Searches for ALP production and decays at kaon factories

Evgueni Goudzovski

UNIVERSITY OF BIRMINGHAM

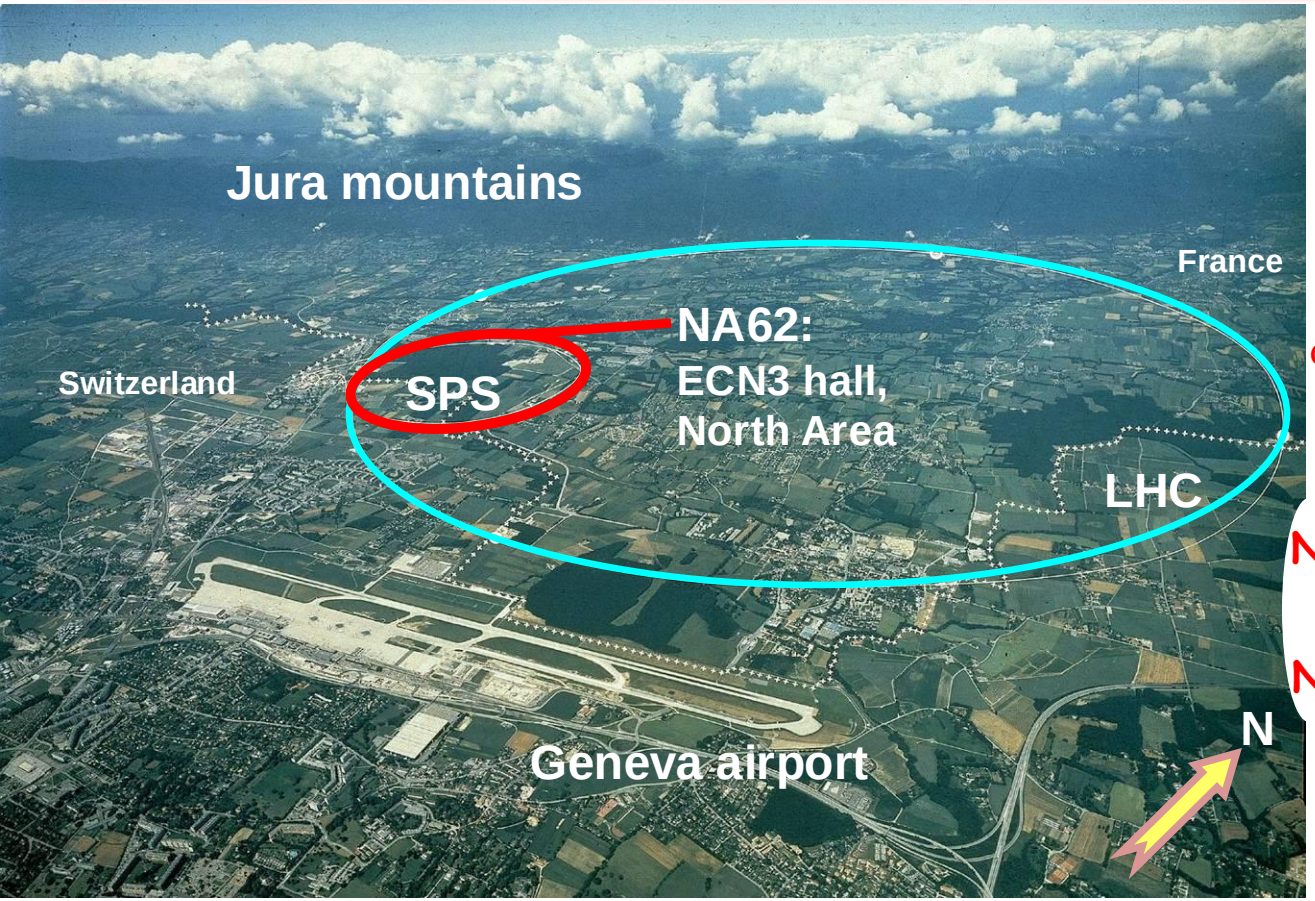
Outline

1) ALP production in kaon decays: NA62, KOTO, OKA
   [experimentally: $K^+ \to \pi^+ X$, $K^+ \to \pi^+ \pi^0 X_{inv}$, $K^+ \to \pi^+ X_{ee} X_{ee}$, $K_L \to \pi^0 X_{inv}$, $K_L \to X_{\gamma\gamma} X_{\gamma\gamma}$]
2) ALP decays with NA62 beam-dump data
   [experimentally: $X \to \ell^+ \ell^-$, $X \to$ hadrons]
3) Summary

Rencontres du Vietnam -- The Axion Quest
ICISE, Quy Nhon • 9 August 2024

Searches for ALP production in kaon decays

Kaon experiments at CERN



Earlier: NA31

NA48 discovery of direct CPV
- 1997: ε'/ε: K_L+K_S
- 1998: K_L+K_S
- 1999: K_L+K_S | K_S HI
- 2000: K_L only | K_S HI
- 2001: K_L+K_S | K_S HI

NA48/1
- 2002: K_S/hyperons

NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

NA62 R_K run
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests

NA62
- 2015: commissioning
- 2016-18: physics run 1
- 2021-: physics run 2

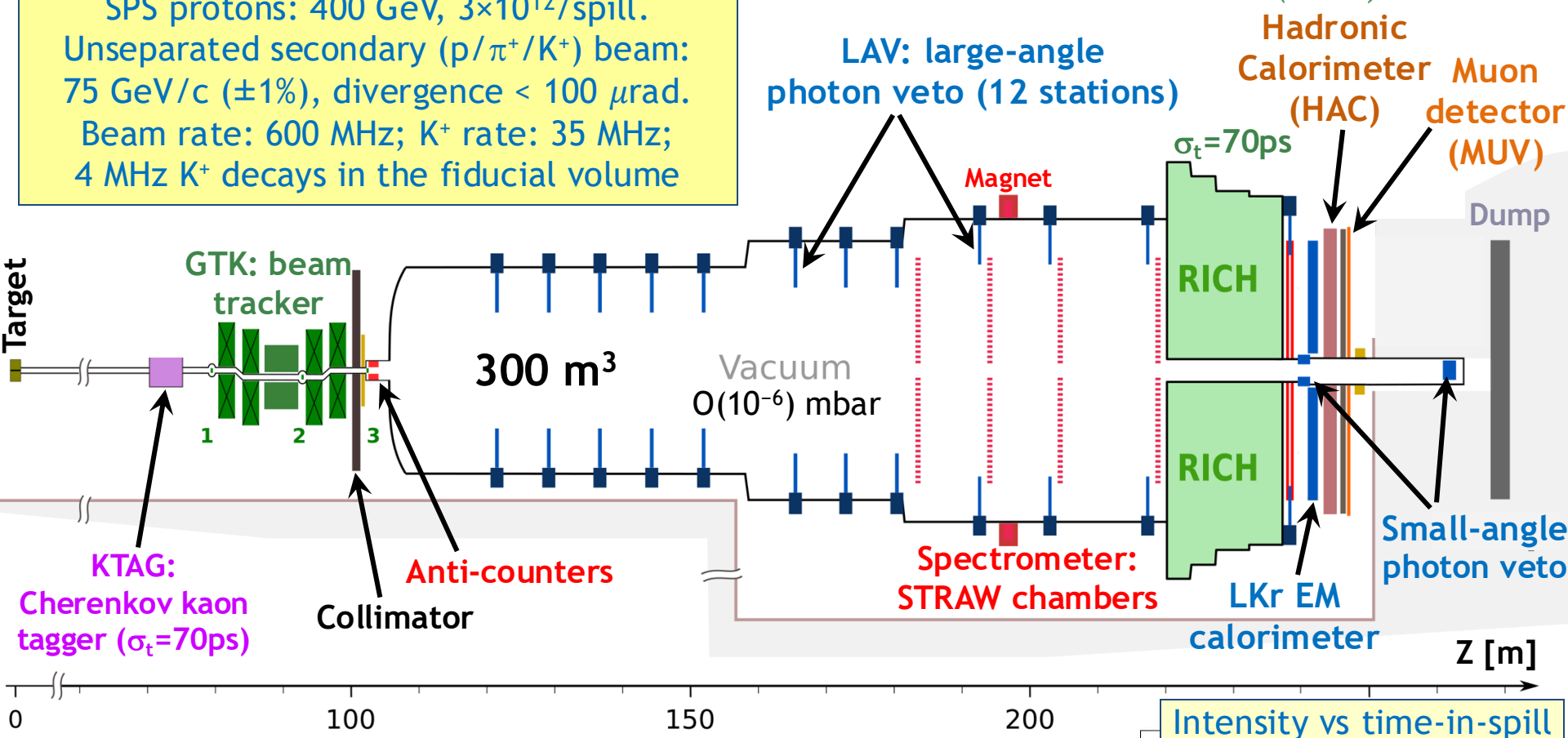
Main NA62 goal: $K^+ \to \pi^+ \nu\nu$ measurement to 15% precision using the decay-in-flight technique.

Currently ~300 participants from ~30 institutions.

NA62 experiment at CERN

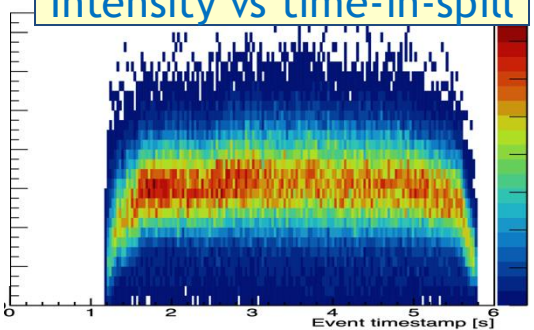
SPS protons: 400 GeV, 3×10^{12}/spill.
Unseparated secondary ($p/\pi^+/K^+$) beam:
75 GeV/c (±1%), divergence < 100 μrad.
Beam rate: 600 MHz; K^+ rate: 35 MHz;
4 MHz K^+ decays in the fiducial volume

JINST 12 (2017) P05025



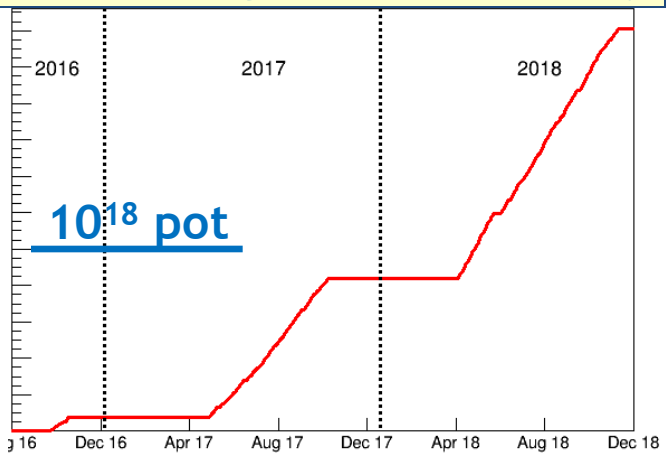
- One year ≈ 2×10^{18} protons on target ≈ 5×10^{12} K^+ decays.
- Beam structure: ideally, uniform over a 4.8 s long spill.
- In practice, significant variations of instantaneous beam intensity during the spill.

