NEW RESULTS FOR SEARCHES OF EXOTIC DECAYS WITH NA62 IN BEAM-DUMP MODE

Jonathan Leon Schubert
on behalf of the NA62 Collaboration

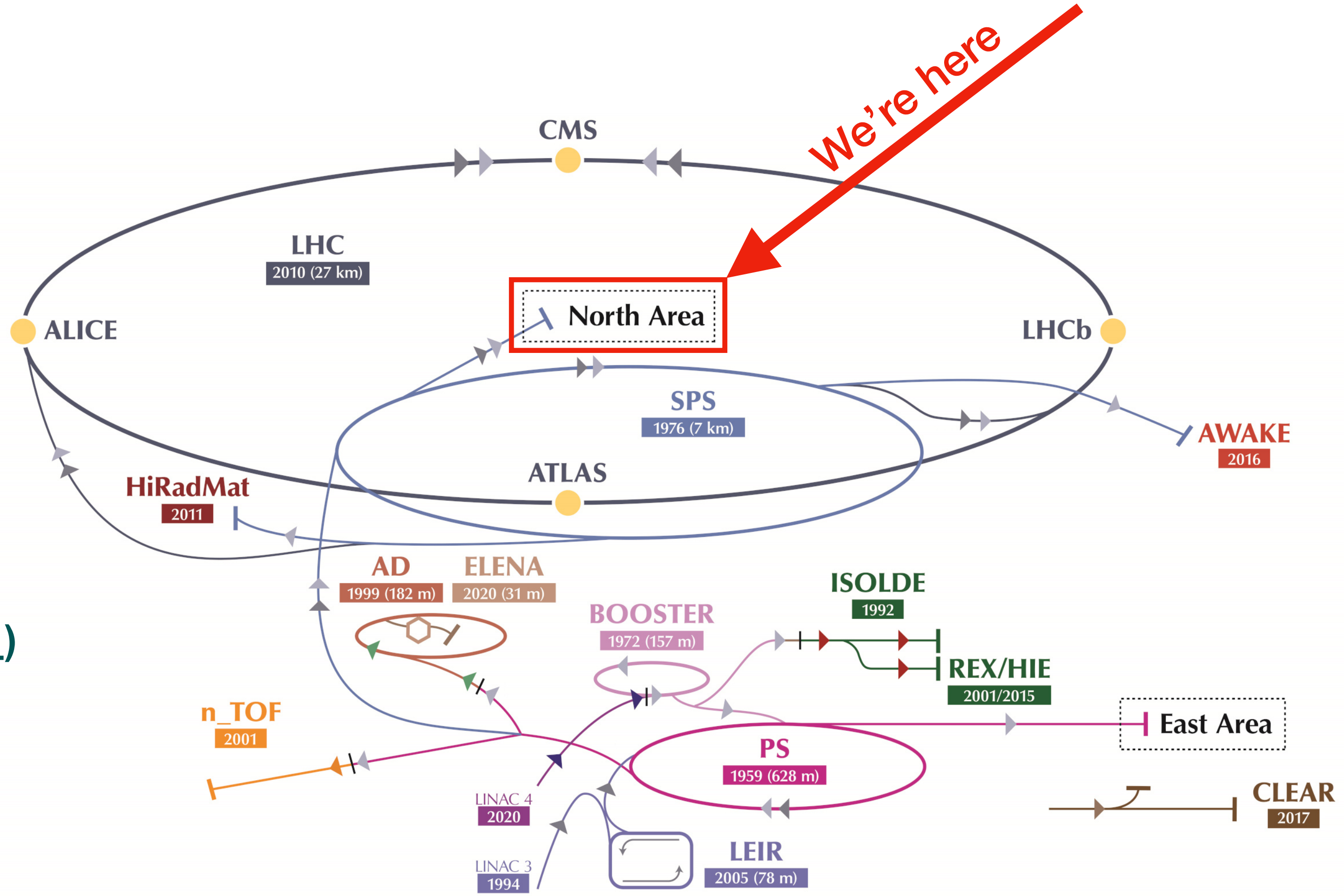
AGENDA FOR THIS TALK

1. The NA62 experiment
    a. Main physics goals
    b. Beam-dump configuration
    c. Background reduction
2. Exotic searches in beam-dump mode
    a. Experimental challenges
    b. Results from the 2021 data sample
    c. Current and near future steps

THE NA62 EXPERIMENT

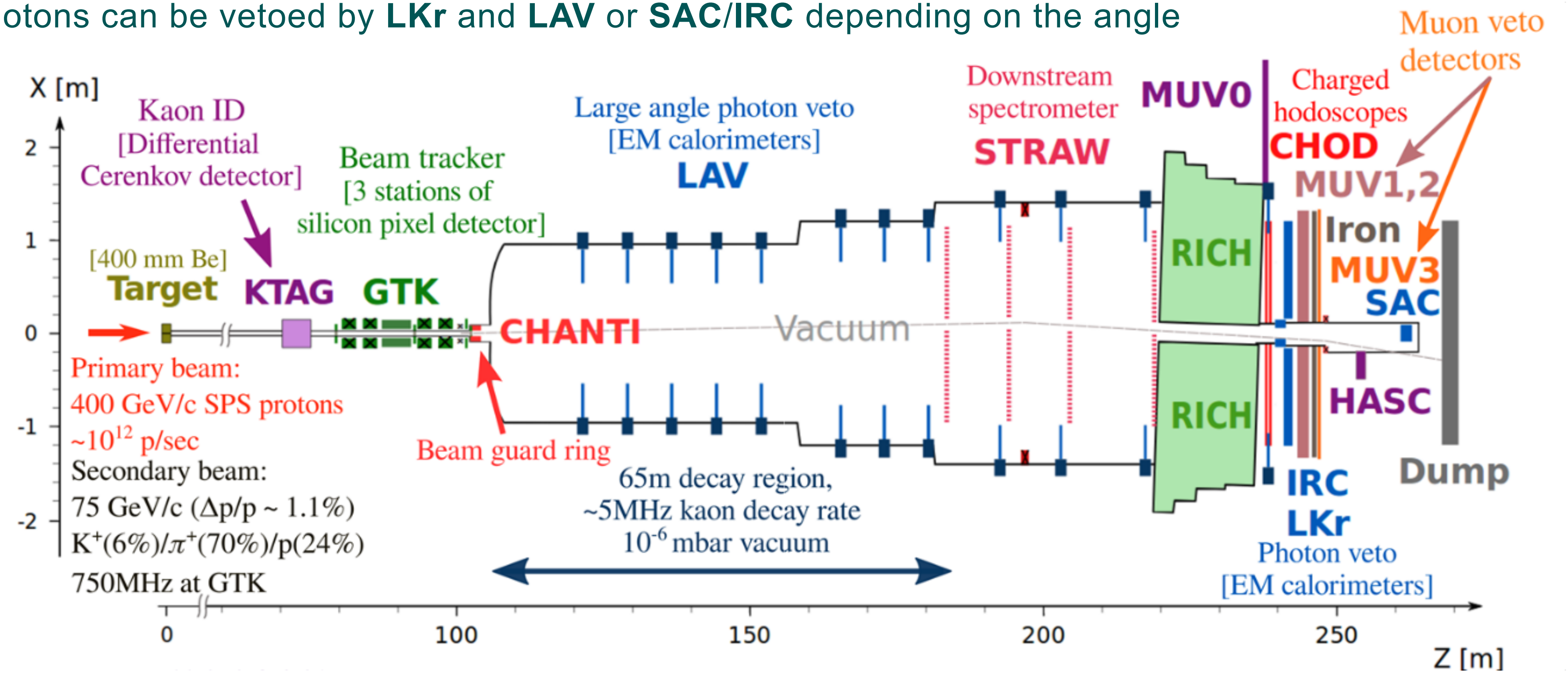
THE NA62 EXPERIMENT
A BRIEF OVERVIEW

- Fixed target experiment in CERN North Area (we get 400GeV SPS protons)
- Main goal of the experiment is to precisely measure the rare decay $K^+ \to \pi^+ \nu \bar{\nu}$
- But also
  - Precision measurements (A. Bizzeti)
  - Rare/forbidden decays (I. Panichi)
  - Direct exotic particle searches



THE NA62 EXPERIMENT
THE DETECTORS IN KAON MODE

- K^+ **tagged by KTAG and 3-mom. determined by GTK**
- Decay products are classified by 3-mom. (**STRAW**), time measured (**CHOD**), PID (**LKr**, **MUV1**, **MUV2**, and **RICH**), where **MUV3** gives μ-ID
- Photons can be vetoed by **LKr** and **LAV** or **SAC**/**IRC** depending on the angle

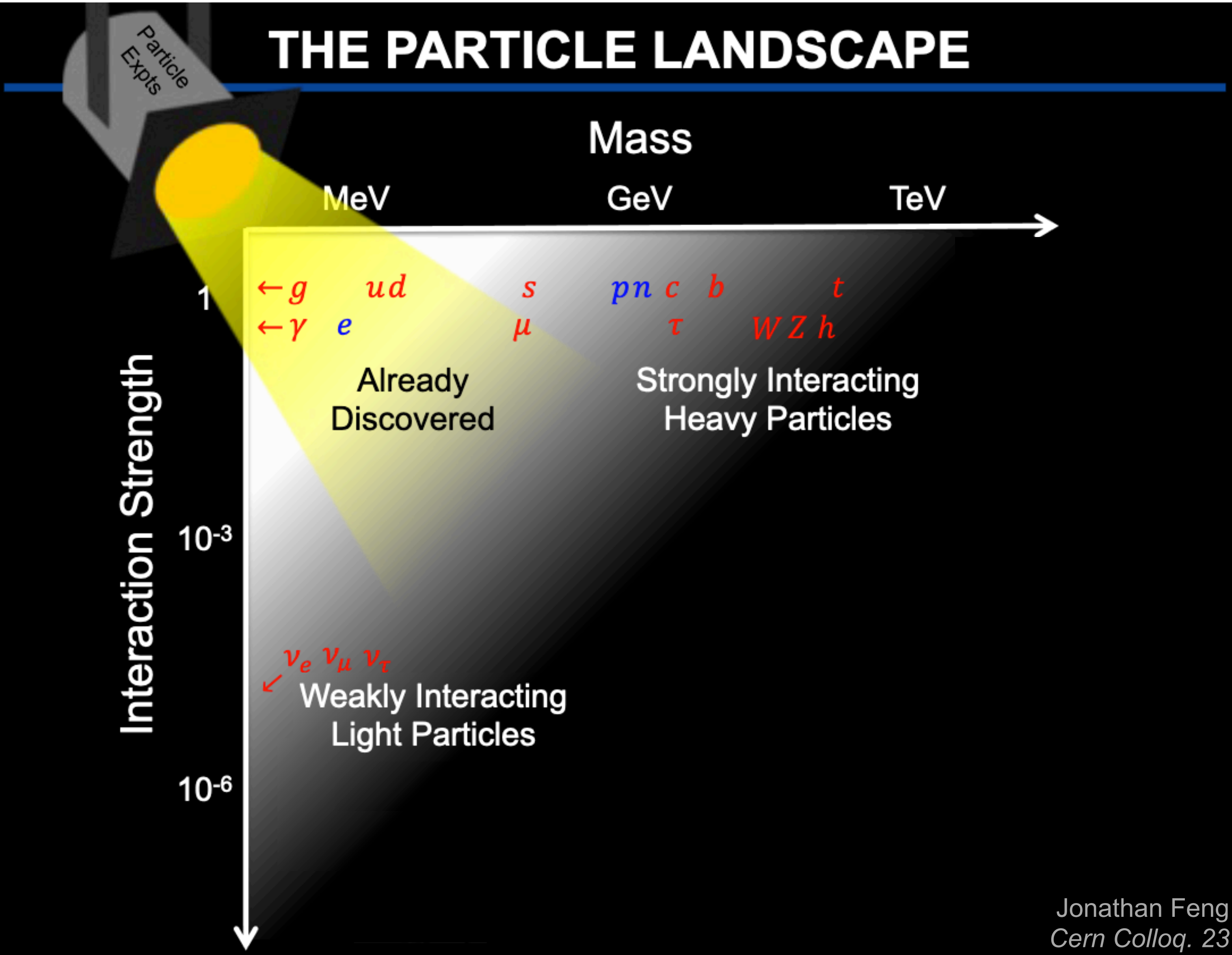


THE NA62 EXPERIMENT

BEAM DUMP MODE — AN ALTERNATIVE RUN MODE

- **NA62 can easily be run in an alternative setting**
  - **Beam dump mode**
  - **High intensity possible using SPS beam**
- **Exploratory data-taking intervals since 2016**
- **Significant data collected 2018 - 2021**
  - **Collected** $(1.4 \pm 0.28) \times 10^{17}\,\mathrm{PoT}$ **in ~10 days in 2021**

WHY GO TO BEAM DUMP MODE   EXOTIC SEARCHES



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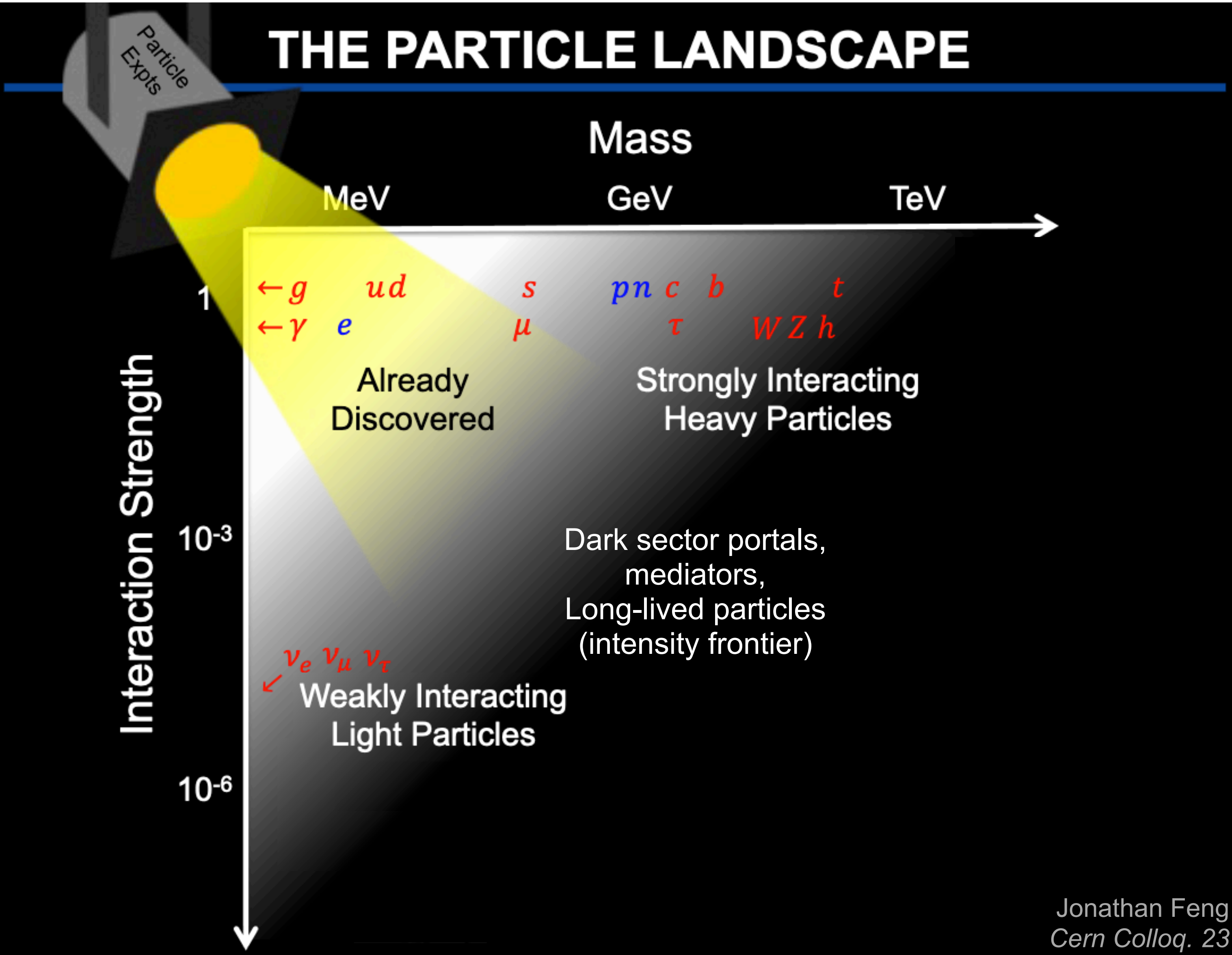
Cern Colloq. 23

