MAX-PLANCK-INSTITUT
FÜR PHYSIK

Technische Universität München

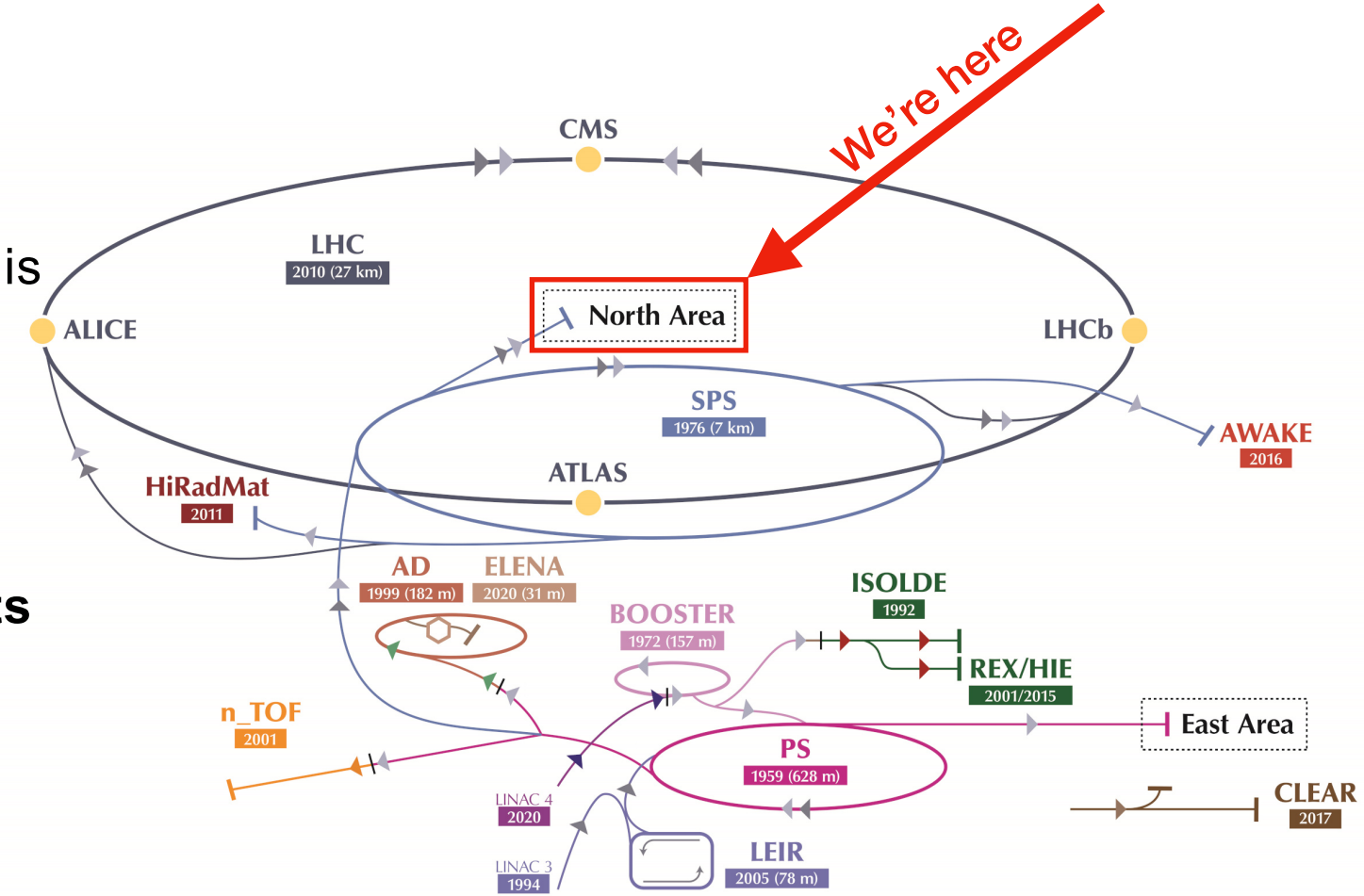
NEW RESULTS FOR SEARCHES OF EXOTIC DECAYS WITH NA62 IN BEAM-DUMP MODE

15th International Workshop
on the Identification of Dark Matter

Jonathan Schubert
for the NA62 collaboration

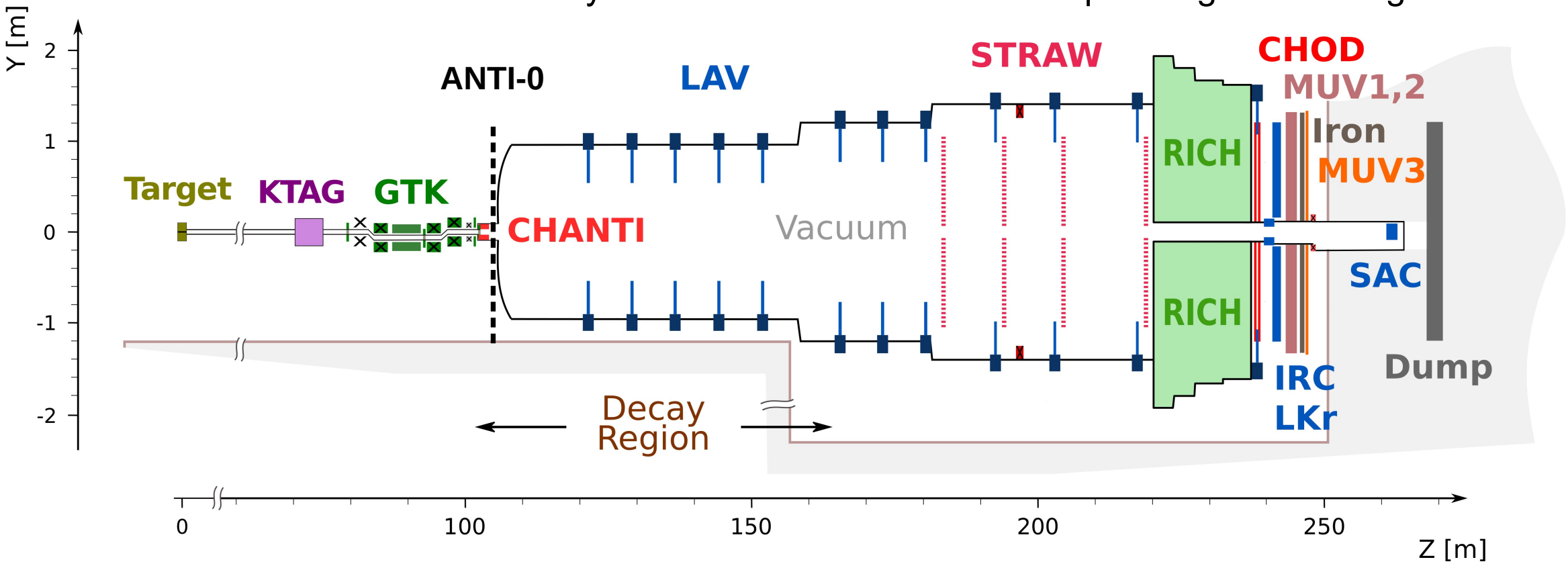
THE NA62 EXPERIMENT
A BRIEF OVERVIEW

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

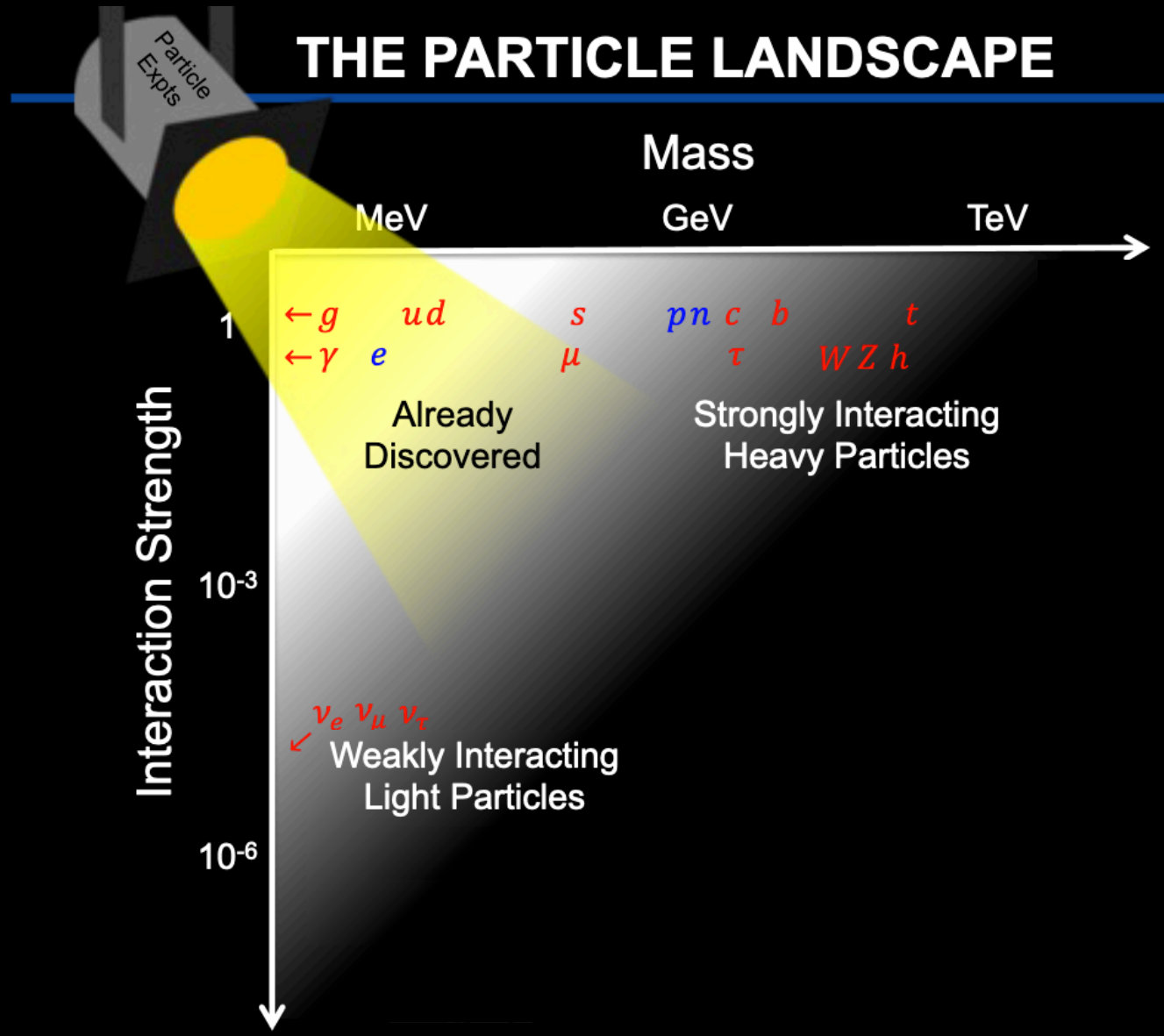


THE NA62 EXPERIMENT
THE DETECTORS IN KAON MODE

- K^+ tagged by KTAG and 3-mom. determined by GTK
- Decay products are classified by 3-mom. (STRAW), time measured (CHOD), PID (LKr, MUV1,2, and RICH), where MUV3 gives μ-ID
- Photons can be vetoed by LKr and LAV or SAC/IRC depending on the angle



HOW WE DISCOVER PARTICLES



adapted from Jonathan Feng's *Cern Colloq. 23*

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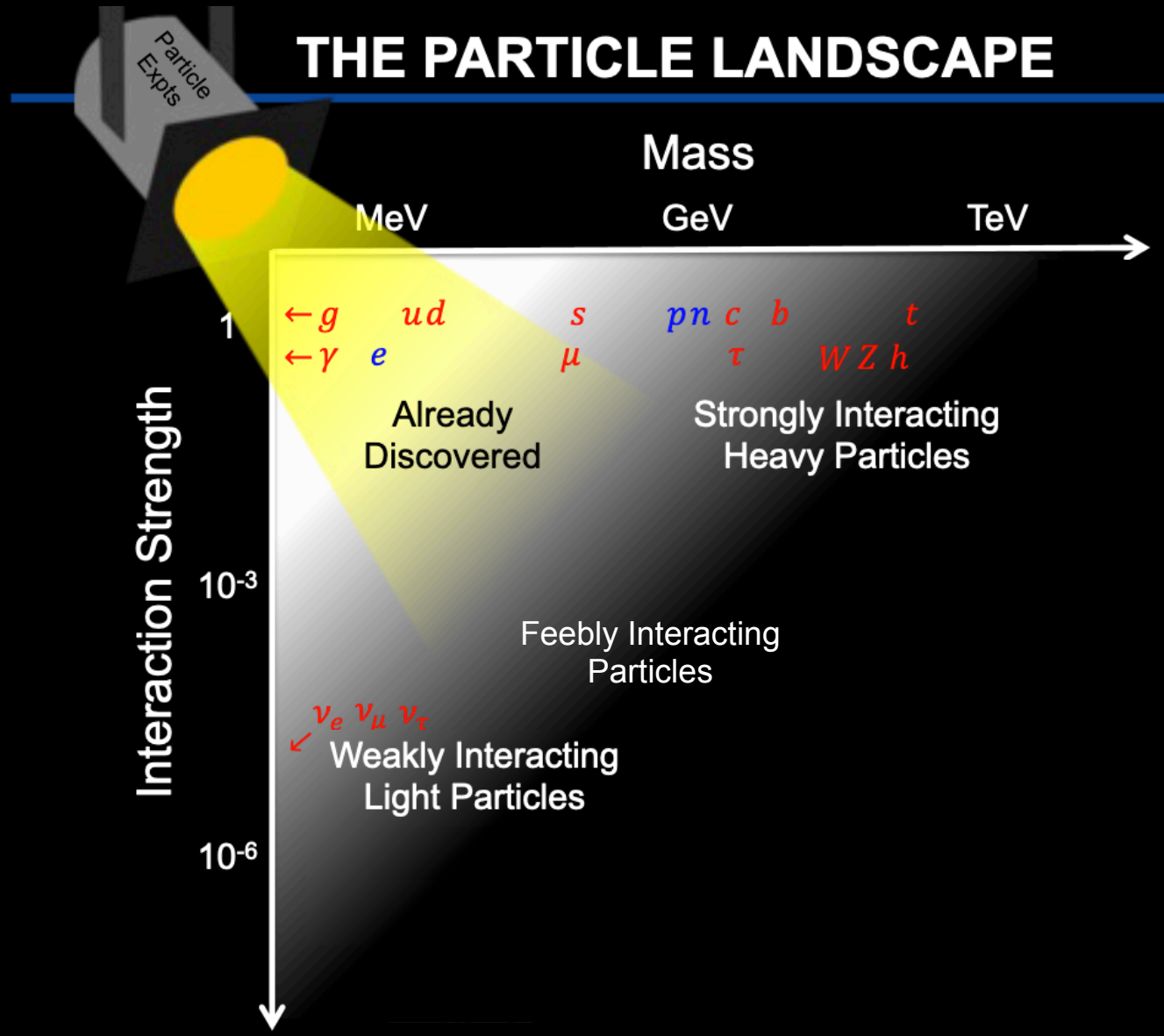

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FEEBLY INTERACTING PARTICLES

Categorisation by spin(parity symmetry)
and commonly organised into Benchmark Cases (BC)

- **Spin 0$^-$** — SM ----- $\frac{C_{gg}}{\Lambda}$ ----- **Axion Like Particle**
  - Coupling for example **to SM gluons** (BC11)
- **Spin 0** — SM ----- $\sin\theta m_f$ ----- **Dark Scalar**
  - Couple to SM fermions prop. to **fermion mass** $\sin\theta m_f$ (BC4)
- Spin 1/2 — SM ------ $F\frac{\text{vev}}{M_R}$ ------- **Heavy Neutral Lepton**
  - Couple to SM Neutrinos with Yukawa-like coupling prop. to $F\text{vev}M_R^{-1}$
- **Spin 1** — SM ------ εq_f ------ **Dark Photon**
  - Couple to SM fermions prop. to **fermion charge** (BC1)

adapted from
Jonathan Feng
Cern Colloq. 23

THE NA62 EXPERIMENT
BEAM DUMP MODE — SCHEMATICALLY

- Target is followed by an achromat selecting fixed secondary beam momentum (incl. Kaons)
- The **collimators of this achromat are movable** and can be **driven into a "*closed position*"** within a few minutes — Meanwhile 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**

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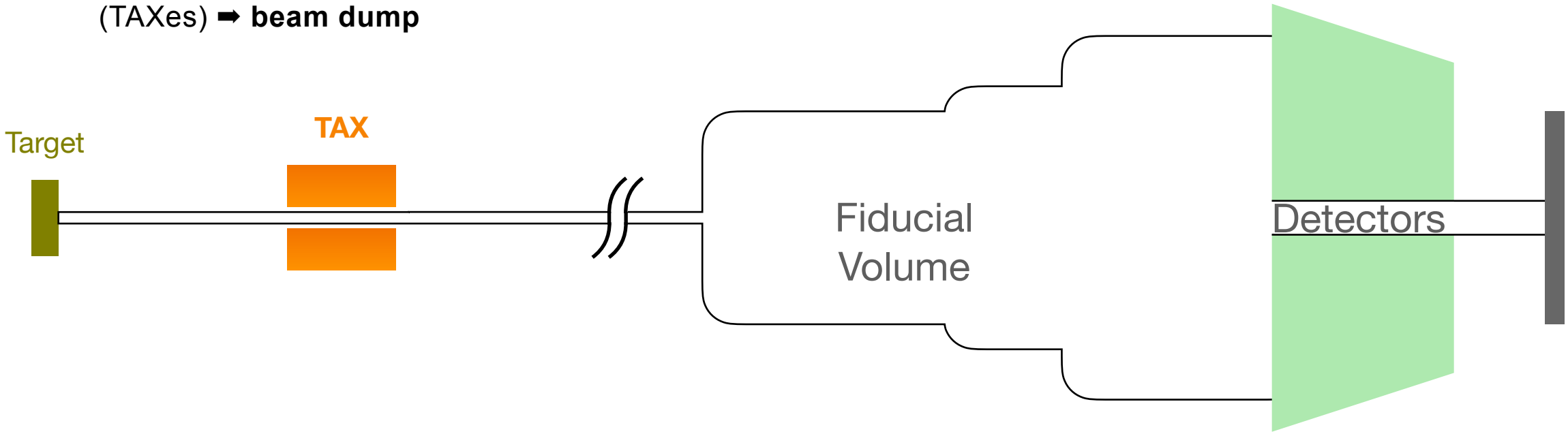