Intensity vs time-in-spill



NA62 datasets

Run 1 integrated luminosity

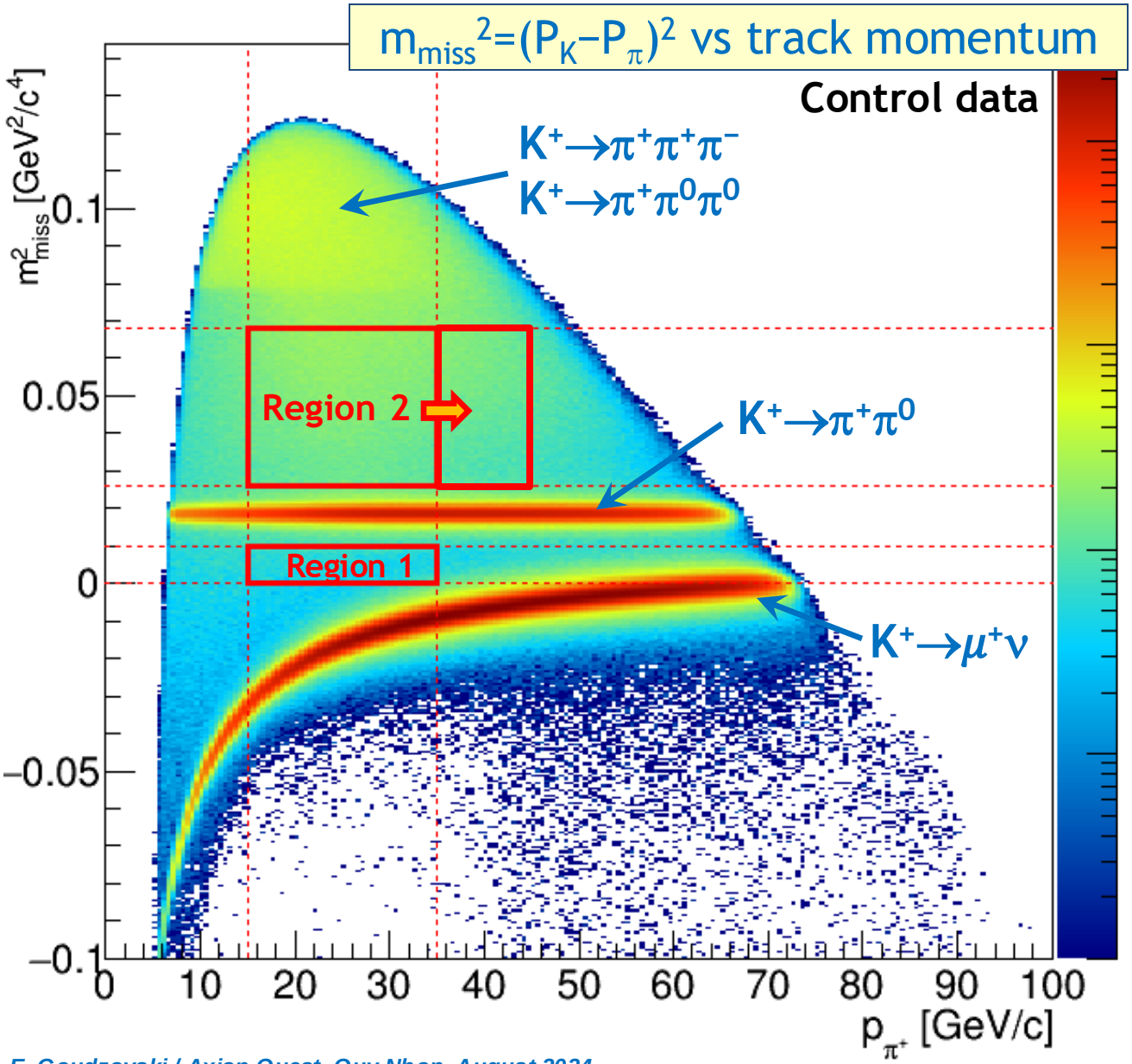


Currently: ~2×10^{18} pot/year, ~5×10^{12} K^+ decays/year

Beam-dump mode: 4×10^{17} pot collected by 2023

- **Run 1 (2016–18)**: $N_K \sim 10^{13}$ useful K^+ decays with the main trigger.
  - ✓ Sample **2016** (30 days, ~1.3×10^{12} ppp): 2×10^{11} useful K^+ decays.
  - ✓ Sample **2017** (160 days, ~1.9×10^{12} ppp): 2×10^{12} useful K^+ decays.
  - ✓ Sample **2018** (217 days, ~2.3×10^{12} ppp): 4×10^{12} useful K^+ decays.
- **Run 2 (2021–)**: in progress (up to 3×10^{12} ppp), approved till 2025.

NA62: $K^+ \to \pi^+ \nu\nu$ measurement



Main K^+ decay modes (>90% of BR) rejected kinematically.

Resolution on m^2_{miss}: $\sigma=1.0\times10^{-3}$ GeV^4/c^2.

Measured kinematic background suppression:

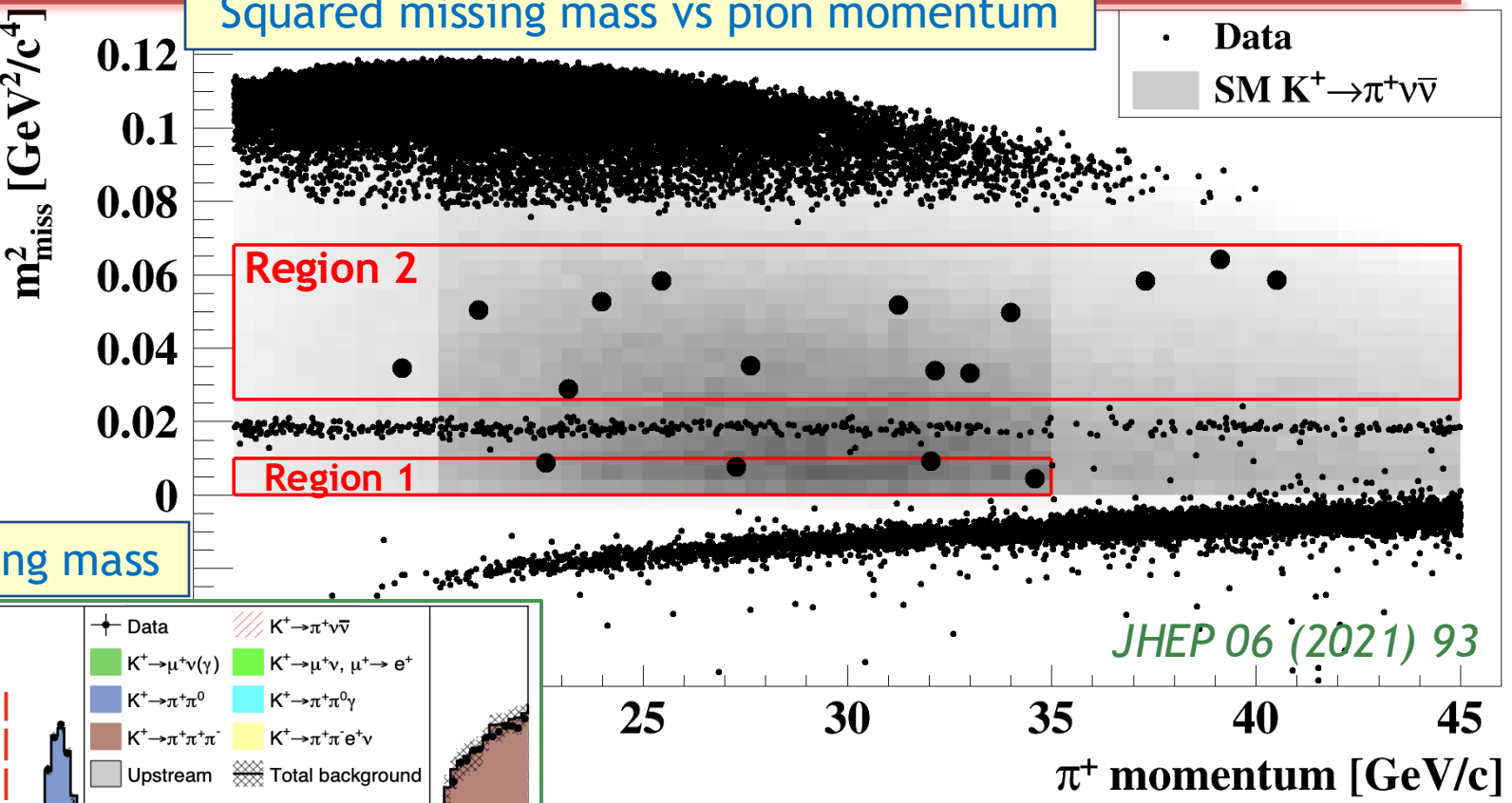
- ✓ $K^+ \to \pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+ \to \mu^+\nu$: 3×10^{-4}.

Further background suppression:

- ✓ PID (calorimeters & RICH): μ suppression ~10^{-8}, π efficiency = 64%.
- ✓ Hermetic photon veto: $\pi^0 \to \gamma\gamma$ rejection factor = 1.4×10^{-8}.

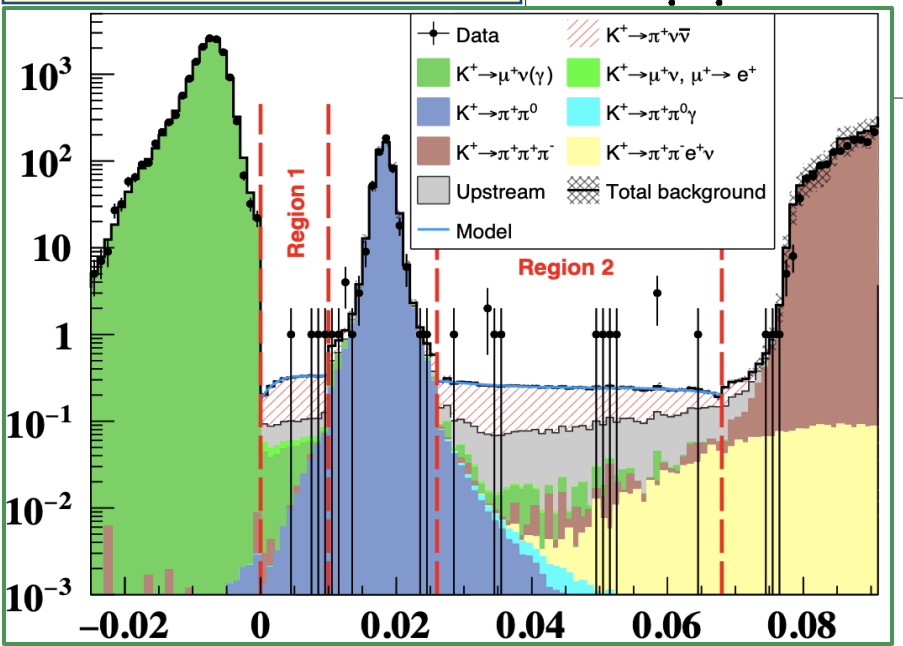
NA62 2018 data (=most of Run 1)

Squared missing mass vs pion momentum



JHEP 06 (2021) 93

Squared missing mass



Full Run 1 data set:

Candidates observed: **20** (17 in 2018 data)

