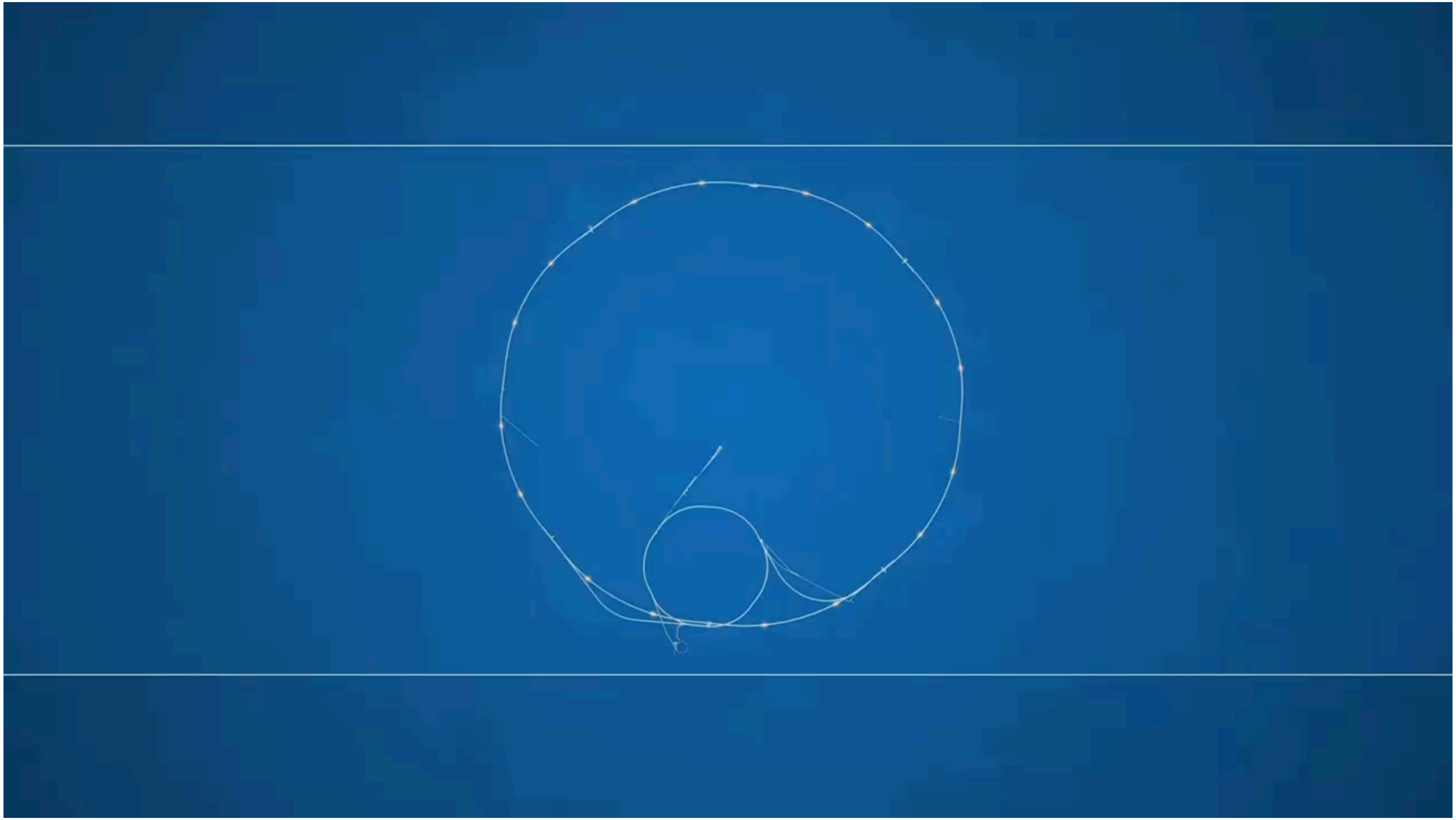
UNIVERSITY OF SUSSEX

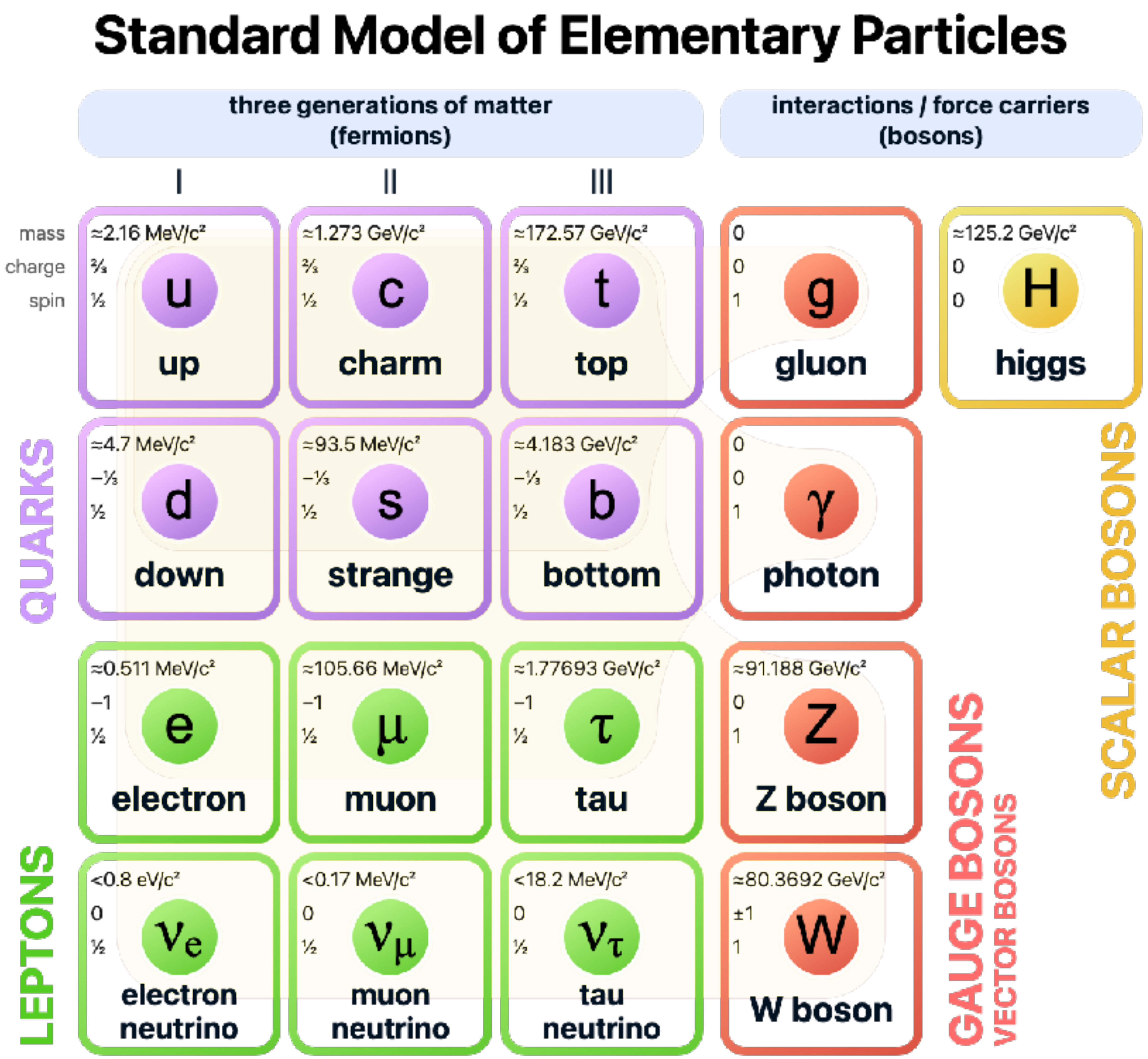
Machine Learning for Collider Particle Physics

Dr. Tom Stevenson
University of Sussex, UK
Online Machine Learning Workshop
ICTP Physics Without Frontiers - Afghanistan
1 October 2025

Introduction



What we are looking for?



- Trying to answer some key questions:
  - What are the fundamental **particles** that make up the universe?
  - What are the fundamental **forces** of the Universe?
  - Can we put together a coherent **theory** to describe how matter and energy work?

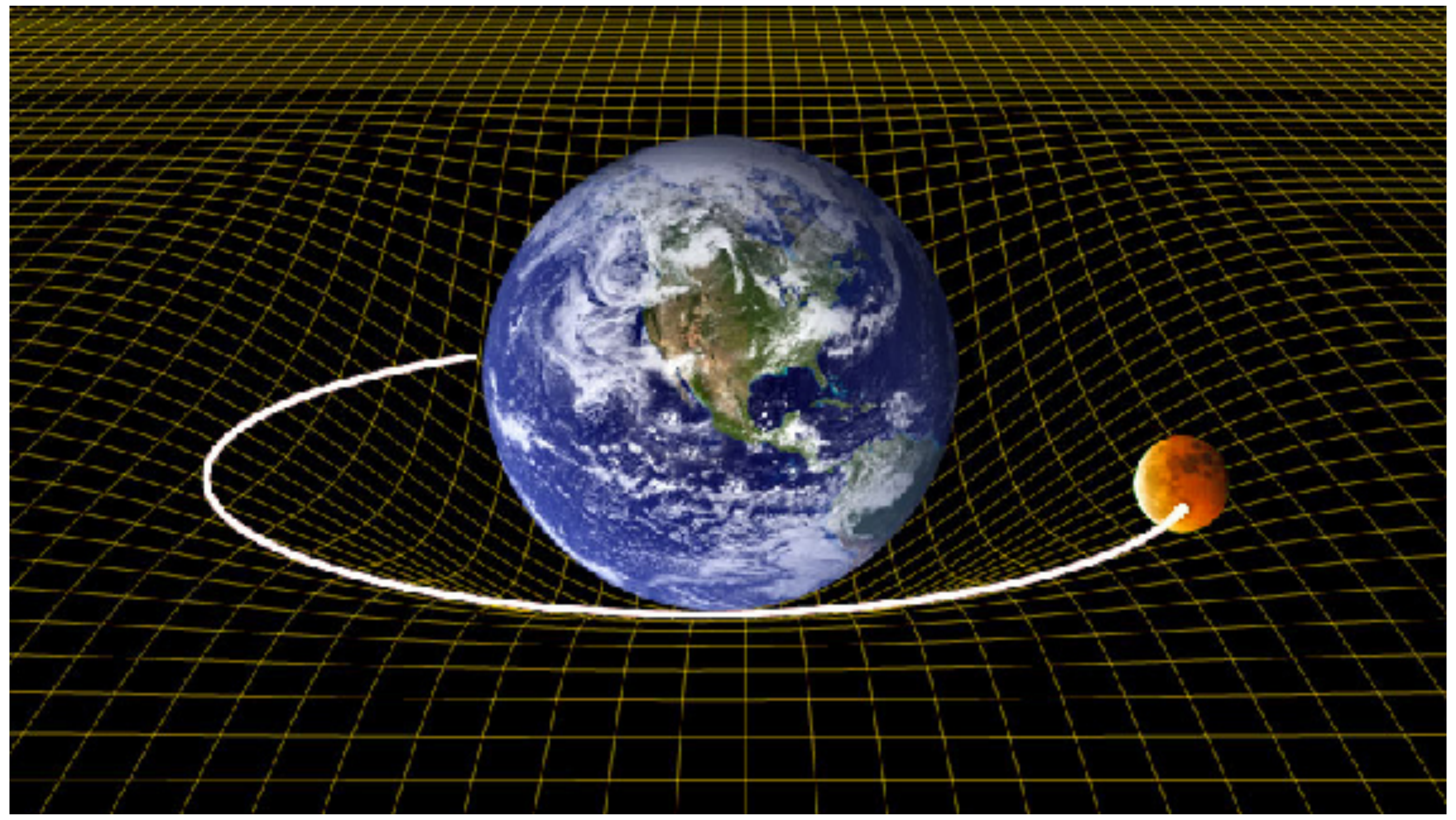
What we are looking for?

- **Particles** interact with each other via fundamental forces mediated by **Gauge Bosons**
- Each fundamental force has a **Quantum Field Theory** that precisely describes which particles can interact via the force, mediated by a gauge boson, and how
- For example electrons can interact via the electromagnetic Force which is mediated by a photon, and described by Quantum Electrodynamics
- Allows us to make simulations to predict what we expect to see

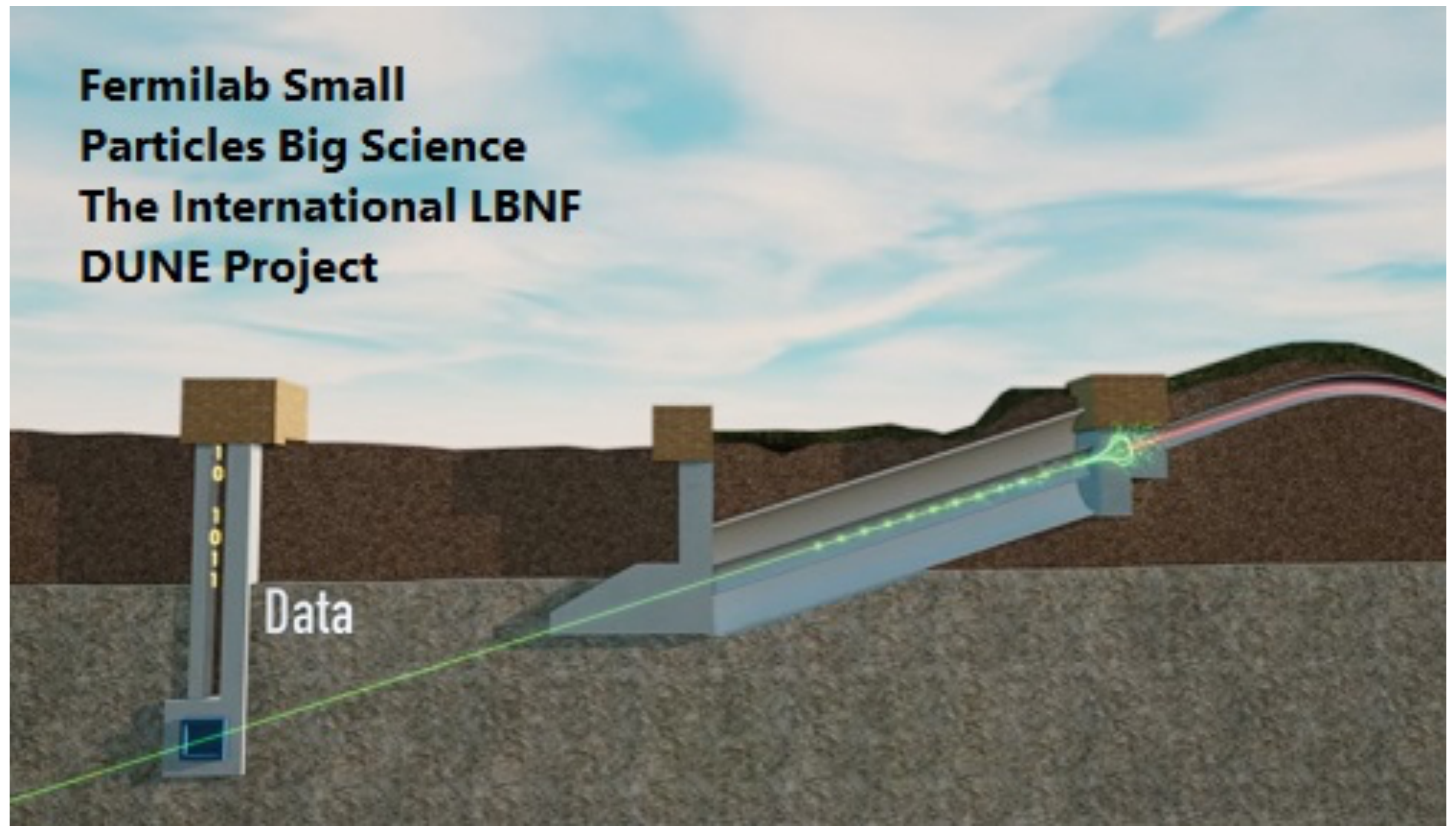
$$
\begin{gathered}
\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \\
\beta_h \left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M (H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-) - \\
\frac{1}{8}g^2\alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2) - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
\frac{1}{2}ig (W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)) + \\
\frac{1}{2}g (W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)) + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\frac{1}{4}g^2W^+_\mu W^-_\mu(H^2 + (\phi^0)^2 + 2\phi^+\phi^-) - \frac{1}{8}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu(H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-) - \\
\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \frac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m_\nu^\lambda)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)) + \\
\frac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2-1-\gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2+\gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt{2}}W^+_\mu((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)) + \\
\frac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\frac{ig}{2M\sqrt{2}}\phi^+(-m_e^\kappa(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m_\nu^\lambda(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa) + \\
\frac{ig}{2M\sqrt{2}}\phi^-\left(m_e^\lambda(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m_\nu^\kappa(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \frac{g}{2}\frac{m_\nu^\lambda}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\frac{g}{2}\frac{m_e^\lambda}{M}H(\bar{e}^\lambda e^\lambda) + \frac{ig}{2}\frac{m_\nu^\lambda}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m_e^\lambda}{M}\phi^0(\bar{e}^\lambda\gamma^5e^\lambda) - \frac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\frac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}}\phi^+(-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j) + \\
\frac{ig}{2M\sqrt{2}}\phi^-\left(m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \\
\frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{G}^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar{G}^aG^bg^c_\mu + \\
\bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2-\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \\
\partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \\
\partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H\right) + \frac{1-2c_w^2}{2c_w}igM(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-) + \\
\frac{1}{2c_w}igM(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-) + igMs_w(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-) + \\
\frac{1}{2}igM(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0) .
\end{gathered}
$$

Some of the unanswered questions…

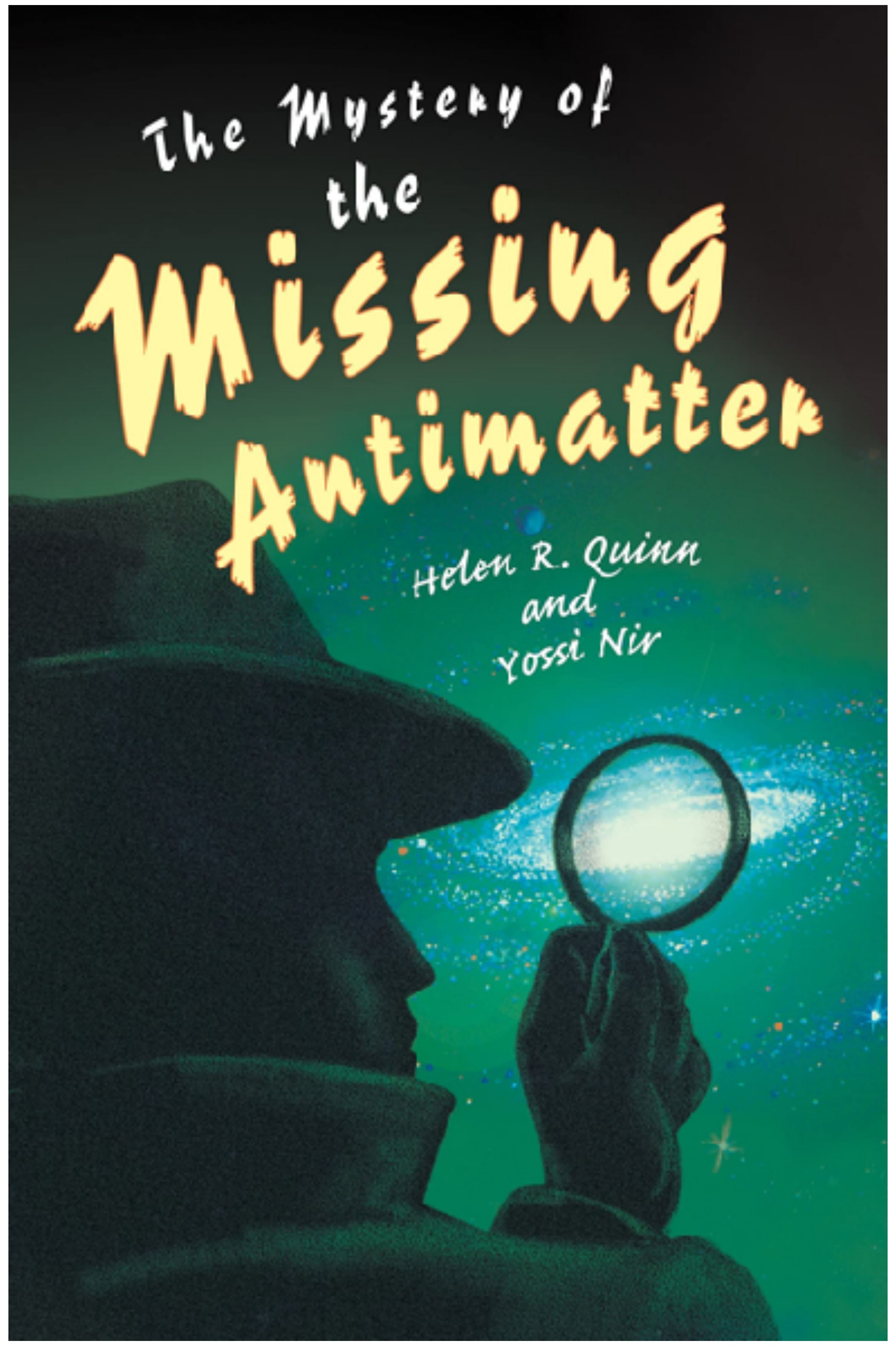
UNIVERSITY OF SUSSEX



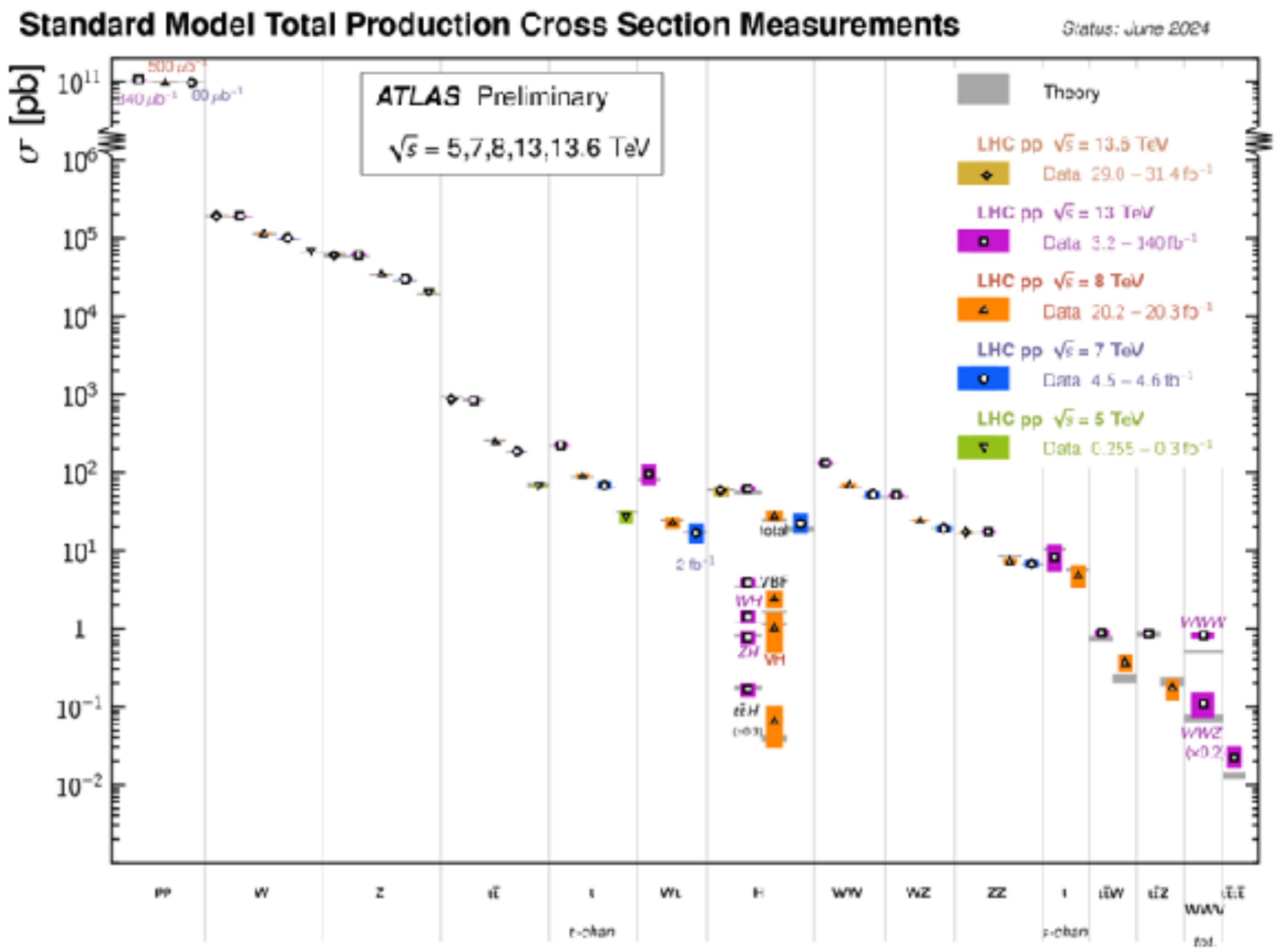
How does gravity fit in?
And where is the graviton?



