Feedback from the *Connecting the Dots* workshop

Jan Stark

Laboratoire des 2 Infinis – Toulouse

32nd International Workshop on Vertex Detectors, Sestri Levante, 16 – 20 October 2023

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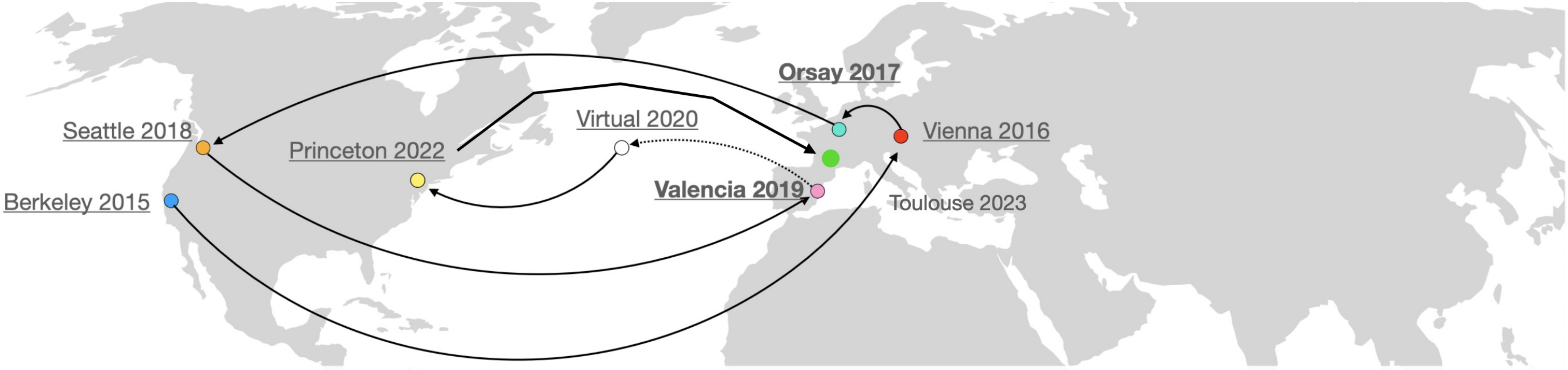
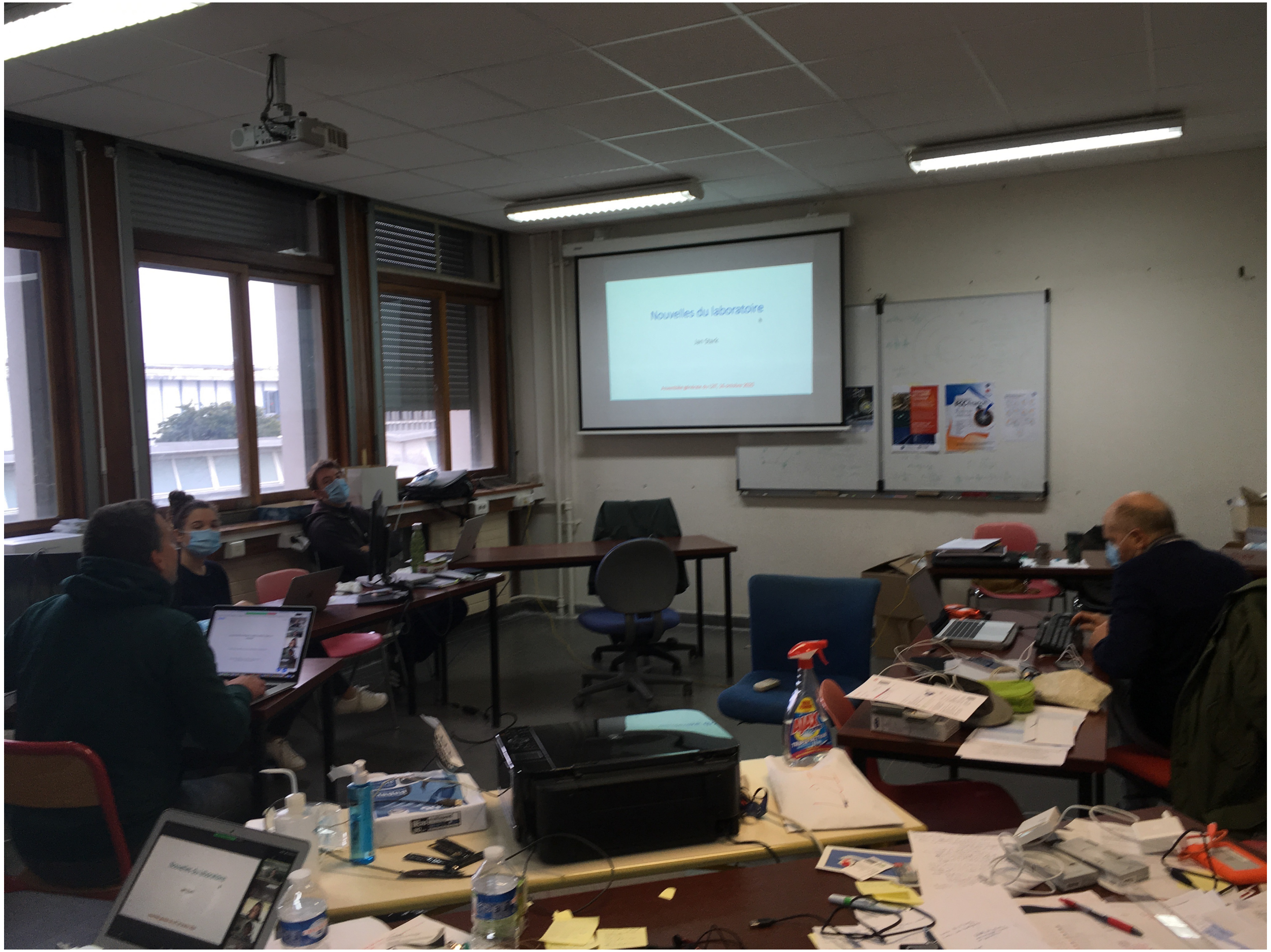
This is by no means intended to be a complete summary.

The “*Connecting the Dots*” series of workshops



The *Connecting The Dots* workshop series brings together experts on track reconstruction and other problems involving pattern recognition in sparsely sampled data. While the main focus will be on High Energy Physics (HEP) detectors, the *Connecting The Dots* workshop is intended to be inclusive across other scientific disciplines wherever similar problems or solutions arise.

L2IT in 2020



The Lab was created by Paul Sabatier University and IN2P3 / CNRS in January 2020 with initially 4 members.

… and now

L2IT

As of today: 27 members

Research at L2IT

Defining feature:
Focus on novel analysis methods

Modelling, simulation and modern analysis techniques are the main focus of L2IT.

We are developing these innovative aspects of research in the fields of nuclear and particle physics and cosmology, in close collaboration with experts from Toulouse's ecosystem of research in computing, artificial intelligence, physics, astronomy and astrophysics.

Development of new methods for simulation and data analysis

What is the shape of the Higgs potential ?
→ its origin
→ its role during the first instants of the Universe
(electroweak baryogenesis ?, emission of gravitational waves ?)

ATLAS

How do gravitational waves propagate in the Universe ?
→ information on the nature of dark energy ?
→ modified gravitation ?

Virgo

LISA

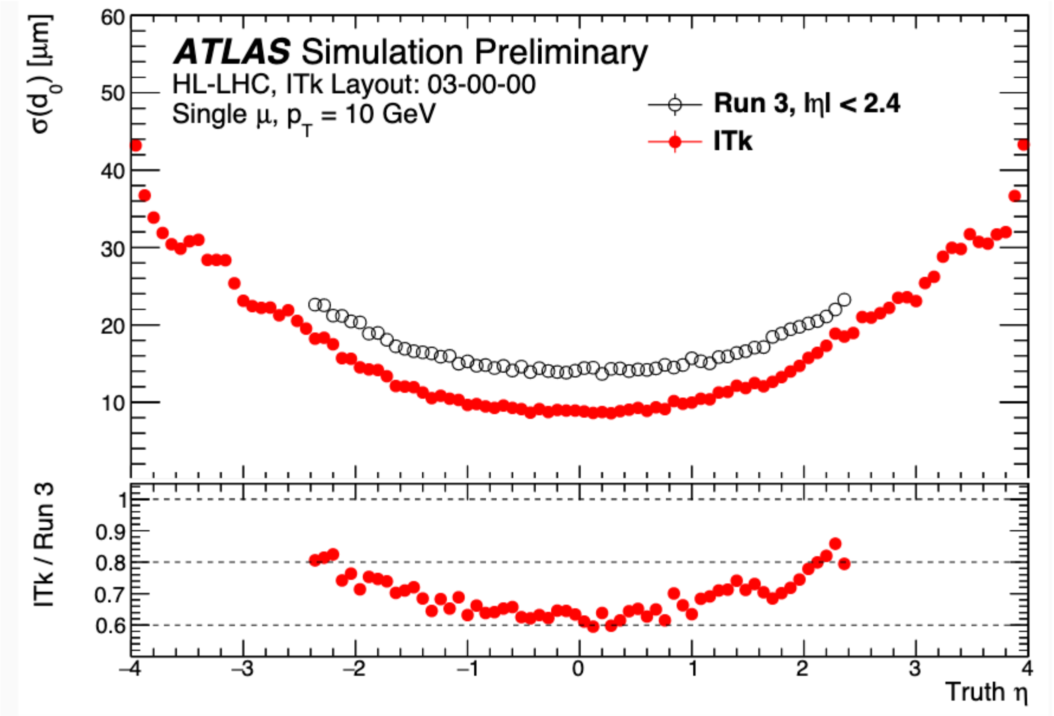
How does nuclear matter behave under extreme conditions (density, pressure) ?
→ compact stars
→ impact on the emission of gravitational waves and neutrinos

