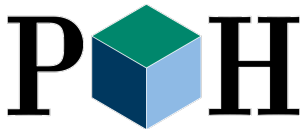


Reconstructing ALP properties from inaccurate observations with ML

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with Felix Kahlhoefer and Torben Ferber

based on [2308.01353]



Light Dark World, 19.09.2023

Inverse problem in high-energy physics

Simulation: ✓

BSM parameters $\theta \longrightarrow$ detector measurements x

Inference: ✗

(real) detector measurements $x \longrightarrow$ BSM parameters θ

Why is it complicated? **No direct access to likelihood**

For instance at LHC:

$$p(x|\theta) = \int dz_d \int dz_s \int dz_p p(x|z_d) p(z_d|z_s) p(z_s|z_p) p(z_p|\theta)$$

Beam-dump experiments at ECN3

Lower energy, higher intensity:

- sensitivity to $m \lesssim 4 \text{ GeV}$
- sensitivity to feebly interacting particles

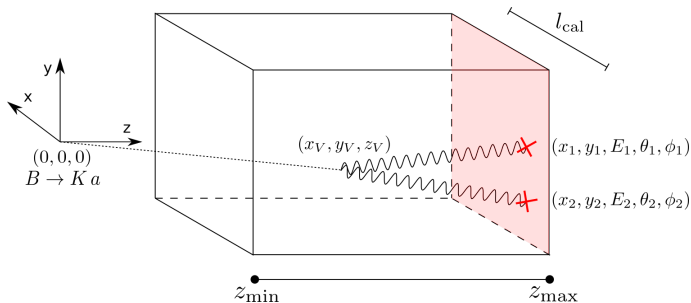
Physical targets:

Looking for dark scalars, **axions/ALPs**, heavy neutral leptons

Different proposals under consideration [report]:

- HIKE/SHADOWS [letter of intent]
- SHiP [letter of intent]

Detector sketch and input variables



Geometry of the detector: $z_{\min} = 10\text{m}$, $z_{\max} = 35\text{m}$, $l_{\text{cal}} = 2.5\text{m}$

Detector readout: hits x_i, y_i , energies E_i , photon direction θ_i, ϕ_i

Problem: inaccurate measurements

We see some signal events and group their features in $\mathbf{x}$,
what can we say about the ALP?

Perfect detector:

- $\mathbf{x} \longrightarrow m_{\gamma\gamma} \longrightarrow m_a$
- $\mathbf{x} \longrightarrow |\mathbf{V}|, \quad |\mathbf{V}| \sim \exp\left(-|\mathbf{V}| \frac{m_a}{|\mathbf{p}_a| c \tau_a}\right)$

Imperfect detector:

- if error is small, should work with $m_{\gamma\gamma}$
- for larger error, signal purity requirements and ad-hoc high-level observables can help
- other?

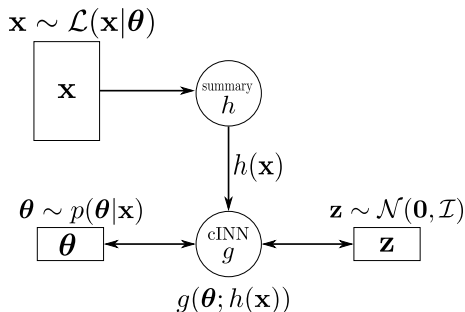
Simulation-based inference

No direct access to likelihood?

Then use the simulations $\rightarrow$ simulation-based inference

One possible approach: use ML to approximate likelihood/posterior

In our case: posterior learnt with conditional invertible neural network



Technical details

Posterior $\rightarrow$ choose a prior:

$$m_a \in [0.1\text{GeV}, 4.5\text{GeV}],$$

$$c\tau_a \in [0.1\text{m}, 100\text{m}]$$

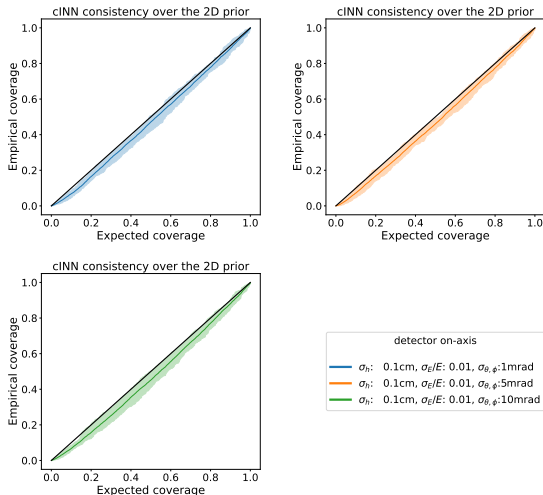
Input parameters:

$$m_a, c\tau_a / m_a$$

Number of seen events: 3

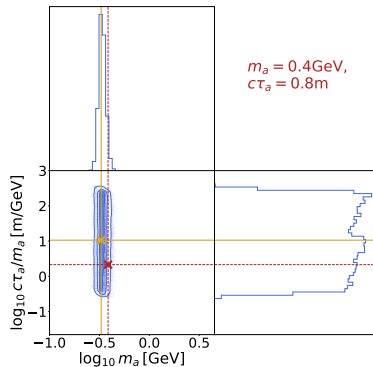
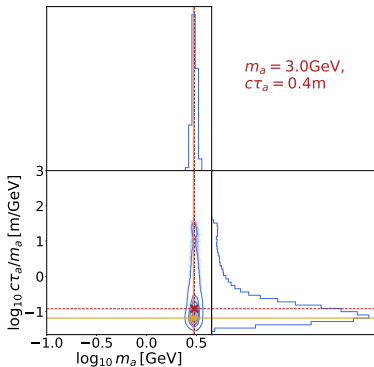
Do we trust the posterior?

Check pp-plot



Posterior: role of mass and lifetime

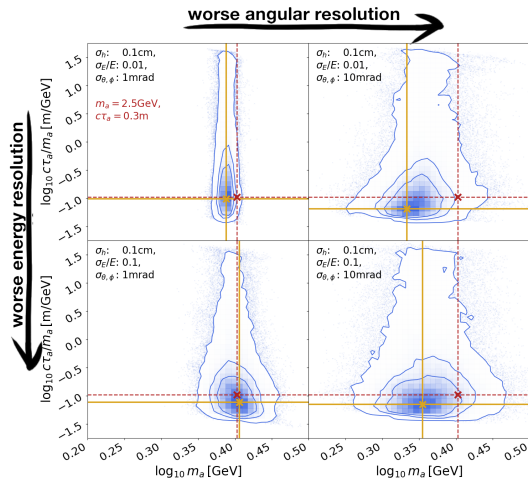
Can we constrain both the mass and the lifetime?
Depends on detector geometry and lifetime value



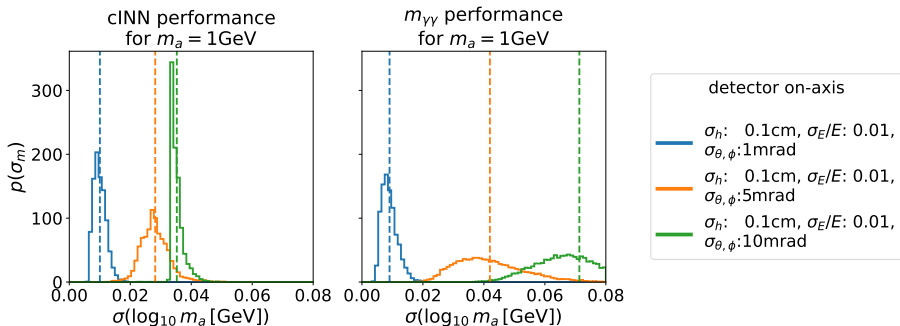
Posterior: role of detector resolution

What if we change the detector?
Then the uncertainties change

Feature resolution	Values scanned
$\sigma(E)/E$	[0.01, 0.05, 0.1]
$\sigma(h)$	[0.1cm]
$\sigma(\theta), \sigma(\phi)$	[1 mrad, 5 mrad, 10 mrad]