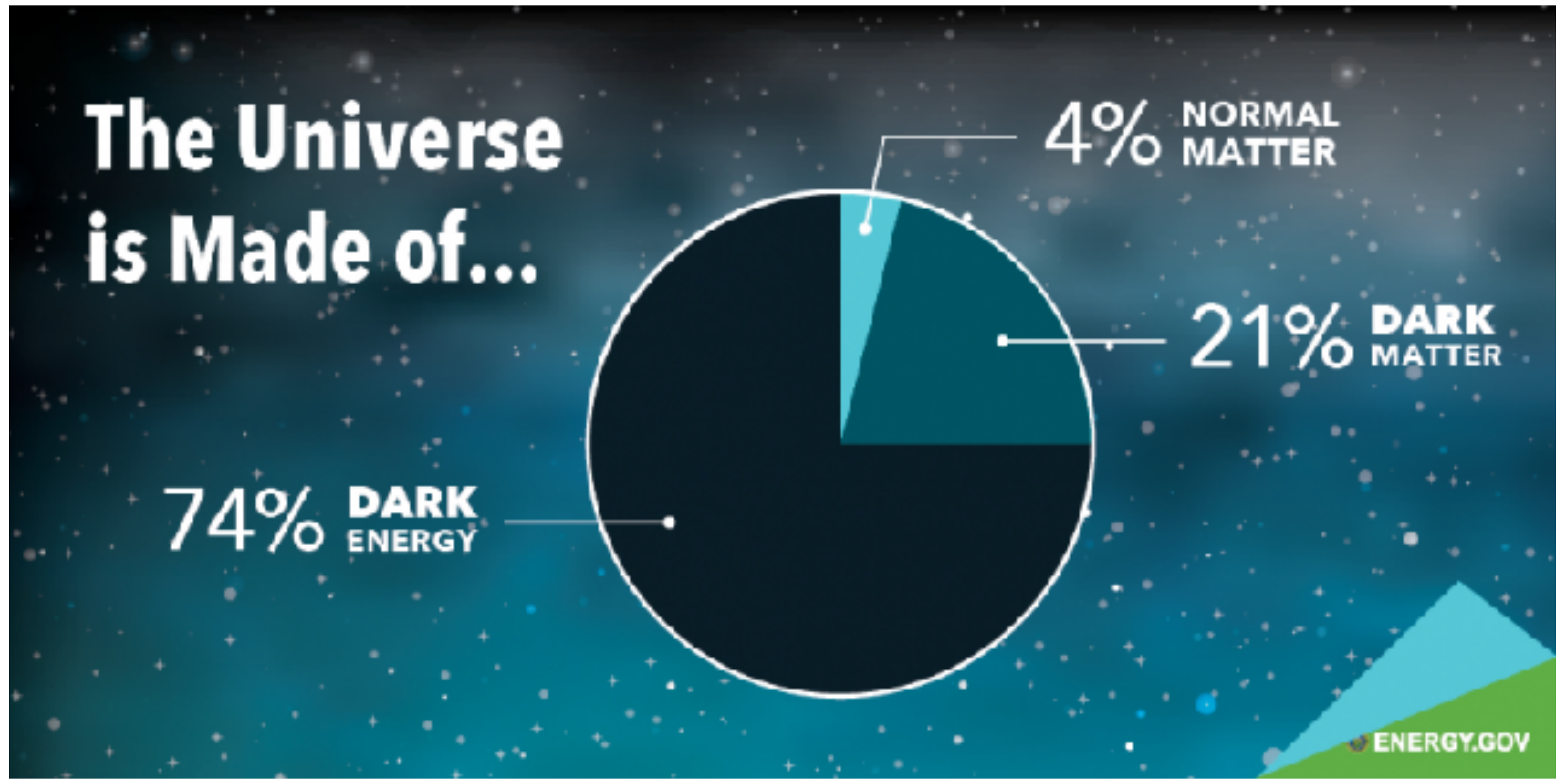
Neutrinos oscillate between flavours
and therefore have mass.
Not predicted by the Standard Model?!



Why is there such a large matter antimatter asymmetry in the universe?

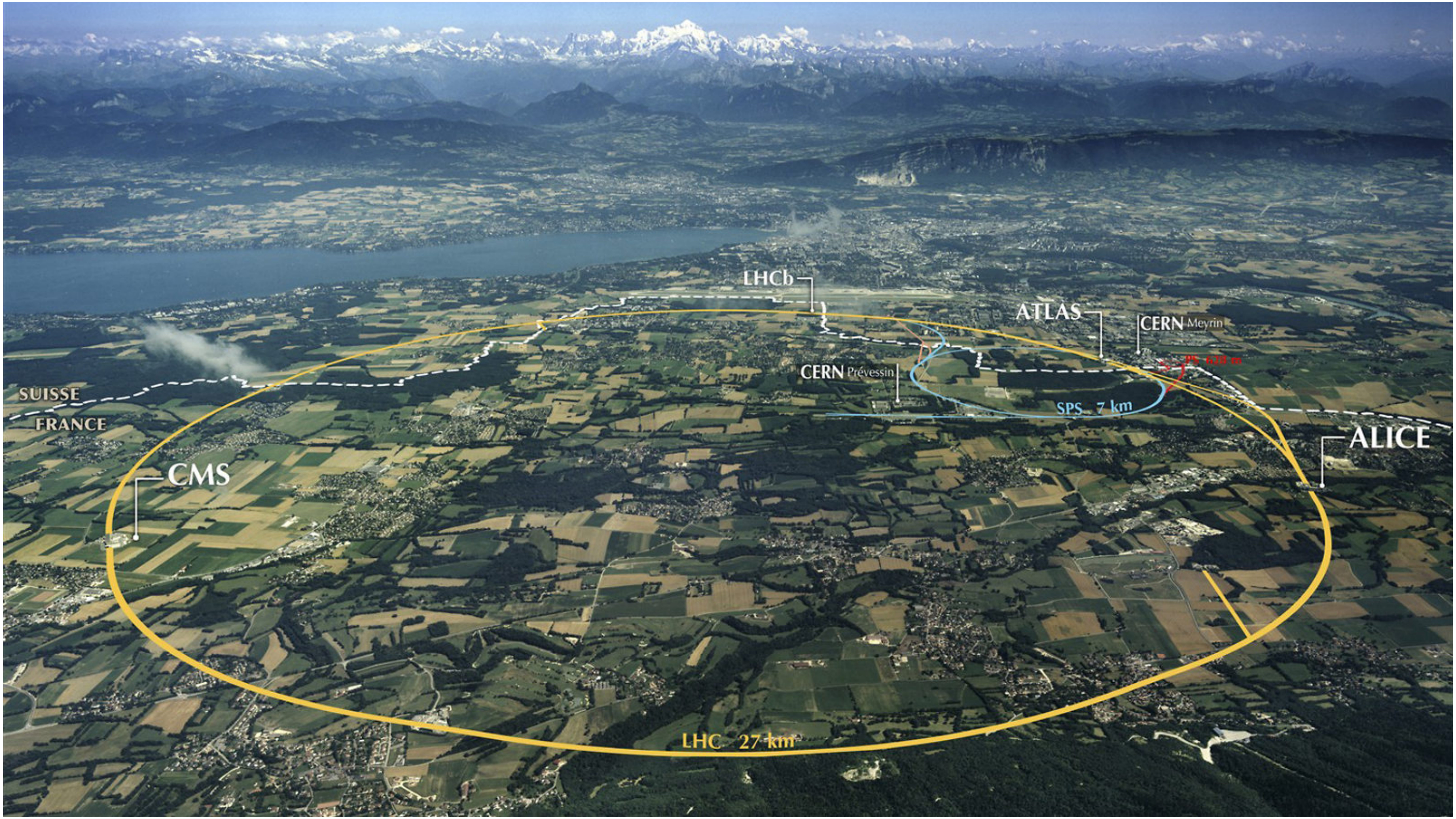


Are there any other particles beyond the Standard Model?
SUSY? More Higgs bosons?



What is dark matter and dark energy?
Weakly interacting massive particles?

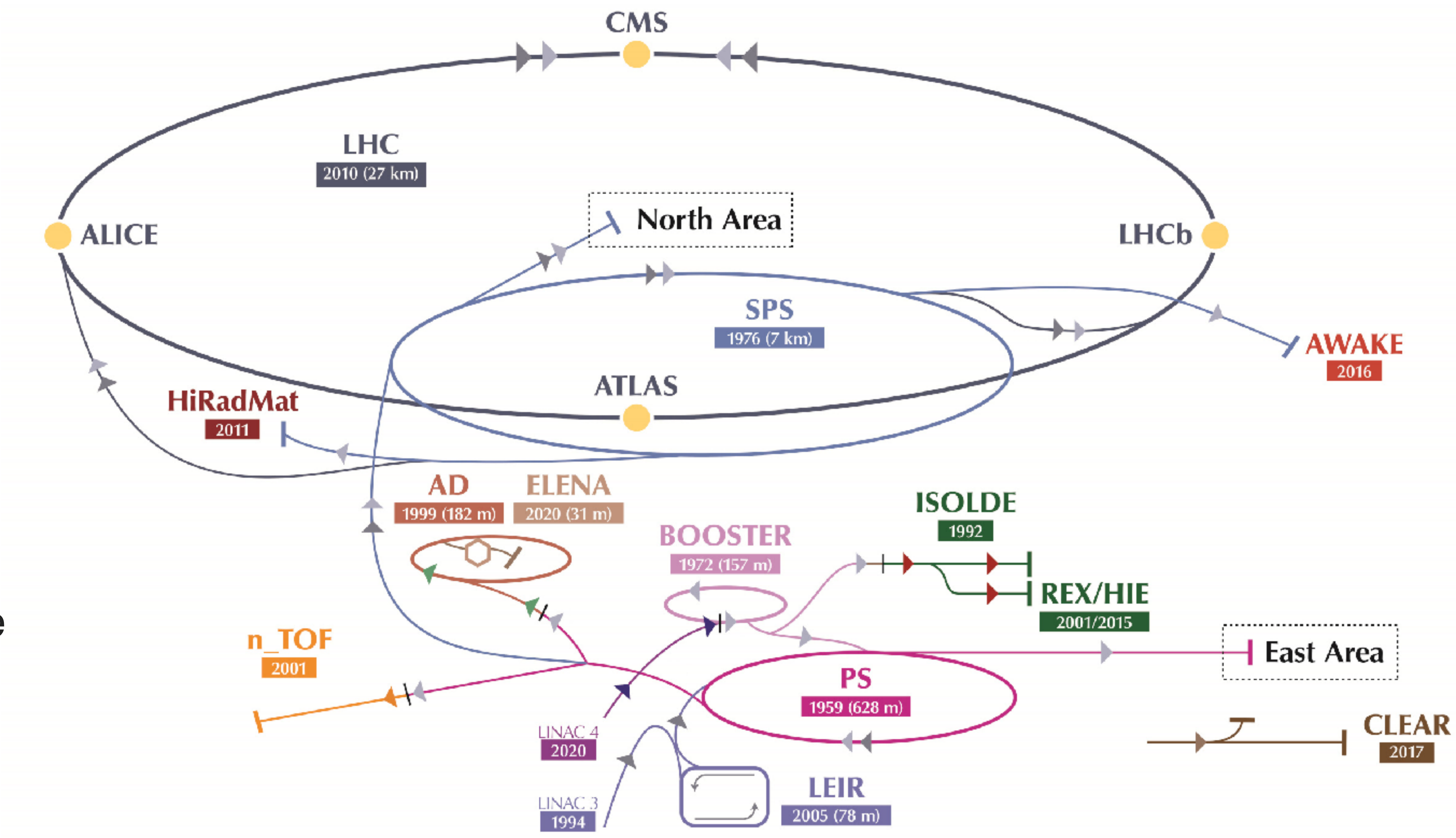
LHC and CERN



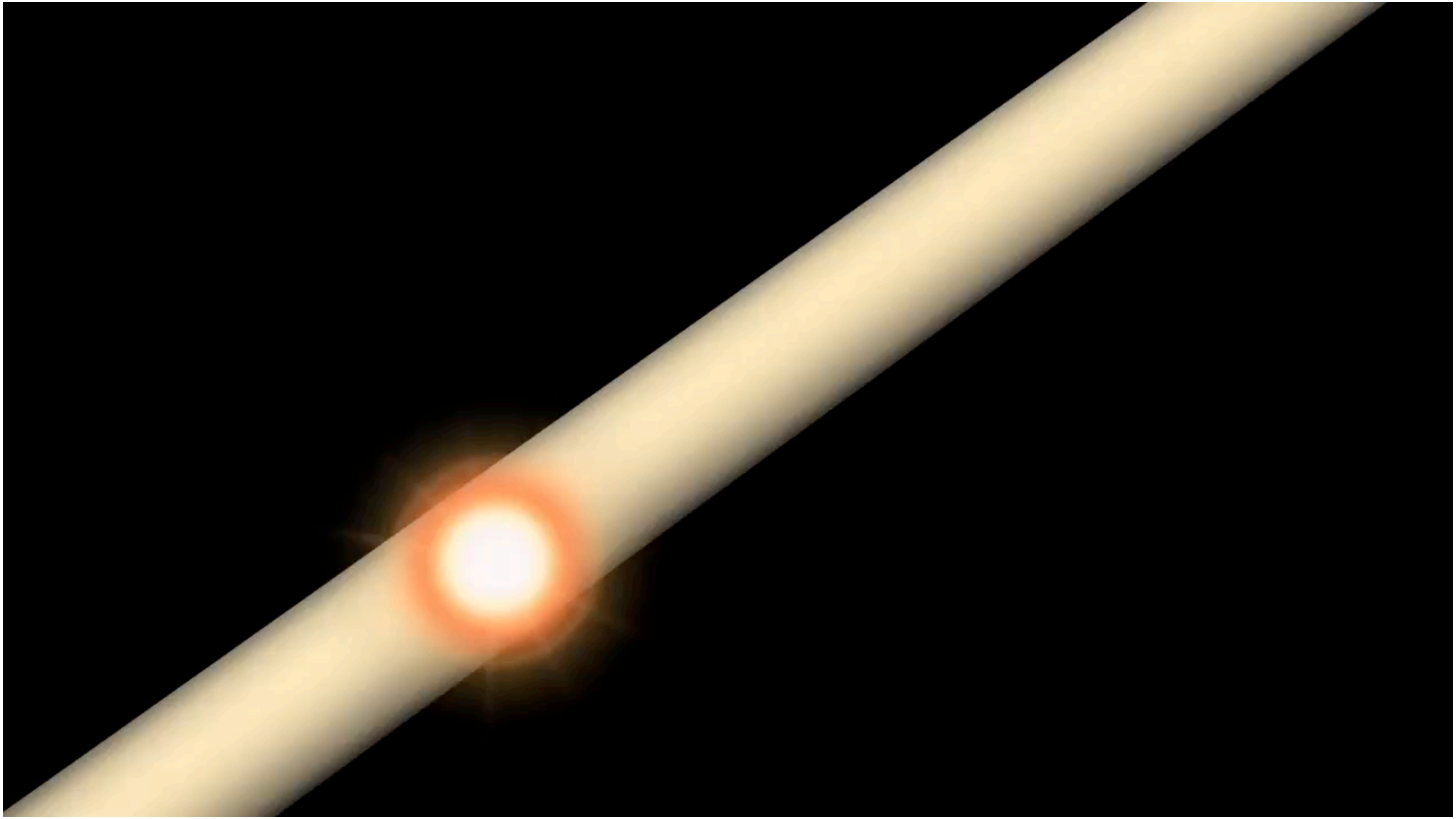
LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

Large Hadron Collider

- LHC is the final and largest stage in a complex of particle accelerators
- Accelerates protons to almost the speed of light before smashing them millions of times a second inside 4 big "general purpose" detectors!
- Lots of smaller experiments on each of the accelerator rings also studying specific physics analyses and applications



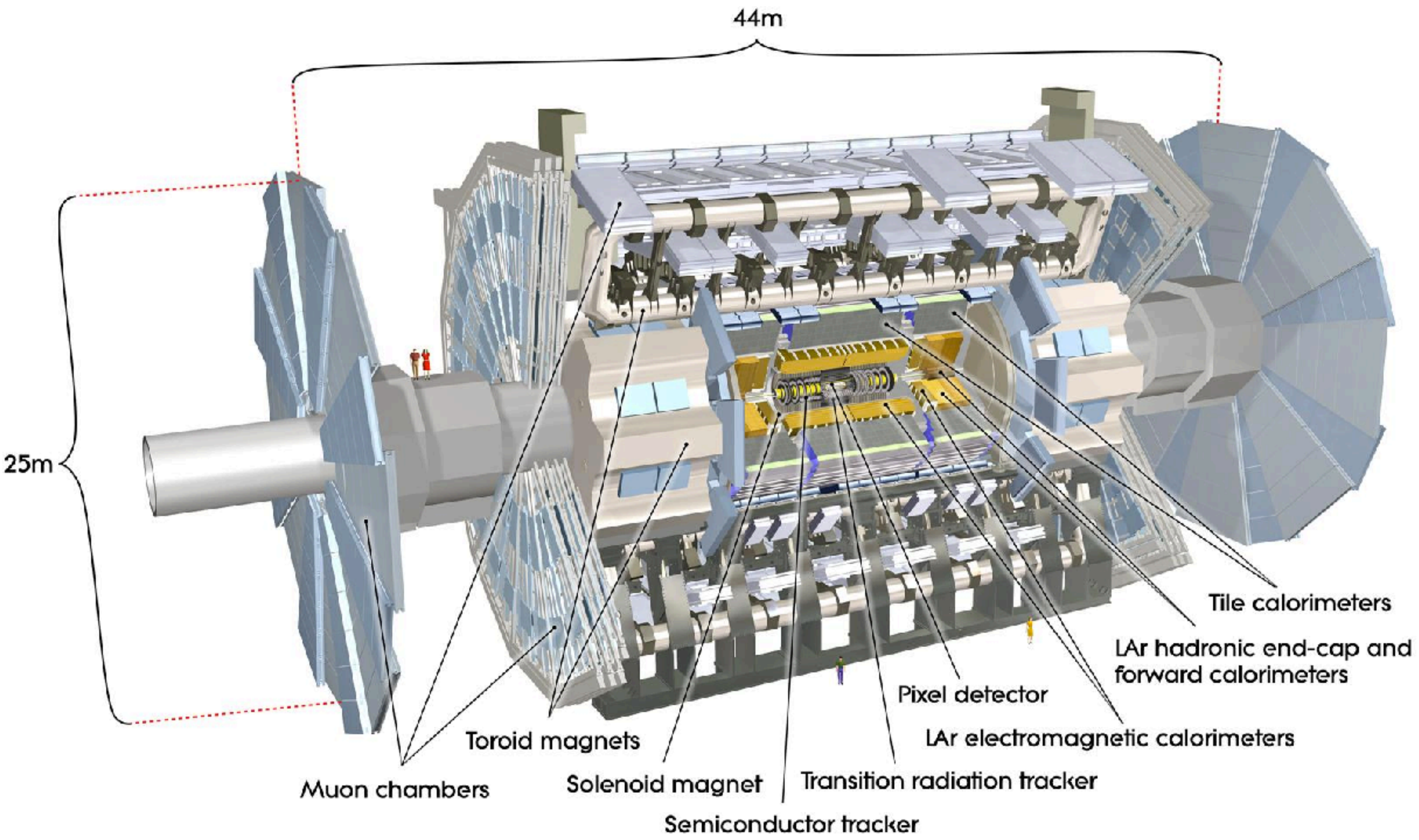
Large Hadron Collider



ATLAS Collaboration

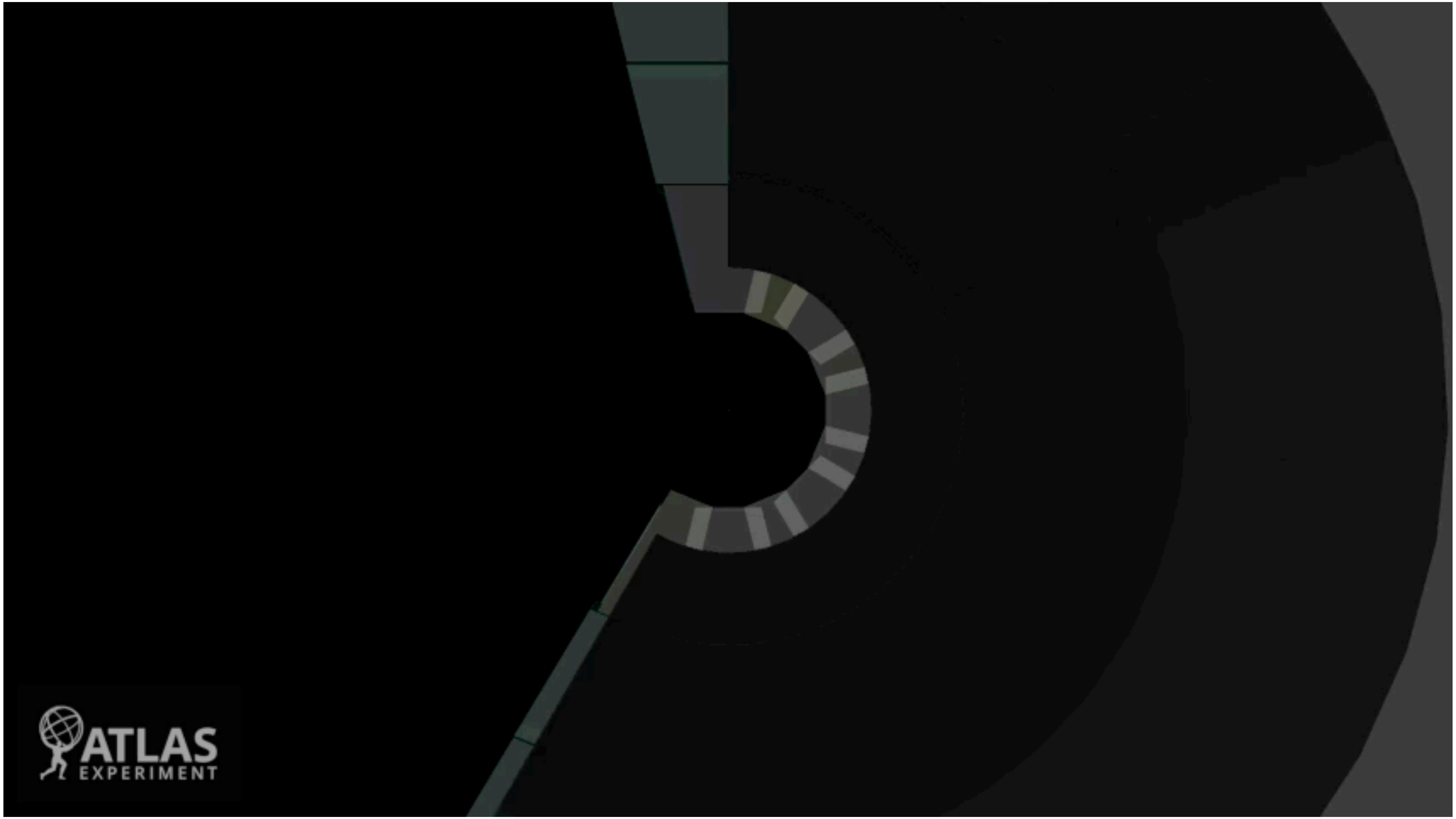
- One of the largest collaborative efforts ever attempted in science
- About 3000 scientific authors
- 170+ institutions from 40 countries
- Around 1200 doctoral students are involved in detector development, data collection and analysis
- The collaboration depends on the efforts of countless engineers, technicians and administrative staff.

