Reconstruction of Long Lived Particles at CMS using graph neural networks

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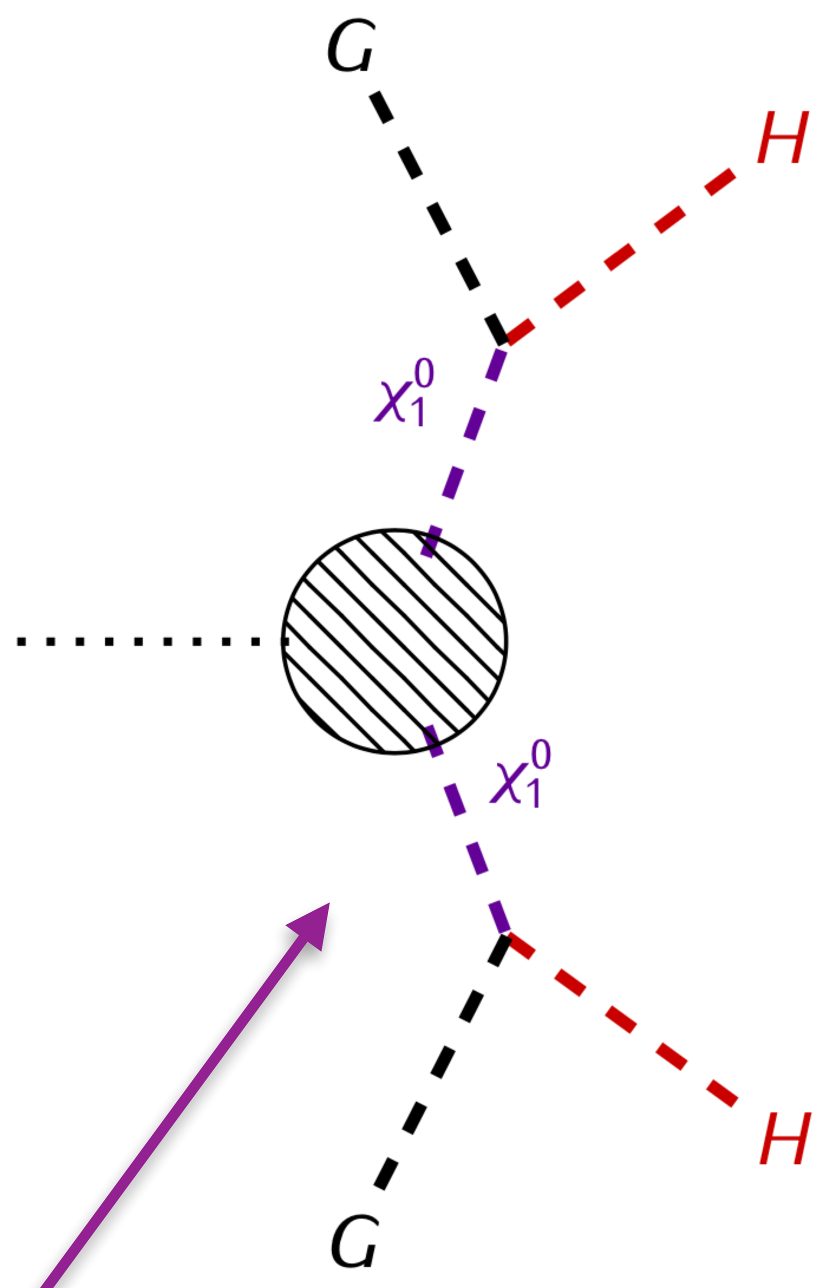
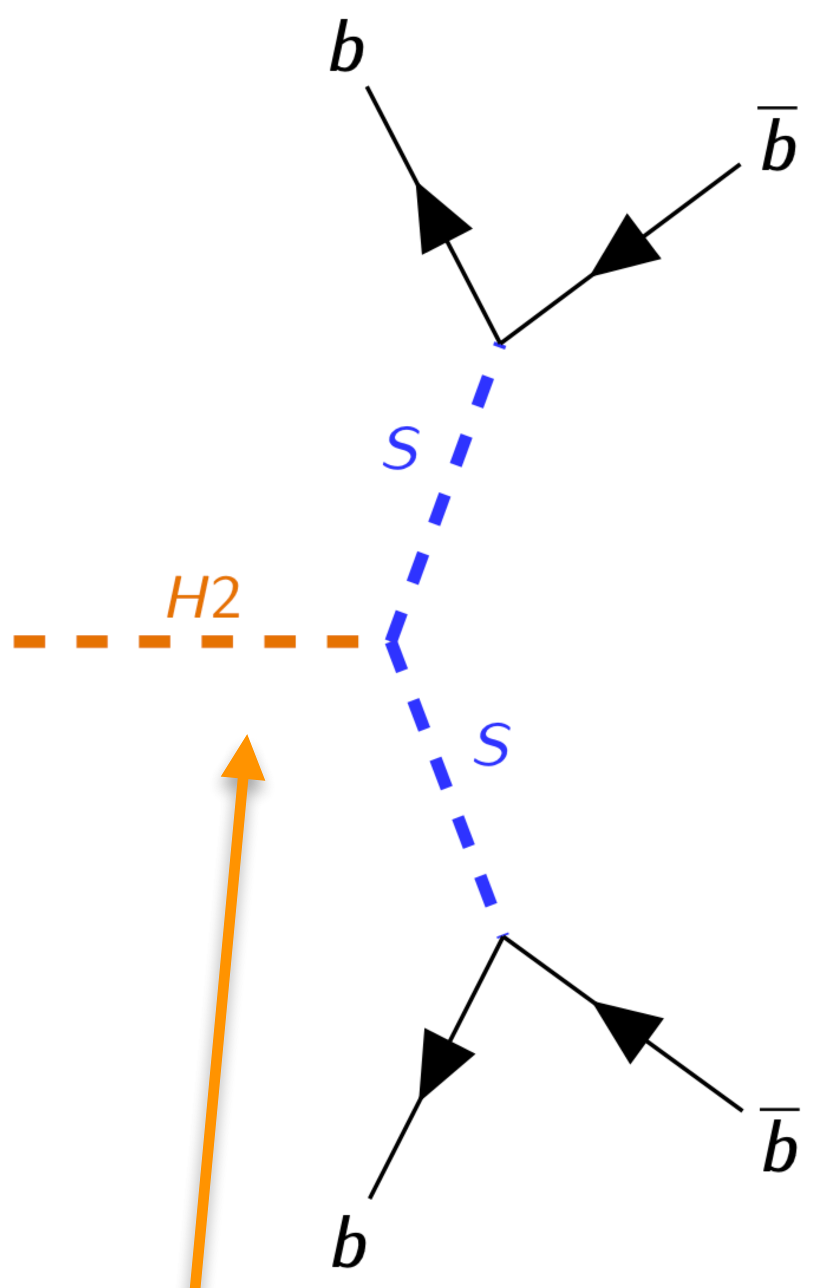
CMS

Introduction: why long lived particles?

