Probing nature by measuring the Higgs boson and enhancing sensitivity with hardware triggers and artificial intelligence

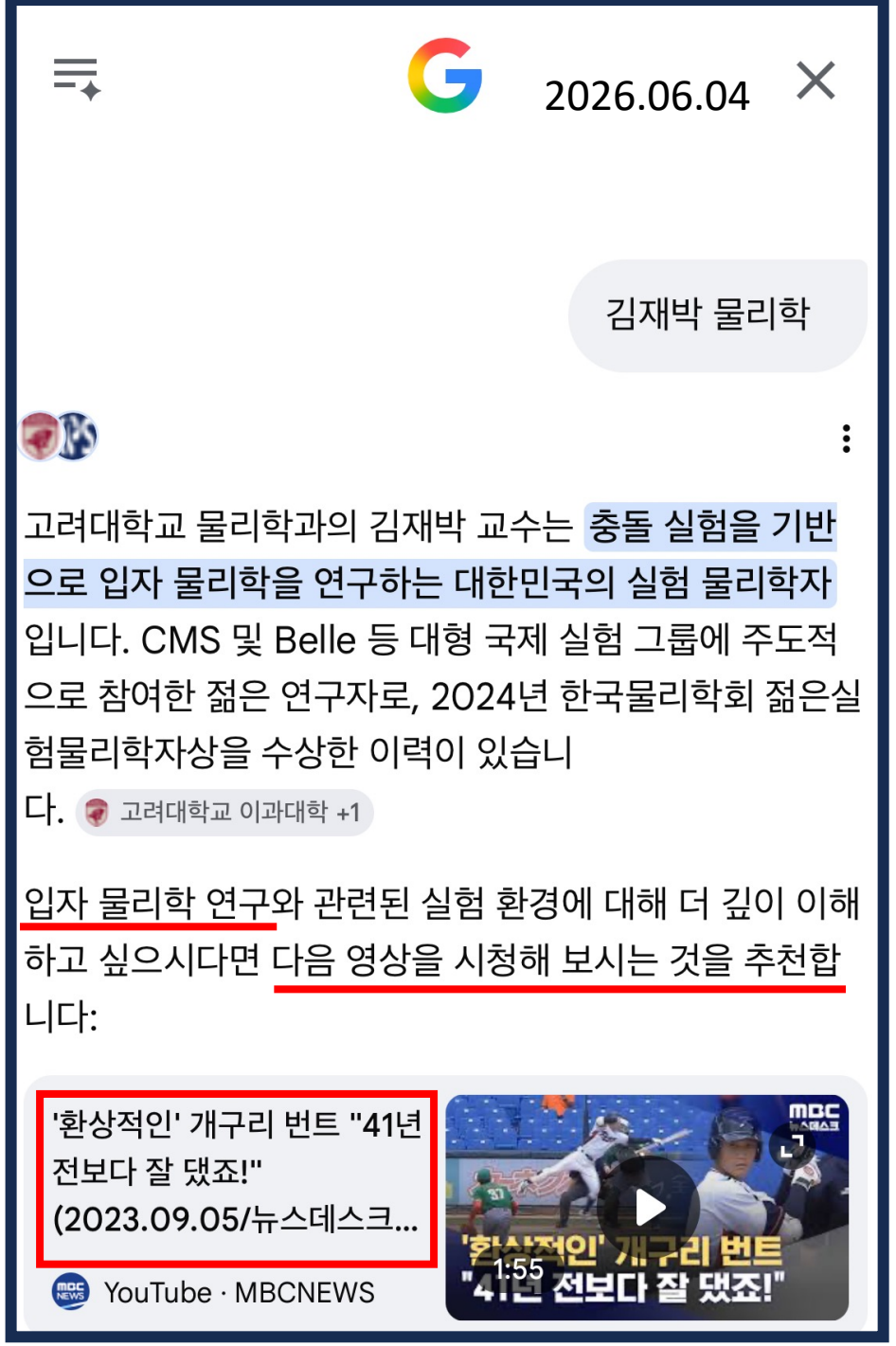
Jaebak Kim (Korea University)

jaebak@korea.ac.kr

약 10년 만에 물리학자로서 이 자리에서 발표하게 되어 감회가 새롭습니다.

인공지능이 아직 제 소개를
제대로 계산하지 못합니다.

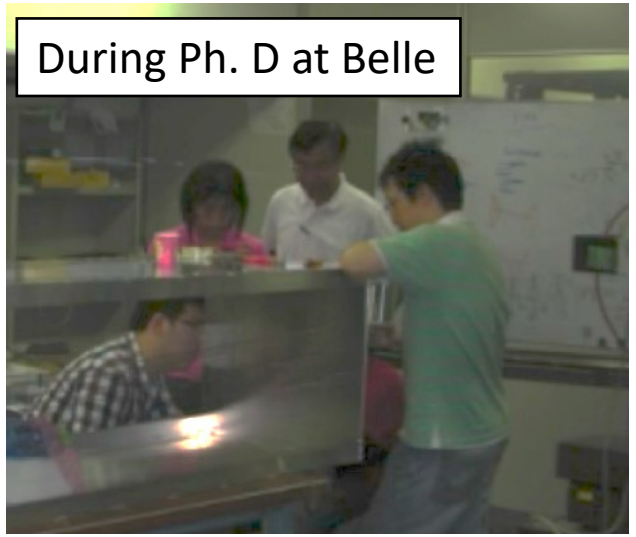
신임 교수로서 간단히 제
소개를 먼저 드리고자 합니다.

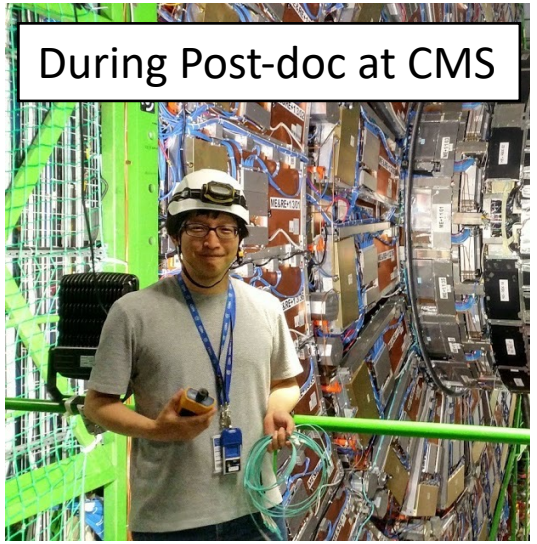


Research history

- Ph. D. on Belle/Belle II experiment
  @ Korea University
  - ➢Search for CP violation in Charm mesons
  - ➢Level 1 CDC track trigger (FPGA)
- Post-doc/Scientist on CMS experiment
  @ University of California, Santa Barbara
  - ➢Search for $HH + p_T^{\text{miss}}$
  - ➢Muon Detector Upgrade Coordinator
- Assistant Professor @ Korea University

  Working with 5 grad-students + α





KU HEP-ex group

Probing Higgs boson and enhancing sensitivity

Main target

Higgs boson

Production

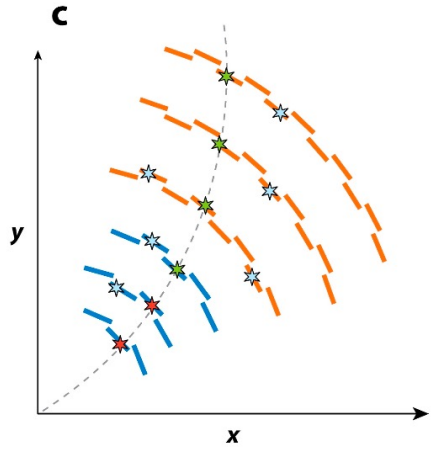
e.g., $HH + p_T^{\text{miss}}$

Decay

e.g., $H \to Z\gamma$

Enhancing

HL-LHC hardware track trigger

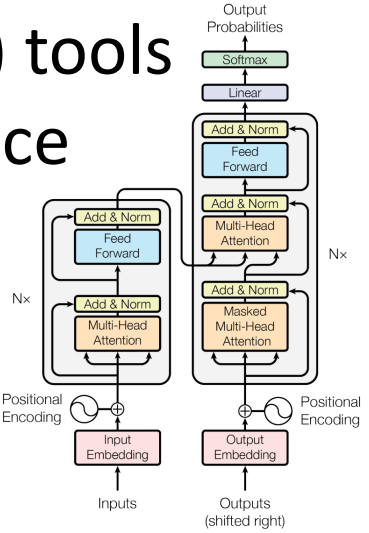


"Tracking Triggers for the HL-LHC"

Machine Learning (ML) tools
E.g., Artificial intelligence

"Attention is All You Need"
Citations 251,236

Transformer



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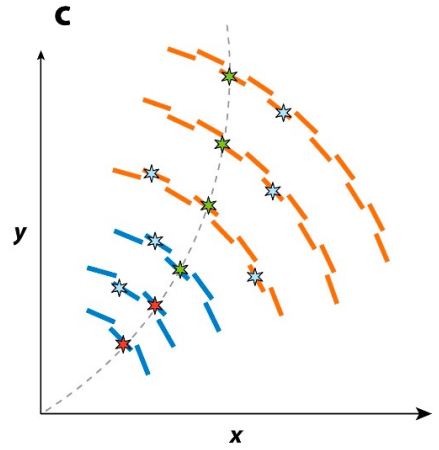
Enhancing

0. Overview of AI in HEP

HL-LHC hardware track trigger 3.



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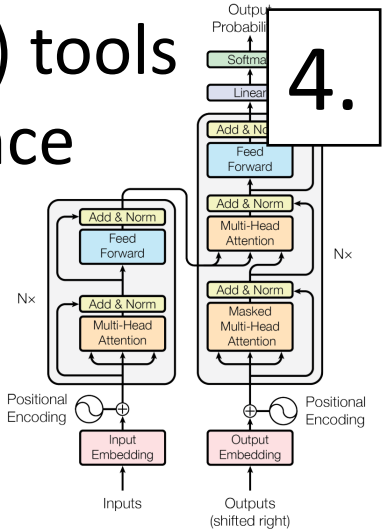

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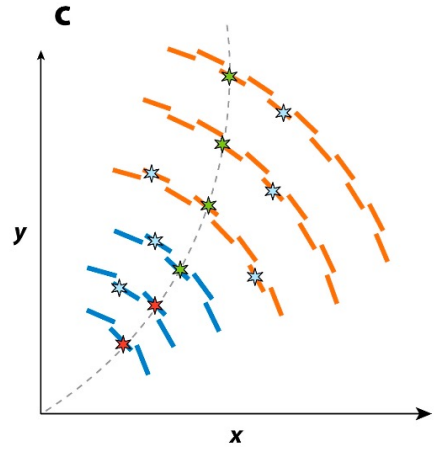

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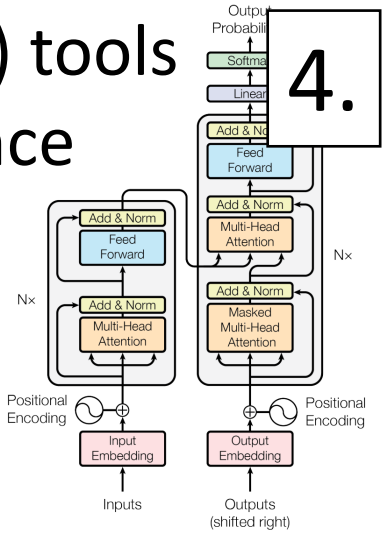


Overview of AI in particle physics

How **has** AI been used in particle physics?

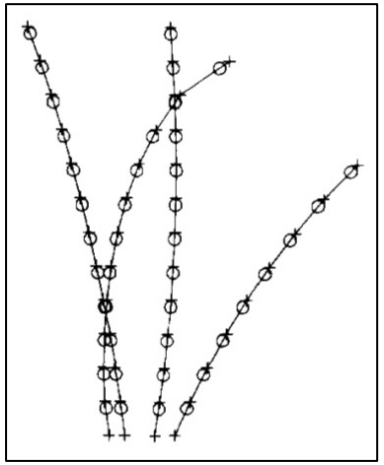
AI papers for HEP since the Seoul Olympics (1988)

How **will** AI be used in particle physics?

How has AI been used in particle physics?

1. Reconstruction / Pattern recognition

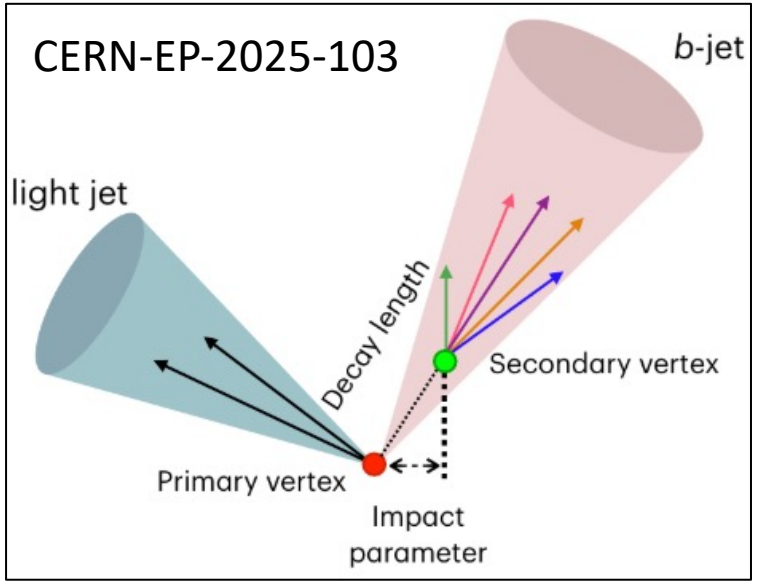
- Hit reconstruction, Track reconstruction, …



Computer Physics Communications
49 (1988) 429–448

2. Classification

- Triggering, Particle identification, …



3. Modeling distributions / Regression

- NNPDF, correcting distributions, estimate background distributions, …

Papers of AI in Particle Physics since Seoul Olympics

First paper that used AI in particle physics.

Year 1988

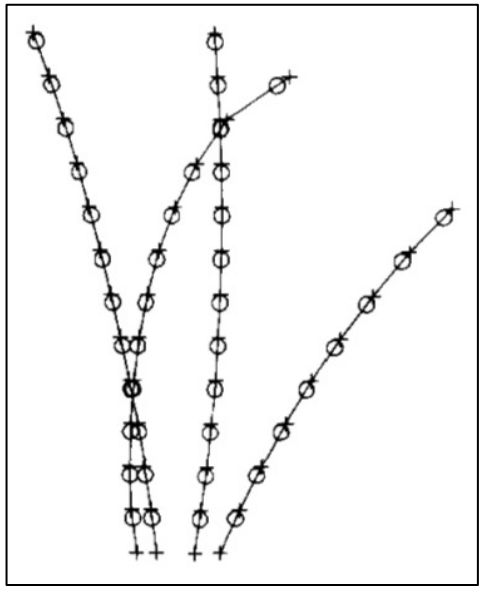
Reconstruction

Computer Physics Communications 49 (1988) 429–448
North-Holland, Amsterdam

NEURAL NETWORKS AND CELLULAR AUTOMATA IN EXPERIMENTAL HIGH ENERGY PHYSICS

B. DENBY
Laboratoire de l'Accélérateur Linéaire, Orsay, France

Track reconstruction:
NN finds lines that
connect detector hits (+).