ATLAS Experiment

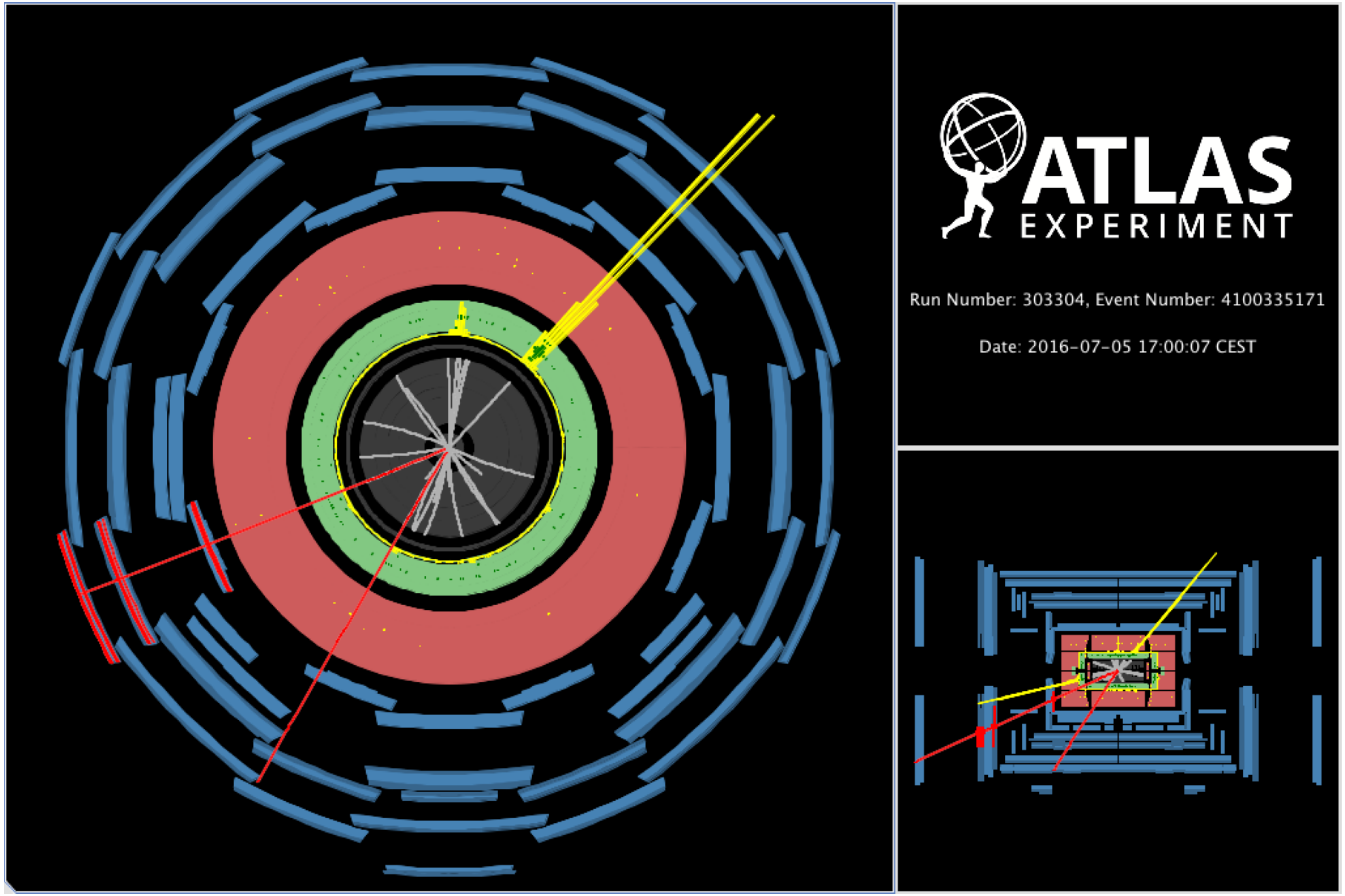


- Largest volume detector ever constructed
- 44m long
- 25m in diameter
- 100m below ground
- Weighs 7,000 tonnes similar to the Eiffel Tower

Particle Collisions in a Particle Detector

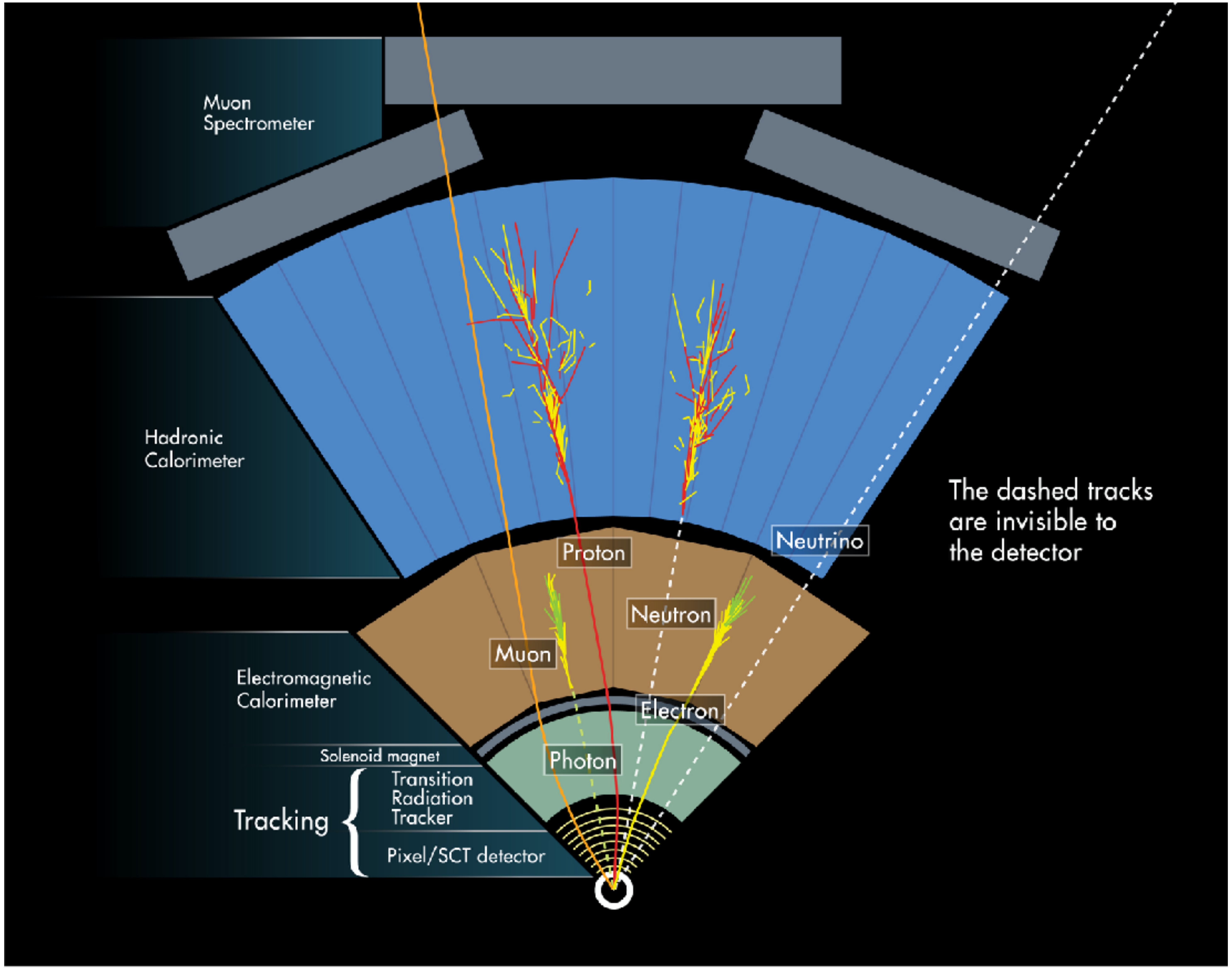


Physics Events



Physics Events

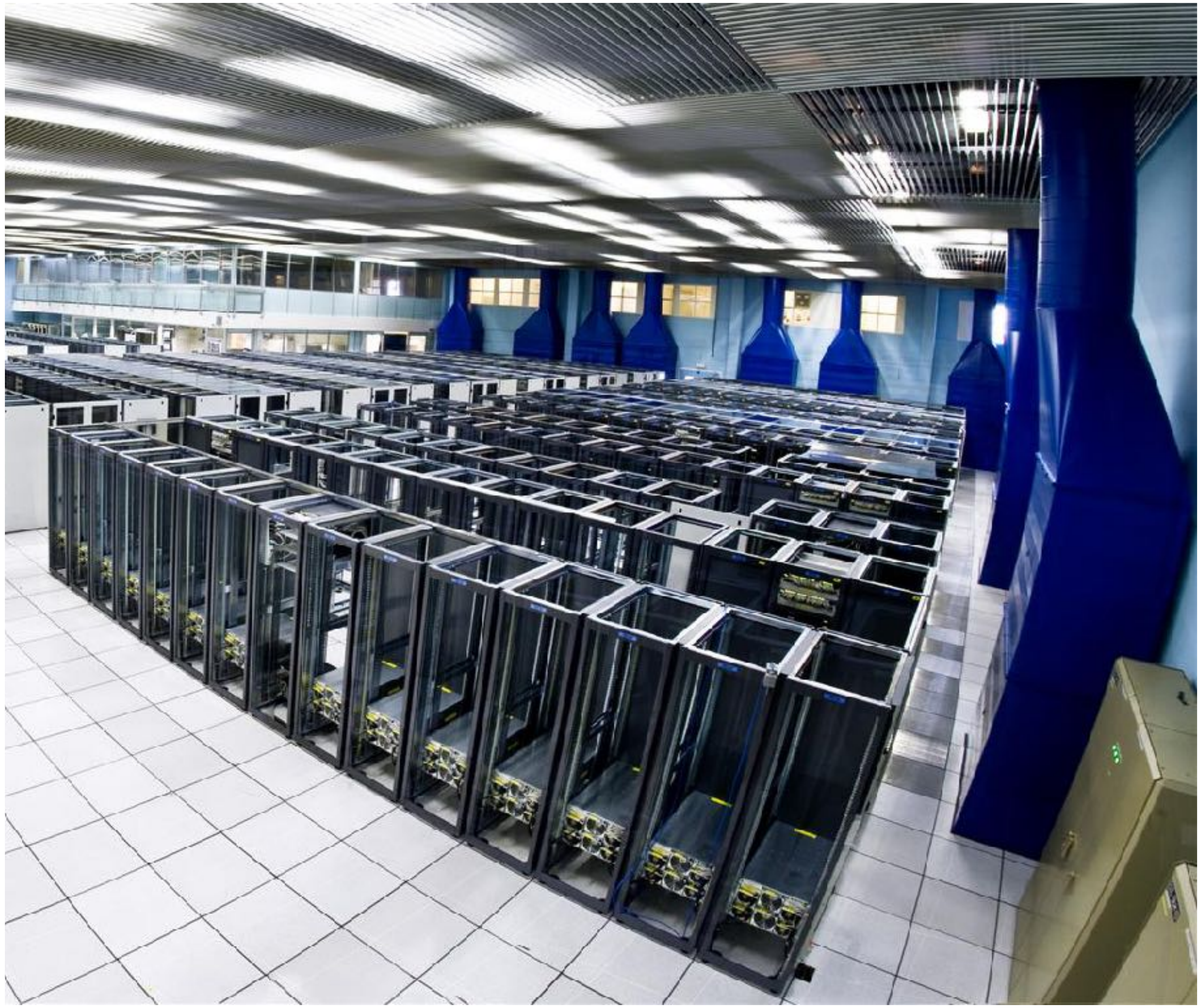
Physics Events



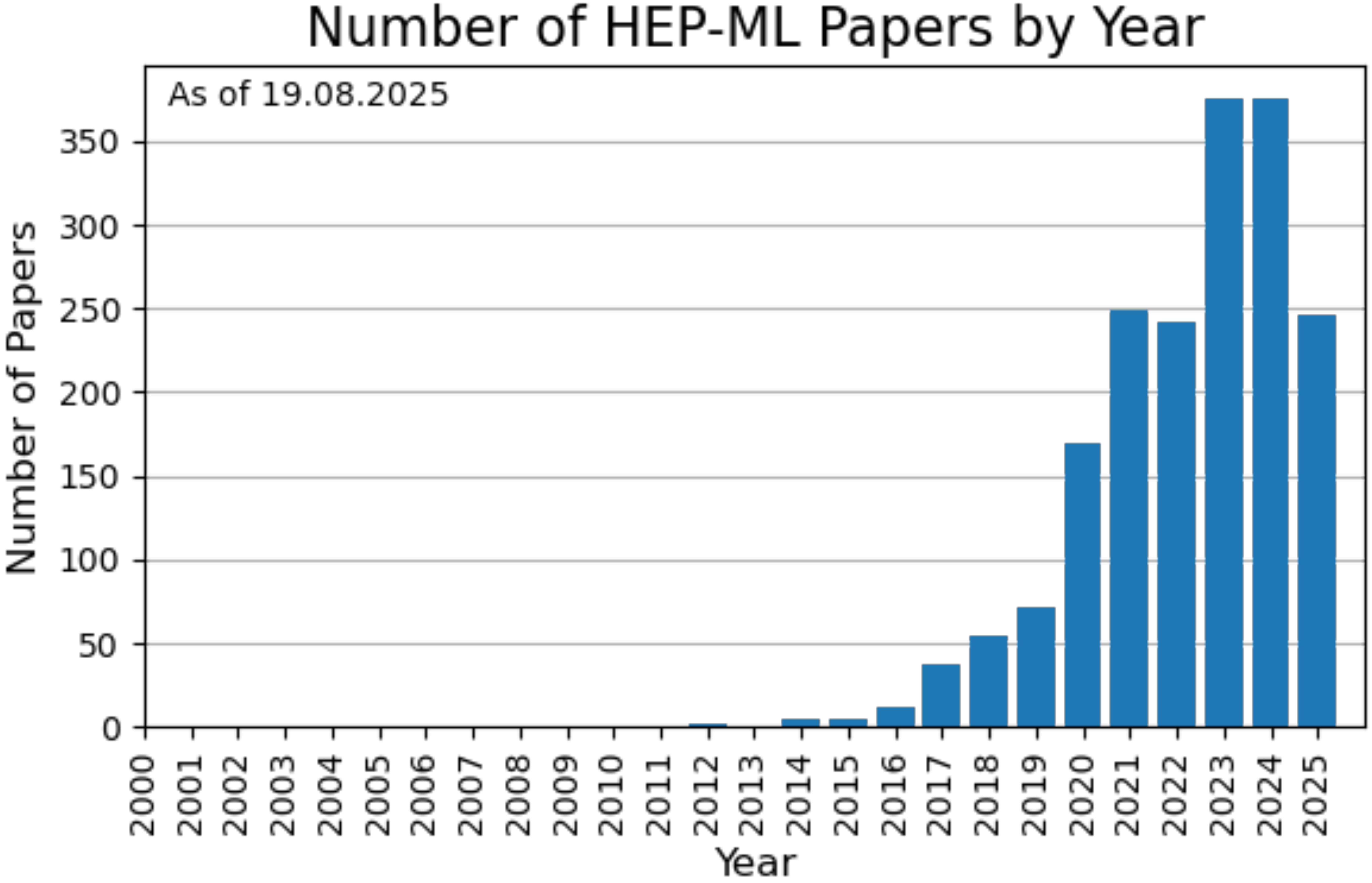
- Inner Tracker: tracks the paths of charged particles, bent in solenoid magnetic field
- Electromagnetic calorimeter: measured energy of Electrons, Photons
- Hadronic calorimeter: measures energy of hadronic jets
- Muon spectrometer: Tracks the paths of muons, bent in toroidal magnetic field

The Worldwide LHC Computing GRID

- WLCG provides global computing resources to analyses, store and distribute the vast data collected by the experiments
- Combines ~1.4 million computing cores and 1.5 exabytes of storage from over 170 sites in 42 countries
- Runs over 2 million tasks per day!
- Used by move than 12000 physicists around to world and is crucial for analysing the LHC data



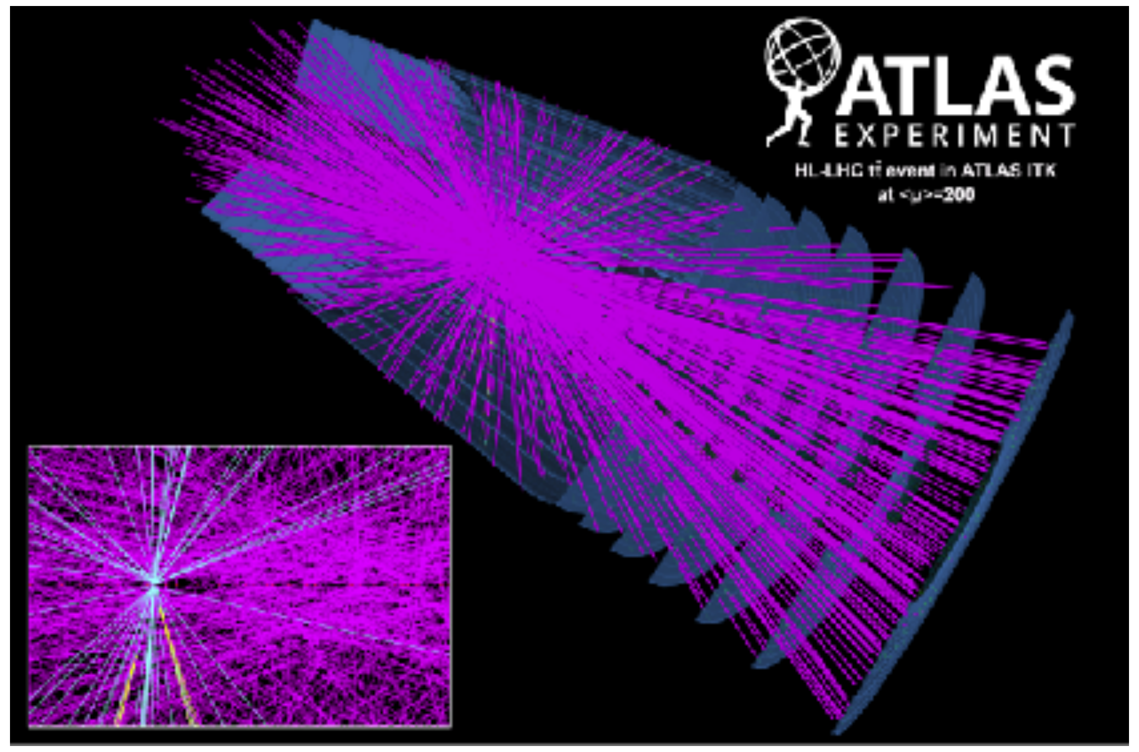
Interest in Machine Learning

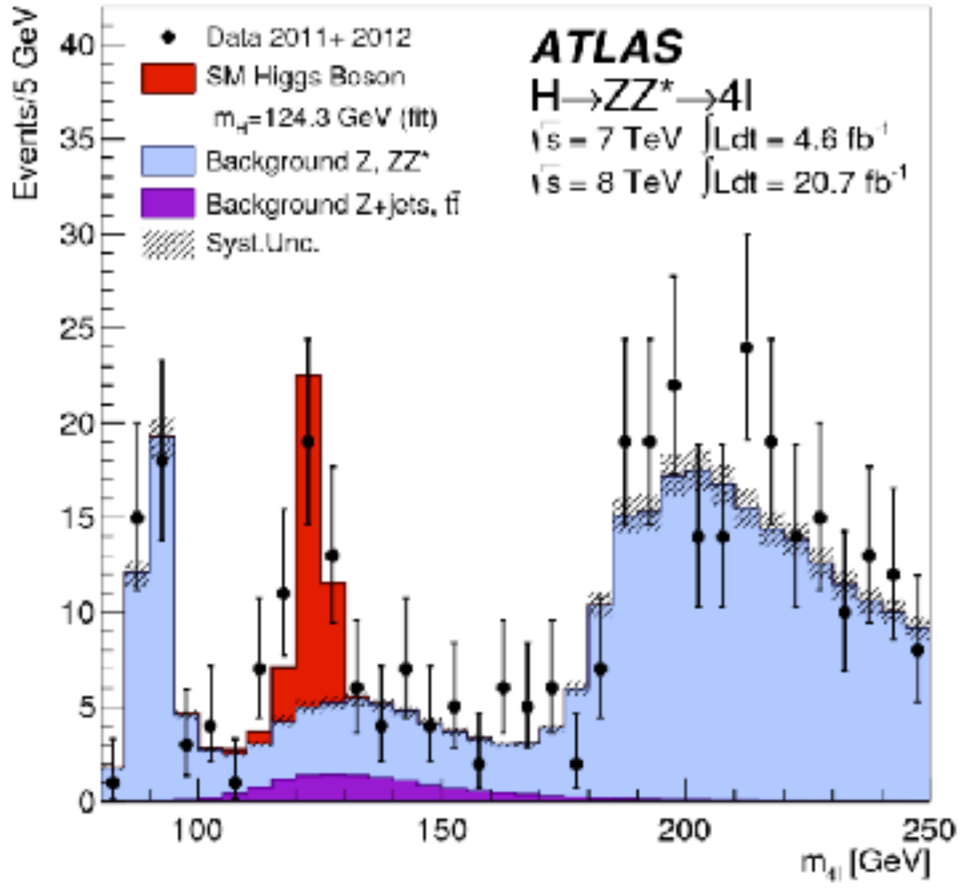


Source: https://iml-wg.github.io/HEPML-LivingReview/

“Analysis Workflow”

