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ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

Reconstruction of multiple calorimetric clusters in the LHCf experiment with machine learning techniques

Giuseppe Piparo[1,2], on behalf of the LHCf collaboration

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INFN Catania Istituto Nazionale di Fisica Nucleare

WHY TO IMPROVE LHCF RECONSTRUCTION WITH ML?

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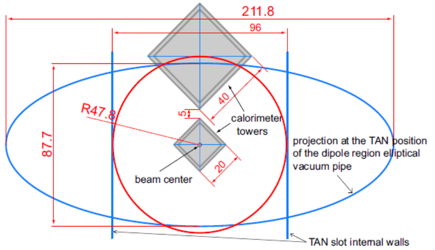
The LHCf Experiment at LHC

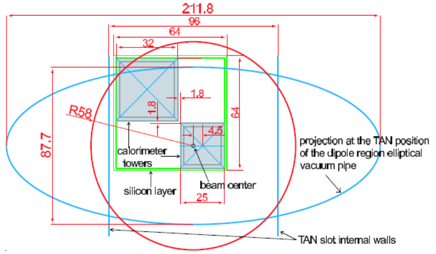
- A **unique experiment** designed to measure neutral particle production in the **forward pseudorapidity region**.
- Composed by two **sampling and immaging** calorimeters (ARM1 & ARM2), located at about ± 141 m from the LHC Interaction Point 1 (IP1).

Transversal view

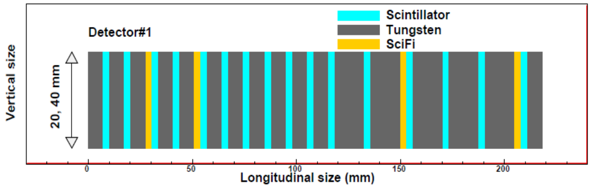
ARM1



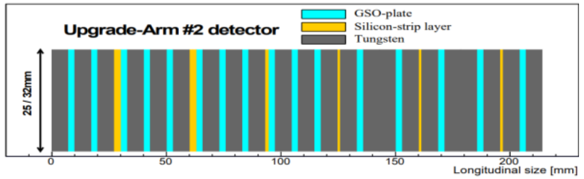
ARM2

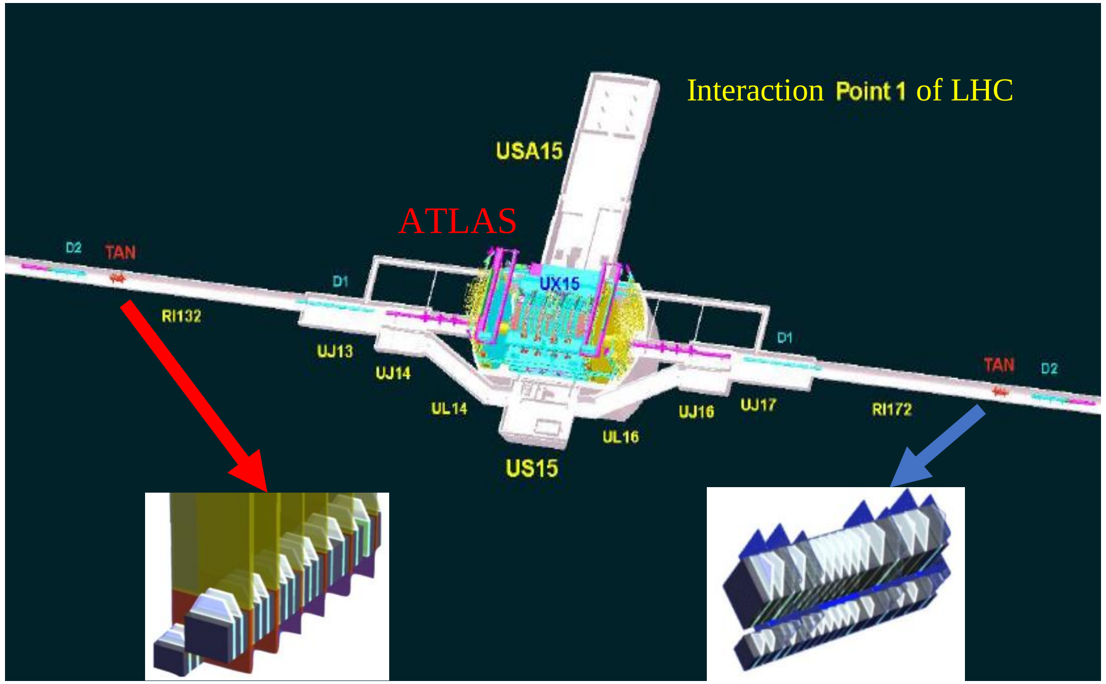


Longitudinal view



$44\ X_0$ and $1.6\ \lambda_I$ deep





LHCF-ARM2

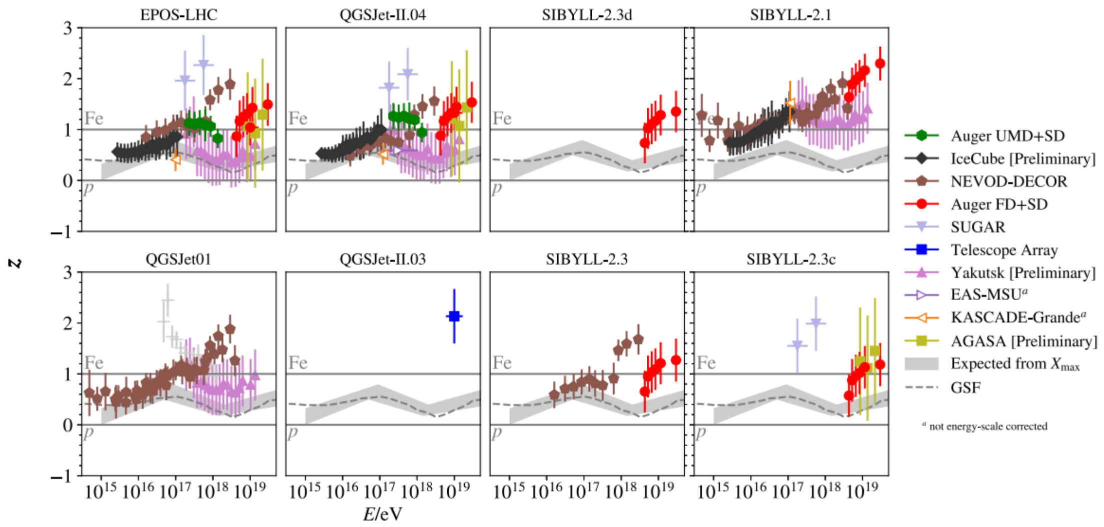
- **Energy resolution** <5% for photons and 35-40% for neutrons
- Tracking with 4 XY **silicon microstrips** layers.
- **Position resolution** $\approx 40\ \mu m$.

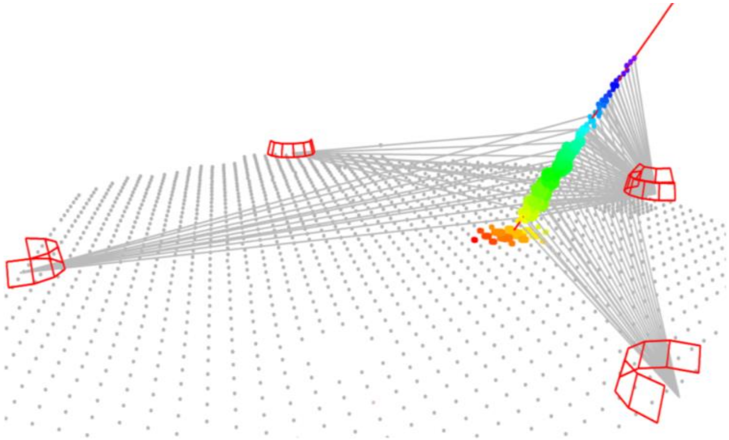
LHCF-ARM1

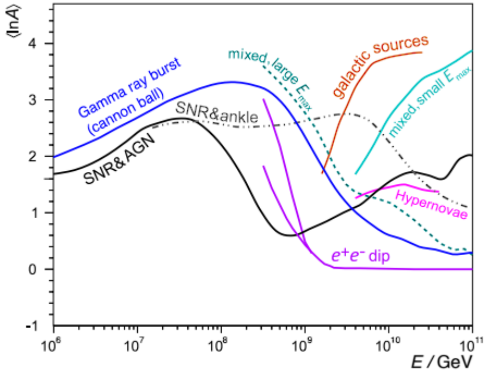
- Same Energy resolution as ARM2.
- Tracking with 4 GSO scintillator layers.
- **Position resolution** $\approx 200\ \mu m$.

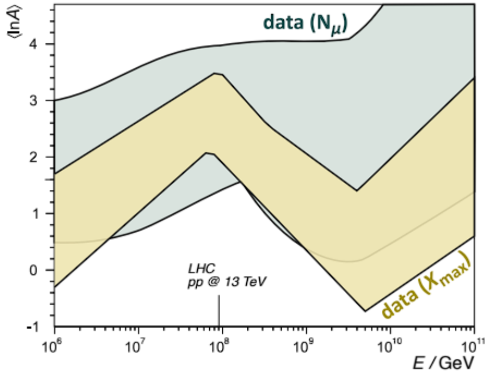
Experimental purpose of LHCf

- The main **hadronic interaction models** (HIM) (like QGSJET, SIBYLL or EPOS) suffer of large discrepancy due to limited understanding of the **soft QCD processes**.
- This is reflected on **large uncertainties** induced in the results of the ground-based cosmic rays experiments, due to the dependency of **air shower modeling** on HIM.
- LHCf provides neutral particles' energy and momentum distributions in the **forward region** to test and calibrate the models.









ASS 367, 1 (2022)

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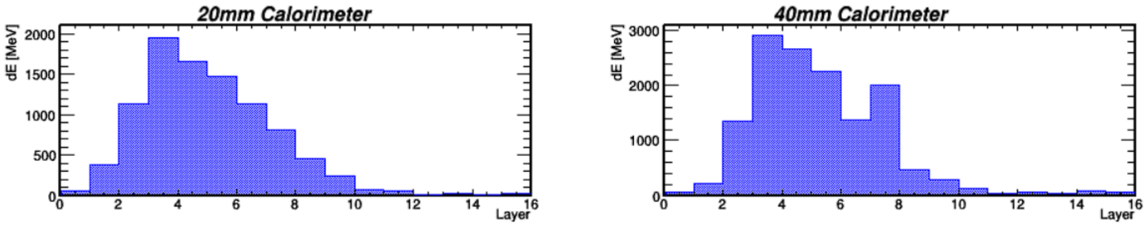
Reconstruction of multiple calorimetric clusters in LHCf

- The total energy is reconstructed by summing the **calibrated energy releases** in the GSO layers. This sum is then converted to the total energy using a function derived from Monte Carlo simulations.

