[Detector of TrackML challenge]

Graph Neural Networks

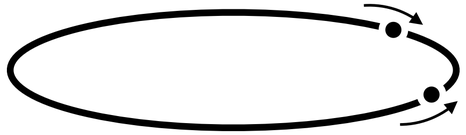
for HEP track reconstruction

A. Salzburger (CERN)

@SaltyBurger

HEP landscape in a nutshell*

COLLIDER

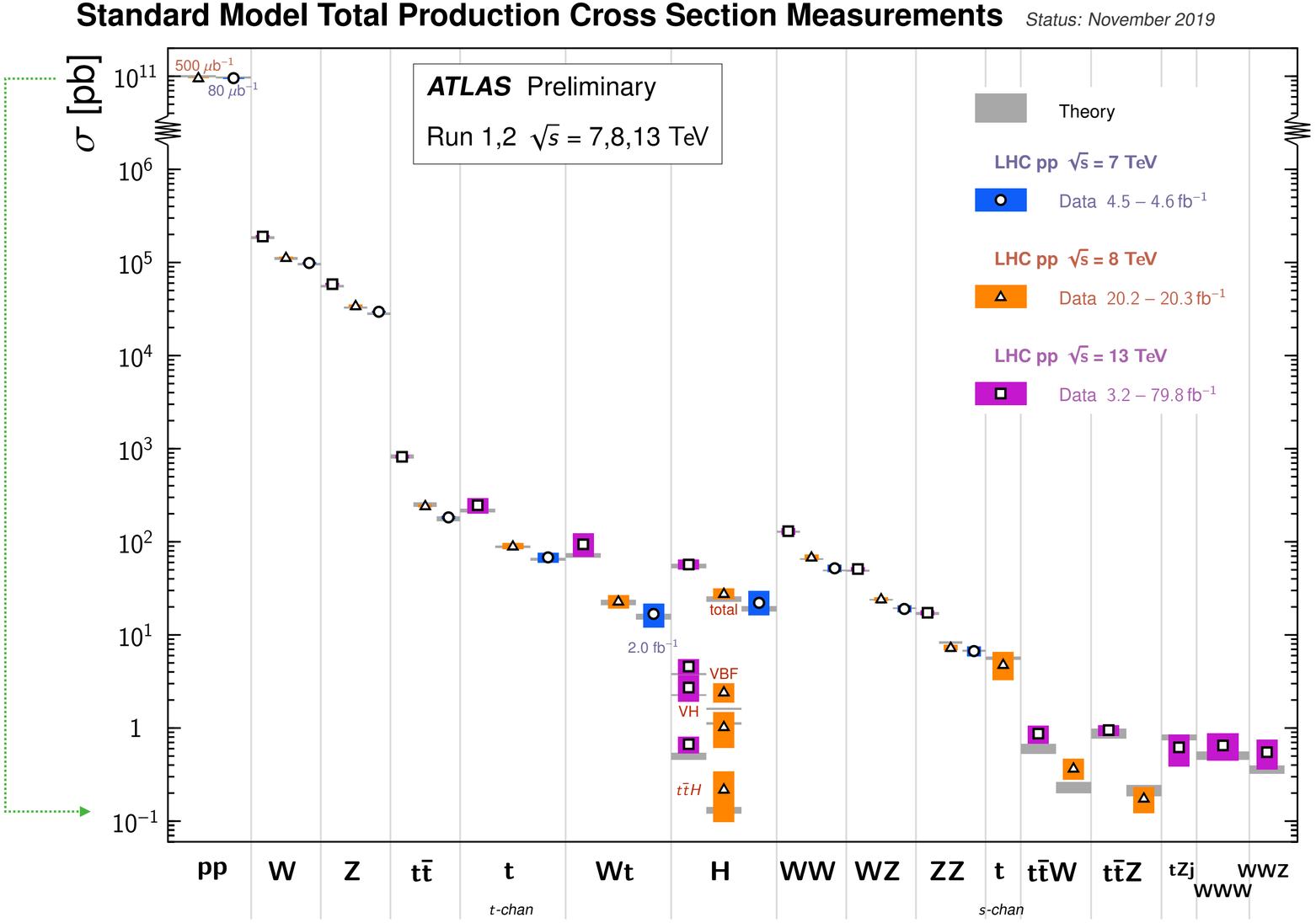


e.g. LHC

$\sqrt{s} = 14$ TeV

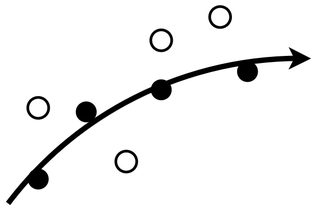
$f_{coll} = 40$ MHz

10^{12}



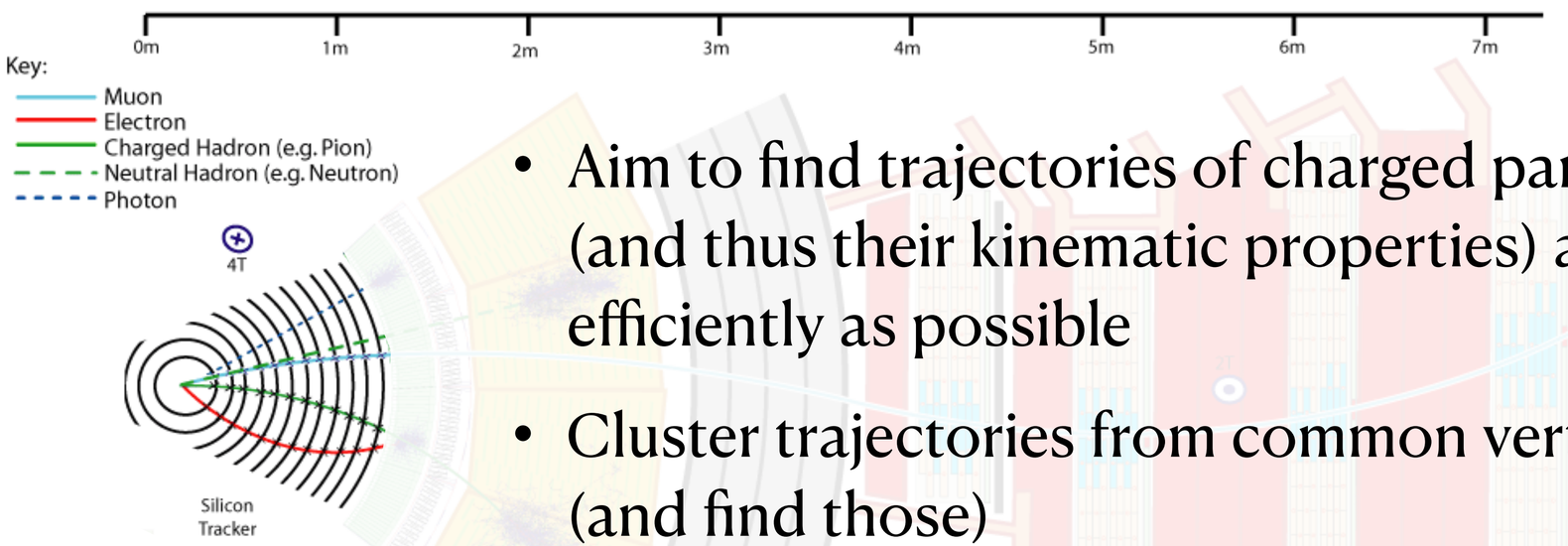
[SM cross section summary, ATLAS]

