Using BDTs as Surrogate Models for BSM searches in ATLAS

(Re)interpretation of the LHC results for new physics
CERN, 25-28 Feb 2025

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In collaboration with:

L.C., A.H., M.Goodsell, ArXiv:2502.10231
T.Chehab , L.C., A.Goudelis, A.H., L.Millot, ArXiv:2502.18021

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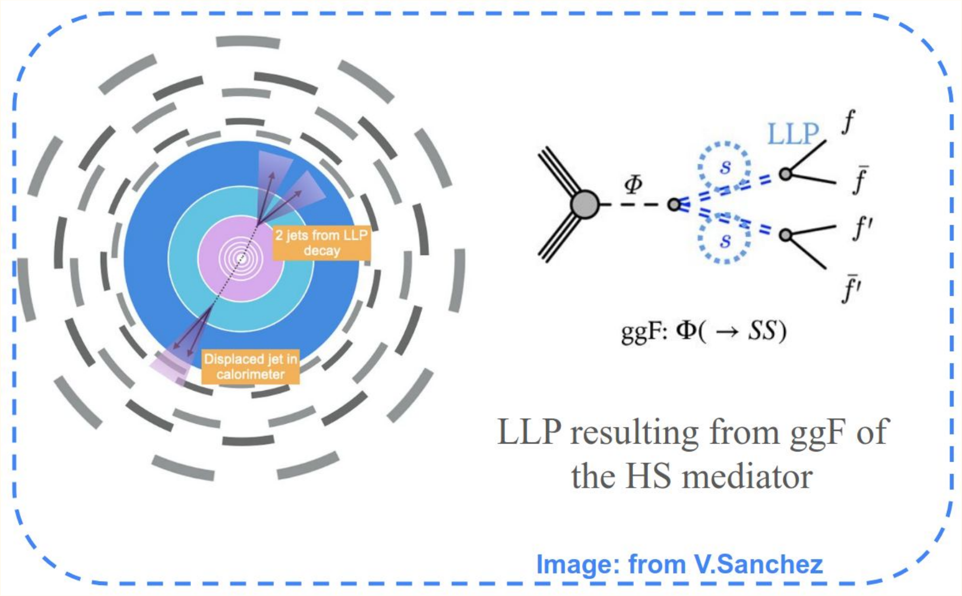
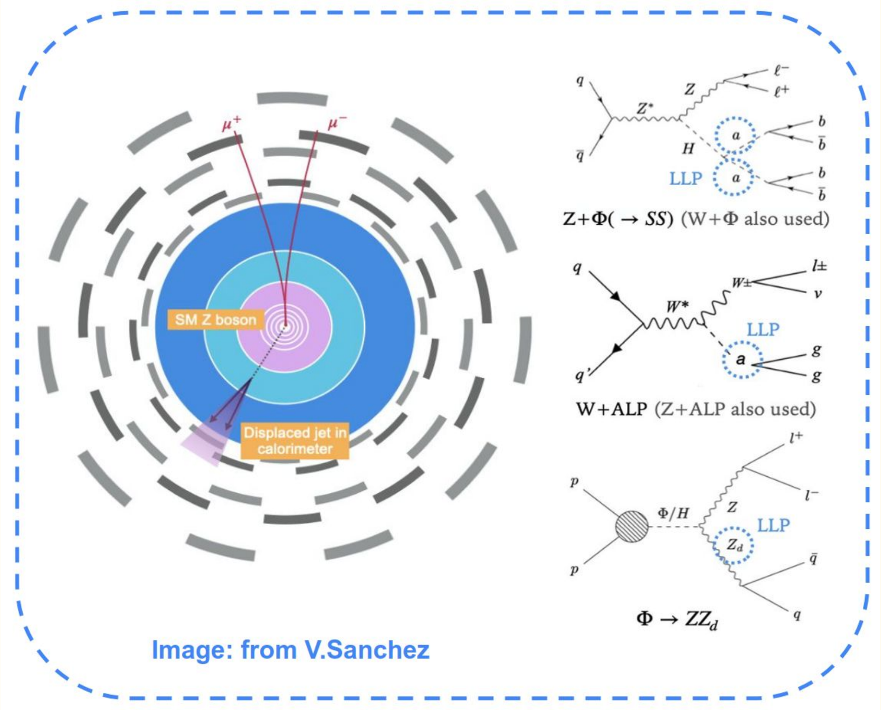
Outline

CalRatio+X Analysis: A case study

"Search for neutral long-lived particles that decay into displaced jets in the ATLAS calorimeter in association with leptons or jets using pp collisions at $\sqrt{s}=13$ TeV",
JHEP 11 (2024) 036, ArXiv:2407.09183

