FPGA for real-time tracking at LUXE experiment

Basic introduction

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SFT meeting 20-07-2023

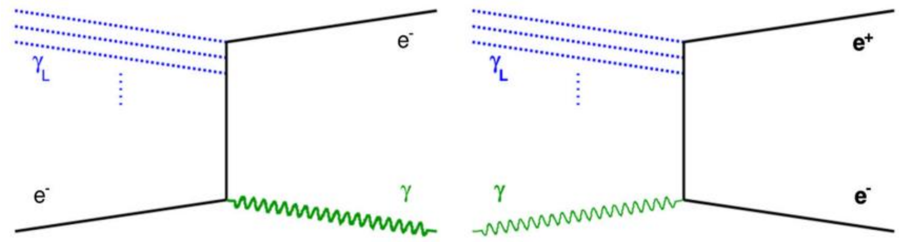
LUXE Experiment

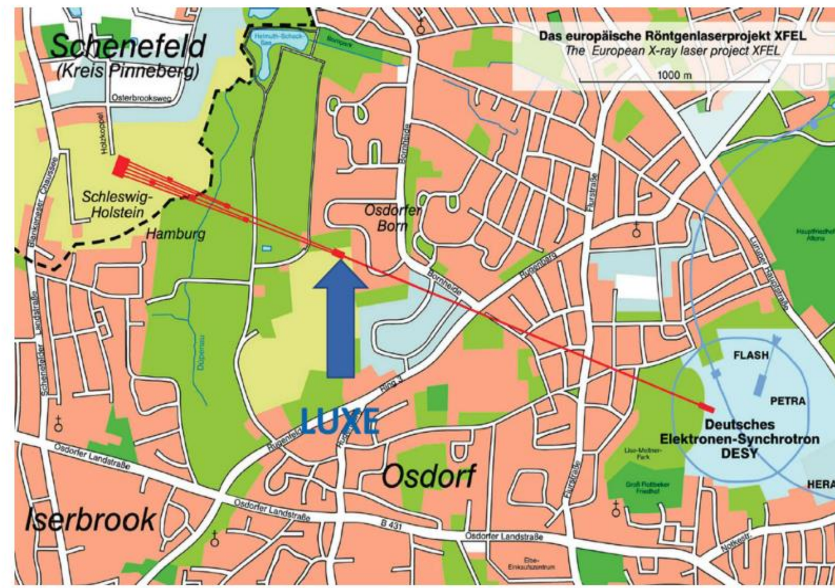
LUXE – LASER und XFEL Experiment

Basic introduction

LUXE aims to explore QED under the high-intensity/high-energy conditions by:

- High-energy electron-photon and photon-photon interactions in the extreme conditions provided by an intense laser focus
- The goals of the Experiment is to exploit:
  - A precision measurements for the field strengths where the coupling to charges becomes non-perturbative
  - High photon flux predicted will enable a sensitive search for new physics beyond the Standard Model
- The initial phase will employ an existing 40 TW laser
- The second phase will utilize a laser power of 350 TW





From perturbative to non-perturbative QED

BOTTOM UP

- Even if we start from our best knowledge of QFT, we can't find an exact solution to our problems
- One has to make approximations (based on educated assumptions) to get close enough to the exact solution

$$y(x) = y_0(x) + \epsilon y_1(x) + \epsilon^2 y_2(x) + \ldots$$

LO NLO NNLO …

- Assuming $\epsilon \ll 1$, each successive power of it is going to be smaller

- Although the perturbation theory has the potential to make it possible to approximate quantities and make predictions, it's not a Cakewalk
- For example, It can be challenging to make expansions of all the field operators in terms of creation and annihilation and truncate their series correctly