Collisions in accelerator ~ 40 million/sec → Look for interesting characteristics (triggers) ~ 100/sec → Reconstruct particles, select events for specific signal, reduce backgrounds → Analysis



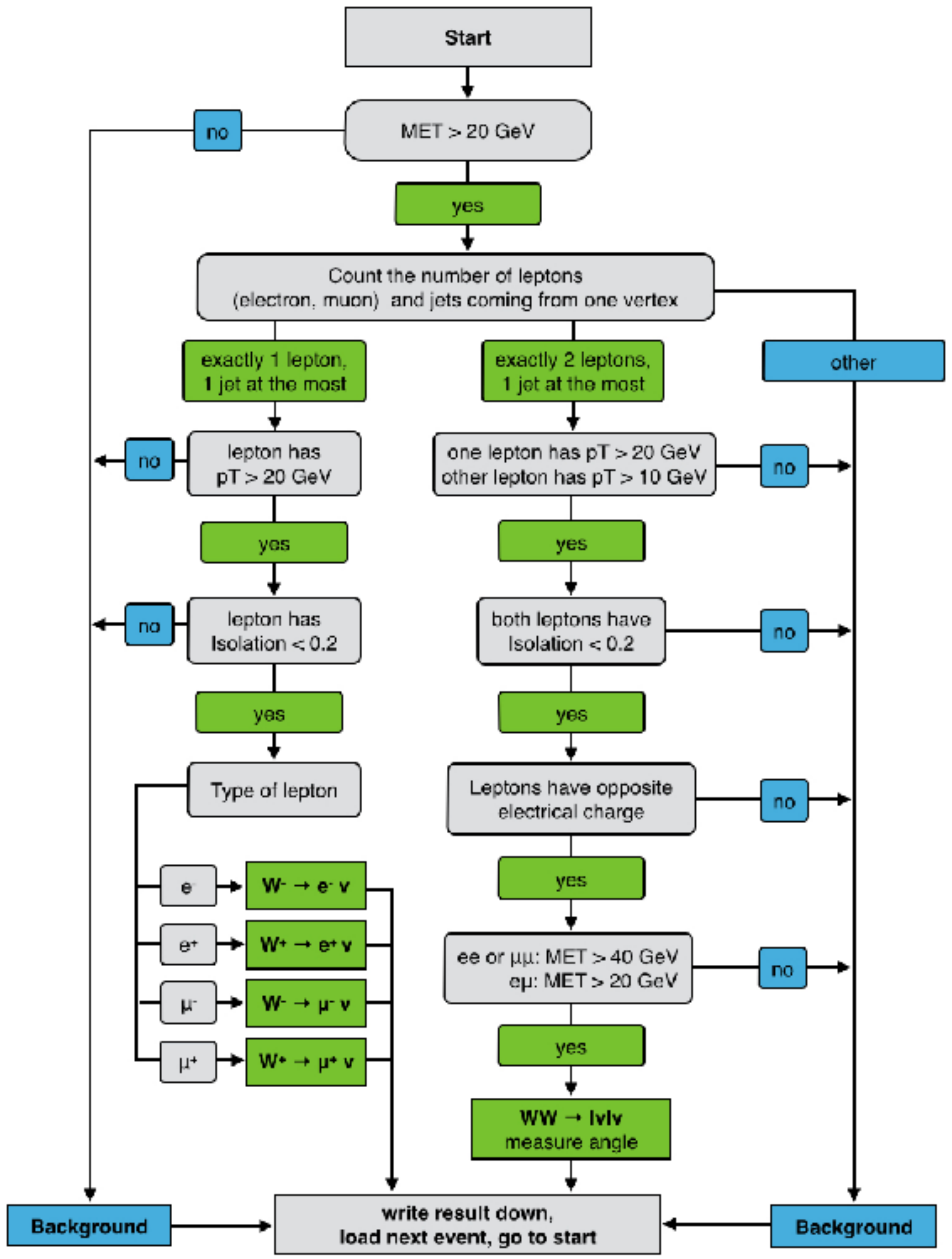


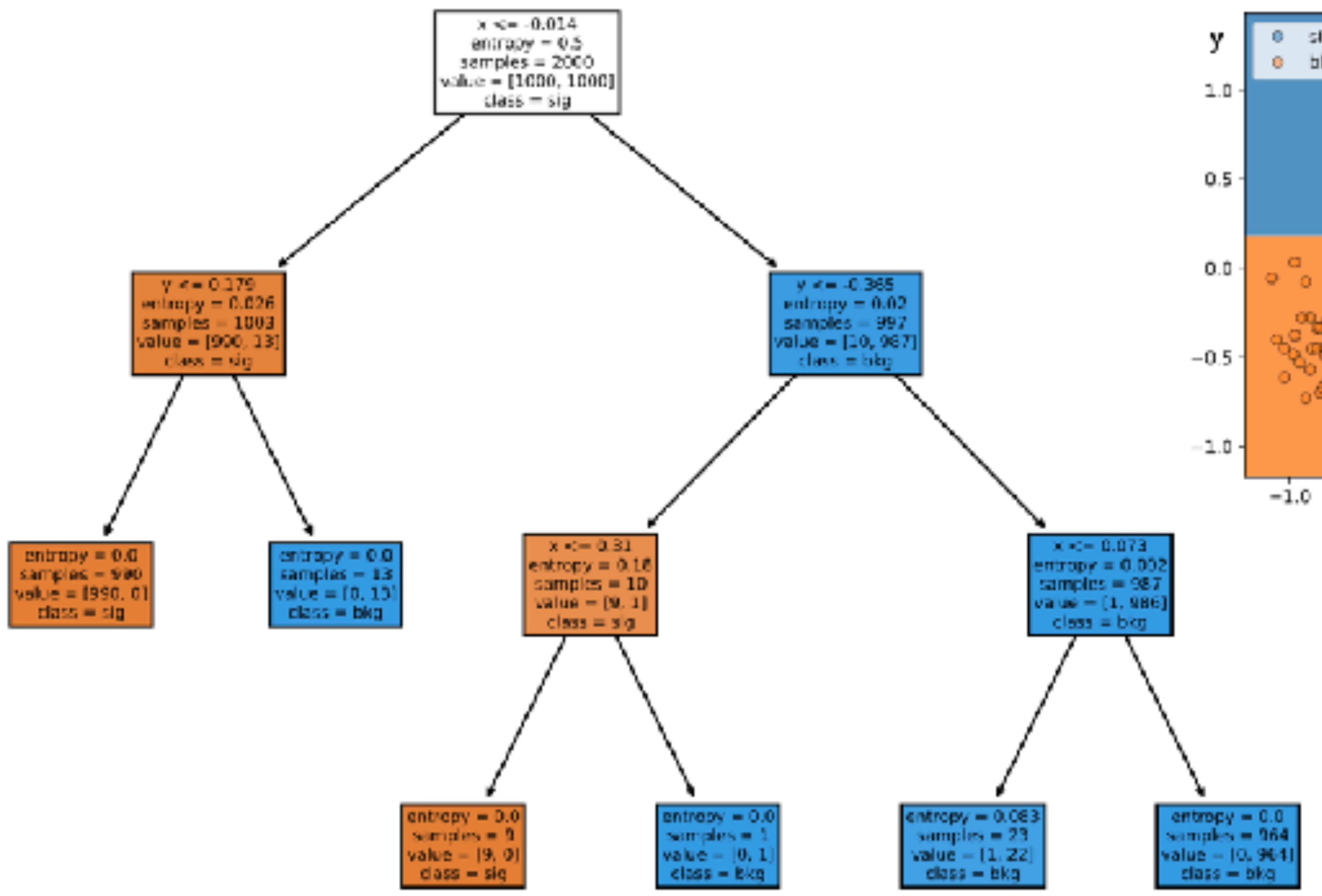
Trigger Systems

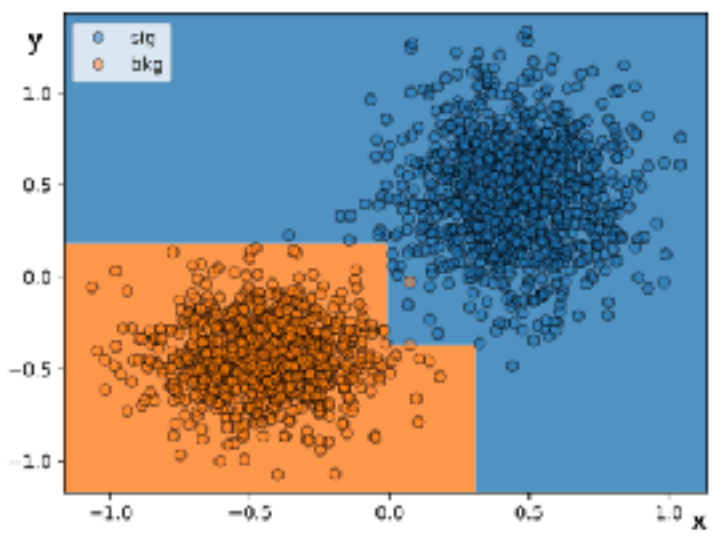
- 1.7 billion collisions each second with a combined data volume of more than 60 million megabytes per second
- The trigger system selects approximately 1000 from these
- The data acquisition system channels the data from the detectors to storage
- Experiments at the LHC continue to incorporate ML into the trigger including using GPUs and FPGAs

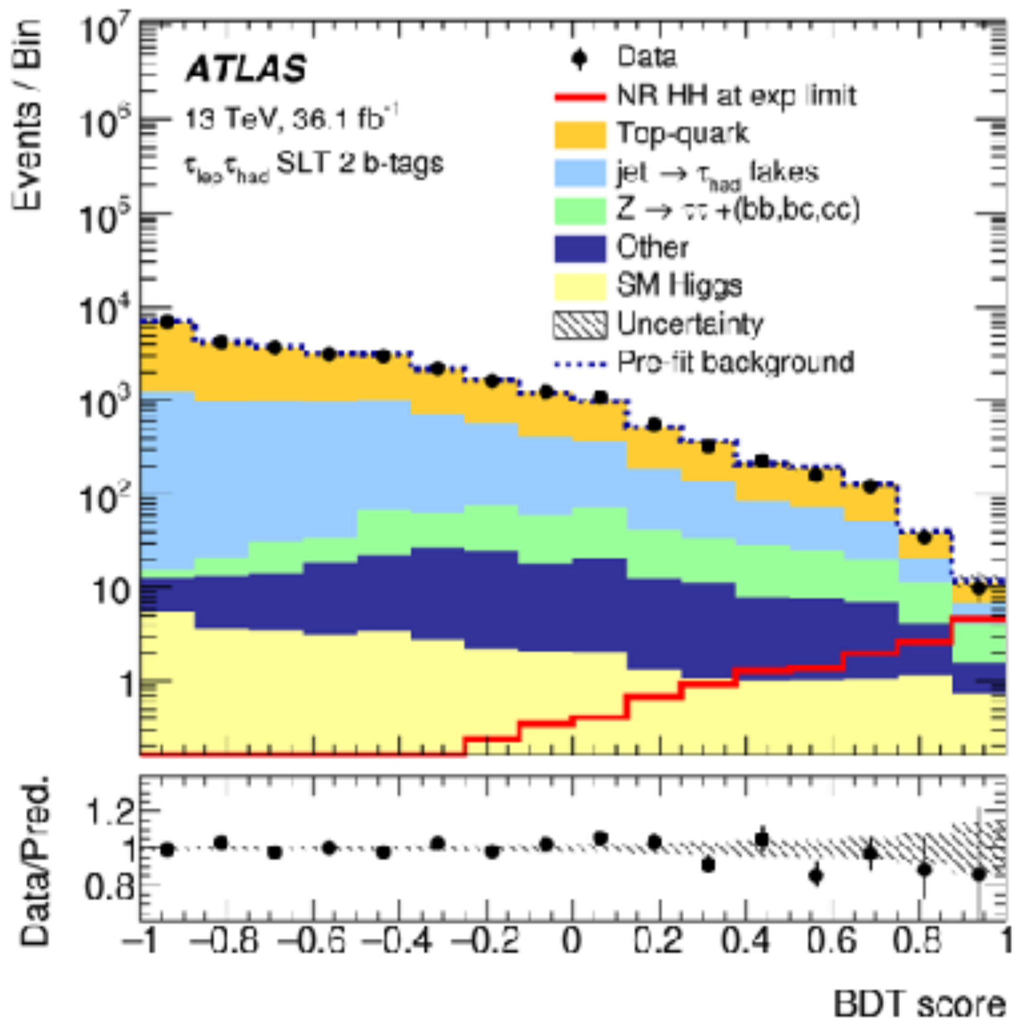
Classification

- Analyses are often hard because we are often looking for rare events in large backgrounds
  - Signal can have similar signature and look very like background
- Classification most common use of ML in analyses
  - Goes beyond simple cut based analysis (as shown in illustration on right)
  - Takes input information and can exploit “higher dimensional” correlations to separate signal from background
  - Lots of different types (SVMs, BDTs, NNs, etc.)

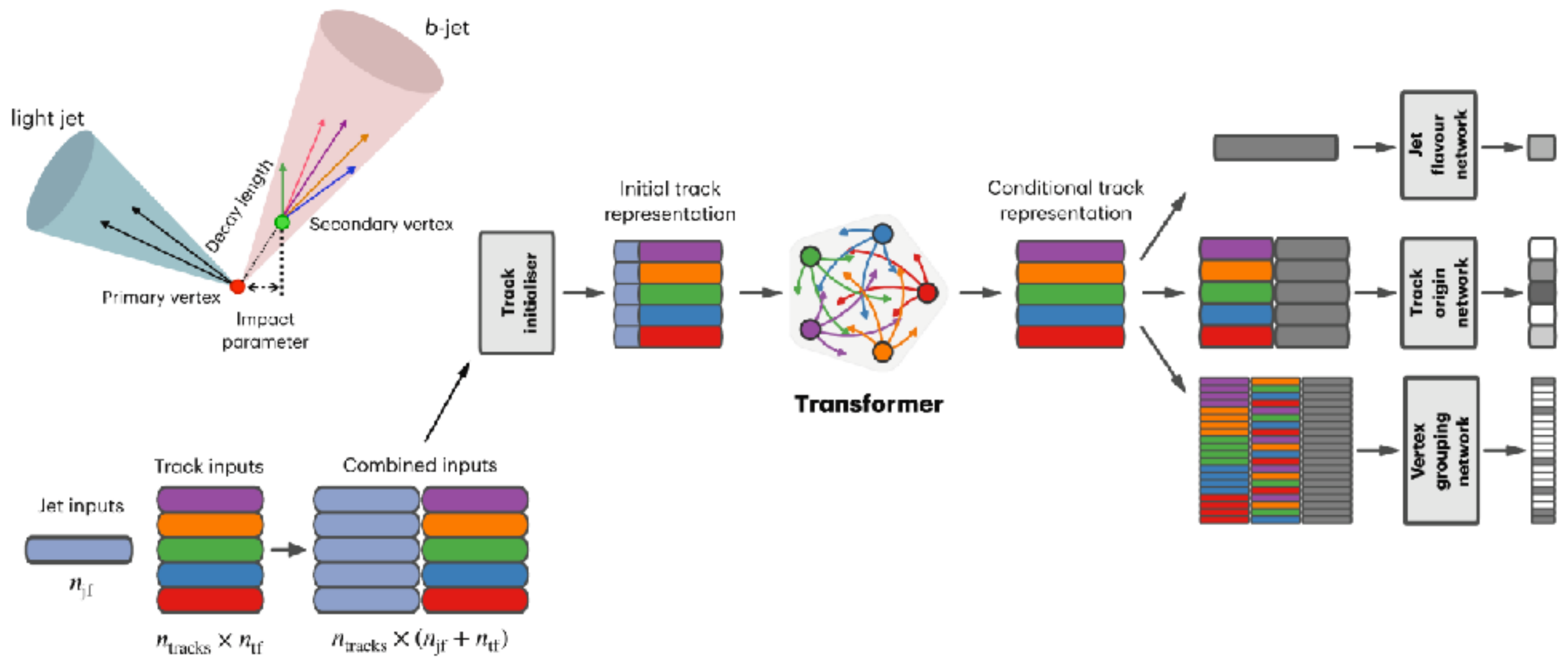






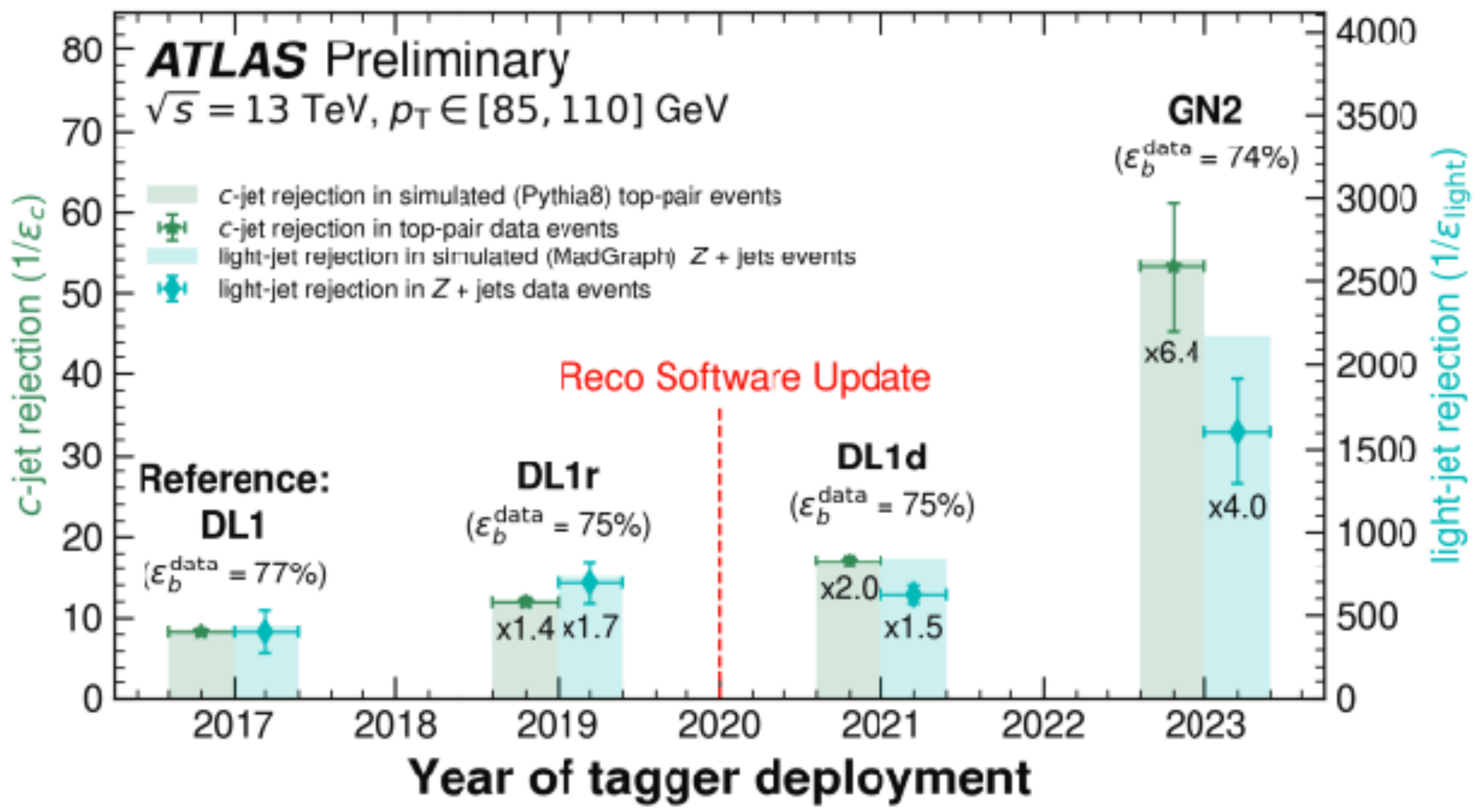


Transformers for Jet Flavour Tagging



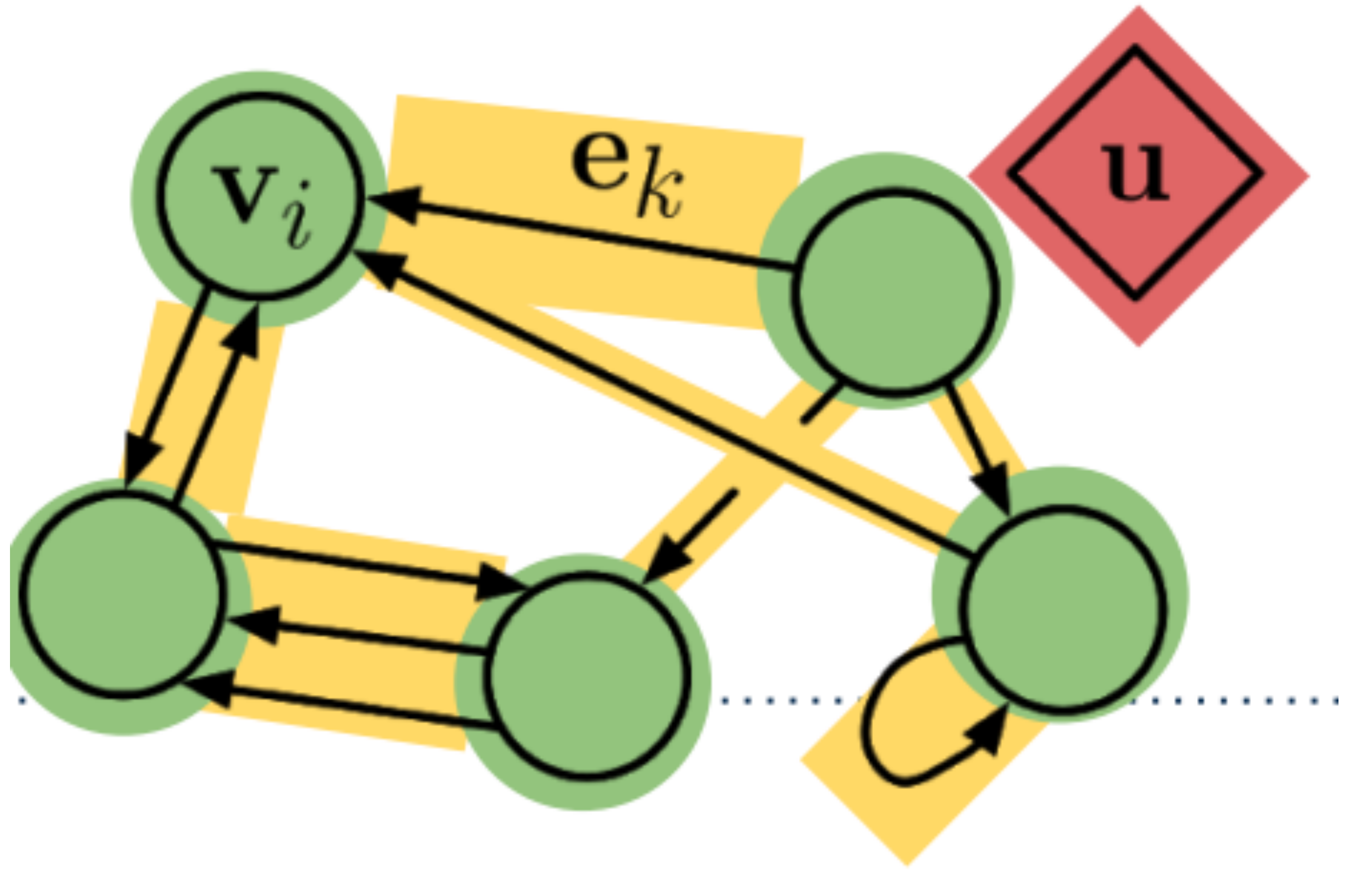
- Most common signals produced in *pp* collisions come from particle jets – collimated sprays of particles created when quarks or gluons transition into hadrons.
- Jets dominate data collected by ATLAS, but identifying what type, or flavour, of quark initiated a jet is highly challenging. Crucial for precise SM measurements and searches for new physics phenomena.