CalRatio+X Analysis

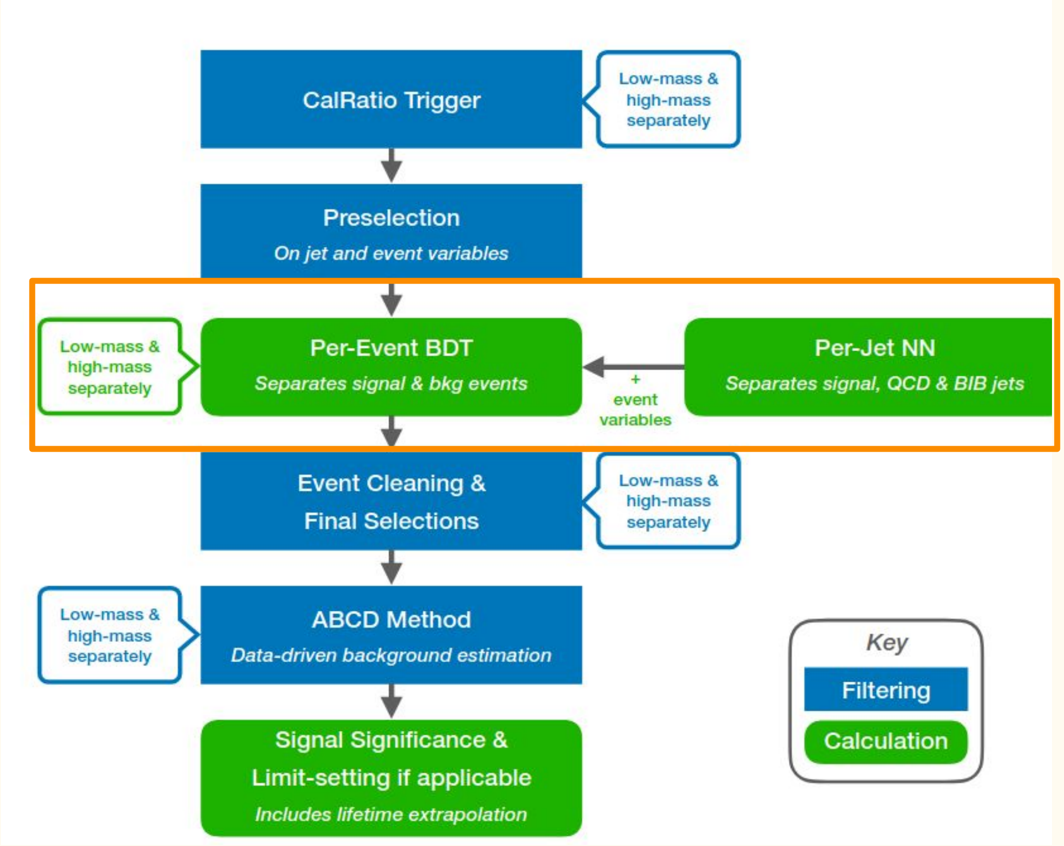




CalRatio + 2J: One LLP reconstructed as two resolved jets (low-boost)

CalRatio + leptons: Access to singly produced LLPs + prompt W/Z

CalRatio+X Analysis

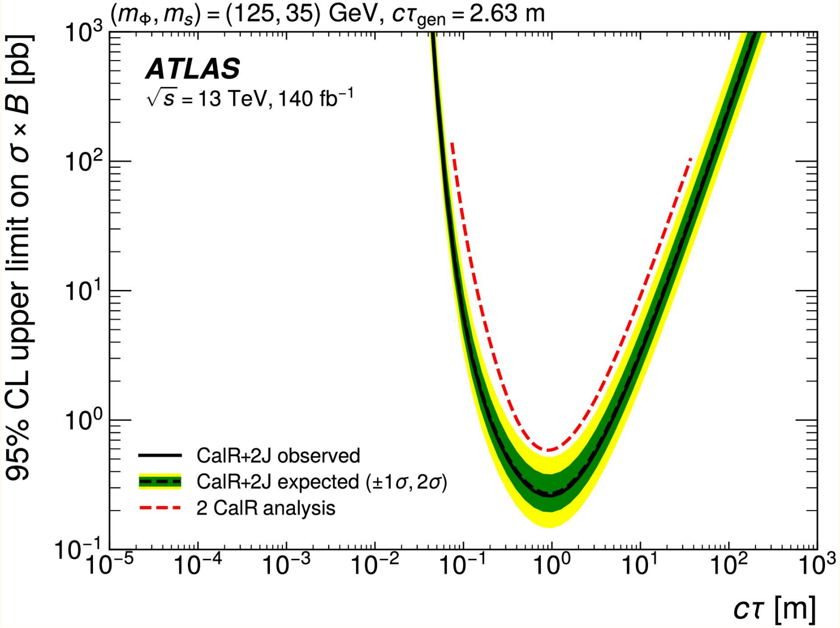


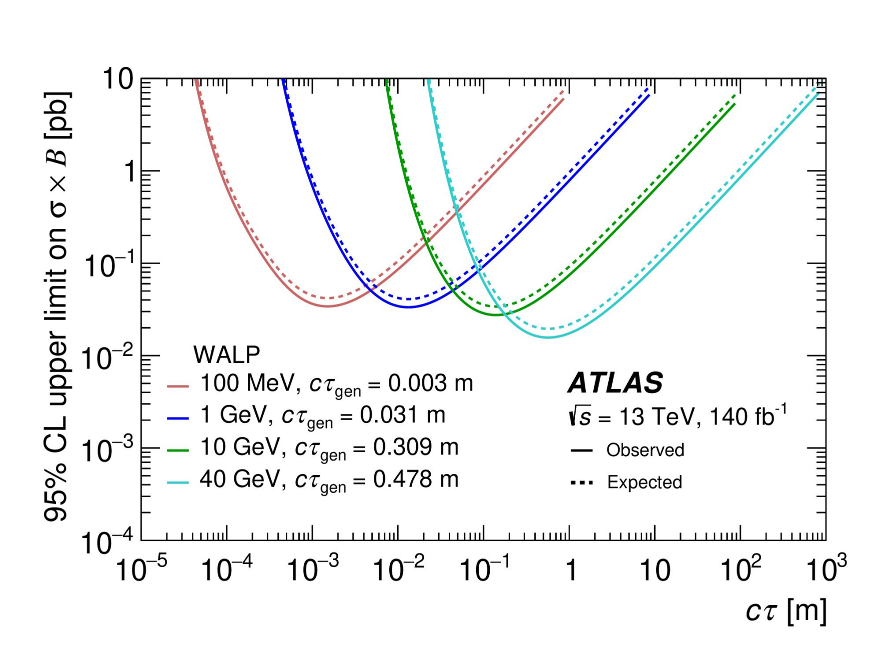
Both channels use a per-jet NN followed by a per-event NN or BDT which render the reinterpretation trickier!

➢ Guidance provided in:

Les Houches guide to reusable ML models in LHC analyses

CalRatio+X Results



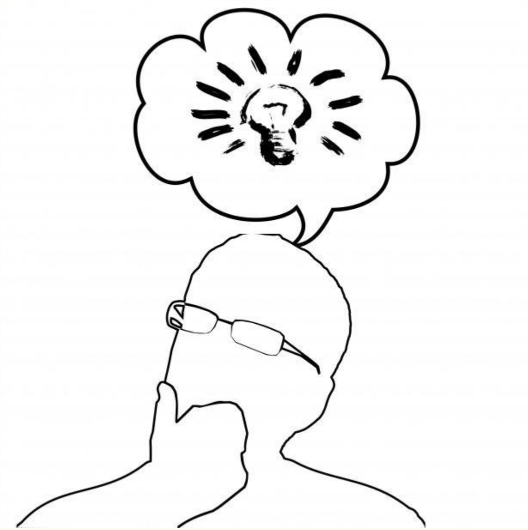


Improvement by up to a factor of 3 over the previous 2CalRatio analysis

First ATLAS limits on photo-phobic ALP models

CalRatio+X Analysis

What do we need to do to make this analysis re-interpretable for other models?