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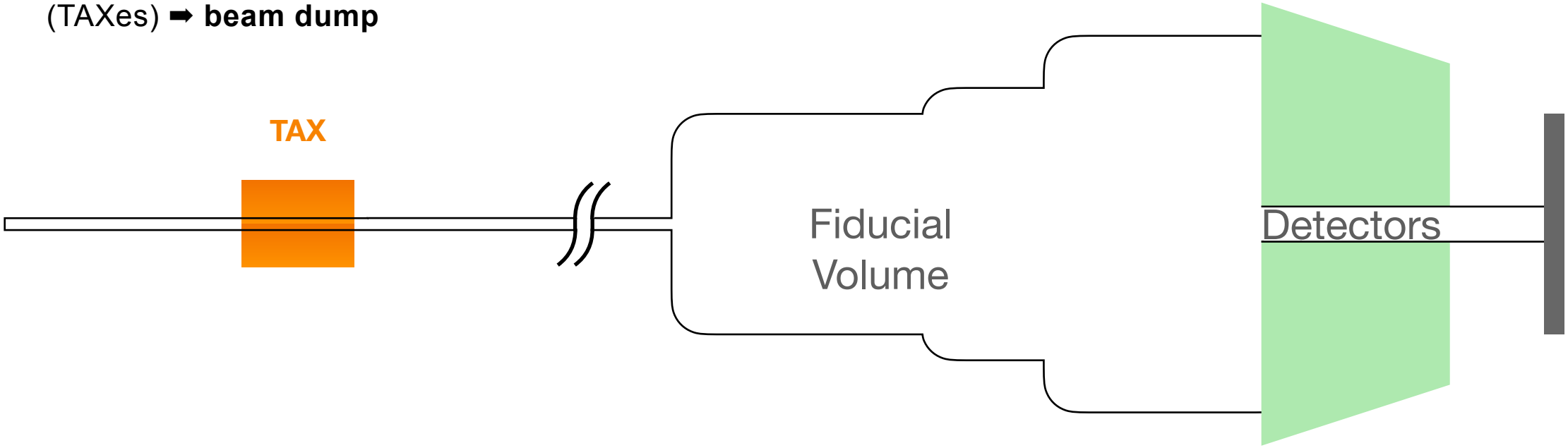

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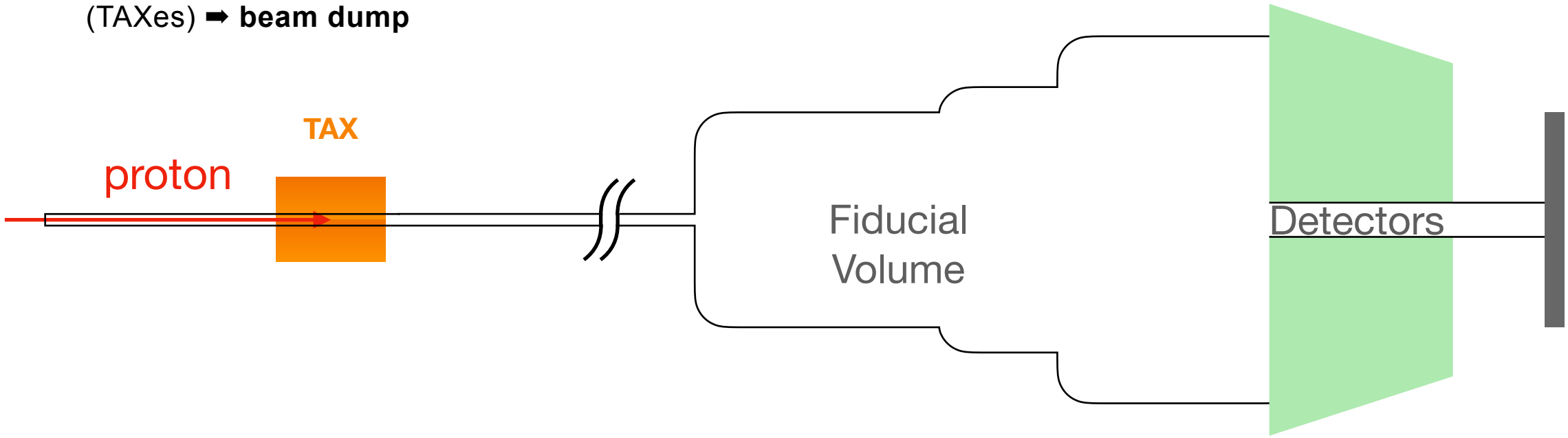

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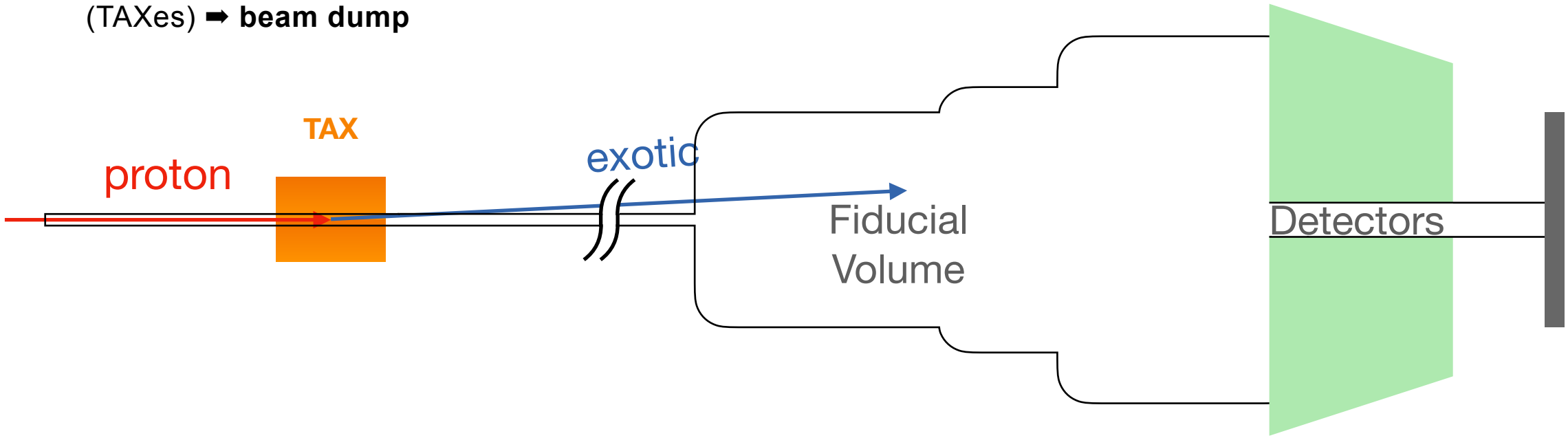

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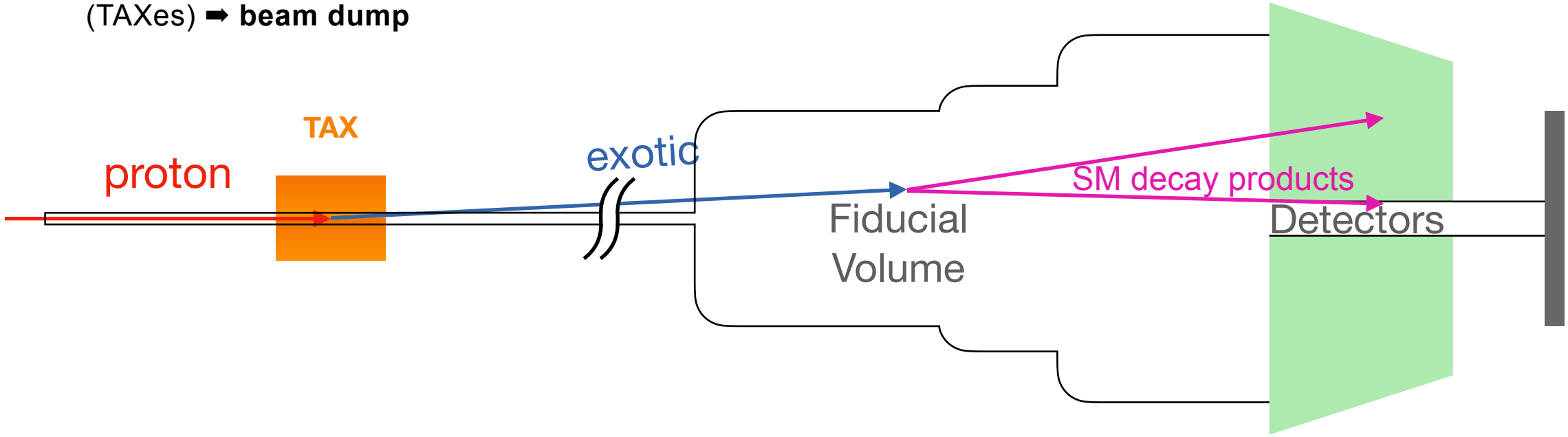

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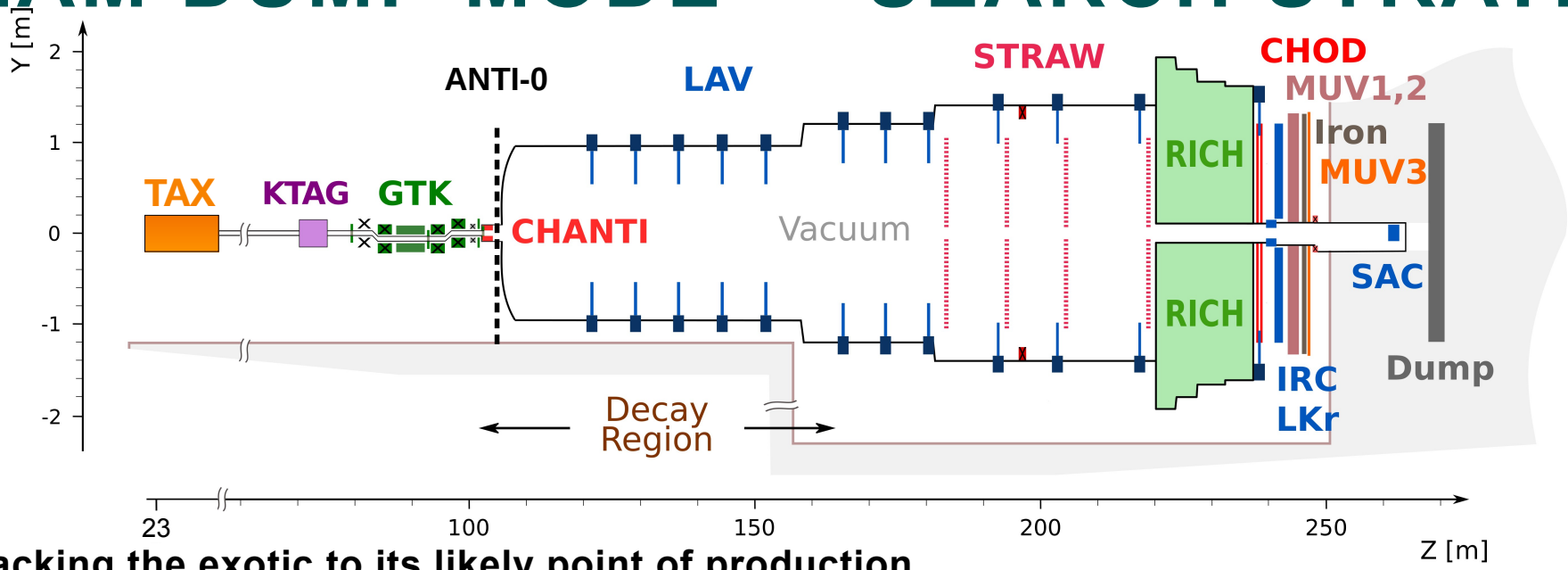

Backtracking the exotic to its likely point of production

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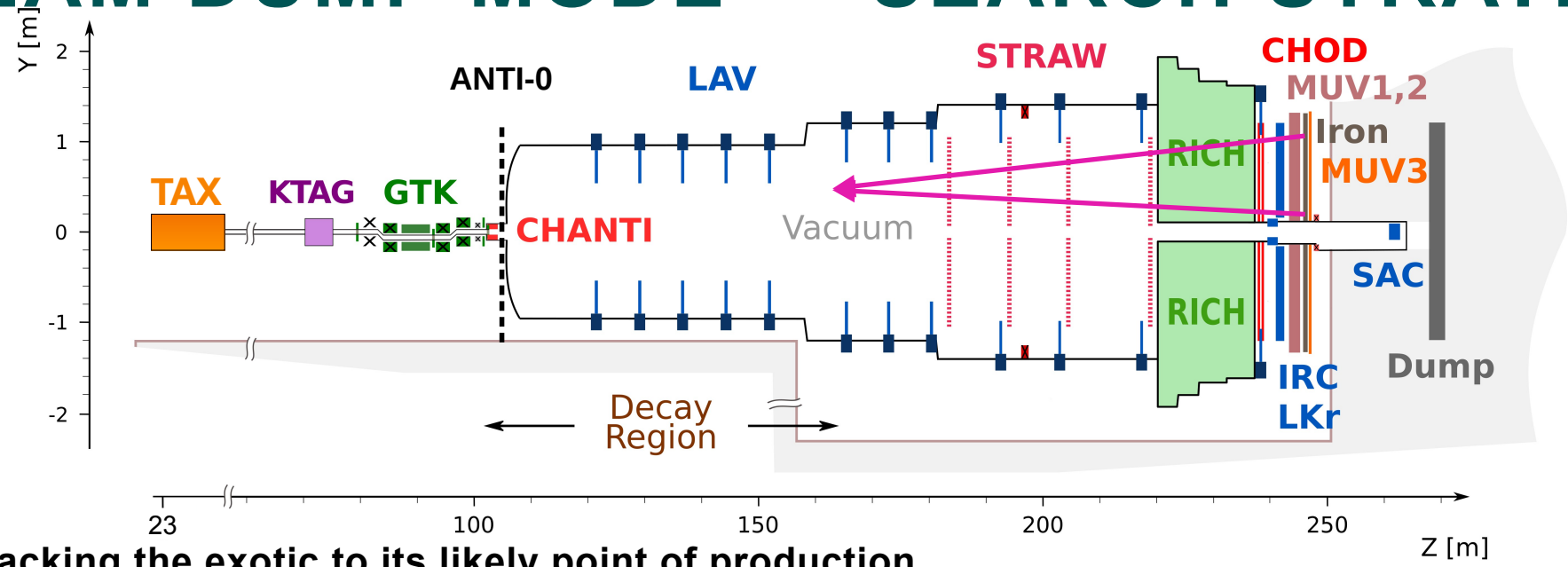

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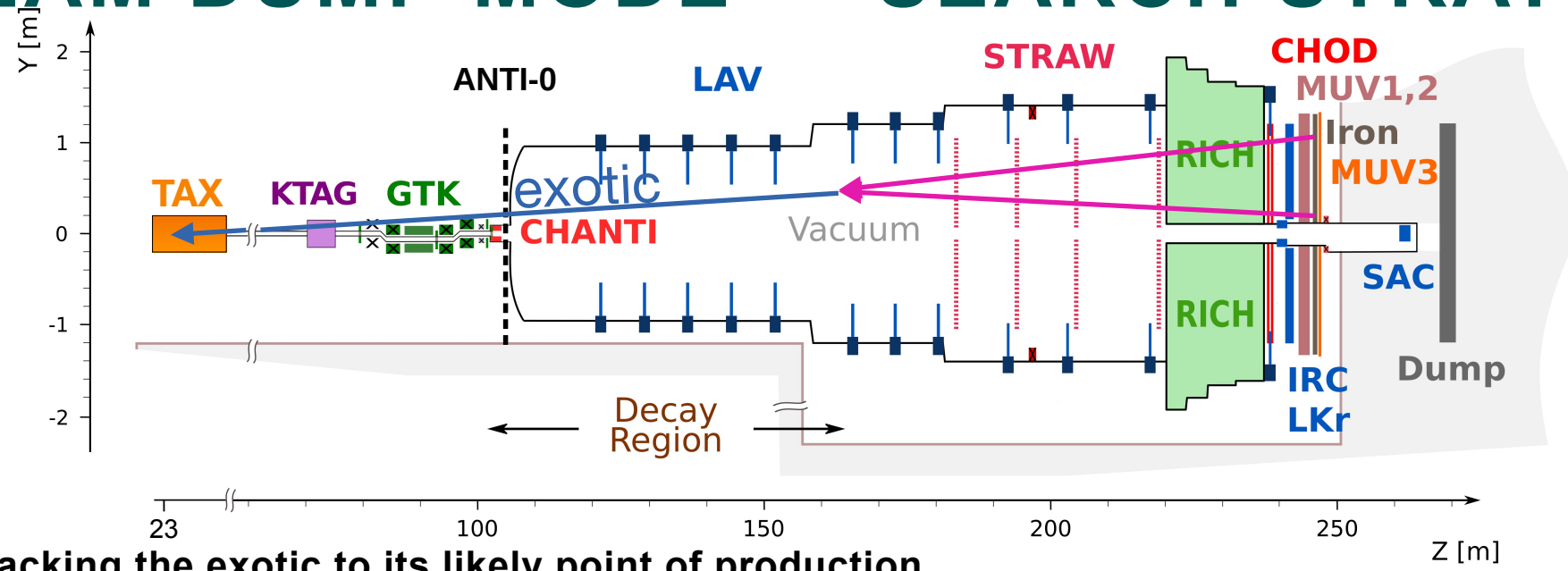

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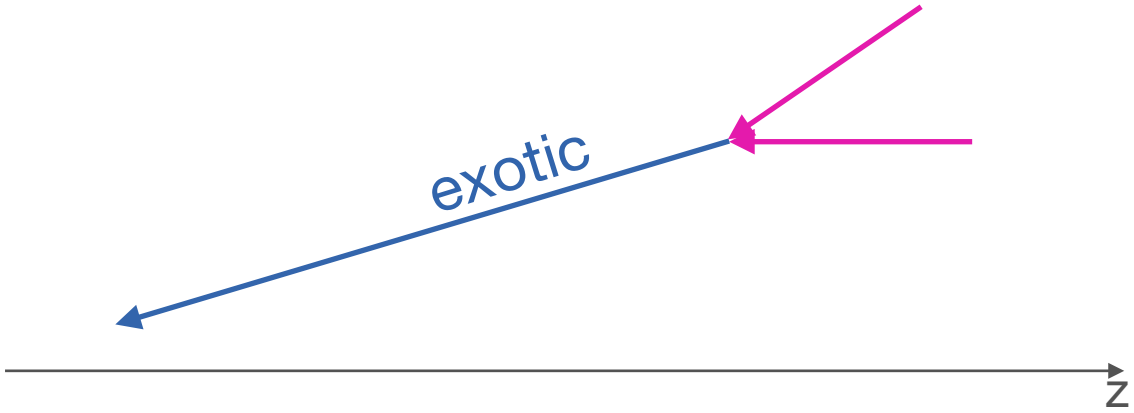

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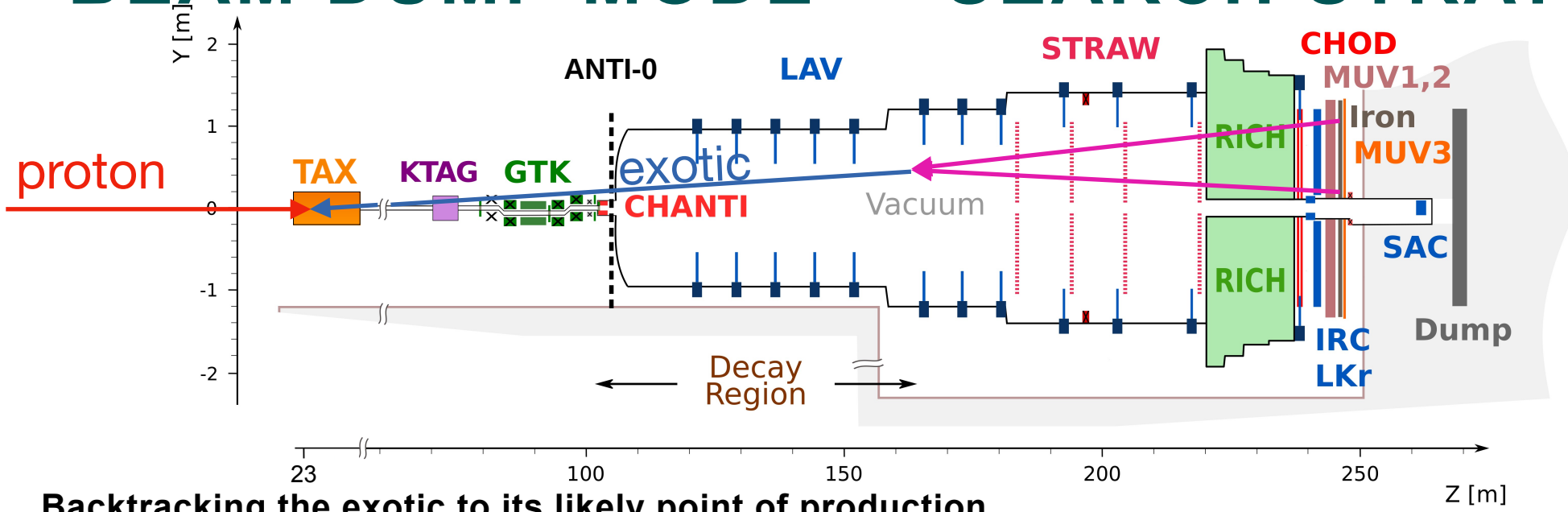

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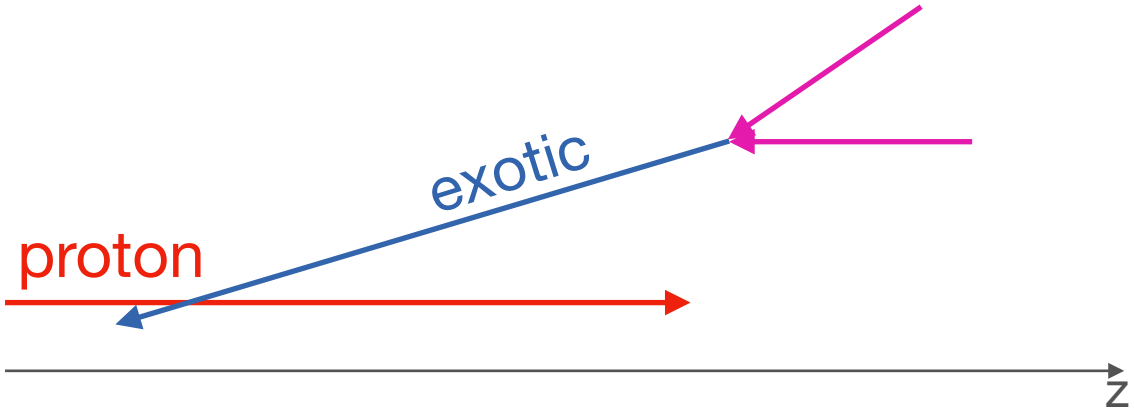

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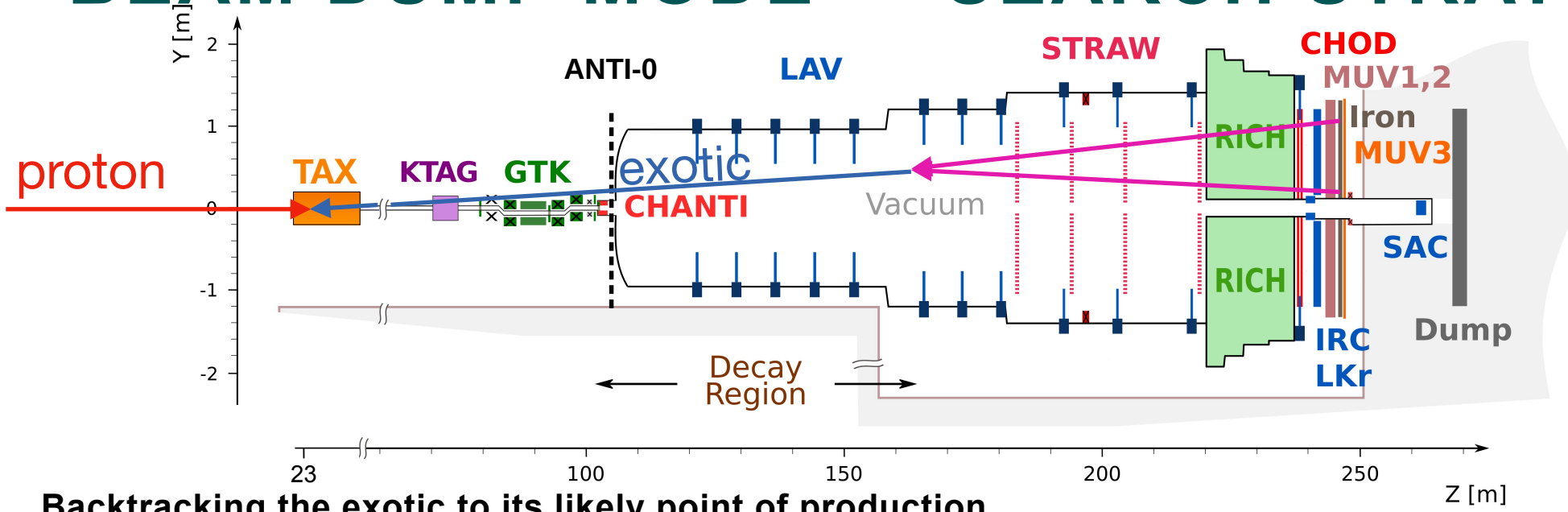

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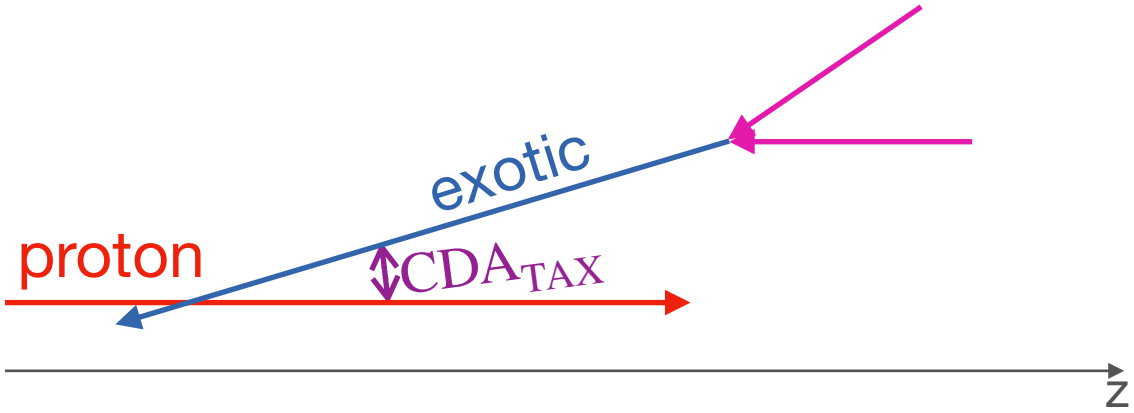

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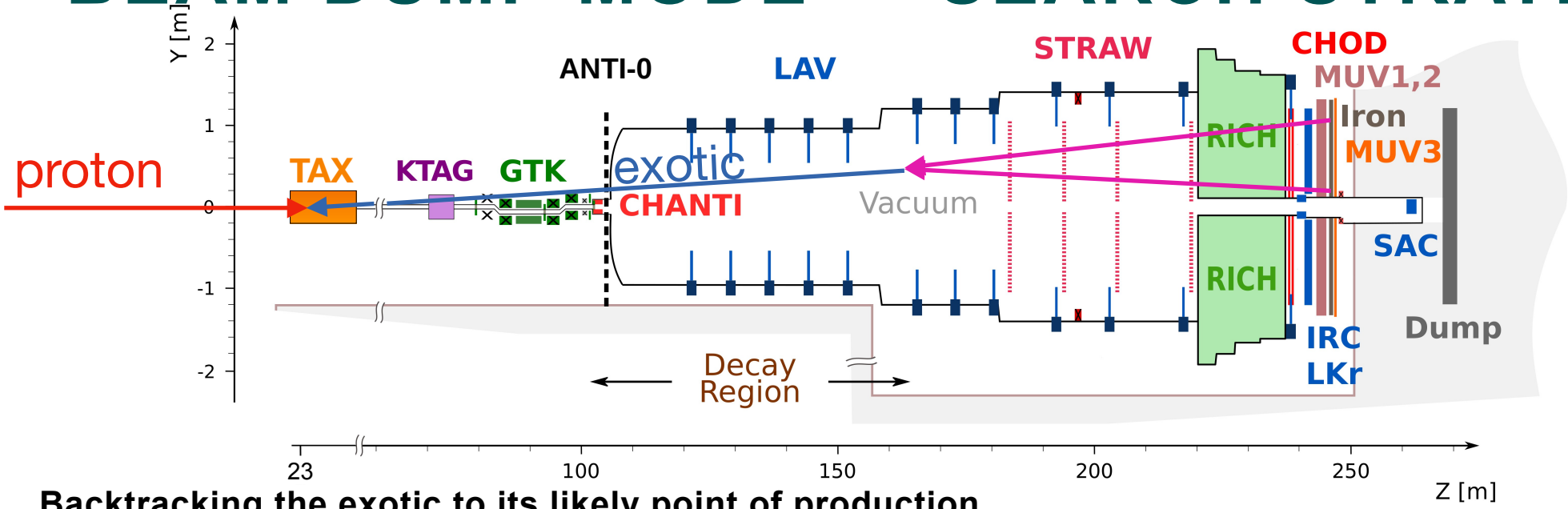

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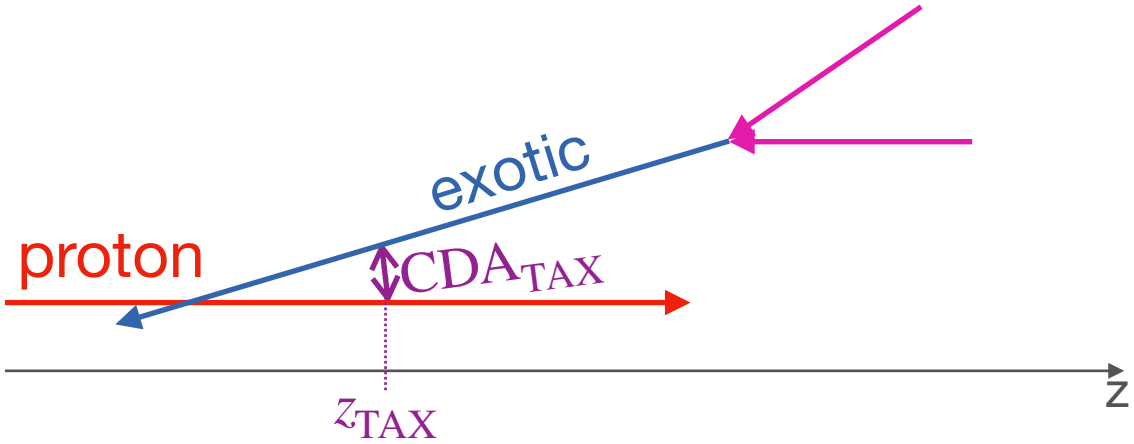

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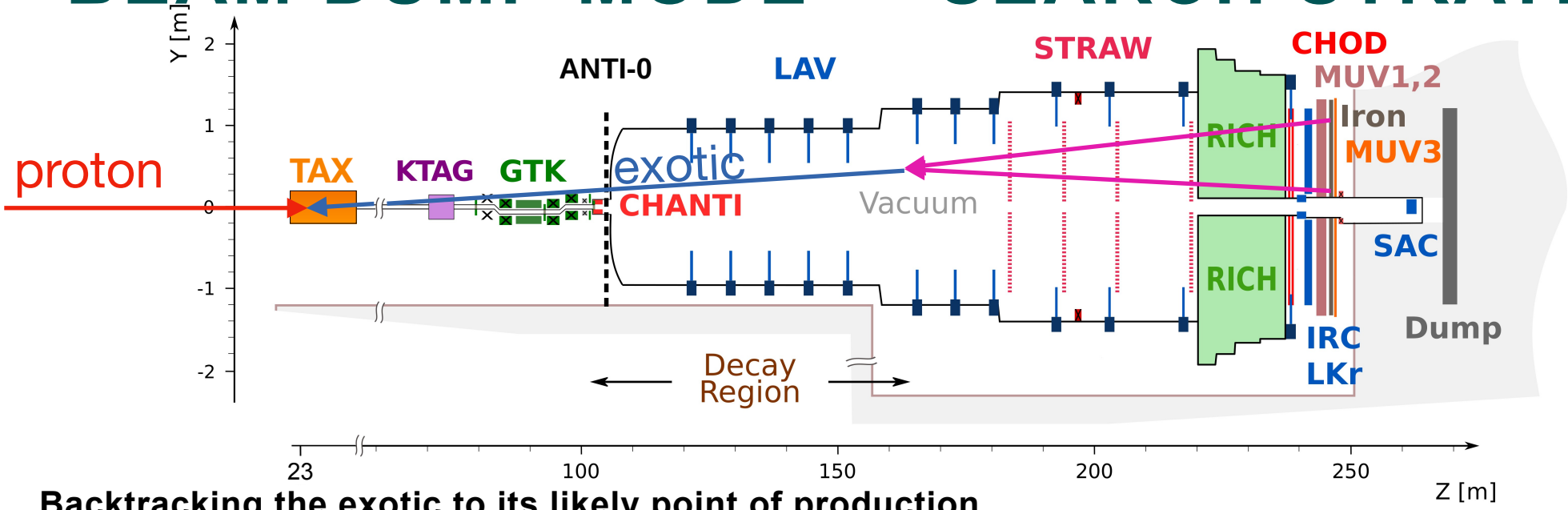

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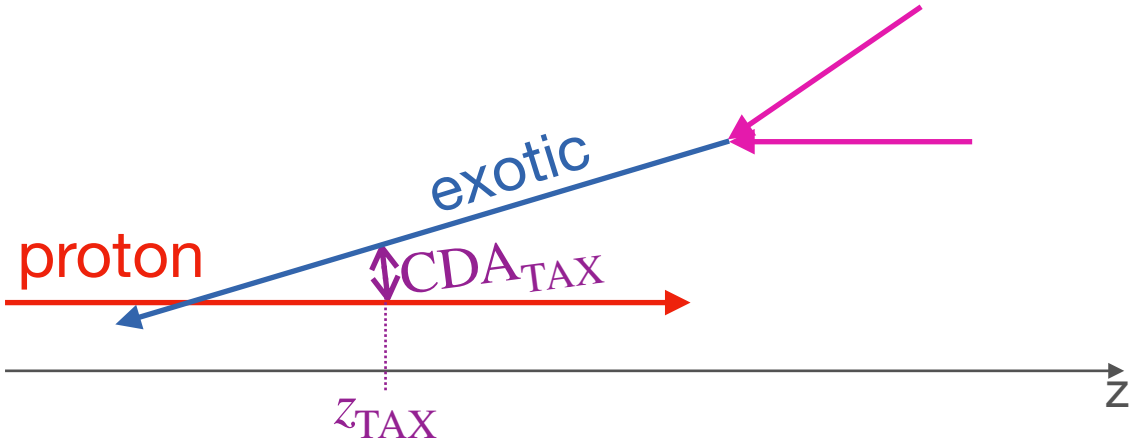

