LHCF- RECONSTRUCTION OF MULTIPLE CALORIMETRIC CLUSTERS

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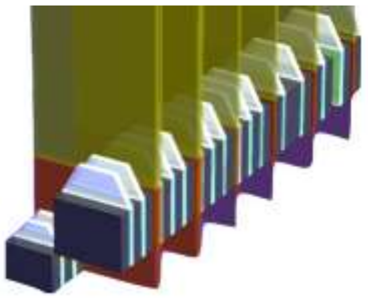
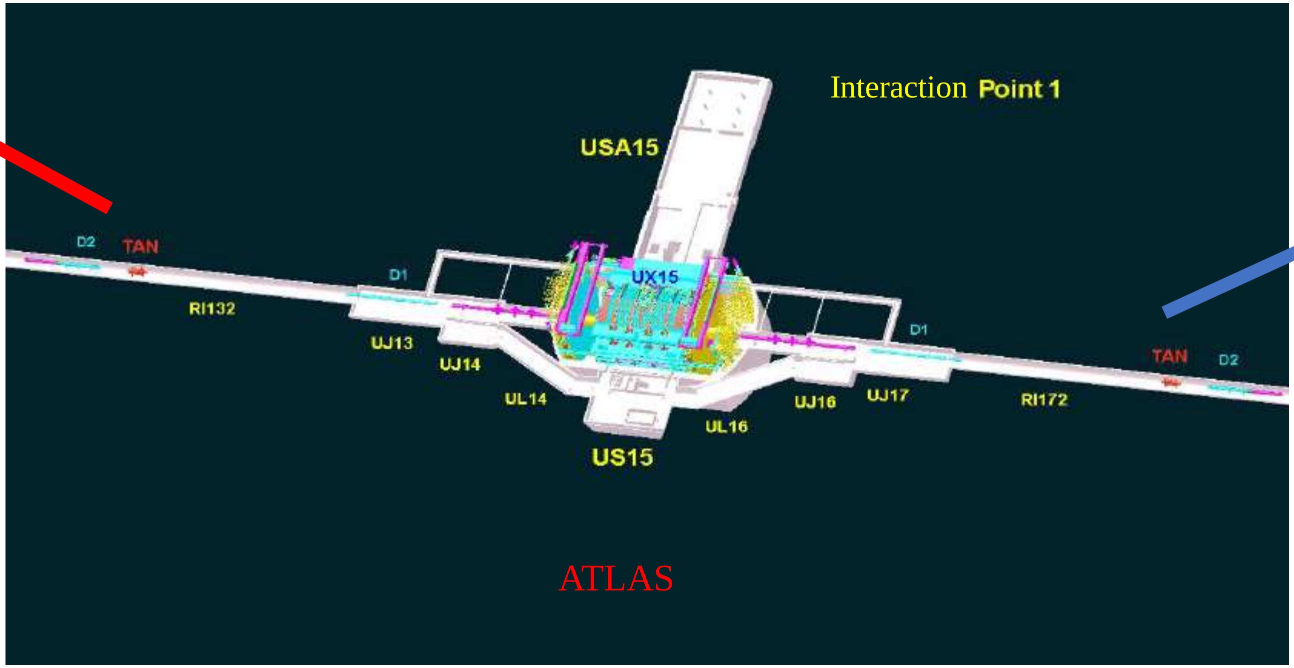
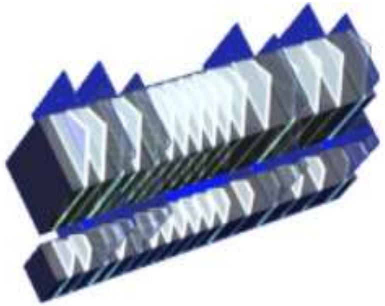
THE LHCF EXPERIMENT

➢A **unique experiment** designed to measure neutral particle production in the **forward pseudorapidity region**.
➢Composed by two **sampling** and calorimeters (ARM1 & ARM2), located at about ±141 m from the LHC Interaction Point 1 (IP1).
➢The aim of LHCf is to provide experimental data needful to tune and calibrate **hadronic interaction models** widely used by ground-based cosmic ray experiments.



LHCF-ARM2





LHCF-ARM1

THE LHCF DETECTORS

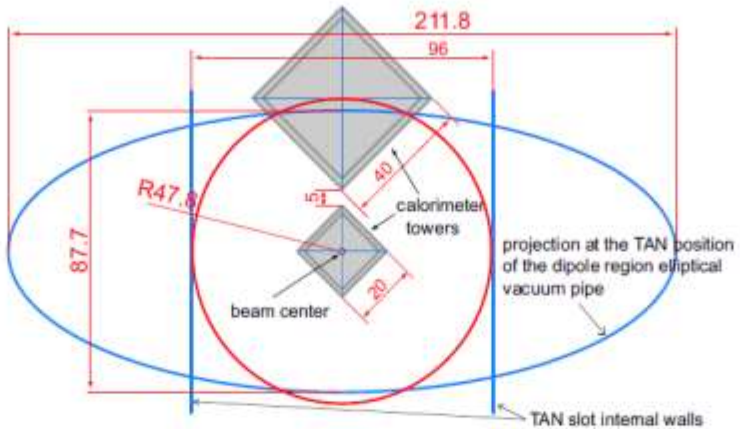
ARM1

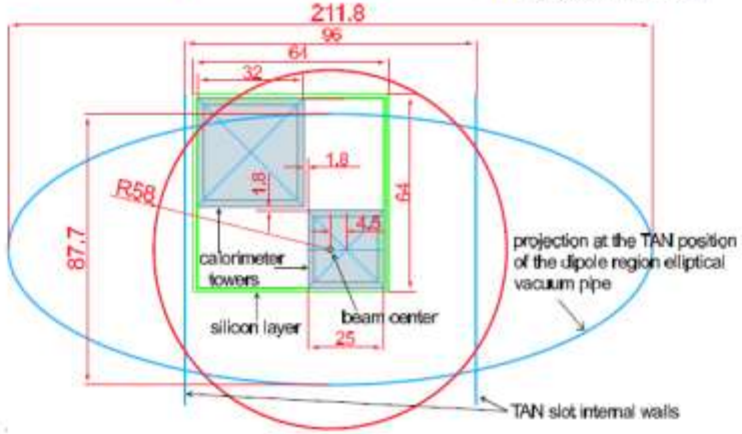
- **Energy resolution** <5% for photons and 35-40% for neutrons.
- Tracking with 4 GSO scintilating layers.
- **Position resolution** $\approx 200\ \mu m$.

ARM2

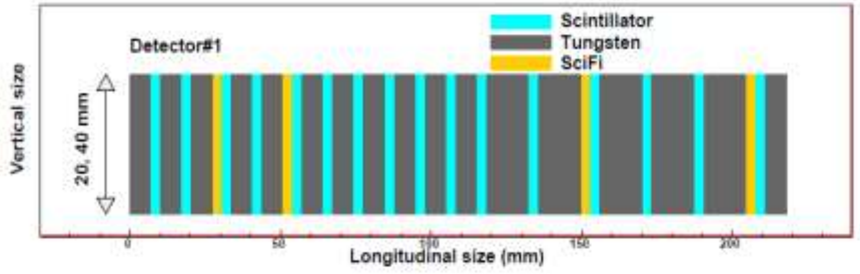
- Same Energy resoultion as ARM1.
- Tracking with 4 XY **silicon microstrips** layers.
- **Position resolution** $\approx 40\ \mu m$.

