# First NA62 search for long-lived new physics particle hadronic decays

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(on behalf of NA62 Collaboration)

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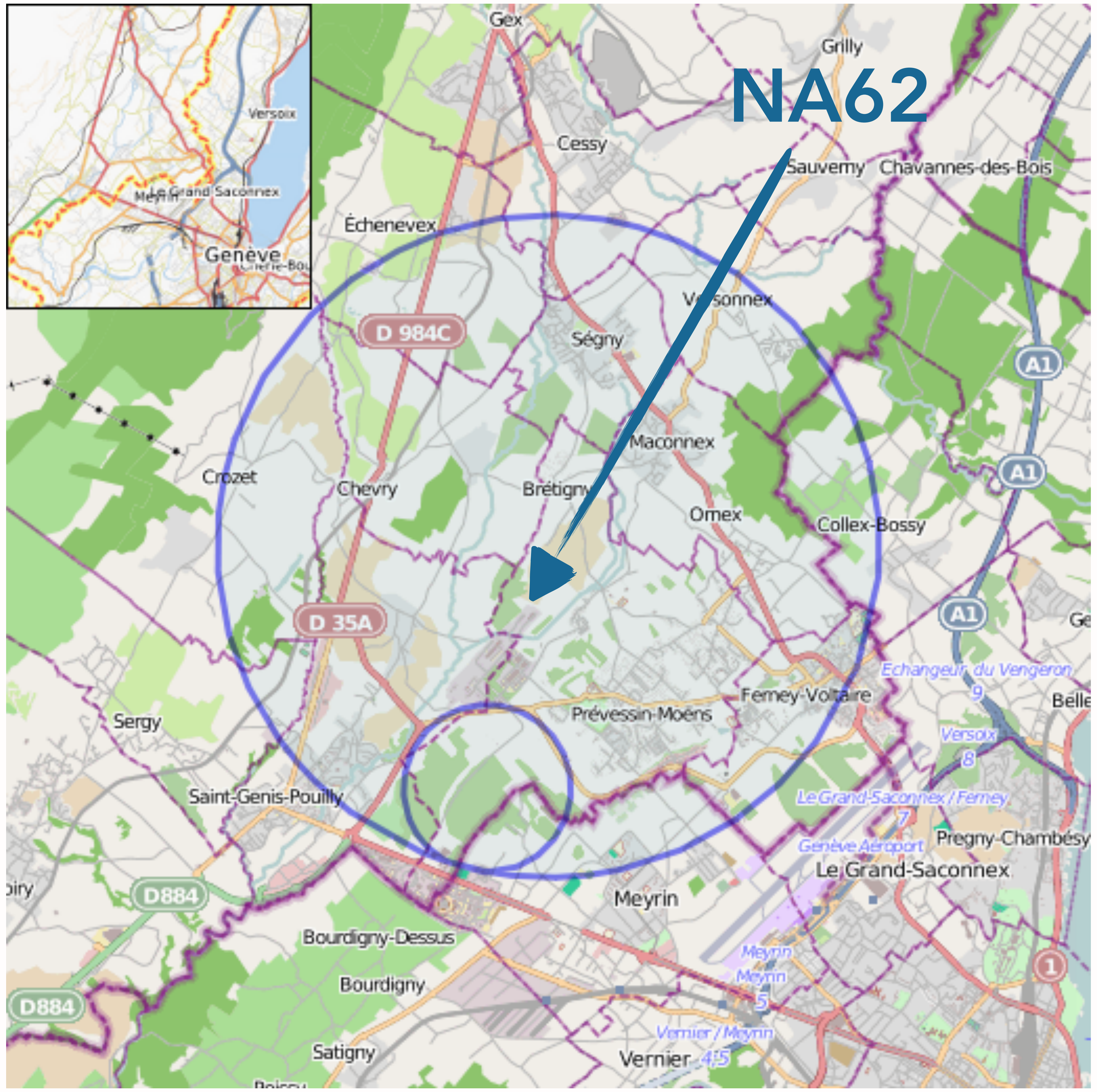
EPS-HEP 2025, PALAIS DU PHARO, MARSEILLE

# A kaon factory at CERN




- Beam from the SPS: **400 GeV/c protons** on Be target
- Secondary 75 GeV/c beam hadrons (70% $\pi$, 24% $p$ and **6%** $K$)
- **Decay in flight:** $K^+$ decay in a 60 meters long volume

**The main aim of NA62 is to study the FCNC process $K^+ \to \pi^+ \nu\bar{\nu}$**

Theory [arXiv:2109.11032]

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

NA62 [JHEP06 (2021) 093] [JHEP 02 (2025) 191]

$$\mathcal{B}_{2016-2022}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.0}_{-2.7}|_{stat}\,{}^{+1.3}_{-1.3}|_{syst}) \times 10^{-11}$$

**Timeline of the NA62 Experiment:**

| 2009-2014 | 2016-2018 | 2019-2021 | 2021-2026 |
|---|---|---|---|
| Detector R&D Installation | Run1 | LS2 upgrade | Run 2 |

# Long lived particles (LLPs): search motivation

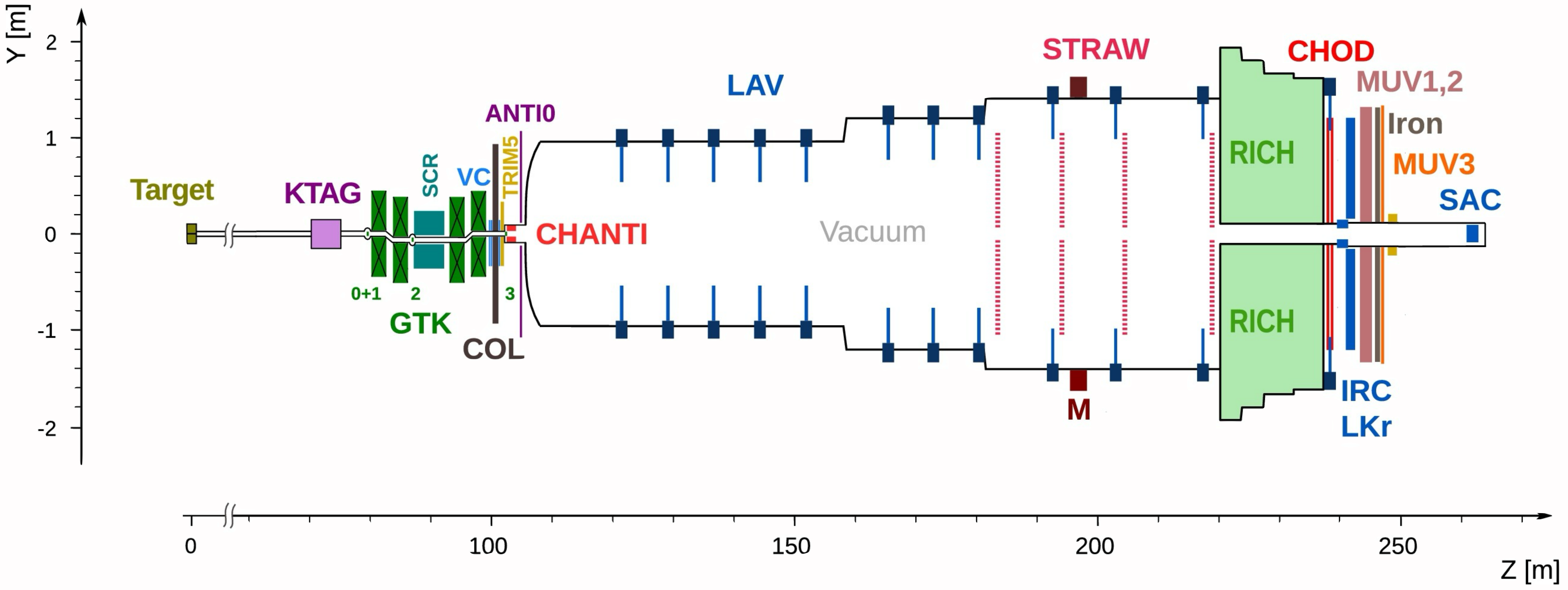
**Search for New Physics (NP) at intensity frontier with fixed-target experiments:**

- Complementary to the energy frontier (LHC) and indirect searches (precision measurements, LNV, etc.)
- Smaller masses (typically MeV-GeV scale) and lower couplings accessible

| | SM portal | PBC | Decay modes | |
|---|---|---|---|---|
| HNL ($N_I$) | $F_{\alpha I}(\bar{L}_\alpha H) N_I$ | BC6-8 | $\pi\ell, K\ell, \ell_1\ell_2\nu$ | |
| Dark Photon (A') | $-(\epsilon/2\, cos\theta_W) F'^{\mu\nu} B_{\mu\nu}$ | BC1-2 | $\ell^+\ell^-$ | $2\pi, 3\pi, 4\pi, 2K, 2K\pi$ |
| Dark scalar (S) | $(\mu S + \lambda S^2) H^\dagger H$ | BC4-5 | $\ell^+\ell^-$ | $2\pi, 4\pi, 2K$ |
| Axion/ALP (a) | $(C_{ff}/\Lambda)\partial_\mu a \tilde{f} \gamma^\mu \gamma^5 f$<br>$(C_{VV}/\Lambda) g a V_{\mu\nu} \tilde{V}^{\mu\nu}$ | BC10<br>BC9,11 | $\ell^+\ell^-$<br>$\gamma\gamma$ | $2\pi\gamma, 3\pi, 4\pi, 2\pi\eta, 2K\pi$ |

} Covered in this talk (Dark Photon, Dark scalar, Axion/ALP)

# Detector overview in kaon mode




## Upstream Detectors

**KTAG:** Cherenkov differential detector

**GTK:** silicon pixel beam tracker

**ANTI0:** veto hodoscope

## Downstream Detectors

**STRAW:** track momentum spectrometer

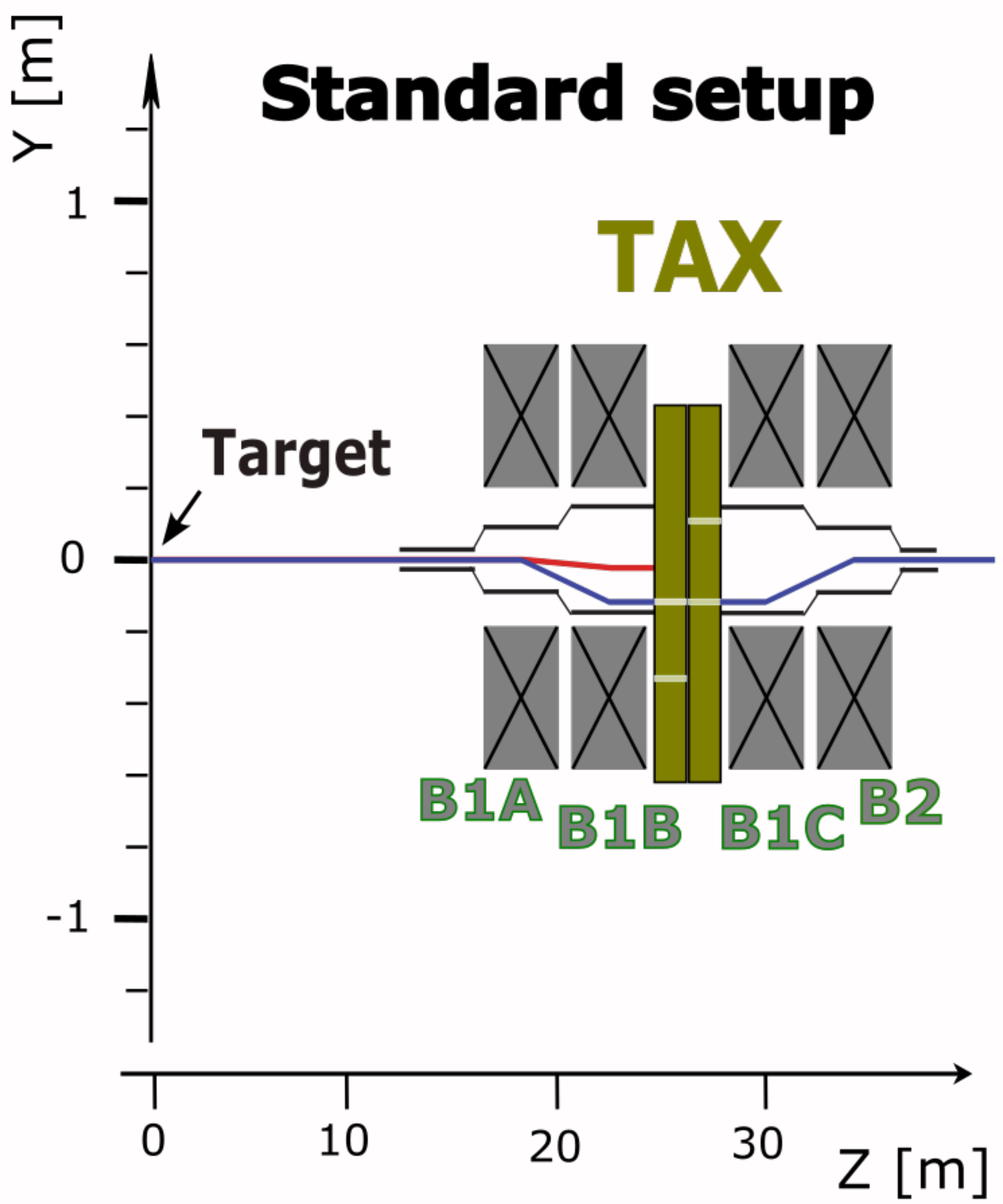
**CHOD:** plastic scintillators for fast charged trigger

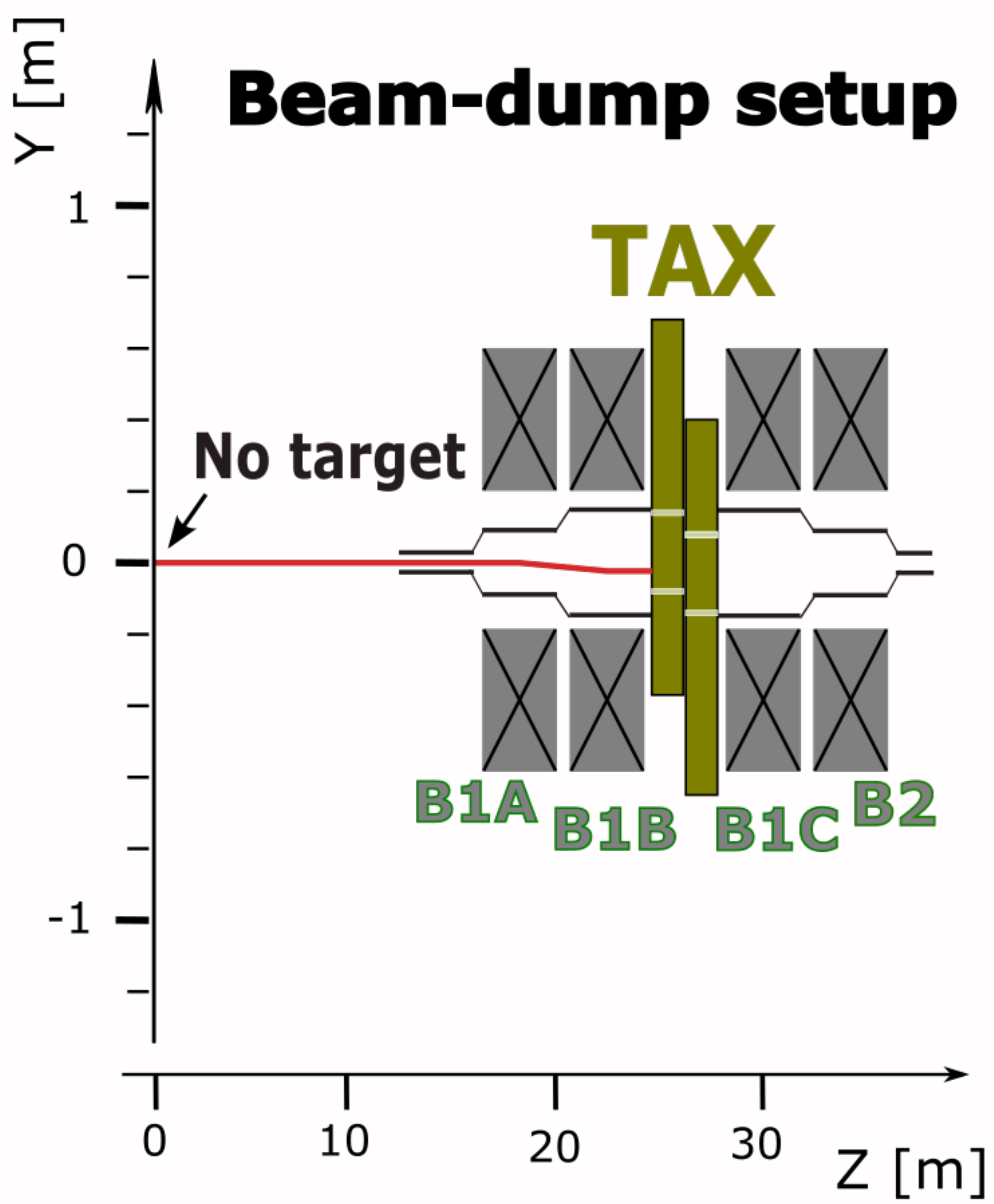
**RICH:** Cherenkov counter for π/μ/e ID

