Accelerating the search for mass bumps using the Data-Directed Paradigm

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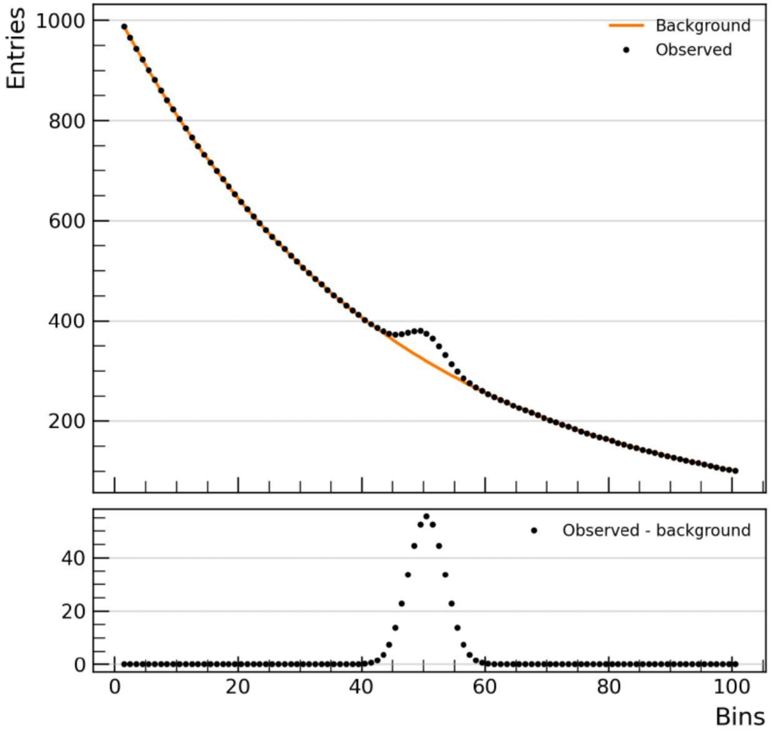
Motivation

★ So far, none of the efforts to find new physics at LHC have succeeded
★ Traditional approach: confirm/exclude theory predictions in **small observable space**
★ Change of approach: scan **all data** for anomalies to motivate specific searches

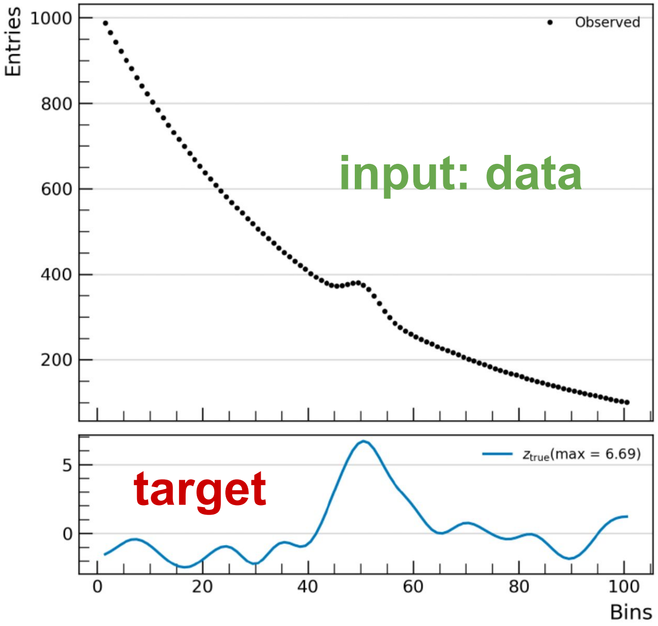
Data-Directed Paradigm

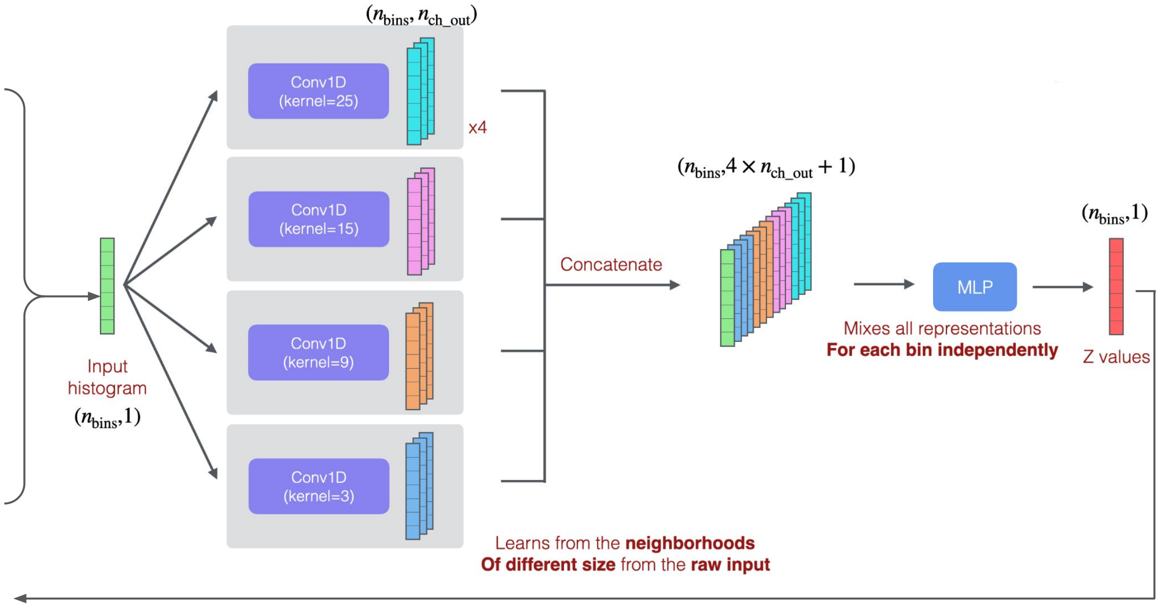
- ★ Smoothly falling mass distributions
- ★ New physics could cluster in data as **bumps** in mass histograms
- ★ Training of a network to find bumps
    - ○ Predicts the **z value**: statistical significance of an excess at each mass value



Predicting the statistical significance using a neural network

ZNet3: supervised learning: both z_{true} and signal width are given in training





Training data

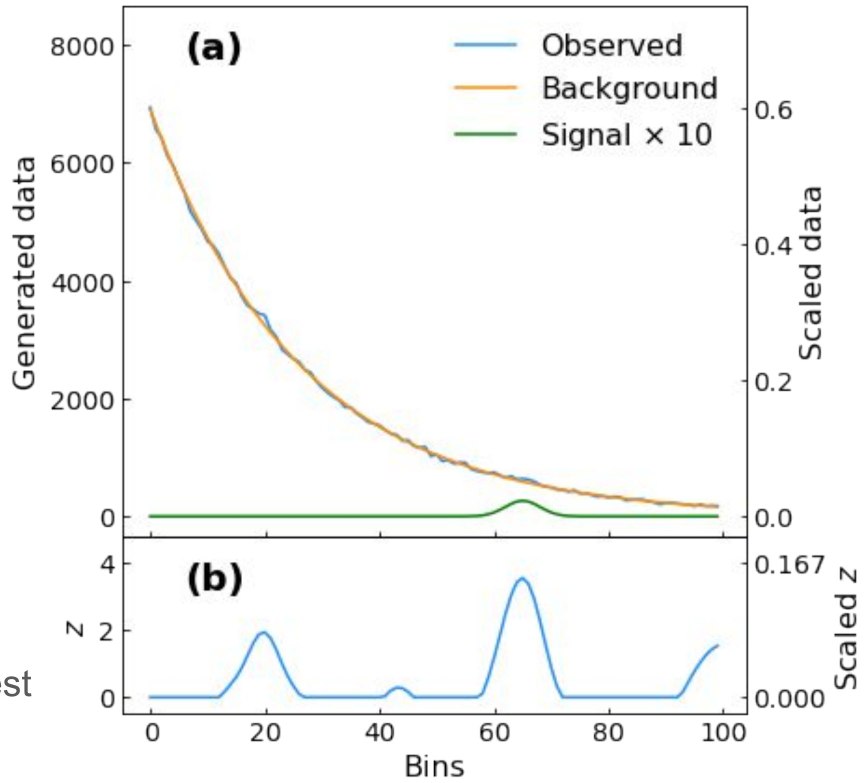
Background distributions:

★ analytical functions and/or simulations

$$be^{-ax}, \quad ax+b, \quad \frac{1}{ax}+b, \quad \frac{1}{ax^2}+b, \quad \frac{1}{ax^3}+b,$$
$$\frac{1}{ax^4}+b, \quad a\left(x-x_2\right)^2+y_2, \quad -a\cdot\ln\left(x\right)+b,$$
$$\left(y_1-y_2\right)\cos\left(a\left(x-b\right)\right)+y_2, \quad \cosh\left(a\left(x-x_2\right)\right)+b$$

Adding the signal:

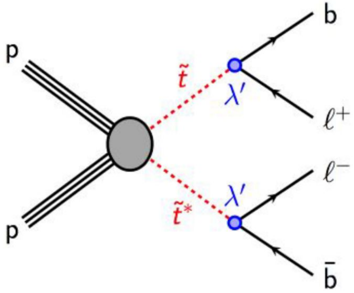
★ select **background**
★ add **gaussian signal**
★ add random fluctuations
★ calculate **true significance** with likelihood-ratio test

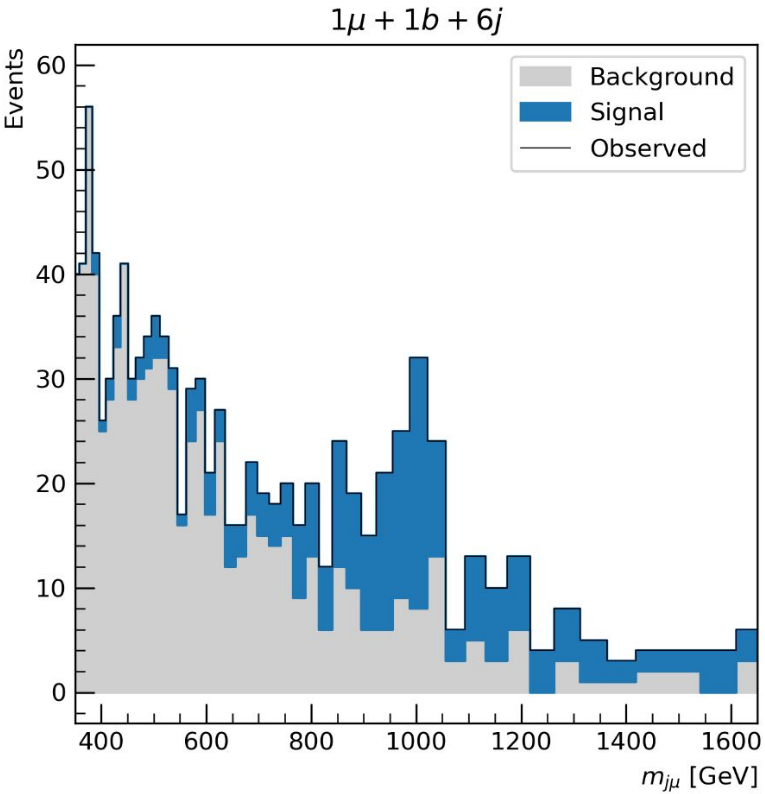


Dark Machines samples

- ★ Simulations including the **highest cross section processes at LHC**
  - ○ Designed for anomaly studies
  - ○ Produced using Madgraph, Pythia, and DELPHES fast detector simulations
- ★ Various simulated **new-physics signals** added to the background

e.g.: RPV stop -> bl

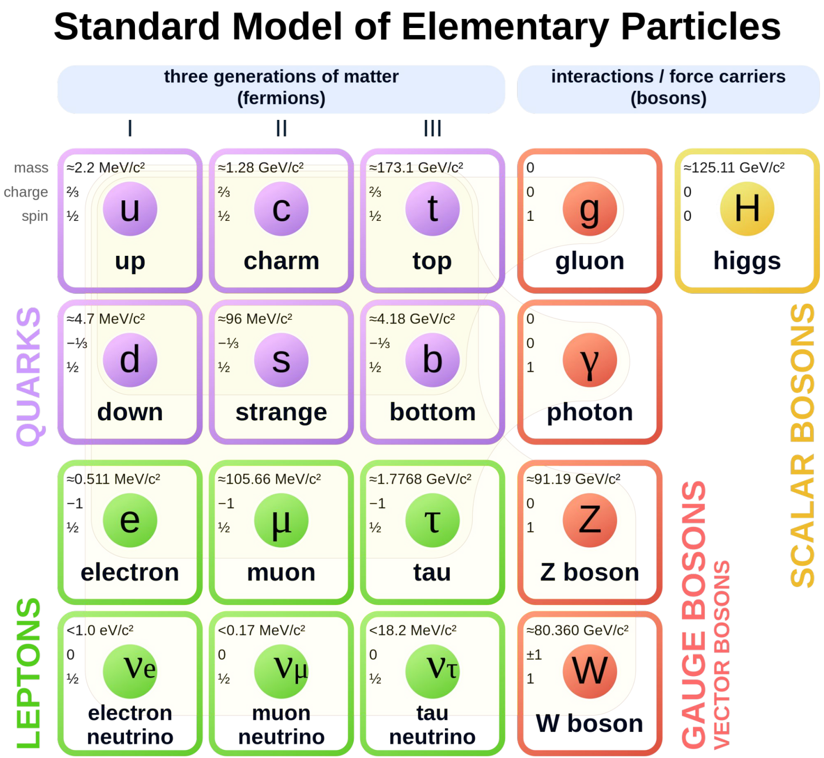


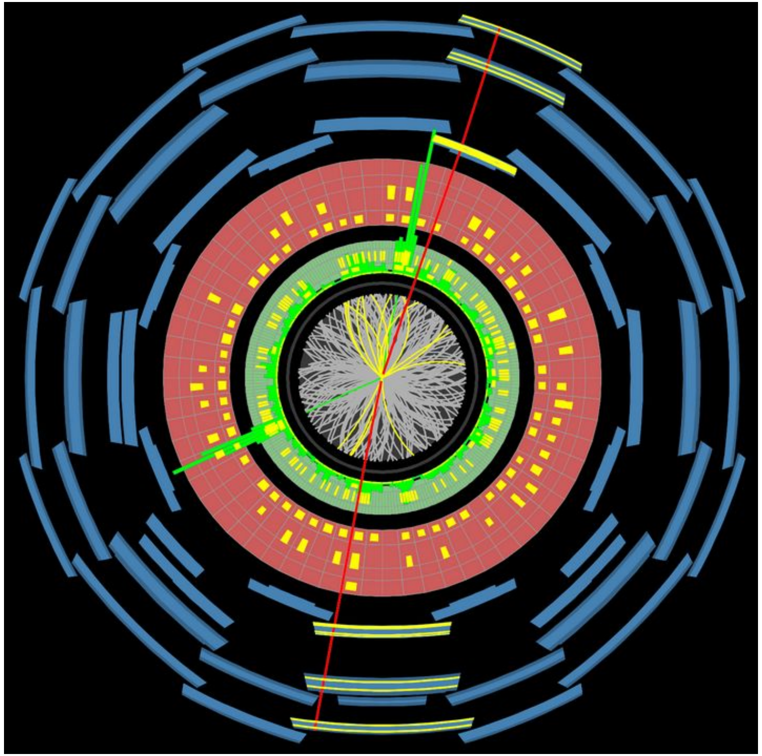


T. Aarrestad et al., SciPost Phys. 12, 043 (2022), arXiv:2105.14027 [hep-ph]

Signatures

Each event consists of a combination of reconstructed physics objects

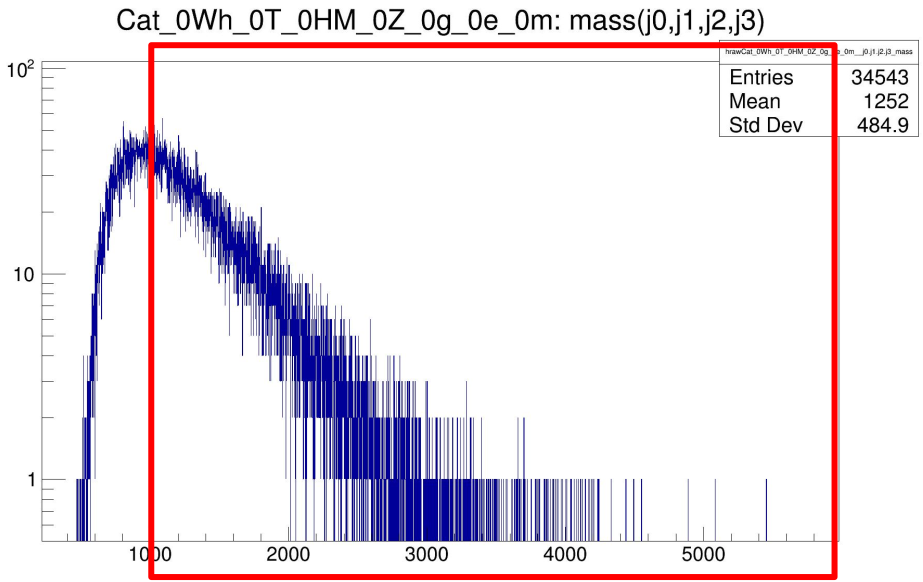




Higgs -> eeμμ

Histogram production

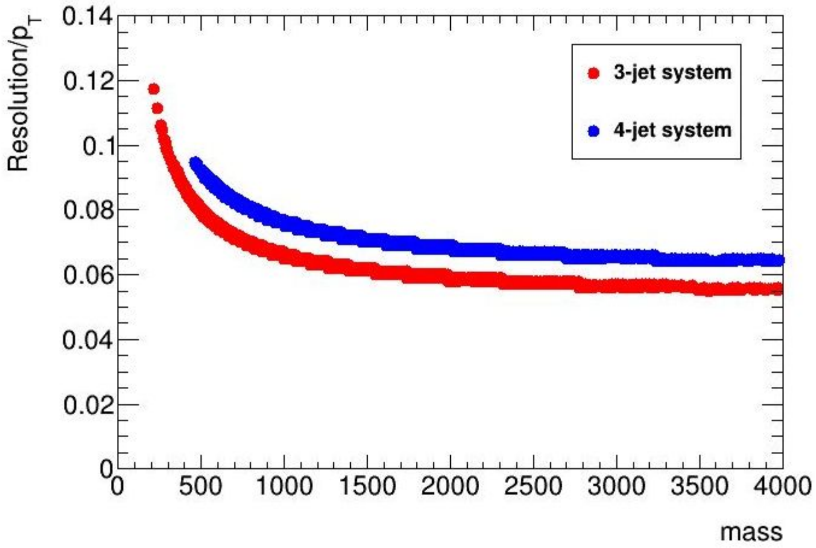
★ Consider all possible signatures:
  ○ e.g.: 1e + 1μ + 3j
★ Compute masses of all possible combinations of objects
  ○ e.g.: mass(e), mass(μ, j0), mass(e, μ,j1),...,mass(e,μ, j0, j1, j2)
★ Zoom in so the histogram starts at the maximum -> smoothly falling

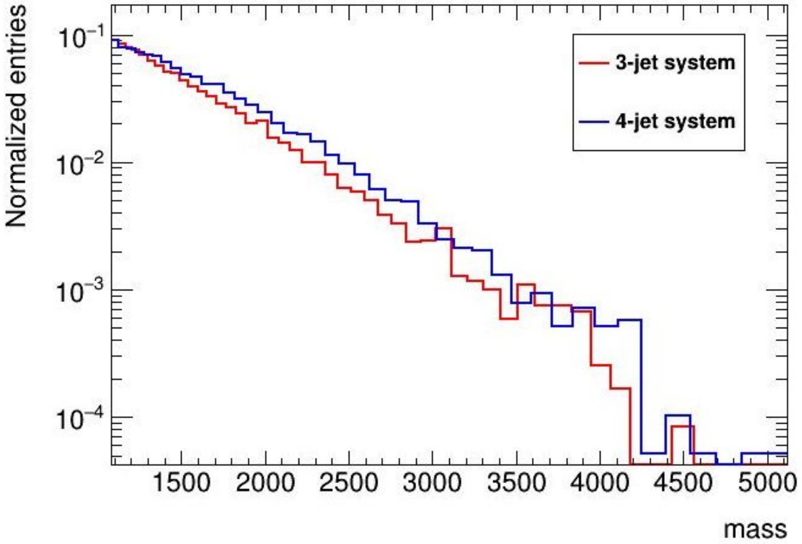


-> **Huge amount of data**: 63 000 signatures with many histograms each

Binning and detector resolution

- ★ Signal is expected to be narrow -> we train the network to find it in few bins
- ★ Adjust binning to ATLAS detector resolution
  - ○ Resolution depends on the objects involved, their $p_{T,}$ and η



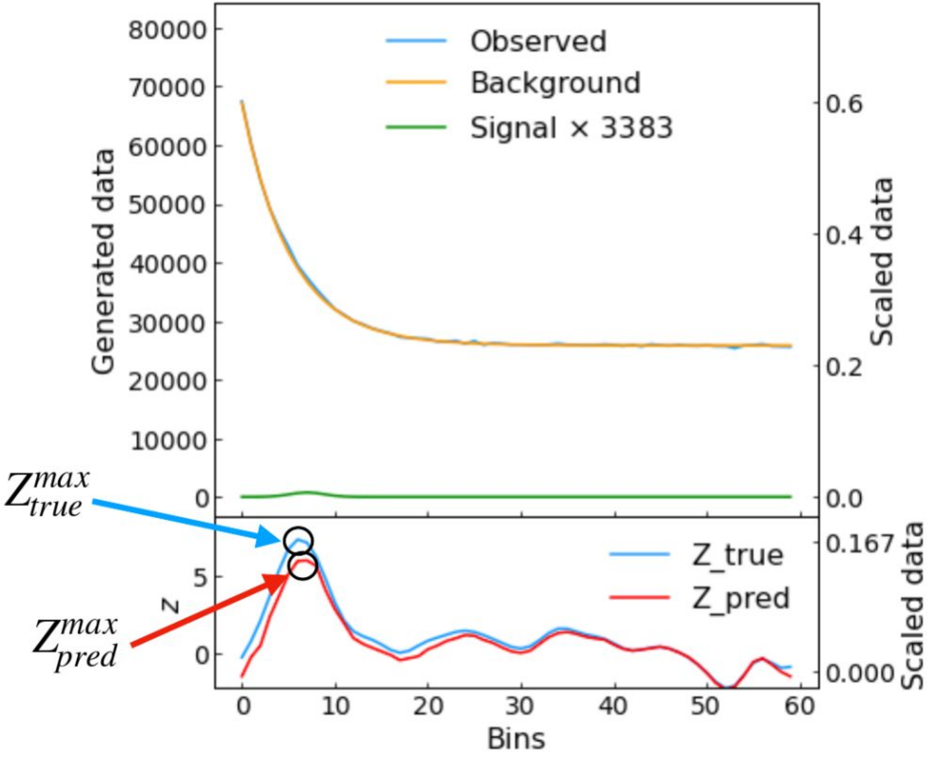


Performance

Performance evaluated in terms of:

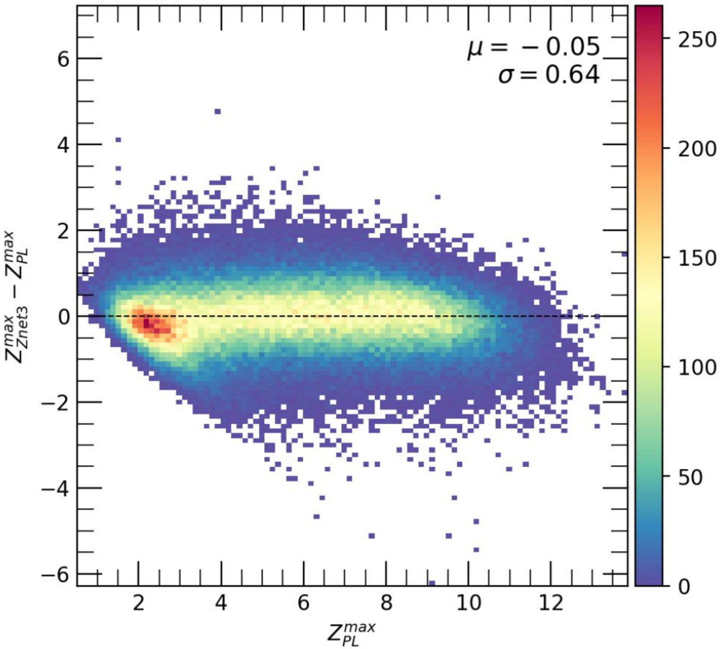
★ Difference between the true and predicted maximum significance: $z_{max,true} - z_{max,pred}$

★ False-positive rate

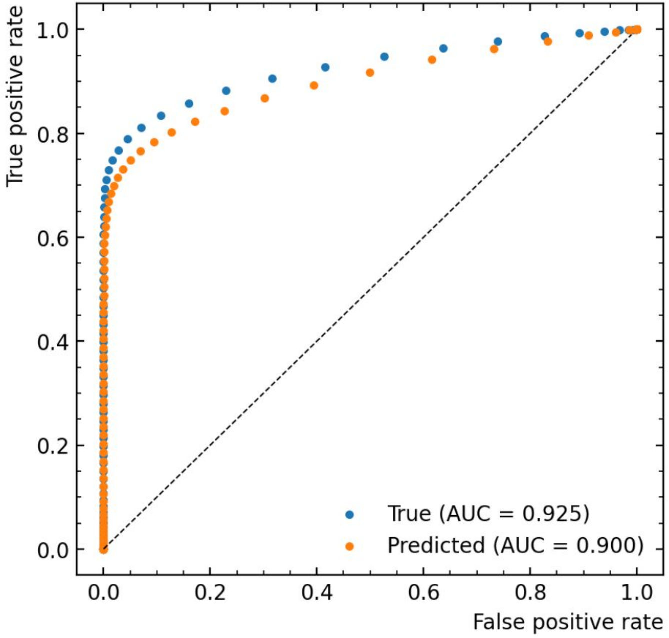


Performance

Prediction of z_{max} is **unbiased** with a variance of 0.64:

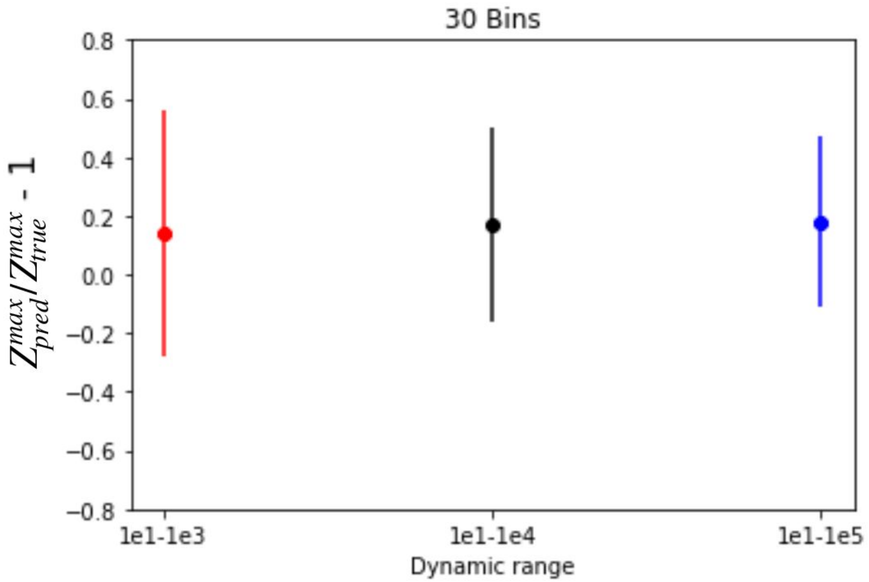


ROC curve: bump detection based on z_{pred} almost as good as based on z_{true}

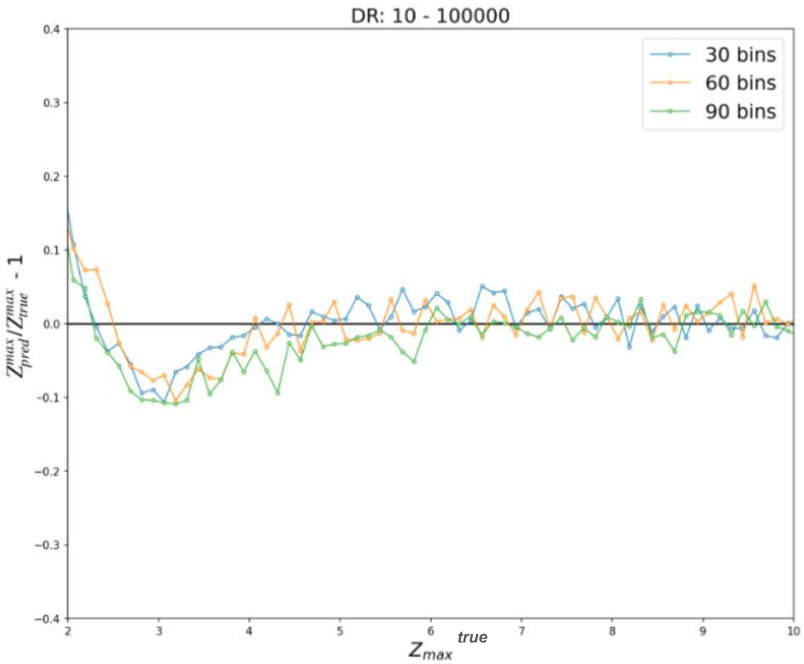


Performance stability

Dynamic range: number of entries per bin



Number of bins per histogramm

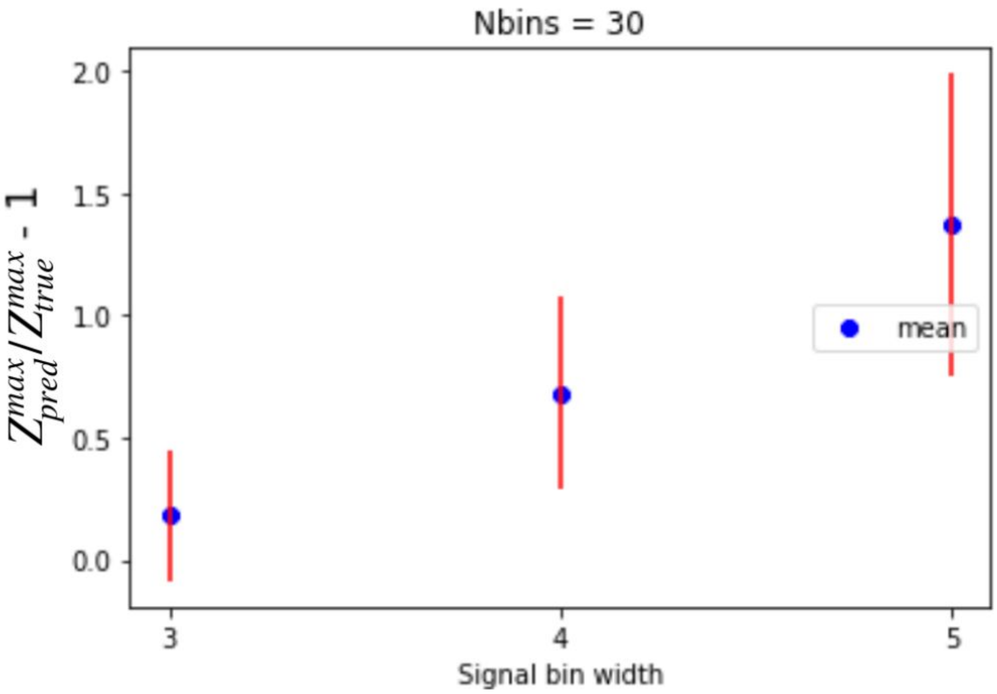


Performance stability

- ★ Training on fixed signal width: 1
- ★ Bias increases with signal width

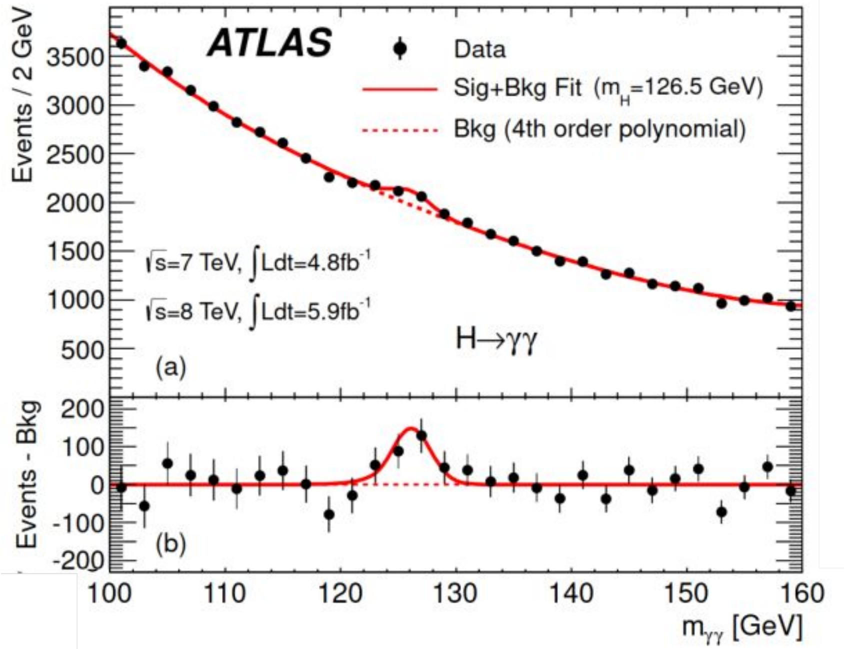
-> important to **adapt binning to experimental resolution**

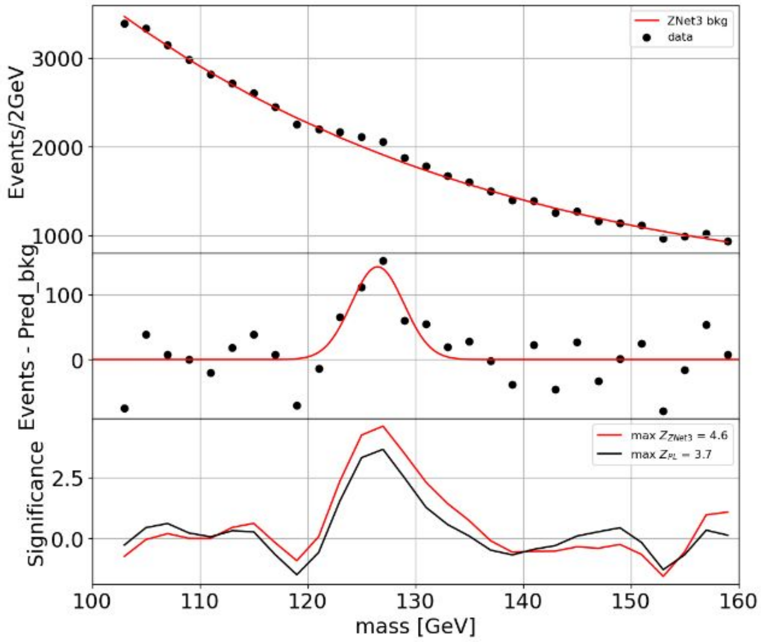
Mean & sigma as a function of signal width



Finding the Higgs bump

DDP was able to find the Higgs bump using the ATLAS plot:



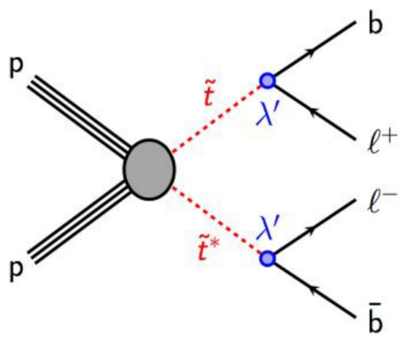


Bump was predicted at **correct mass** with $\mathbf{z_{pred}}$ **= 4.6**
(consistent with z_{true} of 3.7 within method precision)

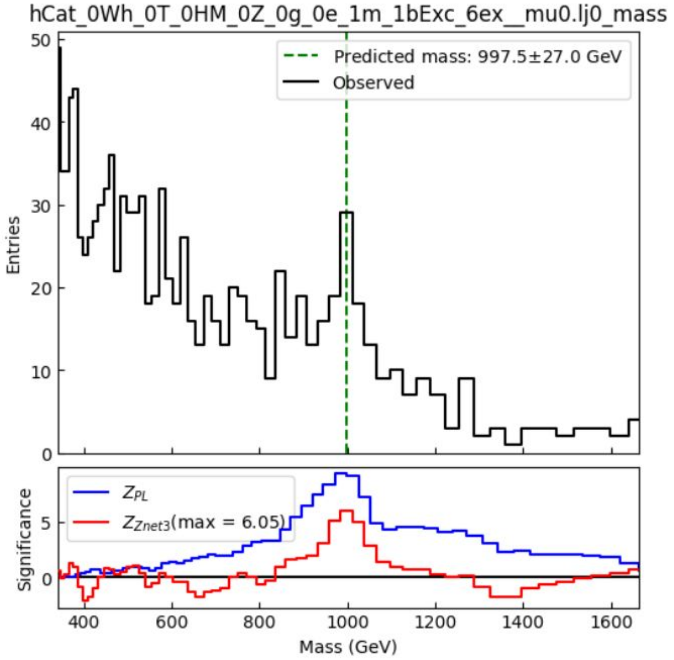
Finding new-physics signals

DDP was successful at finding the injected new-physics signals at correct mass:

RPV stop → bl

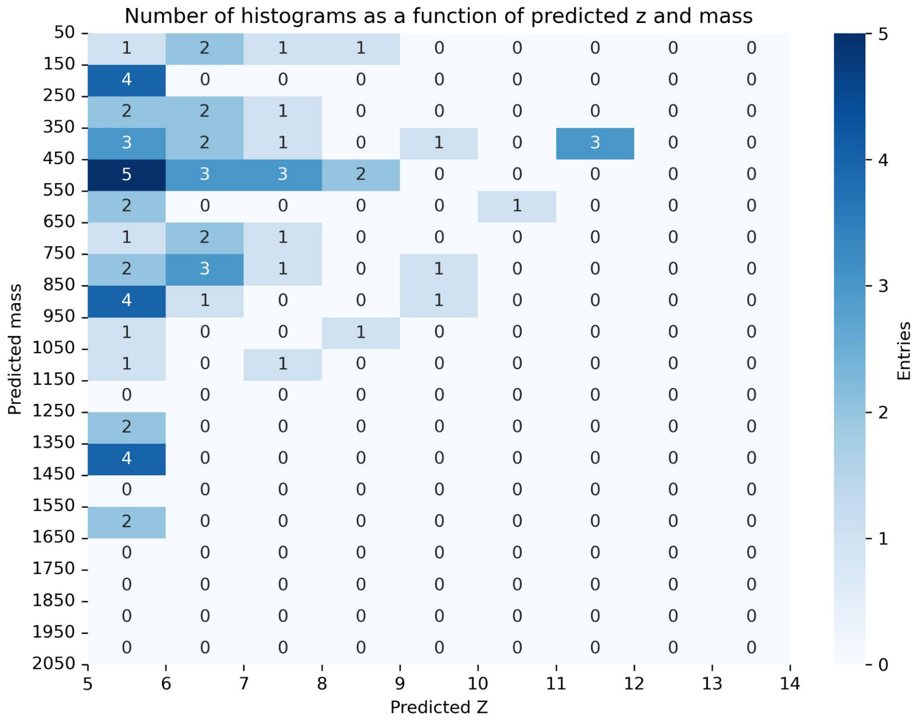


$m(j\mu)$ at 1μ+$1b$+$6j$



Finding new-physics signals

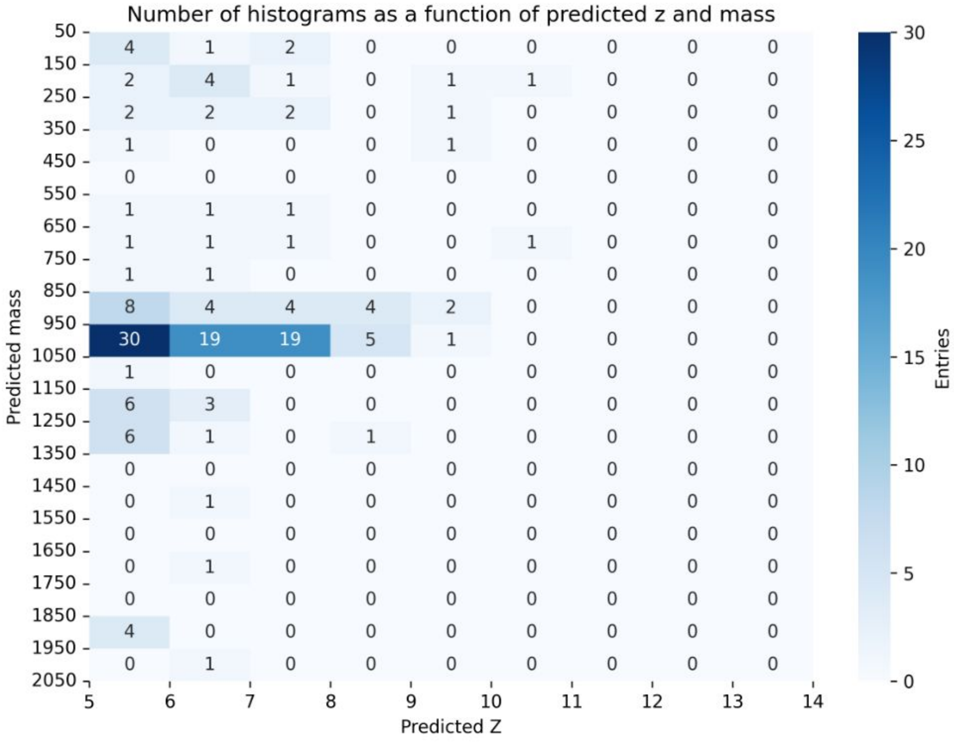
★ Testing over background-only samples results in **false-positive rate of 0.1%**



Background-only histograms with $Z_{max,pred} \geq 5$

Finding new-physics signals

- ★ Signal is usually detected in more than one histogram
- ★ Physics correlations help distinguish between anomaly and false-positives

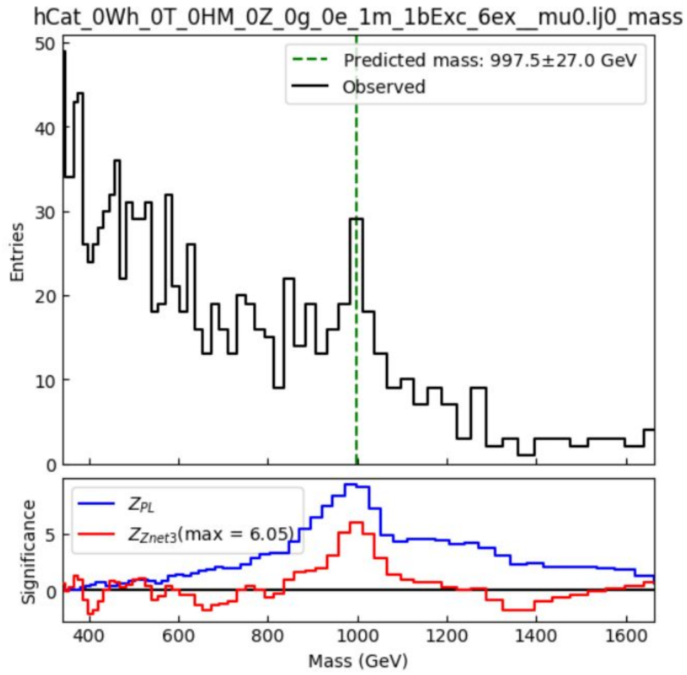


Histograms that find RPV stop -> bl with $Z_{max,pred} \geq 5$

Conclusion

★ DDP is successful at finding bumps
  ○ in analytical **functions**: 1st proof of concept
  ○ in **simulations**: 2nd proof of concept in progress
★ Method scans huge parameter space efficiently
★ Could be used to find interesting signal regions
★ Outlook: apply DDP to ATLAS data

$m(j\mu)$ at 1μ+1b+6j



Backup

Splitting the dataset by jet multiplicity

- ★ We split each signature by jet multiplicity (=number of jets)
- ★ Compare the position of $z_{max,pred}$ in neighboring jet multiplicities to reduce look-elsewhere effect

$z_{max,pred}$ of same signature with different jet multiplicity for a background-only:

6j	3.2
5j	1.7
4j	2.4
3j	1.9
2j	4.5
1j	2.2

mass at $z_{max,pred}$

Splitting the dataset by jet multiplicity

★ Signal should appear at same mass in several histograms with neighboring jet multiplicity

$Z_{max,pred}$ of same signature with different jet multiplicity for a signal:

6j	2.3
5j	1.7
4j	3.4
3j	5.3
2j	3.9
1j	2.2

mass at $z_{max,pred}$

Dark Machines samples

SM processes			
Physics process	Process ID	σ (pb)	N_{tot} ($N_{10\,\text{fb}^{-1}}$)
$pp \to jj(+2j)$	njets	$19718_{H_T>600\text{GeV}}$	415331302 (197179140)
$pp \to l^{\pm}\nu_l(+2j)$	w_jets	$10537_{H_T>100\text{GeV}}$	135692164 (105366237)
$pp \to \gamma j(+2j)$	gam_jets	$7927_{H_T>100\text{GeV}}$	123709226 (79268824)
$pp \to l^+l^-(+2j)$	z_jets	$3753_{H_T>100\text{GeV}}$	60076409 (37529592)
$pp \to t\bar{t}(+2j)$	ttbar	541	13590811 (5412187)
$pp \to t + \text{jets}(+2j)$	single_top	130	7223883 (1297142)
$pp \to \bar{t} + \text{jets}(+2j)$	single_topbar	112	7179922 (1116396)
$pp \to W^+W^-(+2j)$	ww	82.1	17740278 (821354)
$pp \to W^{\pm}t(+2j)$	wtop	57.8	5252172 (577541)
$pp \to W^{\pm}\bar{t}(+2j)$	wtopbar	57.8	4723206 (577541)
$pp \to \gamma\gamma(+2j)$	2gam	47.1	17464818 (470656)
$pp \to W^{\pm}\gamma(+2j)$	Wgam	45.1	18633683 (450672)
$pp \to ZW^{\pm}(+2j)$	zw	31.6	13847321 (315781)
$pp \to Z\gamma(+2j)$	Zgam	29.9	15909980 (299439)
$pp \to ZZ(+2j)$	zz	9.91	7118820 (99092)
$pp \to h(+2j)$	single_higgs	1.94	2596158 (19383)
$pp \to t\bar{t}\gamma(+2j)$	ttbarGam	1.55	95217 (15471)
$pp \to t\bar{t}Z$	ttbarZ	0.59	300000 (5874)
$pp \to t\bar{t}h(+1j)$	ttbarHiggs	0.46	200476 (4568)
$pp \to \gamma t(+2j)$	atop	0.39	2776166 (3947)
$pp \to t\bar{t}W^{\pm}$	ttbarW	0.35	279365 (3495)
$pp \to \gamma\bar{t}(+2j)$	atopbar	0.27	4770857 (2707)
$pp \to Zt(+2j)$	ztop	0.26	3213475 (2554)
$pp \to Z\bar{t}(+2j)$	ztopbar	0.15	2741276 (1524)
$pp \to t\bar{t}t\bar{t}$	4top	0.0097	399999 (96)
$pp \to t\bar{t}W^+W^-$	ttbarWW	0.0085	150000 (85)