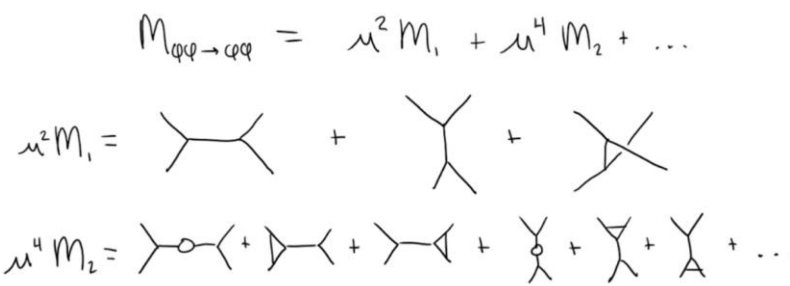
$$\hat{M}_{e^+e^- \to e^+e^-} = -\frac{e^2}{2}\int d^4x_1 d^4x_2 \Big[\Theta(x_1^0 - x_2^0)\Big\{\int\Big(\prod_{i=1}^{6}\frac{d^3p_i}{(2\pi)^{3/2}}\Big)\frac{1}{2\sqrt{p_{2,0}p_{5,0}}}\sum_{\sigma_1\sigma_2\sigma_3\sigma_4\sigma_5\sigma_6}\Big(\bar{v}(\vec{p}_1,\sigma_1)e^{-ip_1\cdot x_1}a^c(\vec{p}_1,\sigma_1)$$
$$+\bar{u}(\vec{p}_1,\sigma_1)e^{ip_1\cdot x_1}a^+(\vec{p}_1,\sigma_1)\Big)\Big(\not{e}(\vec{p}_2,\sigma_2)b(\vec{p}_2,\sigma_2)e^{-ip_2\cdot x_1}+\not{e}^*(\vec{p}_2,\sigma_2)b^+(\vec{p}_2,\sigma_2)e^{ip_2\cdot x_1}\Big)$$
$$\times\Big(u(\vec{p}_3,\sigma_3)e^{-ip_3\cdot x_1}a(\vec{p}_3,\sigma_3)+v(\vec{p}_3,\sigma_3)e^{ip_3\cdot x_1}a^{c+}(\vec{p}_3,\sigma_3)\Big)\Big(\bar{v}(\vec{p}_4,\sigma_4)e^{-ip_4\cdot x_2}a^c(\vec{p}_4,\sigma_4)$$
$$+\bar{u}(\vec{p}_4,\sigma_4)e^{ip_4\cdot x_2}a^+(\vec{p}_4,\sigma_4)\Big)\Big(\not{e}(\vec{p}_5,\sigma_5)b(\vec{p}_5,\sigma_5)e^{-ip_5\cdot x_2}+\not{e}^*(\vec{p}_5,\sigma_2)b^+(\vec{p}_5,\sigma_5)e^{ip_5\cdot x_2}\Big)$$
$$\times\Big(u(\vec{p}_6,\sigma_6)e^{-ip_6\cdot x_2}a(\vec{p}_6,\sigma_6)+v(\vec{p}_6,\sigma_6)e^{ip_6\cdot x_2}a^{c+}(p_6,\sigma_6)\Big)\Big\}+(x_1 \leftrightarrow x_2)\Big]$$

- Faymann made a create job simplifying the expansion of the different orders of perturbation theory (propagators & interactions)

Non-perturbative QED

Faymann diagrams – another representation of the perturbation theory

- The more the corrections (terms/diagrams) the more the precision as long as the couplings (μ) is small



- These couplings are scale dependent, i.e., at certain scale the couplings become large and this leads to breaking the assumption at which the perturbation theory becomes valid.

- In QED the coupling is the so called fine-structure constant (α_{QED})
- Perturbation theory is valid in QED as long as the field strength is well below the Schwinger limit

$$E_{cr} = m_e^2 c^3/(e\hbar) = 1.32 \times 10^{18}\ V/m$$

- Above this limit the vacuum becomes polarized and the production of electron-positron pairs by field-induced tunnelling out of the vacuum, can be observed (Schwinger pair-production)
- The electric and magnetic field strengths of LUXE are three orders of magnitude below the E_{cr}

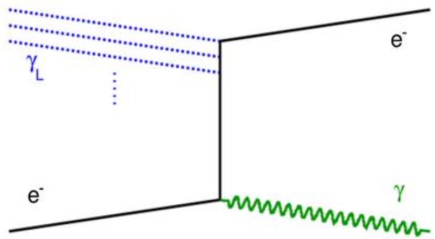
$$10^{14}\ V/m \text{ and } 10^5\ T$$

- But in the reset frame of a boosted electron collide with an angle to the laser field will see the field strength well above the limit

