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Machine Learning for Detection of Low-Energy Photons in the EIC ZDC

EIC Generic R&D 2022 Proposal
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Lynn Wood, Jan Strube, Deven Misra (PNNL)
Michael Murray (U. Kansas)
Yuji Goto, Shima Shimizu, Minho Kim (RIKEN)
Charles Hyde, Vitali Baturin (Old Dominion U.)
Aleksandr Bylinkin (U. Bergen)
Edmundo Garcia (Chicago State U.)

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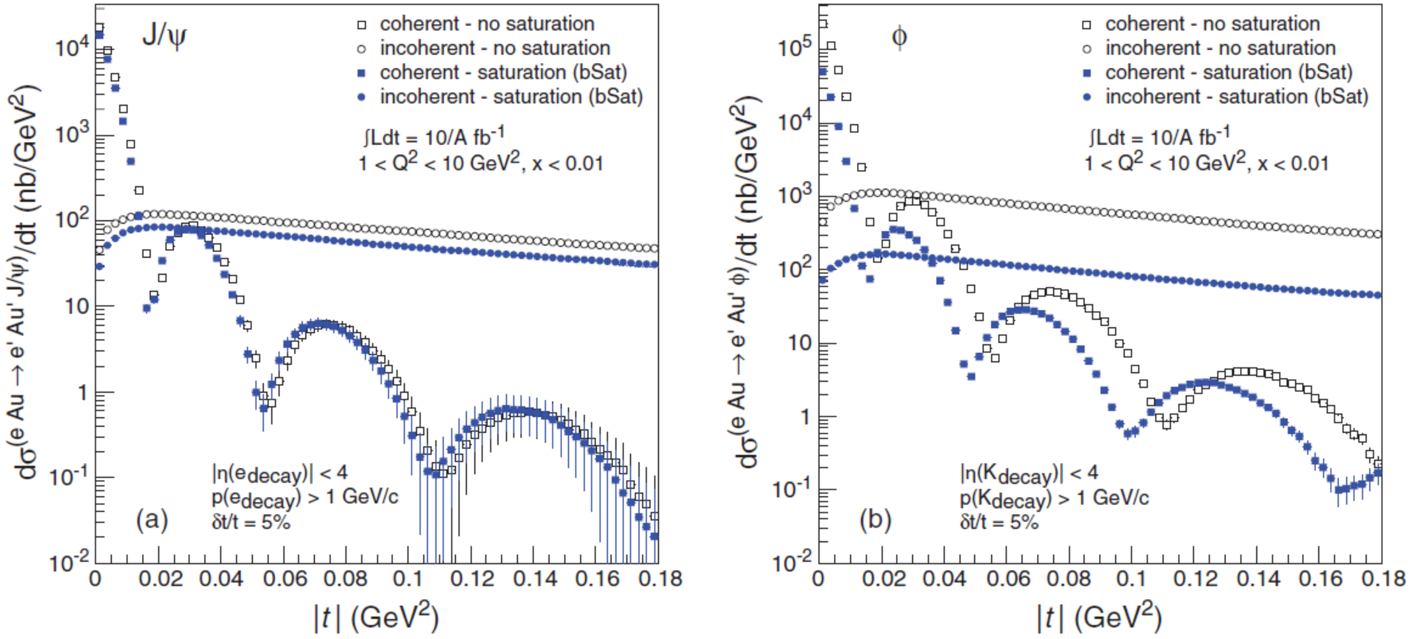
Identifying Event Types with the Far-Forward Detectors

Separating coherent and incoherent production is critical for using vector meson production for nuclear imaging and studies of gluonic fluctuations

The far-forward detectors are critical for distinguishing between:

- coherent diffractive scattering
- incoherent scattering where the nucleus breaks up
- incoherent excitations of the nucleus



Incoherent breakup of the nucleus can relatively easily be identified by detection of spectator neutrons in the ZDC or charged fragments in the Roman Pots

Incoherent excitations are more challenging...