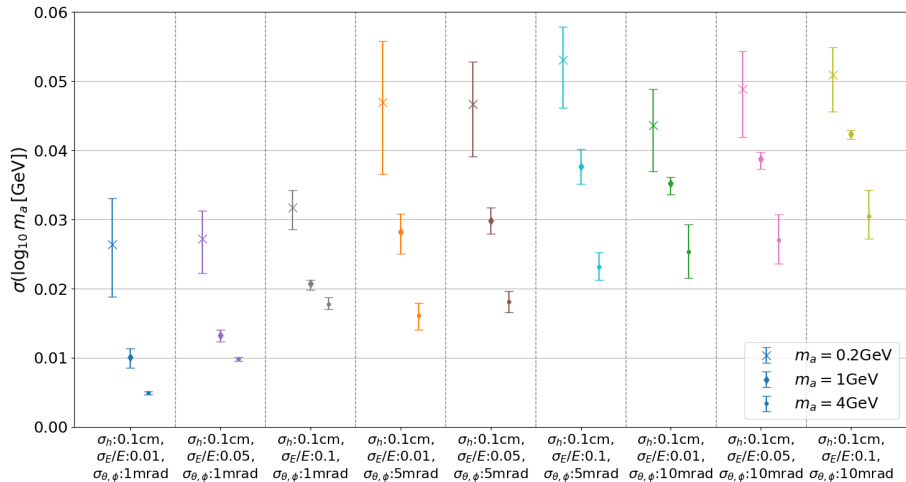


Performance for 1 GeV (role of angle resolution)

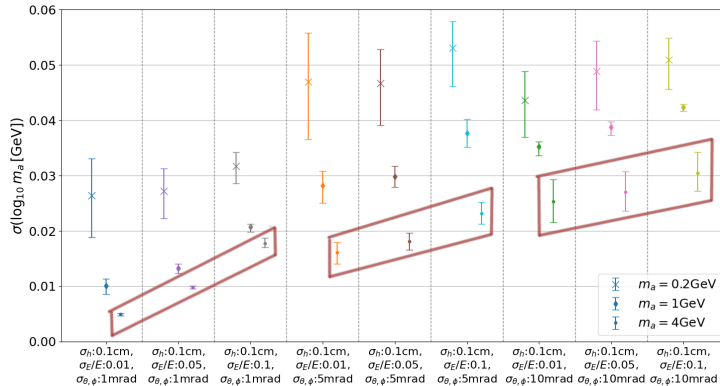


- Agreement with $m_{\gamma\gamma}$ for great resolution
- Considerable outperformance for worse angular resolutions

Performance of different detector setups



Performance of different detector setups (example)



- Major role played by angular resolution
- Interplay between energy and angular resolution

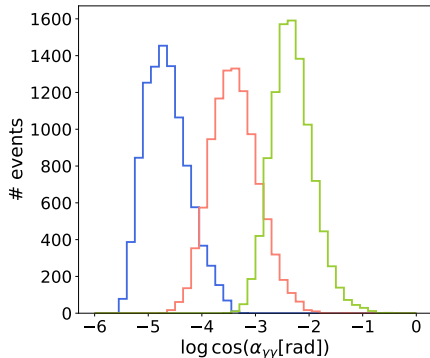
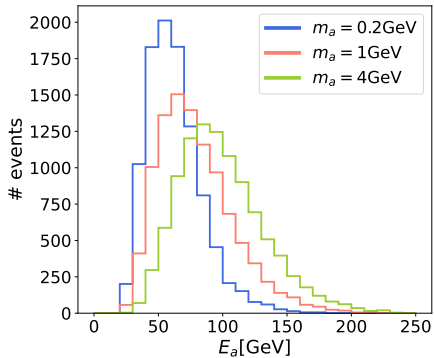
Conclusions

- We can derive fast and reliable parameter estimates **including their uncertainty**
- The considered algorithm **easily adapts** to different setups
- Performance comparisons allow **experimental design**

Thank you!

