Classifying the QCD transition at the CBM experiment with Deep Learning

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The study of QCD matter

Conjunctured QCD phase diagram

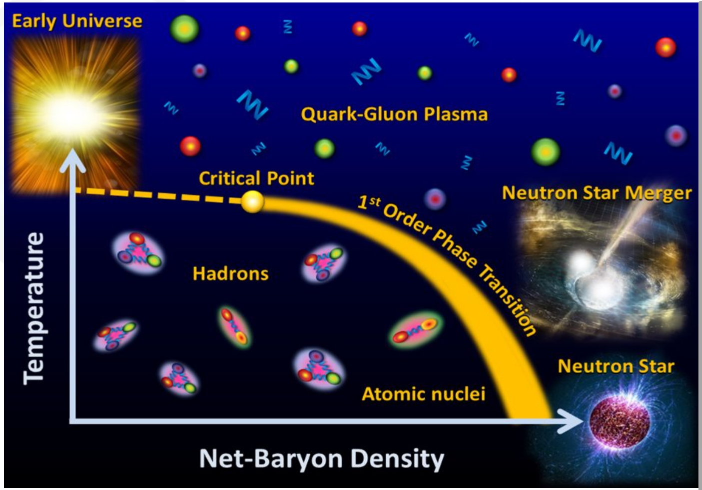
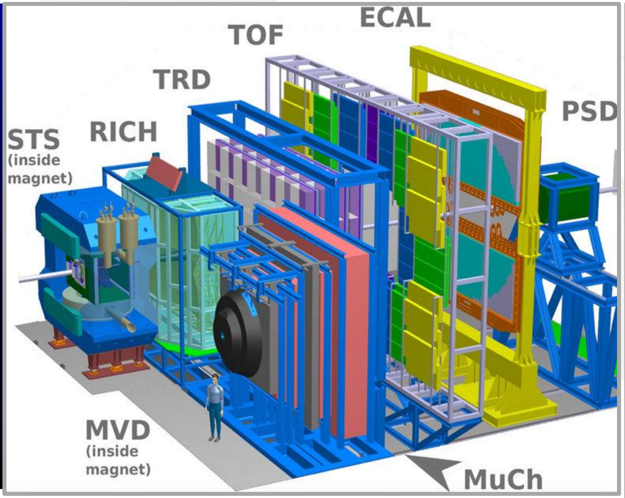


Fig: Senger, Peter. "Astrophysics in the Laboratory—The CBM Experiment at FAIR." *Particles* 3.2 (2020): 320-335.

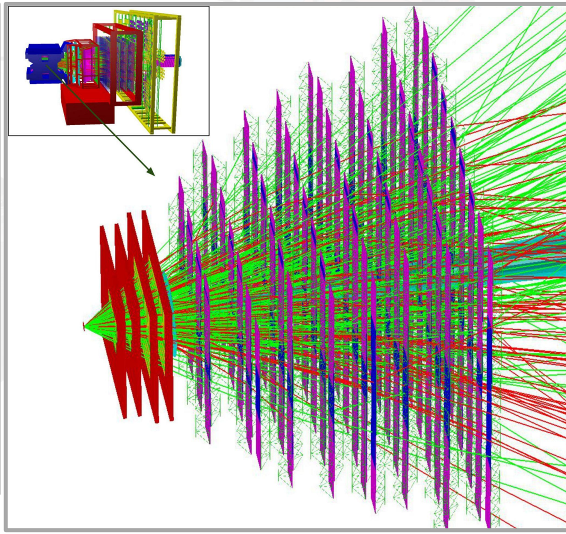
- LQCD-> Smooth crossover at high temperature and small densities
- Is there a phase transition?
- If so, where is the critical point?

The CBM Detector



- Upto 45 AGeV collisions
- 10^7 collisions/ Second
- 1000 tracks per collision
- 1 TBytes/Second raw data

A simulated event in STS + MVD



- MVD -> 4 planes
  Position resolution: 3.5-6 μm
  Secondary vertex resolution: 50 μm
- STS-> 8 planes
  Momentum resolution: 1 %

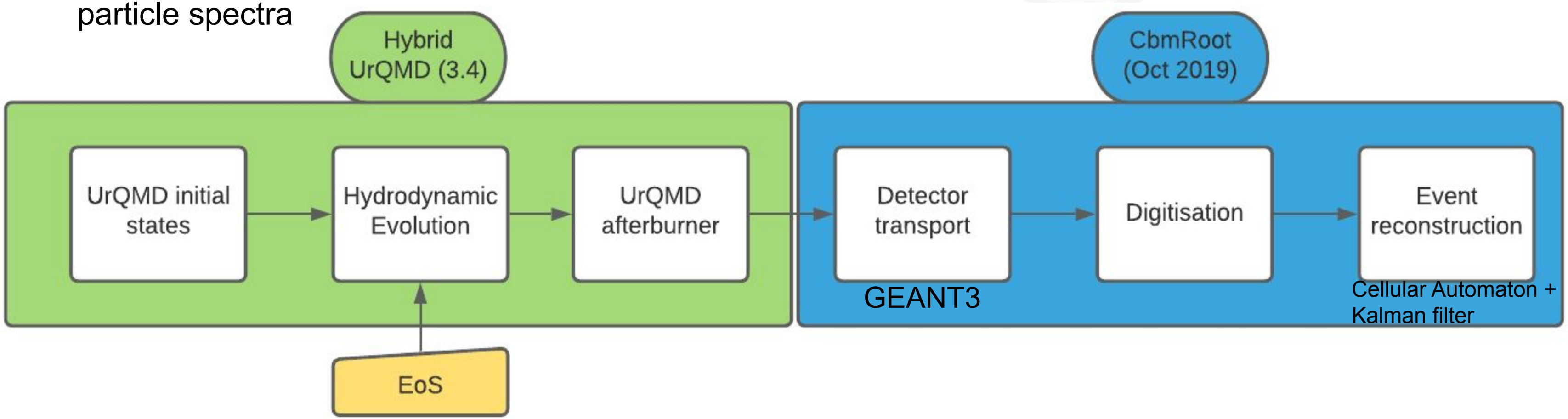
Data preparation

Previous works:

- Pure hydrodynamic study: *Pang, L. G., Zhou, K., Su, N., Petersen, H., Stöcker, H., & Wang, X. N. (2018). Nature communications, 9(1), 1-6.*
  - > 95% accuracy
- Hydrodynamics + afterburner: *Du, Y. L., Zhou, K., Steinheimer, J., Pang, L. G., Motornenko, A., Zong, H. S., ... & Stöcker, H. (2020). The European Physical Journal C, 80(6), 1-17.*
  - Finite particle spectra, hadronic rescattering, resonance decays
  - prediction accuracy depended on smoothness of the particle spectra

The Goal:

- Design a DL based EoS meter for CBM
  - increased uncertainties from electro-weak decays and detector effects
- Train on “experiment like” data
  - avoid biases from user defined selection criterias and analysis algorithms

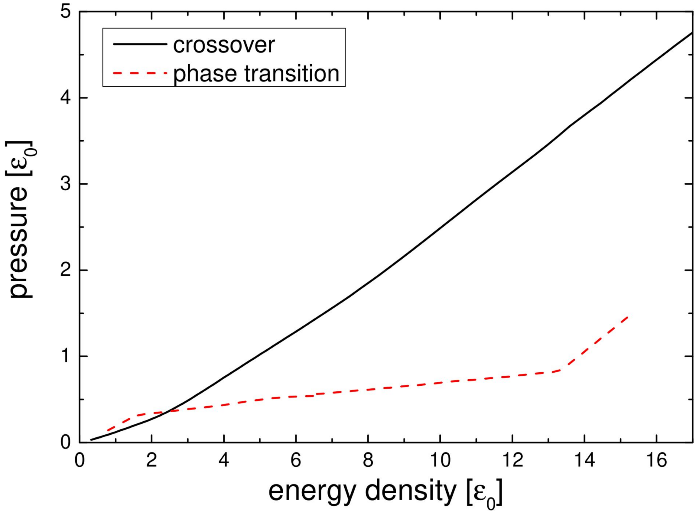


The Equation of State

- Essential input to fluid dynamics evolution
- Provides the pressure of the medium for any given energy and net baryon number densities

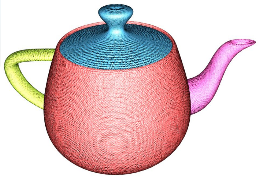
- Incorporates the QCD transition
  - Pressure gradients drives the evolution

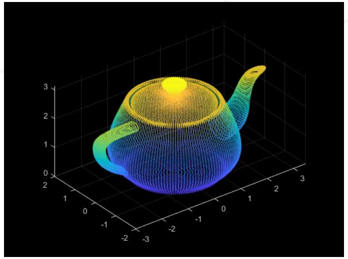
- We use:
  - Maxwell construction between a bag model quark gluon EoS and a gas of pions and nucleons :**First Order Phase transition**
  - Chiral Mean Field hadron-quark EoS : **Crossover**

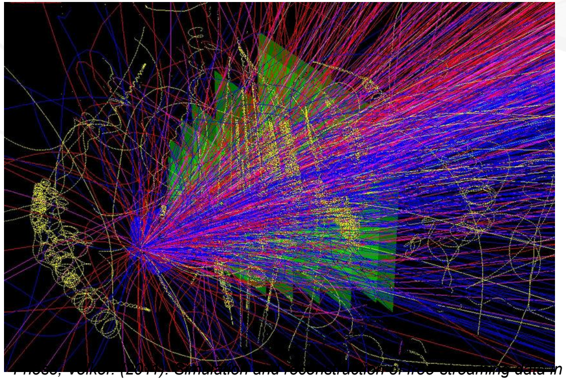


Representing the experimental data

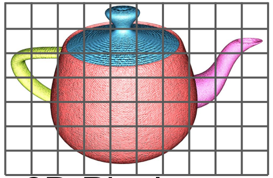
- Experimental data: tracks or hits of particles
  - Each particle is a point in a point cloud
  - The order of input shouldn't affect the output







[illegible] n CBM. Journal of Physics: Conference Series. 331. 032008. 10.1088/1742-6596/331/3/032008.

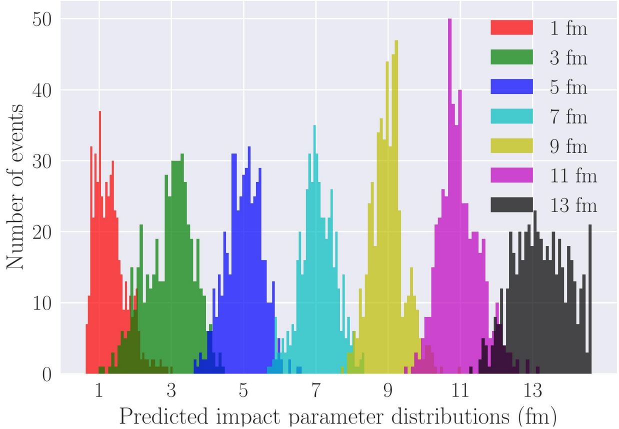


2D Pixel map

- 3D Voxels map
  - voluminous!
- Pointcloud: order invariant 2D array of (x,y,z) coordinates (or other point attributes) of each point
  - Efficient representation for higher dimensions

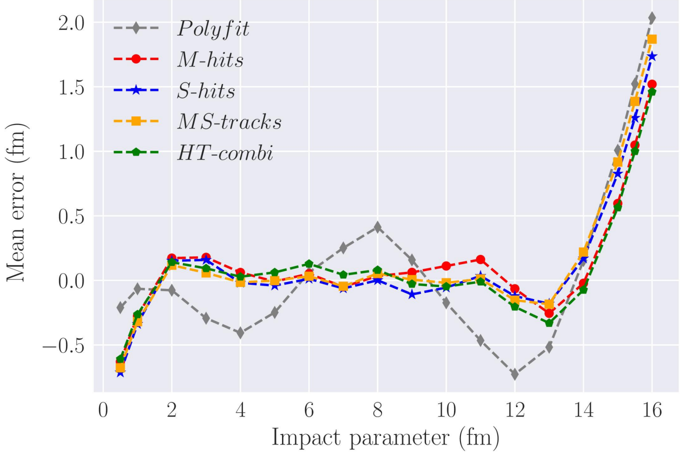
X1,y1,z1,.....
X2,y2,z2,.....
X3,y3,z3......
. . .
xn,yn,zn,.....

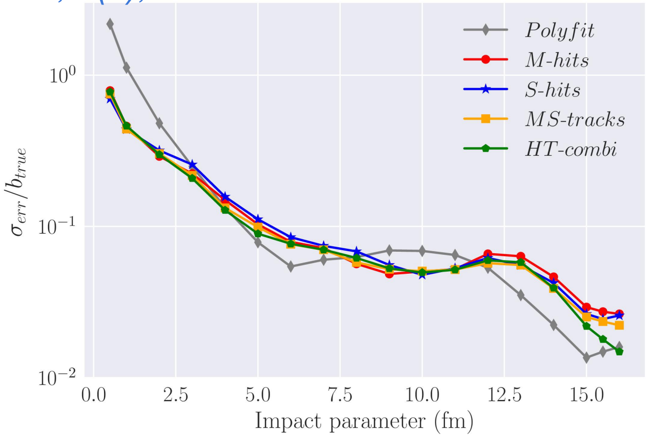
Learning the impact parameter from point cloud data



- PointNet based impact parameter determination
- mean error between -0.3 and 0.2 fm for b= 2- 14 fm

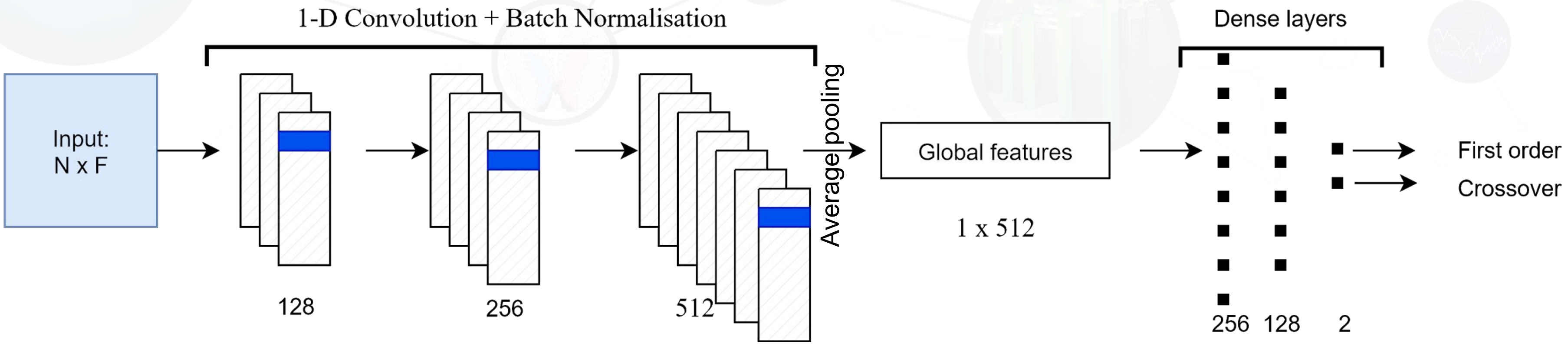
- *A fast centrality-meter for heavy-ion collisions at the CBM experiment*
  Phys.Lett.B 811 (2020) 135872
- *Deep Learning based impact parameter determination for the CBM experiment*
  *Particles **2021**, 4(1), 47-52*





The PointNet model

- DL model to learn from point cloud
- Extracts order invariant global features



- ❑ N = No of particles
- ❑ F = No of features per particle

Training the models

- Au- Au Collisions at 10 AGeV
- 0-7 fm impact parameter (uniform)
- 60000 training samples (30000+ 30000) , 20000 validation samples (10000+ 10000)

- 3 Cases are considered
- All models used similar architecture, hyperparameters
- Differ in the input dimensions

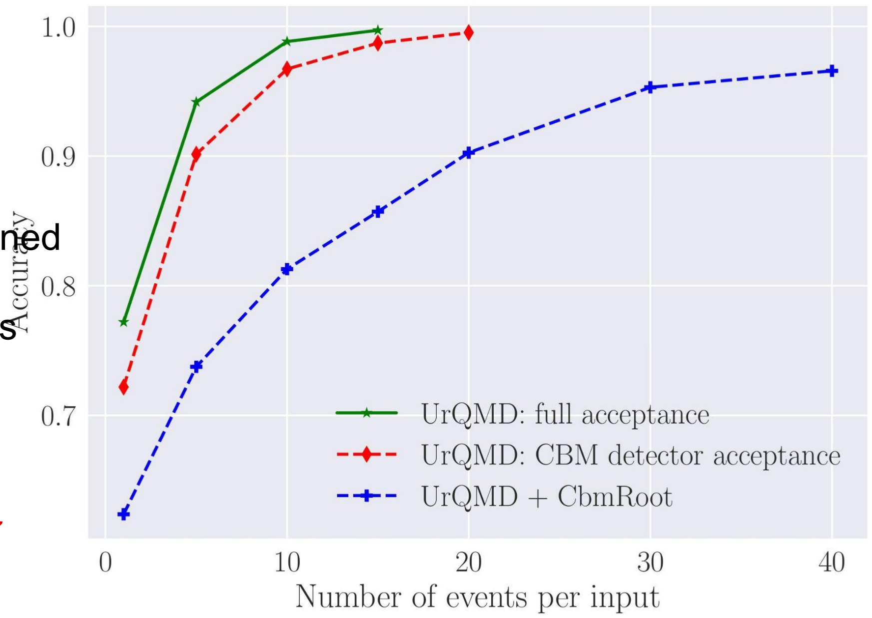
01	UrQMD output	• 4-momentum of all particles • Ideal case: 360° acceptance + 100% detector efficiency
02	UrQMD output with CBM acceptance	• 4-momentum of all particles • 2- 25° acceptance cut
03	UrQMD + CbmRoot	• Reconstructed tracks from the digitised hits in STS • Realistic simulation

Training results

- Decrease in performance with increase in experimental effects
- Accuracy on the event by event data:
  - UrQMD: 77.2%
  - UrQMD+ CBM acceptance: 72.2%
  - UrQMD+ CbmRoot: 62.4%

- Performance improves when events are combined
  - More uncertainties-> More events
  - UrQMD+ CbmRoot: 96.6% with 40 events

- Similar dependency found in *Du, Y. L., Zhou, K., Steinheimer, J., Pang, L. G., Motornenko, A., Zong, H. S., ... & Stöcker, H. (2020). The European Physical Journal C, 80(6), 1-17*
- Increasing the statistics reduces the stochasticity



Centrality dependence

- Can the performance improve with a centrality selection?

		Impact parameter	Validation Accuracy
1	Model-1	0-7 fm	96.6%
2	Model-2	0-3 fm	99.8%
3	Model-3a	0-3 fm	99.65%
4	Model-3b	3-7 fm	81.27%

- All models used combinations of 40 events of STS tracks

- Accuracy increases when trained on events with b< 3fm
- Centrality selection improves accuracy but most data collected goes unused
  - Model 3 can solve this issue

- Trained on events with both b=0-3 fm and b=3-7 fm
- Centrality classes are not mixed when combining events
- Additional input to network which identifies the class of input data

Input parameters for Hydrodynamics evolution

- Several inputs to hydrodynamic simulation re not precisely known.
- A practical DL model should be immune against changes to these parameters

1. Starting time of hydrodynamic evolution:

$$t_{start} = 2R\sqrt{\frac{m}{E_{lab}}}$$

R=radius of nuclei
m=mass of nucleon
E_{lab}= kinetic energy in lab frame

2. Freeze-out energy density (ε) :

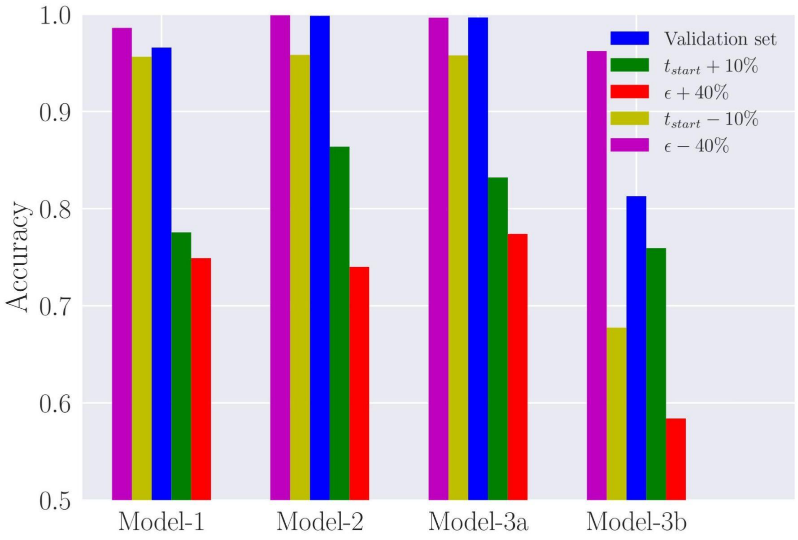
The hydrodynamic evolution happens in a cartesian grid Δx=0.2 fm , 200^3 cells
Hydrodynamic evolution stops when $\varepsilon < 5\varepsilon_o$ for all cells

Particlisation happens from the iso energy density hypersurface using Cooper-Frye formula

$$E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu$$

$f(x,p)$ =boosted Fermi/ Bose distribution
$d\sigma_\mu$ =freezeout hypersurface element

Dependence on t_{start} and ε

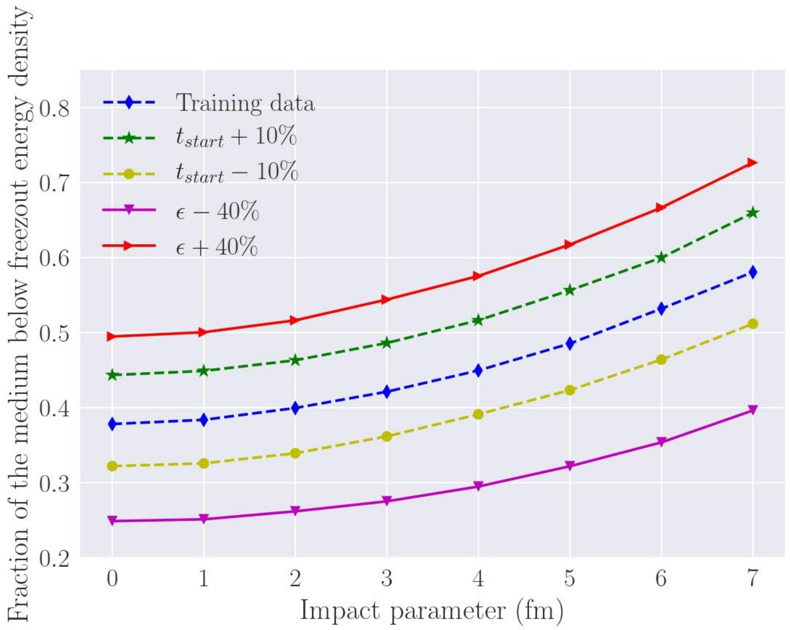


0-7 fm 0-3 fm 0-3 fm 3-7 fm

- Models tested for t_{start}∓10% and ε∓40% from training value
- Decrease in t_{start} and ε doesn't affect the performance
- Increasing these parameters however causes considerable decrease in accuracy

Reasons for dependence on centrality, t_{start} and ε

- For b=0, ~62% of the medium experiences hydro while it is ~42% for b=7
- Decrease in t_{start} or ε increases hydro duration
  - More part of system experience hydro
  - Even for b=0:
    - ~68% for t_{start}-10%
    - ~75% for ε -40%
- Increasing t_{start} or ε decreases hydro duration
  - Small fraction of system experience hydro
  - For b=0:
    - ~55% for t_{start}+10%
    - ~50% for ε +40%
- For peripheral events, decreasing t_{start} or ε could cause as less as ~25% of the medium to experience hydro



Summary

- PointNet based DL models are an efficient tool for identifying phase transition at CBM
  - Accuracy upto 99.8%
  - Online algorithm- Works with experimental data

- The performance of PointNet model is different conditions of experimental uncertainties and detector effects are demonstrated
  - >95% accuracy in a realistic experimental simulation with b 0-7 fm

- Best performance can be achieved with a centrality selection (b=0-3 fm)
  - Method to incorporate peripheral events is demonstrated

- Performance decrease due to increase in t_{start} or ε is merely the limitation caused by the underlying physics

- Any global event feature could be analysed with PointNet