NA64: Results and plans

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International collaboration: 50 researchers from ETH (Zurich), INFN (Genova), Univ. of Bonn (Bonn), JINR (Dubna), LPI, INR, SINP MSU (Moscow), IHEP (Protvino), TPU (Tomsk), SAPHIR(Chile), IFIC(Valencia), **U. York (Toronto)**

1) Light dark matter:

➡ ***Invisible*** decays using 100 GeV electrons: 2016-2022 combined analysis **world-leading sensitivity!**

- Future prospects:
  - ➡ **2023: First LDM results using a e^+ beam**
  - ➡ **2023: First DS exploration using a μ^- beam**
  - ➡ **2023: Proof of principle of NA64h**

2) Constraints on several **New Physics** processes setting also world-reference limits:

- ✦ *Inelastic Dark Matter*
- ✦ *ALPs*
- ✦ *B-L Z'*
- ✦ *L_μ-L_τ Z'*

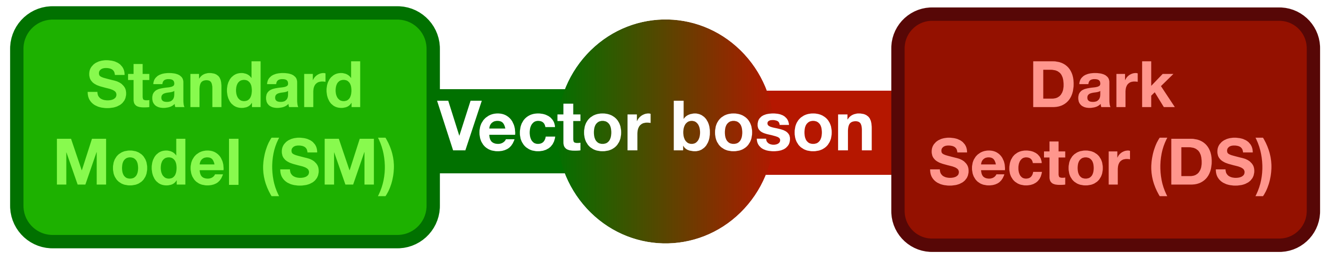
New analysis ongoing with 5 x (2016-2018 statistics)

Key years to demonstrate the robustness of the technique

	2016-2018	2021	2022	2023	Total
NA64e	*Invisible mode* 2.84×10^{11} EOT *Visible mode* 8.4×10^{10}	*Invisible mode* 6×10^{10} EOT	*Invisible mode* 6.3×10^{11} EOT	*Invisible mode* 5.1×10^{11} EOT	***1.5 x 10^{12} EOT***
NA64μ		0.5×10^{10} MOT	4×10^{10} MOT	1.5×10^{11} MOT	
NA64e+			10^{10} e^+OT	1.5×10^{10} e^+OT	
NA64h			2×10^{9} πOT	1.9×10^{10} πOT	

https://na64.web.cern.ch/

Vector portal to Dark Sector

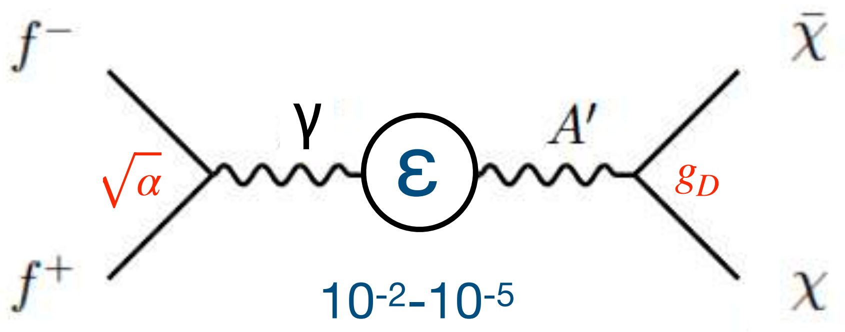


$$L_{Total} = L_{SM} + L_{DS} + L_{Portal}$$

Vector (***Dark Photon, A'***)

U(1)' $\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$

χ : *DM candidate*



$$\mathscr{L}_{\rm DP} = \frac{m^2_{A'}}{2} A'_\mu A'^\mu + A'_\mu \left(g_D \mathscr{J}^\mu_{\rm DS} - e\varepsilon \mathscr{J}^\mu_{\rm EM} \right)$$

Parameter space defined by: $m_{A'}$, m_χ, ε, $\alpha_D = g_D^2/4\pi$

- new massive boson A´ (dark photon) which has kinetic mixing with ordinary photon: $\Delta L = \varepsilon/2\ F^{\mu\nu} A'_{\mu\nu}$
- Production: A´ - bremsstrahlung $e^- Z \rightarrow e^- Z A'$, $s \sim Z^2 \varepsilon^2 / m_{A'}^2$
- Decays:
  - Visible: $A' \rightarrow e^+e^-$, $\mu^+\mu^-$, hadrons,..
  - Invisible: $A' \rightarrow \chi\chi$ if $m_{A'} > 2\, m_\chi$ assuming $a_{DM} \sim a >> \varepsilon$.

    Can explain $(g\text{-}2)_\mu$, astrophys. observations

Cross section for c-DM annihilation:

$$\Omega_\chi \propto \frac{1}{<\sigma v>} \sim \frac{m_\chi^2}{g_\chi^4}$$

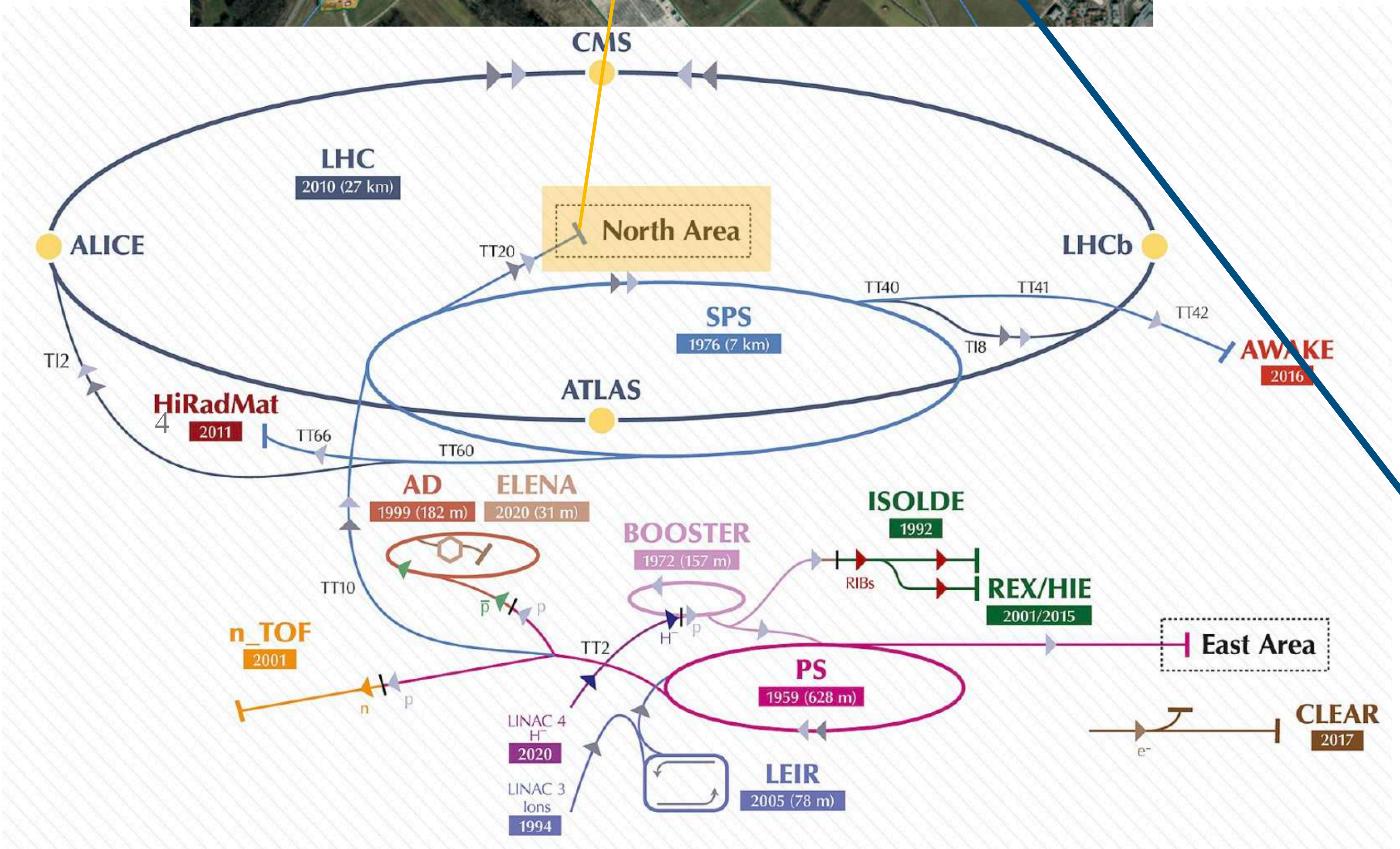
$$\sigma v(\chi\chi \rightarrow A' \rightarrow ff) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2}$$

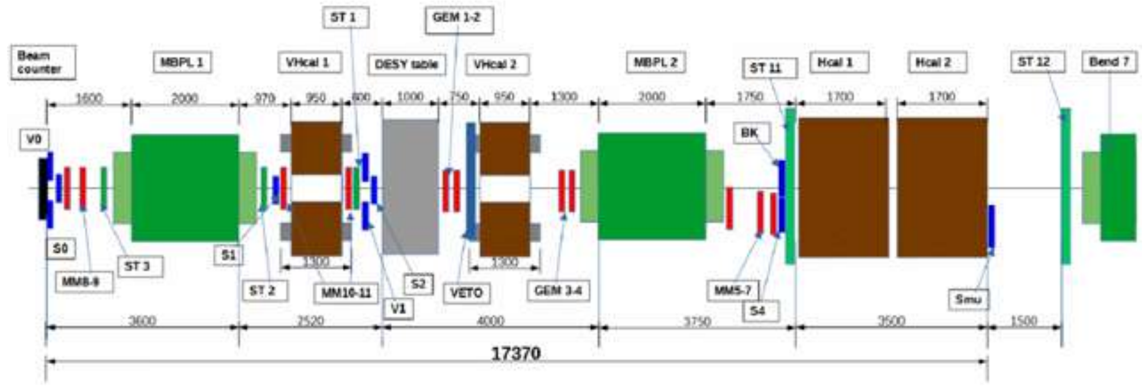
J.Feng, J. Kumar
Phys. Rev. Lett.101231301

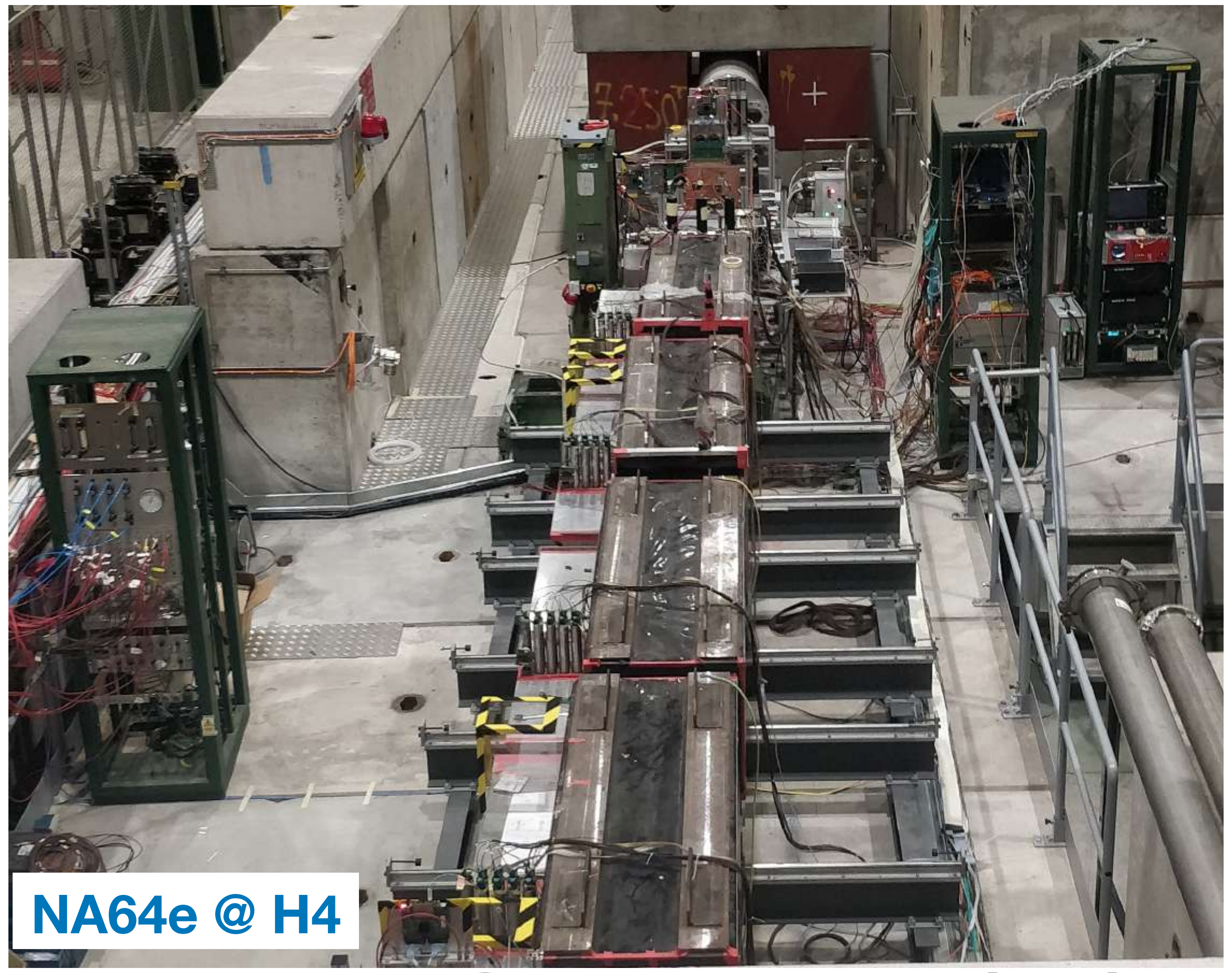
m_χ, g_χ→governed by this new force in a broad parameter space below the EW scale

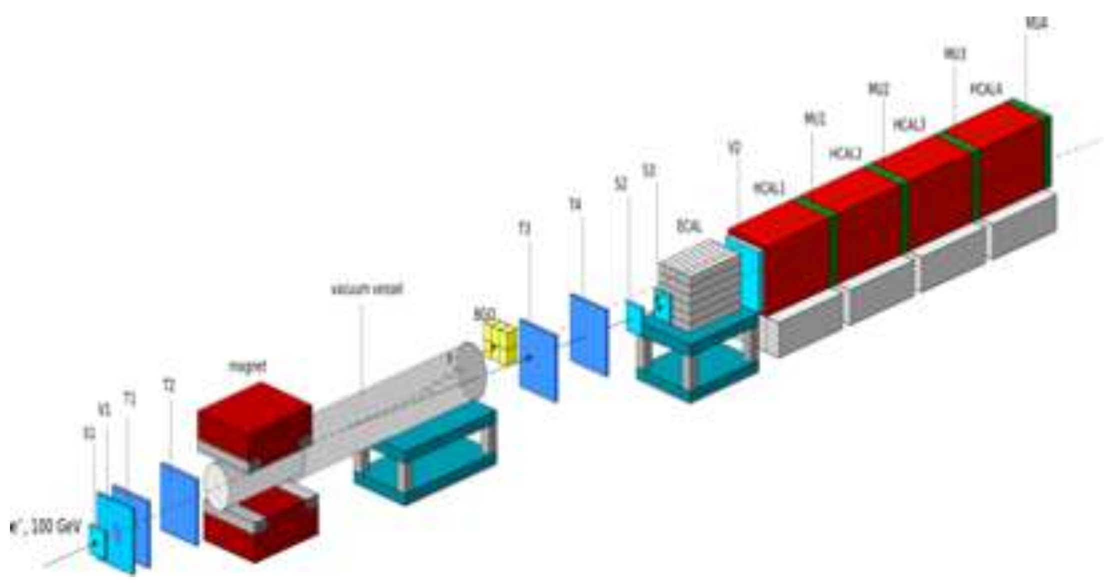
The NA64 experiment

Fixed target experiment at the CERN Super Proton Synchrotron accelerator designed to probe Dark Sector physics.

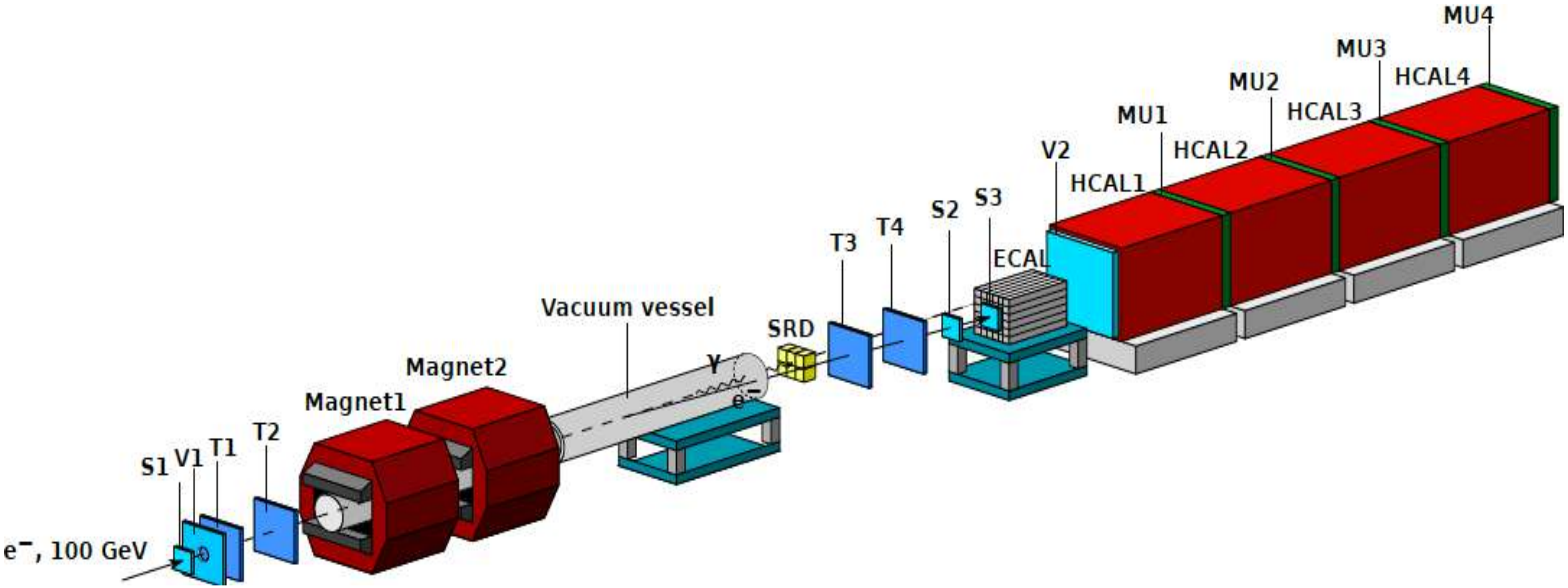








NA64 experiment setup (invisible mode)



Assembling NA64 subdetectors (2015)

NA64 in 2021-2024, permanent place at H4 prepared by the CERN Beam Division

Summary of the NA64 runs at H4

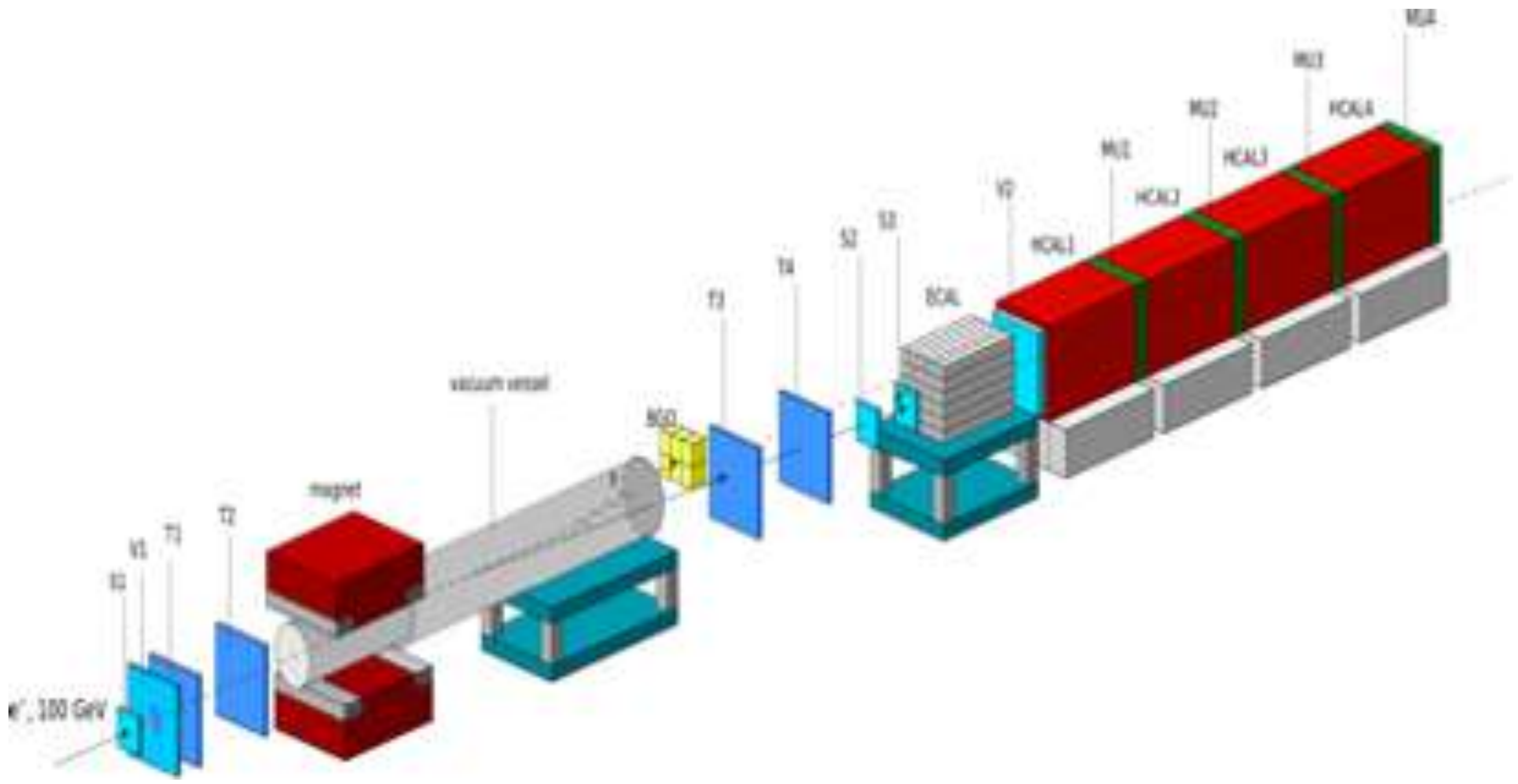
Ø**Invisible mode** configuration, first run 12.10-09.11 2016

- Run 2016 EOT ~ $4.5x10^{10}$, S_0 rate $2÷4x10^6$;
- Run 2017 EOT ~ $5.4x10^{10}$, S_0 rate $4÷6x10^6$
- Run 2018 EOT ~ $1.9x10^{11}$, S_0 rate $6÷8x10^6$
- Run 2021 EOT ~ $5.2x10^{10}$, S_0 rate $4÷5x10^6$
- Run 2022 EOT ~ $6.4x10^{11}$, S_0 rate $5÷7x10^6$
- Run e^+ 2022 EOT ~ $1.0x10^{10}$, S_0 rate $5÷7x10^6$
- Run 2023 EOT ~ $6.0x10^{11}$, S_0 rate $5÷7x10^6$
- Total analysed electrons (2016 – 2022) ~ $9.37x10^{11}$ eot
- Total accumulated (2016 – 2023) ~$1.5x10^{12}$ eot

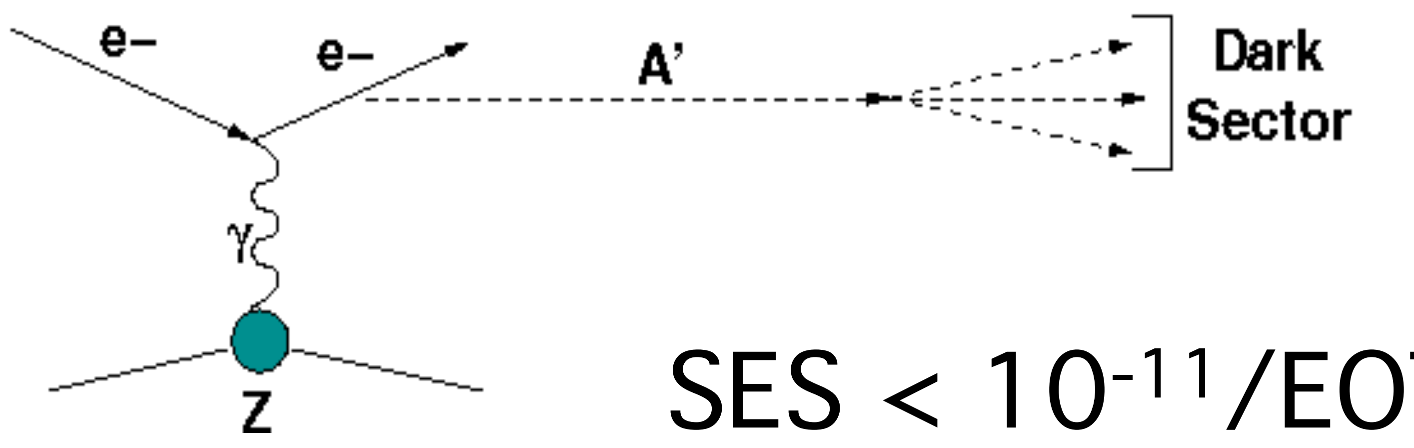
Ø**Visible mode** configuration first run 22.09-01.10 2017

- Subrun 1 WCAL 40X0 EOT ~ $2.4x10^{10}$, S_0 rate ~$3x10^6$
- Subrun 2 WCAL 30X0 EOT ~ $3x10^{10}$, S_0 rate $4\text{-}5x10^6$
- Run 2018 S4 in WCAL EOT ~ $3x10^{10}$, beam 150 GeV
- Total EOT ~ $8.4x10^{10}$

Search for A´->invisible decays at CERN SPS



S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)



SES < 10^{-11}/EOT

Signature:

- in: 100 GeV e- track
- out: $E_{ECAL} < E_0$ shower in ECAL
- no energy in Veto and HCAL

Main components :

- clean 100 GeV e- beam
- e- tagging system: MS+SRD
- hermetic ECAL+HCAL

Background:

- μ, π, K decays in flight
- upstream interactions
- Tail < 50 GeV in the e- beam
- Energy leak from ECAL+HCAL

The NA64 technique

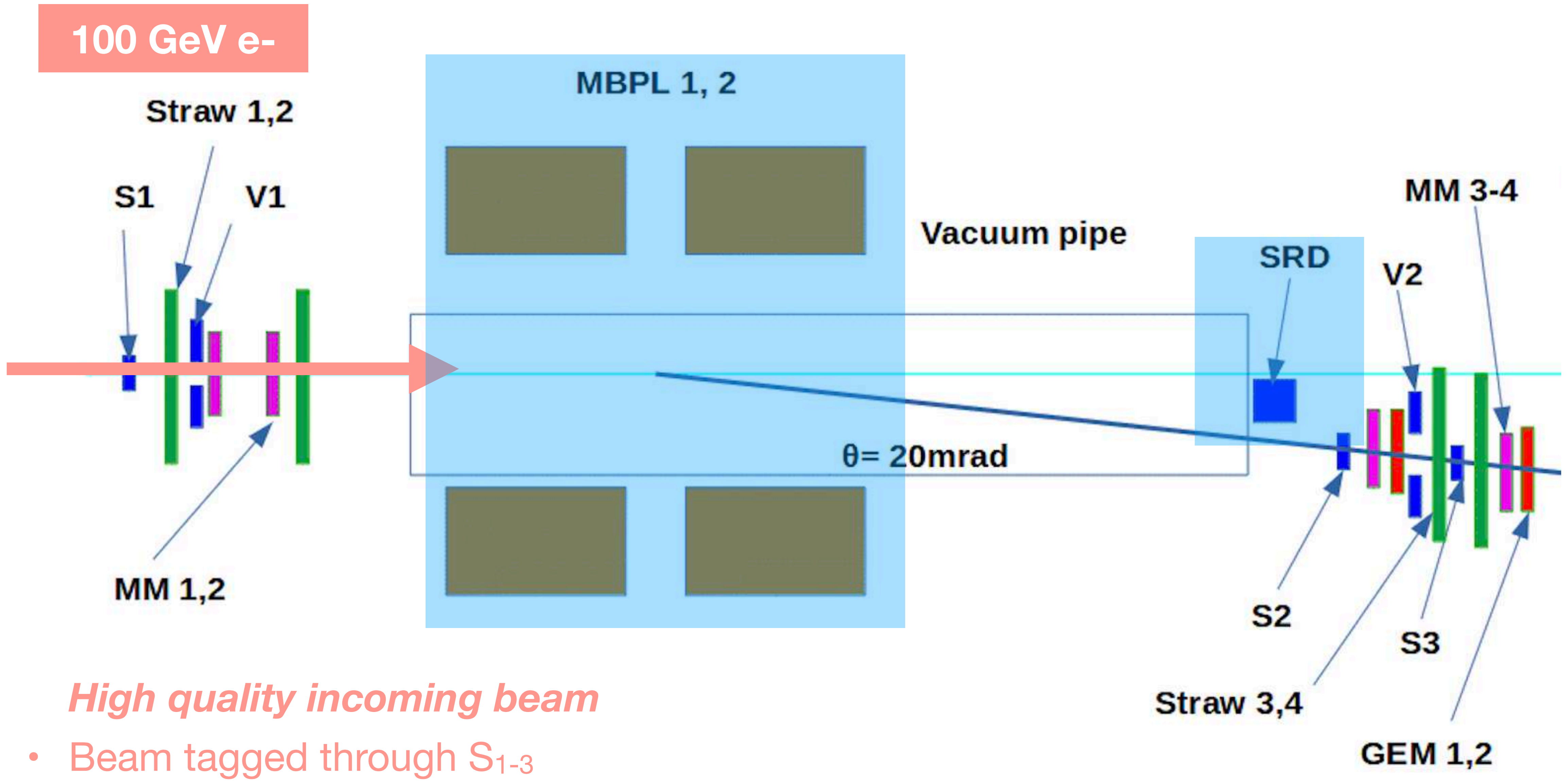
Initial well-defined
e^-, e^+, μ, h beam

S. Andreas et al., arXiv:1312.3309 (2013)
S. N. Gninenko, Phys. Rev. D 89, 075008 (2014)
L. Marsicano et al. Phys. Rev. Lett. 121, 041802

+ Active Dump + Fully hermetic detector

1) Incoming *particle ID* and *momentum* reconstruction

E. Depero et al., NIMA 866 (2017) 196-201
D. Banerjee et al., NIMA881 (2018) 72-81

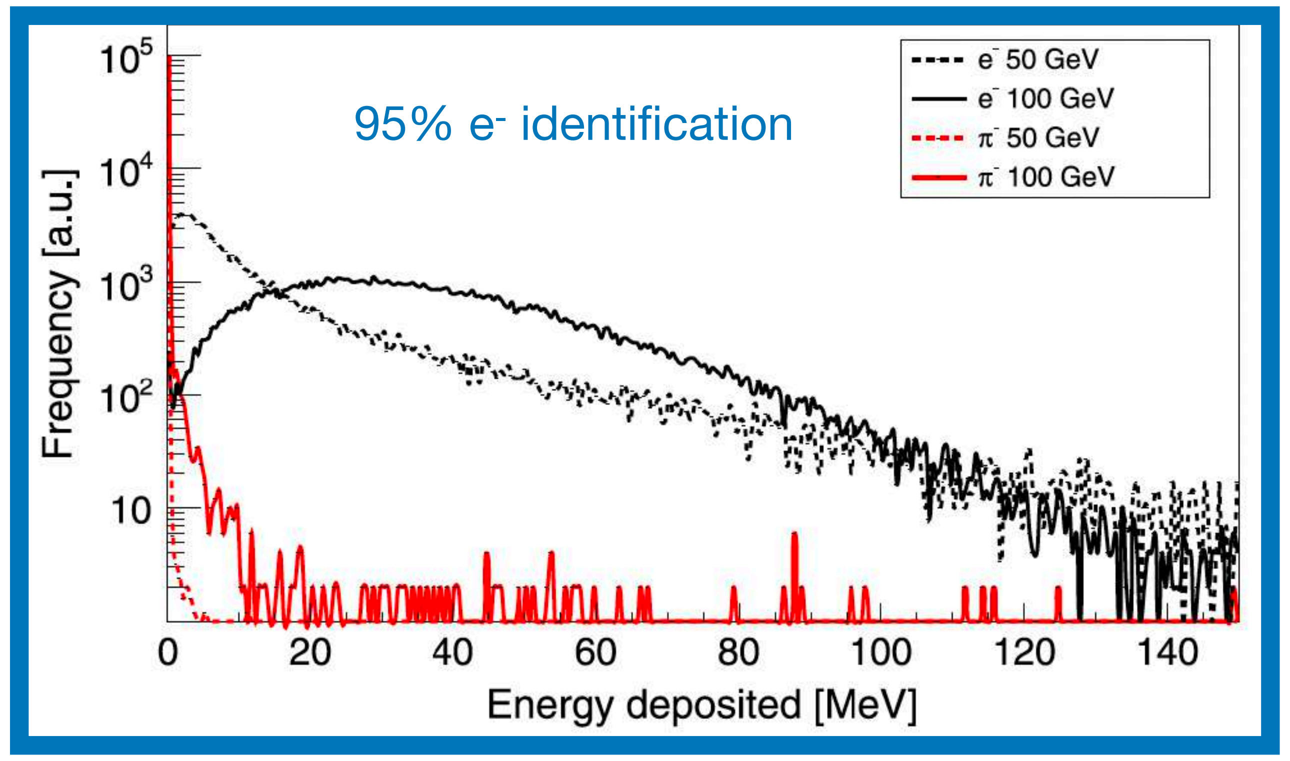


High quality incoming beam

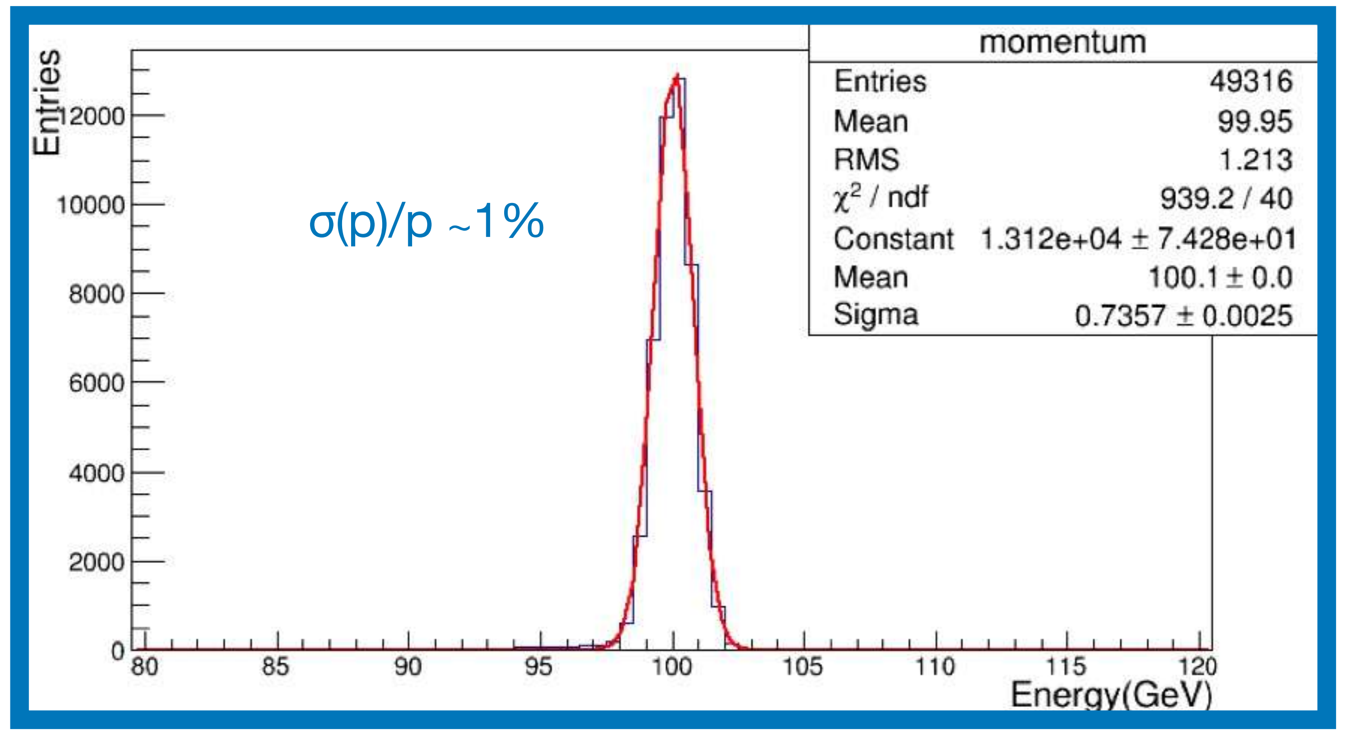
- Beam tagged through S_{1-3}
- H4 Beam Intensity ~$7x10^6 e^-$/spill (4.8s)
- Hadron contamination <0.3%

- ***Tracking system:*** *4 XY multiplexed resistive Micromegas, 2 GEM and 4 straw detectors*

Synchrotron Radiation



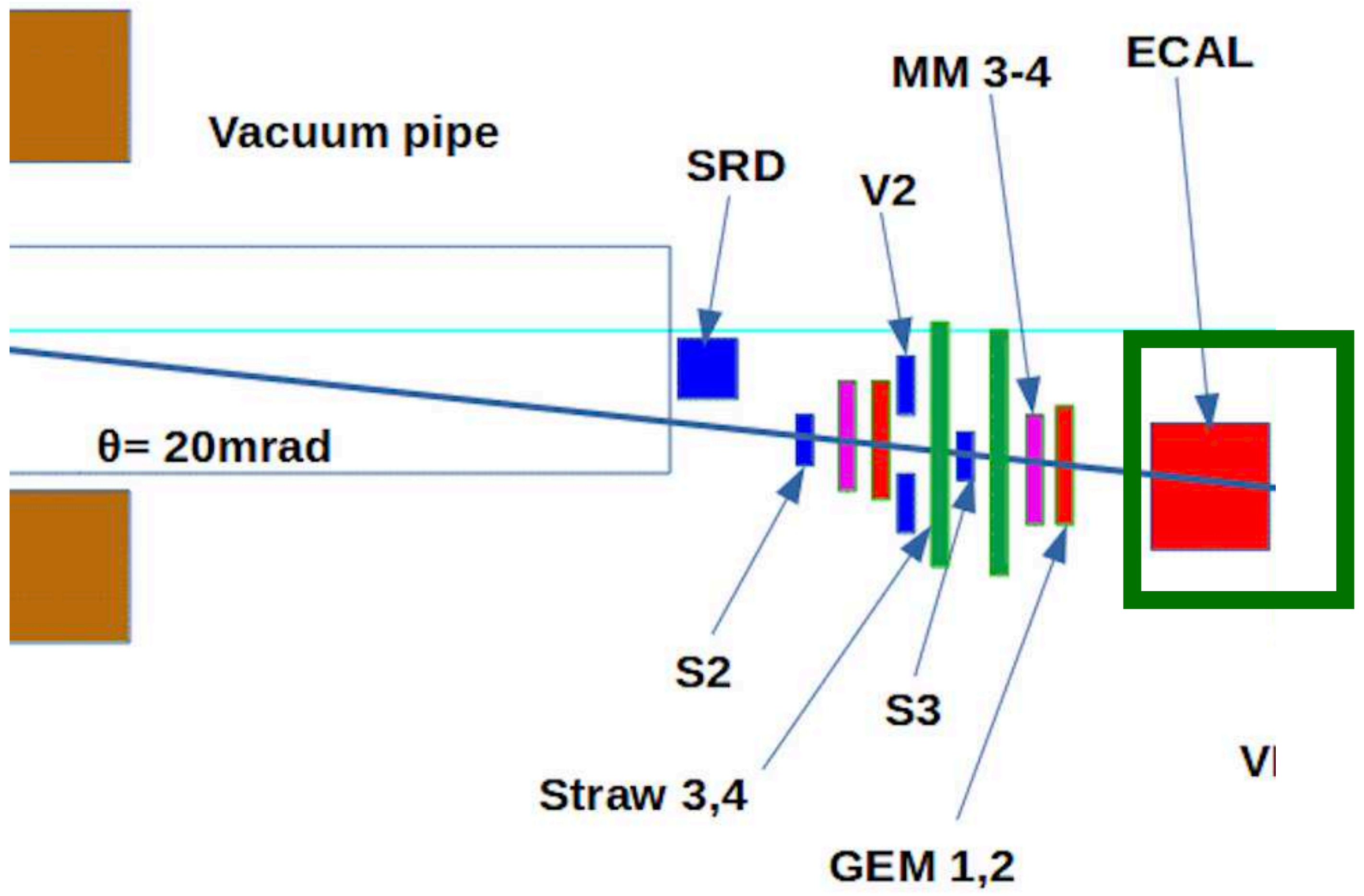
Momentum



The NA64 technique

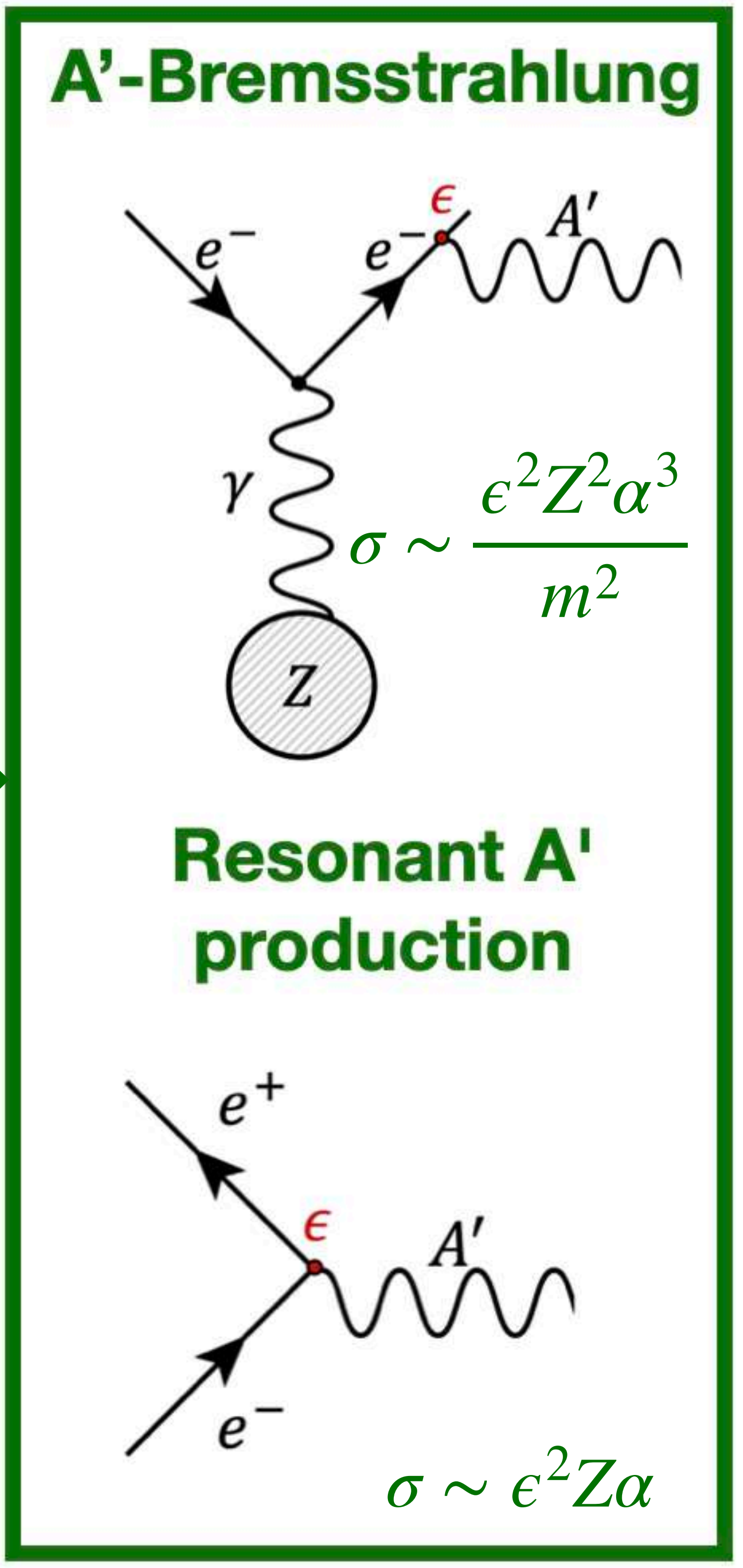
2) Electromagnetic calorimeter (ECAL)

Active target

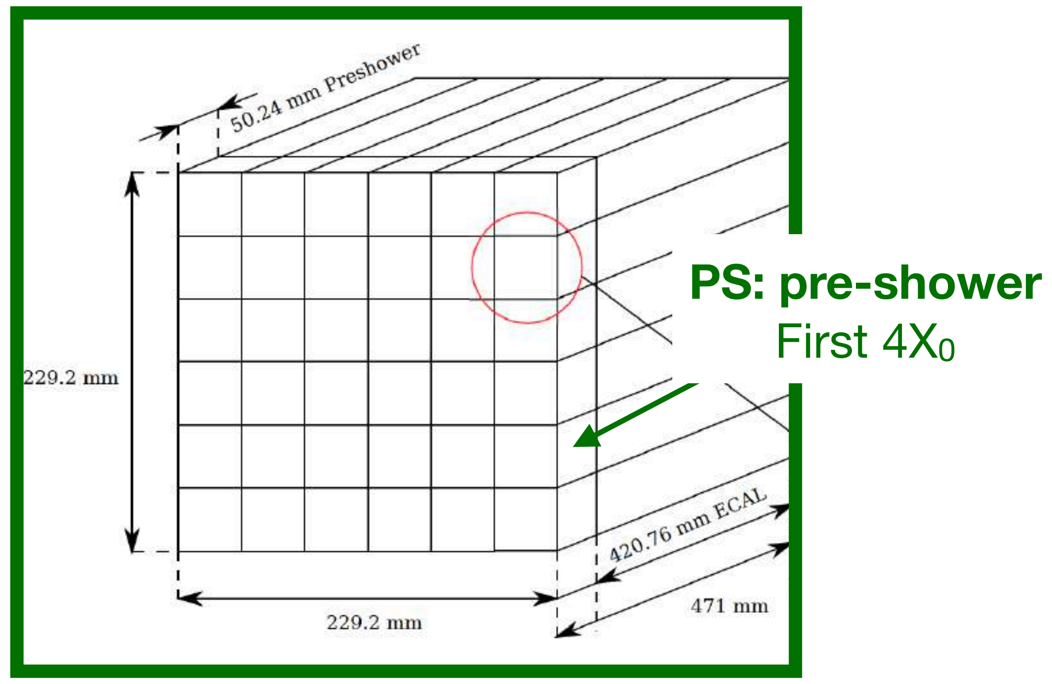


TRIGGER:

$$\Pi S_i \cdot \bar{V}_1 \cdot E_{PS} > 0.3 \text{ GeV} \cdot E_{ECAL} < 90 \text{ GeV}$$

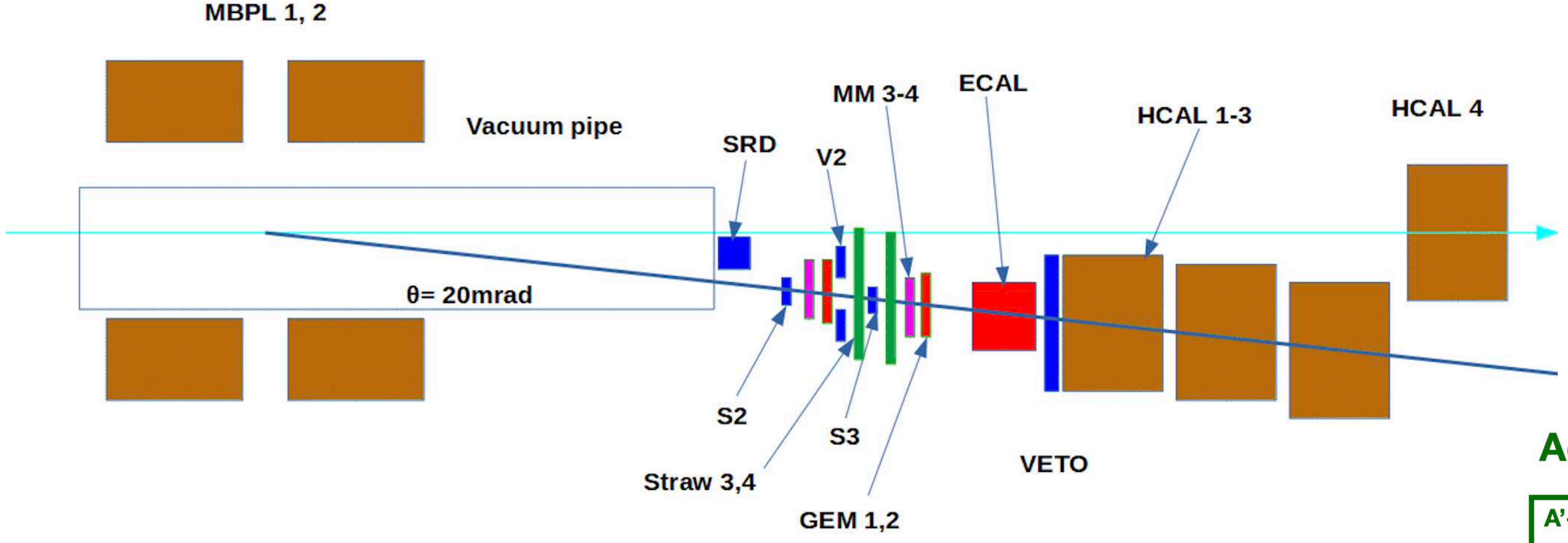


- ➡ Pb-Scintillator sandwich
- ➡ High hermeticity (~40 X_0)
- ➡ Energy resolution ~ 10%/√(E[GeV])



The NA64 technique

3) Fully hermetic detector
VETO+Hadronic calorimeter (HCAL)

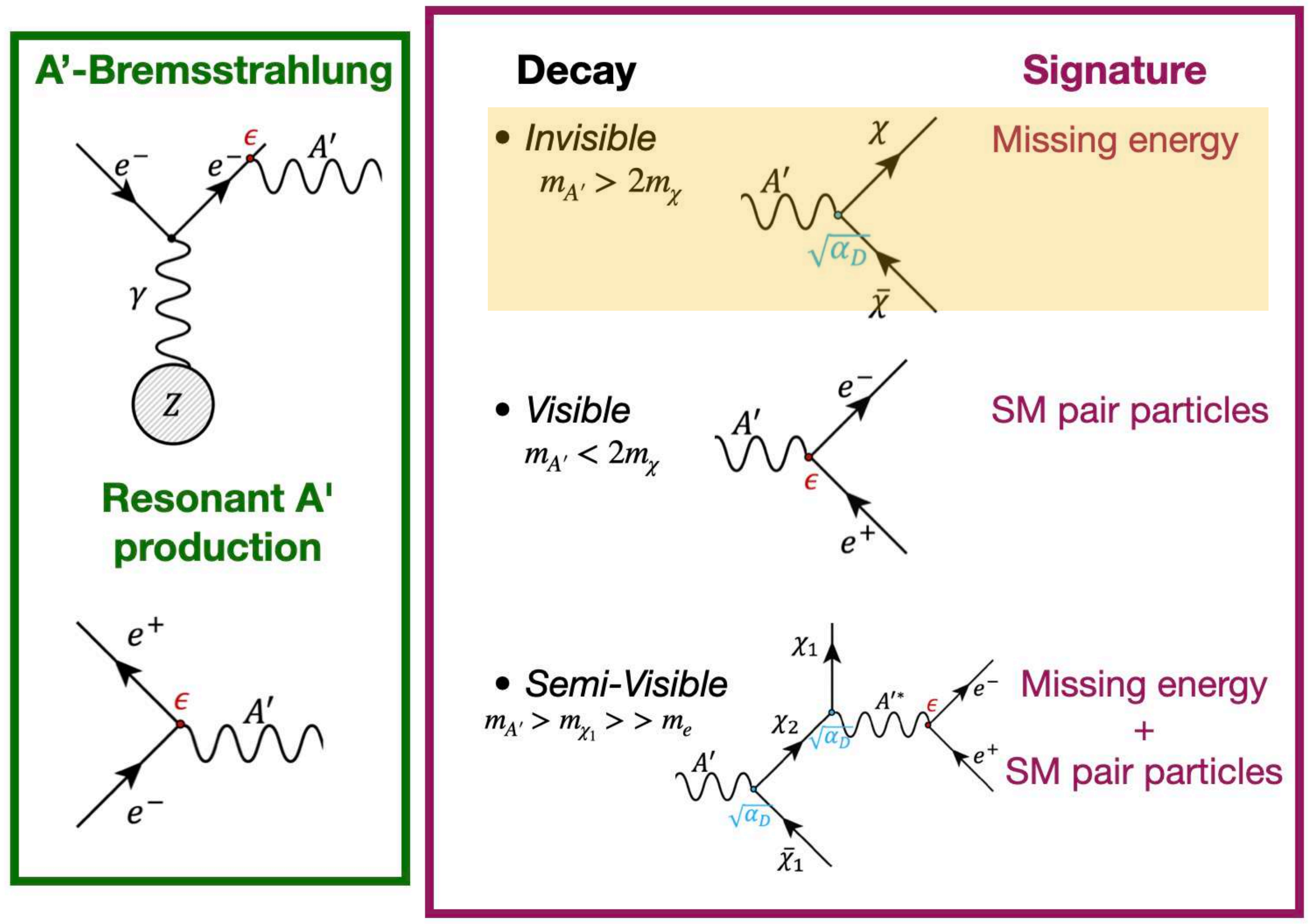


- ➡ Fe-Scintillator sandwich
- ➡ High hermeticity (~28λ)
- ➡ Energy resolution ~ 60%/√(E[GeV])

Dedicated Dark Matter simulation package in fixed target experiments **DMG4** (M.Bondi *et al* Comput. Phys. Commun. 269, 108129 (2021)) developed using GEANT4 (G4) toolkit

Initial well-defined beam
e^-, e^+, μ, π

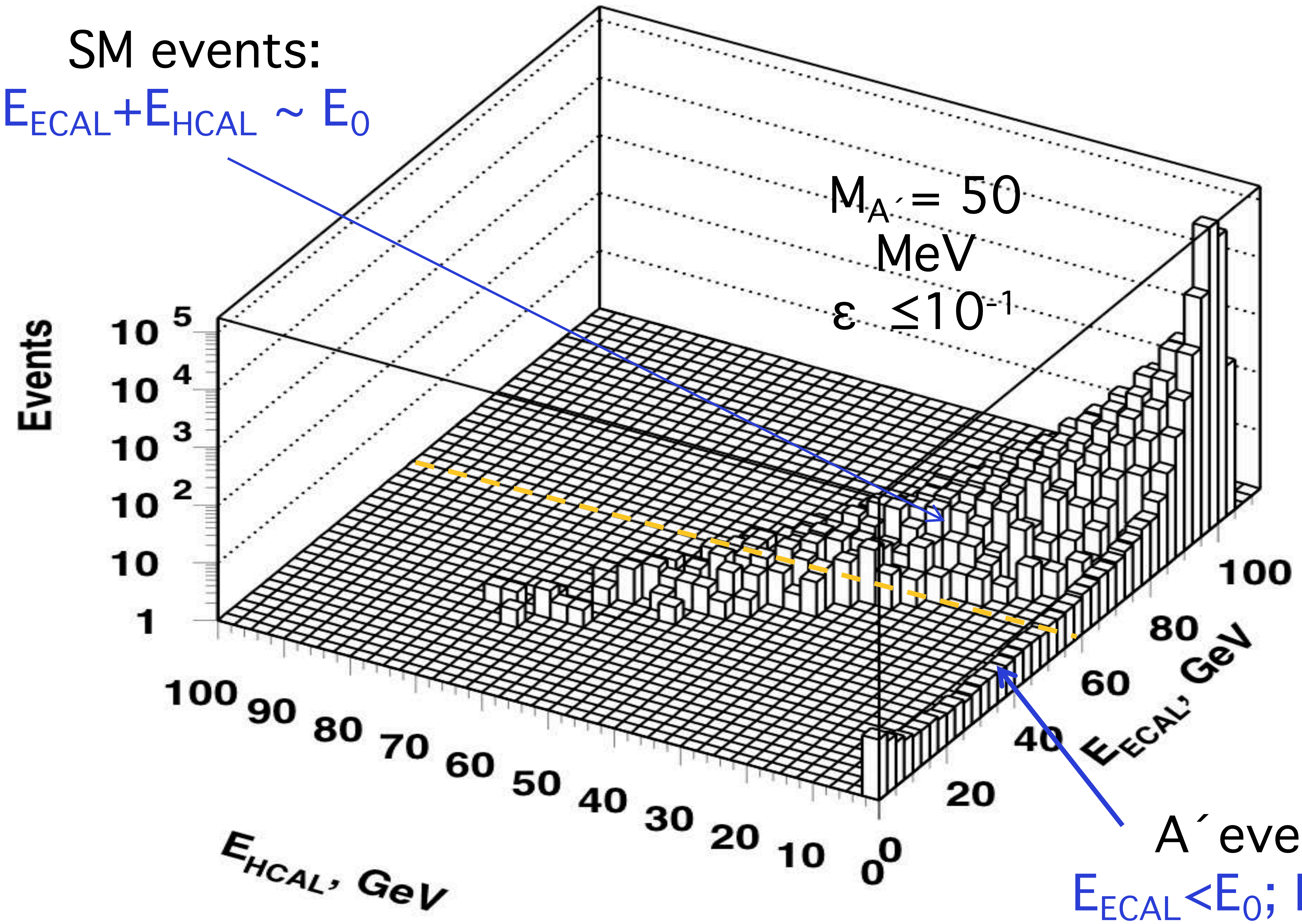
Active Dump + Fully hermetic detector



Simulation of eZ->eZA´; A´-> invisible @ BG

A´emission in the process of e-m shower development.
σ(e⁻Z->e⁻ZA´) (Bjorken et al. 2009)

SM events:
$E_{ECAL}+E_{HCAL} \sim E_0$

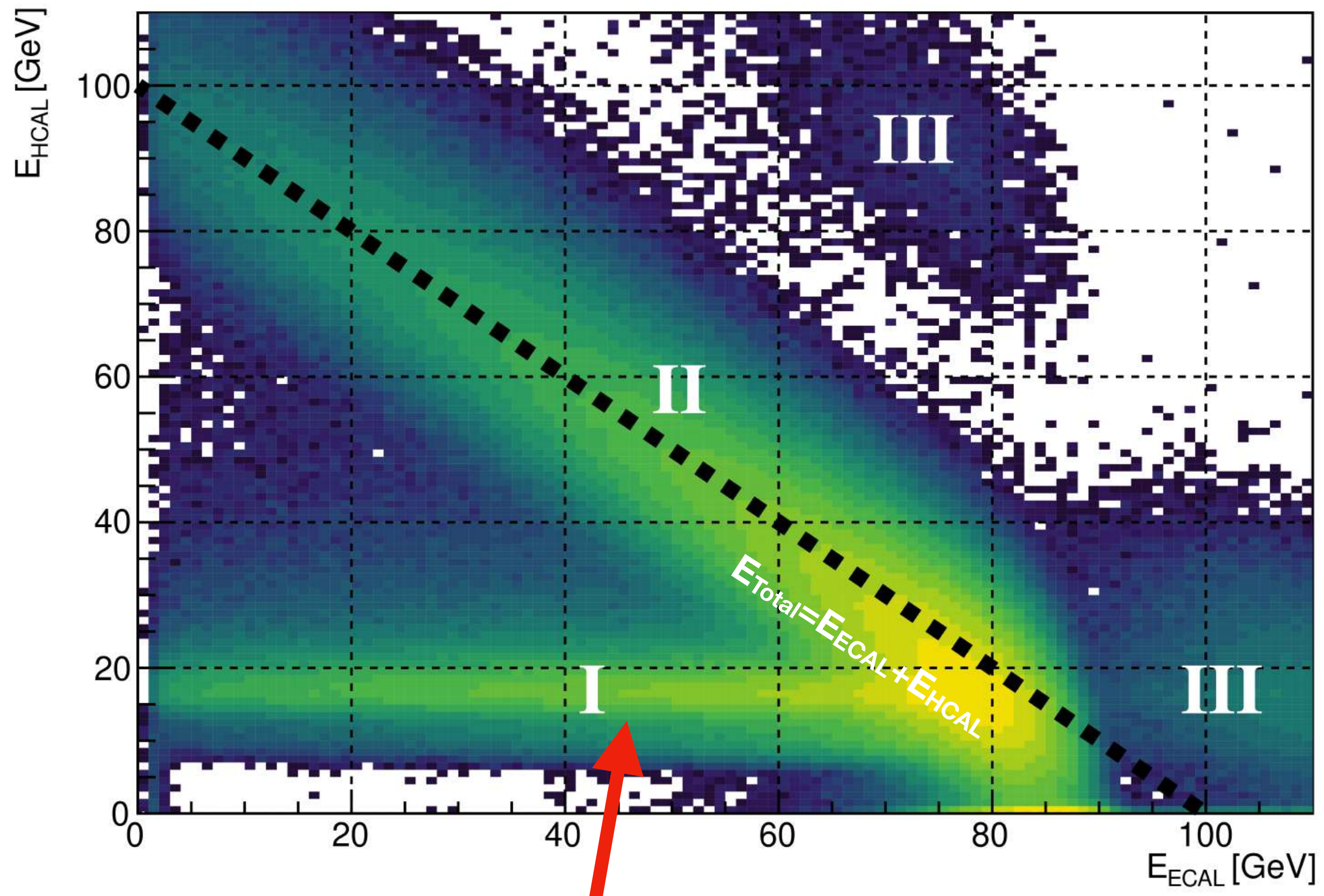


A´events:
$E_{ECAL}<E_0$; $E_{HCAL}=0$

DM processes simulation: DMG4

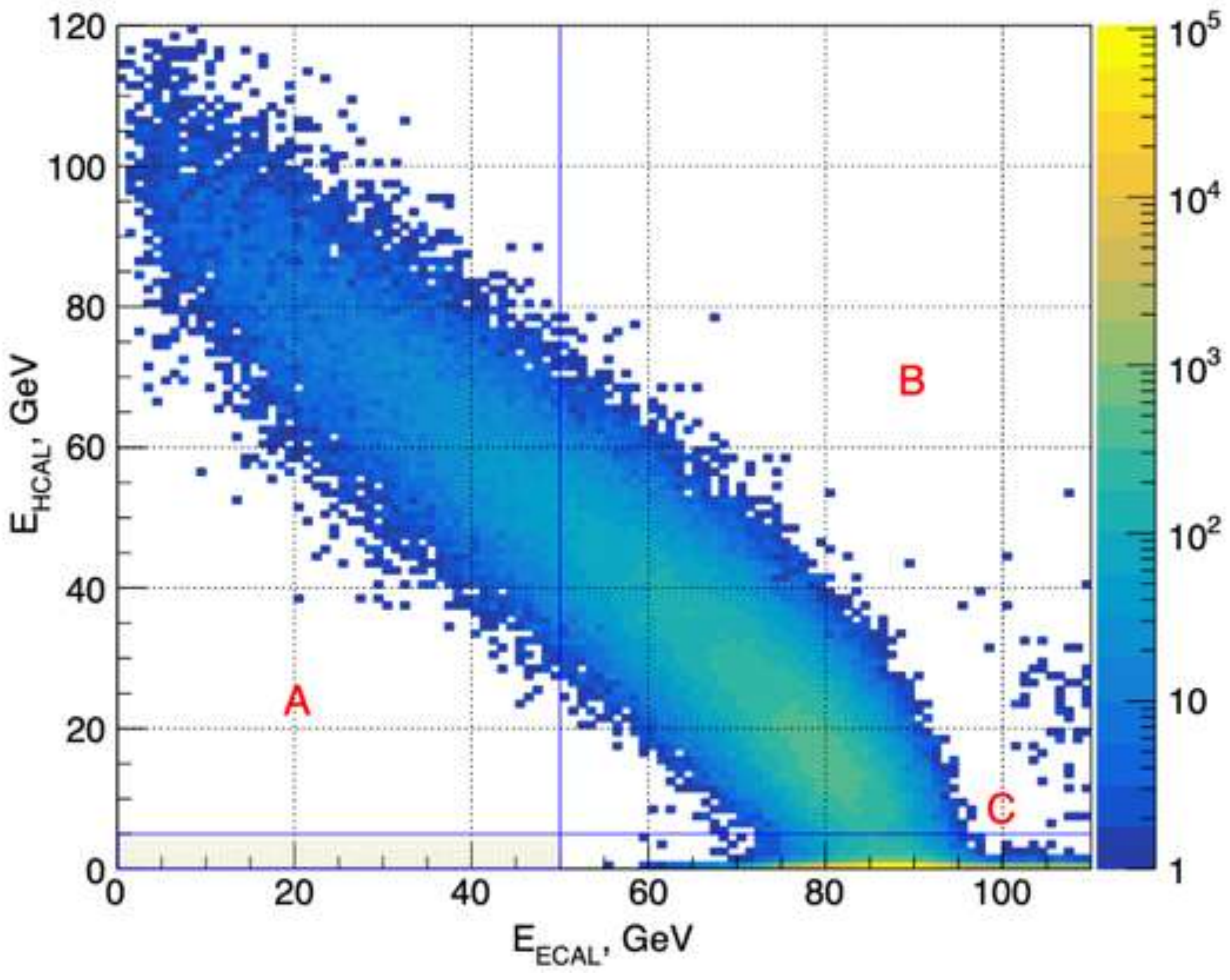
- Fully Geant4 compatible package DMG4 is developed (arXiv:2101.12192 [hep-ph]). Can be used in any full simulation program based on the Geant4 toolkit
- Bremsstrahlung processes off electrons and muons (like $eZ \rightarrow eZA'$), gamma conversion to ALP, annihilation processes (like $e^+e^- \rightarrow A' \rightarrow \chi\chi$) can be simulated
- DM messengers: vector (A'), axial vector, scalar, pseudoscalar, spin 2 (graviton), masses up to 3 GeV
- Invisible and visible (to SM particles) decays
- For the total cross section we use the full matrix element calculations (ETL) (arXiV:1712.05706 [hep-ph]) through the K-factors applied to the IWW cross sections. These K-factors can be as small as 1/15 for electrons at $M_A \sim 1$ GeV
- Simplified IWW approximation in e^{-+} beams for differential cross sections (messenger masses > 1 MeV), sufficient accuracy. Messenger energy and angle are sampled
- Tabulated e^{-+} beams differential cross section for masses < 1 MeV
- Recently implemented WW approximation in muon beams Complicated analytical integration. Messenger energy and recoil muon angle are sampled by default (backup)
- WW formulas are now extended to scalar mediators
- Recently implemented: spin 2 messengers
- Recently implemented: semivisible decays of DM
- Presented at ACAT-2021 and ACAT-2022
- We continue to develop the package (convenience, new processes)

NA64 *invisible* **mode:** *main physics goal* ***LDM***



Event Selection Criteria:

- ✦*Timing information* → Pile up and noise suppression
- ✦*Clean incoming track:* angle + single hit in all trackers, momentum~100 GeV
- ✦*Electron identification:* Synchrotron radiation + Shower profile compatible with e^- in ECAL → Hadron suppression
- ✦No multiple hits in the straw detector (larger acceptance trackers) to reduce the background from e^- interactions upstream
- ✦*No punchthrough: No activity in Veto and in HCALs*

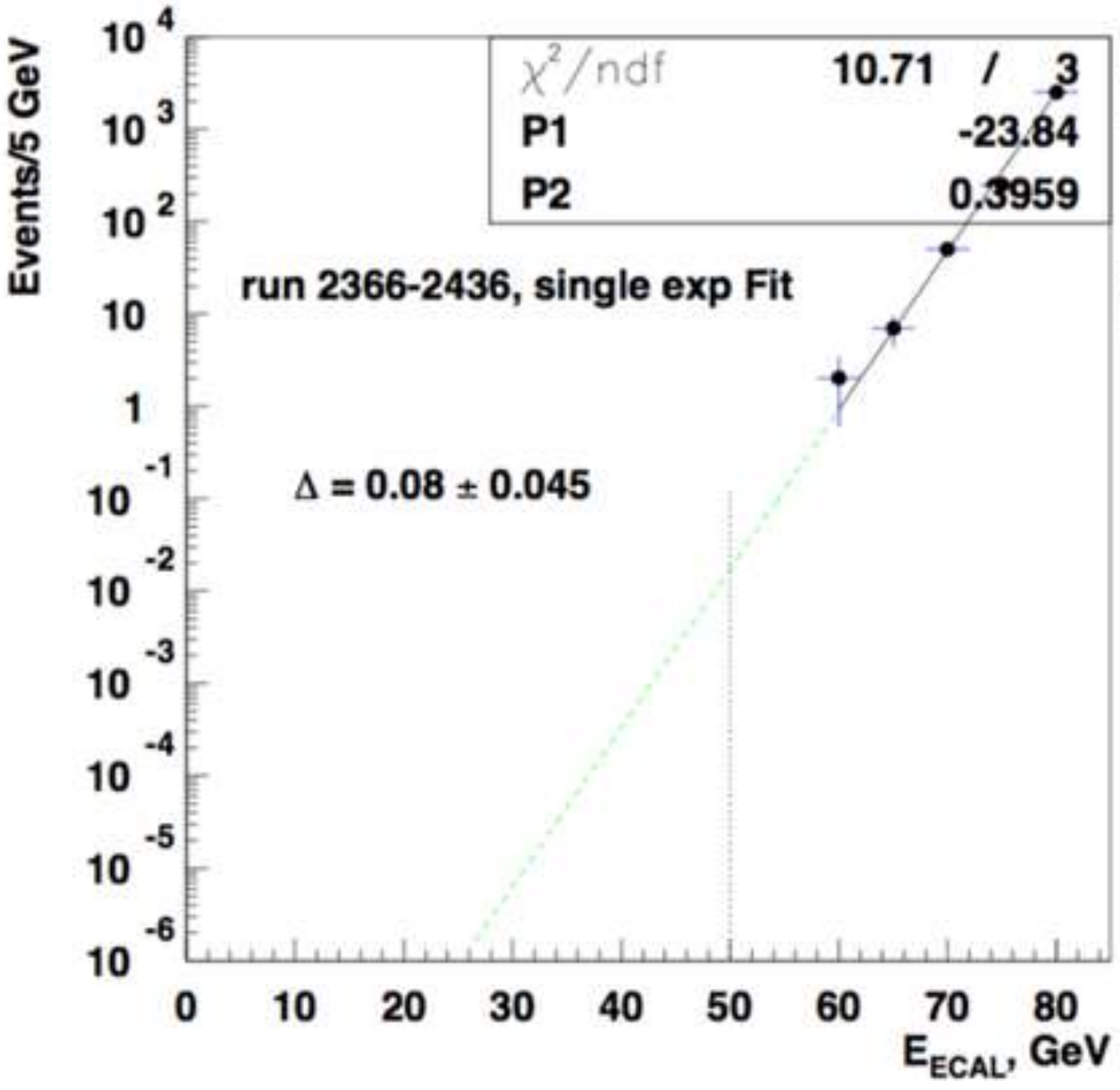


- *QED di-muon production* in the ECAL: $e^-Z \rightarrow e^-Z\gamma; \gamma \rightarrow \mu^+\mu^-$
- Used as a benchmark process to study the accuracy of our MC simulation, detector performance, systematic errors,…

How is this shape formed?

- Electron – nuclear and gamma – nuclear interactions
- The main peak is cut off by trigger requirement $E_{ECAL} < 85$GeV

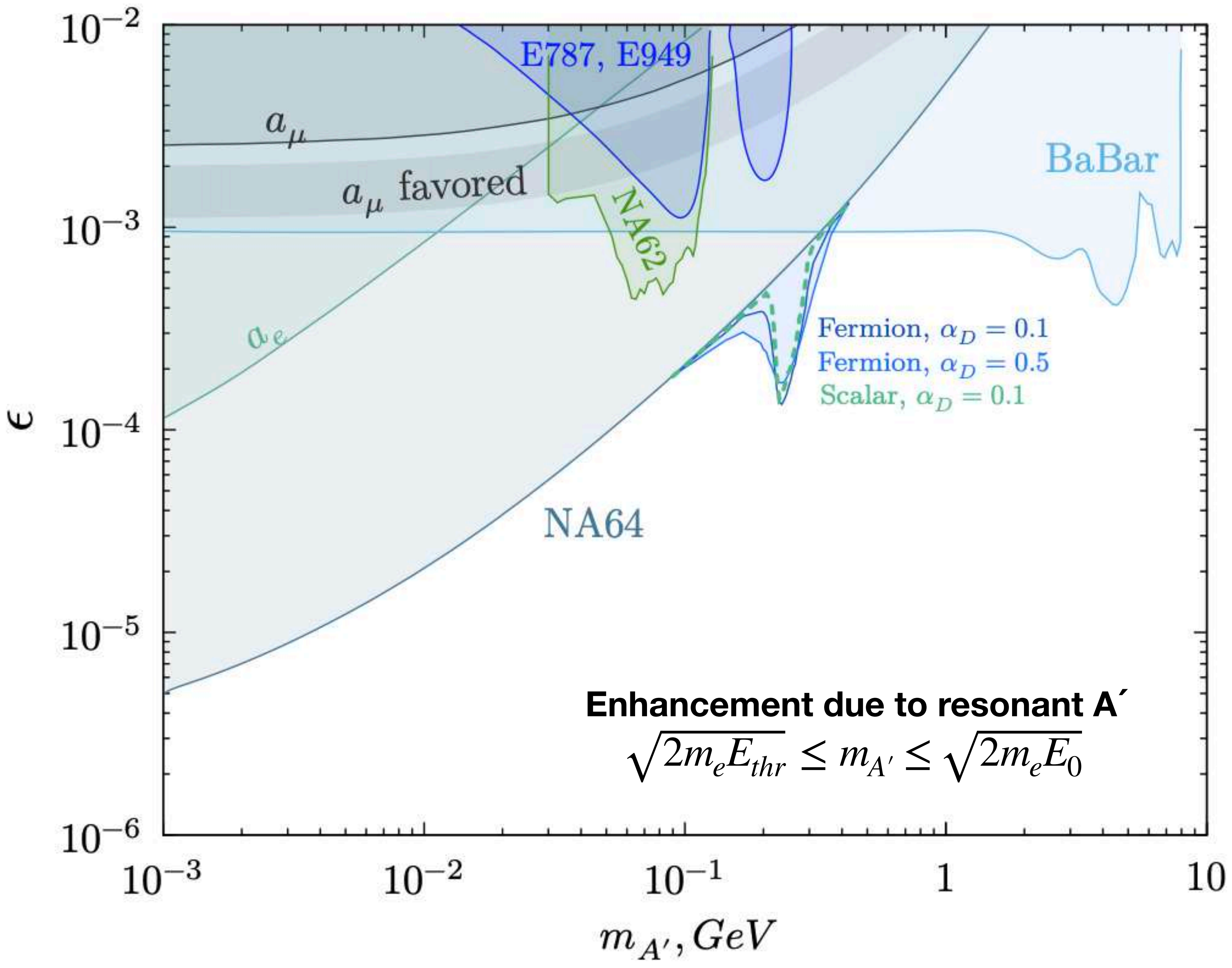
Background: example of extrapolation



Background sources runs 2021 - 2022

Background source	Background, n_b
(i) dimuons losses or decays in the target	0.04 ± 0.01
(ii) $\mu, \pi, K \to e +$ .... decays in the beam line	0.3 ± 0.05
(iii) lost γ, n, K^0 from upstream interactions	0.16 ± 0.12
(iv) Punch-through leading n, K^0_L	< 0.01
Total n_b (conservatively)	0.51 ± 0.13

BG from the beam elements (iii) is suppressed by multiplicity cuts in MM and Straw tubes and by HCAL Topo cuts. Estimated from extrapolation

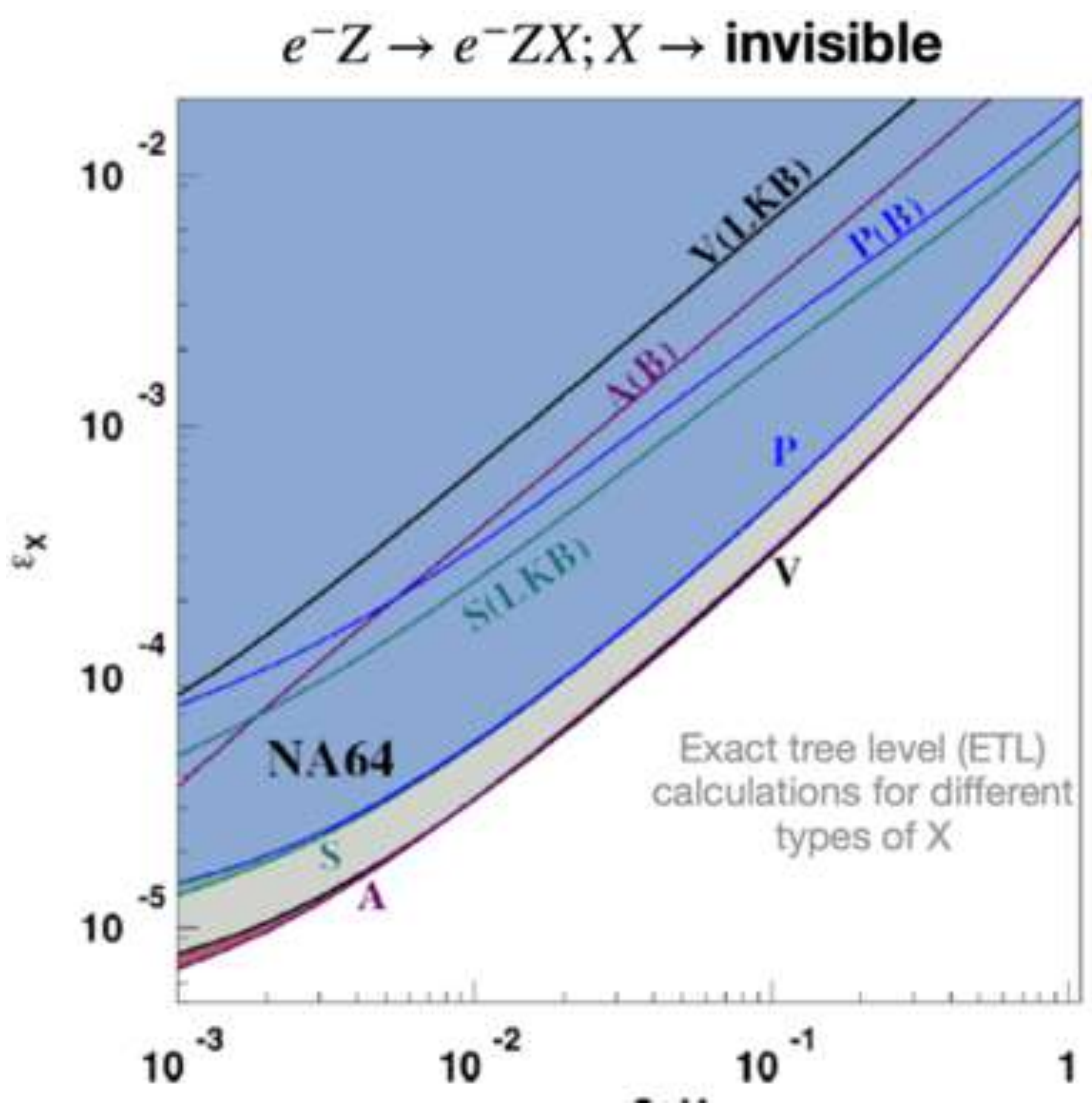


NA64 collaboration, *arXiv:2307.02404* ***(accepted on Phys. Rev. Lett on September 14th, 2023)***

90% C.L zero-background hypothesis

+ Resonant process:
shower positrons on
electrons of the target
$e^+e^- \rightarrow A' \rightarrow \chi\chi$
First addition
to the analysis:
Phys. Rev. D 104, L091701
(2021)

Limits on generic boson and $(g\text{-}2)_e$

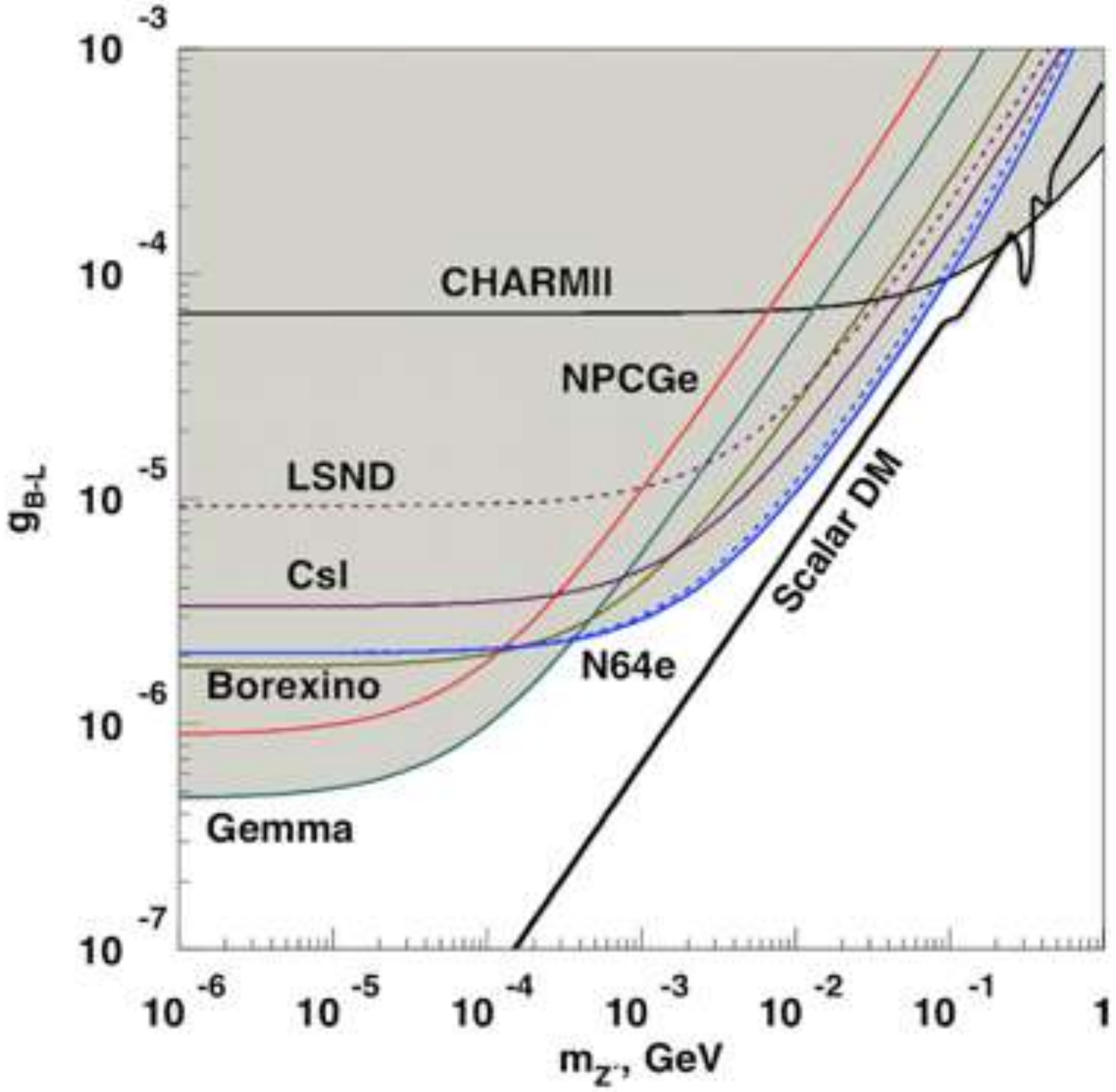


Consider also Scalar, Pseudoscalar, Axial vector
Andreev et al.
PRL 126, 211802 (2021)

Results (tension) on Δa_e :
LKB +1.6σ,
Berkley -2.4σ

In process
+Annihilation
Extend to 1 KeV

Constraints on B-L Z' (decaying to SM particles)

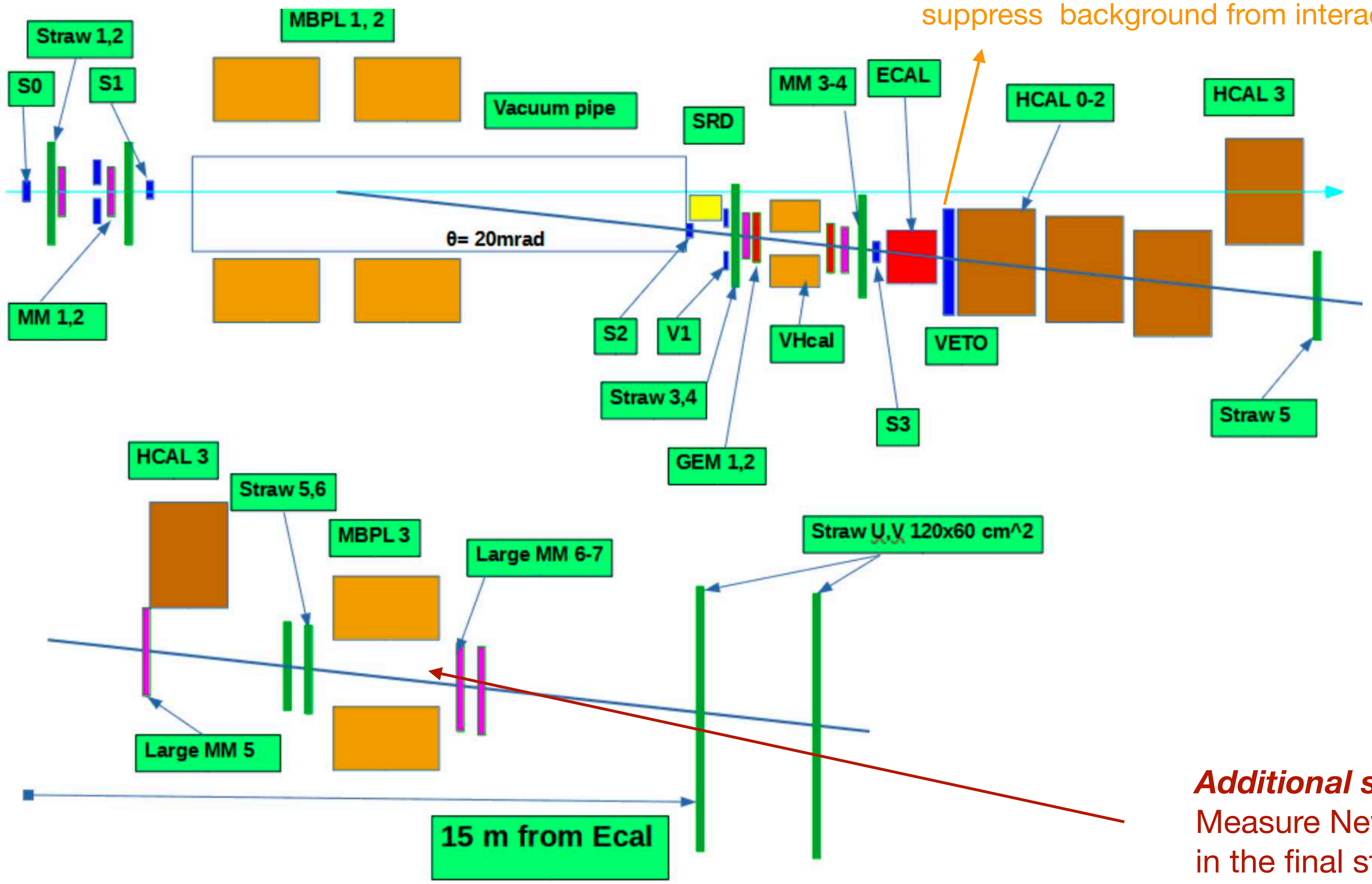


Better sensitivity than neutrino experiments!

Phys. Rev. Lett. (2022)

Continue searches in invisible mode

Veto hadron calorimeter (VHCAL) to further suppress background from interactions upstream

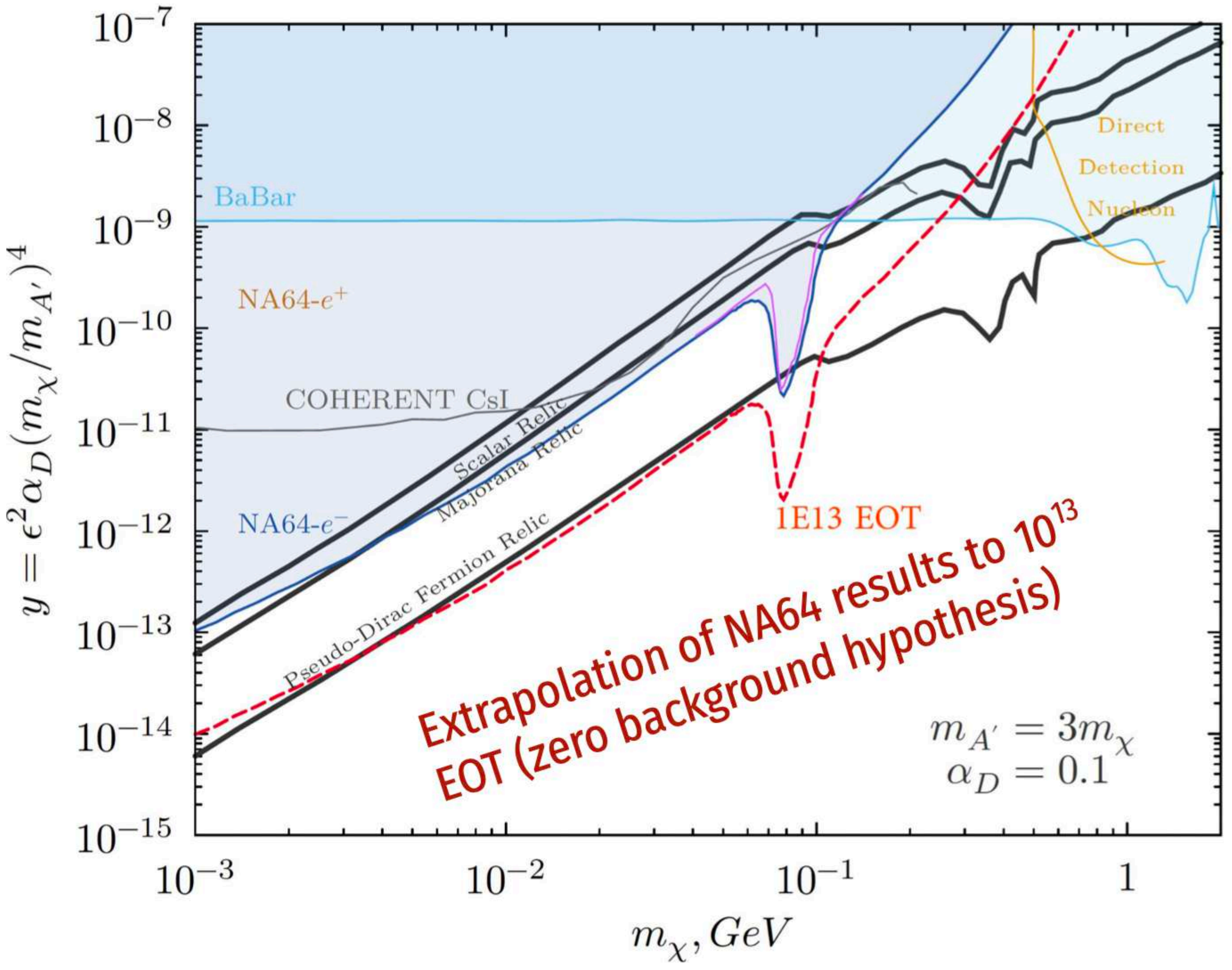


Additional spectrometer:
Measure New Physics processes involving μ in the final state

- New subdetector VHCAL to suppress BG from beam elements and tracker
- Upgrade of DAQ
- Upgrade of electronics
- Upgrade of ECAL

Sensitivity to y and some popular sub-GeV Thermal Dark Matter models

How can we enlarge the sensitivity at higher masses?



Bremsstrahlung A' emission ~$1/m^2_{A'}$ →signal yield suppressed at higher masses

New complementary ideas

- **Positron beam and A' resonant production**

L. Marsicano *et al.* Phys. Rev. Lett. 121, 041802

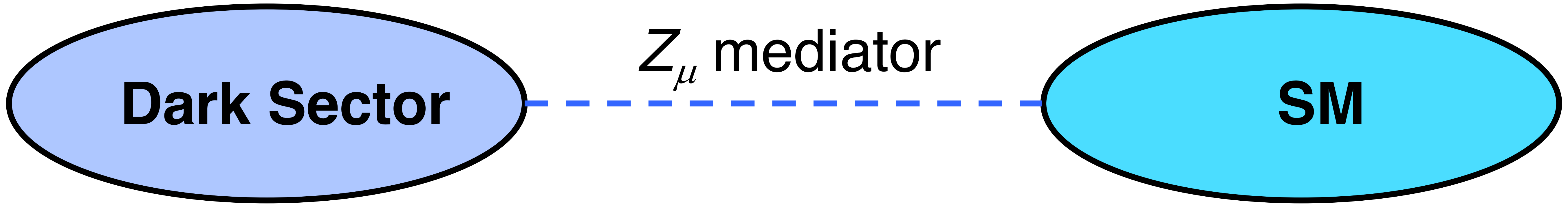
Supported by the ERC Starting Grant 2020 project: POKER "POsitron annihilation into darK mattER" A. Celentano (INFN-Genova)

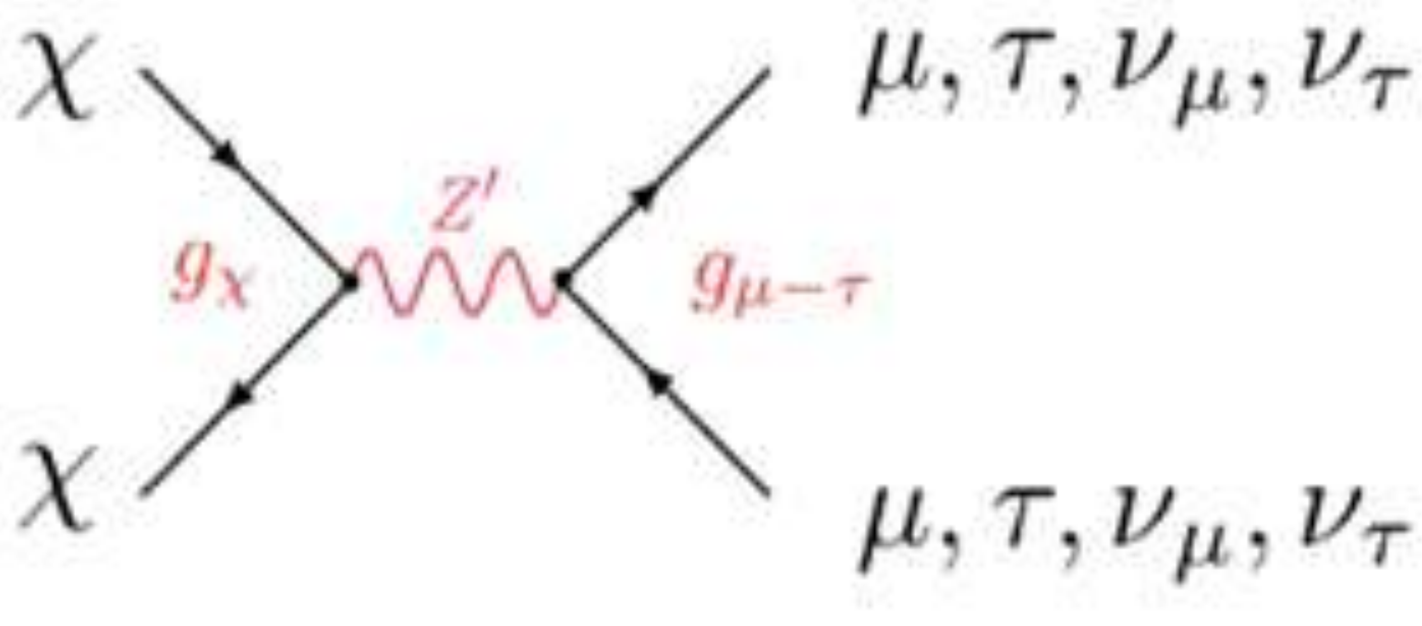
- Use a muon beam: ***NA64μ experiment***

S.Gninenko et al. PLB796, 117 (2019)

D. Banerjee et al. [NA64 Collaboration]. CERN-SPSC-2019-002 / SPSC-P-359, January 14, 2019.

L_μ-L_τ Charged Dark Matter and Z_μ mediator





$$J^\mu_\chi = g_\chi \times \begin{cases} i\chi^* \partial_\mu \chi + h.c. & \text{Complex Scalar} \\ \overline{\chi}_1 \gamma^\mu \chi_2 + h.c. & \text{Pseudo–Dirac Fermion} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{Majorana Fermion} \\ \overline{\chi}\gamma^\mu\chi & \text{Dirac Fermion} \end{cases}$$

Gninenko, Krasnikov 1801.10448

Kahn, Krnjaic, Tran, Whitbeck 1804.03144

- LDM coupled predomimantly to generations 2,3
  - free parameters $m_\chi, m_{Z\mu}$, g_χ, g_μ
  - Z_μ decays:

- $m_{Z\mu} < 2m_\chi$-decays into SM, $Z_\mu \rightarrow \nu\nu, \mu^+\mu^-, \tau^+\tau^-$
- $m_{Z\mu} > 2m_\chi$- invisible decays into DM: $Z_\mu \rightarrow \chi\chi, \nu\nu$,

$\alpha_D >> \alpha_{SM}$, $\alpha_D = g_\chi^2/4\pi$, $\alpha_{SM} = g_\mu^2/4\pi$

- Cross section for χ–DM annihilation:

$\Gamma_{inel} = n_\chi < \sigma v >$

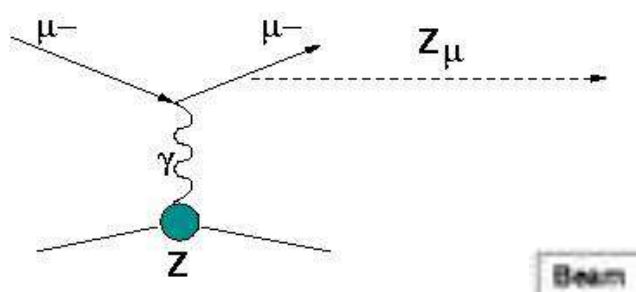
$\sigma v \approx [(g_\chi g_\mu)^2 (m_\chi/m_{A'})^4]/m_\chi^2 = y/m_\chi^2$;

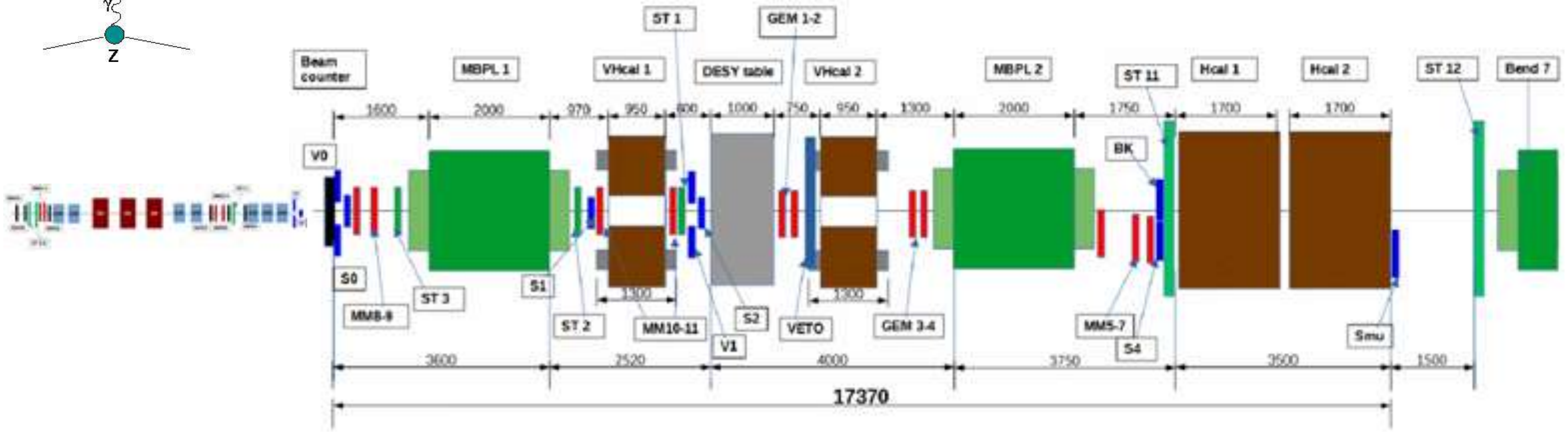
$y = [(g_\chi g_\mu)^2 (m_\chi/m_{A'})^4]$ - useful variable to compare FTE sensitivities

Search for Z_μ in missing energy events on M2 beam

Motivated by $(g\text{-}2)_\mu$ measurements

Proposal NA64μ (2019)





Main components :

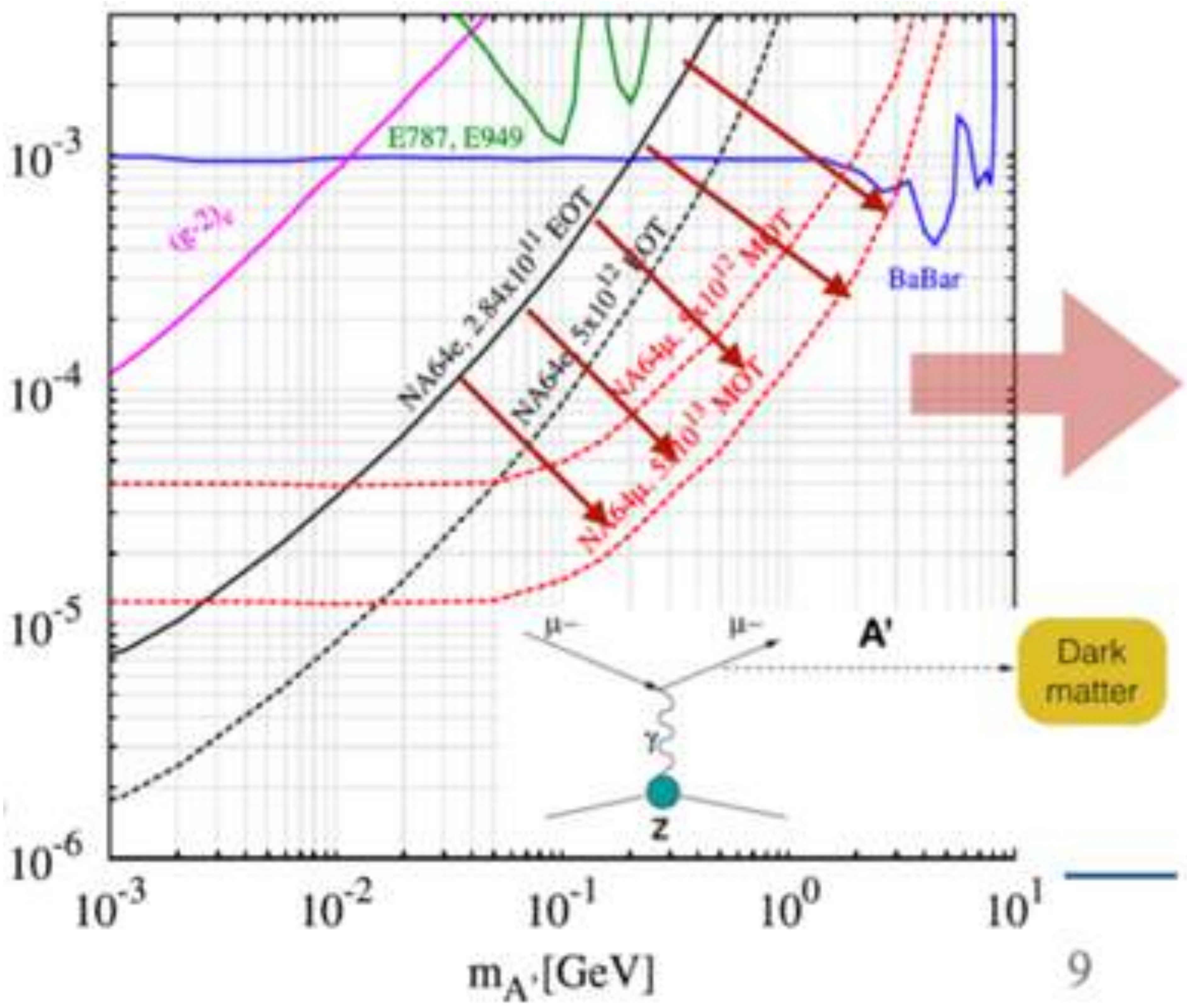
- 100-160 GeV μ- beam, $I_\mu \sim 10^7 \mu$/spill.
- in μ tagging: BMS+MS1(MBPL+tracker)
- out μ tagging: MS2 (2MBPL+tracker)
- 4π fully hermetic ECAL+Veto+ HCAL

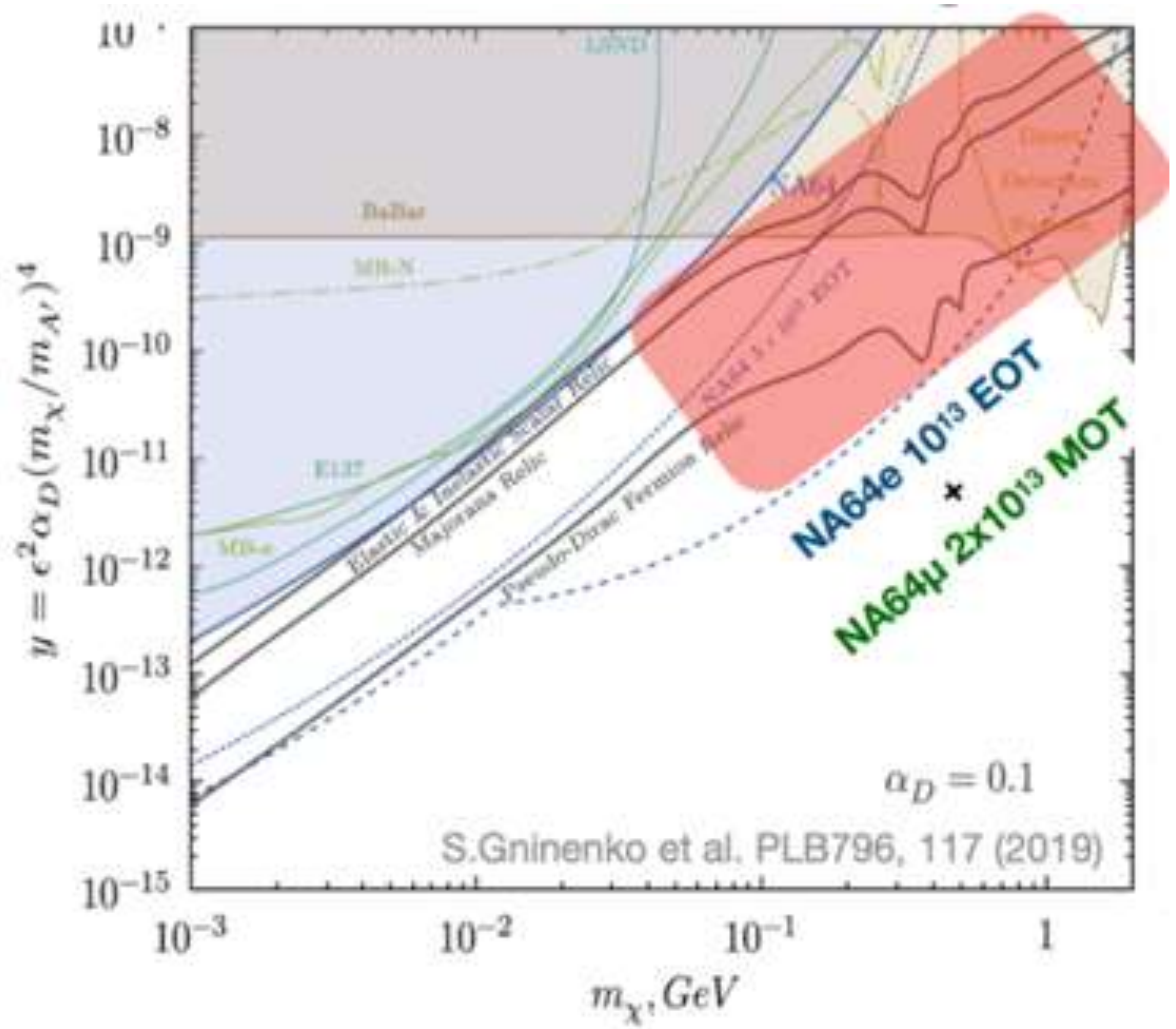
Signature:

- in: 160 GeV μ- track
- out: < 80 GeV μ- track (recoil)
- small energy in the ECAL, Veto, HCAL
- Sensitivity ~ g_μ^2

Searches for A' with NA64μ

Better sensitivity to heavy A' (>100 MeV)





To obtain or improve results in the positron beam: POKER!

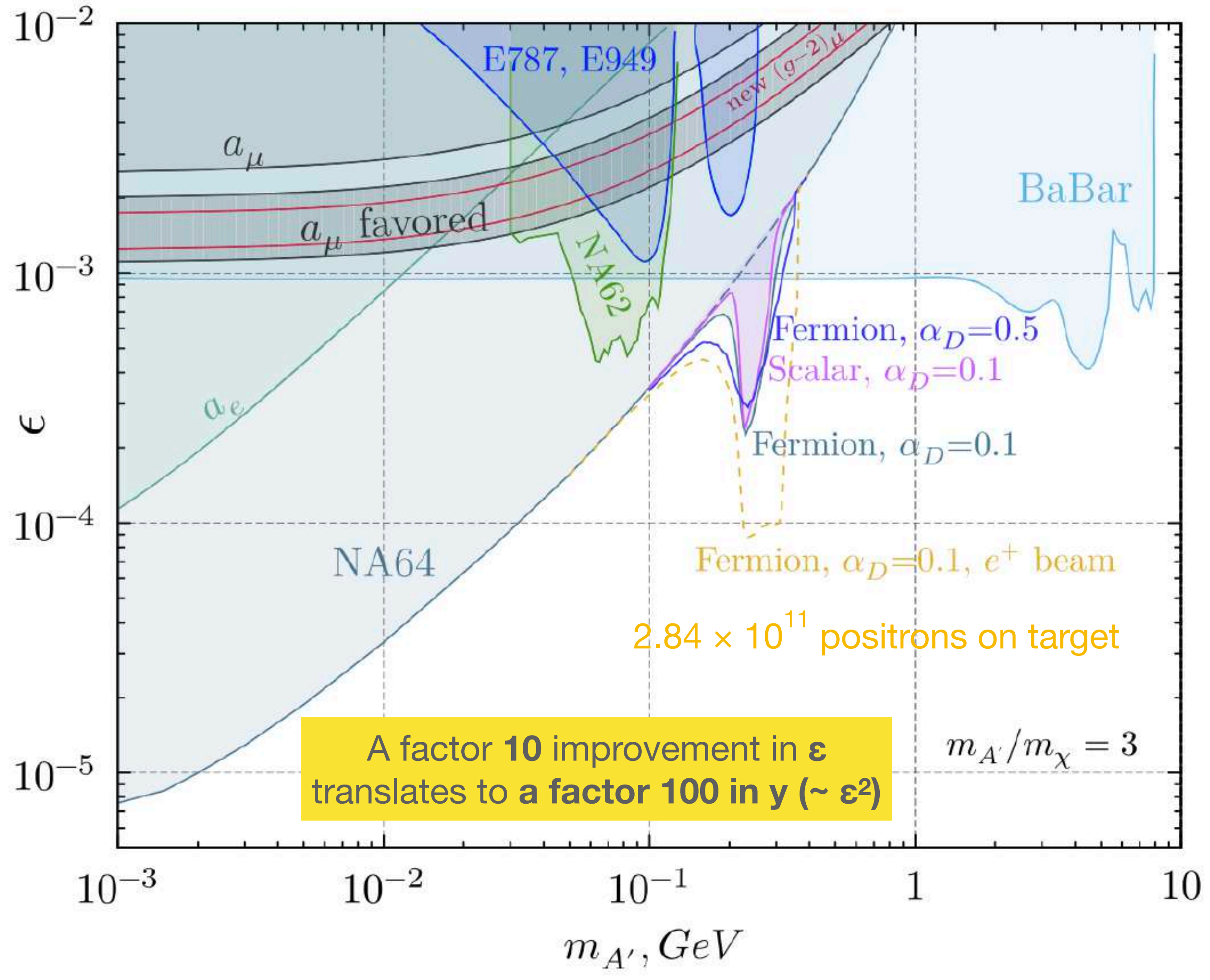
POsitron resonant annihilation into darK mattER

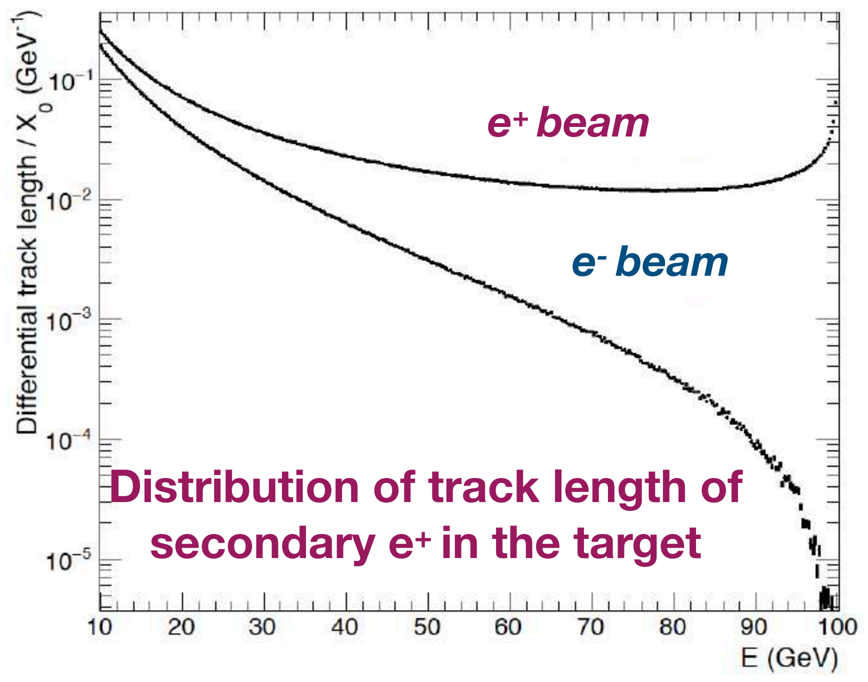
Resonance annihilation *channel* ***using a 100 GeV e+beam.***

$$e^+e^- \to A' \to \chi\bar{\chi}$$

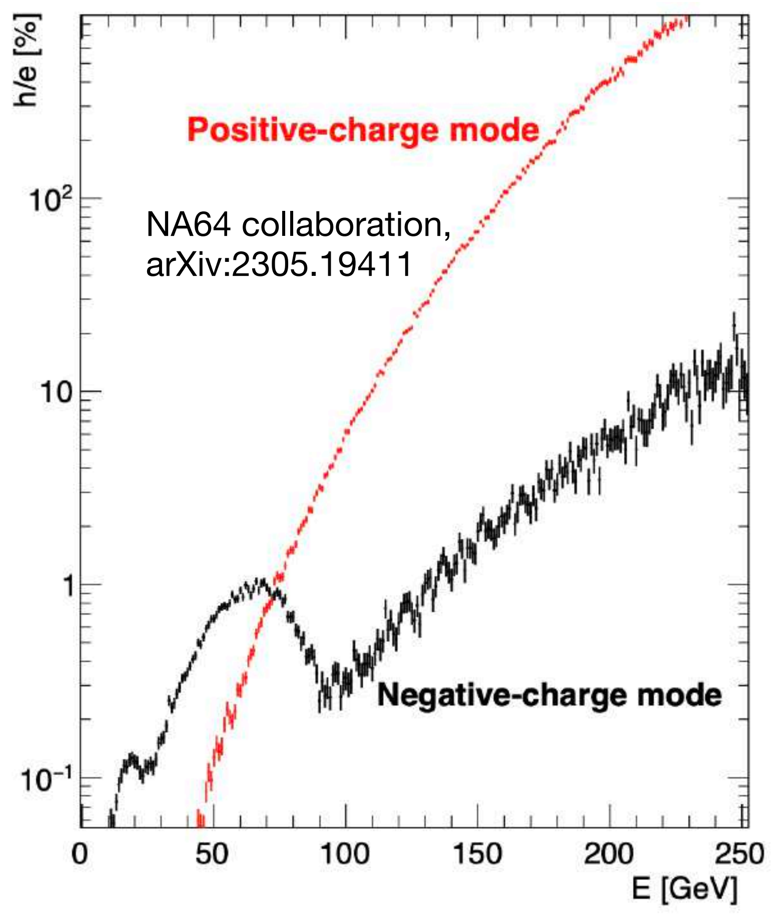
L. Marsicano *et al.* Phys. Rev. Lett. 121, 041802

Supported by the ERC Starting Grant 2020 project: POKER "POsitron annihilation into darK mattER" A. Celentano (INFN-Genova)





Hadron contamination in H4 in e+ mode is significantly higher mainly due to protons from the decay of Λ→pπ-.



- NEXT step: demonstrate the incoming positron energy scan up to 40 GeV and cover the mass range between 140 and 250 MeV for all DM candidates. In **2023*:*** ~1.5x10^{10} e+ on target **using 70 GeV positrons** to demonstrate the possibility to perform energy scan
- An addendum to the SPS committee for a dedicated e+ program at NA64 is in preparation.

Effort led by the group of INFN Genova: A. Celentano

At 100 GeV hadron BG is higher in positron beams
At lower energies the SRD tagging performance drops significantly (E^4)

- New LYSO-based SR detector, homogenious, with high light yield. Prototyping and simulations are in progress
- New active target: PKR-CAL calorimeter. Baseline design: 33.5 *X*0 PbWO4 calorimeter with SiPM readout, 9x9 matrix of 20x20x220 mm crystals, 4 layers

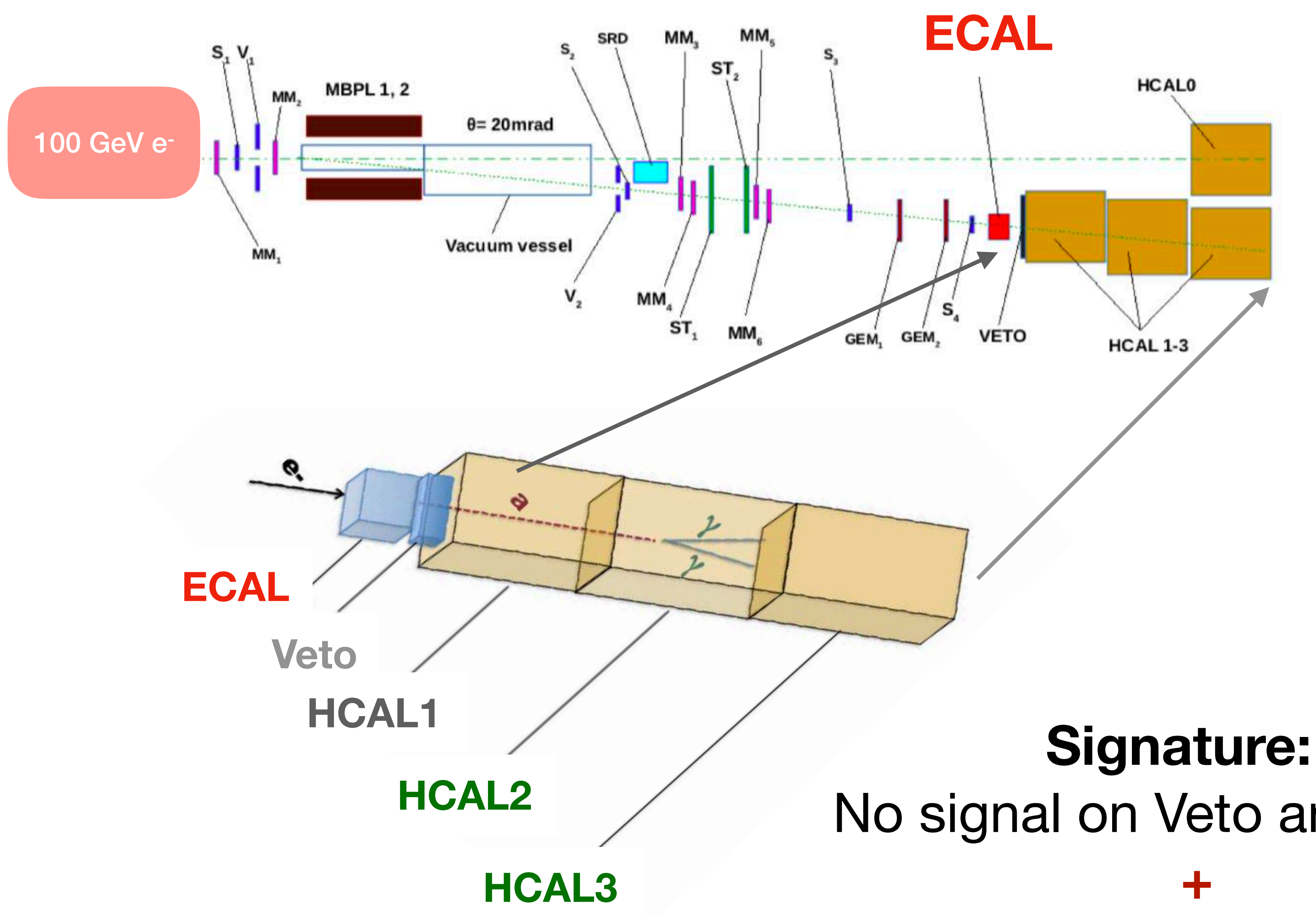
Progress in PKR-CAL development

- Goal: $\sigma/E \sim 2.5\%/E \oplus 0.5\%$
- High radiation doses
- POKERINO prototype tested on H4 beam line this year, analysis in progress, first results promising

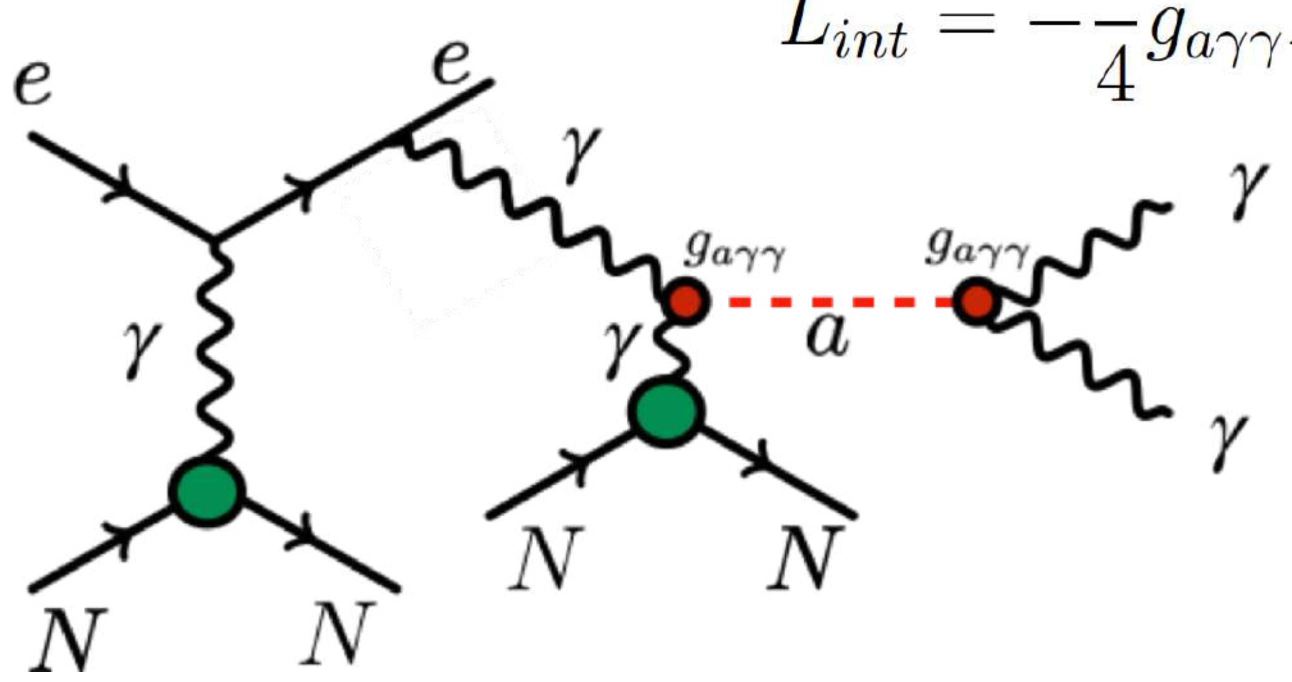
Axion-like particles (ALP) coupled to photons

New way of using the invisible mode geometry: visible decays!

Produced via Primakoff effect of gamma conversion on nuclei

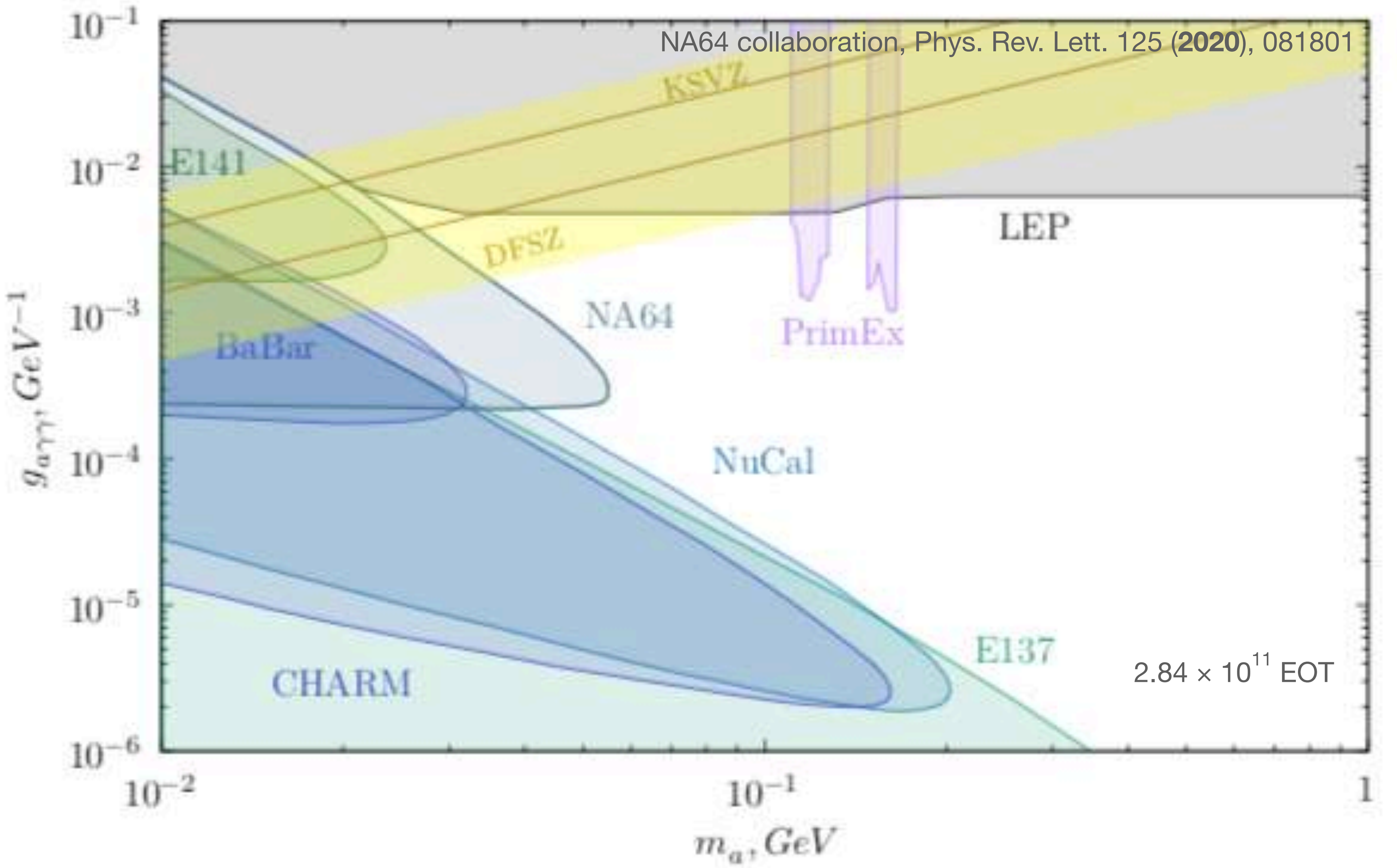


$$L_{int} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$



Main goal

Exploration of the uncovered gap between the beam-dump and LEP searches in the parameter space of benchmark axion models (yellow band)



Signature:

No signal on Veto and HCAL1

\+

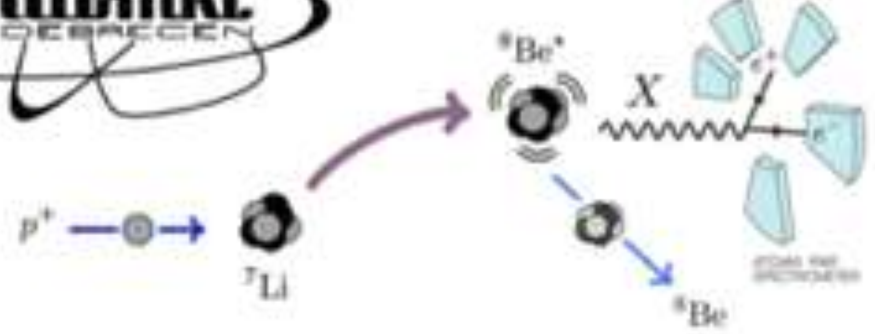
A. ***Visible Decay into γγ*** on HCAL2 || HCAL3

B. ***Decays after HCAL3:*** no activity on HCAL2 & HCAL3

ALP search strategy

- In addition to invisible decays beyond the detector (missing energy signature) look for decays in HCAL2, HCAL3 with HCAL1 as a veto
- Allows softer cuts on energy deposition in ECAL
- Background: punch-through neutrons and K^0
- Final cut on R = (periphery cells)/(central cell), strong suppression of hadrons

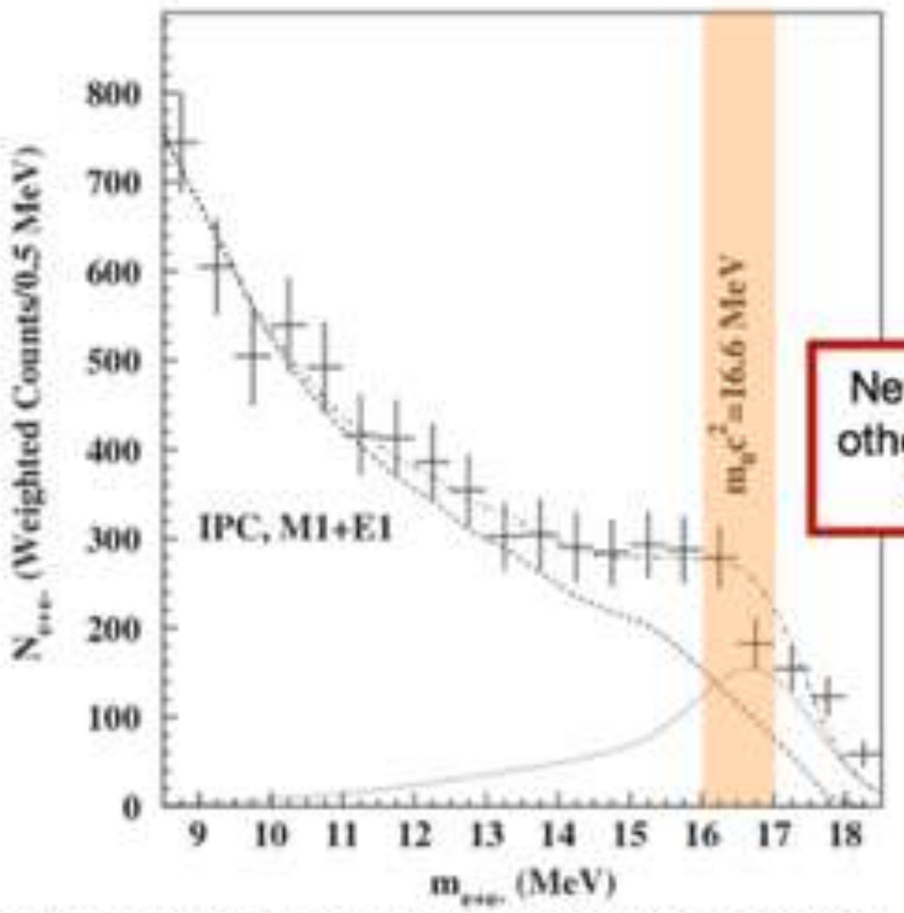
ATOMKI anomaly



- *Scalar, pseudo-scalar, vector, axial-vector* models could explain the anomaly (large literature)
- NA64 addresses the search for X17 in a model independent way, just assuming its non-zero coupling with electrons.
- Vector model used as benchmark.

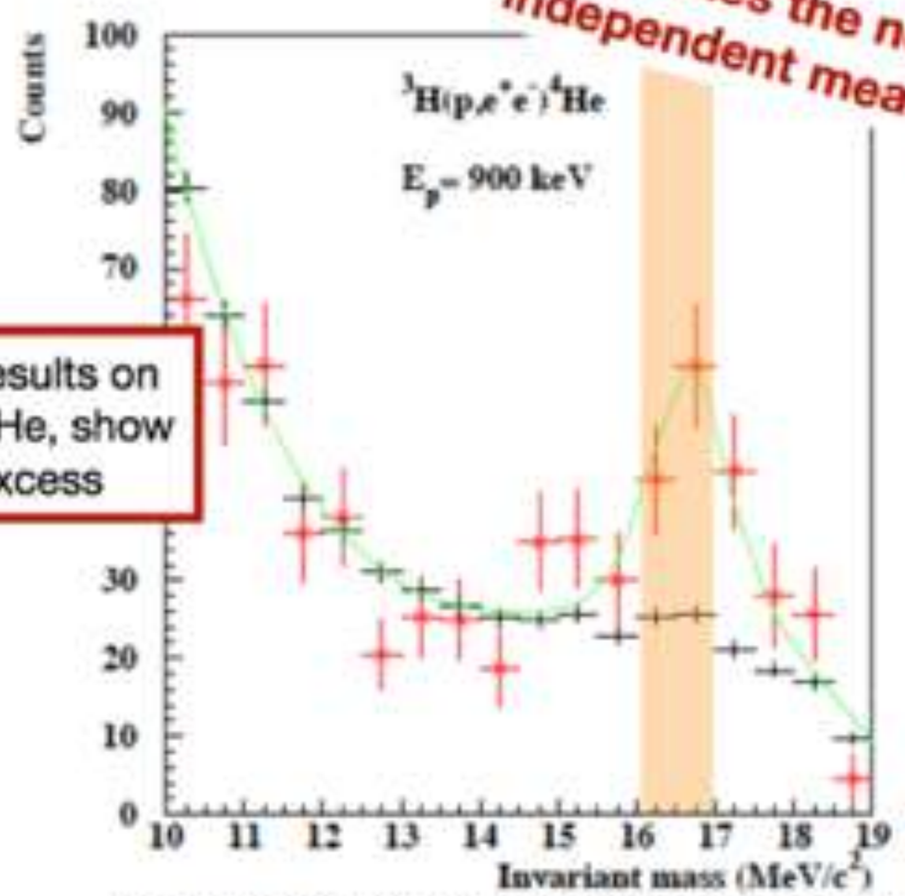
$e^-Z \to e^-ZX_{17};\ X_{17} \to e^+e^-$

Motivates the need of an independent measurement



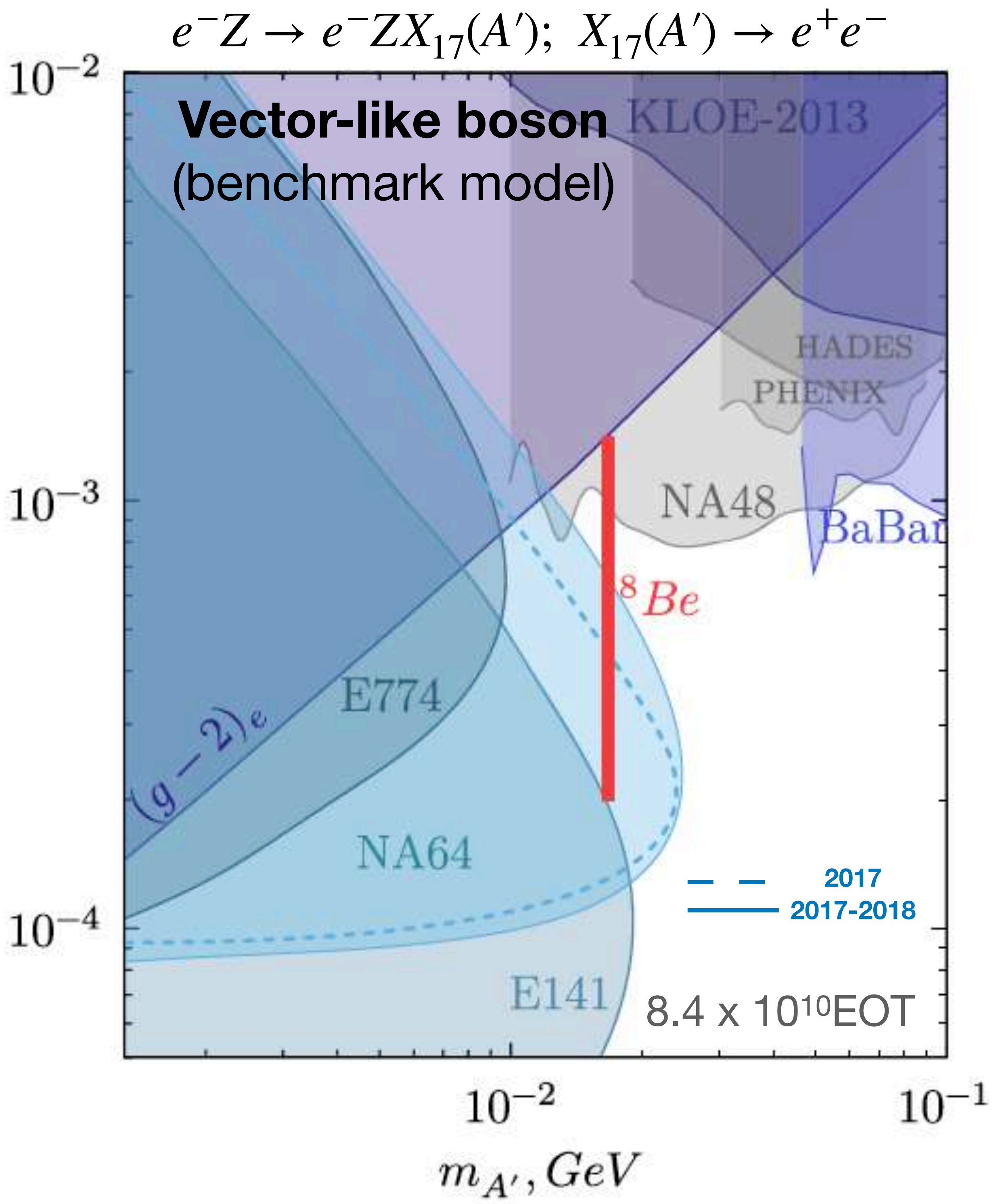
A.J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015)

New recent results on other nuclei, ^{4}He, show a similar excess

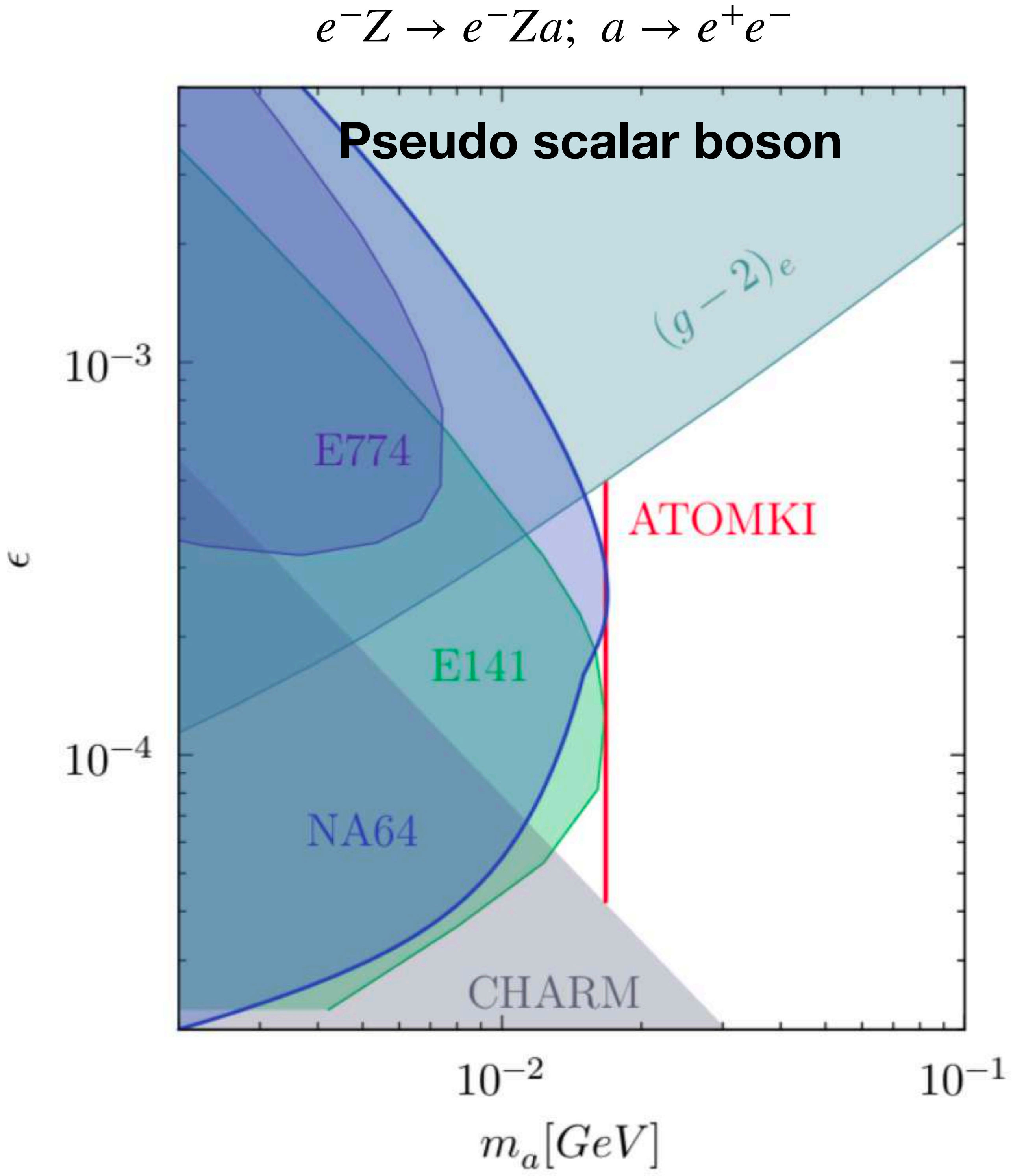


A. J. Krasznahaorkay et. Al Arxiv:1910.10459 (2019)

NA64 *visible* **mode:** *2017-2018 combined analysis*



NA64 collaboration,
PRL 120, 231802 (**2018**), PRD 107, 071101 (R) 2020



NA64 collaboration,
Phys. Rev. D 104 (**2021**) no.11, L111102

Summary and outlook

NA64e⁻

- New area at H4 and setup upgraded
- Total **2016-2023** statistics: **1.5x10^{12} EOT**
  - Analysis of the 2016-2022 with (~10^{12} EOT) completed: **LDM suggested parameter space** probed **for the first time**. World-best sensitivity!
  - Analysis ongoing to probe:
    - The uncovered area for classical axion models and ALPs.
    - New hidden interactions in the neutrino sector, e.g B-L Z'.
    - iDM, Muon g-2 anomaly with A' semi-visible and L_μ-L_τ Z'.
- **Plans to collect 3x10^{12} EOT before LS3.**

NA64μ

- **Total 2021-2023 statistics: 1.9x10^{11} MOT**
  - Analysis of the 2022 data (2x10^{10} MOT) under collaboration review: results indicate that part of the g-2 and LDM parameter space can be probed.
- **Goal to reach 10^{12} MOT before LS3.**

NA64e⁺

- **First LDM results using 100 GeV positrons** (1x10^{10} e^+ on target) demonstrating the feasibility of the technique.
- POKER project
- Hadron contamination level in e^+ beam 10 times larger than in e^- @H4 at 100 GeV.

NA64h

- **Study the potential of NA64 to explore DS weakly coupled to quarks**
  - **2022-2023** 2x10^9 and 1.9x10^{10} π^+ on target (analysis ongoing)

NA64 is an ideal experiment to decisively discover or disprove very interesting predictive LDM models and greatly explore DS in the coming years.

The high-sensitivity NA64 hunt for New Physics has just begun!

Publications since last year

Collaboration papers

1. Y. M. Andreev *et al.* [NA64], ``Probing Light Dark Matter with positron beams at NA64,'' [arXiv:2308.15612 [hep-ex]]
2. Y. M. Andreev *et al.* [NA64], ``Search for Light Dark Matter with NA64 at CERN,'' Phys. Rev. Lett. 131 (2023) no.16, 161801[arXiv:2307.02404 [hep-ex]].
3. Y. M. Andreev *et al.* [NA64],``Search for a light Z' in the $L\mu$-$L\tau$ scenario with the NA64-e experiment at CERN,'' Phys. Rev. D 106 (2022) no.3, 032015 doi:10.1103/PhysRevD.106.032015 [arXiv:2206.03101 [hep-ex]].
4. Y. M. Andreev *et al.* [NA64], ``Search for a New B-L Z' Gauge Boson with the NA64 Experiment at CERN,'' Phys. Rev. Lett. 129 (2022) no.16, 161801 doi:10.1103/PhysRevLett.129.161801 [arXiv:2207.09979 [hep-ex]].
5. Y. M. Andreev *et al.* [NA64], ``Measurement of the intrinsic hadronic contamination in the NA64e high-purity e^+/e^- beam at CERN,'' Nucl. Instrum. Meth. A 1057 (2023), 168776 doi:10.1016/j.nima.2023.168776 [arXiv:2305.19411 [hep-ex]].

Theory/phenomenology papers

1. V. E. Lyubovitskij, A. S. Zhevlakov, A. Kachanovich and S. Kuleshov, ``Dark SU(2) Stueckelberg portal,'' Phys. Rev. D 107, no.5, 055006 (2023) doi:10.1103/PhysRevD.107.055006 [arXiv:2210.05555 [hep-ph]]
2. S. N. Gninenko, N. V. Krasnikov, D. V. Kirpichnikov, ``Search for Light Dark Matter with accelerator and direct detection experiments: comparison and complementarity of recent results,'' [arXiv:2307.14865 [hep-ph]].
3. B. Radics, L. Molina-Bueno, L. Fields., H. Sieber and P. Crivelli, ``Sensitivity potential to a light flavor-changing scalar boson with DUNE and NA64μ,'' Eur. Phys. J. C 83 (2023) no.9, 775 doi:10.1140/epjc/s10052-023-11891-3 [arXiv:2306.07405 [hep-ex]].
4. H. Sieber, D. V. Kirpichnikov, I. V. Voronchikhin, P. Crivelli, S. N. Gninenko, M. M. Kirsanov, N. V. Krasnikov, L. Molina-Bueno and S. K. Sekatskii, ``Probing hidden sectors with a muon beam: implication of spin-0 dark matter mediators for muon (g-2) anomaly and validity of the Weiszacker-Williams approach,'' Phys. Rev. D 108 (2023) no.5, 056018 doi:10.1103/PhysRevD.108.056018 [arXiv:2305.09015 [hep-ph]].
5. M. Mongillo, A. Abdullahi, B. B. Oberhauser, P. Crivelli, M. Hostert, D. Massaro, L. Molina Bueno and S. Pascoli,``Constraining light thermal inelastic dark matter with NA64,'' Eur. Phys. J. C 83 (2023) no.5, 391 doi:10.1140/epjc/s10052-023-11536-5 [arXiv:2302.05414 [hep-ph]].
6. I.V. Voronchikhin and D.V. Kirpichnikov, "Resonant probing spin-0 and spin-2 dark matter mediators with fixed target experiments" Phys. Rev. D 107 (2023) 11, 115034
7. A. S. Zhevlakov, D.V. Kirpichnikov, and V. E. Lyubovitskij, "Lepton flavor violating dark photon" arXiv:2307.10771 [hep-ph].
8. I.V. Voronchikhin and D.V. Kirpichnikov, "Probing hidden spin-2 mediator of dark matter with NA64e, LDMX, NA64μ, and M3", Phys. Rev. D 106 (2022) 11, 115041; arXiv: 2210.00751 [hep-ph]
9. A. S. Zhevlakov, D. V. Kirpichnikov and V. E. Lyubovitskij, ``Implication of the dark axion portal for the EDM of fermions and dark matter probing with NA64e, NA64μ, LDMX, M3, and BaBar,'' Phys. Rev. D 106, no.3, 035018 (2022) doi:10.1103/PhysRevD.106.035018 [arXiv:2204.09978 [hep-ph]].
10. A. Kachanovich, S. Kovalenko, S. Kuleshov, V. E. Lyubovitskij and A. S. Zhevlakov, ``Lepton phenomenology of Stueckelberg portal to dark sector,'' Phys. Rev. D 105, no.7, 075004 (2022) doi:10.1103/PhysRevD.105.075004 [arXiv:2111.12522 [hep-ph]].
11. D. Gorbunov and E. Kriukova, "Dark photon production via elastic proton bremsstrahlung with non-zero momentum transfer" arXiv: 2306.15800 [hep-ph]

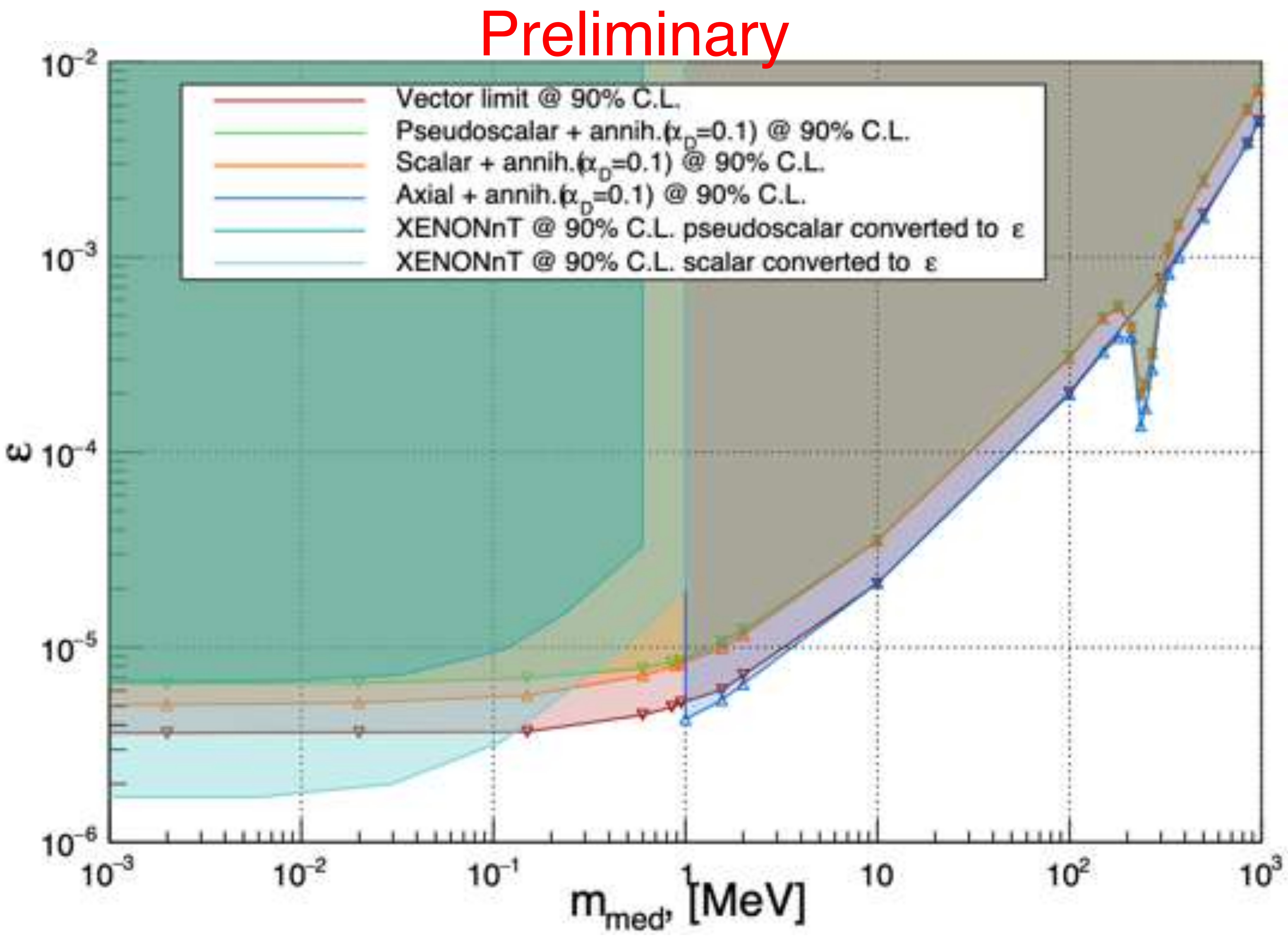
Thanks!

Acknowledgements

NA64 collaboration in particular **P.Crivelli S.Gninenko M.Kirsanov and L. Molina**

Backups

Limits on generic boson, new analysis



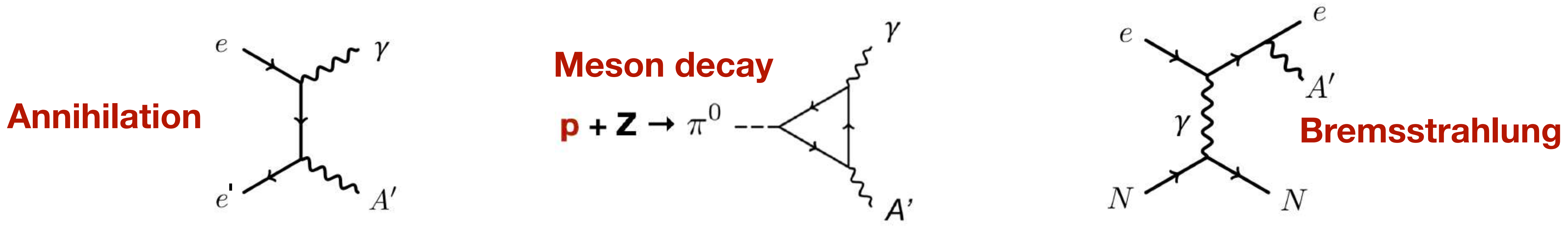
Consider also Scalar, Pseudoscalar, Axial vector

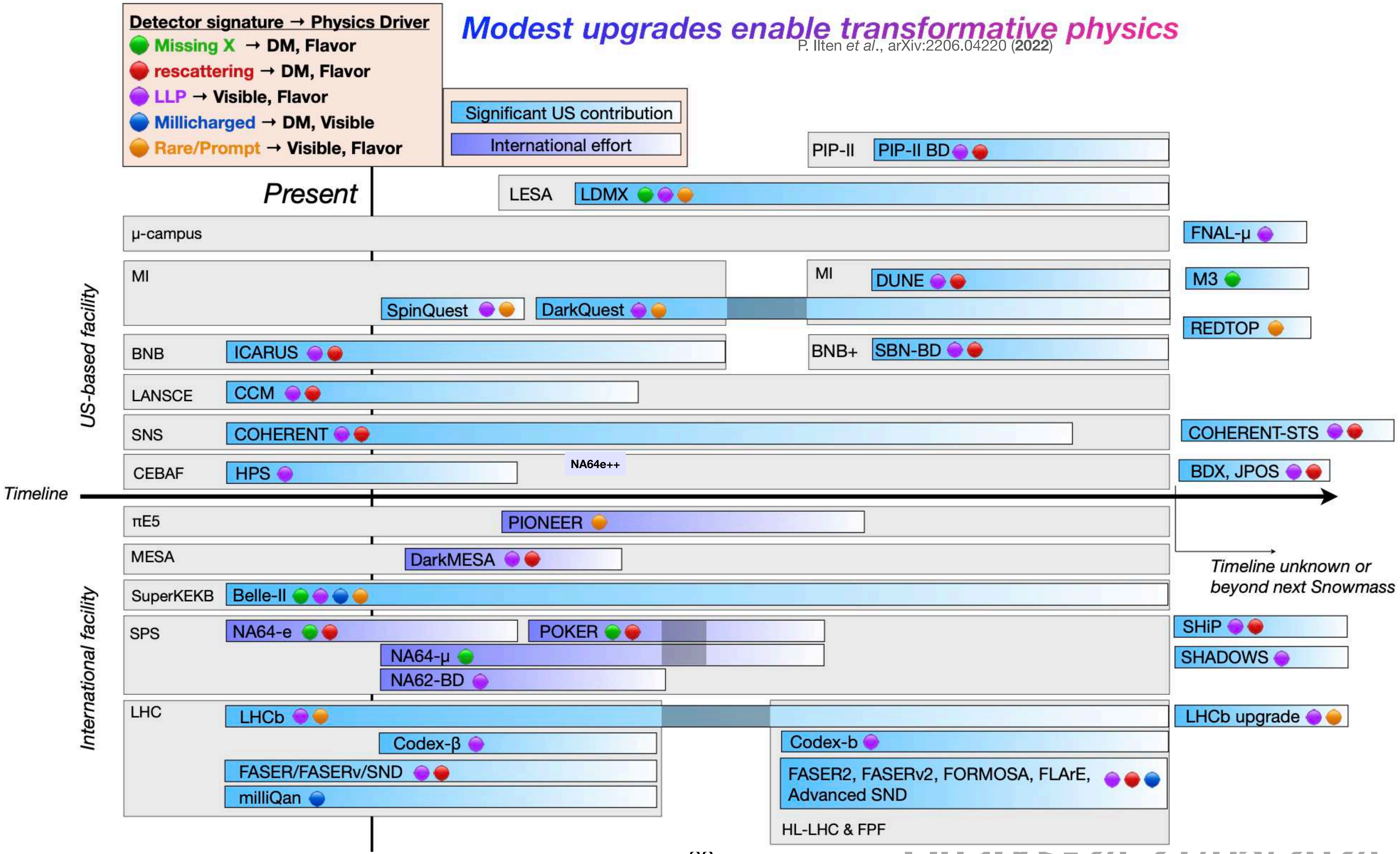
+Annihilation

Extend to 1 KeV

Summary of accelerator-based facilities

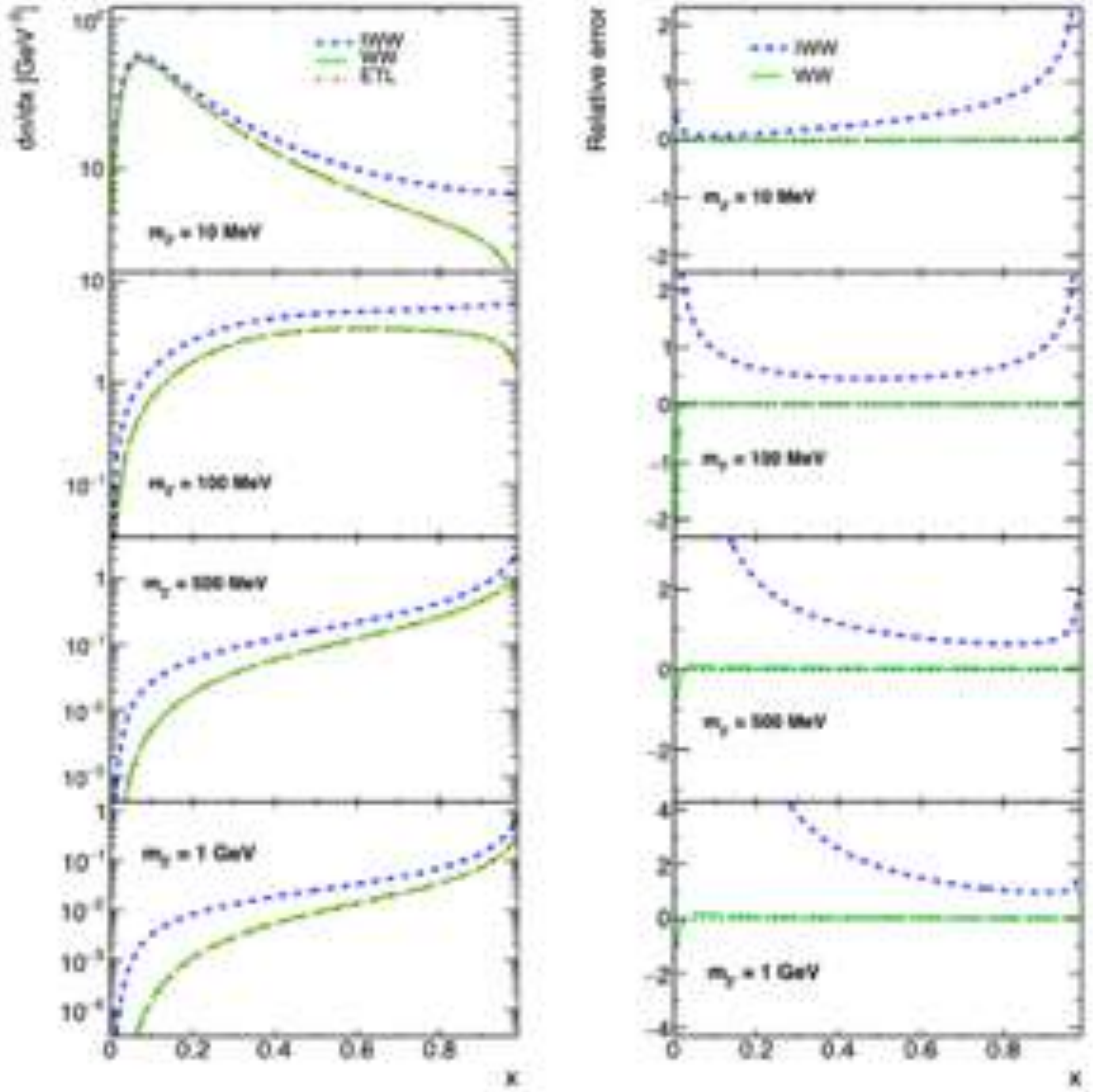
From e^+e^- *collider*, *beam dump* and *kaon factories*, *p, e^-/e^+ and μ fixed target*:





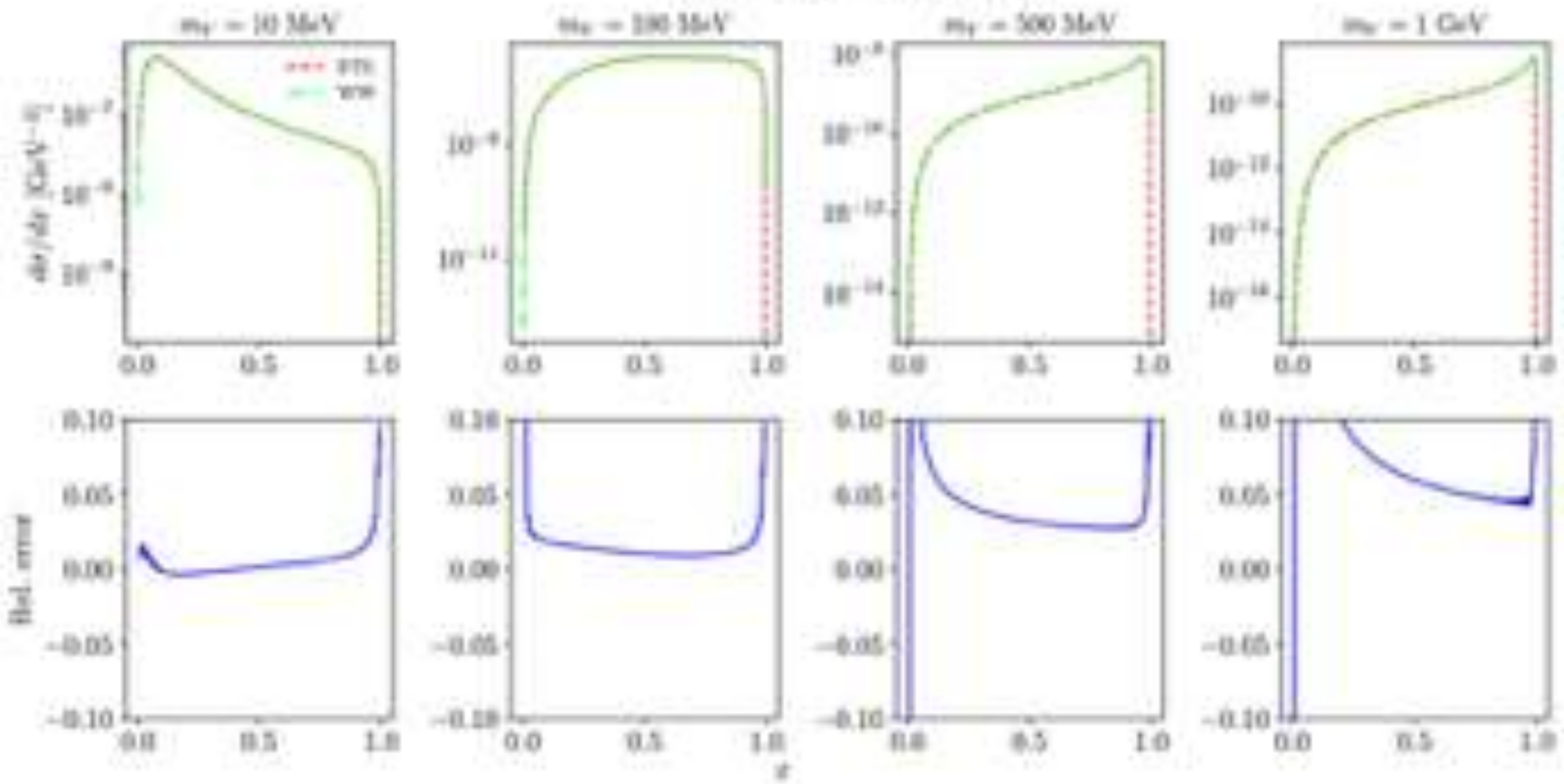
DMG4 muon beams: WW vs ETL

Single-differential cross-sections: vector case cross-check



Our previous work, Phys. Rev. D 104,076012
(numerical WW)

This work (analytical WW)

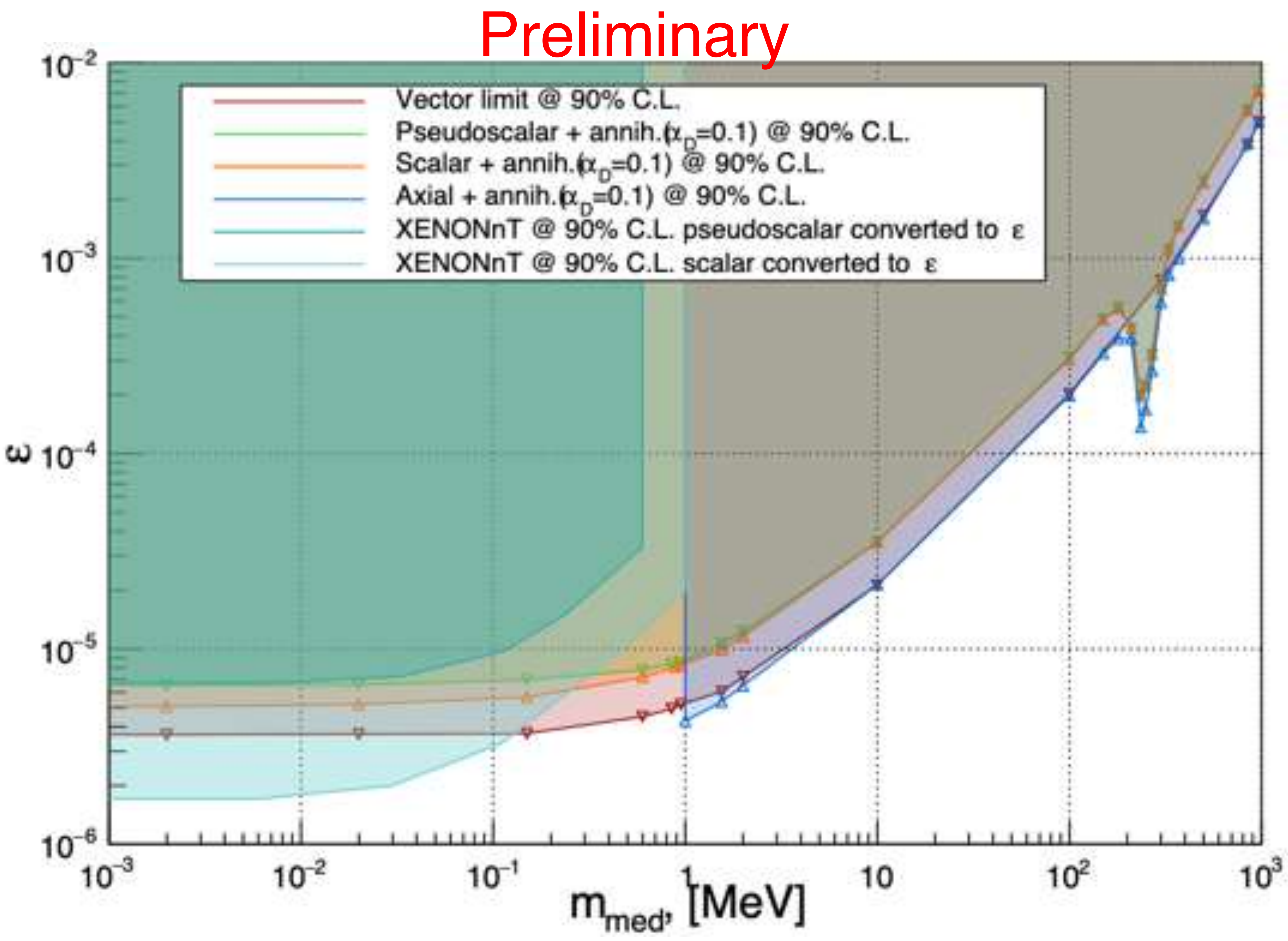


Vector (V)

σ@160 GeV

Mass [MeV]	ETL [GeV^{-2}]	WW [GeV^{-2}]	|rel. err.| [%]
10	1.55e-07	1.56e-07	~0.2
100	2.42e-08	2.45e-08	~1
500	1.57e-09	1.62e-09	~4
1000	2.58e-10	2.74e-10	~6

Limits on generic boson, new analysis



Consider also Scalar, Pseudoscalar, Axial vector

+Annihilation

Extend to 1 KeV


8 4 4 8
7 3 3 7
6 2 2 6
5 1 1 5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