- Standard Model of particles doesn't answer all the questions about matter and interaction
- 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





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

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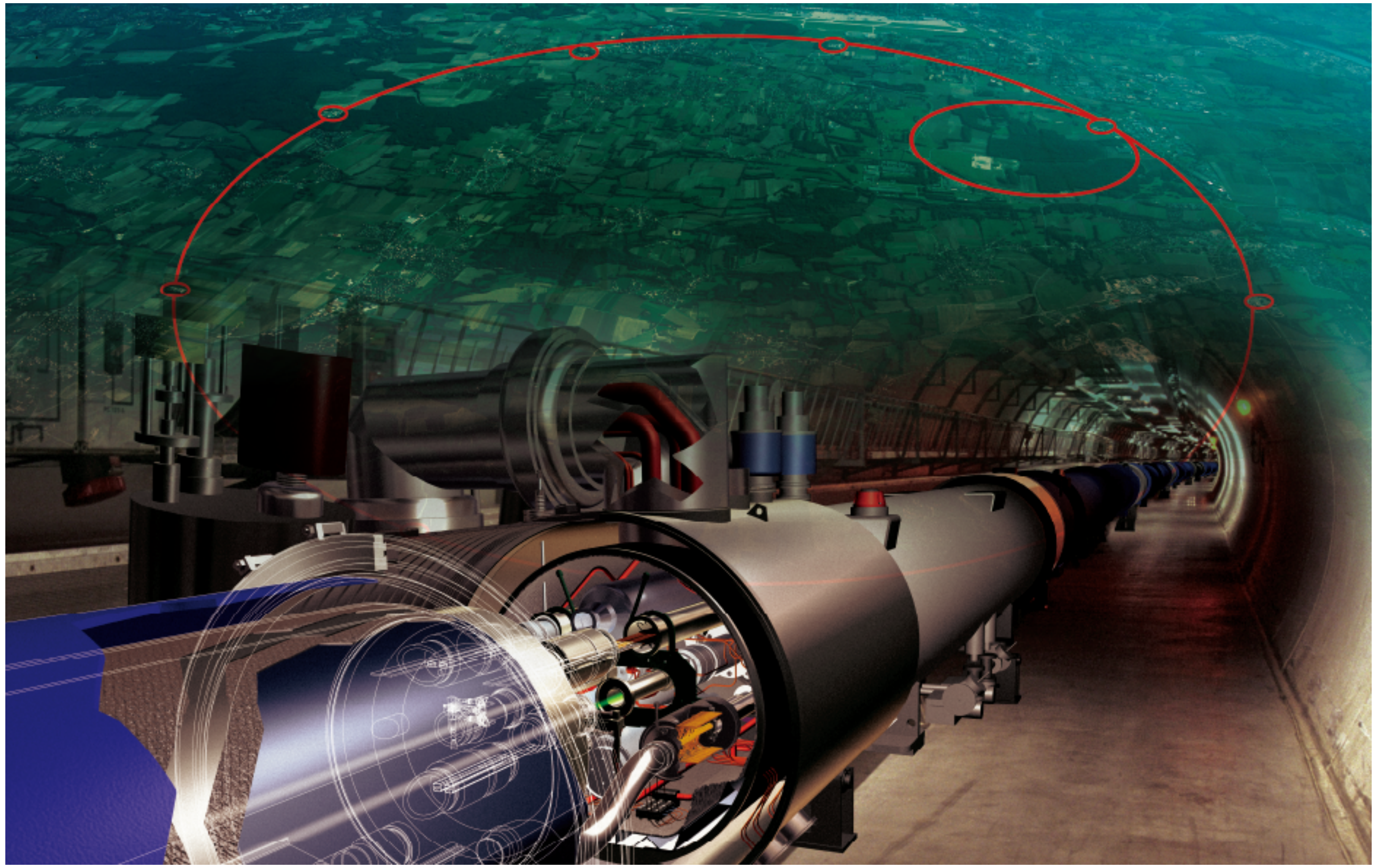
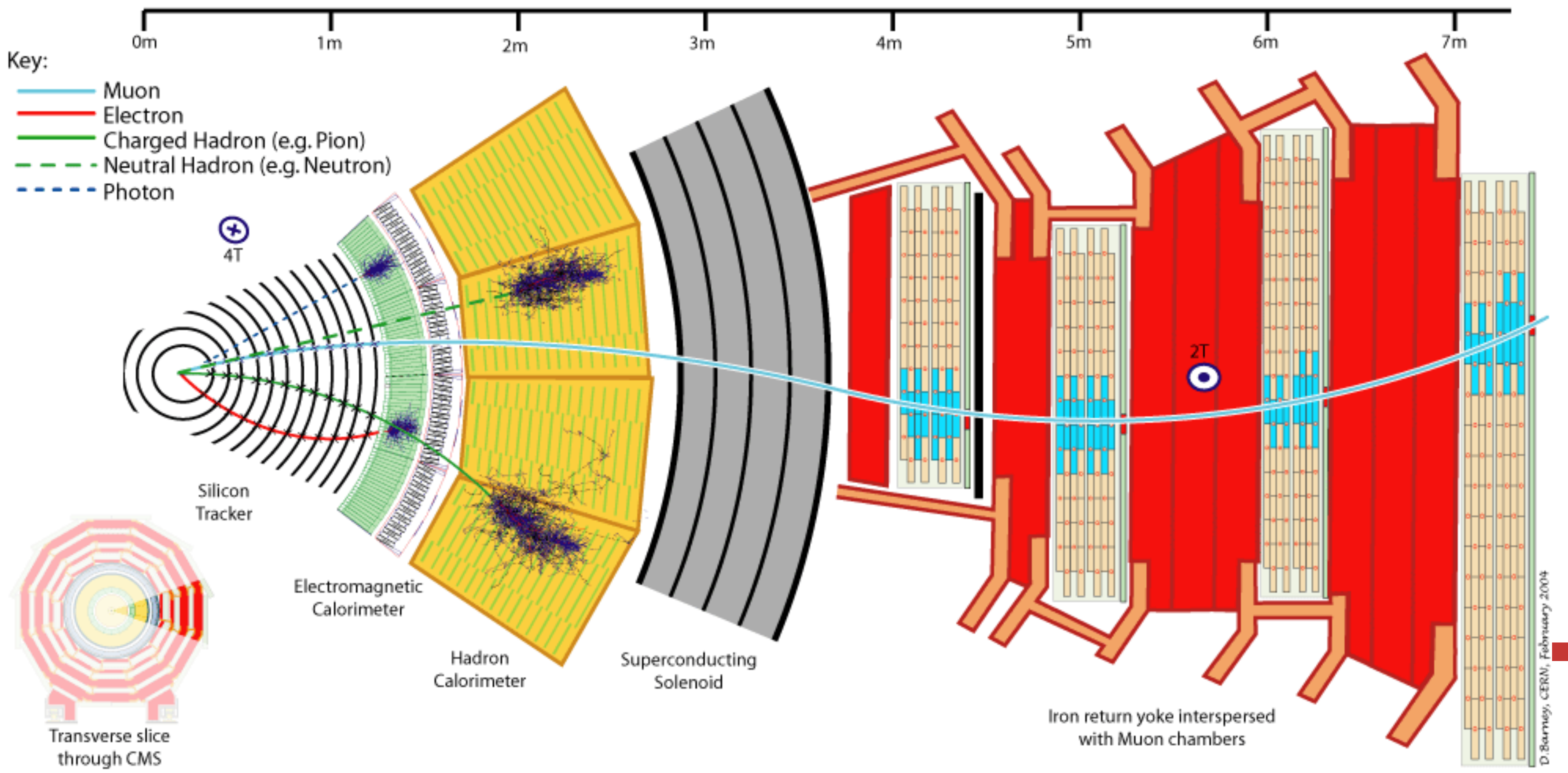
Introduction: LHC and CMS

