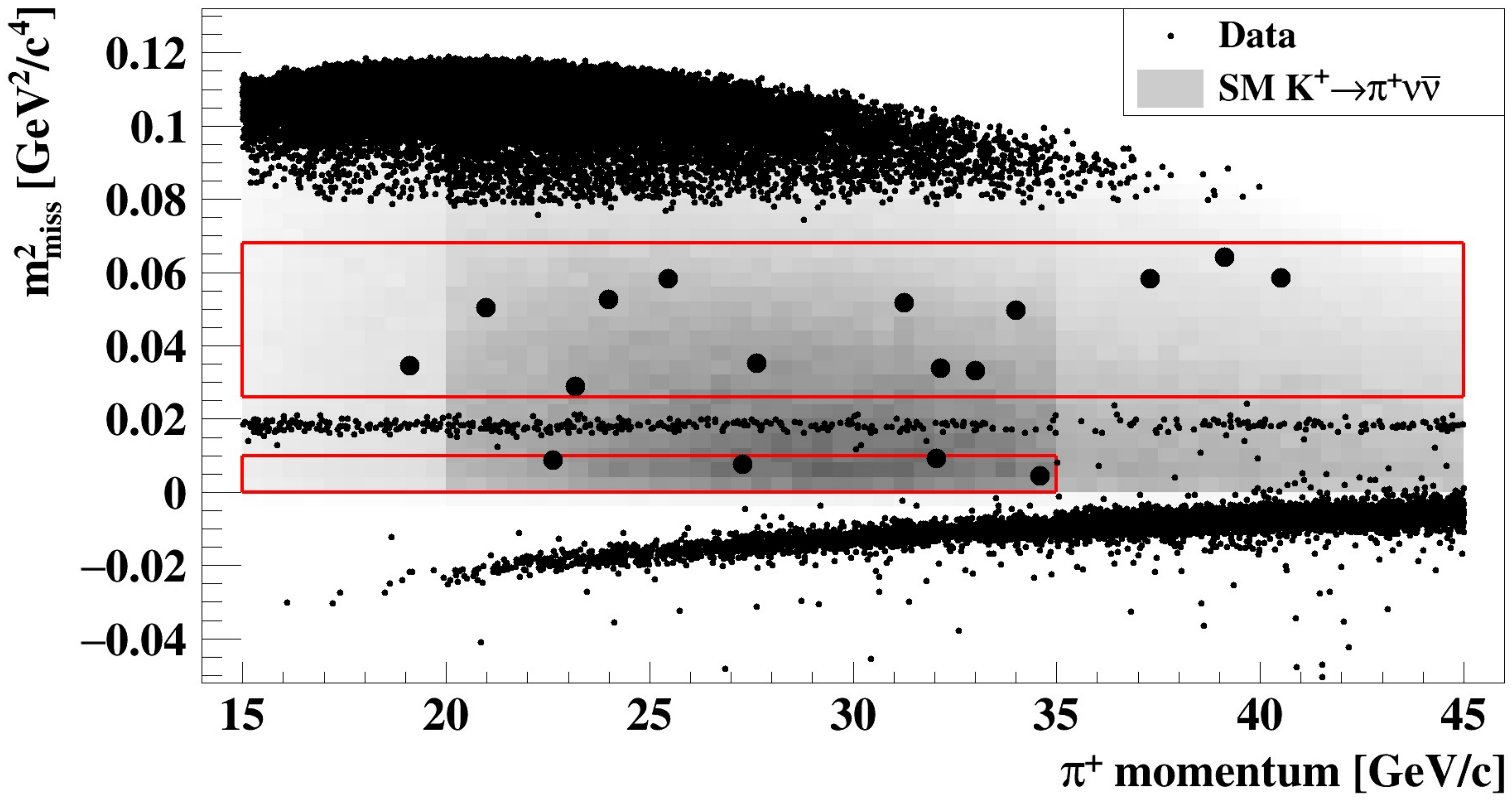
$$SES = (1.11 \pm 0.07_{syst}) \times 10^{-11}$$

Expected events in Signal Regions

Signal and background events expected in the signal regions **for 2018 data**:

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
$K^+ \to \mu^+\nu(\gamma)$	0.49 ± 0.05
$K^+ \to \pi^+\pi^-e^+\nu$	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	$5.28^{+0.99}_{-0.74}$

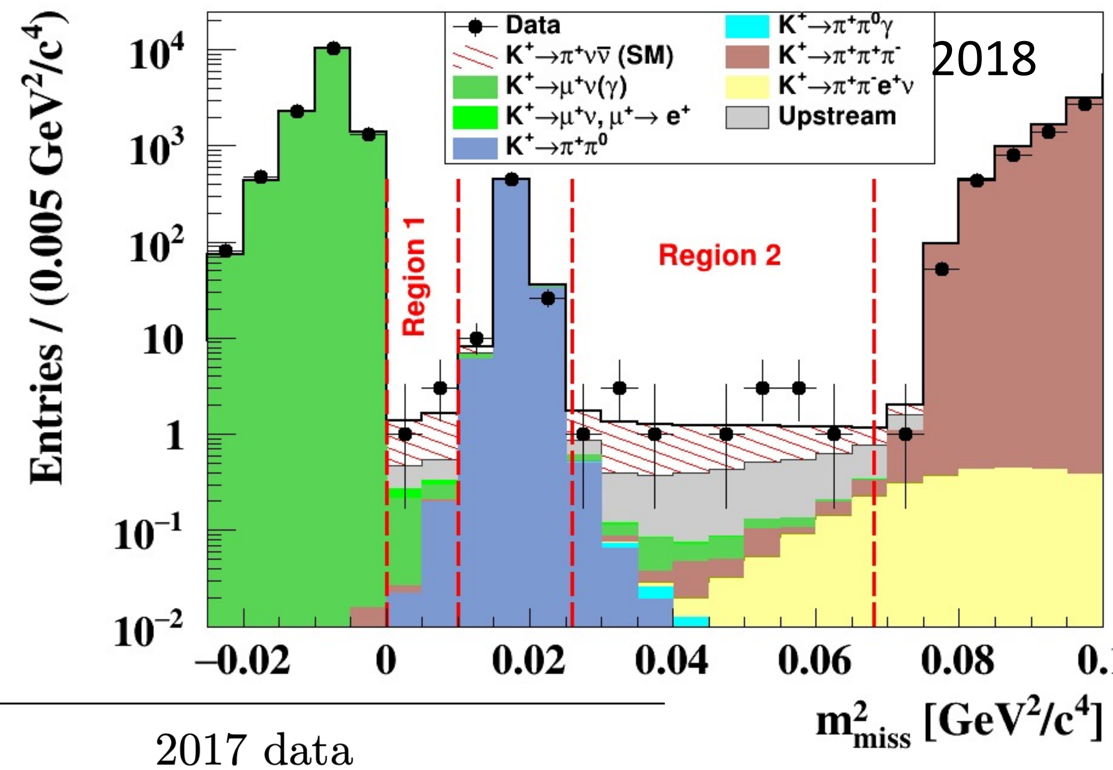
2018 data: box opened



17 events have been observed in 2018 data!