WHY GO TO BEAM DUMP MODE   EXOTIC SEARCHES



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WHY GO TO BEAM DUMP MODE EXOTIC SEARCHES DARK HIGGS, HNLS, DARK PHOTONS

When organising possible examples of new weakly interacting particles, broadly speaking we are left with only a couple of overarching categories

- **Spin 0** SM - - - - - $h^\dagger h \phi_D^\dagger \phi$ - - - - - Dark Scalar

  ➡**Dark Higgs boson** coupling to SM fermions with suppressed coupling prop. to fermion mass $\sin\theta m_f$

- **Spin 1/2** SM - - - - - - $hL\psi_D$ - - - - - - - Dark Fermion

  ➡**Heavy Neutral lepton** coupling to SM neutrinos with suppressed mixing $\sin\theta$

- **Spin 1** SM - - - - - - $F_{\mu\nu}F_D^{\mu\nu}$ - - - - - - Dark Force

  ➡**Dark Photon** coupling to SM fermions with suppressed couplings prop. to fermion charge εq_f

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At the beam dump several of these can be probed in previously unavailable parts of possible parameter space with only few days of data taking

Axion Like Particles can also be viewed as part of this group completing the list of commonly considered light exotics

THE NA62 EXPERIMENT

BEAM DUMP MODE SCHEMATICALLY

- **Target is followed by an achromat selecting 75GeV beam momentum**
- **The collimators of this achromat are movable and can be driven into a "closed position" within a few minutes** — The Beryllium target itself can also be removed within a few minutes
- **In this case, the 400 GeV protons from the SPS impinge directly on several meters of copper/iron (TAXes) ➡ beam dump**
- The above settings can be reverted within $\mathcal{O}(\mathrm{min})$

z

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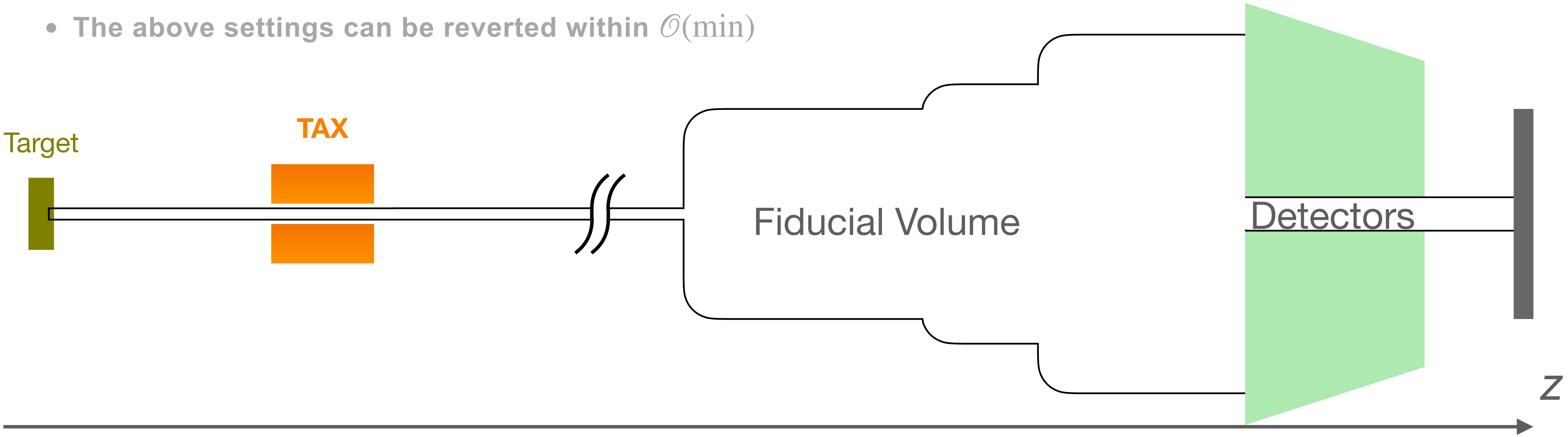

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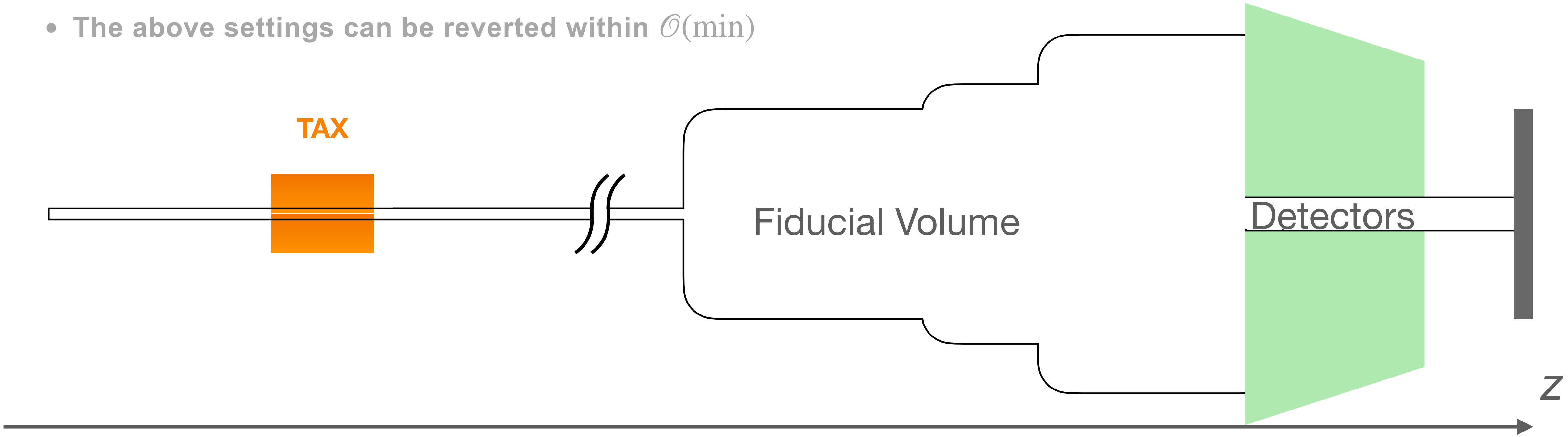

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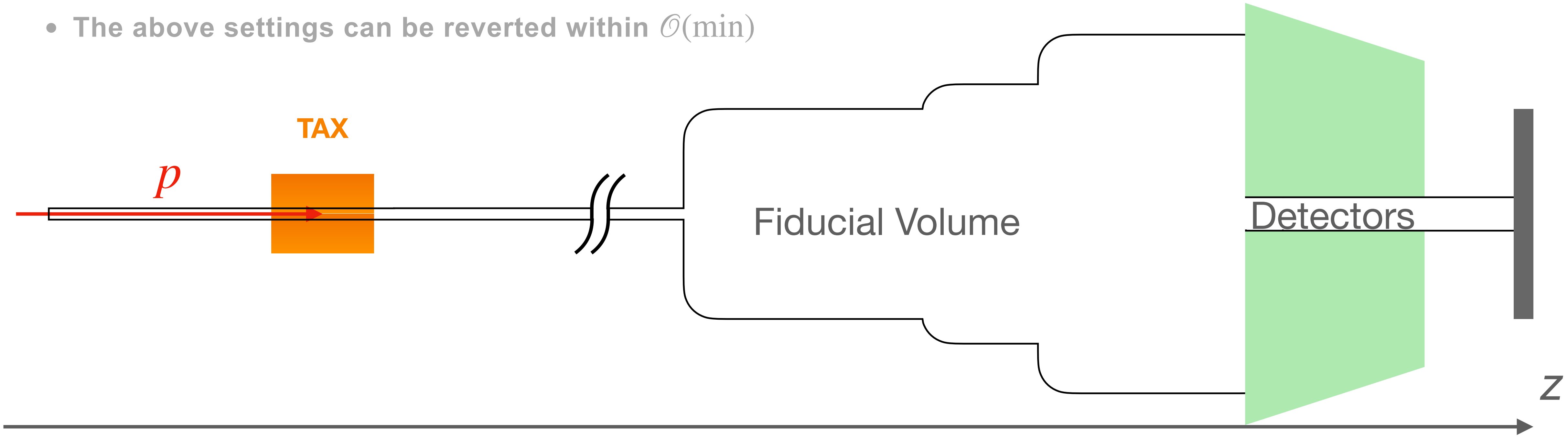

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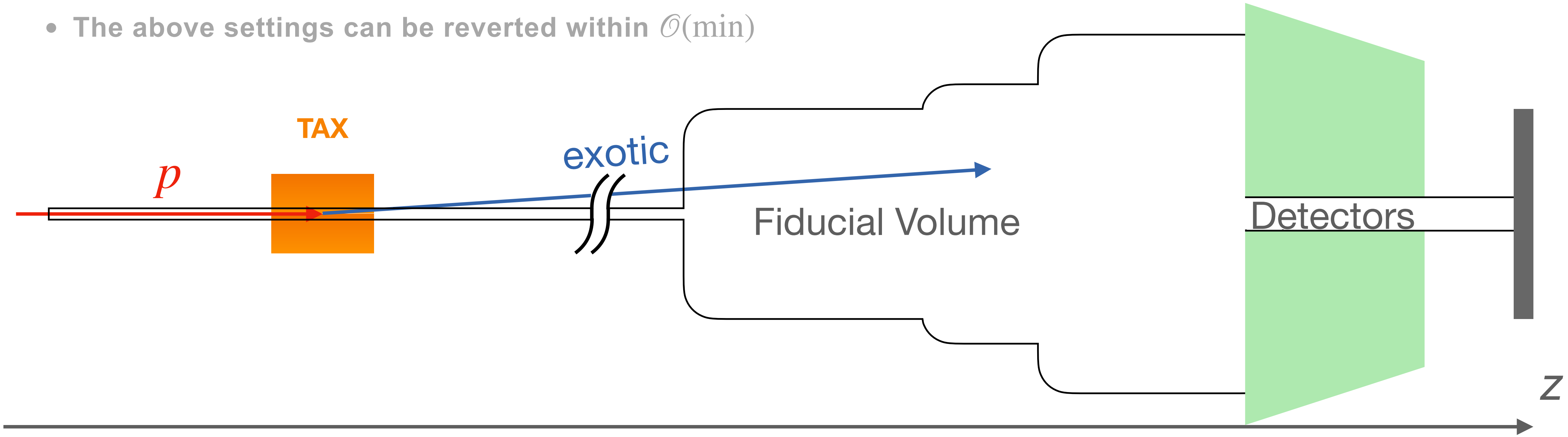