FAZIA at GANIL

Updates from LHC experiments

Updated expected tracking performance of the ATLAS Inner Tracker Upgrade for Phase-II

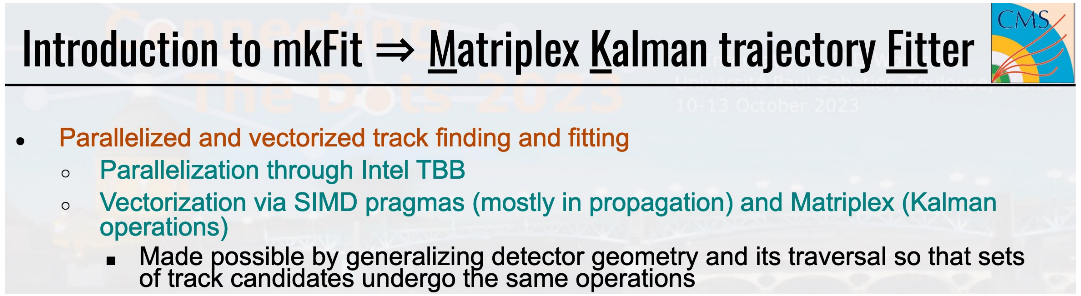
(link to talk)



Also: talk on Long-Lived Particle triggers in the LHC Run 3 (link)

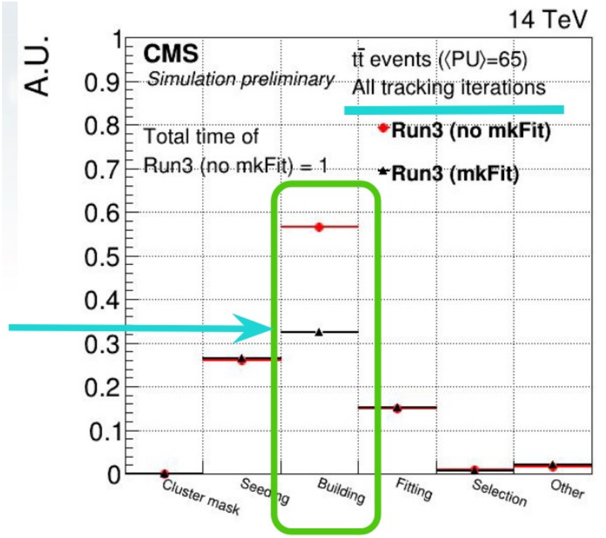
CMS: track reconstruction with mkFit

(link to talk)


Introduction to mkFit ⇒ Matriplex Kalman trajectory Fitter

- Parallelized and vectorized track finding and fitting
  - Parallelization through Intel TBB
  - Vectorization via SIMD pragmas (mostly in propagation) and Matriplex (Kalman operations)
    - Made possible by generalizing detector geometry and its traversal so that sets of track candidates undergo the same operations

mkFit is in production since start of Run 3

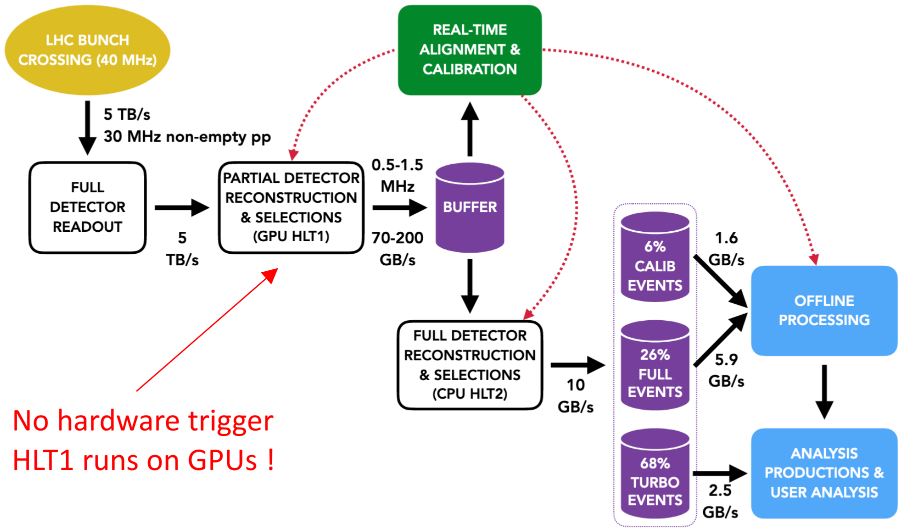


Single-threaded measurements on 1 Intel® Xeon® Gold 6130 CPU @ 2.10GHz, local access to inputs

Updates from LHC experiments and Belle II

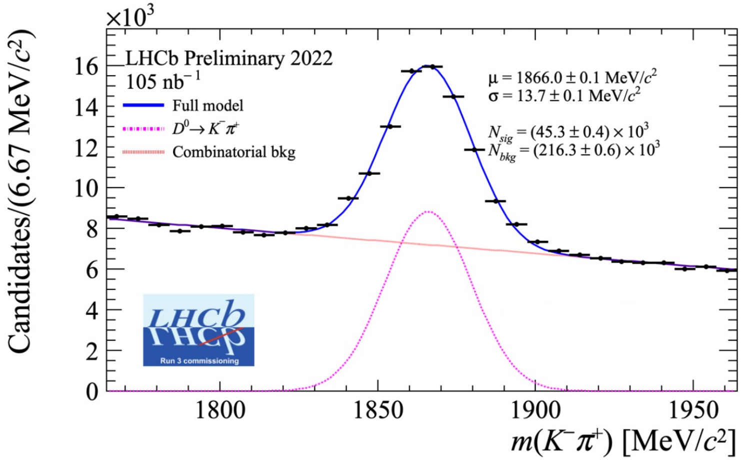
First experience with the LHCb heterogeneous software trigger

(link to talk)



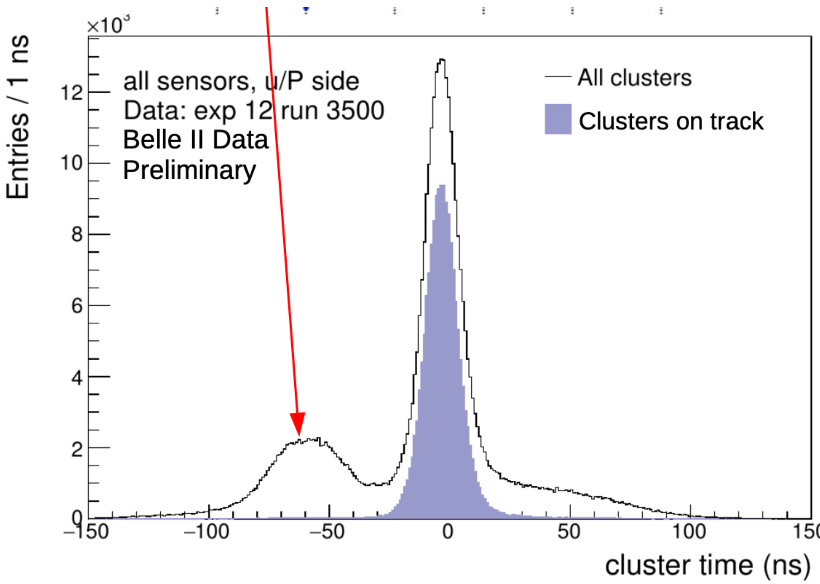
HLT1 is able to find mass peaks in real time !