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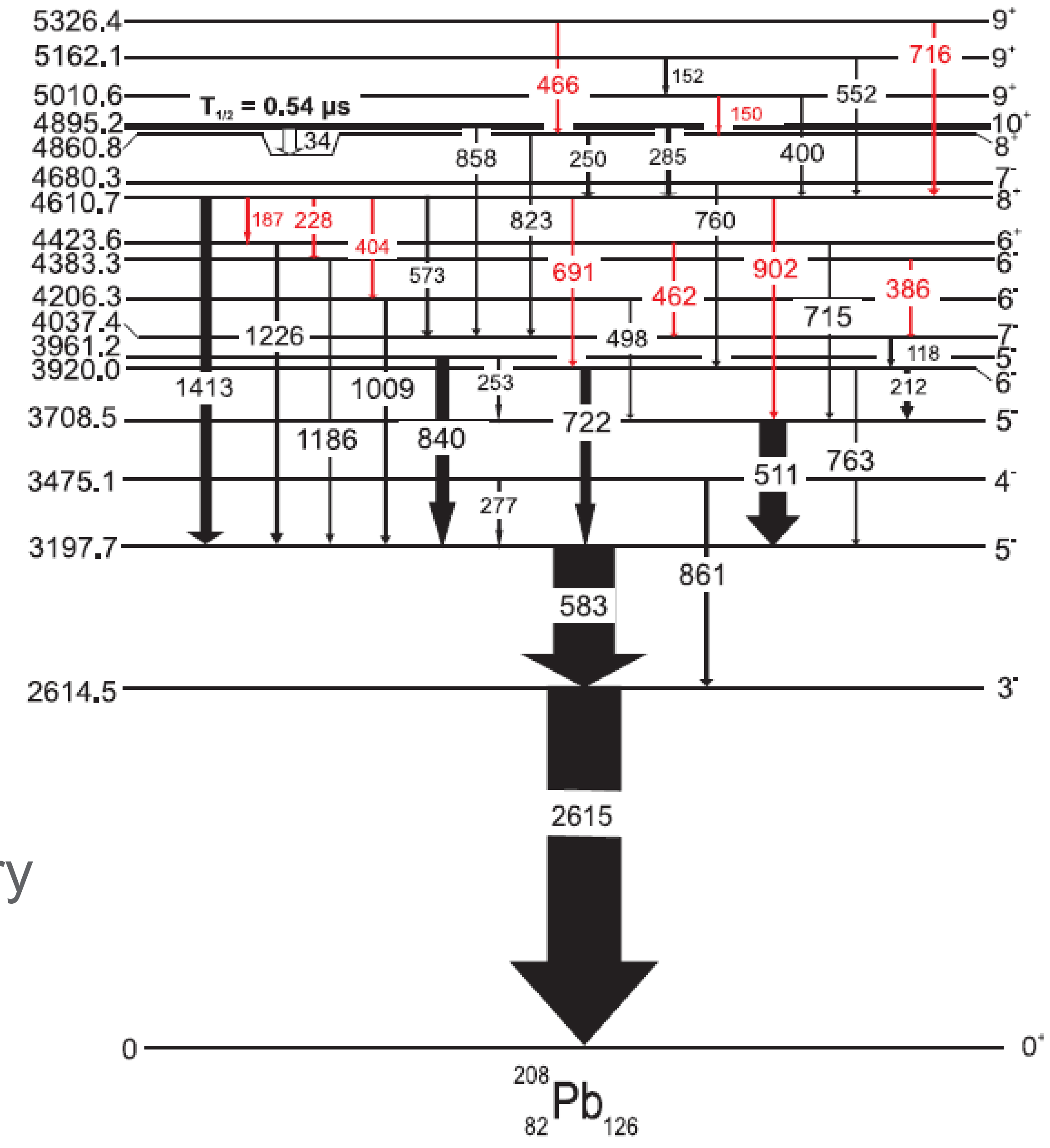
Soft Photon Detection Can Help Veto Incoherent Excited Nucleus Events

The photon decay chain of an excited heavy nucleus is dominated by ~few keV photons – but for doubly-magic nuclei such as ^{208}Pb, every bound-state decay sequence has at least one photon with energy of at least **2.6 MeV**

Assuming a nucleus boost of ~100 GeV/c per nucleon, that photon energy becomes **455 MeV** (or more)

This “soft” photon falls within the ZDC aperture (~4.5 mrad) 20% of the time in the current EPIC geometry

ZDC performance requirements for these photons is >90% detection efficiency, but it has not yet been widely studied – and not in the presence of event backgrounds

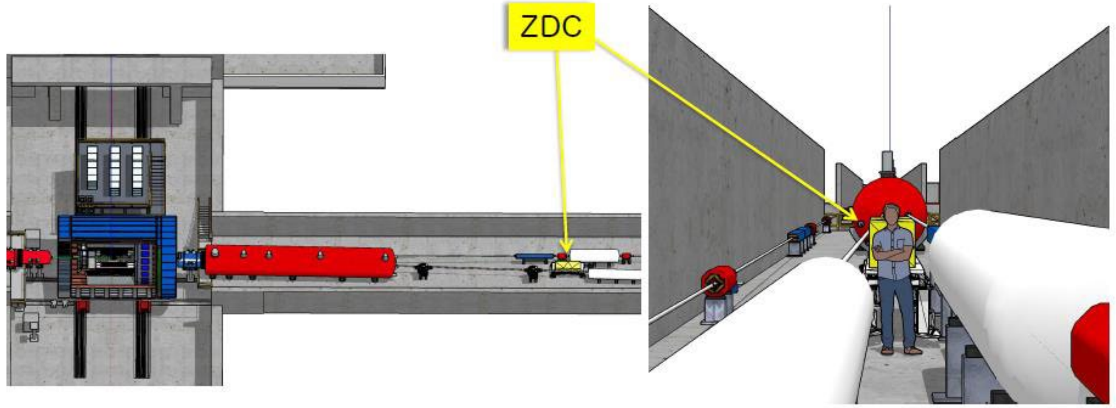


Broda et al., Phys Rev C ***95*** *064308 (2017)*

The Zero Degree Calorimeter (ZDC)

The ZDC is critical for:

- identifying coherent vs. incoherent scattering
- e+A collision geometry measurements
- spectator tagging in e + d/3He
- Asymmetries of leading baryons
- Spectroscopy



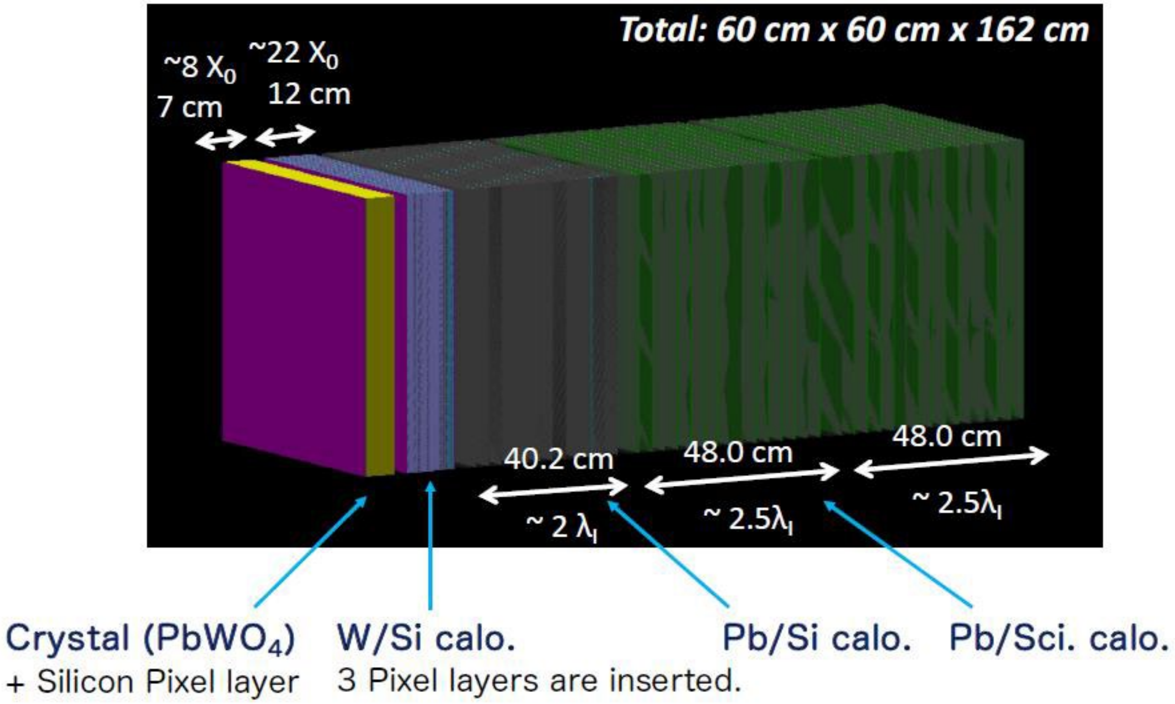
Current design consists of 64 layers:

- 1 x pixelated Si (3mm x 3mm)
- 1 x PbWO4 crystals (3cm x 3cm x 7cm)
- 4 x W/pixelated Si (3mm x 3mm) + 20 x W/pad Si (1cm x 1cm)

EMCAL

- 12 x Pb/pixelated Si (1cm x 1cm)
- 30 x Pb/scintillator (10cm x 10cm)

HCAL

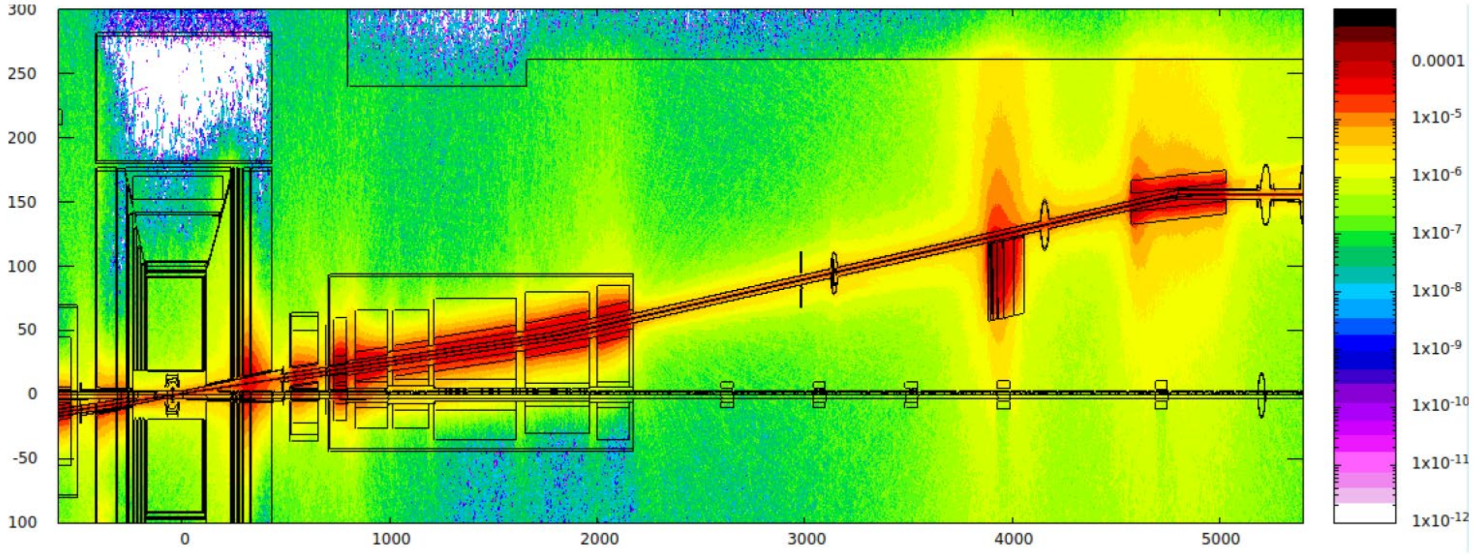


Backgrounds Will Interfere With Soft Photon Detection

There are many sources of background in the far-forward region:

- Neutrons and photons from e and p interactions with the beampipe
- Neutrons from proton-gas interactions in the beam line
- Pion decays and conversions from the IR

