MAX-PLANCK-INSTITUT
FÜR PHYSIK

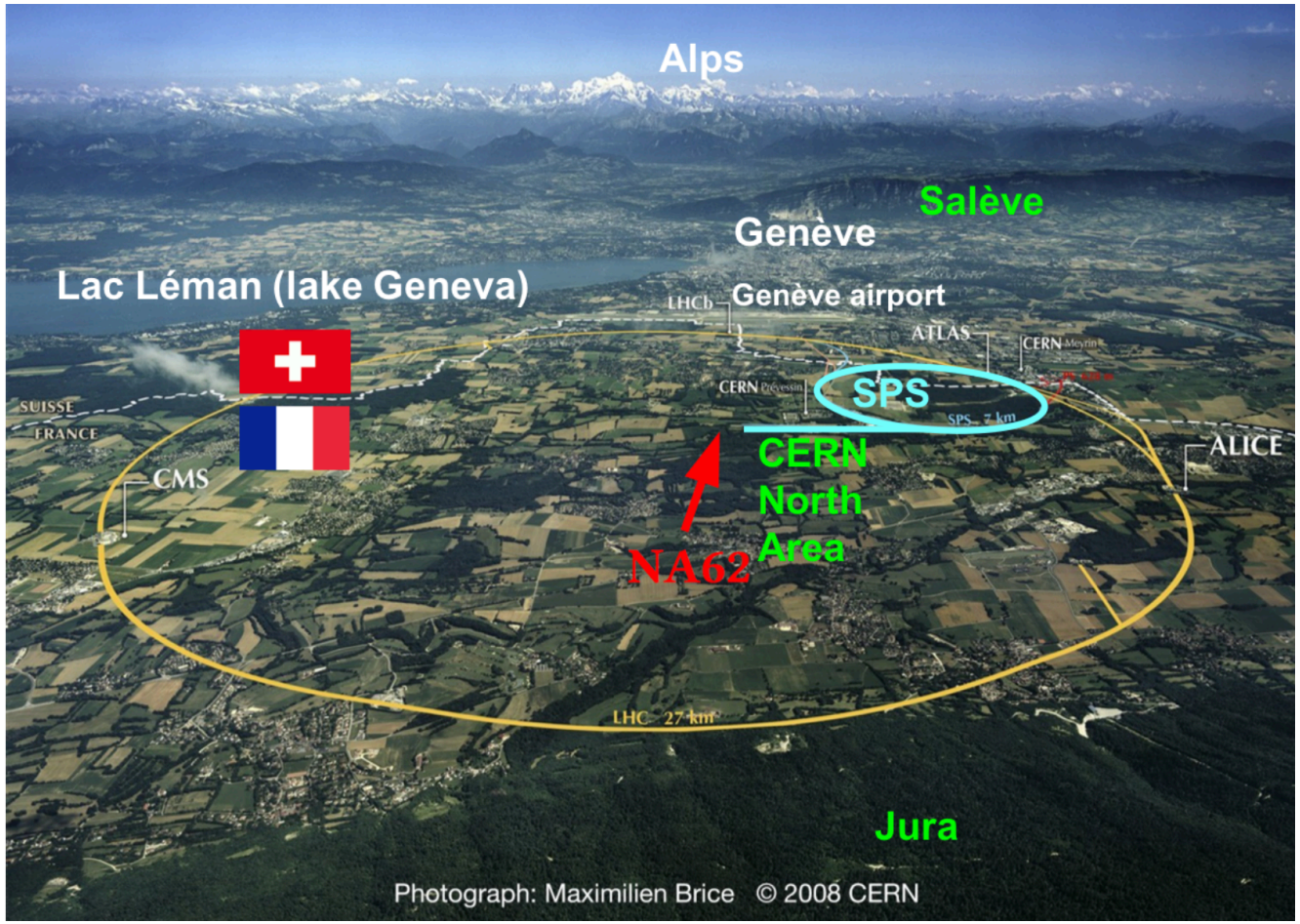
NA62 PROJECT REVIEW 2024

THE SMALLEST BRANCHING FRACTION AND POSSIBLY SOME OF THE WEAKEST COUPLINGS

Jonathan Schubert
for the NA62 working group at MPP

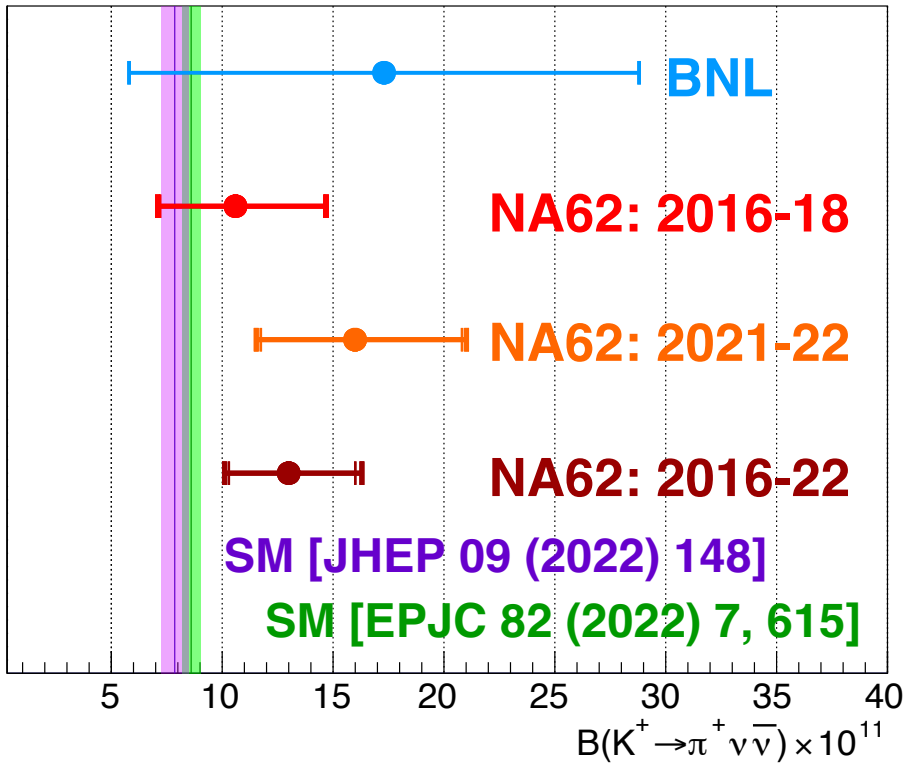
WHAT IS NA62?
THE MUCH TOO SHALLOW OVERVIEW

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



*The nominal goal was to reach below 20% statistical uncertainty before LS3

RECENT HEADLINE RESULT
NA62 KAON PHYSICS



5σ Measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ decay*

- **Lowest branching ratio ever measured at 5σ!**
- **Clean theory predictions for the width**
  - Dominated by short distance contributions
  - Hadronic matrix element can be extracted from $\mathrm{BR}_{K^+ \to \pi^0 \ell^+ \nu_\ell}$ measurements via isospin rotation
- **Presented at CERN Colloquium, publication imminent**
- **Measurement consistent with previous results**
  - **Central value moved up slightly while relative uncertainty decreased ($40\,\% \to 20\,\%$)**
  - **Now we observe (1.5–1.7)σ above SM**
- **Data taking until 2026**

*Background-only hypothesis has p-value of 2×10^{-7}

NA62 AT MPP
PEOPLE

Babette Döbrich
Group Leader

Samet Lezki
Postdoc

Jan Jerhot
Postdoc

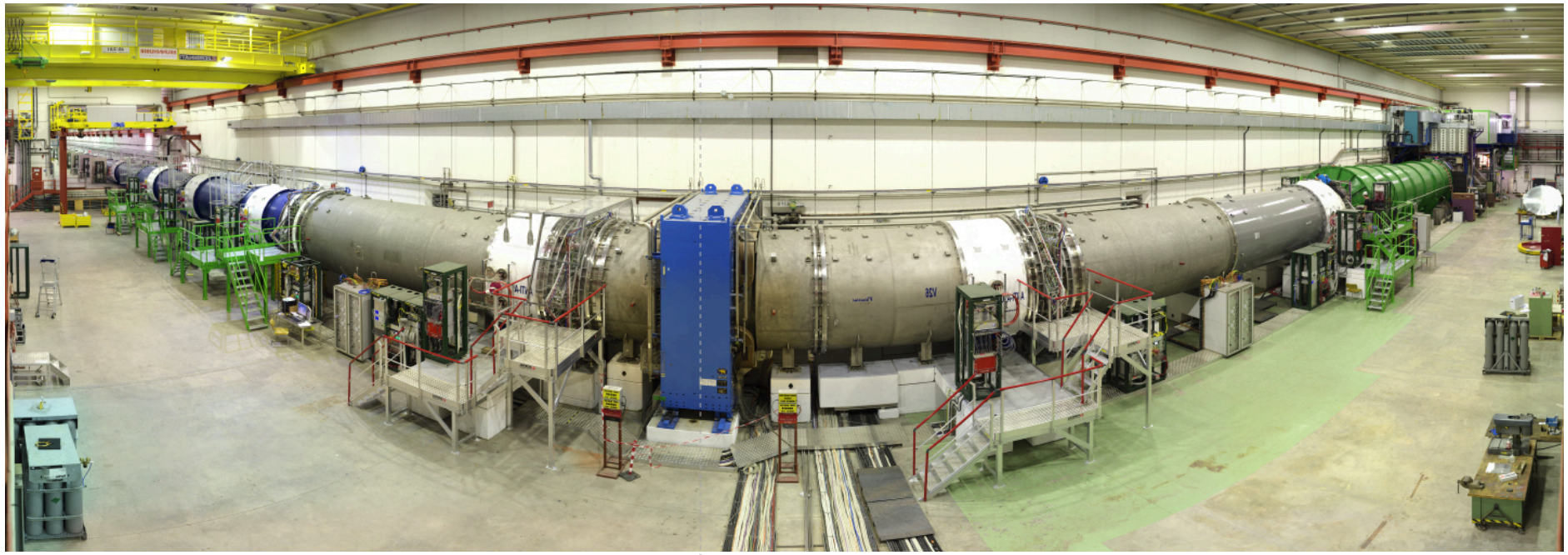
Prisco Lo Chiatto
Postdoc (50%)

Jonathan Schubert
PhD Student

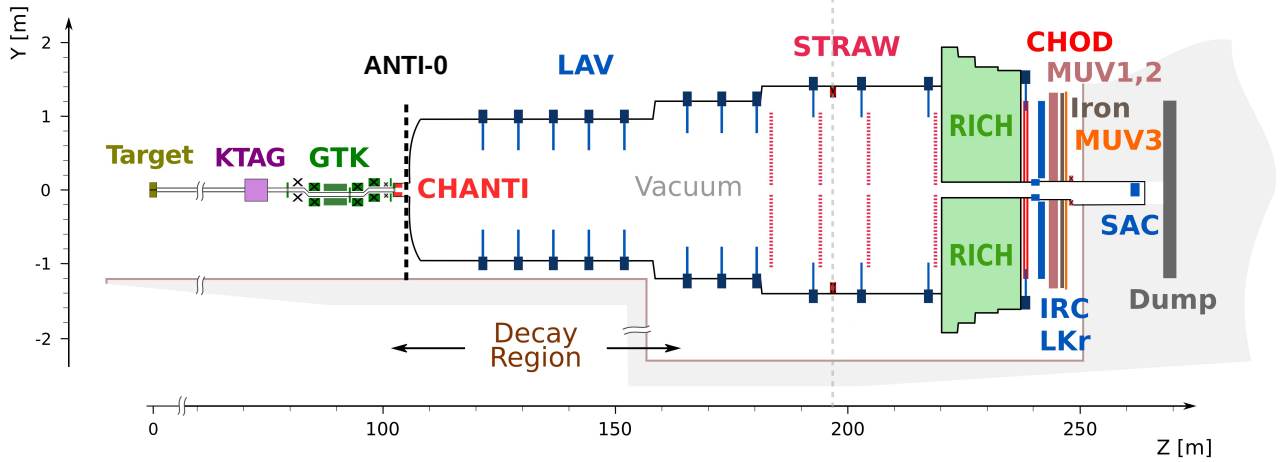
Sri Vrushank Ayyagari
Master's Student

Luca Lombardi
Student Intern

THE NA62 EXPERIMENT (AND ANTI-0 HODOSCOPE)



NA62 experiment as viewed from STRAW bending magnet (mirrored)



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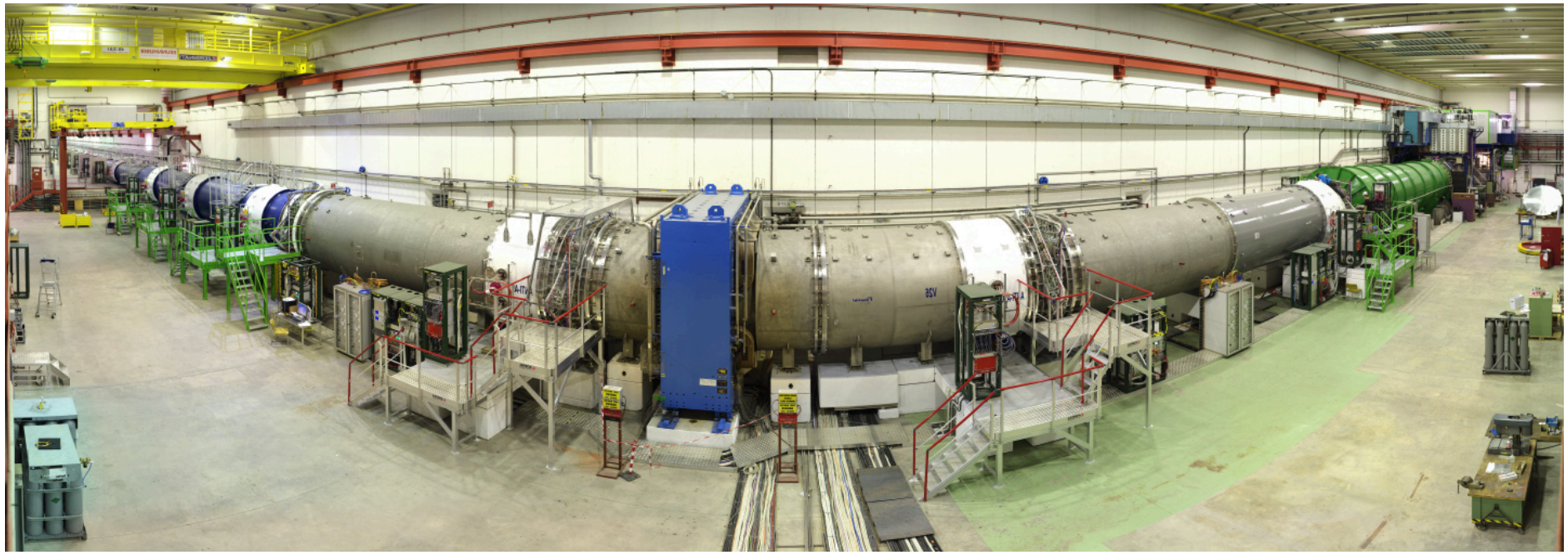
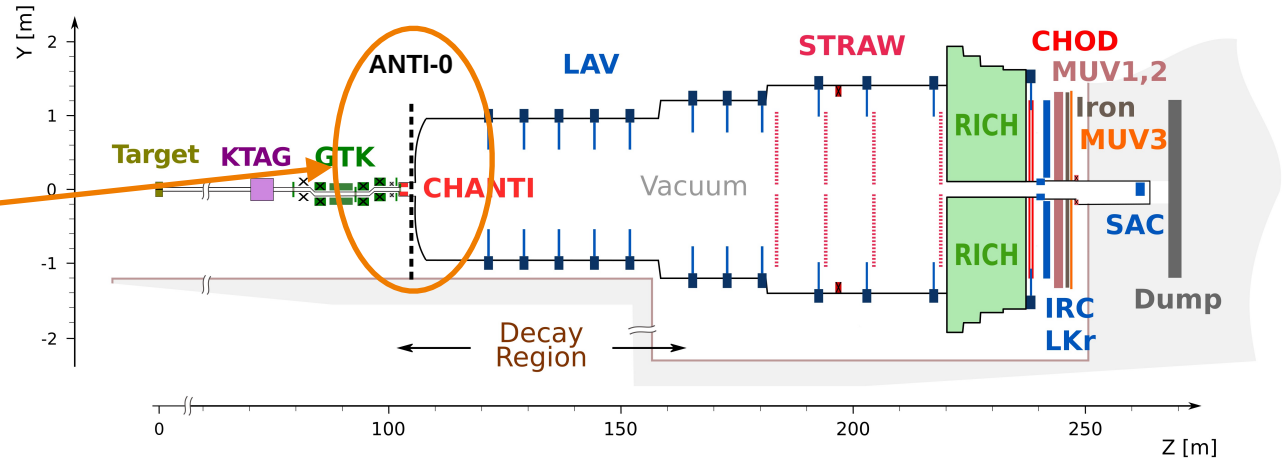


NA62 experiment as viewed from STRAW bending magnet (mirrored)

North Area intensity upgrades will lead to higher rates in detector readouts

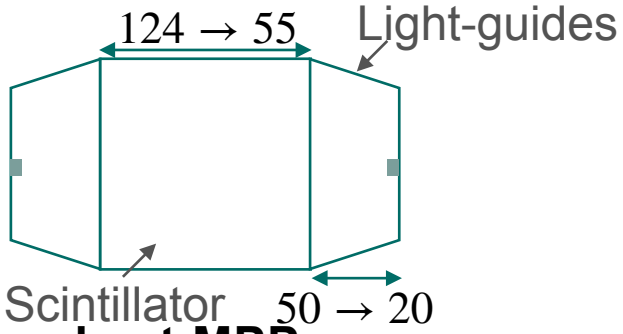
➡ **Need finer granularity hodoscopes to keep readout rate manageable**

➡ **Hodoscope tiles need to shrink**



NEW FINER GRANULARITY HODOSCOPE

- **Required tile-shrinkage:**
  - light guides need to be adjusted to guarantee similar performance



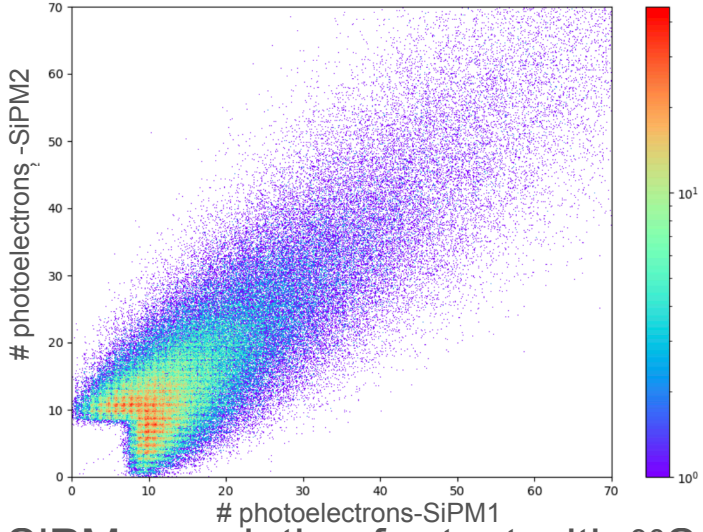
✓ **Light guides designed and made at MPP (big thanks to Alfons Eiterer, Alexander Stürzer, and rest of mechanics department)**

✓ **First Tests performed with ^{90}Sr-source and Cosmics indicated excellent correlation**

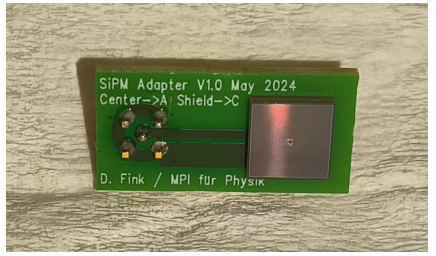
✓ **Design and fabrication at MPP of Mk-II tile featuring**
  - improved light guide design
  - New Hamamatsu SiPMs mounted directly on PCB (**big thanks to David Fink and the electronics department**)

Tests at CERN measuring muons of small polar in 'sandwich set-up' of two Mk-II tiles between two 1cm^3 granularity 3DET hodoscopes