Transversal view

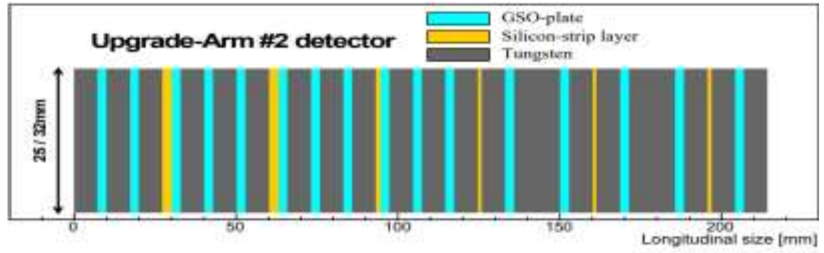




Longitudinal view



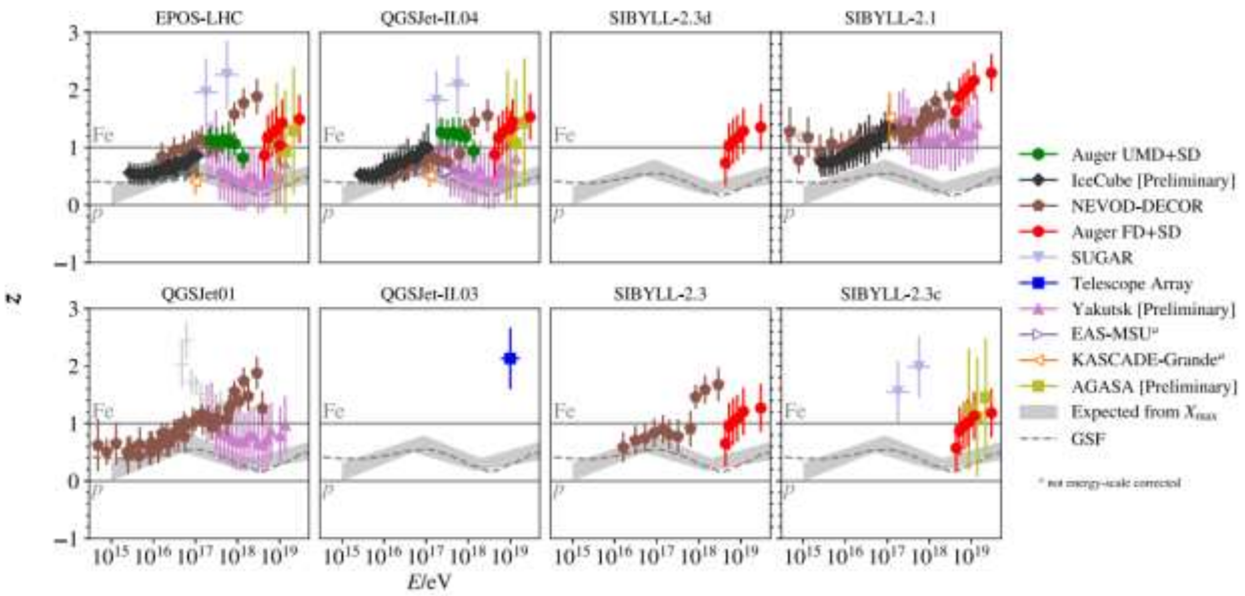
$44\ X_0$ and $1.6\ \lambda_I$ deep



EXPERIMENTAL PURPOSE

- 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 modelling** 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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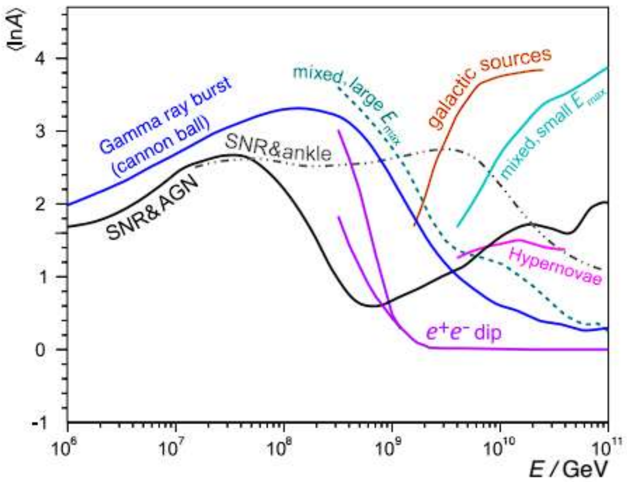
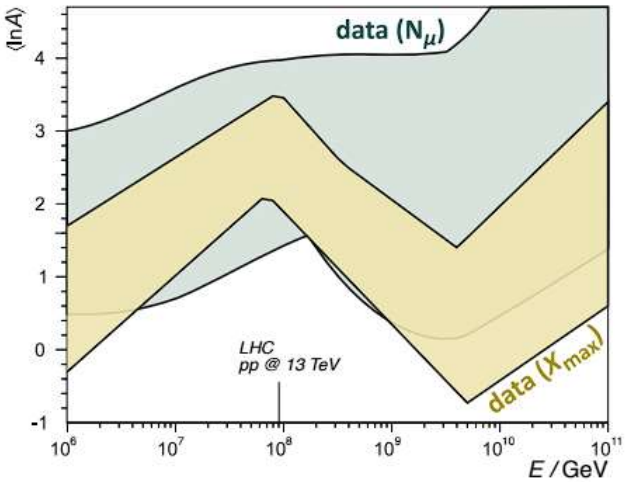
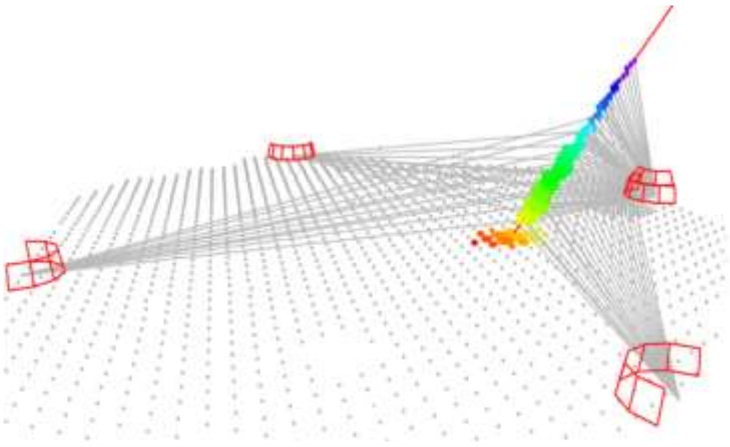
- These informations are essential, since these large uncertainties affect most of the astroparticle experiments!!

ULTRA-HIGH ENERGY COSMIC RAYS

ASS 367, 1 (2022)







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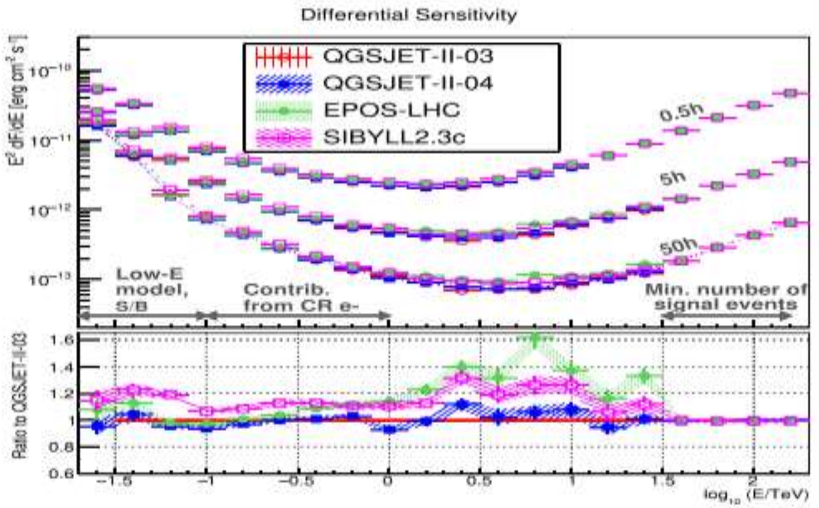
HIGH ENERGY GAMMA RAYS

NIMPR Section A: 553, 268 (2005)



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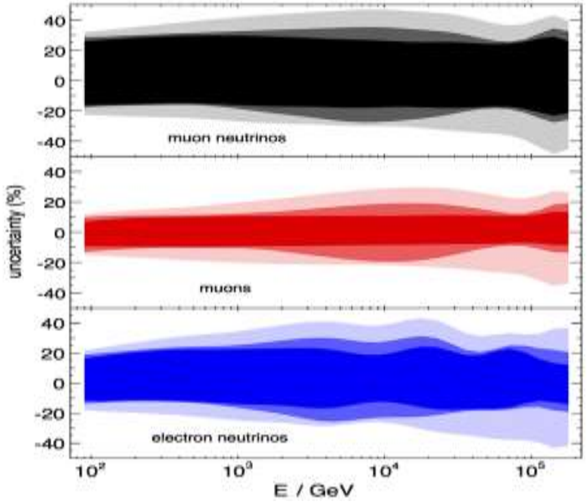
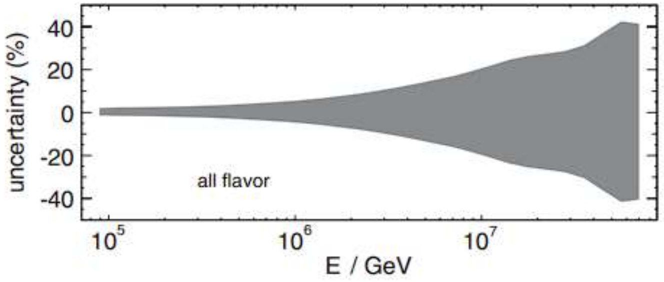
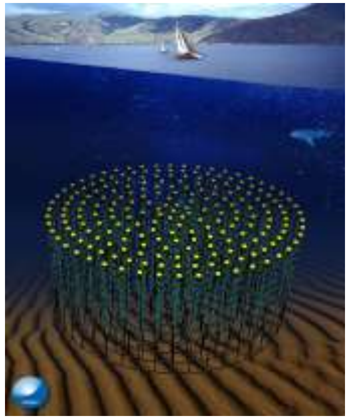
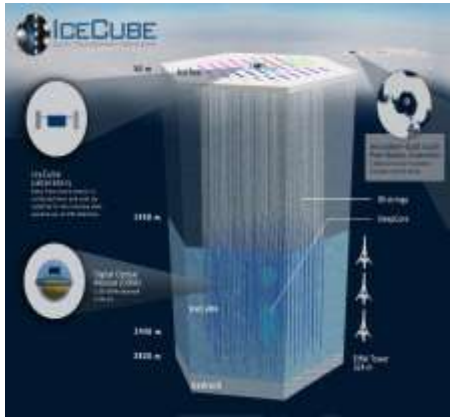
HIGH ENERGY NEUTRINOS