*collider centric view

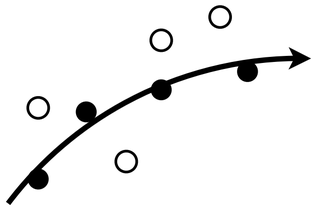


Particle Tracking

Trajectory and vertex finding in tracking detectors



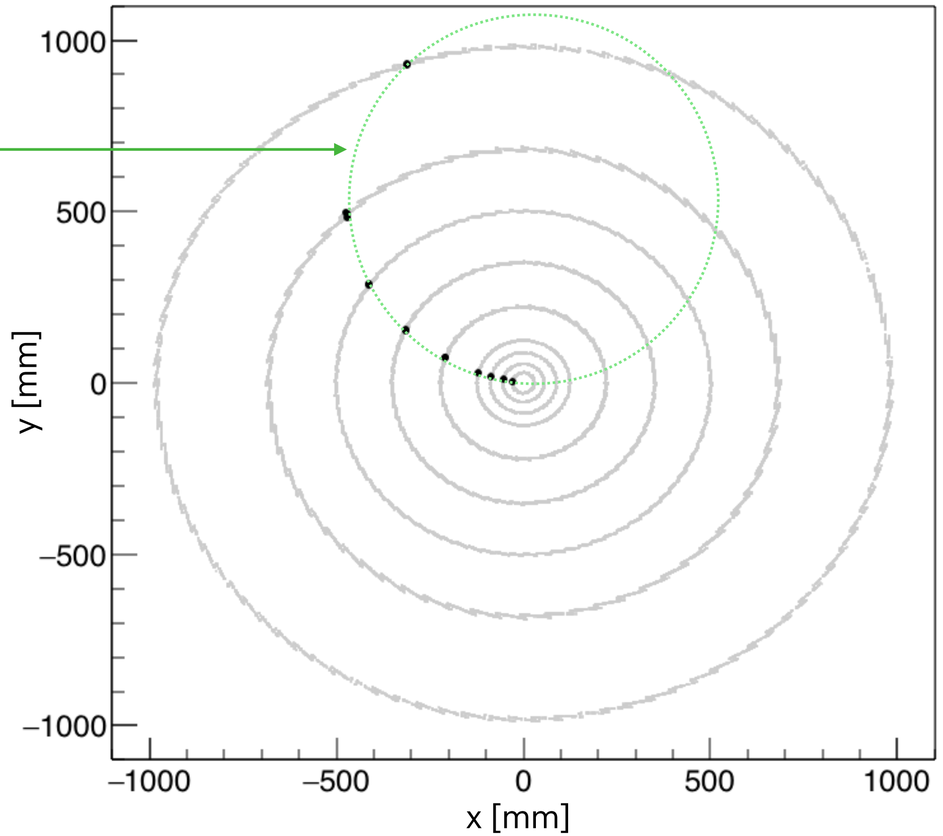
- Aim to find trajectories of charged particles (and thus their kinematic properties) as efficiently as possible
- Cluster trajectories from common vertices (and find those)
- If possible, first particle identification
- Avoid: fake/ghost trajectories, duplicates, ...

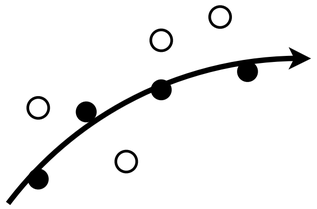


Particle Tracking

Pattern recognition for particle detectors

- Typical pattern recognition problem
  - Effectively a clustering problem
- *Classical* approaches include
  - Global/conformal mapping
  - Track seeding & following
  - Combinatorial filtering





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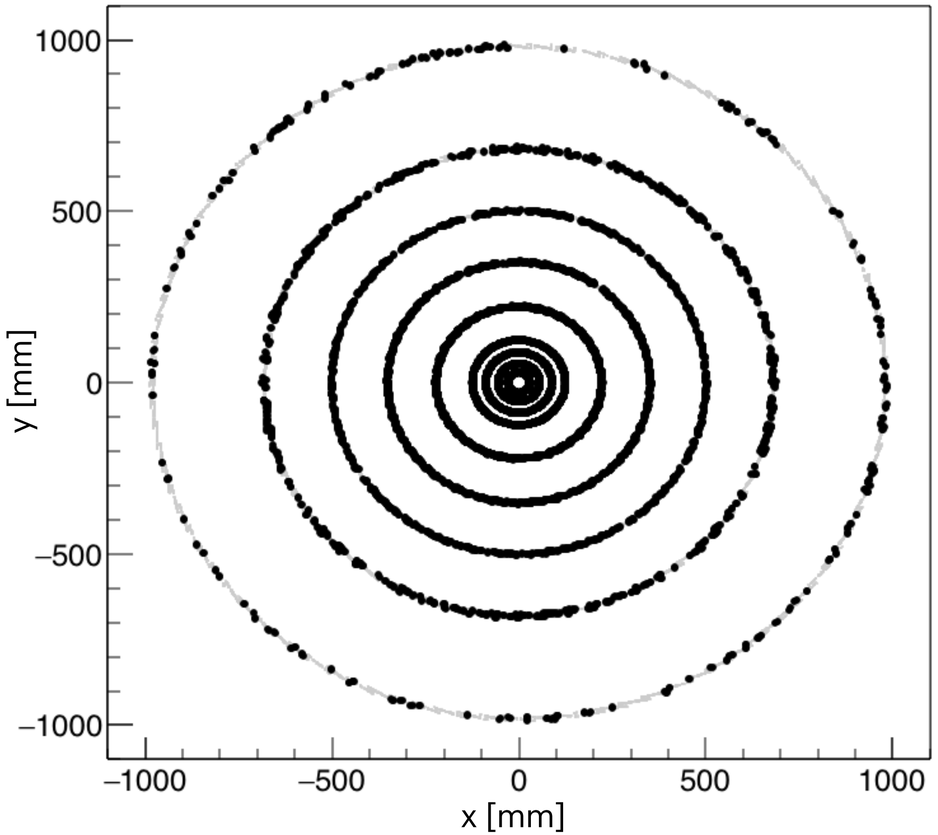
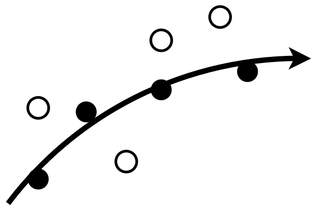
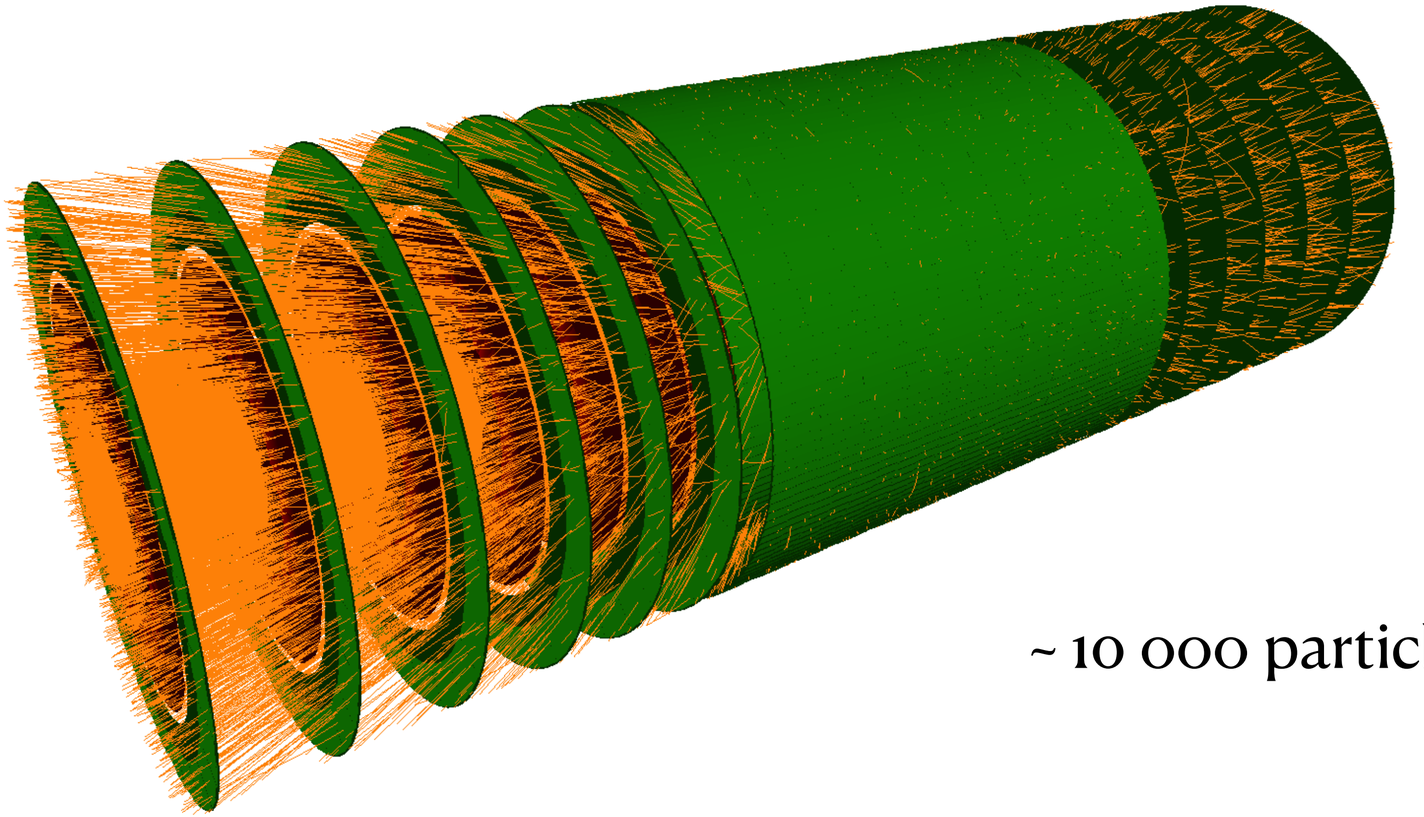