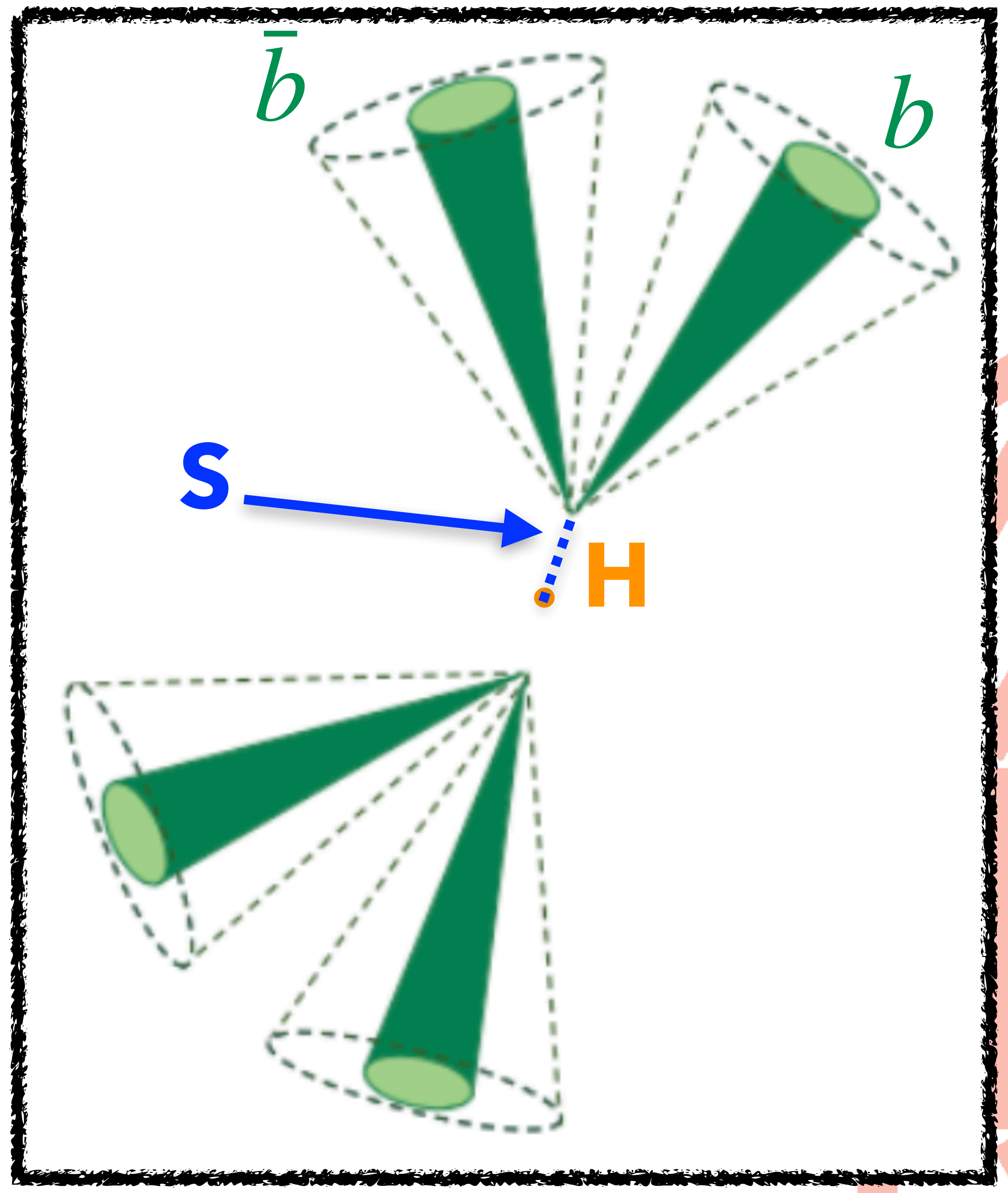


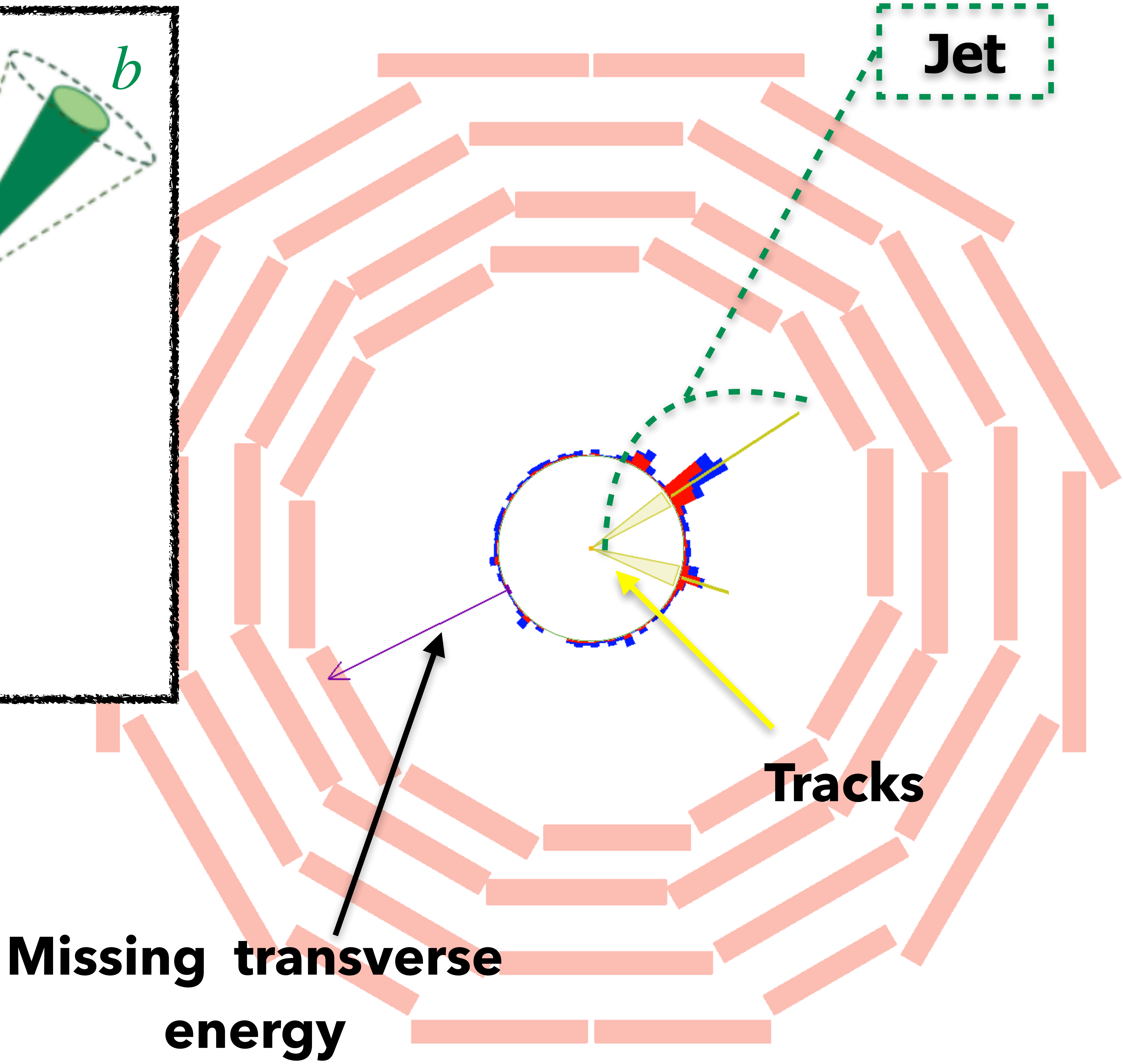
- LHC: proton-proton collisions at energy of 13 TeV
- p-p collisions @ 40 MHz: fast decision → sophisticated trigger systems
- CMS Particle Flow algorithm connects info from sub detectors → precise measurements of momenta and particle identification



