ATLAS detector upgrade strategies

A. Salzburger, CERN
for the ATLAS Collaboration
ICPP Istanbul II, 20-25 June 2011

Introduction

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- LHC performance and physics prospects
  - luminosity figures and run scenarios
  - physics perspectives

ICPP 2011

- The multi-phase detector upgrade plans
  - Phase 0, I, II
- Simulation Strategies & Lessons from Run I
  - lessons for future detector design
  - lessons on detector understanding
  - algorithmic challenges and future technologies
- Considerations & Outlook

some grain of salt ...

http://wiki.chemprime.chemeddl.org/index.php/Lattices_and_Unit_Cells_with_Cultural_Connections

(Possible) LHC time-line

2009 — **Start of LHC - 2009: $\sqrt{s}$ = 900 GeV**

2010, 2011 — **Run 1: $\sqrt{s}$ = 7 TeV** (2012: 8-9 TeV ?) **, L = 2 x 10^{33} cm^{-2}s^{-1}**
Bunch spacing: 75/50/25 (tests 2011, 2012 ?) **ns**
~10 fm^{-1}

2012

2013 — **LHC shutdown to prepare for design energy and *nominal* luminosity**

2014

2015, 2016 — **Run 2: $\sqrt{s}$ = 14 TeV, L = 1 x 10^{34} cm^{-2}s^{-1}**
Bunch spacing: 25 ns ? (what to do with electron clouds ?)
~50 fm^{-1}

2017

2018 — **Injector and LHC Phase-I upgrade to go to *ultimate* luminosity**

2019, 2020, 2021 — **Run 3: $\sqrt{s}$ = 14 TeV, L = 2 x 10^{34} cm^{-2}s^{-1}**
Bunch spacing: 25 ns
~300 fm^{-1}

2022 — **High-luminosity LHC (*HL-LHC*), crab cavities**

2023, ..., **2030** — **Run 4: $\sqrt{s}$ = 14 TeV, L = 5 x 10^{34} cm^{-2}s^{-1}**
Bunch spacing: 25 ns
~3000 fm^{-1}

$\int L\, dt$

Possible ATLAS Upgrade time-line

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Present ATLAS detector

Many outstanding physics and performance results,
improve detector understanding and modeling in simulation

Phase 0

New innermost pixel layer (IBL)
removal of Minimum Bias Scintillators, detector consolidation of Muon System, new neutron shielding

Phase I

Under consideration: new pixel detector based on IBL experience,
warm miniature forward calorimeter, update of the small muon wheel,
trigger adjustments (topological trigger)

Phase II

All new innermost tracking detector, forward calorimeter upgrade,
additional trigger and precision chambers in the muon system, extra neutron shielding

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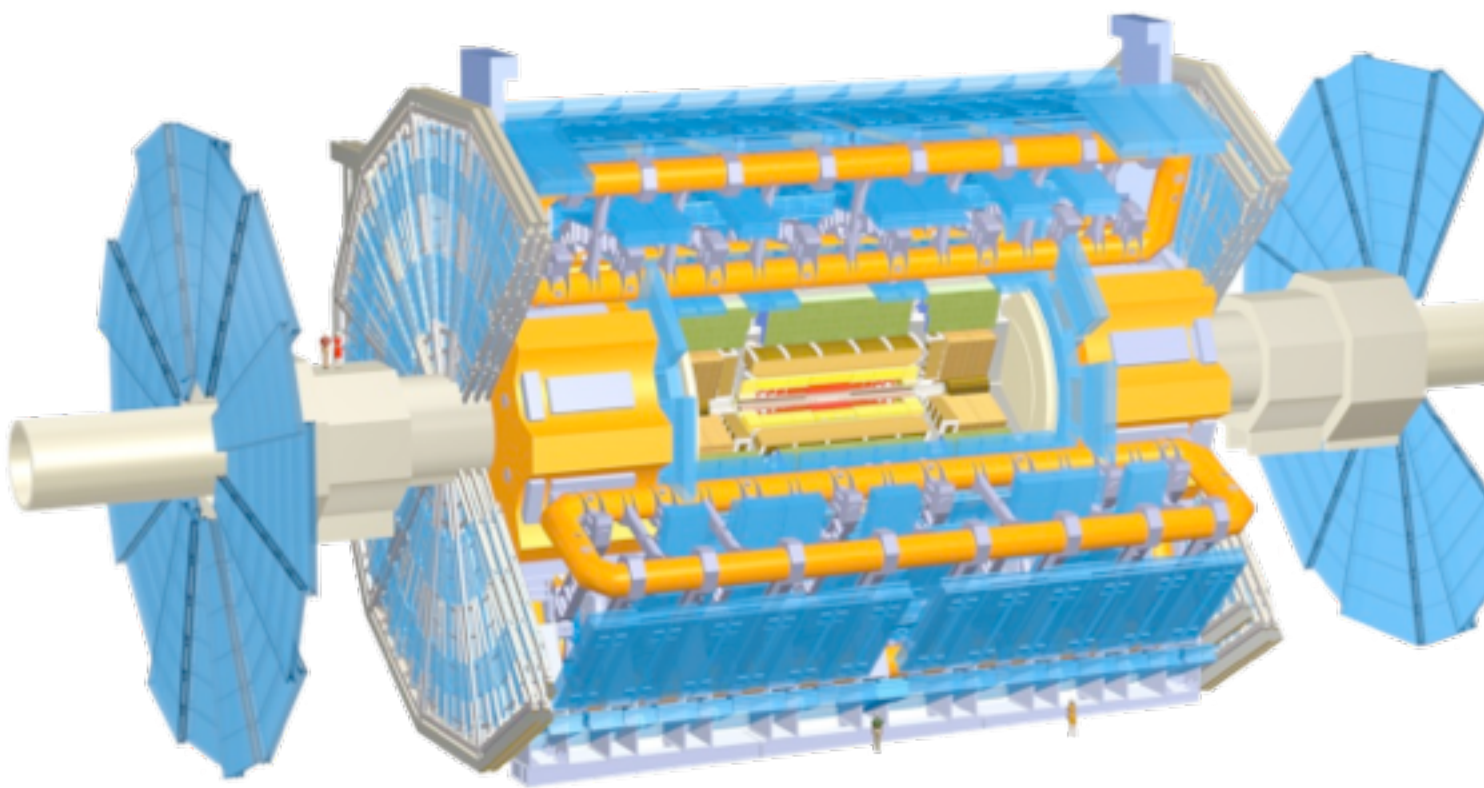
Few words about the present (1)

- We have a great detector at present

details: see talk of N. Benekos



Subdetector	Number of Channels
Pixels	80 M
SCT Silicon Strips	6.3 M
TRT Transition Radiation Tracker	350 k
LAr EM Calorimeter	170 k
Tile calorimeter	9800
Hadronic endcap LAr calorimeter	5600
Forward LAr calorimeter	3500
L1 Calo trigger	7160
LVL1 Muon RPC trigger	370 k
LVL1 Muon TGC trigger	320 k
MDT Muon Drift Tubes	350 k
CSC Cathode Strip Chambers	31 k
RPC Barrel Muon Chambers	370 k
TGC Endcap Muon Chambers	320 k

Status: May 13 - 2011

- It is performing in an outstanding way
  - operational channels very high for all sub-detectors
  - highly efficient data taking and trigger performance
  - in general, excellent description of data through simulation

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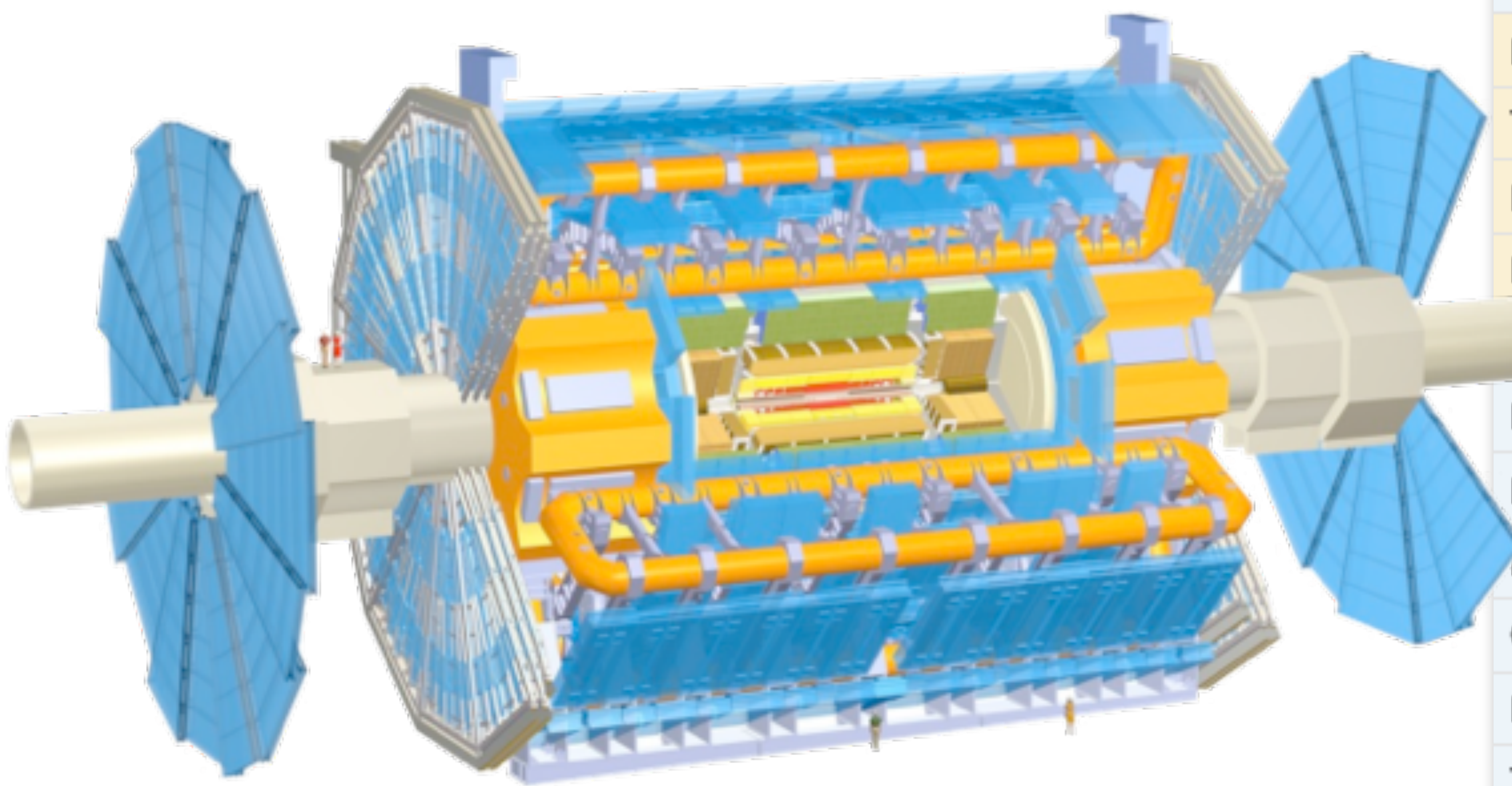

Subdetector	Operational Fraction
Pixels	96.9%
SCT Silicon Strips	99.1%
TRT Transition Radiation Tracker	97.5%
LAr EM Calorimeter	99.5%
Tile calorimeter	97.9%
Hadronic endcap LAr calorimeter	99.6%
Forward LAr calorimeter	99.8%
L1 Calo trigger	99.9%
LVL1 Muon RPC trigger	99.5%
LVL1 Muon TGC trigger	100%
MDT Muon Drift Tubes	99.8%
CSC Cathode Strip Chambers	98.5%
RPC Barrel Muon Chambers	97.0%
TGC Endcap Muon Chambers	98.4%

Status: May 13 - 2011

- It is performing in an outstanding way
  - operational channels very high for all sub-detectors
  - highly efficient data taking and trigger performance
  - in general, excellent description of data through simulation

Few words about the present (2)

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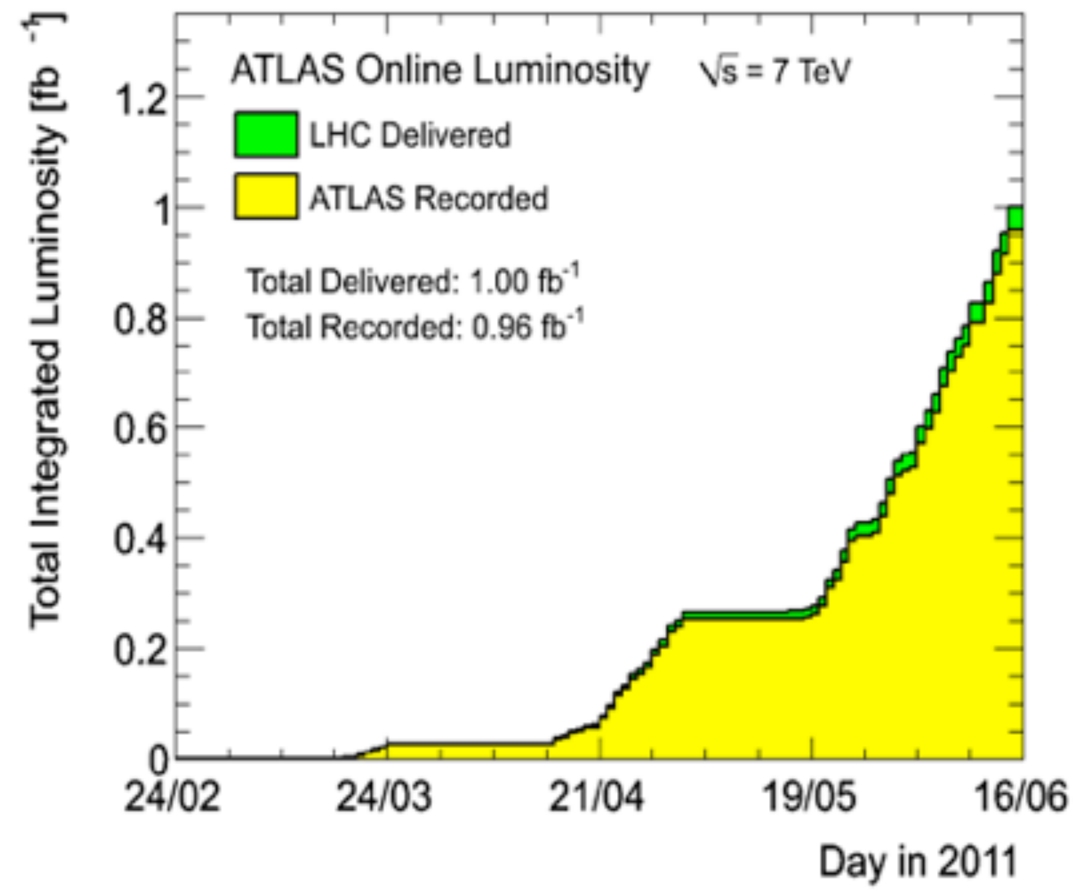
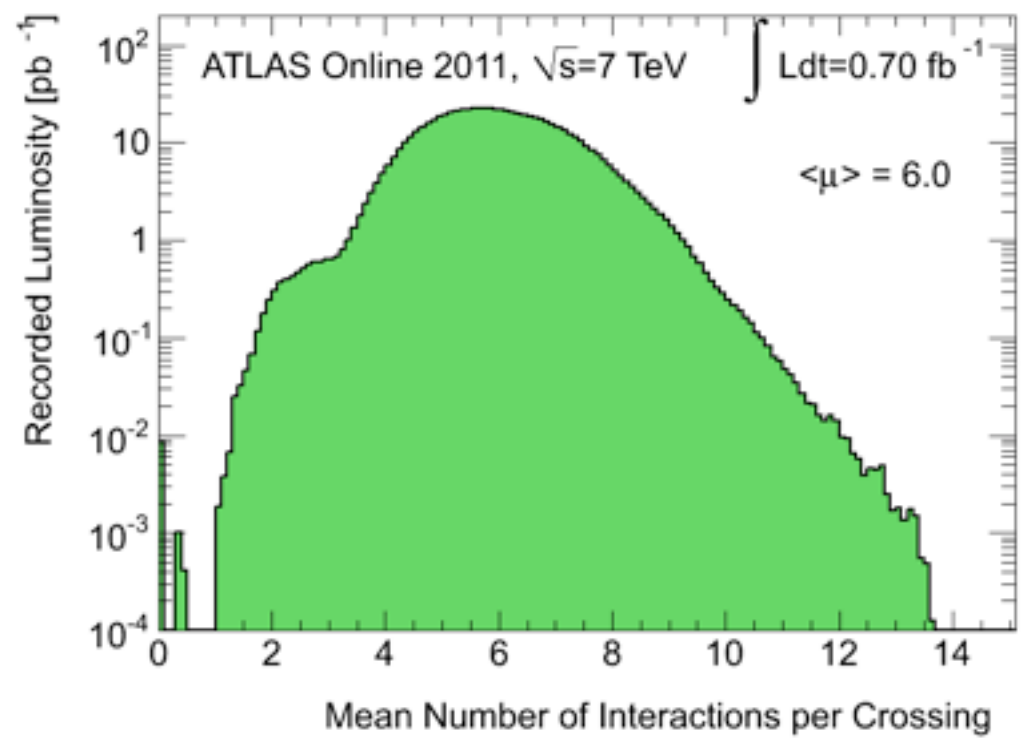
- Highly efficient data taking with present ATLAS detector
  - more than 1 fb^{-1} delivered
- Excellent physics results published
  - presented elsewhere
- 2011 is first year with significant pile-up
  - very important experience for upgrade scenarios
  - heavy ion run was first very-high occupancy test of the ATLAS setup





Few figures about the present (3)

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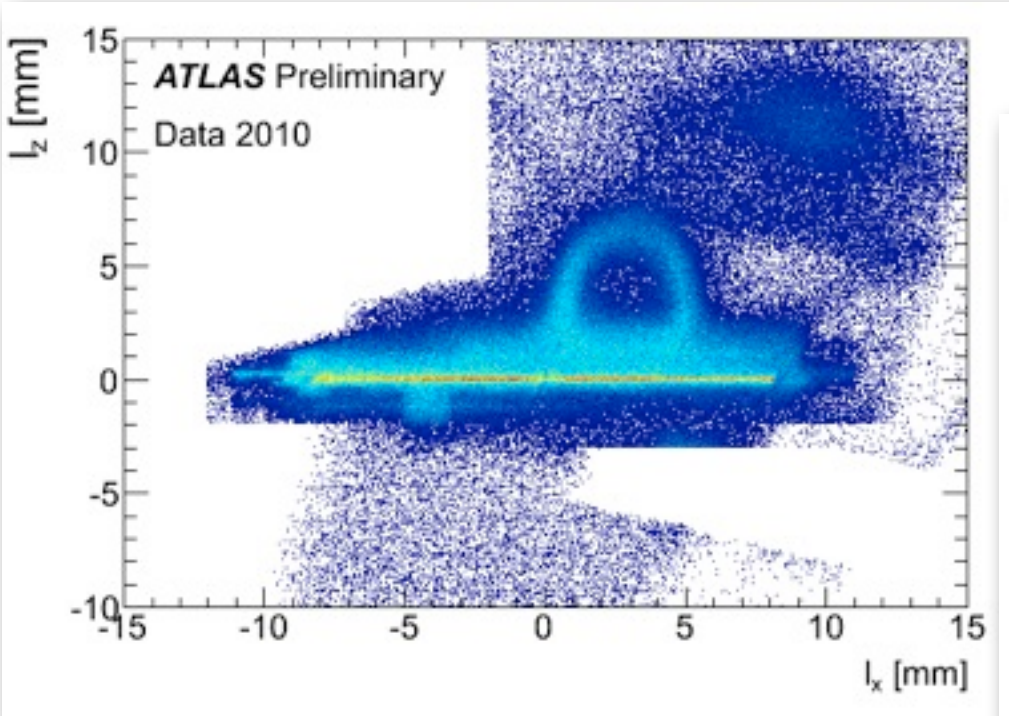
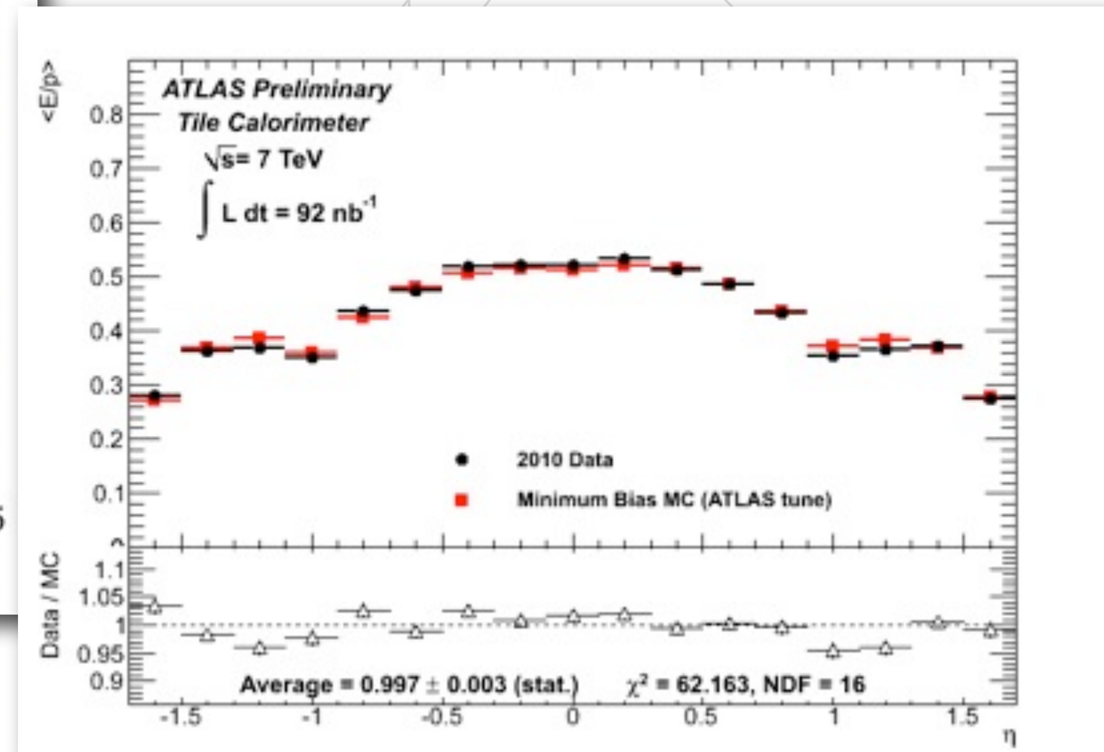


see talk of N. Benekos

from great performance studies



Few figures about the present (3)

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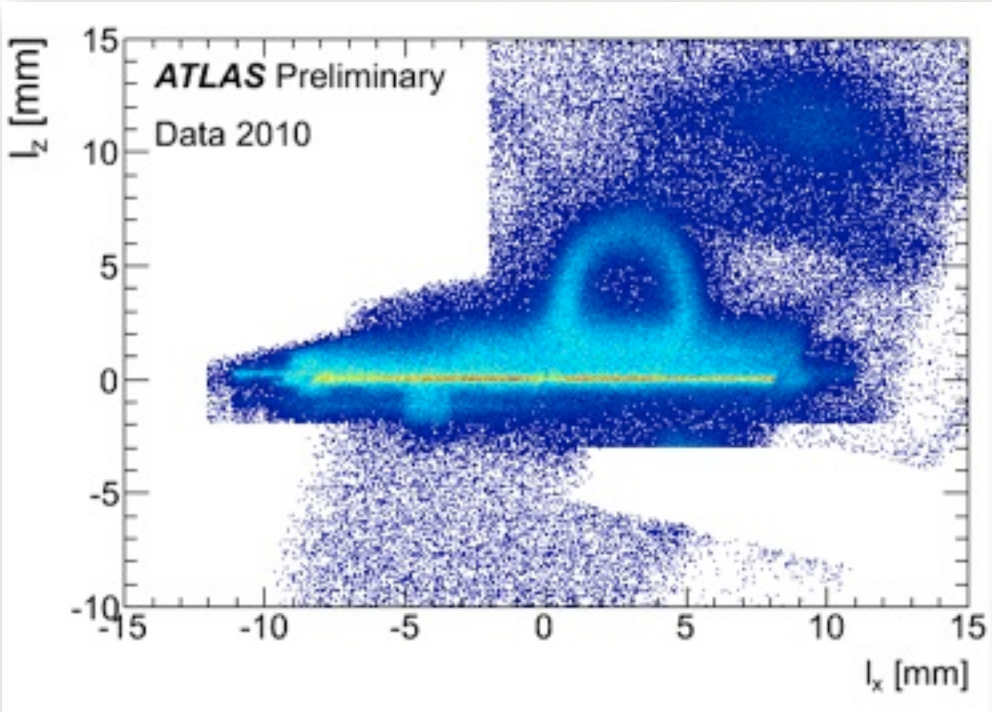
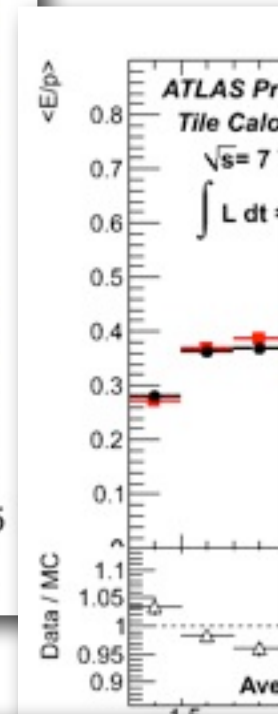
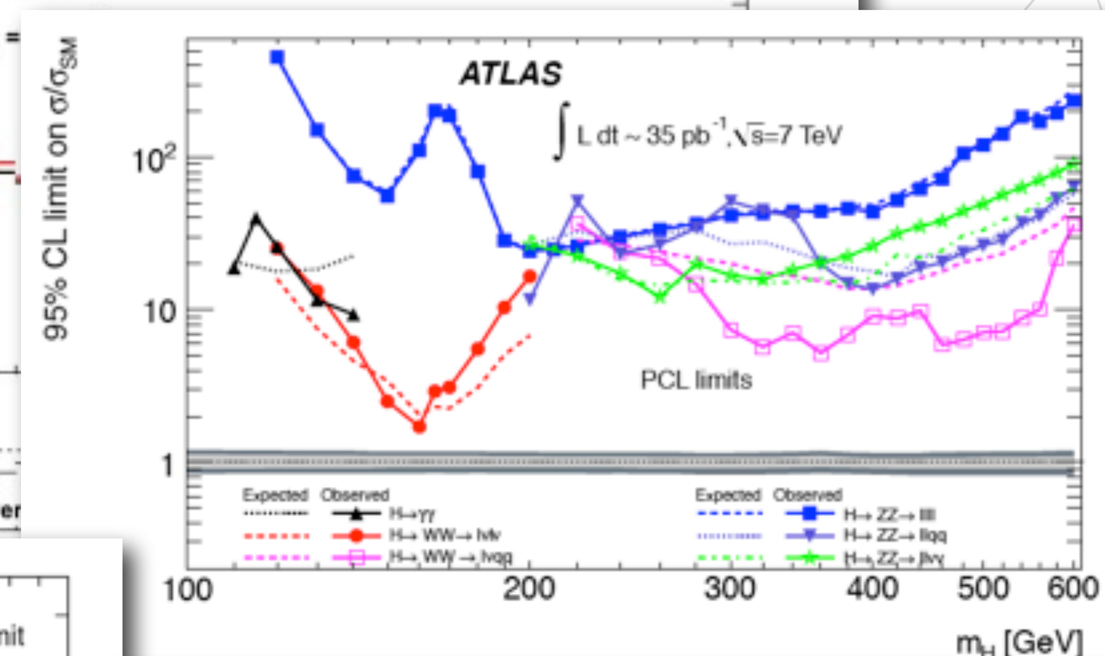
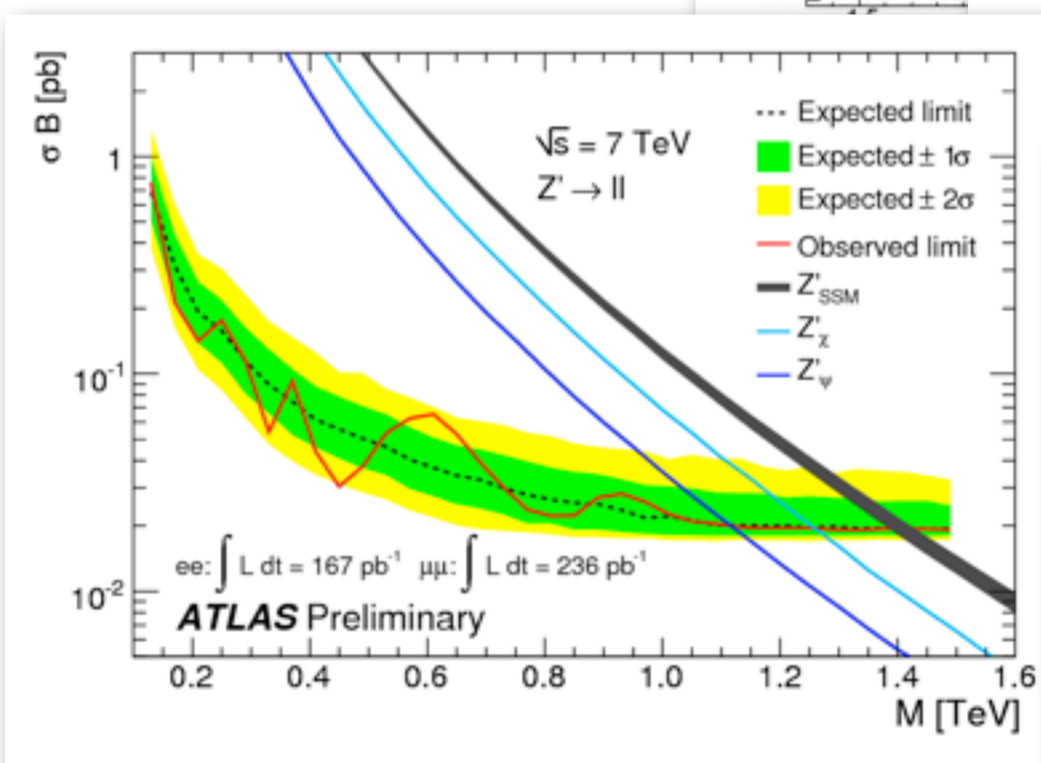
from great performance studies

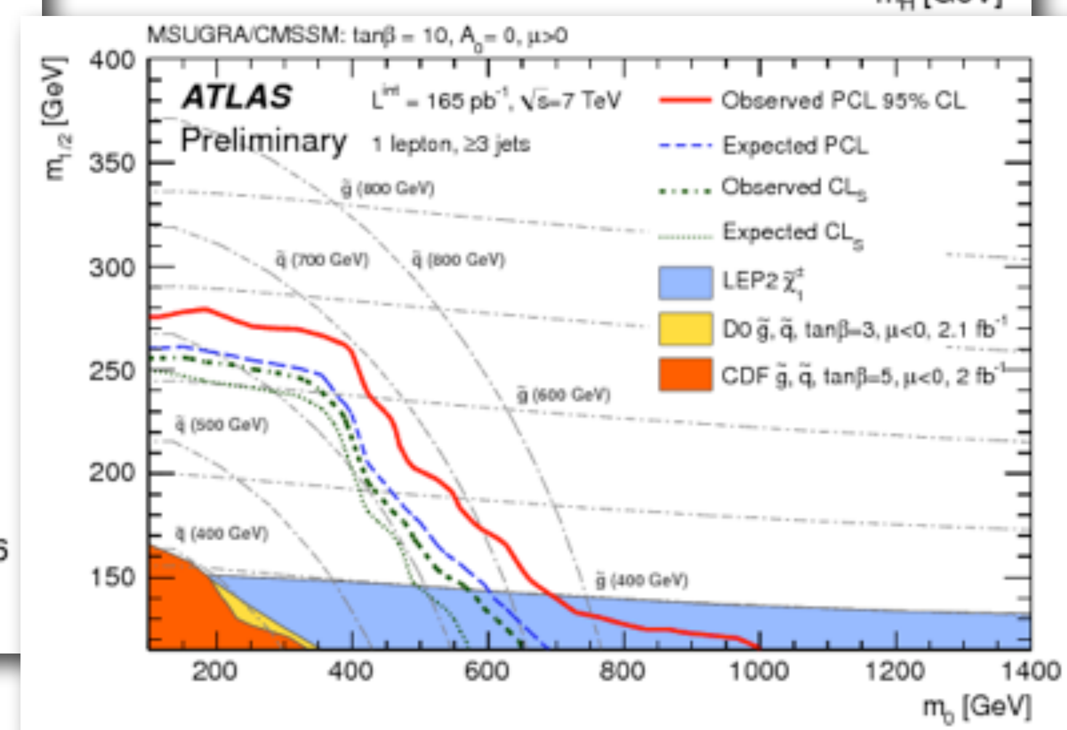


see talk of N. Benekos









to excellent physics results

see talk of R. Hauser

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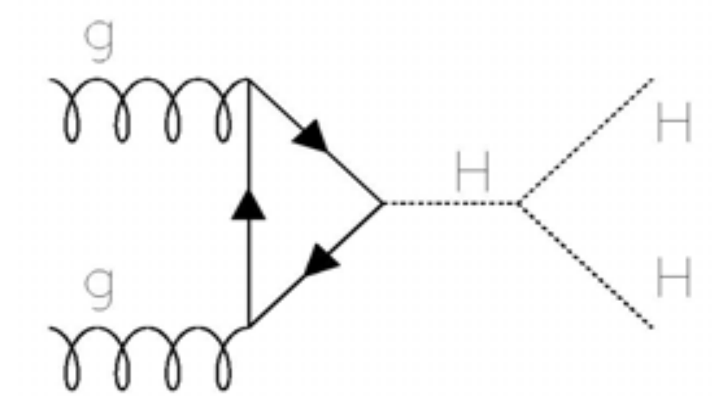
Main motivations for detector upgrade

- Physics motivation for machine upgrade (simplified)
  - the Higgs agenda (simplified):

LHC:		**HL-LHC:**
- discovery, measure mass & width	→	**- cross sections, BR, CP & spin, ...**



Higgs self-coupling

  - the SUSY agenda:
    extend reach for squark/gluino search
    properties of SUSY particles
  - the Unknown agenda:
    new couplings and their gauge bosons (e.g. Z', W')
    quark substructure
    ...

