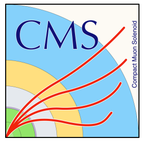
Model-Independent Real-Time Anomaly Detection at CMS Using Knowledge Distillation with CICADA

Kiran Das[2], Pallabi Das[1], Sridhara Dasu[2], **Lino Gerlach**[1], Tom Gorski[2], Andrew Ji[1], Kiley Kennedy[1], Andrew Loeliger[1], Luis Moreno[1], Isobel Ojalvo[1], Adrian Alan Pol, Alexander Savin[2], Varun Sharma[2], Ales Svetek[2], Jesra Tikalsky[2], Ho Fung Tsoi

[1]Princeton University, [2]University of Wisconsin-Madison

Fast Machine Learning for Science Conference
October 16, 2024



Introduction

Theoretical and **experimental** motivations for **New Physics**. But nothing was found @ LHC despite **thousands** of tested hypotheses. Why?

Introduction

Theoretical and **experimental** motivations for **New Physics**. But nothing was found @ LHC despite **thousands** of tested hypotheses. Why?

1.) **No new physics at LHC energies**

Introduction

Theoretical and **experimental** motivations for **New Physics**. But nothing was found @ LHC despite **thousands** of tested hypotheses. Why?

1.) No new physics at LHC energies
2.) It is extremely rare (need more data)

Introduction

Theoretical and **experimental** motivations for **New Physics**. But nothing was found @ LHC despite **thousands** of tested hypotheses. Why?

1.) No new physics at LHC energies
2.) It is extremely rare (need more data)
3.) We are overlooking it (wrong assumptions)

Introduction

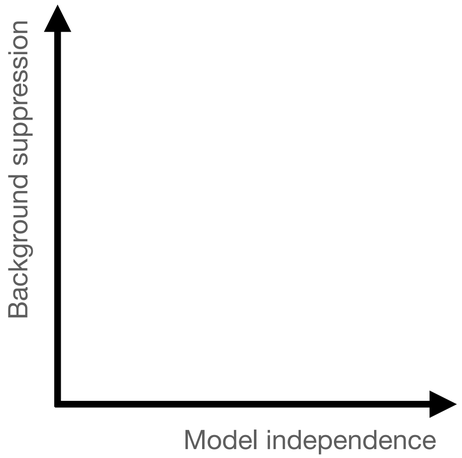
Theoretical and **experimental** motivations for **New Physics**. But nothing was found @ LHC despite **thousands** of tested hypotheses. Why?

1.) No new physics at LHC energies
2.) It is extremely rare (need more data)
3.) We are overlooking it (wrong assumptions)

Introduction

Theoretical and **experimental** motivations for **New Physics**. But nothing was found @ LHC despite **thousands** of tested hypotheses. Why?

1.) No new physics at LHC energies
2.) It is extremely rare (need more data)
3.) We are overlooking it (wrong assumptions)

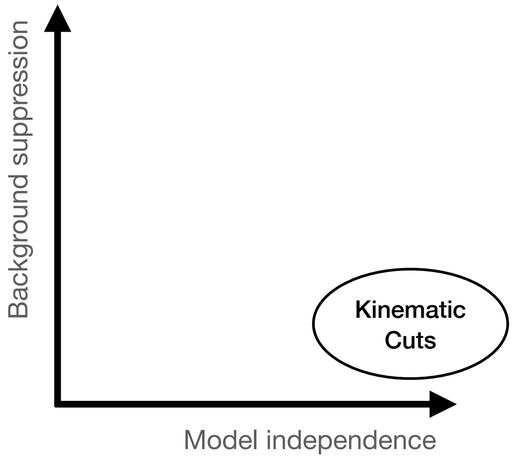


Want trigger algorithm with:

Introduction

Theoretical and **experimental** motivations for **New Physics**. But nothing was found @ LHC despite **thousands** of tested hypotheses. Why?

1.) No new physics at LHC energies
2.) It is extremely rare (need more data)
3.) We are overlooking it (wrong assumptions)



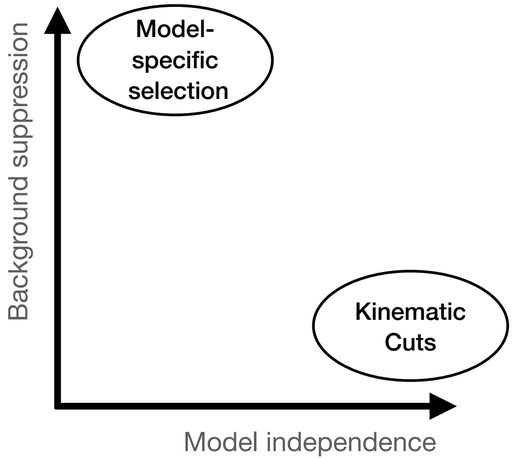
Want trigger algorithm with:

- Model-independence

Introduction

Theoretical and **experimental** motivations for **New Physics**. But nothing was found @ LHC despite **thousands** of tested hypotheses. Why?

1.) No new physics at LHC energies
2.) It is extremely rare (need more data)
3.) We are overlooking it (wrong assumptions)



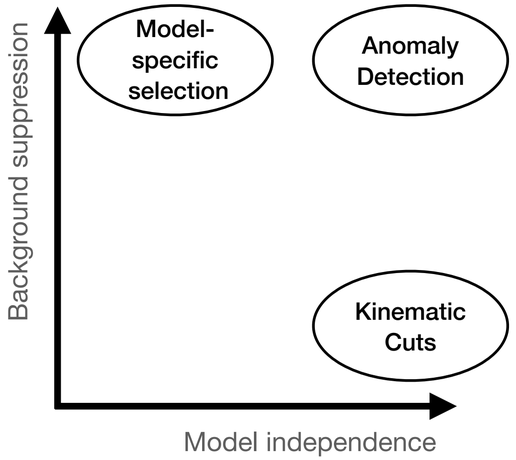
Want trigger algorithm with:

- Model-independence
- Good Background suppression

Introduction

Theoretical and **experimental** motivations for **New Physics**. But nothing was found @ LHC despite **thousands** of tested hypotheses. Why?

