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# Dark sector physics search in missing energy events with the NA64 experiment

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(on behalf of the NA64 collaboration)



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# Outline

- Motivation and method of search
- The NA64 experiment
- Runs in 2016 and 2017
- Simulation of Dark Photon production
- Analysis of data
- Results
- Conclusions

# Motivation

- Possible candidates for new physics: sub-GeV dark sector particles not charged under SM forces, only gravitational interaction,”portal” interactions with SM particles
- Thermal freeze-out of DM-SM could explain relic density, and put constraints on the parameter space
- May affect galactic structure formation, muon $(g\text{-}2)_\mu$, etc
- Parameter space is poorly tested
- Most accessible via portal interactions with SM: gauge kinetic mixing, MeV - GeV mass range, high intensity searches
- Most viable is interaction of DM with SM through a vector portal A’ boson

Dark Sectors 2016 Workshop: Community Report, J.Alexander et al., arxiv: 1608.8632

# Motivation

- New A' vector portal boson (dark photon) could mix kinetically with photon

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m^2_{\rm A'}}{2}A'_\mu A'^\mu + i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_\chi\bar{\chi}\chi - e_{\rm D}\bar{\chi}\gamma^\mu A'_\mu\chi$$

- A' corresponds to new $U(1)_D$ gauge symmetry, $\varepsilon << 1$

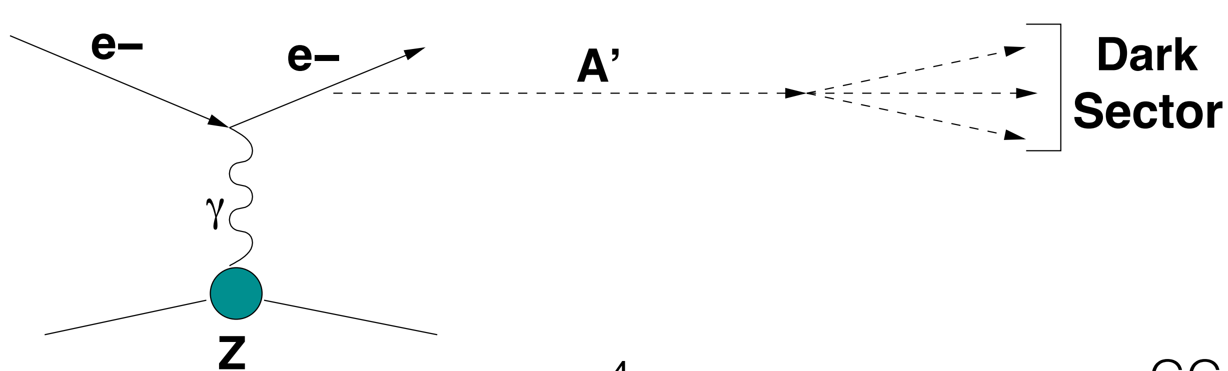
- Requirement of thermal freeze-out of DM-SM annihilation through photon-A' mixing allows to derive relations between the parameters (PRD 91,094026 (2015)).

- Rate of DM annihilation into SM fermions, allows to define signal event rate, y,

$$\langle\sigma v\rangle \propto \underbrace{\alpha_{\rm DM}\epsilon^2(m_\chi^4/m_{\rm A'}^4)}_{y}\,\alpha/m_\chi^2 \qquad \alpha_{DM} = e_D^2/4\pi$$

- Decay channels: visible: e+e-, mu+mu-, hadron, …, invisible: A' ->$\chi\,\bar{\chi}$ if $m_{A'} > 2m_\chi$. It is dominante if $\alpha_{DM} >> \varepsilon$ .

- Production: interaction of high energy electrons in an active beam dump target



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47 researchers from 11 institutes

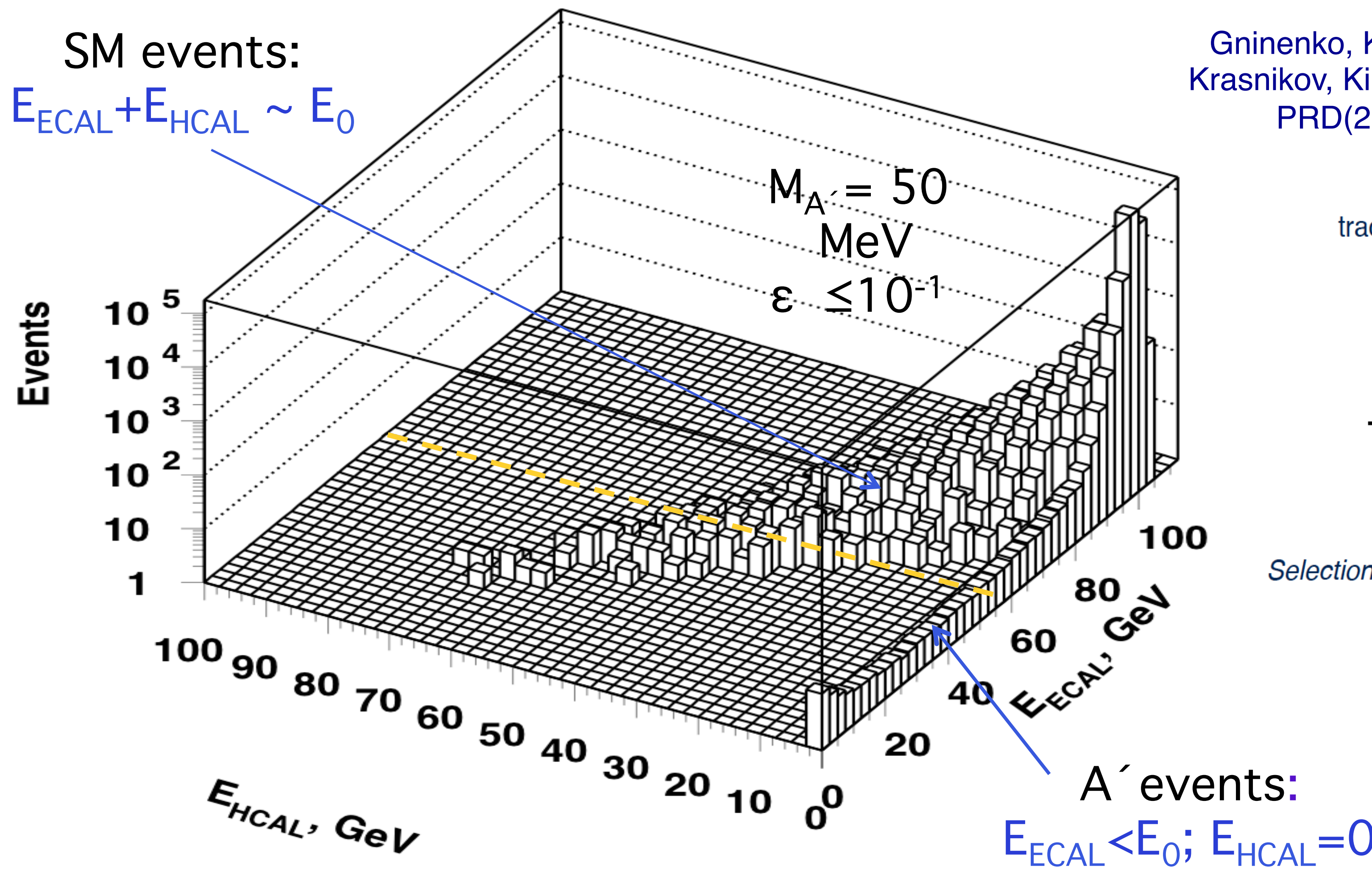
Proposed in 2014, first test beam in 2015