- Consequences for ATLAS
  - harsh radiation environment, still performance needs to be at least comparable to current ATLAS (b-tagging, forward jet reconstruction, trigger ...)

Phase 0 - LHC Conditions & ATLAS Plans

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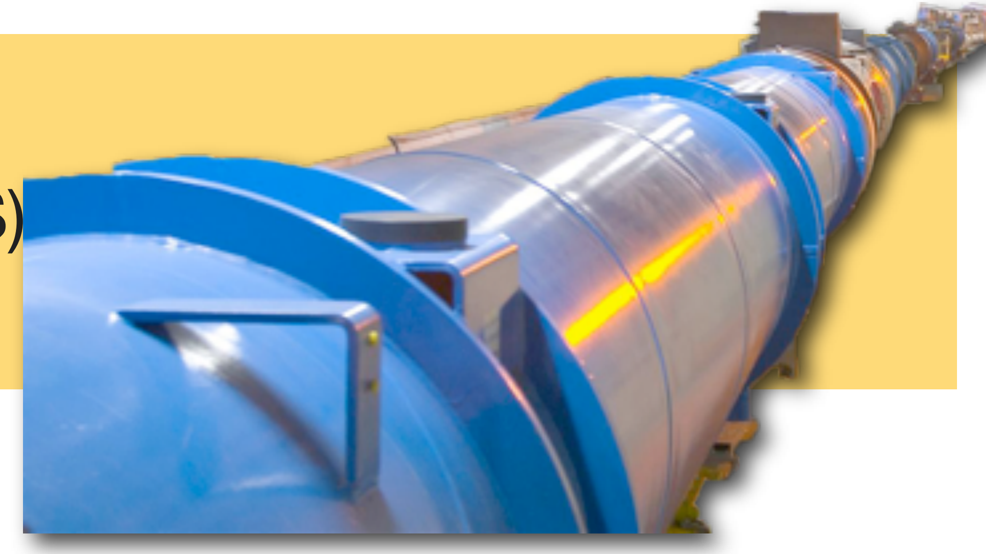
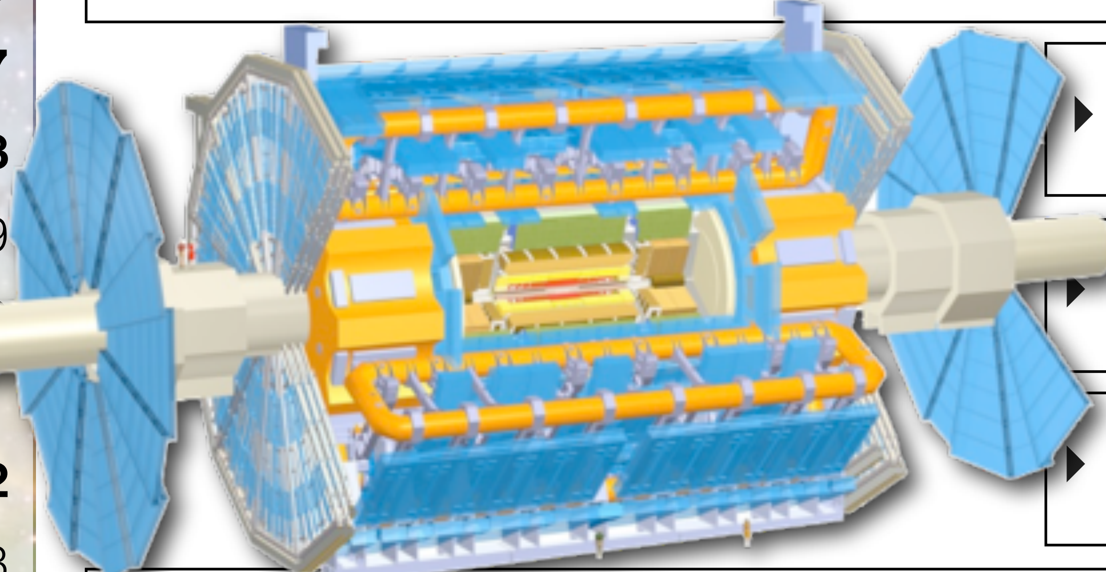
- LHC consolidation phase
- Complete quench protection system (QPS)
- Shutdown: 18 months



- Removal of Minimum Bias Trigger Scintillators



- New neutron shielding on toroid end-cap
- Detector consolidation in Muon System
- New quarter panels for the pixel system
- Replacement of beam pipes, installation of new innermost pixel layer

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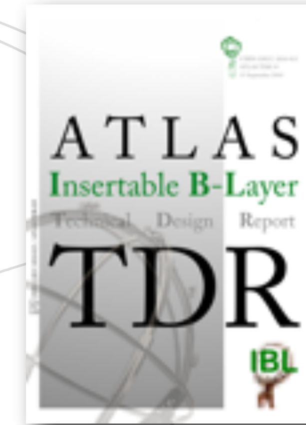
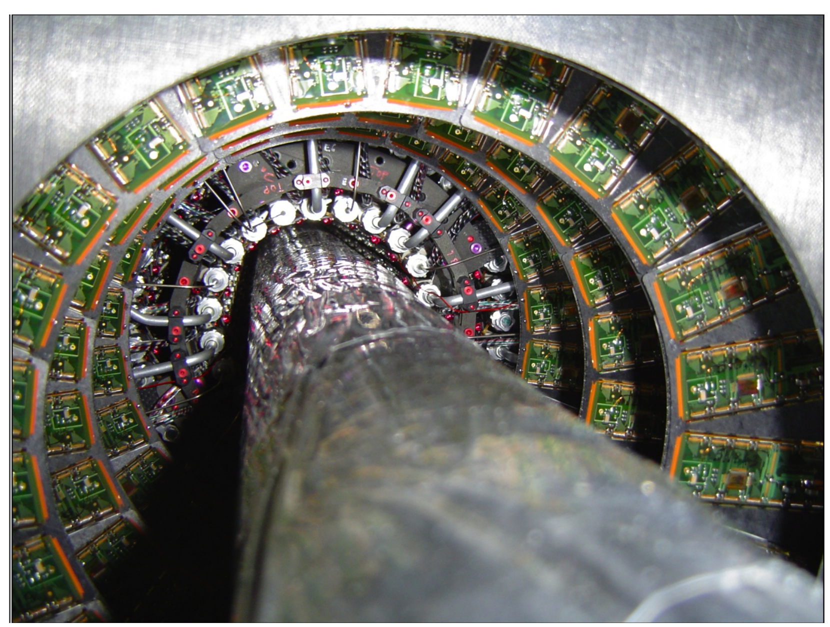
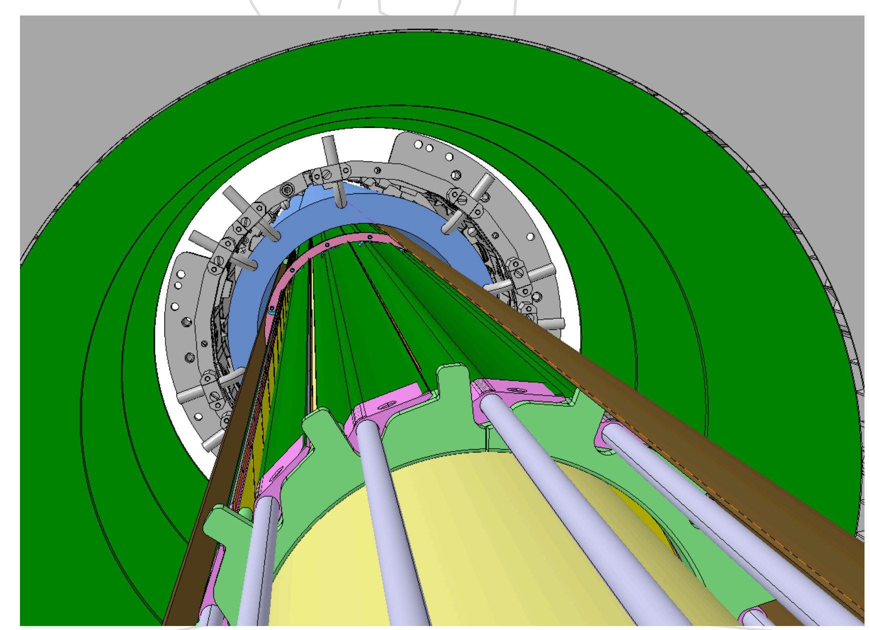
The Insertable B-Layer (IBL)

CERN-LHCC-2010-013



- Excellent vertex detector performance is crucial
  - improvement heavy flavor tagging, primary & secondary vertex reconstruction/separation
- Additional innermost layer will boost tracking performance
  - adds additional redundancy of the detector in case of radiation damage
- Replacement is technically very challenging
  - ATLAS strategy: insert a completely new layer at smaller radius
  - needs decrease of beam pipe radius





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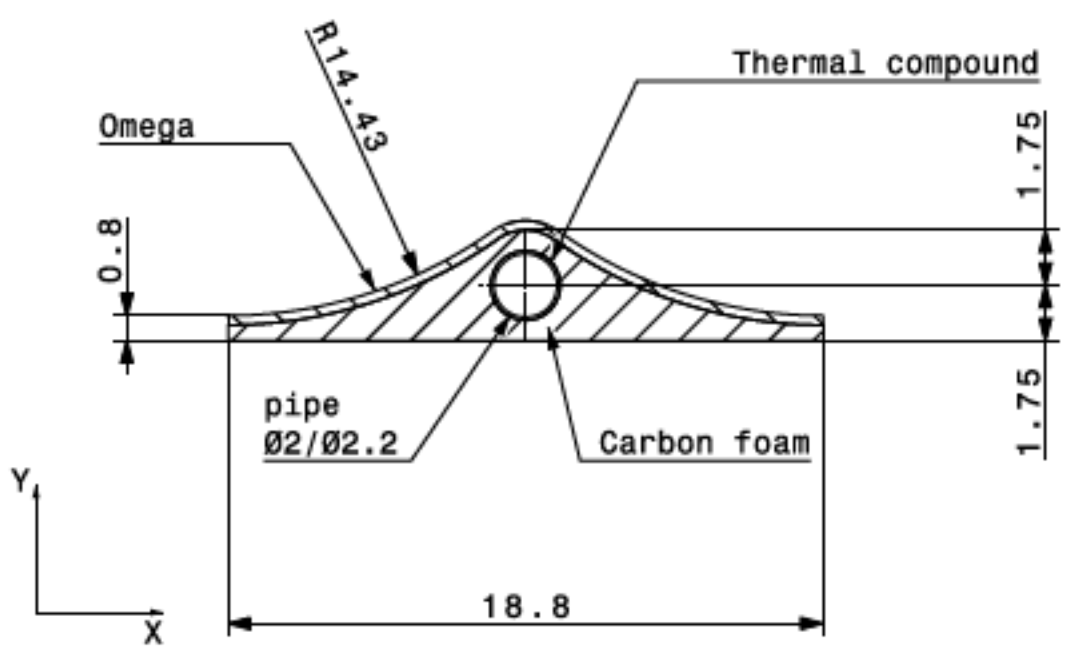
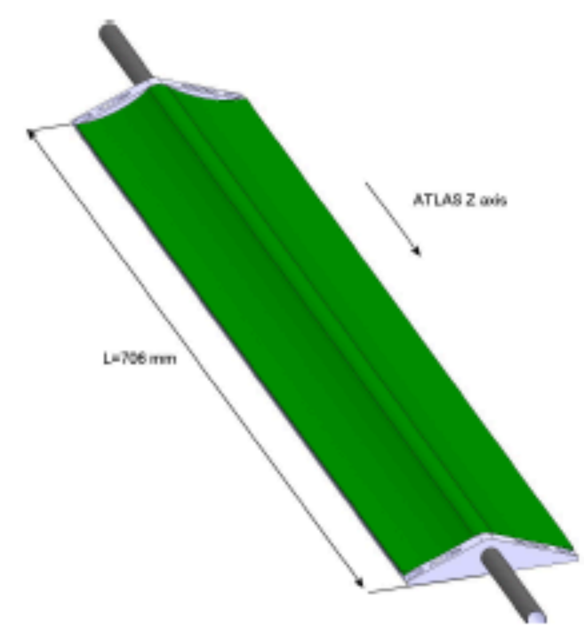
IBL: a technological challenge

- Additional layer inserted increases material budget
  - sensor and support material needs to be minimized
  - the detector has to be powered, read-out and cooled

- New stave design with carbon foam structure
  - low material budget, while building an excellent heat path to cooling pipe





IBL: a technological challenge

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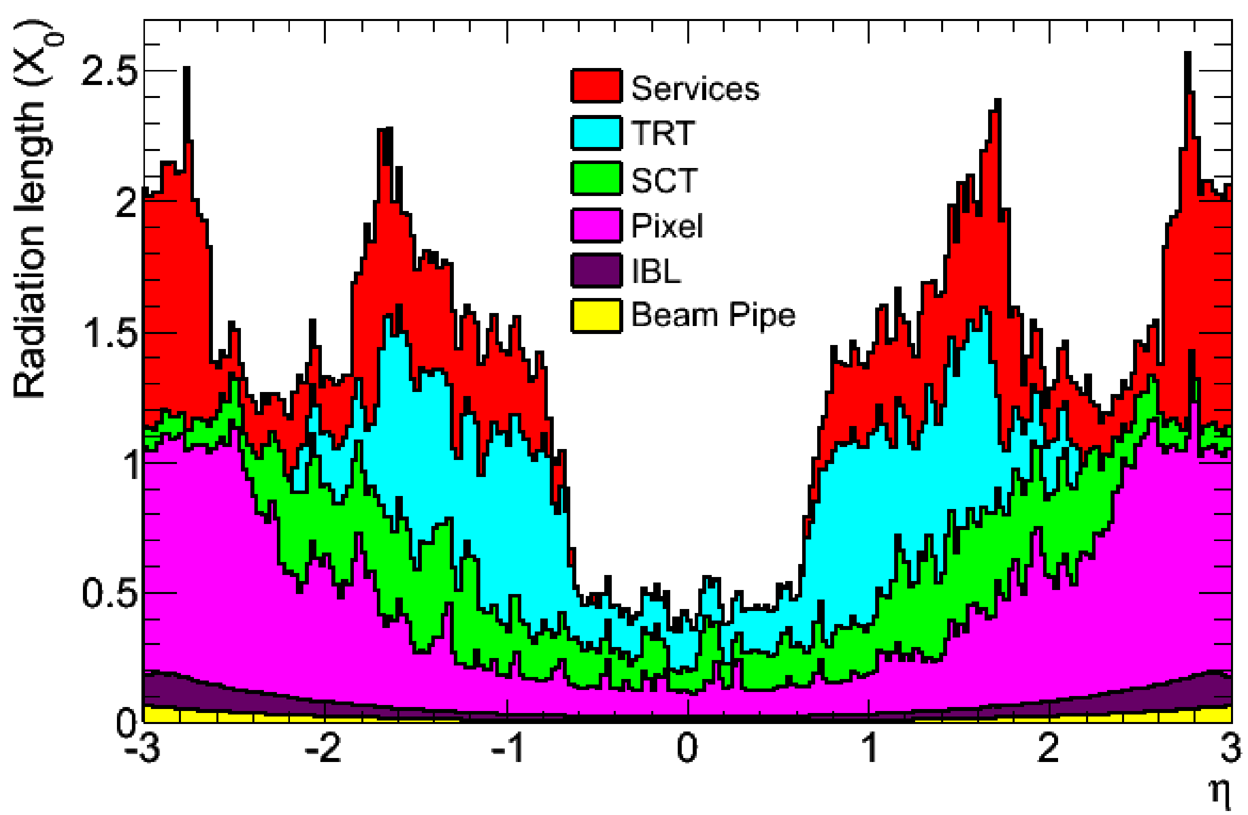

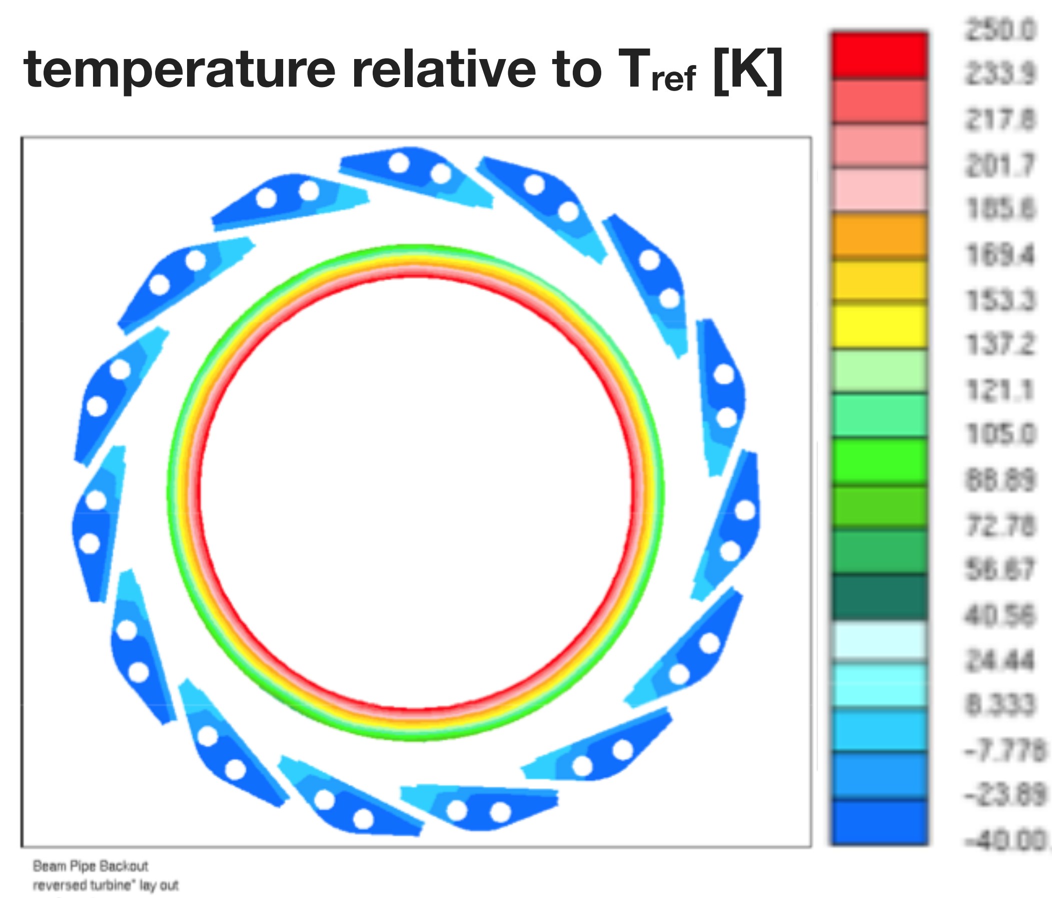

IBL: Sensor & readout technology

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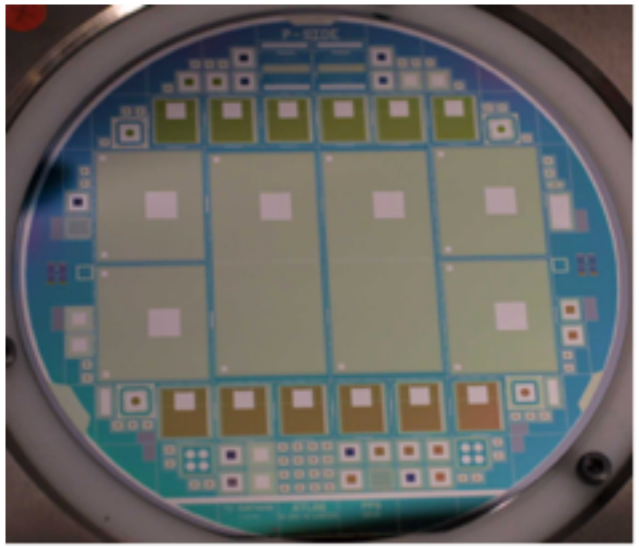
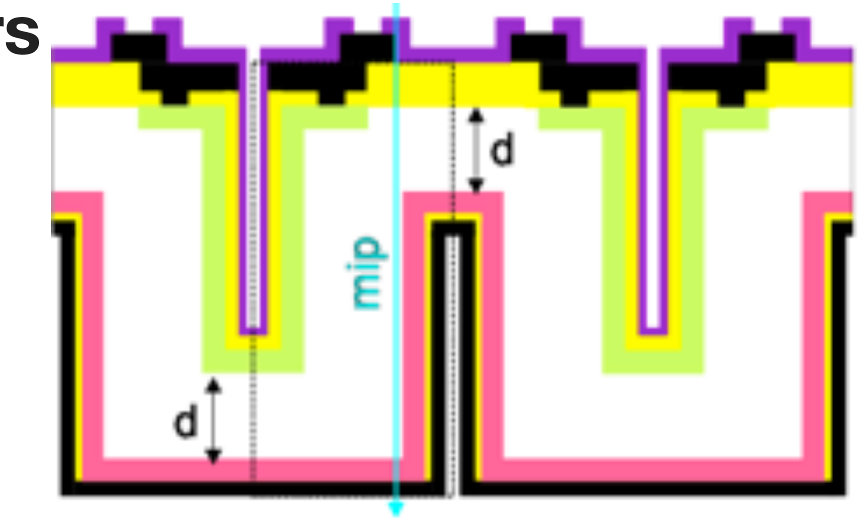
planar pixel sensors



- prototypes with 150-250 μm thickness ordered, delivered & being tested
- 50 x 250 μm pixel size
- well parameterised dose dependence (tested to 2 x 10^{16} n_{eq}/cm^2)

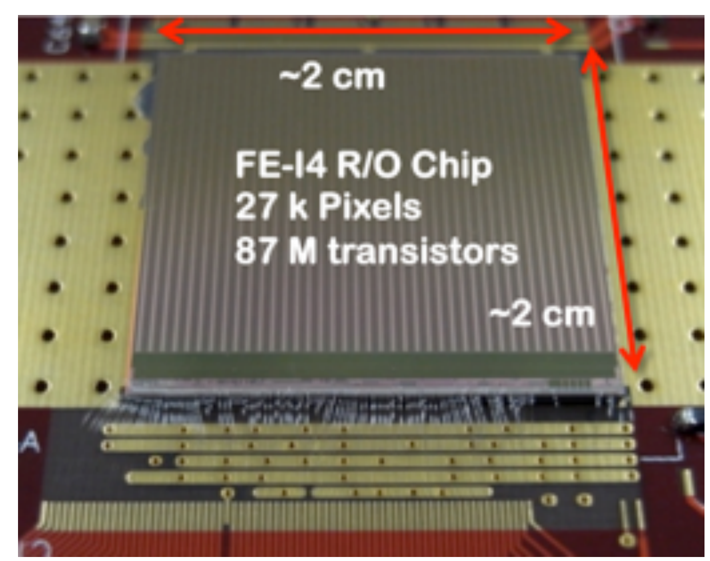
3D sensors



- double-sided 3D layout
- prototype with 230 μm thickness and 200 μm guard has shown good radiation hardness
- low voltage operation after irradiation

New FE-I4 readout chip

- delivered and performing well
- will also set standard for Phase I



Diamond sensor technology postponed to later phases.

IBL: Sensor & readout technology

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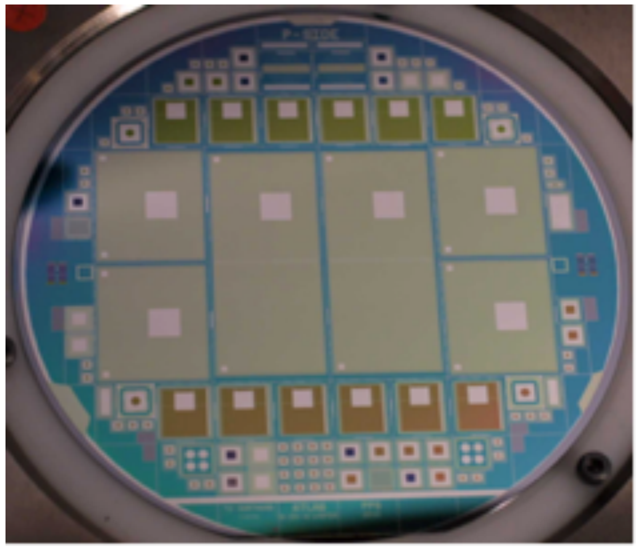

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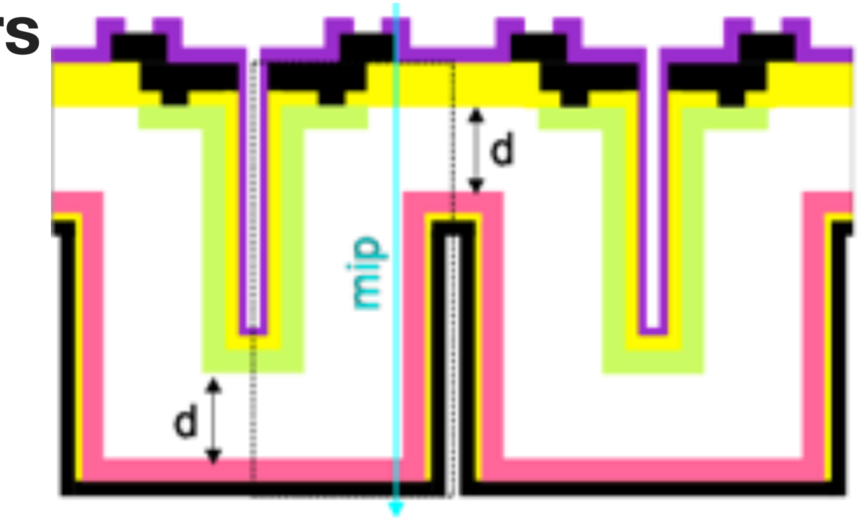

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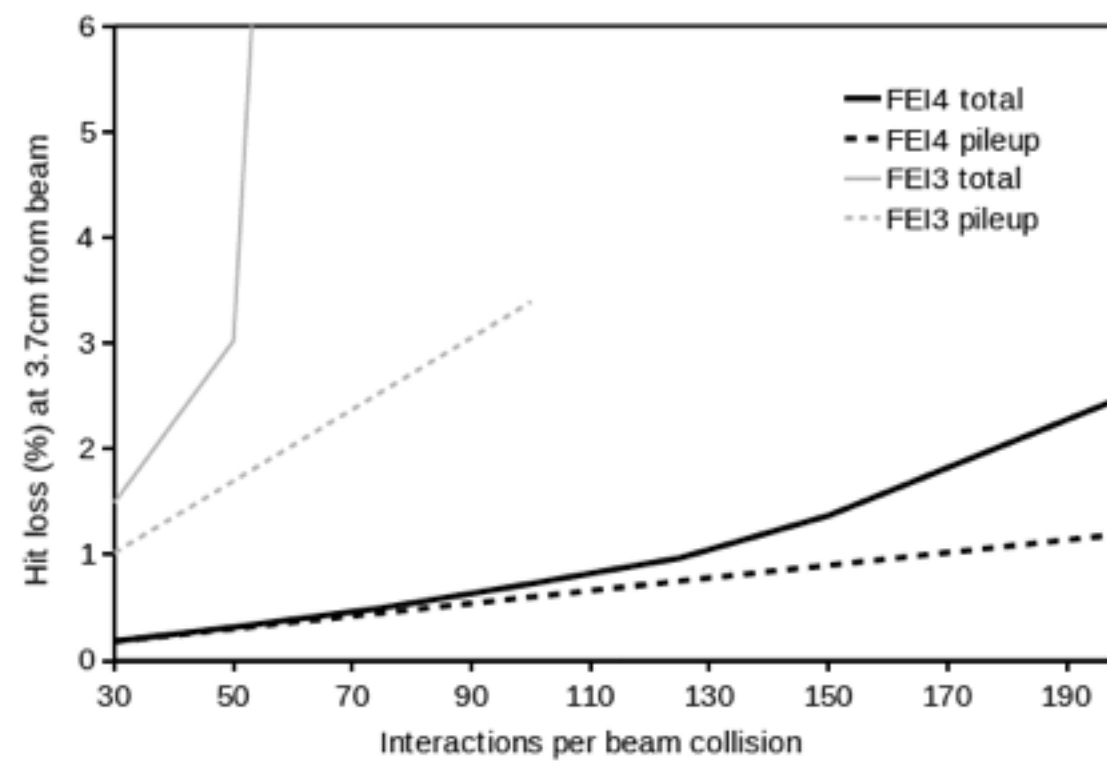

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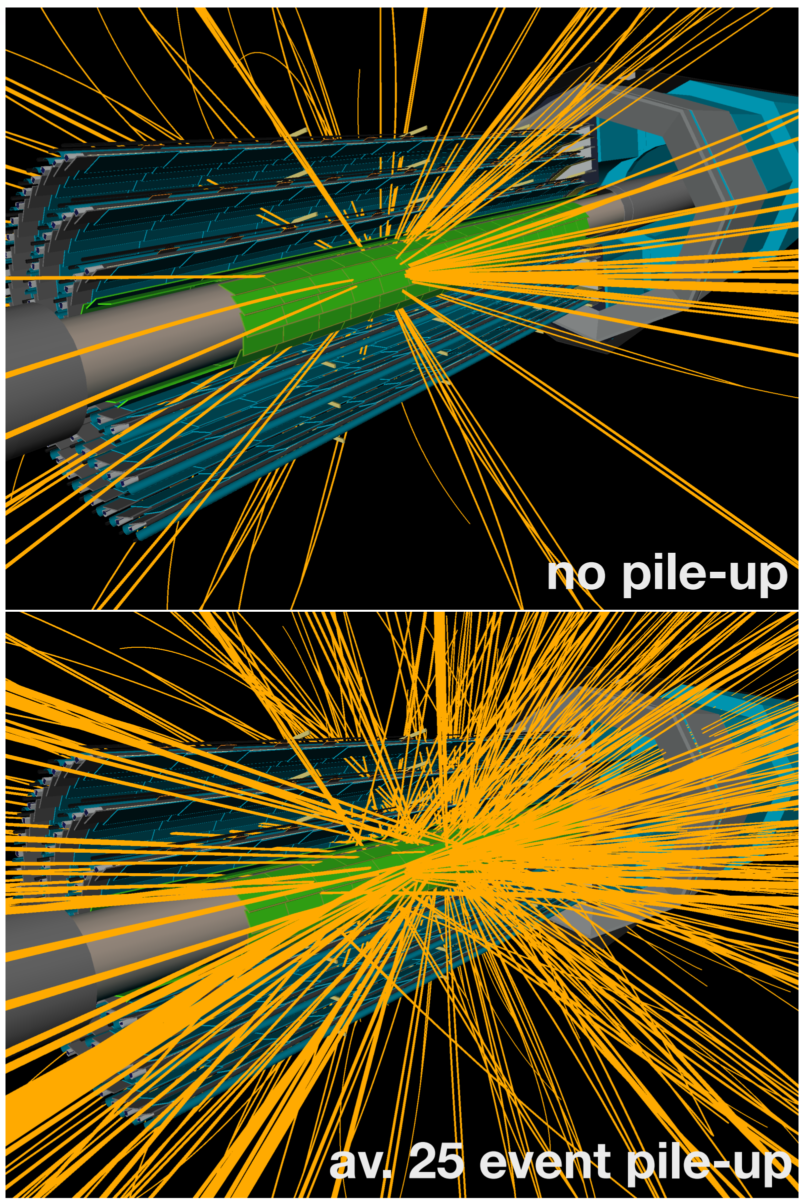
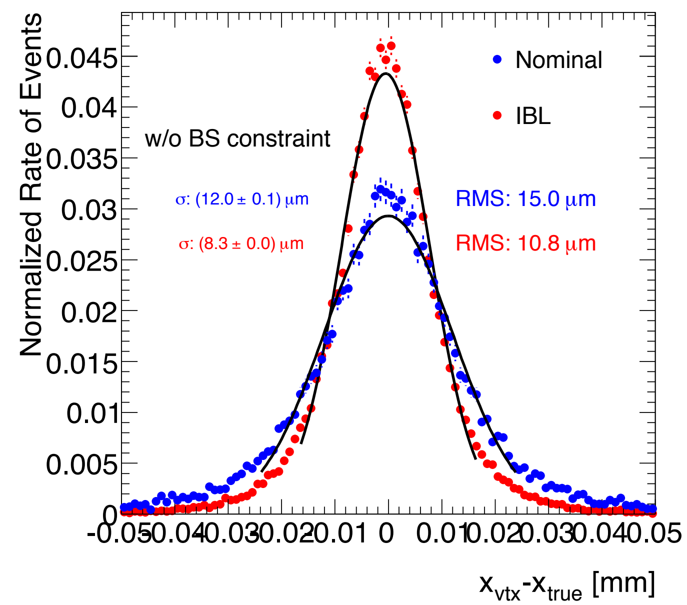
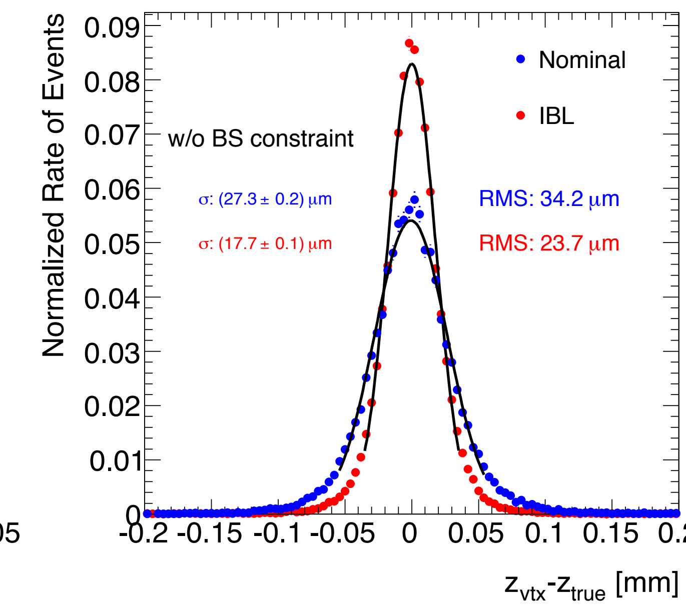
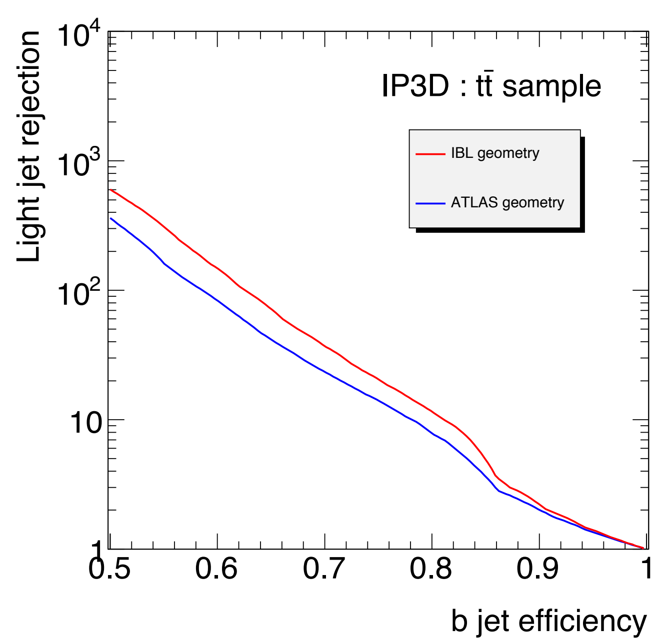
IBL: Performance improvements

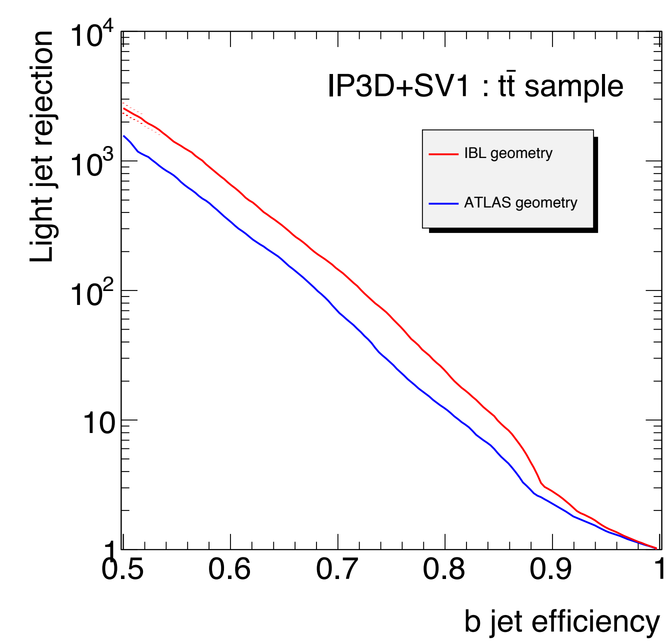
- Simulation shows significant improvements
  - vertex resolution, secondary vertex finding
  - **light jet rejection at constant b-tagging efficiency**
  - IBL studies needed update of track reconstruction (cluster splitting modules)











Phase I - LHC Conditions & ATLAS Plans

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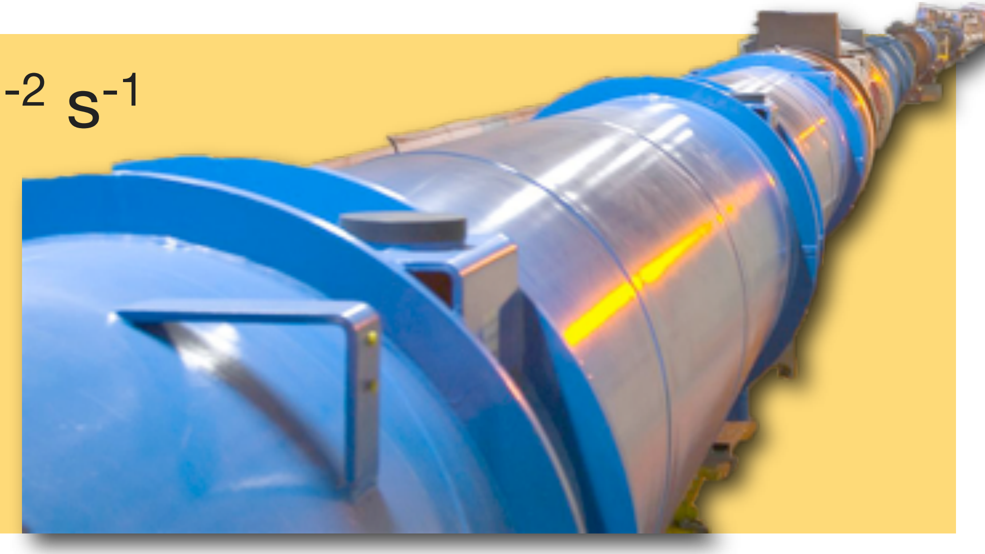
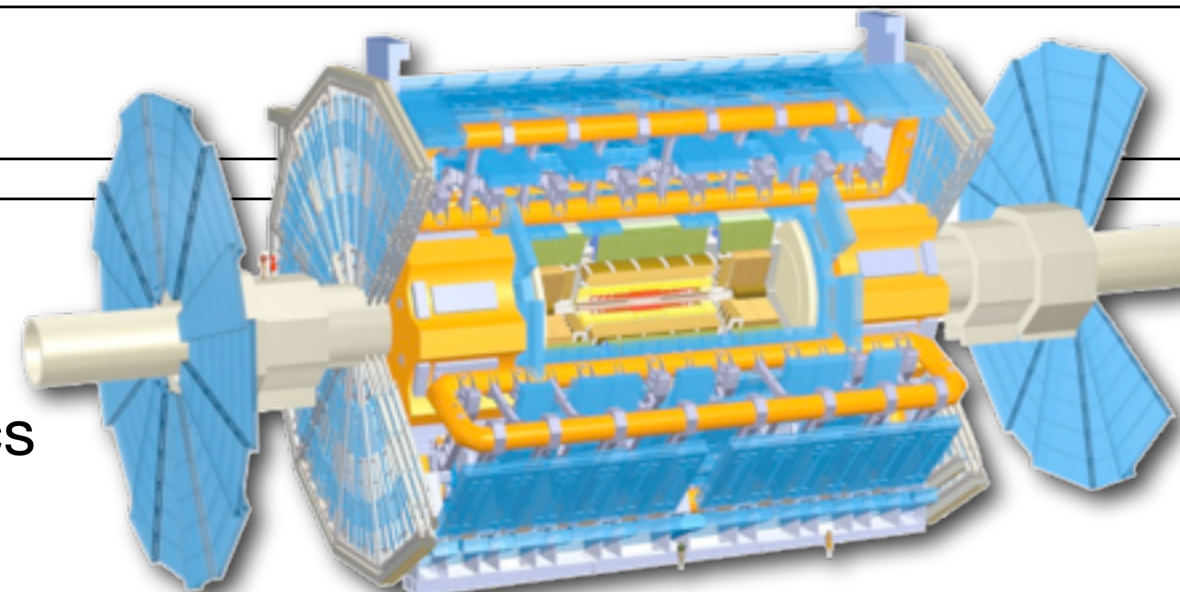
- Peak Luminosity increasing to 2 x 10^{34} cm^{-2} s^{-1}
- Exp. total int. luminosity: 300-400 fb^{-1}
- Shut-down: about 9 months



- Fast Track Trigger for LVL2



- Under consideration:
  - new small muon wheels
  - upgrades to calorimeter electronics and possible new warm miniature forward calorimeter
  - trigger enhancements including topological trigger at L1
  - new non-IBL pixel detector based on IBL experience

New Muon Small Wheels

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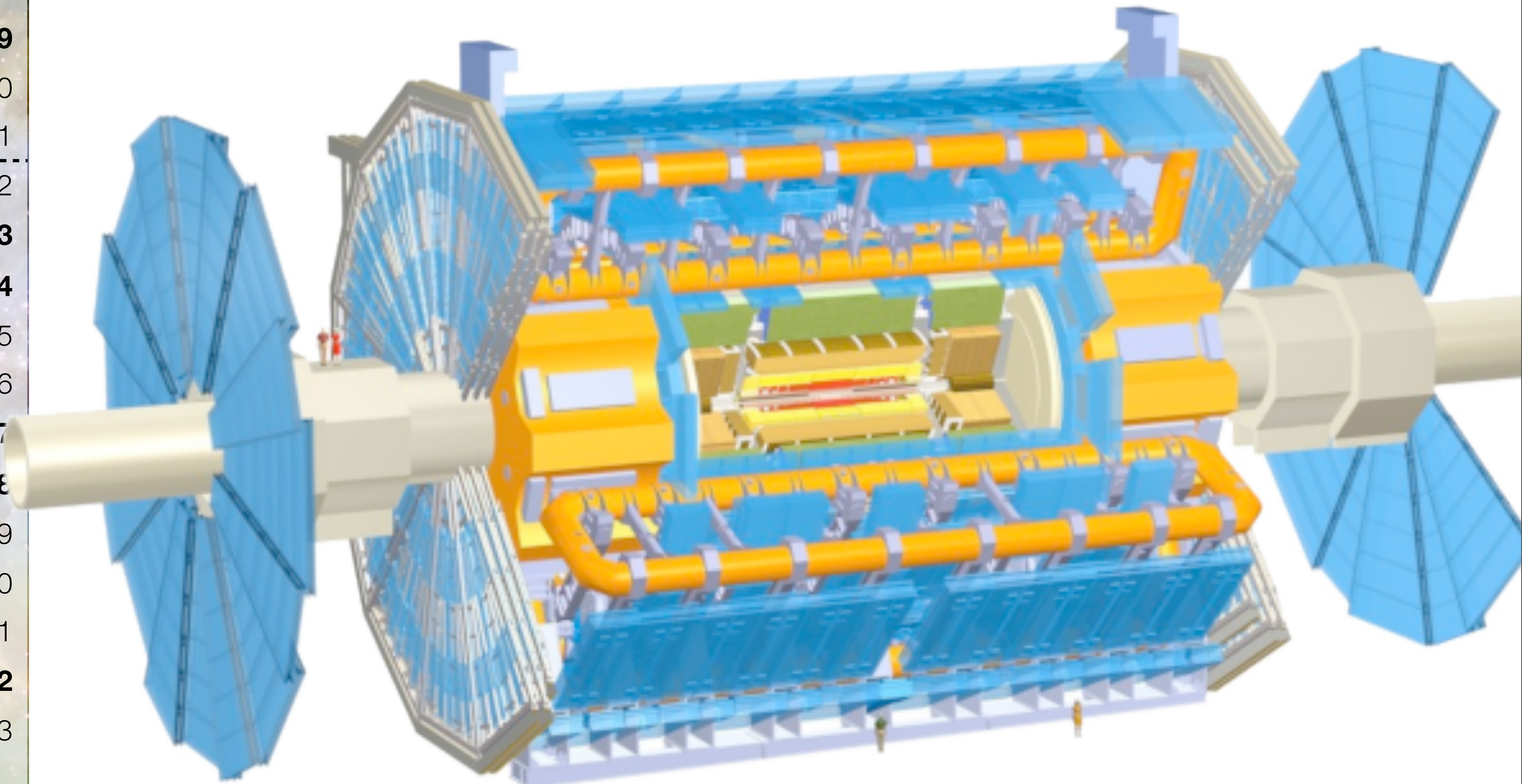

- Higher luminosity will require a significant update of muon forward trigger to reduce fake rate

New Muon Small Wheels

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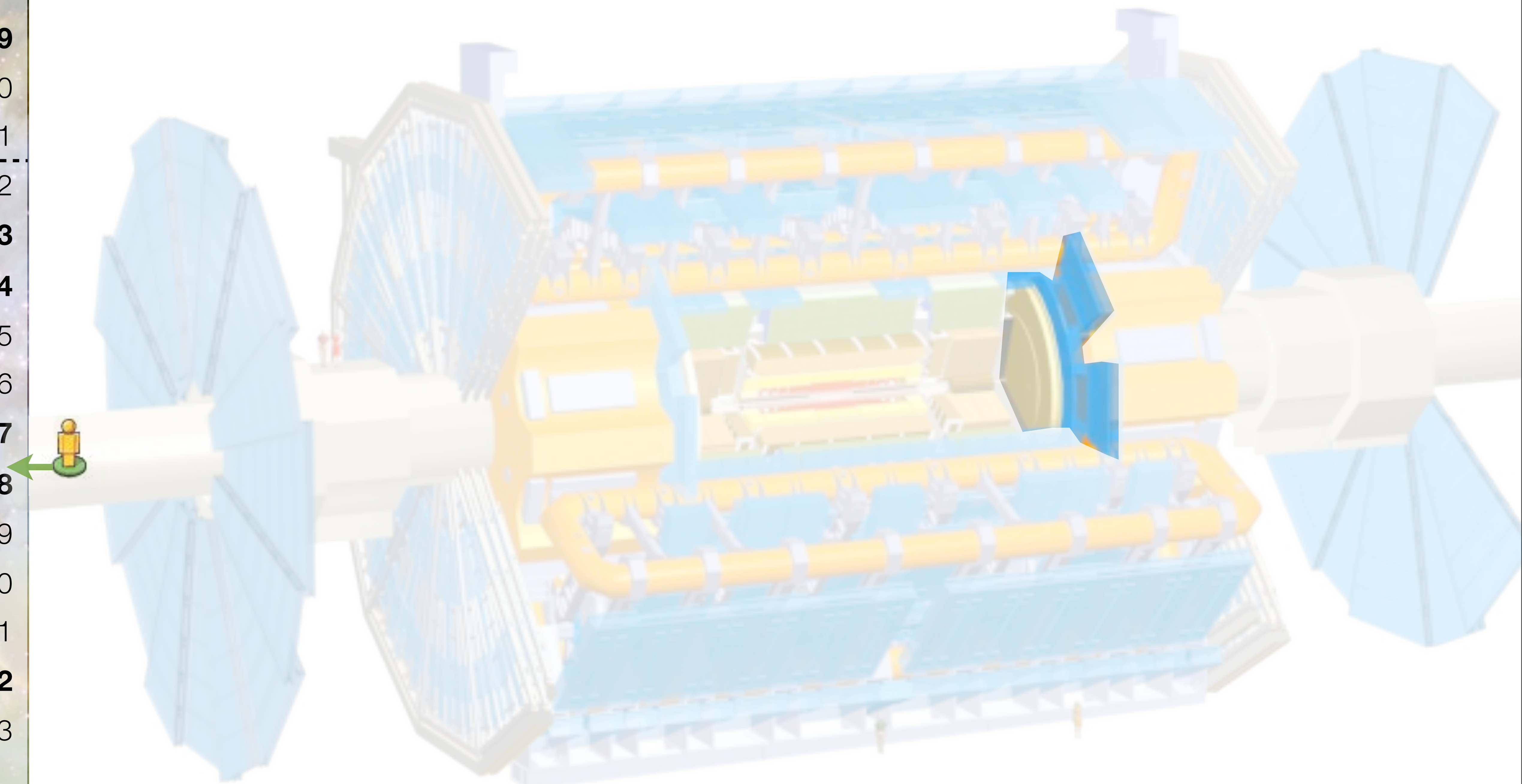

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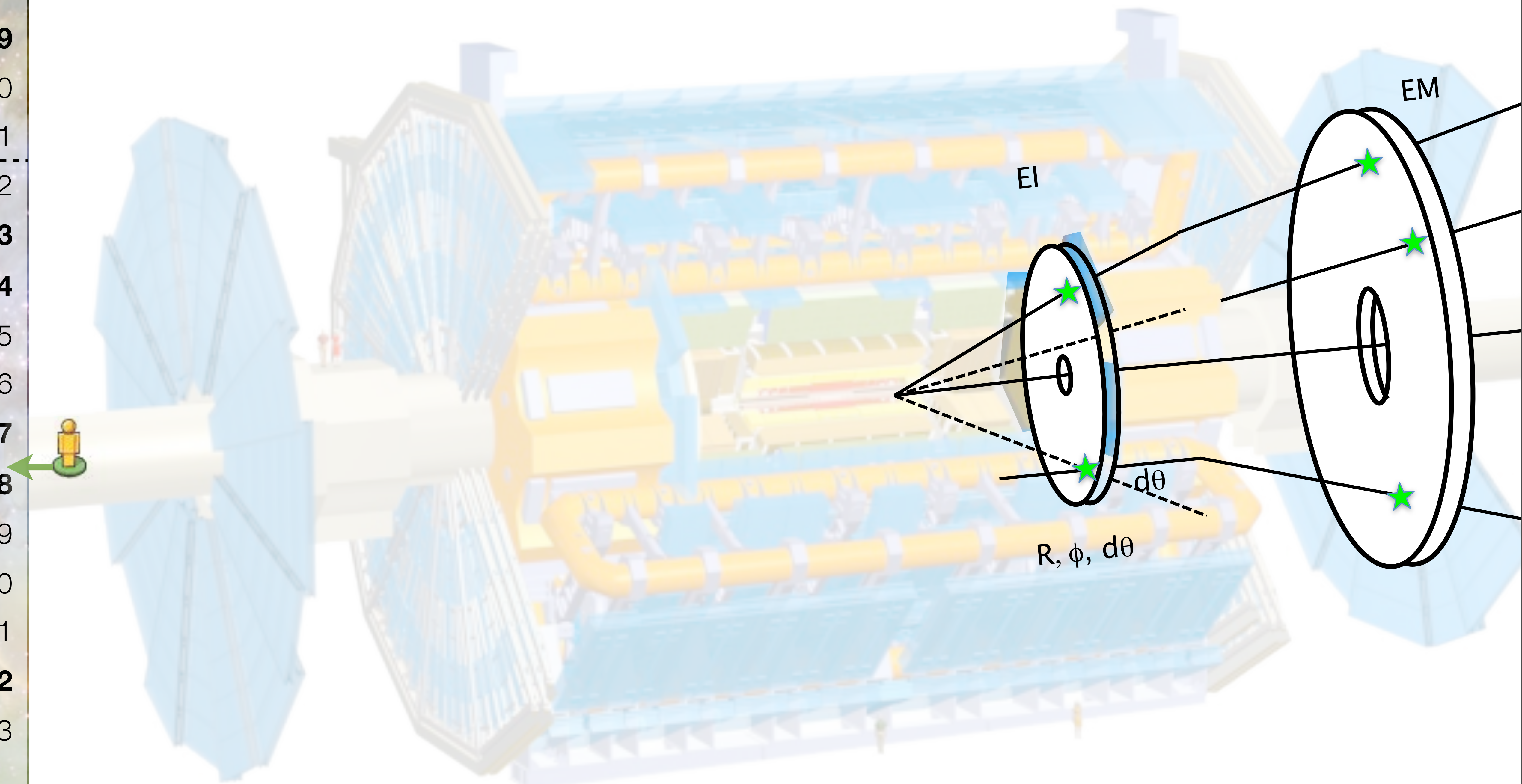

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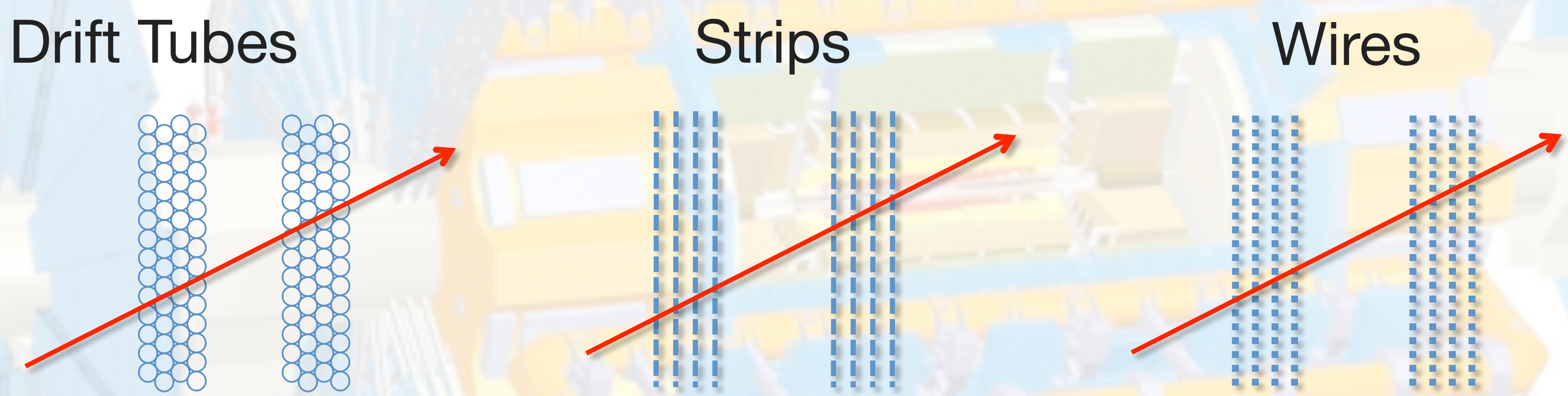
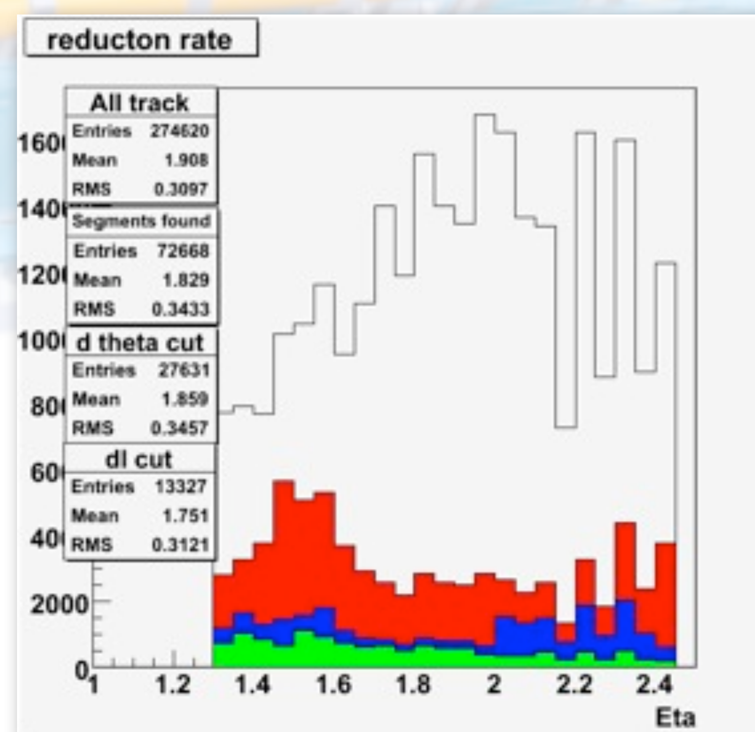
- More precise trigger in the forward region
- Should leave more space for additional neutron shielding
- R&D ongoing for different chamber candidates:



- huge reduction rate of LVL1 muon fake rate can be achieved



New Muon Small Wheels

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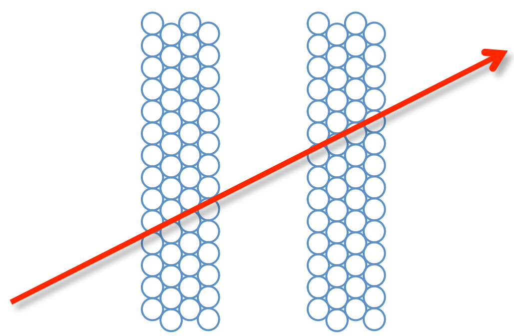
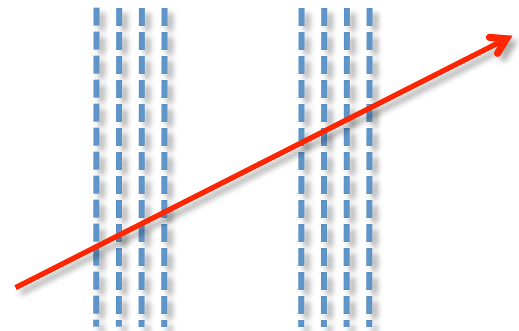
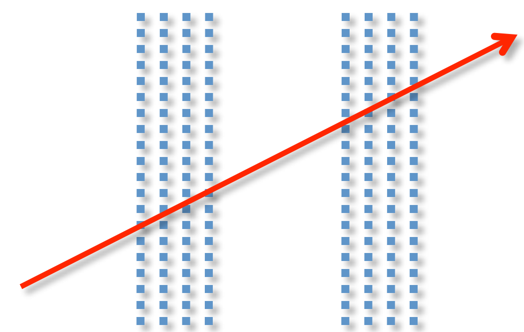


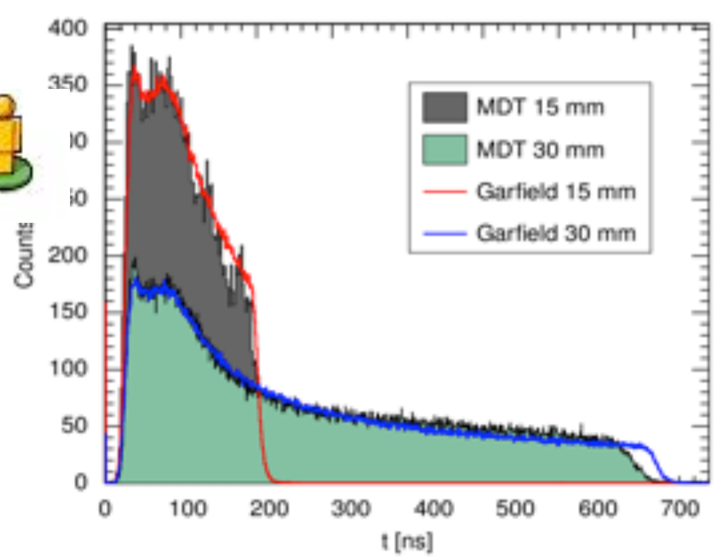
Small Tube MDTs



Large area micromegas

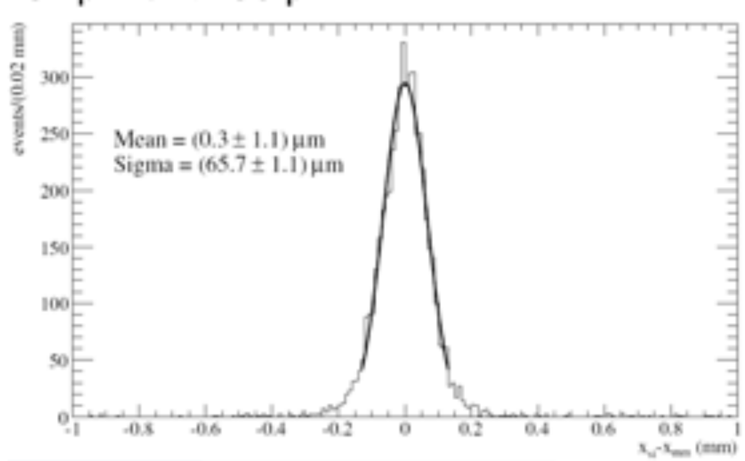


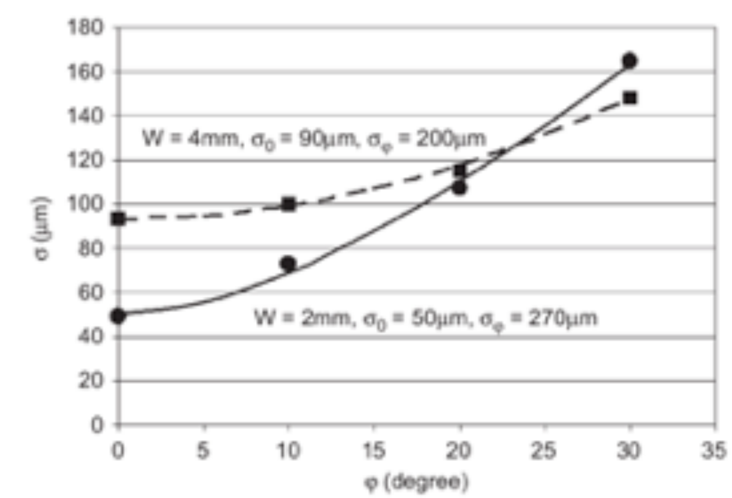
High rate TGCs

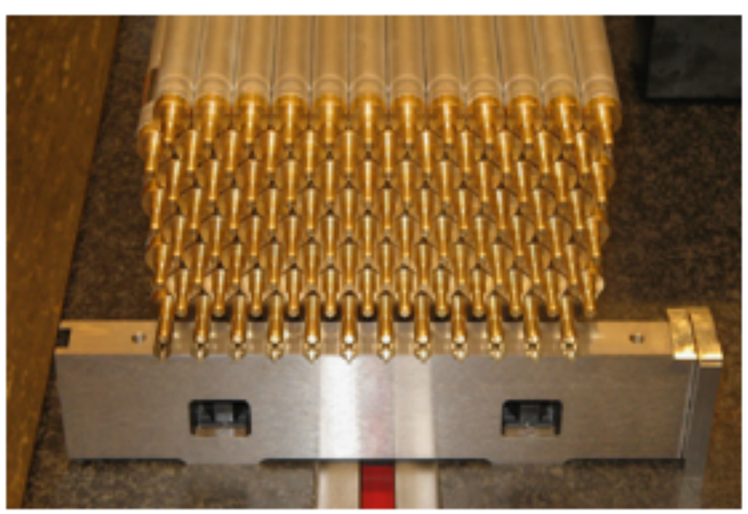


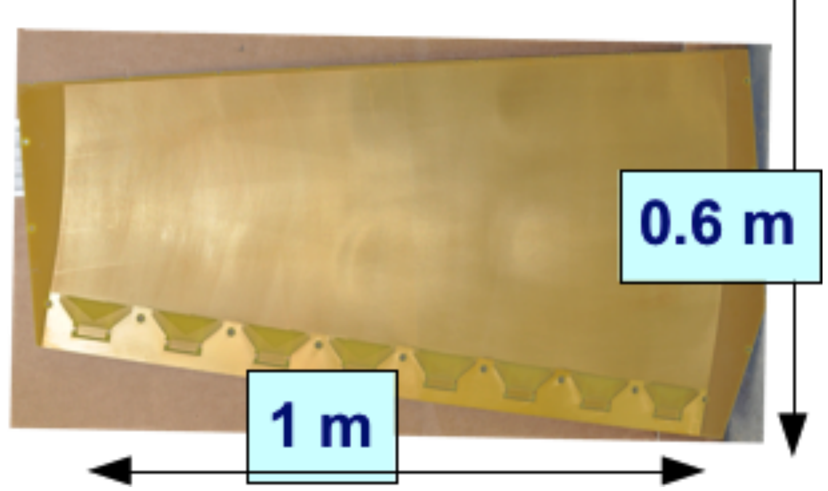
Strip pitch: 250 μm
Strip width: 150 μm

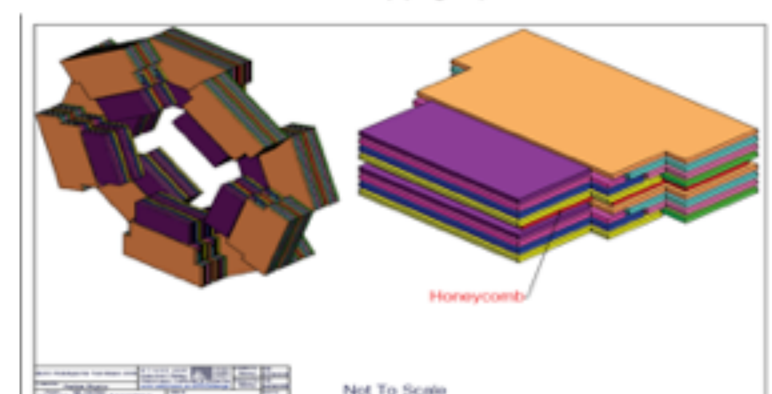
σ_{MM} = (24±7) μm











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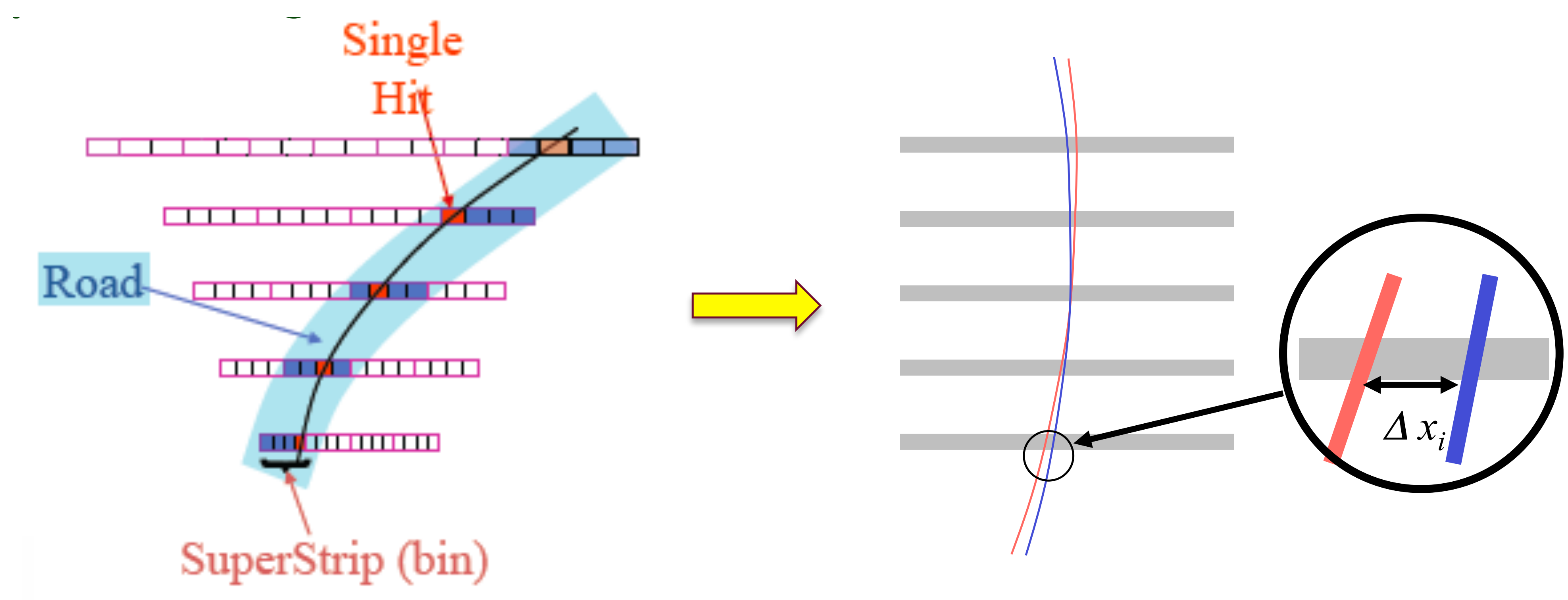
The FTK (Fast TracKer project) at Level 2

- Hardware based track finder
  - complete global tracking at beginning of LVL2
  - massive improvement for b-tagging, τ-identification and lepton isolation



Pattern recognition in coarse resolution (superstrip➔road)

Track fit in full resolution (hits in a road)

$$F(x_1, x_2, x_3, \ldots) \sim a_0 + a_1\Delta x_1 + a_2\Delta x_2 + a_3\Delta x_3 + \ldots = 0$$

- Fast helical track fit on hardware
  performed on DSPs (~ 1ns) in an FPGA

Warm Forward Calorimeter (FCal)

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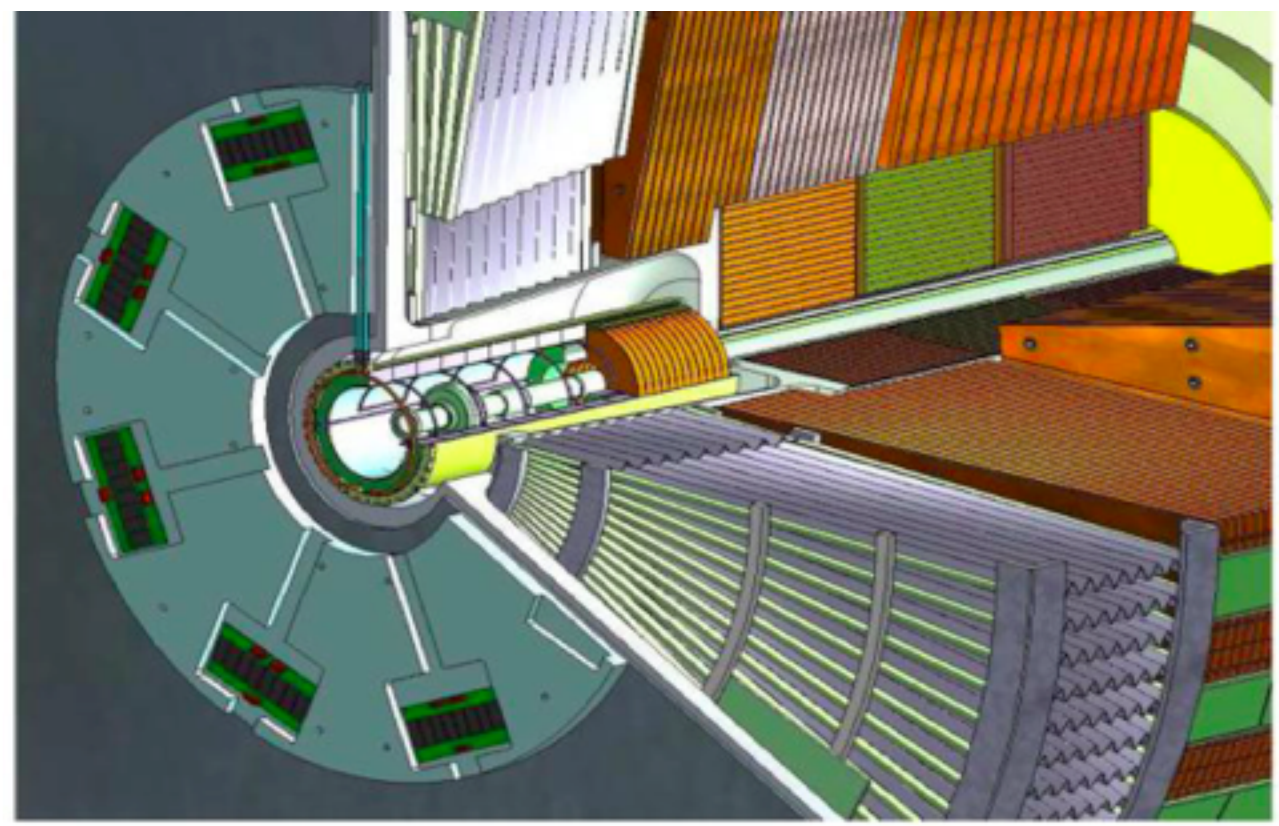
- The liquid Ar forward calorimeter expands to η~4.9
  - very high particle fluxes
  - danger of boiling Ar
  - Ar^+ builds up, may cause voltage drops due to fluctuation of ions
- Placing a miniature (warm) calorimeter in front of FCal
  - absorbs EM jet component (roughly half of the energy)
- Cu absorbers with diamond detectors
  - very radiation hard
  - highly segmented readout
  - placed around the beam-pipe



Phase II - LHC Conditions & ATLAS Plans

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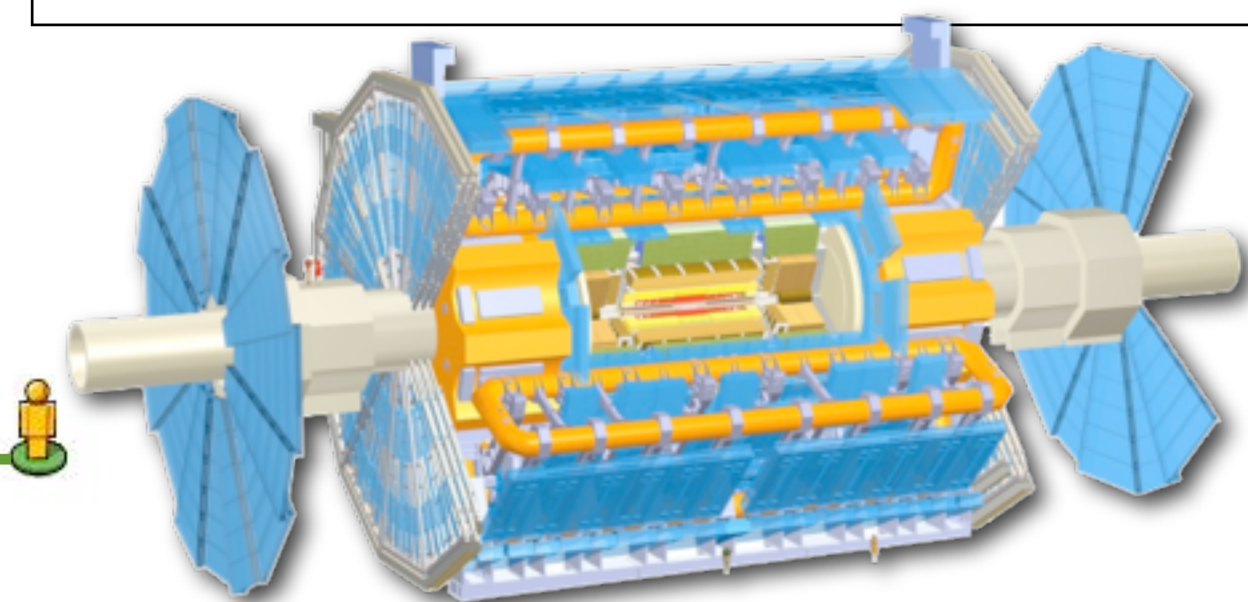
- Luminosity levelling: 5 x 10^{34} cm^{-2} s^{-1} (“beam crabbing”) (~200 interactions per bunch crossing)
- 3000 fb^{-1} good data on tape: high radiation dose to detectors
- Shut-down: 18 months

- All new Inner Detector to cope with higher occupancy



- Possible Muon System upgrade, neutron shielding
- Upgrade to the LAr end-cap calorimeter
- major changes to trigger system and detector electronics with possible L1 track trigger

Magnet system, most of muon and calorimeter systems remain

Phase II - LHC Conditions & ATLAS Plans

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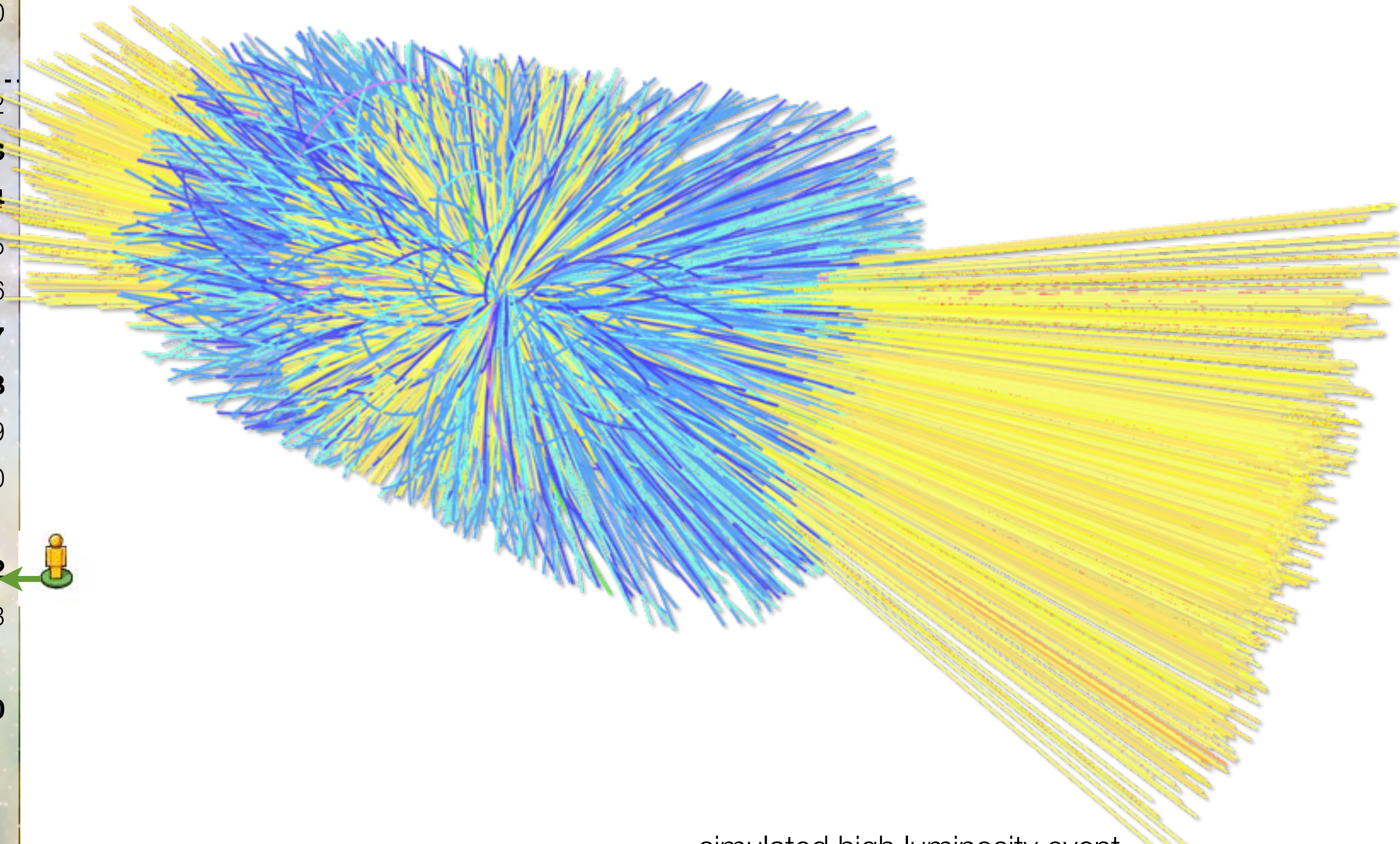

simulated high luminosity event
(generated particles including neutrals)

New ATLAS Inner Tracker

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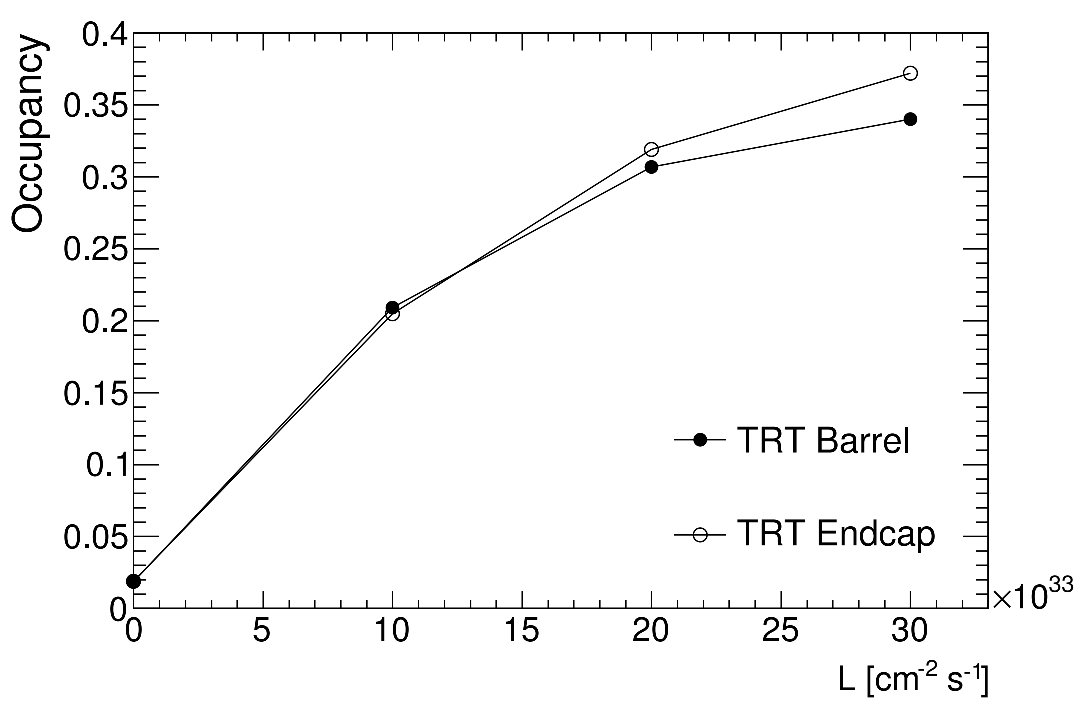
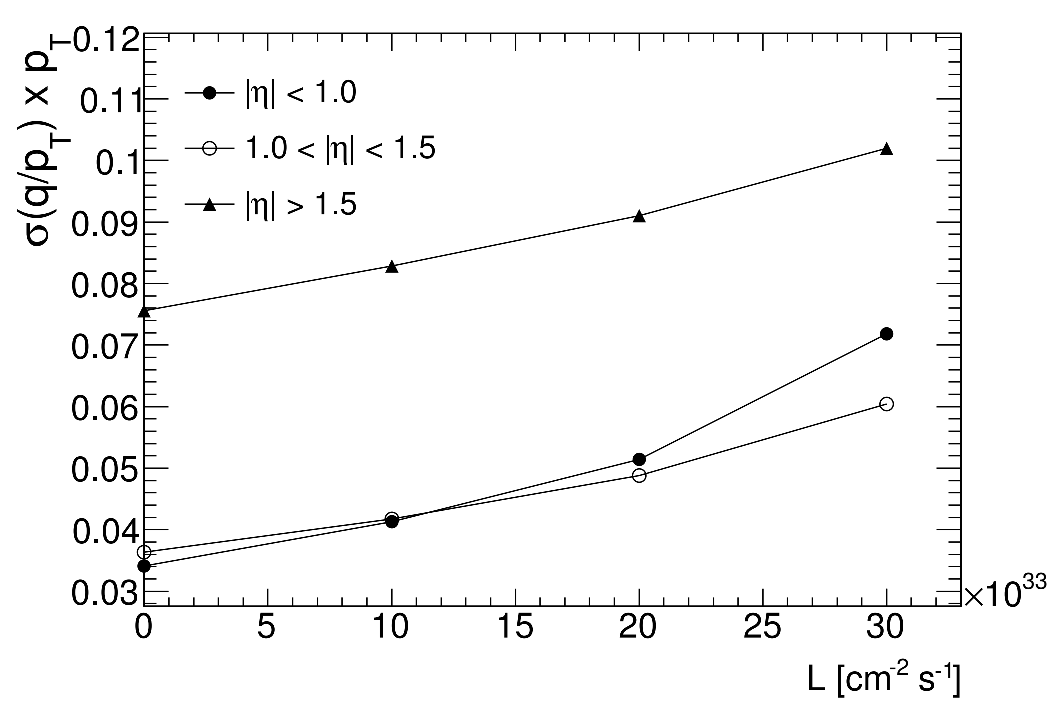
- Pixel: current b-layer will suffer from radiation damage
  - readout and granularity limitations
- SCT: current detector has readout limitations to 2.5 x 10^{34} cm^{-2} s^{-1}
  - also radiation damage: SCT designed for 700 fb^{-1}
- TRT: occupancy is getting too high
  - starts degrading the momentum measurement performance





Complete replacement of the inner tracking system with a new pixel/strip system.

New ATLAS Inner Tracker: strawman layout

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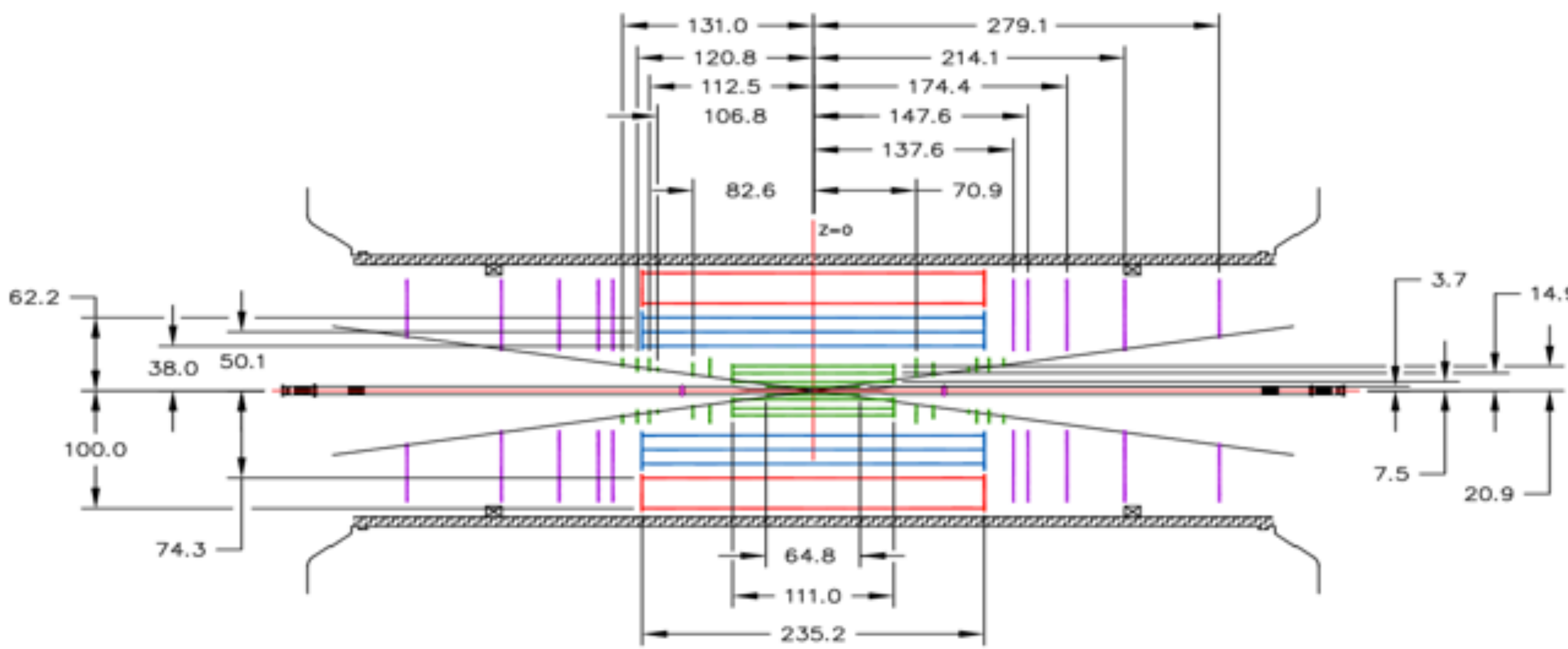
- Classical barrel / end-cap detector used for first design studies

4 layers of pixels to larger radius than now
3 double-layers of short strips (SCT region)
2 double-layers of long strips (TRT region)

Approx. 400 Million pixels (cf 80 Million now)
Approx. 45 Million strips (cf 6.3 Million now)

Granularity tests show hit occupancy under control for pattern recognition



New ATLAS Inner Tracker: layout considerations

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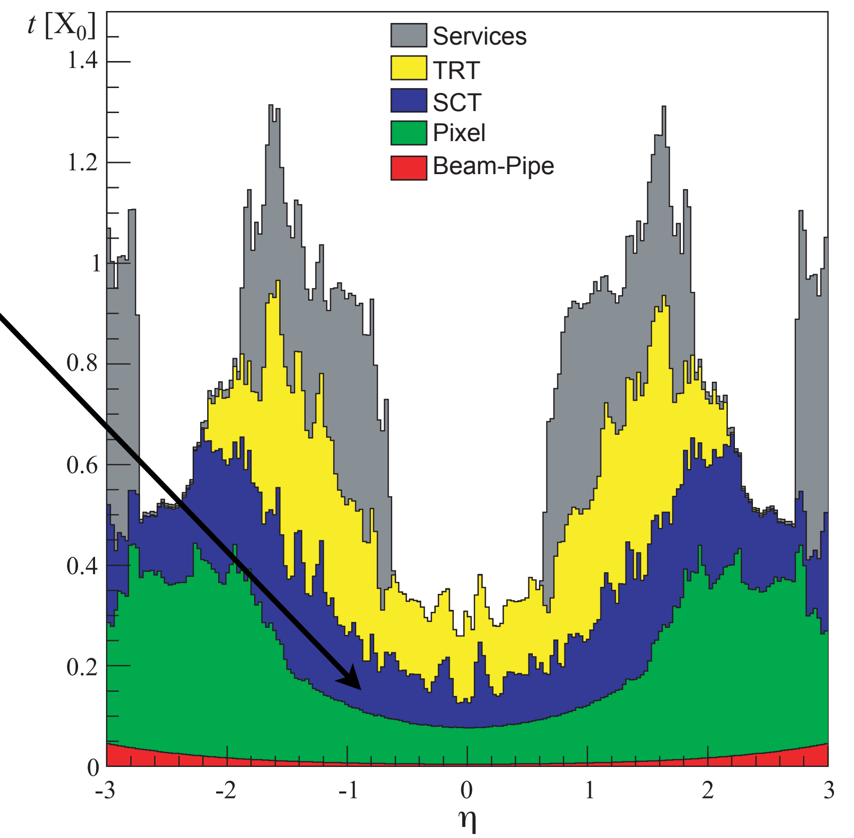
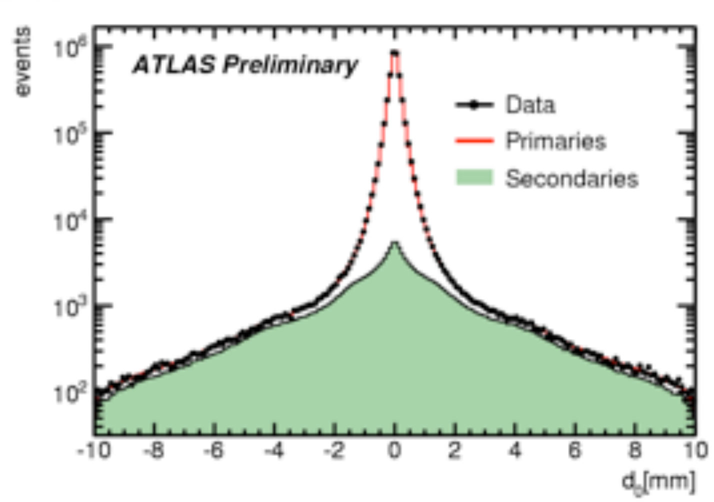
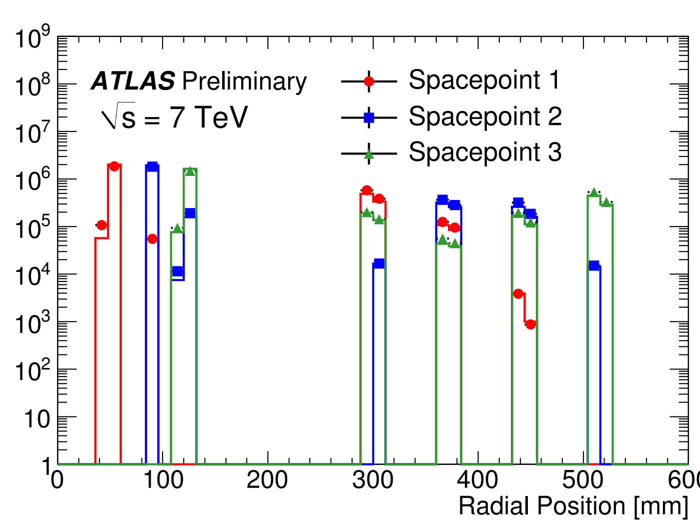
- Learning from current experiences
  - 1/sin(θ) is **not** the dominating component of material distribution
  - barrel/end-cap transition needs to be carefully designed (if any)



- Avoid long extrapolation distances through (inactive) material

- Profit from positive lessons
  - pattern recognition performance
  - data/MC agreement





New ATLAS Inner Tracker: layout considerations

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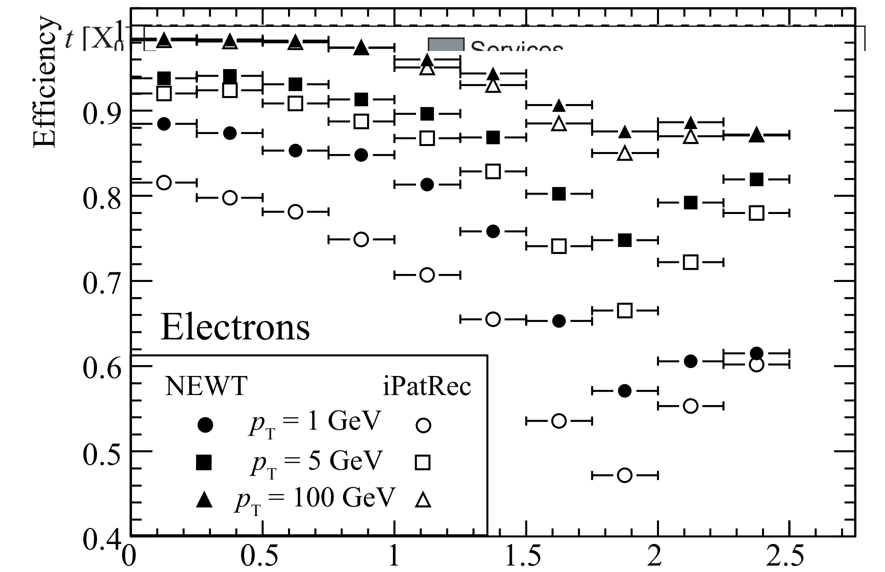

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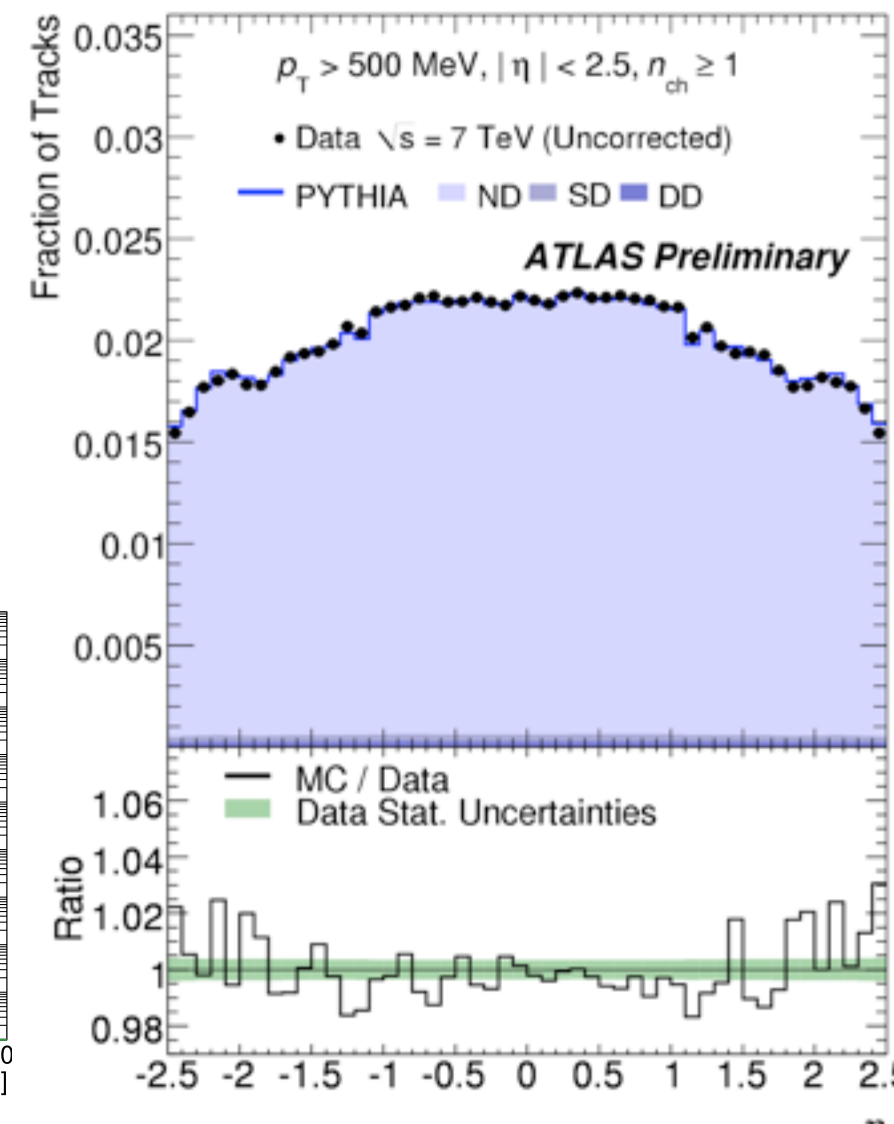

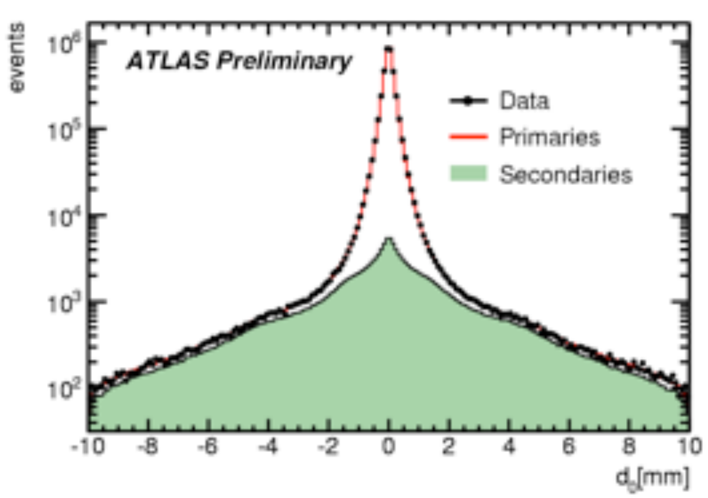

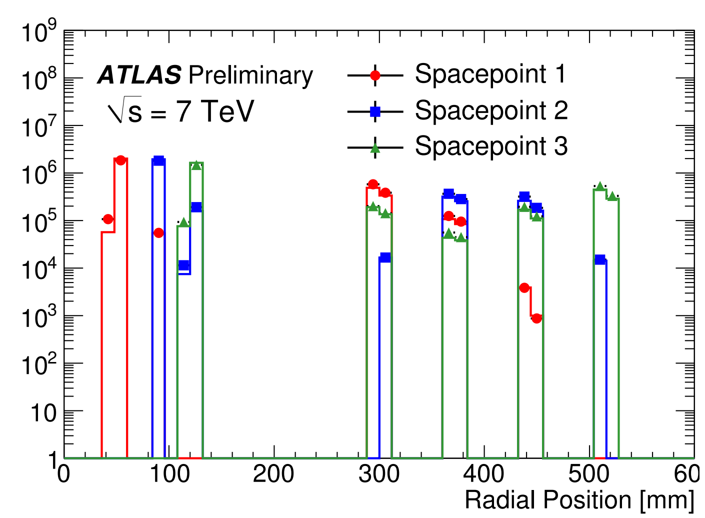

New ATLAS Inner Tracker: conical shapes ?

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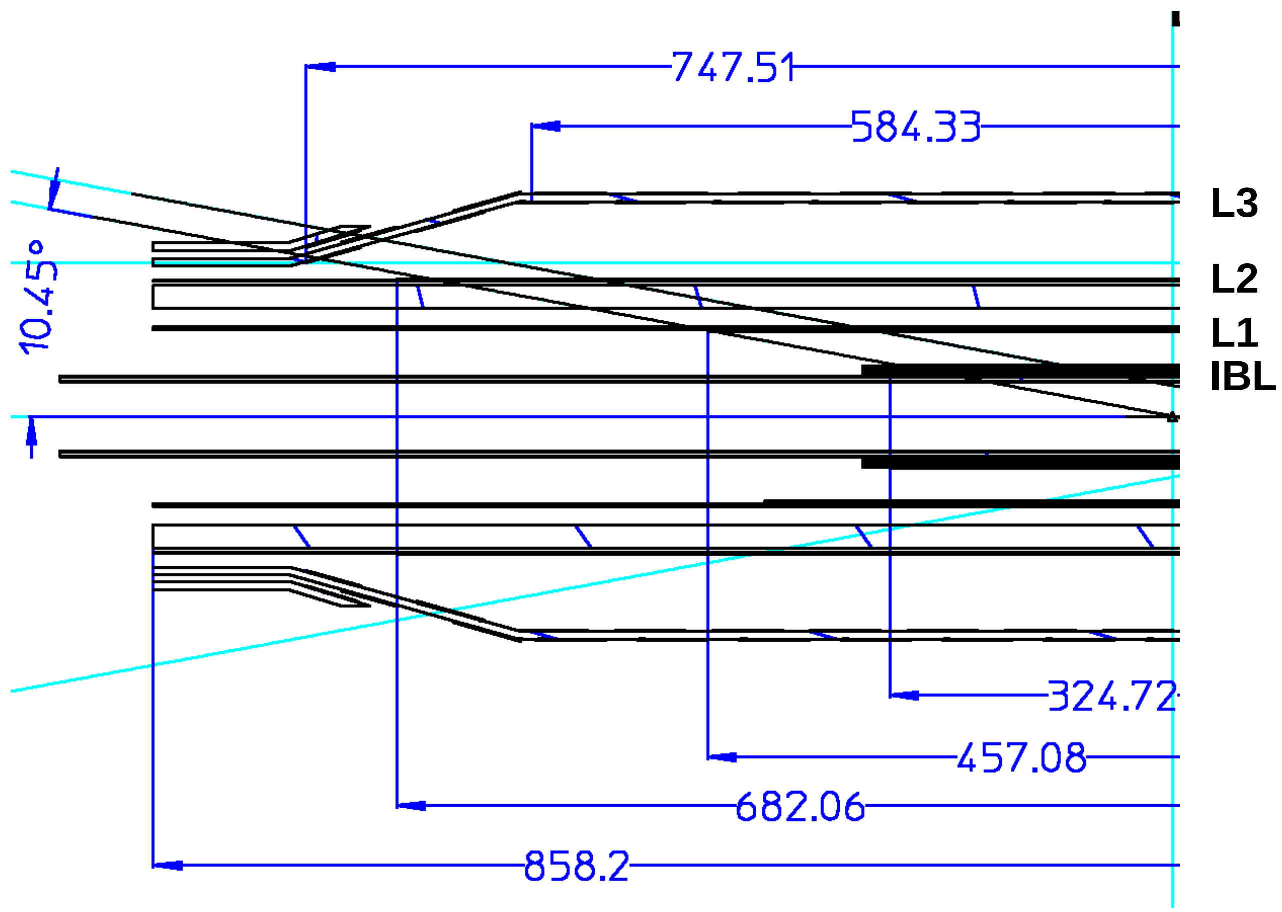
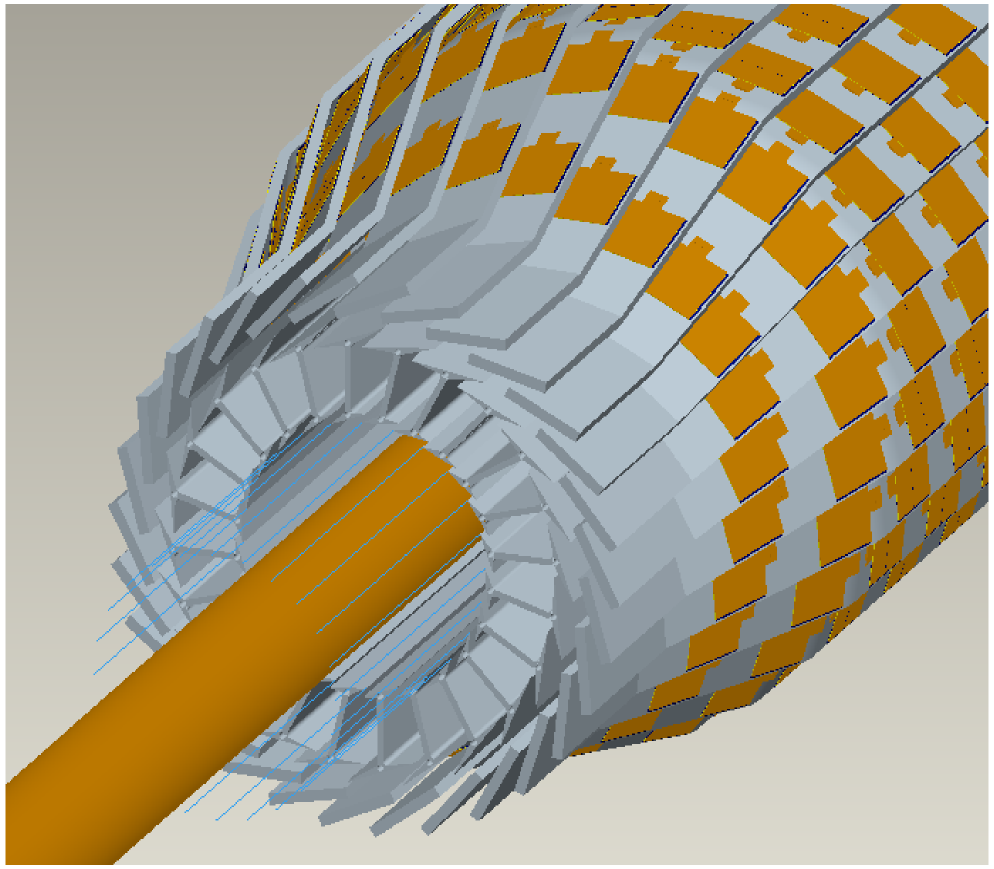
- one prototype is barrel-only setup with conical end-shape
  - optimize tracker coverage while minimizing material budget
  - barrel/end-cap transition needs to be carefully designed (if any)

- first stave prototypes built





Thursday, June 23, 2011

New ATLAS Inner Tracker: conditions & plans

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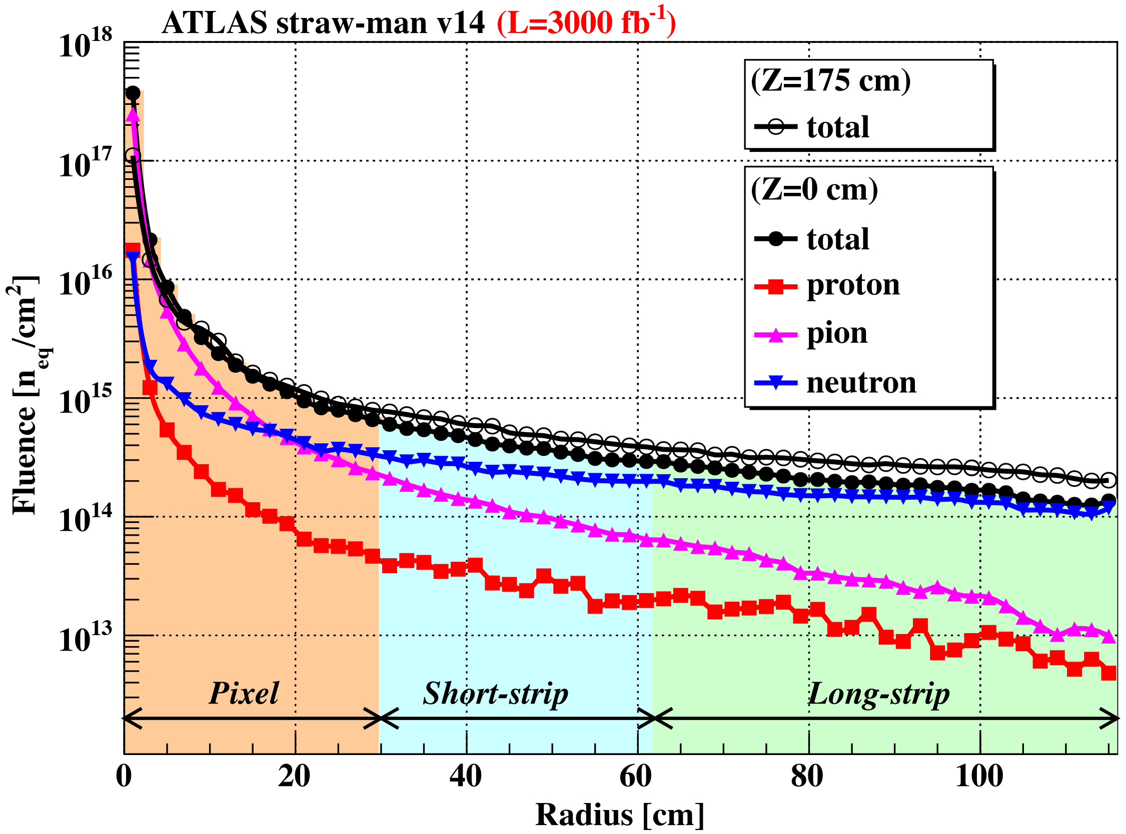
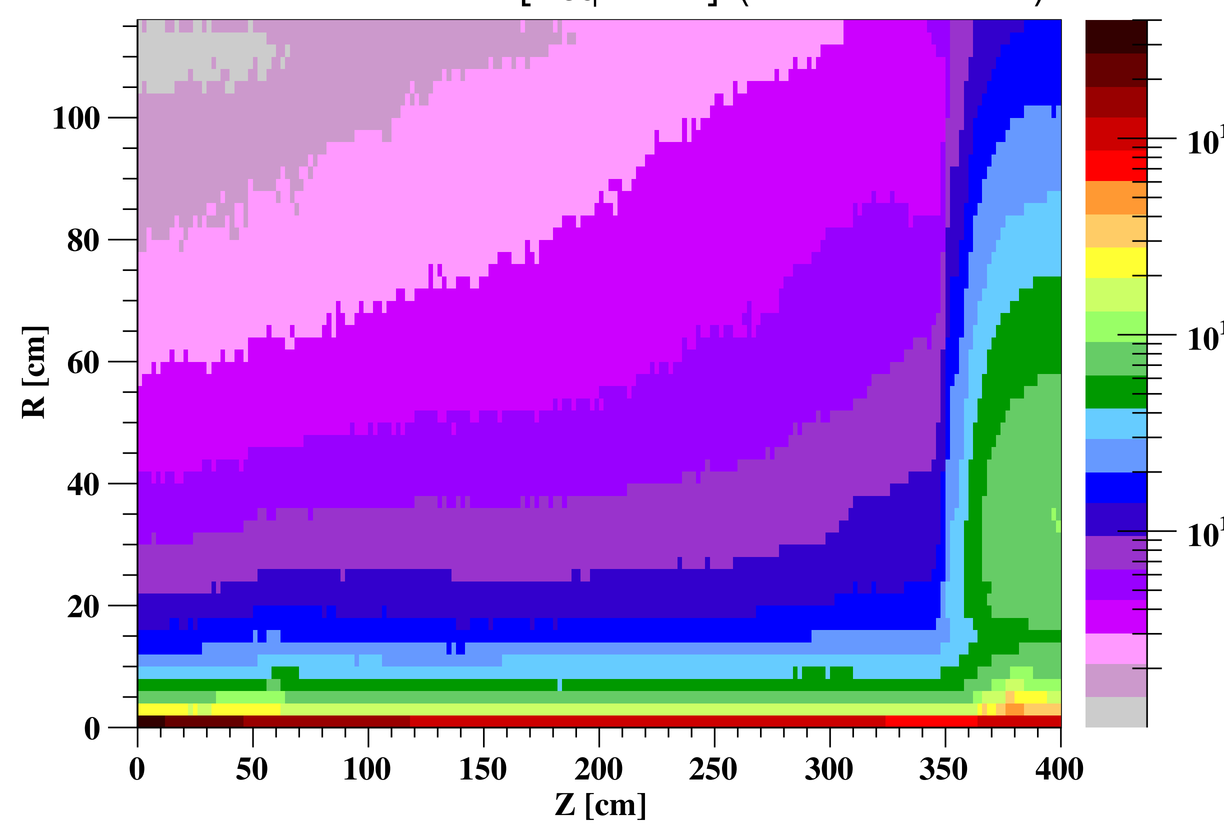
- Very harsh radiation environment



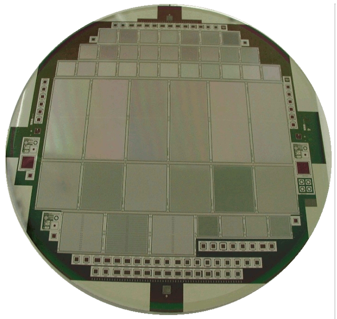
Fluence [n_{eq}/cm^2] (L= 3000 fb^{-1})



- Cooling : planing for evaporative CO_2 cooling
  - large latent heat
  - good heat transfer, will allow for smaller cooling pipes (material budget)

- New powering schema successfully tested
  - DC-DC converters
  - serial powering

New ATLAS Inner Tracker: Pixel R&D



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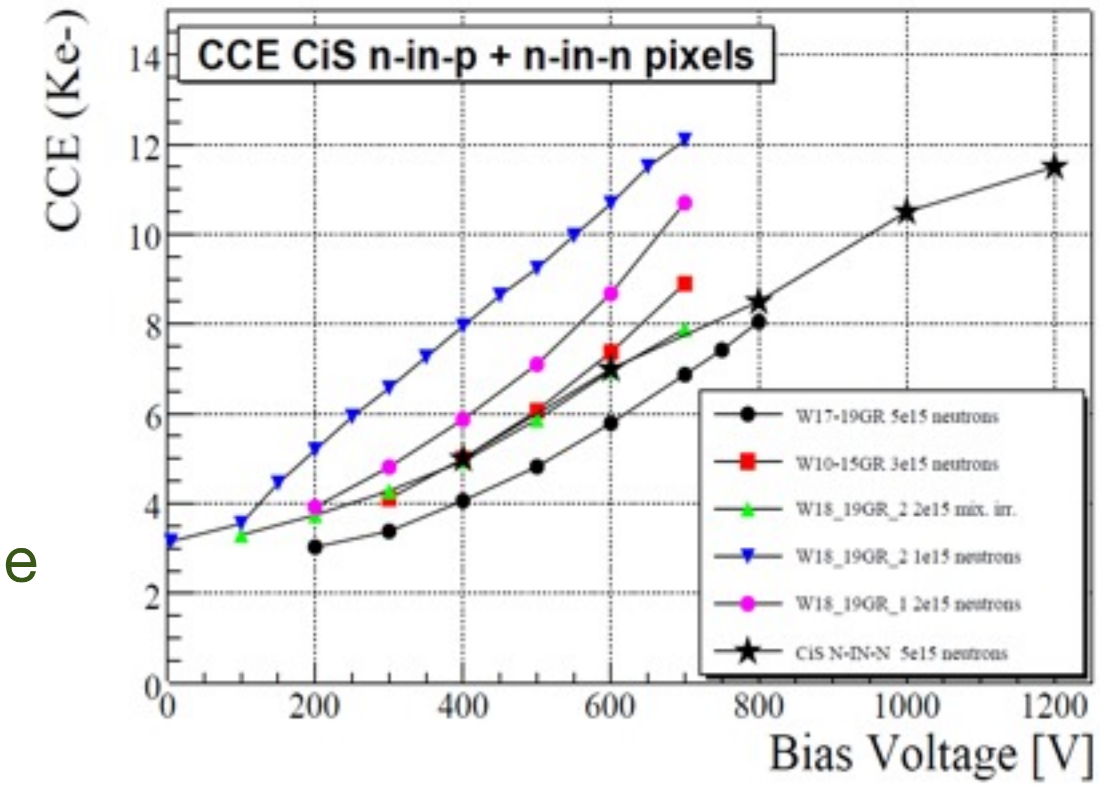
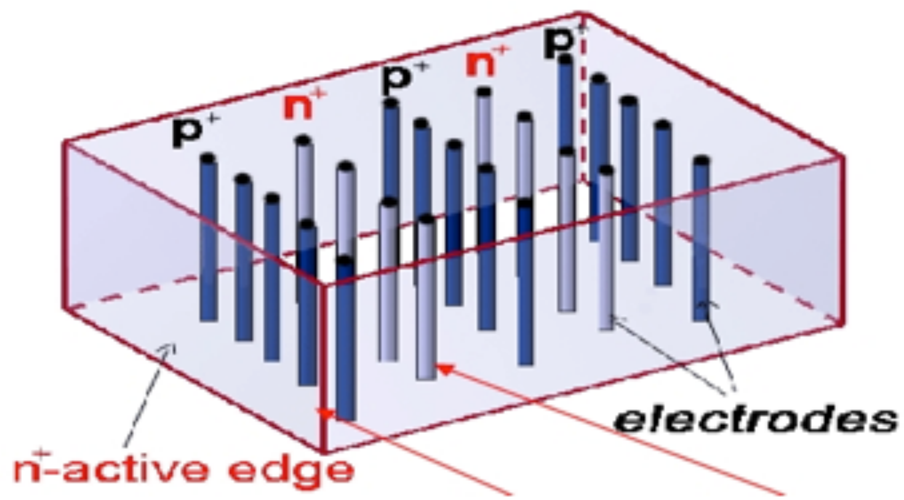
- Continue planar and 3D R&D based on IBL experience:
  - outer layers can work with FE-I4 chip
  - one target is thinning sensor to 150 μm

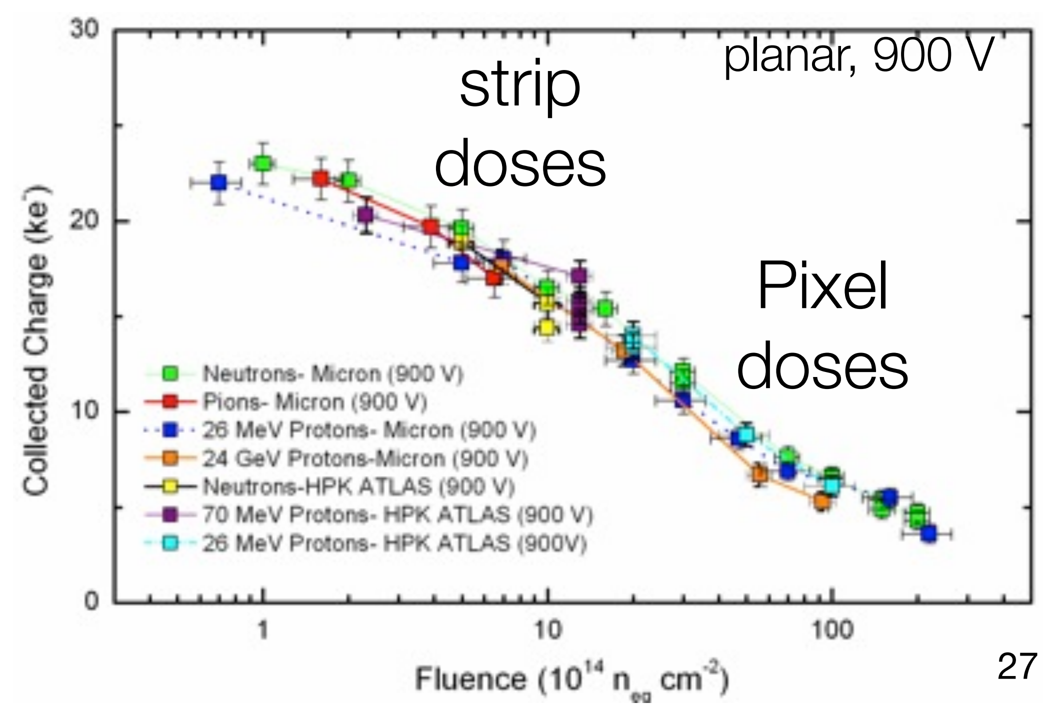


- Several silicon sensors investiaged
  - show comparable characteristics
  - with high enough bias they give acceptable signal-to-noise at 3000 fb^{-1}

- 3D sensors with active gaps



n-in-p FZ radiation studies



- Diamond sensors (more radiation hard)

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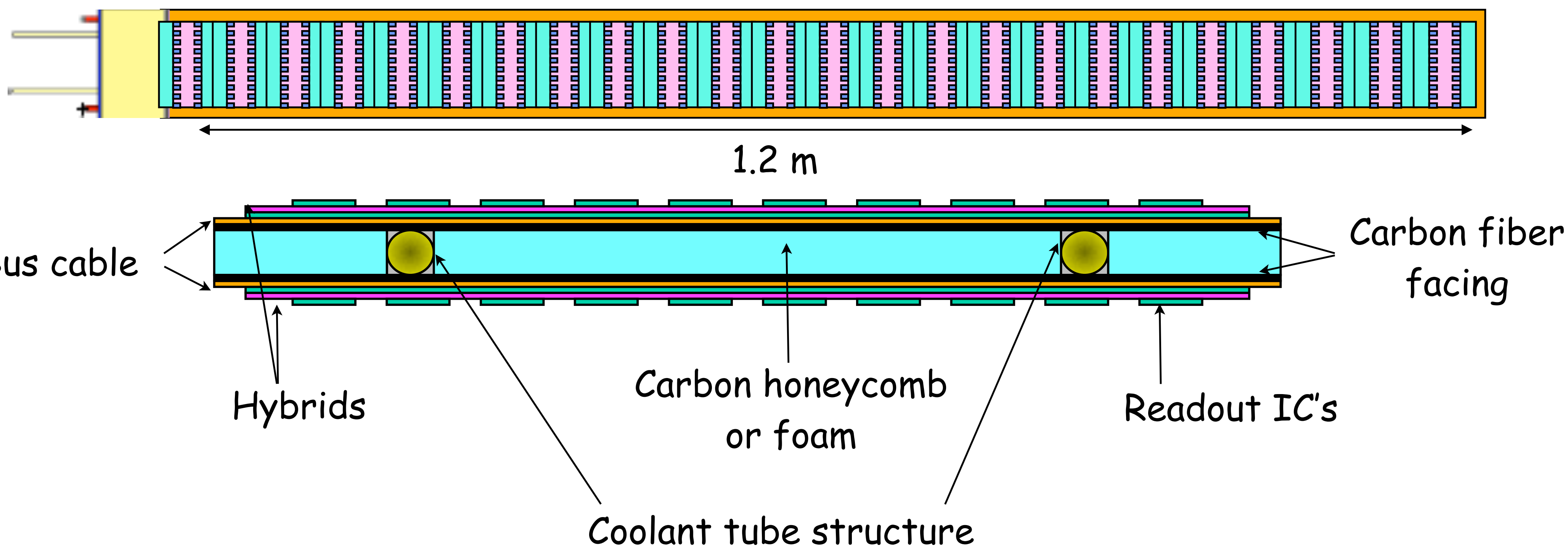
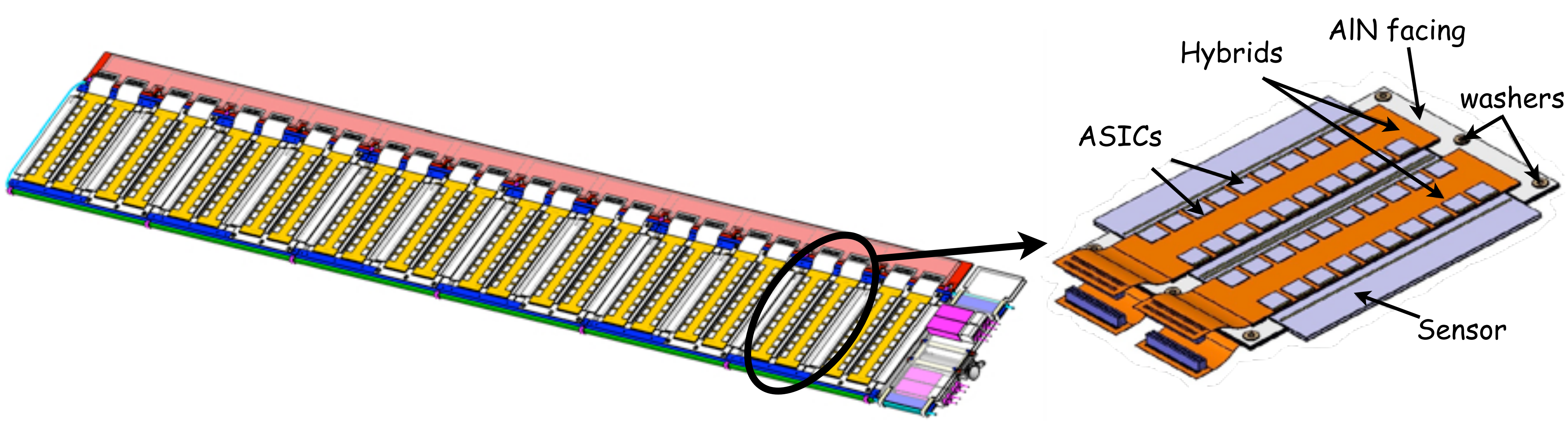
New ATLAS Inner Tracker: strips R&D (1)

- Single-sided modules in STAVE structure



- Double-sided super-modules



New ATLAS Inner Tracker: strips R&D (1)

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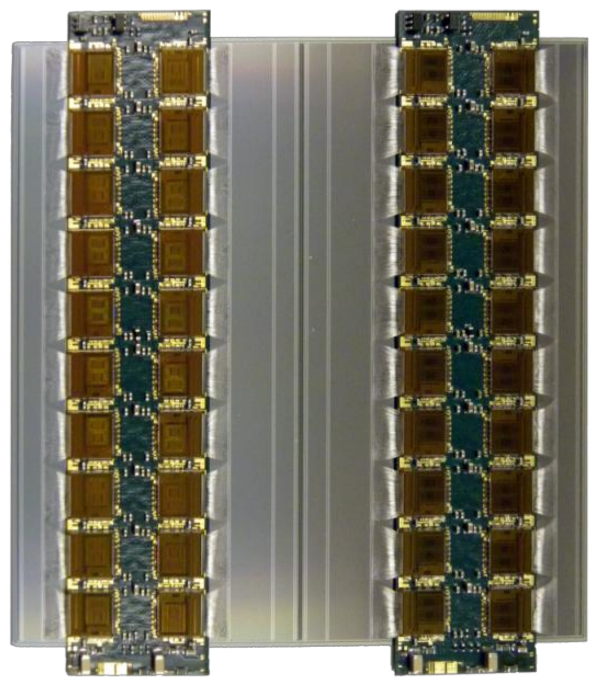
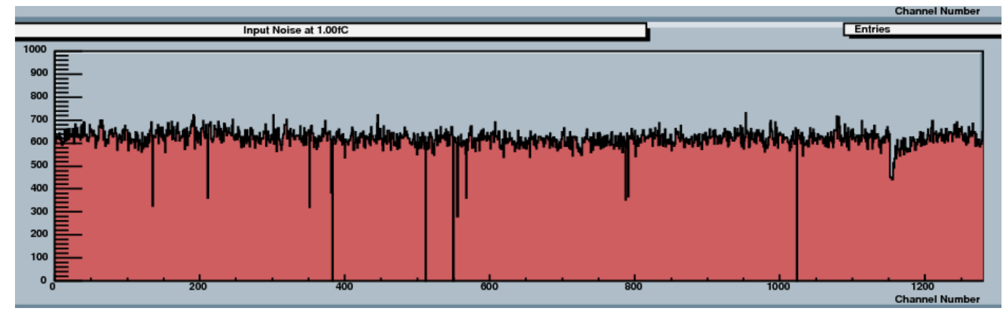
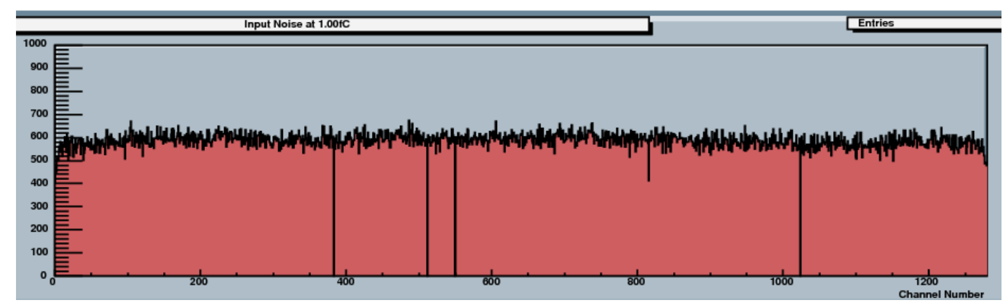
- Single-sided modules in STAVE structure



Outer Column- 615 e-



Inner Column- 601 e-



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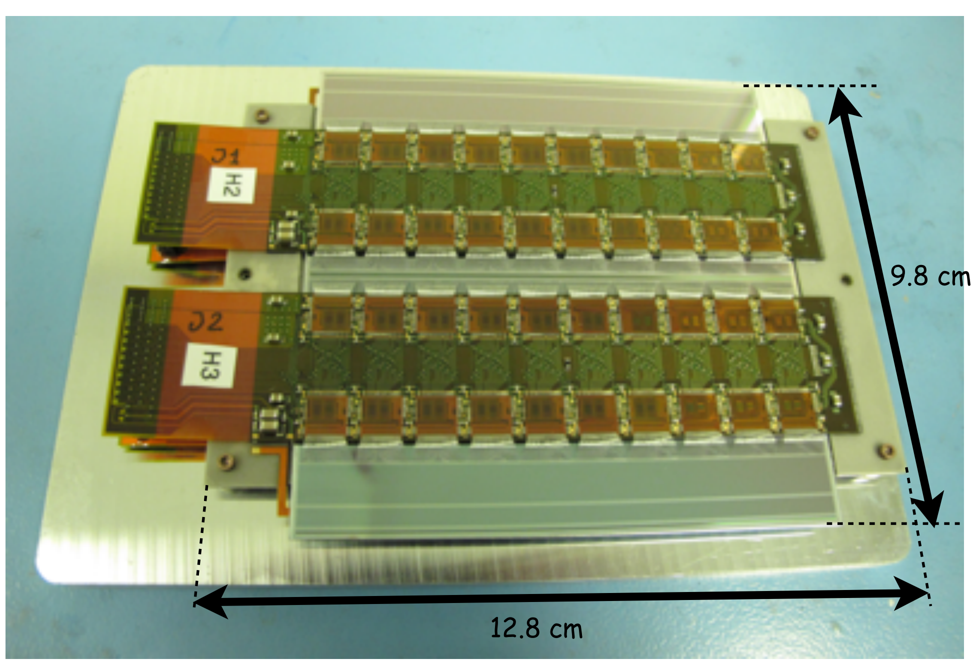

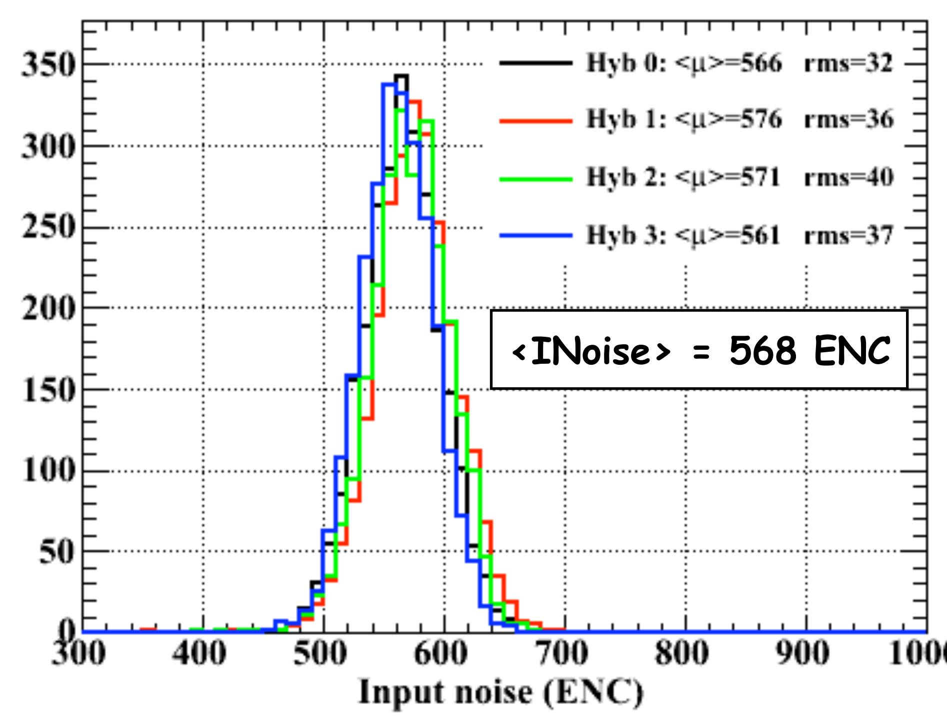

very similar electric performance

Track Trigger at L1

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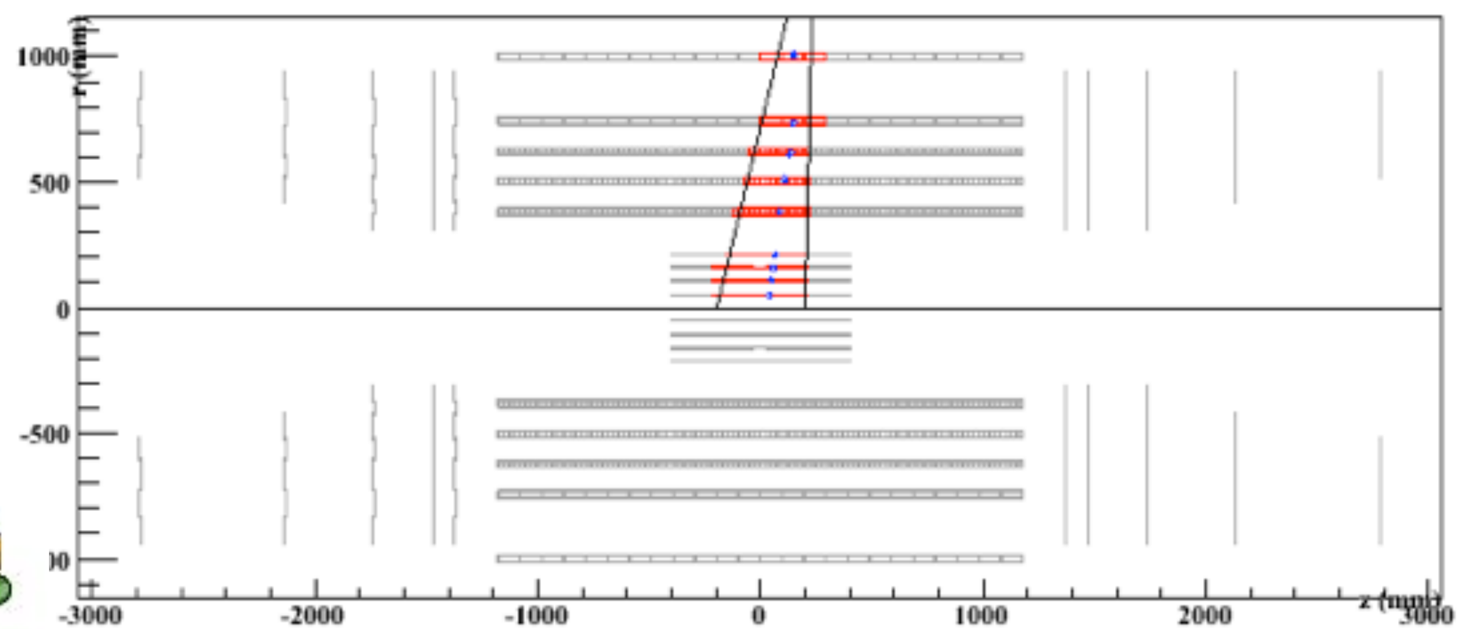
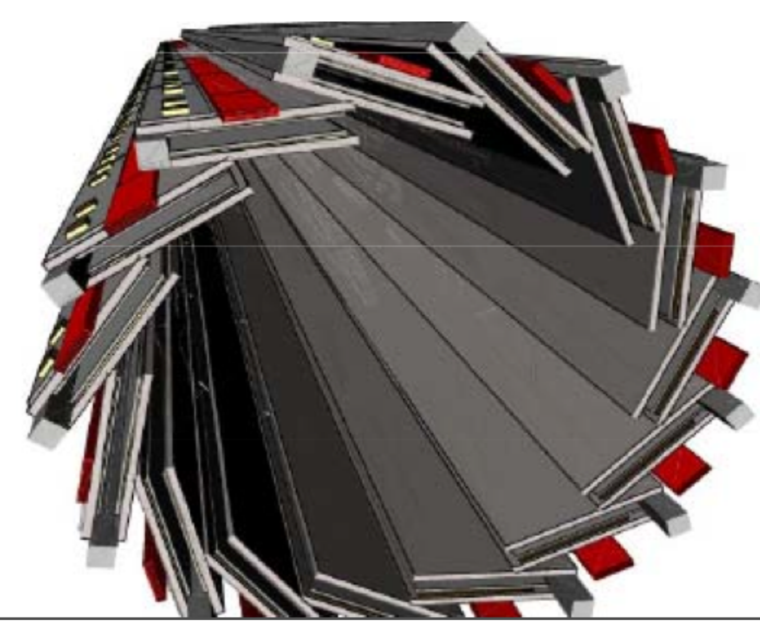
- Option 1: Regional readout at L0 and L1
  - Calo/MS could provide region of interest (ROI)
  - inner tracker modules are read out and hardware trigger confirms presence of a track candidate
  - needs additional data stream in front-end chip



- Option 2: Self-seeded stand-alone
  - used paired modules (omit stereo placement)
  - read out only coincident modules (high p_T)



Calorimeter Upgrade

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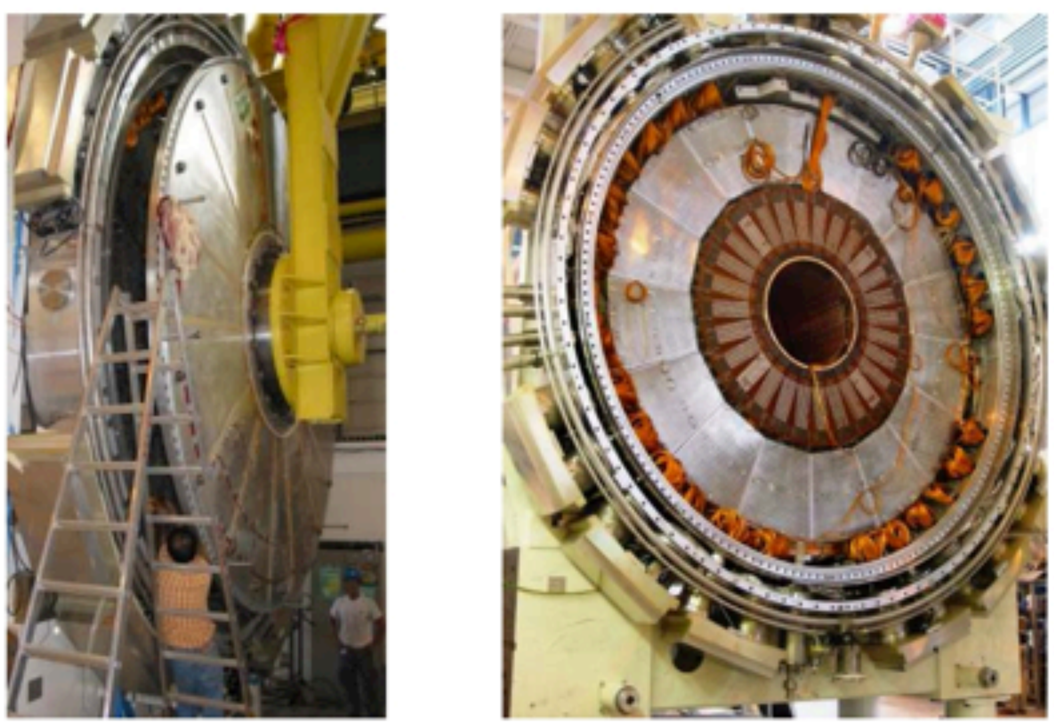
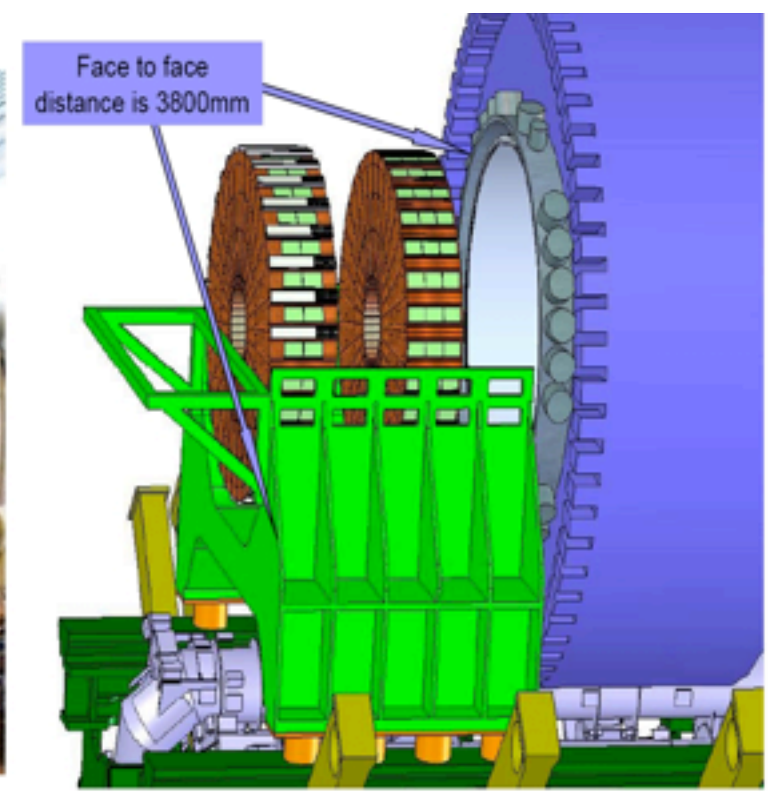
- EM Barrel & Tile Calorimeter will work fine: no upgrade
- One concern:
  Will cold electronics inside end-cap survive 3000 fb^{-1}?
  (initially designed for 1000 fb^{-1})

  If so, miniature warm calorimeter in front of the **FCAL at Phase-I** should be enough to fix HV drop, ion build up, and risk of boiling the Ar.
  If not, need to open up and replace cold electronics (tight within 18 months)

REMOVE COLD COVER TO EXPOSE REAR FACE OF HEC2

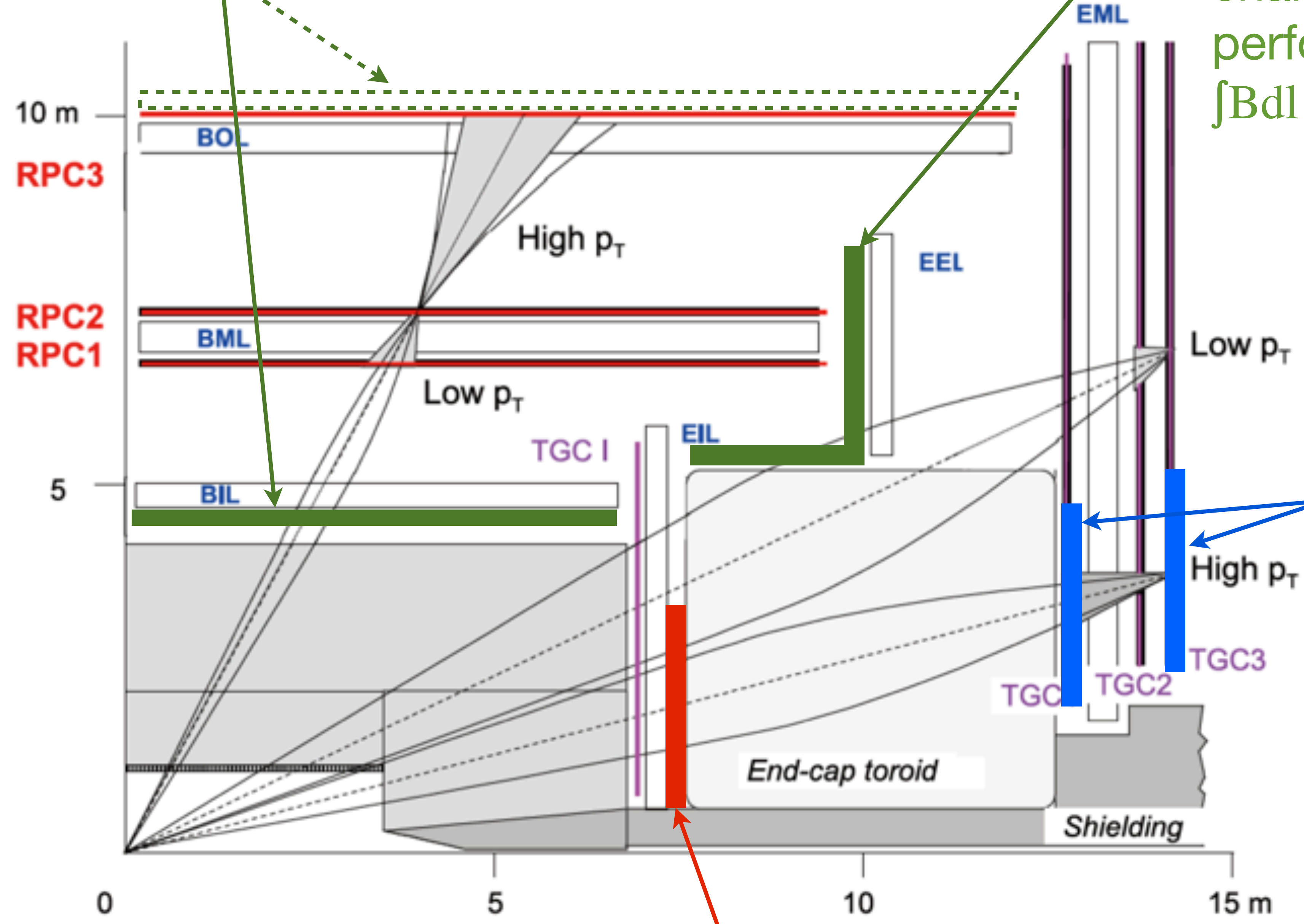




Muon System upgrade considerations

extra doublet with mm resolution (could also be needed for RPC3)

probably add new double of trigger chambers to improve performance in low $\int B dl$ region



replace forward chambers for higher resolution

add extra neutron shielding

Algorithmic challenges & lessons learned

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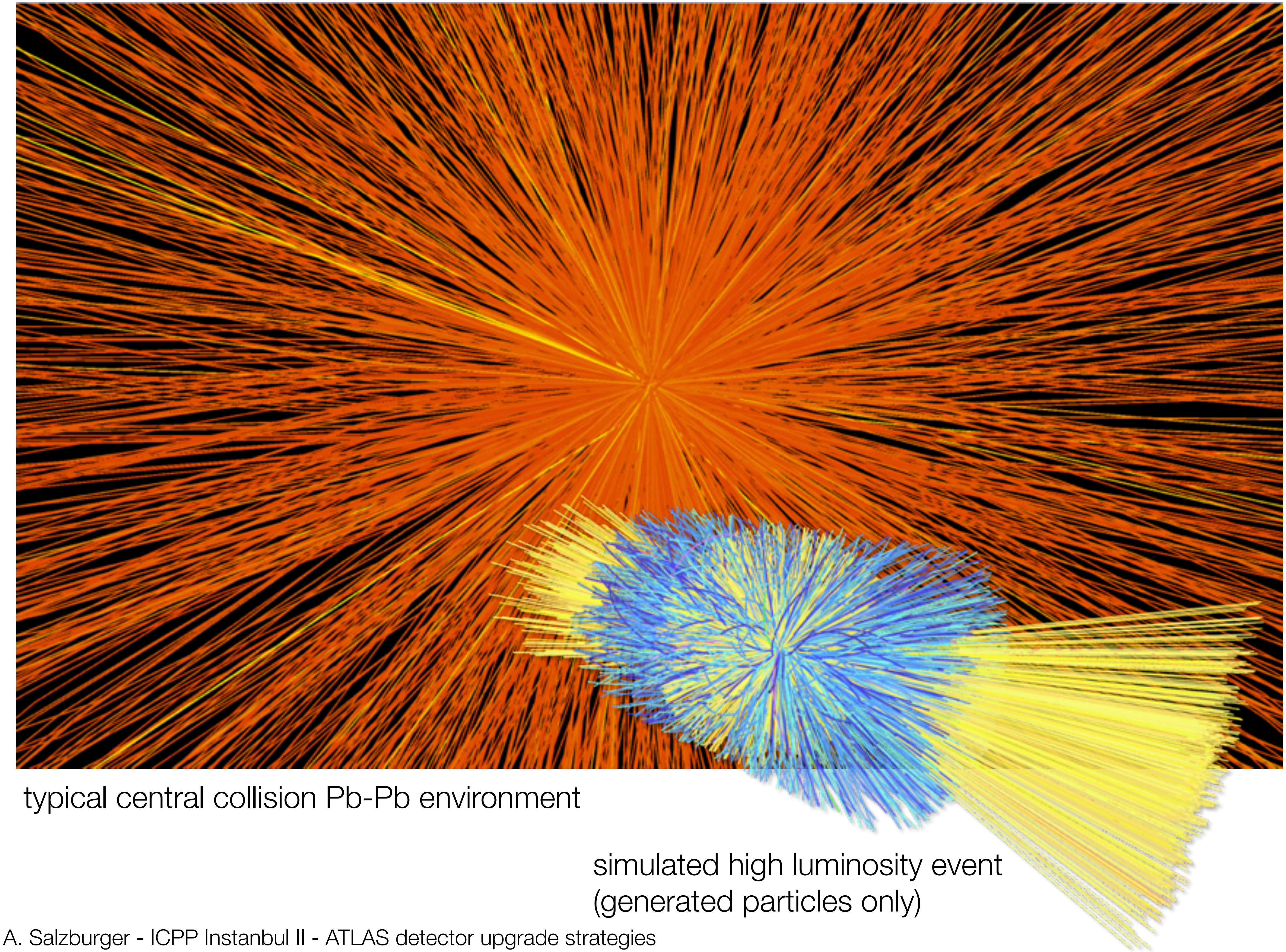

typical central collision Pb-Pb environment

simulated high luminosity event
(generated particles only)

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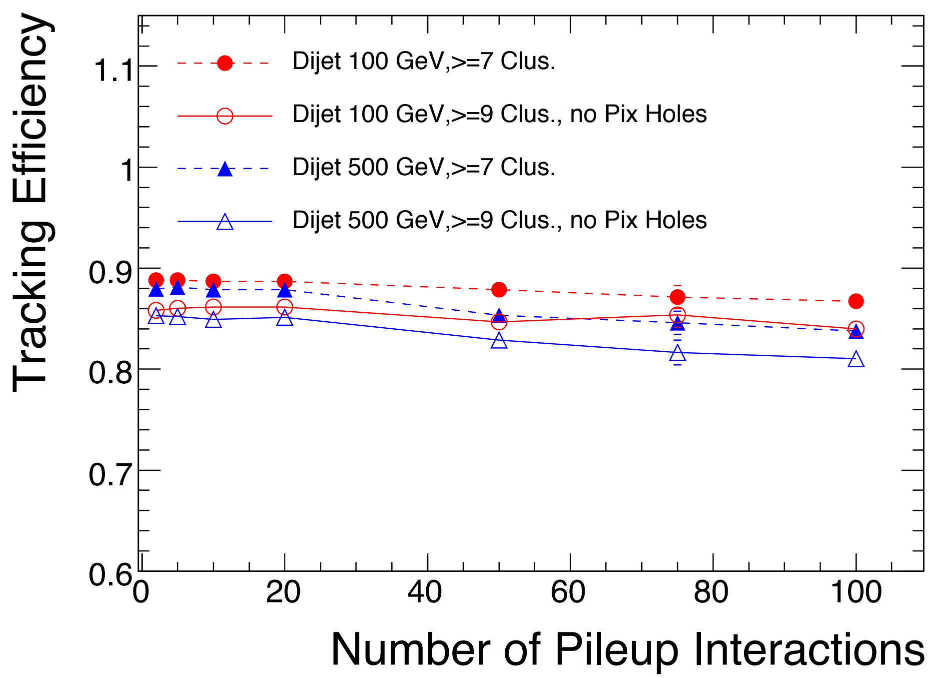
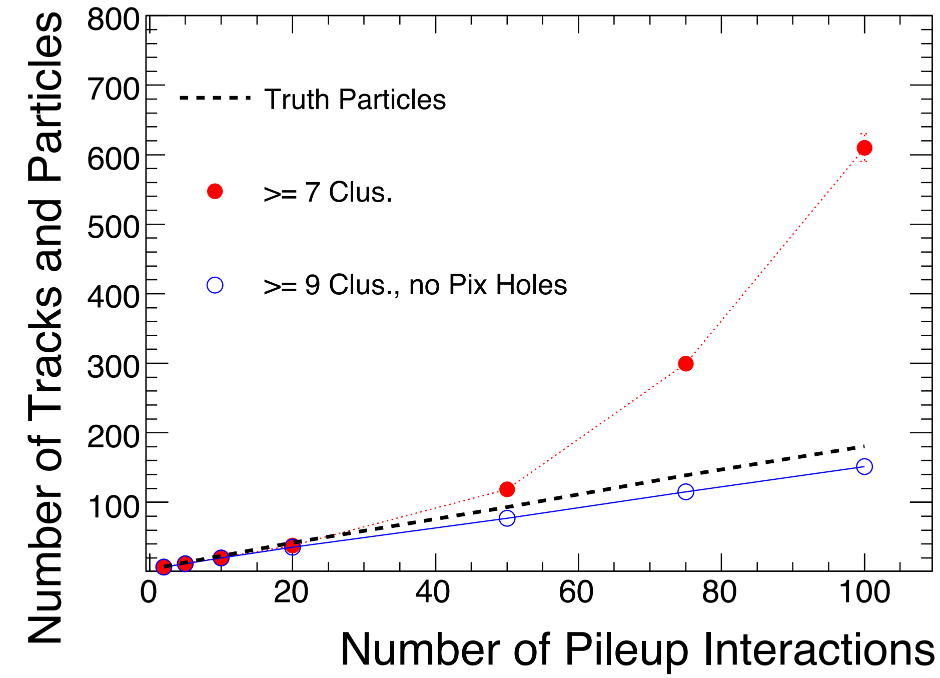
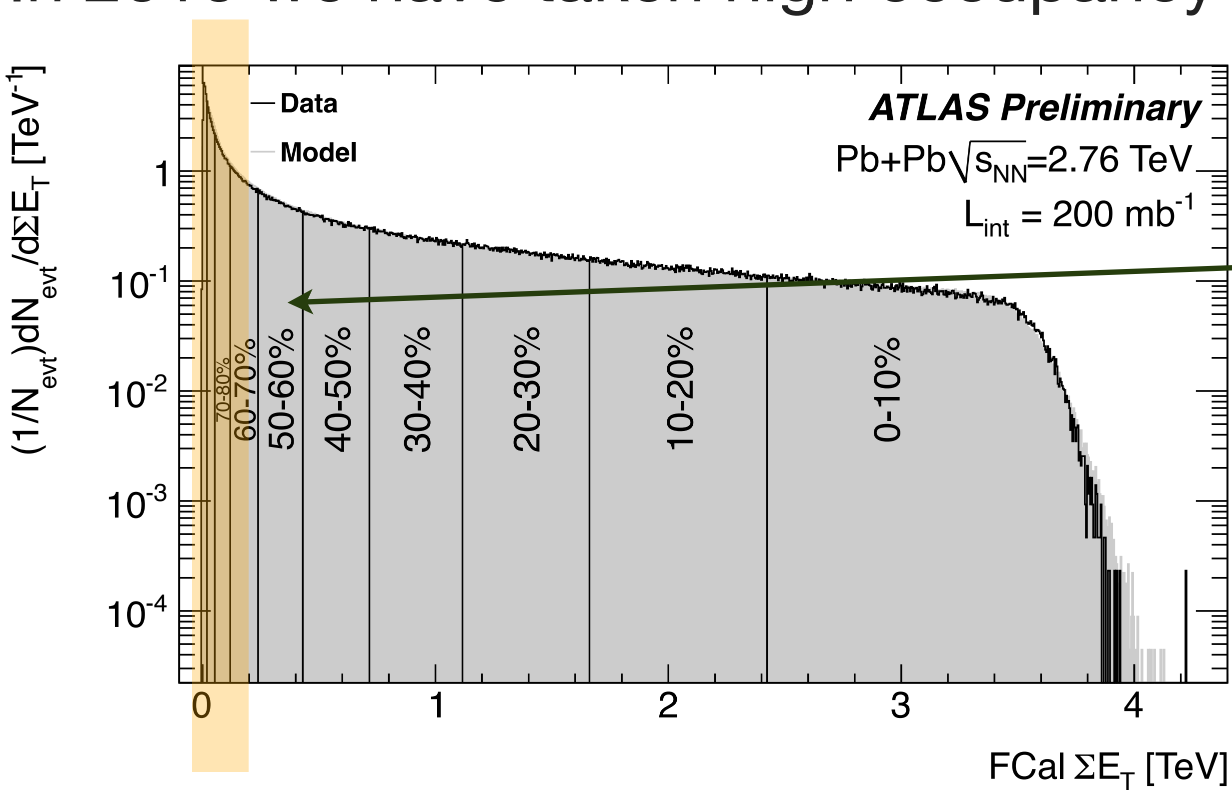
Algorithmic challenges: high occupancy

- Many studies carried out on simulated data to test algorithms in high pile-up scenarios





- In 2010 we have taken high occupancy data: heavy ion collisions



- approximate region covered by 2011 data
- heavy ion collision data can be used for preparation of pile-up scenarios

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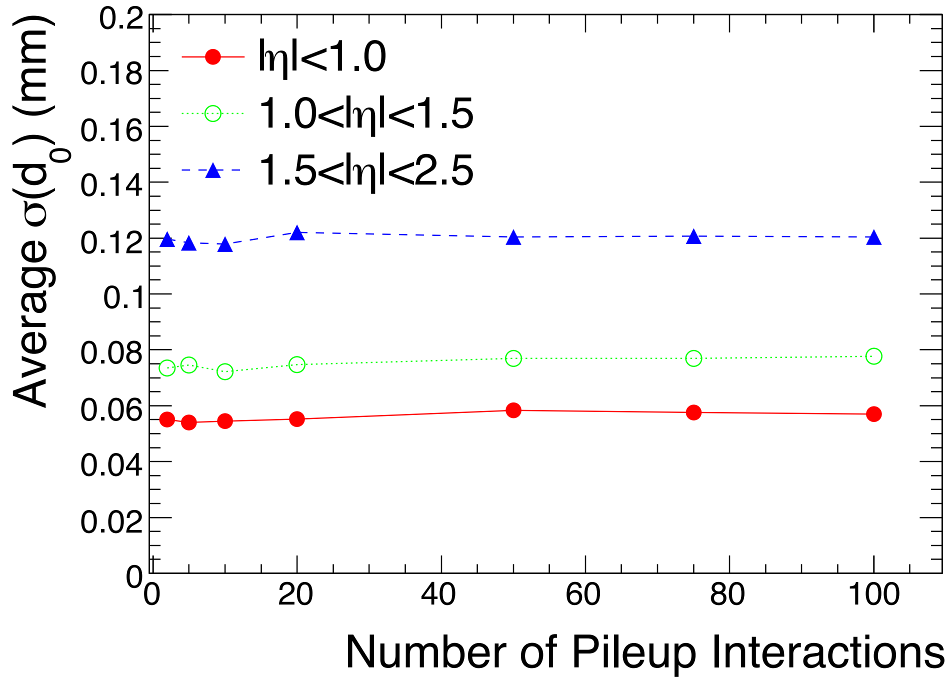
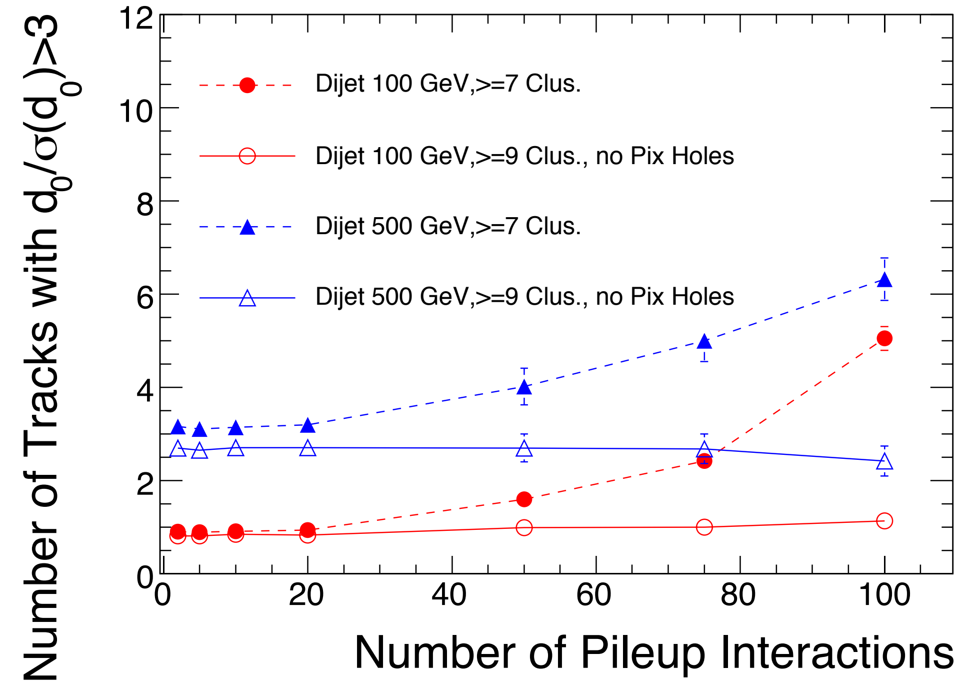
Algorithmic challenges: high occupancy

- Many studies carried out on simulated data to test algorithms in high pile-up scenarios





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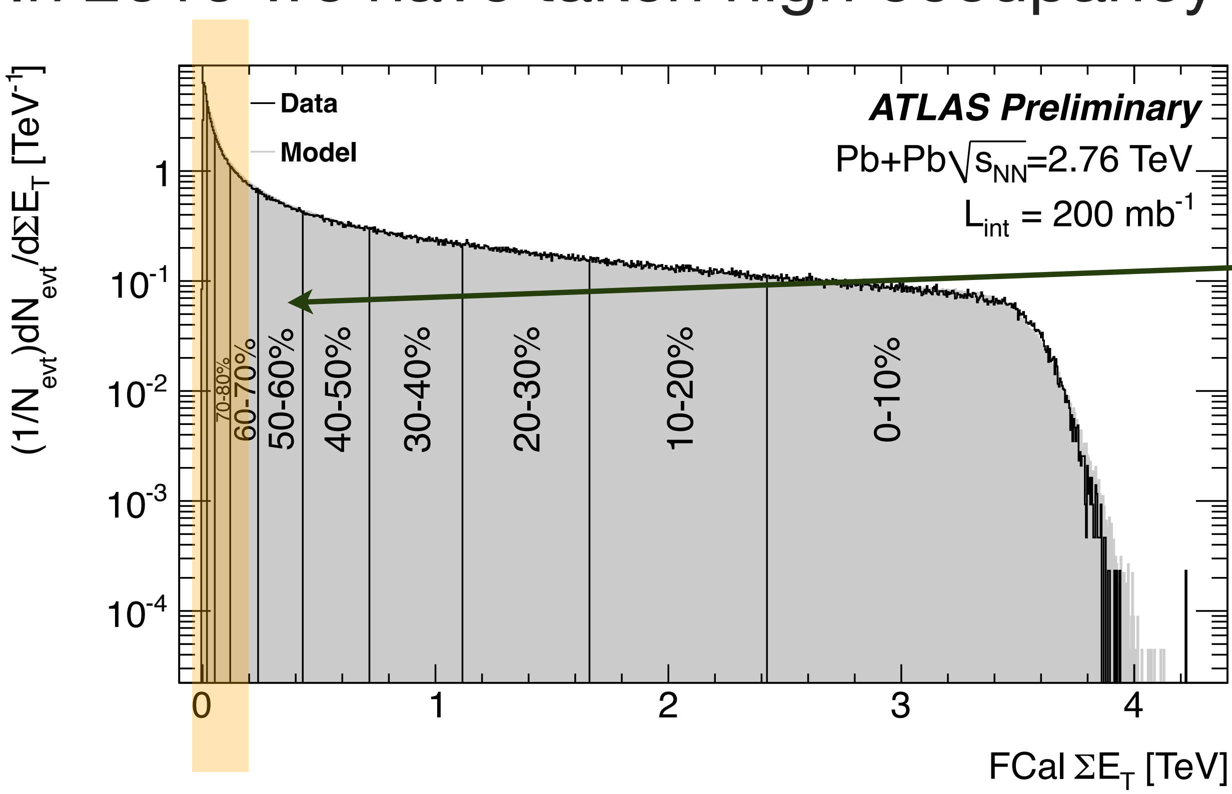

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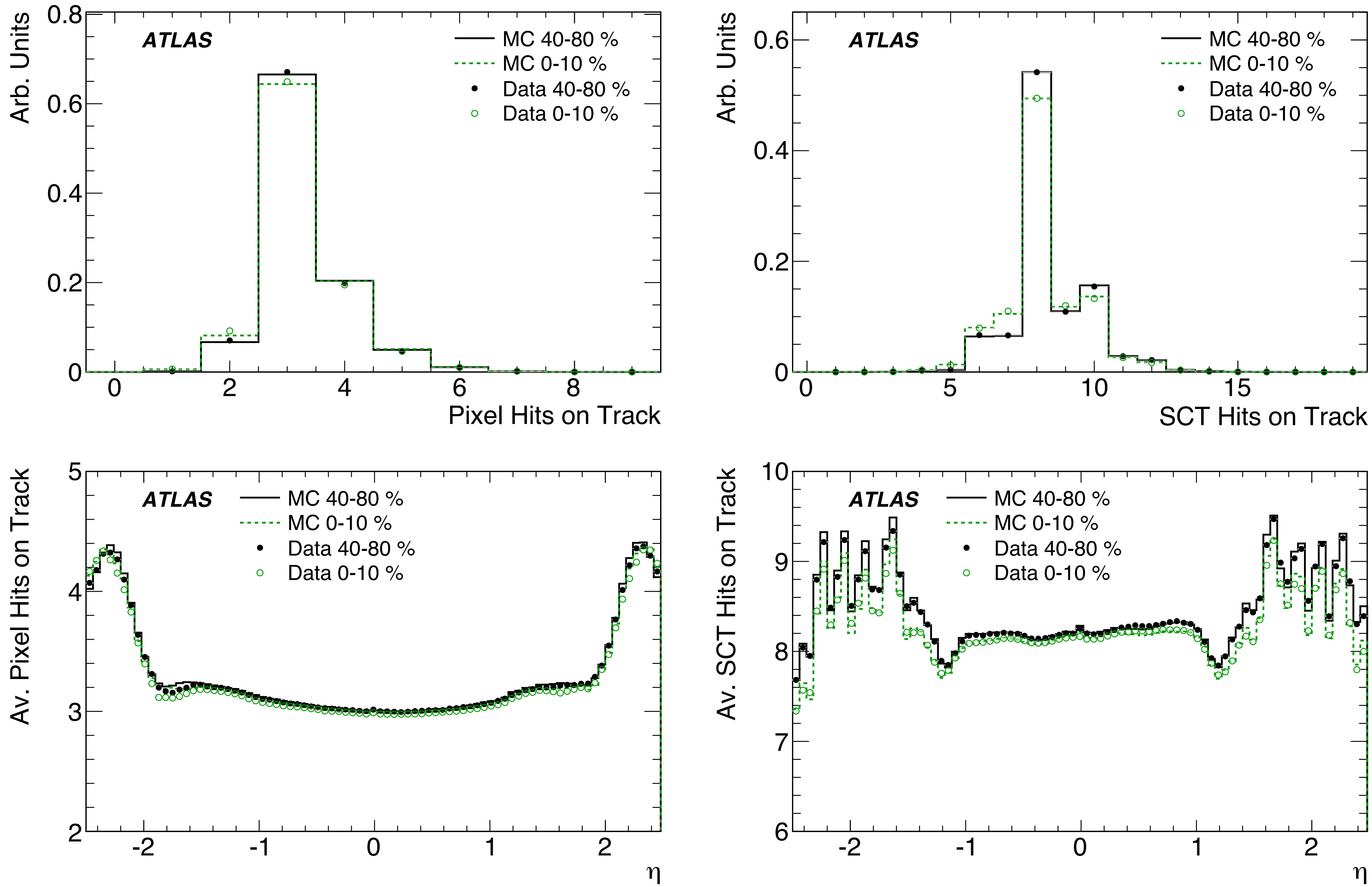
Algorithmic challenges: high occupancy

- Track reconstruction showed excellent performance in high occupancy environment
  - remarkable description by simulation



Algorithmic challenges: simulation strategies (1)