**LKr and MUV1-2:** calorimetric system

**MUV3:** muon veto

# NA62 in beam dump mode




- **Target** lifted from the beam line
- **TAX** collimators serve as dump for the 400 GeV/c proton beam
- Currents of the second pair of **dipoles** set to minimize the flux of muons produced by pion decays within the TAX
- **ANTI0** used as an upstream veto

# Data sample and run conditions

$1.40 \pm 0.28 \times 10^{17}$ POT collected in ~ 10 days of data taking during the 2021 run

## Trigger lines

- **Single track trigger,** at least one signal in the CHOD

  Q1/D, D = 20 → 14 KHz

- **Two-tracks trigger,** at least two in-time signals form CHOD in two different tiles

  H2 → 18 kHz

- **Control trigger** LKr-based to measure efficiency of the charged triggers, 1MeV threshold

- CTRL → 4 kHz

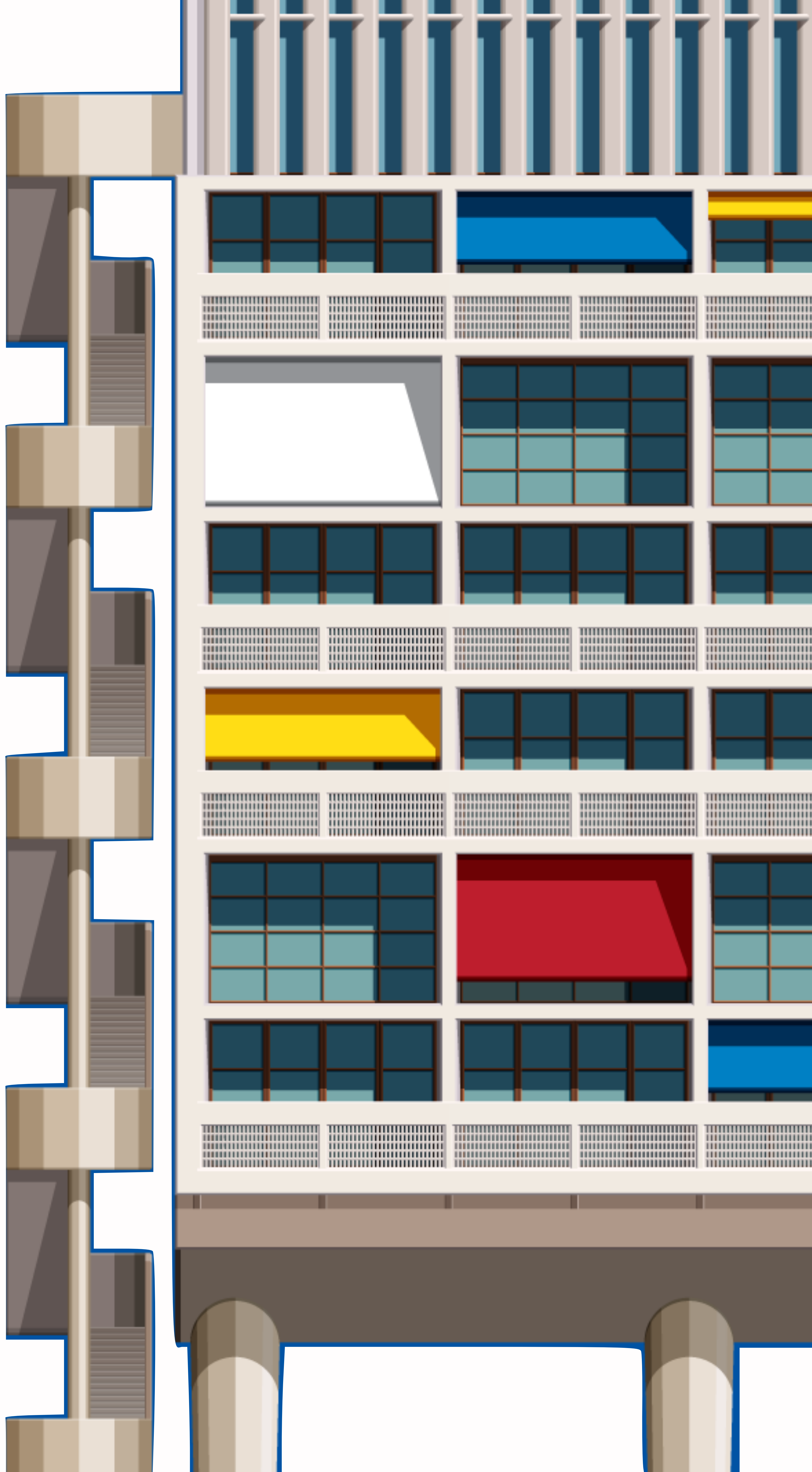
**Q1 trigger efficiency** = 99.8%

**H2 trigger efficiency** = 98%


**NP searches with $\mu^+\mu^-, e^+e^-$ and hadronic $\pi^+\pi^-(\gamma, \pi^0, \eta, 2\pi^0), K^+K^-(\pi^0)$ final states published**

JHEP 09, 035 (2023)    PRL 133(2024) 111802    Eur.Phys.J.C 85 (2025) 5, 571

# Hadronic final states



# Model New Physics searches in hadronic decays

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Numerous possibilities for exotic particle X being a dark photon (DP), dark scalar (DS), axion-like particle (ALP), …

**Decay**

| Decay modes | | |
|---|---|---|
| DP | DS | ALP |
| $\pi^+\pi^-$ | $\pi^+\pi^-$ | $\pi^+\pi^-\gamma$ |
| $\pi^+\pi^-\pi^0$ | | $\pi^+\pi^-\pi^0$ |
| $\pi^+\pi^-\pi^0\pi^0$ | $\pi^+\pi^-\pi^0\pi^0$ | $\pi^+\pi^-\pi^0\pi^0$ |
| | | $\pi^+\pi^-\eta$ |
| $K^+K^-$ | $K^+K^-$ | |
| $K^+K^-\pi^0$ | | $K^+K^-\pi^0$ |

**Production**

- **ALP:** Primakoff (on and off.shell), mixing with $P = \{\pi^0, \eta, \eta'\}, B^{\pm,0} \to K^{\pm,0,(*)}a$
- **DP:** Bremsstrahlung, decay of PS and V particles $P \to A'\gamma, V \to A'P \ \ (V = \{\rho, \omega, \phi\}$ and $(P = \{\pi^0, \eta, \eta'\})$
- **DS:** $B^{\pm,0} \to K^{\pm,0,(*)}S$

**Altogether 61 combinations of production and decay channels studied**

# Analysis strategy

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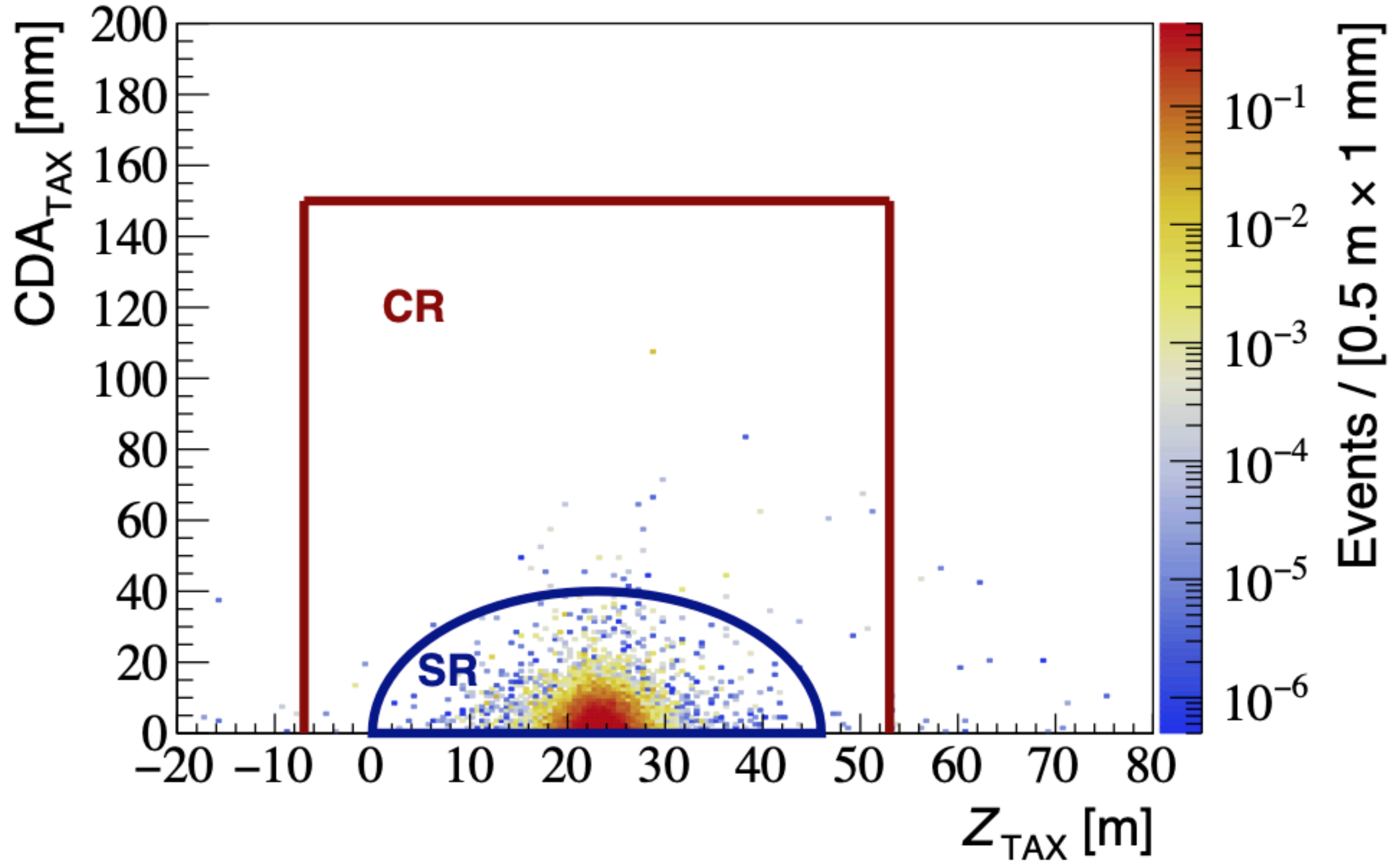
## 2 hadronic track selection:

- **2 good quality tracks** in coincidence with each other and with the trigger
- **BDT particle ID** selecting hadrons (LKr and MUV1-2), MUV3 veto, RICH used for tagging $K^+$
- **No in-time activity** in LAV, SAV and no geometrical associated ANTI0 signal
- decay vertex reconstructed in **FV**
- additionally search **neutral clusters** in LKr




**SR:** ellipse centered at $\{Z_{TAX}, CDA_{TAX}\}$ = {23 m, 0 mm} with semi-axes of 23 m and 40 mm

**CR:** box $CDA_{TAX}$ < 150 mm and −7 m < $Z_{TAX}$ < 53 m

## Search strategy:

- Vertex and LLP kinematic reconstructed from final states is in the NA62 decay region and pointing back to the proton beam interaction point at the TAX.

# Signal efficiency and expected yield

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In model-independent case $(C^i = C^i_{ref},\ BR^f = 1)$ :

$$N^{if}_{exp}(M_X, \Gamma_X) = N_{POT} \times \chi^i_{pp\to X}(C^i_{ref}) \times P^i_{rd} \times A^{if}_{acc}$$

- $\chi_{pp\to X}(C_{ref})$ is LLP production probability for reference coupling
- $P_{rd}$ is the probability to reach NA62 FV and decay therein
- $A_{acc}$ is the product between the signal selection and the trigger acceptance

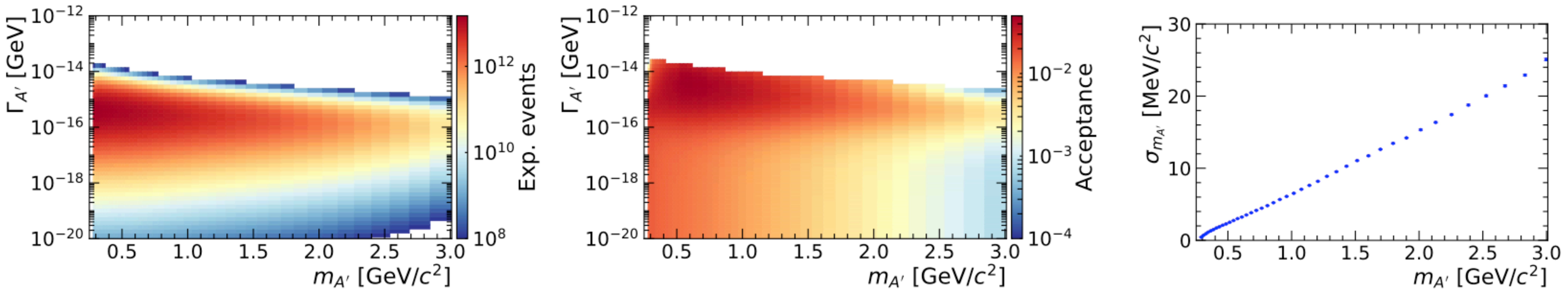


Figure: Left: expected $A' \to \pi^+\pi^-$ yield after full selection, assuming $\varepsilon = 1$ and BR $= 1$. Center: acceptance after full selection for LLPs that reached the FV and decayed therein. Right: Mass resolution of the reconstructed LLP.

**Distributions obtained for 61 combinations of production and decay channels**

# Total background estimation

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## Background contributions:

- combinatorial and neutrino-induced backgrounds: negligible contributions
- prompt background: inelastic interaction of halo muons can produce hadrons
- upstream background: formed by particles that are collected by the GTK achromat

**Number of background events estimated at 68% CL**

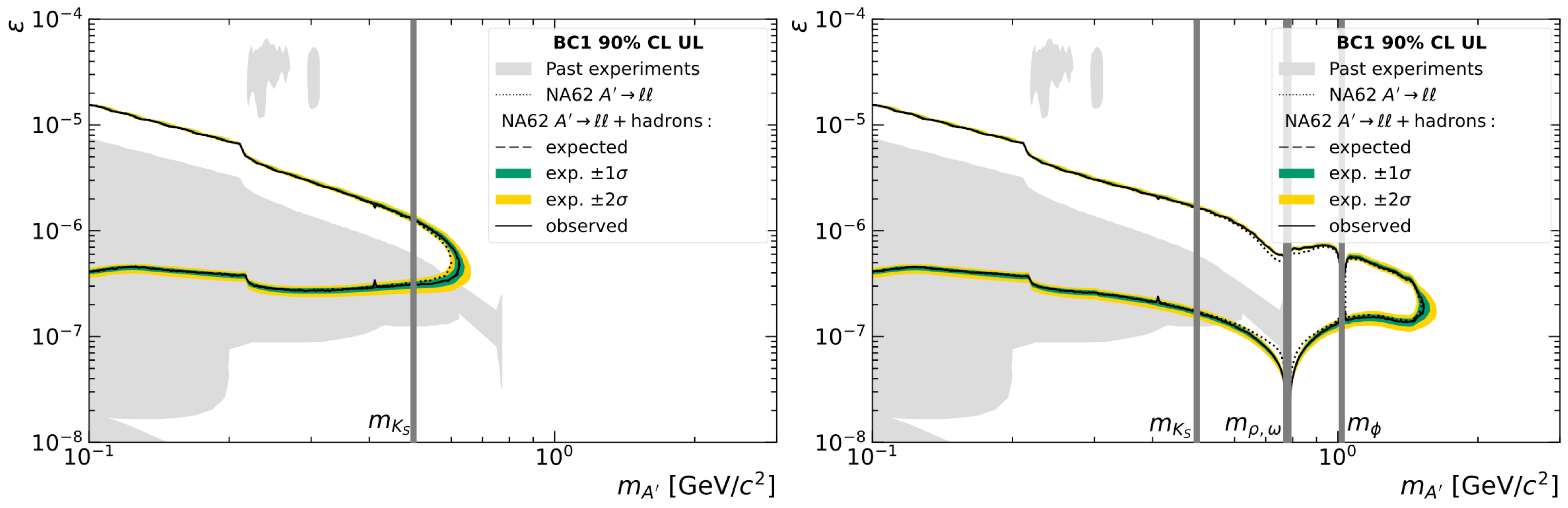
| Channel | $N_{\text{exp,CR}}$ | $N_{\text{exp,SR}}$ | $N^{5\sigma}_{\text{min,SR}}$ | $N^{5\sigma}_{\text{min,SR+CR}}$ |
|---|---|---|---|---|
| $\pi^+\pi^-$ | $0.013 \pm 0.007$ | $0.007 \pm 0.005$ | 3 | 4 |
| $\pi^+\pi^-\gamma$ | $0.031 \pm 0.016$ | $0.007 \pm 0.004$ | 3 | 5 |
| $\pi^+\pi^-\pi^0$ | $(1.3^{+4.4}_{-1.0}) \times 10^{-7}$ | $(1.2^{+4.3}_{-1.0}) \times 10^{-7}$ | 1 | 1 |
| $\pi^+\pi^-\pi^0\pi^0$ | $(1.6^{+7.6}_{-1.4}) \times 10^{-8}$ | $(1.6^{+7.4}_{-1.4}) \times 10^{-8}$ | 1 | 1 |
| $\pi^+\pi^-\eta$ | $(7.3^{+27.0}_{-6.1}) \times 10^{-8}$ | $(7.0^{+26.2}_{-5.8}) \times 10^{-8}$ | 1 | 1 |
| $K^+K^-$ | $(4.7^{+15.7}_{-3.9}) \times 10^{-7}$ | $(4.6^{+15.2}_{-3.8}) \times 10^{-7}$ | 1 | 2 |
| $K^+K^-\pi^0$ | $(1.6^{+3.2}_{-1.2}) \times 10^{-9}$ | $(1.5^{+3.1}_{-1.2}) \times 10^{-9}$ | 1 | 1 |

**background-free hypothesis** not only at $N_{POT} = 1.4 \times 10^{17}$ but also in the future full **Run 2 dataset** of $N_{POT} = 10^{18}$

# Results and interpretation

[Eur.Phys.J.C 85 (2025) 5, 571]

**0 event observed in the all the control and signal regions**




- Public tool ALPINIST used for the model-dependent interpretation:

$$N_{exp}(m_X, C_X) = \sum_{if} BR^f(m_X, C_X) \times (C^i/C^i_{ref})^2 \times N^{if}_{exp}(m_X, \Gamma_X = \Gamma_X(m_X, C_X))$$

- Observed 90% CL contours obtained using the CLs method, combining the result for hadronic and di-lepton final states.

