Neural simulation-based inference for LHC analysis

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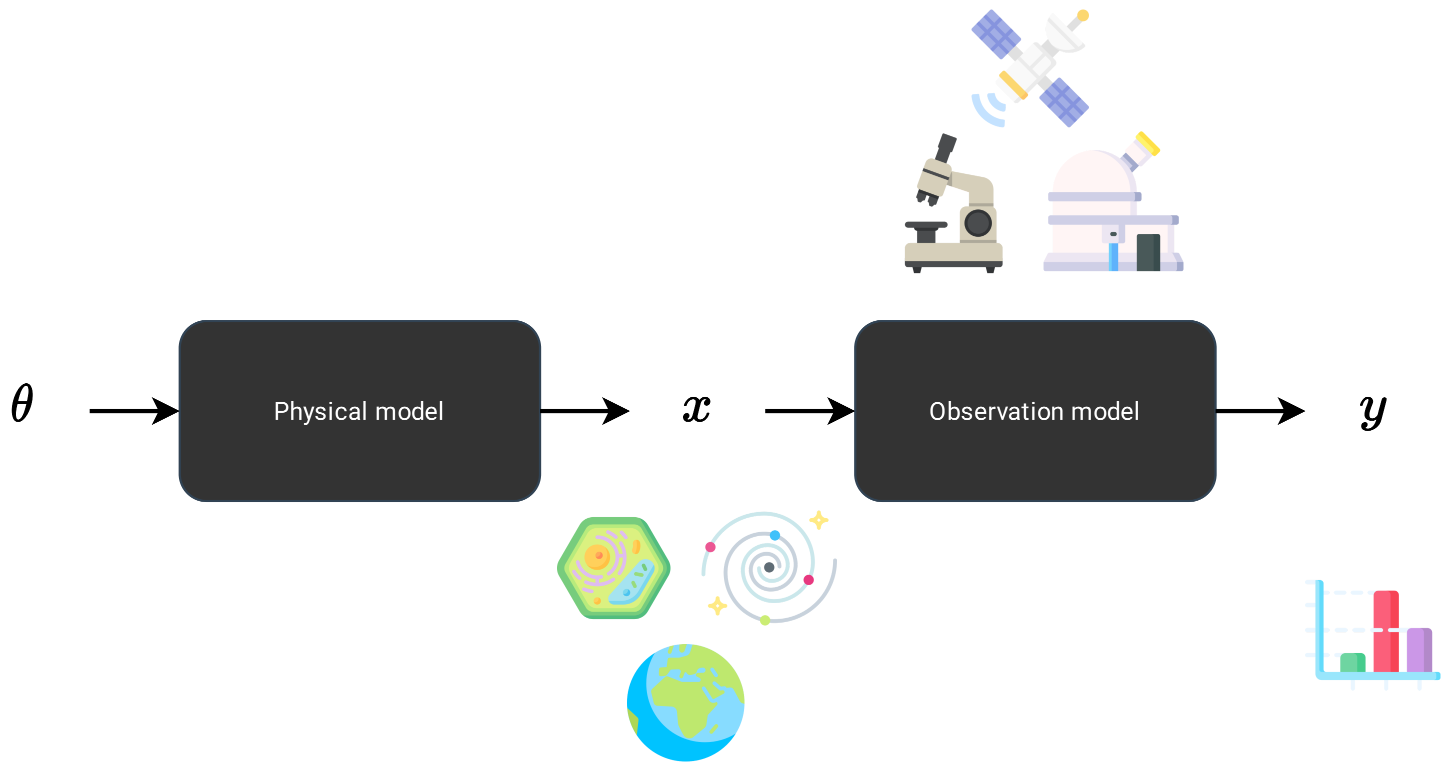