PR D 86, 114024 (2012)









LHCf Publication Table

	γ	neutron	π^0	η^0
Detector Calibration	NIM A, 671, 129 (2012) JINST 12 P03023 (2017)	JINST 9 P03016 (2014)		
p+p 510 GeV (RHICf)	**...submitted to PLB**		Phys. Rev. Lett. 124, 252501 (2021)	
p+p 900 GeV	Phys. Lett. B 715, 298 (2012)			
p+p 7 TeV	Phys. Lett. B 703, 128 (2011)	Phys. Lett. B 750 (2015) 360-366	Phys. Rev. D 86, 092001 (2012) Phys. Rev. D 94 032007 (2016)	
p+p 2.76 TeV			Phys. Rev. C 89, 065209 (2014) Phys. Rev. D 94 032007 (2016)	
p+Pb 5.02TeV				
p+p 13 TeV	PLB 780 (2018) 233-239	JHEP 11 (2018) 073 JHEP 07 (2020) 16	**Analysis ongoing**	~~**Almost complete**~~
p+Pb 8.1TeV	Analysis ongoing			

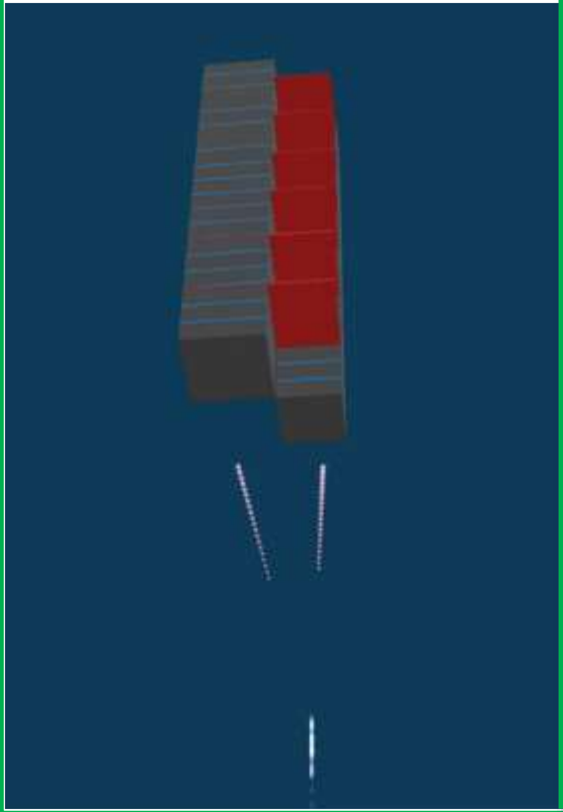
JHEP 2023, 169 (2023)

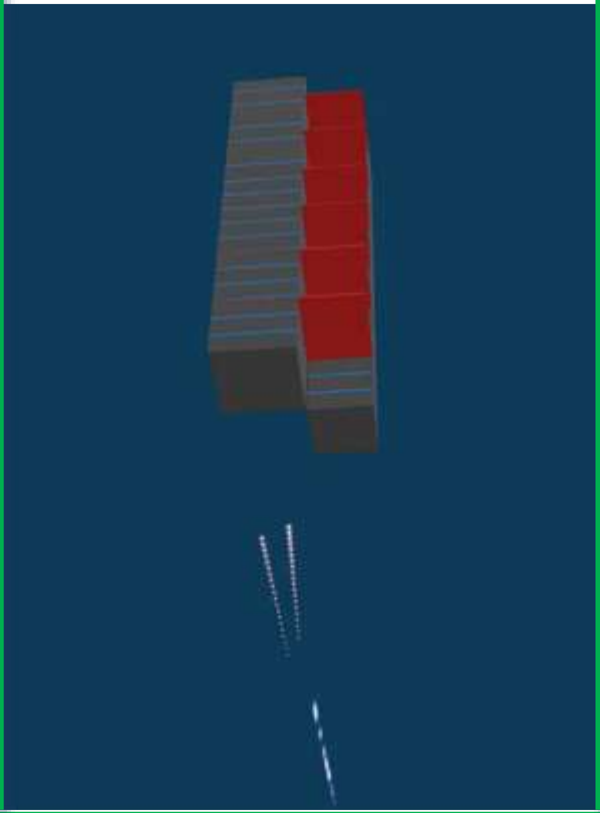
PURPOSE OF THE USE CASE

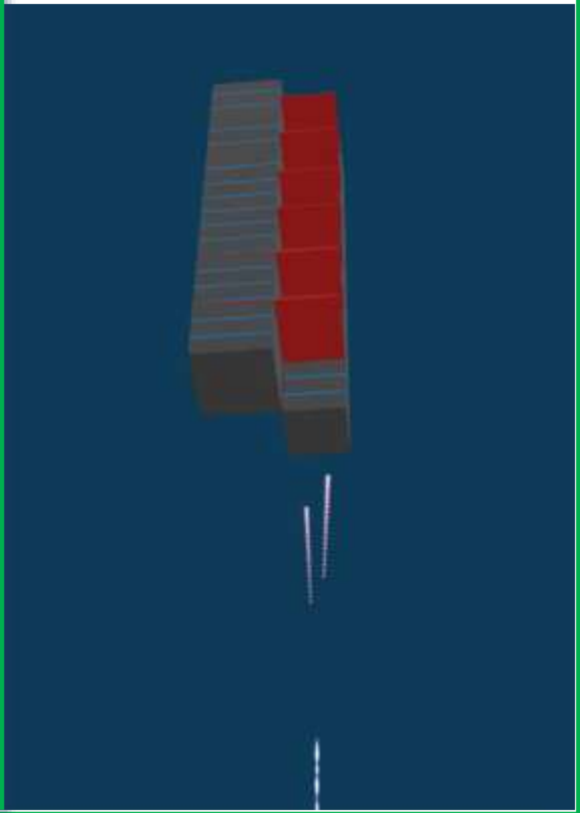
- In LHCf energy and position are reconstructed using the information of calorimetric and tracking detectors, respectively.
- Performances are good in the case of a single particle hitting the detectors (or better, at least one for each tower).
- **But there is a decrease in performances in the case of two or more particles hitting the calorimetric towers!**
- **The purpose of this Use Case is to develop an ML-based method to improve the reconstruction algorithm of LHCf for multiple calorimetric clusters.**

MOTIVATION I: π^0 AND η ANALYSIS

TYPE I	TYPE II LARGE TOWER	TYPE II SMALL TOWER
One photon for each tower	Two photons in the large tower	Two photons in the small tower

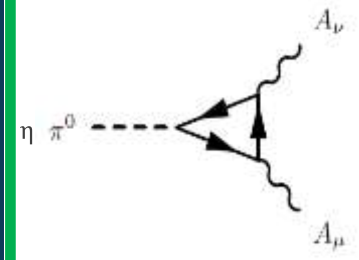




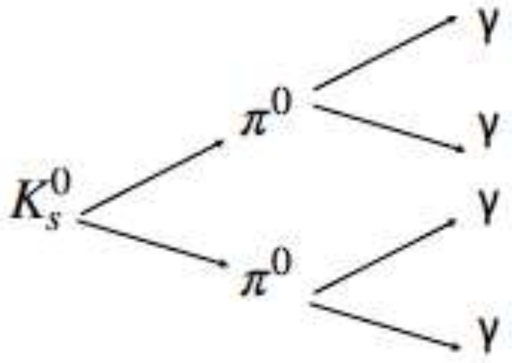


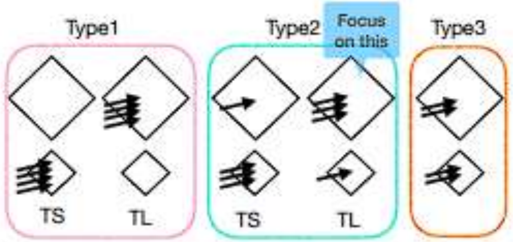
π^0 AND η DECAY

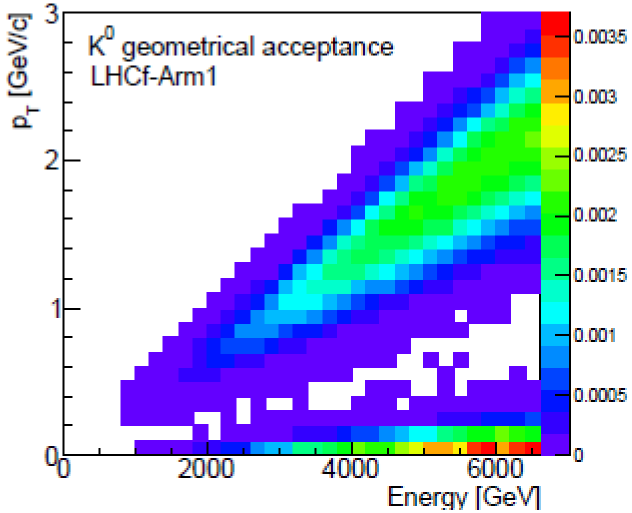
- Both particles decay mainly into **two photons.** $\eta/\pi^0 \rightarrow \gamma\gamma$
- Branching ratio in the case of π^0 is about **98.82%**.
- In the case of η is about **39.36%**.