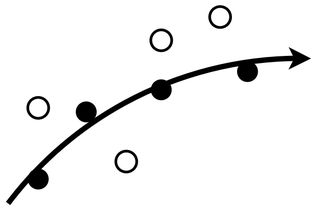


Particle Tracking

Pattern recognition for particle detectors

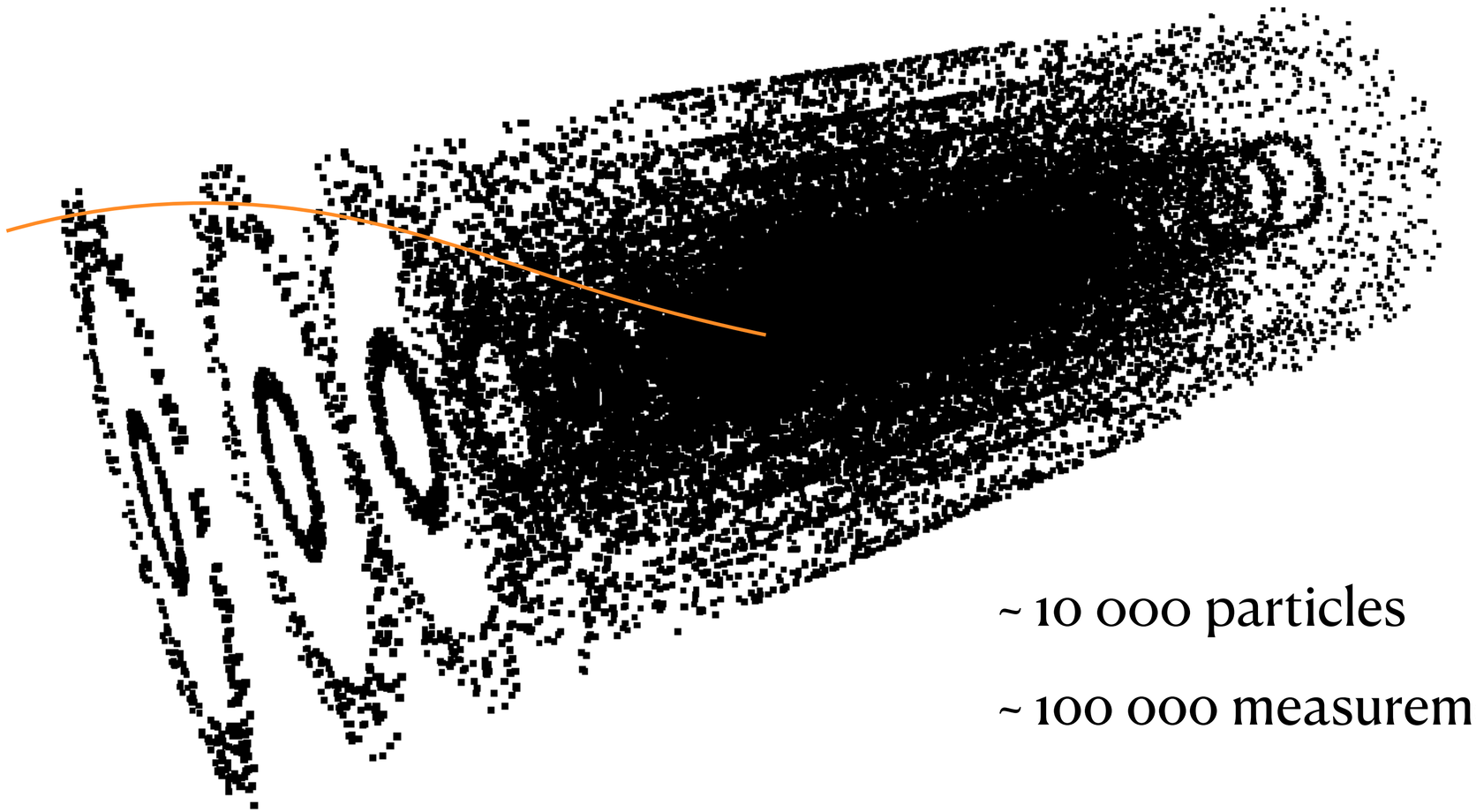


~ 10 000 particles



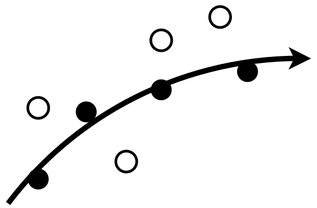
Particle Tracking

Pattern recognition for particle detectors



~ 10 000 particles

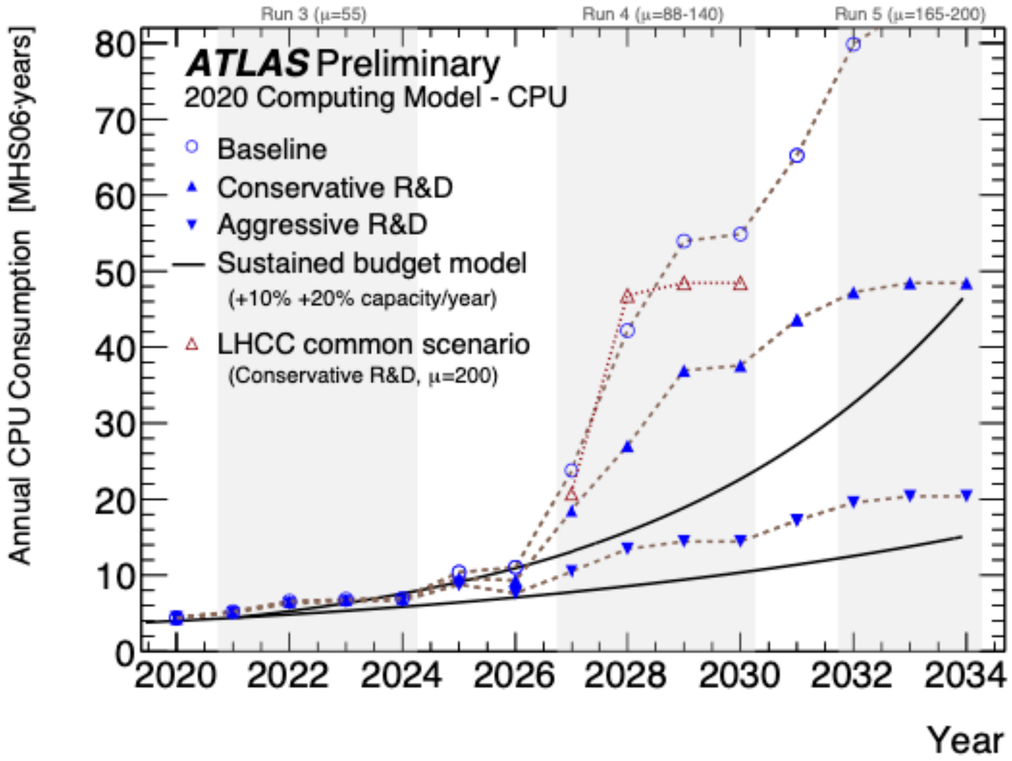
~ 100 000 measurements



Particle Tracking

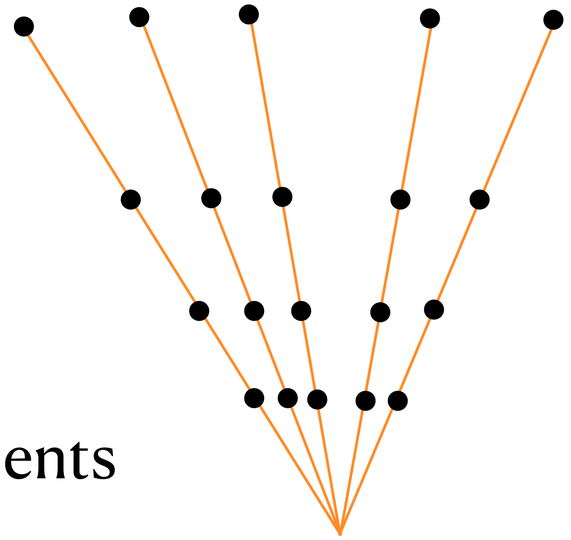
Classical algorithms

- Pattern recognition problem
  - Highly non-linear scaling
- HL-LHC era will put pressure on experiments
  - CPU ressources at current will not be sufficent
