On the Hunt for New Particles at the Large Hadron Collider

Flavia de Almeida Dias

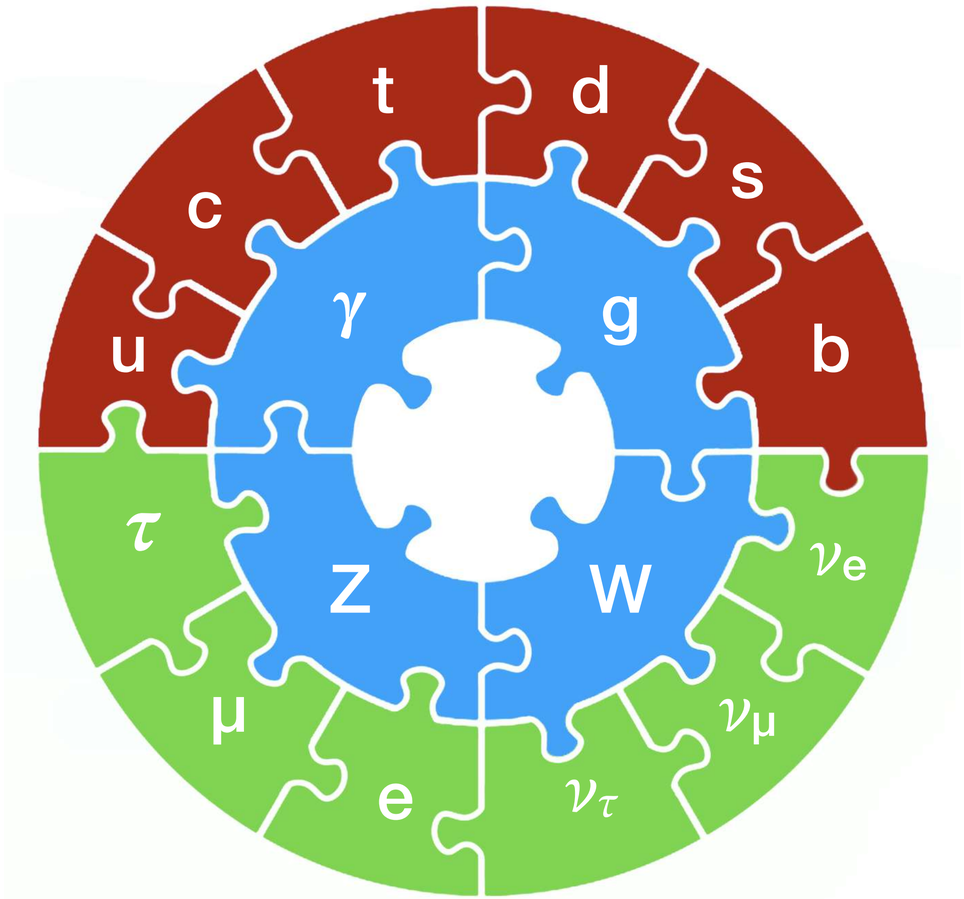
Particle Physics Research Centre Seminar
at Queen Mary University of London

04 June 2025

University of Amsterdam
Institute of Physics

Credit: JWST

Standard Model of Particle Physics



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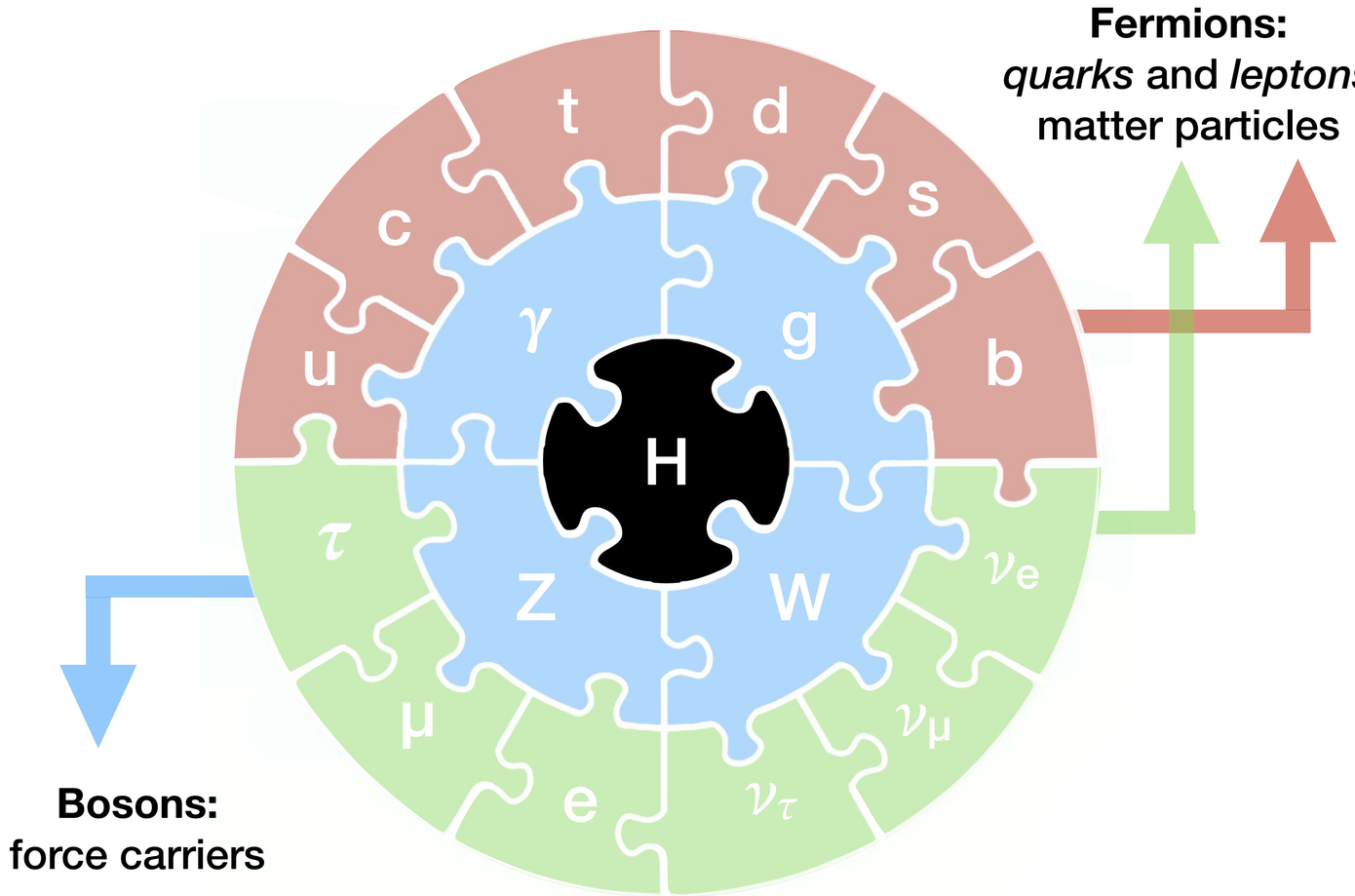

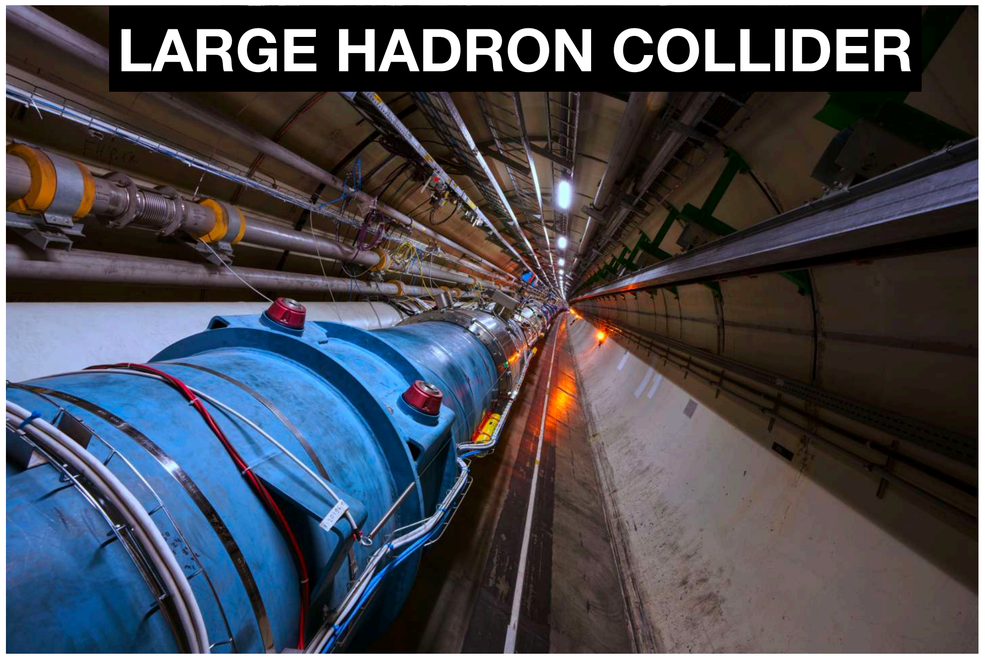

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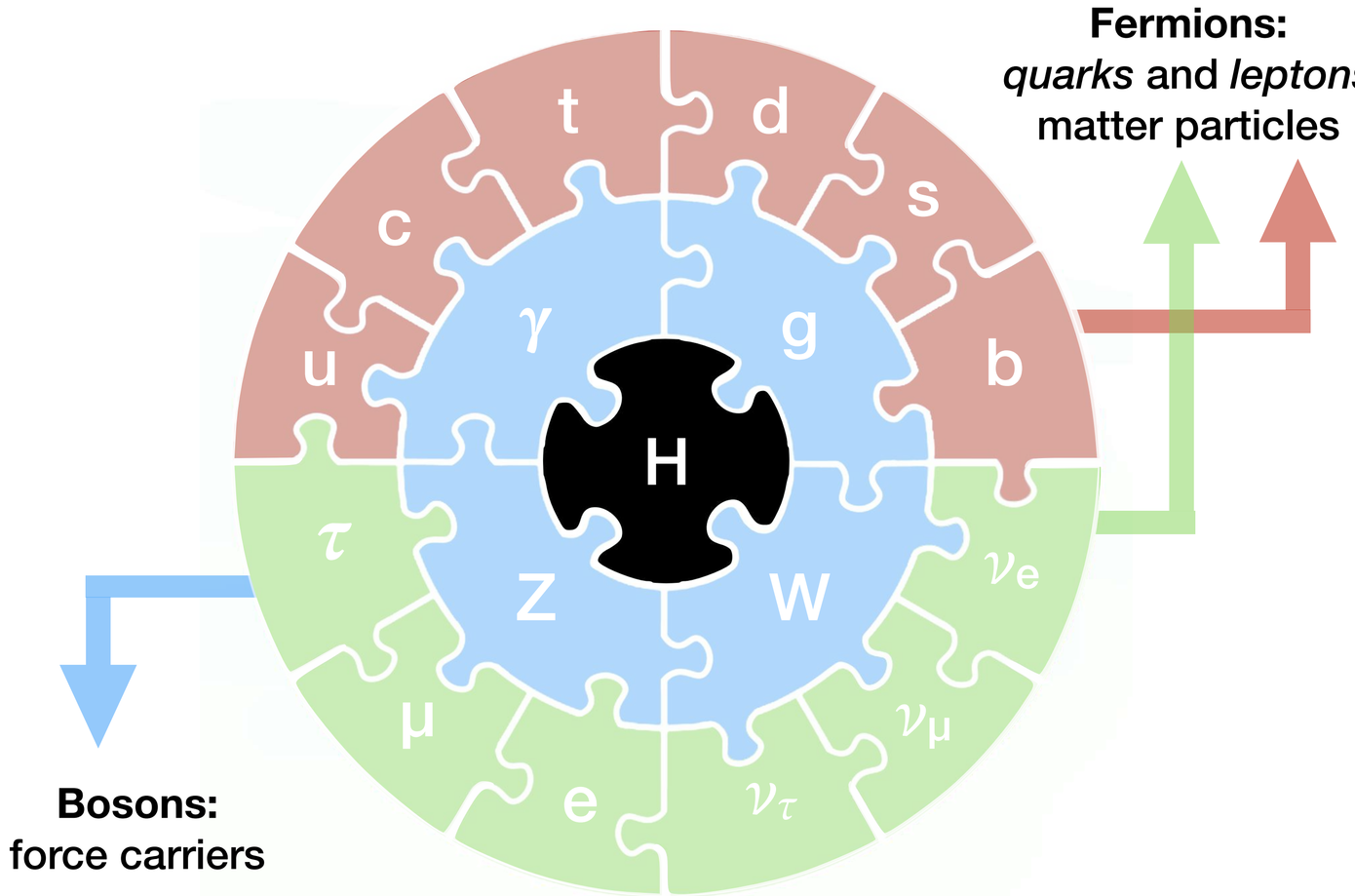
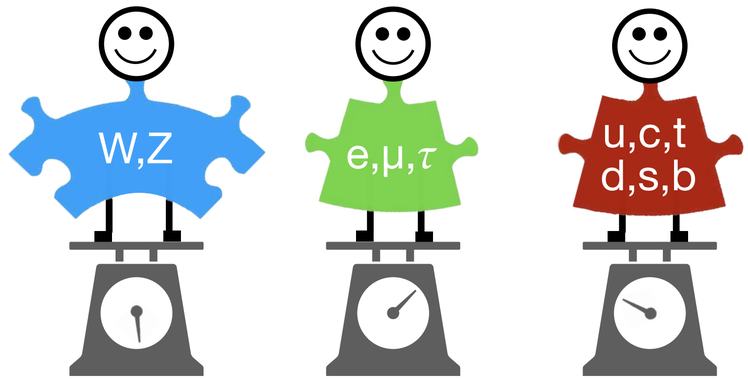
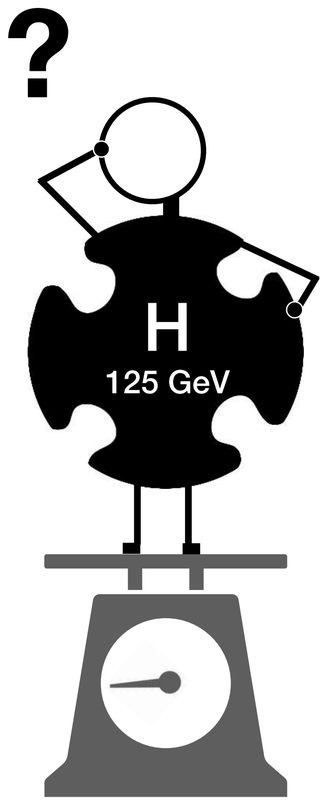


Higgs mechanism



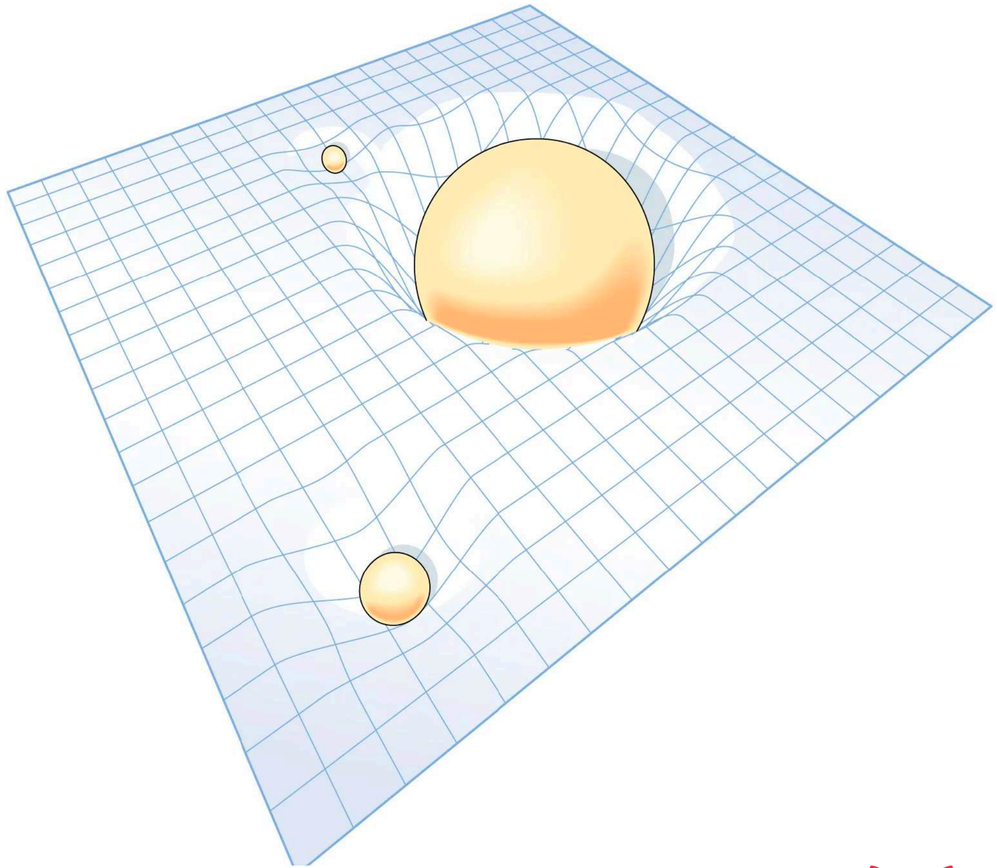
Open questions

Higgs Boson Mass



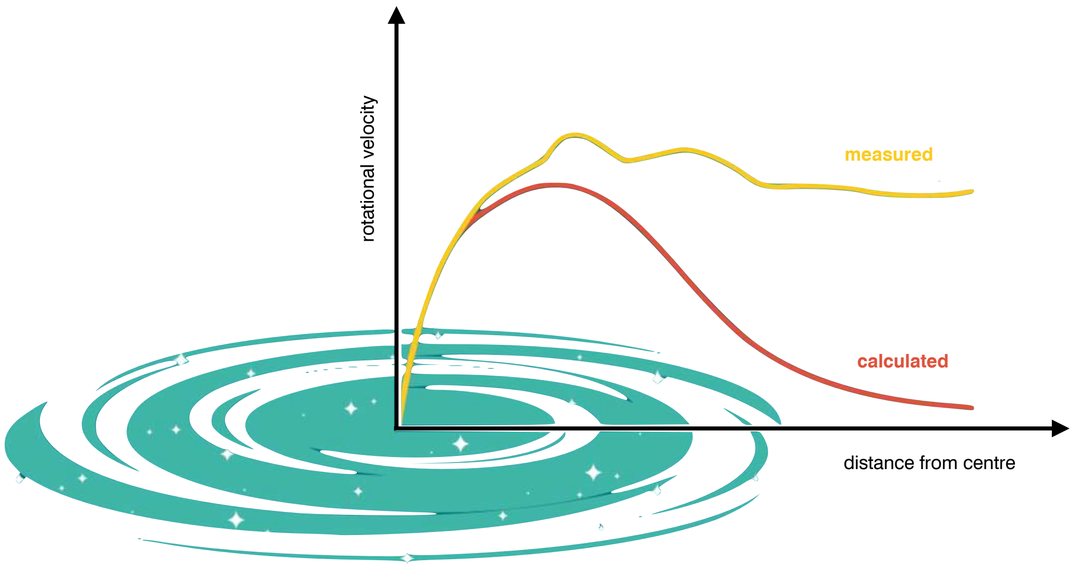
Due to *new particles* or *new interactions*?

Quantum Gravity?



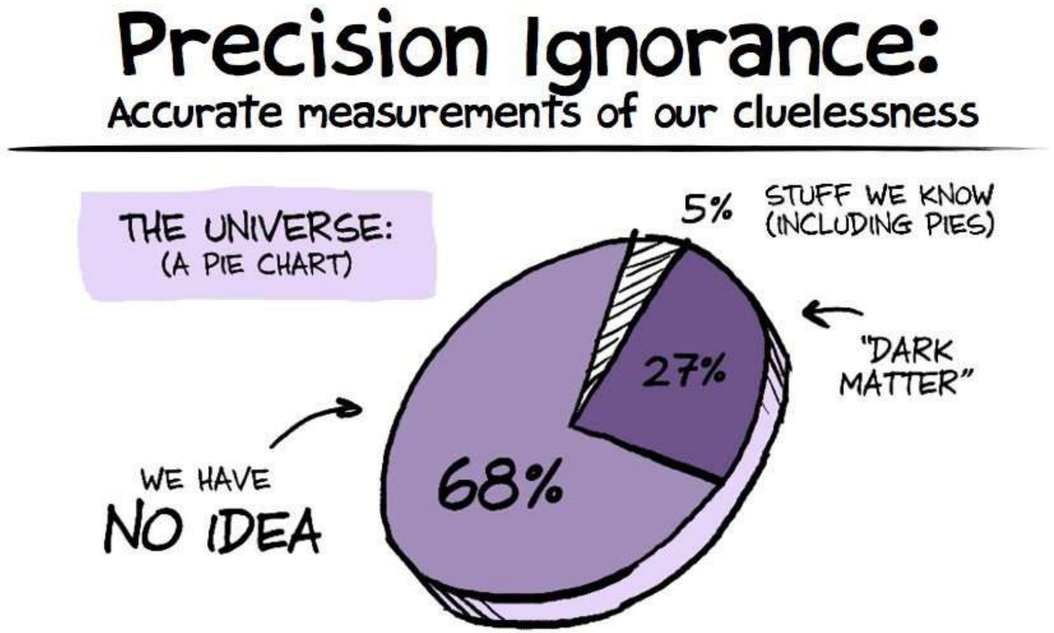
Open questions

Dark Matter



Credit: Higgs Boson & Beyond

Dark Energy

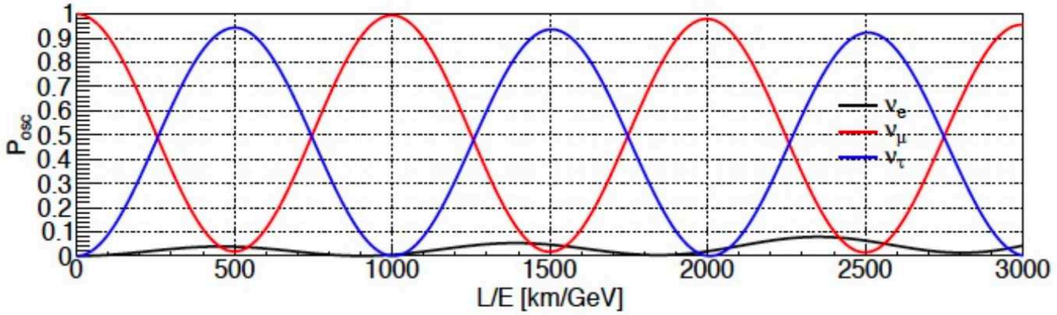


Credit: Cham & Whiteson

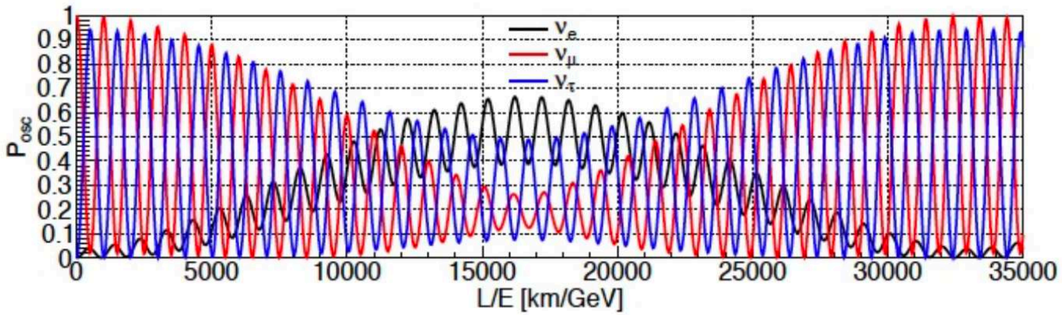
Open questions

Neutrino Masses

Oscillations in vacuum, starting with muon neutrino

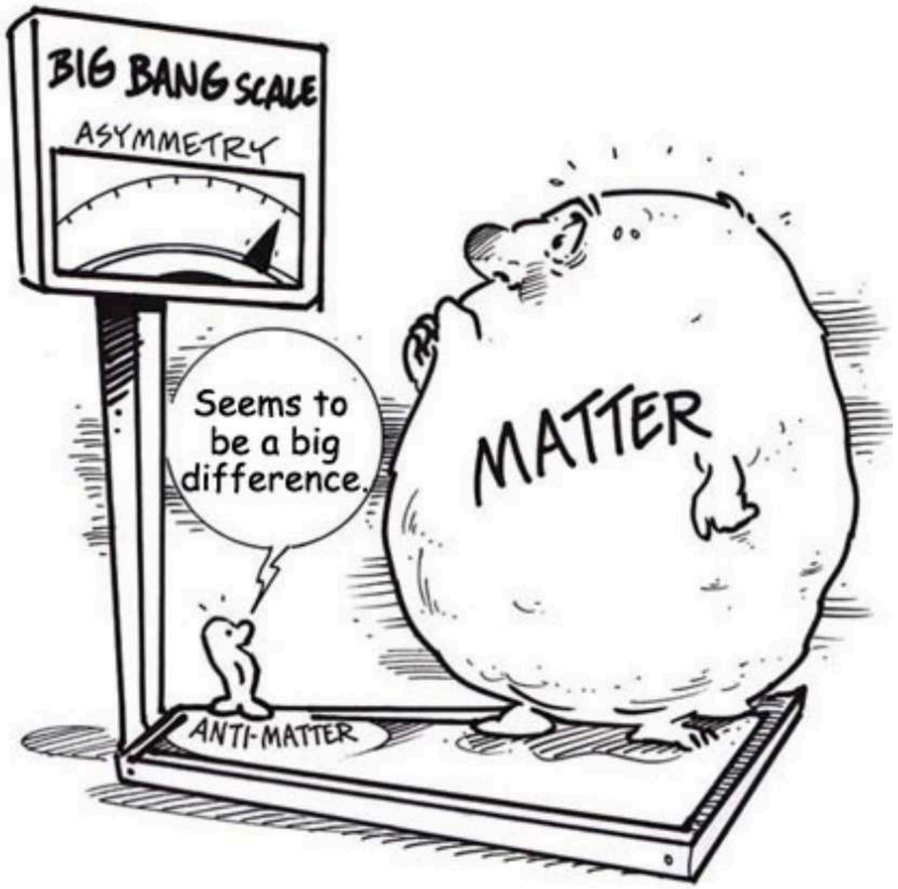


(c) ν_μ, short range



(d) ν_μ, long range

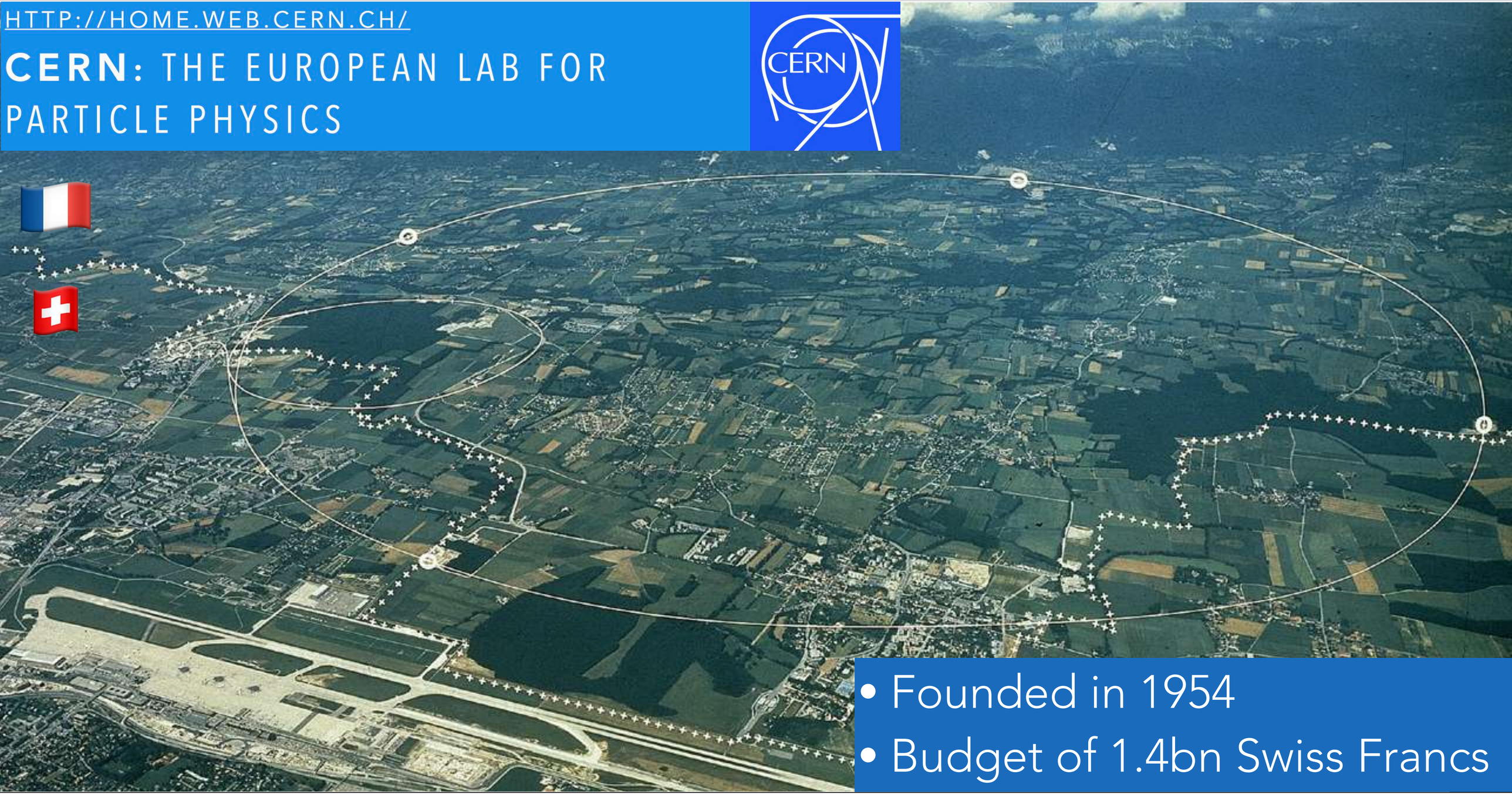
Matter-Antimatter Asymmetry



There must be something new to explain all these open questions!

HTTP://HOME.WEB.CERN.CH/

CERN: THE EUROPEAN LAB FOR PARTICLE PHYSICS



- Founded in 1954
- Budget of 1.4bn Swiss Francs

An European-Centric Global Endeavour

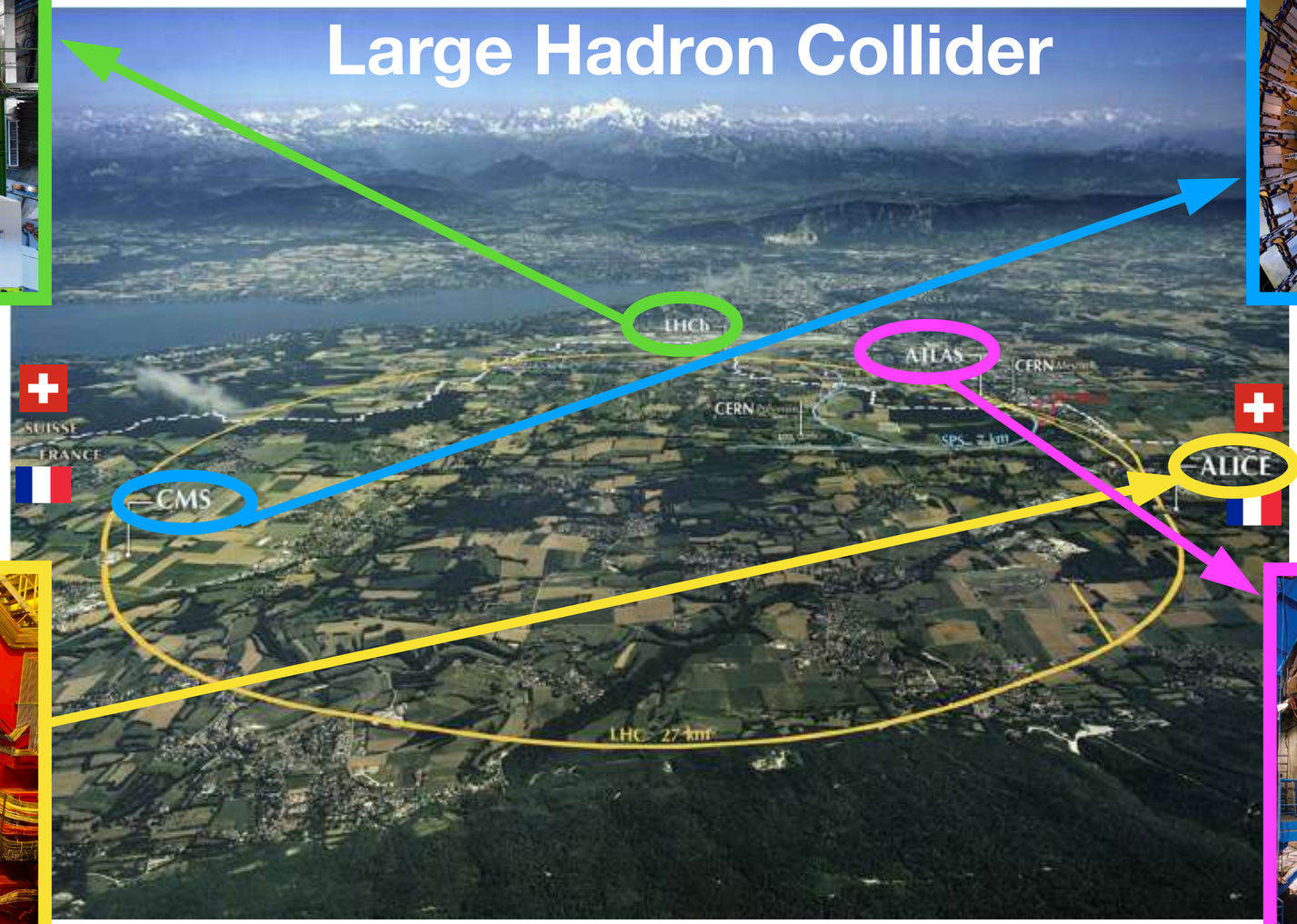
24 Member States (including UK)

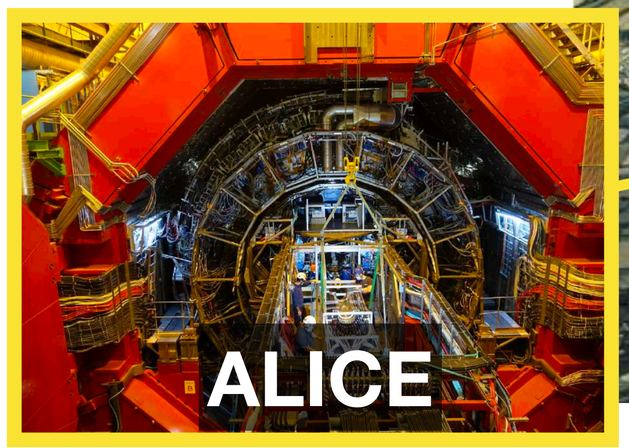
8 Associate Member States (including Brazil)

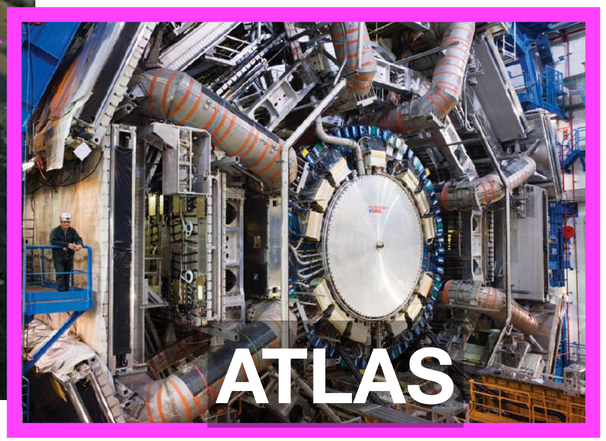
5 Observers (including USA, Japan, EU)

58 Collaborating Non-Member States, Territories and Regions

Over 100 nationalities working in CERN experiments

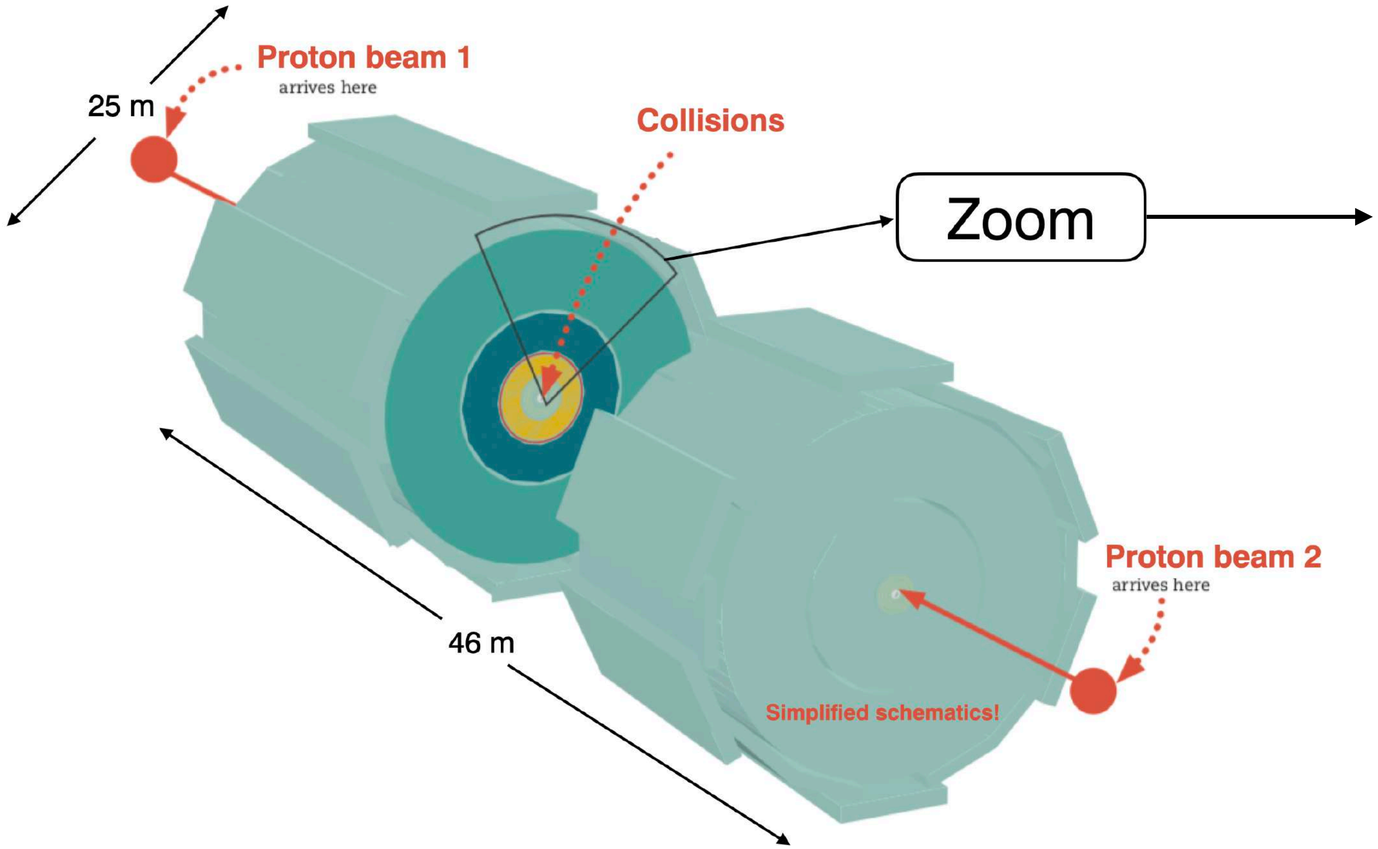


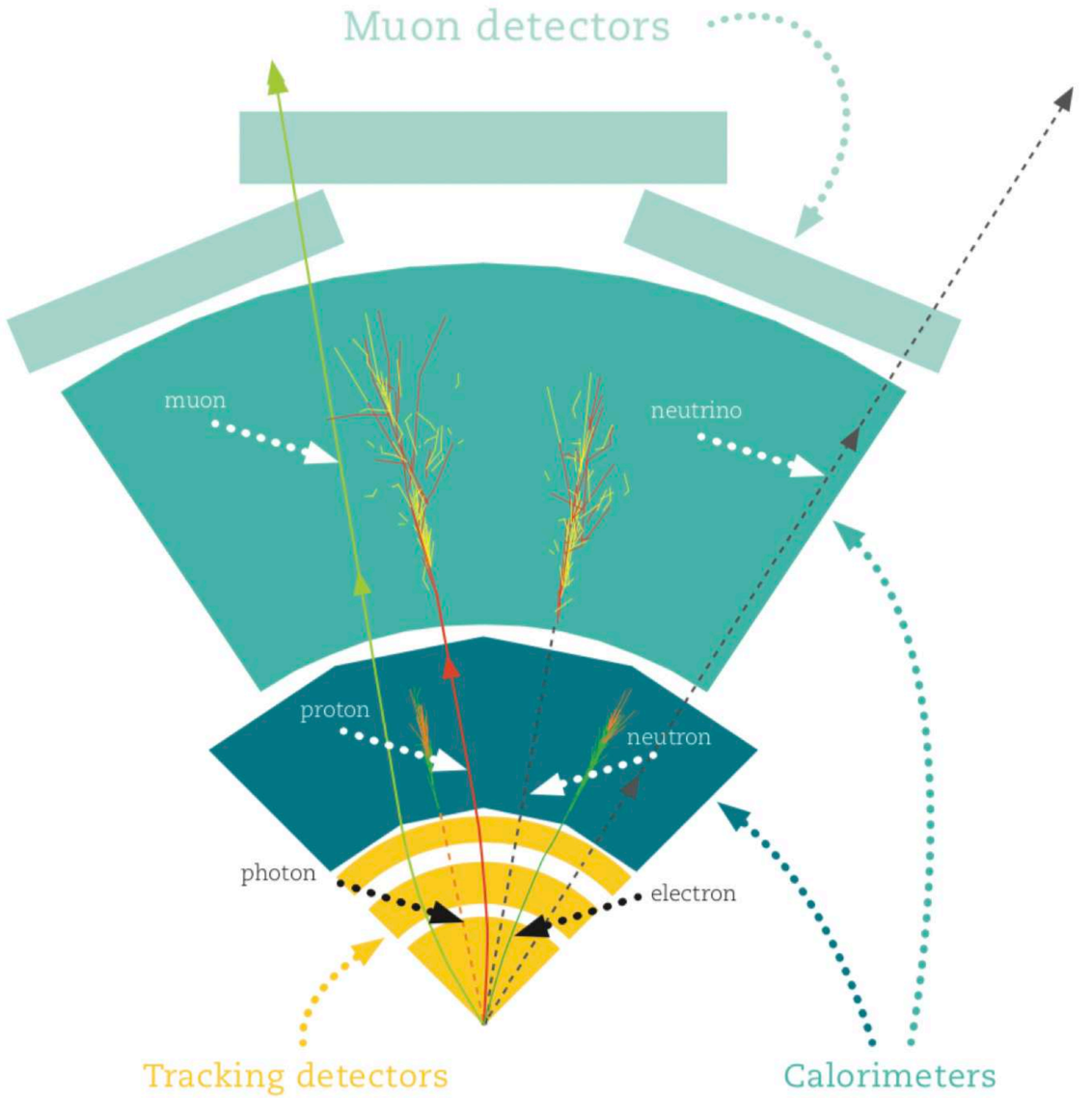




Credit (all images): cds.cern.ch

General-Purpose Particle Detectors





Early Searches Beyond the Standard Model at the LHC

Direct Searches in Colliders

Tevatron (Fermilab, USA)

Up to 1.96 TeV (proton-antiproton)
~10 fb^{-1} delivered integrated luminosity

LHC Run 1 (2009 - 2013)

7 - 8 TeV (proton-proton)
~5+22 fb^{-1} delivered integrated luminosity

Tevatron to LHC Run 1

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MORE ENERGY
HEAVIER PARTICLES

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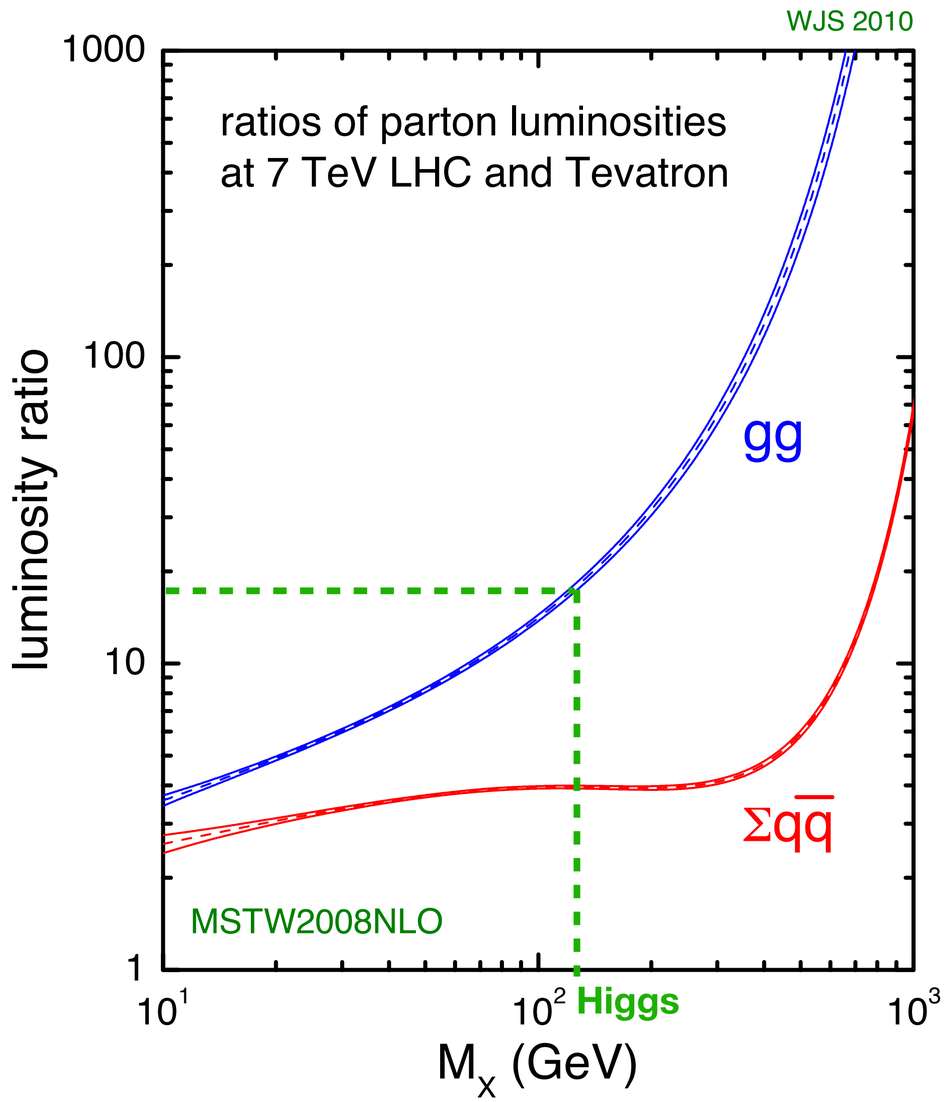

LHC Run 1 to Run 2

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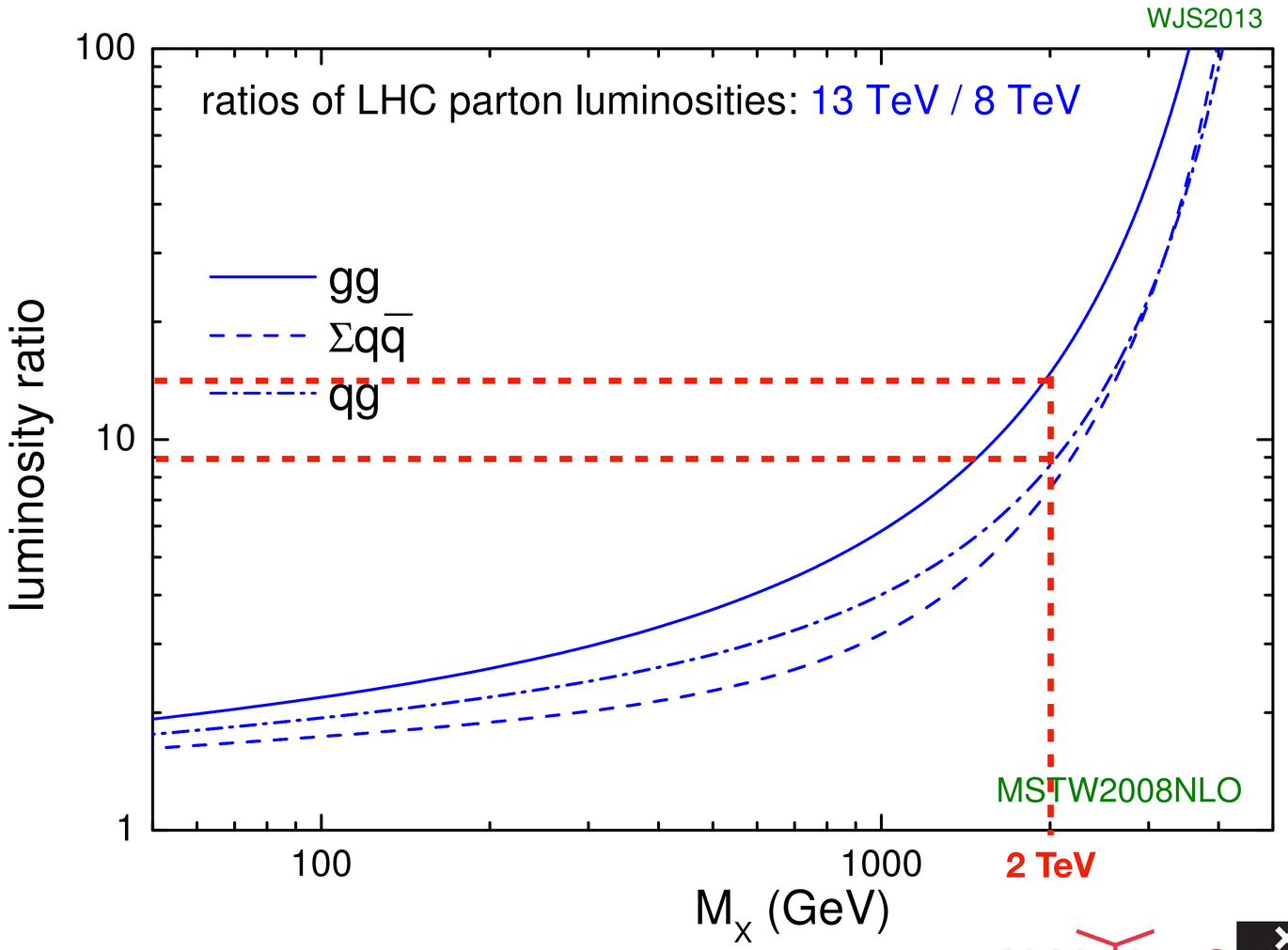
HEAVIER PARTICLES

LHC Run 2 (2015 - 2018)

13 TeV (proton-proton)
~150 fb^{-1} delivered integrated luminosity



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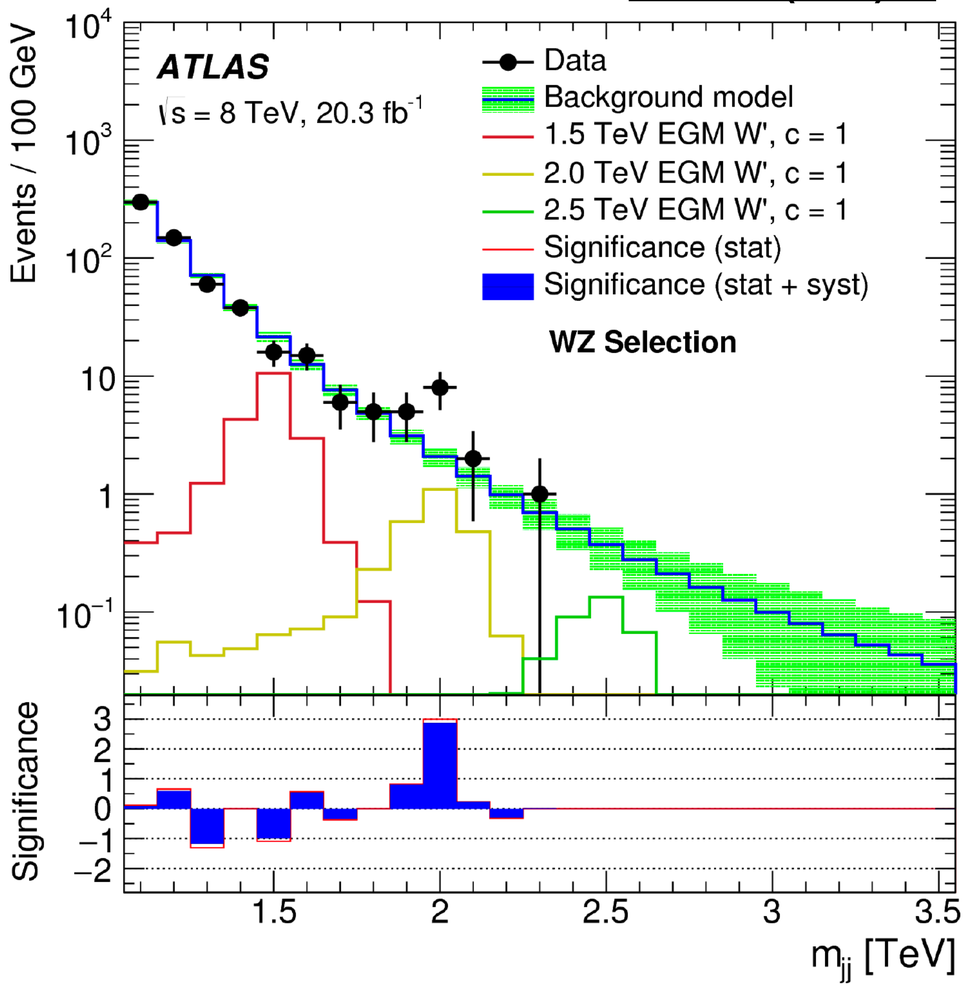

Quickly ruled out with 3.2 fb^{-1} of Run 2 data ☹

With increasing energy in each run, direct searches made sense!

ATLAS Searches Status - Run 2

- Over ~1000 active physicists in searches

  ➡ Full Run-2:

  - ~250 public results
    (~200 papers, ~30 CONF notes, ~20 PUB notes)
  - More legacy Run 2 results still to come
  - ~500 results for all of LHC datasets so far

- Bottomline: no **significant** excess seen in Run 2 searches

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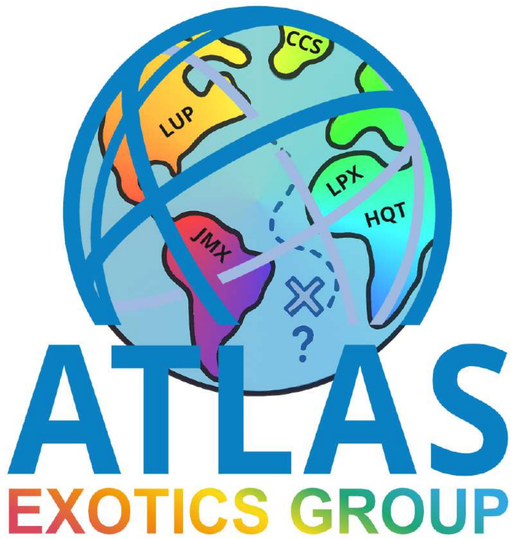
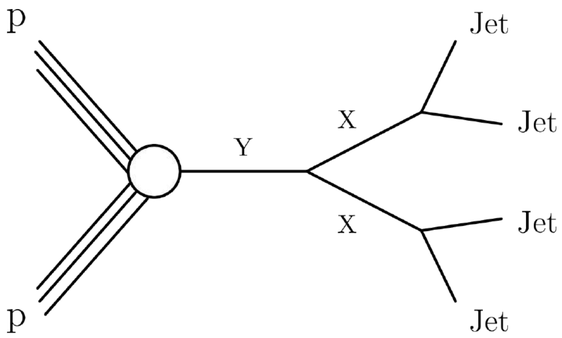
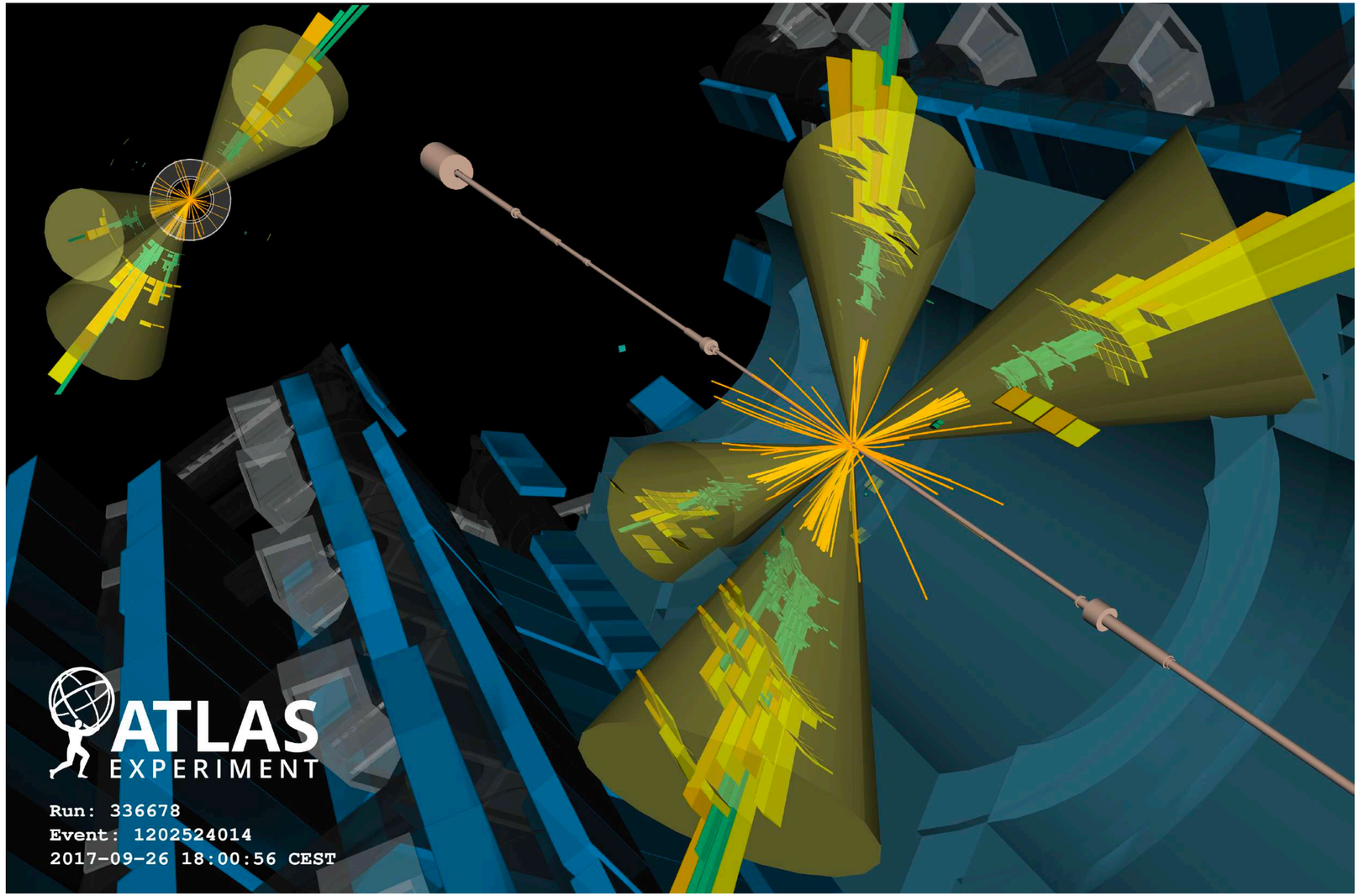
As of October 2024:



Searches in Run 2 - Hints?





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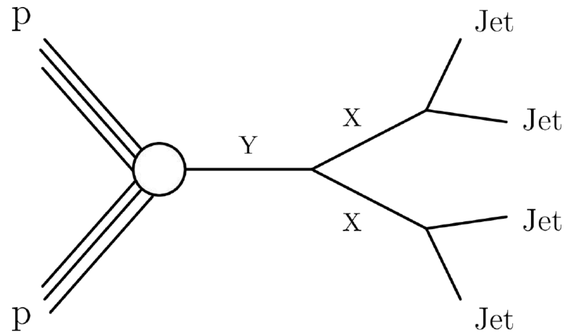
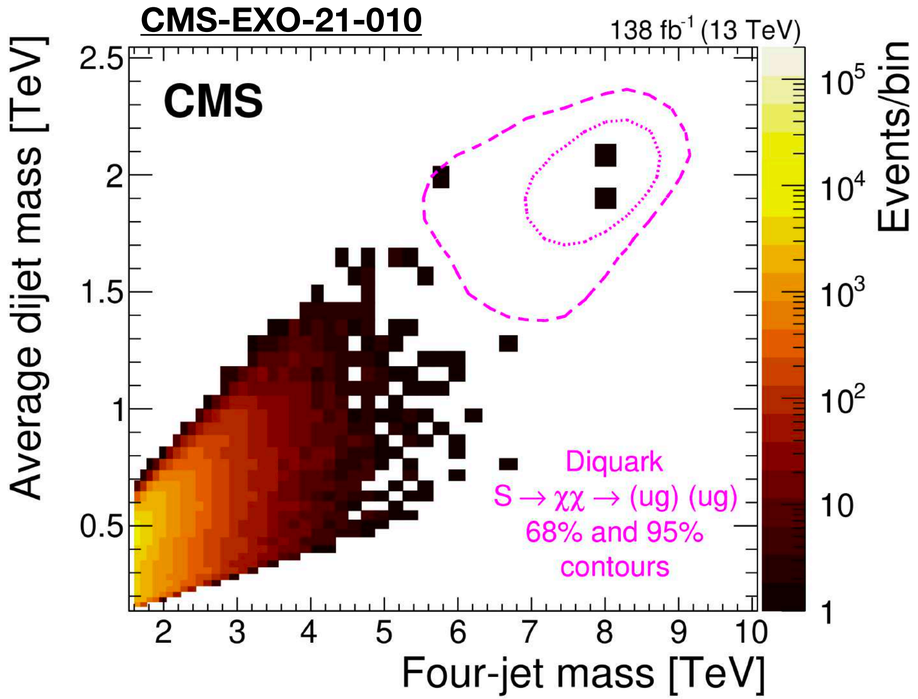
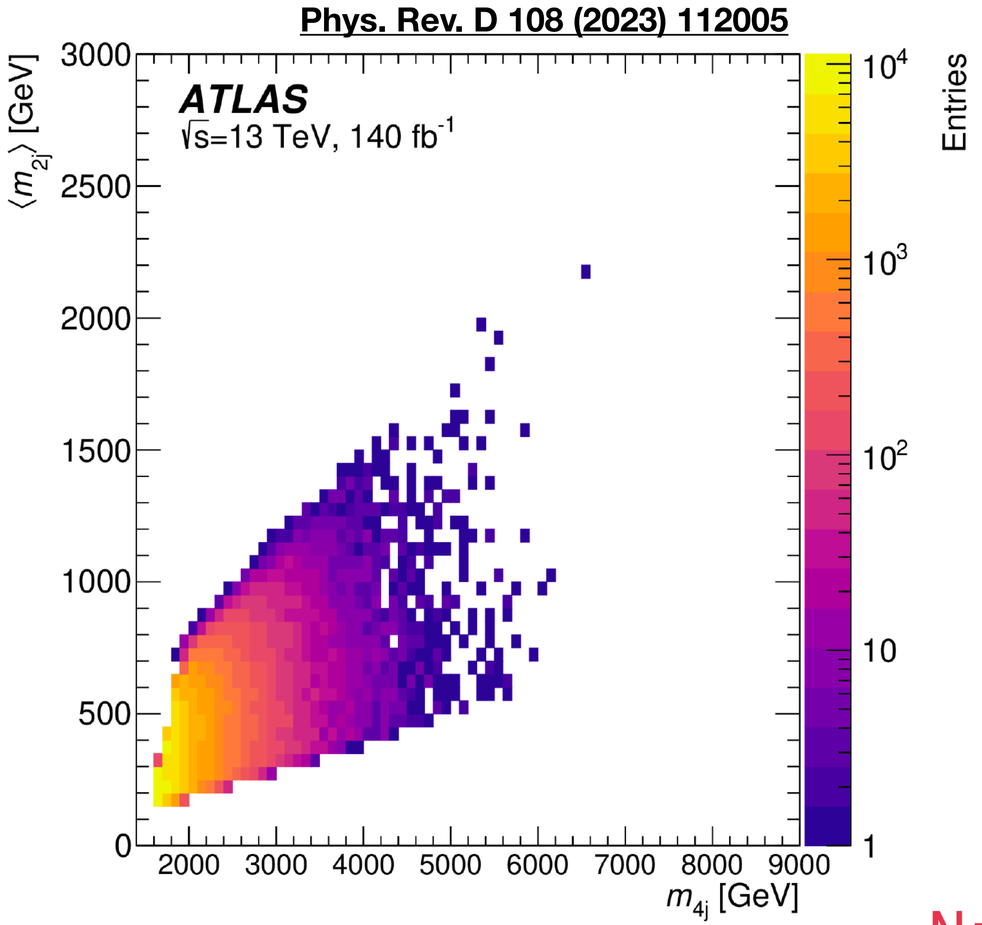




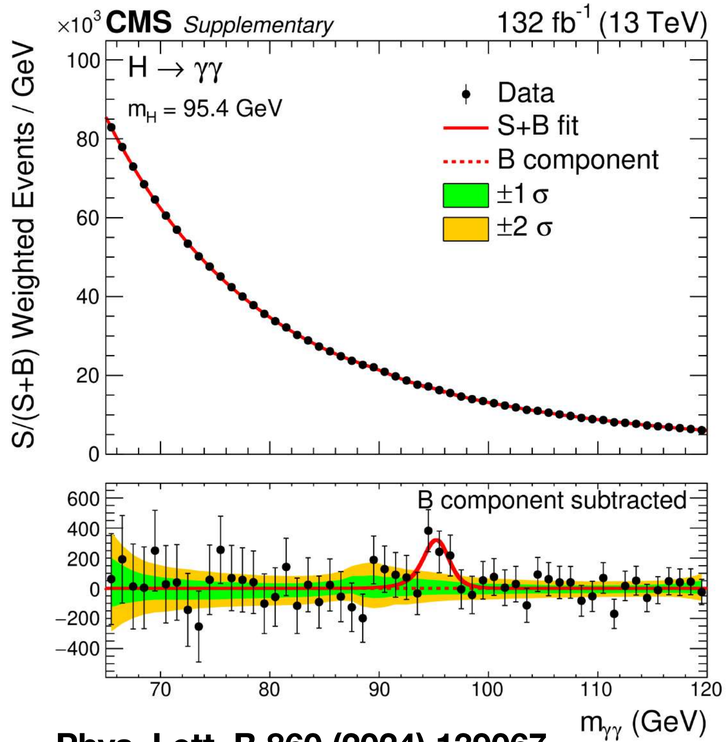
3.9σ (1.6σ) local (global) significance



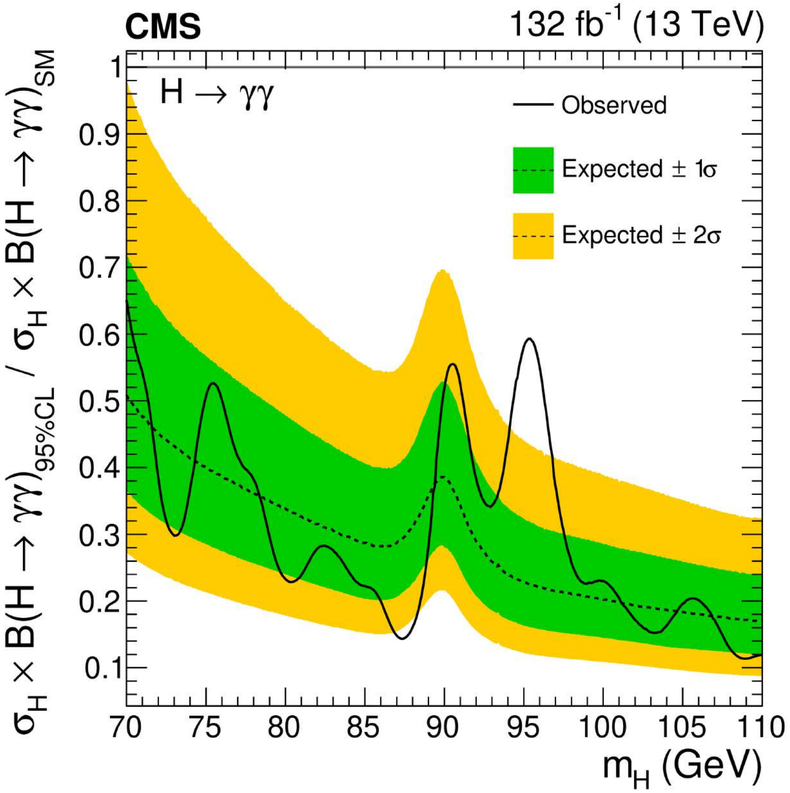
No events at 8 TeV

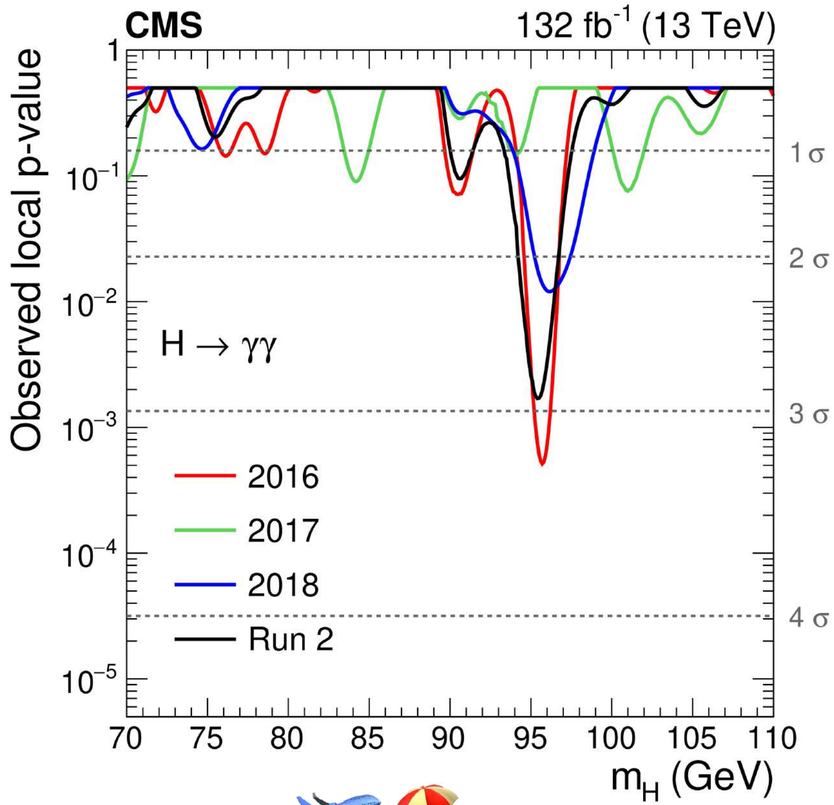
Searches in Run 2 - Hints?

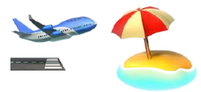
- Higgs-like resonance search in low mass ($70\ \text{GeV} < m_H < 110\ \text{GeV}$) di-photon spectrum



Phys. Lett. B 860 (2024) 139067







2017

Modest excess with ~2.9σ local (1.3σ global) significance at $m_{\gamma\gamma}$ = 95.4 GeV

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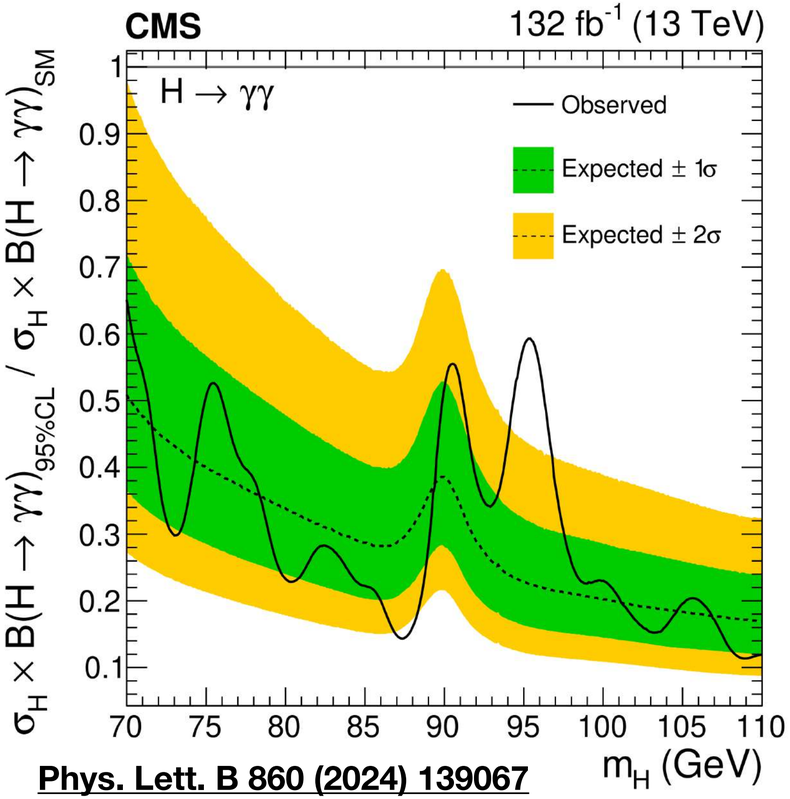

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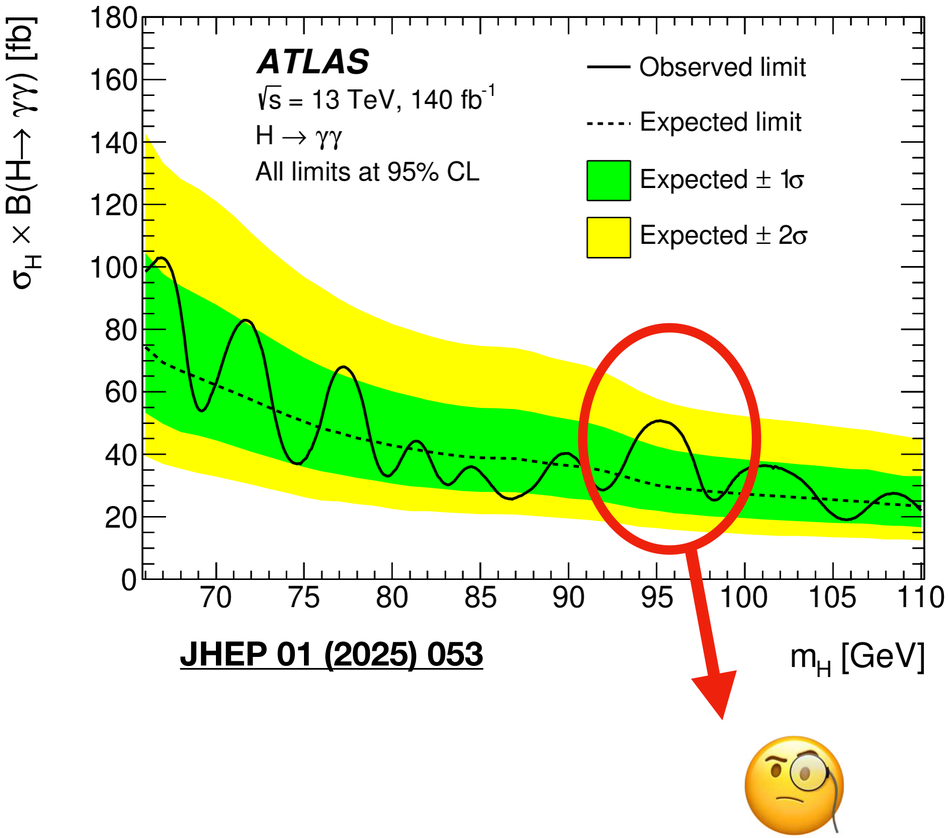
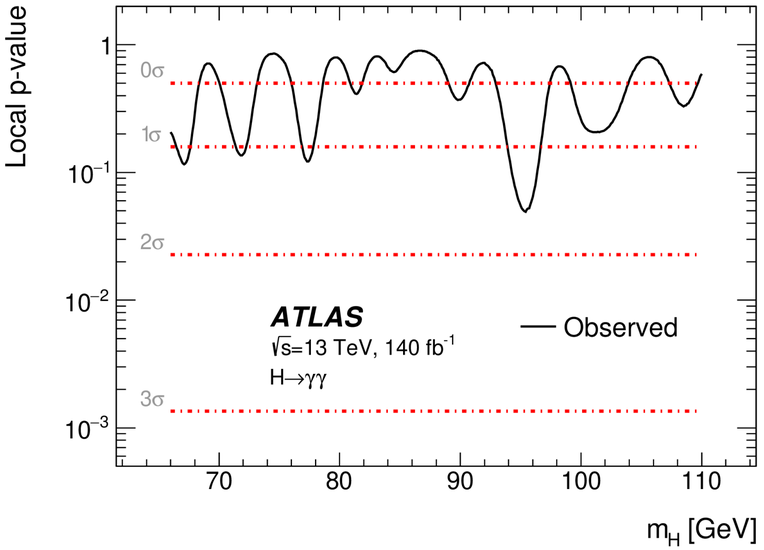


JHEP 01 (2025) 053



LHC Run 2 to Run 3

LHC Run 2 (2015 - 2018)

13 TeV (proton-proton)
~150 fb^{-1} delivered integrated luminosity

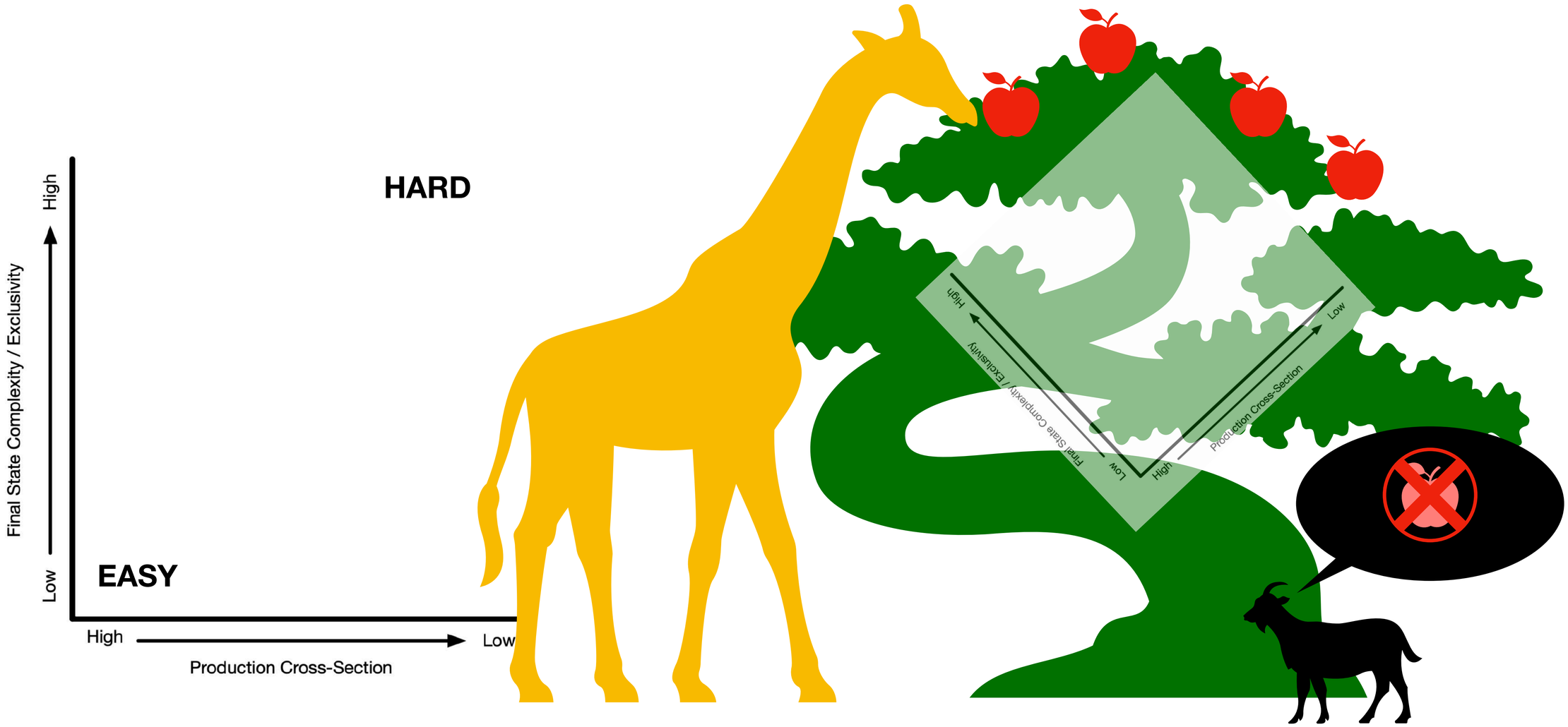
MORE DATA
~SAME ENERGY

LHC Run 3 (2022 - 2026)

13.6 TeV (proton-proton)
~200 fb^{-1} delivered integrated luminosity
~300 fb^{-1} planned by the end of the run

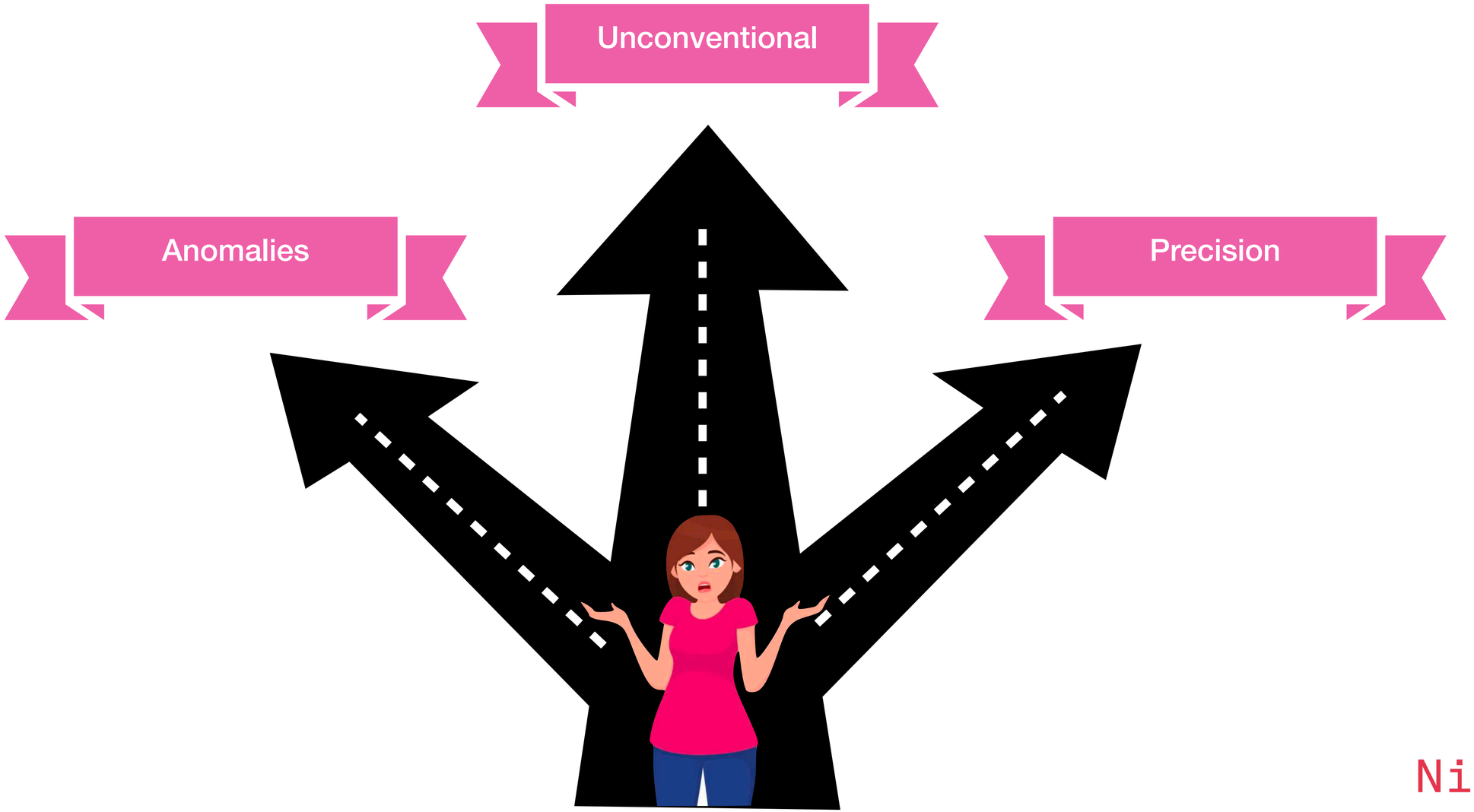
BSM Searches

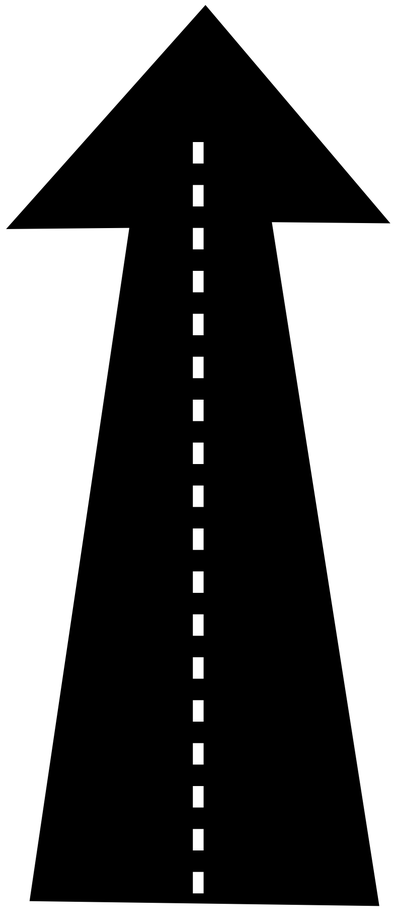
Analogy adapted from Dr. Dan Hayden from MSU



Disclaimer: biology not scientifically sound!

Searches in Run 3 and Beyond





Unconventional Signatures

Unconventional Signatures in the ATLAS Detector

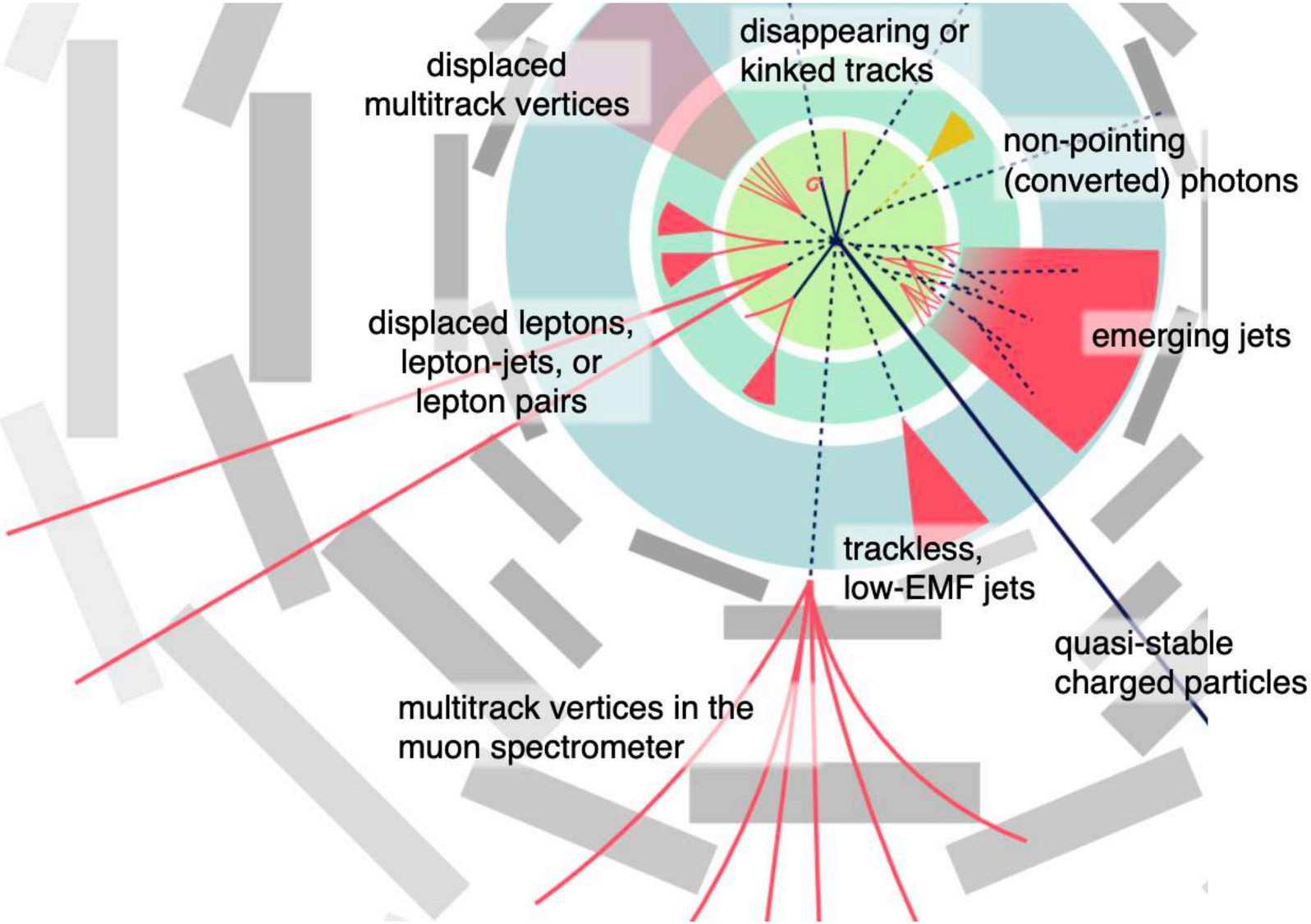


Figure from H. Russell

Unconventional Signatures in the ATLAS Detector

ATLAS & CMS were not designed for LLP searches: custom reconstruction and techniques needed for these unusual signatures!

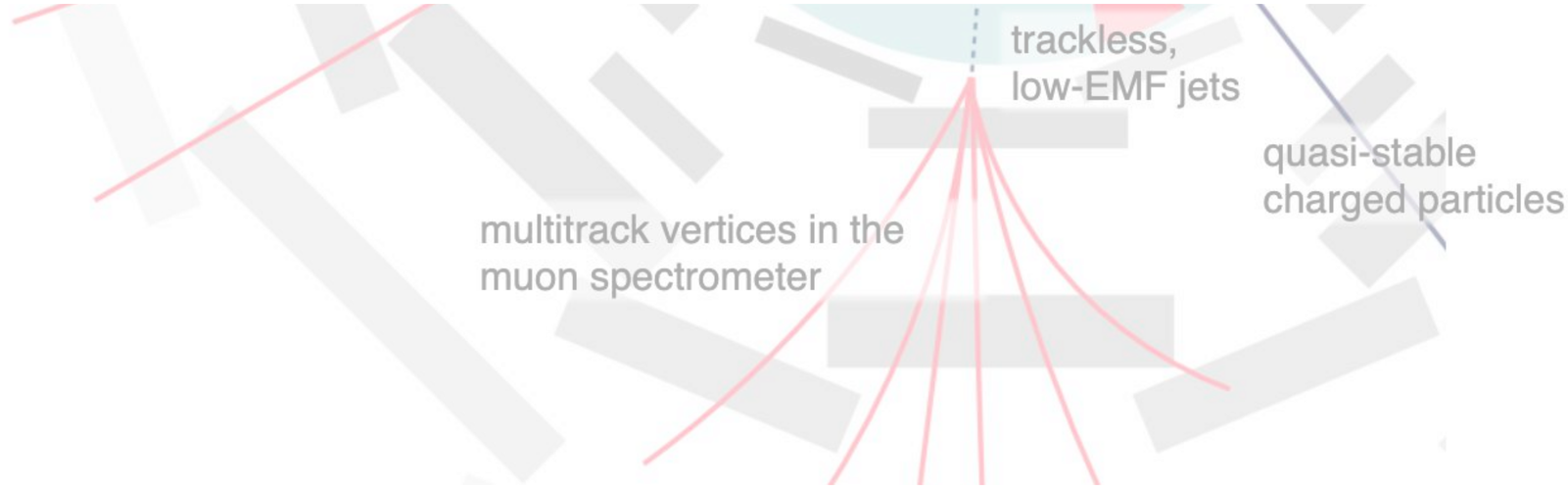


Figure from H. Russell

Dark Matter Searches: Beyond WIMP

- Hidden sector DM models
  - ➡ DM sector with its own forces, scalars, gauge bosons, which is separate from the SM
  - ➡ Connected by a small operator: via gravity or other new particles mediators (dark photon, sterile neutrino, axion, pseudo-scalar, axial vector) - *"portals"*

Dark Matter Searches: Dark QCD

- Unusual topologies and hidden corners of the phase space
  - ➡ **Dark jets**: Dark hadrons decaying promptly in a QCD-like fashion (visibly)
  - ➡ **Semi-visible jets**: Partial decays into visible sector
  - ➡ **Emerging jets**: Dark hadrons undergoing displaced decays in a QCD-like fashion

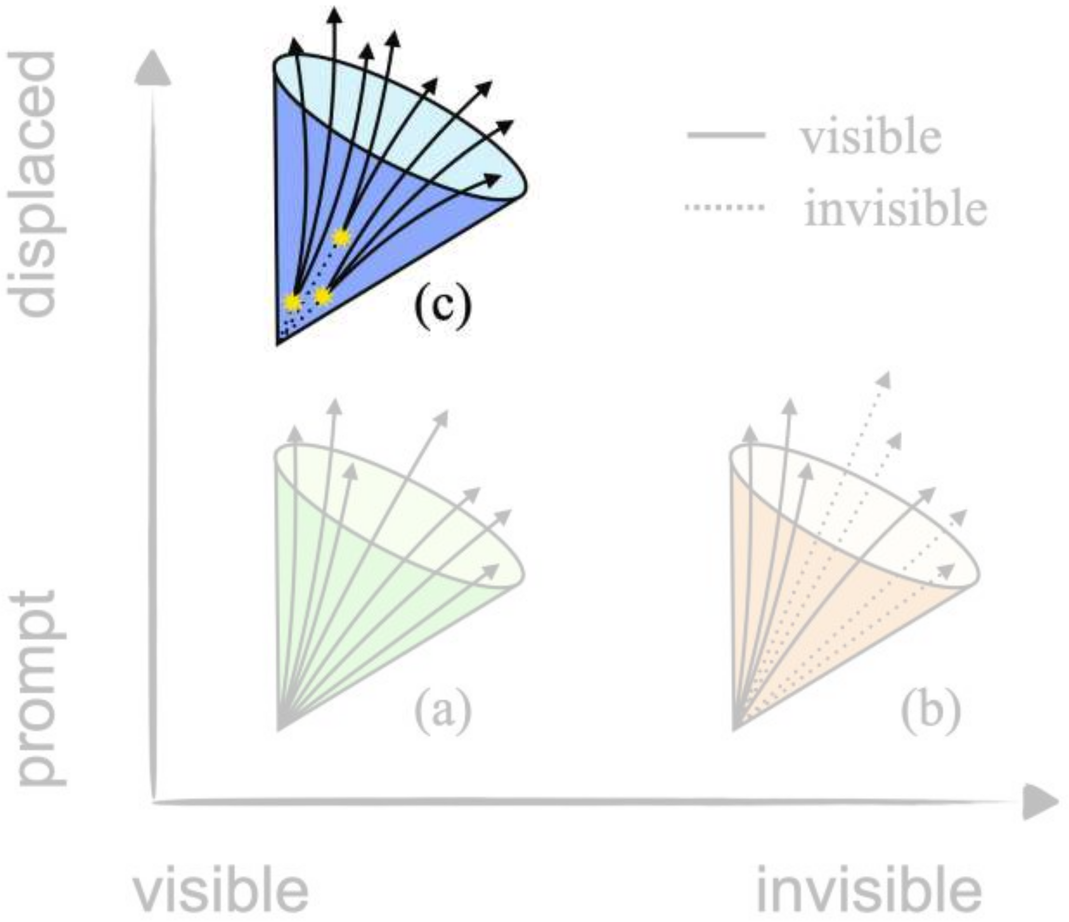
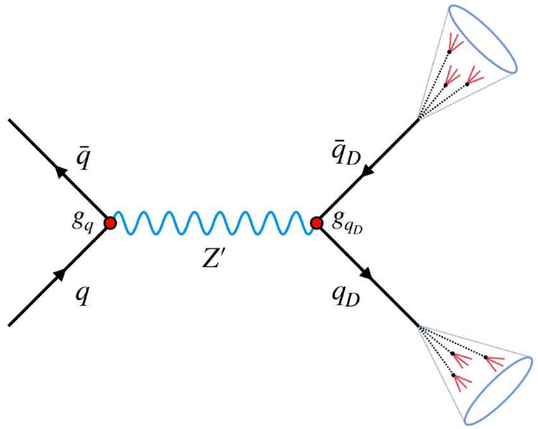


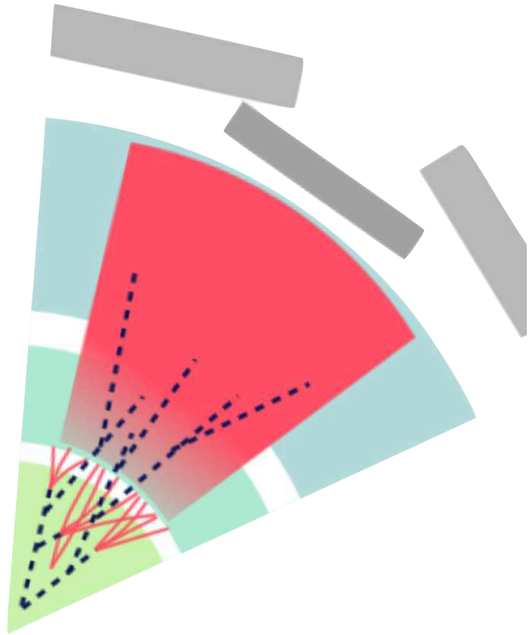
Image source

Emerging Jets - Run 3 Data

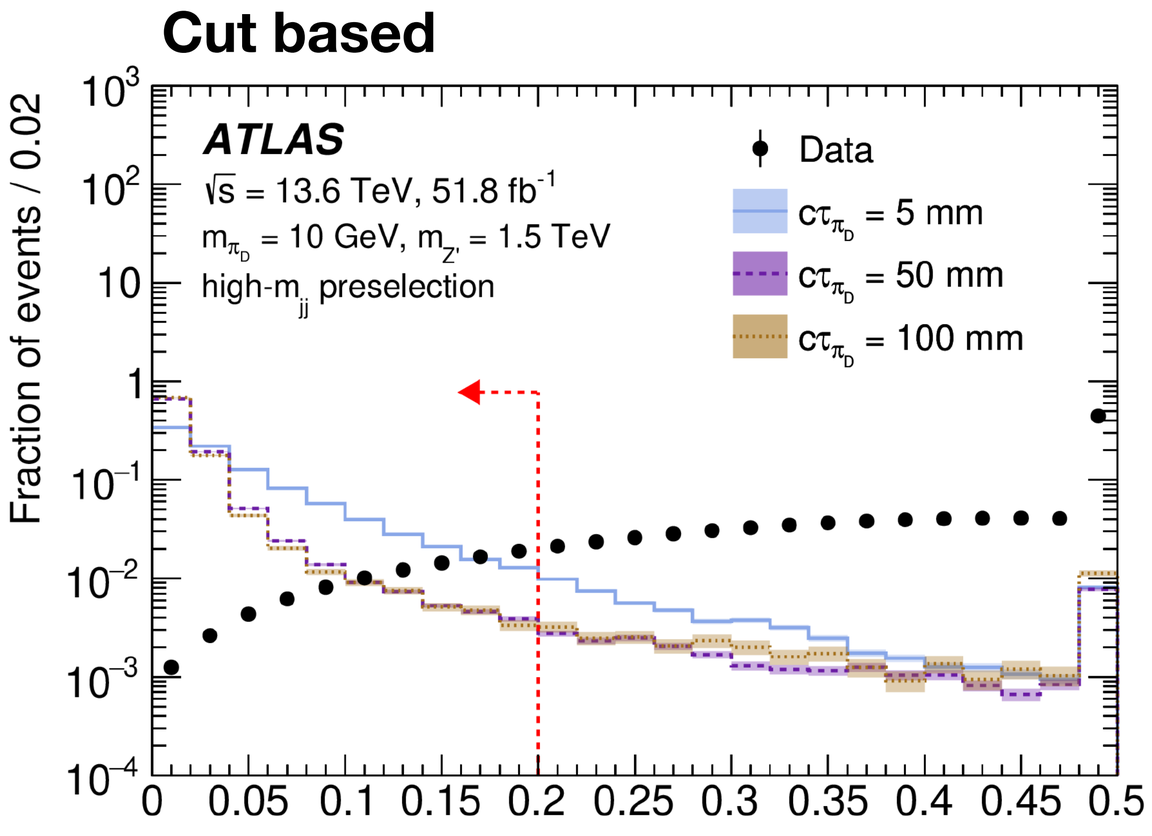
New!

arXiv.org:2505.02429





Special Run-3 trigger!



$$\mathrm{PTF} = \frac{\sum_{\mathrm{trk}\subseteq\Delta R<1.2} p_{\mathrm{T}}^{\mathrm{trk}}}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

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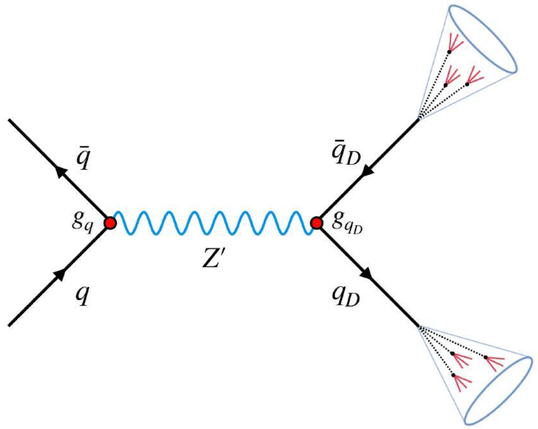
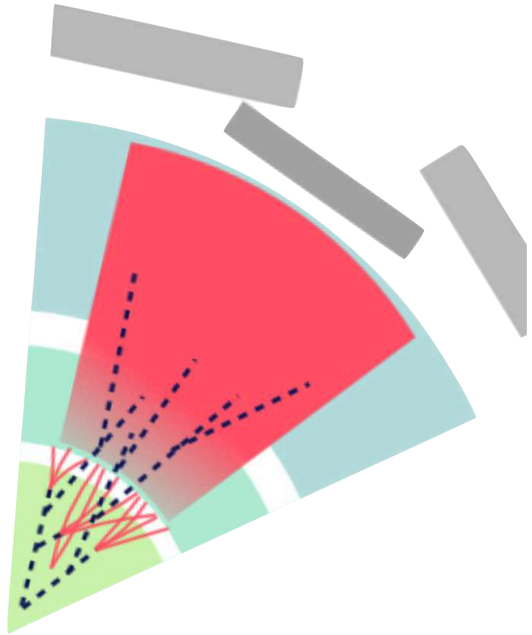
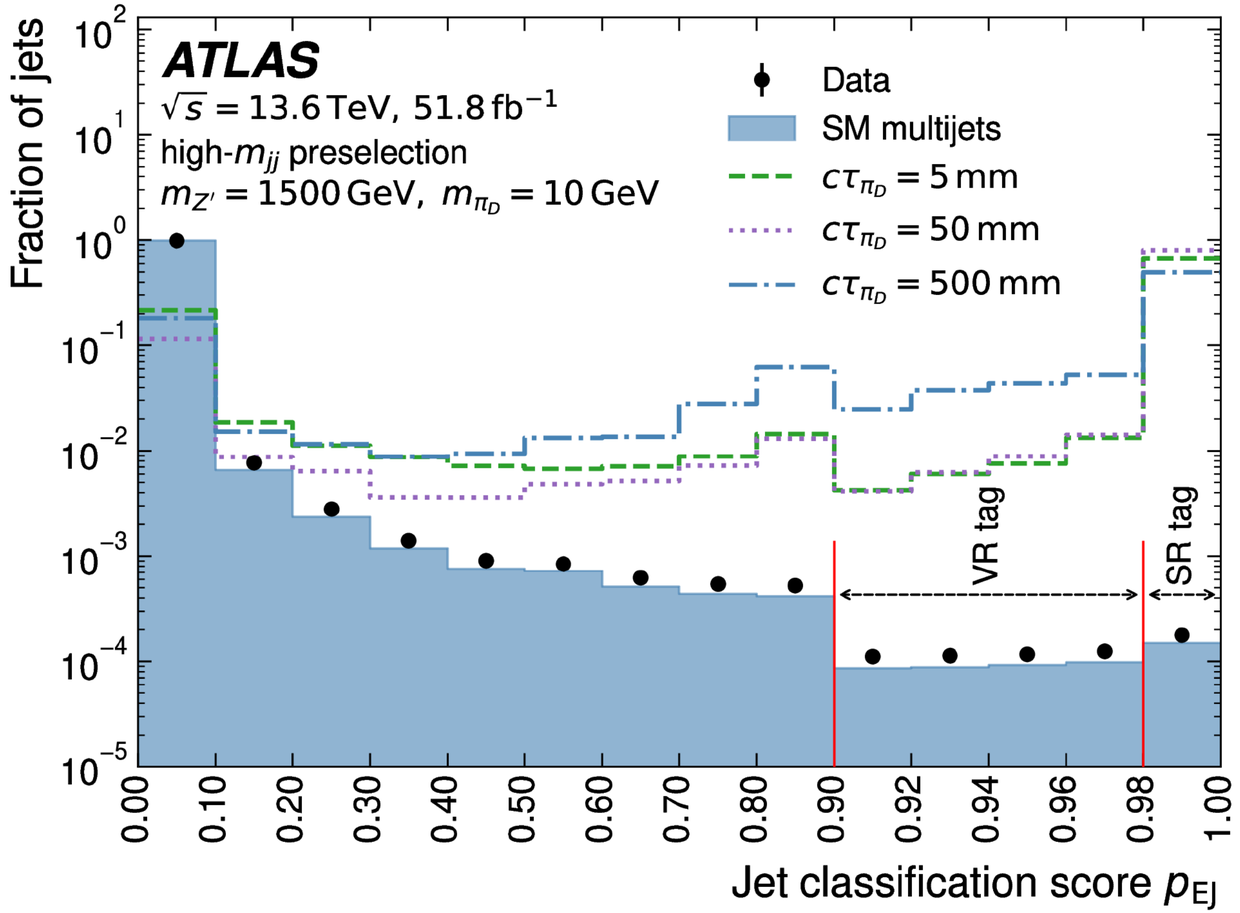




Special Run-3 trigger!

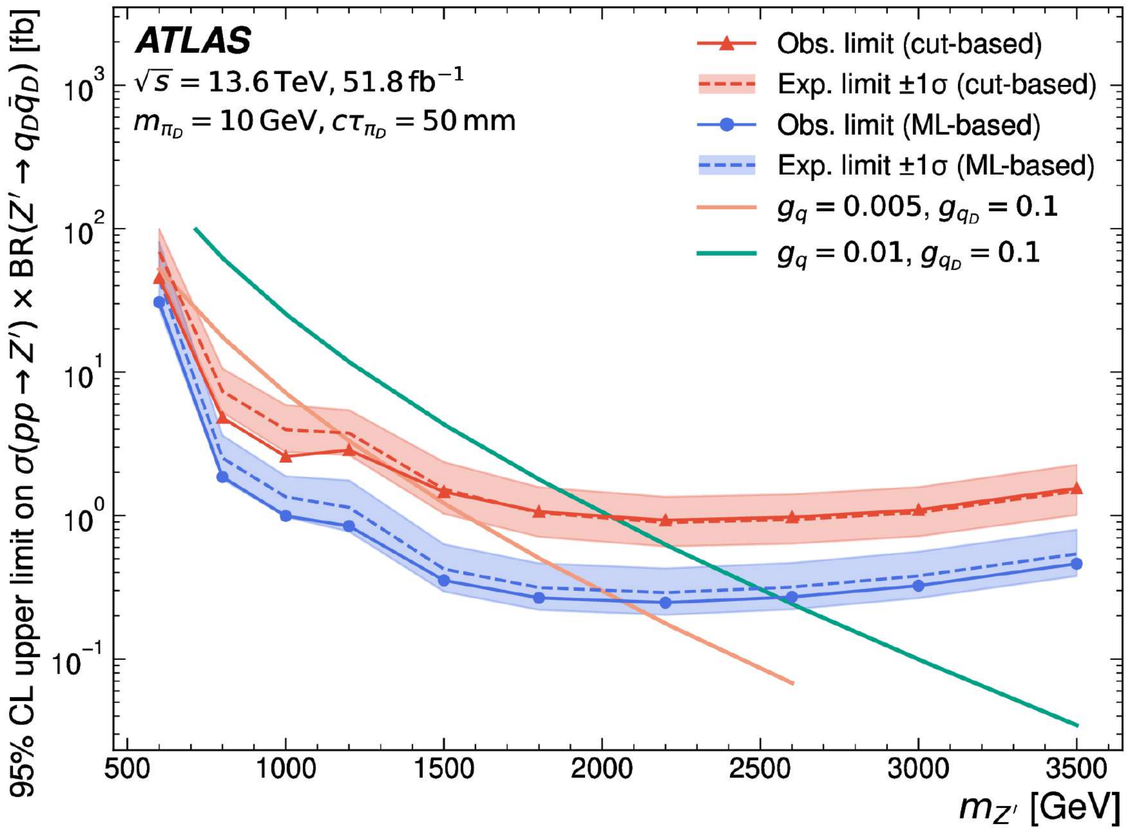
Machine Learning Classifier



Emerging Jets - Run 3 Data

New!

Fixed π_D lifetime, as a function of Z' mass



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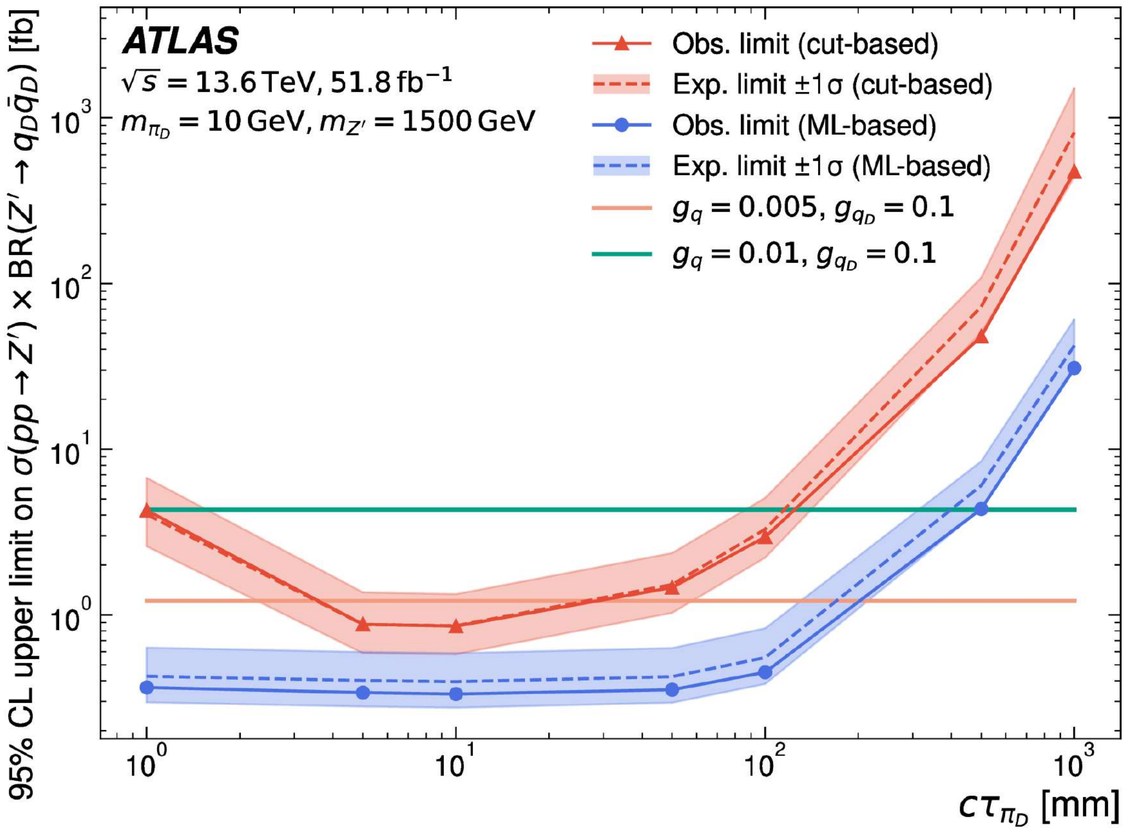

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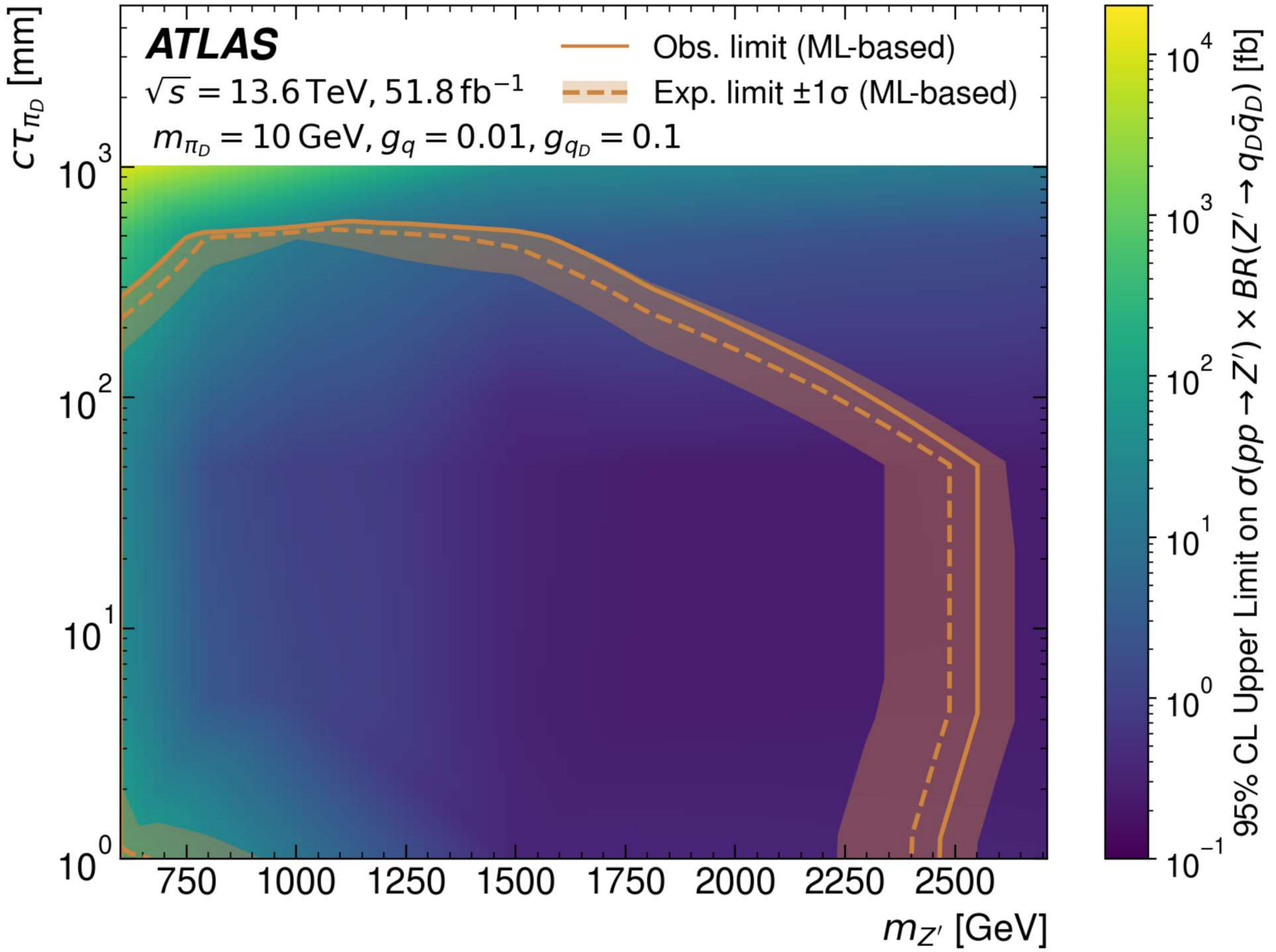
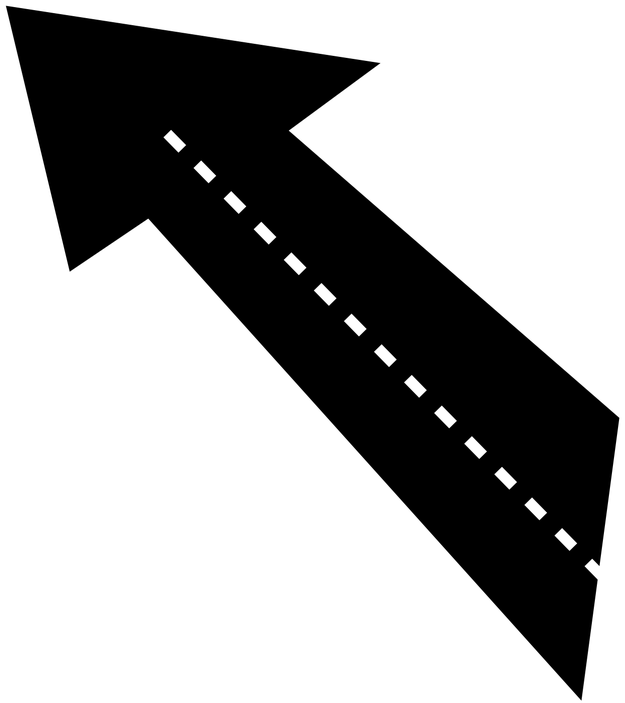


arXiv.org:2505.02429

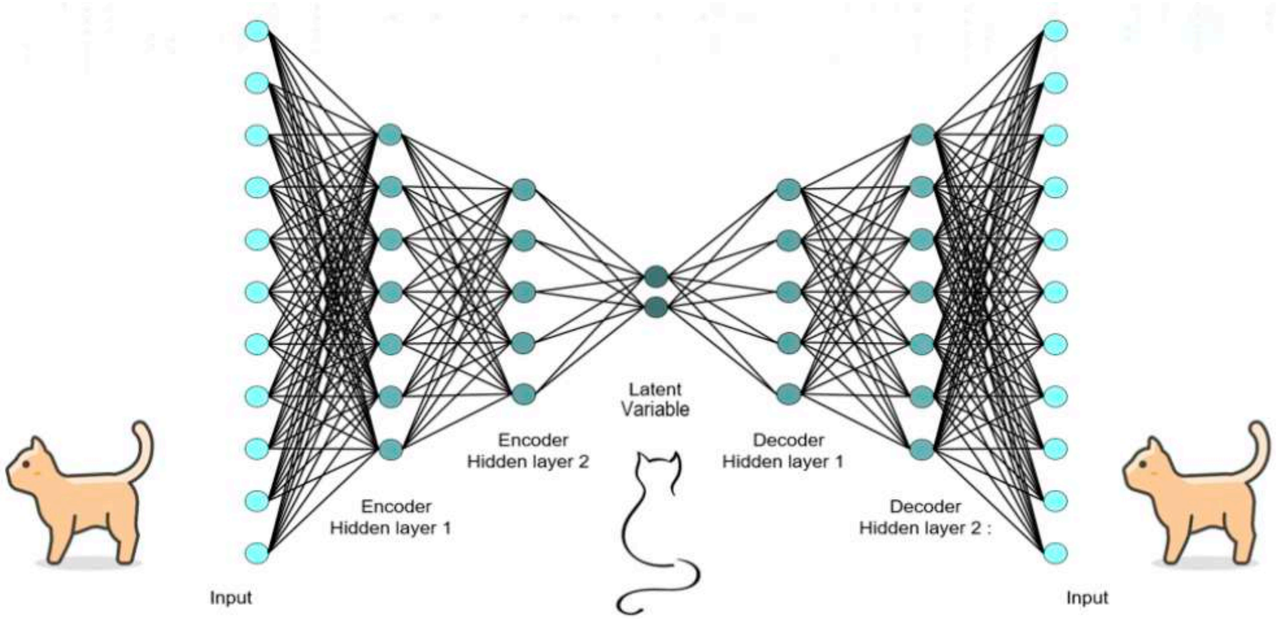


Anomaly Detection

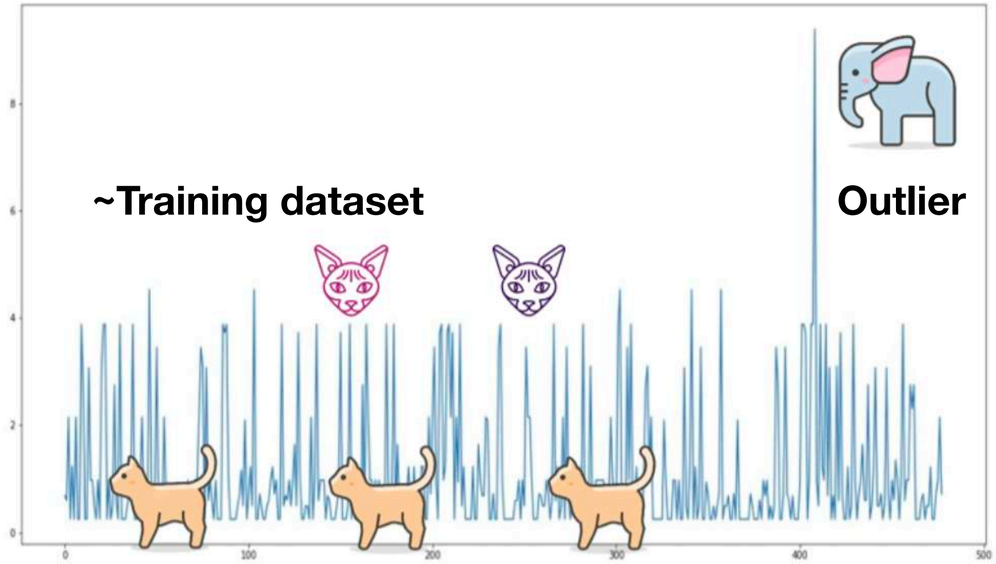
Anomaly Detection in a Nutshell

Images from Jess Garcia

Model-agnostic (ish), unsupervised search: assume new particles are **rare**
(i.e. it is OK if there are some elephants in the training dataset, as long as most of it are cats)



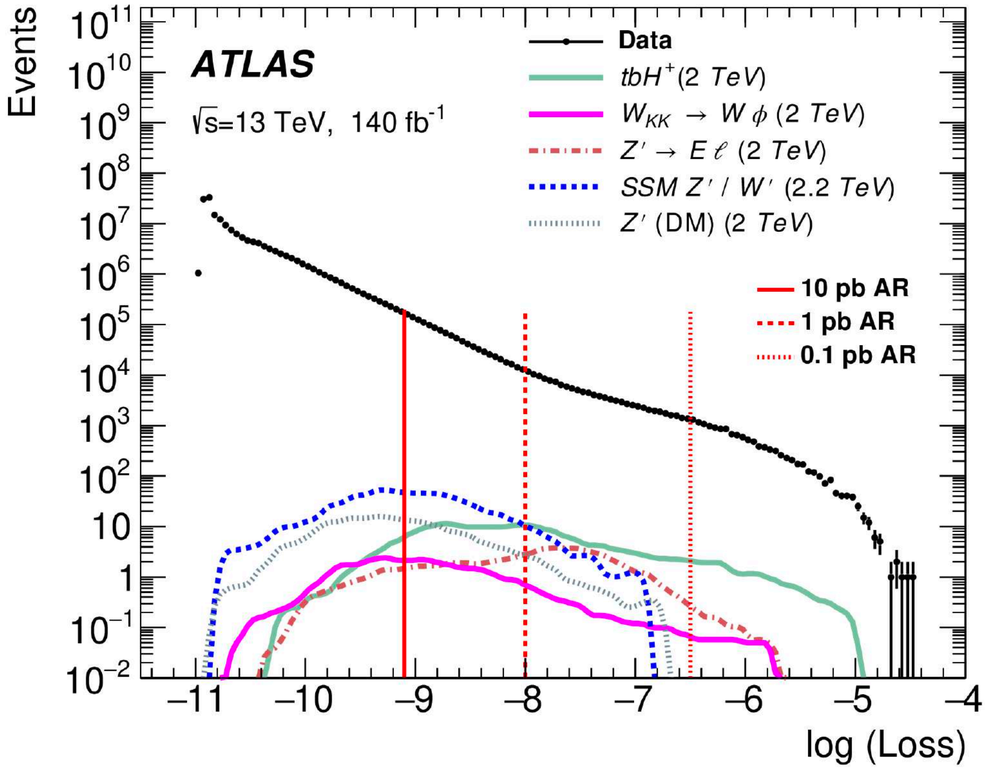
Autoencoder architecture



Reconstruction loss

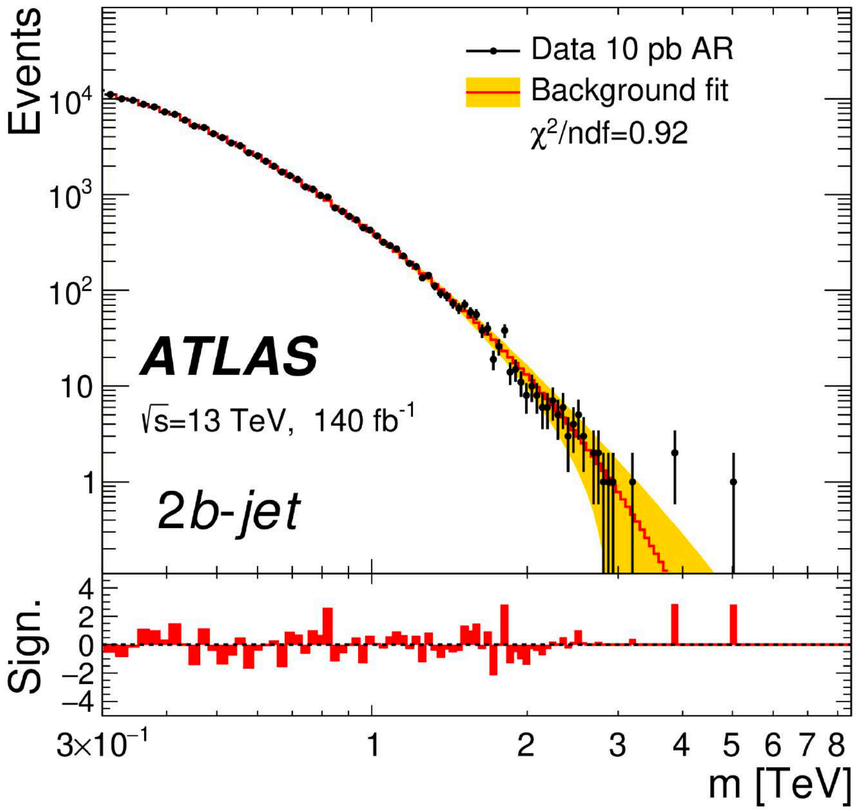
Anomaly Detection in ATLAS

- Use a specific slice of the data (single lepton triggers) to train the unsupervised machine learning algorithm



Physics Briefing

Phys. Rev. Lett. 132 (2024) 081801

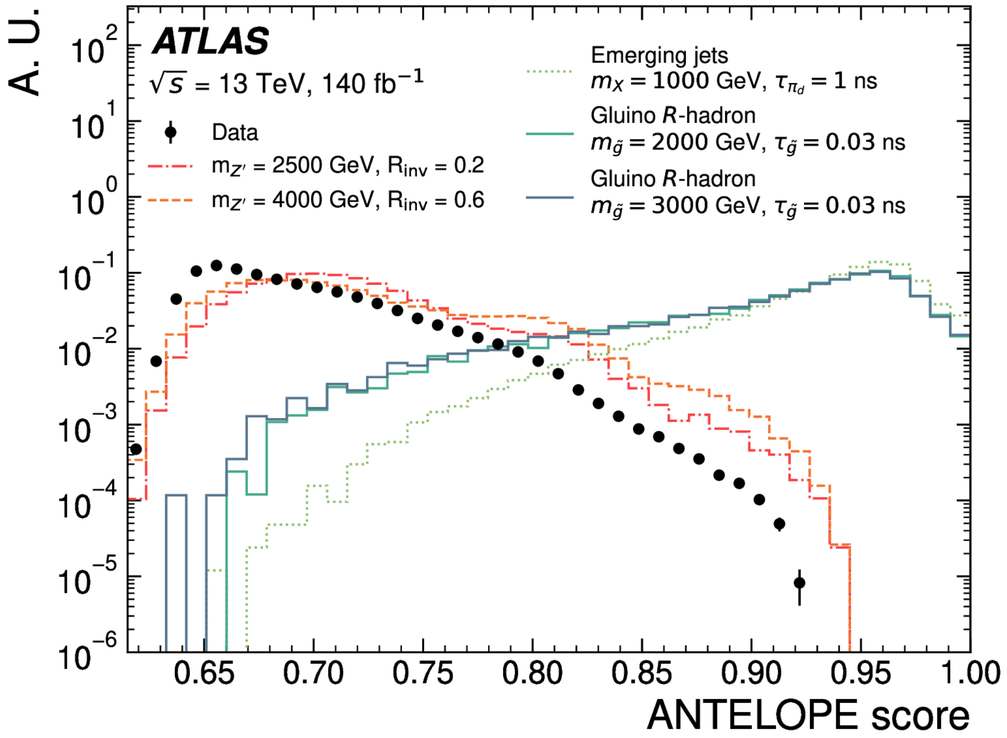


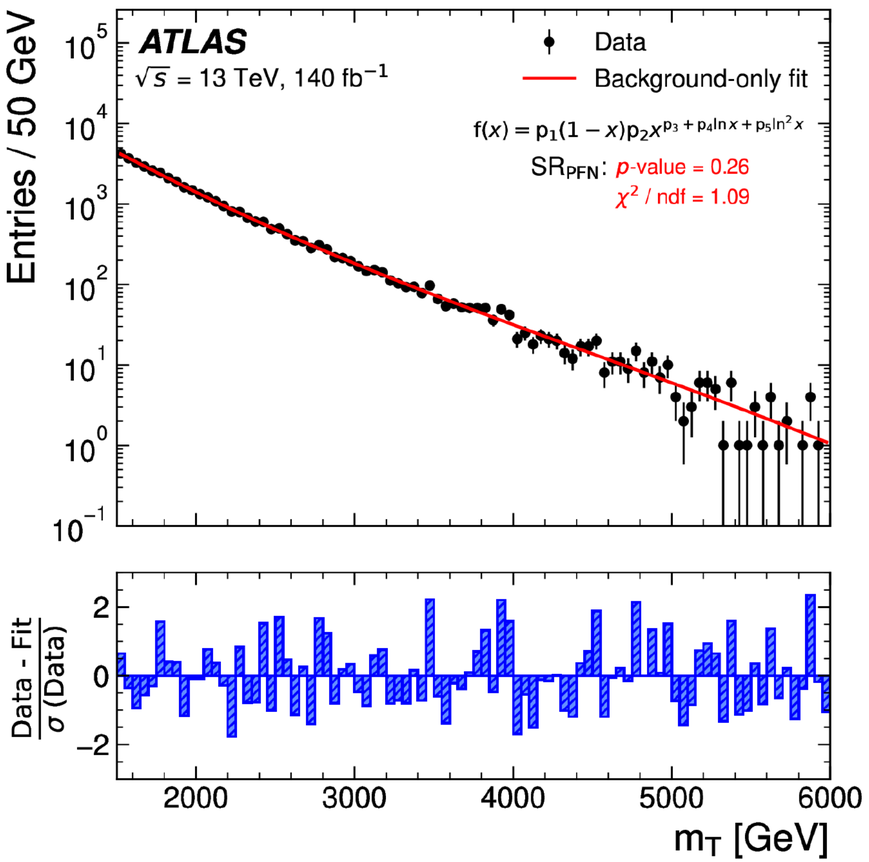
Anomaly Detection in Jets

New!

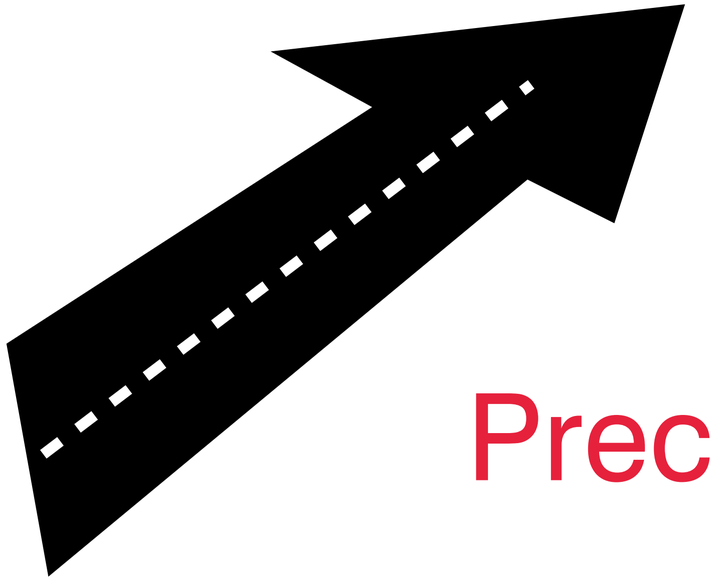
Analysis from M. Bona and S. Valjee here at QMUL!

arXiv.org:2505.01634



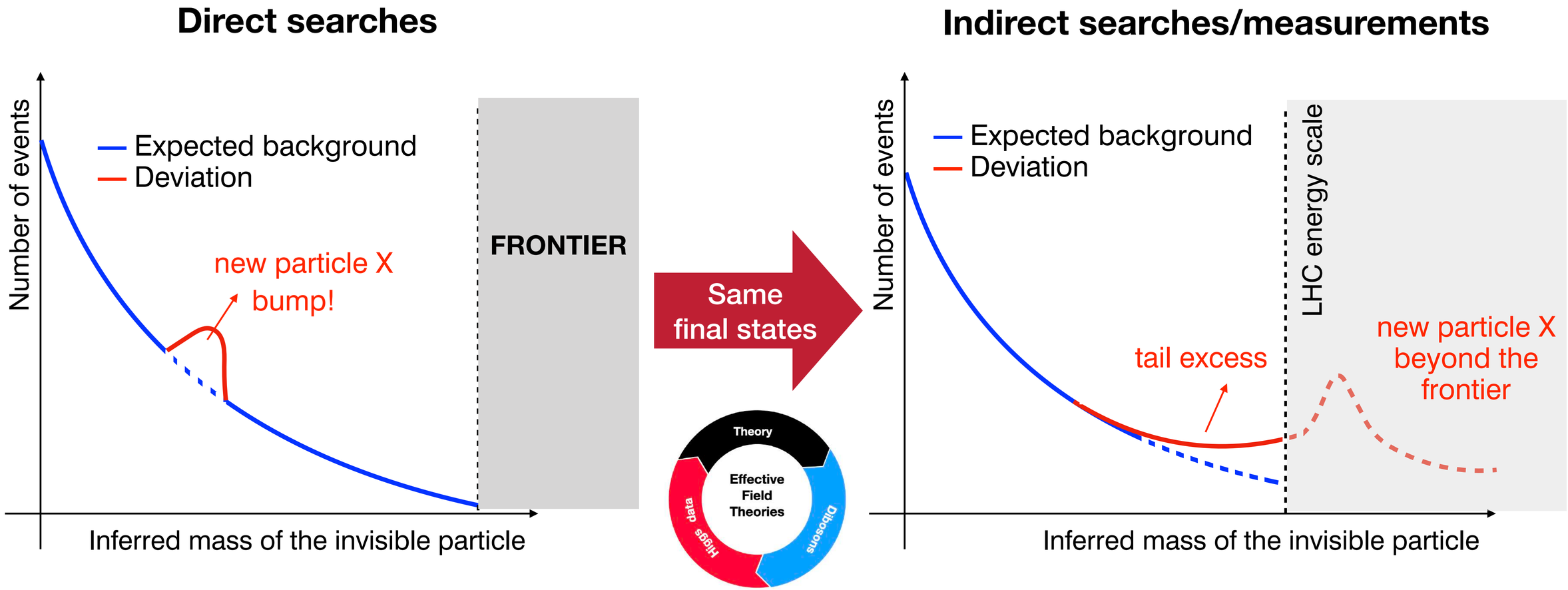


ANomaly deTEction on particle fLOw latent sPacE (ANTELOPE)



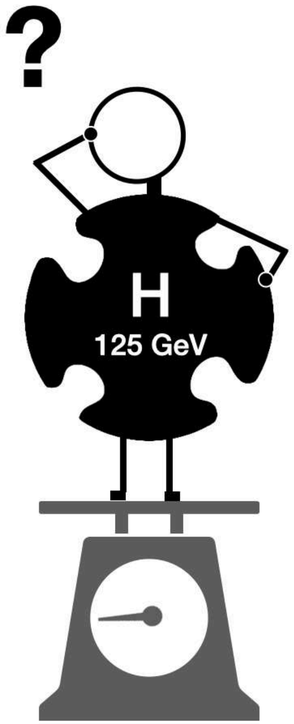
Precision Measurements as Indirect Searches

Beyond the Energy Frontier

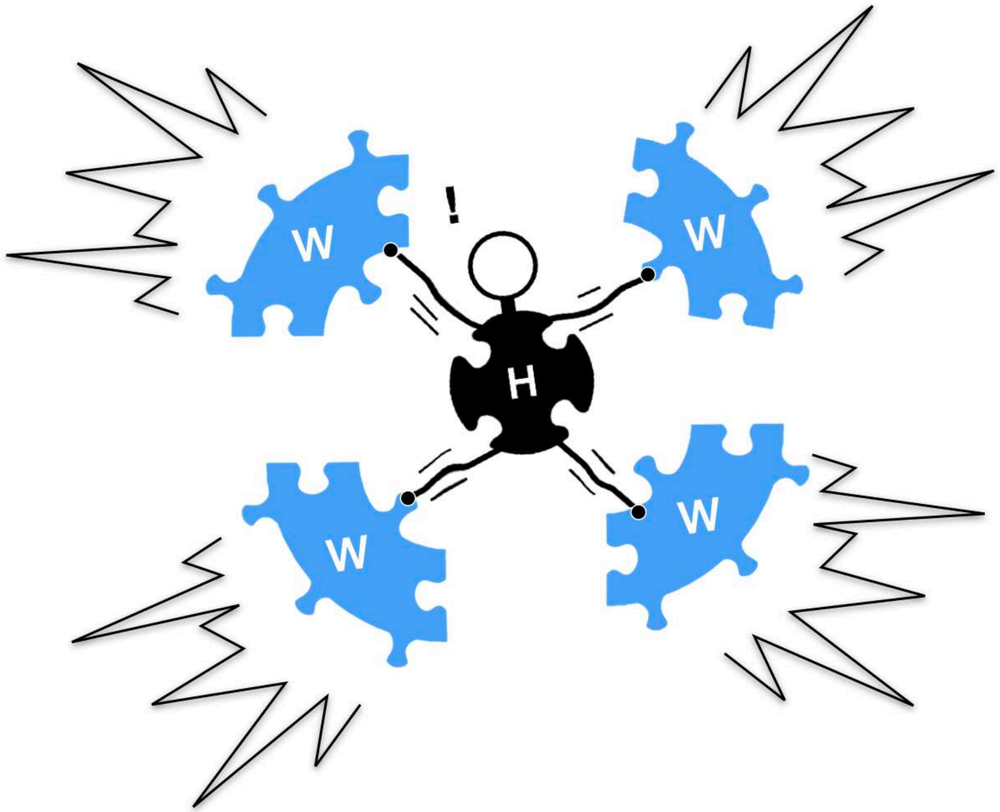


Precise Measurements ⇔ Searches

- Exploiting the Electroweak sector with dibosons (WW, WZ, ZZ)



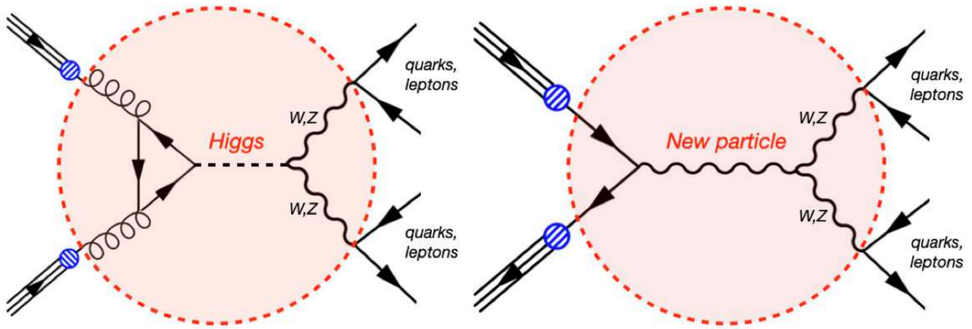
Due to *new particles* or *new interactions*?



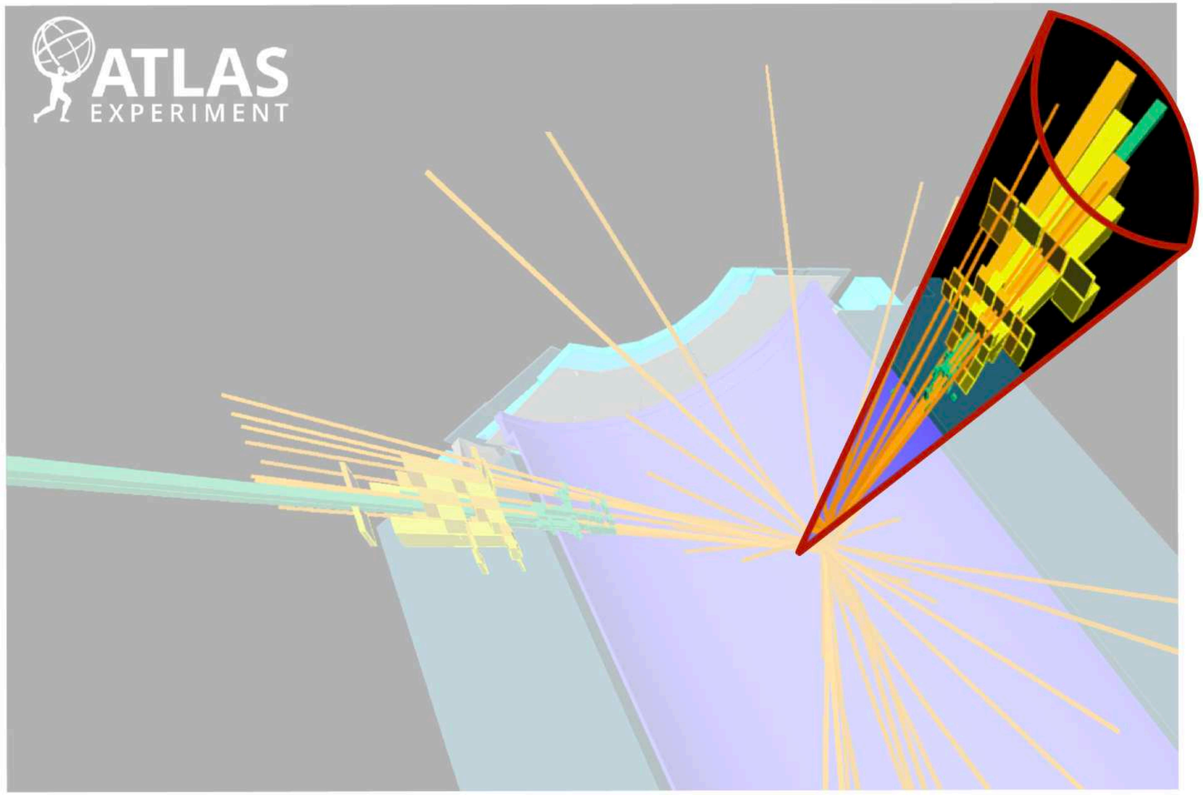
Deep connection to *diboson processes*

Precise Measurements ⇔ Searches

- Exploiting the Electroweak sector with dibosons (WW, WZ, ZZ)



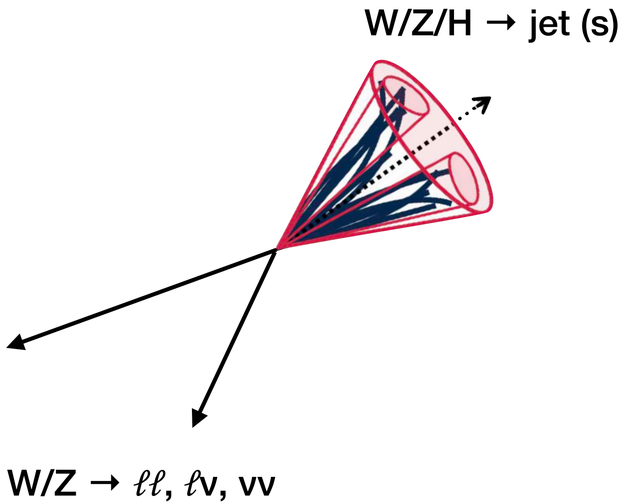
- Semi-leptonic and hadronic final states
- W / Z → qq
  - ➡ Higher statistics (probe higher energy)
  - ➡ Harder to measure and model background

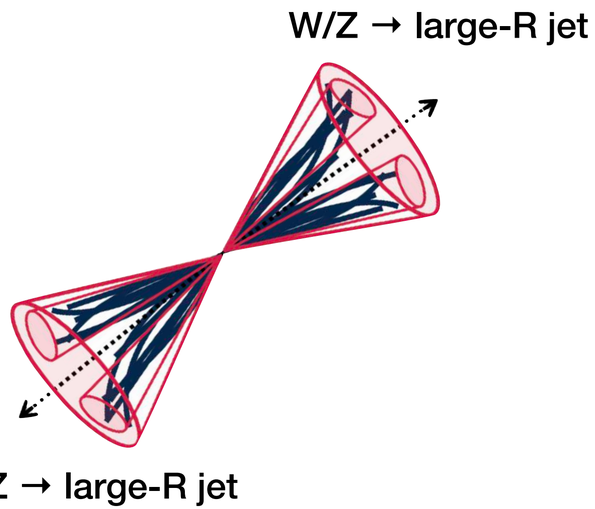


Large W/Z pT: large-radius jets, jet substructure

Precise Measurements ⇔ Searches

- Exploiting the Electroweak sector with dibosons (WW, WZ, ZZ)

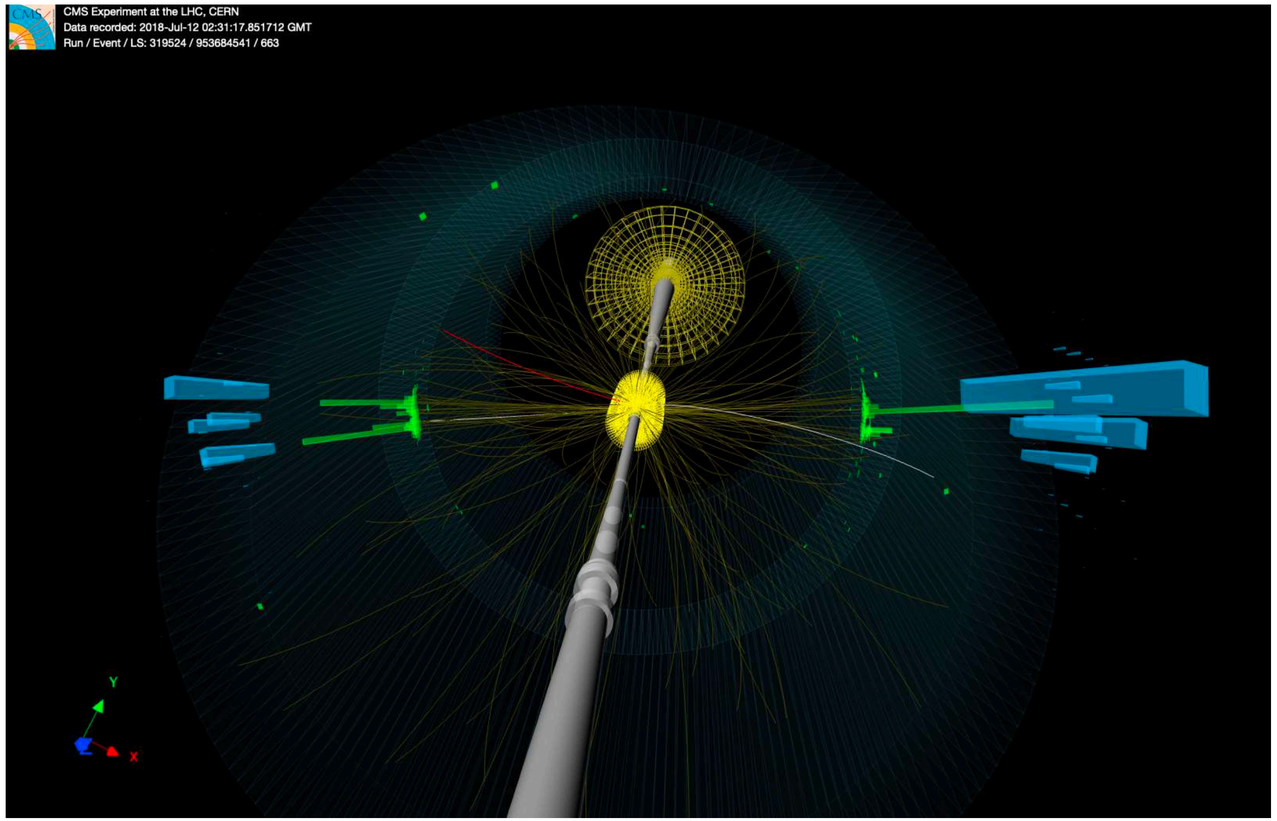


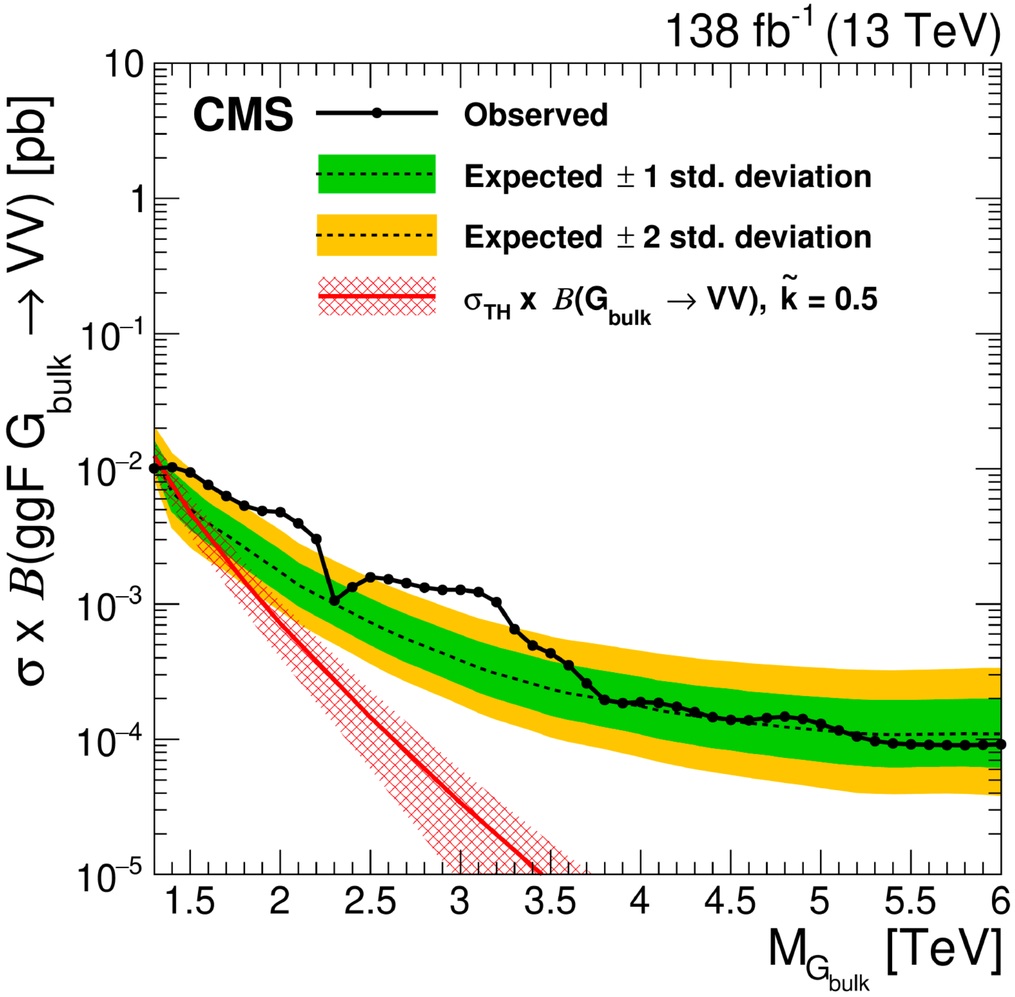


In progress!

- Integrate with Higgs data and ATLAS EFT Global Fit efforts

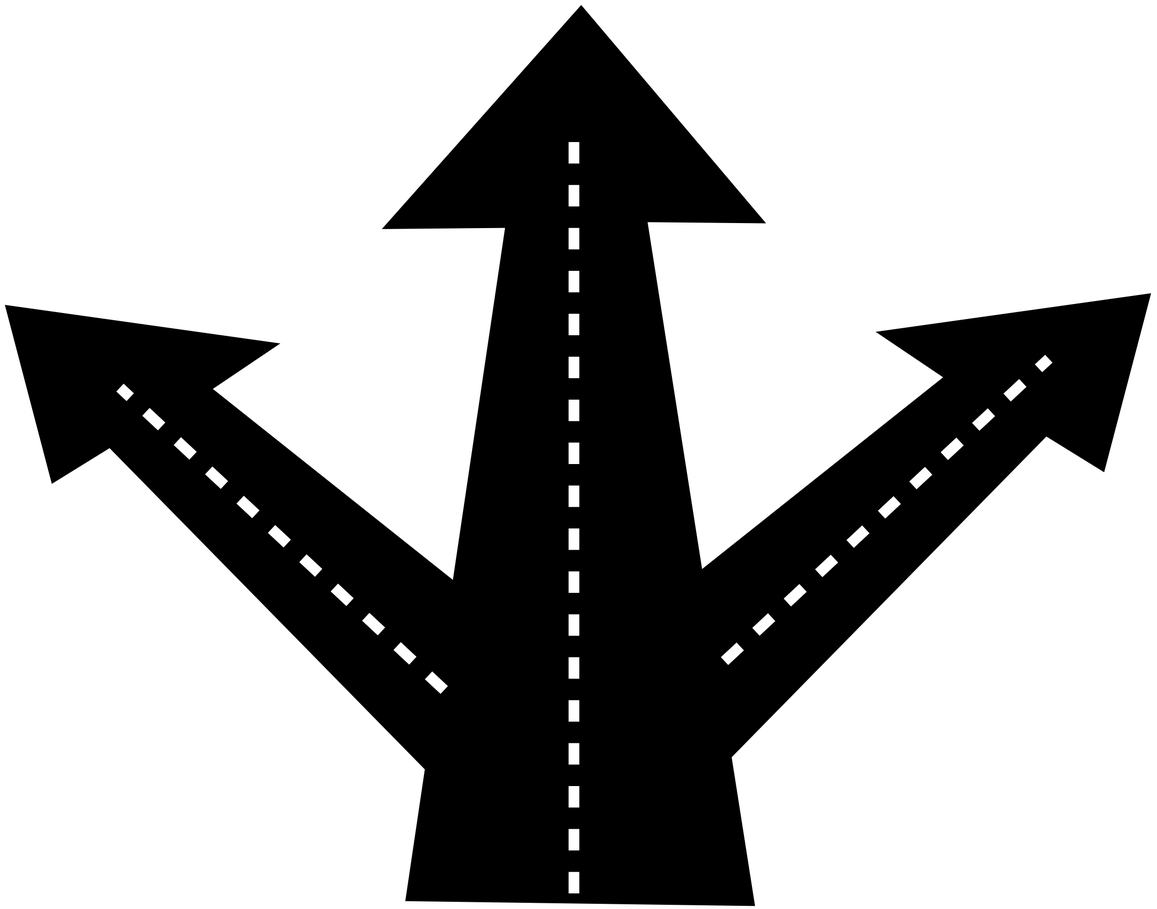
Hadronic Dibosons Strike Again!





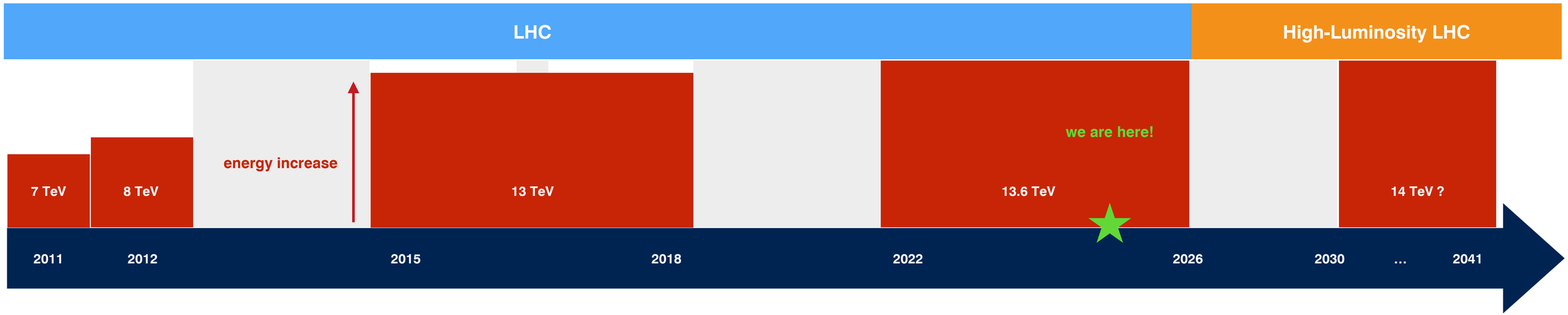
ATLAS public result cannot confirm or rule out!
Update in progress

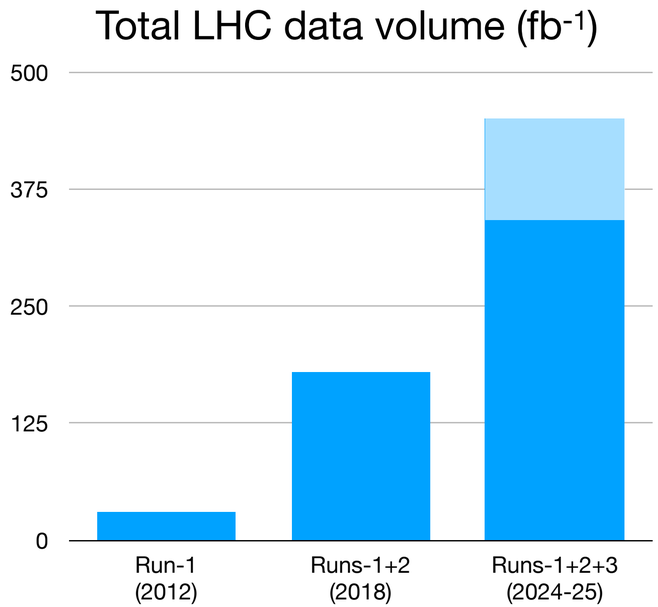
Phys. Lett. B 844 (2023) 137813

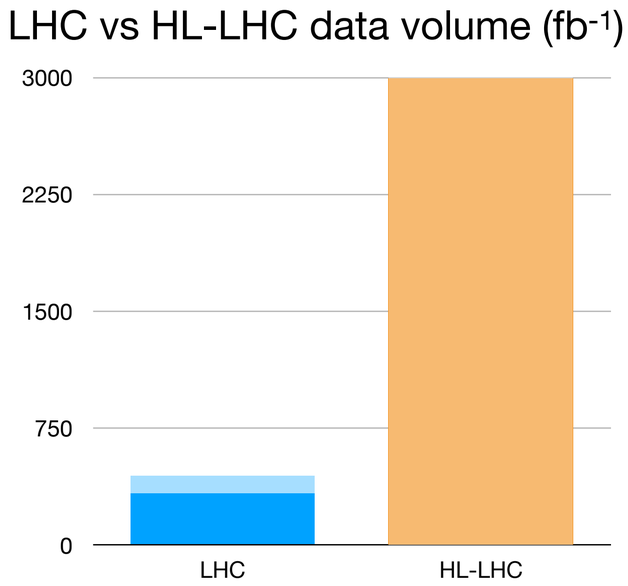


Future Prospects

More data = Sharper images

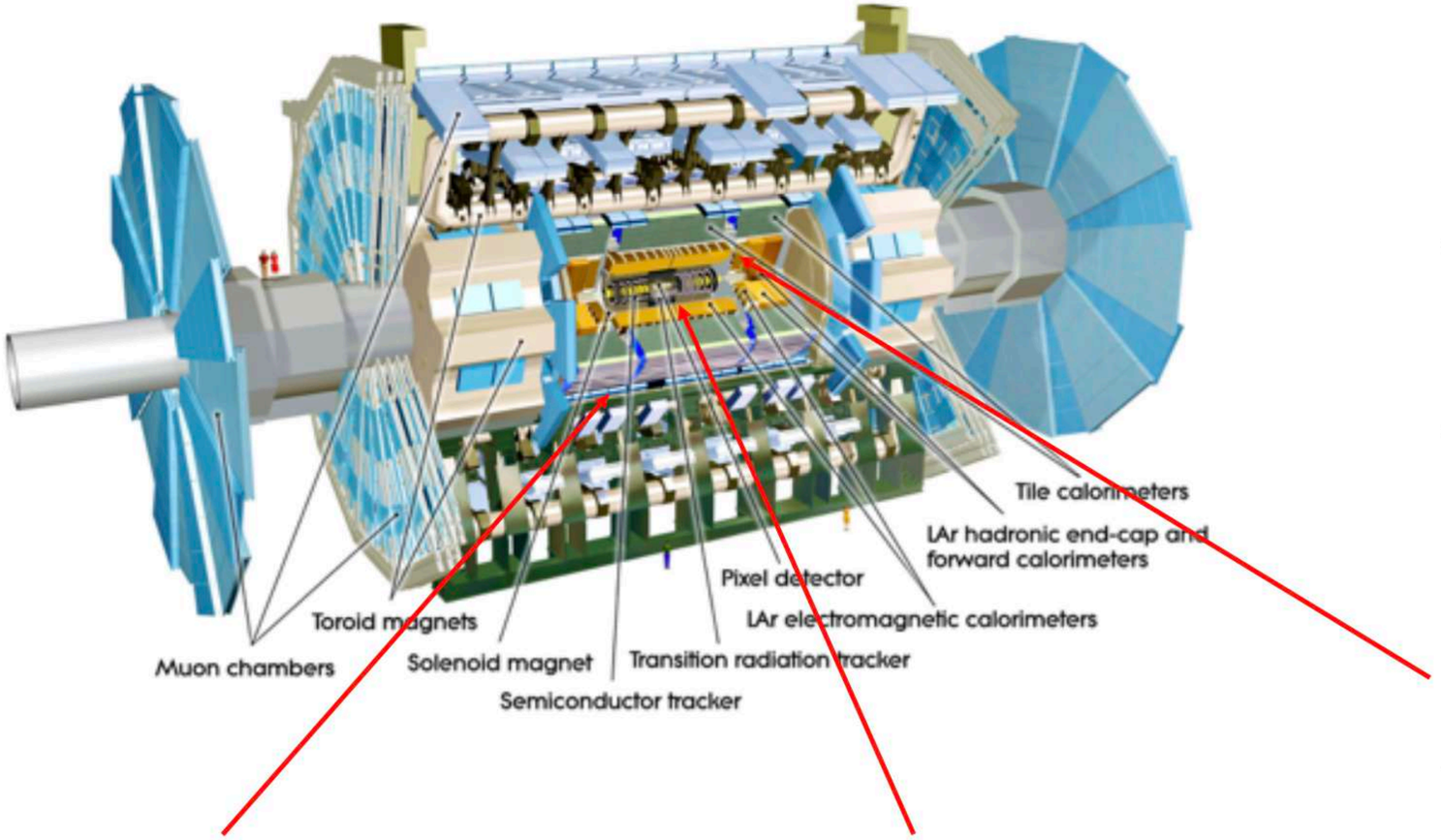






ATLAS Phase-2 Upgrade for HL-LHC

From G. Unal



Upgraded Trigger and Data Acquisition system

Level-0 Trigger at 1 MHz

Improved High-Level Trigger (150 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter

Tile Calorimeter

Muon system

High Granularity Timing Detector (HGTD)

Forward region ($2.4 < |\eta| < 4.0$)

Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

New Inner Tracking Detector (ITk)

All silicon, up to $|\eta| = 4$

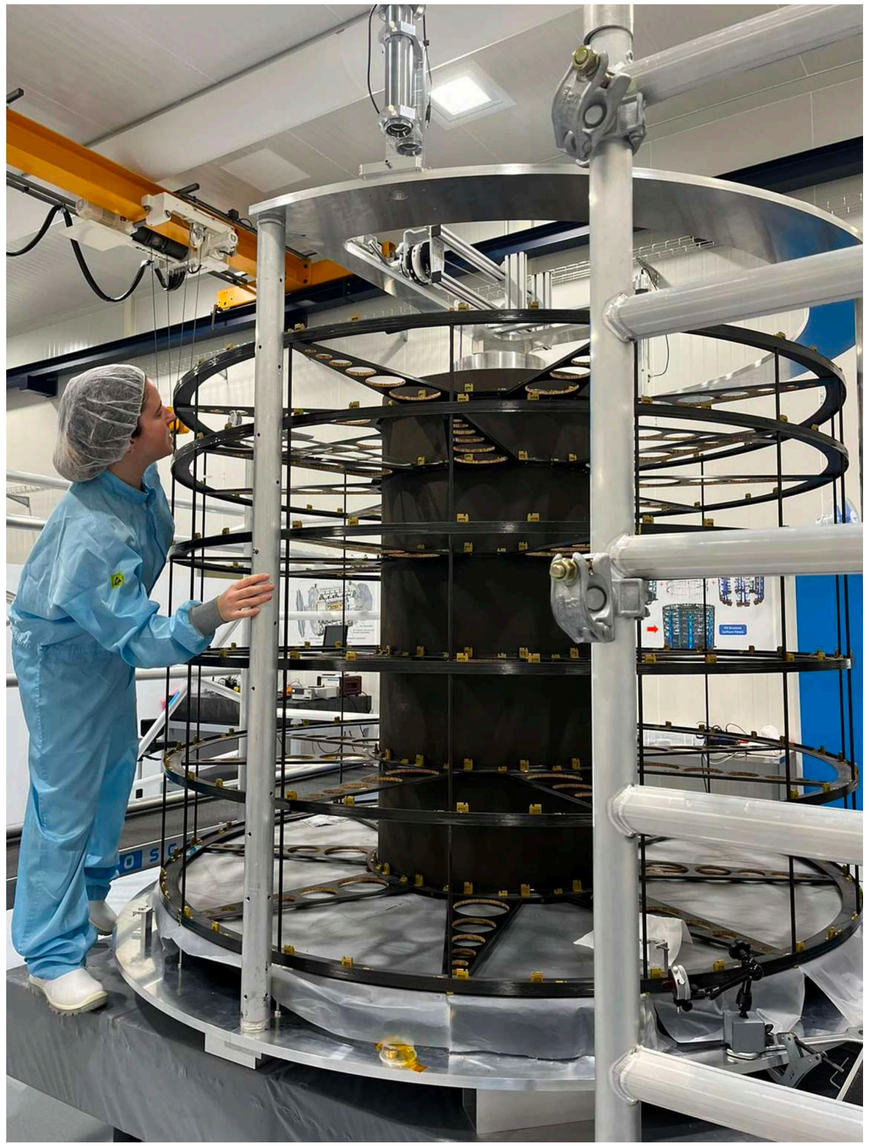
Additional small upgrades

Luminosity detectors (1% precision goal)

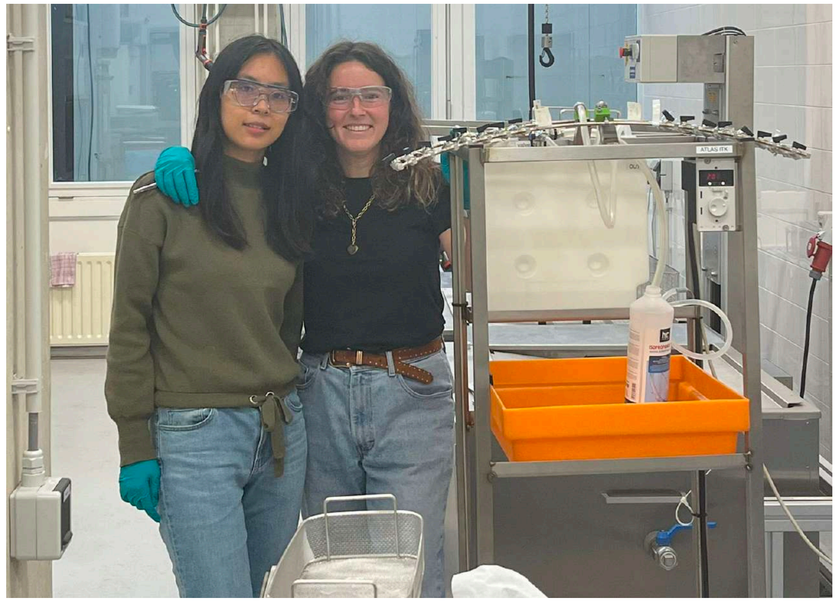
HL-ZDC

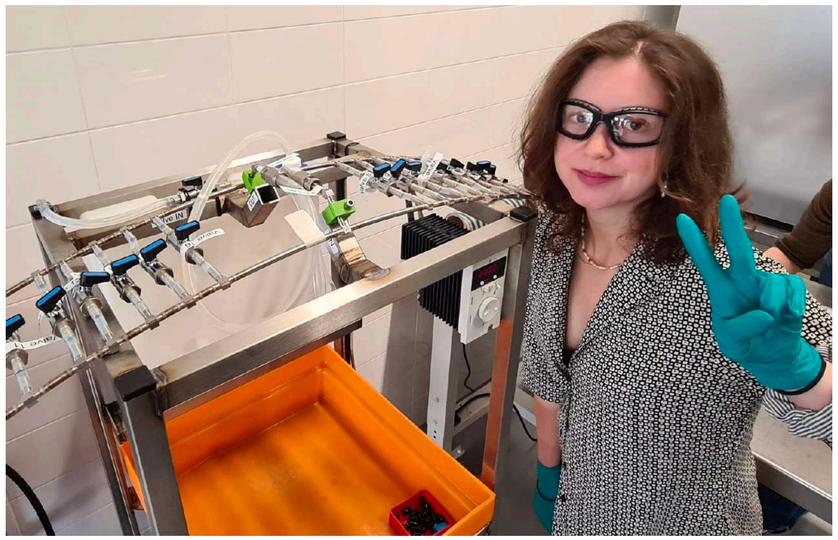
Detailed scope described in 7 TDRs approved by the CERN Research Board in 2017, 2018, 2020

ITk and HGTD at Nikhef

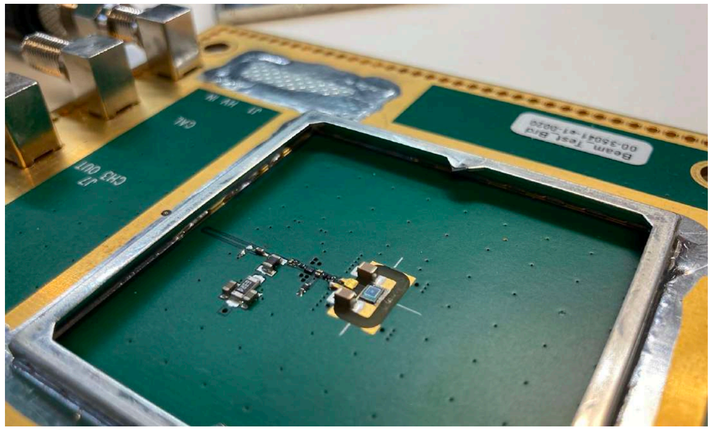


ITk endcap mechanical structure

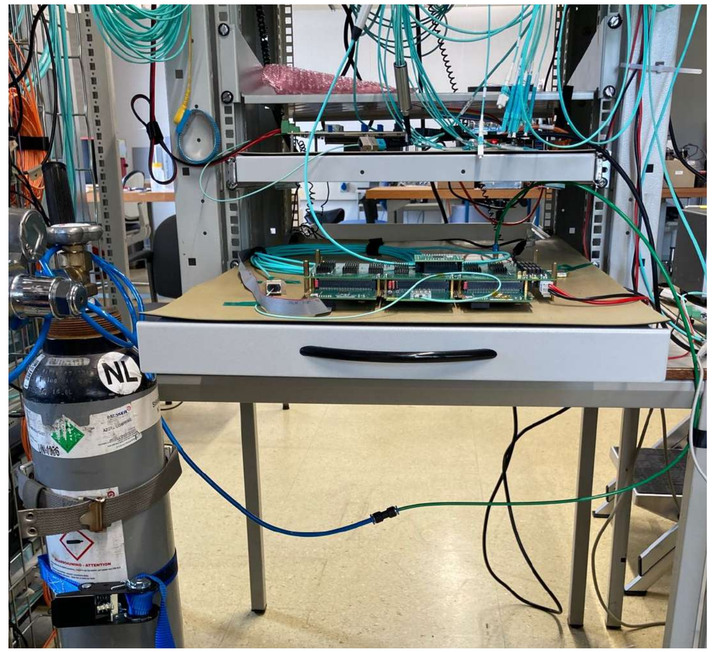




ITk flushing setup



LGAD sensor on a test carrier board



FELIX+HGTD readout

Leaving no stone unturned

Leaving no stone unturned

Summary and Outlook

- LHC is performing well and a lot of exciting new results are available and upcoming
  - ➡ We have not found new particles Beyond the Standard Model yet
  - ➡ Discovery machine ⇒ precision machine
  - ➡ Take advantage of all current and future (Run-3/HL-LHC) data to stress-test the Standard Model
  - ➡ Tackle searches for new physics in novel, unconventional and indirect ways

Image by brgfx on Freepik