Introduction: LLPs signatures at CMS

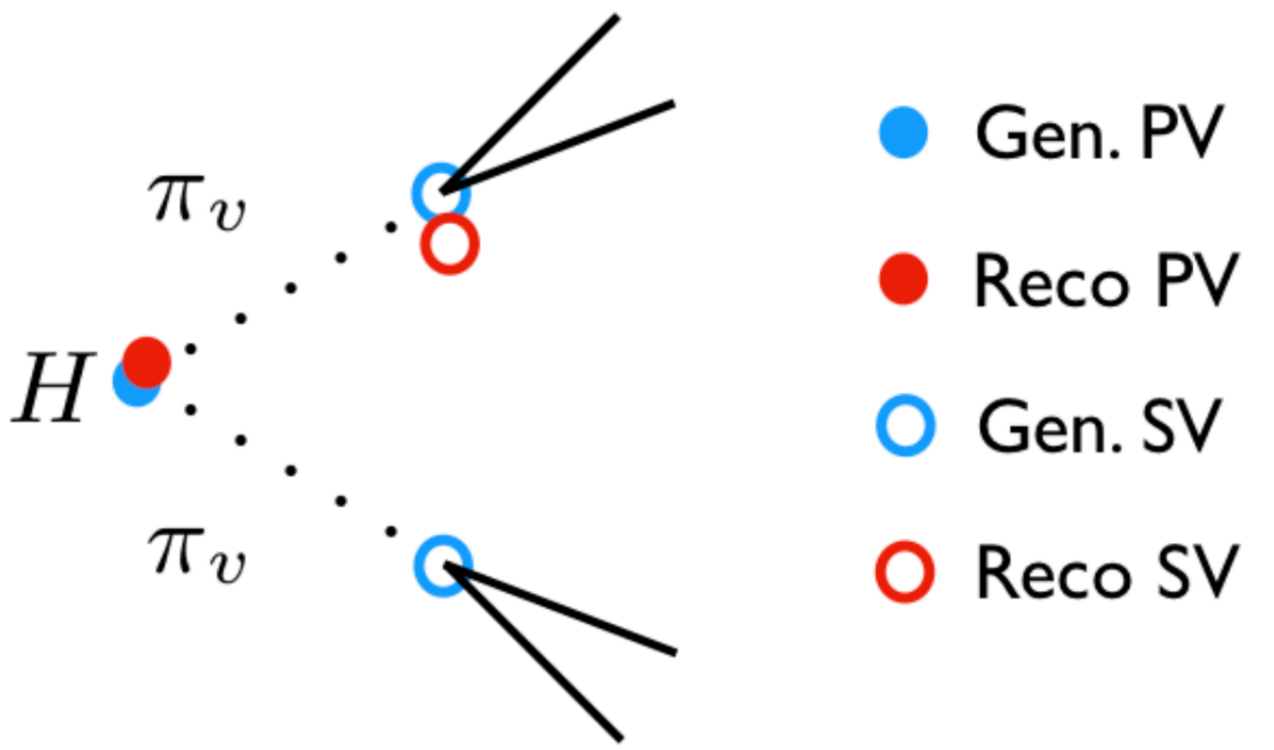
- b-quarks: due to strong interaction, they hadronize in a **jet** of particles
- They are produced with a certain delay (lifetime cτ) affecting the topology
- Decays in <u>tracker system</u>:
  - **Tracks** are displaced w.r.t. p-p collision point
- Decays in <u>calorimeters</u>:
  - Few tracks associated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