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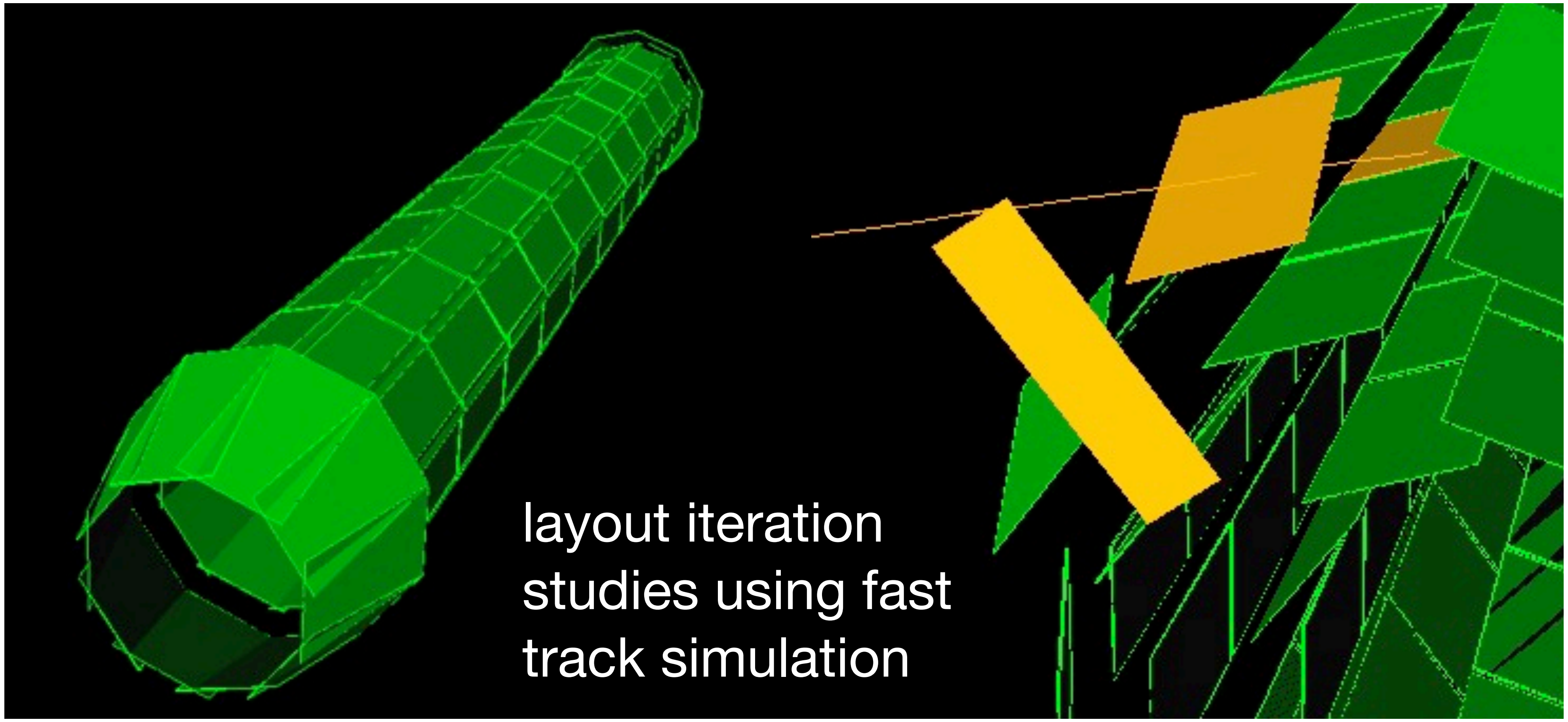
- Main simulation engine in ATLAS: Geant4
  - upgrade layouts integrated into general ALTAS framework (IBL, Phase-2 Inner Tracker, muon small wheels, etc.)
- Alternative, fast track simulation exists for fast detector design studies
  - helps to iterate on the different layout concepts
  - helps to develop/update pattern recognition modules



Algorithmic challenges: simulation strategies (2)

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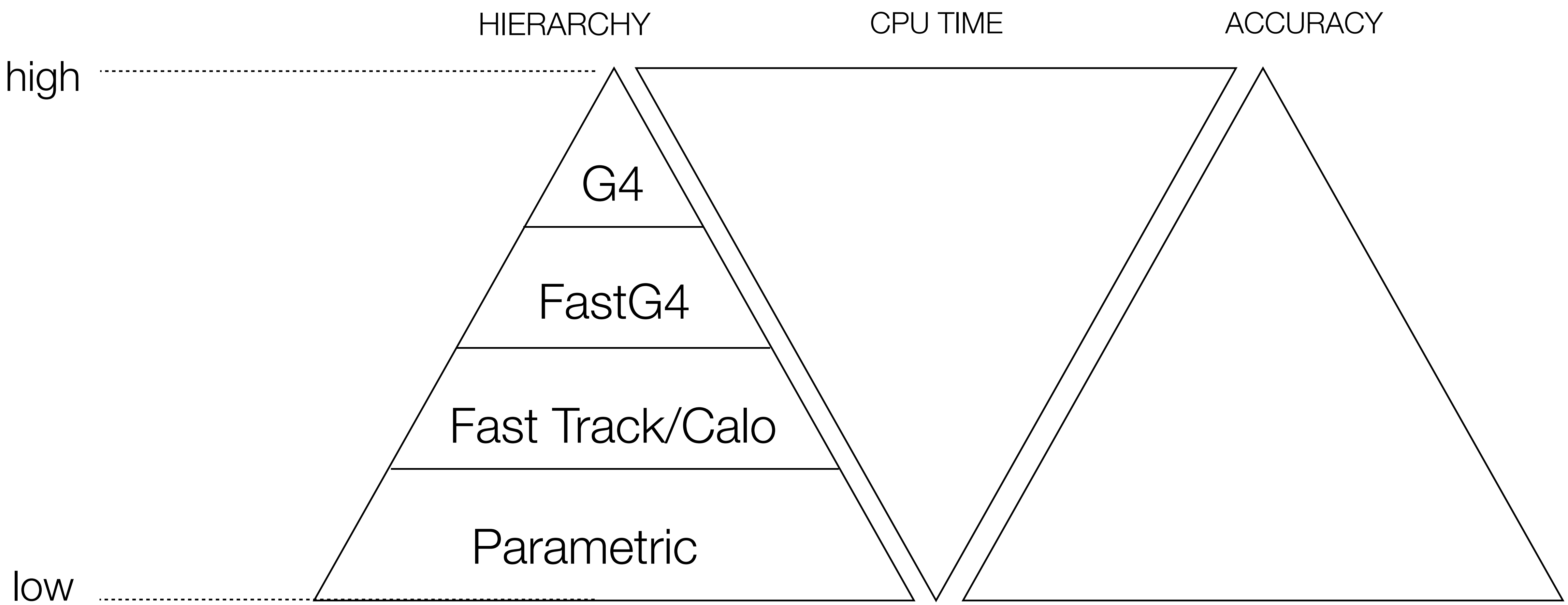
- high occupancy environment imposes stringent challenge on simulation and pattern recognition
  - mixture of full and fast simulation techniques will be needed
  - careful evaluation of MC techniques used for physics simulation

- ATLAS uses both full and fast Monte Carlo techniques
  - upgrade project integrated in these efforts
  - but also reconstruction needs new concepts (online/offline)



Algorithmic challenges: simulation strategies (2)

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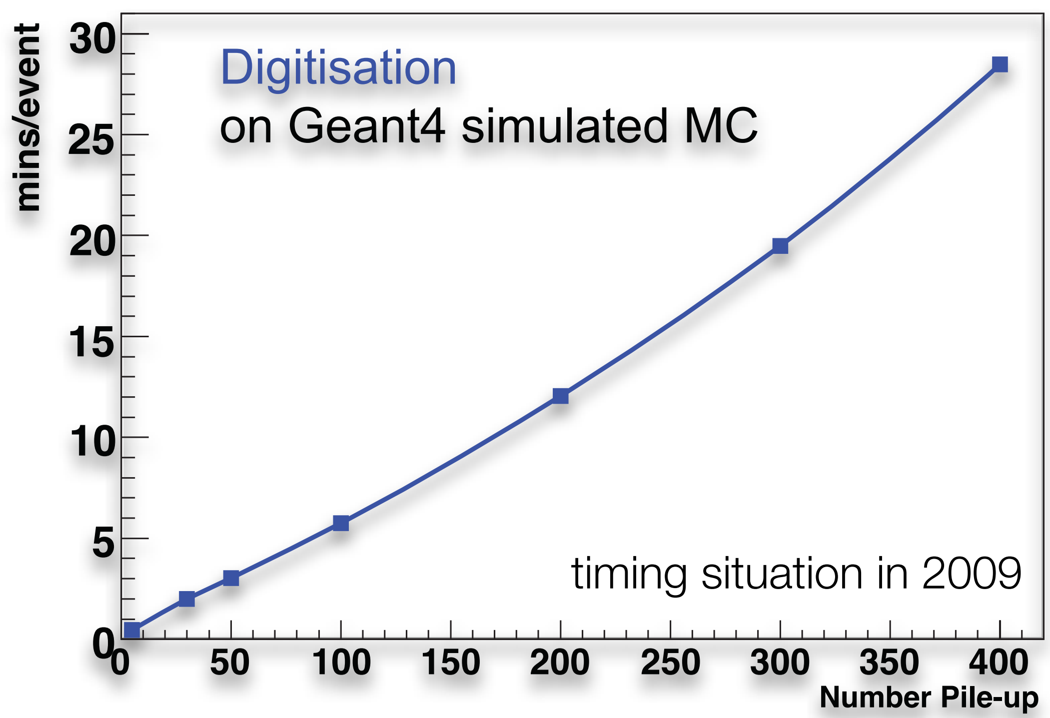
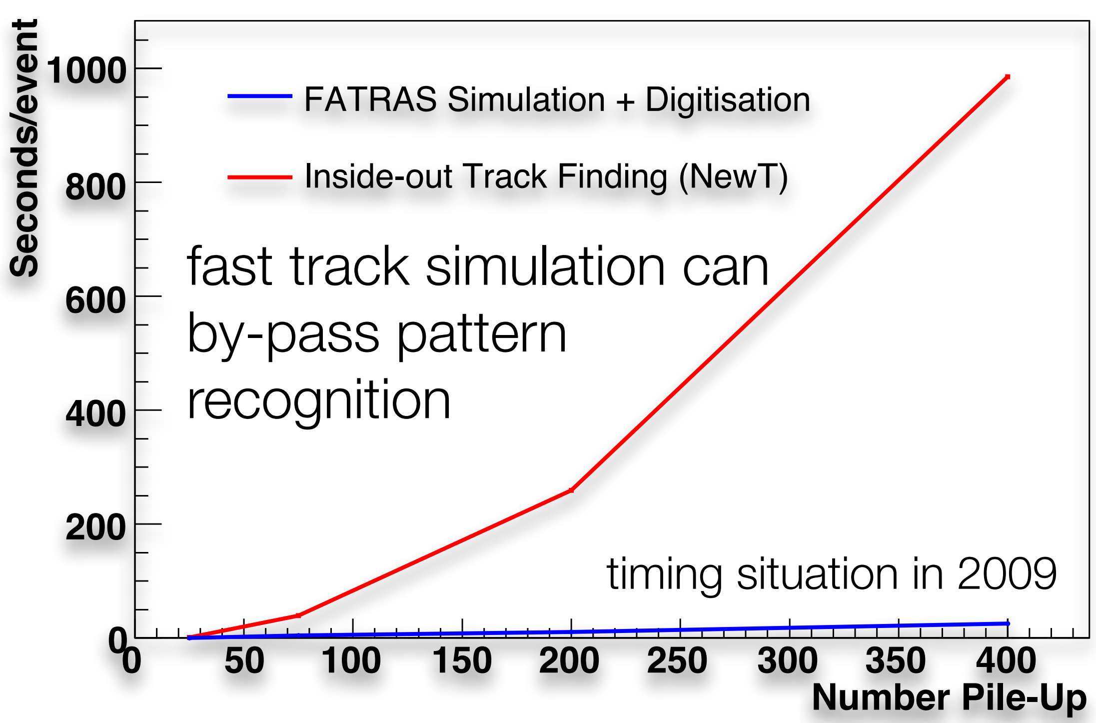
- high occupancy environment imposes stringent challenge on simulation and pattern recognition
  - mixture of full and fast simulation techniques will be needed
  - careful evaluation of MC techniques used for physics simulation

- ATLAS uses both full and fast Monte Carlo techniques
  - upgrade project integrated in these efforts
  - but also reconstruction needs new concepts (online/offline)





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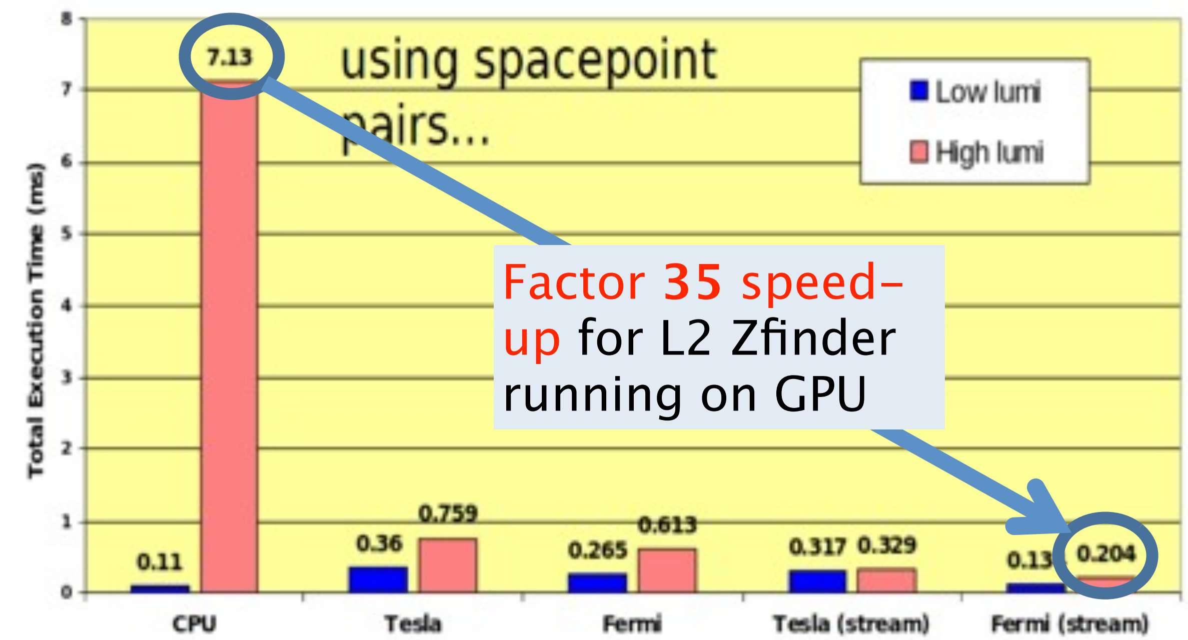
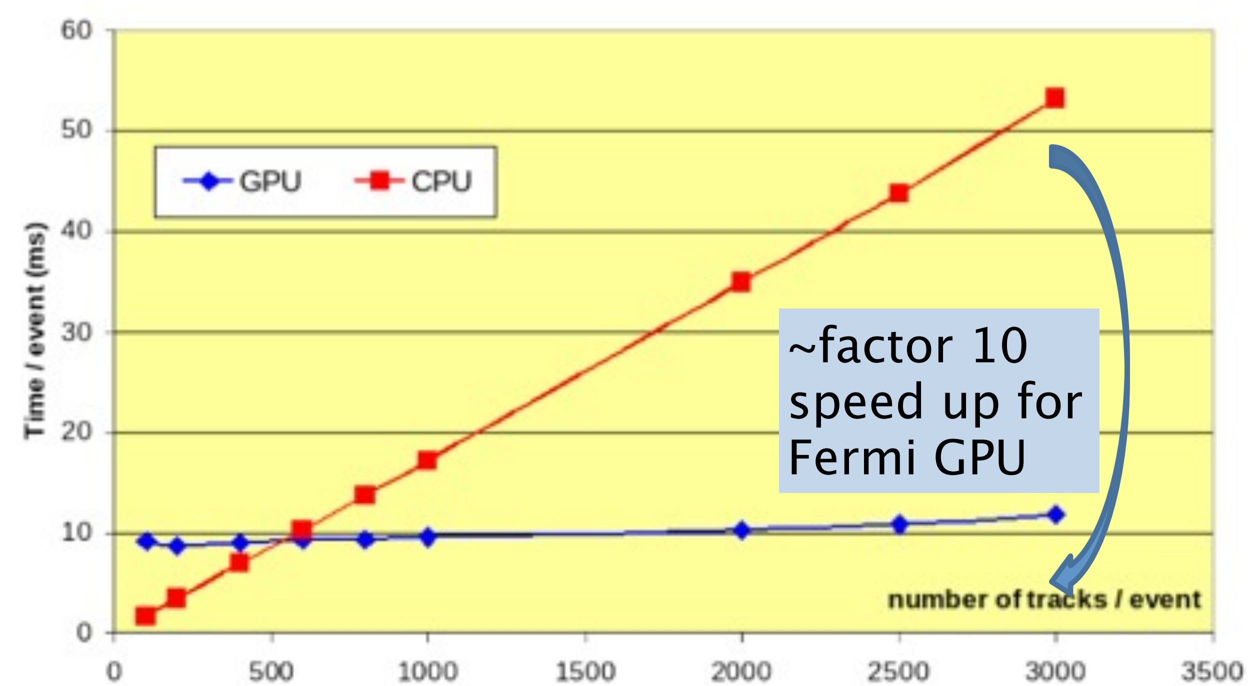
Algorithmic challenges: use of GPU in HLT

- Current studies ongoing to evaluate the gain from parallelism for upgrade environment

- Level 2 track trigger code ported to use GPUs
  - compare to usage vs CPU in low and high luminosity environment
  - tested on different architectures



- First offline modules also ported to GPUs and show similar performance gains



Conclusions & (obviously) Outlook

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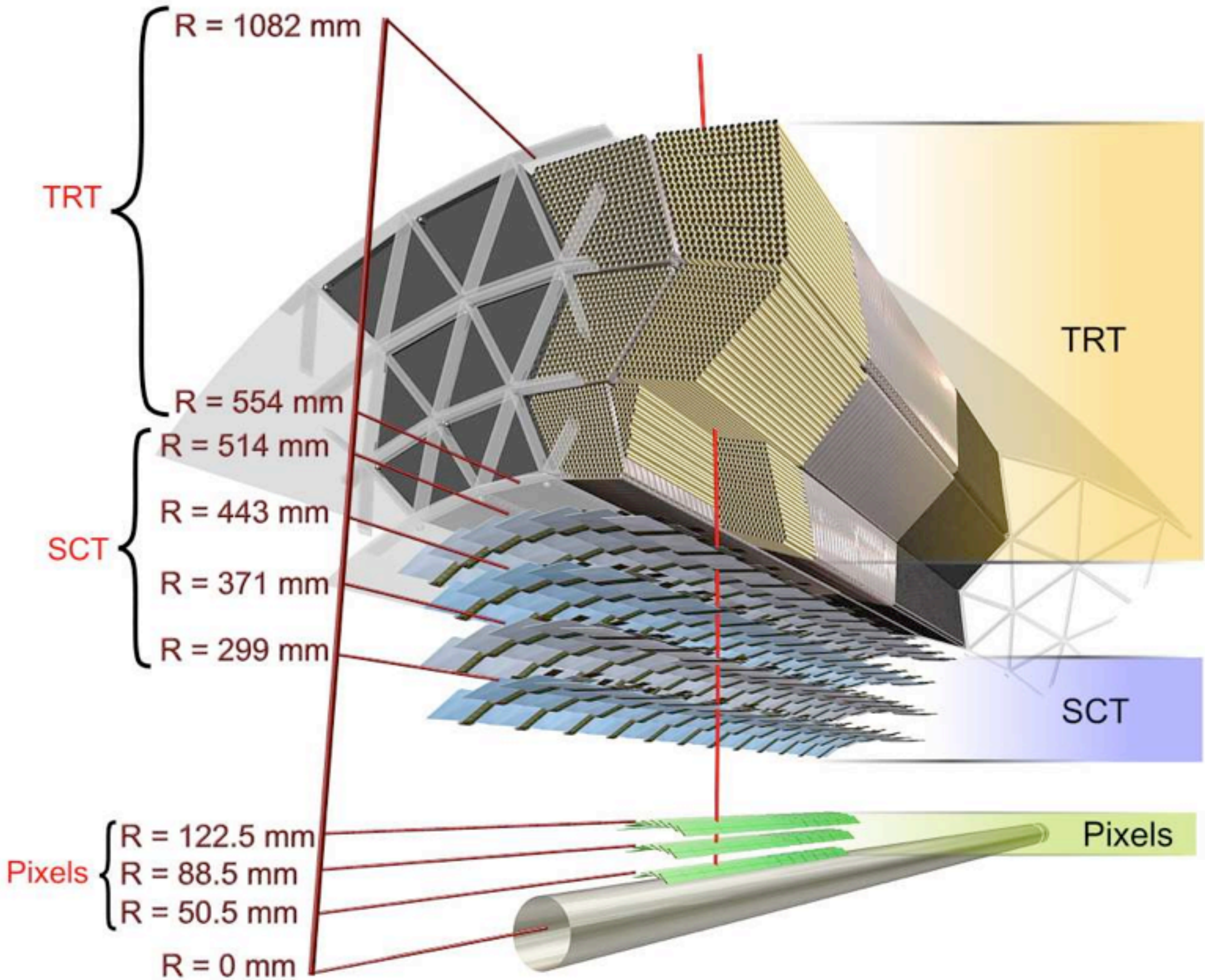
- Huge success of LHC data taking let's us look forward to future LHC upgrades (motivated by physics requirements)

- Learned many lessons from current data taking period (Run I)
  - detector is performing very well (p-p and Pb-Pb collision)
  - description of data by simulation is excellent (confidence for design studies)

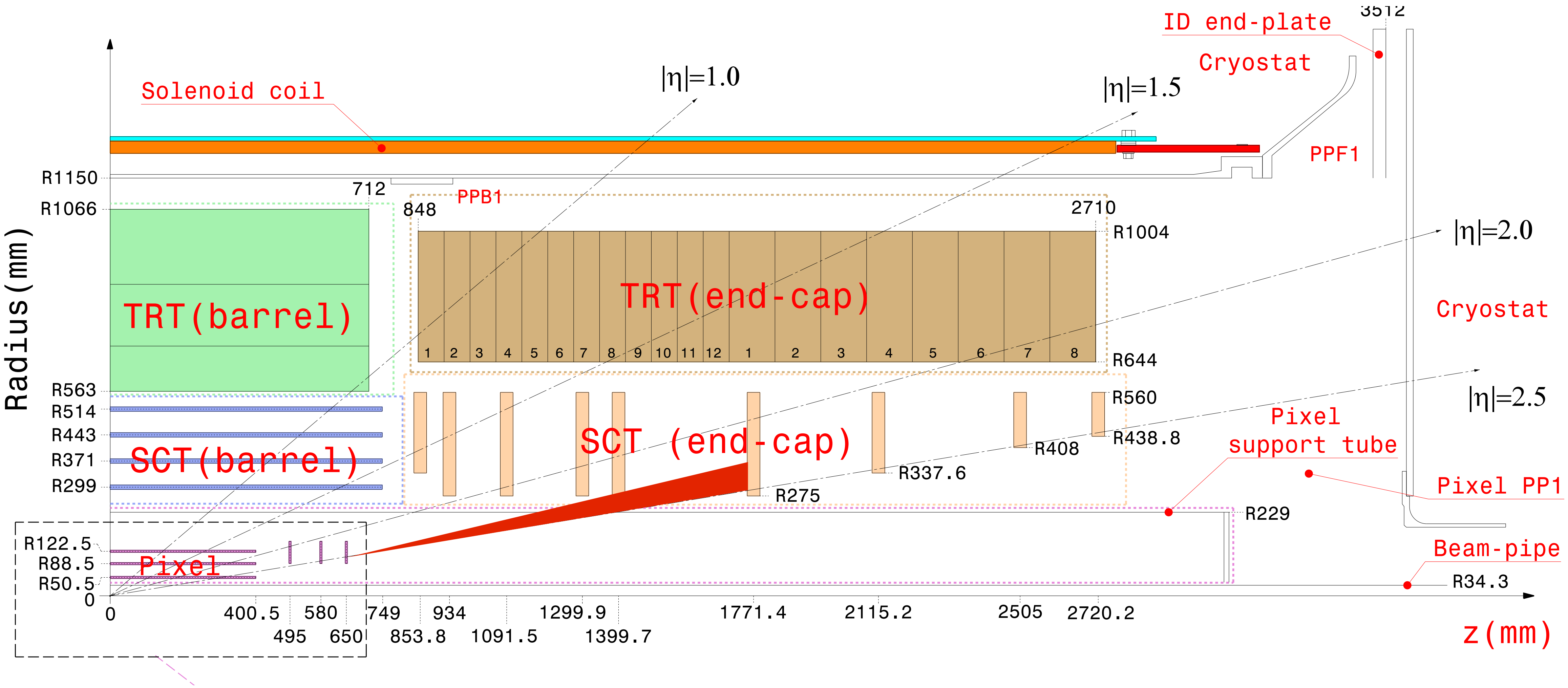
- ATLAS is planing a multi-phase upgrade program
  - Phase 0 as early as 2013/14, IBL project was a boost to R&D
  - coherent planning for Phase I & II on the way

- Technological challenge to cope with high luminosity environment
  - new hardware components
  - new algorithmic solutions ins simulation/reconstruction

- By today ATLAS has recorded more than 1 fb^{-1} !
  Looking forward to the remaining 2999 and the results they'll bring ;-)



R = 1082 mm
TRT
R = 554 mm
R = 514 mm
R = 443 mm
SCT
R = 371 mm
R = 299 mm
R = 122.5 mm
Pixels
R = 88.5 mm
R = 50.5 mm
R = 0 mm
TRT
SCT
Pixels



Radius (mm)
z (mm)
Solenoid coil
ID end-plate
Cryostat
PPF1
PPB1
Cryostat
TRT (barrel)
TRT (end-cap)
SCT (barrel)
SCT (end-cap)
Pixel
Pixel support tube
Pixel PP1
Beam-pipe
|η|=1.0
|η|=1.5
|η|=2.0
|η|=2.5
R1150
R1066
R563
R514
R443
R371
R299
R122.5
R88.5
R50.5
0
712
848
2710
3512
R1004
R644
R560
R438.8
R408
R337.6
R275
R229
R34.3
1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8
0
400.5
495
580
650
749
853.8
934
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1299.9
1399.7
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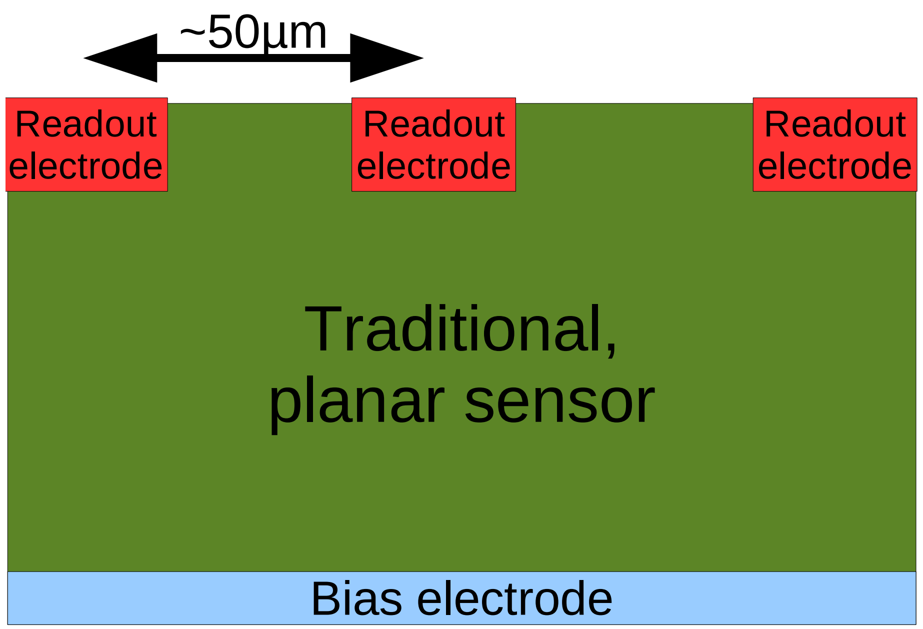
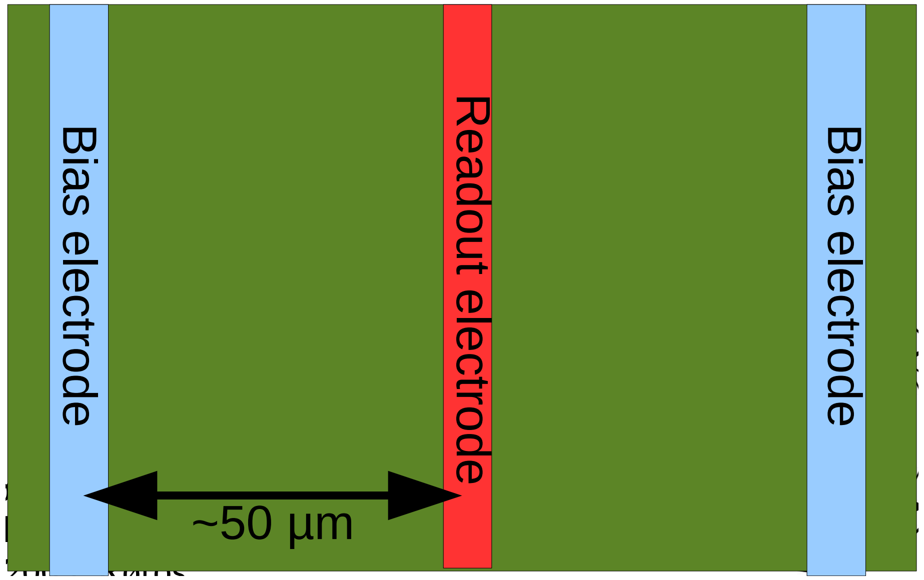
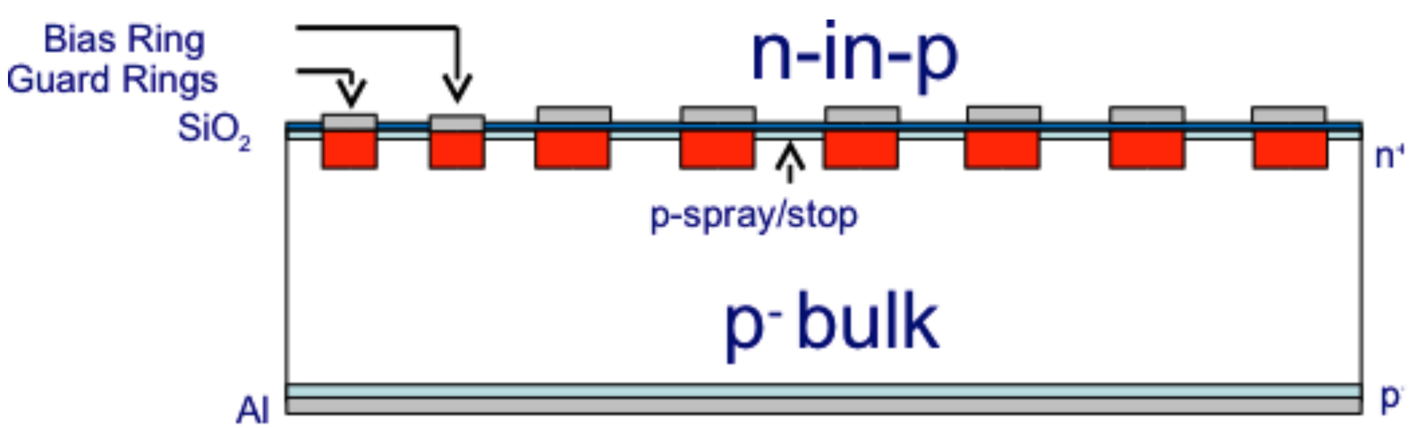
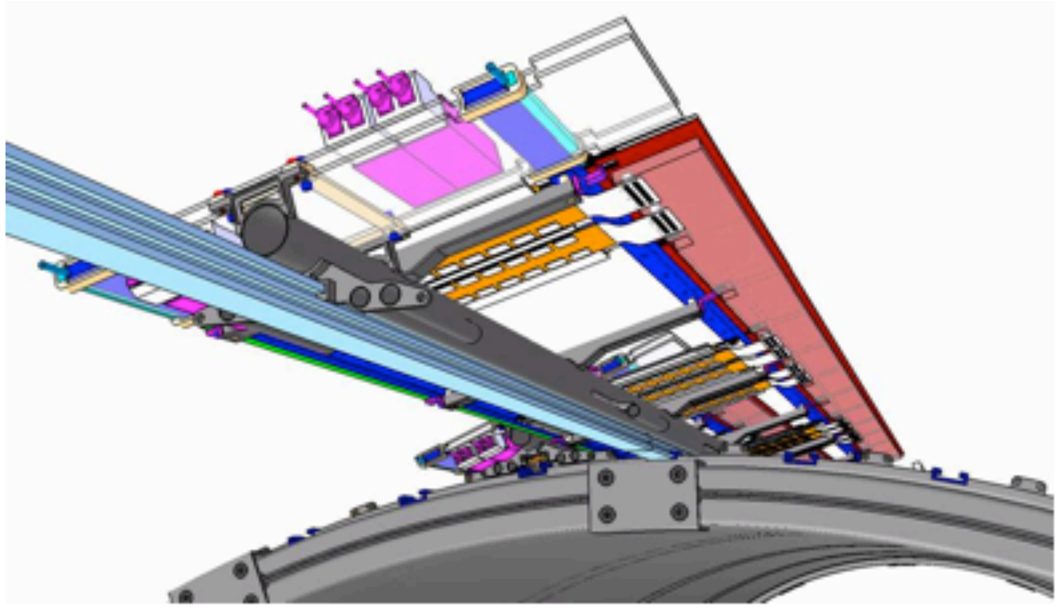
2115.2
2505
2720.2

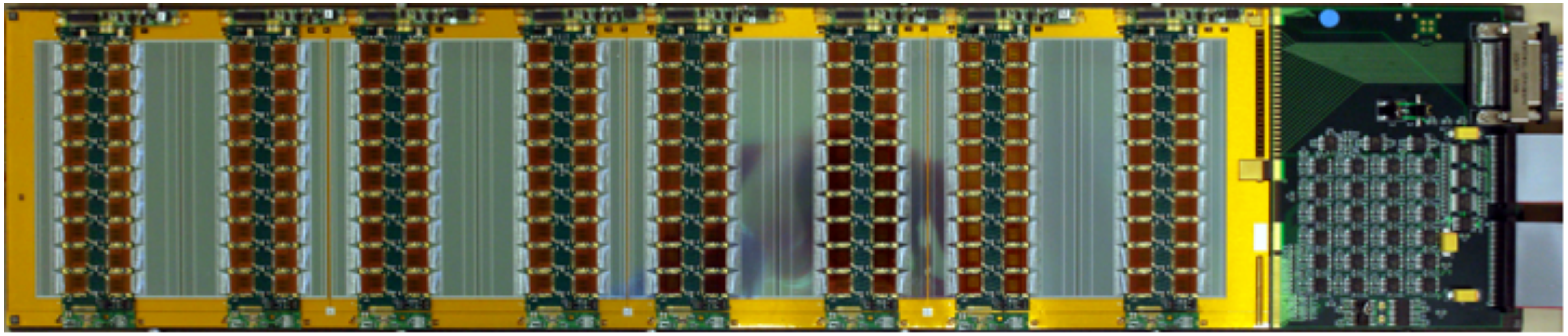

~50μm
Readout electrode
Readout electrode
Readout electrode
Traditional, planar sensor
Bias electrode


Bias electrode
Readout electrode
Bias electrode
~50 μm

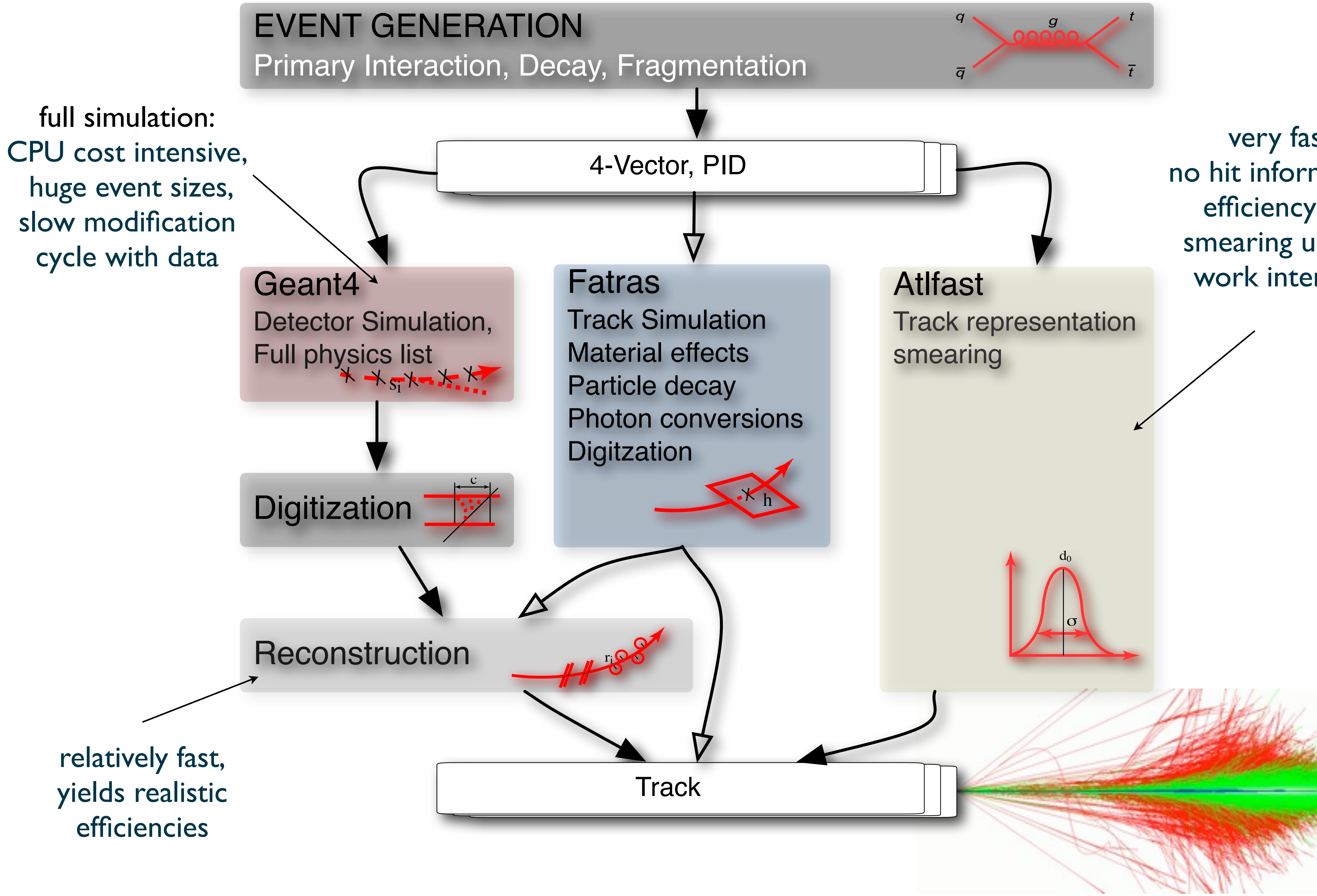


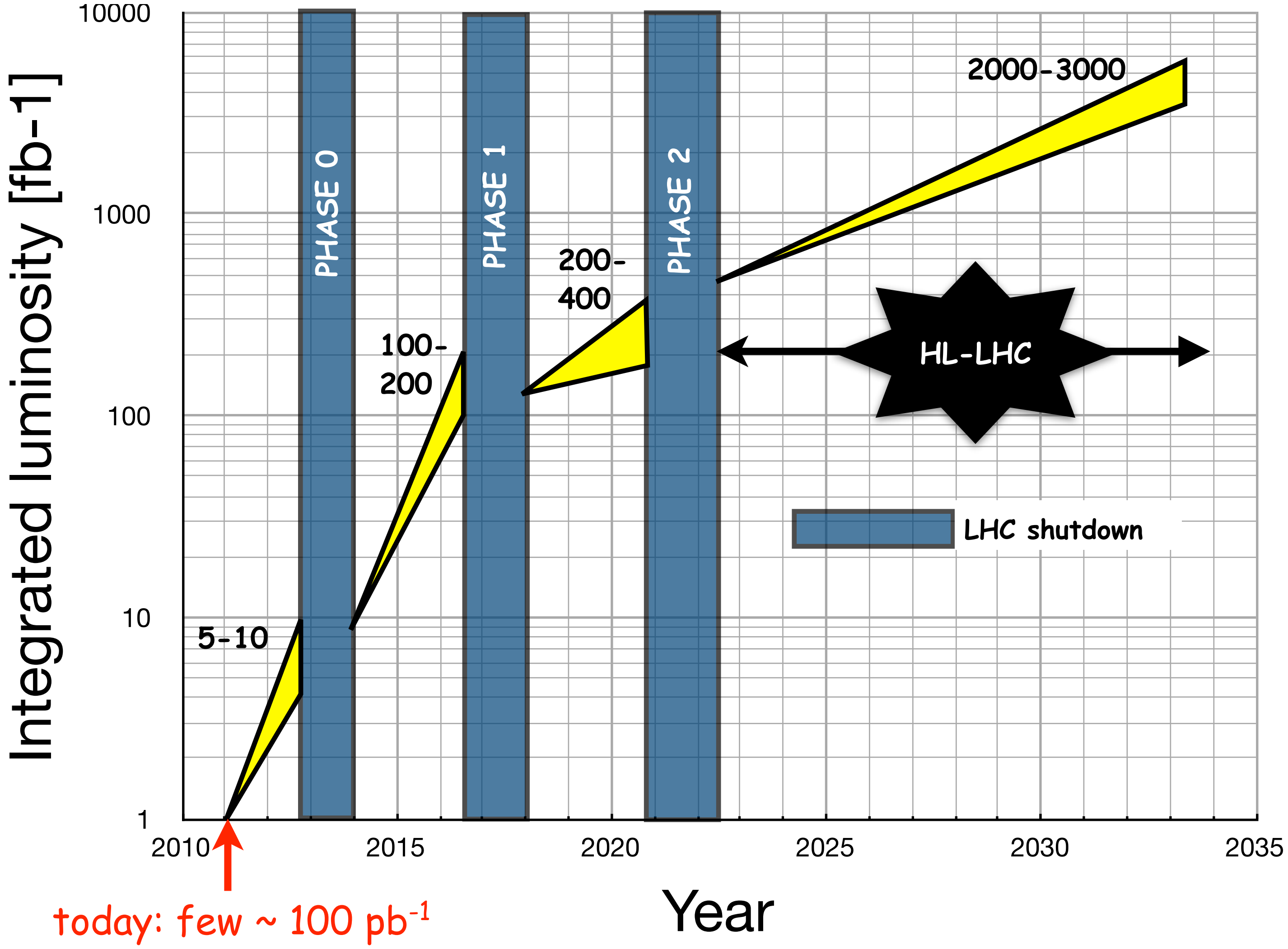


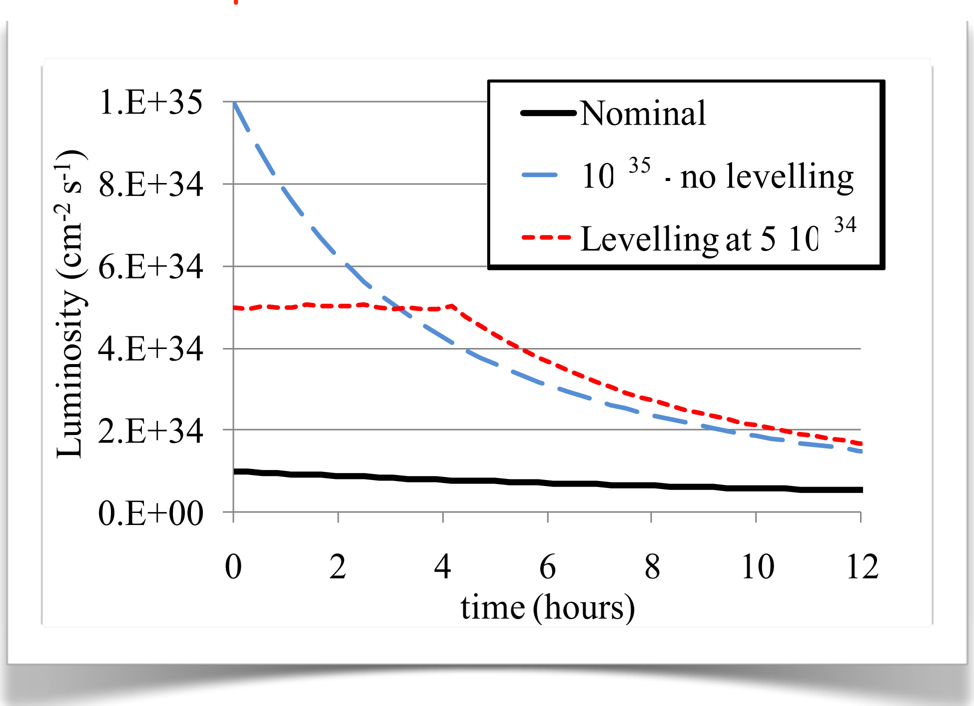
- Micro-Strips:
  - chose n-in-p (currently p-in-n) : faster signal collection, cheaper production, doesn’t need full depletion (prototype delivered by Hamamatsu)

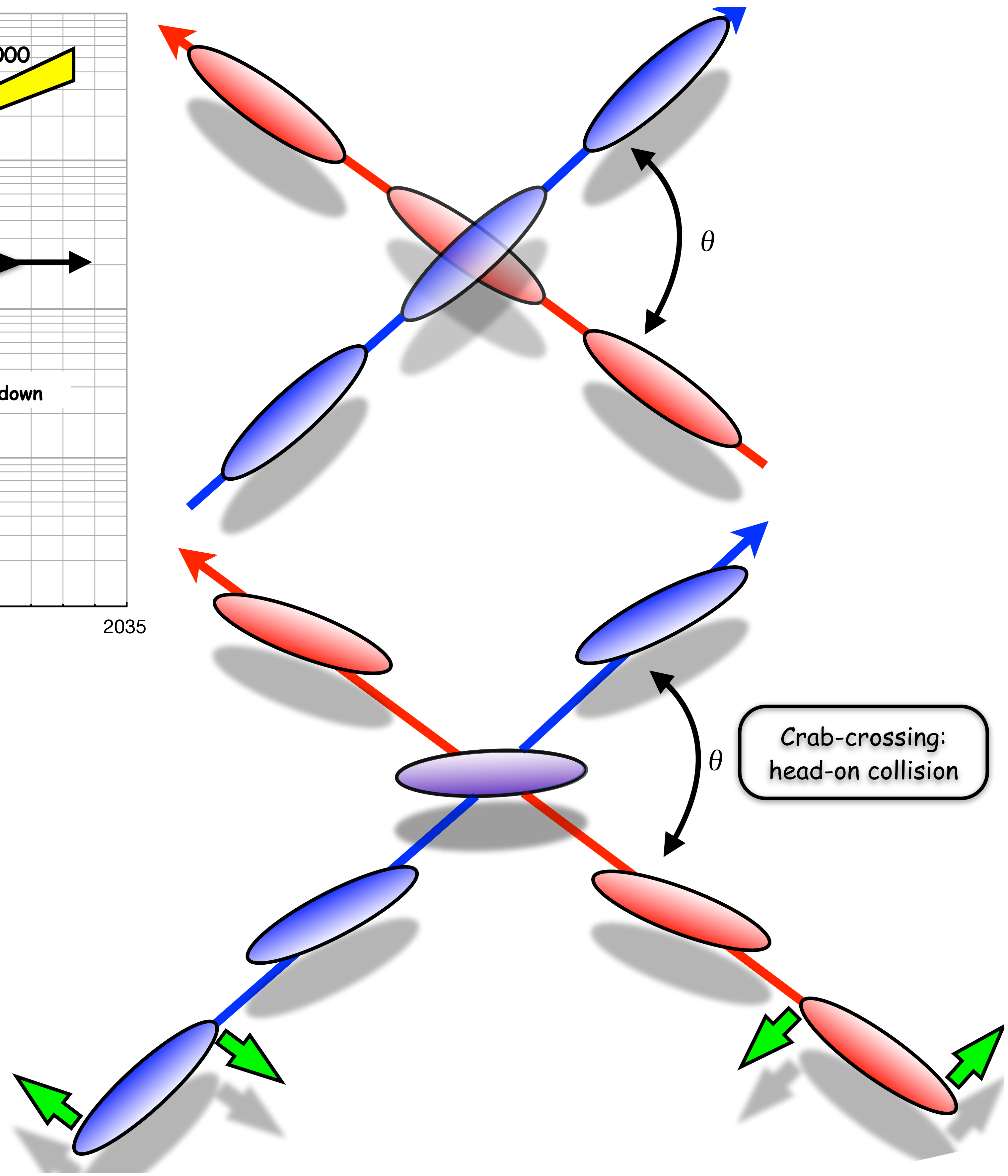


very good and uniform front end performance (noise, gain, pedestal, threshold); low dead channel count


EVENT GENERATION
Primary Interaction, Decay, Fragmentation
q
g
t
q̄
t̄
full simulation:
CPU cost intensive,
huge event sizes,
slow modification
cycle with data
4-Vector, PID
very fast,
no hit information,
efficiency =1,
smearing update
work intensive
Geant4
Detector Simulation,
Full physics list
Fatras
Track Simulation
Material effects
Particle decay
Photon conversions
Digitization
Atlfast
Track representation
smearing
Digitization
Reconstruction
relatively fast,
yields realistic
efficiencies
Track


Integrated luminosity [fb-1]
10000
1000
100
10
1
2010
2015
2020
2025
2030
2035
Year
PHASE 0
PHASE 1
PHASE 2
5-10
100-
200
200-
400
2000-3000
HL-LHC
LHC shutdown
today: few ~ 100 pb-1


Luminosity (cm-2 s-1)
1.E+35
8.E+34
6.E+34
4.E+34
2.E+34
0.E+00
0
2
4
6
8
10
12
time (hours)
Nominal
10 35 - no levelling
Levelling at 5 10 34


θ
θ
Crab-crossing:
head-on collision

Cavern background

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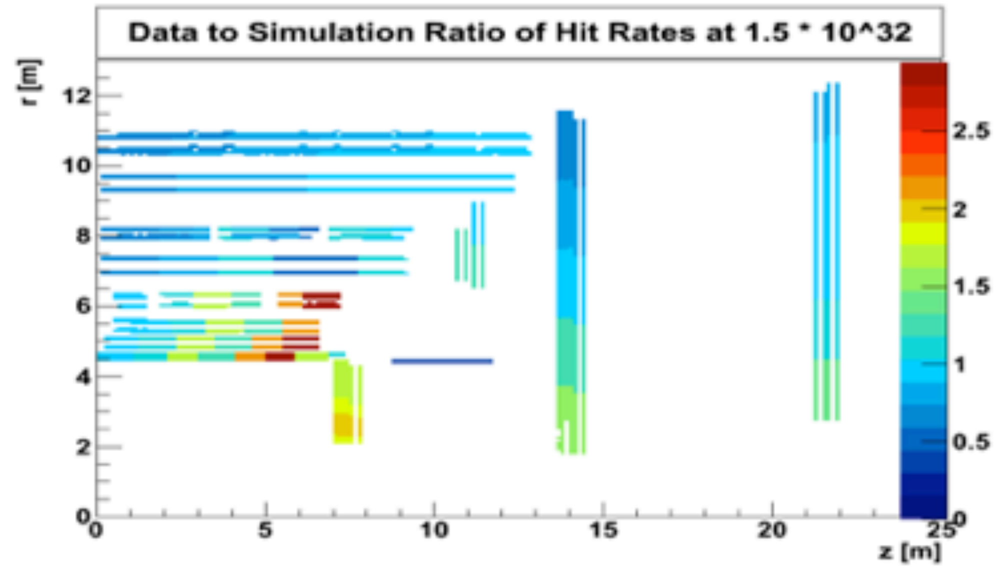
Studies to bring in MDT trigger with coarse readout (25 ns tdc) **at level-1**:
The longer L1 latency at sLHC gives time for this -- Sharpens up trigger a lot

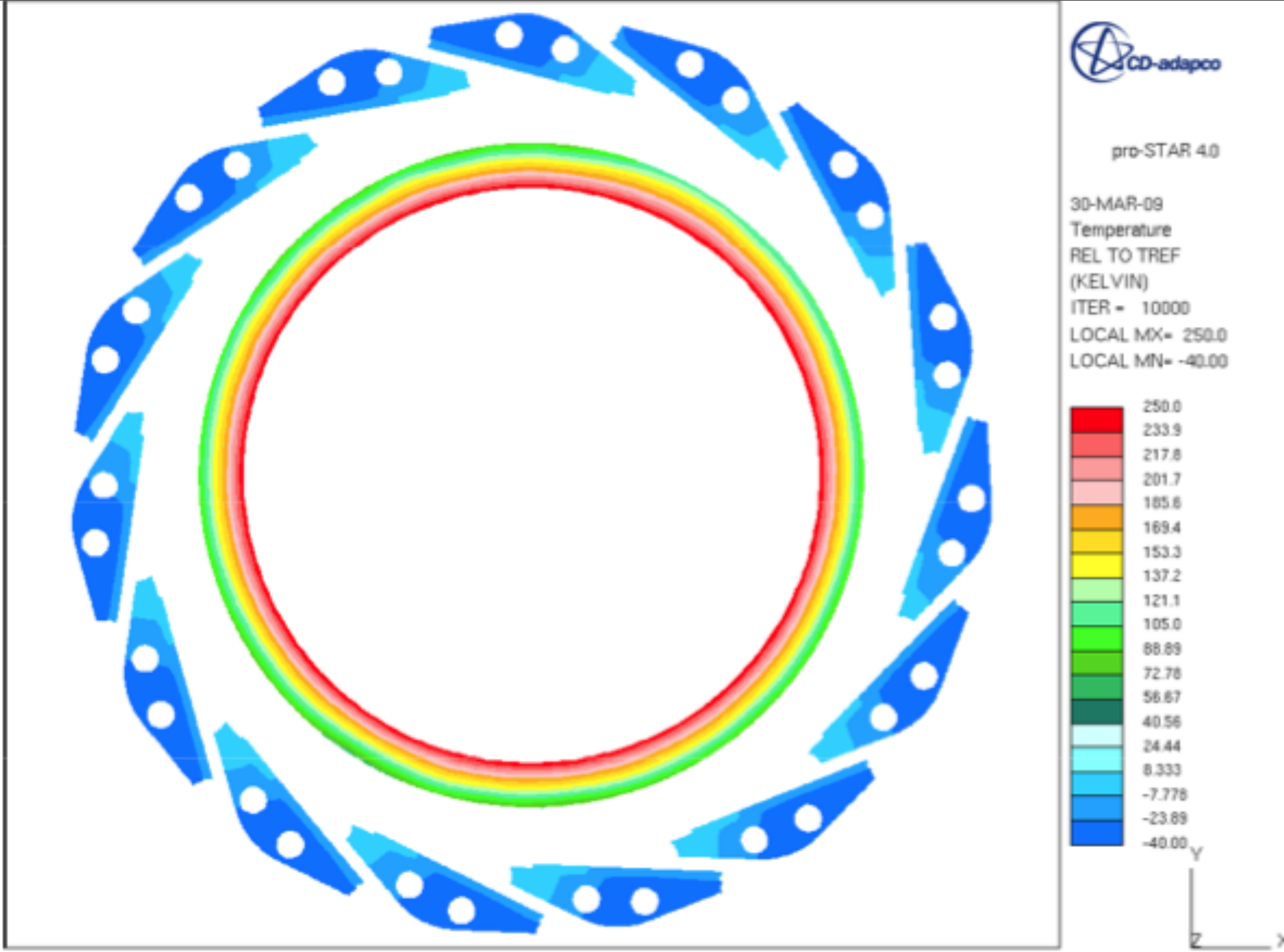
Readout electronics of some muon chambers is inaccessible, and suffers if L1 latency goes beyond current 3 μs. We need to develop a means to store the hits off detector until L1 arrives: e.g. use a local muon trigger

Beryllium beam-pipe in place of aluminium (Phase-0) pipe through calorimeters: big reduction in background rate

Data with LHC-on gives measurement of muon hit rates. Scaling up from 10^{32} cm^{-2} s^{-1} to nominal can be compared to predictions made long ago of the cavern back-ground. Many uncertainties meant we allowed for a safety factor 5 in the muon design...preliminary results suggest
(i) For most of the muon system, actual rate is a bit lower
(ii) For hottest regions, it is 1.6 to 2.4 x higher
- hopefully we can confirm soon that most of the muon system will function well

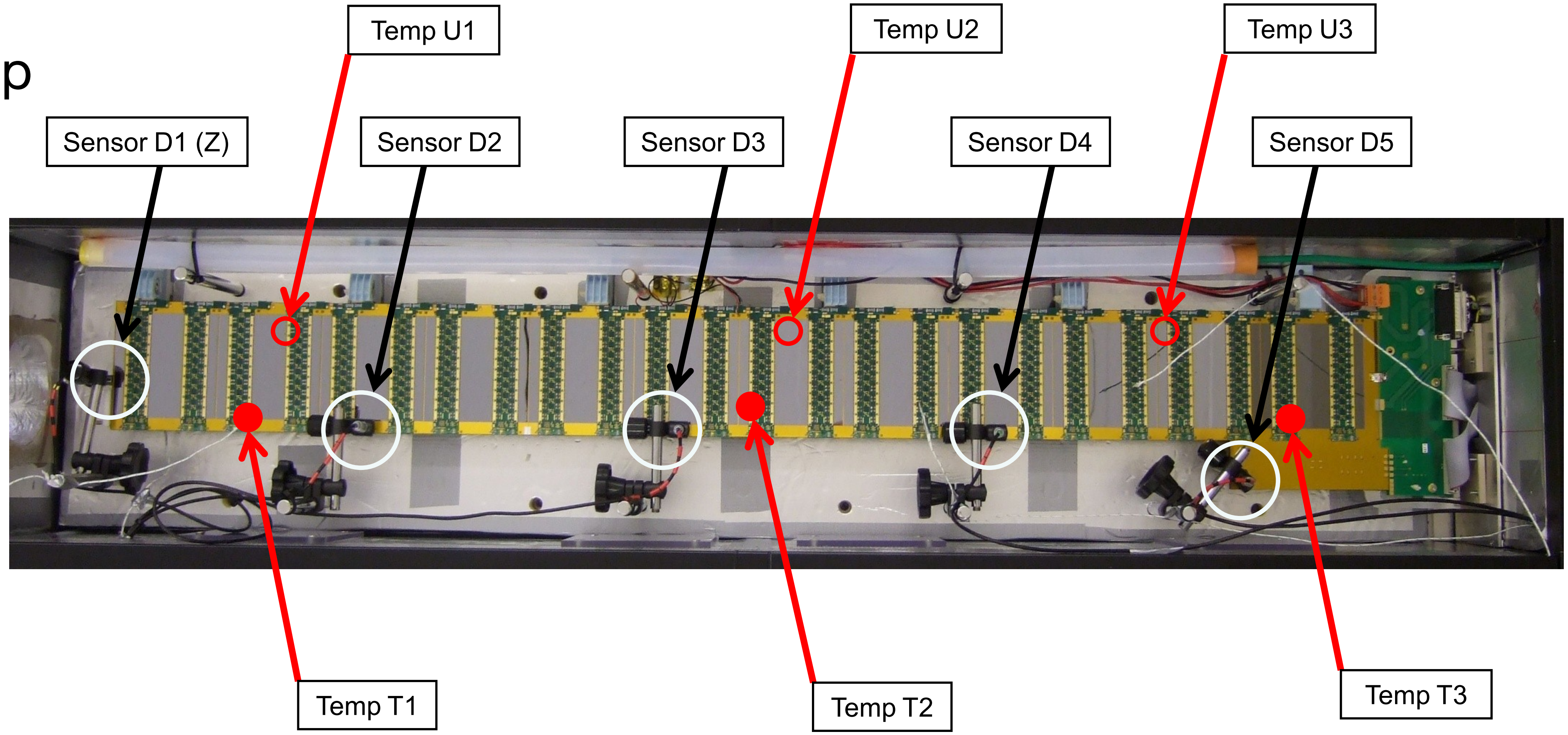


Ratio of actual to predicted muon hit rates, latest simulation and measurment

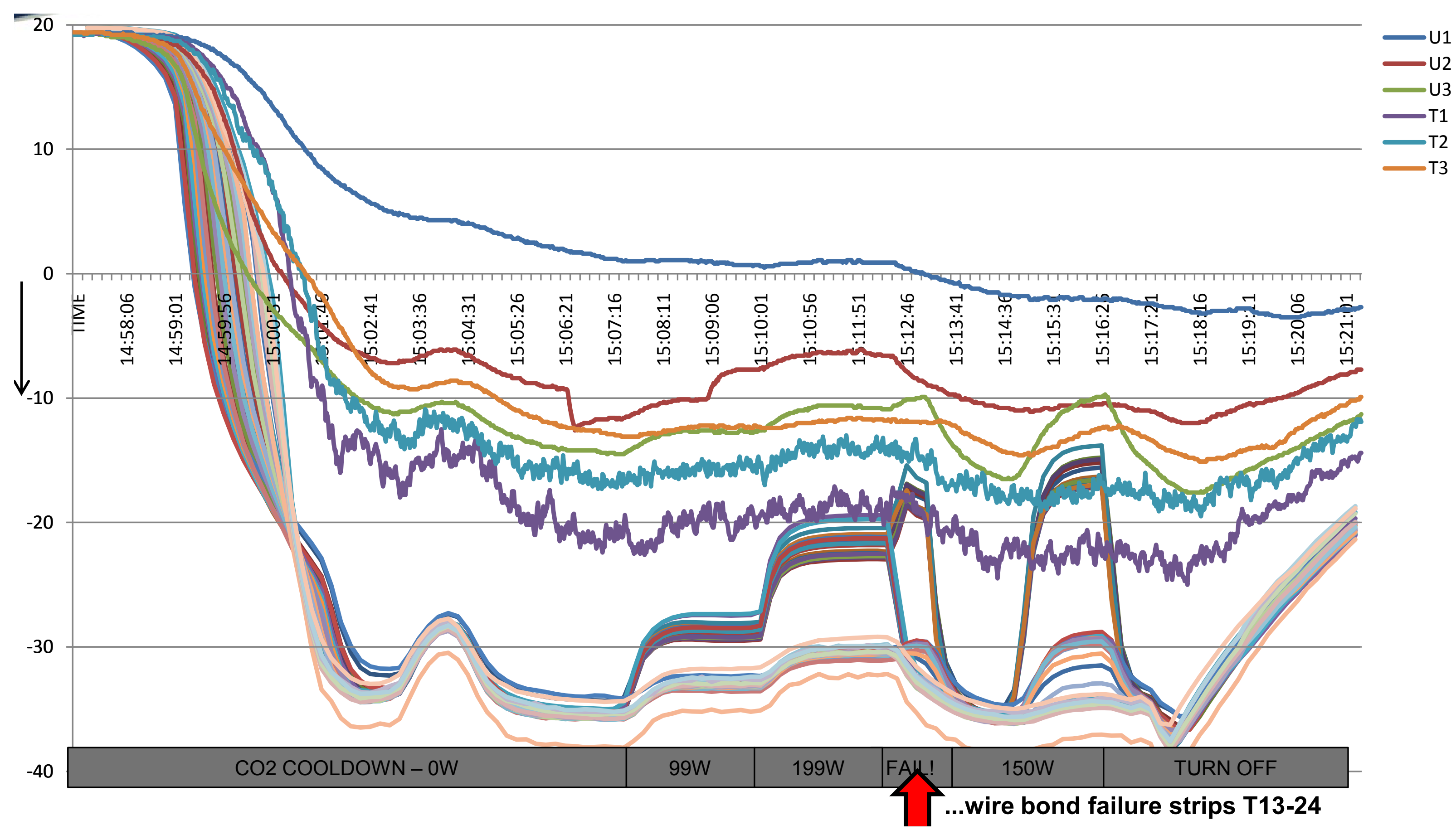


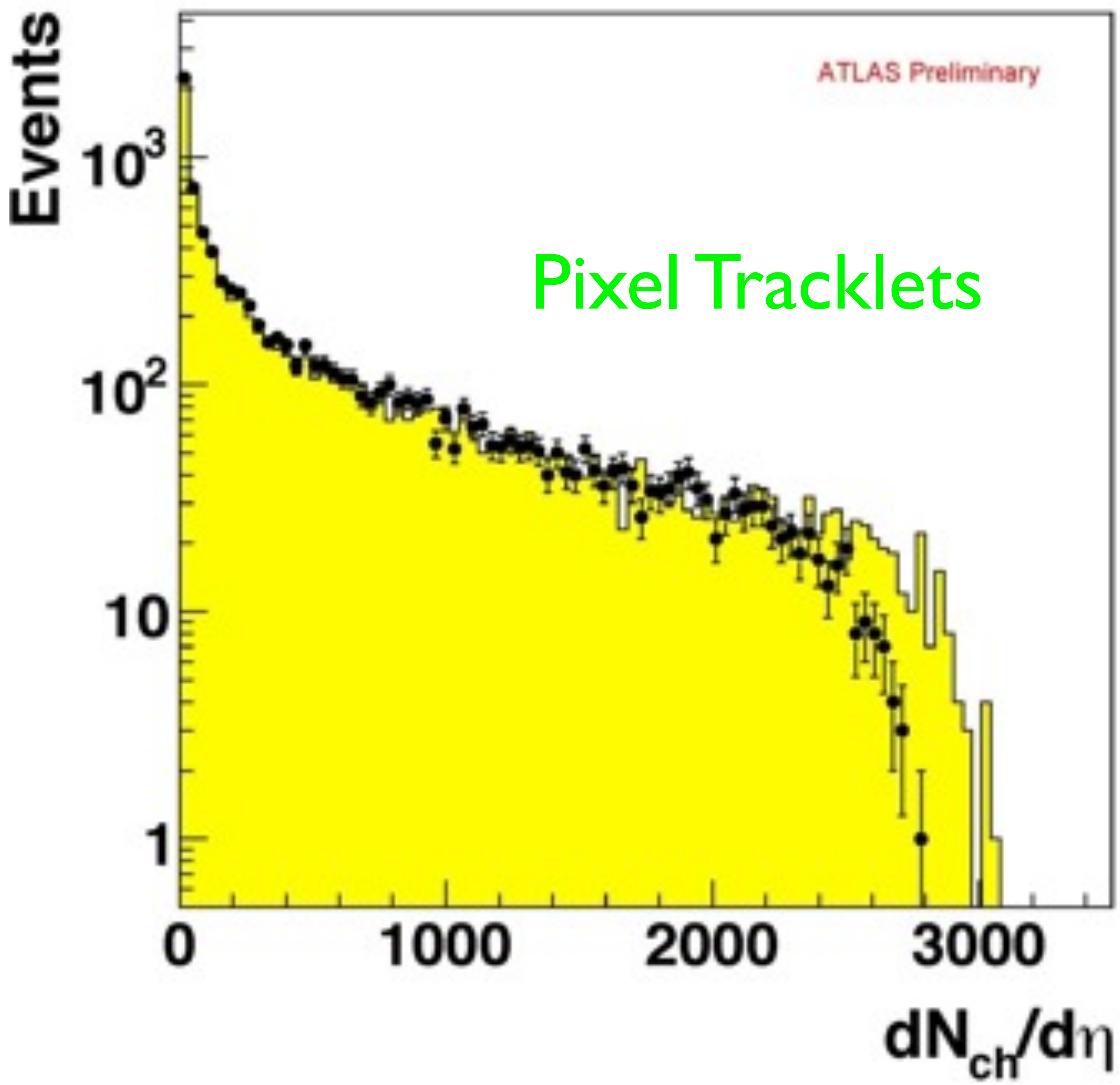
Beam Pipe Backout
reversed turbine" lay out
configuration 24

test setup



one side of the stave fully powered




ATLAS Preliminary
Pixel Tracklets
Events
10³
10²
10
1
0
1000
2000
3000
dN_ch/dη