# Results and interpretation

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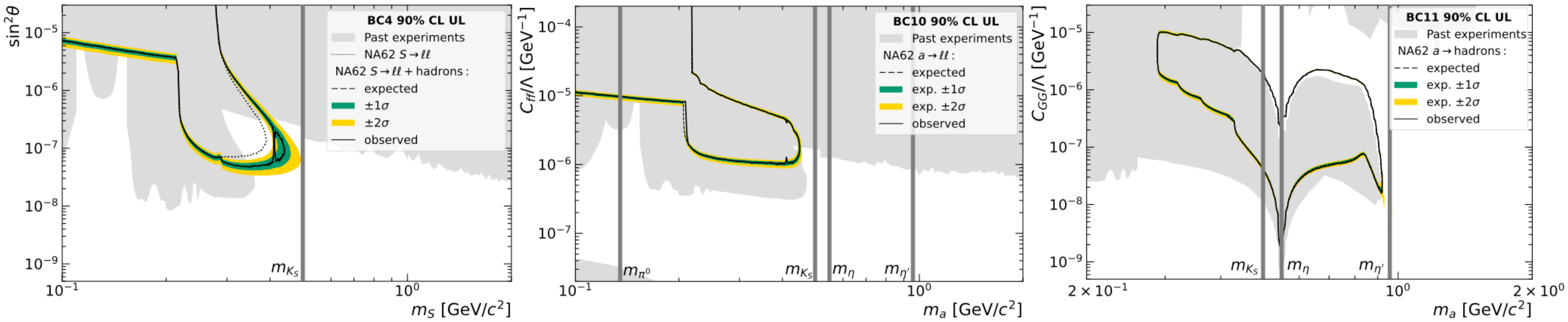
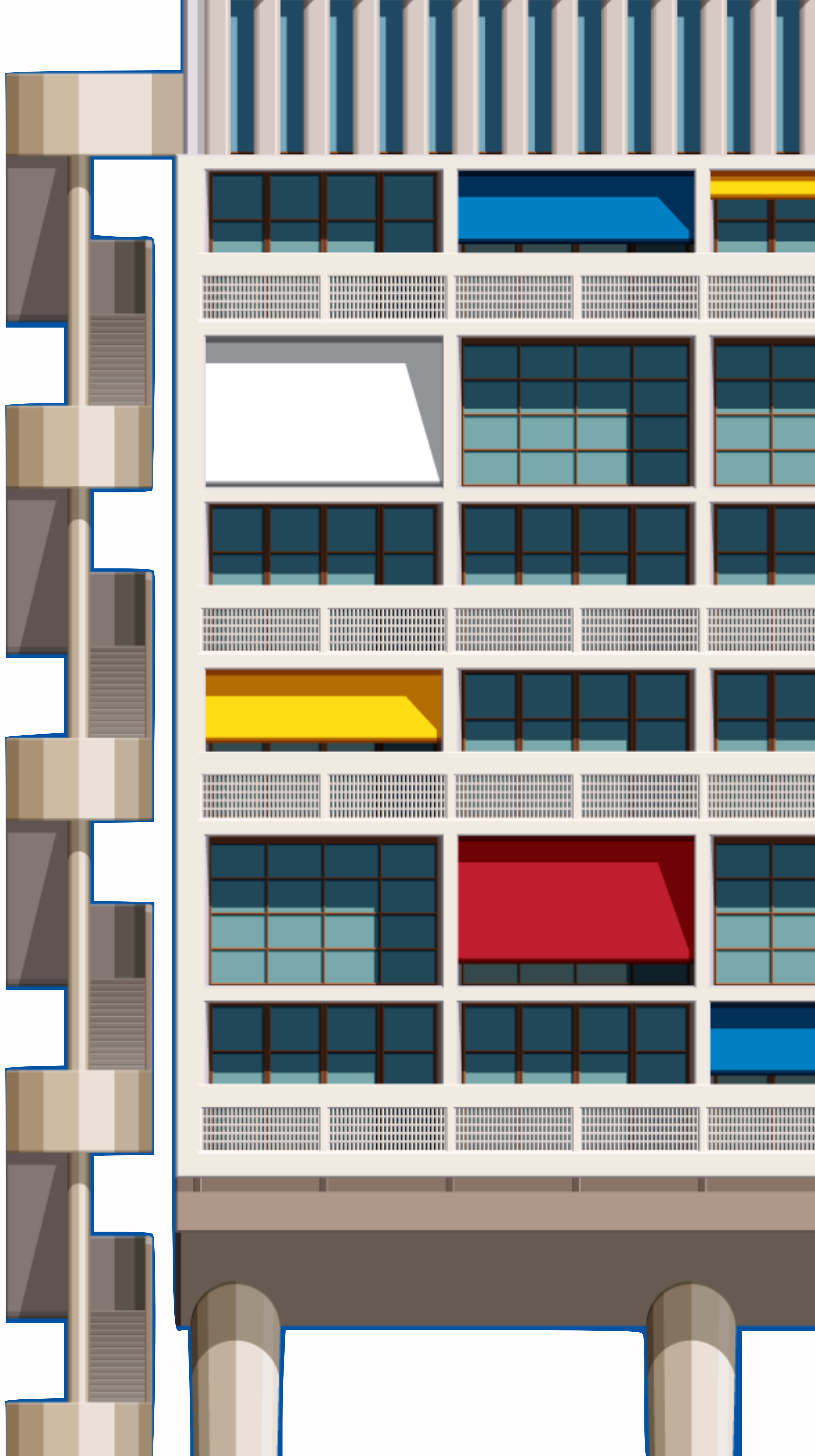


# Summary

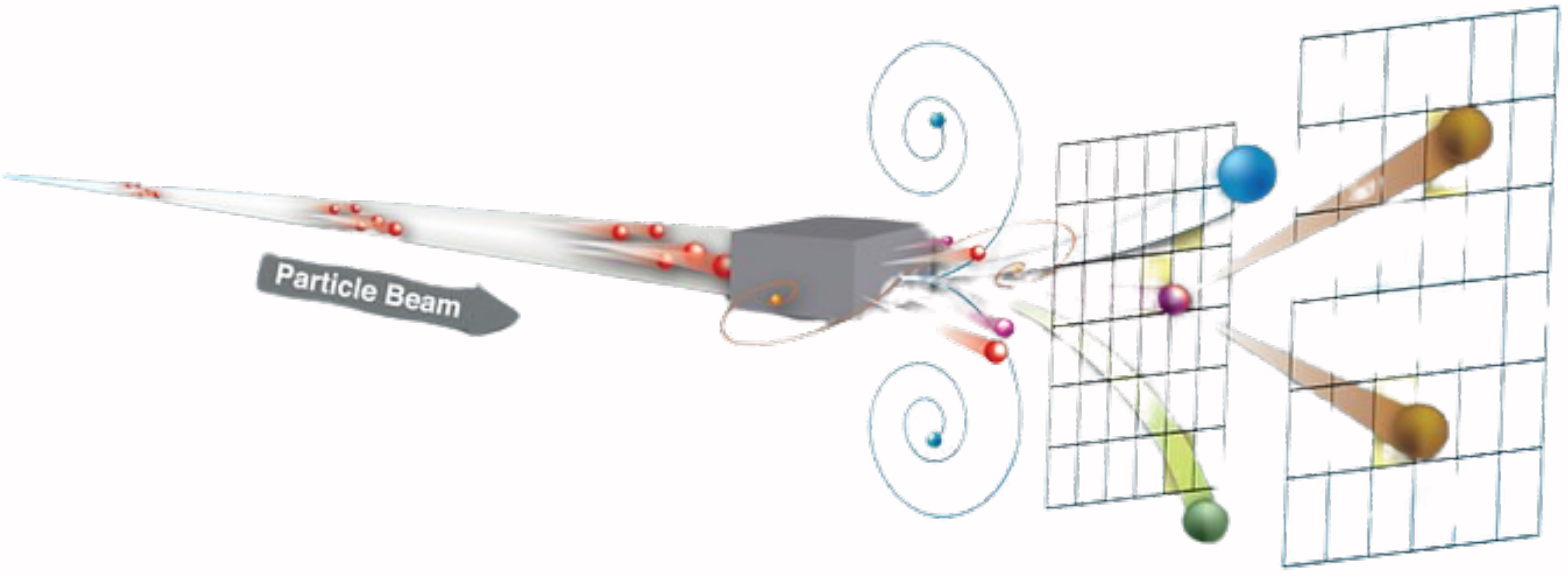
- The first search for production and decay of an exotic particle in hadronic final states from data collected by the NA62 experiment in beam-dump mode has been presented with no observation of new physics signals;
- With $(1.40 \pm 0.28) \times 10^{17}$ POT a 90% CL upper limits have been set, exploring new regions of the parameter space
- Much more data already collected ( $6 \times 10^{17}$ POT)
- Plan to collect $10^{18}$ POT in beam-dump mode by the LHC LS3 with interesting perspectives on dark photons, ALPs, dark scalars and HNLs;
- Searches for exotic particles decaying into semi-leptonic or di-gamma final states using beam-dump data are in progress.

Thanks for your attention!

# Backup

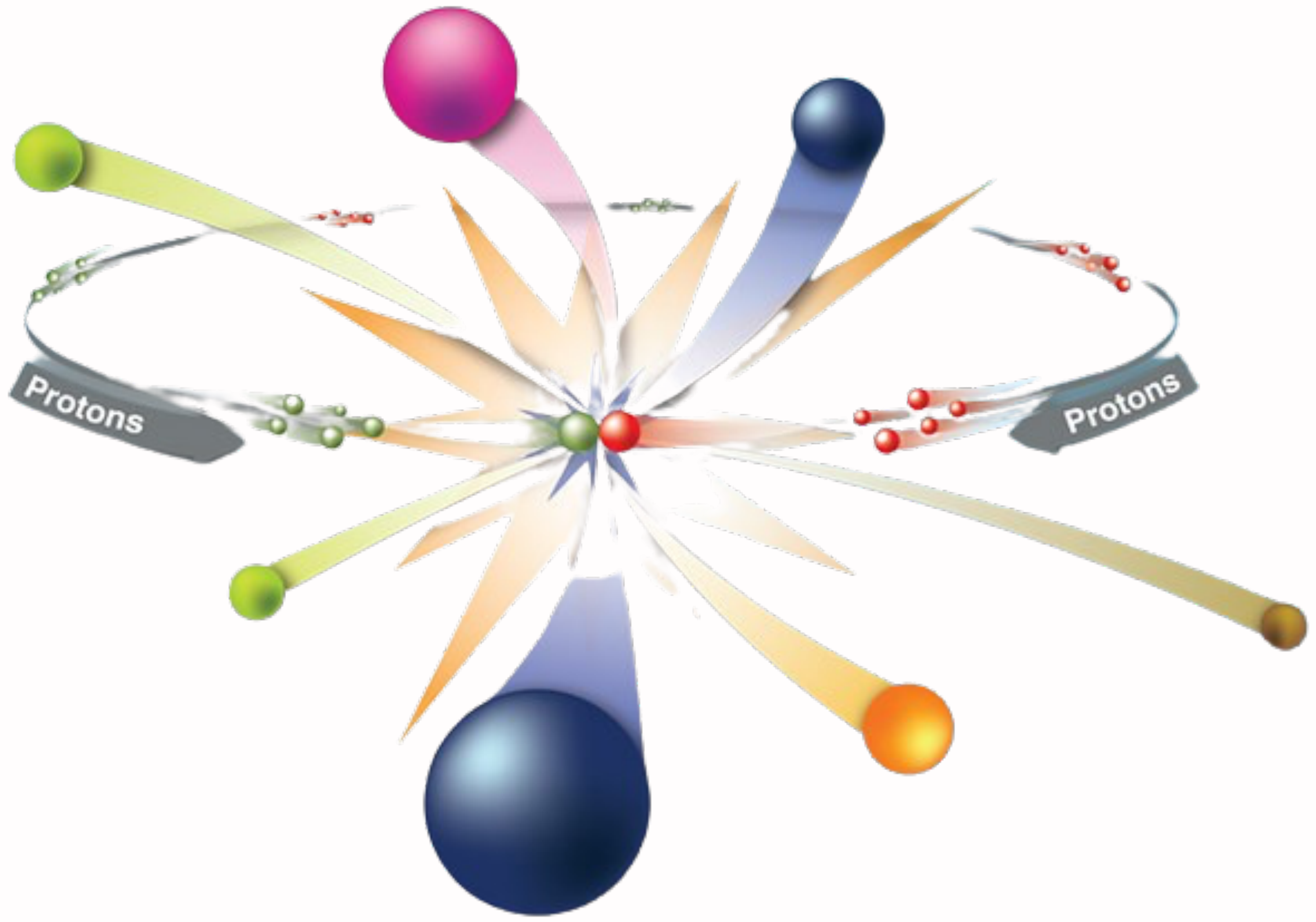


# Beam dump vs. collider searches




The event rate can be very high

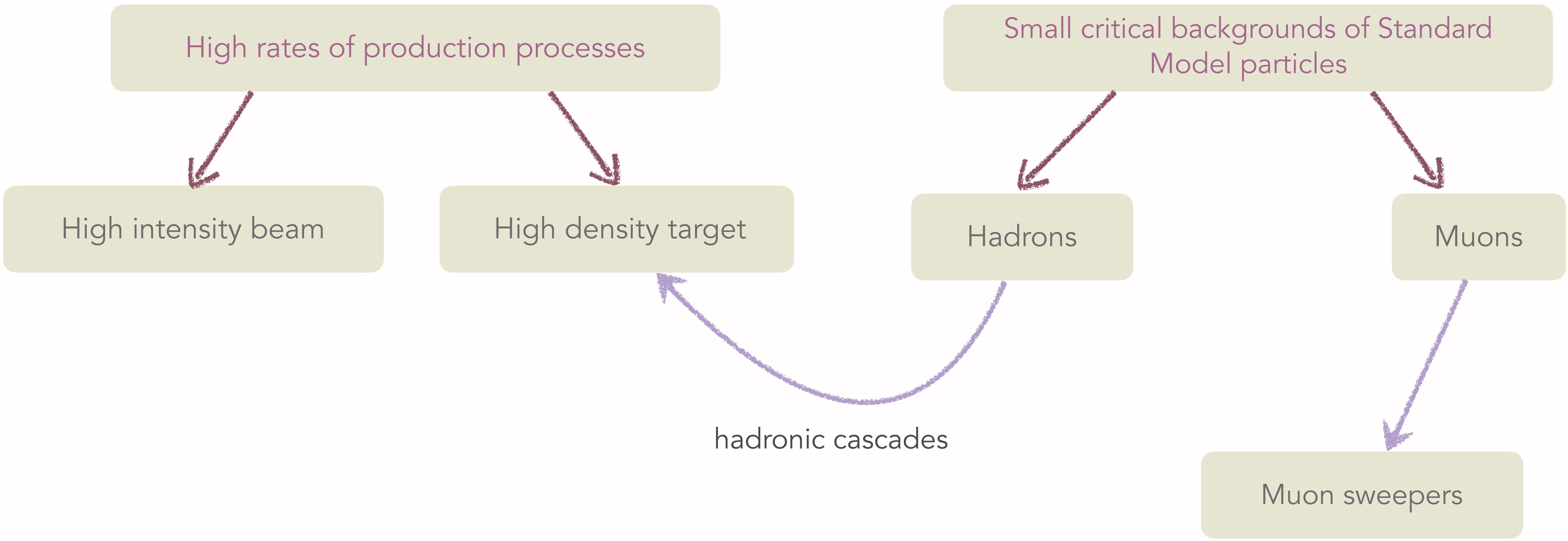
- ➡ Compared to colliding beams, experiments are relatively easy to arrange.
- ➡ The energy available to generate new particles is a small fraction of the beam energy.
- ➡ Production of **beam of secondary particles** that may be stable, unstable, charged or neutral, solving the impossibility of accelerating unstable or neutral particles directly