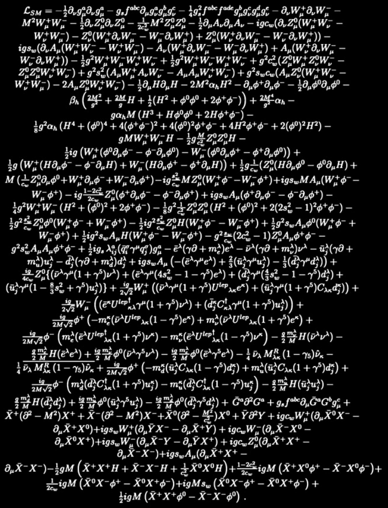
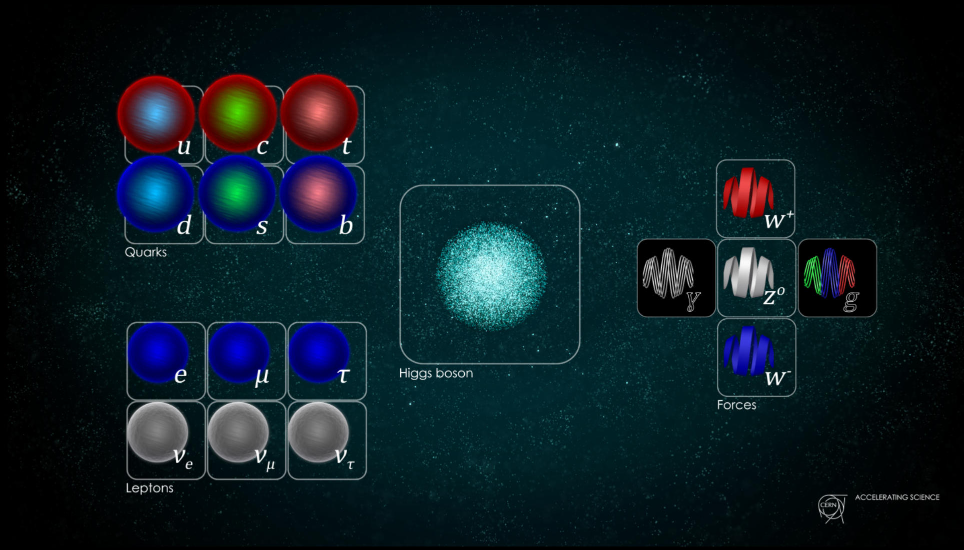
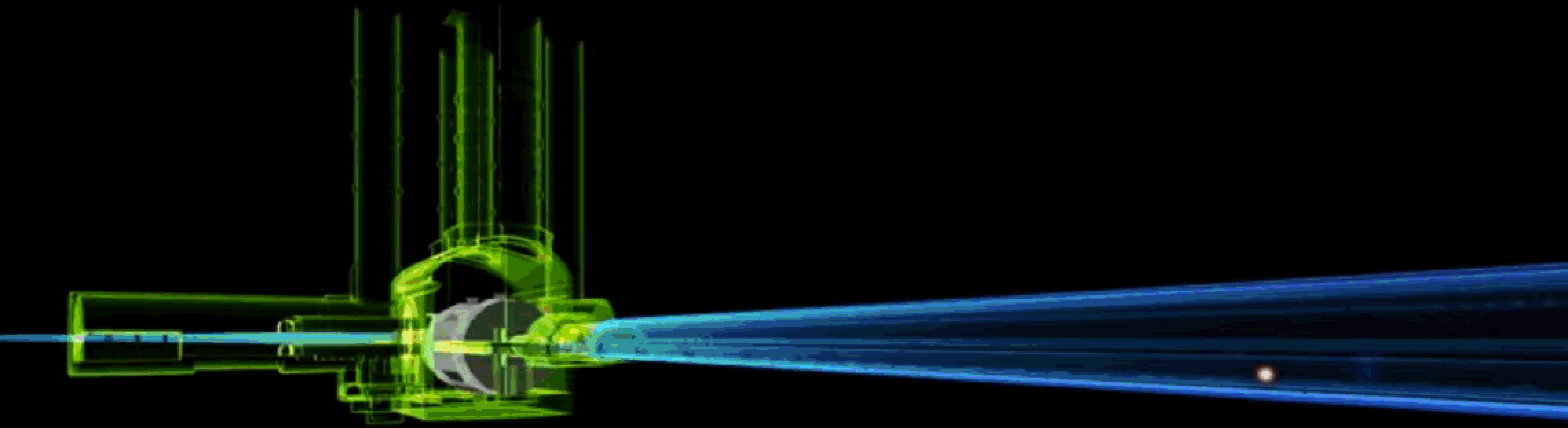

θ
Physical model
x
Observation model
y

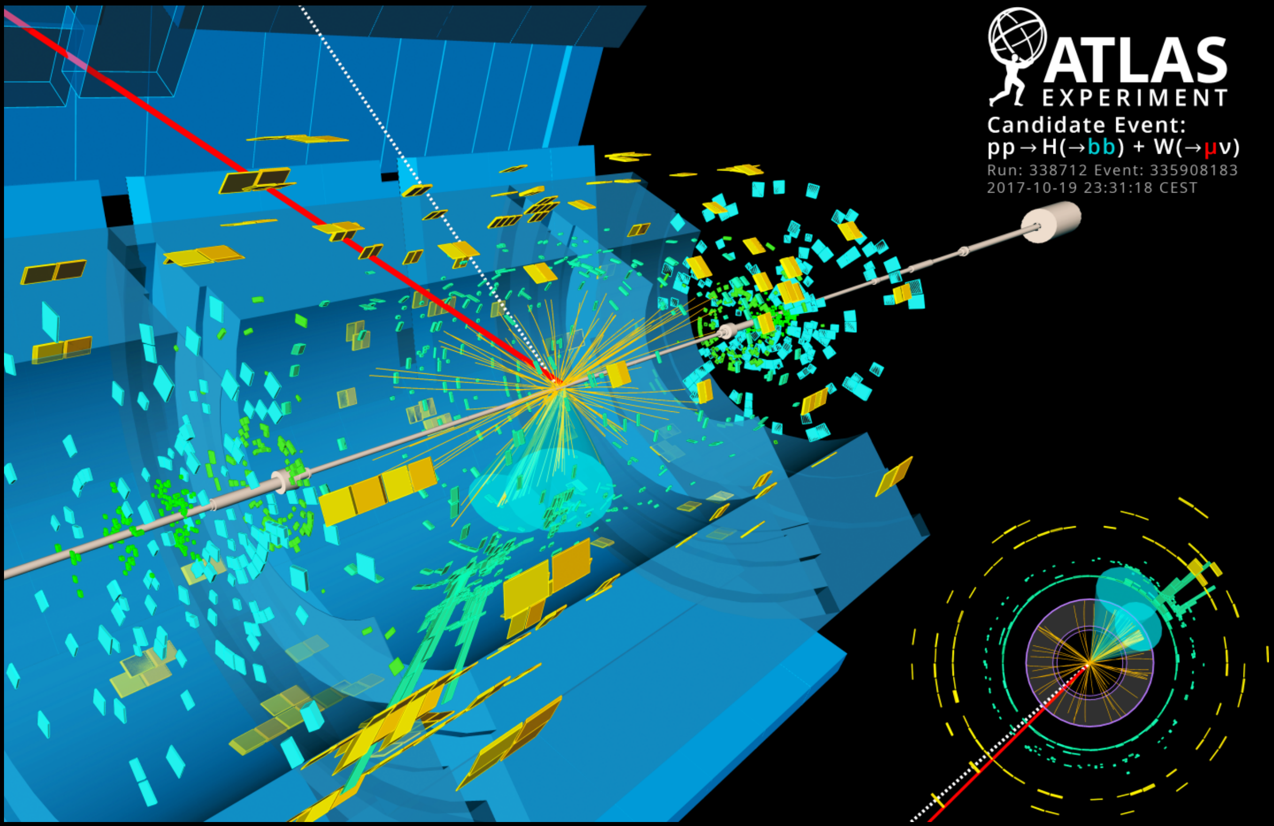




$$\theta = \{m_e, m_\mu, m_\tau, \dots\}$$



$$x, y \sim p(x|\theta)p(y|x)$$

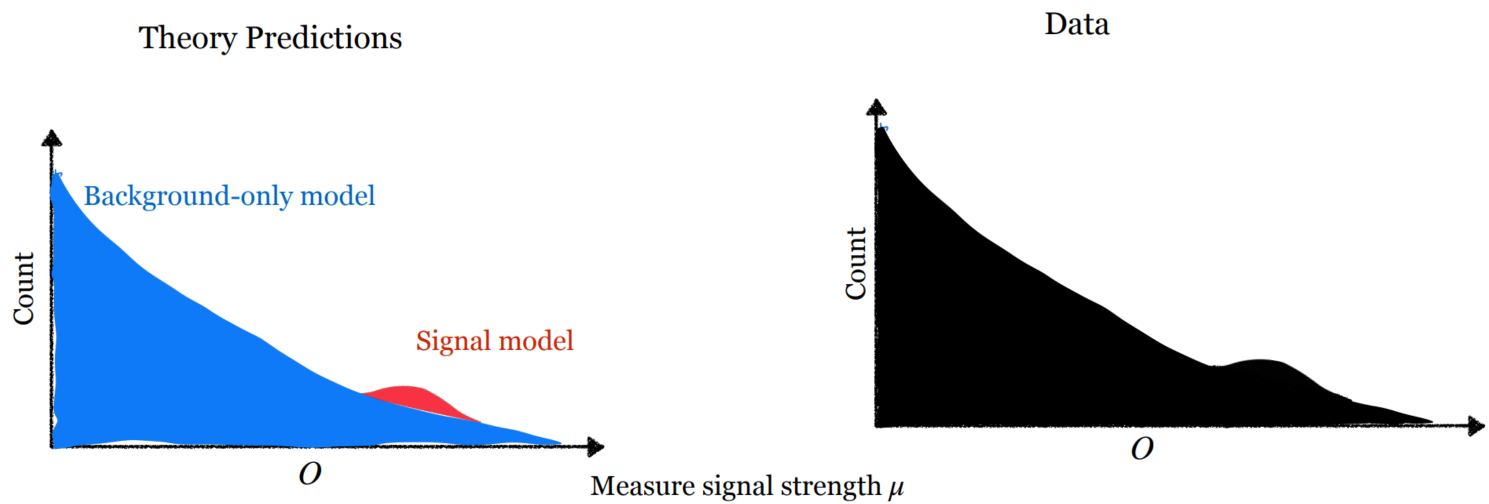

ATLAS
EXPERIMENT
Candidate Event:
pp→H(→bb) + W(→μν)
Run: 338712 Event: 335908183
2017-10-19 23:31:18 CEST

Bump hunting at the LHC

Assuming a background+signal model

$$p(x|\mu) = \frac{\mu\nu_{\mathrm{S}}p_{\mathrm{S}}(x) + \nu_{\mathrm{B}}p_{\mathrm{B}}(x)}{\mu\nu_{\mathrm{S}} + \nu_{\mathrm{B}}},$$