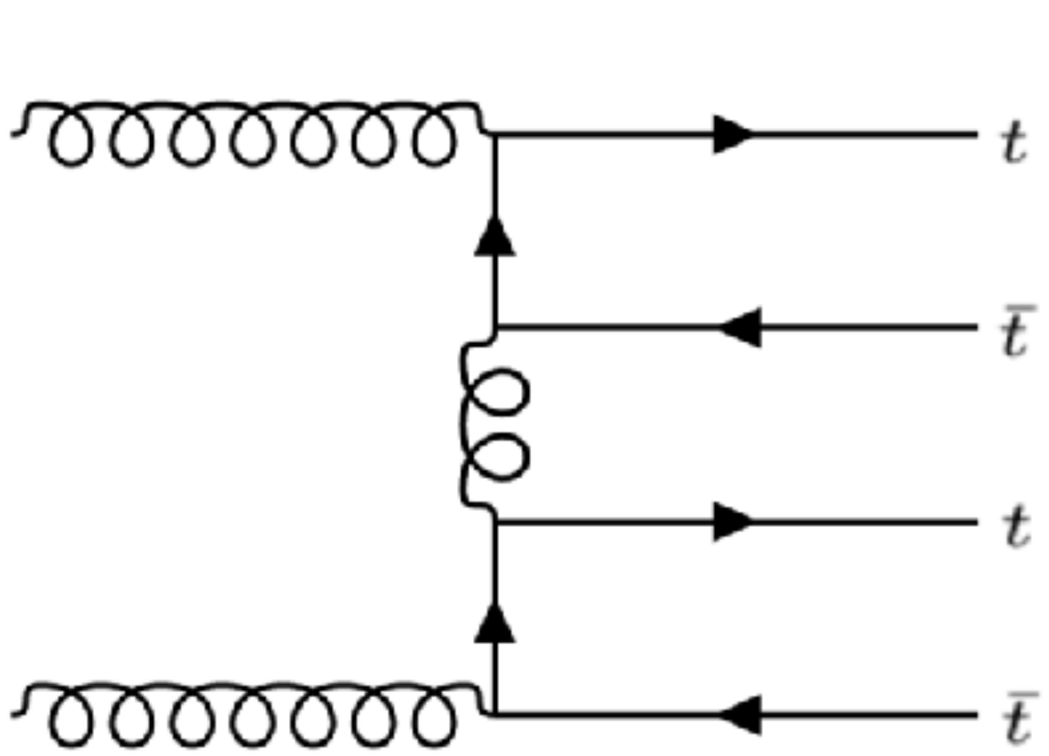
- ATLAS has deployed GN2, a new jet flavour tagging algorithm:
  - Powered by a Transformer, type of NN allows model to directly analyse information about jets, eliminating the need for intermediate hand-crafted algorithms.
- Primary goal to predict the flavour of a jet, but can also incorporate auxiliary training objectives aimed at identifying the underlying process that generated it
  - Enhance model's performance and provide deeper insight into the specific physics signatures model has learned
- GN2 brings a huge performance leap compared to its predecessor
  - 3x (1.6x) better c-jet (light-jet) rejection in simulated top-quark-pair events
  - Improved the most recent di-Higgs measurement by 20%

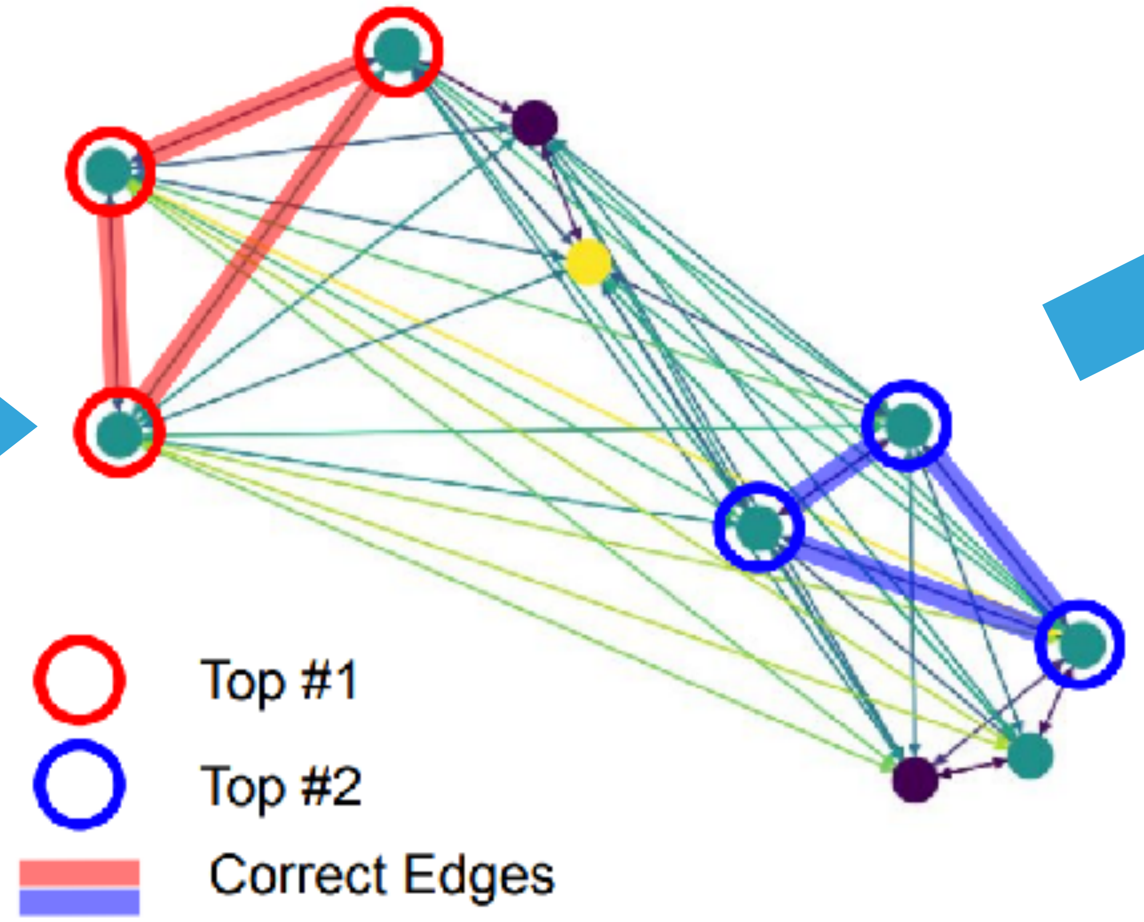


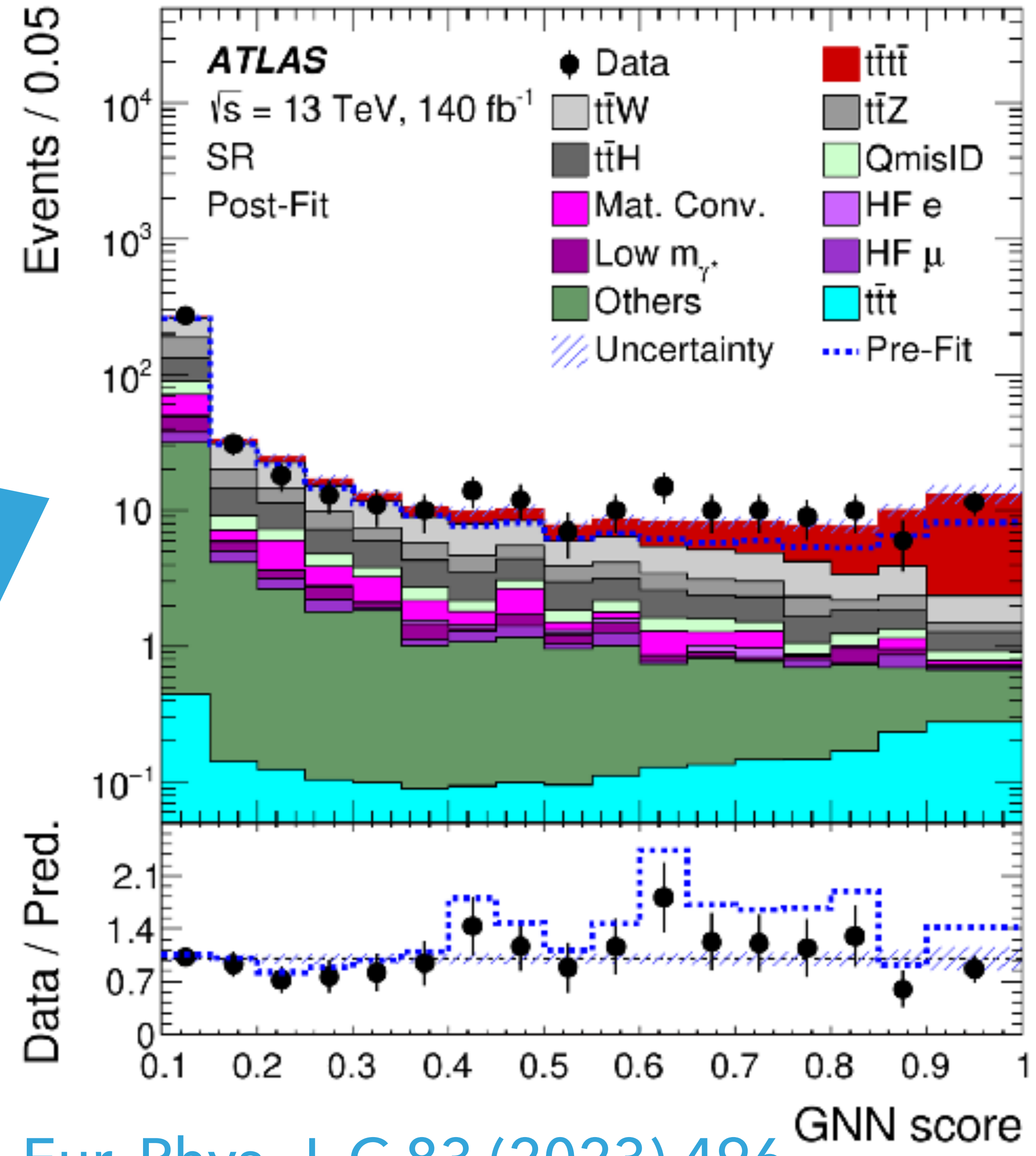
GNNs for Reconstruction

- Particle reconstruction: identify lighter particles that come from the same heavier particle decay
- Graph Neural Networks (Intro.) can build particle candidates in events based on “graphs”, in each graph
  - Reconstructed objects are nodes. (objects=jets, leptons)
  - The edges are bidirectional and connect all pairs of reconstructed objects.
  - There are also global features (Number of jets, total energy).
- GNN is used to predict identity of edges, used to separate edges connecting 2 objects from the same heavy particle decay and those not from the same particle decay by edge scores
- Finally, edge identities, are used to construct particle candidates





