



Detecting High-Momentum Muons at the LHC: The ATLAS Approach

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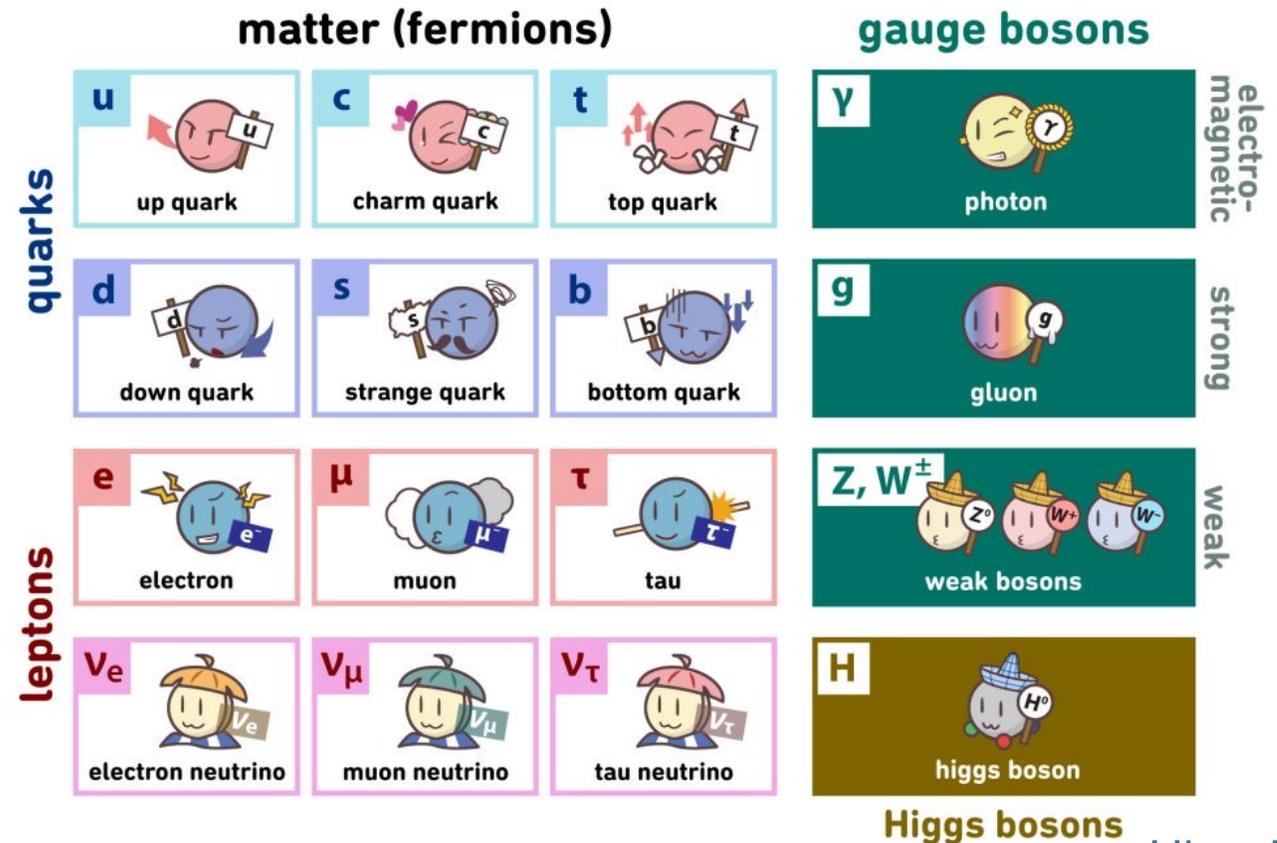
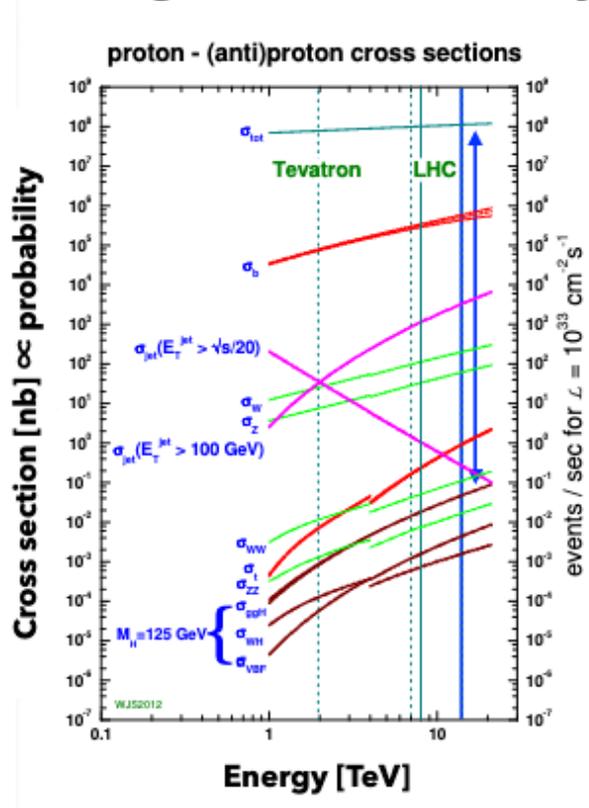
4 March 2026

QMUL seminar

Introduction

While the Standard Model is remarkably successful, it remains incomplete; Aim to uncover "cracks" in the theory and search for new physics by using collision

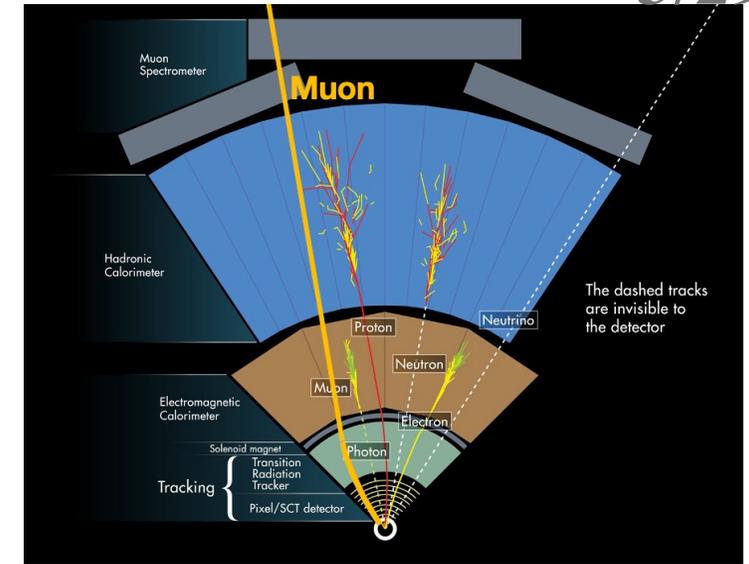
Interesting collisions are very rare.



Muon detection at the ATLAS

High-momentum muons are a clear signature of interesting proton collisions.

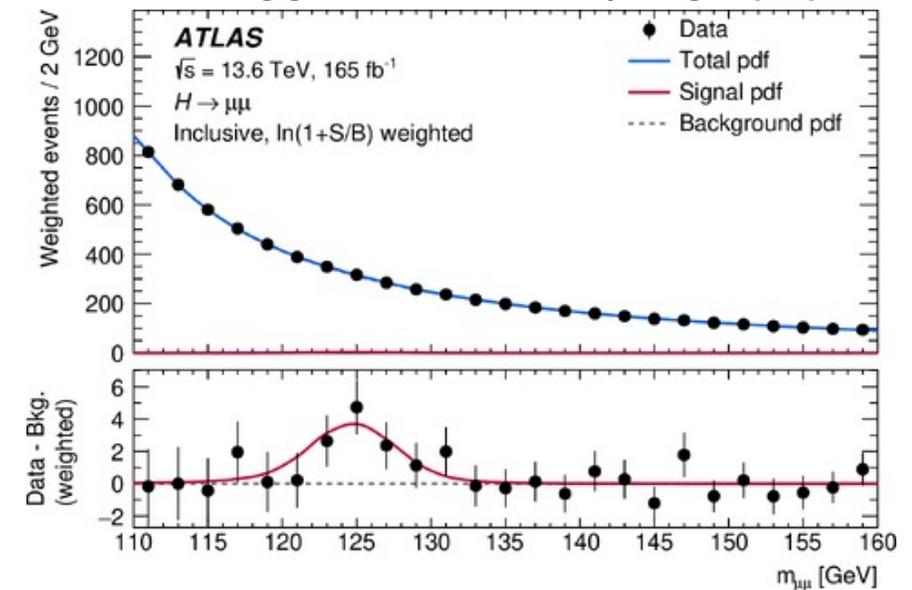
- Key in Higgs, EW, BSM searches



Example: Probing the Higgs Yukawa Coupling

- **The Target:** Direct probe of the Higgs Yukawa coupling to 2nd-generation fermions
- To produce and detect rare Higgs events,
We need for High-Energy & High-Luminosity!

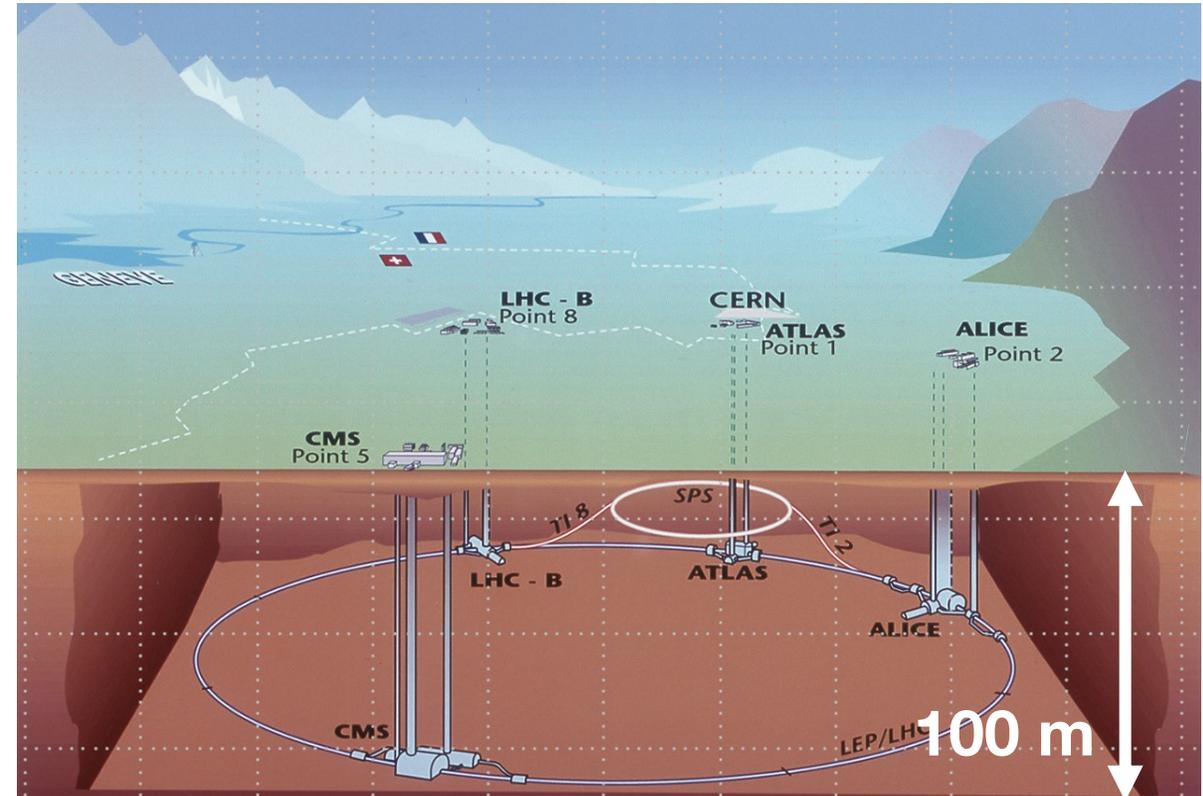
Higgs Yukawa coupling [paper](#)



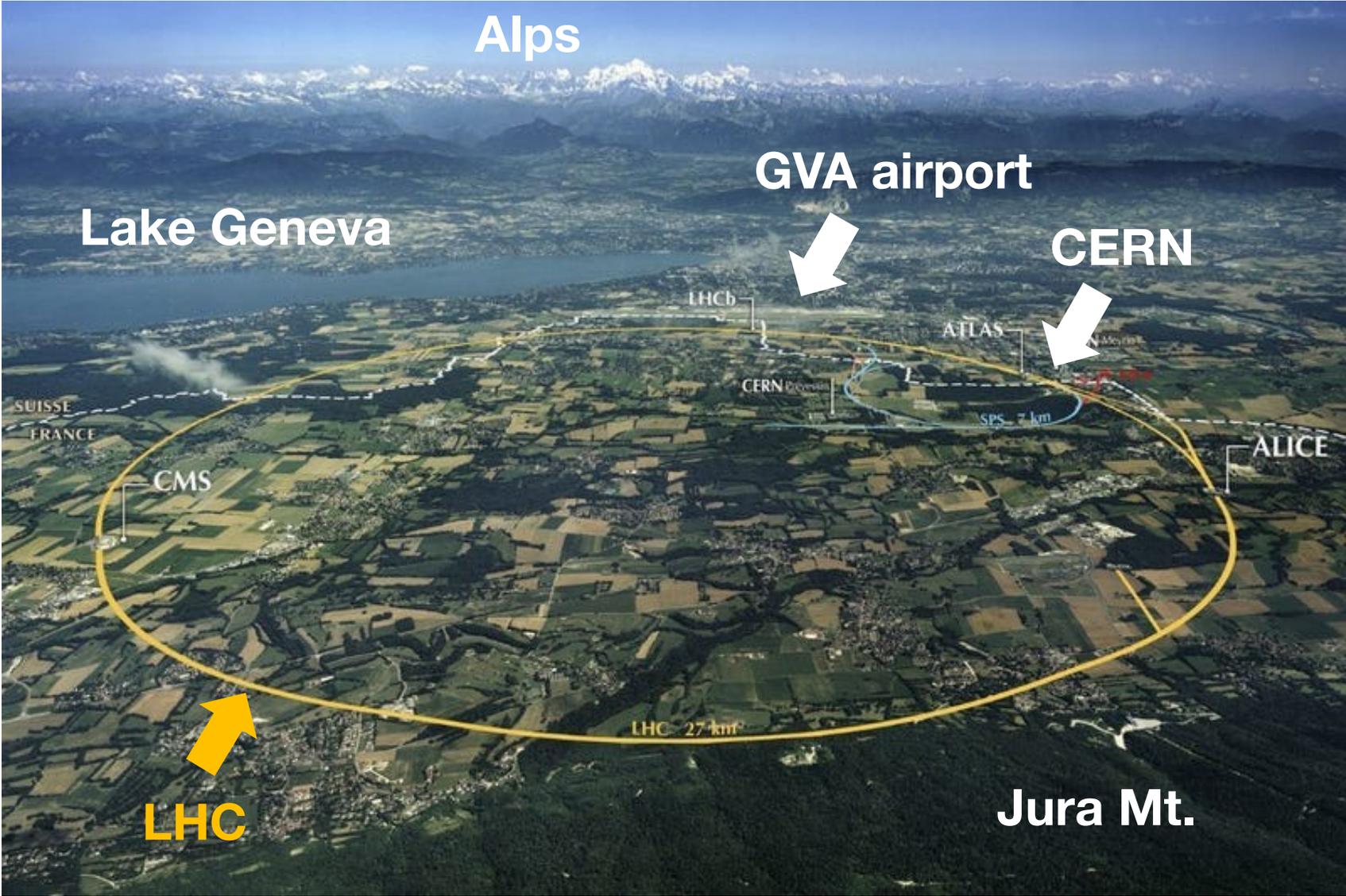
Large Hadron Collider (LHC) overview

Proton-proton collider

- 27 km circumference
- Center-of-mass energy:
 $\sqrt{s} = 13.6 \text{ TeV}$
- produces **~100 GeV muons**
- Luminosity: $\sim 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Rate: 40 MHz
- pileup: ~60