  - R&D needed
    - computing/software
    - new algorithms

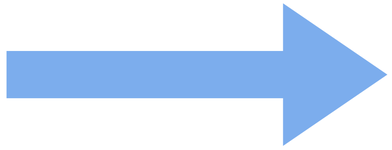


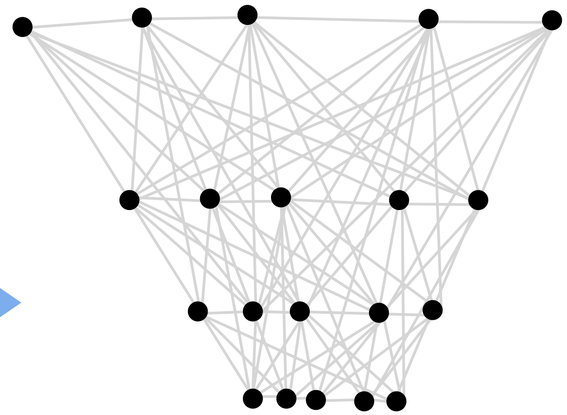
Graph Neural Networks

for particle tracking - **principles**



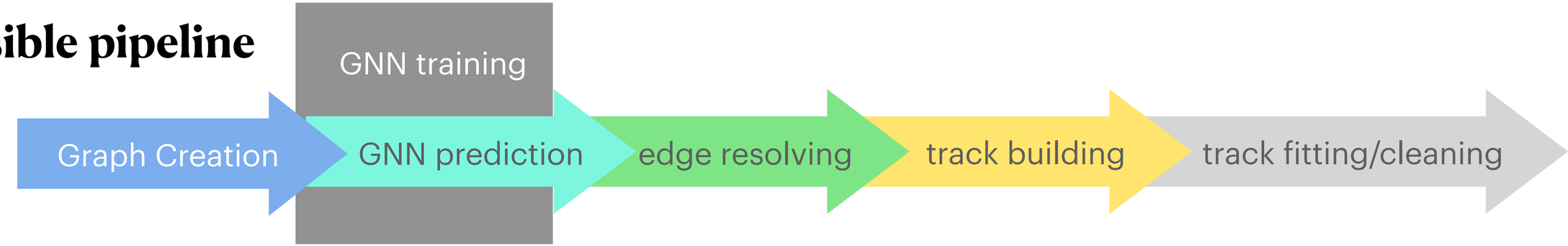
measurements
(hits)





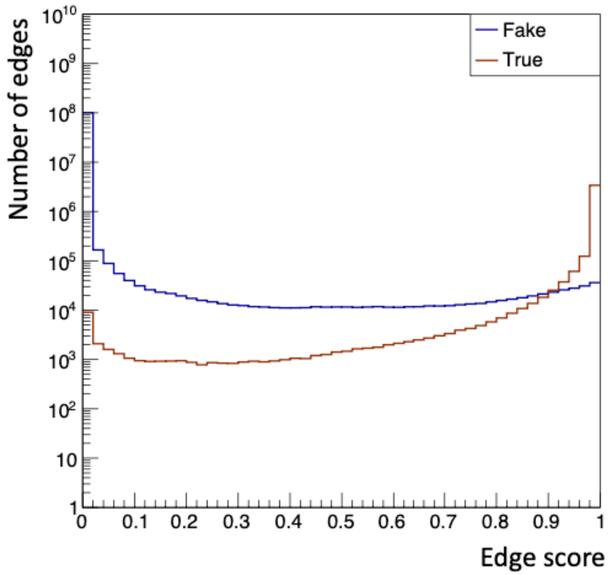
graph representation

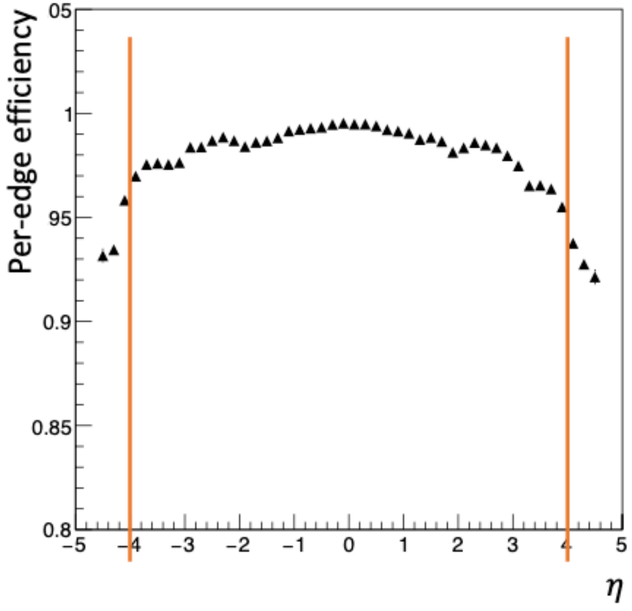
Possible pipeline

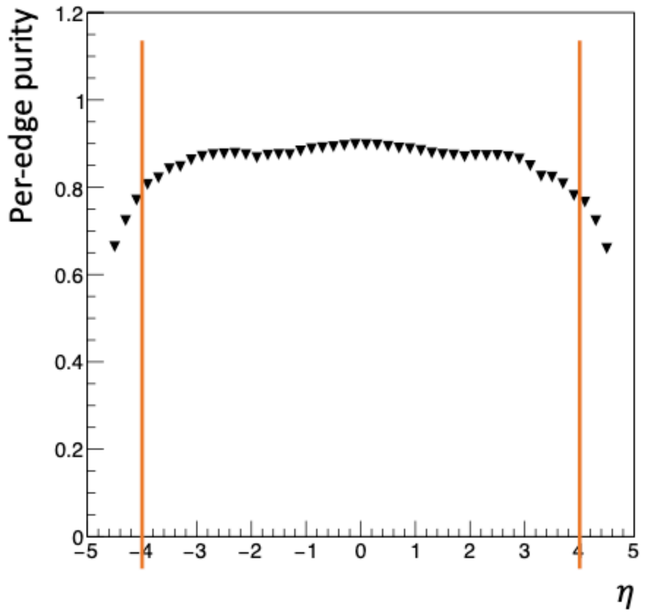


Graph Neural Networks

for particle tracking - **examples**







- Example performance on TrackML dataset
  - Clear separation, high efficiency & purity