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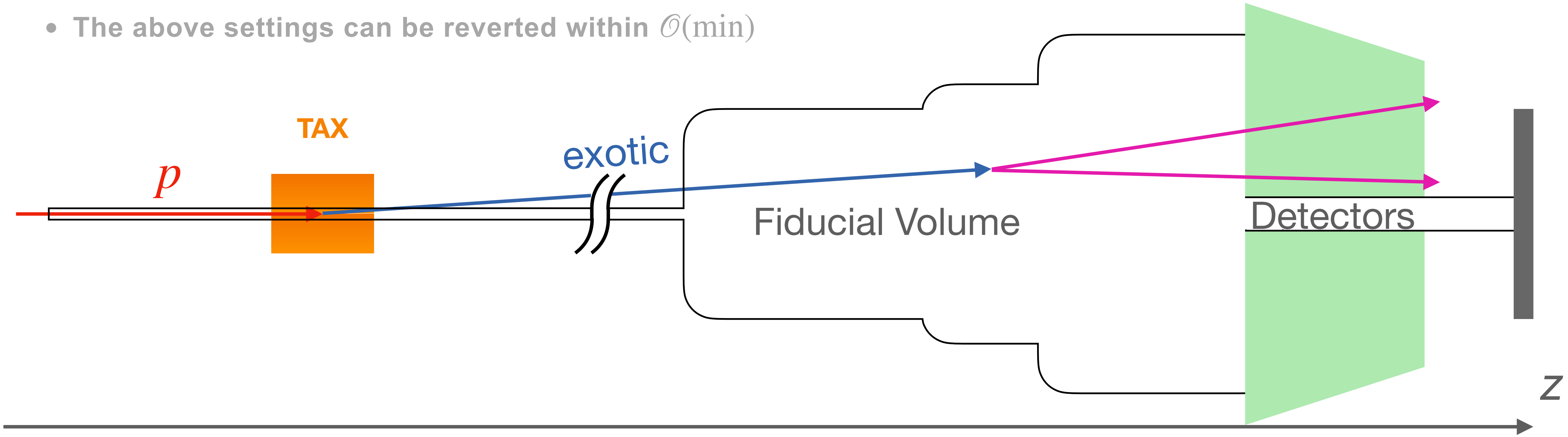
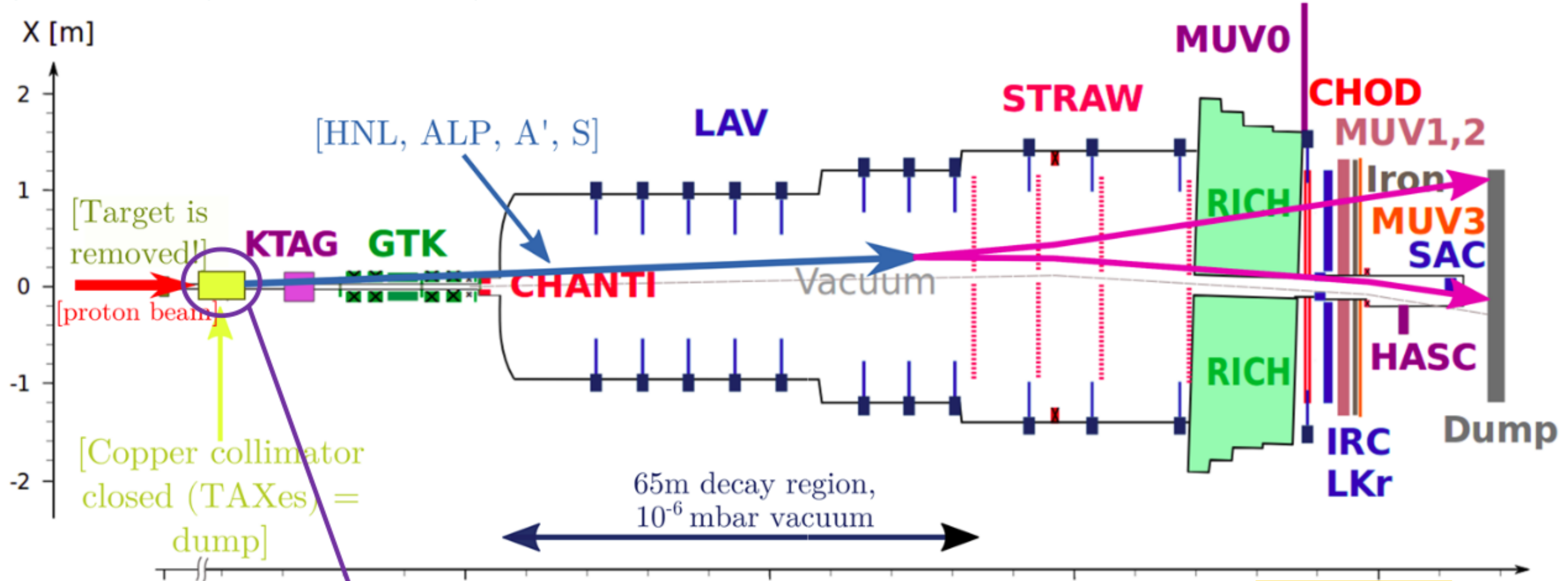
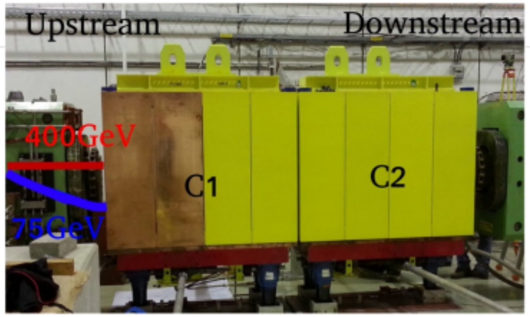
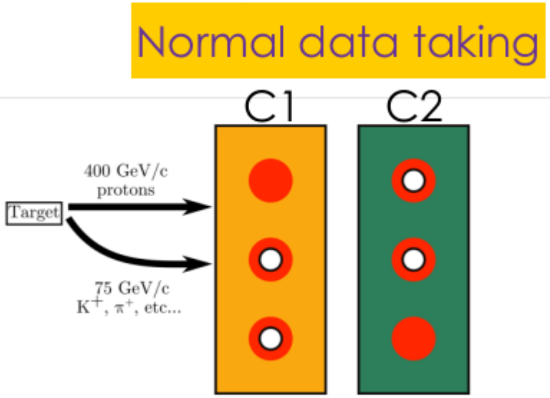


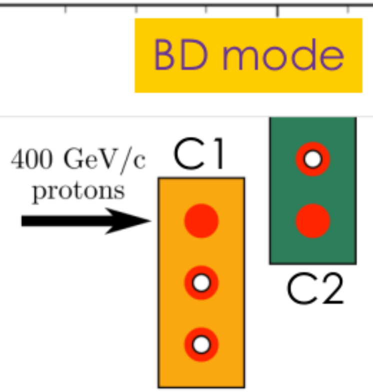
THE NA62 EXPERIMENT

BEAM DUMP MODE IN MORE DETAIL



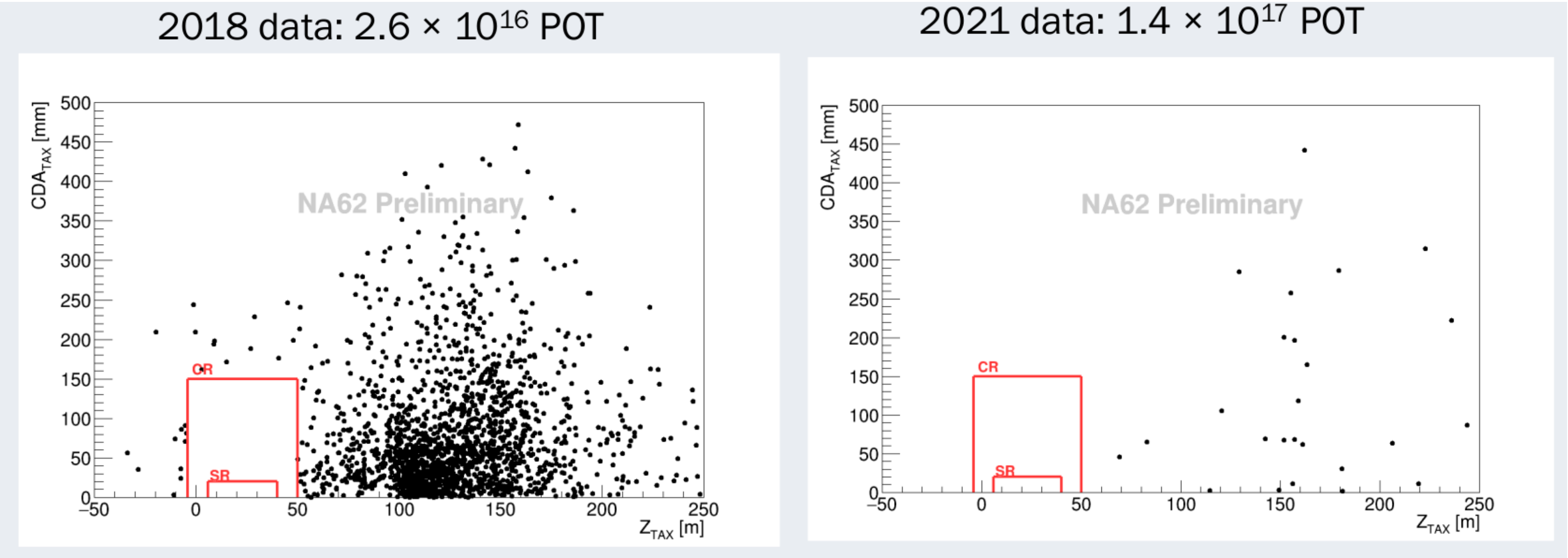






EXOTIC SEARCHES IN BEAM DUMP MODE
REDUCING BACKGROUNDS

- **Using TAX magnets to sweep muons**
- **Additional upstream magnet tuned to increase muon sweeping (studied with help from *PBC*)**
- **Compared to 2018, background rejection was increased by O(200) on most 2-track channels despite higher intensity**



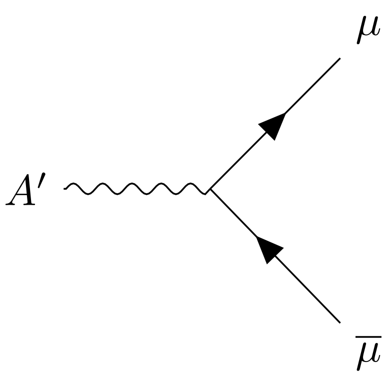
Example $\mu\bar{\mu}$-analysis (which we will see later)

EXOTIC SEARCHES IN BEAM DUMP MODE

ANALYSES
BEAM DUMP MODE SEARCHES FOR DARK PHOTONS

Dark photon couples to SM fermions with couplings proportional to fermion charge εq_f

➡Two obvious final state candidates present themselves for beam dump analysis



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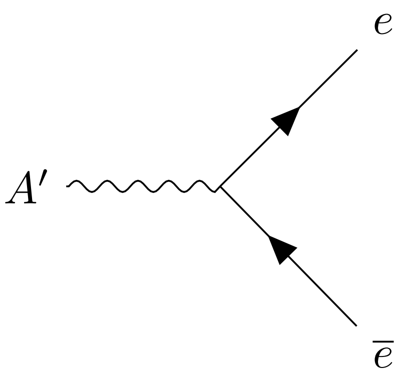

[forthcoming]

ANALYSES

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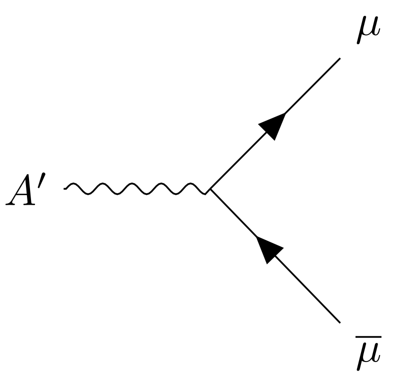

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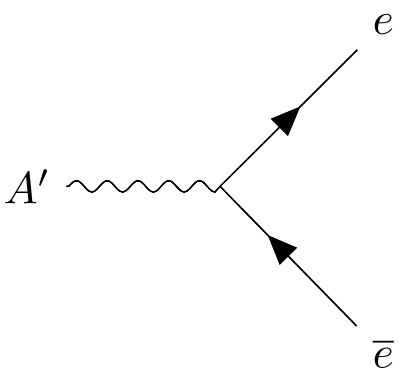
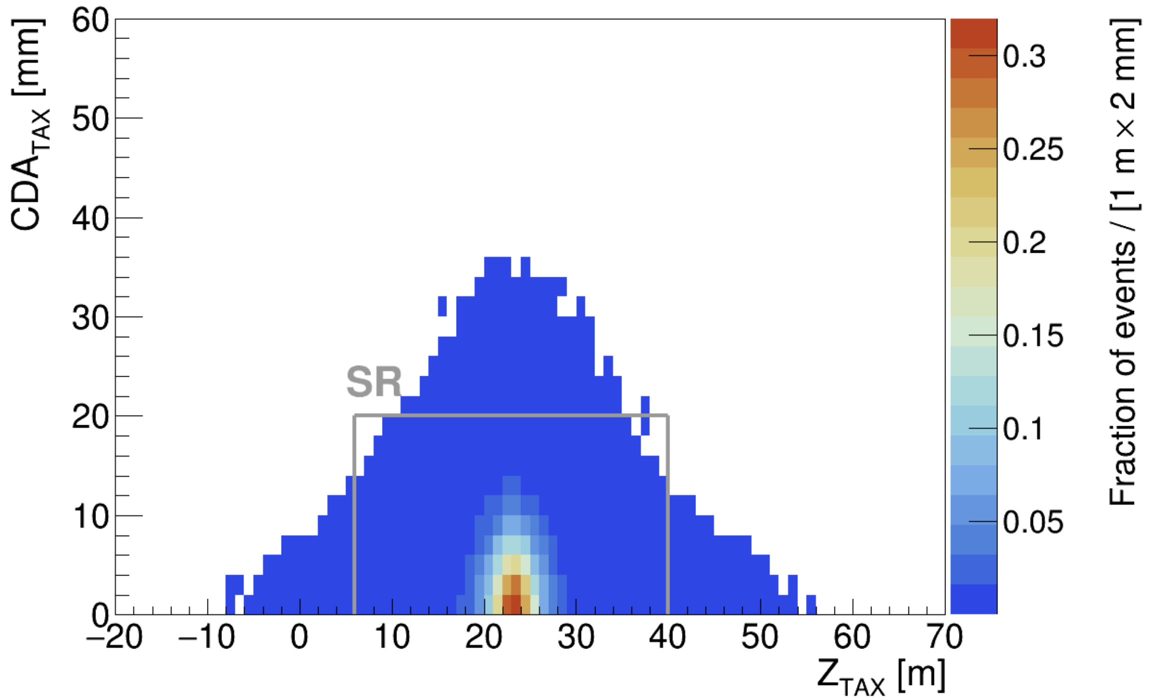


[forthcoming]

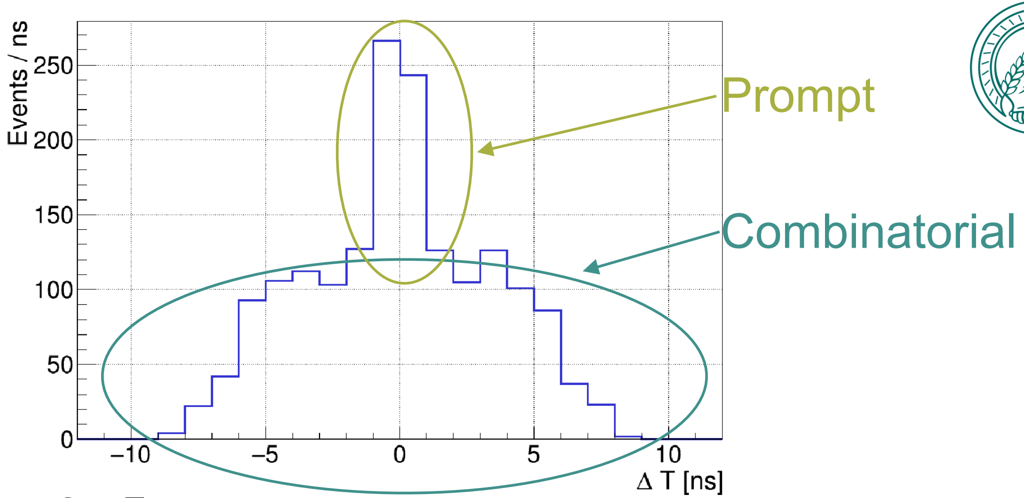
ANALYSES
STRATEGY FOR $A' \to \mu\bar{\mu}$

- **Pointing** Exploit expectation of CDA between beam direction at the TAX entrance
- **Event selection** Track quality, timing coincidence, PID with calorimeter and muon detector, …
- **Veto** No in-time activity in Large Angle Vetos
- **Signal Region** SR and Control Region (CR) kept blind up to collaboration approval



