Searching for Uncovered and Unexpected New Physics at the Energy Frontier

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6 February 2023

Panofsky Fellowship Seminar

Nevis Laboratories
Columbia University

ATLAS EXPERIMENT

Outline

1. **Past:** motivation for new fundamental physics

2. **Present:** novel ATLAS searches
    - Long lived particles
    - Heavy resonances & anomaly detection

3. **Future:** the High Luminosity LHC upgrade & beyond the LHC

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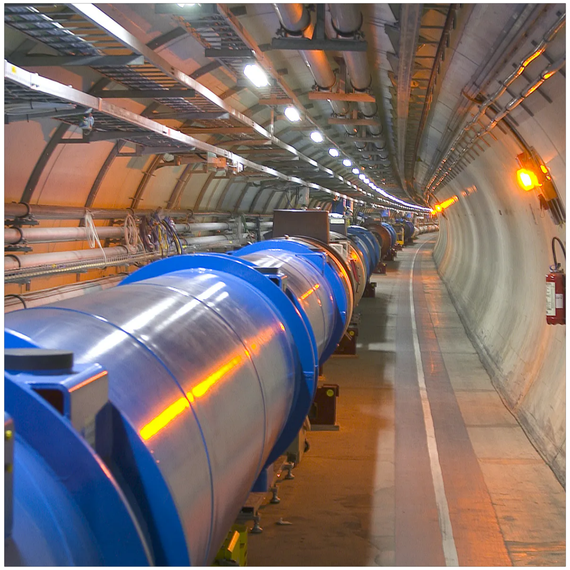
Collider Experiment Strategy

High Energy Accelerator



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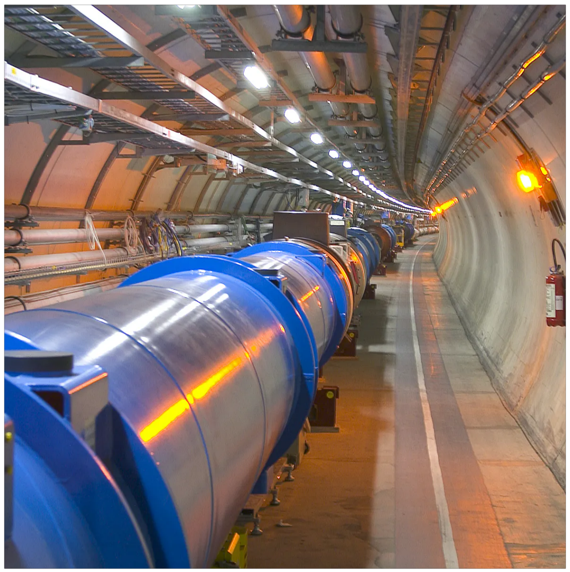
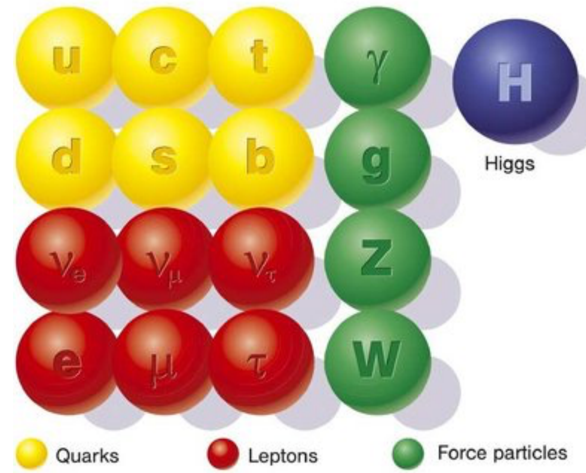
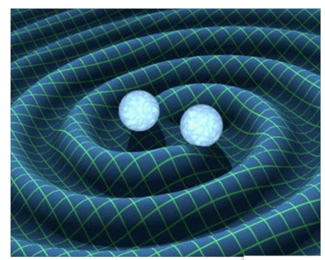


Physics Results

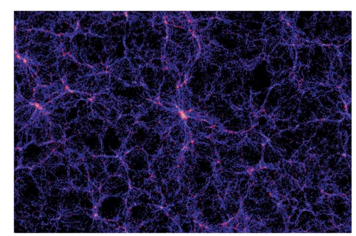
The Standard Model



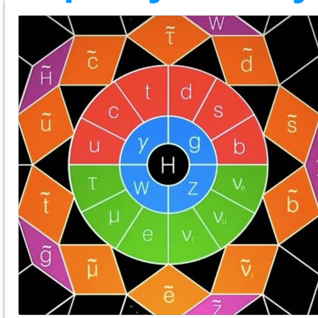
Gravity?



Dark Matter?



Supersymmetry?



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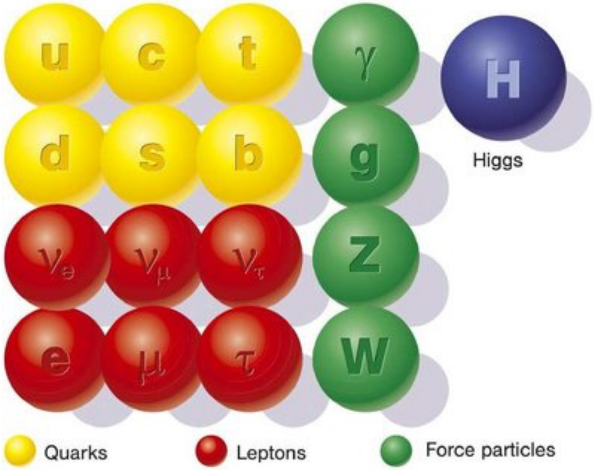

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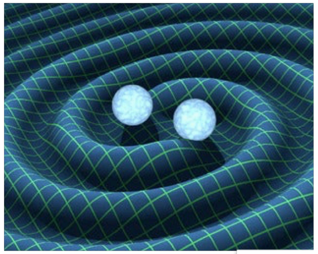

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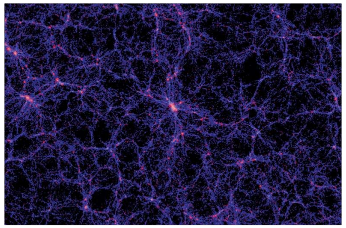

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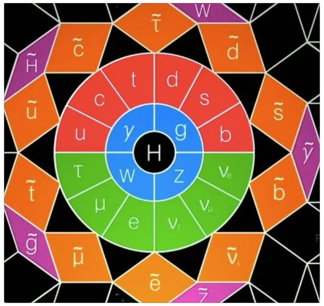
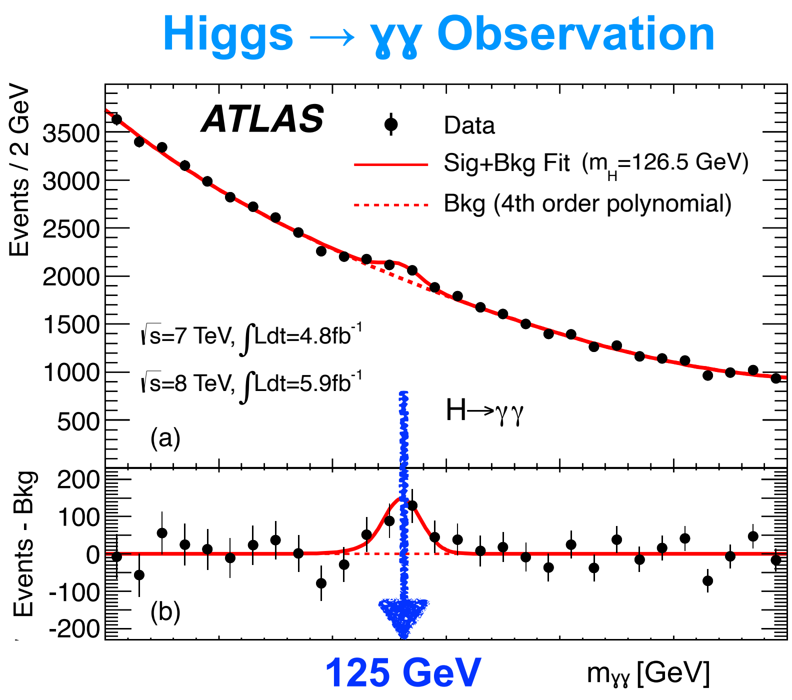


Collider Experiment Strategy

Maximize chances to discover new physics!

The Higgs Boson

- **Higgs boson discovery** at the Large Hadron Collider in 2012 “completes” the Standard Model
  - Least precision measurements on its mass, couplings, branching ratios…
  - Emphasizes **TeV mass scale** for new physics: mitigate fine tuning in Standard Model, Higgs coupling to particle mass



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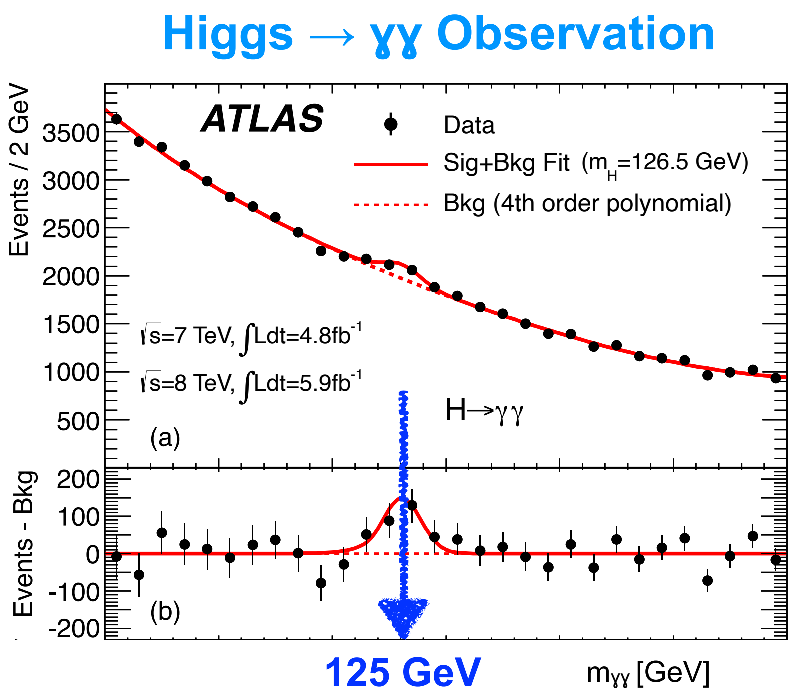

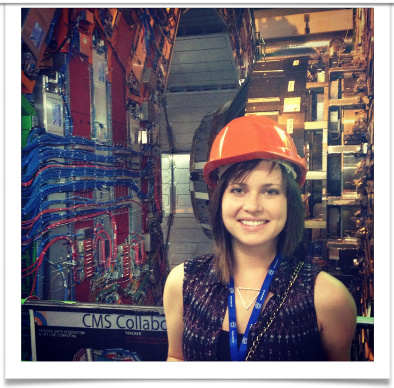

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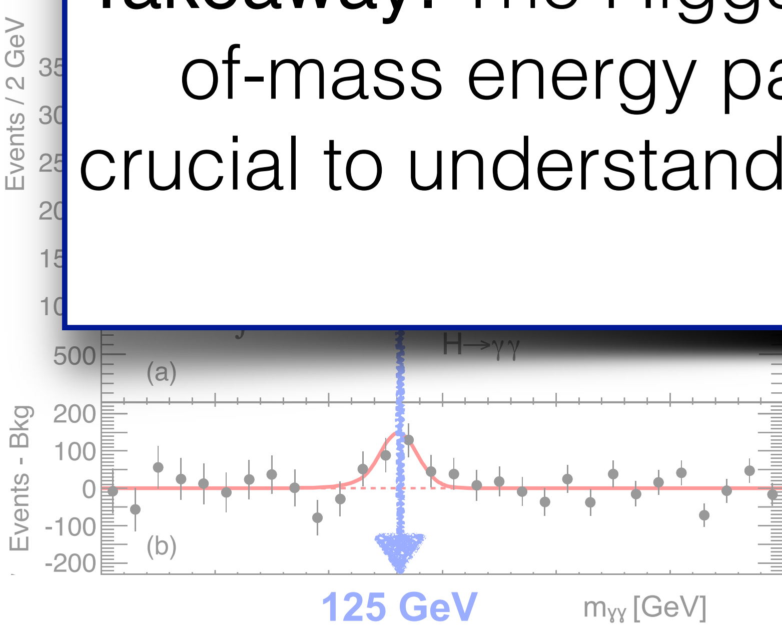
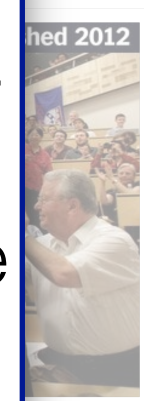
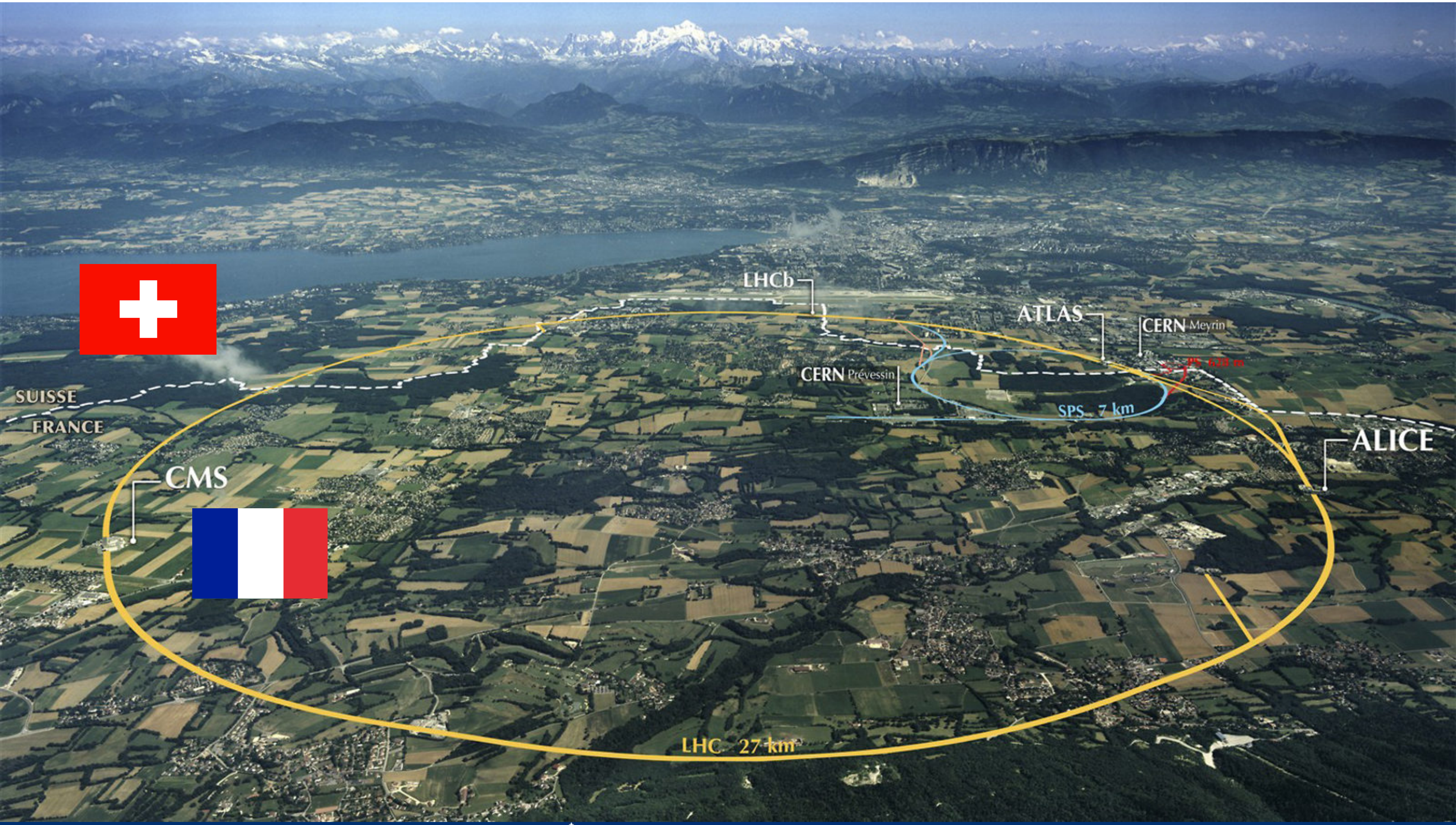
Takeaway: The Higgs boson & high center-of-mass energy particle collisions are crucial to understand fundamental universe





The Large Hadron Collider

- 27 km synchrotron at CERN colliding protons at $\sqrt{s}$ = 13 TeV



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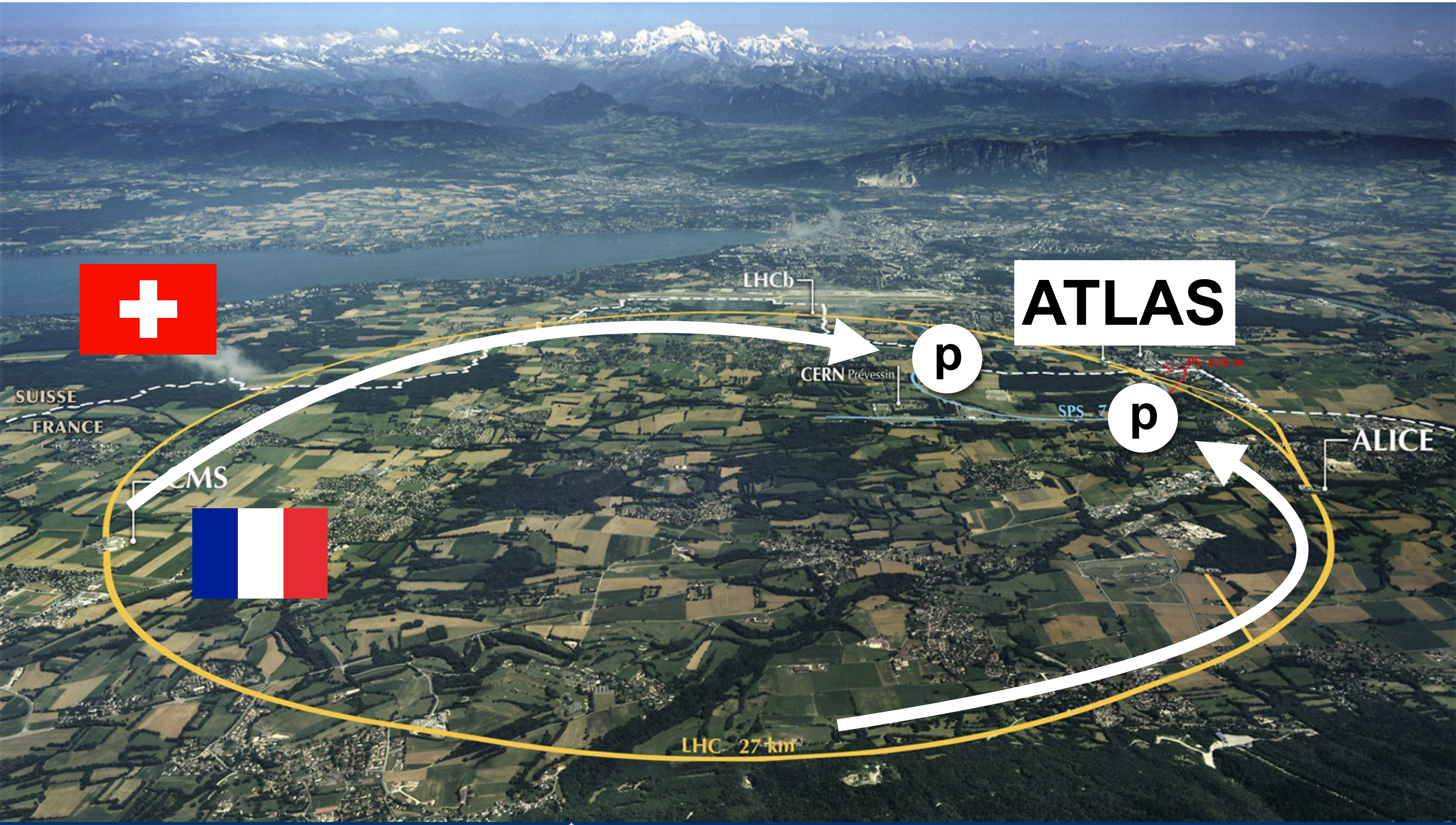
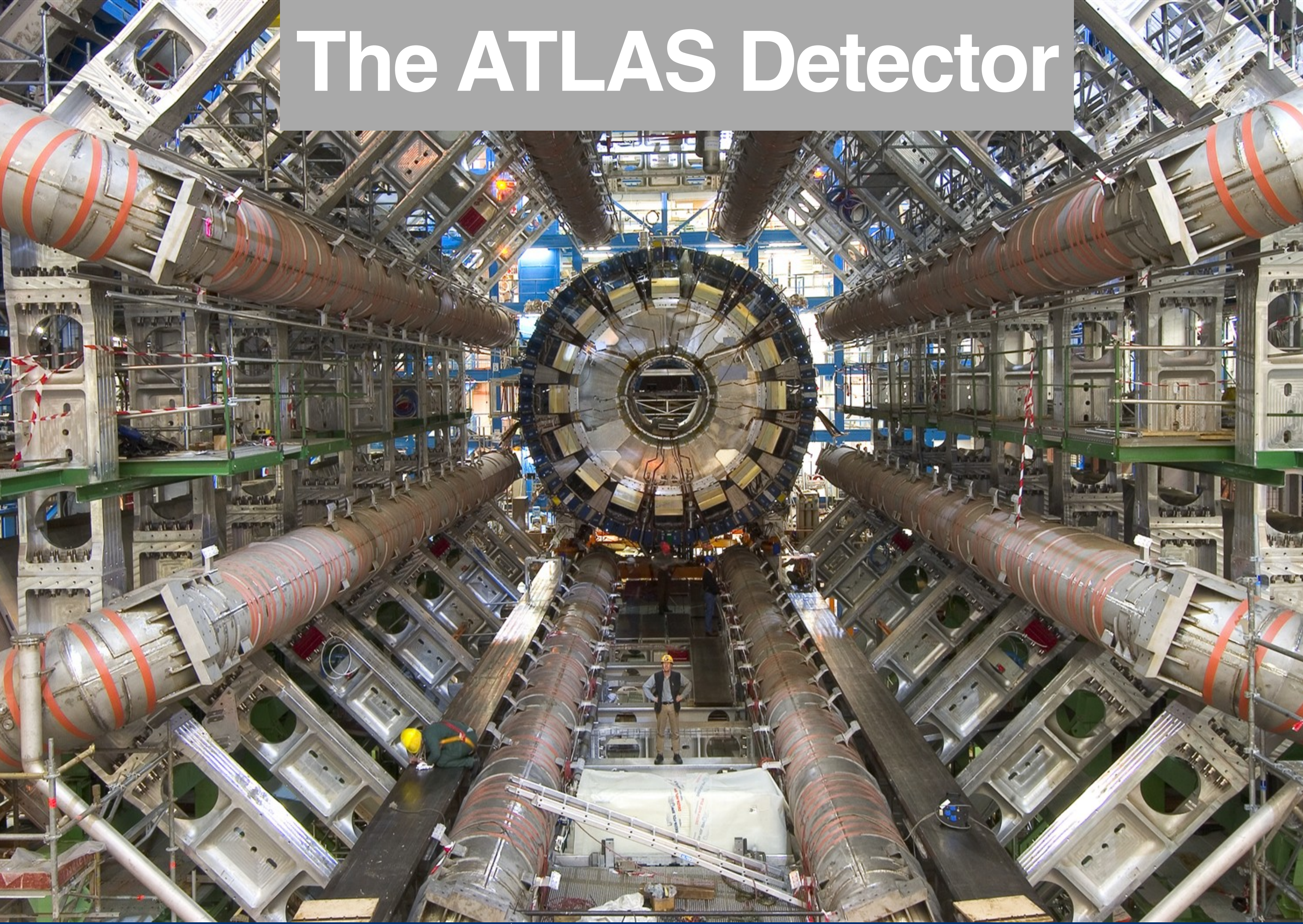


The ATLAS Detector



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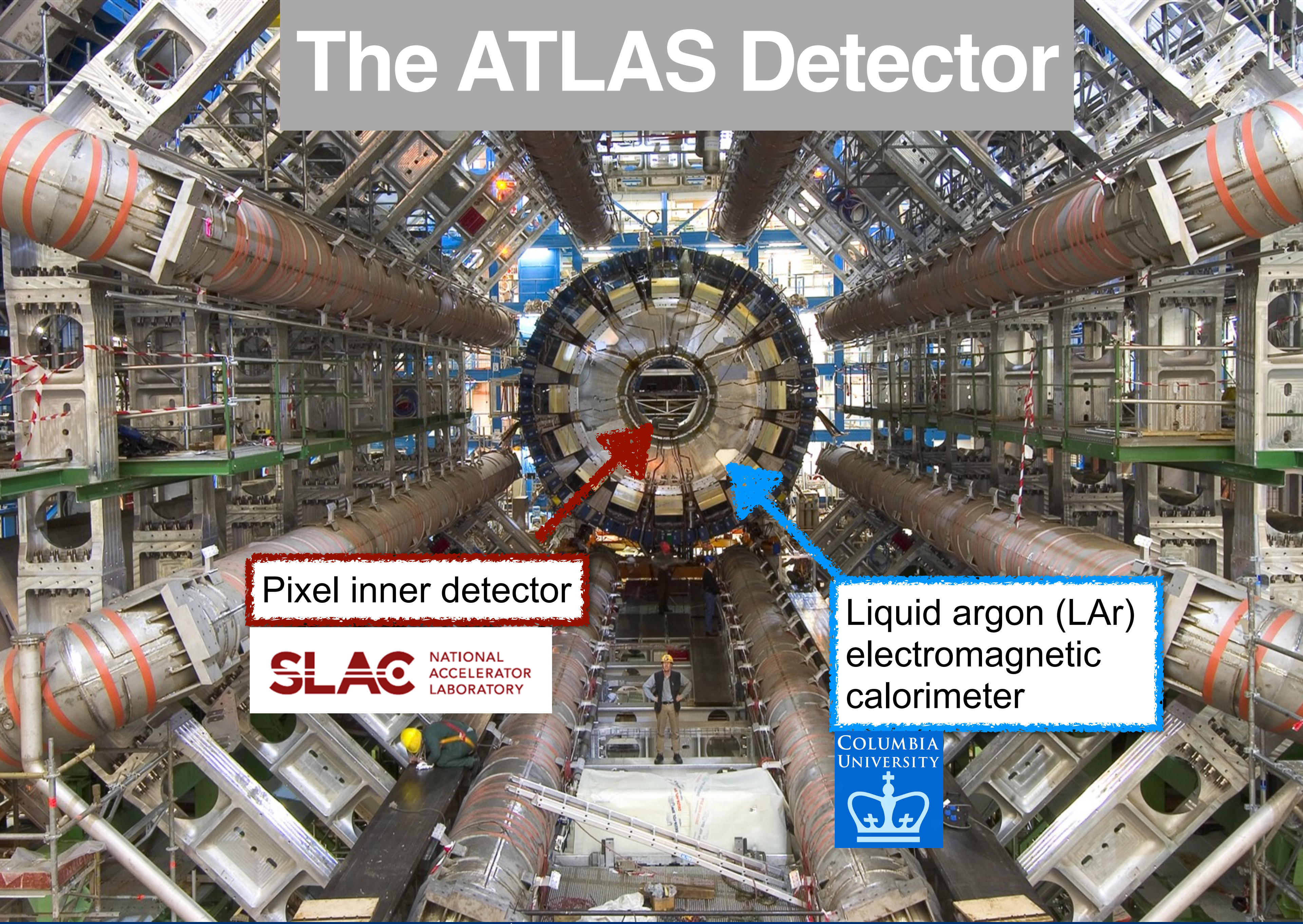
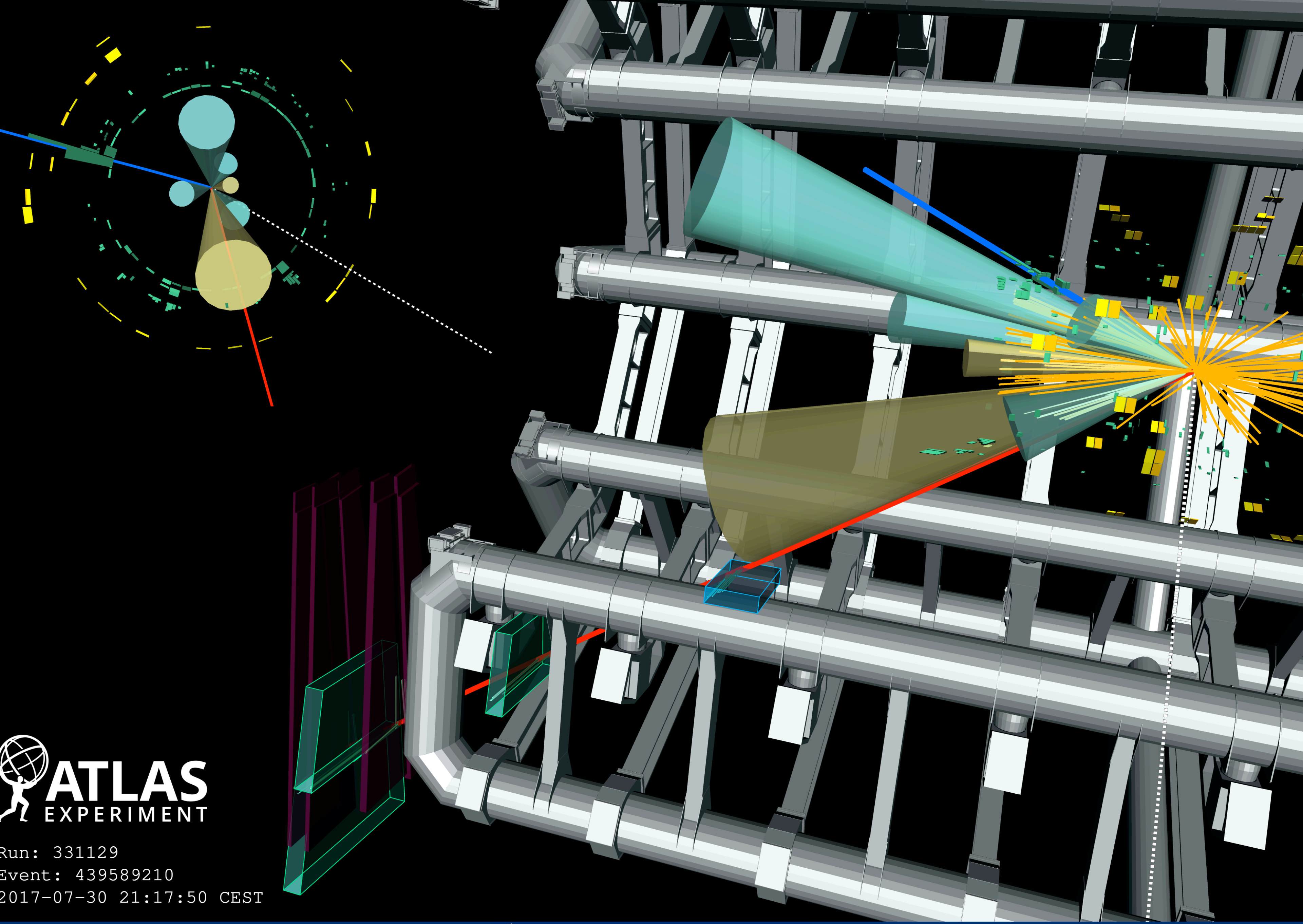
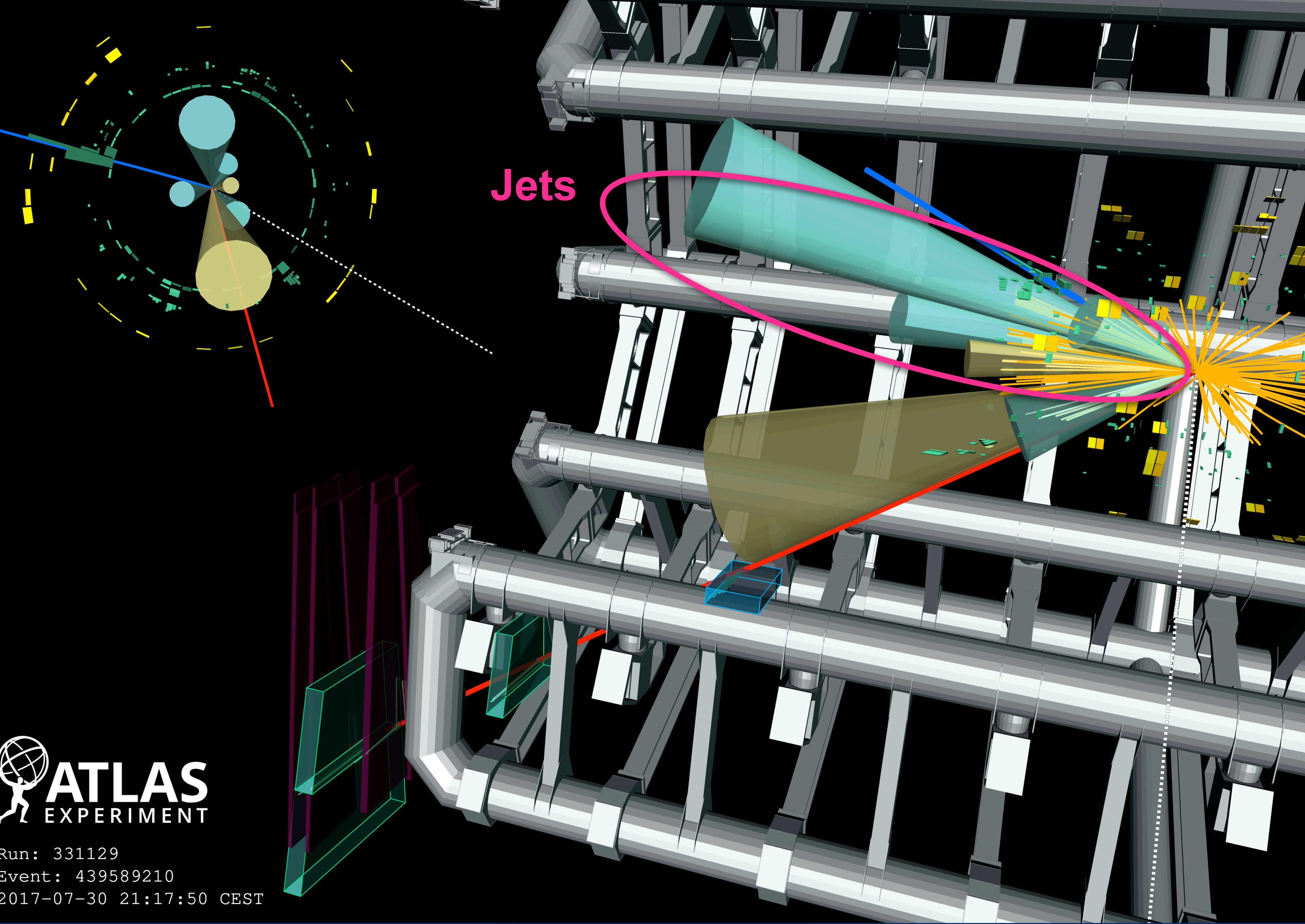



ATLAS
EXPERIMENT
Run: 331129
Event: 439589210
2017-07-30 21:17:50 CEST


Jets
ATLAS
EXPERIMENT
Run: 331129
Event: 439589210
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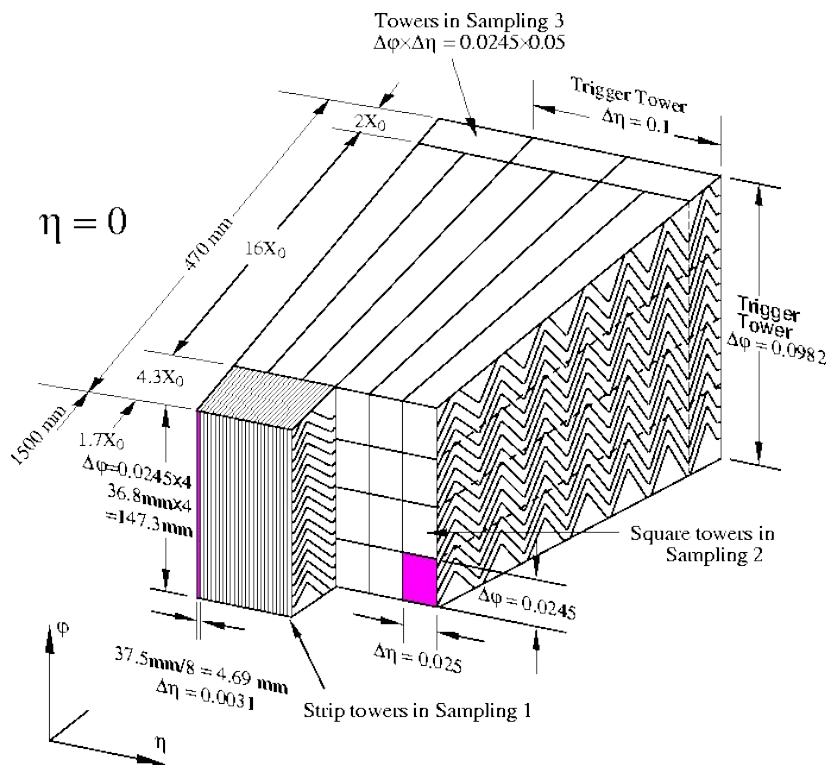
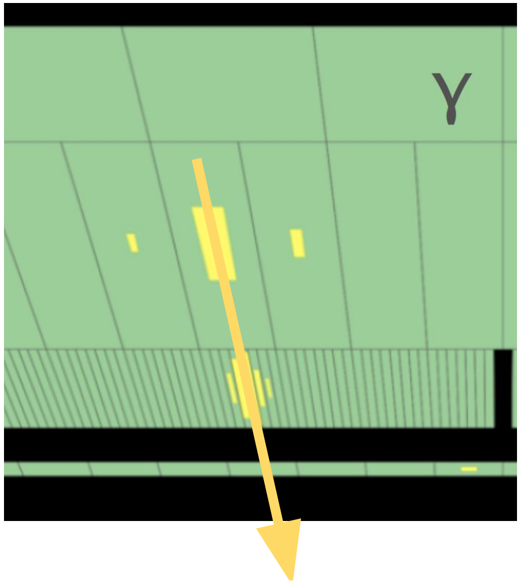
ATLAS LAr EM Calorimeter

- Sampling calorimeter with accordion geometry of active (LAr) and absorber (lead); three layers in barrel
  - Key measurements of Higgs →γγ discovery channel
- Readout electronics system samples calorimeter cells at LHC frequency of 40 MHz and sends a digitized pulse off the detector

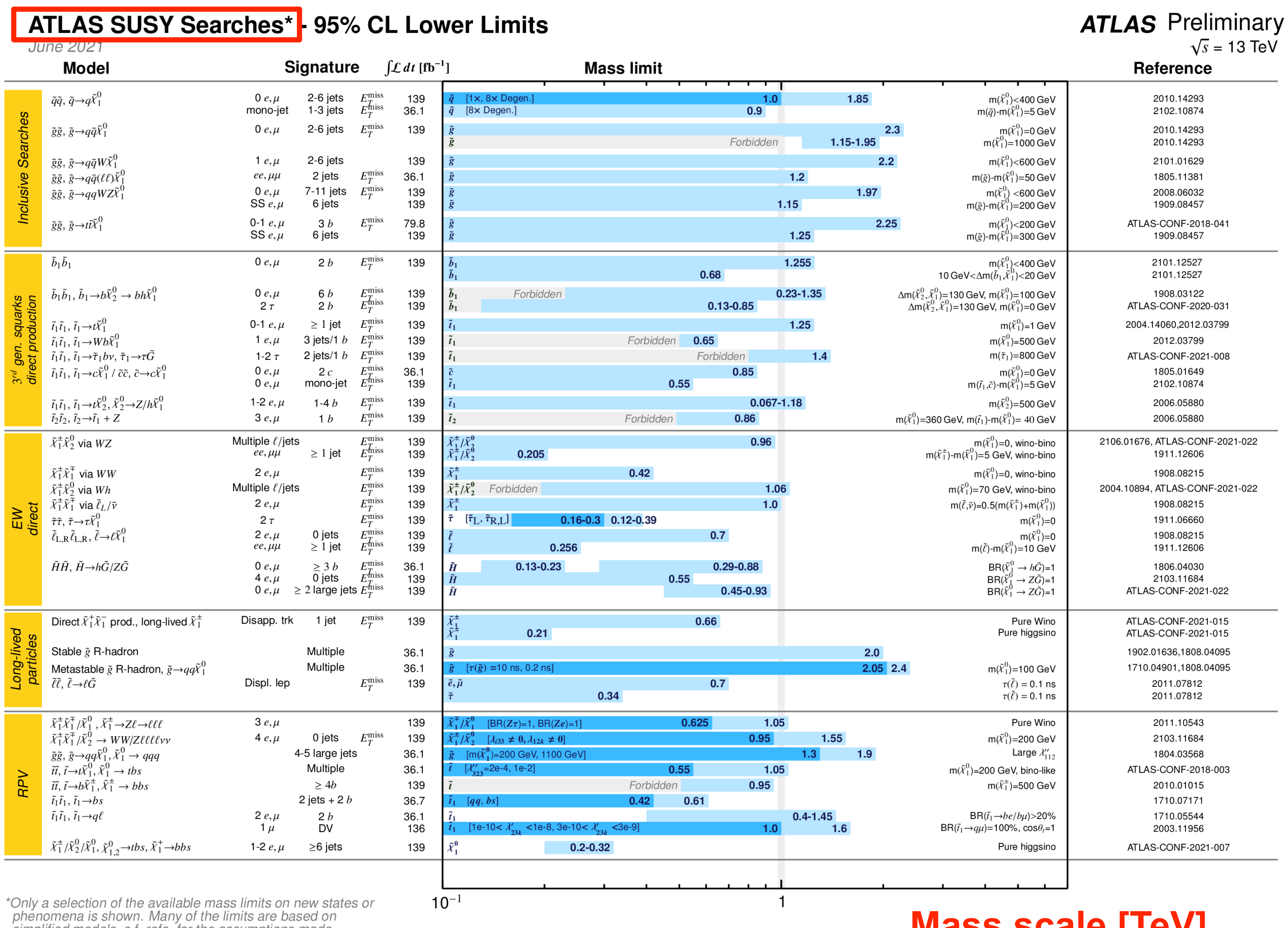


Photon in LAr Calo



Where To Look For New Physics?

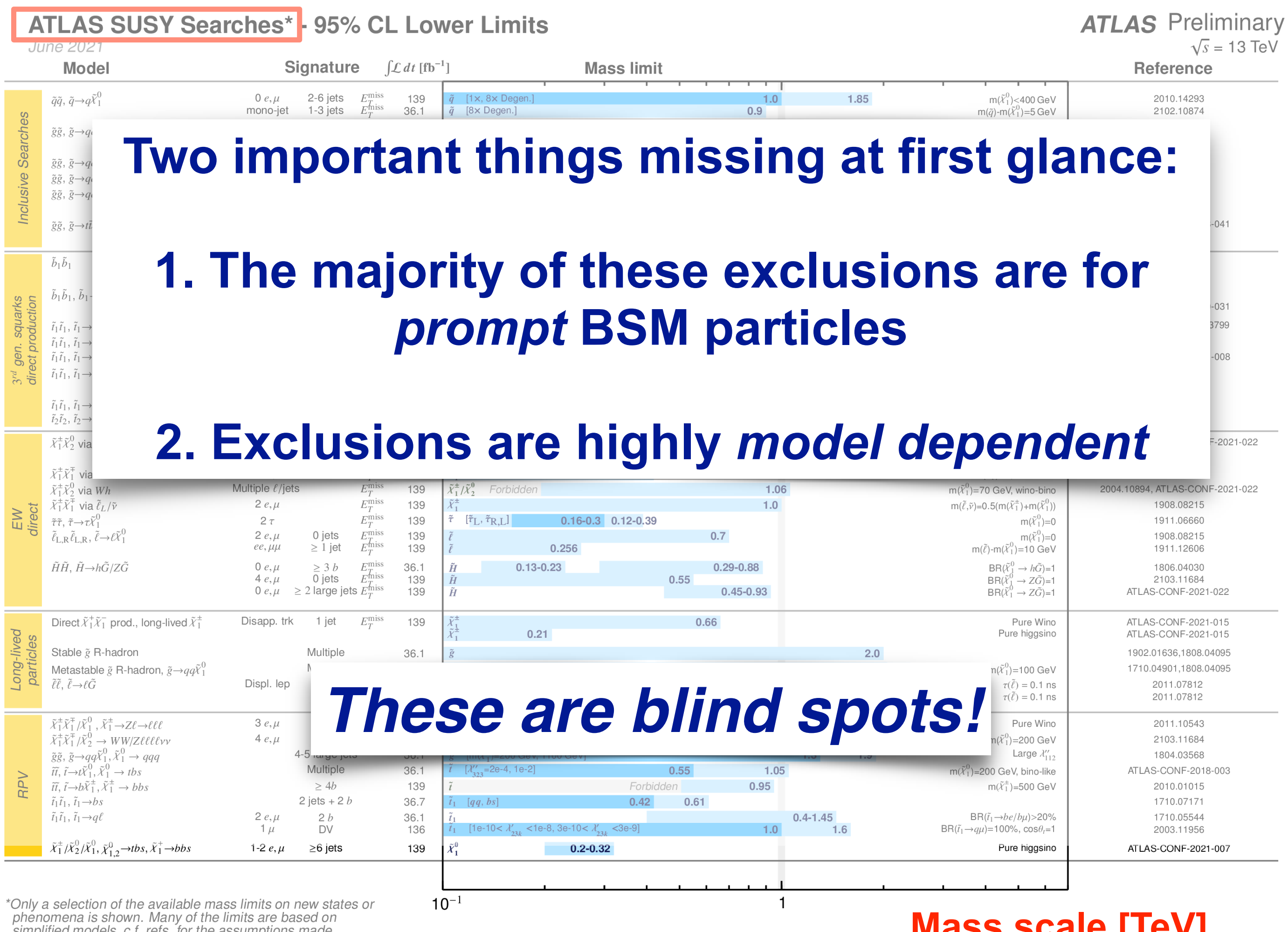
~TeV scale exclusions across many final states?



Mass scale [TeV]

Where To Look For New Physics?

~~~TeV scale exclusions across many final states?~~



Two important things missing at first glance:

1. The majority of these exclusions are for *prompt* BSM particles

2. Exclusions are highly *model dependent*

These are blind spots!

Mass scale [TeV]
~~~

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   - Long lived particles
   - Heavy resonances & anomaly detection

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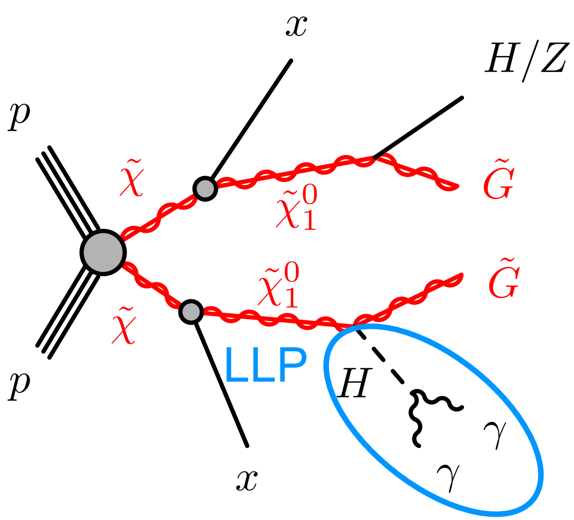
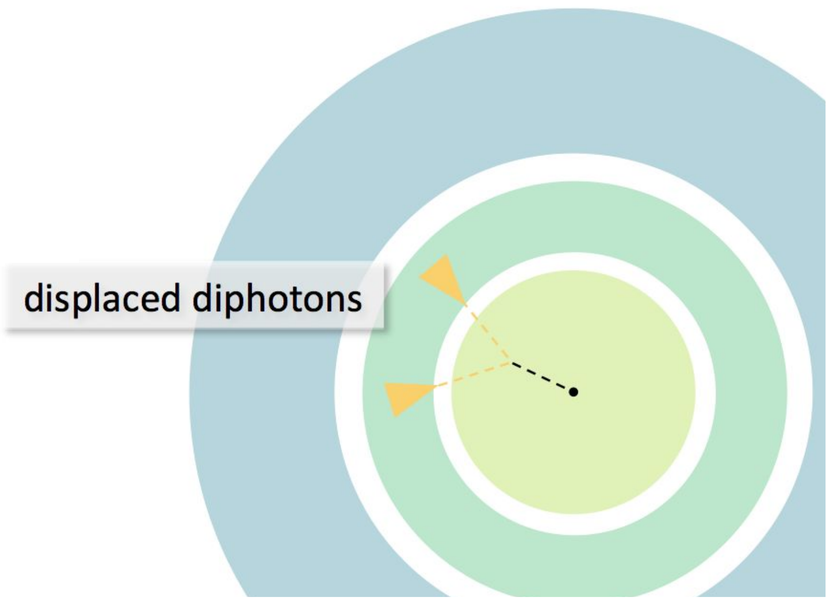
1. Long-Lived Particles

- **Problem**: the majority of collider experimental exclusions pertain to *promptly decaying* new particles
  - Long-lived particles (LLPs) are theoretically well-motivated (eg. small couplings in supersymmetry, dark sectors)
  - But their decays are challenging to reconstruct: create final state objects that are
    - *displaced* (produced off the beam line); and
    - *delayed* (late with respect to bunch crossing)

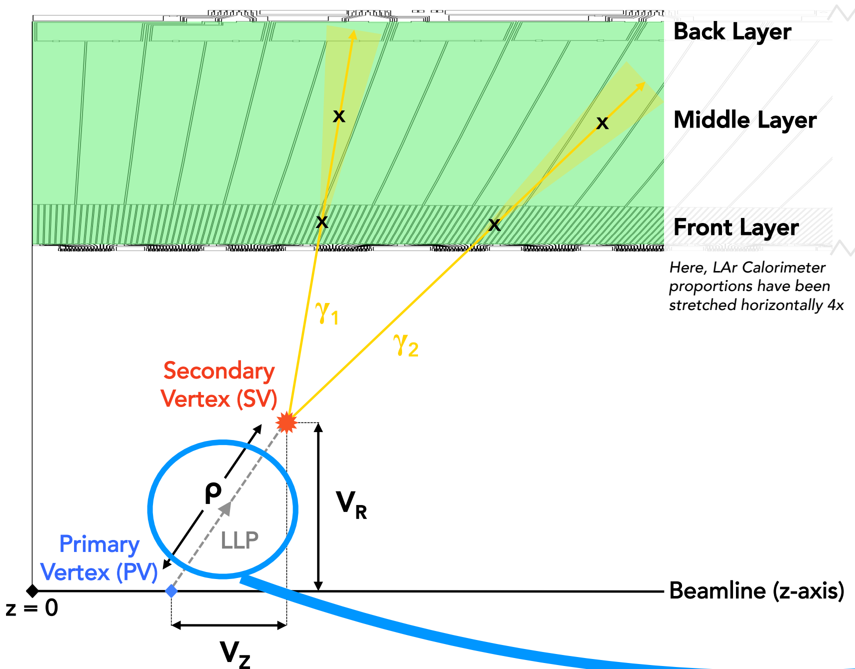
➡ <u>Example</u>: generic new long-lived particles χ producing a displaced H→ɣɣ decay



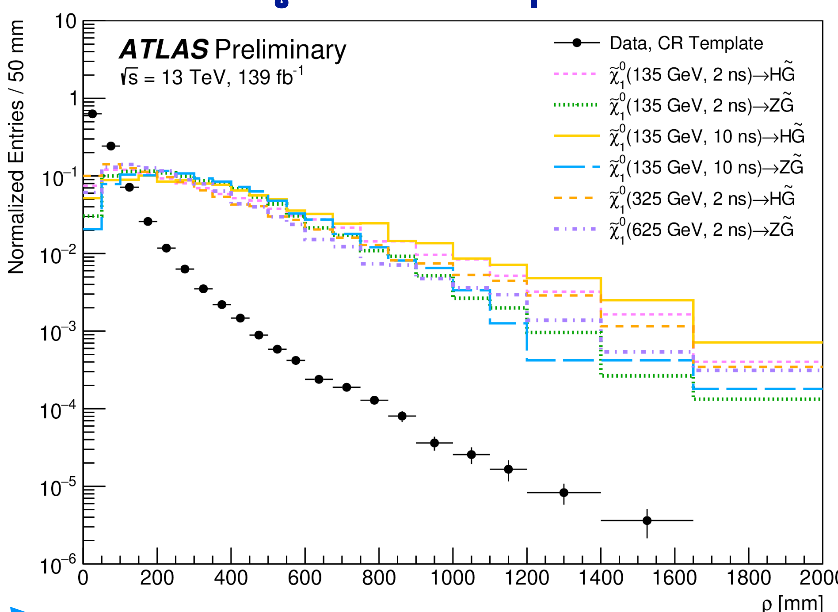


LAr for Delayed Photons

- **Collaboration**: work with **engineers** to ensure the detector and its readout electronics are robust and precise
- **Solution**: creation of new analysis techniques based on precision low-level detector info
  - Timing: ATLAS LAr calorimeter provides timing measurement from ECAL cells with ~200 ps resolution
  - Spatial: LAr calo segmented into multiple layers, which allow us to get photon's direction of flight
  - *New* ❗ For sensitivity to displaced di-e/ɣ vertices, combine directional info of 2 paths to localize vertex position in 2D (V_r, V_z)



Di-e/ɣ Vertex Displacement

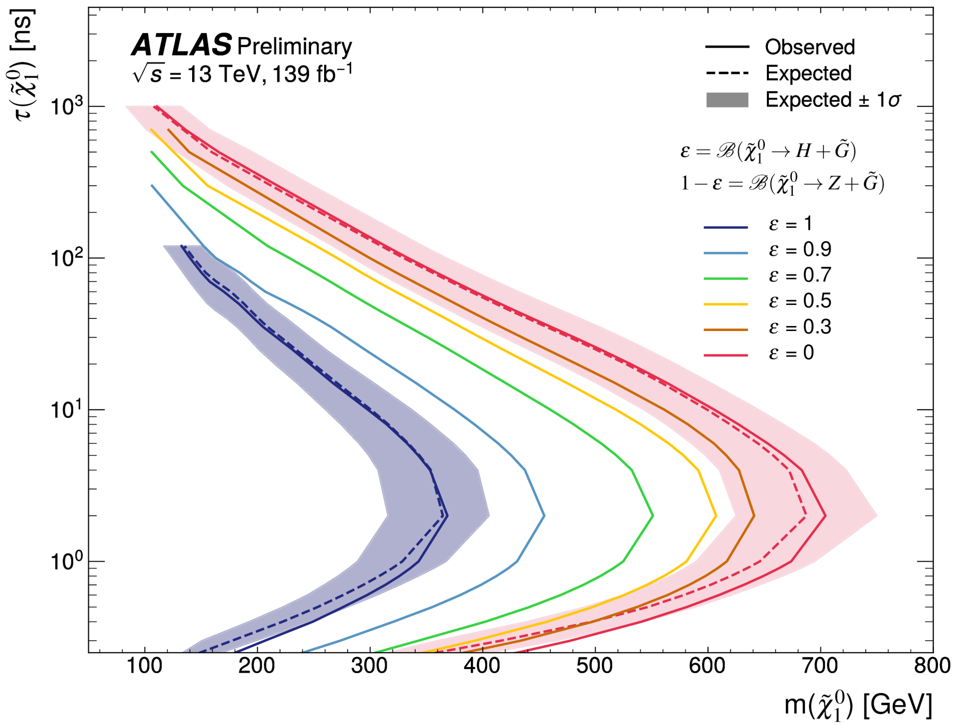


Displaced Diphoton Results

- No significant excess above SM background
  - Sensitive to LLPs with ~100s GeV mass and 0.1 ns < τ < 1000 ns

➡Takeaway: LLP to e/ɣ tools validated & primed for use in future searches

LLP Lifetime

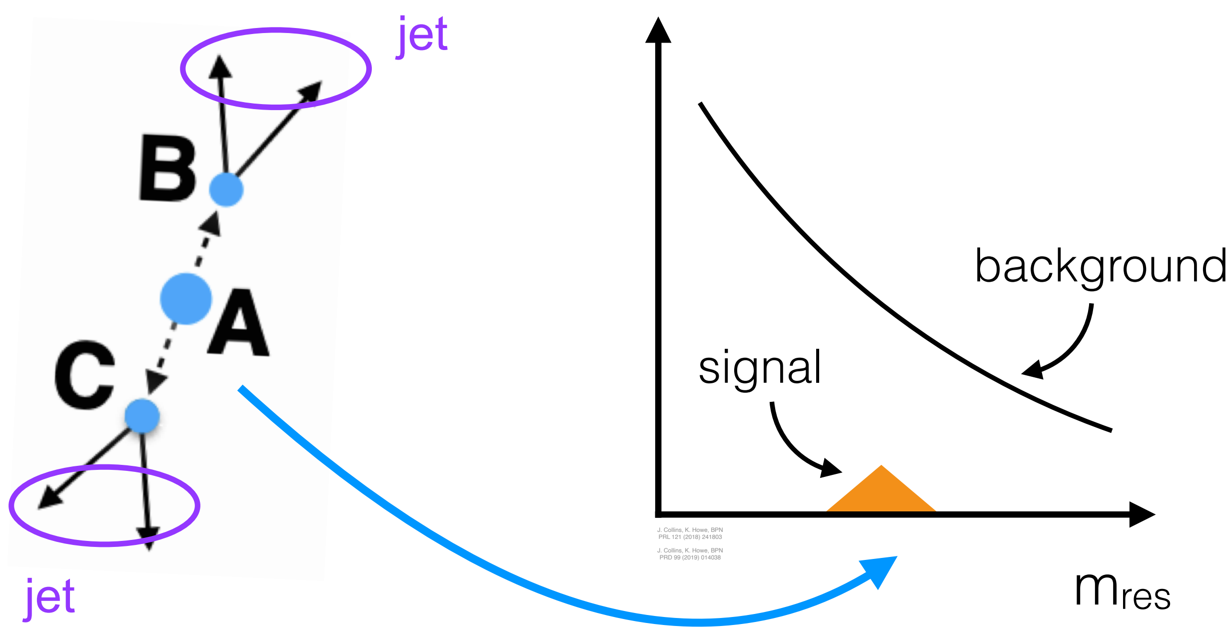


LLP Mass

[2209.01029, ATLAS-CONF-2022-051]

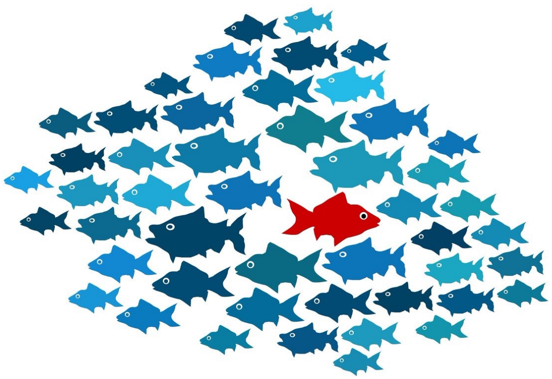
2. Heavy Particles

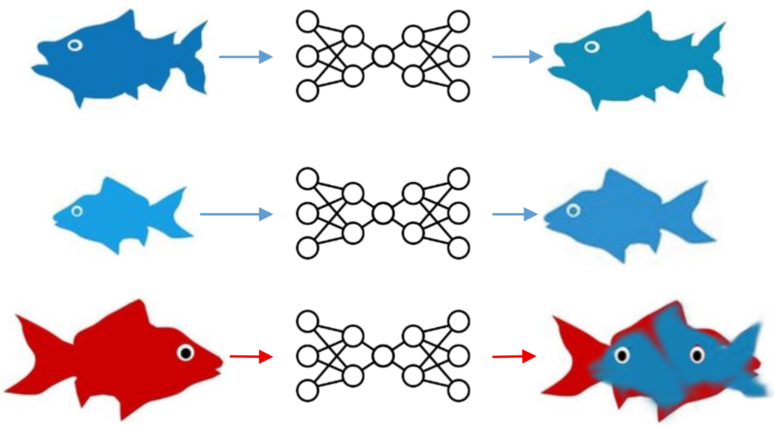
- **Problem**: we need heavy (~TeV scale) new particles & haven't found them
  - TeV-scale new physics motivated by Higgs mass & directly accessible at the LHC
  - High mass A creates high momentum B and C: *boosting* means decay products overlap; reconstruct each daughter as ***single large-radius jet with substructure***
  - Highly generic signature: we cannot rely on having a full analysis for every topology

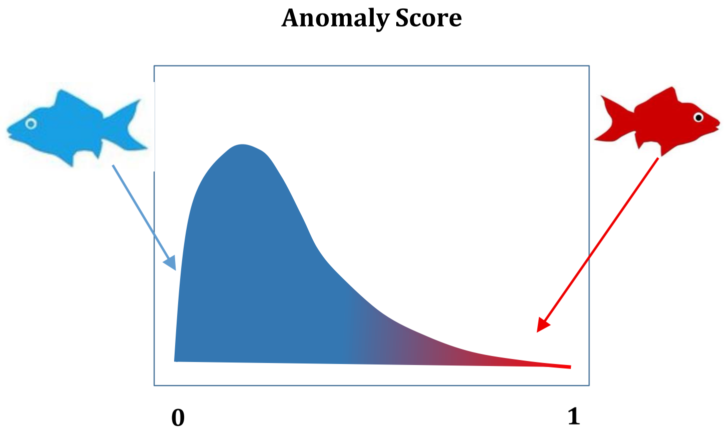


Machine Learning & Anomaly Detection

- **Collaboration**: computer/data scientists with sophisticated machine learning algorithms for signal model-independent *anomaly detection*
  - Goal: identify features of the data that are inconsistent with a background-only model
- Strategy: train an ML architecture to reconstruct its input
  - Unsupervised: train over unlabeled events (data)
  - Rarer events with unusual features will be poorly reconstructed → reconstruction accuracy is a good discriminant



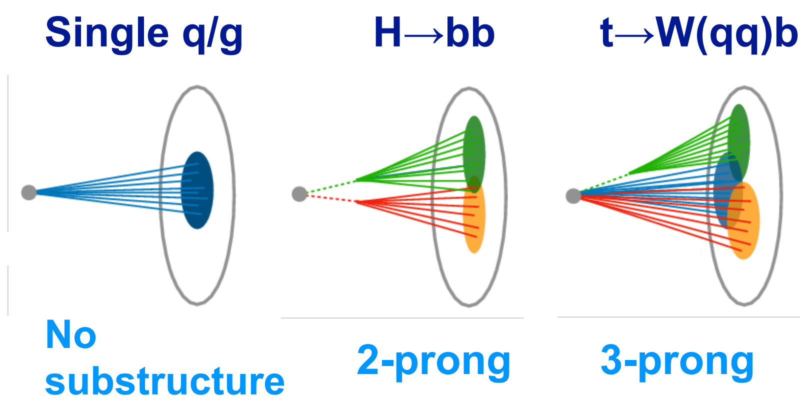


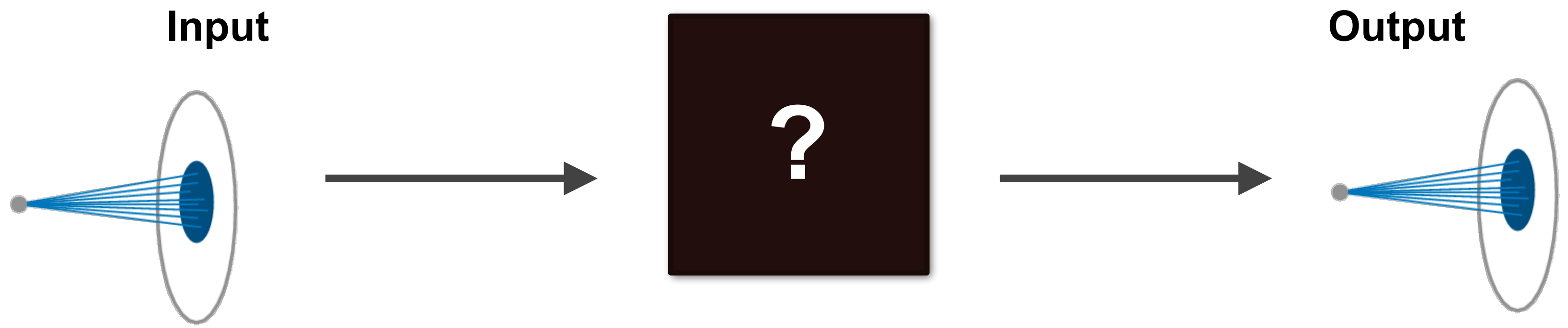


A. Kahn

Autoencoders for Jets

- Input: jets are composed of constituent particles with "prongs" if distinct particles exist within the jet
    - Model jets as a sequence of constituent 4-vectors

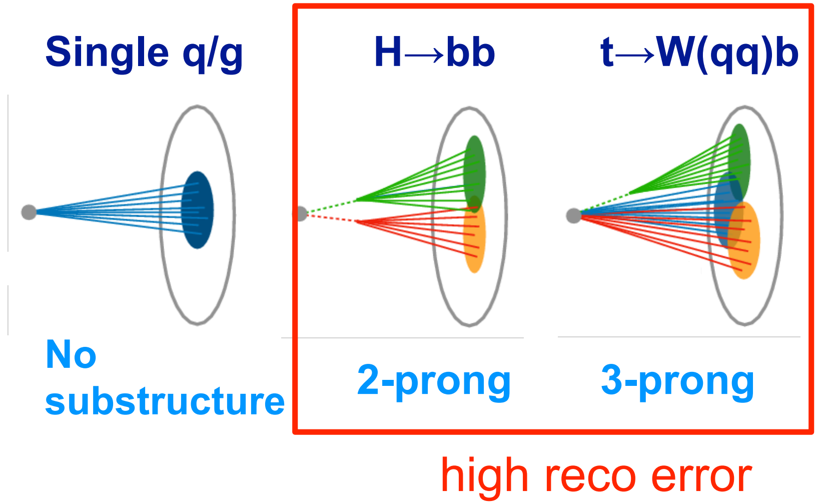


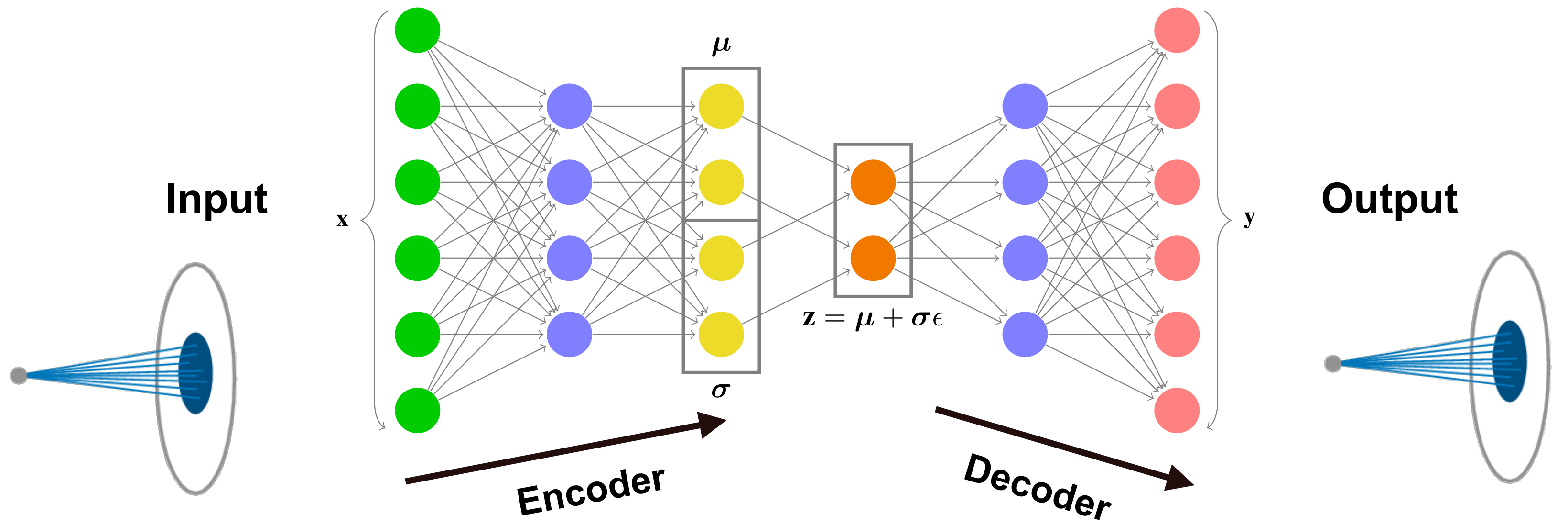


Autoencoders for Jets

- Input: jets are composed of constituent particles with “prongs” if distinct particles exist within the jet
  - Model jets as a sequence of constituent 4-vectors
- **Autoencoder:** generative model that *encodes* input in lower-dimensional latent space, *decodes* from latent space, and checks reconstruction error

➡ Variational recurrent neural network (VRNN): variational autoencoder embedded in recurrent architecture (sequence modeling) to generate *per-jet anomaly score*

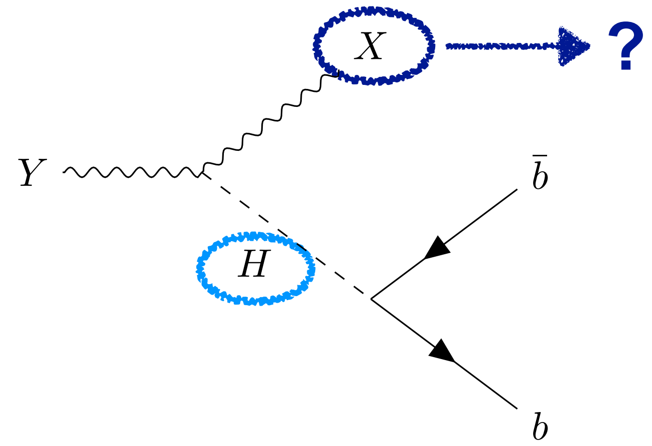




Y→XH Analysis

- **Solution**: ML-based taggers for a generic Y→XH process

1. Novel neural net-based algorithm for tagging boosted H→bb topology
2. VRNN trained without labels over full Run 2 dataset of high momentum large-R jets
   - Per-jet anomaly score provides signal-model-independent selection of anomalous X candidate jets



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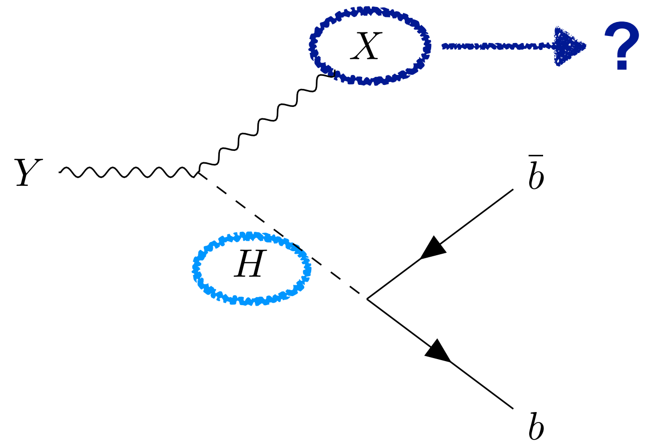
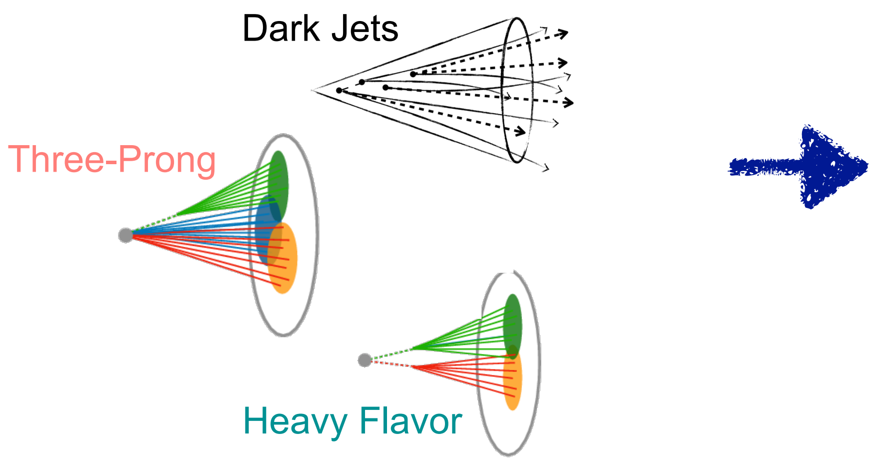
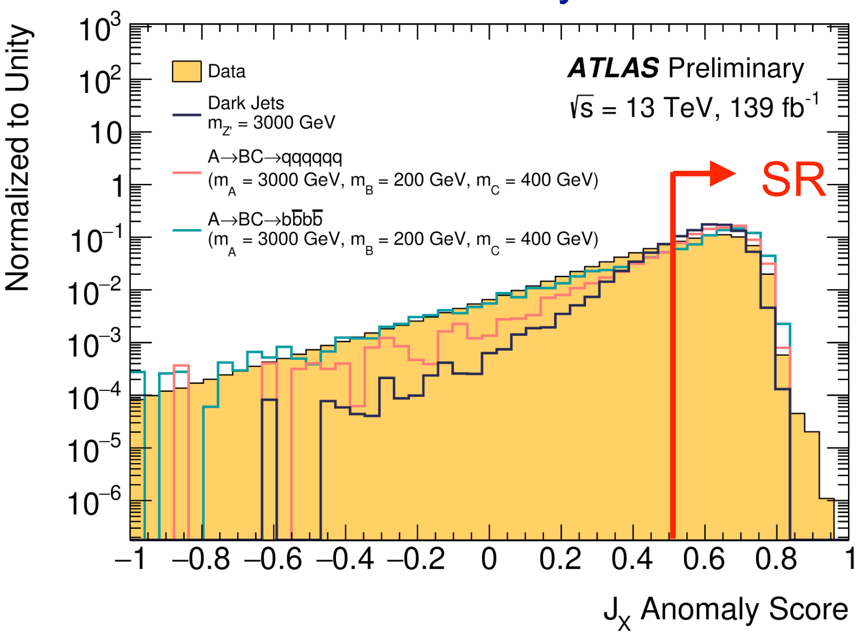


Possible Signal Jet Models



Jet Anomaly Score

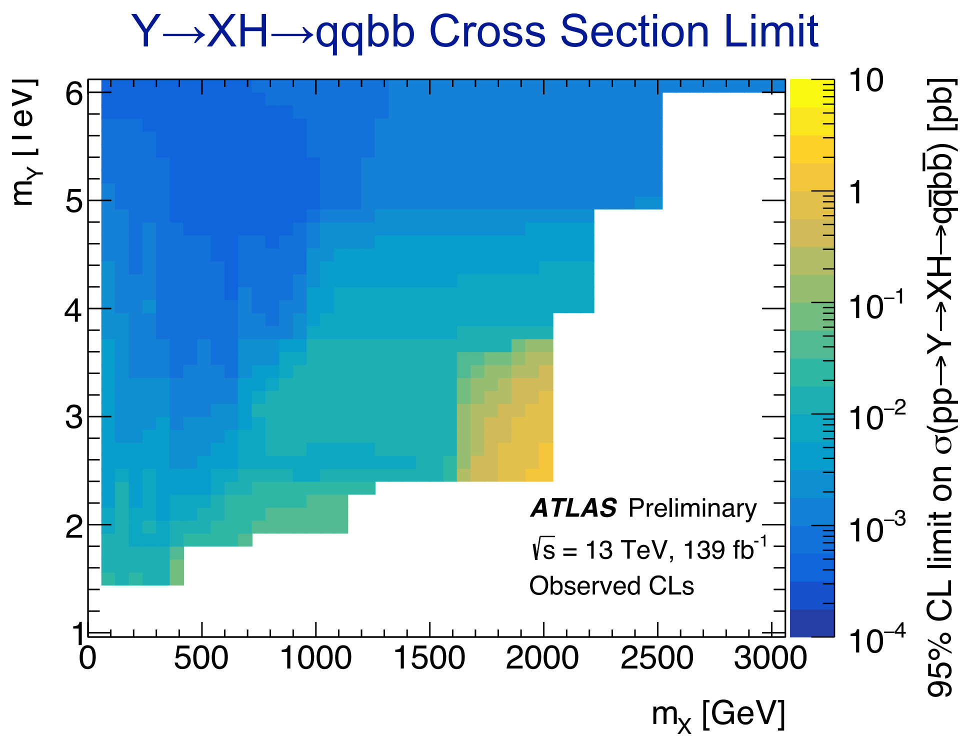


Y→XH Results

- Fit invariant mass of X and H for excesses in overlapping windows of m_X
- No significant excess in data: interpret in nominal X→qq, sensitive up to 6 TeV resonance mass

➡ **First application of fully unsupervised machine learning to an ATLAS analysis**

➡ **Takeaway: anomaly detection tools & searches are the future!**



[ATLAS-CONF-2022-045]

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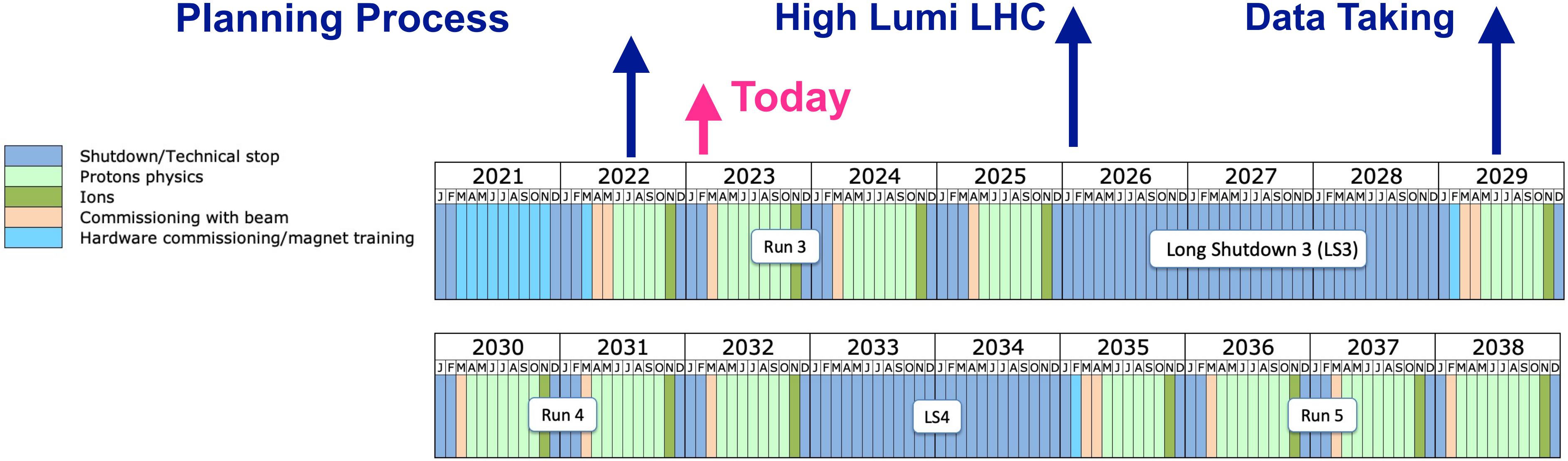
The Future of the LHC

2022: Snowmass Community Planning Process

2026: Upgrade for High Lumi LHC

2029: HL-LHC Data Taking



- **High Luminosity LHC (HL-LHC) in ~2029**: up to 200 simultaneous pp collisions to give better handle on very rare new physics processes
  - **ATLAS & CMS detectors**: many subsystems must be upgraded for high occupancy/trigger rates

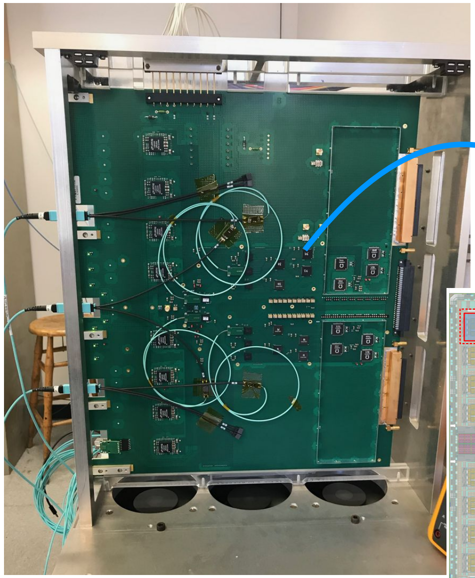
➡ As of now, we've only recorded ~5% of anticipated total lumi!

HL-LHC LAr On-Detector Readout

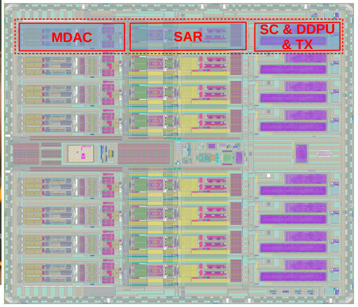
- LAr calorimeter must function for 10 years of HL-LHC operation (~3000-4000 fb^{-1})
  - Entirely new electronics system to accommodate higher bandwidth for trigger and radiation tolerance
- Columbia responsible for the analog-digital converter (ADC) ASIC and the Front-End Board (FEB2)
  - COLUTA ADC: full custom 40 MSPS in 65nm CMOS with 8 channels
  - Slice Testboard = pre-prototype of FEB2 (32 of 128 channels)
  - For large pulses, energy resolution < 0.02% (cf. spec 0.25%), timing resolution ~50 ps

➡Takeaway: custom ASICs are key for unique HEP DAQ needs; instrumentation experts/engineers are crucial

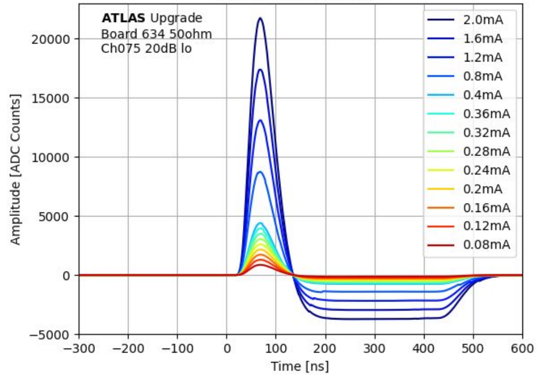
Slice Testboard



COLUTAv4



LAr Pulses



COLUTA Radiation Testing

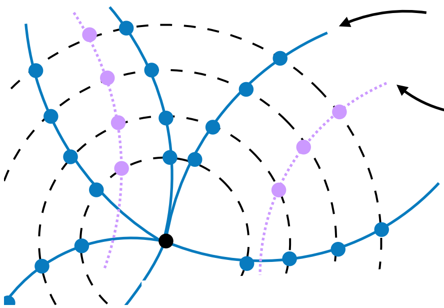
Future Vision

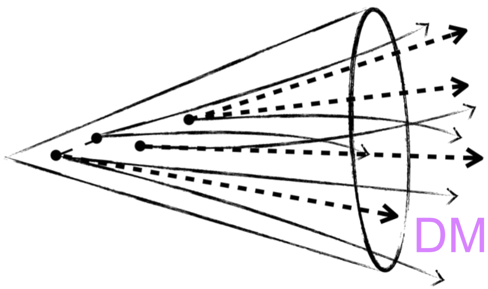
Don't lose sight of new scientific discovery as both the ultimate end goal and a real possibility!

- How can we best exploit the unique LHC environment while we have it?
- How can we ensure continued success of particle physics into the far future?
- How do we foster connections among "data sciences" for long-term mutual benefit?

Short-Term: Run 3 at the LHC

1. Continue searching!
   - New LLP triggers: unprecedented sensitivity to novel signatures, eg. via *large-radius tracking*
   - Build out end-to-end anomaly detection search pipeline for ATLAS, from data acquisition to final results
     - Ex. generic selection of *dark QCD signatures*
   - Keep connecting to the Higgs: expertise within SLAC ATLAS group





2. Prepare for Runs 4-5:
   - Ensure successful HL-LHC detector upgrade: aim to keep a hand in ATLAS upgrade and operations (collaborating with SLAC silicon ITk responsibilities)
   - Shared interest with SLAC on precision timing & Run 5 potential

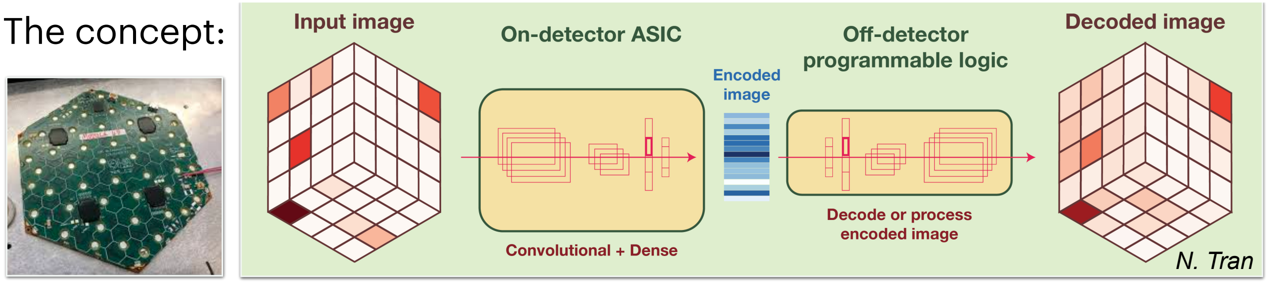
SLAC

Mid-Term: Instrumentation Advances

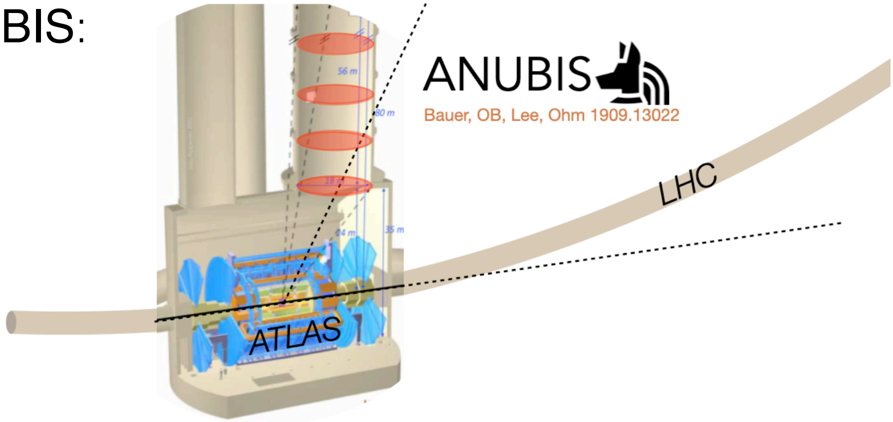
1. **Fast ML** algorithms for real-time scenarios (FPGAs, ASICs)
   - Application in ATLAS data acquisition: ***anomaly detection trigger stream*** could record never-before-seen events and handles to BSM physics
   - Many uses beyond HEP: collaborate with other directorates (ex. LCLS-II data acquisition upgrades, TID infrastructure)

SLAC

The concept:



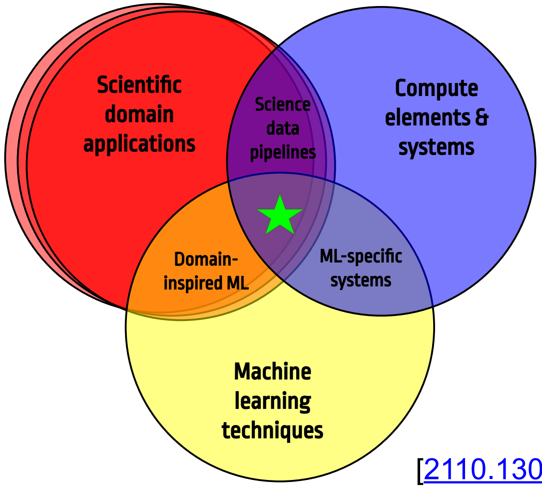
2. LHC-adjacent LLP experiments, eg. **ANUBIS**: cover very long lifetime phase space on smaller budgets
   - Opportunity to pursue precision timing/tracking ideas: could provide continuity for existing SLAC silicon infrastructure



Long-Term: Beyond the LHC

- **Future colliders**
  - Colliders are unique tools!
    - Novel C^3 opportunity taking off with SLAC leadership
  - Personal interest in future silicon high-granularity calorimeters & readout technology
  - Experienced advocate and community organizer for long-term strategic planning (eg. Snowmass, APS)

- **Cross-field applications of fast ML/ anomaly detection across sciences**
  - *Accelerator control & optimization, data reduction,* eg. at LCLS
  - *Model-independent/real-time classification,* eg. DUNE, automatic phase identification at SSRL



[2110.13041]

Conclusions

- **Now more than ever, particle physics has a well-diversified search effort with exciting discovery prospects**
  - My focus: novel search ideas and machine learning applications (long-lived particles, anomaly detection)

- Performance of **instrumentation** is crucial…
  - Ensure success of ATLAS HL-LHC upgrades and brainstorm future readout advances

- .. as is the quality of the **scientific community**
  - Key collaboration avenues beyond EPP: Technology Innovation, LCLS, Accelerator, and more
  - Ongoing commitment to cultivating inclusive & equitable organization of the field

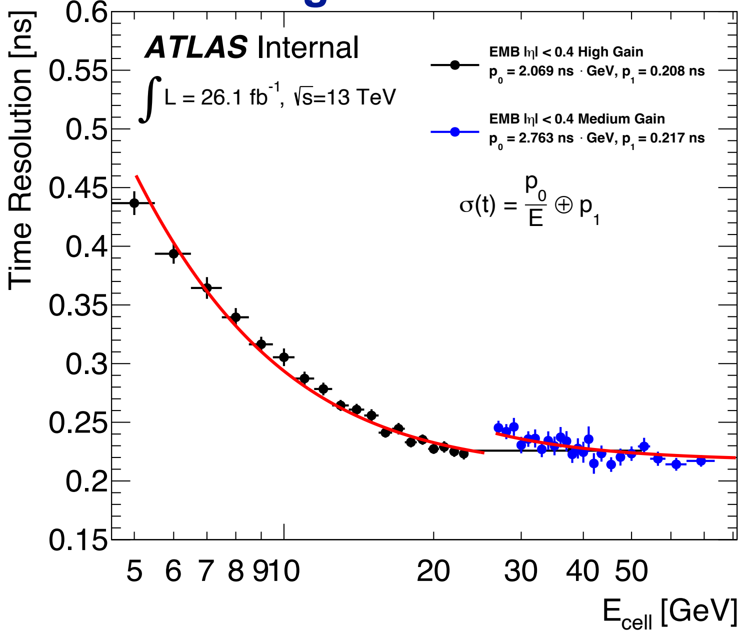
- **International collider research** provides unique reach towards BSM prospects
  - Long-term planning for future experimental program can start now!

Backup

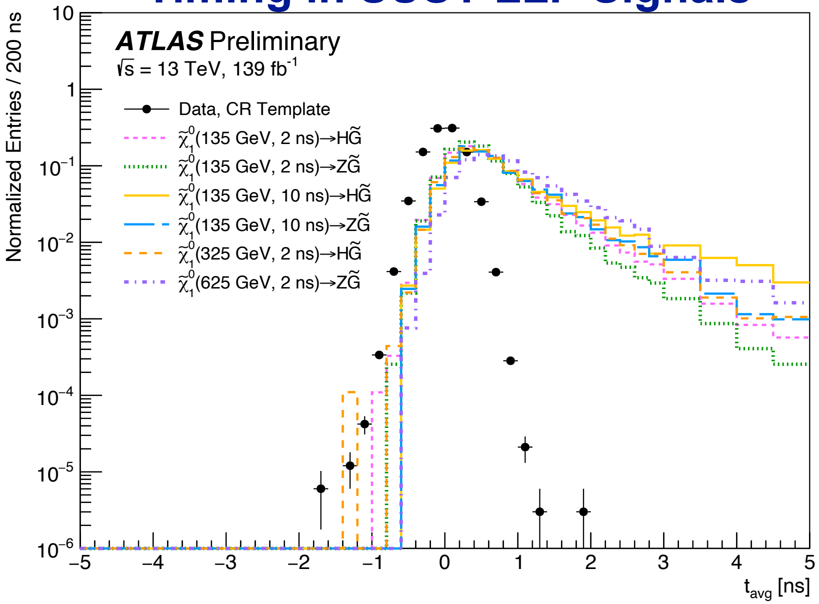
LLPs in LAr: Timing

- Calculated from calorimeter samples using LAr optimal filtering coefficients (OFCs)
  - Determined by middle layer maximum energy deposit ($maxE_{cell}$)
  - Online ~1 ns resolution, calibrate offline with W→eν/Z→ee to reach **~200 ps** (dominated by beamspread)
- Photons from the decay of an LLP will be *late* with respect to the bunch crossing time: timing is highly discriminating for LLPs with lifetimes O(ns)

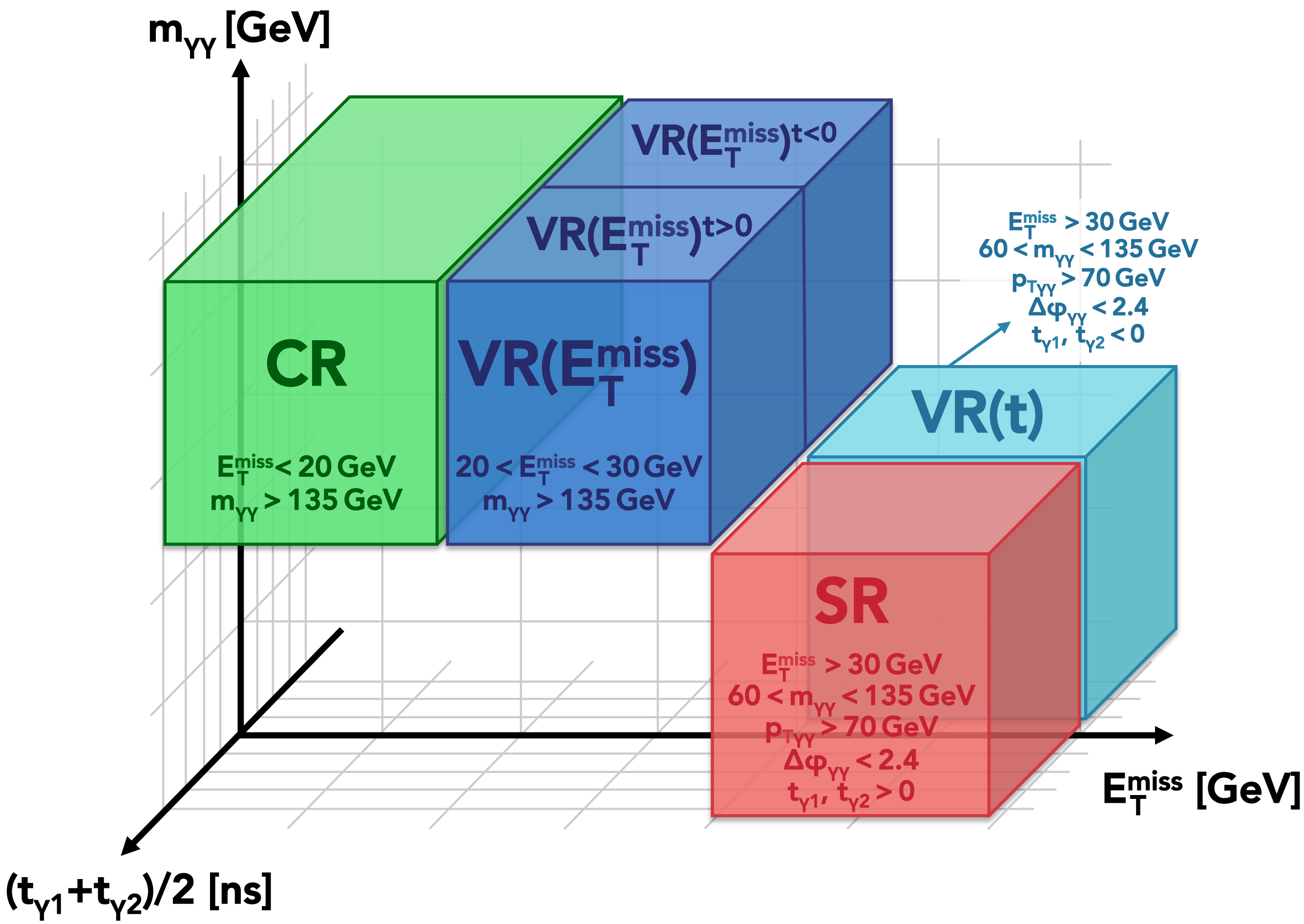
Timing Resolution vs. E



Timing in SUSY LLP Signals



Displaced Diphoton Vertices



LLPs Towards Run 3

- *Run 2 Highlights*
  - LLPs → e/ɣ objects
  - **Displaced (high d_0) leptons**: exclude pair-produced slepton decays up to ~500 GeV for ~0.1 ns lifetimes (flavor dependent) using extended tracking out to 30cm

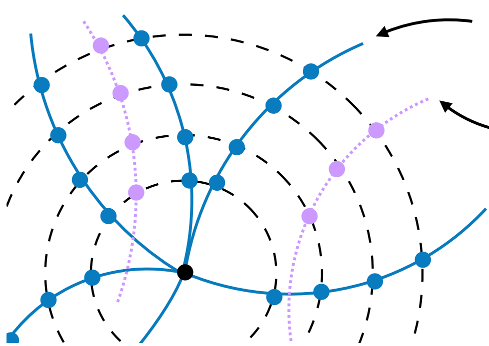
Run 2 Displaced Leptons

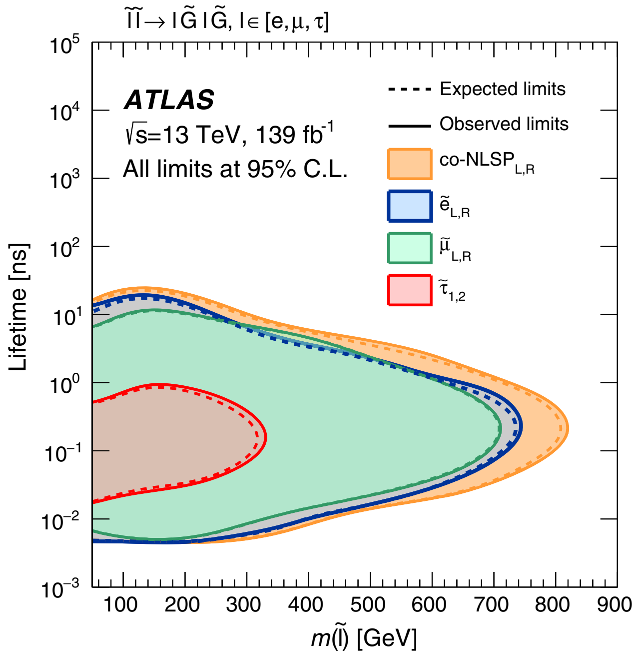
[PRL 127 (2021) 051802]

Topology	Trigger*
if $\geq e$, $p_T >$ 160 GeV	HLT_g140_loose
else if $\geq 2e$, $p_T >$ 60 GeV	HLT_2g50_loose[5]
else if $\geq 1\mu$, $p_T >$ 60 GeV, $\|\eta\| < 1.07$	HLT_mu60_0eta105_msonly

**no tracking in triggers*

- ❗ *New for Run 3:*
  - **Large radius tracking**: additional ID tracking pass run after standard tracking on leftover hits with relaxed tracking cuts
  - **Displaced lepton triggers**: considerable expansion of trigger acceptance d_0 and lower p_T threshold by including LRT





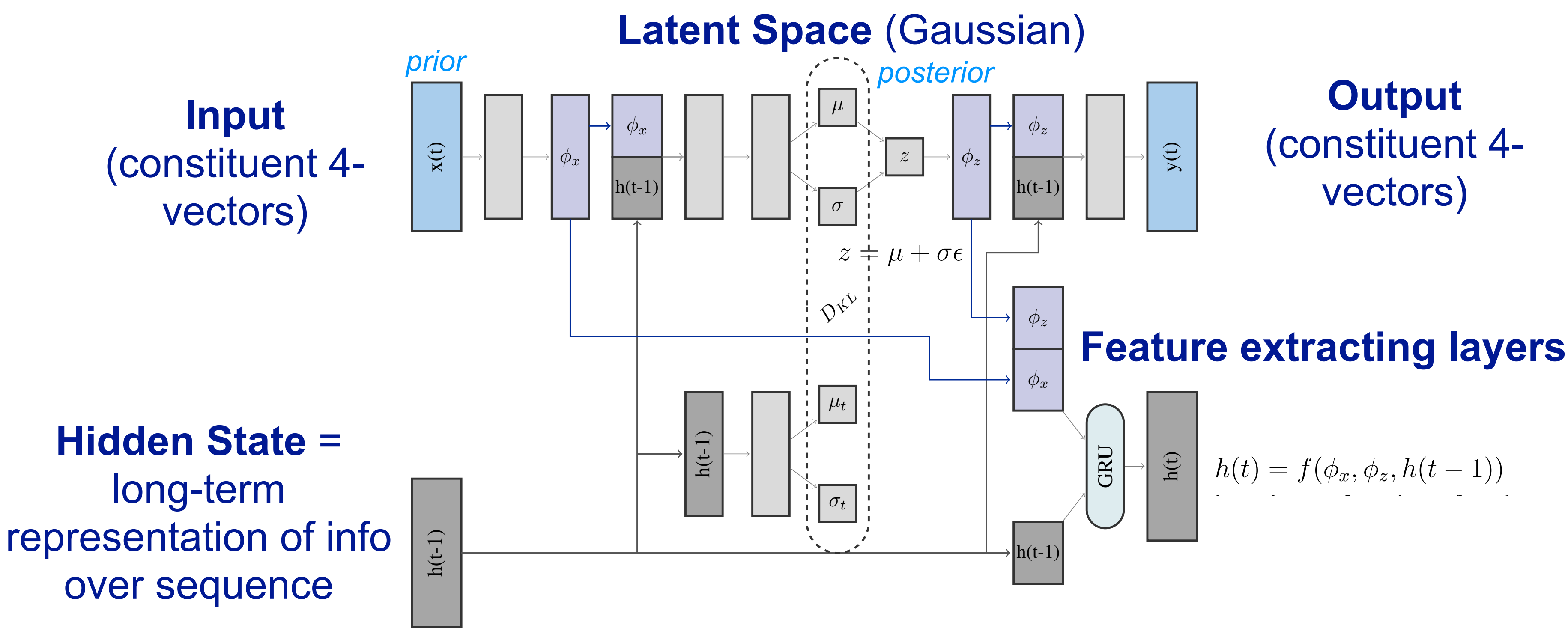
VRNN Architecture

- **Variational RNN:** recurrent neural network (RNN) that updates a VAE latent space at each time step; accommodates variable-length input sequences
- Define *anomaly score* per jet as a function of the KL divergence loss term: $AS = 1 - e^{-D_{KL}}$
- Train directly on data (avoid data/MC discrepancies in QCD)

$$\mathcal{L}(t) = |\mathbf{y}(t) - \mathbf{x}(t)|^2 + \lambda D_{KL}(z||z_t)$$

Mean-squared reconstruction error

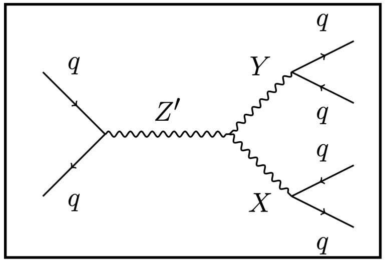
Kullback-Leibler Divergence



VRNN in Action

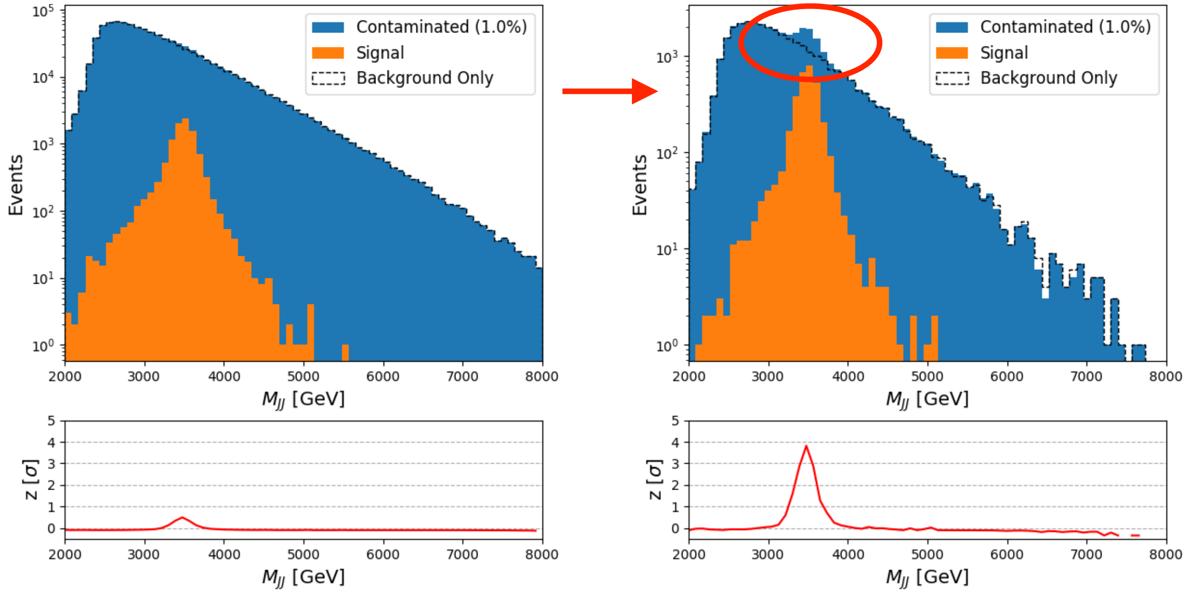
- VRNN for anomalous jet tagging developed in simulation via the LHC Olympics community anomaly detection challenge [2101.08320]
- Achieve sensitivity with resulting jet-level anomaly score to both 2- and 3-particle decays over QCD/multijet

➡VRNN paper published using this dataset [2105.09274]



m_{JJ}, QCD + signal

No Selection



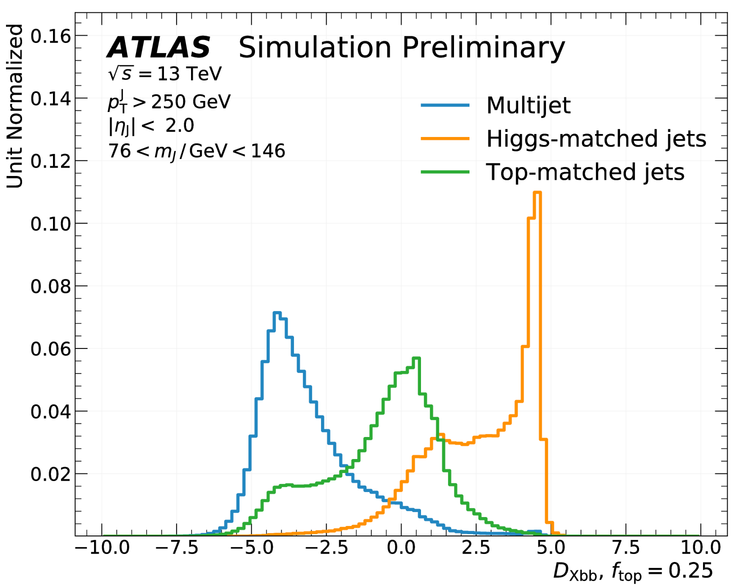
Cut on VRNN anomaly score

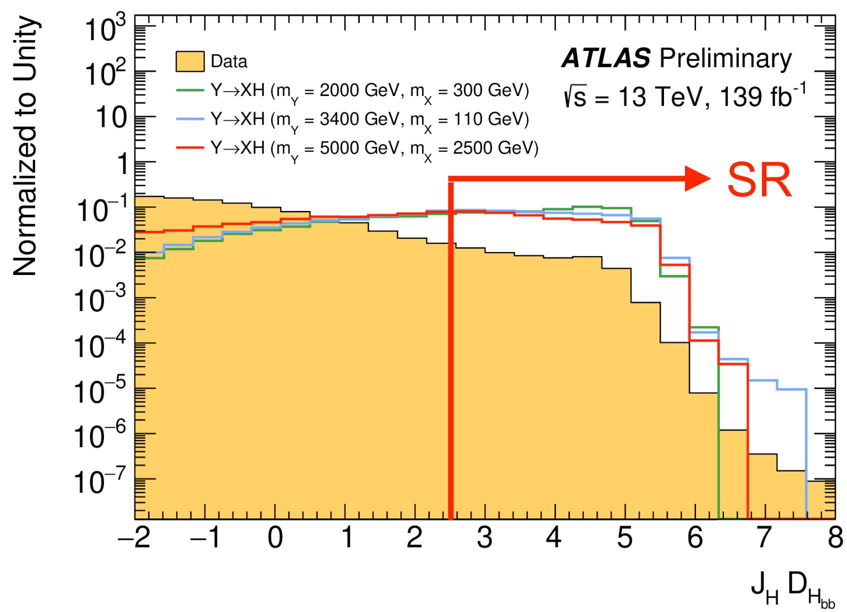
Neural Net $H \to b\bar{b}$ Tagging

- Neural net-based double b-tag algorithm to select Higgs vs. dijet or top backgrounds [ATL-PHYS-PUB-2020-019]
  - Train over large-R jet p_T/η and up to 3 subjet b-tagging scores
  - Outputs: three class probabilities → discriminant D_{Hbb}

➡ Tag Higgs boson using 60% WP and ftop=0.25 as per central FTag recommendation

$$D_{Xbb} = \ln \frac{p_H}{f_{\text{top}} \cdot p_t + (1 - f_{\text{top}}) \cdot p_{\text{QCD}}}$$

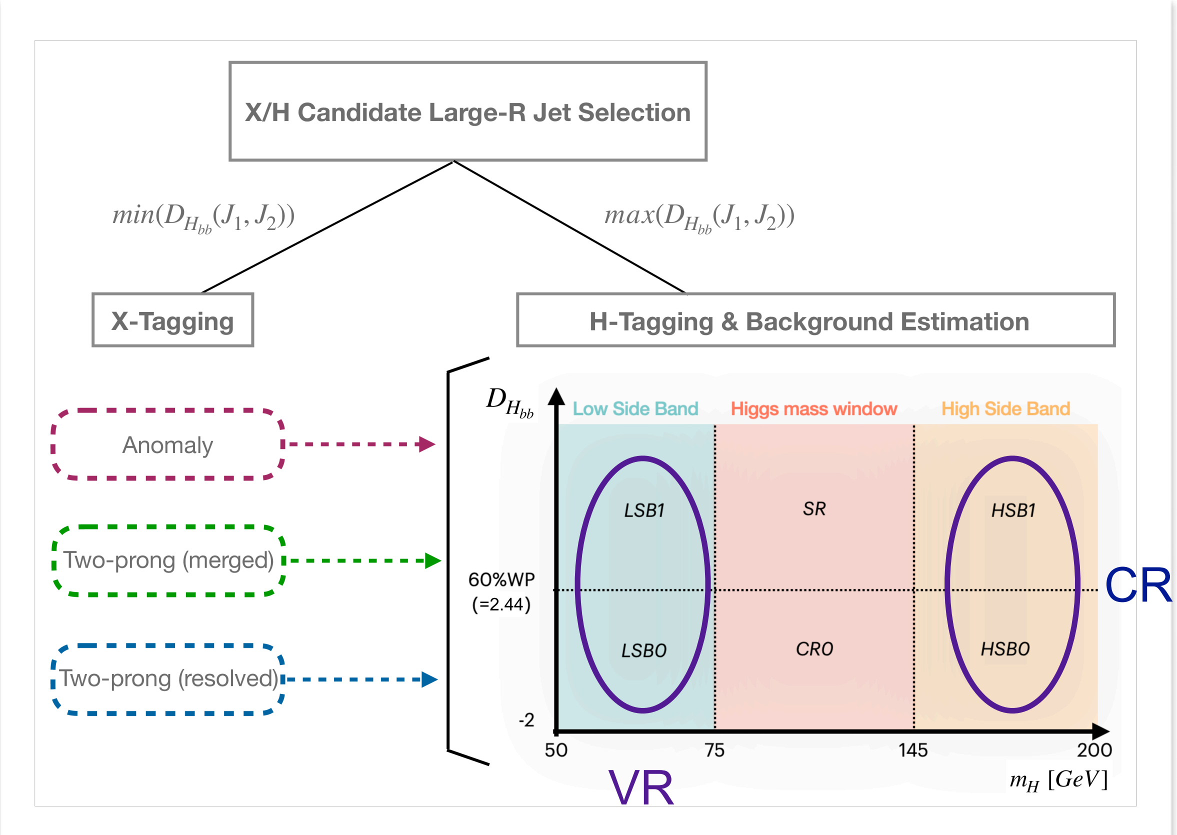




Analysis Flow

1. **Large-R jet trigger**: $J_1(p_T)$ > 500 GeV and m_{JJ} > 1.3 TeV
2. **Ambiguity resolution**: jet with highest D_{Hbb} score is Higgs candidate
3. **X-tagging**: AS of X candidate > 0.5 (plus 2-prong regions)
4. **Higgs tagging**: D_{Hbb} of H candidate > 2.44

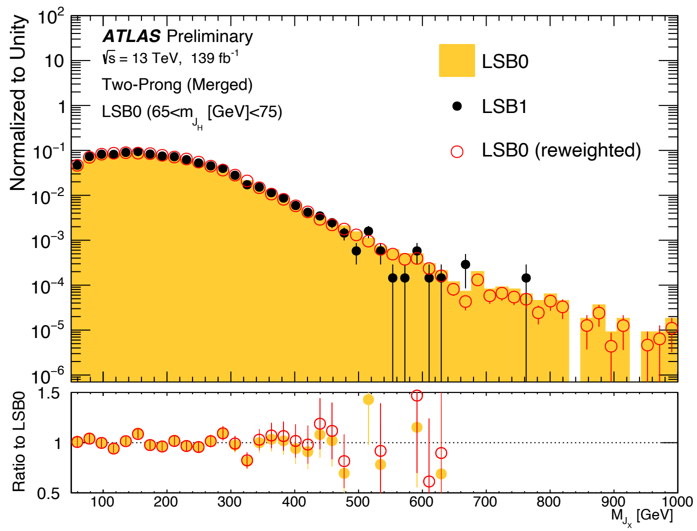
- **SR selection**: 75 < m_H < 145 GeV
- **Background estimation**: DNN-derived reweights for untagged high sideband (HSB0→HSB1)
- **Validation**: low sideband (LSB)



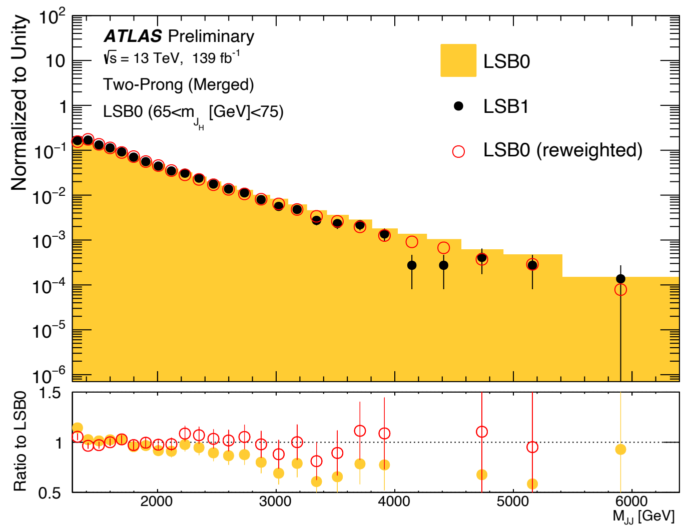
Background Estimation

- Fully data-driven background estimation (~97% multijet processes)
- Derived from data template in high Higgs mass sideband that fails H tagger score, reweighted to shape in H-tagged region
- Build **DNN** to provide a reweight for each event
  - 3 fully-connected inner layers, 20 neurons each
  - Train inclusively in X-tagging over variables associated to the Higgs large-R jet (4 vector, 4-vectors of leading & subleading track jets associated to Higgs, # tracks)
  - Minimized on log-likelihood ratio of tagged to untagged regions'
- Systematics on DNN training region, statistical power of training sample, LSB non-closure

LSB Validation



m(X)



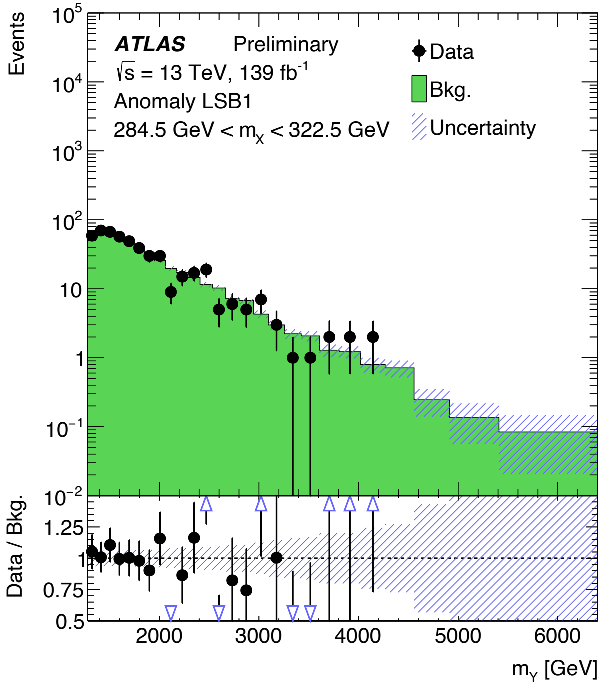
m(XH)

Y→XH Statistical Analysis

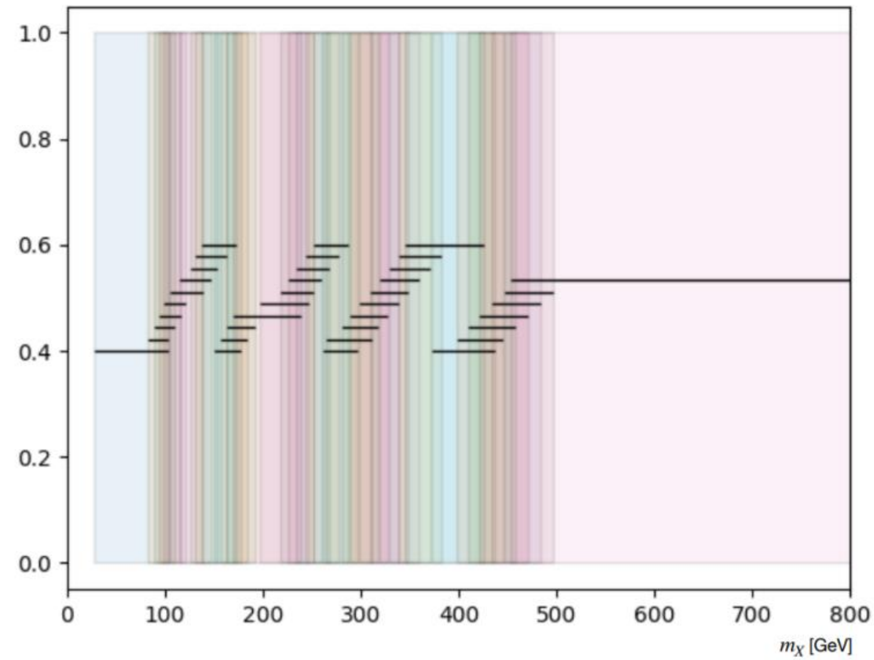
- Fit m_Y across overlapping categories of m_X
  - Bins chosen based on signal mass resolution
- Use BumpHunter as signal model-independent "excess finder" [1101.0390]
  - No significant (p-val < 0.01) excess across m_X bins in the LSB VR

➡ No interpretation in anomaly region (no signal systematics)

Post-fit LSB



m_X Windows



Y→XH Systematic Uncertainties

Background

- Determined inclusively in m_x, and then applied to each exclusive m_x bin

1. DNN Source Systematic
   - Difference in resulting mJJ distribution due to the choice of training region
   - O(1-10)% effect across mJJ
2. DNN Bootstrap Systematic
   - Statistical error from neural network performance determined via the bootstrap procedure
   - O(1)% effect across mJJ
3. Non-Closure Systematic
   - Determined in the LSB as the difference between reweighted LSB0 and LSB1 data, with smoothing
   - Characterizes additional mis-estimation of data in the VR after determining weighting parameters from the HSB
   - Negligible for low mJJ, O(10)% effect in the tails

Signal

- Flat luminosity uncertainty of 1.7% (as measured with LUCID)
- Jet uncertainties implemented with standard variations from jet/E^{miss}_T CP group
  - Included for both large-R (merged and resolved) and small-R (resolved only) jets
  - Rtrk Baseline, Modeling, Tracking, TotalStat, Closure uncertainties
  - JER Mass and p_T variations
- PDF variation uncertainties
  - ISR/FSR included as flat 3% uncertainty
- XbbSF uncertainties

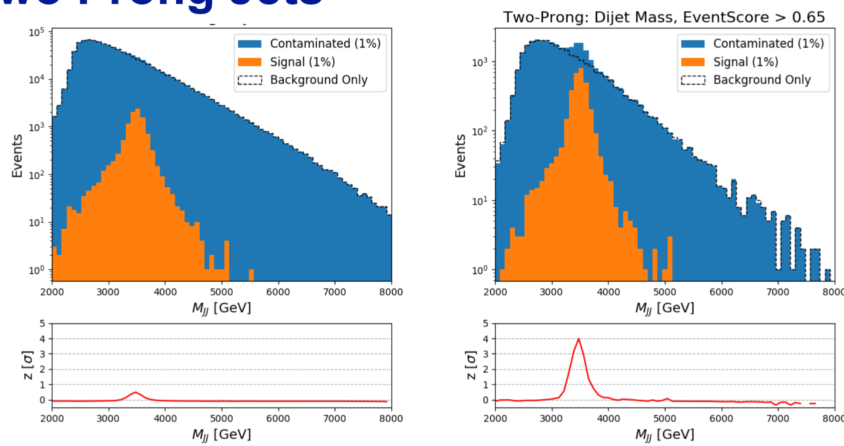
VRNN Anomaly Score

- **Preprocessing (right)**
- **Sequence Ordering:** decreasing kt distance from hardest constituent
- **Training:** 16 neurons per intermediate layer, 500 epochs
- **Results**: sensitive to 2 and 3 prong signals, while less mass correlated than typical high-level substructure variables

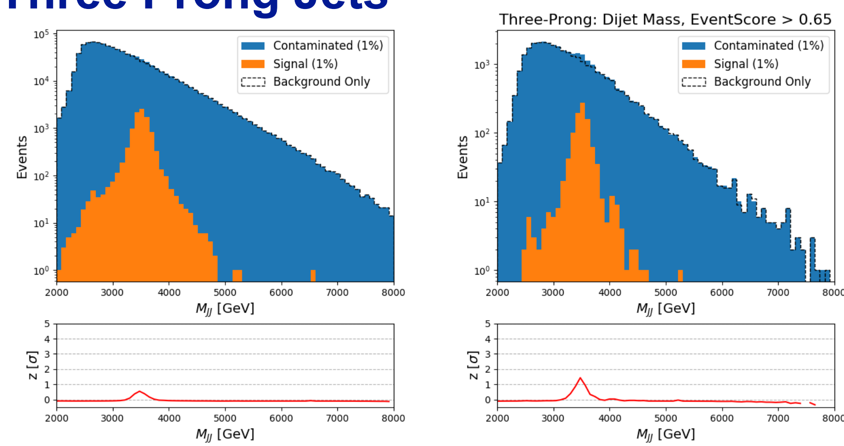
Algorithm 1: Jet Boosting

Start
Boost jet in z direction until $\eta_{Jet} = 0$
Rotate jet about z axis until $\phi_{Jet} = 0$
Rescale jet mass to 0.25GeV
Boost jet along its axis until E_{Jet} =1GeV
Rotate jet about x axis until hardest constituent has $\eta_1 = 0, \phi_1 > 0$
if *Any constituents have* $\Delta R > 1$ **then**
  Remove all constituents with $\Delta R > 1$
  Rebuild jet with remaining constituents
  Repeat from start
else
  continue
end
if *Number of constituents* > 20 **then**
  Keep up-to the first 20 constituents, ordered in p_T
  Rebuild jet with remaining constituents
  Repeat from start
else
  continue
end
Reflect constituents about ϕ axis such that the second hardest constituent has $\eta_2 > 0$

Two Prong Jets

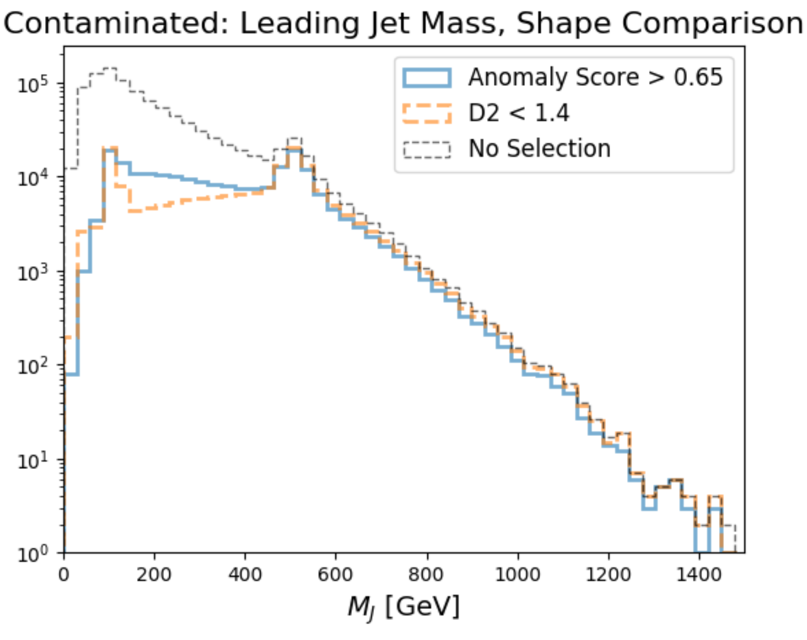


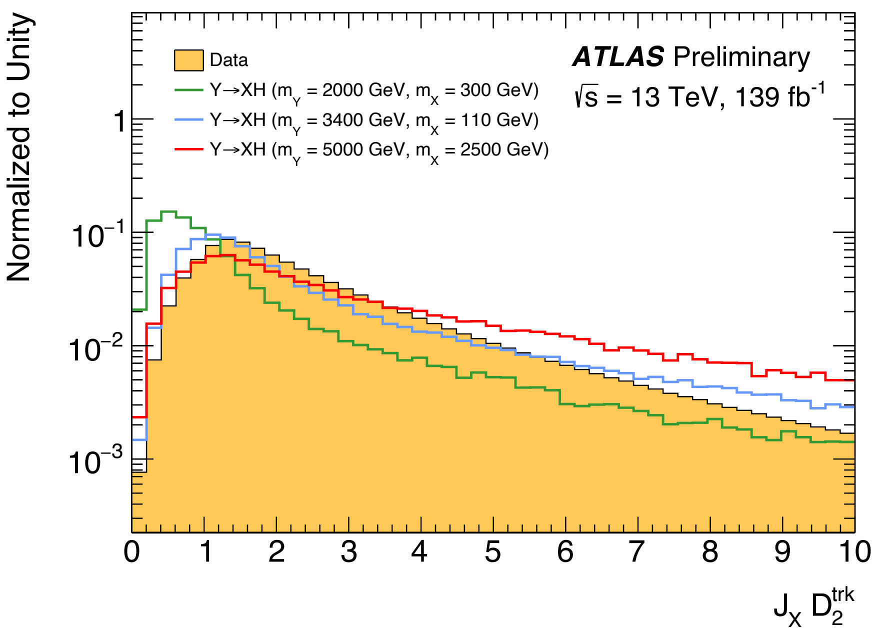
Three Prong Jets



AS Comparison to D2

- Dataset = 2-prong % contaminated
  - Selections: D2 < 1.4 / AS > 0.65 (equivalent background rejection)
  - AS creates less mass sculpting than substructure variables
- In Y→XH→qqbb, cut on $D2_{trk}$ < 1.2 (merged) or > 1.2 (resolved)



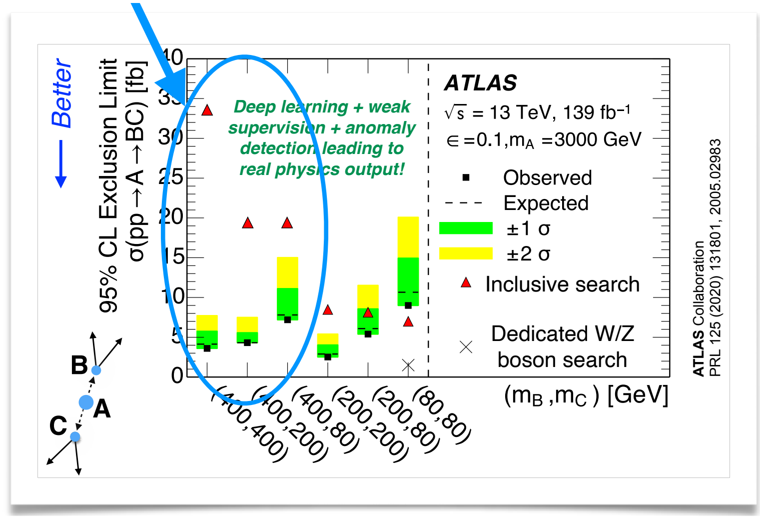


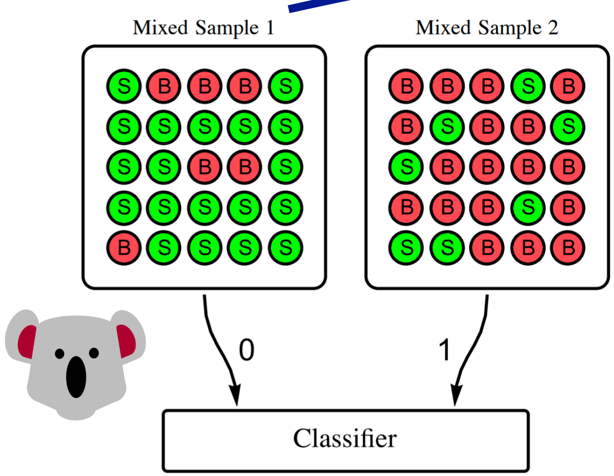
CWoLa Weakly Supervised Learning

- Classification without labels (CWoLa) [1708.02949]: NN trained in signal region vs. sideband is sensitive to signal vs. background characteristics
  - SR and SB defined in windows of mJJ, each region has different fraction of signal
  - NN input training features = two leading jet masses

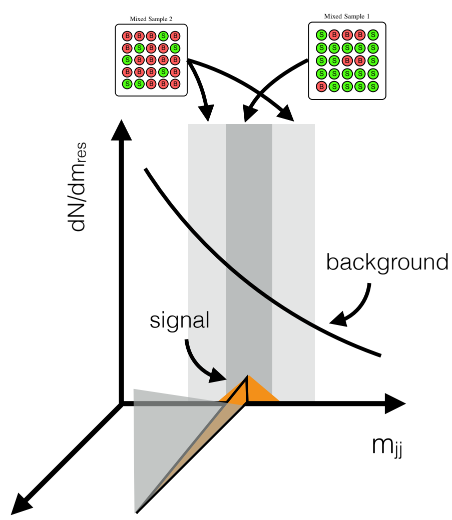
➡ First application of **weakly supervised** learning from ATLAS! [PRL 125 131801]

➡ Outperforms inclusive search at high mass hypotheses



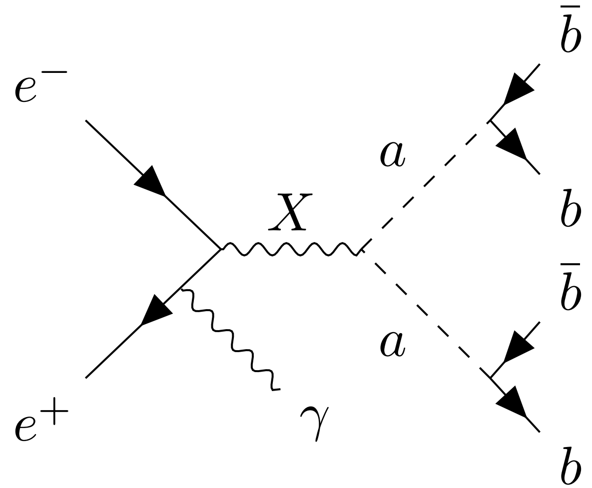


1708.02949, 1805.02664

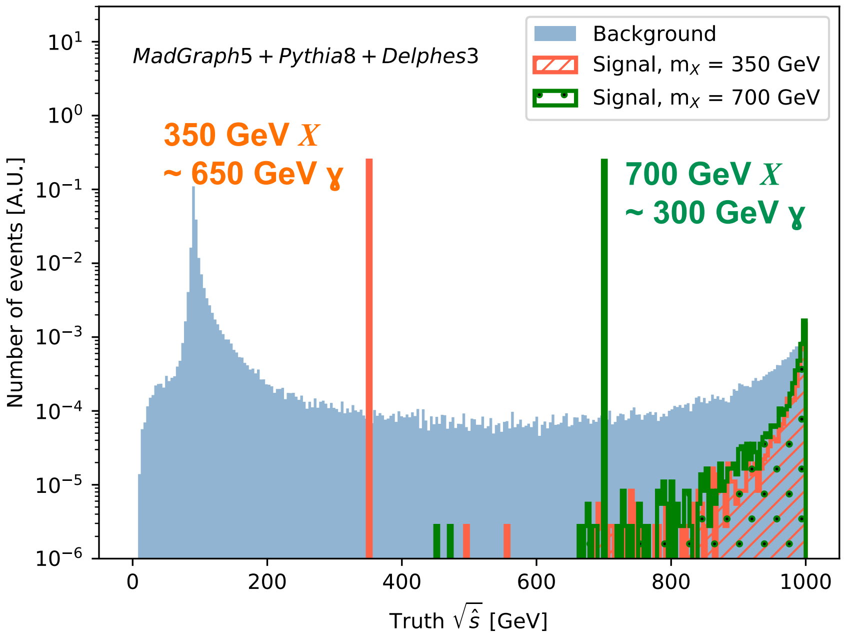


CWoLa in e+e- Collisions

- **Radiative return:** "scan" new particle masses with ISR photons, à la dijet invariant mass bump hunts
- Apply CWoLa method with *high- and variable-dimensional inputs* with [Particle Flow Networks](): model an event as an unordered, variable-length set of jets
  - Up to 15 jets per event & 10 features per jet: 4 vector (pT, η, ϕ, m), b-tagging bit, 5 N-subjettiness variables
  - ➡150 input features per event



e+e- √s = 1 TeV



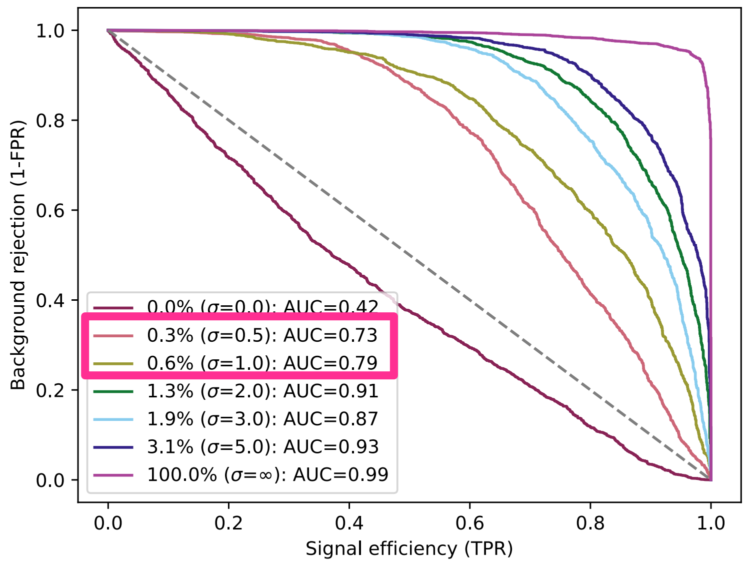
[arXiv:2108.13451]

CWoLa in e+e- Collisions

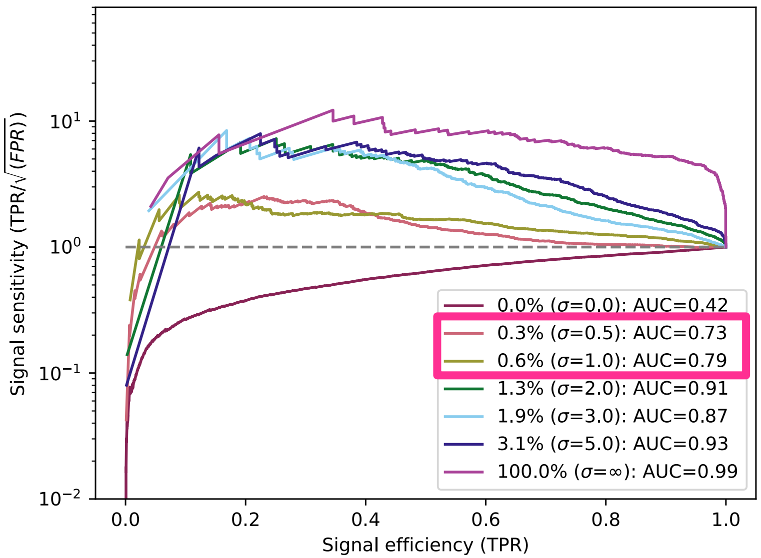
- Select signal and background in ±25 GeV windows in √s around the resonance mass (SR = [675, 725)) with sideband in ±50 GeV windows on either side (SB = [625,675) U [725,775))
- Train with a variety of signal contaminations: σ=0.0, 0.5, 1.0, 2.0, 3.0, 5.0, and ∞ (eg. all S vs. all B)
- Significance Improvement Characteristic (**SIC**): sensitivity proxy that gives multiplicative factor by which the NN can improve signal significance

➡**Enhance sensitivity to signal contaminations** down to 0.3% by a factor of ~3

ROC: X=700 GeV vs. bkg



SIC: X=700 GeV vs. bkg



[arXiv:2108.13451]

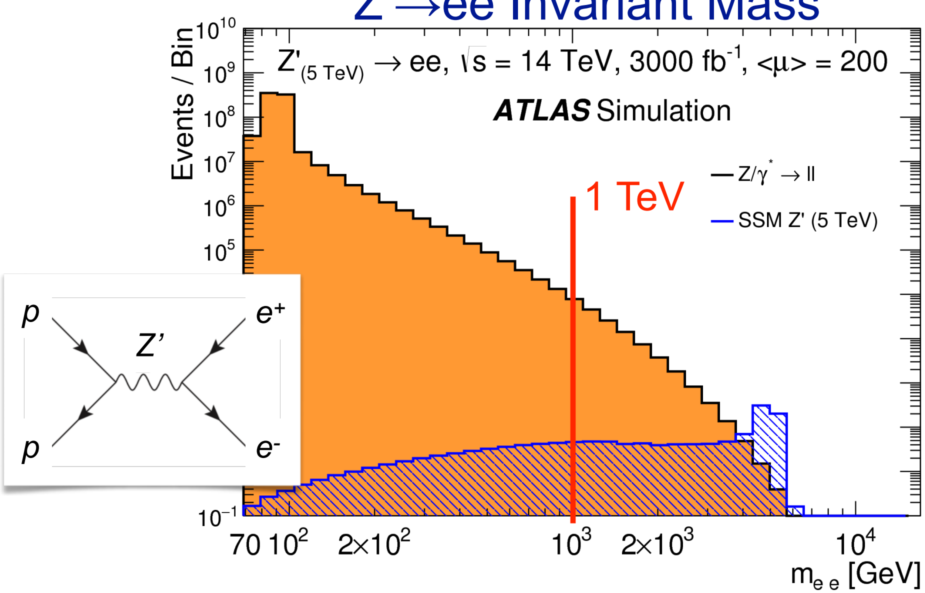
HL-LHC Upgrade: Physics

- Key physics drivers motivate precision reconstruction of electron/photon energy & time
  1. High expected dynamic range (eg. massive Z'→ee with high E electrons)
  2. Precise mass resolution for measurements of key SM processes (eg. di-Higgs: small, narrow $m_{\gamma\gamma}$ peak on top of large irreducible background)
  3. Ensure that photons from H→γγ are mostly digitized on High gain and minimize gain intercalibration systematic → new 2 gain scheme

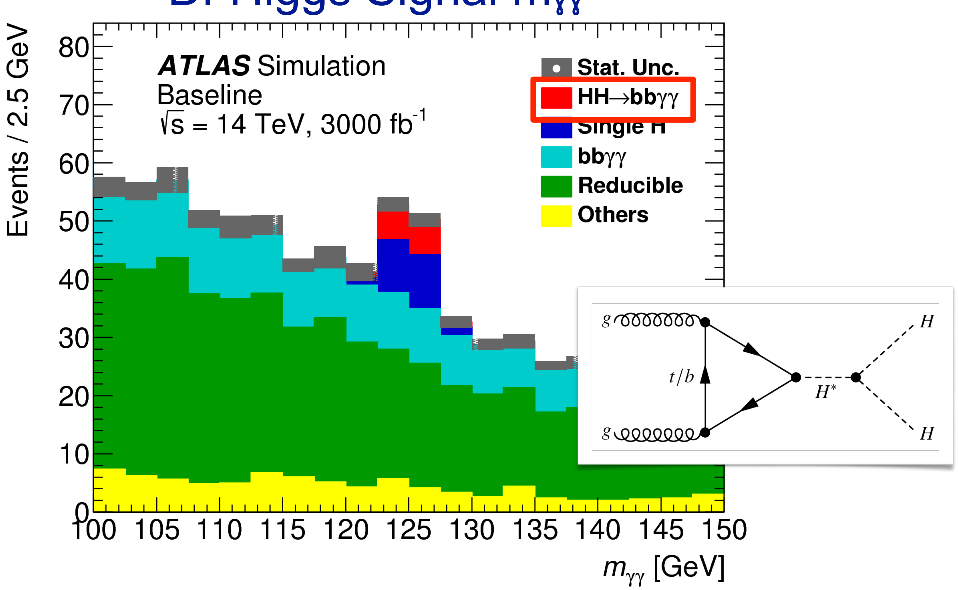
Resolutions [GeV]	ggF	HH
Pessimistic	2.64	2.06
Optimistic	1.99	1.62

ATLAS-TDR-027

Z'→ee Invariant Mass



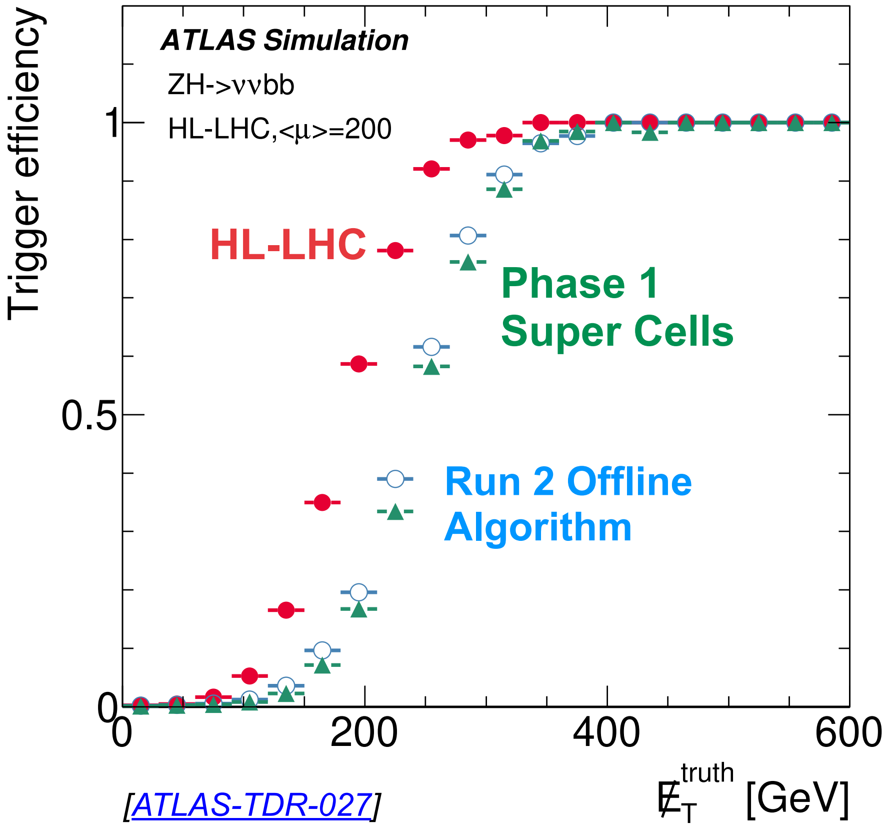
Di-Higgs Signal $m_{\gamma\gamma}$



HL-LHC Upgrade: Triggering

- New trigger/DAQ requirements: rate will be increased 10x to 1 MHz, latency 5-10x to 10 μs
- Motivates a new LAr readout architecture → free-running all digital design with no on-detector pipeline
  - **Already installed ("Phase-I")**: Super Cells to provide finer granularity to trigger
- For HL-LHC: Read out *entire LAr calorimeter with full precision* at 40 MHz LHC bunch crossing frequency
  - Data rate = 40 MHz x 16 bits x 2 gains x **128 chans** x 1524 boards = **~350 Tbps**
  - Results in lower trigger turn-on curves
  - Maintain ability to trigger on low-p_T objects

HL-LHC E_T^{miss} Trigger Turn On



[ATLAS-TDR-027]

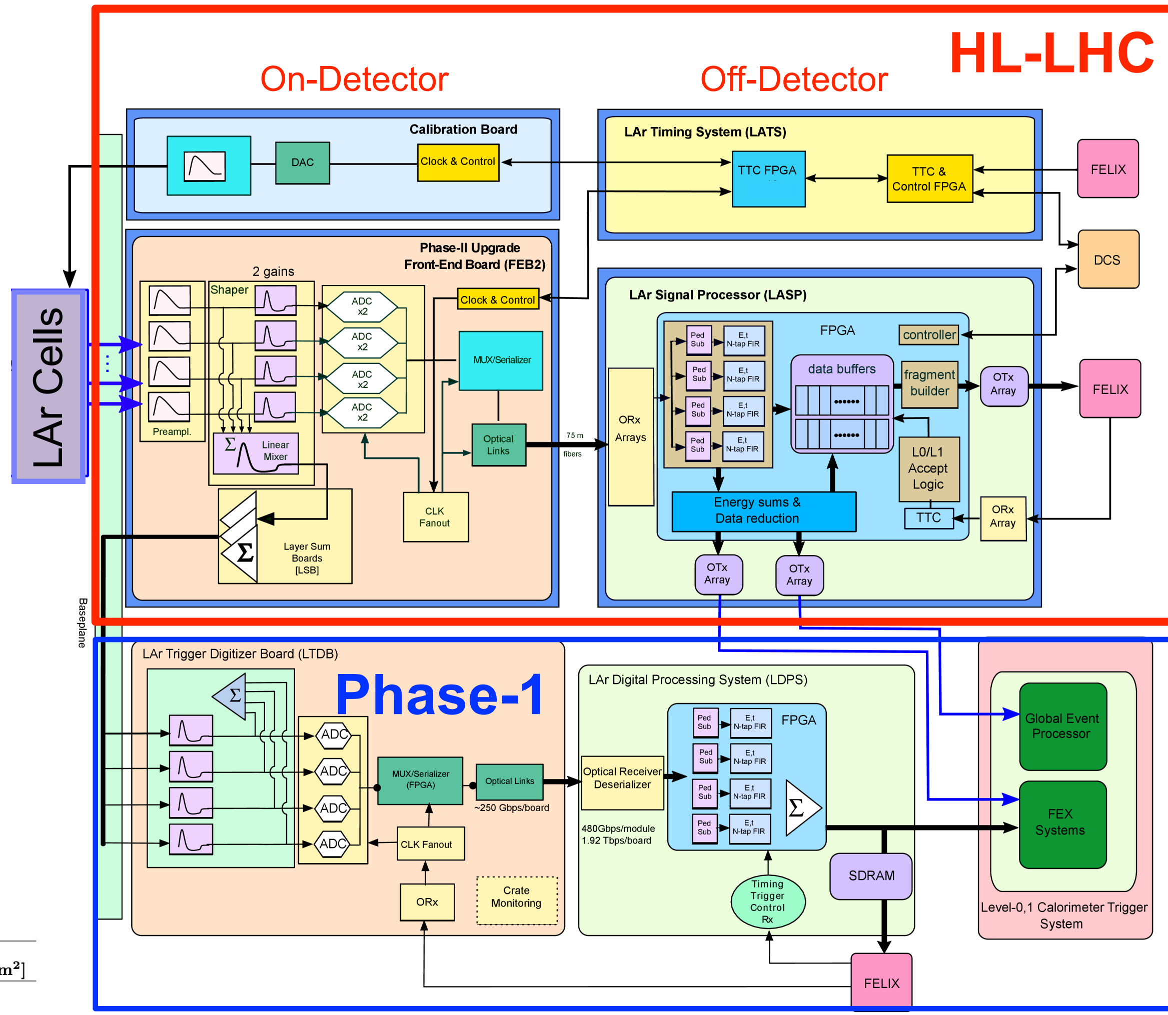
HL-LHC Readout

- Phase-I: installed 2019-2022 & commissioning now!

HL-LHC:

- Cover full energy range expected in a single cell (~50 MeV electronic noise to ~3 TeV)
- 16-bit DR 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)

	TID [Gy]	NIEL [n_{eq}/cm^2]	SEE [$h_{>20\,MeV}/cm^2$]
FEC (barrel)	1400 (1.5)	4.1×10^{13} (2)	1.0×10^{13} (3)
FEC (endcap)	210 (1.5)	6.0×10^{12} (2)	1.2×10^{12} (3)
LVPS between TileCal fingers (barrel)	430 (1.5)	1.1×10^{13} (2)	2.8×10^{12} (3)
HEC and FEC LVPS (endcap)	81 (1.5)	2.0×10^{12} (2)	4.1×10^{11} (3)
LVPS new position (barrel)	18 (1.5)	5.1×10^{11} (2)	1.1×10^{11} (3)
LVPS new position (endcap)	33 (1.5)	5.2×10^{11} (2)	8.6×10^{10} (3)



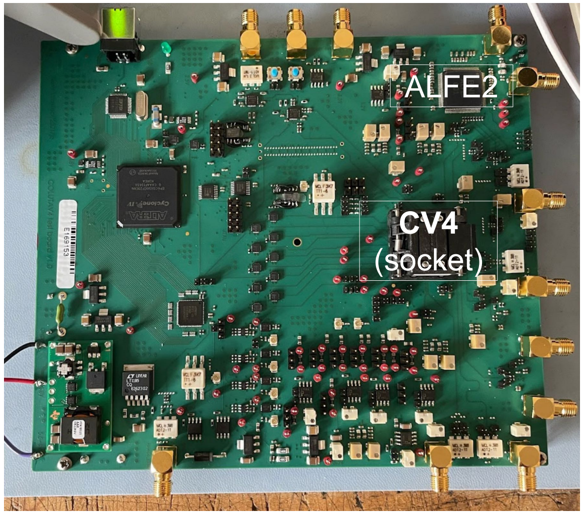
ADC Characterization

- COLUTA ADC ASIC: full custom 40 MSPS in 65nm CMOS with 8 channels
  - > 14 bit dynamic range with > 11 bit ENOB
  - Radiation tolerance: irradiate chip & measure SEUs, TID, NIEL (full HL-LHC dose in ~few hours)

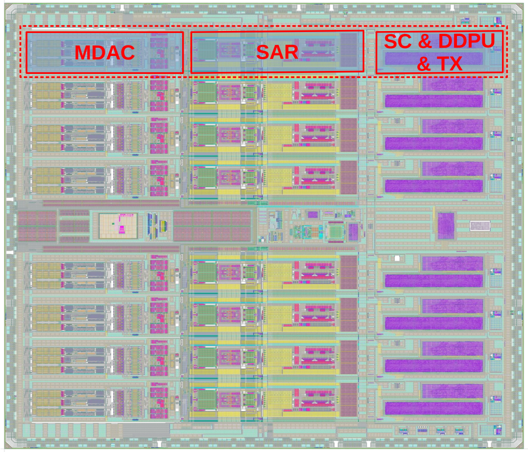
➡ **Takeaways: custom ASICs are key for unique HEP DAQ needs**

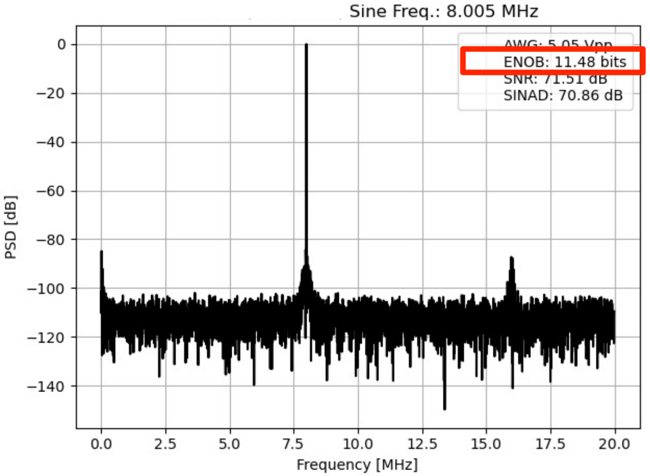
- Final Design Review in October to start pre-production (need 80k chips total produced & tested)

ADC Testboard



COLUTAv4



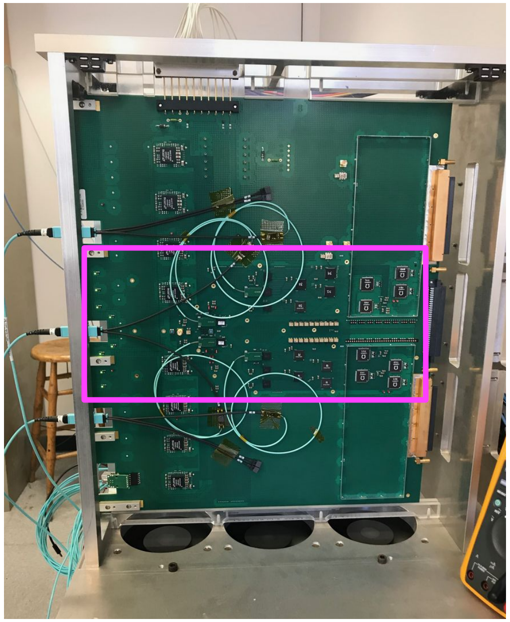


Radiation Testing

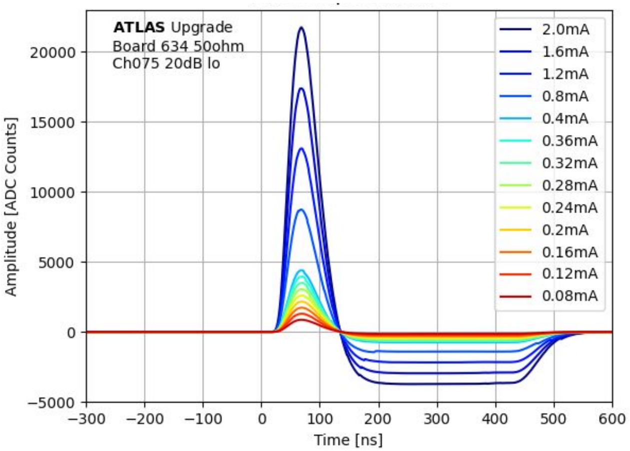
Slice Testboard

- Slice Testboard = pre-prototype of FEB2 (32 of 128 channels)
- Characterize performance of 3 custom ASICs in full readout chain (PA/S, ADC, lpGBT)
- For large pulses, energy resolution < 0.02% (cf. spec 0.25%), timing resolution ~50 ps (dominated by system jitter)

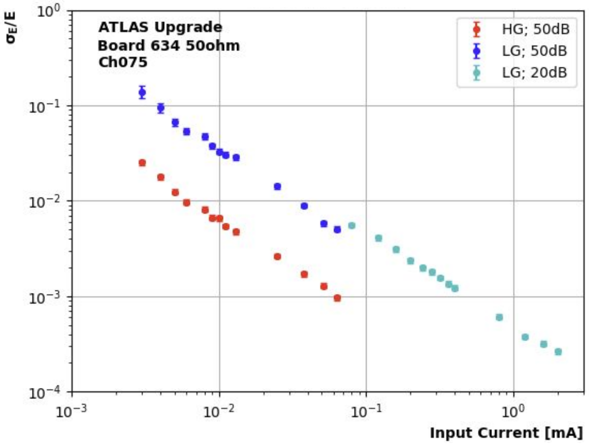
➡ **Takeaways: front end design is as crucial to experimental success as detector itself**
- Preliminary Design Review in December: full 128-channel FEB2 prototype + system tests



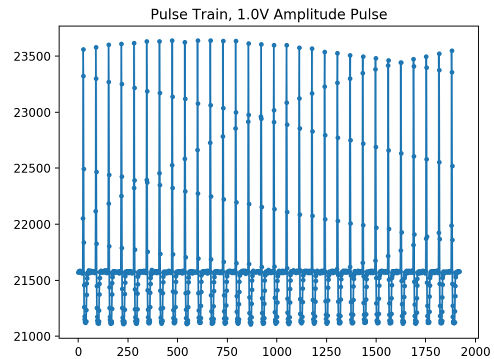
LAr Pulses

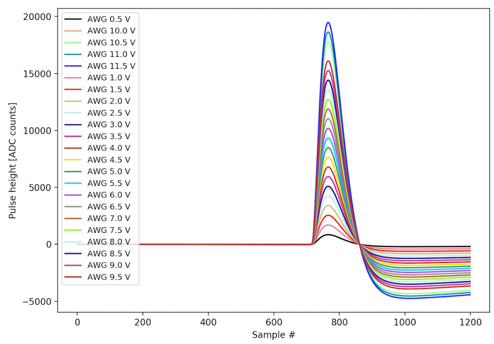


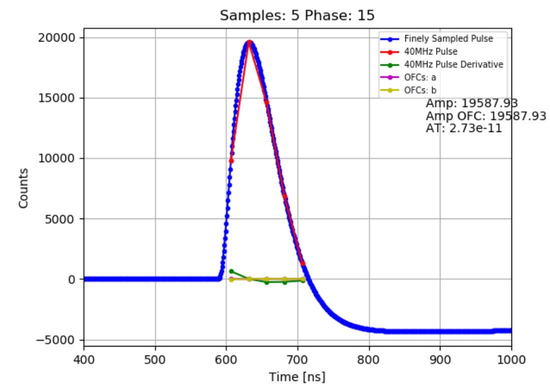
Energy Resolution



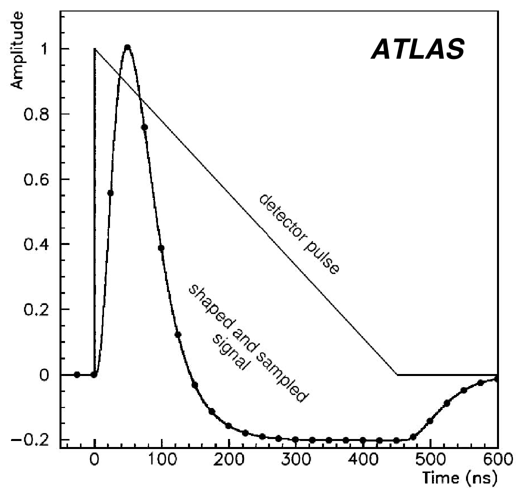
LAr Pulse Analysis







AWG sends a pulse train of known amplitude to ADC chip, sampled at different phases → Pulse train is interleaved to reconstruct fine pulse for each amp. Check that maxima and zero point match across amplitudes → Samples from one phase (containing peak) and derivatives are used to calculate OFCs, then used to find energy and timing of each pulse



Optimal Filtering Coefficients

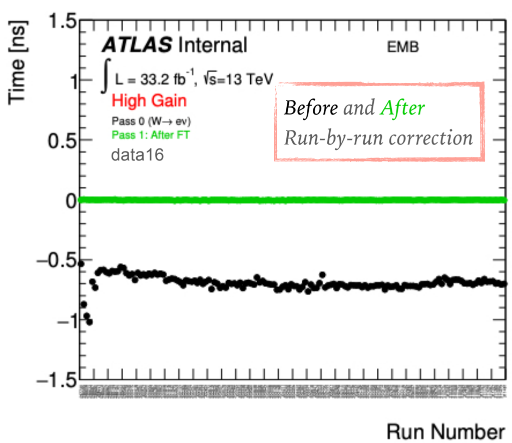
$$A = \sum_i a_i S_i,$$

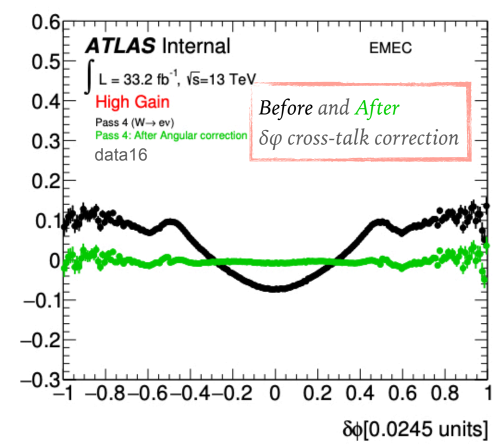
$$\tau = \frac{1}{A} \sum_i b_i S_i$$

Offline LAr Timing Calibration

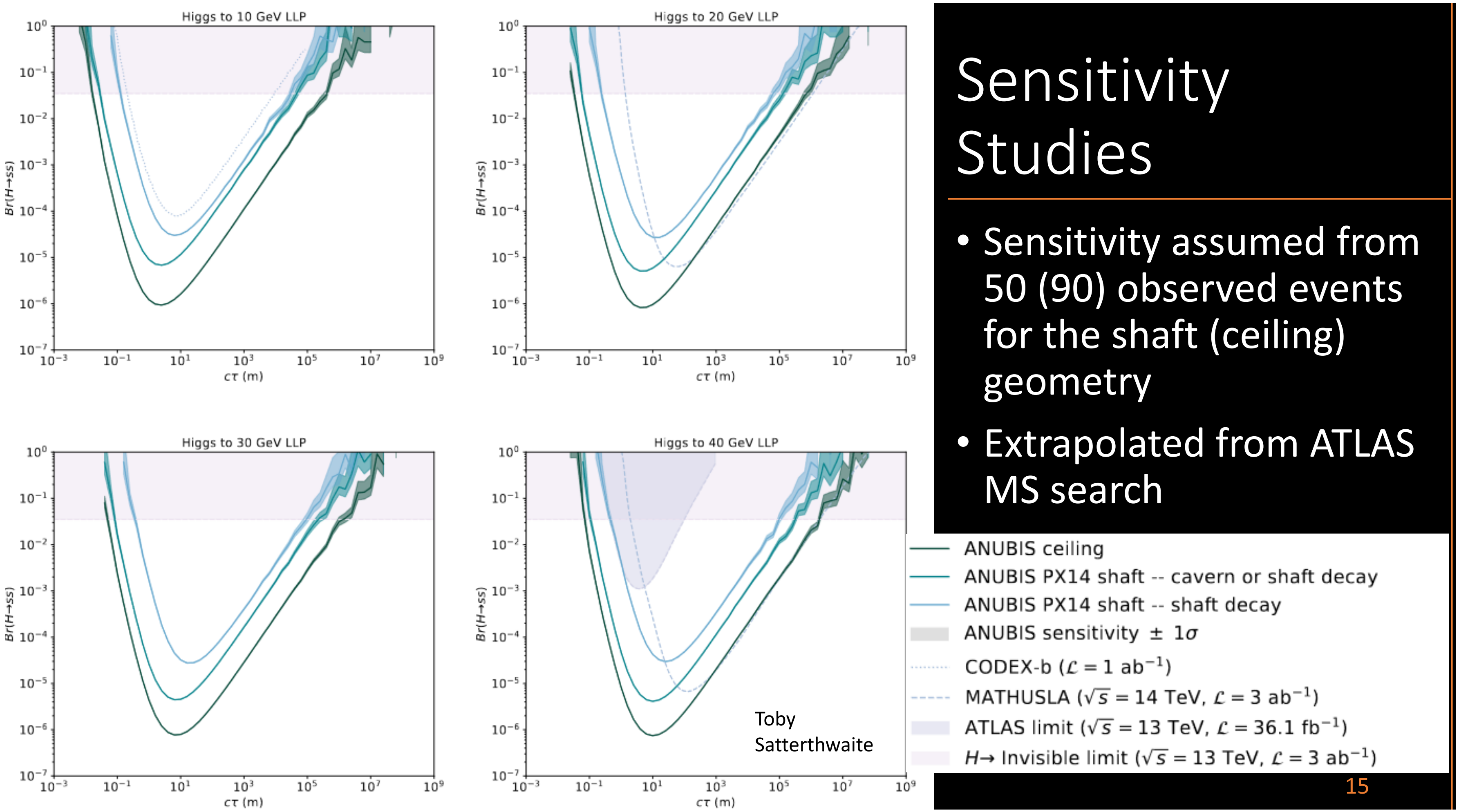
- Times are calibrated offline via a series of passes to synchronize cells and improve resolutions for analysis use
  - Uses electrons from Wev data to calibrate, Zee data to validate
  - Studies have shown (as expected from MC) that electrons and photons behave similarly for timing purposes
- Corrections obtained per gain and per IOV (interval of validity for OFCs) for cells
- ~10 channels (of ~46K) per year are flagged as "bad" for time variations within an IOV

- Calibration achieved via a series of passes to empirically remove averaged/fitted variations
  - Pass 0: time-of-flight (TOF) from PV to cell
  - Pass 1: average time per FEB
  - Pass 2: average time per channel
  - Pass 3: energy-dependence (by slot)
  - Pass 4: middle-layer cross-talk (by slot, based on $\delta\eta$, $\delta\varphi$)
  - Pass 5: inter-layer cross-talk (by slot, based on f_1, f_3)
  - Pass 6: average time per channel (pass 2 repeated)
    - Added because patterns re-emerged after applying other passes (passes are actually subtly correlated with each other)





ANUBIS Sensitivity



J. Burr, LLP Forum [8 Dec 2022]

Resources

- ❖ Research team
  - 1 postdoc + 2 PhD students + 1 (partial) firmware engineer for ~3 years
  - Encourage & mentor students through dedicated funding opportunities, eg. NSF GRFP applications

- ❖ Labs (in order of space)
  - Electronics development: fast ML to FPGAs (FPGA development board)
  - ANUBIS/small-scale LLP detectors
  - Future calorimeter development

- ❖ **Miscellaneous:** travel for self/team, summer salary, etc.

- ❖ Grant strategy
  - Establish sole funding: NSF CAREER/DOE Early Career, Sloan, Simons, etc.
  - Join SLAC ATLAS base grant at next renewal
  - Dedicated AI initiative grants (eg. "Artificial Intelligence Research for High Energy Physics" from DOE)
  - Dedicated FOAs for inclusion (eg. RENEW, FAIR)

Societal Benefits

- Technological spillover; eg. MRIs/proton therapy, World Wide Web
  - LHC as a “sandbox” for data science & engineering
- Training a skilled future workforce
- Outreach opportunities & enhanced scientific literacy in general public

[CERN Courier, 2018]