Simulation based inference for axions at colliders

Alessandro Morandini
work in progress with Felix Kahlhoefer and ETP

Karlsruher Institut für Technologie

Swyft workshop, Future applications, 25.01.2023

Inverse problem at LHC

LHC chain simulation: MadGraph + Pythia + Delphes

Input: BSM parameters θ → Output: detector measurements

Inference:

Input: (real) detector measurements x → Output: BSM parameters θ

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

$$p(x|\theta) = \int \mathrm{d}z_d \int \mathrm{d}z_s \int \mathrm{d}z_p \, p(x|z_d) p(z_d|z_s) p(z_s|z_p) p(z_p|\theta)$$

Beamdump experiments

Simpler (?) setup: **beamdump experiment**

Theoretical motivation:

looking for sub-GeV new particles

Experimental motivation:

lower energy, higher intensity, lower cost

Sensitivity in range $100\mathrm{MeV} - 4\mathrm{GeV}$

Sensitivity to dark scalars, **axions/ALPs**, heavy neutral leptons

SHADOWS and LUXE-NPOD

Two specific examples (ETP at KIT work on these)

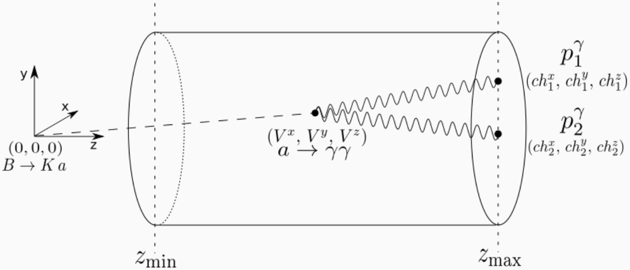
SHADOWS: [2110.08025]

- located at LHC, close to NA62
- proton energy of 400GeV
- $B \to K + a$

LUXE-NPOD: [2107.13554]

- located at DESY
- electron-laser collision, $E(e^-) \sim 16\text{GeV}$
- $\gamma + N \to N + a$

Simulation



Dataset:

- 100k unweighted events ($\mathcal{O}(10s)$, but depends on m_a, τ_a)
- $z_{\rm min} = 10$m$, z_{\rm max} = 100$m
- $m_a \in [0.1\,\text{GeV}, 4\,\text{GeV}]$, $\tau_a \in [0.01\text{m}, 10\text{m}]$ (with log-priors)

Observables (perfect scenario)

What can we measure?

- calorimeter hits of the photons
- four-momenta of the photons
- decay vertex position (maybe reconstructed through ML)

If that was the real case, no need for complicated stuff for inference

$m_{\gamma\gamma} \to m_a$

$c\tau \sim \frac{m_a}{|\vec{p}_a|} |\vec{V}| w(z_{\text{min}}, z_{\text{max}})$

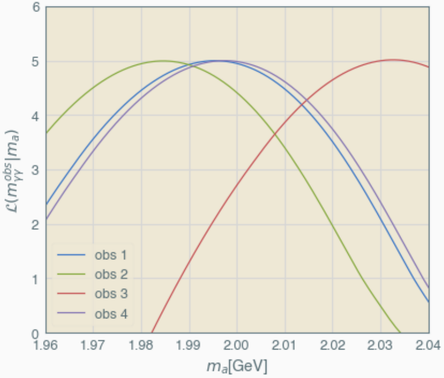
Issue 1: imperfect reconstruction

In a very ideal scenario:
we might measure **all the observables**,
but with some error

Still use high level observable,
but it is necessary to learn the distribution

Likelihoods can be easily combined

Safety check: verify coverage

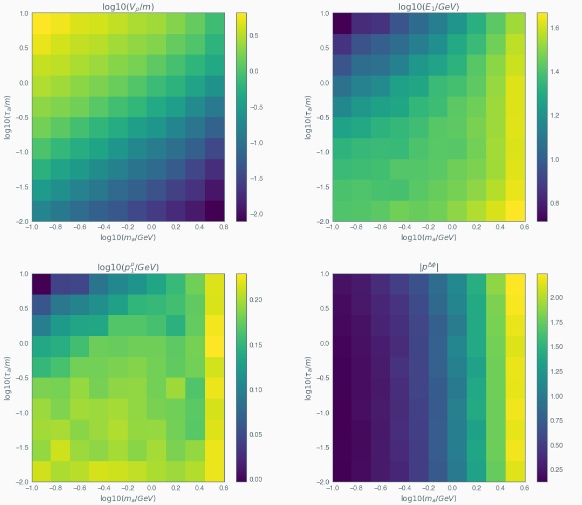


Issue 2: missing information

In a realistic scenario:
we cannot measure some quantity
(e.g. no vertex tracking)