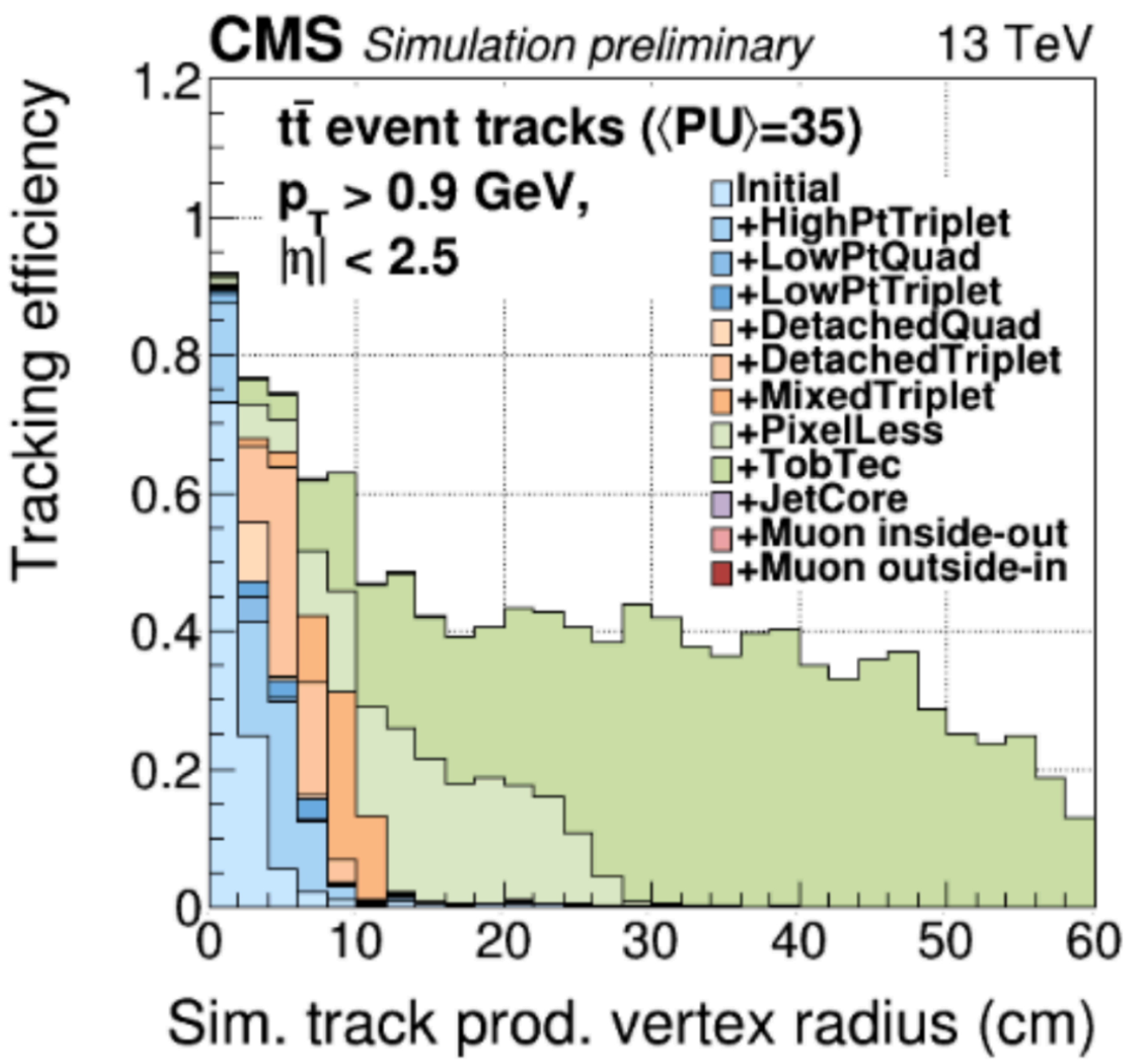




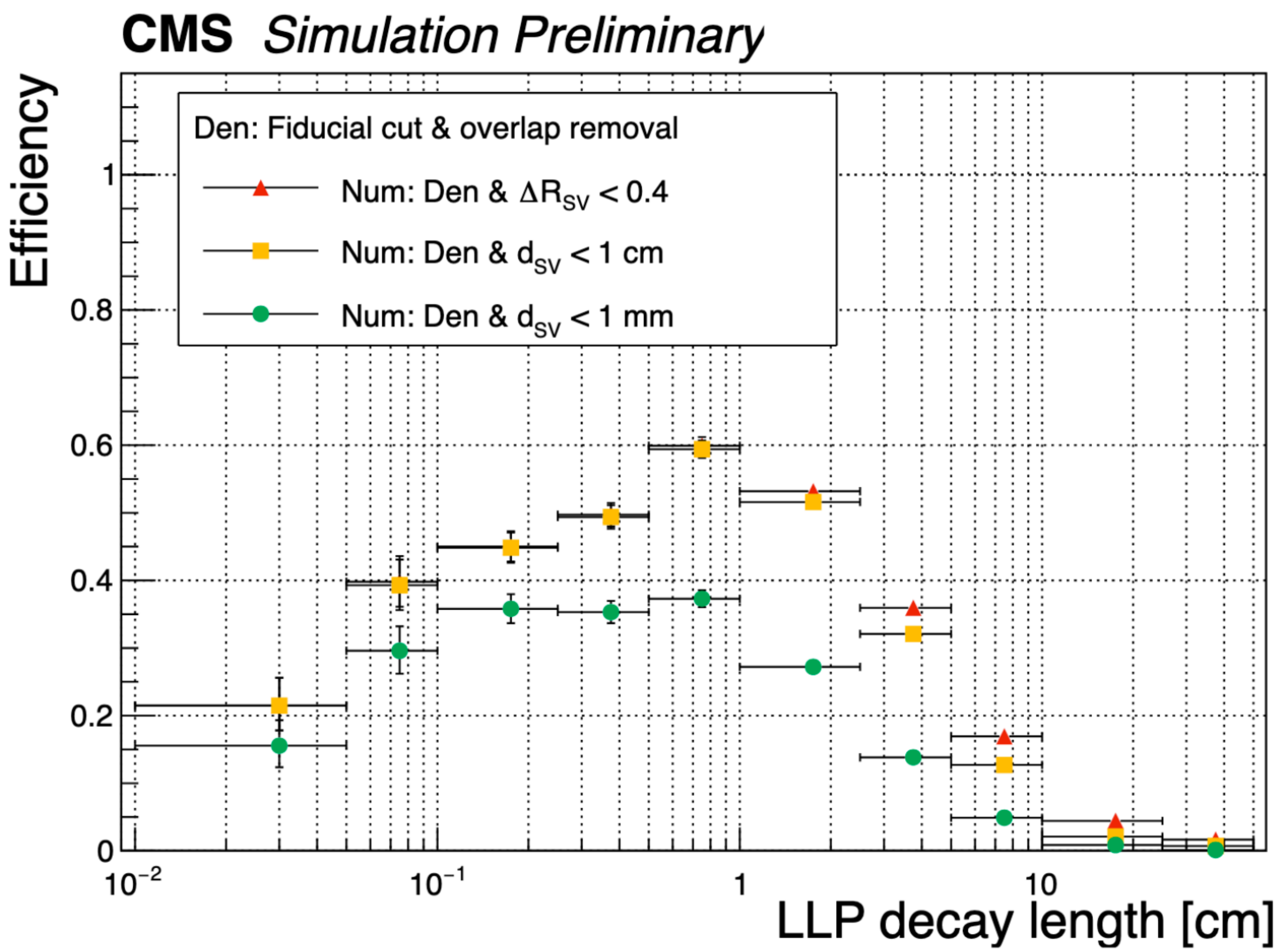
Tracker lifetimes: why LLPs reconstruction is challenging

- CMS reconstruction designed for particles close to collision point
- Displacement → loss of efficiency
  - Displaced tracks are lost
  - Displaced vertices are lost
- ML approach to recover vertices?