Year 1992

Classification

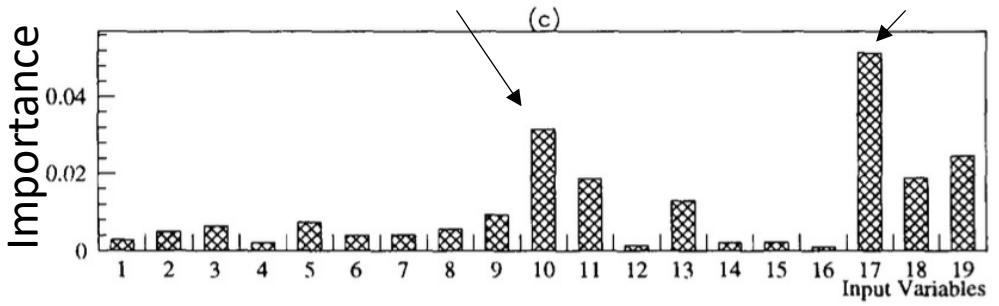
Physics Letters B 295 (1992) 383–395
North-Holland

Classification of the hadronic decays of the Z^0 into b and c quark pairs using a neural network

DELPHI Collaboration

Energetic di-jet mass

Track parameter



e^+e^- collision experiment from 1989 to 2000 up to $\sqrt{s} = 209$ GeV

Papers of AI in Particle Physics since Seoul Olympics

Year 1997

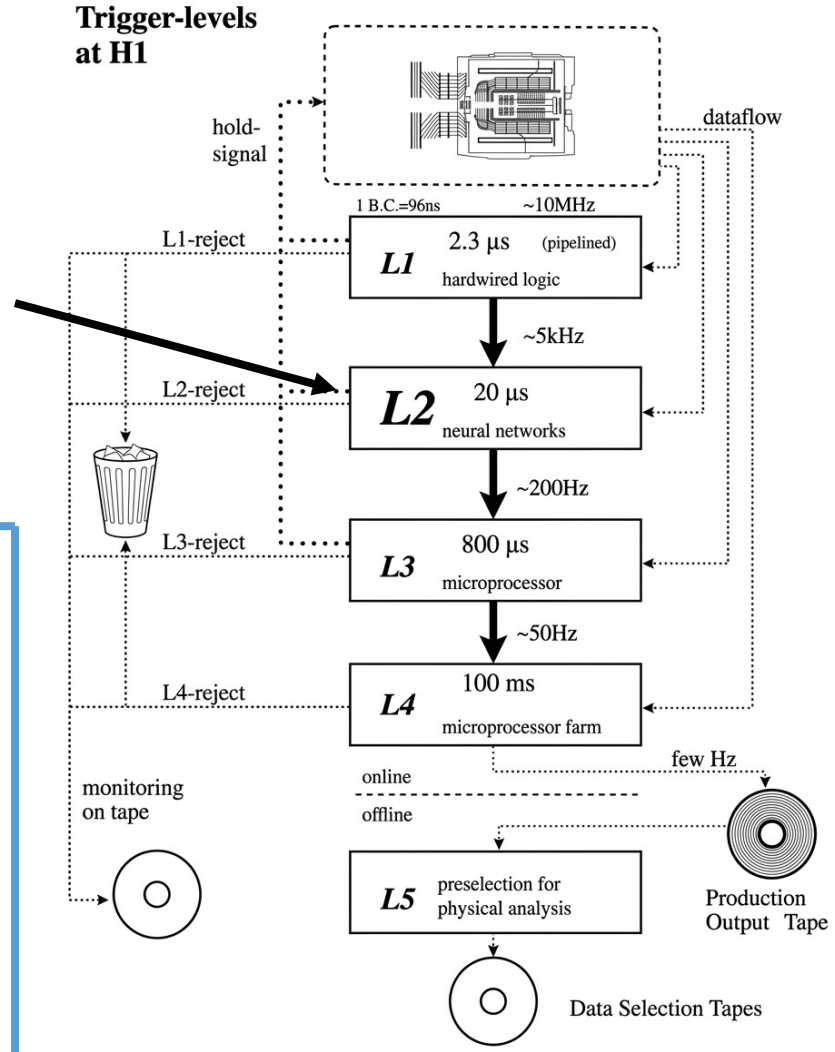
Classification

Nuclear Instruments and Methods in Physics Research A 389 (1997) 128–133

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Realization of a second level neural network trigger for the H1 experiment at HERA

$e\ p$ collision experiment from 1992 to 2007 at $\sqrt{s} = 320$ GeV



Year 2009

Modeling

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B 809 (2009) 1–63

NUCLEAR PHYSICS B

www.elsevier.com/locate/nuclphysb

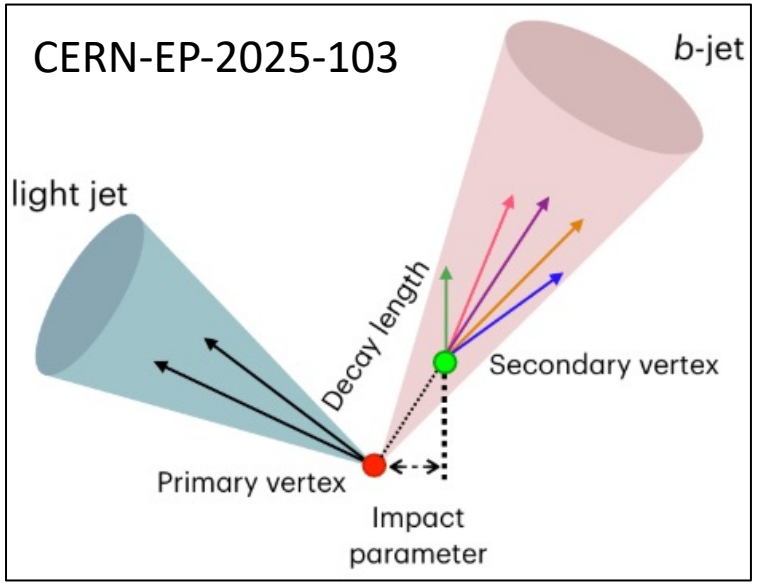
A determination of parton distributions with faithful uncertainty estimation

NNPDF Collaboration

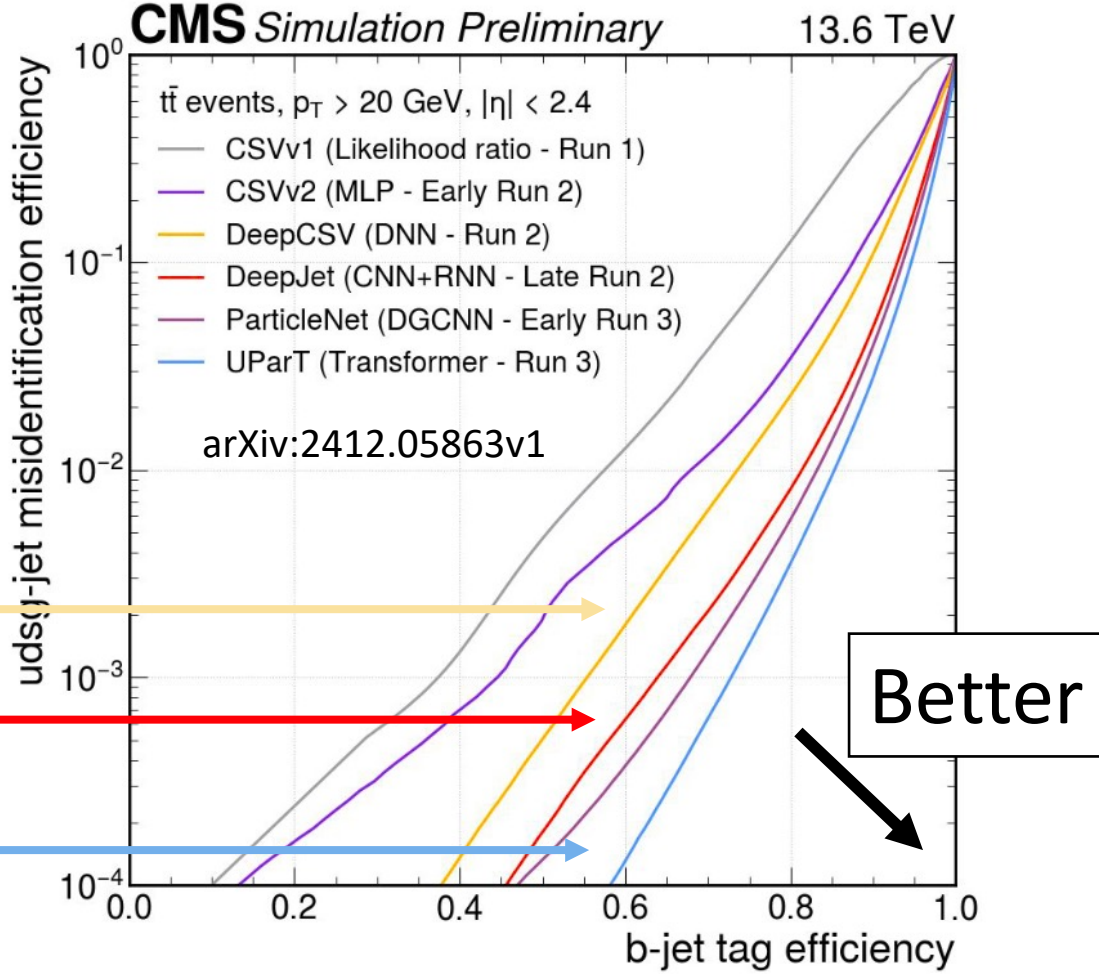
Papers of AI in Particle Physics since Seoul Olympics

Year 2016-present: b-jet tagging

Classification



- Algorithms
  - ➢DeepCSV (2016): Deep MLP
  - ➢DeepJet (2018): CNN + RNN
  - ➢UParT (2022): Transformer NN



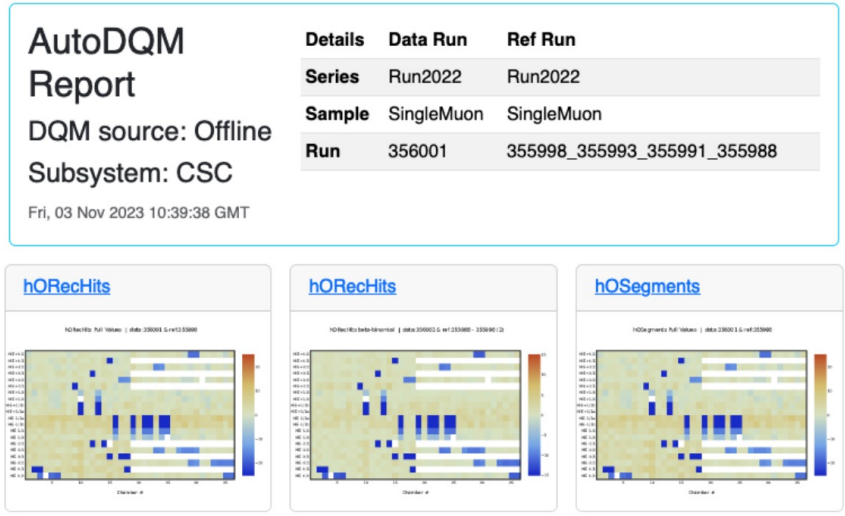
How **will** AI be used in particle physics?

- Past AI usage
  1. Reconstruction
  2. Classification
  3. Modeling distributions

- Additional current/future AI usage

  ChatGPT

  1. Coding & Documentation
  2. Differentiable experiment design optimization
  3. Experiment monitoring ←
  4. And more …



"Anomaly detection for automated data quality monitoring in the CMS detector"

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e.g., $HH + p_T^{\text{miss}}$

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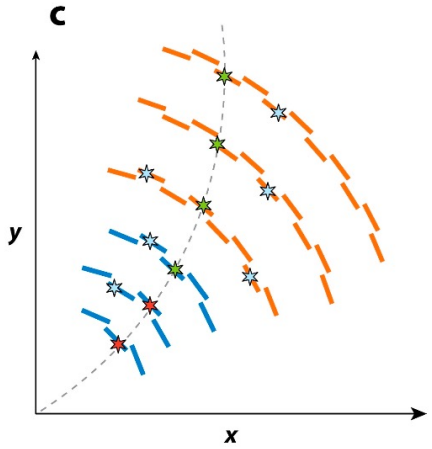

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Machine Learning (ML) tools E.g., Artificial intelligence 4.