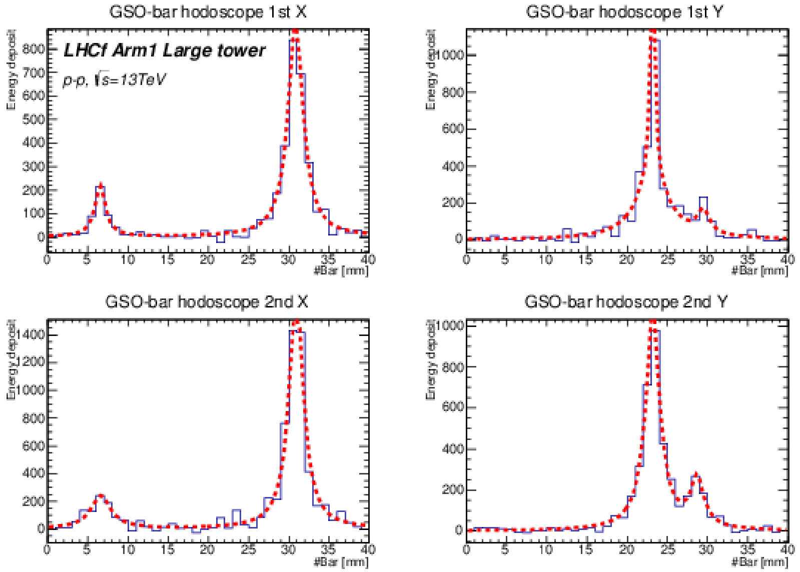
Energy releases



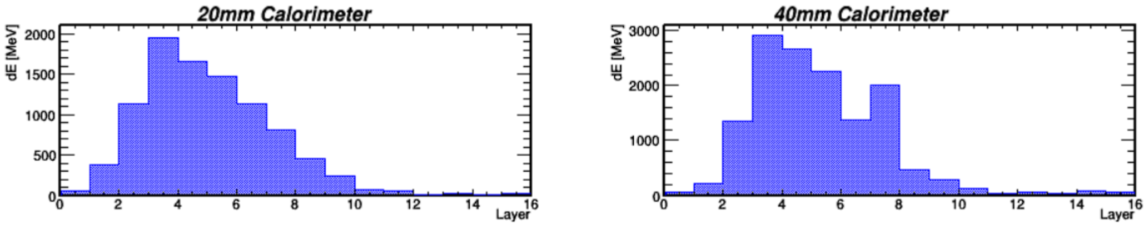
Reconstruction of multiple calorimetric clusters in LHCf

- The total energy is reconstructed by summing the **calibrated energy releases** in the GSO layers. This sum is then converted to the total energy using a function derived from Monte Carlo simulations.
- To reconstruct the position of hitting particles, we use the **transversal profile** of tracking detectors, by finding the peaks using TSpectrum and fitting them with a **3-component Lorentzian function for each peak**.
- The current energy-sharing method uses the **ratio of peak heights** for each particle to share the energy between the events.

Transversal profile with 2 clusters



Energy releases



3-components Lorentzian function

$$f(x) = p_0 \left[\frac{p_2}{\frac{(x-p_1)^2}{p_3} + p_3} + \frac{p_4}{\frac{(x-p_1)^2}{p_5} + p_5} + \frac{1 - p_2 - p_4}{\frac{(x-p_1)^2}{p_6} + p_6} \right]$$

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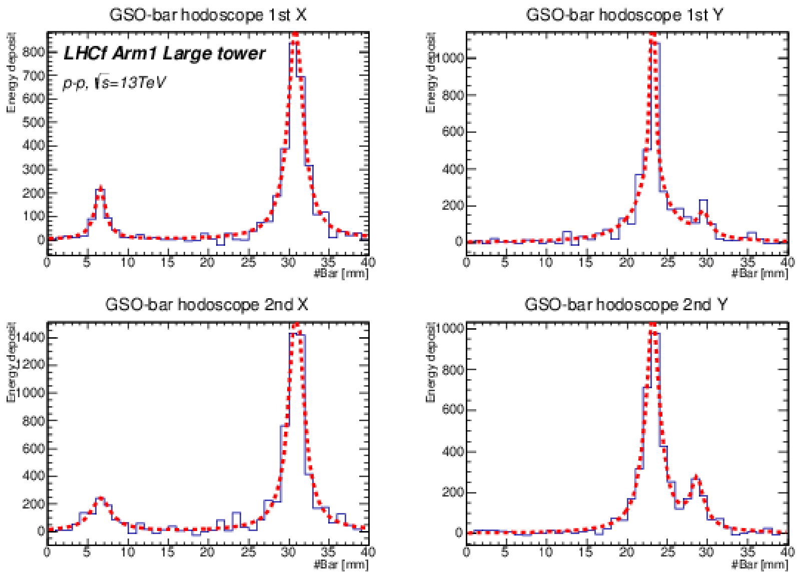
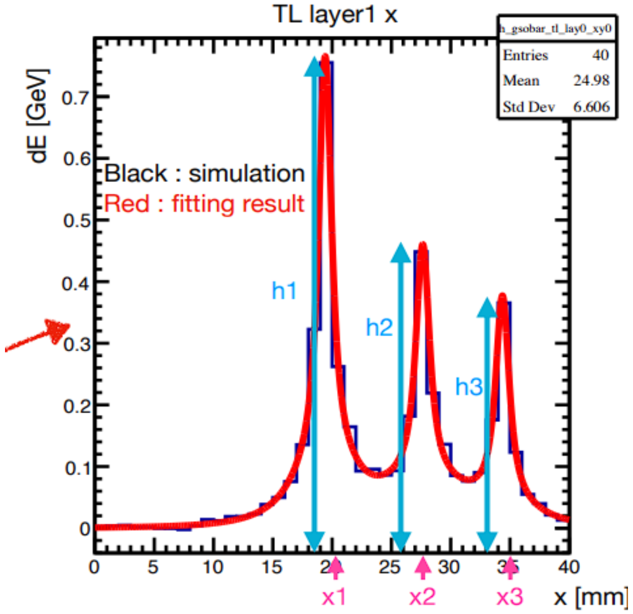
- The current energy-sharing method uses the **ratio of peak heights** for each particle to share the energy between the events.
- This method was initially developed to determine the energy when **two photons** hit the same detector tower. We are now extending this approach to handle cases involving **three or four photons** and to account for **the presence of neutrons**.

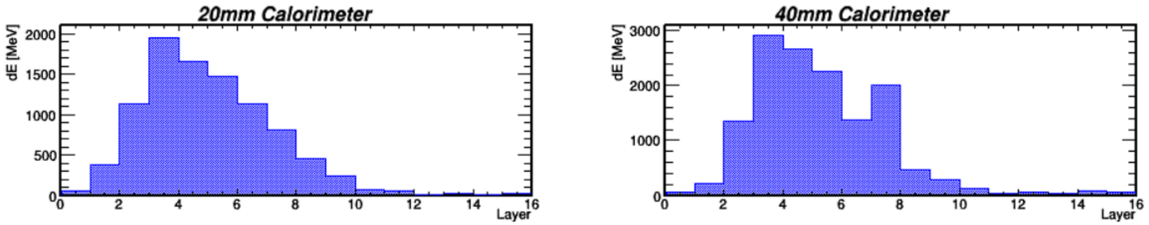
Transversal profile with 2 clusters



Transversal profile with 3 clusters



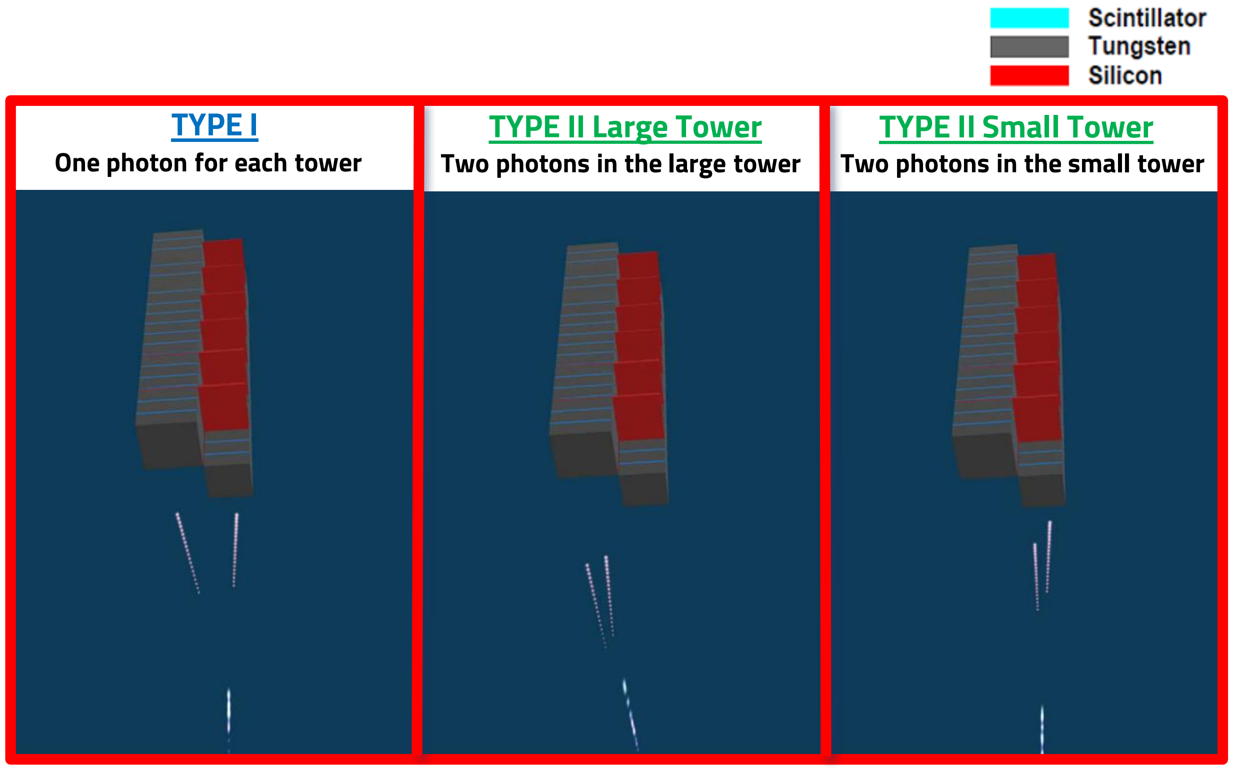
Energy releases



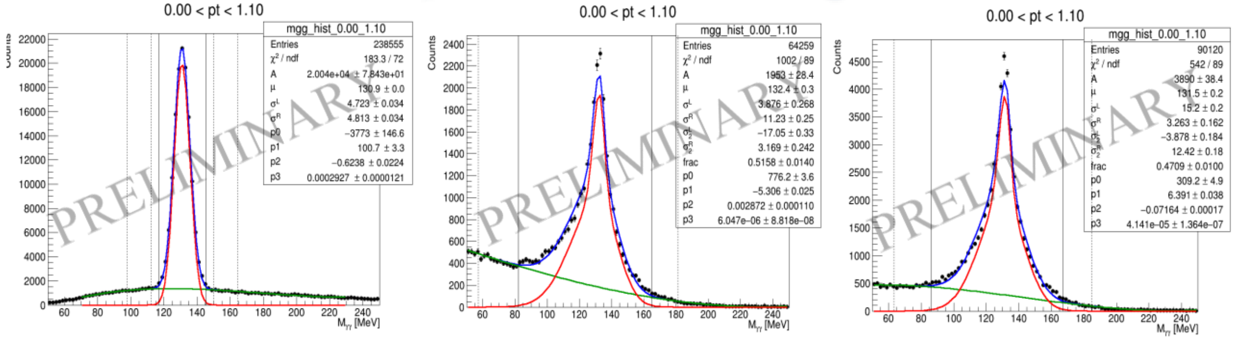
3-components Lorentzian function

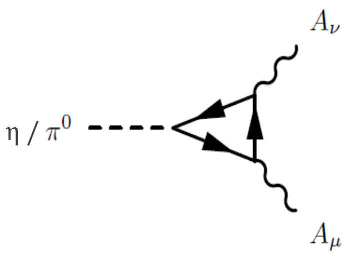
$$f(x) = p_0 \left[\frac{p_2}{\frac{(x-p_1)^2}{p_3} + p_3} + \frac{p_4}{\frac{(x-p_1)^2}{p_5} + p_5} + \frac{1 - p_2 - p_4}{\frac{(x-p_1)^2}{p_6} + p_6} \right]$$