Shown here: $D^0 \to K^- \pi^+$



Belle II track finding using precise timing information

(link to talk)



	Hit time grouping off	Hit time grouping on	Relative difference
Track finding efficiency	93.67 ± 0.24 %	93.69 ± 0.24 %	+0.02 %
Charge efficiency	98.68 ± 0.11 %	98.74 ± 0.11 %	+0.06 %
Fake rate	9.55 ± 0.29 %	4.37 ± 0.20 %	-54.26 %
Clone rate	3.81 ± 0.19 %	3.56 ± 0.18 %	-6.62 %

ACTS is everywhere

- Experiment-independent toolkit for tracking
  - In-use or in evaluation by a number of experiments!
- Modern software, unit tested, continuous integration
- Minimal external dependencies
- Ready for multi-threading by design

ATLAS stepper transcribed to ACTS

```
double PC = pVector[4] * C[0]
  + pVector[5] * C[1] + pVector[6] * C[2];
double Bn = 1. / PC;

double Bx2 = -A[2] * pVector[29];
double Bx3 = A[1] * pVector[38]
  - A[2] * pVector[37];

double By2 = A[2] * pVector[28];
double By3 = A[2] * pVector[36]
  - A[0] * pVector[38];

double Bz2 = A[0] * pVector[29]
  - A[1] * pVector[28];
double Bz3 = A[0] * pVector[37]
  - A[1] * pVector[36];

double B2 = B[0] * Bx2 + B[1]
  * By2 + B[2] * Bz2;
double B3 = B[0] * Bx3 + B[1]
  * By3 + B[2] * Bz3;
```

ACTS reimplemented EigenStepper

```
boundToCurvilinearJacobian(direction,
                           boundToFreeJacobian,
                           freeTransportJacobian,
                           freeToPathDerivatives,
                           fullTransportJacobian);

boundCovariance = fullTransportJacobian
                  * boundCovariance
                  * fullTransportJacobian.transpose();

reinitializeJacobians(freeTransportJacobian,
                      freeToPathDerivatives,
                      boundToFreeJacobian,
                      direction);
```

🚨 **Software written 30+ years before with no one still around who wrote it is not maintainable!**

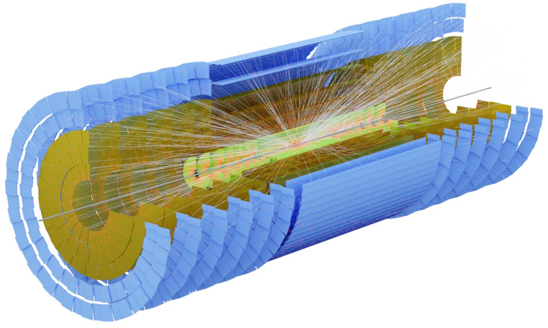
*not *exactly* identical code

Paul Gessinger 2023-10-10 — CTD 2023 13

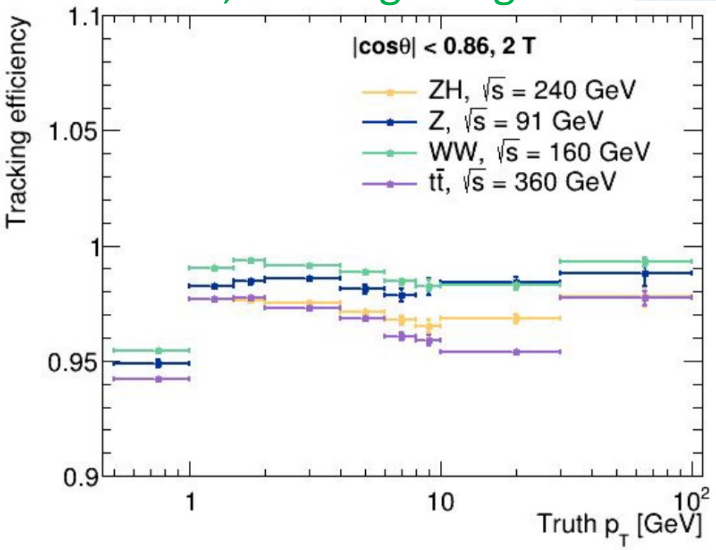
(link to talk)

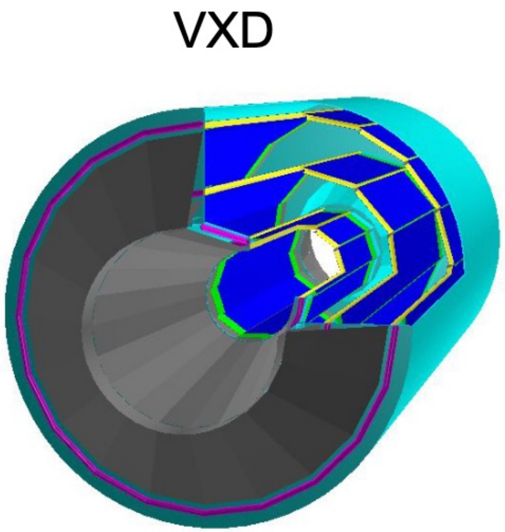
ACTS is everywhere

ACTS-based track reconstruction for Open Data Detector (link to talk)



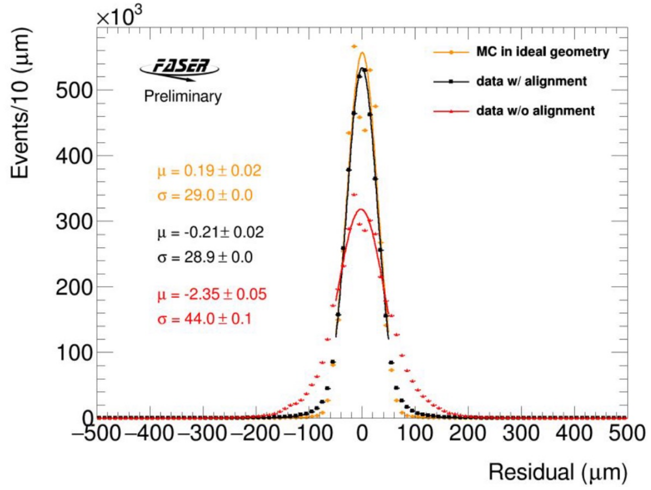
CEPC, tracking using ACTS (link to talk)



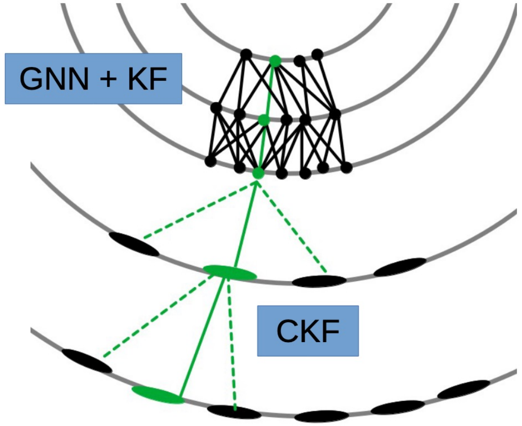


FASER (LLP detector at LHC) tracking with ACTS

plot from alignment studies



(link to talk)



Combining GNN and Kalman filter in ACTS

(link to talk)

Graph Neural Networks (GNN)

One colleague suggested
I show you a slide like this.

Say "GNN" one more time, I dare you !

Photo: "Pulp Fiction" (Miramax)

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One colleague suggested
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Say "GNN" one more time, I dare you !

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But jokes apart, GNN are an extremely powerful tool that will likely have a huge impact on our field.