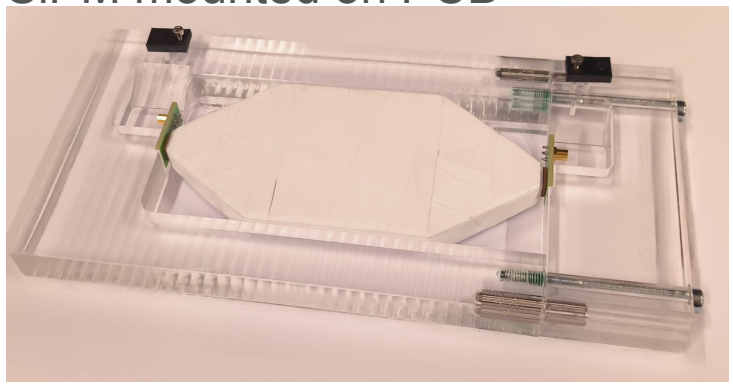
- **Sub-1cm^2-granularity tiles could be useful for any experiment with high intensity exposure**



SiPM correlation for test with ^{90}Sr source



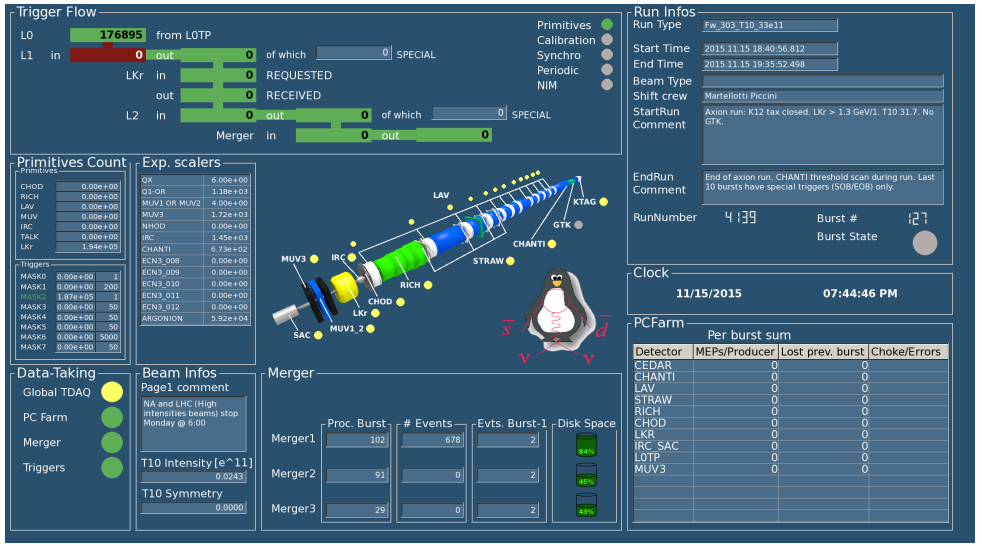
SiPM mounted on PCB



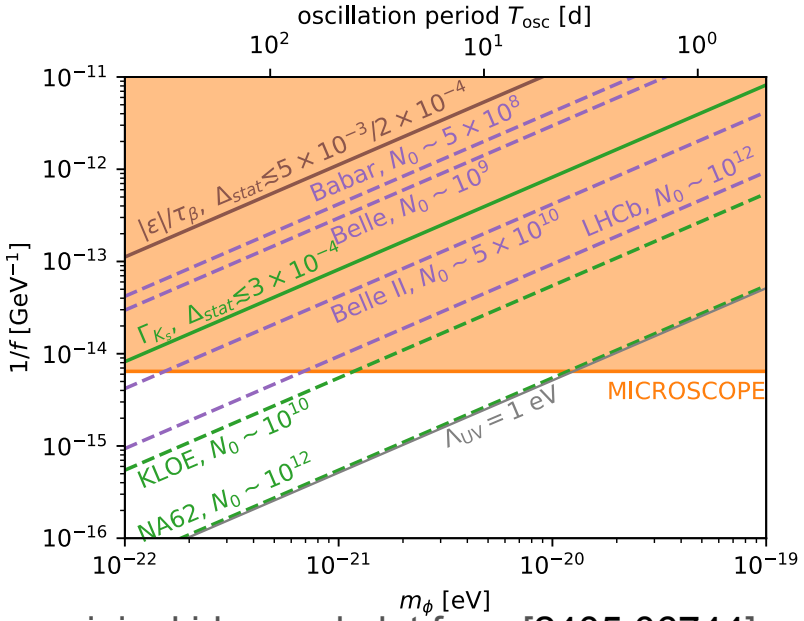
Mk-II tile fitted on plate

NA62 AT MPP
WHAT WE DO

- **Hardware**
  - Upgrade Studies
  - Expert roles
- **Run Control**
  - Handles trigger and data acquisition
  - Maintained and developed at MPP
- **Sensitivity analyses (theory)**
  - Unique experiment with (in-)direct sensitivity to numerous effects
  - Dedicated NA62 sensitivity studies at MPP
  - Example: Nelson-Barr ultra-light dark matter leading to CKM-value oscillation
- **Exotics Working Group**
  - Co-convenership
  - Direct BSM searches
  - Phenomenology for direct searches



Screenshot of the NA62 big screen



original idea and plot from [2405.06744]

NA62 BEAM DUMP DATA-TAKING ALTERNATIVE RUN-MODE

- K production target followed by an achromat *selecting* secondary beam at fixed momentum
- **Collimators of this achromat are movable** and can be driven into **‘*closed position*’**
- The K production target can also be removed easily
- **400 GeV protons** from SPS **impinge directly on several meters of copper/iron** (TAXes)
  - Beam dump set-up (target and absorber)
  - Pointing approach eliminates already very small background levels
  - Model independent search approach

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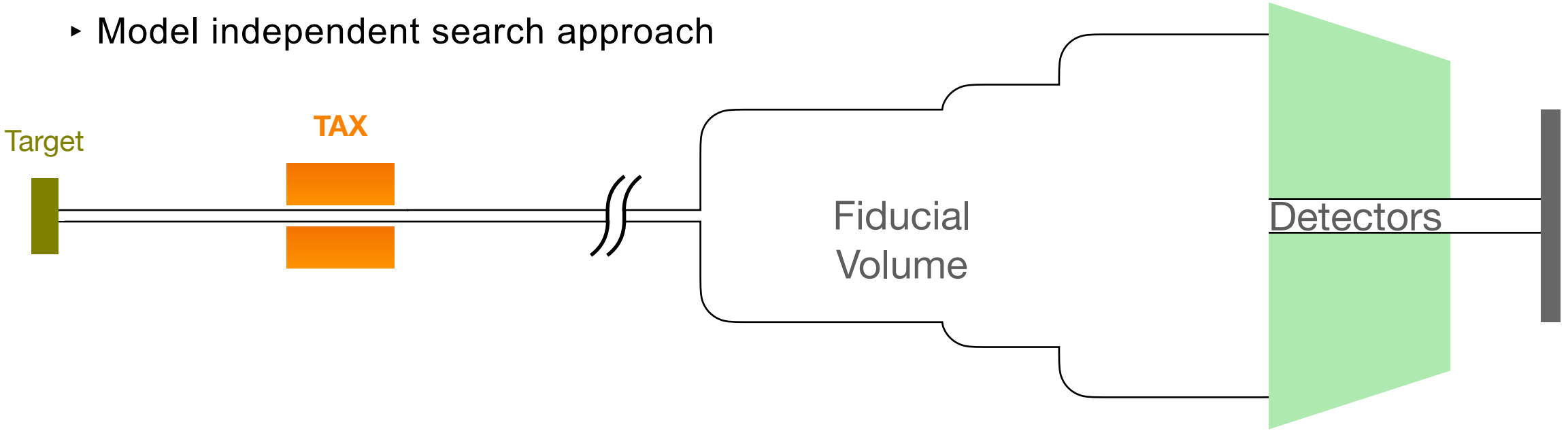

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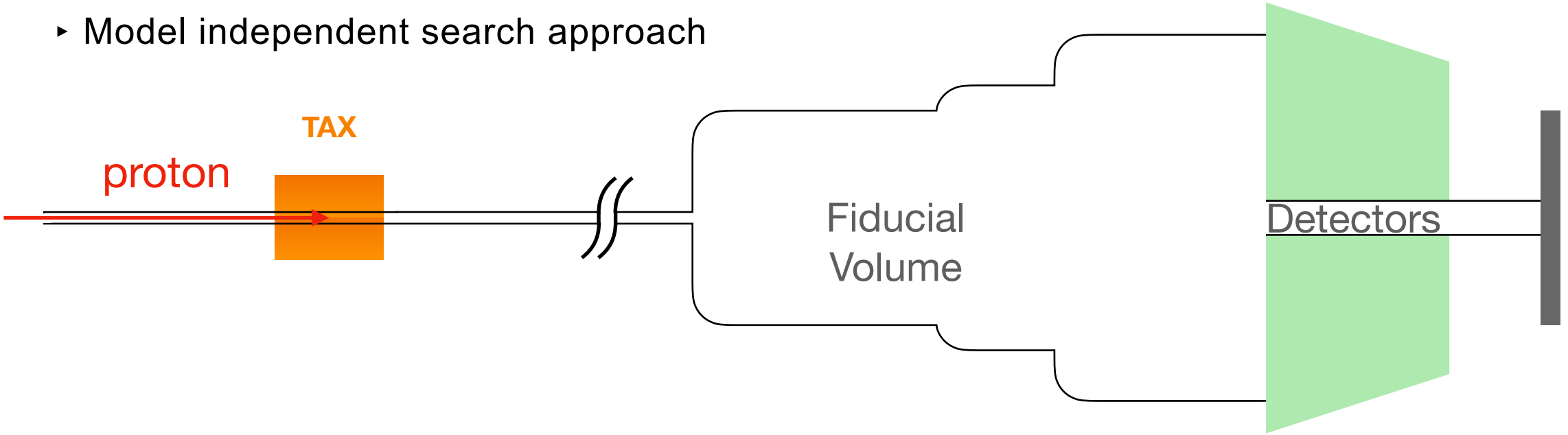

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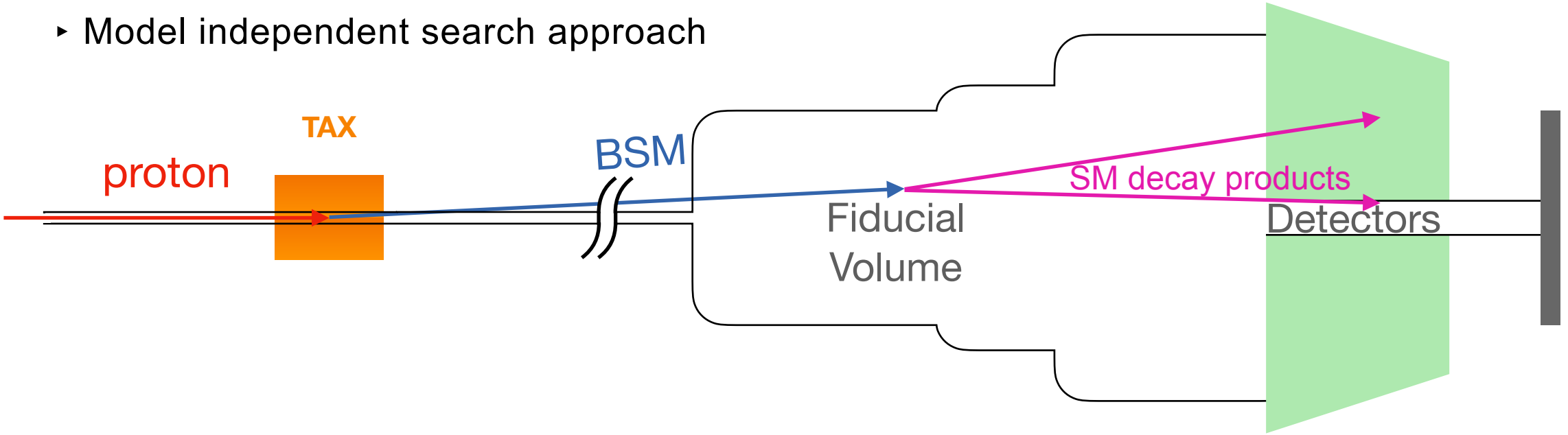


MODEL-INDEPENDENT SEARCHES USING DUMP-MODE DATA

✓ **Lepton-pair final states**

- Background mainly due to accidental combination (μ) and prompt upstream scattering events (e)
- No significant excess observed
- Published in JHEP (μ) and PRL (e)

✓ **Charged hadronic final states**

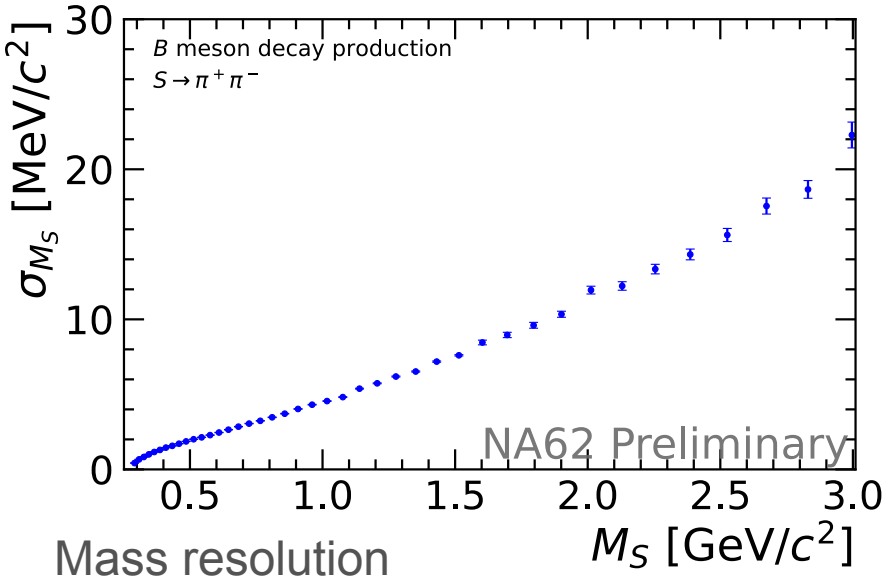
- Background mainly from upstream kaon events
- No events observed
- Presented at Moriond, publication imminent

Semi-leptonic

- Likely dominated by prompt upstream scattering events
- Targets models complementary to previous studies

Di-gamma final states

- No track information available (Enormous effort to study possible backgrounds)



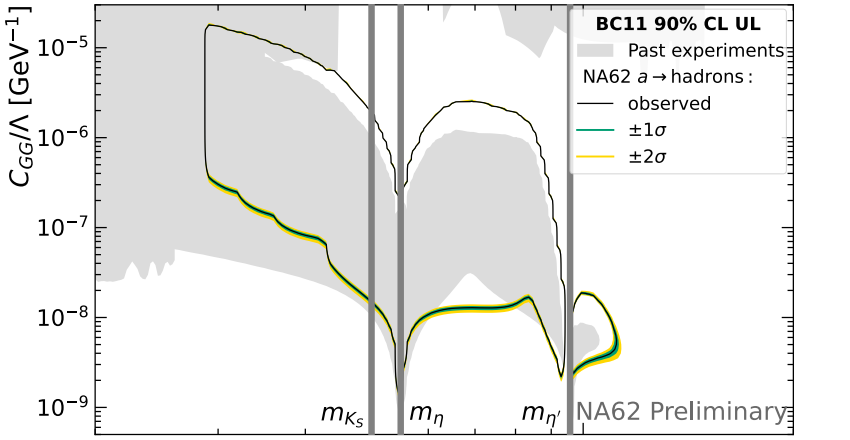
Mass resolution

channel	$\pi^+\pi^-$	$\pi^+\pi^-\pi^0$	K^+K^-
$N_{\text{obs}}(>5\sigma)$	3	1	1

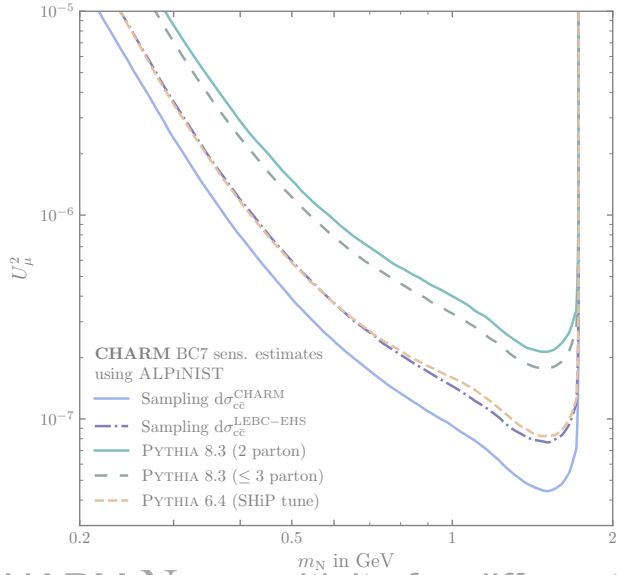
Global significances in case of observed events (selected channels)

MODEL-DEPENDENT INTERPRETATION OF SUCH ANALYSES (USING ALPINIST)

- **Final states can be interpreted as Feebly Interacting Particles** (Usual suspects are Dark Photon, Dark Scalar, Axion-Like-Particles and Heavy Neutral Leptons)
- **Absence of signal excludes parameter space of these models, which requires**
  - knowledge of production spectra
  - weighting algorithm for mass-width pairs assumed in MC
- **Facilitated by ALPINIST framework developed and maintained here at MPP**
- **Recent phenomenology study regarding**
  - validation of production spectra
  - review of experimental sensitivities with consistent underlying assumptions



Gluon-coupled ALP excl.



CHARM N_μ sensitivity for different SM input assumptions

ALPINIST comes with Toy-MC to evaluate sensitivities ahead of search

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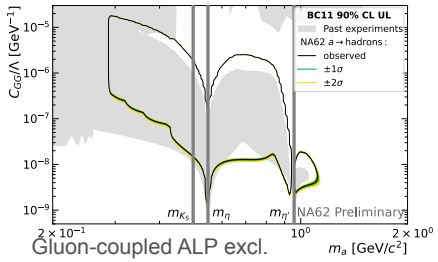

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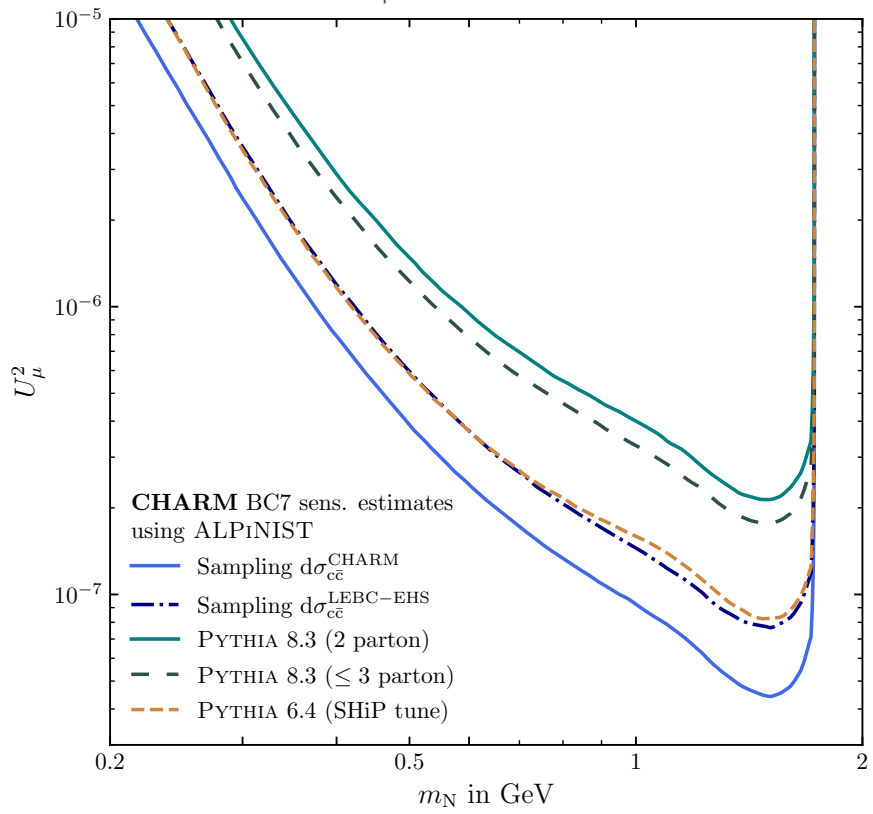