The Idea

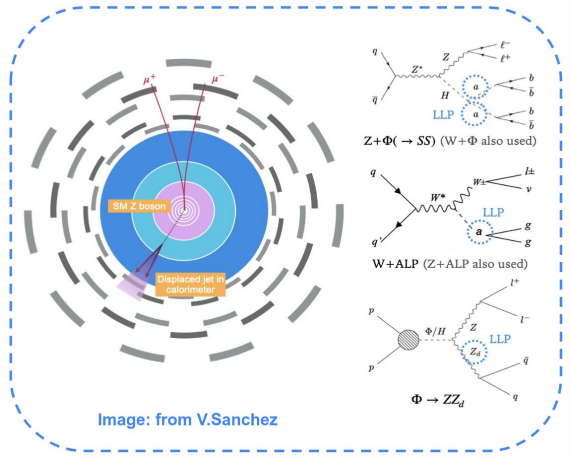
L.Corpe, A.Haddad, M.Goodsell, "*Recasting the ATLAS search for displaced hadronic jets in the ATLAS calorimeter with additional jets or leptons using surrogate models*", ArXiv:2502.10231

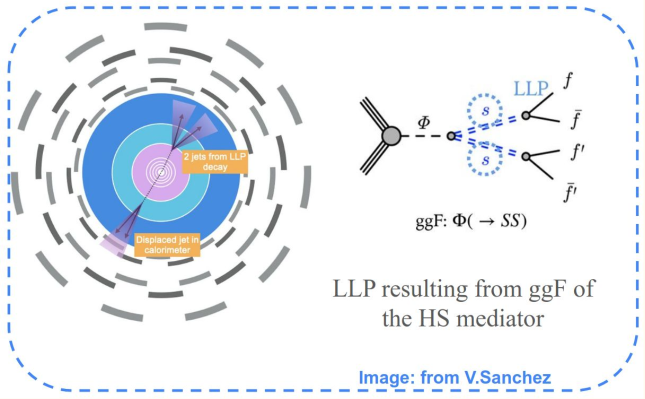
Seed Idea

Event selection probability (should) depend only on decay properties:

- Position (Lxy, Lz, η)
- Flavor (gg, ff)
- Momentum pT
- Mass of the LLP*

not the internal details of the model !

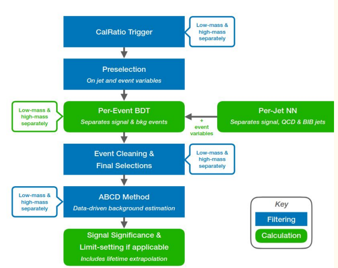




*previously, we said that we were including the transverse energy, by in fact we were using the transverse mass !

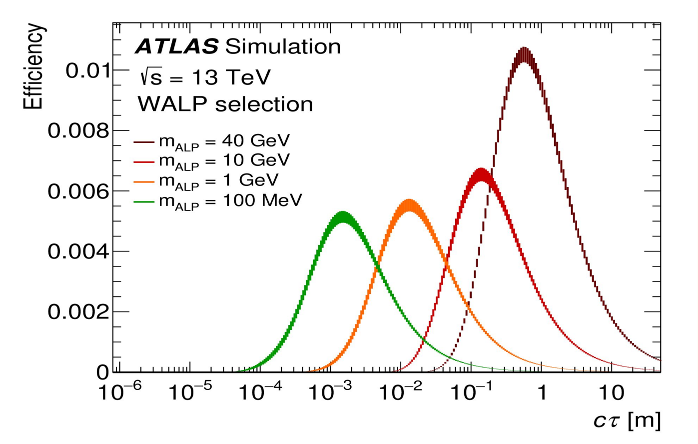
How to re-interpret ?

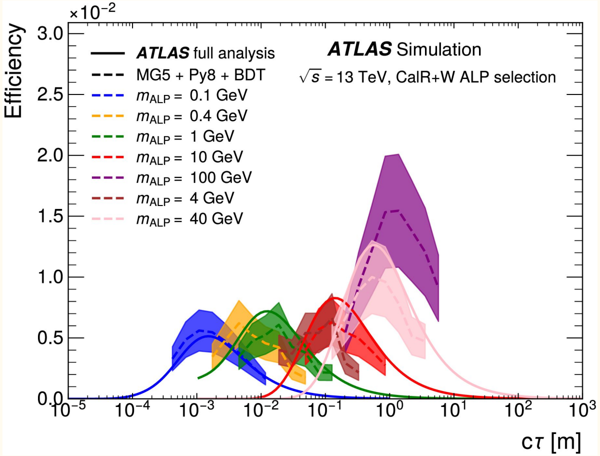
- The main idea is to build a Boosted Decision Tree (BDT) trained on truth-level kinematic information (about the LLPs and associated prompt objects) and event-level efficiencies:



→ What theorist call a "Surrogate Model" ! (SuMos)