Some background analyses have been done for potential Si damage from neutrons



Unfortunately, simulations of **event** backgrounds have not yet been done and proper event mixing is still not present in the current EIC software framework

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Machine Learning Approaches

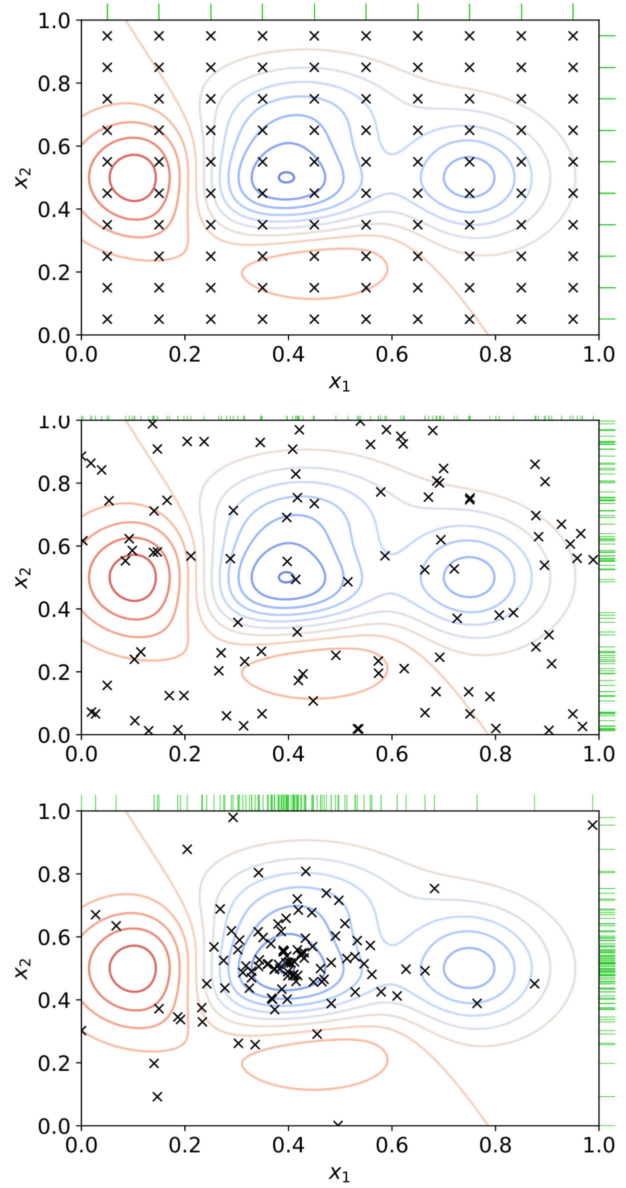
The ability to clearly identify soft photons will depend on the resolution of multiple detector parameters (energy, position, timing, etc.)

- There are many potential parameters (channels) in the ZDC

Hyperparameter Optimization is a machine learning method of tuning for a set of optimal hyperparameters, which are used to control the values of actual parameters (e.g. by weighting)

- Different optimization methods are possible: exhaustive grid search, random search, Bayesian, gradient based, etc.
- These results will not only identify what parameters are most important to identifying soft photons, but can also provide input as to optimal required resolutions and/or improved detector designs

This will also help ensure that this physics channel will not be affected by any potential data reduction or compression measures taken to reduce data flow to the DAQ system



Other Potential Machine Learning Approaches

The combination of the spatial and temporal structure of neutron vs. photon clusters could be accommodated by **Graph Neural Networks**, which have been used with some success to reconstruct high-energy clusters in the CMS HGCAL. The extension to lower energies and incorporation of time information would likely require more significant development, with relevant expertise at PNNL.

Two-dimensional "jet image" methods have applied **Convolutional Image Recognition** networks to the reconstruction of events in 2D at the LHC and in the MicroBoone liquid argon TPC. These methods could be extended to the 3D structure of the ZDC, with the further addition of shower timing information.

While our optimization will initially be limited to low-energy physics, it is quite likely that findings translate to the general case, particularly since we intend to include background in our simulation.