Motivation I: Type II π^0 and η analysis



- The analyses of π^0 and η are two of the **main physics targets** of the LHCf experiment.
- They are identified by their decay into two photons through the analysis of **invariant mass spectra**.
- These two photons can either hit different detector towers (**Type I events**) or both enter the same tower (**Type II events**).
- **Type II events** analysis is less precise due to the complexity of reconstructing **two photons in a single tower.**

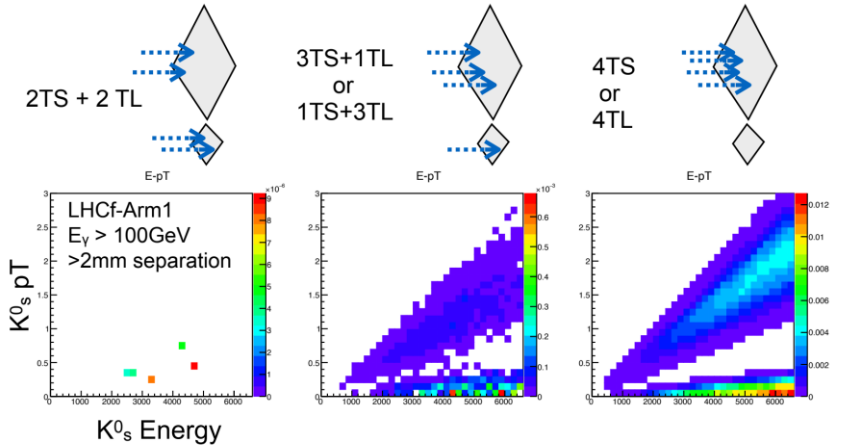


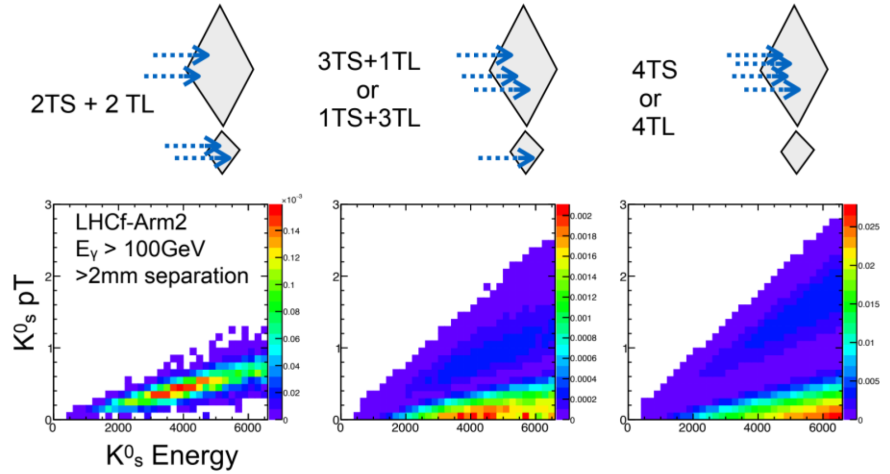


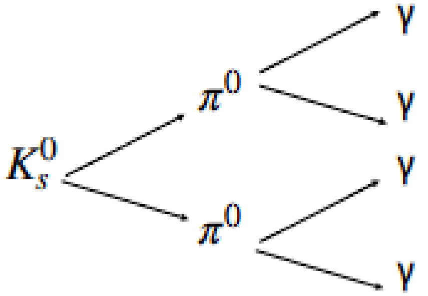
- Both particles decay mainly into **two photons:**
  - $\eta/\pi^0 \rightarrow \gamma\gamma$
- Branching ratio in the case of π^0 is about **98.82%**.
- In the case of η is about **39.36%**.

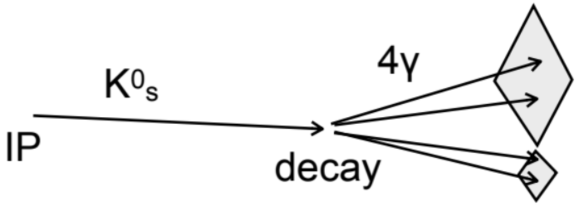
Motivation II: K^0 analysis

- K_S^0 measurements are critical for inferring the production of charged K mesons in EAS, which are significant sources of **TeV-PeV atmospheric neutrinos,** and to understanding **strange quark** forward production.
- Understanding K_S^0 production helps improve **models of hadronic interactions** in cosmic ray showers.
- K_S^0 events often involve **multiple calorimetric hits**, requiring the reconstruction of three or four particles.



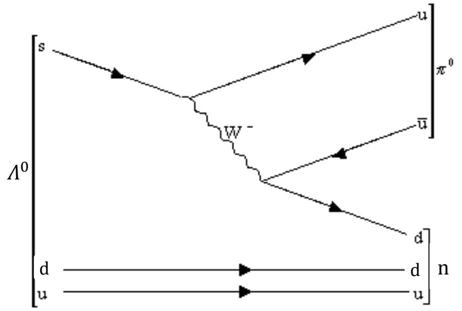


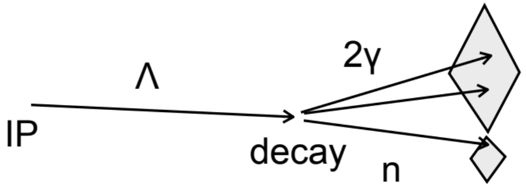


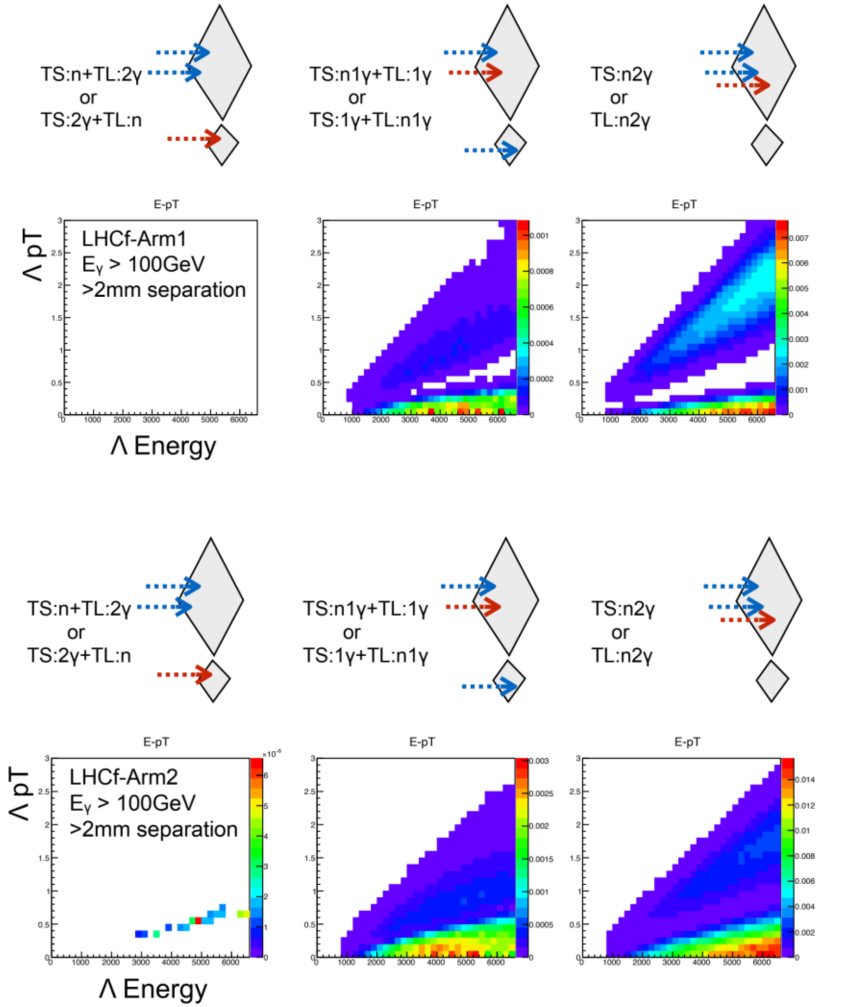


Motivation III: Λ^0 analysis

- Λ^0 baryons are key to understanding **forward strange particle production** and **hadronization** in high-energy collisions.
- Accurate Λ^0 measurements refine models of strange quark behavior and improve QCD process predictions.
- Λ^0 decays produce **complex event topologies**, involving mainly one or two photons and a neutron in a single tower.
- Effective reconstruction requires **distinguishing between different particle types** and precisely determining their energies and positions, which is challenging due to **overlapping signals** and varied interaction characteristics.







DEVELOPMENT STATUS

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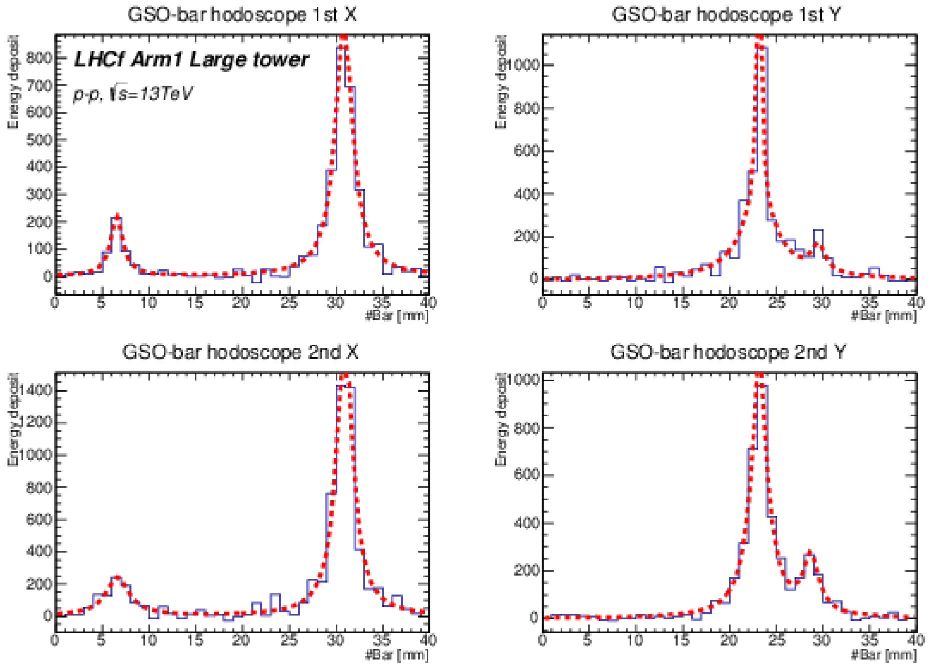
Machine Learning in the LHCf multi-hit reconstruction pipeline

- There are **several steps** of the LHCf multihit-hit reconstruction that can be improved using **ML methods**:
  - **Peak identification** and inference on the **number of hits** (actually performed with TSpectrum).
  - **Position reconstruction** (actually performed by fitting the identified peaks).
  - **Energy sharing** (actually performed using the ratio of peak heights in the layer with the highest energy release).
- **In this first stage we are focusing on the last point, in the case of two photons hitting the same tower of the LHCf-Arm2 detector.**
- This will permit **to improve the analysis** of π^0 and η and to find the best models and methods to analyze events with 3 or 4 photons or with the presence of a neutron for K_s^0 and Λ^0 analysis.