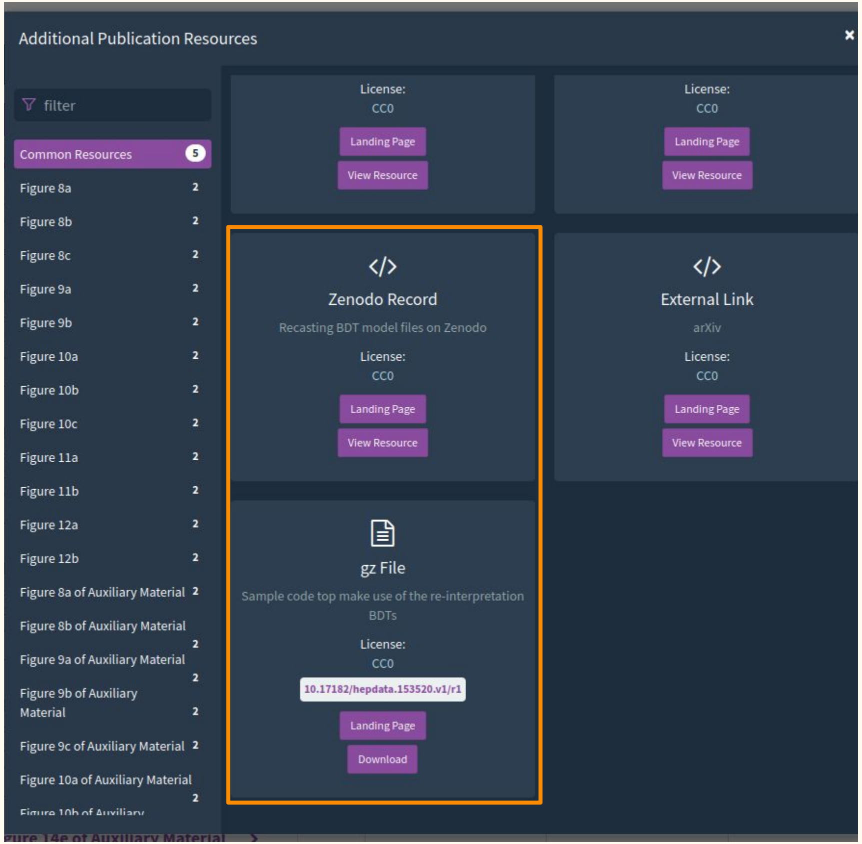
- The BDT can estimate the likelihood that events from a new model would have been captured by the prior analysis—classifying them as selected in each region of the ABCD plane or remaining unselected.

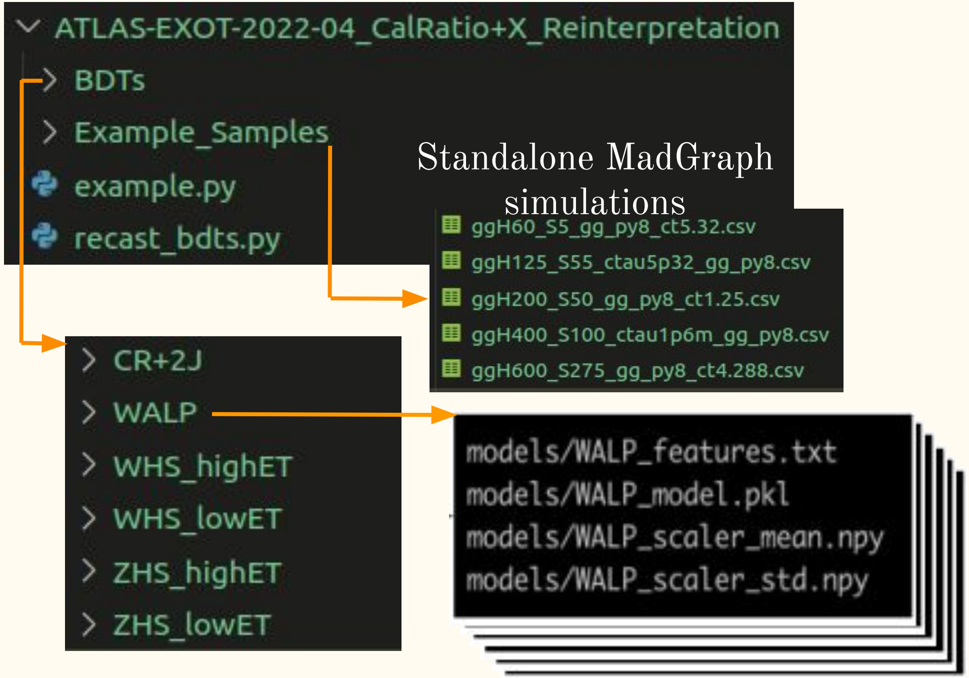




What is available ?

HEPData/ins2807458





+ ONNX files with pipelines for data pre-scaling and BDT evaluation in Zenodo/14610411

After an exchange with theorists at IRN Terascale @ IP2I Lyon

Method Validation

L.Corpe, A.Haddad, M.Goodsell, "*Recasting the ATLAS search for displaced hadronic jets in the ATLAS calorimeter with additional jets or leptons using surrogate models*", ArXiv:2502.10231