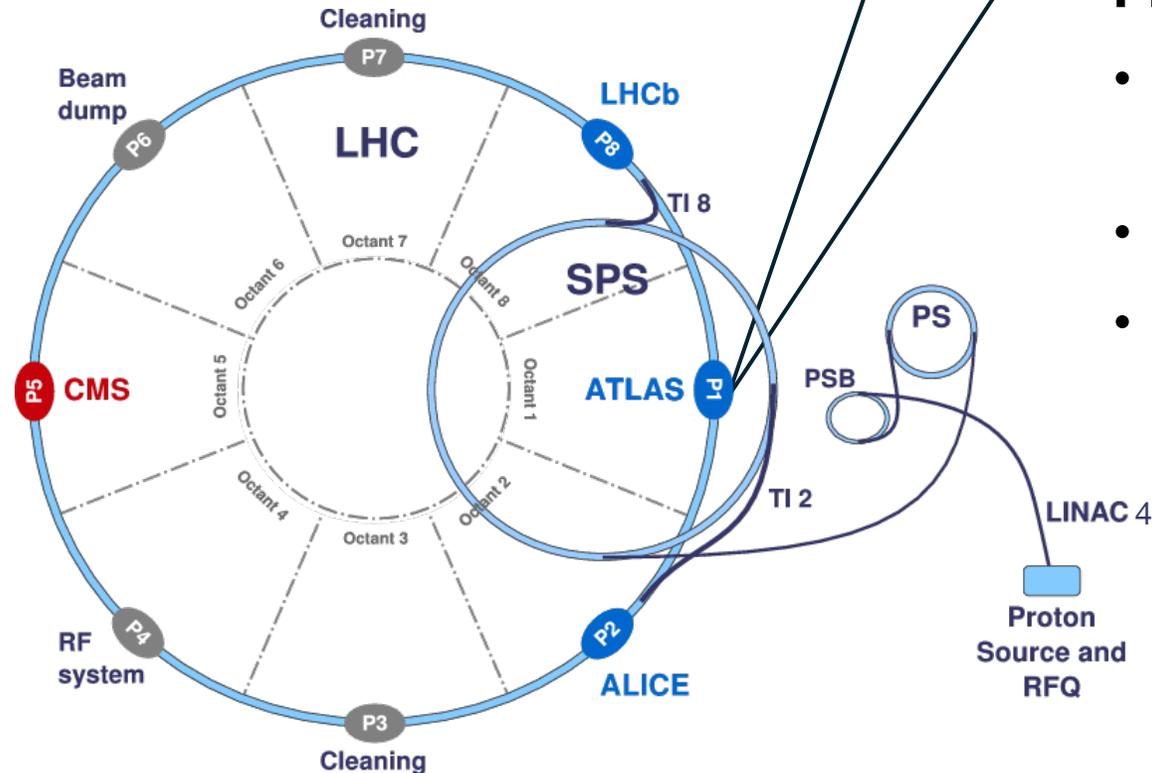
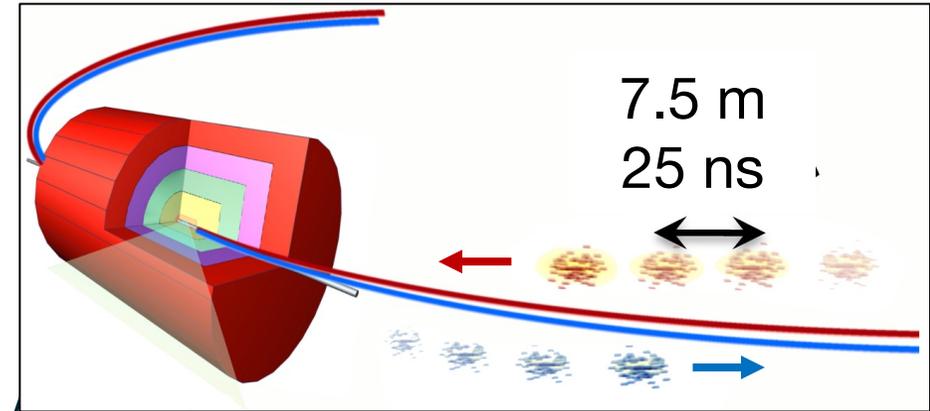
LHC aerial view



Accelerator complex

LHC:

- The speed of protons is $\beta \approx 1$
- Each bunch gets squeezed down to $16 \times 16 \mu\text{m}^2$
- Much bigger than an atom, collision is rare



Proton Synchrotron (PS):

- Generate 25 ns bunch spacing
→ 40 MHz collision rate
- # of proton per bunch: 10^{11}
- $\beta \approx 0.87$

Linac4:

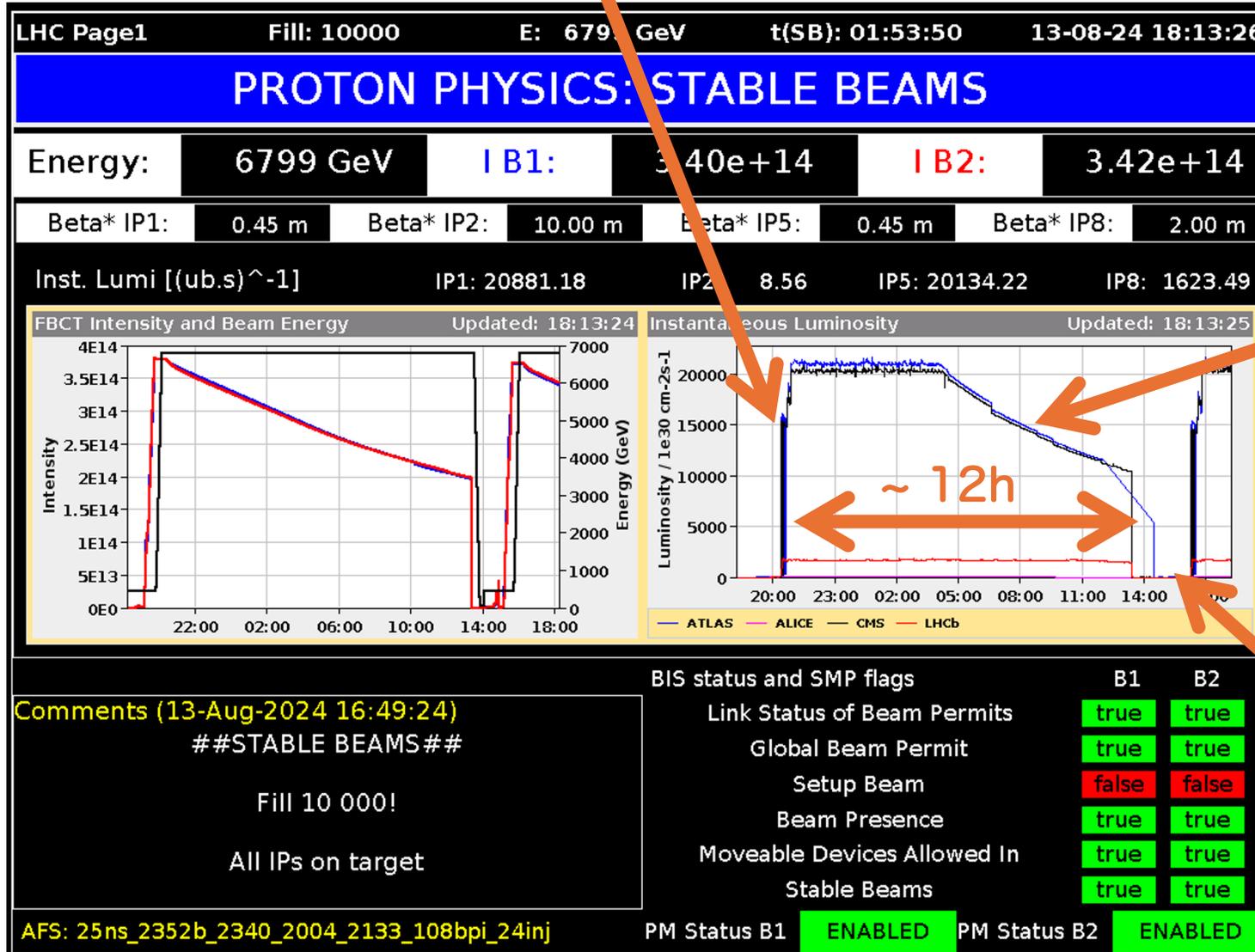
- The source of proton beams
- $\beta \approx 0.3$

LHC running

7/29

You can check from [here](#)

start collision



gradually depleted

prepare next beam: ~1h

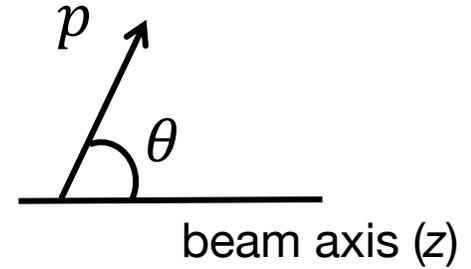
Why Pseudorapidity?

Pseudorapidity (η): Defined from the polar angle θ with respect to the beam axis:

$$\eta = -\ln \tan\left(\frac{\theta}{2}\right)$$

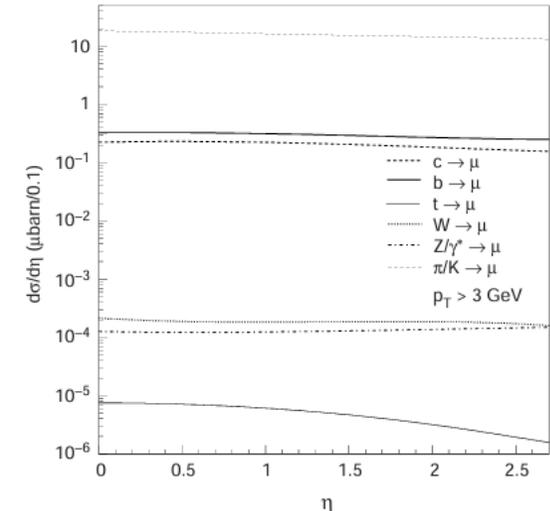
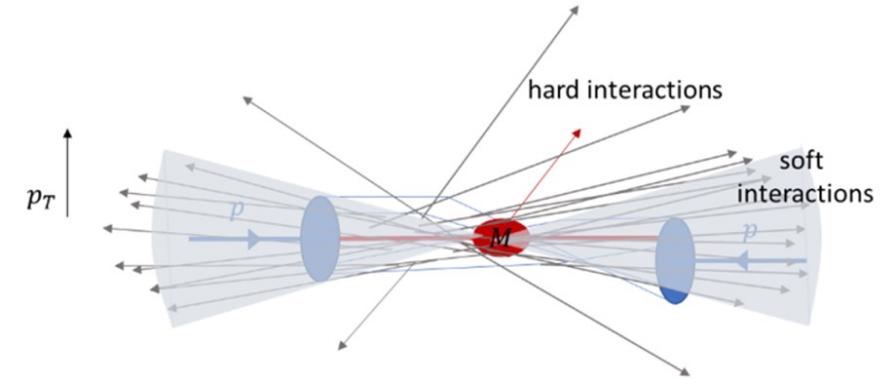
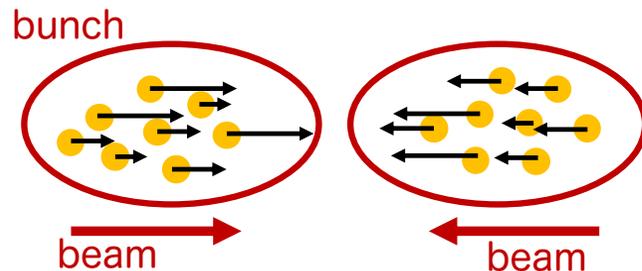
High-energy limit ($p \gg m$): η approaches rapidity y

$$y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right) \rightarrow \eta$$



Parton Dynamics and Boost Invariance:

- Colliding partons carry random momentum fractions, causing the center-of-mass system to boost
- While particles cluster at small θ in the lab frame, η expands this region to provide a uniform view of the collision



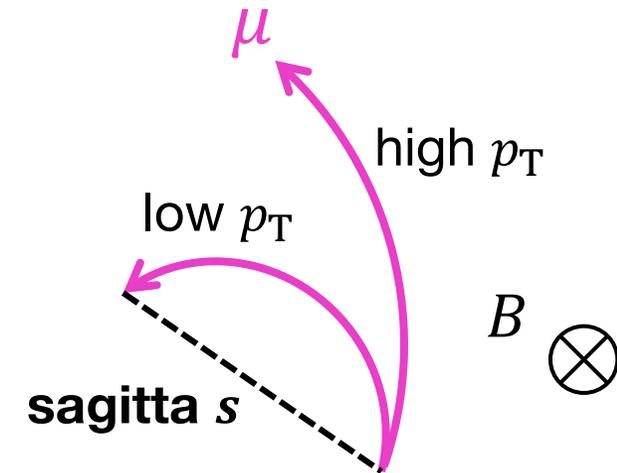
Particle production is nearly flat in η

Physics requirements to muon detector

High momentum resolution

- $\delta p_T/p_T \sim 3\%$ at 100 GeV and $\sim 10\%$ at 1 TeV
- Allowing both SM measurements and new physics searches containing high-momentum final-state muons
- Requires massive $B \cdot L^2$ to measure **sagitta** s

- $s \sim \frac{0.3BL^2}{8p_T}$, (B : Magnetic field [T], L : Trajectory length [m])

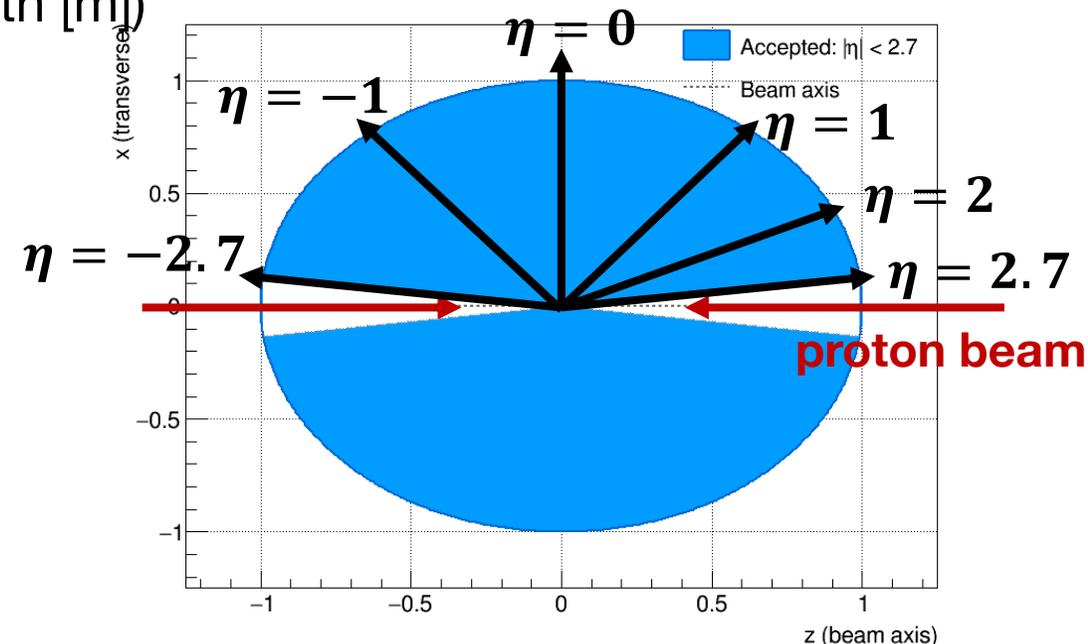


Wide η coverage

- 85% of muons in $H \rightarrow 4\mu$ lie within $|\eta| < 2.7$
- Maximize acceptance while controlling background