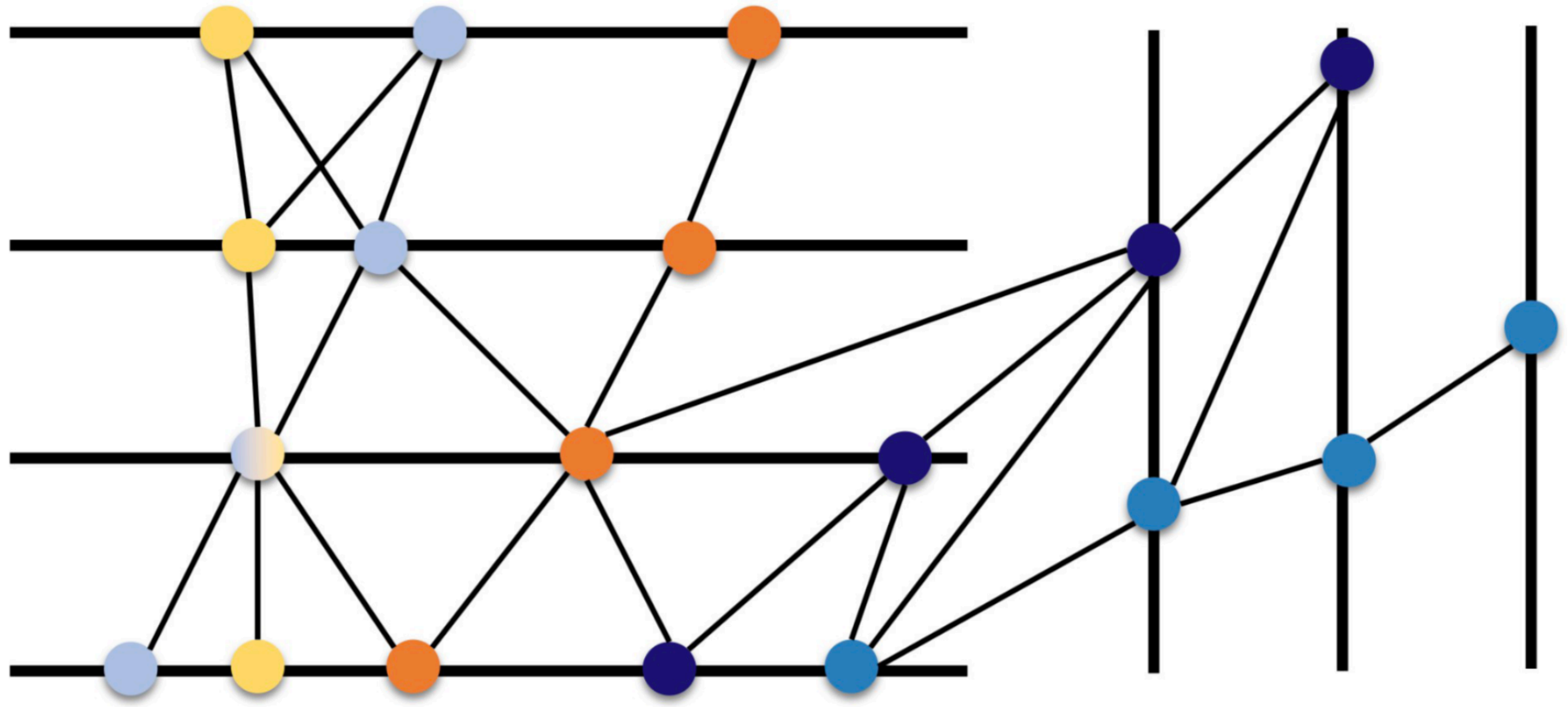
arXiv:1405.6569

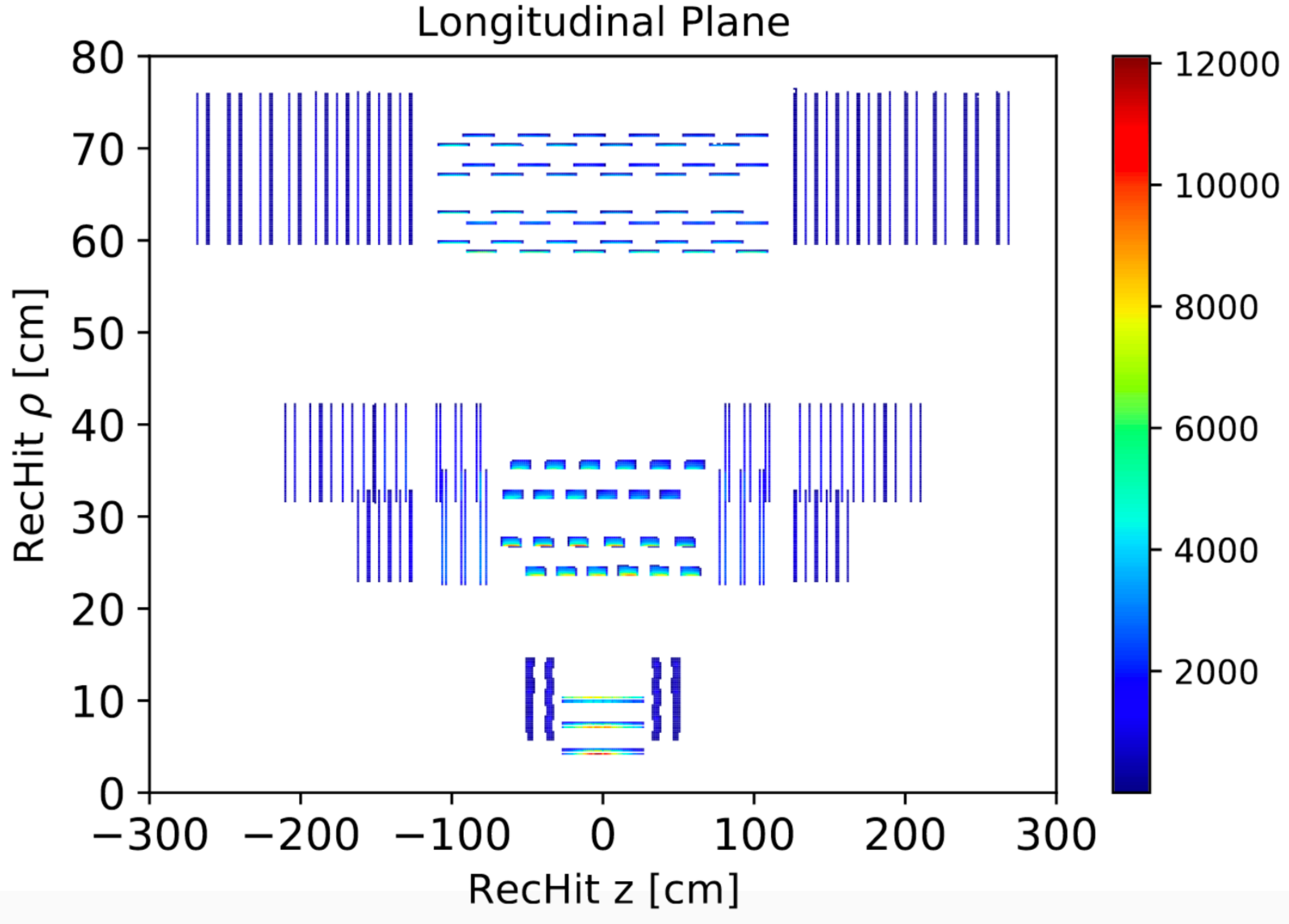


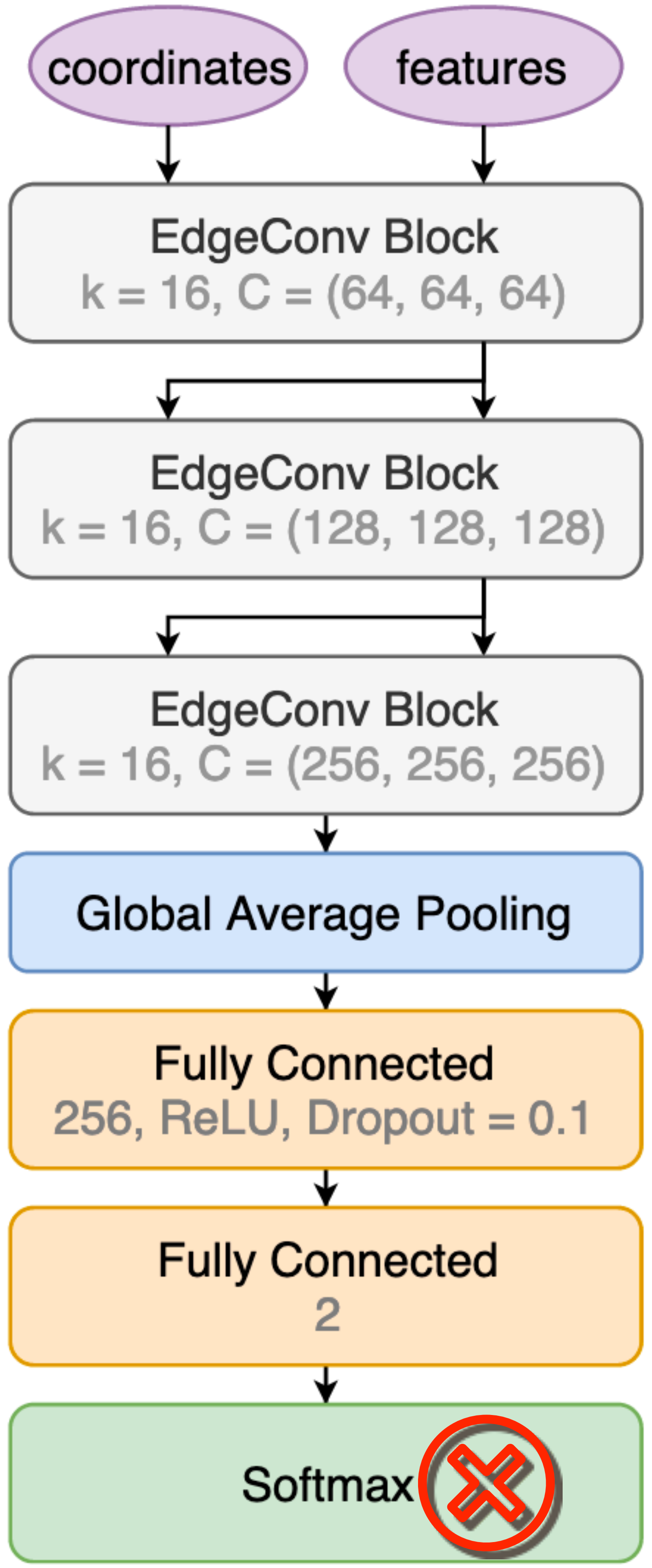
Tracker lifetimes: displaced vertices with graph network