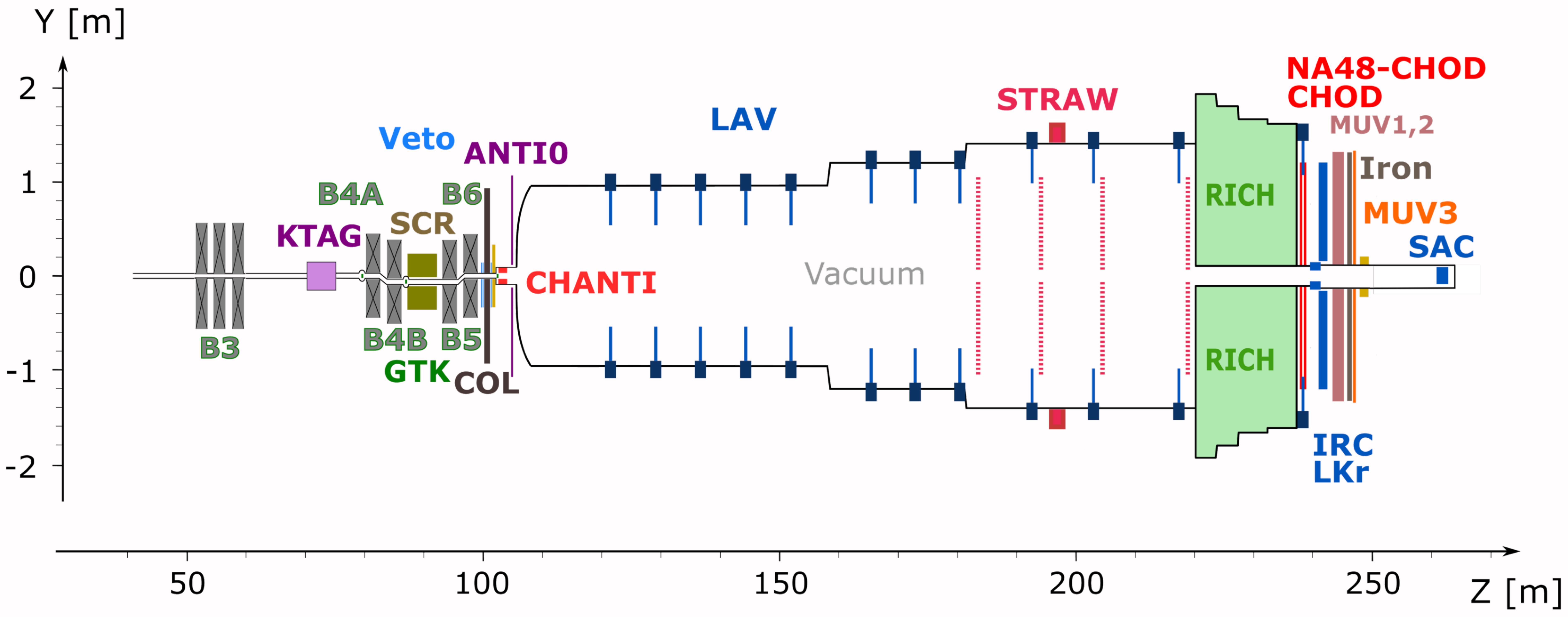

The energy available for the production of new particles is twice as high as the beam energy

- ➡ The **luminosity** is **low** compared to experiments with fixed targets
- ➡ A large **variety** of process can be studied

# Beam dump: experimental requirements



# Detector overview in kaon mode



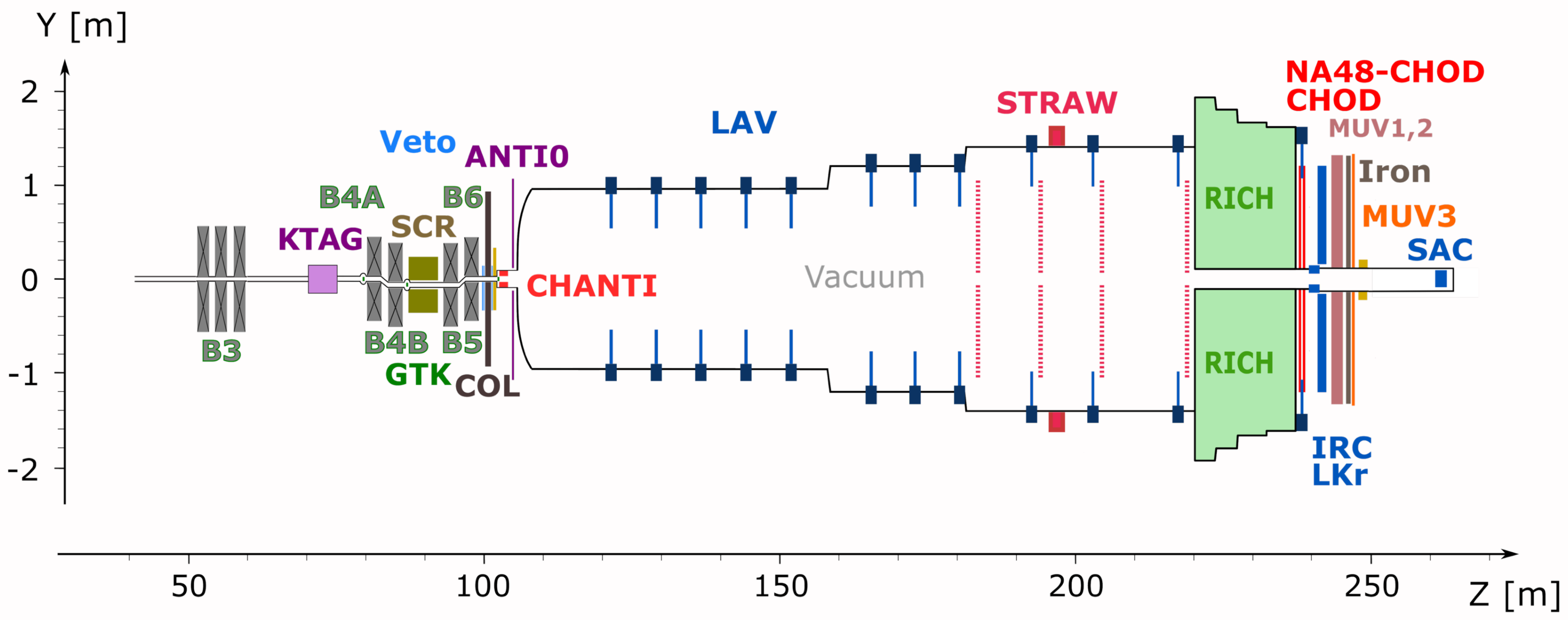

## Performances

- GTK-KTAG-RICH time resolution $\mathcal{O}(100\,ps)$
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $\mathcal{O}(10^7)$ muon rejection for $15 < p(\pi^+) < 35\ GeV$
- $\mathcal{O}(10^8)$ π rejection for $E(\pi^0) > 40\,GeV$

## Resolution

- Spectrometer $\sigma_p/p = (0.30 \oplus 0.005 \times p)\,\%$ [GeV/c]
- CHOD and NewCHOD resolution of 600 and 200 ps
- LKr $\sigma_E/E = (4.8/\sqrt{E} \oplus 11/E \oplus 0.9)\,\%$ [GeV]

# Detector overview in beam dump mode




### Sweeping

- B3 a triplet of magnetization-satured dipole magnets
- SCR a toroidally-magnetized iron collimator
- B5 and B6 magnets

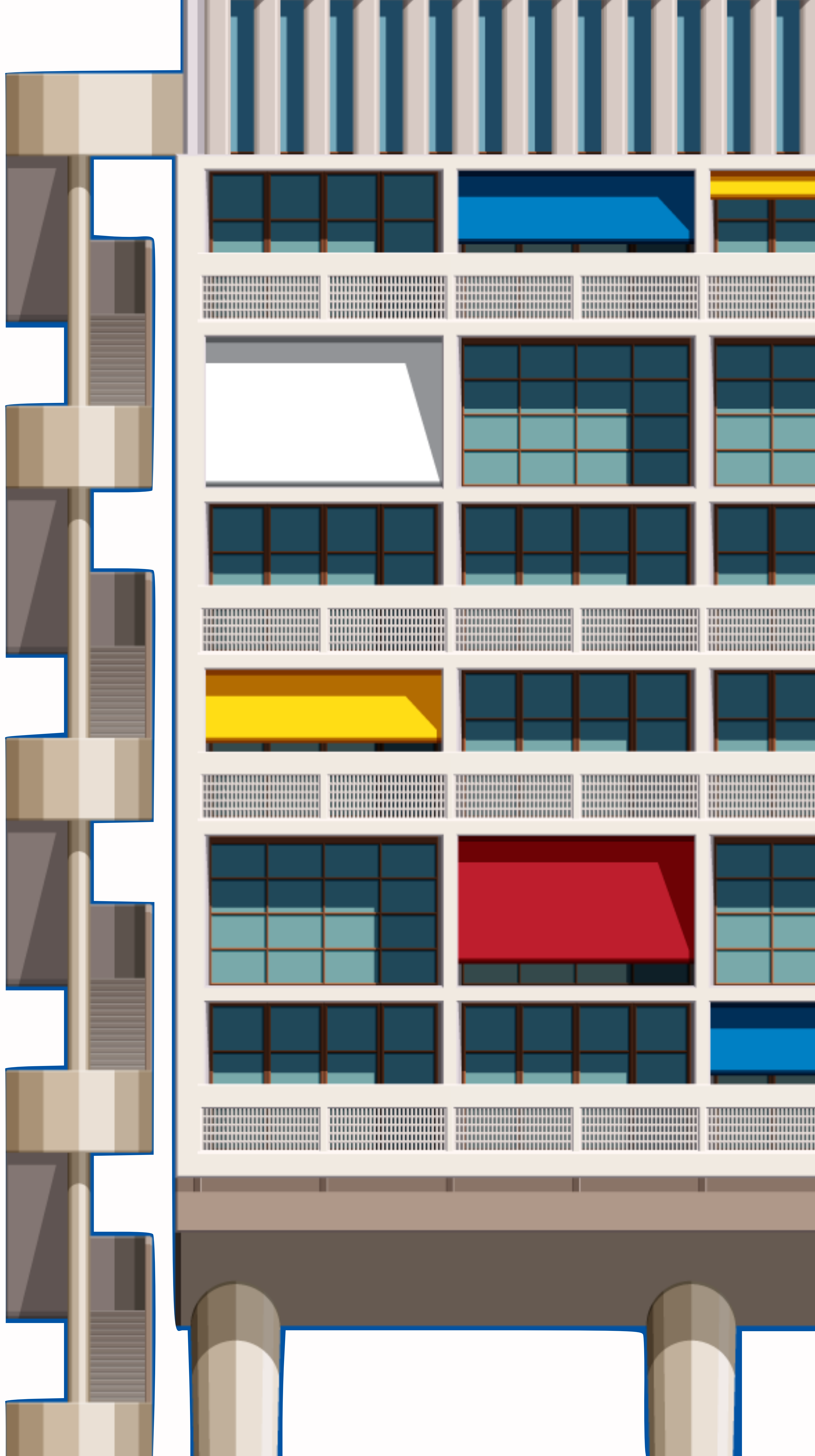
### Upstream

- COL cleaning collimator
- ANTI0 scintillator hodoscope

### Downstream

- STRAW spectrometer for momentum and direction measurements
- LKr, LAV, IRC and SAC photon veto system

$$A' \to \ell^+\ell^-$$

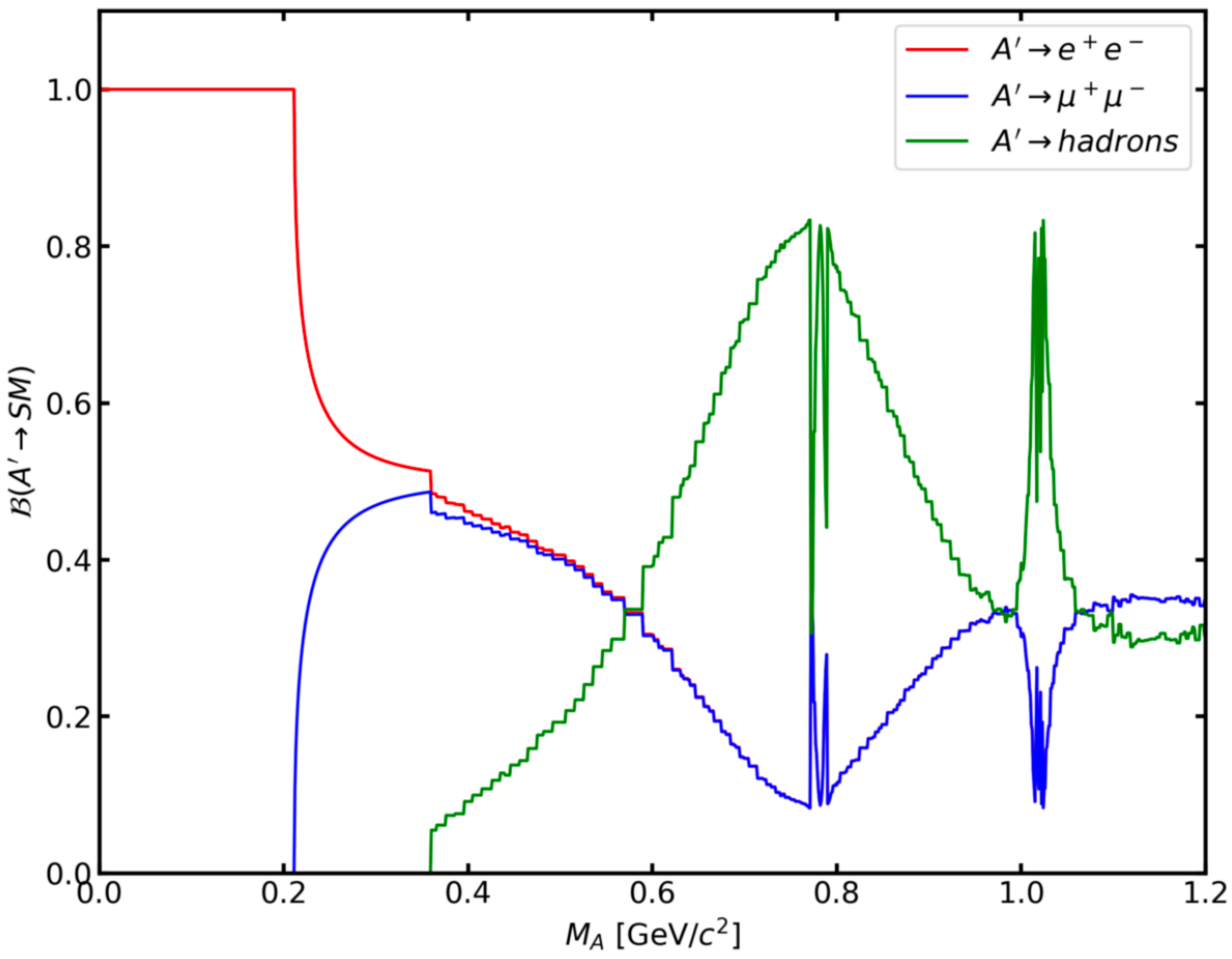


# Dark photon: a detailed view

- New vector field $F'_{\mu\nu}$ symmetric under a new U(1) symmetry feebly interacting with the SM fields
- A minimal extension to the SM: kinetic mixing with the SM hypercharge

