Reconstruction of Long Lived Particles at CMS using graph neural networks

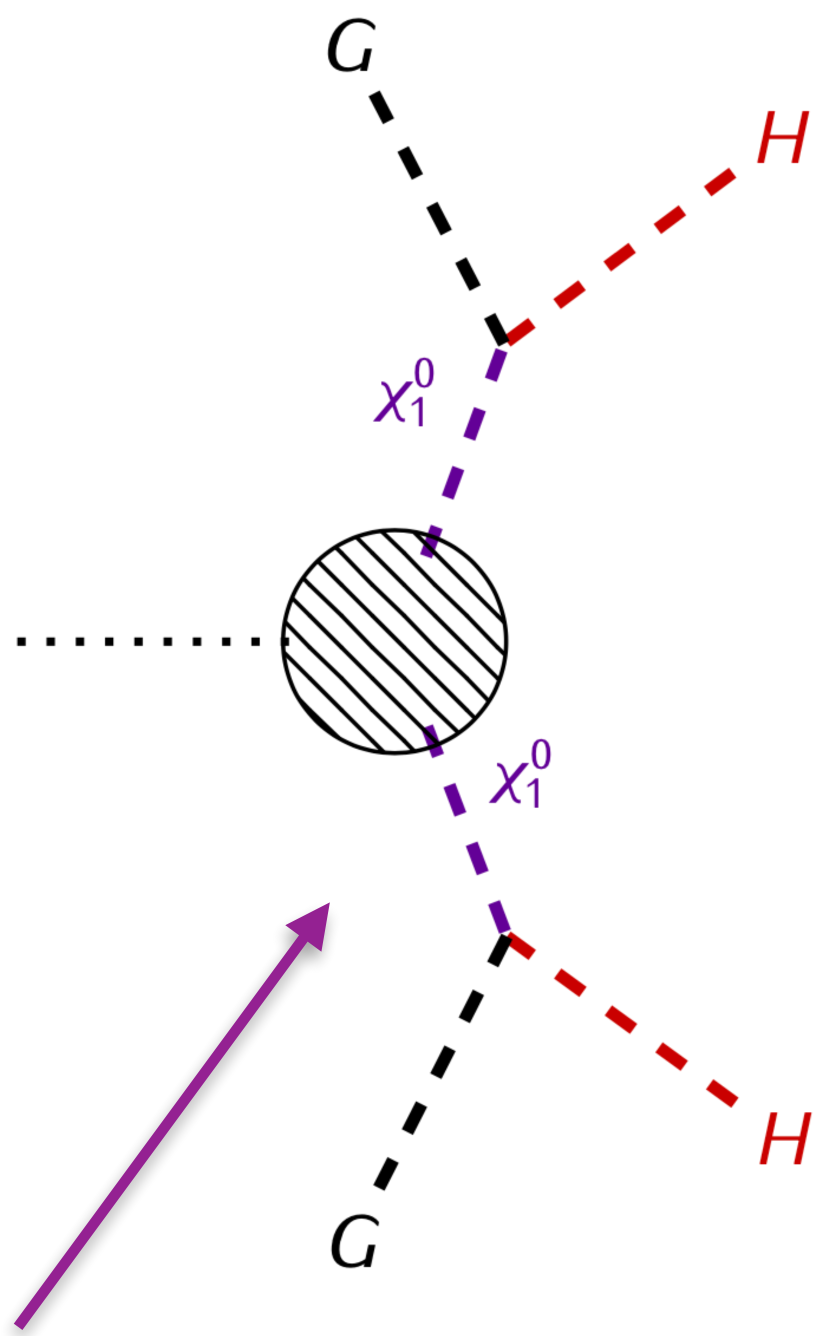
Lisa Benato, Julia Heiken, Gregor Kasieczka, Tobias Lösche, Karla Peña, Imahn Shekhzadeh
(Hamburg University)

Artur Apresyan, Jiajing Mao, Cristián Peña, Si Xie (Fermilab, Caltech)

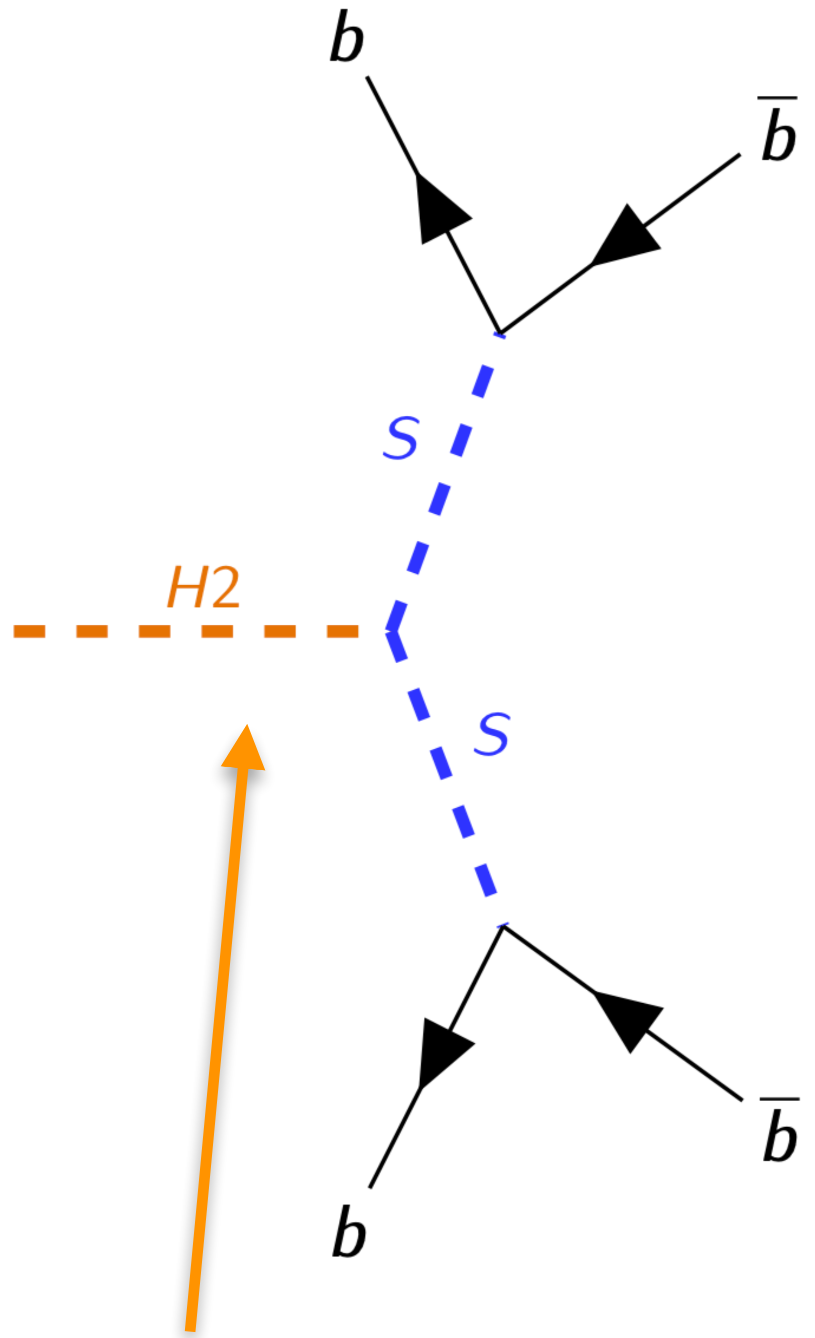
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE
Bundesministerium für Bildung und Forschung
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft
CMS

Introduction: why long lived particles?