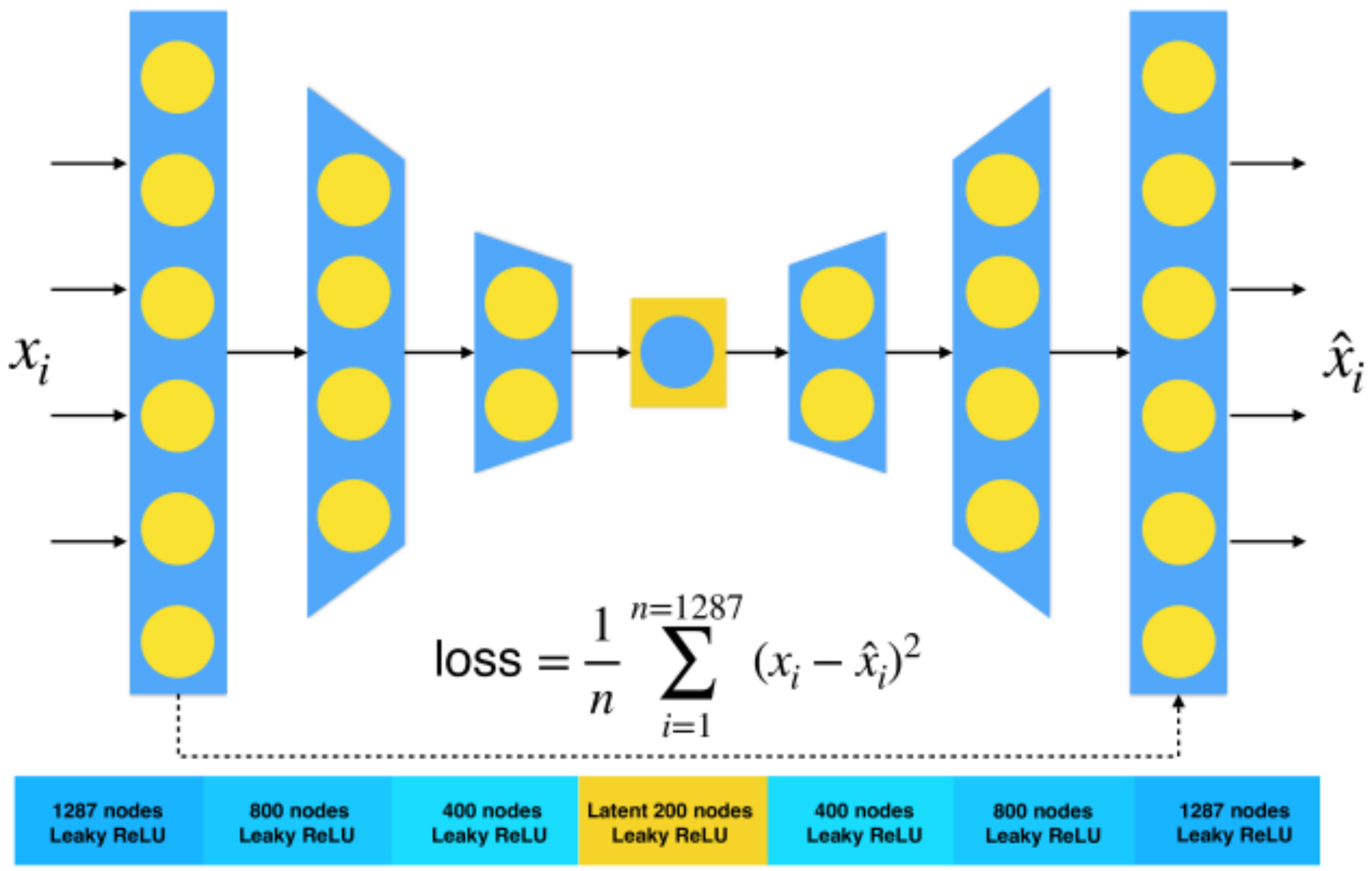




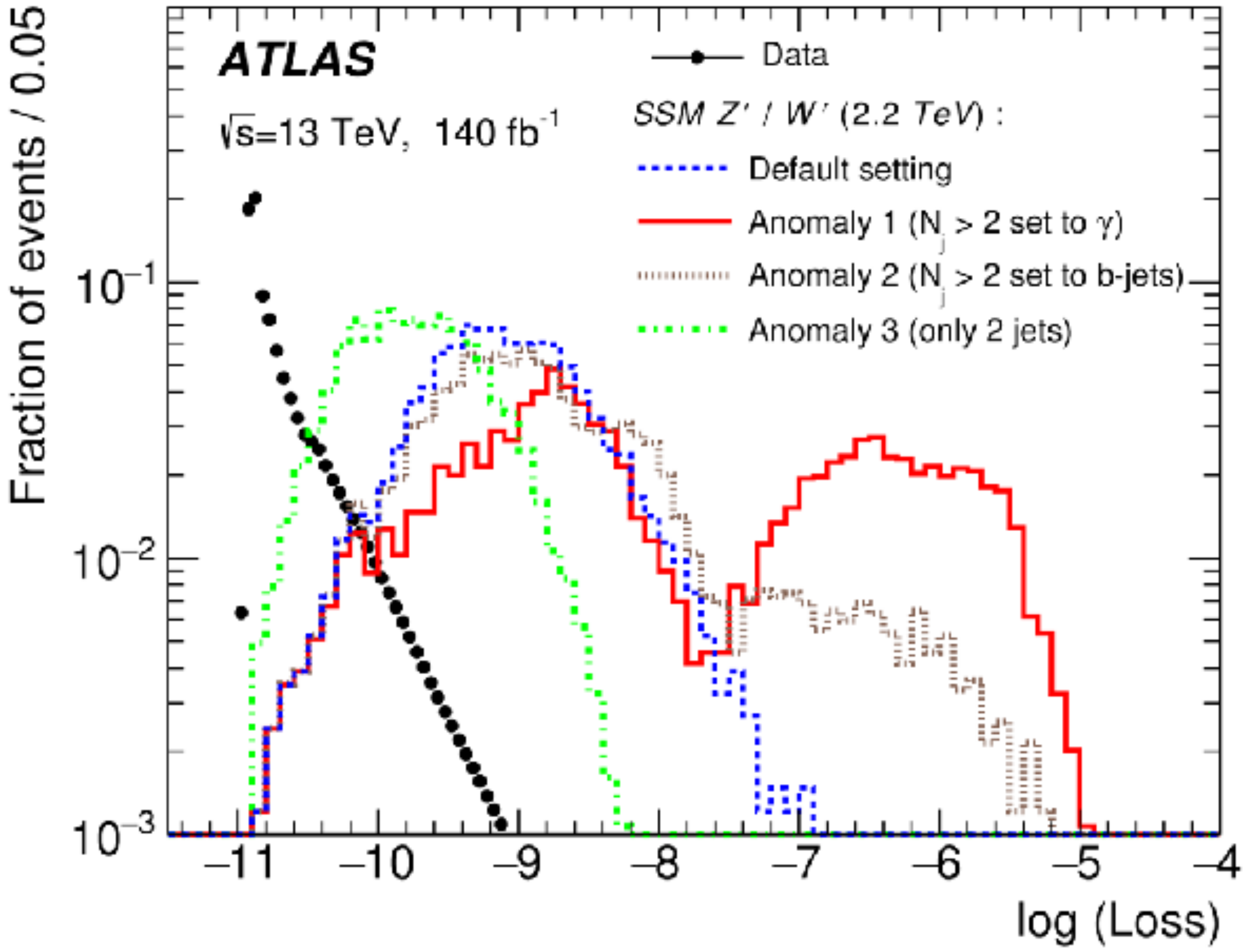
Eur. Phys. J. C 83 (2023) 496

https://atlas.cern/Updates/Briefing/Anomaly-Detection

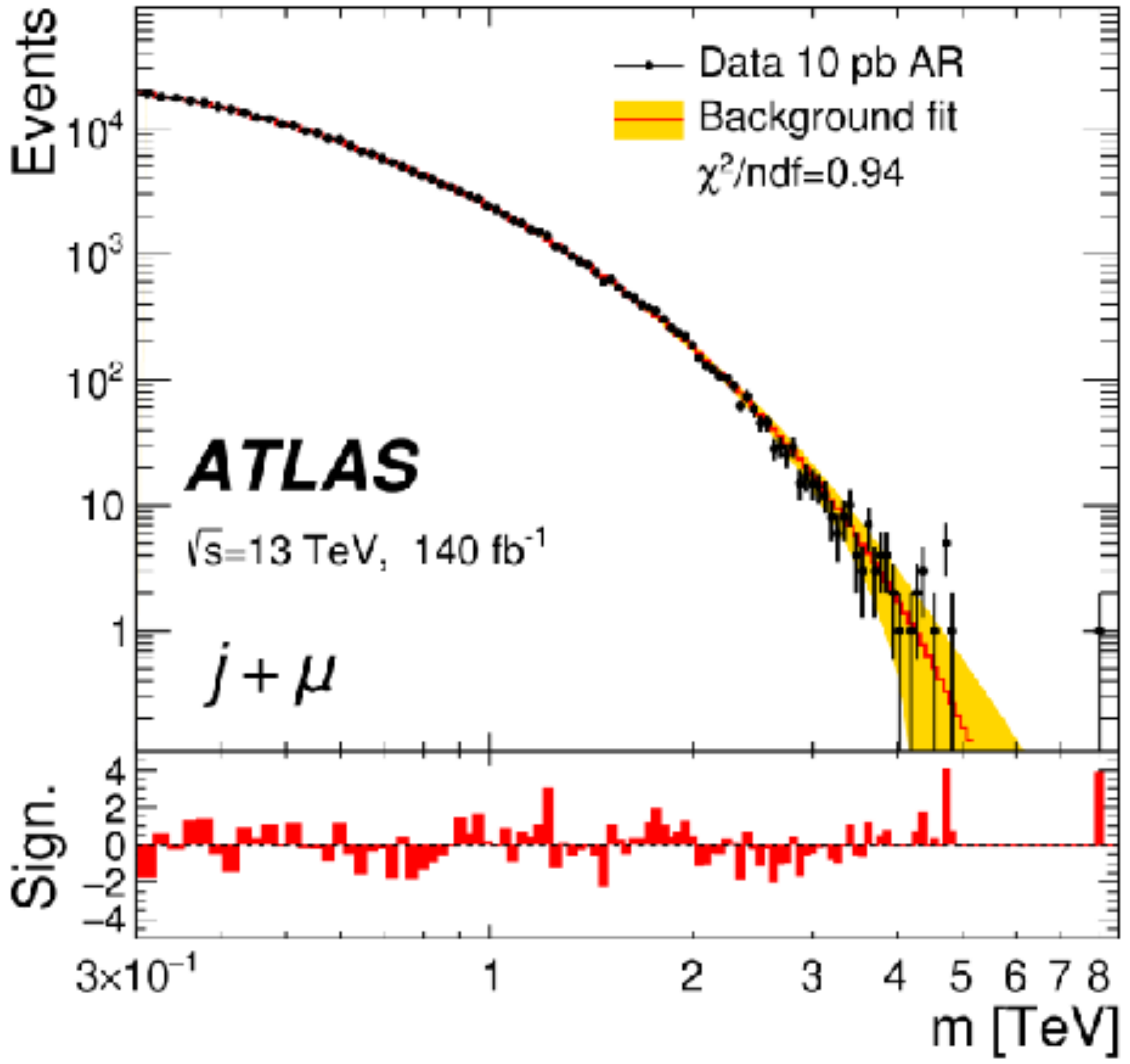
Anomaly Detection



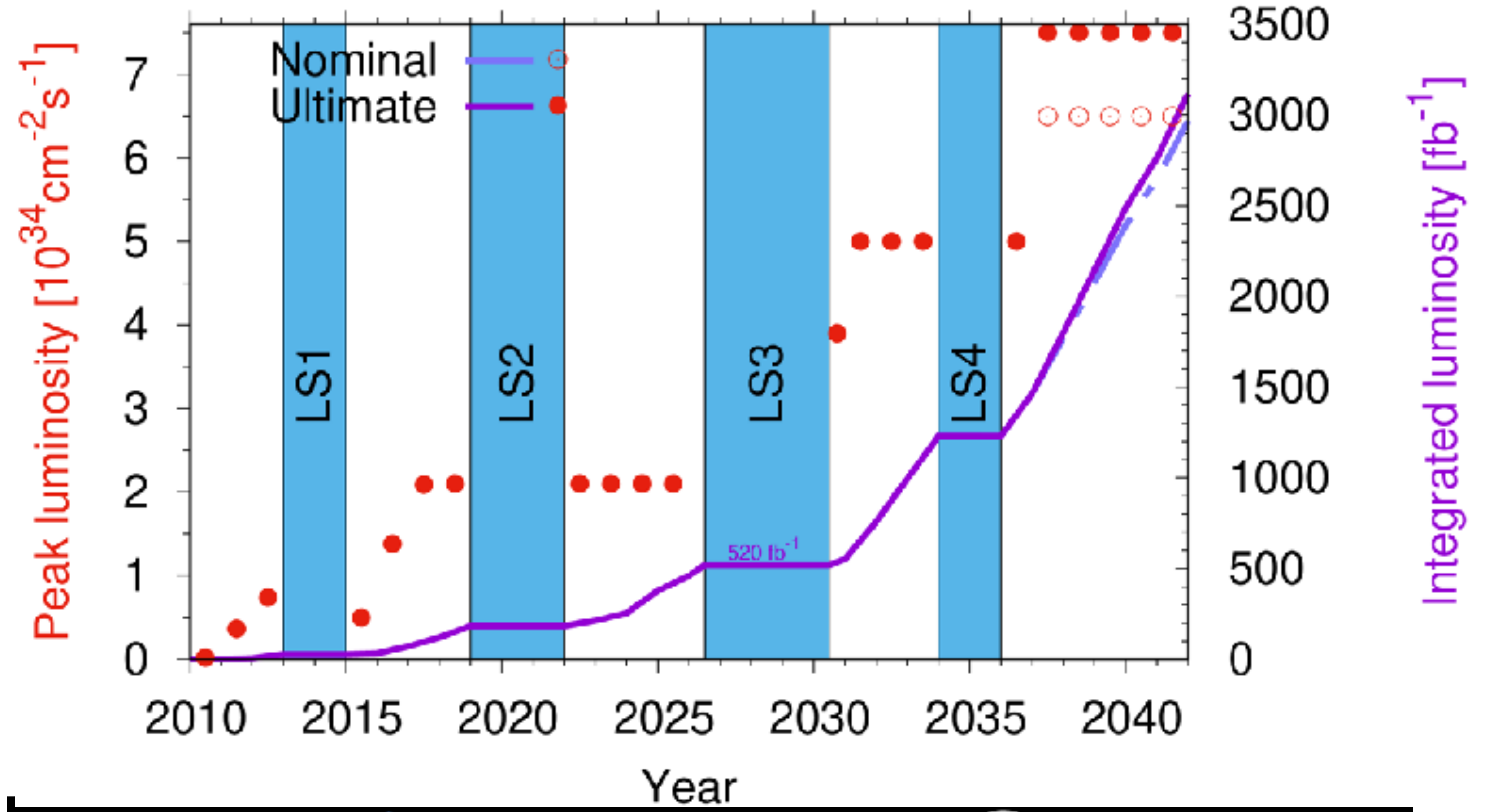
- Unsupervised ML offers new style of analyses which is completely agnostic to types of new physics models and to any expectations
- Complex NN with millions of interconnections between "neurons" trained on real data
- After training NN can recognise "typical" LHC collisions and filter them out, leaving behind only the unrecognised or "atypical" collision events
- Events with large differences are "anomalies" since the algorithm finds itself in "trouble" in identifying such events

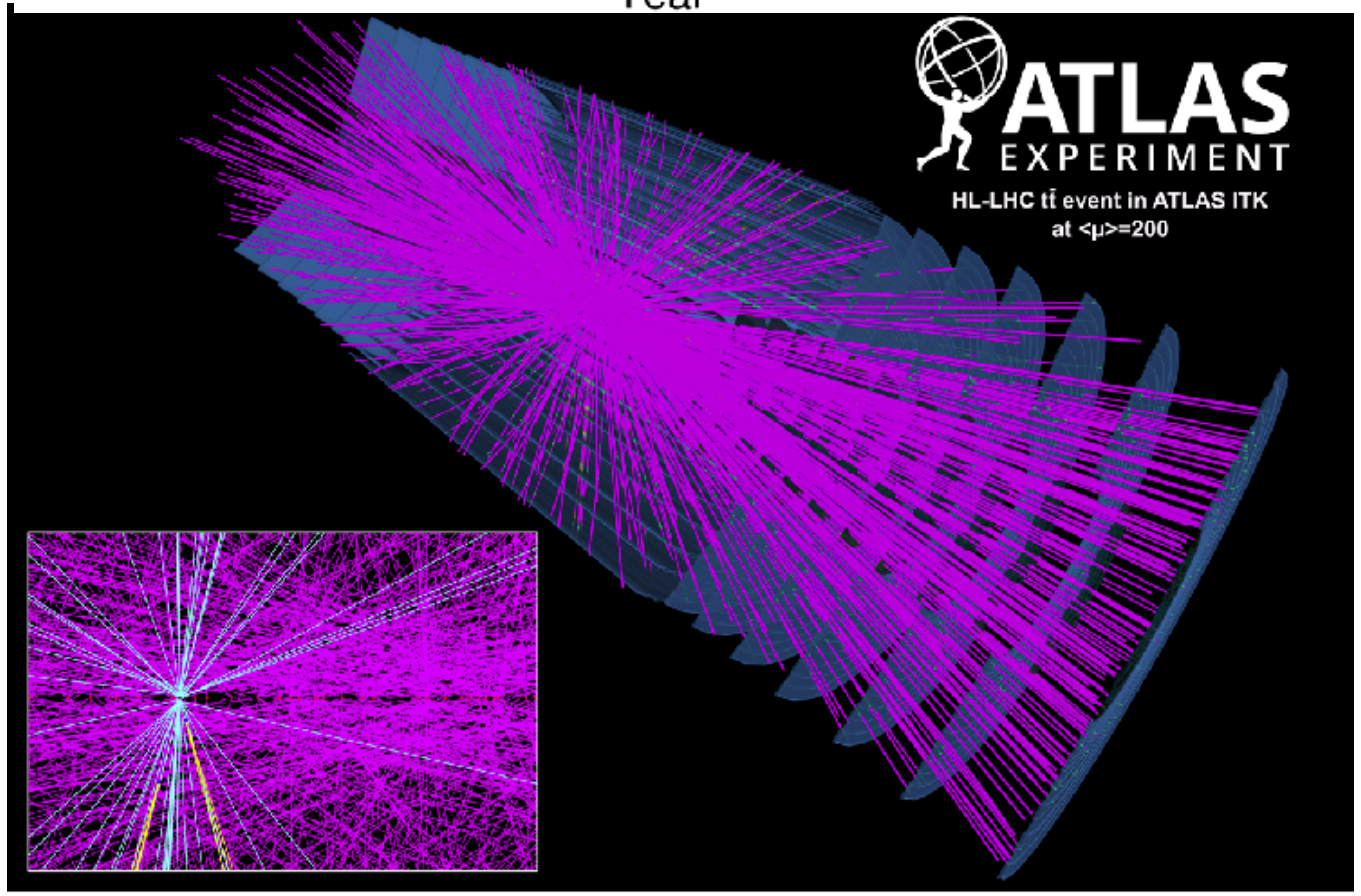


- Chances the anomalous events belong to new physics phenomena are high
- Look at the anomalous events, reconstruct the invariant masses of the particles in the collision, and decide if they can be described by a SM process

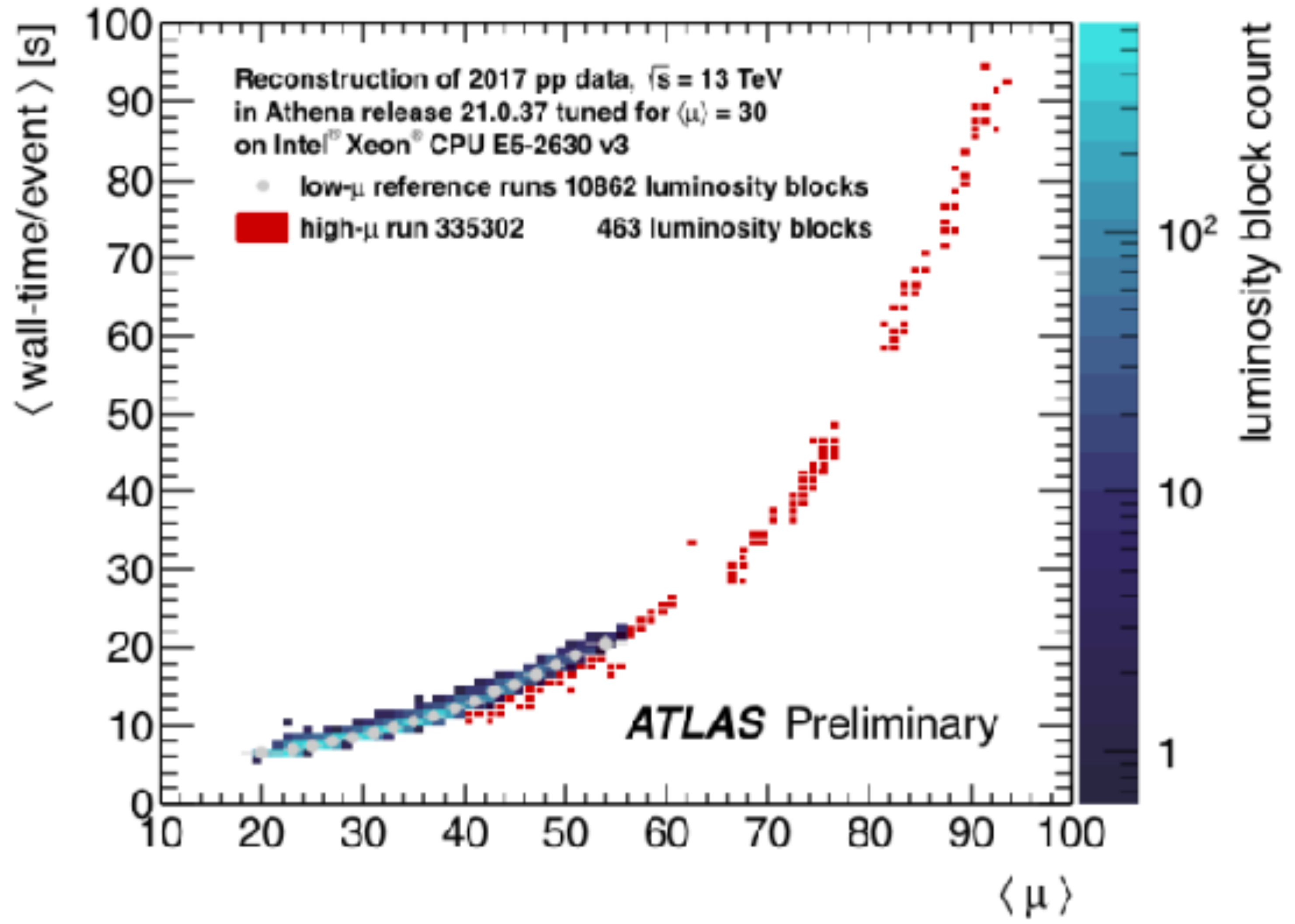


High Luminosity LHC





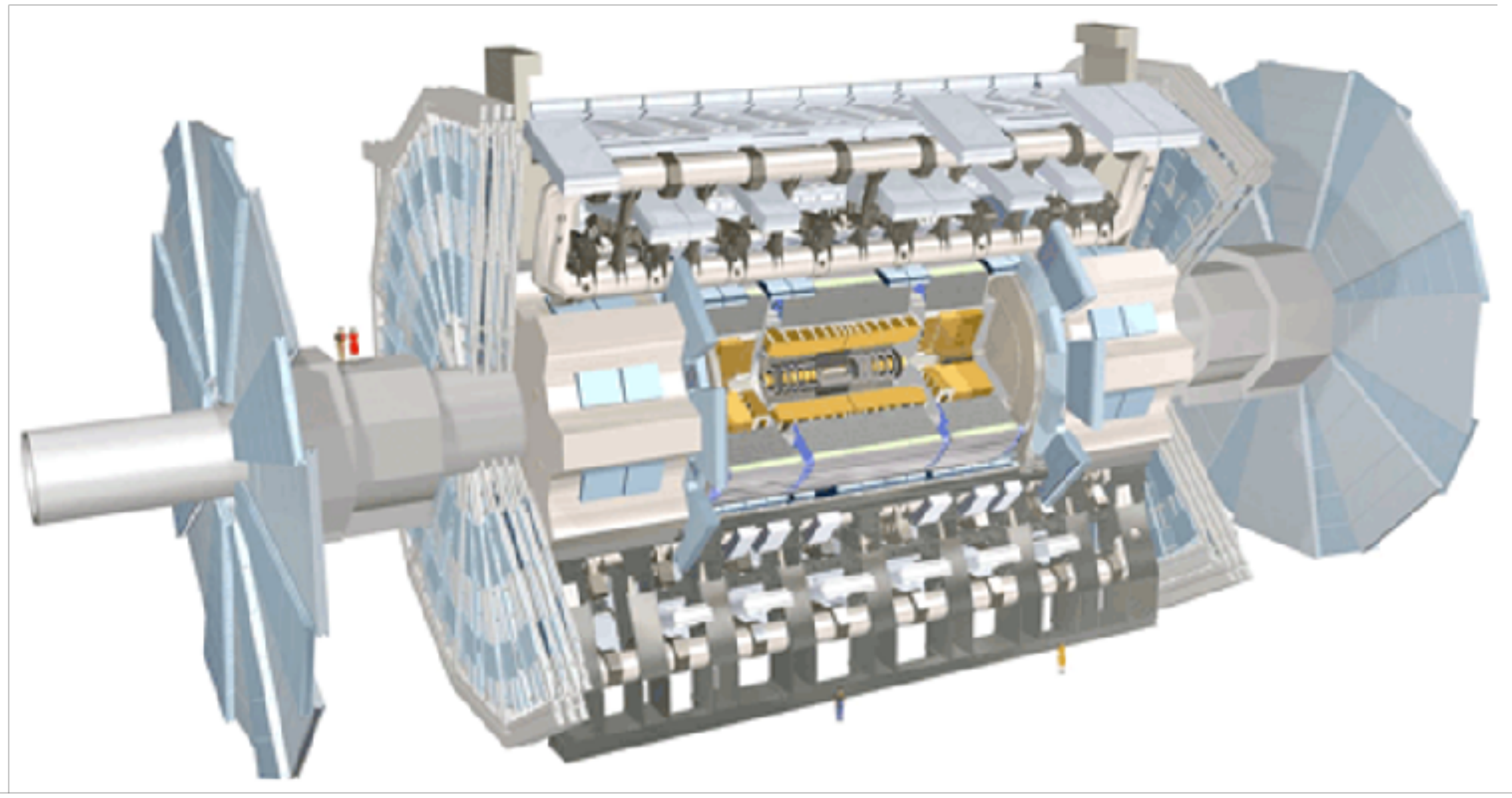
- High Luminosity LHC will bring significant increase in the amount of data but also significant challenges
- Much more dense environments in the detector with many more simultaneous events
- ML will be key to being able to process the vast amount of information that is collected

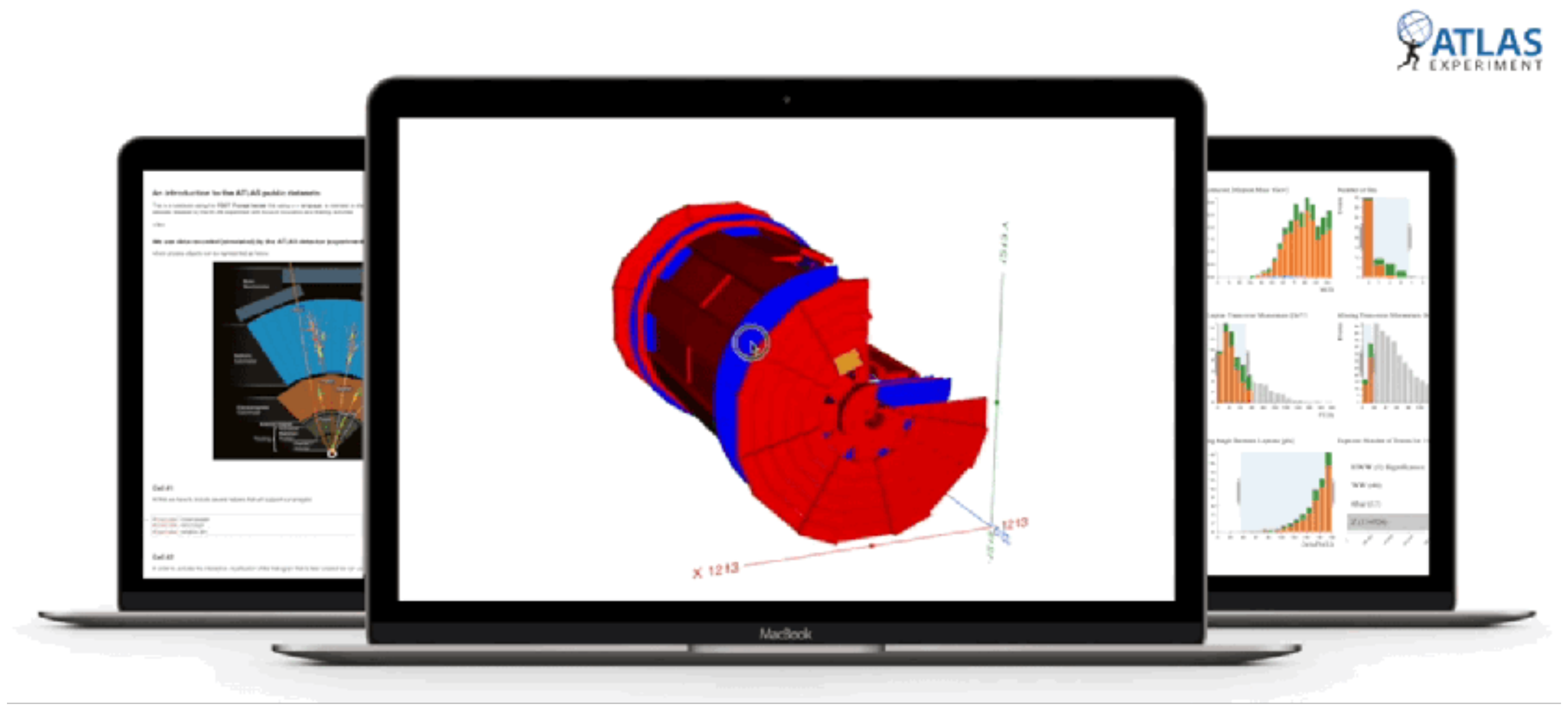


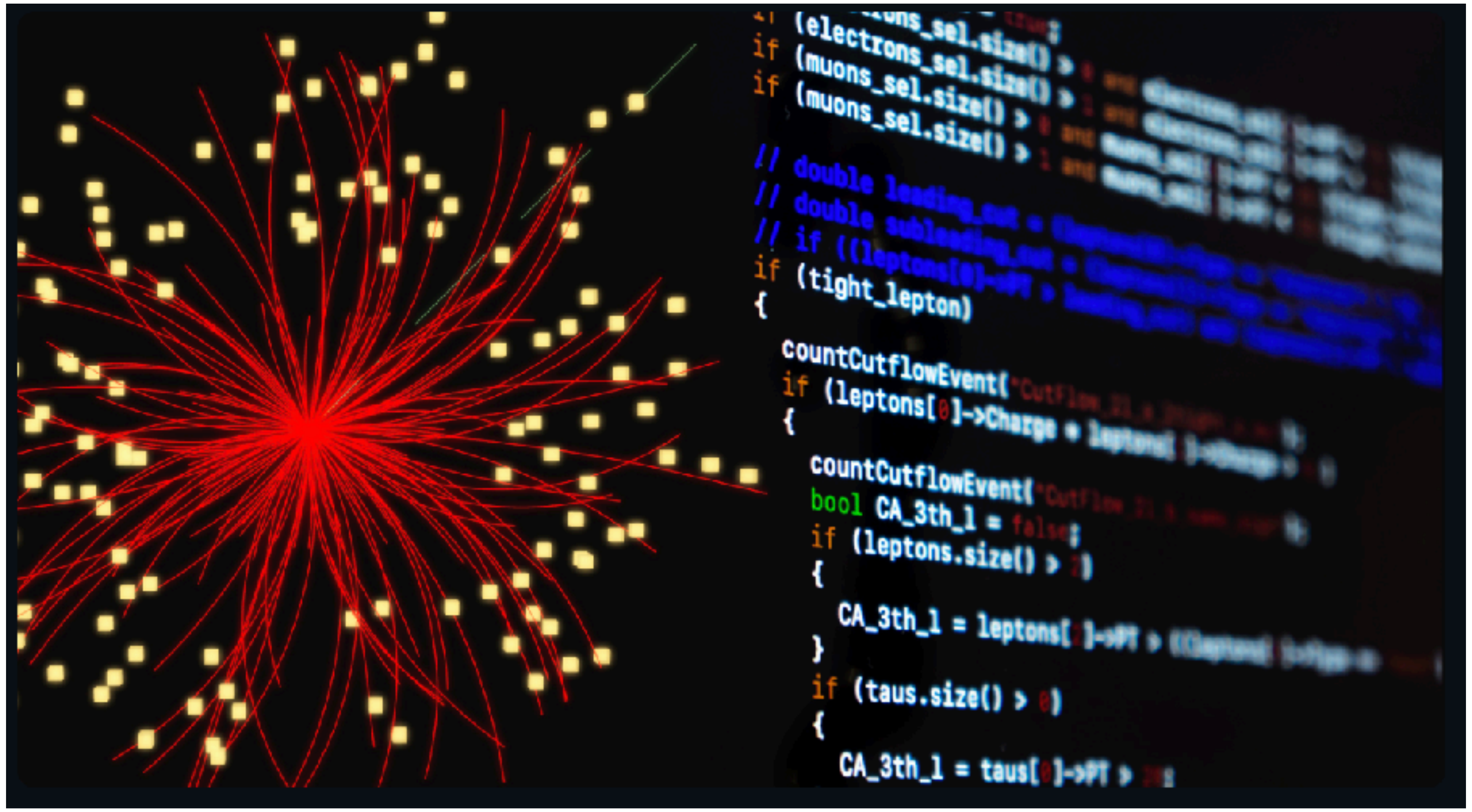
ATLAS Open Data

UNIVERSITY OF SUSSEX

The ATLAS experiment is dedicated to providing our **data**, **software**, **tools** and **educational toolkits** to the public, students and scientists



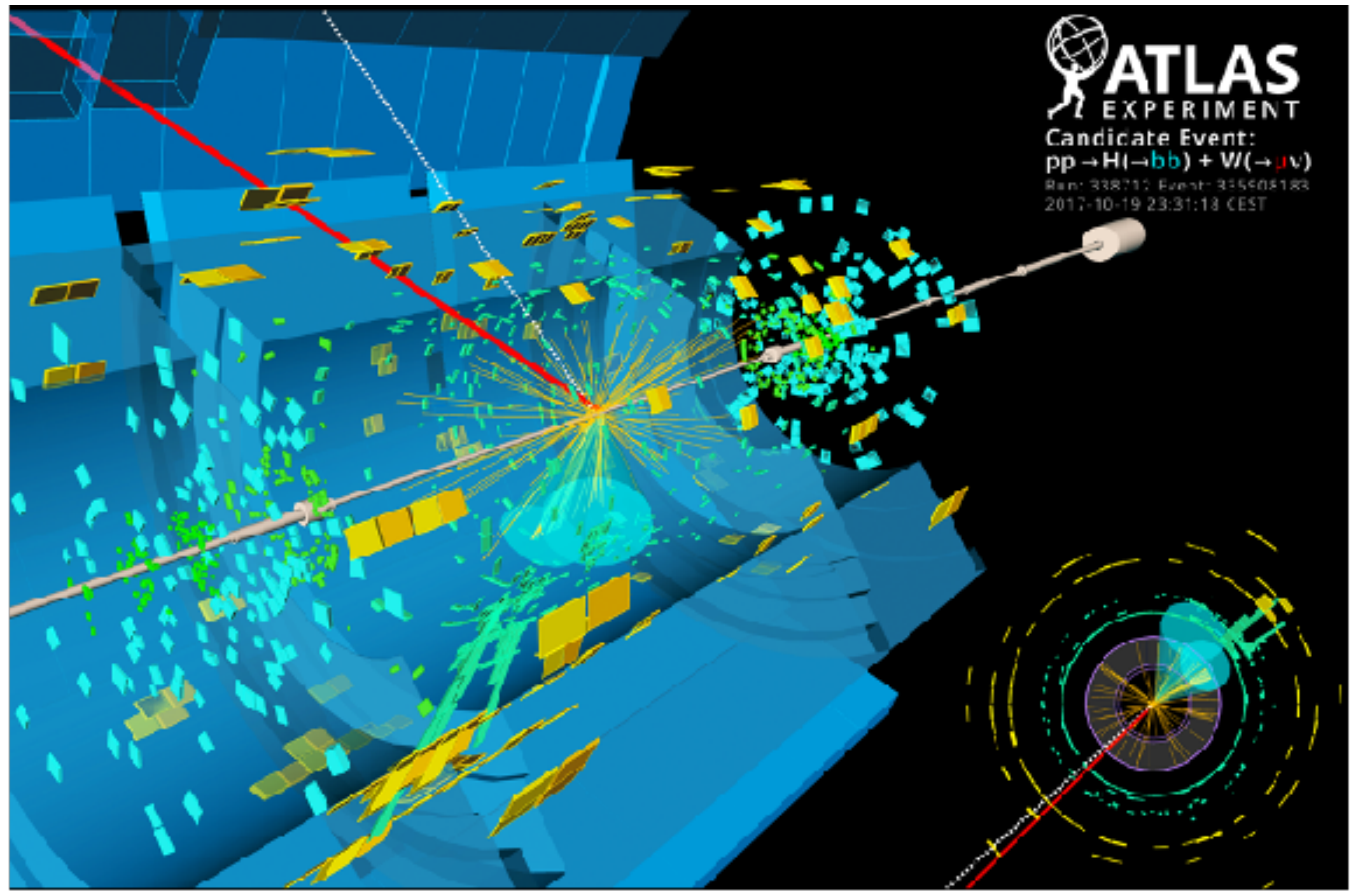




[13 TeV Open Data Link]

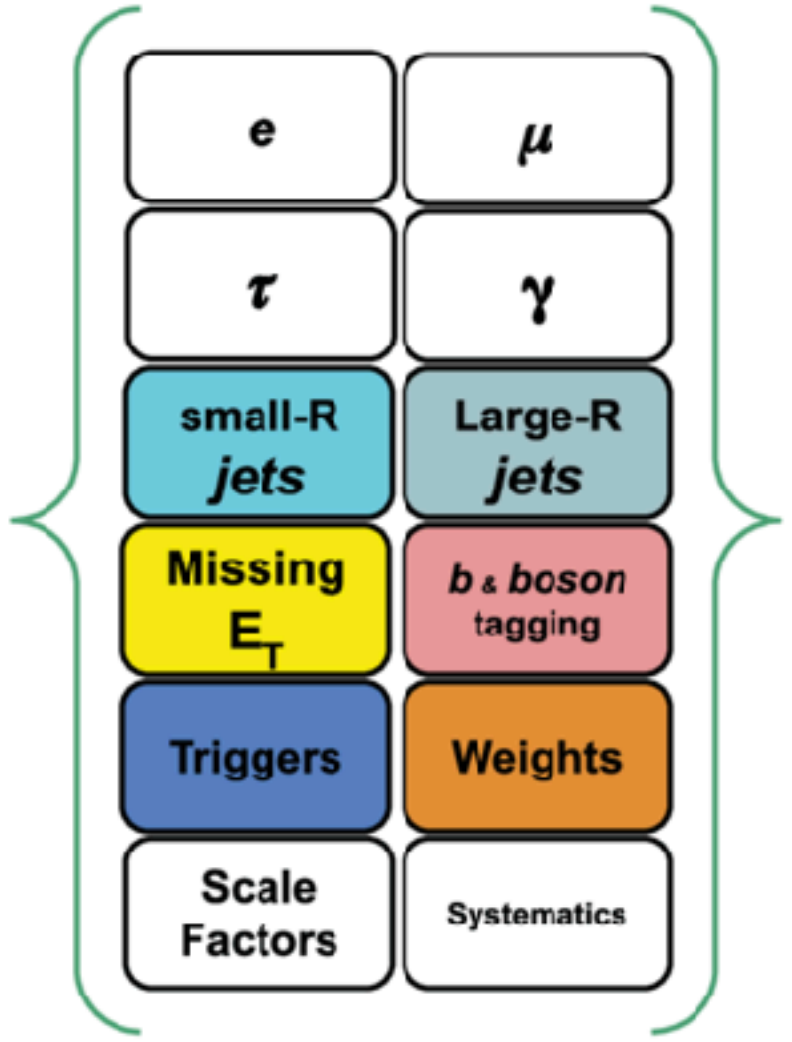
ATLAS Open Data

- **Real collision data**, AND simulated data
- Datasets processed in ROOT format – easy to use!
- Millions of proton proton **events**. Each event has some physics objects (see below) and they have properties



One example **event** (happens to have a higgs candidate!)

13 TeV TTree



~**90** variables

Tuple branch name	C++ type	Variable description
runNumber	int	number uniquely identifying ATLAS data-taking run
eventNumber	int	event number and run number combined uniquely identifies event
channelNumber	int	number uniquely identifying ATLAS simulated dataset
mcWeight	float	weight of a simulated event
XSection	float	total cross-section, including filter efficiency and higher-order correction factor
SumWeights	float	generated sum of weights for MC process
scaleFactor_PILEUP	float	scale-factor for pileup reweighting
scaleFactor_ELE	float	scale-factor for electron efficiency
scaleFactor_MUON	float	scale-factor for muon efficiency
scaleFactor_PHOTON	float	scale-factor for photon efficiency
scaleFactor_TAU	float	scale-factor for tau efficiency
scaleFactor_BTAG	float	scale-factor for b-tagging algorithm @70% efficiency
scaleFactor_LepTRIGGER	float	scale-factor for lepton triggers
scaleFactor_PhotonTRIGGER	float	scale-factor for photon triggers
trigE	bool	boolean whether event passes a single-electron trigger
trigM	bool	boolean whether event passes a single-muon trigger
trigP	bool	boolean whether event passes a diphoton trigger
lep_n	int	number of pre-selected leptons
lep_truthMatched	vector<bool>	boolean indicating whether the lepton is matched to a simulated lepton
lep_trigMatched	vector<bool>	boolean indicating whether the lepton is the one triggering the event
lep_pt	vector<float>	transverse momentum of the lepton
lep_eta	vector<float>	pseudo-rapidity, η, of the lepton
lep_phi	vector<float>	azimuthal angle, ϕ, of the lepton
lep_E	vector<float>	energy of the lepton
lep_z0	vector<float>	z-coordinate of the track associated to the lepton wrt. primary vertex
lep_charge	vector<int>	charge of the lepton
lep_type	vector<int>	number signifying the lepton type (e or μ)
lep_isTightID	vector<bool>	boolean indicating whether lepton satisfies tight ID reconstruction criteria
lep_ptcone30	vector<float>	scalar sum of track p_T in a cone of R=0.3 around lepton, used for tracking isolation
lep_etcone20	vector<float>	scalar sum of track E_T in a cone of R=0.2 around lepton, used for calorimeter isolation
lep_trackd0pvunbiased	vector<float>	d_0 of track associated to lepton at point of closest approach (p.c.a.)
lep_tracksigd0pvunbiased	vector<float>	d_0 significance of the track associated to lepton at the p.c.a.
met_et	float	transverse energy of the missing momentum vector
met_phi	float	azimuthal angle of the missing momentum vector
jet_n	int	number of pre-selected jets
jet_pt	vector<float>	transverse momentum of the jet
jet_eta	vector<float>	pseudo-rapidity, η, of the jet
jet_phi	vector<float>	azimuthal angle, ϕ, of the jet
jet_E	vector<float>	energy of the jet
jet_jvt	vector<float>	jet vertex tagger discriminant [21] of the jet
jet_trueflav	vector<int>	flavour of the simulated jet
jet_truthMatched	vector<bool>	boolean indicating whether the jet is matched to a simulated jet
jet_MV2c10	vector<float>	output from the multivariate b-tagging algorithm [22] of the jet

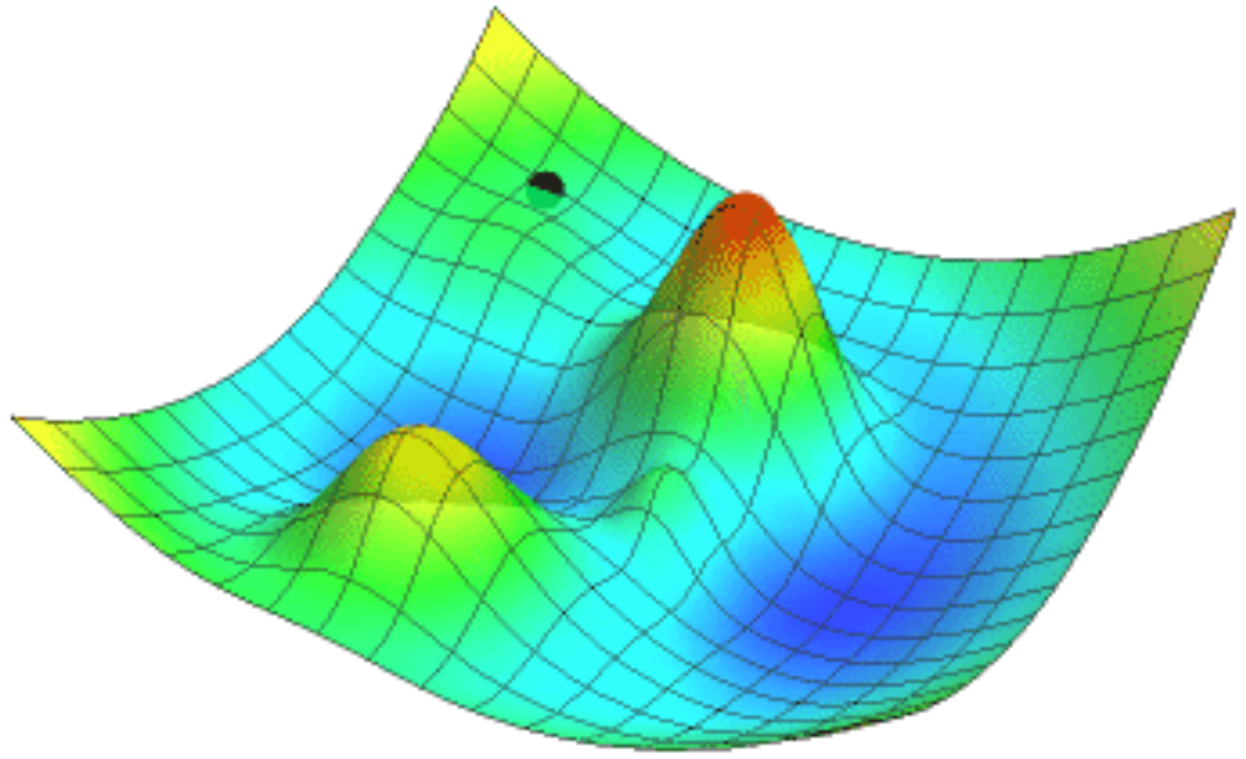
Tuple branch name	C++ type	Variable description
photon_n	int	number of pre-selected photons
photon_truthMatched	vector<bool>	boolean indicating whether the photon is matched to a simulated photon
photon_trigMatched	vector<bool>	boolean indicating whether the photon is the one triggering the event
photon_pt	vector<float>	transverse momentum of the photon
photon_eta	vector<float>	pseudo-rapidity of the photon
photon_phi	vector<float>	azimuthal angle of the photon
photon_E	vector<float>	energy of the photon
photon_isTightID	vector<bool>	boolean indicating whether photon satisfies tight identification reconstruction criteria
photon_ptcone30	vector<float>	scalar sum of track p_T in a cone of R=0.3 around photon
photon_etcone20	vector<float>	scalar sum of track E_T in a cone of R=0.2 around photon
photon_convType	vector<int>	information whether and where the photon was converted
largeRjet_n	int	number of pre-selected large-R jets
largeRjet_pt	vector<float>	transverse momentum of the large-R jet
largeRjet_eta	vector<float>	pseudo-rapidity of the large-R jet
largeRjet_phi	vector<float>	azimuthal angle of the large-R jet
largeRjet_E	vector<float>	energy of the large-R jet
largeRjet_m	vector<float>	invariant mass of the large-R jet
largeRjet_truthMatched	vector<int>	information whether the large-R jet is matched to a simulated large-R jet
largeRjet_D2	vector<float>	weight from algorithm [57] for W/Z-boson tagging
largeRjet_tau32	vector<float>	weight from algorithm [57] for top-quark tagging
tau_n	int	number of pre-selected hadronically decaying τ-lepton
tau_pt	vector<float>	transverse momentum of the hadronically decaying τ-lepton
tau_eta	vector<float>	pseudo-rapidity of the hadronically decaying τ-lepton
tau_phi	vector<float>	azimuthal angle of the hadronically decaying τ-lepton
tau_E	vector<float>	energy of the hadronically decaying τ-lepton
tau_charge	vector<int>	charge of the hadronically decaying τ-lepton
tau_isTightID	vector<bool>	boolean indicating whether hadronically decaying τ-lepton satisfies tight ID reconstruction criteria
tau_truthMatched	vector<bool>	boolean indicating whether the hadronically decaying τ-lepton is matched to a simulated τ-lepton
tau_trigMatched	vector<bool>	boolean signifying whether the τ-lepton is the one triggering the event
tau_nTracks	vector<int>	number of tracks in the hadronically decaying τ-lepton decay
tau_BDTid	vector<float>	output of the multivariate algorithm [24] discriminating hadronically decaying τ-leptons from jets
ditau_m	float	di-τ invariant mass using the missing-mass calculator [54]
lep_pt_syst	vector<float>	single component syst. uncert. (lepton momentum scale and resolution [36,15]) affecting lep_pt
met_et_syst	float	single component syst. uncert. (E_T^{miss} scale and resolution [30]) affecting met_pt
jet_pt_syst	vector<float>	single component syst. uncert. (jet energy scale [37]) affecting jet_pt
photon_pt_syst	vector<float>	single component syst. uncert. (photon energy scale and resolution [16]) affecting photon_pt
largeRjet_pt_syst	vector<float>	single component syst. uncert. (large-R jet energy resolution [37]) affecting largeRjet_pt
tau_pt_syst	vector<float>	single component syst. uncert. (τ-lepton reconstruction and energy scale [24]) affecting tau_pt

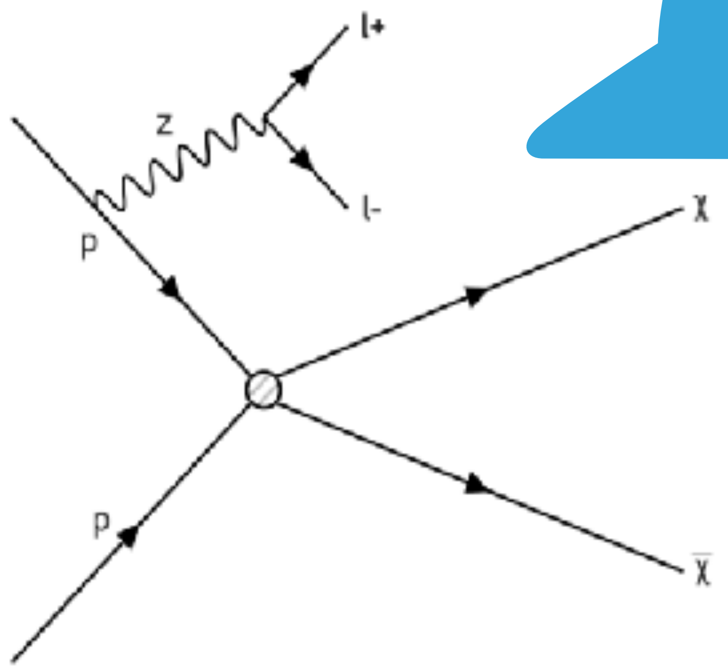
Full list of variables

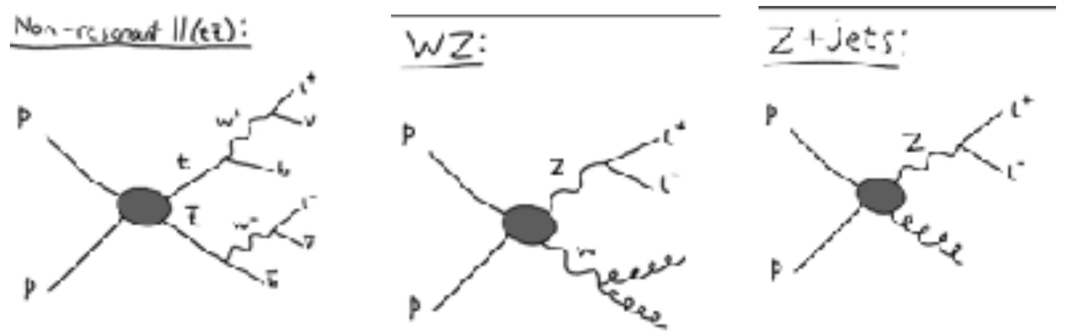
[13 TeV Open Data Link]

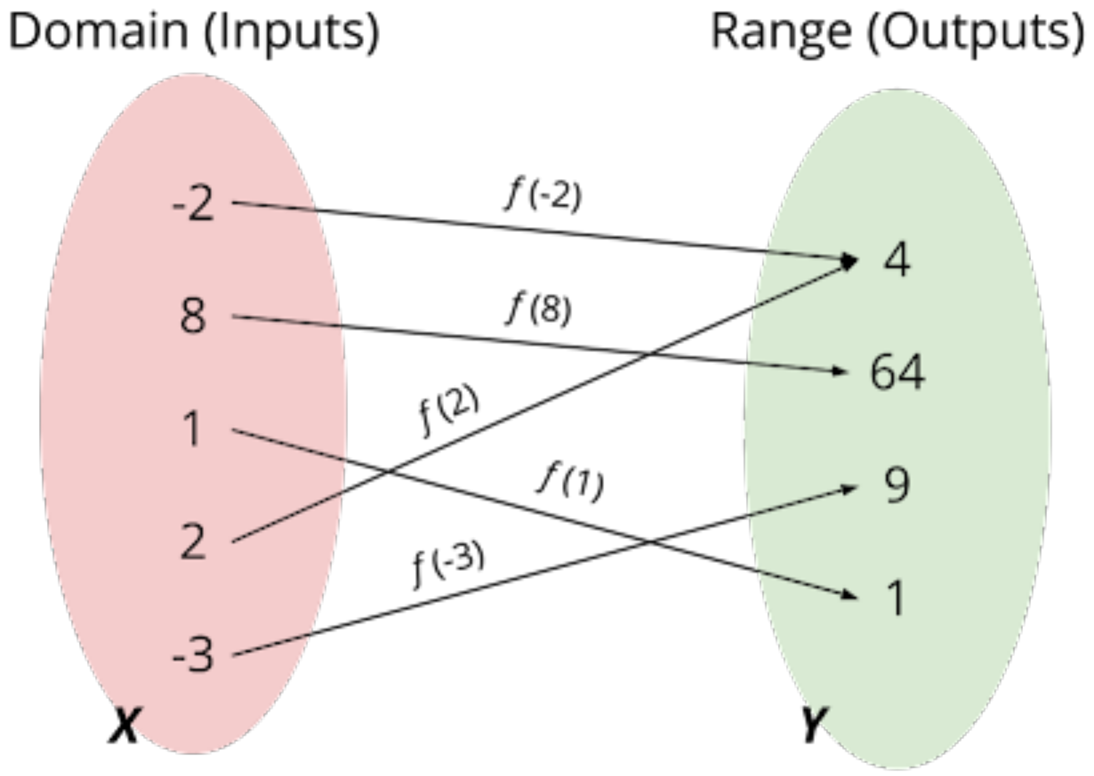
ATLAS Open Data Machine Learning Workbooks