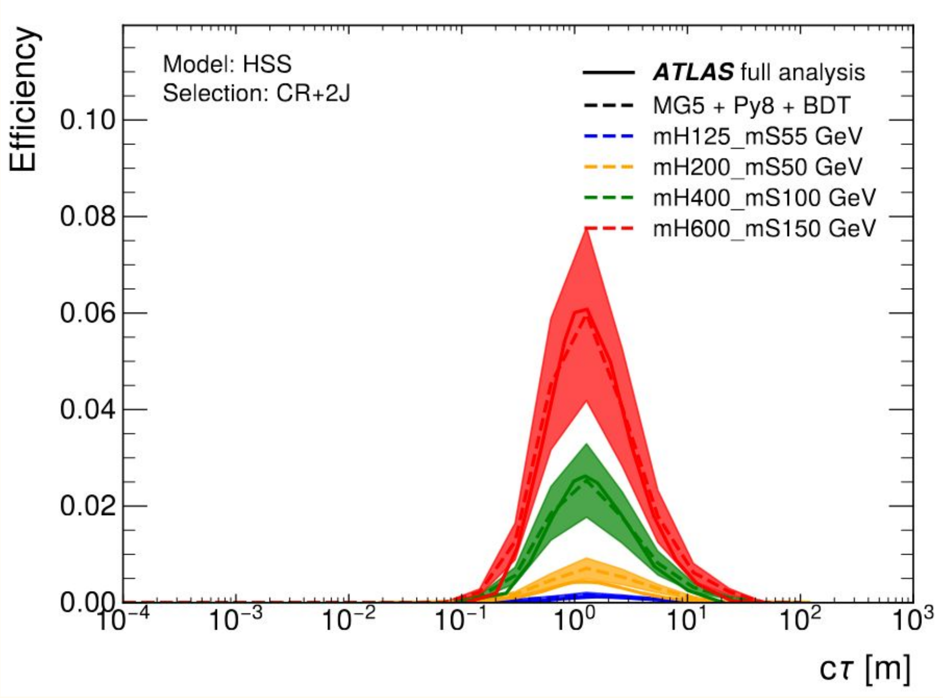
Method Validation using provided files

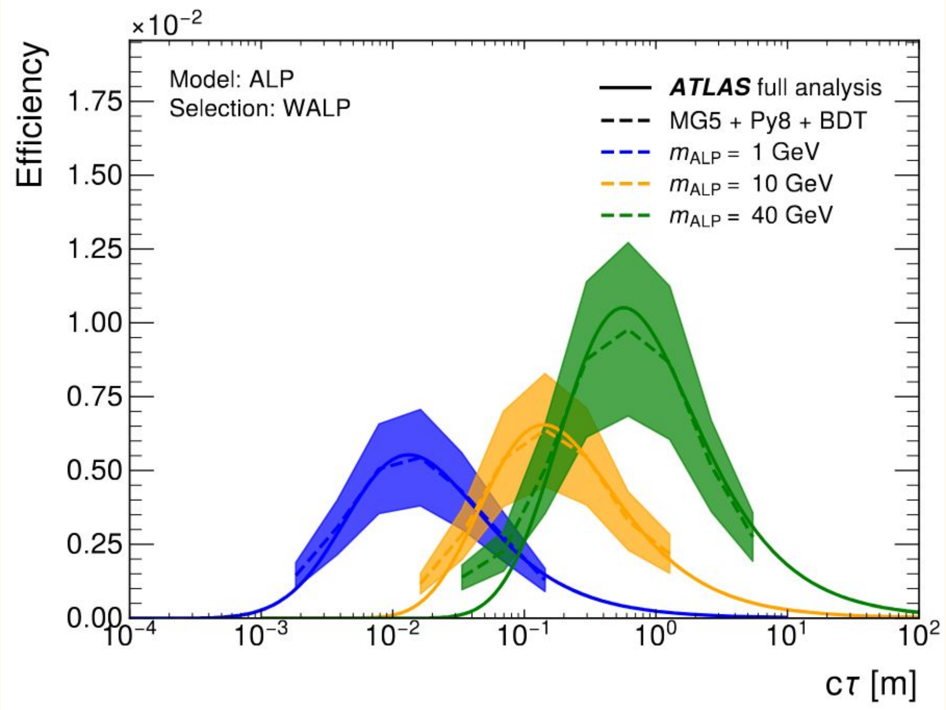
```
===
Sample ./Example_Samples/ggH125_S55_ctau5p32_gg_py8.csv has efficiency in the Region A of CR+2J selection of 0.09 %
===
Sample ./Example_Samples/ggH600_S275_gg_py8_ct4.288.csv has efficiency in the Region A of CR+2J selection of 2.46 %
===
```

	CalR+2J selection	Main dataset	BIB dataset	HS $m_\Phi = 125$ GeV $m_S = 55$ GeV	HS $m_\Phi = 600$ GeV $m_S = 275$ GeV
Preselection	CalRatio triggers			1.4%	11%
	≥ 3 clean jets			0.60%	7.7%
	$\sum \Delta R_{\text{min}} > 0.5$	5,738,136	446,794	0.59%	7.6%
Event cleaning	Trigger matching	2,068,592	154,986	0.53%	6.5%
	-3 ns $< t <$ 15 ns	2,609,223	99,398	0.51%	5.8%
	$\log_{10}(E_{\text{H}}/E_{\text{EM}}) > -1.5$	2,289,758	89,380	0.46%	5.1%
	$\lvert\eta\rvert \notin (1.45, 1.55)$	2,068,592	80,555	0.41%	4.5%
	$\text{NN}_{\text{CalR+2J}} \geq 3$	30,097	408	0.35%	4.4%
Region A	$\sum \Delta R_{\text{min}} \geq 0.71$, $\text{NN}_{\text{CalR+2J}} \geq 7.61$	92	2	0.10%	2.8%
Region B	$\sum \Delta R_{\text{min}} < 0.71$, $\text{NN}_{\text{CalR+2J}} \geq 7.61$	18	1	0.00%	0.01%
Region C	$\sum \Delta R_{\text{min}} \geq 0.71$, $\text{NN}_{\text{CalR+2J}} < 7.61$	25213	328	0.24%	1.6%
Region D	$\sum \Delta R_{\text{min}} < 0.71$, $\text{NN}_{\text{CalR+2J}} < 7.61$	4774	77	0.01%	0.04%

Method Validation using independent Framework

GitHub/RecastingCodes/CalRatio+X





And many more in ArXiv:2502.10231

Where does the 25% closure uncertainty come from?

	Efficiency in A	Efficiency in B	Efficiency in C	Efficiency in D
testing input file selection_mALP0p1GeV_W_selLLP_w.root				
Real	0.49%	0.15%	0.22%	0.06%
BDT	0.46%	0.13%	0.19%	0.06%
Relative diff	*-6.1%*	*-13.3%*	*-13.6%*	*0.0%*
testing input file selection_mALP10GeV_W_highctau_selLLP_w.root				
Real	0.39%	0.12%	0.15%	0.05%
BDT	0.38%	0.11%	0.14%	0.05%
Relative diff	*-2.6%*	*-8.3%*	*-6.7%*	*0.0%*
testing input file selection_mALP10GeV_W_selLLP_w.root				
Real	0.56%	0.18%	0.18%	0.06%
BDT	0.53%	0.16%	0.18%	0.06%
Relative diff	*-5.4%*	*-11.1%*	*0.0%*	*0.0%*
testing input file selection_mALP1GeV_W_selLLP_w.root				
Real	0.48%	0.15%	0.23%	0.07%
BDT	0.46%	0.15%	0.19%	0.06%
Relative diff	*-4.2%*	*0.0%*	*-17.4%*	*-14.3%*
testing input file selection_mALP40GeV_W_selLLP_w.root				
Real	1.09%	0.32%	0.17%	0.06%
BDT	1.01%	0.29%	0.17%	0.06%
Relative diff	*-7.3%*	*-9.4%*	*0.0%*	*0.0%*

The Importance of output-format !