1.) No new physics at LHC energies
2.) It is extremely rare (need more data)
3.) We are overlooking it (wrong assumptions)



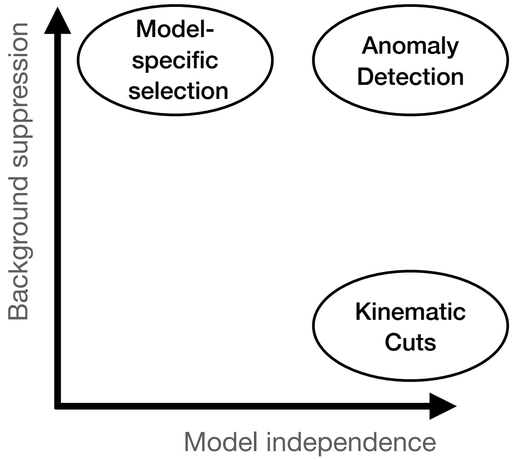
Want trigger algorithm with:

- Model-independence
- Good Background suppression

Introduction

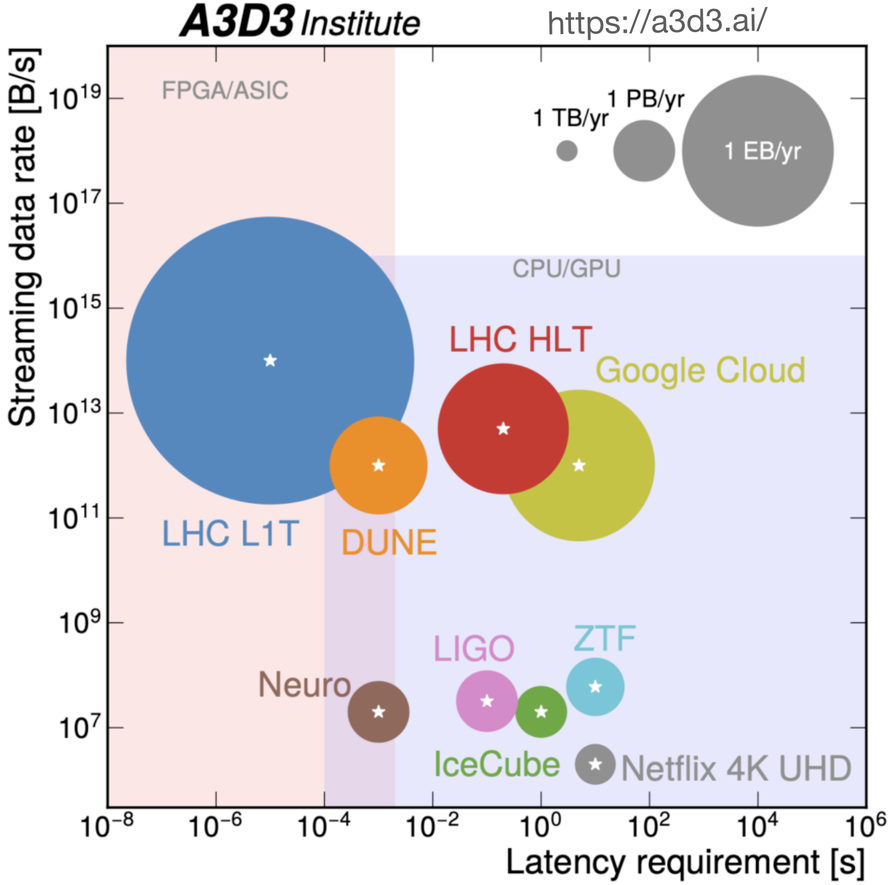
Theoretical and **experimental** motivations for **New Physics**. But nothing was found @ LHC despite **thousands** of tested hypotheses. Why?

1.) No new physics at LHC energies
2.) It is extremely rare (need more data)
3.) We are overlooking it (wrong assumptions)



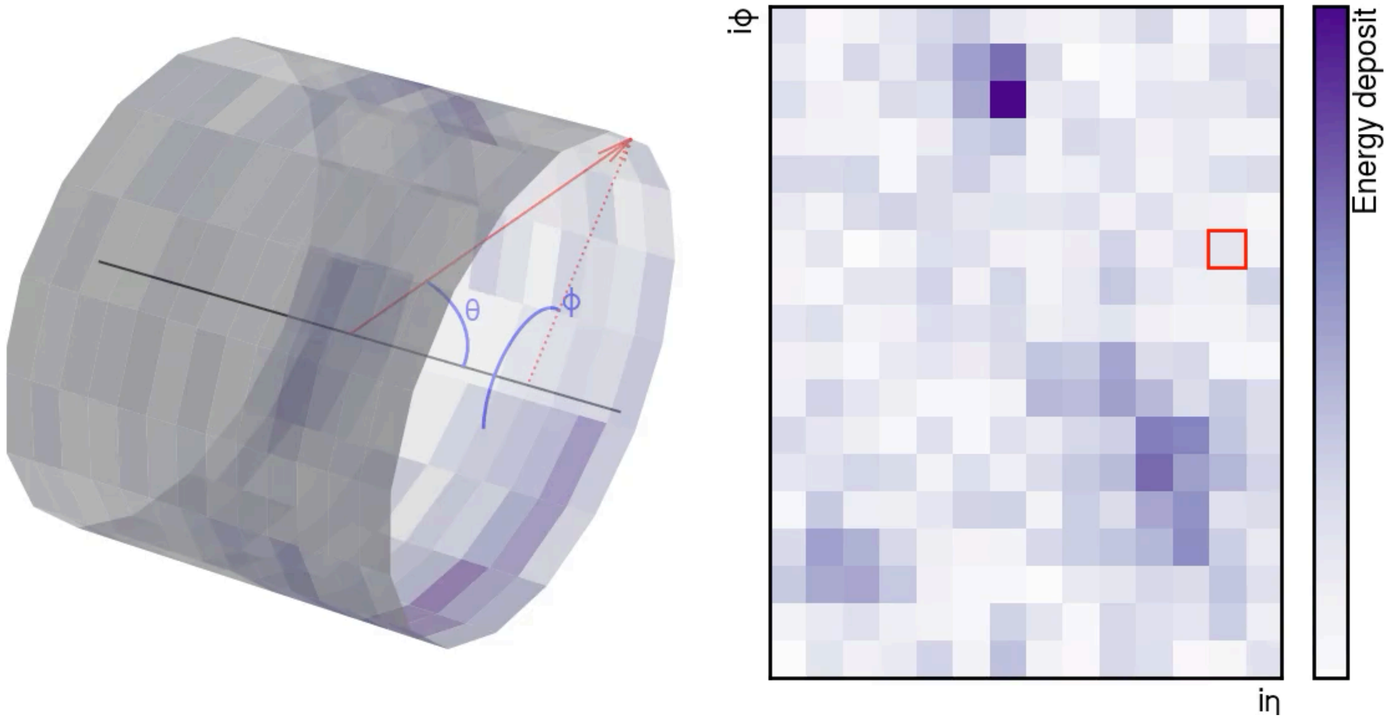
Want trigger algorithm with:

- Model-independence
- Good Background suppression
- Fulfills computing requirements @ L1T
  ~1μs latency, ~1PB/s throughput