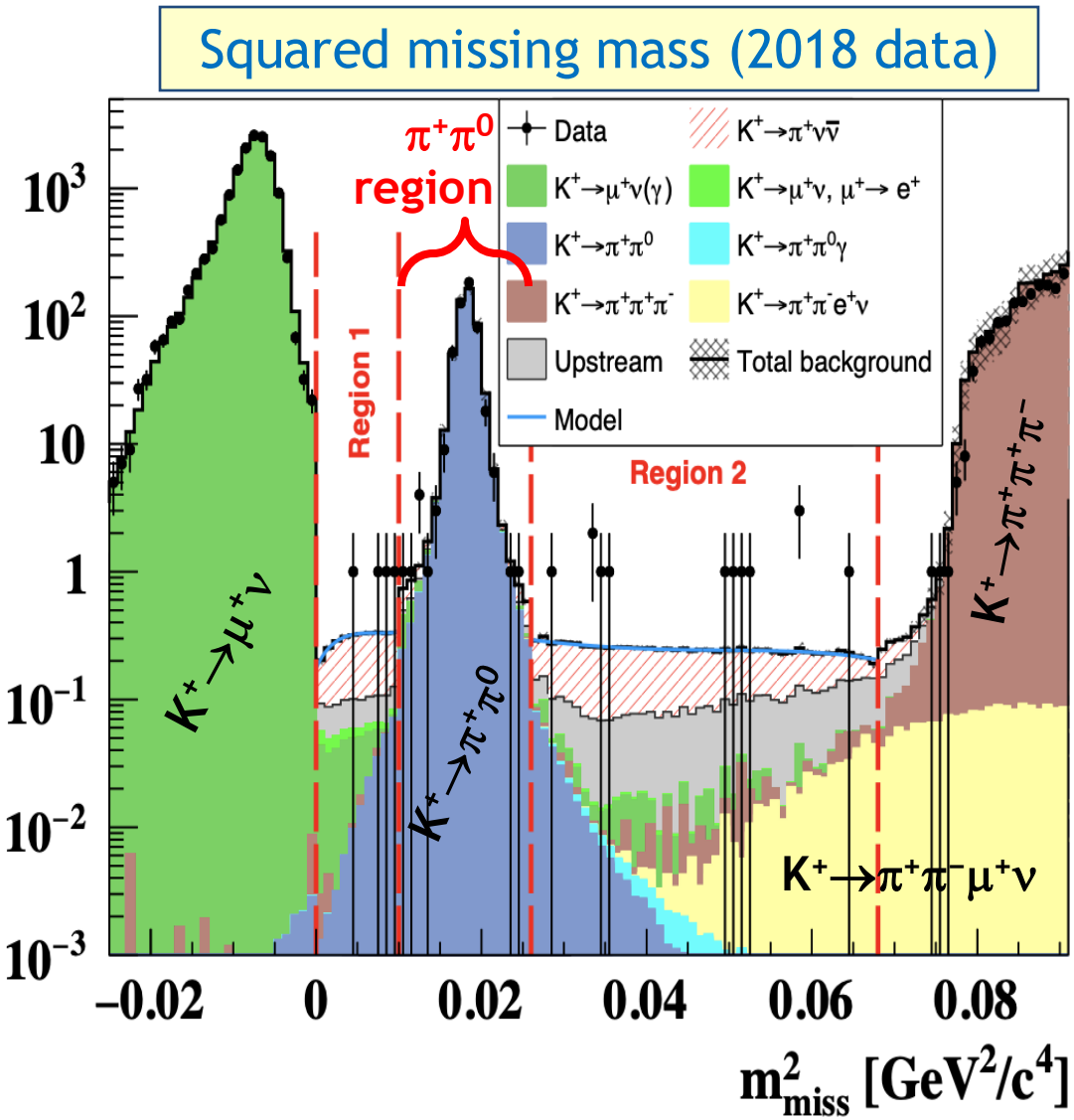
Expected background: $7.03^{+1.05}_{-0.82}$

Expected SM $K_{\pi\nu\nu}$ events:

$10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

NA62: search for $K^+ \to \pi^+ X_{inv}$

JHEP 02 (2021) 201, JHEP 06 (2021) 93



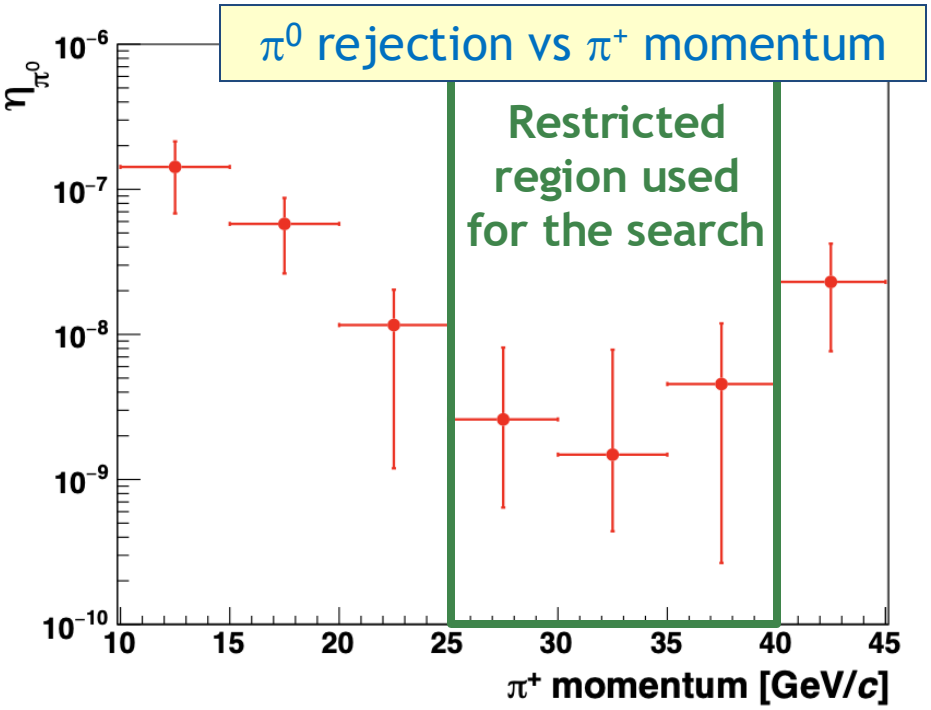
- Signal regions **R1**, **R2**: search for $K^+ \to \pi^+ X$ (X=invisible), $0 \le m_X \le 110$ MeV/c^2 and $154 \le m_X \le 260$ MeV/c^2.
  - ✓ Interpretation: dark scalar, QCD axion, ALP, axiflavon.
  - ✓ Main background: $K^+ \to \pi^+ \nu\nu$.
- The $\pi^+\pi^0$ region: search for $\pi^0 \to$ invisible.
  - ✓ Negligible SM rate ($\pi^0 \to 4\nu$).
  - ✓ Observation = BSM physics.
  - ✓ Reduction of $\pi^0 \to \gamma\gamma$ background: optimised π^+ momentum range.
  - ✓ Interpretation as $K^+ \to \pi^+ X$, with m_X between R1 and R2.

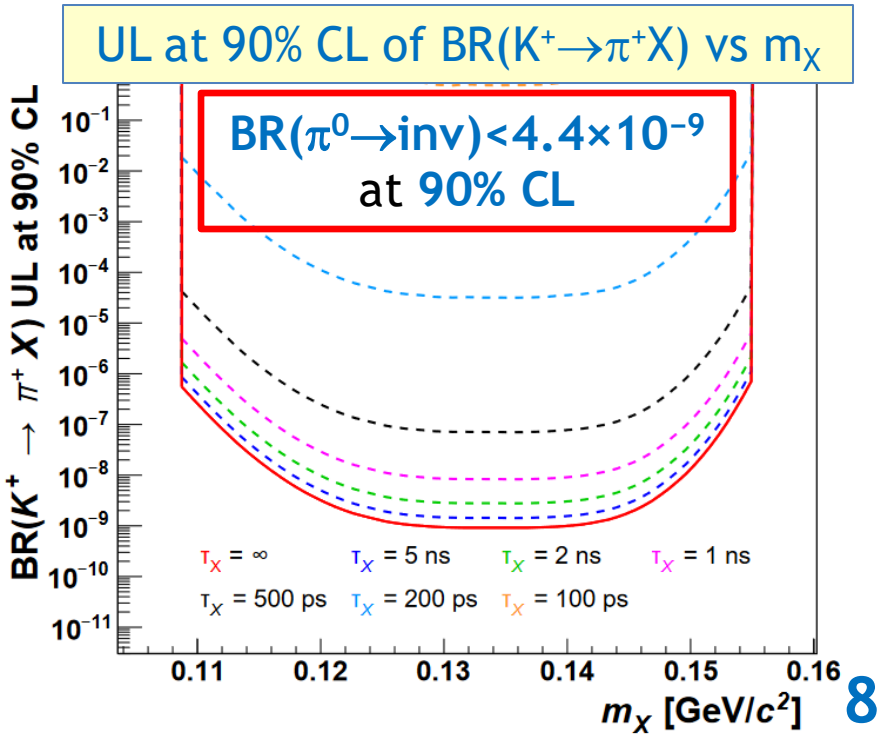
NA62: search for $\pi^0 \to$ invisible

- Rejection of ($K^+ \to \pi^+\pi^0(\gamma)$, $\pi^0 \to \gamma\gamma$) decays: simulations based on single-photon efficiency measurements with $K^+ \to \pi^+\pi^0$ decays. *JHEP 02 (2021) 201*
- Rejection of $\pi^0 \to \gamma\gamma$ decays for $K^+ \to \pi^+\nu\nu$ analysis: $\varepsilon \approx 10^{-8}$.
- For $\pi^0 \to$ invisible search ($25 < p_\pi < 40$ GeV/c): $\varepsilon = (2.8^{+5.9}_{-2.1}) \times 10^{-9}$

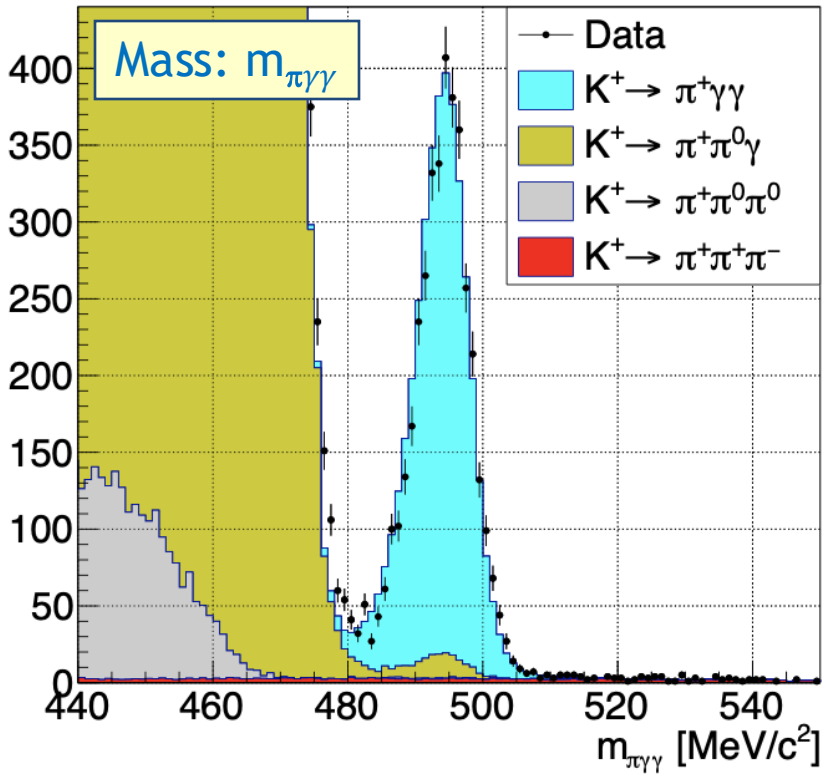
Search for $\pi^0 \to$ invisible: (~10% of NA62 Run 1 dataset, 4×10^9 tagged π^0 mesons)