Low trigger threshold

- Triggering from low p_T (~ 5 GeV) is required for various physics analyses



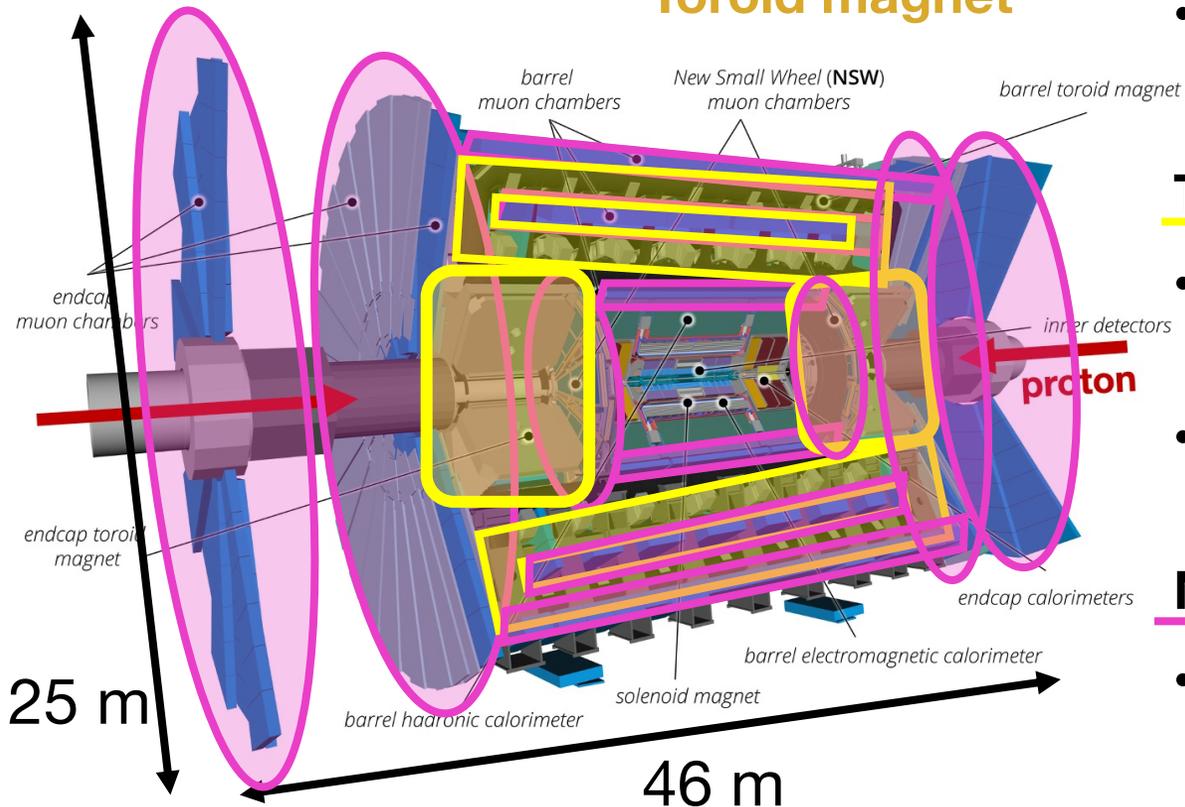
ATLAS detector overview

World's largest general-purpose particle detector

- Dimensions: 46 m long, 25 m high
- Total weight: ~7,000 t

Muon spectrometer

Toroid magnet



Toroid Magnet System:

- Defining feature of ATLAS: 1 Barrel and 2 Endcap toroids
- **Air-core design** to minimize multiple scattering for high precision measurement

Muon Instrumentation:

- Integrated with the magnets to provide **independent momentum measurement**

Magnet System: Engineered for High- p_T Muon

Toroidal Configuration:

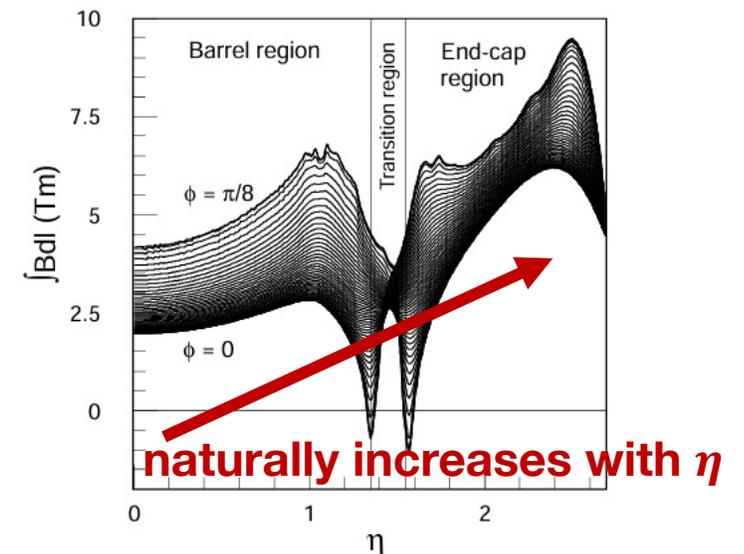
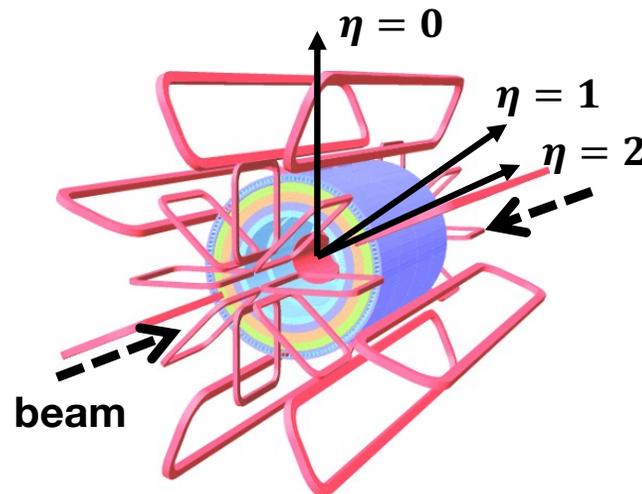
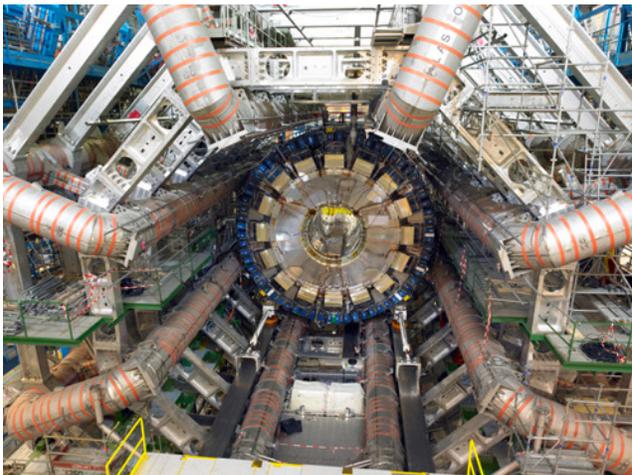
- Provides a magnetic field surrounding the collision axis with cylindrical symmetry

Bending Power Optimization (sagitta: $s \sim BL^2/p_T$):

- Integrated magnetic field ($\int Bdl$) typically provides **3 T·m in the barrel** and **6 T·m in the endcap**
- Utilizes a vast air-core volume to maximize the bending lever arm L

Ensuring Seamless Acceptance ($|\eta| < 2.7$)

- Minimizing low-field pockets, the barrel and endcap toroids are radially overlapped

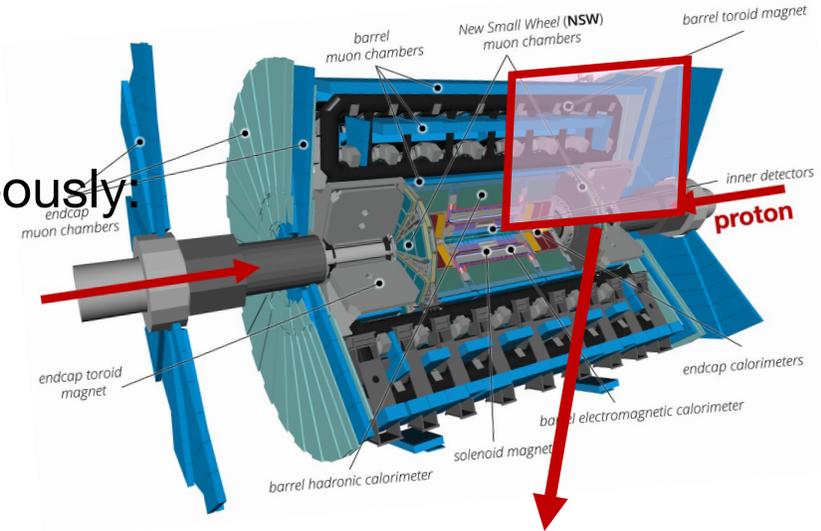


Muon Spectrometer: Precision vs Trigger

Why two different detector systems?

➤ Spectrometer must handle two conflicting requirements simultaneously:

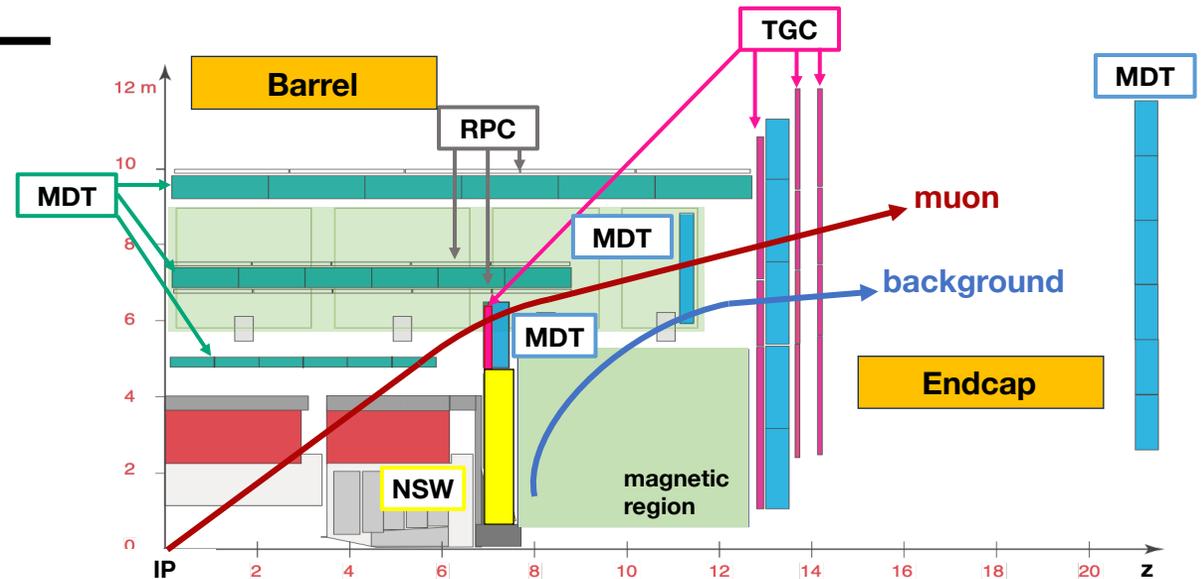
- 1. Precision Tracking:** To measure the sagitta s with μm accuracy
- 2. Fast triggering:** To identify the bunch crossing (every 25 ns)



Chambers

Main Usage

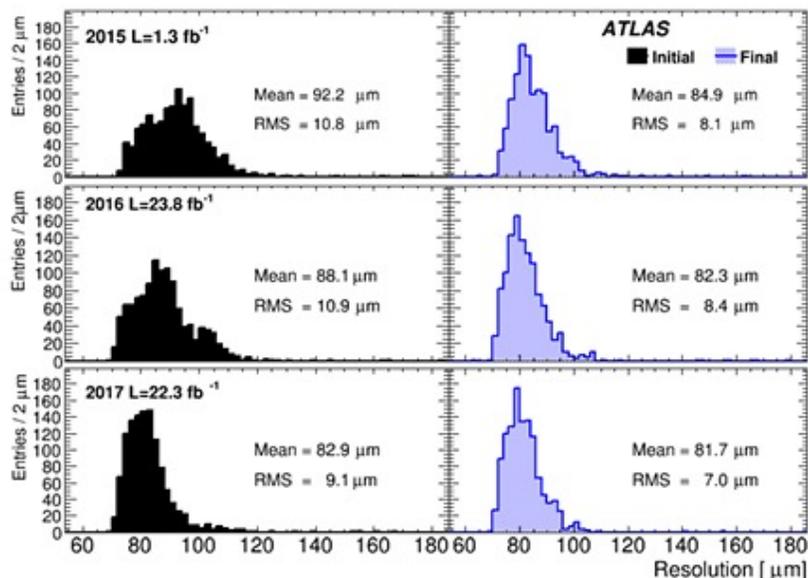
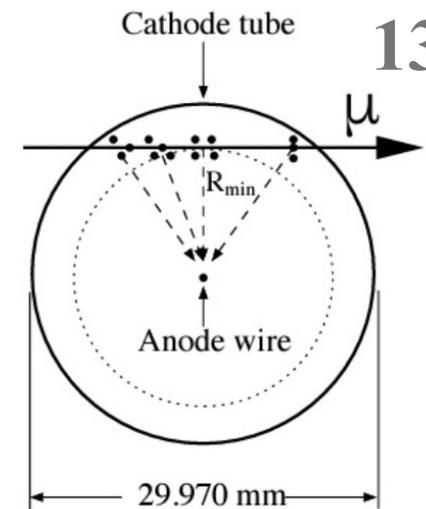
Monitored Drift Tubes (MDT)	Tracking
Resistive Plate Chamber (RPC)	Trigger
Thin Gap Chamber (TGC)	Trigger
New Small Wheel (NSW)	
└ Micromegas (MMG)	Tracking & Trigger
└ Small-strip TGC (sTGC)	Tracking & Trigger



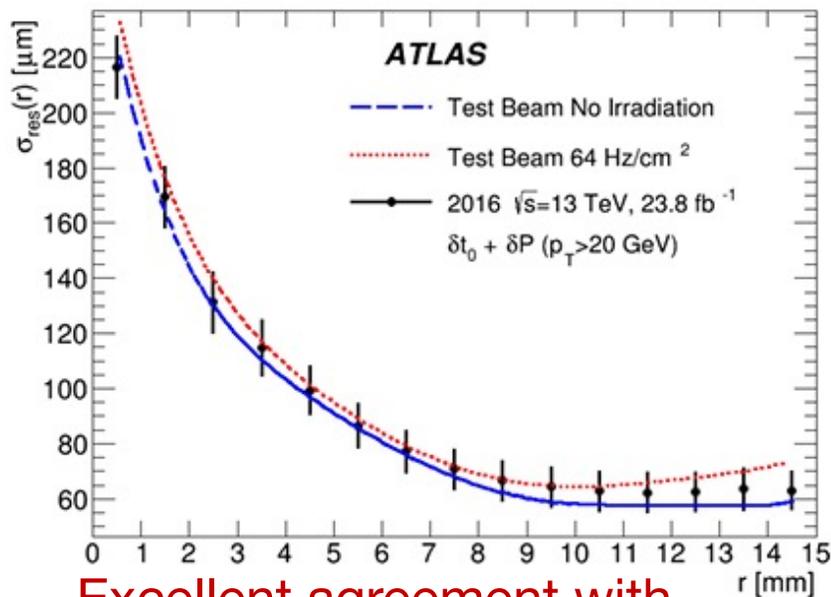
Monitored Drift Tube (MDT)

High-Precision Tracking for Sagitta Measurement

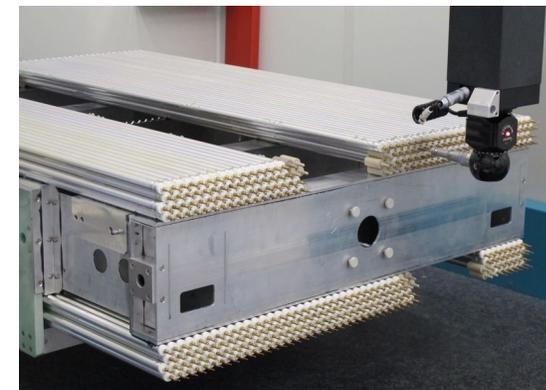
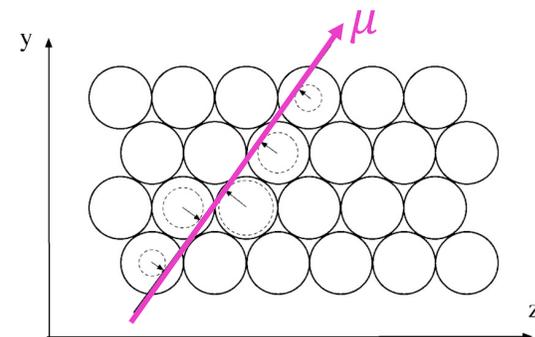
- **Goal:** Determine momentum with 10% resolution for 1 TeV muons
- **Single-tube Accuracy:** $\sigma \sim 80 \mu\text{m}$ achieved using Ar+CO₂ gas at 3 bar
- **Multilayer Structure:**
2 × 3-4 layers provide 6–8 hits per track for robust reconstruction



Average resolution: $81.7 \pm 2.2 \mu\text{m}$



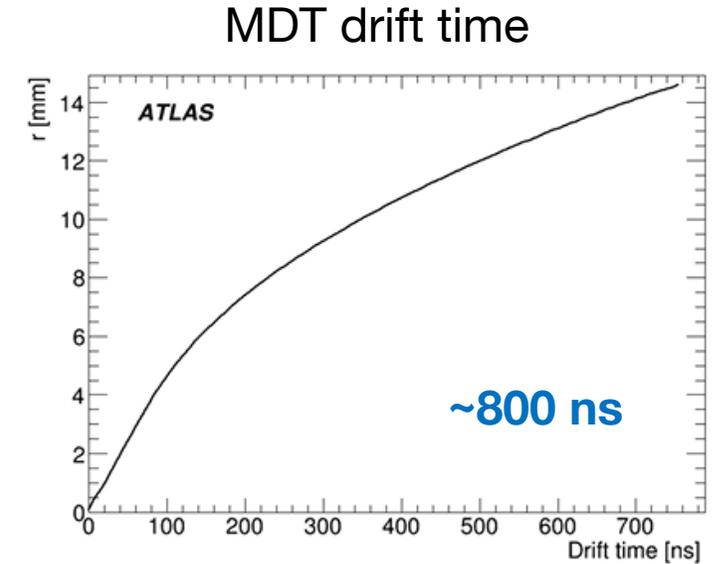
Excellent agreement with expectations across all drift radii



RPC & TGC: fast triggering

Mission: 25 ns Bunch Crossing Identification (BCID)

- **Challenge:**
MDT signals are too slow ($\sim \mu s$) to identify within 25 ns
- **Solution:**
High-speed detectors providing a Level-1 Trigger



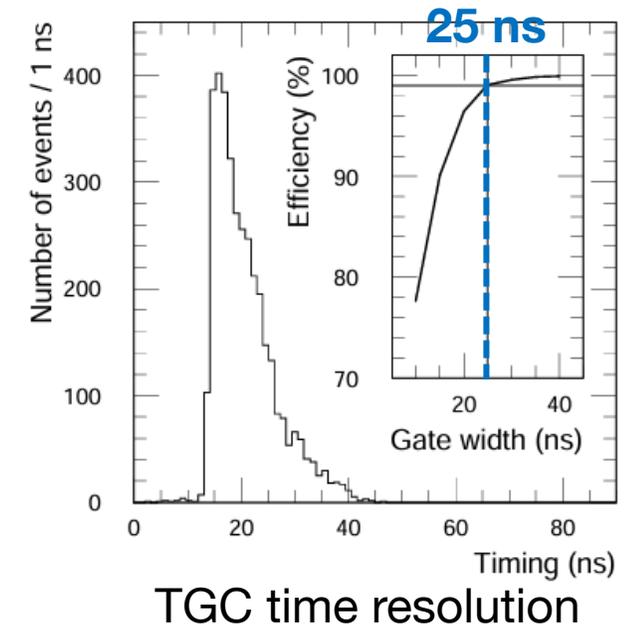
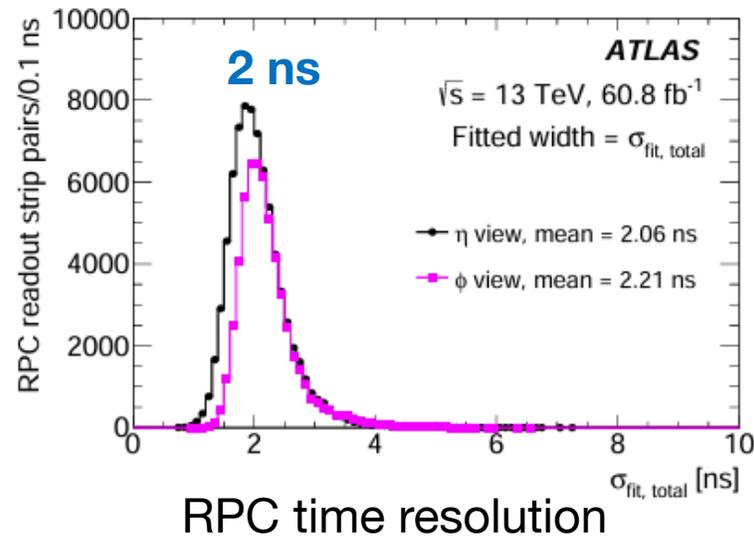
Optimized technologies for each region

RPC (Resistive Plate Chamber) – Barrel

- Parallel-plate gas detector with uniform electric field

TGC (Thin Gap Chamber) – Endcap

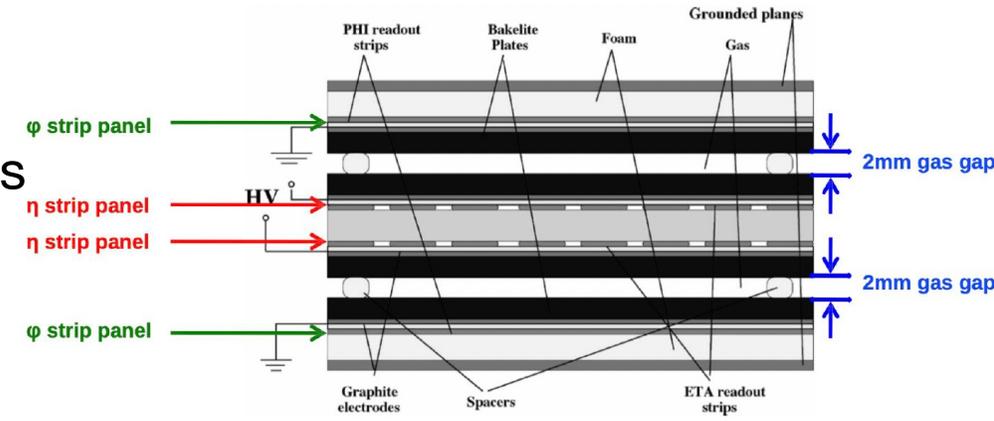
- Narrow gas gap between wire and cathode
→ very fast signal response



RPC – Why is the resolution so precise?

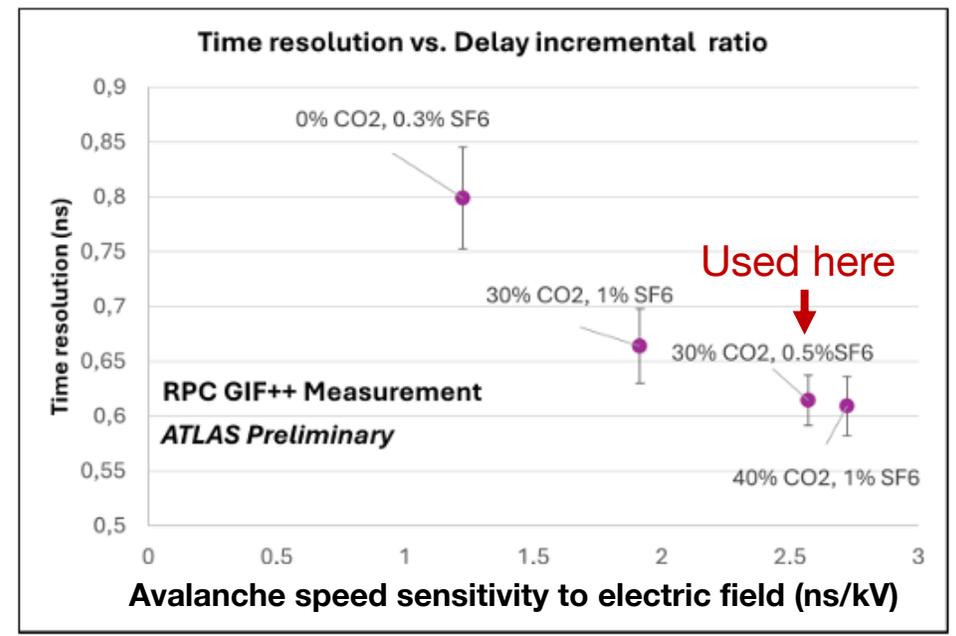
Structure: Parallel Plate Design

- **Narrow 2mm Gas Gap:** Created by two thin resistive plates
- **Gas:** $C_2H_2F_4 + CO_2 + C_4H_{10} + SF_6$ (64.5%, 30%, 5%, 0.5%)
- **High voltage:** 9.6 kV
 - Uniform high electric field (4.8 kV/mm)
- The entire gas gap acts as an active amplification region



Detection Mechanism: Eliminating Time Jitter

- **Immediate Avalanche formation:** Ionization is amplified locally at the point of impact
- **Negligible drift time:** Uses induced current from rapid electron movement for immediate signal response



TGC – Why is it so fast in the harsh Endcap?

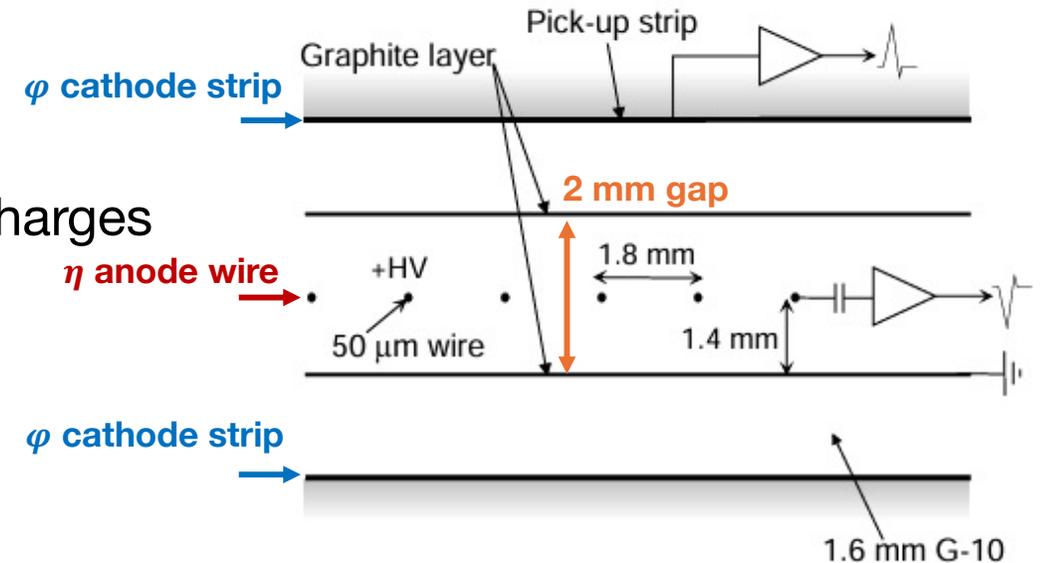
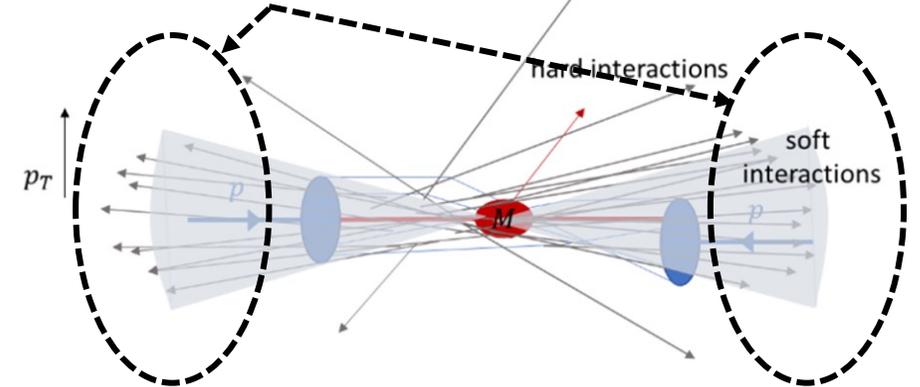
Structure: Thin Gap Design

- **Narrow 2.8mm Gas Gap:**
 - Wire-cathode distance is only **1.4 mm**
 - Strong electric field near the wire
- **Operates in limited-proportional mode (2.8 kV)**
 - Stable pulse height even for small primary ionization

Resilience in High-Rate Environments

- **Gas mixture: CO₂ + n-pentane (55%, 45%)**
 - Strong UV quenching suppresses secondary discharges
 - Stable operation at high background rates
- **Thin gap structure**
 - Fast removal of positive ions
 - Maintains performance in high particle flux

Endcap: High-rate environment



Constraints and Challenges of the Muon Trigger 17/29

25 ns proton collisions → cannot record all events

Two-level trigger system:

1. Level-1 (L1) trigger (Hardware-based):

- Fast decision during data taking
- Latency $< 2.5 \mu\text{s}$
- Rate reduction: 40 MHz → 100 kHz

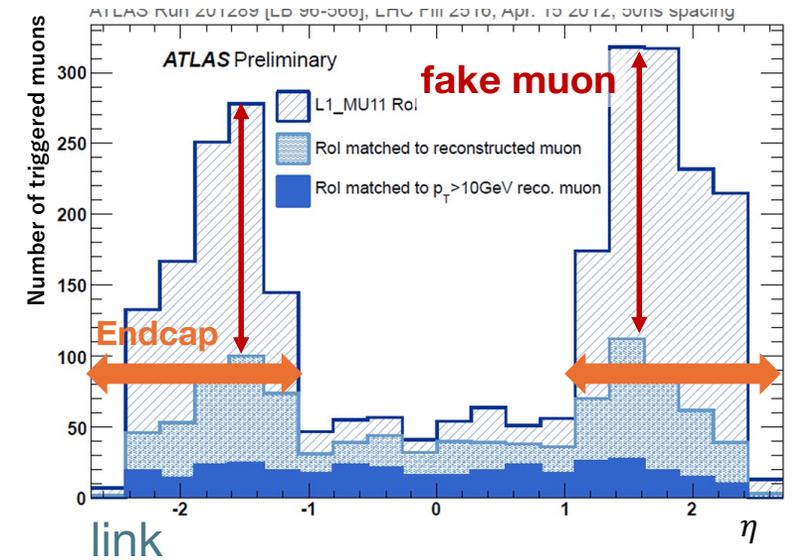
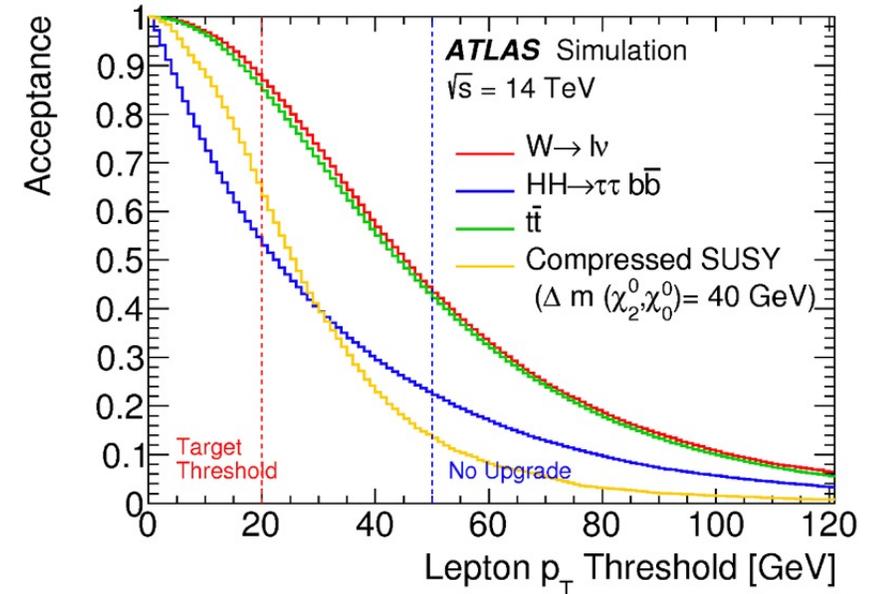
2. High Level Trigger (HLT) (Software-based):

- Rate reduction: 100 kHz → ~3 kHz

Physics requires low- p_T muons

- However, the trigger rate is limited by bandwidth constraints
- Suppressing the L1 rate is essential
- ~80% of the muon trigger rate came from endcap
- Most of these are fake muon trigger

charged particle not originating from IP



New Small Wheel (NSW)