LUXE

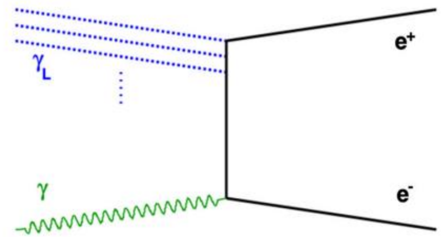
Main idea

Compton scattering process



$$e^- + n\gamma_L \rightarrow e^- + \gamma$$

Breit–Wheeler process



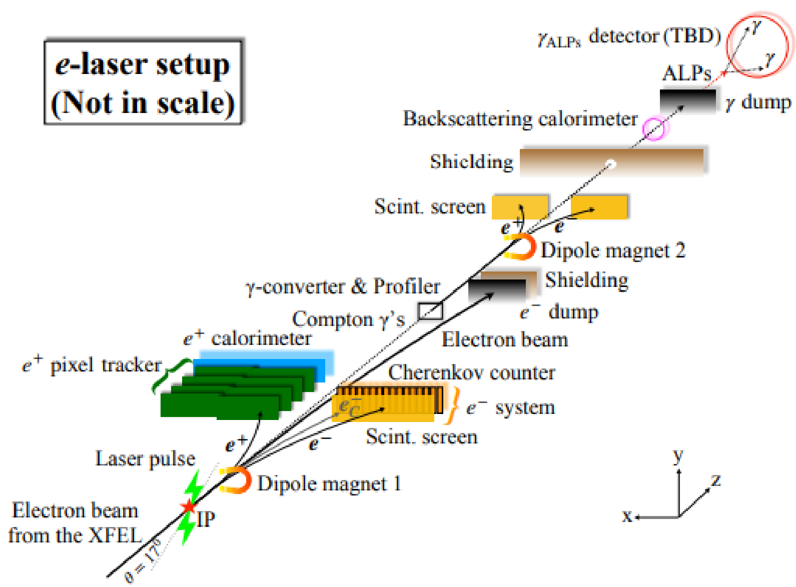
$$\gamma + n'\gamma_L \rightarrow e^+e^-$$

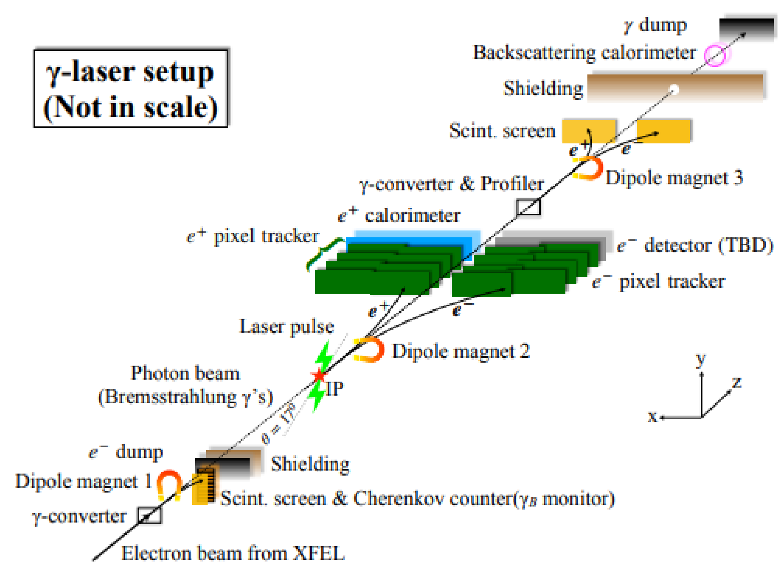
$\xi \ll 1$ pretubative

$\xi \geq 1$ non-pretubative

the two process can happend in only one process $e^- + n\gamma_L \rightarrow e^+e^-$

But with a rate that highly dependent on the field strength



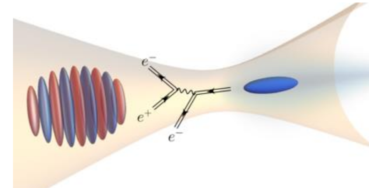


LUXE Experiment Simulations

LUXE simulation

A working example

https://github.com/tgblackburn/ptarmigan



Simulate the interaction between a high-energy particle beam and an intense laser pulse

All of Ptarmigan's default dependencies are Rust crates, which are downloaded automatically by Cargo

```
to run full chen of simulation -->
you need to install cargo to be able to build the dependencies of the ptarmigan
0- curl https://sh.rustup.rs -sSf | sh and then add to the bashrc
  source "$HOME/.cargo/env"

1- use https://github.com/tgblackburn/ptarmigan/tree/master
  # which produces .h5 file formate using a yaml file specific to the expriment
  cargo build --release --features with-mpi,hdf5-output -j 12
  # on naf you need to remove with-mpi
1.1 ./target/release/ptarmigan path/to/input.yaml

2- pass it to the transformer script h5_to_slcio.py to get an .slcio
  you need some dependencies from the key4hep

3- pass this to ddsim
    ddsim --compactFile ${luxegeo_DIR}/LUXETracker.xml \
    --numberOfEvents -1 \
    --inputFiles /path/to/slcio_file
    --outputFile positrons_tracker_edm4hep.root
```

.h5

transformer script to get an .slcio
Has dependencies from the key4hep

luxegeo DD4hep

https://github.com/LUXEsoftware/luxegeo

complete solution for full detector description

LUXE simulation

Parameters

- Most important parameters:
  - Beam:
    - N = 1000000
    - Distribution = normal
    - Collision angle = -17.2 degree
    - Gamma = 16.5
  - Laser:
    - a0 = 7.0 (intensity parameter)
    - Laser energy = 1.2 Joule
    - Tau = 30.0
    - Polarization = circular

- Analysis is then done with edm4hep

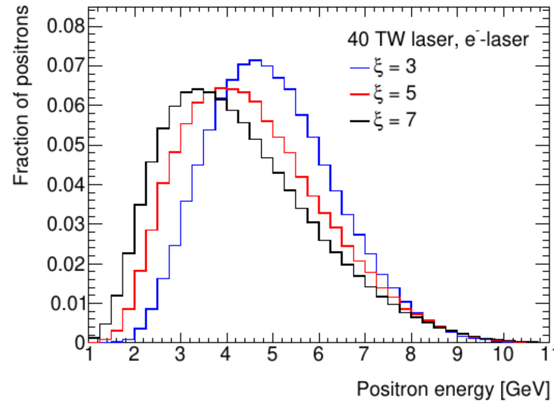
Example of the yaml file

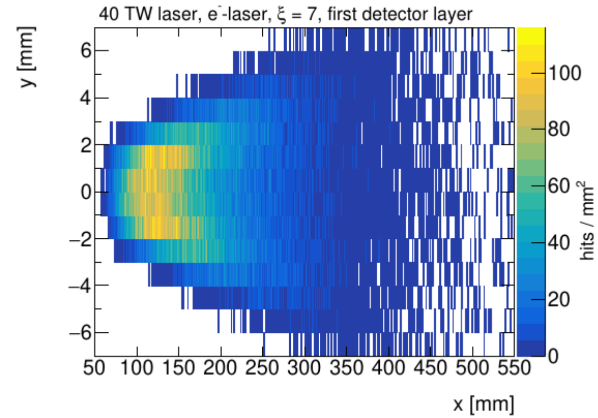
```yaml
control:
  dt_multiplier: 0.05
  radiation_reaction: true
  pair_creation: true
  rng_seed: 0
  increase_pair_rate_by: 1.5e9 / 1.0e6

laser:
  a0: a0
  wavelength: wavelength
  fwhm_duration: tau * femto
  waist: 147.839 * sqrt(laser_energy) * wavelength / (a0 * sqrt(tau))
  polarization: circular

beam:
  n: 1000000
  species: electron
  charge: 1.5e9 * e
  gamma: initial_gamma
  sigma: 0.001 * initial_gamma
  radius: [5.0 * micro, normally_distributed]
  length: 24.0 * micro
  collision_angle: -17.2 * degree
  rms_divergence: 8.672 * micro

output:
  ident: auto
  dump_all_particles: hdf5
  discard_background_e: true
  coordinate_system: beam
  units: hep

constants:
  a0: 7.0
  laser_energy: 1.2 # joules
  wavelength: 0.8 * micro
  tau: 30.0 # fs
  initial_gamma: 16.5 * GeV / (me * c^2)
```

Validation

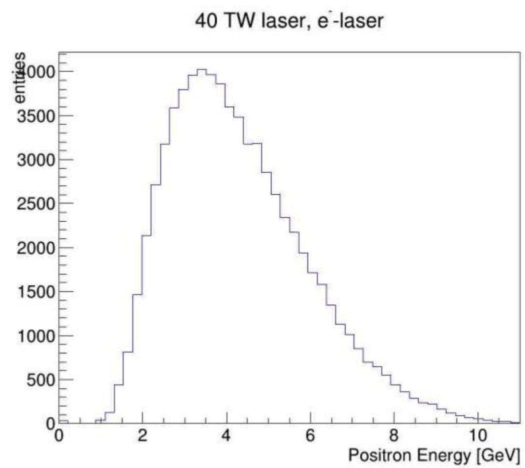
Comparing with LUXE quantum paper (2304.01690)

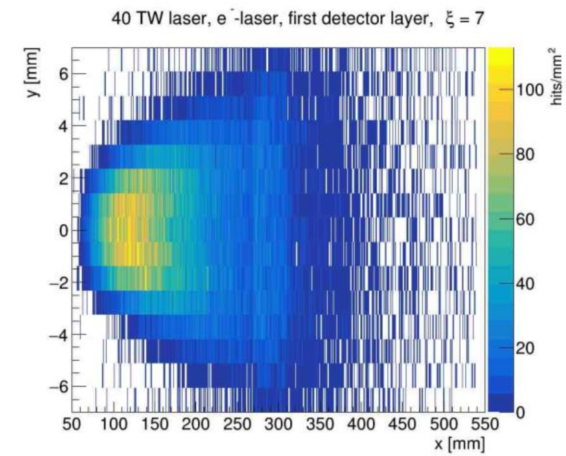
2304.01690





My production



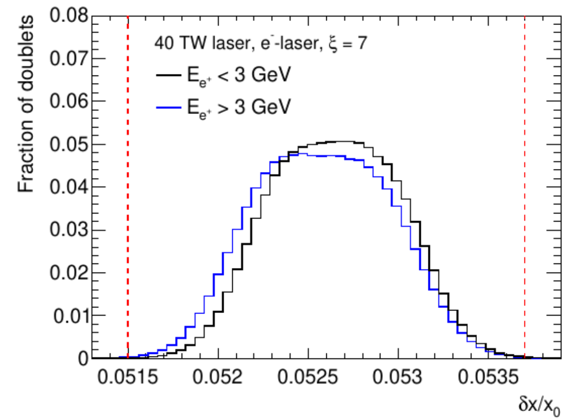


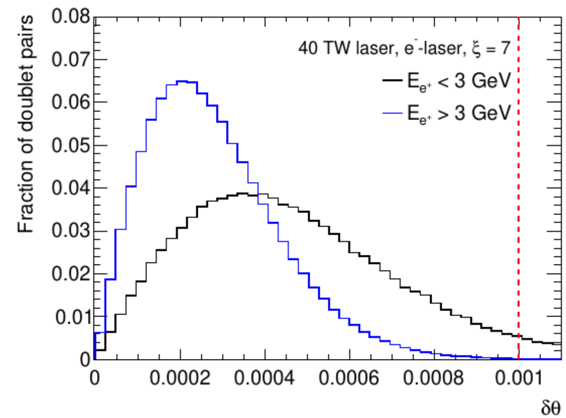
LUXE Experiment
next steps
toward track finding

Pattern recognition

Starting point – preselection

- define doublets/triplets, as a set of two/three hits in consecutive detector layers
- Apply pre-selection to doublet/triplets to reduce the combinatorial candidates
- Efficiency must be as close as possible to 100% by matching with a real positron
- Doublets are required to satisfy a pre-selection based on the ratio δx/x0
- δx is the difference of the x coordinates for the two hits composing the doublet
- x0 indicates the x coordinate on the detector layer closest to the interaction point
- For true doublets allow a window of 3 sigma around the mean of δx/x0
- combining doublet candidates to make triplets buy cutting on the maximum angle between the doublets

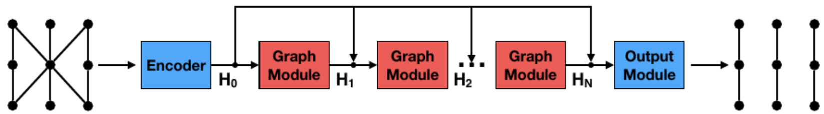




Training

GNN (2003.11603) and others

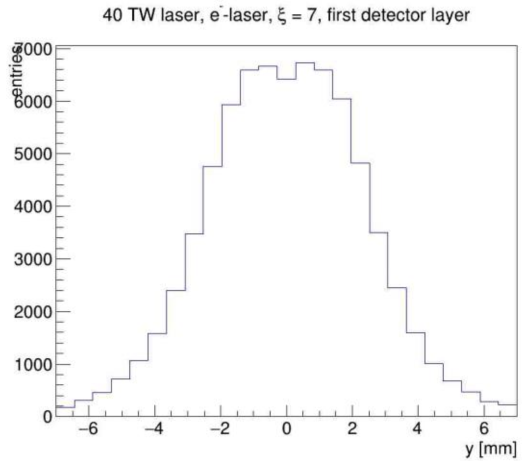
- Standard GNN architecture

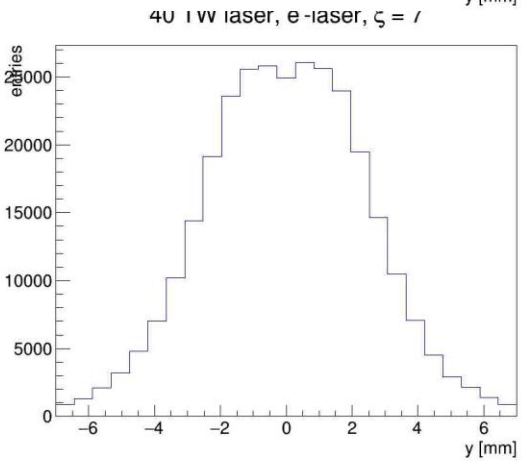


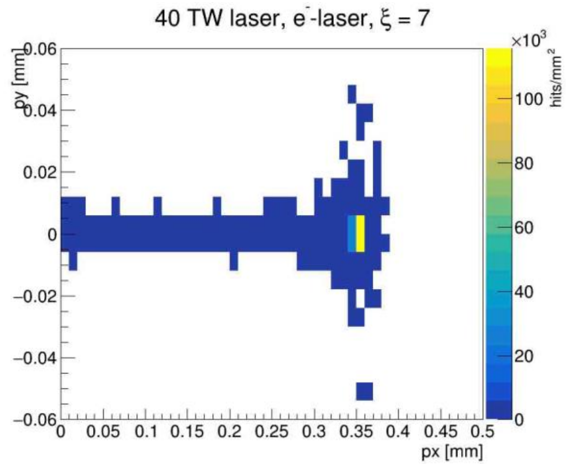
- Encoder: transforms input node and edge features into their latent representations
- Graph module: performs message passing to update latent features
- Output module: computes edge classification scores
- Can be slow for high particle occupancy

- Possible candidates to replace GNNs:
  - Deep sets (with self-attention)
  - LSTM
  - Transforemers
  - … etc

Thank You


40 TW laser, e-laser, ξ = 7, first detector layer
entries
7000
6000
5000
4000
3000
2000
1000
0
−6
−4
−2
0
2
4
6
y [mm]


40 TW laser, e-laser, ξ = 7
entries
25000
20000
15000
10000
5000
0
−6
−4
−2
0
2
4
6
y [mm]


40 TW laser, e-laser, ξ = 7
py [mm]
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
px [mm]
×10^3
hits/mm^2
100
80
60
40
20
0