- **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

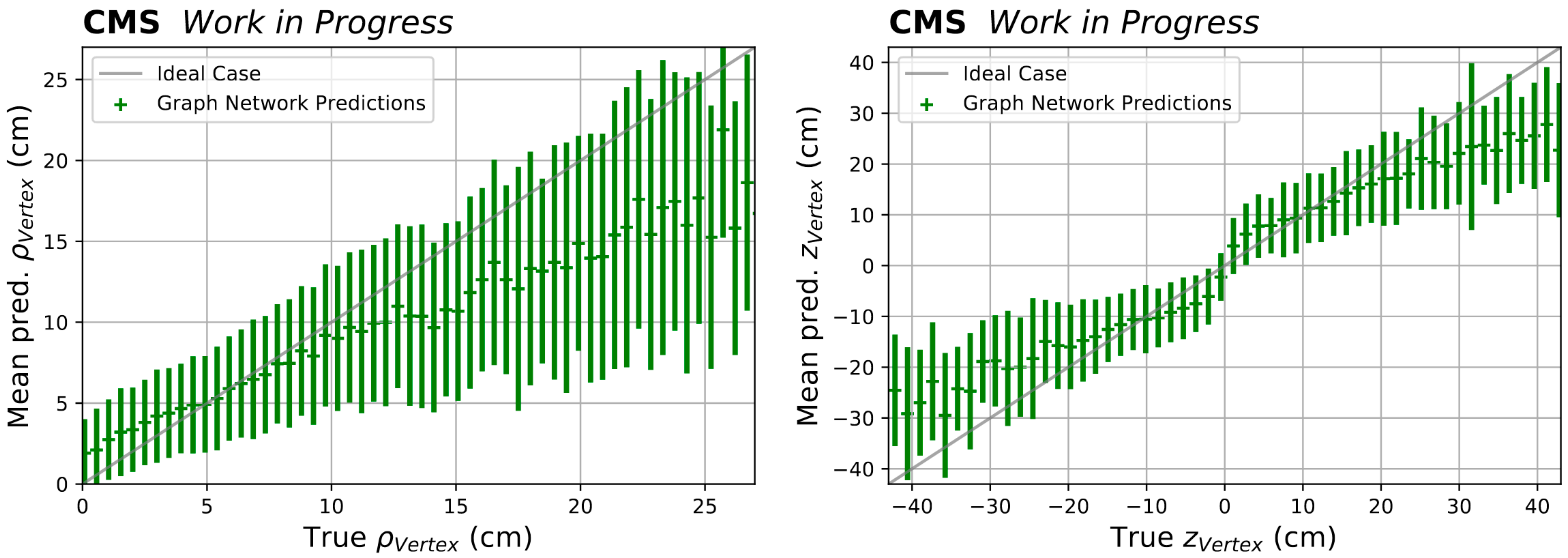






arXiv:1902.08570

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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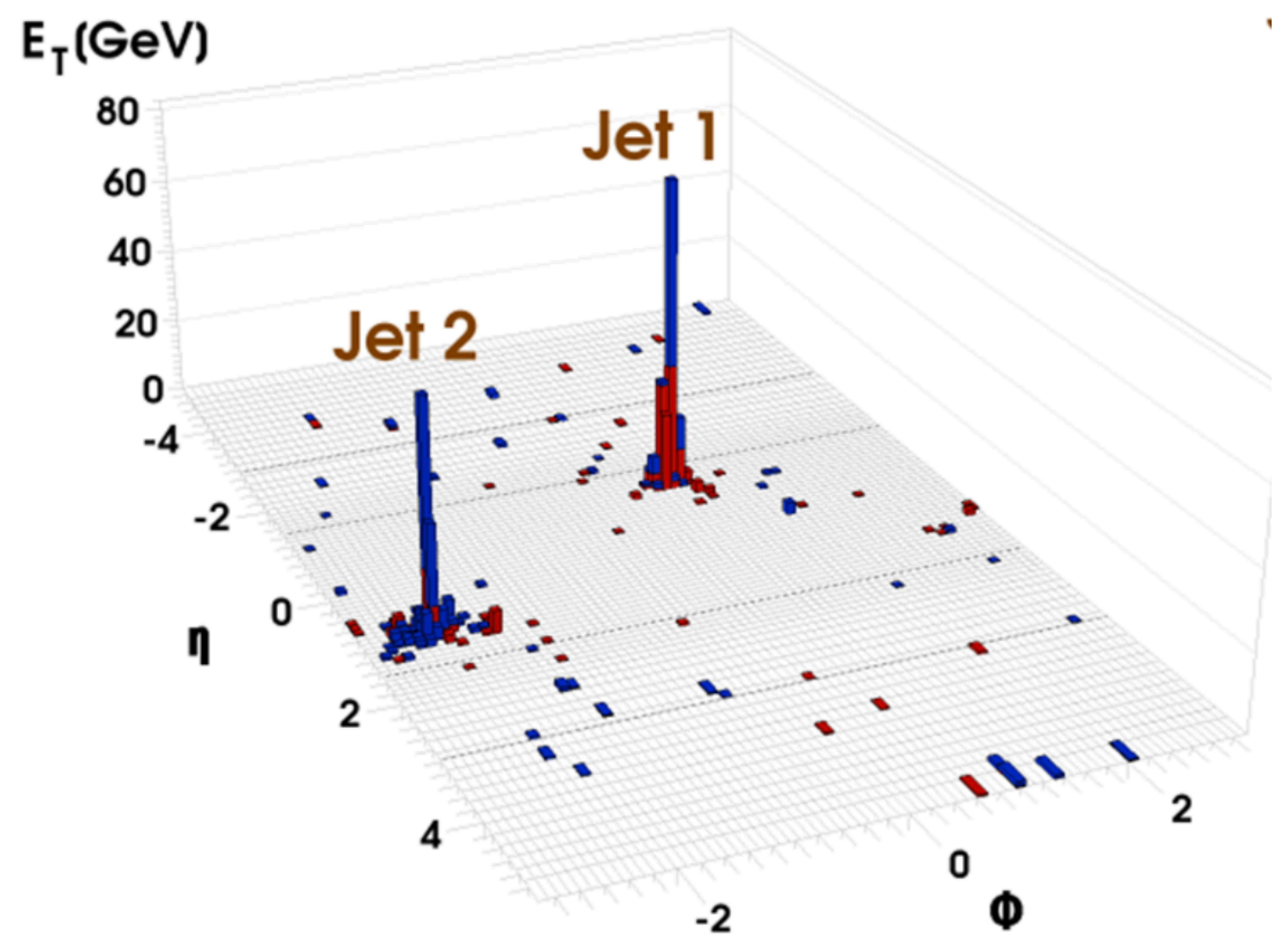
Calorimeter lifetimes: graph network for displaced jet tagging