Use available information,
find **informative variables**

Combine information cleverly



Simulation based inference to counteract issues

Same approach for imperfect reconstruction and missing information

We do not have $\mathscr{L}(x|m_a, \tau_a)$, but we can try to **approximate it**

Different ML algorithm return different PDFs,
but they are all based on the same event generation scheme:

- $(m_a, \tau_a) \sim p(m_a)p(\tau_a)$ (sample parameters according to prior)
- $x \sim \mathscr{L}(x|m_a, \tau_a)$ (use simulator to derive x)
- Feed (m_a, τ_a, x) to ML which returns $\tilde{\mathscr{L}}(x|m_a, \tau_a)$ or other PDF
- Use approximated likelihood/posterior to perform inference

ML algorithms for NLE or NPE

- Normalizing flows (NF):

Input $(x, m, \tau) \quad \rightarrow p(x, m, \tau) = \mathscr{L}(x|m, \tau)\, p(m)\, p(\tau)$

- Conditional invertible neural network (cINN):

Input (x), condition $(m, \tau) \quad \rightarrow \mathscr{L}(x|m, \tau)$

Input (m, τ), condition $(x) \quad \rightarrow p(m, \tau|x) = \mathscr{L}(x|m, \tau)\, p(m)\, p(\tau) / p(x)$

- Classifier:

Input $x_1 \sim \mathscr{L}(x|m, \tau)$, $x_0 \sim \mathscr{L}(x|m_0, \tau_0) \quad \rightarrow \mathscr{L}(x|m, \tau) / \mathscr{L}(x|m_0, \tau_0)$

- All algorithms implemented and checked in simple scenarios

Issue (opportunity?) 3: detector design

Previous tasks are not easy, but doable with established ML methods

SHADOWS and LUXE are not finalized:
we **do not know** the experimental properties

This raises the question:
what should we measure and how well?

How much do we need vertex reconstruction?
How precise should be the angular resolution?
How long does the detector need to be?

Outlook: when things get complicated

At this stage we have:

- a couple model parameters
- $\mathcal{O}(10)$ observables

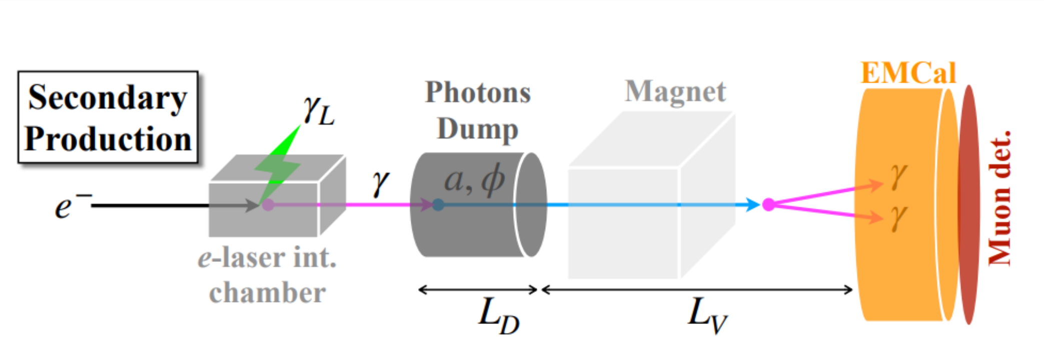
We might require efficient and reliable inference software when considering different detector scenarios

New parameters to be introduced:

- detector resolution for each observable
- experimental geometric size
- which observables are measured

BACKUP

LUXE design



Secondary Production
γ_L
e^-
γ
e-laser int. chamber
Photons Dump
a, ϕ
Magnet
EMCal
γ
γ
Muon det.
L_D
L_V