Graph Neural Networks (GNN)

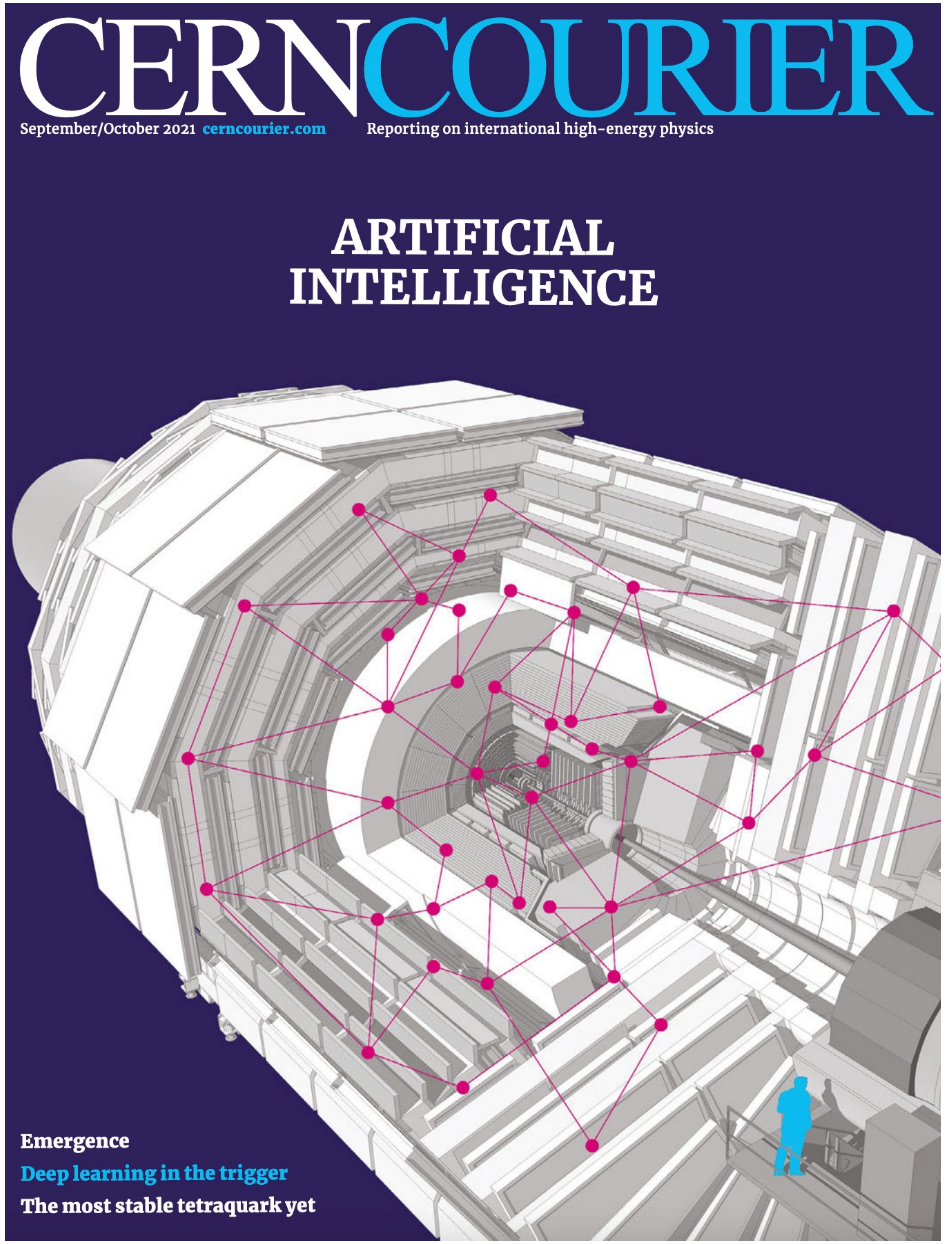
Data from HEP detectors in general,
and tracking detectors in particular, are sparse.

ATLAS ITk tracker at HL-LHC:
- 9 billion channels
- “only” 300k hits in one given event

The detectors are inhomogeneous
(combine different technologies)
and have complex geometry.

Such data are hard to represent as images.

Graphs are a natural tools to represent such data.
GNNs are neural networks that operate on
graphs of any topology and complexity.

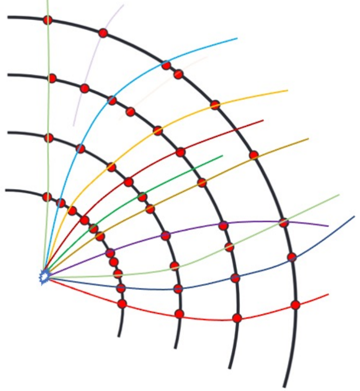


GNN

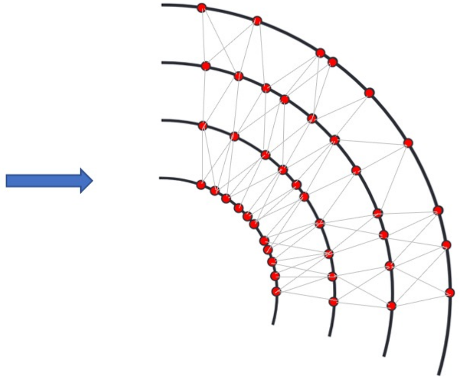
Physics Performance of the ATLAS GNN4ITk track reconstruction chain
[(link to talk)]

ITk = new inner tracker
ATLAS HL-LHC

Charged particles leave hits in the detector



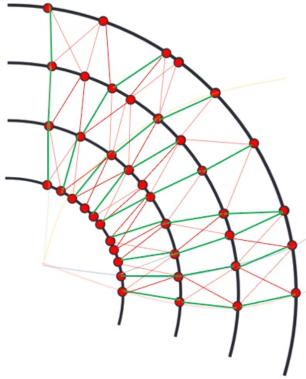
Represent the data using a graph



One node of the graph = one hit in the detector

Connect two nodes using an edge
if "it seems possible" that the two hits
are two (consecutive) hits on a track

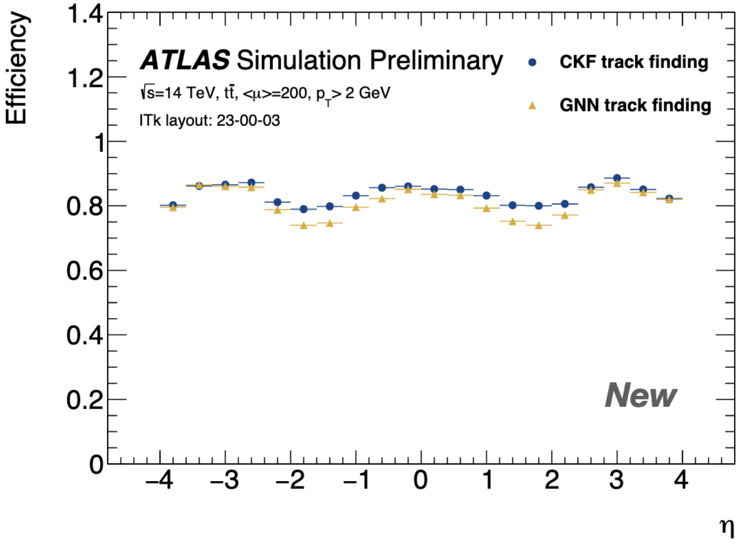
Goal:
classify the edges of the graph



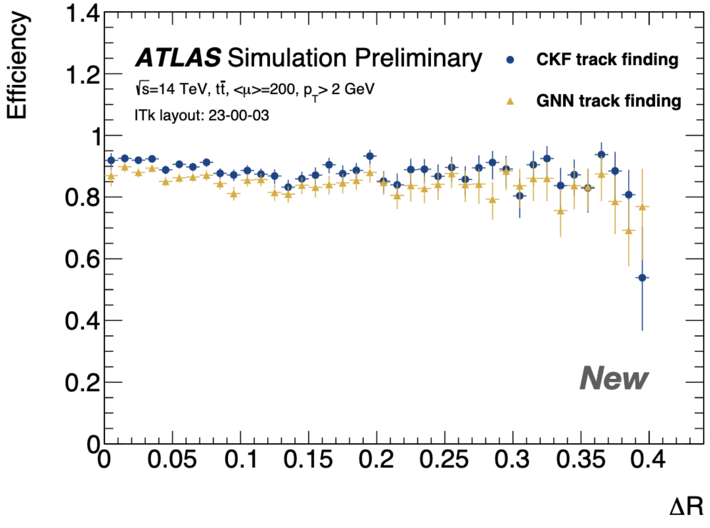
High classification score
=> **high probability** that the edge is part of a track

Low classification score
=> **low probability** that the edge is part of a track

Competitive physics performance



… including in dense environments (jets)



GNN can readily be run massively parallel on GPUs.

This is not obvious for classical algorithms (in particular the Kalman filter with Navigation in complex detector geometries).

GNN

GNN-based pipeline for track finding in the Velo at LHCb

Allen: current HLT1, classical algorithms on GPU

Ext4velo: ML algorithm (GNN-based) on GPU

3. Track-Finding Performance

Category	Metric	Allen	Etx4velo $d^2_{\max} = 0.010$ ($s_{\text{triplet}} > 0.32$)	Etx4velo $d^2_{\max} = 0.020$ ($s_{\text{triplet}} > 0.36$)
Long, no electrons ✓ In acceptance ✓ Reconstructible in the velo ✓ Reconstructible in the SciFi ✓ Not an electron	Efficiency	99.26%	99.28%	99.51%
	Clone rate	2.54%	0.96%	0.89%
	Hit efficiency	96.46%	98.73%	98.90%
	Hit Purity	99.78%	99.94%	99.94%
Long electrons ✓ In acceptance ✓ Reconstructible in the velo ✓ Reconstructible in the SciFi ✓ Electron	Efficiency	97.11%	98.80%	99.22%
	Clone rate	4,25%	7.42%	7.31%
	Hit efficiency	95.24%	96.54%	96.79%
	Hit purity	97.11%	98.46%	98.46%
Long, from strange ✓ In acceptance ✓ Reconstructible in the velo ✓ Decays from a strange *Good proxy for displaced tracks*	Efficiency	97.69%	97.50%	98.06%
	Clone rate	2.50%	0.92%	0.81%
	Hit efficiency	97.69%	98.22%	98.77%
	Hit purity	99.34%	99.68%	99.68%
X	Ghost rate	2.18%	0.76%	0.81%

- Evaluation with 5,000 events
- **Track matched to a particle** if at least 70% of its hits belong to this particle
- Allen algorithm described in arXiv:2207.03936v2
- 2 different GNN trainings for $d^2_{\max} = 0.010$ and $d^2_{\max} = 0.020$

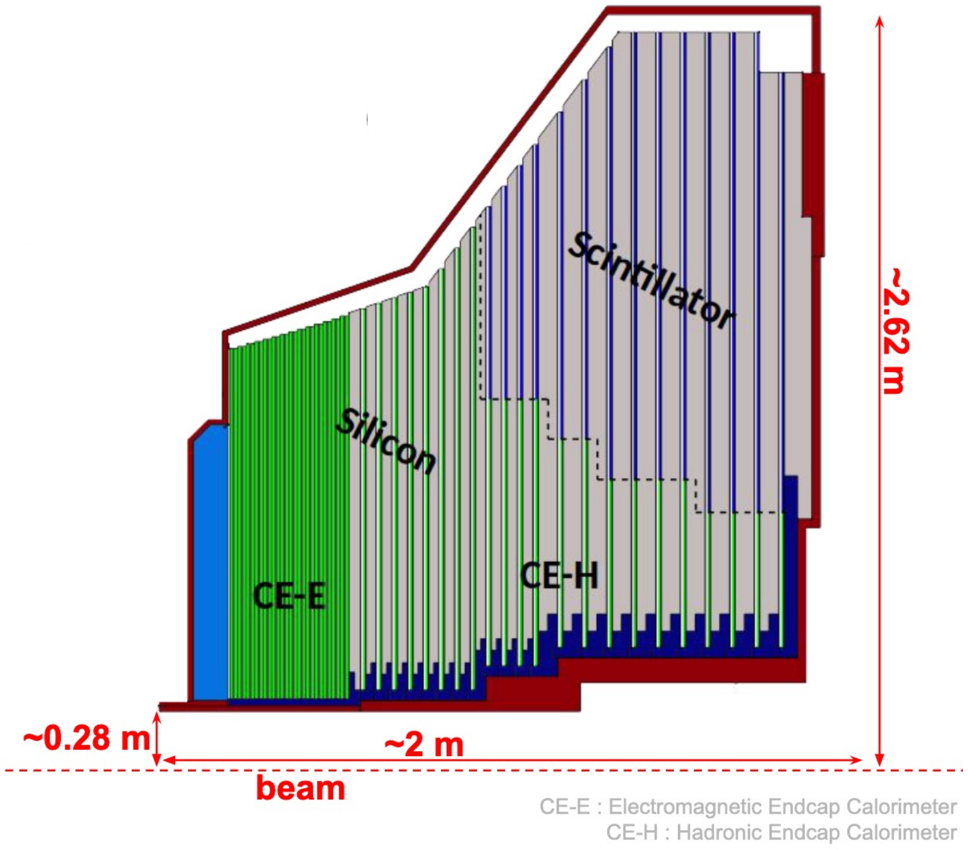
Long categories

Worse — Better

(link to talk)

Data from detectors other than trackers

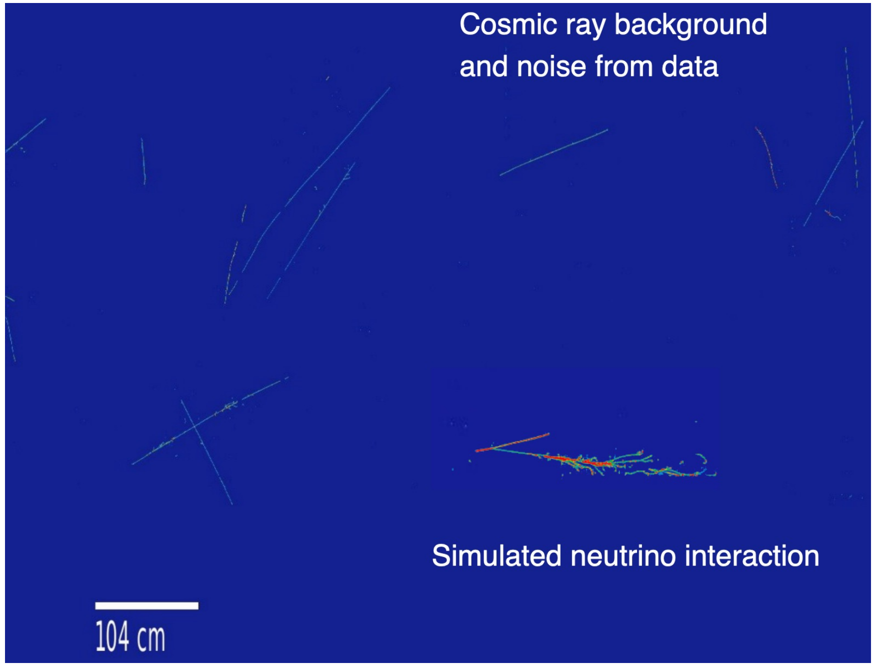
CMS at HL-LHC: HGCAL (high-granularity calorimeter)



k4Clue clustering algorithm (talk)

Kalman filter for muon reconstruction in HGCAL (talk)

Reconstruction in LArTPC detectors (link to talk)



- NuGraph2 is a multi-purpose GNN architecture for reconstructing neutrino interactions in LArTPC
  - Efficiently reject background detector hits.
  - Classify detector hits according to particle type.
  - Lightweight network, allowing fast inference on CPU and GPU.
  - Preliminary results for vertexing are promising.

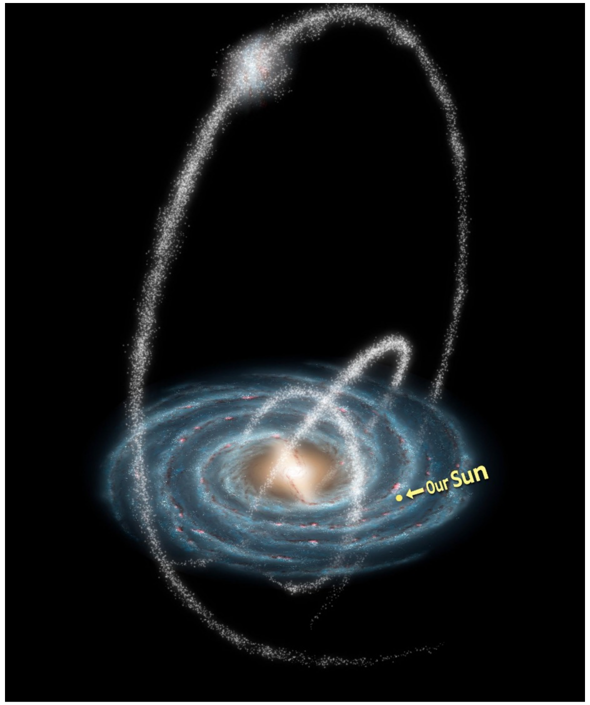
Data from detectors other than trackers

Application of HEP track reconstruction methods to Gaia data

(link to talk)

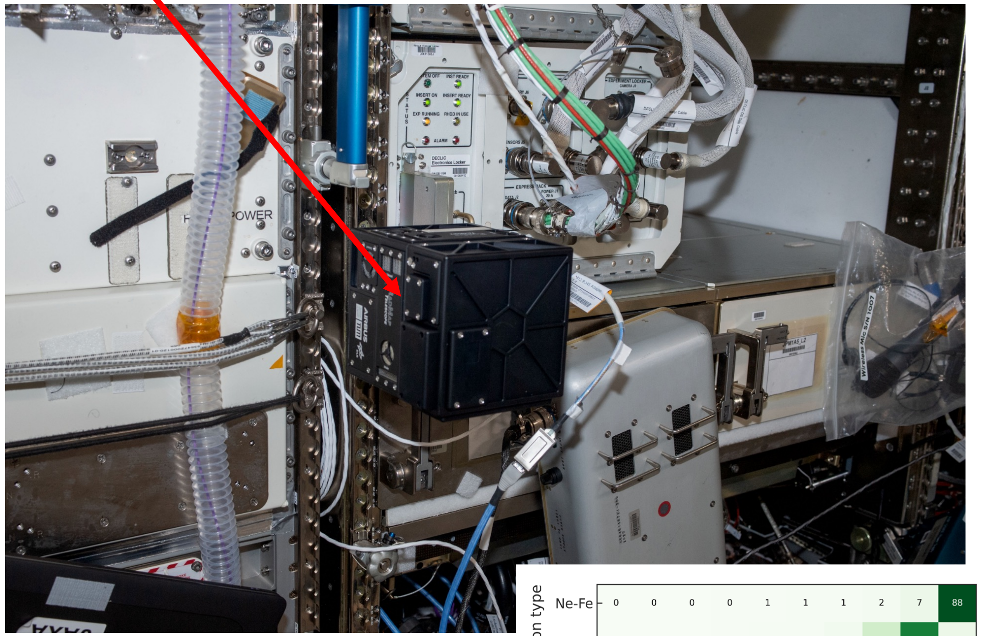
Galactic Structure and Stellar Streams

- Galaxies reside inside a dark matter (DM) halo
- DM halos play a major role in galaxy formation and evolution
- Different stellar populations provide insights into the DM distribution across our galaxy through their progenitors' merging histories.
- In particular, orbits of *stellar streams* show accretion patterns of new matter into our galaxy.



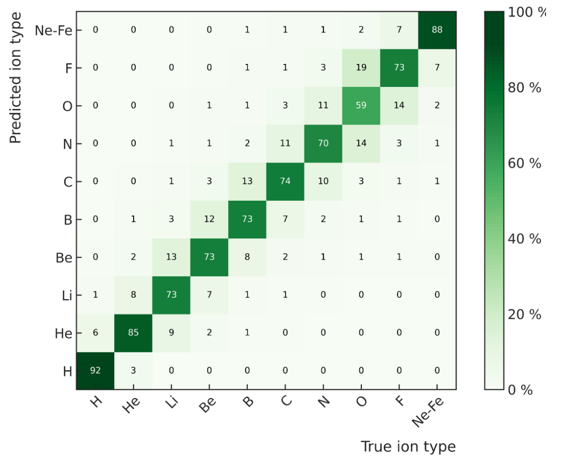
The RadMap Telescope onboard the International Space Station (1024 scintillating plastic fibres)

(link to talk)



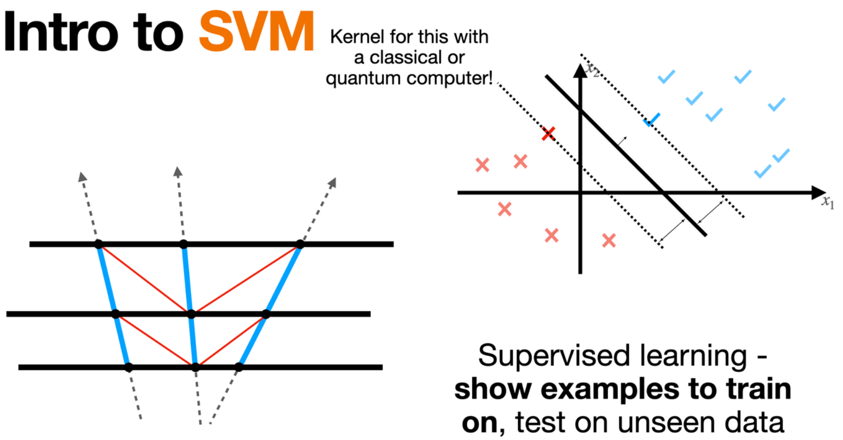
Identify different isotopes in the space radiation

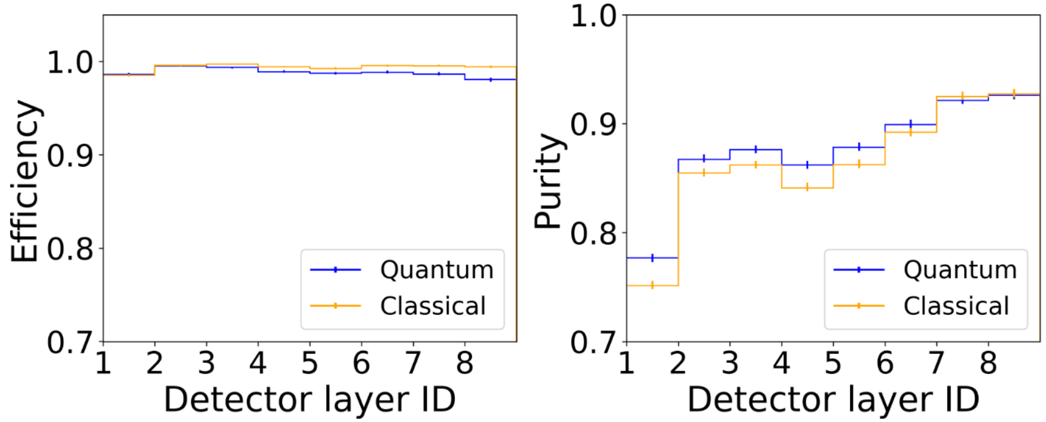
NN-based event reconstruction



“Blue sky”

Reconstructing charged particle track segments with a quantum-enhanced support vector machine (SVP) ([link to talk](#))





NOTE: All results shown here are obtained on a *classical computer pretending to be a quantum computer*

Object condensation (GNN, non-quantum)
- for track reconstruction at the HL-LHC (two talks: [link](#) and [link](#))
- for end-to-end reconstruction in highly granular calorimeters (talk: [link](#))

Application of Quantum Annealing with Graph Neural Network preselection in Particle Tracking at LHC ([link to talk](#))

Co-located mini-workshop on real-time tracking (on “triggering using tracks”)

09:00	**Directions in Realtime Tracking : Everything, Everywhere, All at Once**	*Kristian Hahn*	*Auditorium, Le Village*	09:00 - 09:30
	Level-1 Tracking at CMS for the HL-LHC	*Sara Fiorendi*	*Auditorium, Le Village*	09:30 - 09:52
10:00	**Standalone track reconstruction and matching algorithms for the GPU-based High Level Trigger at LHCb**	*Louis Henry*	*Auditorium, Le Village*	09:52 - 10:14
	FPGA-based architecture for a real-time track reconstruction in the LHCb Scintillating Fibre Tracker beyond Run 3	*Michael J. Morello*		
	Coffee		*Place du village, Le Village*	10:40 - 11:10
11:00	**A real-time demonstrator of track reconstruction with FPGAs at LHCb**	*Francesco Terzuoli*	*Auditorium, Le Village*	11:10 - 11:32
	Trigger Level Tracking With Neural Networks on Heterogeneous Computing Systems	*Alex Gekow*	*Auditorium, Le Village*	11:32 - 11:54
12:00	**Track reconstruction for the ATLAS Phase-II High-Level Trigger using Graph Neural Networks on FPGAs**	*Sachin Gupta*	*Auditorium, Le Village*	11:54 - 12:16
	Studies on track finding algorithms based on machine learning with GPU and FPGA	*Francesco Armando Di Bello*	*Auditorium, Le Village*	12:16 - 12:38
13:00	**Lunch**		*Place du village, Le Village*	12:40 - 13:40

From the (excellent) introductory talk (link):

- **Everything** : Displaced/non-standard tracking, 4D tracking, extended track features
- **Everywhere** : expanding coverage, higher granularity
  - Also, wider application of RT tracking in HEP ...
- **All at once** : pixel in hardware tracking, more intelligence in the front ends, broader movement toward the triggerless model,