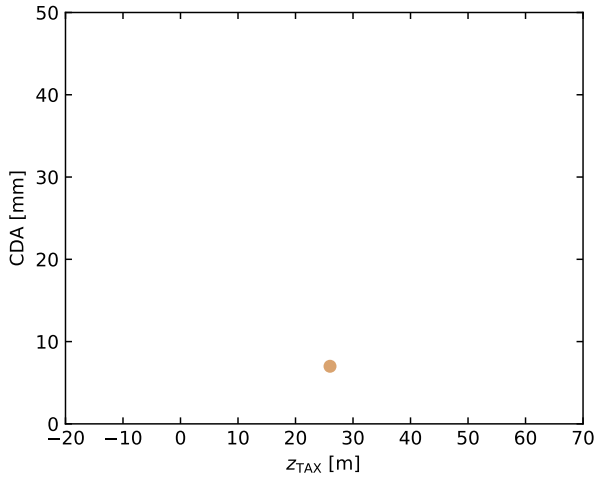

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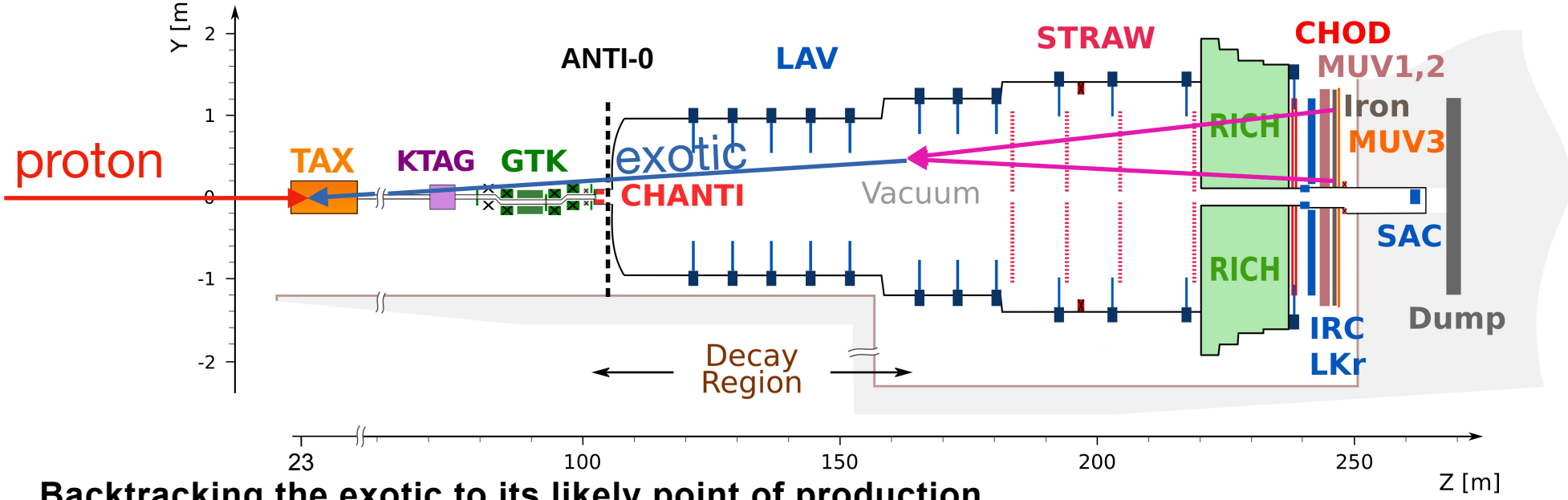

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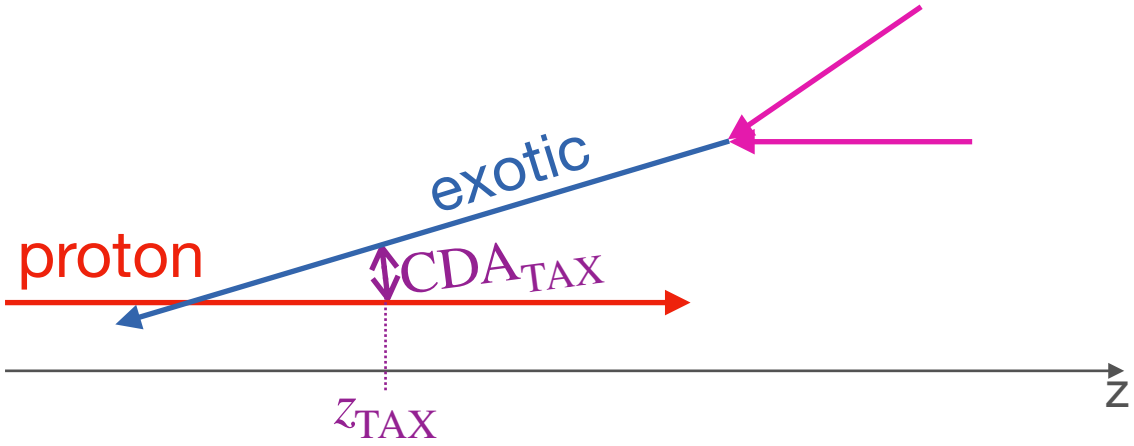

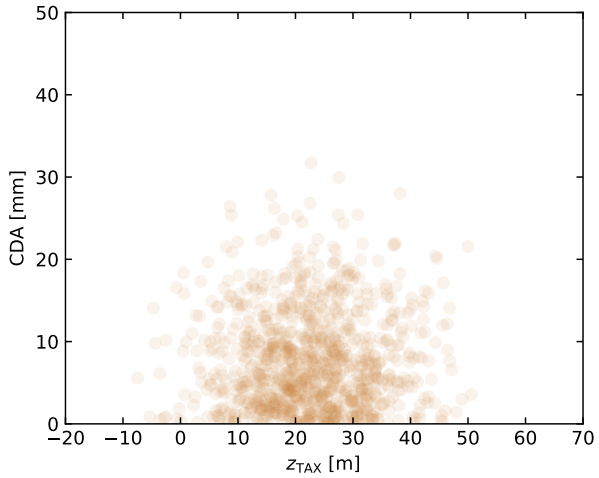

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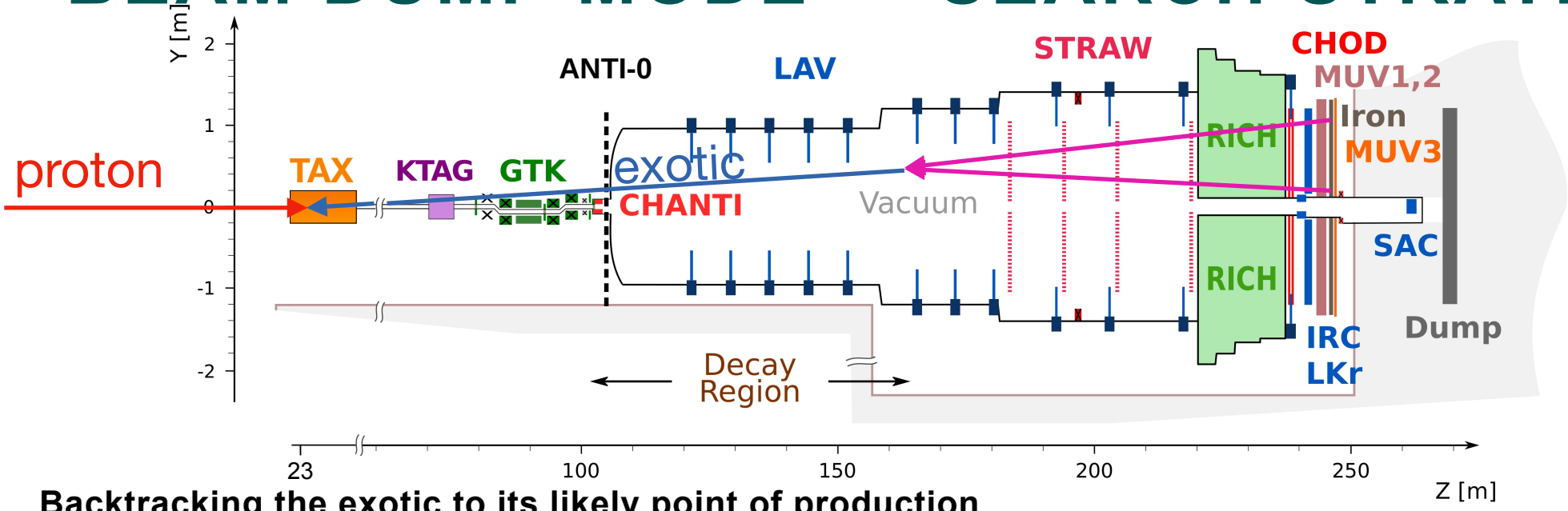

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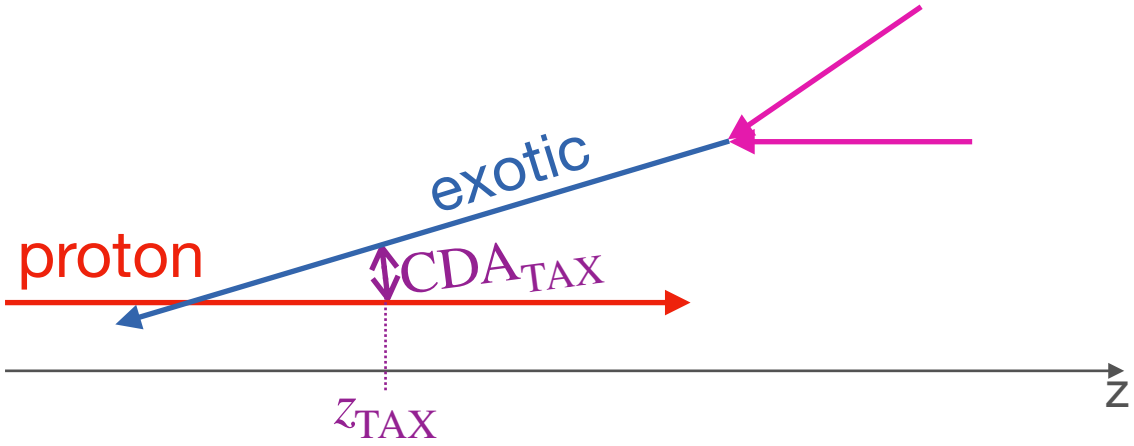

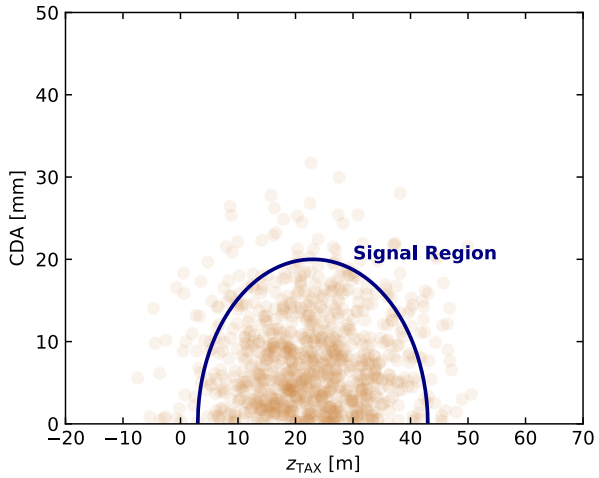

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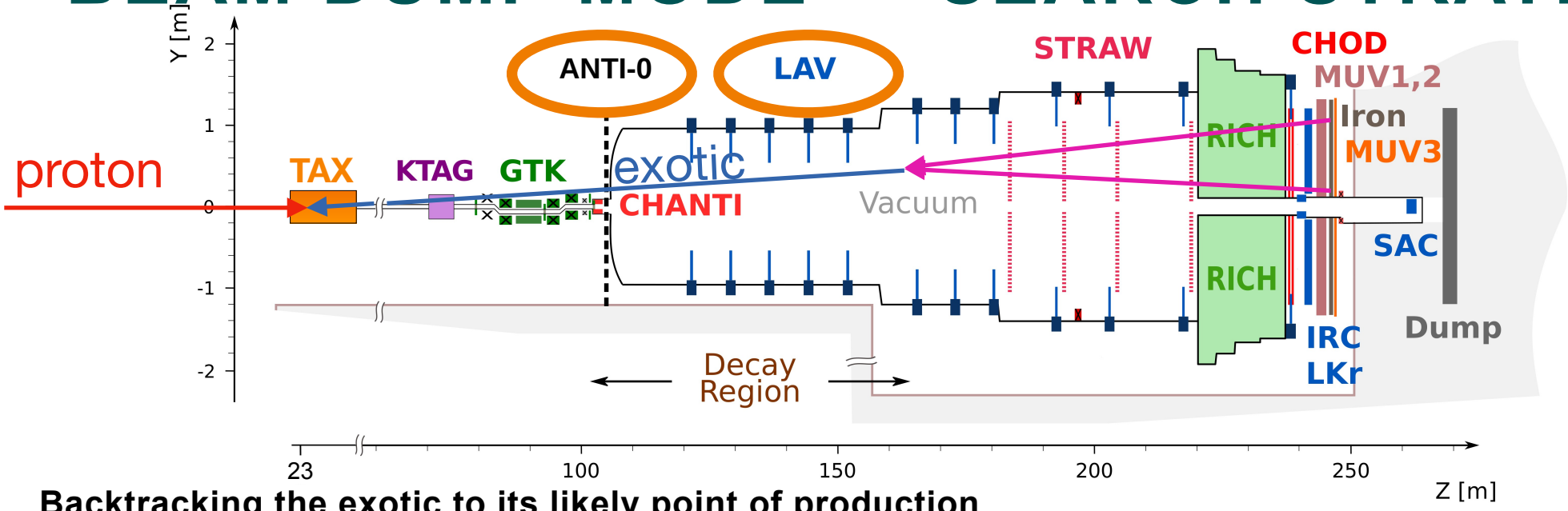

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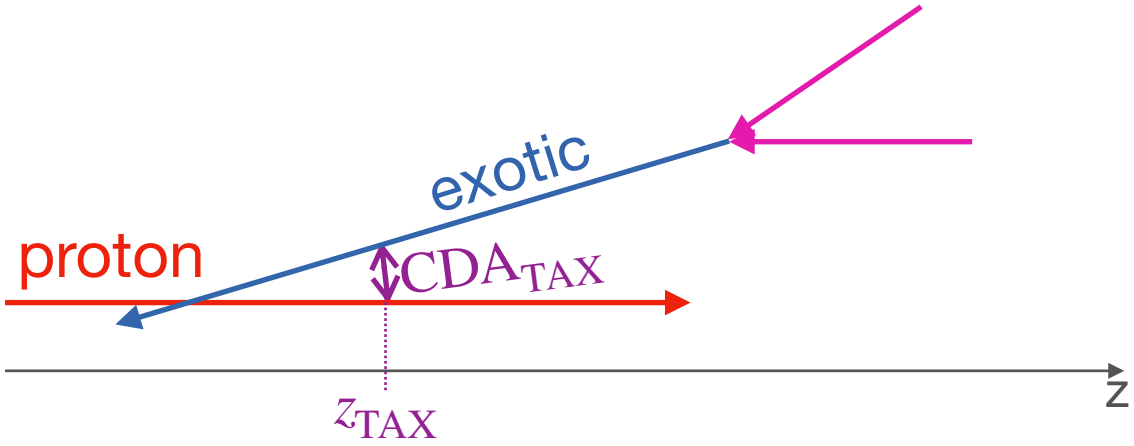
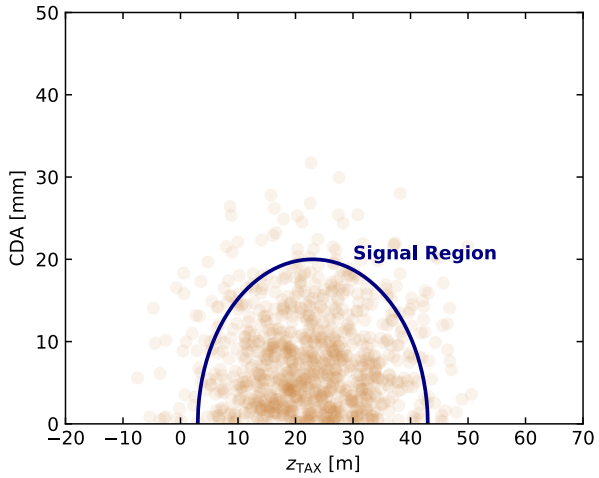
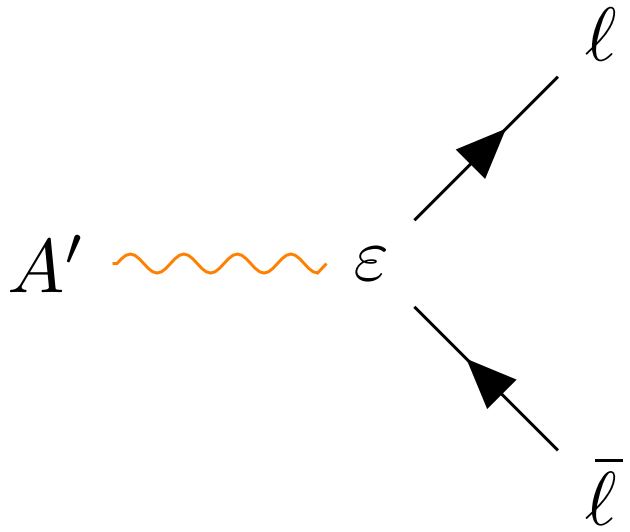




PAST SEARCHES WITH THE NA62 BEAM DUMP

Dark photon A' can couple to SM leptons with suppression ε

- **Two-lepton searches already performed at NA62**



[2303.08666, 2312.12055]

Disclaimer: these are only illustrative examples.
The searches are performed in a model independent way

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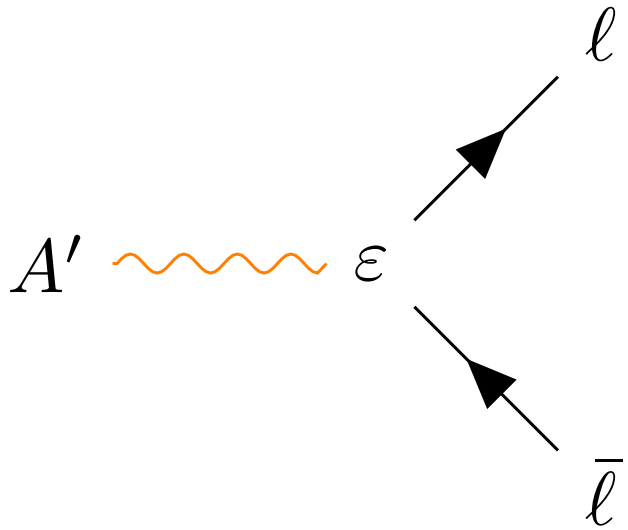
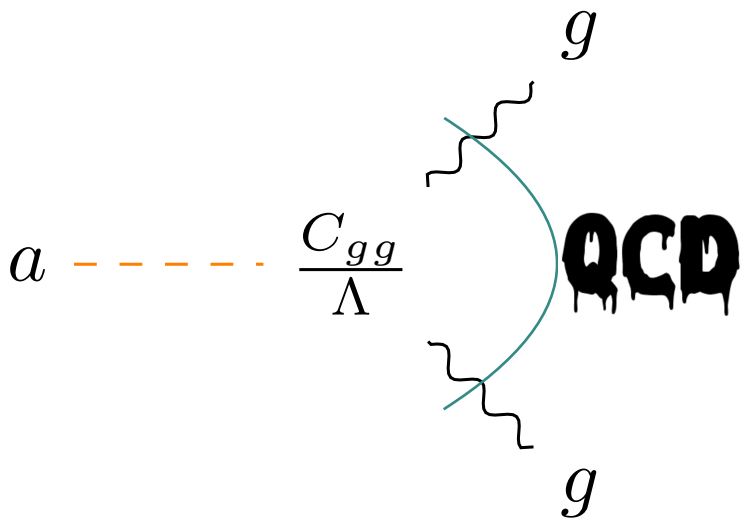


[2303.08666, 2312.12055]

Axion-Like-Particle a can couple to gluon pair with coupling $\frac{C_{gg}}{\Lambda}$

- **Search for hadronic final states**



[forthcoming]

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EXOTIC SIGNAL MODELLING FOR HADRONIC FINAL STATES

Numerous exotic models can potentially decay into this class of final states

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^-	
$K^+K^-\pi^0$		$K^+K^-\pi^0$

These can be produced in various mechanisms:

- **Dark Photon**
  - Dark Bremsstrahlung
  - Mixing with vector mesons ($\rho, \omega\, \phi$)
- **Dark Scalar**
  - Beauty meson decay ($B^{\pm,0} \to K^{\pm,0,(*)}S$)
- **Axion Like Particles**
  - Primakoff (on- and off-shell)
  - mixing with pseudoscalar mesons (π^0, η, η')
  - Beauty meson decay ($B^{\pm,0} \to K^{\pm,0,(*)}a$)

Total of 36 combinations to be studied.