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Work Done So Far

Current EIC work at PNNL is being funded on DOE SULI internship and program development funds for supervision

Efforts have focused on getting the dd4hep ZDC simulation up and running

- Currently pioneering the validation of dd4hep geometry and detector simulation
- Submitted various issues and pull requests for dd4hep and ZDC

Next steps:

- Digitization not in the geometry design, must be done in software – preliminary code
- Initial support for machine learning development

Proposal Tasking

1) Generation of simulated data and backgrounds as a training set [RIKEN, Bergen, Old Dominion, Chicago State]

- RIKEN and U. Bergen are experienced with far-forward detector simulations
- Old Dominion has investigated beam backgrounds previously
- Chicago State is closely involved with the ALICE FoCal, on which the current ZDC design is based

2) Development of an initial ML method for identifying low-energy photons [PNNL, Kansas]

- PNNL has extensive ML capabilities and has successfully implemented ML models on high-energy physics detectors at the Belle II experiment at KEK.

3) Evaluation and optimization of the method [PNNL, Kansas]

- Iteration and improvement, including potential optimization of transverse segmentation of various layers.

4) Investigation and identification of further possible work [all]:

- Generalizing the solutions identified for other far-forward particle ID capabilities → *Transfer Learning*
- Evaluation of scaling the ML method to support real-time analysis on the detector

Resources Required

PNNL – project management, machine learning model development and optimization

- Staff support for project management and supervision of students and junior staff

University of Kansas – simulation, machine learning model development and optimization

- Grad student support, including partial year spent at PNNL

RIKEN – ZDC geometry and simulations

- *No funding is requested*

Old Dominion University – far-forward backgrounds

- Postdoc support for background generation

University of Bergen – calorimeter simulations

- *No funding is requested*

Chicago State U. – input from FoCal development and simulations

- *No funding is requested*

Every effort will be taken to leverage student support programs (SULI, SCGSR, NSIP, Young Women in Science, etc.)

PNNL also has strong internal support for internship programs with MSI, including involvement in NNSA's MSIPP program, an existing relationship with U. Hawaii and a new partnership with U. Texas El Paso

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Maximizing Detection Efficiency of Soft Photons Maximizes Physics

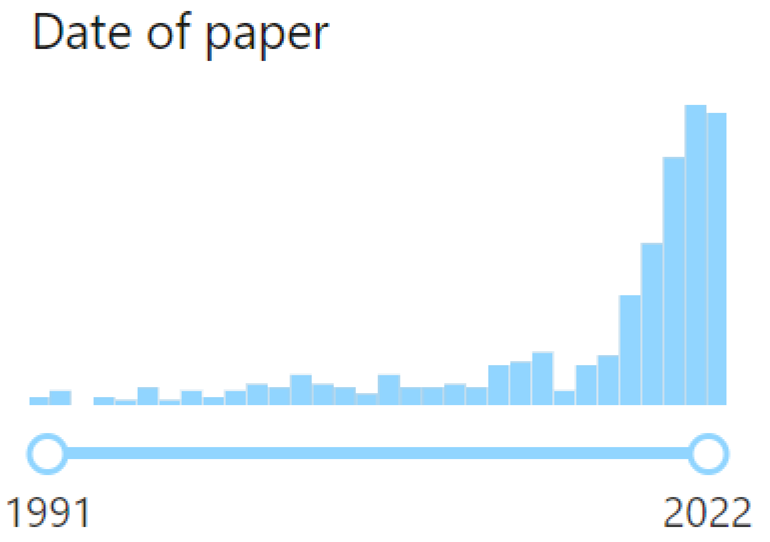
The need for tagging of soft photons to identify incoherent excitation is called out as a fundamental requirement in the Yellow Report – we propose to improve upon traditional methods to maximize physics

Why Machine Learning?

Driven by modern computing capability and “big data”, machine learning is rapidly becoming a critical tool in our field of research, with many potential applications

This proposal is one such application, where the ability of a machine learning model to simultaneously analyze and optimize across many channels of data is likely to provide improvements over the current deterministic analysis methods

Inspire-HEP search – Nov 2022



Nuclear physics articles that mention machine learning

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Extra Slides

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