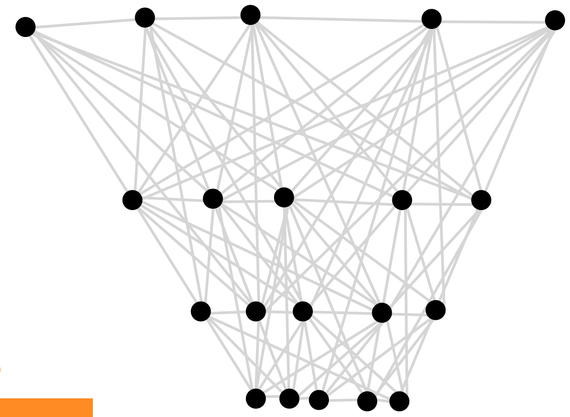
https://indico.cern.ch/event/948465/contributions/4323573

Particle Tracking Machine Learning Challenge [Phase 1][Phase 2]

Graph Neural Networks

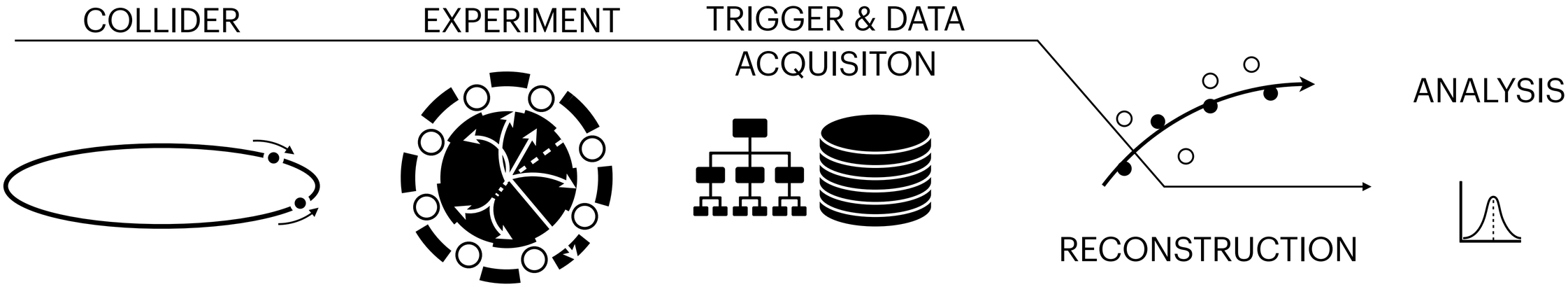
for particle tracking - **challenges & opportunities**

- Size of the Graph tends to be a challenge
  - Possibility to strip by exclusion rules
  - possibility segmentation
  - GNN prediction on high memory GPU / on FPGAs



graph representation

suitable for high level trigger application



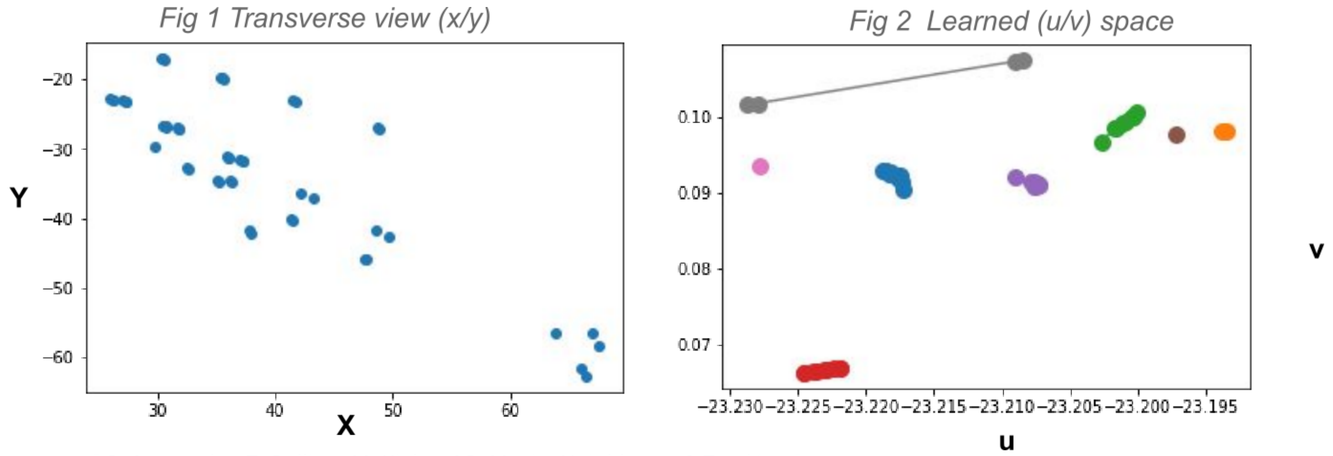
Graph Neural Networks

for particle tracking - **friends, family & opportunity**

- Pioneering work by Exa.TrkX project and some other R&D groups

https://indico.cern.ch/event/948465/contributions/4323753
https://indico.cern.ch/event/948465/contributions/4323573

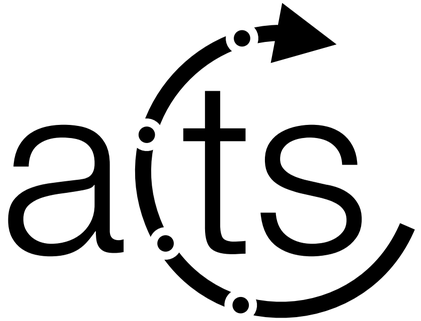
- Potential combination with
  - Metric learning
    (GNN in learned space)
  - Data hashing



[S. Amrouche, T. Golling, M. Kiehn, AS: Music, Neighbours & Tracking]
[S. Amrouche, N. Calace, T. Golling, M. Kiehm. AS : Hashing & similarity learning]

Graph Neural Networks

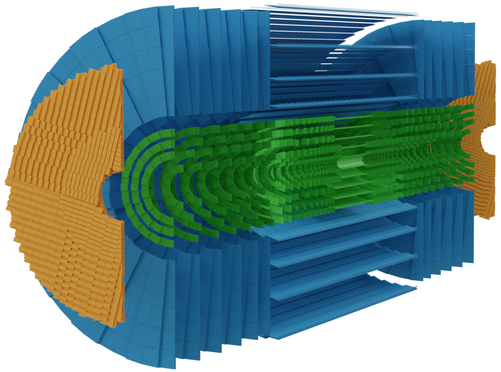
for particle tracking - **embedding**



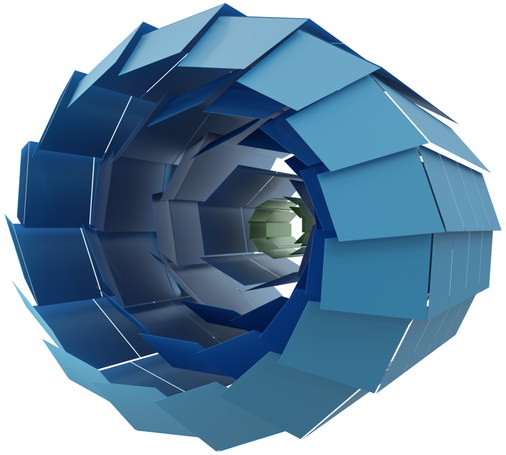
https://arxiv.org/abs/2106.13593

- Detector/framework agnostic track reconstruction toolkit
  - track fitting/cleaning
- Fast/full simulation capabilities
- Used for TrackML dataset creation
- Dedicated ML R&D line:
  - GNNs tracking & vertexing
  - Hashing
  - Classifications