ANALYSIS STRATEGY

Hadron pair track selection

- **two good quality tracks** within **time coincidence** of one another and trigger ($|\Delta t_{\mathrm{CHOD}}| < 5$ ns)
- Boosted Decision Tree based particle ID (Tracker+calorimeters, and RICH for tagging kaons)
- no in-time activity in veto systems (ANTI0, LAV, SAV, MUV3)
- good quality decay **vertex reconstructed** inside of **fiducial volume**

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Search strategy (once we found two tracks)

- additionally search **neutral clusters in E.cal.** (LKr) to reconstruct γ, π^0, η using time coincidence and opening angle
- reconstructed exotic particle momentum **traced back** to closest distance with proton beam and definition of **Signal Region** around expected production point
- Signal and control regions remain **masked** until final approval

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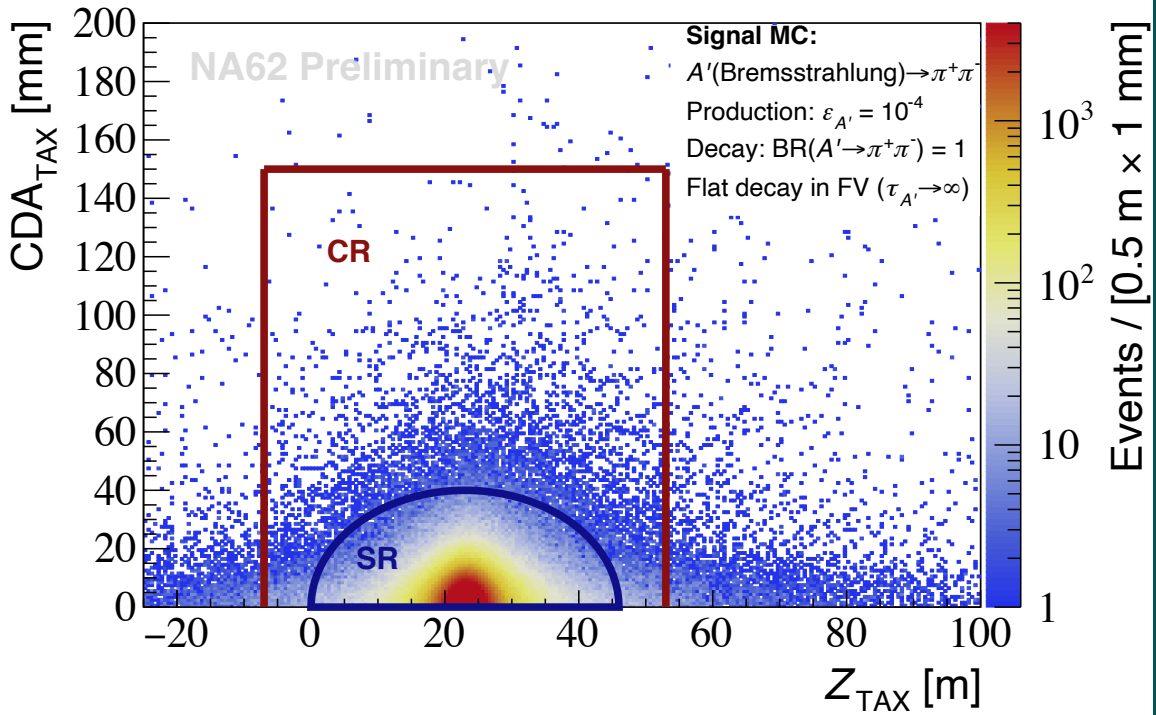


$A' \to \pi^+\pi^-$ Signal MC with signal (SR) and control region (CR)

BACKGROUNDS
OVERVIEW IN THREE CATEGORIES

Combinatorial and neutrino-induced backgrounds

- giving only negligible contributions ($N_{\mathrm{exp}}^{\mathrm{single\,track}} < 10^{-3}$)

Prompt background (inelastic interactions of halo muons producing hadrons)

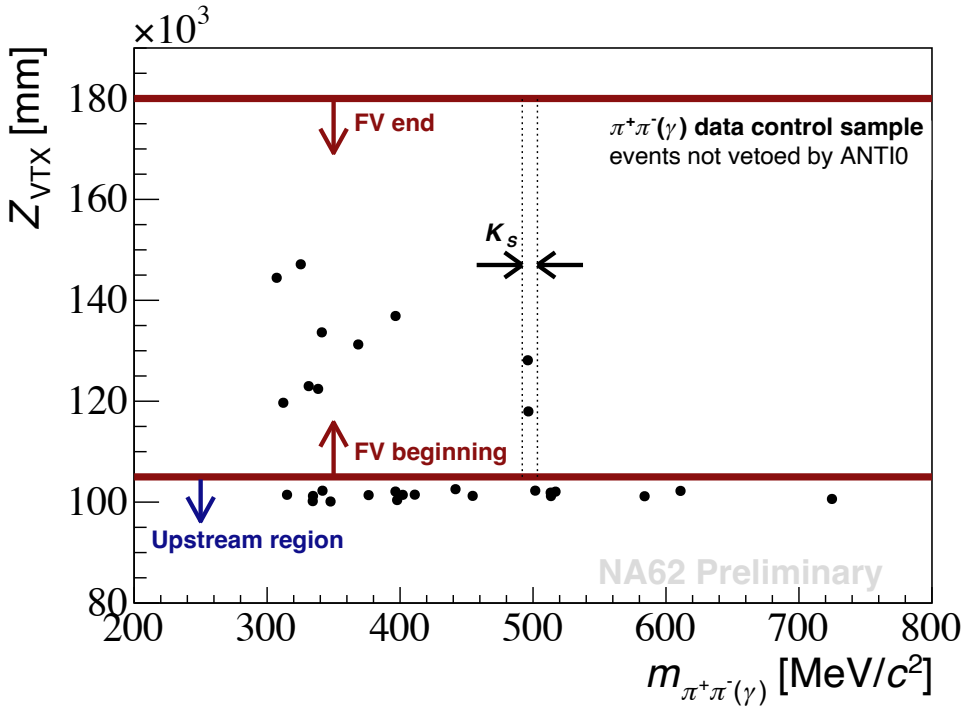
- estimated with data-driven backward MC evaluation of muon halo
- MC sat. equivalent $N_{\mathrm{PoT}} = 1.53 \times 10^{17}$exceeds data stat.
- control sample (in ANTI0 acceptance+no vetoes applied)
  - $N_{\mathrm{exp}} = 1.8 \pm 1.4$ with $N_{\mathrm{obs}} = 1$ in upstream region
  - $N_{\mathrm{exp}} = 0.20 \pm 0.15$ with $N_{\mathrm{obs}} = 1$ in fiducial volume
- after applying **full selection criteria $N_{\mathrm{exp}} < 10^{-4}$ for all channels** in CR and SR

Upstream background (likely beam remnant interaction with GTK achromat)

BACKGROUNDS UPSTREAM IN DEPTH

Control sample (no Anti0 veto) contained

- 19 upstream events
  - vetoed by Anti0
- 2 $K_S \to \pi^+\pi^-$
  - mask 3σ window in $m_{\pi\pi}$ around m_{K_S}



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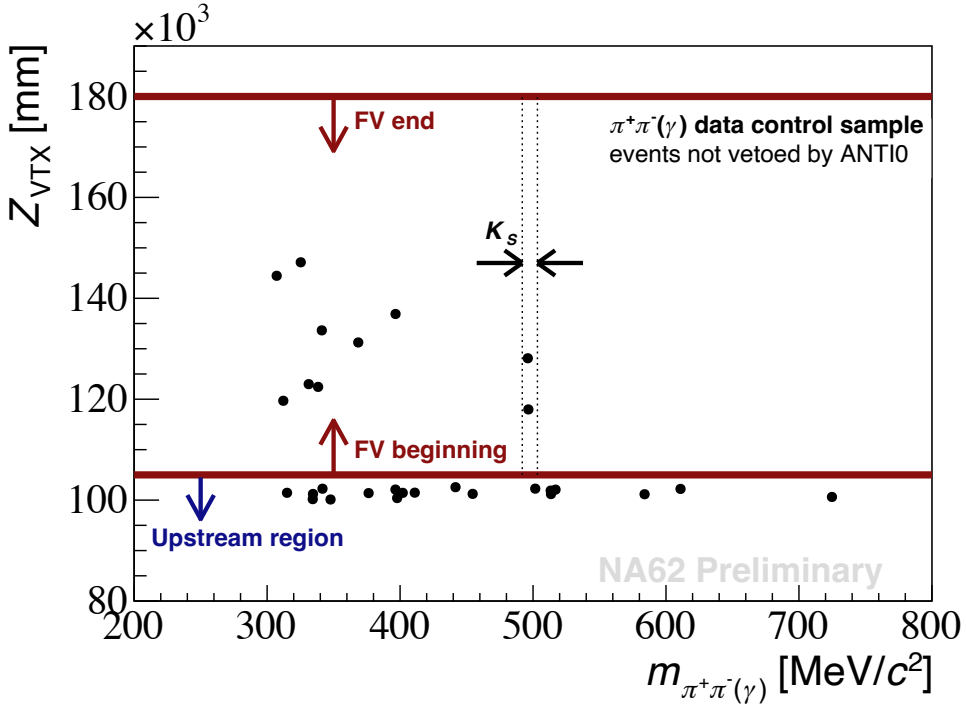
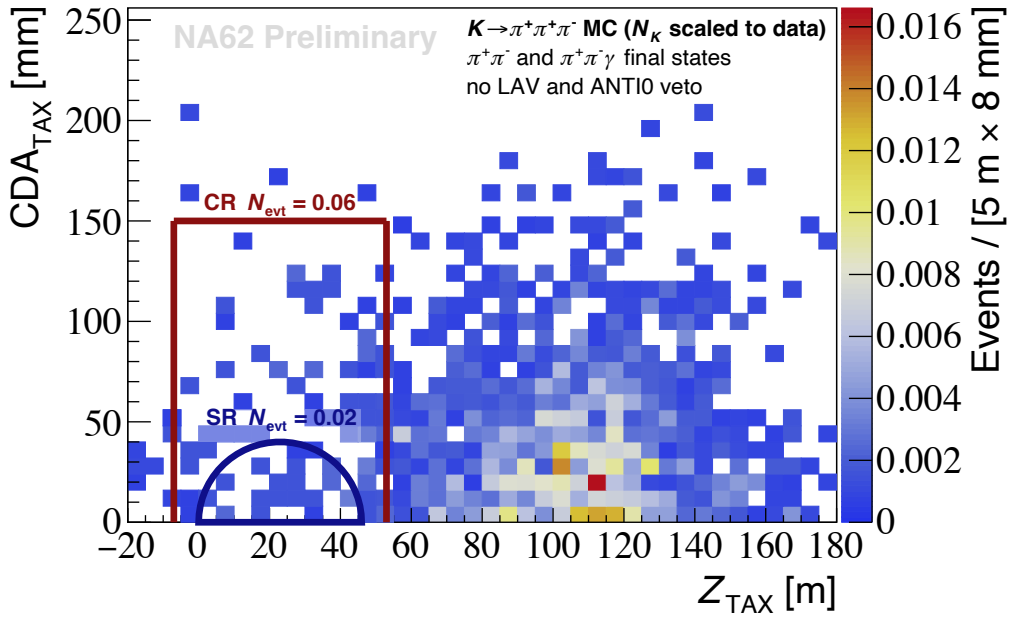
- 8 $K^+ \to \pi^+\pi^+\pi^-$ (8 ± 4 exp.)
  - Id as $6 \times \pi^+\pi^-$ and $2 \times \pi^+\pi^-\gamma$
  - 1 obs. (1.0 ± 0.5 exp.) after requiring Anti0 acceptance





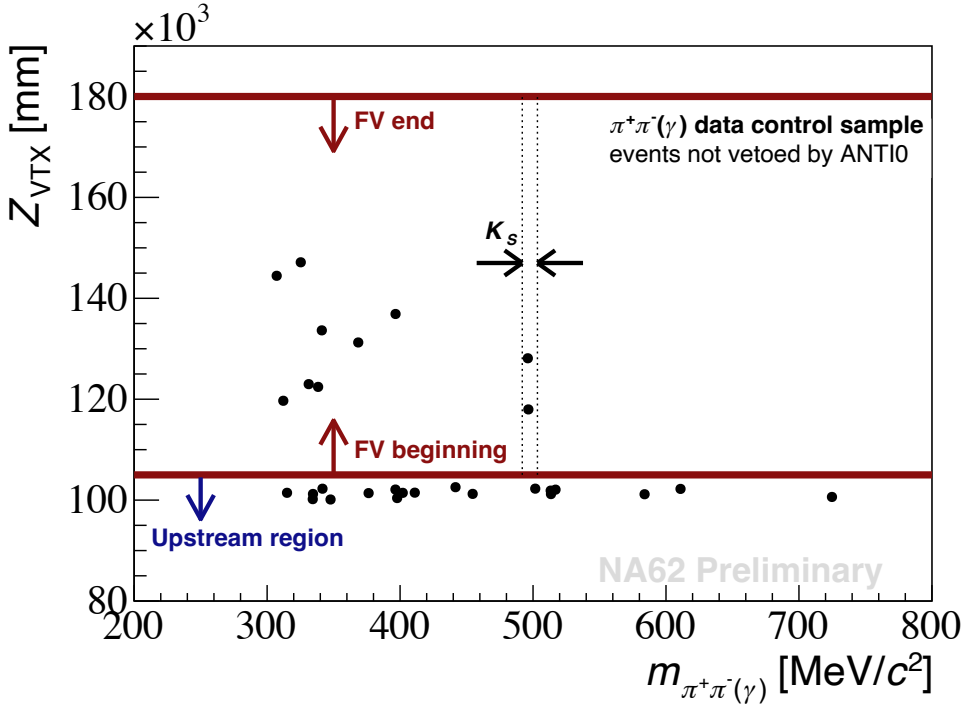
BACKGROUNDS UPSTREAM IN DEPTH

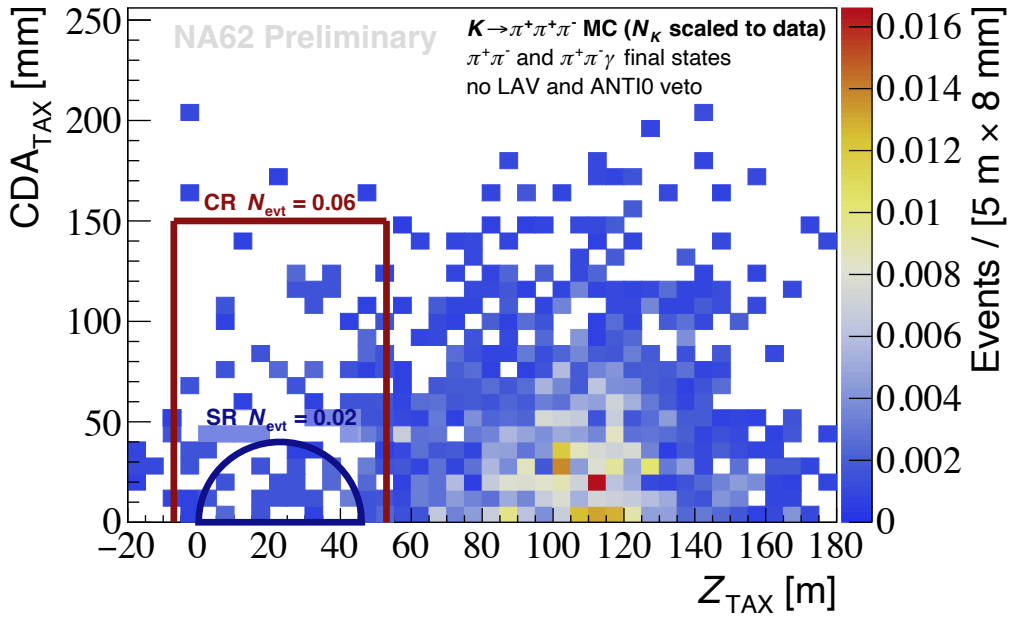
Control sample (no Anti0 veto) contained

- 19 upstream events
  - vetoed by Anti0
- 2 $K_S \to \pi^+\pi^-$
  - mask 3σ window in $m_{\pi\pi}$ around m_{K_S}
- 8 $K^+ \to \pi^+\pi^+\pi^-$ (8 ± 4 exp.)
  - Id as $6 \times \pi^+\pi^-$ and $2 \times \pi^+\pi^-\gamma$
  - 1 obs. (1.0 ± 0.5 exp.) after requiring Anti0 acceptance