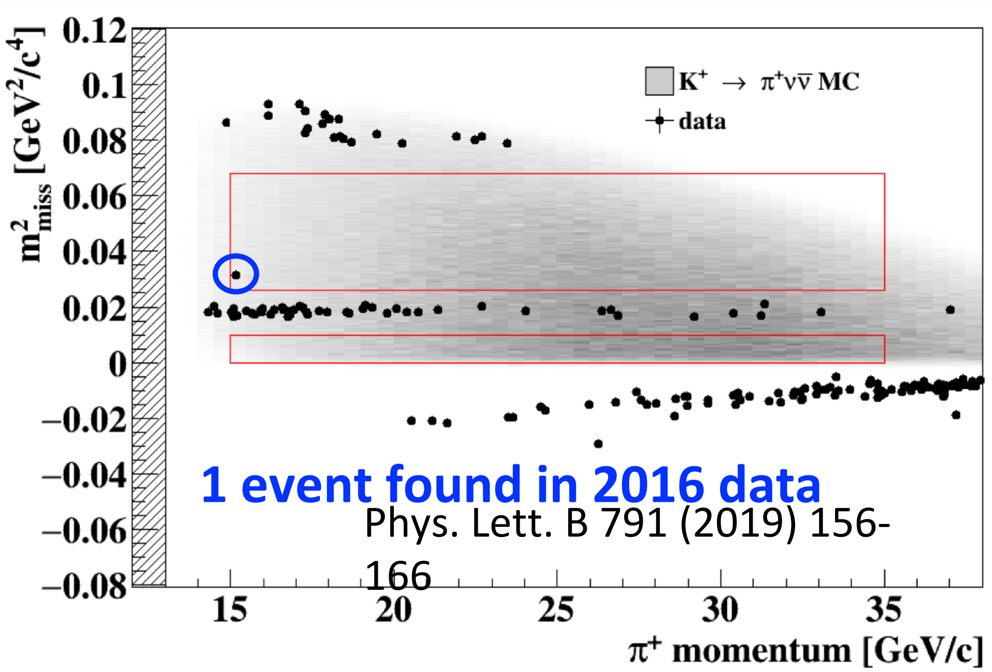
NA62 experiment results

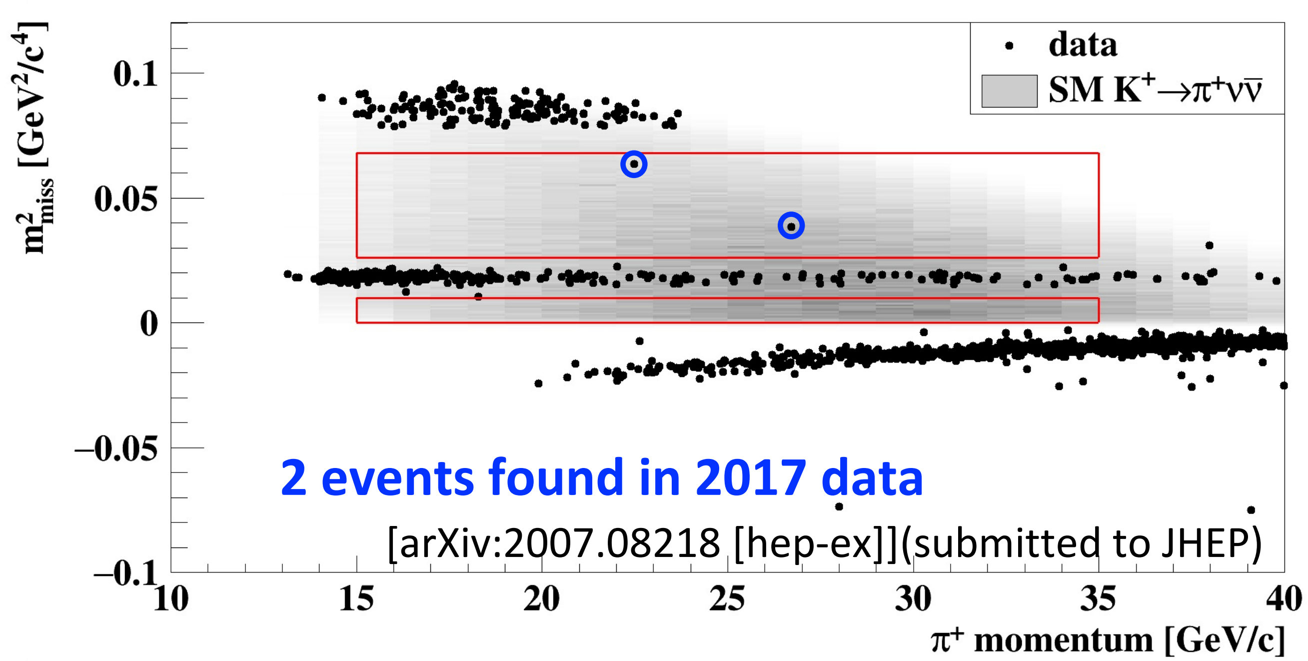
M$^2_{miss}$ distribution for 2018 data integrated over the full π^+ momentum.
—> Data-MC comparison



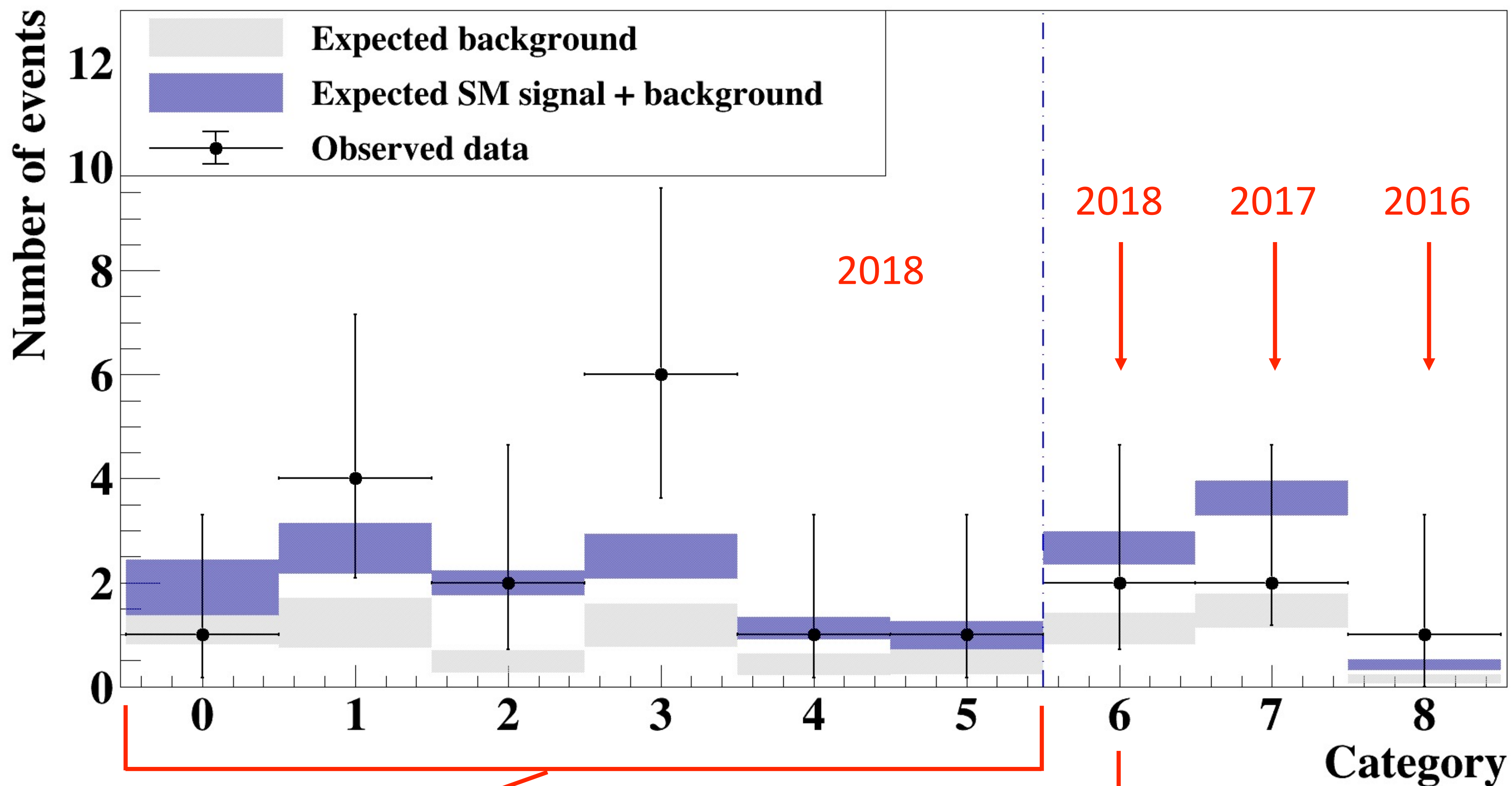
Final BR($K^+\to\pi^+\nu\nu$) measurement is obtained combining with 2016 and 2017 NA62 data results