ATLAS ITk

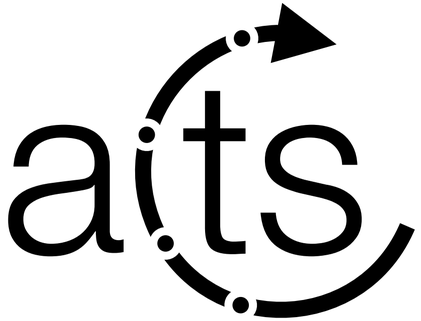


Belle-II



Graph Neural Networks

for particle tracking - **embedding**



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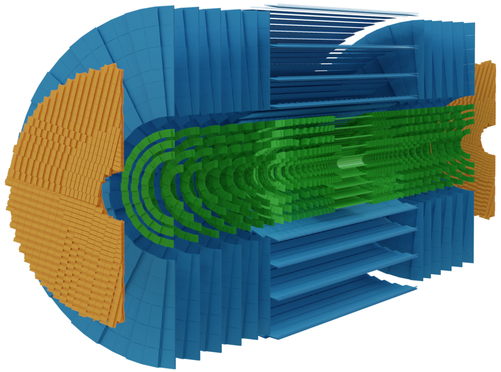
Detector/framework agnostic track reconstruction toolkit

- test transferability of approach
- direct usage in some experiments (ACTS is part of e.g. ATLAS, sPHENIX production software stack)

ATLAS ITk



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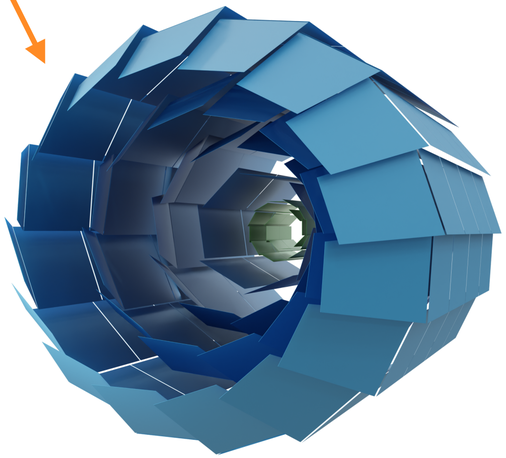

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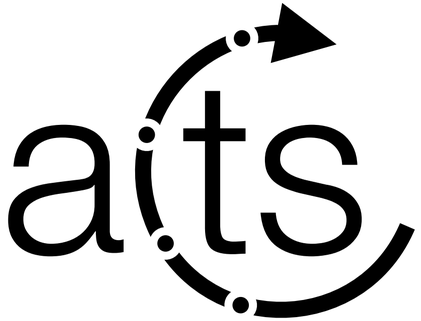

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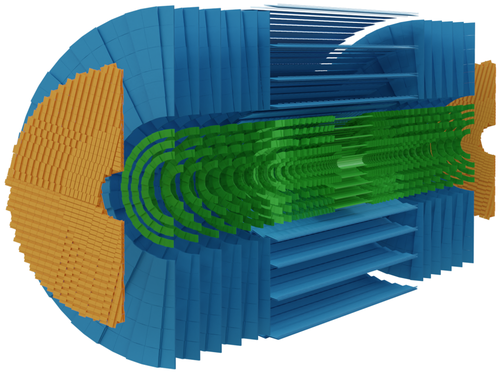
  - GNNs tracking & vertexing
  - Hashing
  - Classifications

• Non ML components available
+ downstream algorithms
(e.g. vertex reconstruction)

ATLAS ITk



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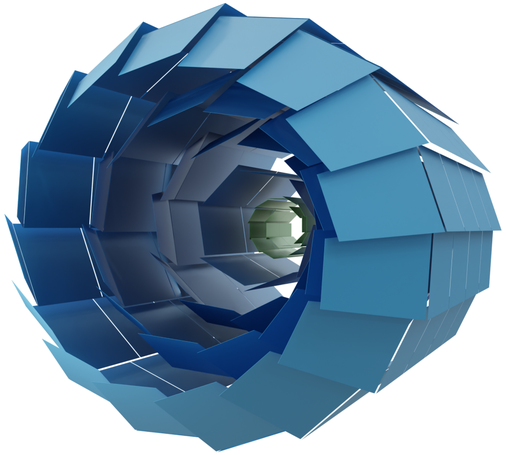

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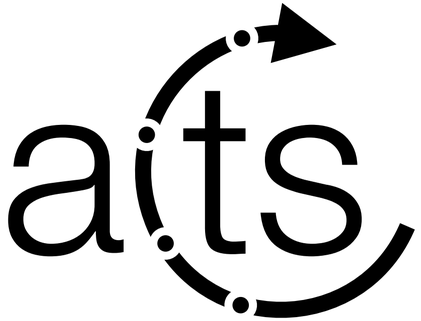

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- Detector/framework agnostic track reconstruction toolkit
  - track fitting/cleaning
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Fits into ACTS R&D projects + exchange with other R&D groups

- Dedicated ML R&D line:
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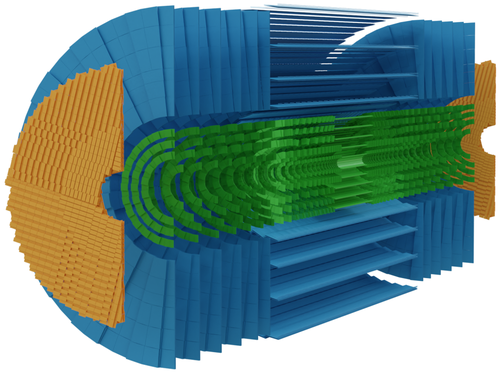

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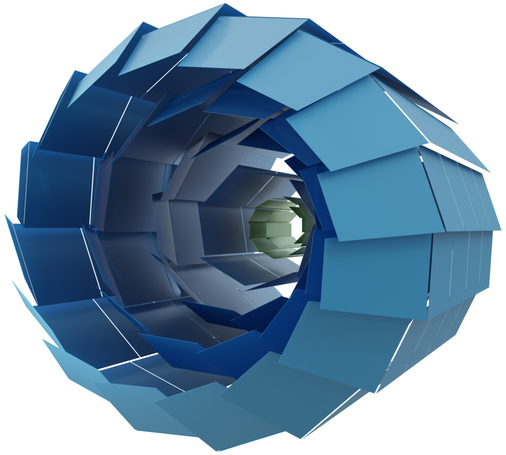


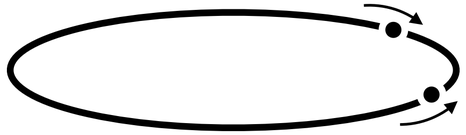
Conclusions & Food

- Graph Neural Networks offer a great possibility for track reconstruction
  - Pioneered already by Exa.TrkX and other groups
  - Can build upon their ground work & profit from CERNs unique involvement into track reconstruction @ (HL-)LHC

- Potential for usage in Event filter
  - Maximise throughput on GPUs/heterogenous hardware

HEP landscape in a nutshell*

COLLIDER



e.g. LHC

$\sqrt{s} = 14$ TeV

$f_{coll} = 40$ MHz

Image: CERN

*collider centric view

HEP landscape in a nutshell*

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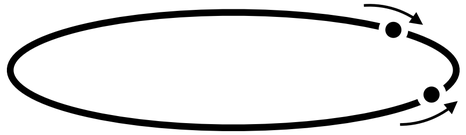