Channel	$N_{\mathrm{exp,CR}} \pm \delta N_{\mathrm{exp,CR}}$	$N_{\mathrm{exp,SR}} \pm \delta N_{\mathrm{exp,SR}}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004

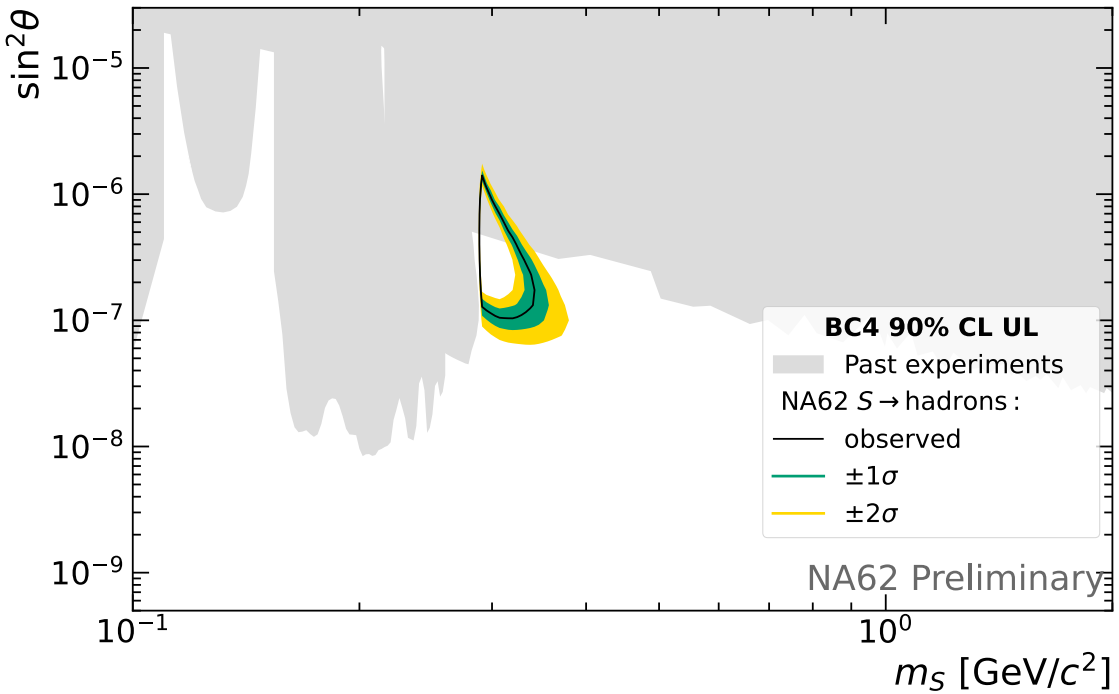
$K_{4\ell}$ simulated and gave only negligible backgrounds

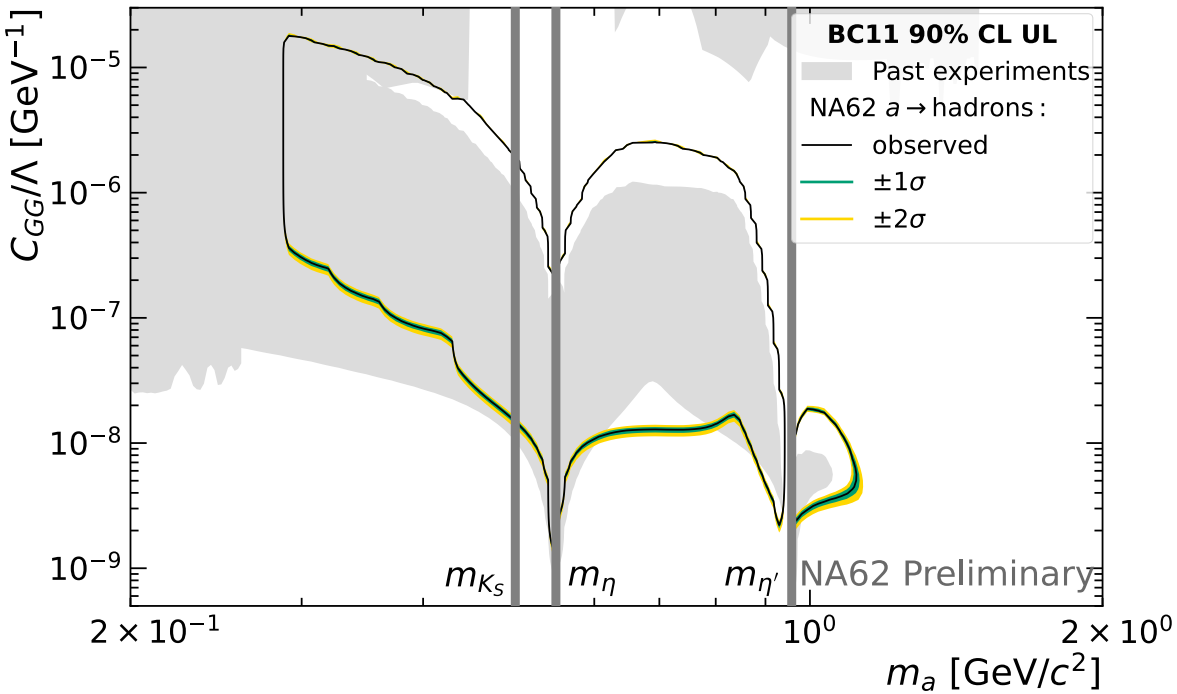




FINAL RESULT

Upon opening 0 events were found in all Control and Signal Regions





Stand alone **parameter exclusions on Dark Scalar** (BC4) and **gluon coupled Axion Like Particle** (BC11)

CONCLUSIONS

1. Presented preliminary result covers the search for the decay of an **exotic particle to a hadronic final state** on the 2021 data set collected by the NA62 experiment in beam-dump mode
   - **No event compatible with a new physics signal was observed**
   - **Complements leptonic final states** analyses analysis by exploring new parameter space
2. Searches for **semi-leptonic** and **di-gamma** final states are **ongoing**
3. **Data-taking ongoing** (new sample collected in 2023) with a **total of 10^{18} PoT expected** by LHC LS3
   - Exciting prospects for searches for Dark Photons, Dark Scalars, Heavy Neutral Leptons, and Axion Like Particles

BACKUPS

SIGNAL SENSITIVITY

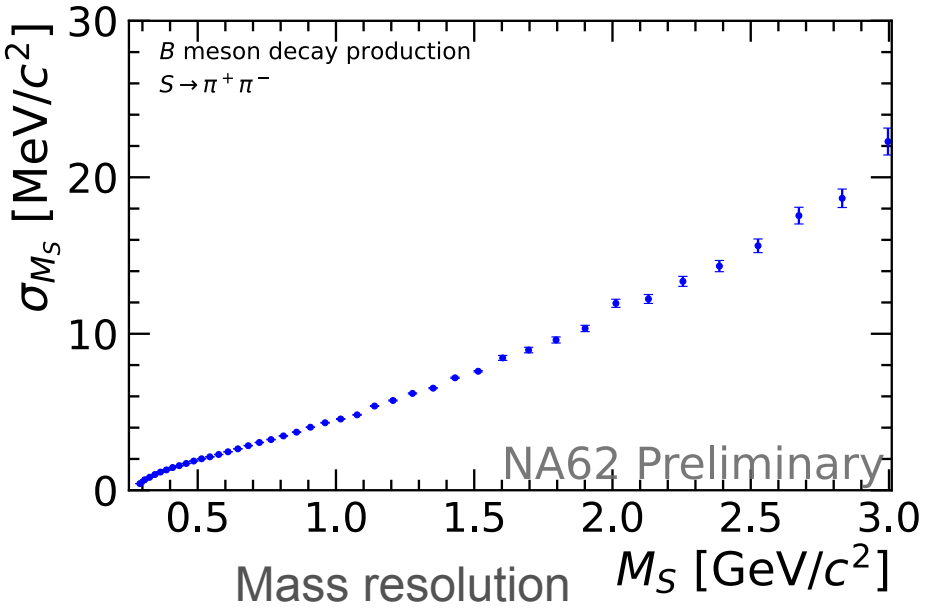
$$N_{\mathrm{exp}}(m_X, \Gamma_X) = N_{\mathrm{PoT}} \chi_{pp\to X}(g_{\mathrm{ref}}) P_{\mathrm{rd}} A_{\mathrm{acc}} A_{\mathrm{trig}}$$

$\chi_{pp\to X}(g_{\mathrm{ref}})$ exotic production probability

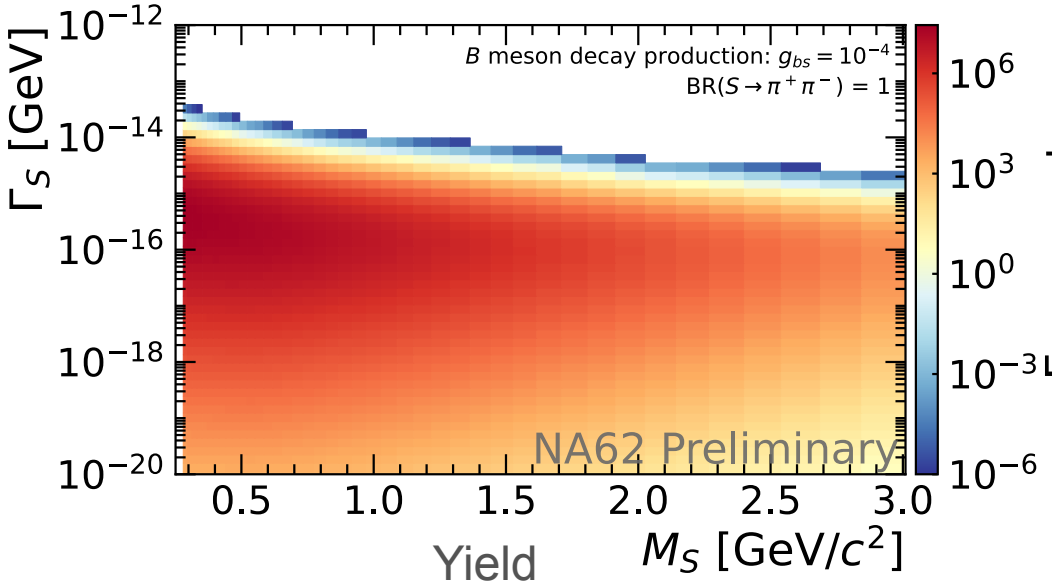
P_{rd} probability to reach the decay volume

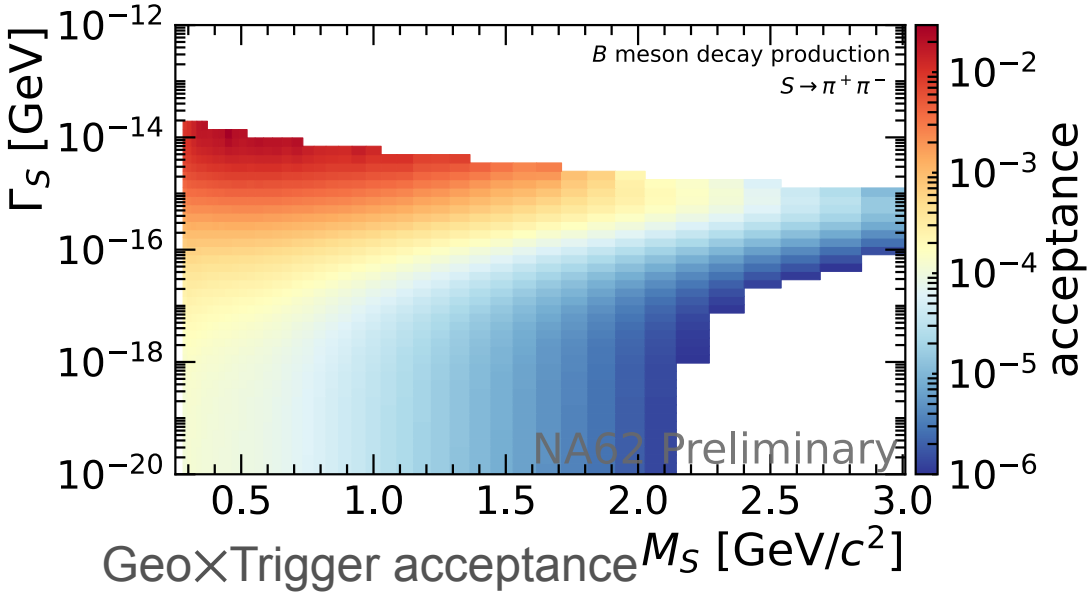
A_{acc} geometrical acceptance

A_{trig} trigger acceptance



Example for $B \to S \to \pi^+\pi^-$ below





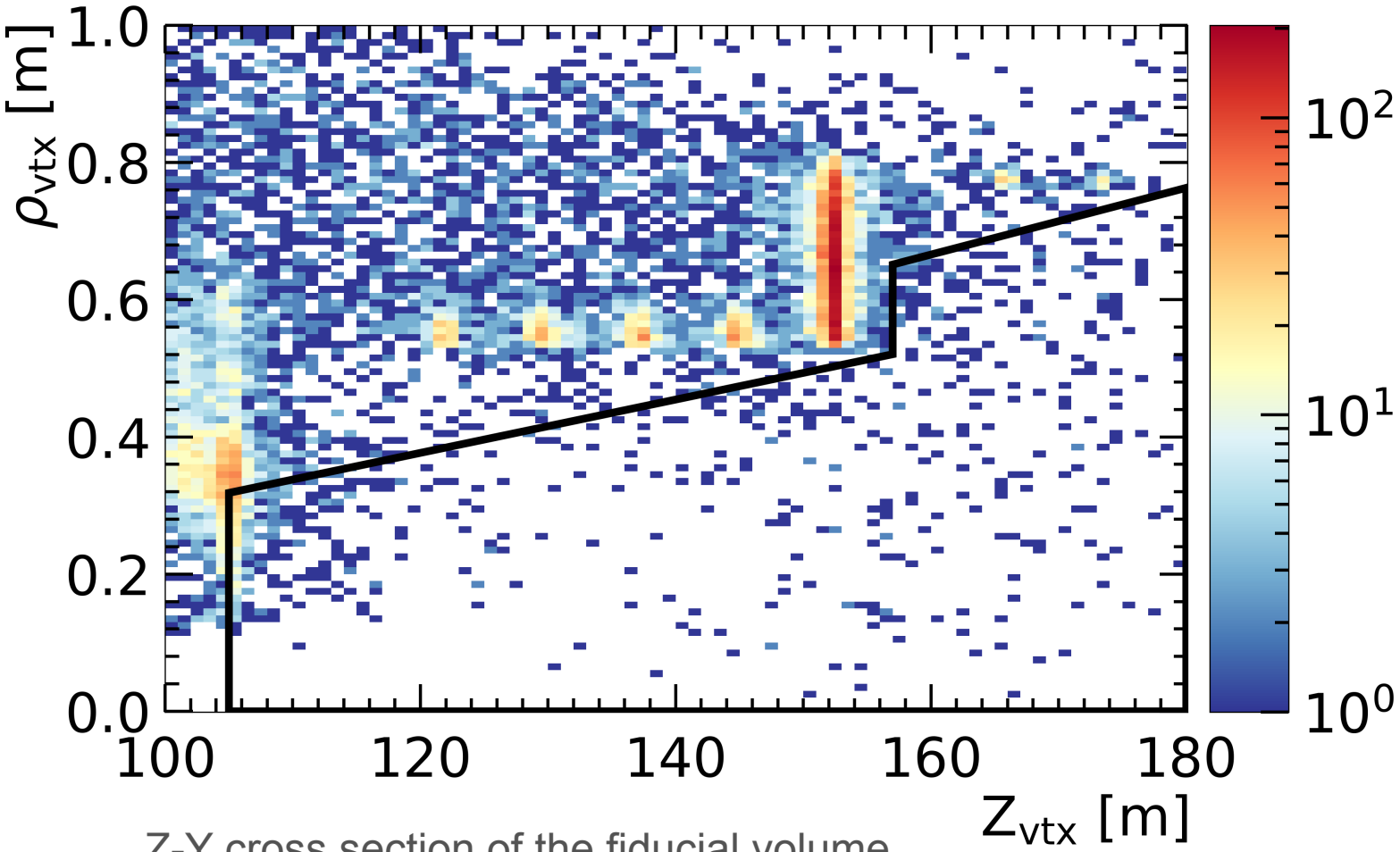
WHAT IS A GOOD QUALITY TRACK?

- Reconstructed momentum is higher than 10 GeV
- **Momentum reconstructed with good-quality** (χ^2 < 20 and a difference between momentum before and after the track fit < 20 GeV/c)
- Reconstructed **hits in at least three STRAW chambers**
- Within **geometrical acceptance** of the ANTI0, (New)CHOD, LKr, MUV1, MUV2, MUV3 detectors and outside the geometrical acceptance of LAV12
- **Away from any other track** by at least 20 mm at the first STRAW chamber to reduce the probability of sharing the same STRAW hits, as is typical of fake tracks
- When extrapolated at the LKr front plane, must be at least 200 mm distant from any other track, so to **avoid possible cluster overlapping**
- Associated to at least one NewCHOD candidate
- Track projection at the LKr is away from a dead LKr cell by more than 30 mm

THE FIDUCIAL VOLUME

Fiducial volume optimised to exclude secondary interactions in LAV stations 1–8

Example for $e\bar{e}$ two track data events below



Z-Y cross section of the fiducial volume

BACKGROUNDS BY CHANNELS
PROMPT BACKGROUND

Table 2: Summary of expected number of prompt background events at 68% CL for all studied decay channels in CR and SR after full selection.