CHARM N_μ sensitivity for different SM input assumptions

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SUMMARY

NA62 is a very versatile experiment with broad, world-leading physics program

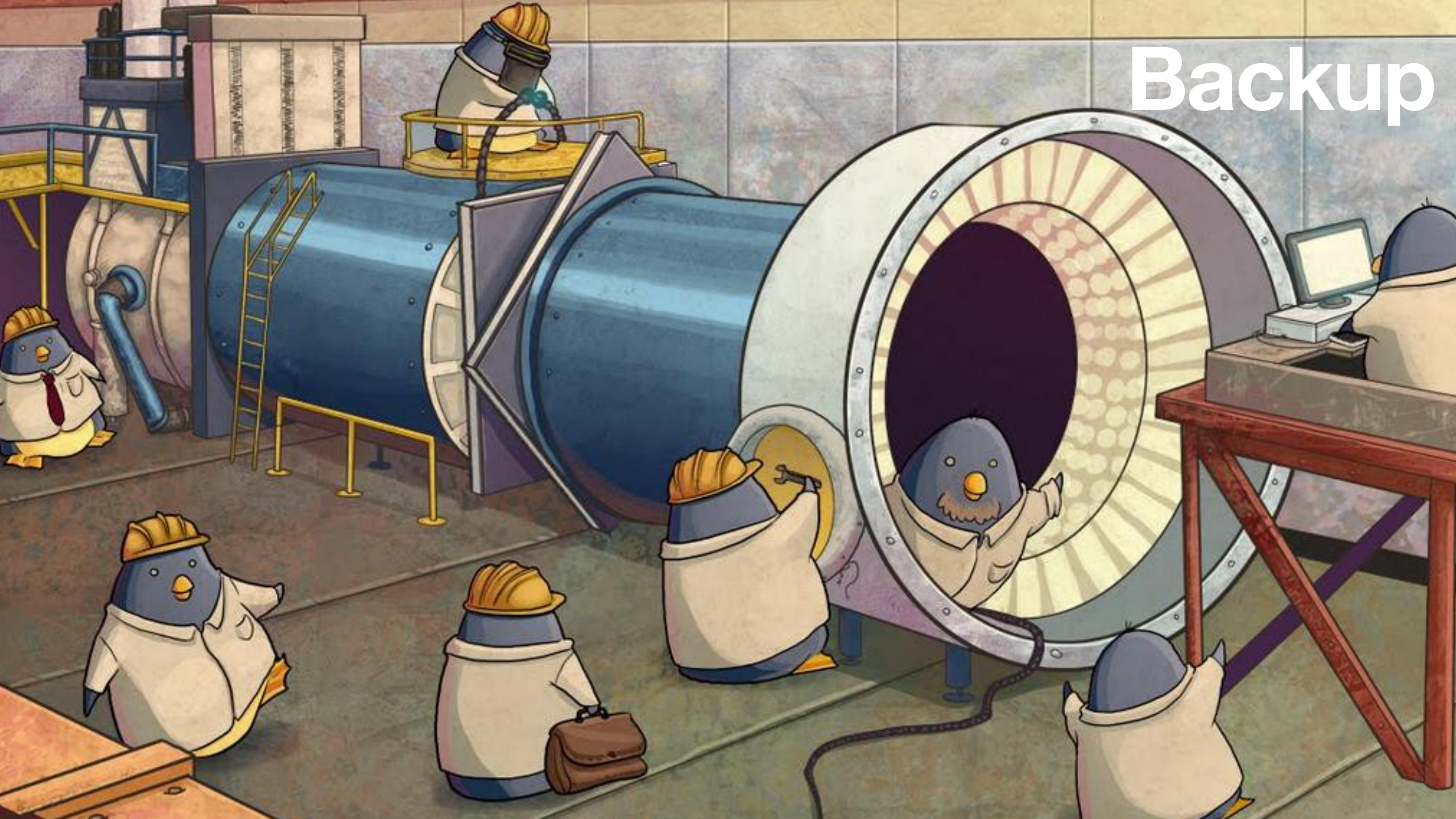
NA62@MPP has hit the ground running

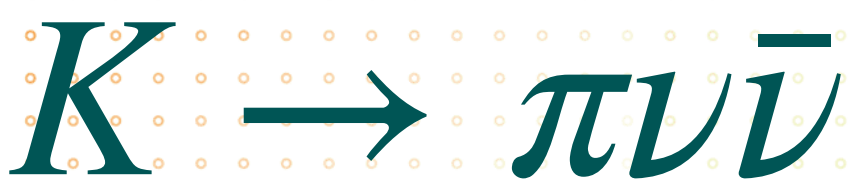
- **Group growing steadily since started in Autumn 2022**
- **Vital work to keep the experiment running (run control, expert roles, improvement studies)**
- **Leading role for dump-mode physics within the collaboration (co-convenership, bulk of analyses, phenomenological interpretations)**

2024 NA62 collaboration week Birmingham

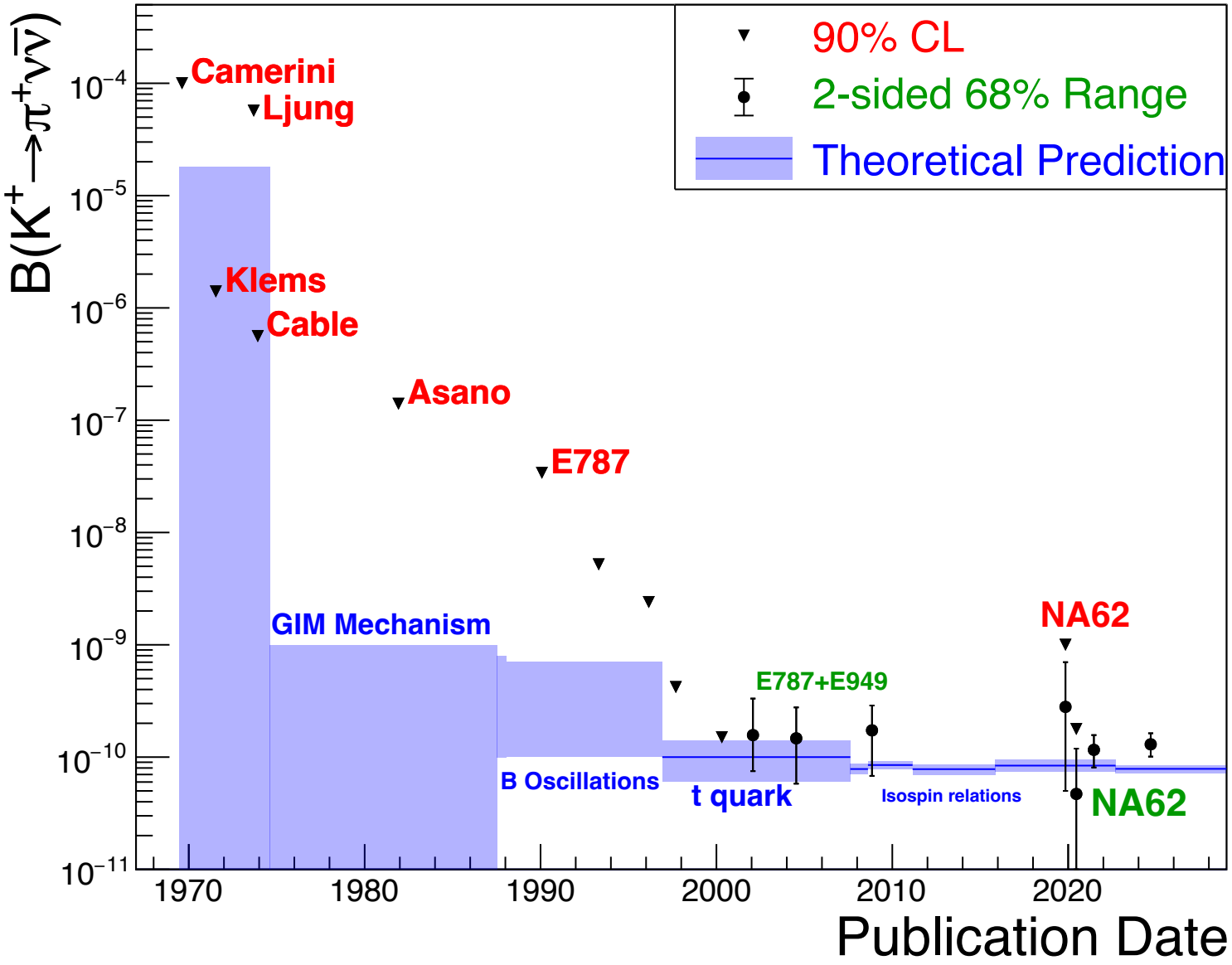
We are very grateful to the electronics and mechanics department, as well as administration with a special thanks to Ina Wacker

Come talk to us about your favourite model, you don't even have to take the stairs :)


Backup


$K \to \pi\nu\bar{\nu}$

HISTORY OF $K \to \pi\nu\bar{\nu}$



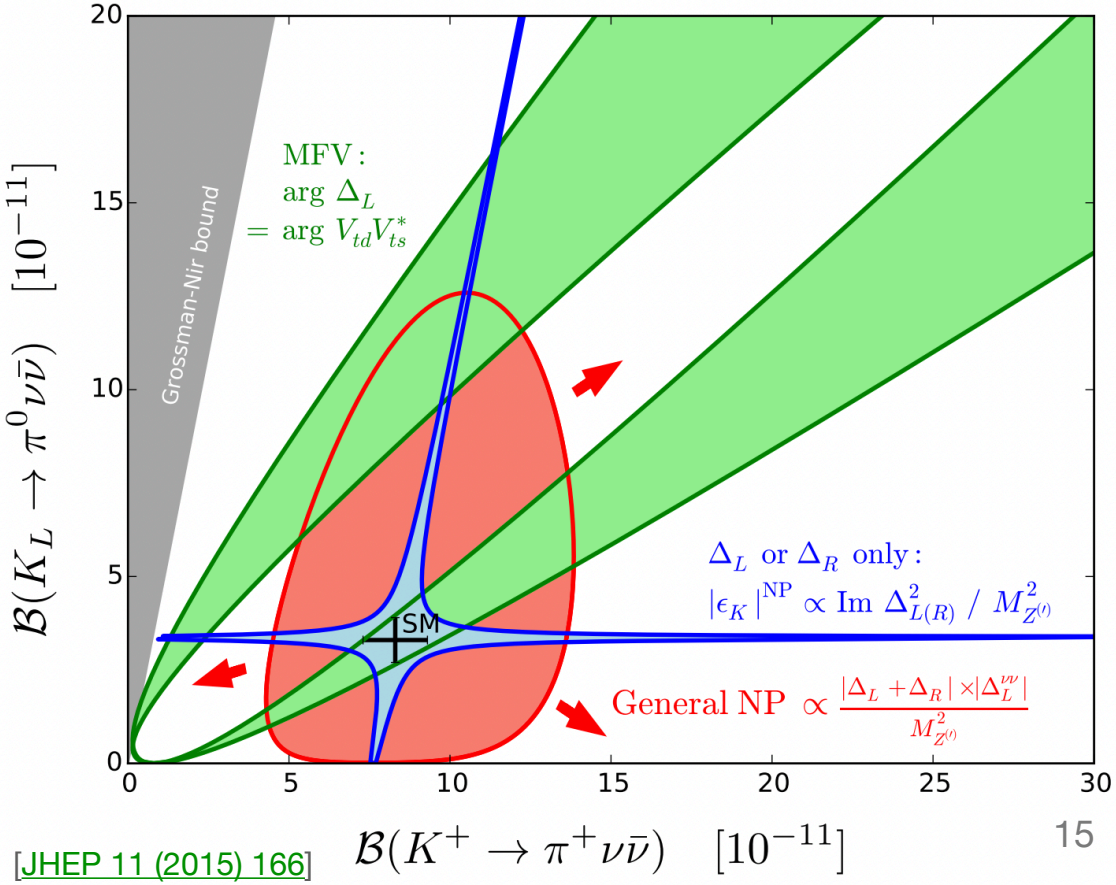
$K \to \pi\nu\bar{\nu}$: Beyond the Standard Model

- Correlations between BSM contributions to BRs of K^+ and K_L modes [JHEP 11 (2015) 166].
  - Must measure both to discriminate between BSM scenarios.
- Correlations with other observables (ε'/ε, ΔM_B, B-decays) [JHEP 12 (2020) 097] [PLB 809 (2020) 135769].
- Leptoquarks [EPJ.C 82 (2022) 4, 320], Interplay between CC and FCNC [JHEP 07 (2023) 029], NP in neutrino sector [EPJ.C 84 (2024) 7, 680] and additional scalar/tensor contributions [JHEP 12 (2020) 186][arXiv:2405.06742] …
- **Green:** CKM-like flavour structure
  - Models with Minimal Flavour Violation
- **Blue:** new flavour-violating interactions where LH or RH currents dominate
  - Z' models with pure LH/RH couplings
- **Red:** general NP models without above constraints
- **Grossman-Nir Bound:** model-independent relation

[PLB 398 (1997) 163-168]

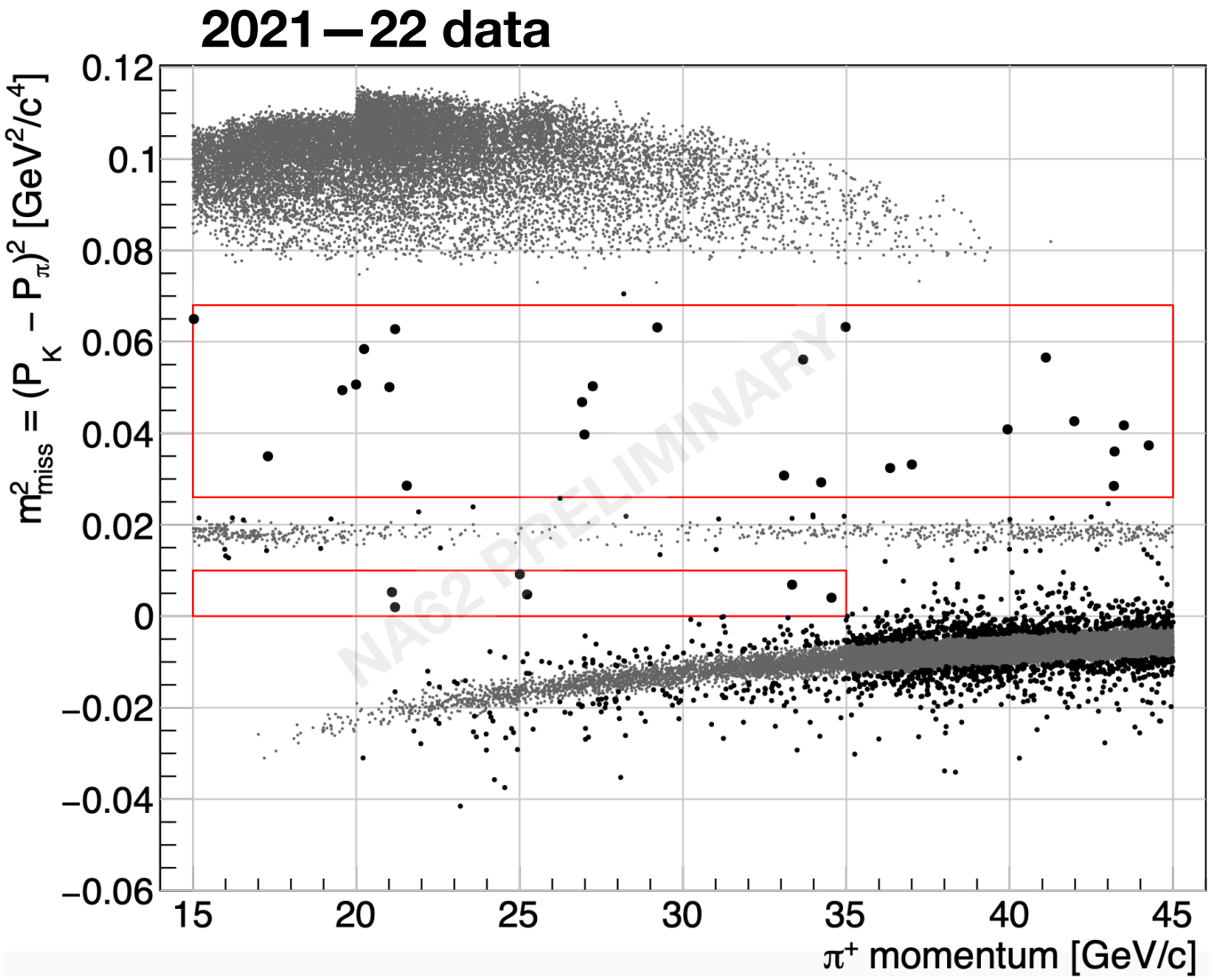
$$\frac{\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})}{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})}\frac{\tau_{K^+}}{\tau_{K_L}} \lesssim 1$$

$$\Rightarrow \mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \lesssim 4.3\,\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$$



[JHEP 11 (2015) 166]

Signal regions

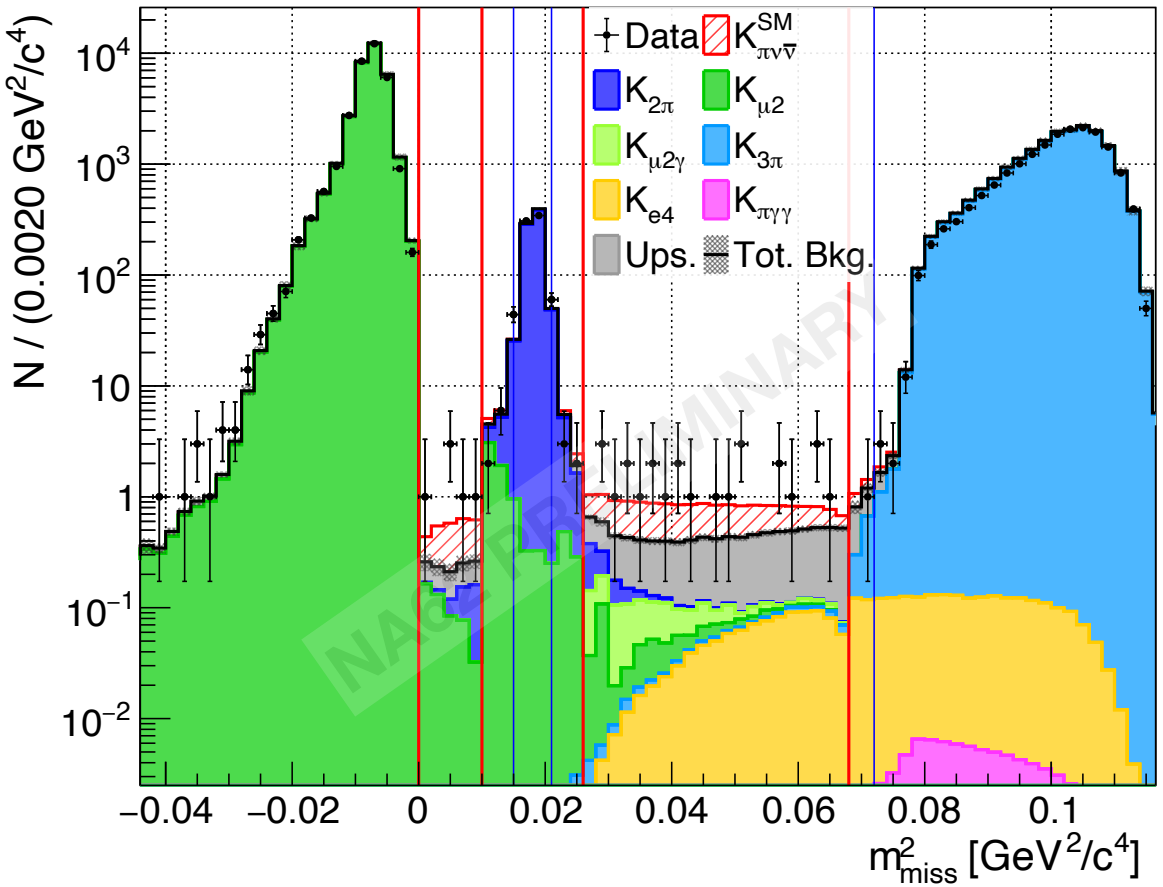


Expected SM signal, $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

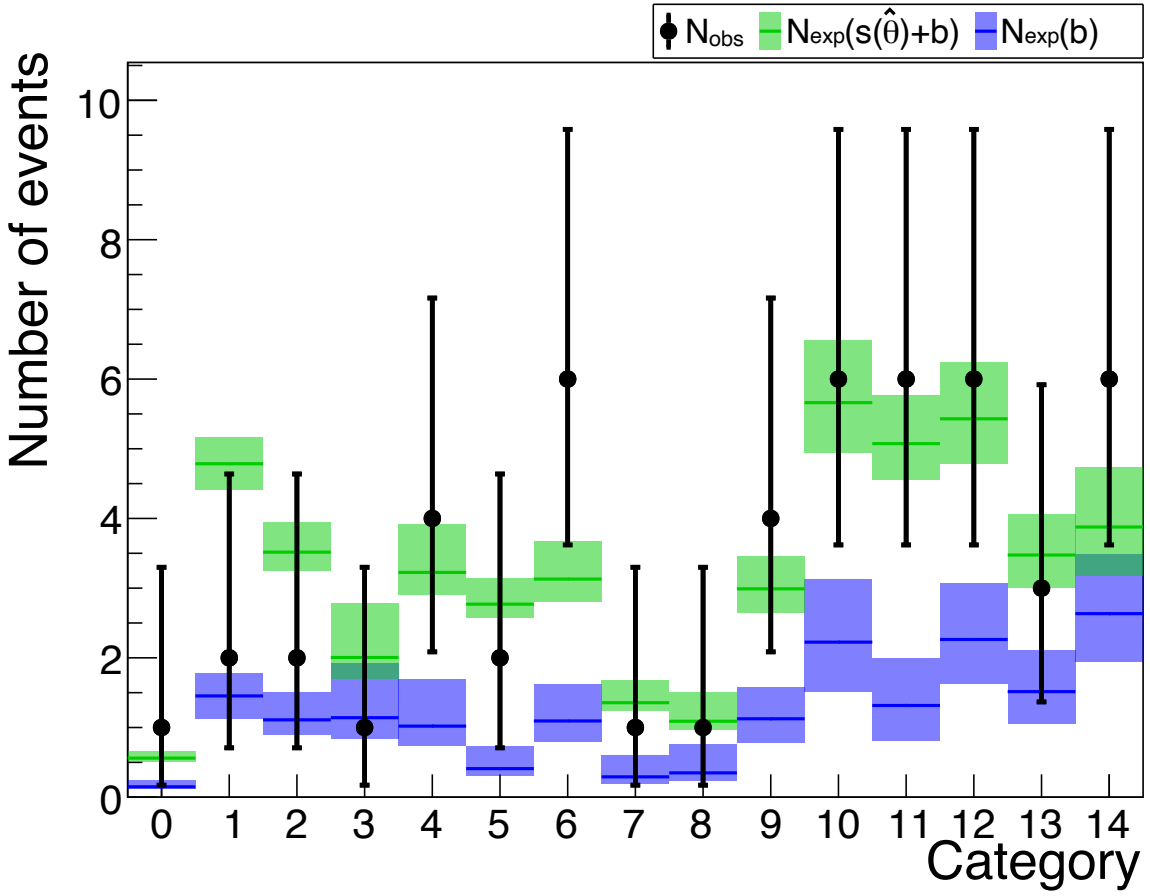
Expected background, $N_{bg} = 11.0^{+2.1}_{-1.9}$

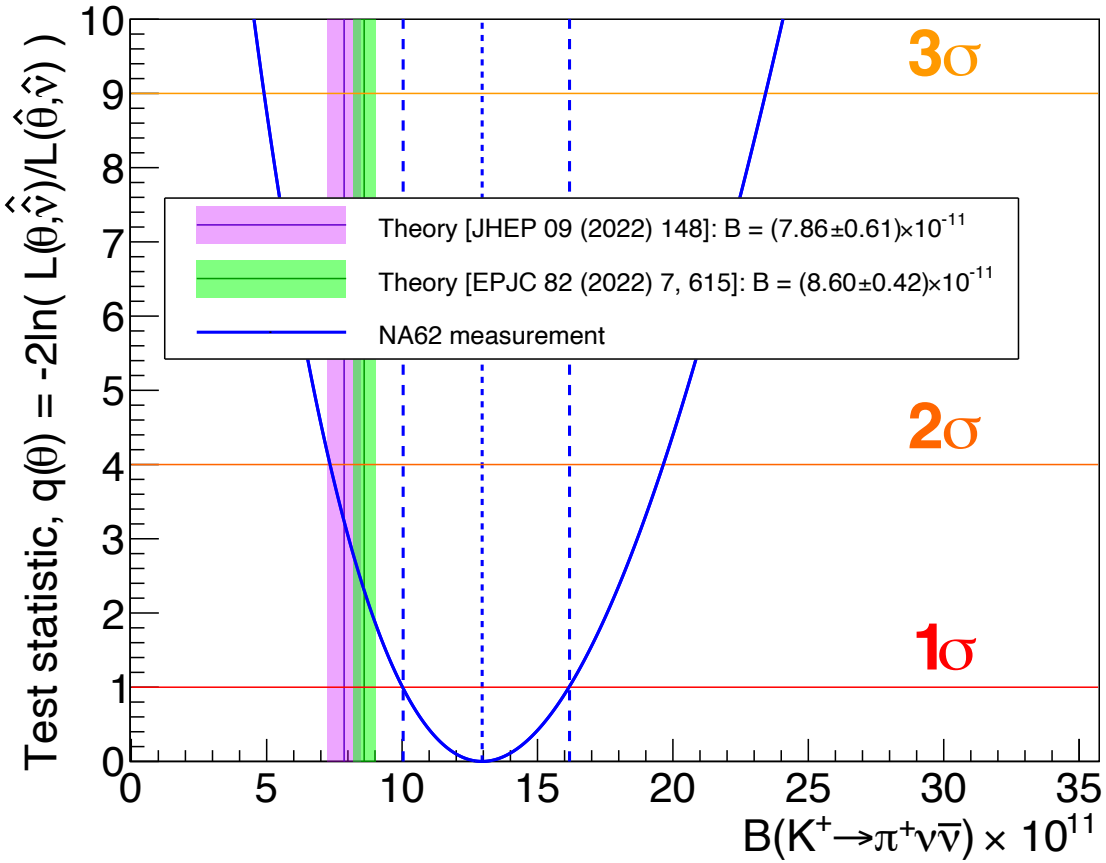
Observed, $N_{obs} = 31$

1D projection with differential background predictions & SM signal expectation [not a fit]:



SIGNAL EVALUATION





HARDWARE

NEW FINER GRANULARITY HODOSCOPE MATERIAL SPECIFICATIONS

Table 1: The specifications of the plastic scintillator UPS-923A [3].

Scintillator	UPS-923A
Manufacturer	Institute for Scintillation Materials (ISMa)
Base	Polystyrene
Primary fluor	2% PTP
Secondary fluor	0.03% POPOP
Rise time (ns)	0.9
Decay time(ns)	~2-3
Wavelength - max emission (nm)	418
Light output, % of anthracene	56

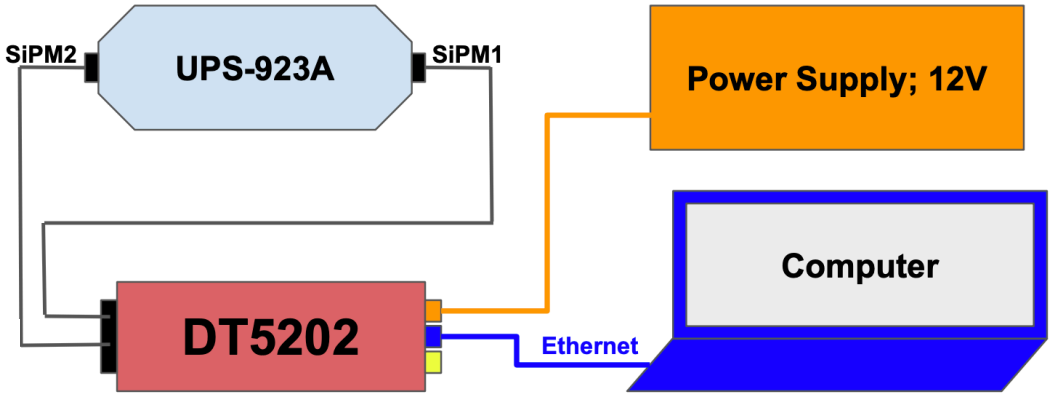
Table 2: Optical Properties of CRYLON High Impact for Scintillator Light Guides [4].

Brand	CRYLON
Manufacturer	3A Composites
Base	PMMA
Refractive index	1.492
Light transmission	92%
Density	1.19 g/cm^3
Haze	$<$ 1%
Total solar energy transmission	86%
Gloss value	100%

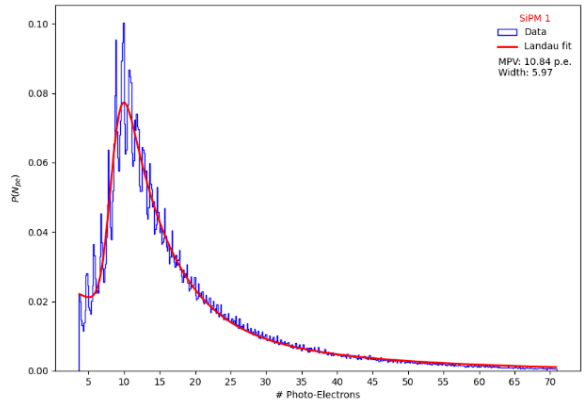
NEW FINER GRANULARITY HODOSCOPE
^{90}SR TEST

First tests with first prototype have been done by mounting two Hamamatsu S13360-6050CS SiPMs using CAEN-DT5202 readout

Data type	SiPM 1		SiPM 2	
	MPV (p.e.)	Width (p.e.)	MPV (p.e.)	Width (p.e.)
^{90}Sr source	10.84	5.97	10.98	5.64
Cosmics	11.74	6.20	9.86	5.57



Experimental Setup



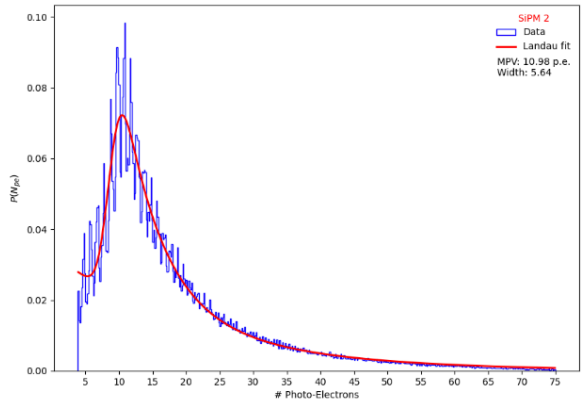
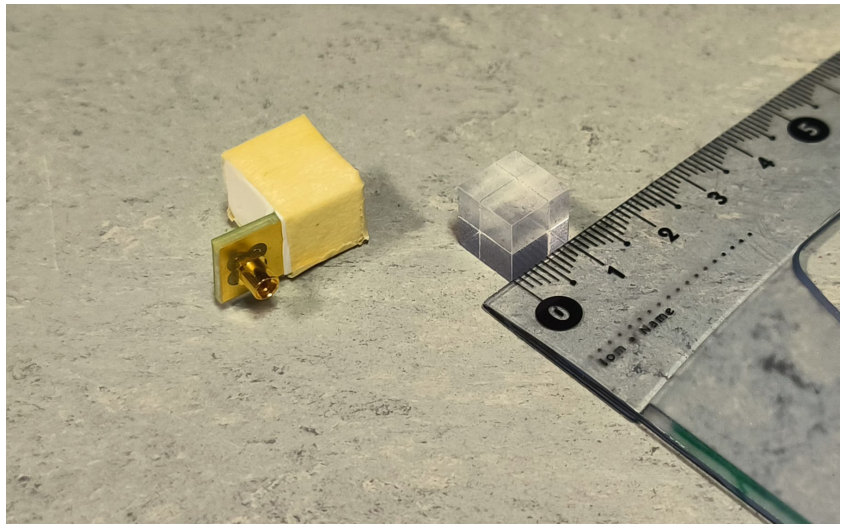
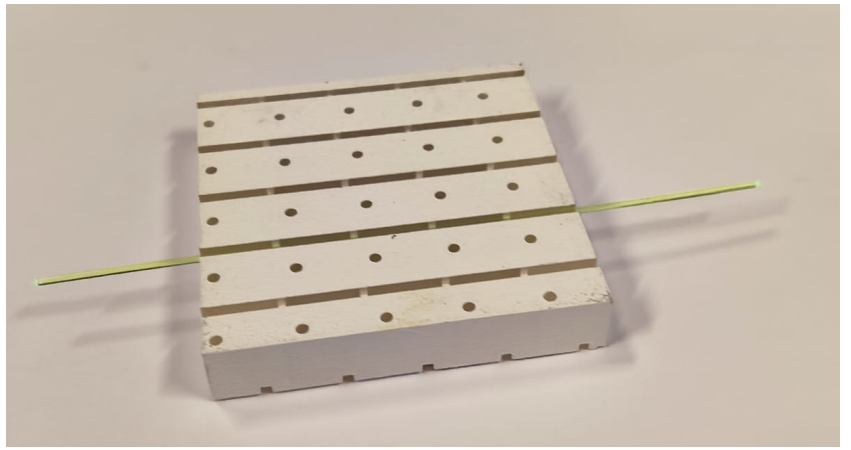


Figure 9: Charge spectra for two SiPMs coupled to the UPS-923A scintillator exposed to ^{90}Sr radiation are illustrated. The data for each SiPM was fitted with a Landau distribution. The Most Probable Value (MPV) from the fit approximates to 11 photo-electrons (p.e.), reflecting the central tendency of the scintillator's light-yield distribution under the given radioactive exposure.

NEW FINER GRANULARITY HODOSCOPE ONGOING TESTS OF THE MK-II TILE

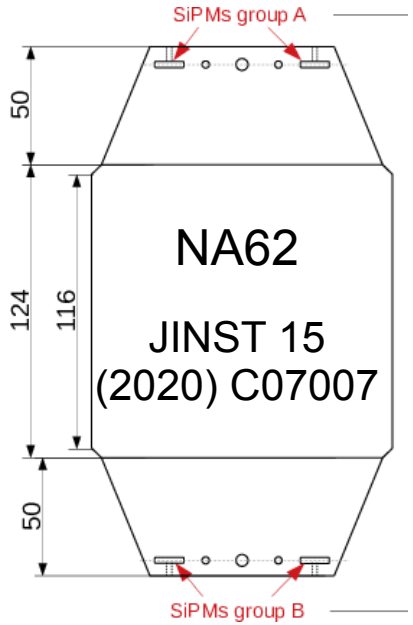
- Tests at CERN measuring muons of small
  polar in ‘sandwich set-up’ of two Mk-II tiles between two 1cm3 granularity 3DE hodoscopes (3D printed hodoscopes)
  - Checking uniformity
  - Great handle on light yield proportionality



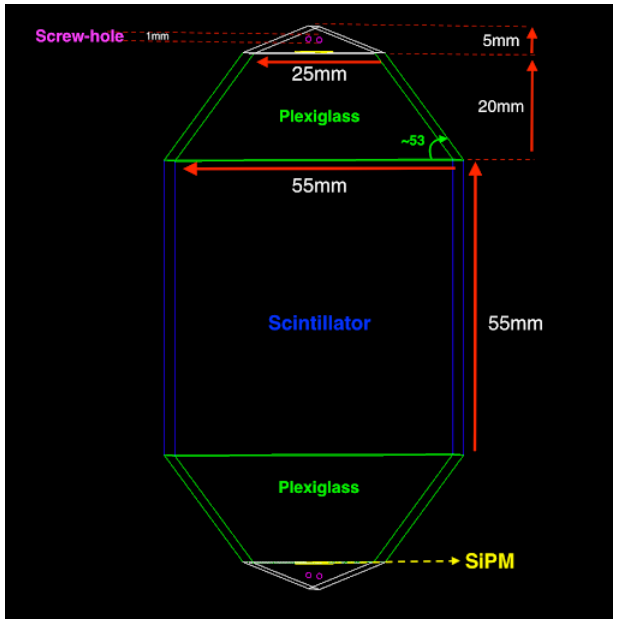


5 x 5 cm2 hodoscope with 1 cm2 granularity, produced with 3D printer by 3DET Collaboration.
see PoS PANIC2021 (2022) 086 and JINST 15 (2020) P10019

NA62 VS. UPDATED HODOSCOPE UNIT DETAILED COMPARISON

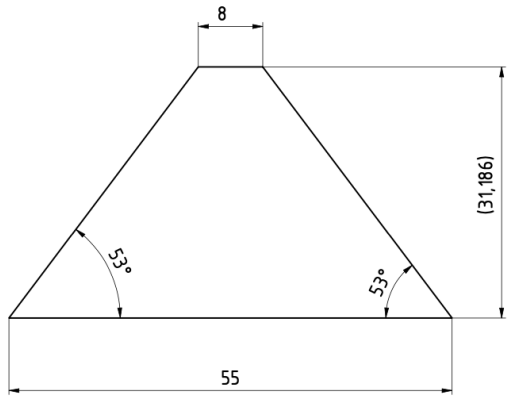


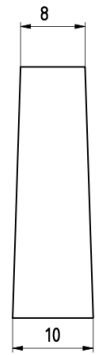
Current NA62 Anti-0 tile



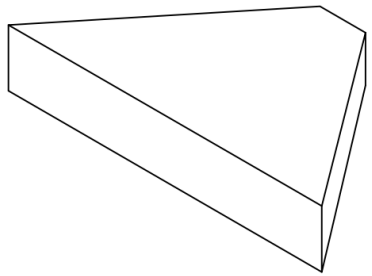
Mk-I high granularity design

NEW FINER GRANULARITY HODOSCOPE LIGHT GUIDE





alle Innen- und Außen-Flächen 100% transparent

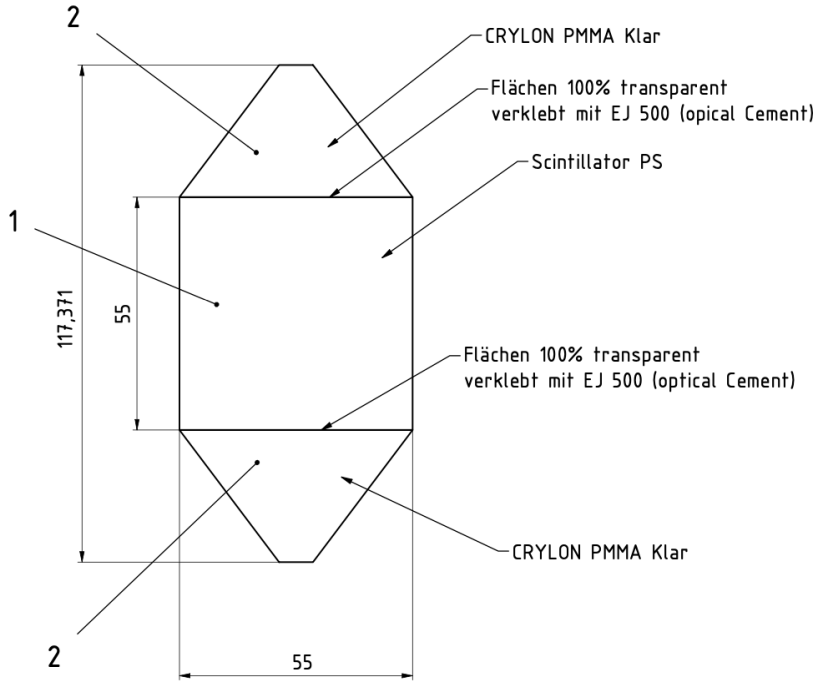


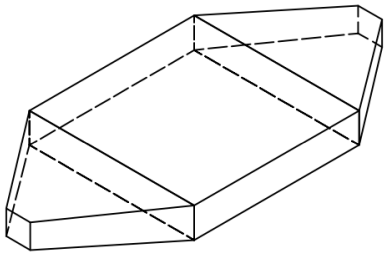
Freigegeben
06.05.2024

Revisionsverlauf			
Nr.:	Beschreibung	Datum	Name
a			

-0,1 +0,1	MAX-PLANCK-INSTITUT FÜR PHYSIK	Rz 16	
		Gewicht in kg: 0,011	Einheiten: mm
Erstellt: 06.05.2024	Projekt: HIKE ANTI0_V3 PMMA	Maße ohne Toleranzangabe nach DIN ISO 2768 m K	
Design: S. Lezki		Werkstoff: PMMA	
Zeichnung: EIT			
Maßstab: 2 : 1	Bezeichnung: ANTI0_V3_PMMA	Zeichnungsnummer / EDV Nr.: ANTI0_V3_PMMA.idw	
		Blatt: 1 von 1	Version: 2024-05-10-08:22
		A3 (297 x 420)	

NEW FINER GRANULARITY HODOSCOPE
NEW TILE





alle Aussenflächen 100% transparent poliert

1	1	Scintillator	ANTI0_V1_Scintillator.ipt	UPS 923A
2	2	ANTI0_V3_PMMA	ANTI0_V3_PMMA.ipt	PMMA
Teil	St.	Benennung	Dateiname	Werkstoff
Stückliste				

Freigegeben
10.05.2024

Revisionsverlauf			
Nr.:	Beschreibung	Datum	Name
a			

MAX-PLANCK-INSTITUT FÜR PHYSIK

Rz 16

Gewicht in kg: | Einheiten: mm

Erstellt 06.05.2024
Design S. Lezki
Zeichnung EIT

Projekt:
HIKE
ANTI 0 Tile
Scintillator_KPL_V3

Maße ohne Toleranzangabe nach DIN ISO 2768 m K

Werkstoff

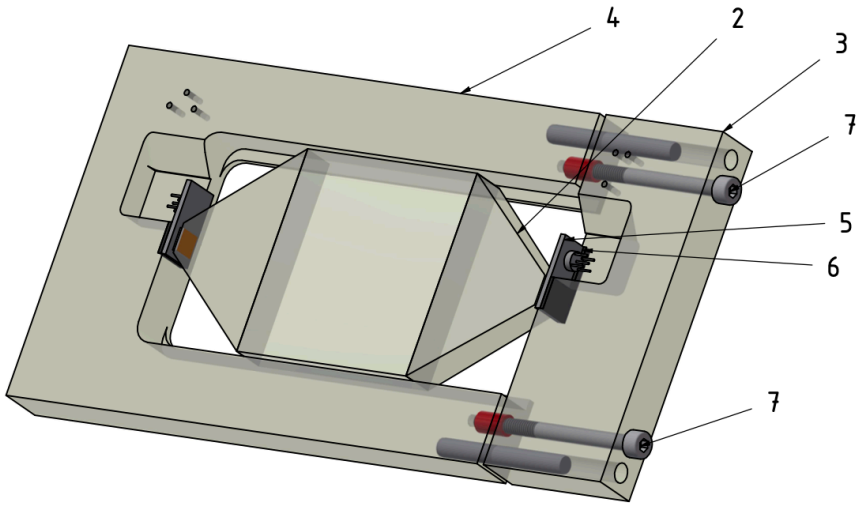
Maßstab 1 : 1

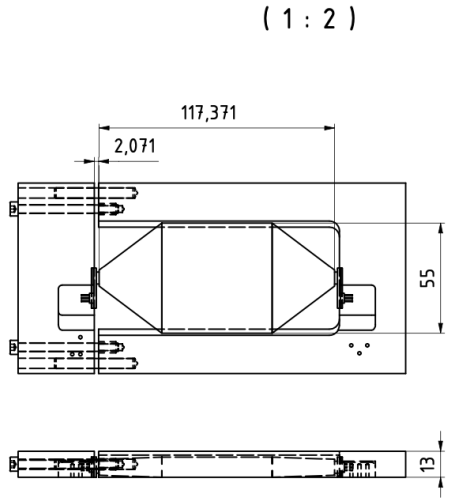
Bezeichnung:
Scintillator_KPL_V3
Scintillator_KPL_V3

Zeichnungsnummer / EDV Nr.:
ANTI0_V3_kpl.idw

Blatt: 1 von 1 | Version: 2024-05-10-08:24
A3 (297 x 420)

NEW FINER GRANULARITY HODOSCOPE
NEW TILE PLATE





many thanks to Alfons & Alexander

1	2	Zyl-Stift, durchgehärtet, m6	-	St (blank)	Ø5m6x40	ISO 8734	(DIN 6325)
2	1	Scintillator_KPL_V3	ANTI0_V3_kpl.iam				
3	1	ANTI0_V1_PMMA	ANTI0_V3_PMMA_Klebevorrichtung_Bügel.ipt	PMMA			
4	1	ANTI0_V1_PMMA	ANTI0_V3_PMMA_Klebevorrichtung_Rahmen.ipt	PMMA			
5	2		ANTI0_V3_Sensor.ipt	Generisch			
6	2		Klebefilz_1mm.ipt	Gummi			
7	2	Zylinderschraube	-	St 8.8 vz	M4x50	ISO 4762	
8	2		Helikoil_M4.ipt	V2A			
Teil	St.	Benennung	Dateiname	Werkstoff	Abmessungen	Norm	Bemerkung

Stückliste

Freigegeben
10.05.24

Revisionsverlauf			
Nr.:	Beschreibung	Datum	Name
a			

MAX-PLANCK-INSTITUT FÜR PHYSIK

Rz 16

Erstellt 10.05.2024
Design EIT
Zeichnung EIT

Projekt:
HIKE
SCINTILLATOR DEVICE KPL
ASM DEVICE

Gewicht in kg: | Einheiten: mm

Maße ohne Toleranzangabe nach DIN ISO 2768 m K

Werkstoff

Maßstab 1 : 1

Bezeichnung:
SCINTILLATOR-DEVICE V3 KPL

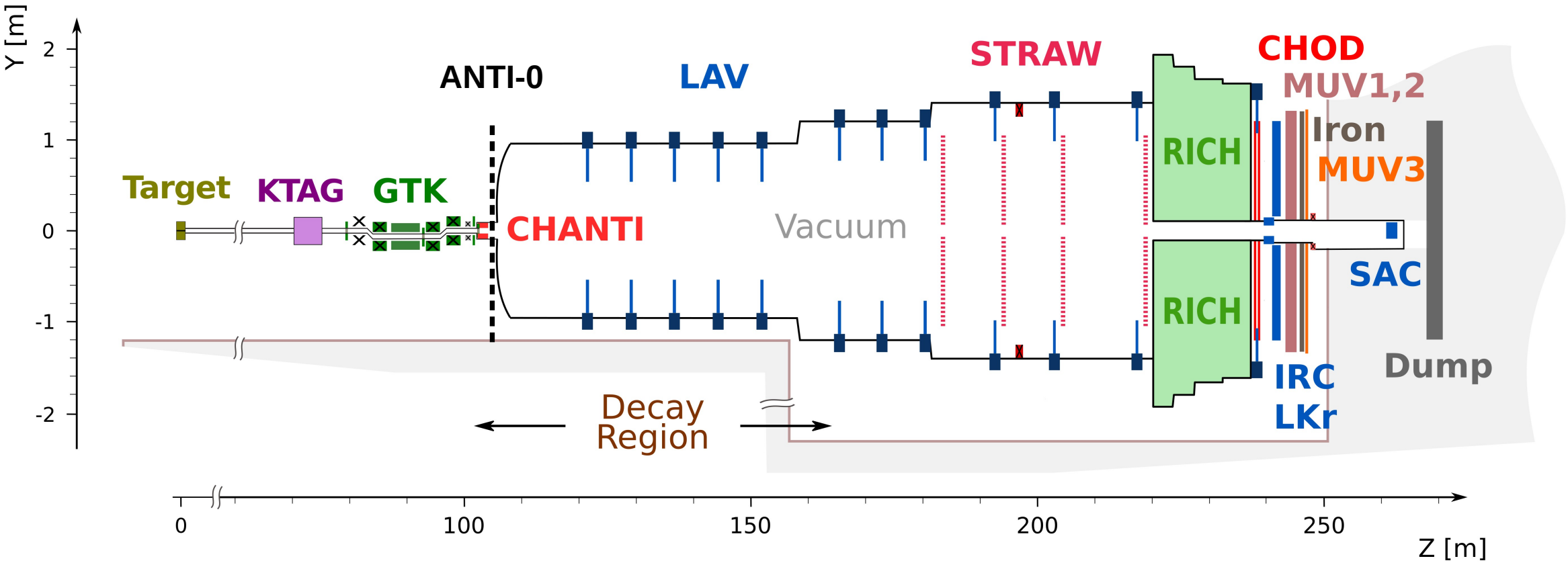
Zeichnungsnummer / EDV Nr.:
ANTI0_V3_Vorrichtung_

Blatt: 1 von 1 | Version: 2024-05-10-10:12
A3 (297 x 420)

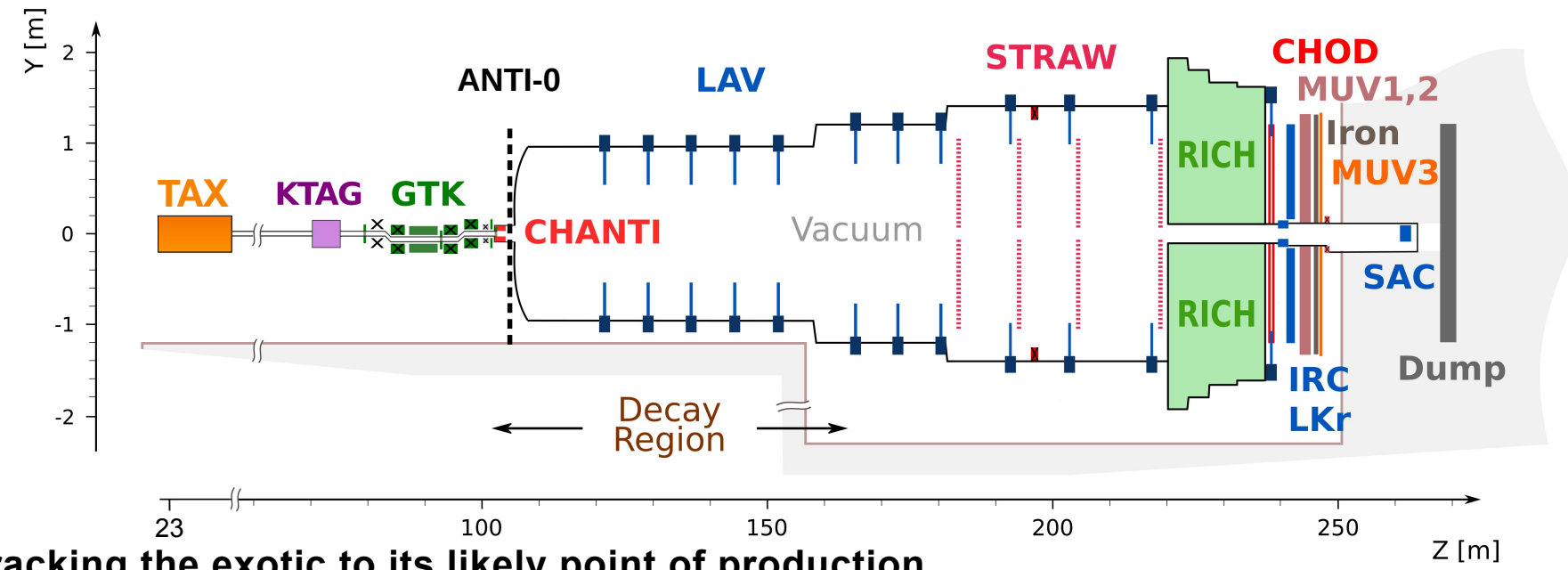
NA62 GEOMETRY

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

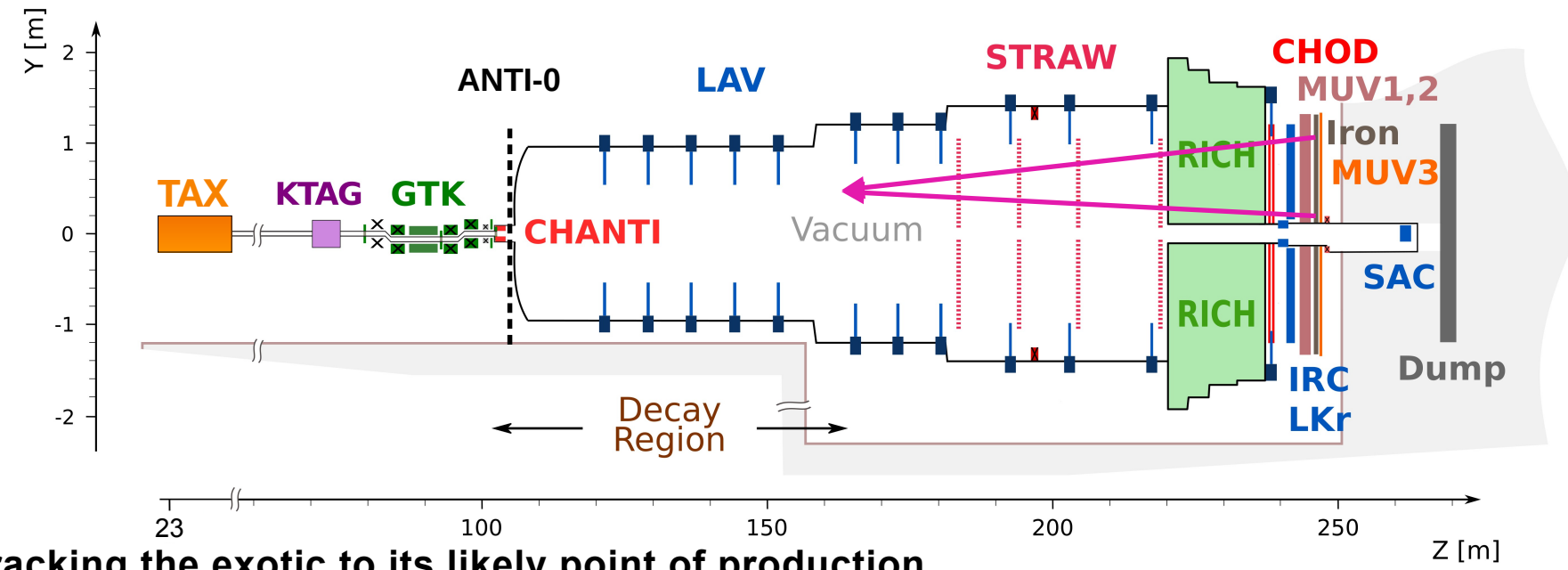


THE NA62 EXPERIMENT
BEAM DUMP MODE — SEARCH STRATEGY



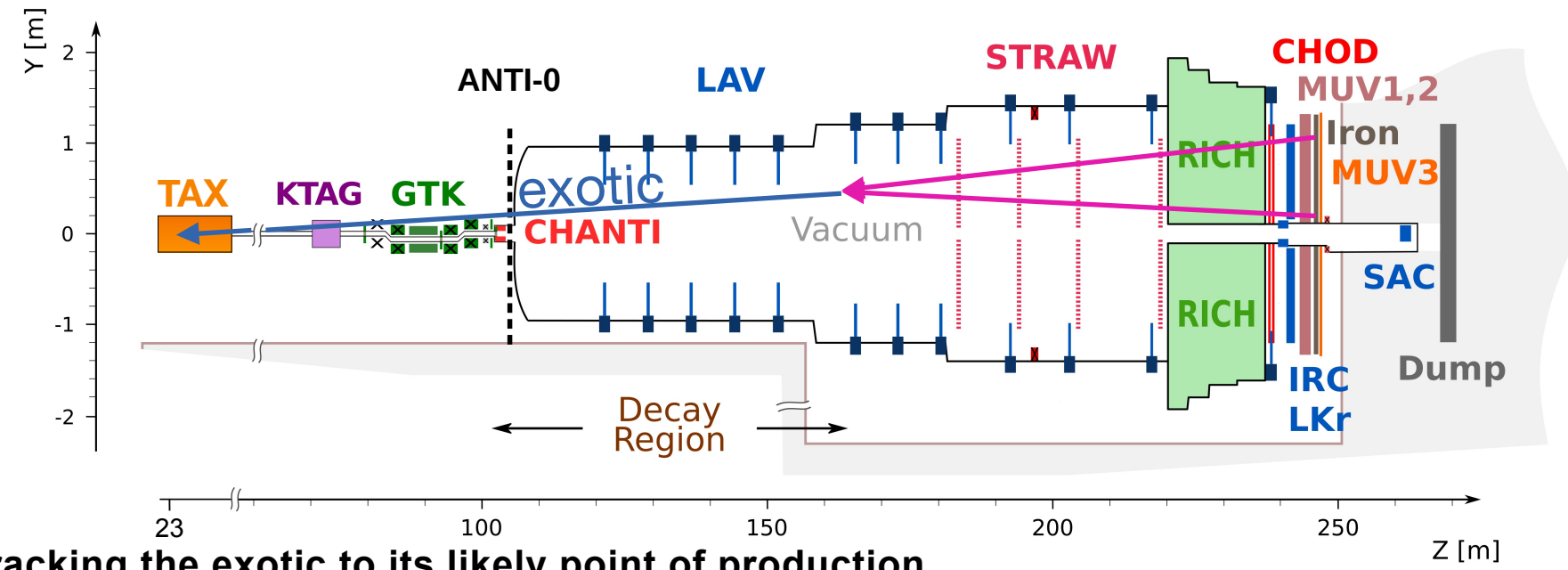
Backtracking the exotic to its likely point of production

THE NA62 EXPERIMENT
BEAM DUMP MODE — SEARCH STRATEGY

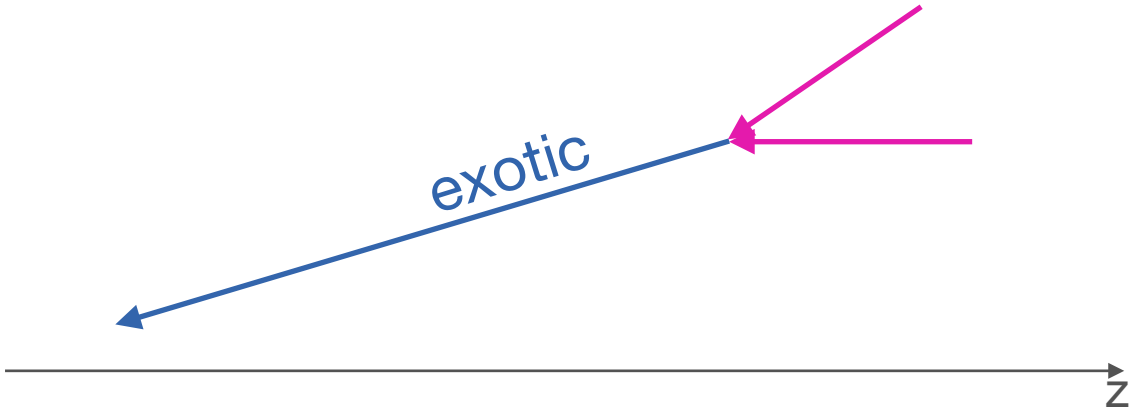


Backtracking the exotic to its likely point of production

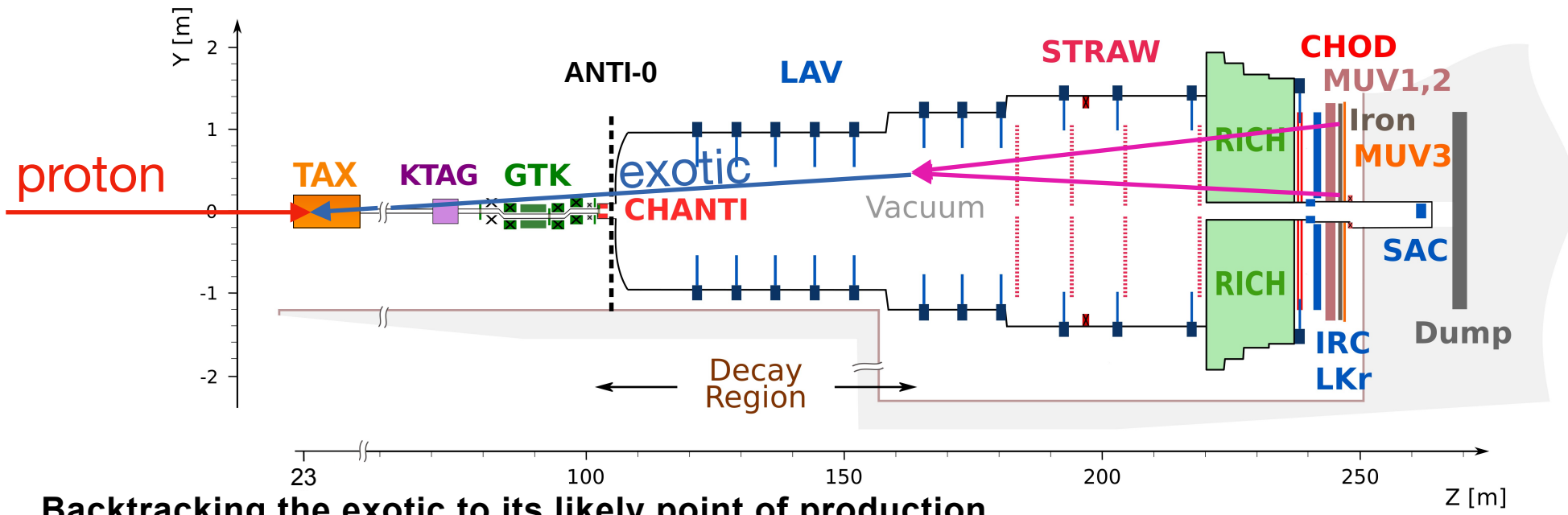
THE NA62 EXPERIMENT
BEAM DUMP MODE — SEARCH STRATEGY



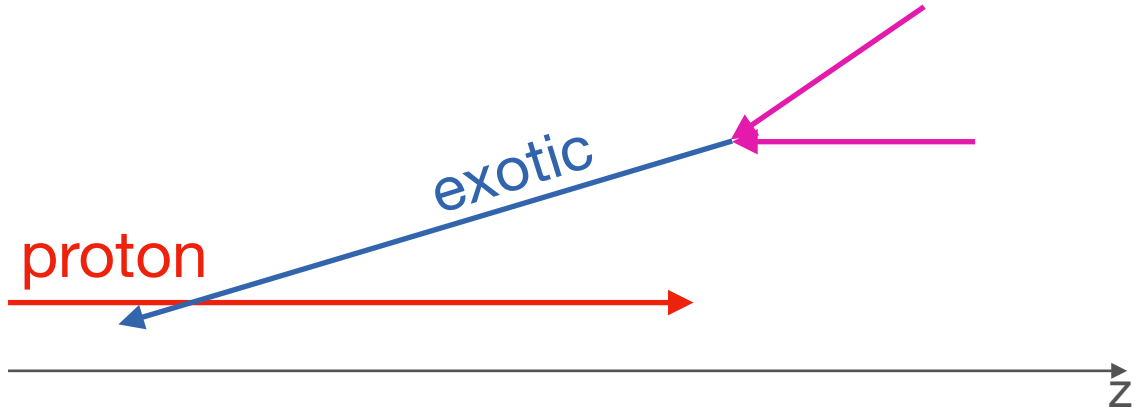
Backtracking the exotic to its likely point of production



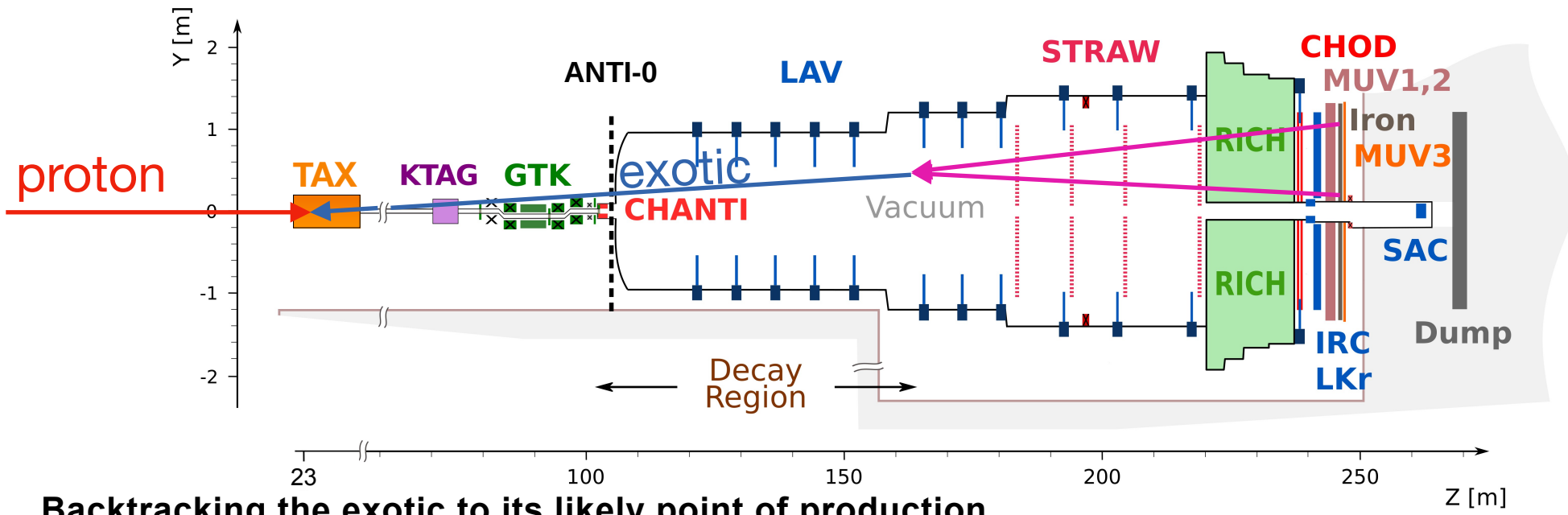
THE NA62 EXPERIMENT
BEAM DUMP MODE — SEARCH STRATEGY



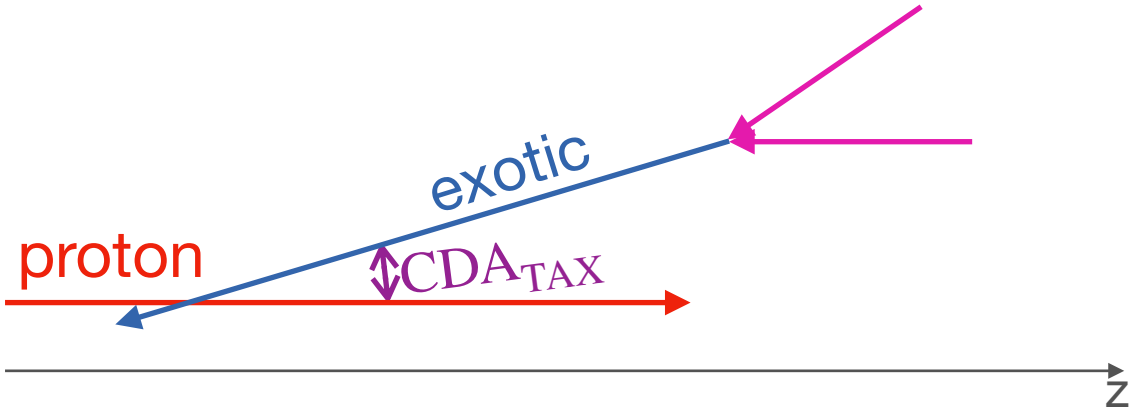
Backtracking the exotic to its likely point of production



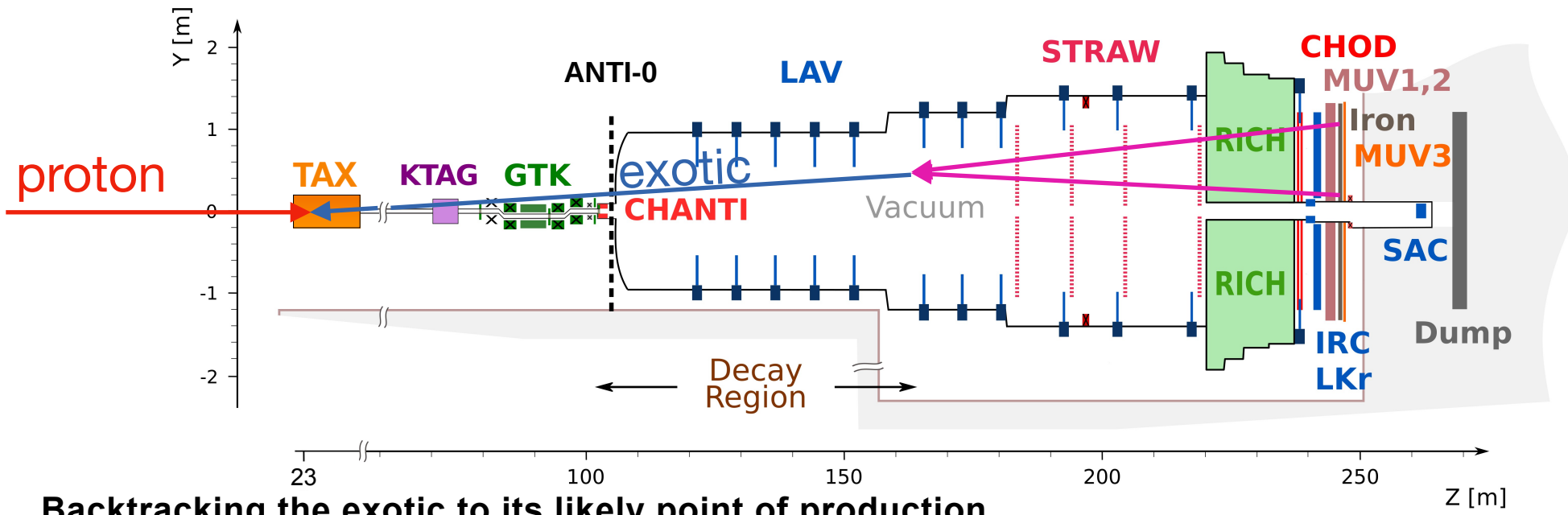
THE NA62 EXPERIMENT
BEAM DUMP MODE — SEARCH STRATEGY



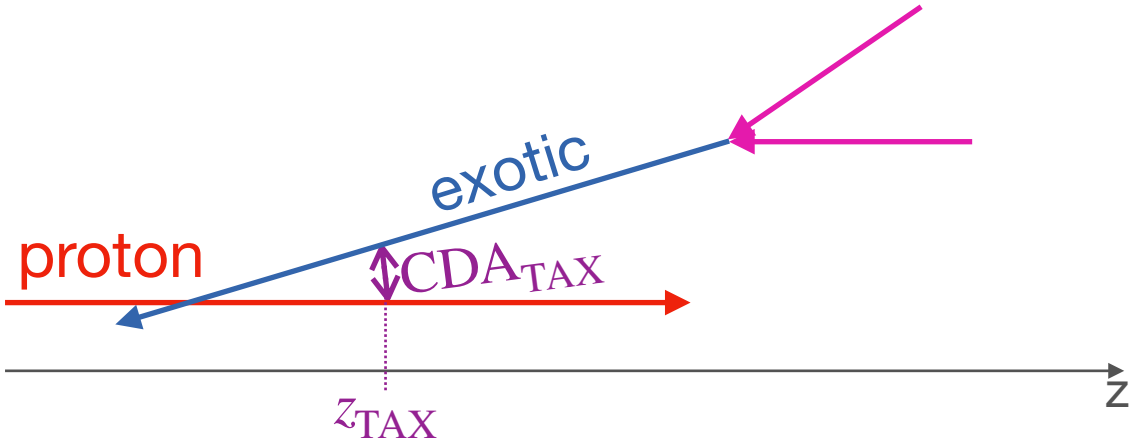
Backtracking the exotic to its likely point of production



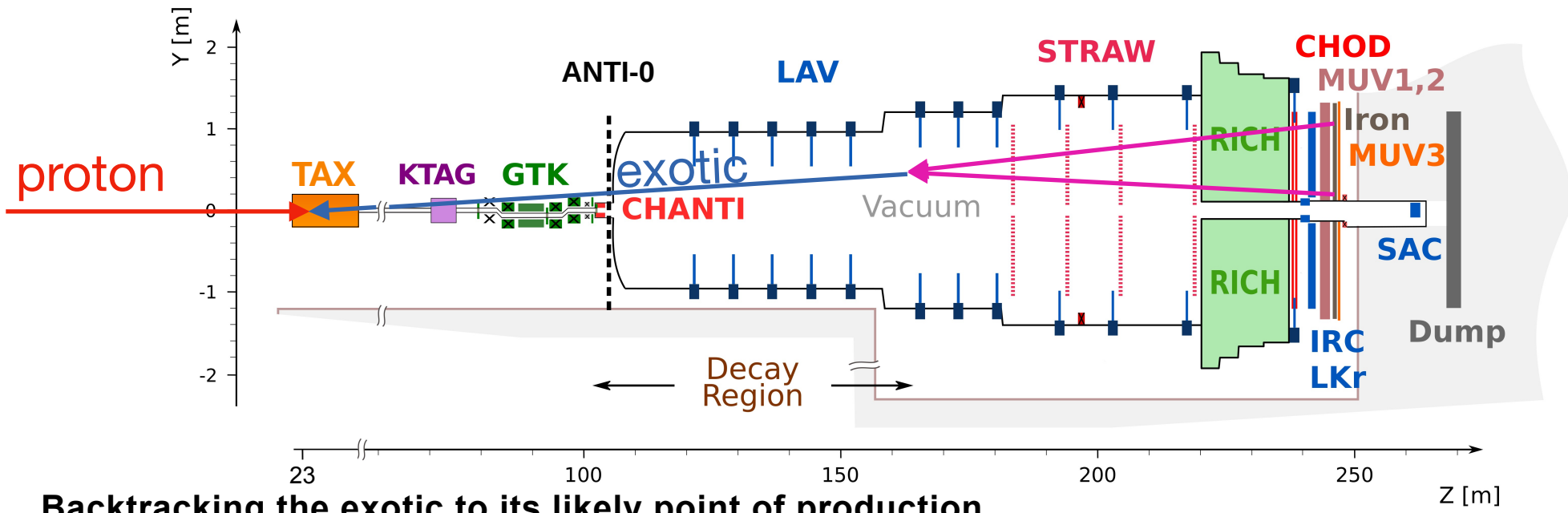
THE NA62 EXPERIMENT
BEAM DUMP MODE — SEARCH STRATEGY



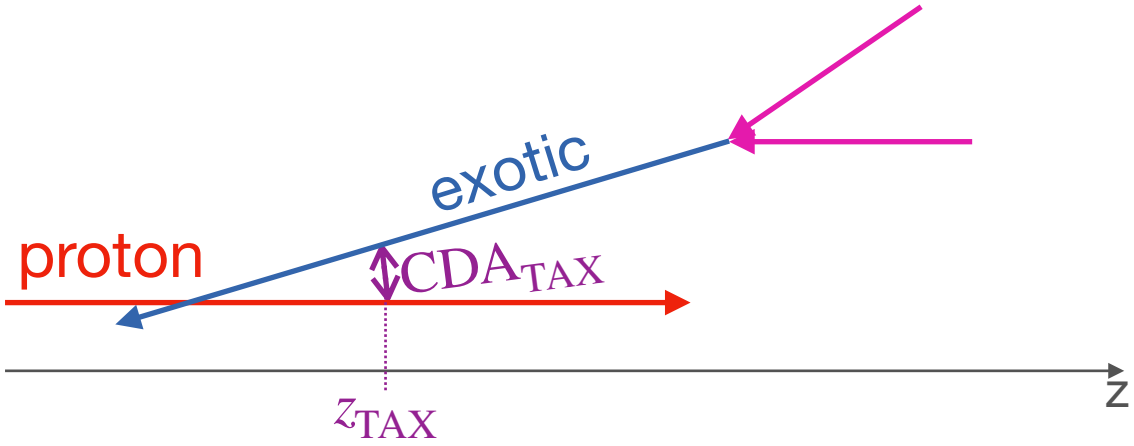
Backtracking the exotic to its likely point of production

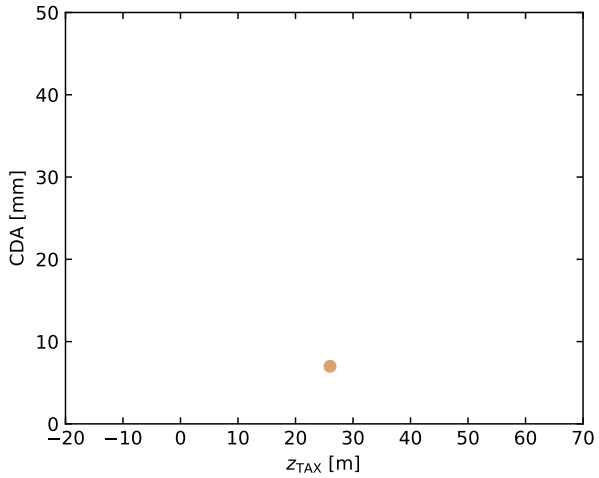


THE NA62 EXPERIMENT
BEAM DUMP MODE — SEARCH STRATEGY

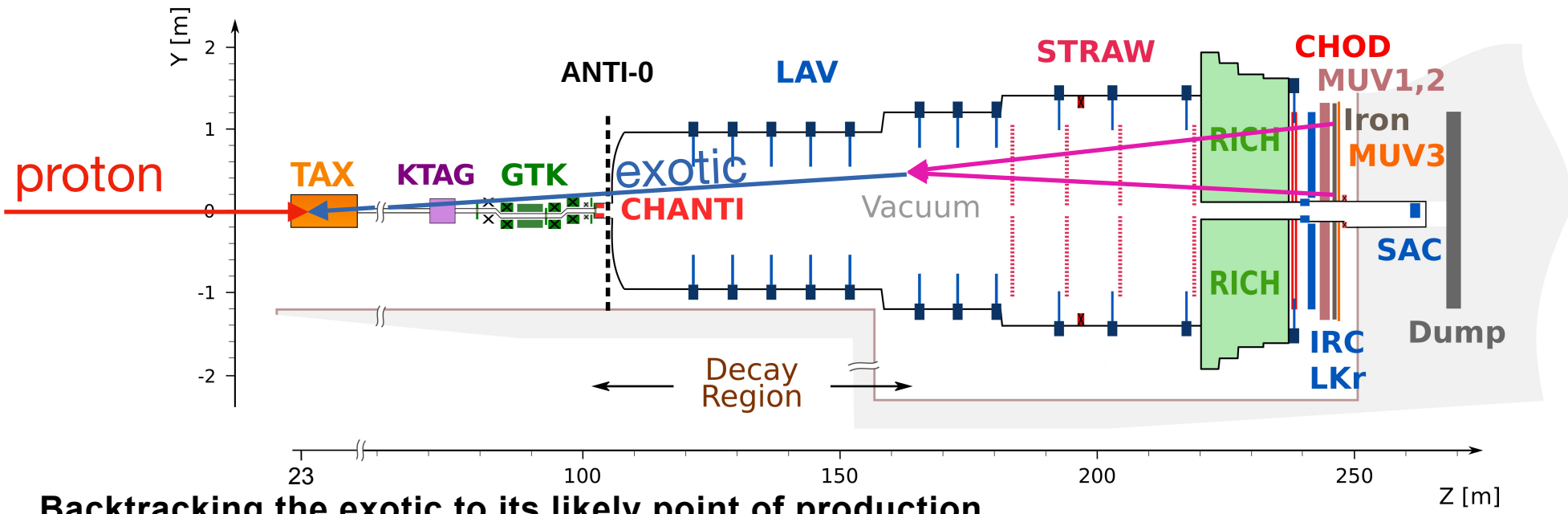


Backtracking the exotic to its likely point of production





THE NA62 EXPERIMENT
BEAM DUMP MODE — SEARCH STRATEGY



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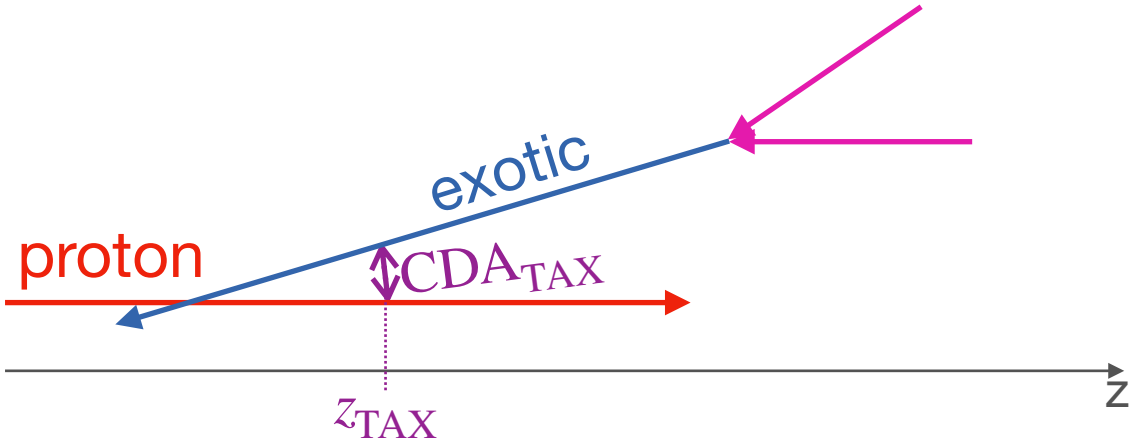
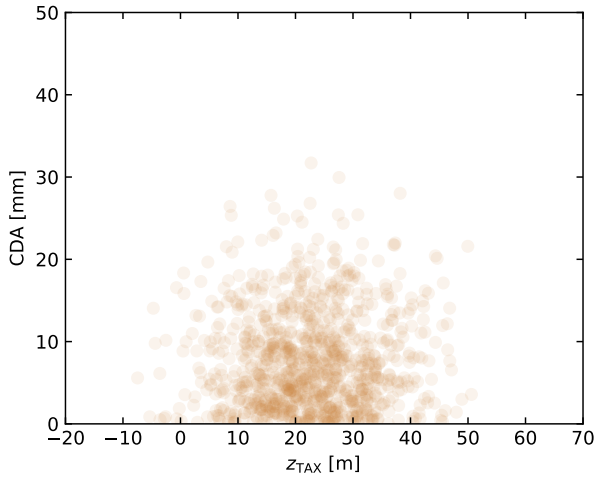
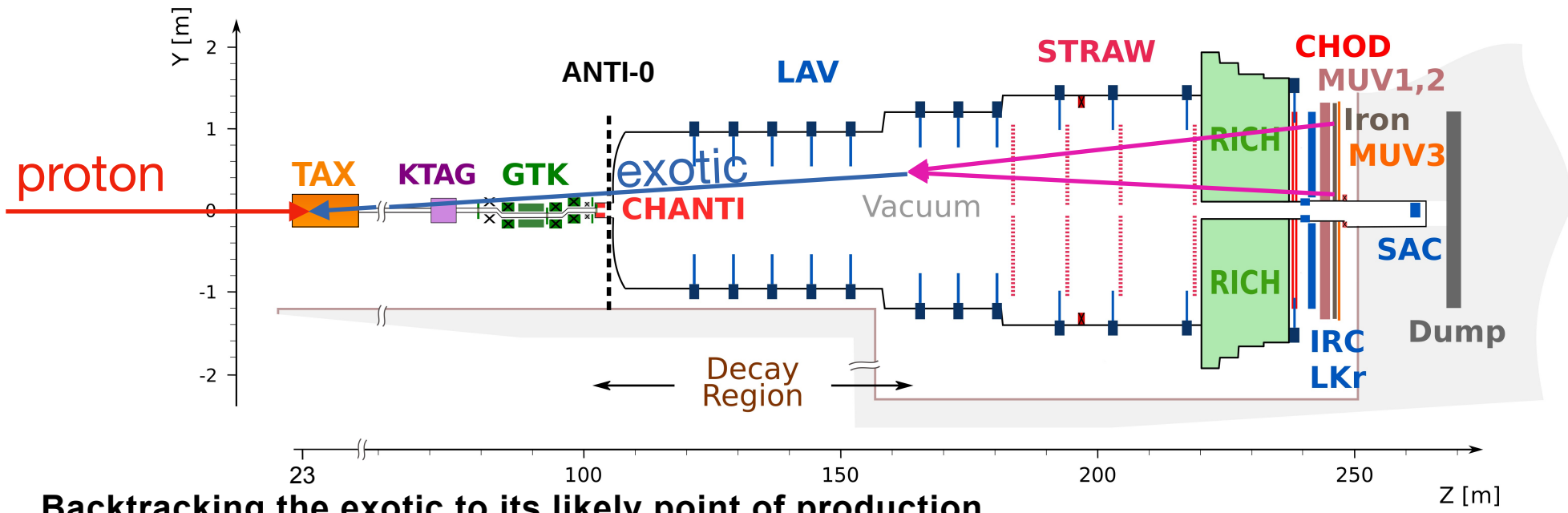




THE NA62 EXPERIMENT
BEAM DUMP MODE — SEARCH STRATEGY



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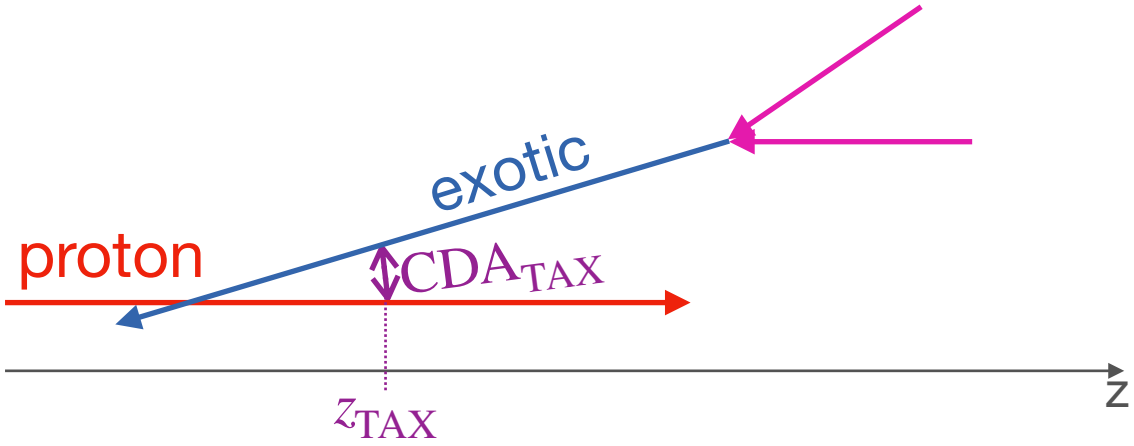
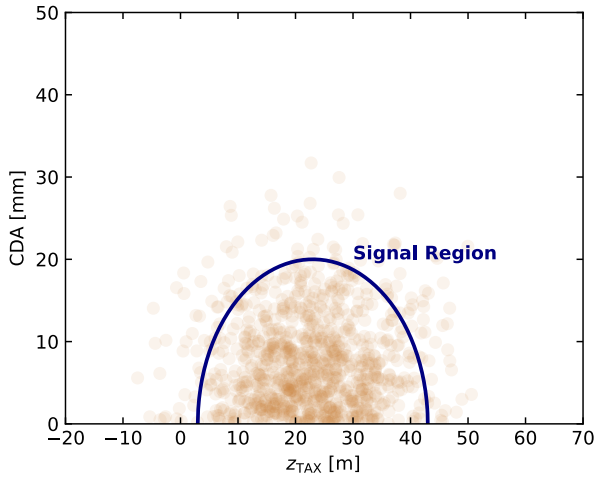
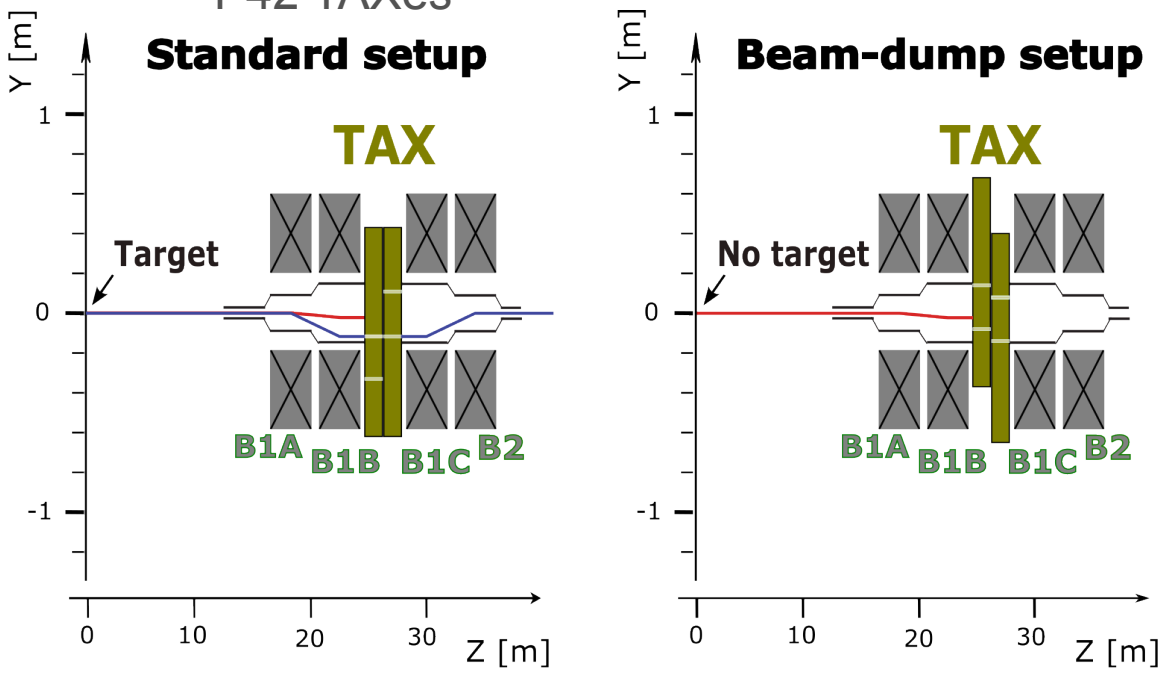




THE NA62 EXPERIMENT
TAX SET-UP IN MORE DETAIL

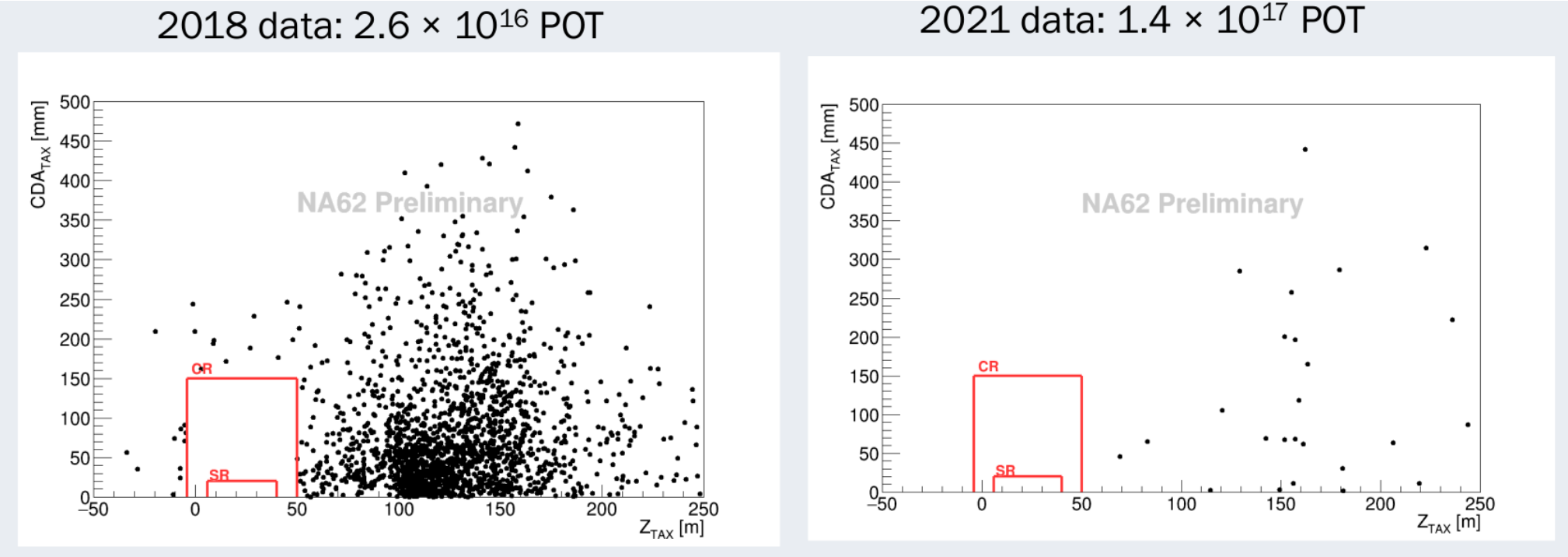
P42 TAXes



DUMP-MODE SEARCHES

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**



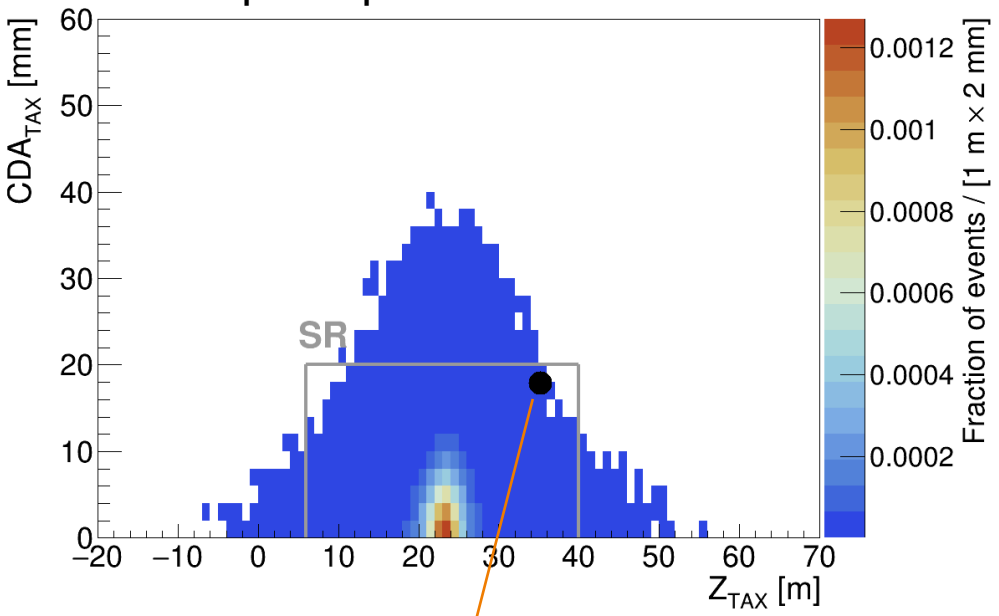
EVENT DETAILS FROM $\mu\bar{\mu}$ SEARCH

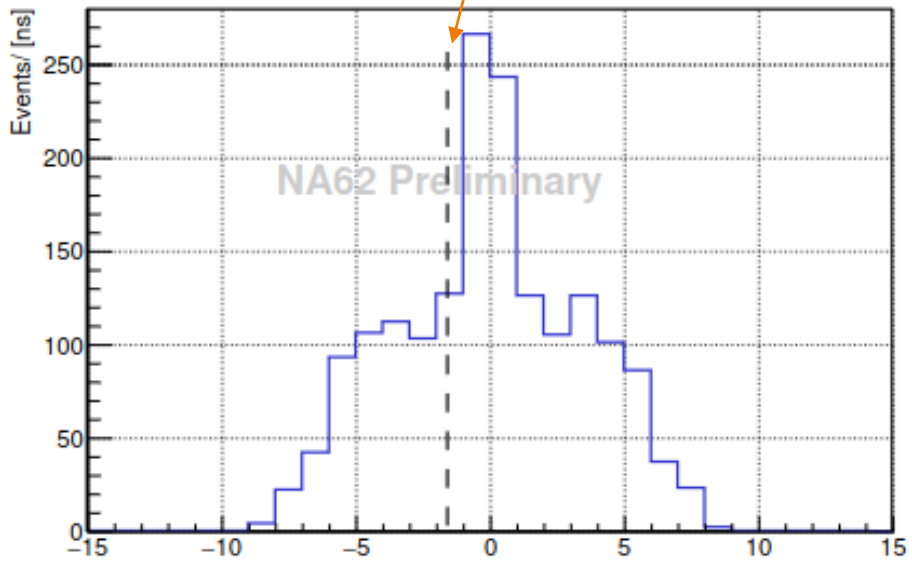
Region	Combinatorial	Prompt	Upstream-prompt
CR	0.17 ± 0.02	< 0.004	< 0.069
SR	0.016 ± 0.002	< 0.0004	< 0.007

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

- **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**
  - $z_{\mathrm{TAX}} = 38.2\,\mathrm{m}$
  - $\mathrm{CDA_{FV}} = 17\,\mathrm{mm}$

Expected signal sensitivity
Superimposed with data





BACKGROUNDS IN $e\bar{e}$ SEARCH

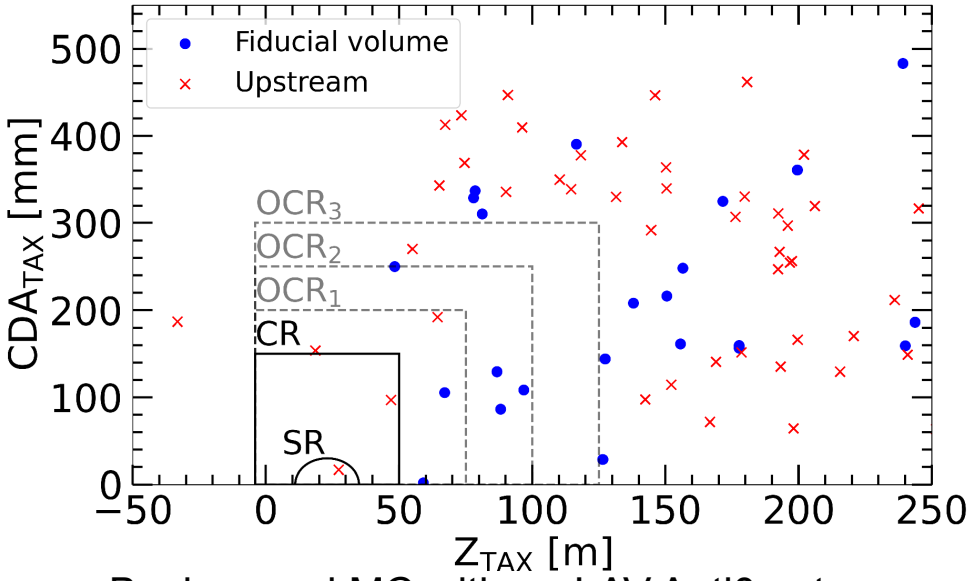
$$N_{\mathrm{bkg}}^{\mathrm{CR,SR}} = N_{\mathrm{bkg}}^{\mathrm{inFW}}(1-\eta_{\mathrm{LAV\ ANTI0}})(1-\eta_{\mathrm{CR,SR}})$$

which results in

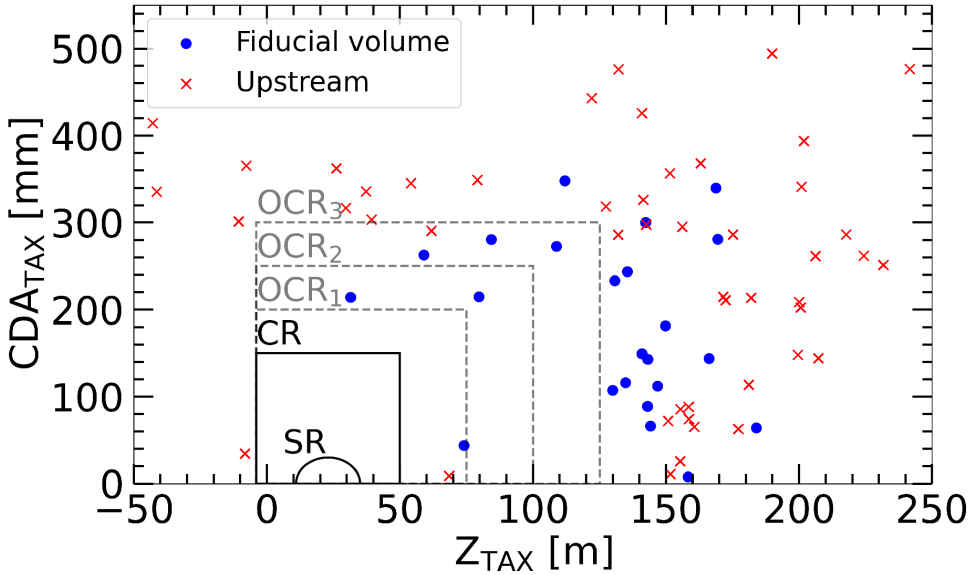
$$N_{\mathrm{bkg}}^{\mathrm{SR}} = 0.0094^{+0.049}_{-0.009}\ @\,90\,\%\,\mathrm{CL}$$