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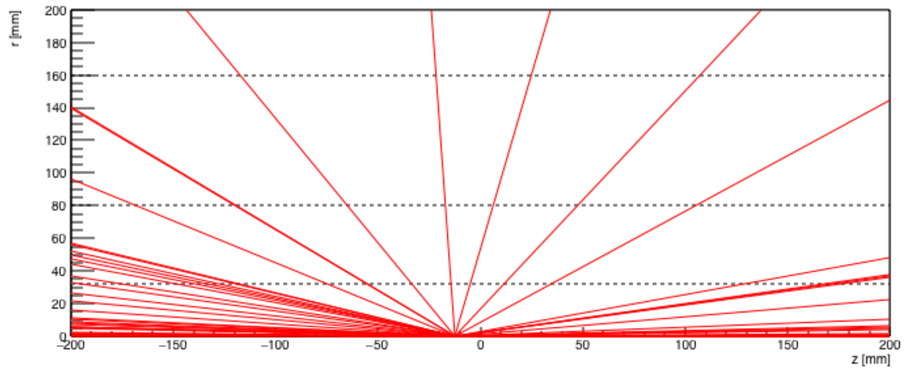
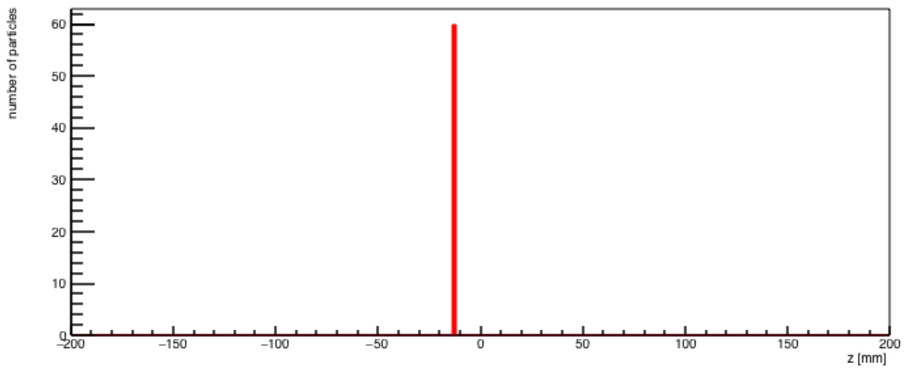
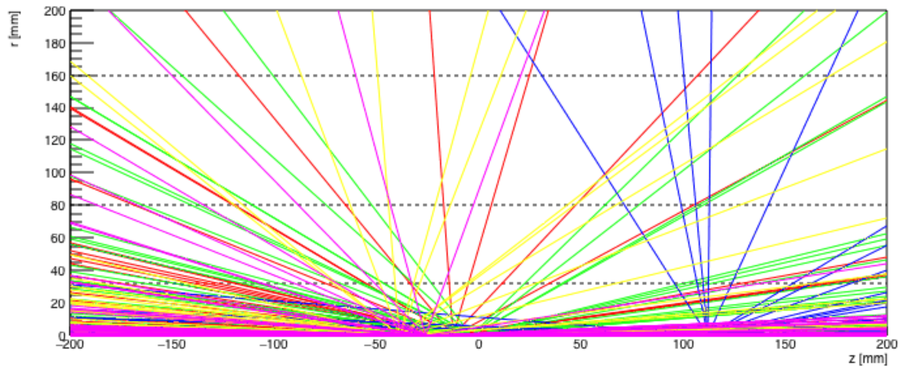
$< \mu > \approx 200$

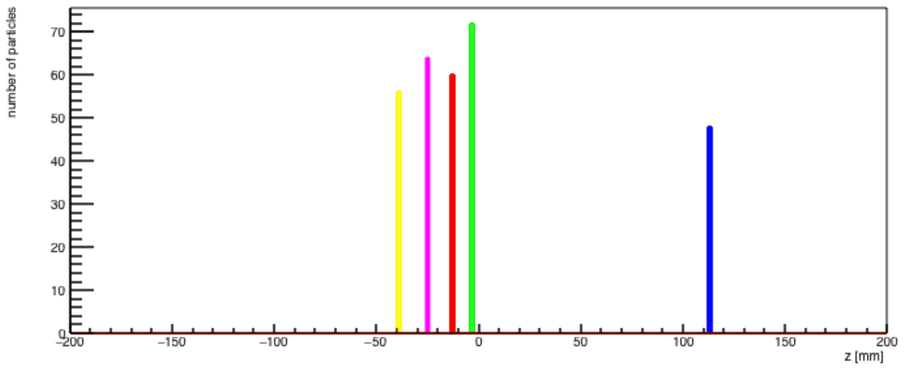




$< \mu > = 1$

START-UP OF LHC (2009)
1 single P-P collision





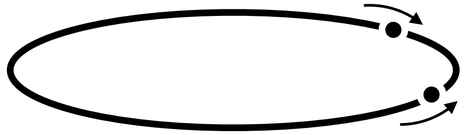
$< \mu > = 5$

EARLY RUN-1 OF LHC (2010)
5 instantaneous P-P collision

*collider centric view

HEP landscape in a nutshell*

COLLIDER



e.g. LHC

$\sqrt{s} = 14$ TeV

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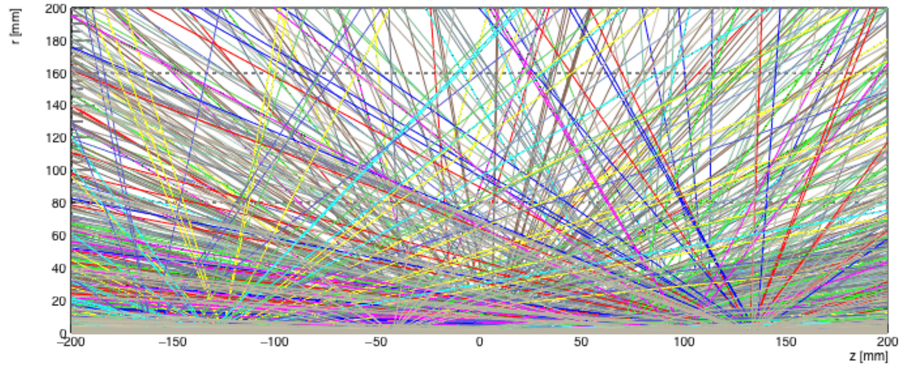
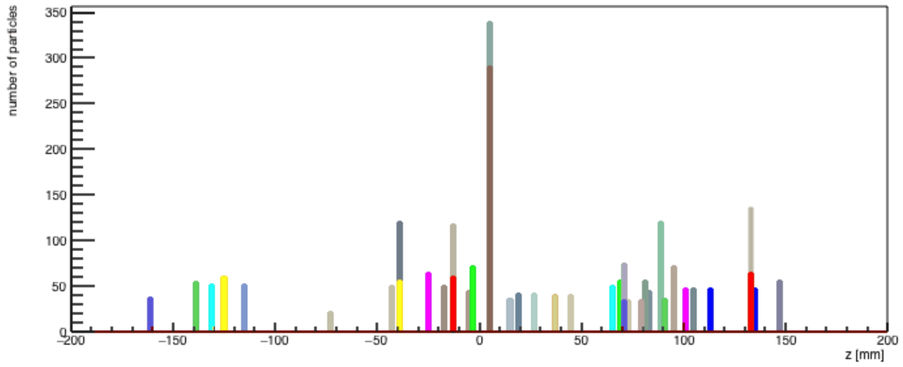
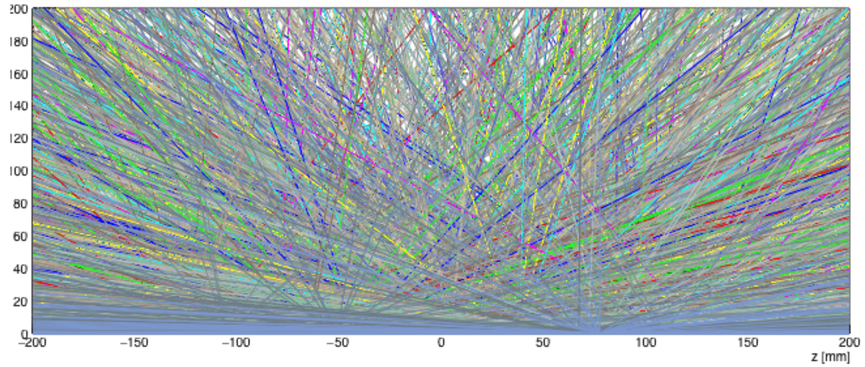
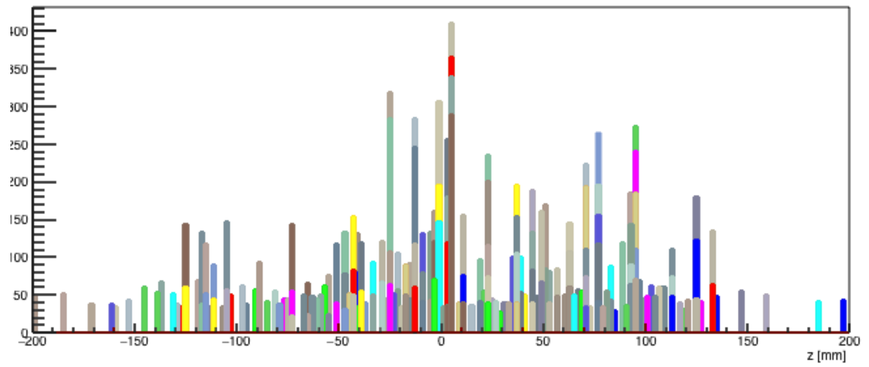