CICADA - Inputs

Calorimeter **I**mage **C**onvolutional **A**nomaly **D**etection **A**lgorithm

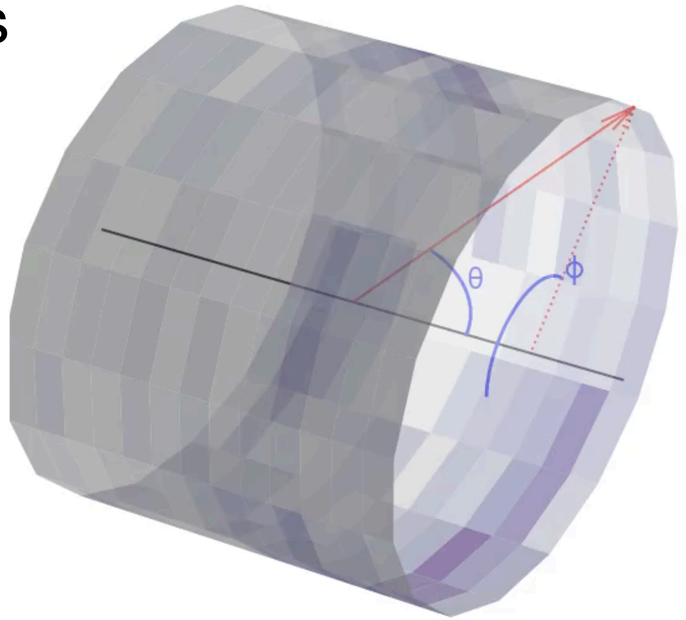


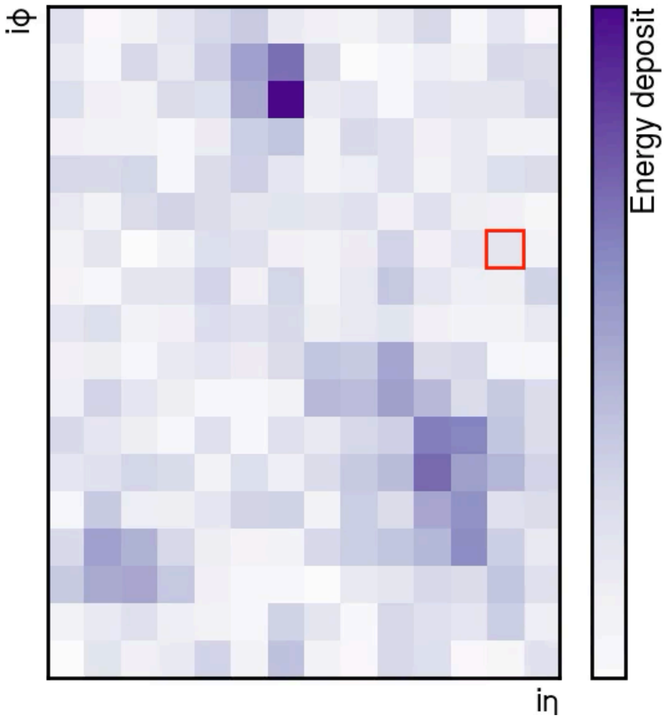
Schematic depiction of CMS calorimeter
Randomly generated data

CICADA - Inputs

Calorimeter **I**mage **C**onvolutional **A**nomaly **D**etection **A**lgorithm

- CMS deploys cylindrical calorimeters



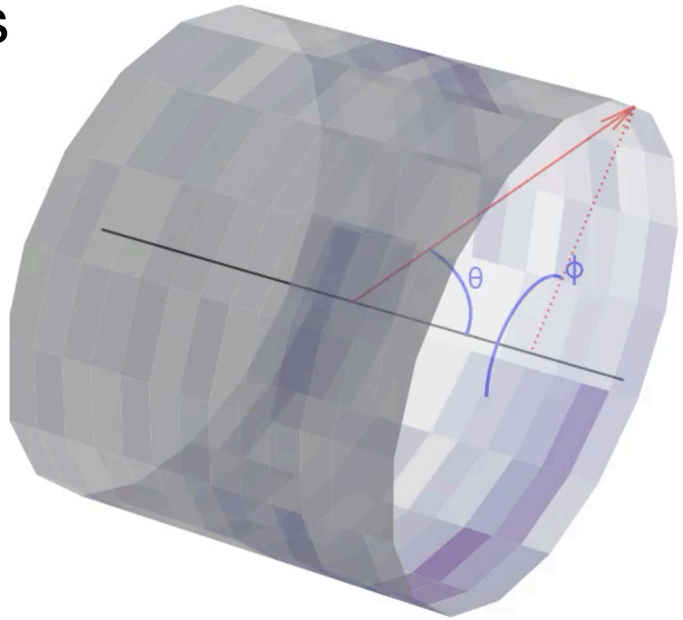


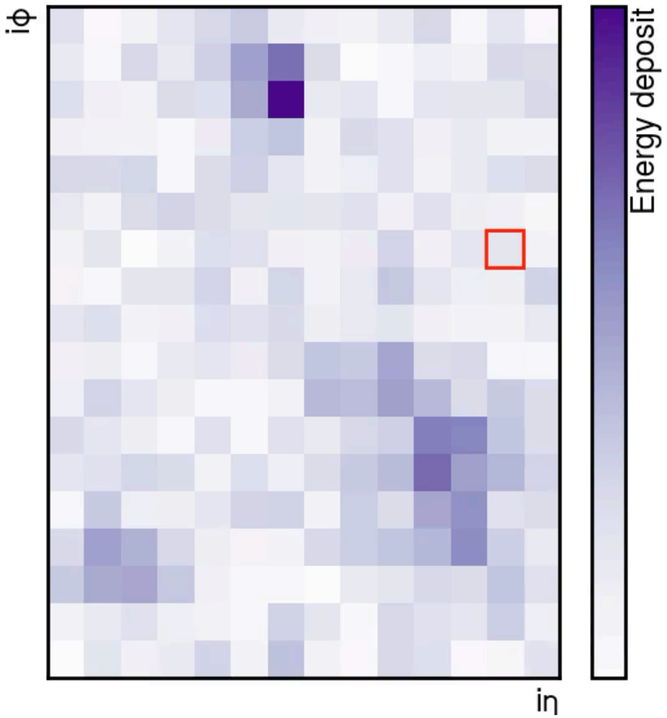
Schematic depiction of CMS calorimeter
Randomly generated data

