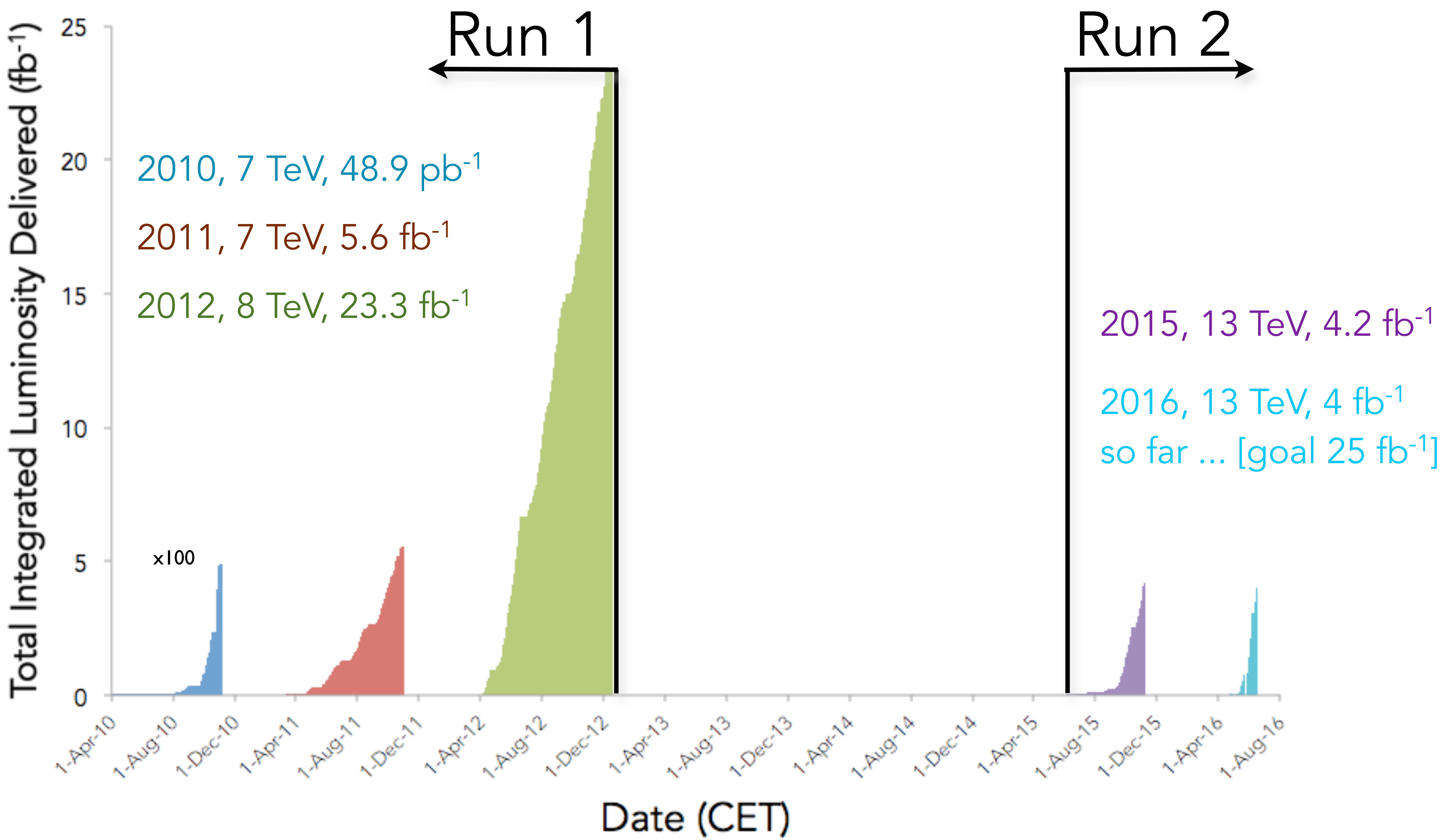
Upgrades to the ATLAS detector at the LHC

Brigitte Vachon
McGill University

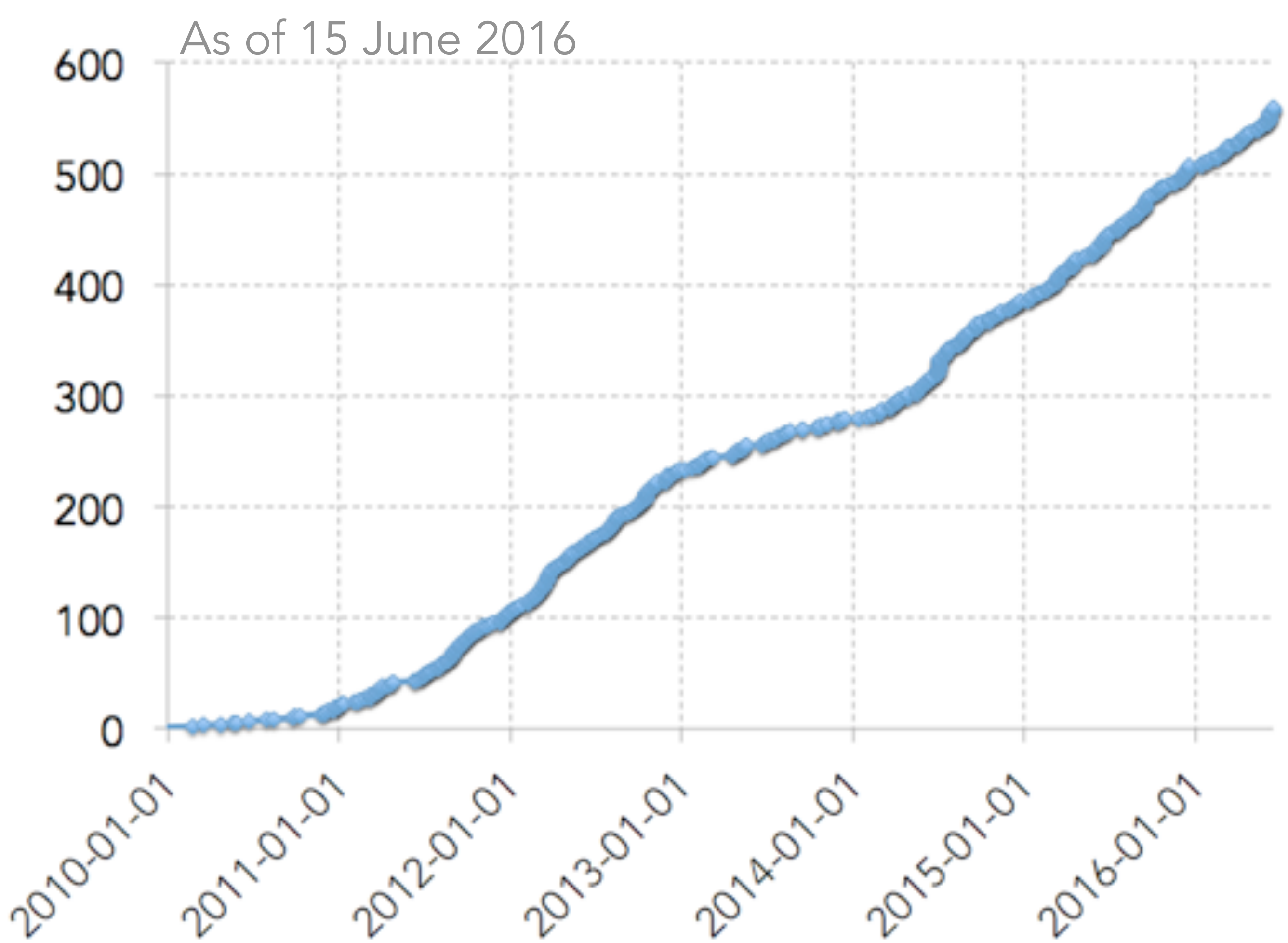
On behalf of the
ATLAS-Canada group

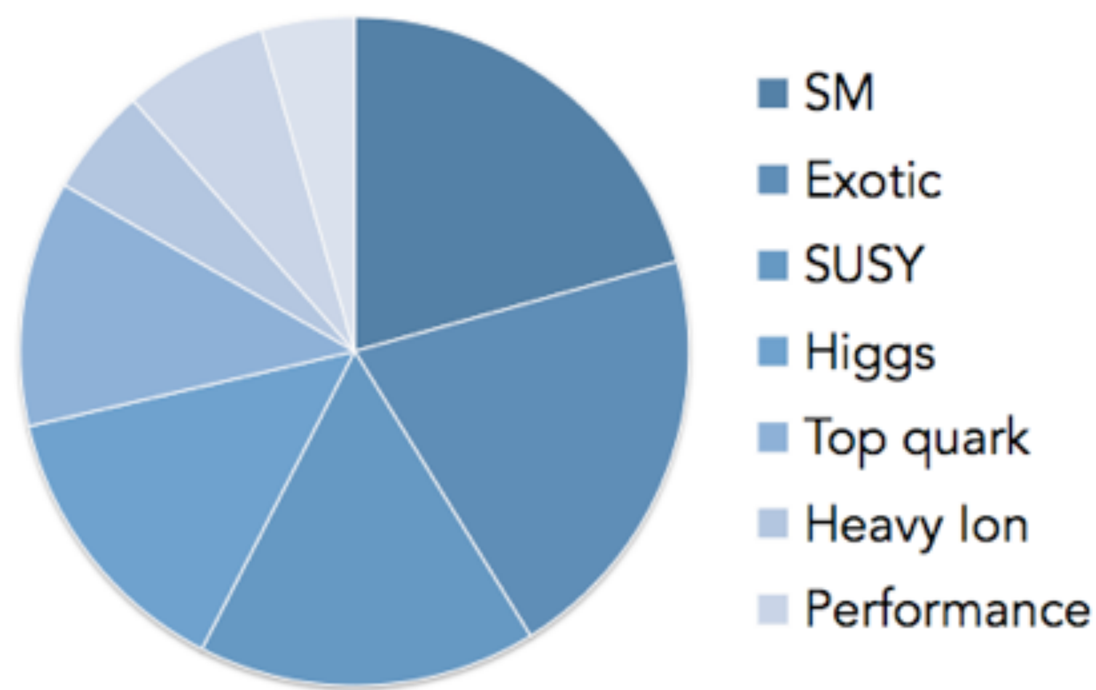
LHC Operation



ATLAS experiment physics output

- Higgs boson discovery in 2012 for which Nobel prize was awarded to Higgs and Englert in 2013 (with ATLAS and CMS mention in the citation). [Phys. Lett. B 716 (2012) 1-29,, Phys. Lett. B 716 (2012) 30]
- More than 500 published papers so far on a variety of topics.

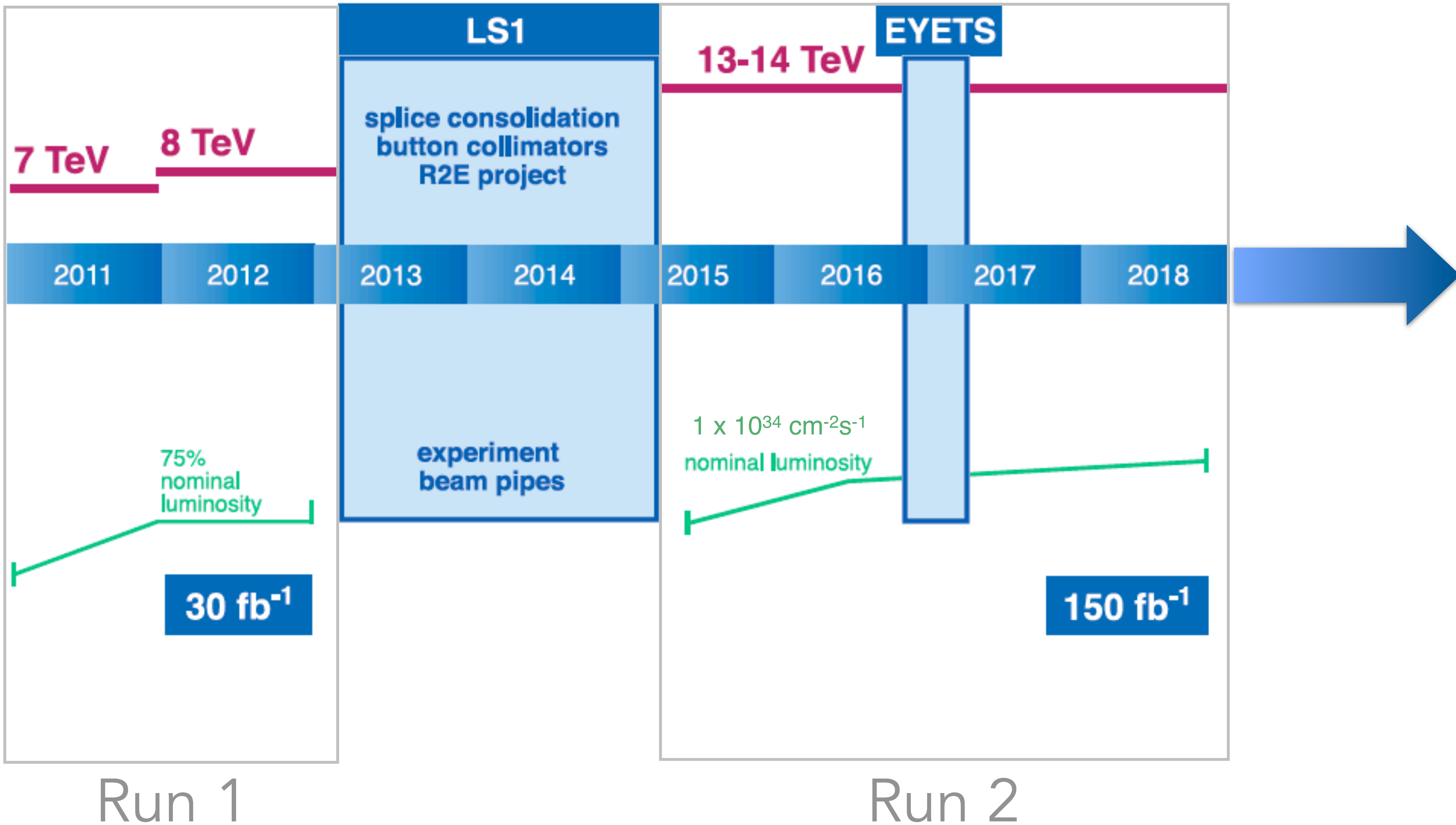




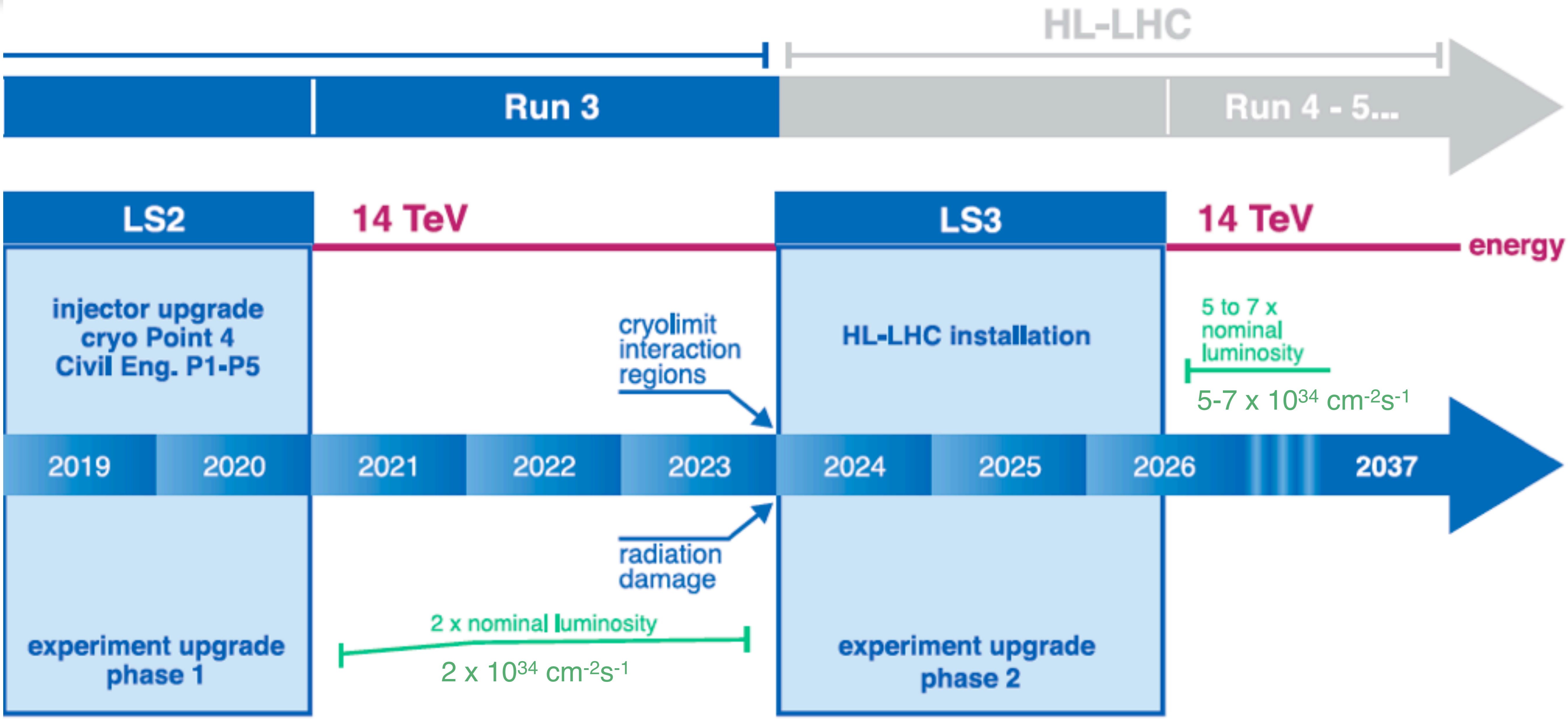
Physics motivation.. now what?

- Study properties of Higgs boson.
- Explore electroweak symmetry breaking through study of boson-boson scattering processes.
- Search for new phenomena.
- Search for Dark Matter.
- Test validity of Standard Model through detailed studies of known SM processes.
    - Fully explore electroweak TeV scale.

LHC Schedule



LHC Schedule

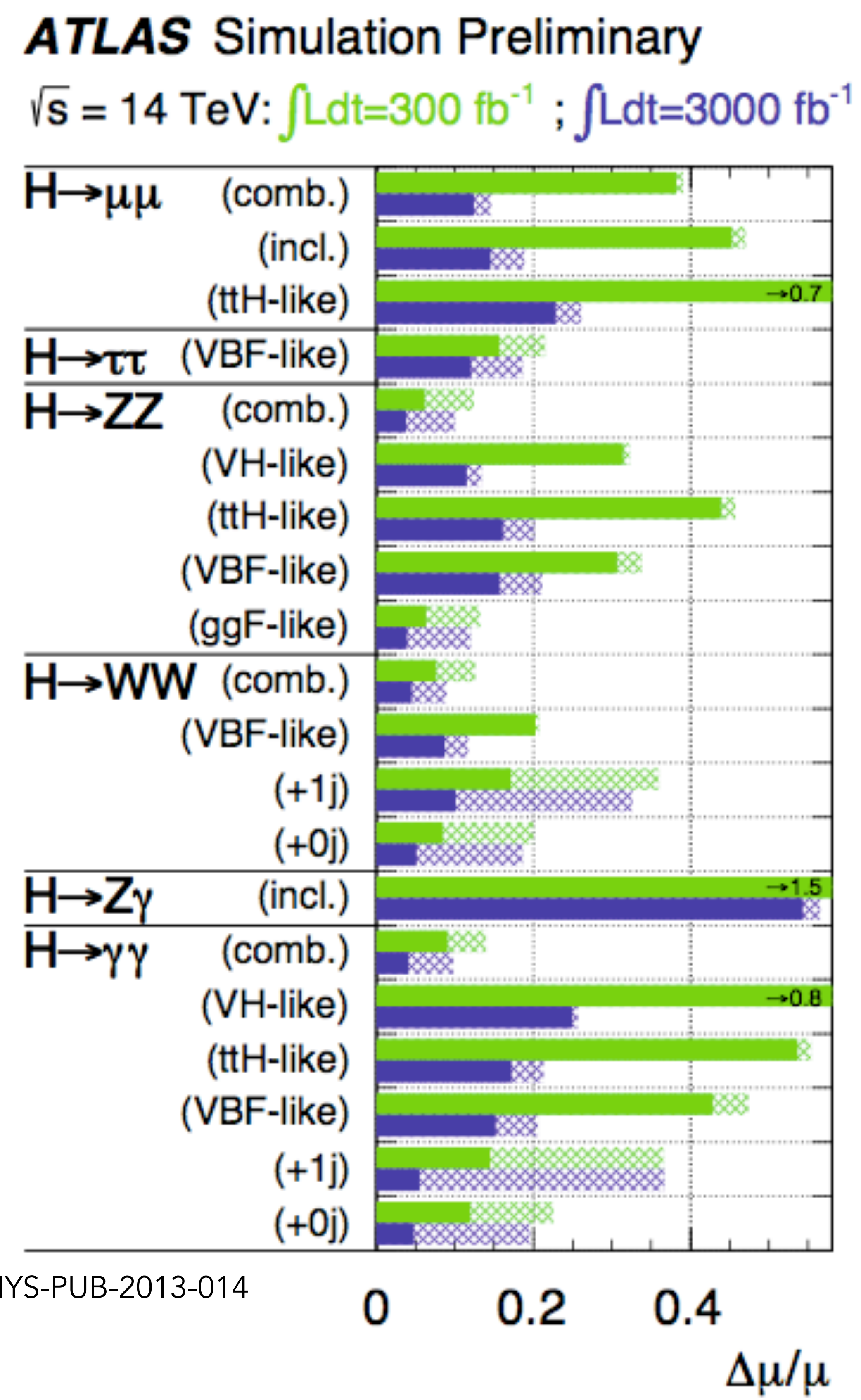


- New muon small wheel
- LAr calorimeter electronics
- Fast TracKer (FTK)
- Trigger/DAQ

- Inner Tracker (ITk)
- LAr calorimeter electronics
- Forward calorimeter upgrade
- Trigger/DAQ

Higgs prospects

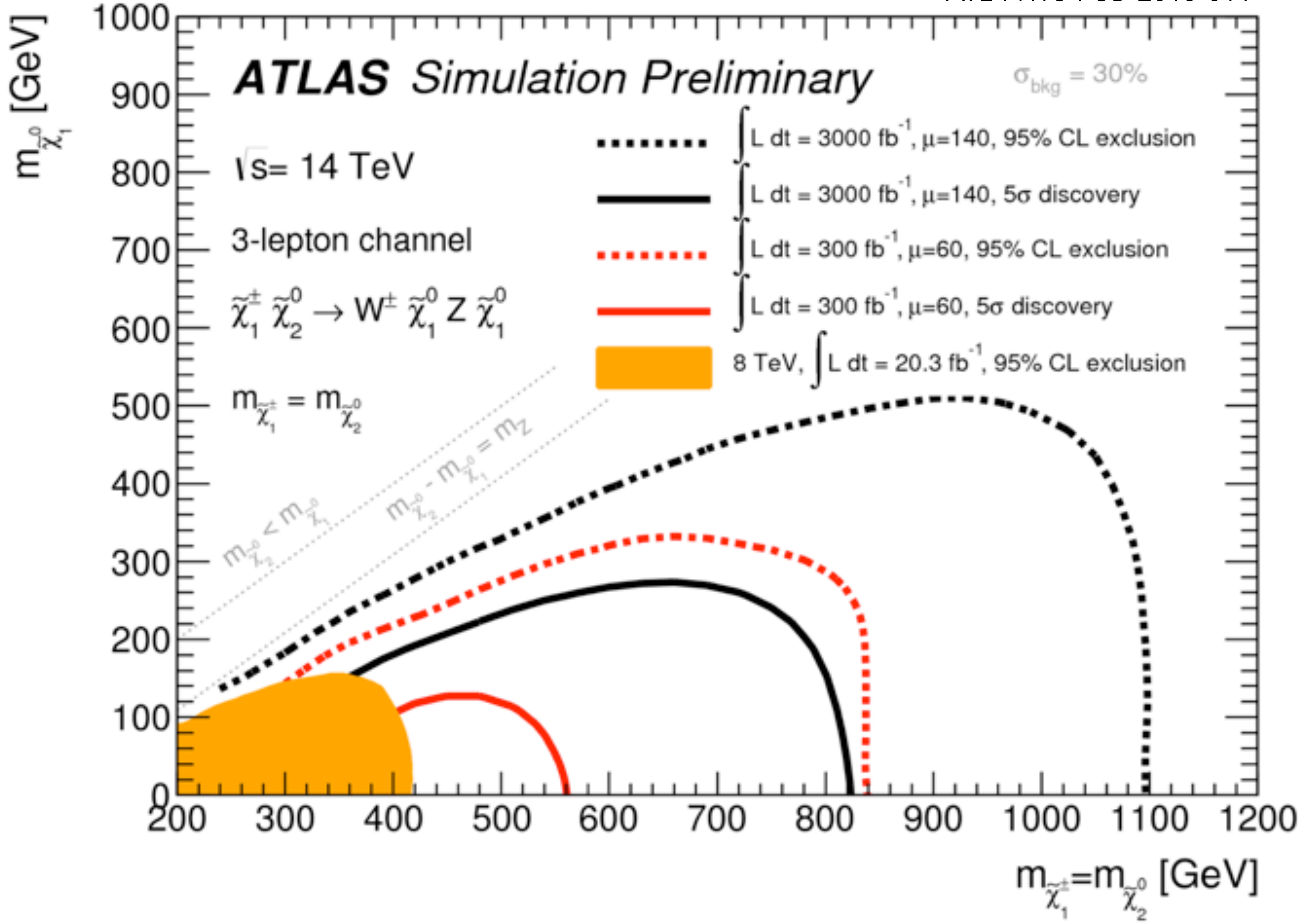
Projections of relative uncertainty on the total signal strength μ for different Higgs final states for 300 fb^{-1} and 3000 fb^{-1}.

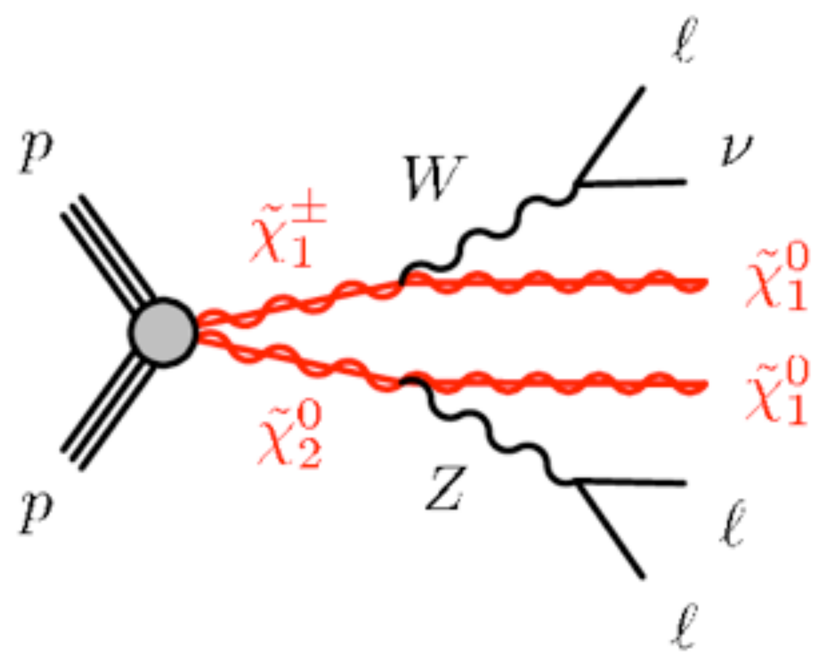


ATL-PHYS-PUB-2013-014

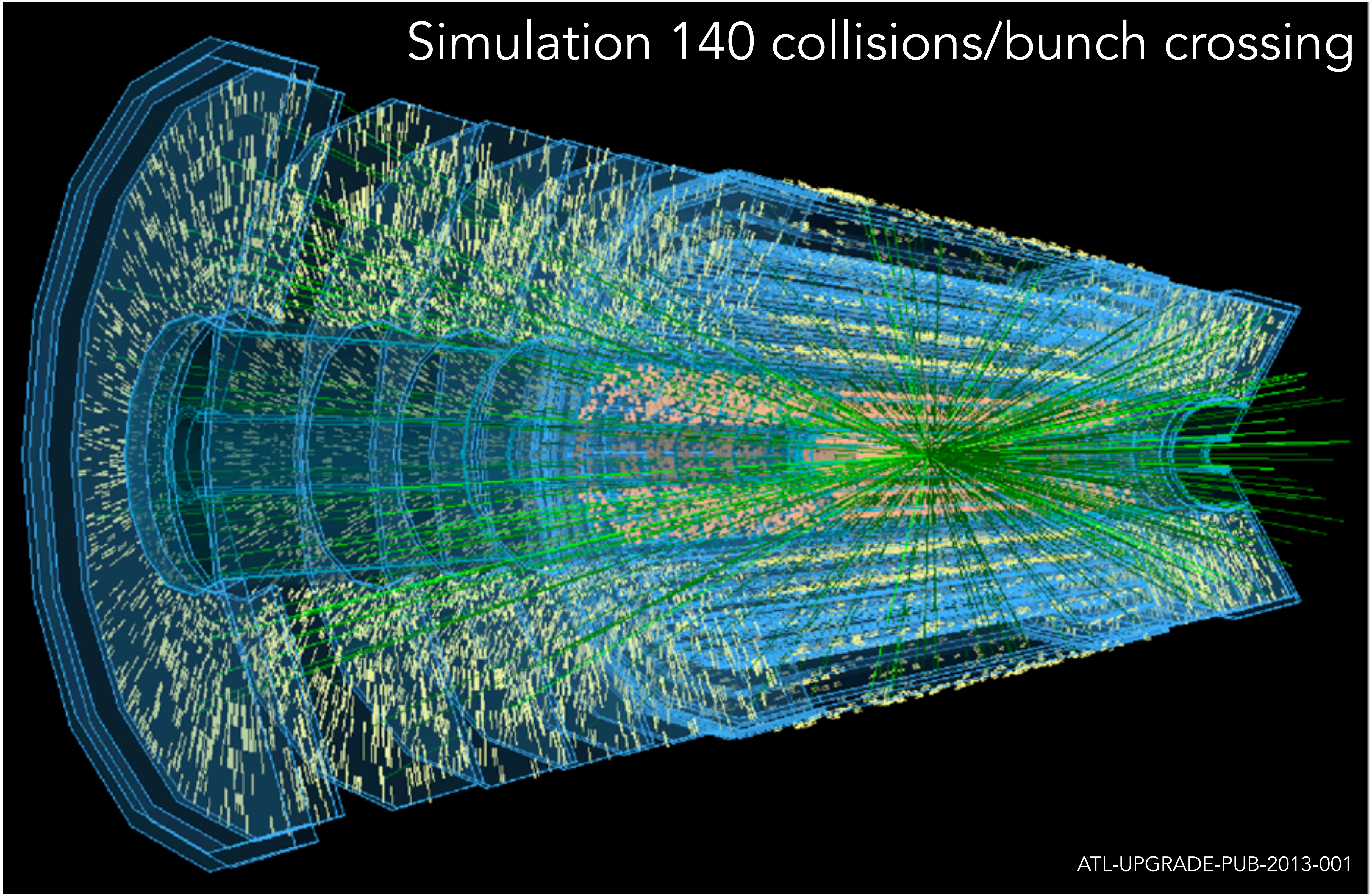
SUSY prospects

ATL-PHYS-PUB-2013-011





The Challenge



The Challenge

- Physics goals require ability to efficiently identify and precisely measure the energy/trajectory of electrons/photons, muons, taus, b-jets, jets, over a wide energy range.

- High rate environment
  - Must retain ability to ***trigger*** on physics objects down to ~ 20-30 GeV with high efficiency and low fake rate.

- High multiplicity/occupancy environment
  - Excellent detector performance required for mitigation of high level of pile-up at HL-LHC (7.5 x 10^{34} $cm^{-2}s^{-1}$, μ ~ 200)

- High radiation environment
  - Detector must sustain radiation levels expected at HL-LHC

ATLAS Upgrades

- Phase-1 upgrades (2019-20)
  - New muon small wheel
  - Liquid argon calorimeter electronics
  - Fast TracKer (FTK)
  - Trigger/DAQ
- Phase-2 upgrades (2024-26)
  - Liquid argon calorimeter electronics
  - Forward calorimeter upgrade
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  - Trigger/DAQ

ATLAS Upgrades

- Phase-1 upgrades (2019-20)
  - New muon small wheel
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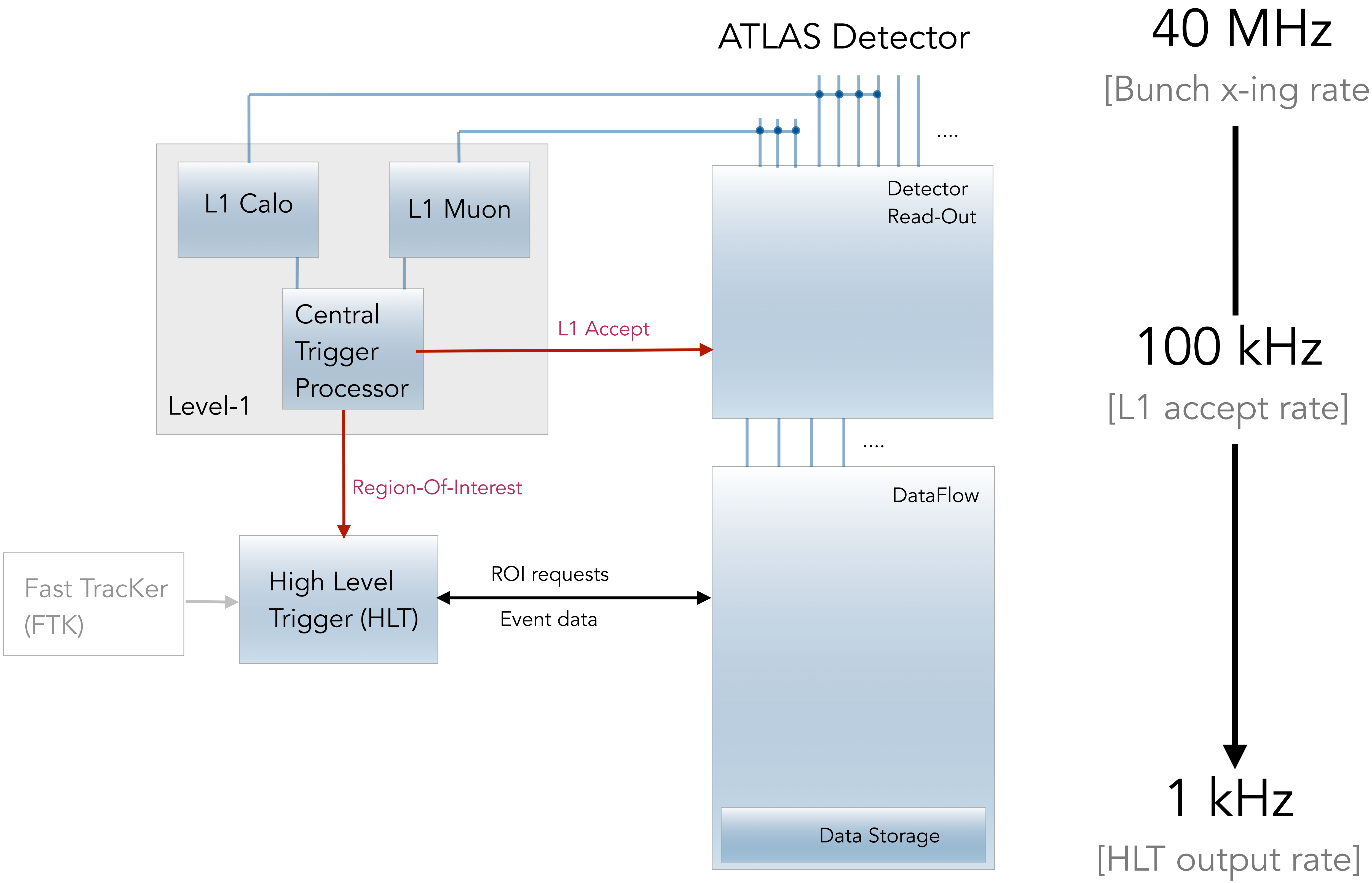
  - Trigger/DAQ

To allow the ATLAS experiment to efficiently trigger and record data at instantaneous luminosities that are up to **three** times that of the original LHC design while maintaining trigger thresholds close to those used in the initial run of the LHC.

ATLAS Trigger System



ATLAS Upgrades

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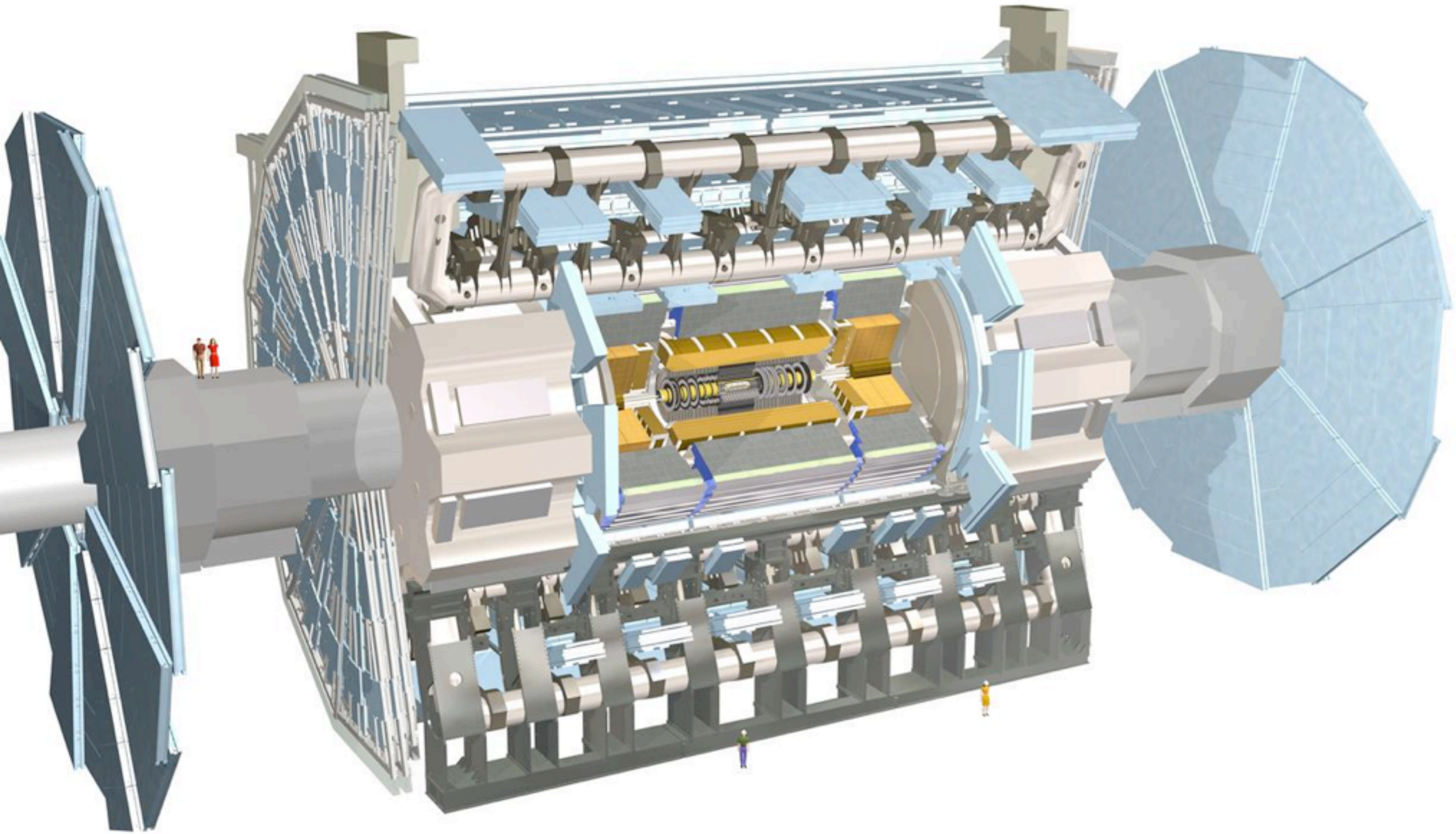
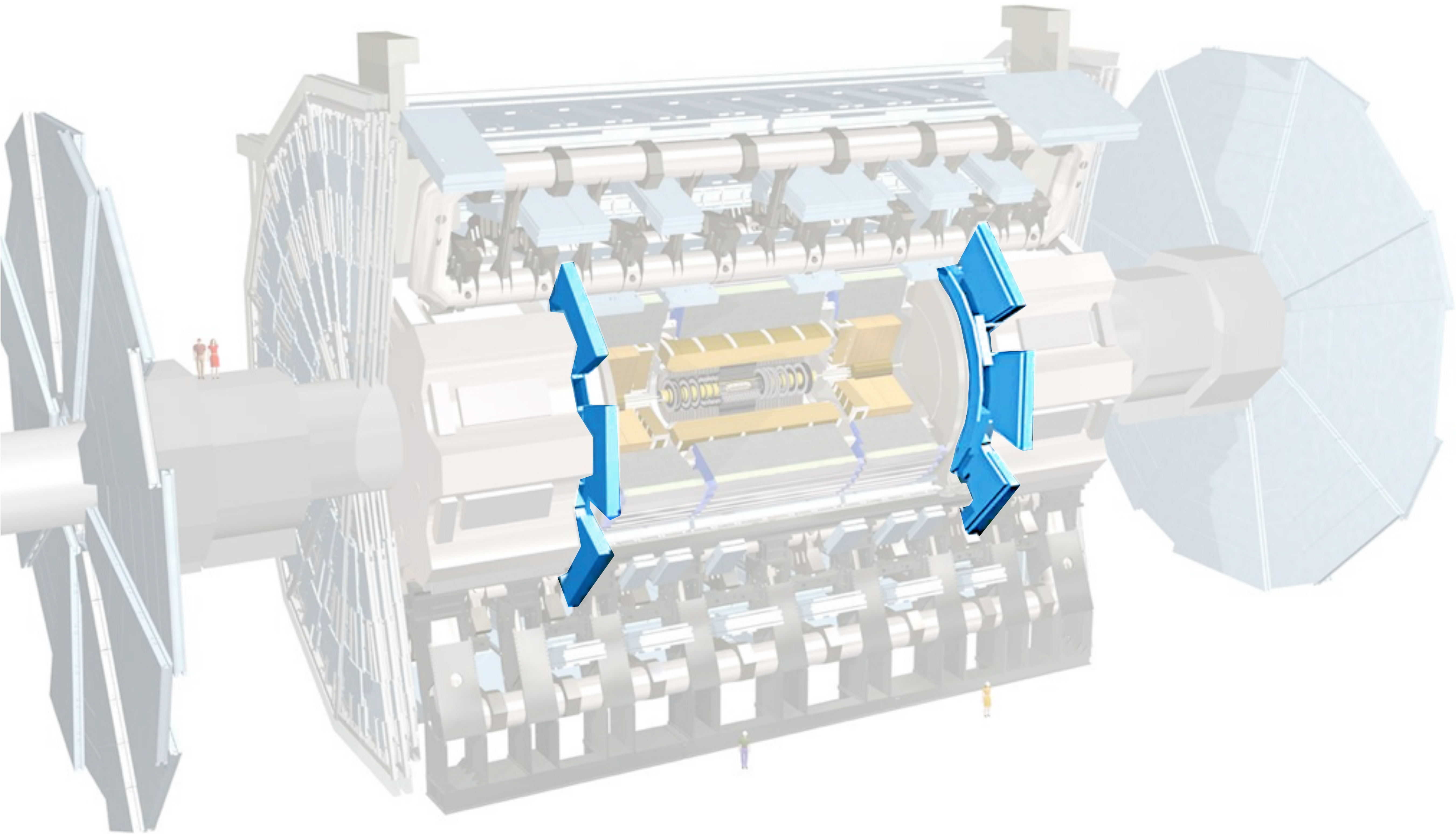
Phase-1: New muon small wheel



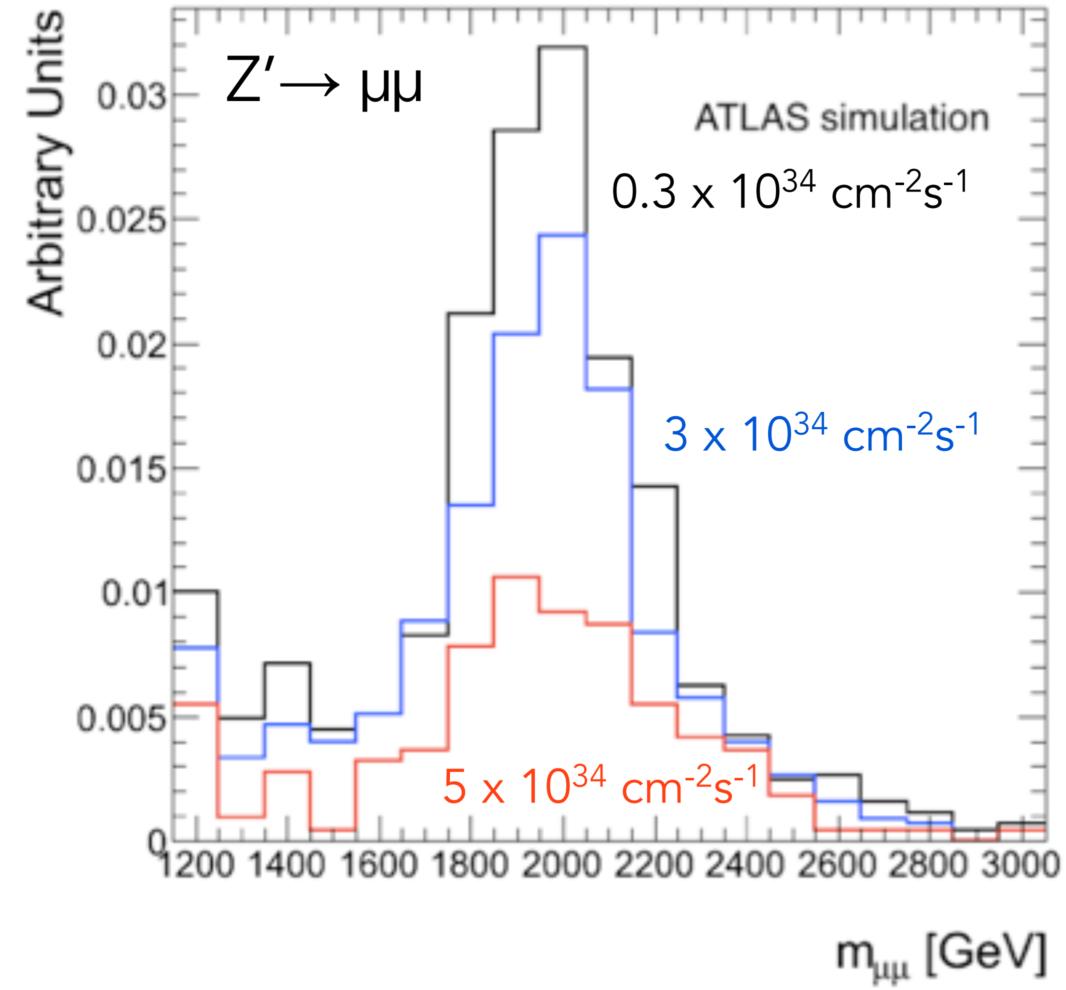
Phase-1: New muon small wheel

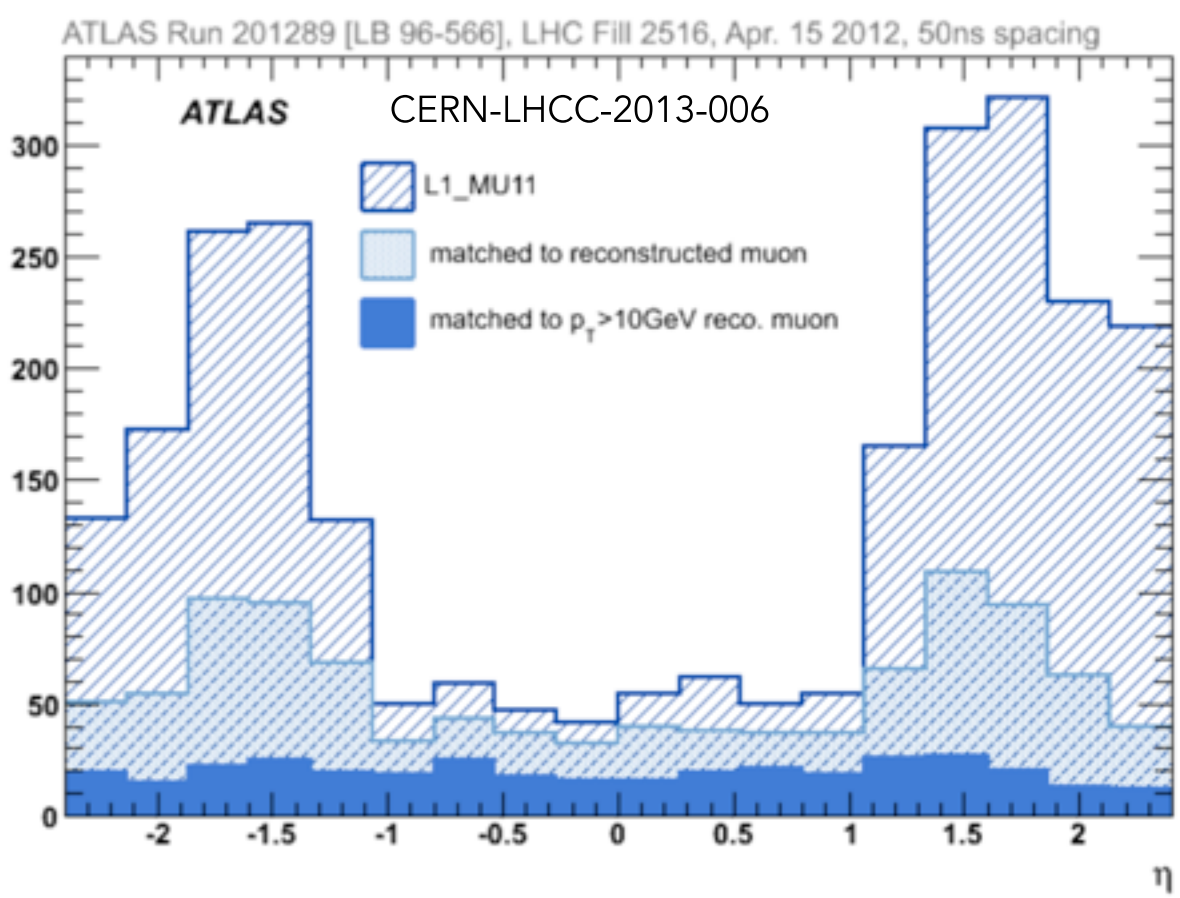


Phase-1: New muon small wheel

Challenges at high luminosity:

Degradation of **muon tracking efficiency and momentum resolution** due to high occupancy.





L1 muon trigger rate dominated by fakes and increasing proportionally with inst. luminosity.

Phase-1: New muon small wheel

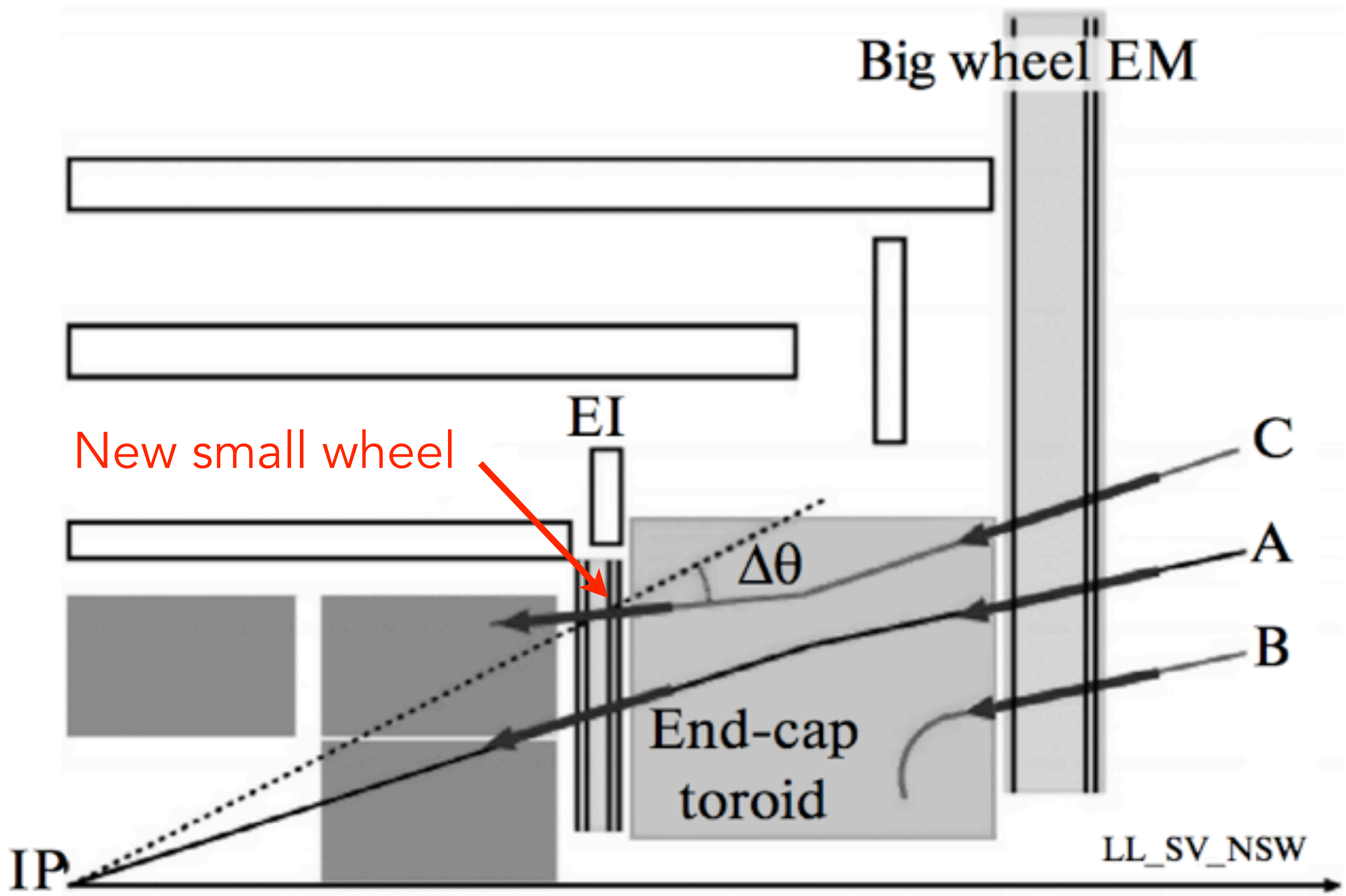
Solution: New muon small wheel that provides

- Precision tracking with performance at high lumi at least comparable to lower luminosity.
- Identification by trigger system of muon segments to confirm that muons originate from interaction point.

Need 1 mrad angular resolution (< 100 μm single-hit resolution).

High muon detection efficiency (> 95%) over entire (large!) detector area and for rates of ~15-20 kHz/cm^2.

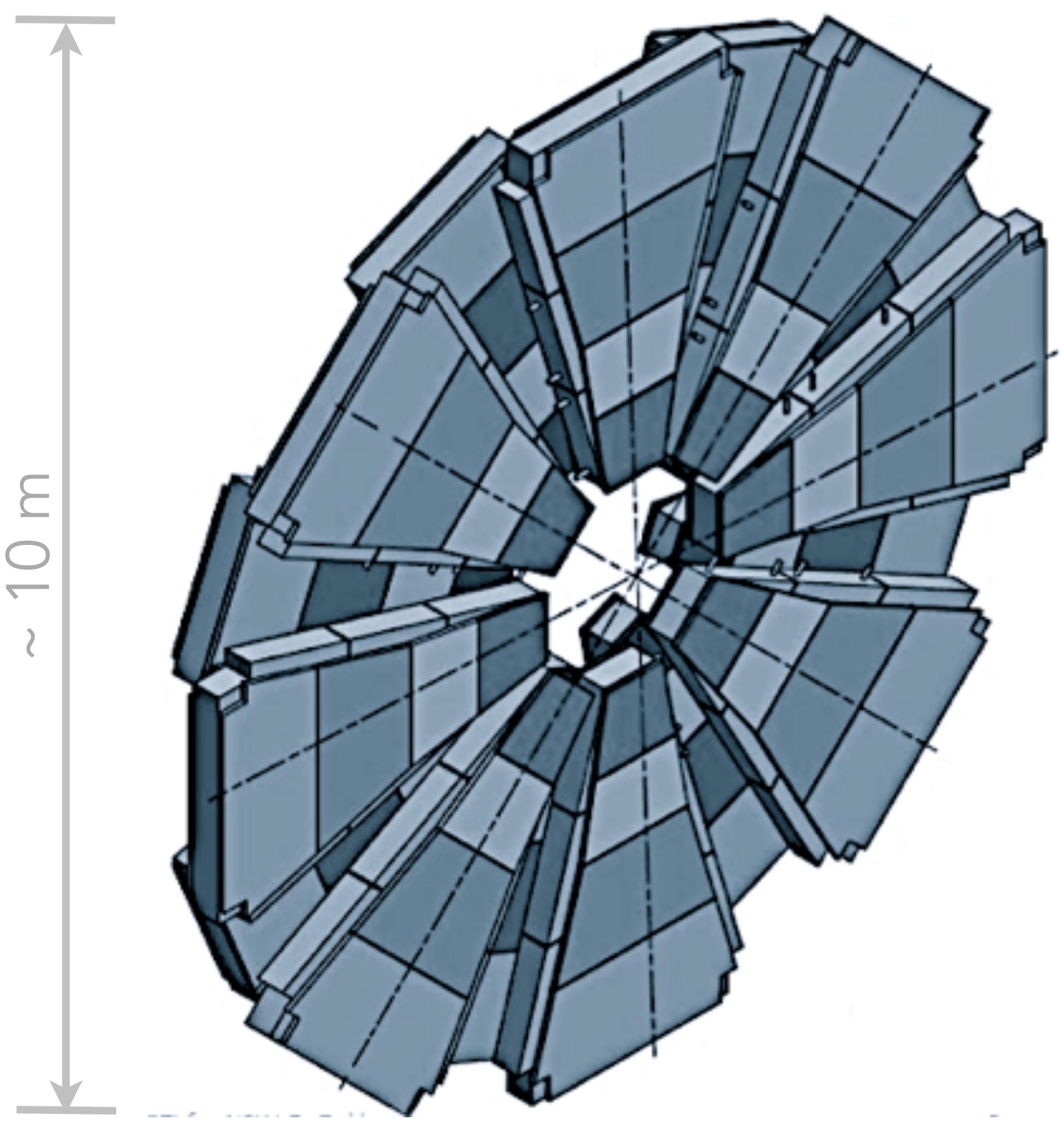
Maintain performance > 10 years.

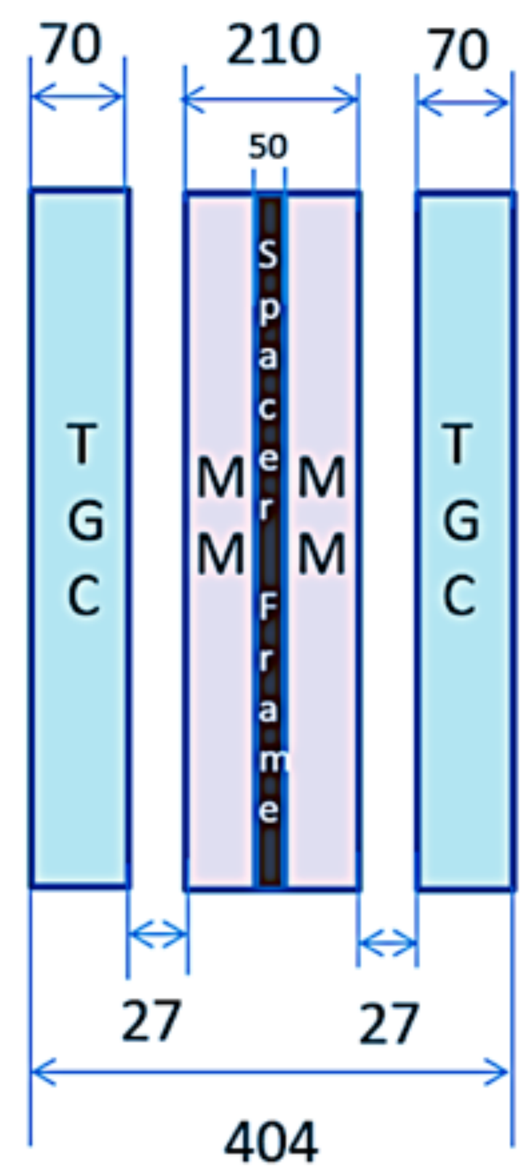


Physics of Particles and Nuclei, 2016, Vol. 47, No. 2, pp. 270–289.

Phase-1: New muon small wheel

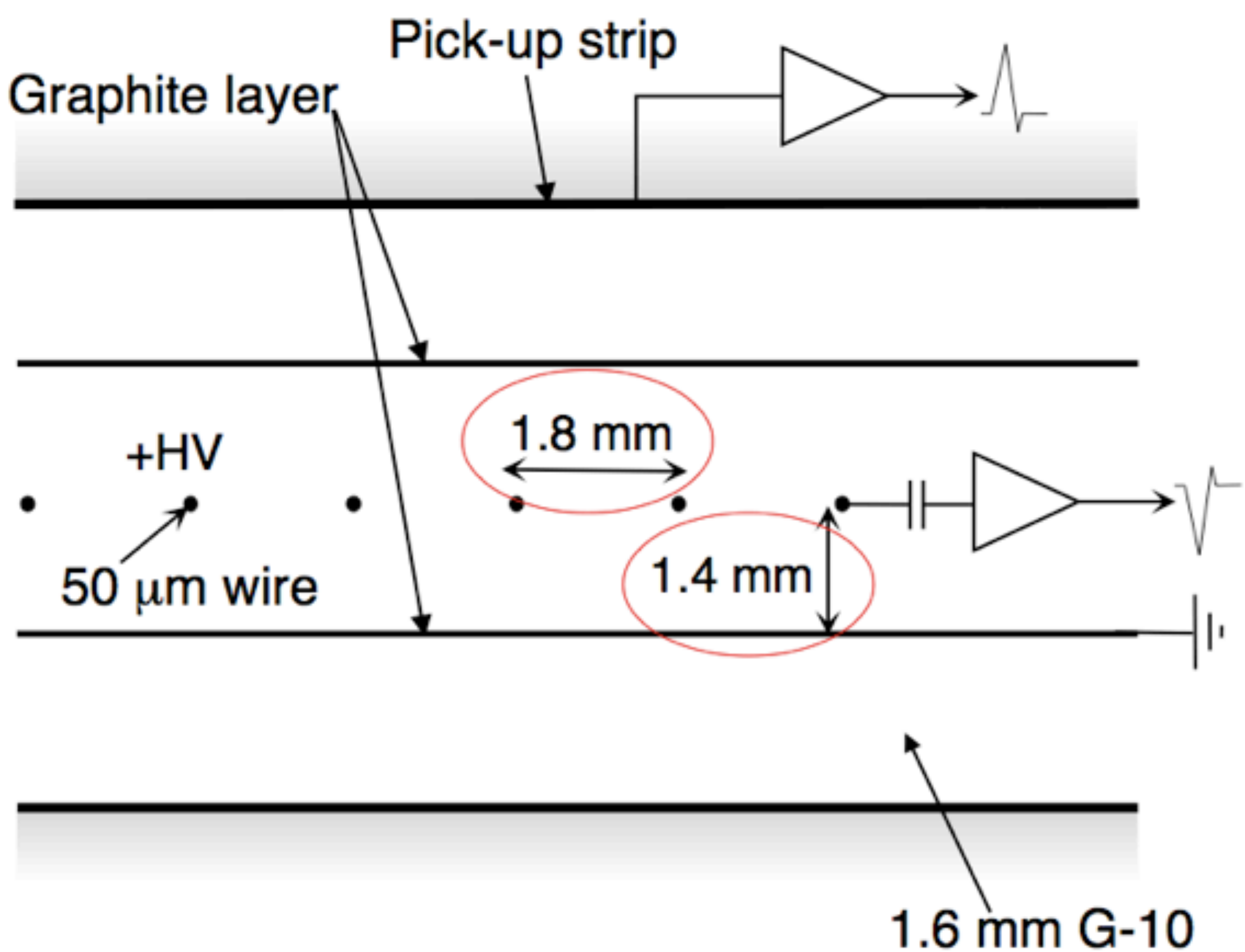
Trigger ⇨ Thin Gap Chambers 🍁
Precision tracker ⇨ MicroMegas



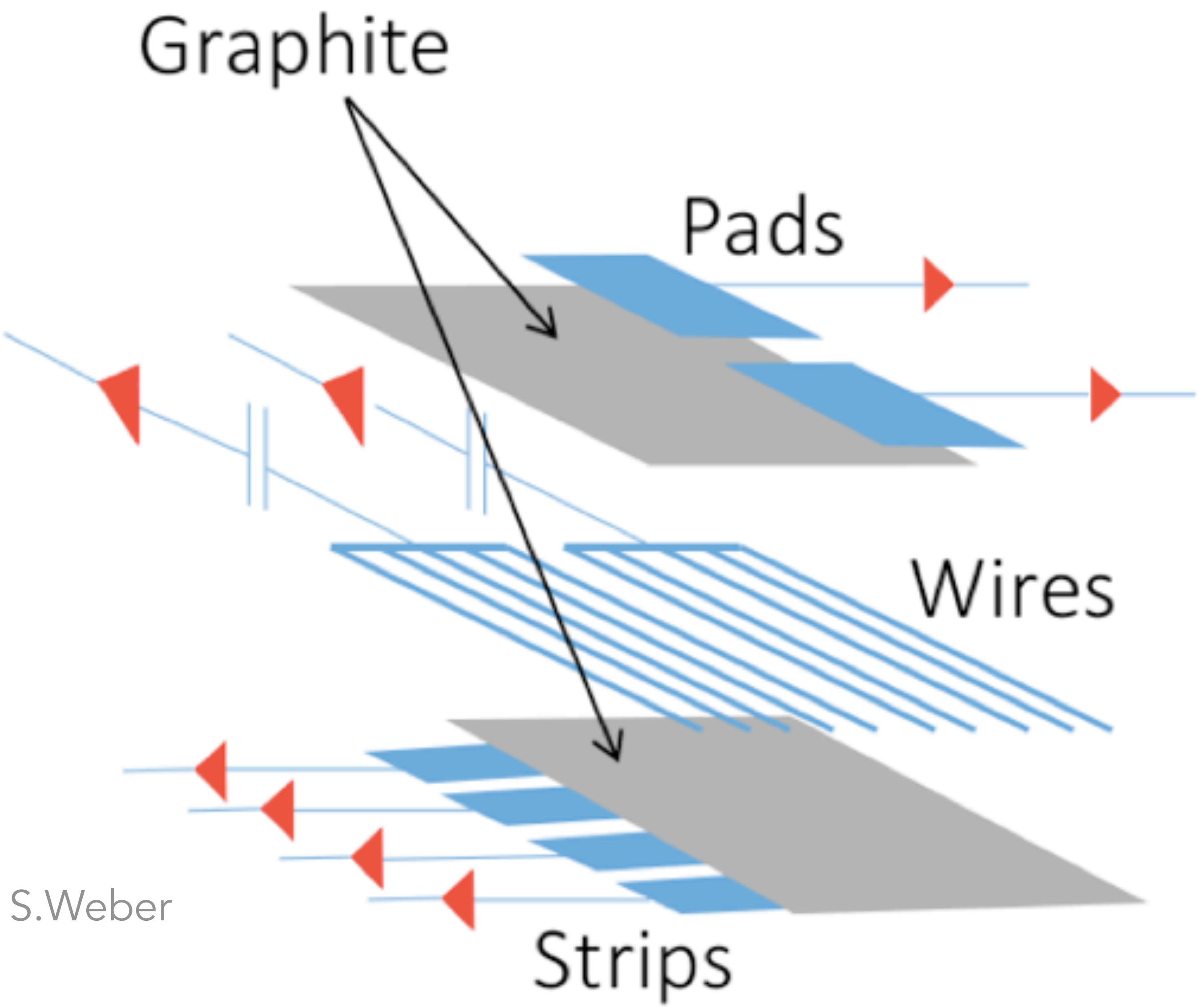


Phase-1: Thin Gap Chambers

Multiwire proportional chamber with the characteristic that the wire-to-cathode distance is smaller than the wire-to-wire distance.



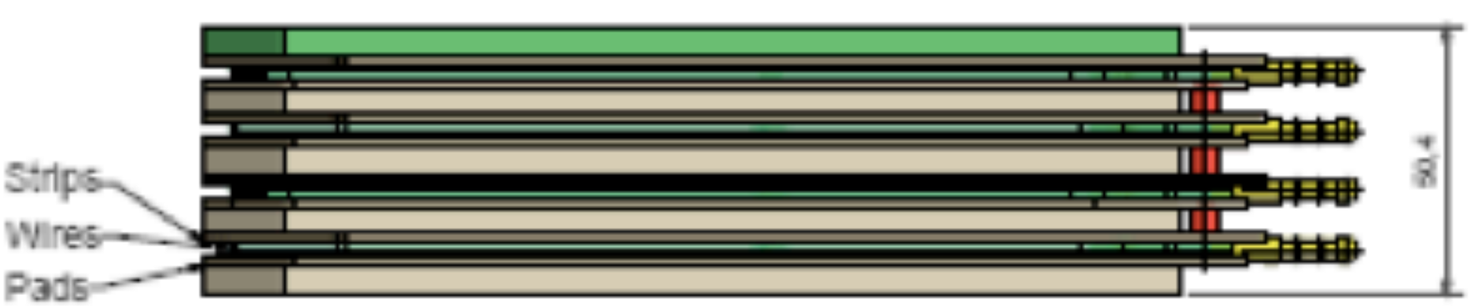
Phase-1: Thin Gap Chambers



Pads: Trigger and region of interest for strip readout.

Strips: Precision tracking (η)

Wires: Second coordinate (ϕ)



TGC quadruplet

Phase-1: TGC production in Canada

TRIUMF

- QA/QC on received parts (frames, wire supports, spacer buttons)
- Resistive layer coating (graphite spraying)
- Assembly of cathode boards (half gaps)

Carleton UNIVERSITY

- Anode wire winding
- Gap / doublet / quadruplet assembly
- Adaptor board mounting
- Shipment of quads to McGill

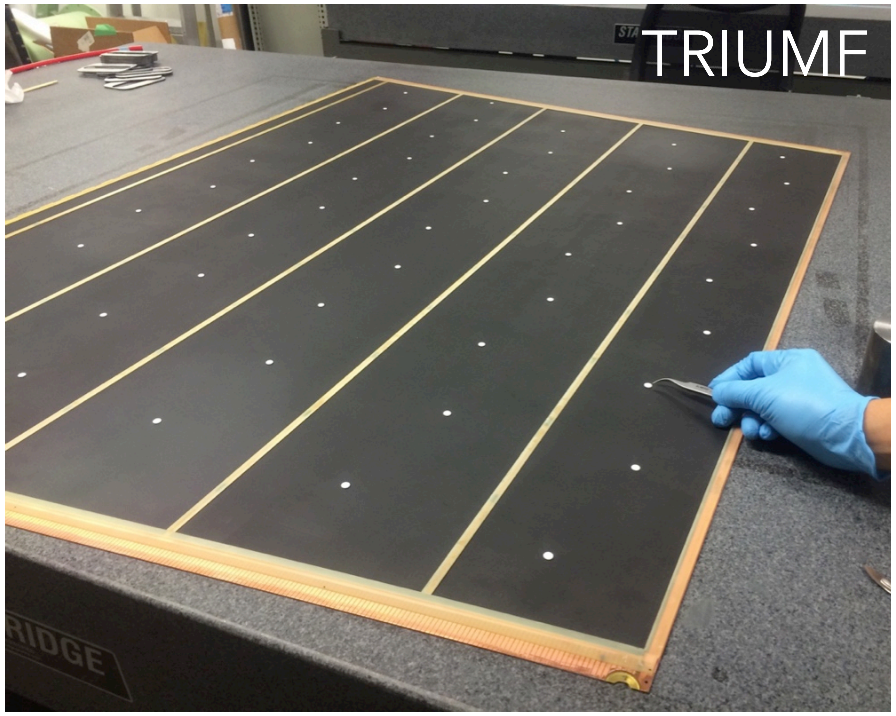
McGill UNIVERSITY

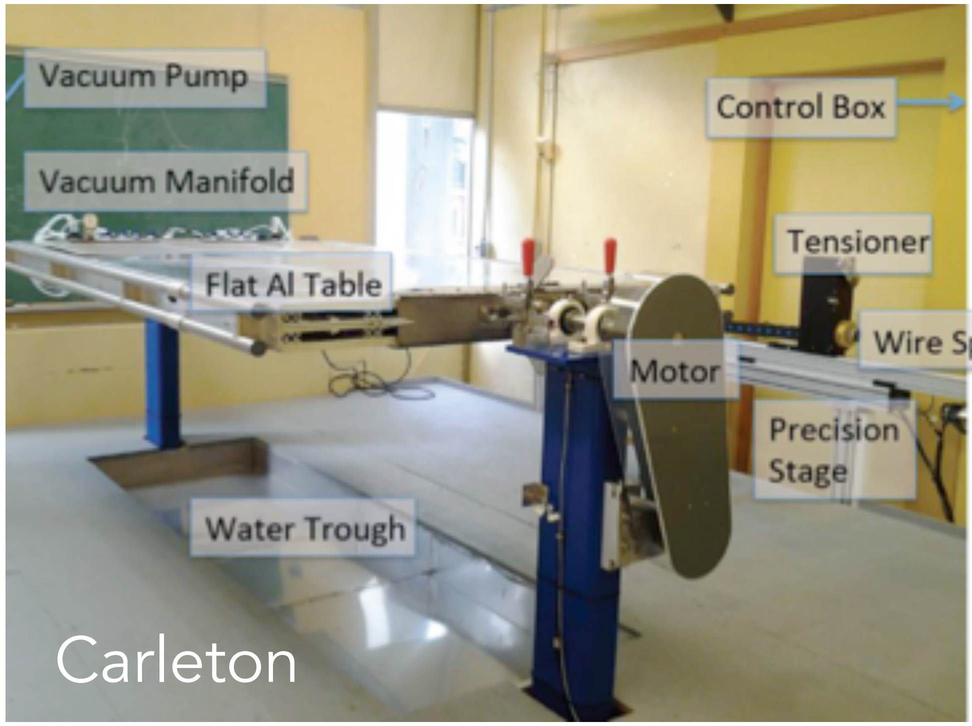
- Cosmic ray testing
- Shipment to Geneva

Phase-1: TGC production in Canada

Canadian infrastructure ready and undergoing qualification for production.

Production expected to begin this Fall 2016.





ATLAS Upgrades

- Phase-1 upgrades (2019-20)
  - New muon small wheel
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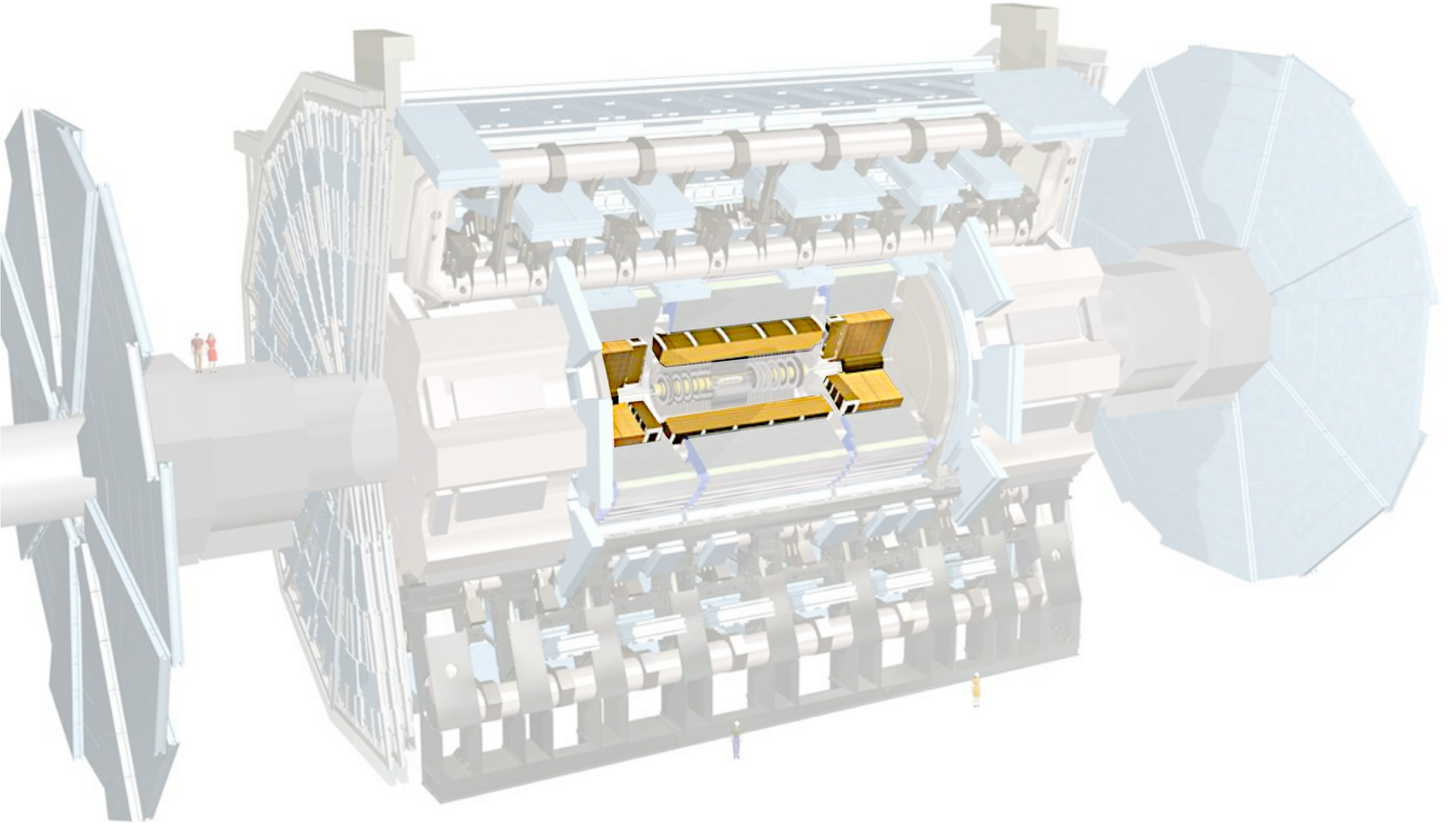
Phase-1: LAr calorimeter electronics

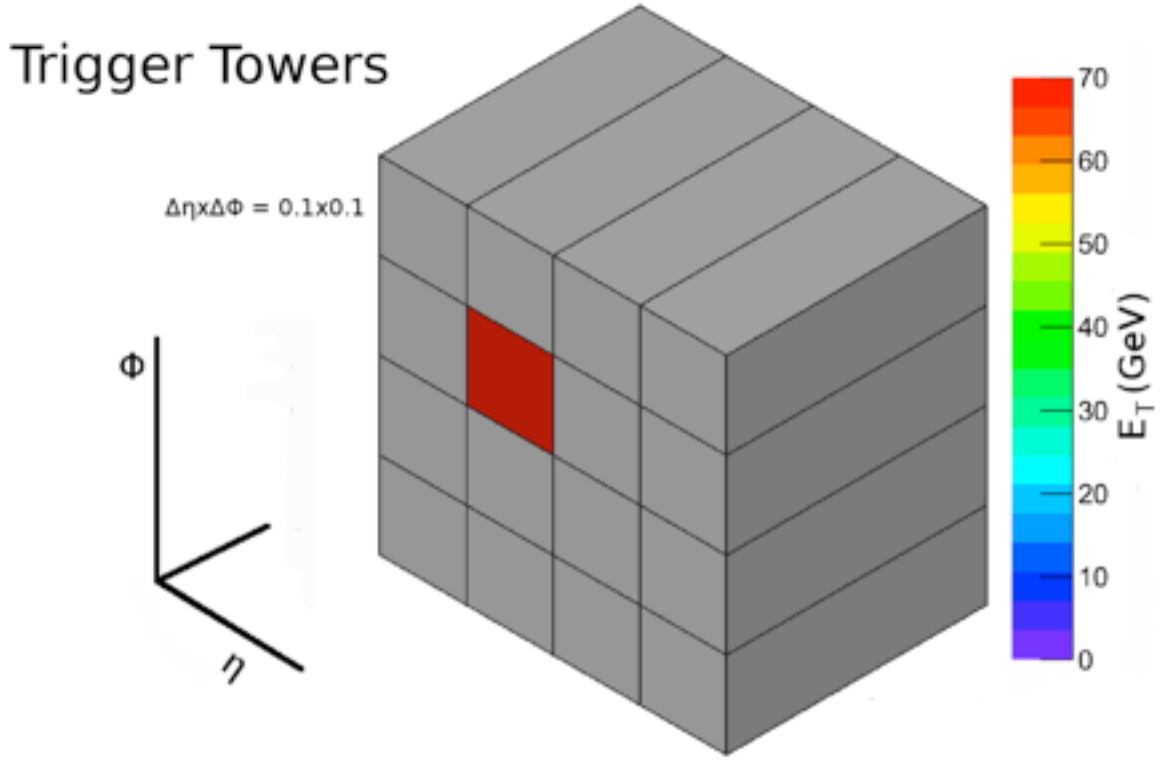


Phase-1: LAr calorimeter electronics

Goal: Maintain energy thresholds of L1 triggers at values comparable to those used in Run 1 despite increases in instantaneous luminosity (up to $L = 3\times10^{34}\ cm^{-2}s^{-1}$) and pileup (up to $\langle\mu\rangle = 80$).

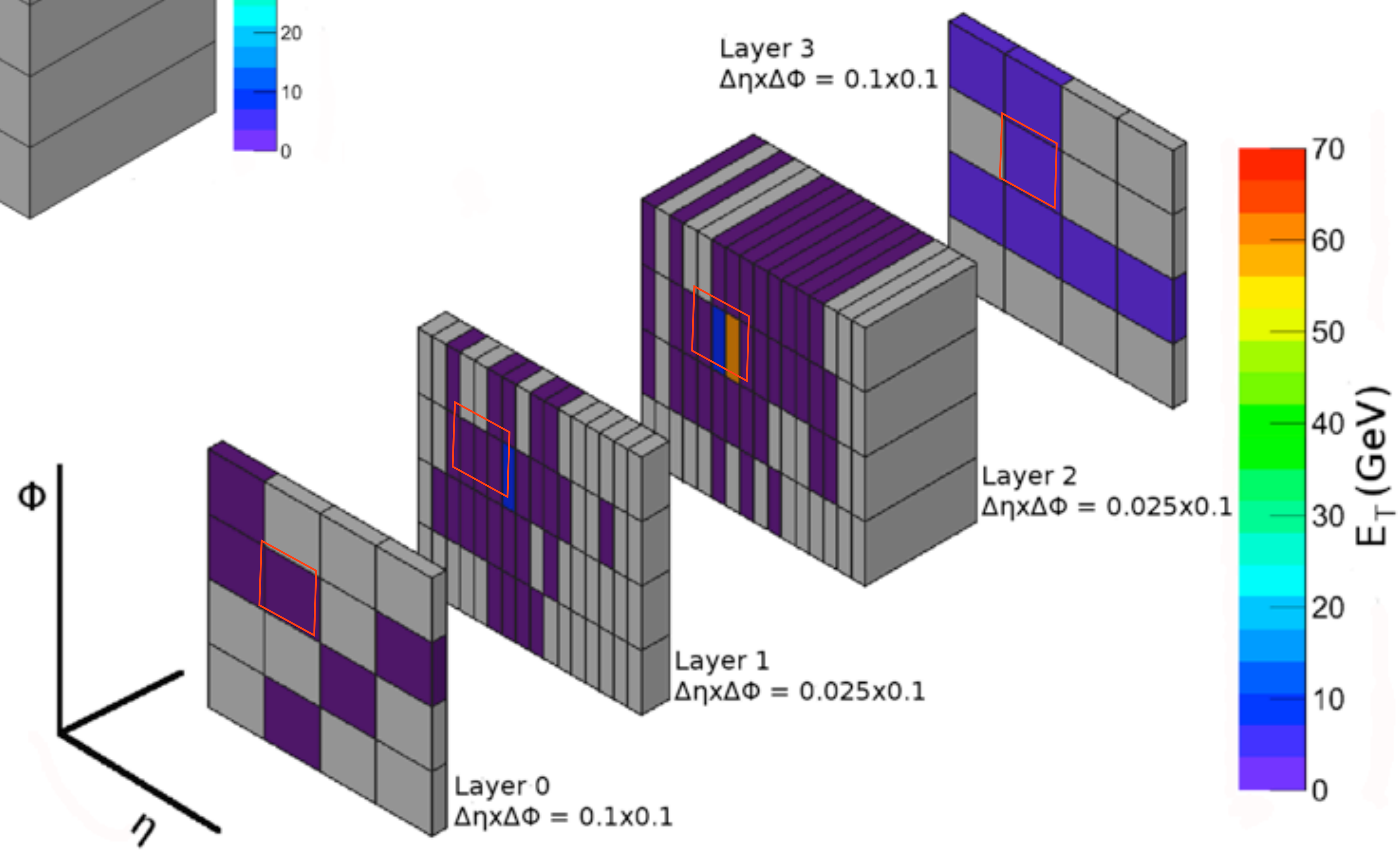
Upgrade electronics to provide to the L1 trigger processors
- higher granularity
- higher energy/spatial resolution
- longitudinal shower information

Phase-1: LAr calorimeter electronics



Current L1 electron trigger

Upgraded L1 electron trigger

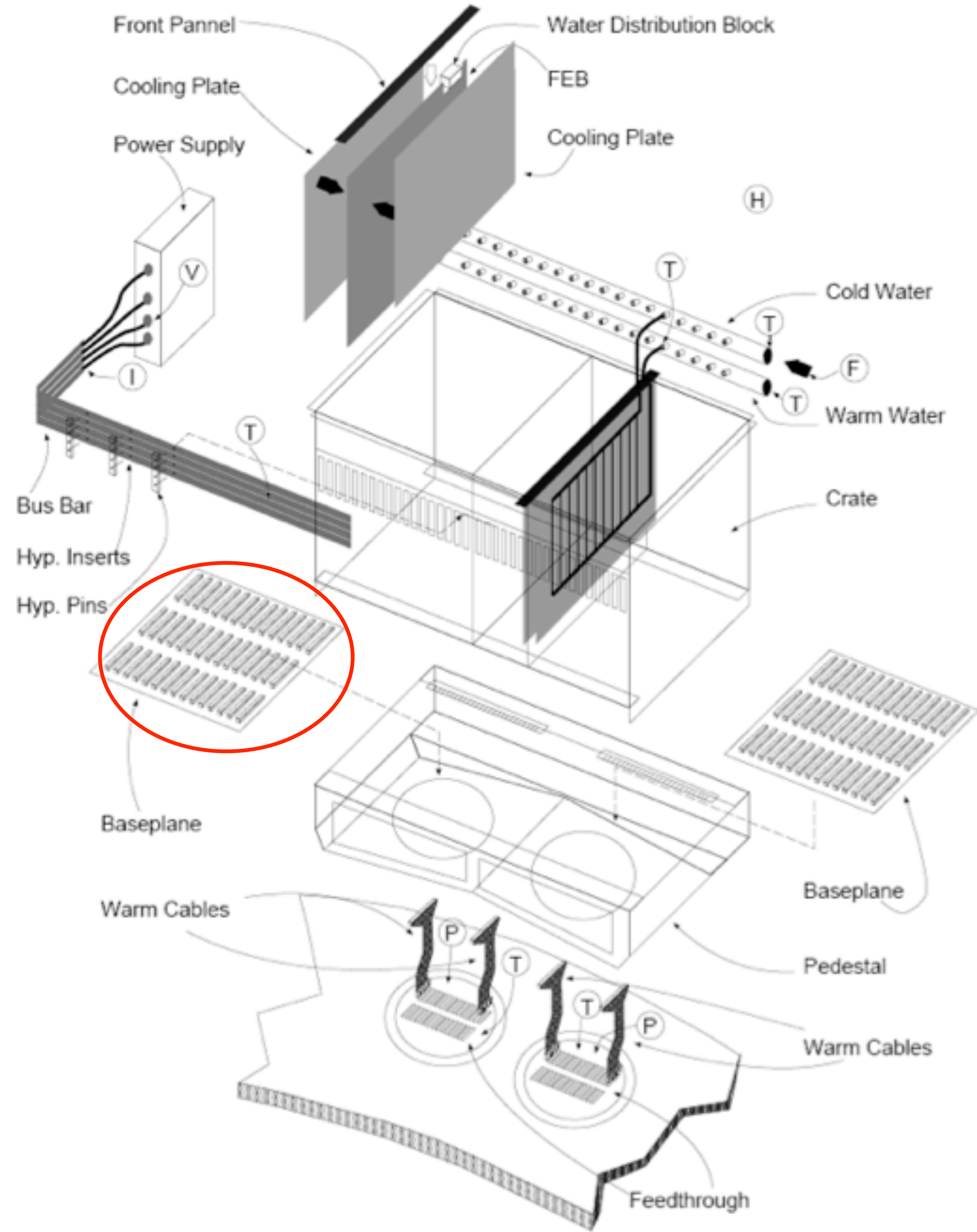


Phase-1: LAr calorimeter electronics

- New baseplane

New electronics data processing frontend boards

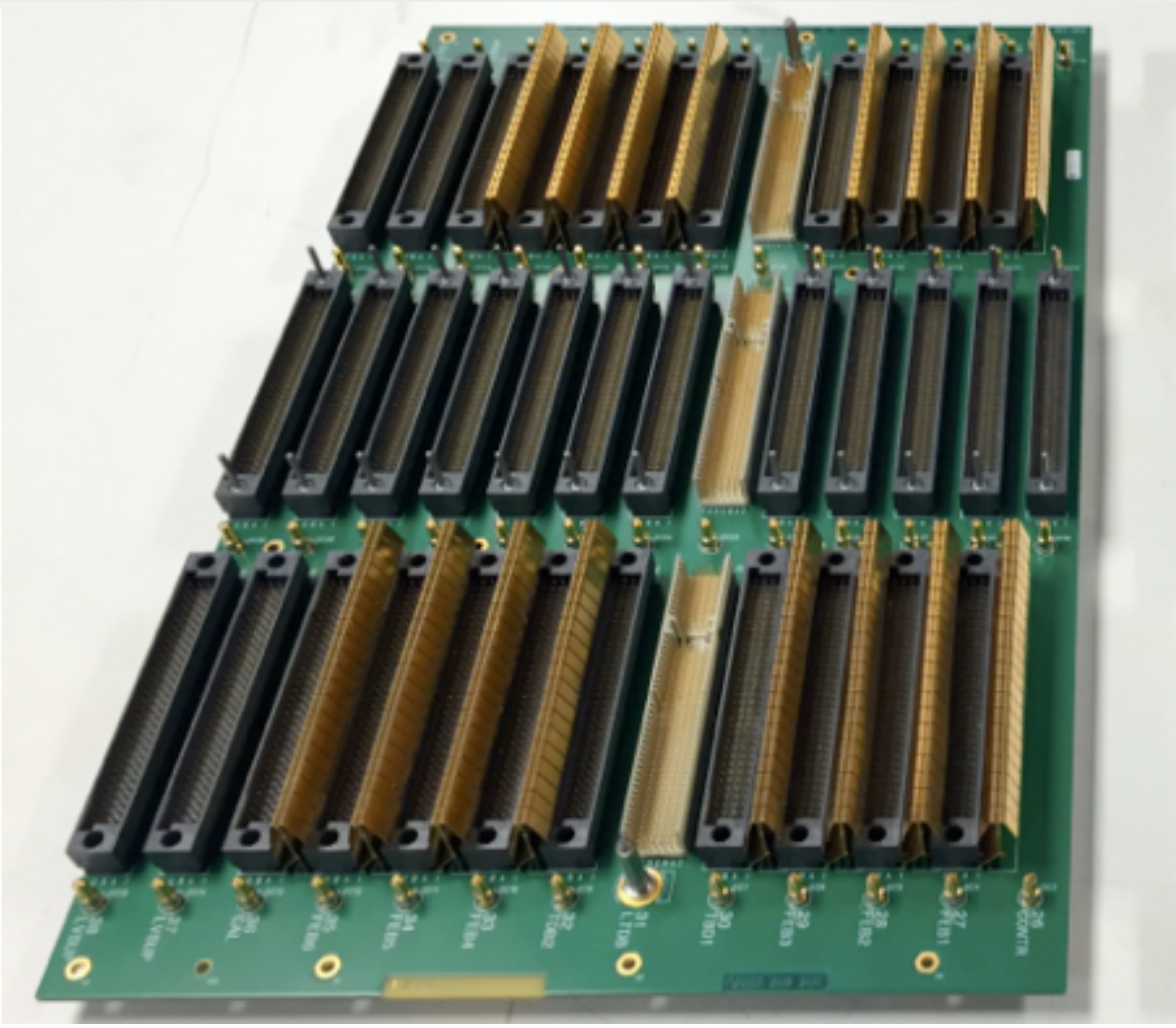
New backend electronics.



Phase-1: LAr calorimeter electronics

UVic, TRIUMF

Design, prototyping, building and testing eight new baseplanes for the Canadian-built Hadronic End-cap Calorimeter (HEC).



Pre-production baseplane at TRIUMF

- Design approved in 2015
- Pre-production boards have been produced and are being tested
- Final review Fall 2016
- Production following approval

ATLAS Upgrades

Address detector radiation damage, and improve ATLAS detector to cope with 5 to 7 x nominal instantaneous luminosity beyond design. Preserve and improve on current detection capabilities.

- Phase-2 upgrades (2024-26)
  - Liquid argon calorimeter electronics
  - Forward calorimeter upgrade
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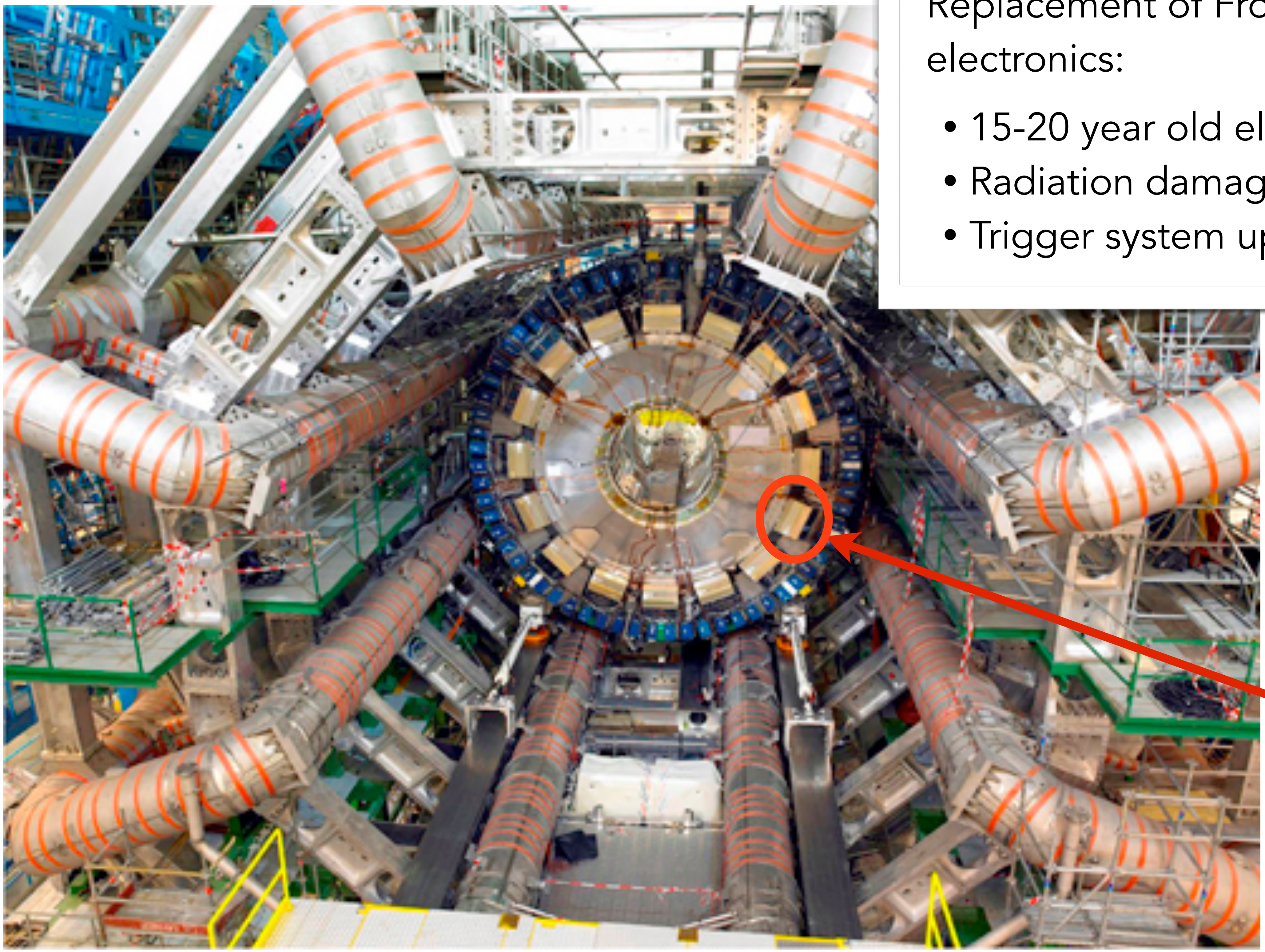
Phase-2: LAr calorimeter electronics

Replacement of FrontEnd and BackEnd electronics:

- 15-20 year old electronics
- Radiation damage
- Trigger system upgrade requirements



FE electronics crates

Phase-2: LAr calorimeter electronics

Legacy readout architecture

Analog on-detector
Level-1 pipeline

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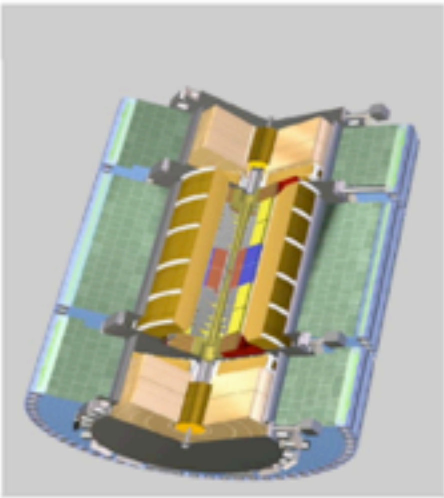
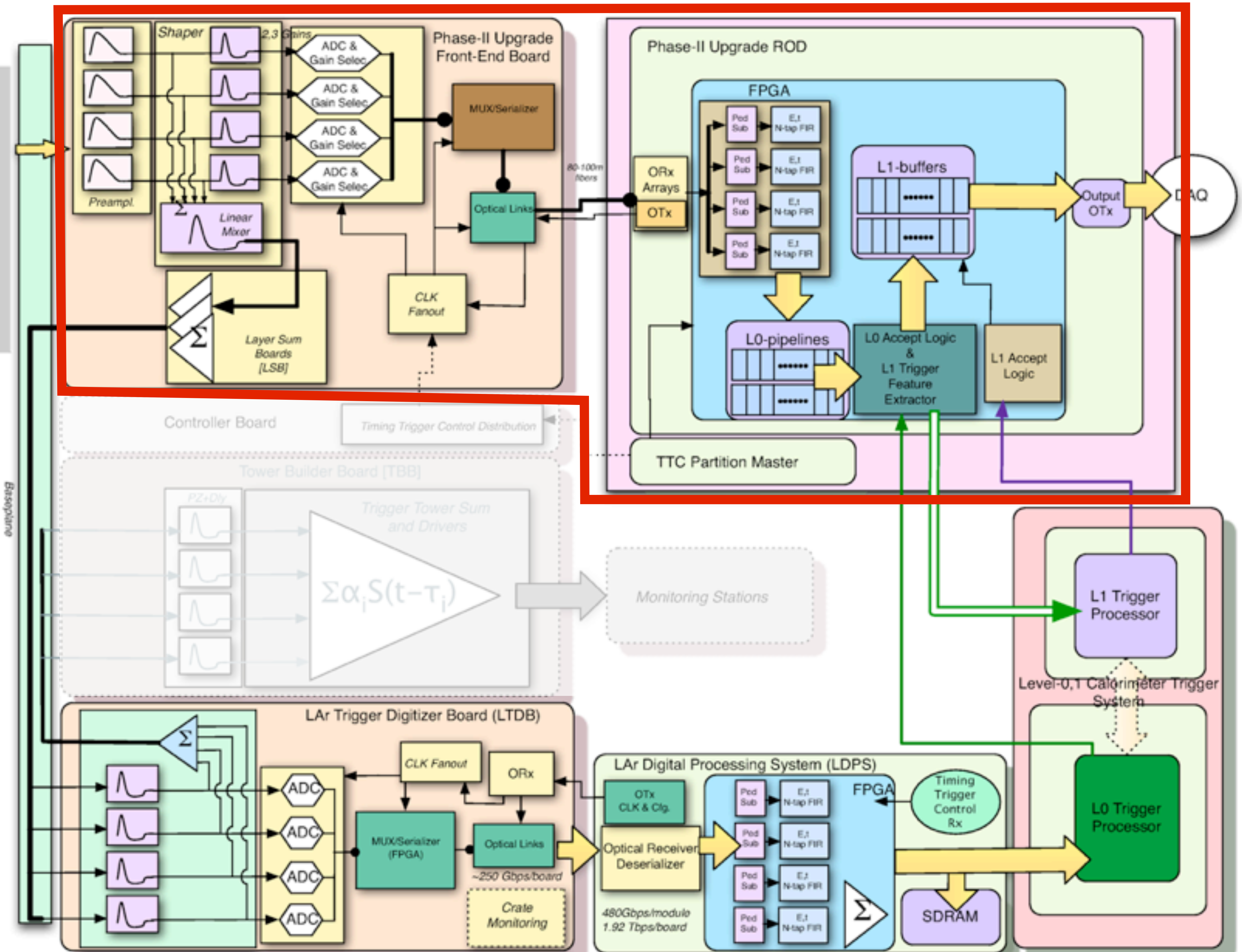
Possible new readout architecture

Signals from all calorimeter cells digitized at 40(80) MHz and sent off-detector for data processing and filtering.

Phase-2: LAr calorimeter electronics





Phase-2: LAr calorimeter electronics

Proposed Canadian contributions (TRIUMF, UVic, McGill)

- Focus on FrontEnd electronics for the Hadronic Endcap Calorimeter
  - Part of Hadronic Endcap Calorimeter built in Canada, substantial expertise in Canada
  - Unique LAr calorimeter system → cold preamplifiers in cryostat.
  - Help define specs for "warm" amplifier, design of amplifier, construct full mock-up readout chain for validation, simulation, and possible FrontEnd boards testing.
- BackEnd electronics
  - Development of optimal filtering algorithms and firmware development contributions.

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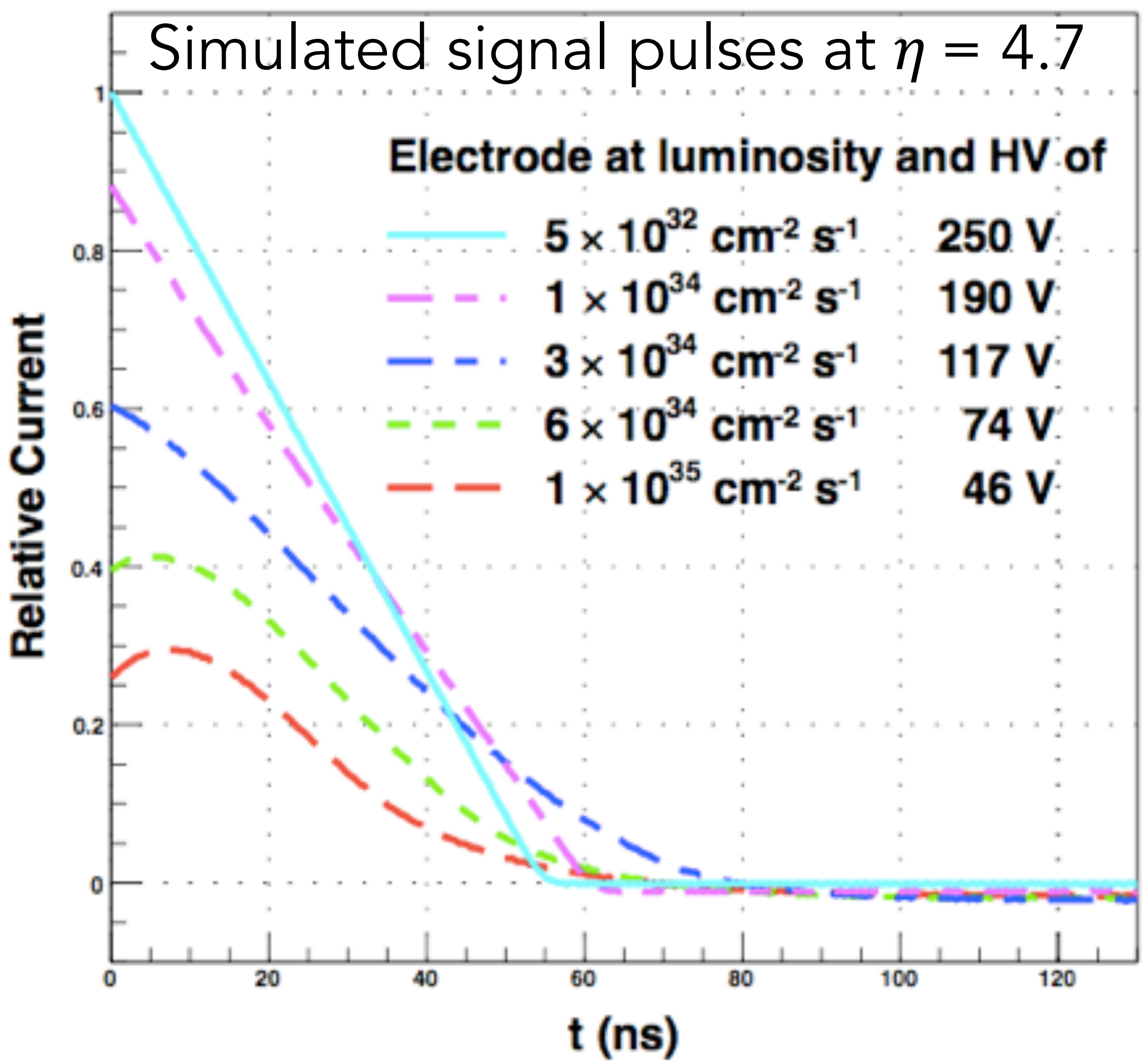
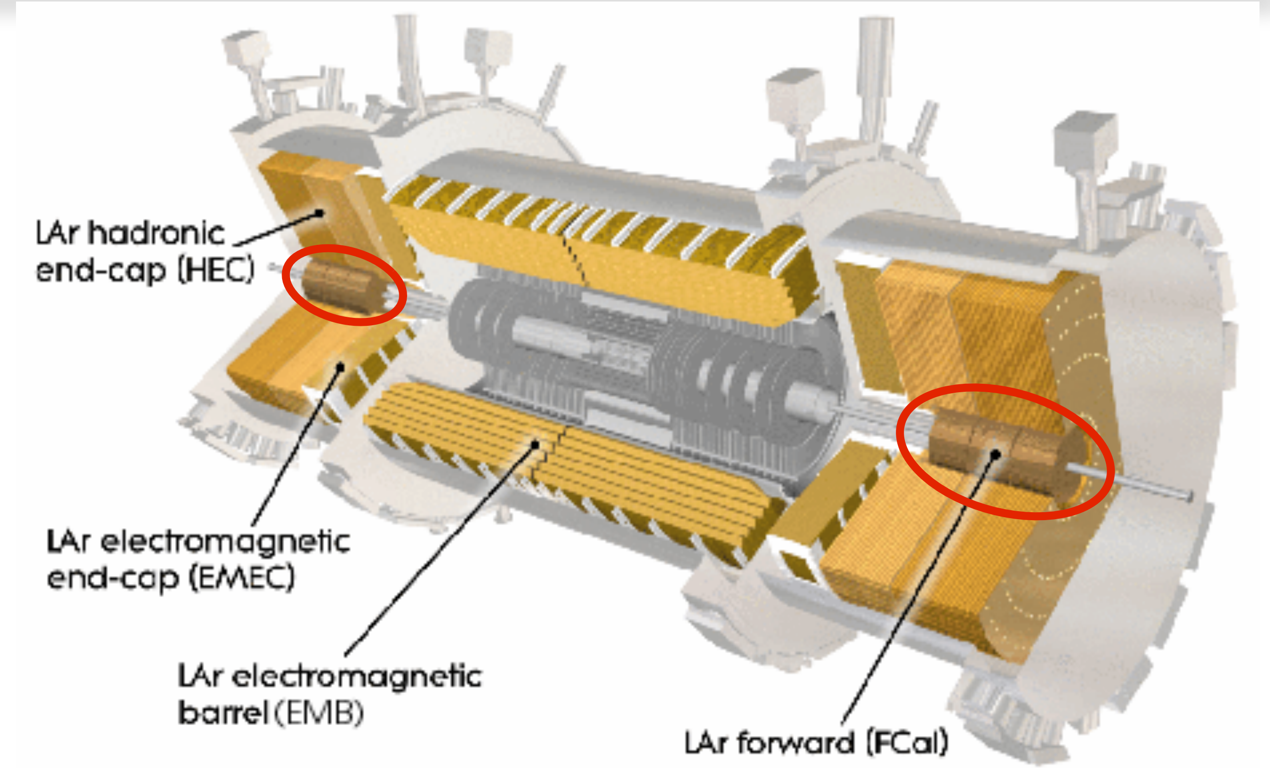
Phase-2: Forward calorimeter upgrade

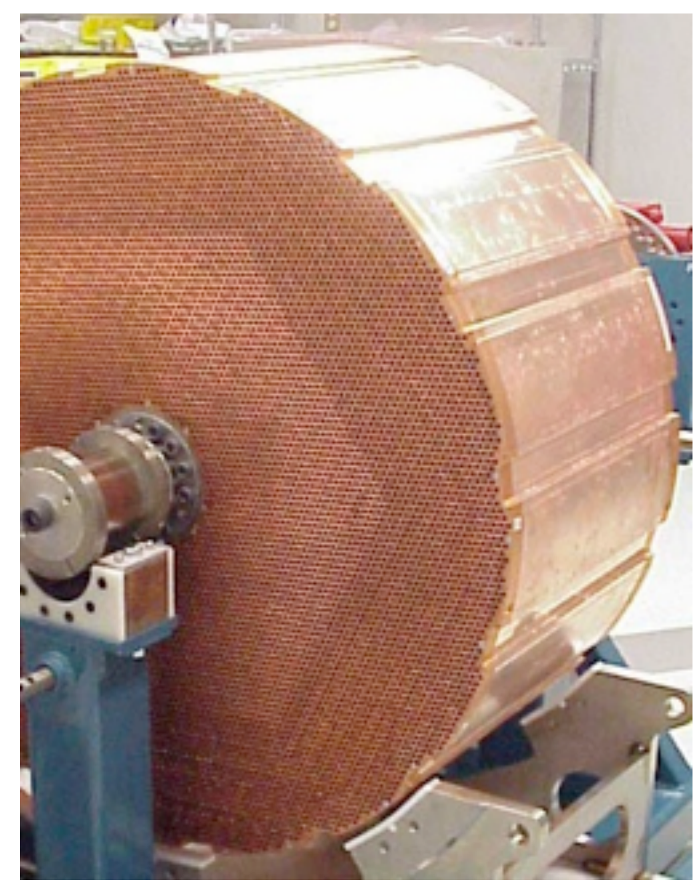
Degraded forward calorimeter performance at HL-LHC

- Ion buildup
- HV sagging

CERN-LHCC-2012-022







Phase-2: Forward calorimeter upgrade

Two options being considered:

1) Replace entire FCAL by new sFCAL
2) Do nothing

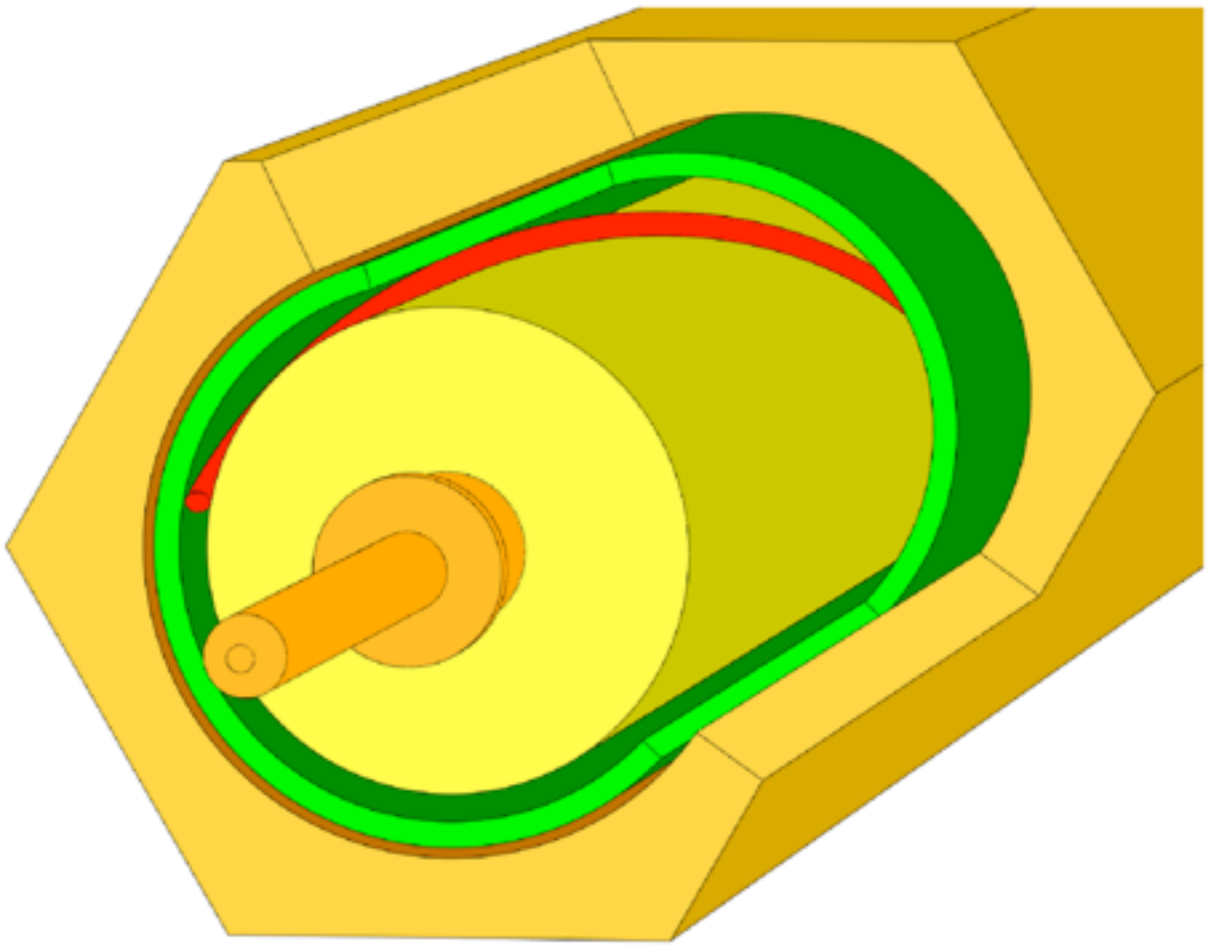
Phase-2: Forward calorimeter upgrade

Two options being considered:

1) Replace entire FCAL by new sFCAL

2) Do nothing

- Reduced size of LAr gap from 260 μm to ~ 100 μm.
- Improved readout granularity.



Phase-2: Forward calorimeter upgrade

Two options being considered:

1) Replace entire FCAL by new sFCAL
2) Do nothing

Studies of precise extent of performance deterioration and risk assessment underway.

⇩

Decision expected by end of July 2016.

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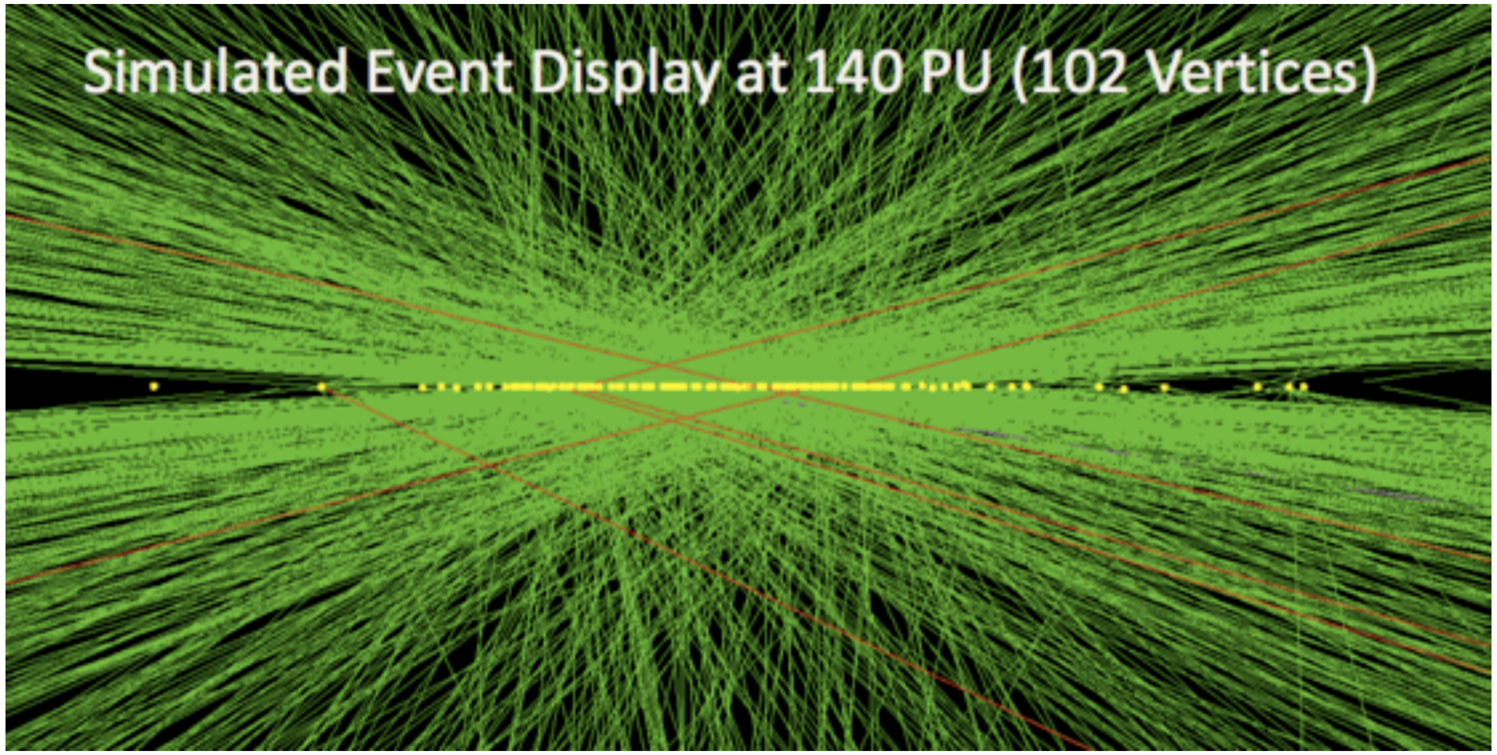
Phase-2: Inner Tracker

Highly performant tracker essential for all ATLAS physics program.

The tracker must reconstruct primary vertices and identify the one associated with the hard scattering event of interest.

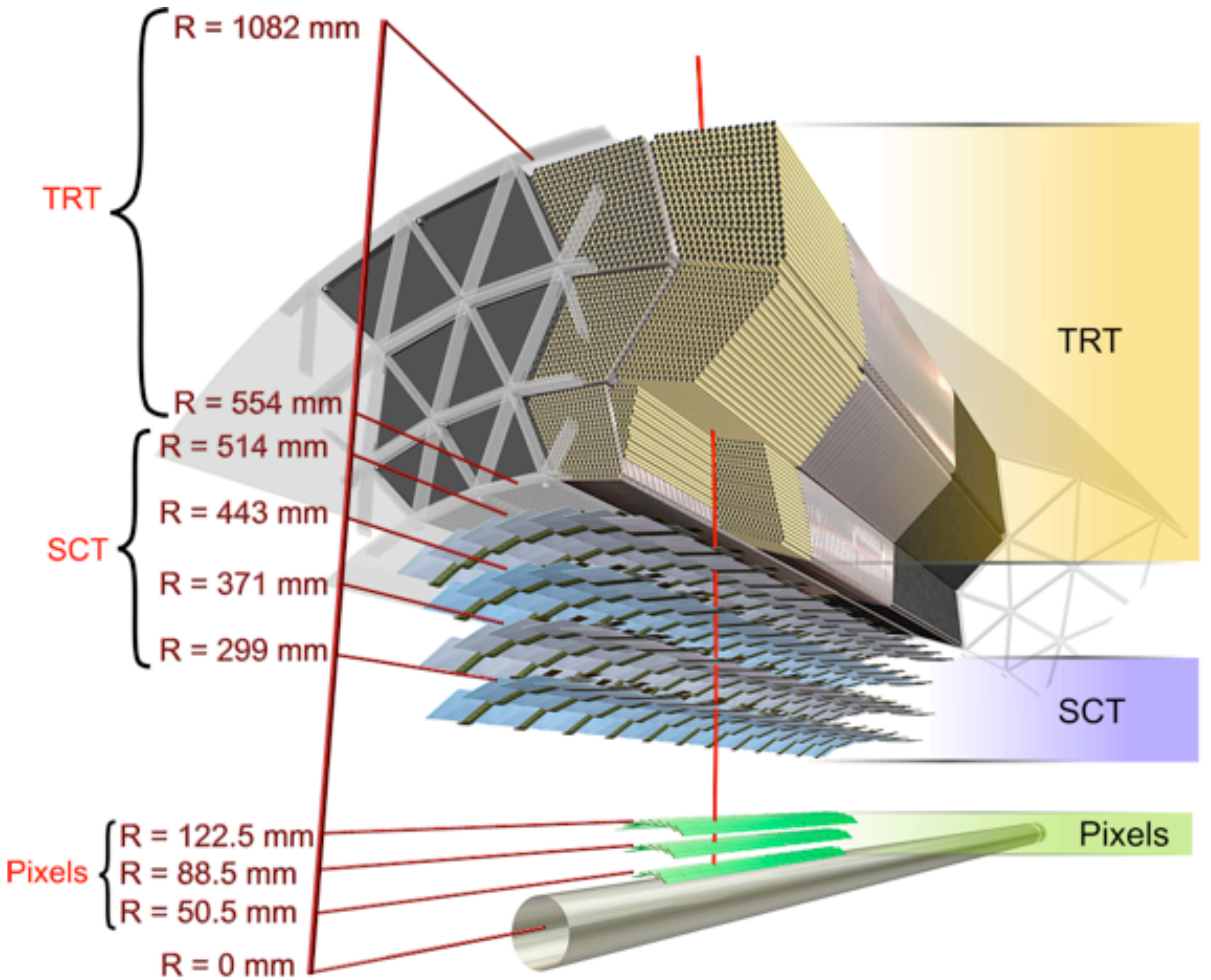
Vertex information increasingly used to improve jet energy measurements, identify isolated particles, and in reconstructing missing transverse energy.

Need to withstand radiation conditions at HL-LHC.



Phase-2: Inner Tracker

Existing inner detector cannot survive planned high luminosity operation at HL-LHC nor meet performance requirements.

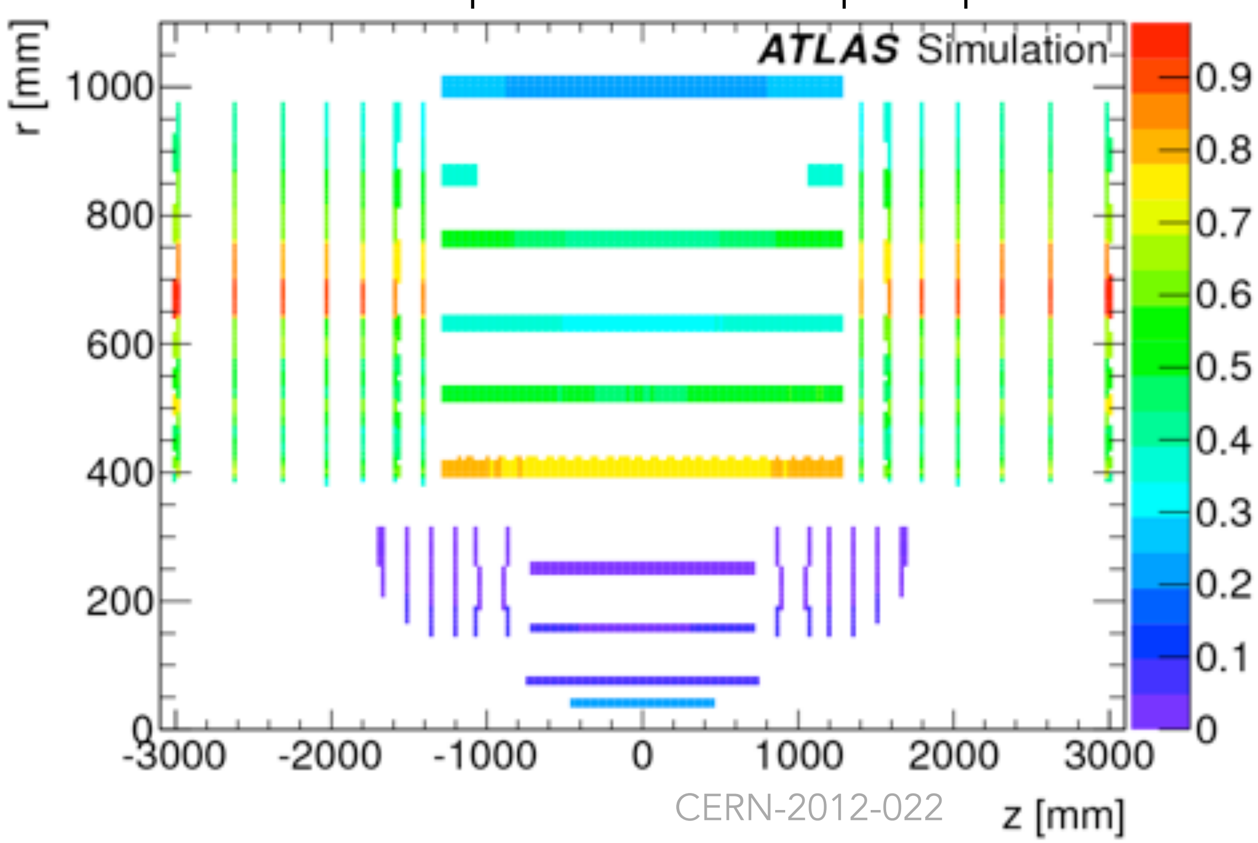


Phase-2: Inner Tracker

Existing inner detector cannot survive planned high luminosity operation at HL-LHC nor meet performance requirements.

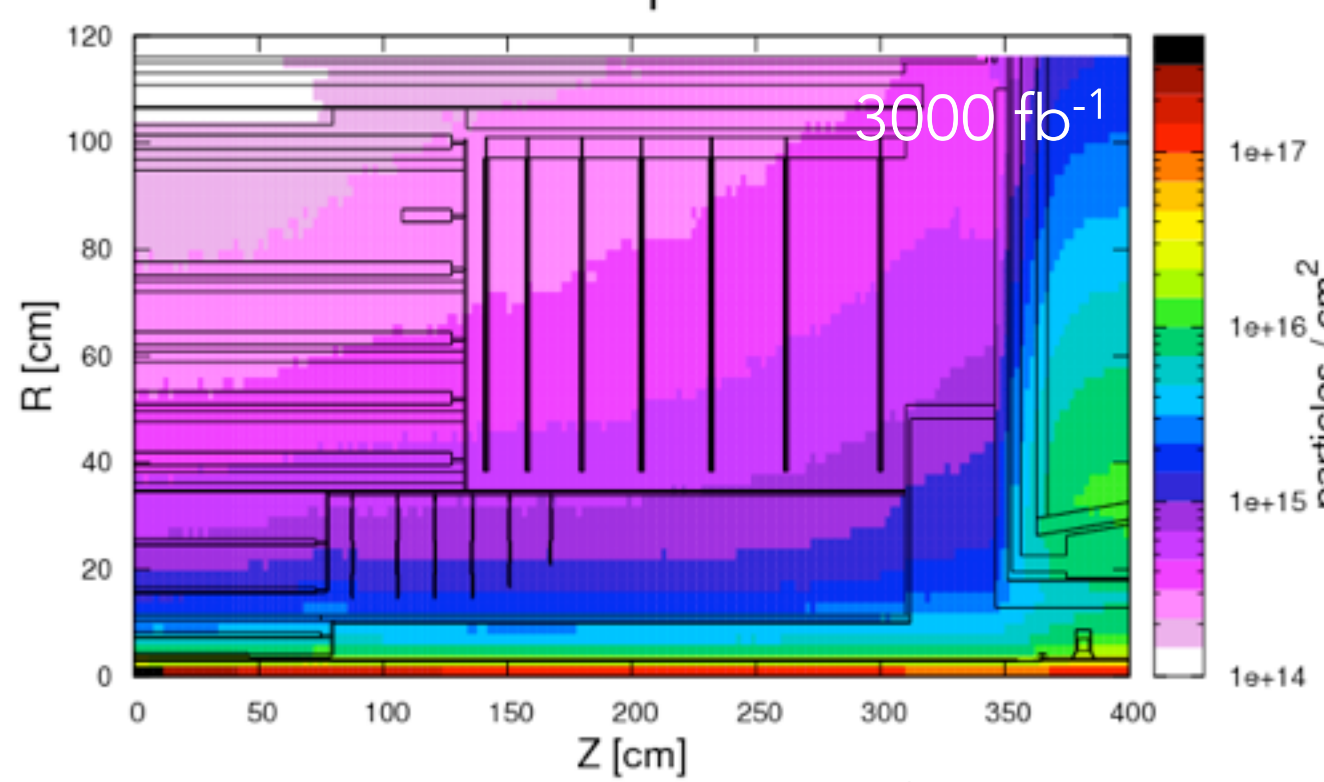
- Radiation damage
- Occupancy
- Bandwidth saturation

Channel occupancies with 200 pile-up events



CERN-2012-022

1 MeV neutron equivalent fluence



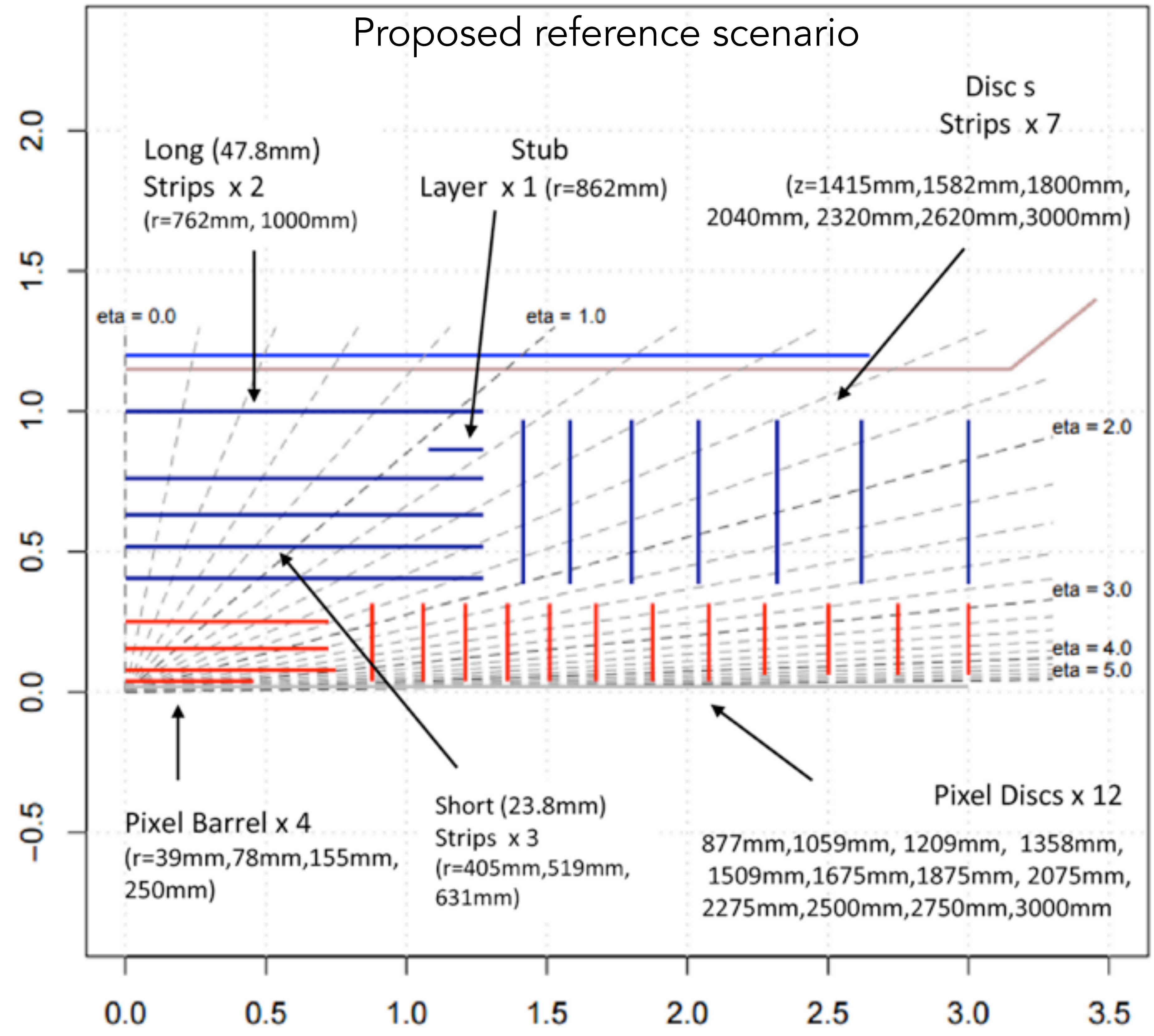
CERN-2012-022

Phase-2: Inner Tracker

All silicon detector (pixels and strips)

About 200 m^2 of silicon!

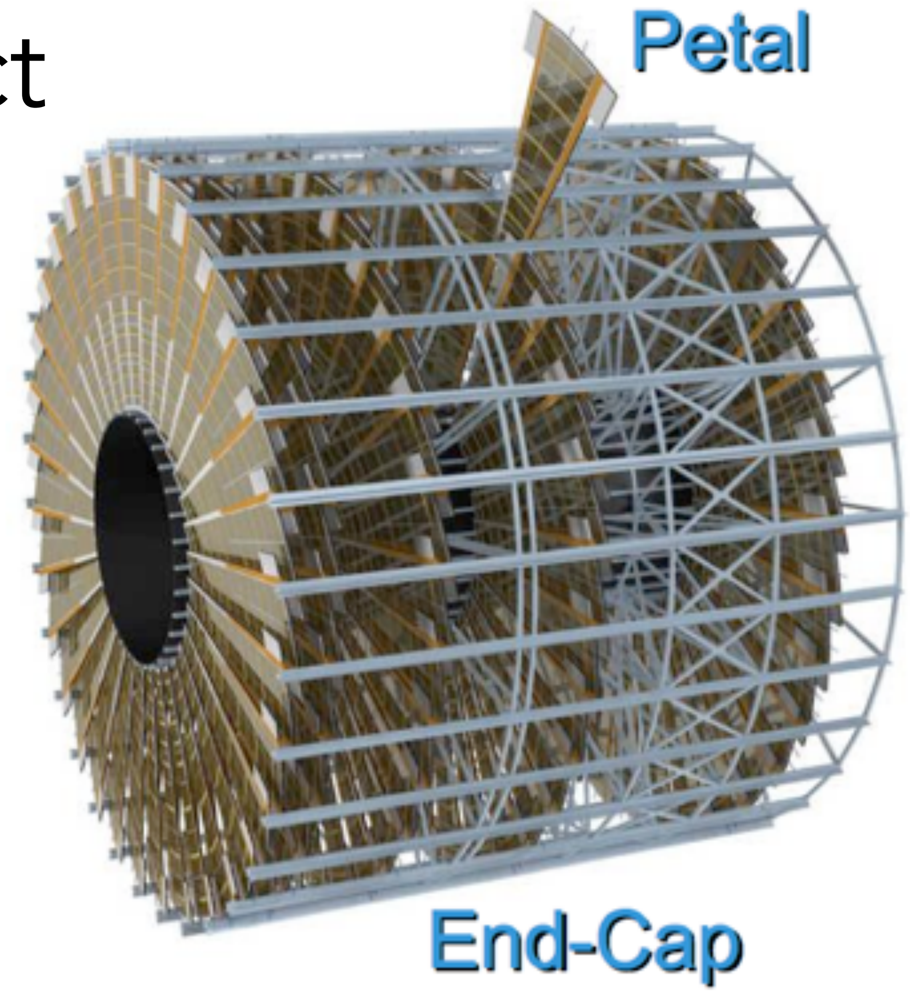
Approximately half the cost/efforts of Phase-2 upgrades.



Phase-2: Inner Tracker

Canadian group plans to construct modules of the endcap strips detector. 🍁

- ~ 1,500 modules (out of 18,000)
- ~ 2.6 wheels (84 petals)



Eastern cluster (Carleton, Montreal, Toronto, York)

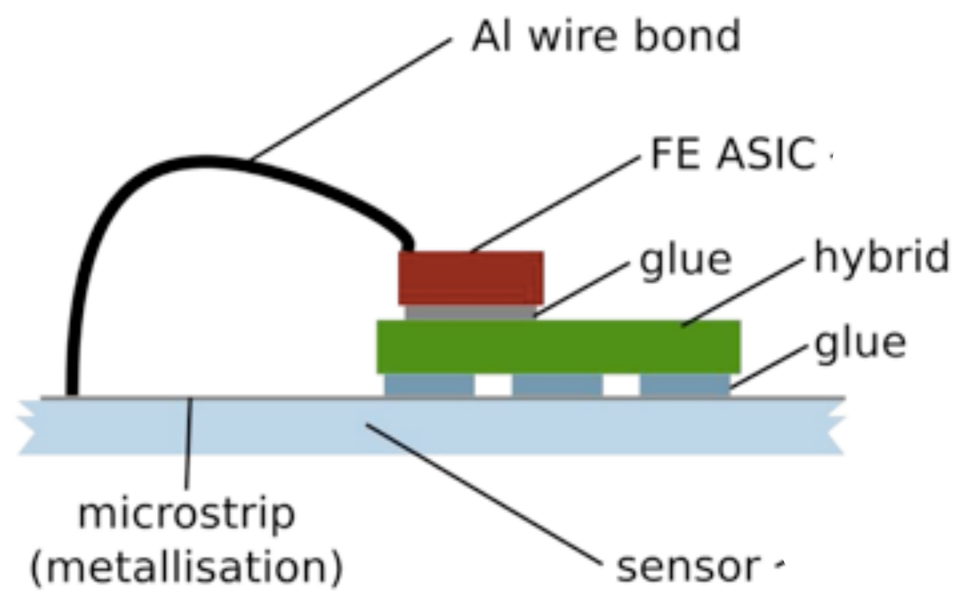
- Industry partnership for some production steps

Western cluster (SFU, TRIUMF, UBC)

- Module production and petal placement at TRIUMF.

Phase-2: Inner Tracker

ITk strip module production



Glue ASIC to hybrid

↓

Wire bond ASIC to hybrid

↓

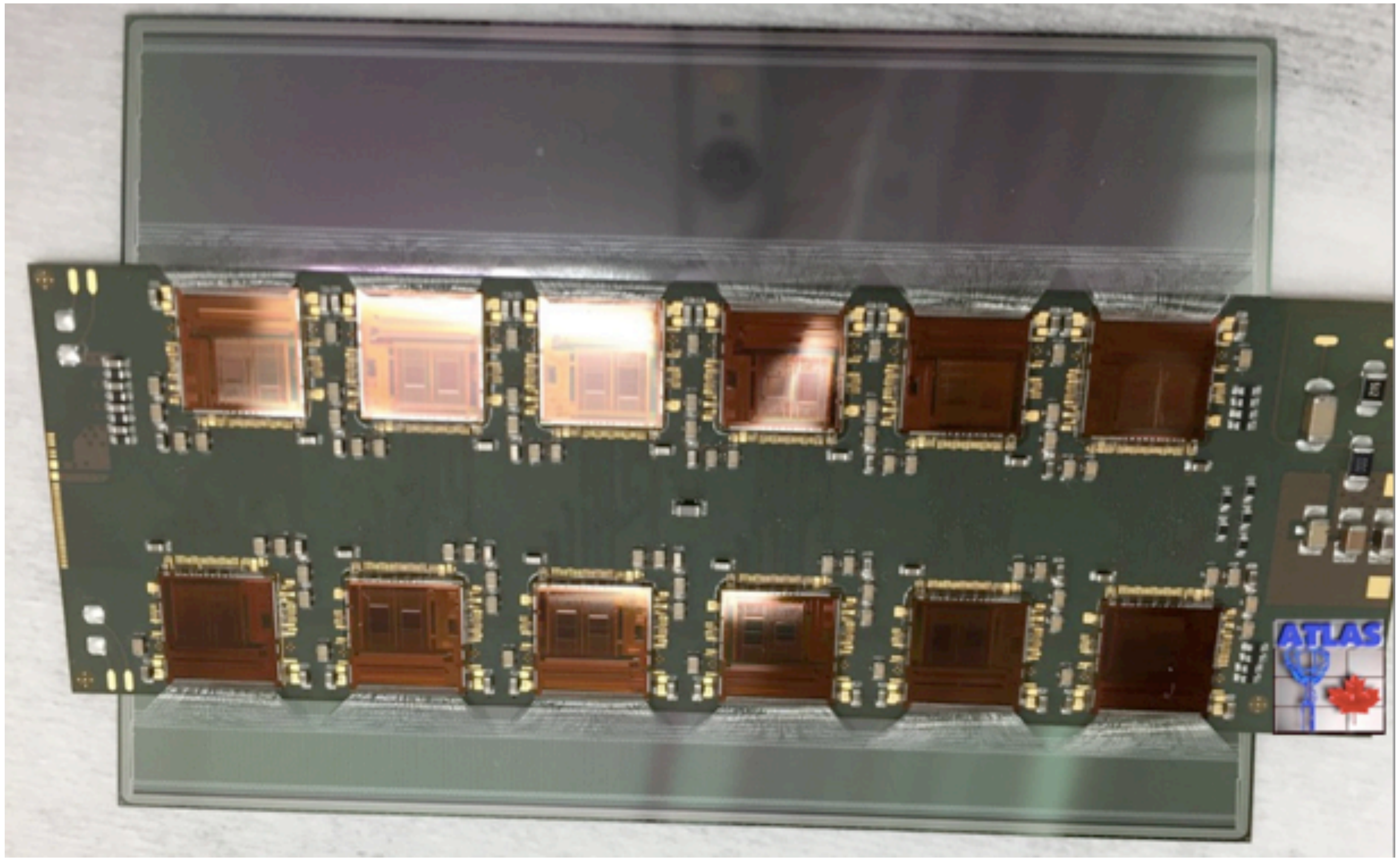
Glue hybrid to sensor

↓

Wire bond ASIC to sensor

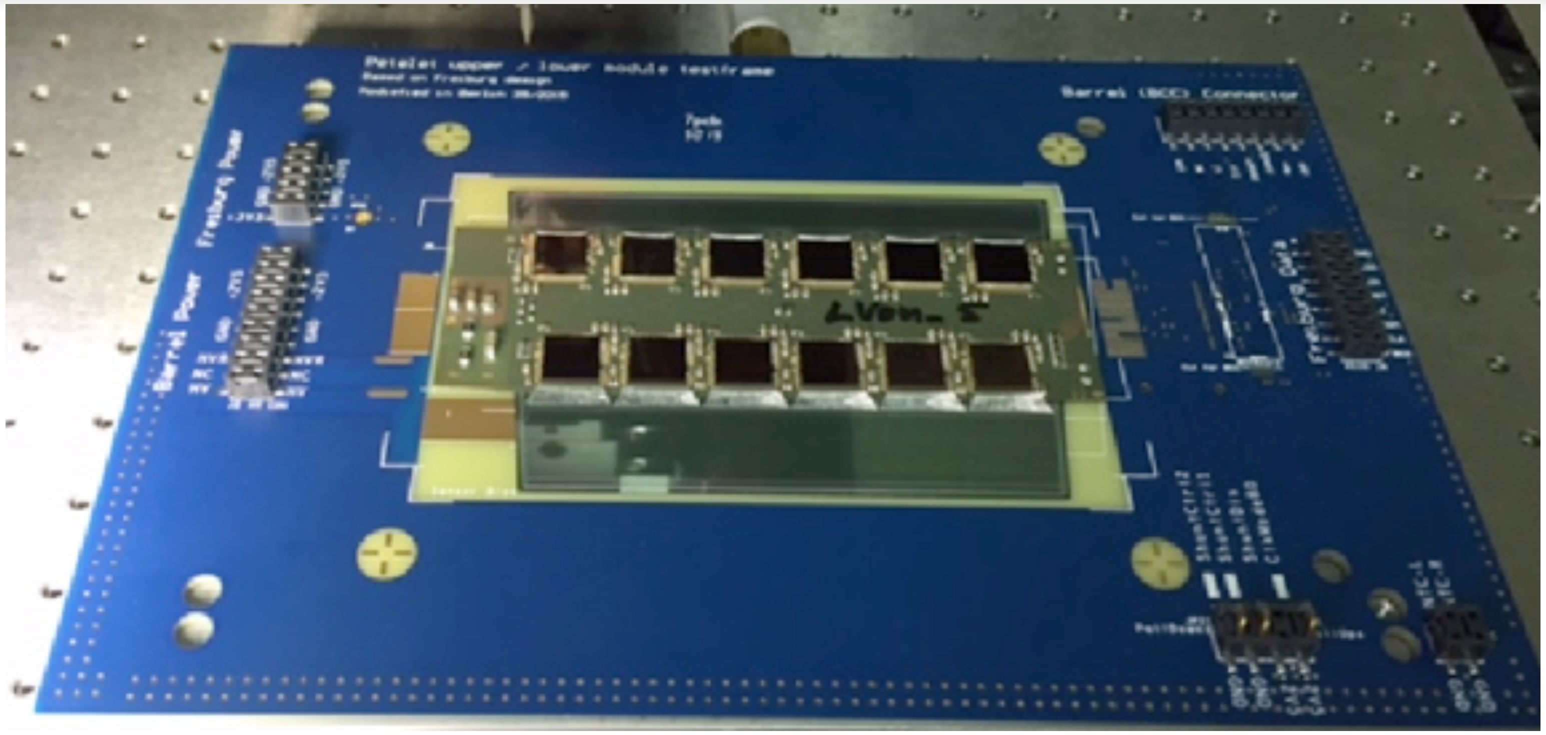
↓

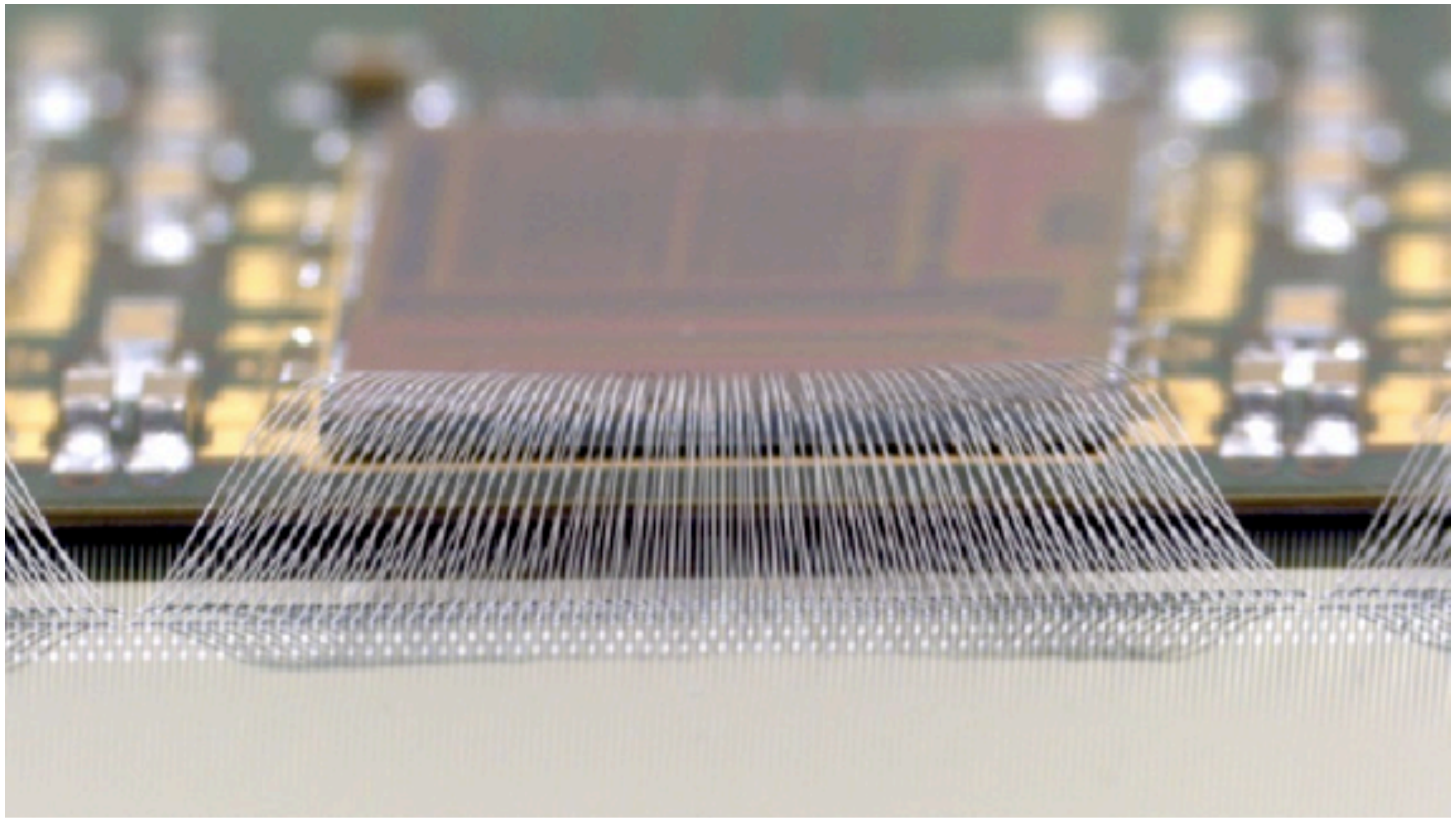
Assemble modules into petals.



Phase-2: Inner Tracker

Both Eastern and Western sites have succeeded in producing a prototype module.





Next steps:

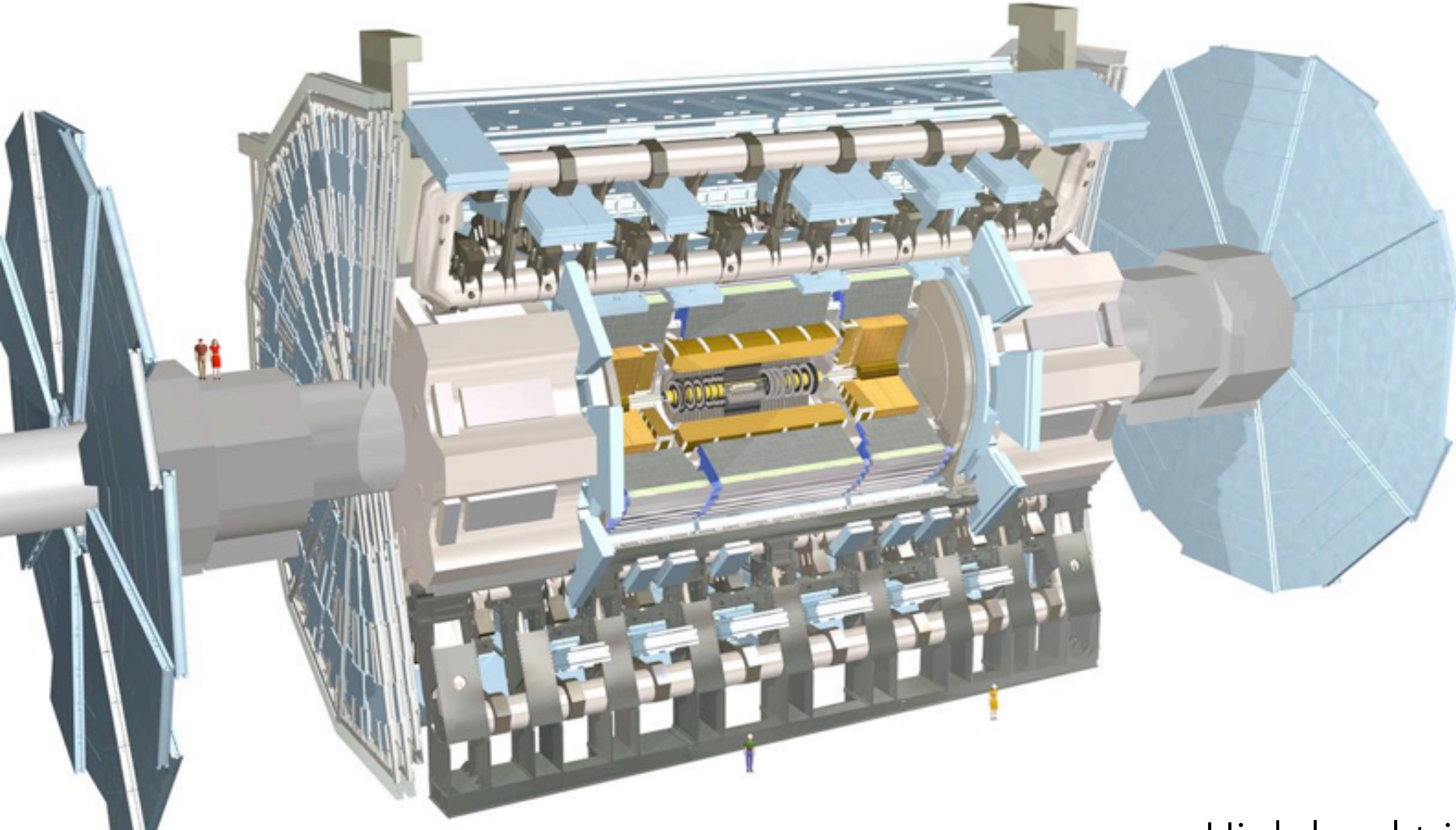
- Qualify 2 production sites over the next year.
- Prepare for pre-production ~ 2017.
- Start full production ~ 2018.

Summary

- Rich ATLAS physics program over the next ~ 20 years.
- LHC approved upgrade plan to deliver 3000 fb^{-1} at 14 TeV.
- Major upgrades to the ATLAS detector are needed to maintain adequate physics performance.
  - Phase-1 (2019-20)
  - Phase-2 (2024-26)
- Important Canadian contributions to ATLAS upgrades commensurate with Canadian representation.
  - Muon small wheel, LAr electronics, Inner tracker, (forward calorimeter)
- Excellent (hardware) training opportunities for students.

Backup

Canadian hardware contributions



- Hadronic Endcap LAr Calorimeter
- Hadronic Forward LAr Calorimeter
- LAr calorimeter FE electronics
- LAr endcap signal feedthroughs

- High level trigger
- Beam conditions monitors (lumi)
- Cavern bkg monitors (lumi)
- LUCID luminosity monitor
- Inner detector readout

Phase-1: New muon small wheel

Provide 1 mrad angular resolution (< 100 μm single-hit resolution)

High muon detection efficiency (> 95%) over entire (large!) detector area

Operate efficiently for > 10 years

Tolerate high particle fluence expected during running period

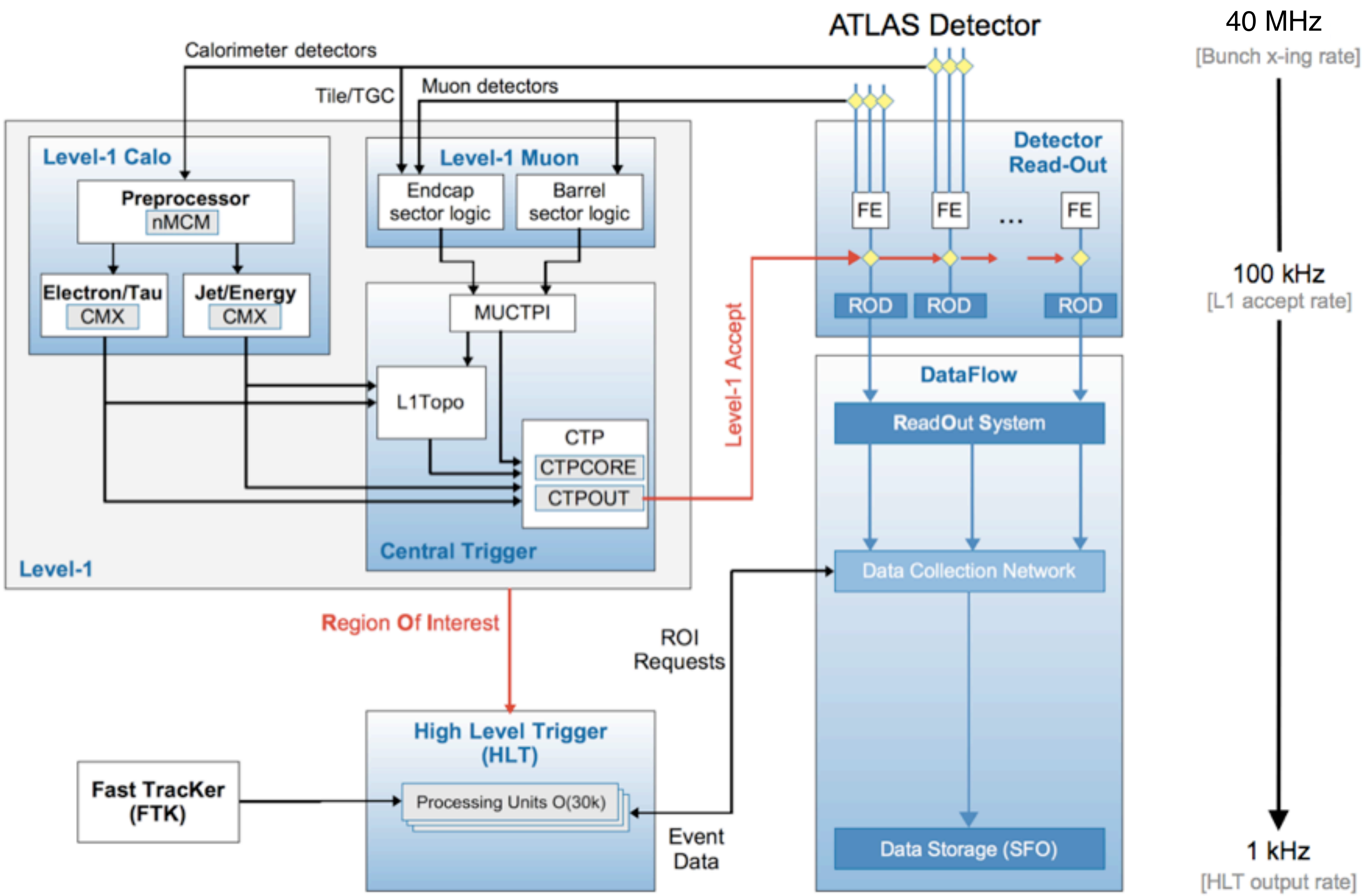
Neutron flux with E > 20 MeV greater than 2×10^{11} cm^{-2} $year^{-1}$

Total Ionizing Dose over 10 years ~ 0.5 Mrad

No significant aging reducing efficiency for up to about 1 C/cm^2

High efficiency up to rates of ~ 15 kHz/cm^2

ATLAS trigger system

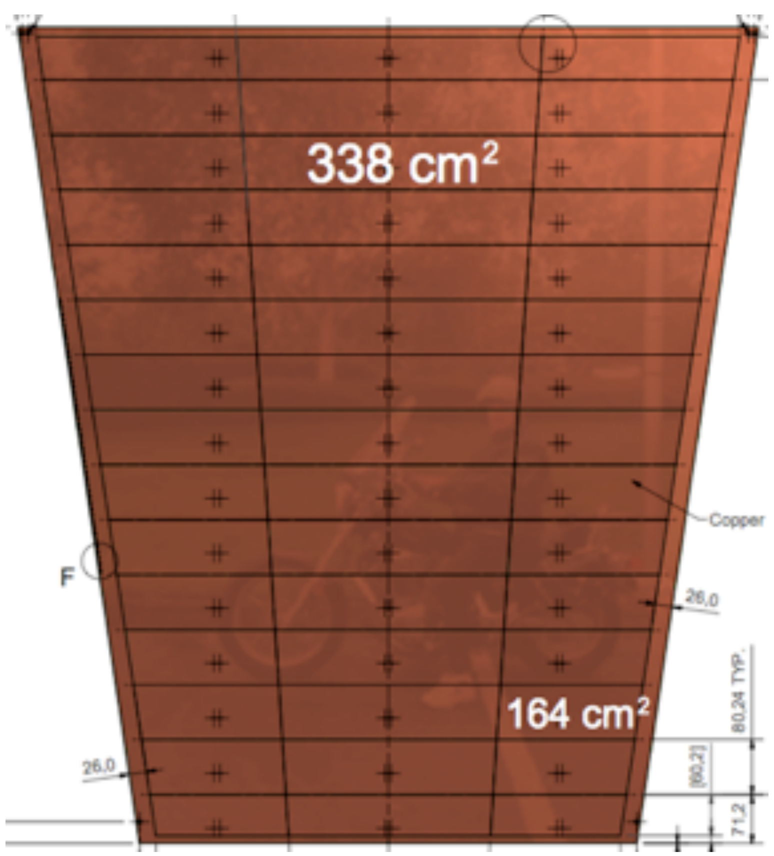


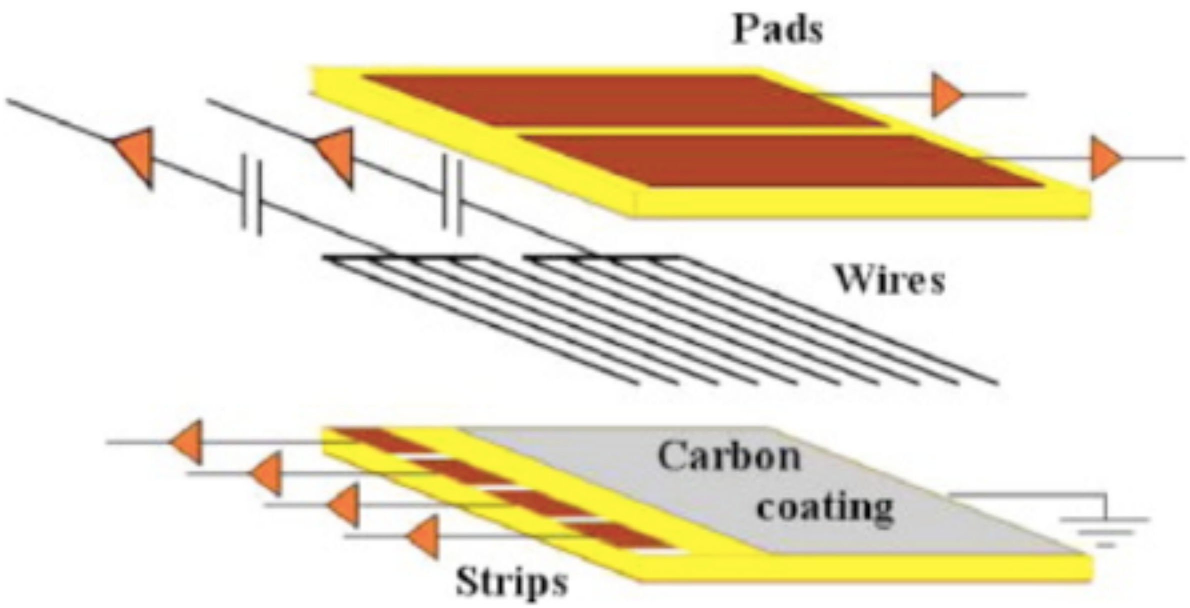
Phase-1: Thin Gap Chambers

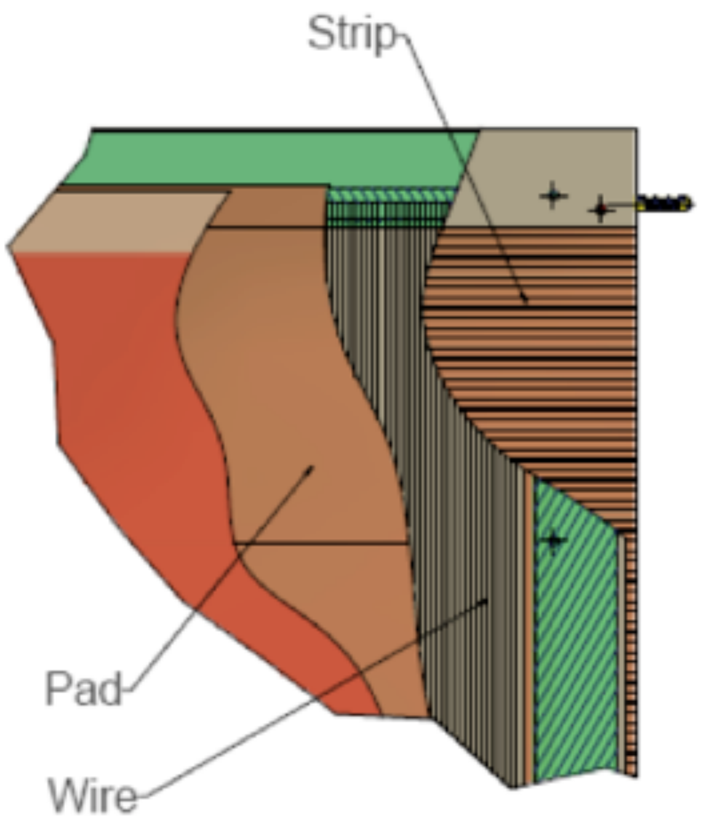
Wires (~ 30 wires ganged together)

Strips with 3.2 mm pitch
Pitch optimized to get best spatial resolution with lowest number of readout channels.

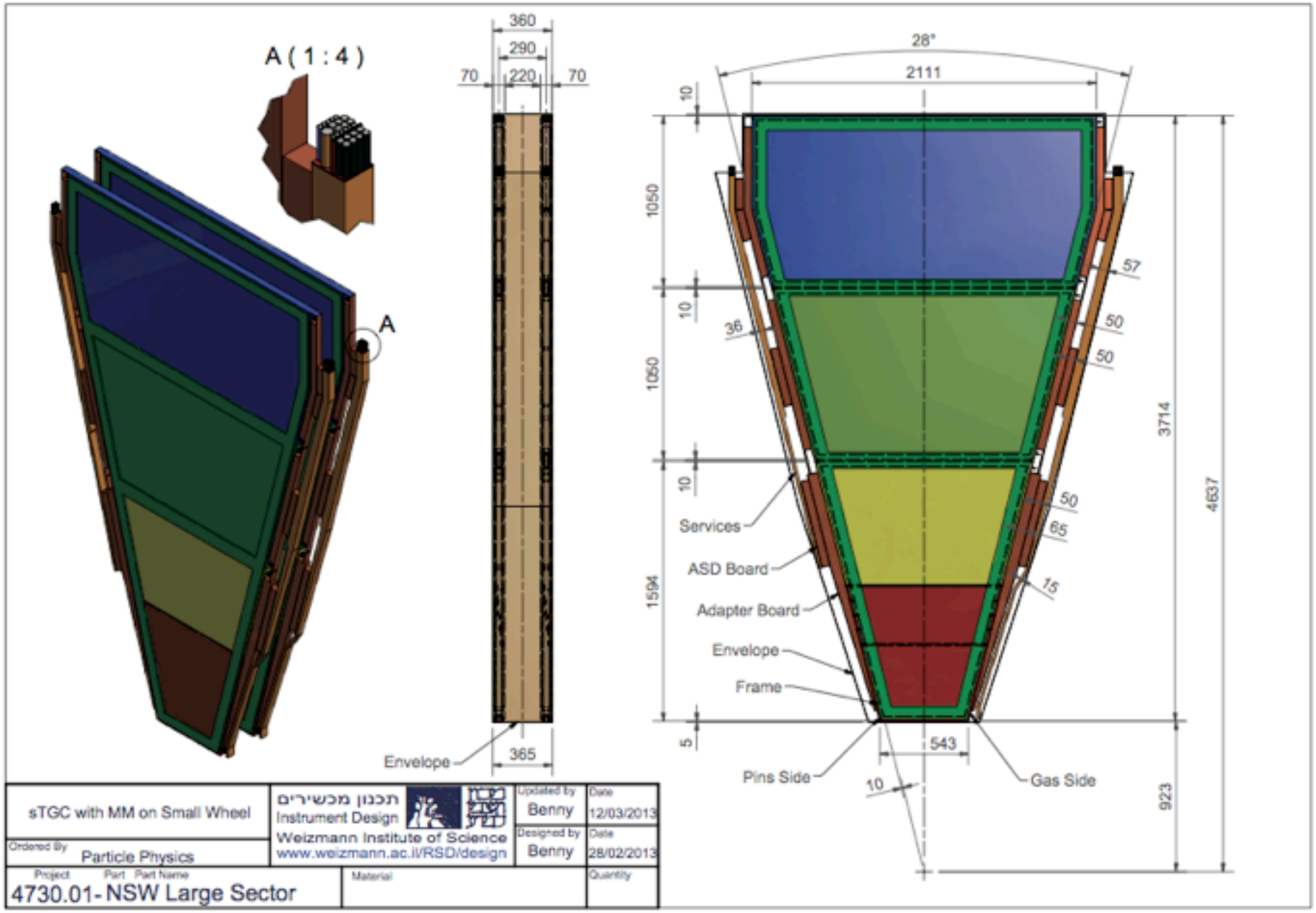
Pads (varying sizes)



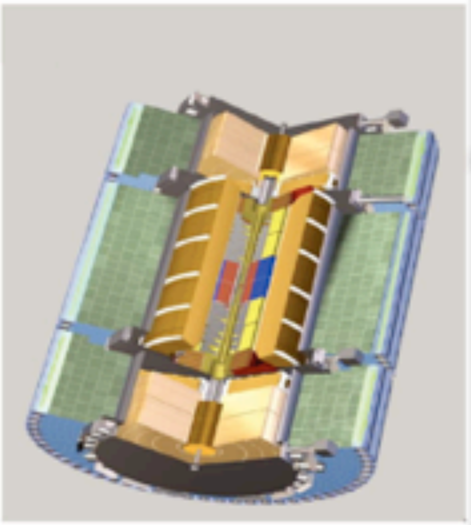


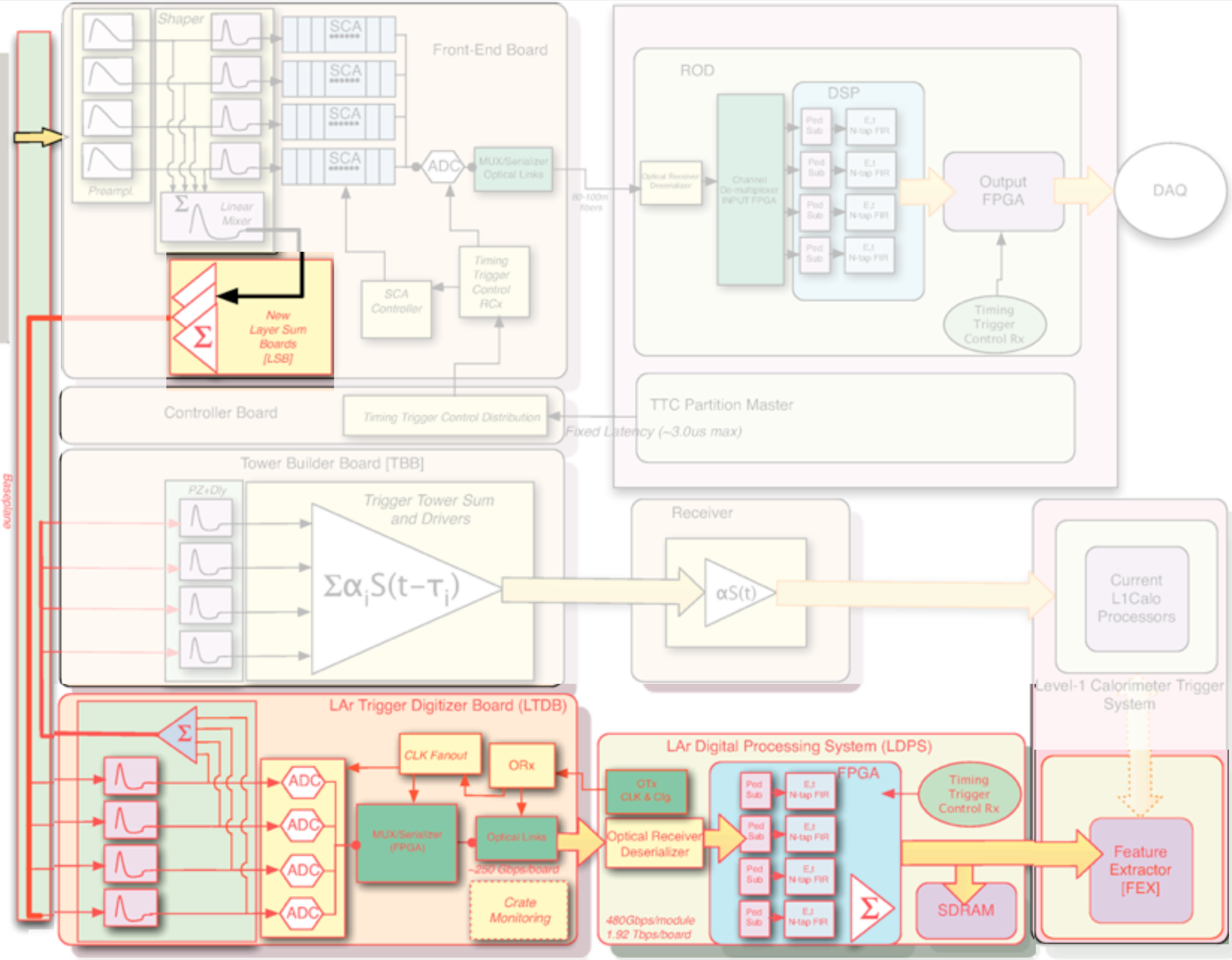


Phase-1: TGC Quadruplets



Phase-1: LAr calorimeter electronics





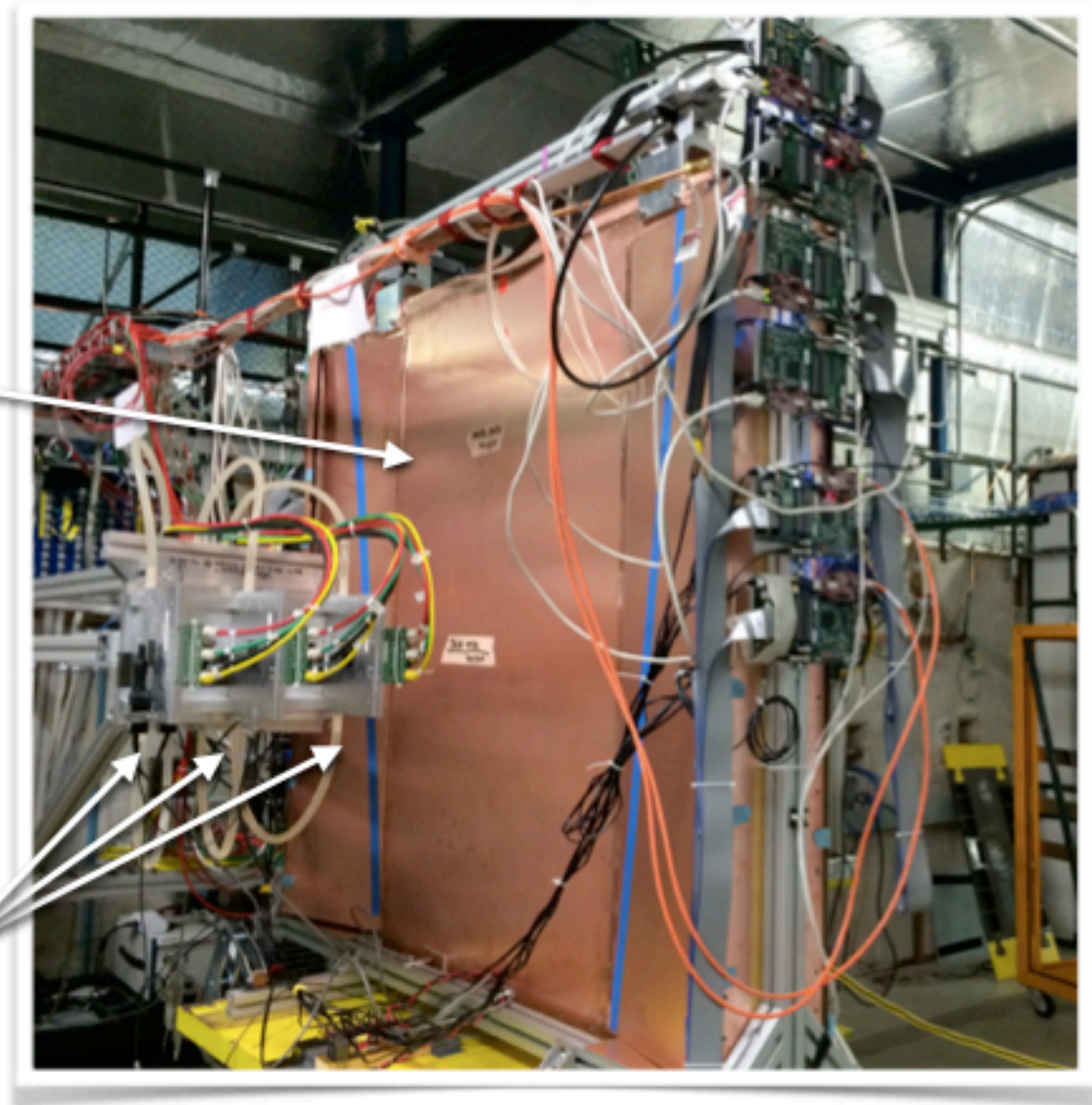
TGC testbeam

Experimental setup at Fermilab

sTGC quadruplet
(Module -1)
Operating voltage 2.9 kV
Gas: 55% CO_2, 45% n-pentane
Readout: VMM1

Beam
32 GeV pions
Rate ~1kHz/cm^2

3+3 pixel layer telescope
(3 layers on the other side)



sTGC chamber on top of a movable table,
allowed beam testing different regions of the chamber