$$-\frac{\epsilon}{2}F'^{\mu\nu}B_{\mu\nu}$$

M(A') and ε are free parameters

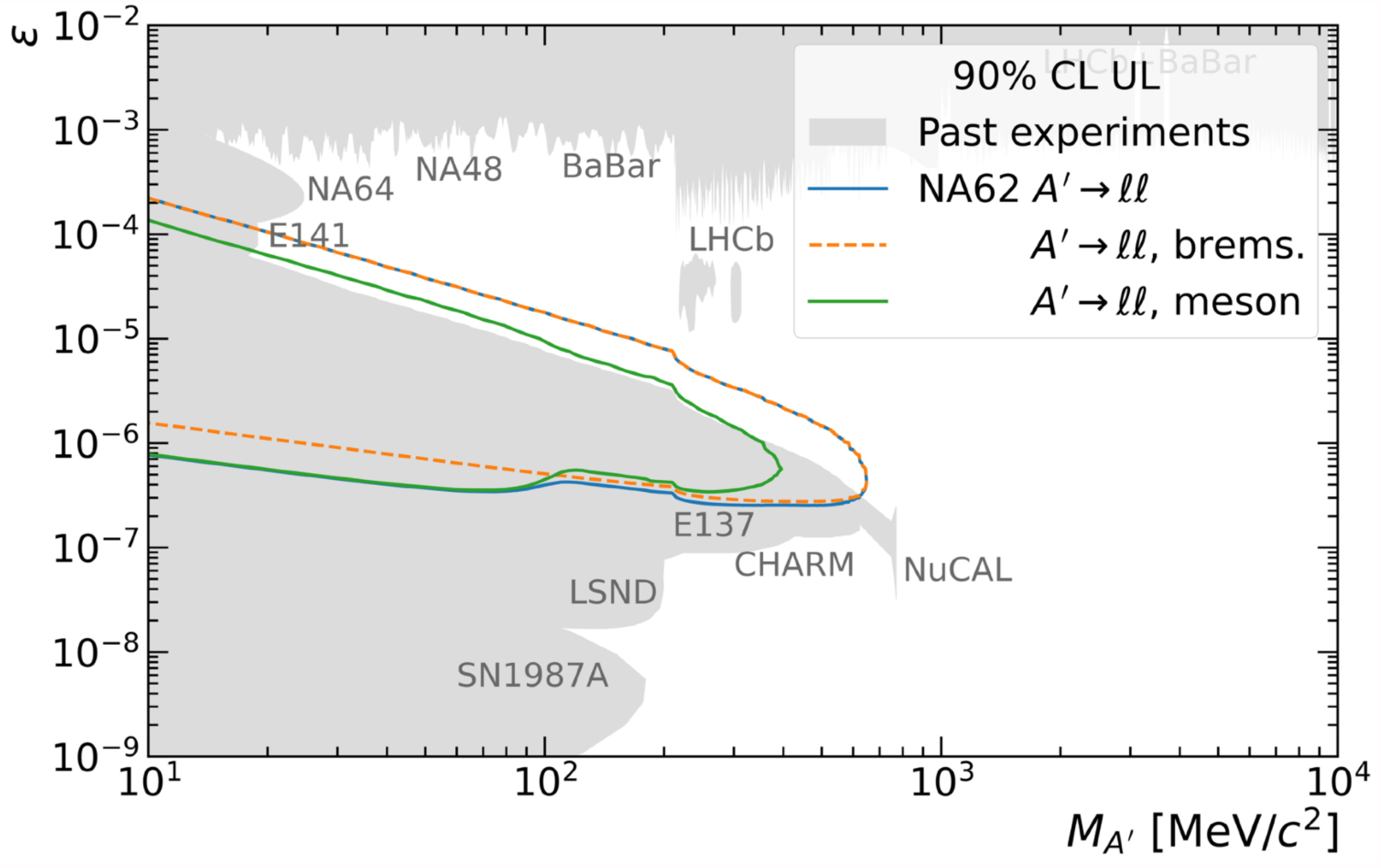



Decay width dominated by lepton antilepton final states for M(A')< 700 MeV

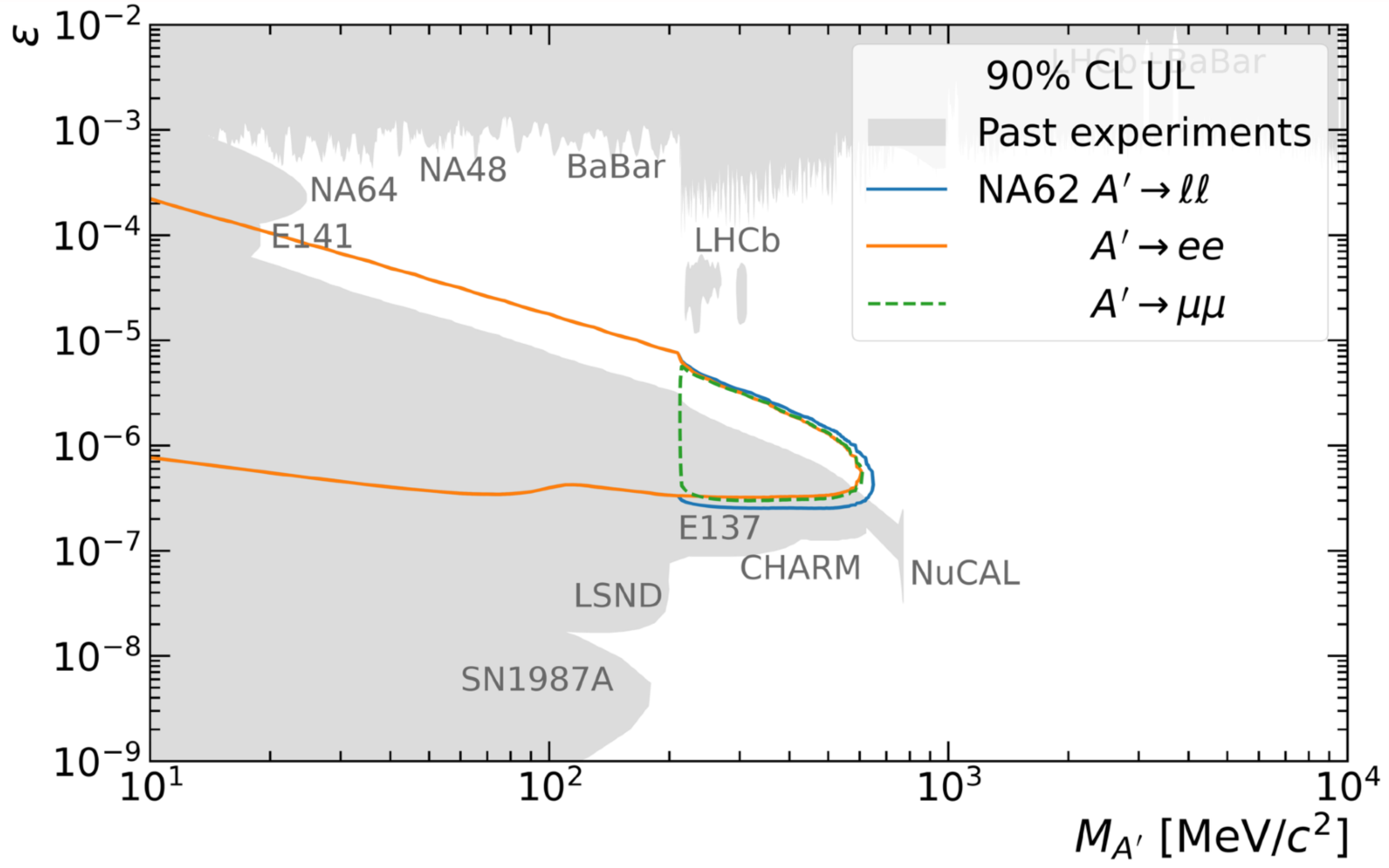
# Search for DP in NA62 beam dump

Two production mechanisms are in action in proton-nucleus interaction scenario:

1. Bremsstrahlung production: pN→A’X
2. Meson-mediated production: pN→MX, M→A’γ ($\pi^0$, η), where M = $\pi^0$, $\eta^{(\prime)}$, ρ, ω, etc.




**Sensitivity per production mechanism assuming 0 observed events in 1.4×10[17] POT**




**Sensitivity per decay mode assuming 0 observed events in 1.4×10[17] POT**

# DP searches in $\ell^+\ell^-$ final states

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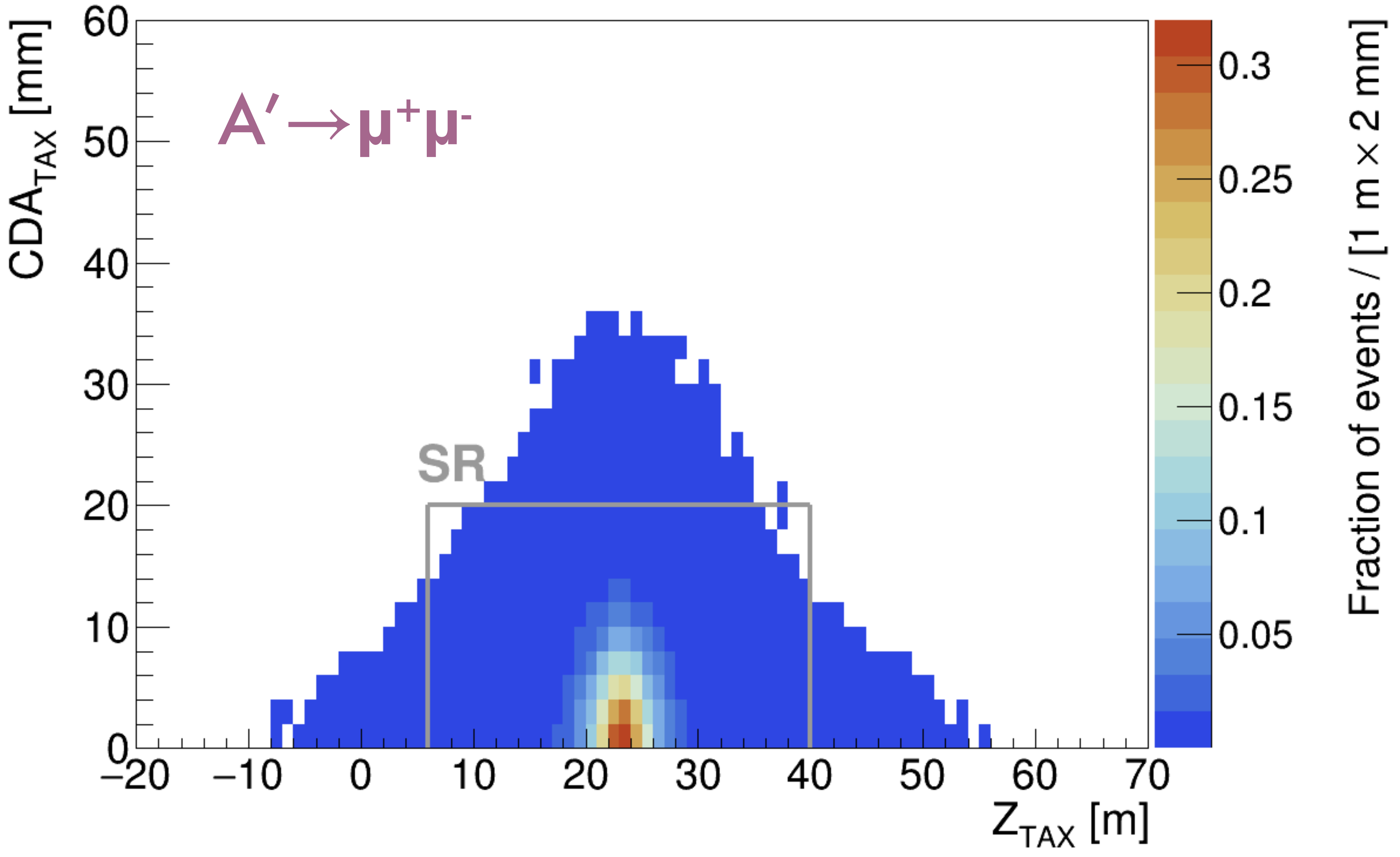
Signal signature

- $\ell^+\ell^-$ vertex in the NA62 fiducial volume
- Primary production vertex close to the proton TAX interaction point

## Event selection

- Good quality tracks with timing in coincidence with each other and the trigger
- PID with LKr and MUV3
- In $e^+e^-$ analysis: decay region & PID optimization and no in-time activity in muon veto detector MUV3
- No in-time activity in LAV (and ANTI0 in $e^+e^-$)
- Signal region (SR) selection (redefinition of SR for $e^+e^-$)

Signal region is kept blinded till the analysis freezing




$CDA_{TAX}$ closest distance of approach between the beam direction at the TAX entrance and $\ell^+\ell^-$ direction $\sigma_{CDA} \sim 7\,mm$

$Z_{TAX}$ longitudinal position $\sigma_Z \sim 5.5\,mm$

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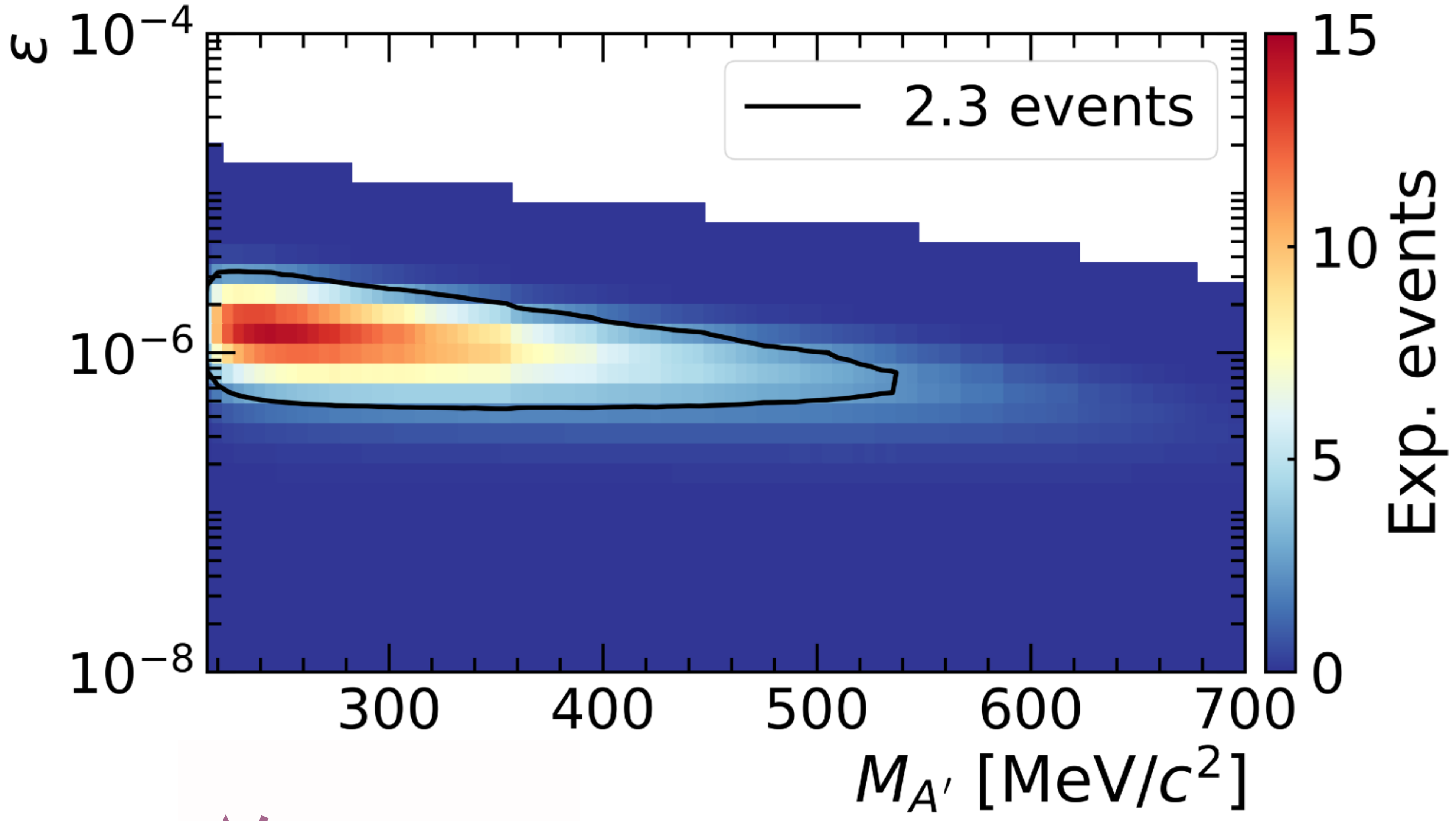
# Expected yield on $A' \to \ell^+\ell^-$

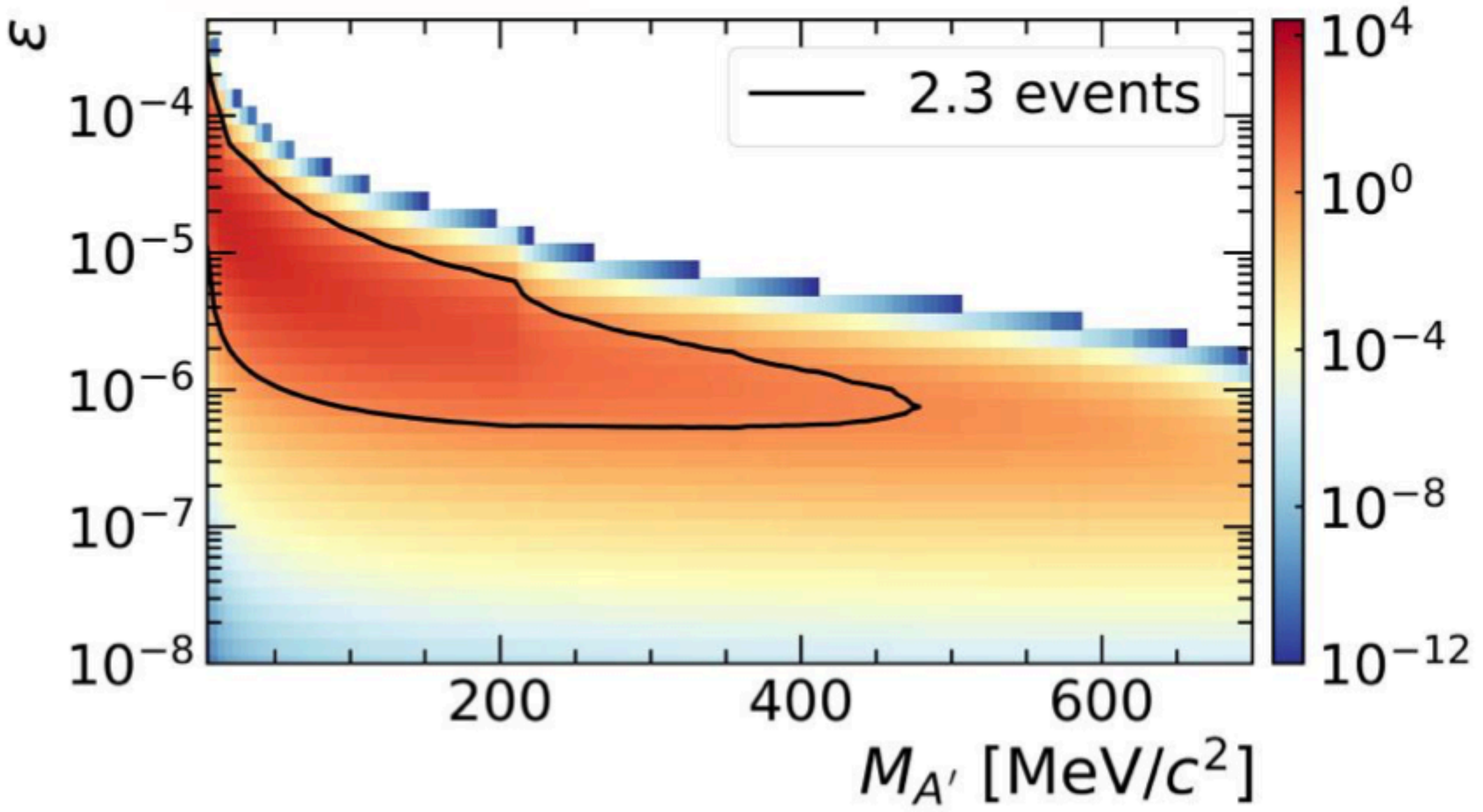
$$N_{exp} = POT \times P(pN \to A') \times \mathscr{B}(A' \to \ell^+\ell^-) \times P_D \times A_{sel}$$

- POT = $1.40 \pm 0.28 \times 10^{17}$, proton on target collected in 2021
- $P(pN \to A')$ DP production probability
- $\mathscr{B}(A' \to \ell^+\ell^-)$ decay branching fraction
- $P_D$ probability for DP to reach the NA62 fiducial volume and decay therein
- $A_{sel}$ signal selection and trigger efficiencies

$A' \to \mu^+\mu^-$




$A' \to e^+e^-$



# Background studies

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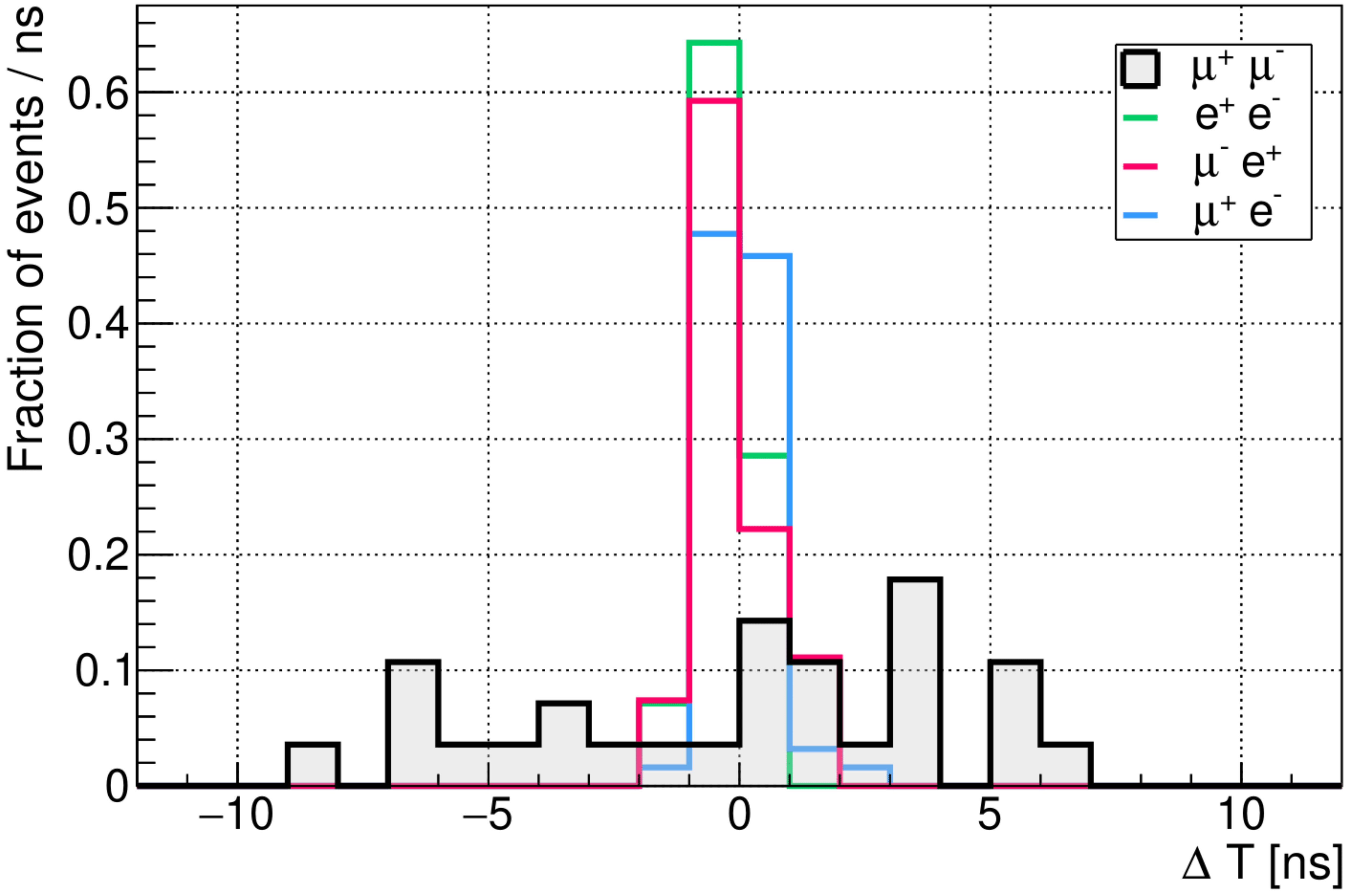
The main expected backgrounds can be divided in two categories

**Combinatorial background:**

- Random superposition of two uncorrelated "halo" muons
- Dominant for $A' \rightarrow \mu^+\mu^-$

**Prompt background:**

- Secondary interactions of incoming muons with the material traversed
- Dominant for for $A' \rightarrow e^+e^-$



# Results for $A' \to \ell^+\ell^-$

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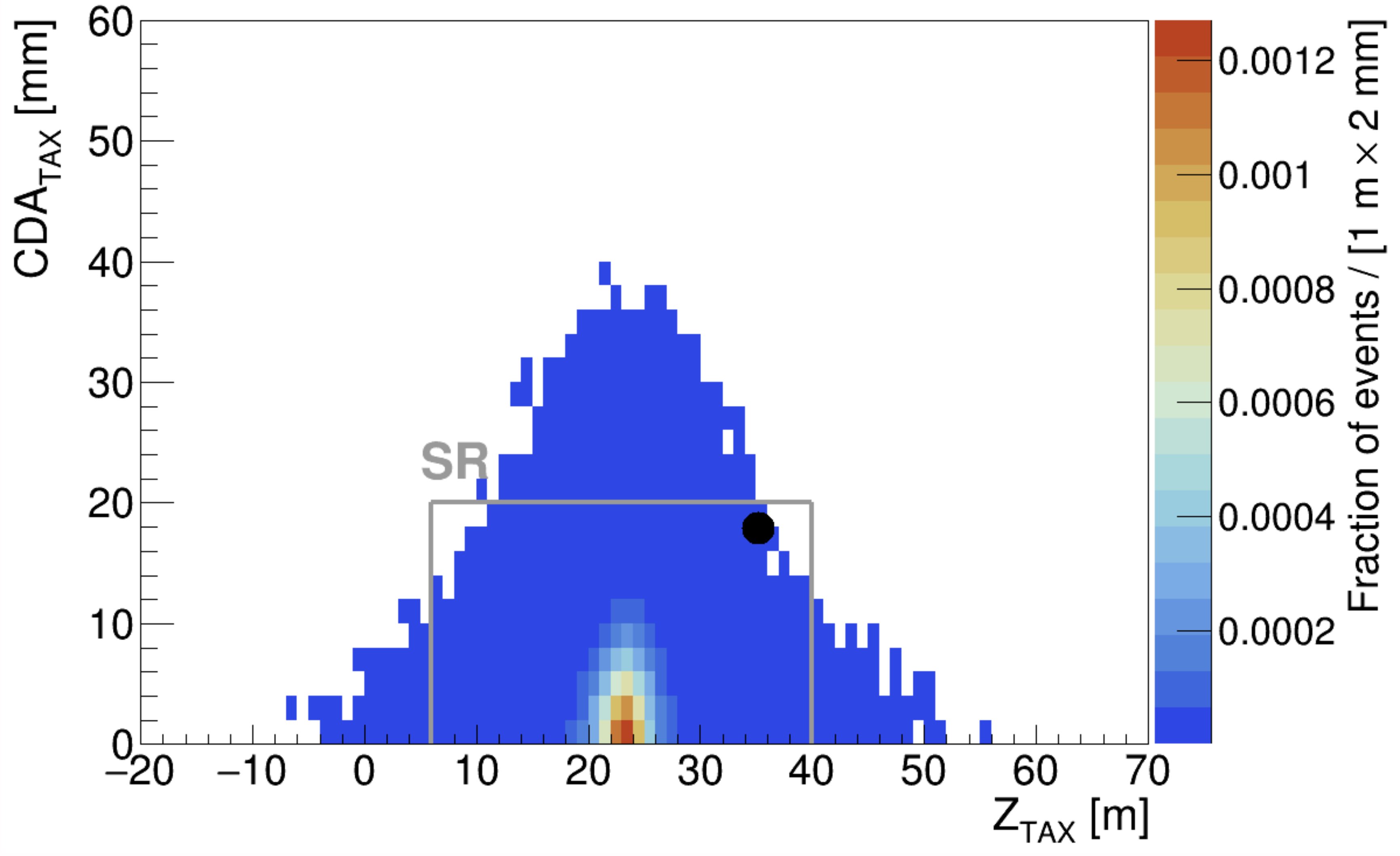


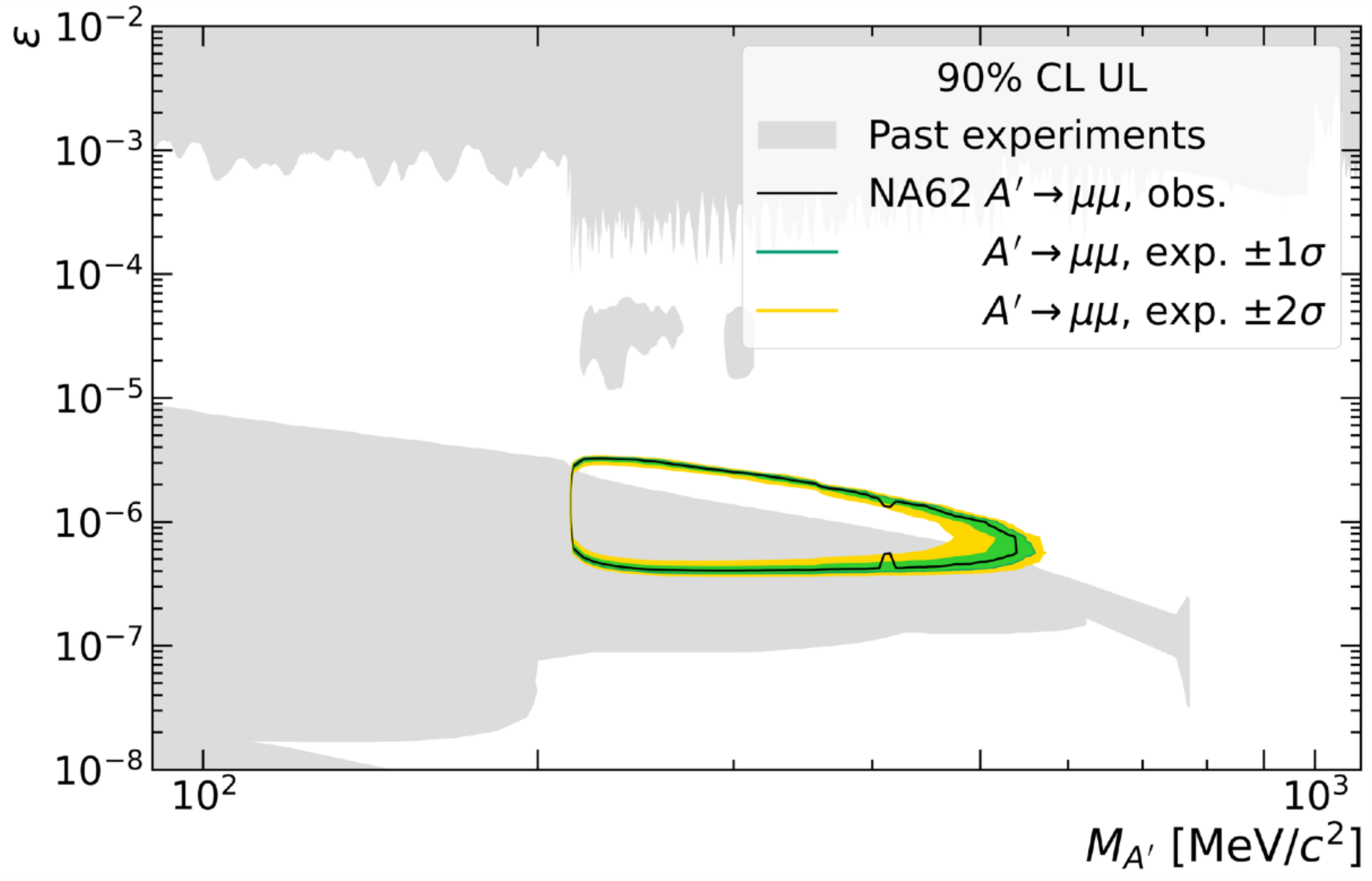


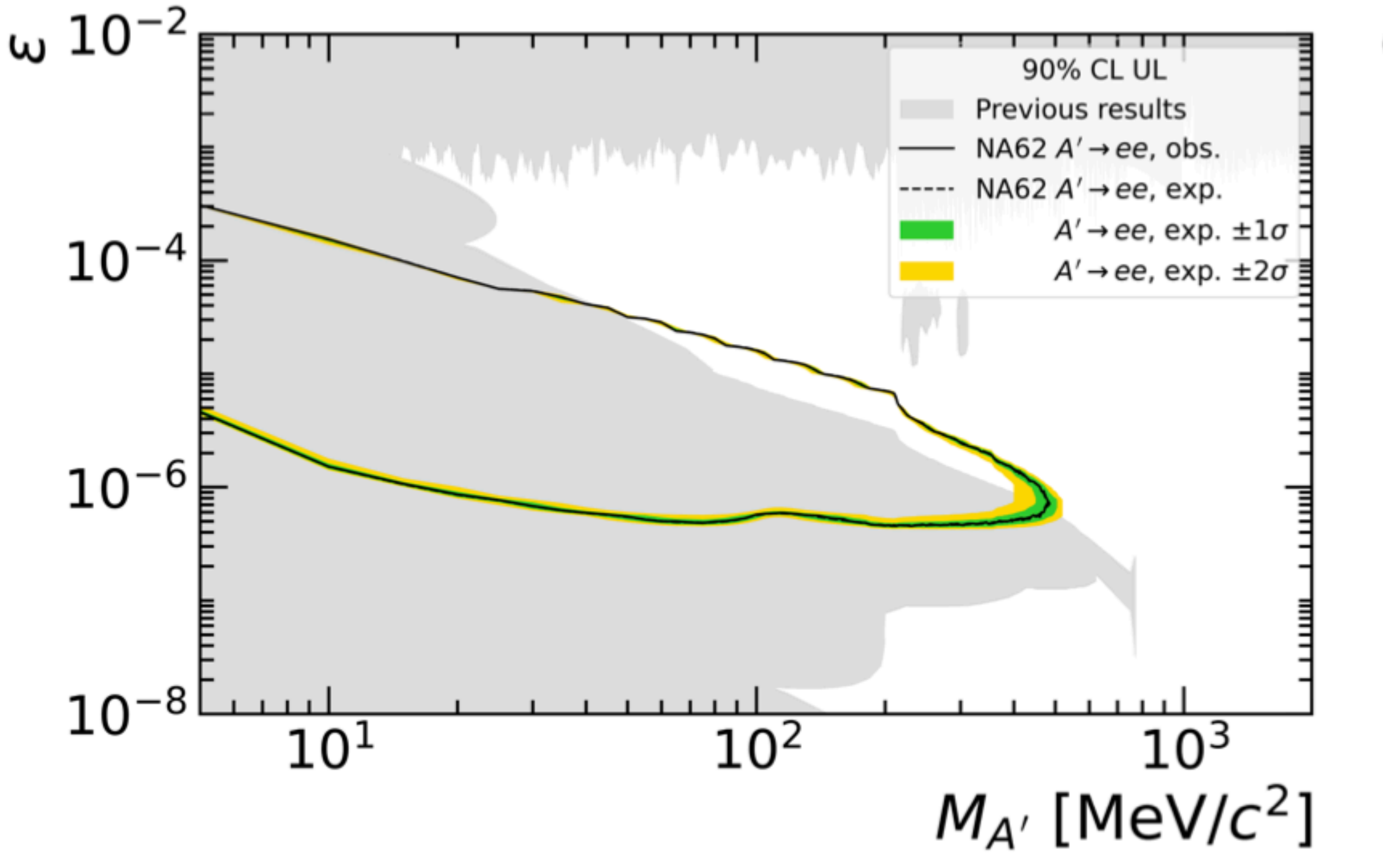


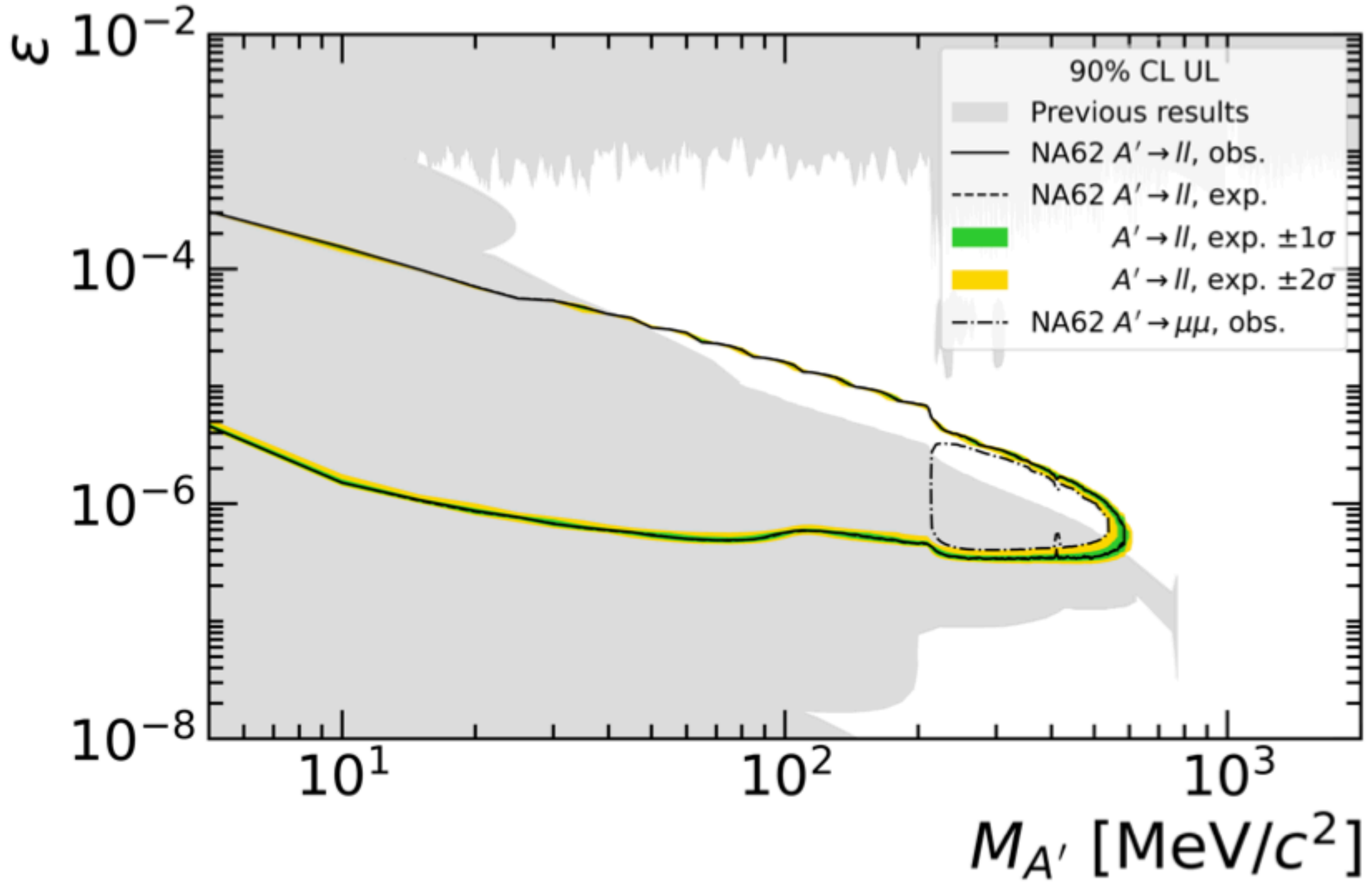


$A' \to \mu^+\mu^-$ $N_{obs}$ = 1 (2.6 $\sigma$ global significance)

$A' \to e^+e^-$ $N_{obs}$ = 0

# Details on the $A' \to \mu^+\mu^-$ observed event

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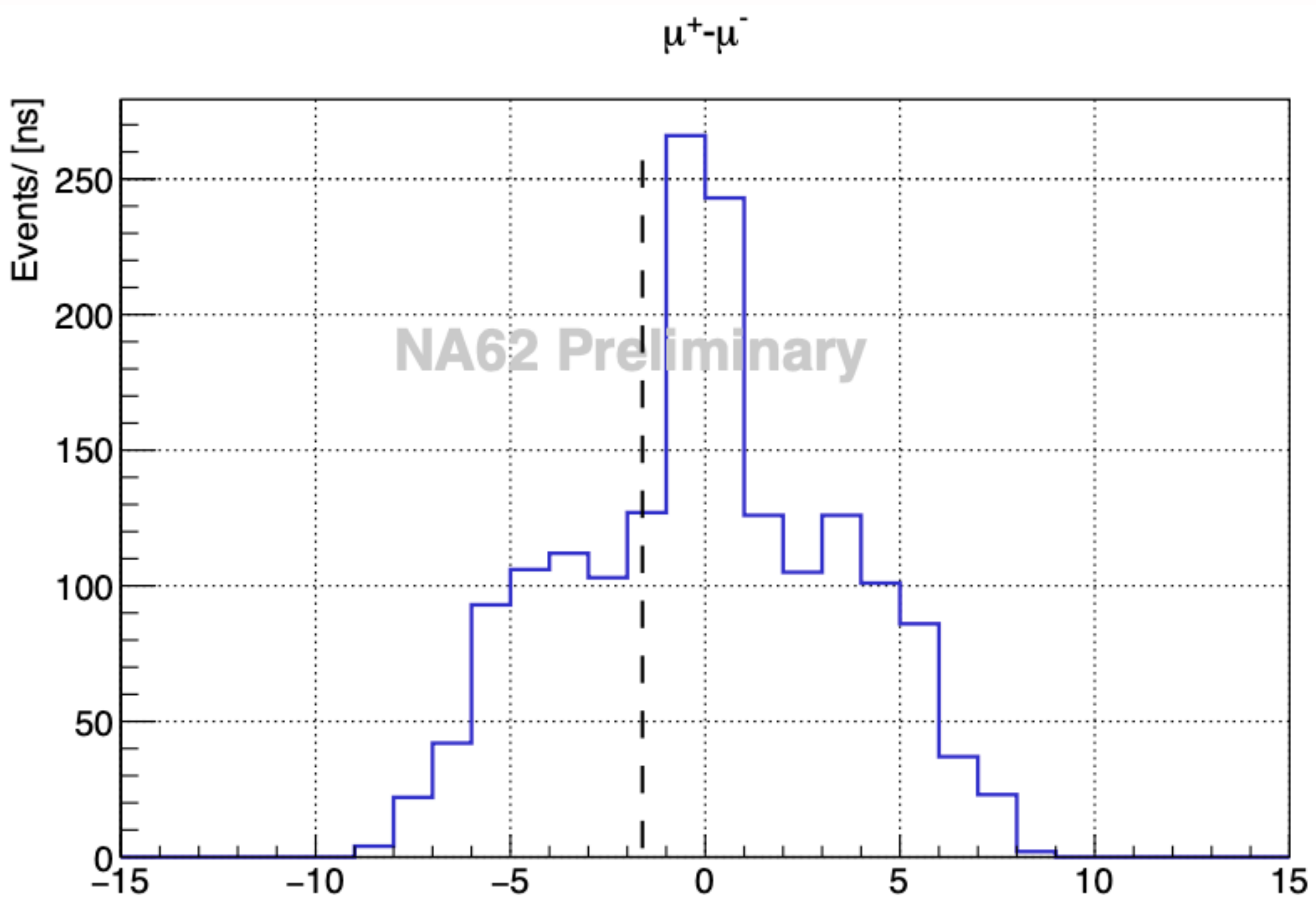
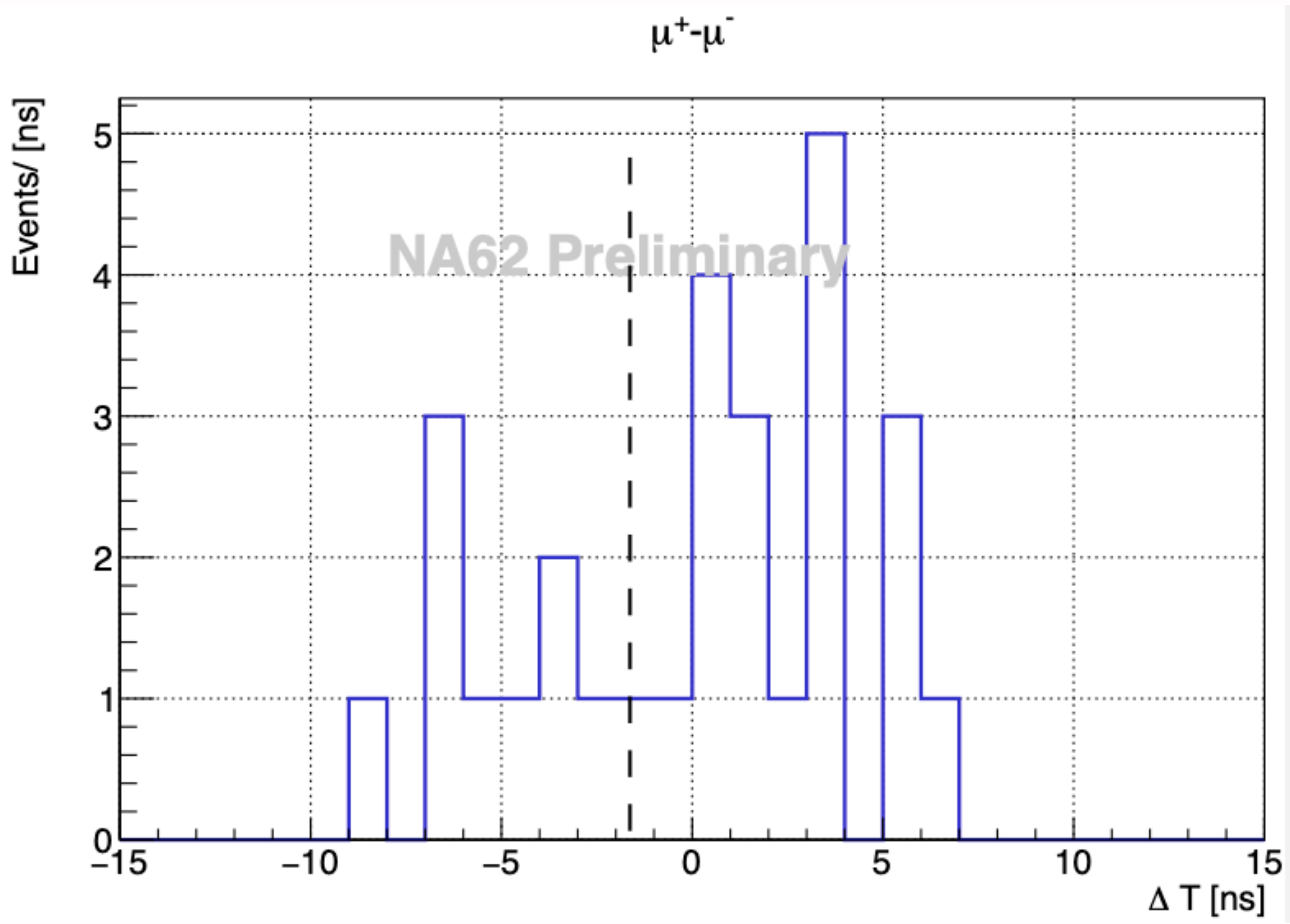
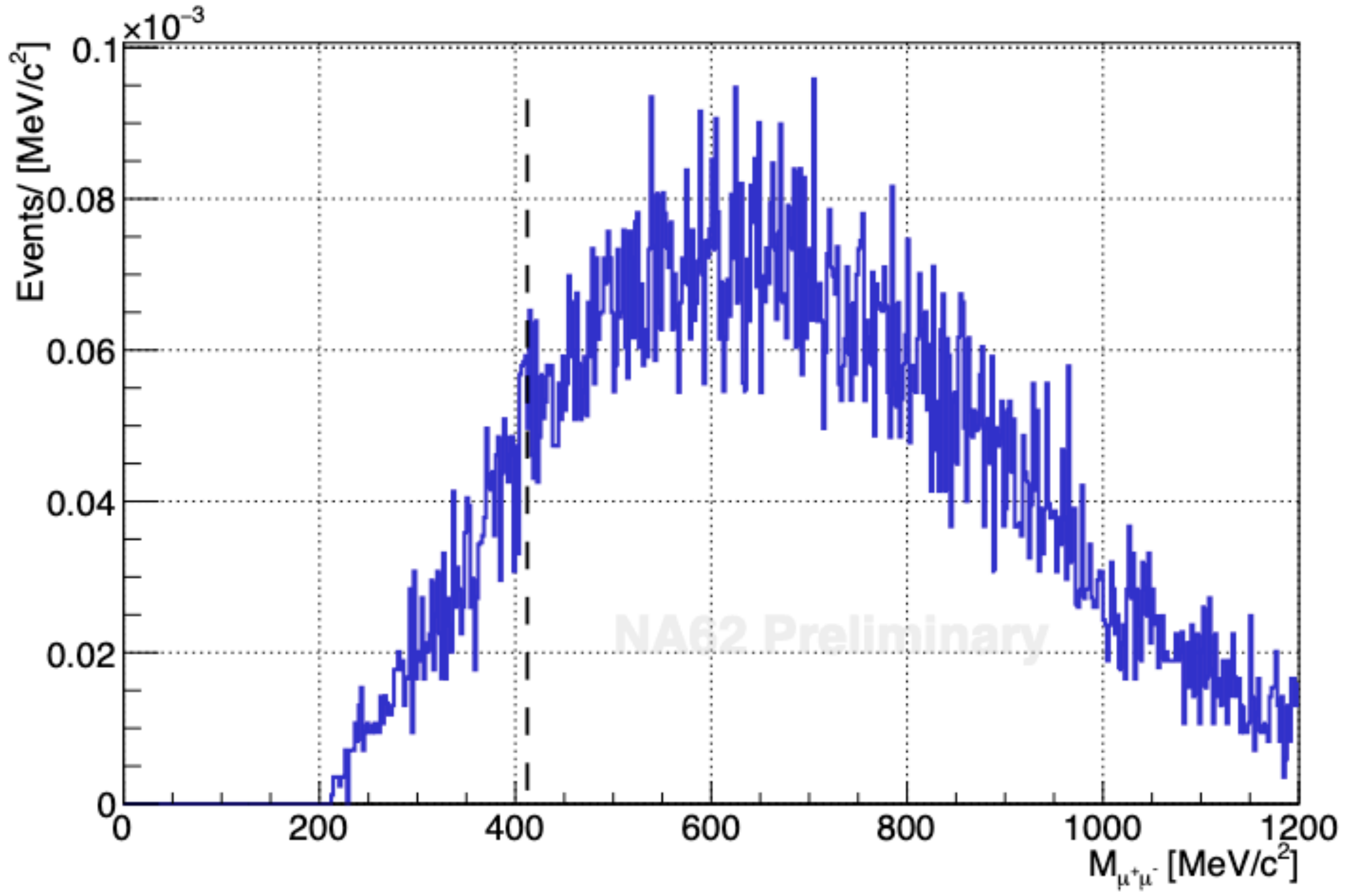
- invariant mass: $m_{\mu\mu} = 411$ MeV
- time difference: $\Delta T = -1.69$ ns
- momenta:
  - P ($\mu^+$) = 99.5 GeV/c
  - P ($\mu^-$) = 39.6 GeV/c
- $z_{FV}$ = 157.8 m
- $CDA_{FV}$ = 382 mm
- $z_{TAX}$ = 17 mm
- E/p($\mu^+$) = 0.008
- E/p($\mu^-$) = 0.018




Before LAV veto (CR & SR blind)




Final events selected (CR & SR blind)



# Model independent limit for $a \to \mu^+\mu^-$

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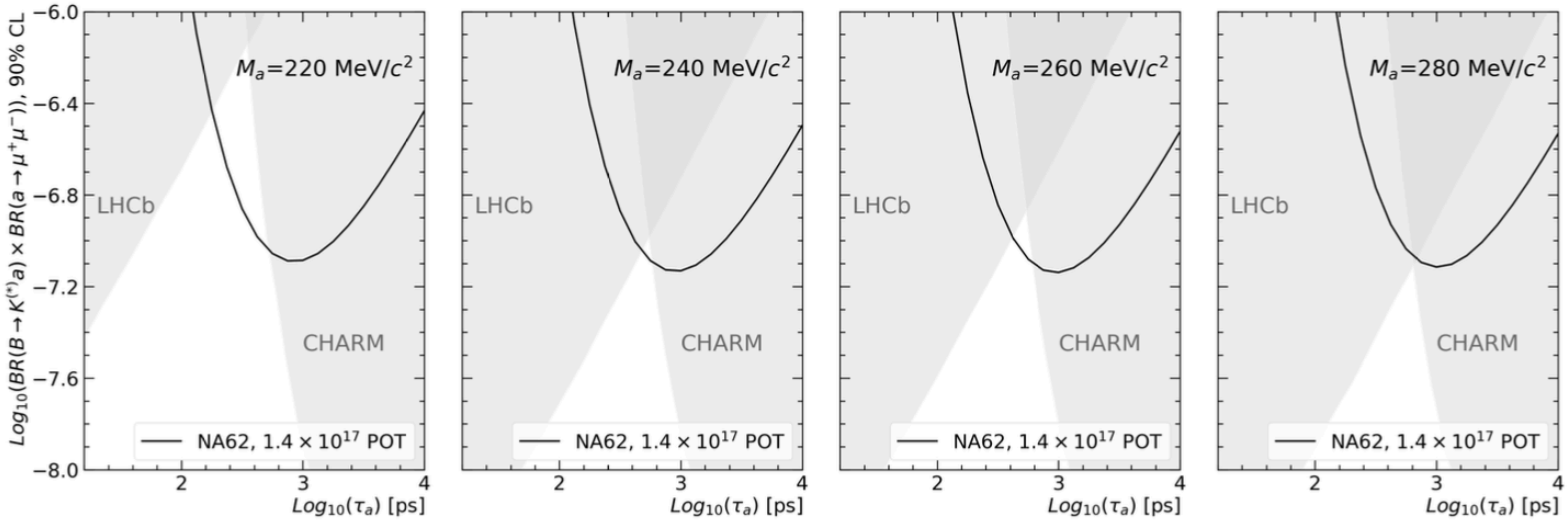
- The result is interpreted in terms of the emission of axion-like particles in a model-independent approach. [Phys. Lett. B 790 (2019) 537]
- Set limits in $BR(B \to K^*a) \times BR(a \to \mu^+\mu^-)$ vs. $\tau_a$ parameter space for each mass separately
- The result is found to improve on previous limits for masses below 280 MeV/c².



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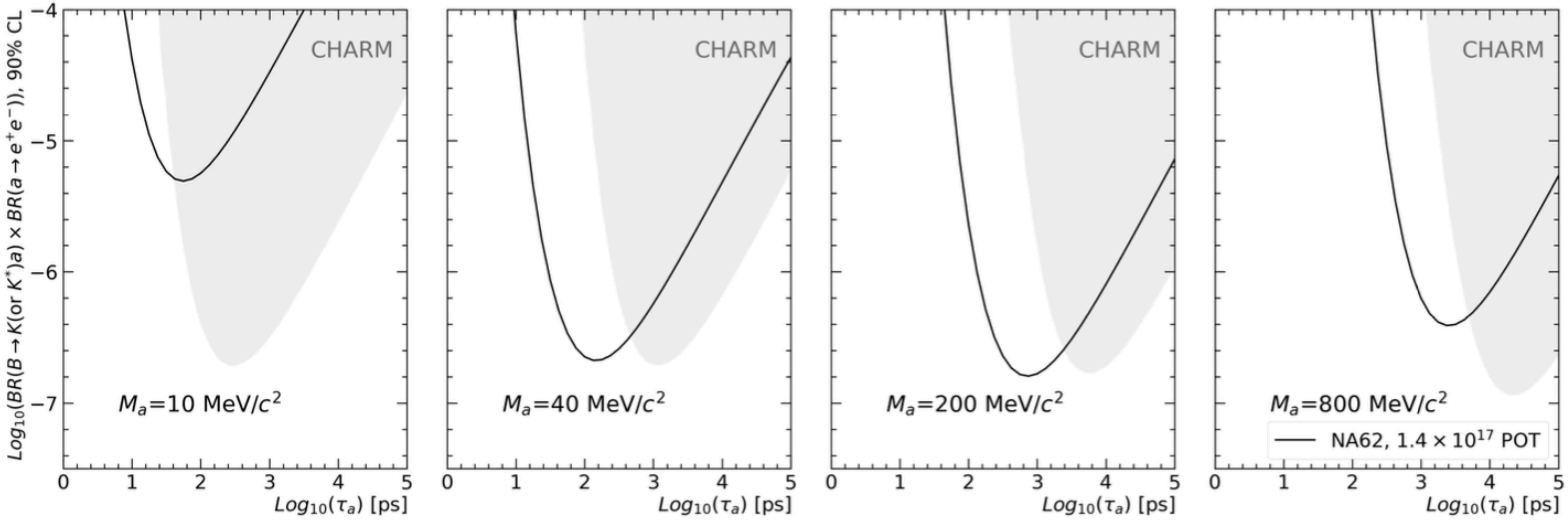
PRL 133(2024) 111802

- The result is interpreted in terms of the emission of axion-like particles in a model-independent approach. [Phys. Lett. B 790 (2019) 537]
- Set limits in $BR(B \to K^*a) \times BR(a \to e^+e^-)$ vs. $\tau_a$ parameter space for each mass separately

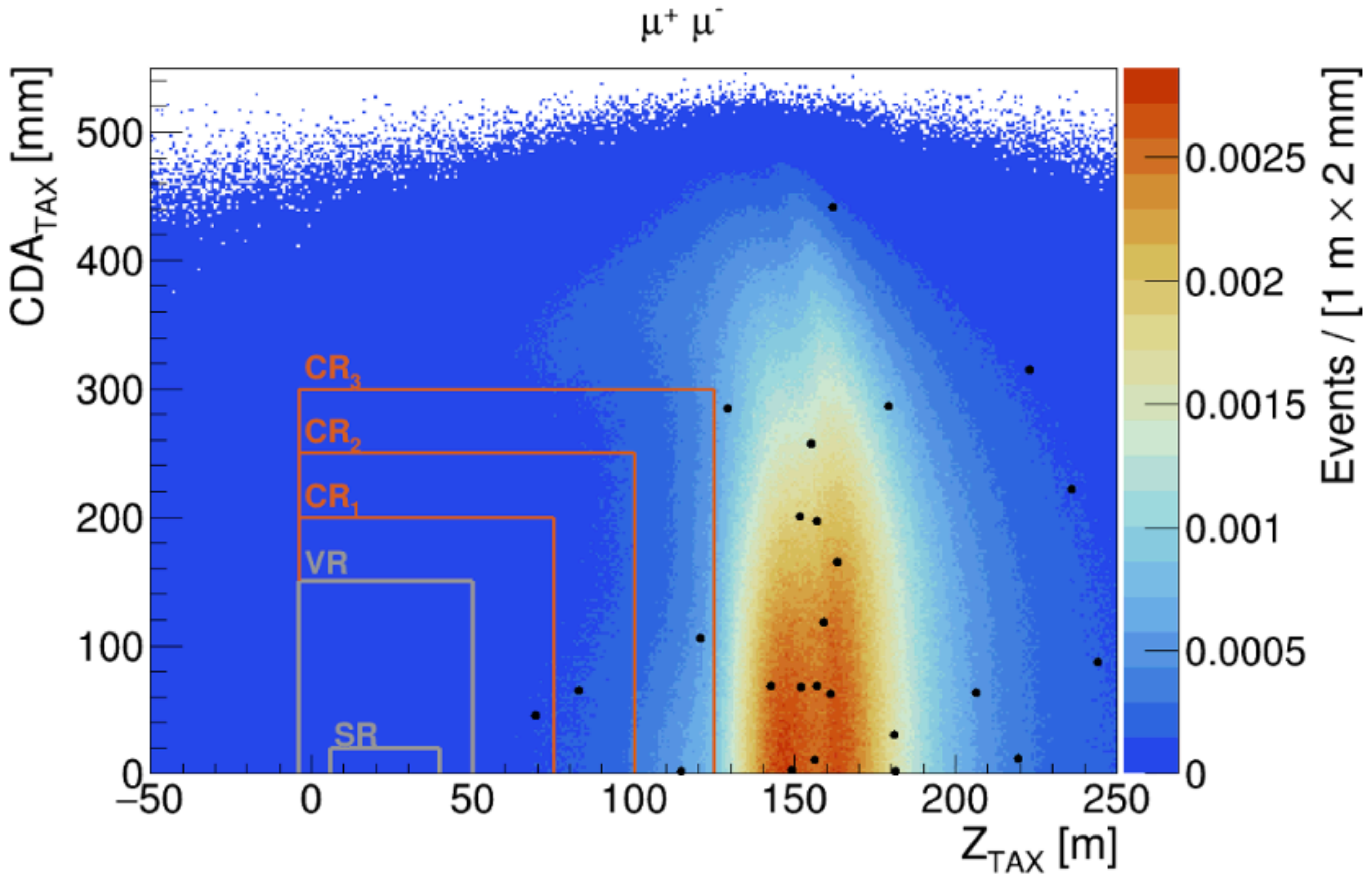


# Background summary

JHEP 09, 035 (2023)
PRL 133(2024) 111802

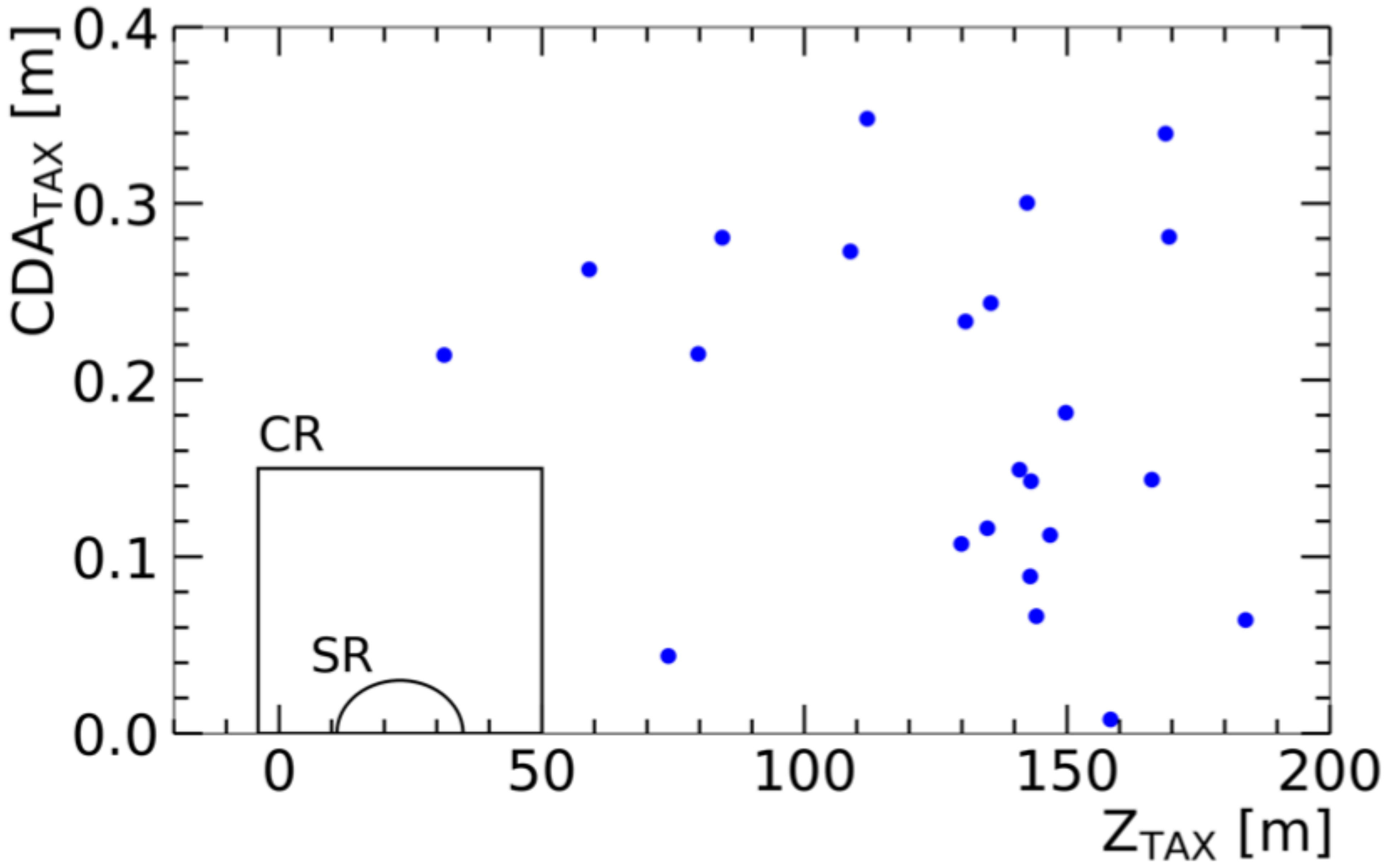
A′→μ⁺μ⁻

| | Combinatorial | Prompt @90% C.L. | Upstream prompt @90% C.L |
|---|---|---|---|
| Validation Region | 0.17 ± 0.02 | < 0.004 | < 0.069 |
| Signal Region | 0.016 ± 0.002 | < 0.0004 | < 0.007 |

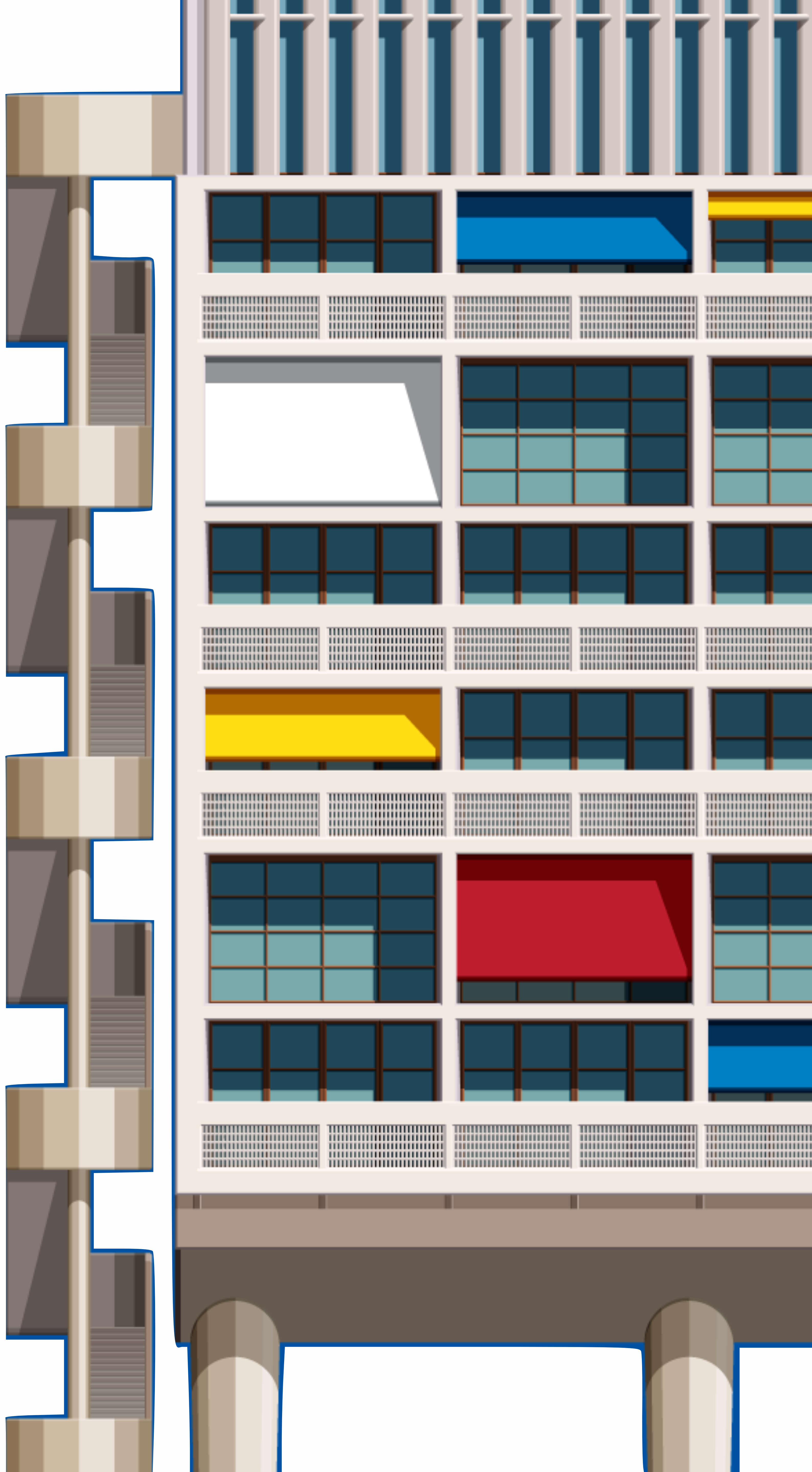



A′→e⁺e⁻

$$N_{bkg}^{CR} = 0.0097^{+0.049}_{-0.009} @ 90\,\%\,C.L.$$
$$N_{bkg}^{SR} = 0.0094^{+0.049}_{-0.009} @ 90\,\%\,C.L.$$



# Hadronic final states



# Background studies

Eur.Phys.J.C 85 (2025) 5, 571

**Background contributions:**

- combinatorial and neutrino-induced backgrounds: negligible contributions
- prompt background: inelastic interaction of halo muons can produce hadrons
- upstream background: formed by particles that are collected by the GTK achromat

# Background studies

[Eur.Phys.J.C 85 (2025) 5, 571]

## Background contributions:

- combinatorial and neutrino-induced backgrounds: negligible contributions
- prompt background: inelastic interaction of halo muons can produce hadrons
- upstream background: formed by particles that are collected by the GTK achromat

- Background from secondaries of μ interactions with the traversed material (hadron photo-production);
- Dominating for $e^+e^-$ ($N^{ee}_{exp} \sim 10^{-2}$) some contribution to hadrons ($N^{\pi\pi}_{exp} < 10^{-4}$).
- Estimation using data-driven backward MC with measured $\mu$ halo + unfolding for correct kinematics

# Background studies



## Background contributions:

- combinatorial and neutrino-induced backgrounds: negligible contributions
- prompt background: inelastic interaction of halo muons can produce hadrons
- upstream background: formed by particles that are collected by the GTK achromat

- Background from upstream kaons entering the FV via non-instrumented ANTI0 hole;
- Dominating for hadrons ($N^{\pi\pi}_{exp} \sim 10^{-2}$), negligible for leptons;
- Simulation based on single $K^+$ selected in data and forced to decay in the FV.