CICADA - Inputs

Calorimeter **I**mage **C**onvolutional **A**nomaly **D**etection **A**lgorithm

- CMS deploys cylindrical calorimeters
- Sum energy deposits pixel-wise



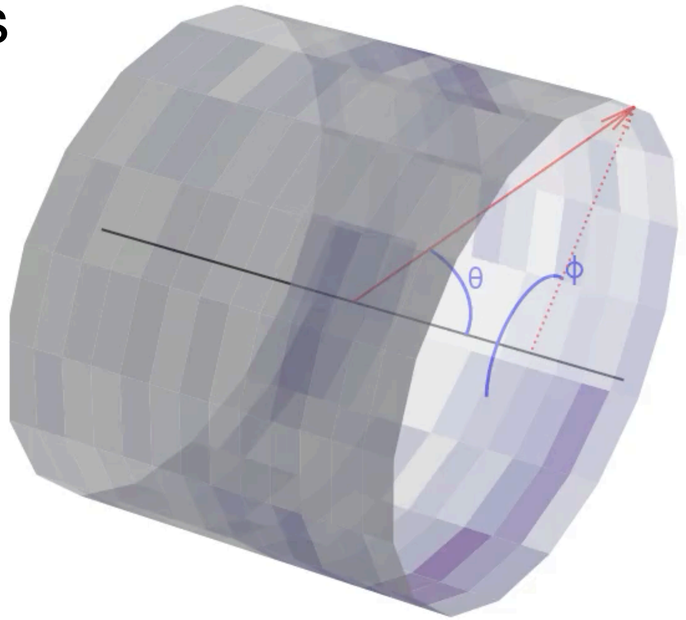


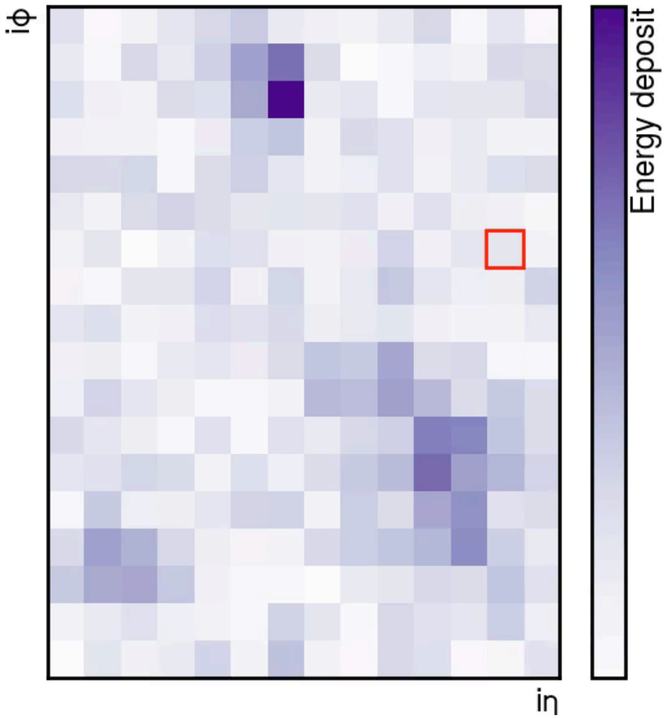
Schematic depiction of CMS calorimeter
Randomly generated data

CICADA - Inputs

Calorimeter **I**mage **C**onvolutional **A**nomaly **D**etection **A**lgorithm

- CMS deploys cylindrical calorimeters
- Sum energy deposits pixel-wise
- Unroll to get image-like data



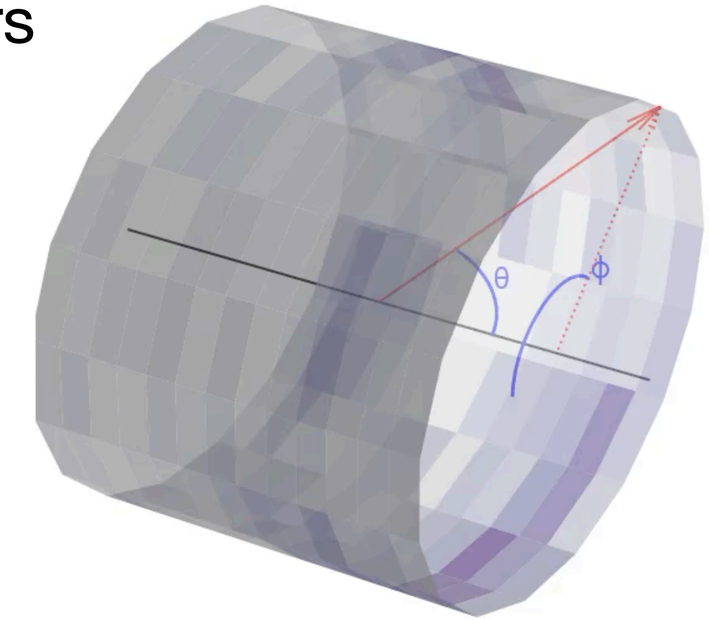


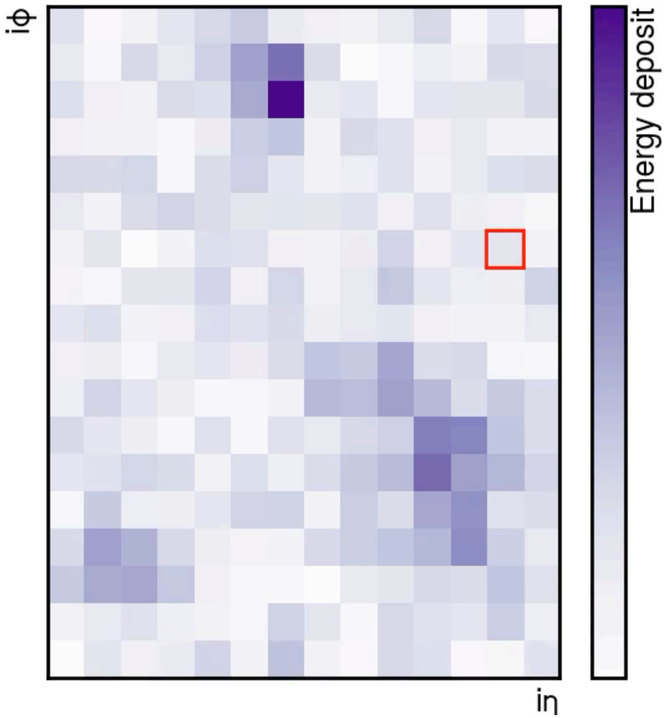
Schematic depiction of CMS calorimeter
Randomly generated data

CICADA - Inputs

Calorimeter **I**mage **C**onvolutional **A**nomaly **D**etection **A**lgorithm

- CMS deploys cylindrical calorimeters
- Sum energy deposits pixel-wise
- Unroll to get image-like data
- Deploy convolutional neural nets