"Attention is All You Need"
Citations 251,236

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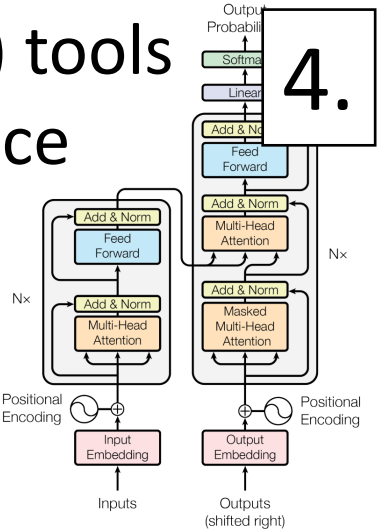


Higgs boson measurements

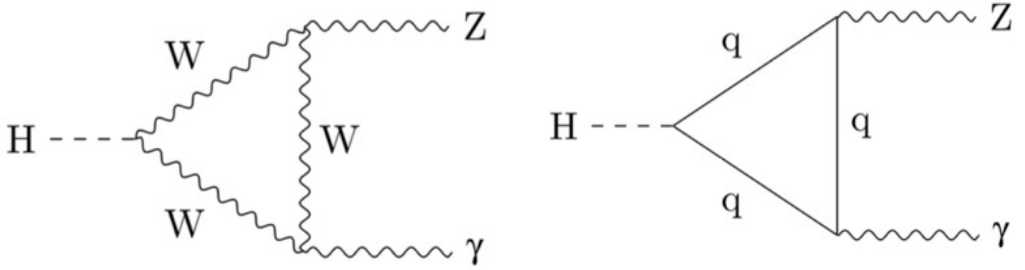
$H \to Z\gamma$ and $HH + p_T^{\mathrm{miss}}$

Search for $H \to Z\gamma$

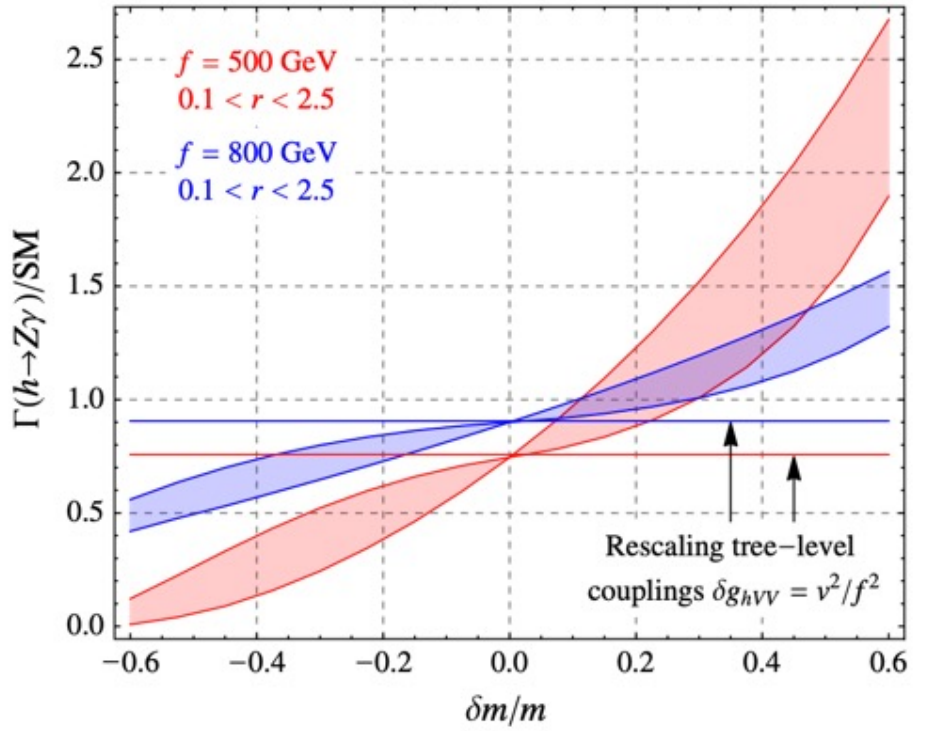
- Motivation:
  - ➢ Close to finding evidence of decay at single experiment (CMS 1.9σ)

    CMS-PAS-HIG-25-010

  - ➢ **Sensitive to new particles**
    - ❖ E.g., Composite Nambu-Goldstone Higgs model
      - ○ Small modifications to $H \to \gamma\gamma$
      - ○ Large modifications to $H \to Z\gamma$



$\mathcal{B}(H \to Z\gamma)\mathcal{B}(Z \to \ell^+\ell^-) \approx 1.1\times10^{-4}$



"New Prospects for Higgs Compositeness in h→Zγ"

Our group's 2026 CMS result

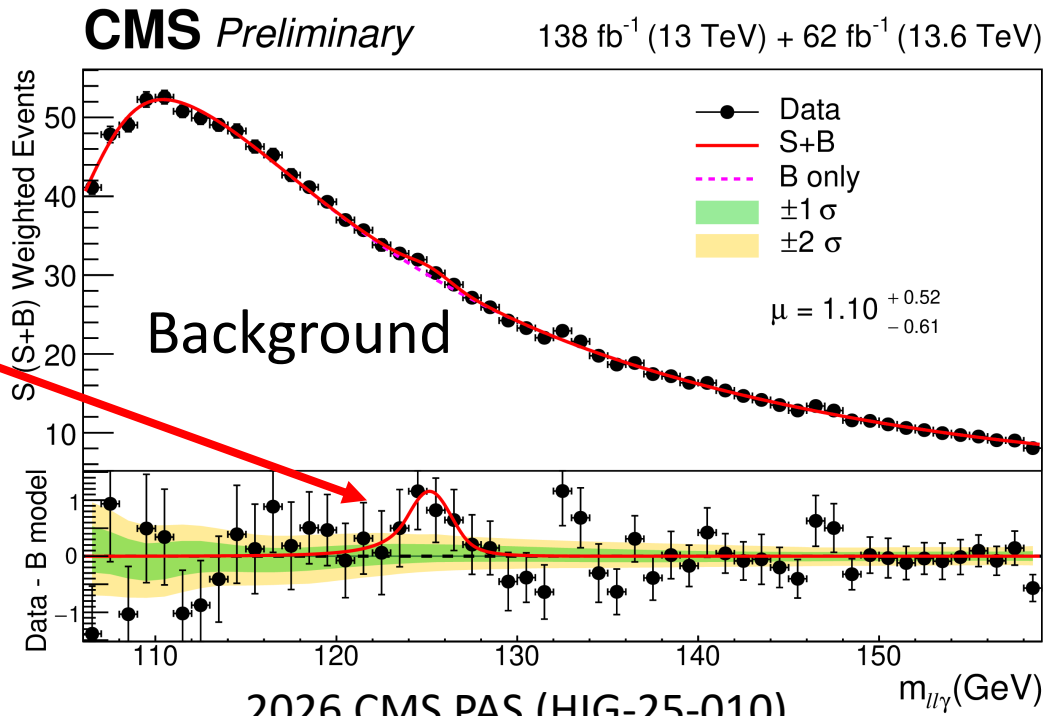
- Extracted signal yield by fitting $m(\ell\ell\gamma)$ over smooth background

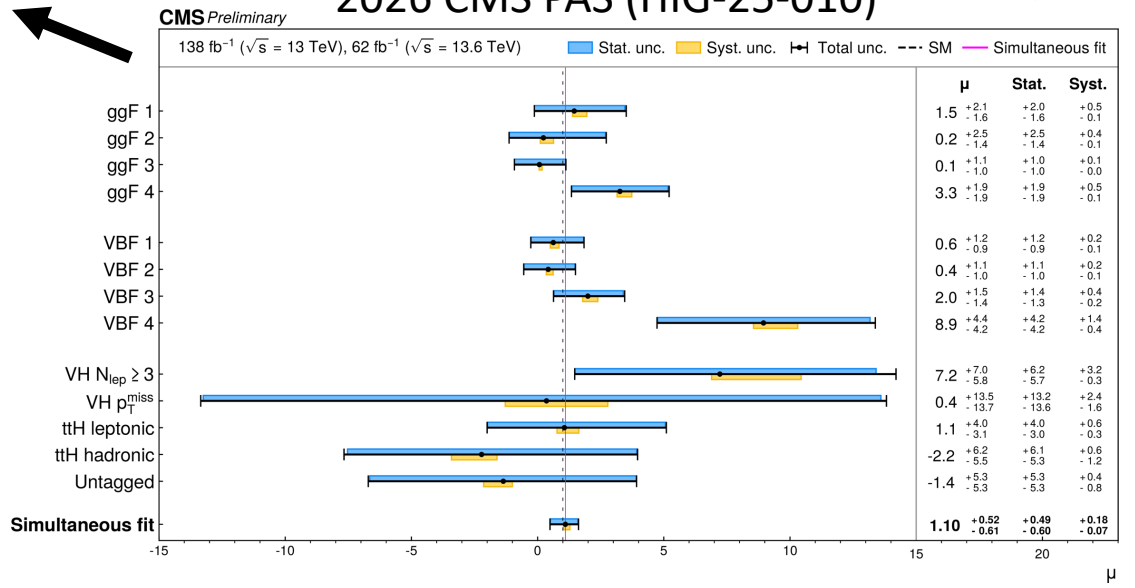
ML: Machine Learning

- Used ML to create 13 categories, and got $\mu = 1.1^{+0.5}_{-0.6}$ and 1.9σ with 200 fb^{-1} data.

- **Improved** expected **significance by 30%** compared to previous result using 138 fb^{-1} data.

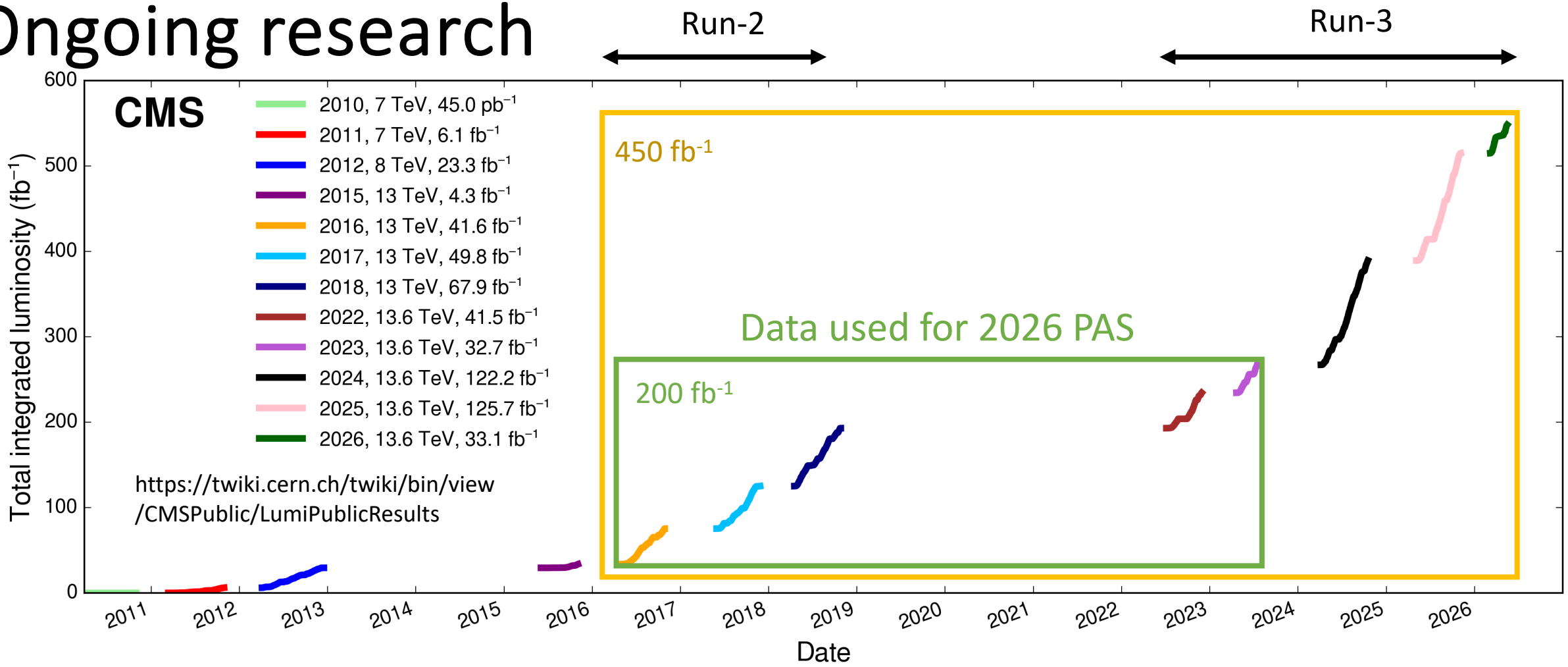
Higgs signal





PAS: Physics Analysis Summary

Ongoing research



1. Going through CMS reviews for 2026 PAS to **publish paper this year**.

2. Including remaining Run-3 data and enhancing sensitivity

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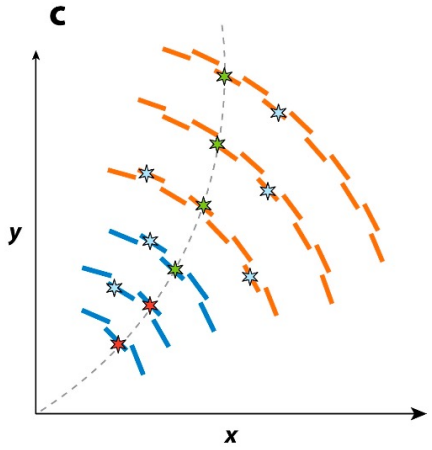

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Machine Learning (ML) tools E.g., Artificial intelligence 4.

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Citations 251,236

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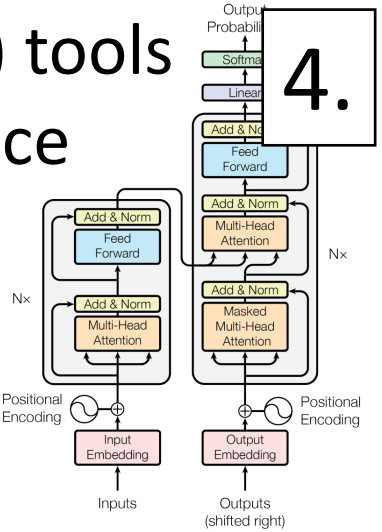
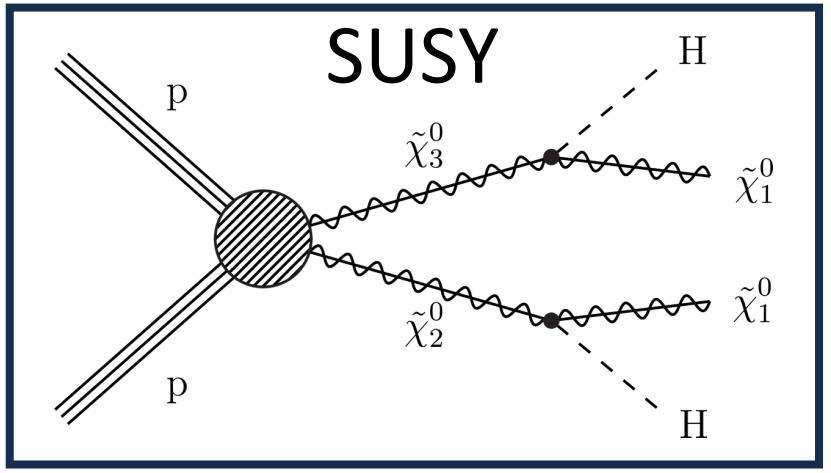
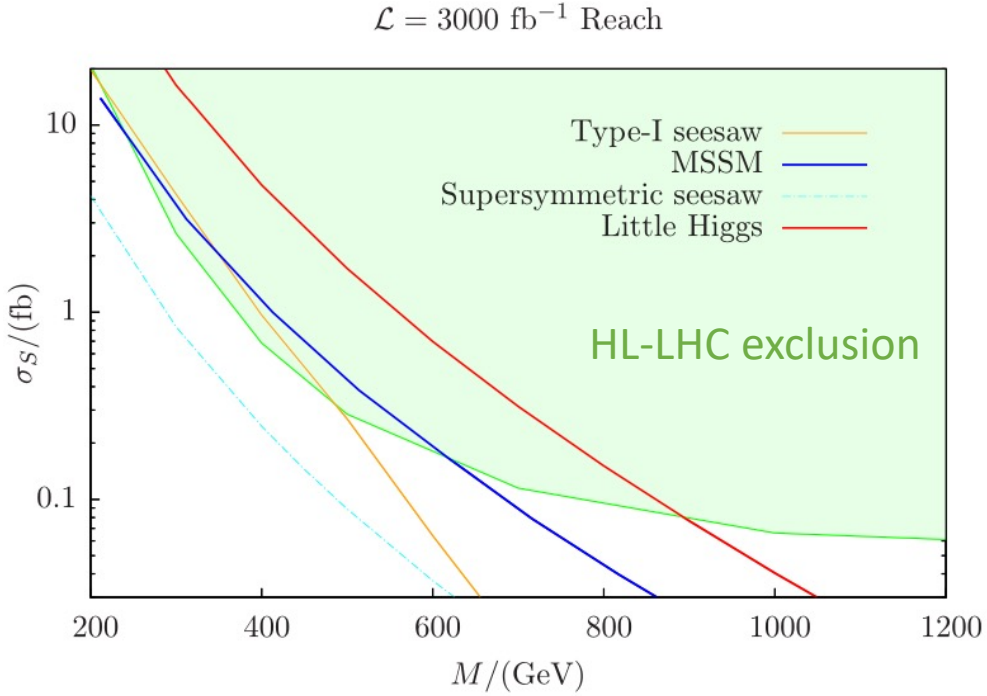