Signal event MC distribution

BACKGROUND ESTIMATION



Δt of $\mu\bar{\mu}$ tracks selected without LAV veto

The main expected backgrounds can be divided in two categories

Prompt

Secondary interactions of incident muons in traversed material (ie. $\pi \to \mu$)

➡Kinematics estimate from single track backward MC (using PUMAS*)

➡Relative MC uncertainty $\sim 50\,\%$

Combinatorial

Accidental combination of unrelated muons by vertex reconstruction

➡Simulated using random in-time coincidence of single track events

➡Event weight uncertainty $\sim 15\,\%$

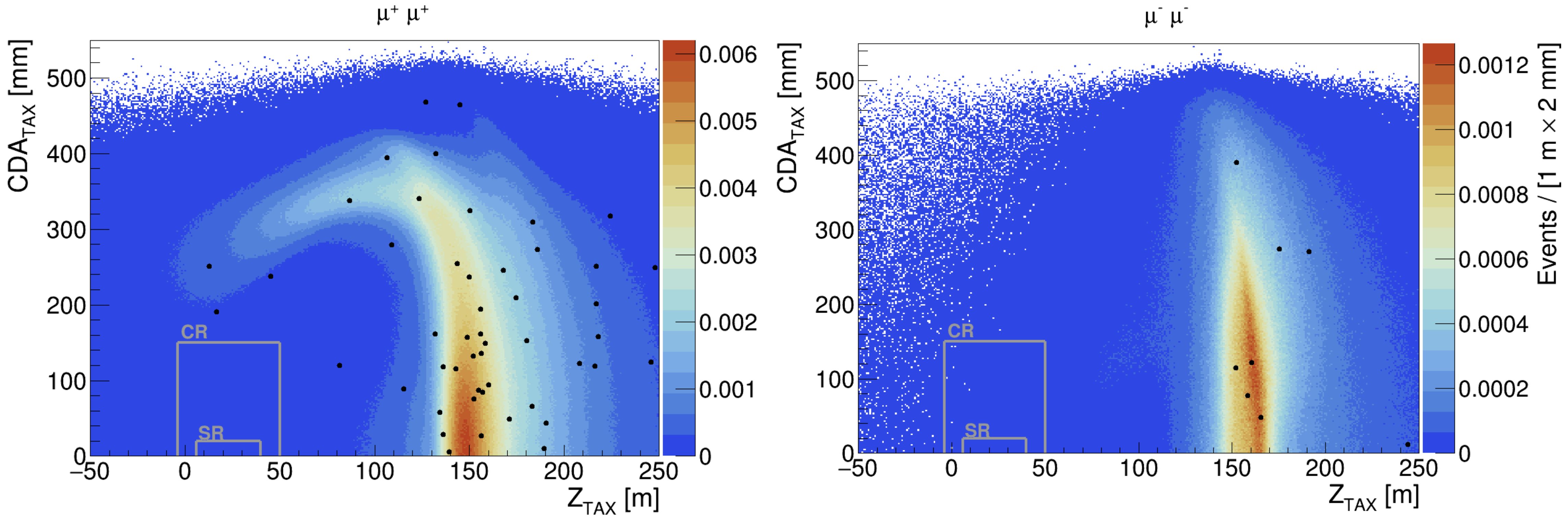
Region	Combinatorial	Prompt	Upstream-prompt
CR	0.17 ± 0.02	< 0.004	< 0.069
SR	0.016 ± 0.002	< 0.0004	< 0.007

Summary of expected number of background events for $A' \to \mu\bar{\mu}$

*A muon back tracing tool

BACKGROUND VALIDATION

Validating the Combinatorial background estimation against Data using reconstructed same sign final states (open signal and control region)



Data superimposed as black dots on MC distribution

Peculiar shape due to focusing elements

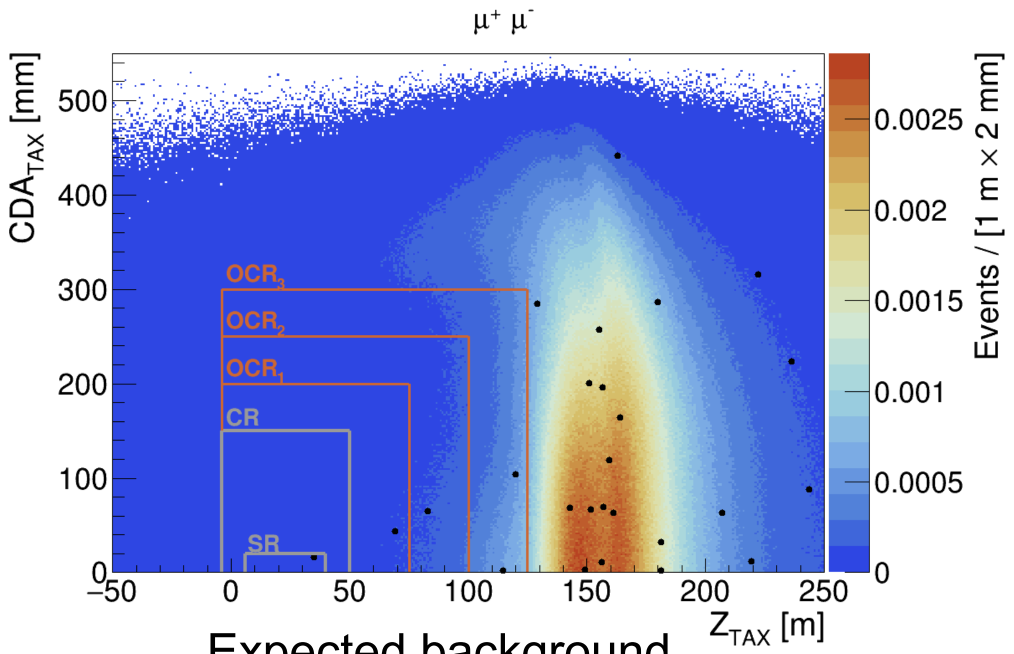
RESULTS
DATA MC COMPARISON

Open Signal and Control Regions:
1 event in SR, 0 events in CR

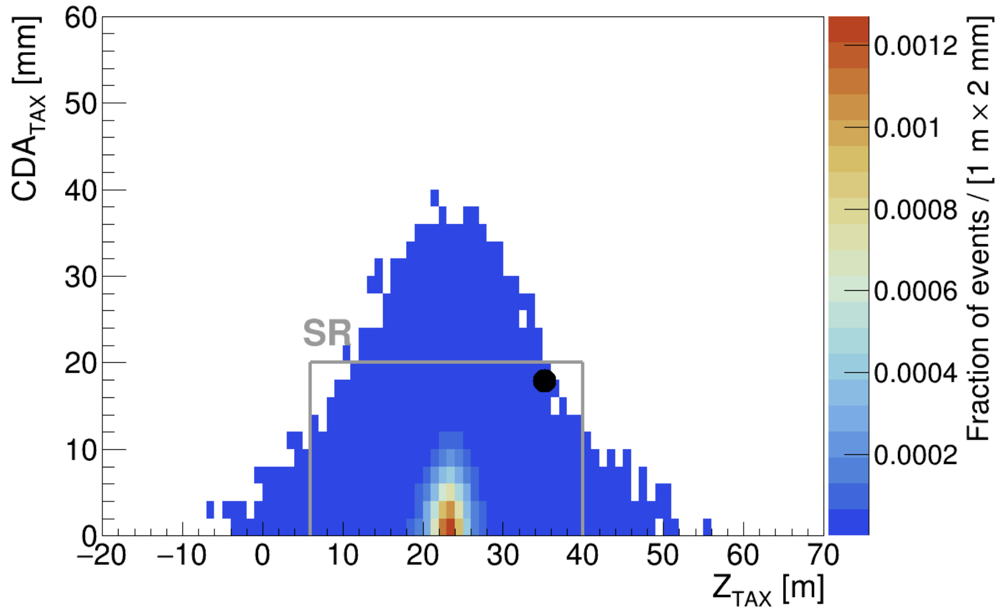
- **Probability to observe SM event in SR is only** $1.6\,\%$
- **Total uncertainty on selection efficiency is only** $3\,\%$
- **However, event on tail end of SR and** Δt **is** 2σ **away from signal event mean**

  ➡**could be interpreted as combinatorial background event**

- **Invariant mass of event was** $411\,\mathrm{MeV}$

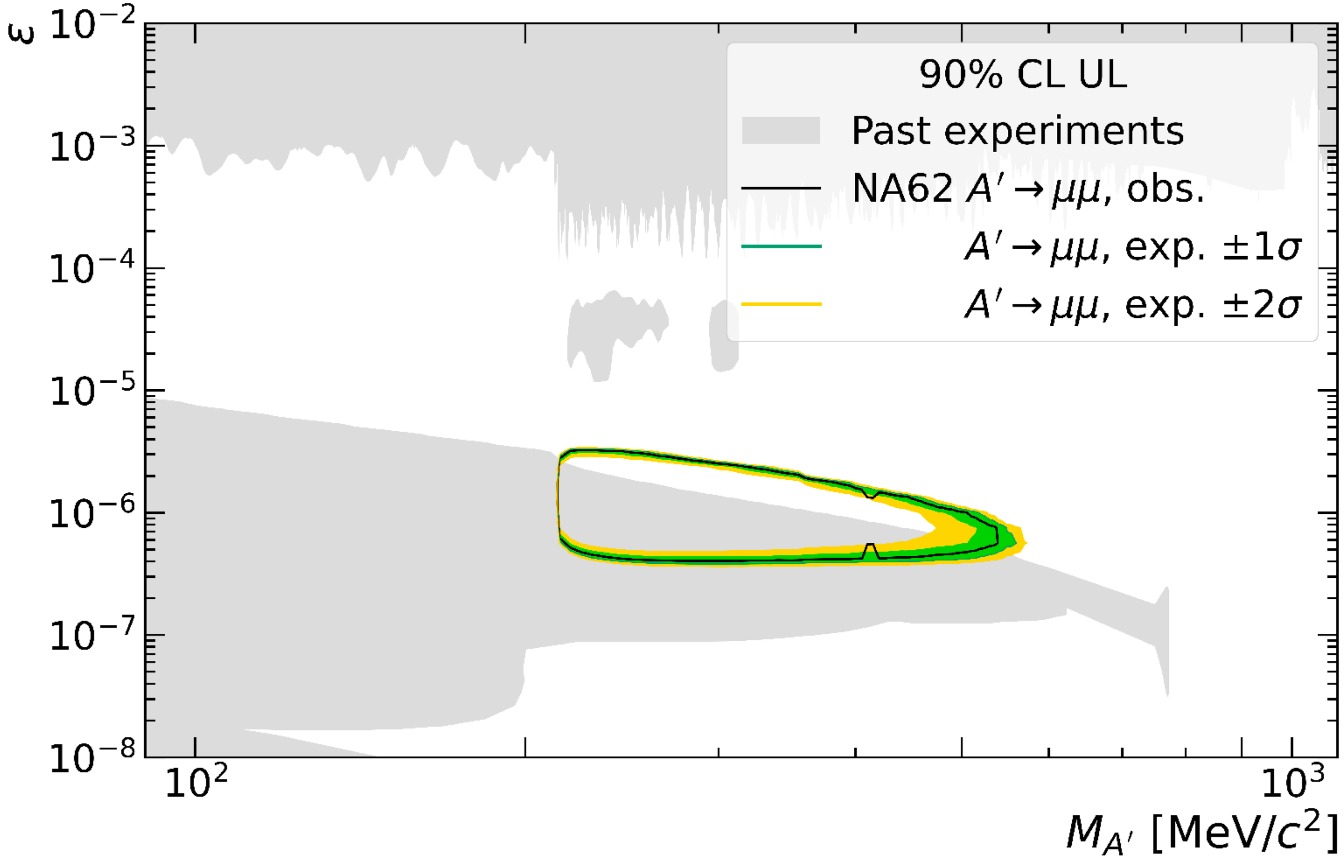


Expected background



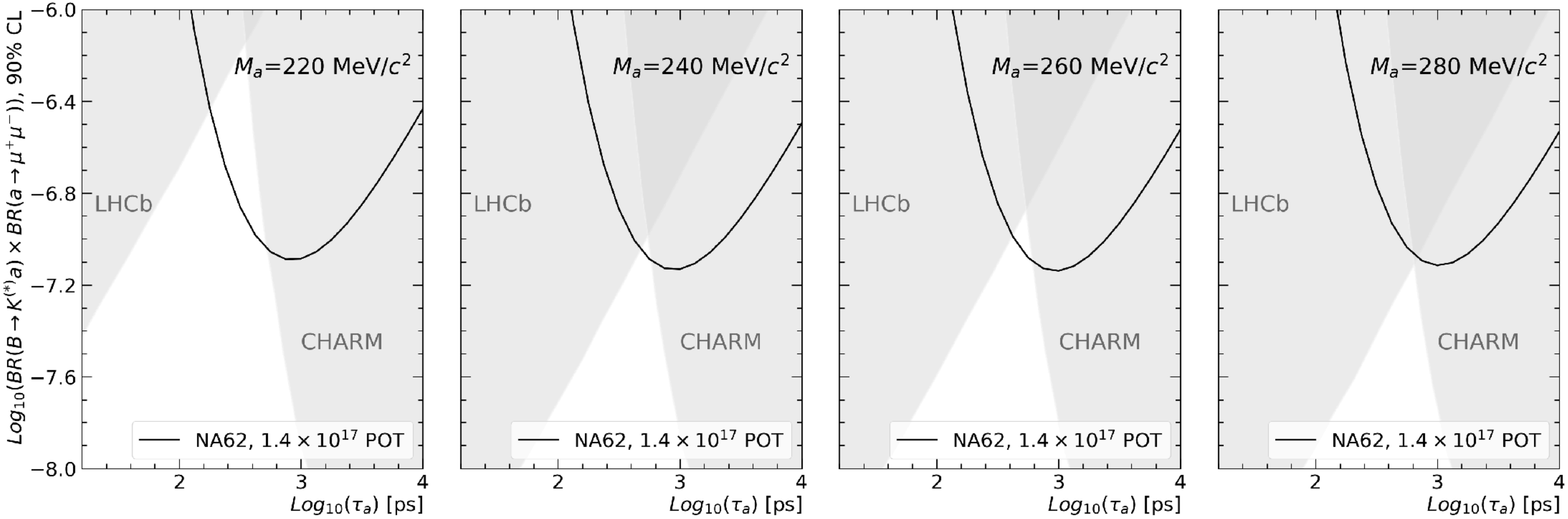
Expected signal sensitivity

RESULTS
IN TERMS OF EXOTIC EXCLUSION



Exclusion on DP parameter space resulting from $A' \rightarrow \mu\bar{\mu}$ search