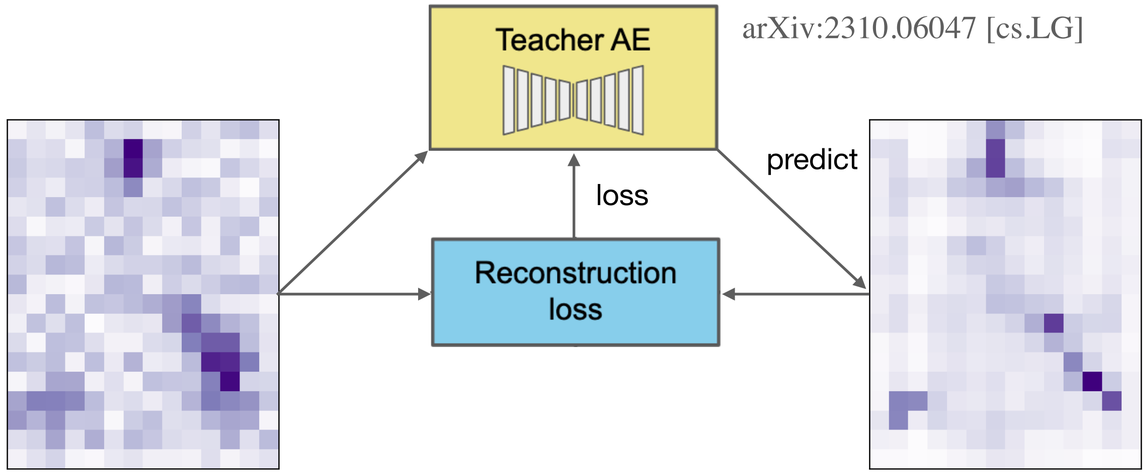




Schematic depiction of CMS calorimeter
Randomly generated data

Training & Knowledge Distillation

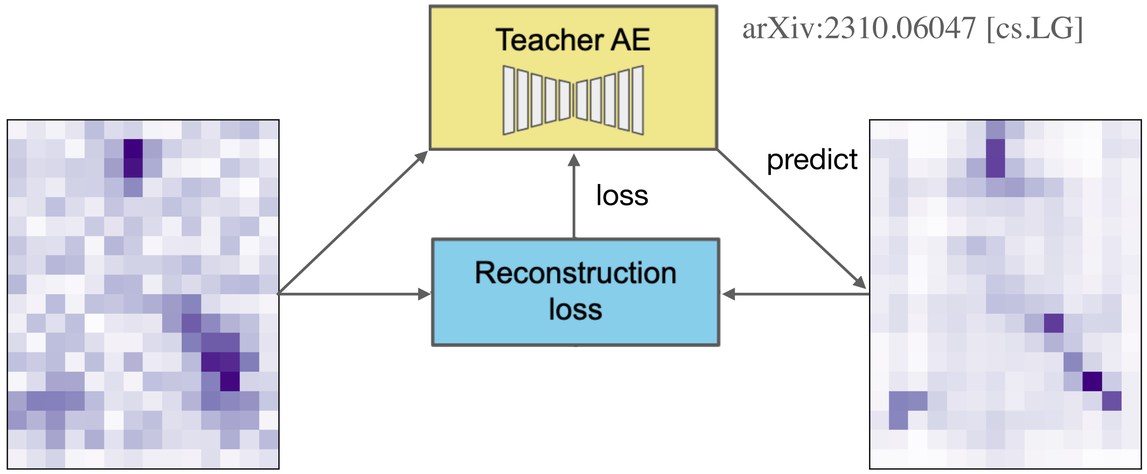
Signal model independent: unsupervised learning



Training & Knowledge Distillation

Signal model independent: unsupervised learning

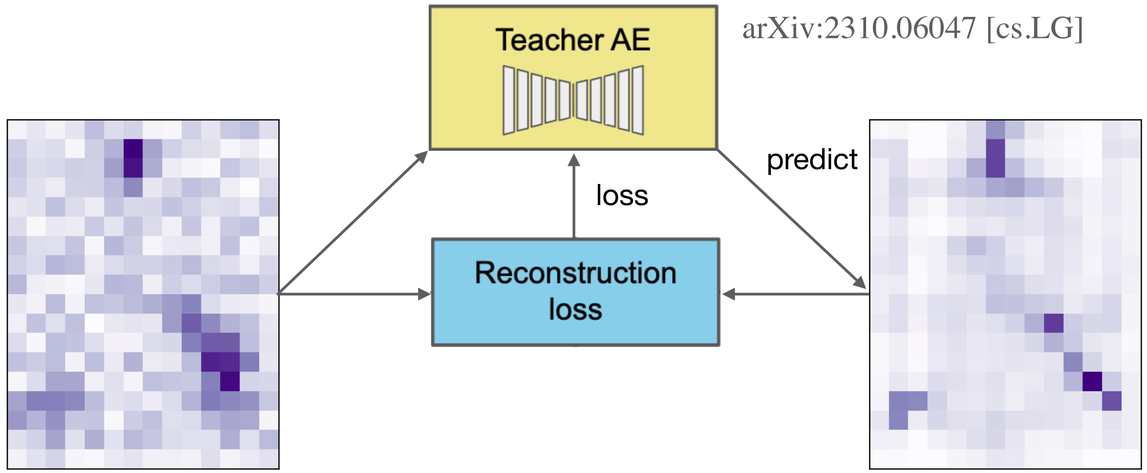
- Train Auto-Encoder on **Zero Bias** data



Training & Knowledge Distillation

Signal model independent: unsupervised learning

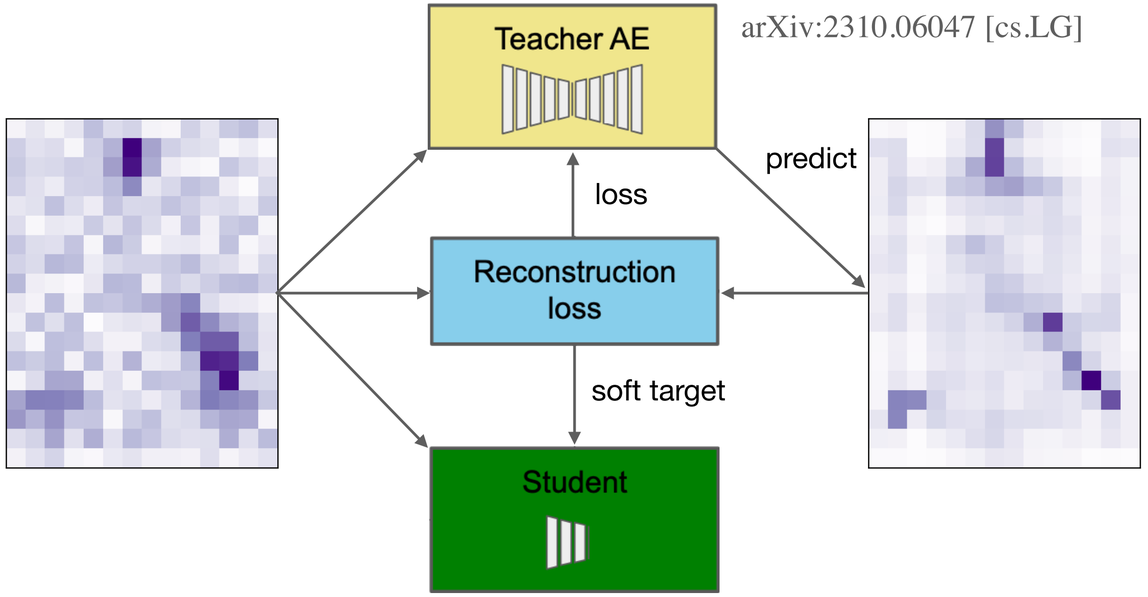
- Train Auto-Encoder on **Zero Bias** data
- Reconstruction loss as **Anomaly Score**