$< \mu > = 40$

RUN1/2
~40 instantaneous P-P collision





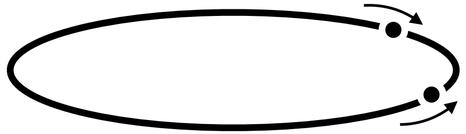
$< \mu > = 200$

HL-LHC (exp. 2027)
~200 instantaneous P-P collision

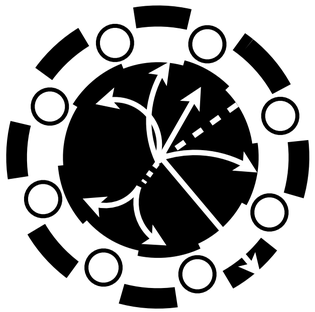
*collider centric view

HEP landscape in a nutshell - data path

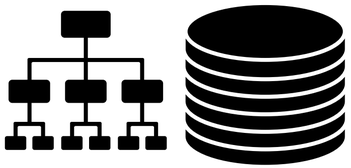
COLLIDER



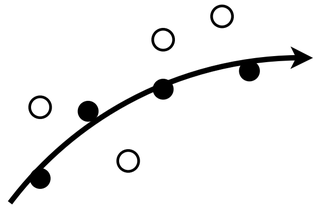
EXPERIMENT



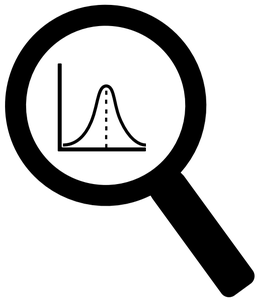
TRIGGER & DATA ACQUISITON



RECONSTRUCTION



ANALYSIS



HEP landscape in a nutshell - MC path

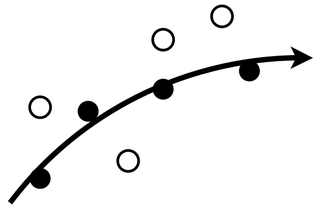
COLLIDER

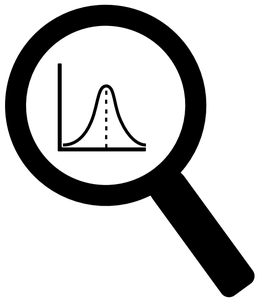
EXPERIMENT

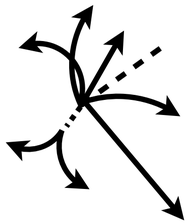
TRIGGER & DATA ACQUISITON

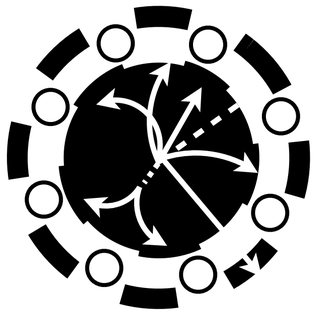
RECONSTRUCTION

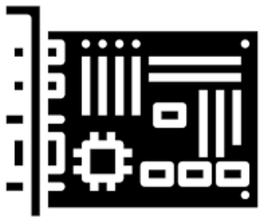
ANALYSIS











EVENT GENERATION

DETECTOR SIMULATION

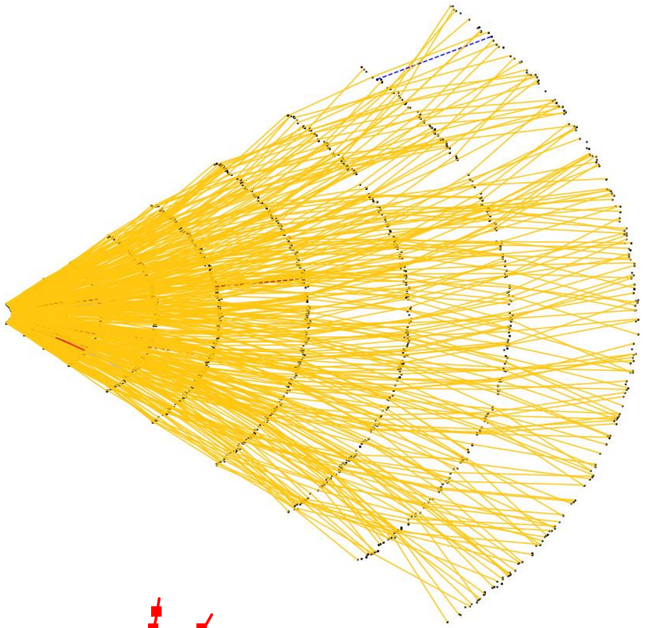
SIGNAL SIMULATION

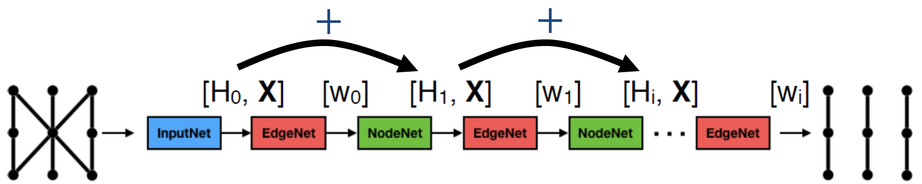
*collider centric view

End-to-end Tracking attempts

The “my job is done by a machine” scenario

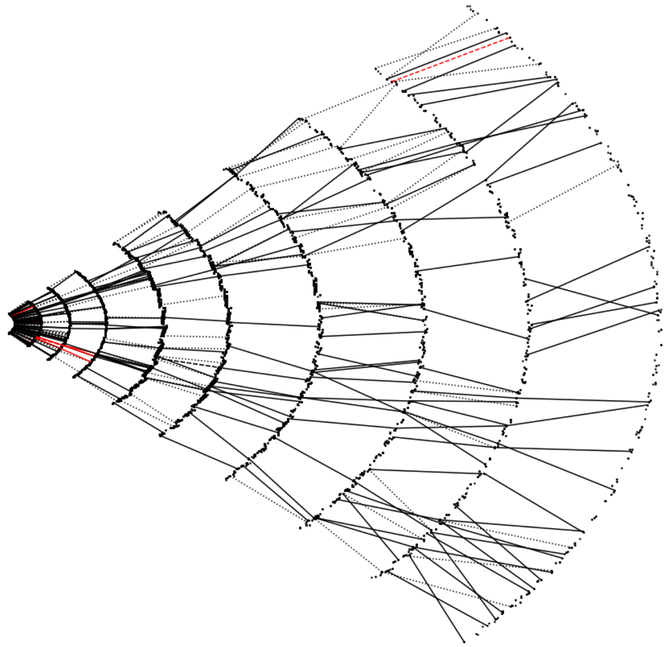
- Exa.TrkX project applies a Graph Neural Network (GNN) approach
  - Build nodes and edges, classify edges [0, 1] and eventually drop them





- Attention Message Passing with Residuals

Kipf, Thomas N., and Max Welling. "Semi-supervised classification with graph convolutional networks." *arXiv preprint arXiv:1609.02907* (2016).



TrackML Particle Tracking Machine Learning Challenge [Phase 1][Phase 2]