Expected events	2016 data	2017 data
$K^+\to\pi^+\nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$	$2.16 \pm 0.12_{stat} \pm 0.26_{ext}$
Total background	$0.152^{+0.092}_{-0.033}{}_{stat} \pm 0.013_{syst}$	$1.5 \pm 0.2_{stat} \pm 0.2_{syst}$





Results



80% of the 2018 dataset:
5 GeV/c wide bins from 15 to 45 GeV/c

20% of the 2018 dataset, with old hardware configuration integrated over momentum

Run 1 combined result:

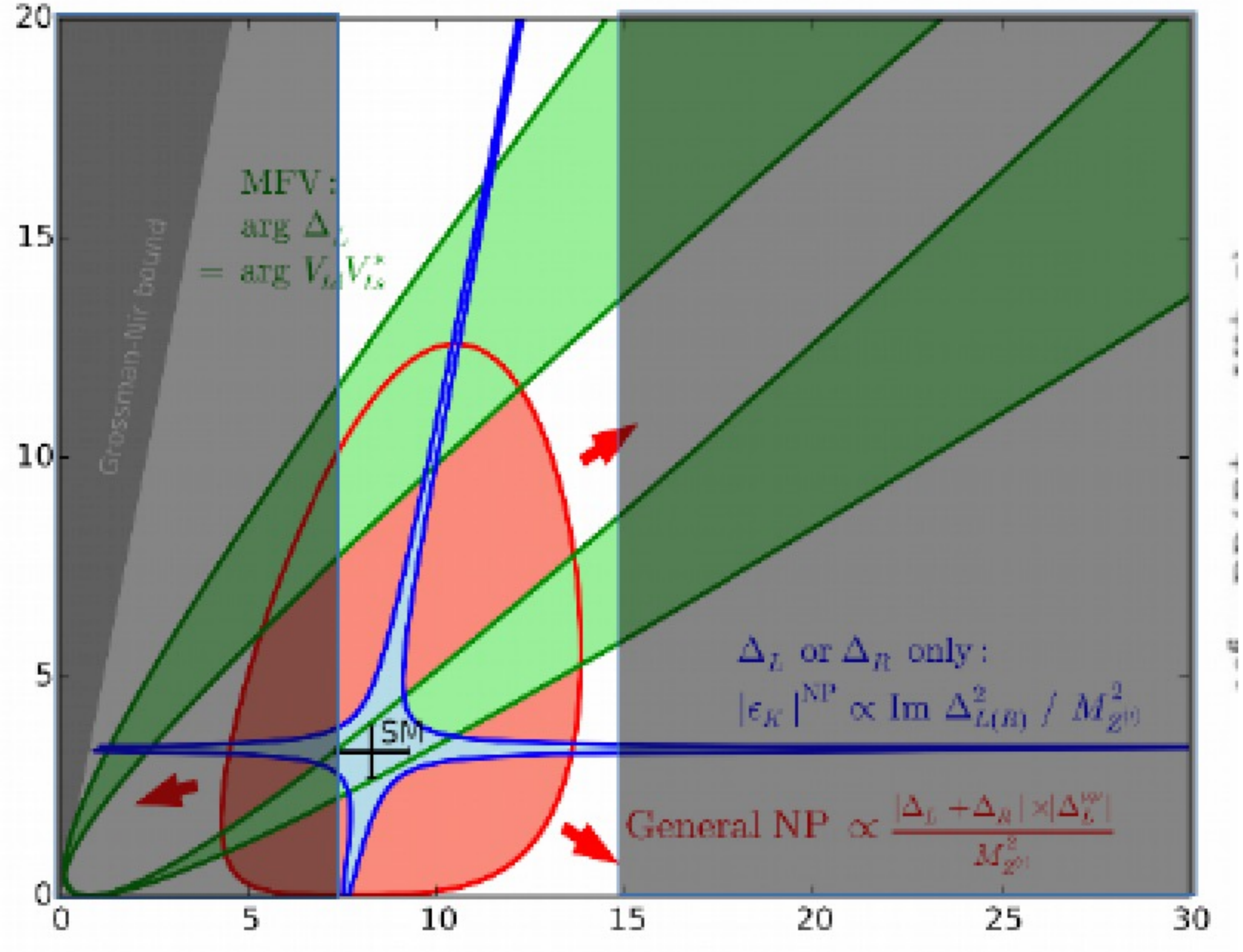
$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}{}_{stat.} \pm 0.9_{syst.}) \times 10^{-11} (3.4\sigma \text{ significance})$$

Maximum likelihood fit using signal and background expectation in each category

K → πνν̄ and new physics

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

BR($K_L \to \pi^0 \nu\bar{\nu}$) × 10^{11}



BR($K^+ \to \pi^+ \nu\bar{\nu}$) × 10^{11}

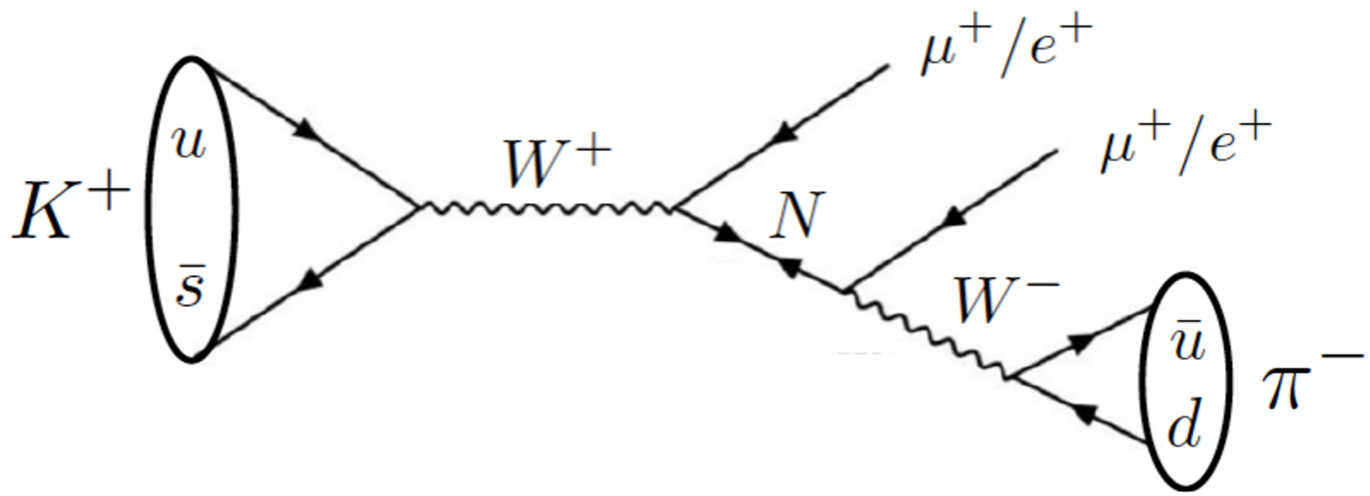
Large deviation from the SM expectation seems to be excluded