Search for $HH + p_T^{\text{miss}}$

[Motivation]

- Searching for BSM Di-Higgs production with p_T^{miss}
- Probes many BSM models
  - ➢SUSY:
    - $pp \to \tilde{\chi}_3^0 \tilde{\chi}_2^0 \to HH + \tilde{\chi}_1^0 \tilde{\chi}_1^0$
  - ➢Little Higgs:
    - $pp \to Z_H Z_H \to HH + A_H A_H$





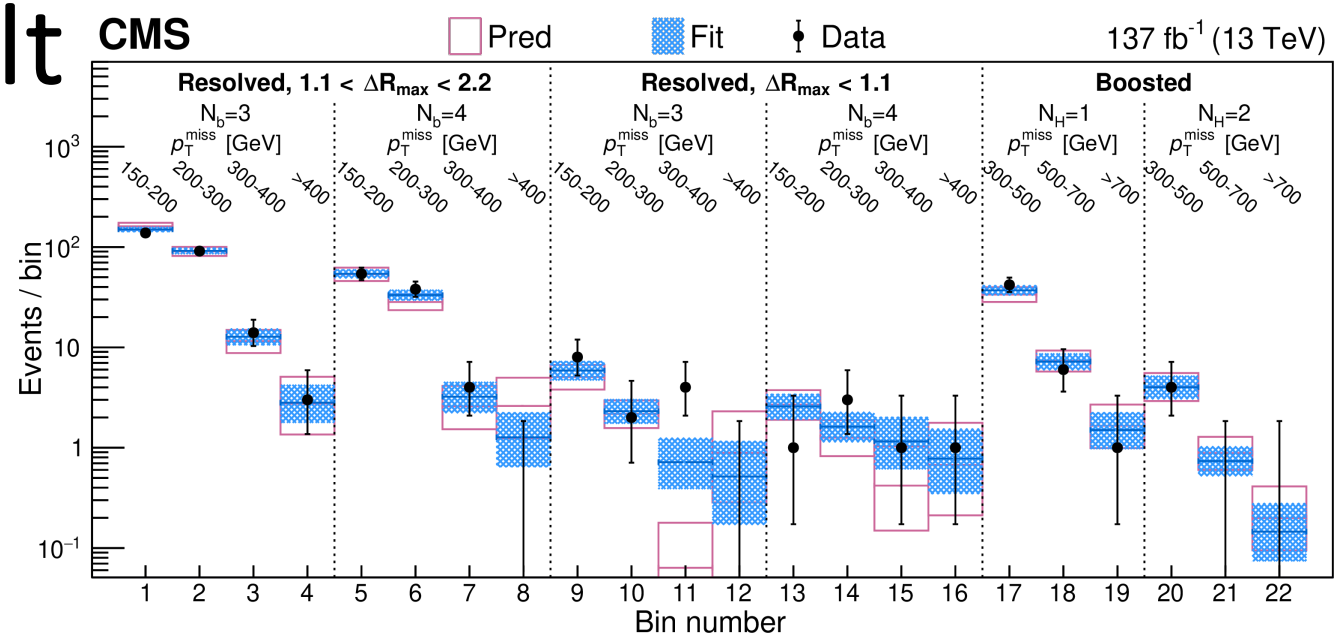
"New Physics Opportunities in the Boosted Di-Higgs-Boson Plus Missing Transverse Energy Signature" KIAS 고병원 교수님

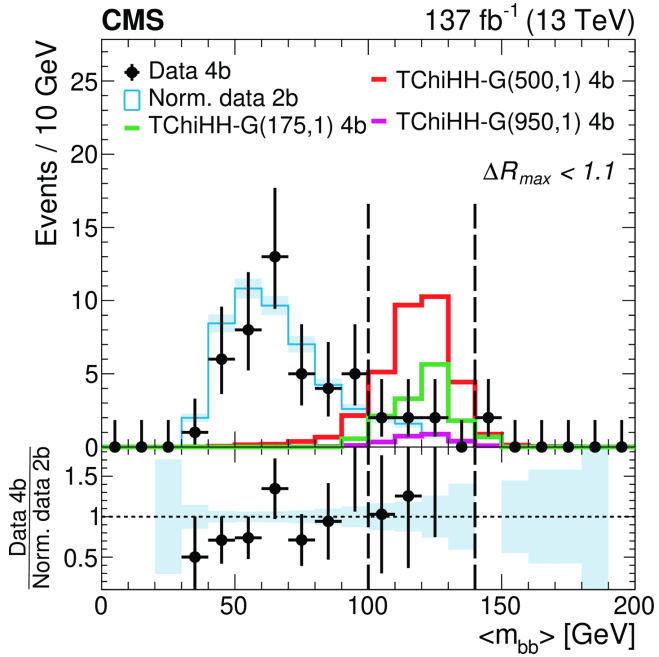
Our group's Run-2 result

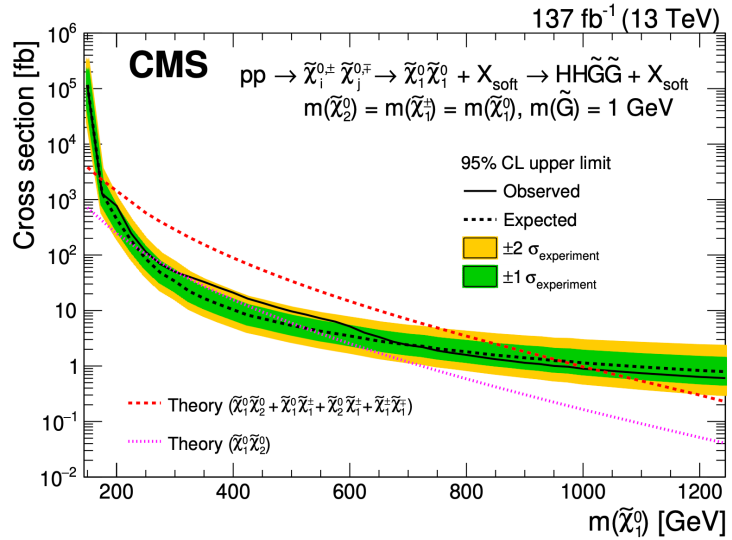
- Split data into 22 categories and apply ABCD method using Higgs mass and b-jet category.

- Set 95% CL limits in $m_{\tilde{\chi}_1^0}$ for simplified SUSY model.

  - **Improved by 30%** compared to previous result.



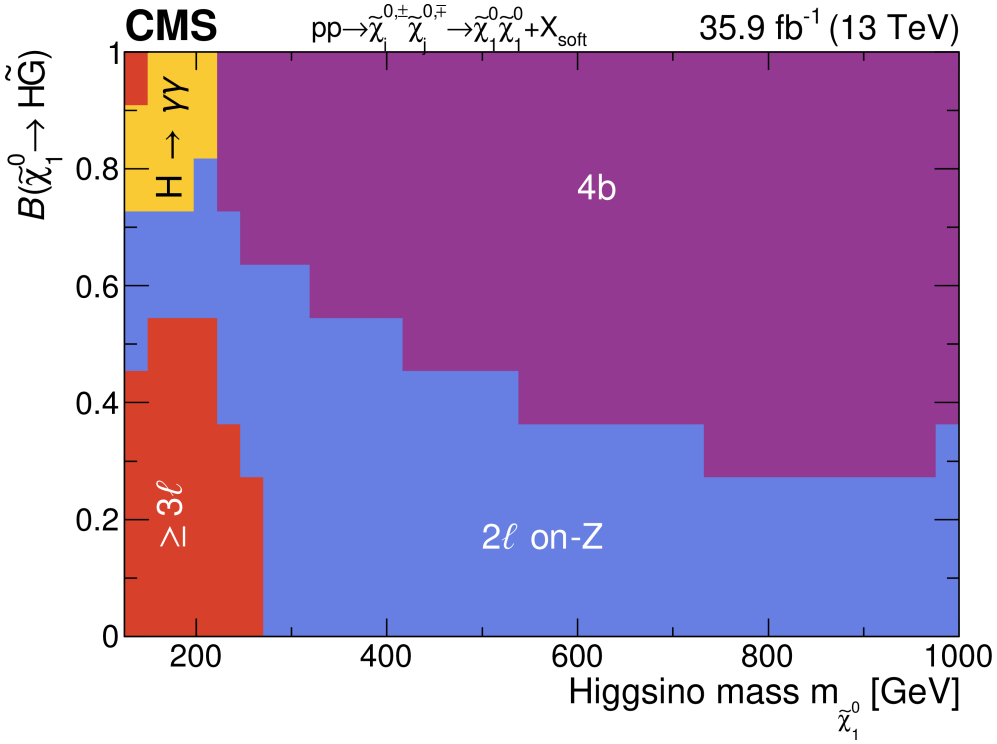




Ongoing research

1. Analyzing neutralinos having different final states

JHEP 03 (2018) 160



- $H(b\bar{b})H(b\bar{b}) + p_T^{\text{miss}}$
- $H(b\bar{b})H(\gamma\gamma) + p_T^{\text{miss}}$
- $H(b\bar{b})Z(\ell\ell) + p_T^{\text{miss}}$
- Adding channels improves model coverage.

2. Enhancing sensitivity to $H(b\bar{b})H(b\bar{b}) + p_T^{\text{miss}}$

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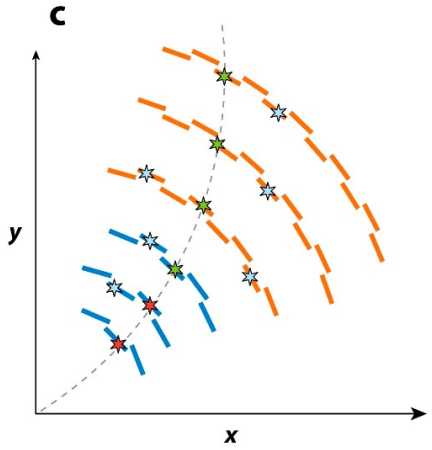

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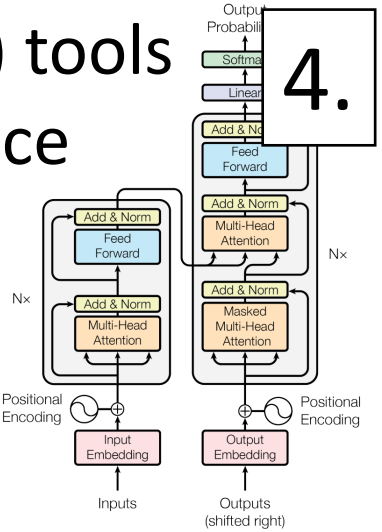


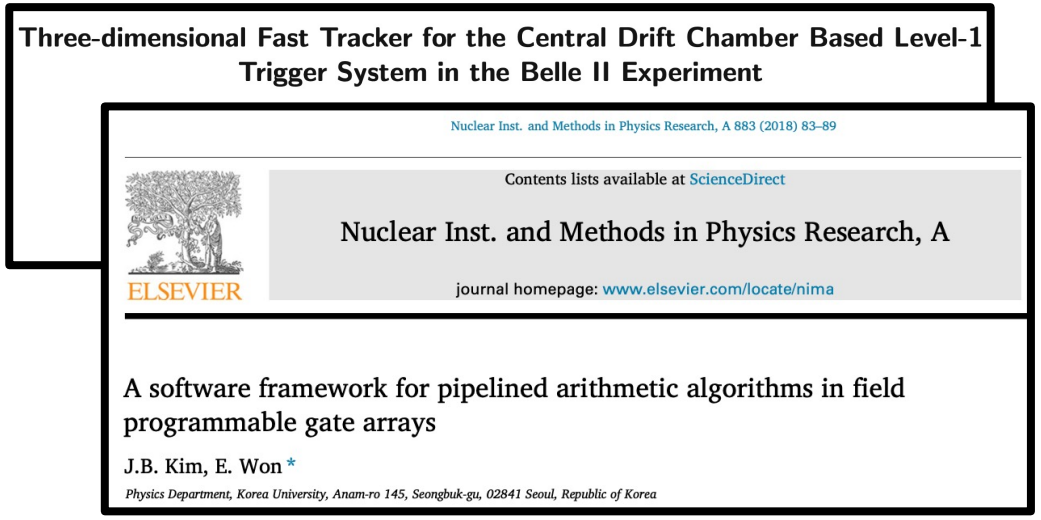
Hardware Trigger research for High-Luminosity LHC (HL-LHC)

Enhancing measurement **efficiencies**

Hardware (level 1) track trigger in experiments

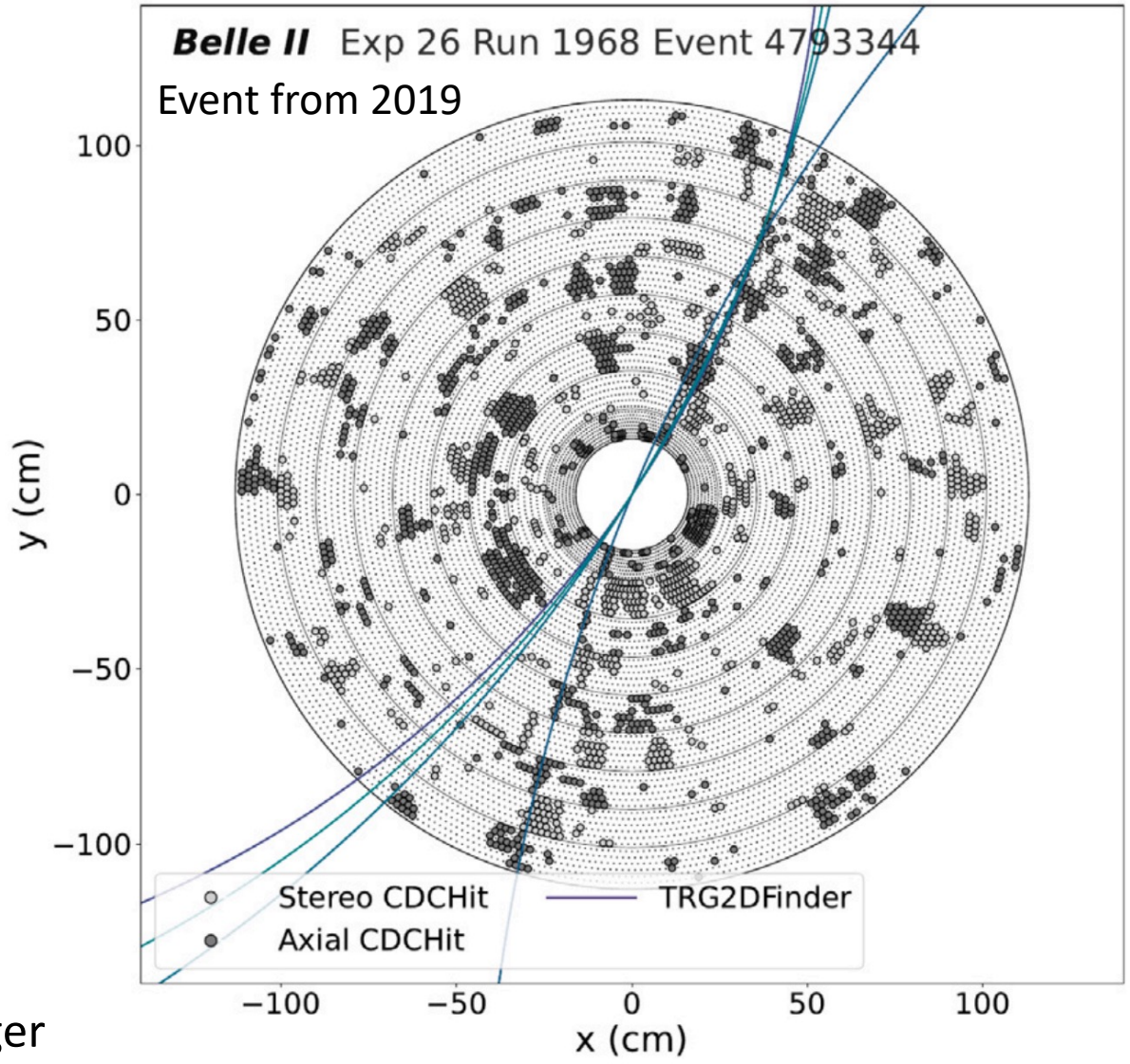
- Hardware track trigger allows highly efficient experiments.

