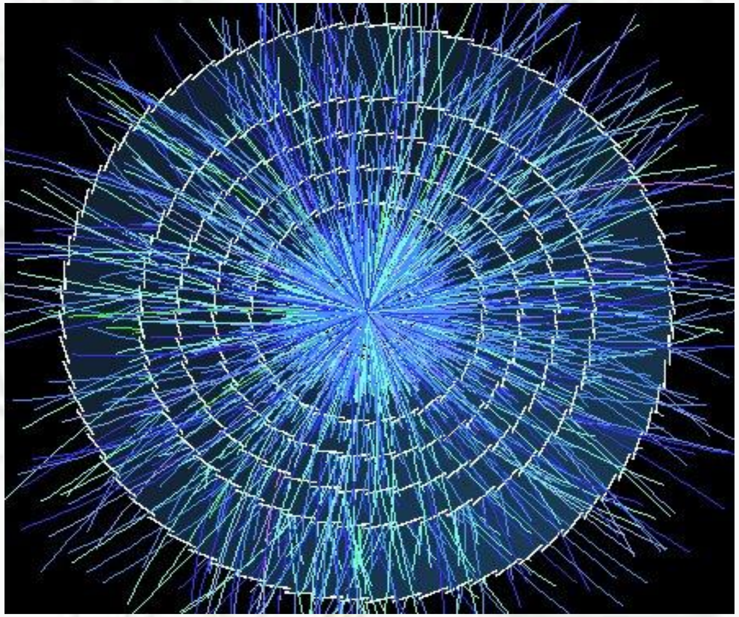
Semiconductor Tracking and Vertex Detectors at Future High Energy Physics Experiments

Phil Allport
The University of Liverpool

28/09/10

3rd Marie Curie Particle Detectors (**MC-PAD**) Network Training Event

- **Brief Overview of the Large Hadron Collider**
- **Detectors and Technologies**
- **Recent Performance**
- **LHCb and ALICE Upgrade Plans**
- **ATLAS and CMS at the super-LHC**
- **Conclusions**



The **L**arge **H**adron **C**ollider Accelerator

Experiments at the LHC

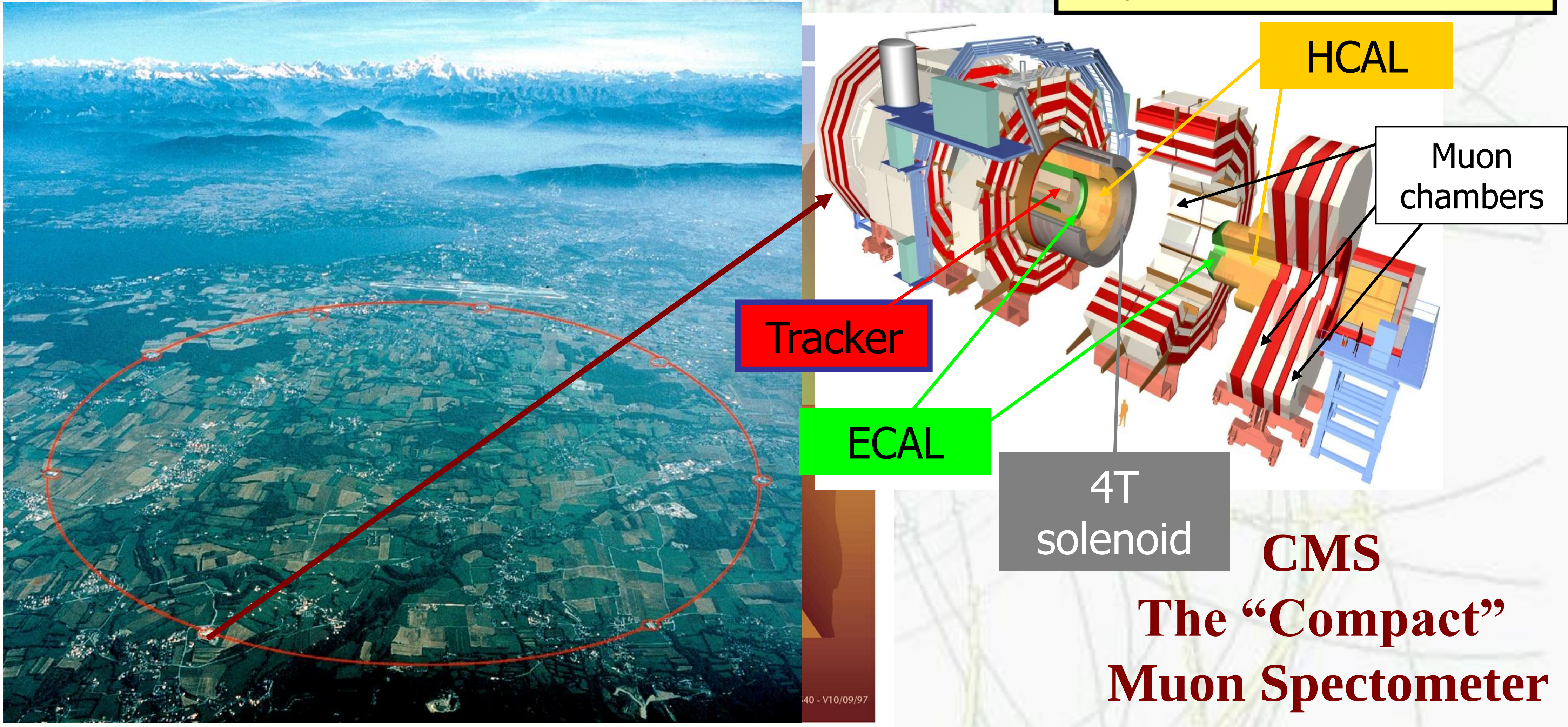
Collider Experiments

CERN Geneva

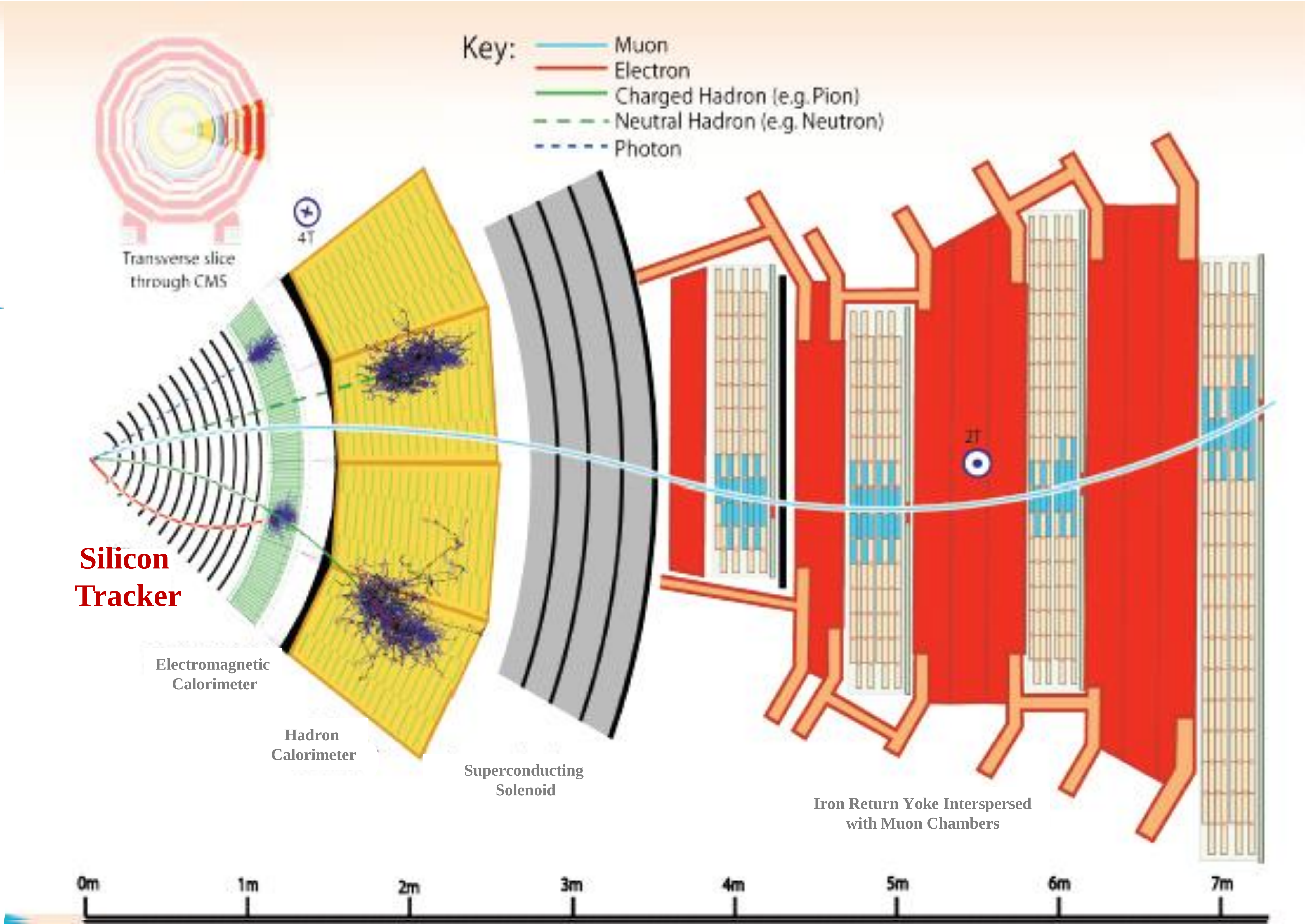
2 Giant General Purpose Detectors at the LHC

The Large Hadron Collider 14 TeV: Proton on Proton

Total weight: 12,500 t
Overall diameter: 15 m
Overall length 21.6 m
Magnetic field 4 T



CMS
The "Compact" Muon Spectometer


Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
Transverse slice through CMS
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron Return Yoke Interspersed with Muon Chambers
0m
1m
2m
3m
4m
5m
6m
7m

Physics of Micro-strip Silicon Detectors

- **Highly segmented silicon detectors have been used in Particle Physics experiments for nearly 30 years**
- **The principle application has been to detect the passage of ionising radiation with high spatial resolution and good efficiency.**

- **Segmentation → position**
- **Depletion depth → efficiency**
- $(W_{Depletion} = \{2\rho\mu\varepsilon(V_{ext} + V_{bi})\}^{½})$

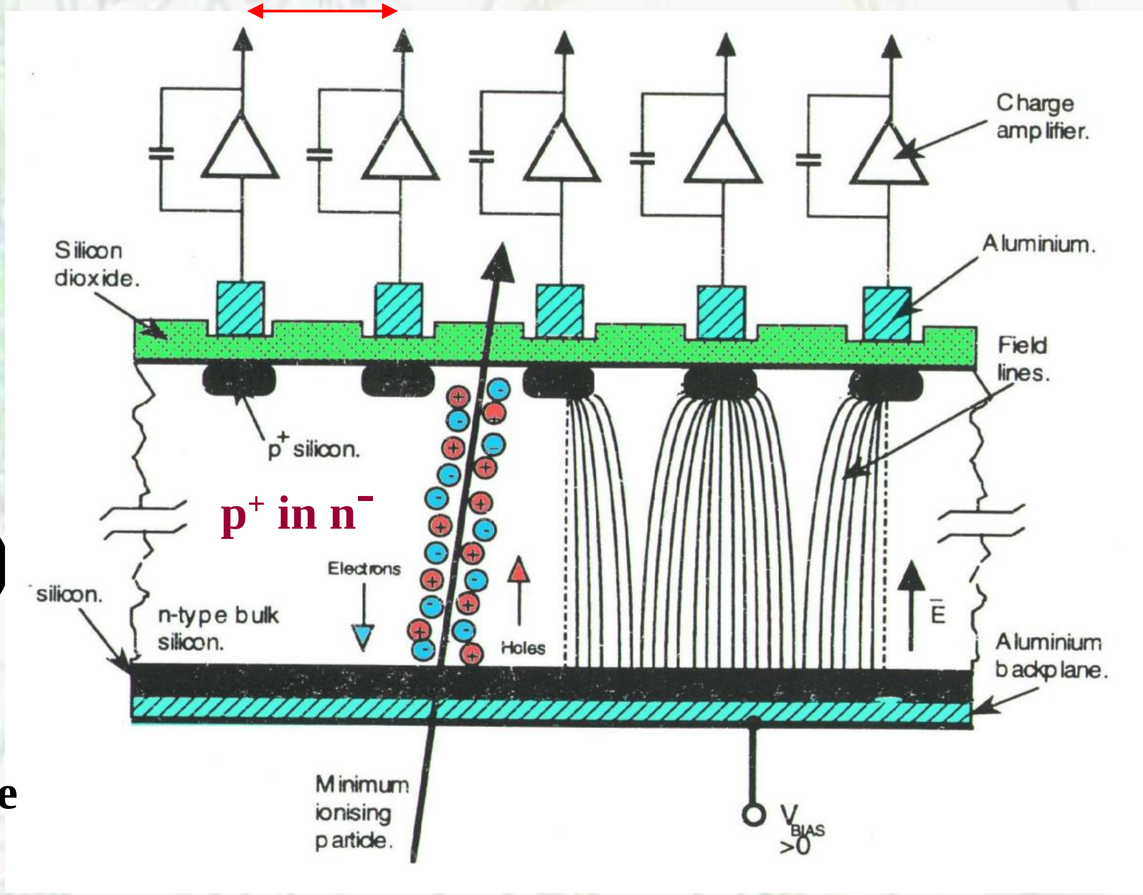
Resistivity

Mobility

Applied Voltage

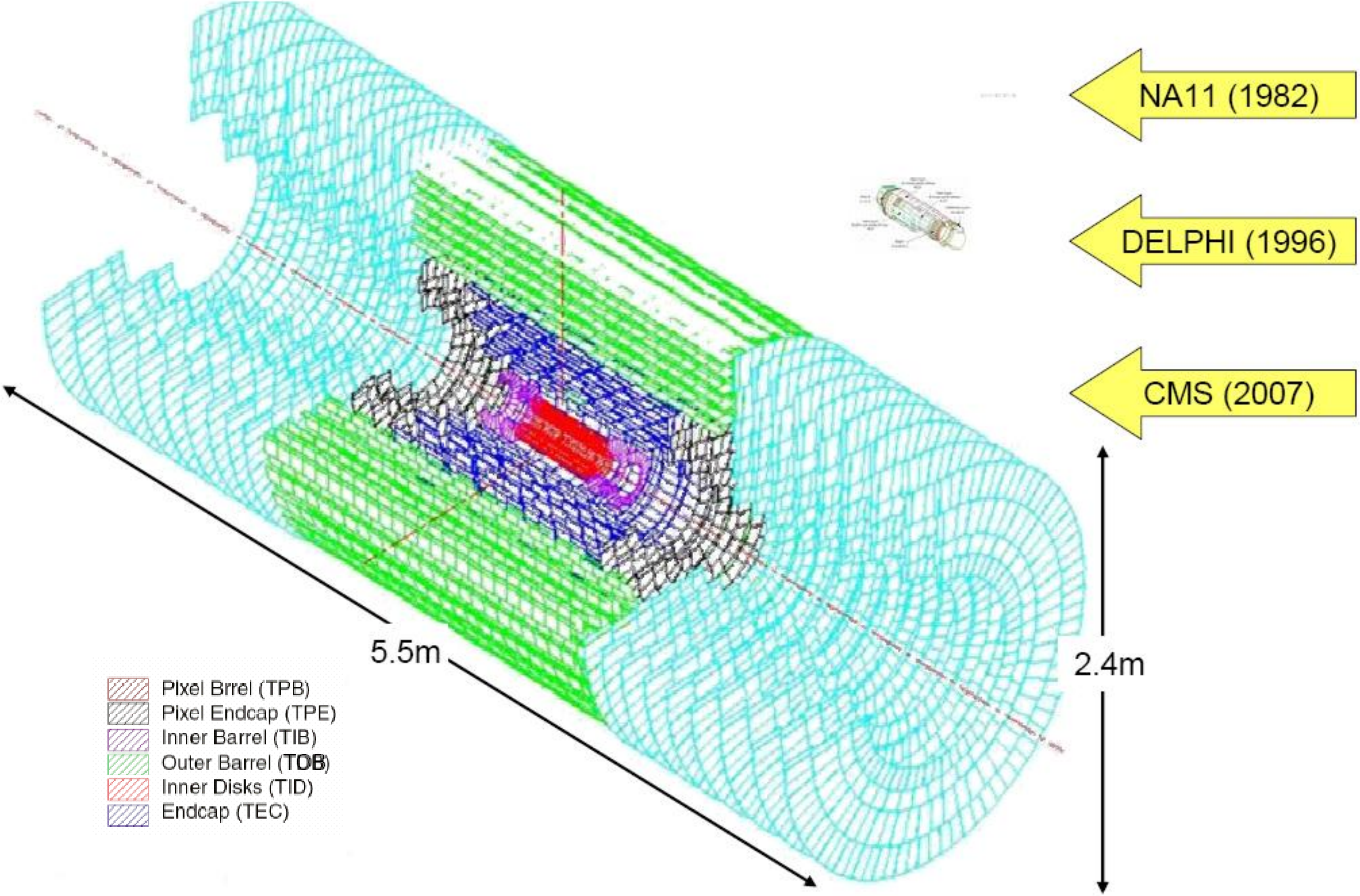
- **~80e/h pairs/µm produced by passage of minimum ionising particle, 'mip'**

Pitch ~ 50µm



Resolution ~ 5µm

CMS Silicon Tracker: Largest Ever Built



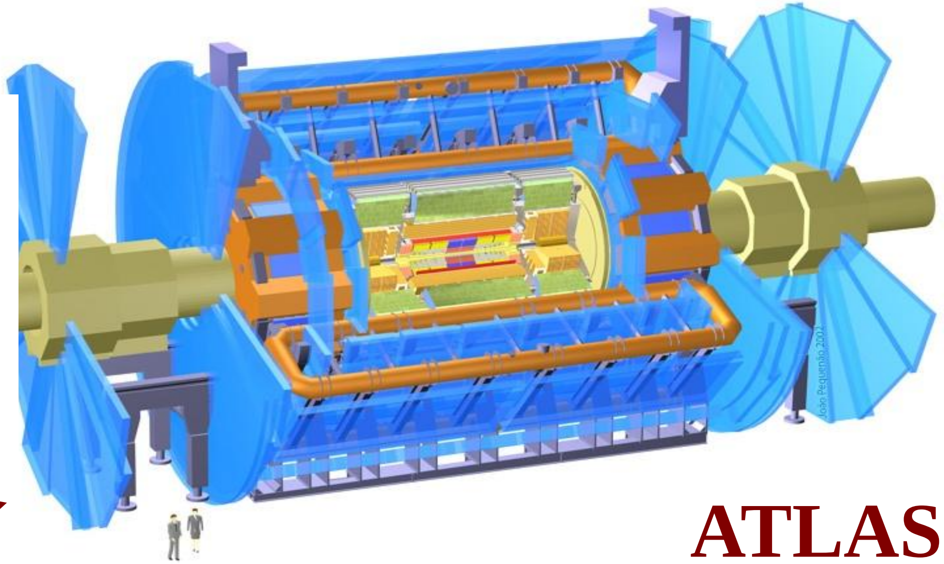
Experiments at the LHC

Collider Experiments

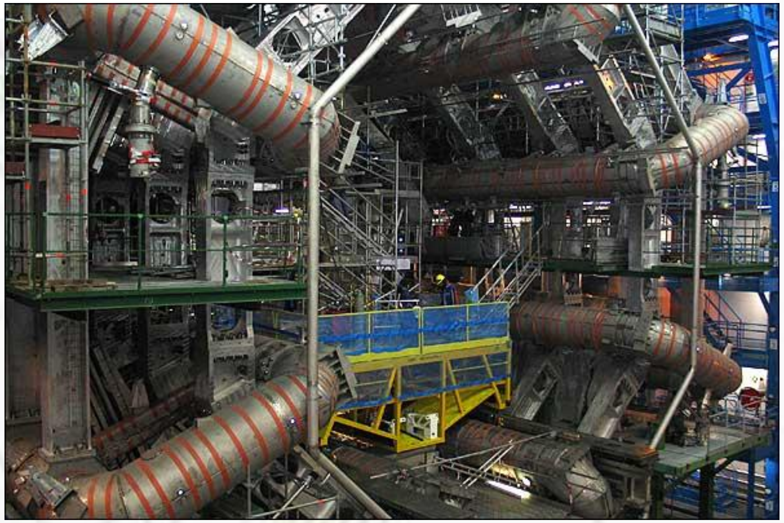
CERN Geneva

The Large Hadron Collider 14 TeV: Proton on Proton

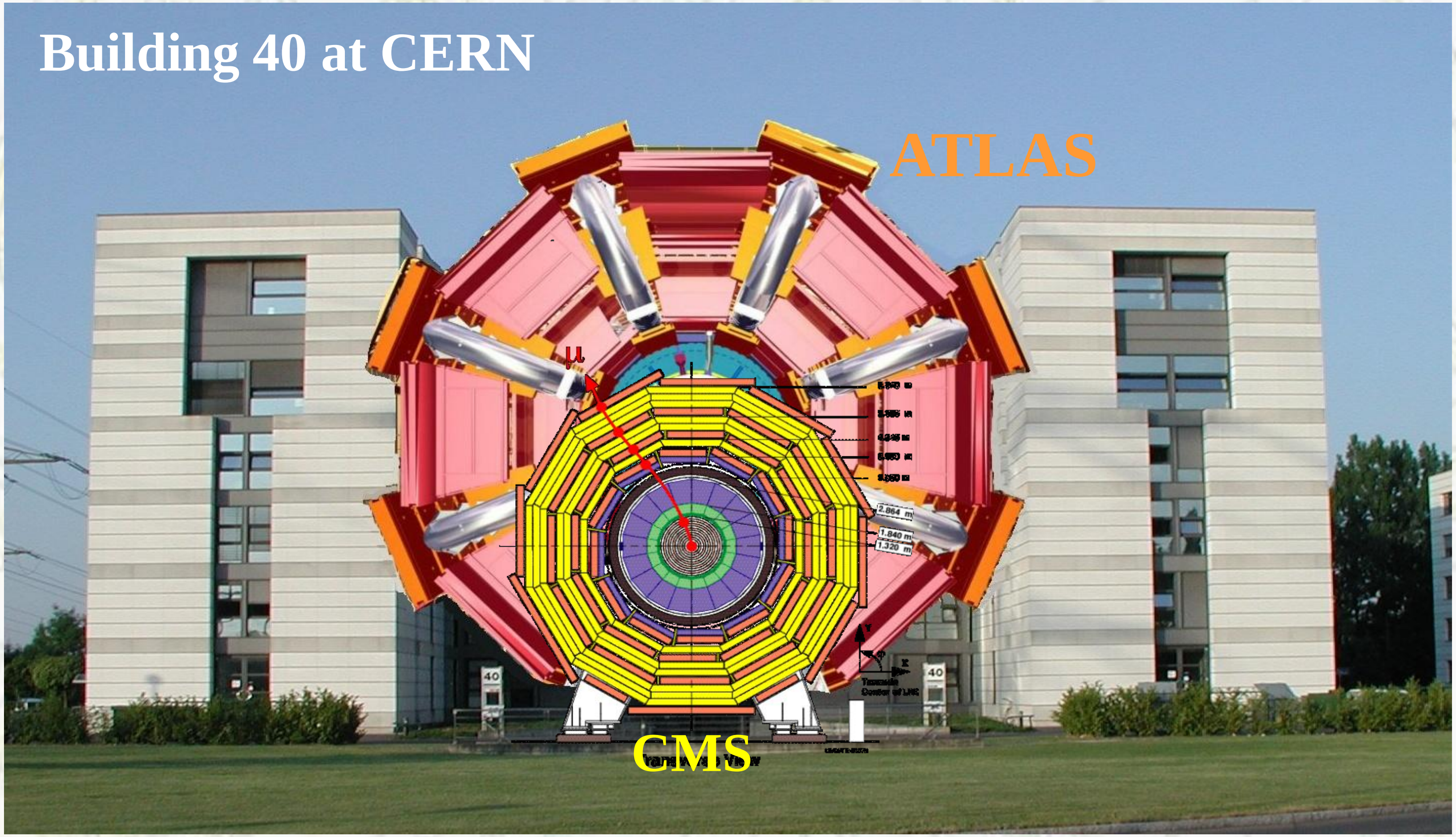
The other Giant General Purpose Detector at the LHC



ATLAS



Experiments at the LHC



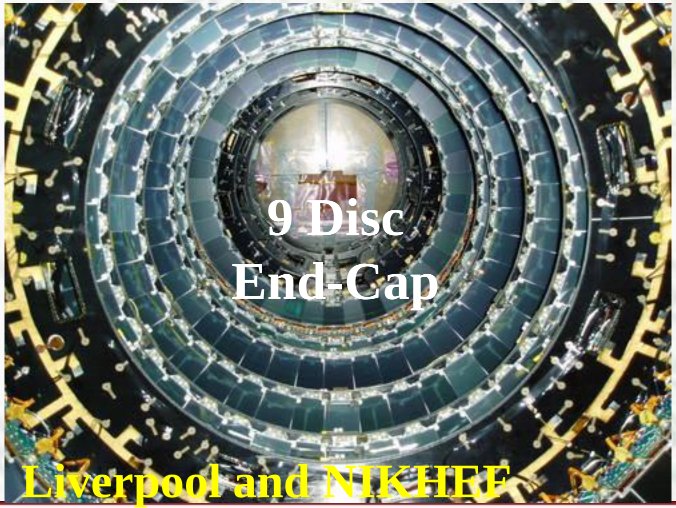
- ATLAS, CMS, ALICE and LHCb
- Detector Technologies
  - Noble gases, scintillators, crystals, Cherenkov, …
  - Silicon Micro-strip Tracking Detectors

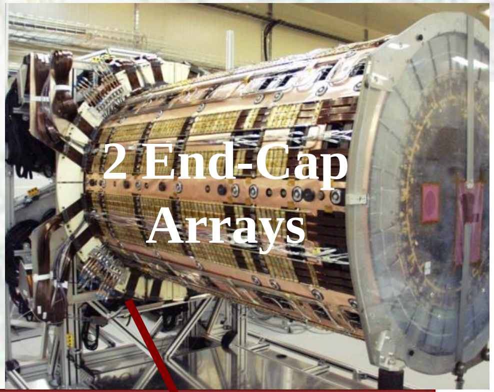
ATLAS Silicon Detector Tracker

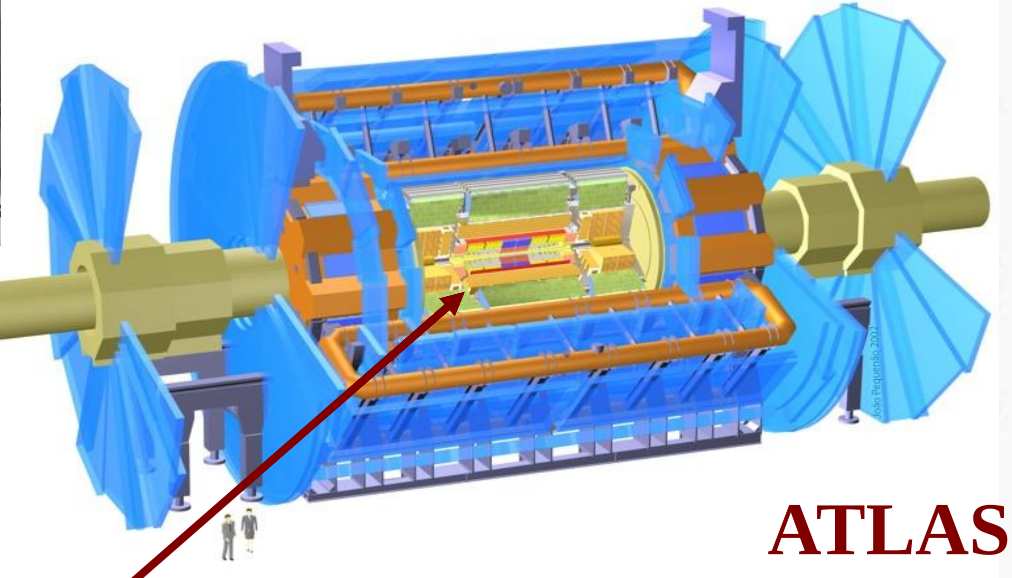
2112 Barrel and 1976 End-Cap Double-Sided Modules

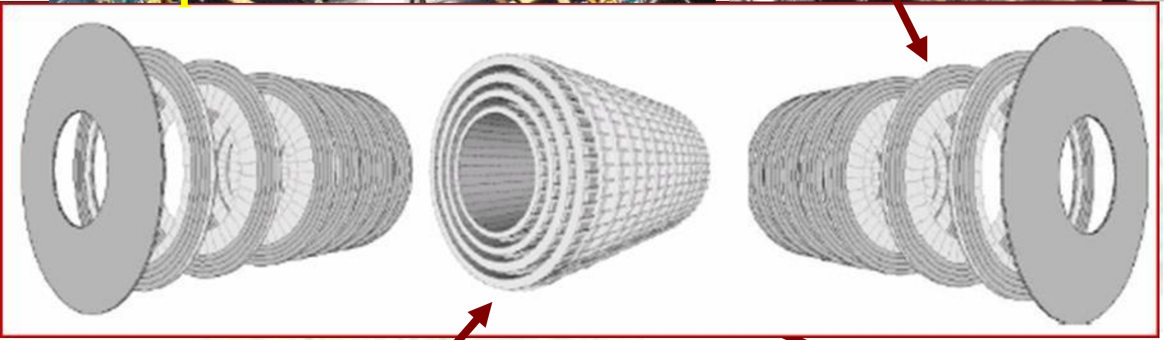
61m^2 of silicon micro-strip detectors

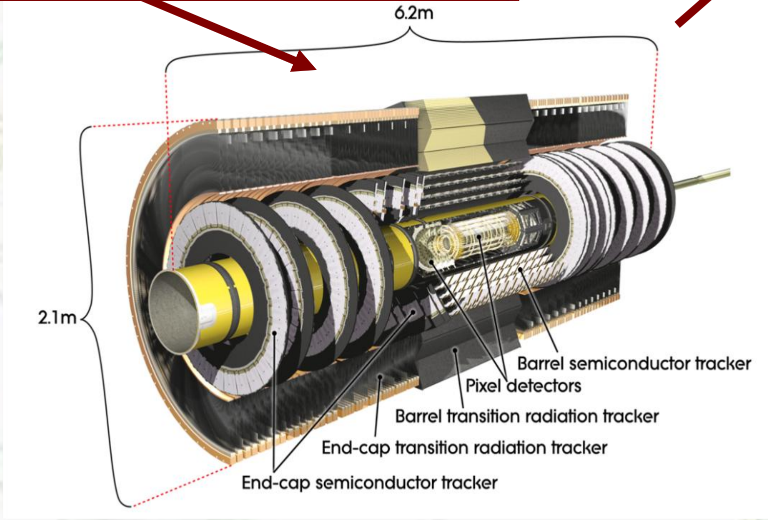
~20,000 separate sensors ordered





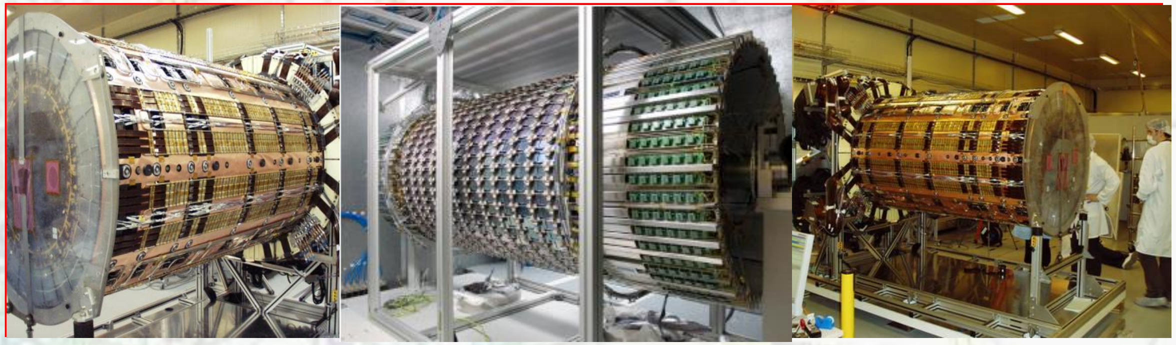




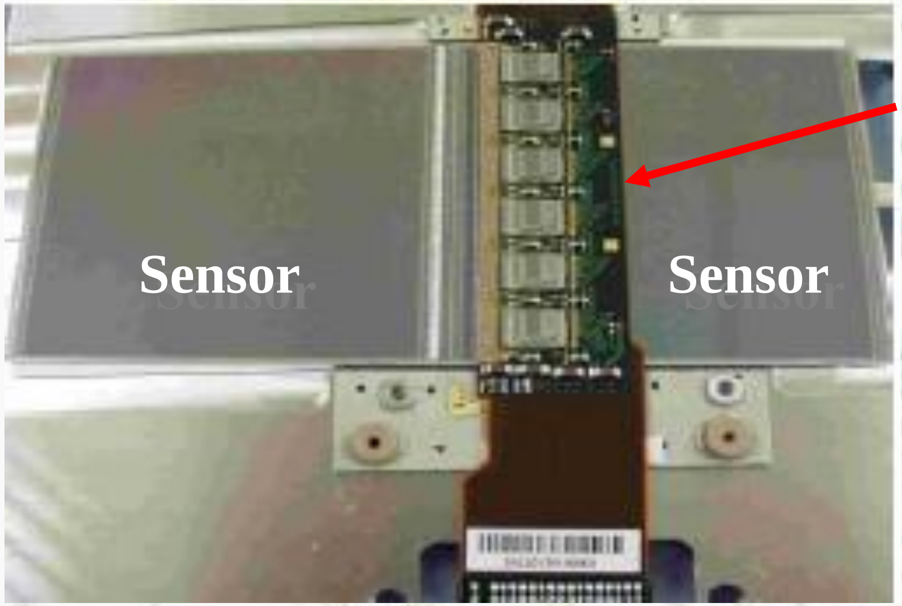


ATLAS SCT Module Designs

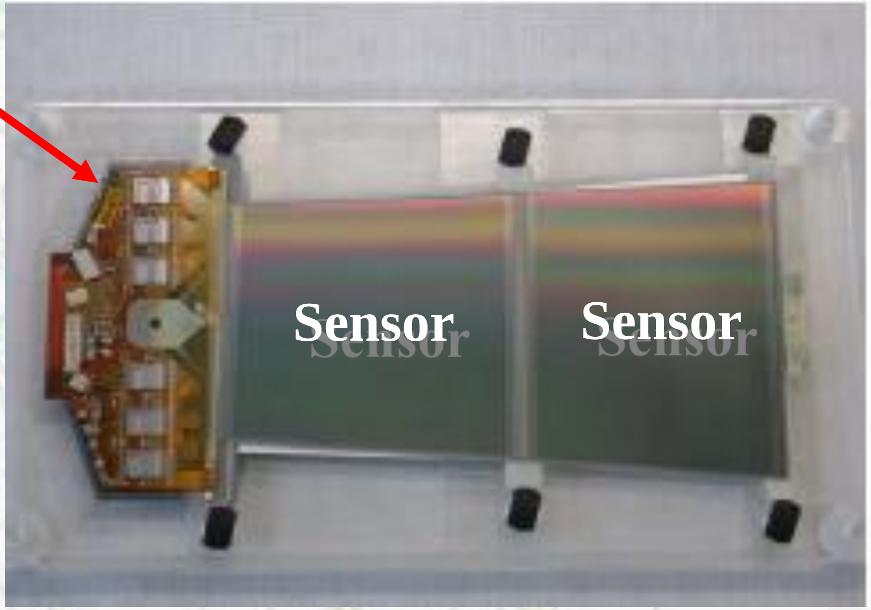
ATLAS Tracker Based on Barrel and Disc Supports



Effectively two styles of double-sided modules (2 6cm long) each sensor ~6cm wide (768 strips of 80µm pitch per side)

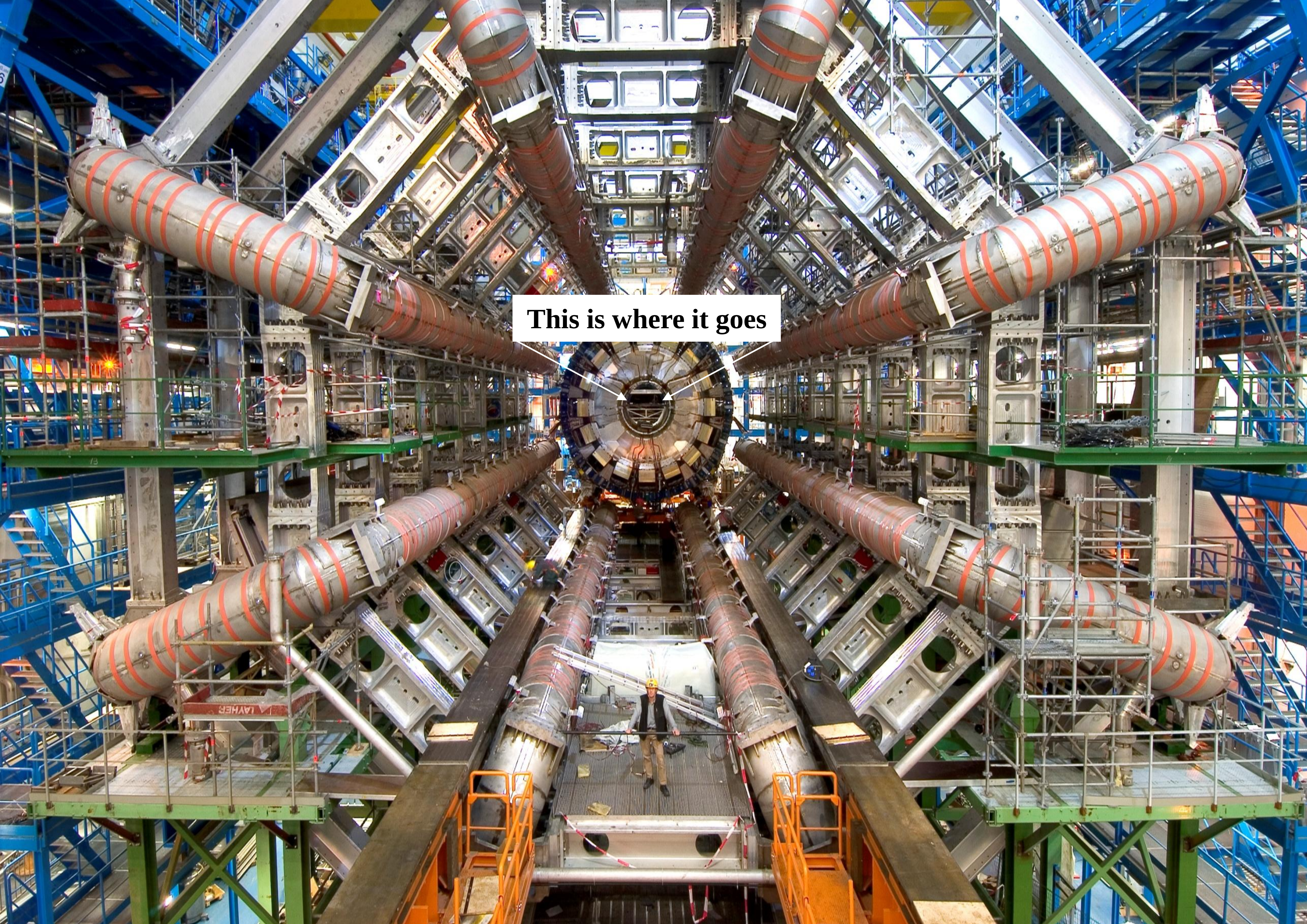


Hybrid cards carrying read-out chips and multilayer interconnect circuit



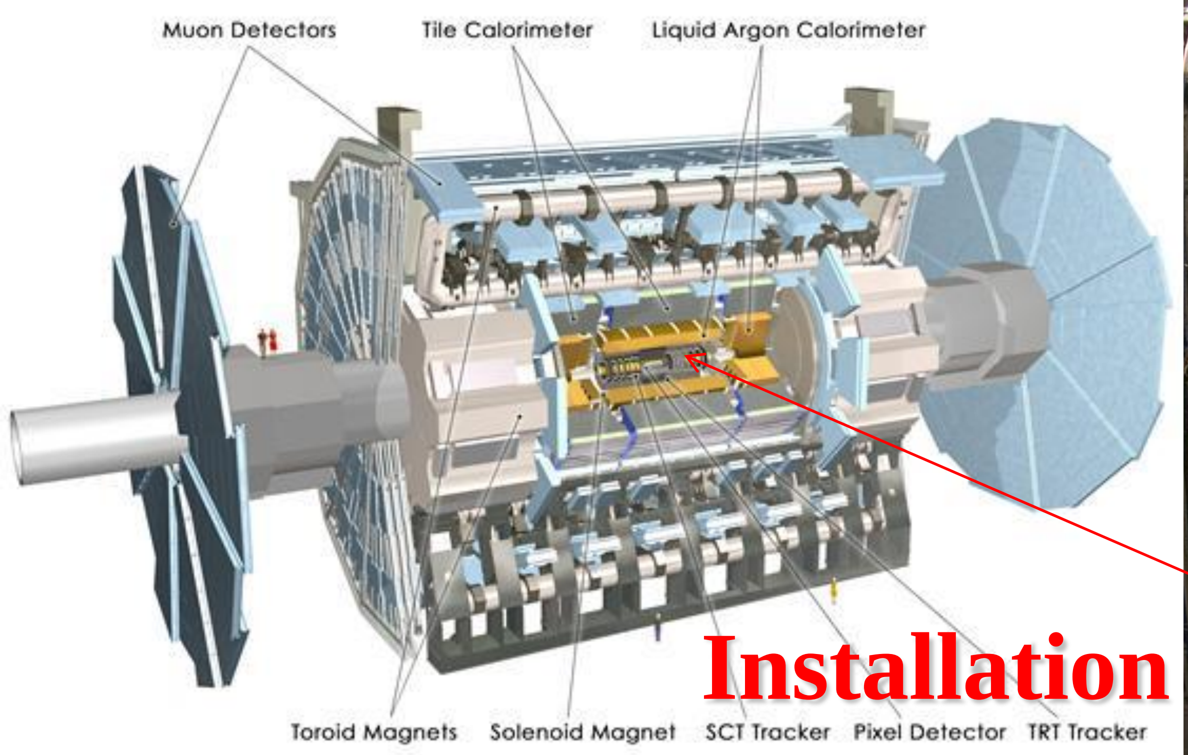
Barrel Modules
(Hybrid bridge above sensors)

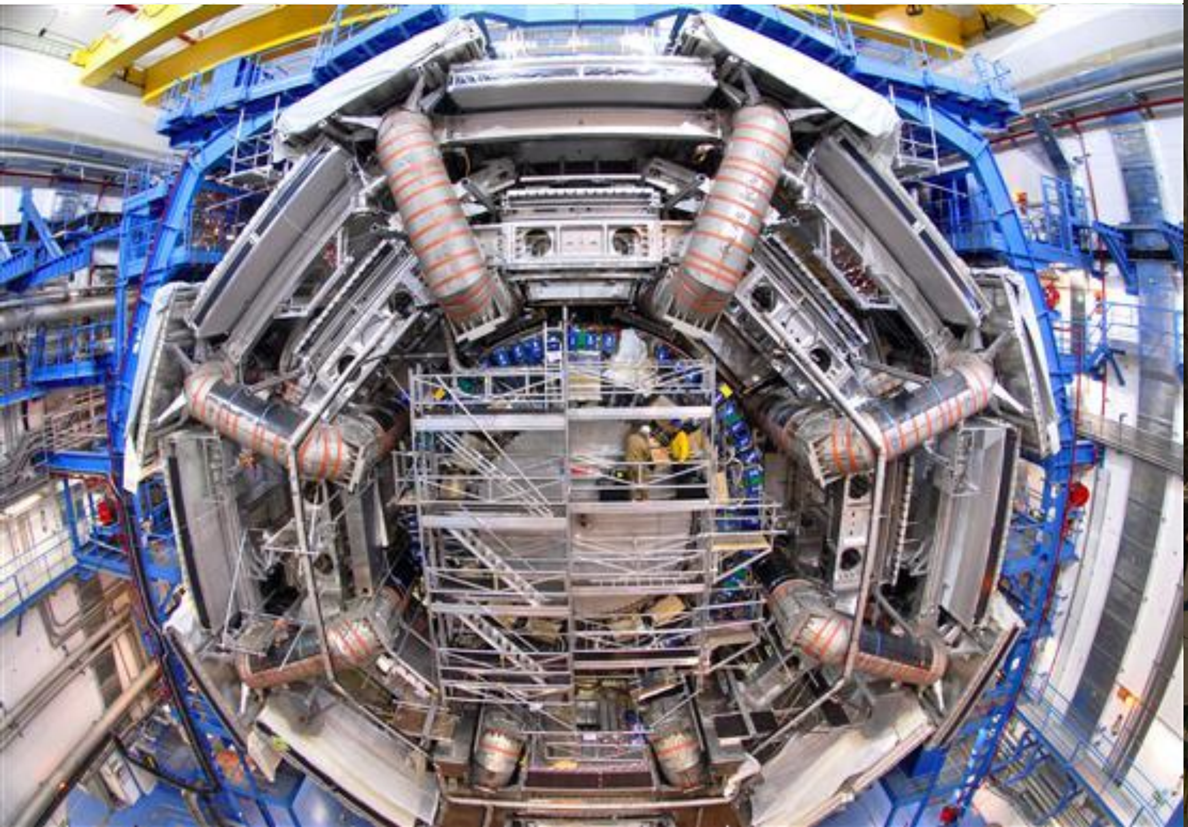
Forward Modules
(Hybrid at module end)