SuMos Successfully included in HackAnlysis
(with minimal fuss or difficulties)

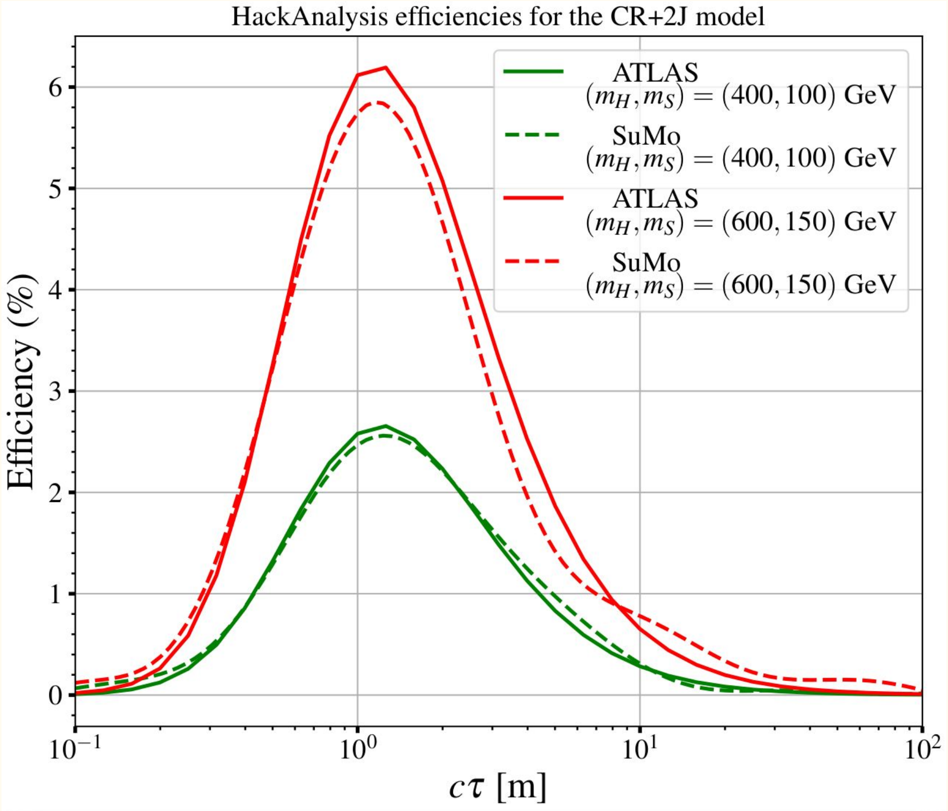
Version 2.3 released!

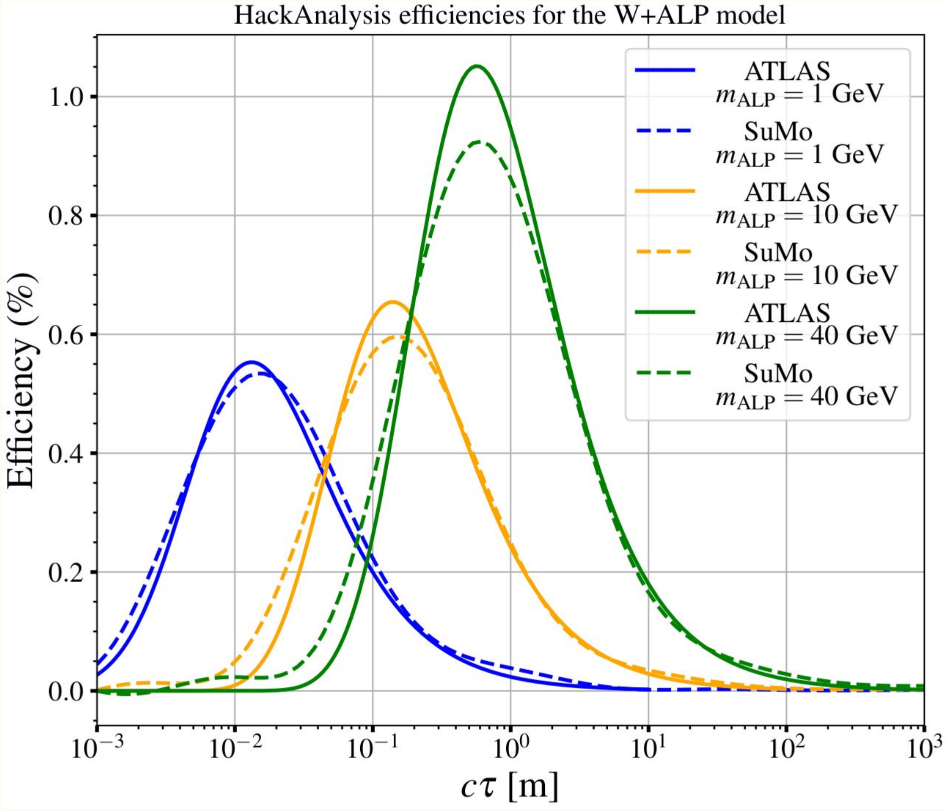
Posted on February 17, 2025 |

Version 2.3 has been released, to go along with the paper arXiv:2502.10231 with Louie Corpe and Abdelhamid Haddad!

This includes several new ingredients, such as a *no jets* detector mode, updates to the ONNX interface, updates to the statistics routines, etc. There is also a new script `download_data.py` to download the required ONNX models from the zenodo repository, and some example BSMArt templates.

Method Validation using HackAnalysis Framework





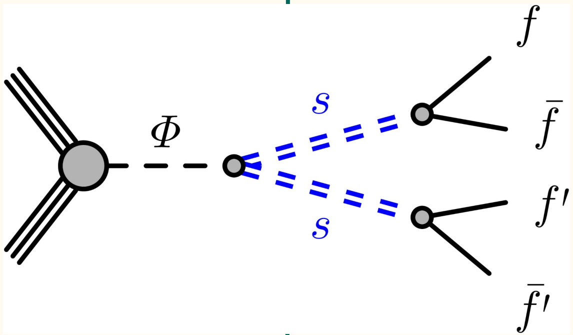
Similarly, an implementation in MadAnalysis should be straightforward !