- Developed with FPGAs



My primary author papers using FPGAs for Belle II level 1 trigger

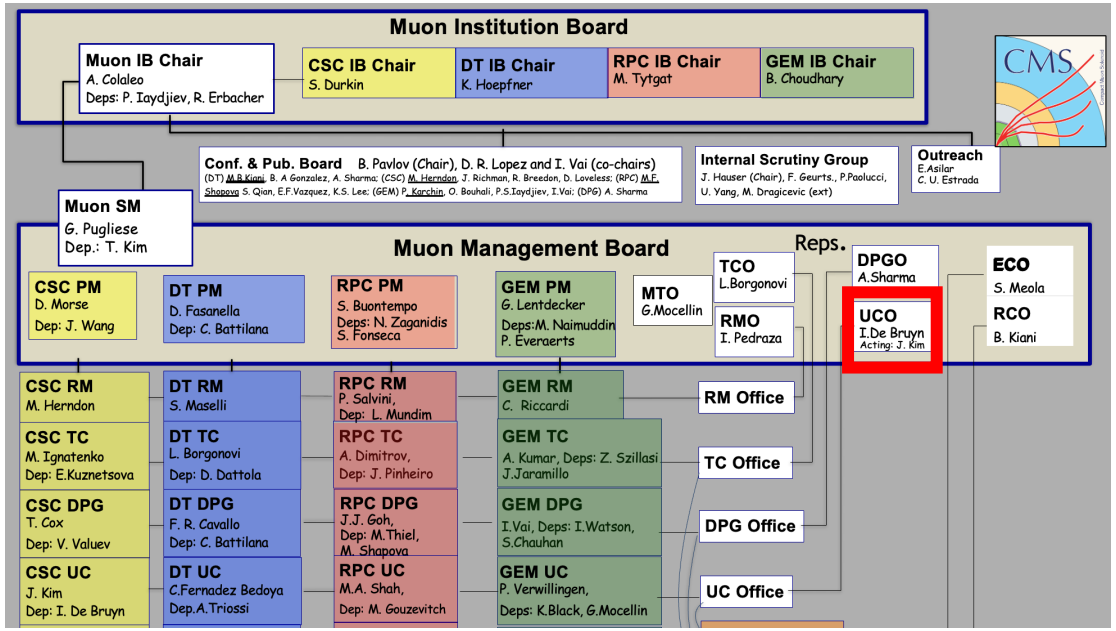
NIMA 1078 (2025) 170577



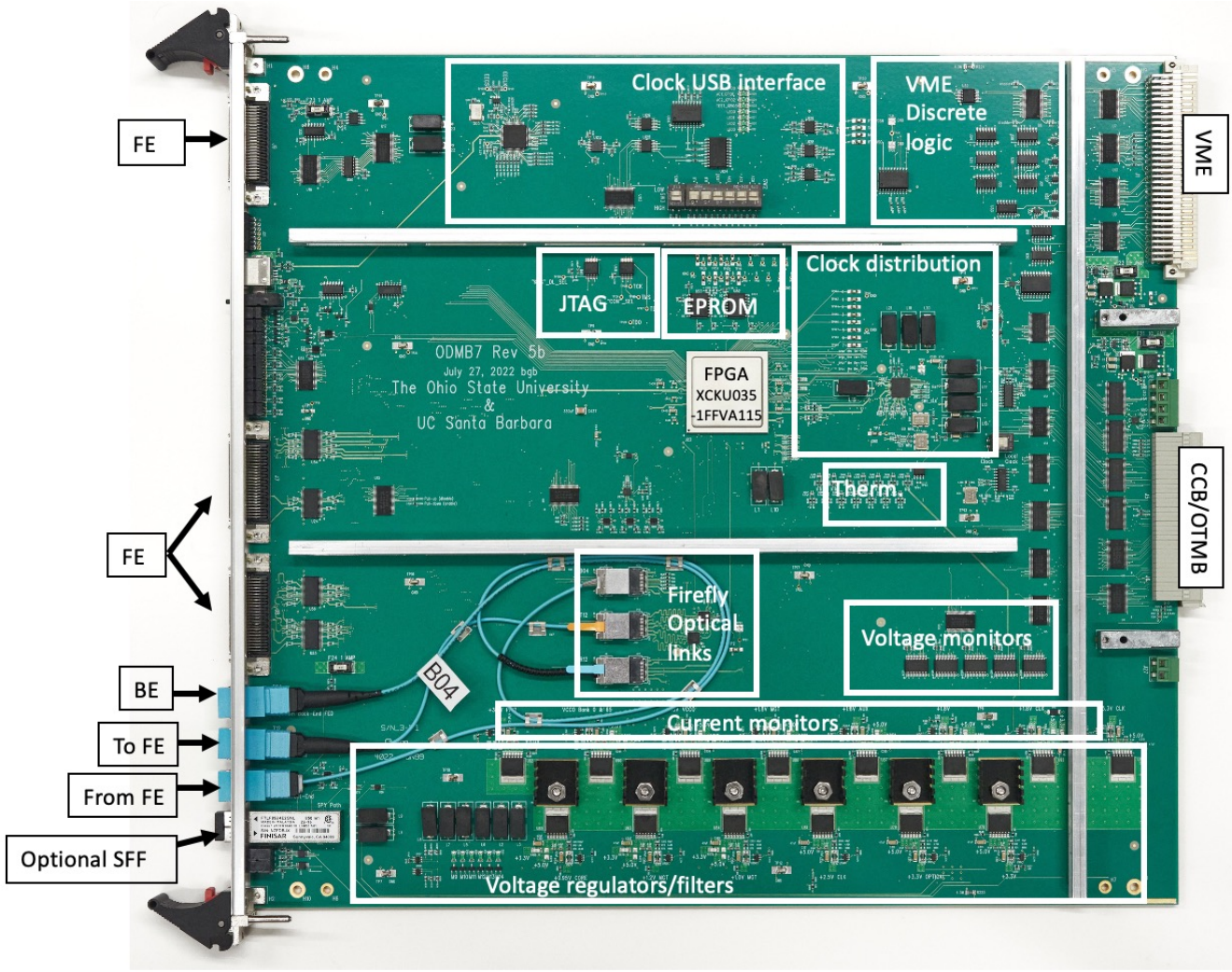
FPGA for experiments

- Developed FPGA board for CMS.

- Served as acting Upgrade coordinator for CMS Muon group.



My co-developed CMS CSC DAQ board



FPGA for experiments

Now helping others learn about FPGAs with support from communittee

Syllabus of "FPGA-BASED DIGITAL SYSTEM DESIGN FOR PHYSICS EXPERIMENTS"

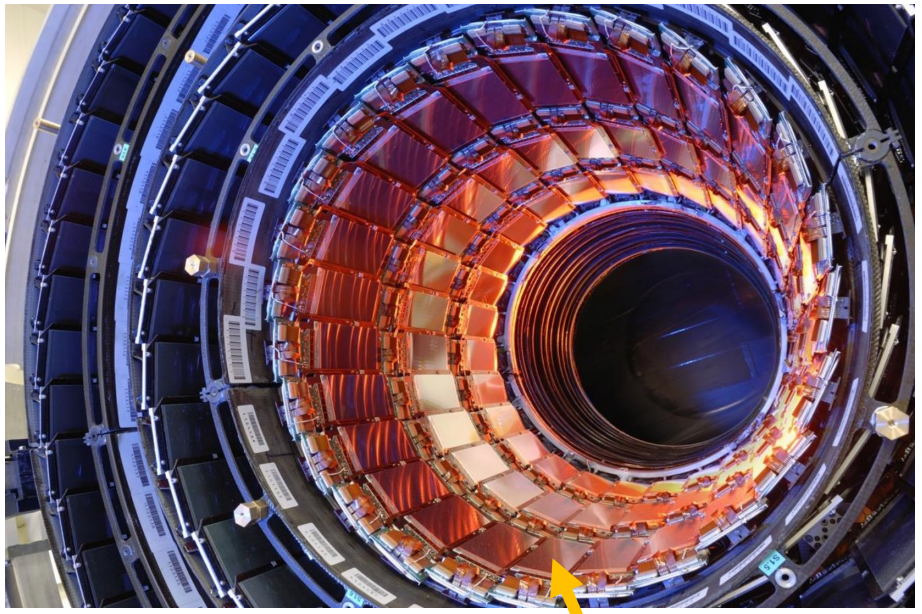
Professor: Jaebak Kim (jaebak@korea.ac.kr)

Course goals:

- Learn about Field Programmable Gate Arrays (FPGA)
- Make firmware for Physics experiments

CMS hardware track trigger for HL-LHC research

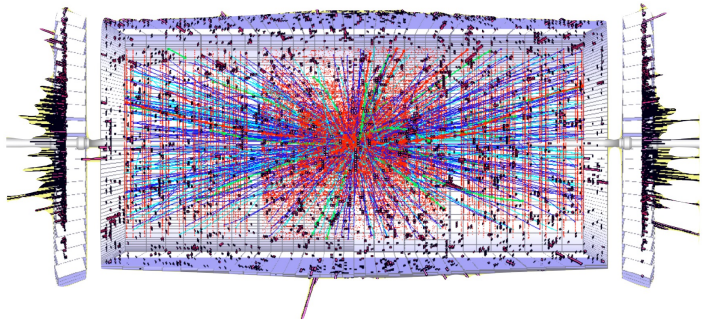
https://cmsexperiment.web.cern.ch/detector/identifying-tracks



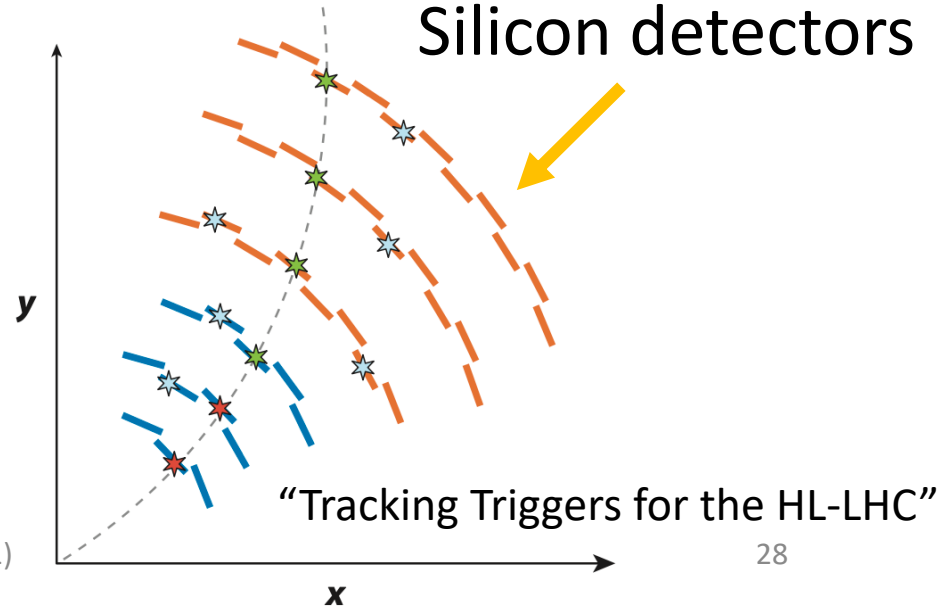
- CMS is developing hardware track trigger for silicon detector for HL-LHC.

- Challenges due to large number of hits at HL-LHC.