A more precise measurement is needed

LFV and LNV in Kaon decays

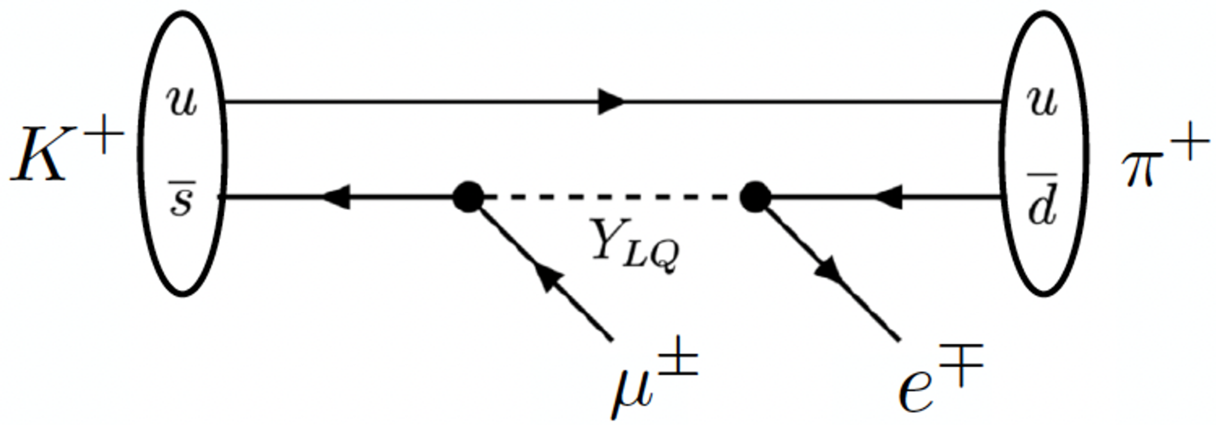
- Lepton Number (**L**) and Lepton Flavour (**L_e, L_μ, L_τ**) are foreseen in some BSM theories: conservation laws in SM are not imposed by any local gauge symmetry

- **Lepton number violation:**



eg: $K^+ \rightarrow \pi^- \mu^+ e^+$
$\Delta L=2$ via Majorana neutrinos
(analogue to 0νββ decays)

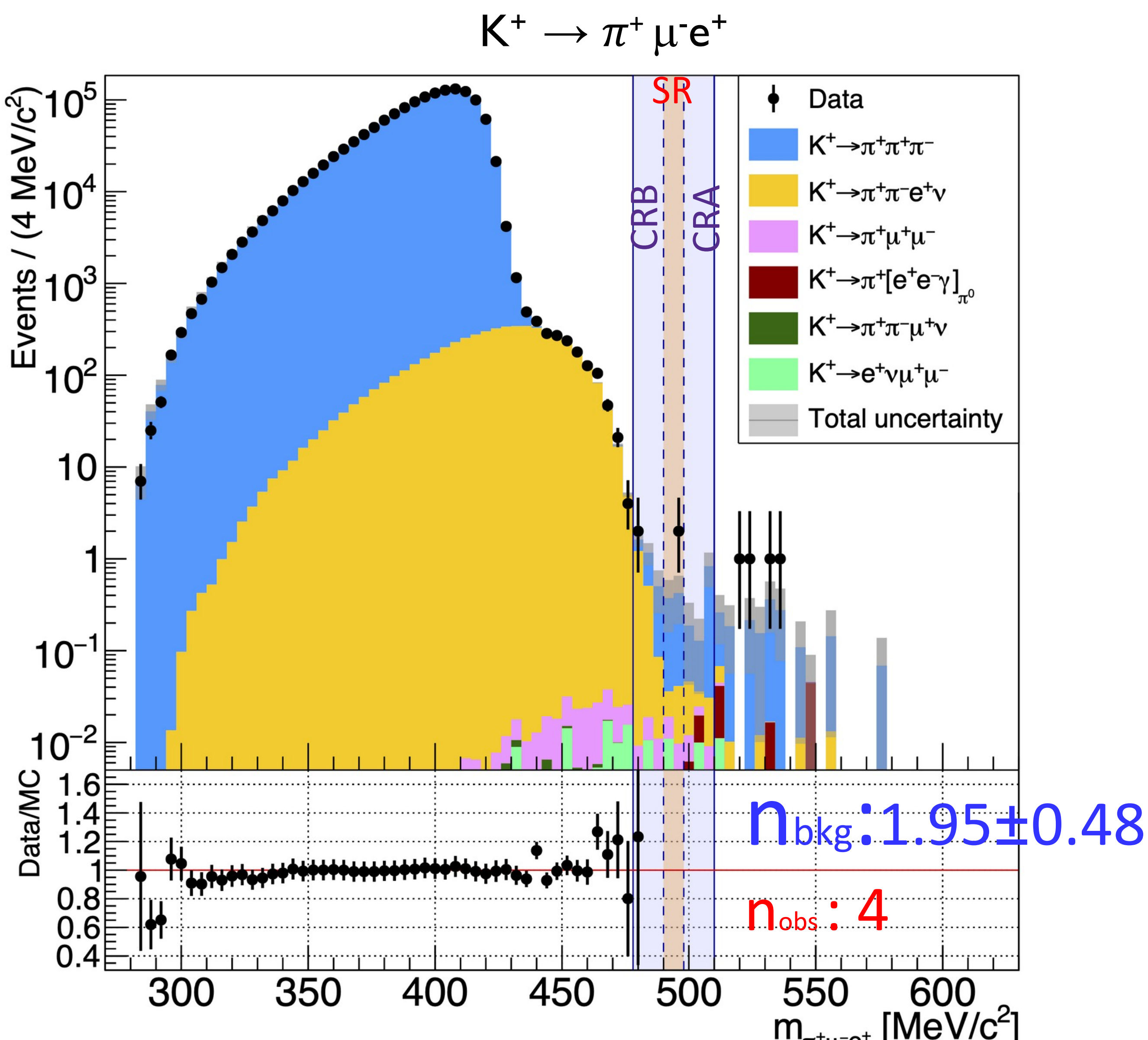
- **Lepton flavour violation:**

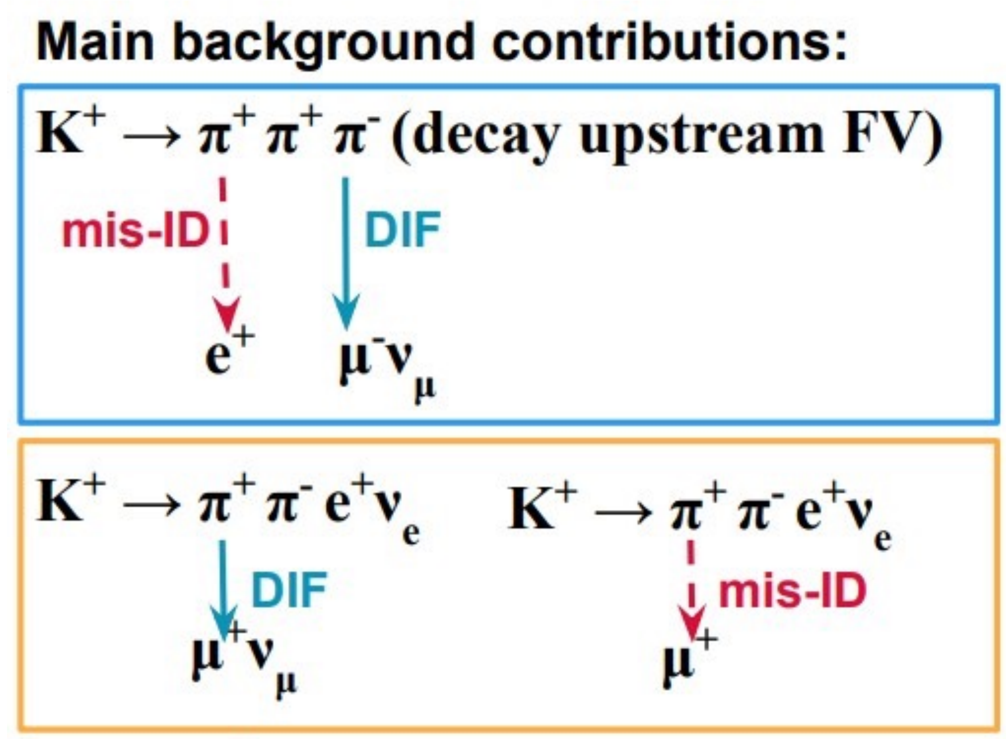


eg: $K^+ \rightarrow \pi^+ \mu^- e^+$
$\Delta L_e=1$ and $\Delta L_\mu=1$
Via leptoquark, Z'..

$K^+ \to \pi^\pm \mu^\mp e^+$ ($\pi^0 \to \mu^- e^+$)

- Experimental signature: 3 charged tracks with $\pi^\pm \mu^\mp e^+$
- Consistent with closed kinematics K^+ decay
- The invariant mass $M_{\pi\nu e}$ of the three selected tracks build under the $\pi\mu e$ is used to distinguish between signal and background (σ_M~1.4 MeV)
- $K^+ \to \pi^+ \pi^0(\pi^0 \to \mu^- e^+)$ additional constraint on the mass of the two leptons: $M_{\mu e}$ compatible with π^0 mass
- Main bkg π mis-ID and decay in flight measured with data
- Normalized with $K^+ \to \pi^+\pi^+\pi^-$





	N_{CRB}	N_{CRA}
Total exp. bkg	3.41 ± 0.54	1.27 ± 0.40
Observed events	2	0

NA62 LNV/LVF results

	Previous UL @ 90% C.L	NA62 UL @ 90% C.L		
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	2017 data → improved by factor 2	Phys. Lett. B 797 (2019) 134794
$K^+ \rightarrow \pi^- e^+ e^+$	6.4×10^{-10}	2.2×10^{-10}	2017 data → improved by factor 3	
$K^+ \rightarrow \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11}	2017+2018 data → improved by factor 12	PRL 127 131802 (2021)
$K^+ \rightarrow \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11}	2017+2018 data → improved by factor 8	
$\pi^0 \rightarrow \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}	2017+2018 data → improved by factor 13	
$K^+ \rightarrow \pi^+ \mu^+ e^-$	1.3×10^{-11}	-	sensitivity similar to the previous search	
$\pi^0 \rightarrow \mu^+ e^-$	3.8×10^{-10}	-	sensitivity similar to the previous search	
$K^+ \rightarrow \mu^- \nu e^+ e^+$	2.1×10^{-8}	-	Ongoing analysis: 2017 data $S.E.S \sim 1 \times 10^{-10}$	
$K^+ \rightarrow e^- \nu \mu^+ \mu^+$	no limit	-	Ongoing analysis: 2017 data $S.E.S \sim 5 \times 10^{-11}$	

1 order of magnitude improvements compared to previous searches
Upper limits at 90% CL:

Heavy neutral leptons

- Right handed neutrinos or Heavy Neutral Leptons (HNL) are included in several extension of the Standard Model and the can generate neutrino masses via the see-saw mechanism O(100 MeV) HNL masses ([Phys. Lett. B 620 (2005) 17])

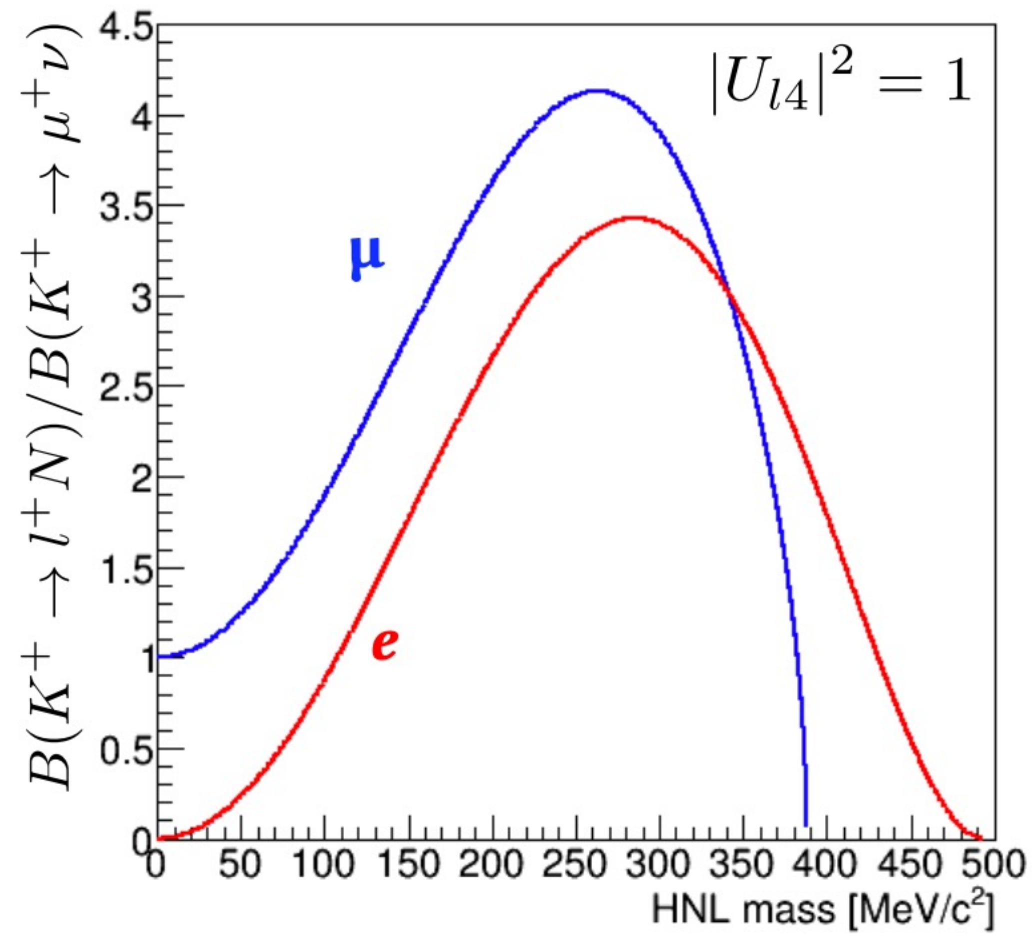
- HNL produced in decays has similar experimental signature to the SM decay $K^+ \to l^+\nu$ assuming HNL lifetime greater than 50 ns (decay products escape detection)

Branching ratio for the electron and muon modes

$$B(K^+ \to l^+ N) \sim B(K^+ \to l^+ \nu) \cdot \rho_l(m_N) \cdot |U_{l4}|^2$$

- $\rho(m_N)$ –kinematic factor , O(1)

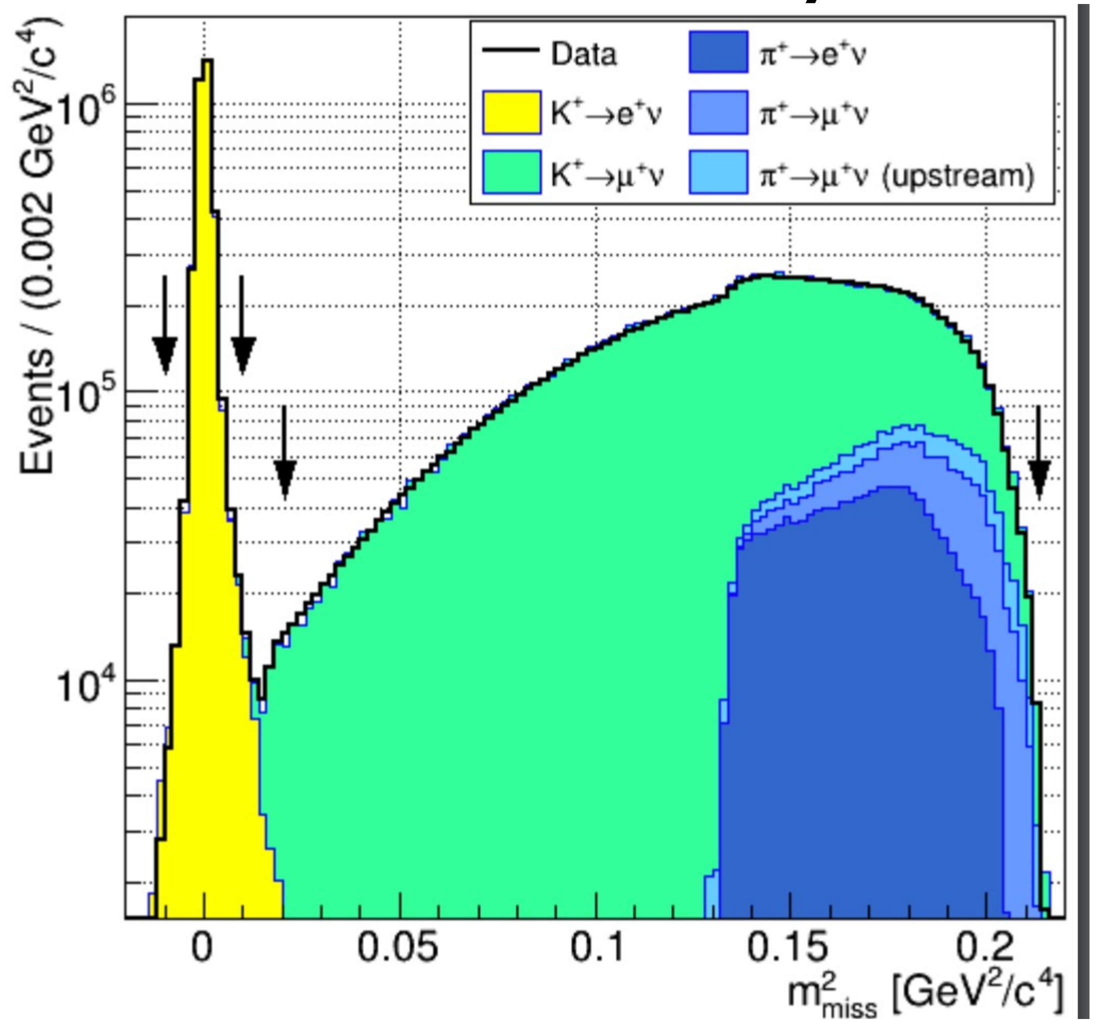
- $|U_{l4}|^2$ – the squared neutrino mixing parameter

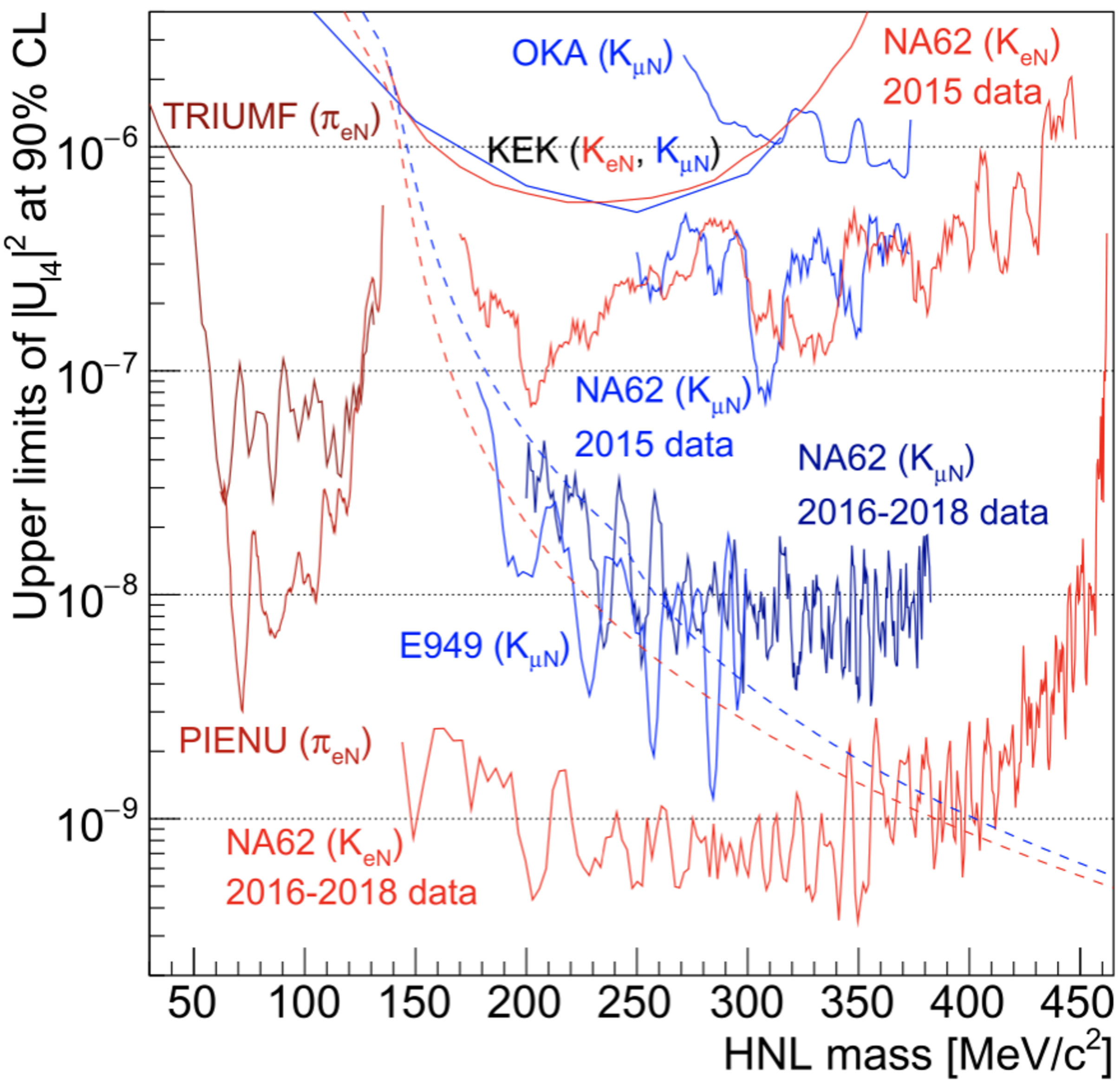


Heavy neutral leptons

EVENT selection: Precise track reconstruction, $K^+/e^+/\mu^+$ PID, match the two tracks, O(100ps) detector time resolution to veto extra in-time activity .
Experimental signature of the $K^+ \to l^+N$ decay Sharp bump in the positive m^2_{miss} side-band of the SM $K^+ \to l^+\nu$ decays

$K^+ \to e^+\nu$ decays





$|U_{e4}|^2 \sim 10^{-9}$ in the 144 – 462 MeV/c² mass range
$|U_{\mu4}|^2 \sim 10^{-8}$ in the 200 – 384 MeV/c² mass range

O(10^{-9}) limits on $|U_{e4}|^2$ Big Bang nucleosynthesis (BBN) allowed range (dashed lines) excluded up to 340 MeV/c²

PLB 807 (2020) 135599 PLB 816 (2021) 136259

NA62 conclusion and future prospects

- **NA62 succeeded in measuring BR($K^+ \to \pi^+\nu\nu$) with the decay-in-flight technique**
  - 20 events observed in 2016+2017+2018 data (Run1) with total expected background~7
  - Most precise measurement obtained so far has been reached

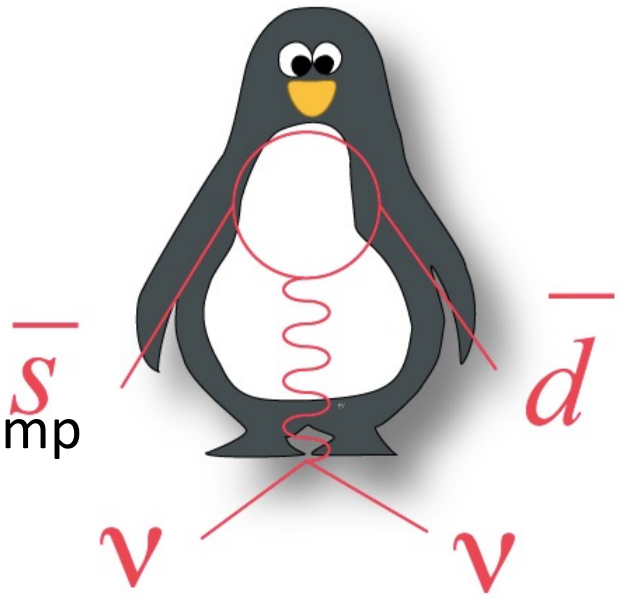
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}{}_{stat.} \pm 0.9_{syst.}) \times 10^{-11} (3.4\sigma \text{ significance})$$

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

- LFV/LNV: 1 order of magnitude improvements compared to previous searches
  Upper limits at 90% CL:

- Worlds best limits on $|Ue_4|^2$ and $|U\mu_4|^2$

- **2021-2025**
  - NA62 is taking data for a Run2
  - Upgrades in experimental setup:
    - 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



Thank you for the attention from NA62 collaboration!

Backup

SM branching ratio

Hadronic matrix element obtained from BR(K_{e3}) via isospin rotation

Loop functions favor top contribution

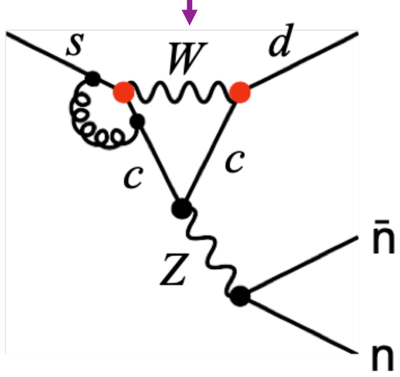
QCD corrections for charm diagrams contribute to uncertainty

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\lambda_t}{\lambda^5} X(x_t) \right)^2$$

~~CP~~

$$\kappa_+ = r_{K^+} \frac{3\alpha^2 \mathrm{BR}(K^+ \to \pi^0 e^+ \nu)}{2\pi^2 \sin^4 \theta_W} \lambda^8$$



$$\lambda_c = V_{cs} V_{cd}^*$$
$$\lambda_t = V_{td} V_{ts}^*$$
$$\lambda = V_{us}$$
$$x_t = m_t^2 / m_W^2$$

Buras, A.J., Buttazzo, D. et al. JHEP. (2015)033

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

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

Theoretical error budget from the SM input parameters:

V_{cb}	0.83	10%
γ	0.56	7%
$P_c^{SD} + \delta P_{c,u}$	0.39	5%
X_t+ other	0.12	1.5%

V_{ub}	0.50	15%
γ	0.24	7%
V_{cb}	0.24	7%
X_t+ other	0.05	1.5%

Upstream background evaluation

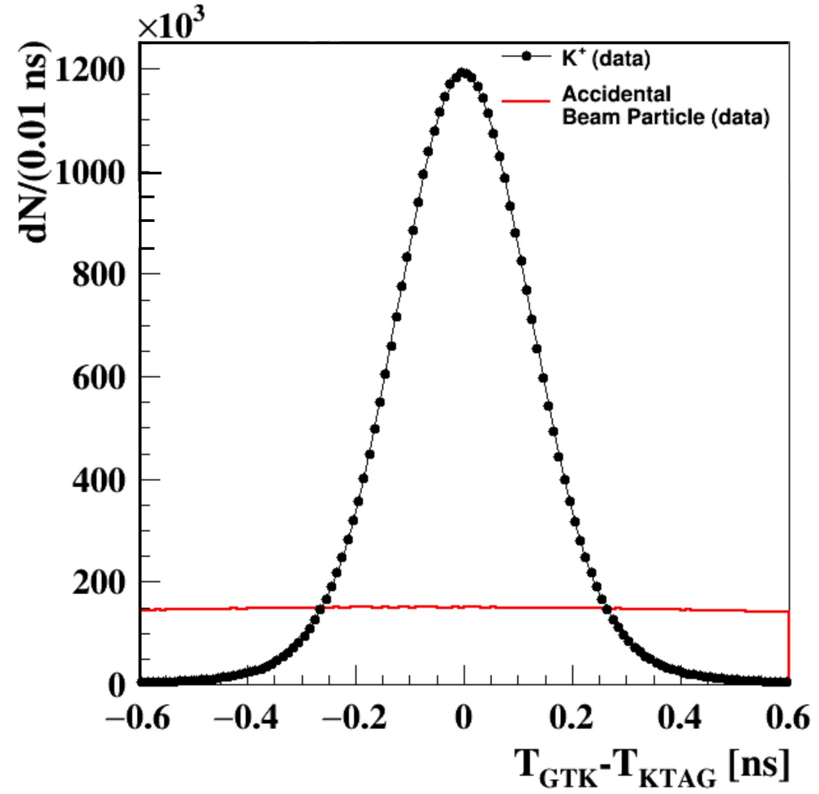
$$N^{bg}_{upstream} = N^{\pi^+}_{upstream} \cdot P^{reco}_{pileup} \cdot P^{matching}_{K-\pi}$$

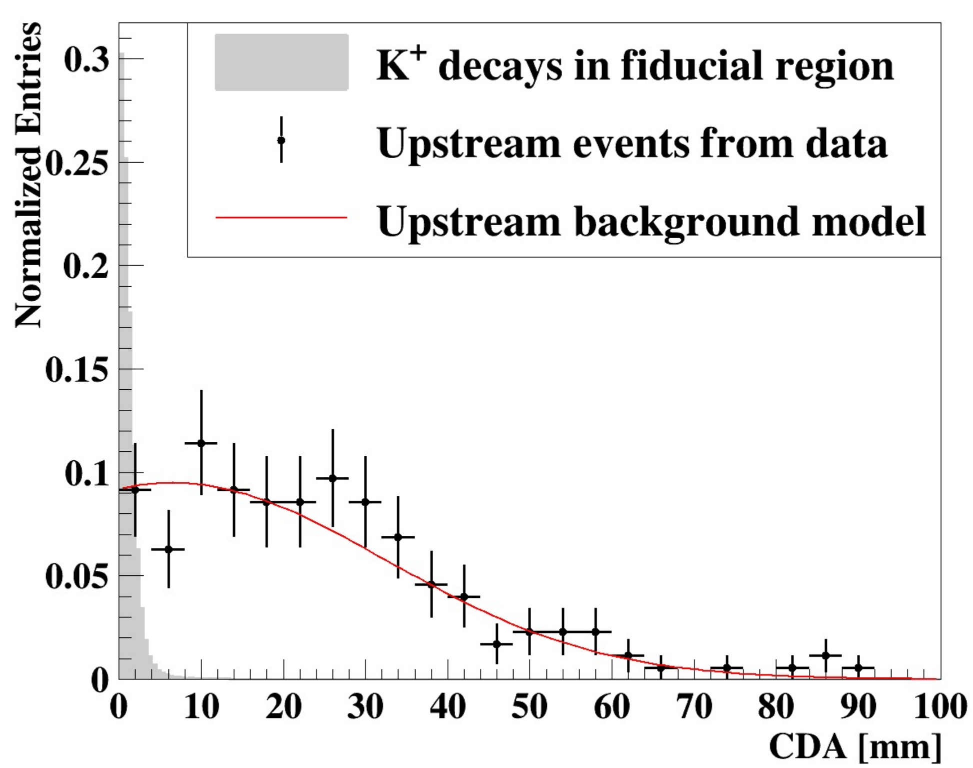
Events with a downstream 15-35 GeV/c π^+ originating upstream of GTK3

Probability that a π^+ from the beam is reconstructed in the GTK

Probability that the downstream π^+ is matched to a GTK track

Number of events after πνν selection in a sample enriched of upstream background



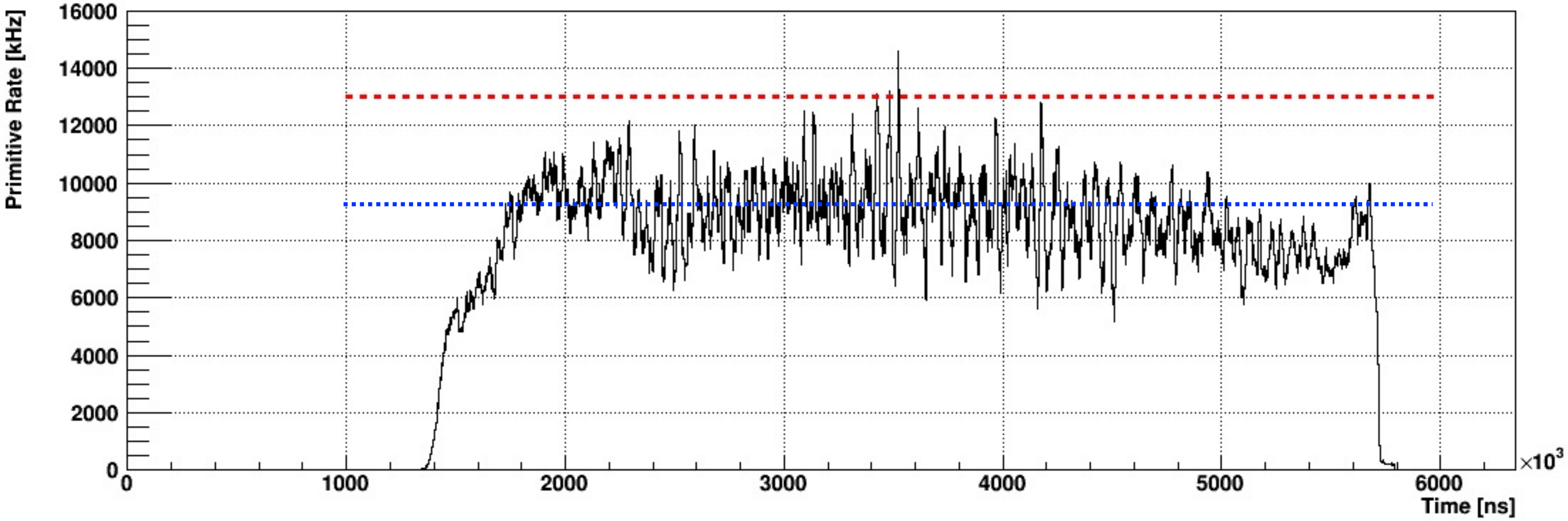


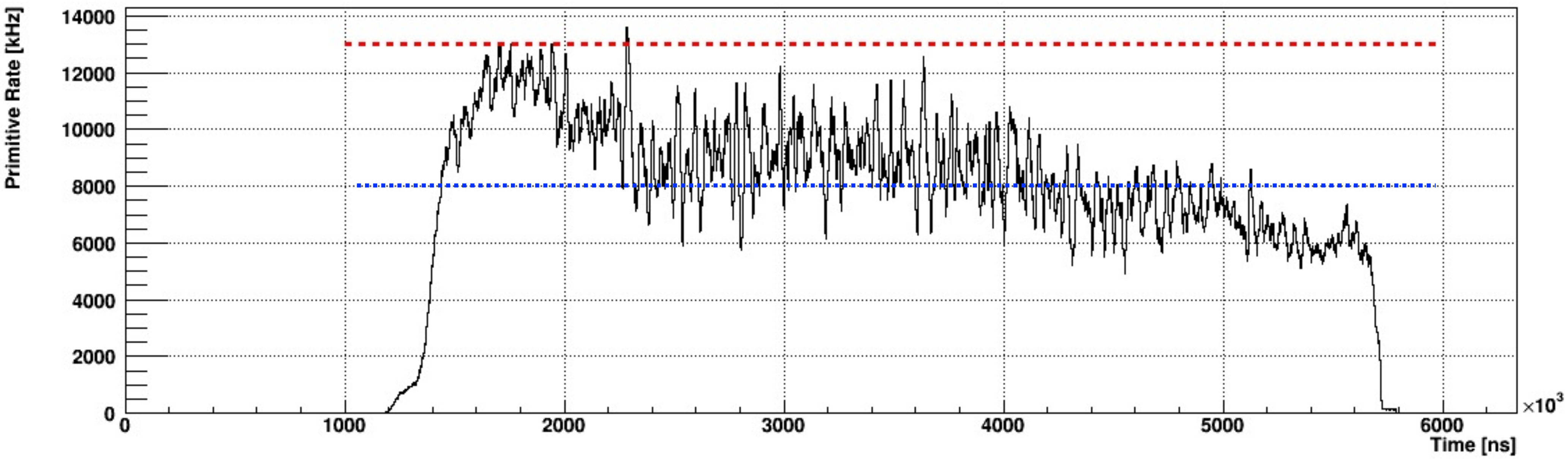
Closest distance of approach

Probability to be on time · probability to have CDA < 4 mm (matching cut)

Proton bunch profile

Examples of beam burst time profile:





Different instantaneous intensities