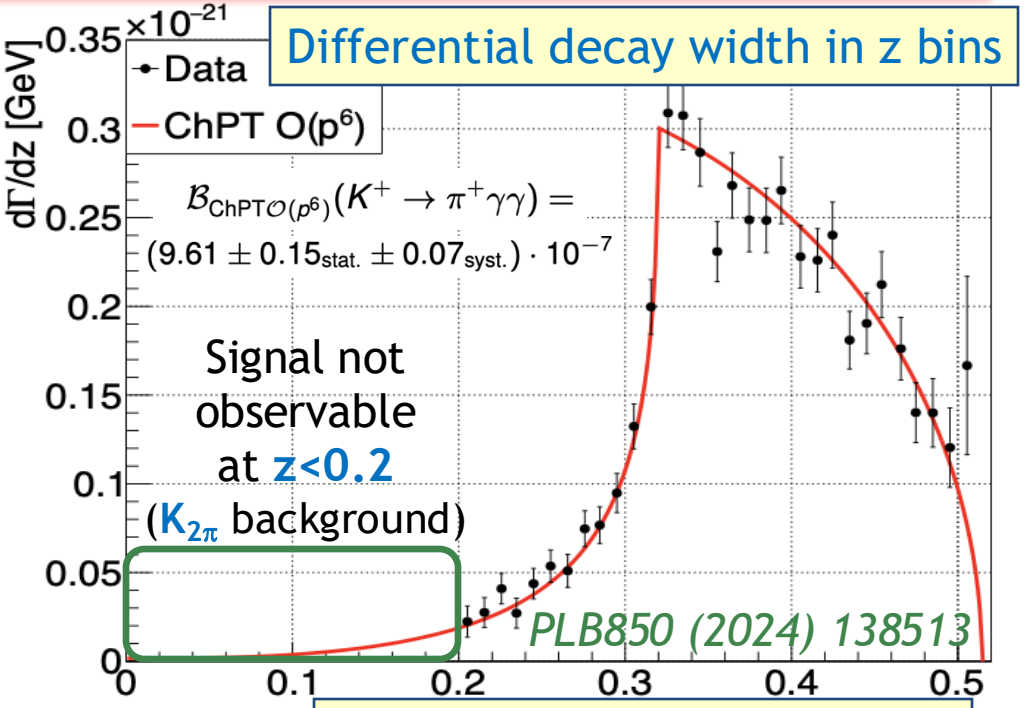
- $K_{\pi\nu\nu}$ trigger and selection used, with $0.015 < m^2_{miss} < 0.021$ GeV^2/c^4.
- Expected $\pi^0 \to \gamma\gamma$ events: 10^{+22}_{-8}, events observed: 12.

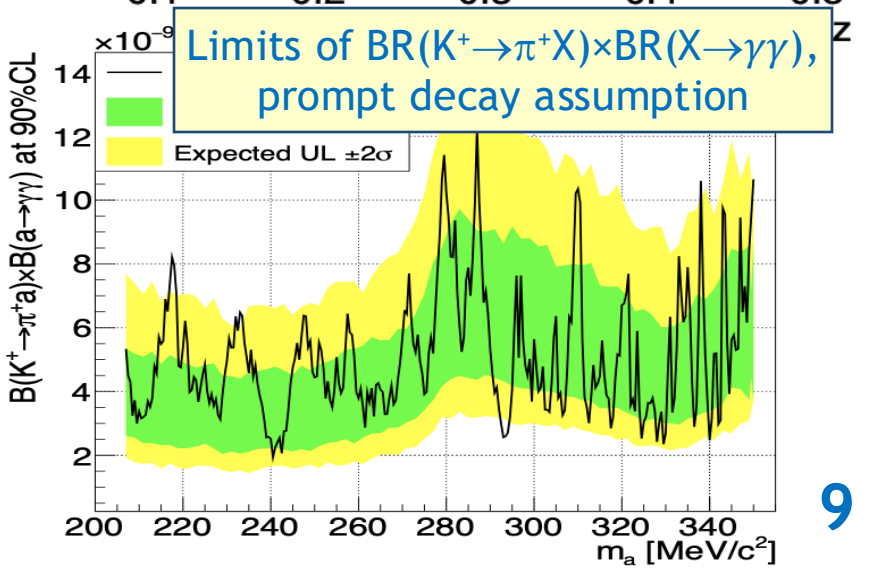




NA62: $K^+ \to \pi^+\gamma\gamma$ and $K^+ \to \pi^+ X_{\gamma\gamma}$



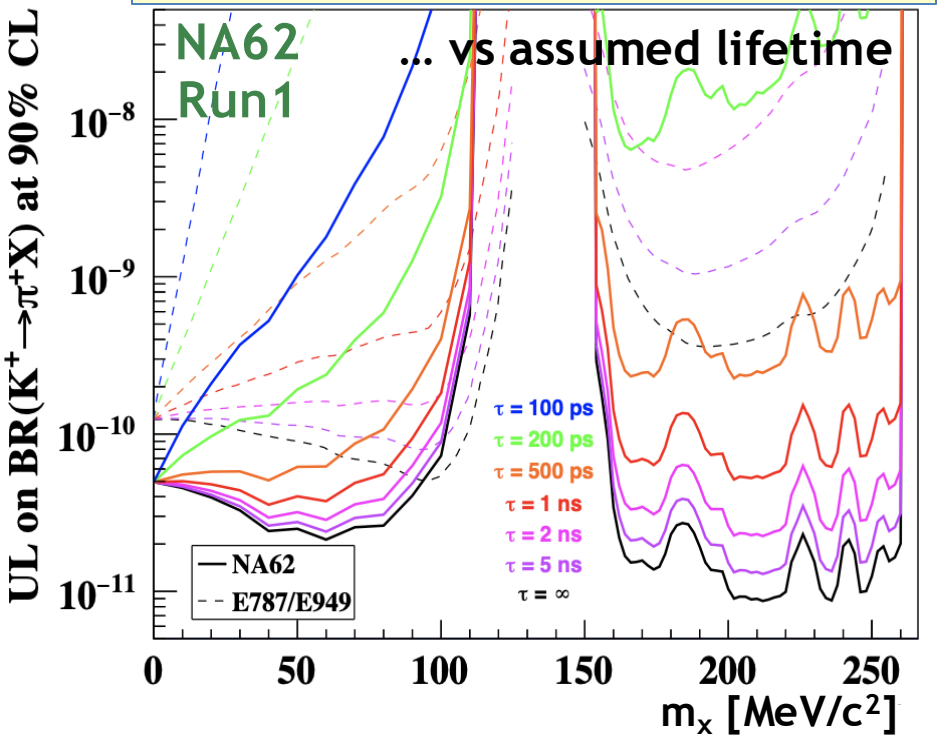




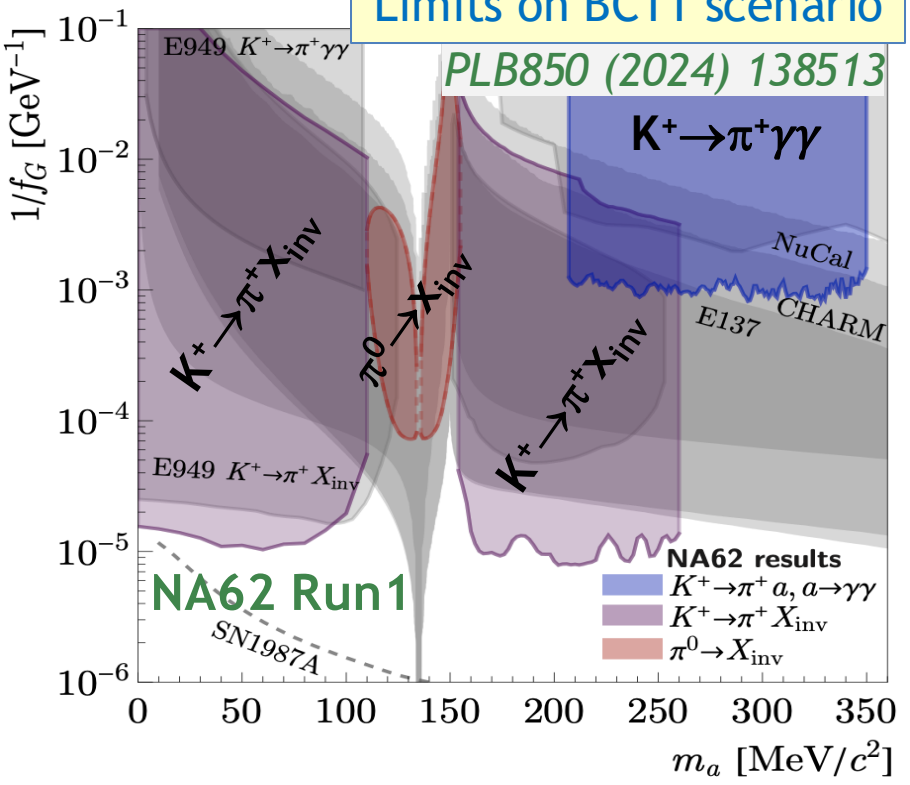
- Downscaled control trigger lines.
- Normalisation: $K^+ \to \pi^+\pi^0$ decay, effectively $(5.55 \pm 0.03) \times 10^{10}$ decays.
- Candidates observed: **3984**.
- Expected background: **291±14**.
- Kinematic variable $z=(m_{\gamma\gamma}/m_K)^2$ computed using (K−π) missing mass.

Searches for K→πX: summary

UL@90% CL of BR($K^+\to\pi^+X_{inv}$) vs m_X



Limits on BC11 scenario

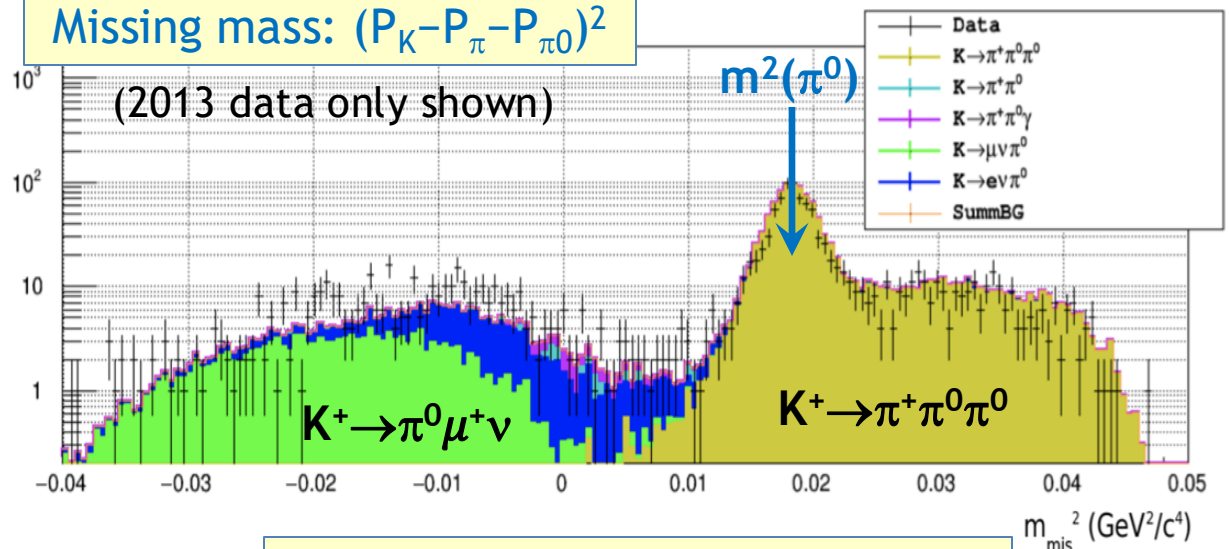


- NA62 improves on BNL-E949 *[PRD79 (2009) 092004]* over most of m_X range.
- Interpretation shown here: PBC scenario BC11 (ALP coupling to gluons).
- For $m_a<3m_\pi$, the dominant decay mode is $a\to\gamma\gamma$.
- $K^+\to\pi^+\gamma\gamma$ is sensitive up to ALP lifetime of 3 ns;
  $K^+\to\pi^+\nu\nu$ is sensitive to longer lifetimes (ALP becomes invisible).
- Scenario BC10 (ALP coupling to fermions, partial dataset): *JHEP 02 (2021) 201*.