Training & Knowledge Distillation

Signal model independent: unsupervised learning

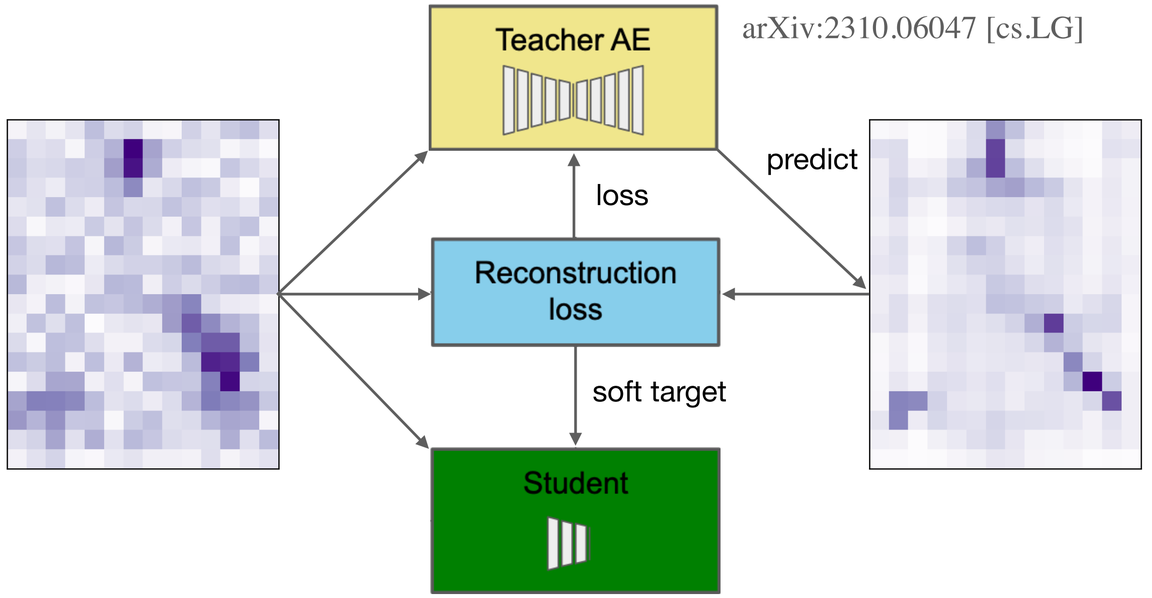
- Train Auto-Encoder on **Zero Bias** data
- Reconstruction loss as **Anomaly Score**
- Transfer **Knowledge** from large AE**:**
  - Train smaller model on anomaly score directly

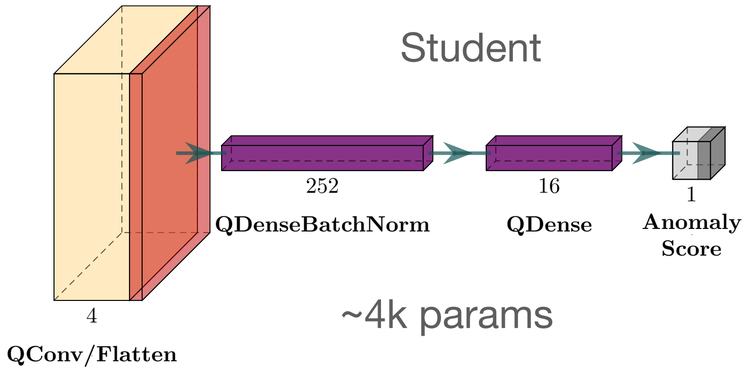


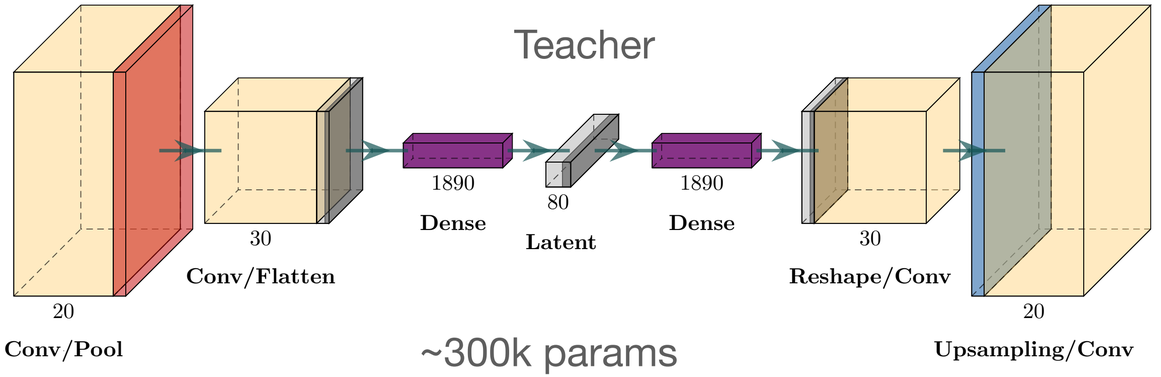
Training & Knowledge Distillation

Signal model independent: unsupervised learning

- Train Auto-Encoder on **Zero Bias** data
- Reconstruction loss as **Anomaly Score**
- Transfer **Knowledge** from large AE**:**
  - Train smaller model on anomaly score directly







Deployment

Deployment

Train teacher with
tensorflow & **keras**

Deployment

Train teacher with **tensorflow** & **keras**

Quantization aware student training with **QKeras**

Deployment

Train teacher with **tensorflow** & **keras**

Quantization aware student training with **QKeras**

Translate trained NN into C++ with **hls4ml**

Deployment


Model
Quantized model
hls4ml
C++/HLS project
Hardware
Train teacher with **tensorflow** & **keras**
Quantization aware student training with **QKeras**
Translate trained NN into C++ with **hls4ml**
Produce FPGA code from C++ with **Xilinx HLS**

Deployment

Train teacher with **tensorflow** & **keras**

Quantization aware student training with **QKeras**

Translate trained NN into C++ with **hls4ml**

Produce FPGA code from C++ with **Xilinx HLS**

Deploy on **AMD Virtex** FPGA chip

Deployment

Model → Quantized model → hls4ml → C++/HLS project → Hardware

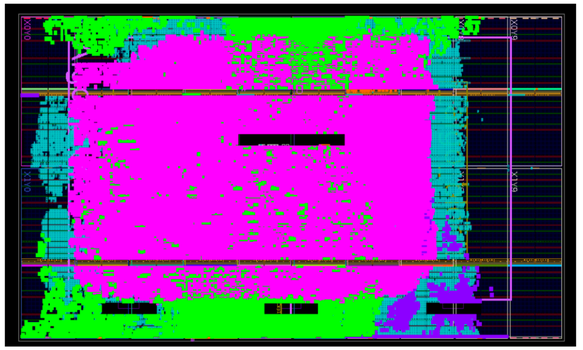
Train teacher with **tensorflow** & **keras**

Quantization aware student training with **QKeras**

Translate trained NN into C++ with **hls4ml**

Produce FPGA code from C++ with **Xilinx HLS**

Deploy on **AMD Virtex** FPGA chip



from Luis Moreno

Deployment

Model → Quantized model → hls4ml → C++/HLS project → Hardware

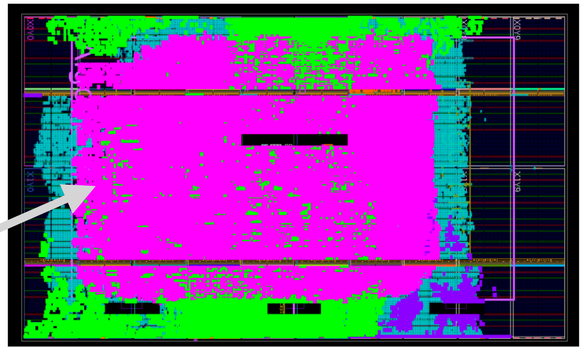
Train teacher with **tensorflow** & **keras**

Quantization aware student training with **QKeras**

Translate trained NN into C++ with **hls4ml**

Produce FPGA code from C++ with **Xilinx HLS**

Deploy on **AMD Virtex** FPGA chip



CICADA

from Luis Moreno

Deployment

Model → Quantized model → hls4ml → C++/HLS project → Hardware

Train teacher with **tensorflow** & **keras**

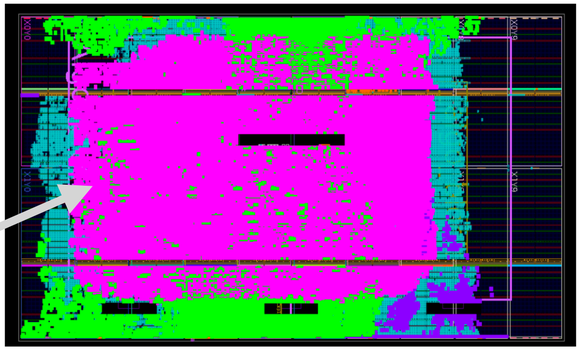
Quantization aware student training with **QKeras**

Translate trained NN into C++ with **hls4ml**

Produce FPGA code from C++ with **Xilinx HLS**

Deploy on **AMD Virtex** FPGA chip

Final Latency: 8BX (0.2 μs)



from Luis Moreno

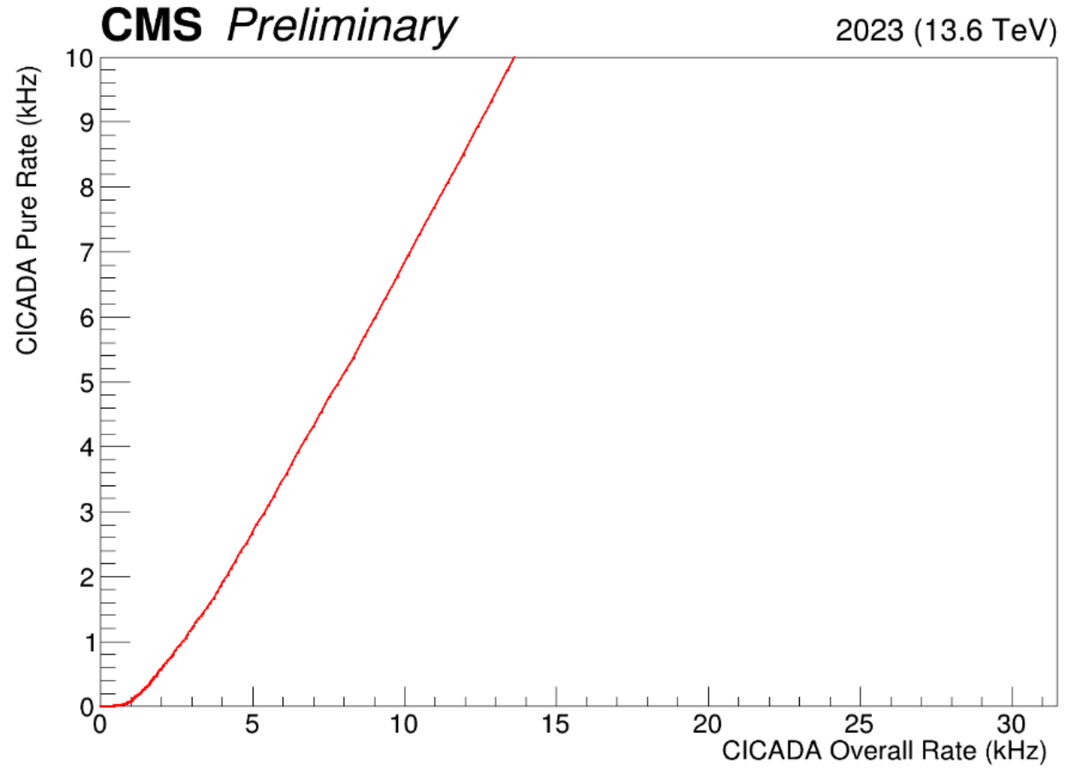
Conclusion & Outlook

Conclusion & Outlook

- Performance tests on simulated & real CMS data show good performance

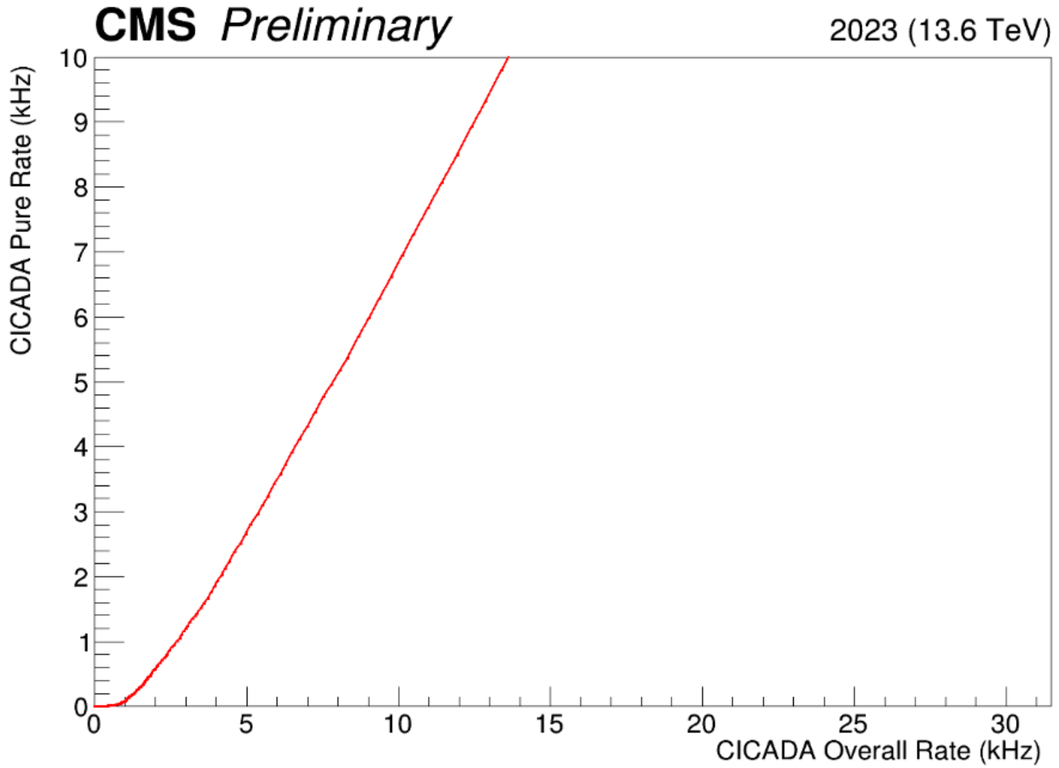
Conclusion & Outlook

- Performance tests on simulated & real CMS data show good performance
- Latest CICADA model has been deployed & records data since last week!