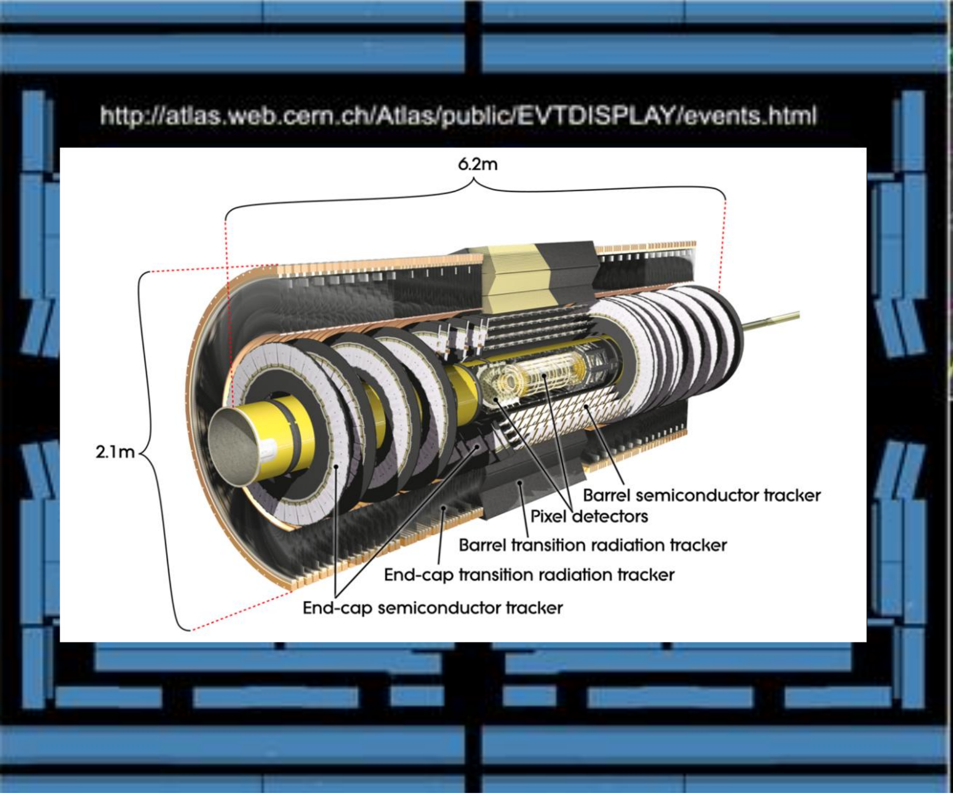
This is where it goes

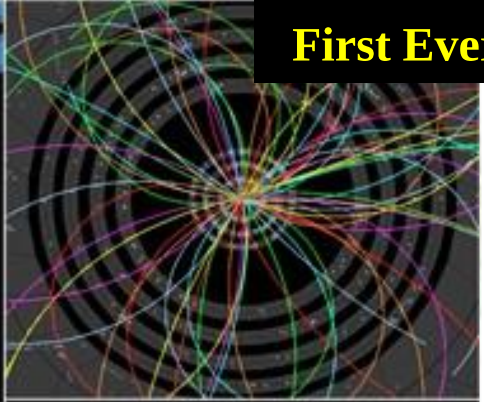
Installation in ATLAS





First Ever LHC Collisions: 23rd November 2009

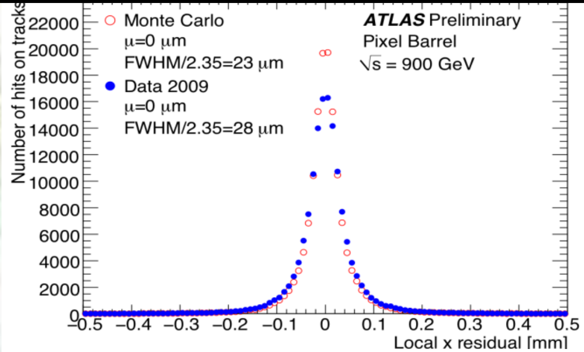


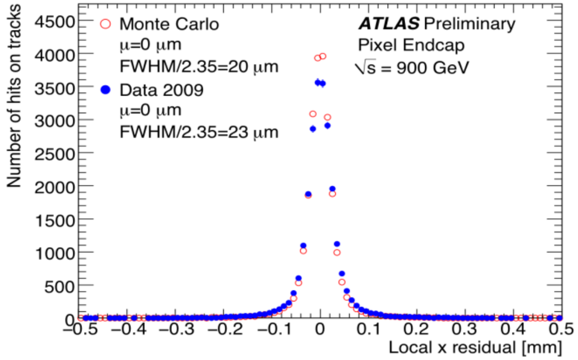


ATLAS EXPERIMENT

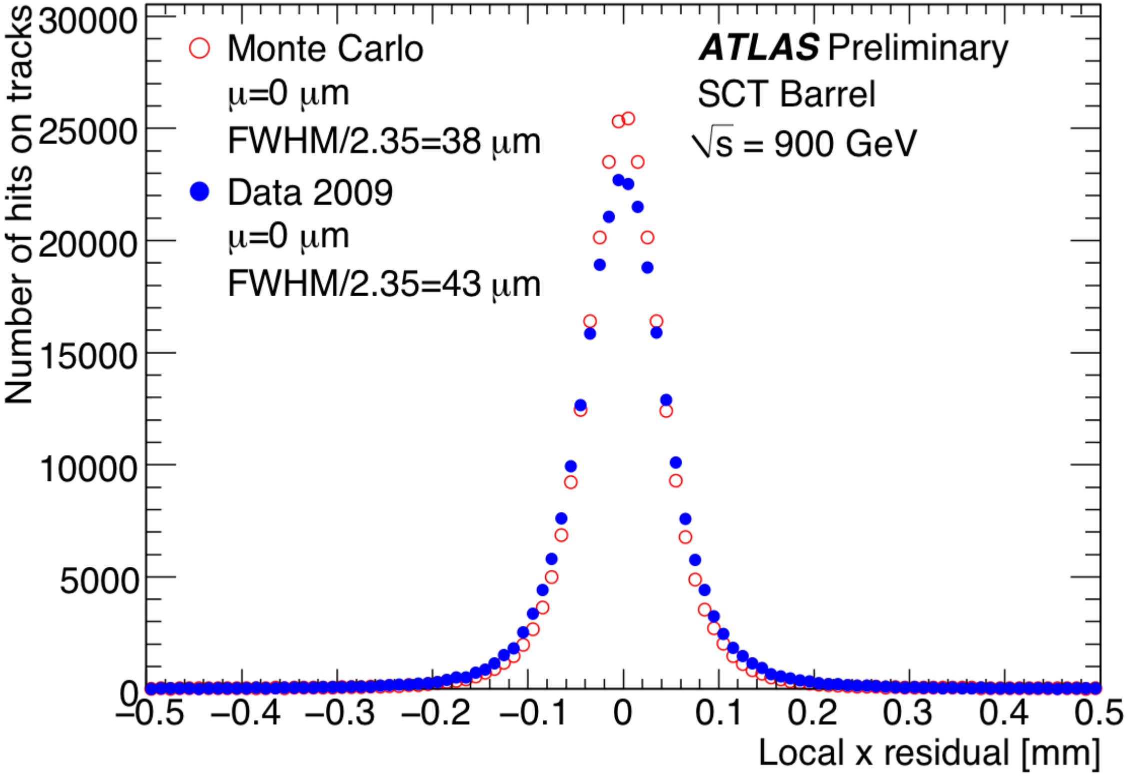
Run Number: 152166, Event Number: 451982

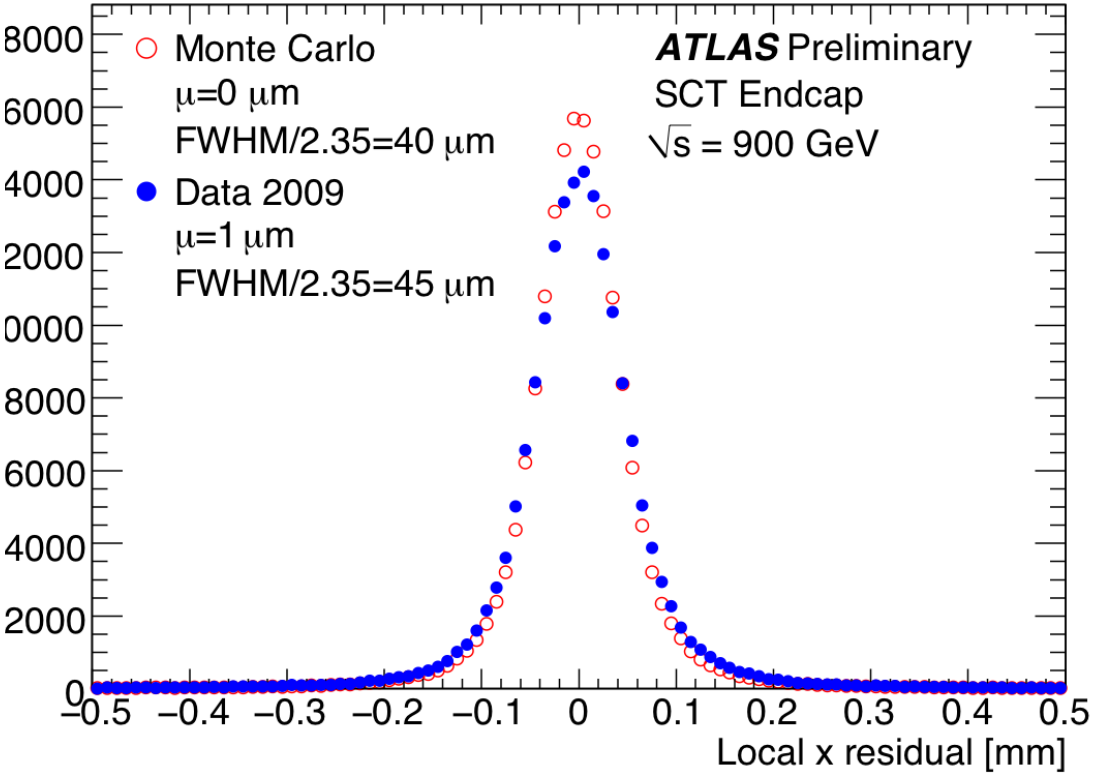
Date: 2010-03-30 13:28:15 CEST





ALICE





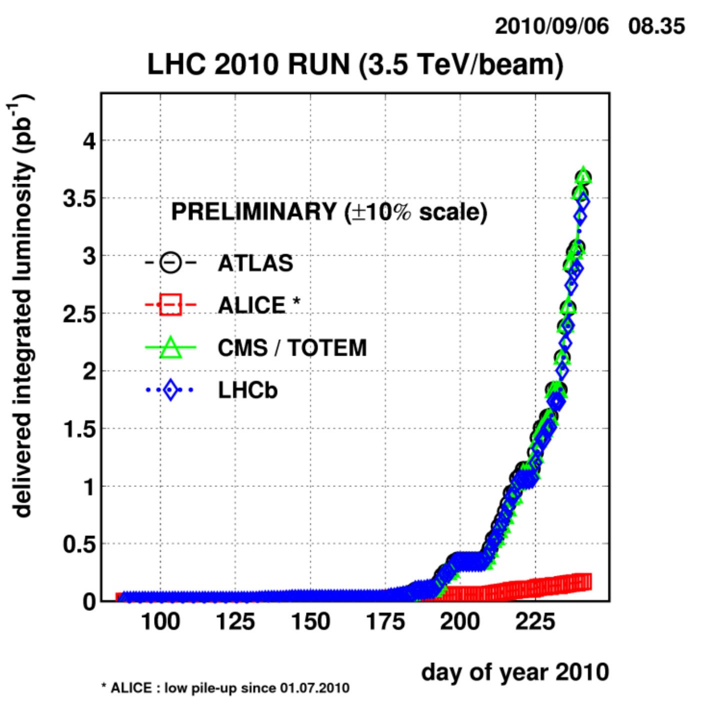
LHC Machine Performance in 2010

"Luminosity" measured in units of b^{-1} per second (or $cm^{-2}s^{-1}$) since this multiplied by σ gives event rate 1b (barn) is $10^{-28}m^2$ or 100 fm^2

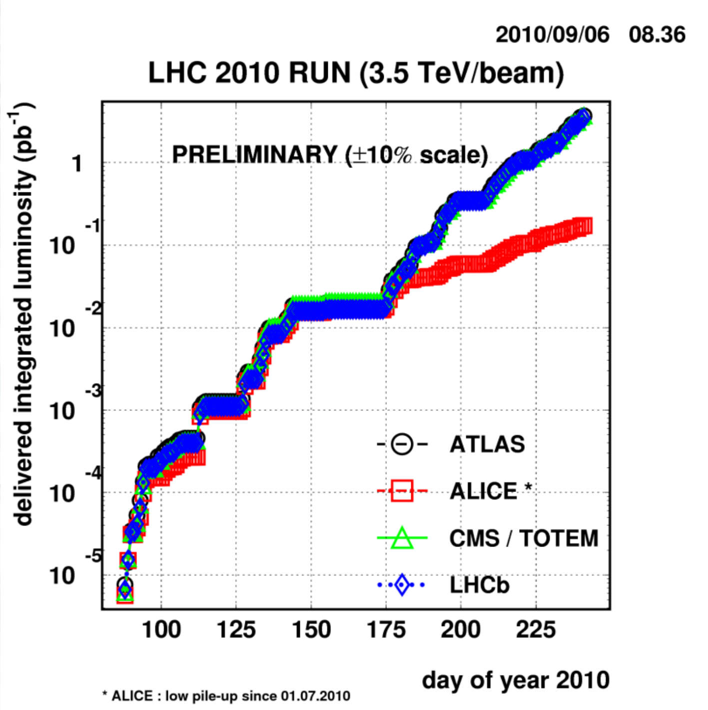
Cross-section (σ) is a measure of the probability of a process per flux of incoming particles, so if luminosity, $\mathcal{L}$, represents the flux as seen be all the protons in one beam of oncoming protons in the other, this multiplied by the total cross-section, σ_{pp}, is the total event rate.

For sub-processes, the idea of a cross-section can still be used to give the event rate for that sub-process when multiplied by $\mathcal{L}$

Linear



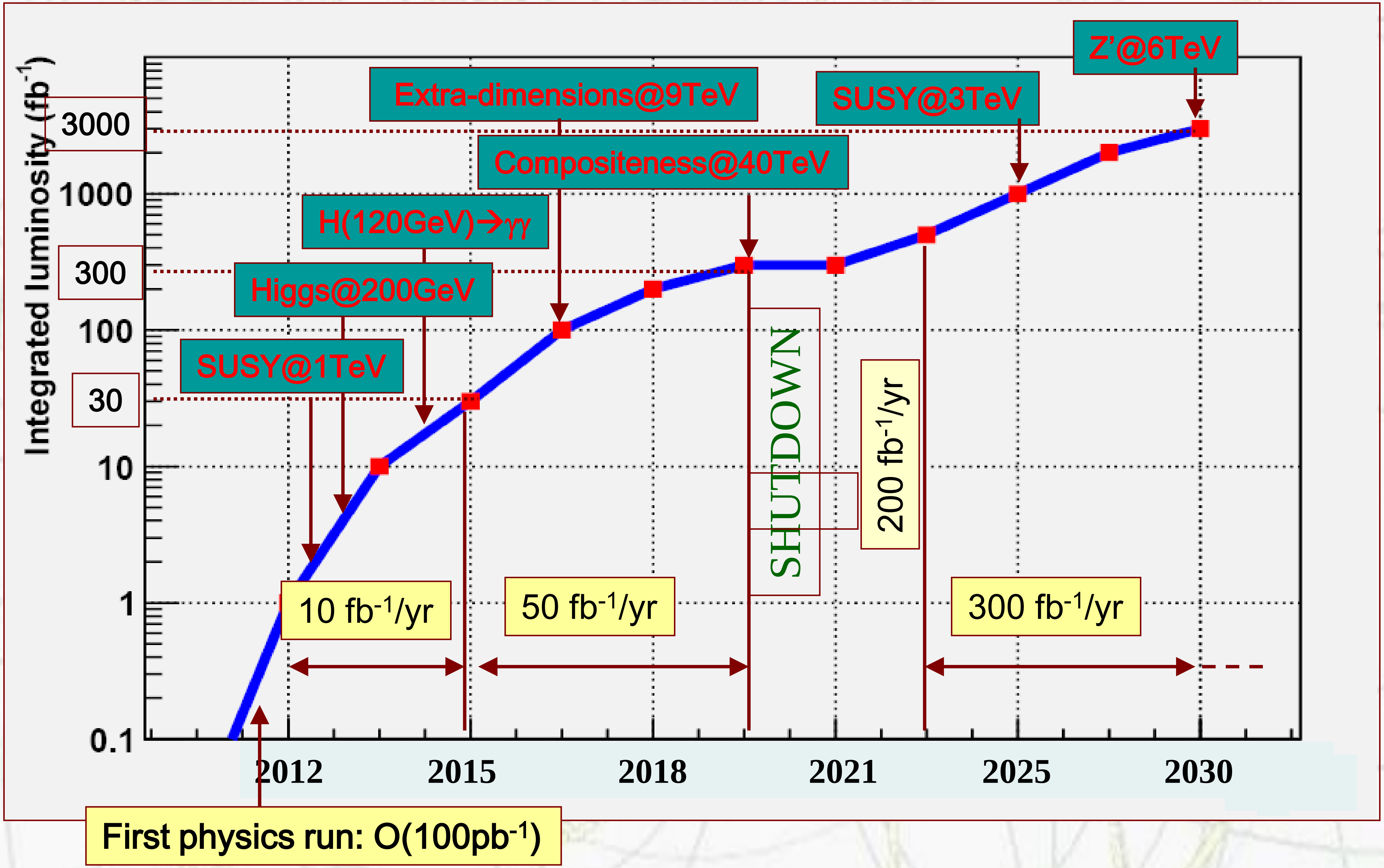
Logarithmic



The design number of protons per bunch, 1.1 x 10^{11}, was first achieved 10th June 2010 and is now routine. The emphasis now is to increase the number of bunches circulating at any time in the LHC and then to further improve the final focus. Record luminosity: ~ 4 x 10^{31} $cm^{-2}s^{-1}$ achieved 24th September

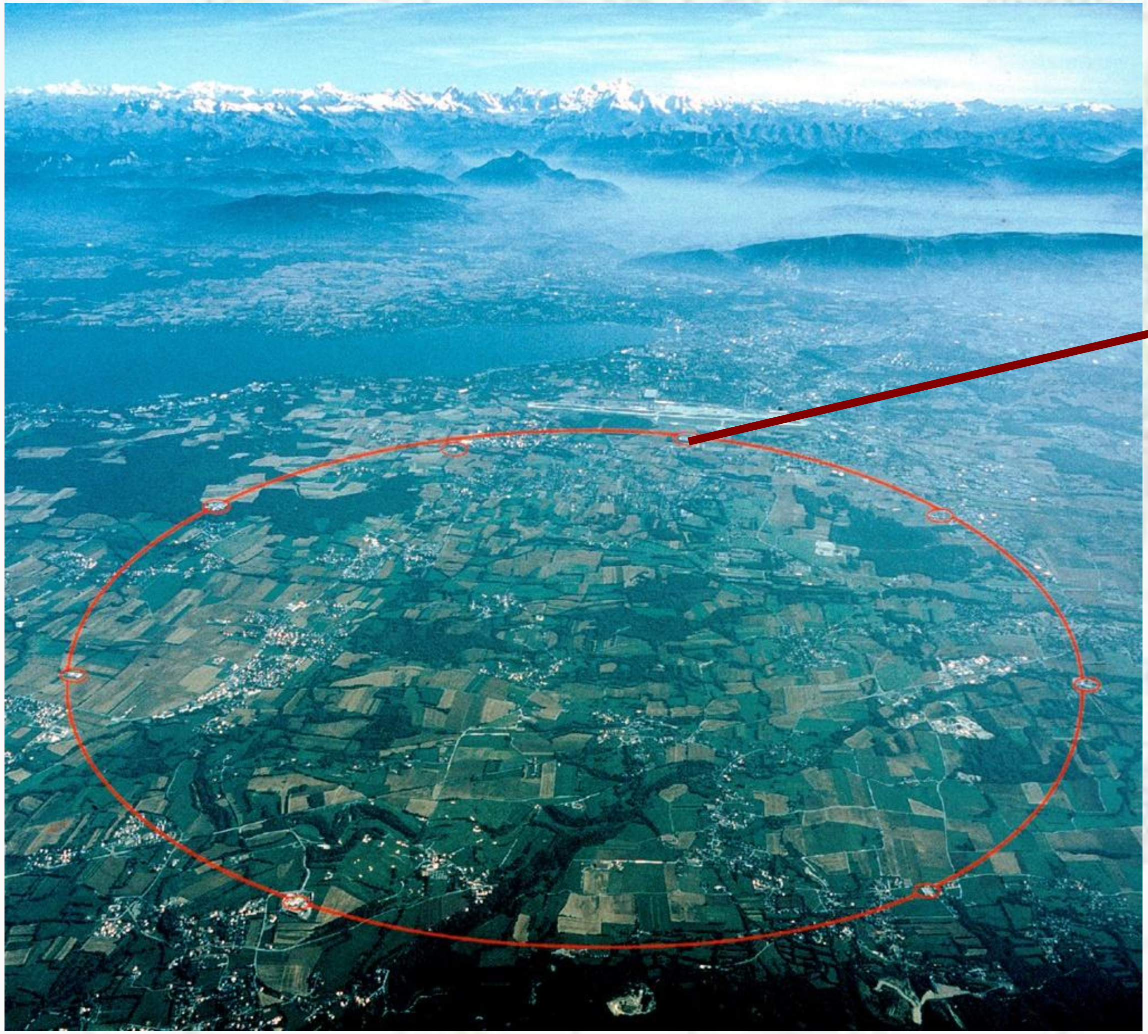
Examples of Possible ATLAS/CMS Physics Reach by Year

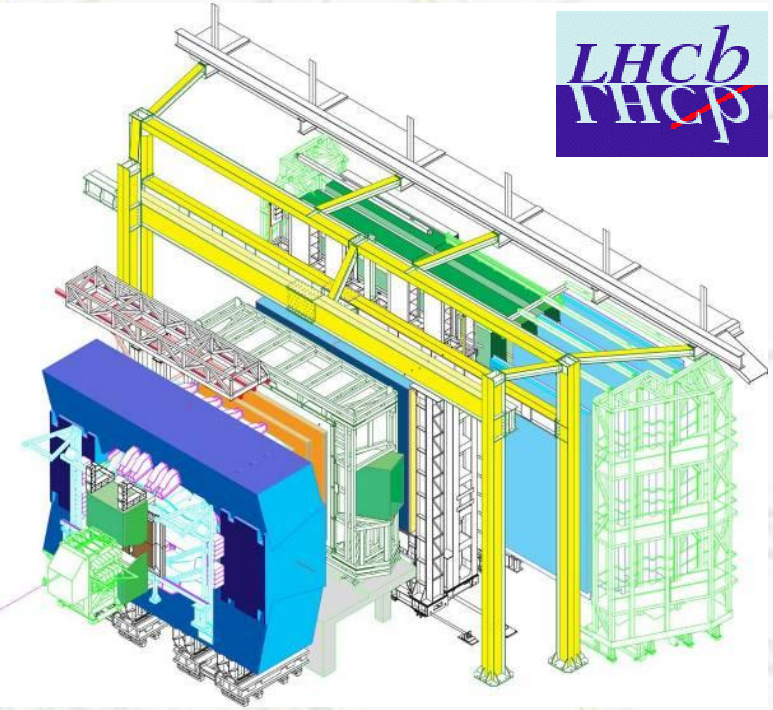
(“Integrated Luminosity” is luminosity × time and is a measure of number of total number of events)



Experiments at the LHC

Collider Experiments





LHCb

High Statistics B Physics

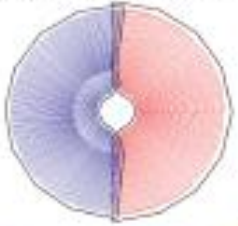
Sensitivity to new physics through being sensitive to subtle effects or rare phenomena

Complementary physics reach to ATLAS and CMS

LHCb Status Report

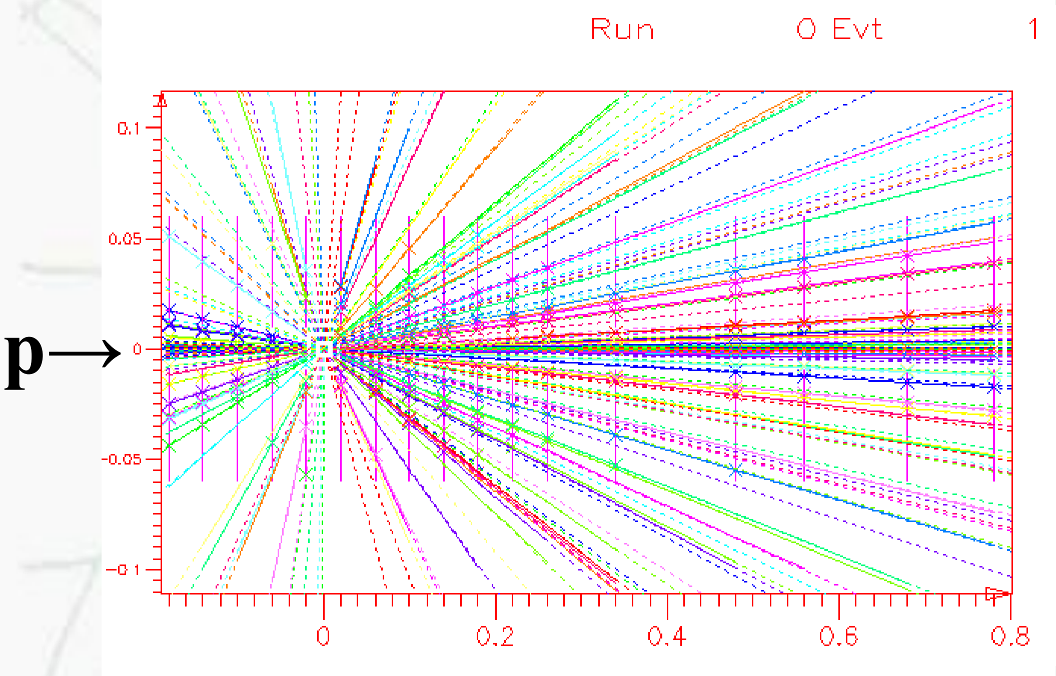
Andrei Golutvin
Imperial College ITEP / CERN

21 stations of Si wafer pairs with *r* and f strip readout

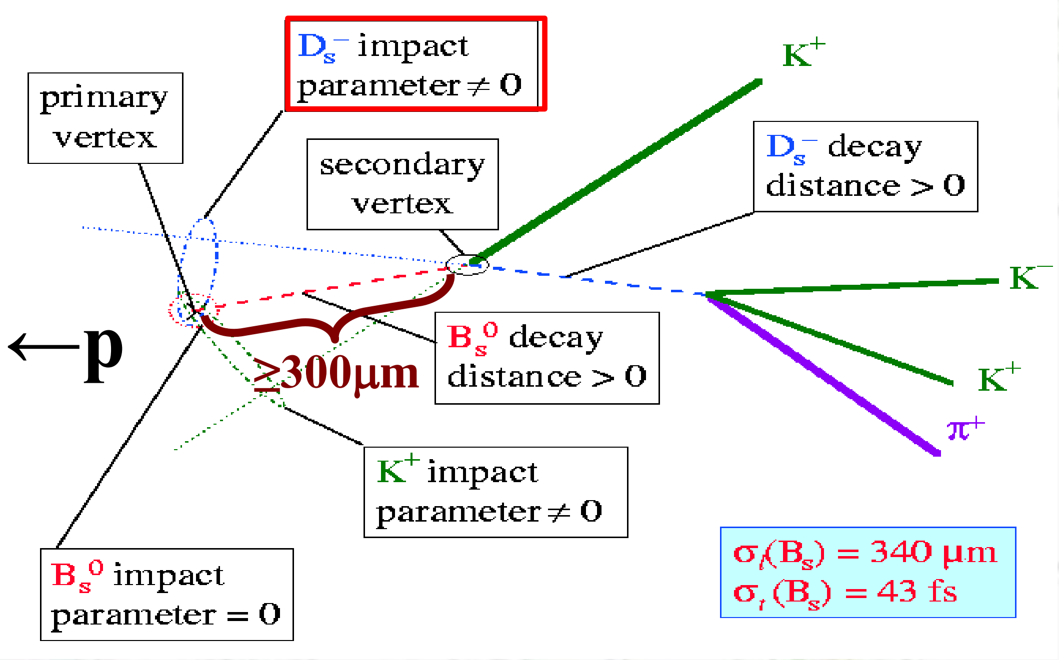


B-tagging with Highly Segmented Detectors

- **Nearly all early applications of silicon micro-strip detectors were to detect and measure particles with pico-second (10^{-12}) lifetimes such that (taking account of special relativity) $\beta\gamma c\tau \geq 300\mu m$**
- **This meant the primary goal was to locate primary (collision) and secondary vertices (as is the case in LHCb)**



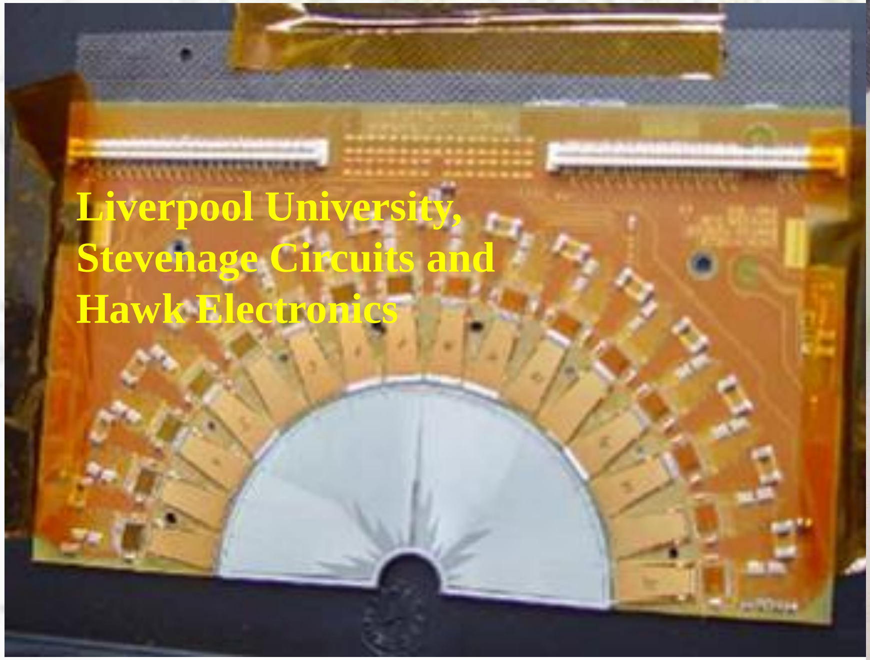
Side on view of 7 TeV on 7 TeV proton collision



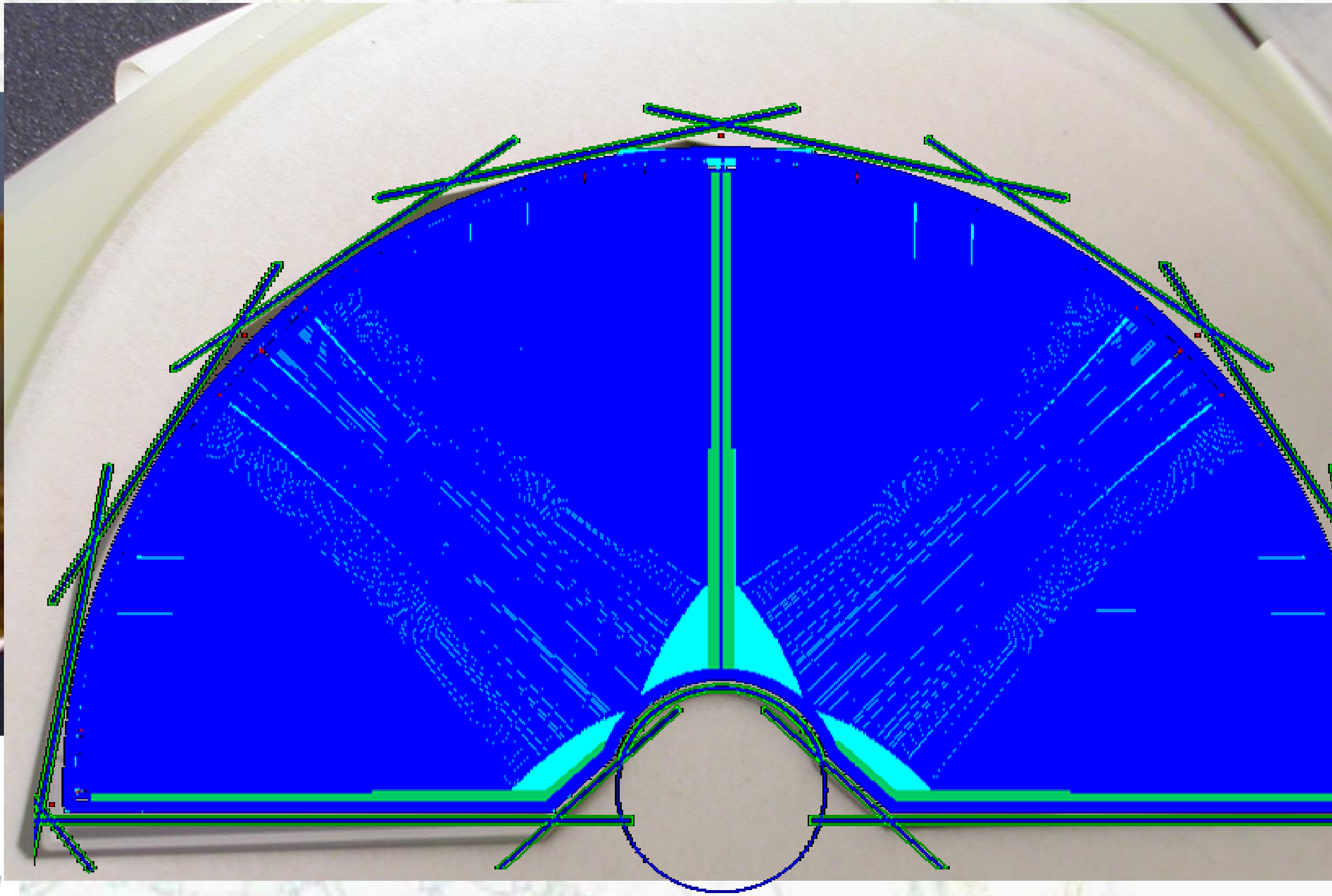
Zoom in showing just particles from B_S-meson decay

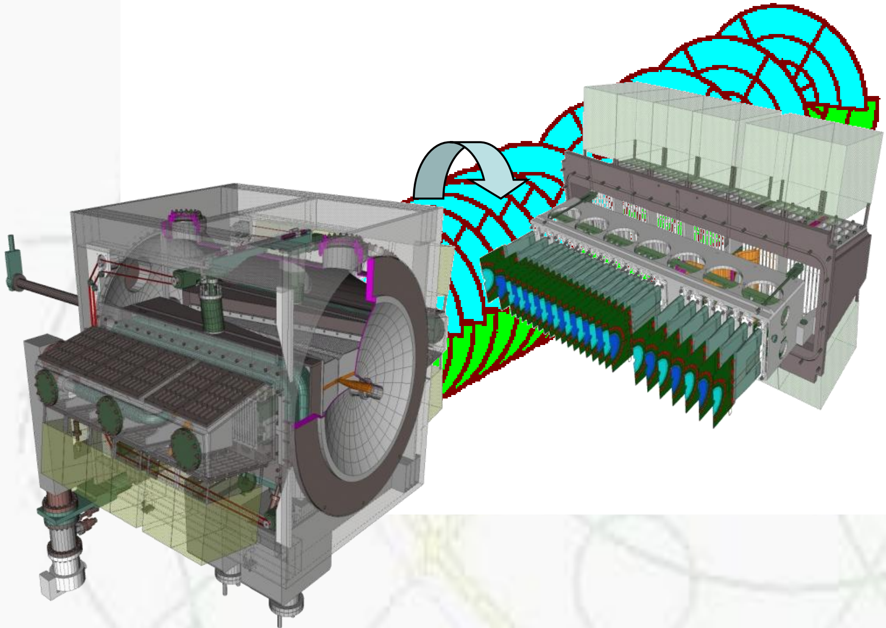
- **In all four major LHC experiments silicon used for vertexing and as primary charged particle tracking detectors for highest radiation environments**

LHCb Vertex Locator Modules



Liverpool University, Stevenage Circuits and Hawk Electronics



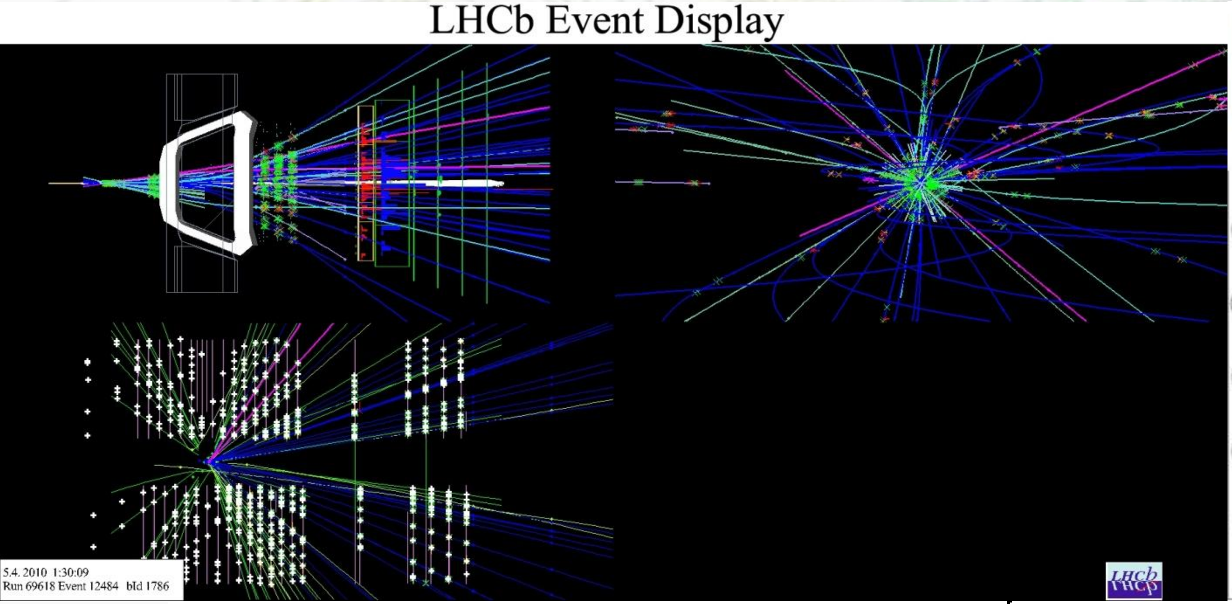


At the LHC B-mesons are mostly produced in pairs going predominantly near the beam axis (forward region)

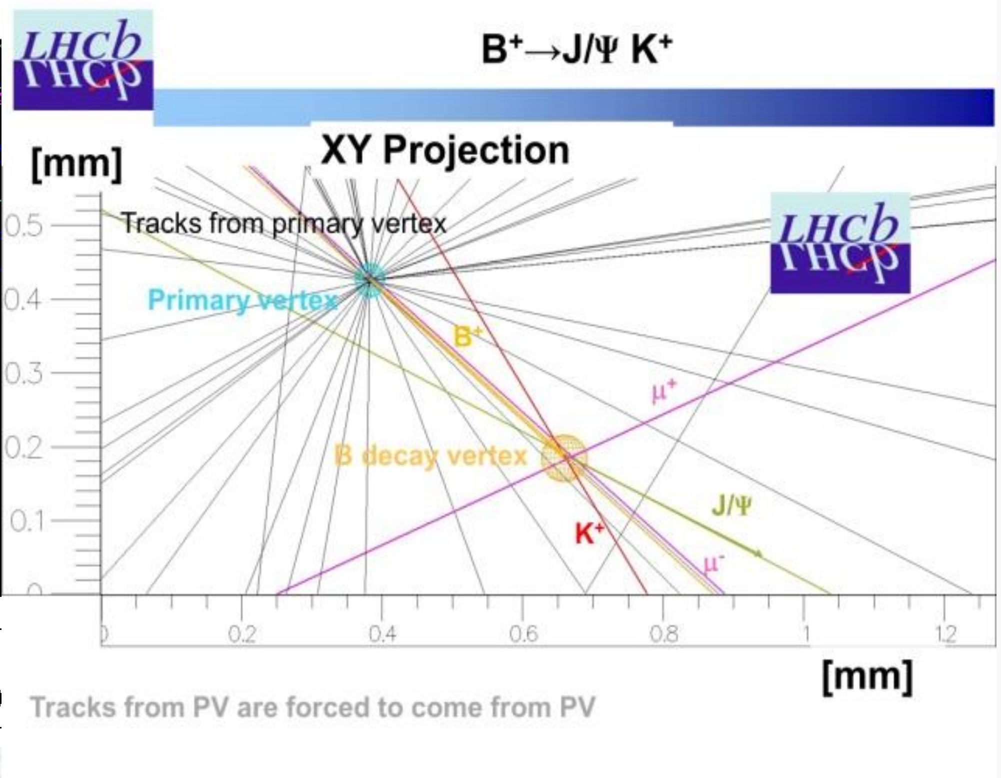
LHCb will collect up to 10^{12} b-pairs /year and the detector is optimized to study B-mesons

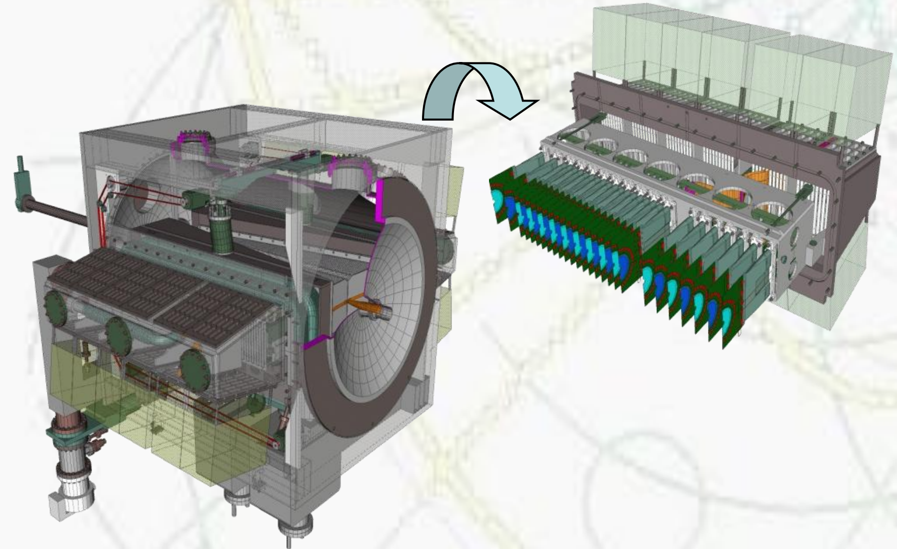
B decays are identified using the fact that their lifetime of 10^{-12} s makes it possible (with accurate enough tracking) to see that some tracks come from a displaced vertex.

LHCb Vertex Locator: First B Event



B_s^0 impact parameter = 0





At the LHC B-mesons are mostly produced in pairs going predominantly near the beam axis (forward region)

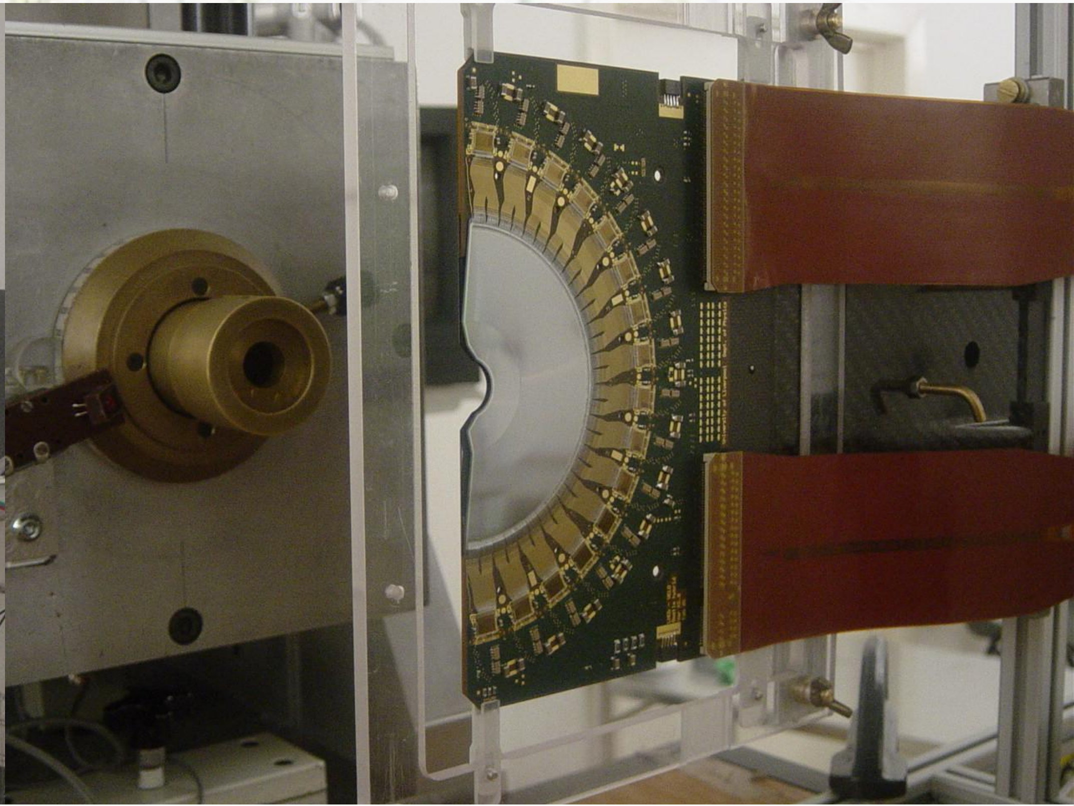
LHCb will see production of up to 10^{12} b-pairs /year and the detector is optimized to study B-mesons

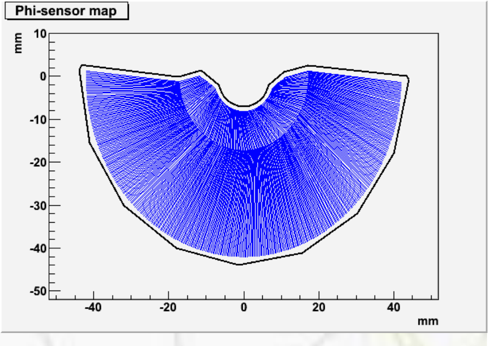
B decays are identified using the fact that their lifetime of 10^{-12} s makes it possible (with accurate enough tracking) to see that some tracks come from a displaced vertex.

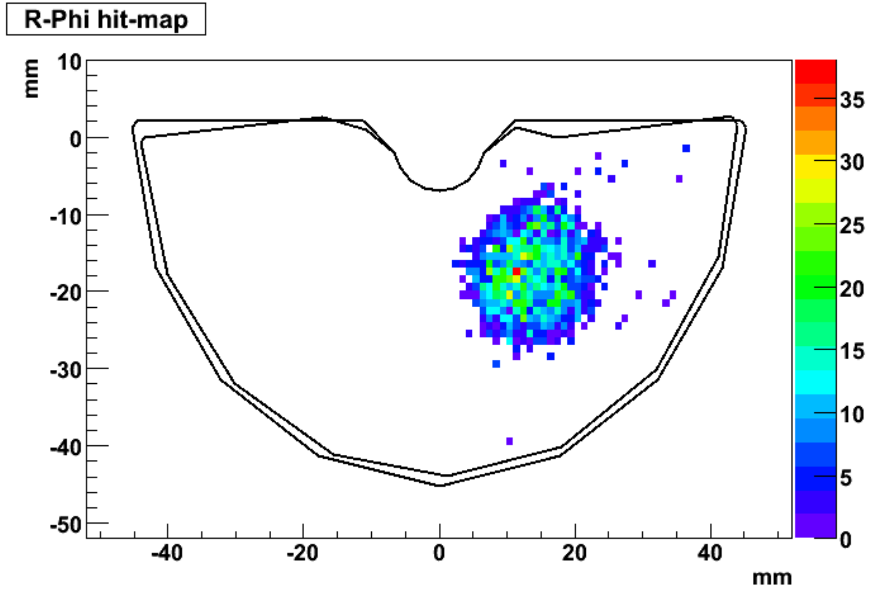

CERN
NIKHEF
SYRACUSE UNIVERSITY
FOUNDED AD 1870
VERTEX LOCATOR
ASIC Labor Heidelberg
LPHE
UNIVERSITY of GLASGOW
Normal

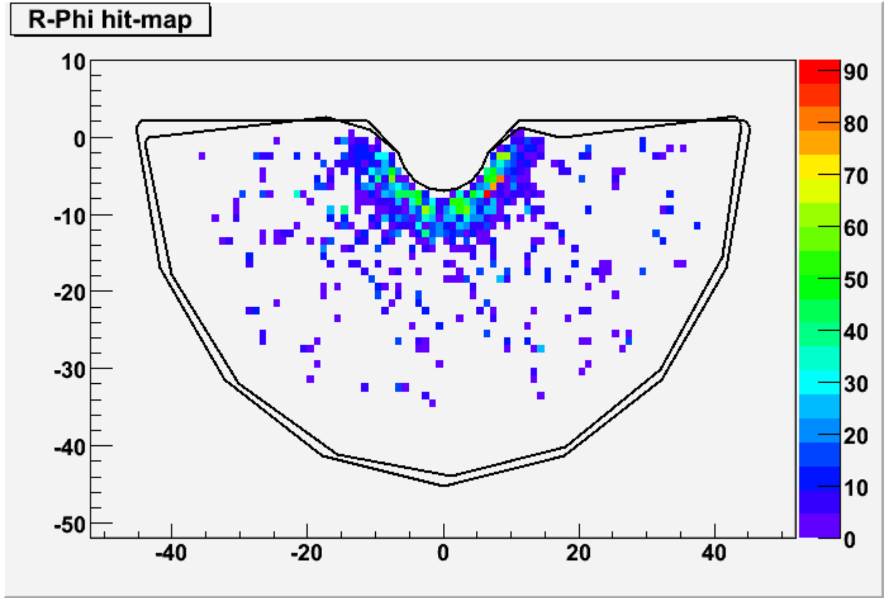
LHCb Vertex Locator: Other Uses

Clatterbridge Centre for Oncology
Proton Therapy Facility









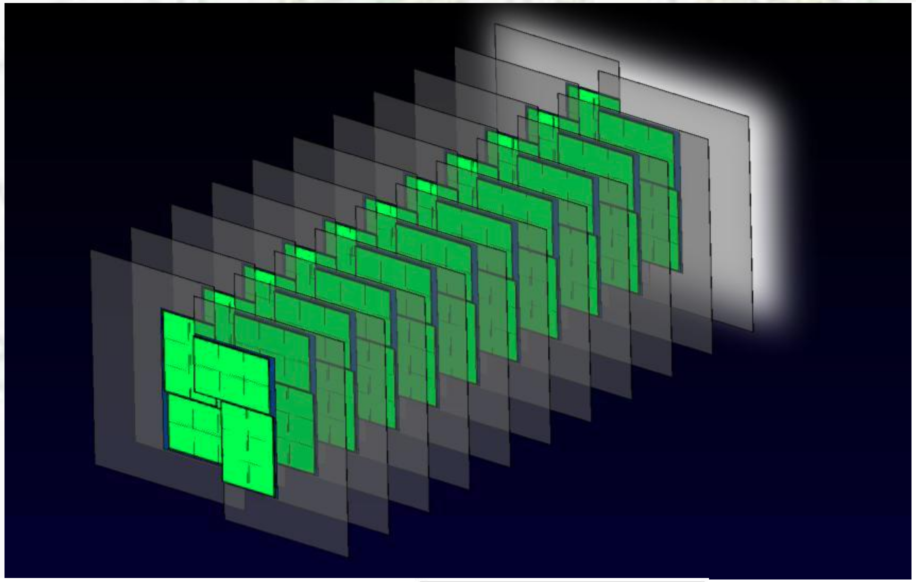
LHCb Back-to-Back Sensor Module

LHCb Upgrade schedule

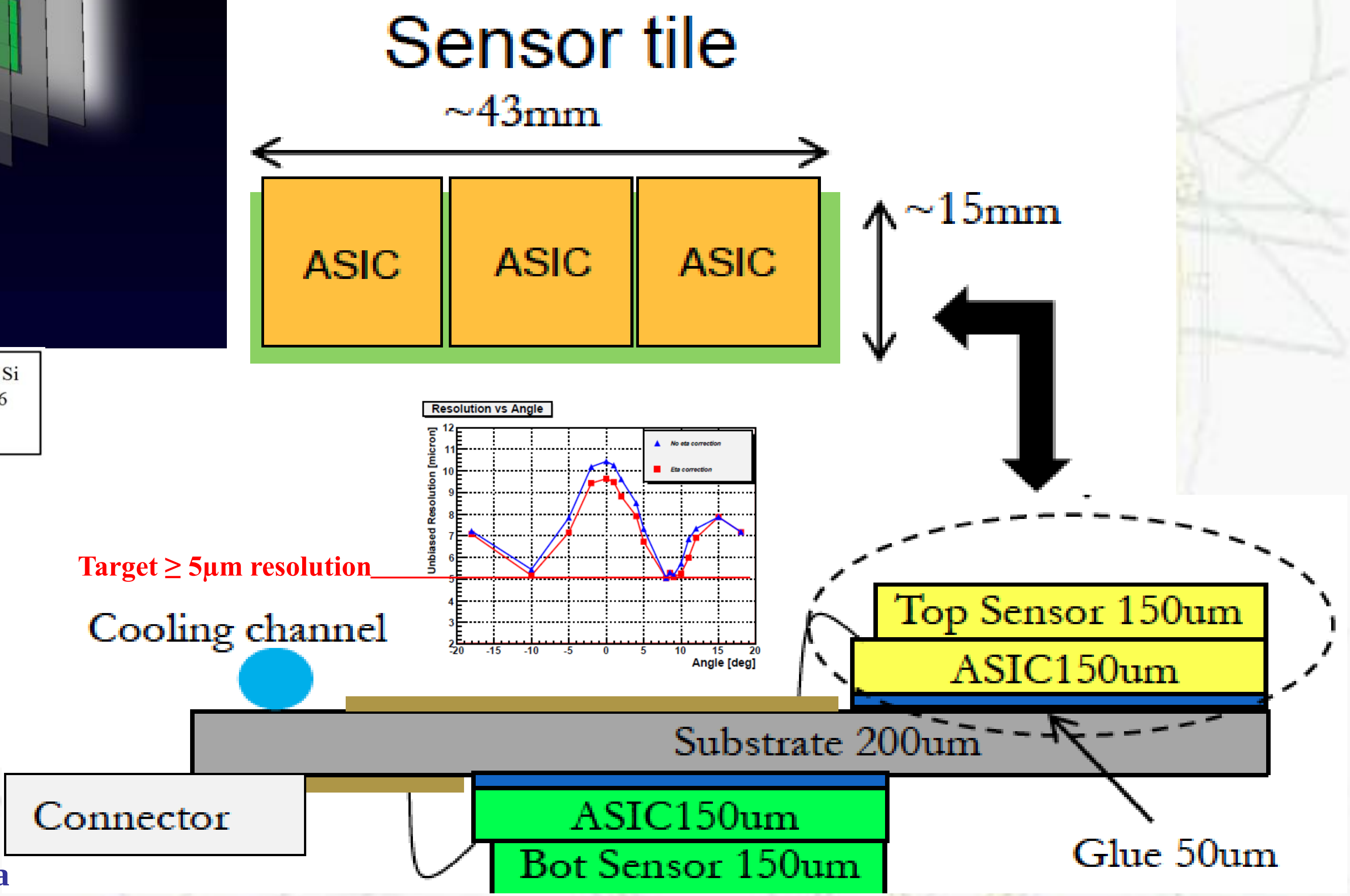
- **Phase I: 2016 LHC long shutdown**
  - Novel pixel based vertex detector (VELOPIX)
  - New front end electronics
  - New trigger and data acquisition concept to achieve better efficiency for hadronic B decays
  - RICH photon detector replacement
  - New track trigger and inner tracker triggering systems

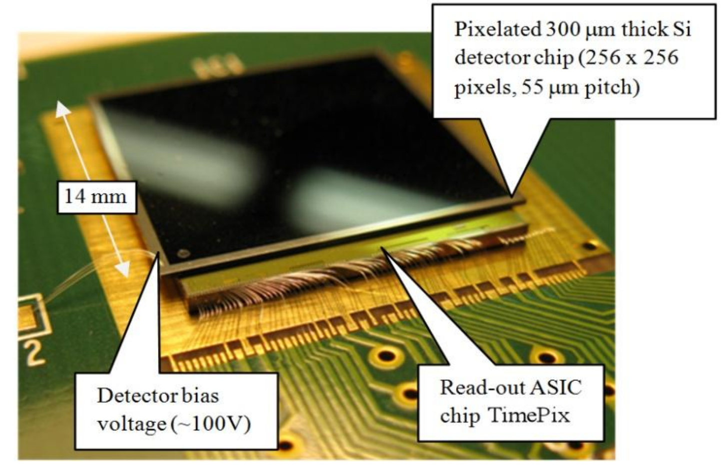
- **Phase II: 2020 LHC shutdown for luminosity upgrade**
  - new hadron ID system based on precision time of flight
  - Better electromagnetic calorimeter segmentation
  - Change to inner and outer tracking geometry

LHCb VELO PIXEL Upgrade



ASIC IS AN ARRAY OF 256X256 SQUARE PIXELS (55 µm X 55 µm)





VELOPIX development of TIMEPIX2 from MEDIPIX collaboration with clustering of sparsified information, data formatting, buffering, and multi-Gbit output links for 40 MHz operation

ALICE upgrade plans

2010 Hadron Collider Physics Symposium

August 23-27, 2010

University of Toronto,
Toronto, Canada

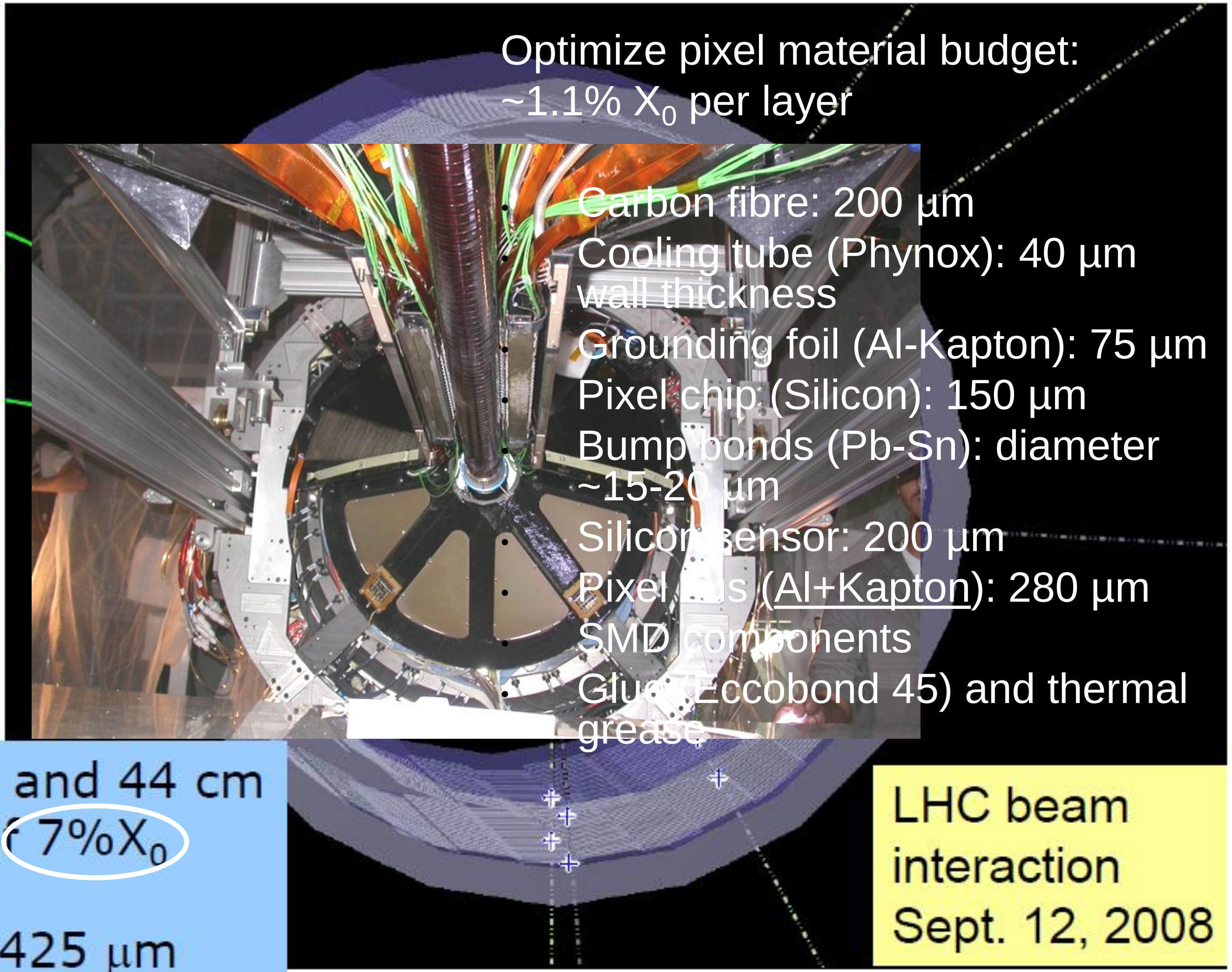
Rene Bellwied
Wayne State University

Outline:
- Motivation
- Machine upgrades
- Luminosity upgrades
- Detector upgrades
- Future of heavy ions

HCP 2010, TORONTO

Inner Tracking System upgrade

- Present 6 detector layers based on three silicon technologies:
  - SPD (Si pixels)
  - SDD (Si Drift)
  - SSD (Si strips)
- Unique level-zero trigger (fast OR)



Optimize pixel material budget:
~1.1% X_0 per layer

- Carbon fibre: 200 µm
- Cooling tube (Phynox): 40 µm wall thickness
- Grounding foil (Al-Kapton): 75 µm
- Pixel chip (Silicon): 150 µm
- Bump bonds (Pb-Sn): diameter ~15-20 µm
- Silicon sensor: 200 µm
- Pixel bus (Al+Kapton): 280 µm
- SMD components
- Glue (Eccobond 45) and thermal grease

LHC beam interaction Sept. 12, 2008

Radii: 4, 7, 15, 24, 39, and 44 cm
Total material budget of 7%X_0 (normal incidence)
Pixel size 50 µm times 425 µm
Beam pipe radius 2.98 cm

Inner Tracking System upgrade

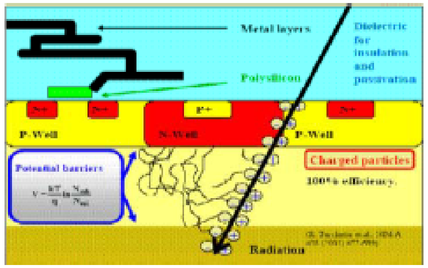
Improving the impact parameter resolution by a factor two or better will:

- increase sensitivity to charm by factor 100;
- give access to charmed baryons (baryon/meson ratio in charm sector to test recombination);
- allow study of exclusive B decays;
- allows first measurement of total B production cross section down to zero P_T;
- Improve flavour tagging.

Monolithic Pixel Detectors

- **Goal**: a monolithic detector in standard very deep submicron CMOS technology
- **Advantages**: cost, material budget (50 um thickness), yield, low noise, high granularity (10x10 um), radiation hard, low power consumption (20 mW/cm^2)
- Disadvantages: Charge collection by drift, serial readout

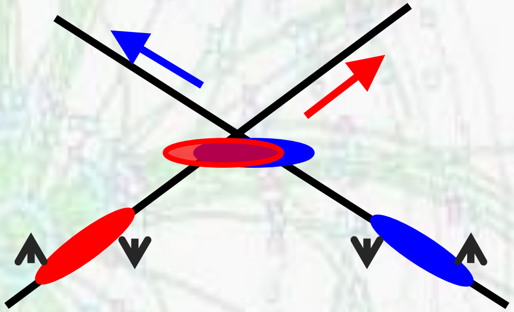
- **R&D activities: MIMOSA and LePix**
  - **LePix: : non-standard processing on high resistivity substrate**
    - Advanced CMOS deep submicron technologies (130 nm and beyond) can be implemented on ≥100 Ωcm (~ 30μm depletion at 100 V)
  - **MIMOSA: 'traditional' monolithic detectors, MAPS-based with serial readout**
    - P-type low-resistivity Si hosting n-type "charge collectors"
      - signal created in epitaxial layer (low doping)
        $Q \sim 80$ e-h/mm → signal $\leq 1000\ e^-$
      - charge sensing through n-well/p-epi junction
      - excess carriers propagate (thermally) to diode

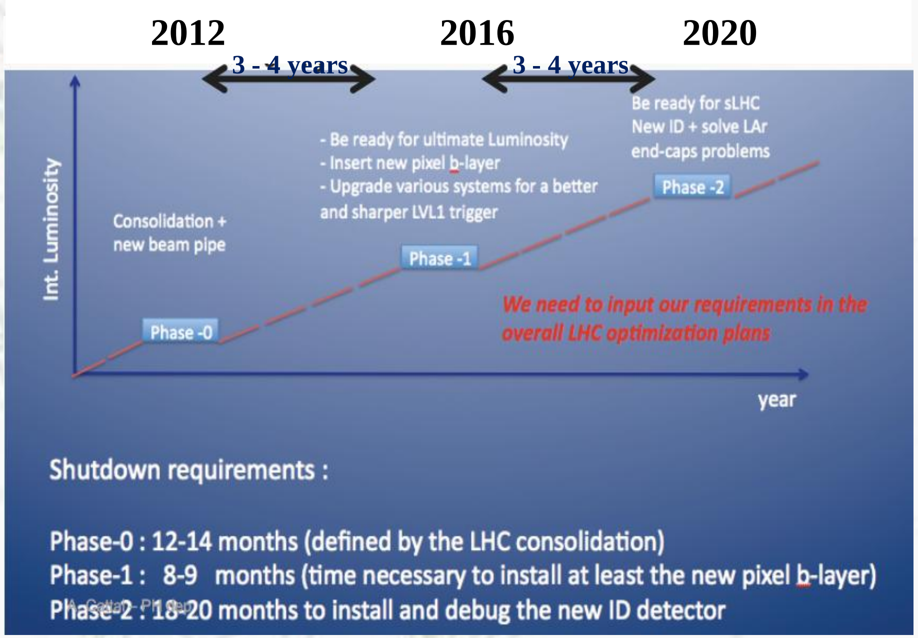


    - Prototype: MIMOSA-22, binary output, integrated zero-suppression, 18.4μm pitch, 1152 columns x 576 rows, ~110μs readout time

Upgrading the LHC for High Luminosity

- With modest investment, the LHC can run at **much higher collision rates**, greatly increasing the scope to search for new particles and study rare processes
- Expected Development in Luminosity
  - Phase-I (after 5 years)
    - Up to ~ 60fb^{-1}/year
    - Experiments need:
      - New vertex detectors
      - New off-line electronics
      - …
  - Phase-II (after 10 years)
    - Up to ~ 300fb^{-1}/year
    - Experiments need:
      - Complete tracker replacement
      - Much improved on-line filtering
      - New read-out for many subsystems
      - …





Shutdown requirements :

Phase-0 : 12-14 months (defined by the LHC consolidation)
Phase-1 : 8-9 months (time necessary to install at least the new pixel b-layer)
Phase-2 : 18-20 months to install and debug the new ID detector

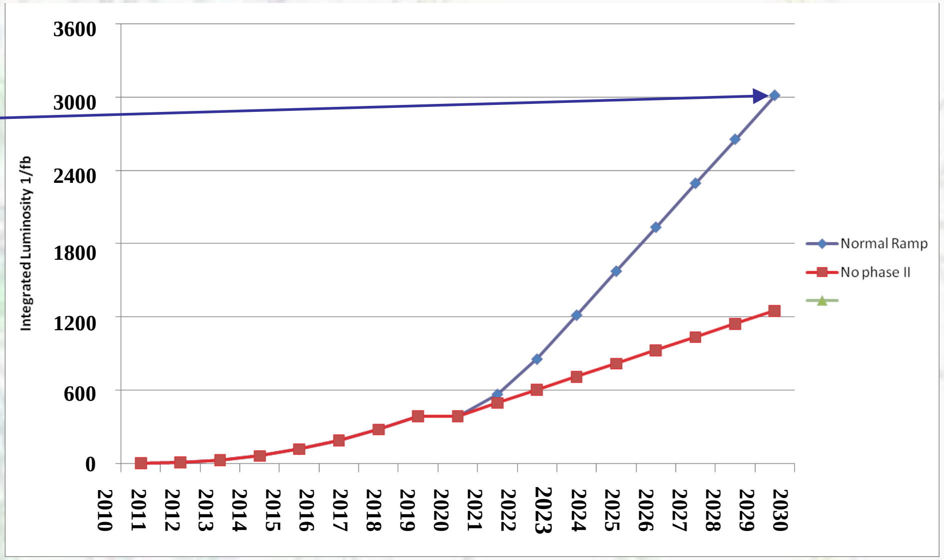
Upgrading the Experiments

To keep ATLAS and CMS running beyond ~10 years requires tracker replacement

Current trackers designed to survive up to 10Mrad in strip detectors (≤ 700 fb^{-1})

For the luminosity-upgrade the new trackers will have to cope with:

- **much higher integrated doses (need to plan for ≥ 3000 fb^{-1})**

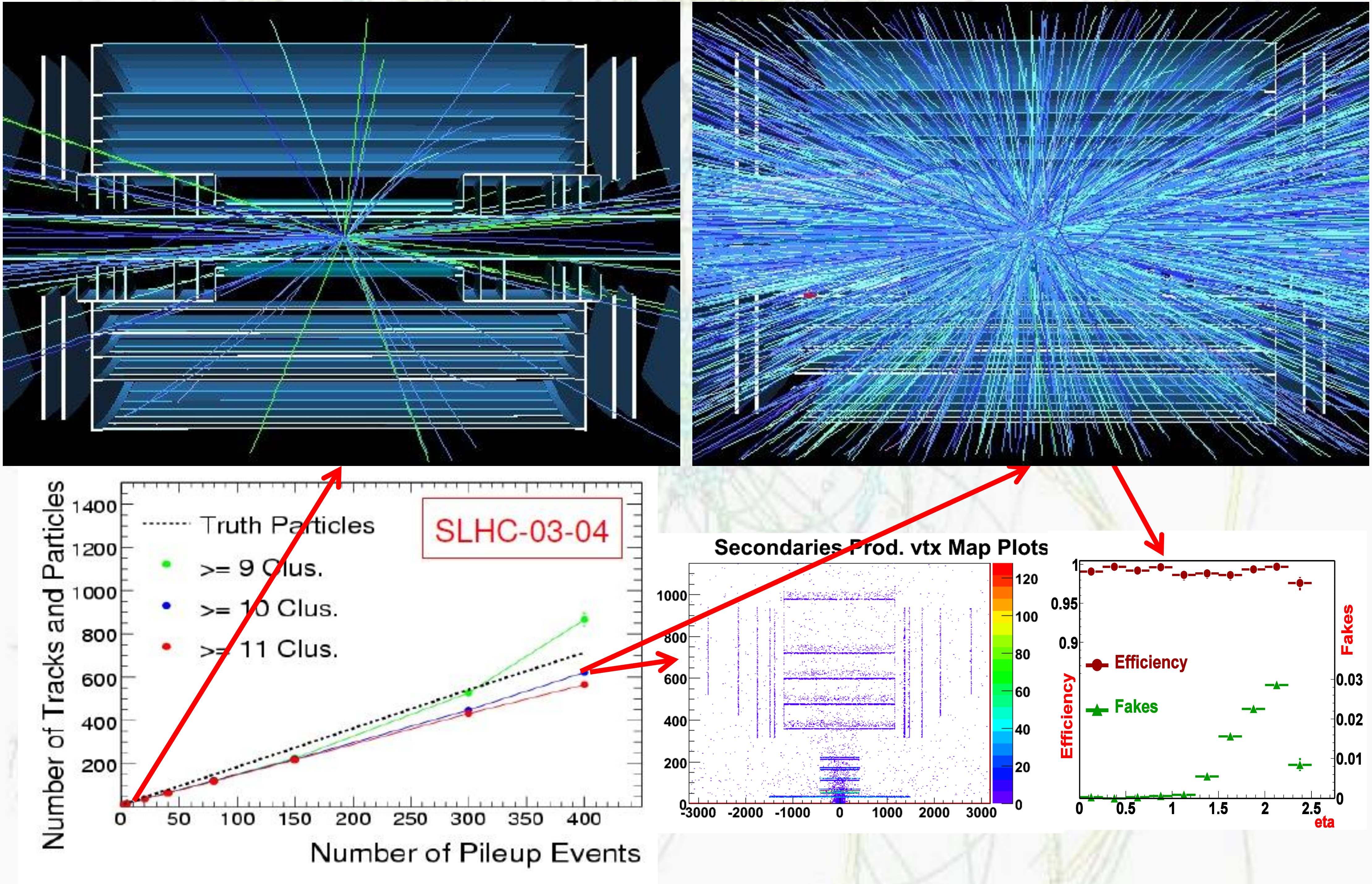


- **much higher occupancy levels (up to 400 collisions per beam crossing)**
- **Installation inside an existing 4π coverage experiment**
- **Budgets are likely to be such that replacement trackers, while needing higher performance to cope with the extreme environment, cannot cost more than the ones they replace**

To install a new tracker in ~2020, require Technical Design Report 2014/15

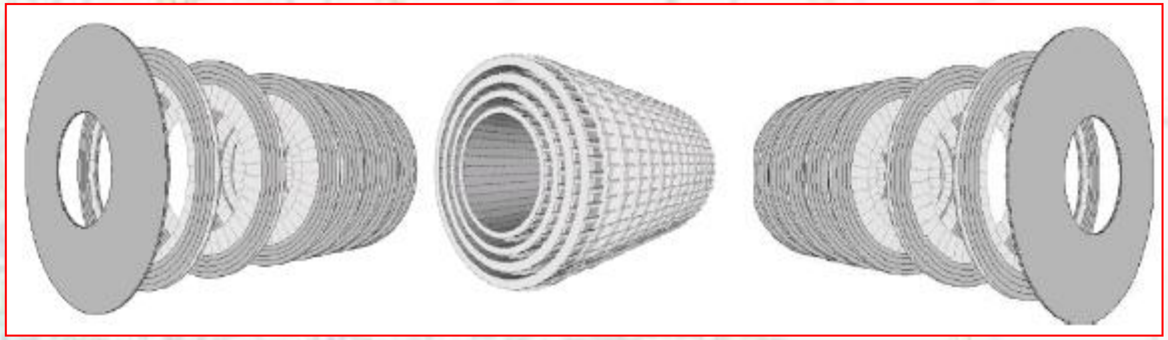
(Note the ATLAS Tracker TDR: April 1997; CMS Tracker TDR: April 1998)

ATLAS All-Silicon Tracker Upgrade

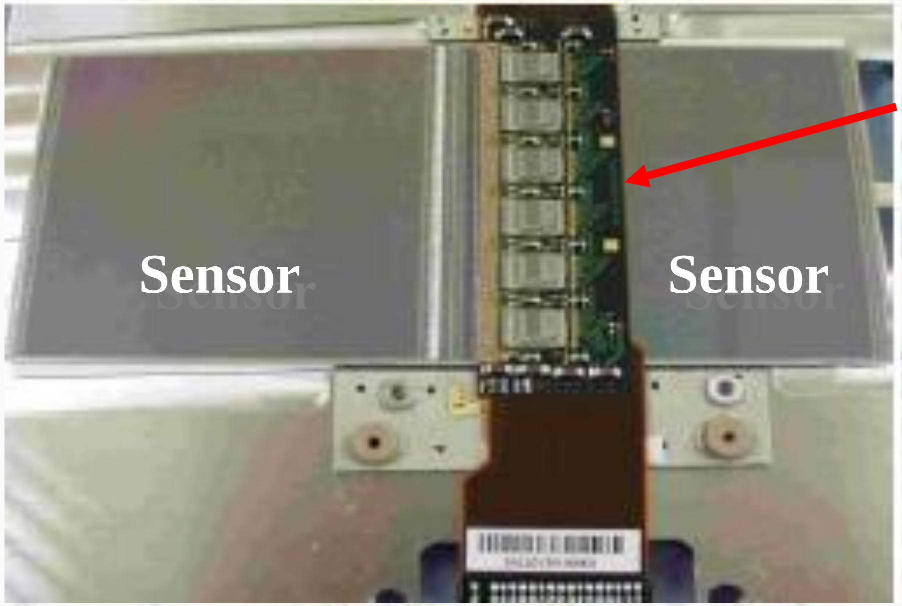


Current SCT ATLAS Module Designs

ATLAS Tracker Based on Barrel and Disc Supports

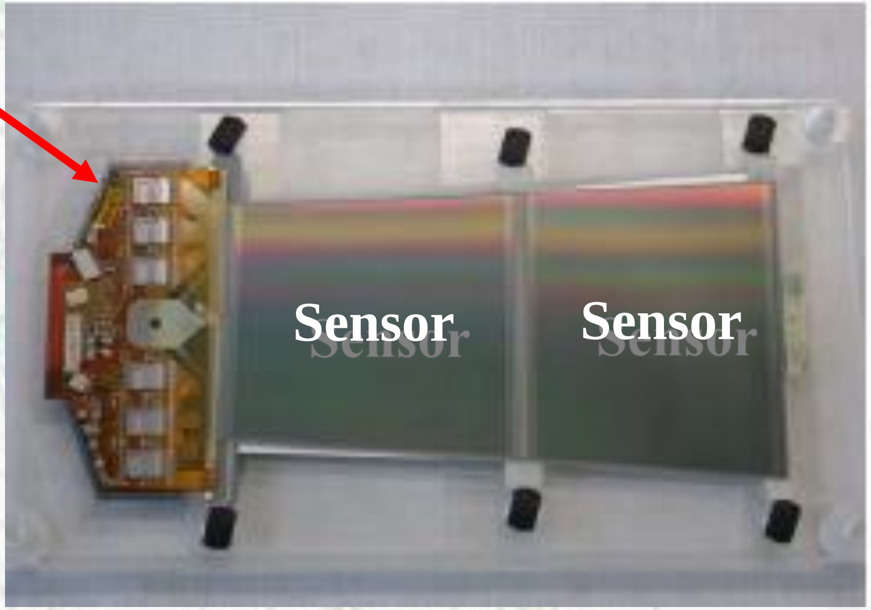


Effectively two styles of double-sided modules (2 6cm long) each sensor ~6cm wide (768 strips of 80µm pitch per side)



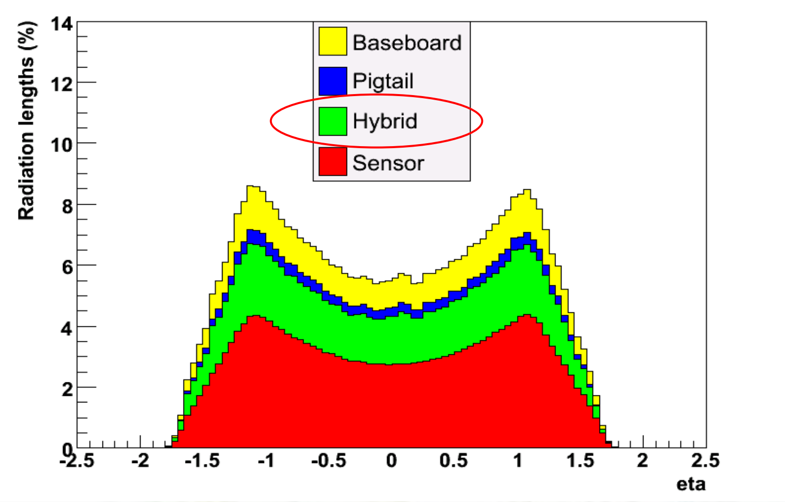
Barrel Modules
(Hybrid bridge above sensors)

Hybrid cards carrying read-out chips and multilayer interconnect circuit



Forward Modules
(Hybrid at module end)

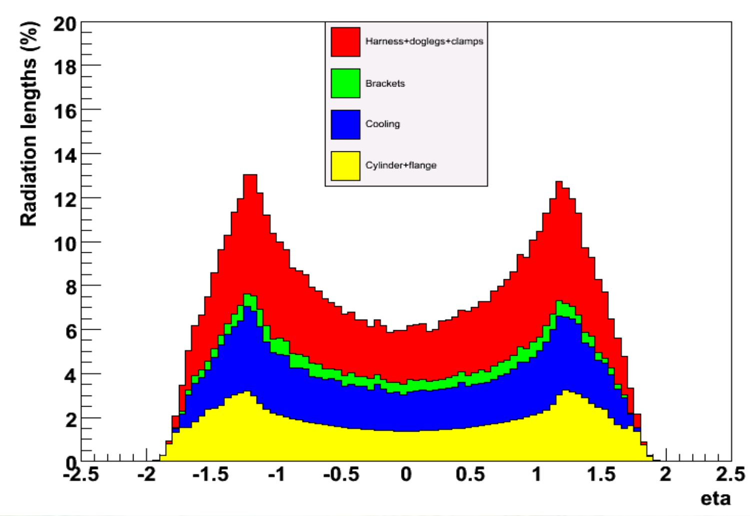
Current Silicon Microstrip (SCT) Material



Current Silicon Tracker
(4 barrel strip layers)

Module Material

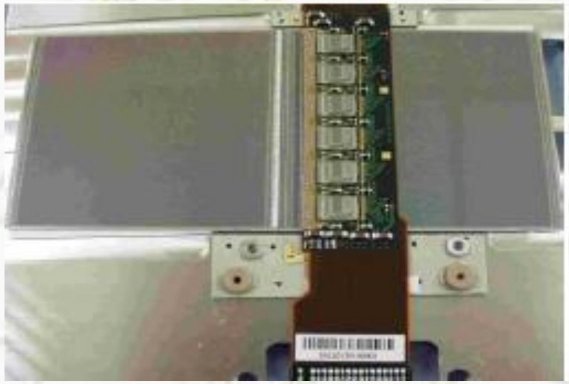
Support Material



Old ATLAS Barrel Module

12 ASIC of 300μm thickness for double-sided module read-out

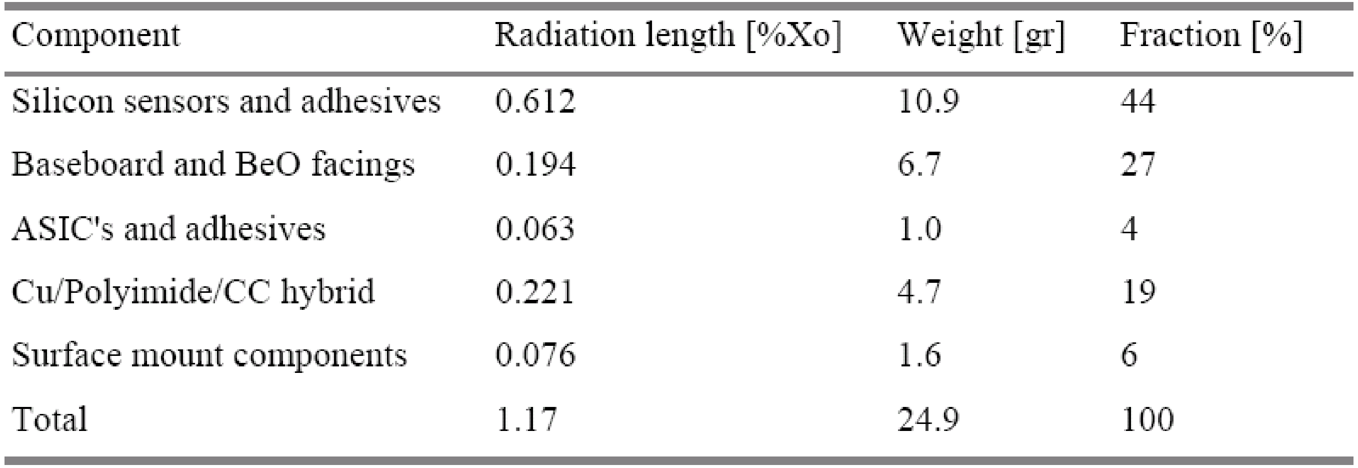
(*ie* just 6 read-out chips per side)



New ATLAS sLHC-Tracker Module will have 80 ASICs in two hybrid fingers for just one-sided read-out

“The barrel modules of the ATLAS semiconductor tracker”. Nucl.Instrum.Meth.A568:642-671,2006.

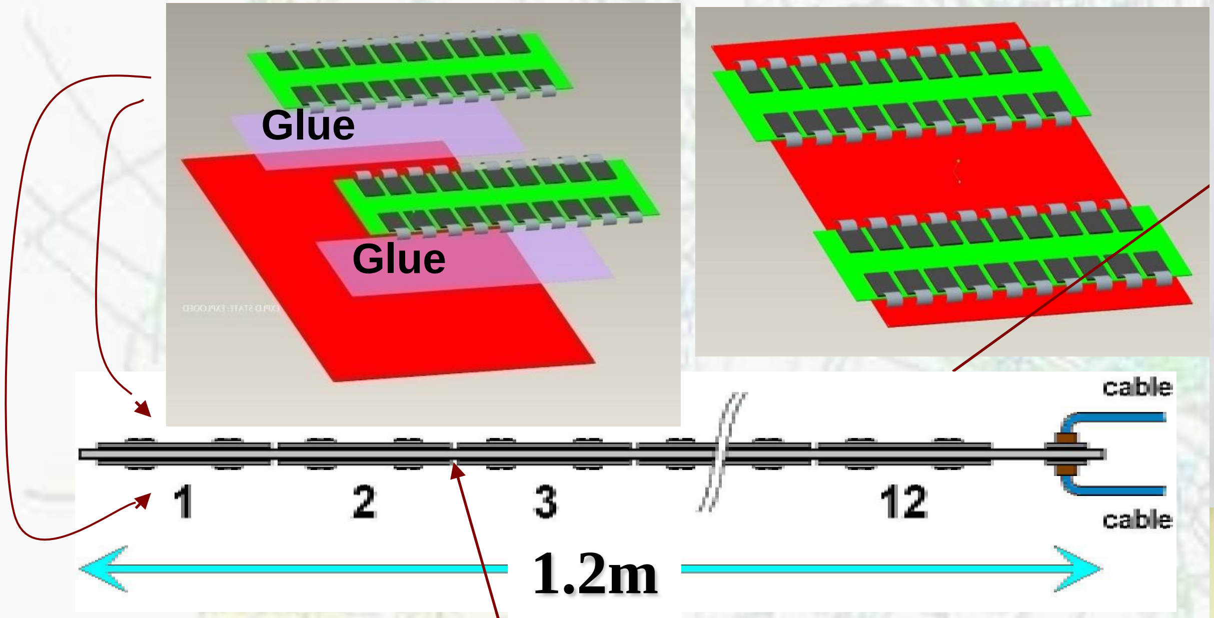
Table 1
Radiation lengths and weights estimated for the SCT barrel module

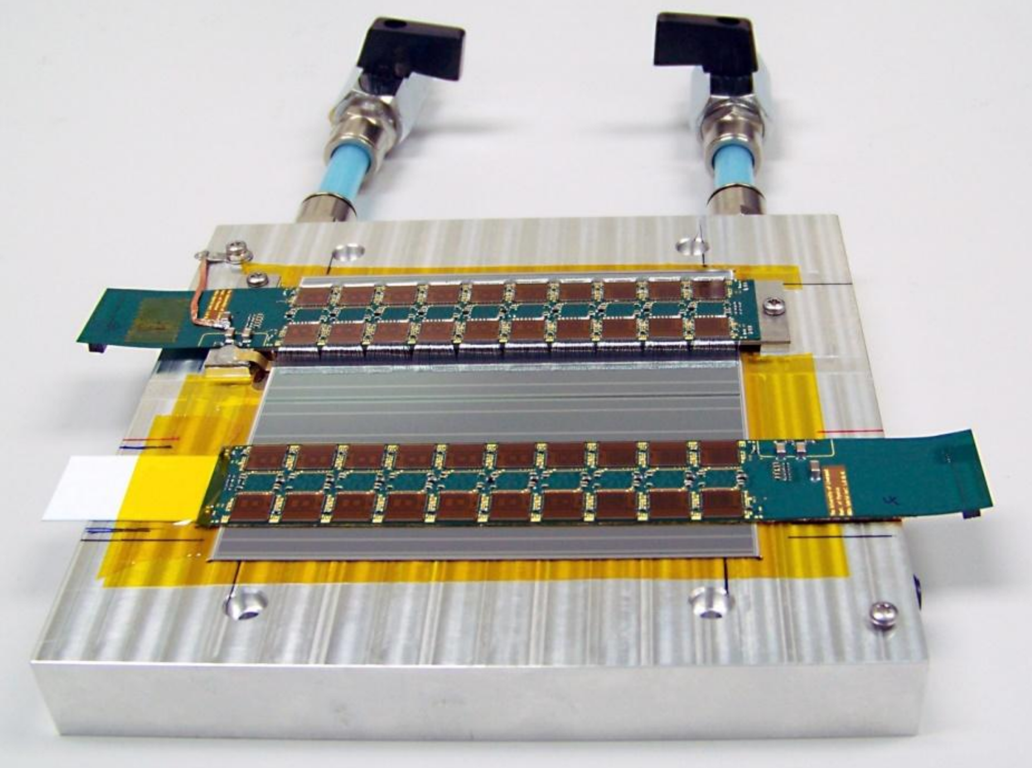


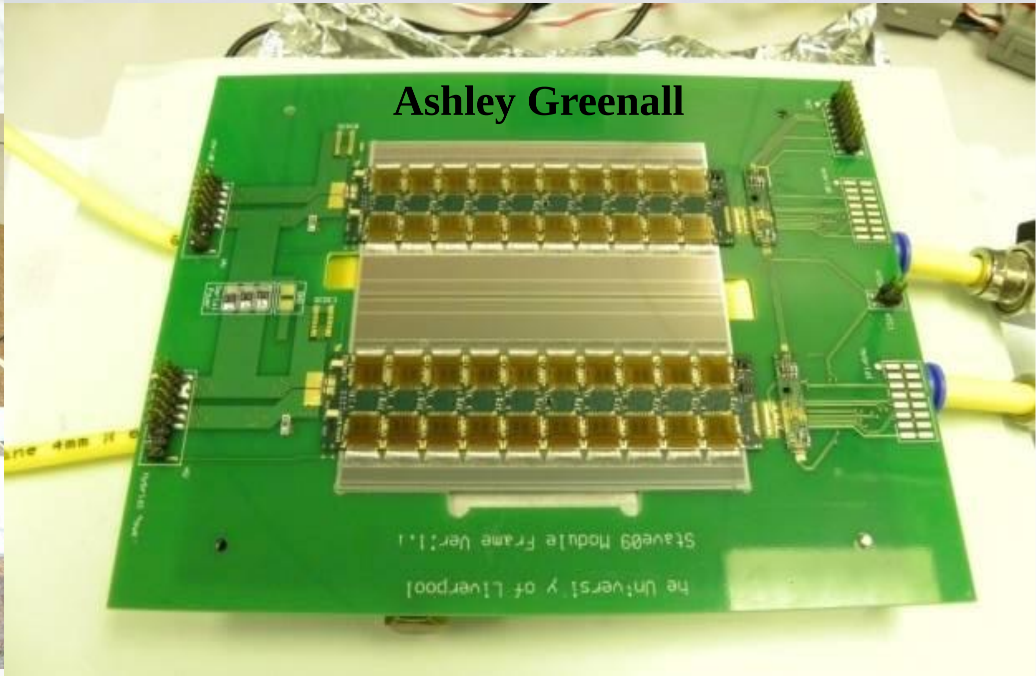
Component	Radiation length [%Xo]	Weight [gr]	Fraction [%]
Silicon sensors and adhesives	0.612	10.9	44
Baseboard and BeO facings	0.194	6.7	27
ASIC's and adhesives	0.063	1.0	4
Cu/Polyimide/CC hybrid	0.221	4.7	19
Surface mount components	0.076	1.6	6
Total	1.17	24.9	100

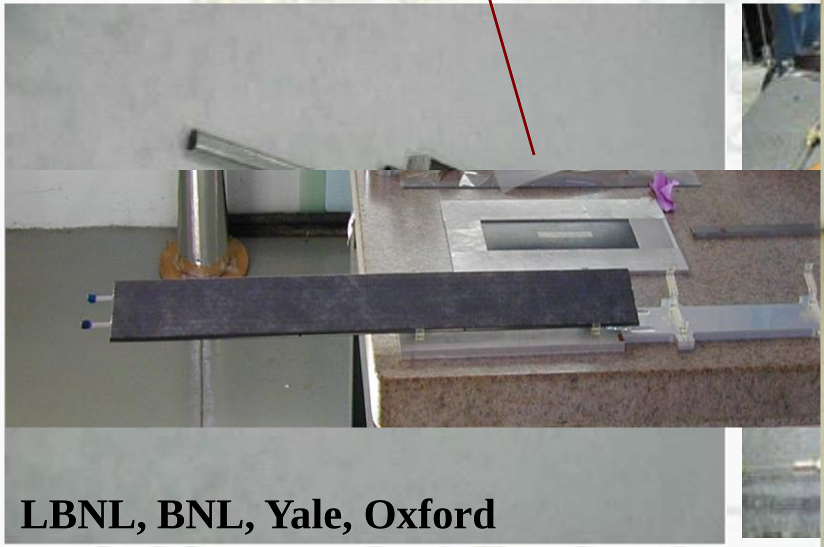
Hybrid area per module roughly ×2 at sLHC - much higher R/O granularity

Stave: Hybrids **glued** to Sensors **glued** to Bus Tape **glued** to Cooling Substrate



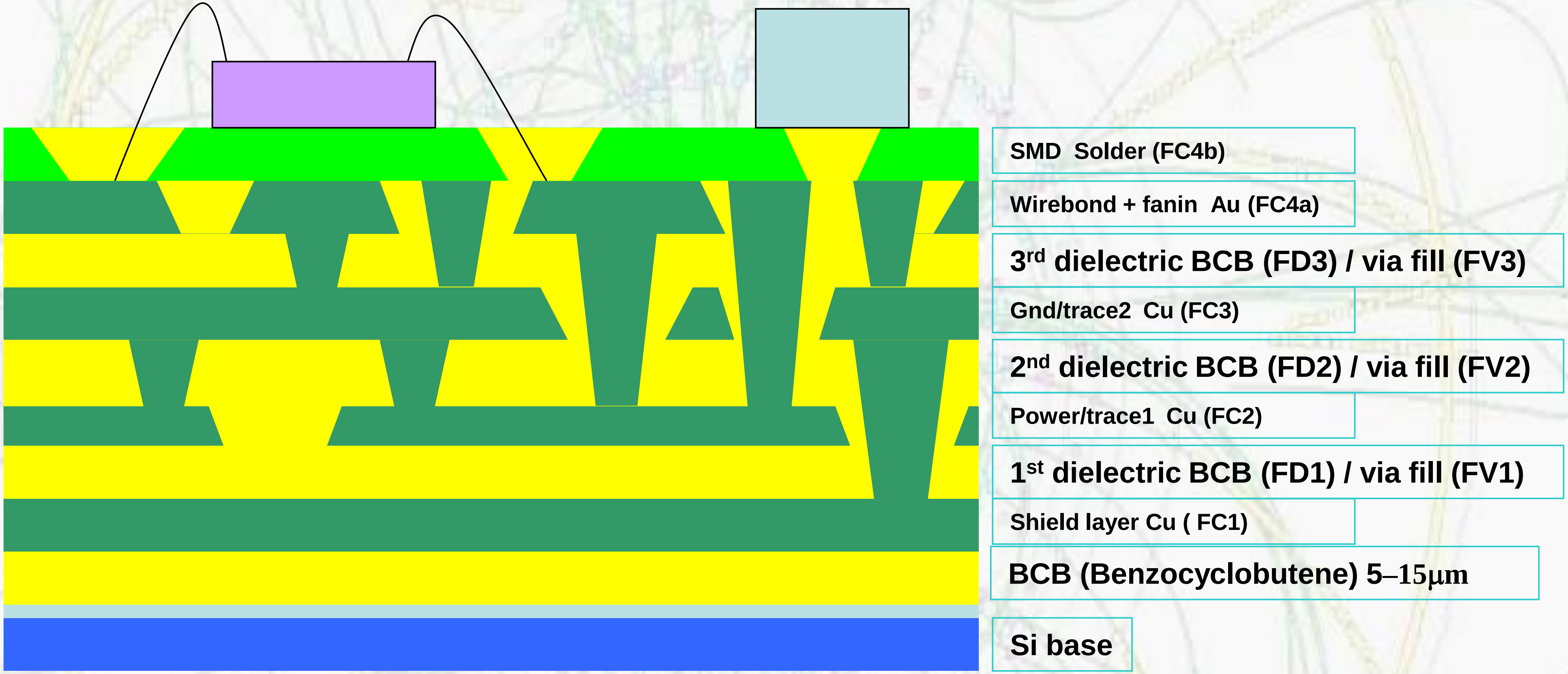



Ashley Greenall


LBNL, BNL, Yale, Oxford

Direct Processing of Hybrid Circuit on Silicon Sensor

(Ultimate reduction in mass and assembly complexity.)



SMD Solder (FC4b)

Wirebond + fanin Au (FC4a)

3rd dielectric BCB (FD3) / via fill (FV3)

Gnd/trace2 Cu (FC3)

2nd dielectric BCB (FD2) / via fill (FV2)

Power/trace1 Cu (FC2)

1st dielectric BCB (FD1) / via fill (FV1)

Shield layer Cu (FC1)

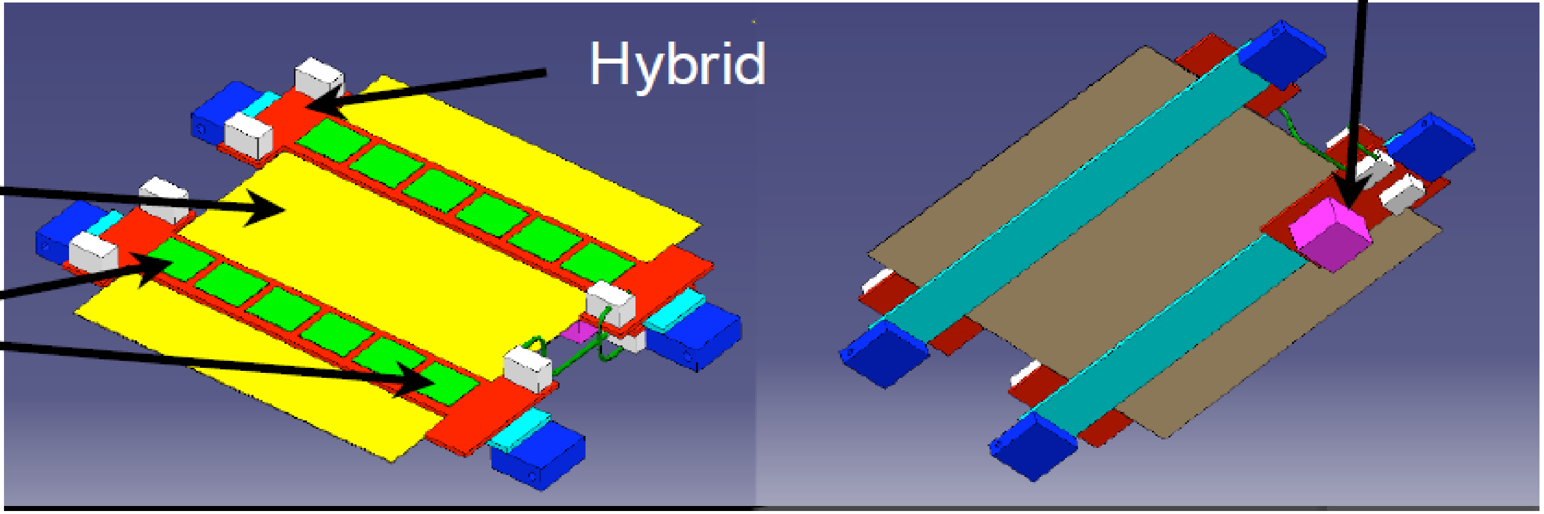
BCB (Benzocyclobutene) 5–15µm

Si base

Does away with need for hybrid substrate and thick-film processing.
Prototyping for ATLAS underway with several European manufacturers.

CMS Tracker Replacement Module Concept

- Front end ASIC going to submission: CBC
  - Evolution of APV25
  - 130nm technology
  - Binary non-sparsified readout
  - Low power (<0.5mW/channel)
  - Optimised for 25 to 50 mm strips
- First module/ladder concept developed



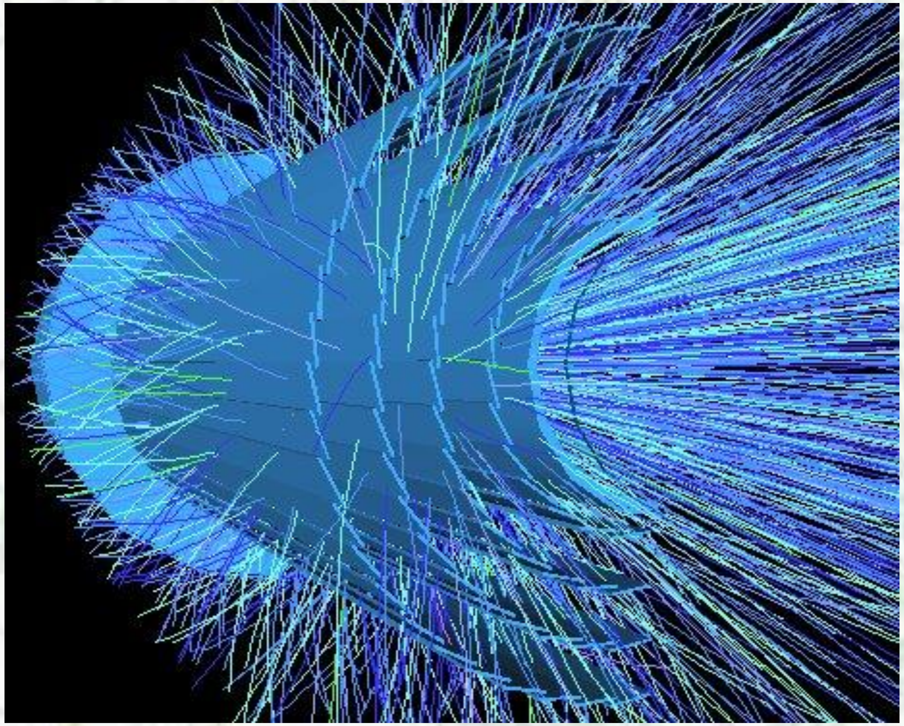
Sensor: 4x25mm strips

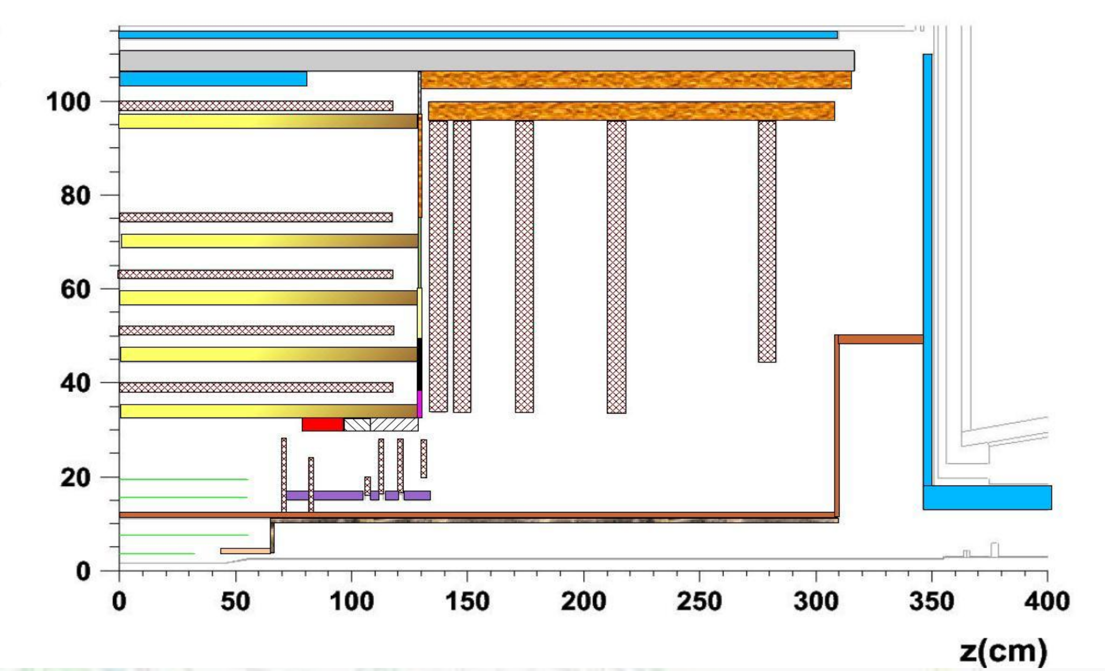
12 CBCs wirebonded from both sides

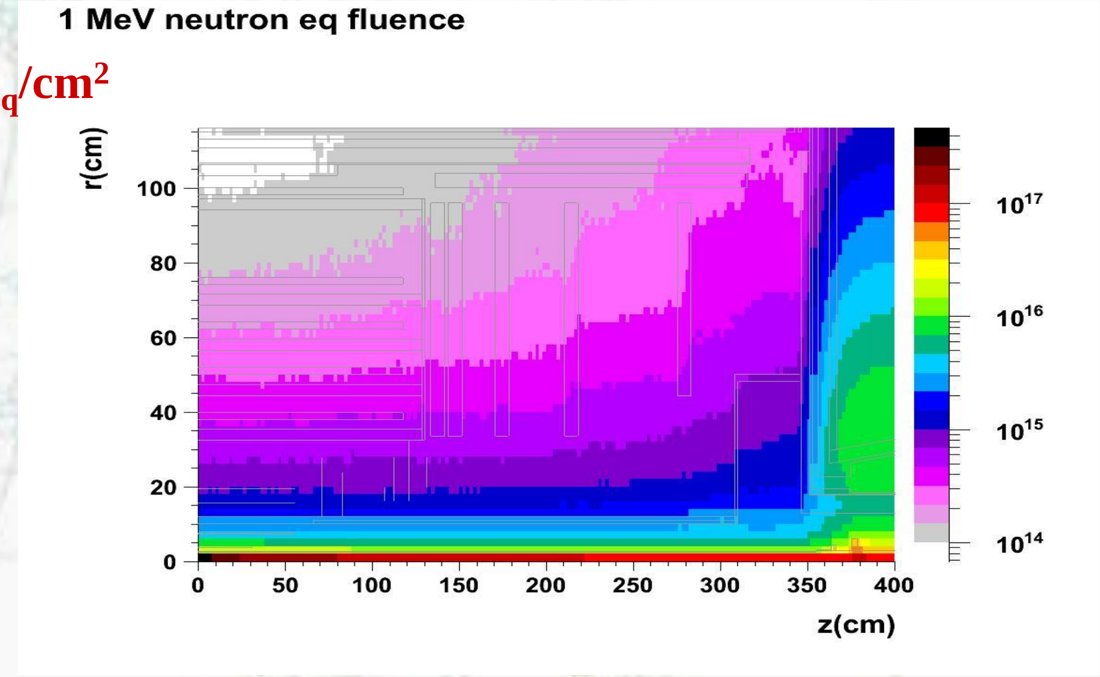
Hybrid

DC/DC converter

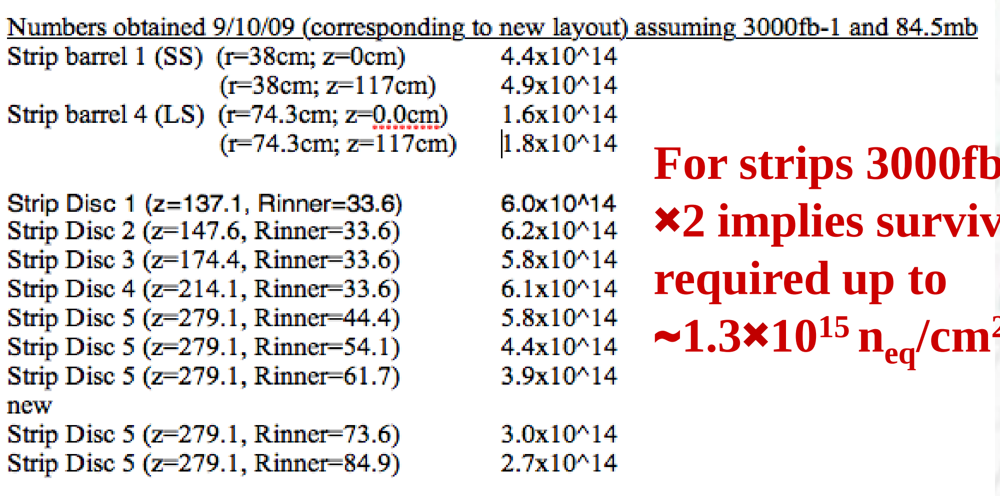
Radiation Background Simulation







At inner pixel radii - target survival to 1-2×10^{16} n_{eq}/cm^2



Numbers obtained 9/10/09 (corresponding to new layout) assuming 3000fb-1 and 84.5mb

Strip barrel 1 (SS)	(r=38cm; z=0cm)	4.4x10^14
	(r=38cm; z=117cm)	4.9x10^14
Strip barrel 4 (LS)	(r=74.3cm; z=0.0cm)	1.6x10^14
	(r=74.3cm; z=117cm)	1.8x10^14
Strip Disc 1 (z=137.1, Rinner=33.6)		6.0x10^14
Strip Disc 2 (z=147.6, Rinner=33.6)		6.2x10^14
Strip Disc 3 (z=174.4, Rinner=33.6)		5.8x10^14
Strip Disc 4 (z=214.1, Rinner=33.6)		6.1x10^14
Strip Disc 5 (z=279.1, Rinner=44.4)		5.8x10^14
Strip Disc 5 (z=279.1, Rinner=54.1)		4.4x10^14
Strip Disc 5 (z=279.1, Rinner=61.7)		3.9x10^14
new		
Strip Disc 5 (z=279.1, Rinner=73.6)		3.0x10^14
Strip Disc 5 (z=279.1, Rinner=84.9)		2.7x10^14

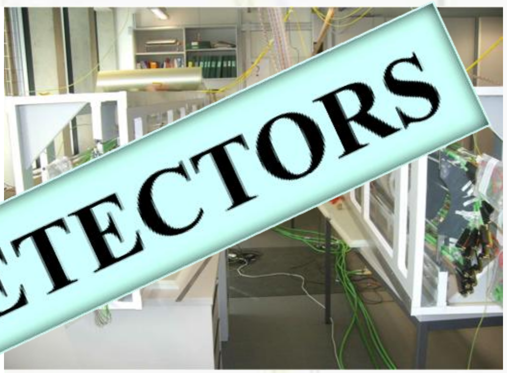
For strips 3000fb^{-1} ×2 implies survival required up to ~1.3×10^{15} n_{eq}/cm^2

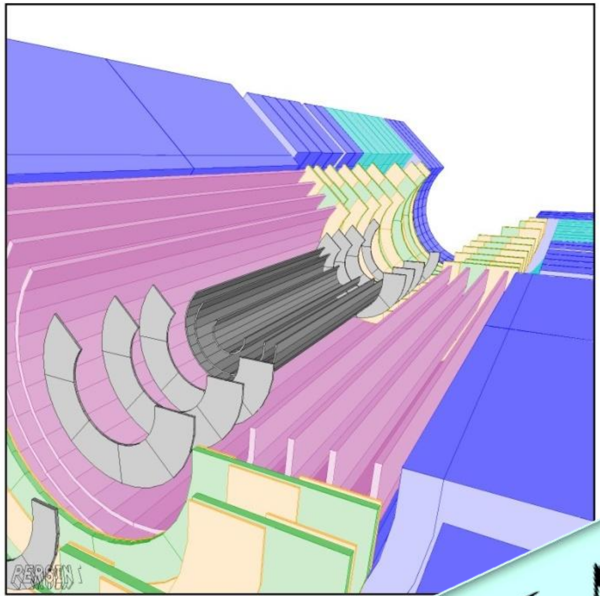
Technology in Current Highest Dose Regions

LHC vertex detectors closes to the interaction point:

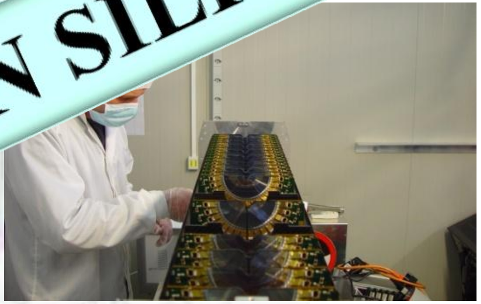
- Required to be very radiation hard and to be very finely segmented because of the very high density of tracks close to primary collisions
- Doses $5 - 10 \times 10^{14}\ n_{eq}cm^{-2}$ (~100 Mrad)
- 0.05mm ×0.4mm pixels

(40 million images per second)



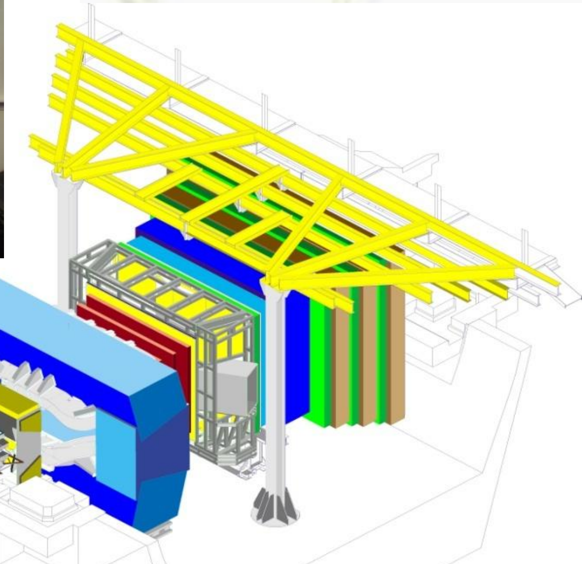


ATLAS 100 million



ALL USE PLANAR N-IN-N SILICON DETECTORS

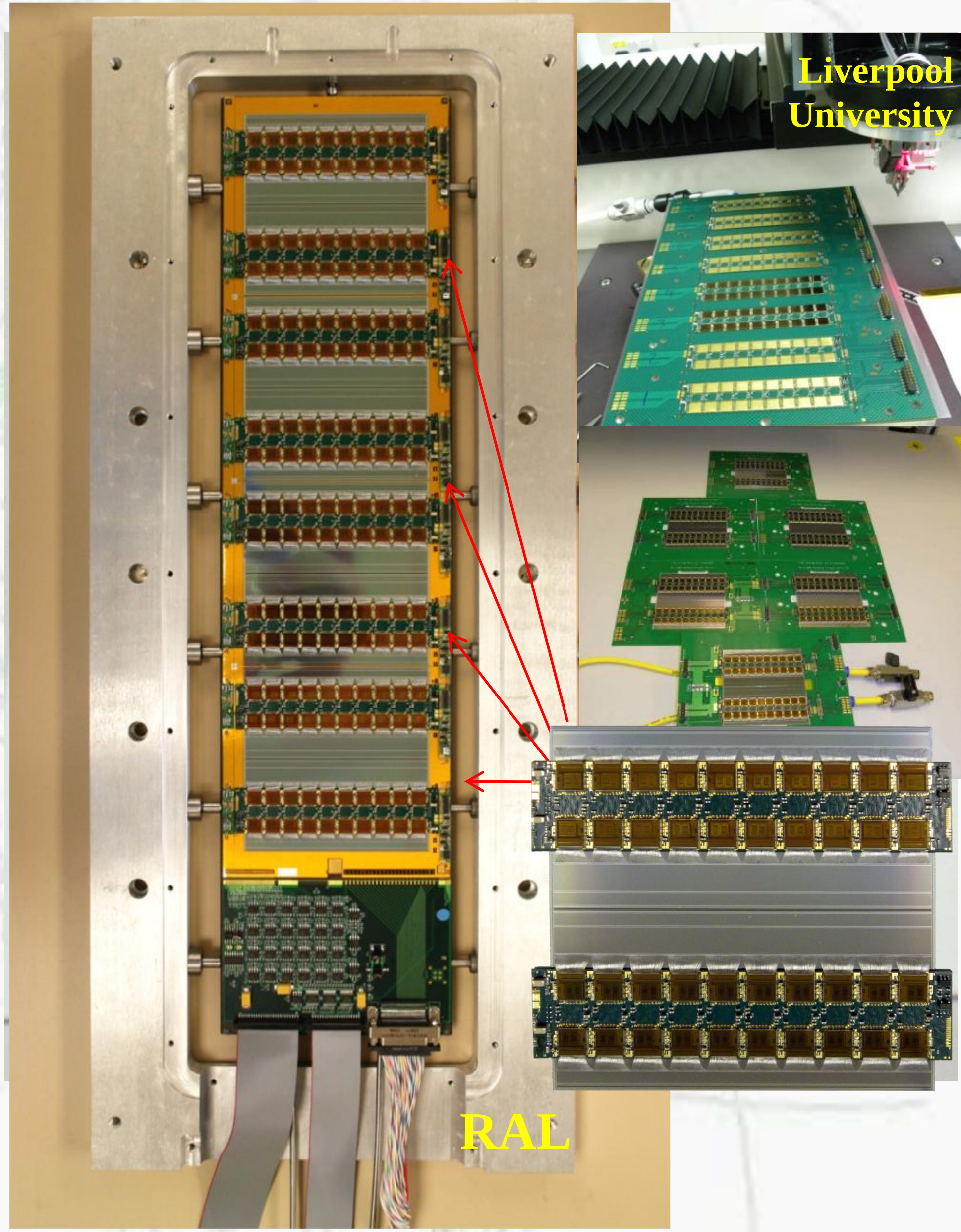
LHCb
Vertex Locator
Z(mm)=0-990



Motivations for P-type Silicon Wafers

Starting with a p^--type substrate offers the advantages of single-sided processing while keeping n^+-side read-out:

- Processing Costs (~50% cheaper).
- Greater potential choice of suppliers.
- High fields always on the same side.
- Easy of handling during testing.
- No delicate back-side implanted structures to be considered in module design or mechanical assembly.

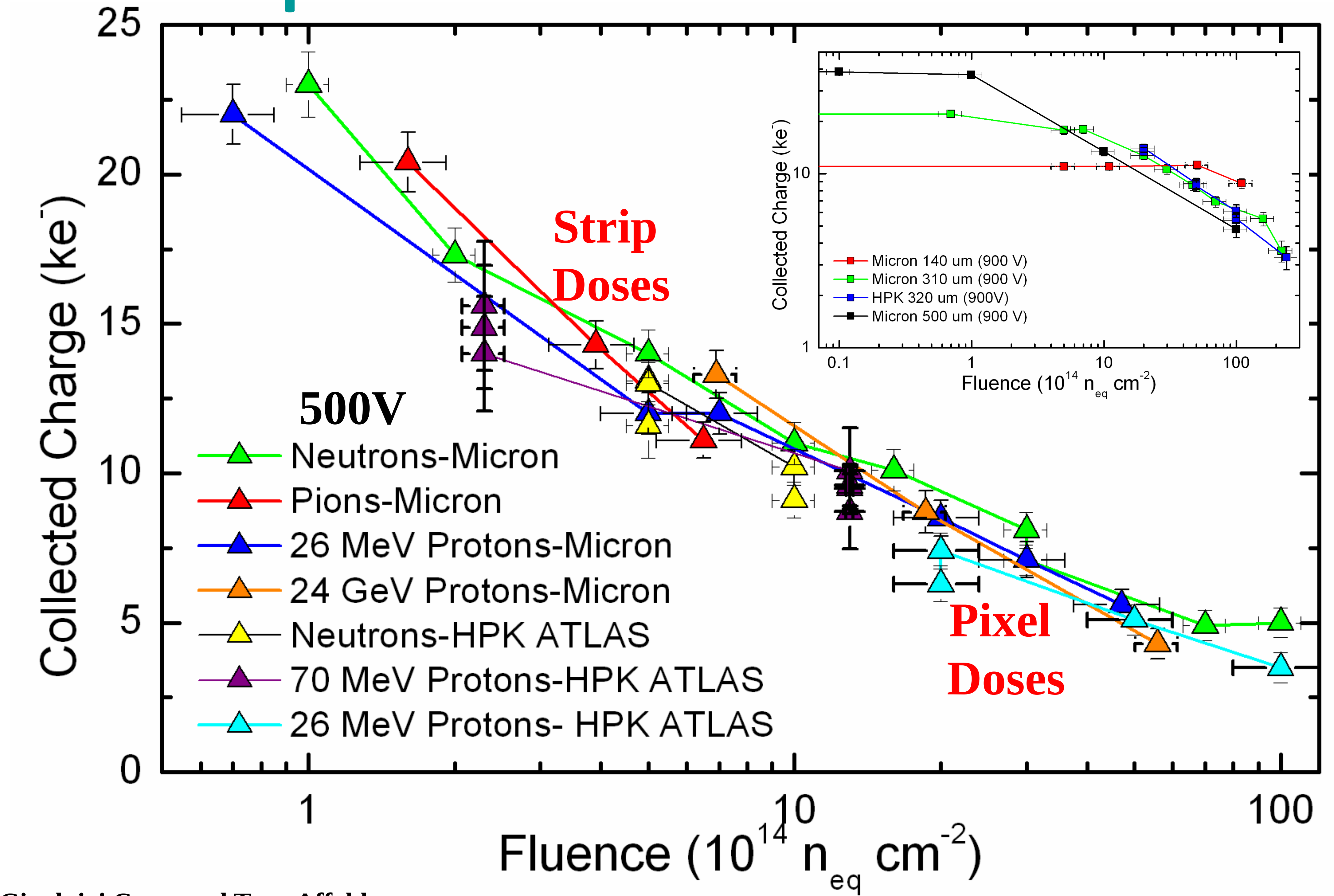


So far, capacitively coupled, polysilicon biased p-type devices fabricated to ATLAS provided mask designs by:

- Micron Semiconductor (UK) Ltd
- CiS Erfurt (Germany)
- CNM Barcelona (Spain)
- ITC Trento (Italy)
- Hamamatsu Photonics HPK (Japan)

(Including full-size 10cm ×10cm prototype)

n-in-p Planar FZ Sensor Irradiations

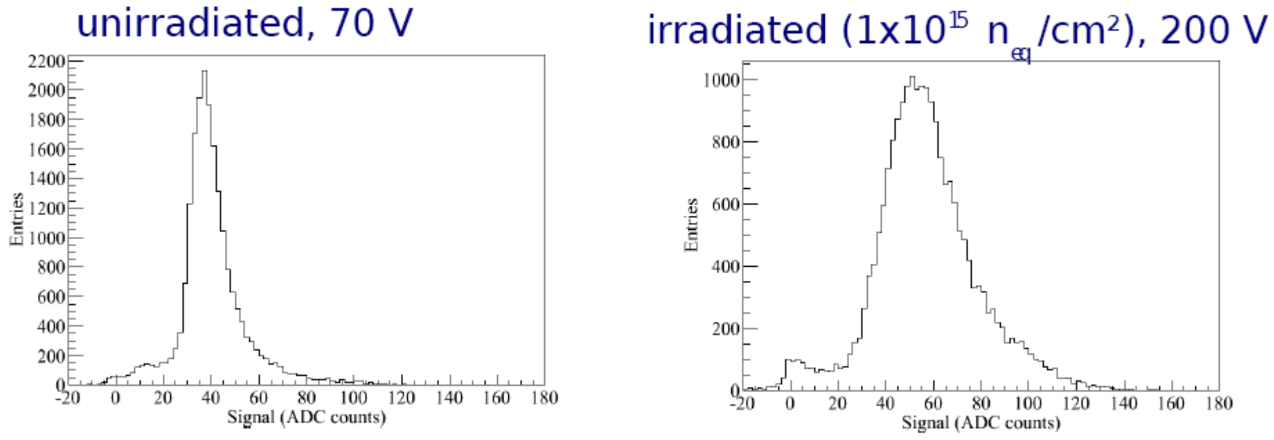


Gianluigi Casse and Tony Affolder,

Alternative Technologies to Planar Silicon

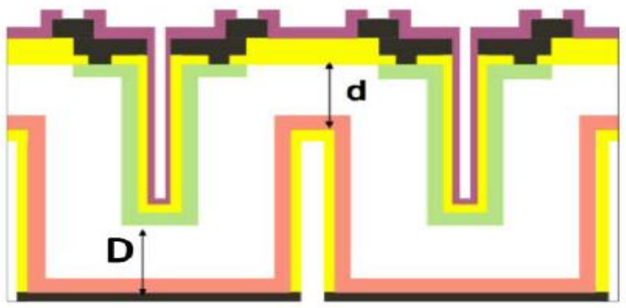
3D Sensors with Doped Through Silicon Columns

- Signal of the channel closest to the track point of impact


unirradiated, 70 V

irradiated (1×10^{15} n_{eq}/cm²), 200 V

Double Side Double Type Column



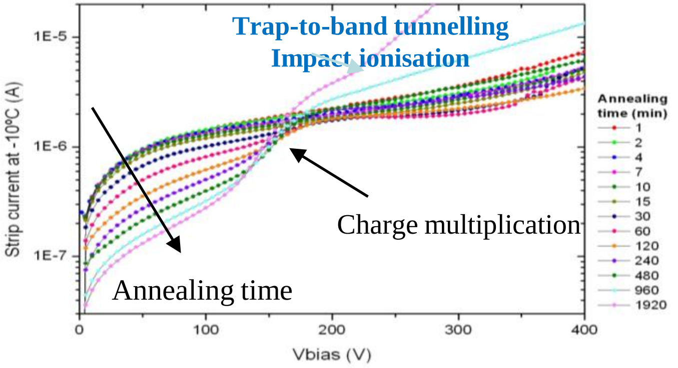
- FBK/IRST:completed a FE-I3 run. Full 3D in the next run.
- CNM: being completed and bump bonded to

- Higher signal after irradiation than before

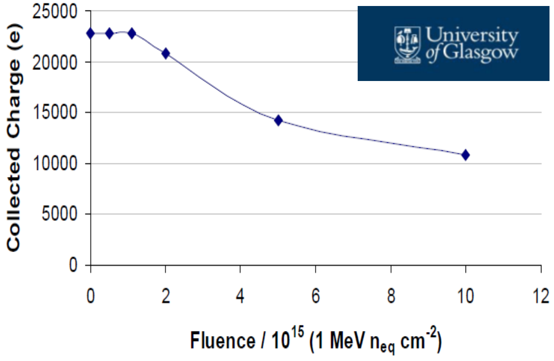
  → Charge multiplication!

- Entries at low signal values: charge sharing, tracks going straight through columns

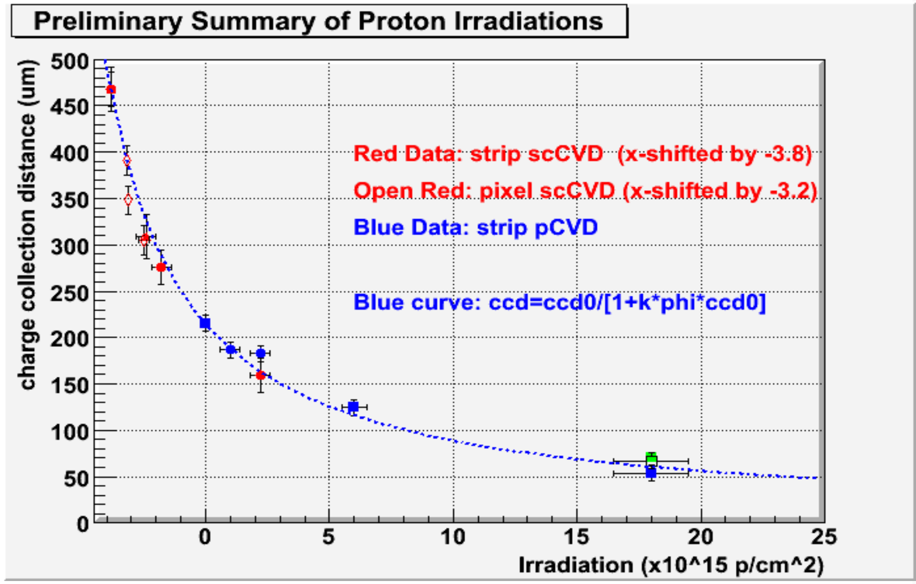
Leakage current, -10°C, 10^{16} n_{eq}/cm²



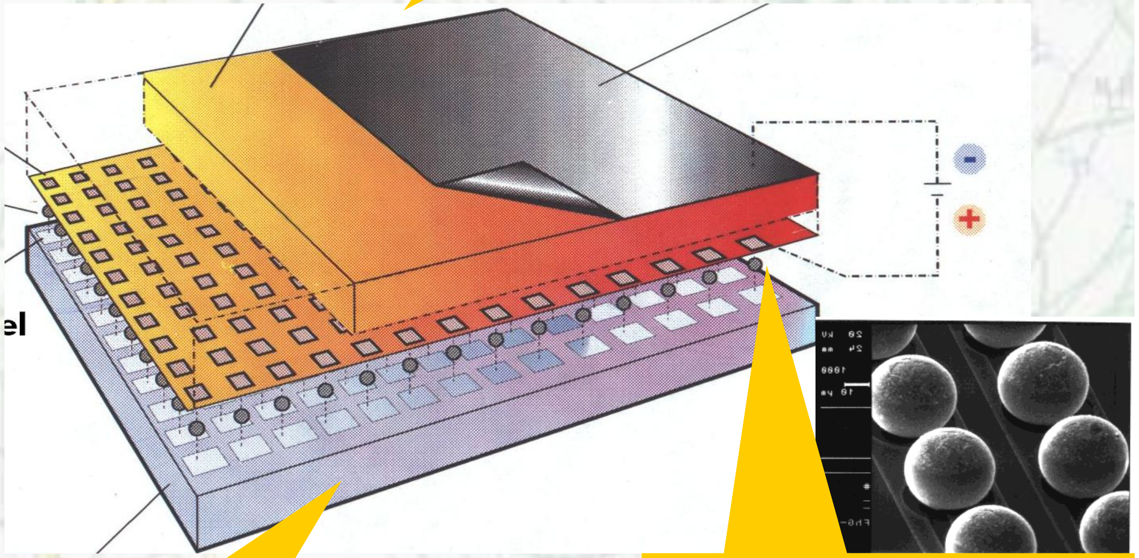
V_{bias} fixed at 150V



Planar CVD Diamond: Poly-crystalline or Single Crystal



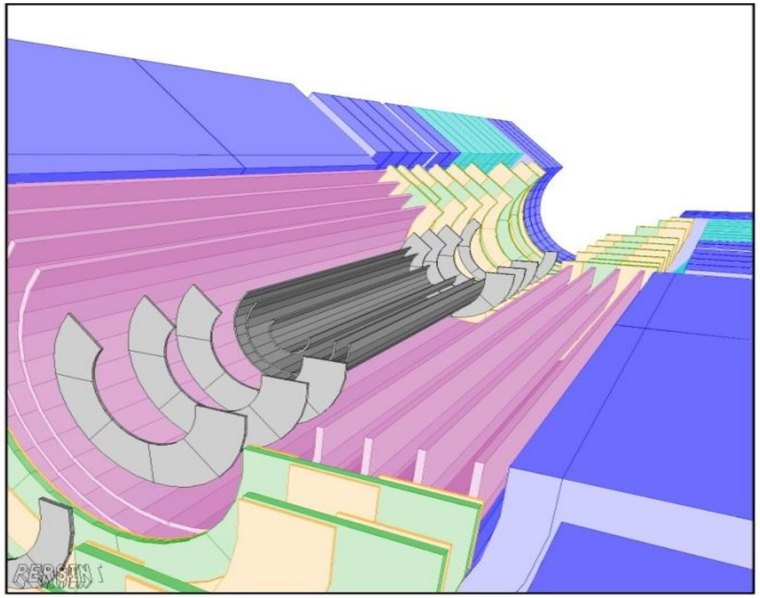
ATLAS Pixel Module Upgrade

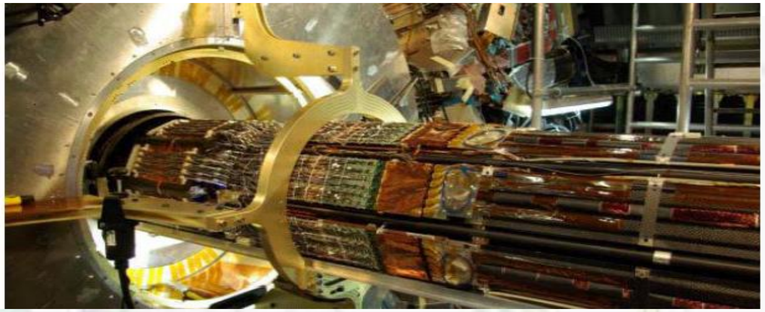


Silicon sensor

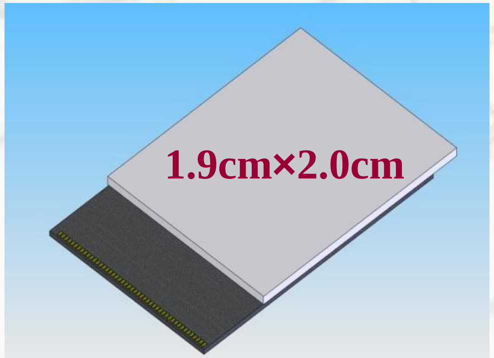
Readout chip

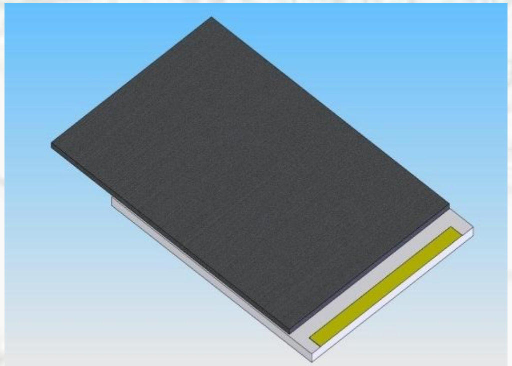
Bump bond connection

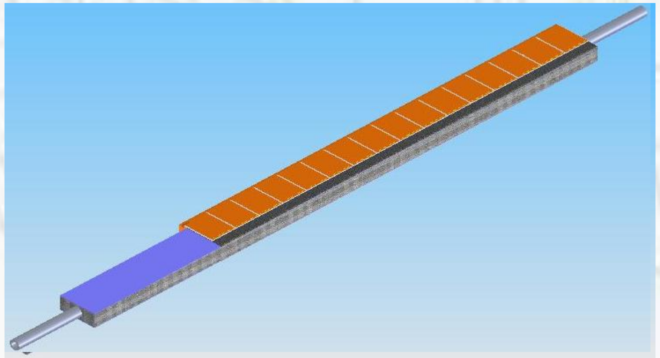




→ Single chip pixel modules on stave for insertable b-layer (IBL) (2016 shutdown)







ATLAS Pixel Upgrade ASIC

- **New Front-End chip (FE-I4) for smaller pixel dimensions being delivered**
- **Fabricated for Phase-I b-layer replacement (IBL)**

→ an intermediate step towards the full upgrade.

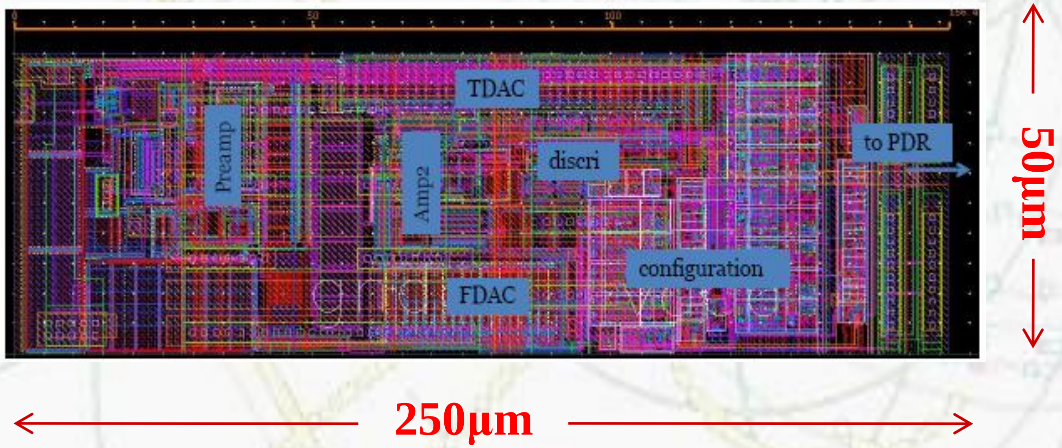
Performance improvements for the detector

(issues more related to FE chip):

- **Reduce radius → Improve radiation hardness planar , 3D sensors, diamond, gas, …?)**
- **Reduce pixel cell size and architecture related dead time**
  (→ deign FE using 0.13 µm 8 metal CMOS)
- **increase the module live fraction**
  → increase chip size, 19×20 mm^2

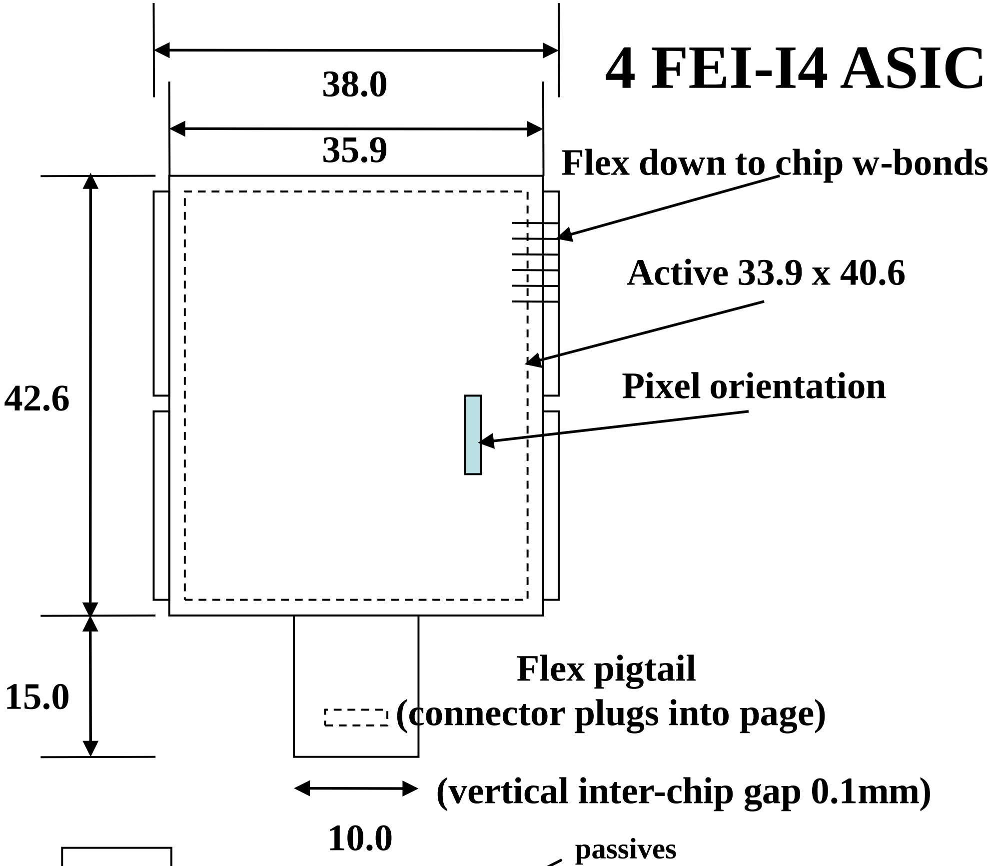
Main Parameter	*Value*	*Unit*
Pixel size	50 x 250	µm^2
Input	DC-coupled negative polarity	
Normal pixel input capacitance range	300÷500	fF
In-time threshold with 20ns gate	4000	e
Two-hit time resolution	400	ns
DC leakage current tolerance	100	nA
Single channel ENC sigma (400fF)	300	e
Tuned threshold dispersion	100	e
Analog supply current/pixel @400fF	10	µA
Radiation tolerance	200	MRad
Acquisition mode	Data driven with time stamp	
Time stamp precision	8	bits
Single chip data output rate	160	Mb/s

FE-I4 (B-layer Replacement) Specifications: main parameters



SLHC Phase-II Pixels Outer Layer Stave Concept

4 FEI-I4 ASIC module



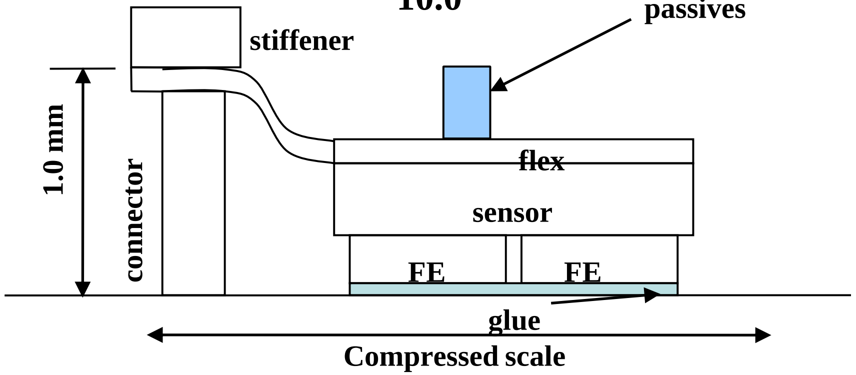
Flex down to chip w-bonds

Active 33.9 x 40.6

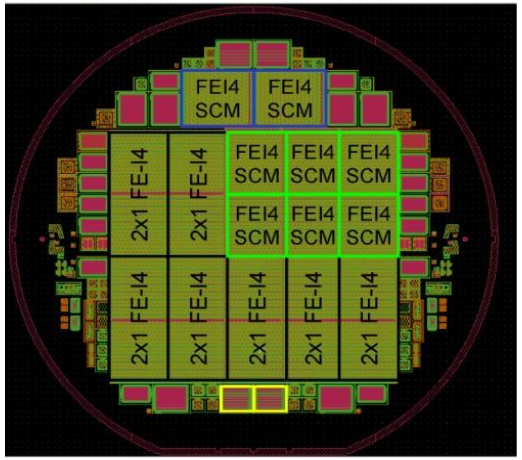
Pixel orientation

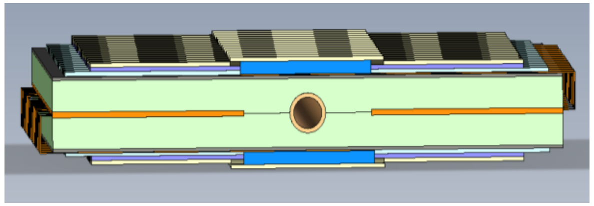
Flex pigtail (connector plugs into page)

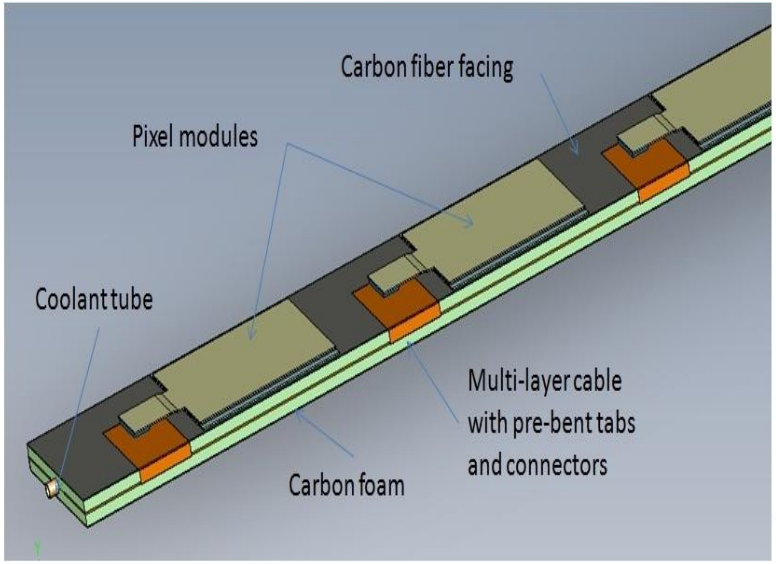
(vertical inter-chip gap 0.1mm)



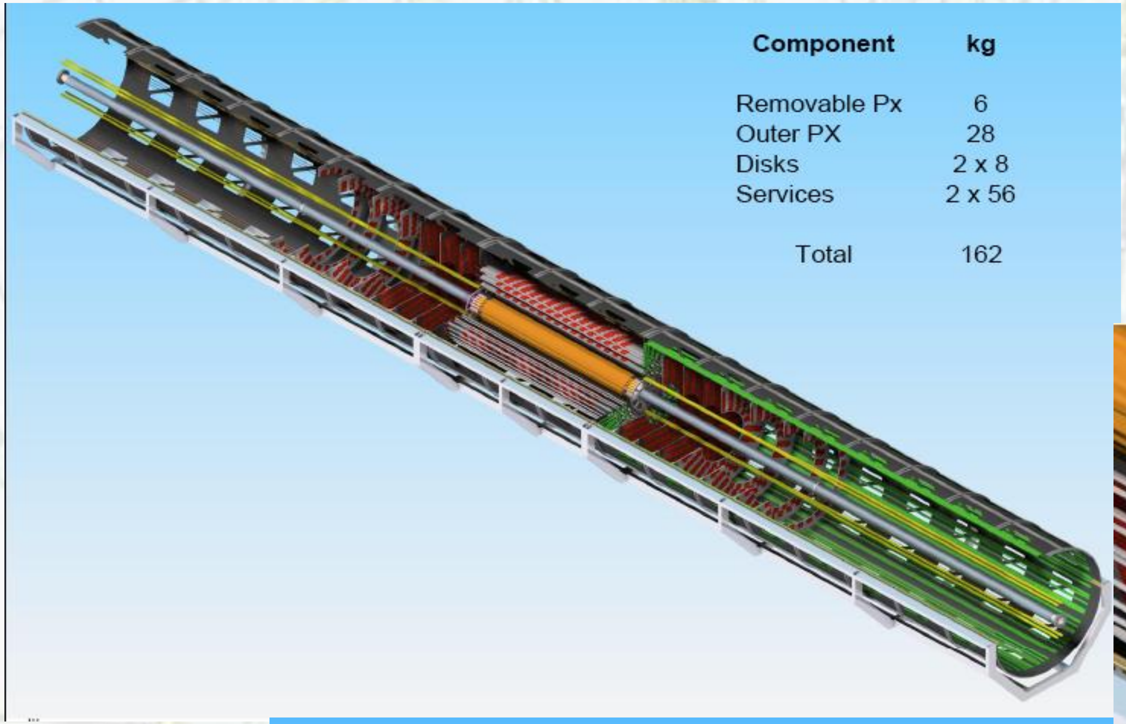
4 FEI-I4 compatible sensors from IBL project suitable for prototyping





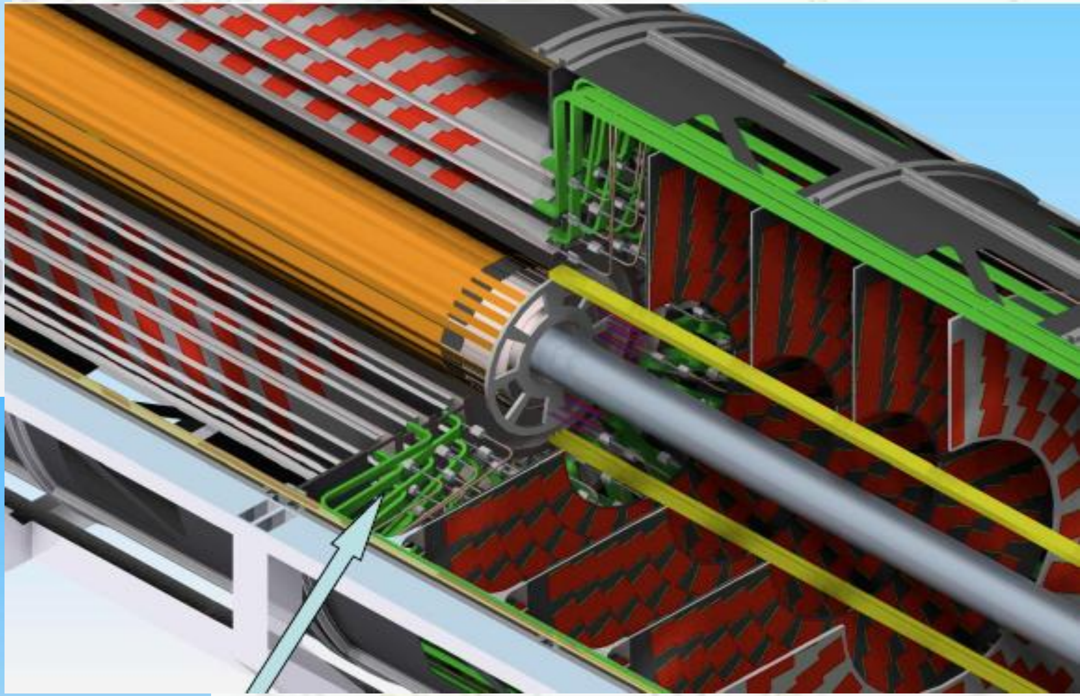


Possible Phase-II Pixel Mechanics

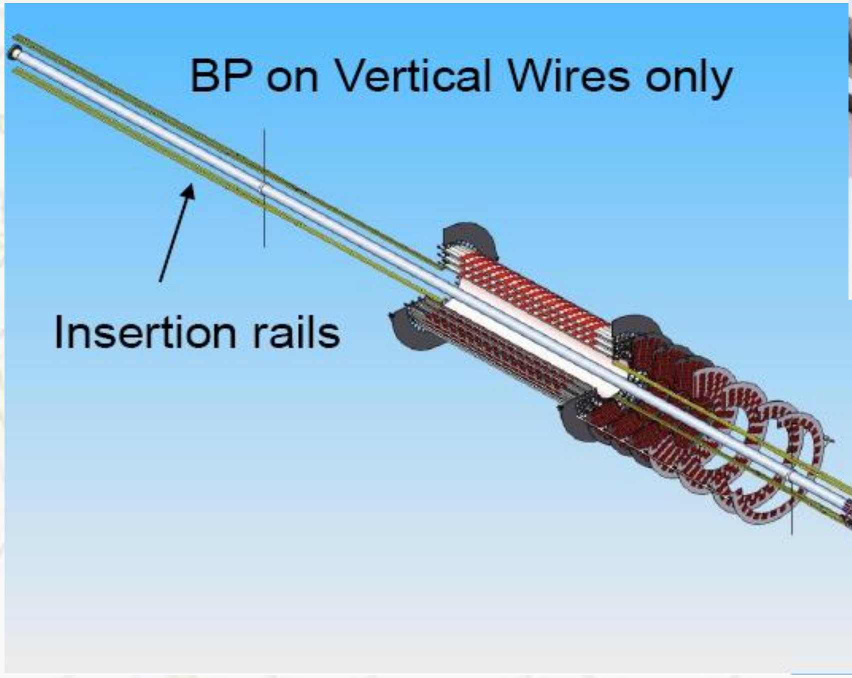


Component	kg
Removable Px	6
Outer PX	28
Disks	2 x 8
Services	2 x 56
Total	162

Independent thermal enclosure for replacement pixel package

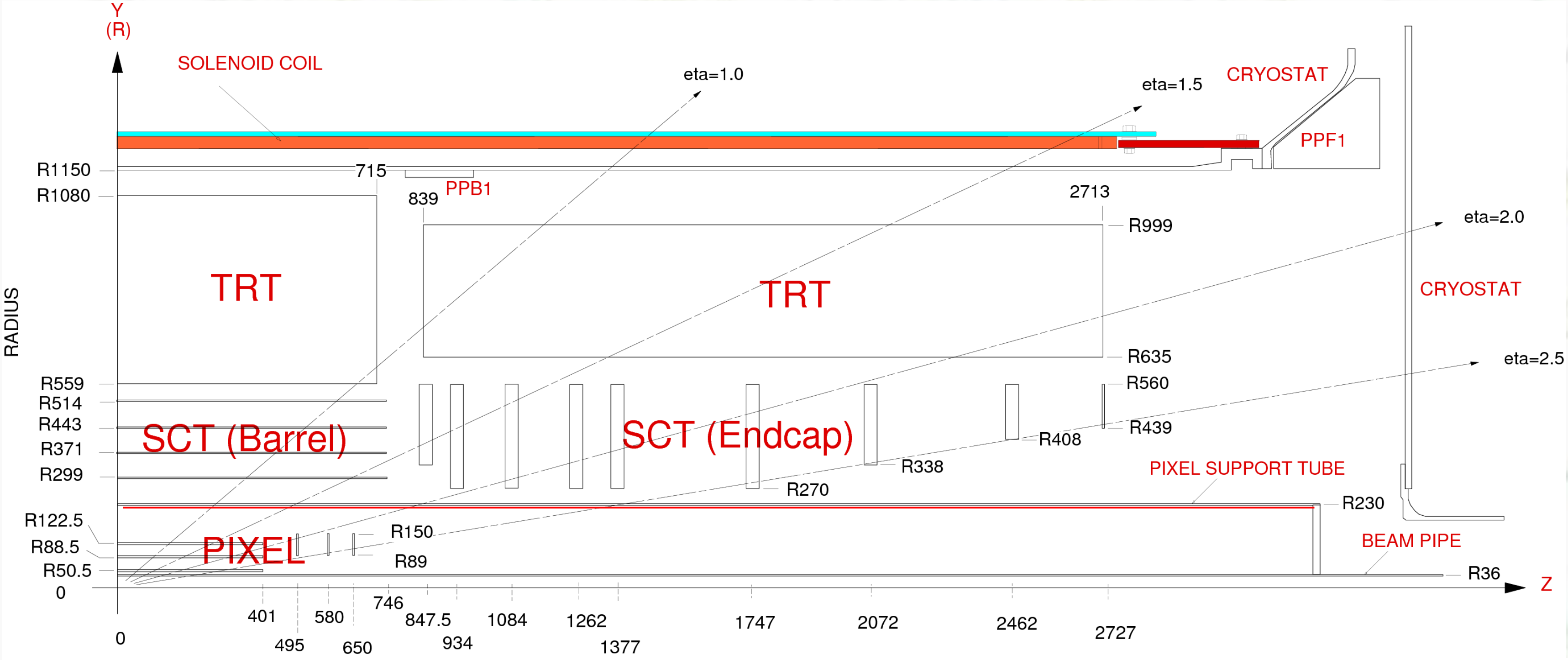


SLAC



IBL remains separately insertable

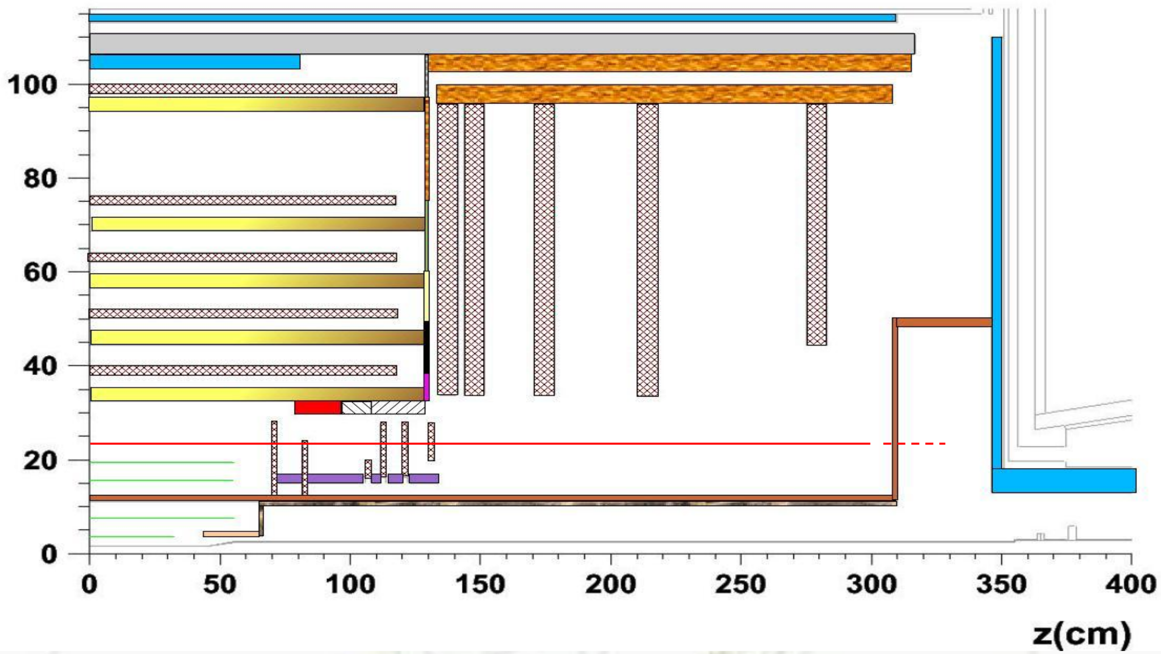
Independently Installable Pixels



Consistent with installation within current pixel radii

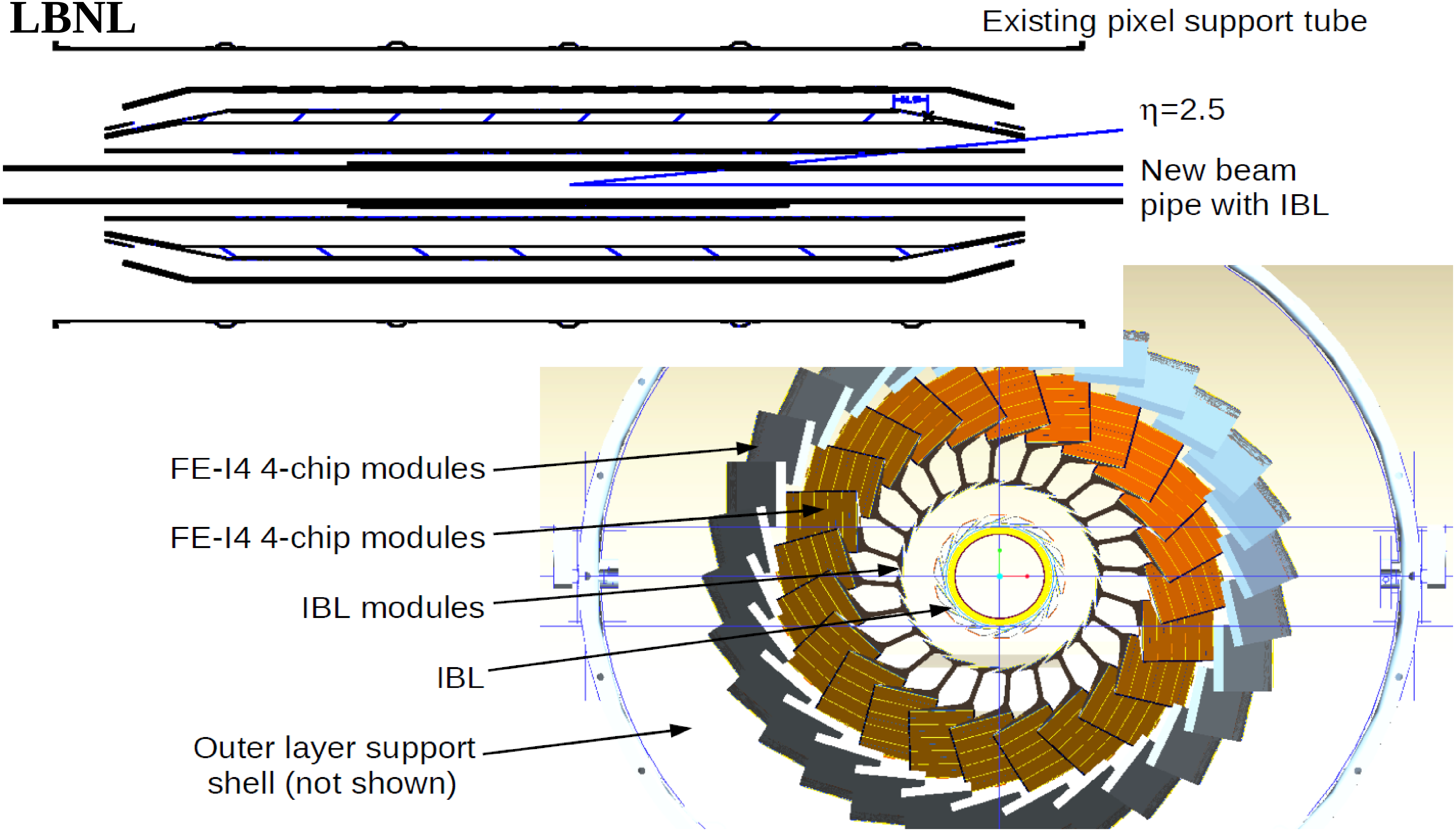
Current SCT quarter section layout showing pixel support tube at 23cm radius

Proposed All-silicon tracker layout showing radius of current pixel support tube.



Independently Installable Phase-II Pixel Design

LBNL



Existing pixel support tube

η=2.5

New beam pipe with IBL

FE-I4 4-chip modules

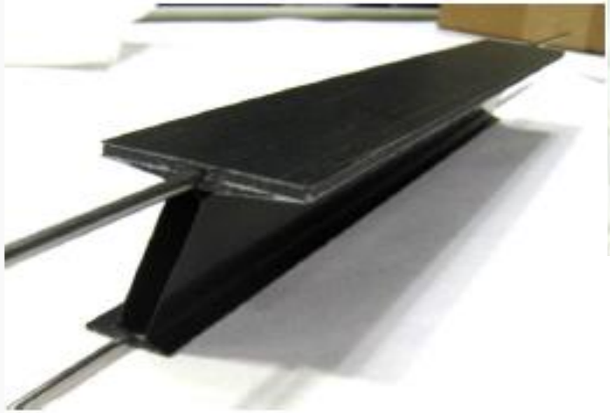
FE-I4 4-chip modules

IBL modules

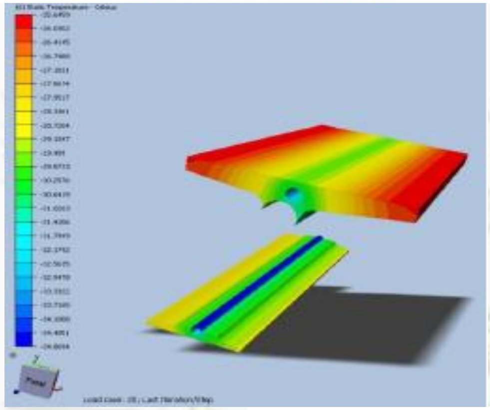
IBL

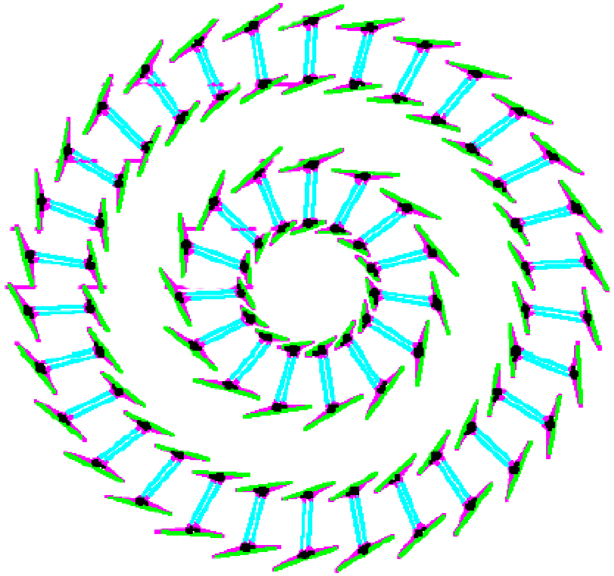
Outer layer support shell (not shown)

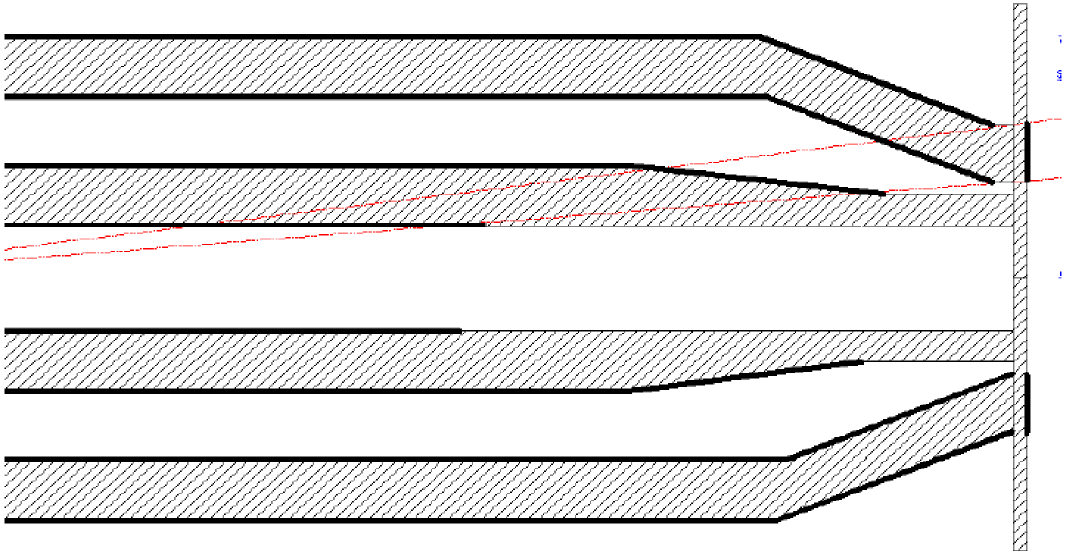
Material Reduction



I-beam prototype, LBNL 2010



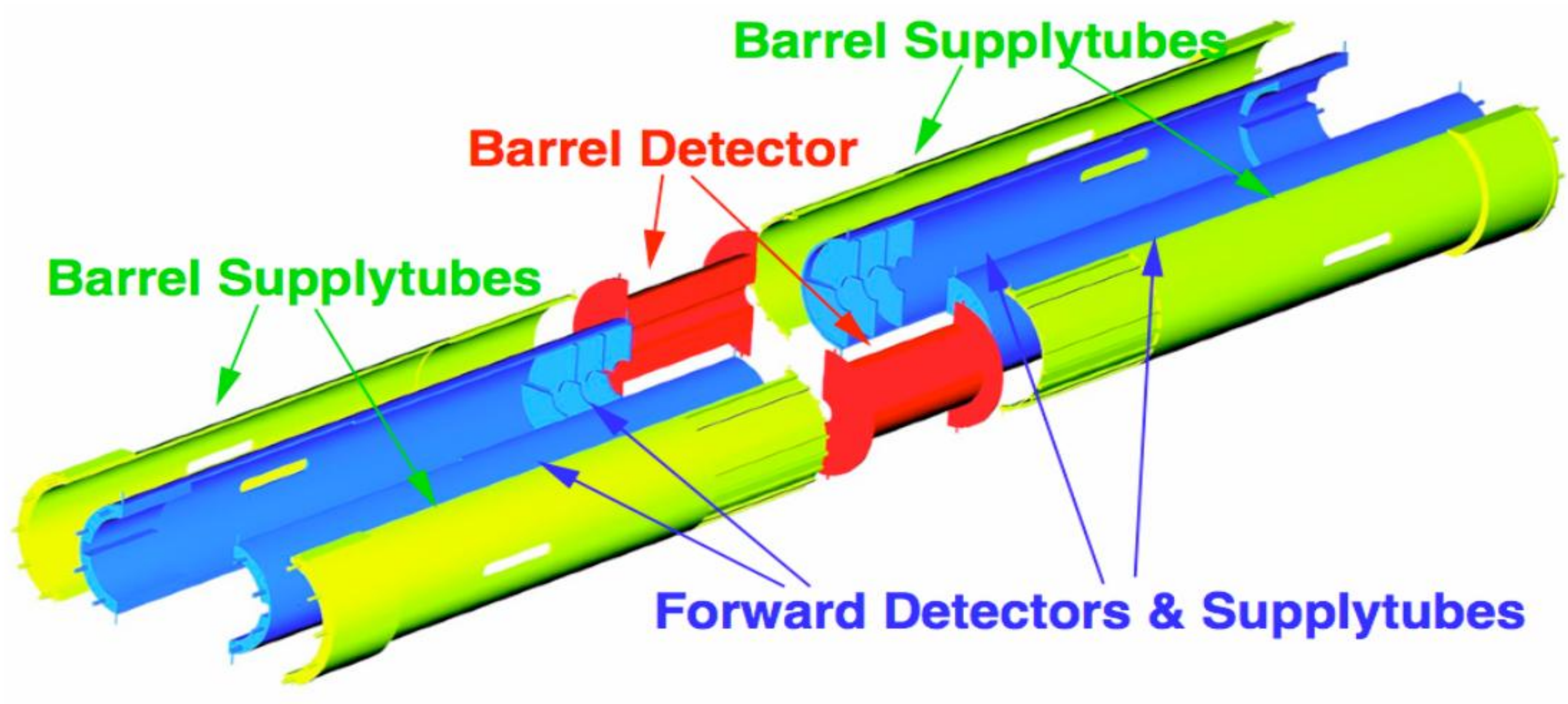




LBNL

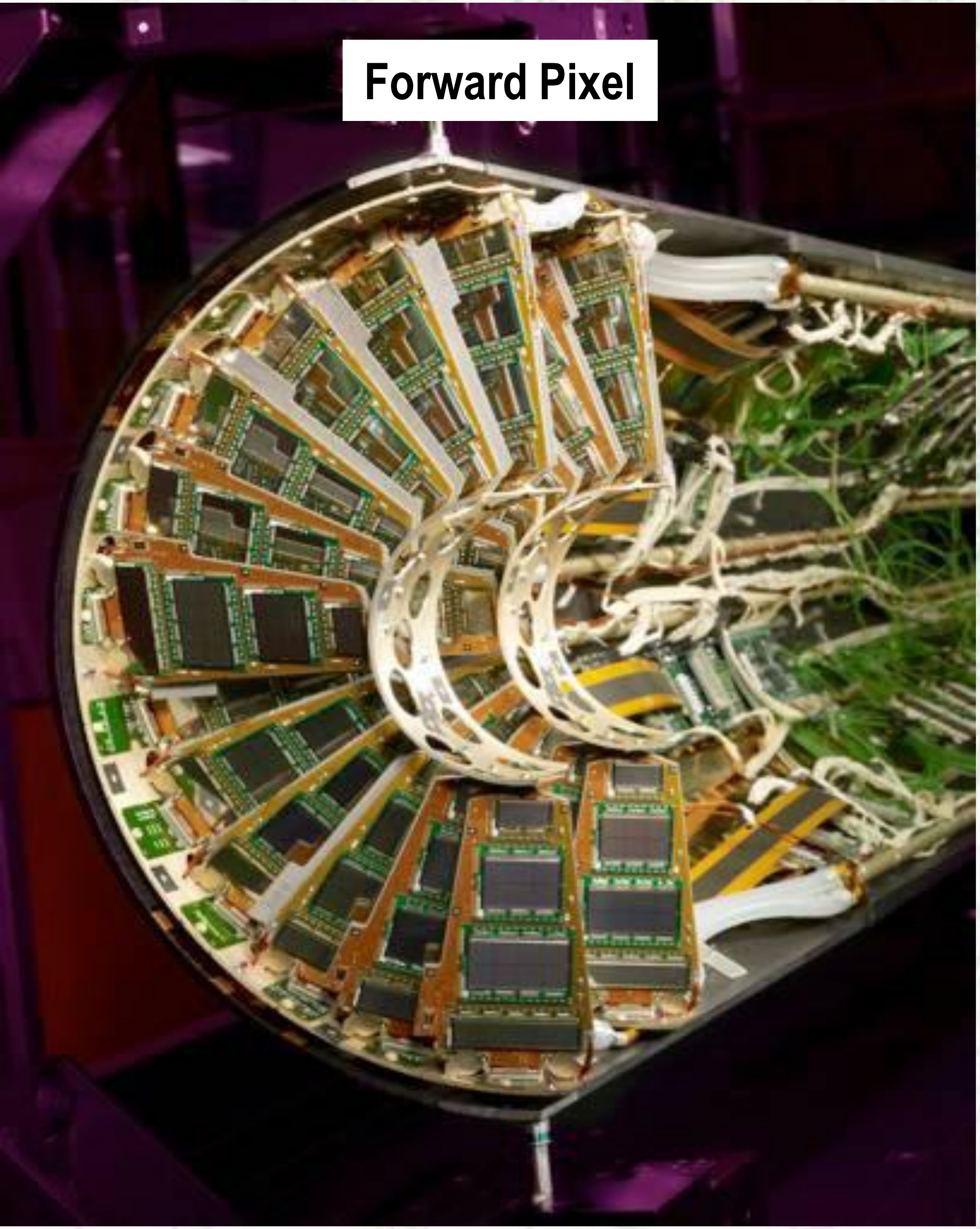
	Present detector + IBL	Double I-Beam
Number of channels	92 M	276 M
Global supports mass	8.3 kg	2.1 kg
Local supports mass	6.6 kg	5.6 kg (meas.)
Silicon mass equivalent of all mechanics	5.7 kg	2.8 kg
Sensor + chip mass	2.9 kg	4.4 kg (*)
Total silicon equivalent	8.7 kg	7.2 kg

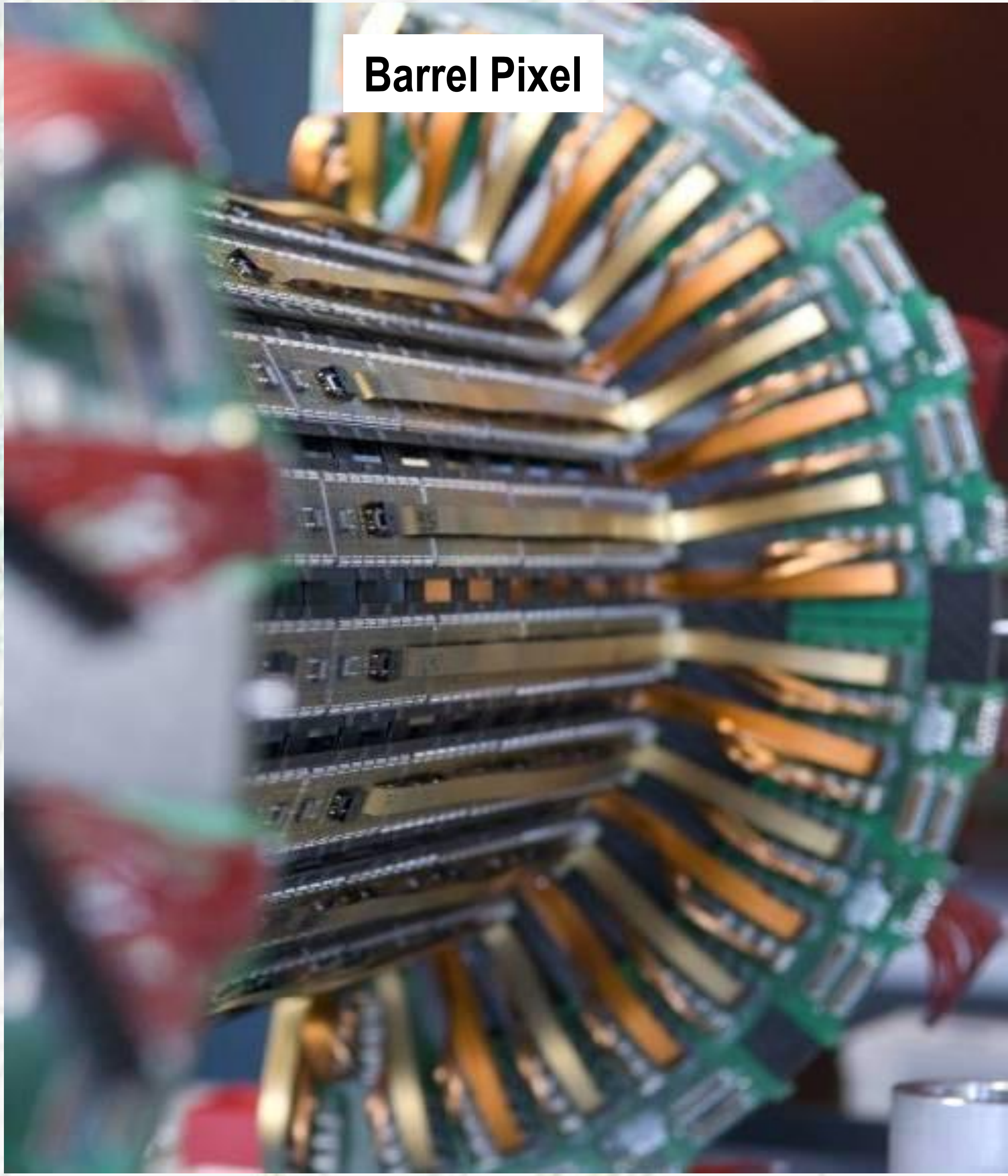
CMS Pixel System



- Designed for fast insertion (beam pipe bake out)
- Will be done in regular shutdown
- Can be replaced by improved system

Current CMS Pixel Detector



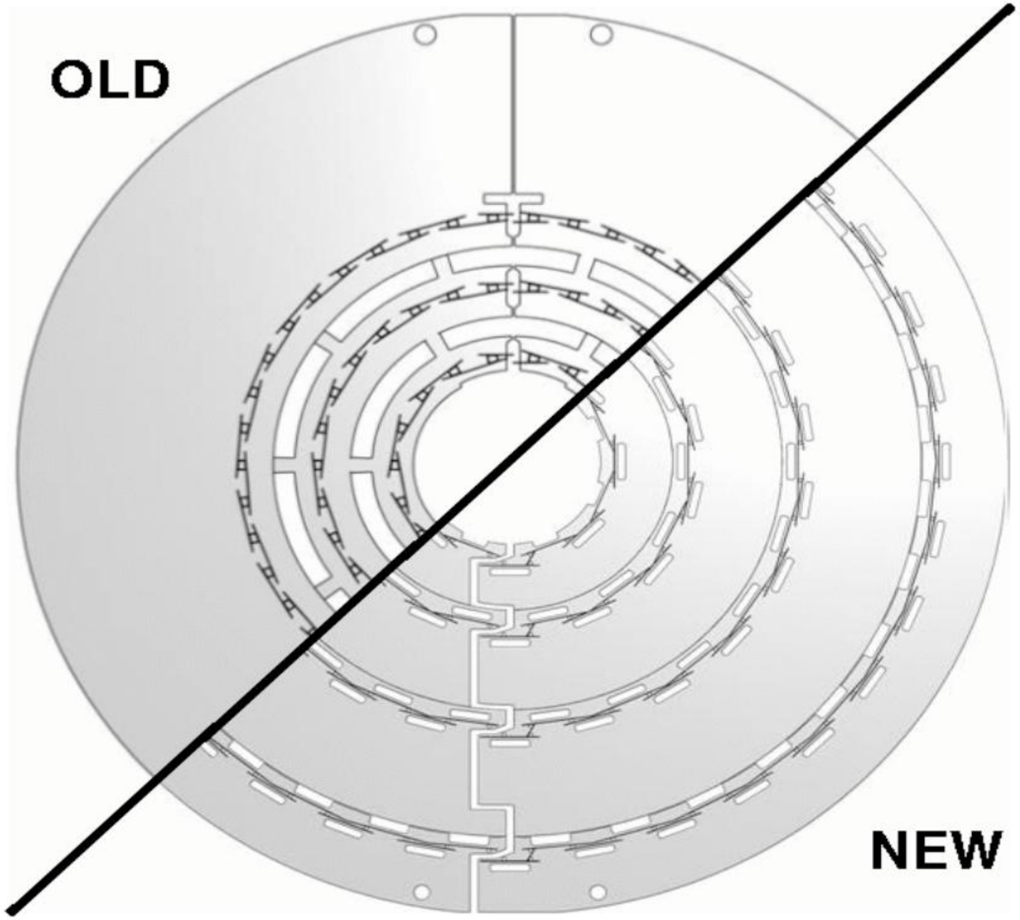


Mechanics of Barrel

Add 4th layer :

- layers @ 39,68,109 & 160 mm
- beam pipe clearance 4 mm
- 8 modules along z (1216 total)
- ‘ultra‘ light support structure

CO_2 based cooling system



Mechanics of Disks

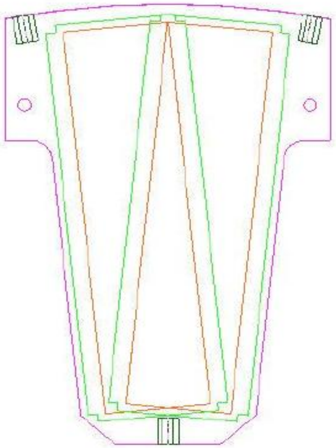
Inner & outer ring of blades

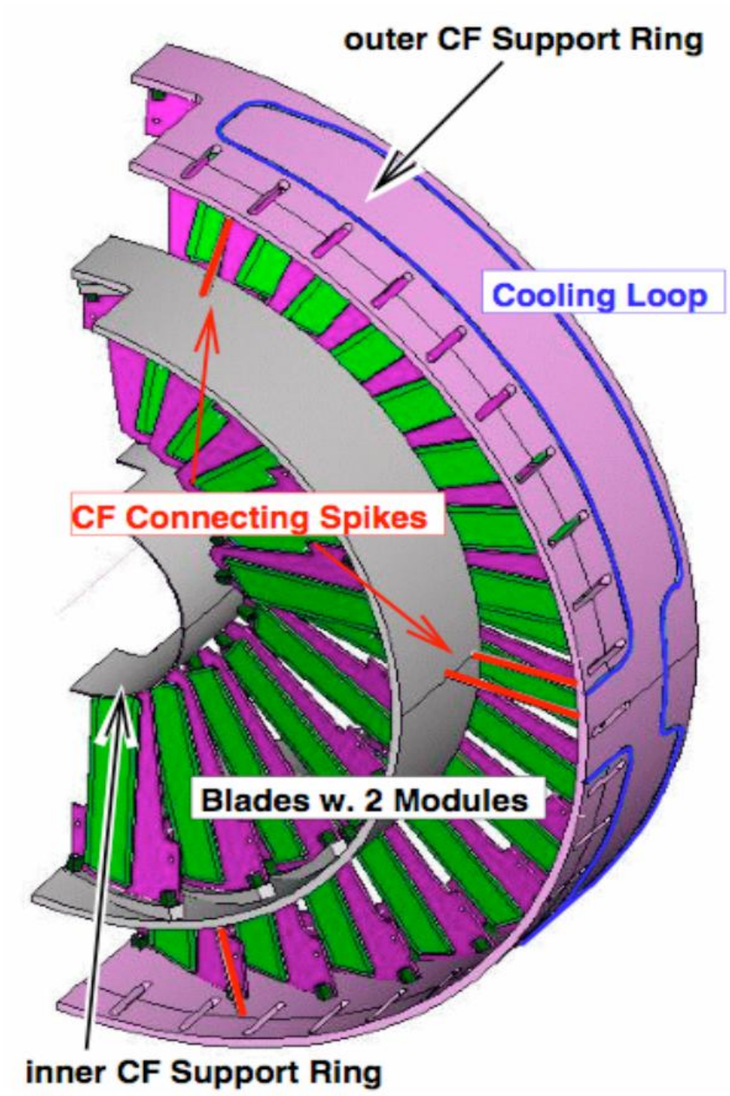
CO_2 tubes embedded in half disk support:

- support cylinder:
  - Carbon carbon
  - Grooves for cooling tube
  - Stainless steel tube:
  - 1.8mm OD, 100μm wall

Blades:

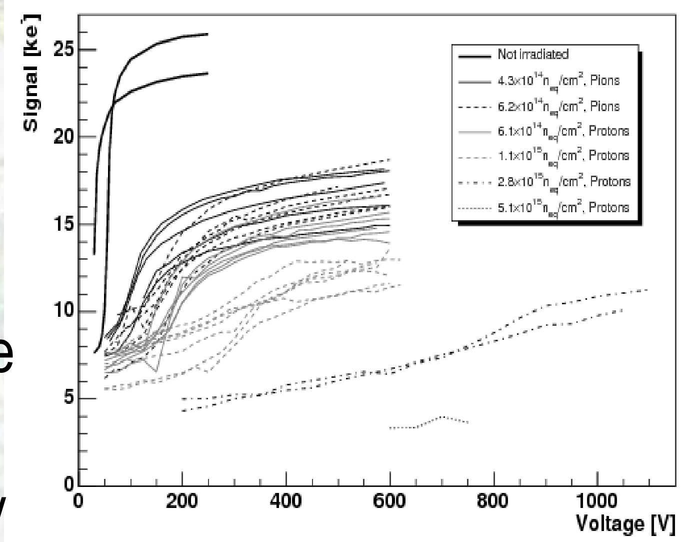
- all identical
- Rotated by 20° radial
- Tilted by 12° (inner ring)
- 2 modules per blade (ϕ overlap)
- individually replaceable

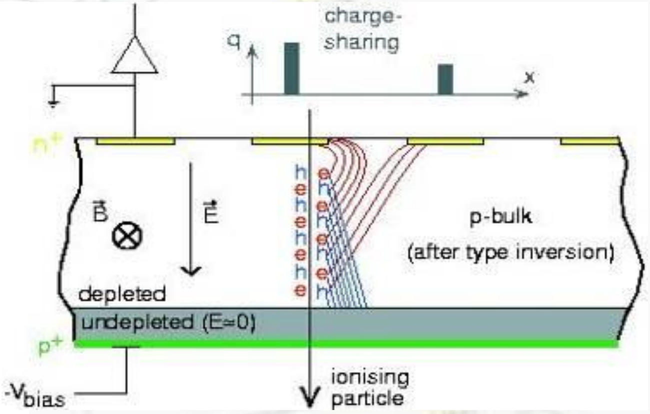


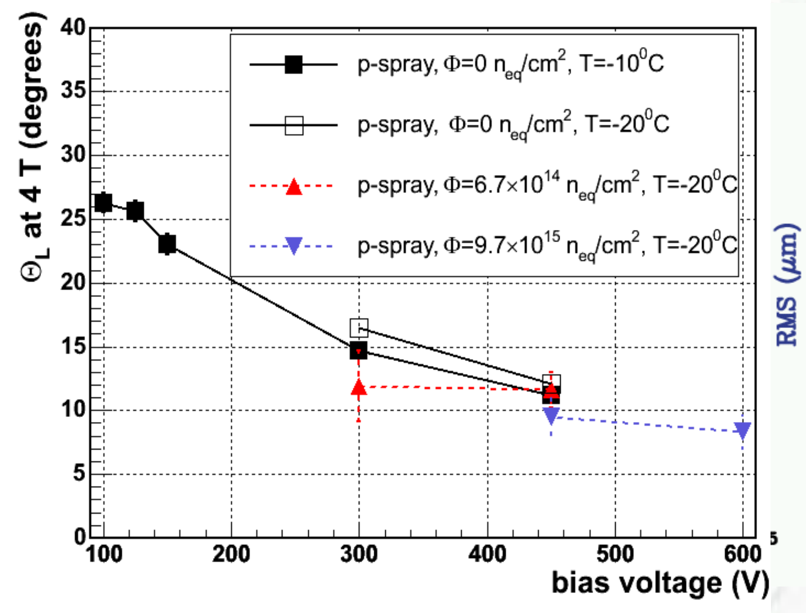


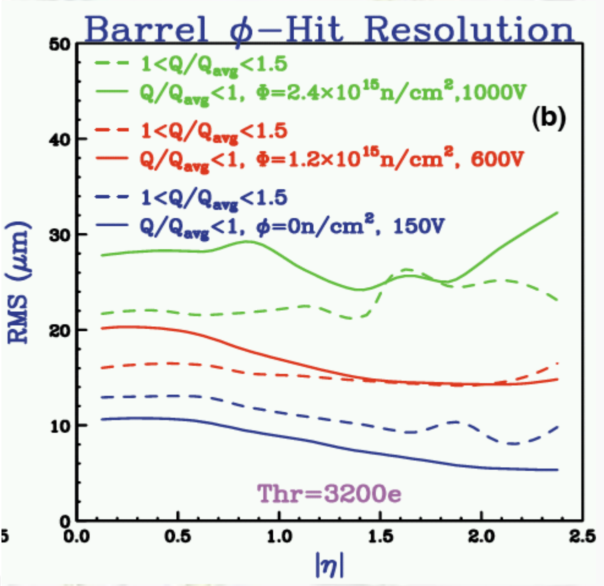
CMS Irradiation Results

- Highly irradiated sensors operative up to 1kV
- No signal saturation with bias for $\Phi > 2\times10^{15} n_{eq}/cm^2$
  - Is this a already a hint for charge multiplication?
- High electric field reduces mobility of charge carriers
- Lorentz angle is also reduced
- Fraction of double hits is reduced
- Resolution slowly degrades up to the binary value (pitch/sqrt(12) ~ 30μm with current pitch)



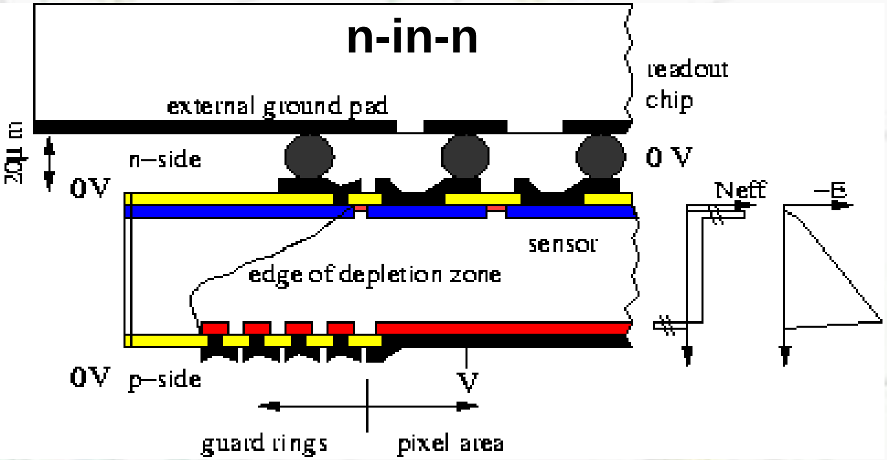


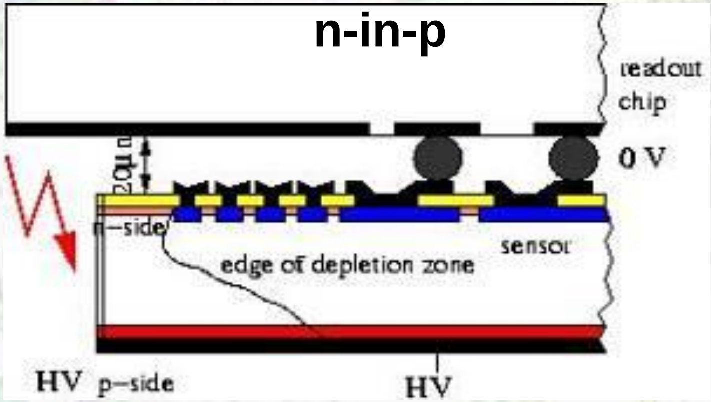


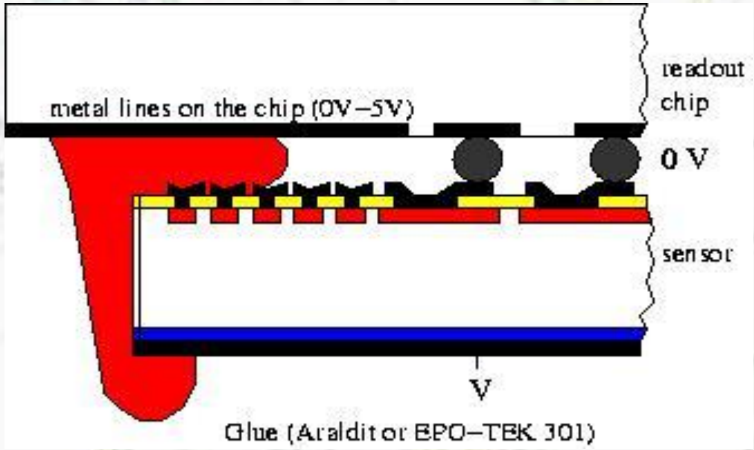


CMS Single-Sided (n-in-p) Sensors

- **Present CMS pixel detector uses n-in-n-sensors**
  - double sided processing (back side is structured)
  - all sensor edges at ground
  - most expensive part of the module (only bump-bonding is more expensive)
- **Exploring n-in-p sensors as alternative**
  - recent studies show radiation hardness
  - single sided process promise price benefit of factor 2-3
    - important as the pixel area will be doubled
  - Absence of guard rings on back side lead to fear of (destructive) sparking to the ROC

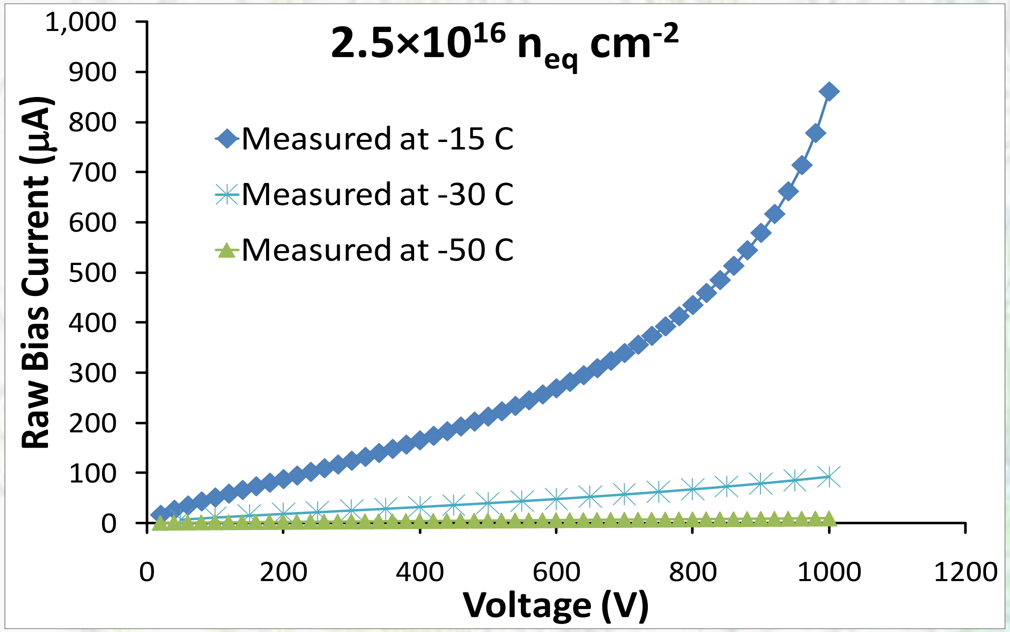


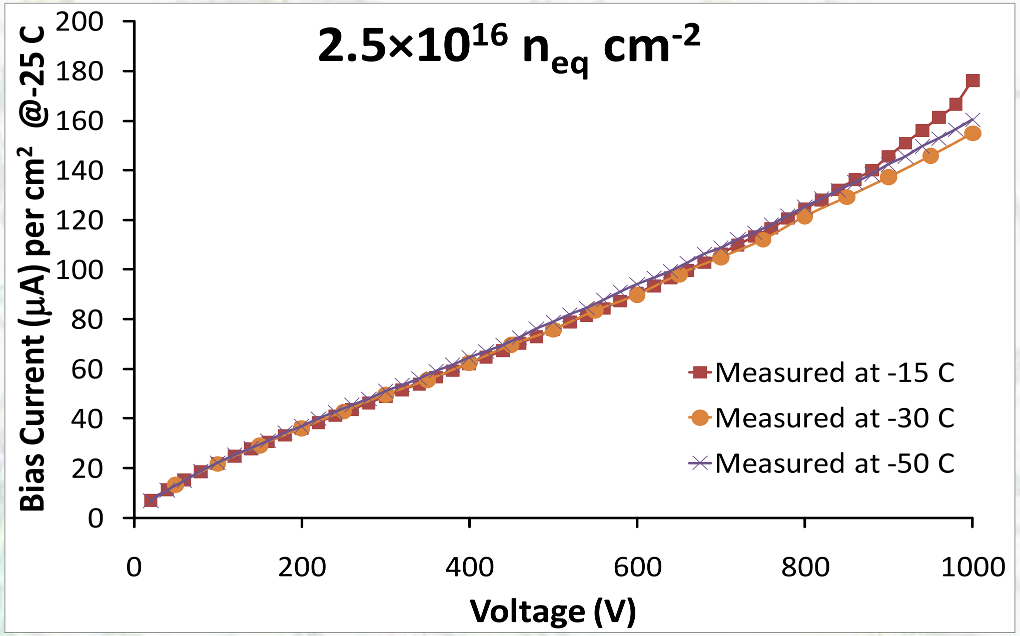




T. Rohe et al. Planar sensors for the upgrade of the CMS pixel detector, Pixel2020, Sep. 6-10, Grindelwald, CH

Heavily Irradiated Micron n-in-p Pixel Sensor IV



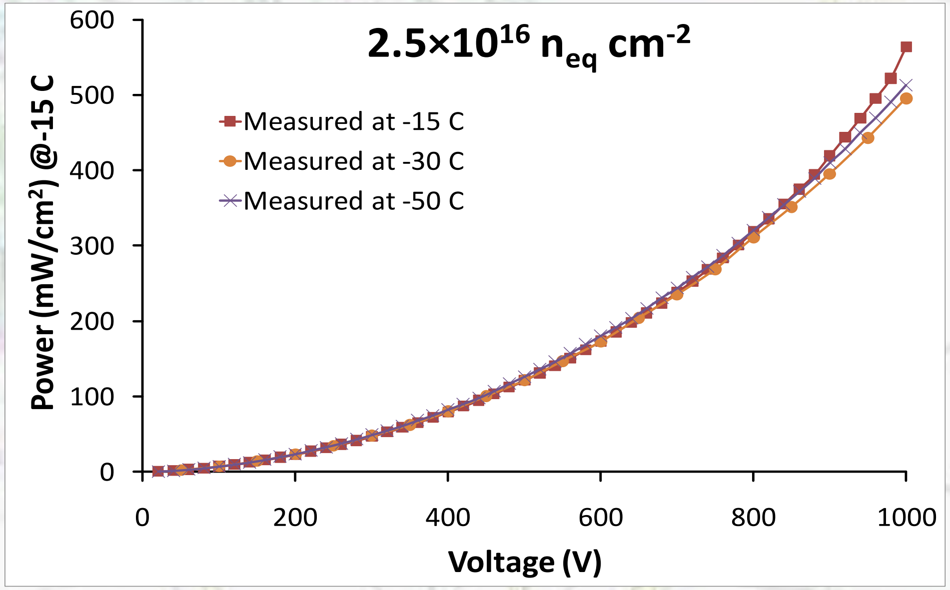


Thermistor glued to surface of detector and covered to reduce the coupling to air

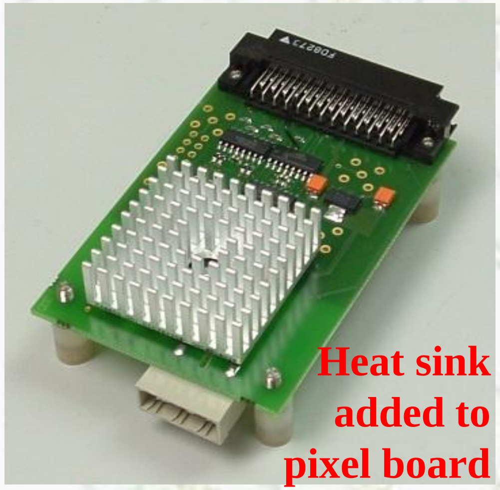
Found a 7 degree increase in sensor temperature during run at -15 C

After correcting the current point-by-point with standard temperature correction, all curves are consistent and straight

Previous planar p-type power over-estimated at 900 V by a factor of 2



Micron n-in-p Irradiated FE-I3 Pixel Package

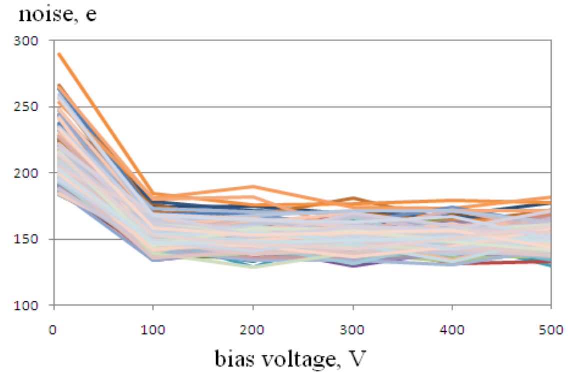


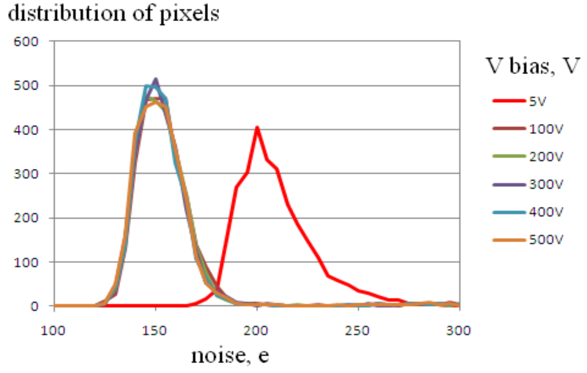
Heat sink added to pixel board

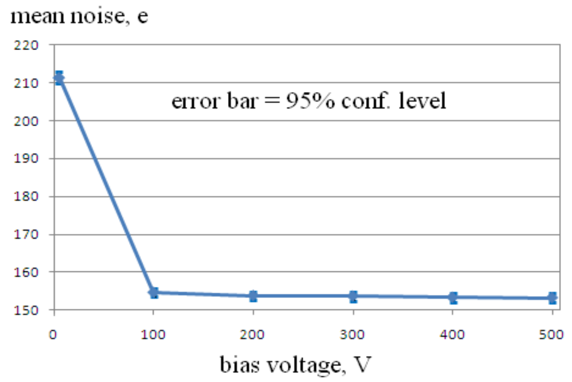
Measurements pre-irradiation and at doses of 4×10^{15} n$_{eq}$ cm^{-2} and 9×10^{15} n$_{eq}$ cm^{-2} all show no evidence of edge breakdown at 500V.

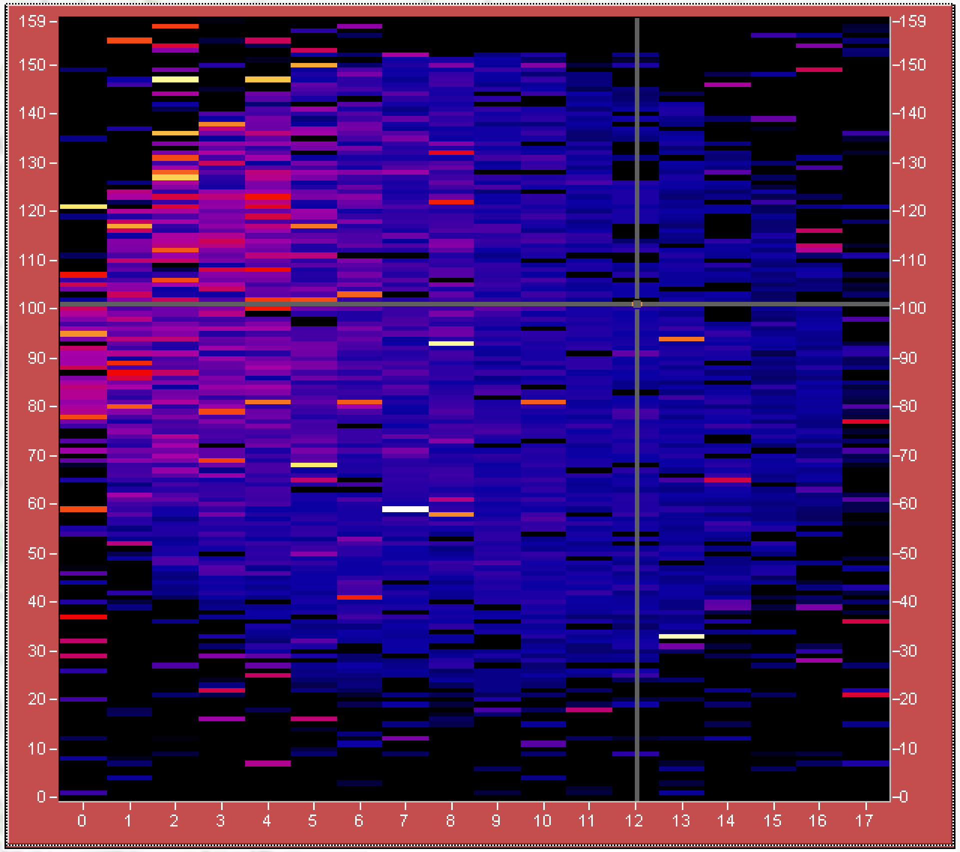
FE-I3 ASIC surprisingly robust but number of dead channels does increase at doses well above design target.

Hybrid #0 @50 deg. C

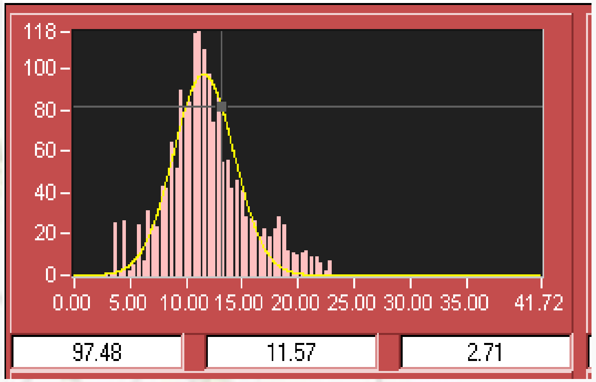








After irradiation to 1.5 ×10^{16} p/cm^2 At CERN PS (9×10^{15} n$_{eq}$ cm^{-2}) peak charge at 500V is ~4000e (Threshold 3500e -26 C, I$_b$ 44uA)

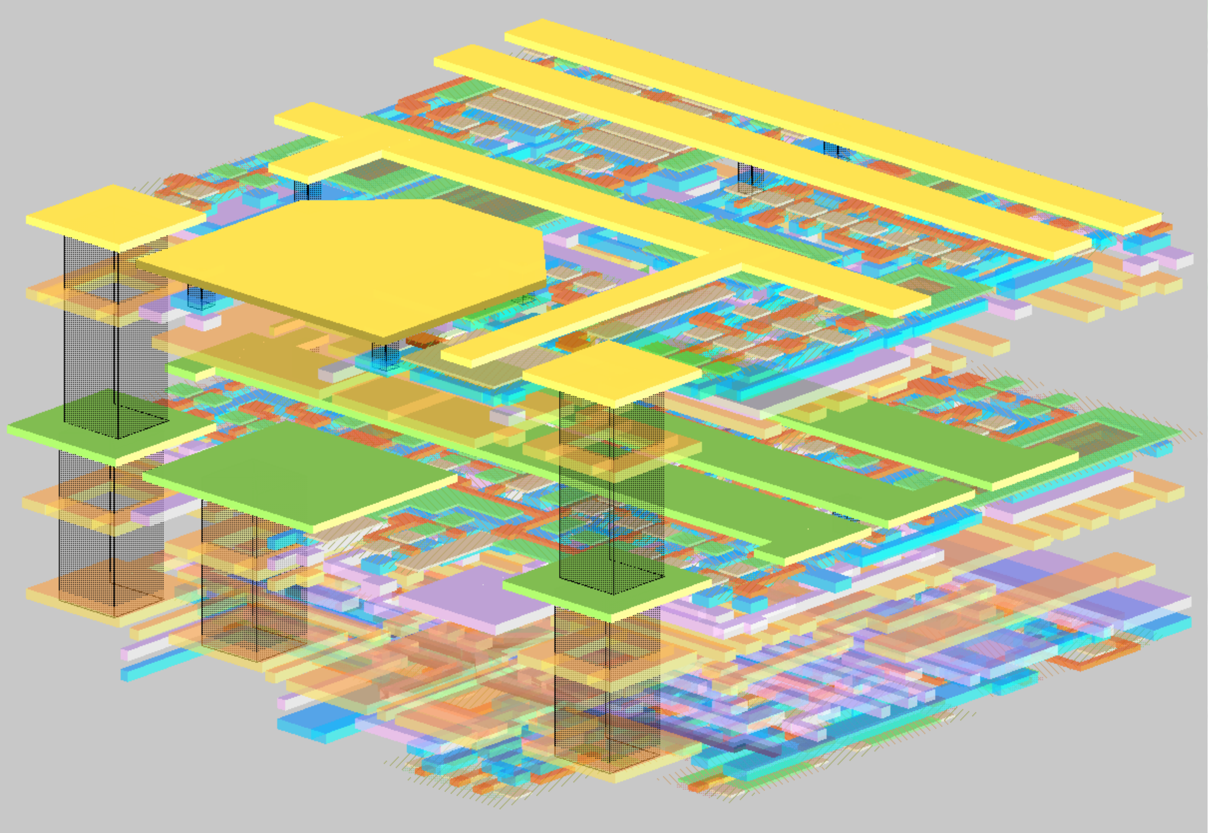


Ultimate Interconnection: Vertical Integration

Ideal solution for reducing material and easing assembly in detector system is to integrate electronics and sensors into a single item

… if affordable

- This has been a "dream" for many years
- More complex detectors, low mass
- Liberate us from bump/wire bonding



Many different aspects of these new technologies such as SLID (solid liquid inter-diffusion), TSV (through silicon vias), ICV (inter-chip vias) as well as more highly integrated concepts.

Commercial technologies becoming available for custom design:
IBM, NEC, Elpida, OKI, Tohoku, DALSA, Tezzaron, Ziptronix, Chartered, TSMC, RPI, IMEC……..

But are they all, or even, are any technologies radiation hard?

Conclusions

- **The current LHC experiments required order-of-magnitude greater size, speed, granularity and radiation hardness than previous experiments.**
- **Nevertheless, all LHC experiments are performing exceptionally well.**
- **LHC performance is exceeding expectations and hopes are high for 2010/11.**
- **By the end of the decade there should be enough to revolutionise our understanding of physics at the TeV scale.**
- **However, the effective energy reach and ability to consolidate discoveries at the LHC are both enhanced significantly by a high luminosity upgrade.**
- **With 3000fb^{-1}, the full potential of the LHC complex for energy frontier physics can be exploited.**
- **Such a super-LHC requires granularity and radiation hardness in the tracking detectors that are, again, a factor of 10 greater than before.**
- **A number of other future facilities are being actively planned, but some options will depend on the outcome of current experiments.**
- **Particle physics is poised on the brink of an era of unprecedented new discovery potential and technology development opportunities.**

Back-up Material

Introduction: What Everything is Made from

Distance

1 m

1 nm

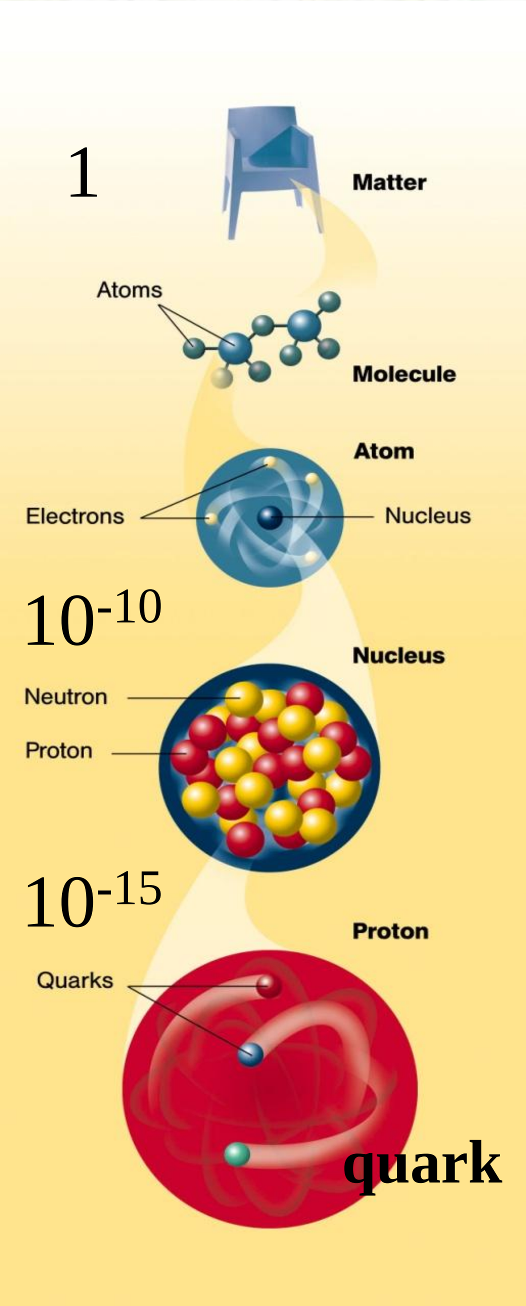
0.1 nm

10 fm

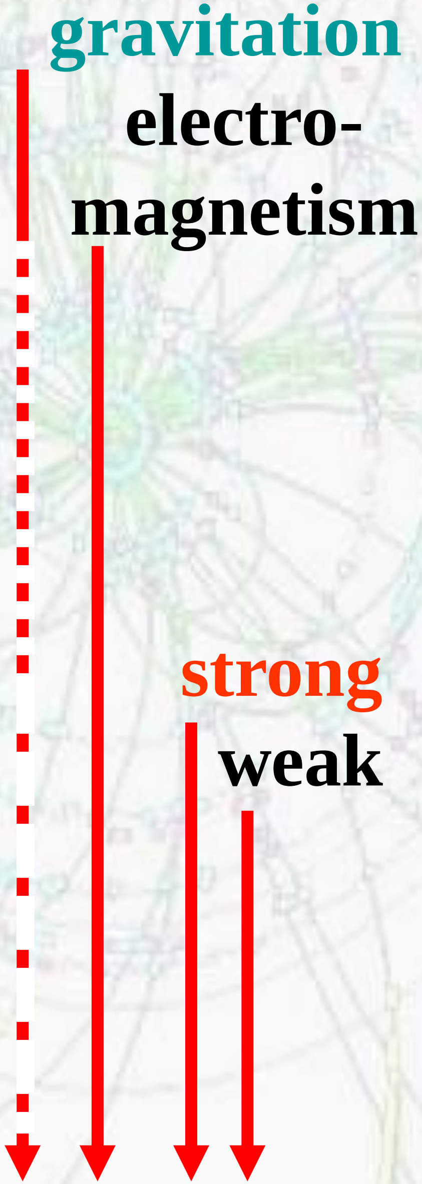
1 fm

<< 1 fm

? fm



Forces



gravitation

electro-magnetism

strong

weak

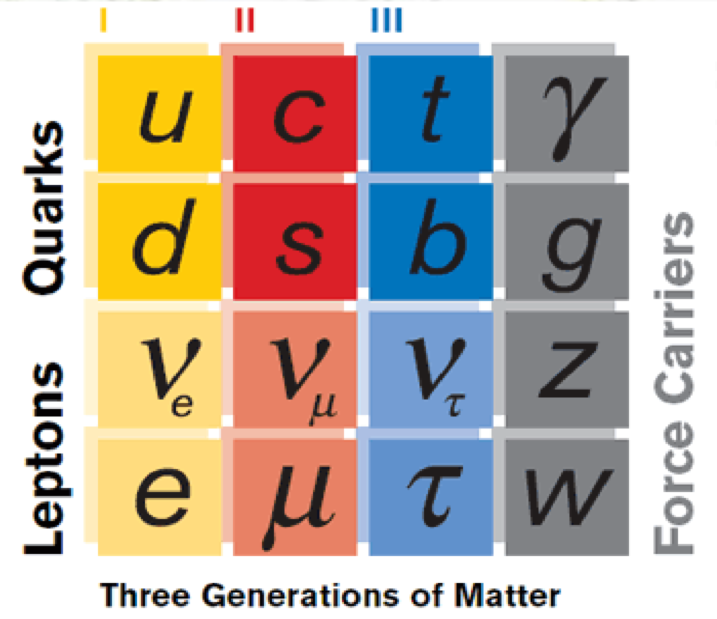
Energy	Radiation
0.01 eV	IR
0.1 eV	light
>1 eV	UV
10 keV	X-rays
1 MeV	α β γ
0.1 GeV	hadrons
1 GeV	partons
100 GeV	Z/W
TeV	?

The Standard Model

- Matter is made out of fermions:
  - 3 generations of quarks and leptons
- Forces are carried by Bosons:
  - Electroweak: γ,W,Z
  - Strong: gluons

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4958
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01644
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21582
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.376
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	172.4 ± 1.2	172.5

July 2008



Three Generations of Matter

Remarkably successful description of known phenomena:

- **predicted the existence of charm, bottom, top quarks, tau neutrino, W and Z bosons.**
- **Very good fit to the experimental data so far**

but ...

What We Don’t Know: the Higgs

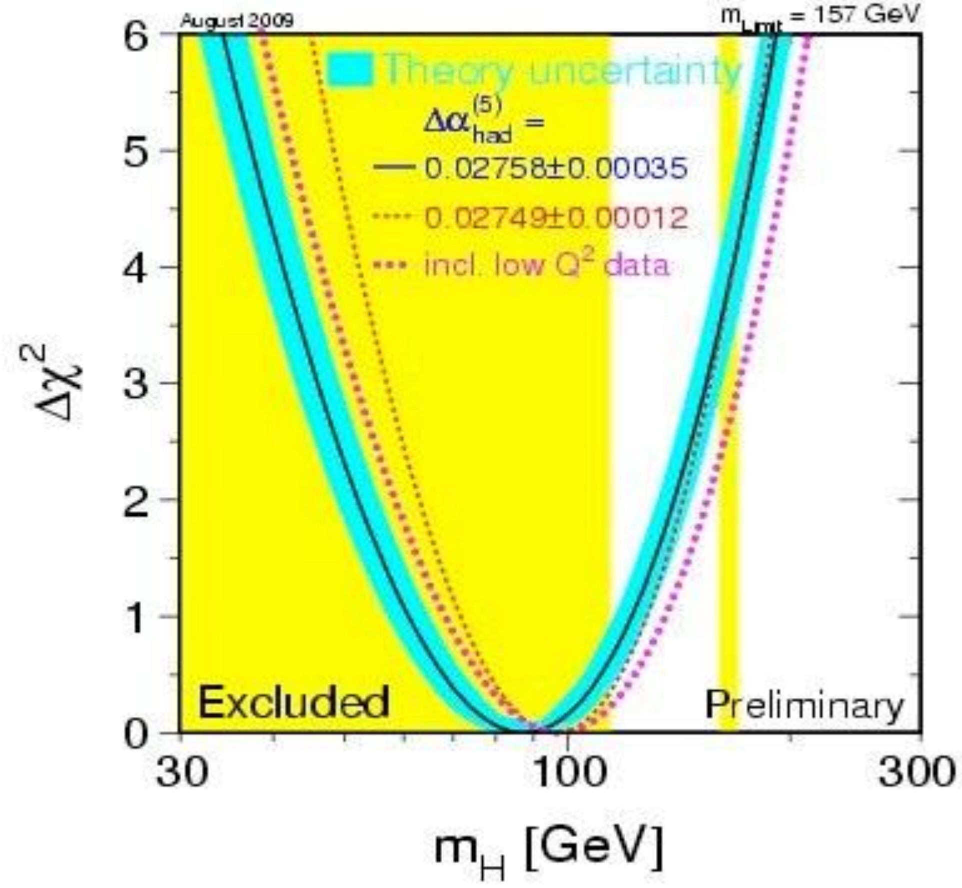
- **What is the origin of masses?**

  → Within SM, **Higgs field** gives mass to Particles (E-W symmetry breaking)
- SM predicts existence of a new massive neutral particle

  Not found yet!
- Theory does not predict its mass
- LEP limit: m_H>114 GeV @ 95% CL
- Indirect limit from EW data:

  - Preferred value: $m_H = 84^{+34}_{-26}$ GeV

  - m_H < 154 GeV @ 95% CL



with α_S (M_Z) = 0.1185 0.0026, $\Delta\alpha_S(5)_{had}$=0.02758 0.00035

WOULD THE HIGGS DISCOVERY COMPLETE OUR UNDERSTANDING OF NATURE ?

Beyond SM: the Unknown

The Standard Model is theoretically incomplete

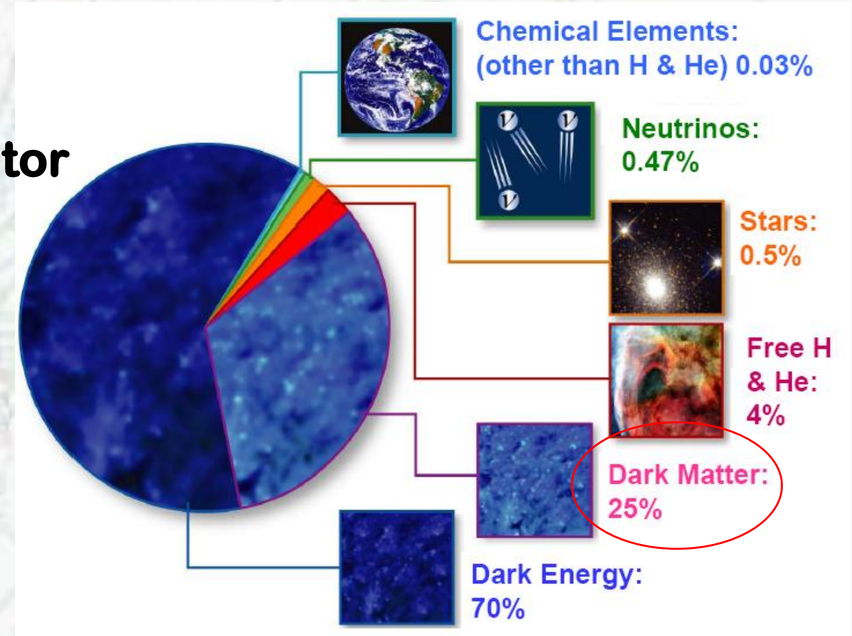
$\Delta m_H^2 \sim \Lambda^2$

$\Lambda = M_{pl}$?

- **Mass hierarchy problem**

→ radiative correction in Higgs sector

- **Unification**
- **Dark Matter**
- **Matter-antimatter asymmetry**

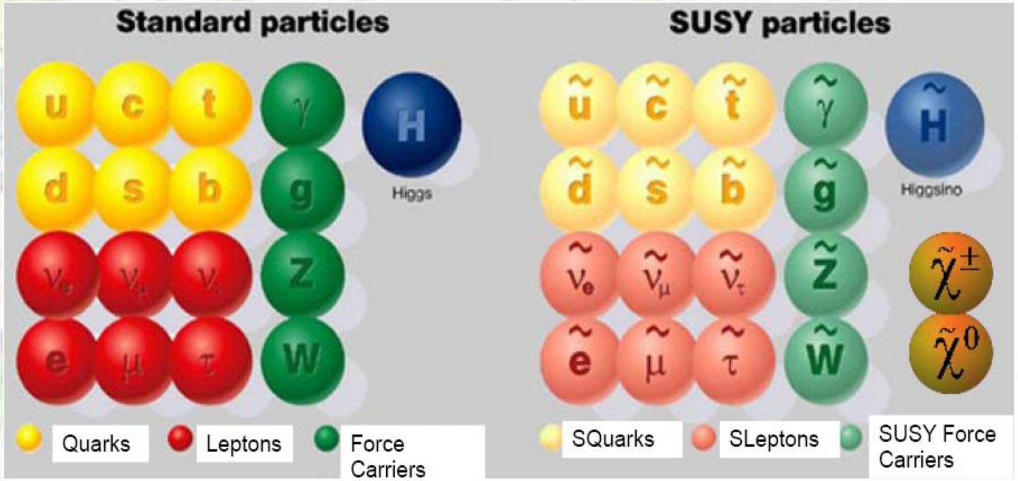


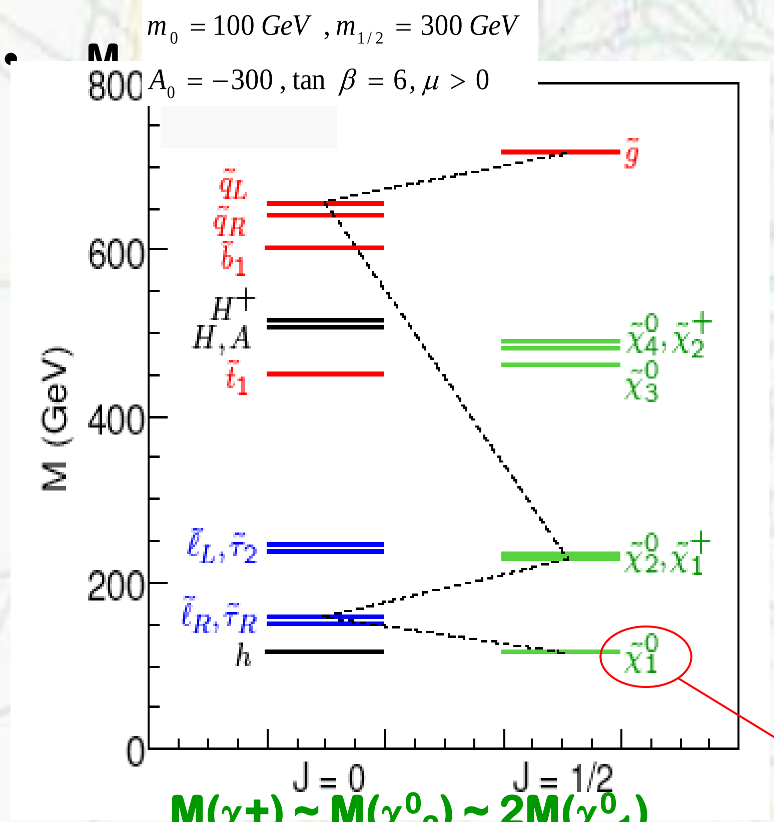
- Many possible new particles and theories
  - SuperSymmetry
  - Extra Dimension
  - New Gauge groups (Z’, W’)
  - New fermions (e*, t’, b’ …)
  - …

Can show up in direct searches or as subtle deviations in precision measurements

Search for SuperSymmetry

- **New spin-based symmetry relating fermions and bosons**
- **Minimal SuperSymmetric SM(MSSM):**
  - Mirror spectrum of particles
  - Enlarged Higgs sector: two doublets (5 physical states)
- **M**





$m_0 = 100\ GeV\ , m_{1/2} = 300\ GeV$

$A_0 = -300\ , \tan\ \beta = 6, \mu > 0$

$M(\chi+) \sim M(\chi^0_2) \sim 2M(\chi^0_1)$

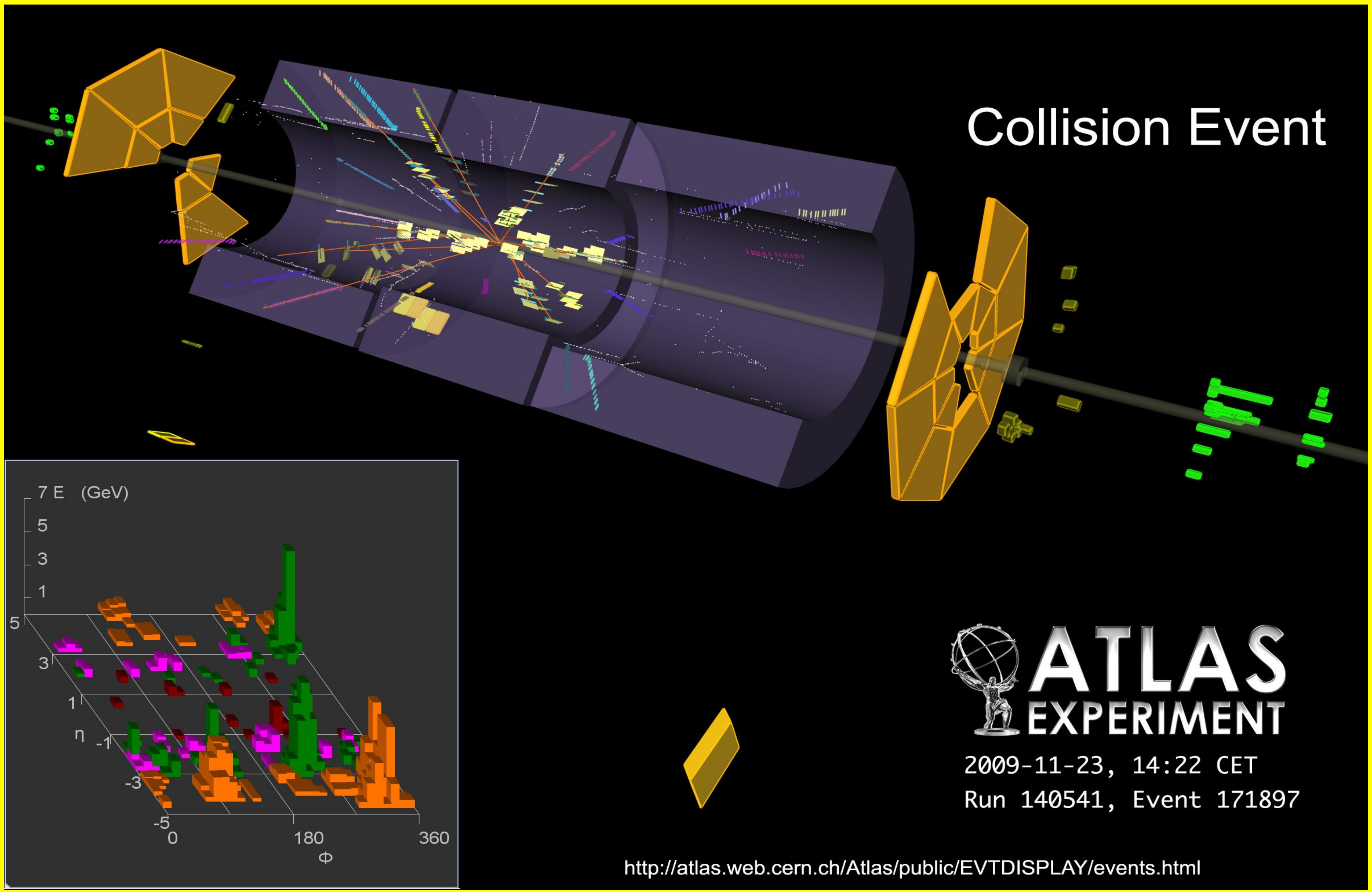
$M(\tilde{g}) \sim 3M(\chi+)$

- **Many searches but so far nothing seen and expected masses are above what could be probed at energies before the LHC**
  - charginos/neutralinos > 165 GeV
  - squarks > 390 GeV (all gluino masses)
  - gluinos > 280 GeV (all squark masses)
  - Selptons > 100 GeV
  - stop > 200 GeV
  - sbottom > 240 GeV
  - limits on new higgs

In this model, there is a spin-half partner to the photon that hardly interacts at all but is predicted to have the right range of masses and primordial densities to be the Dark Matter required by cosmologists.

Real data starting at last ….

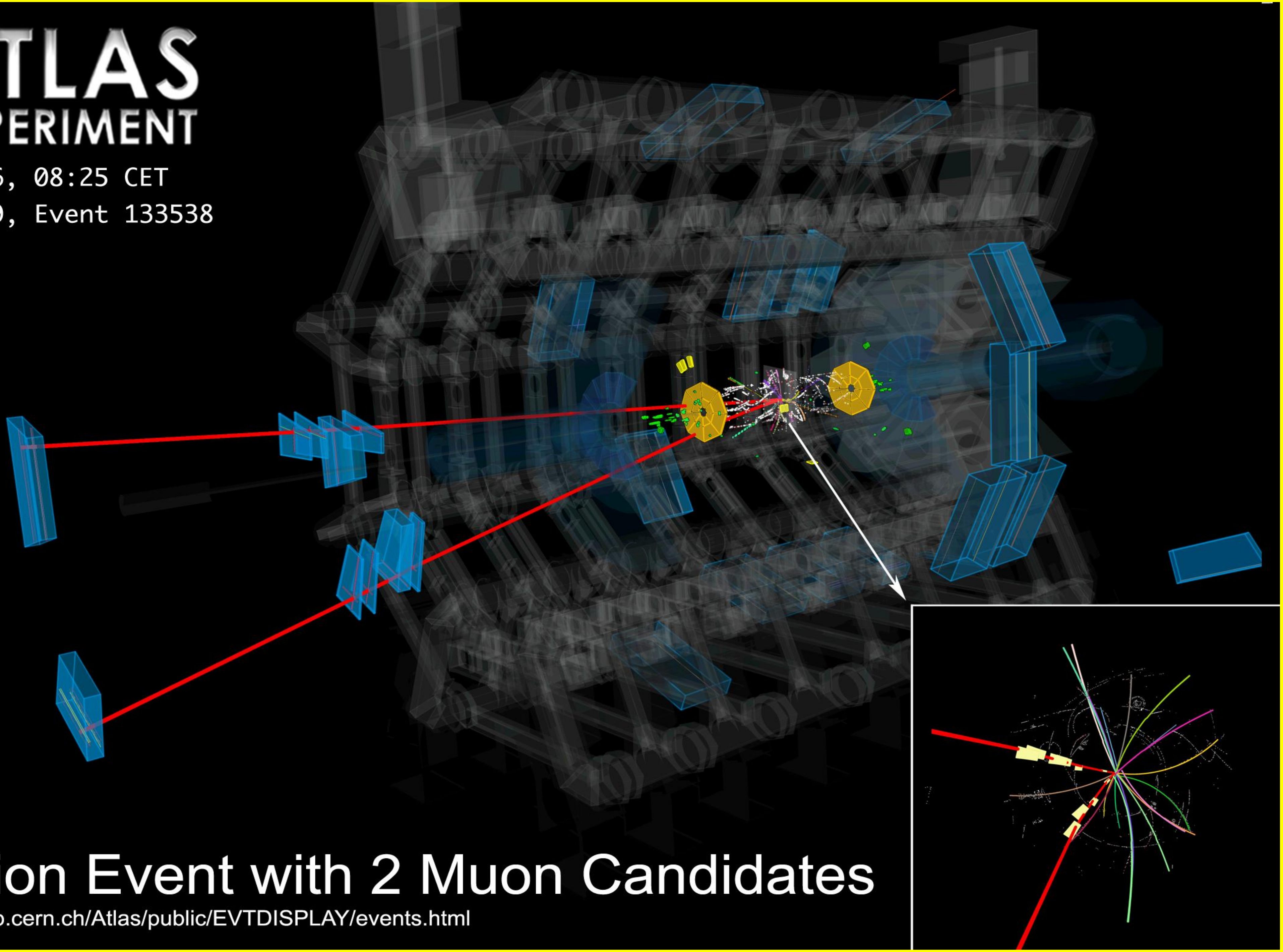
Monday 23 November: first collisions at $\sqrt{s}$ = 900 GeV !
→ ATLAS records ~ 200 events (first one observed at 14:22)



2009-11-23, 14:22 CET
Run 140541, Event 171897

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

ATLAS EXPERIMENT

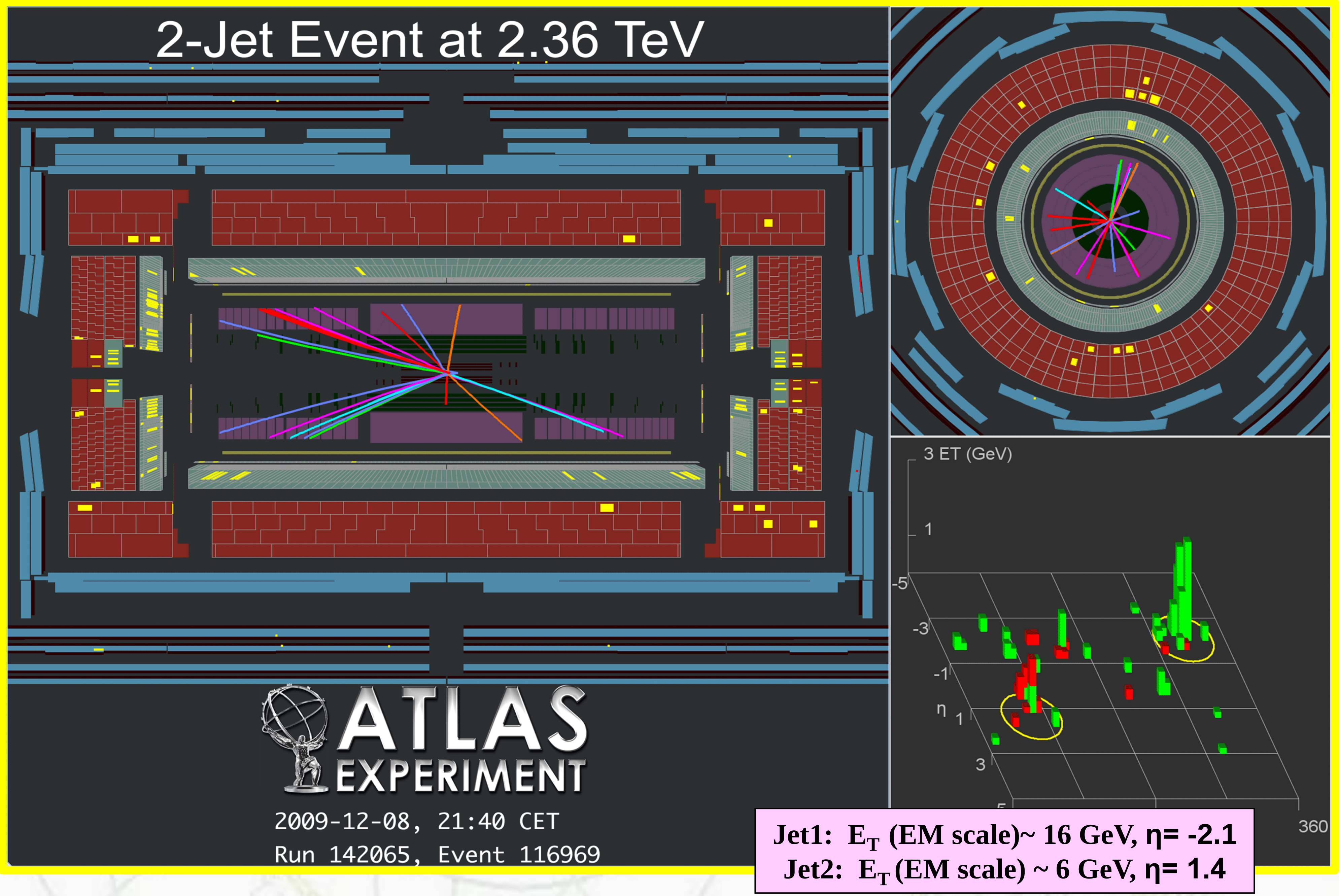


2009-12-06, 08:25 CET
Run 141749, Event 133538

Collision Event with 2 Muon Candidates

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

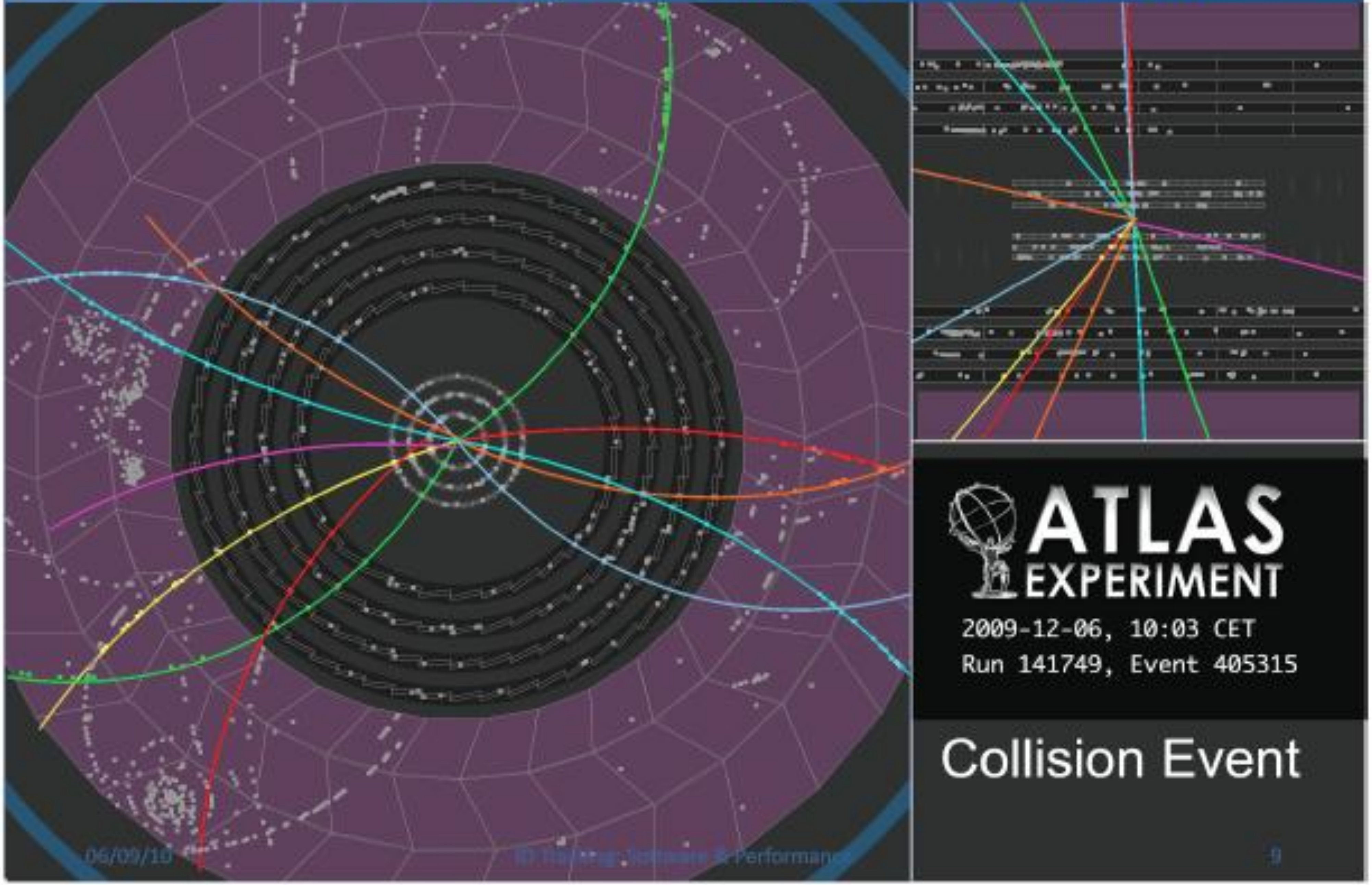
8, 14, 16 December: collisions at $\sqrt{s}$ = 2.36 TeV (world record energy)
→ATLAS records ~ 34000 proton-proton collision events



2009-12-08, 21:40 CET
Run 142065, Event 116969

Jet1: E_T (EM scale)~ 16 GeV, η= -2.1
Jet2: E_T (EM scale) ~ 6 GeV, η= 1.4

Collisions with ID Fully Powered…



Physics Reach at the LHC

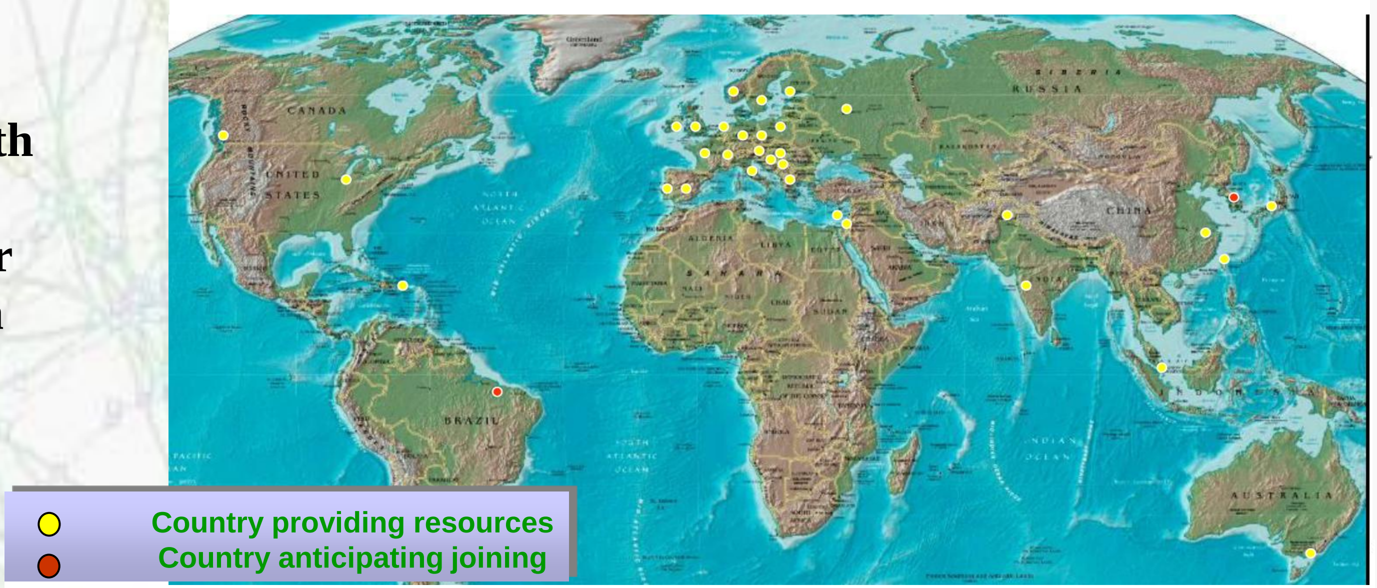
The challenge of the LHC is to cope with proton-proton collisions at GHz rates leading to up to 10^{16} collision events per year, but where only a tiny fraction can be sensibly recorded

Most events do not correspond to the proton's constituents undergoing the head-on collisions that have the energies to make new particles

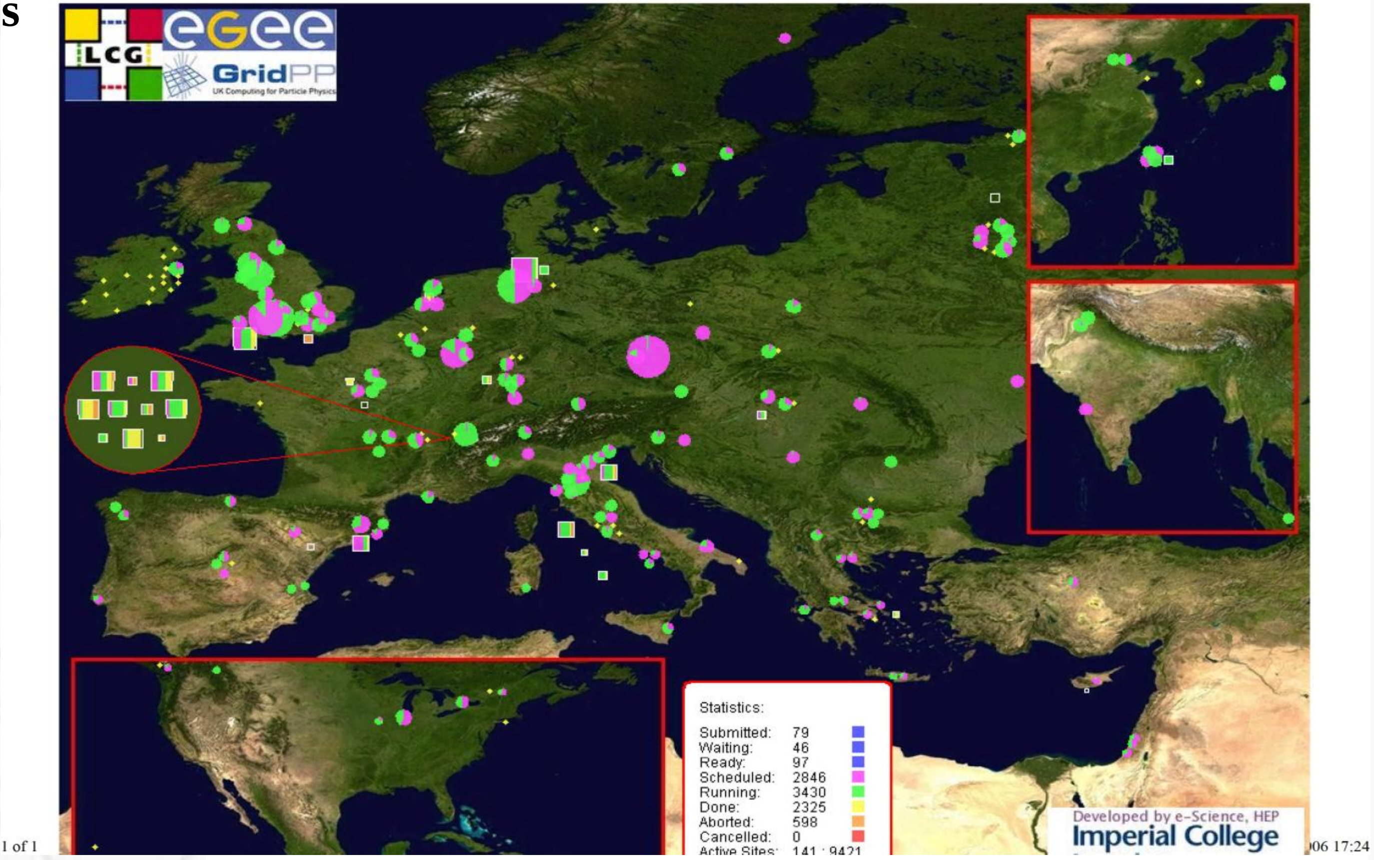
Requires factors of several million fast, on-line, intelligent data filtering

Even then, many tens of Petabytes per year need storing and processing

→ Worldwide LHC Computing Grid (WLCG of 100,000 processors at over 130 sites in 34 countries http://lcg.web.cern.ch/LCG/public/)

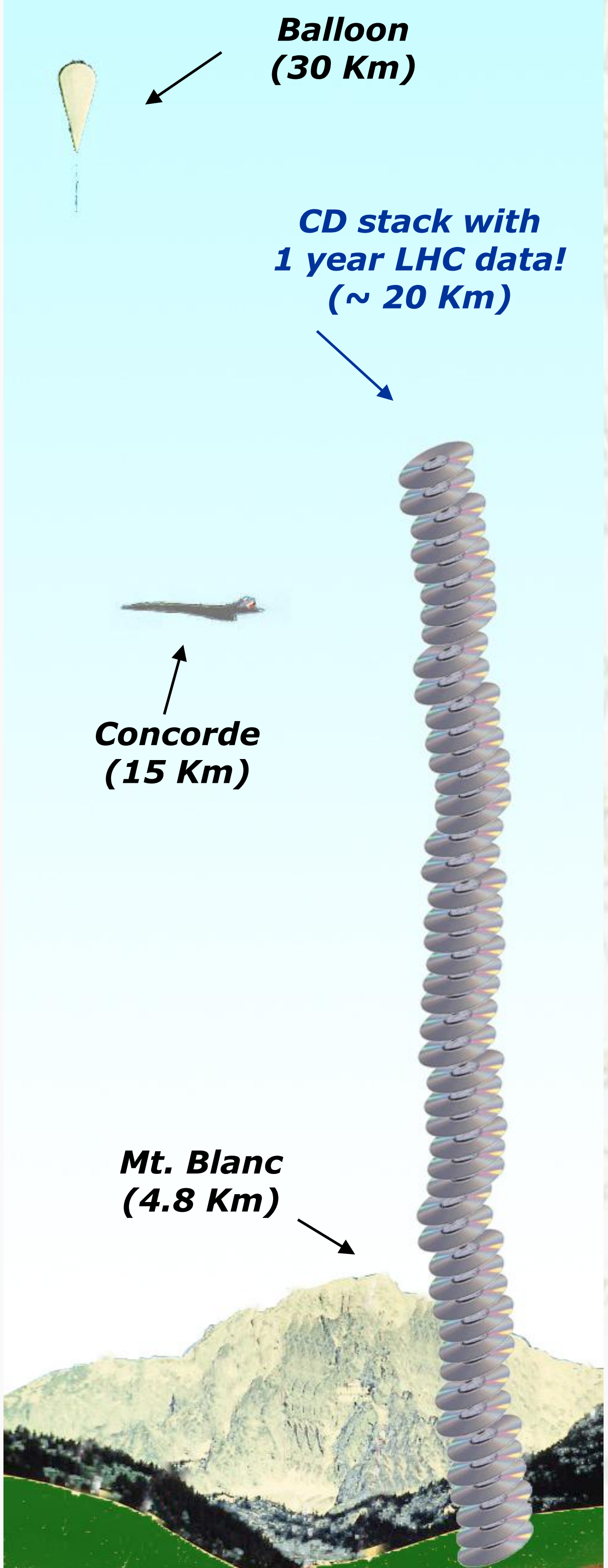


○ Country providing resources
● Country anticipating joining



Statistics:

Submitted: 79 🟦
Waiting: 46 🟦
Ready: 97 🟦
Scheduled: 2846 🟪
Running: 3430 🟩
Done: 2325 🟨
Aborted: 598 🟧
Cancelled: 0 🟥
Active Sites: 141 : 9421



Balloon (30 Km)

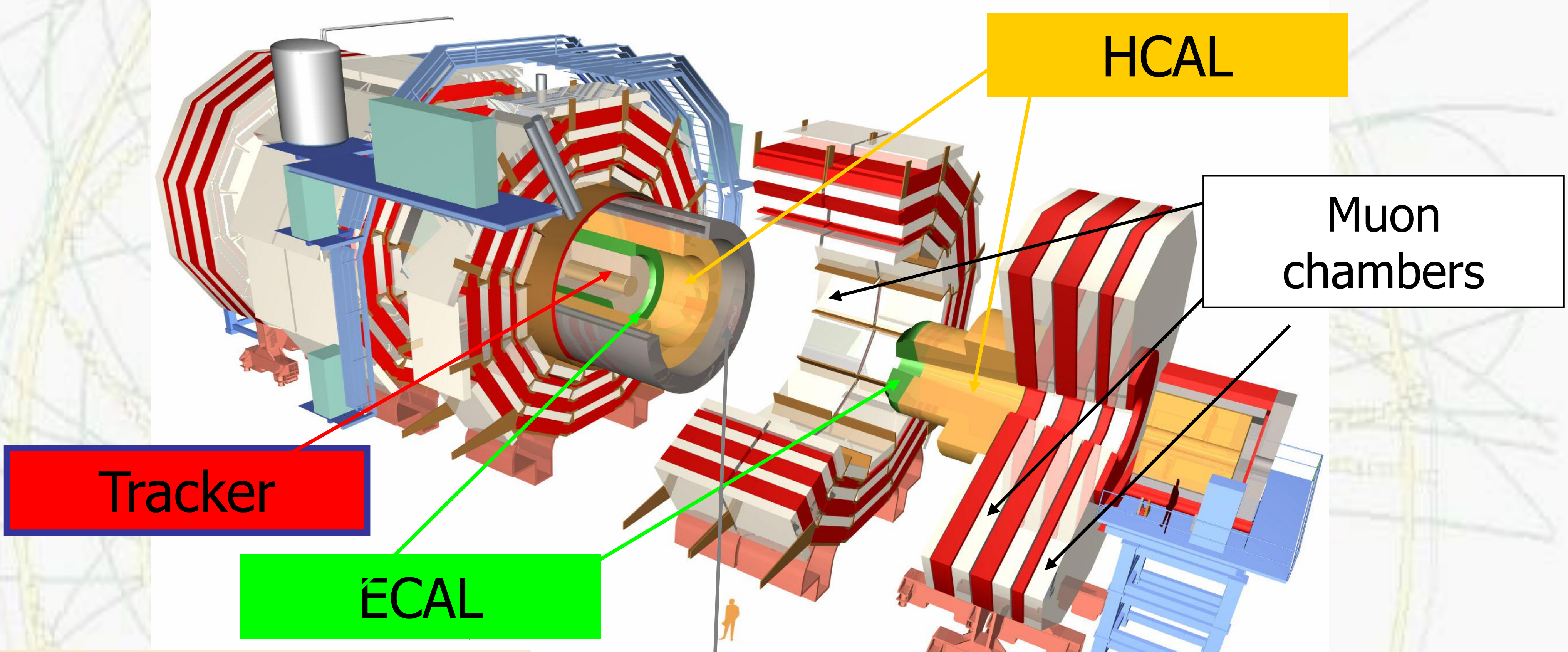
CD stack with 1 year LHC data! (~ 20 Km)

Concorde (15 Km)

Mt. Blanc (4.8 Km)

CER N: LHC Computing Grid Tier-0

CMS: The Compact Muon Solenoid



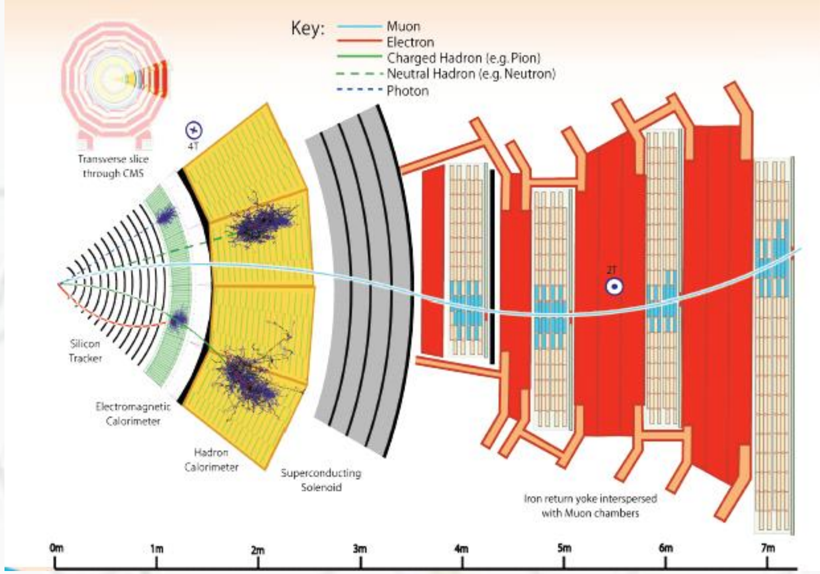
HCAL

Muon chambers

Tracker

ECAL

4T solenoid



Total weight: 12,500 t
Overall diameter: 15 m
Overall length 21.6 m
Magnetic field 4 T

Examples of Expected Physics Gain

(Physics case for **3000 fb^{-1}** much better known after LHC first data analysed)

See Eur. Phys. J. C39(2005)293

- Precision Standard Model physics with up to 10 data (sensitive to new physics)
  - Higgs couplings (eg $\mu^+\mu^-$) and sensitivity to self-couplings
  - Triple and quartic gauge couplings
  - Strongly coupled vector-boson scattering (if there is no Higgs)
  - Rare top decays through FCNC

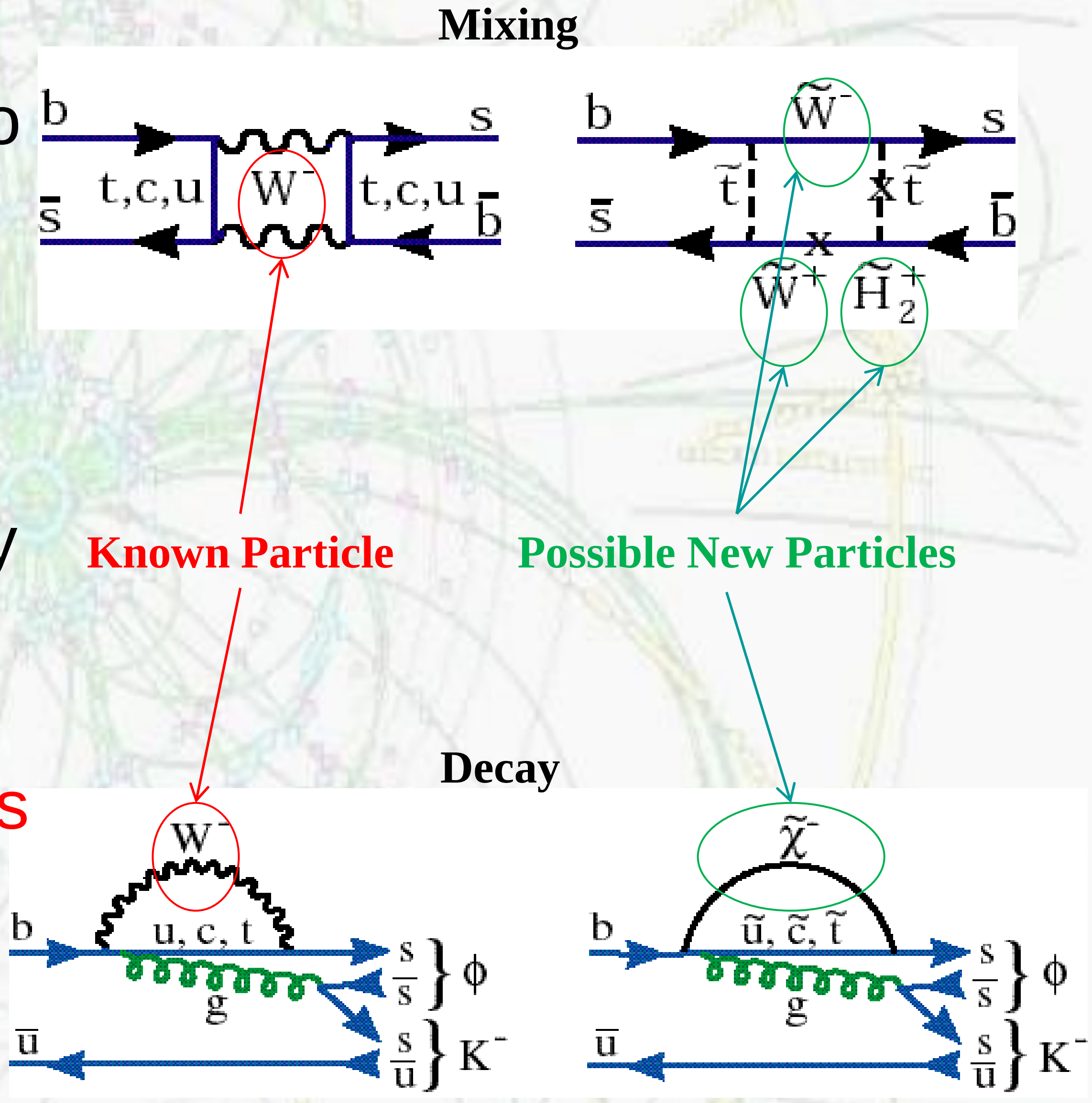
- Extended mass reach for new particles (by additional ~0.5 to 1 TeV):
  - Heavy Higgs-bosons, extra gauge bosons, resonances in extra-dimension models, SuperSymmetry particles (if relatively heavy).

- SuperSymmetry (if relatively light, already discovered at LHC)
  - complete the particle spectrum
  - access rare decay channels and measure branching ratios
  - improve precision (e.g. to test against WMAP results)

- Because of statistics and mass reach, SLHC is to a large degree complementary to Linear Collider – LHC/SLHC can pair produce particles of ≥ TeV masses which couple predominantly through the strong interaction.

Upgraded LHCb Reach

- To study even rarer processes need to upgrade the detector to cope with multiple interactions per beam crossing (Go from short strips to 55μm×55μm pixels)
- Look for consequences for b-decays of new physics possibly found by ATLAS or CMS
- Upgrading will allow us to precisely measure these effects
- Complementary to studies possible using ATLAS and CMS and with other future proposed facilities eg “SuperB”


Mixing

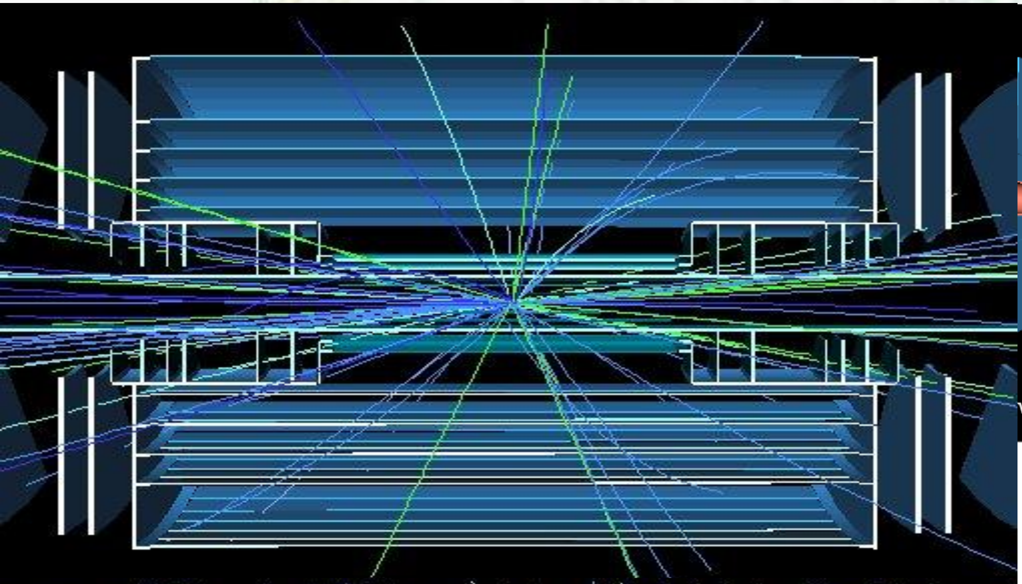
Known Particle

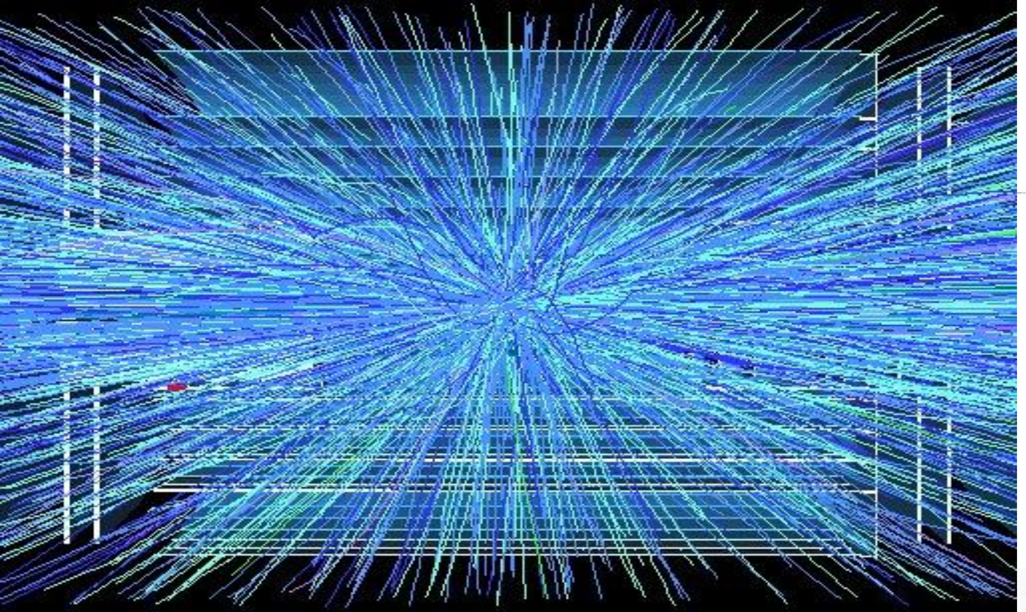
Possible New Particles

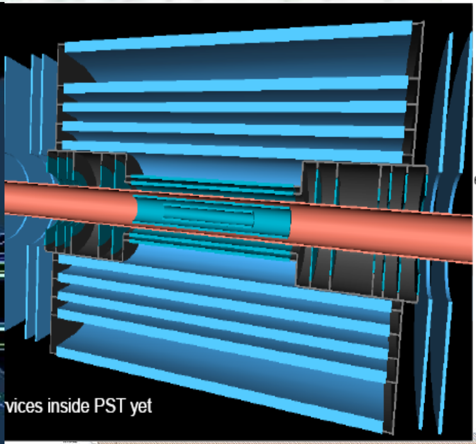
Decay

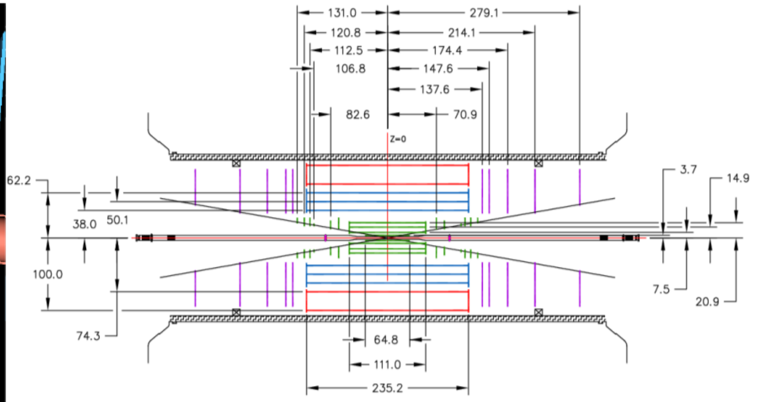
ATLAS Tracker Upgrade Layout

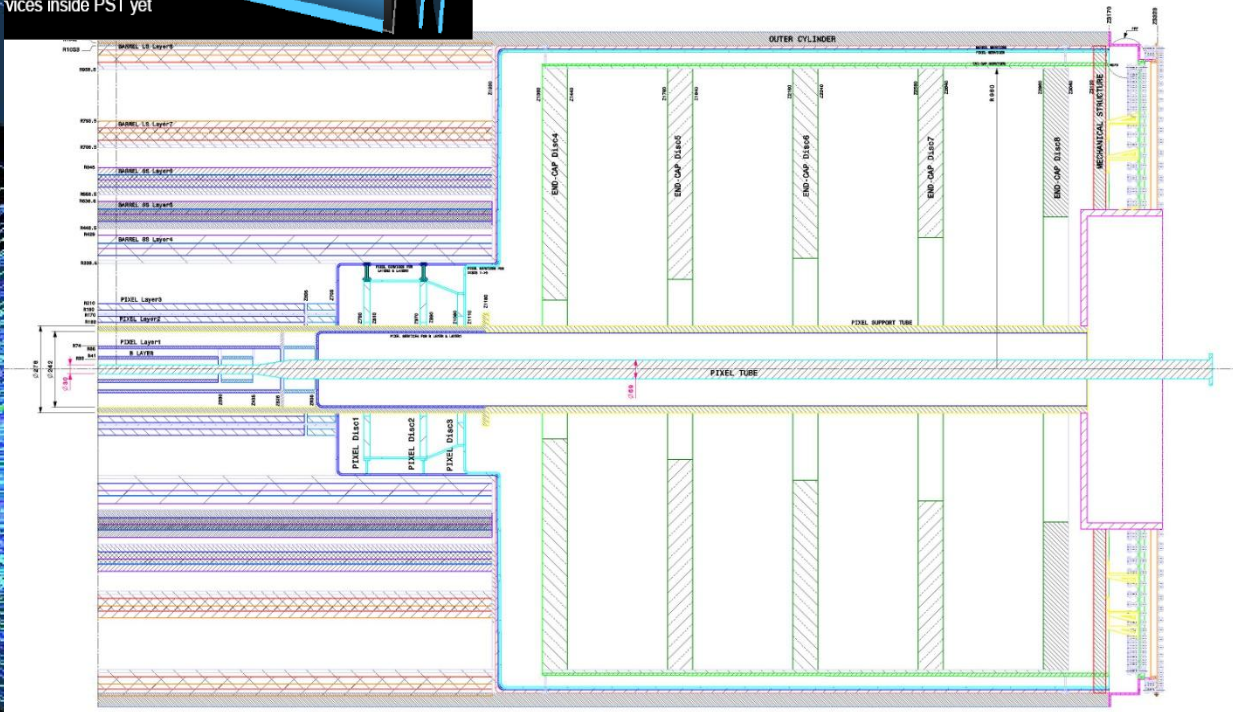
Barrel Pixel Tracker Layers: r = 3.7cm, 7.5cm, 15cm, 21cm
Short Strip (2.4 cm) μ-strips (stereo layers): r = 38cm, 50cm, 62cm
Long Strip (9.6 cm) μ-strips (stereo layers): r = 74cm, 100cm



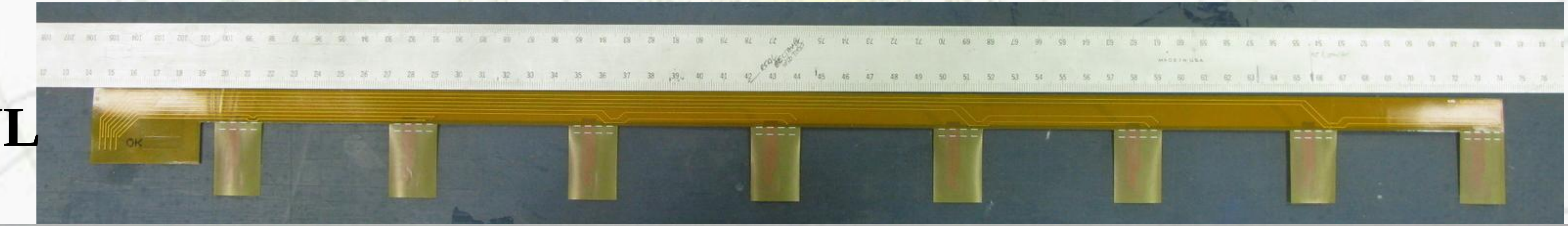


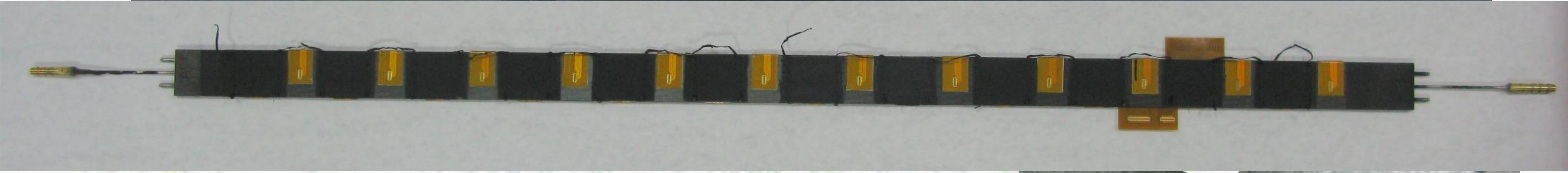




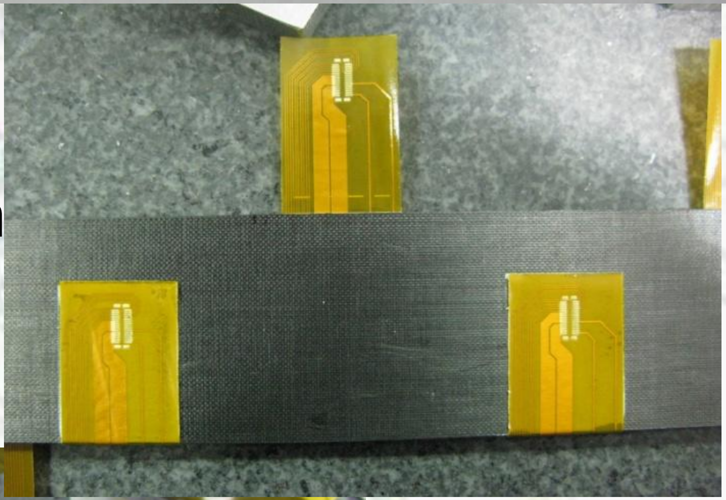


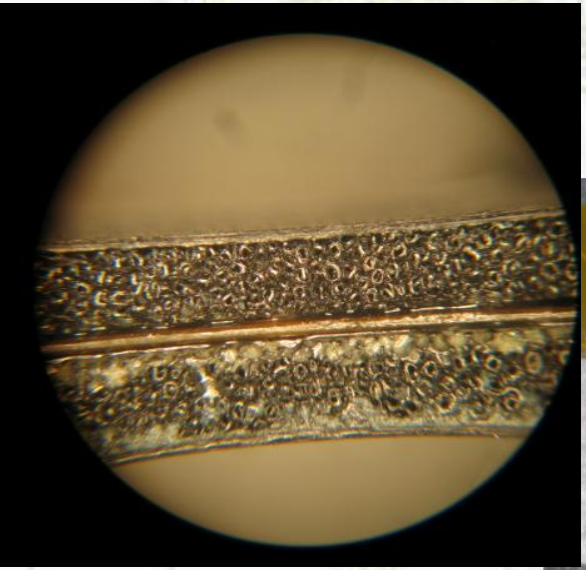
LBNL





- Prototype cables made
- Embedded (glued) into 1m long stave
- Thermal, mechanical electrical testing just startin

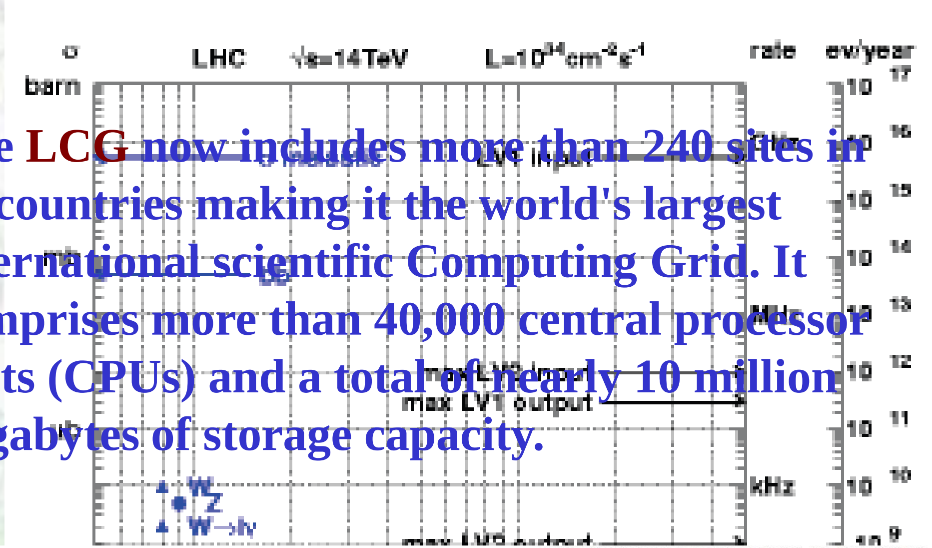




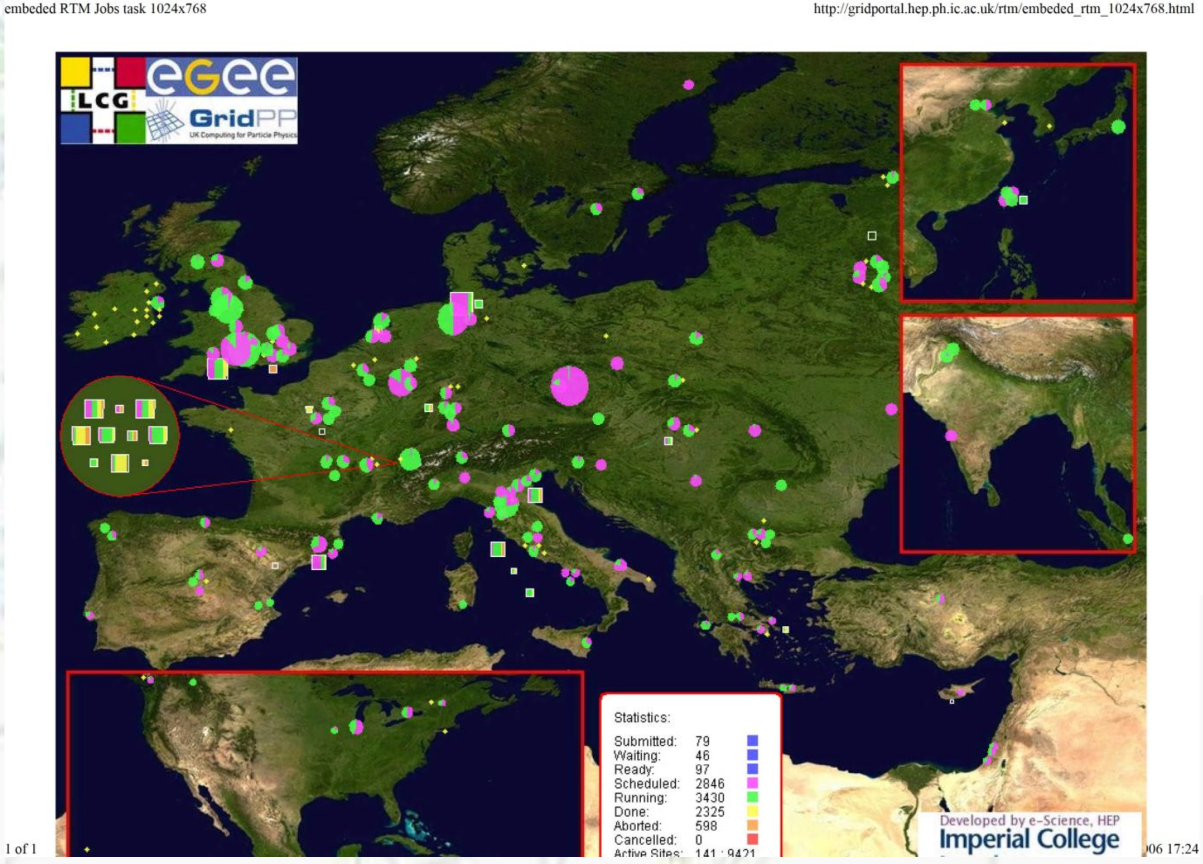
Data Processing Issues at the LHC

The problem of the data deluge at the LHC both prompted sophisticated on-detector data reduction using a multi-tiered filtering "event triggering" and developments to harness internationally distributed large processing arrays and mass-storage, "Grid technologies".