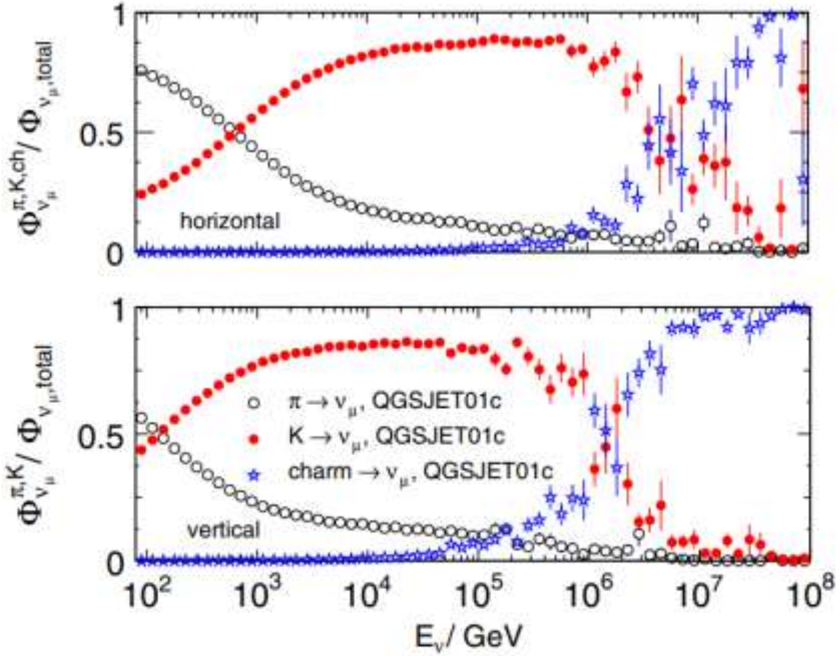
K^0 detection in LHCf







K mesons as main source of TeV-PeV atmosperic neutrinos

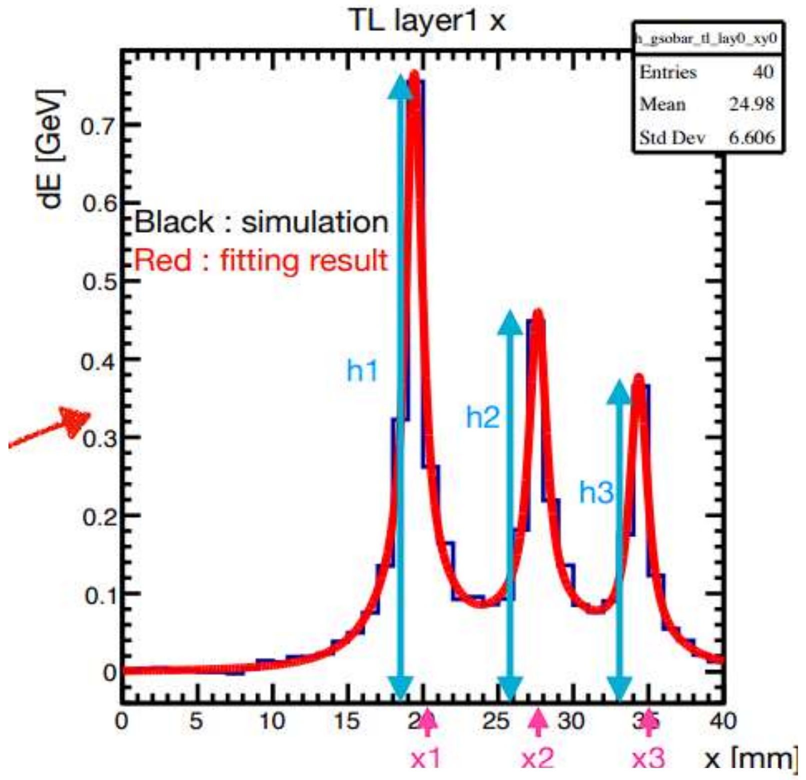


In this case, it's necessary to reconstruct at least three calorimetric hits!

NEW ENERGY SHARING METHOD FOR MULTI-HIT EVENTS

- **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.
- this work aims to find an **alternative method** to share the energy between multi-hit particles. This will be performed using **Machine Learning techniques**.
- For the moment, two methods were tested based **on Boosted Decision Trees** (BDT) and **Deep Neural Networks** (DNN), using 2 and 3 hit test datasets based on QGSJET II-04 full simulation of Arm2 events.
- To evaluate the performances, we used the metric **root mean squared error** (rmse) between true and predicted results.

An example of transverse profile with 3 clusters



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

3-components Lorentzian function

DATASET PREPARATION

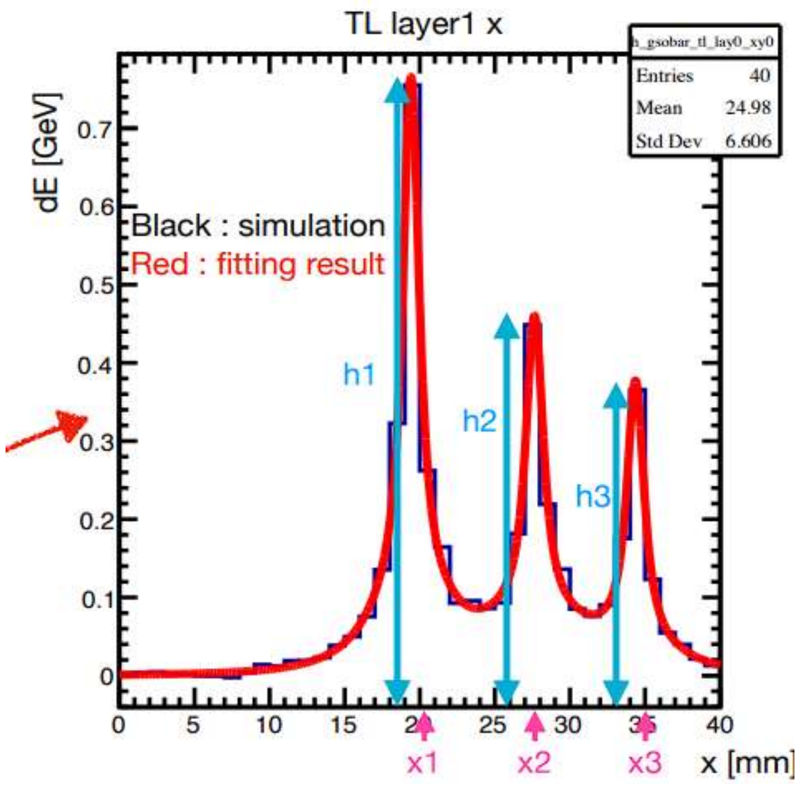
- To make inferences on energies of multi-hit events (2 and 3 hit for each tower) we used as input for the BDTs and DNN **the fit results of the silicon transverse profile.**

- Currently, the analysis has been carried out using **only photons** for simplicity. Two separate analyses were carried out for 2- and 3-hit events

- In particular, the fit parameters for **each particle** (2 or 3) for **each view** (x and y) for the first two **silicon plane pairs** were used as input variables (56 and 84 inputs for 2 and 3 particles, respectively).

- Different models were constructed and trained for **each tower**.

An example of transverse profile with 3 clusters



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3-components Lorentzian function

METHODOLOGIES

GRADIENT BOOSTING DECISION TREES (XGBOOST)

- The inference of single photon energies was performed using **2 (3) separated XGBoost models**, one for each particle of the event.
- Predicted energies were corrected to consider the constraint $\boldsymbol{E_1 + E_2(+\,E_3) = E_{tot}}$. Each energy is multiplied for the ratio between the sum of predicted energies and the total energy.
- **It is not the most orthodox method but gives good results**
- Hyper-parameters of the 2 (3) models are optimized by using the **Optuna library**, a package based on the **Bayesian optimization** (less effective, but also less resource/time-consuming with respect to grid-search)

DEEP NEURAL NETWORK (TENSORFLOW+KERAS)

- In this case, a single model was developed**, able to predict the 2 (3) energies at the same time.**
- Using the **softmax output layer** it was possible to obtain a prediction that respect the $\boldsymbol{E_1 + E_2(+\,E_3) = E_{tot}}$ constraint by default. In this case, the model directly predict the **percentage of energy** for each particle.
- **It is an orthodox method but actually gives worst results.**
- Hyper-parameters of the model are not currently optimized. A first test was performed by using a 5 hidden layer model with 256-128-64-32-16 neurons.
- To limit the overfitting a **dropout rate of 10%** for each layer was considered.

XGBoost Optimization Grid

```python
def objective_E1(trial):
    # Definizione dello spazio dei parametri per E1_tow1_mc
    param = {
        'lambda': trial.suggest_loguniform('lambda', 1e-8, 10.0),
        'alpha': trial.suggest_loguniform('alpha', 1e-8, 10.0),
        'colsample_bytree': trial.suggest_float('colsample_bytree', 0.1, 1),
        'subsample': trial.suggest_float('subsample', 0.1, 1),
        'learning_rate': trial.suggest_float('learning_rate', 0.01, 0.3),
        'n_estimators': trial.suggest_int('n_estimators', 100, 10000),
        'max_depth': trial.suggest_int('max_depth', 3, 20),
        'min_child_weight': trial.suggest_int('min_child_weight', 0, 10),
        'objective': 'reg:squarederror'
    }
    model = xgb.XGBRegressor(**param, missing=np.inf)
    model.fit(X_train, Y_train.iloc[:, 0])  # E1_tow1_mc
    preds = model.predict(X_test)
    rmse = np.sqrt(mean_squared_error(Y_test.iloc[:, 0], preds))
    return rmse
```

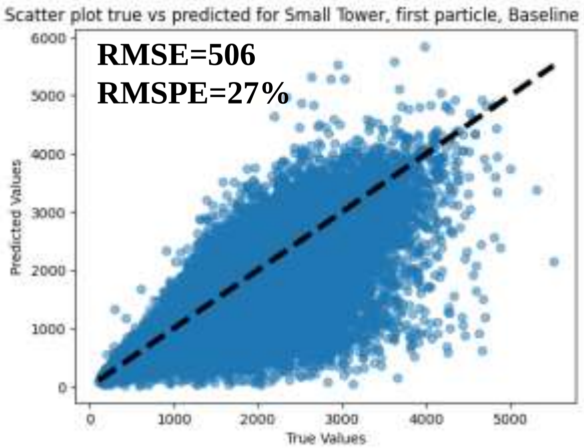
Typical values of the number of weak learners are always very high and near to the maximum limit

Results for two photons on Small Tower

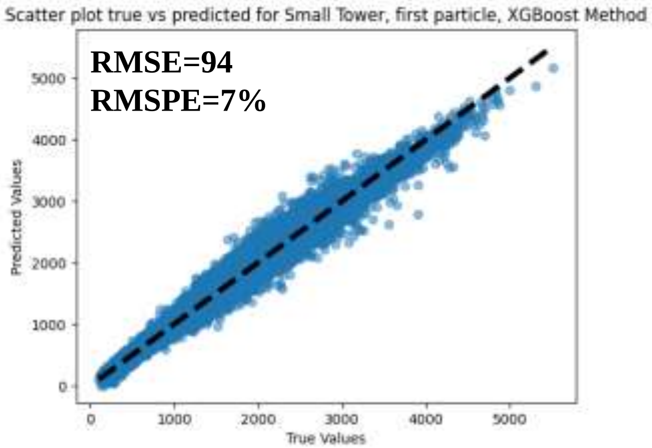
N_{train}=66547
N_{test}=66547

1° PHOTON

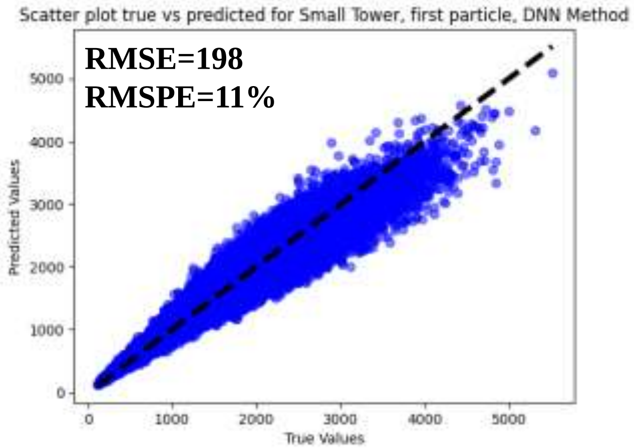
BASELINE



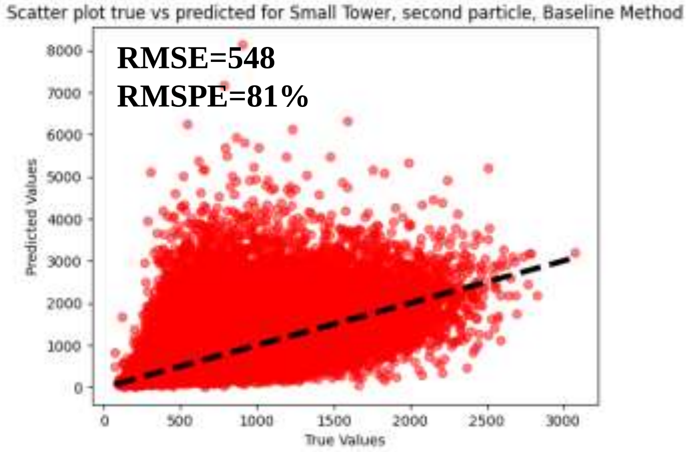
XGBOOST

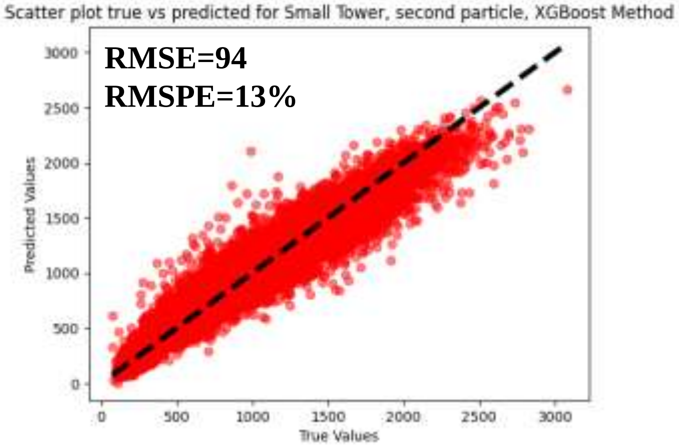


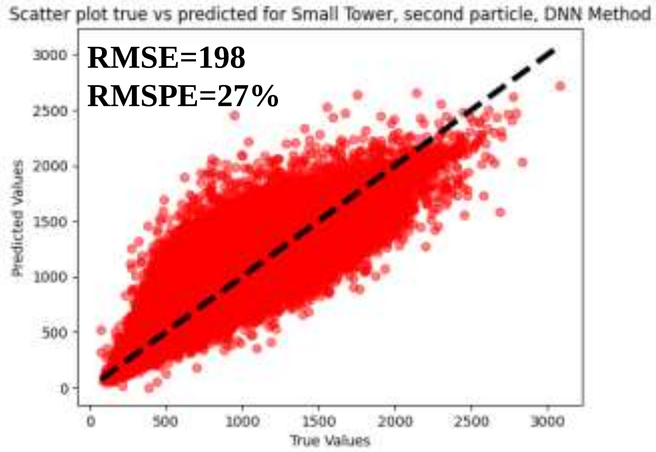
DNN



2° PHOTON







RESULTS FOR TWO PHOTONS ON SMALL TOWER

N_{train}=66547
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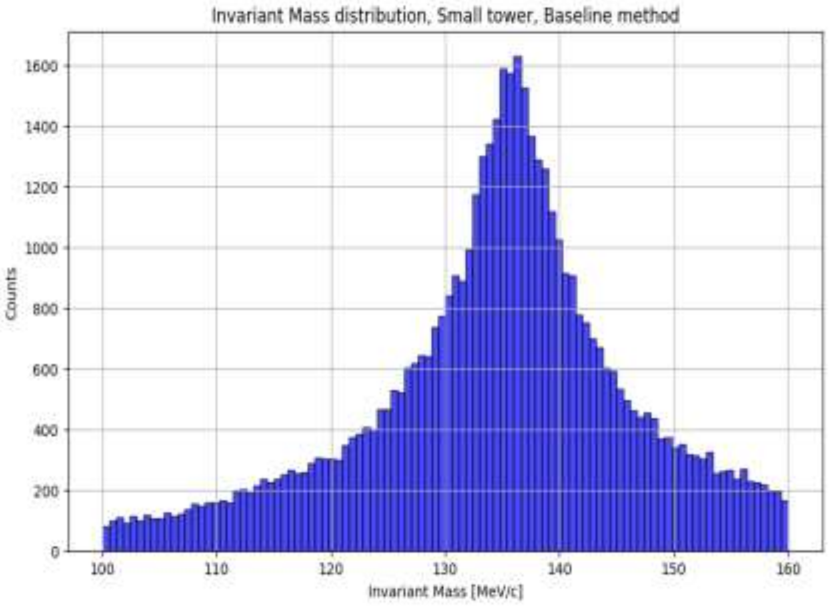
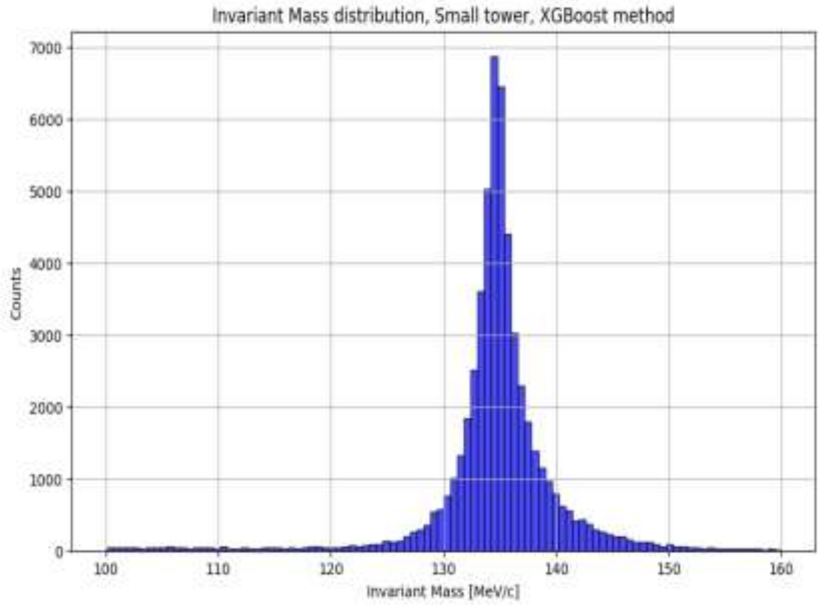
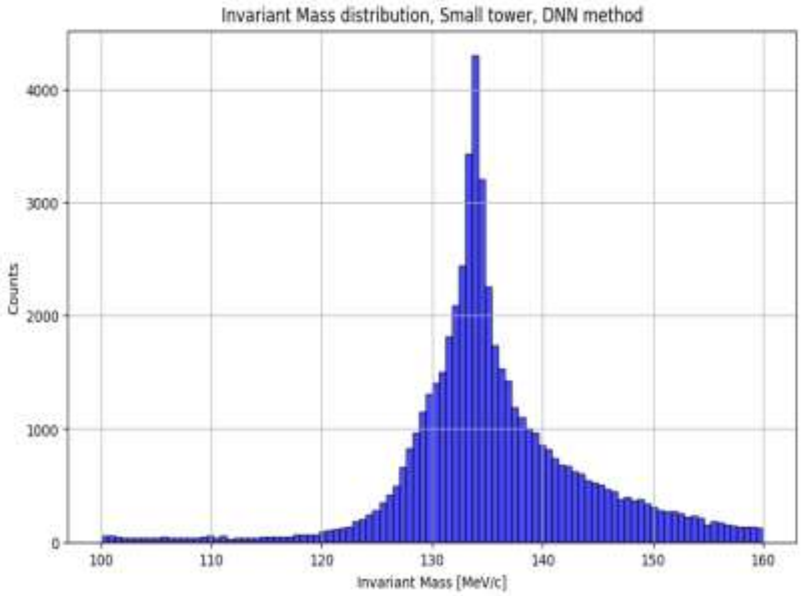
BASELINE



XGBOOST



DNN

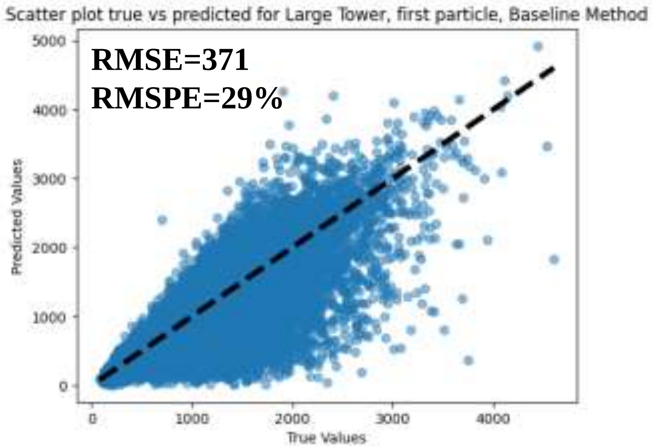


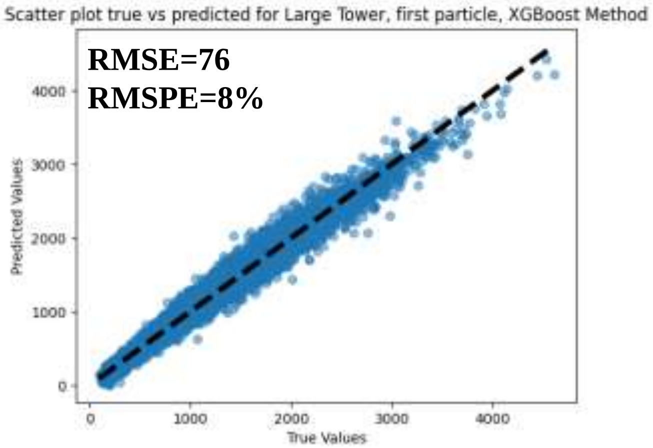
RESULTS FOR TWO PHOTONS ON LARGE TOWER

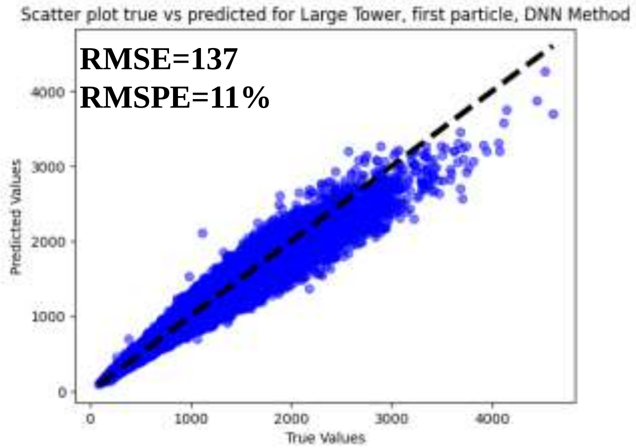
N_{train}=29992
N_{test}=29992

BASELINE | **XGBOOST** | **DNN**

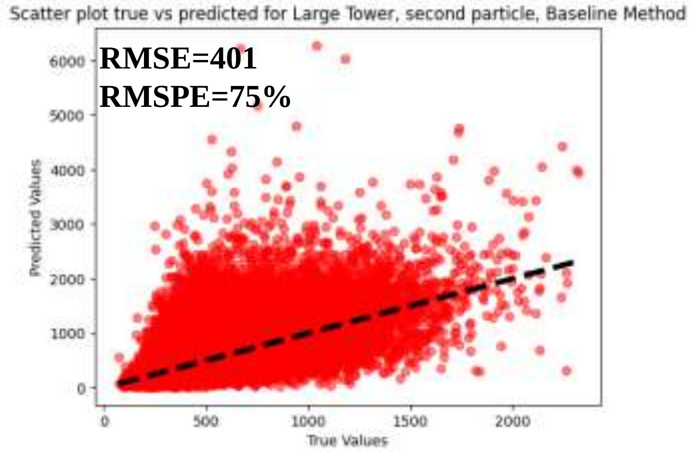
1° PHOTON

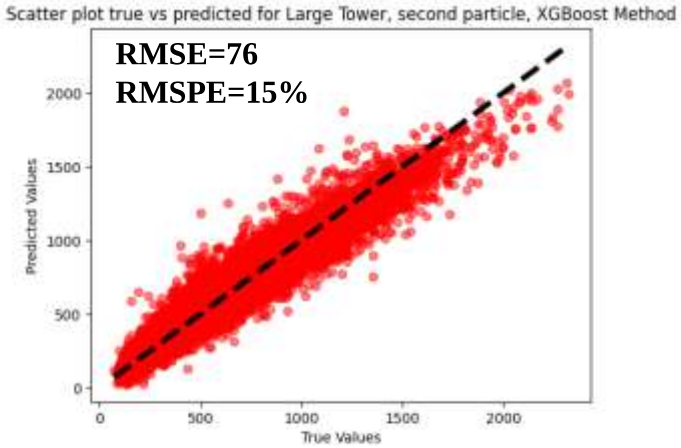


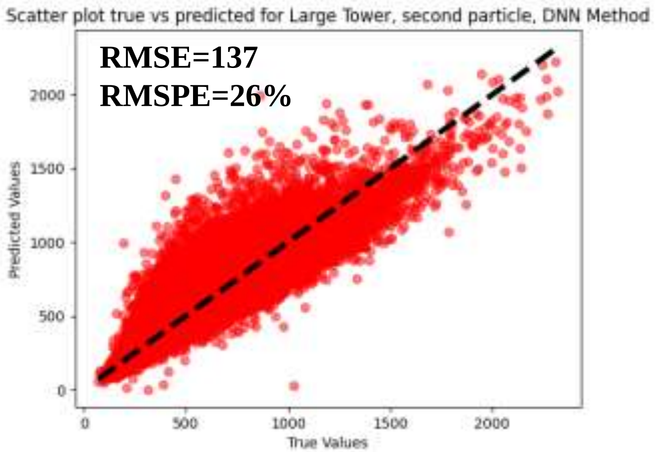




2° PHOTON







RESULTS FOR TWO PHOTONS ON LARGE TOWER

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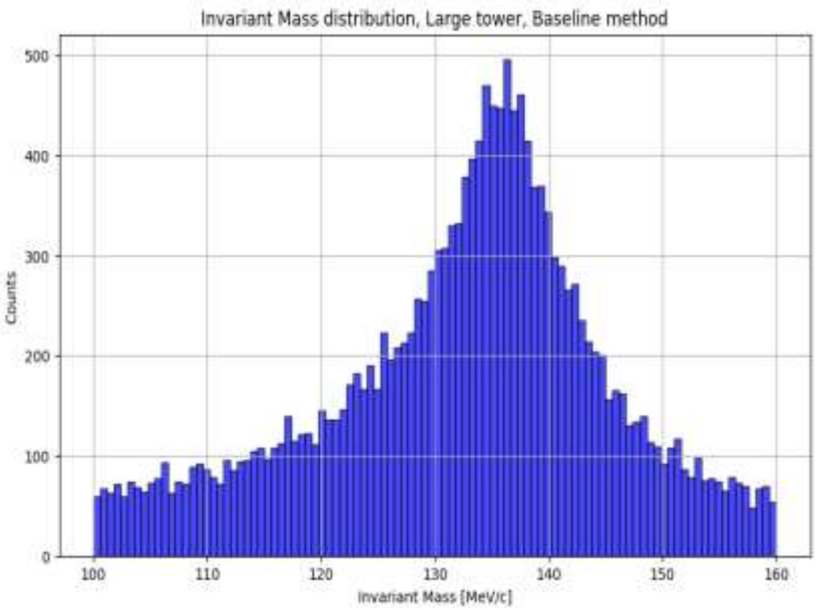
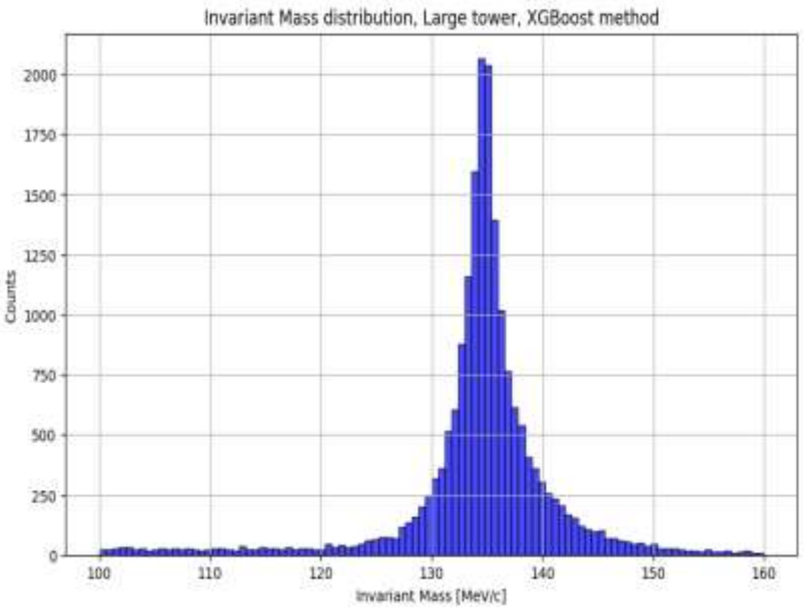
N_{test}=29992

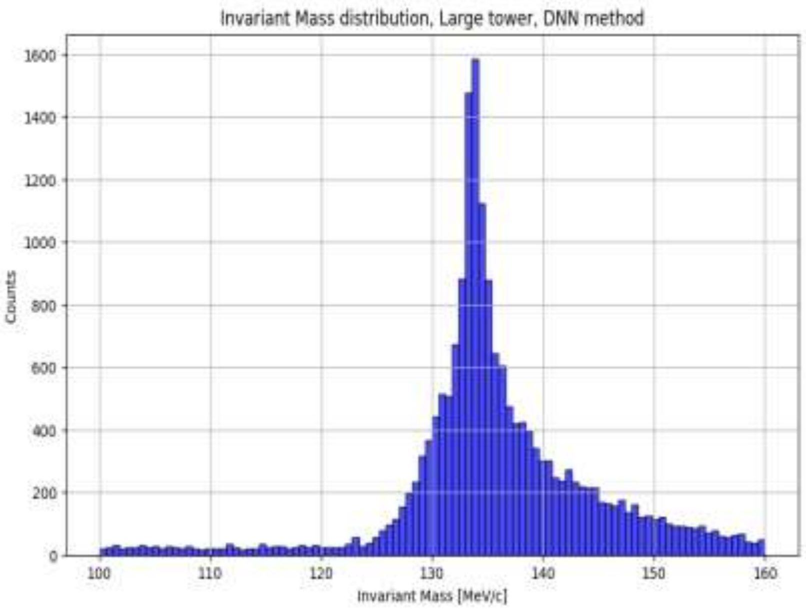
BASELINE



XGBOOST



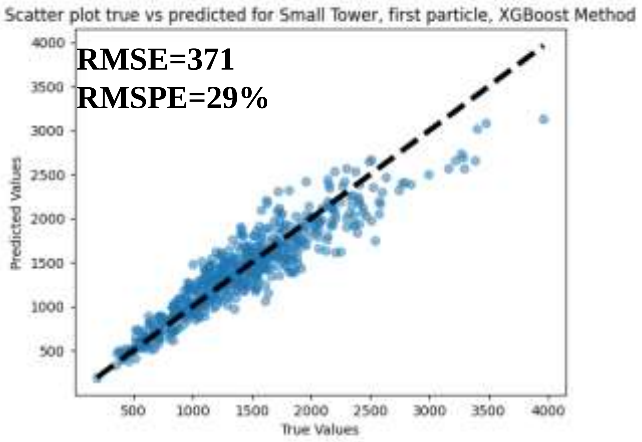
DNN

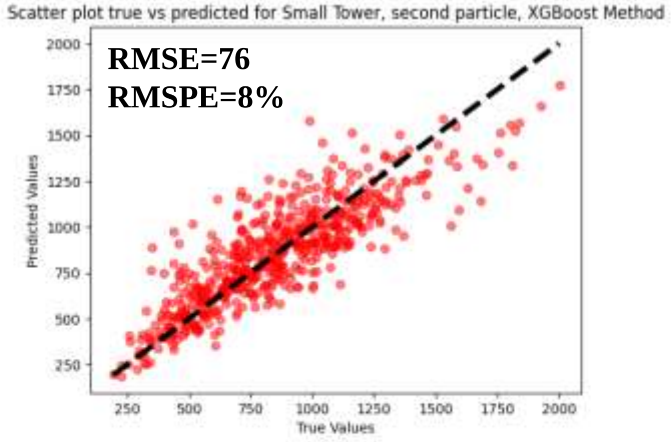


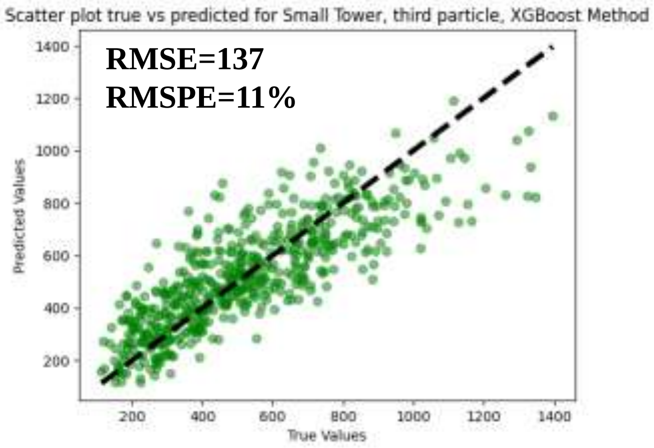
RESULTS FOR THREE PHOTONS ON SMALL TOWER

N_{train}=567
N_{test}=567

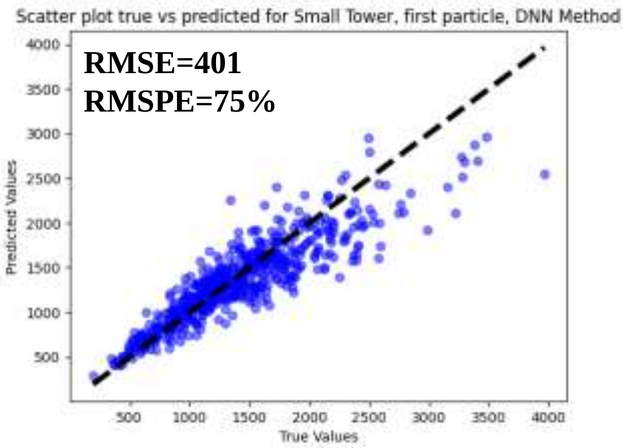
XGBOOST

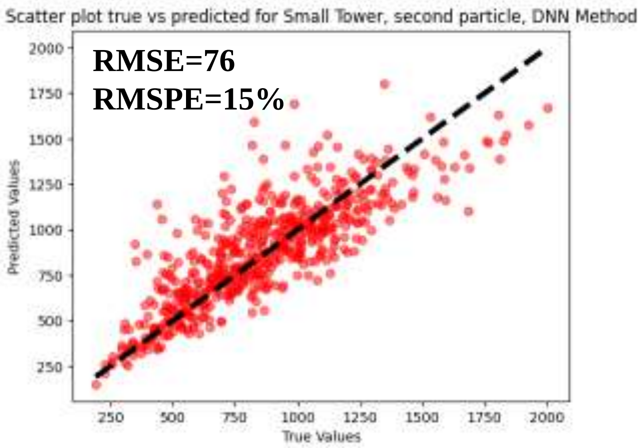


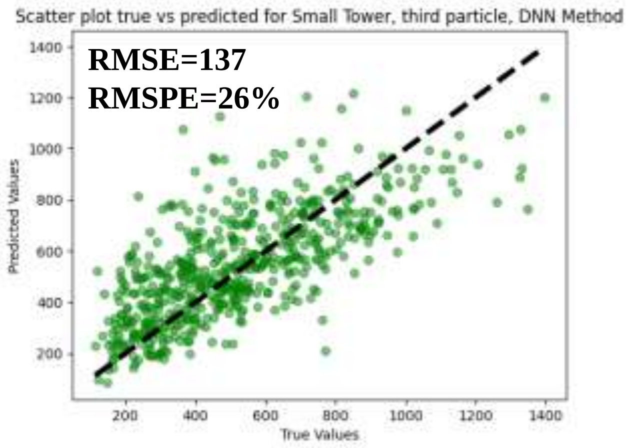




DNN



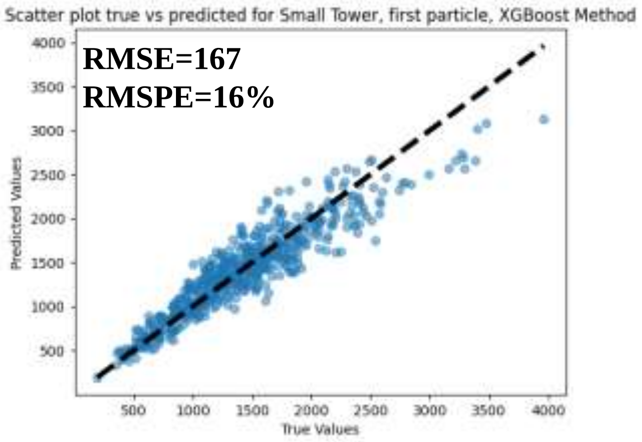


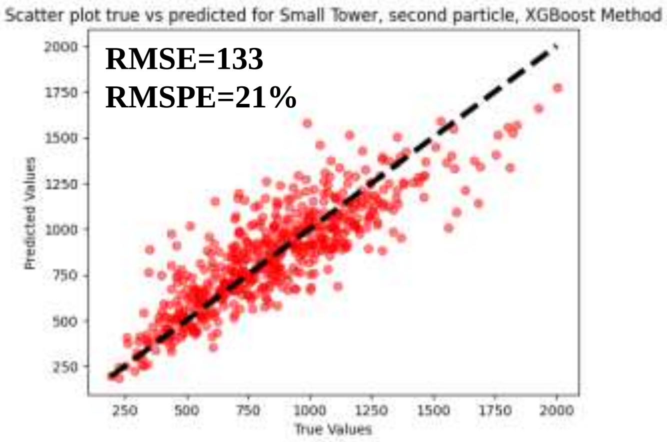


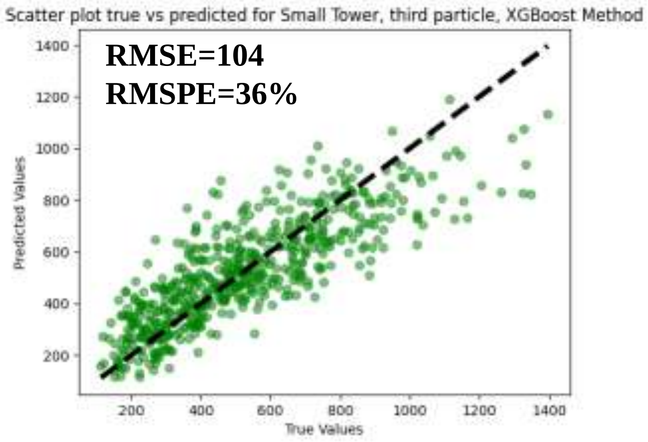
RESULTS FOR THREE PHOTONS ON LARGE TOWER

N_{train}=381
N_{test}=381

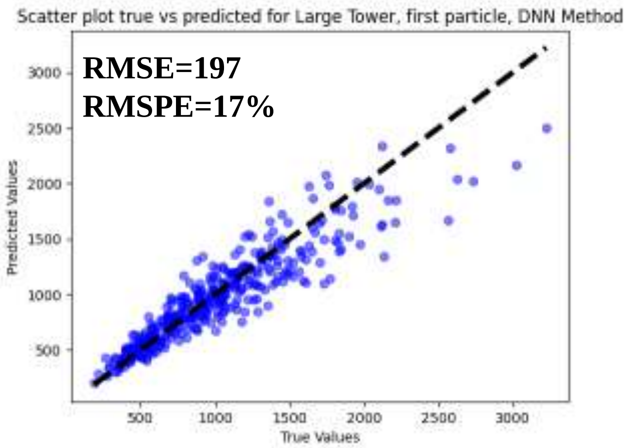
XGBOOST

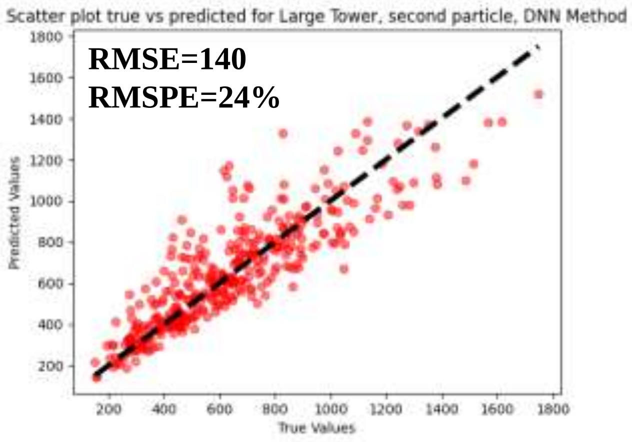


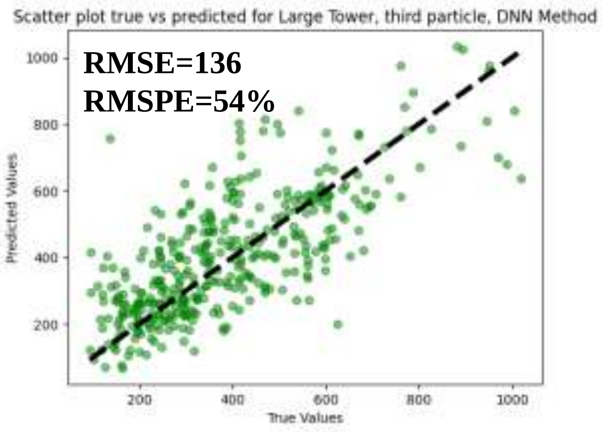




DNN







NEXT STEPS

- A first step forward should be the **increase of the statistics, especially for 3-hit events.** This will permit us to obtain better results and to validate them better (k-Folding).

- It could be a good idea to test new input features, such as the **energy deposits** in the calorimetric layers.

- Also, **a better understanding of the methodology and possible improvements could be required (Suggestions by all of you are very welcome!).**

- A **deeper optimization phase** could be helpful to improve the performances of the models.

- Finally, it will be necessary **to validate the future official results with other datasets**, for example, based on other models, like the one already simulated with EPOS-LHC as the generator.

THANK YOU FOR THE ATTENTION

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