# Method of search for A’ -> invisible

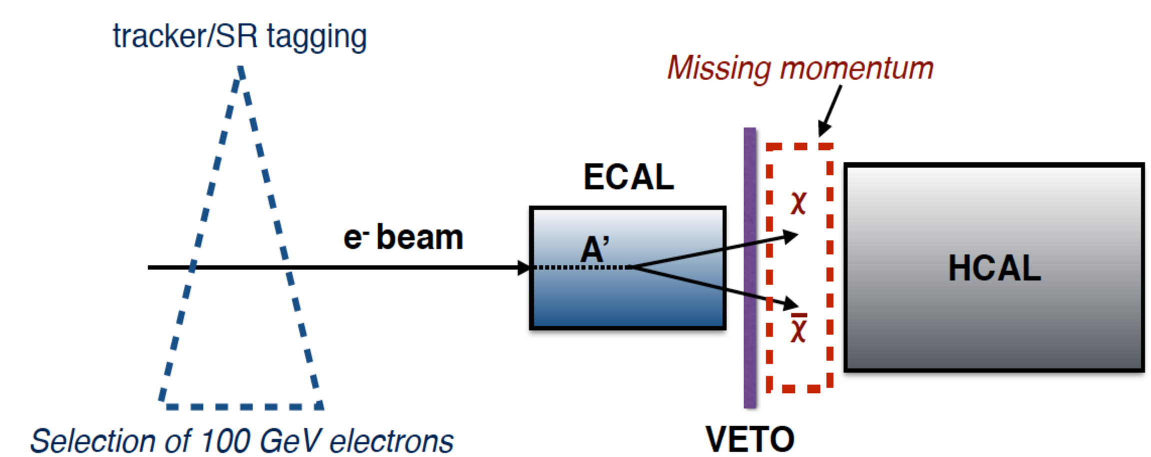
- If realised by nature, any source of photons will produce all kinematically possible massive A’ states with the appropriate mixing strength: e.g. kinetic mixing with bremsstrahlung photons in the reaction of high-energy electrons from a beam absorbed in an active beam dump.
- Followed by the prompt decay A’ -> invisible into DM particles: $e^- Z \to e^- Z A'$; $A' \to \chi \bar{\chi}$
- A fraction of the beam energy, f, is carried away by $\chi$ particles, penetrating the target without interactions, $E_{A'} = f E_0$
- The remaining part of the beam energy is deposited in the target: $E_e = (1-f) E_0$
- Signal signature: excess of events above background with
  - single isolated energy e-m shower with energy $E_e < E_0$
  - missing energy $E_{miss} = E_{A'} = E_0 - E_e$
- Number of A’ produced per electron on target (EOT):

$$n_{A'}(\epsilon, m_{A'}, E_0) = \frac{\rho N_A}{A_{Pb}} \sum_i n(E_0, E_e, s)\sigma^{A'}(E_e)\Delta s_i$$