"Connecting the dots 2020"



Silicon detectors

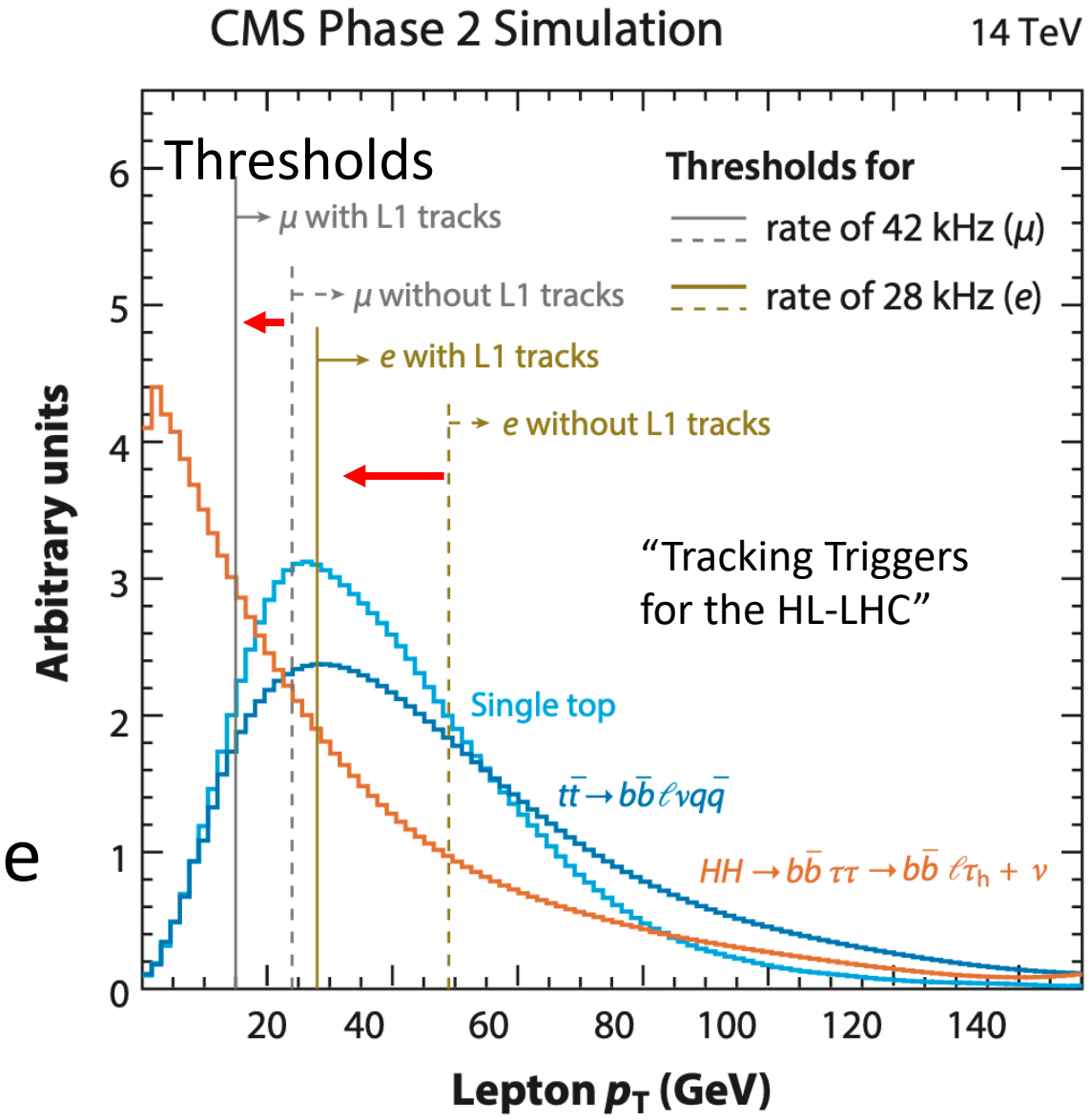


Our group has started working on this project

Track trigger enhance physics sensitivity

- Hardware track trigger increases sensitivity to many physics processes

- Di-Higgs search becomes more sensitive to low m_{HH} region, where Higgs self-coupling contribution is large



Contents for today's talk

Main target

Higgs boson

Production

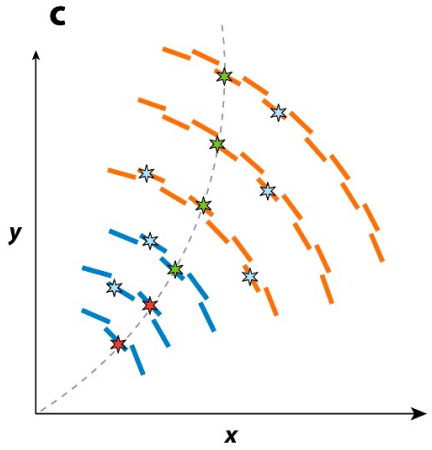
e.g., $HH + p_T^{\text{miss}}$

Decay

e.g., $H \to Z\gamma$

Enhancing

HL-LHC hardware track trigger

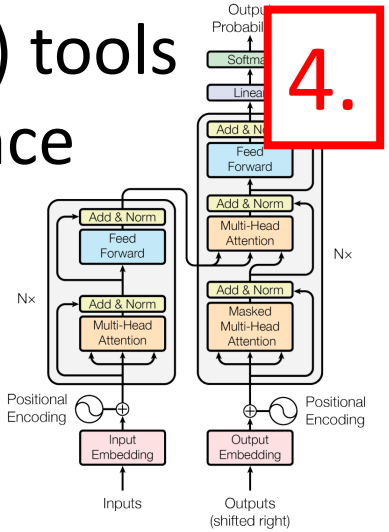


"Tracking Triggers for the HL-LHC"

Machine Learning (ML) tools
E.g., Artificial intelligence

4.

"Attention is All You Need"
Citations 251,236



Transformer

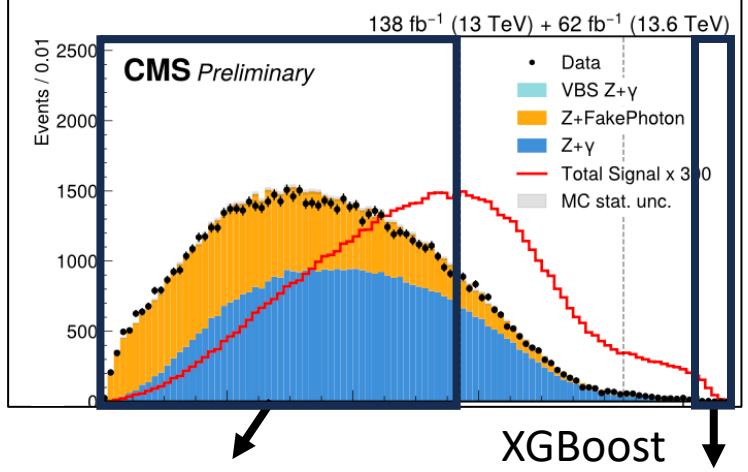
Artificial Intelligence research

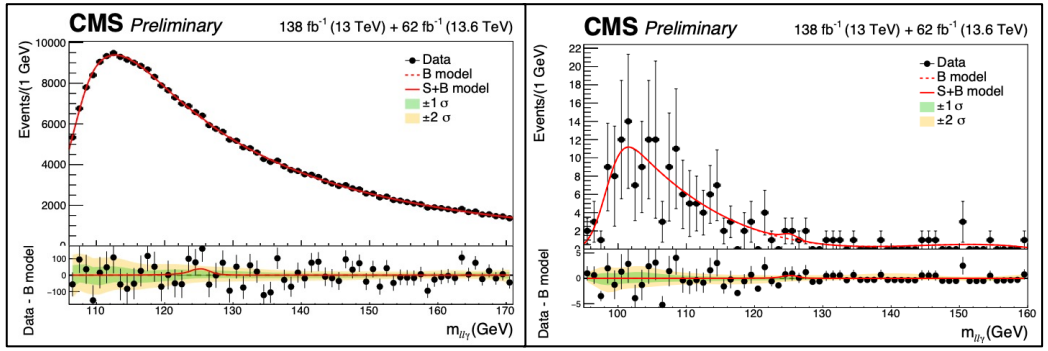
Enhance measurement **sensitivity**

- Analysis strategy based AI classification
- Efficient AI on FPGA
- New platforms for AI

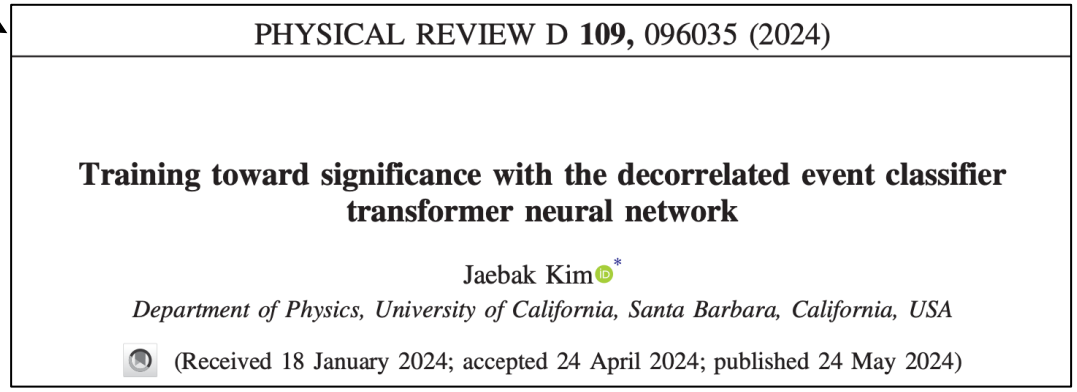
Enhancing $H \to Z\gamma$ with AI

- Machine learning (ML) classifies events into bins. Signal extracted with $m_{\ell\ell\gamma}$ distribution.





- Analysis strategy based AI
  - ➢Optimized for expected significance
  - ➢Avoid sculpting $m_{\ell\ell\gamma}$ distribution


PHYSICAL REVIEW D **109,** 096035 (2024)

Training toward significance with the decorrelated event classifier transformer neural network

Jaebak Kim*

Department of Physics, University of California, Santa Barbara, California, USA

(Received 18 January 2024; accepted 24 April 2024; published 24 May 2024)

- Future research: Consider fit stability.

  Also working on AI for other analysis strategies.

Combining FPGA research with AI research

Nuclear Inst. and Methods in Physics Research, A 883 (2018) 83–89

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

A software framework for pipelined arithmetic algorithms in field programmable gate arrays

J.B. Kim, E. Won *

Physics Department, Korea University, Anam-ro 145, Seongbuk-gu, 02841 Seoul, Republic of Korea

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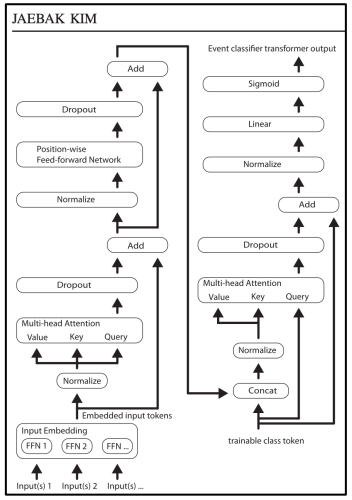

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Training toward significance with the decorrelated event classifier transformer neural network

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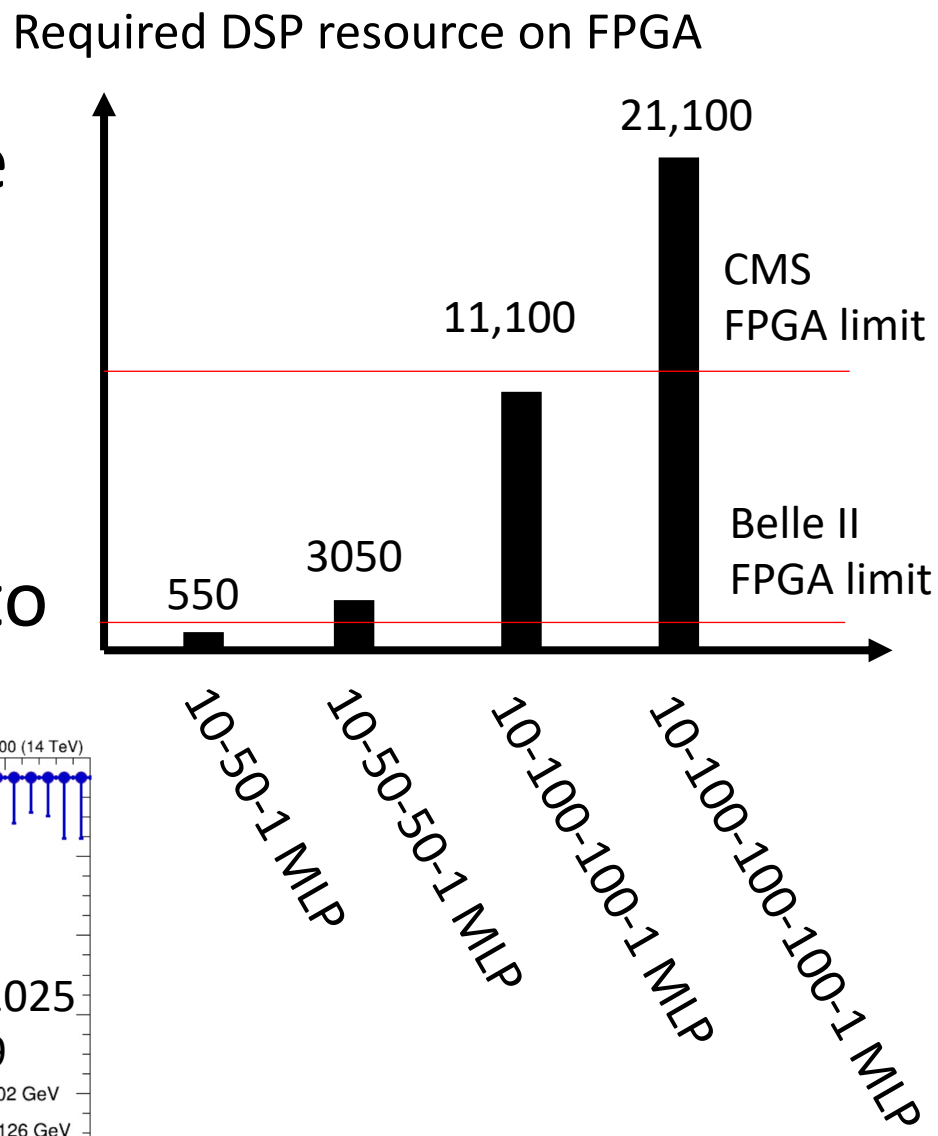
= One of my research directions

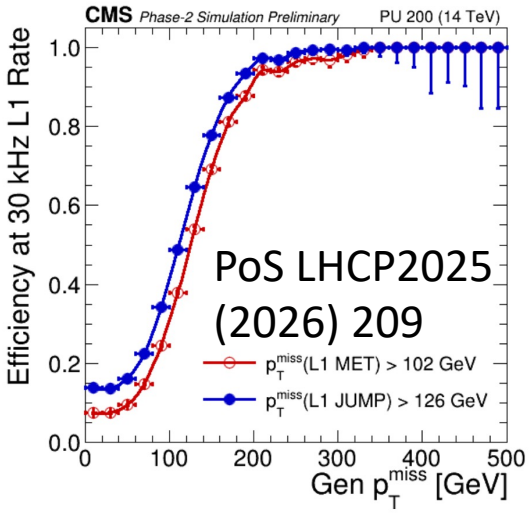
Efficient AI on FPGA

- Difficult to implement large AI on FPGAs due to resource constraints

- Researching efficient ML methods on FPGA to improve p_T^{miss} trigger efficiency