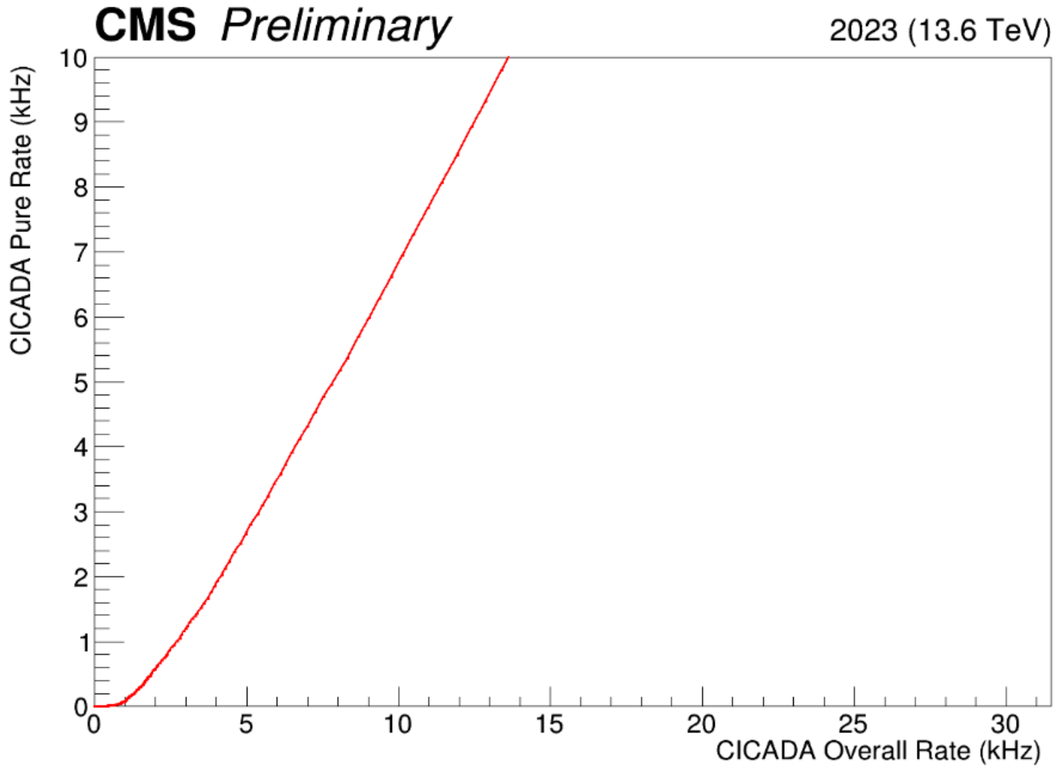
Conclusion & Outlook

- Performance tests on simulated & real CMS data show good performance
- Latest CICADA model has been deployed & records data since last week!
- **R**eal-time **A**nomaly **D**etection (**RAD**):
  Cooperation w/ DUNE (see next talk by Jack)



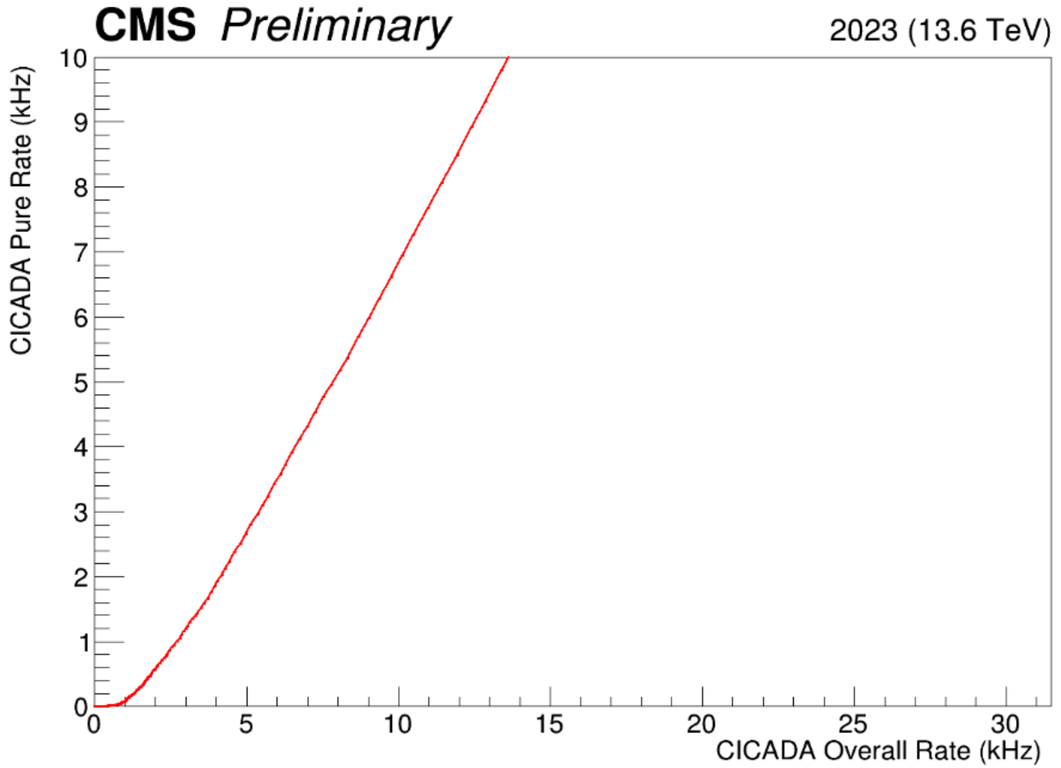
Conclusion & Outlook

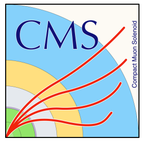
- Performance tests on simulated & real CMS data show good performance
- Latest CICADA model has been deployed & records data since last week!
- **R**eal-time **A**nomaly **D**etection (**RAD**):
  Cooperation w/ DUNE (see next talk by Jack)
- Working on first physics analysis w/
  CICADA-triggered data



Conclusion & Outlook

- Performance tests on simulated & real CMS data show good performance
- Latest CICADA model has been deployed & records data since last week!
- **R**eal-time **A**nomaly **D**etection (**RAD**):
  Cooperation w/ DUNE (see next talk by Jack)
- Working on first physics analysis w/
  CICADA-triggered data
- Working on common paper with **AXOL1T1L**





Backup

CMS Trigger System