the discovery of a signal can be formulated as a statistical hypothesis test of the null hypothesis $\mu = 0$ against the alternative hypothesis $\mu > 0$.



Because of Neyman-Pearson's lemma, the likelihood ratio

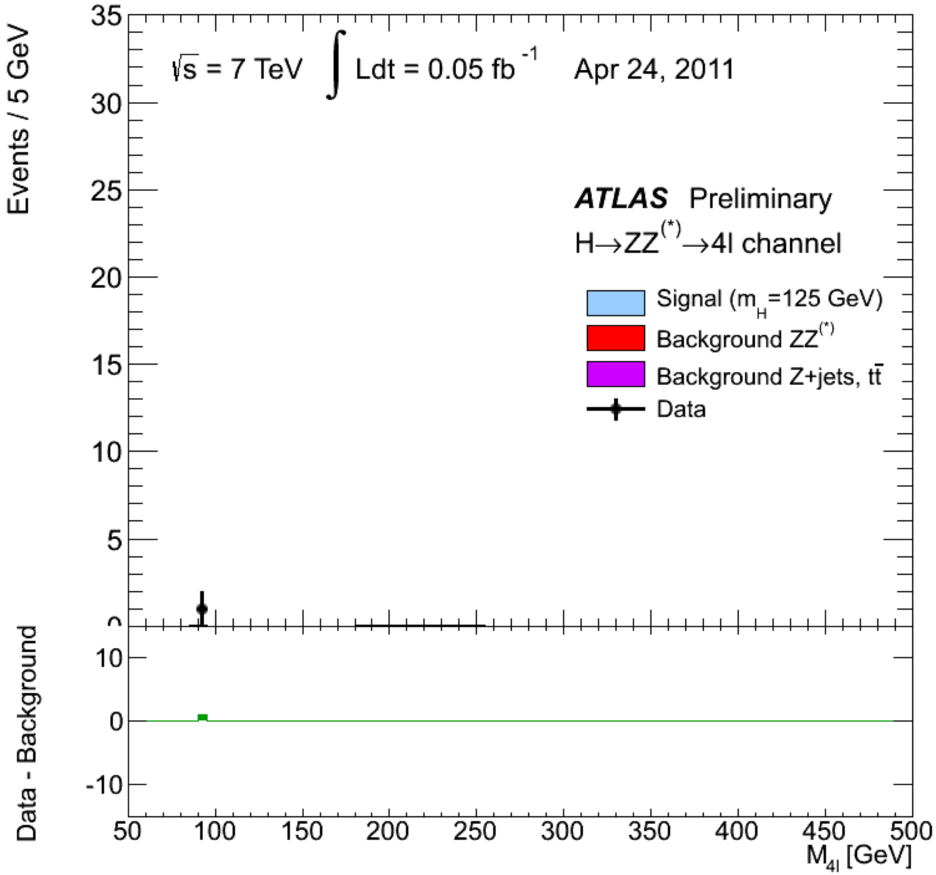
$$\frac{p(x|\mu)}{p(x|\mu=0)} = \frac{1}{\mu\nu_{\mathrm{S}} + \nu_{\mathrm{B}}} \left(\mu\nu_{\mathrm{S}} \frac{p_{\mathrm{S}}(x)}{p_{\mathrm{B}}(x)} + \nu_{\mathrm{B}} \right)$$