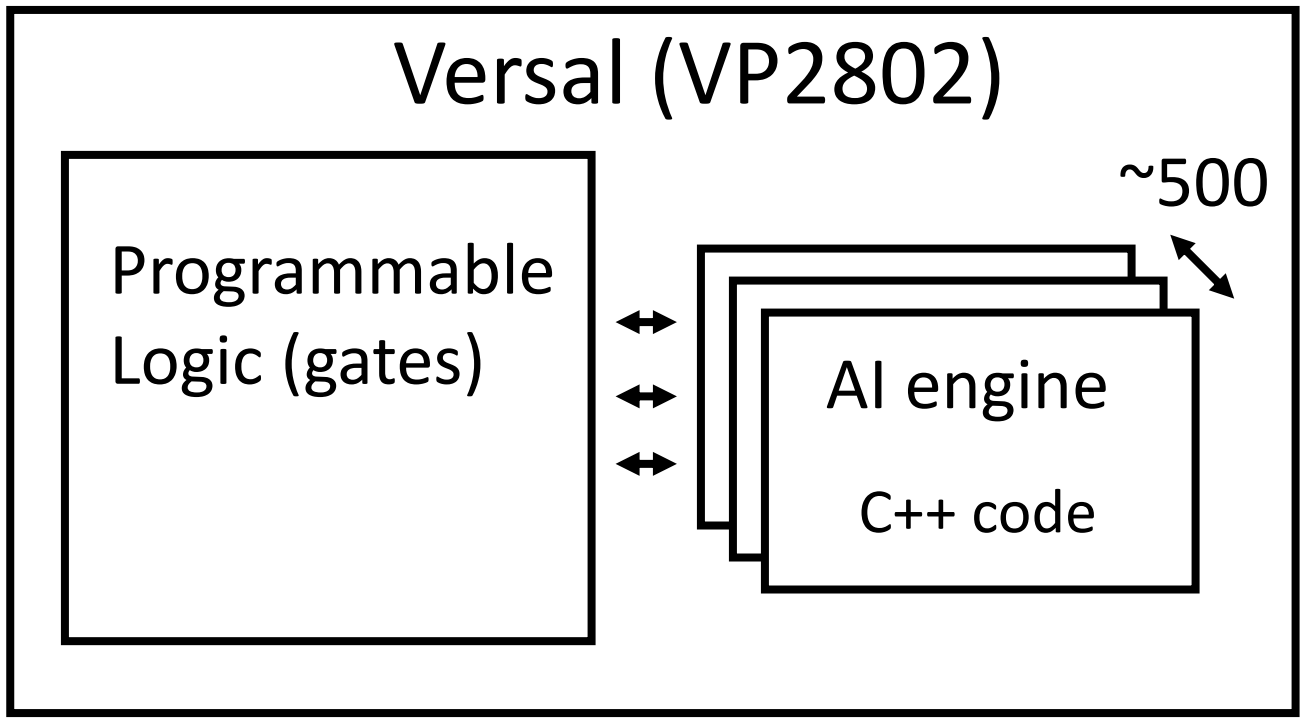
MLP: Multi-Layer Perceptron



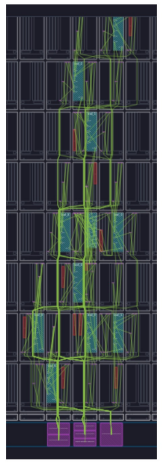
New platforms for AI

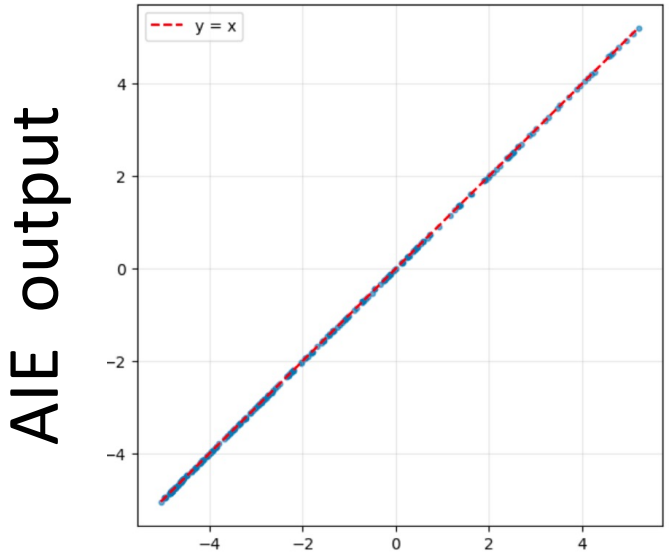
- AMD has Versal FPGAs that have AI Engines (AIE)

- Researching the use of AIE for trigger applications
  - ➢ E.g., BDT on AIEs



AIE tiles



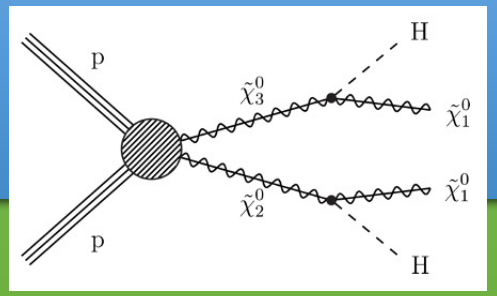


Conclusion: Research program

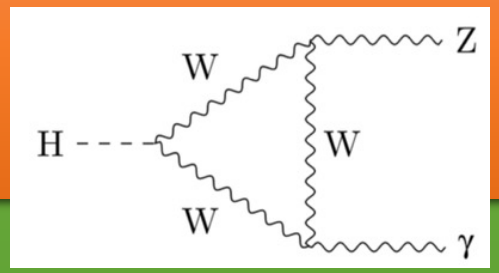
Main target

Higgs boson

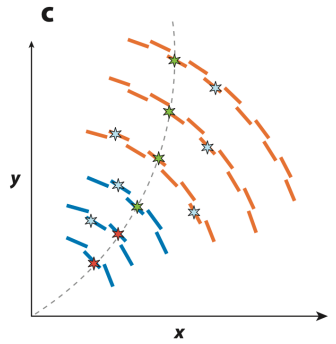
Production



Decay



Enhancing

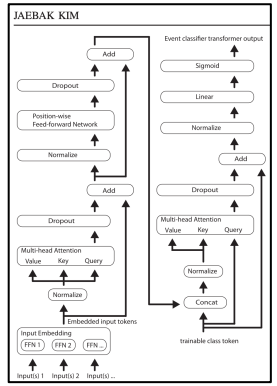


"Tracking Triggers for the HL-LHC"

HL-LHC hardware track trigger (FPGA)

+

Artificial Intelligence research

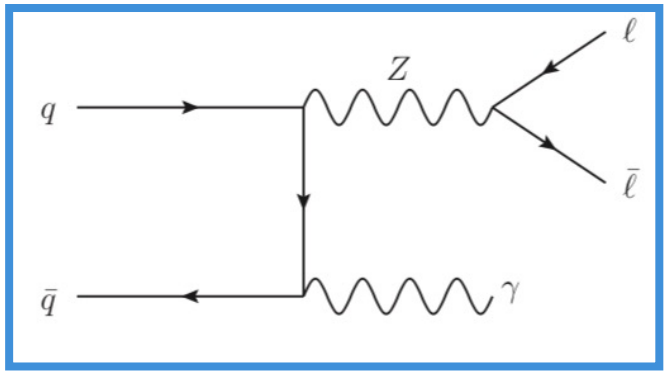


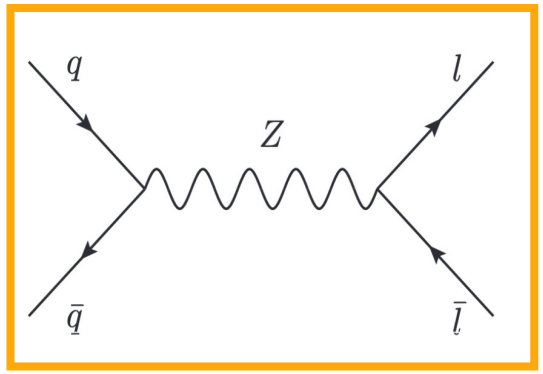
Probing nature with Higgs boson.
Enhancing with trigger and AI.

Backup

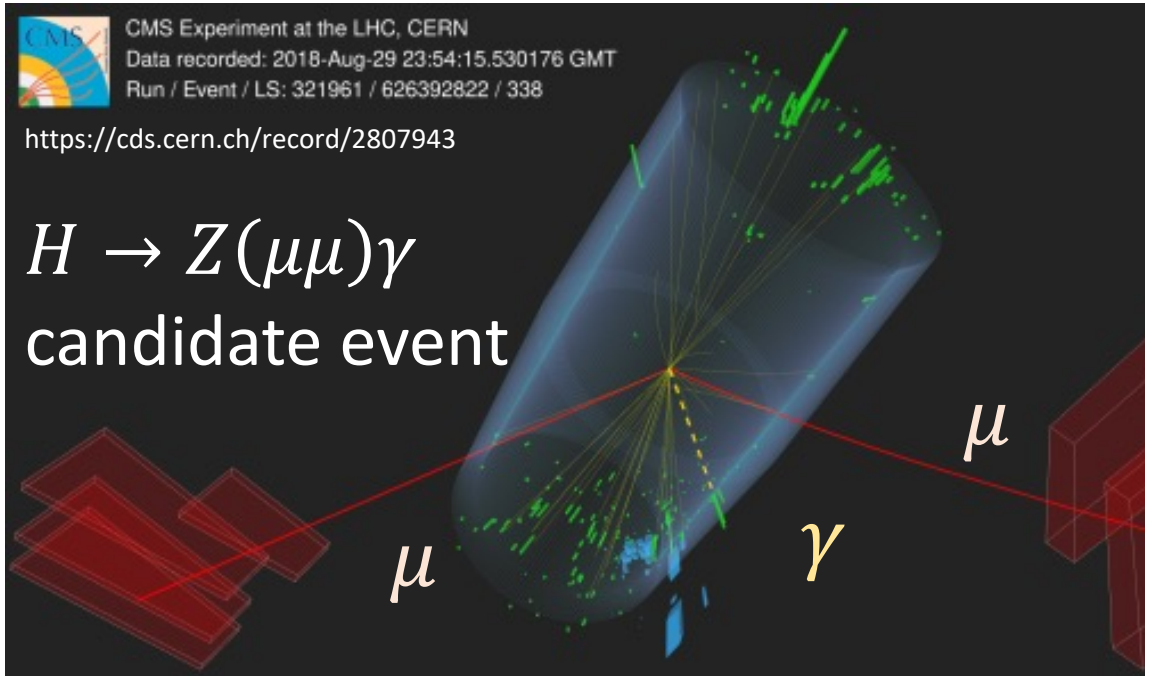
Analysis strategy

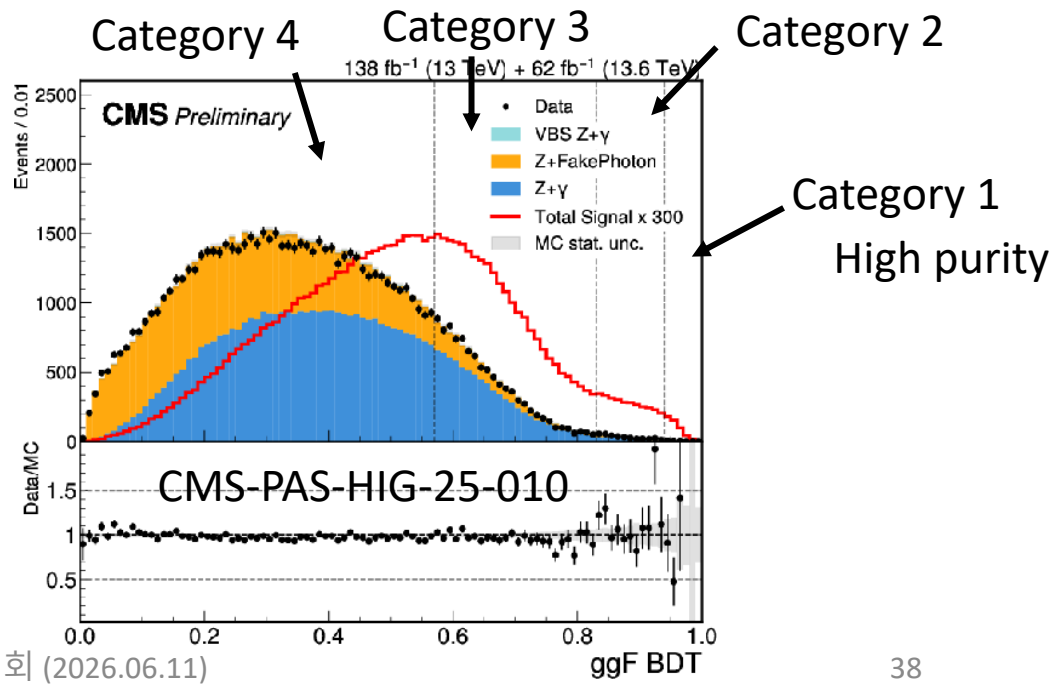
- Reconstruct $Z(\ell^+\ell^-)\gamma$
  - ➢Backgrounds: $Z\gamma$, Z + fake γ





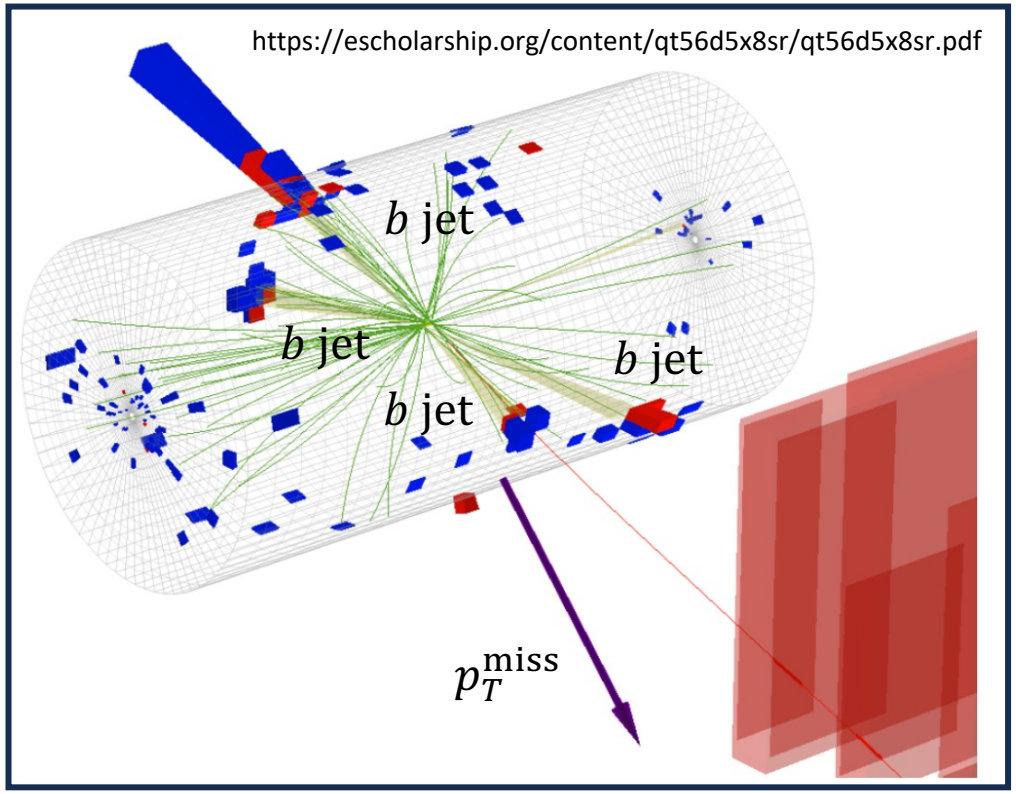
- Use BDT to categorize events to enhance sensitivity

