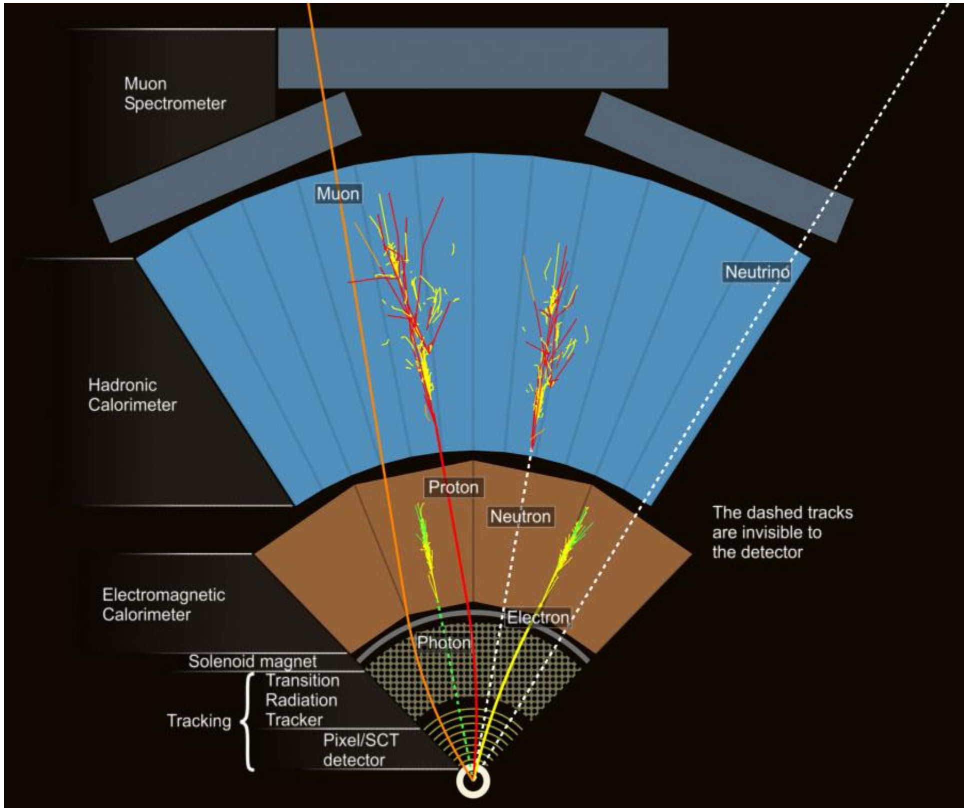
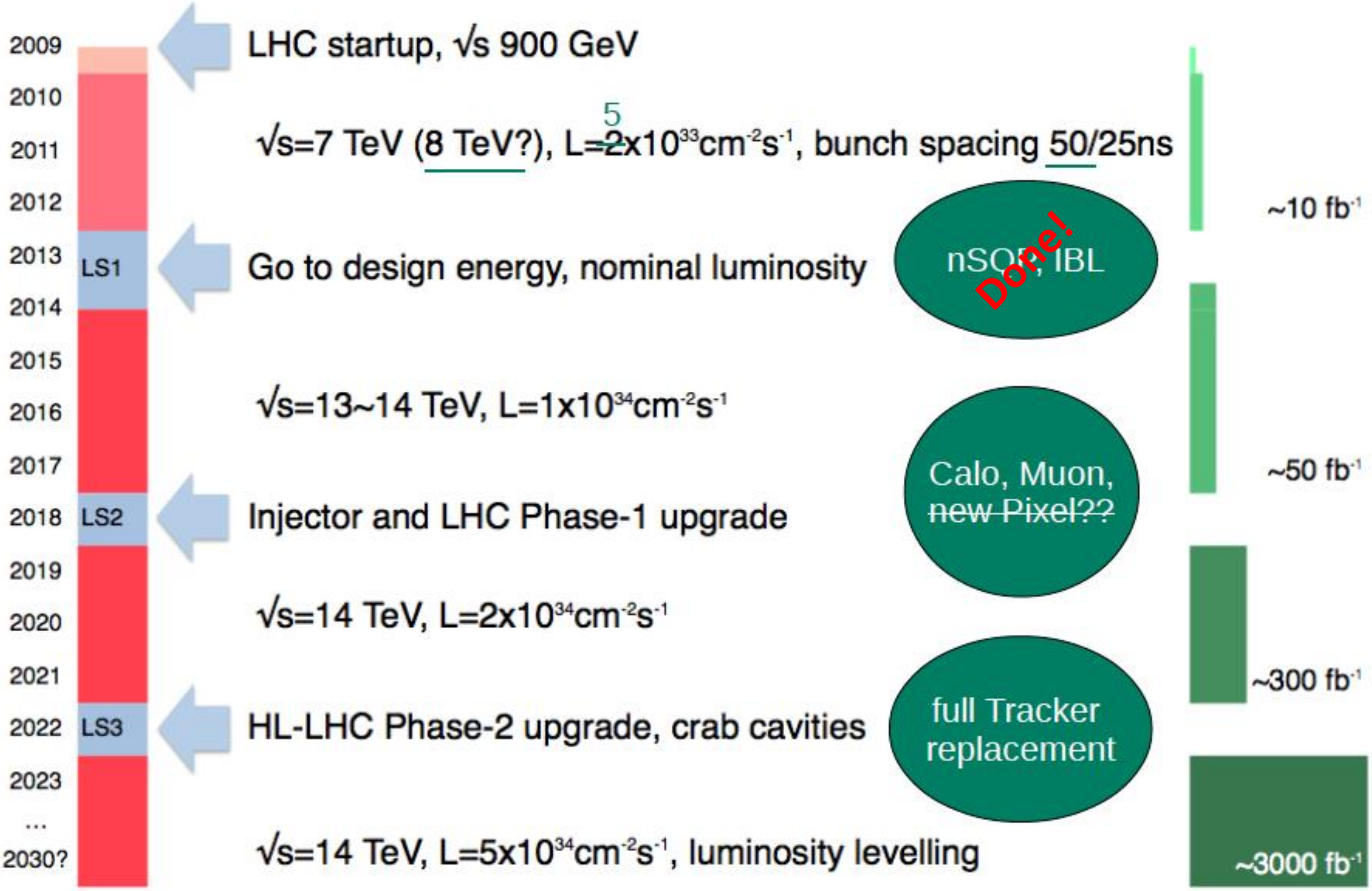
ATLAS New Detector Technologies for HL-LHC

A good particle detector

- What do we need to reconstruct these challenging events? Measure
  - Momentum
  - Energy
  - add-ons: dE/dx, charge, particle ID
- How can we measure energies? Calorimeters…
- How can we measure momentum? Curvature in magnetic field…
  - Superconducting 2T solenoid
  - Tracking detector; Si and TRT
  - lever arm important
    - precision in µm
  - muons partially very stiff
    - better measure after calorimeter
    - toroidal field



LHC Upgrade Schedule



LHC startup, $\sqrt{s}$ 900 GeV

$\sqrt{s}$=7 TeV (8 TeV?), L=~~2~~ 5 x10^{33}cm^{-2}s^{-1}, bunch spacing 50/25ns

Go to design energy, nominal luminosity

nSQP, IBL Done!

$\sqrt{s}$=13~14 TeV, L=1x10^{34}cm^{-2}s^{-1}

Injector and LHC Phase-1 upgrade

Calo, Muon, ~~new Pixel??~~

$\sqrt{s}$=14 TeV, L=2x10^{34}cm^{-2}s^{-1}

HL-LHC Phase-2 upgrade, crab cavities

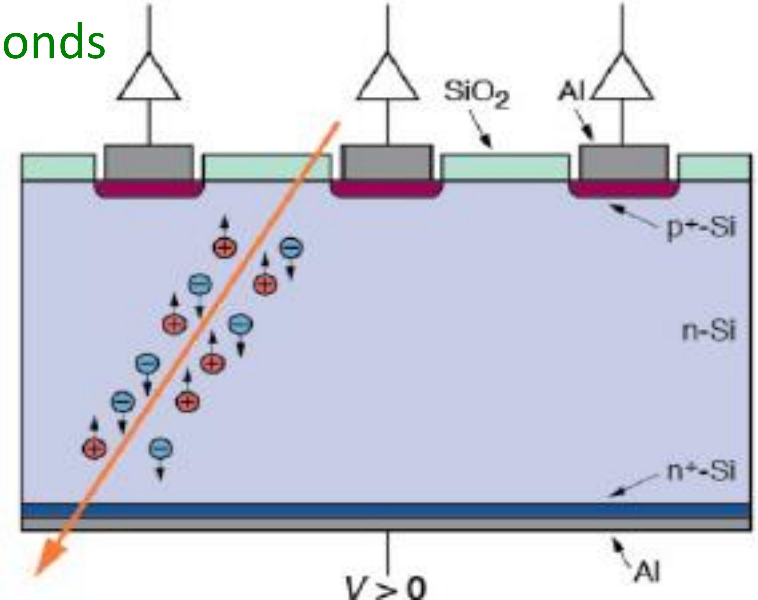
full Tracker replacement

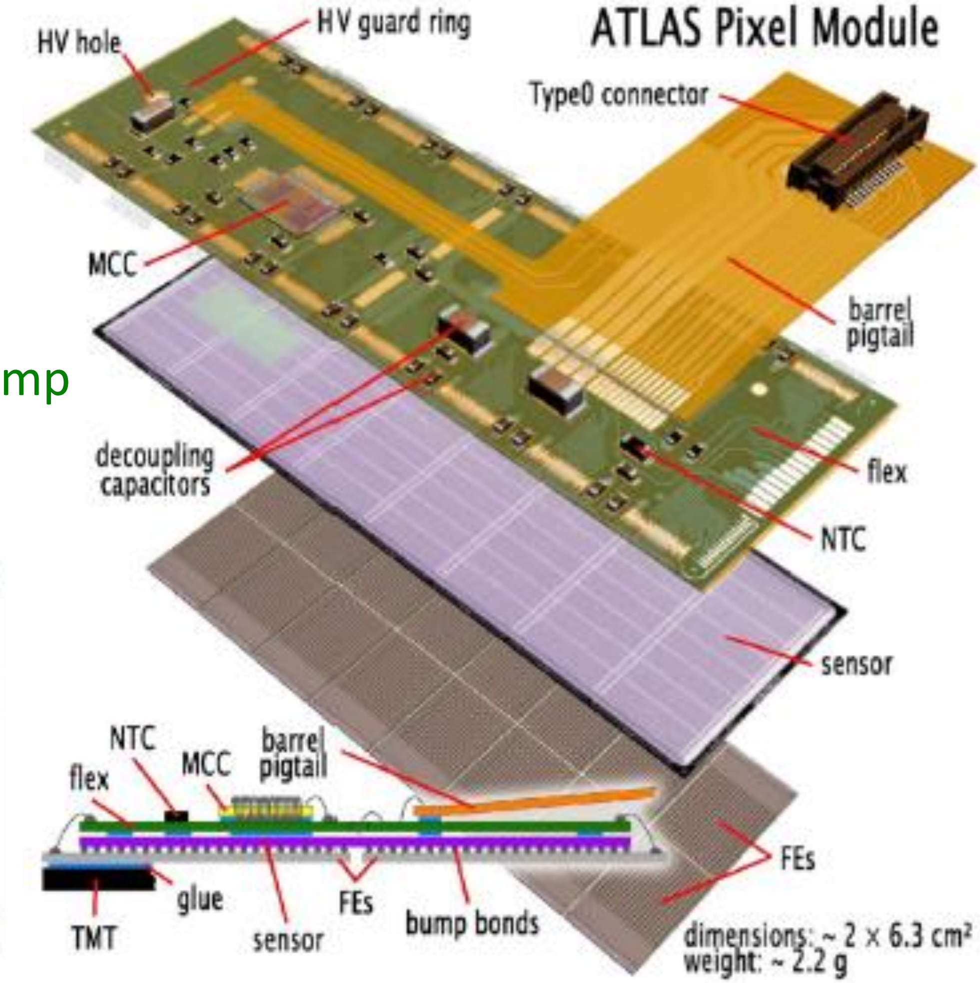
$\sqrt{s}$=14 TeV, L=5x10^{34}cm^{-2}s^{-1}, luminosity levelling

ATLAS Inner Detector

Si Tracker Operation

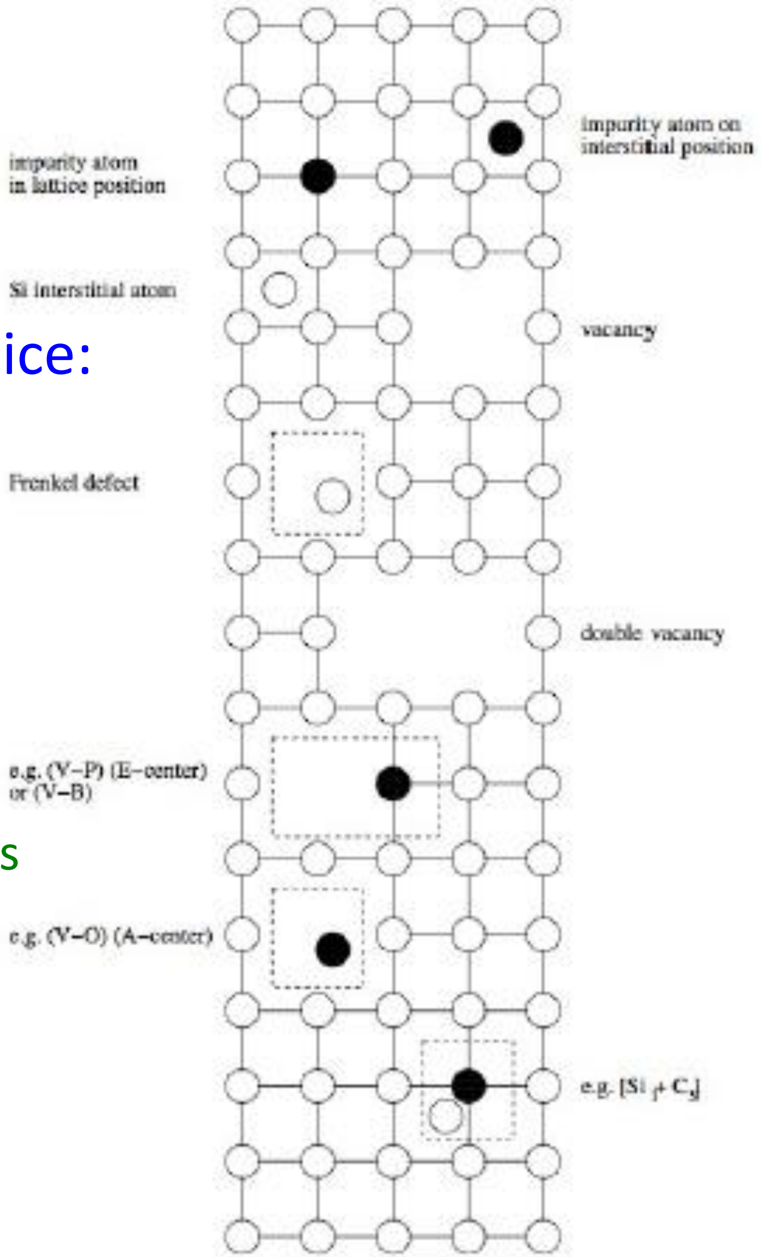
- Interaction of charged particles with matter
  - main effect: ionization, generation electron-hole pairs in Si bulk
- Patterned side: many pixel/strip electrodes
- Apply electric field over bulk
- Charges drift, induce signal on electrodes
- Small signal, needs amplification
  - dedicated readout ASICs
  - connection with sensors via wire/bump bonds





Si Sensors Radiation Damage

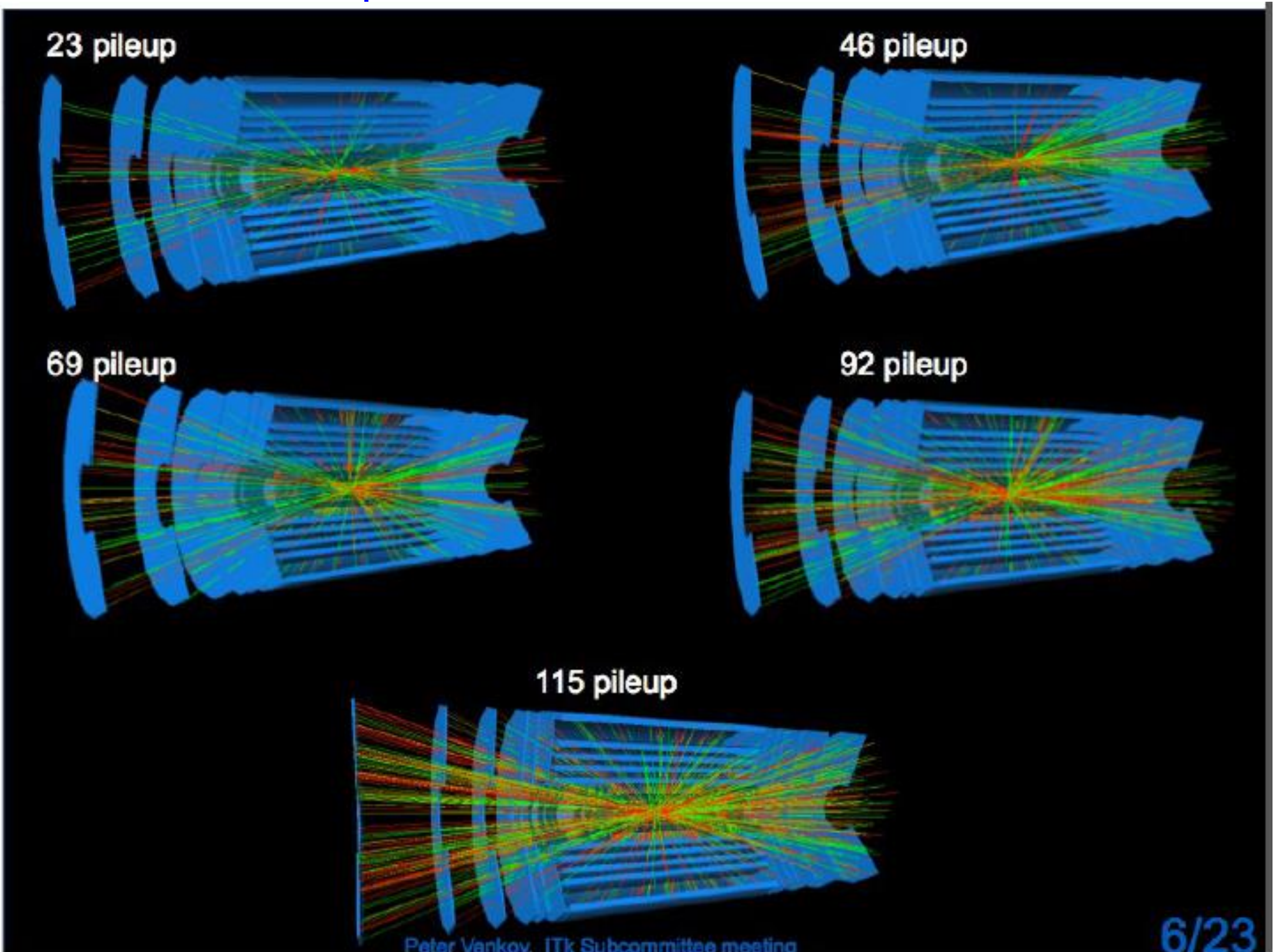
- Si sensors get damaged by radiation:
  - lattice atoms get moved around…
- 3 effects as result of damage to crystal lattice:
  - charge-carrier trapping
    - loss of induced charge -> signal loss
  - leakage current
    - more noise -> more cooling needed
  - change of N_{eff}/V_{dep} -> higher bias voltages
- Unit of radiation damage
  - Particle fluence per 1 MeV equivalent neutrons
- Occasionally of relevance as well
  - Dose (oxide charges, electronics)



Challenge One: Occupancy

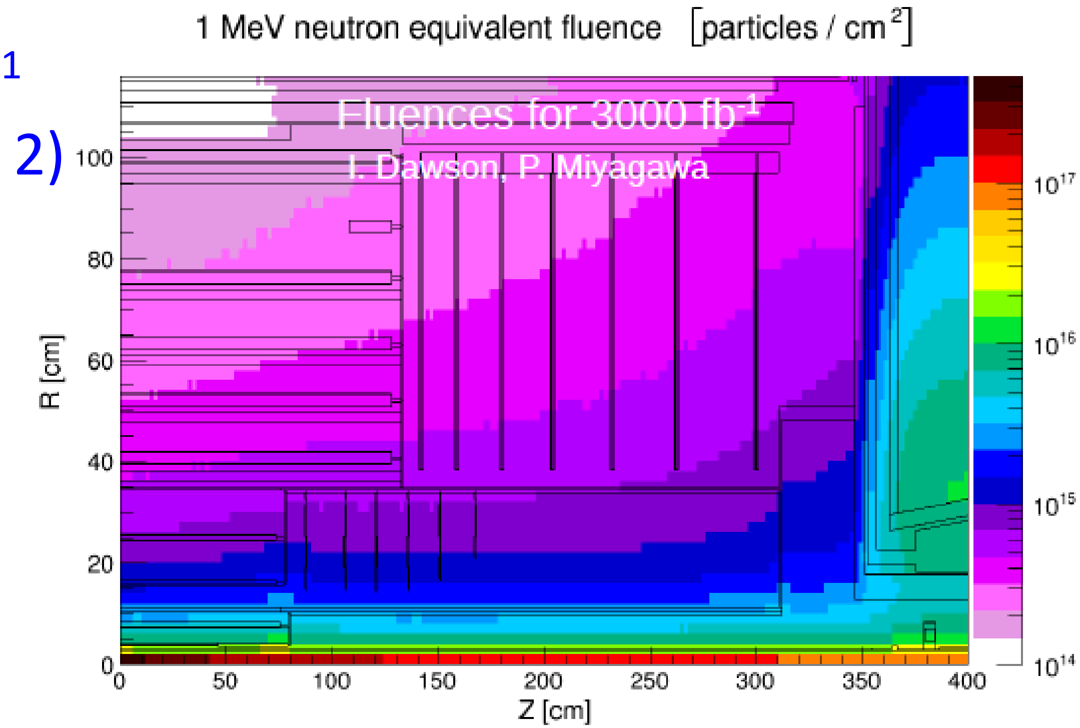
Occupancy will rise: depending on scenario and luminosity

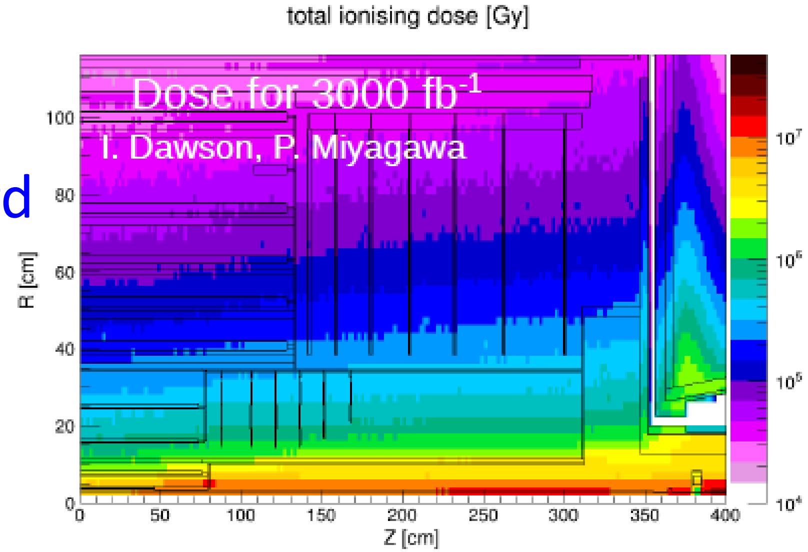
- 100-200 (400 for 50ns) pileup events
- up to 14000 tracks per BC!



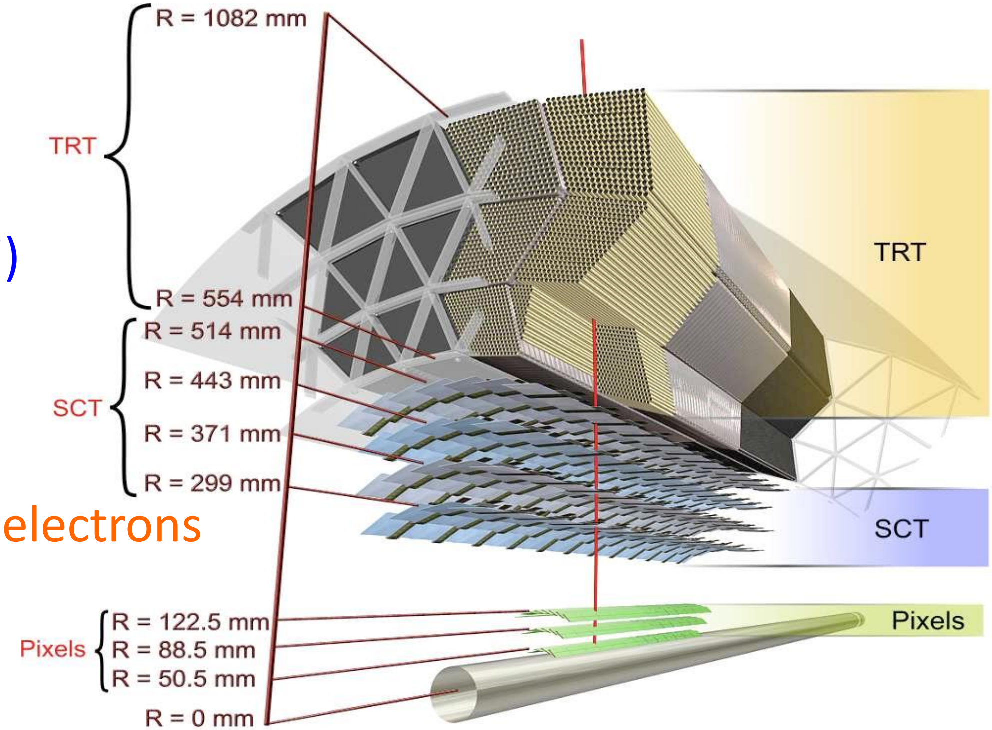
Challenge Two: Radiation Damage

- Integrated luminosity 3000 fb^{-1}
- Yields (include safety factor of 2)
  - 4 -5 cm radius:
    - ~1-2 × 10^{16} n_{eq} cm^{-2}
    - ~750-1500 MRad
  - 25 cm radius:
    - ~1-2 × 10^{15} n_{eq} cm^{-2}
    - ~50-100 MRad
    - several m^2 of Si
  - Strip radius
    - up to ~10^{15} n_{eq} cm^{-2}
    - up to ~60MRad
    - up to 200 m^2 of Si
- New ID sensors need to be more rad-hard and cheaper (more area to cover)





HL-LHC: What to Upgrade? How?



Components needing upgrade:

- TRT
  - Occupancy-limited beyond $\sim 2 \times 10^{34}$ cm^{-2} s^{-1} (40% at inner radii)
  - Replace by all-Si tracker
- SCT
  - Radiation damage-limited
    p-in-p collect holes -> n-in-p collect electrons
  - Occupancy limited (long strips)
    replace with short at inner radii
  - Trigger rate mitigation
    self-seeded track trigger; RoI trigger
- Pixel
  - Radiation damage for inner-most layers (new sensors R&D)
  - Data rate limited
    inefficiency at b-layer above 3×10^{34} cm^{-2} s^{-1}
    - Replace with new readout chip
  - Better resolution for pileup rejection
  - Very forward tracking

Si Sensors; Inner Layers

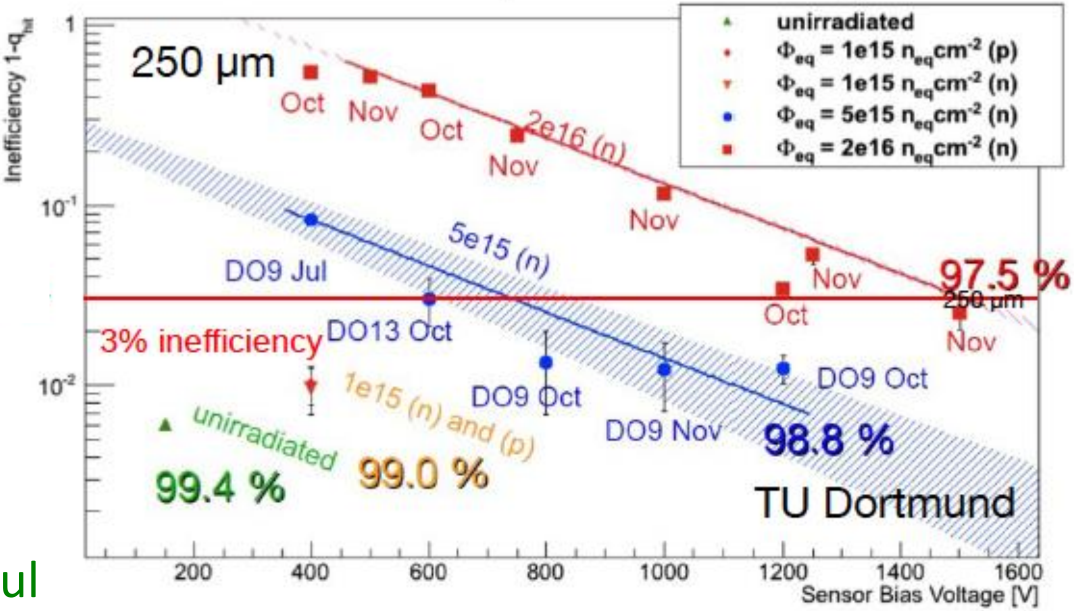
Highest fluences, trapping dominant effect:

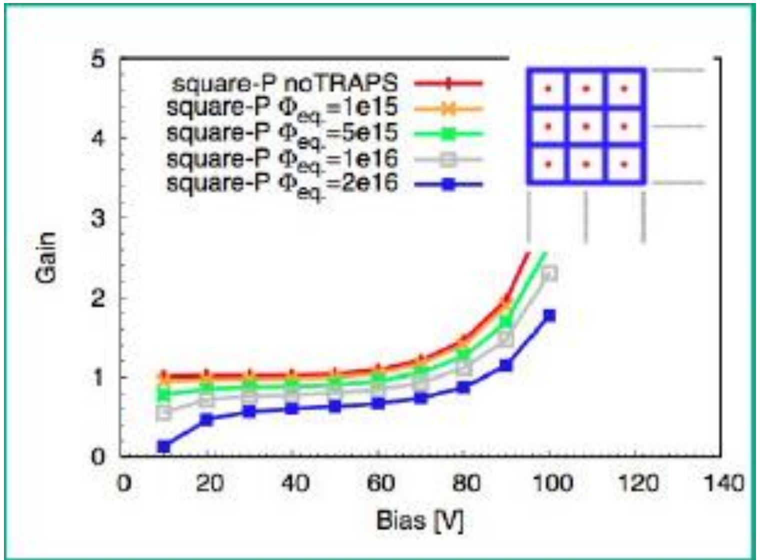
1) Reduce drift time

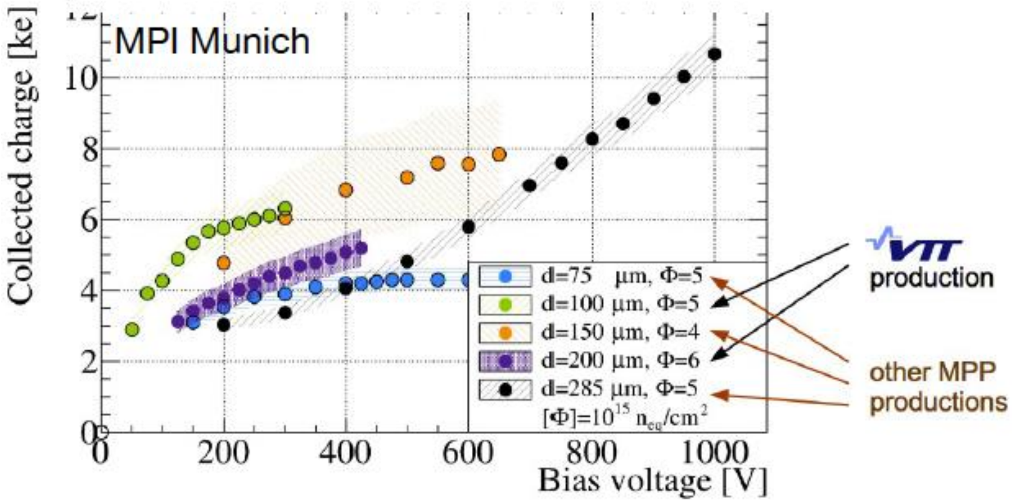
- Increase field
    - Stable up to 2kV
    - <3% efficiency loss
- Thin Si sensor
    - Demonstrated down to 75µm
    - 100-150µm industrial process

2) Reduce drift length

- 3D Si sensor; IBL production successful
- BUT: non-standard process, low volume







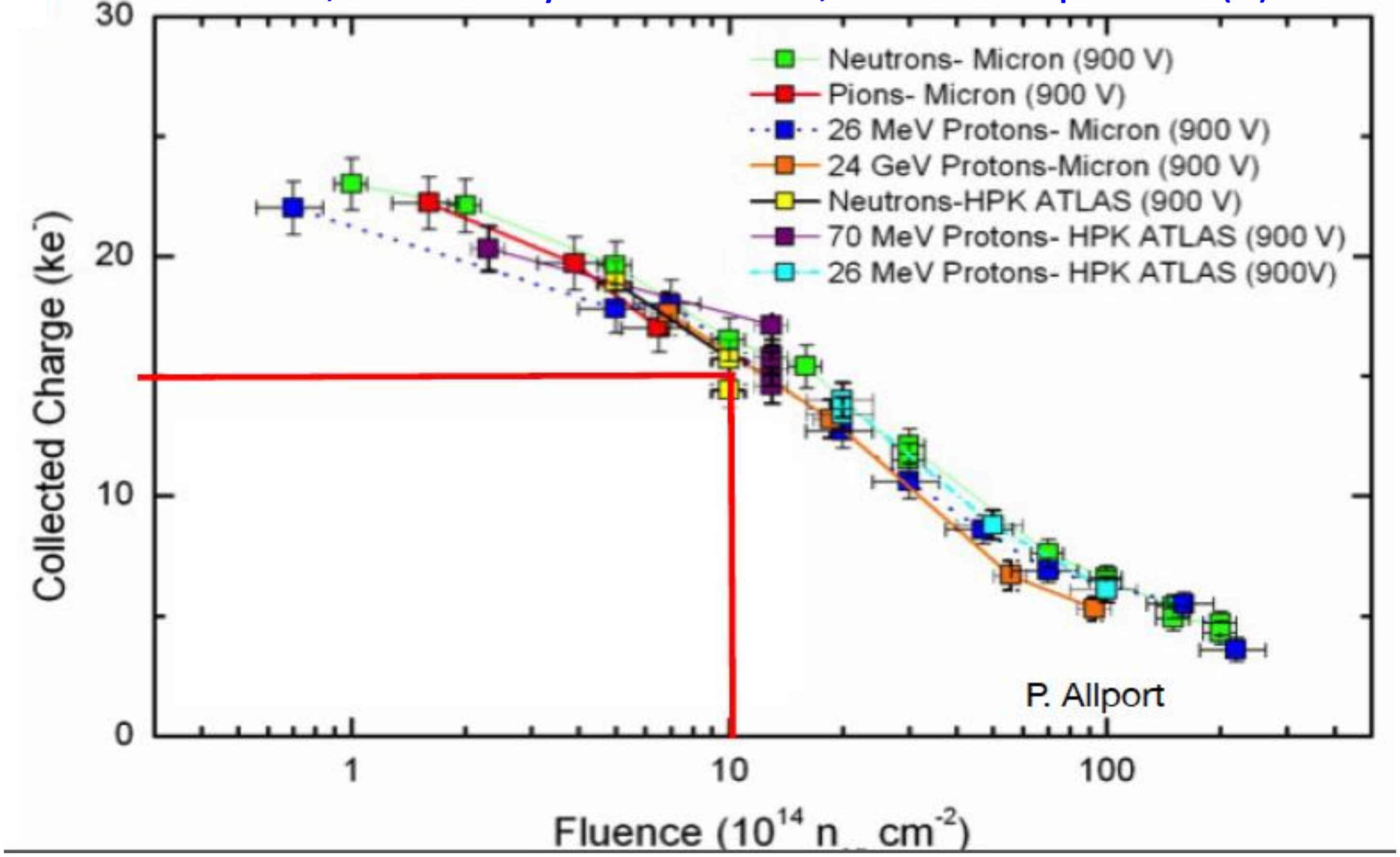
Si Sensors; Outer Layers

Rad-hardness up to 2 × 10^{15} n_{eq} cm^{-2} at 600V bias already established

- Costs main concern (>10 m^2 area)

Larger radii: Si strips collected charge with n-in-p strips

- Collected charge >14000 e^- at 900 V bias; perfect
- Sensor self-heating due to leakage current; sufficient operation temperature
- Production on 6” wafers; less costly than before, still too expensive(?)



Punch line: hybrid detectors rad-hard enough;
lots of experience with them;
could be used

BUT: Expensive!

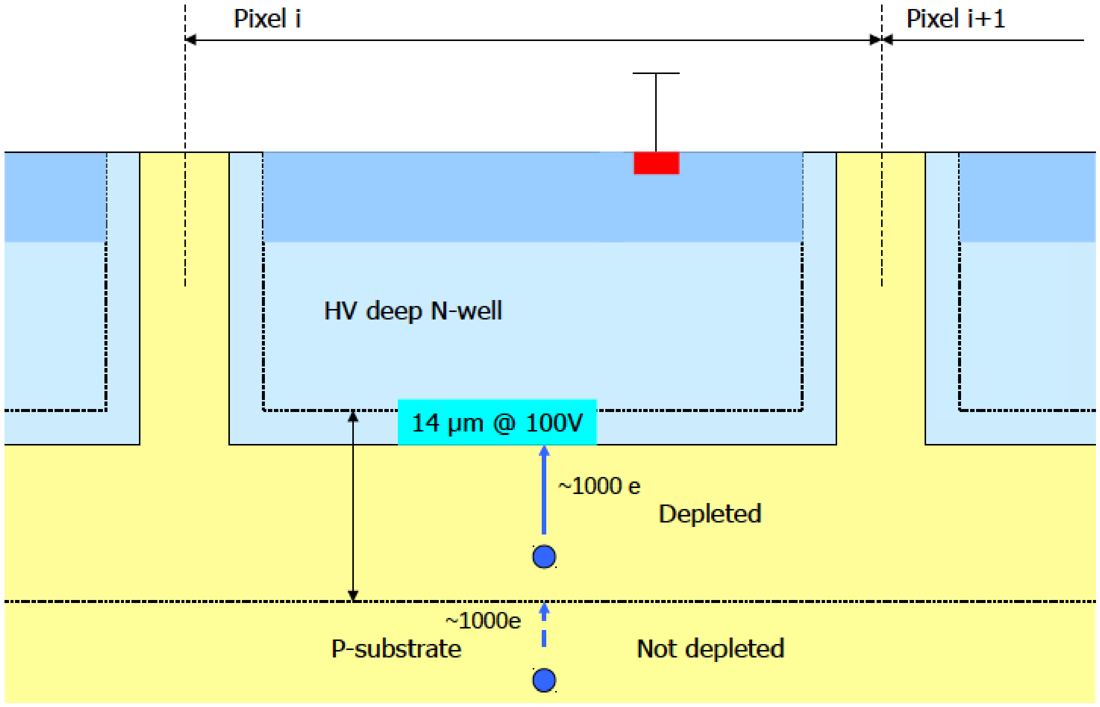
Hybridization expensive

Sensor processes non-standard and on small wafers

Rad-Hard and Cheap?

Basic idea: explore industry standard CMOS processes for sensors

- Commercially available by variety of foundries
- Low cost per area; as cheap as chips for large volumes
- Thin active layer
  - Useful to disentangle tracks within boosted jets and large eta
- Two basic flavors:
  - HV-CMOS; highest possible bias, smallest drift time
  - HR-CMOS; specialized imaging processes

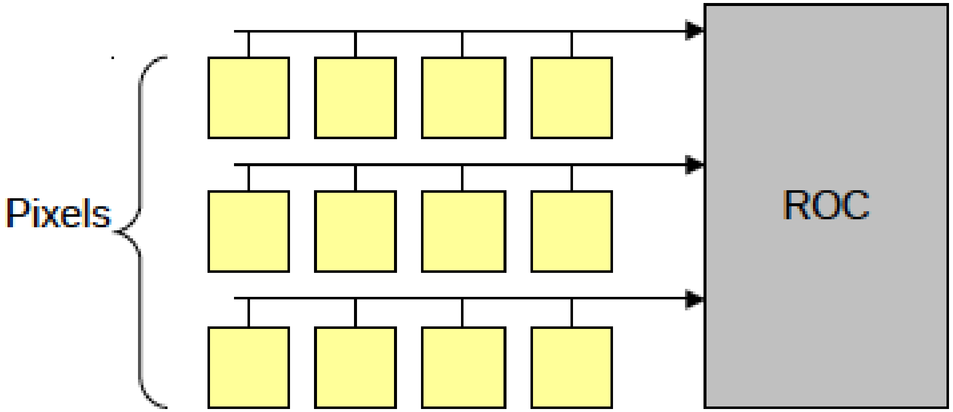


- Essentially in n-in-p sensor
- 1k-2k e^-; ~OK to work with…
- Implement additional circuits:
  - first amplifier stage
  - discriminators, logic,…

Particularly suitable for pixel trackers

Towards Active Sensors

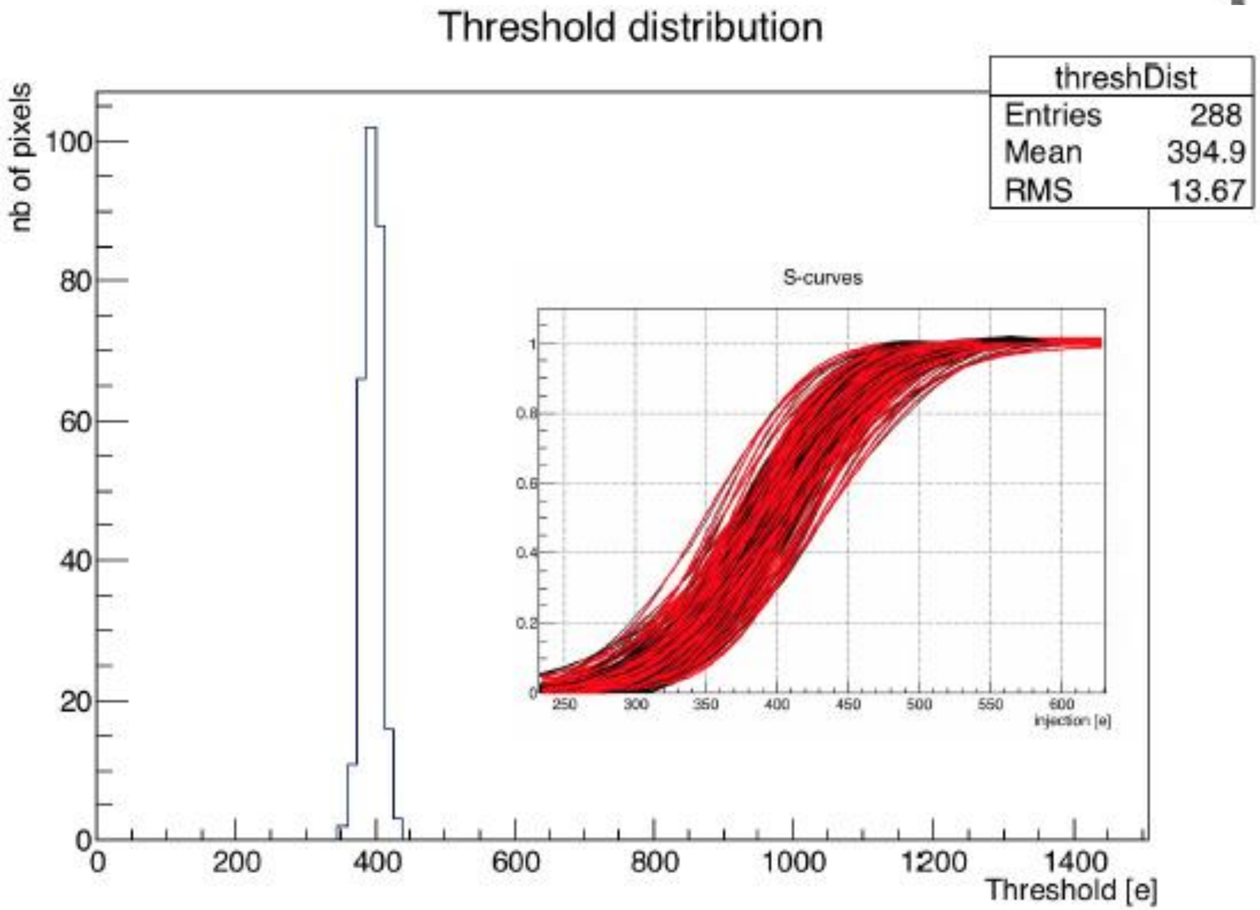
- Existing prototypes not suitable for HL-LHC:
  - readout too slow
  - time resolution not compatible with 40 MHz operation
  - high-speed digital circuits might introduce noise
- Idea: use HV-CMOS is combination with existing readout technology
  - fully transparent, can be easily compared to existing sensors
  - can be combined with existing readout chips
  - makes use of highly optimized readout circuits
- Basic building block: small pixels (lower capacitance, noise)
  - can be connected to match existing readout granularity
    - e.g. larger pixels and/or strips

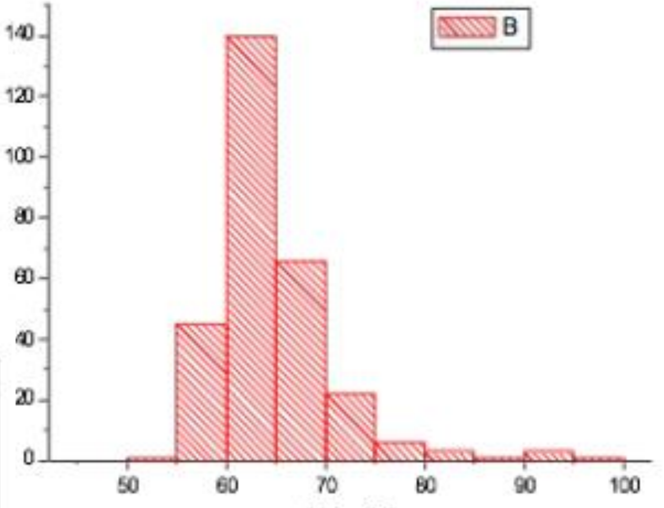


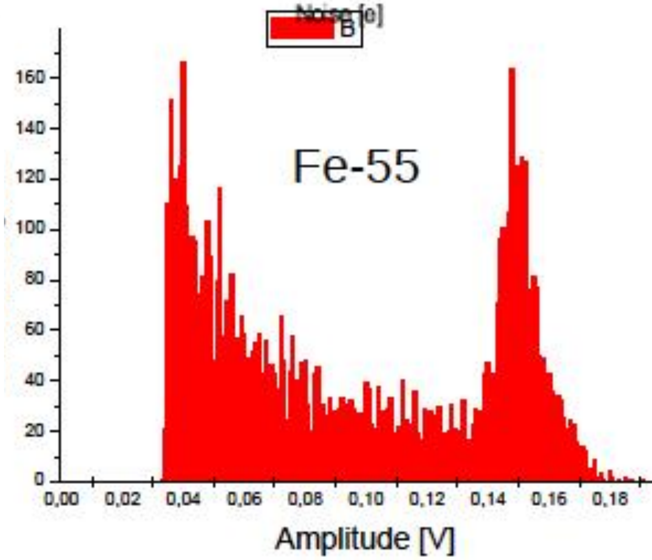
Sensible pixel sizes:
20×120 μm² to 50×125 μm²

A glimpse of an ATLAS Pixel Prototype

- **H18_v4:**
  - Focused on ATLAS pixel readout
  - 25×250 μm^2 pixels, several noise improvements
  - Tunings to 300-40 electrons
  - >95% efficiency after irradiation

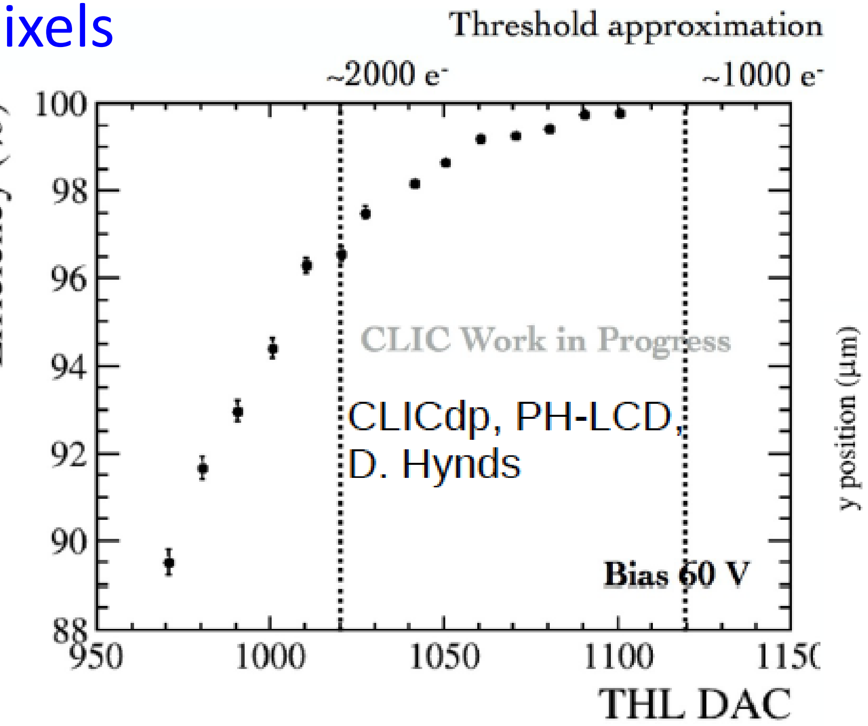




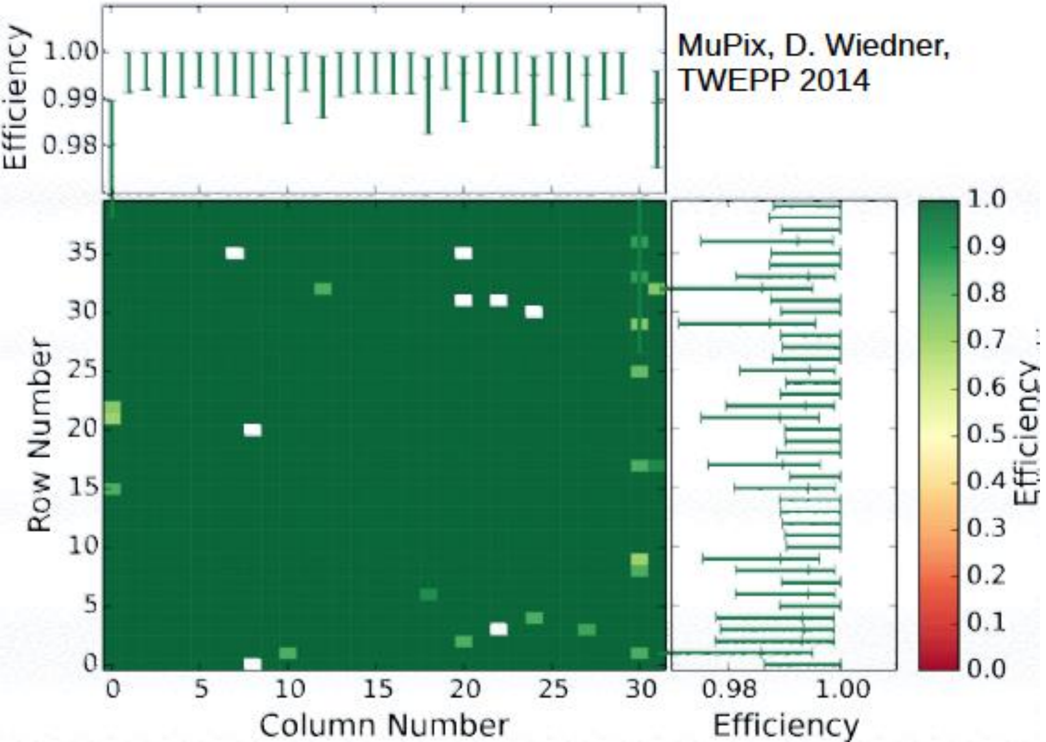


A glimpse beyond ATLAS

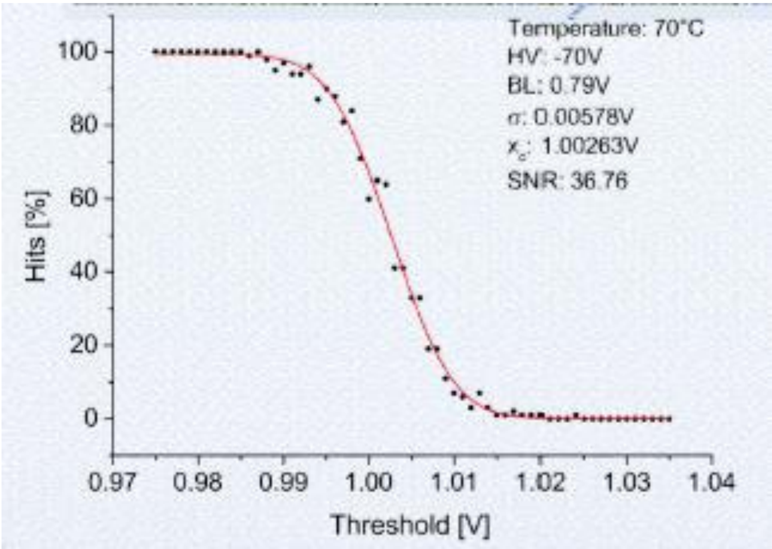
- H18_v3 use for CLIC with 25×25 µm^2 pixels
  - Excellent noise performance
  - Efficiency >99.7% for 1000 e$^-$ threshold
- mu3e experiment at PSI: MuPix chip
  - 80µm × 92µm pixel size
  - >99% efficiency measured in test beam
  - timing looks promising



CLICdp, PH-LCD,
D. Hynds



MuPix, D. Wiedner,
TWEPP 2014

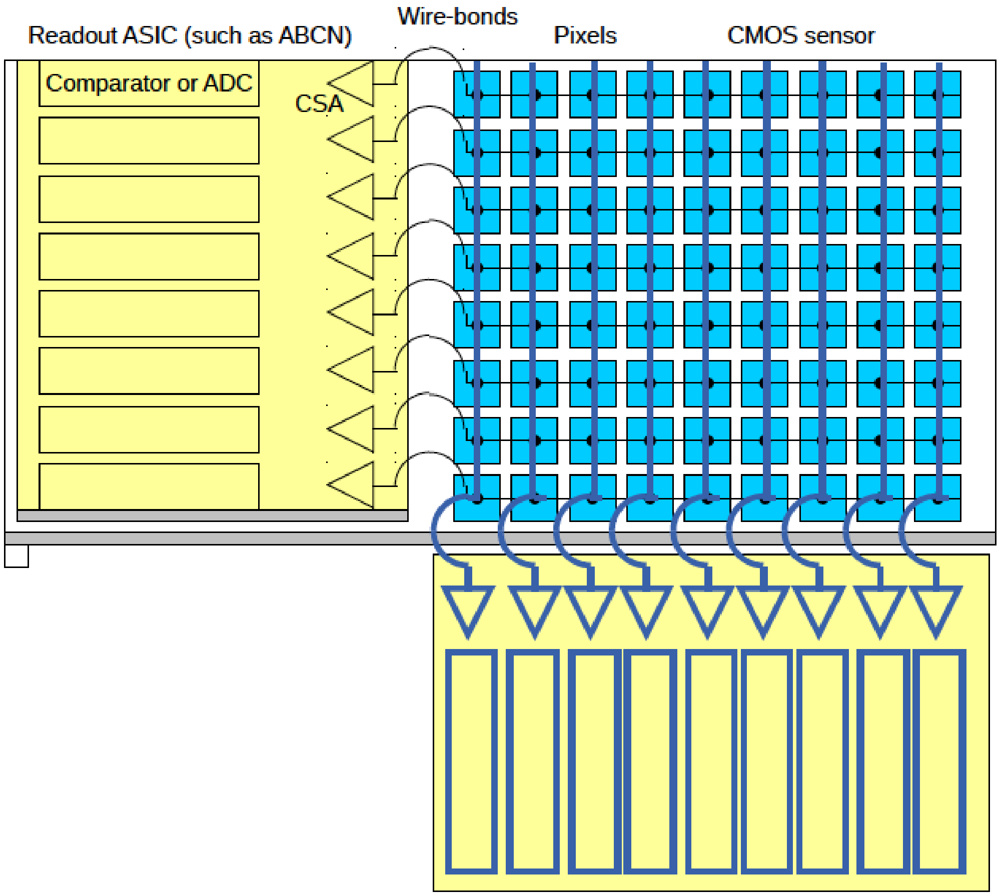


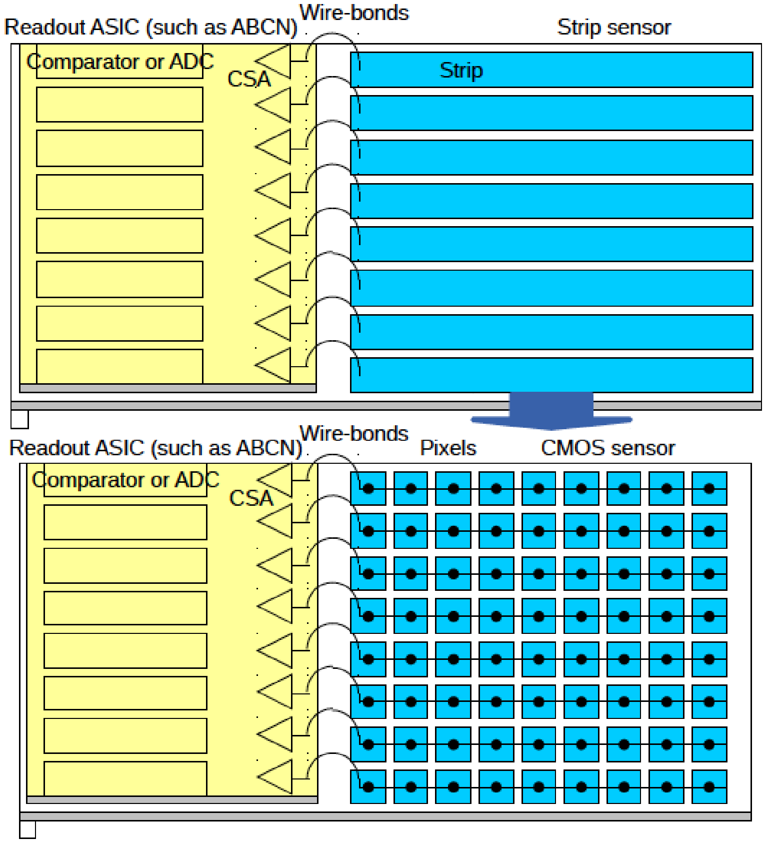
A glimpse beyond Pixels: Strips

- Very large area (200 m^2)
    - Cost very important
- Occupancy very low, BUT
- Trigger, readout challenging

Idea:

Sum all pixels in virtual strip

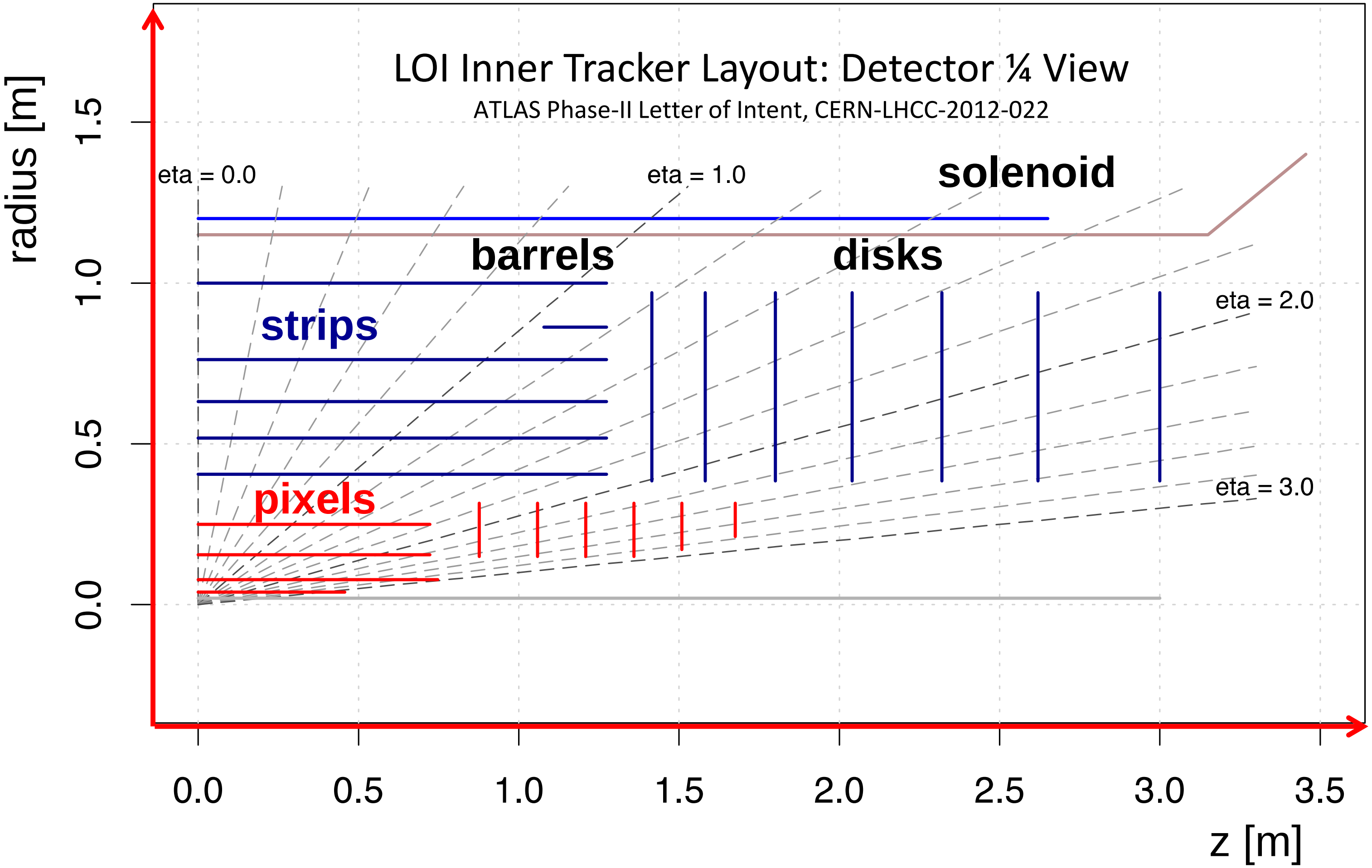




- Digital signal, multiple connections possible
    - crossed strips
    - strips with double length, half pitch in r-ϕ
    - combinations to resolve ambiguities
        - pixel precision with ~4N channels instead of N^2
- **First ATLAS prototype H35_v1**

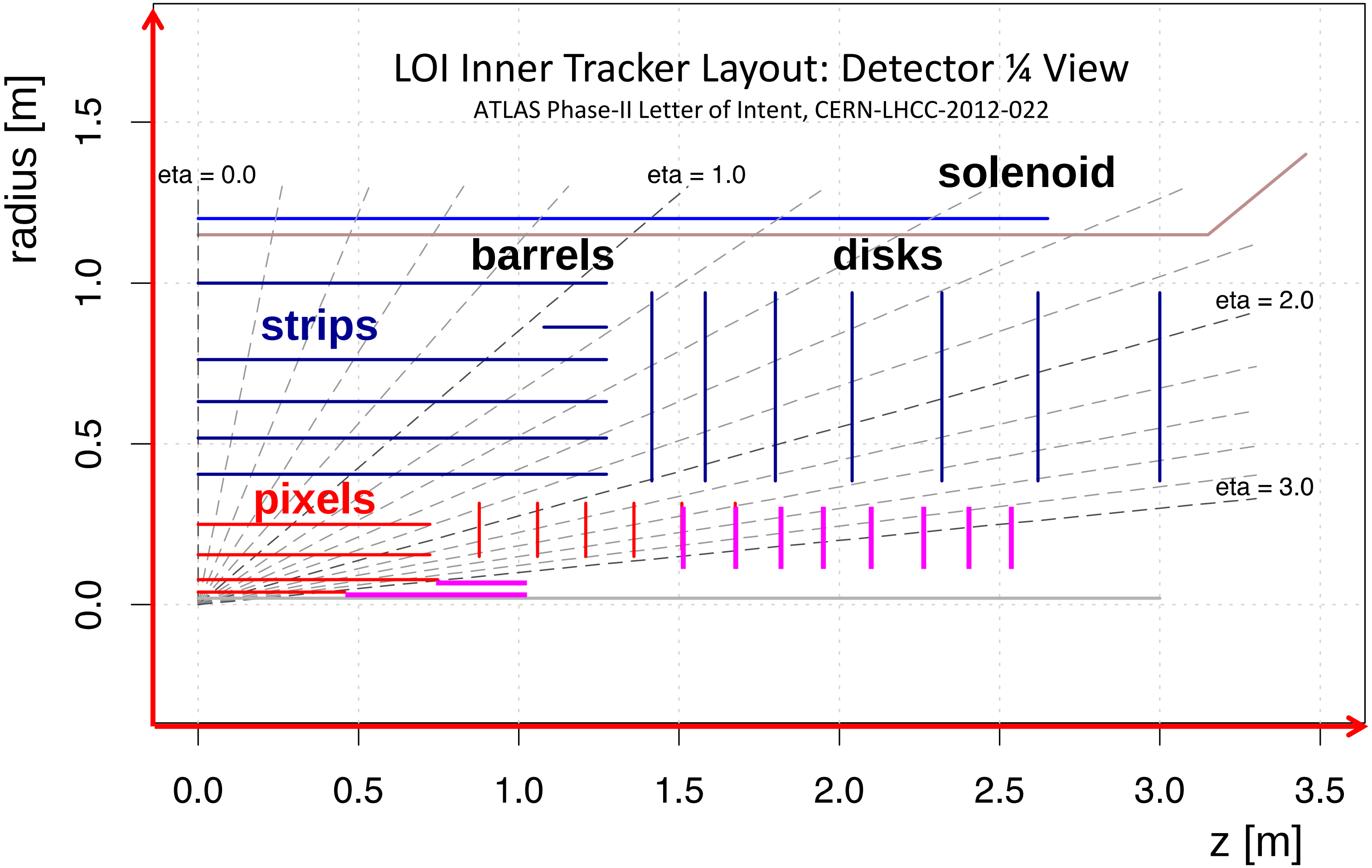
Forward Tracking Extension

- Nominal tracker provides coverage up to |η| ~ 2.7



Forward Tracking Extension

- Nominal tracker provides coverage up to |η| ~ 2.7
- Considering tracking extension up to |η| ~ 4
  - Extend innermost pixel barrels and/or add extra endcap disks



Forward Tracking Extension-Physics Impact

- Consider impact on physics, for example:
  - Vector boson fusion/scattering with forward jets
  - bbH with forward b-jets
  - Higgs (e.g. $H \longrightarrow ZZ \longrightarrow 4\ell$, signal acceptance ~ lepton acceptance^4)
  - Forward/diffractive physics, minimum bias, underlying event
- From improvements in performance:
  - Forward tracks for vertexing and jet-vertex association
  - Larger acceptance for electrons/muons
  - b-tagging for forward jets
  - Improved jets/MET reconstruction using forward tracks (PU suppression, calibration, etc)

Strong physics case; potential sensor challenges:

- Mass production; rad-hardness
- square pixels/small eta pitch

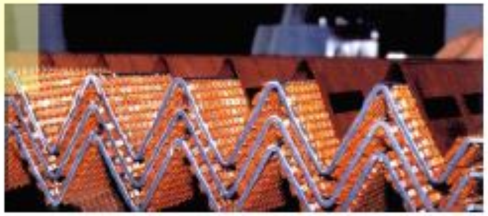
➡ **HV-CMOS?**

ATLAS Calorimeter

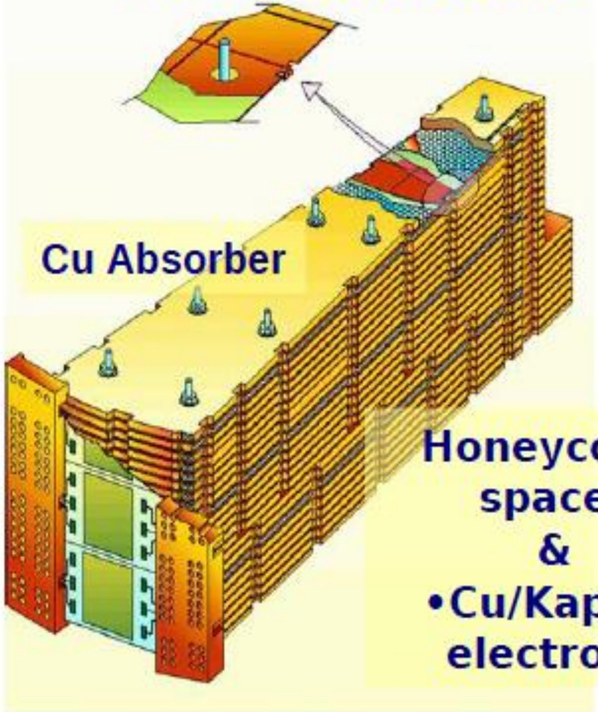
LAr Technologies

EM Cal Structure

Pb Absorber
- **Honeycomb spacer**
- **Cu/Kapton electrode**



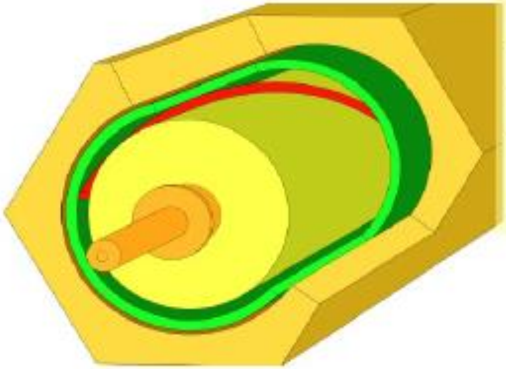
HEC Structure



Cu Absorber

Honeycomb spacer
&
- **Cu/Kapton electrode**

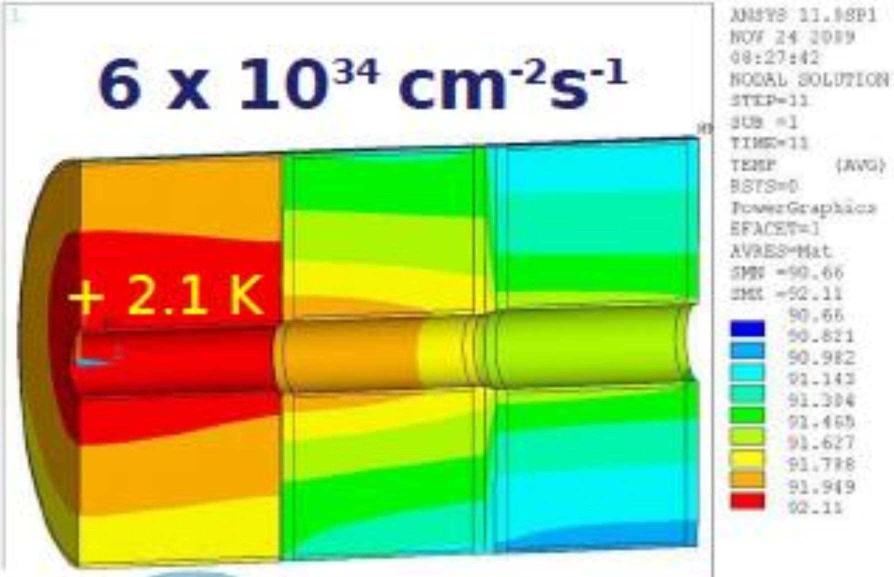
FCal Structure

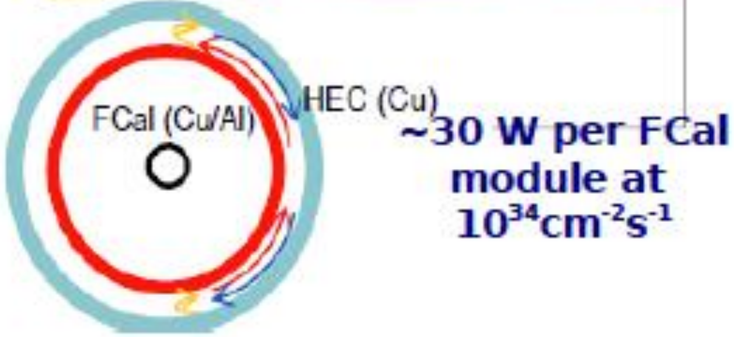


Electrode Rods &
Absorber Matrix
Cu (FCal1) 269 µm
W (FCal2/3)
376/508 µm

FCAL at HL-LHC

- FCAL-1: Cu+LAr , FCAL2/3: W+LAr
  - Designed for up to 10^{34} cm^{-2} s^{-1}
- At HL-LHC, pulse shapes from inner most FCAL radius will degrade:
  - Ar^{+} build up: field & signal distortion
  - High HV currents: voltage drop
  - Heat due to energy depositions
    - May lead to LAr bubbling





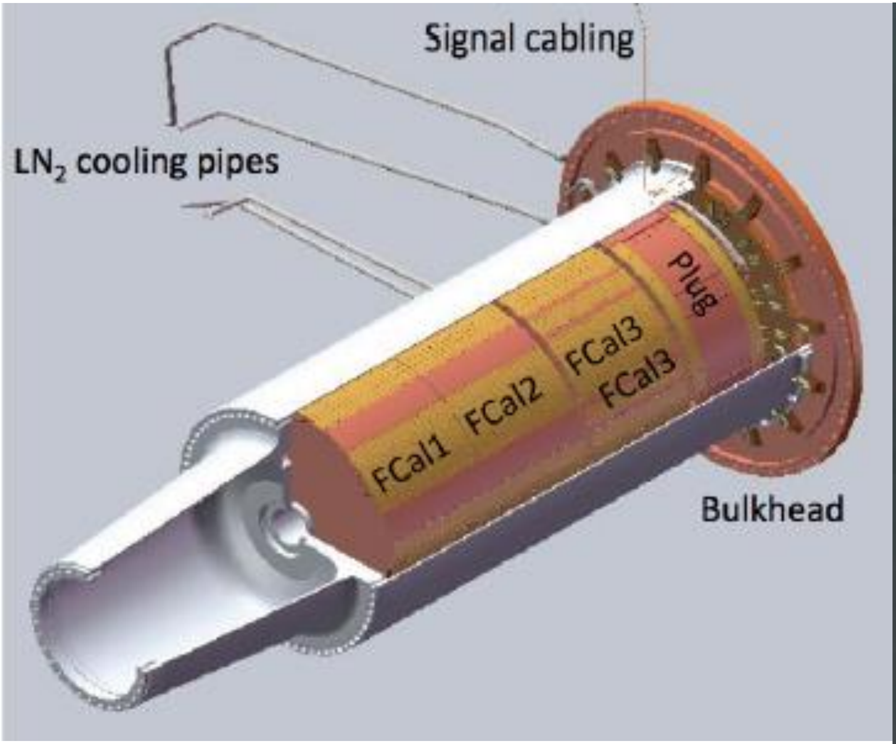
~30 W per FCal module at 10^{34}cm^{-2}s^{-1}

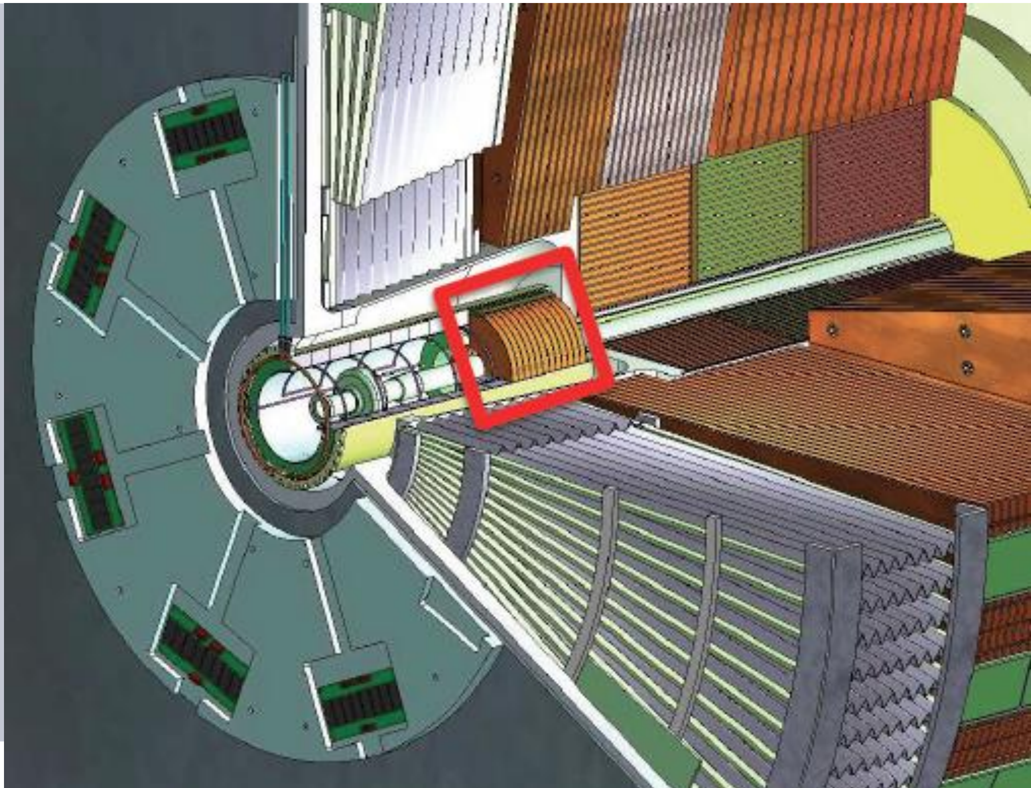
- **Two options to consider:**
- Replace FCAL1 by sFCAL
  - Smaller LAr gaps
- MiniFCAL in front of current FCAL

FCAL Upgrade Options

- **sFCAL:**
- Easier to optimize design
- Requires to open cryostat
- Implement 100µm LAr gaps
    - Instead of 269µm at FCAL1
- Introduce cooling loops

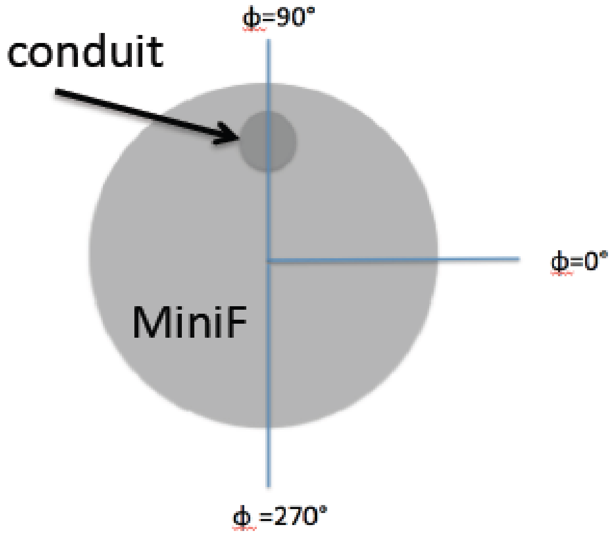
- **MiniFCAL:**
- Install new calorimeter in front
    - Absorb part of increased flux
- Must be extremely rad-hard
- Important: minimize material in front
- Cold: Cu+LAr FCAL1 like with 100µm gaps
- Warm: Diamond sensor

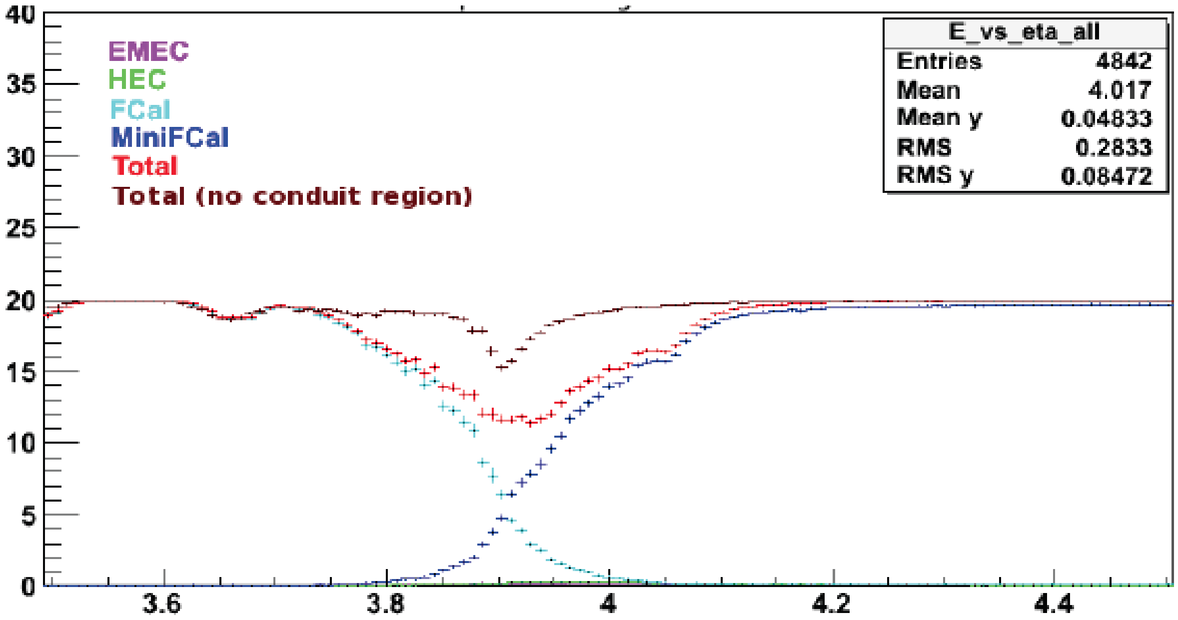


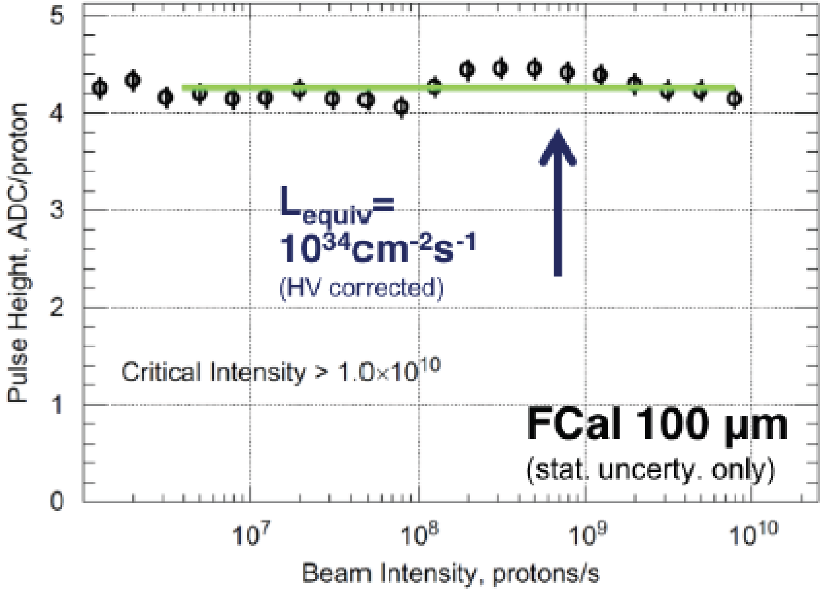


Upgraded FCAL Performance

Main concern asymmetry introduced by conduit



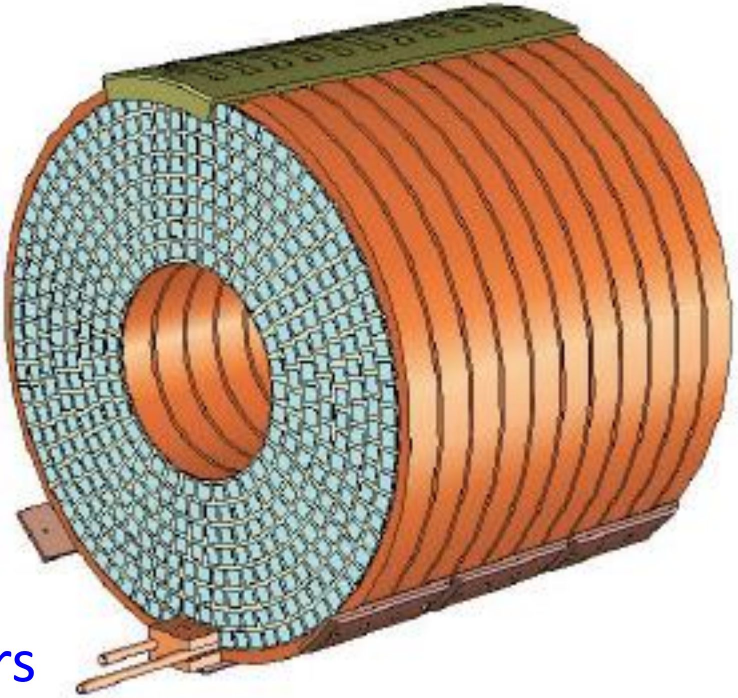




Critical intensity above proposed HL-LHC $\mathcal{L}_{inst}$

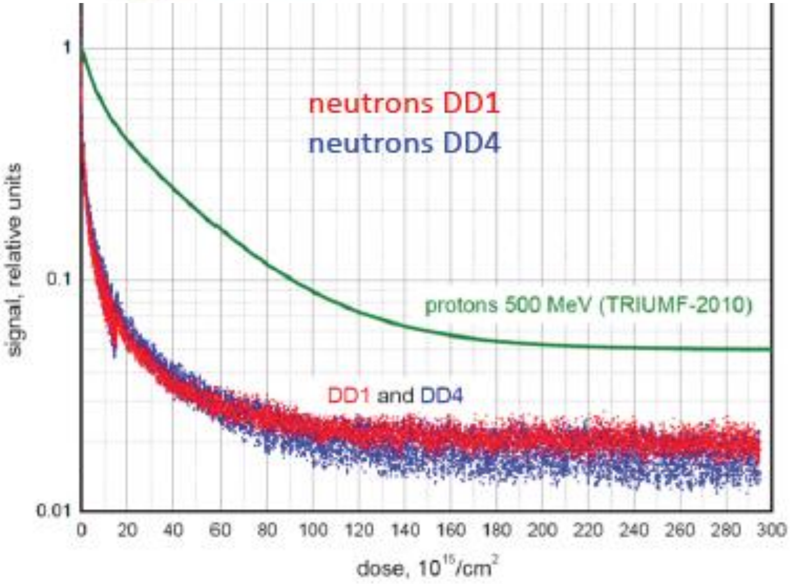
Same electrode design as in Mini-FCAL option

Mini-FCAL (Cu/pCVD Diamond)



- 12 Cu plates with 11 sensor planes
    - ~8000 diamond sensors per side
    - Water cooling
- Initial irradiation studies at TRIUMF
    - 2×10^{17} p/cm^2 , 5% response after full dose
- Calibration complicated because:
    - Need for channel ganging in r-z (dose varies)
- Diamond supplier (DDL) shut down in 2012
- Neutron irradiation more harmful to sensors
    - Lower response than in the case of protons

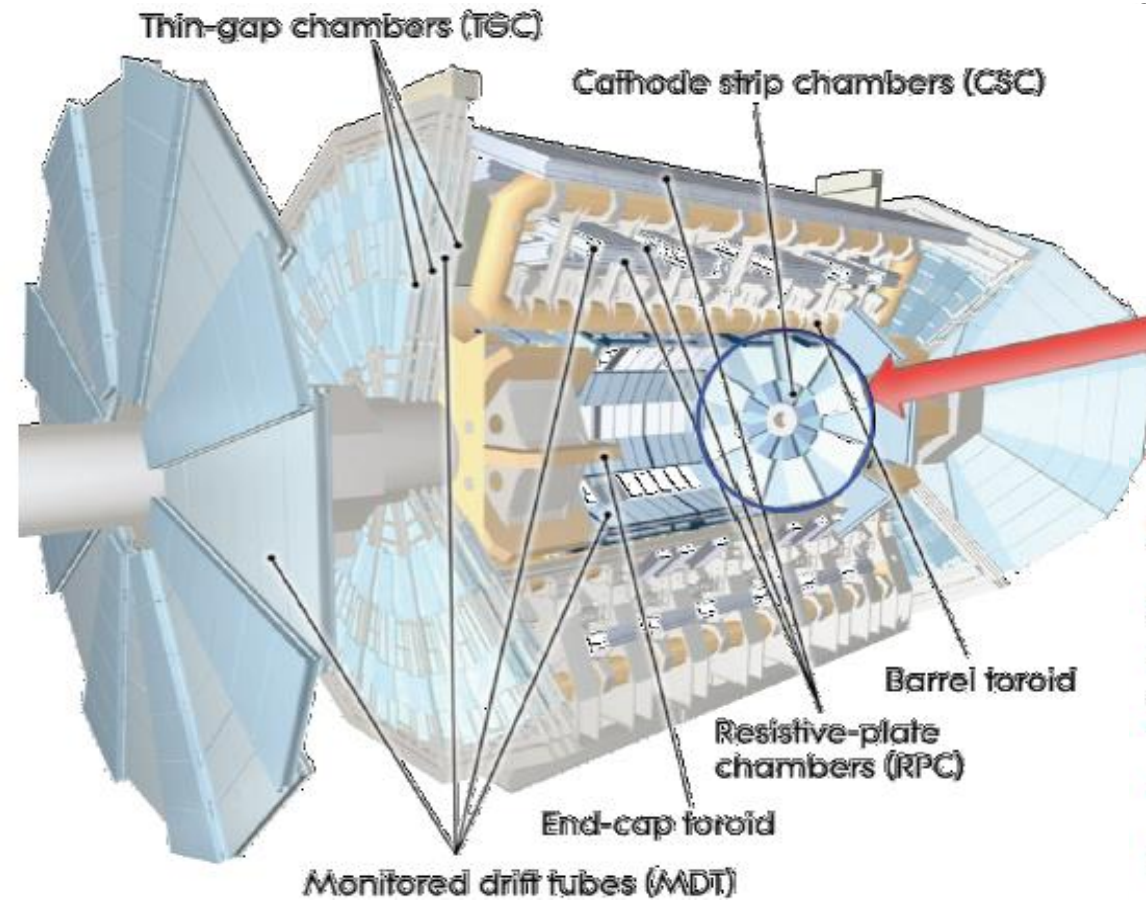
- **Solution currently disfavored**



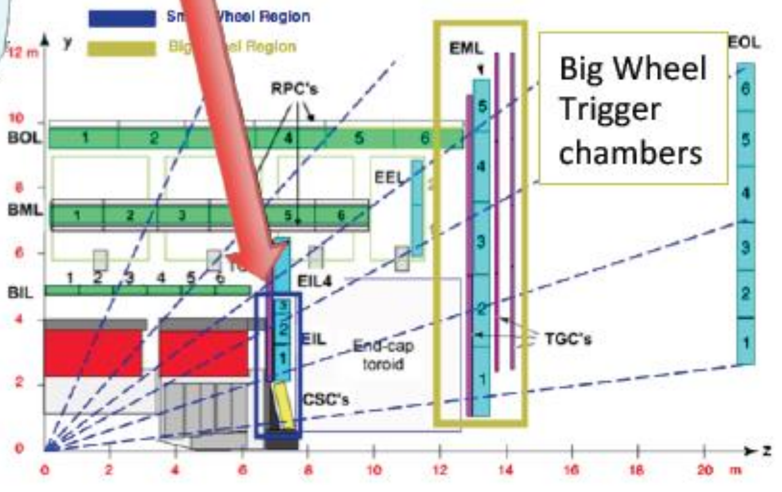
ATLAS Muon Spectrometer

New Small Wheel (NSW)

- Motivated by the increase in background rate for $\mathcal{L}_{\text{inst}}$=2-5$\times 10^{34}$ cm^{-2} s^{-1} during Run-3 and HL-LHC
- Replace with fast, high rate, precision detectors
- Coverage: $1.2 < |\eta| < 2.7$



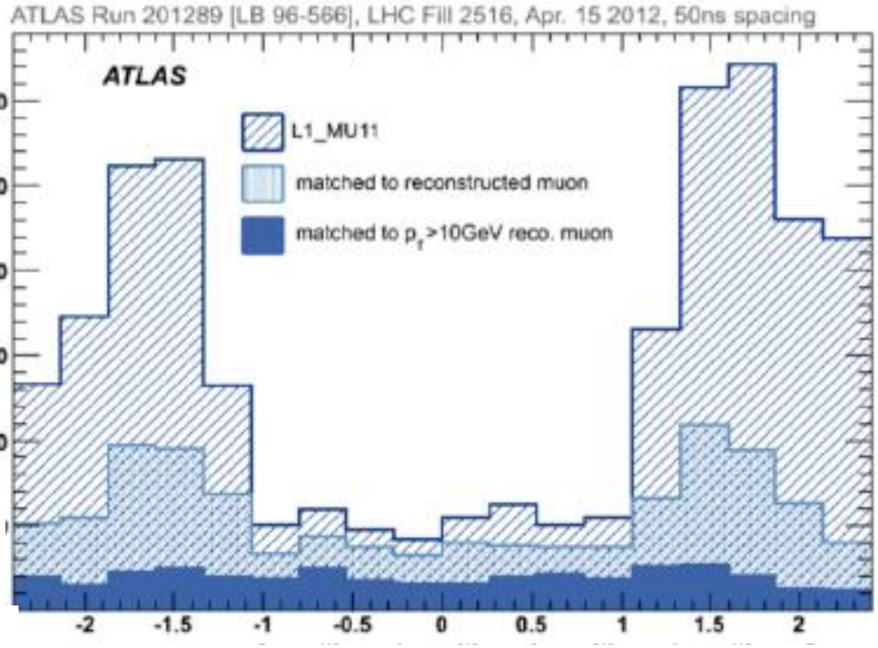
Small Wheel

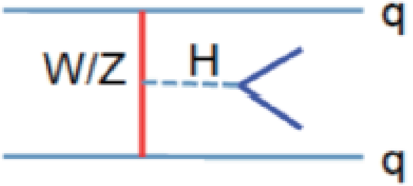


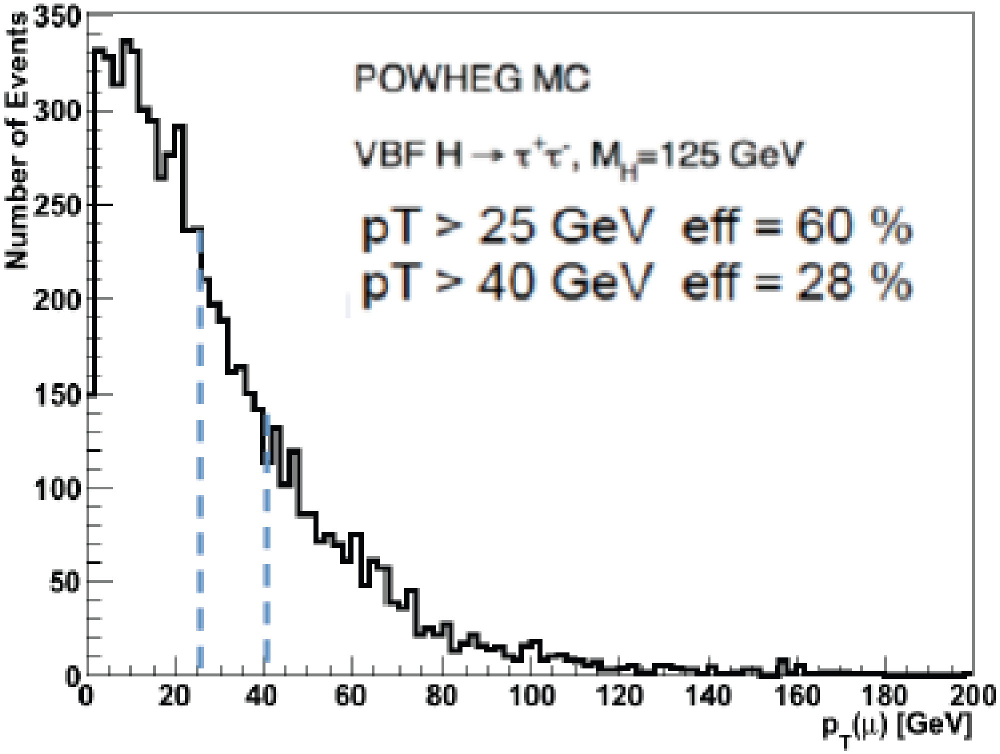
Big Wheel Trigger chambers

Physics Motivation

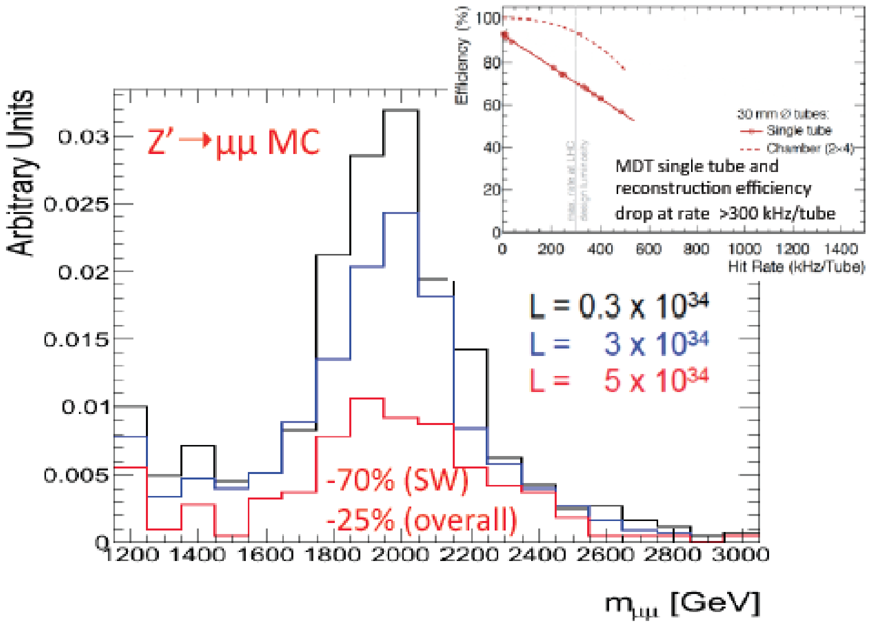
- Forward muon triggers have high fake rate
  - Raising p_T threshold results in significant physics loss
- Current SW cannot cope with 15 kHz/cm^2
  - Would exceed 20kHz available bandwidth





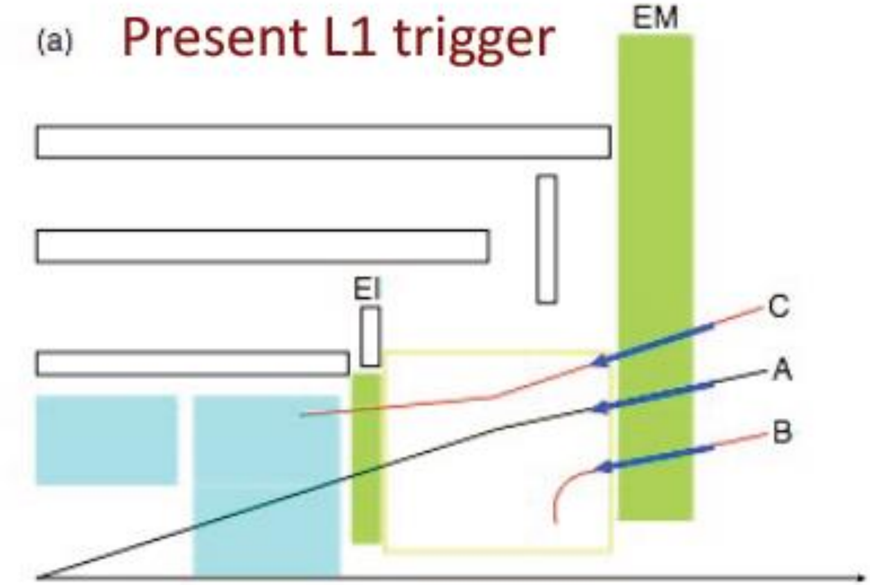


pT > 25 GeV eff = 60 %
pT > 40 GeV eff = 28 %



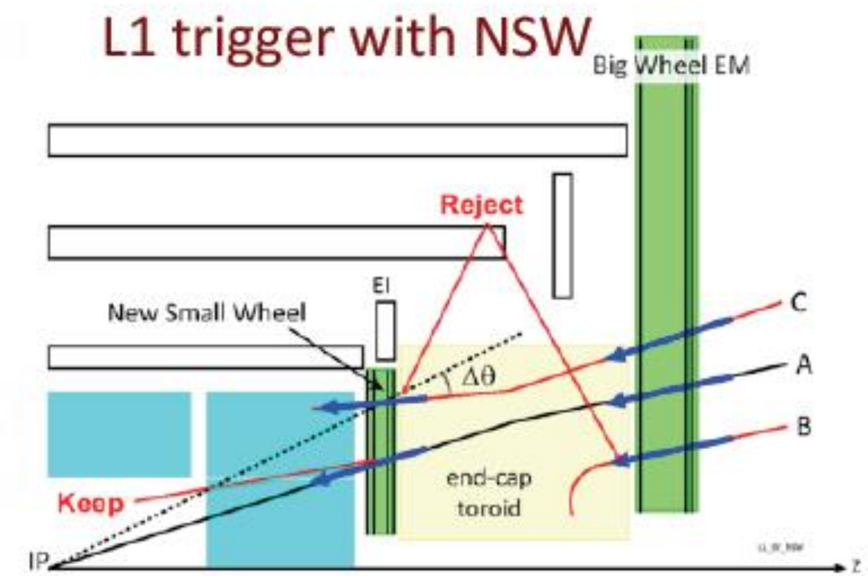
MDT single tube and reconstruction efficiency drop at rate >300 kHz/tube

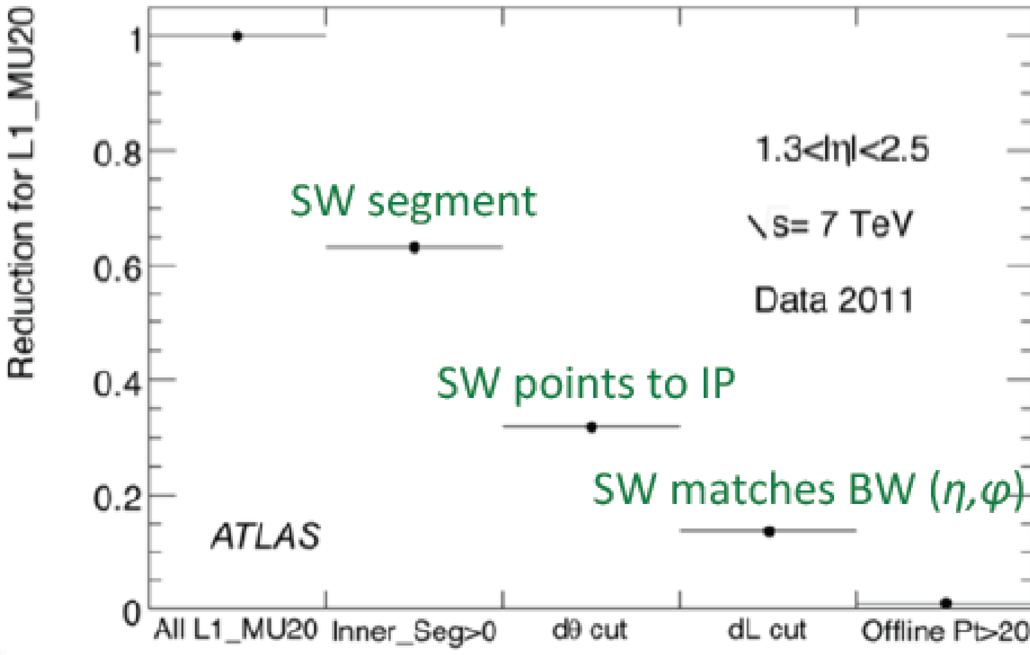
Enhanced Muon Trigger


(a) Present L1 trigger

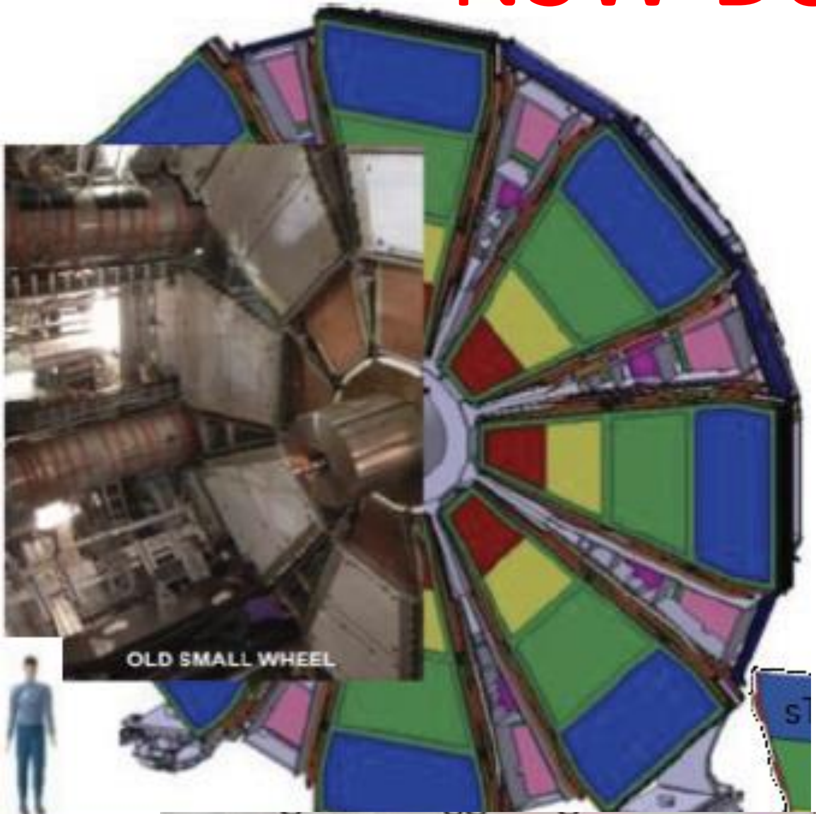
NSW provides improved forward muon trigger and improved tracking:

- 100μm tracking precision efficient at HL-LHC
- σ_θ~1mrad segment pointing resolution to IP


L1 trigger with NSW



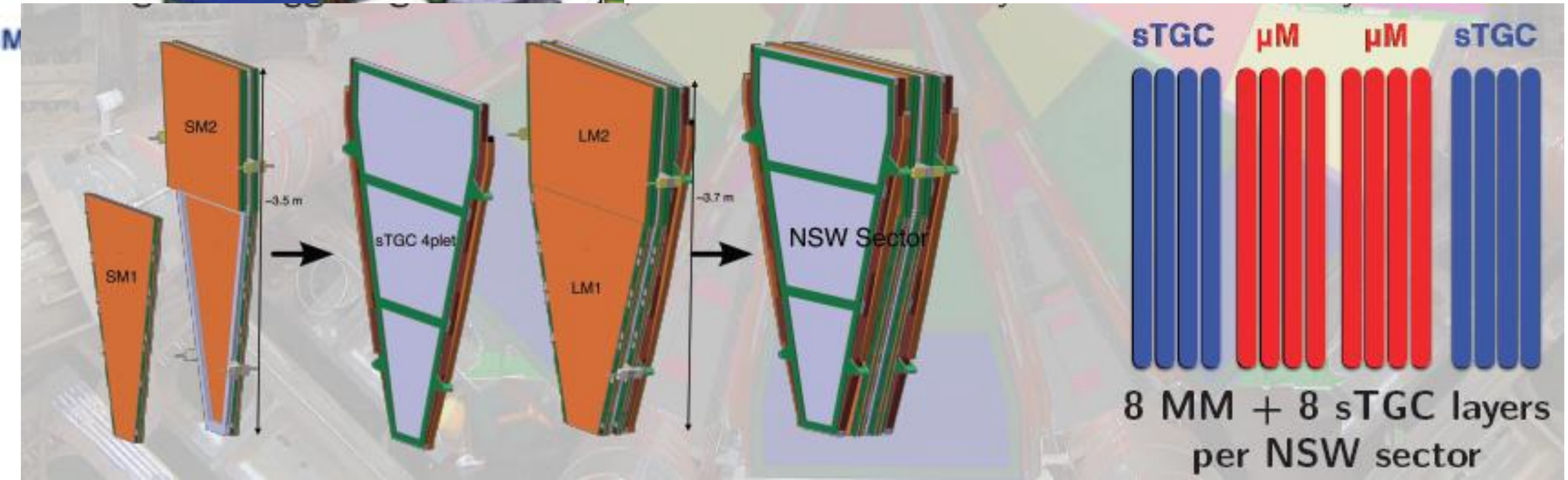
NSW Detector Layout



NSW utilizes two detector technologies:

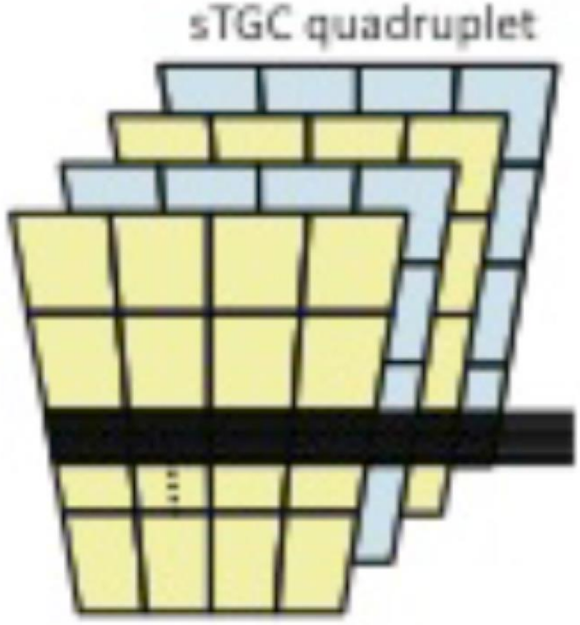
- Small strip Thin Gap Chambers (sTGC)
  - Provide primary muon trigger
- Micromegas (MM)
  - Provide precision muon tracking

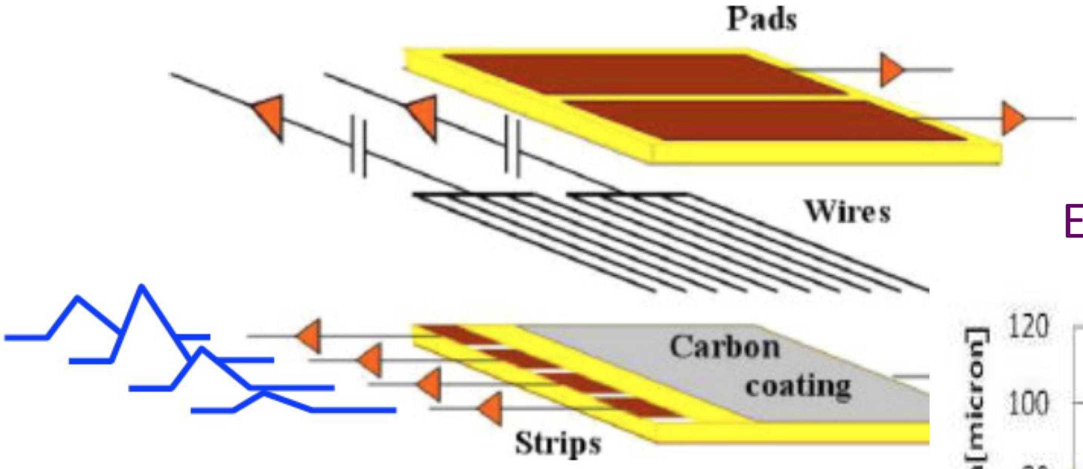
- 16 sectors per wheel
  - 8 large, 8 small
- 8 detection layers per sector and per technology
  - Subdivided into 2 quadruplets each



sTGC Technology

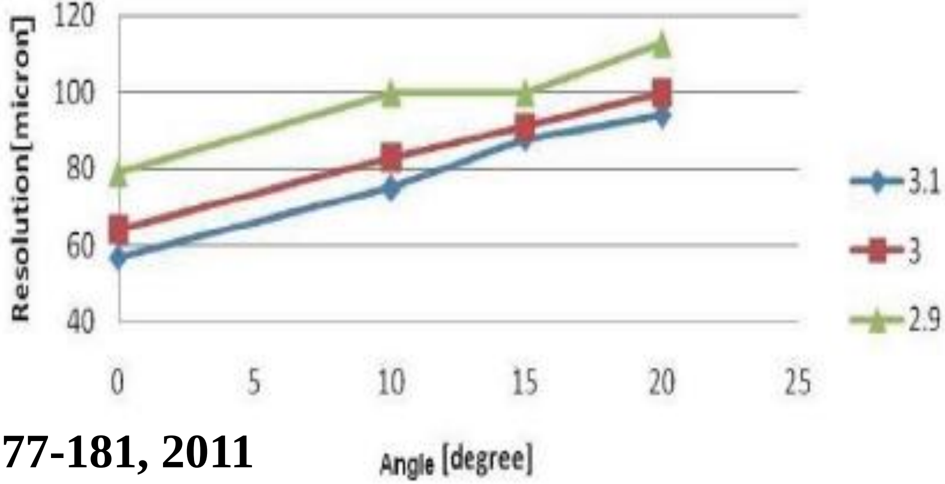
- Based on proven TGC technology
  - Thin-gap wire chambers (2.8 mm gap)
  - Strip charge readout (3.2mm pitch)
  - Pad 3-out-4 coincidence defines RoI
  - Use self-quenching gas
    - 45% n-pentane, 55% CO_2.
  - Operate at 2.9 kV





(a) a

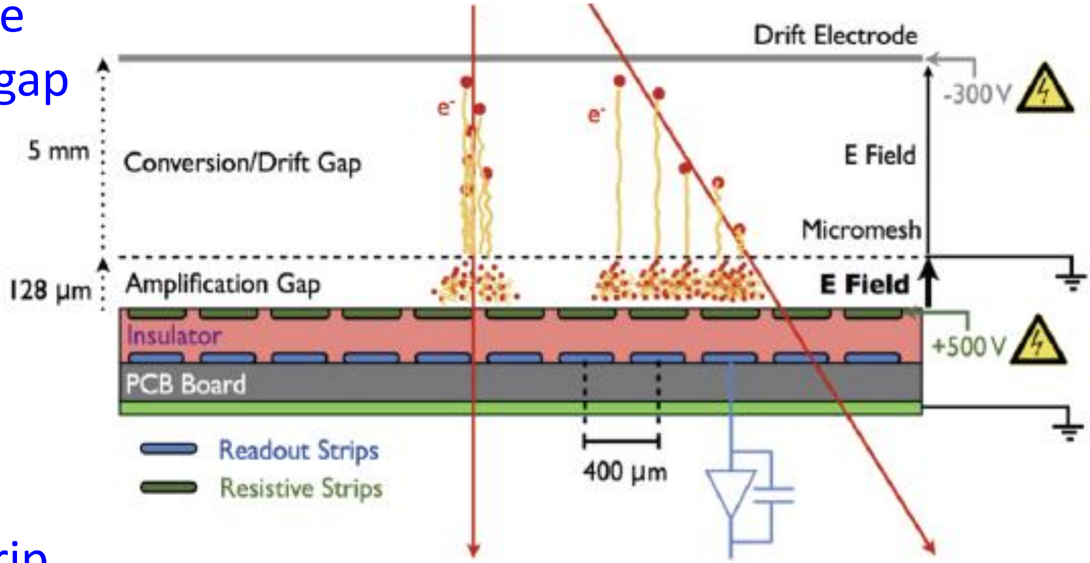
Extensive testing of sTGC prototypes (2010-2014)

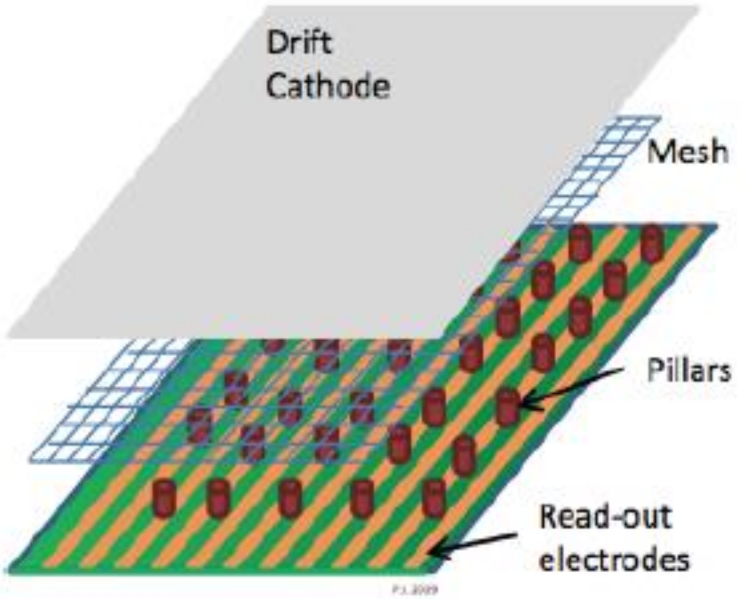


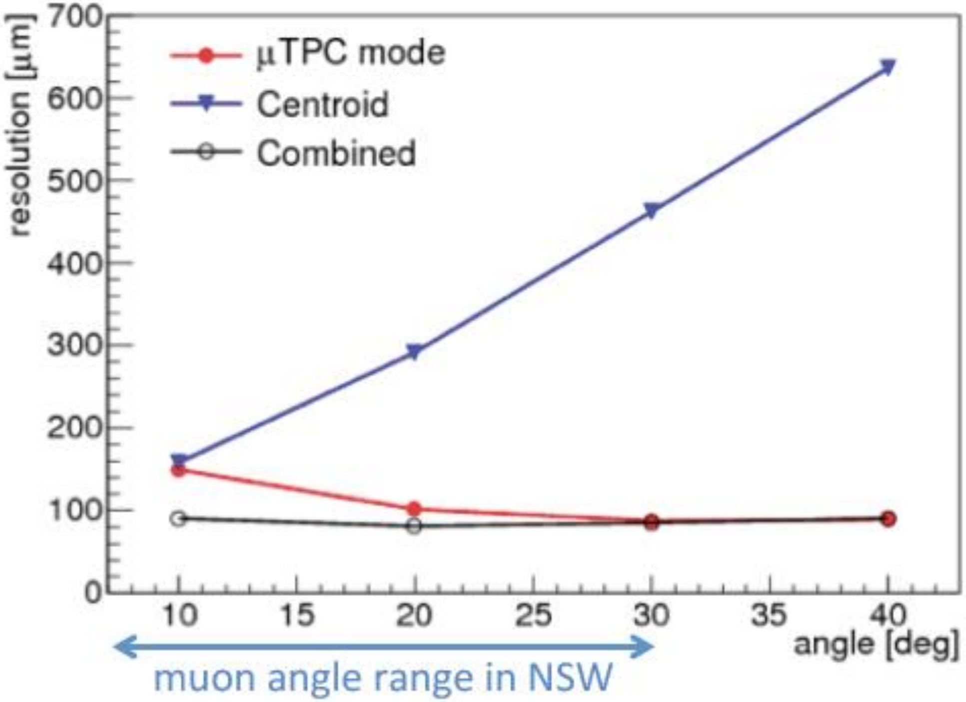
NIM A:628, 177-181, 2011

Micromegas Technology

- Novel technology exhibiting high rate capability due to thin amplification gap and small space-charge effects
- Parallel plate chambers
    - Drift gap (5 mm) E≈0.6 kV/cm
    - Amplification gap (128µm) E ≈ 39kV/cm
    - e^- drift towards mesh (95%) transp.
    - Gas mixture, Ar+7% CO_2, gain ~10^4
- Spark tolerant by adding resistive strip layer, 5-20 MOhm/cm







ATLAS HL-LHC Upgrade Goals

Physics

Study EWSB Mechanism	precision meas's of Higgs couplings (5-30%), Higgs self-coupling
Probe for signatures of New Physics	SUSY, Extra Dimensions, ...
Measure rare decay modes	Higgs, B, top, ...

Detector Requirements

Example Physics/Detector Motivation	**Requirement**
complex SUSY cascades	Trigger & reconstruct low p_T e/μ
$H \rightarrow \tau\tau$	Trigger on τ's
High-mass gauge bosons	Good lepton e/μ momentum resolution at high p_T
Complex SUSY cascades	Identify Heavy Flavors
Resonances in top pairs, W, Z, H	Reconstruct leptons & b's in boosted topologies
VBF, Missing ET	Preserve acceptance in forward region
Efficient tracking with small fake rates	Radiation Tolerance and Granularity
Compatibility with new trigger system	Impacts Front End electronics