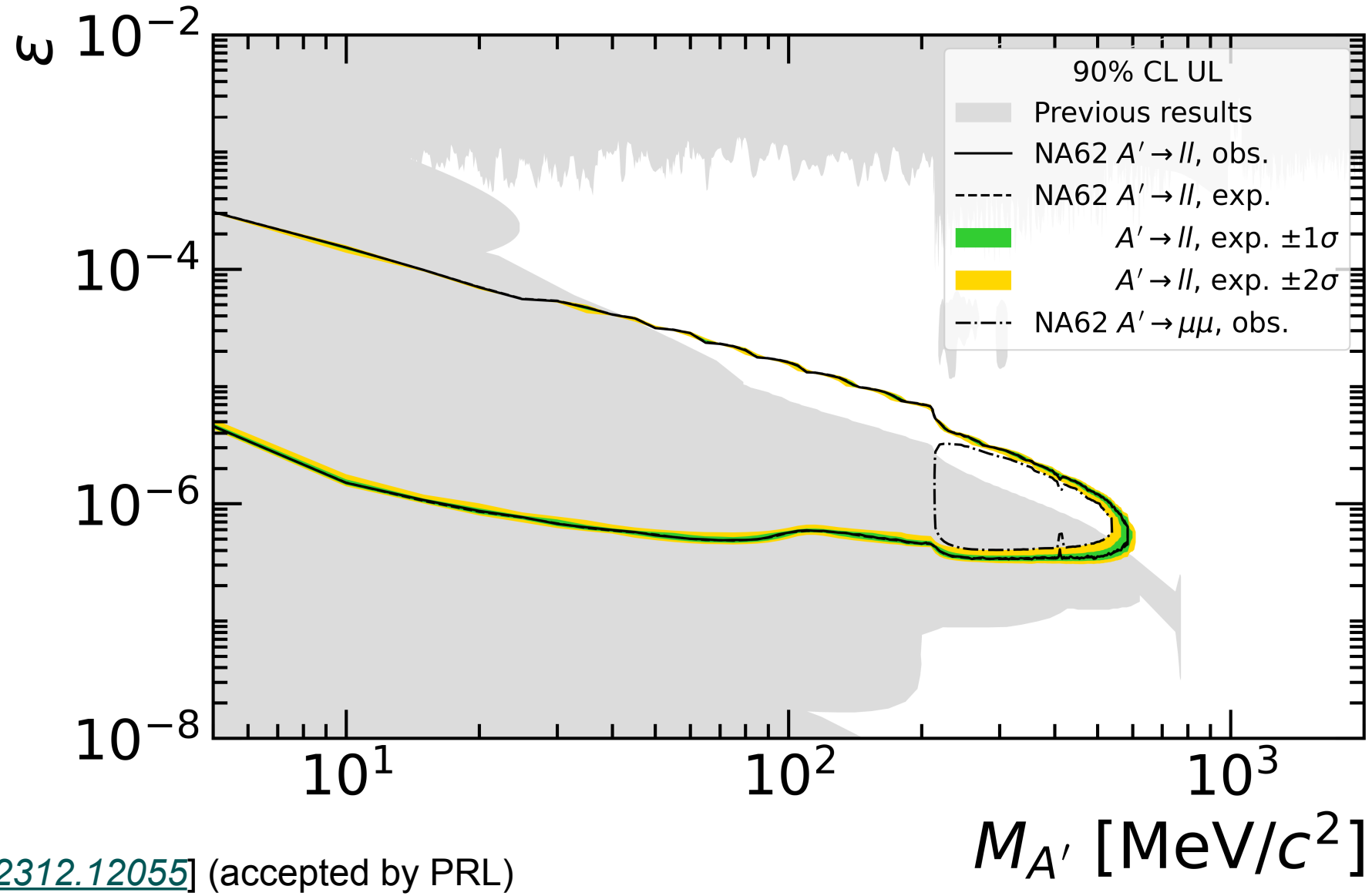
Channel	$N_{\mathrm{exp,CR}} \pm \delta N_{\mathrm{exp,CR}}$	$N_{\mathrm{exp,SR}} \pm \delta N_{\mathrm{exp,SR}}$
$\pi^+\pi^-$	$(5.7^{+18.5}_{-4.7}) \times 10^{-5}$	$(5.5^{+18.0}_{-4.5}) \times 10^{-5}$
$\pi^+\pi^-\gamma$	$(1.7^{+5.3}_{-1.4}) \times 10^{-5}$	$(1.6^{+5.2}_{-1.3}) \times 10^{-5}$
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$
K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$

BACKGROUNDS BY CHANNELS
GLOBAL SIGNIFICANCE LEVELS

Table 1: Summary of total expected number of background events at 68% CL for all studied decay channels in CR and SR after full selection. Needed number of observed events $N_{\rm obs}$ for p-value more than 5σ from background-only hypothesis in SR and SR+CR (global significance, flat background in $m_{\rm inv}$ assumption).

Channel	$N_{\rm exp,CR} \pm \delta N_{\rm exp,CR}$	$N_{\rm exp,SR} \pm \delta N_{\rm exp,SR}$	$N^{p>5\sigma}_{\rm obs,SR}$	$N^{p>5\sigma}_{\rm obs,SR+CR}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 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

DARK PHOTON EXCLUSION



See [2312.12055] (accepted by PRL)

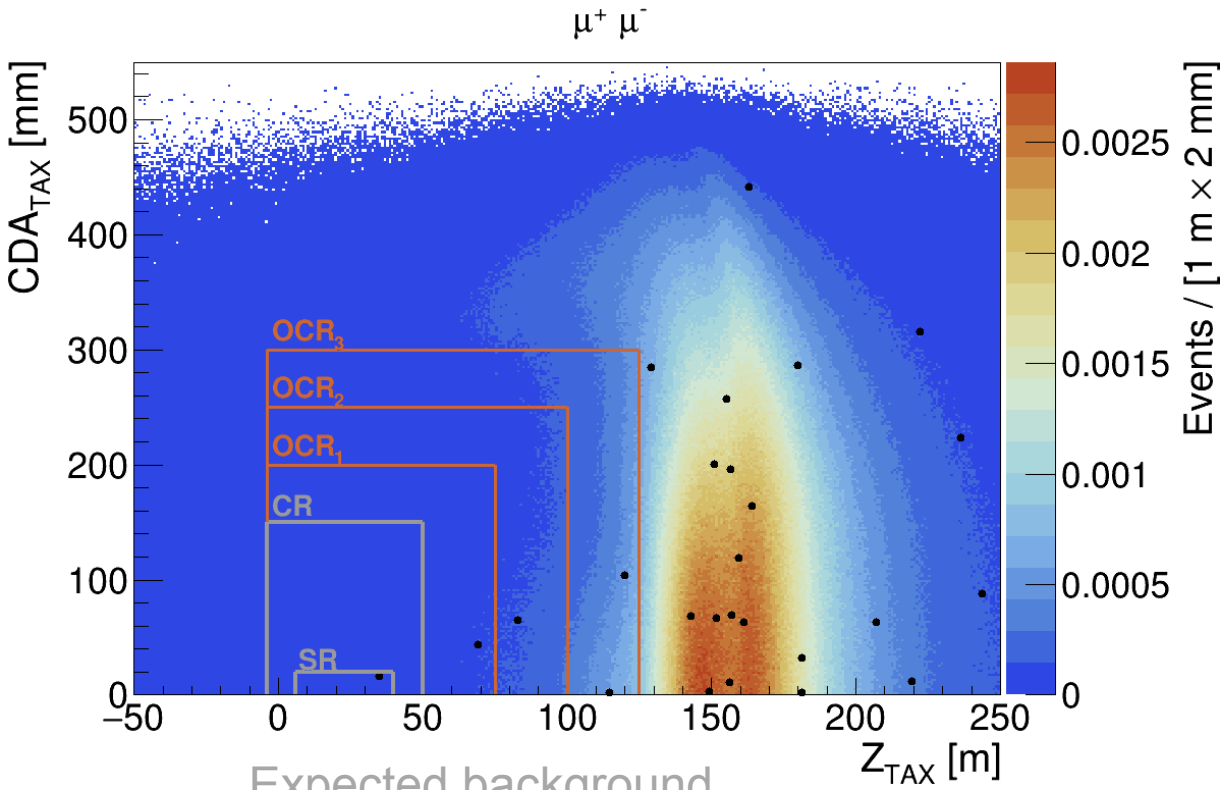
RESULTS FROM $\mu\bar{\mu}$ SEARCH

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**

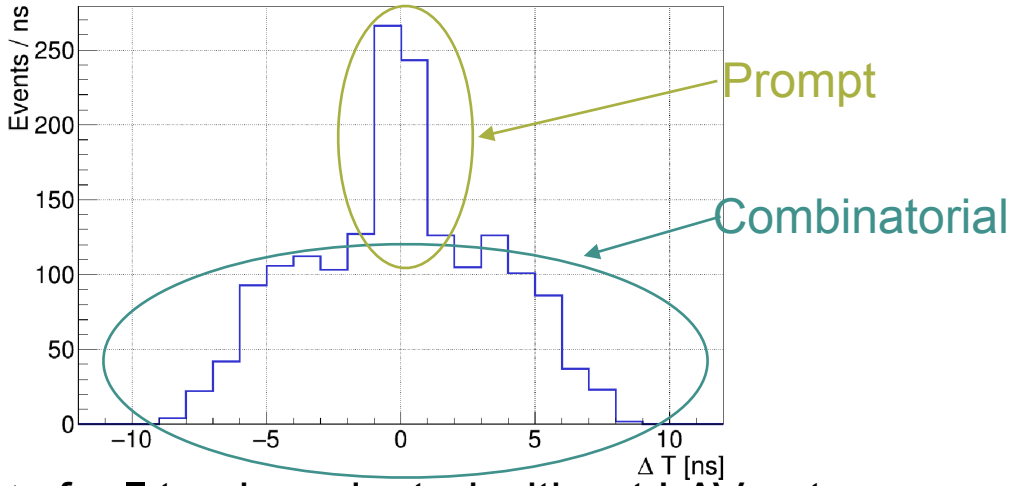
- **Invariant mass of event was** $411\,\mathrm{MeV}$



Expected background superimposed with data

See also [*JHEP09(2023)035*]

BACKGROUNDS IN $\mu\bar{\mu}$ SEARCH



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 $\sim 15\,\%$

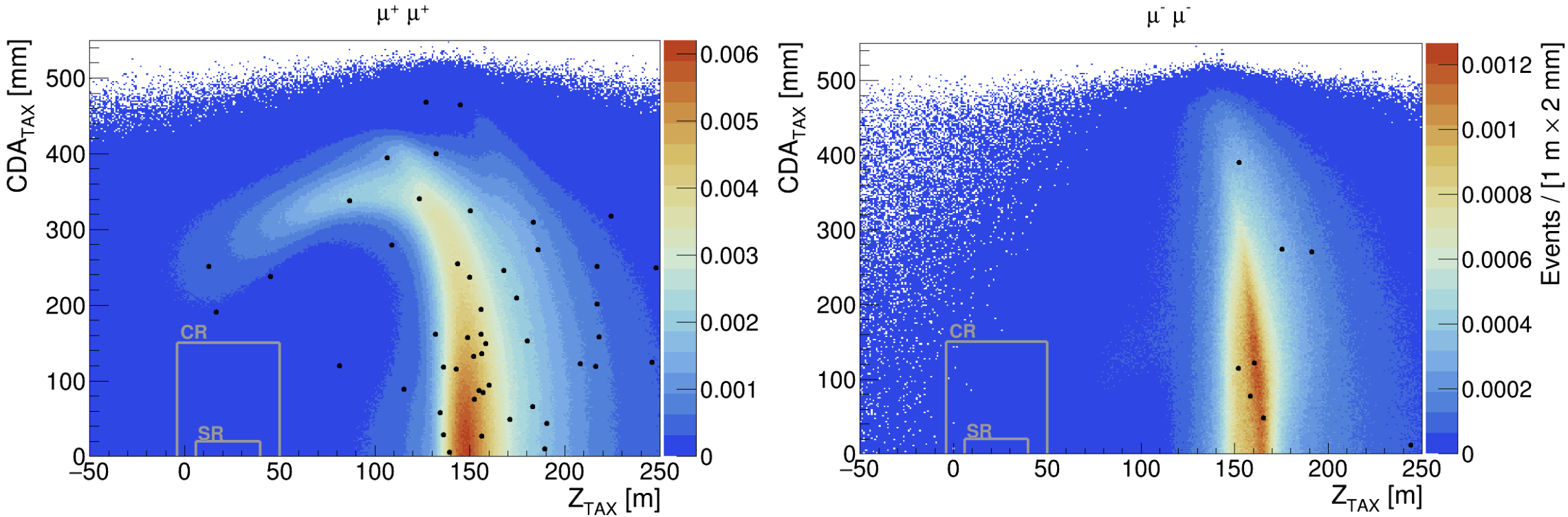
Region	Combinatorial	Prompt	Upstream-prompt
CR	0.17 ± 0.02	< 0.004	< 0.069
SR	0.016 ± 0.002	< 0.0004	< 0.007

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)

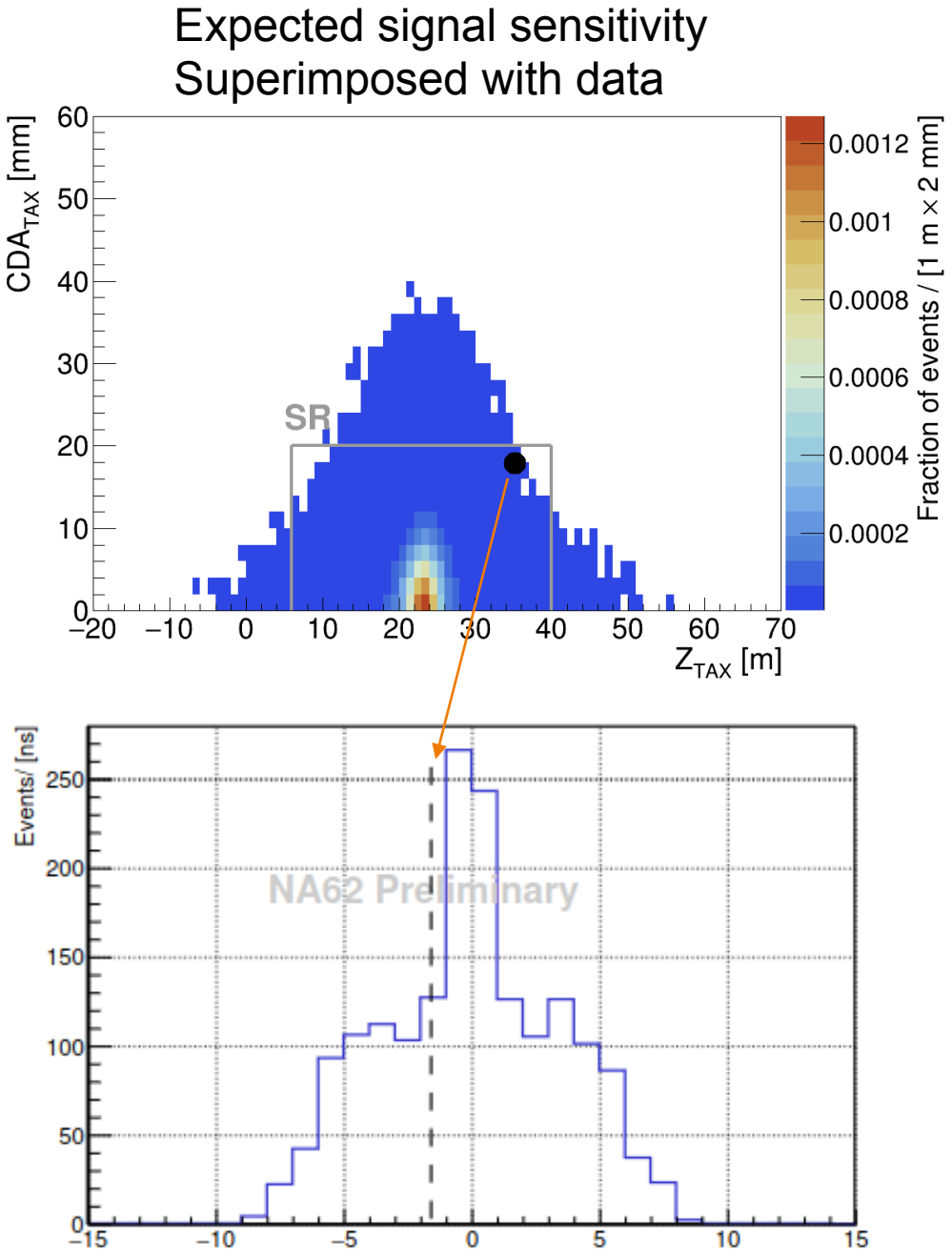


Data superimposed as black dots on MC distribution

Peculiar shape due to focusing elements

EVENT DETAILS FROM $\mu\bar{\mu}$ SEARCH

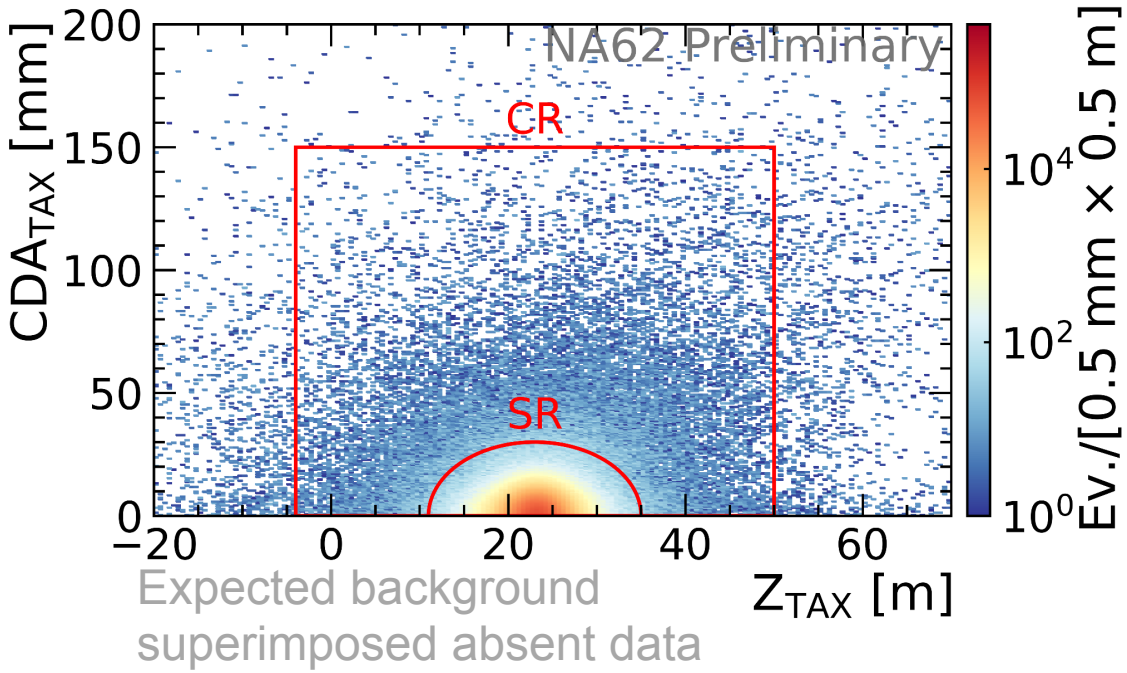
- **Invariant mass** $M_{\mu\mu} = 411\,\mathrm{MeV}$
- **Time difference** $\Delta t = -1.69\,\mathrm{ns}$
- **Momenta**
  - $p(\bar{\mu}) = 99.5\,\mathrm{GeV\,c^{-1}}$
  - $E/p(\bar{\mu}) = 0.008$
  - $p(\mu) = 39.6\,\mathrm{GeV\,c^{-1}}$
  - $E/p(\mu) = 0.018$
- **Vertex**
  - $z_{\mathrm{TAX}} =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