# Simulation of eZ->ezA’; A’ -> invisible



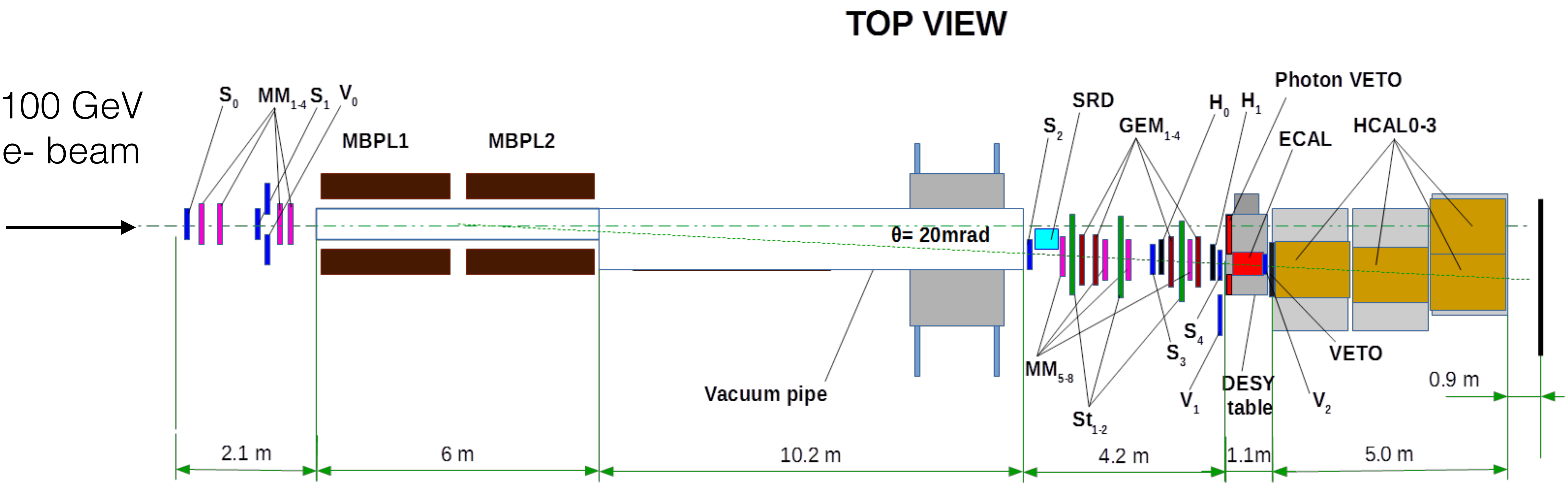

Gninenko, Kirsanov, Krasnikov, Kirpichnikov PRD(2016)




- Geant4 and A’ emission in the e-m shower development.
- Cross section from Bjorken et al. 2009.
- Sensitivity ~ $\varepsilon^2$ (A’ production vertex) - while for beam dump experiments ~ $\varepsilon^2\alpha_D$ (+ A’ decay and $\chi$ scattering off electrons in the target detector).
- For small ε mixing parameter this scheme has great advantage.

# NA64 experiment setup invisible search mode

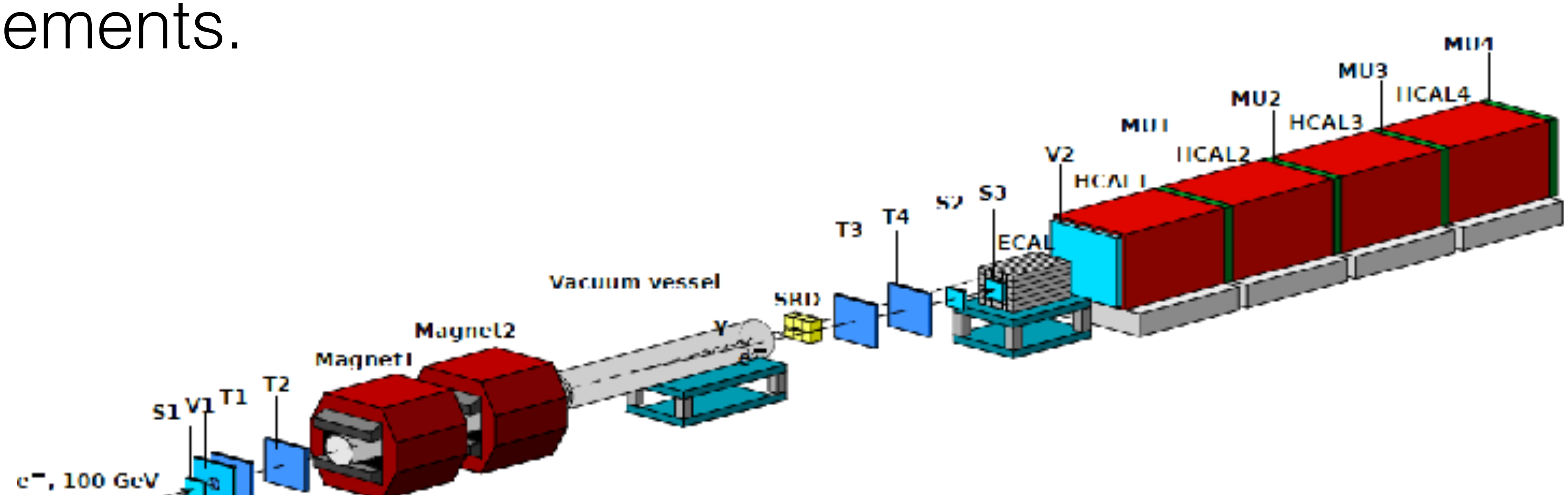
100 GeV
e- beam



# NA64 experiment setup

# Key moments in reconstruction

- Synchrotron Radiation detector (SRD) made as lead - scintillator sandwich used to suppress pions and other heavier then e- particles from the beam.
- The shower profile in the ECAL is compared to profile of true electrons in order to suppress wrong particles.
- Micromegas track detectors are used to reconstruct the momentum of e- before the ECAL  to suppress small fraction of soft electrons from interaction in beam line elements.