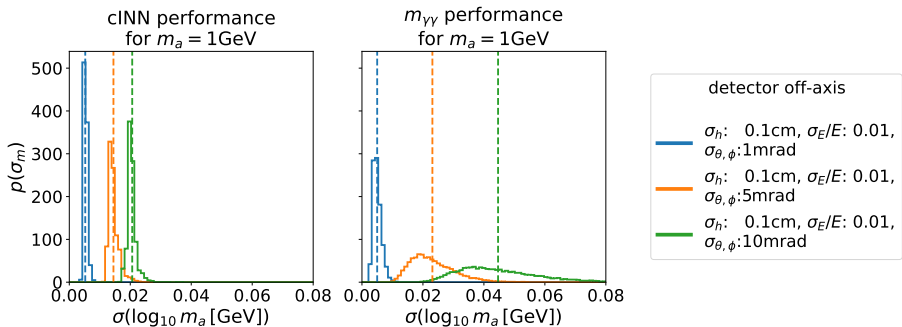
BACKUP

Variable distributions



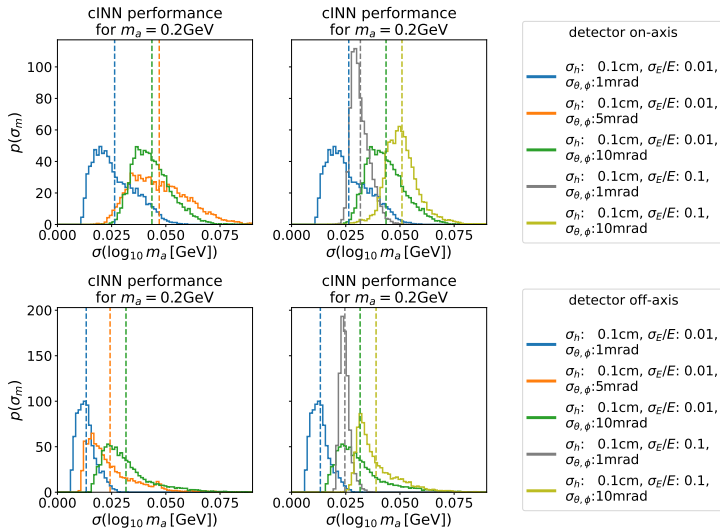
- Mass information also in energy distribution
- Angles useful to infer the mass (but hardest feature to measure)

Performance for 1 GeV (displaced case)

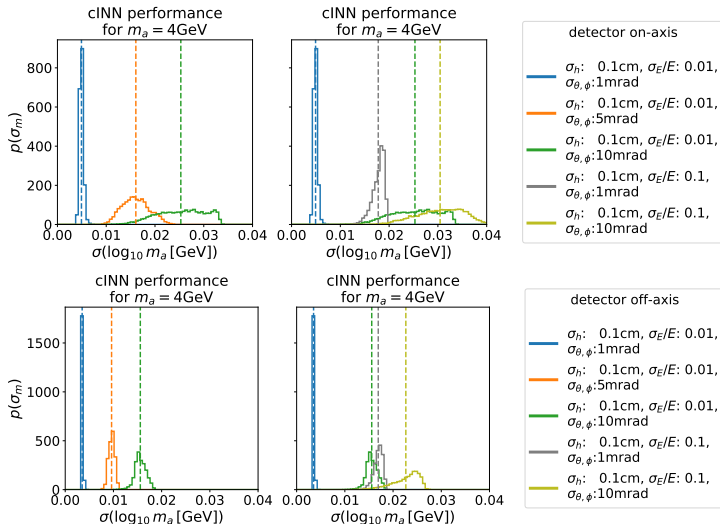


- Same conclusions as in non-displaced case
- Smaller parameter uncertainty (for same number of seen events!)

Performance for 0.2 GeV



Performance for 4 GeV



Performance of different detector setups