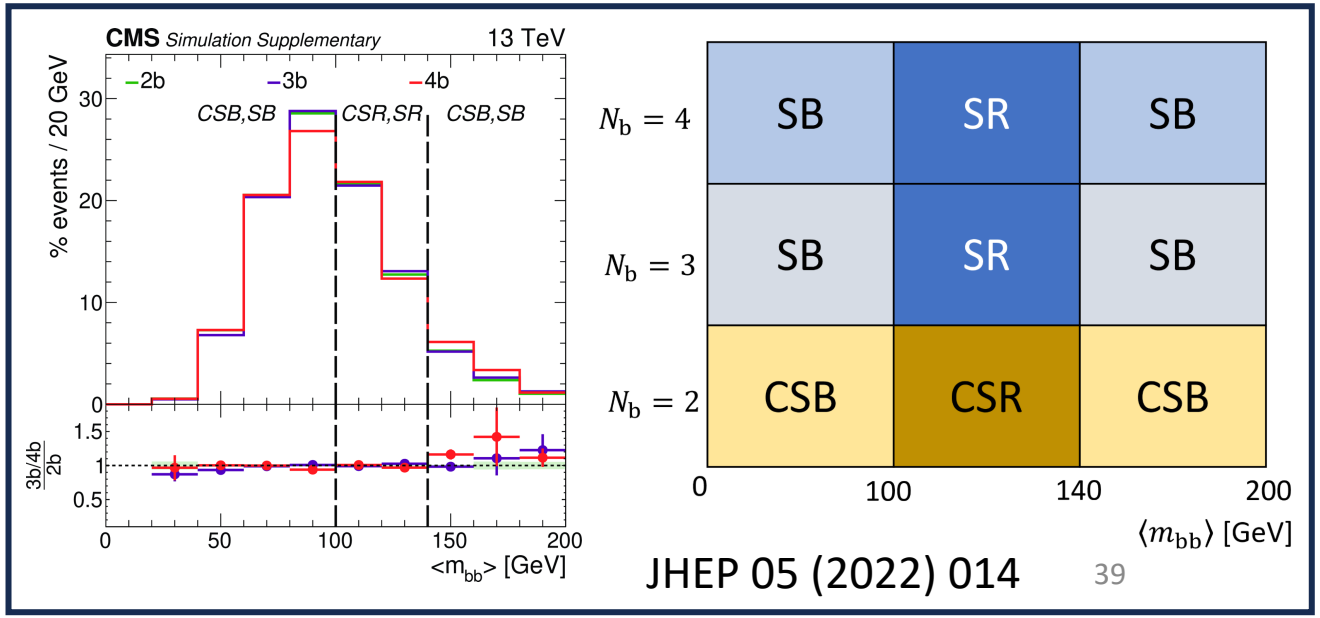




Analysis strategy

- Reconstruct Di-Higgs, with each Higgs from two b-jets.
  - ➢ $H(b\bar{b})H(b\bar{b}) + p_T^{\text{miss}}$
- Background: $2b$-jet + fakes
  - ➢ $t\bar{t}$ and $Z \to \nu\bar{\nu}$ processes
- Extract signal with ABCD method





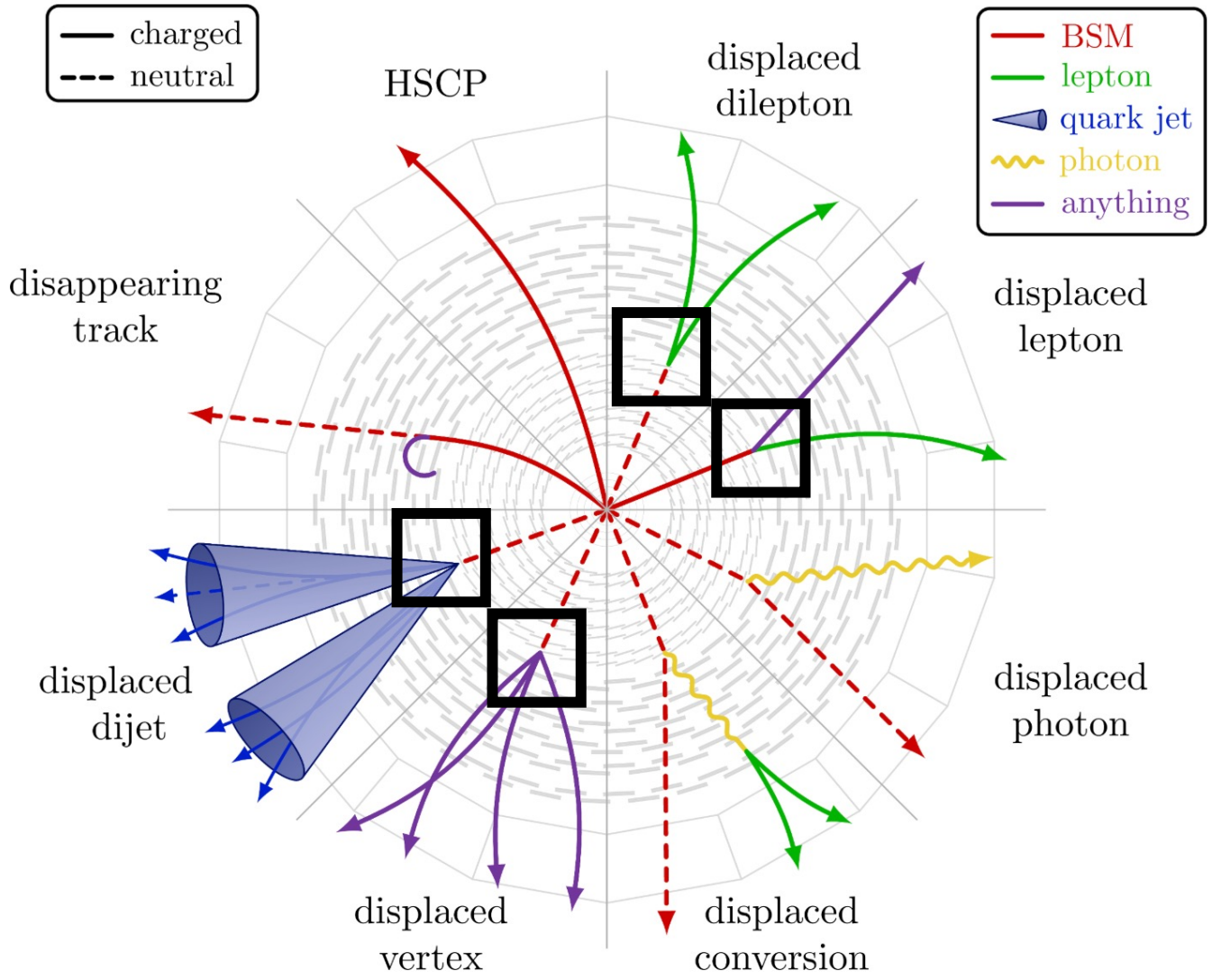
JHEP 05 (2022) 014

CMS displaced track hardware trigger research

- CMS is also developing a displaced track trigger, that enhances sensitivity to BSM long-lived particles.

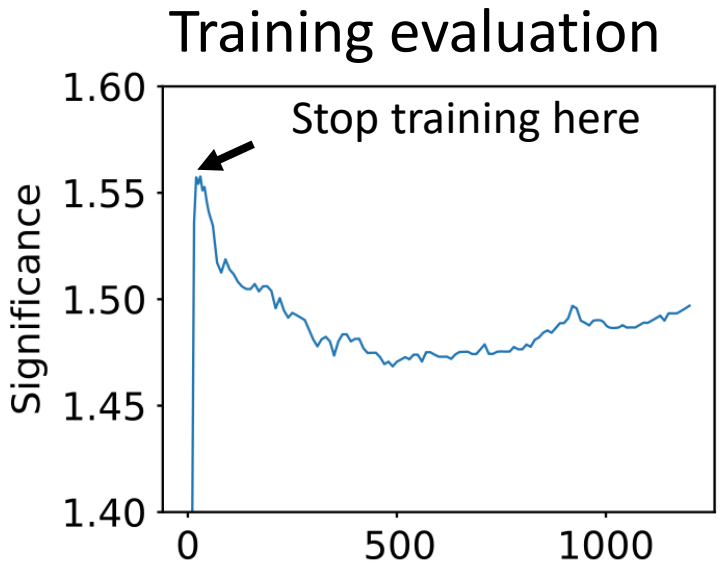
Our group is focusing on displaced tracks

https://tikz.net/bsm_longlived/

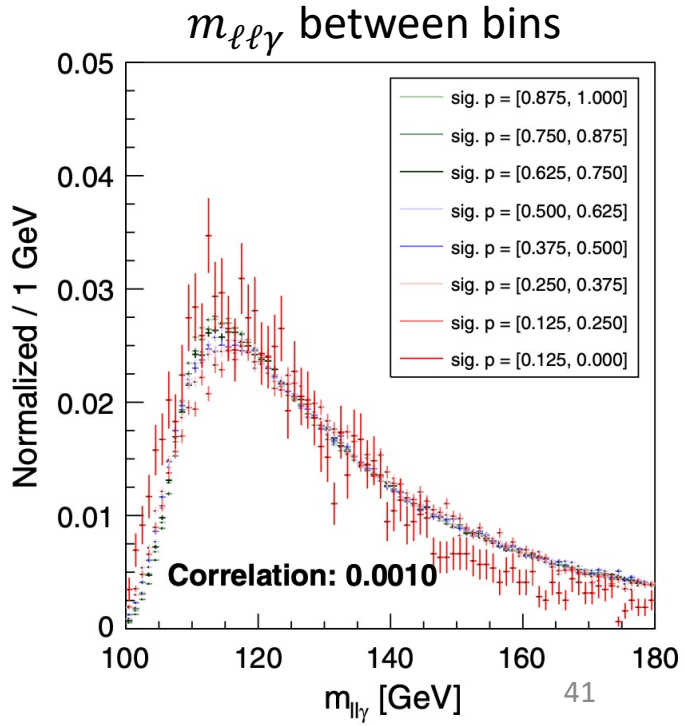


Enhancing $H \to Z\gamma$ with AI

- Optimized for expected significance
  - ➢Loss and “early stopping” based on significance.
  - ➢Use effective Transformer architecture
    = Foundation of modern
    Large Language Models
- Avoid sculpting $m_{\ell\ell\gamma}$ distribution
  - ➢Use distance-correlation regularization
    “Robust jet classifiers through distance correlation”
- Future research: Consider fit stability.
  Also working on AI for other analysis strategies.



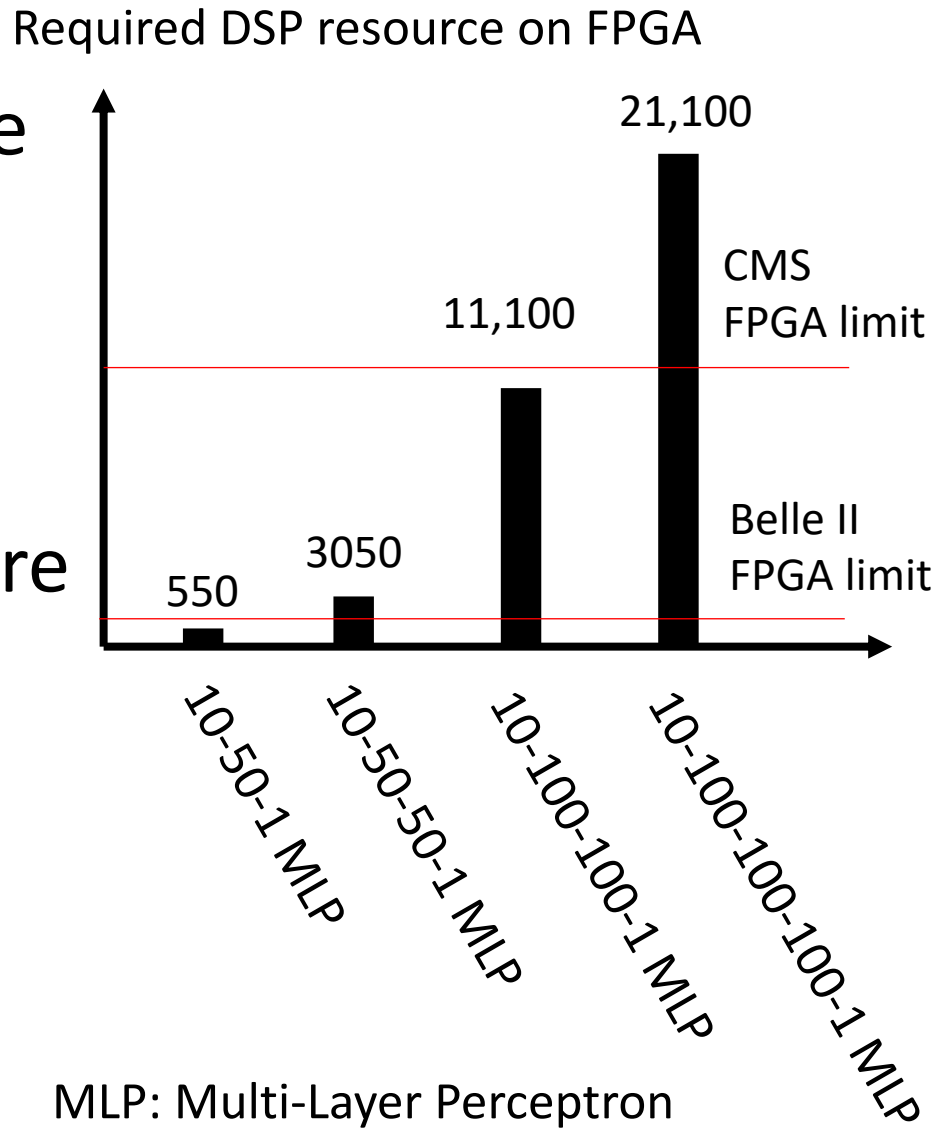
PRD 109, 096035 (2024)



Efficient AI on FPGA

- Difficult to implement large AI on FPGAs due to resource constraints

- Need to optimize neural network architecture for FPGAs
  - ➢ E.g., Alternative network structures, pruning nodes, reducing bits, …



MLP: Multi-Layer Perceptron

Efficient AI on FPGA research

- Researching ML methods on FPGA to improve p_T^{miss} trigger efficiency

• Researching ML methods on FPGA to improve p_T^{miss} trigger efficiency

PoS LHCP2025 (2026) 209

- Efficient ML on FPGA can also be used to develop “smart sensors” to reduce trigger rates

“Smart pixel sensors: towards on-sensor filtering of pixel clusters with deep learning”