RESULTS
IN TERMS OF EXOTIC EXCLUSION



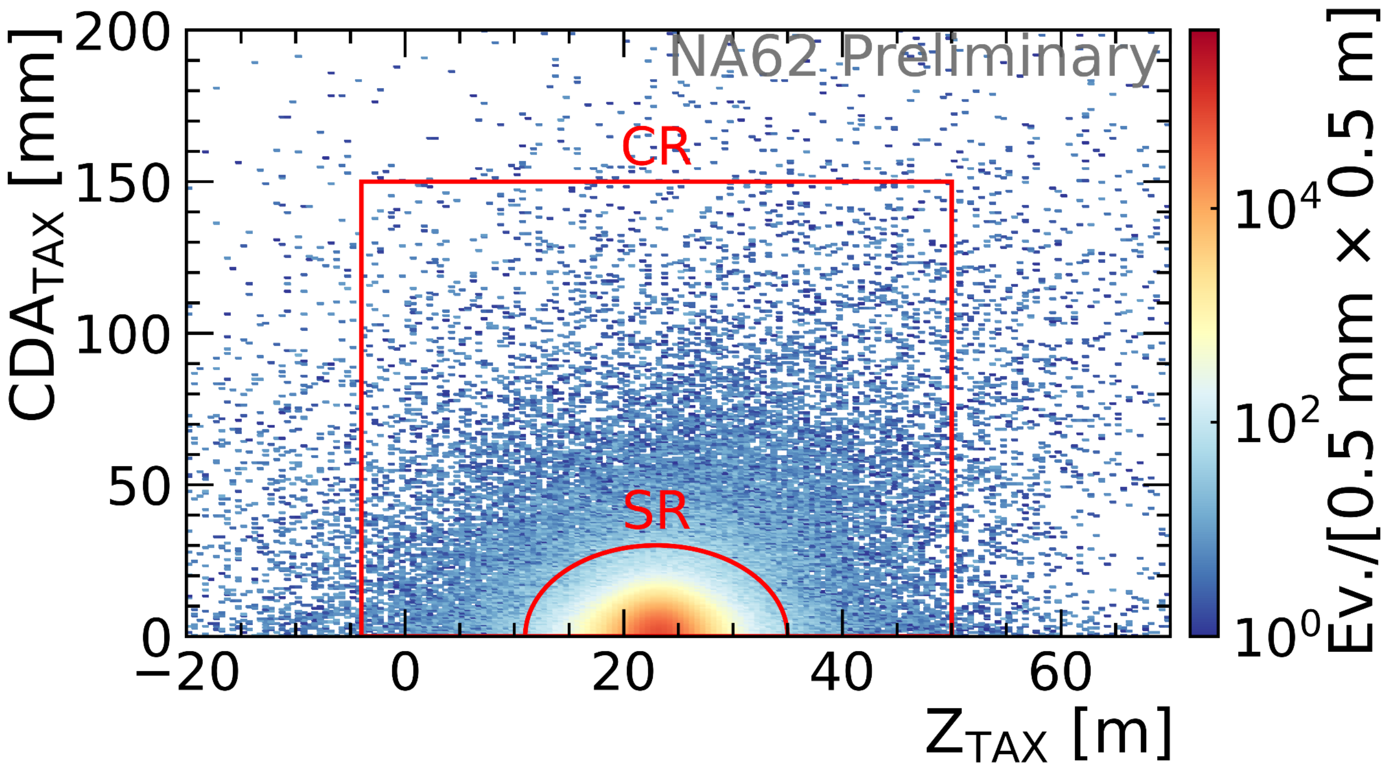
Model independent exclusion for an ALP produced in B meson decay

ANALYSES

WHAT CHANGES FOR $e\bar{e}$

Strategy

- **Update to Decay (cone shaped) and Signal Region (see plot)**
- **Veto on in-time activity in the muon veto detector (MUV3), Anti0, and LAV**

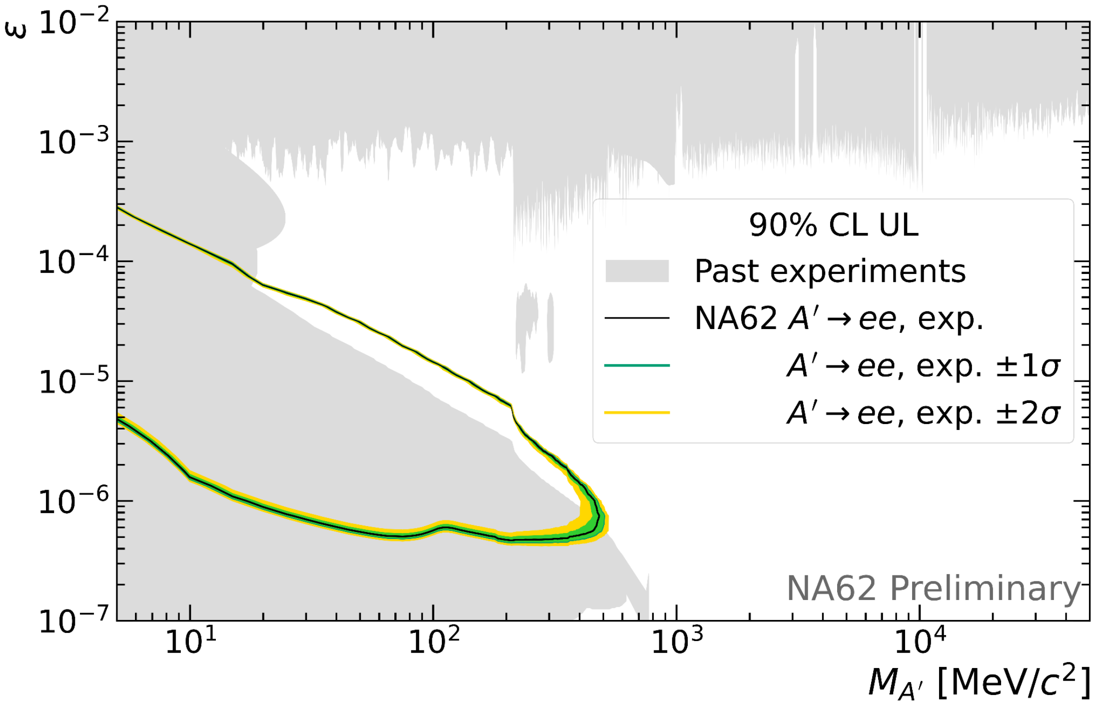


Results

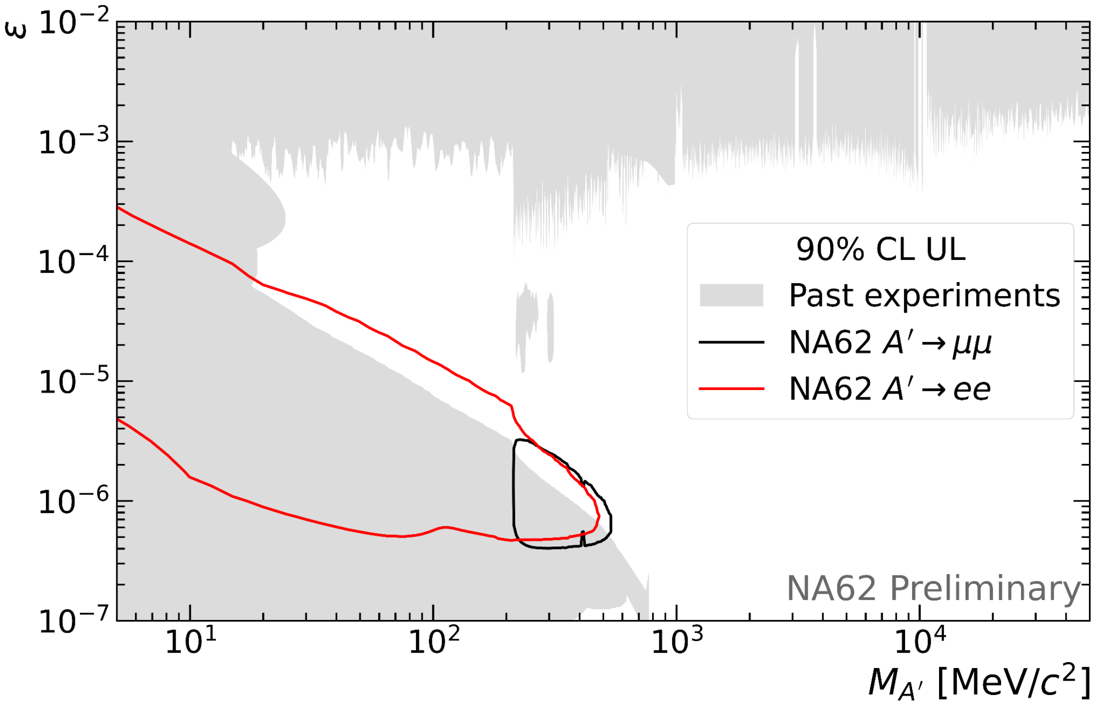
➡No events observed

RESULTS

INCLUDING $e\bar{e}$ ANALYSIS



Only $e\bar{e}$



Comparing exclusion regions

statistical combination forthcoming

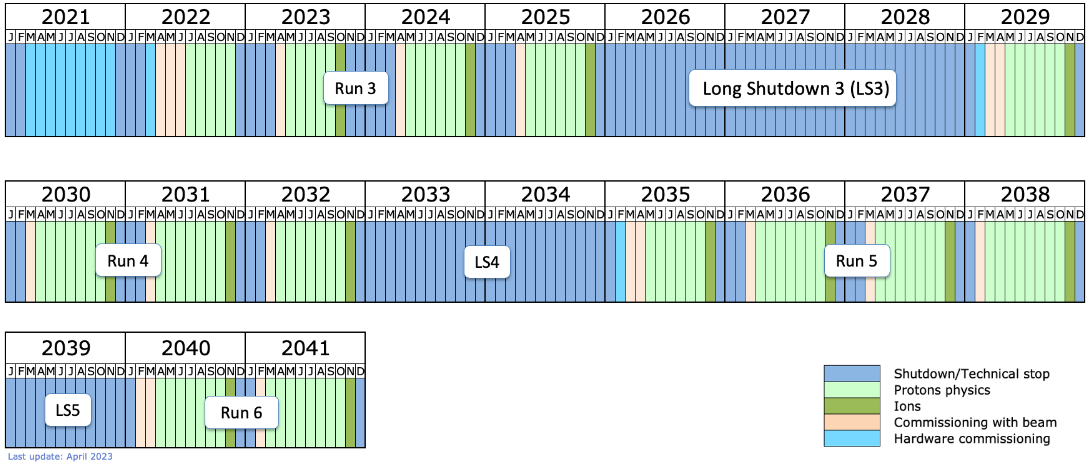
FORESEEABLE NEXT STEPS

- **Analyses ongoing with current data-set γγ, π π γ, μπ…**

  ➡ **other final states also mean other exotics**

- **Additional data taken this run** (current total reached $\sim 4 \times 10^{17}\,\mathrm{PoT}$)

- **Data taking at NA62 until at least 2025**



➡**Planning stage for Post 2028**

➡**For expected sensitivity see HIKE LoI**

EXTRA SLIDES

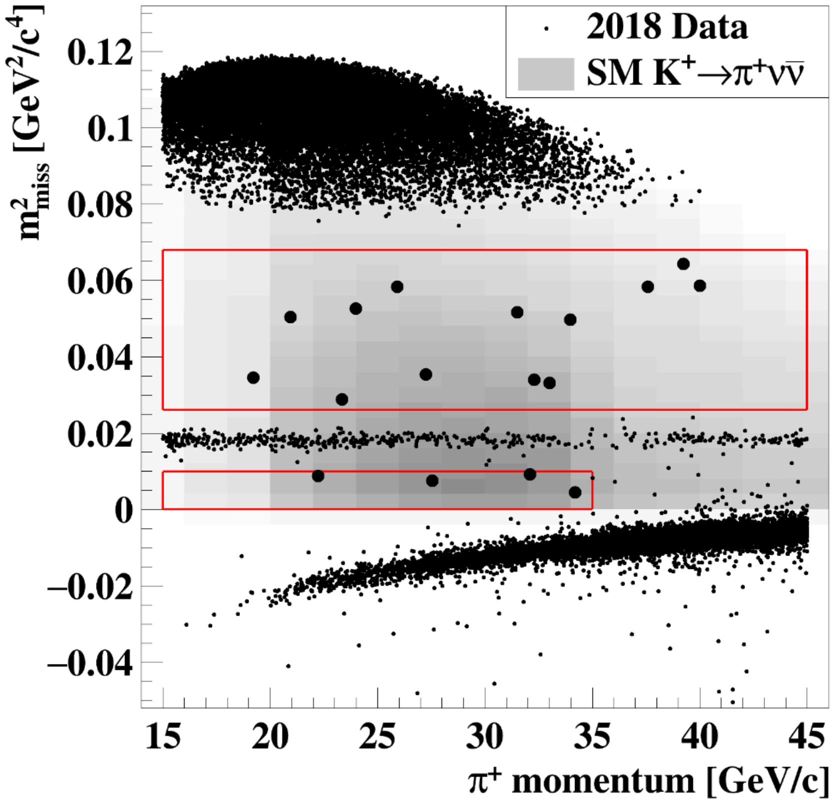
WHY THE DETECTOR IS DESIGNED THIS WAY? HOW DOES IT WORK IN KAON MODE

$K^+ \to \pi^+ \nu\bar{\nu}$ **results from RUN1**

$m^2_{\text{miss}} = (p_{K^+} - p_{\pi^+})^2$ **is all we got**

➡ **we need**

$\mathcal{O}(100\text{ps})$	**timing**
$\sim 10^3$	**Kin. background suppression**
$\sim 10^8$	**Muon suppression**
$\sim 10^8$	π^0 **suppression**



$N^{\text{exp}}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.43_{\text{syst}} \pm 1.19_{\text{ext}}$