- Standard Model of particles doesn't answer all the questions about matter and interaction (dark matter, gravity, Higgs mass divergences at Planck scale)
- Extensions of SM predict partners of SM particles (**SUSY**), or **dark sectors** communicating with SM only via Higgs boson –> solves the Higgs mass divergences!
- Final state of interest: bb (predominant decay of Higgs)
- New particles are **long lived**: peculiar signatures in a detector @ LHC
- New particles can have different masses: different kinematical features

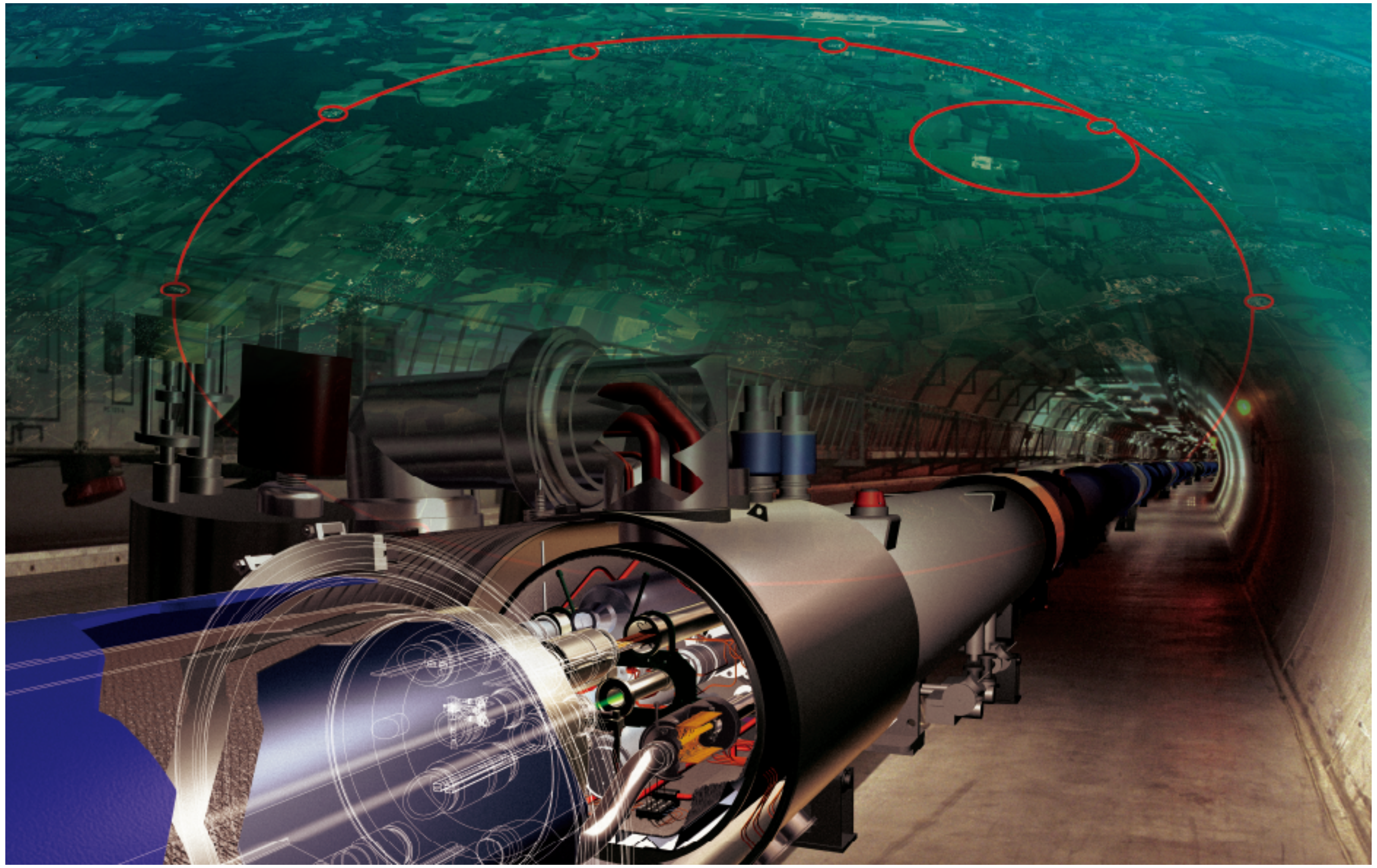


SUSY: $XX \rightarrow HH\tilde{G}\tilde{G} \rightarrow b\bar{b}b\bar{b}\tilde{G}\tilde{G}$
X is long lived
H is SM Higgs
G is light and undetected

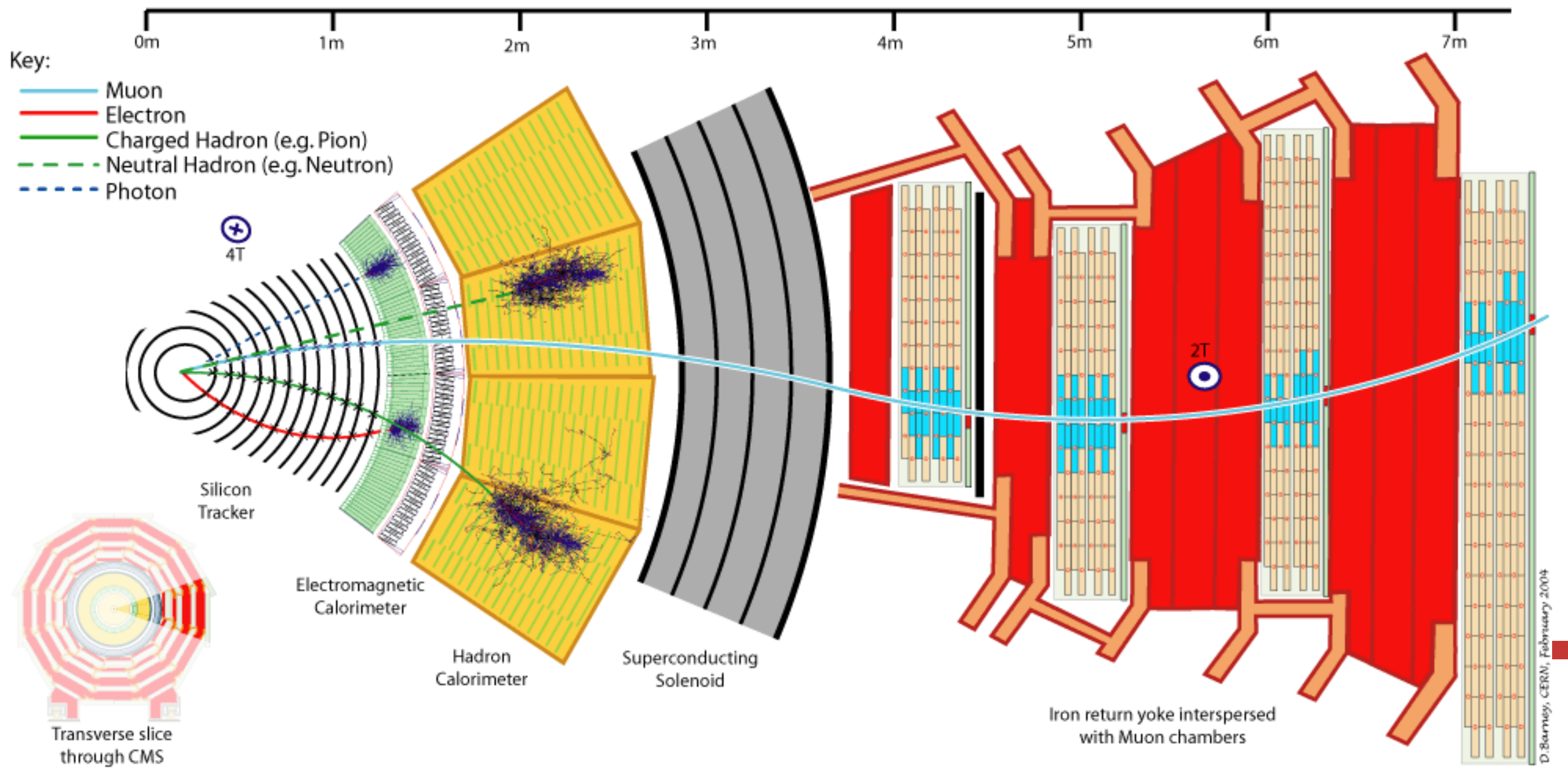


BSM Higgs: $H2 \rightarrow SS \rightarrow b\bar{b}b\bar{b}$
S is long lived
H2 can also be the SM Higgs