Transversal profile with 2 clusters



3-components Lorentzian function

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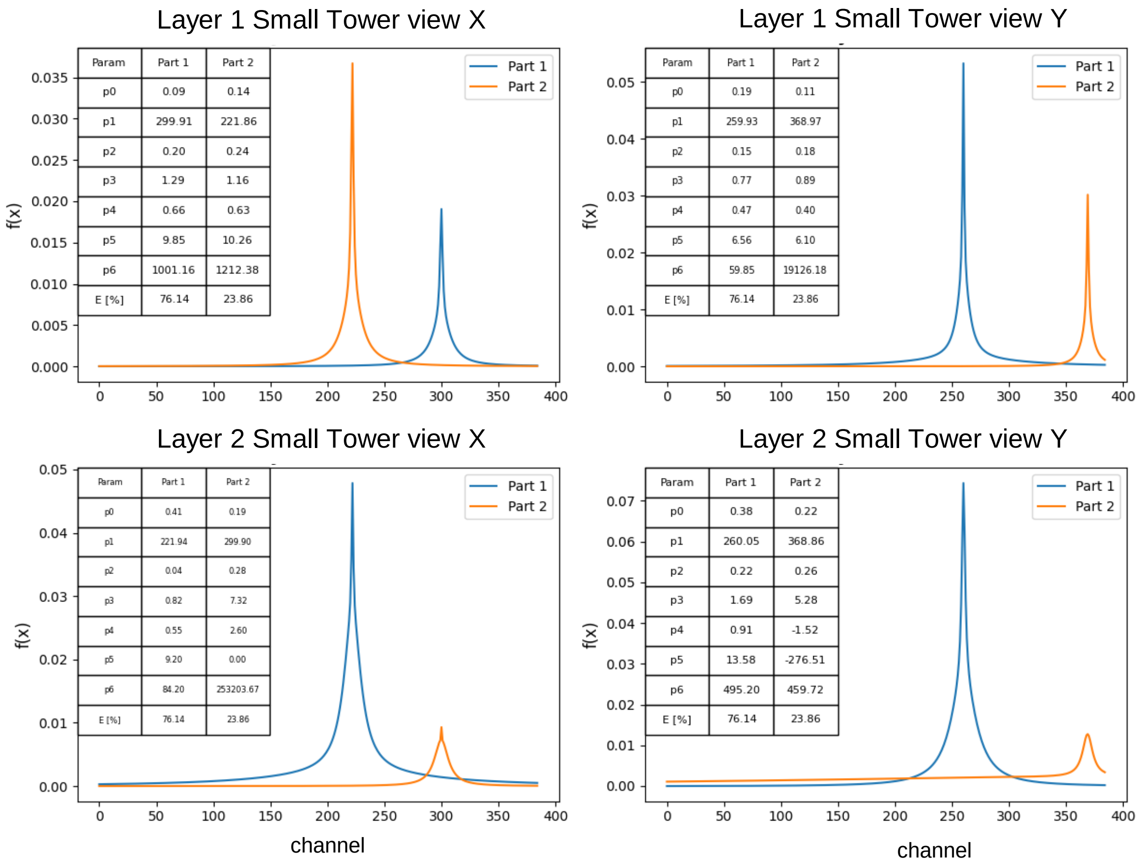
Dataset preparation

- To make inferences on energies of two-hit events we used as input for the **the fit results of the silicon transverse profile** in the first 4 layers.
- The dataset was obtained by a **full MC simulation** (collision generation, transport and interaction with the detector) of p-p collisions at $\sqrt{s}$=13 TeV, using as generator the model **QGSJETII-04**.
- Different models were constructed and trained for **each tower**.
- In particular, the 7 fit parameters for **each particle,** for **each view** (x and y) for the first two **silicon plane pairs** were used as input variables (56 input variables).



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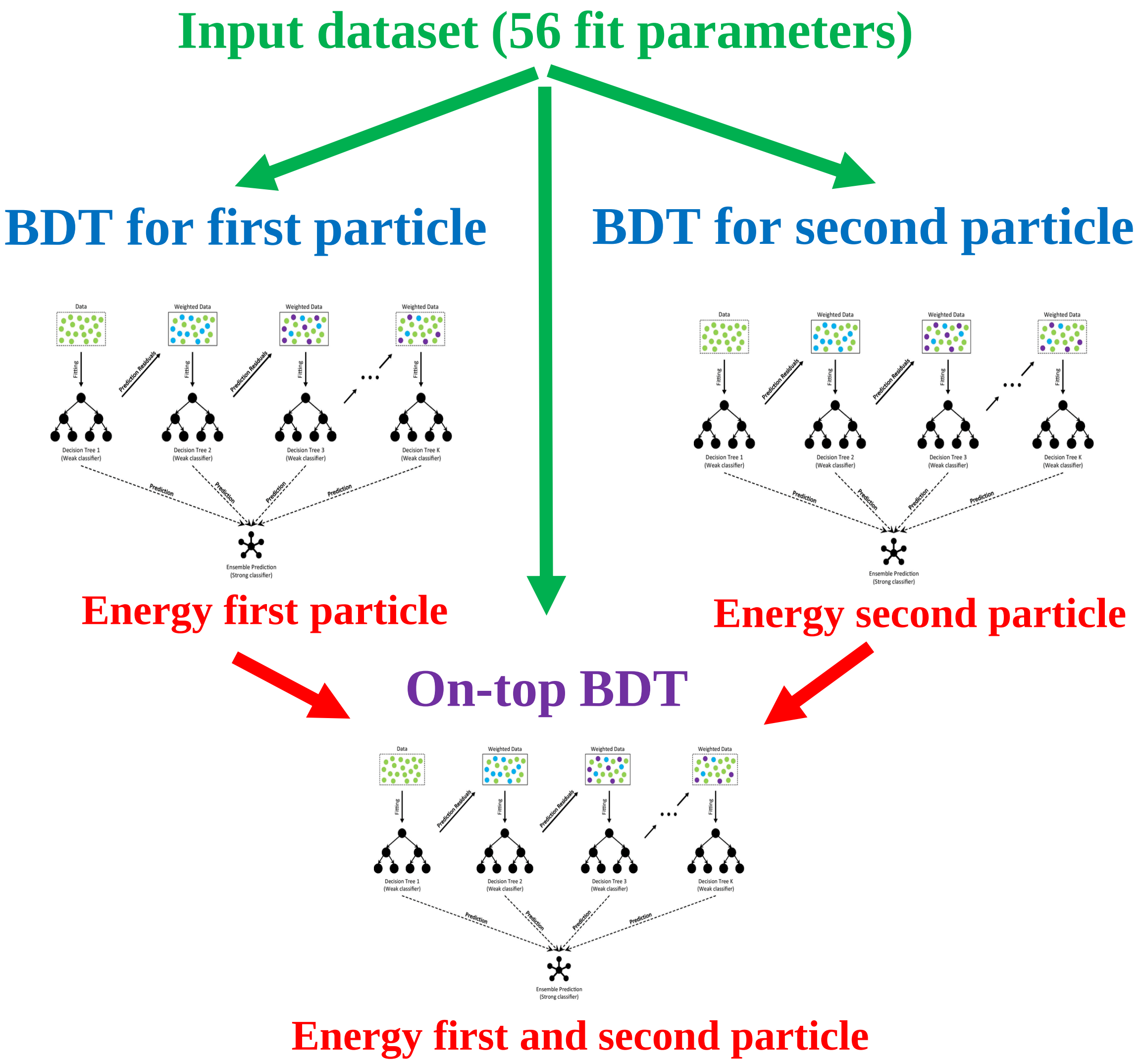
Tested models

- We tested two similar approaches, both based on **gradient-boosting decision trees (BDTs)**.

- Two **ensemble models** were constructed, consisting of **two BDTs on a first level** to make inferences on the single energy of each of the two photons, and an **on-top BDT** which, based on the predictions of the previous two combined with the input dataset, would make inference on the energy of both particles.



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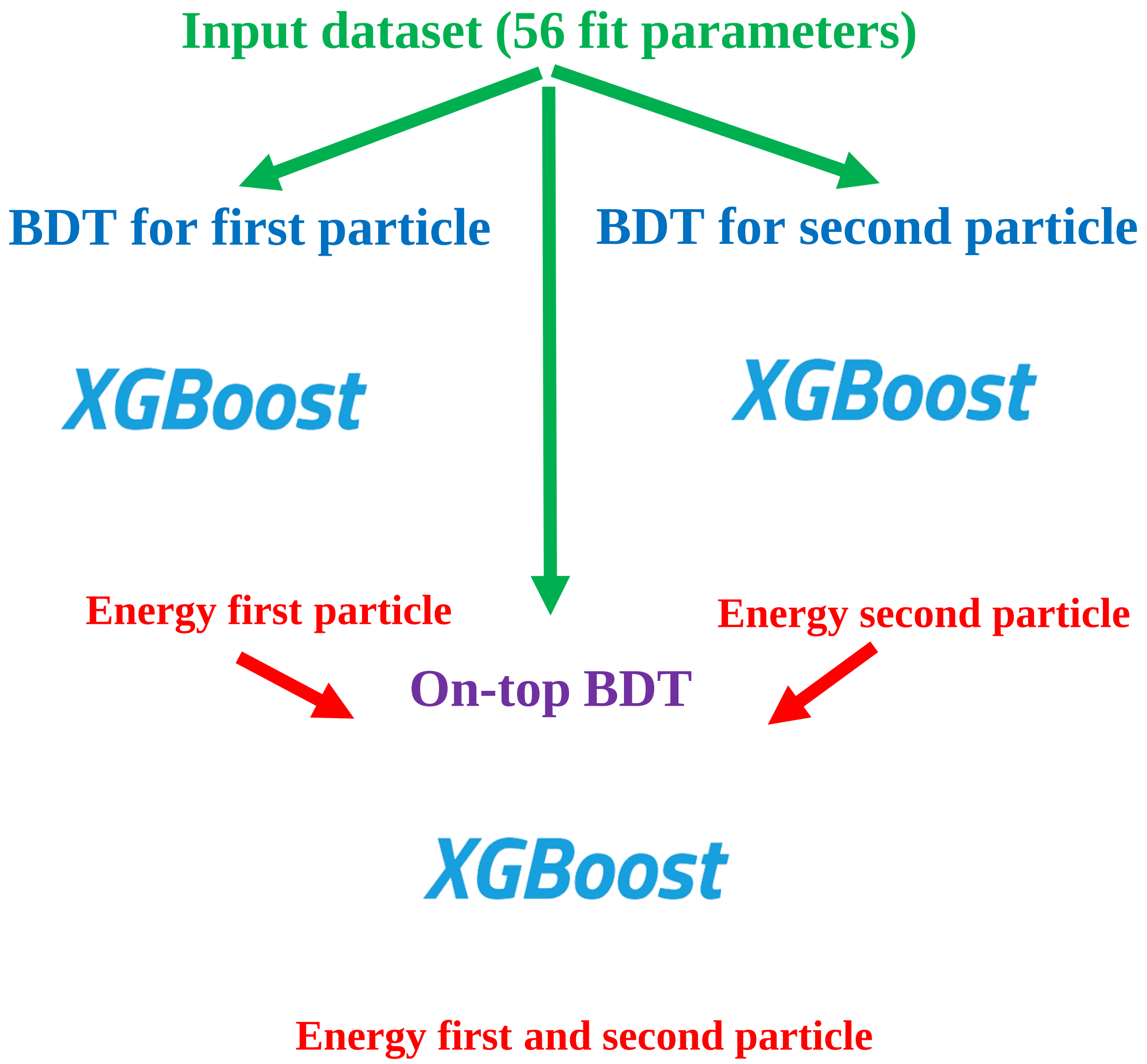
- In particular, the two libraries used for the test are **XGBoost** and **CatBoost**, which were initialized with similar values of the hyperparameters (e.g. **300k weak learners** and **depth of each tree equal to three**).
- The **RMSE** was used as a metric for the evaluation.