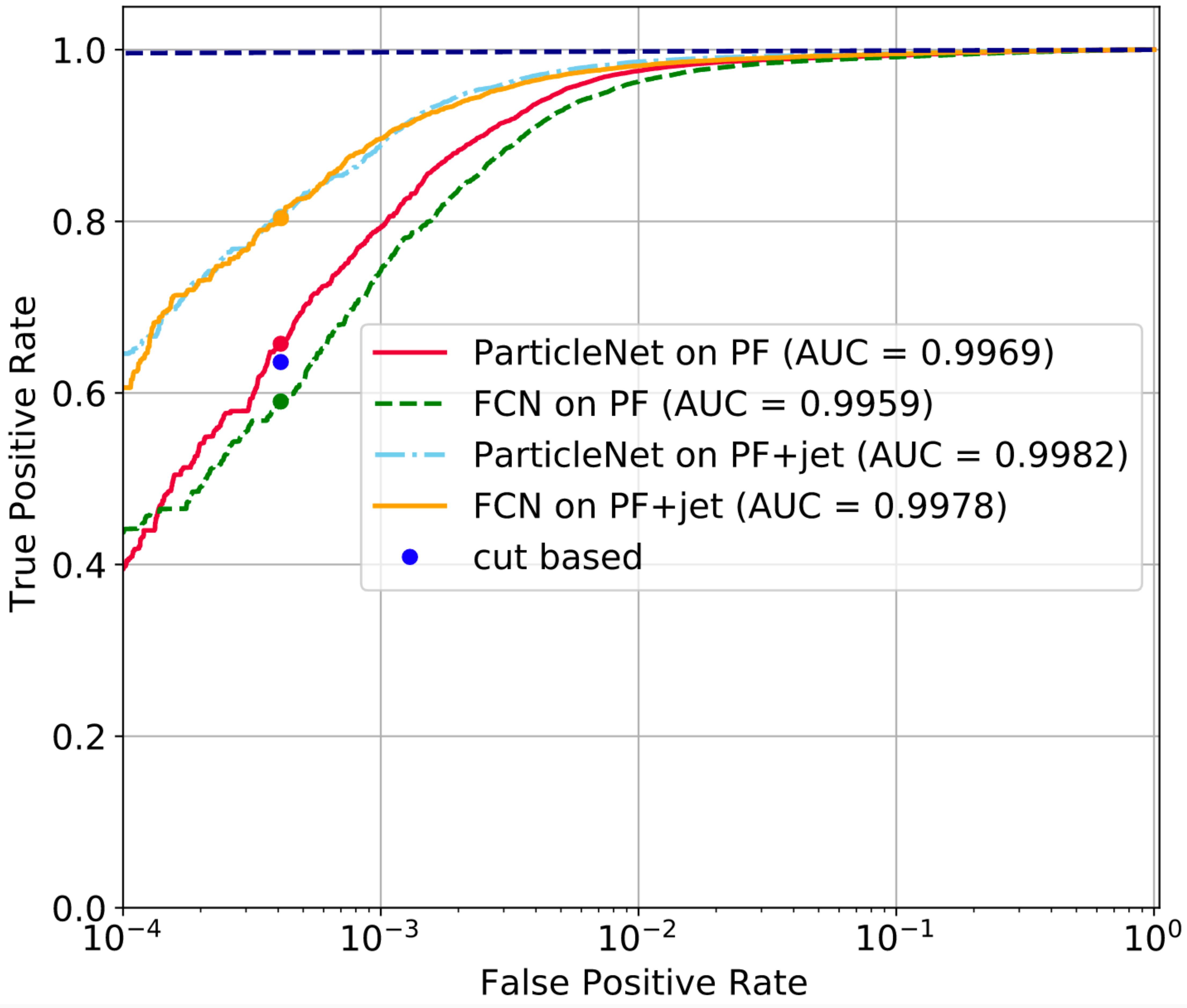
- **Jet** interpreted as clouds of **PF constituents**:
  - First 25 jet constituents with $p_T > 1$ GeV (points)
  - Points coordinates: euclidean distance (η, φ) as metric among *k*-nearest neighbours
  - Points features: energy, pT, charge, number of hits in tracker/pixel
- ParticleNet architecture:
  - Optimised k-nn and number of edge conv blocks
  - Additional shortcut to jet-level variables describing displacement (calorimeter time)



- Training:
  - Signal: jets matched to a LLP decay in calorimeter
  - Background: inclusive SM processes, weighted with x-sec

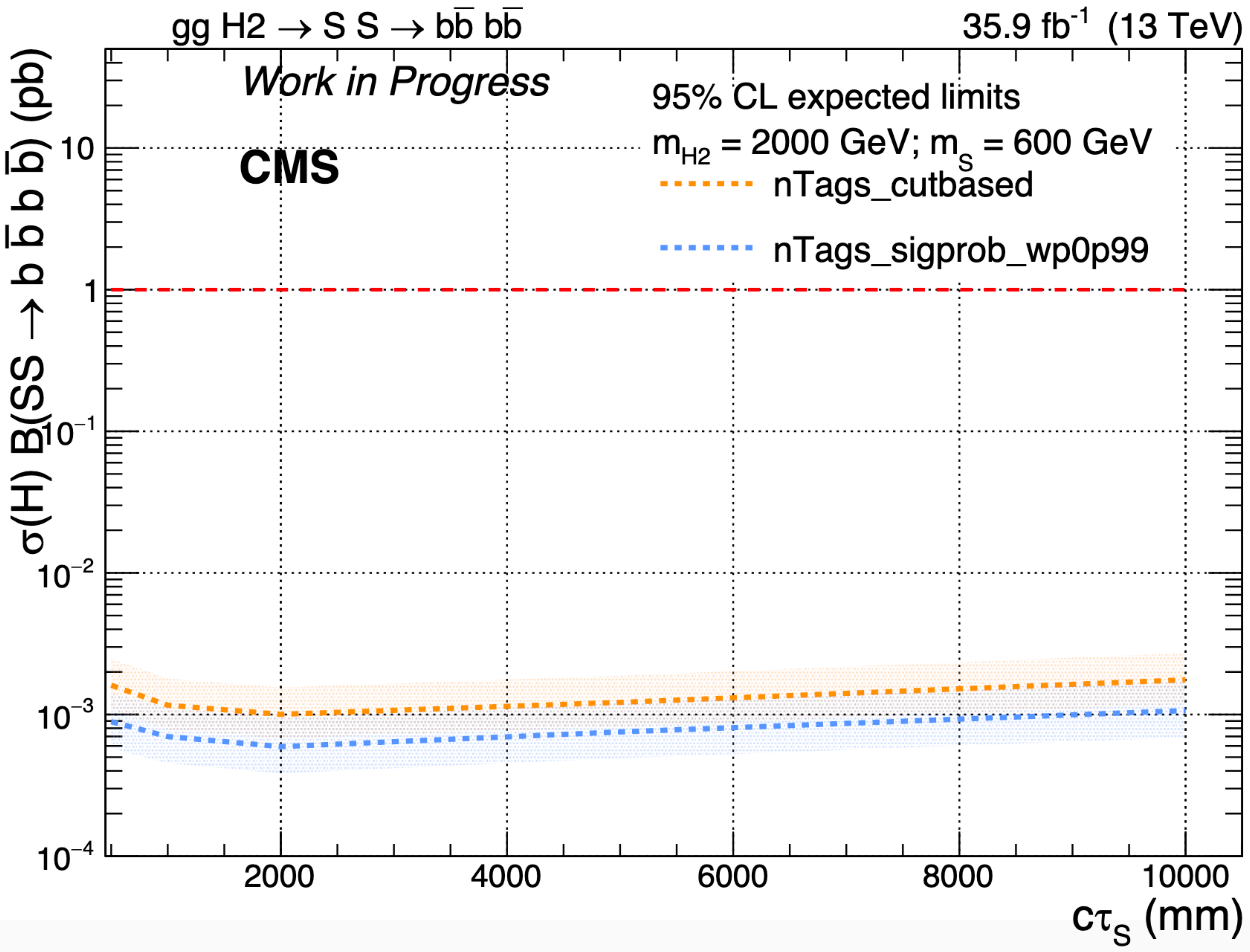
Calorimeter lifetimes: graph network performances

- Benchmark (blue dot): cut based approach, selecting jet-level variables
- Red curve: ParticleNet using only jet constituents
- Light blue curve: ParticleNet with shortcut to 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
- Limits vs proper decay length
  - Graph network: improvement by a factor 2 w.r.t. cut based
- Perspectives:
  - Extend to heavier masses
  - Tweak the architecture, use more features for jet constituents



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: