Results and prospects from the NA62 experiment at CERN

19/10/2023

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On behalf of the NA62 collaboration

MENU2023 - Mainz - Germany

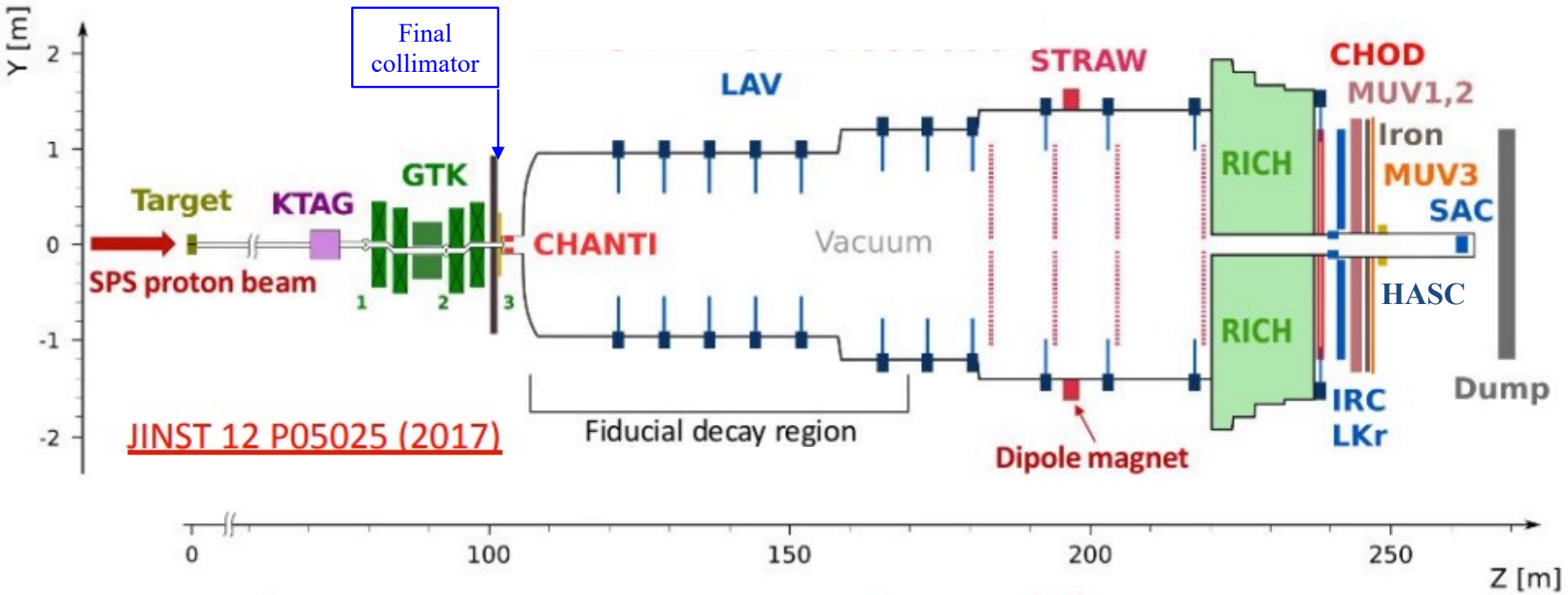
The NA62 Experiment

NA62 Collaboration consists of ~200 participants from 33 institutions:
Almaty, Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Florence, Glasgow, Lancaster, Lausanne, Liverpool, LNF, Louvain, Mainz, Marseille, Merced, Moscow, Munich, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosi, SLAC, Turin, TRIUMF, Vancouver UBC

Main goal: measurement of BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)

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

NA62: The beam



SPS Proton beam:

- 400 GeV/c protons impinging on the beryllium target
- $3.3 \cdot 10^{12}$ proton/spill
- ~4 s effective spill length
- ~ 10^{18} POT/year

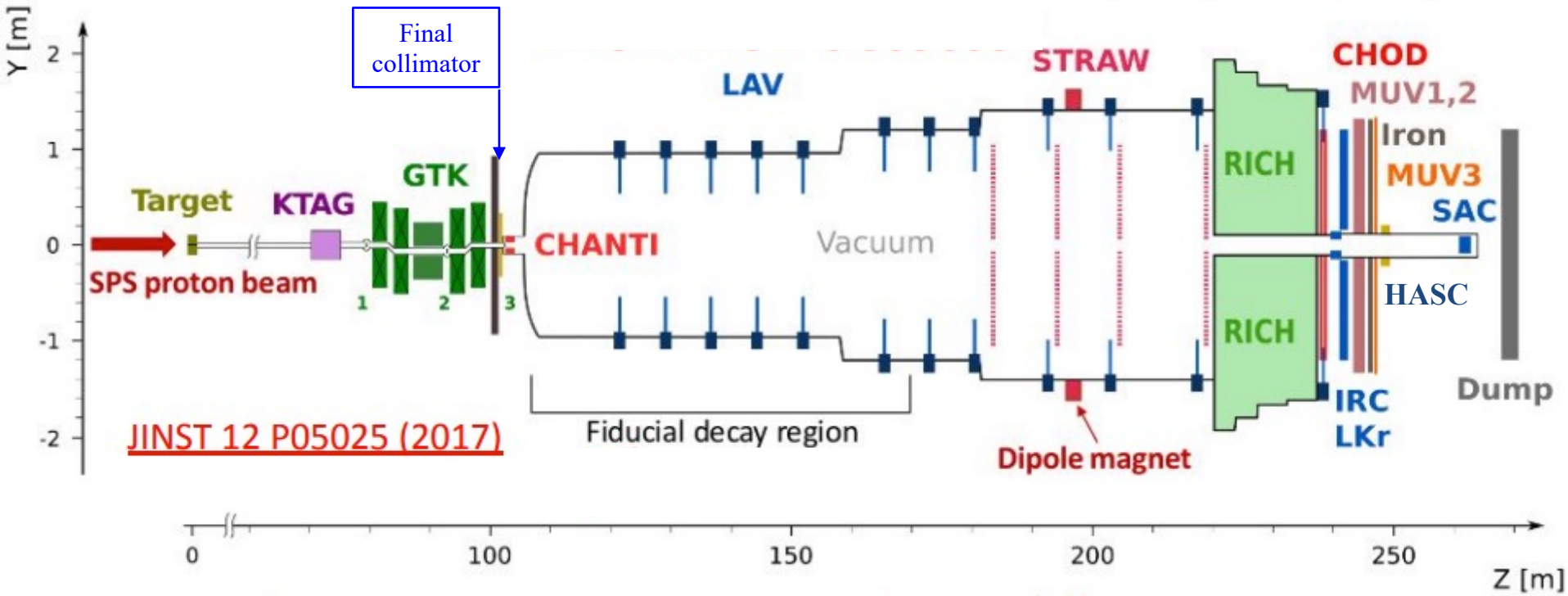
Secondary beam:

- 75 GeV/c momentum, 1% bite
- 100 mrad divergence (RMS)
- 60×30 mm^2 transverse size
- 70% pions, 24% protons, 6% kaons
- Rate: 750 MHz at GTK3

Decay region:

- 75 m long fiducial region
- Decaying kaons: ~13%
- Kaon decays rate: ~ 6 MHz.
- Vacuum ~ O(10^{-6}) mbar

NA62: The detector



- KTAG: Cherenkov threshold counter
- GTK: Si pixel beam tracker
- CHANTI: ring stations of scintillator slabs
- LAV: lead glass ring calorimeters
- STRAW: straw magnetic spectrometer
- RICH: Ring Imaging Cherenkov counter
- MUV0: off-acceptance plane of scintillators
- NA48CHOD: 2 planes of scintillator slabs
- NEWCHOD: one plane of scintillator pads
- IRC: inner ring shashlik calorimeter
- LKr: electromagnetic calorimeter filled with liquid krypton
- MUV1,2: hadron calorimeter
- MUV3: plane of scintillator pads for muon veto
- HASC: near beam lead–scintillator calorimeter
- SAC: small angle shashlik calorimeter

Status of the experiment

- Three years of data taking for physics completed (Run 1): **2016-2018**
- During 2019-2020 SPS shut down several upgrades to the experimental apparatus:
  - Fourth GTK station
  - New Hadron Sampling Calorimeter (HASC) at small angle
  - New scintillator veto detector at the beginning of fiducial region (ANTI0)
  - New SiPMs in the CHANTI Detector
  - Improvements on trigger and readout systems
- Run 2: data taking restarted in 2021 until 2025 (end of LHC run 3)

→ 3 years of new data already collected!

NA62 is not only $\pi\nu\nu$, extensive physics program:

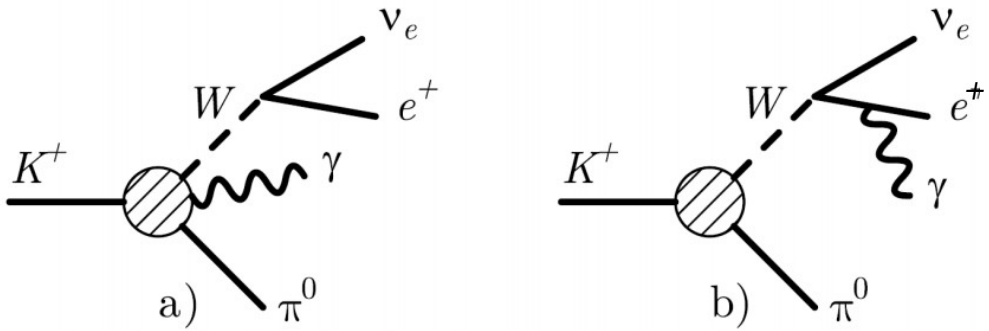
- Precision measurements on charged Kaon decays → $K^+ \to \pi^0 e^+ \nu\gamma$
- Measurements and search of rare charged Kaon decays → $K^+ \to \pi^+ e^+ e^- e^+ e^-$
- Search for forbidden charged kaon decays → $K^+ \to \mu^- \nu e^+ e^+$
- Search for new particles in charged kaon decays
- Search for exotic particles produced at the target → $A' \to \mu^+\mu^-$, $A' \to e^+e^-$

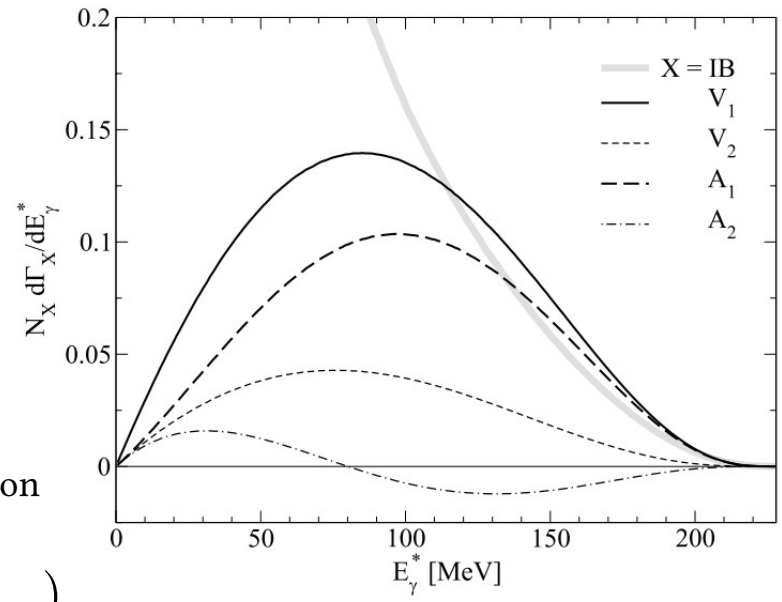
Measurement of the BR and T-violation parameter in the radiative decay $K^+ \rightarrow \pi^0 e^+ \nu \gamma$

[JHEP 09 (2023) 040]

The $K^+ \rightarrow \pi^0 e^+ \nu\gamma$ decay

DE (a) + IB (b) + INT





Divergent amplitude for $\mathbf{E_\gamma} \rightarrow 0$ and $\Theta_{e,\gamma} \rightarrow 0$ due to the IB contribution

$$R_j = \frac{Br(K_{e3}\gamma^j)}{Br(K_{e3})} = \frac{Br(K^+ \rightarrow \pi^0 e^+ \nu\gamma | E^j_\gamma, \theta^j_{e,\gamma})}{Br(K^+ \rightarrow \pi^0 e^+ \nu)}$$

EPJC 50 (2007) 557-571

	E_γ cut (*)	$\Theta_{e,\gamma}$ cut (*)	$O(p^6)$ ChPT	ISTRA+	OKA
R_1 (x10^2)	$E_\gamma > 10$ MeV	$\Theta_{e,\gamma} > 10°$	1.804 ± 0.021	1.81 ± 0.03 ± 0.07	1.990 ± 0.017 ± 0.021
R_2 (x10^2)	$E_\gamma > 30$ MeV	$\Theta_{e,\gamma} > 20°$	0.640 ± 0.008	0.63 ± 0.02 ± 0.03	0.587 ± 0.010 ± 0.015
R_3 (x10^2)	$E_\gamma > 10$ MeV	$0.6 < \cos(\Theta_{e,\gamma}) > 0.9$	0.559 ± 0.006	0.47 ± 0.02 ± 0.03	0.532 ± 0.010 ± 0.012

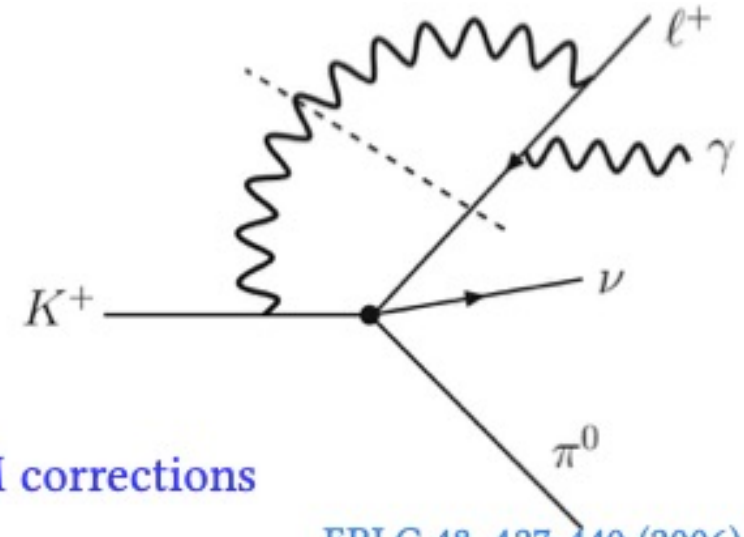
(*) in the kaon rest frame

- Most recent theoretical calculations PAN 74 (2011) 1214-1222
  - $R_2 = (0.54 \pm 0.02) \times 10^{-2}$

The T-asymmetry

- T–odd observable ξ (in the kaon rest frame)

$$\xi = \frac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{m_K^3}; A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$



EPJ C 48, 427-440 (2006)

- Non–zero A_ξ values due to NLO (one–loop) EM corrections

➜ SM expectations at the level of [10^{-5}-10^{-4}] for A_ξ

- State of the art:

	S_1	S_2	S_3
$A_\xi^{\mathrm{OKA}} \quad \times 10^3$	$-0.1 \pm 3.9_{\mathrm{stat}} \pm 1.7_{\mathrm{syst}}$	$-4.4 \pm 7.9_{\mathrm{stat}} \pm 1.9_{\mathrm{syst}}$	$7.0 \pm 8.1_{\mathrm{stat}} \pm 1.5_{\mathrm{syst}}$

Measurement strategy

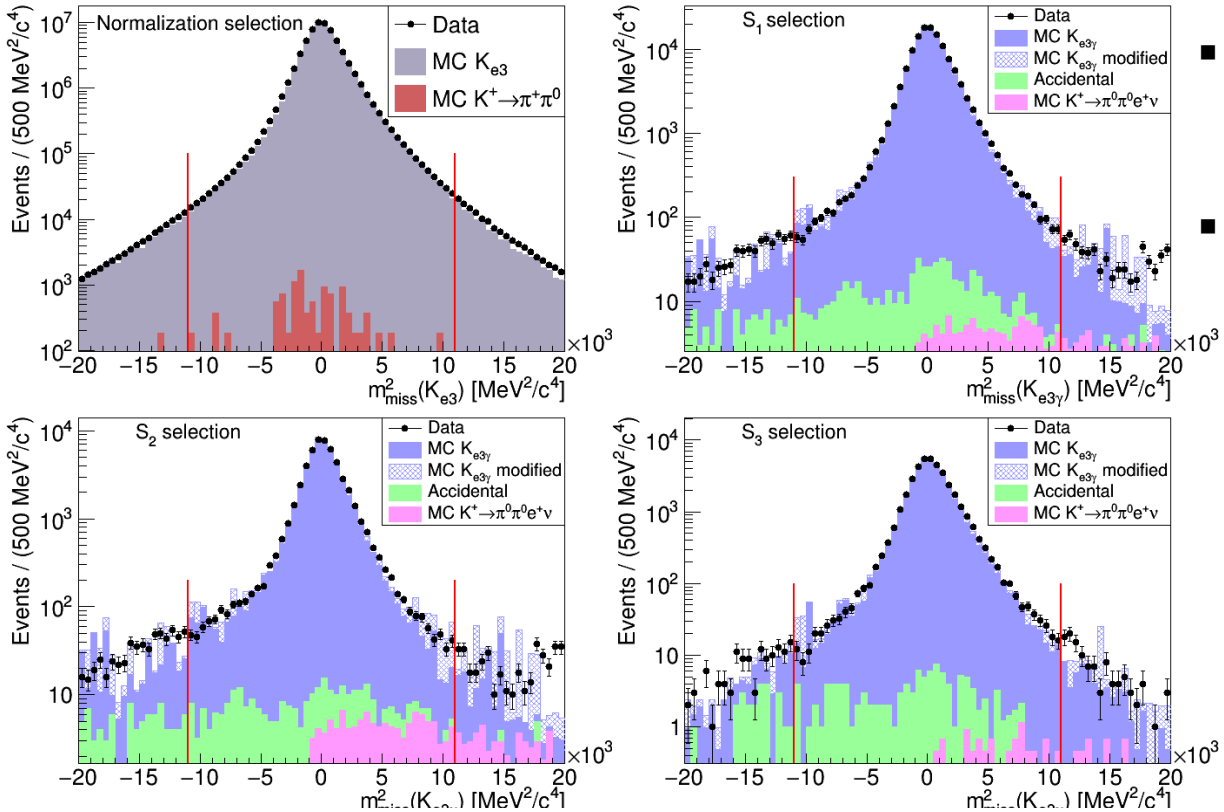
$$R_j = \frac{Br(K_{e3}\gamma^j)}{Br(K_{e3})} = \frac{N^{obs}_{K_{e3}\gamma^j} - N^{bkg}_{K_{e3}\gamma^j}}{N^{obs}_{K_{e3}} - N^{bkg}_{K_{e3}}} \cdot \frac{A_{K_{e3}}}{A_{K_{e3}\gamma^j}} \cdot \frac{\epsilon^{trig}_{K_{e3}}}{\epsilon^{trig}_{K_{e3}\gamma^j}}$$

- Full 2017 and 2018 data sets are analyzed
- Signal($K_{e3}\gamma$) and normalization (K_{e3}) channels share most of the selection criteria (except the radiative photon)
  - First order cancellation of systematic effects
- Trigger efficiencies measured on data: the same between signal and normalization to 1 per mill

- Signal selection:
  - Relies on excellent **e**$^+$ and **K**$^+$ PID + track association to reconstruct the decay vertex
  - $\pi^0 \longrightarrow \gamma\gamma$ tagging: calorimetric selection with cuts on the di-photon invariant mass
  - Radiative γ: isolated Lkr cluster away from the extrapolated electron to suppress bremsstrahlung photons
  - Kinematic selection: using two main observables

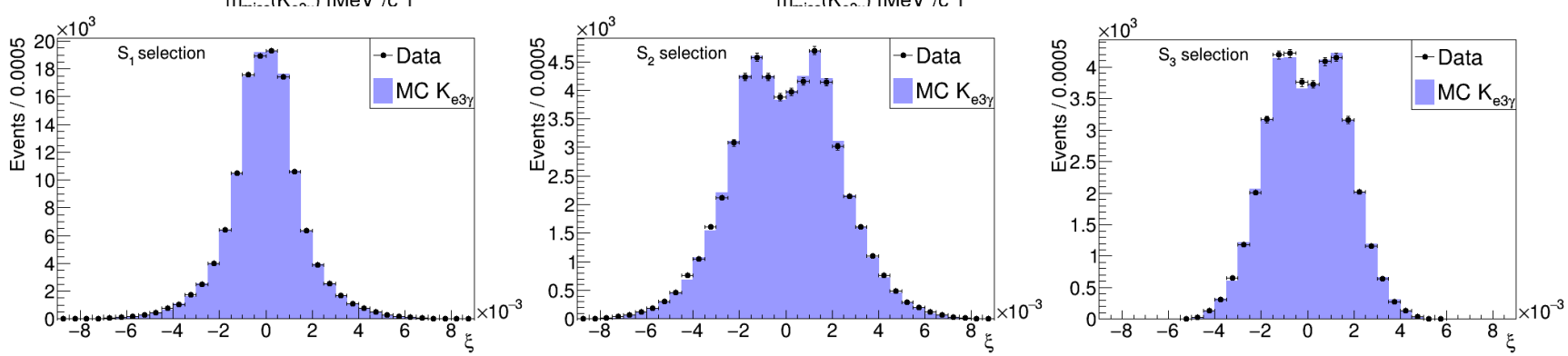
$$m^2_{miss}(K_{e3}\gamma) = (P_K - P_e - P_{\pi^0} - P_\gamma)^2 = m^2(\nu)$$
$$m^2_{miss}(K_{e3}) = (P_K - P_e - P_{\pi^0})^2 = m^2(\nu\gamma)$$

Signal and normalization



- 66×10^6 selected background-free normalization events: B/S ~ 10^{-4}
- Signal event selected:
  - 130×10^3 in S_1
  - 54×10^3 in S_2
  - 39×10^3 in S_3

ξ



Results

Error budged for R_j measurements:

	$\delta R_1/R_1$	$\delta R_2/R_2$	$\delta R_3/R_3$
Statistical	0.3%	0.4%	0.5%
Limited MC sample size	0.2%	0.4%	0.4%
Background estimation	0.1%	0.2%	0.1%
LKr response modelling	0.4%	0.5%	0.4%
Photon veto correction	0.3%	0.4%	0.3%
Theoretical model	0.1%	0.5%	0.1%
Total systematic	0.6%	0.9%	0.7%
Total	0.7%	1.0%	0.8%

Results for R:

$$R_1 \times 10^2 = 1.715 \pm 0.005_{\text{stat}} \pm 0.010_{\text{syst}} = 1.715 \pm 0.011$$

$$R_2 \times 10^2 = 0.609 \pm 0.003_{\text{stat}} \pm 0.006_{\text{syst}} = 0.609 \pm 0.006$$

$$R_3 \times 10^2 = 0.533 \pm 0.003_{\text{stat}} \pm 0.004_{\text{syst}} = 0.533 \pm 0.004$$

Results for A_ξ ($\times 10^2$):

S_1	S_2	S_3
$-1.2 \pm 2.8_{\text{stat}} \pm 1.9_{\text{syst}}$	$-3.4 \pm 4.3_{\text{stat}} \pm 3.0_{\text{syst}}$	$-9.1 \pm 5.1_{\text{stat}} \pm 3.5_{\text{syst}}$

- The main systematic uncertainty comes from the modelling of the electromagnetic calorimeter (LKr) response to low energy photons
- NA62 measurements of Rj smaller than $O(p^6)$ ChPT by 5% relative (disagreement: 3 std deviations)
- Improvement on experimental precision of R_j measurements by a factor > 2
- Improvement on A_ξ error with respect to the previous experimental results

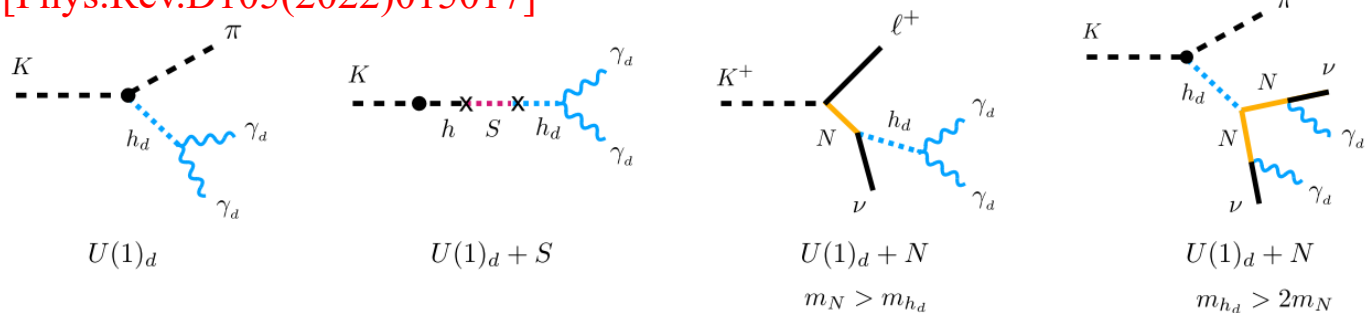
Search for the decay $K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$

[Physics Letters B 846 (2023) 138193]

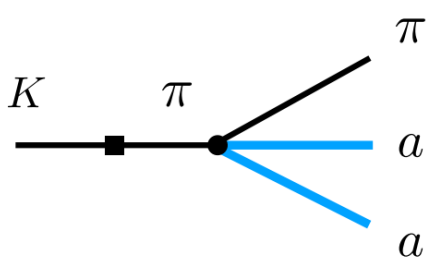
$K^+ \to \pi^+ e^+ e^- e^+ e^-$: motivations

- K^+ **decays in prompt dark cascade** with multiple DS mediators
  - $K^+ \to \pi^+ S, S \to A'A', A' \to e^+e^-$ involving a dark scalar (S) promptly decaying into DP (A')

[Phys.Rev.D105(2022)015017]



- Probe **short-lived QCD axions** (a) through the $K^+ \to \pi^+ a a$, $a \to e^+e^-$ process

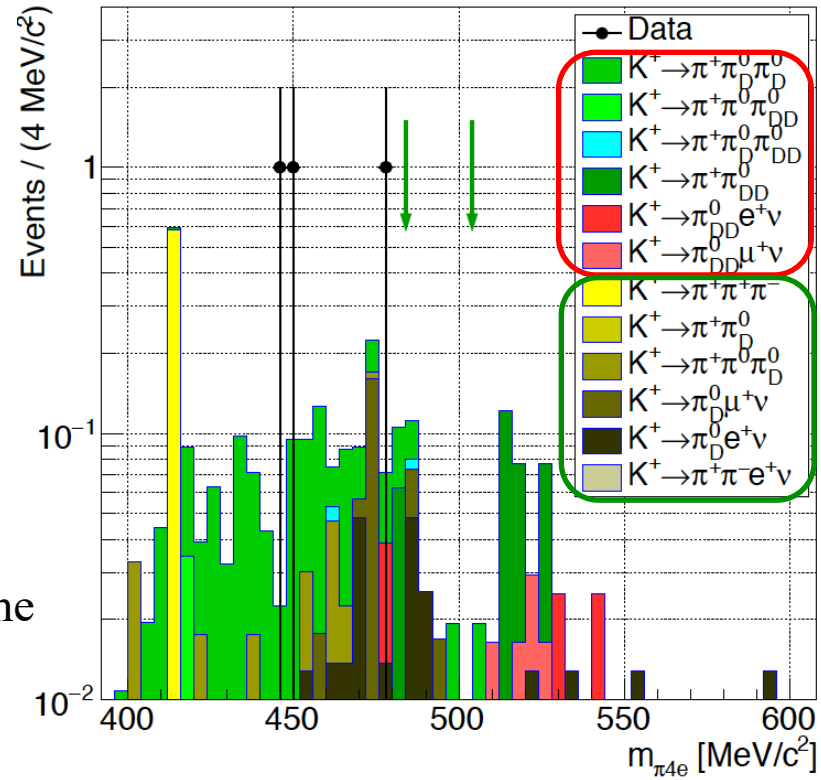


  - If m_a=17 MeV, $BR(K^+ \to \pi^+ a a) > 2 \times 10^{-8}$ is predicted
  - possibility for a conclusive test of QCD axion explanation for the "17 MeV" anomaly [Phys.Rev.D103(2021)055018, Eur.Phys.J.C83(2023)230]
- $K^+ \to \pi^+ e^+ e^- e^+ e^-$: heavily **suppressed SM** process (outside the π^0 pole)
  - $BR^{SM}_{LO}(K^+ \to \pi 4e$, **non resonant**$) = (7.2 \pm 0.7) \times 10^{-11}$ [Phys. Rev. D 106 (2022) L071301]

Search and limits

- Search on data collected in 2017 and 2018
- $K^+_{flux} = (8.58 \pm 0.19_{stat} \pm 0.07_{MC} \pm 0.41_{ext}) \times 10^{11}$ measured using $\boldsymbol{K^+ \to \pi^+ \pi^0_{DD}}$
- **Events with 5-track** vertex $Q_{ToT}=+1$
- Total momentum consistent with K^+ beam one
- **Invariant mass $\boldsymbol{m_{\pi 4e}}$** used as discriminant variable and blind analysis strategy
- Expected background and signal acc. from MC

- **Backgrounds from 5 & 7 tracks K^+ decays**
- **Backgrounds from 3-tracks K^+decays** + a $K_{3\pi}$ in time
- Observed events in Signal Region = 0
- Expected bkg events in SR = (0.18 ± 0.14)



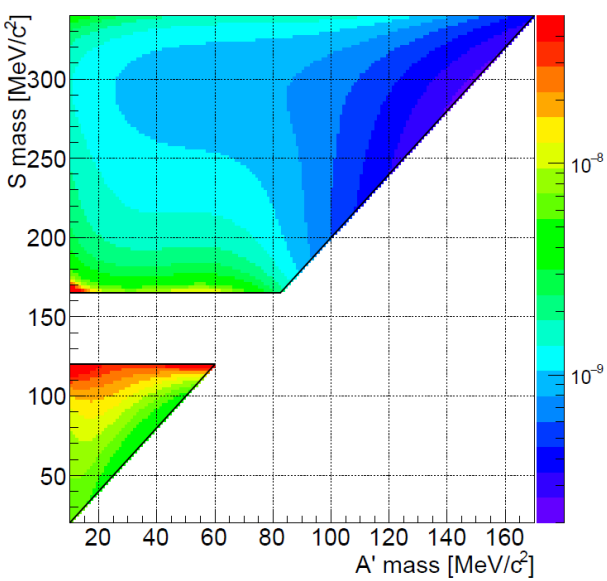
$$\boldsymbol{BR(K^+ \to \pi^+ e^+ e^- e^+ e^-, \text{ non resonant}) < 1.4 \times 10^{-8} \text{ @ } 90\% \text{ CL}}$$

limit is O(200) larger w.r.t. SM expectations

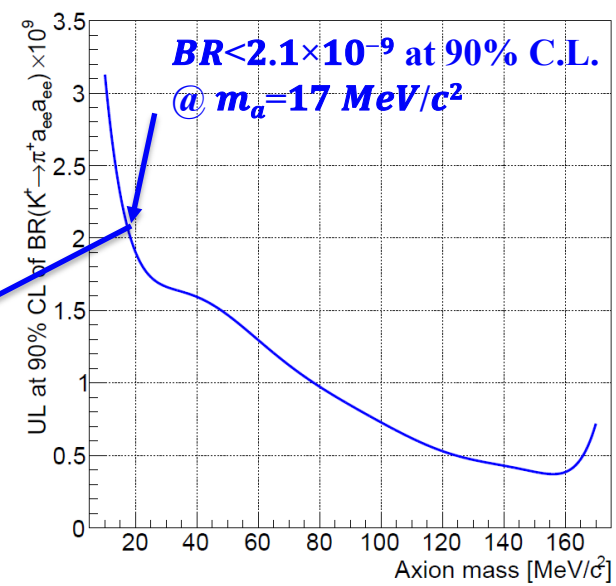
Dark sector and axion limits

- Same $K\pi 4e$ selection + 2 identical $m_{e^+e^-}$ masses
- Use the same signal region as $K\pi 4e$:
- Exp. bkg events in SR = (0.0004 ± 0.0004) Observed events in SR = 0
- Whole NA62 Run1 data set. Dark scalar/Axion mass scan in step of 5 MeV/c^2.

S dark scalar (A' dark photon) $K^+ \to \pi^+ S, S \to A'A', A' \to e^+e^-$	Short-lived QCD axion: $K^+ \to \pi^+ aa$ with prompt $a \to e^+e^-$



Exclude the QCD axion as a solution for the X17 anomaly.
From Theory:
$BR(K^+ \to \pi^+ aa) > 2\times10^{-8}$
$@\ m_a = 17\ MeV/c^2$



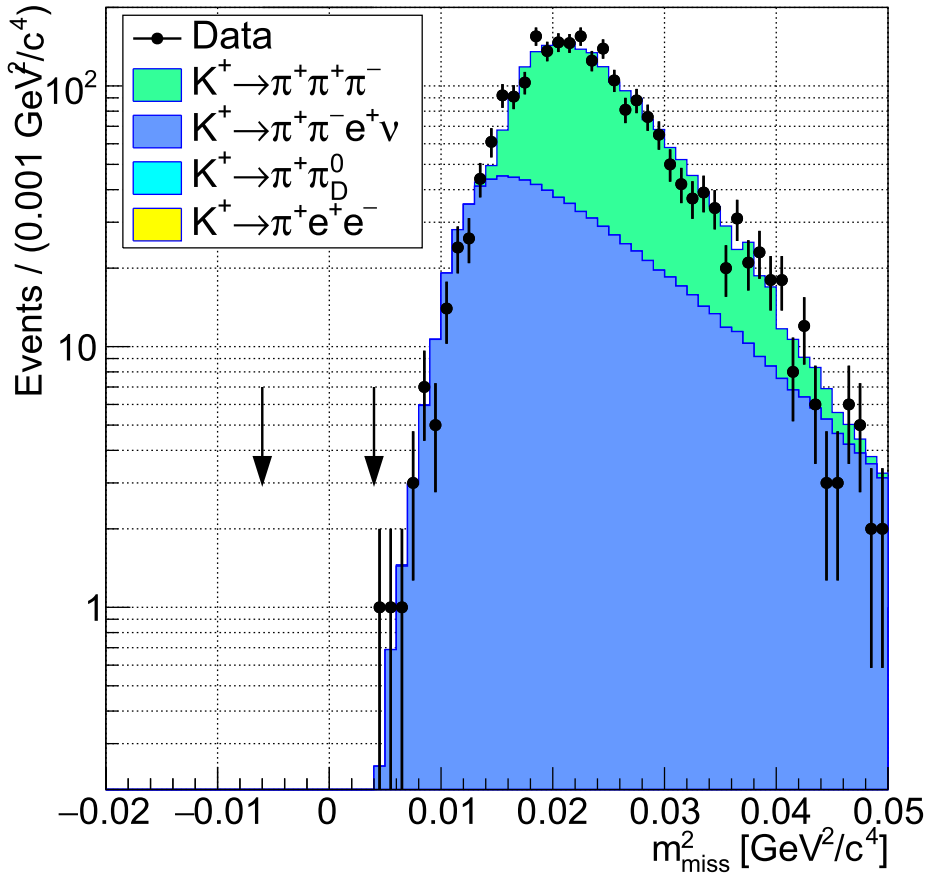
Search for LN/LF violating decay $K^+ \rightarrow \mu^- \nu e^+ e^+$

[*Physics Letters B 838 (2023) 137679*]

Search for $K^+ \to \mu^- \nu e^+ e^+$

- Either lepton flavour or lepton number is violated, depending on the neutrino flavour.
- Normalisation to the SM decay $K^+ \to \pi^+ e^+ e^-$, number of K^+ decaying in the FV: $(1.97 \pm 0.02_{\text{stat}} \pm 0.02_{\text{syst}} \pm 0.06_{\text{ext}}) \times 10^{12}$
- Signal region defined on the squared missing mass: $m^2_{\text{miss}} = (P_K - P_\mu - P_{e1} - P_{e2})^2$
- Backgrounds:

Mode / Region	Lower	Signal	Upper
$K^+ \to \pi^+\pi^+\pi^-$	< 0.07	< 0.07	1412 ± 11
$K^+ \to \pi^+\pi^- e^+\nu$	0.01 ± 0.01	0.16 ± 0.02	867 ± 1
$K^+ \to \pi^+\pi^+\pi^-$ (upstream)	< 0.03	0.06 ± 0.03	1.5 ± 0.3
$K^+ \to \pi^+\pi^- e^+\nu$ (upstream)	0.01 ± 0.01	0.01 ± 0.01	0.14 ± 0.03
$K^+ \to \pi^0_D e^+\nu$	0.02 ± 0.01	0.01 ± 0.01	0.02 ± 0.01
$K^+ \to e^+\nu\mu^+\mu^-$	< 0.01	< 0.01	0.05 ± 0.02
Total expected	0.04 ± 0.02	0.26 ± 0.04	2281 ± 11
Data	0	0	2271



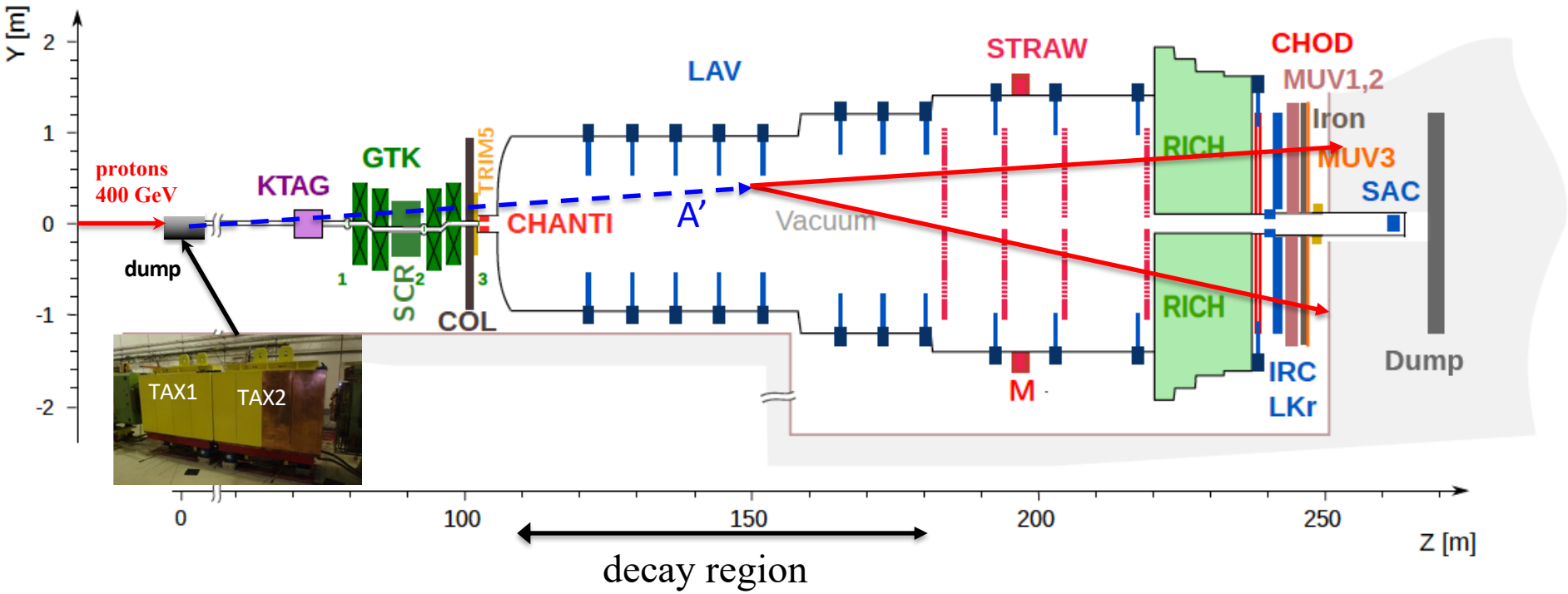
Expected background: 0.26±0.04 evt
Candidates observed: 0
$BR(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11}$ at 90% CL

Search for dark photons in the NA62 beam dump mode

$A' \rightarrow \mu^+\mu^-$ [*JHEP* 09 (2023) 035]

$A' \rightarrow e^+e^-$ (preliminary)

NA62 beam dump mode



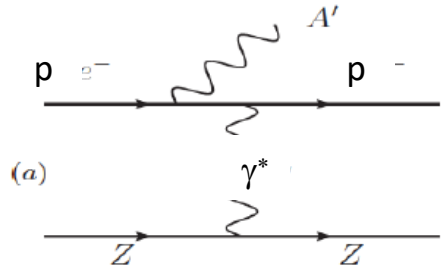
- **400 GeV SPS protons** absorbed by K12 TAX copper collimators: **Target + dump**
- **A'** produced by proton strahlung or meson decays
- **A' decays** in the decay region if γct is big enough (γ >1000)
- **Lepton pairs (e^+e^-, $\mu^+\mu^-$)** are detected by NA62 exp.
- Total of **1.4×10^{17}** protons on dump collected **in 2021** (10 days of special run)

Production and decay

A′ production proceeds via p-bremsstrahlung or mesons decays

- Proton-bremsstrahlung [Phys. Lett. B 731 (2014) 320]:

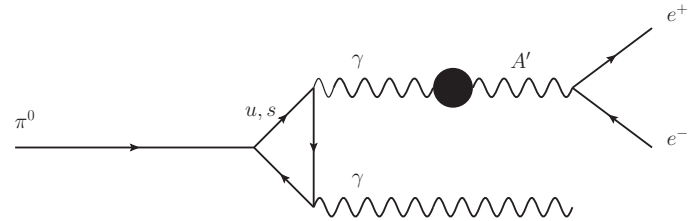
  $\gamma^* p \to A' p',$



- Meson decays:

$pN \to MX$, where $M = \pi^0, \eta^{(\prime)}, \rho, \omega, \phi,$

$$
\begin{aligned}
M &\to \gamma A' && \text{for } M = \pi^0, \eta^{(\prime)};\\
M &\to \pi^0 A' && \text{for } M = \eta', \rho, \omega, \phi;\\
M &\to \eta A' && \text{for } M = \rho, \omega, \phi.
\end{aligned}
$$

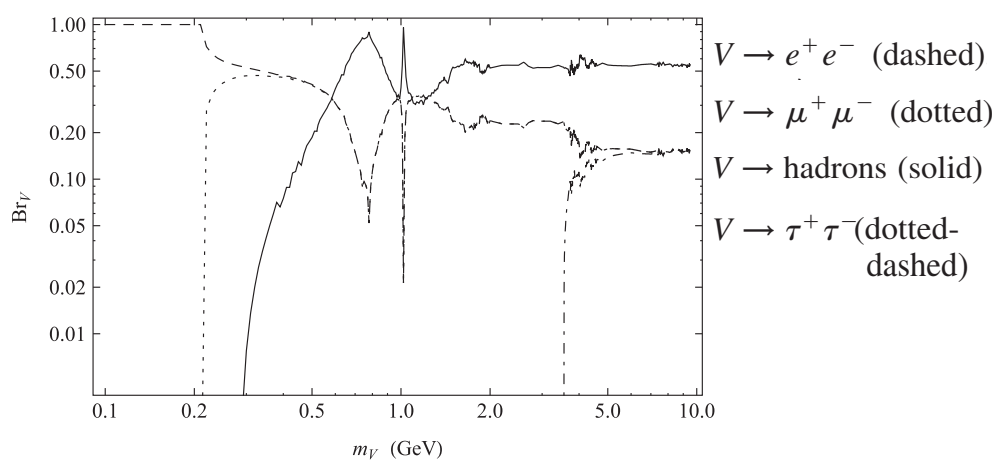


A′ decays to leptons pairs for $M_{A'}$<500 MeV

Dominant decays at NA62 are:

- ➢ $A' \to e^+e^-$ (100% for $M_{A'}$<210 MeV)
- ➢ $A' \to \mu^+\mu^-$ (only if $M_{A'}$>210 MeV)

[Phys. Review D 79, 115008 (2009)]



A' → $\mu^+\mu^-$ search technique

Event selection: Track quality, timing coincidence, PID with calorimeter and muon detector

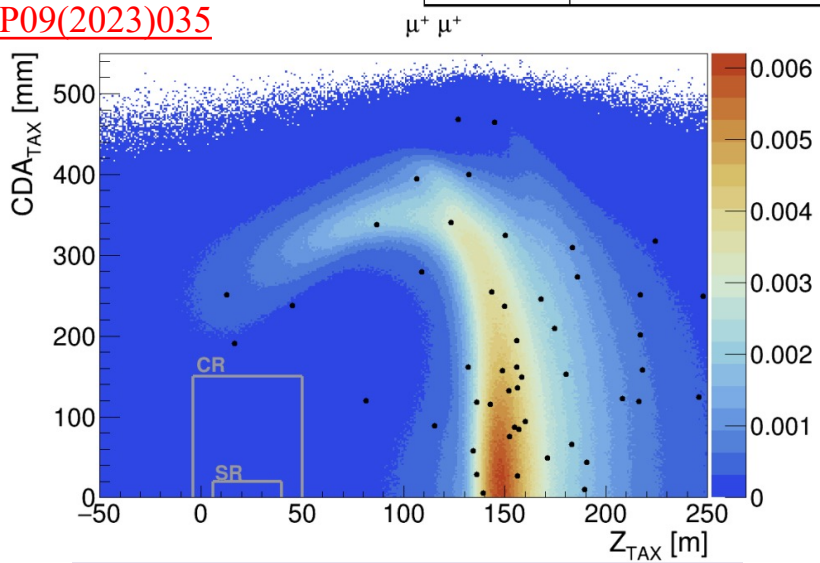
No Photons and no in-time activity in Large Angle Vetos

Decay Vertex match: A' decay point P_{CDA} compatible with beam extrapolation
Closest Distance of Approach (CDA) between the dark photon line of flight and the proton beam direction at the TAX entrance.

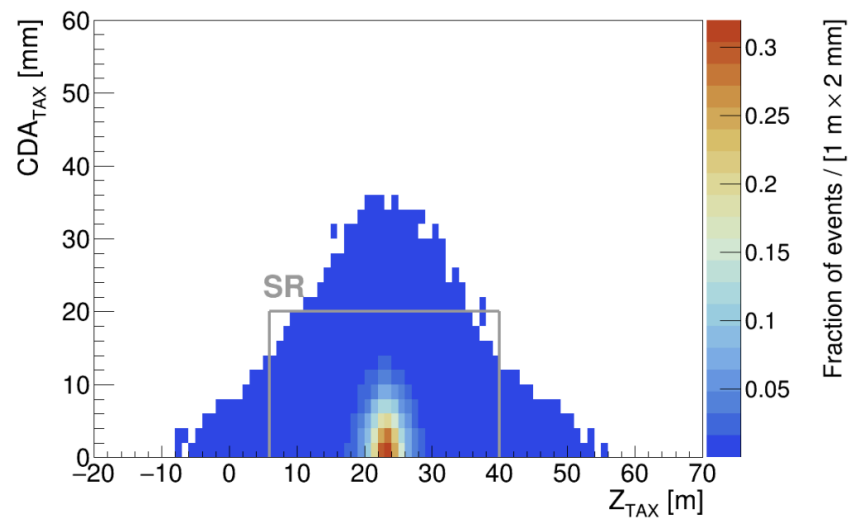
Blind analysis with control regions used for MC background estimate validation

Region	Combinatorial	Prompt	Upstream-prompt
CR	0.17 ± 0.02	< 0.004	< 0.069
SR	0.016 ± 0.002	< 0.0004	< 0.007

JHEP09(2023)035



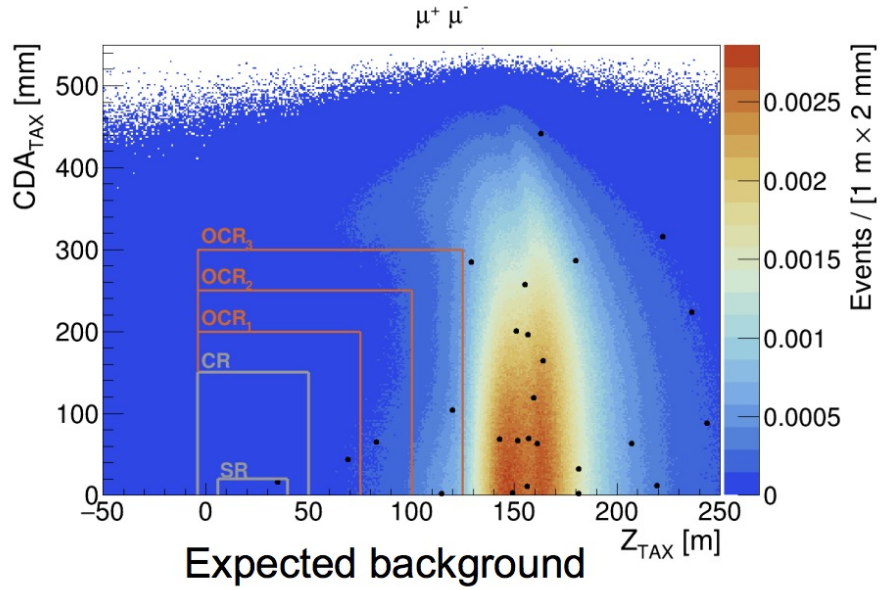
Same sign event MC BG validation



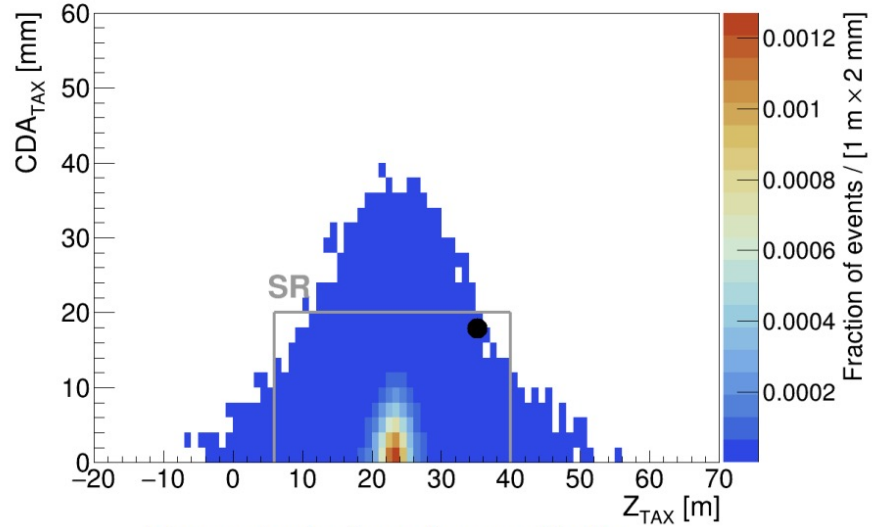
A' → $\mu^+\mu^-$ MC: signal region definition

Opening the box

- Open Signal and Control Regions:
  0 events in CR 1 event in SR, black dot
- **Probability** to observe **SM** event in SR is only **1.6%**
- However, event on **tail end of SR** and the **Δt** between the tracks is **2σ** away from zero
- Invariant mass of event was 411 MeV
- **Observed event could be interpreted as combinatorial background fluctuation**



Expected background



Expected signal sensitivity

Exclusion limits

Black line: **observed** limit
Green filled: **1s** confidence level
Yellow filled: **2s** confidence level
Grey filled: **Already excluded** regions

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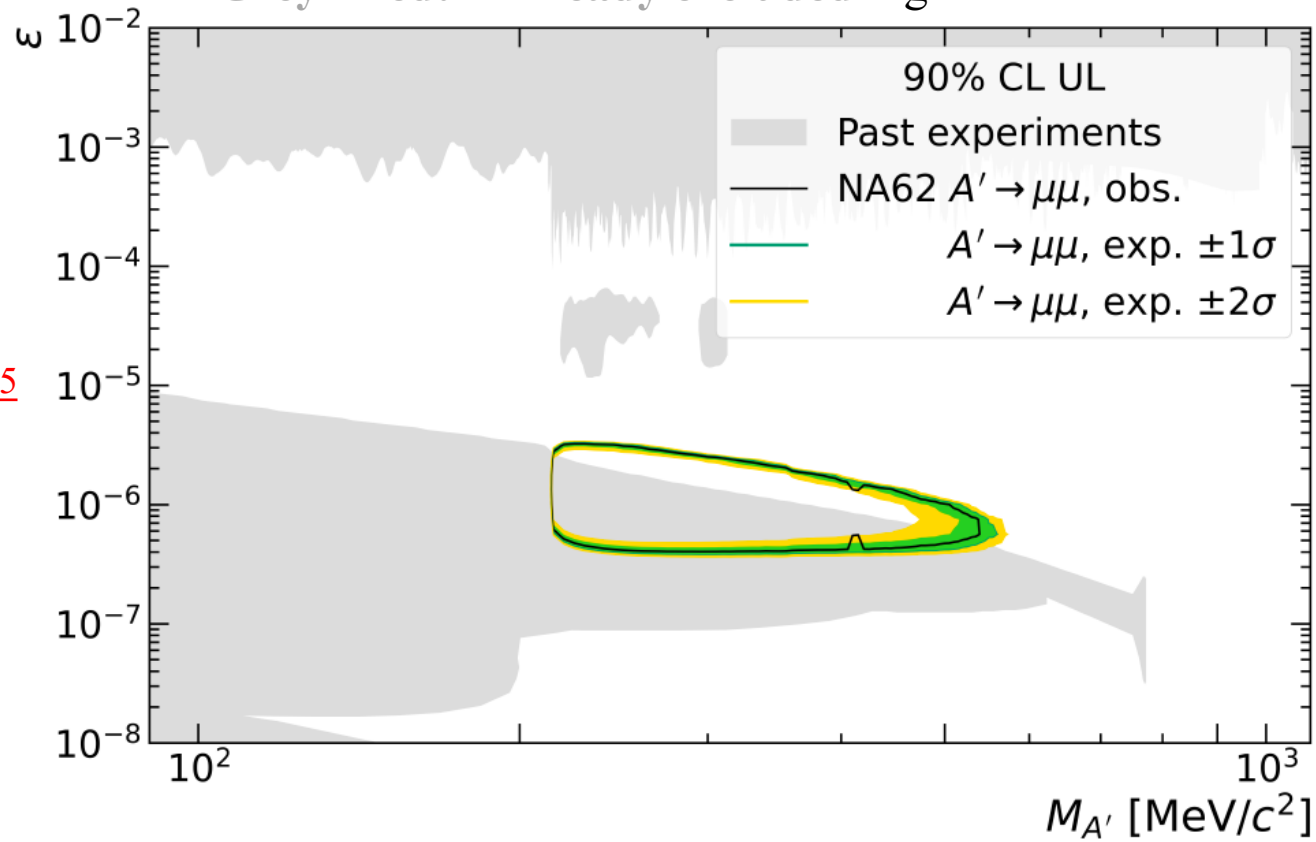
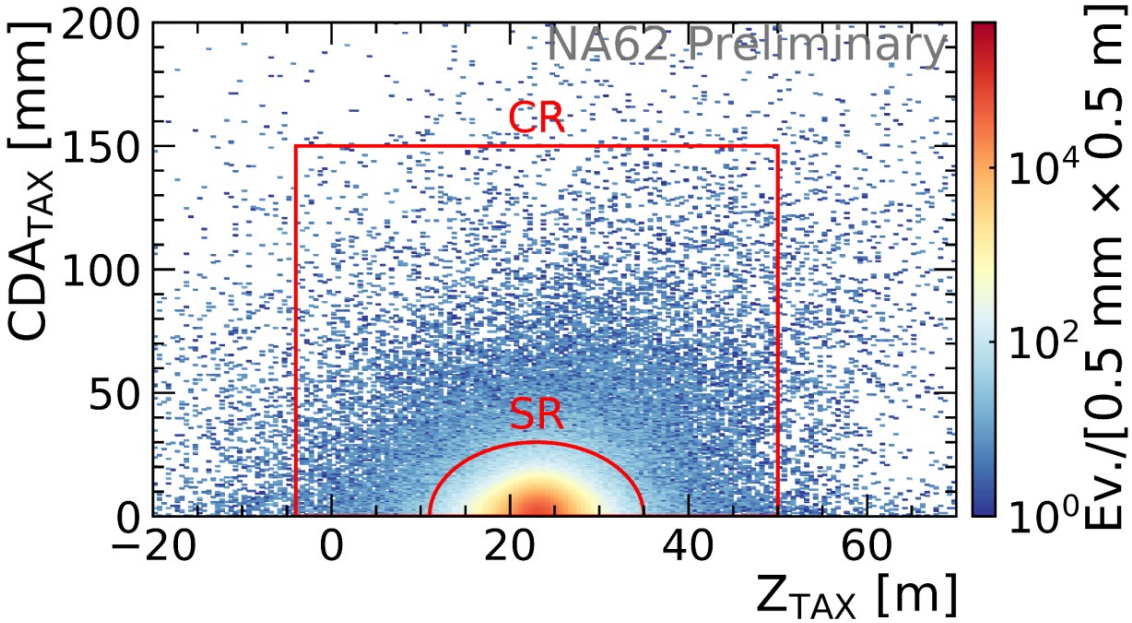


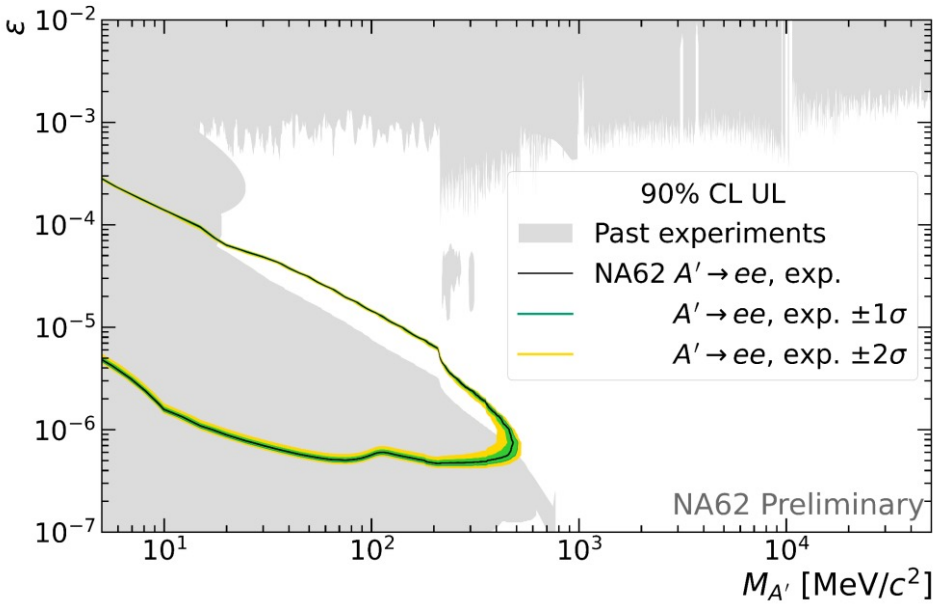
Improved 90% CL limit on DP in the mass range **215 MeV/c² <$M_{A'}$<550 MeV/c²**

The A′ → e^+e^- channel

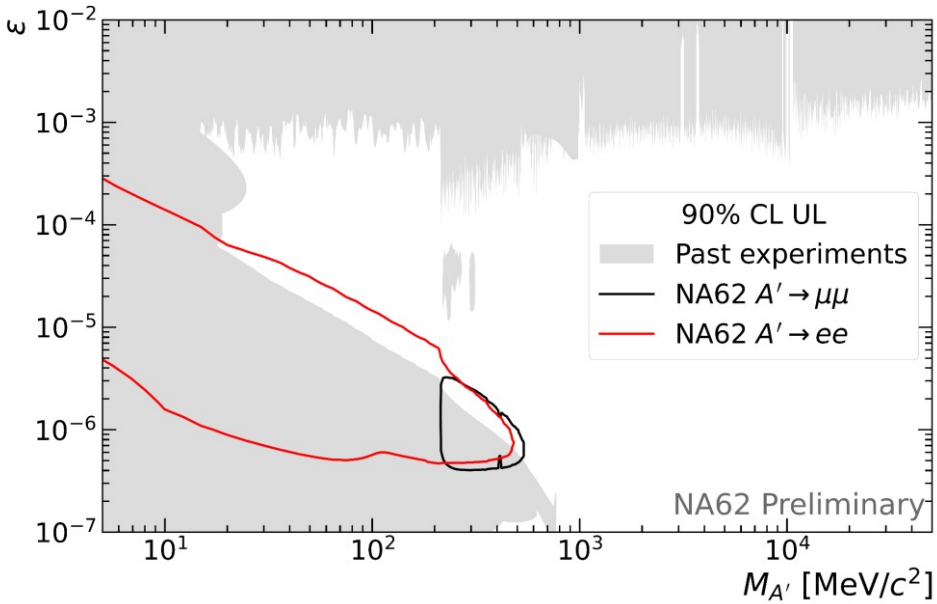
- Access to the mass region $M_{A'} < 210$ MeV/c^2
- Signal and control regions redefined (different kinematics)
- **PID** changed to select electrons, **Veto** on in-time activity in the muon detector (MUV3)
- Same **blind analysis** technique as in A′→ $\mu^+\mu^-$ (expected SM background < 0.06 events)
- **No events found in the SR after unblinding!**



Combined results A' → $\ell^+\ell^-$



Results for **A' → e^+e^- channel only**



Combined results for **A'→e^+e^-** and **A'→$\mu^+\mu^-$**

- **NA62 dump mode results for 2-leptons decays improve 90% CL limit** on DP in the mass range **20 MeV/c^2 <$M_{A'}$<550 MeV/c^2**
- Analysis on additional final states γγ, π π γ, μπ… ongoing on 2021 data set

Conclusions

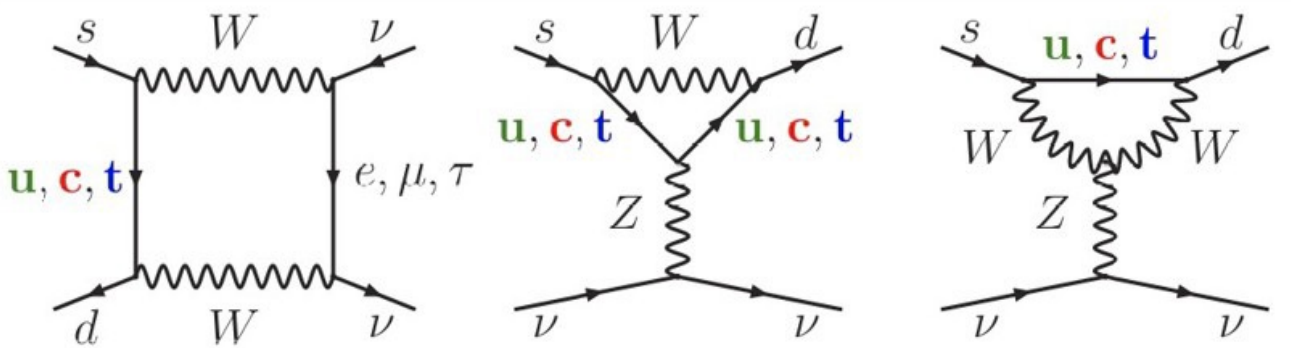
- The NA62 collaboration is continuing to fully exploit the data collected during Run 1:
  - $K^+ \rightarrow \pi^0 e^+ \nu\gamma$ decay: new measurements of the BR and new limits on T-asymmetry parameter ξ
  - New limits on the search of dark photons and QCD axions from the non resonant decay $K^+ \rightarrow \pi^+ e^+ e^- e^+ e^-$
  - First search of the LF/LN violation decay $K^+ \rightarrow \mu^- \nu e^+ e^+$

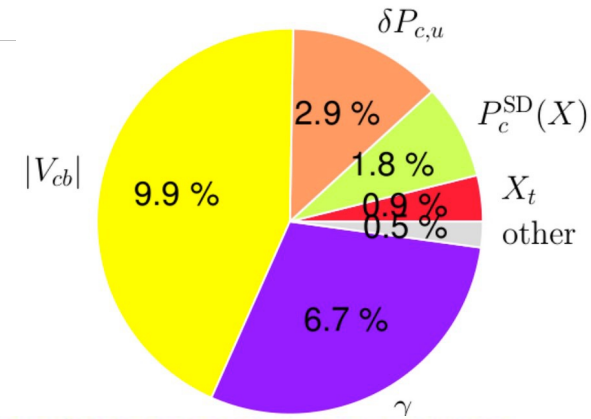
- Meanwhile, after important hardware upgrades installed during LS2 (2019-2020), the data taking restarted in 2021 for Run 2 (2021-2025) and new results, based on these data, are incoming:
  - New limits on dark photon search from 2021 beam dump run:
    - $A' \rightarrow \mu^+ \mu^-$
    - $A' \rightarrow e^+ e^-$

- Stay tuned! (new results, new proposal – HIKE)

SPARES

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





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

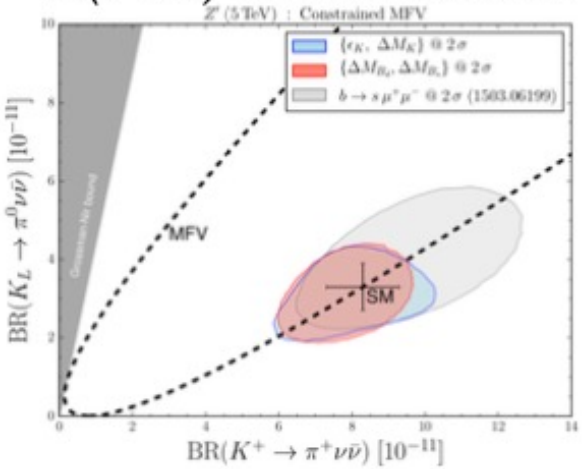
- FCNC loop processes: s → d coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with K_{l3} decays (per mill precision)
- SM predictions: Buras. et. al., JHEP11(2015)033 **$BR(K^+ \rightarrow \pi^+\nu\nu) = (0.84 \pm 0.10)\times10^{-10}$**

New SM calculations:
Buras, Venturini (arXiv:2109.11032): $(0.860 \pm 0.042)\times10^{-10}$
Brod, Gorbahn, Stamou (*PoS* BEAUTY2020 (2021) 056): $(0.773 \pm 0.061)\times10^{-10}$

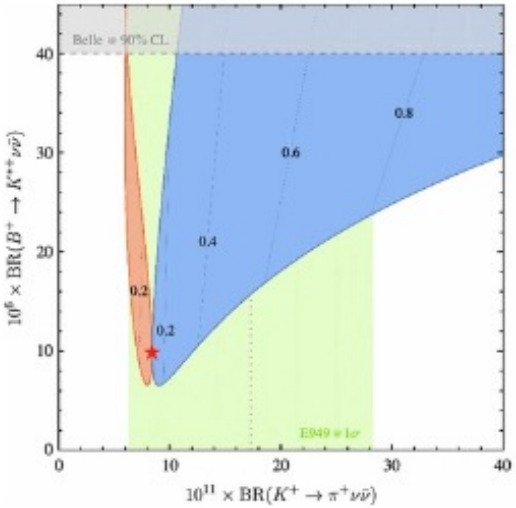
$K^+ \rightarrow \pi^+\nu\bar{\nu}$ beyond SM

- 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)]
- MFV analyses [S. Descotes-Genon, S.Fajfer et. al., PLB 80 (2020) 135769]
- Constraints from existing measurements (correlations model dependent)

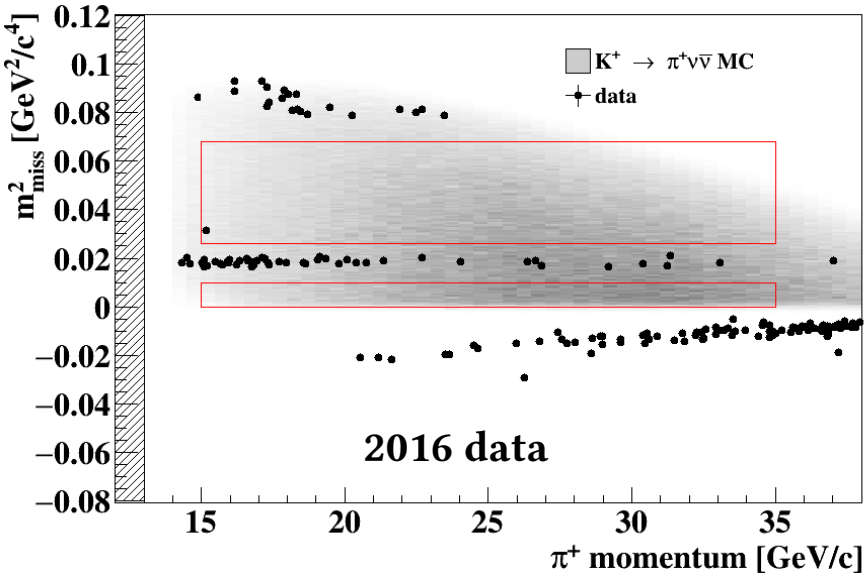
Z'(5 TeV) in Constrained MFV

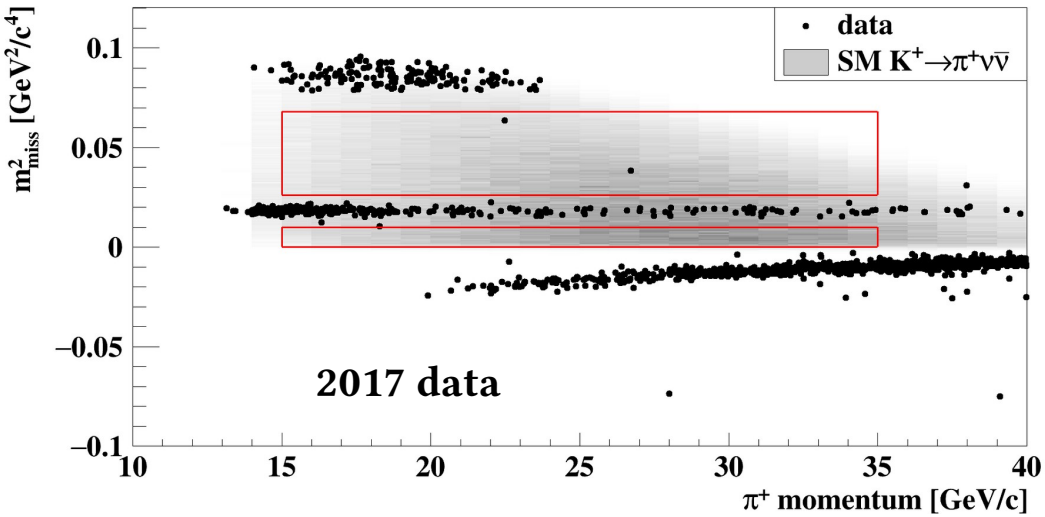


LFU violation



Results from 2016 and 2017

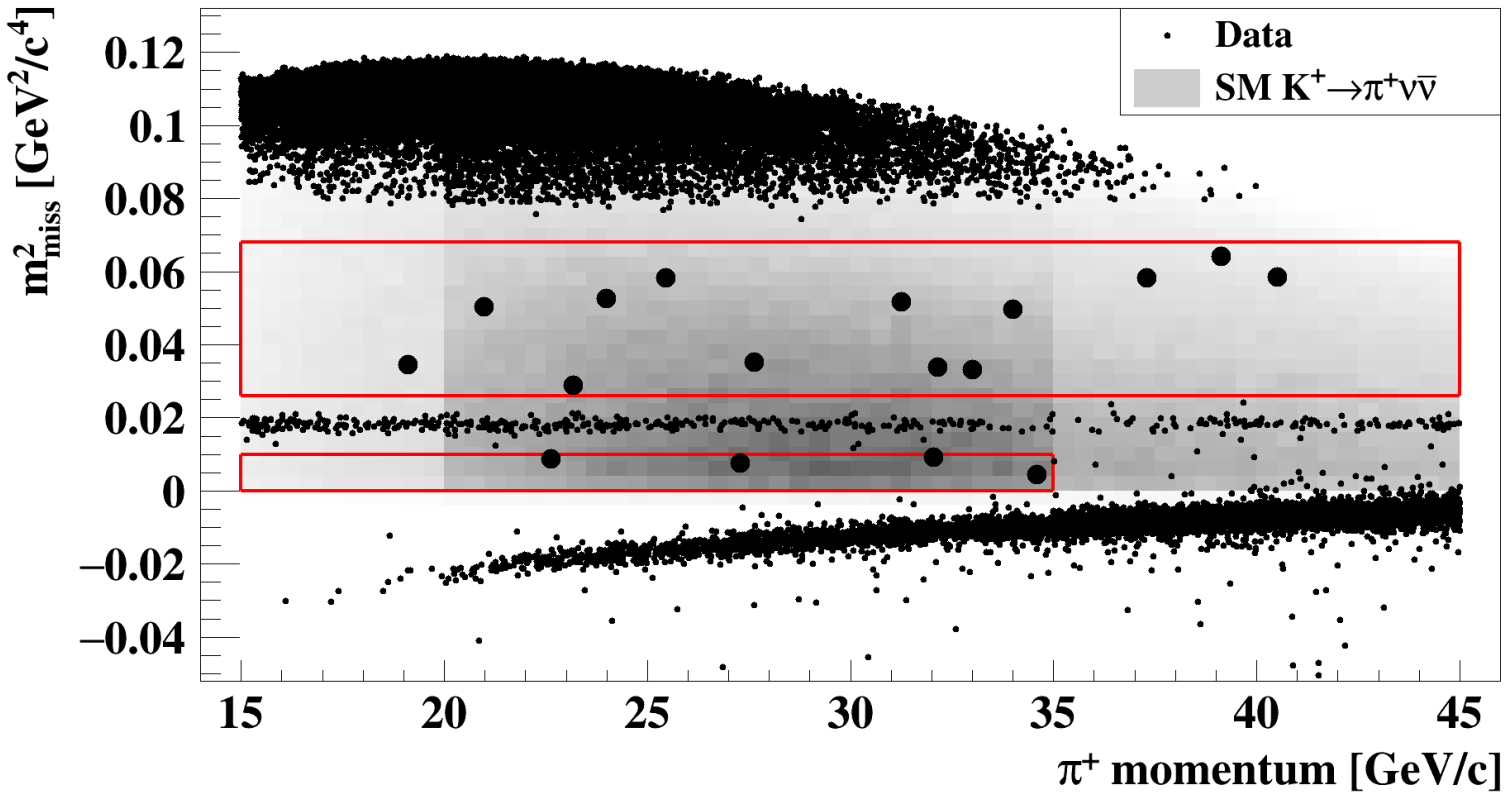




- 1 events observed
- $Br(K^+ \longrightarrow \pi^+\nu\nu) < 14 \times 10^{-10}$ @ 90% CL
  Phys. Lett. B 791 (2019) 156-166

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

Results from 2018 data



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

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