RESULTS FROM $e\bar{e}$ SEARCH

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

- **Probability to observe SM event in SR is** $1.6\,\%$
- **Statistical combination with $\mu\bar{\mu}$ search excludes dark photons in parameter space compatible with thermal relic density constraints**

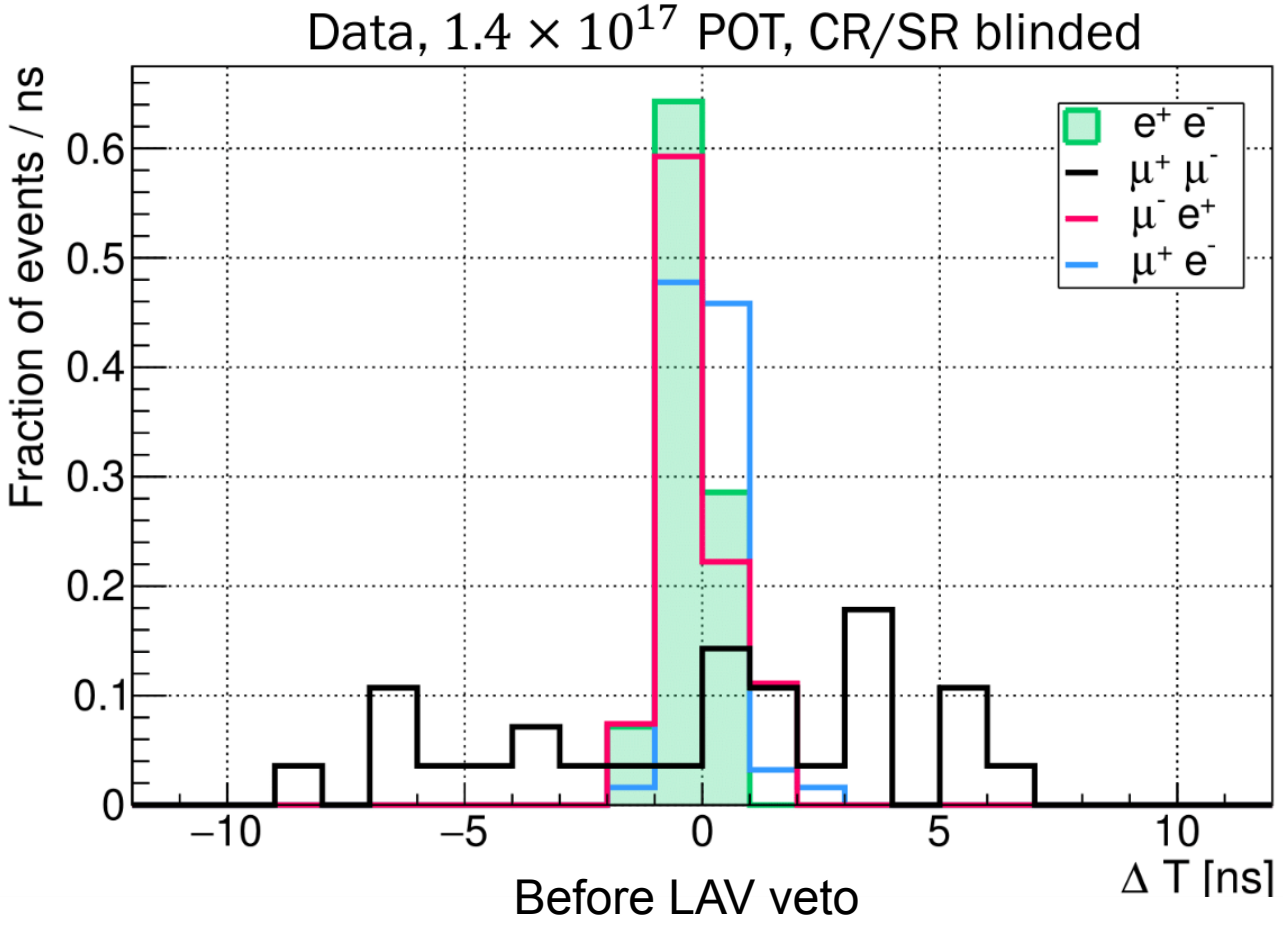


See also [2312.12055] (accepted by PRL)

BACKGROUNDS IN 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	$0.008^{+0.018}_{-0.006}$



BACKGROUNDS IN $e\bar{e}$ SEARCH

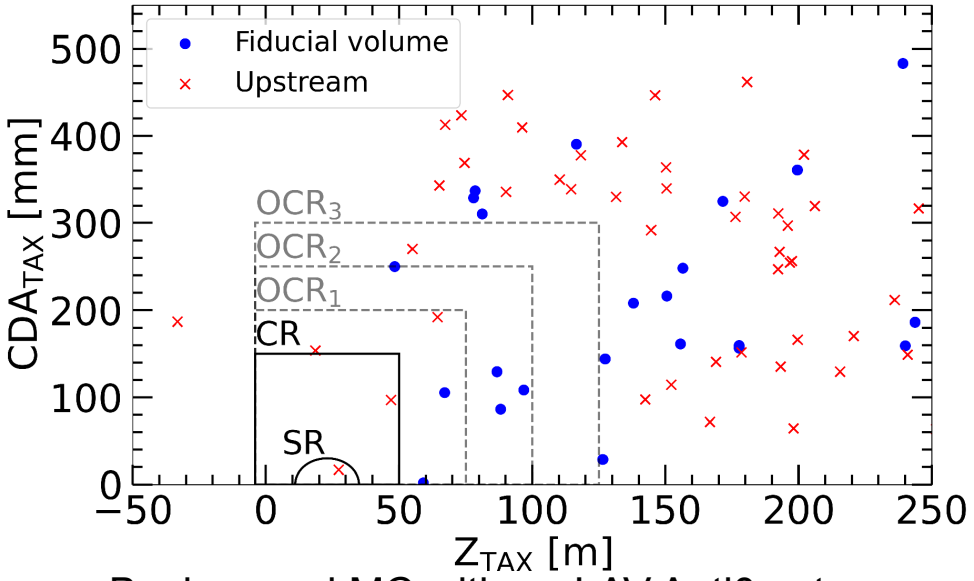
$$N_{\mathrm{bkg}}^{\mathrm{CR,SR}} = N_{\mathrm{bkg}}^{\mathrm{inFW}}(1-\eta_{\mathrm{LAV\ ANTI0}})(1-\eta_{\mathrm{CR,SR}})$$

which results in

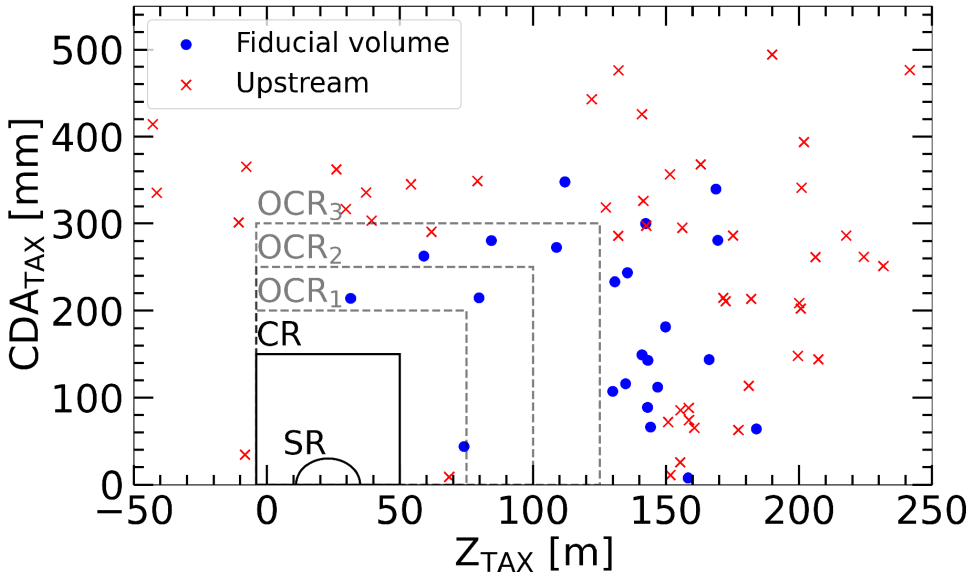
$$N_{\mathrm{bkg}}^{\mathrm{SR}} = 0.0094^{+0.049}_{-0.009}\ @\,90\,\%\,\mathrm{CL}$$

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

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



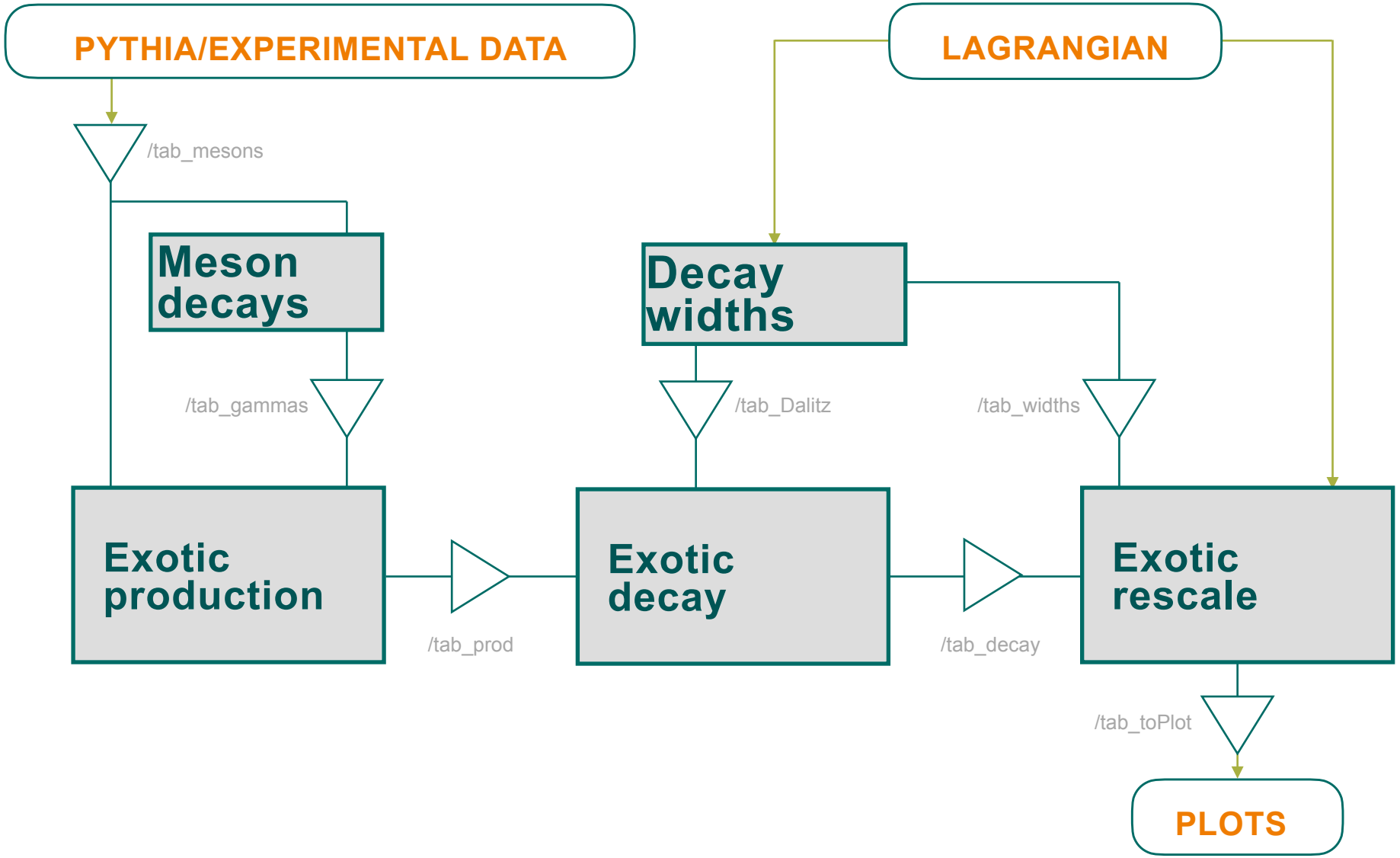
Background MC with no LAV,Anti0 veto



Background Data with no LAV,Anti0 veto

SR and CR blinded

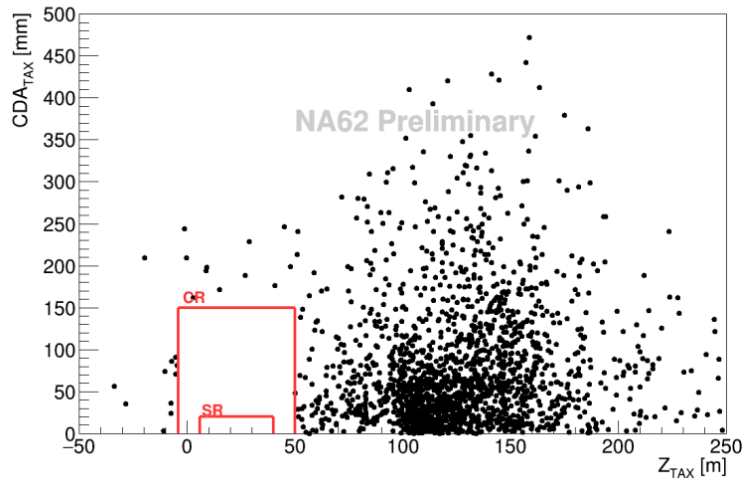
ALPINIST


PYTHIA/EXPERIMENTAL DATA
LAGRANGIAN
/tab_mesons
Meson decays
Decay widths
/tab_gammas
/tab_Dalitz
/tab_widths
Exotic production
Exotic decay
Exotic rescale
/tab_prod
/tab_decay
/tab_toPlot
PLOTS

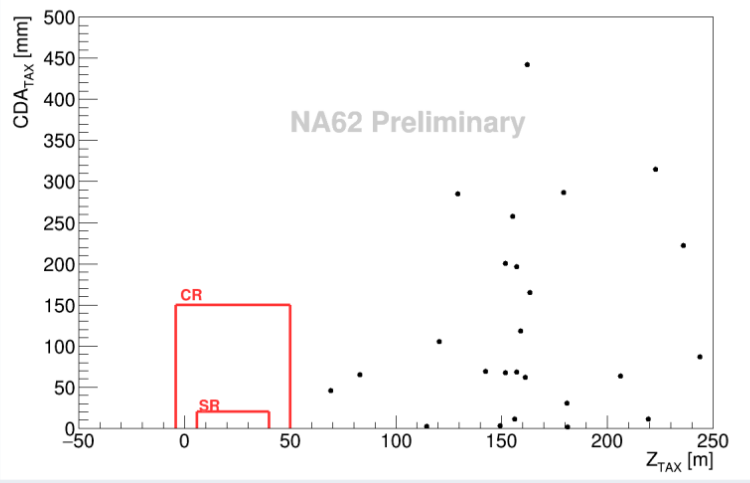
EXOTIC SEARCHES IN BEAM DUMP MODE REDUCING BACKGROUNDS

- **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**

2018 data: 2.6×10^{16} POT



2021 data: 1.4×10^{17} POT



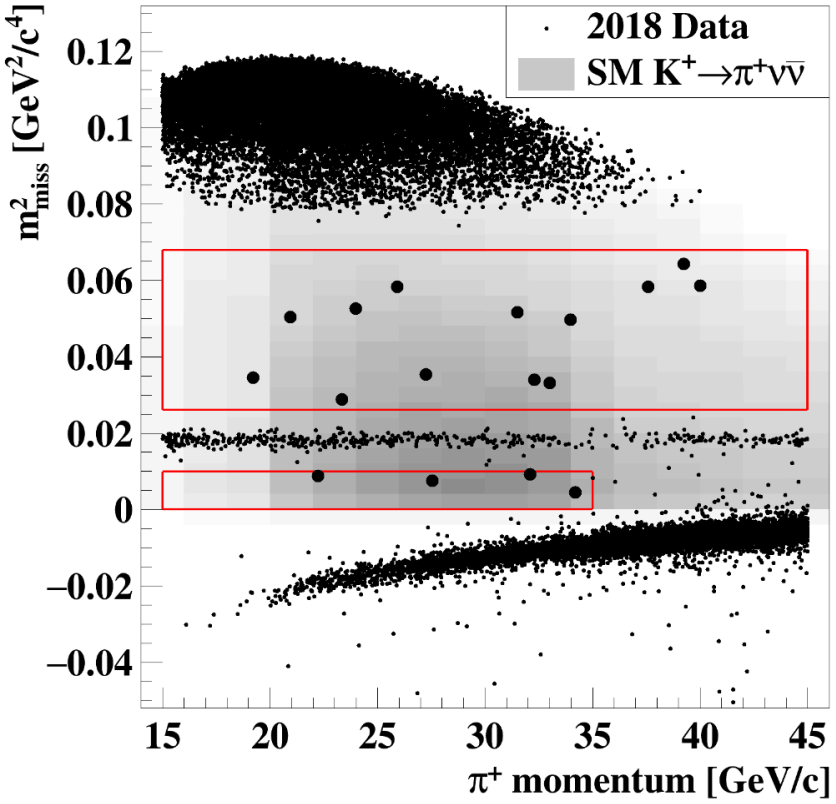
WHY THE DETECTOR IS DESIGNED THIS WAY? HOW DOES IT WORK IN KAON MODE

$K^+ \to \pi^+ \nu\bar{\nu}$ 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*]