Conclusions/observations

- Workshop format, no parallel sessions

- Excellent mix of material from running experiments, R&D and "blue sky" studies

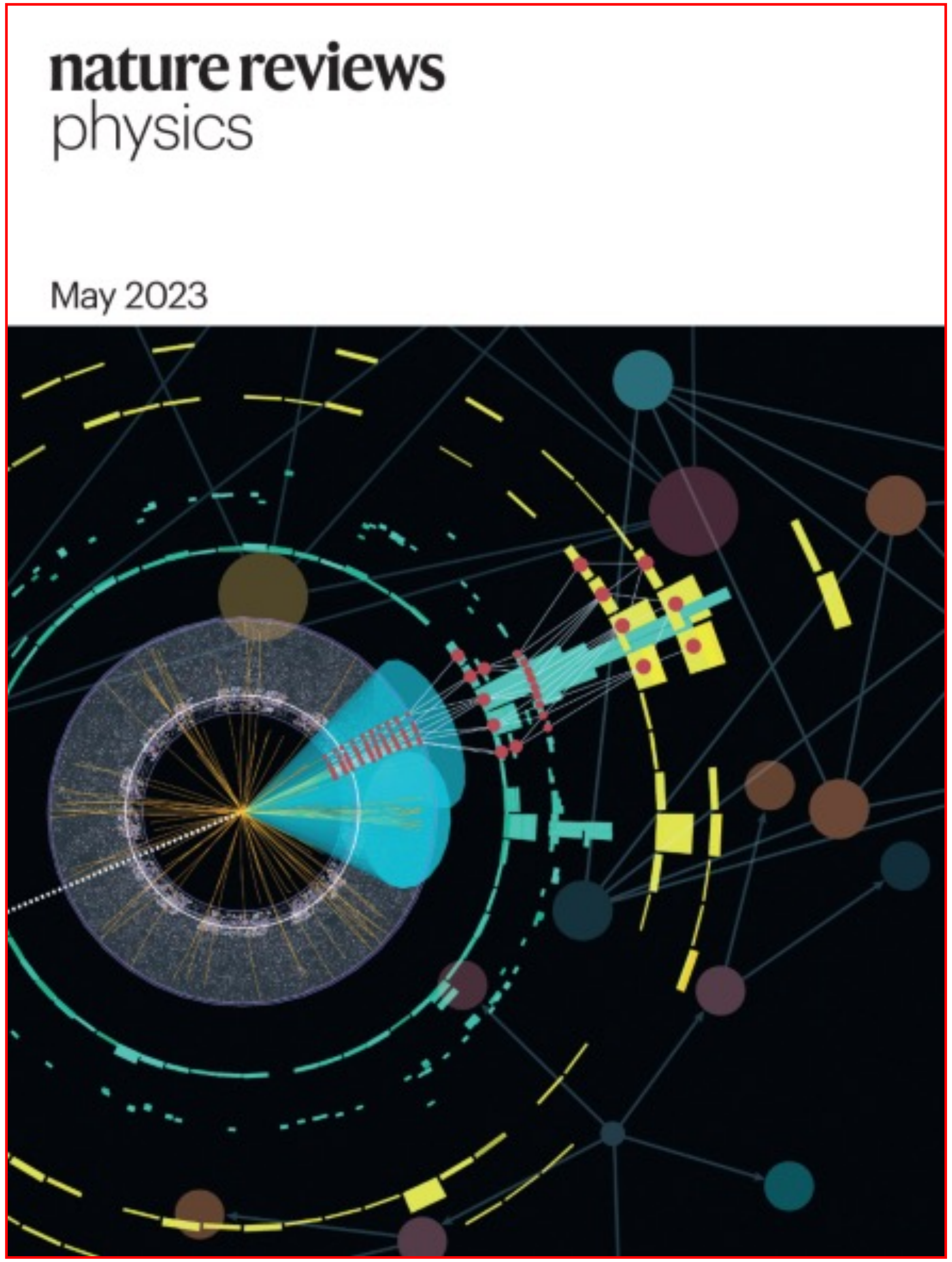
- Lots of new material released just in time for the workshop

- This was a lively workshop. Discussions all the time (sessions, breaks, social events, …)

- Very young audience.

A big "thank you" to all participants.

Additional material



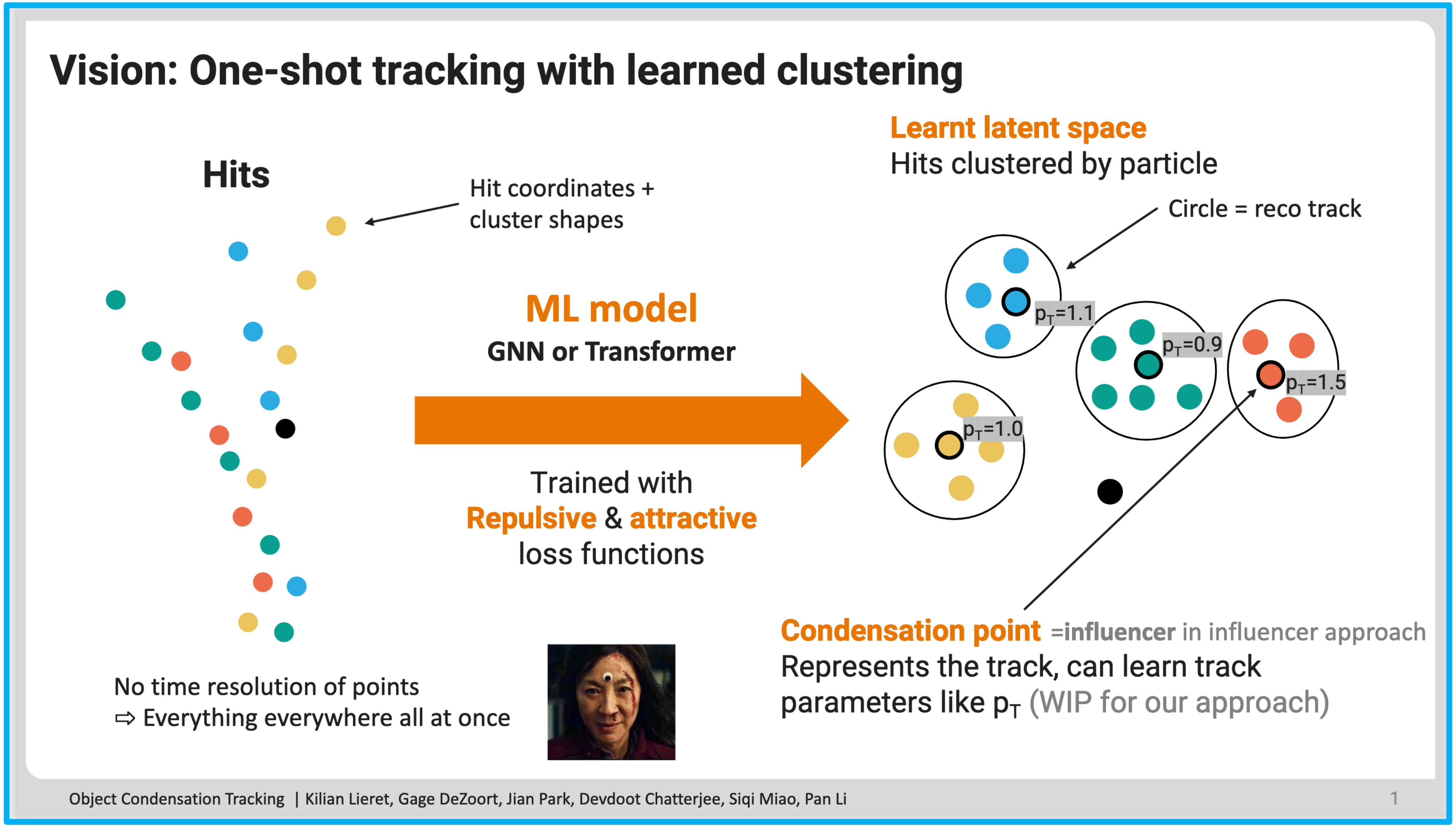
Graph neural networks at the Large Hadron Collider

Gage DeZoort, Peter W. Battaglia, Catherine Biscarat & Jean-Roch Vlimant

Nature Reviews Physics **5**, 281–303 (2023) | Cite this article

(clickable link)