Introduction: LHC and CMS

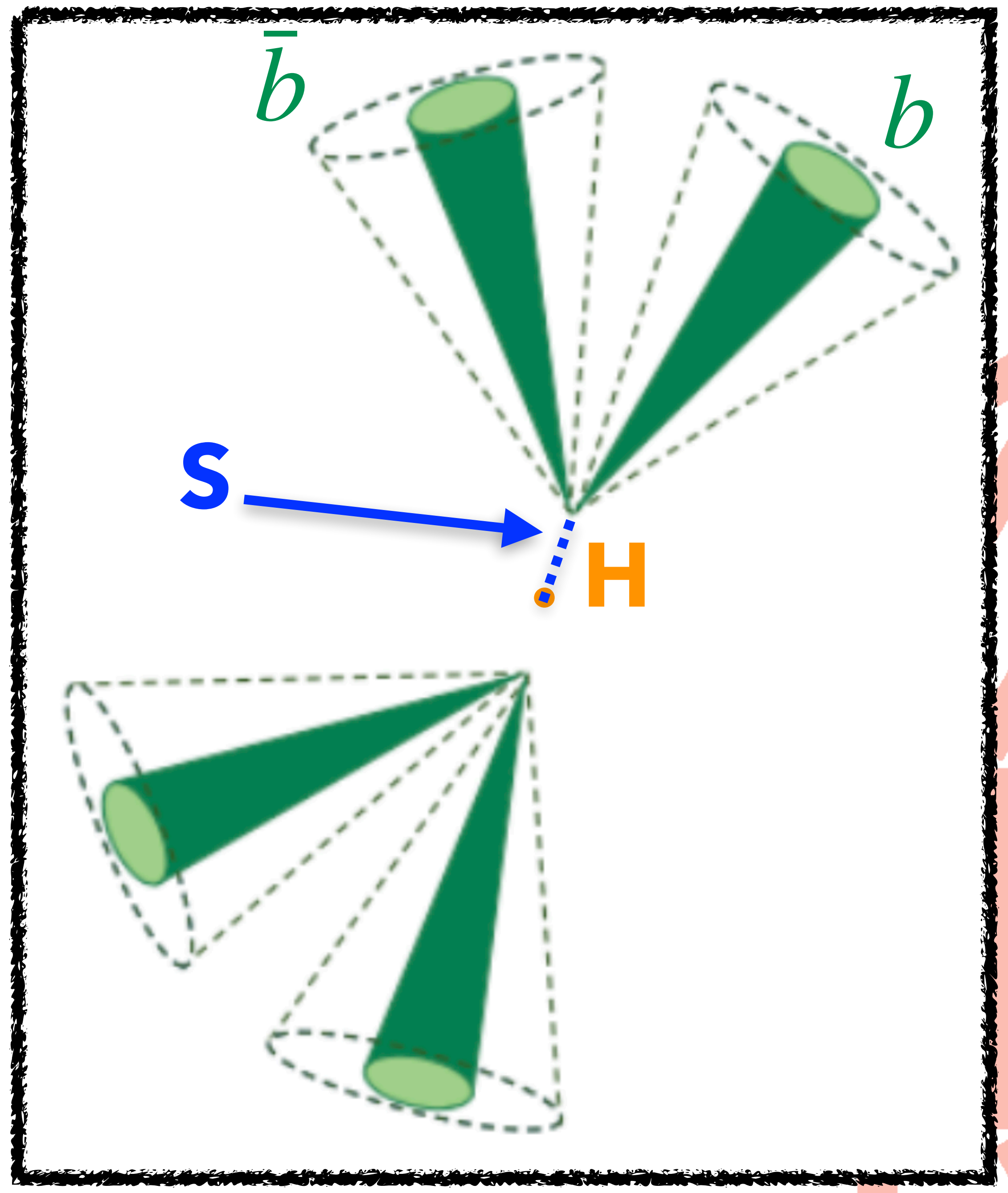


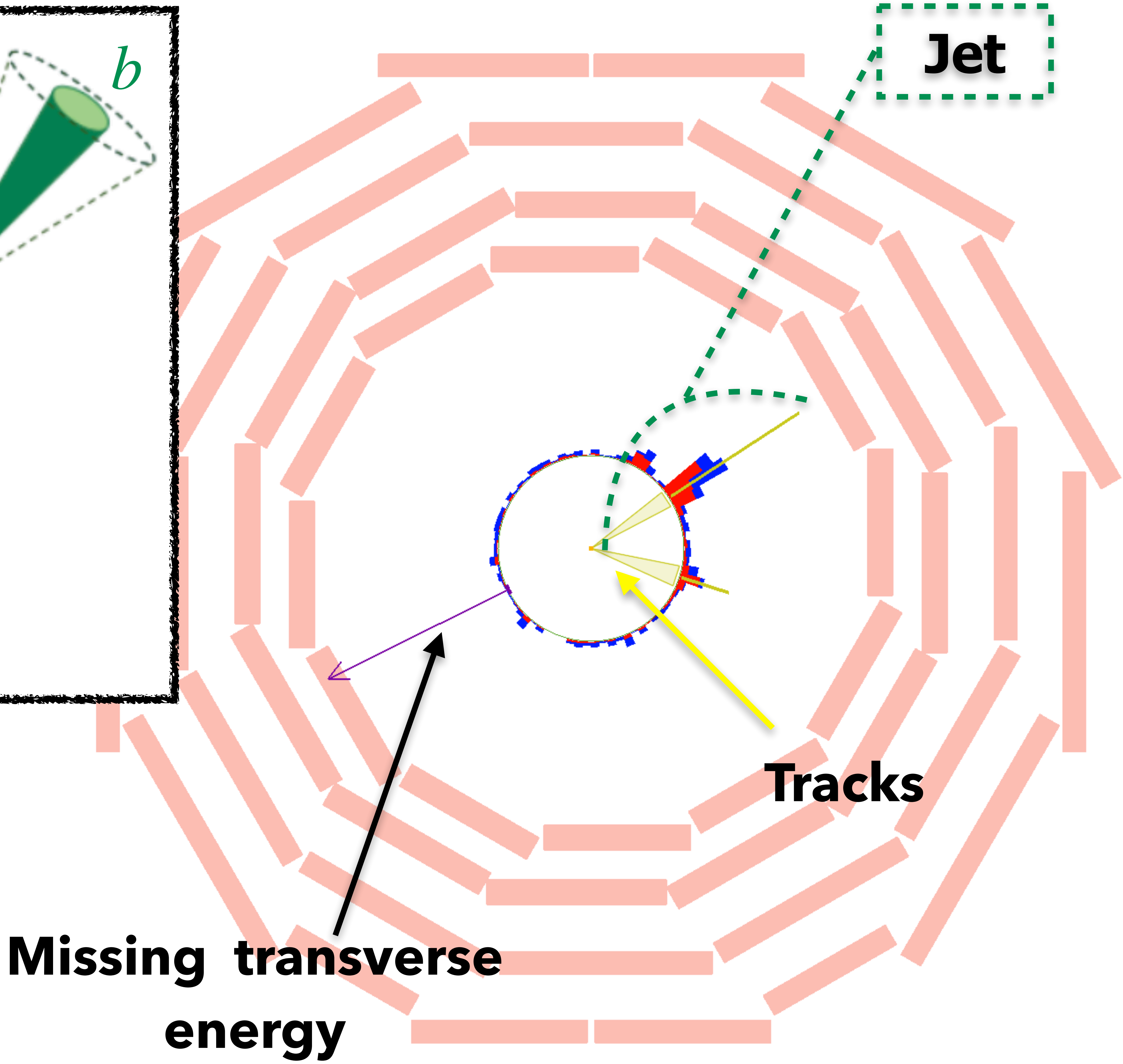
- LHC: proton-proton collisions at energy of 13 TeV
- p-p collisions happens at the experiments at 40 MHz: fast decision –> sophisticated trigger systems
- CMS organised in layers to detect different particles
- Particle Flow algorithm connects info from sub detectors –> precise measurements of momenta and particle identification