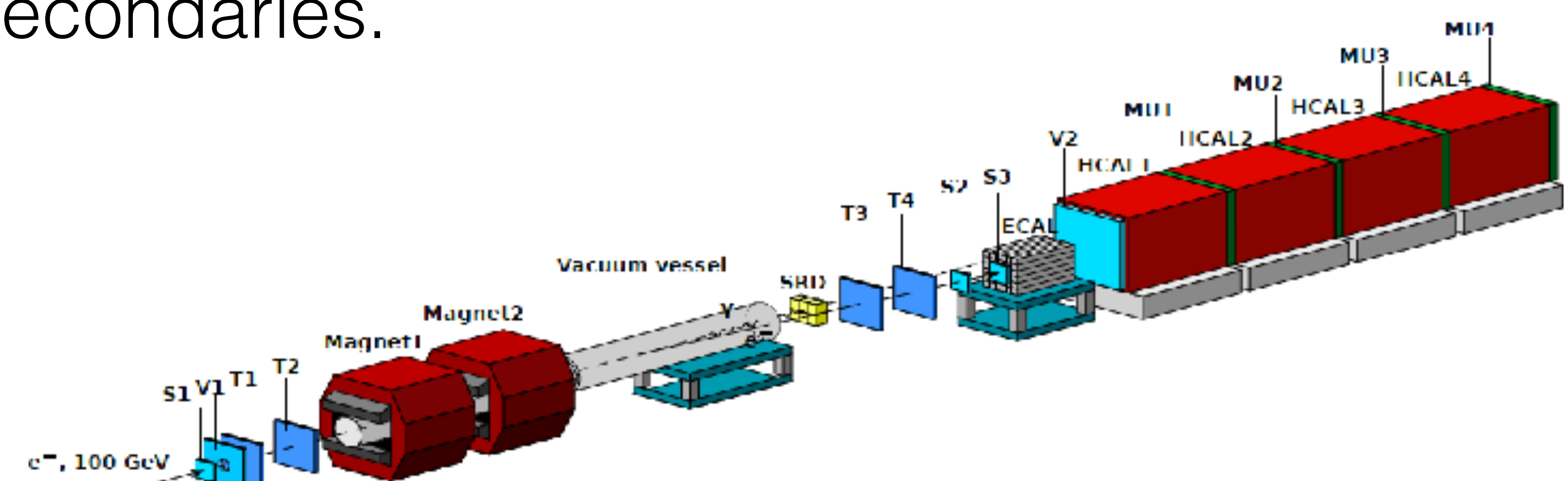


# Key moments in reconstruction

- Each ECAL module is 40 $X_0$ with a 4$X_0$ preshower initial part, electron energy resolution: dE/E ~ 0.1/$\sqrt{E}$

- Requiring in-time between SRDs combined with ECAL longitudinal and lateral shower information: $\pi$/e- < $10^{-5}$, 95% e- ID efficency (NIM A 866 (2017) 196).

- V2 after ECAL to veto charged secondaries, and HCAL (30 $\lambda_{int}$, Fe+Sc) to veto on muons or hadronic secondaries.

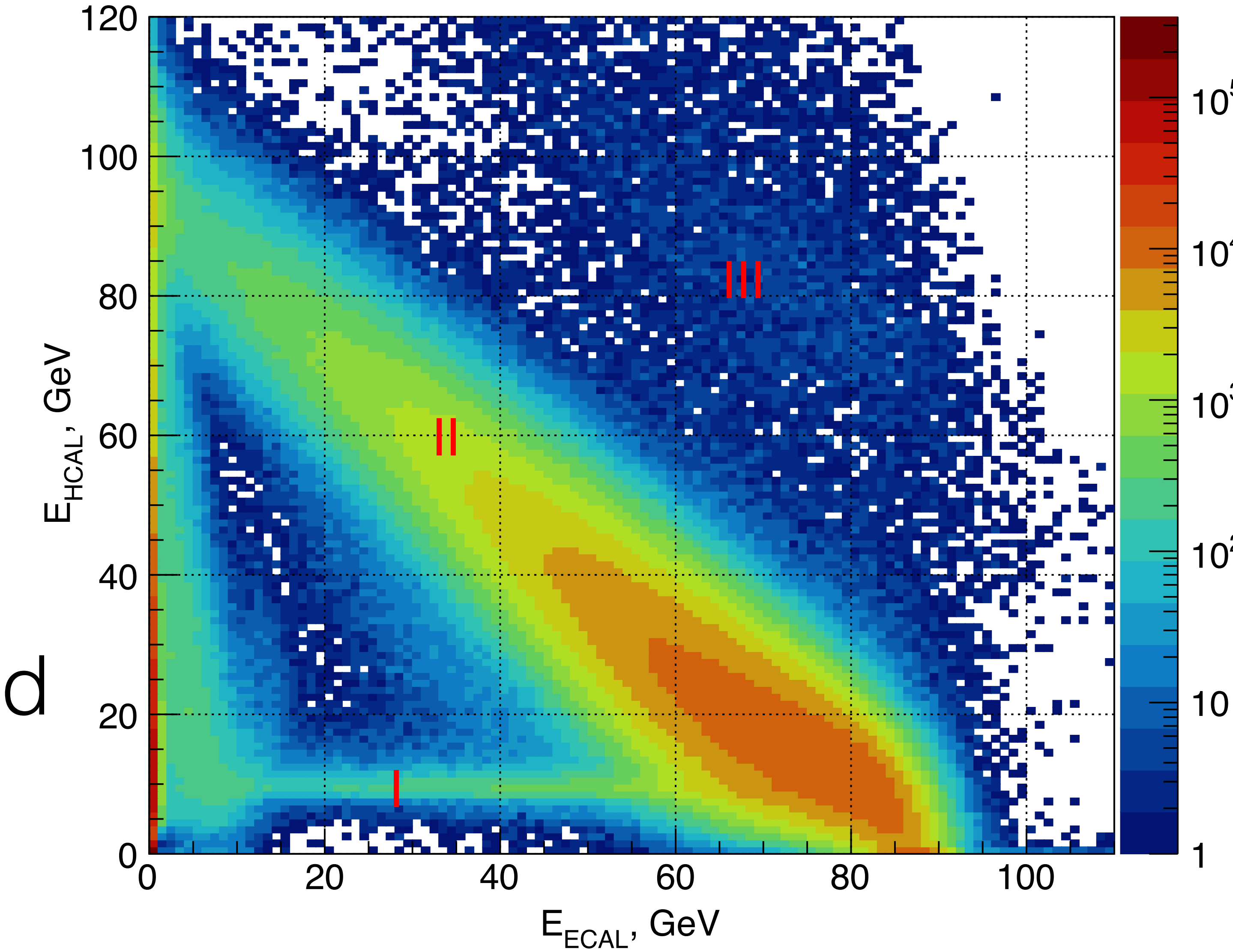


# Data taking in 2016

- 1st Run period: 29.06-13.07 (2w)
- 2nd Run period: 12.10-09.11 (4w)
  - Low intensity: $n_{EOT} = 2.3 \times 10^{10}$ (~$1.4$-$2 \times 10^{6}$ e- /spill)
  - Medium intensity: $n_{EOT} = 1.1 \times 10^{10}$ (~$3$-$3.5 \times 10^{6}$ e- / spill)
  - High intensity: $n_{EOT} = 0.9 \times 10^{10}$ (~$4.5$-$5 \times 10^{6}$ e- /spill)
- $Tr(A') = \Pi S_i \times V1 \times PS(>E_{PS}) \times ECAL(<E_{ECAL})$