Object condensation tracking

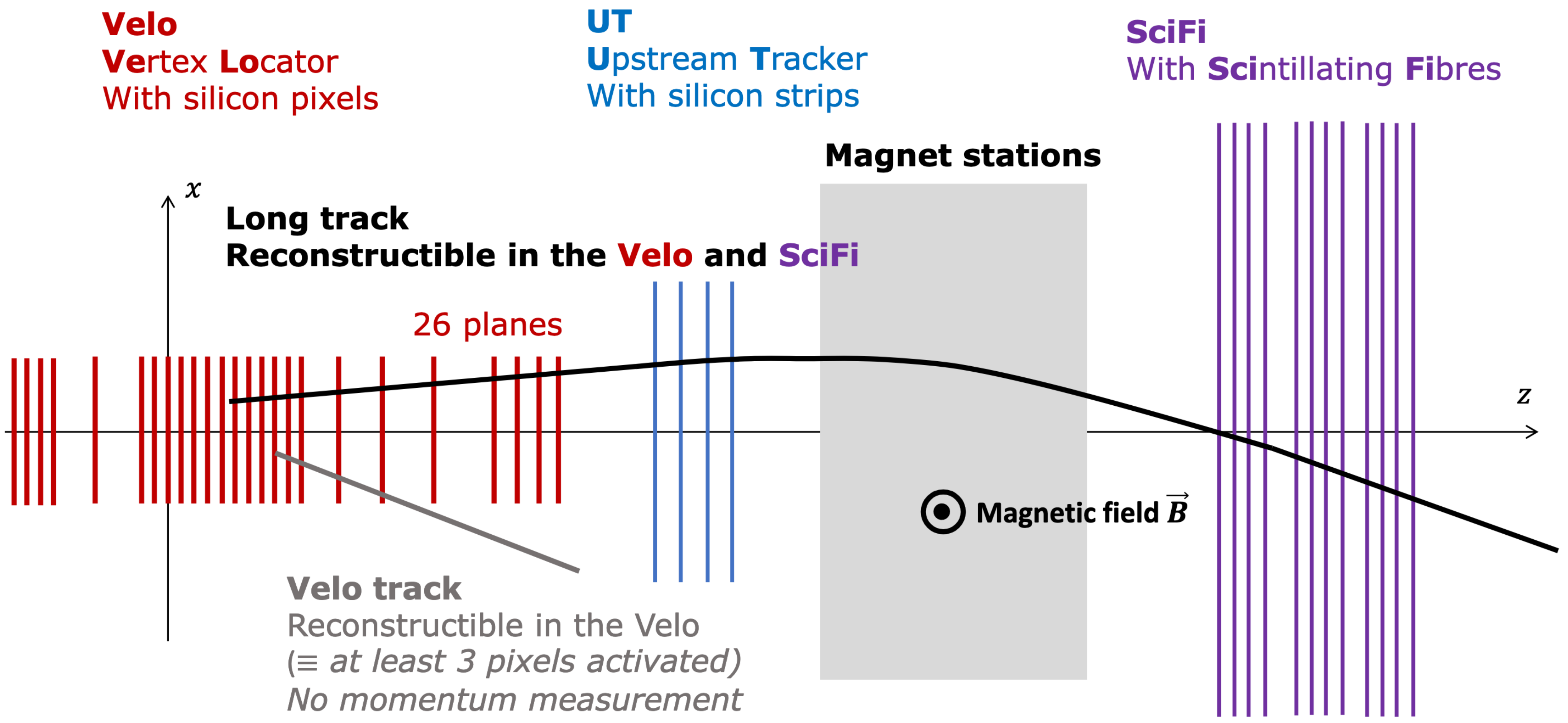


[(link to talk)]

LHCb Detector in Run 3

7

Tracks



(link to talk)

Research topics at L2IT

Development of new methods
for simulation and data analysis

What is the shape of the
Higgs potential ?
→ its origin
→ its role during the first instants
of the Universe
(electroweak baryogenesis ?,
emission of gravitational waves ?)

How do gravitational waves
propagate in the Universe ?
→ information on the nature of
dark energy ?
→ modified gravitation ?

How does nuclear matter
behave under extreme conditions
(density, pressure) ?
→ compact stars
→ impact on the emission of
gravitational waves and
neutrinos

Research topics at L2IT

new methods
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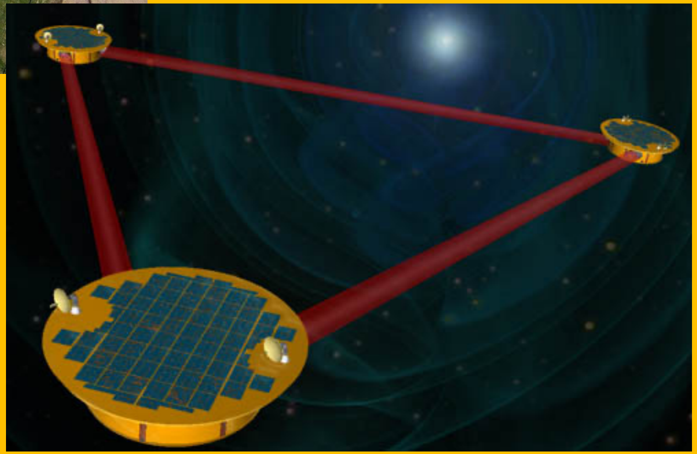
Virgo detector



Future
LISA mission
(3 satellites)

Research topics at L2IT

What is the shape of the Higgs potential ?
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(density, p
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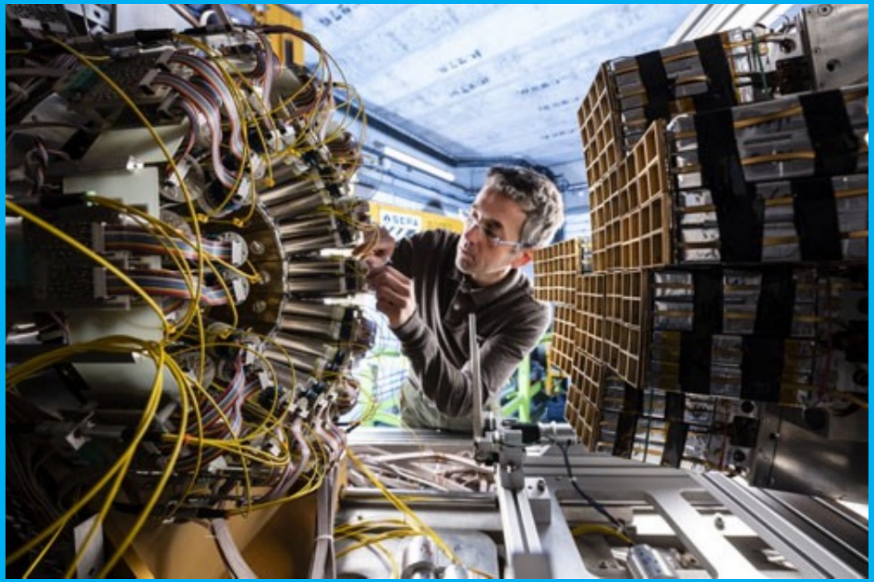
Nuclear physics



INDRA-FAZIA experiment at
Grand Accélérateur National d'Ions Lourds
(GANIL, Caen)

Research topics at L2IT

What is the shape of th
Higgs potential ?
→ its origin
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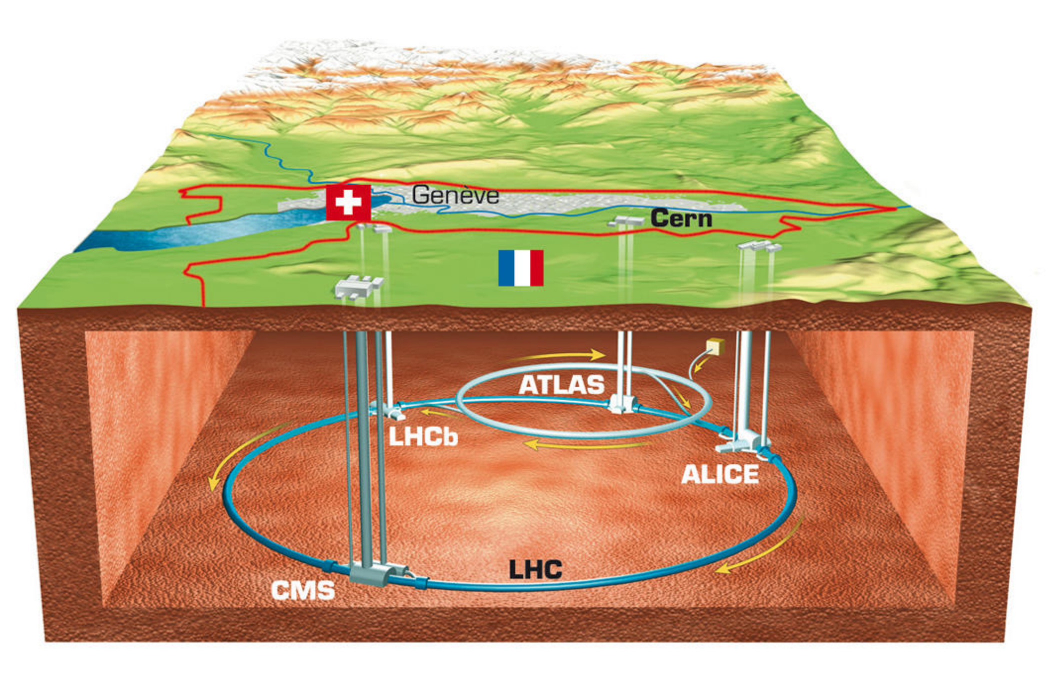
emission of gravitationa

Physique des particules



ATLAS experiment at CERN

gravitational waves and
neutrinos

Research topics at L2IT

Defining feature:
Focus on novel analysis methods

Modelling, simulation and modern analysis techniques are the main focus of L2IT.

We are developing these innovative aspects of research in the fields of nuclear and particle physics and cosmology, in close collaboration with experts from Toulouse's ecosystem of research in computing, artificial intelligence, physics, astronomy and astrophysics.

→ impact on the emission of gravitational waves and neutrinos