Introduction: LLPs signatures at CMS

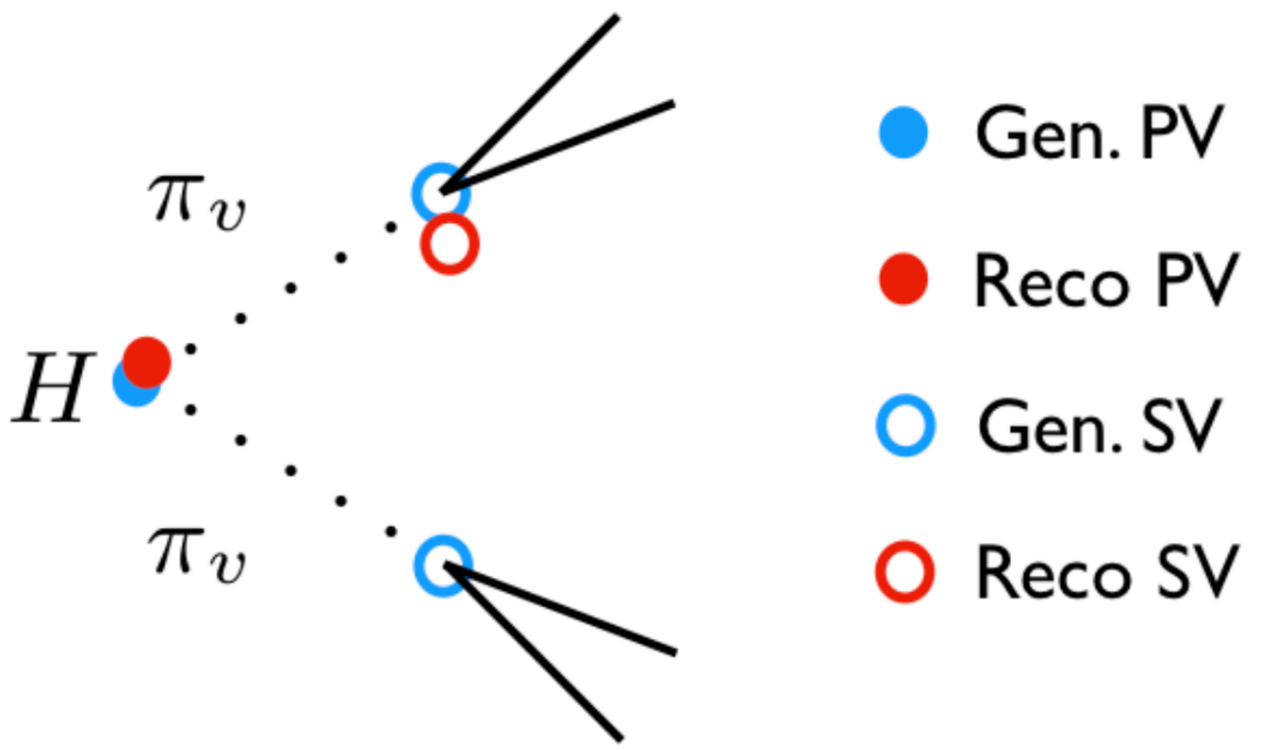
- b-quarks: due to strong interaction, they hadronize in a **jet** of particles
- They are produced with a certain delay (lifetime cτ) affecting the topology
- Decays in <u>tracker system</u>:
  - **Tracks** are displaced w.r.t. p-p collision point
- Decays in <u>calorimeters</u>:
  - Few tracks associated to a jet –> particles appear as neutral because they miss corresponding tracks
  - Large **energy deposits** in **calorimeters**
  - Calorimeter crystals measure a certain delay w.r.t. p-p collision