OKA at IHEP-Protvino: $K^+ \to \pi^+\pi^0 X_{inv}$

EPJ C84 (2024) 3

Missing mass: $(P_K - P_\pi - P_{\pi 0})^2$



OKA experiment:

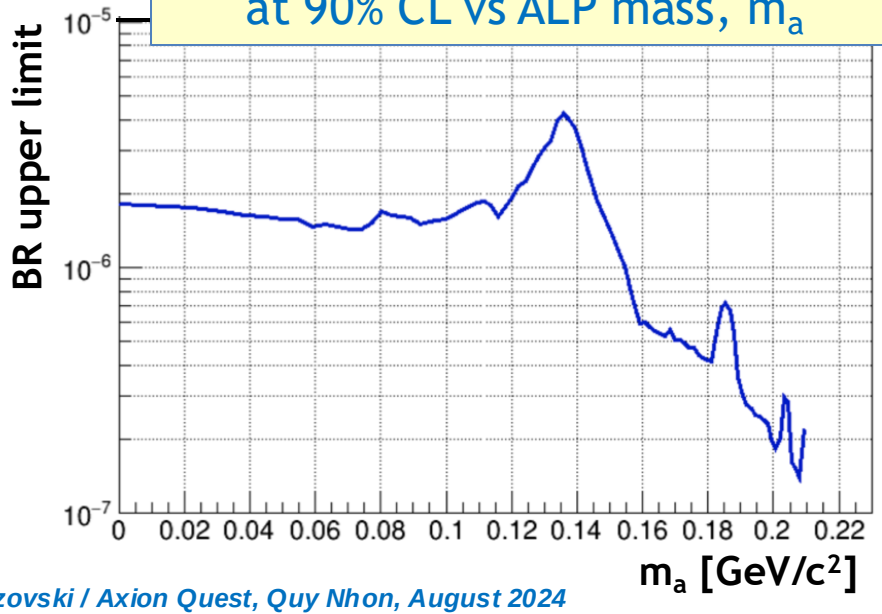
K^+ decays in flight,
18 GeV/c beam,
2012–2013 dataset.

$K^+ \to \pi^+\pi^0 a$ decay density:
Camalich et al., PRD 102 (2020) 015023

$$\frac{d\Gamma(K^+ \to \pi^+\pi^0 a)}{ds} = \frac{1}{|F_{sd}^A|^2} \frac{(m_{K^+}^2 - s)^3}{1536\pi^3 m_K^5} \beta \times \left(F_p^2 + \beta^2 G_p^2 + 2\beta F_p G_p\right)$$

$$s = (p_{\pi_1} + p_{\pi_2})^2 \text{ and } \beta^2 = 1 - 4m_\pi^2/s$$

Upper limits of BR($K^+ \to \pi^+\pi^0 a$) at 90% CL vs ALP mass, m_a

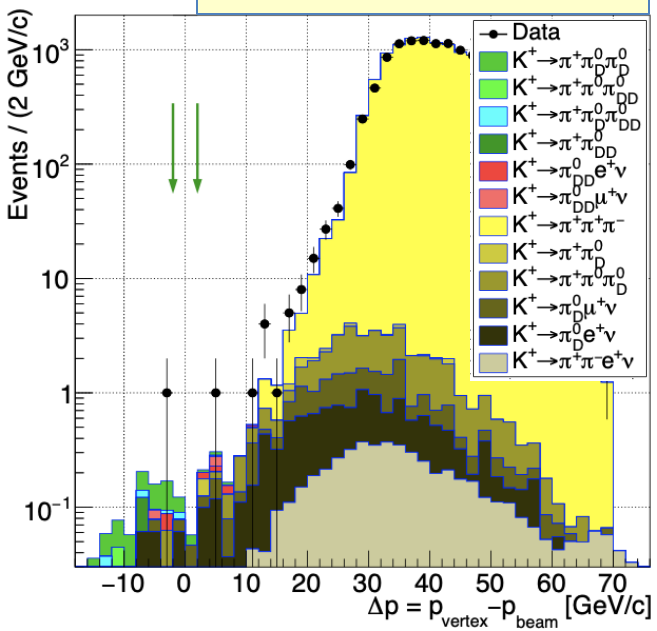


Prospects at NA62:
upper limits of $O(10^{-7})$
on BR($K^+ \to \pi^+\pi^0 a$)
with a downscaled
control-trigger sample

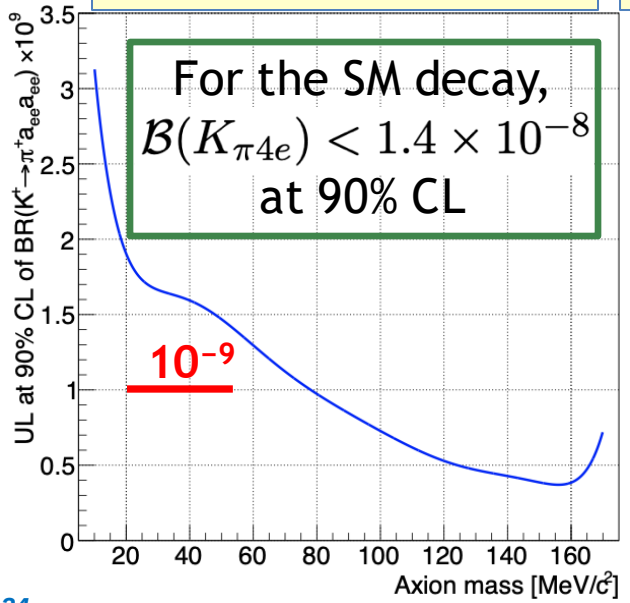
NA62: search for $K^+ \to \pi^+ X_{ee} X_{ee}$

- NA62 Run 1, multi-electron trigger, $N_K = 8.6 \times 10^{11}$. *PLB846 (2023) 138193*
- Production and prompt decays of axion pairs, $K^+ \to \pi^+ aa$, $a \to e^+e^-$: exclusion of the QCD axion explanation for the "17 MeV anomaly".
  - ✓ Expect $BR(K^+ \to \pi^+ aa) > 2 \times 10^{-8}$ for $m_a = 17$ MeV.
    [Alves, PRD103 (2021) 055018; Hostert and Pospelov, PRD105 (2022) 015017]
- Prompt dark cascade involving a dark scalar (S) and dark photons (A'): $K^+ \to \pi^+ S$, $S \to A'A'$, $A' \to e^+e^-$.
- SM rate: $BR_{SM}(K^+ \to \pi^+ e^+e^-e^+e^-) = (7.2 \pm 0.7) \times 10^{-11}$ [Husek, PRD106 (2022) L071301]

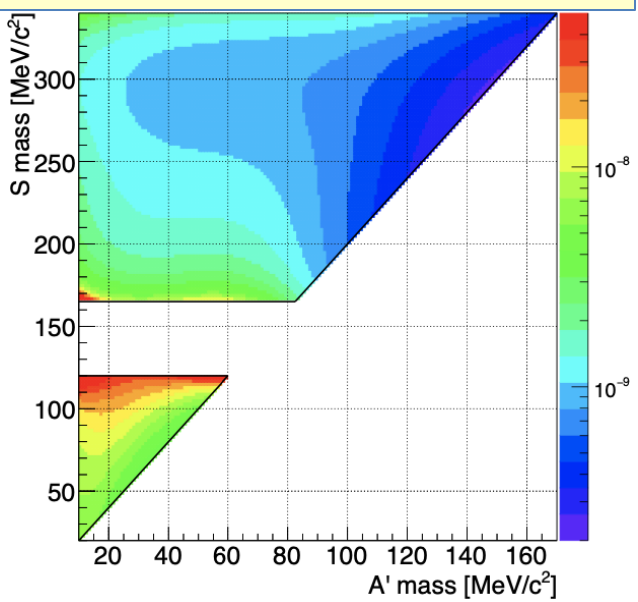
Momentum excess



UL at 90% CL of $BR(K^+ \to \pi^+ a_{ee} a_{ee})$ vs m_a

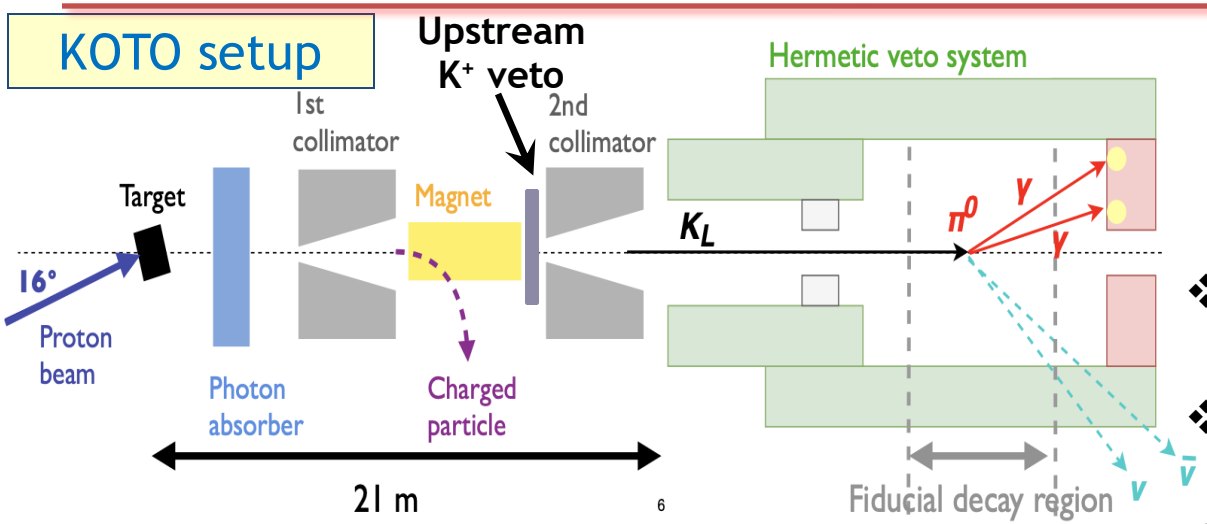


UL of $BR(K^+ \to \pi^+ S, S \to A'_{ee} A'_{ee})$ vs $(m_{A'}, m_S)$



KOTO experiment at J-PARC

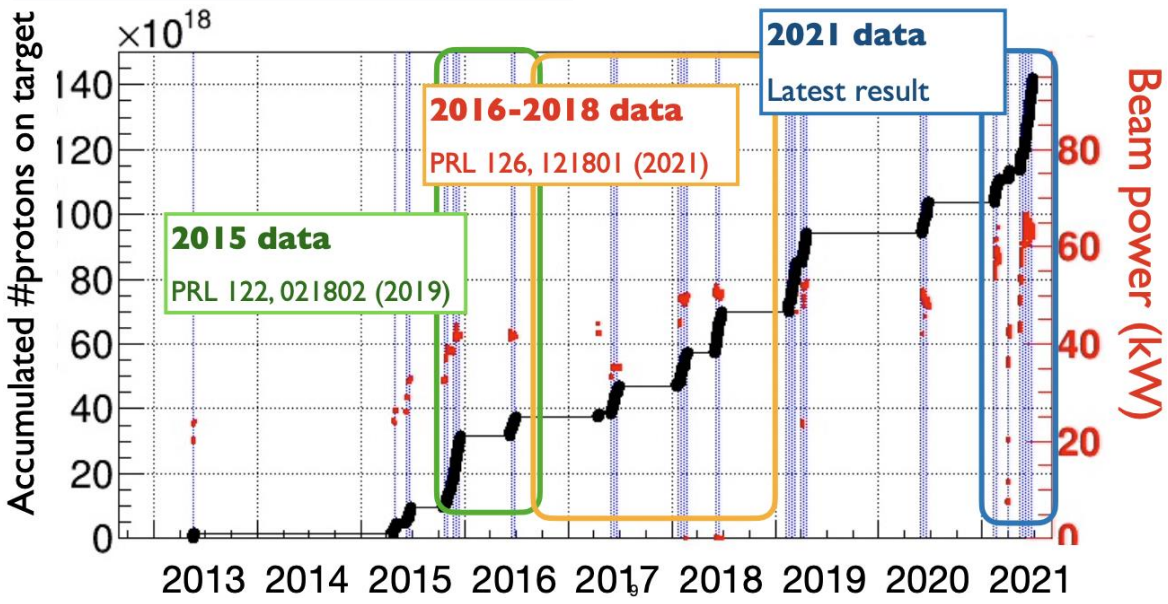
KOTO setup



Primary goal:
search for $K_L \to \pi^0 \nu\nu$
with a sensitivity $< 10^{-10}$

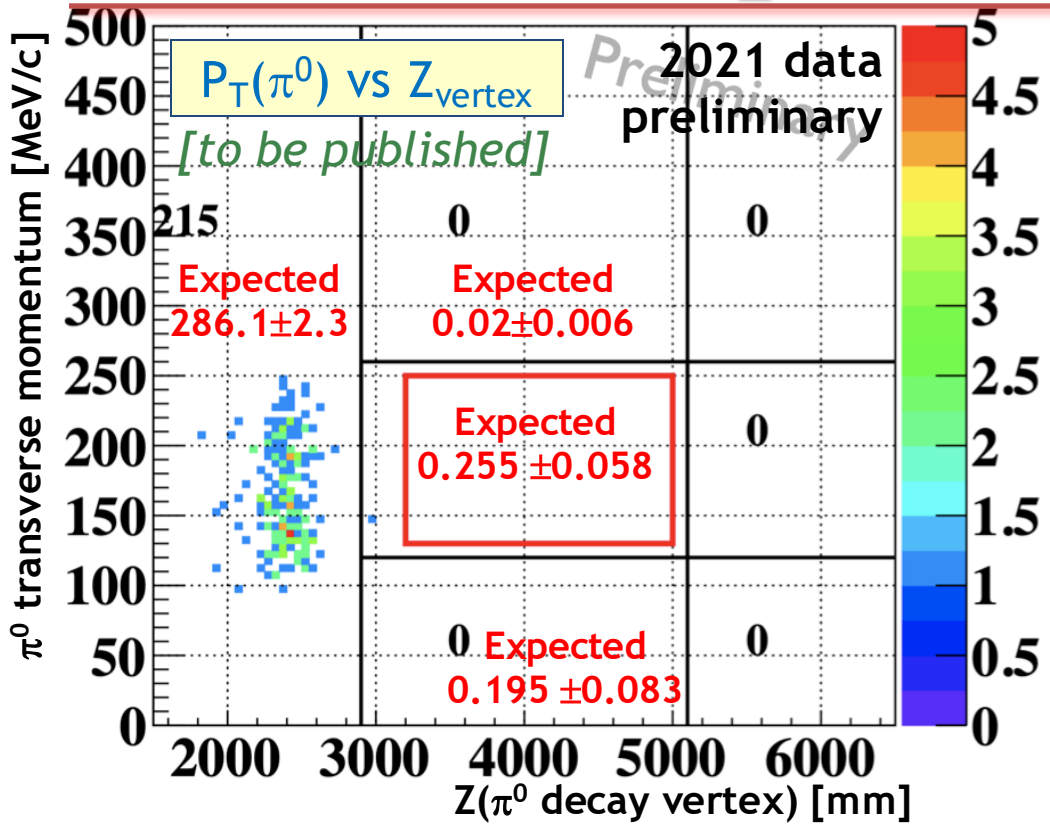
- Primary proton beam: **30 GeV**; **60 kW = 6.6×10^{13}/5.2 s**.
- Secondary K_L beam: peak momentum **1.4 GeV/c**.
- Beam composition: K_L, neutrons, photons.
- Decay region length: **~2 m**.
- Hermetic photon detector, including CsI calorimeter.
- Progressive improvements to the setup; upstream K^+ veto installed in **2021**.
- Data taking until **2027**.

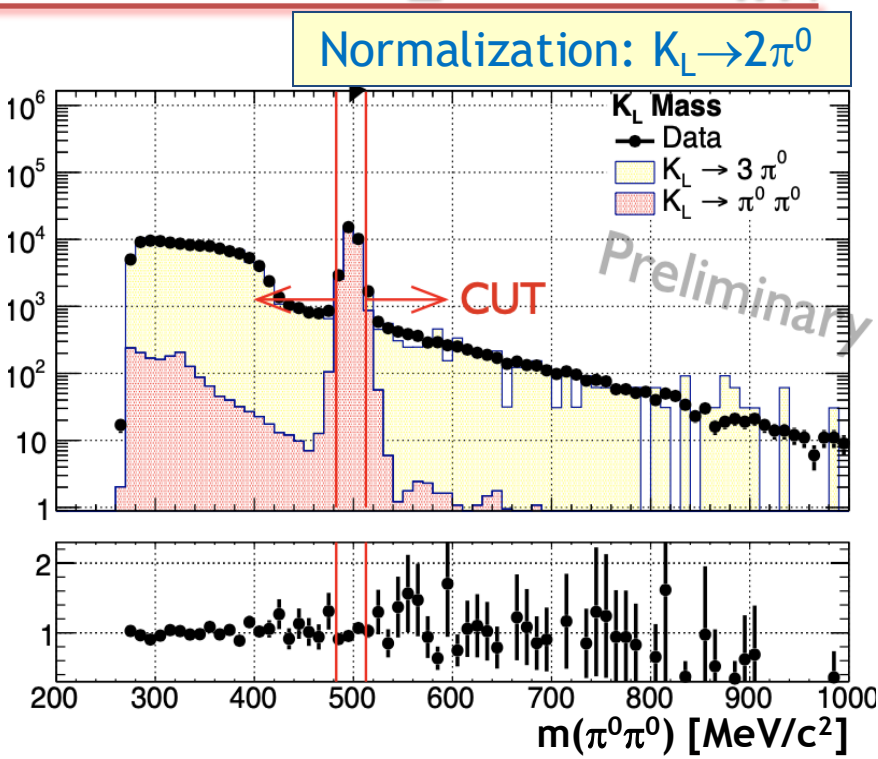
KOTO data collection

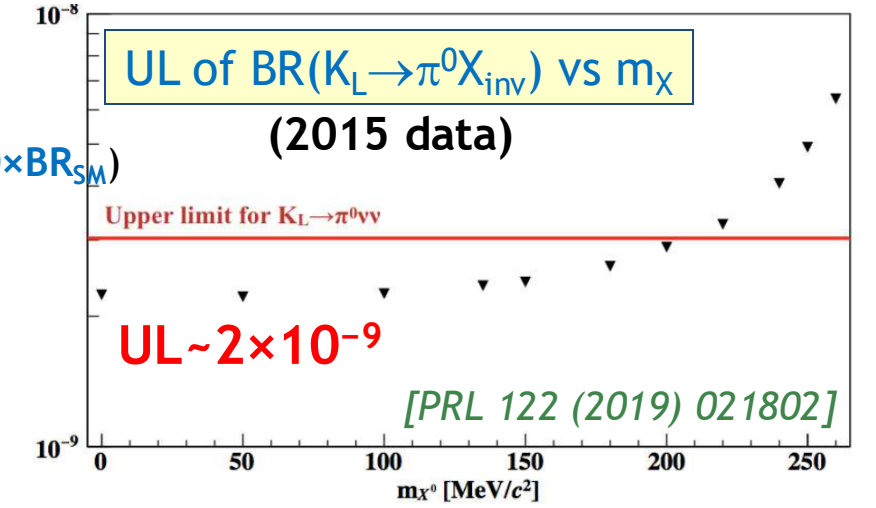


[PRL 122 (2019) 021802]
[PRL 126 (2021) 121801]