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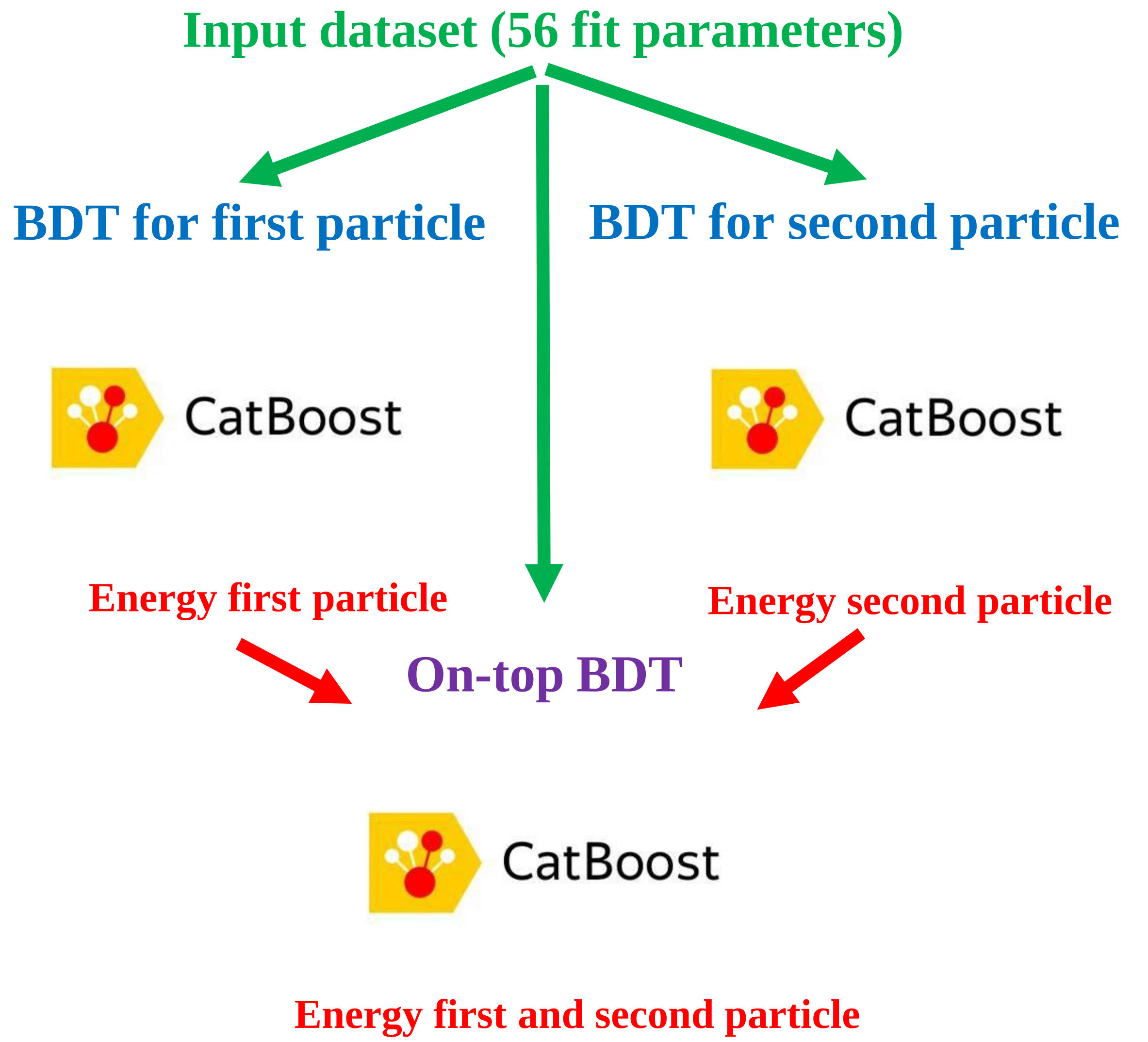

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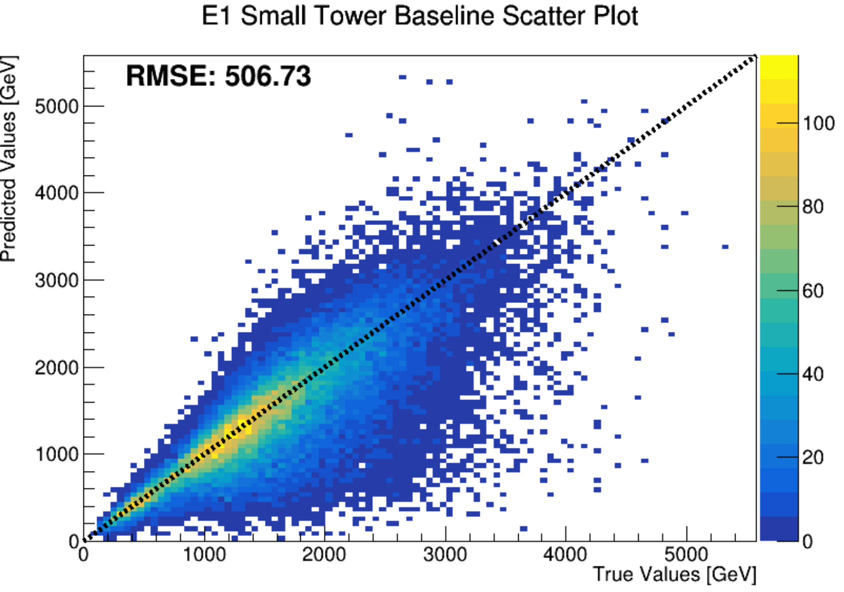
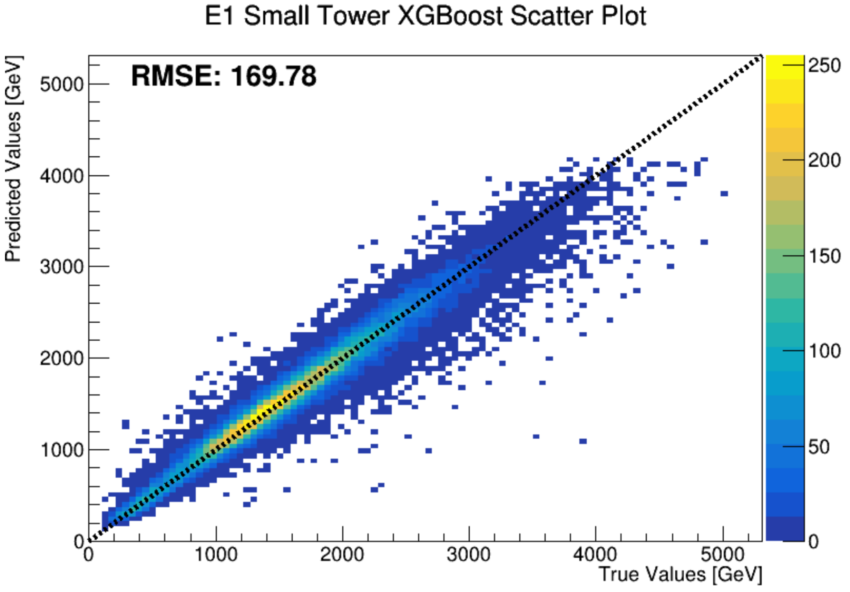
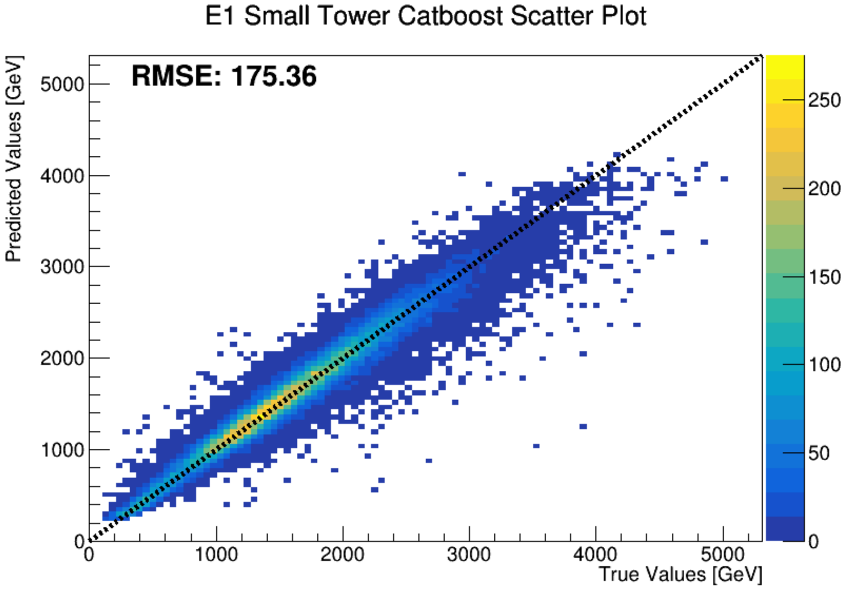
Results of first particle energy in Small Tower

Train events = 93k
Test events = 40k

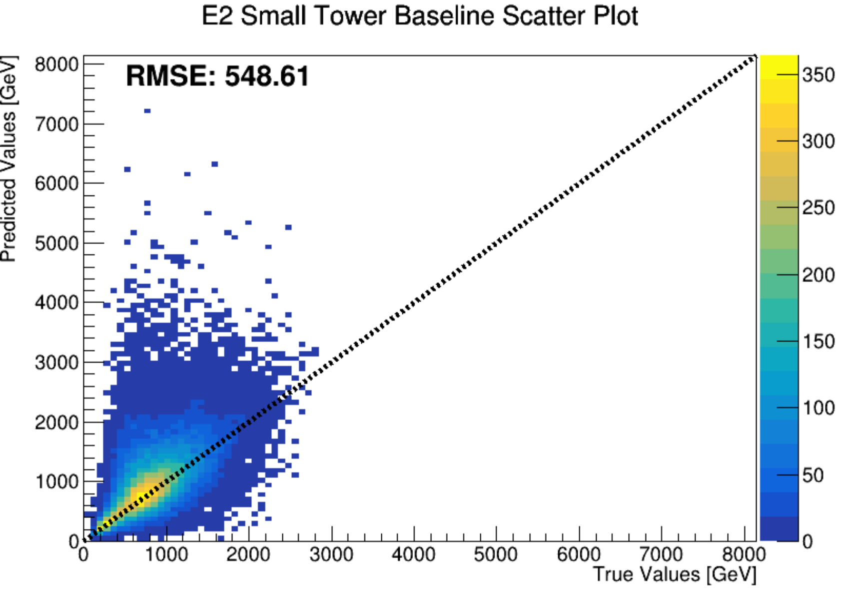


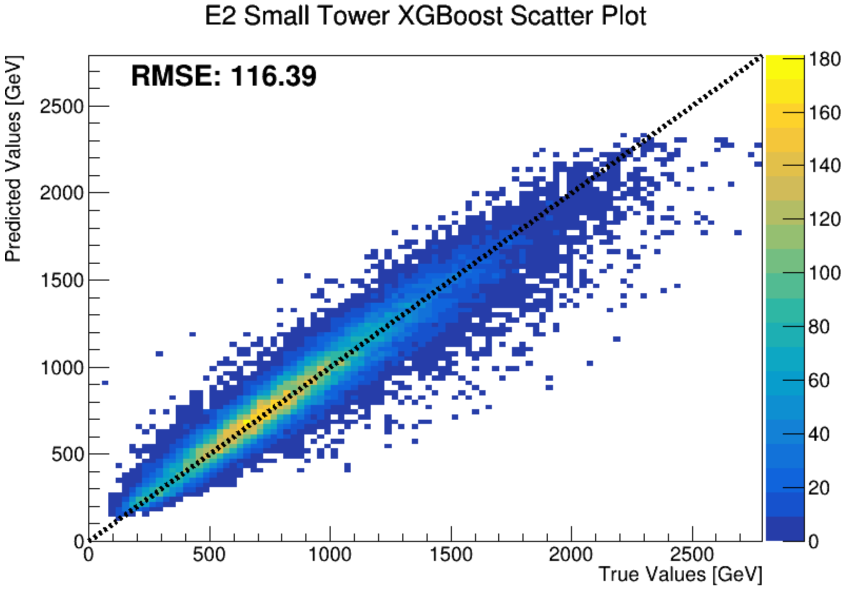


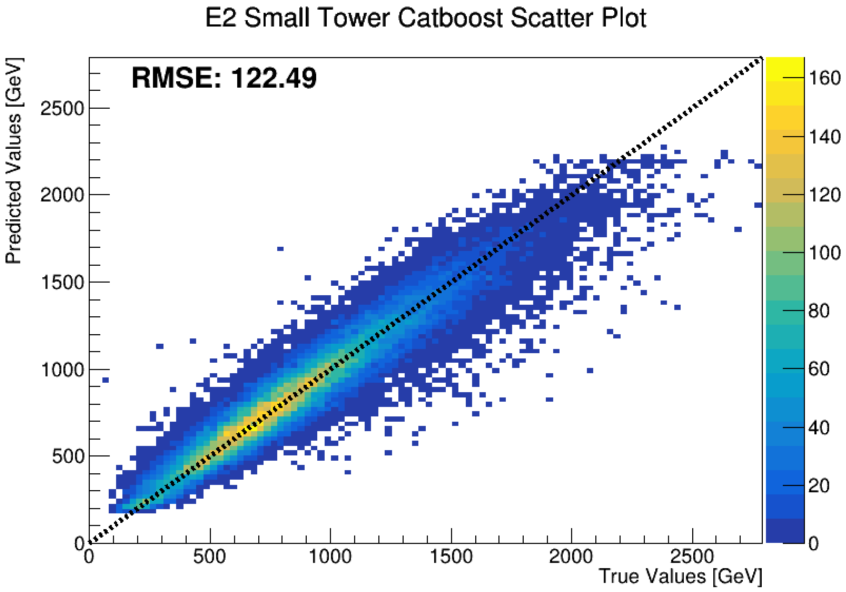


Results of second particle energy in Small Tower

Train events = 93k
Test events = 40k







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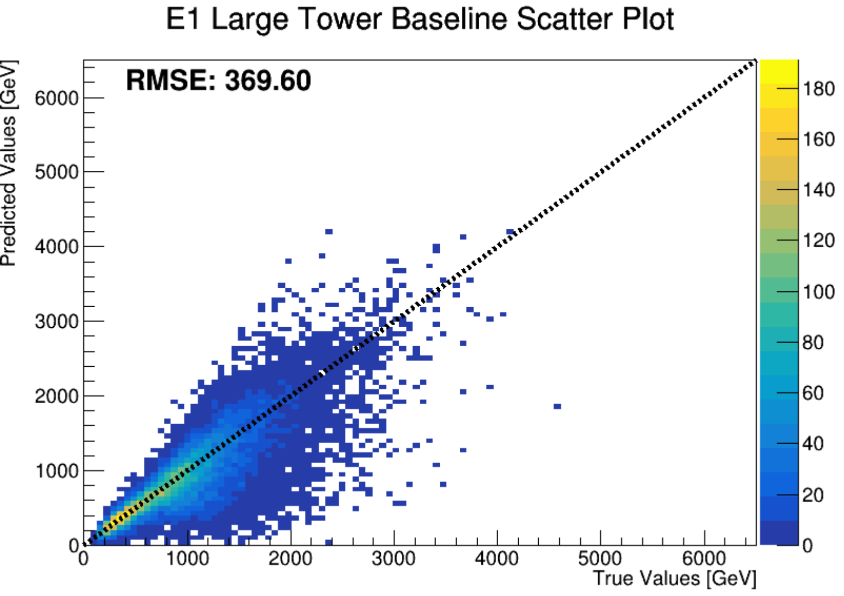
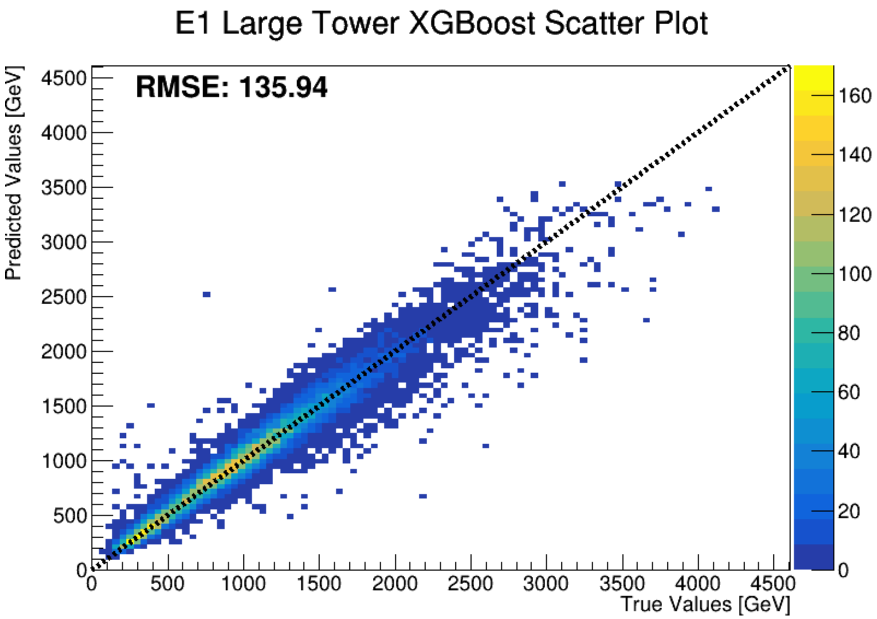
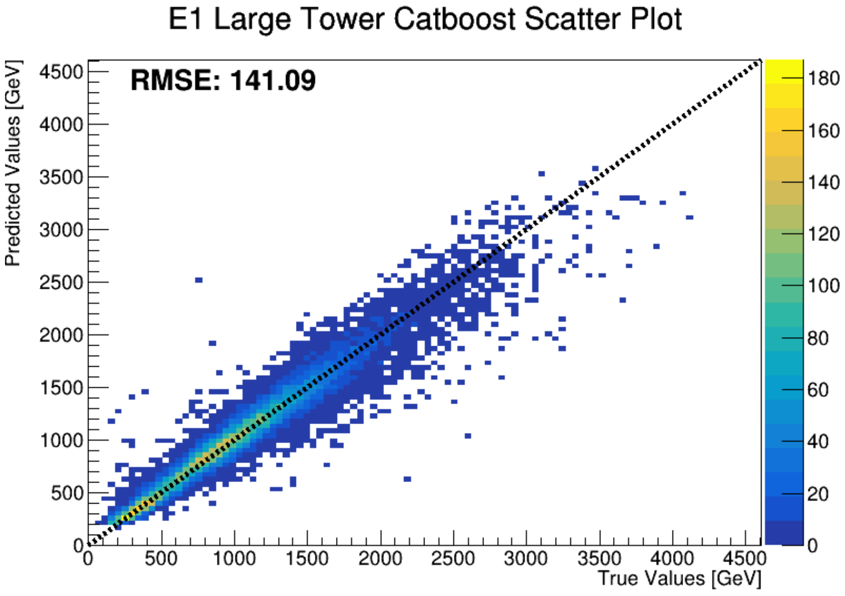
Results of first particle energy in Large Tower

Train events = 42k
Test events = 18k







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Results of second particle energy in Large Tower

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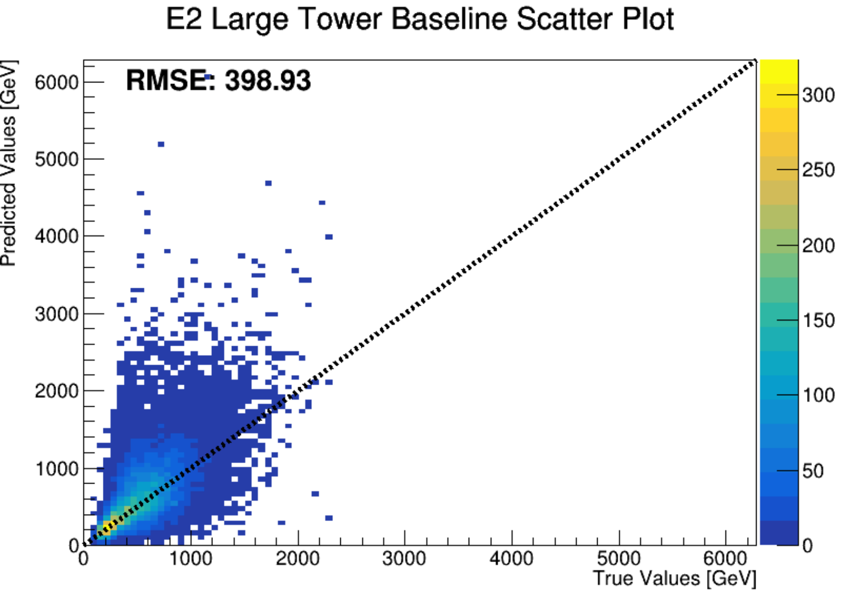
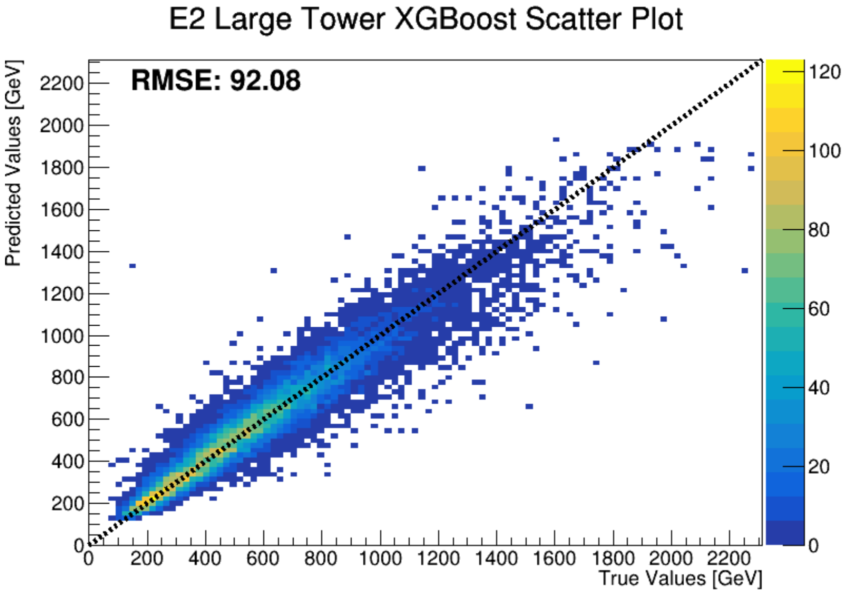
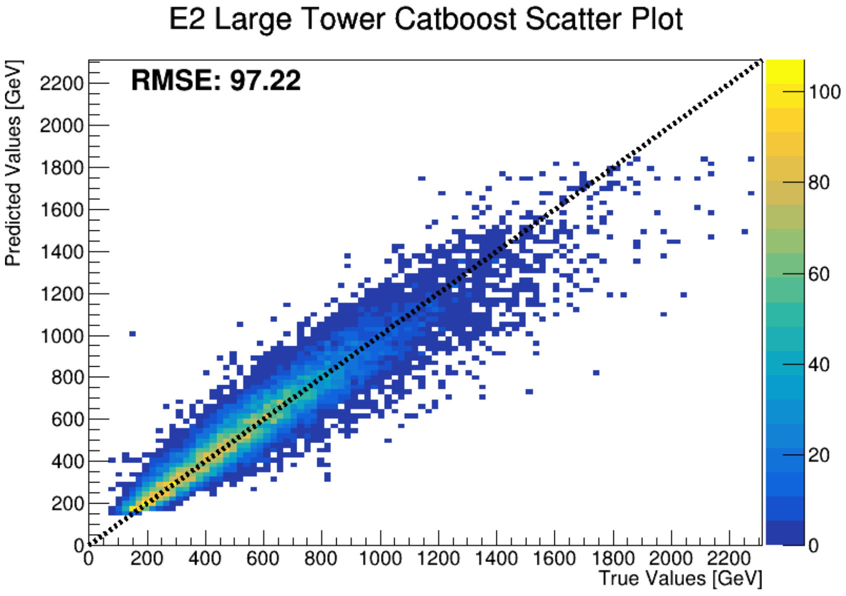


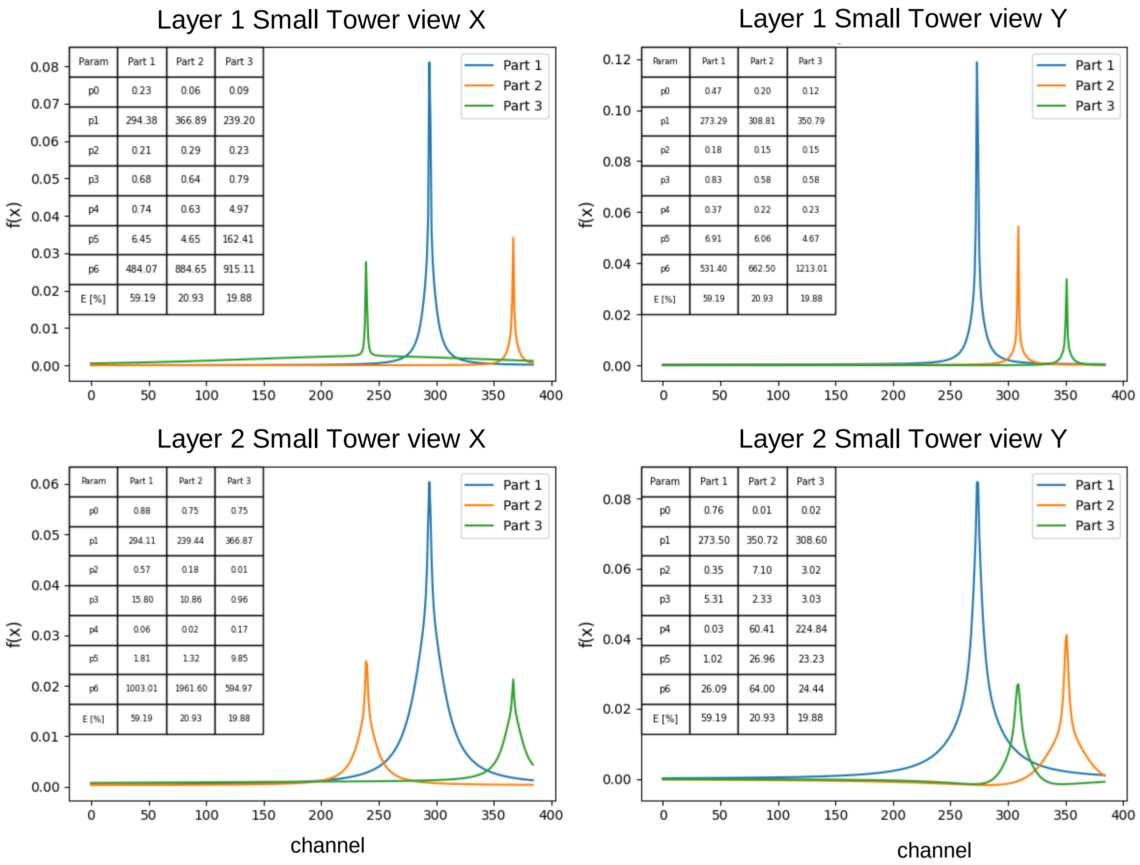




FUTURE PROSPECTS

Prospects: extend to more than two hits

- Current methods are primarily designed for events with up to **two particles** hitting the same detector tower.
- Extending these techniques to handle more complex scenarios with **three or four hits** is crucial for comprehensive multi-hit event reconstruction.
- Increased number of hits leads to significant signal overlap, making accurate deconvolution more challenging.
- We performed preliminary **tests** using a 3-hits dataset, but with low statistics (O(1k) events).



Layer 1 Small Tower view X

Param	Part 1	Part 2	Part 3
p0	0.23	0.06	0.09
p1	294.38	366.89	239.20
p2	0.21	0.29	0.23
p3	0.68	0.64	0.79
p4	0.74	0.63	4.97
p5	6.45	4.65	162.41
p6	484.07	884.65	915.11
E [%]	59.19	20.93	19.88

Layer 1 Small Tower view Y

Param	Part 1	Part 2	Part 3
p0	0.47	0.20	0.12
p1	273.29	308.81	350.79
p2	0.18	0.15	0.15
p3	0.83	0.58	0.58
p4	0.37	0.22	0.23
p5	6.91	6.06	4.67
p6	531.40	662.50	1213.01
E [%]	59.19	20.93	19.88

Layer 2 Small Tower view X

Param	Part 1	Part 2	Part 3
p0	0.88	0.75	0.75
p1	294.11	239.44	366.87
p2	0.57	0.18	0.01
p3	15.80	10.86	0.96
p4	0.06	0.02	0.17
p5	1.81	1.32	9.85
p6	1003.01	1961.60	594.97
E [%]	59.19	20.93	19.88

Layer 2 Small Tower view Y

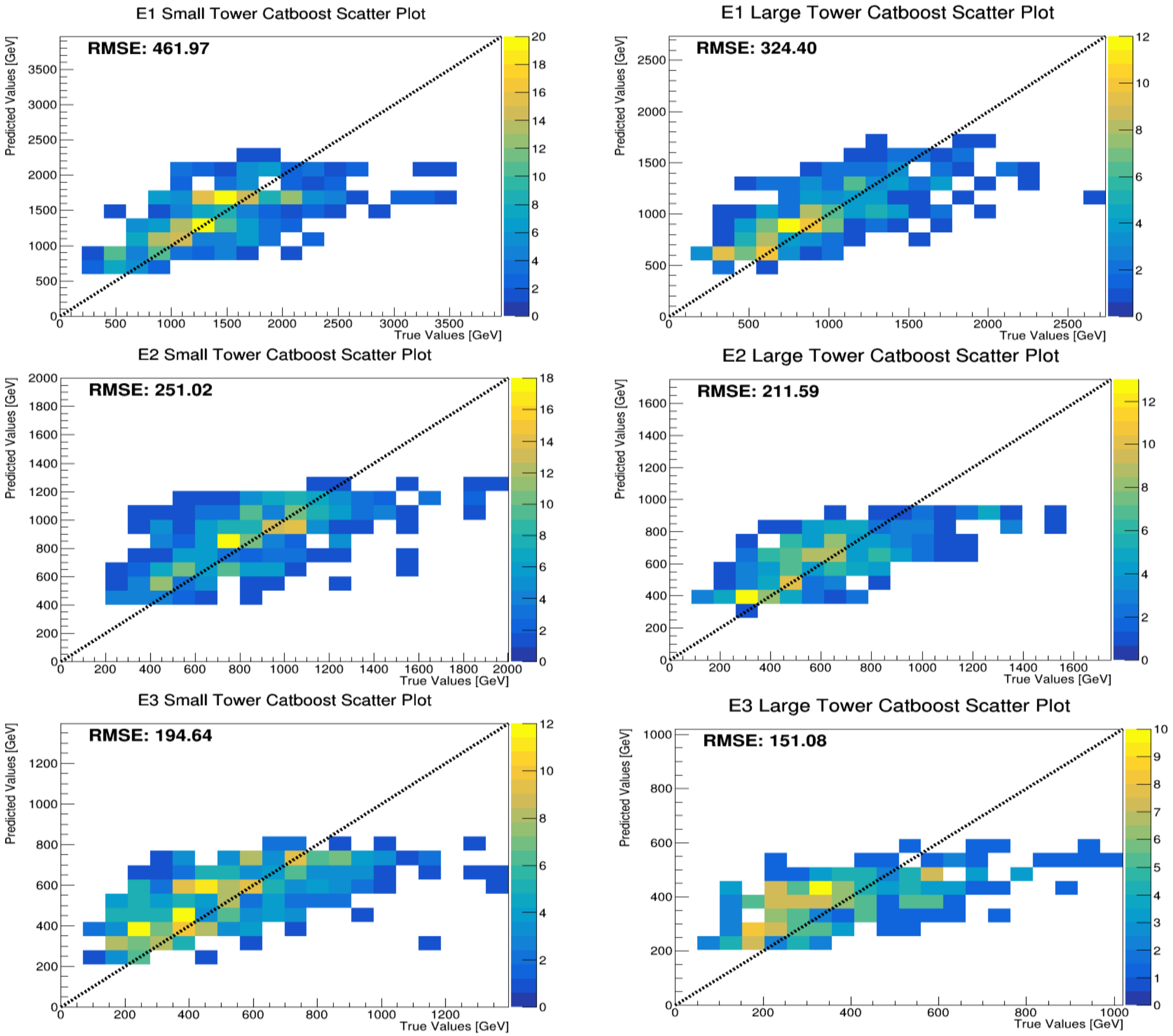
Param	Part 1	Part 2	Part 3
p0	0.76	0.01	0.02
p1	273.50	350.72	308.60
p2	0.35	7.10	3.02
p3	5.31	2.33	3.03
p4	0.03	60.41	224.84
p5	1.02	26.96	23.23
p6	26.09	64.00	24.44
E [%]	59.19	20.93	19.88

3-components Lorentzian function

$$f(x) = p_0 \left[\frac{p_2}{\frac{(x-p_1)^2}{p_3} + p_3} + \frac{p_4}{\frac{(x-p_1)^2}{p_5} + p_5} + \frac{1-p_2-p_4}{\frac{(x-p_1)^2}{p_6} + p_6} \right]$$

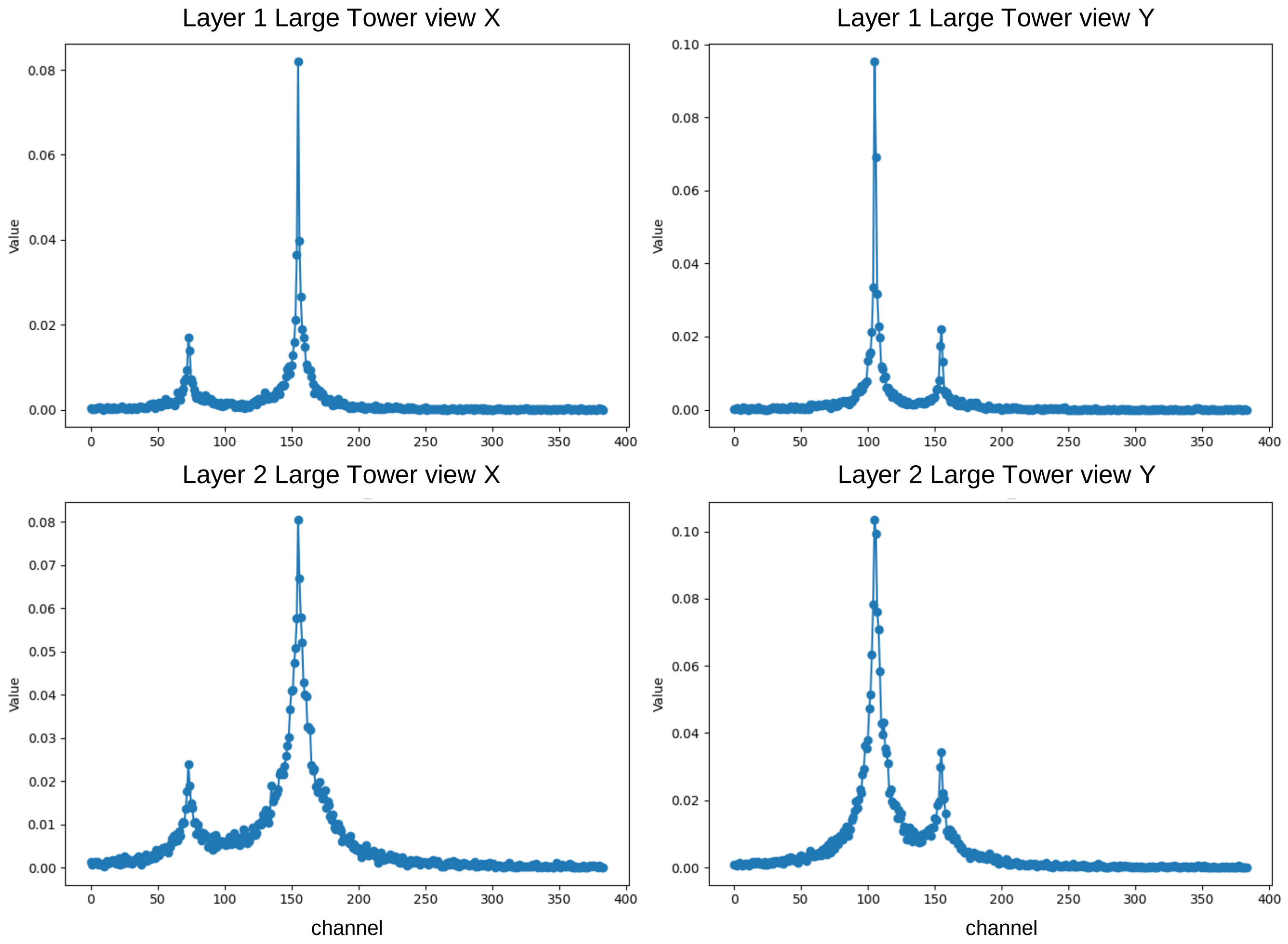
Prospects: extend to more than two hits

- Current methods are primarily designed for events with up to **two particles** hitting the same detector tower.
- Extending these techniques to handle more complex scenarios with **three or four hits** is crucial for comprehensive multi-hit event reconstruction.
- Increased number of hits leads to significant signal overlap, making accurate deconvolution more challenging.
- We performed preliminary **tests** using a 3-hits dataset, but with low statistics (O(1k) events).
- First results are encouraging, but more statistics is needed.



Prospects: use of the raw transverse distribution of position detectors

- We are exploring the use of **raw transverse distribution data** from position detectors, moving away from relying solely on fit parameters.
- This approach leverages the raw signals directly from the detectors to potentially enhance the **accuracy of particle reconstruction**.
- Test perfomed on a different dataset, created using the same methodology but with a new simulation of p-p collisions at $\sqrt{s}$=13 TeV (QGSJET II-04 as generator).



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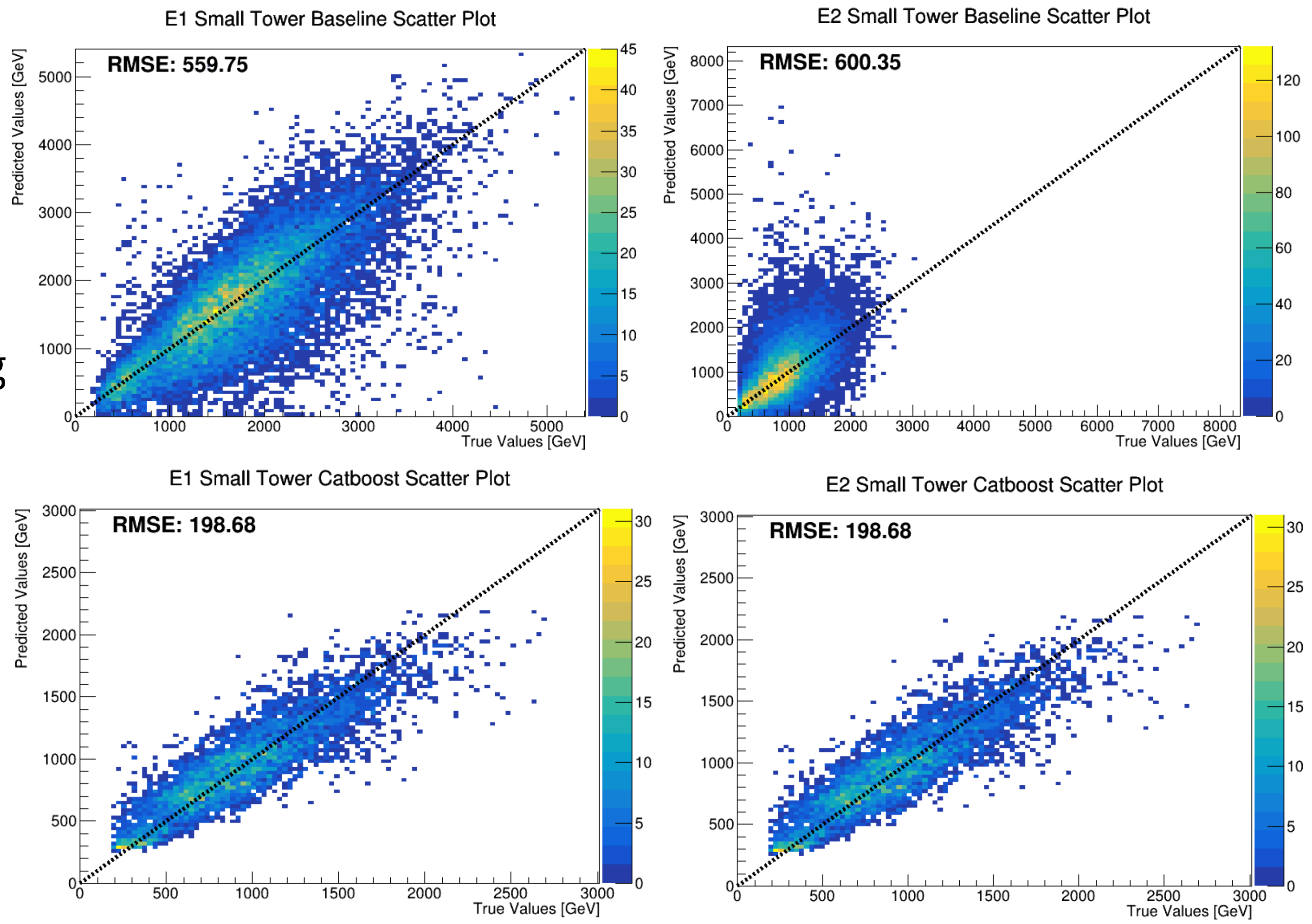
- Only O(20k) events, improvements are expected by increasing the statistics.



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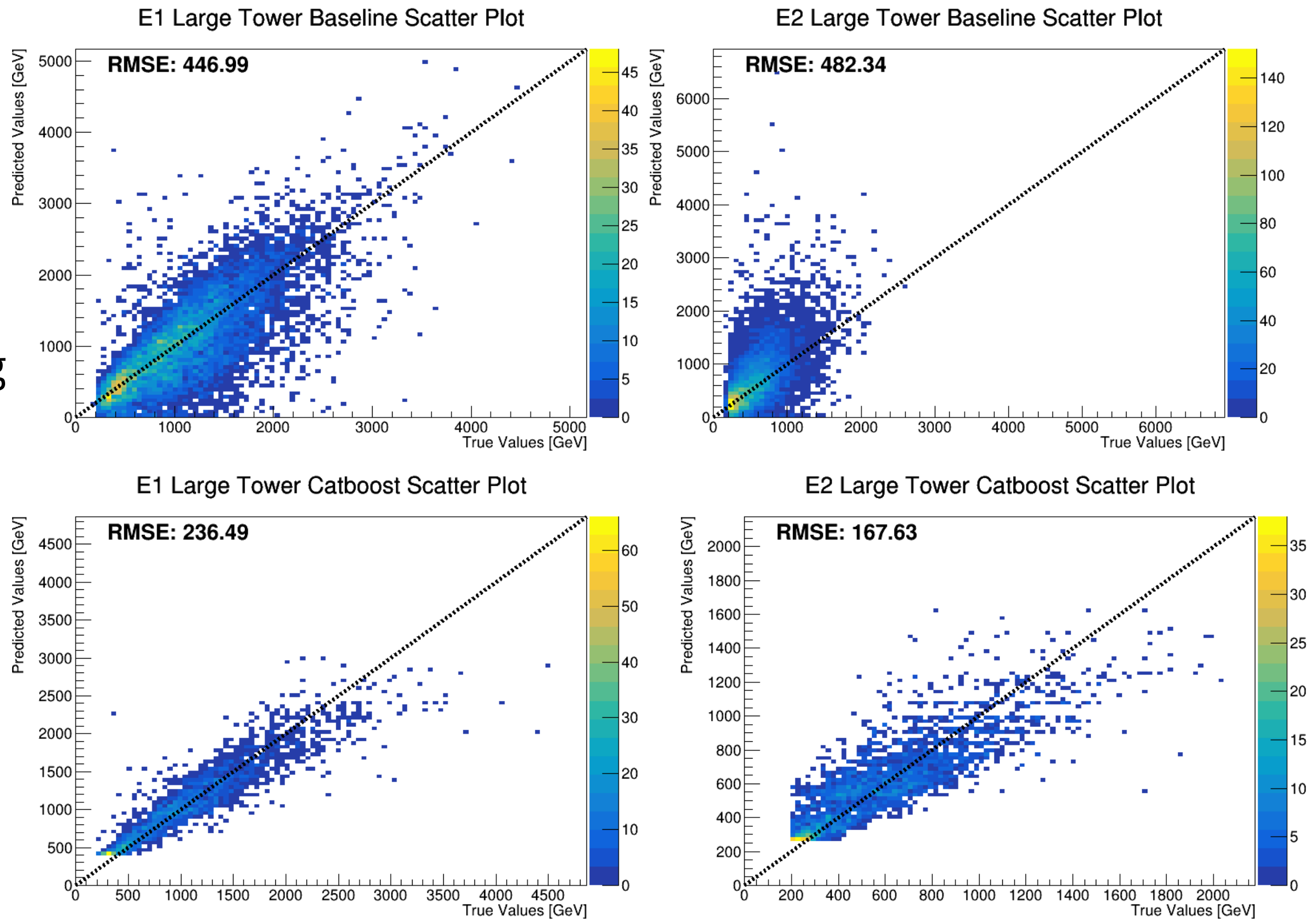

Summary

- The LHCf experiment measures neutral particle production in the forward pseudorapidity region to improve hadronic interaction models used in the cosmic rays field.
- Machine learning can **enhance the reconstruction of calorimetric clusters**, particularly for complex events involving multiple particles.
- Focus areas include energy sharing and position reconstruction, improving π^0 and η event analyses and opening new physics channels such as K_s^0 and Λ^0.
- **Two-Hit Events:** Improved accuracy in energy reconstruction using ensemble methods based on CatBoost and XGBoost.
- **Three-Hit Events:** Very preliminary results indicate potential for handling more complex scenarios, though additional data and refinement are needed.
- **Four hit studies, the possible presence of a neutron and improved position reconstruction using ML are foreseen, probably using raw transverse distribution data.**

Thanks for the attention!

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