# ECAL vs HCAL energy

- Region I: dimuon events
- Region II: $E_{ECAL} + E_{HCAL} = 100$ GeV
- Region III: pile-up of e- and beam hadrons (1-20%)

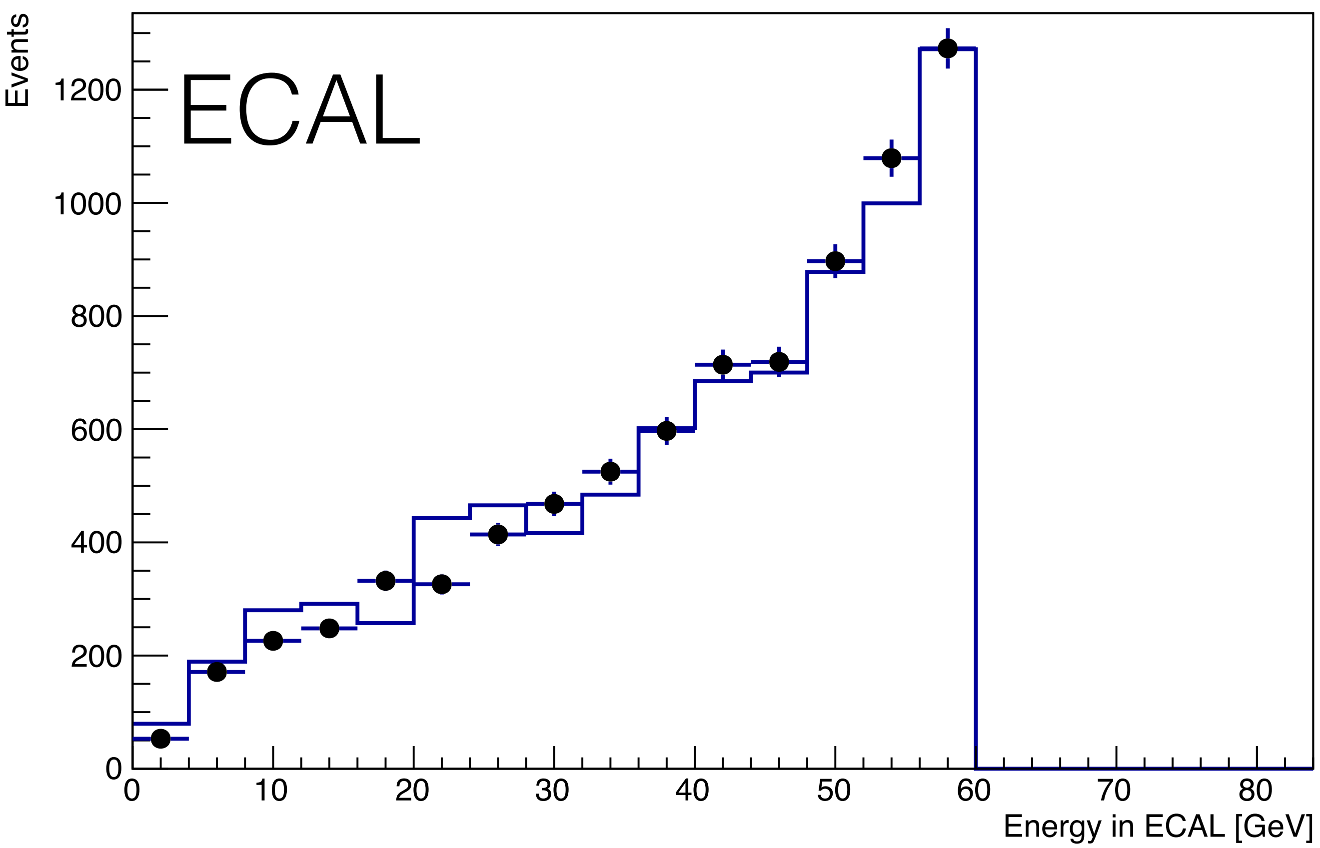


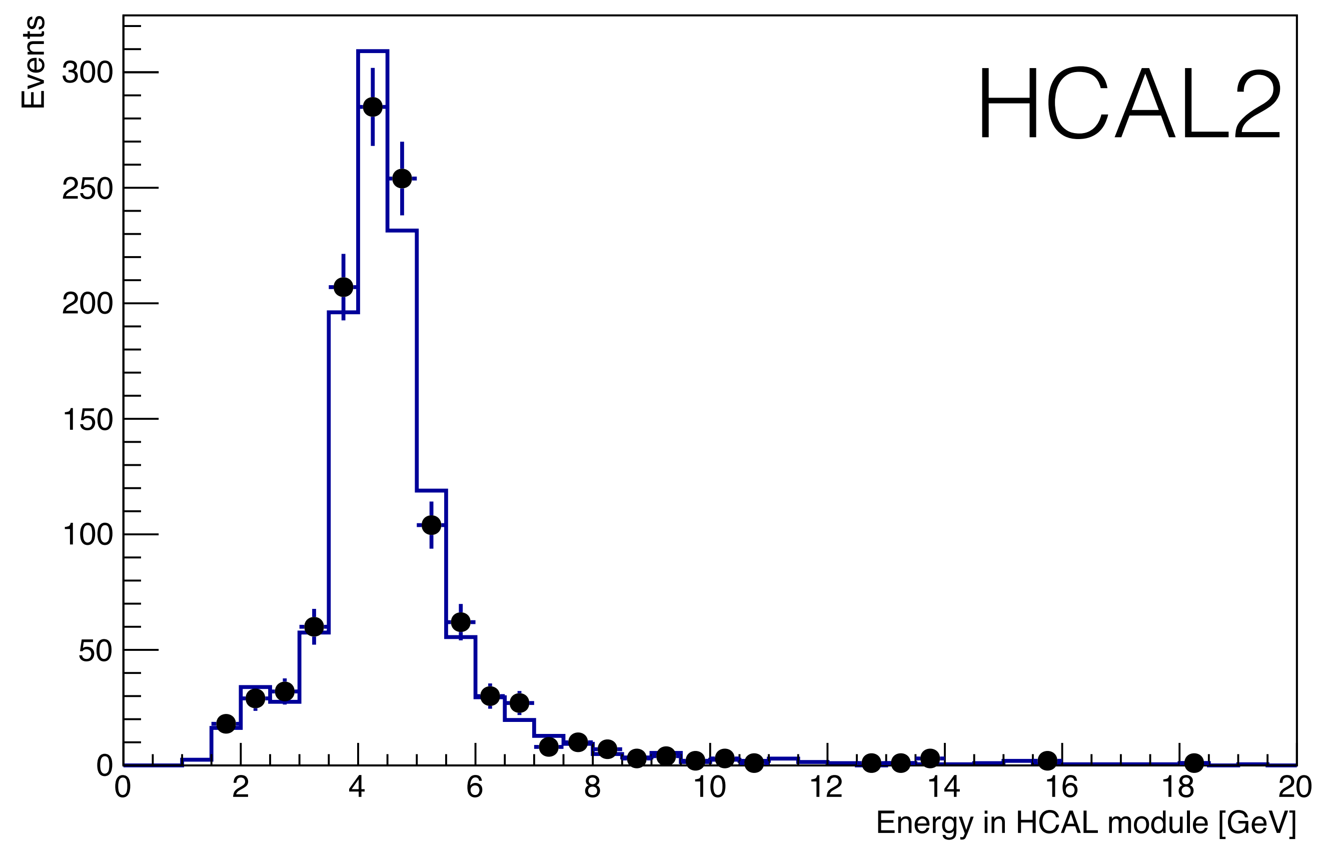

Only SRD selection to be e- event

# Dimuon production as reference

- Rare process gamma to muon conversion (eZ->eZγ;γ->μμ), many similarities with our signal. Available in G4, off by default.
- Can be used to estimate corrections to signal reconstruction efficiency and uncertainties in A' yield calculations
- HCAL energy around 10 GeV.
- $\sim 10^4$ dimuon pairs detected in HCAL in 2016 run period.
- MC simulation: cross section have been biased in G4 by a factor of 200 to have good statistics.
- MC compared with Data.

# Dimuon reconstruction




| Data sample | beam intensity, $10^6$ | $n_{tot}$, $10^6$ | $n_{2\mu}^{MC}$ | $n_{2\mu}^{data}$ | Efficiency |
|---|---|---|---|---|---|
| run I | 1.8 | 171 | 1223 | 1124 | 0.92 |
| run II | 3.2 | 208.5 | 1491 | 1268 | 0.85 |
| run III | 4.6 | 597 | 4271 | 3417 | 0.81 |

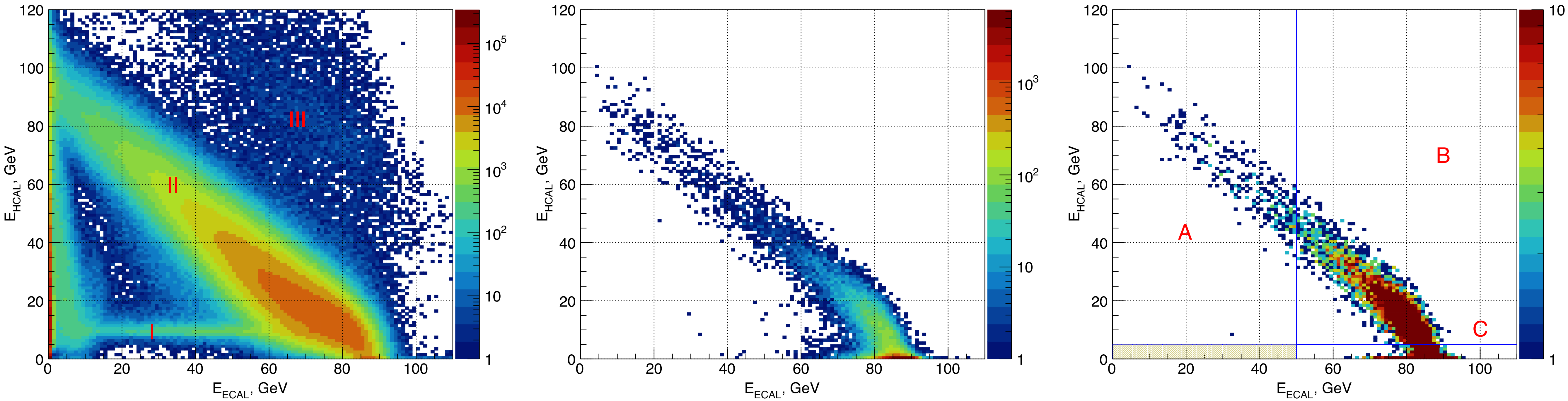
# Analysis: efficiency and uncertainties

| Efficiency | Value, uncertainty | sample |
|---|---|---|
| number of collected EOT, $n_{EOT}$ | $1 \pm 0.02$ | $e^-$ Data |
| incoming $e^-$ selection cuts, $\epsilon_e$ | $0.58 \pm 0.03$ | $e^-$ Data |
| $A'$ yield, $\epsilon_{A'}$ | $\epsilon$, $m_{A'}$ dependent, 10% | MC, Dimuons |
| ECAL selection cuts, $\epsilon_{ECAL}$ | $0.93 \pm 0.06$ | Data, Dimuons |
| Veto cut, $\epsilon_V$ | $0.94 \pm 0.03$ | Data, MC |
| HCAL selection cuts, $\epsilon_{HCAL}$ | $0.98 \pm 0.02$ | Data, MC |
| Total | $0.50 \pm 0.13$ | |

- Values correspond to high-intensity run.
- Total efficiency varying 0.73±0.12 to 0.50±0.13.
- ECAL and incoming e- selection most rate dependent.

# Analysis cuts

Medium beam intensity




- Left: only SRD cut to be e- events

- Middle: all selection but cut against upstream interactions (Tracker hit multiplicity, and lateral energy spread and time spread in HCAL cells)

- Right: final event selection

# Backgrounds

- Leak of energy through holes, cracks in the detector
  - X-Y scan of ECAL and HCAL - no significant E leak found
- Detector hermeticity: photo-nuclear reaction producing neutrons, charged hardons escaping detection in HCAL (non-herm)
  - pion beam test, Data-MC comparison, single hadron prod. prob. $<10^{-4}$, non hermeticity $< 10^{-9}$, overall negligible $< 10^{-13}$
- Large transverse fluctuations from hadronic showers, long lived neutral emitted at large angles: similar to previous estimates
- Upstream interactions: requires precise knowledge of dead material in the beam line
  - SRD, V2, tracker suppression of secondaries
  - HCAL: lateral E and time spread compared with that expected from single electrons interacting in the ECAL target
  - estimation from data control regions
- Particle in-flight decays
  - SRD, ECAL energy and incoming track angle

# Backgrounds

| Background source | Estimated number of events, $n_b$ |
|---|---|
| hermeticity: punchthrough $\gamma$'s, cracks, .. | $< 0.001$ |
| loss of hadrons from $e^- Z \to e^- + hadrons$ | $< 0.001$ |
| loss of muons from $e^- Z \to e^- Z\gamma; \gamma \to \mu^+\mu^-$ | $0.005 \pm 0.001$ |
| $\mu \to e\nu\nu$, $\pi$, $K \to e\nu$, $K_{e3}$ decays | $0.02 \pm 0.004$ |
| $e^-$ interactions in the beam line materials | $0.09 \pm 0.03$ |
| $\mu, \pi, K$ interactions in the target | $0.008 \pm 0.002$ |
| accidental SR tag and $e^-$ from $\mu, \pi, K$ decays | $< 0.001$ |
| Total $n_b$ | $0.12 \pm 0.04$ |

- Dominant contribution from upstream interactions
- 30% uncertainty also mainly due to upstream interactions
- Estimated from extrapolation of background control regions to signal region

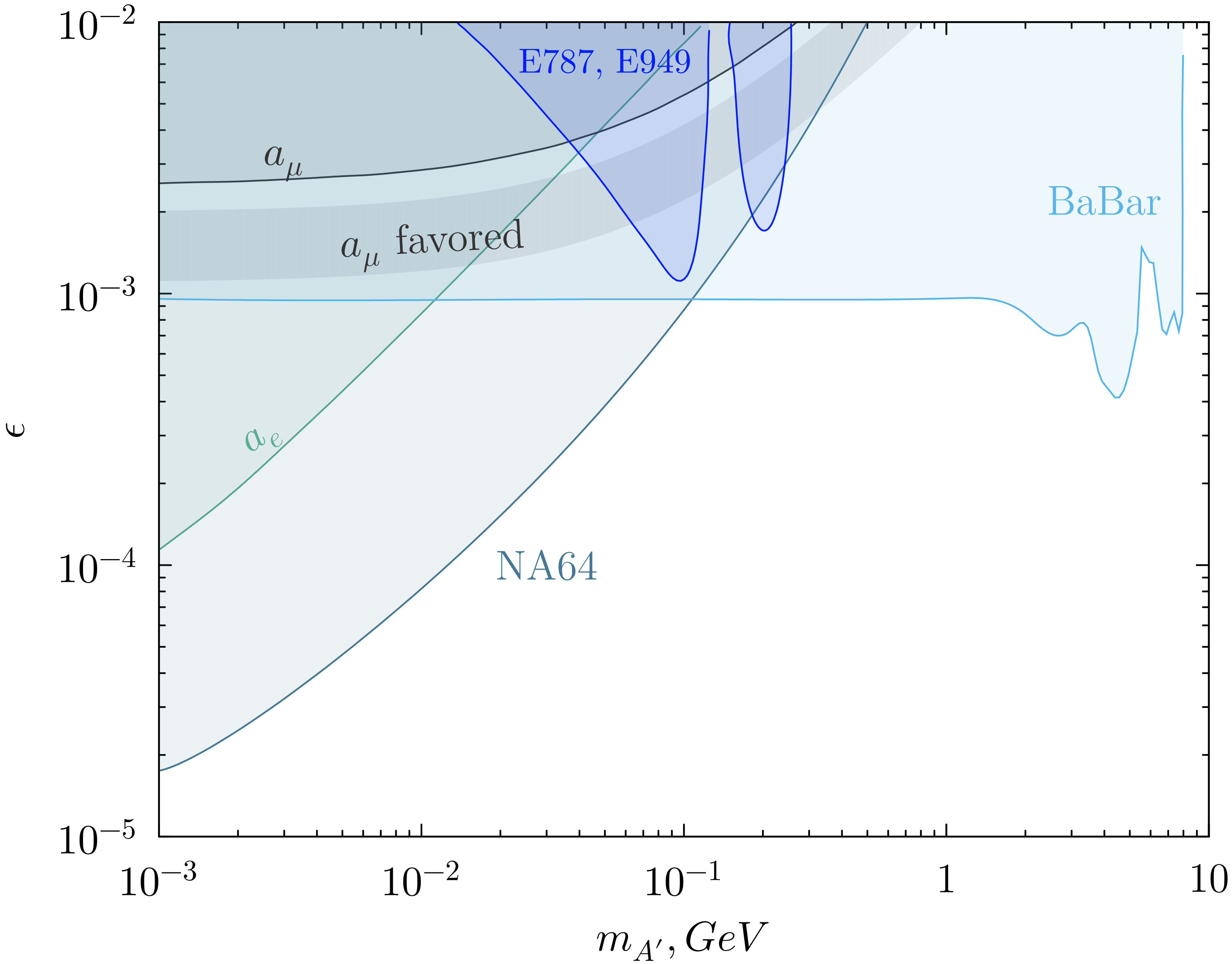
# Analysis

- Data collected from 2016 runs are divided in 3 bins: low, medium and high intensity beam.
- For each bin the background, efficiency corrections and uncertainties are estimated.
- A cut optimisation for the maximum sensitivity was performed for ECAL cut.
- The expected sensitivity was calculated with the Profile Likelihood method with RooStats, using the PL as test statistics, and taking the asymptotic approximation.

$$N_{A'} = \sum_{i=1}^{3} N^i_{A'} = \sum_{i=1}^{3} n^i_{EOT}\epsilon^i_{tot}n^i_{A'}(\epsilon, m_{A'}, \Delta E_e)$$

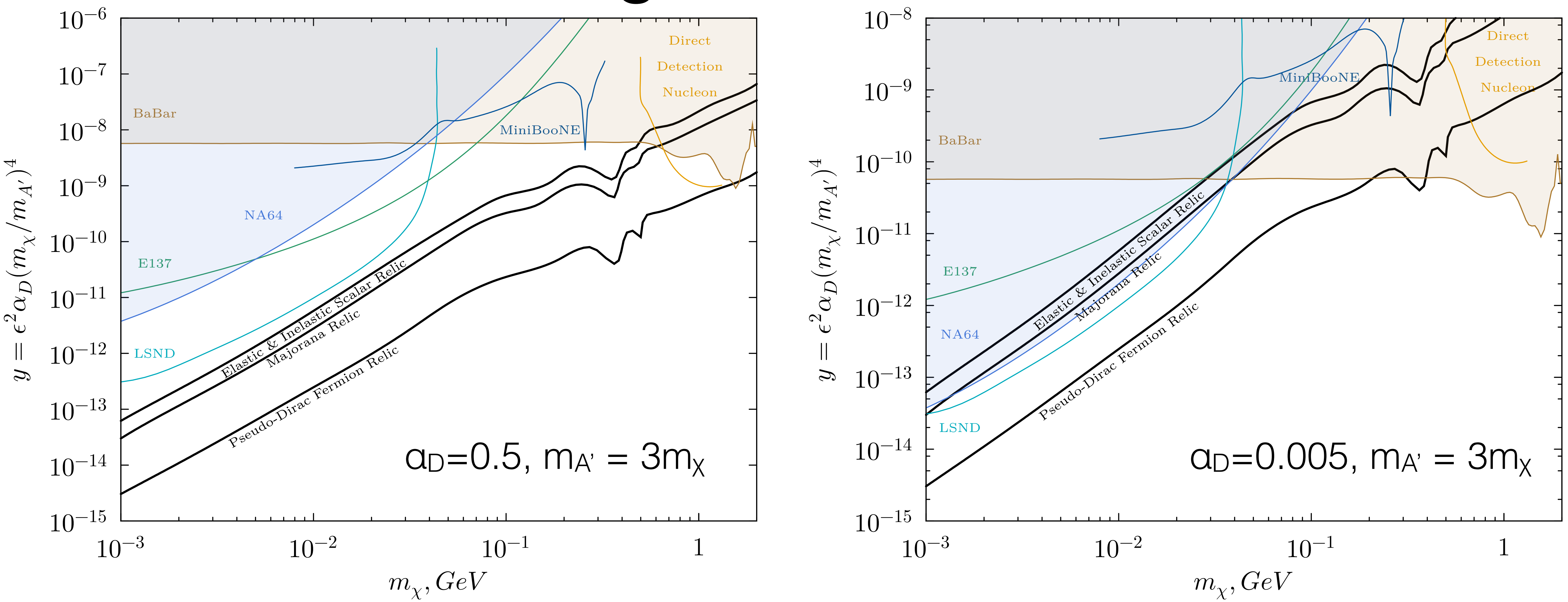
- Each ith entry for each data: simulating signal events for beam conditions and reconstructing w/ selection criteria, and efficiency corrections.
- Results also cross checked with simple limit from Poisson signal model with log-normal used for systematic uncertainty terms. Results agree within %.

# Results on A’ parameters




- Best limits in the region 0.001 - 0.1 GeV.
- Muon g-2 favoured parameter region for vector mediator model excluded.
- Phys. Rev. Letters **118**, 011802 (2017)

# Results on light thermal dark matter




- LTDM models can be classified into spin and mass of DM and mediators, here only considering vector mediator.
- Assuming limits from prev. slide, constraints on DM annihilation freeze out.
- Results obtained for LSND, E137 and MiniBoone with $10^{22}$, $10^{19}$ and $10^{20}$ POT.
- NA64 obtained with only ~4x$10^{10}$ EOT. With ~4x1011 EOT NA64 can cover all beam dump exclusion areas.

# Conclusions

- Search is performed for sub-GeV dark photon mediated production of dark matter by NA64, using $4.3 \times 10^{10}$ 100 GeV electrons.
- No evidence of such events found.
- Derived upper limits on A'-γ mixing strength in the mass range 1-500 MeV, allowing to exclude vector mediator model solution for the muon g-2 anomaly.
- Assuming these limits and constraints on DM ann. freeze out NA64 managed to exceed also limits on LTDM scenarios.
- NA64 continues to increase statistics in the near future and extend searches for dark matter and new physics at CERN SPS.
- Just finished our 2017 run, collecting additional $5 \times 10^{10}$ electrons:
  - Runs finished both with invisible and visible mode, sensitivity to exclude $\varepsilon = [5 \times 10^{-5}, 10^{-3}]$, covering light X boson ($^{8}$Be) favoured parameter region
  - Data under evaluation