Solution for the endcap challenge

- The new detector combining tracking and trigger capabilities

NSW configuration

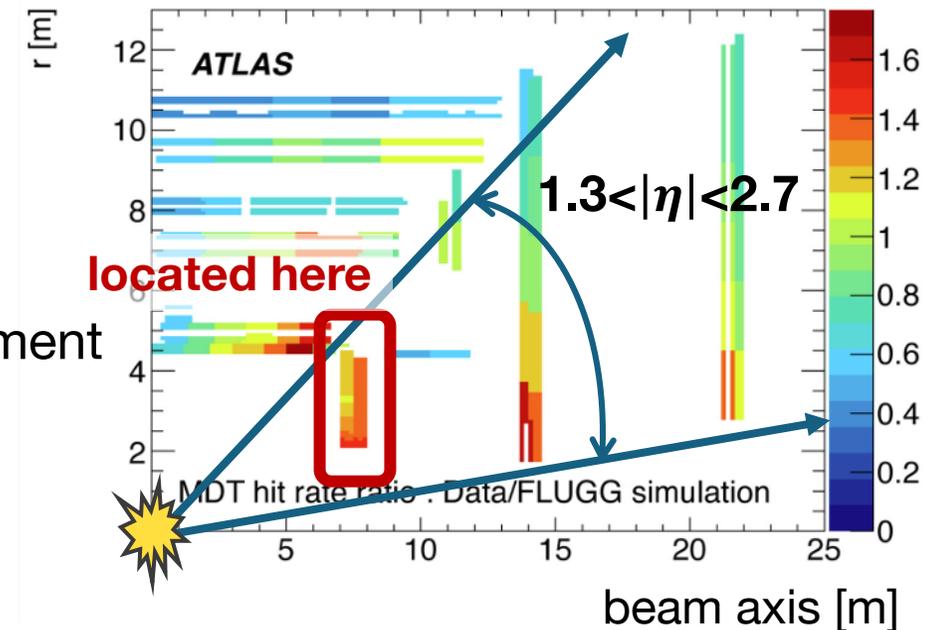
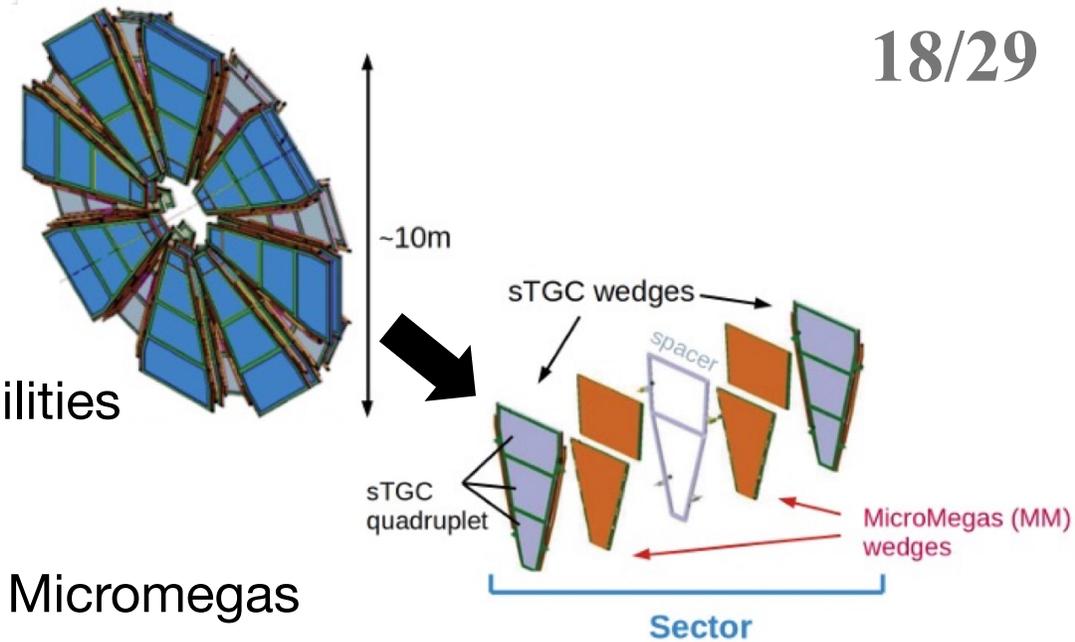
- Two detector technologies: small-strip TGC (sTGC) and Micromegas
- 16 layers in total (8 layers each for sTGC and Micromegas)

Reduction of trigger rates

- Coincidence with TGC to suppress fake muons

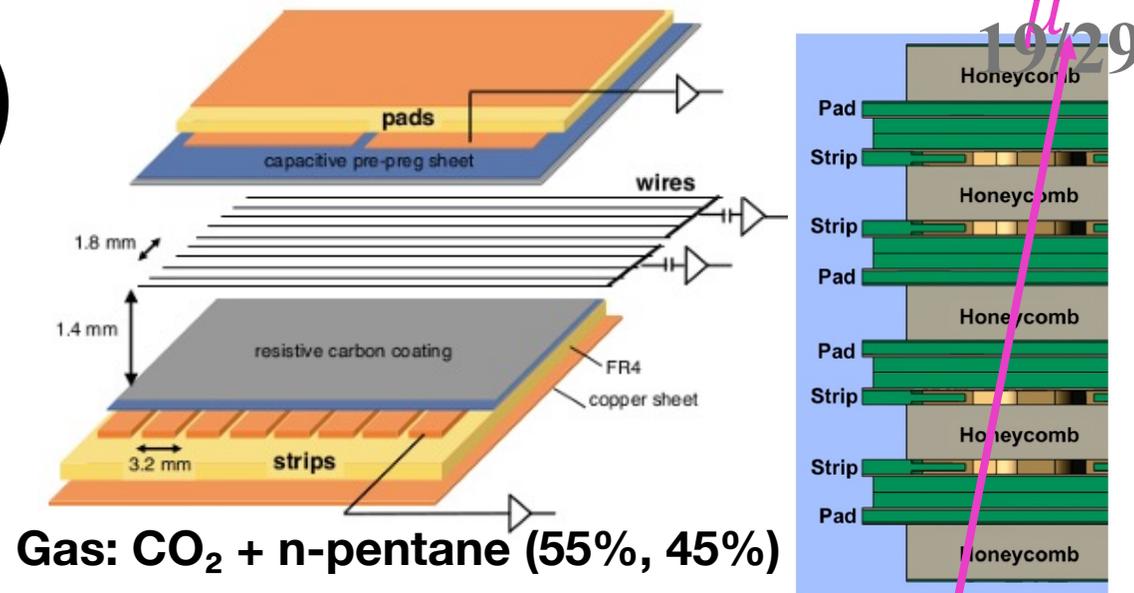
Designed for high hit rates

- High- η endcap region exposed to high background environment
- Short drift distance and multi-layer structure



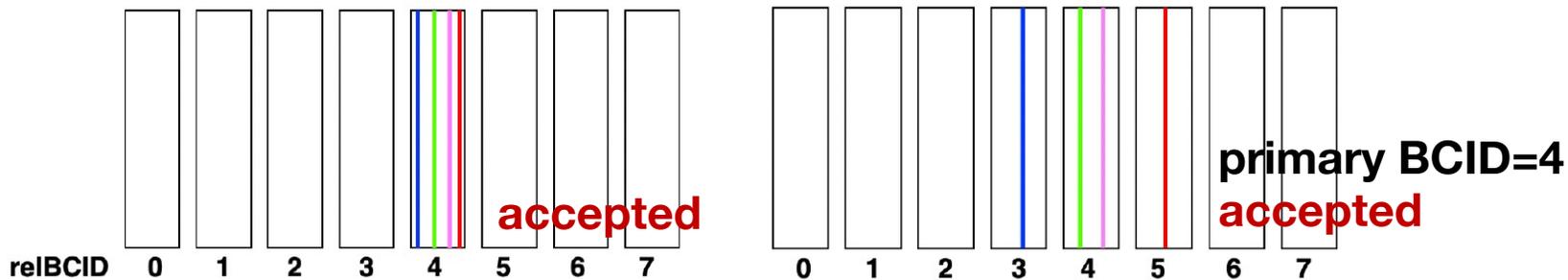
small-strip TGC (sTGC)

	direction	pitch	
wire	ϕ	1.8 mm	
strip	η	3.2 mm	← tracking
Pad	$\eta \times \phi$		← coarse, fast triggering

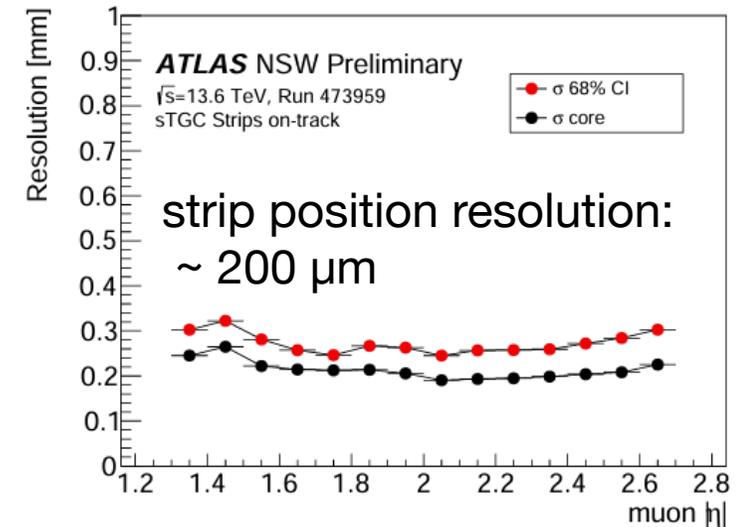


Detection Mechanism

- Avalanche amplification occurs near the wires, inducing charge on strips and pads
- Strip signals are read out in the region selected by the pad trigger
- Time window:
 - Trigger condition: pad coincidence in 3 out of 4 layers
 - Hits from 4 layers are read out over 8 BCIDs
 - A primary BCID is selected; hits within ± 1 BCID are accepted



*BCID=25 ns bunch crossing



Micromegas

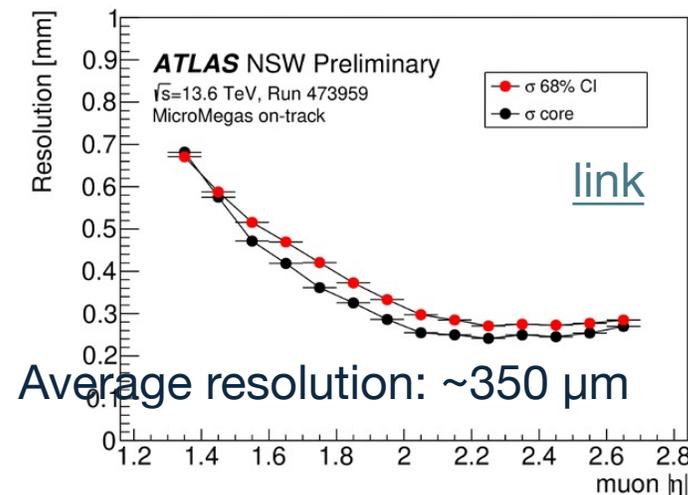
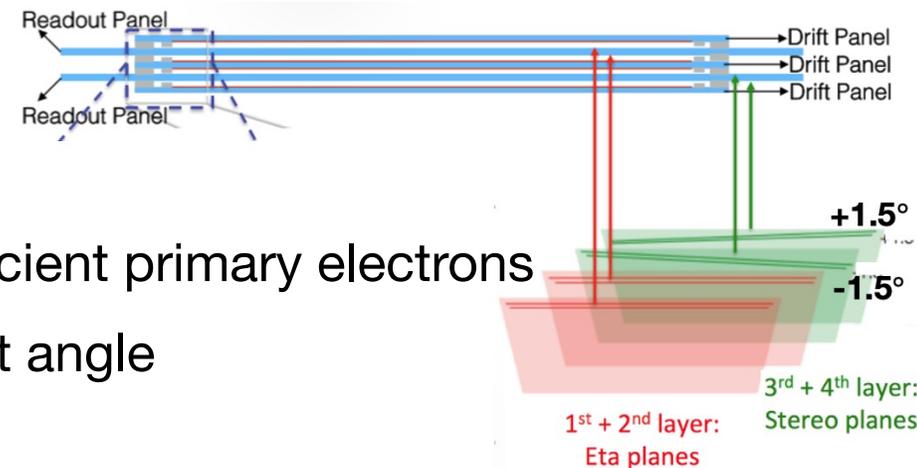
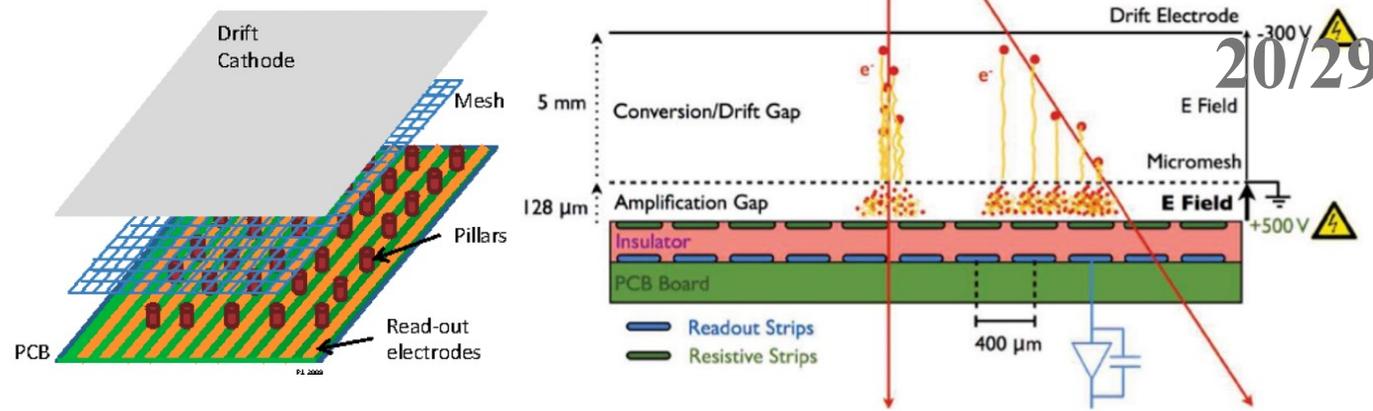
- Micromesh gaseous structure
- Gas: Ar+CO₂+isobutane (93%, 5%, 2%)
- Strips are tilted by 1.5° to enable two-dimensional readout

Precision tracking: Drift gap (5 mm)

- Wide gap increases ionization probability and produces sufficient primary electrons
- Allows sampling of multiple points depending on the incident angle
- Fast and precise tracking over a wide range of track angles

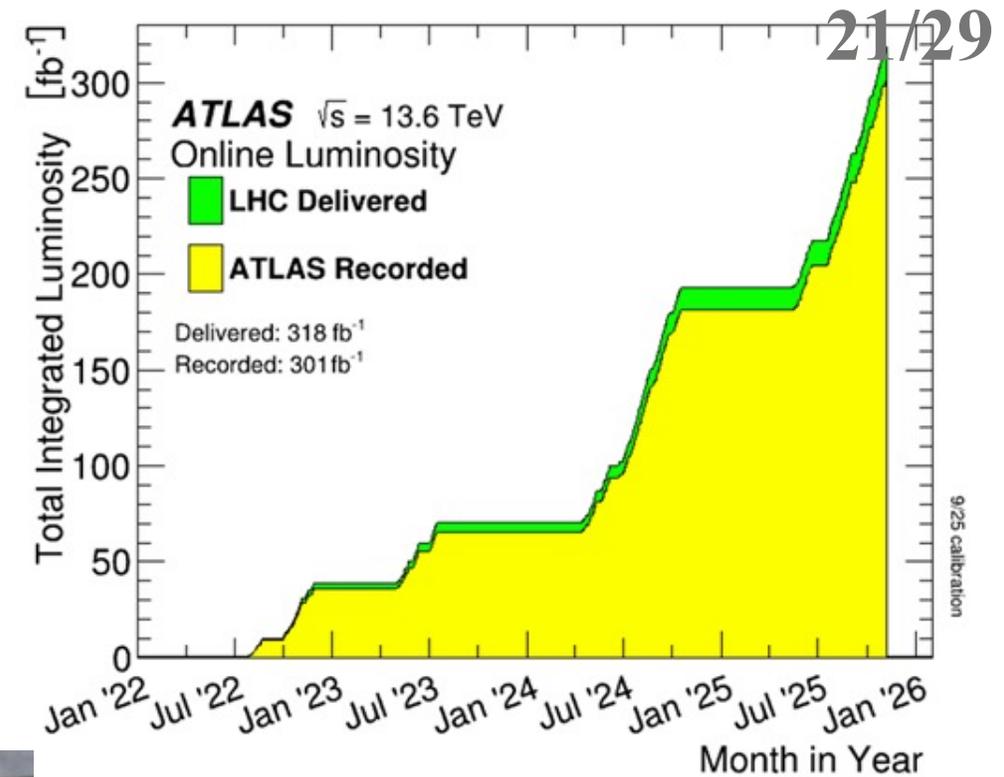
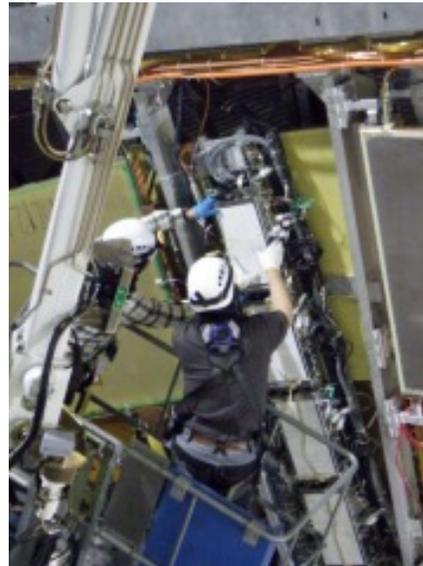
High-rate capability: Amplification gap (128 μm)

- Narrow gap creates a uniform electric field
- Stable high gain while suppressing discharges
- Rapid ion evacuation reduces space-charge effects



Run 3 — Good Shape!

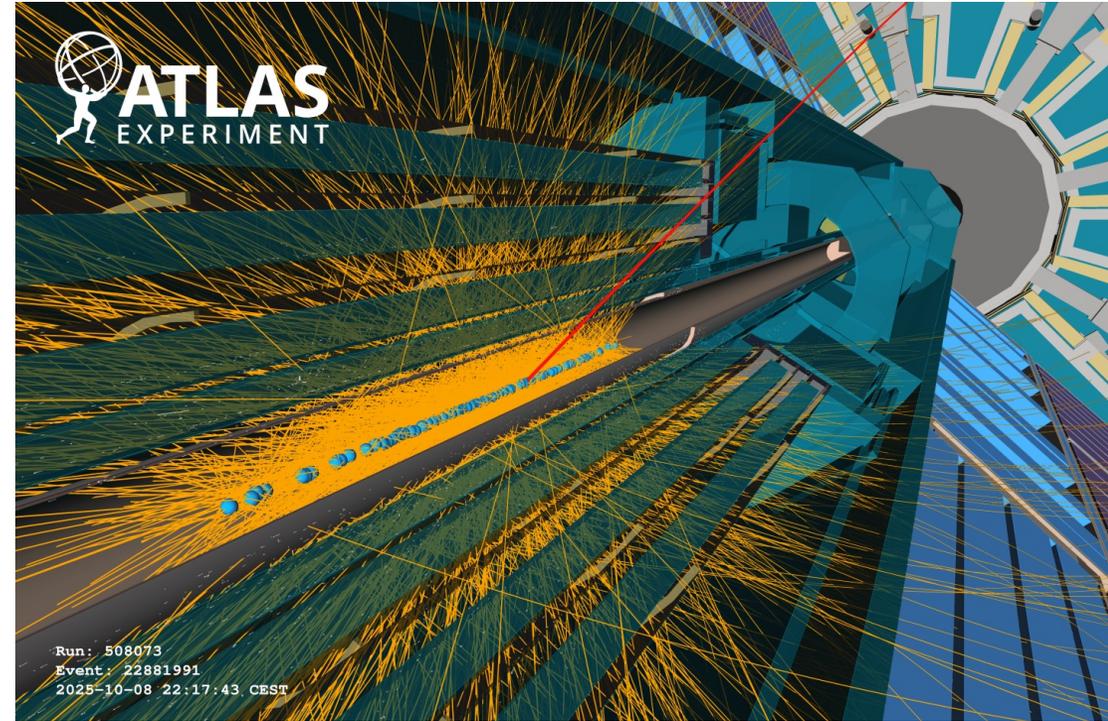
- Over 300 fb⁻¹ delivered in Run3
- ATLAS pp data taking efficiency: ~95%
 - Continuous effort from numerous people from experts, on-calls to ACR shifters
- 2026, Last year of Run 3
 - Luminosity prediction is 34.3 fb⁻¹



What's High Luminosity LHC?

Increase statistics through high-luminosity collisions to search for new physics

- Start of operation: ~2030
- Luminosity $5 - 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Pileup: 140-200
- Center-of-mass energy: $\sqrt{s} = 13.6\text{-}14 \text{ TeV}$
- Target integrated luminosity: 3000-4000 fb^{-1}



2025/10/08: high pileup collisions
(pileup=150)

Limitations of current system

- Detector ageing due to long-term operation in higher-than-expected luminosity and pileup conditions
- Increased hit and track rates at HL-LHC
 - Readout limitations of the current TDAQ system

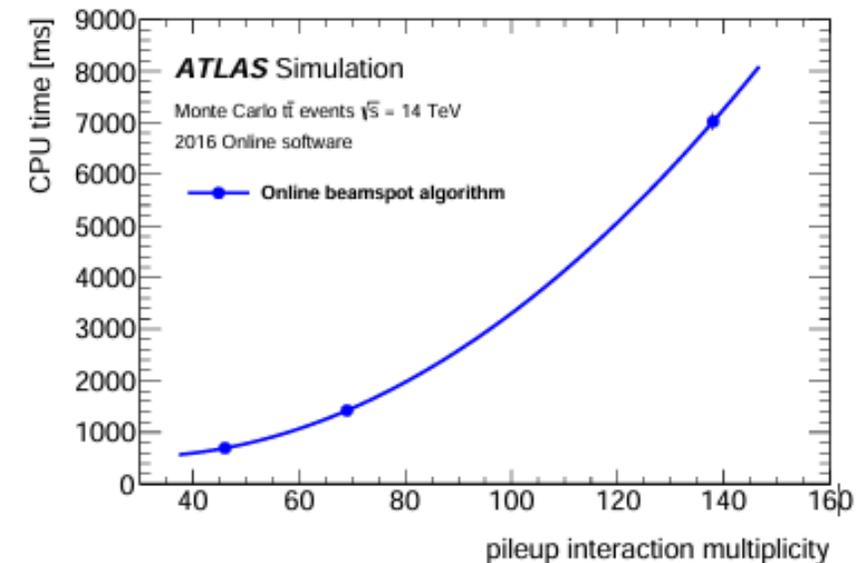
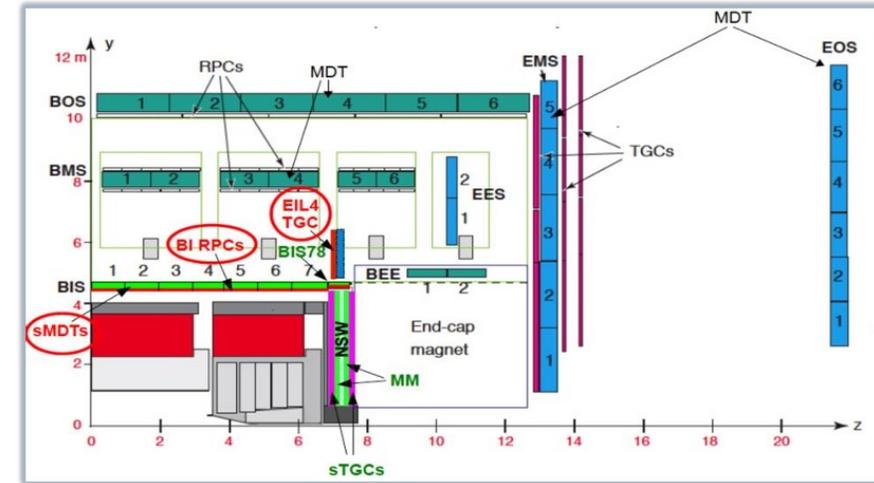
➤ Upgrade detector and readout electronics (Phase-2 upgrade)

Detector upgrade:

- Newly installed EIL4 TGC, RPC BI, and sMDT
- Maintain the acceptance

TDAQ upgrade:

- Newly and fully replaced readout circuits
- Upgrade trigger logic with improved momentum discrimination



Phase-2 upgrade: Detector

Redundancy is ensured by increasing the number of detector layers

small-diameter MDT (sMDT)

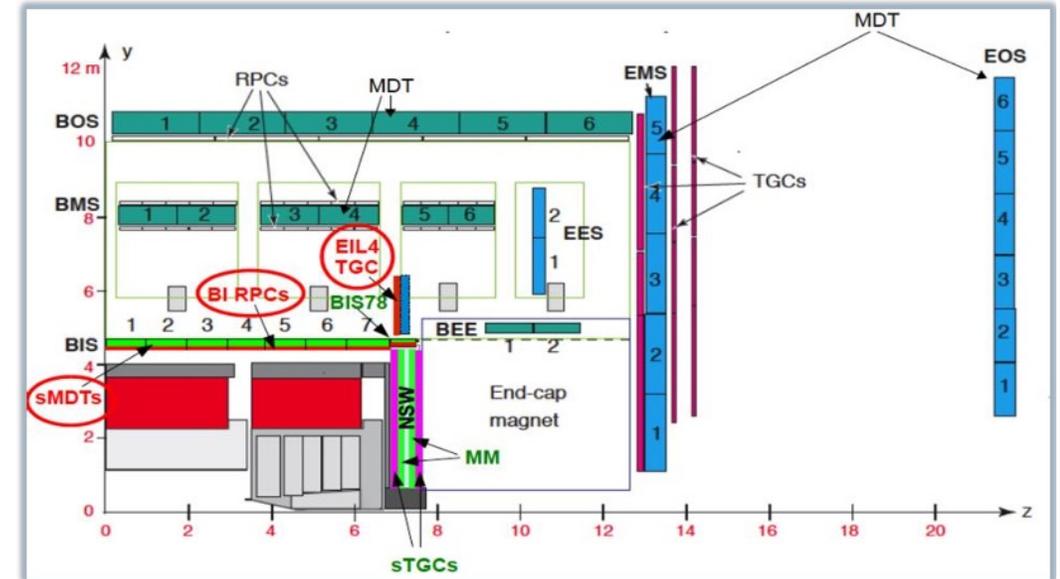
- Newly installed, 8 layers
- diameter: 15 mm (half of original MDT)
- Short drift time → low occupancy in high hit rate

RPC BI

- Newly installed, 3 layers
- Acceptance and redundancy recovered through coincidence with existing RPCs

EIL4 TGC

- Fully Replaced, 2 layers → 3 layers
- Fake muon trigger rate suppressed via coincidence with the existing TGCs



→ **Focus on TGC upgrade in the following slides**

Phase-2 upgrade: TGC Trigger DAQ

New components:

PS Board

- Adjusts timing and sends all hit data every 25 ns

JATHub board

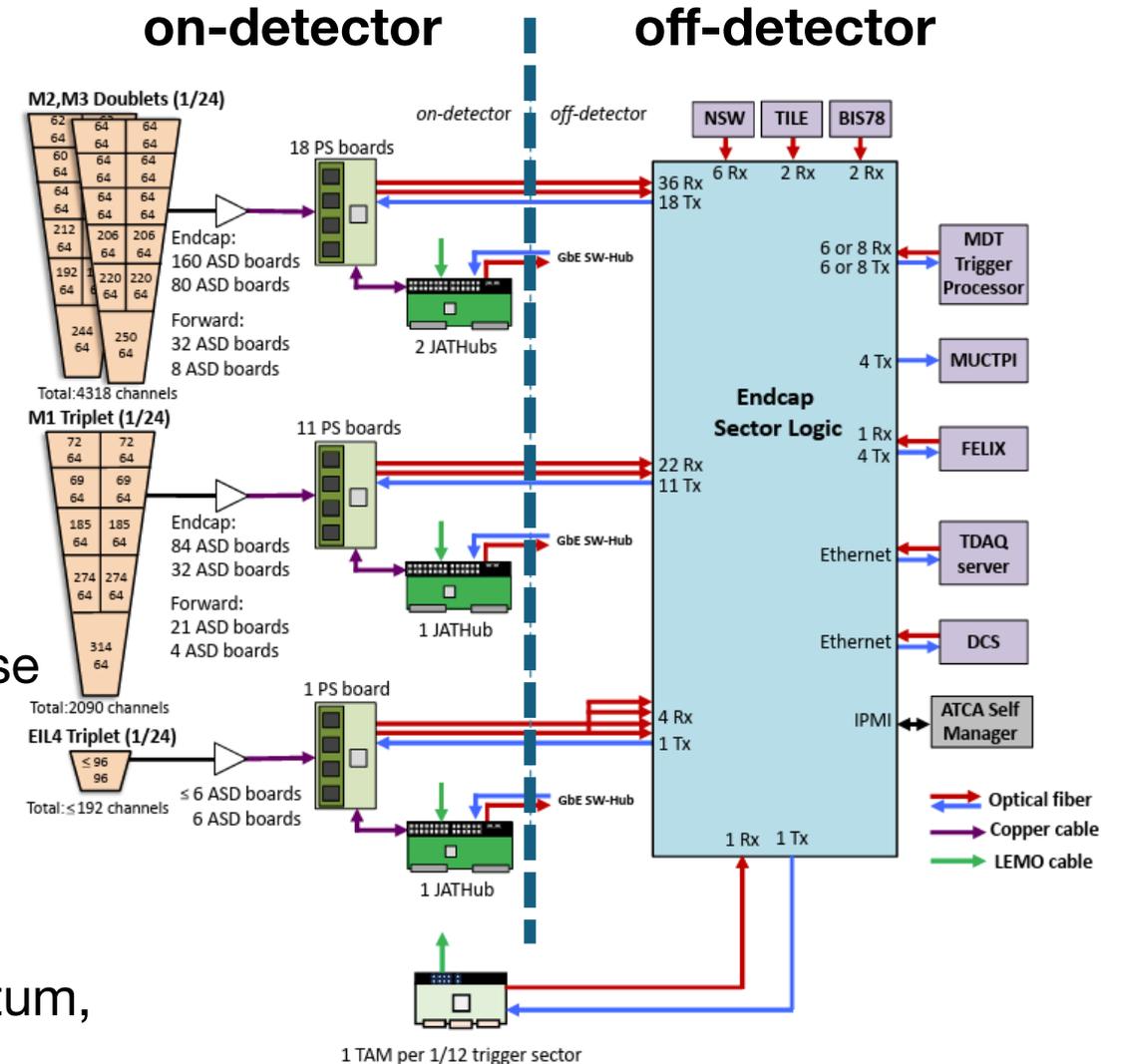
- Monitor the FPGA on the PS board and recover from errors

TAM module

- Used for clock skew measurements and clock phase alignment

SL Board

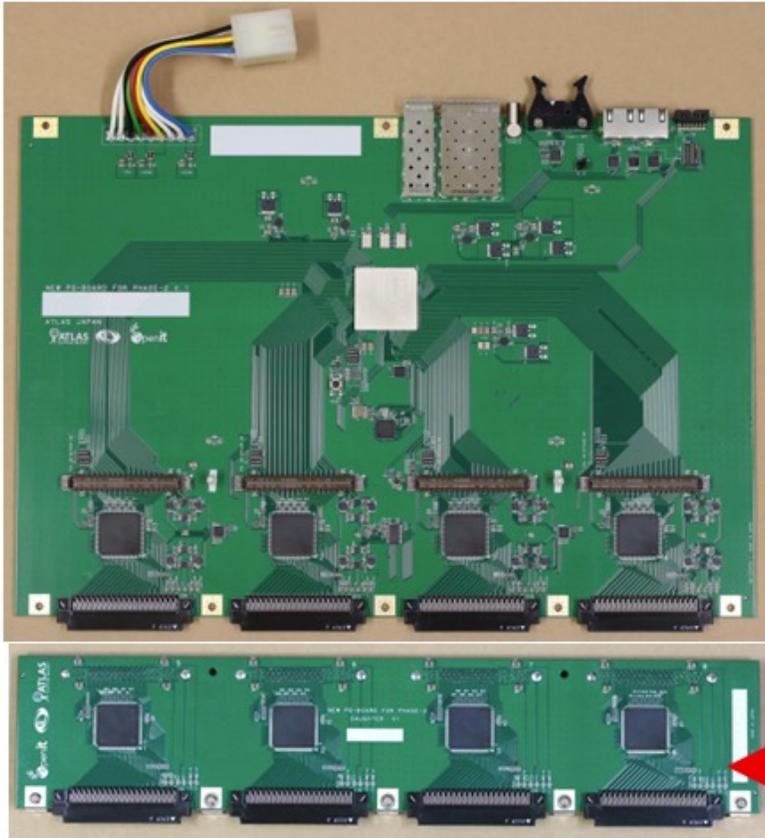
- Combine information from multiple muon detectors
- Reconstructs tracks, calculates transverse momentum, and reduces muon candidates to six



Schematic diagram of Phase2 TGC/L0 muon system

Major electronics

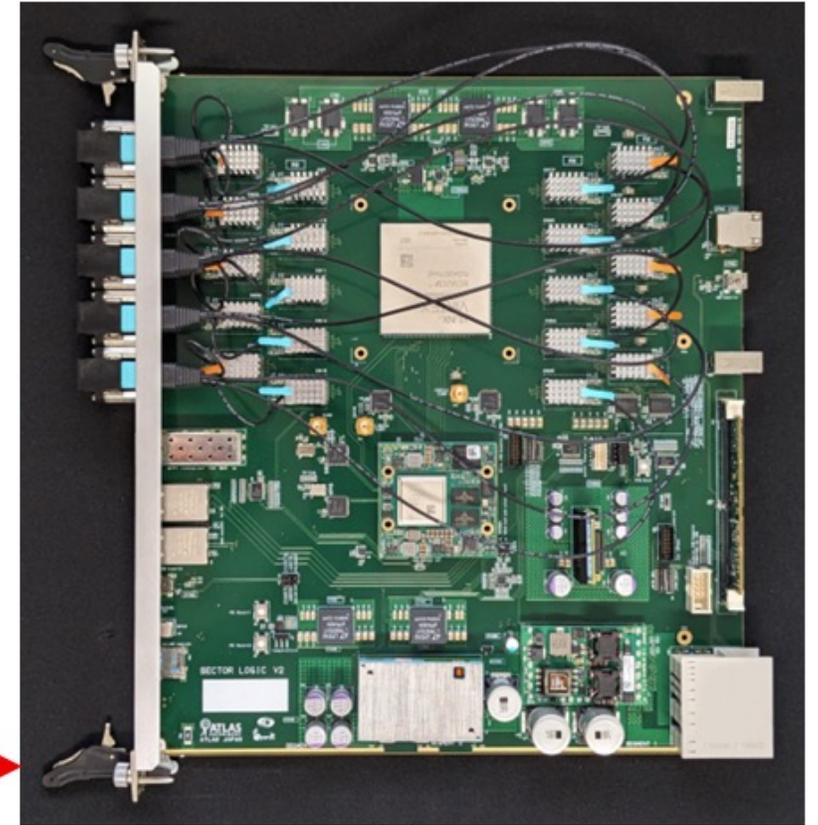
PS board production completed
1434 to be installed



TAM module, JATHub module
Production completed
Timing calibration & SEU recovery



L0Muon Sector Logic (TDAQ)
Preproduction has been started

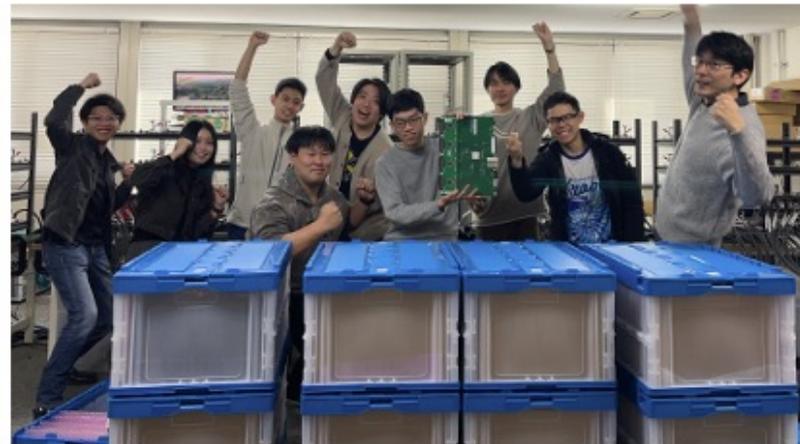
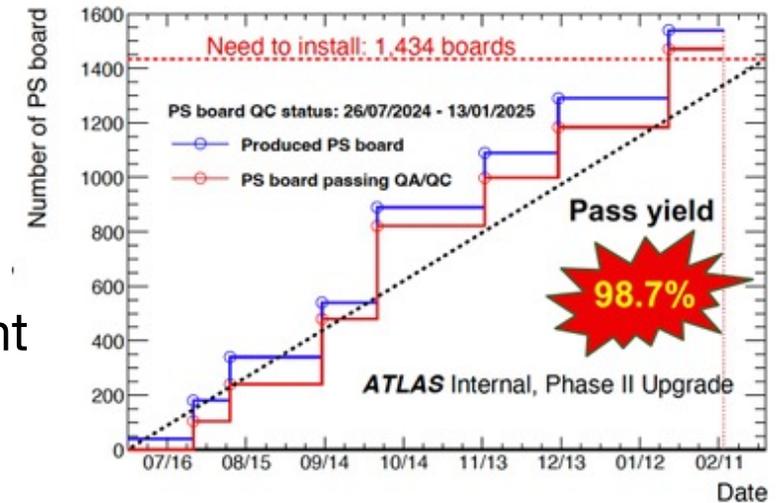


8Gbps x 4,176 fibers

QAQC campaign for new electronics

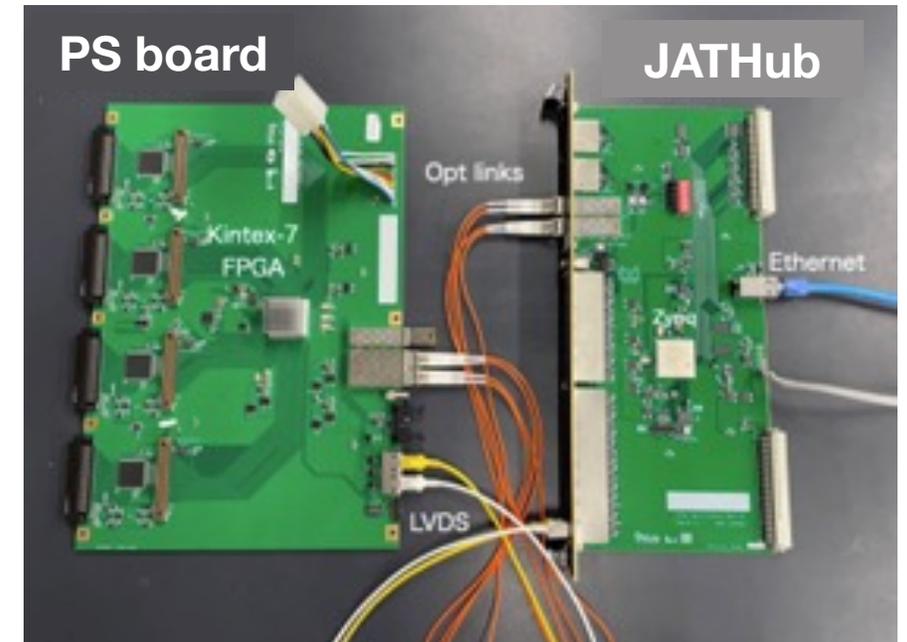
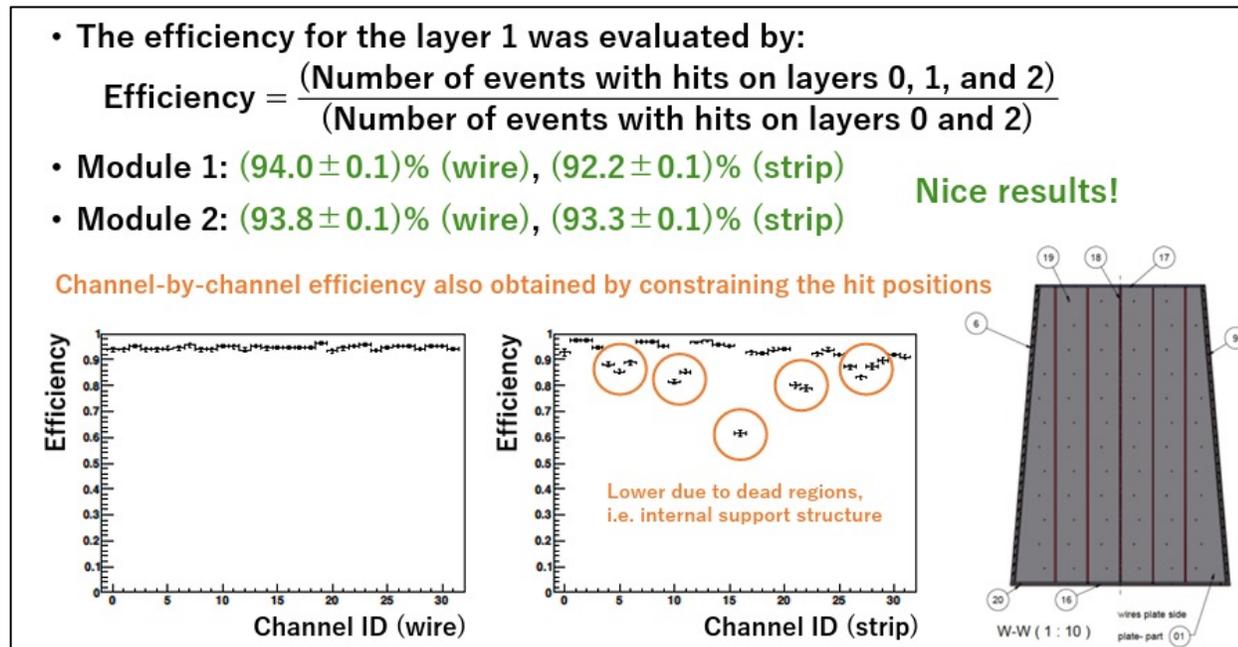
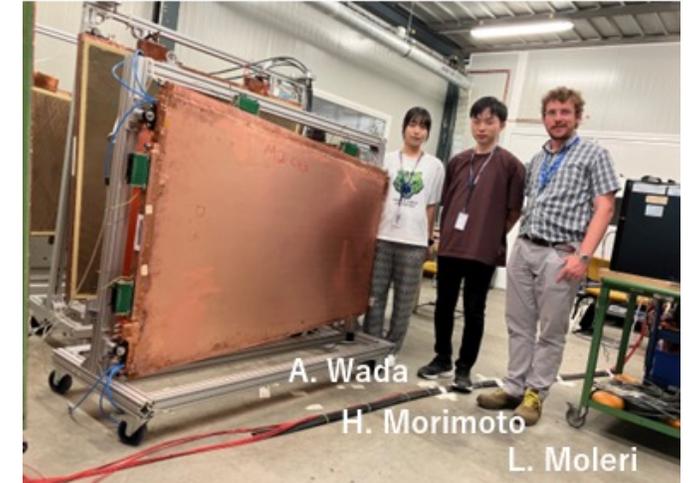
All Production and Tests Completed for PS, JATHub boards

- Seven production and testing campaigns were successfully conducted at KEK in Japan, aligned with each batch arrival
- This was made possible thanks to the dedicated efforts of early-career scientists, including graduate students
- The required number of qualified boards are now ready for shipment



Evaluation of EIL4 TGC detector

- EIL4: TGC with three detector layers
- Using the new Phase-2 TDAQ electronics
 - System-level commissioning demonstration
- Noise level and efficiency are fine



using the new Phase-2 electronics

Upgrade preparations are well underway!

Summary

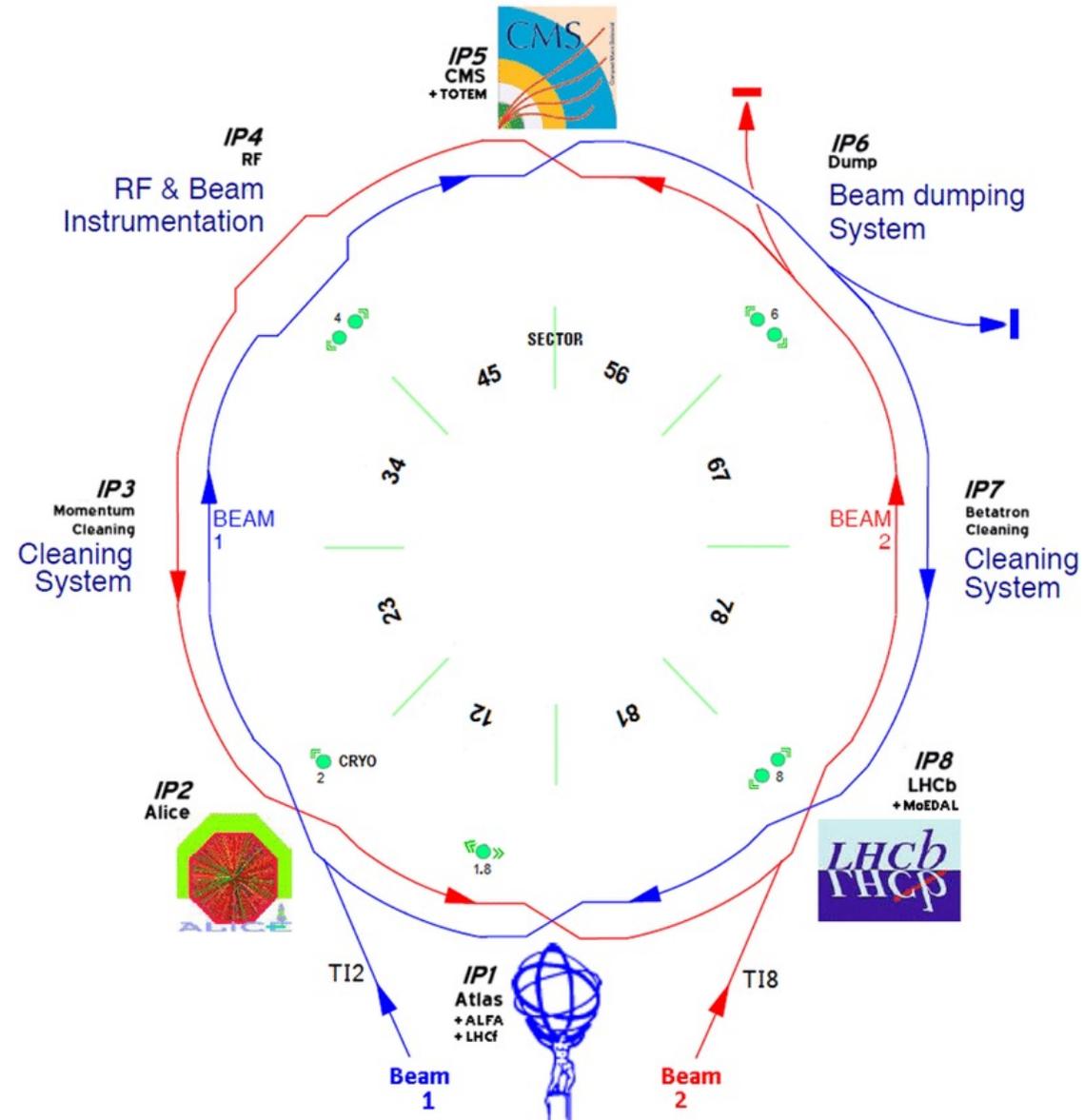
- The ATLAS experiment studies high-energy proton–proton collisions to perform precision tests of the Standard Model and searches for new physics
- The ATLAS muon spectrometer is **designed to precisely measure muons and efficiently trigger** on rare events over a wide momentum
- With the upcoming High-Luminosity LHC, **higher luminosity and increased pileup require detector and electronics upgrades**
- New detector systems and upgraded readout electronics are being developed and prepared for installation in ATLAS
- With precise tracking and excellent timing performance, the muon system continues to play a central role in the ATLAS physics

Thank you!

Backup



LHC beamline schematics

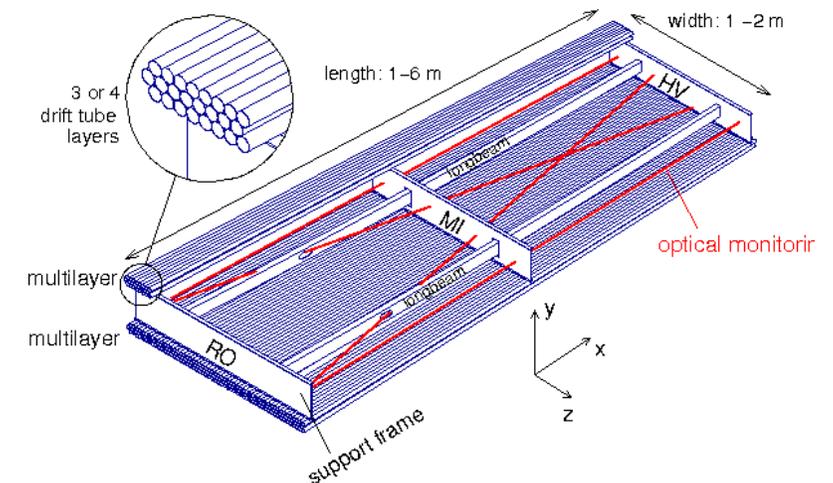


[link](#)

MDT Alignment

The "Monitored" Alignment

- **Challenge:** Deformations of several mm due to gravity and temperature
- **Optical Monitoring:**
Internal optical sensors track chamber torsion and sagging at the micron level
- **Global alignment:** A network of optical beams monitors relative positions across the 25 m spectrometer
- **Achieved Performance:** Sagitta correction accuracy of $30\ \mu\text{m}$ (r.m.s.)



Requirements for TGC electronics

Total Ionising Dose (TID)

Requirement: up to 180 Gy

Test: gamma irradiation



Non Ionising Energy Loss (NIEL)

Requirement: up to 1.6×10^{12} n/cm²

Test: neutron irradiation

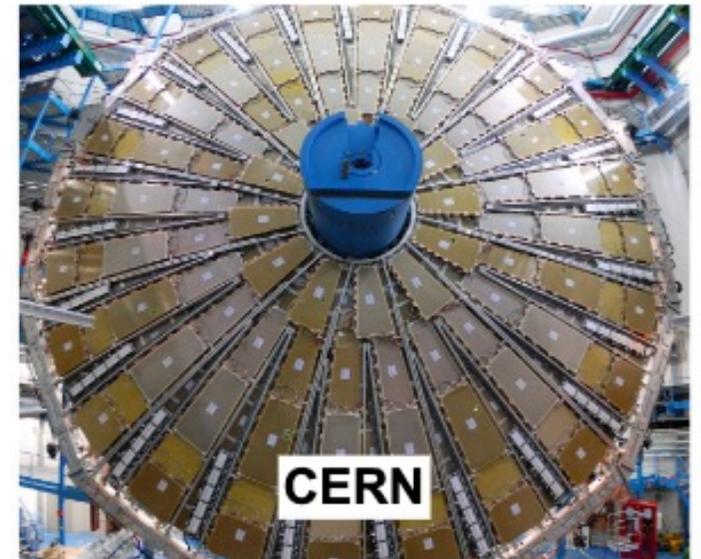


Single Event Effects (SEE)

Estimation: 9.8×10^2 /cm²s ($L=7.5 \times 10^{34}$ /cm²s)

Test: hadron irradiation

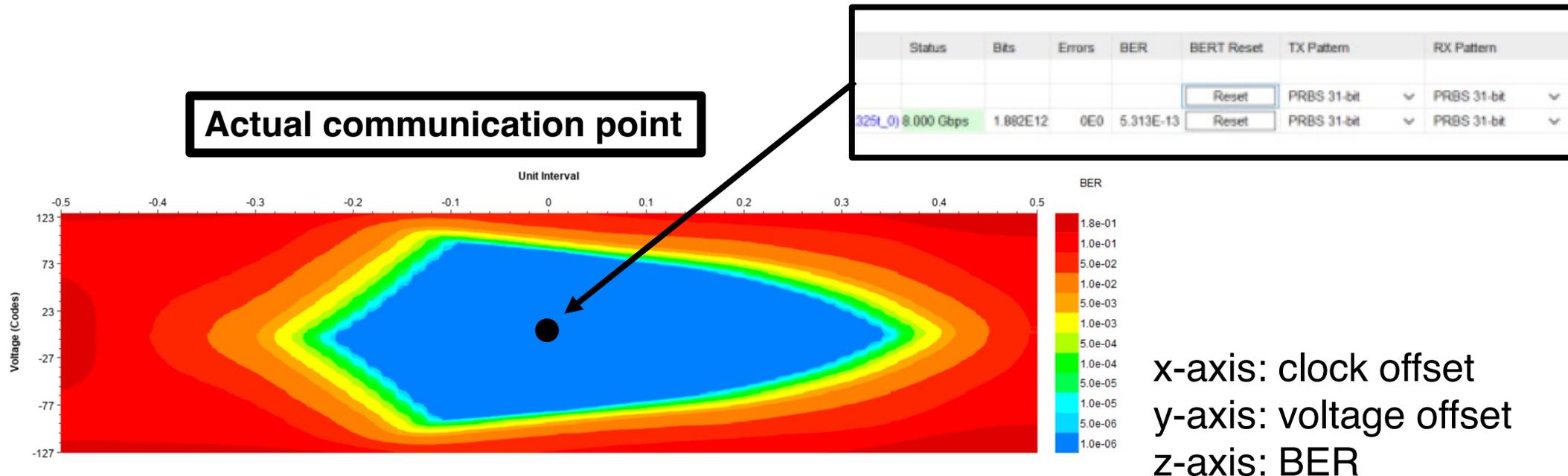
Demonstration: in the TGC detector area



Radiation Tolerance test

Type	RTC (on TGC)	SRL/4000fb ⁻¹	SF _{sim}	SF _{test}	SF _{loc}
TID	11 Gy	7.3 Gy	1.5	1	1
NIEL	4.3 × 10 ¹¹ /cm ²	2.2 × 10 ¹¹ /cm ²	1.5	1.3	1
SEE	1.6 × 10 ¹¹ /cm ²	5.1 × 10 ¹⁰ /cm ²	1.5	2	1

- Measure BER to evaluate the quality of optical communication.
 - Taking into account the offsets in clock phase and data voltage.
- BER (Bit Error Ratio):
the number of detected errors / the number of transmitted bits
- Open UI: The ratio of the no-error (blue) area to the total area



Irradiation test for on detector modules

- Confirmed enough tolerance for permanent hard damages due to NIEL and TID
- Radiation Tolerance Criteria (RTC)
 - $RTC = SRL^* \times SF_{sim} \times SF_{test} \times SF_{lot}$
- 3 irradiation tests are conducted
 - TID: **Cumulative threshold voltage shift** and leakage current increase
 - NIEL: **Permanent displacement damage** in the semiconductor lattice
 - SEE: **Transient bit-flips (SEU)** or latch-ups caused by single-particle strikes

***SRL**: Simulated Radiation Level on TGC, for an integrated luminosity of 4000 fb^{-1}

Highest check point before failure

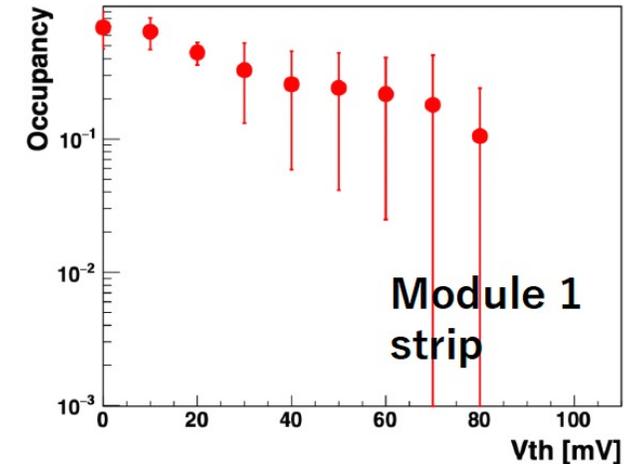
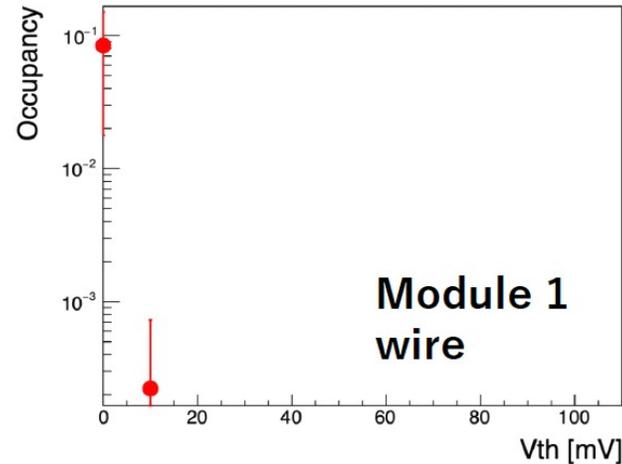
	TID	NIEL	SEE
Gamma	64 Gy		
Hadron	57 Gy	$8.2 \times 10^{11} / \text{cm}^2$	$2.7 \times 10^{11} / \text{cm}^2$
Neutron		$2.0 \times 10^{13} / \text{cm}^2$	
RTC	11 Gy	$4.3 \times 10^{11} / \text{cm}^2$	$1.6 \times 10^{11} / \text{cm}^2$



Noise Measurement: Result

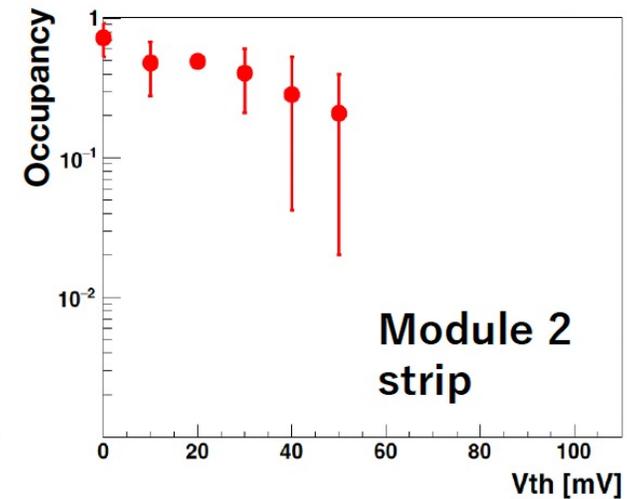
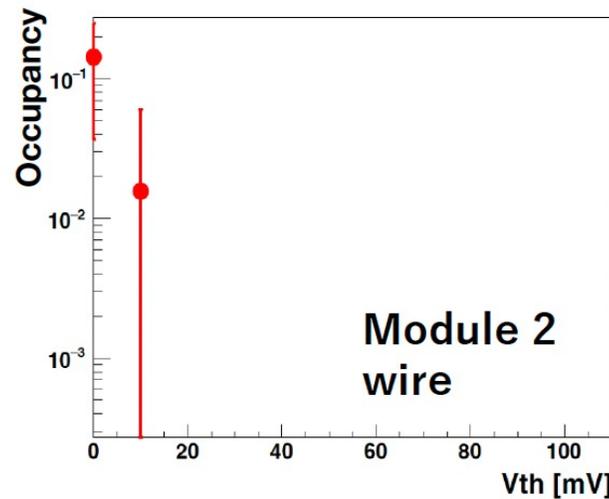
Module 1

- 11k events taken
- Zero occupancy for
 - $V_{th} \geq 20$ mV (wire)
 - $V_{th} \geq 90$ mV (strip)



Module 2

- 1M events taken
- Zero occupancy for
 - $V_{th} \geq 20$ mV (wire)
 - $V_{th} \geq 60$ mV (strip)



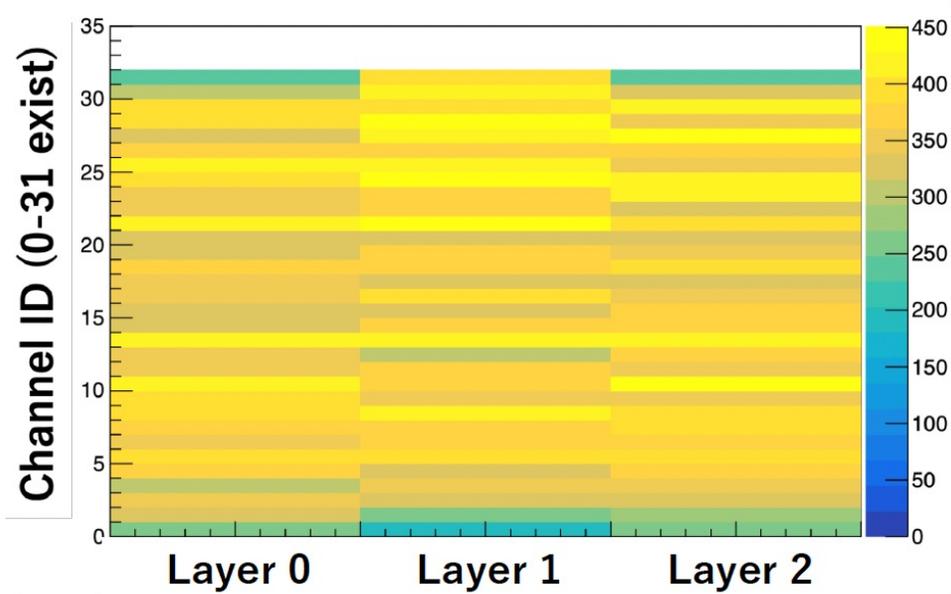
Noise level fine for the operation

Nominal V_{th} at Point 1: 60 mV (wire), 70 mV (strip)
with exceptions (up to ~300 mV) for ~1% chambers

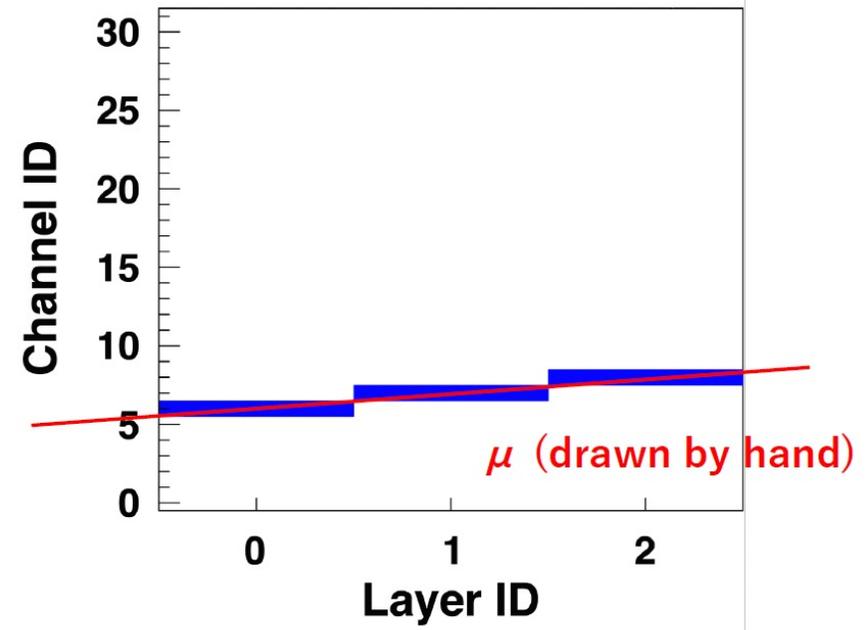
Efficiency Measurement: Data Taking

- The data taken when **at least two layers have a hit**
- **$V_{th} = 100$ mV** (low noise but still fine for minimum ionizing particles)
- **Nominal gas CO₂+n-pentane** and **nominal HV (2800 V)** supplied

Typical hit map (wire)



Typical event display (wire)



Overview: TDAQ for HL-LHC

LHC TDAQ data flow

40 MHz

Level-1 (L1) Trigger

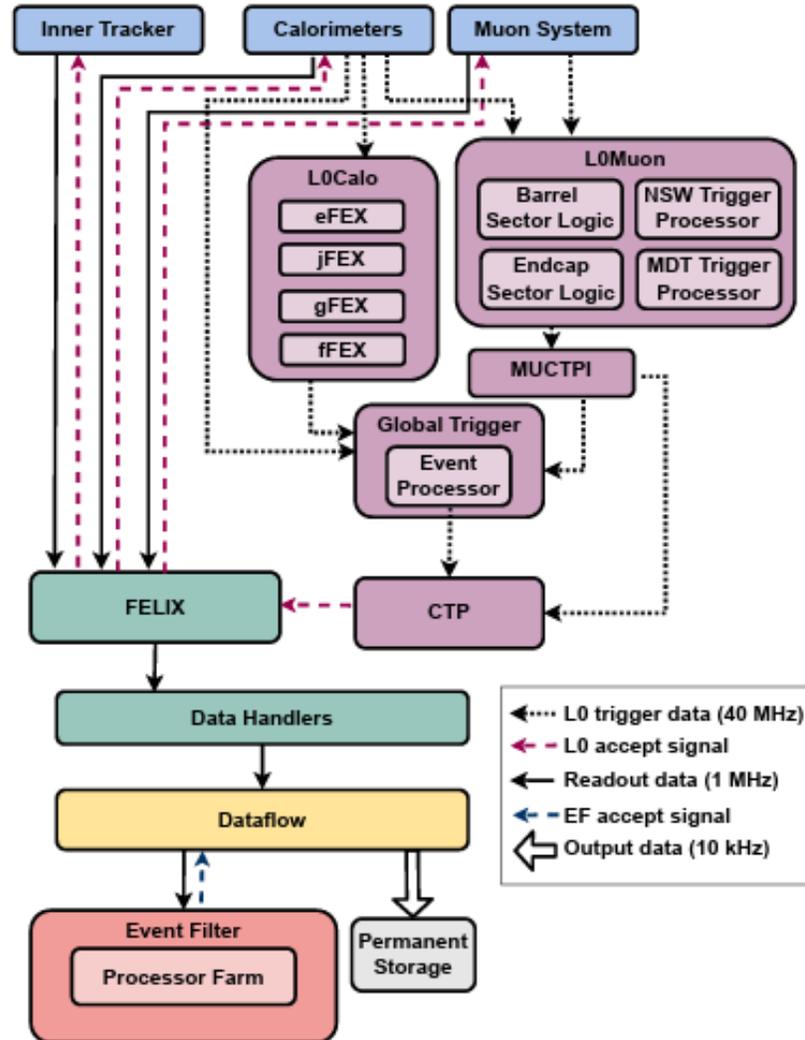
Latency: 2.5 μ s

100 kHz

Data Acquisition (DAQ)

High Level Trigger (HLT)

3 kHz



HL-LHC TDAQ data flow

40 MHz

Level-0 (L0) Trigger

Latency: 10 μ s

1 MHz

Data Acquisition (DAQ)

Event building at 1 MHz
Compression, storage, and transfer to offline at 10 kHz

Event Filter (EF)

10 kHz

Define a Region of Interest (RoI) for muons above the p_T threshold

Level-0 muon trigger concept

- Up to Run 3, muon candidates were identified using only RPC and TGC
- With increased latency, MDT hit can now be used at L0 for improved muon selection

Baseline trigger concept:

1. TGC (RPC) independently identify muon candidates and define the **Region of Interest (RoI)**
2. RoI is then shared with the
3. The MDT combines the RoI with its high-precision hit information to return a refined p_T measurement