is the most powerful test statistic.

For a well-chosen summary statistic $s(x)$, the signal-to-background ratio can be approximated as

$$\frac{p_{\mathrm{S}}(x)}{p_{\mathrm{B}}(x)} \approx \frac{p_{\mathrm{S}}(s(x))}{p_{\mathrm{B}}(s(x))}$$

by filling histograms of $s(x)$ for signal and background events.

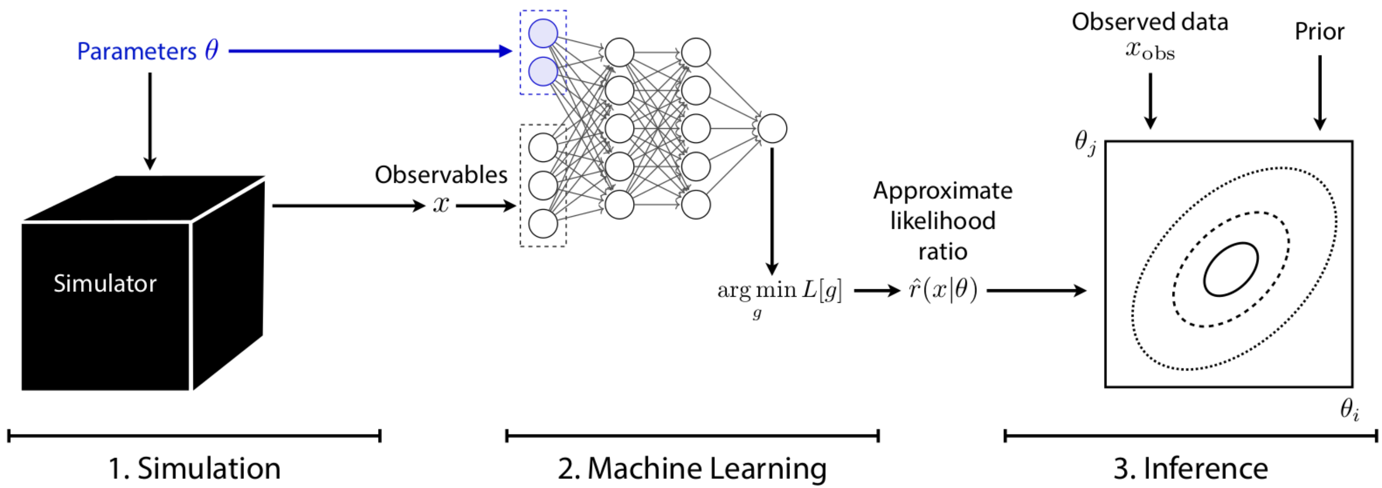

√s = 7 TeV ∫ Ldt = 0.05 fb⁻¹ Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
35
30
25
20
15
10
5
0
Data - Background
10
0
-10
50
100
150
200
250
300
350
400
450
500
M_4l [GeV]


ALFR. NOBEL
NAT. MDCCC XXXIII
OB. MDCCC XCVI

Wait a minute...