Method Application

T.Chehab , L.Corpe, A.Goudelis, A.Haddad, L.Millot, "*Constraints on asymmetric production of long-lived scalars at the Large Hadron Collider*", **ArXiv:2502.18021**

HAHM Recap.

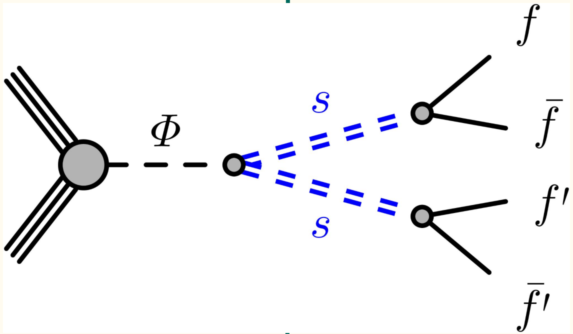
Generic HAHM scalar sector:



- $h \sim \Phi$ and S a LLP
- Events are generated for chosen $m_{\Phi,S}$ pairs
- Macroscopic lifetime imposed post-hoc

An Asymmetric HAHM

Generic HAHM scalar sector:



What if S1 ≠ S2 ?

- $h \sim \Phi$ and S a LLP
- Events are generated for chosen $m_{\Phi,S}$ pairs
- Macroscopic lifetime imposed post-hoc

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_{\rm QCD} - \frac{m_\Phi^2}{2}\Phi^2 - \frac{m_{S_1}^2}{2}S_1^2 - \frac{m_{S_2}^2}{2}S_2^2 + \frac{1}{\Lambda}\Phi G_{\mu\nu}G^{\mu\nu} + \kappa v \Phi S_1 S_2 + \sum_f \left(y_1 \frac{\sqrt{2}m_f}{v} S_1 f\bar{f} + y_2 \frac{\sqrt{2}m_f}{v} S_2 f\bar{f} \right)$$

- $m_{\Phi,S1,S2}$ generated triplet
- Easily parameterized in terms of physically measurable quantities!

WARNING!

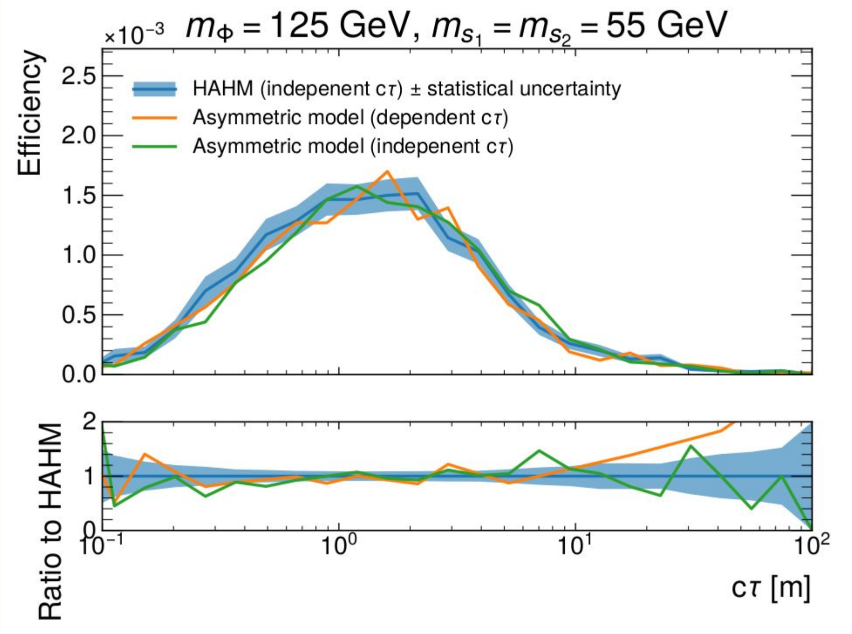
In both cases, those “tricks” introduce some phenomenological inconsistencies

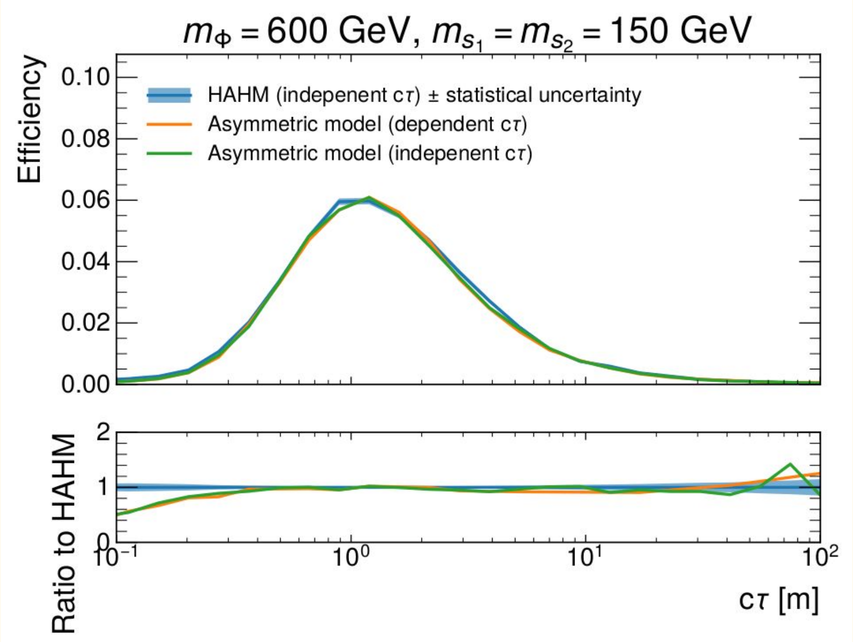
But rather to be a practical model to explore asymmetric signature while still being as “phenomenologically consistent” as possible

More details in ArXiv:2502.18021

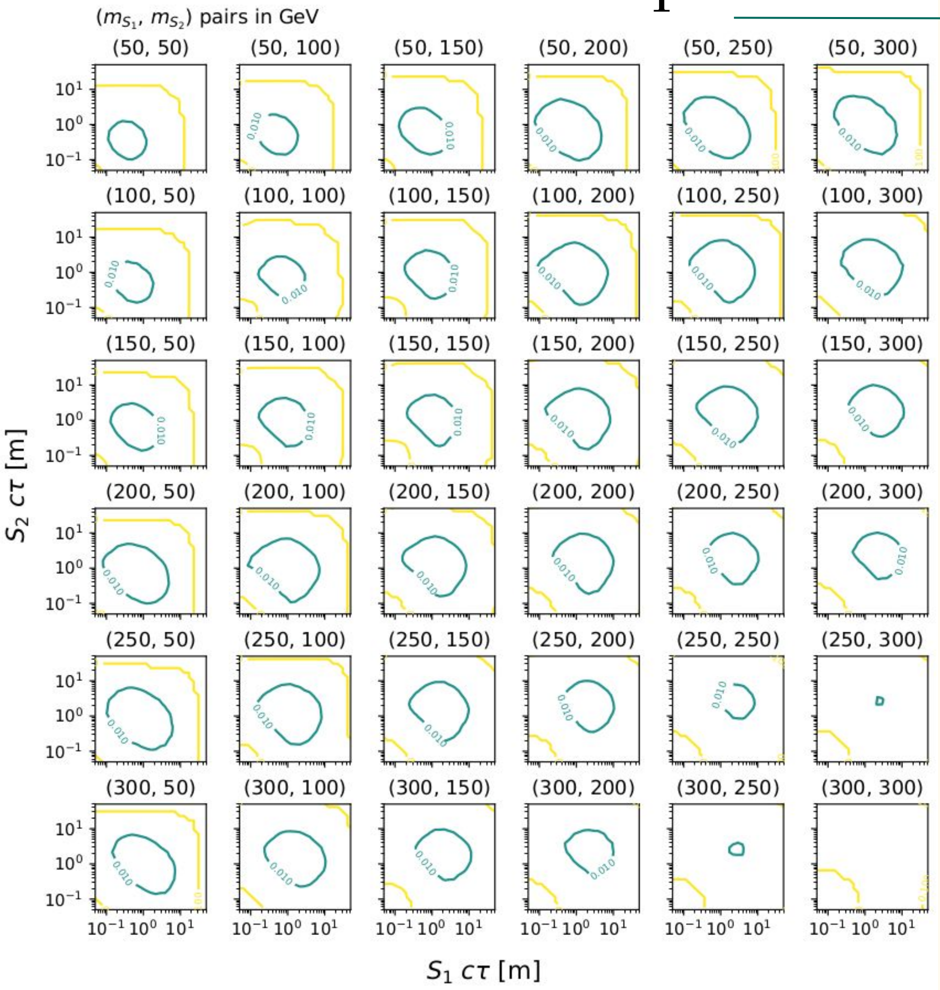
Asymmetric Model Validation

Agreement of HAHM with asymmetric model
+ treating cτ as independent parameter





CalRatio Re-interpretation of the Asymmetric HAHM



The observed 95%CL exclusion on $\sigma \times$BF as a function of the two LLP decay lengths:

- The cyan contour delimits regions excluded at 0.01 pb,
- The yellow at 0.05 pb.

We can use the SuMos to probe asymmetric production for the first time, impossible with previous recasting material for this type of search.

Conclusion

Conclusion

- **Reinterpretation material** based on BDTs (in both pickle and ONNX formats) has been developed for the CalRatio + X ATLAS analysis, tested and validated standalone, and subsequently integrated within the **HackAnalysis** Framework.

→ The method checks all the boxes for obeying the **FAIR principle**.

- This method seems well suited to LLP searches but **could also be extended to any BSM search** which uses ML as part of their selection and which could not be re-interpreted before.

- Furthermore, we evaluated the method using a variant of the HAHM model featuring two distinct LLPs (with different masses and/or lifetimes), and the **results are highly encouraging** for the future of this approach.

Backup

What is available ?

HEPData/ins2807458

```
ATLAS-EXOT-2022-04_CalRatio+X_Reinterpretation
  > BDTs
  > Example_Samples
    example.py
    recast_bdts.py
```

```
ggH60_S5_gg_py8_ct5.32.csv
ggH125_S55_ctau5p32_gg_py8.csv
ggH200_S50_gg_py8_ct1.25.csv
ggH400_S100_ctau1p6m_gg_py8.csv
ggH600_S275_gg_py8_ct4.288.csv
```

Standalone MadGraph simulations

1

```
wget -O files-archive.zip https://zenodo.org/api/records/12957031/files-archive
unzip files-archive.zip -d files-archive

mv files-archive/* "$main_folder/BDTs"

rm files-archive.zip
rm -rf files-archive

rm "$main_folder/BDTs/reinterpretationMaterials.tar.gz"

for tarfile in "$main_folder/BDTs"/*.tar.gz; do
        foldername="${tarfile%.tar.gz}"  # Remove the .tar.gz extension
        mkdir "$foldername"

        echo -e "\e[36mExtracting \"$tarfile\" to \"$foldername\"...\e[0m"
        tar -xzvf "$tarfile" -C "$foldername"

        rm "$tarfile"
done
```

2

```
main_folder="ATLAS-EXOT-2022-04_CalRatio+X_Reinterpretation"
mkdir -p "$main_folder"

mkdir -p "$main_folder/BDTs"
mkdir -p "$main_folder/Example_Samples"

curl -OJLH "Accept: application/x-tar"
https://doi.org/10.17182/hepdata.153520.v1/r1

tar -xzvf reinterpretationMaterials.tar.gz

mv reinterpretationMaterials/*.csv "$main_folder/Example_Samples"

mv reinterpretationMaterials/*.py "$main_folder"

rm -f reinterpretationMaterials.tar.gz
rm -rf reinterpretationMaterials
```

```
> CR+2J
> WALP
> WHS_highET
> WHS_lowET
> ZHS_highET
> ZHS_lowET
```

```
models/WALP_features.txt
models/WALP_model.pkl
models/WALP_scaler_mean.npy
models/WALP_scaler_std.npy
```

"How to make your data FAIR"

F indable

A ccessible

I interoperable

R e-usable