KOTO: $K_L \to \pi^0\nu\nu$ and $K_L \to \pi^0 X_{inv}$





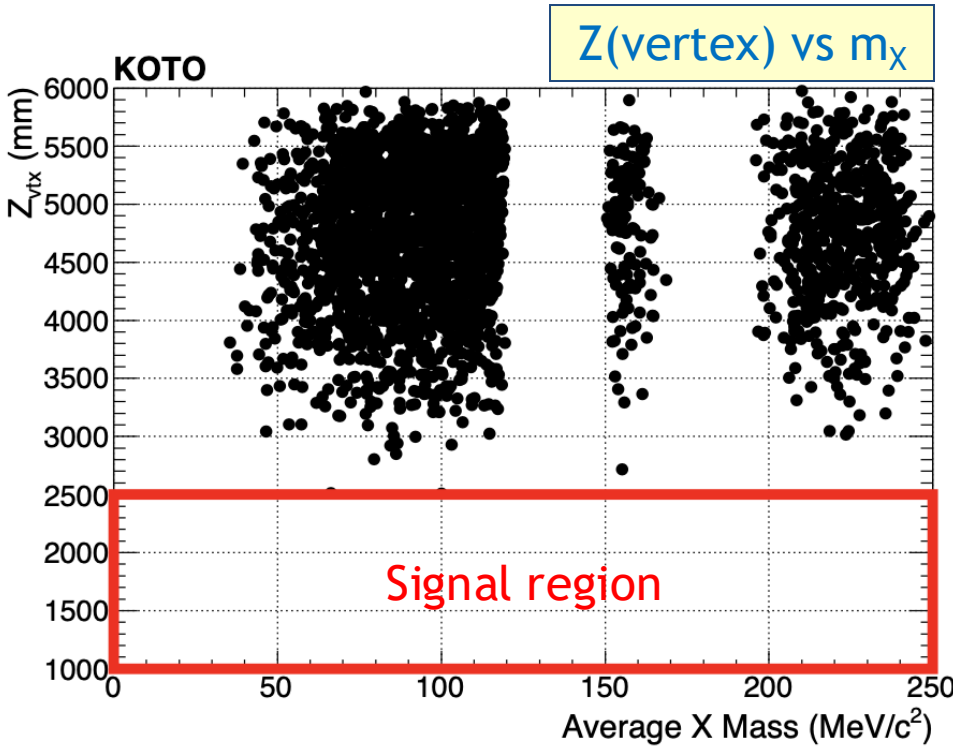


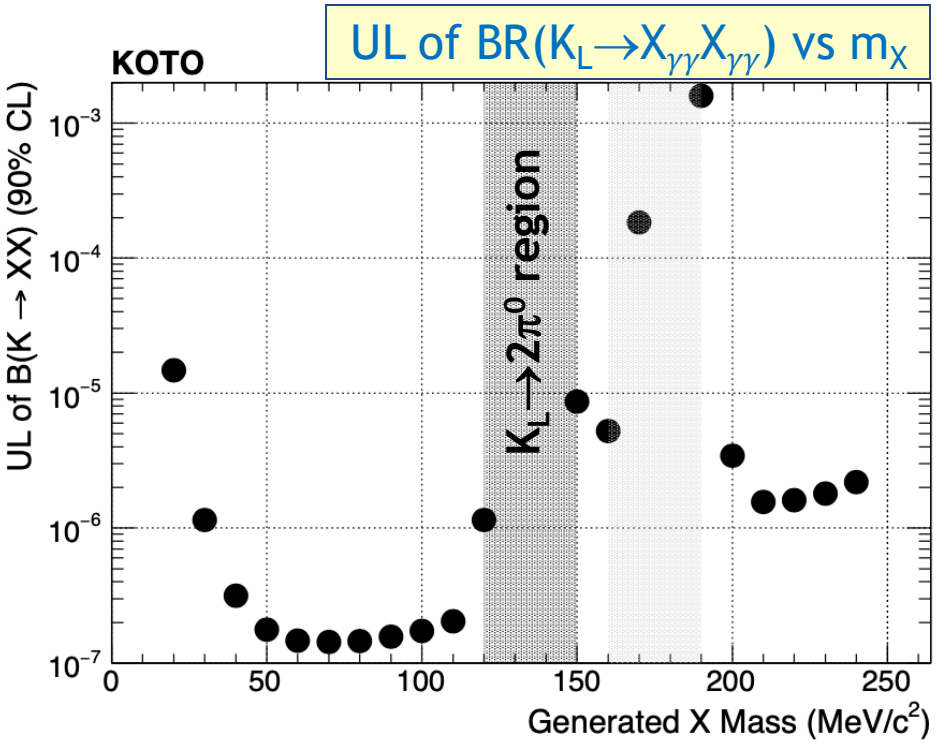
- Number of K_L decays: $N_K = 6.8\times10^{12}$.
- Single-event sensitivity: $BR_{SES} = 8.7\times10^{-10}$ ($30\times BR_{SM}$)
- Background: 0.255 ± 0.058 events ($K_L \to 2\pi^0$, $K^+ \to \pi^0 e^+ \nu$, …). No candidates in the data.
- Result: $BR(K_L \to \pi^0\nu\nu) < 2.0\times10^{-9}$ at 90% CL.
- Search for $a \to \gamma\gamma$ decays of ALPs produced in the target: *Afik et al., PRD108 (2023) 5*.

KOTO: search for $K_L \to X_{\gamma\gamma} X_{\gamma\gamma}$

PRL 130 (2023) 111801

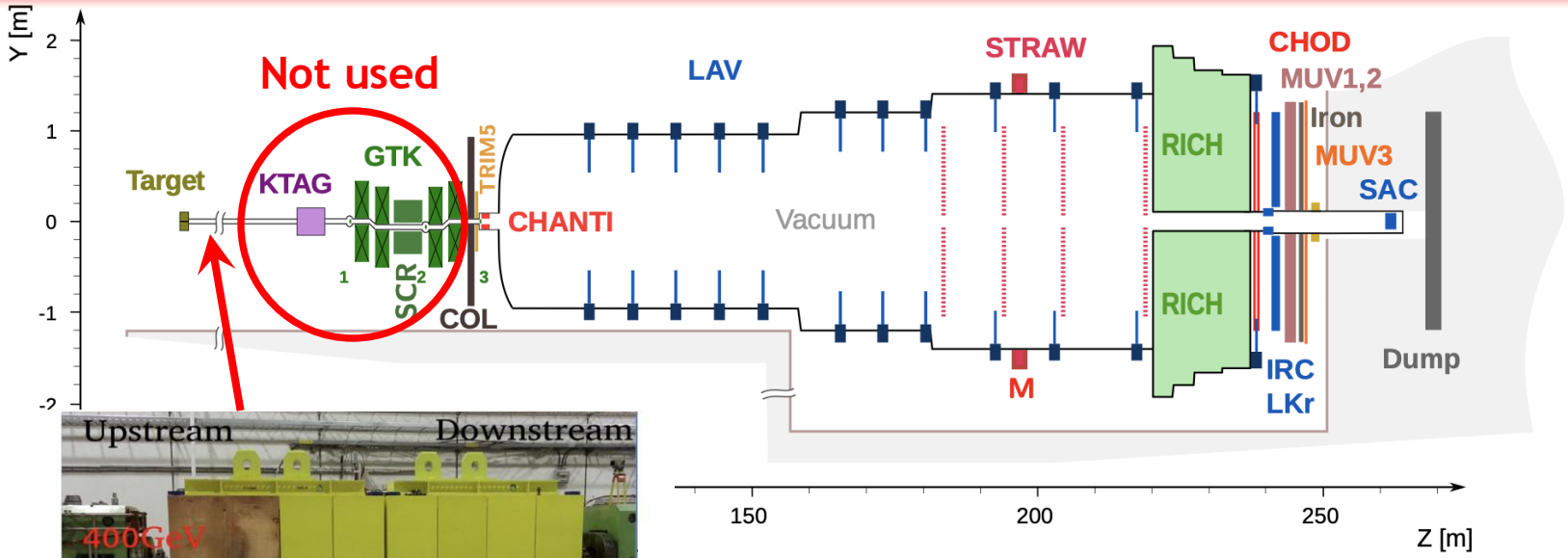
- Dataset: one month in **2018**, a dedicated trigger line.
- Proton beam power: **51 kW**; total exposure: **1.1×10^{19}** pot.
- Main background: **$K_L \to 3\pi^0$** with undetected photons or cluster fusion.
- Signal acceptance reduced at **m_X>150 MeV/c^2** by anti-**$K_L \to 3\pi^0$** selection.
- No data events observed in the signal region.

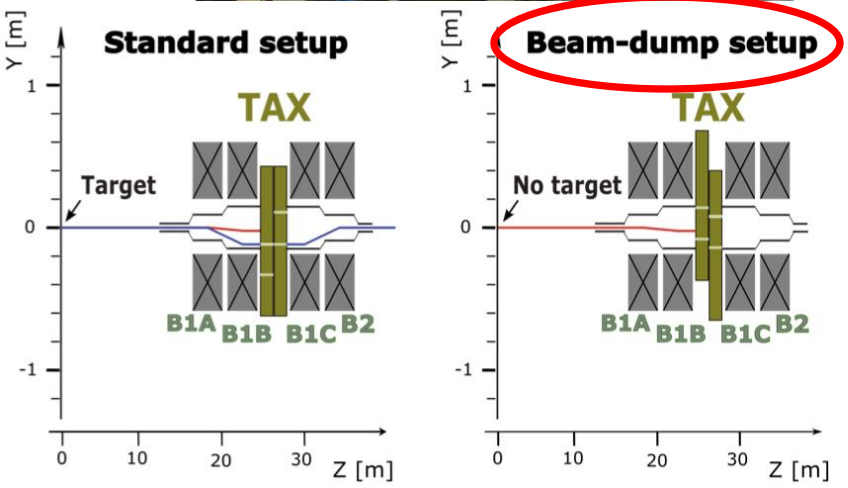




Searches for ALP decays with NA62 beam-dump data

NA62 in beam-dump mode





Beam-dump data-taking conditions:

- Beryllium target removed.
- TAX collimator closed and used as dump.

Dataset analysed:

- Beam-dump sample **2021** (**10** days).
- Minimum-bias trigger; **1.4×10^{17}** pot.
- Planning to collect **10^{18}** pot by **2025**.

Final states considered:

- **$a\to e^+e^-$**: *arXiv:2312.12055*.
- **$a\to\mu^+\mu^-$**: *JHEP 09 (2023) 35*.
- **$a\to$hadrons**: to be published.

NA62 in dump mode: $a \to \ell^+\ell^-$

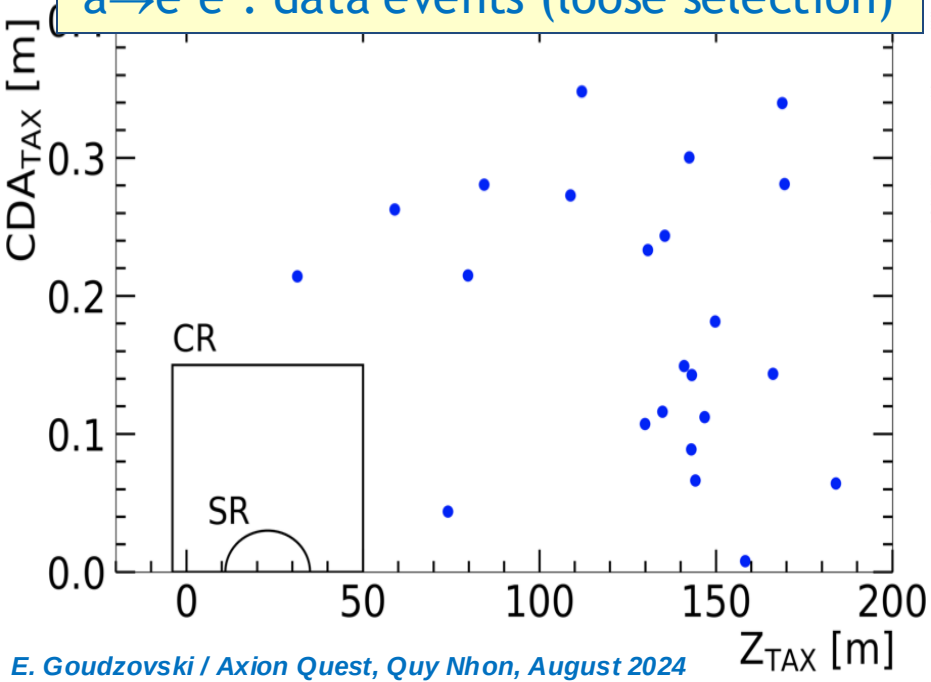
Event selection:

- Di-lepton vertex and momentum: ALP trajectory ($a \to \ell^+\ell^-$).
- ALP production point: closest approach (ALP trajectory, proton beam axis).
- Signal region (SR): distance of approach (CDA) and Z_{vertex} plane.

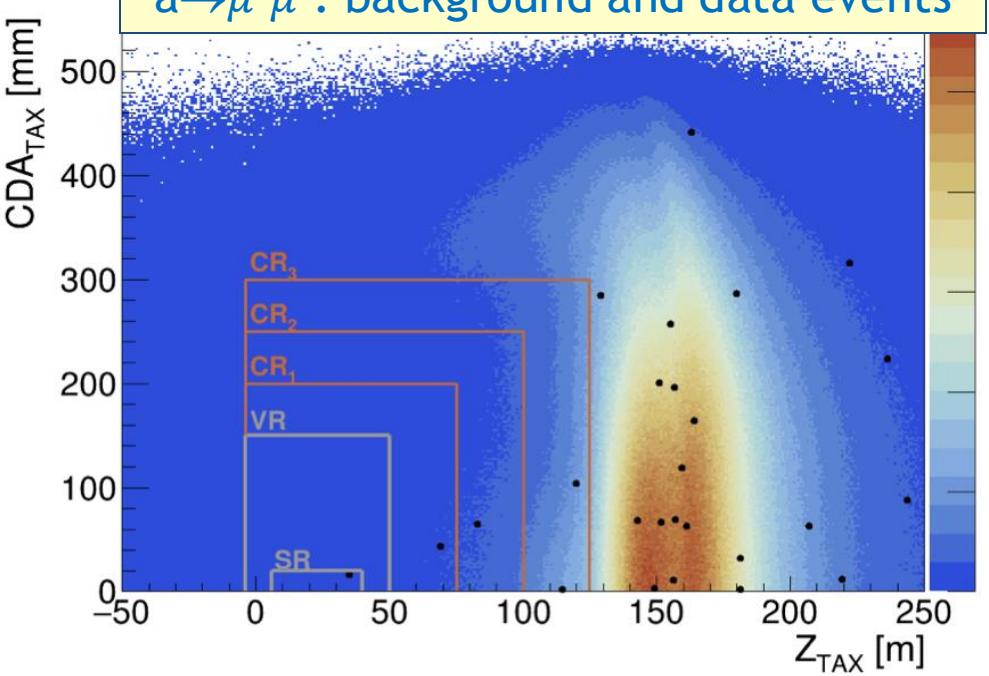
Backgrounds:

- Prompt, halo muon interactions in the material upstream decay volume.
  - ✓ Dominant for $a \to e^+e^-$: $N_{bkg}=9.4\times10^{-3}$; no data events observed.
- Combinatorial, coincidence of unrelated leptons in space and time.
  - ✓ Dominant for $a \to \mu^+\mu^-$: $N_{bkg}=0.016\pm0.002$; one data event, $m_{\mu\mu}=411$ MeV.

$a \to e^+e^-$: data events (loose selection)

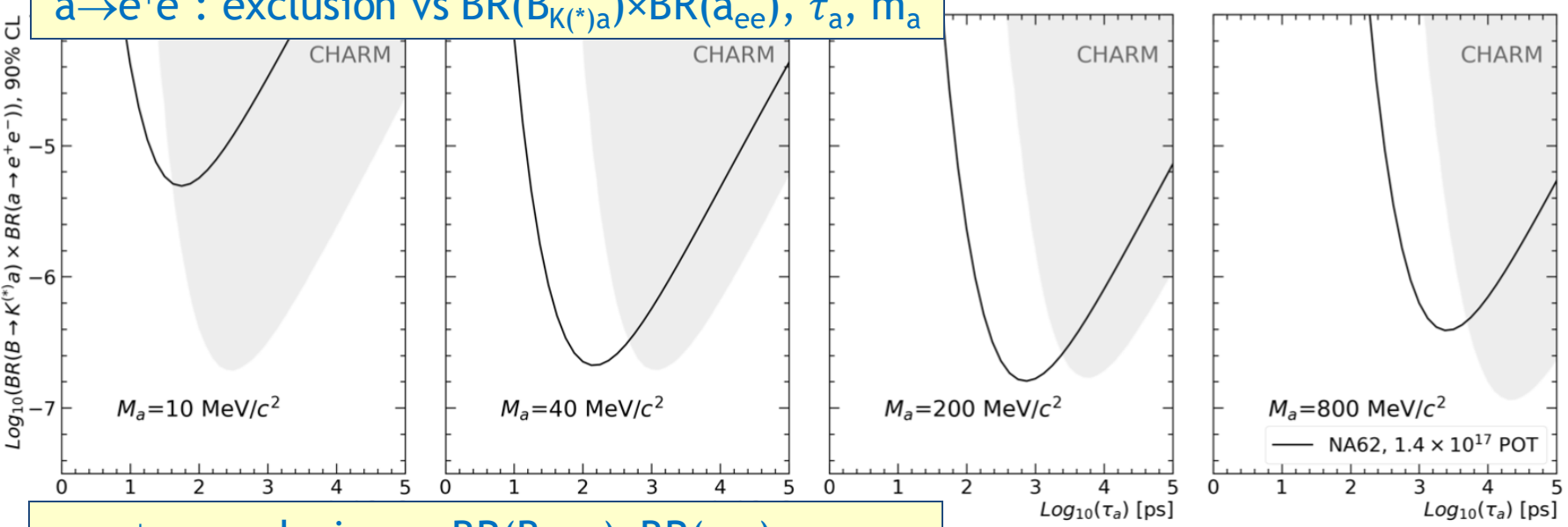


$a \to \mu^+\mu^-$: background and data events

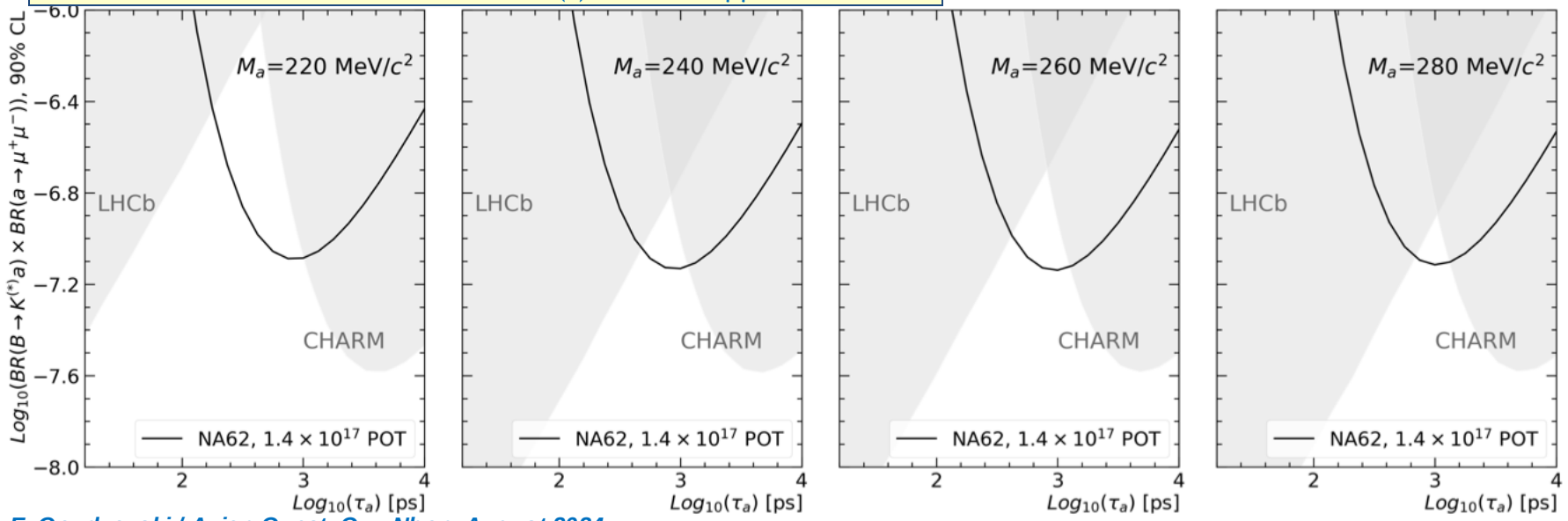


Results: search for $a \to \ell^+\ell^-$

$a \to e^+e^-$: exclusion vs $BR(B_{K(*)a}) \times BR(a_{ee})$, τ_a, m_a



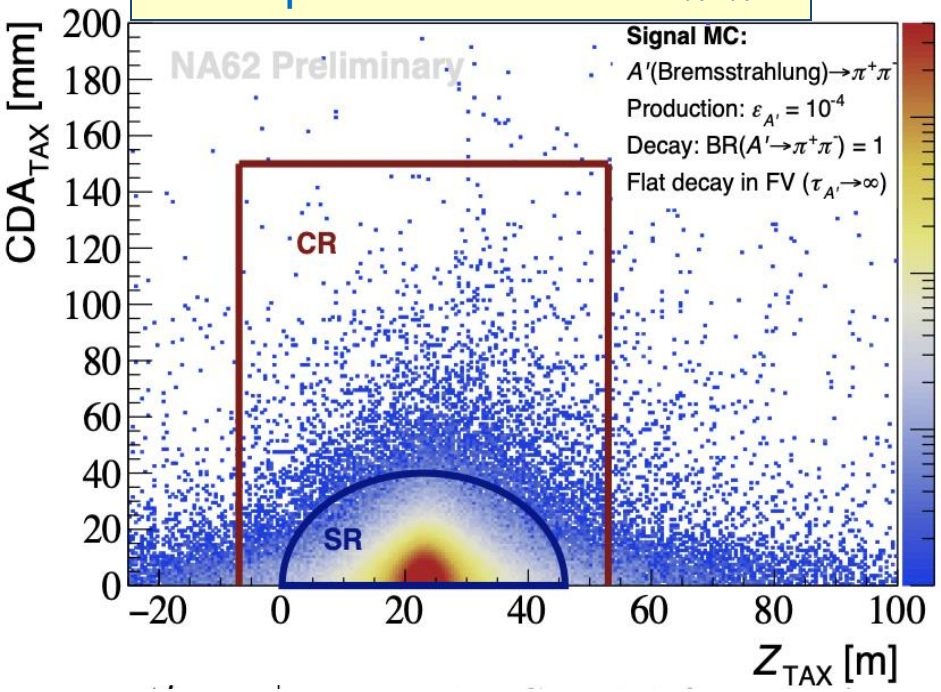
$a \to \mu^+\mu^-$: exclusion vs $BR(B_{K(*)a}) \times BR(a_{\mu\mu})$, τ_a, m_a



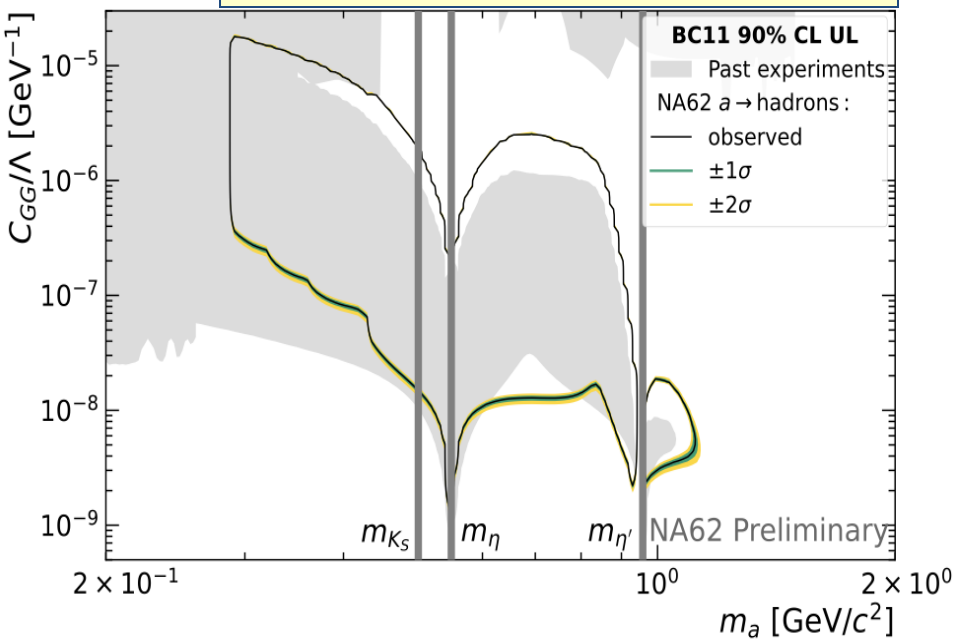
NA62 dump mode: a→hadrons

- ALP production considered: Primakoff mixing with (π^0,η,η'); $B \to K^{(*)}a$.
- ALP decay modes considered:
  $a \to \pi^+\pi^-\gamma$, $a \to \pi^+\pi^-\pi^0_{\gamma\gamma}$, $a \to \pi^+\pi^-\pi^0_{\gamma\gamma}\pi^0_{\gamma\gamma}$, $a \to \pi^+\pi^-\eta_{\gamma\gamma}$, $a \to K^+K^-\pi^0_{\gamma\gamma}$.
- Event selection and signal regions: similar to the $a \to \ell^+\ell^-$ case; photons detected by the LKr calorimeter.
- No data events observed in the control and signal regions.
- Scenario BC11 considered (ALP coupling to gluons).

Example: simulated $X \to \pi^+\pi^-$



BC11 exclusion: a→hadrons



Summary

- Kaon decays: a unique probe for new physics.
  - ✓ Large decay samples are available (~10^{13} events).
  - ✓ Often simple and clean final states, with low backgrounds.
- A wide programme of hidden-sector searches (including ALP production) in kaon decays is pursued at the kaon factories.
  - ✓ K^+ decays: NA62, OKA;
  - ✓ K_L decays: KOTO.
- Competitive limits on ALP production have been obtained with a partial NA62 beam-dump dataset.
- NA62 and KOTO are accumulating data: new results with improved sensitivity are expected in future.