- How do we pick the right summary statistic s?
- Don't we lose in statistical power by binning the data?

Neural simulation-based inference



Run simulator and save data

Train NN classifier, interpret as likelihood ratio estimator

Amortized: cheap to repeat for new data

Learn the statistic $s(\cdot)$ with a neural network approximating the per-event likelihood ratio $r(x|\mu) = \frac{p(x|\mu)}{p(x|\mu=0)}$ itself!

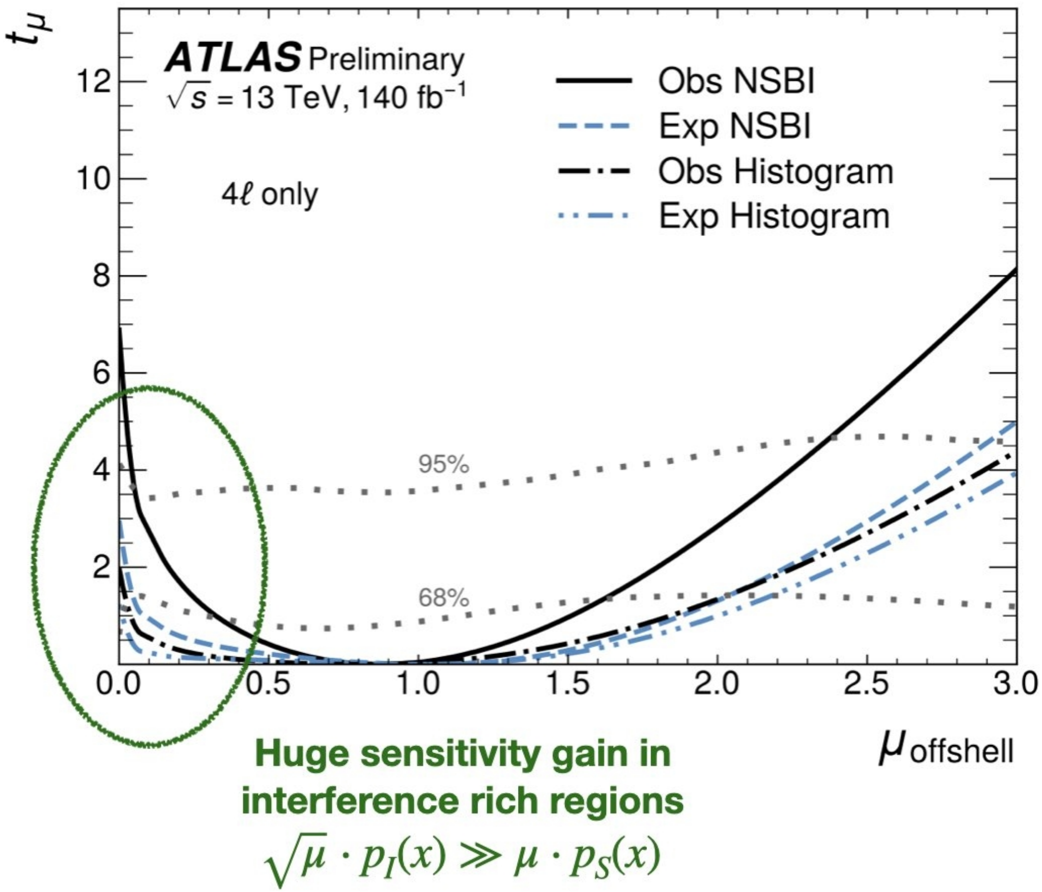
—

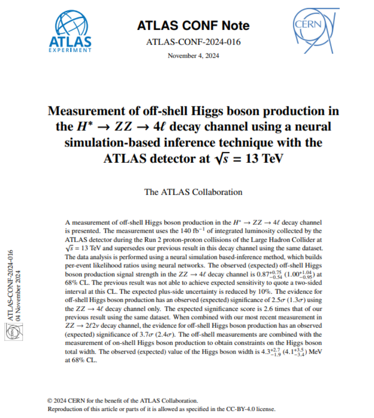
Credits: Cranmer et al, 2015; Brehmer et al, 2018.