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

➡**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

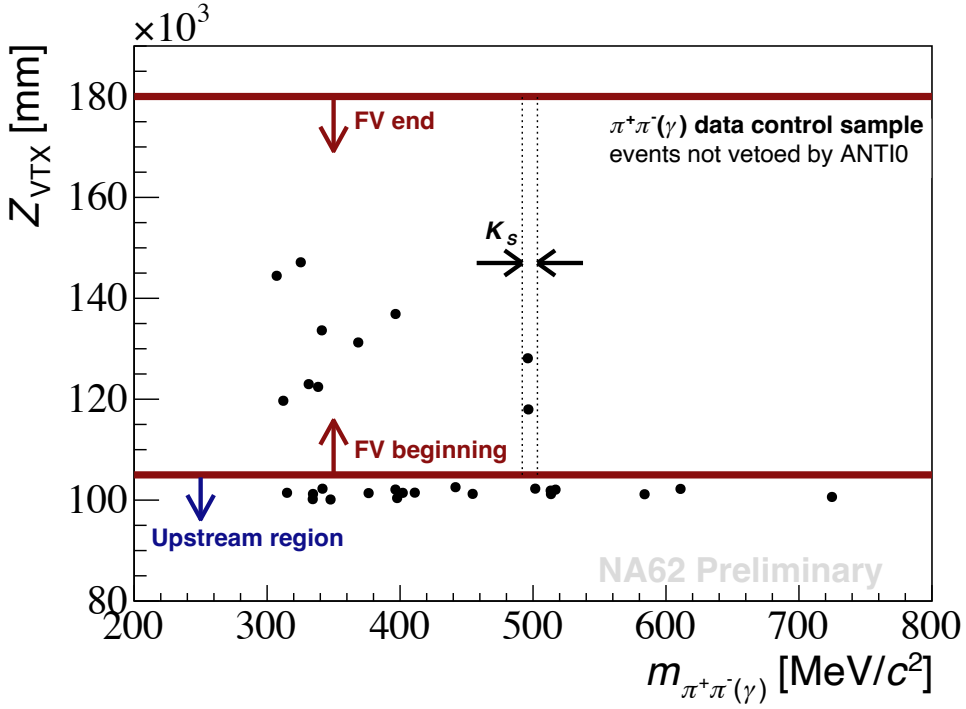
BACKGROUNDS UPSTREAM IN DEPTH

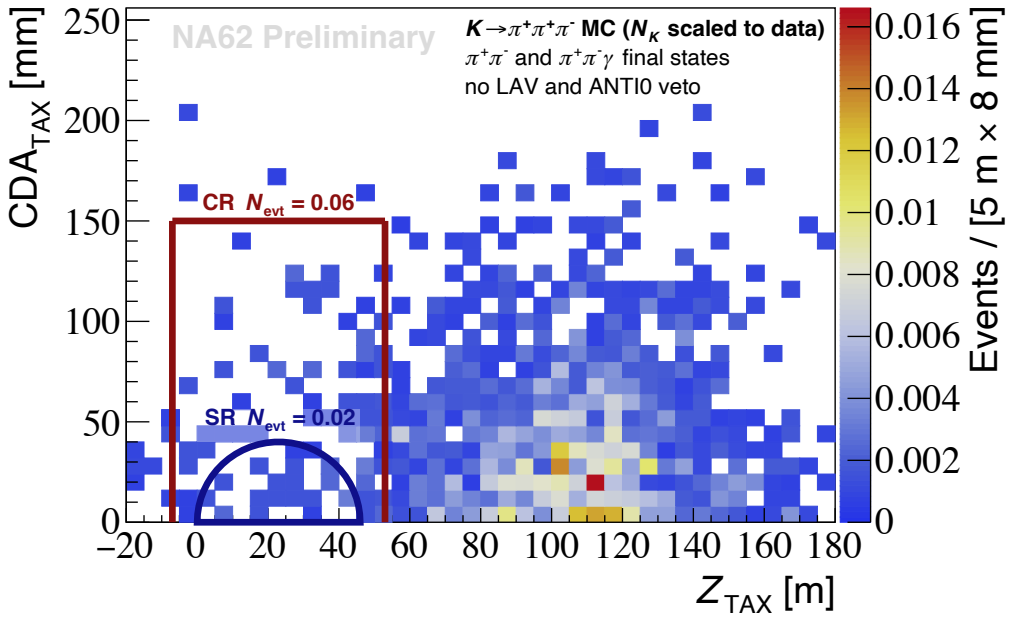
Control sample (no Anti0 veto) contained

- 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

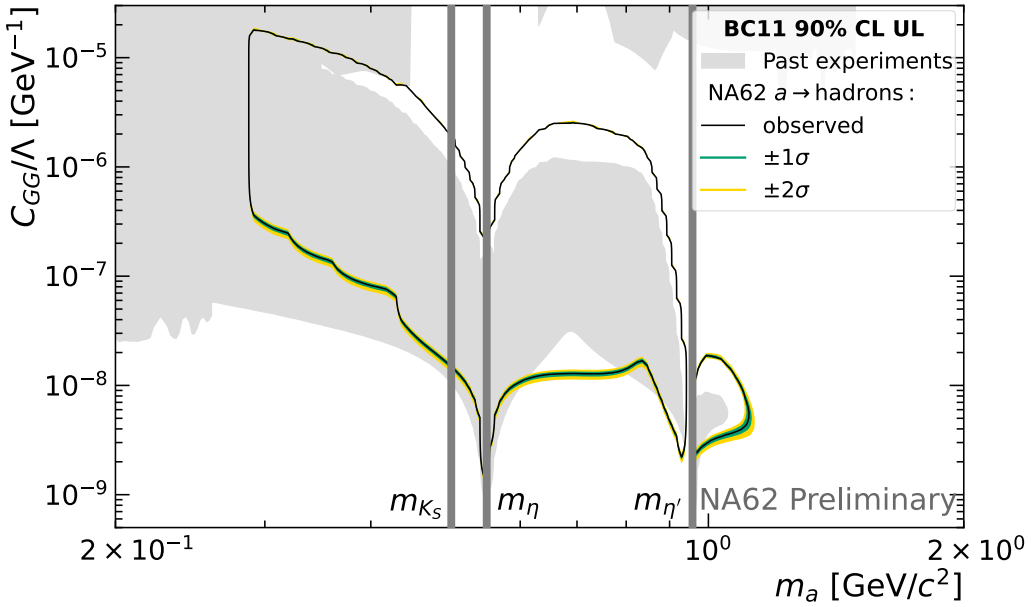
$K_{4\ell}$ simulated and gave only negligible backgrounds

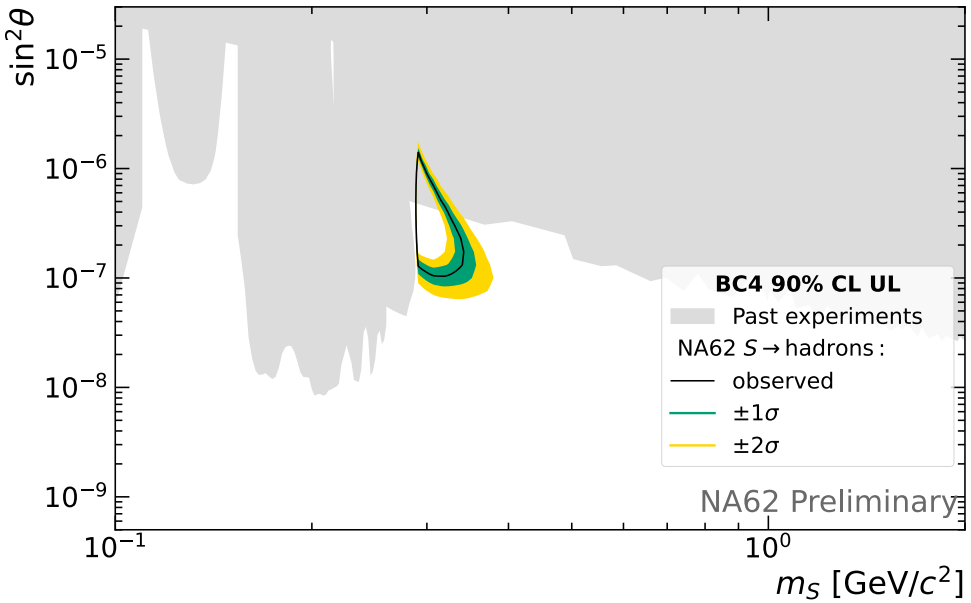


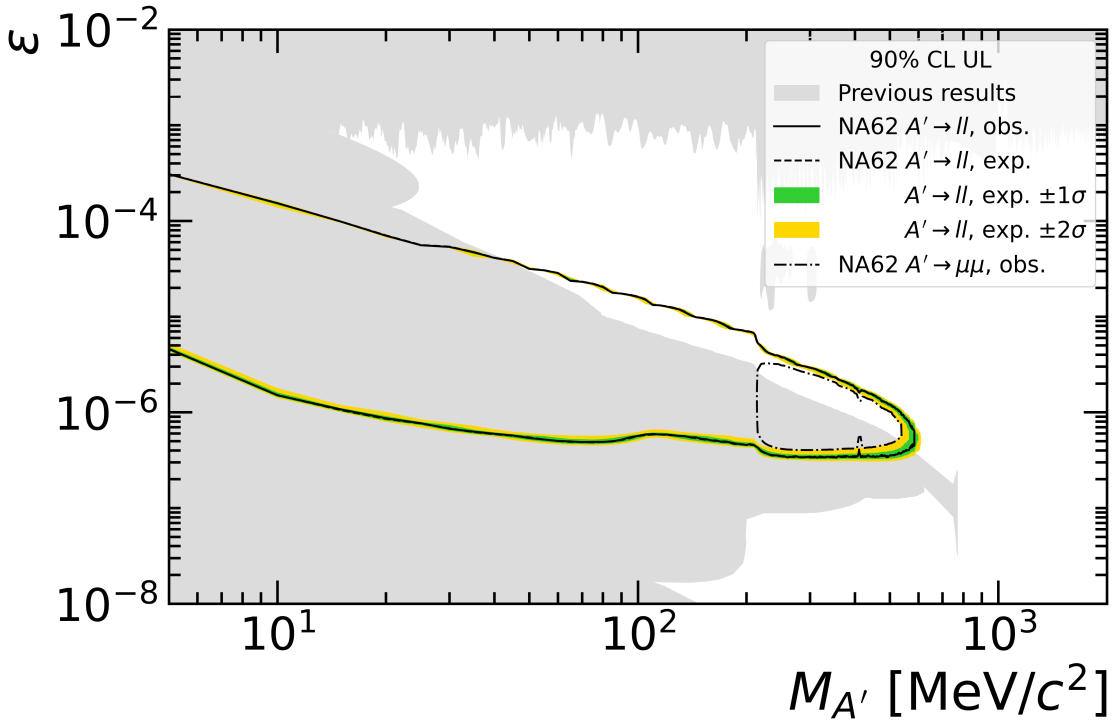


SENSITIVITIES AND ALPINIST

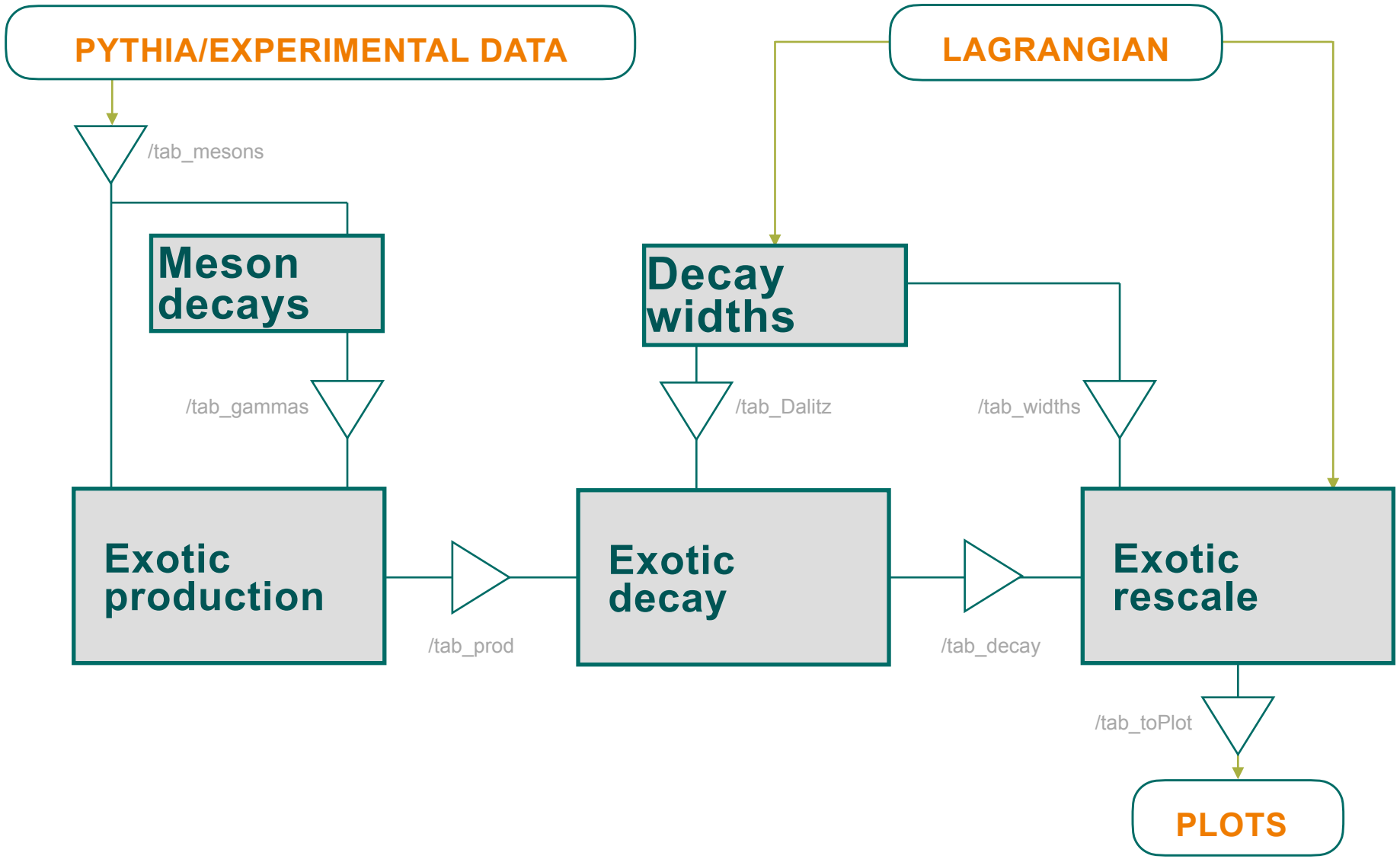
EXCLUSIONS REACHED



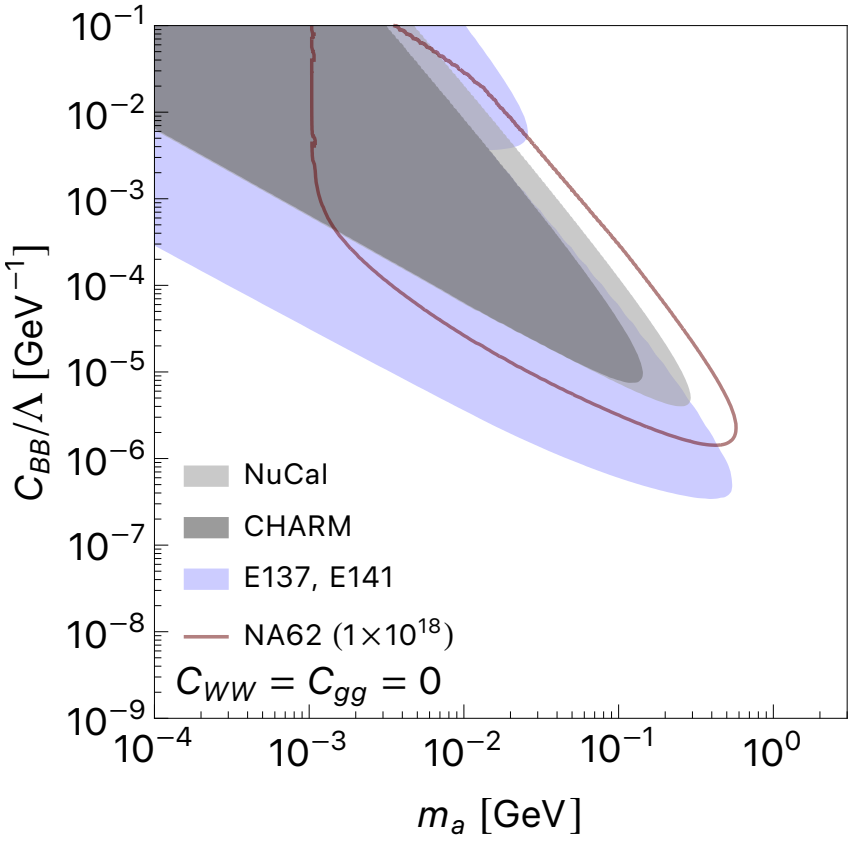




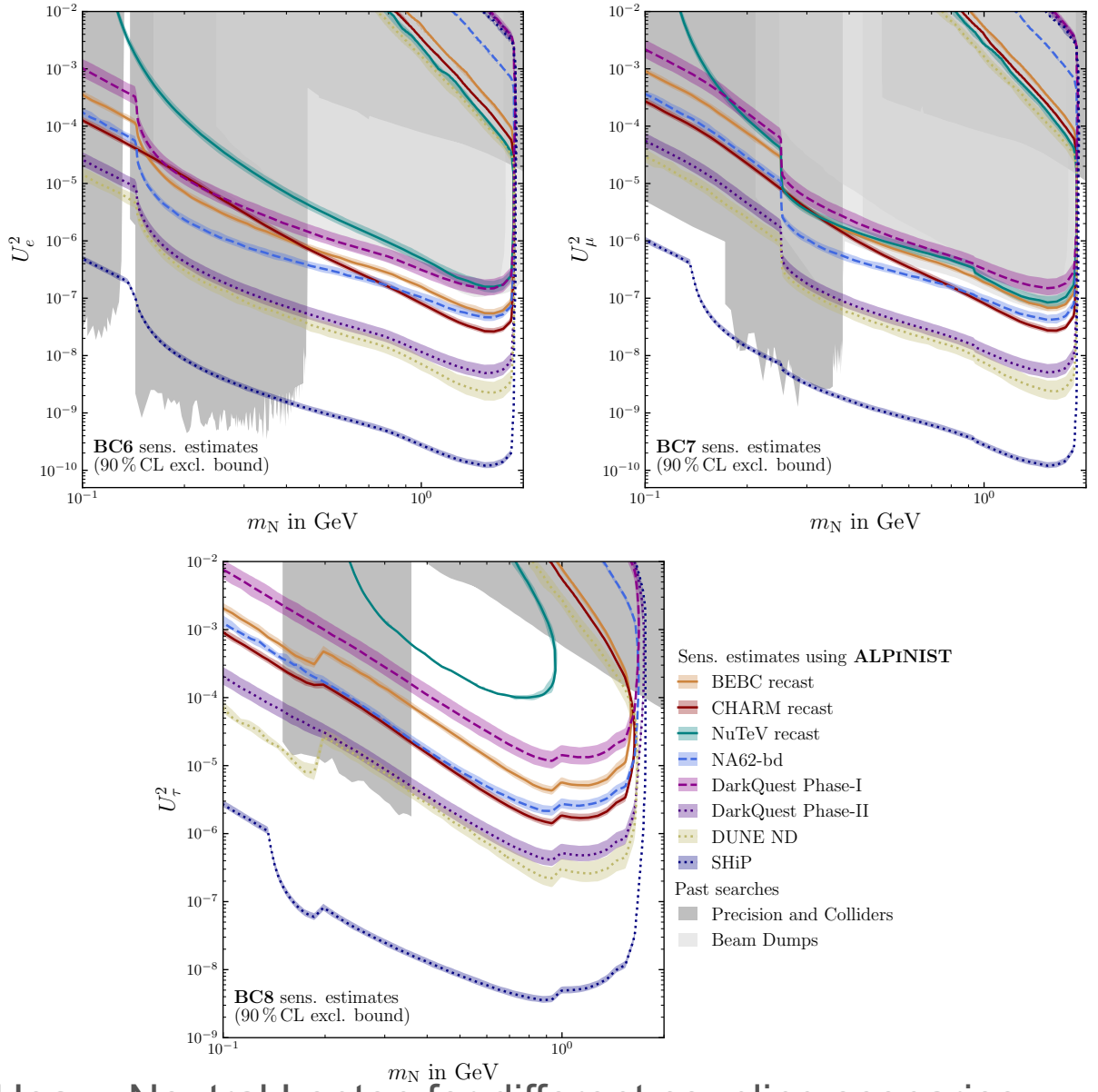
ALPINIST SCHEMATIC LAYOUT



NA62 SENSITIVITY ESTIMATES



Gluon Coupled ALP



Heavy Neutral Lepton for different coupling scenarios