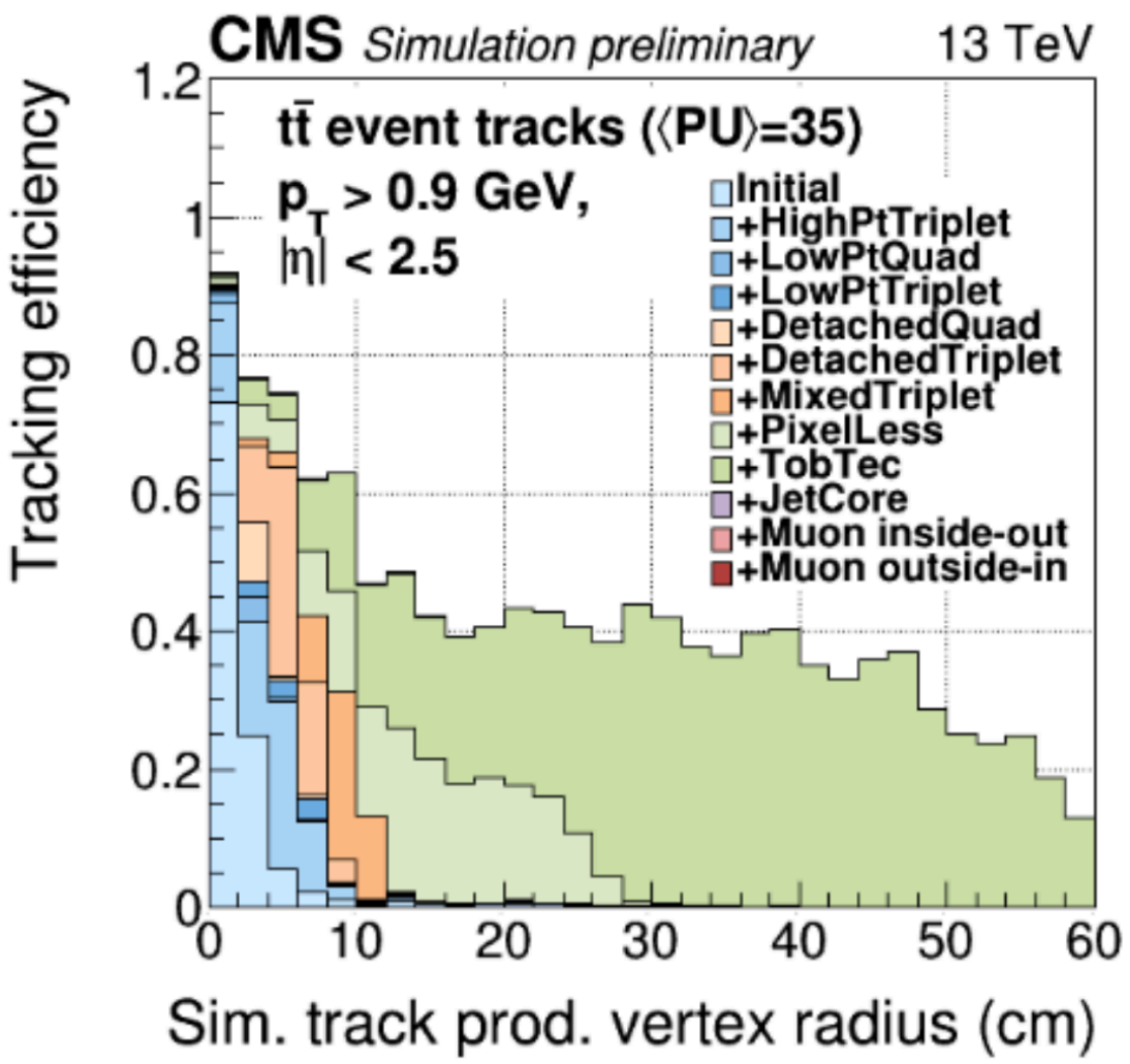




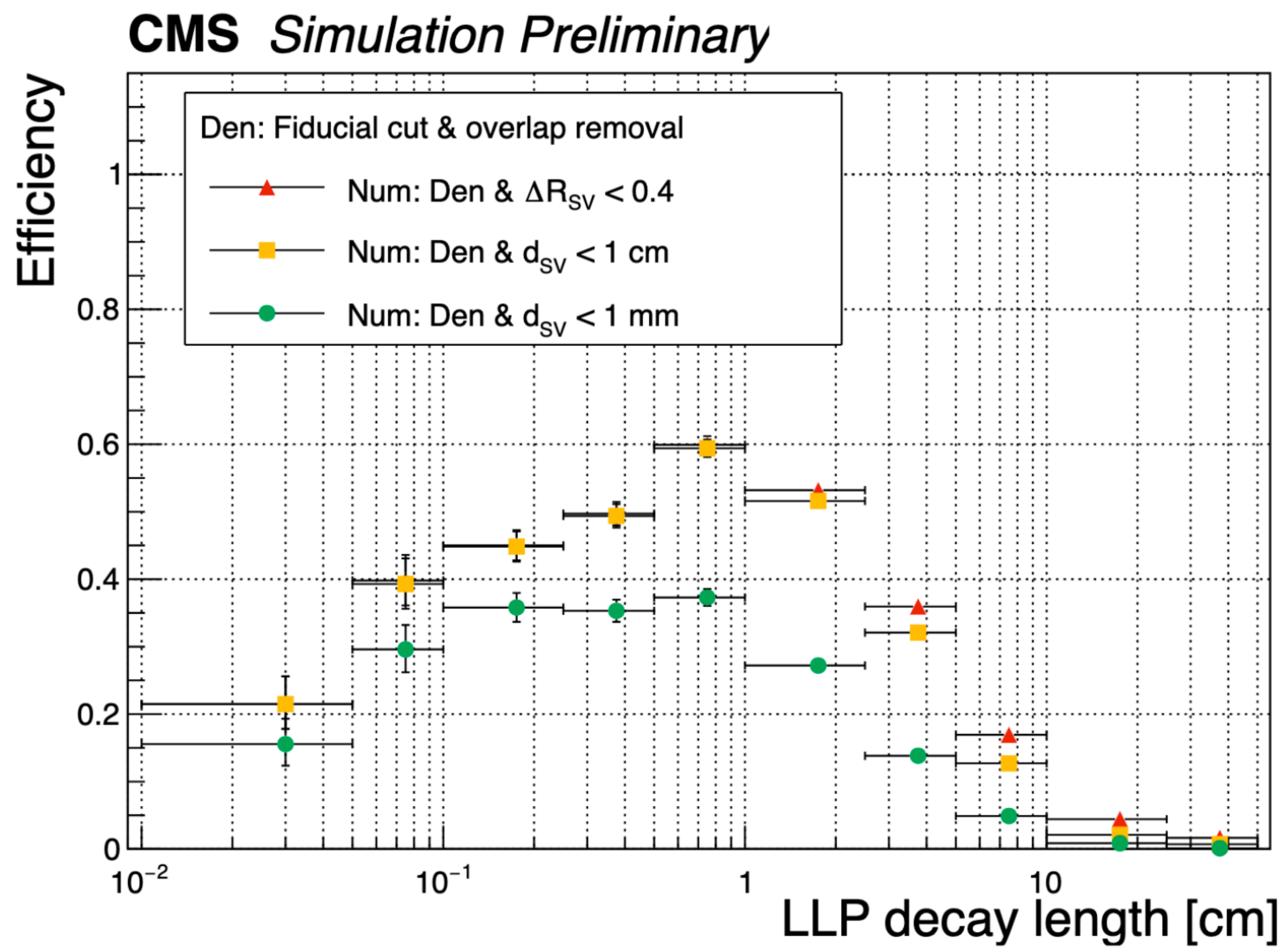
Tracker lifetimes: why LLPs reconstruction is challenging

- CMS reconstruction designed for particles close to collision point
- Displacement –> loss of efficiency
- Track reconstruction challenging!
  - Displaced tracks are lost
  - Displaced vertices are lost
- Can we reconstruct LLP decay vertices with ML?





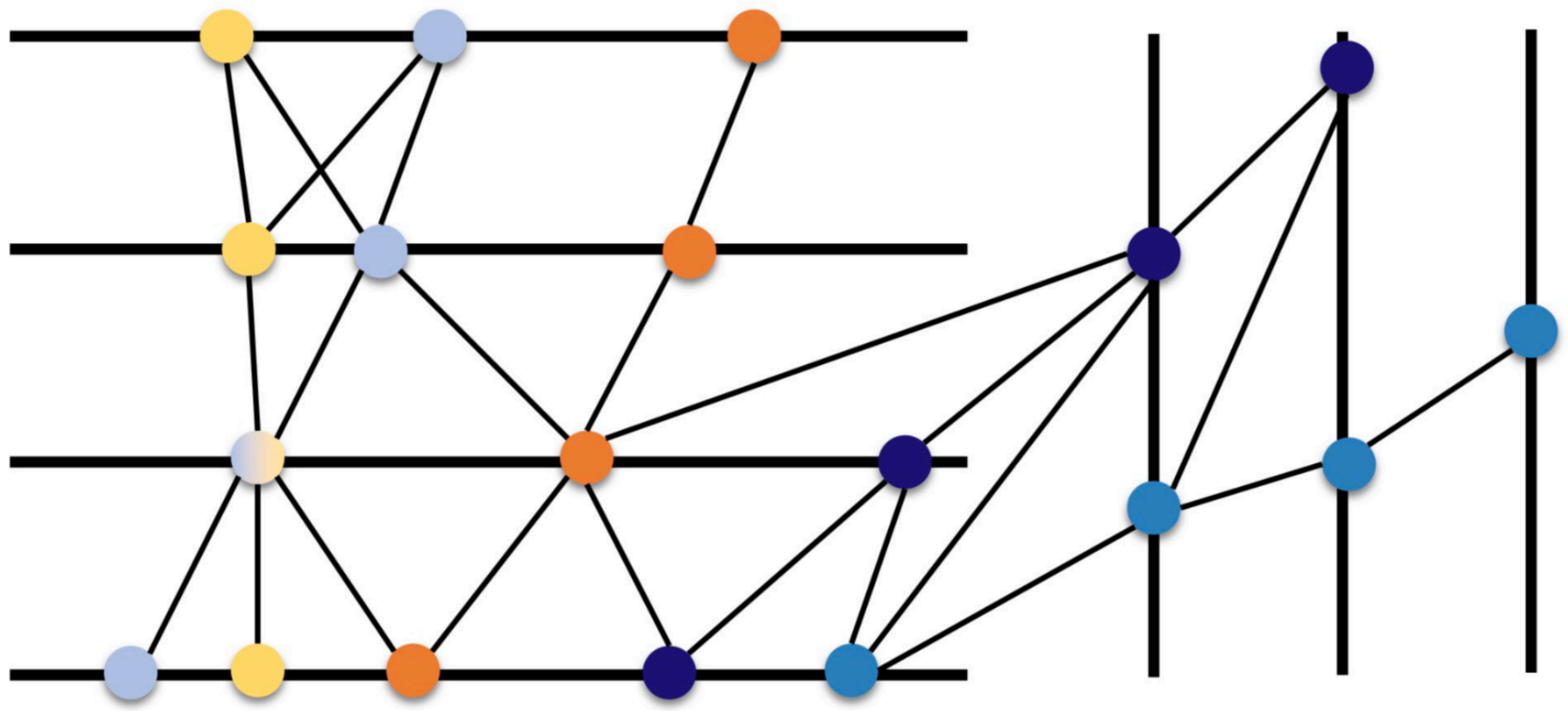
arXiv:1405.6569

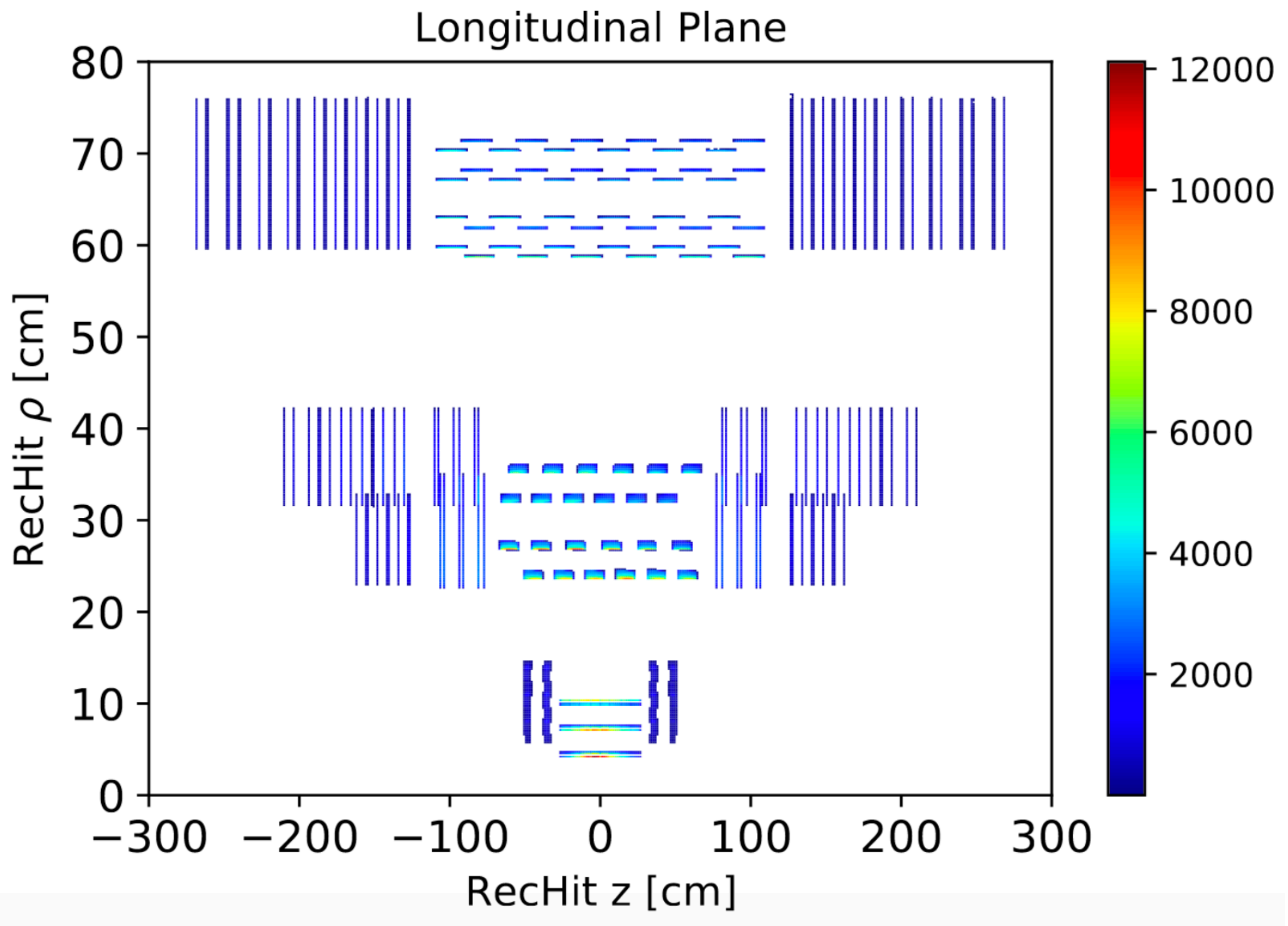


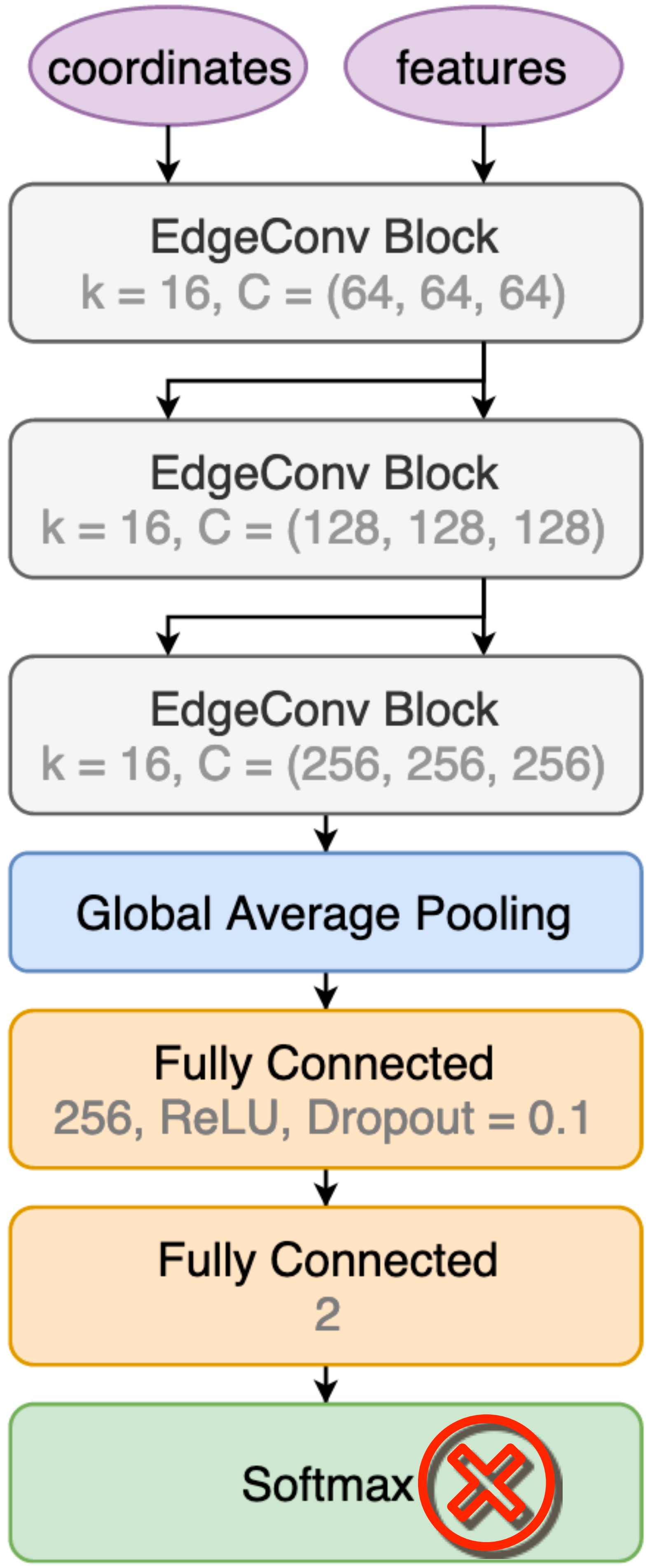
Tracker lifetimes: displaced vertices with graph network

- **Track**: collection of **hits**
- Ideal inputs for a graph network architecture!
- Graph construction:
  - One tracker hit per node (up to 1500 hits)
  - Features (per hit): x, y, z
  - Coordinates (per hit): η, φ
- Adapt ParticleNet architecture to a regression problem:
  - MSE loss
  - No softmax

arXiv:1810.06111







arXiv:1902.08570

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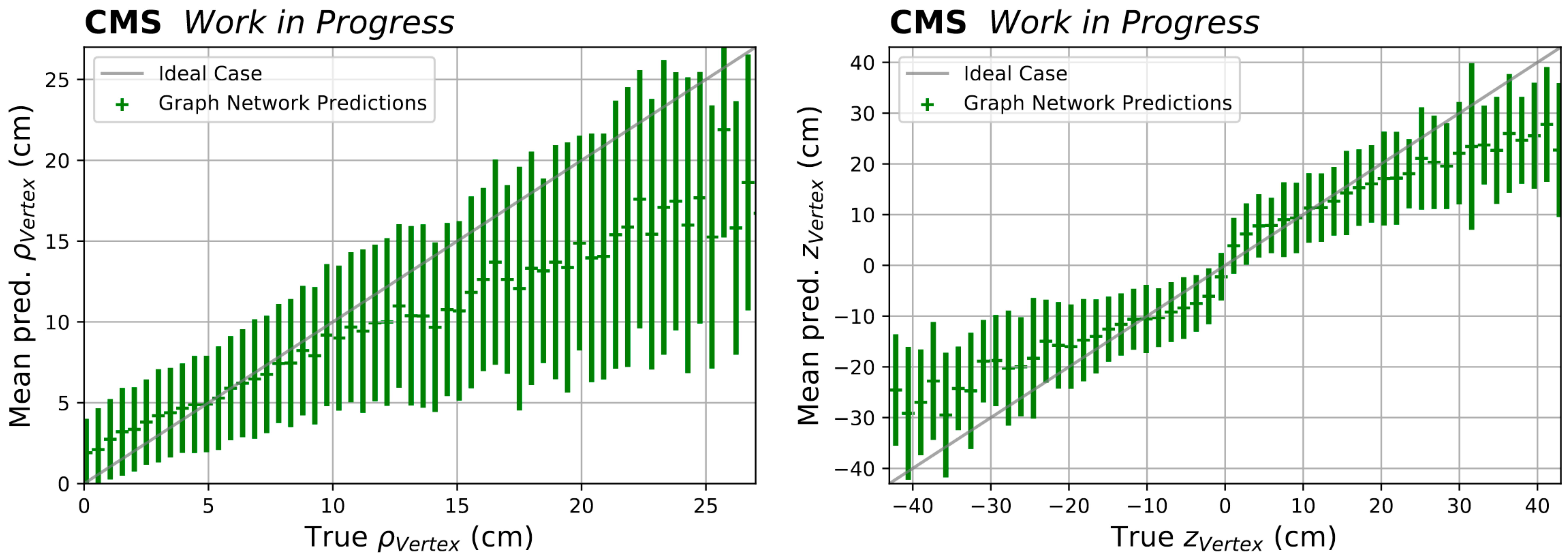
Tracker lifetimes: graph network results



- Network can predict the vertex position
- Better performances for short displacement –> next: train on larger displacement
- Better loss function? Tweaking the architecture?
- Coming soon: test on background

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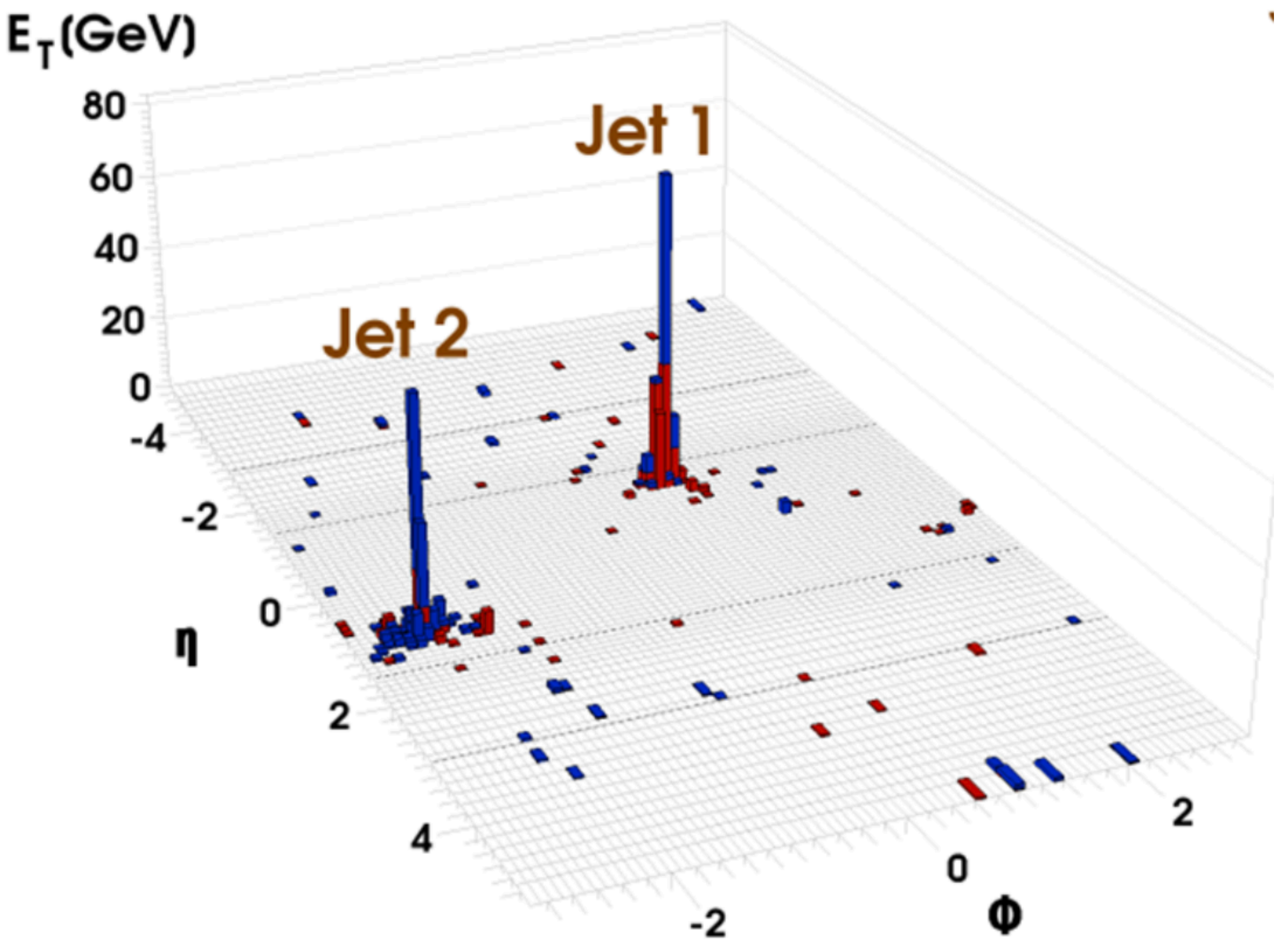
Calorimeter lifetimes: graph network for displaced jet tagging

- **Jet** interpreted as clouds of **PF constituents**:
  - First 25 jet constituents with $p_T > 1$ GeV (points)
  - Points coordinates: euclidean distance (η, φ) as metric among k-nearest neighbours
  - Points features: energy, pT, charge, number of hits in tracker/pixel

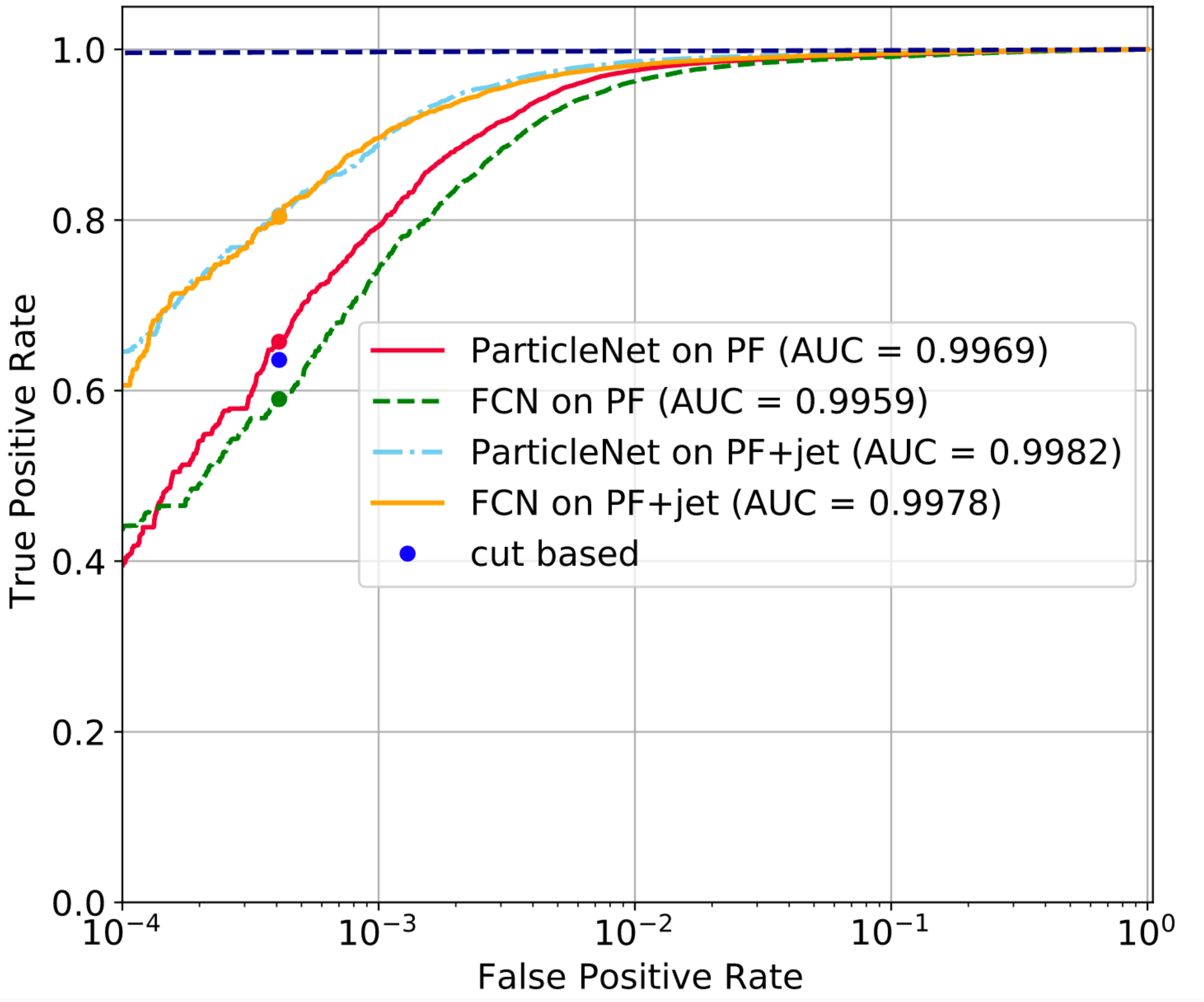
- ParticleNet architecture:
  - Optimised k-nn and number of edge conv blocks
  - Additional shortcut to jet-level variables describing displacement (average time and energy of ECAL/HCAL rec hits, variables comparing the energy of the tracks inside jet vs jet energy, and angular separation between tracks and jet axis)



- Training:
  - Signal: jets matched to a LLP decay in calorimeter
  - Background: inclusive SM processes, weighted with x-sec
  - Technical challenge: large dataset –> limits of CPU/GPU RAM capacity

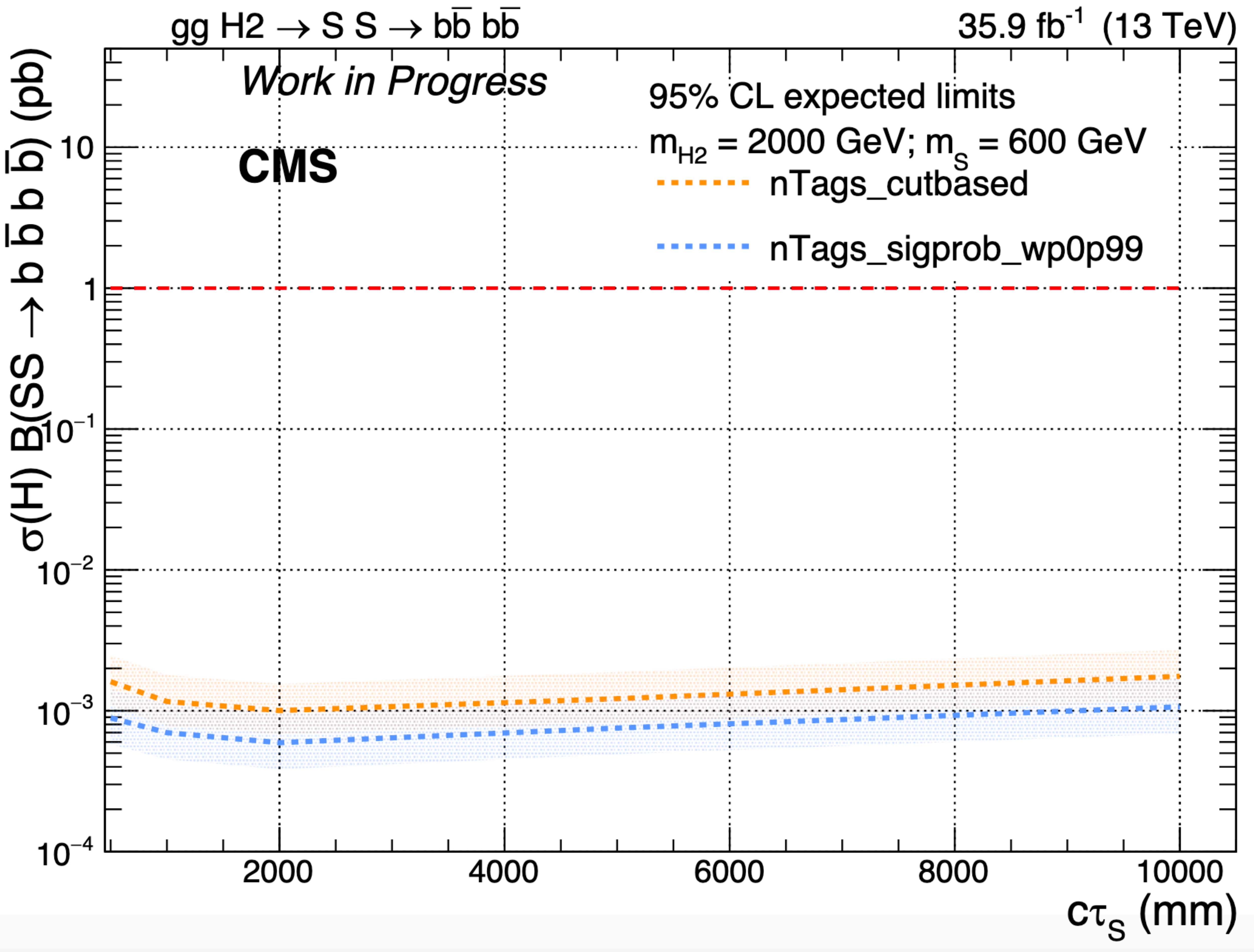
Calorimeter lifetimes: graph network performances

- Benchmark (blue dot): cut based approach, selecting jet-level variables
- Red curve: ParticleNet using only jet constituents
- Green curve: simple fully connected network (FCN) with jet constituents as inputs (coordinates and features)
- Light blue curve: ParticleNet with shortcut to jet-level variables
- Orange: simple FCN on jet constituents + jet-level variables
- At the same background rejection: 1.3 better signal efficiency (per-jet)
- Signal region: 2 tagged jets –> improvement by factor 1.8



Calorimeter lifetimes: graph network results

- Impact of the graph net jet tagger: quantified with 95% CL exclusion limits
- Trained on a signal model (SUSY), tested on another (dark heavy Higgs)
- Limits vs proper decay length
  - MC based, stat. uncertainties only
  - Graph network: improvement by a factor 2 w.r.t. cut based
- Perspectives:
  - Extend to heavier masses (boosted topology, collimated decay products –> large-cone jets)
  - Tweak the architecture and use more features for jet constituents
  - Try graph net directly on calorimeter hits



Backup

Graph network for tracker: details

Datasets:

- Training: 27,942
- Validation: 9,314
- Test: 9,314

Number of RecHits: 1500

Training hyperparameters:

- Optimizer: Adam
- Cyclic LR with:
  - min = 5×10^{-6}
  - max = 10^{-4}
  - step size = 10 epochs
- Number of epochs: 321
- Batch size: 72

Model performance: