Séminaire du DPhP - CEA Saclay – 17 June 2024

LATEST ATLAS SEARCHES FOR NEW PHYSICS WITH TOP QUARKS AND PERSPECTIVES ON FUTURE DETECTORS

TIM ANDEEN
Associate Professor, The University of Texas at Austin
Jean d'Alembert Fellow, Université Paris-Saclay

TEXAS
The University of Texas at Austin

July 4, 2012

What do you do *after* you discover a new particle?

Keep working!

April 22, 2022

Large hadron collider: A revamp that could revolutionise physics

By Pallab Ghosh
Science correspondent

17 hours ago | Comments

A hundred metres underground at the heart of the LHC: I'm shown around a "majestic cathedral to science"

CNN World Audio TV Channels

Scientists restart Large Hadron Collider in quest for dark matter

By Sara Spary, CNN

Updated 9:04 AM ET, Fri April 22, 2022

Scientists at the European Organization for Nuclear Research (CERN) switched on the world's largest and most powerful particle accelerator on Friday, after a three year hiatus.

(CNN) — Deep underneath the Alps, on the Swiss-French border, something significant just happened in the world of physics. The Large Hadron Collider, Earth's most powerful particle accelerator, was restarted on Friday morning after a three-year hiatus for upgrades

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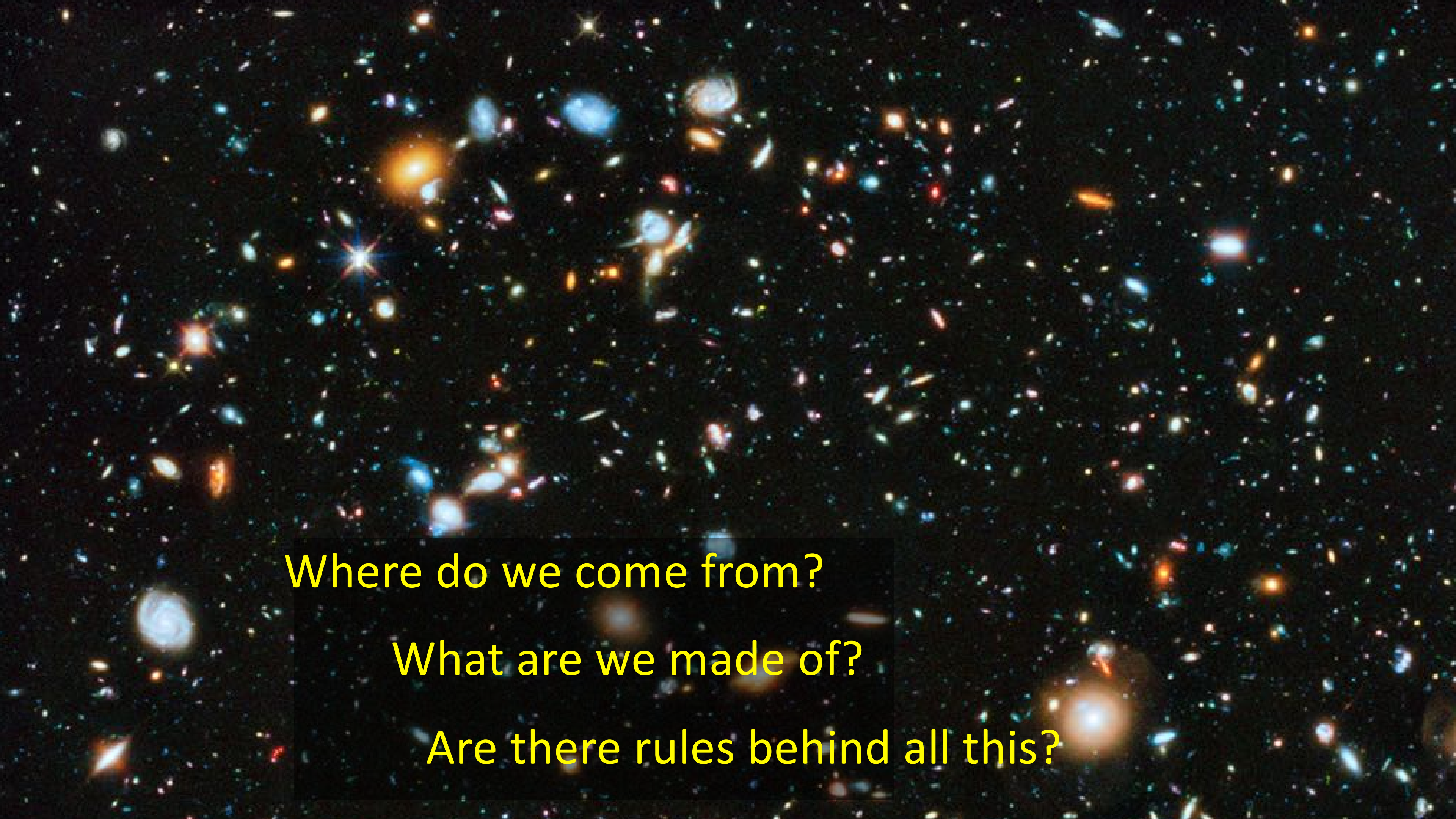
Large Hadron Collider

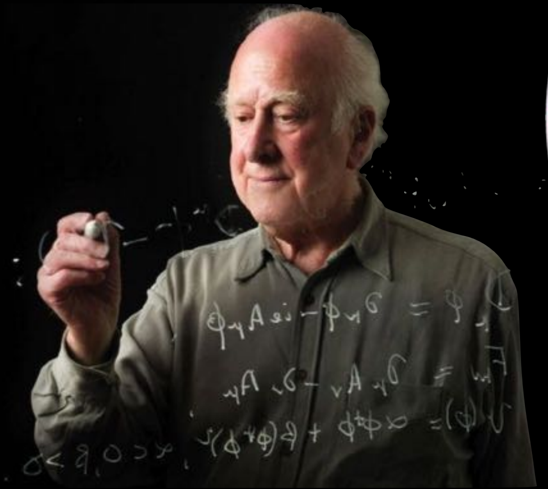
Large Hadron Collider to restart and hunt for a fifth force of nature

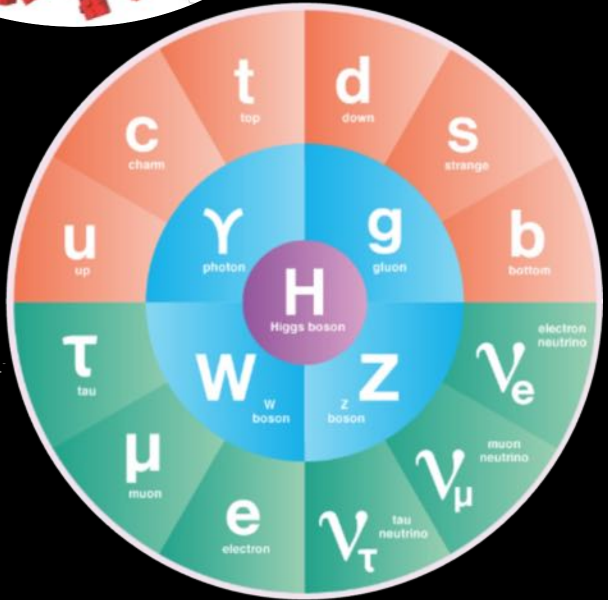
Latest run is expected to scrutinise findings from last year that may turn into another blockbuster discovery


Where do we come from?
What are we made of?
Are there rules behind all this?

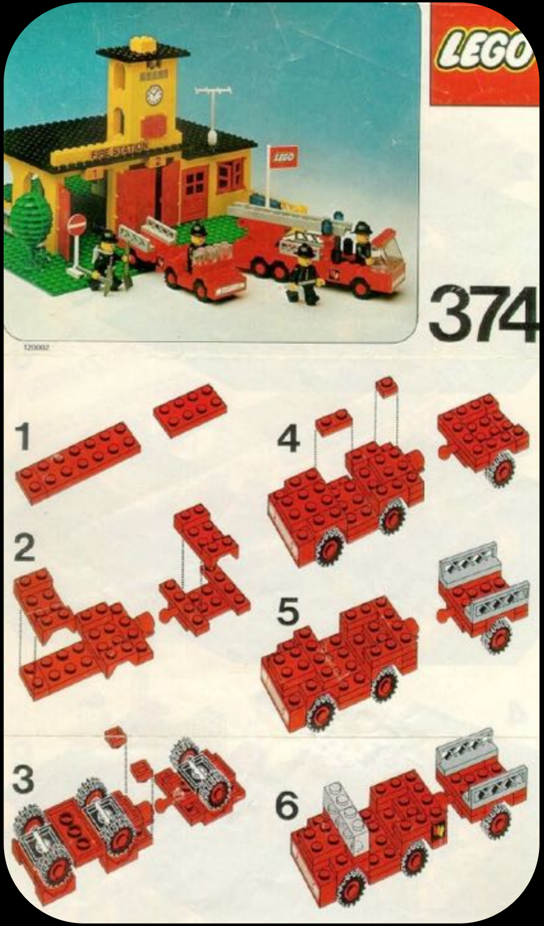
Our Building Blocks

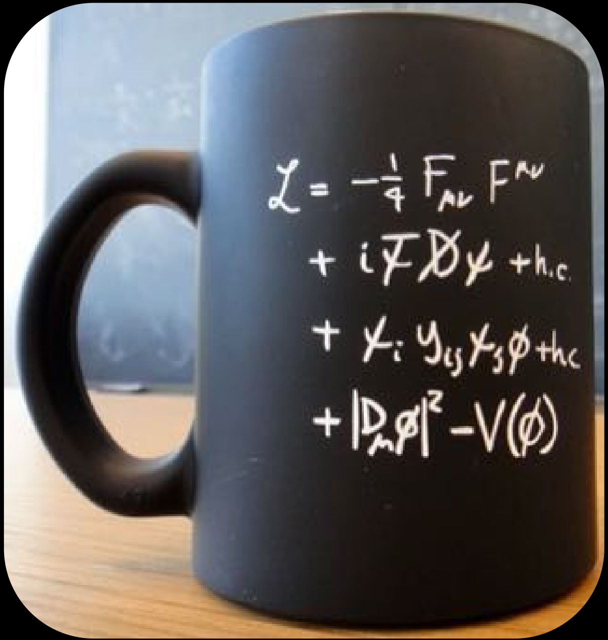
FERMIONS	BOSONS
MATTER	FORCE CARRIERS
Quarks	Gauge Bosons
Leptons	Higgs Boson





Our Instructions





A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 17 October 1967)

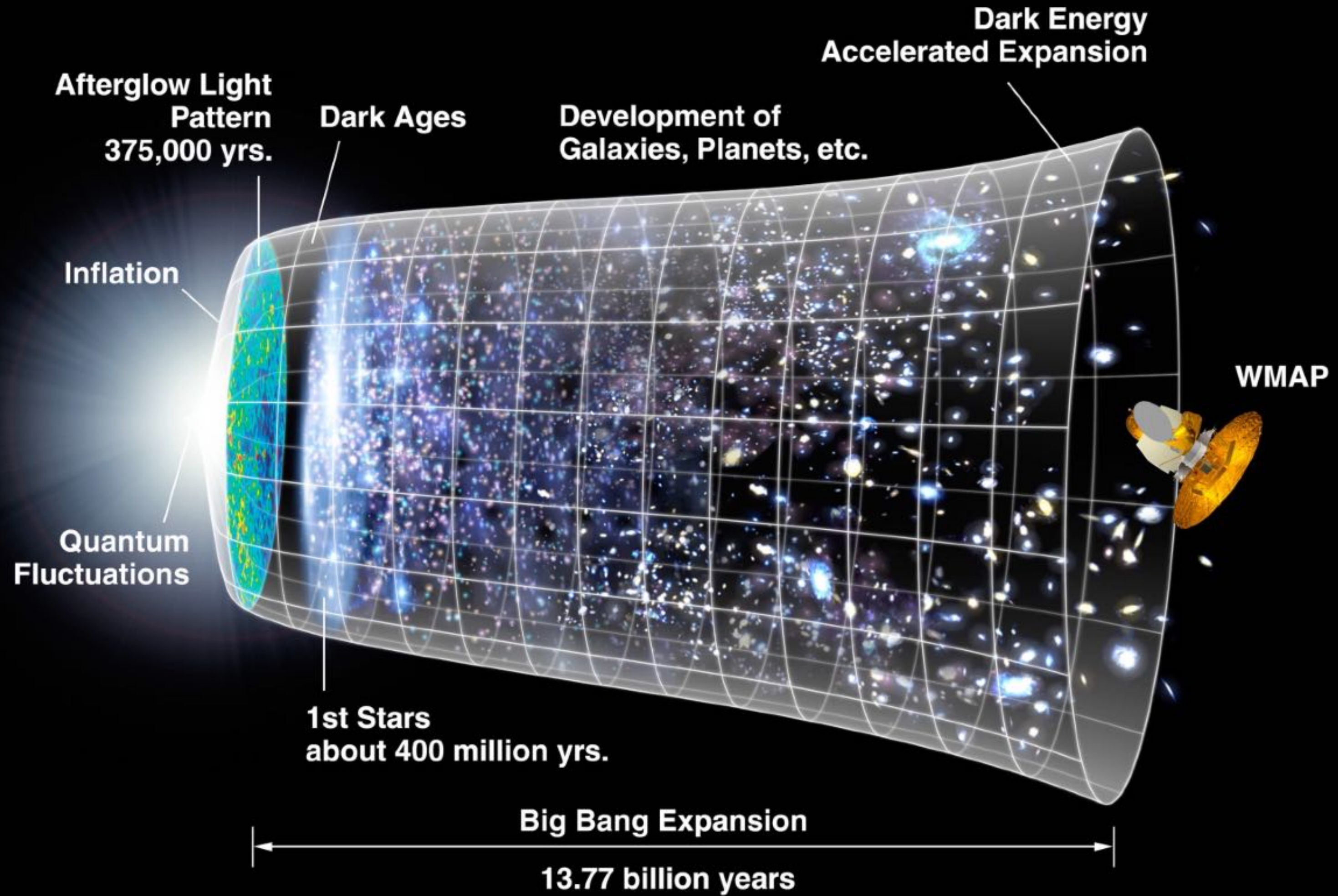
Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \qquad (2)$$

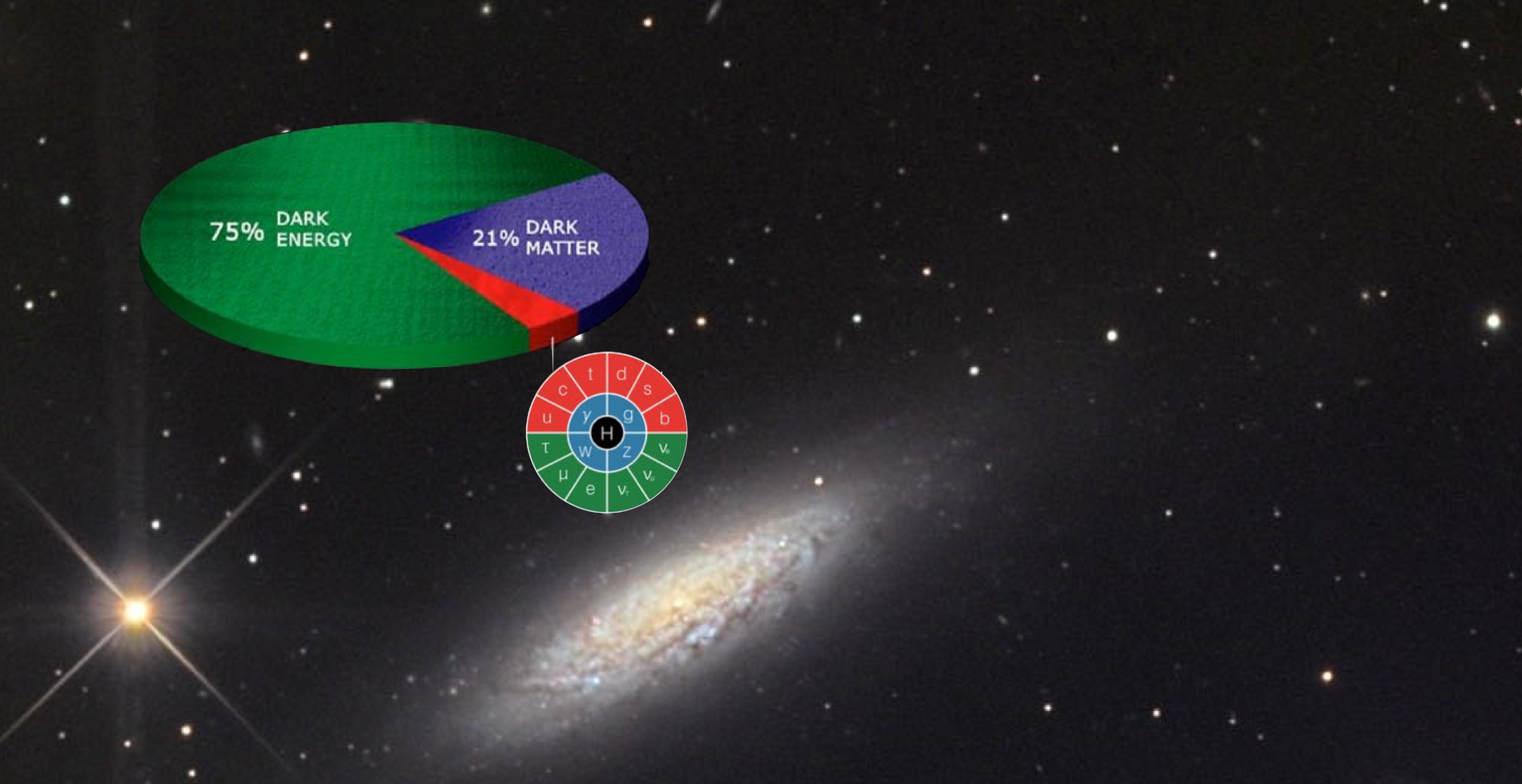
The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L - \bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting

Where did we come from and where are we going?

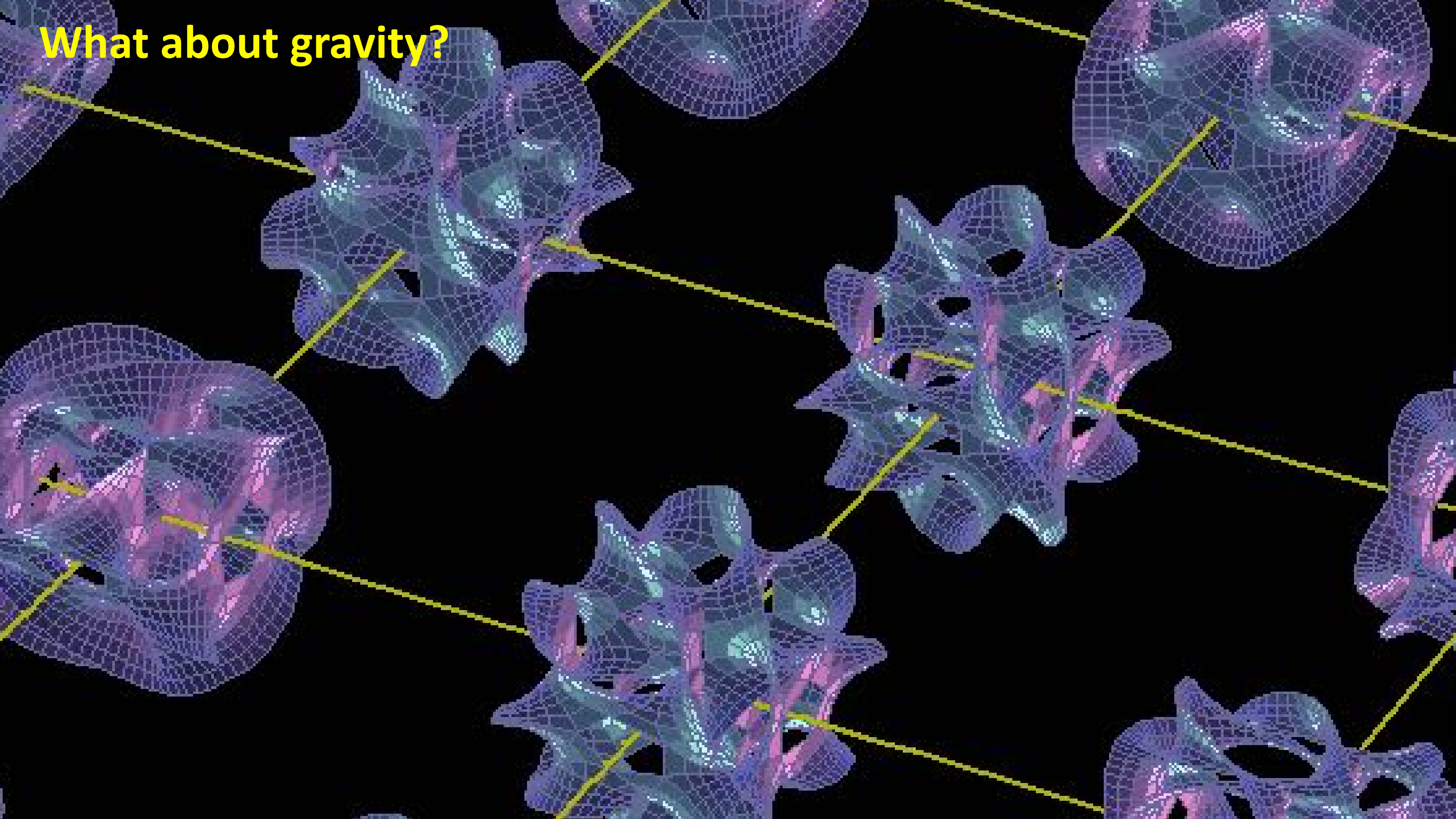


Where is the anti-matter?

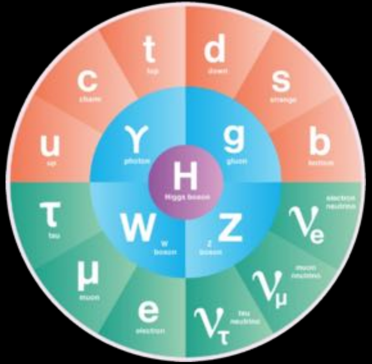
What is dark matter?



What about gravity?



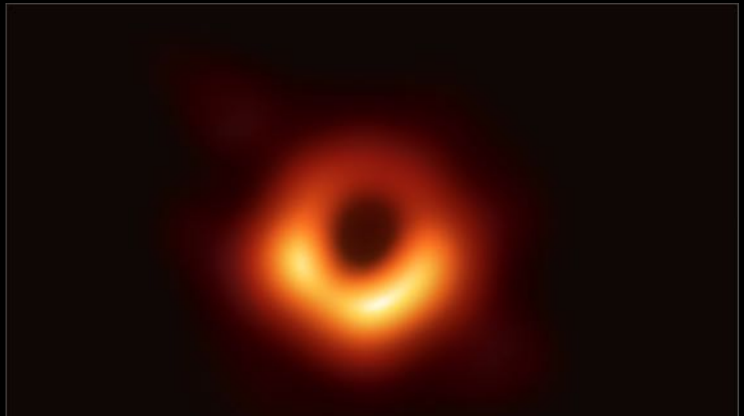
The Limits of the Standard Model



Above some energy our theoretical description is no longer applicable.

<u>Example</u>: Newtonian Gravity works great for football,

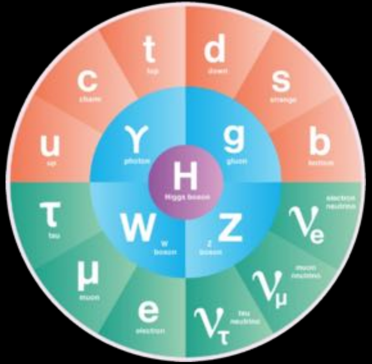
but we need relativity to understand black holes



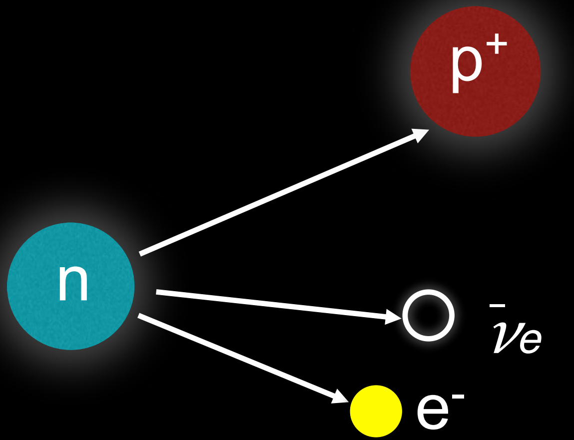
NASA Event Horizon Telescope - center of M87 Galaxy

Effective Theories

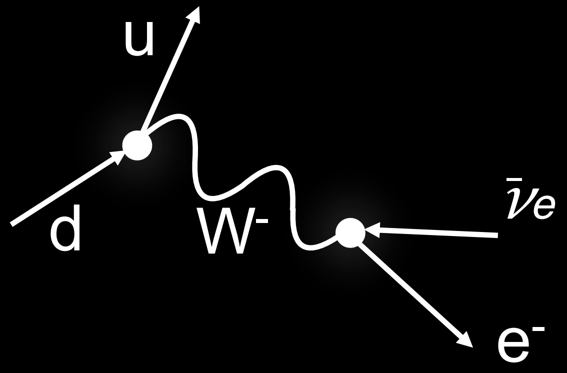
Above some energy our theoretical description is no longer applicable.



<u>Example</u>: Fermi's theory of weak interactions is a highly successful *effective* theory at "low" energies,



at higher energies we discover the microscopic description is the Electroweak Theory

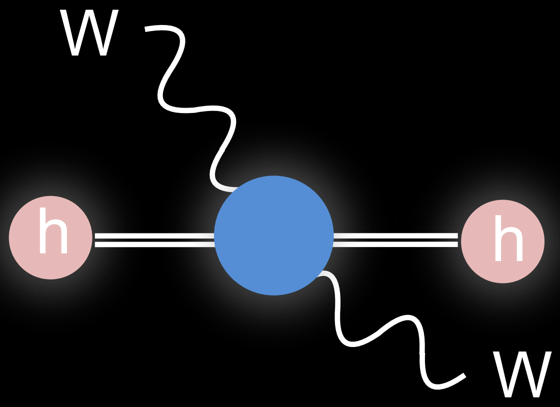


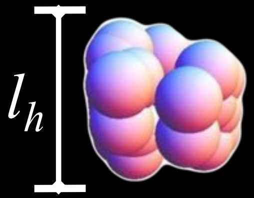
Composite Higgs?

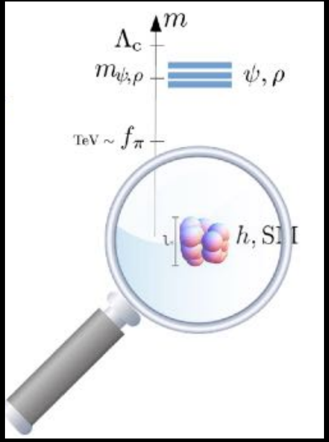
At what energy does the Standard Model stop working?

Question: What can we learn from the Higgs boson?

Is the Higgs just the lightest bound state of new, massive particles we have yet to discover?

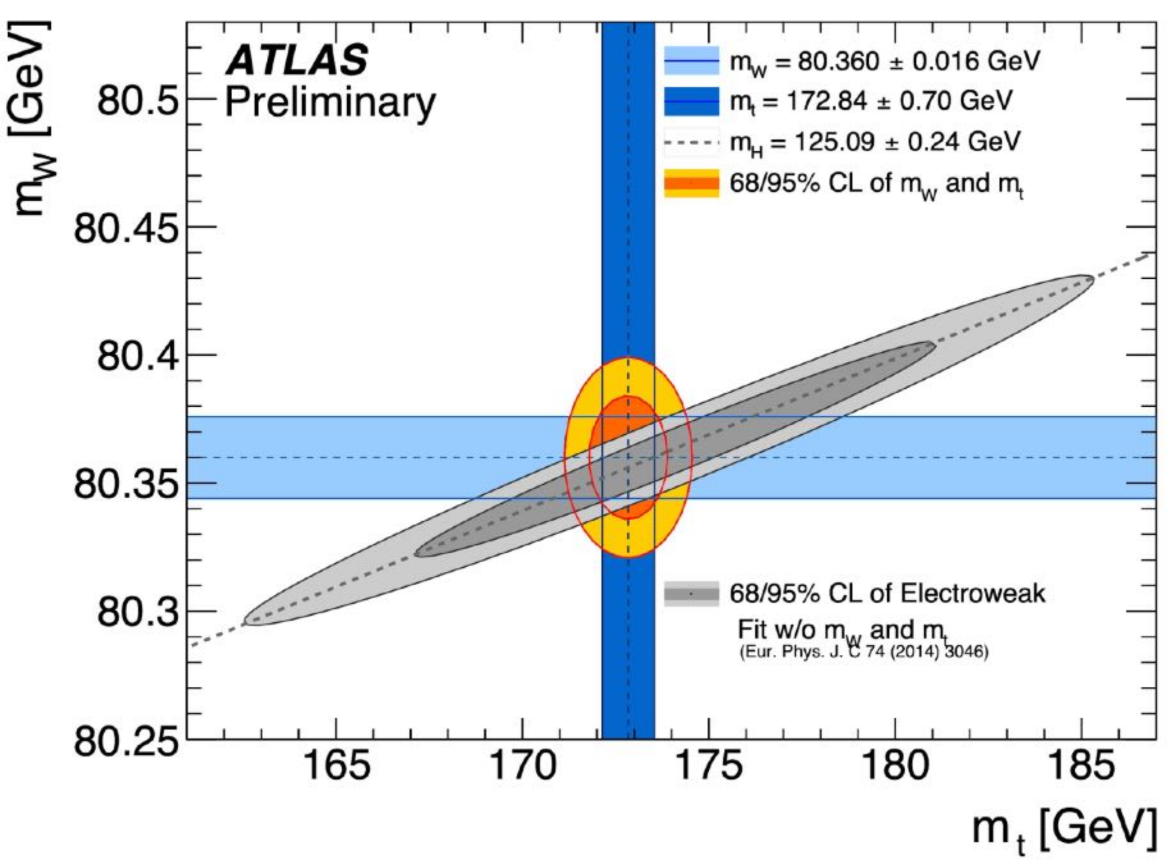






Testing the Limits - Precision Measurements

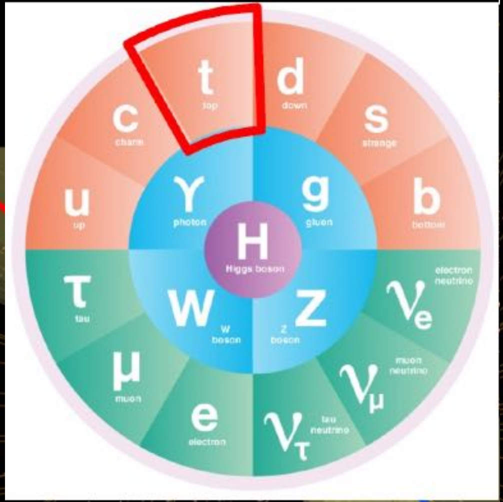
Measure the top quark mass and W boson mass to find out if the model works!

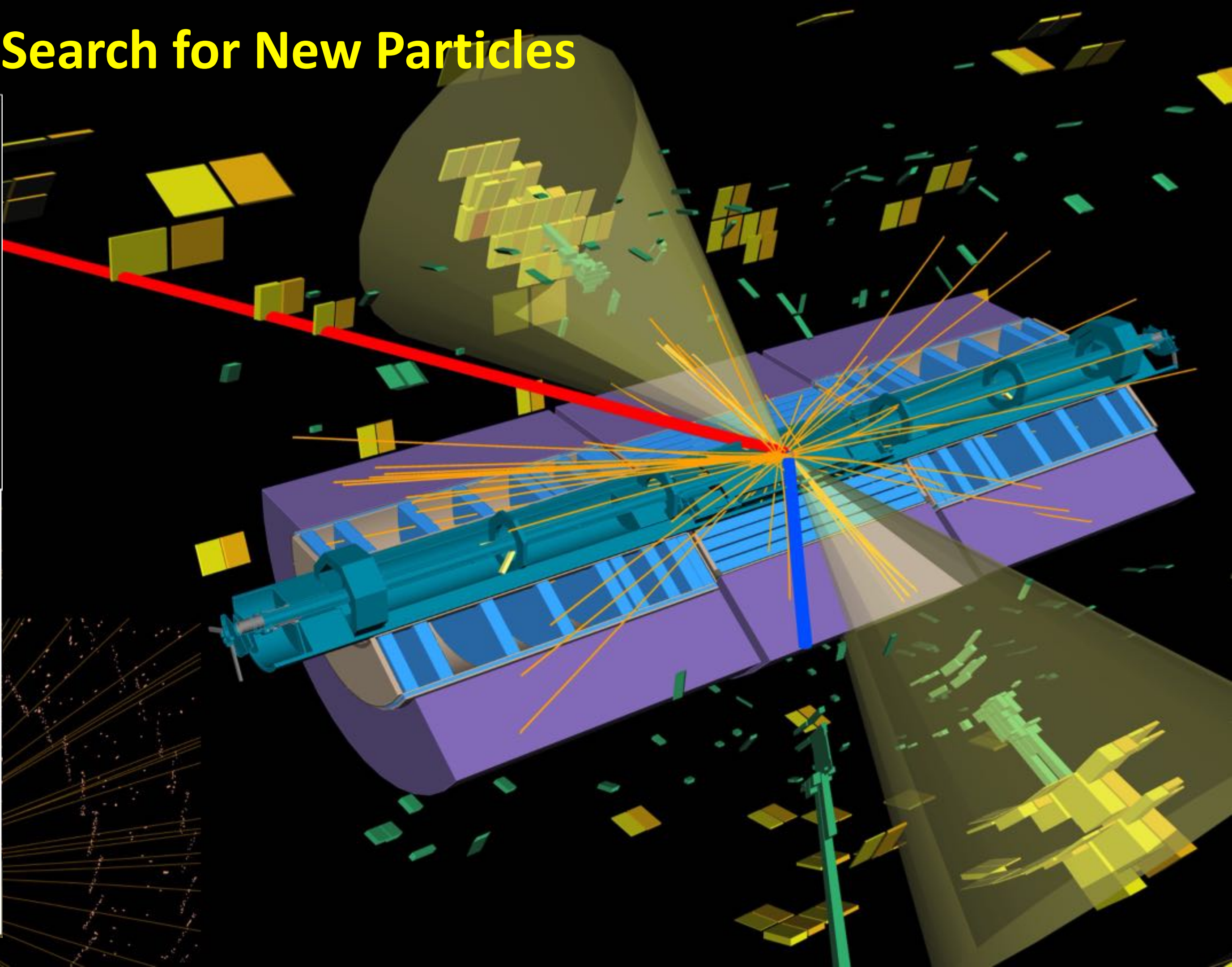


Testing the Limits – Search for New Particles

Where to look?

Here is one of the top quark events observed in the ATLAS detector, from the **275 million** top quarks produced. The most on Earth!

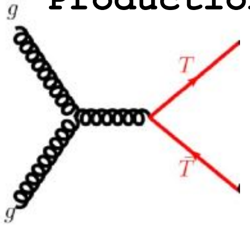




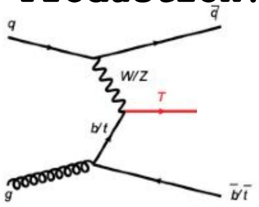
Searches for new physics with Top Quarks

- New data have created an exciting time for **direct** searches for BSM physics at ATLAS and CMS.
- Vector-like quarks (VLQ) are an important signature in many of the new models – particularly Composite Higgs Models.
- **VLQs** are colored spin-1/2 fermions but their **L/R-handed** components transform the same way under gauge transformations
  - Evade limitations on quark extensions of the SM
  - Can be "partners" to SM quarks with the same charges (e.g. $T_{2/3}$, $B_{-1/3}$) or can have more exotic charges ($X_{5/3}$, $Y_{-4/3}$...)
  - In simplified models VLQ mix with their SM partners to regulate the Higgs boson mass
    - Assumed to mix predominately with 3rd gen. SM partners
  - Less simple models may include new resonance decaying to VLQ, or VLQ decaying to BSM particle.

Pair Production:



Single Production:



Decay:

$T \to Wb$ Br~0.5
$T \to Ht$ Br~0.25
$T \to Zt$ Br~0.25

$B \to Wt$ Br~0.5
$B \to Hb$ Br~0.25
$B \to Zb$ Br~0.25

$X \to Wt$ Br~1.0
$Y \to Wb$ Br~1.0

What are Vector-Like Quarks?

A fermion is **vector-like** under a gauge group
if its left-handed and right-handed chiralities transform in the **same way**

e.g. SM quarks are vector-like under $SU(3)_c$ but are chiral under $SU(2) \times U(1)_Y$

Why "vector-like"?

$$\mathcal{L}_W = g/\sqrt{2}\, j^{\mu\pm} W^{\pm}_{\mu}$$ Charged current Lagrangian

SM Chiral fermions

$$j^\mu_L = \bar{f}_L \gamma^\mu f'_L \qquad j^\mu_R = 0$$

$$j^\mu = j^\mu_L + j^\mu_R = \bar{f}\gamma^\mu (1-\gamma^5) f'$$

V-A structure

Vector-like fermions

$$j^\mu_L = \bar{f}_L \gamma^\mu f'_L \qquad j^\mu_R = \bar{f}_R \gamma^\mu f'_R$$

$$j^\mu = j^\mu_L + j^\mu_R = \bar{f}\gamma^\mu f'$$

V structure

Peculiar Properties

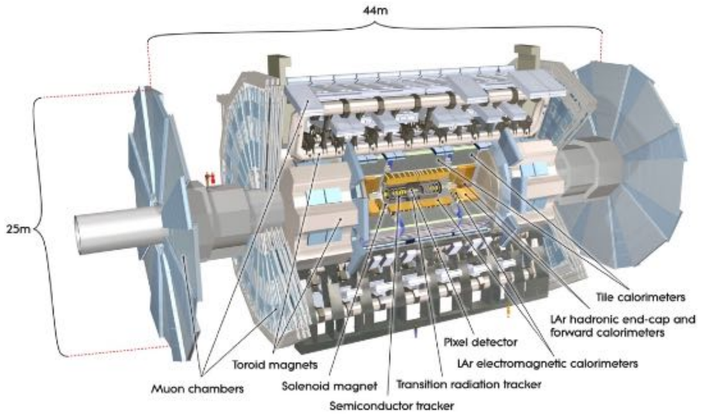
$\mathcal{L}_M = -M\bar{\psi}\psi$ Gauge invariant mass term without the Higgs

No need to add both quarks and leptons: axial anomalies are automatically absent

Slide borrowed from Luca Panizzi

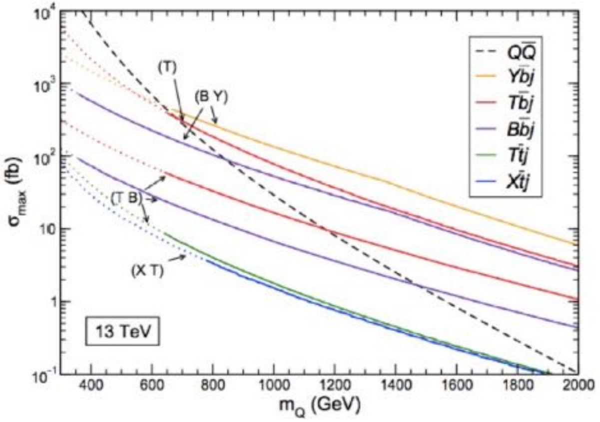
Searching for VLQ in 2024

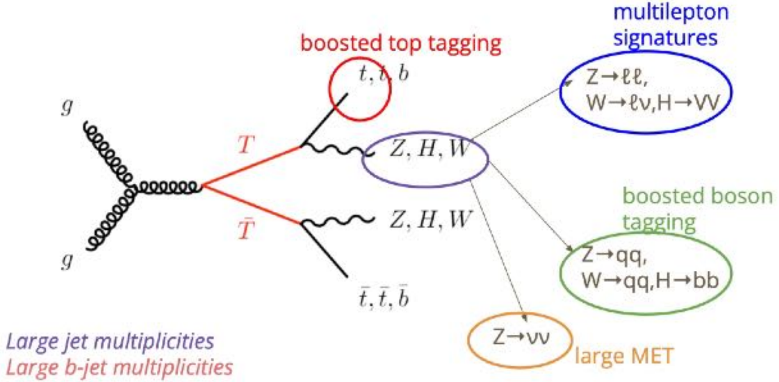
- Multitude of complex final states
  - » **Broad program of searches at ATLAS and CMS.**
- Analyses of full Run 2 (~139 fb^{-1}) dataset discussed today.
- **How to find VLQ?**
  - – Exploit new (machine learning, AI) techniques in all-hadronic (boosted) object tagging, event classification of multi-lepton final states, and more.



VLQ Production and Decay

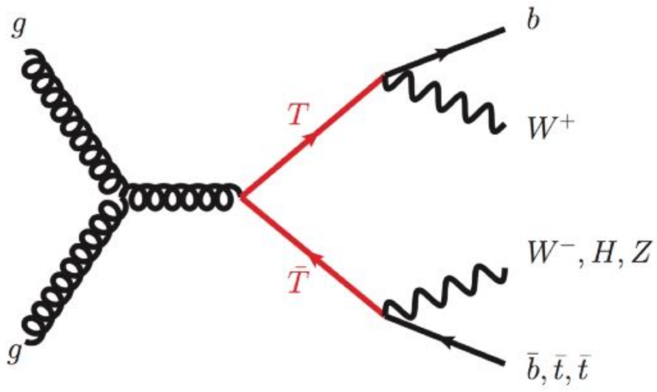
- **Pair production** dominates at low-intermediate masses
  - Strong production; model-independent
- **Single production** takes over at high mass
  - Increasing limits on VLQ masses from past ATLAS searches shifted focus of the first full Run-2 searches towards single production
  - Can directly probe coupling ($\sigma \sim \kappa^2$)
- Many possible final states in both cases
- ATLAS employs divide and conquer strategy:
  - Individual searches according to final state
  - Statistical combination to extend reach
- Production and decays via BSM particles expected in UV-complete models
  - Mostly uncovered by current ATLAS searches

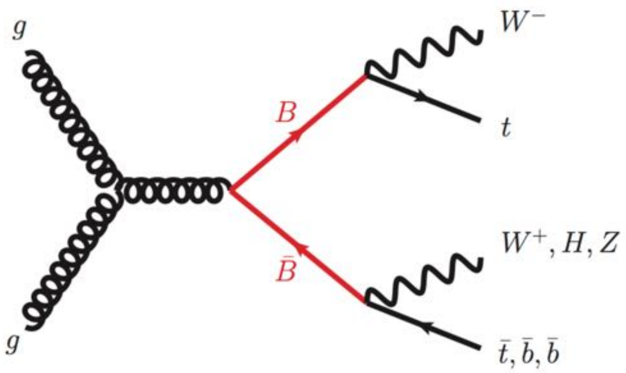




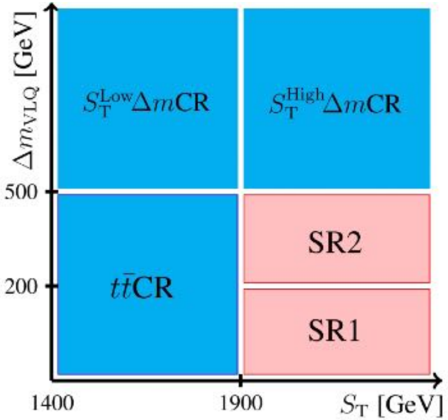
Search for *VL T* and *B* Pair Production

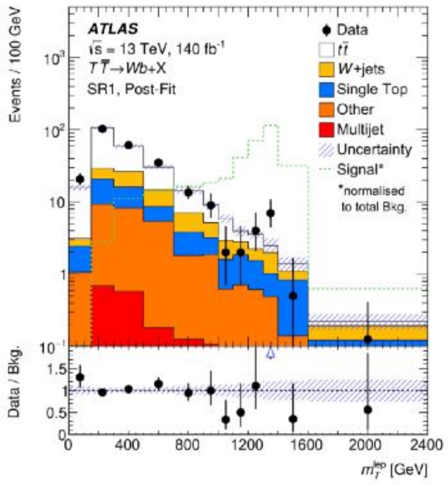
Phys. Lett. B 854 (2024) 138743





- Optimized for the *TT→WbWb* channel with one W boson decaying leptonically and the other hadronically.
- High-pT hadronically decaying W bosons are tagged as a large-radius (large-R) jets.
- Backgrounds modeled as function of scaler sum of E_T in event.
- Reconstructed mass of VLQ is discriminant.

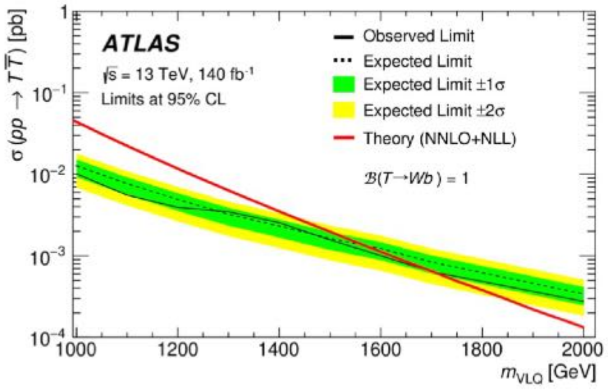


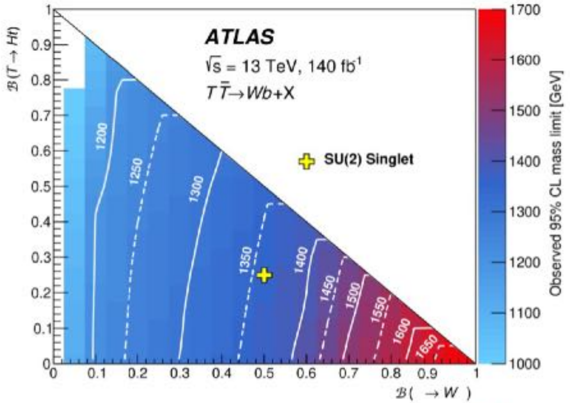


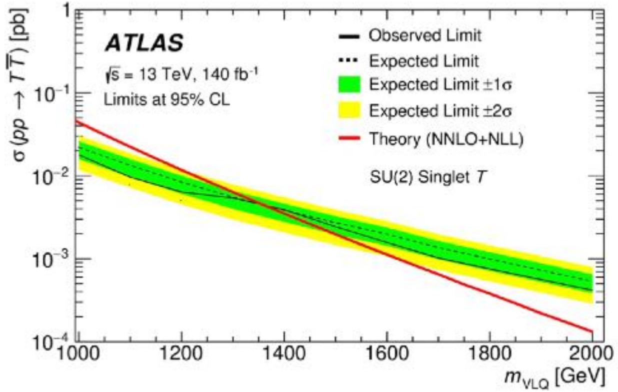
Search for *VL T* and *B* Pair Production

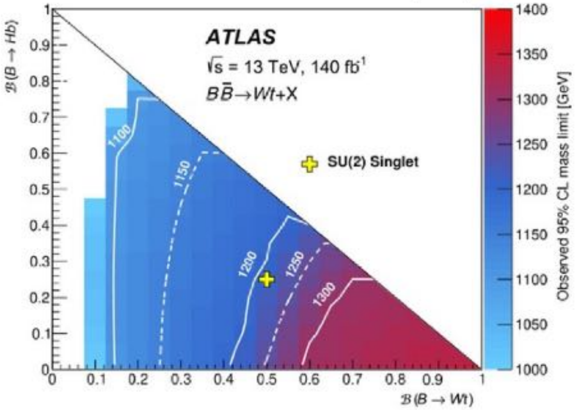
Phys. Lett. B 854 (2024) 138743

- No excess observed.
- Exclude VLQ T/Y with 100% branching ratio to Wb at 95% CL for masses below 1700 GeV.
- Limits set as a function of mass and branching ratio.
- Optimized for $TT \rightarrow Wb + X$
- also consider similar final state for $BB \rightarrow Wt + X$









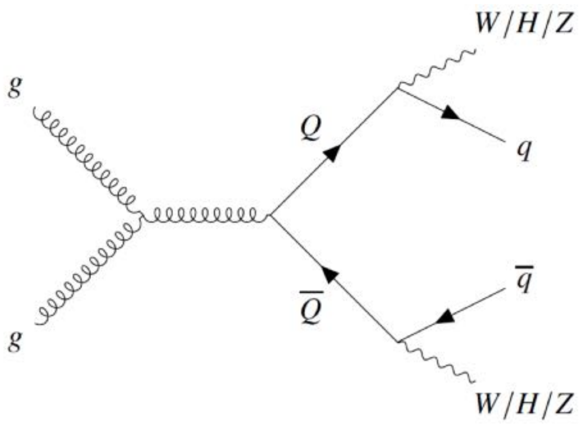
Search for *VLQ* coupling to *light quarks*

e-print arXiv:2405.19862

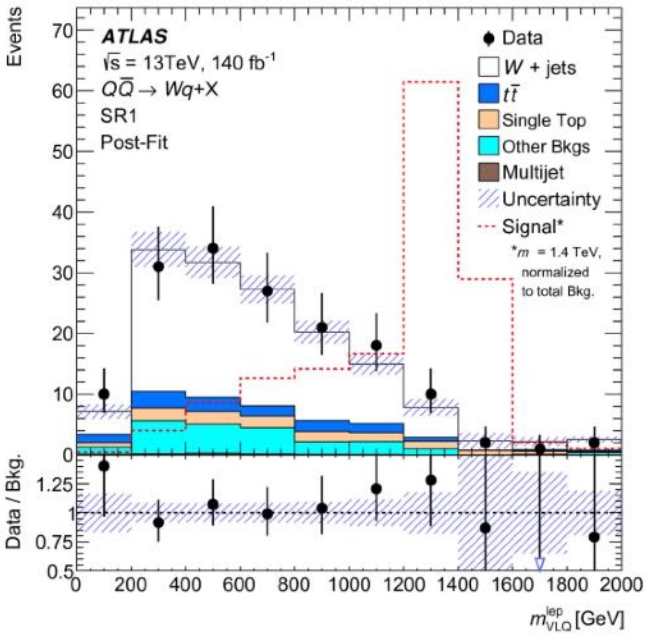
ATLAS EXPERIMENT

New result

- Nearly all searches for VLQ focus on coupling to SM top and bottom. However, we should not neglect possibility of coupling to light quarks!



- Search for $QQ \rightarrow Qq + X$ follows previous analysis strategy closely.
- Rejection of b-quark events eliminates previously dominate ttbar background.
- Remaining backgrounds determined through iterative data-driven procedure.



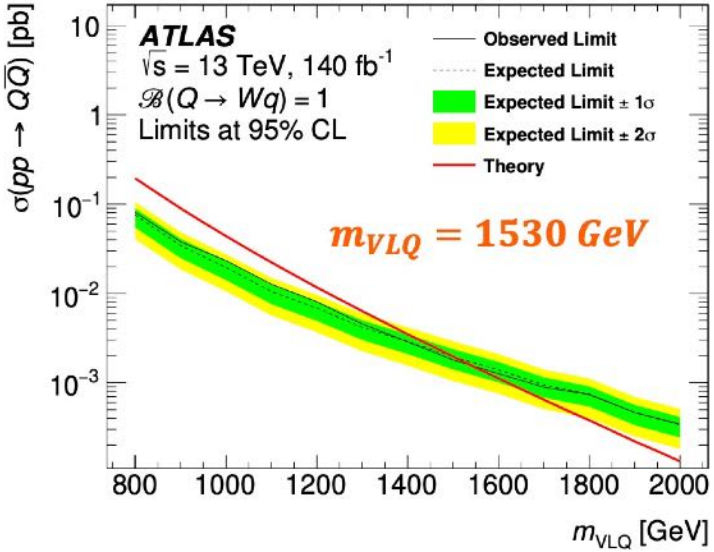
Search for *VLQ* coupling to *light quarks*

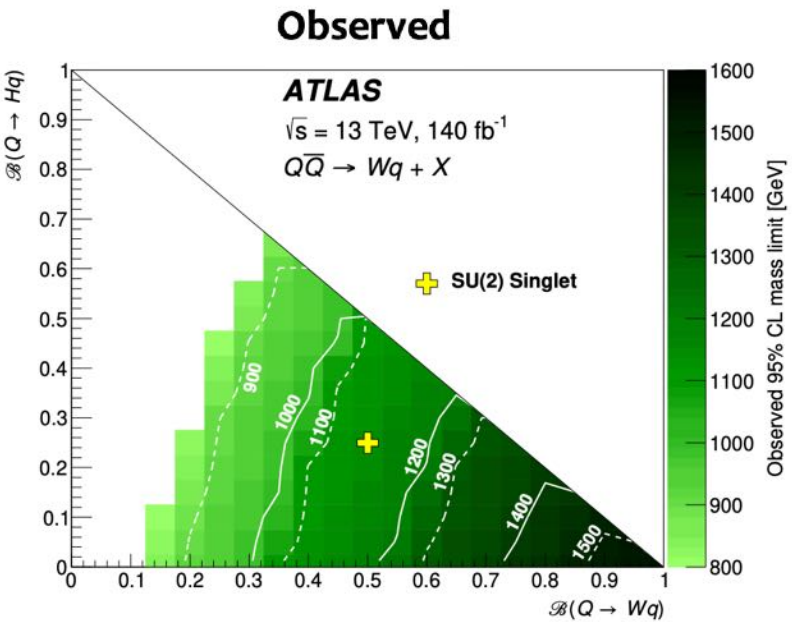
e-print arXiv:2405.19862

ATLAS EXPERIMENT

New result

$\mathcal{BR}(Q \to Wq) = 1$

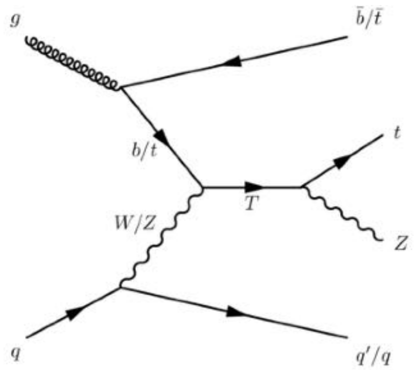




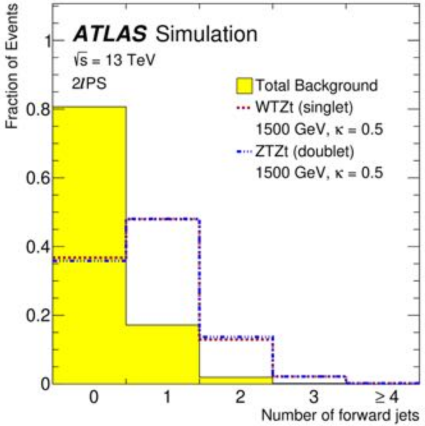
- No excess observed.
- Limits set as a function of mass and branching ratio.
- Exclude VLQs (Q) with masses below 1530 GeV at 95% CL for Br($Q \to Wq$) = 1
  - Previous limit was 690 GeV!

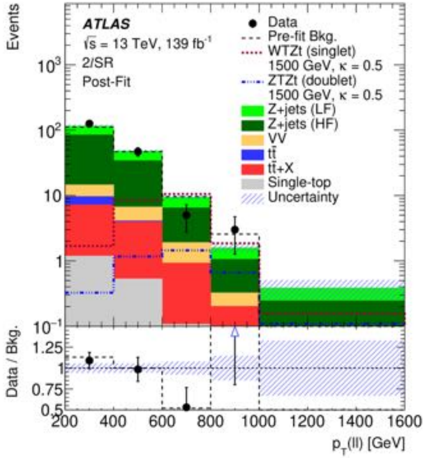
Search for *VL T* Single Production

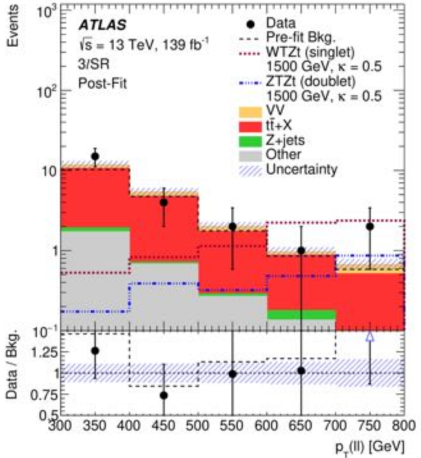
PRD 109 (2024) 12012



- Dedicated search for *VL T* with opposite sign, multi-lepton event selection.
- Split into **2 lepton and 3 or more lepton** SR.
- In 2L region identify top candidate based on large radius jet p_T, mass, and associated *b*-tagged track jets
- Fit using reconstructed *Z* boson candidate pT spectrum.





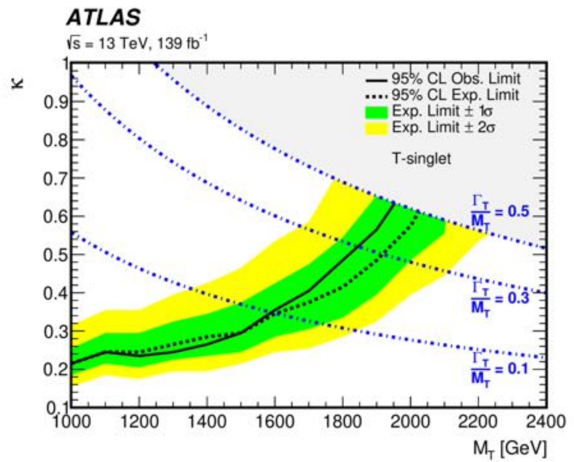


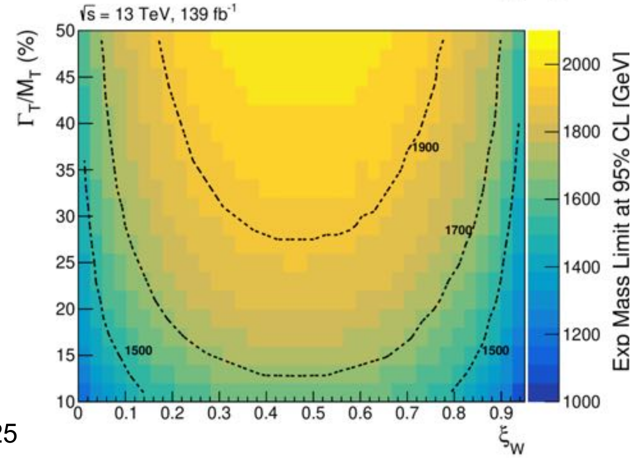
Search for *VL T* Single Production

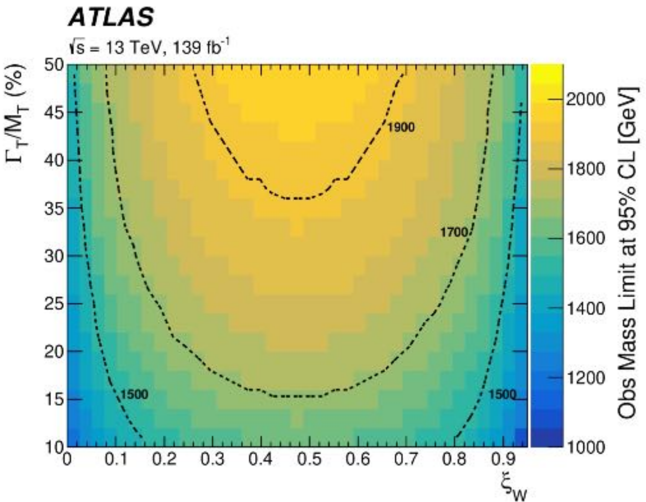
[PRD 109 (2024) 12012]

ATLAS EXPERIMENT

- No excesses observed.
- Exclude production of a single VLQ (T) for masses below 1975 GeV assuming a coupling to the top quark κ_t = 0.64 and a branching ratio for $T \rightarrow Zt$ of 25% (singlet).
- Single production of VLQ depends on mass and coupling (and coupling related to width and *BR*).
- Developed a novel presentation of the limits that show the relative width and Br in a consistent way [1,2].
- Particularly useful in combining results from ATLAS and comparing (or combining) results from CMS.





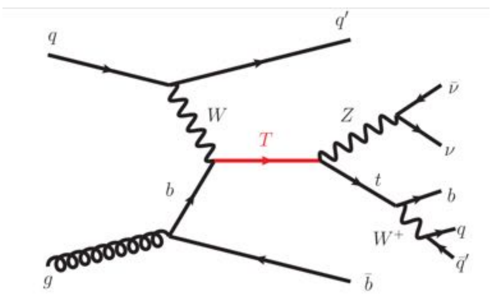


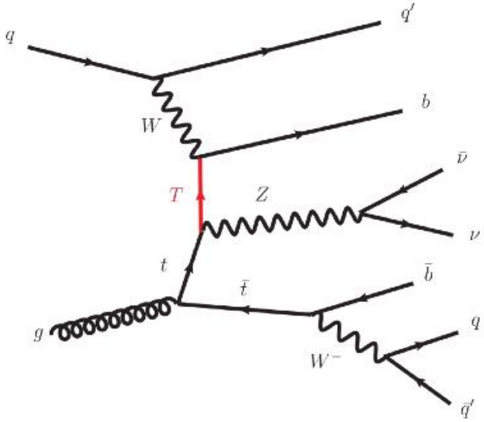
[1] Roy, TA, *Non-resonant diagrams for single production of top and bottom partners*. Phys. Lett. B. 2022 July; 833(2022).

[2] Roy, Nikiforou, Castro, TA, *Novel Interpretation Strategy for Searches of Singly Produced Vector-like Quarks at the LHC*, Phys. Rev. D 101, 115027 (2020)

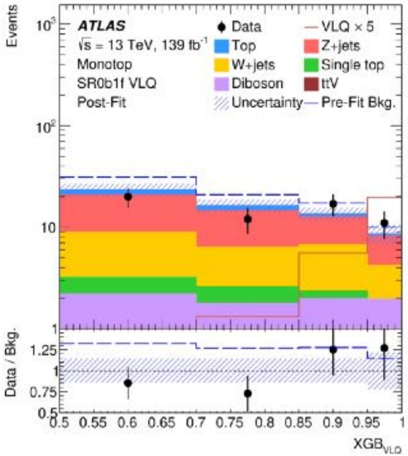
Search for boosted top quark and missing E_T

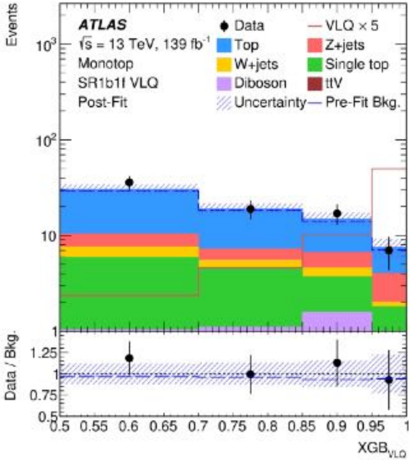
JHEP 05 (2024) 263





- Exploit "monotop" search – single top final state with large missing E_T (and **0 leptons**).
  - Search for Dark Matter and VLQ using slightly different signal regions.
- Apply Deep Neural Network (DNN) based identification of large-R jet originated from hadronically decaying top
- Signal events are separated from background using eXtreme Gradient-Boosted (XGBOOST) Decision Tree (BDT). BDT score is the final discriminant.

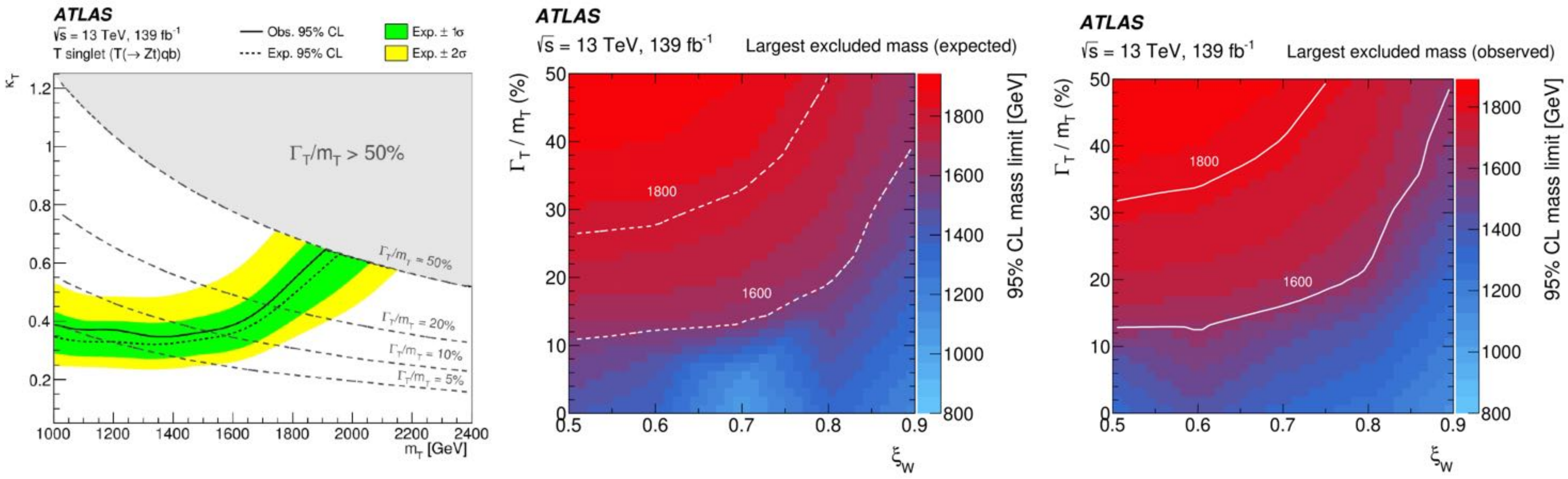




Search for boosted top quark and missing E_T

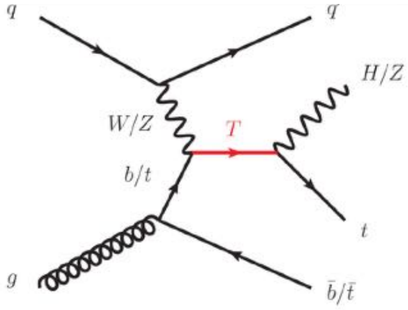
JHEP 05 (2024) 263

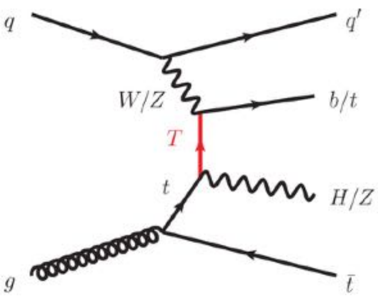
- No excesses observed.
- Exclude production of a single VLQ (T) for masses below 1.8 TeV assuming a coupling to the top quark κ_t = 0.5 and a branching ratio for $T \rightarrow Zt$ of 25% (singlet).
- Use the same procedure as the previous result to display limits vs relative width, coupling and mass.

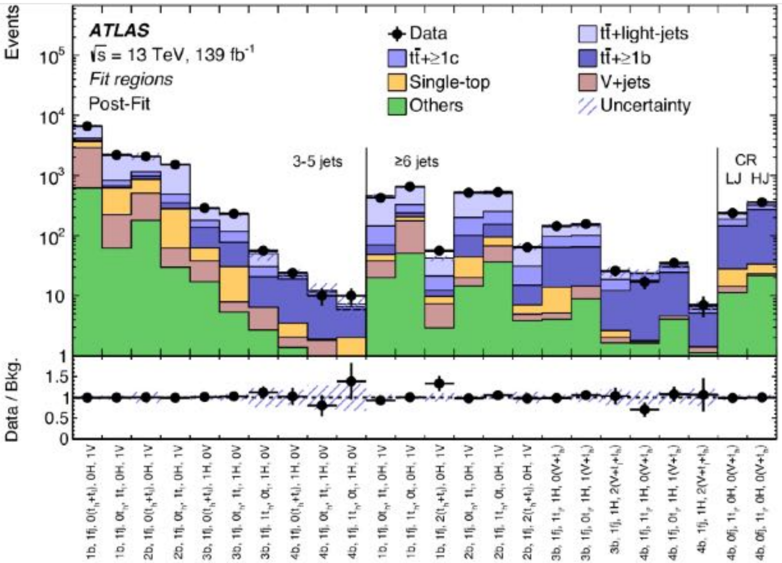


Search for VLQ decays to Higgs or Z bosons

JHEP 08 (2023) 153





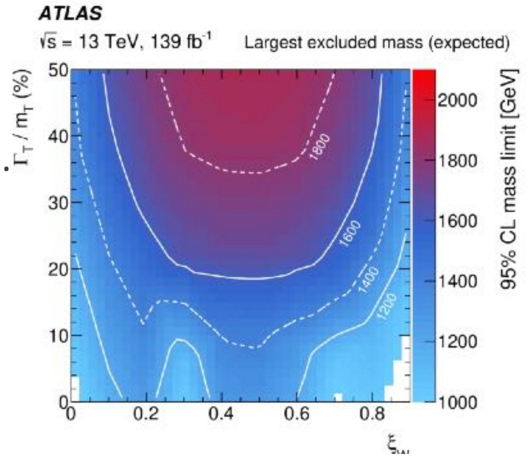


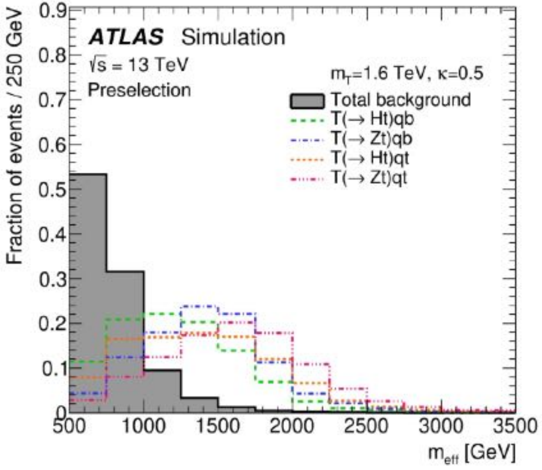
- Analysis targets final states with **1l**, multiple jets and b−jets using 139 fb−1 data collected with the ATLAS detector
  - Presence of boosted resonance used to discriminate between signal and background
- Wide range of couplings of the VLQ to W , Z and h bosons probed compared to previous search thanks to more data, better kinematic selections, improved top-tagging.
- Fit includes 24 signal regions.

Search for VLQ decays to Higgs or Z bosons

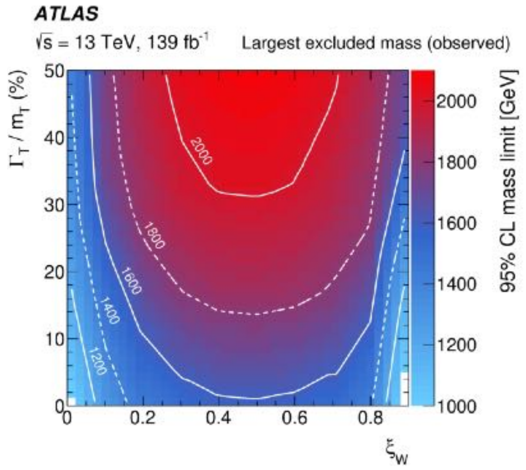
JHEP 08 (2023) 153

- Reconstructed M_{eff} used to discriminate signal and background.
  - Dominate backgrounds vary based on region: ttbar, single top and V+jets.
- No excesses observed.
- Exclude production of a single VLQ (T) for masses below 2.3 TeV assuming a coupling to the top quark κ_t = 0.53 and a branching ratio for $T \rightarrow Zt$ of 25% (singlet).



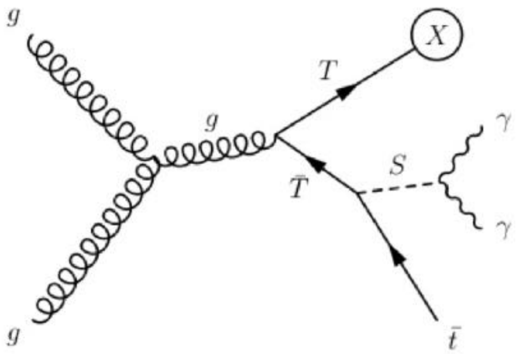


	LJ, 2b, ≥1fj, $0t_h$, $\geq 1t_l$, 0H, ≥1V	LJ, ≥4b, ≥1fj, $0t_h$, $\geq 1t_l$, ≥1H, 0V	HJ, 2b, ≥1fj, $\geq 2(t_h+t_l)$, 0H, ≥1V	HJ, ≥4b, ≥1fj, ≥1H, $\geq 2(V+t_l+t_h)$
T singlet (m_T = 1.6 TeV, κ = 0.5)	31.8 ± 4.9	7.2 ± 3.5	1.3 ± 0.4	1.0 ± 0.5
T doublet (m_T = 1.6 TeV, κ = 0.5)	21.8 ± 2.4	8.5 ± 5.6	7.3 ± 2.1	7.1 ± 4.5
$t\bar{t}$+light-jets	1170 ± 210	1.6 ± 2	39.1 ± 9.5	0.49 ± 0.29
$t\bar{t}$+≥1c	143 ± 80	1.5 ± 1.3	15.3 ± 9.9	0.86 ± 0.58
$t\bar{t}$+≥1b	57 ± 32	4.8 ± 3.9	6.1 ± 4.3	2.6 ± 2
Single-top	250 ± 50	0.66 ± 0.87	7.3 ± 7.5	<0.001
$t\bar{t}W/Z$	13.2 ± 3.1	0.33 ± 0.19	2.5 ± 1.1	0.22 ± 0.82
$t\bar{t}H$	1.5 ± 0.2	0.51 ± 0.15	0.34 ± 0.14	0.42 ± 0.12
W+jets	25.7 ± 9.4	0.70 ± 1.3	1.2 ± 1.1	0.24 ± 0.15
Z+jets	4.4 ± 1.7	<0.001	0.25 ± 0.10	0.007 ± 0.007
Dibosons	3.8 ± 1.4	0.02 ± 0.03	0.21 ± 0.15	<0.001
Multijet	12.9 ± 7.3	0.025 ± 0.017	0.61 ± 0.46	0.16 ± 0.14
Rare backgrounds	2.0 ± 0.3	0.03 ± 0.04	0.25 ± 0.14	0.33 ± 0.06
Total background	1690 ± 280	10.2 ± 4.8	73 ± 20	5.4 ± 2.5
Data	1519	10	64	7



...and More

- **Broad program of ATLAS VLQ searches** from Run 2 wrapping up. For single production:
  - Multi-b B→bH(bb)
  - All-hadronic T→H(bb)t
  - 1ℓ+multi-jet/b T→H(bb)t/Z(qq)t
  - ℓ+ℓ-/3ℓ T→Z(ℓℓ)t
  - Monotop/VLQ 0 and 1 lepton



- **Looking ahead**: In realistic (UV complete) models VLQs do not appear in isolation

- Expect scalar and vector resonances to appear
  - VLQ decays to BSM particles can weaken existing bounds on VLQ mass
- New production channels can appear through the decay of BSM resonances to VLQs


There is a vast landscape
in which new physics
can be hiding.

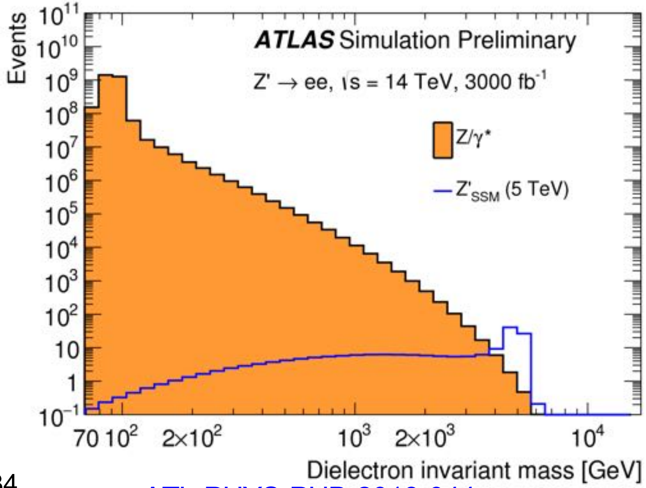
Upgrading the LHC


Upgrading
ATLAS

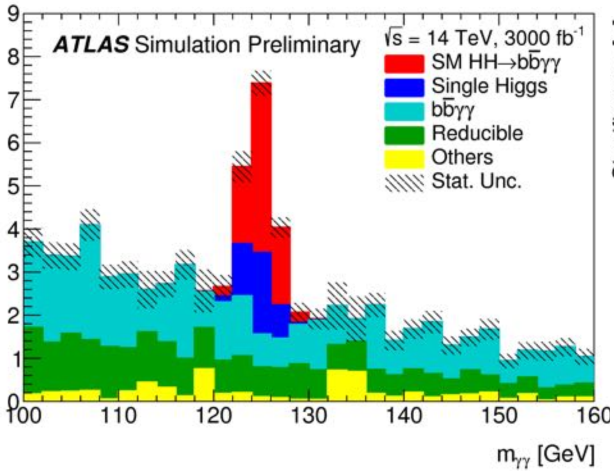
- The ATLAS physics program at the High Lumi (HL)-LHC will focus on key Standard Model measurements and the continued search for new physics.
  - Electron and photon energy, position and timing measurements are critical drivers of the upgrade requirements for the LAr calorimeter electronics.

Very high energy electrons from eg. massive Z' decay → high dynamic range.

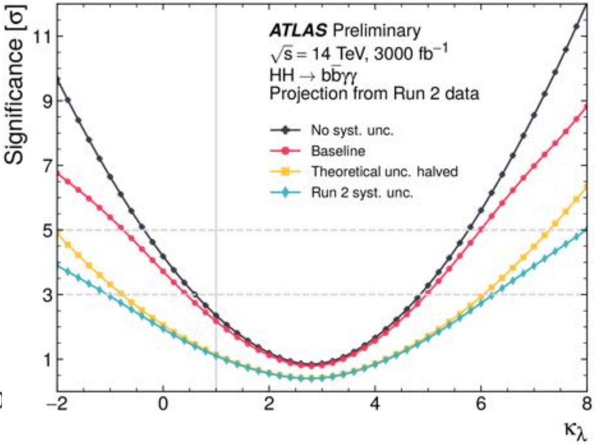
Precise mass resolution (small peak on large background) needed for eg. di-Higgs observation.



ATL-PHYS-PUB-2018-044



ATL-PHYS-PUB-2018-053

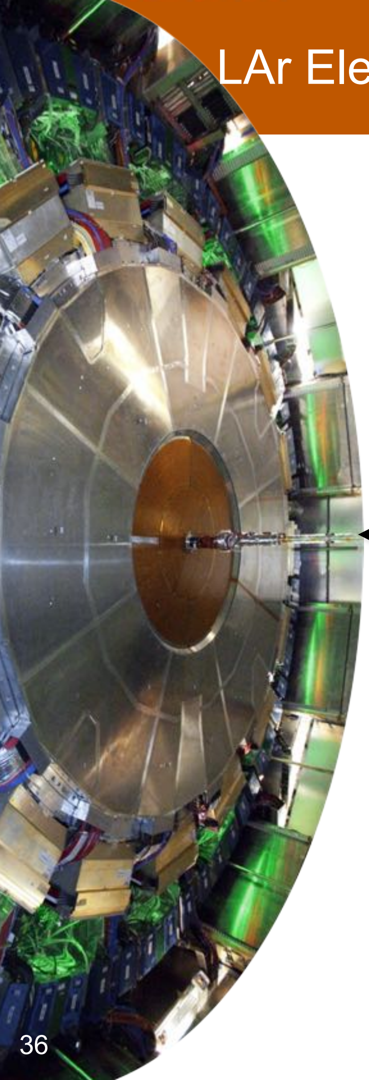


ATL-PHYS-PUB-2022-018

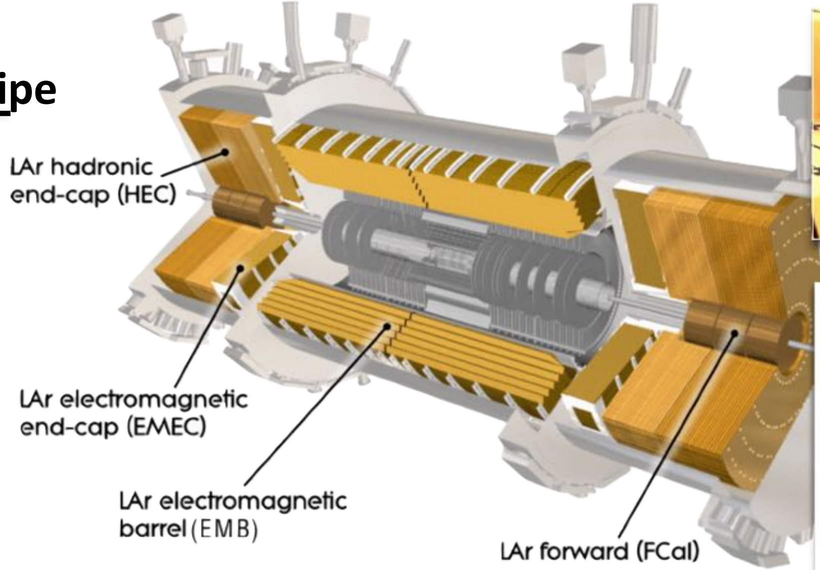
HL-LHC – When?

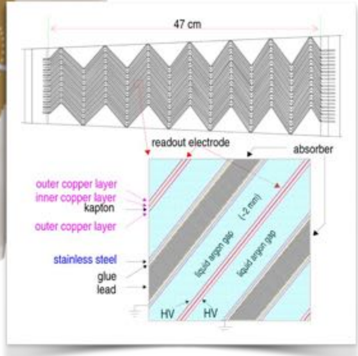
- **In 2029 the HL-LHC experiments are scheduled to start taking data**. Will provide up to 7x design luminosity with up to 200 simultaneous collisions.
- The LAr calorimeters themselves are expected to operate reliably throughout HL-LHC.
- **LAr electronic readout requires complete replacement to cope with increased rates and radiation exposure.** Will be installed 2026-2028.
  - Free-running, all digital design to provide full calorimeter information (***350 Tbps***!) for improved trigger decisions.
    - Trigger/DAQ rate increased 10x to 1 MHz, latency increased 5-10x to 10 us.
  - On-detector readout, dubbed the Front-end Board (FEB) is located on the cryostat for improved analog performance. Challenges: high radiation, high mag. field, limited access.
  - Off-detector readout process digital signals and determine the energy and timing for each cell.

LAr Electromagnetic Calorimeter – What we're upgrading

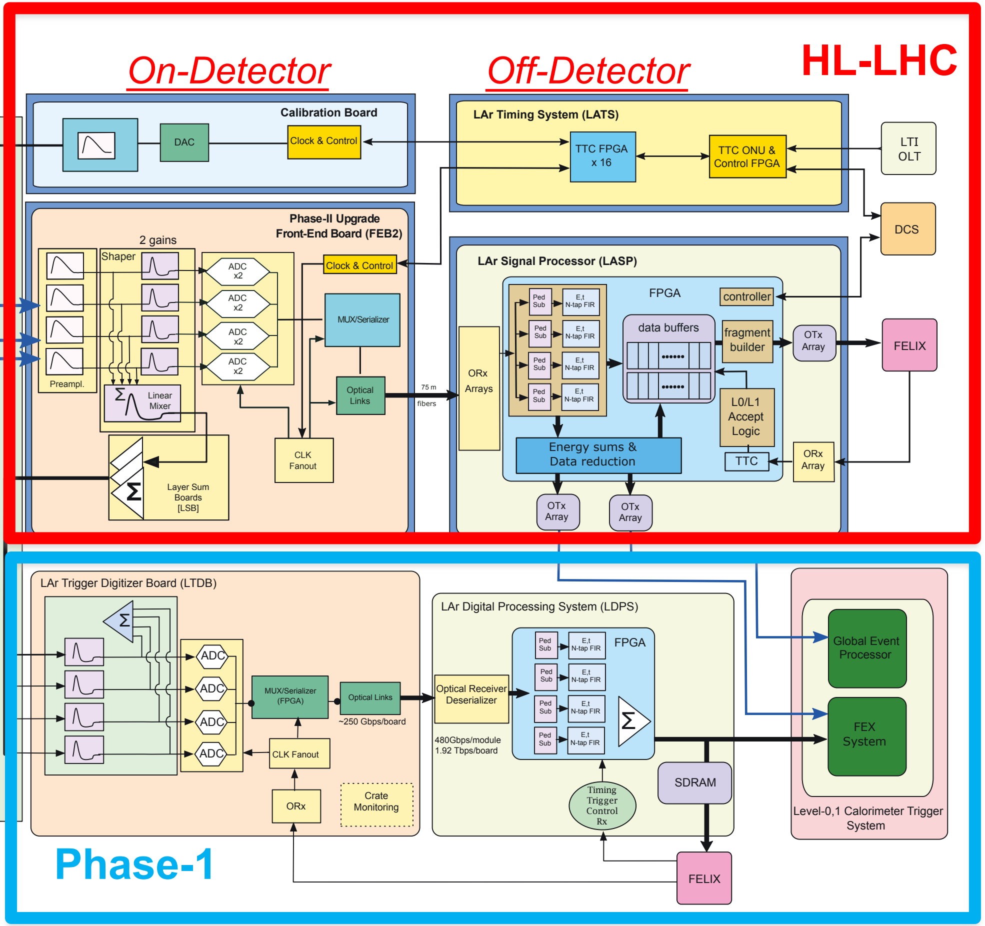


- Measures energy, position and timing of electromagnetic showers (photons, electrons, jets).
- Sampling design with active (LAr) and passive (lead) layers in accordion geometry with three layers in barrel cryostat.
- Readout electronics sample 182k cells at 40 MHz and send digitized pulse off the detector for analysis and triggering.





LAr Calorimeter Readout @ HL-LHC



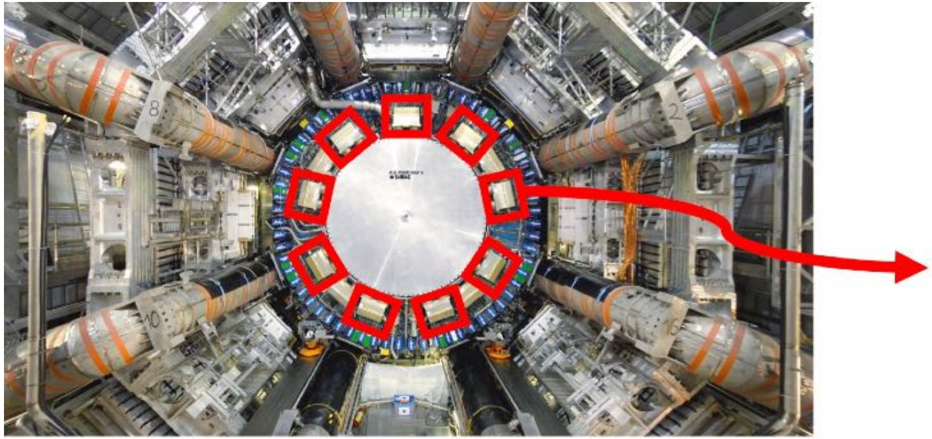
HL-LHC

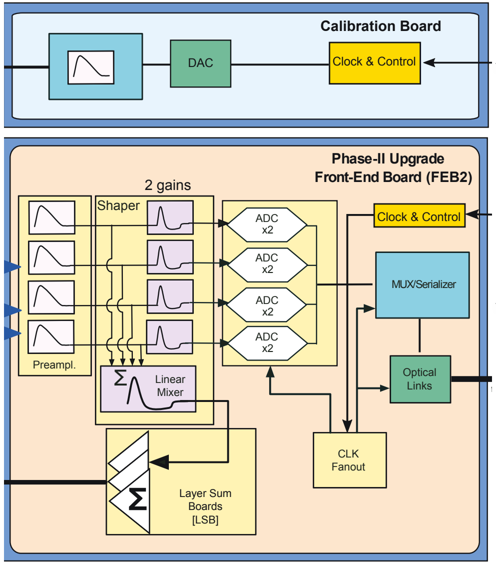
- Cover full energy range expected in a single cell (~50 MeV electronic noise to ~3 TeV)
- 16-bit Dynamic Range with 11-bit precision (implemented in 2 overlapping 14-bit gain scales)
- Nonlinearity < 0.1% up to ~300 GeV
- Electronics noise < minimum ionizing particle (MIP) energy / intrinsic LAr resolution
- Radiation tolerance: full HL-LHC dose, eg. max TID 1400 Gy (1.5), NIEL < 4.1 x 10^{13} n_{eq}/cm^2 (2)

Phase-1

- Installed and commissioned 2019-2022, part of Run 3 readout.

On-Detector LAr upgrade electronics





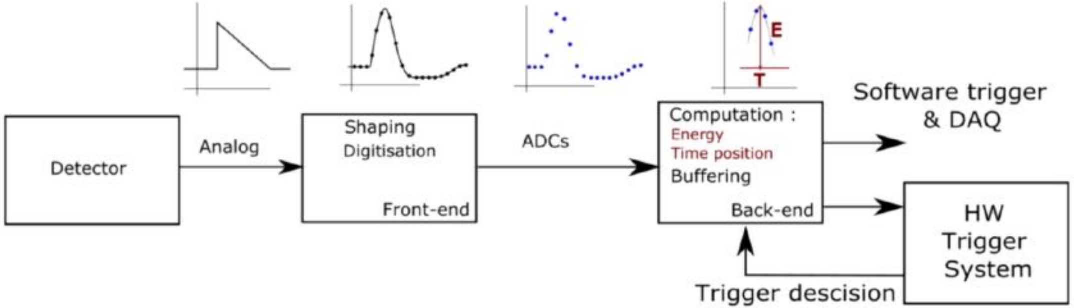
Calibration:

- Pulsar and DAC

Front End Board:

- PreAmp/Shaper(PA/S)
- ADC

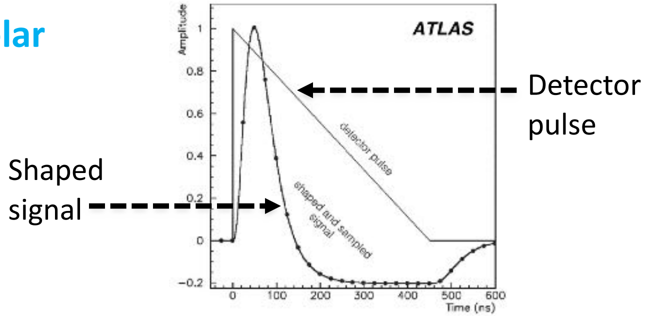
On-detector readout includes four LAr-specific ASICs.

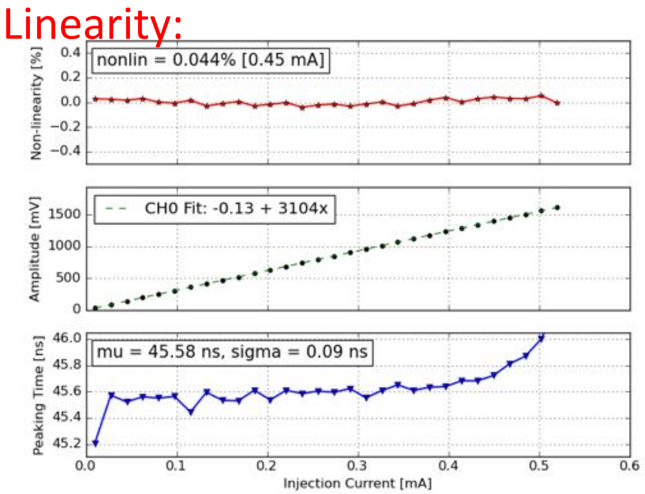


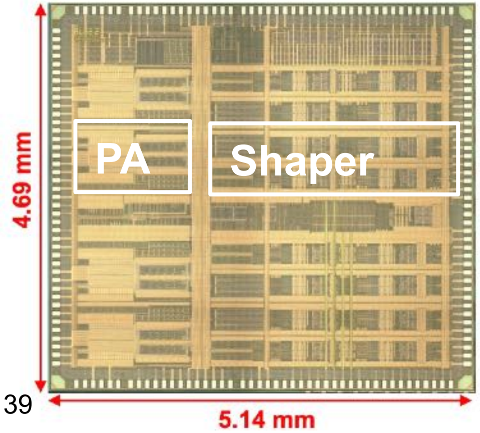
On-Detector – LAr PreAmp/Shaper

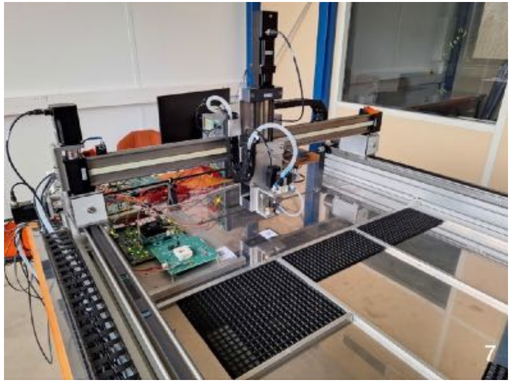
Analog processing of signals (amplification and split to 2 gain scales, bipolar CR-(RC) shaping function) for differential outputs to ADC and L0 trigger

- **ALFE2**: custom ASIC designed in 130 nm CMOS (~50k needed)
  - 4 Channel input, 9 Channel output (4 x 2 gains + Trigger sum of 4 chs.)
  - Input impedance and dynamic range programmability (25 and 50 Ohm)
  - Input impedance tuning < 2.5% steps
  - Peaking time tuning (15 ± 5 ns, 1 ns steps)
  - Preamplifier DC level tuning 200, 2.3 V ± 50 mV
  - DC output tuning, 600 mV ± 360 mV, 30 mV steps
- In production now, with robotic mass-testing







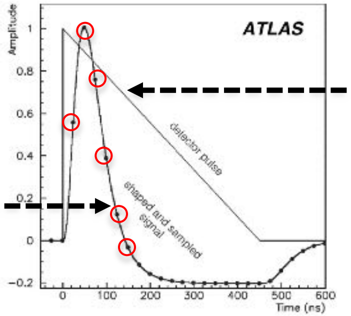


On-Detector – LAr ADC

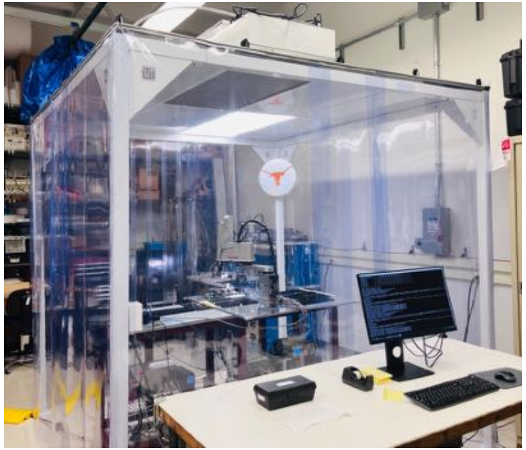
Digitization of PA/S outputs at bunch crossing rate of 40 MHz with 14-bit dynamic range and > 11-bit precision

- **COLUTA**: custom ASIC in 65 nm CMOS (~50k needed)
  - 8 channel (4 LAr chs. x 2 gains), Multiplying DAC (3 bits) + 12 bit Successive Approximation Register (SAR) 15-bit ADC.
  - 40 MHz sampling, with >11-bit precision
  - Digital Data Processing Unit (DDPU) applies calibrations and transmits data at 640 Mbps.
  - Fully compatible with PA/S
  - eLink interface to lpGBT (optical transmission off-detector)
- In production now, with robotic mass-testing

Shaped and **sampled** signal

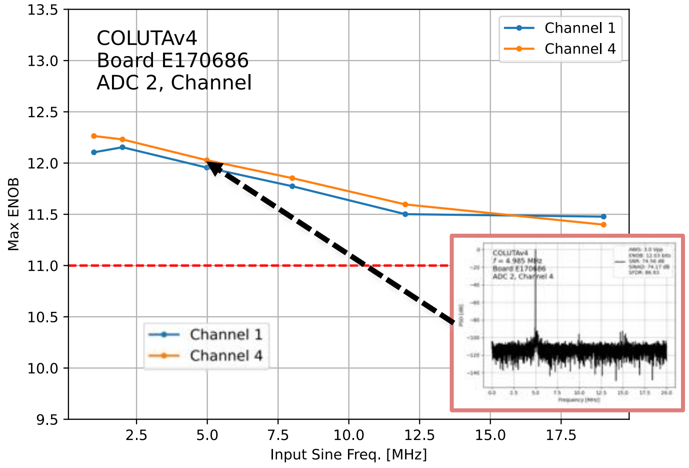


Detector pulse



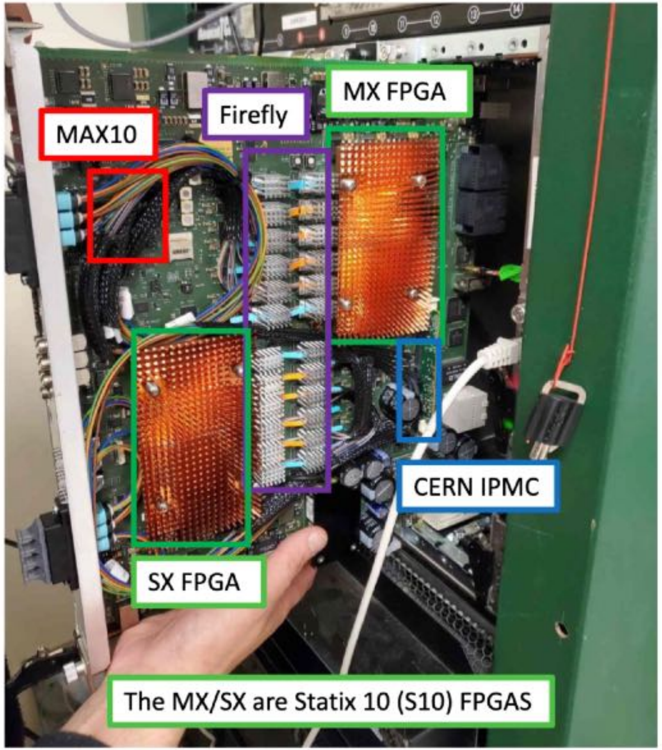
CEA-Saclay

Precision:



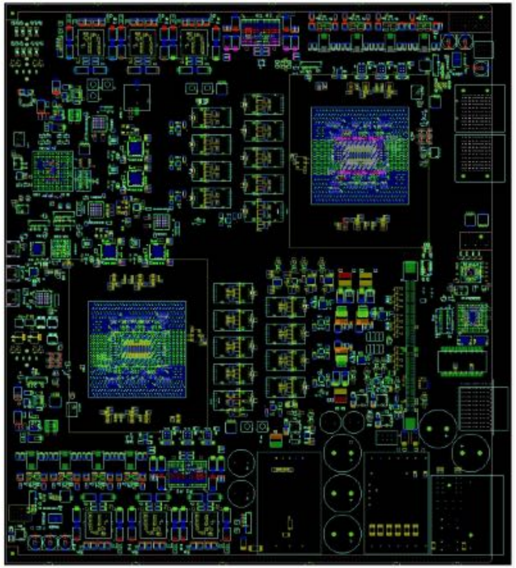
Off-Detector – LAr Signal Processor (LASP)

- LASP test board



Applies digital filtering to waveforms from FEB2, calculates energy & time, and transmits to trigger and DAQ (in FPGA online)

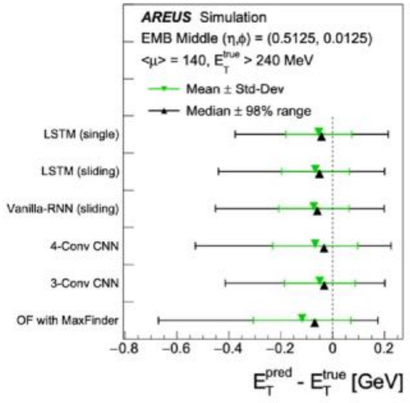
- LASP Main Blade (ATCA) + Smart Rear Transition Module (SRTM):
  - 200-278 of each board, 6-8 FEB2 per blade (2 FPGAs), outputs to L1 and TDAQ at 25 Gbps
- LASP-T2 testboard (STRATRIX10 FPGA) under test with SRTM HW.
  - Power sequencing, FPGA configuration and programing, I^2C links validated.
  - Regular monitoring of current/voltage/temperature.
- Next steps:
  - Full prototype board design underway.
  - Integration of testboard with FEB2 prototype underway.

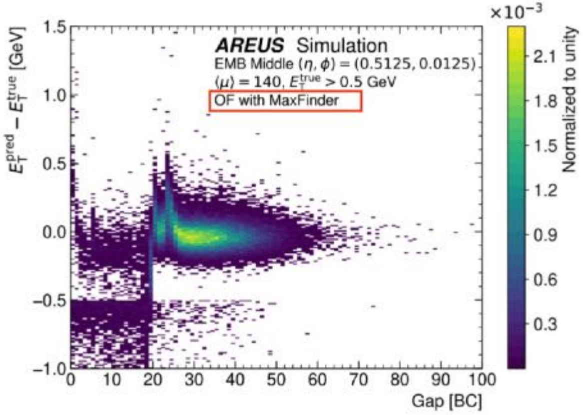


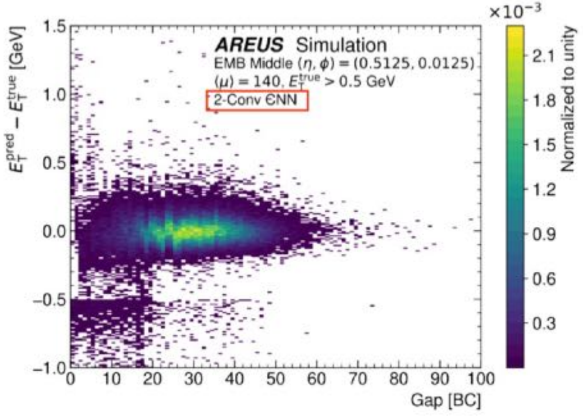
- LASP prototype design

LASP – Machine Learning on FPGAs

- Current energy and timing calculation (digital signal processing) uses Optimal Filtering (OF), modern machine learning techniques may allow us to improve energy and timing calculations in a high pileup environment
- Convolutional and Recurrent Neural Networks (CNN and RNN) are being investigated and show promise.
  - Trade offs between FPGA usage and power.

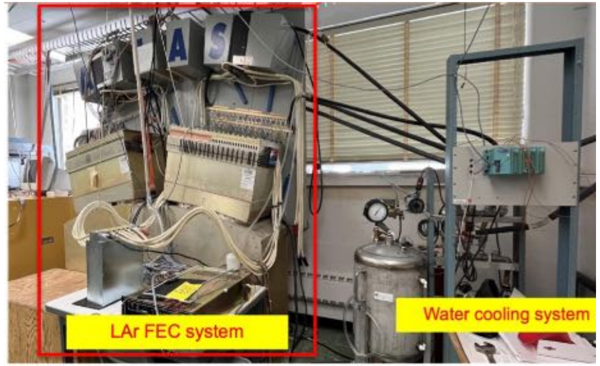


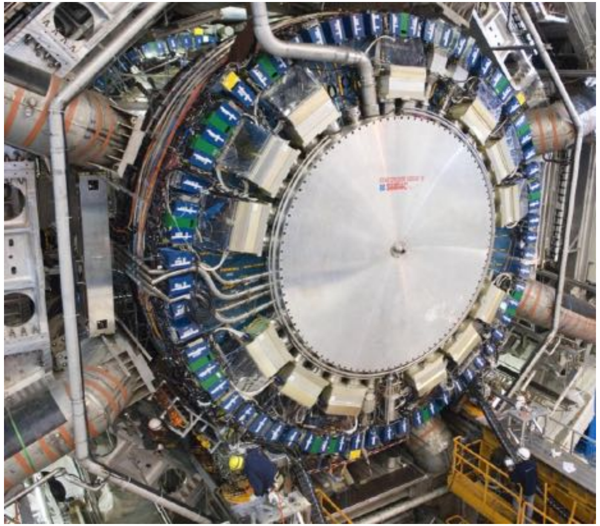




ATLAS Upgrade Outlook

- The LAr calorimeter is vital to the success of the physics program at ATLAS in the HL-LHC
  - Current LAr readout does not meet HL-LHC trigger requirements, nor will it survive full HL-LHC radiation dose.
  - All LAr electronics (on- and off-detector) will be replaced by **2029** for HL-LHC operation (except cold preamp/summing in HEC).
  - Designed to run through **2041**.
- Major progress on all LAr HL-LHC upgrade components
  - Full custom LAr-specific ASICs in pre-production. Meet specifications for analog performance.
  - Front-end board prototype design complete, off-detector signal processing (LASP) testboards running and firmware design on track.
  - Preparing for full slice + systems test (calibrations + FEB2 + LASP)
- On schedule for installation into ATLAS cavern beginning in **2027**, after the end of LHC Run 3.

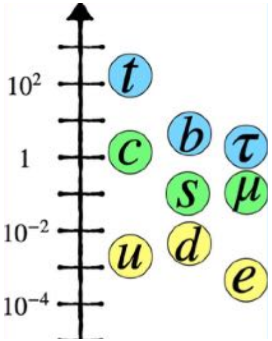


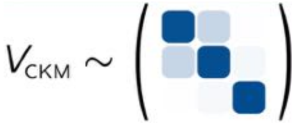



FCC
SUISSE
FRANCE
Genève
Annecy
LHC
What about after 2041?

We’re not running out out questions!

Mass [GeV]





Figures from A. Greljo

$$\langle q\bar{q}\rangle \to \pi^0$$

$$\langle ??\rangle \to H^0$$

- What is the Dark Sector?
- Where do the mass and flavor patterns come from (and why are neutrinos so different)?
- What is the Higgs Potential?
- Is the SM as Effective Theory?

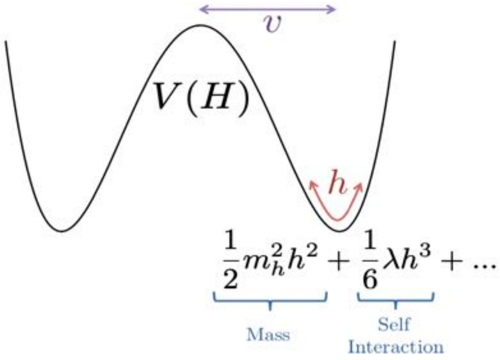


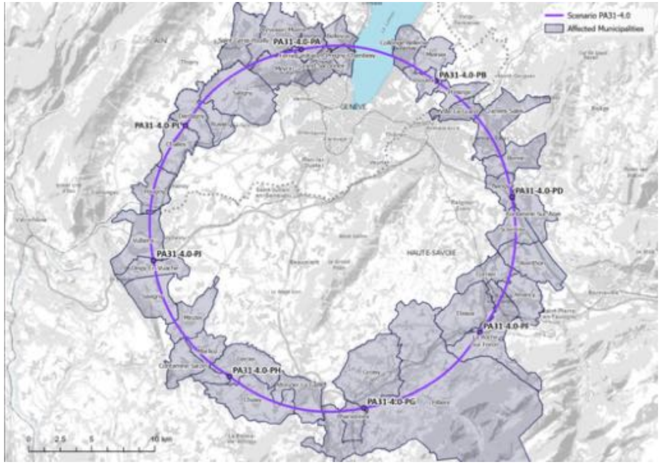
Figure from M. McCullough

FCC-ee

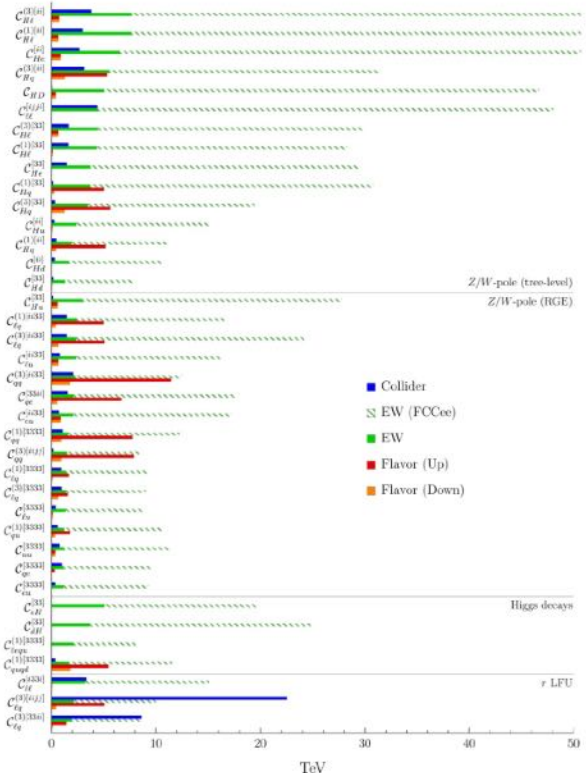
FCC-ee: ultimate precision with

- **~100 000 Z / second (!)**
  - 1 Z / second at LEP
- **~10 000 W / hour**
  - 20 000 W in 5 years at LEP
- **~1 500 Higgs bosons / day**
  - 10-20 times more than ILC
- **~1 500 top quarks / day**

… in each detector



FCC-ee projections (green hash)



Figures from 2311.00020

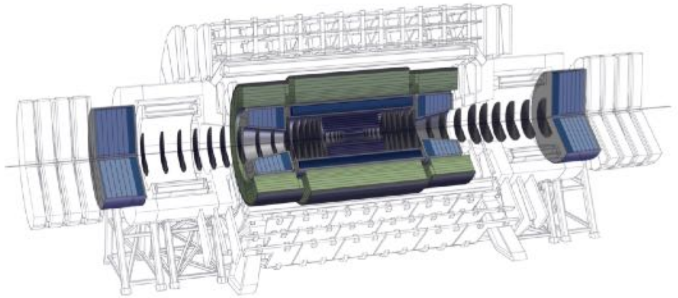
- Highest luminosity at Z, W, ZH energies of all proposed Higgs and EW factories → ultra-precise measurements of Higgs boson and other EW parameters a → indirect exploration of next energy scale
- Mature technology. First stage for energy frontier FCC-hh.

FCC-ee Detector Concept

Proposed general-purpose detector for FCC-ee

- **Recently dubbed ALLEGRO**
  - A Lepton-Lepton collider Experiment with Granular Read-Out
- High-granularity noble-liquid ECAL a central feature
  - LAr or LKr as active medium, Pb or W absorbers
  - Multi-layer PCB as readout electrode
- Vertex detector, drift chamber and ECAL inside 2 T solenoid magnet, sharing cryostat
- HCAL and muon system outside solenoid
- Optimized for full FCC-ee physics program

Combines good intrinsic energy resolution + radiation hardness and stability + high granularity



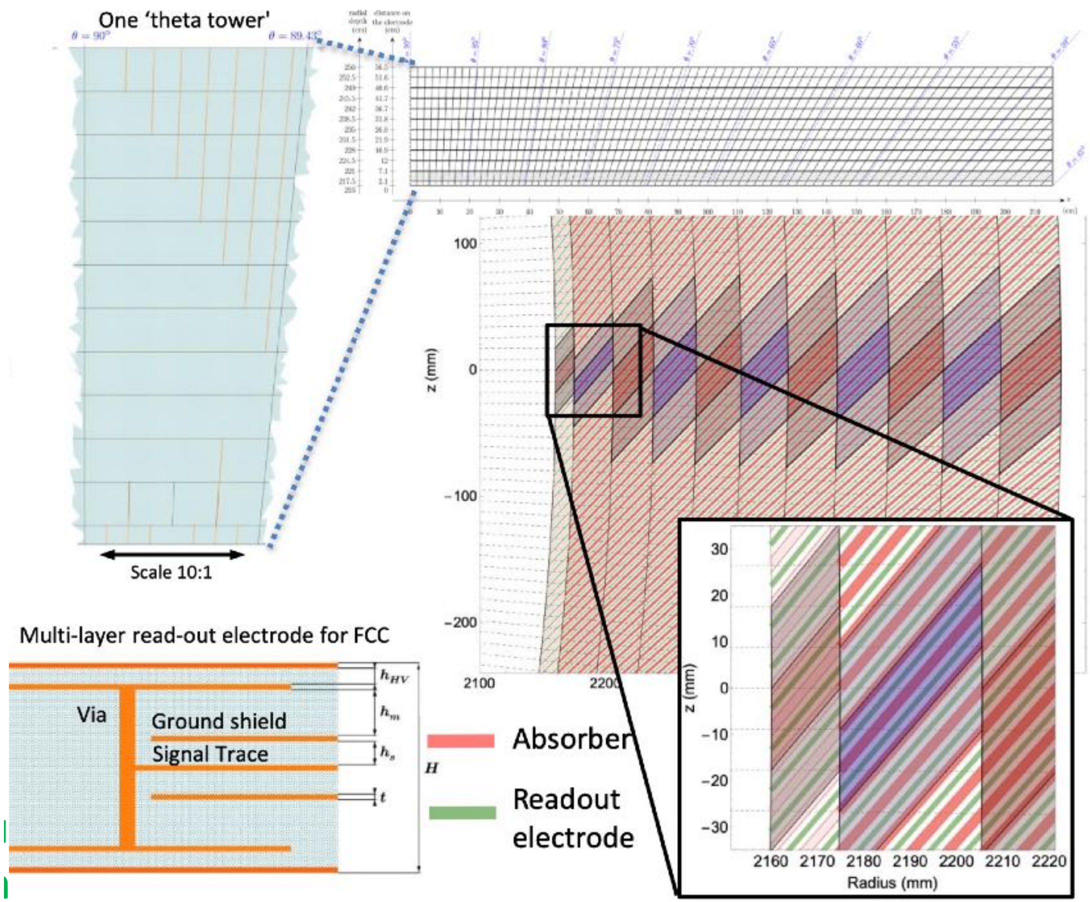
High Granularity Noble-Liquid Calorimeter

Baseline design

- 1536 straight inclined (50.4°) 1.8 mm Pb absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4 mm LAr gaps
- 40 cm deep (≈ 22 X_0)
- Segmentation:
  - $\Delta\theta$ = 10 (2.5) mrad for regular (1st comp. strip) cells,
  - $\Delta\phi$ = 8 mrad
  - Cell size in strips: 5.4mm x 17.8mm x 30mm
- 11 longitudinal compartments

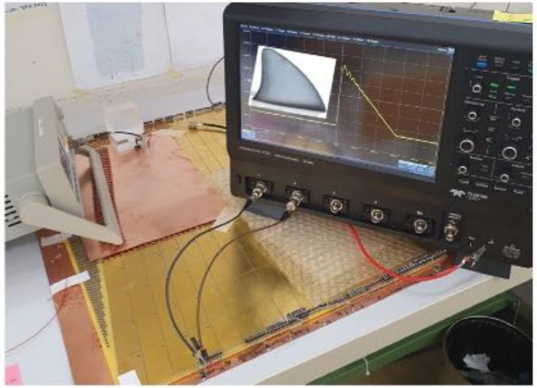
Possible Options

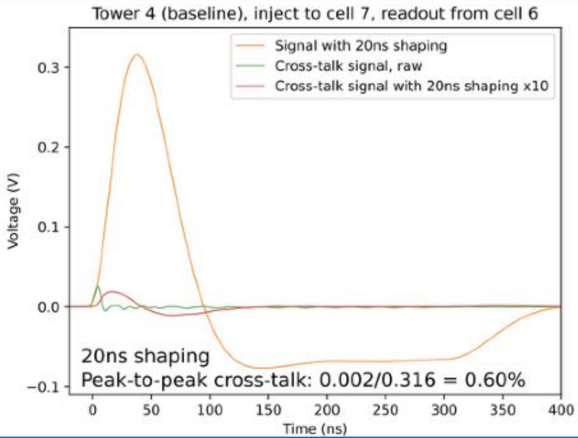
- Absorbers with growing thickness
- Granularity optimization
- Al or carbon fiber cryostat
- Warm or cold electronics



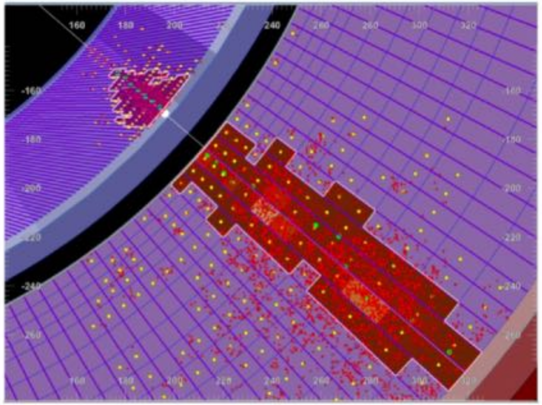
ALLEGRO – Measurement and Simulation

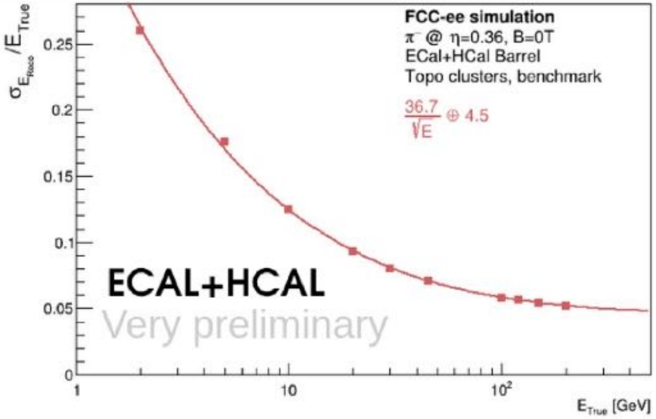
- Printed circuit board (PCB) technology allows "arbitrarily high granularity
  - Signal traces inside the electrode
  - Target: at least 10x ATLAS granularity
- CERN prototype PCB 58 cm × 44 cm





- Full-Sim of ALLEGRO being built to FCC-SW
- Optimal granularity & materials being studied with simulations
- Find optimal granularity for π^0/γ separation
- LAr or LKr as liquid, Pb or W as absorbers





ALLEGRO Detector Concept - Outlook

Allegro: a general-purpose FCC-ee detector concept

- Focus is a high granularity Noble Liquid calorimeter
- Prototyping electrodes and absorbers now
- Test-beam prototype to be built by 2027-28
- Work towards readout electronics will start soon.
- ECFA DRD6 Calorimetry collaboration founded in April
  - **Team is growing fast, already 20 institutions.**

The Past and the Future

Frontispiece 1655 The tradition of technology : Landmarks of Western technology. Leonard C. Bruno. Library of Congress, 1995

→

400 years

ESO Extremely Large Telescope – rendering, under construction

Historical Perspective

50 years of Liquid Argon Calorimeters!

NUCLEAR INSTRUMENTS AND METHODS 120 (1974) 221–236; © NORTH-HOLLAND PUBLISHING CO.

LIQUID-ARGON IONIZATION CHAMBERS AS TOTAL-ABSORPTION DETECTORS*

W. J. WILLIS†

Department of Physics, Yale University, New Haven, Connecticut 06520, U.S.A.

and

V. RADEKA

Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

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A new detector for the measurement of energy by total absorption, based on the use of multiple-plate ion chambers, is described. The use of liquid argon as the working medium and optimized readout results in an electronic noise contribution to the resolution of less than 0.1 GeV, in a large detector. The use of thin plates, 0.1 radiation length, ensures that sampling fluctuations are small. The technique allows absolute calibration and very good gain stability. Tests on a detector large enough to absorb a high-energy electromagnetic shower are described, where the energy resolution is limited by the residual sampling fluctuations.

1. Principles and limitations of calorimetric detectors

If a high-energy particle enters a sufficiently large block of matter, all of its energy will be transformed into ionization and eventually into heat, with certain important exceptions. Thus, detectors relying on total absorption to measure particle energy are often called calorimeters. The ionization released is a good measure of the energy, and we shall be describing an ionization calorimeter which functions by collection of the charge due to the ionization, without charge multiplication within the device.

The design of calorimeters has been reviewed by Murzin[1]), but we give here a brief discussion of the limitations of these devices to explain why we have adopted our solution. We will not discuss here the complex mechanisms by which the particles develop cascade showers and gradually convert their energy into ionization. The unavoidable exceptions to the statement that all the energy appears in the calorimeter are the origin of basic limitations to the precision of energy measurements. These are:

i) particle leakage back out of the surface through which the high-energy particle enters;

ii) the energy carried off by neutrinos, and, in practice, some muons;

iii) the energy required to remove nucleons from complex nuclei.

Without exception, the effects which limit the energy resolution are more serious for incident hadrons than for incident electrons or photons. Thus, the first effect above can be appreciable for incident hadrons of low energy ($\lesssim 2$ GeV), but is always rather small for electrons. Effect (ii) comes mainly from positive pions which come to rest, which then convert about 135 MeV into undetected energy. This effect can be calculated[2]), and is most prominent for incident pions in the several-GeV region. Effect (iii) is very small for electrons but can average about 30% of the total for hadrons, falling quite slowly with energy[3]).

Other effects which may be present in practical detectors are:

iv) energy leakage from the sides and the back of the absorber;

v) sampling fluctuations;

vi) saturation of response on densely ionizing particles;

vii) non-uniform response;

viii) noise.

Effect (iv) is determined by the size of the absorber as measured by radiation lengths for the electromagnetic component, or by interaction lengths for the hadronic component. Roughly speaking, this effect requires that the length of the absorber be greater than 10 to 20 radiation lengths, and greater than 5 to 10 interaction lengths, depending on the particle energy and the resolution desired. In most materials (aluminum and heavier) the radiation length is much shorter than

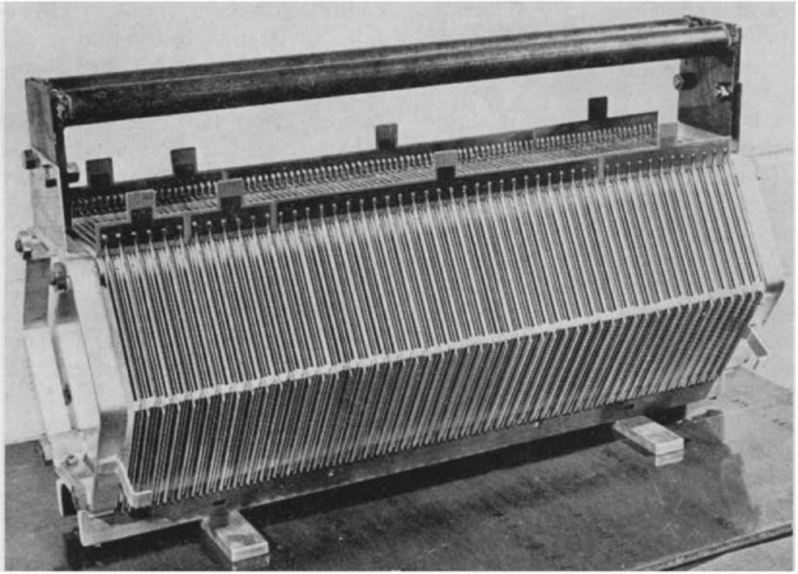


Fig. 10. Large test chamber with 200 steel plates, 1.5 mm thick, with 2.0 mm gaps.

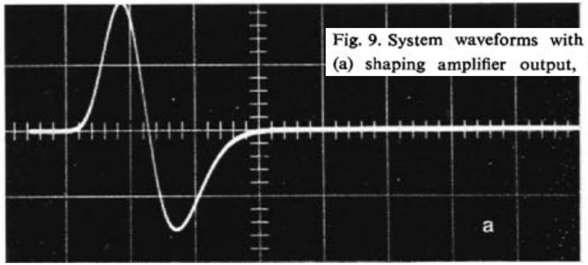
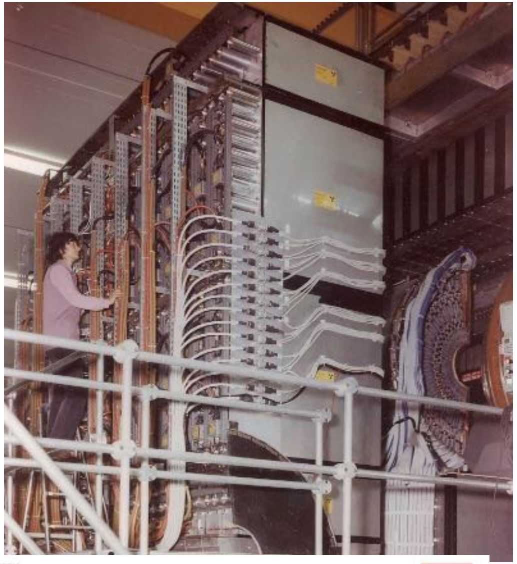


Fig. 9. System waveforms with bipolar shaping: (a) shaping amplifier output, horizontal scale 0.5 μs/div.;

Historical Calorimeters

R807/ISR, Mark II, Cello, NA31, Helios, SLD, D0, H1, ATLAS…

All made major discoveries and contributions.



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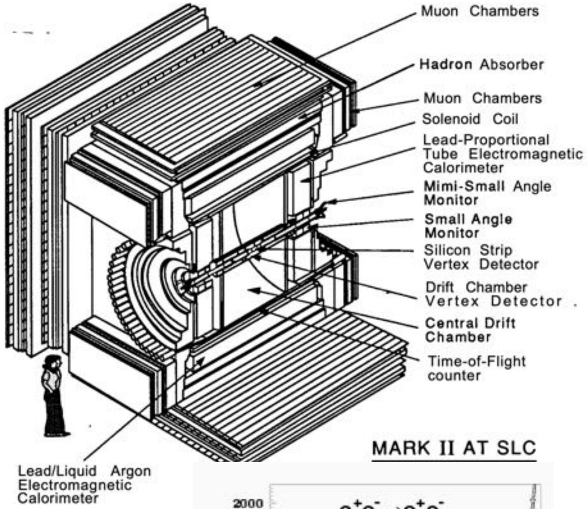
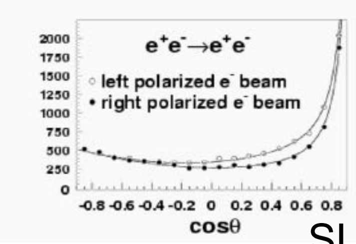
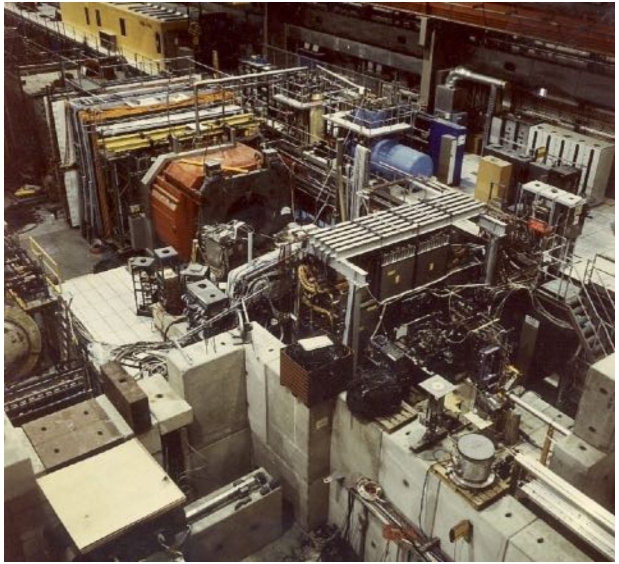
Direct production of high pT single photons in pp collisions at the CERN ISR







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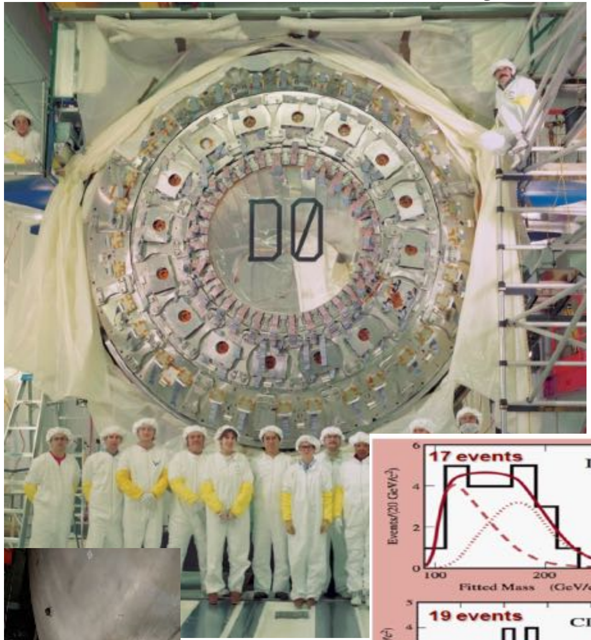
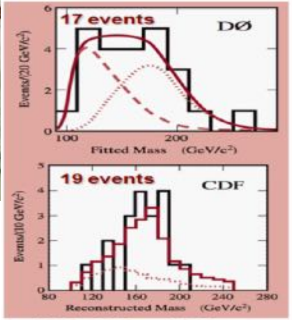
Historical (and contemporary) Calorimeters

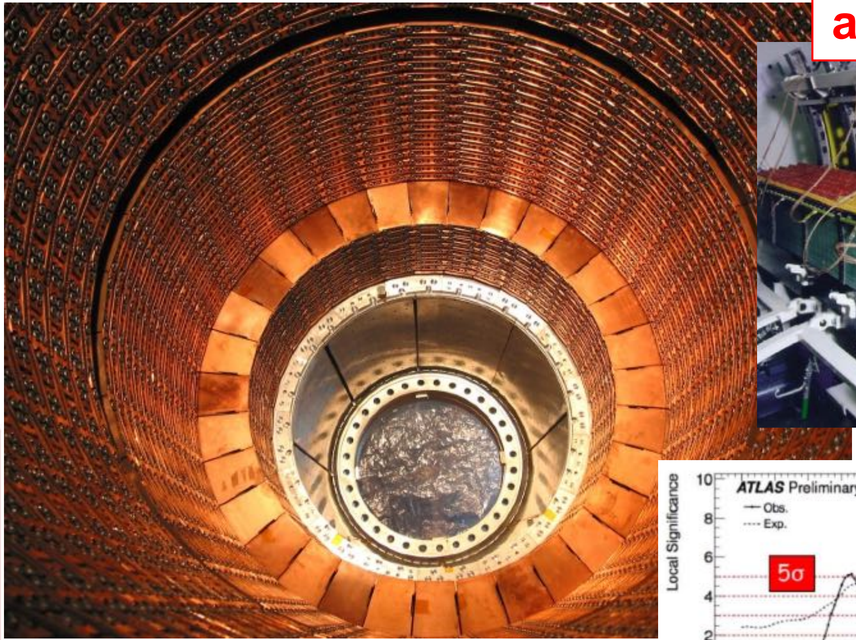
R807/ISR, Mark II, Cello, NA31, Helios, SLD, D0, H1, ATLAS…

All made major discoveries and contributions.

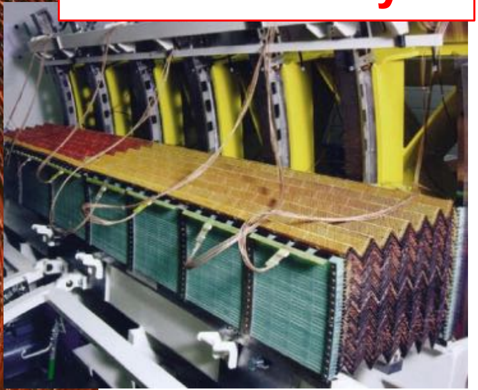


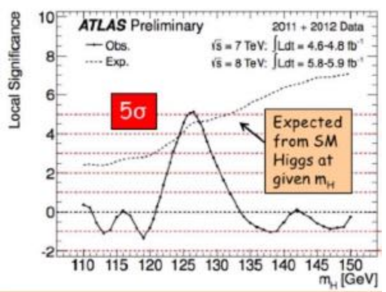


1995, CDF and DØ



Barrel assembly at CEA-Saclay





The Future?

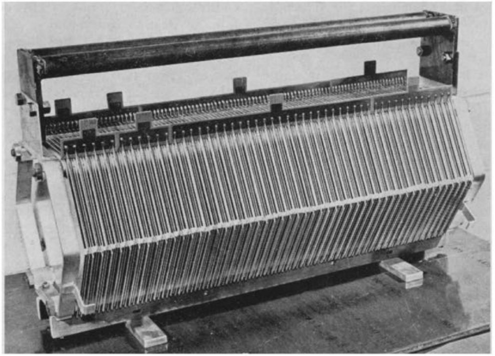
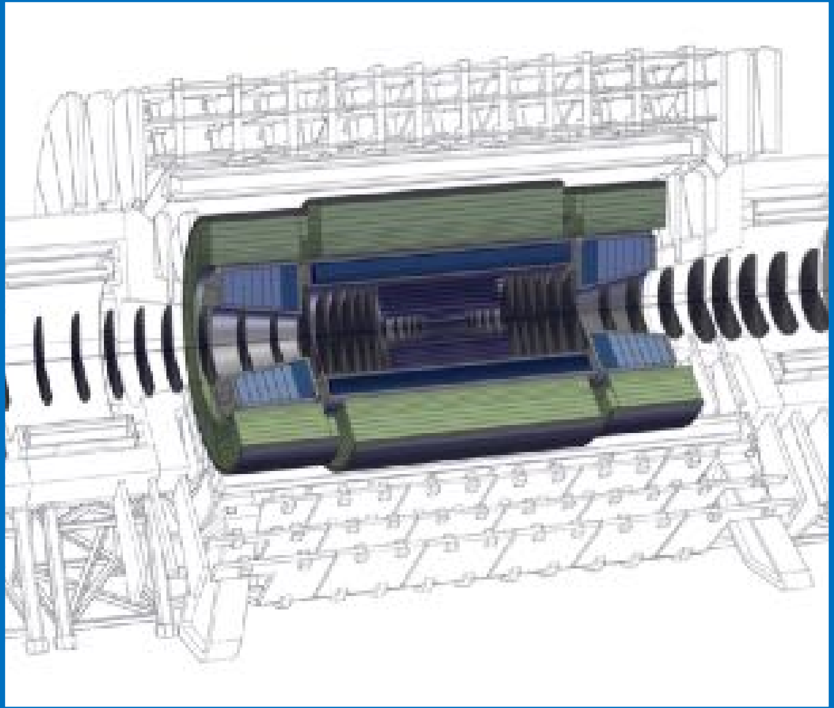
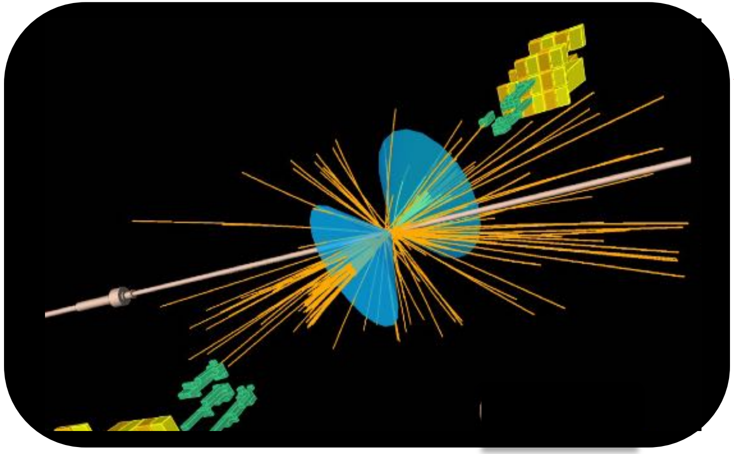


Fig. 10. Large test chamber with 200 steel plates, 1.5 mm thick, with 2.0 mm gaps.

70 years?

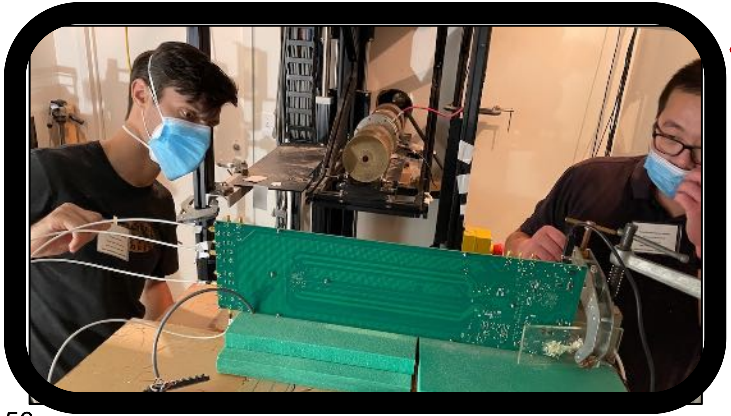


It is a great time for collider physics!



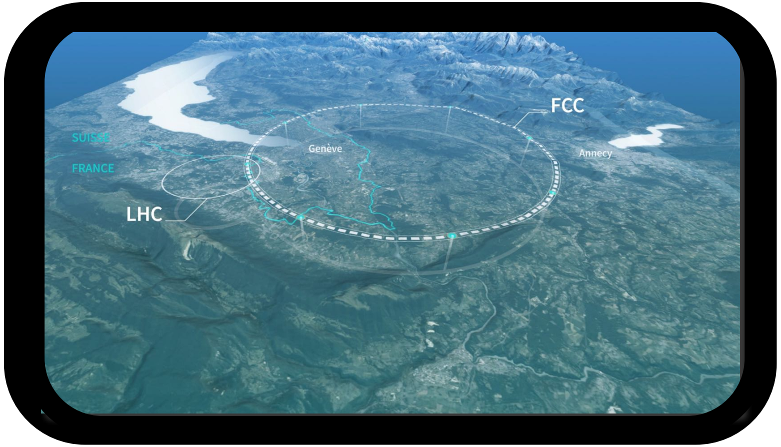
We are analyzing the largest dataset we have ever amassed.

We are collecting data at the highest energies ever.



We are building major upgrades (in some cases entirely new detectors!) for the HL-LHC.

And we are imagining, designing and planning the next big experiments.

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The University of Texas at Austin
Just starting on the path to new discoveries….

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