UNIVERSITY OF SUSSEX





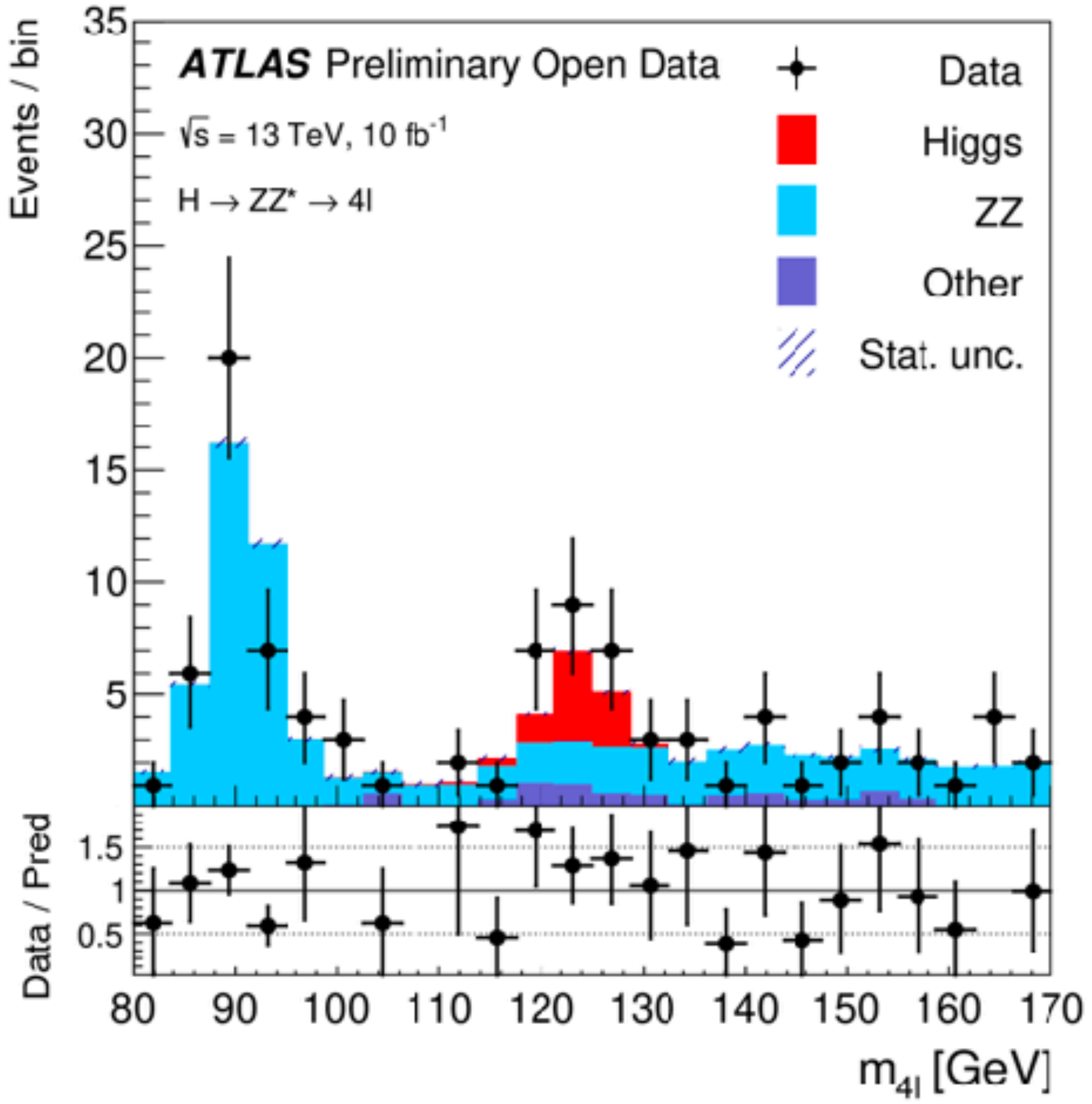


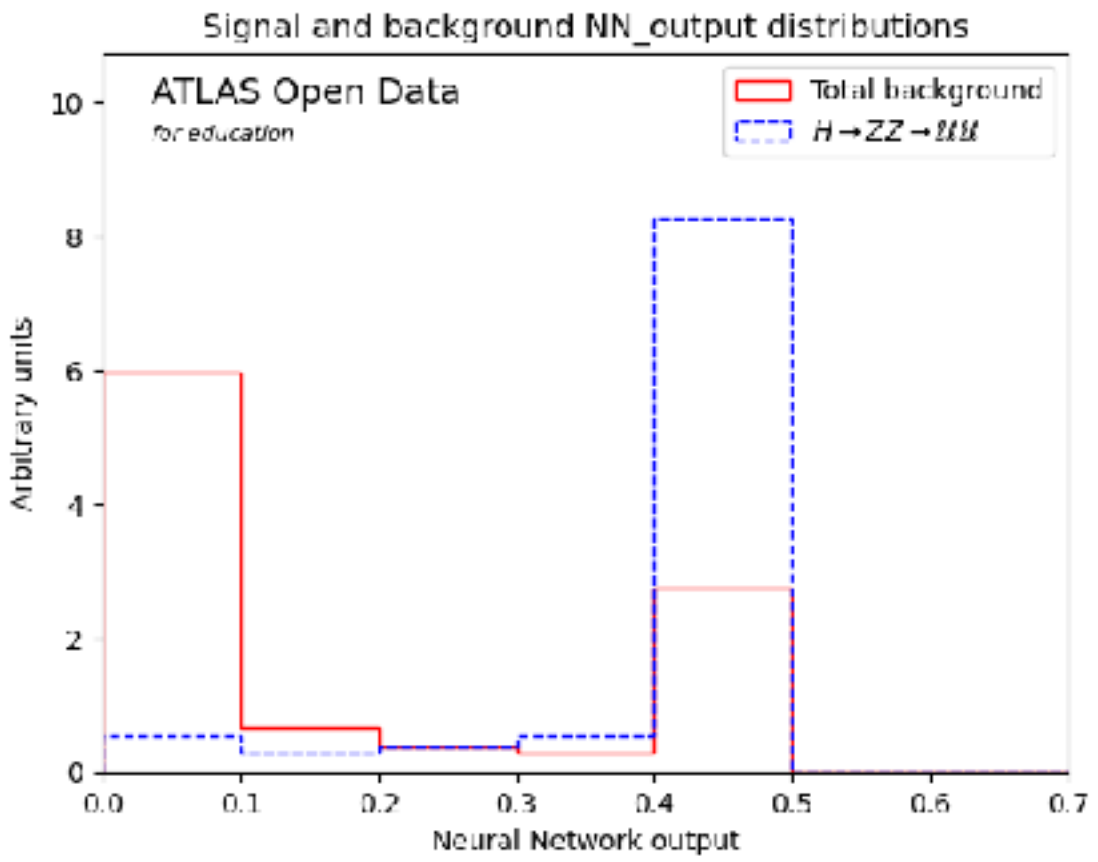


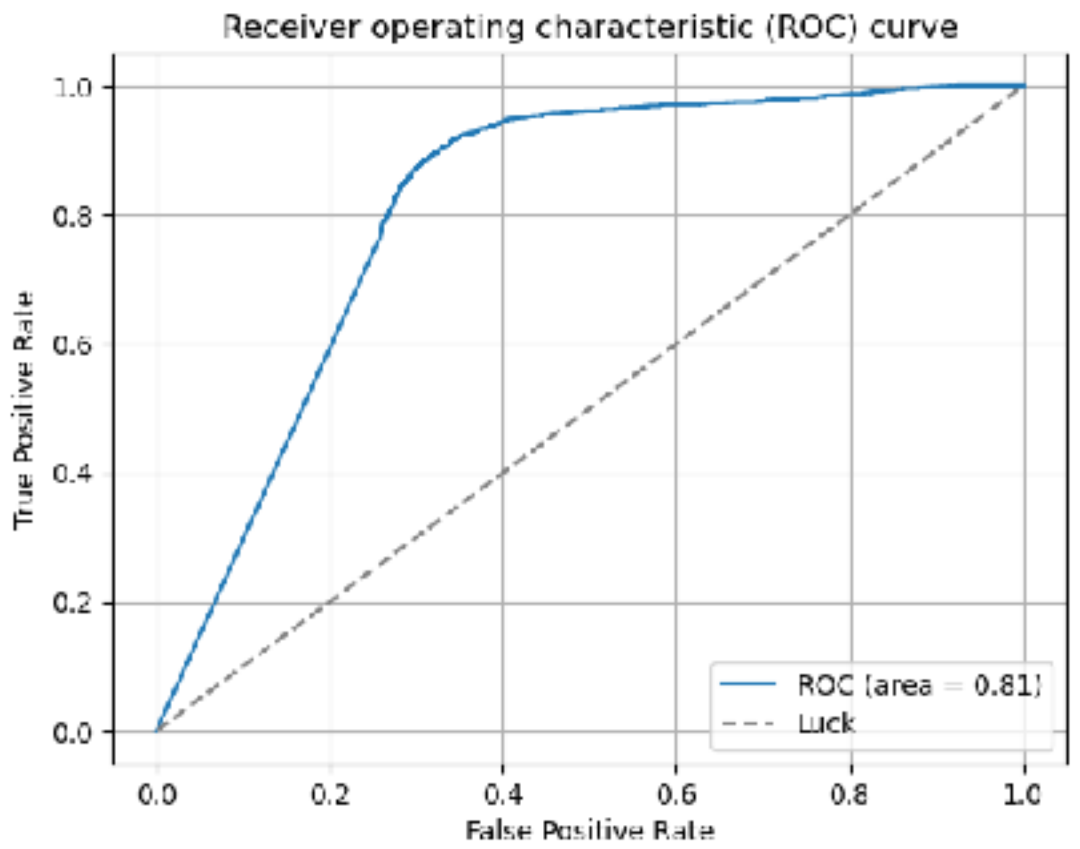
	totalWeight	sum_lep_charge	lead_lep_pt	sublead_lep_pt	mll	ETmiss	dRll	dp
0	0.041298	0	113.229602	37.342027	91.874195	124.311867	1.568130	
1	0.042212	0	89.615922	31.122283	87.832052	105.491891	1.697633	
2	0.061651	0	112.169008	85.336797	87.878298	170.239734	1.030940	
3	0.067919	0	108.710273	93.620256	89.113704	221.266453	0.872517	
4	0.085524	0	85.937289	40.265805	88.230021	132.649672	1.573029	

[Search for Dark Matter Machine Learning Workbook]

Currently being updated but hopefully back soon



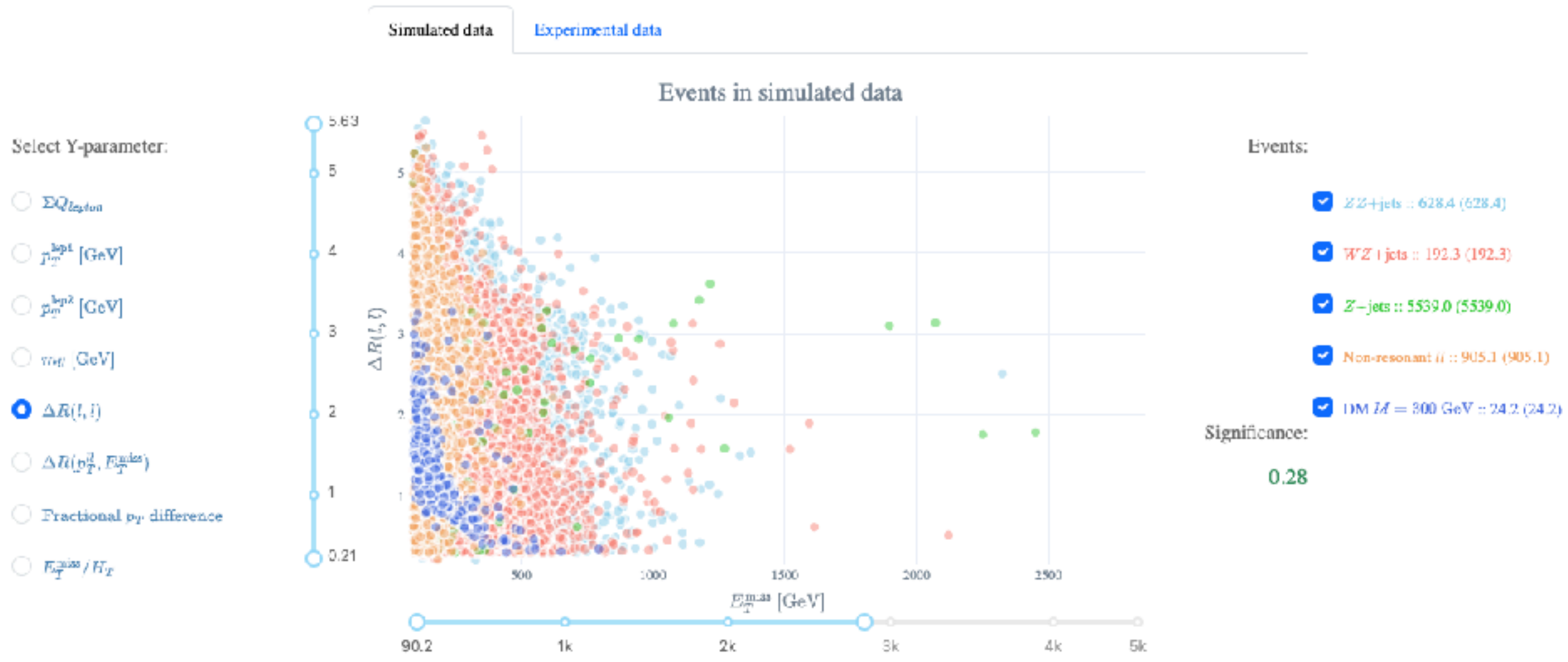




[Rediscover the Higgs Boson Yourself with a Neural Network!]

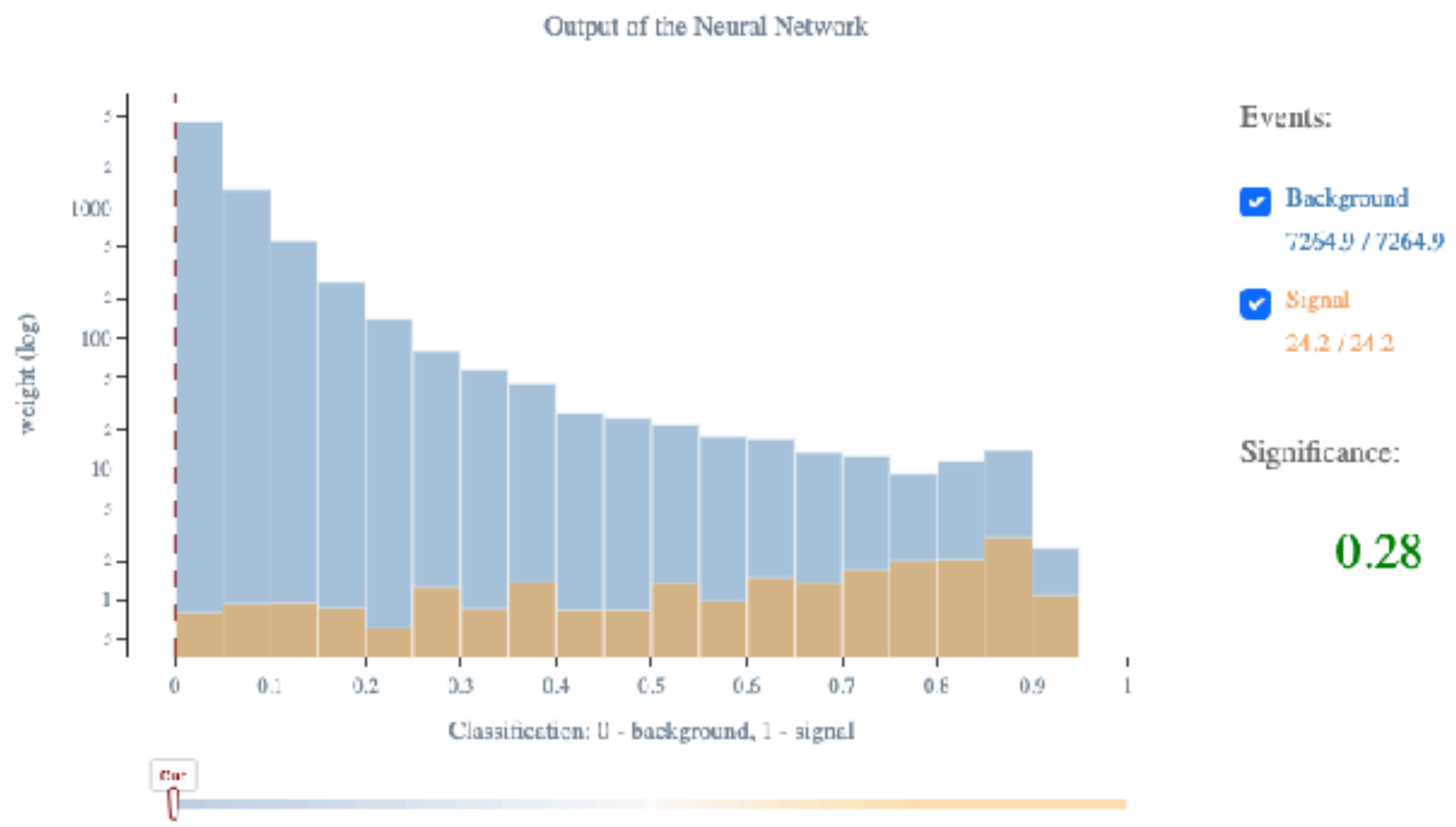
ATLAS Open Data ML Visualisation

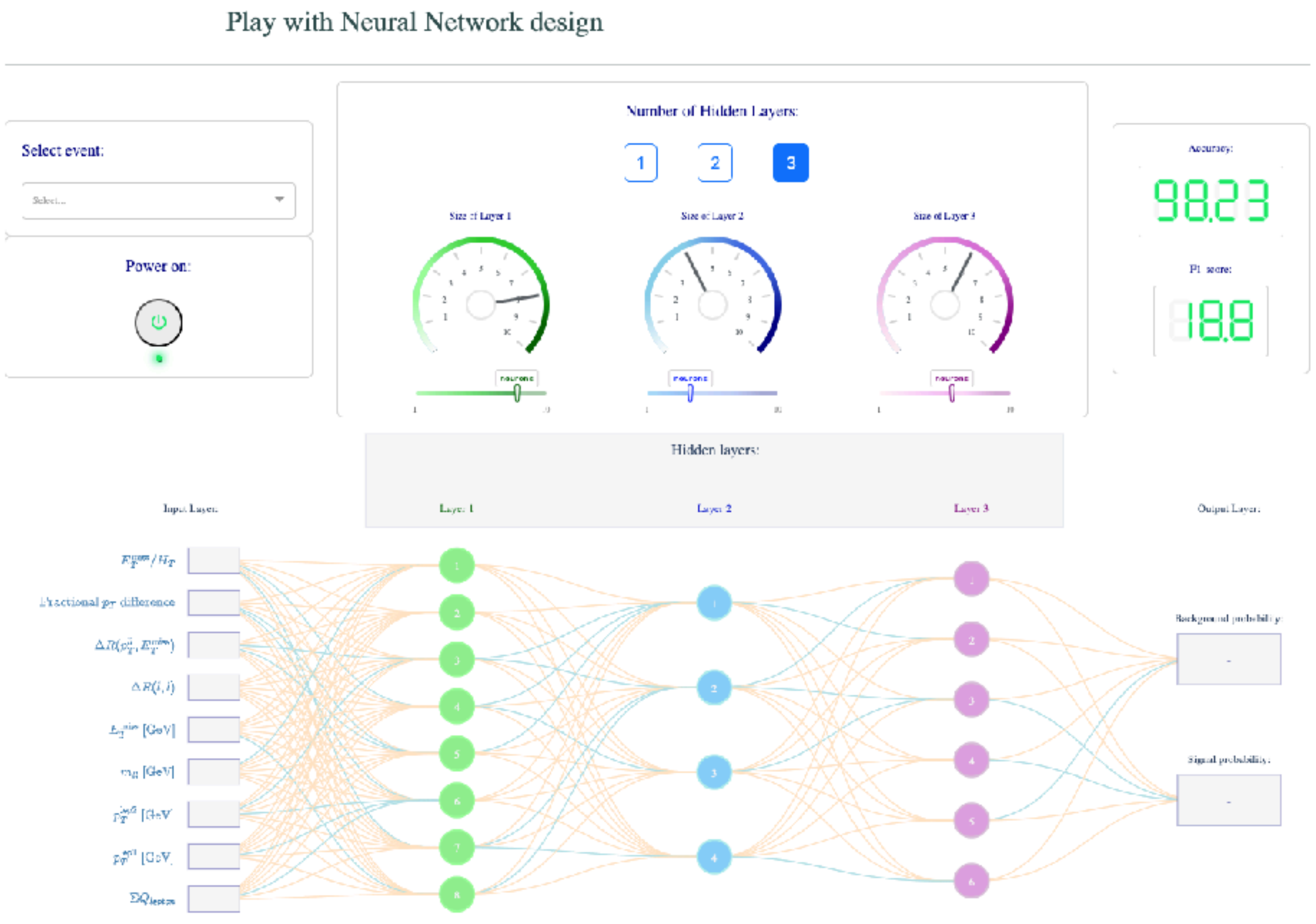
UNIVERSITY OF SUSSEX



https://ml-visual-dashboard-atlas-open-data.app.cern.ch/

- Interactive dashboard to explore the use of machine learning to search for Dark Matter





Summary

- The LHC continues to probe the Standard Model of Particle Physics and to search for new physics beyond it
- Machine learning is core to the work being done currently at the LHC and vital in the future
- Lots of different ways in which ML is used in the experiments from classification to reconstruction
  - Only a few interesting examples shown, many more out there to explore!
- ATLAS Open Data provides many exciting examples of analyses with real collision and simulated data for you to explore!

Thanks!

Happy to answer questions!