From a prototype to a full ATLAS analysis

Measurement of the off-shell Higgs boson production in the $H^* \to ZZ \to 4\ell$ decay channel, while

- accounting for quantum interference effects,
- accounting for systematic uncertainties,
- extending the Neyman construction for unbinned analysis,
- validating, validating, validating to convince the collaboration.





ATLAS CONF Note
ATLAS-CONF-2024-016
November 4, 2024

Measurement of off-shell Higgs boson production in the $H^* \to ZZ \to 4\ell$ decay channel using a neural simulation-based inference technique with the ATLAS detector at $\sqrt{s}$ = 13 TeV

The ATLAS Collaboration

A measurement of off-shell Higgs boson production in the $H^* \to ZZ \to 4\ell$ decay channel is presented. The measurement uses the 140 fb^{-1} of integrated luminosity collected by the ATLAS detector during the Run 2 proton-proton collisions of the Large Hadron Collider at $\sqrt{s}$ = 13 TeV and supersedes our previous result in this decay channel using the same dataset. The data analysis is performed using a neural simulation based-inference method, which builds per-event likelihood ratios using neural networks. The observed (expected) off-shell Higgs boson production signal strength in the $ZZ \to 4\ell$ decay channel is $0.87^{+0.75}_{-0.54}$ ($1.00^{+1.04}_{-0.95}$) at 68% CL. The previous result was not able to achieve expected sensitivity to quote a two-sided interval at this CL. The expected plus-side uncertainty is reduced by 10%. The evidence for off-shell Higgs boson production has an observed (expected) significance of 2.5σ (1.3σ) using the $ZZ \to 4\ell$ decay channel only. The expected significance score is 2.6 times that of our previous result using the same dataset. When combined with our most recent measurement in $ZZ \to 2\ell 2\nu$ decay channel, the evidence for off-shell Higgs boson production has an observed (expected) significance of 3.7σ (2.4σ). The off-shell measurements are combined with the measurement of on-shell Higgs boson production to obtain constraints on the Higgs boson total width. The observed (expected) value of the Higgs boson width is $4.3^{+2.7}_{-1.9}$ ($4.1^{+3.5}_{-3.4}$) MeV at 68% CL.

ATLAS-CONF-2024-016
04 November 2024

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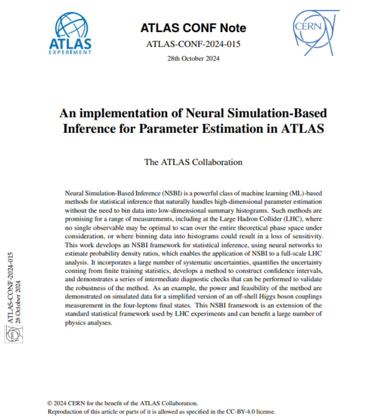

ATLAS CONF Note
ATLAS-CONF-2024-015
28th October 2024

An implementation of Neural Simulation-Based Inference for Parameter Estimation in ATLAS

The ATLAS Collaboration

Neural Simulation-Based Inference (NSBI) is a powerful class of machine learning (ML)-based methods for statistical inference that naturally handles high-dimensional parameter estimation without the need to bin data into low-dimensional summary histograms. Such methods are promising for a range of measurements, including at the Large Hadron Collider (LHC), where no single observable may be optimal to scan over the entire theoretical phase space under consideration, or where binning data into histograms could result in a loss of sensitivity. This work develops an NSBI framework for statistical inference, using neural networks to estimate probability density ratios, which enables the application of NSBI to a full-scale LHC analysis. It incorporates a large number of systematic uncertainties, quantifies the uncertainty coming from finite training statistics, develops a method to construct confidence intervals, and demonstrates a series of intermediate diagnostic checks that can be performed to validate the robustness of the method. As an example, the power and feasibility of the method are demonstrated on simulated data for a simplified version of an off-shell Higgs boson couplings measurement in the four-leptons final states. This NSBI framework is an extension of the standard statistical framework used by LHC experiments and can benefit a large number of physics analyses.

ATLAS-CONF-2024-015
28 October 2024

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The off-shell Higgs boson production signal strength is $\mu = 0.87^{+0.75}_{-0.54}$.

Credits: ATLAS Collaboration, 2024a; ATLAS Collaboration, 2024b.

Next steps

- The ATLAS NSBI analysis is the first of hopefully many.
- Methodological and computational challenges remain for its wider adoption.

The end.