$N^{\text{exp}}_{\text{bkg}} = 7.03^{+1.05}_{-0.82}$

$N^{\text{obs}}_{\pi\nu\bar{\nu}} = 20$

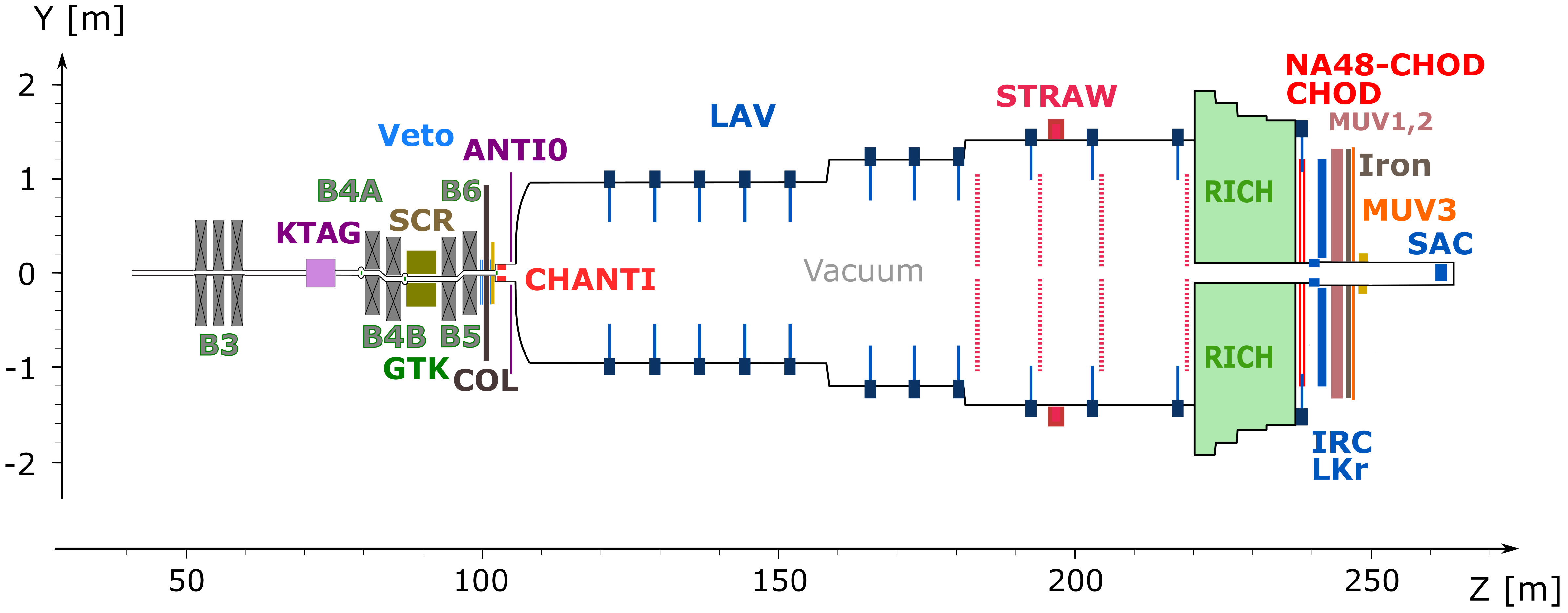
$\text{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.4}|_{\text{stat}} \pm 0.9_{\text{syst}}\right) \times 10^{-11}$

at $68\,\%$ **CL which corresponds to 3.2σ evidence for this decay**

[JHEP 06(2021)093]

THE NA62 EXPERIMENT

DETECTORS FOR 2021 DATA TAKING



PROMPT BACKGROUND IMPACT ON SR AND CR

Table 1: Expected numbers of prompt-background events for $N_p = 1.4 \times 10^{17}$ obtained from simulations. The signal selection is applied, and events in the SR or CR are excluded. The uncertainties quoted are statistical; the second uncertainty in the last column is systematic.

μ-μ	μ-π	Other	Total
0.235 ± 0.177	0.038 ± 0.019	0.004 ± 0.003	$0.28 \pm 0.19 \pm 0.20$

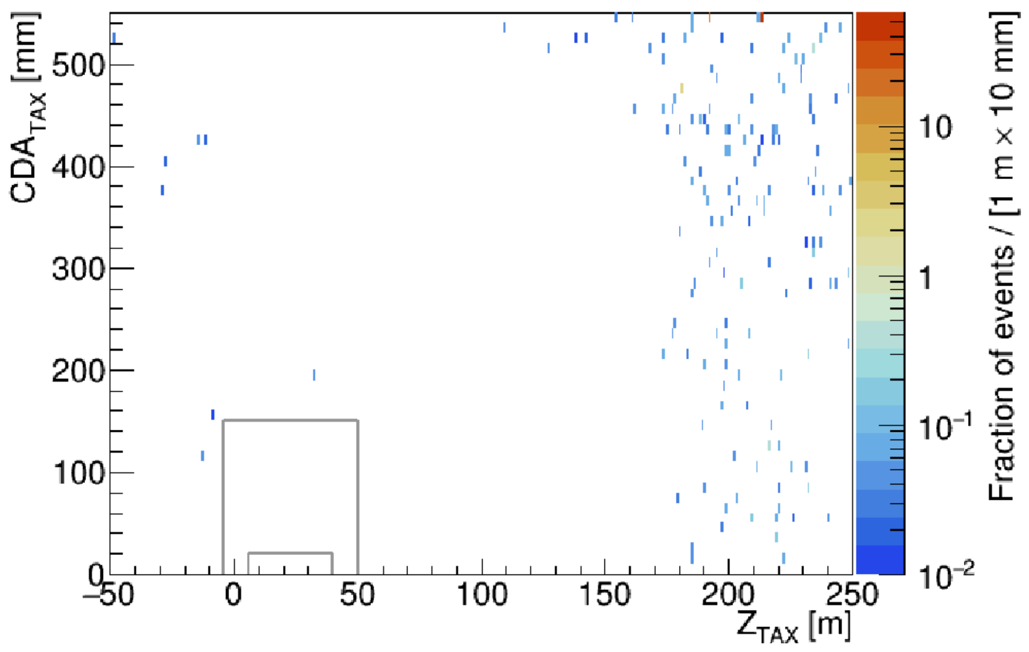
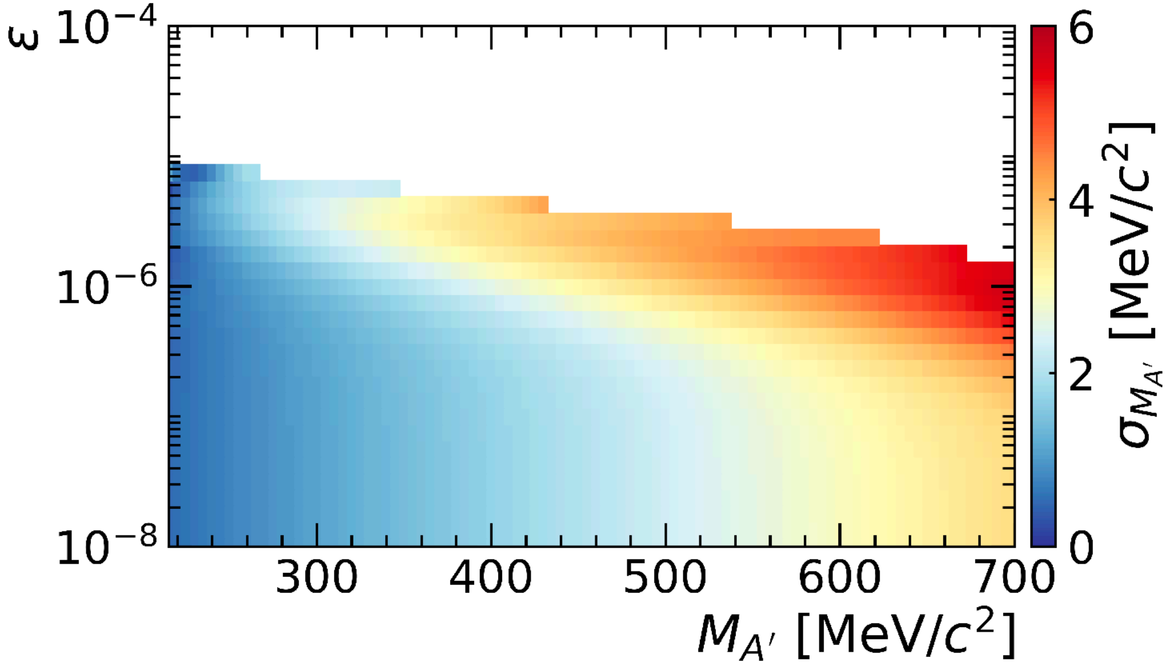


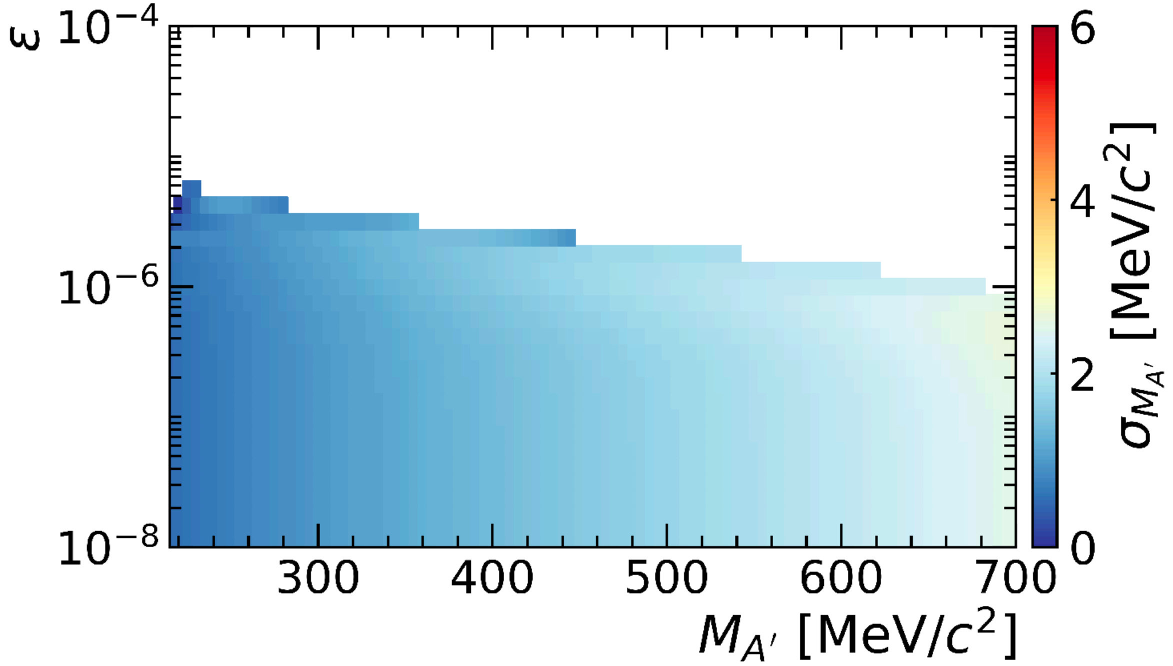
Figure 8: $\mu^+\mu^-$ expected background distribution of the prompt component before the LAV veto condition, in the (Z_{TAX}, $\mathrm{CDA}_{\mathrm{TAX}}$) plane. The rectangles are the external contours of SR and CR regions.

INVARIANT MASS RESOLUTION

Mass resolution as a function of the A' mass and coupling constant.



Production through bremsstrahlung

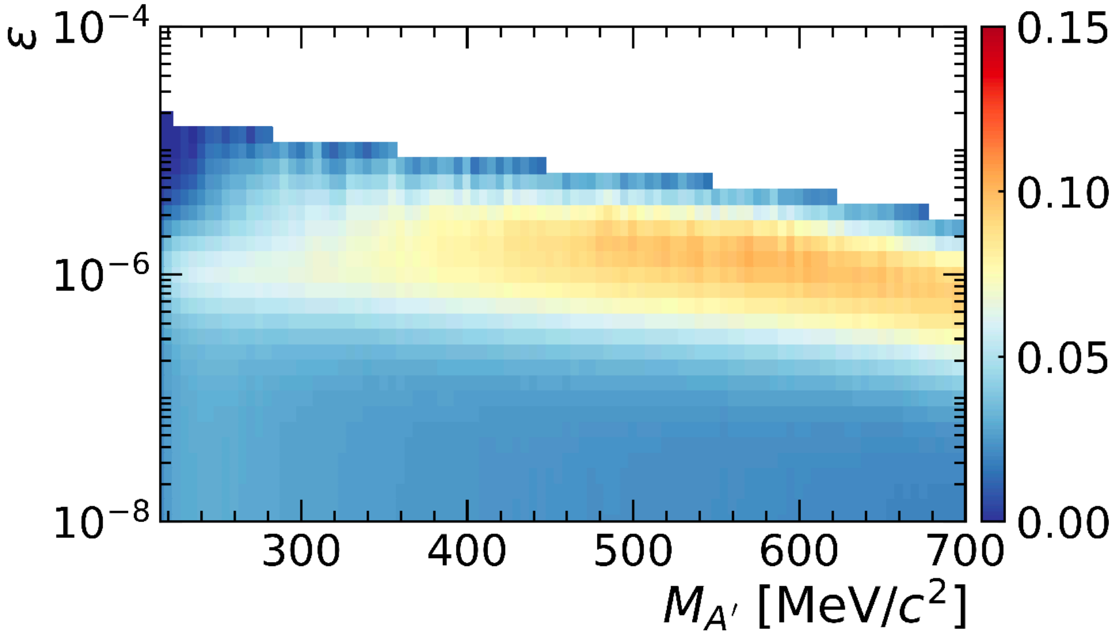


Meson decay production

SELECTION EFFICIENCY

Different Kinematics expected due to varying lifetime lead to varying selection efficiency

Below are distributions for $\epsilon_{\mathrm{acc}} \times \epsilon_{\mathrm{trig}}$



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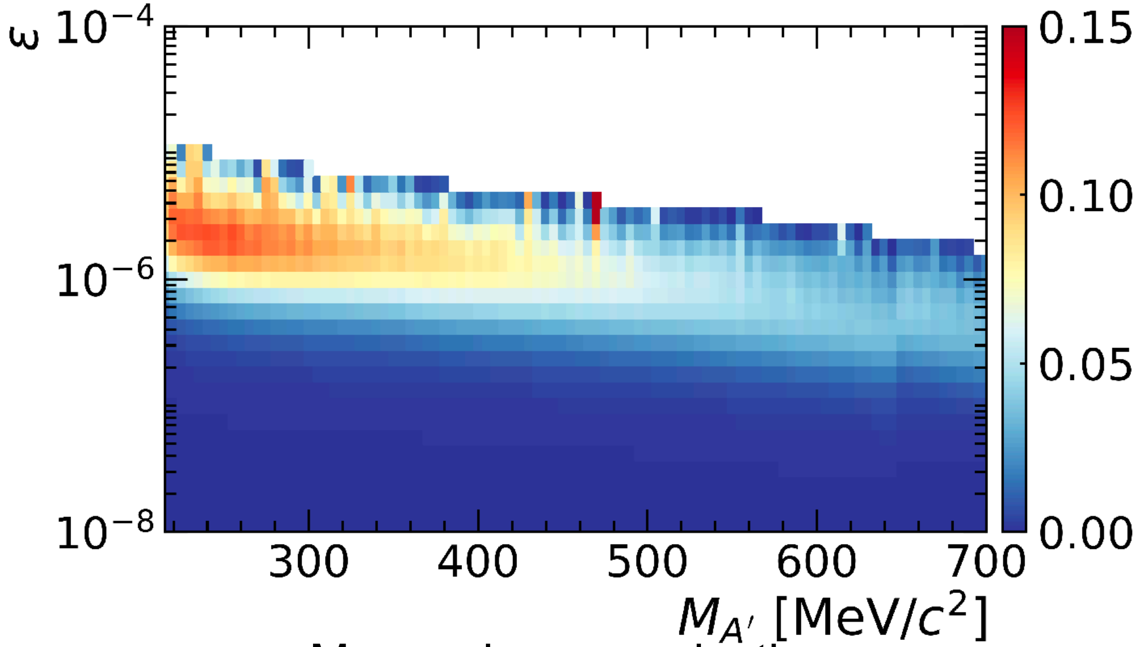
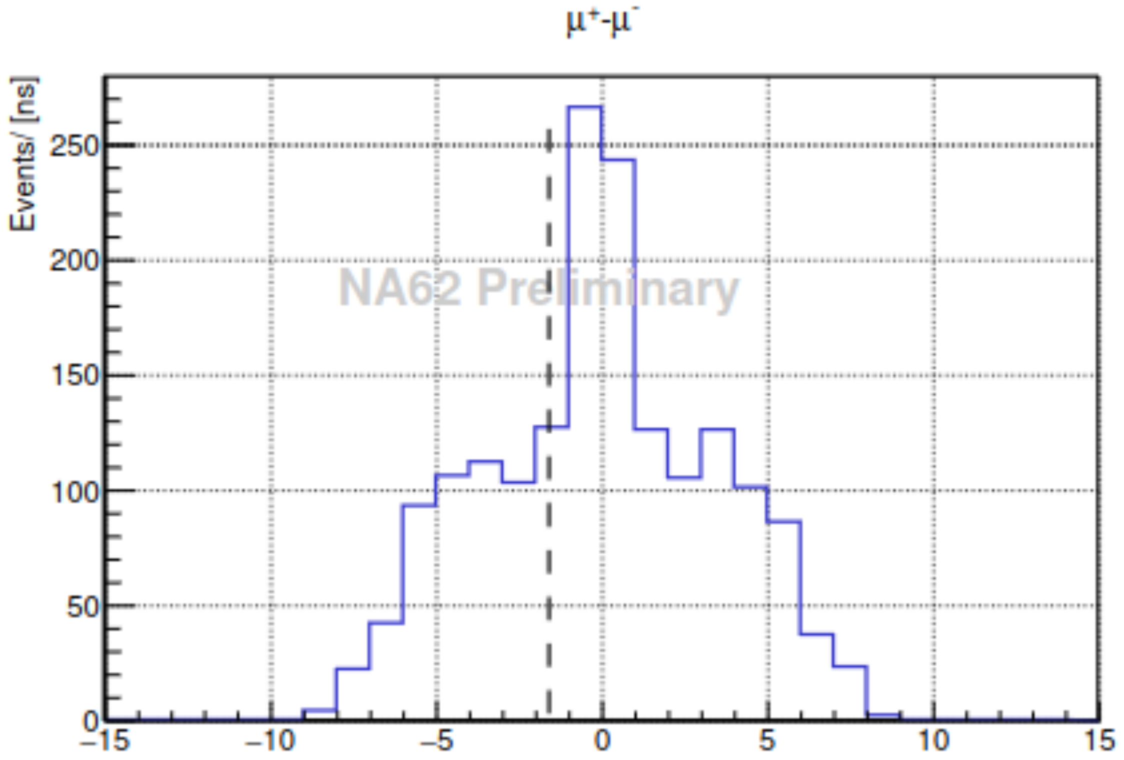


Meson decay production

DETAILS OF THE OBSERVED EVENT

- **Invariant mass** $M_{\mu\mu} = 411\,\mathrm{MeV}$
- **Time difference** $\Delta t = -1.69\,\mathrm{ns}$
- **Momenta**
  - $p(\bar{\mu}) = 99.5\,\mathrm{GeV\,c^{-1}}$
  - $E/p(\bar{\mu}) = 0.008$
  - $p(\mu) = 39.6\,\mathrm{GeV\,c^{-1}}$
  - $E/p(\mu) = 0.018$
- **Vertex**
  - $z_{\mathrm{TAX}} = 38.2\,\mathrm{m}$
  - $\mathrm{CDA_{FV}} = 17\,\mathrm{mm}$



MORE ON CHANGES FOR $e\bar{e}$ SEARCH

Updated PID

- electrons would not leave track in MUV3 so selecting relevant particles happens only in LKR
- high energy electrons can end up in the same clusters as their associated photons

➡Stronger distinction criteria for electrons vs photons in LKR

(Momentum dependent definition of direct vs. radiative radius, discarding multi direct events,

for electrons: $1 - 0.0013 \times \max(p\,[\mathrm{GeV}/c] - 100, 50) < E/p < 1.05$ with no ass. MUV3 activity within 5 ns)

Updated fiducial volume

- Issues with pairs created by muons if vertex behind LAV5 station

➡Union of 2 cones both with tips at TAX and bases at LAV5 and LAV8

(Z = 152.393 m, R = 536.5 mm and Z = 180.923 m R = 767.5 mm)

Updated Reconstruction

- Measured event in $\mu\bar{\mu}$ search could have been upstream background (even if N_{exp} very low)

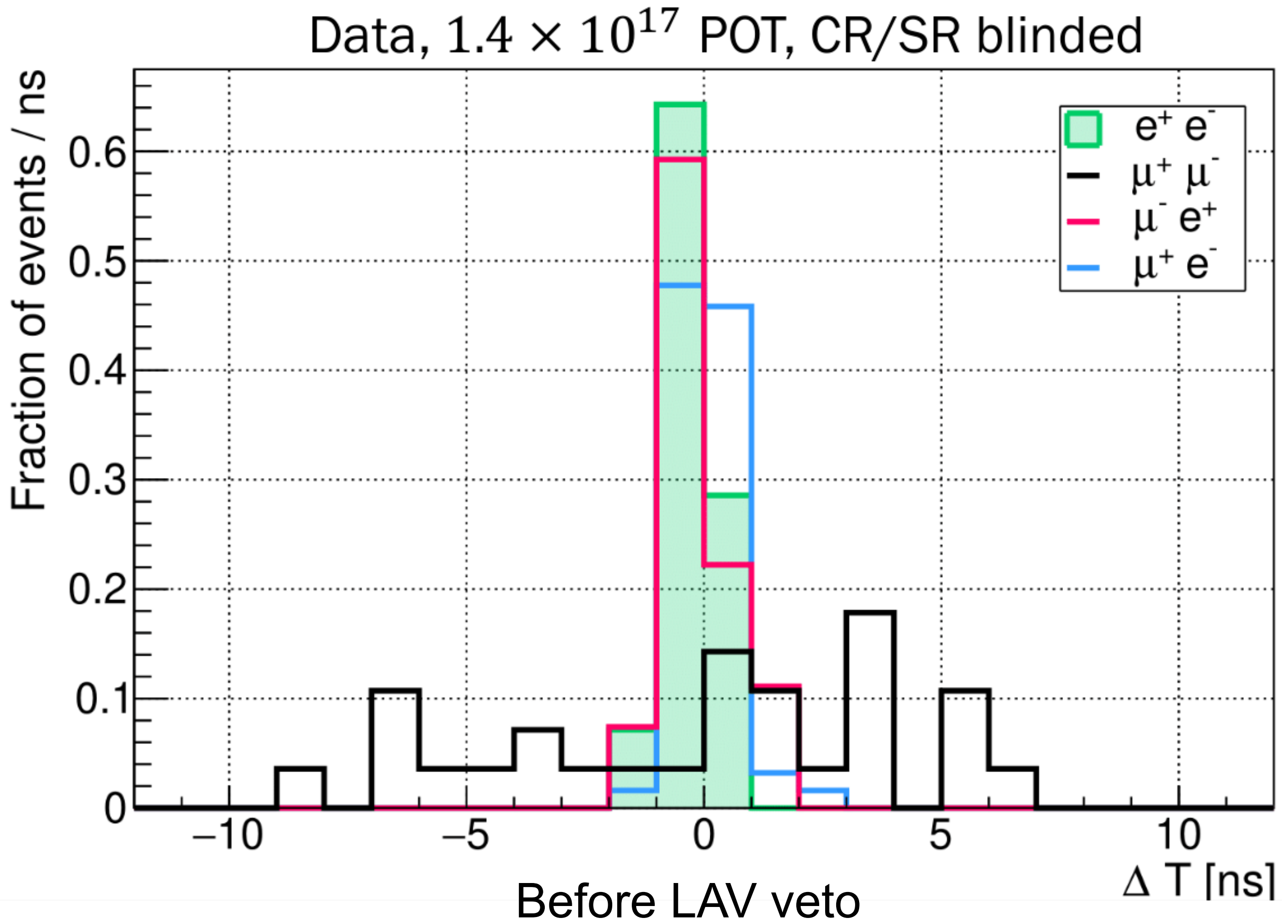
➡Rejecting every event with activity in active surface upstream of FV

(hit position is within 200 mm and within 5 ns of track time)

BACKGROUNDS IN $e\bar{e}$ SEARCH

- **Combinatorial estimated as before (turns out negligible)**
- **Dominant in this analysis: prompt background**
- **Component estimated using the rejection probabilities (η) of the LAV, ANTI0, SR, CR cuts**

Condition	$N_{\text{exp}} \pm \delta N_{\text{exp}}$	$1-\eta$
e^+e^- PID	59.9 ± 6.7	–
e^+e^- PID, LAV-ANTI0	0.72 ± 0.72	$0.012^{+0.020}_{-0.008}$
e^+e^- PID, CR	0.51 ± 0.51	$0.009^{+0.018}_{-0.006}$
e^+e^- PID, SR	0.47 ± 0.47	$0.008^{+0.018}_{-0.006}$



Before LAV veto

BACKGROUNDS IN $e\bar{e}$ SEARCH

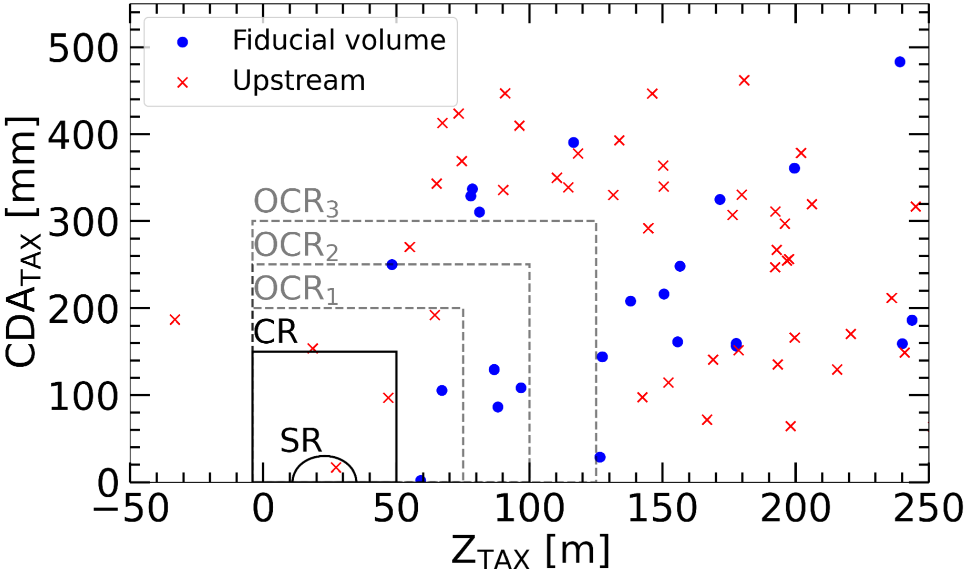
$$N^{\mathrm{CR,SR}}_{\mathrm{bkg}} = N^{\mathrm{inFW}}_{\mathrm{bkg}}(1 - \eta_{\mathrm{LAV\ ANTI0}})(1 - \eta_{\mathrm{CR,SR}})$$

which results in

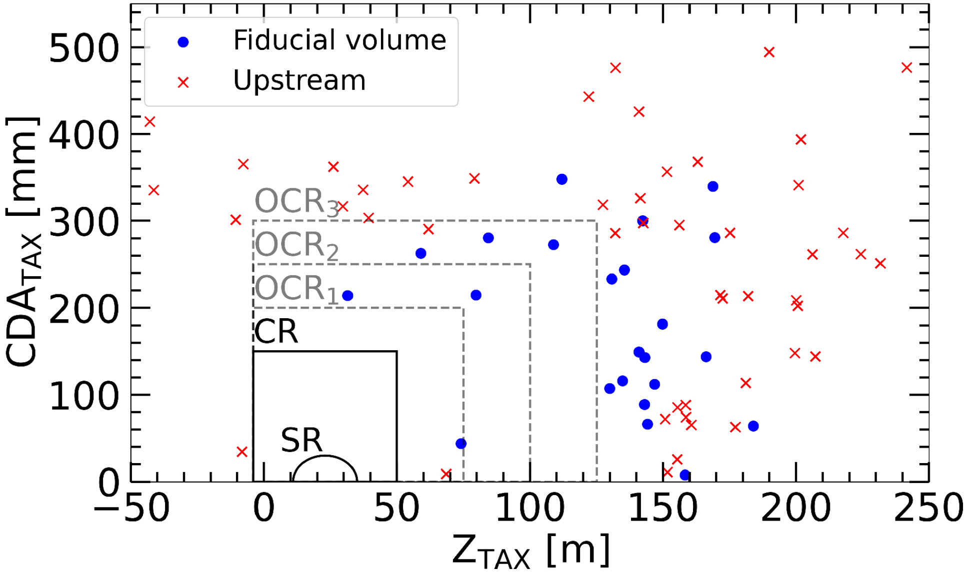
$$N^{\mathrm{SR}}_{\mathrm{bkg}} = 0.0094^{+0.049}_{-0.009} \,@\, 90\,\%\ \mathrm{CL}$$

$$N^{\mathrm{CR}}_{\mathrm{bkg}} = 0.0097^{+0.049}_{-0.009} \,@\, 90\,\%\ \mathrm{CL}$$

➡Probability to observe SM event in SR again at $1.6\,\%$

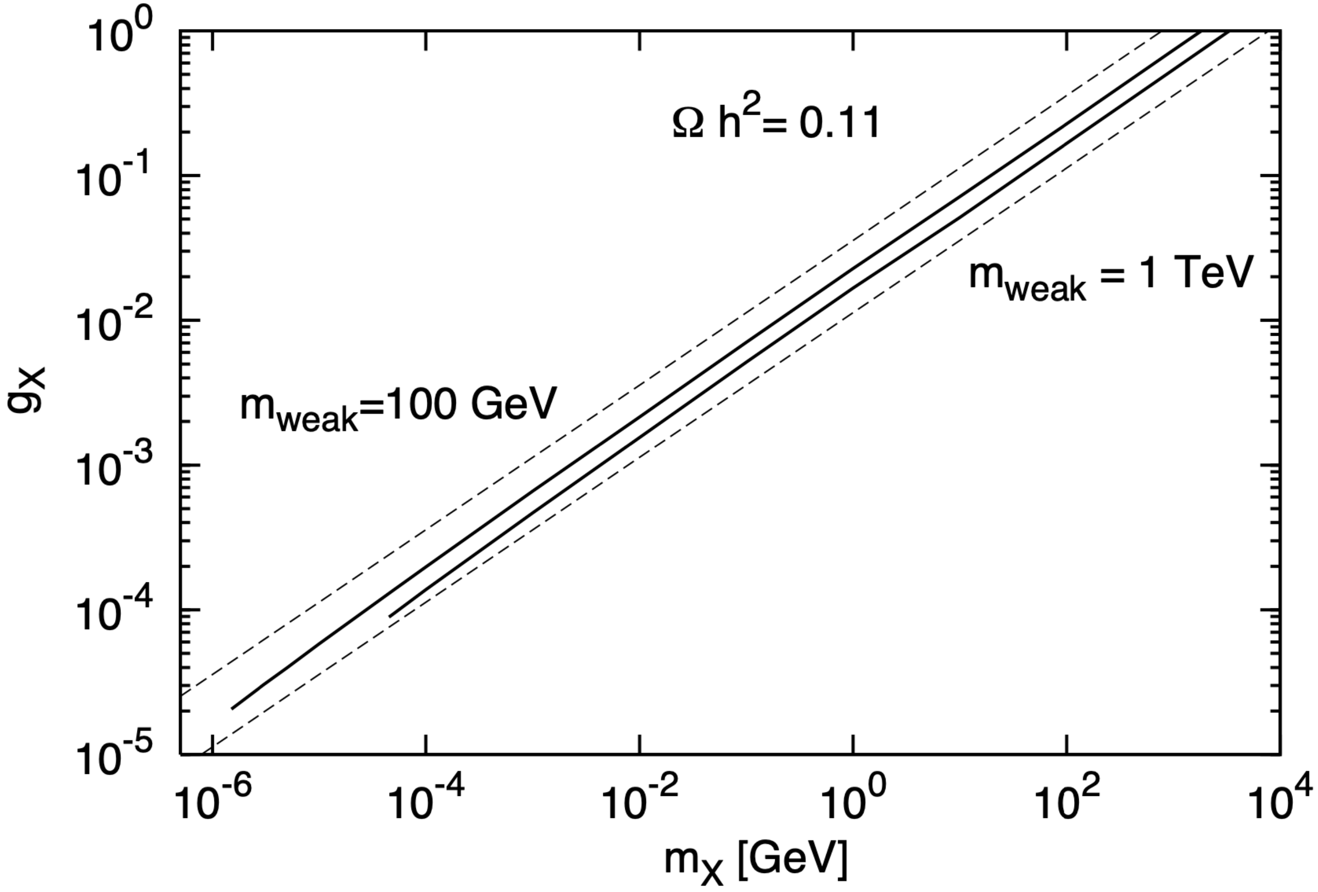


Background MC with no LAV,Anti0 veto



Background Data with no LAV,Anti0 veto
SR and CR blinded

WHY THE TARGETED DP PARAMETER SPACE IS INTERESTING
THERMAL RELIC DARK MATTER

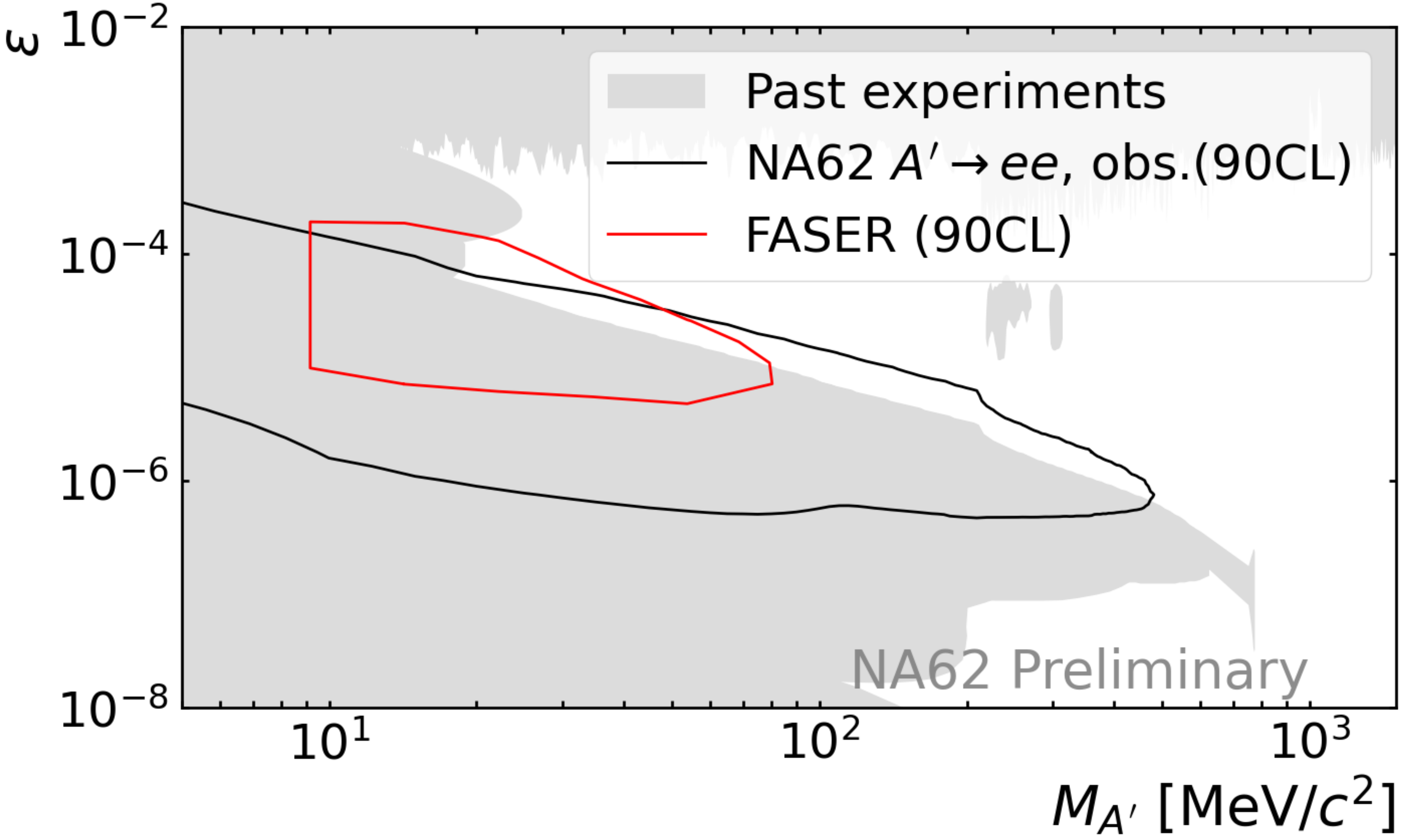


Wimples miracle [0808.2318] where dark photon coupling to mass ratio is 'just right' to give the correct amount of dark matter in the Universe.

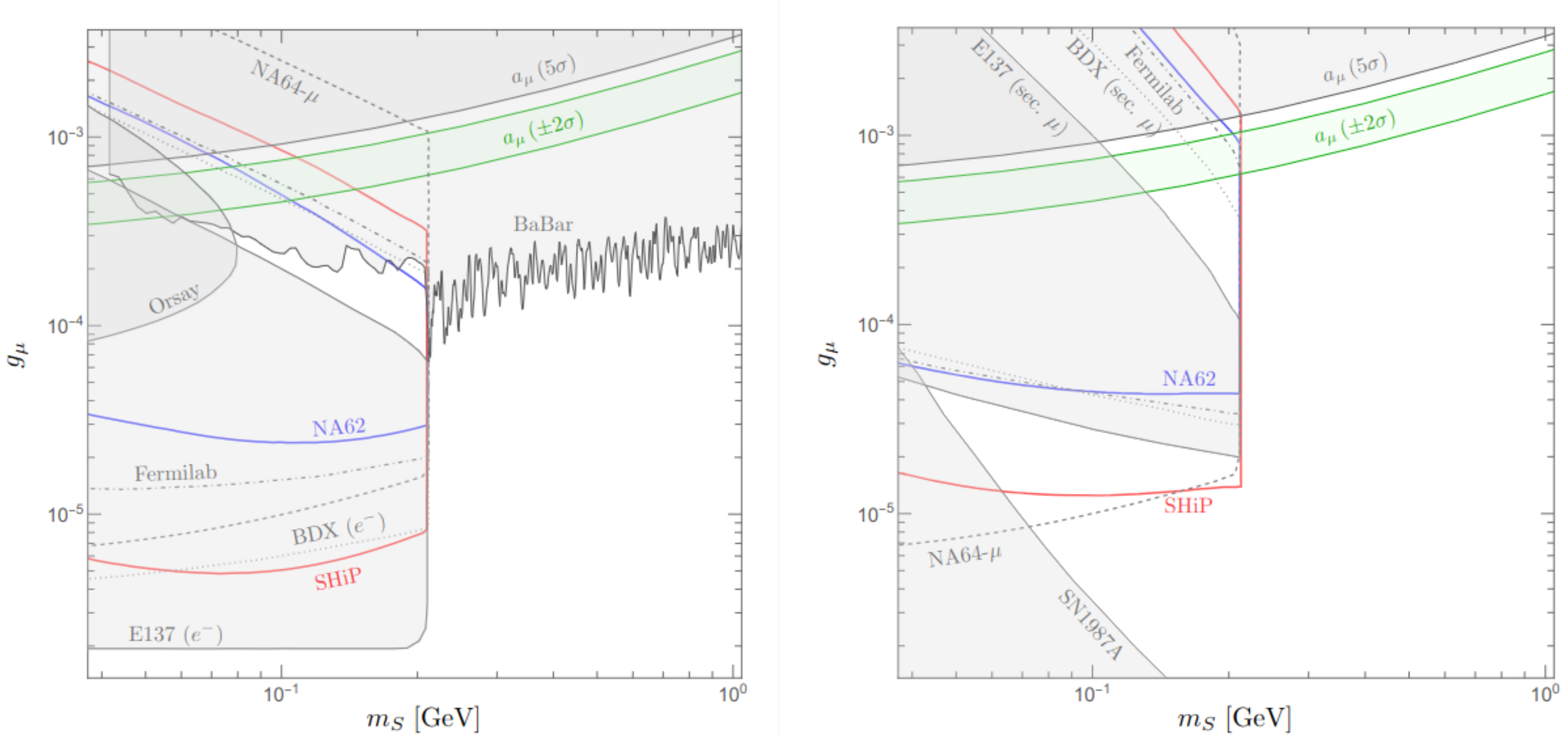
See [2005.01515] for a more recent review.

$$\Omega_X h^2 \sim \frac{(4m_X^2 - m_{A'}^2)^2}{\varepsilon^2 m_X^2}$$

UNOFFICIAL COMPARISON WITH NEW FASER RESULTS



FUTURE SEARCHES AT NA62 BEAM DUMP PREDICTED SENSITIVITY FOR DARK SCALARS

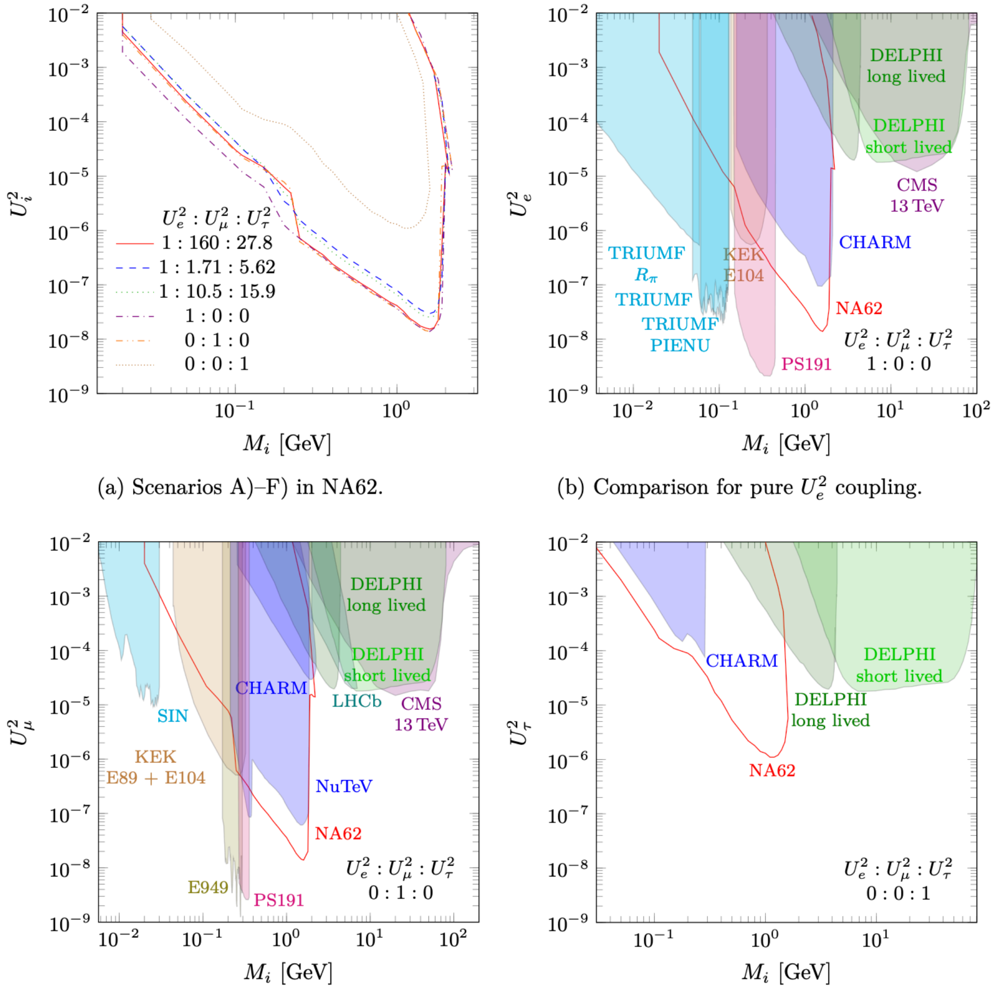


(a) Leptophilic Model

(b) Muonphilic Model

[2205.09870]

FUTURE SEARCHES AT NA62 BEAM DUMP
PREDICTED SENSITIVITY FOR HEAVY NEUTRAL LEPTONS



(a) Scenarios A)–F) in NA62.

(b) Comparison for pure U_e^2 coupling.

(c) Comparison for pure U_μ^2 coupling.

(d) Comparison for pure U_τ^2 coupling.

[1801.04207]