'The Large Hadron Collider (LHC), currently being built at CERN near Geneva, is the largest scientific instrument on the planet. When it operates at full capacity, it will produce roughly 15 Petabytes (15 million Gigabytes) of data annually, which thousands of scientists around the world will access and analyse.
The mission of the LHC Computing Grid (LCG) Project is to build and maintain a data storage and analysis infrastructure for the entire high energy physics community that will use the LHC.'



The LCG now includes more than 240 sites in 45 countries making it the world's largest international scientific Computing Grid. It comprises more than 40,000 central processor units (CPUs) and a total of nearly 10 million Gigabytes of storage capacity.


embeded RTM Jobs task 1024x768

http://gridportal.hep.ph.ic.ac.uk/rtm/embeded_rtm_1024x768.html

Statistics:

Submitted:	79	🟦
Waiting:	46	🟦
Ready:	97	🟦
Scheduled:	2846	🟪
Running:	3430	🟩
Done:	2325	🟨
Aborted:	598	🟧
Cancelled:	0	🟥
Active Sites:	141 : 9421	

Developed by e-Science, HEP
Imperial College

1 of 1

)06 17:24

CMS Planning for Upgrade Project

- The SLHC planning assumptions keep changing in the light of experience with the machine and different ideas for achieving high luminosity running in a decade's time

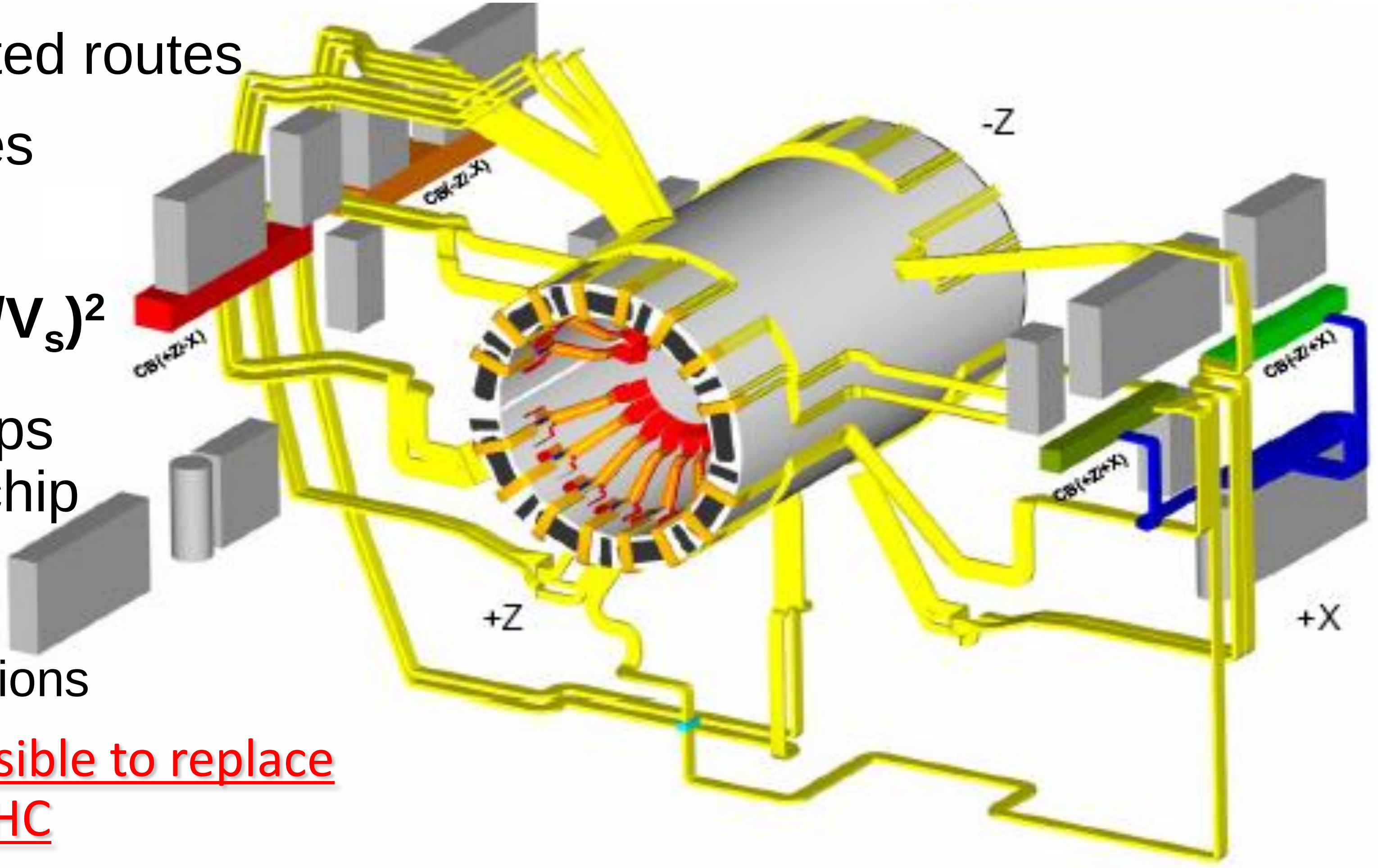
- Developing and building a new tracker requires ~10 years
  - 5 years R&D
  - 2 years Qualification
  - 3 years Construction
  - 6 months Installation and Ready for Commissioning

- NB – even this is aggressive
  - System design and attention to QA are important considerations from a very early stage
  - Cost was a driver for LHC detectors from day one

CMS Tracker Services

- Major constraint on upgraded system
  - Complex, congested routes
  - Heat load of cables must be removed
  - $\mathbf{P_{cable} = R_{cable}(P_{FE}/V_s)^2}$
  - Cable voltage drops exceed read-out chip supply voltages
    - limited tolerance to voltage excursions

Installation of services was one of the most difficult jobs to complete CMS

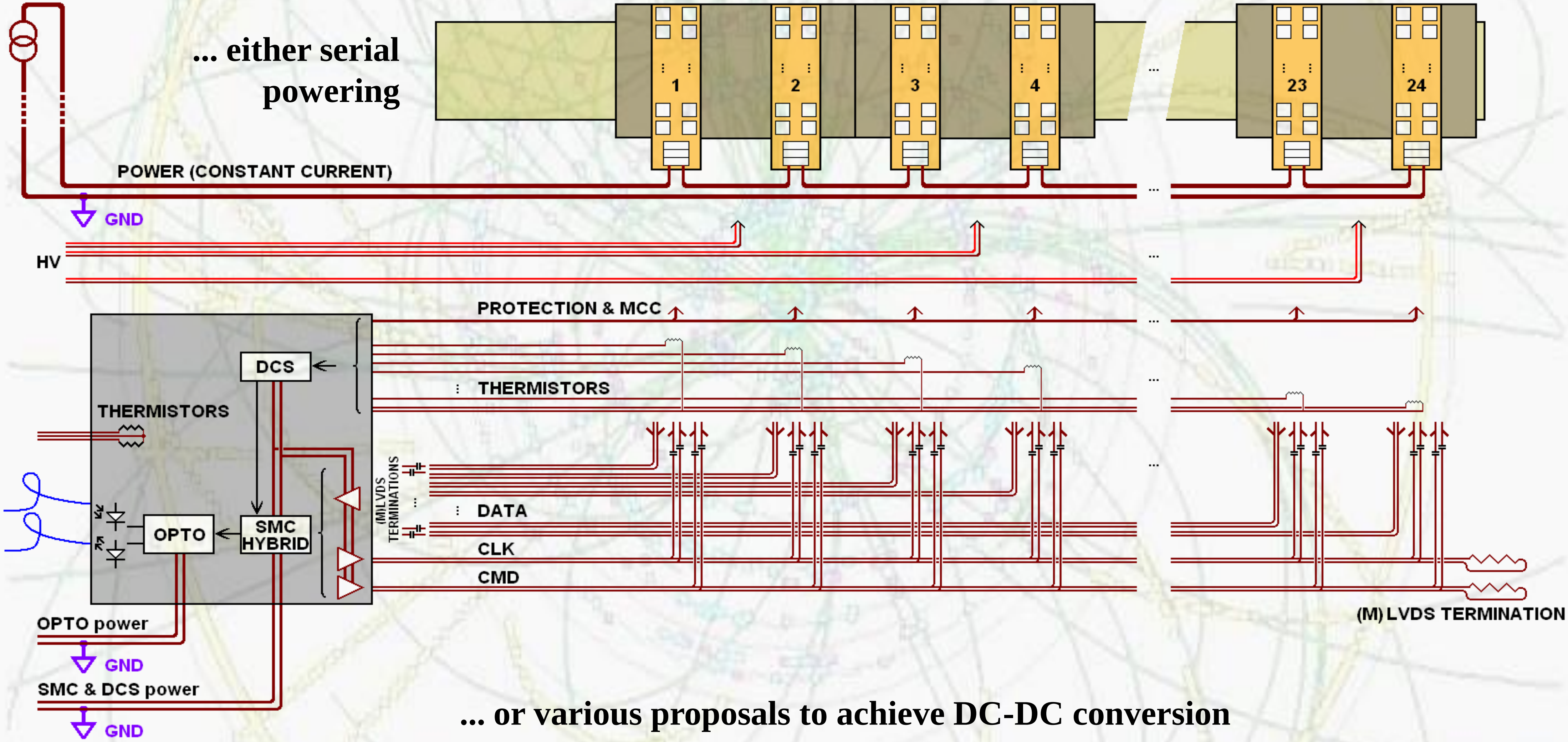


It will probably be impossible to replace cables and cooling for sLHC

$P_{FE} \approx 33$kW I=15,500A $P_S = 300$kVA

ATLAS Stave Electrical Concepts

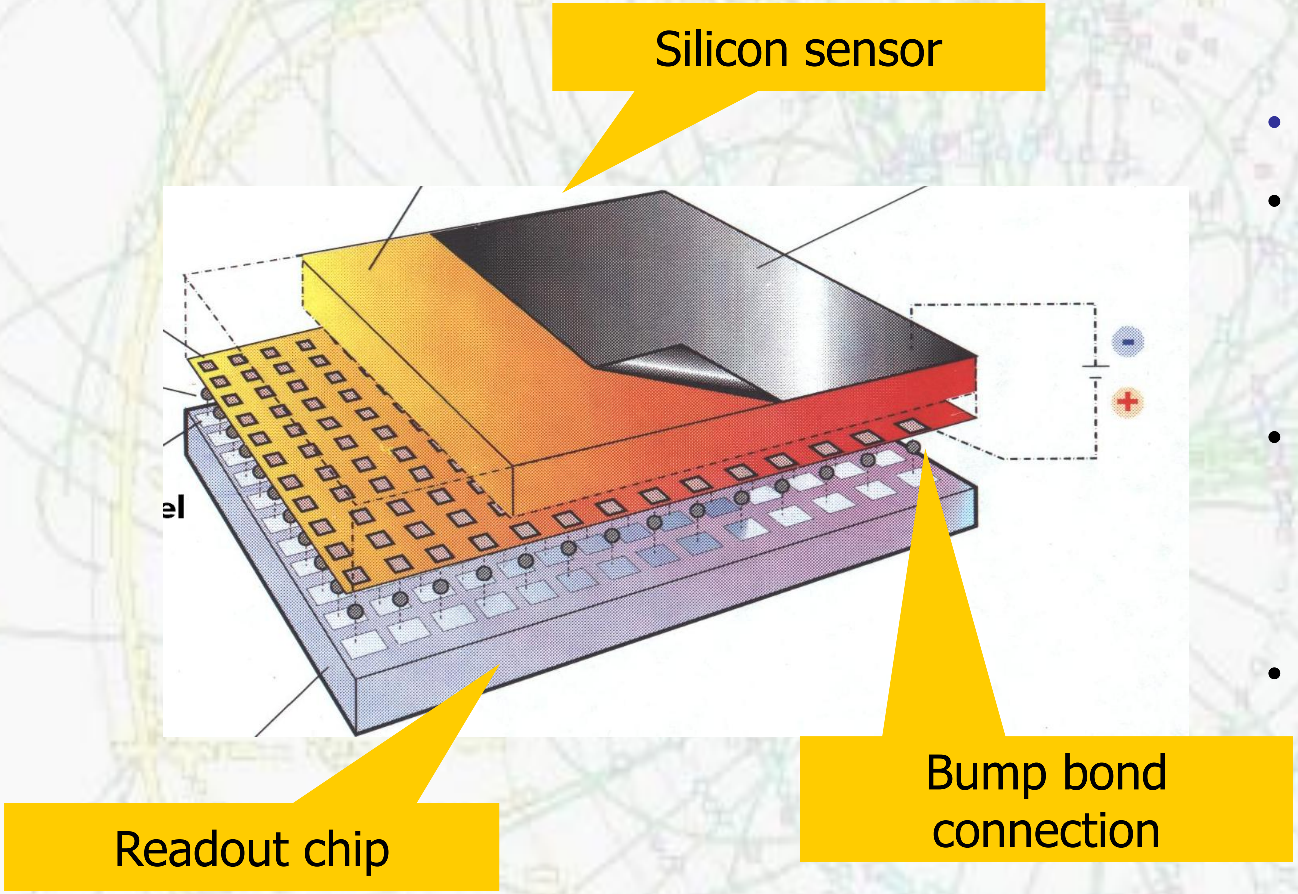
Need to bring in power at low current and high voltage but deep sub-micron ASICs operate at lower and lower voltages



... either serial powering

... or various proposals to achieve DC-DC conversion (Step down voltage at each module)

Hybrid Pixel Detectors



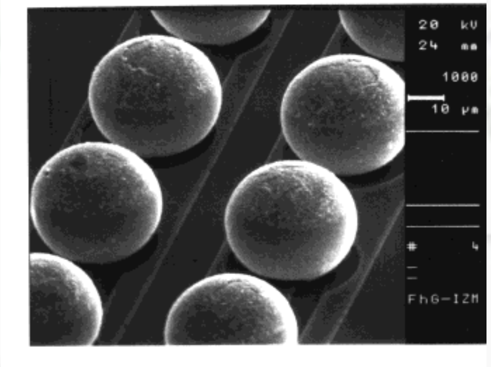
Silicon sensor

Bump bond connection

Readout chip

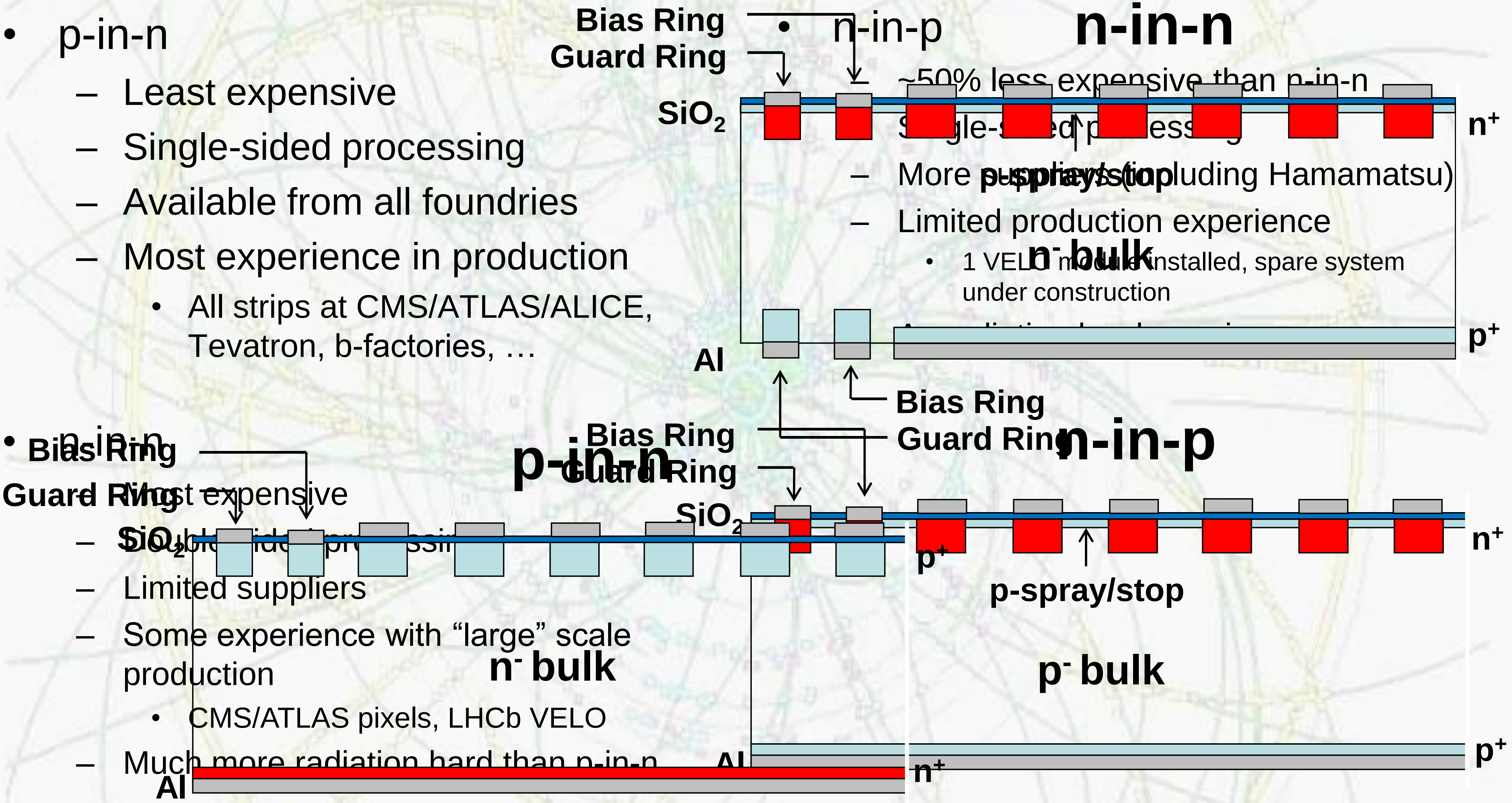
- **Hybrid pixel detector:**
- **The sensor and the readout electronic are realized in different semiconductor substrates**
- **Size of the electronic readout pixels is equal to the size of the sensor pixels**
- **The connection between the electronic and the sensor is done via bump bond connections**

- **Bump bond technology:**
- **Size: 20 µm, pitch: 50 µm**
- **In (AMS) & PbSn (IZM) used for ATLAS pixel**



Geometry Choices

- p-in-n
  - Least expensive
  - Single-sided processing
  - Available from all foundries
  - Most experience in production
    - All strips at CMS/ATLAS/ALICE, Tevatron, b-factories, …
- n-in-p
  - ~50% less expensive than n-in-n
  - Single-sided processing
  - More suppliers (including Hamamatsu)
  - Limited production experience
    - 1 VELO module installed, spare system under construction
  - [illegible]
- n-in-n
  - Most expensive
  - Double-sided processing
  - Limited suppliers
  - Some experience with “large” scale production
    - CMS/ATLAS pixels, LHCb VELO
  - Much more radiation hard than p-in-n



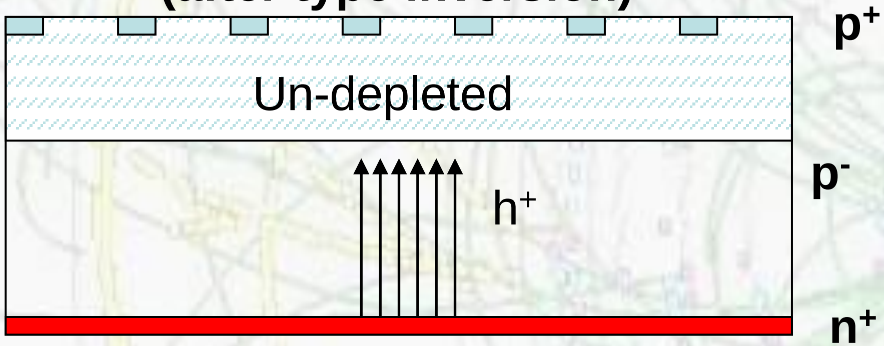
P-strip vs. N-strip Readout

Effect of trapping on the Charge Collection Efficiency (CCE)

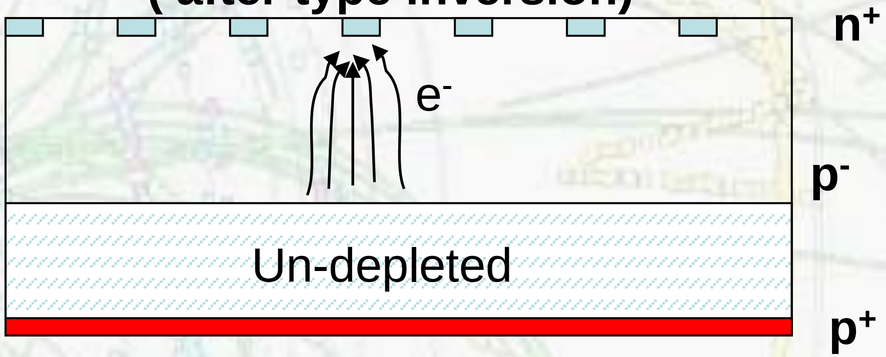
$$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$$

t_C is collection “time”, τ_{tr} is effective trapping time

**“Standard” p-in-n geometry
(after type inversion)**



**“New” n-in-p geometry
“New” n-in-n geometry
(after type inversion)**



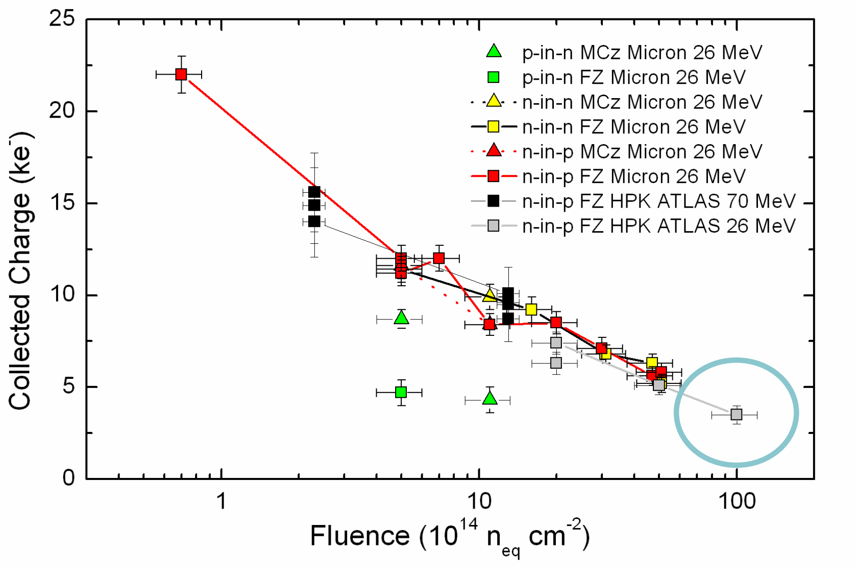
Type inversion turns lightly doped material to “p” type

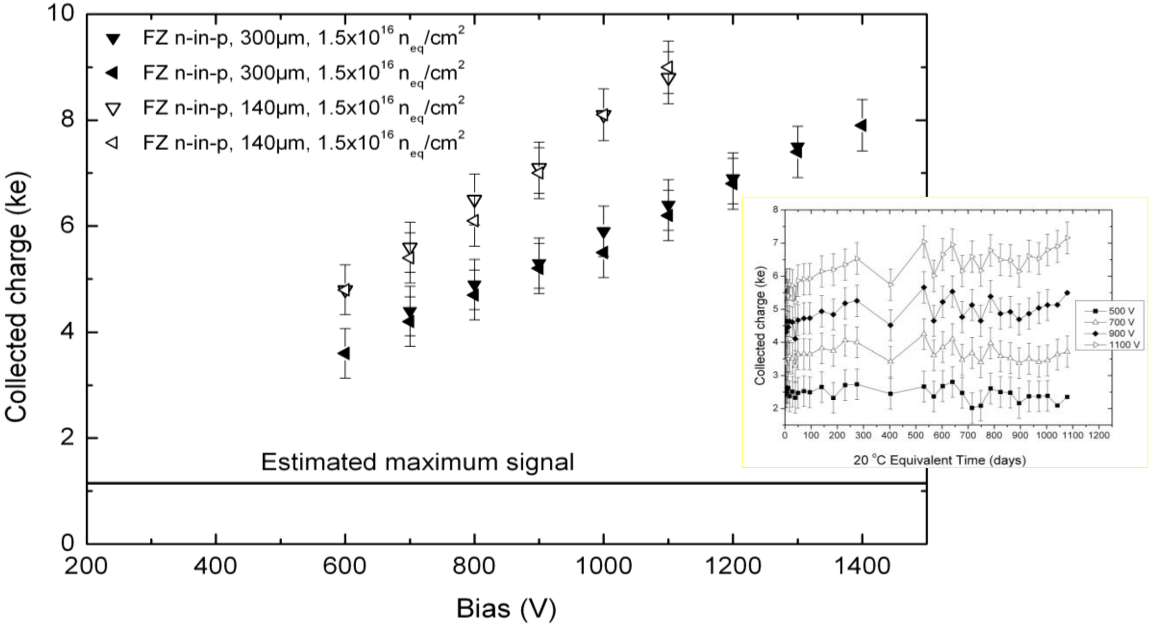
- Holes collected
- Deposited charge cannot reach electrode
  - Charge spread over many strips
  - Lower signal

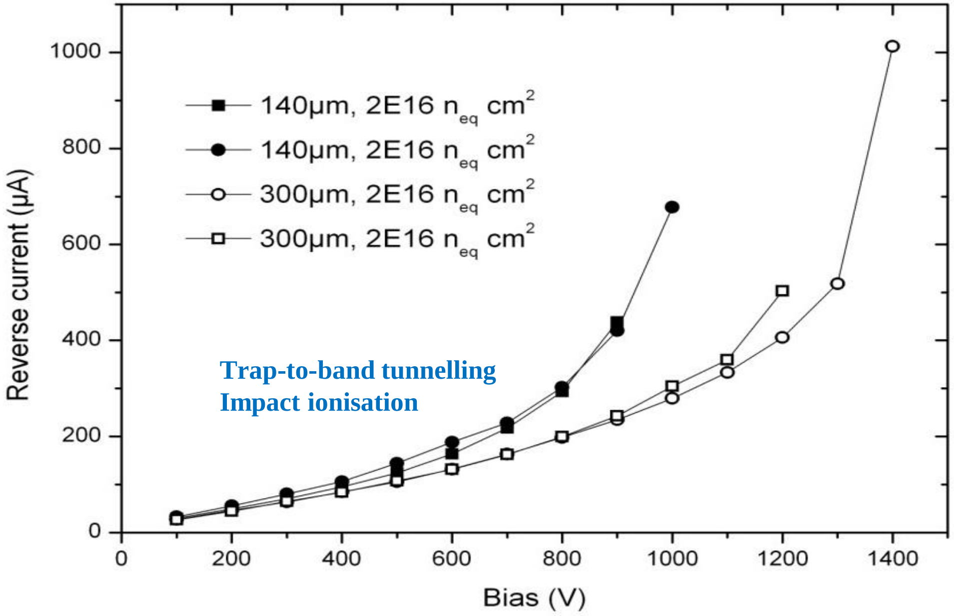
- Electron collected
  - Higher mobility and ~33% smaller trapping constant
- Deposited charge can reach electrode

n-in-p Planar Sensors at Extreme Doses

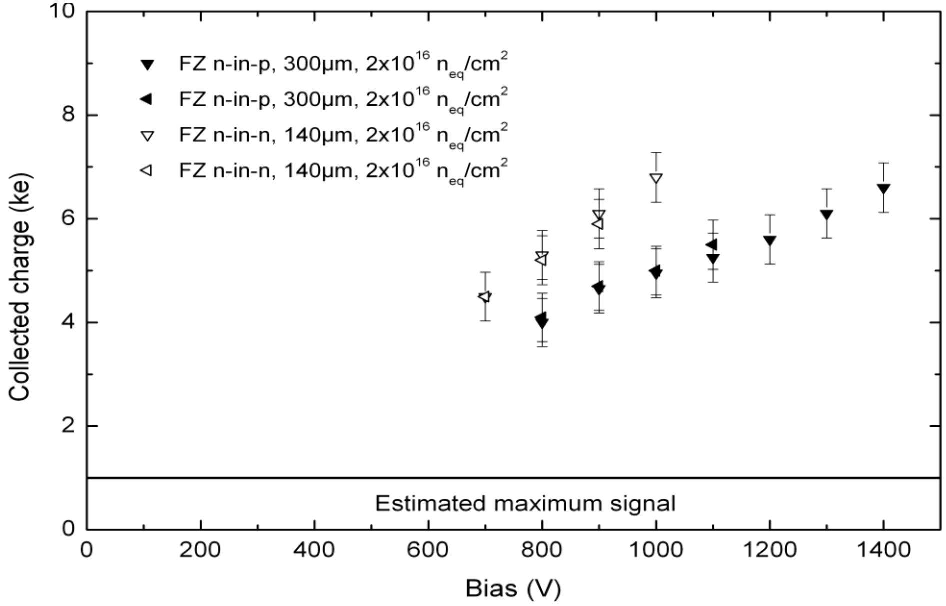
1 and 2x10^{16} n_{eq} (innermost pixel layers at sLHC)





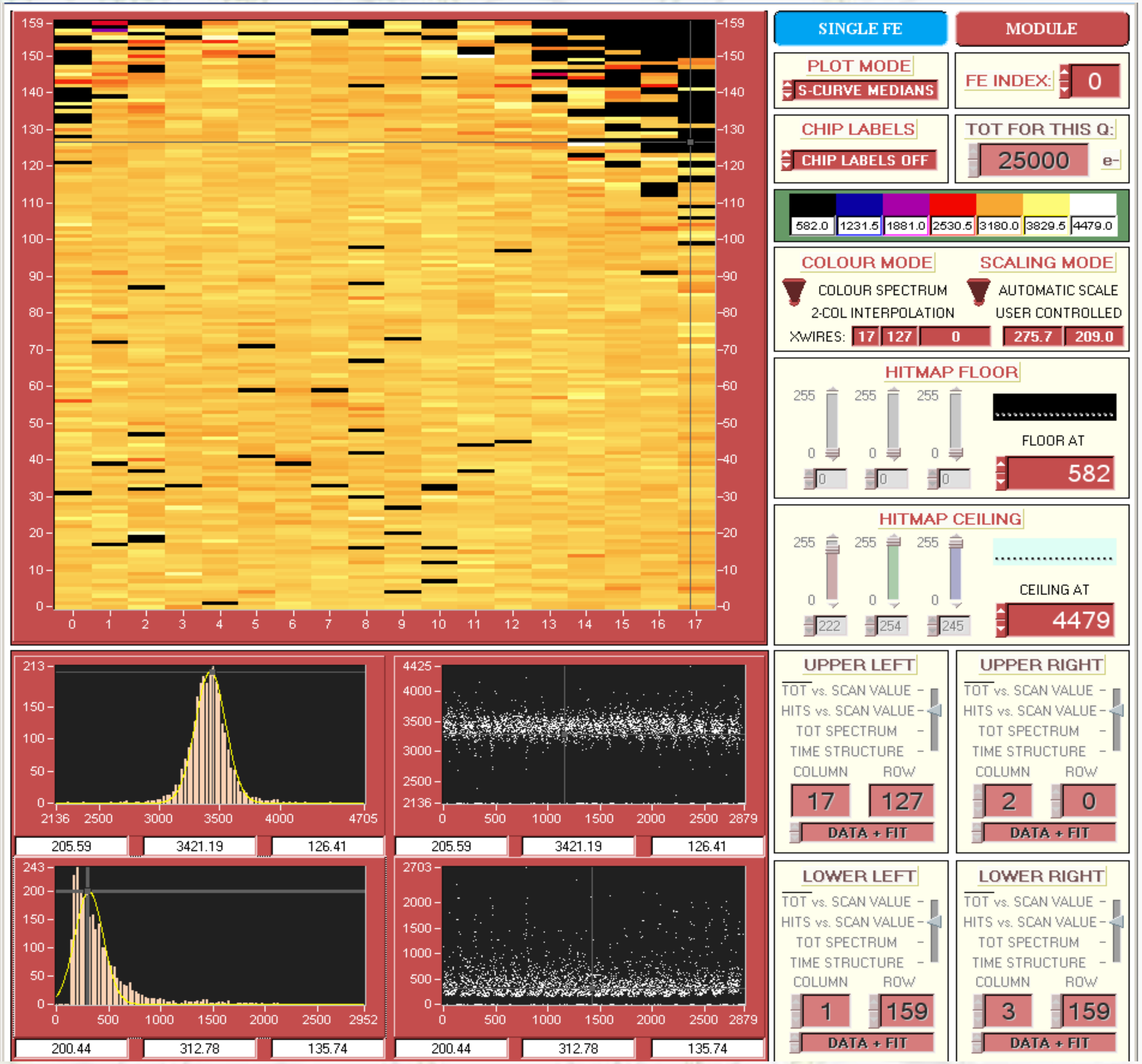


Trap-to-band tunnelling
Impact ionisation



FEI3 SCM 4×10^{15} n_{eq} cm^{-2} Trimmed

- Measured at 500 V bias @-26 C
  - Most pixels trimmable
  - Noise and thresholds good
- Next step will be a source run. With an expected signal of ~5 ke^- and <thr>=3500, we should see some of the landau at 500 V
- Once measured will increase bias voltage slowly and repeat



PLOT MODE: S-CURVE MEDIANS

FE INDEX: 0

CHIP LABELS: CHIP LABELS OFF

TOT FOR THIS Q: 25000 e-

COLOUR MODE: COLOUR SPECTRUM

SCALING MODE: AUTOMATIC SCALE

XWIRES: 17 127 0 275.7 209.0

HITMAP FLOOR: 255 255 255 / 0 0 0 / 0 0 0

FLOOR AT 582

HITMAP CEILING: 255 255 255 / 0 0 0 / 222 254 245

CEILING AT 4479

UPPER LEFT: COLUMN 17 ROW 127

UPPER RIGHT: COLUMN 2 ROW 0

LOWER LEFT: COLUMN 1 ROW 159

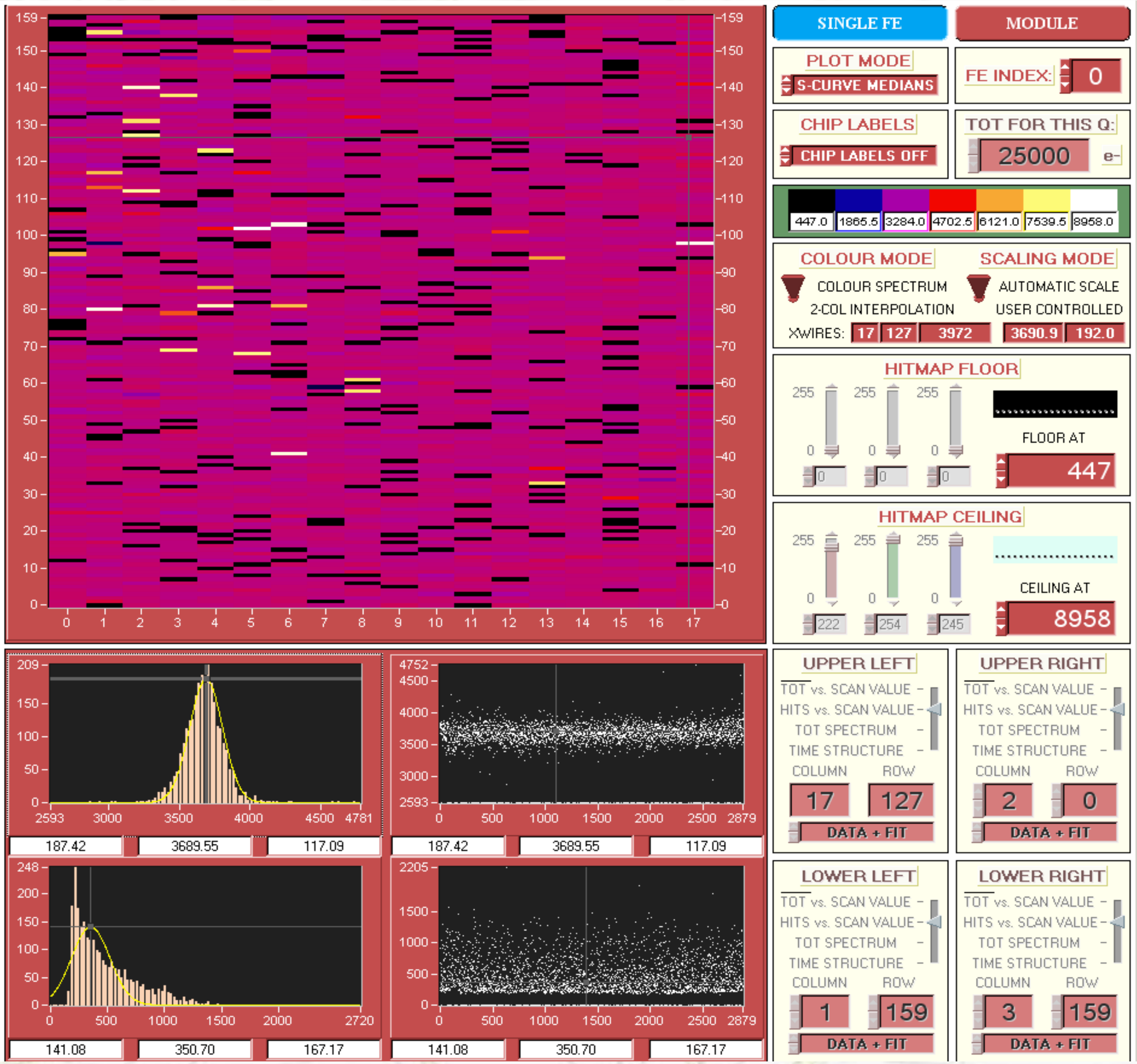
LOWER RIGHT: COLUMN 3 ROW 159

205.59	3421.19	126.41
205.59	3421.19	126.41

200.44	312.78	135.74
200.44	312.78	135.74

FEI3 SCM 9×10^{15} n_{eq} cm^{-2} Trimmed

- Measured at 500 V bias @-26 C
  - Most pixels trimmable
  - Noise and thresholds good
- Next step will be a source run. Will need at least 800V to get to an expected signal of ~5 ke$^-$ and <thr>=3700, to some of the landau at 500 V
- Once measured will increase bias voltage slowly and repeat



PLOT MODE: S-CURVE MEDIANS

FE INDEX: 0

CHIP LABELS: CHIP LABELS OFF

TOT FOR THIS Q: 25000 e-

447.0	1865.5	3284.0	4702.5	6121.0	7539.5	8958.0

COLOUR MODE: COLOUR SPECTRUM

SCALING MODE: AUTOMATIC SCALE

XWIRES: 17 127 3972 3690.9 192.0

HITMAP FLOOR: 255 255 255 0 0 0 0 0 0 FLOOR AT 447

HITMAP CEILING: 255 255 255 0 0 0 222 254 245 CEILING AT 8958

UPPER LEFT: COLUMN 17 ROW 127 DATA + FIT

UPPER RIGHT: COLUMN 2 ROW 0 DATA + FIT

LOWER LEFT: COLUMN 1 ROW 159 DATA + FIT

LOWER RIGHT: COLUMN 3 ROW 159 DATA + FIT

187.42 3689.55 117.09

187.42 3689.55 117.09

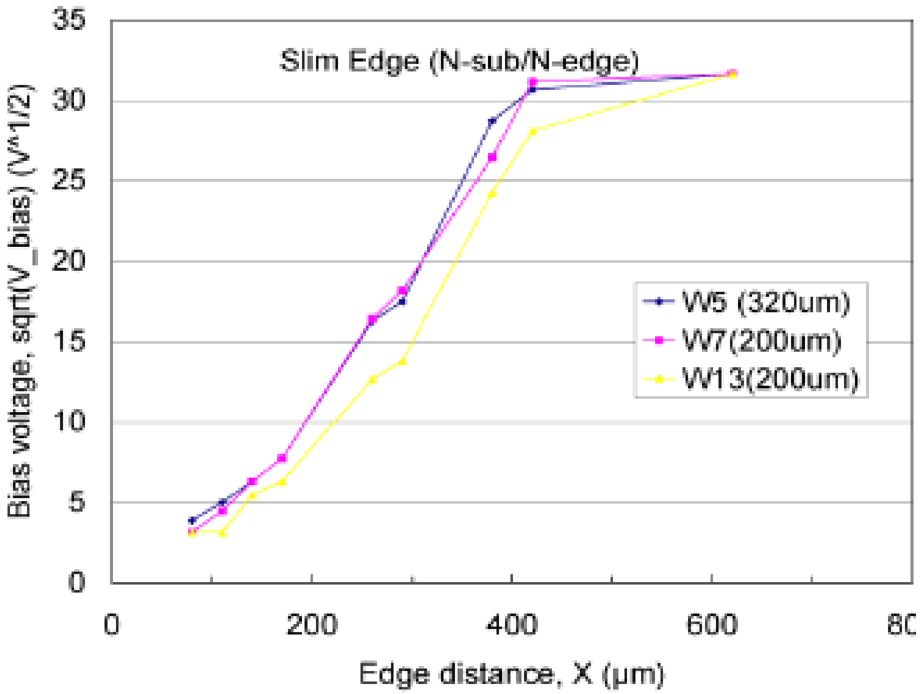
141.08 350.70 167.17

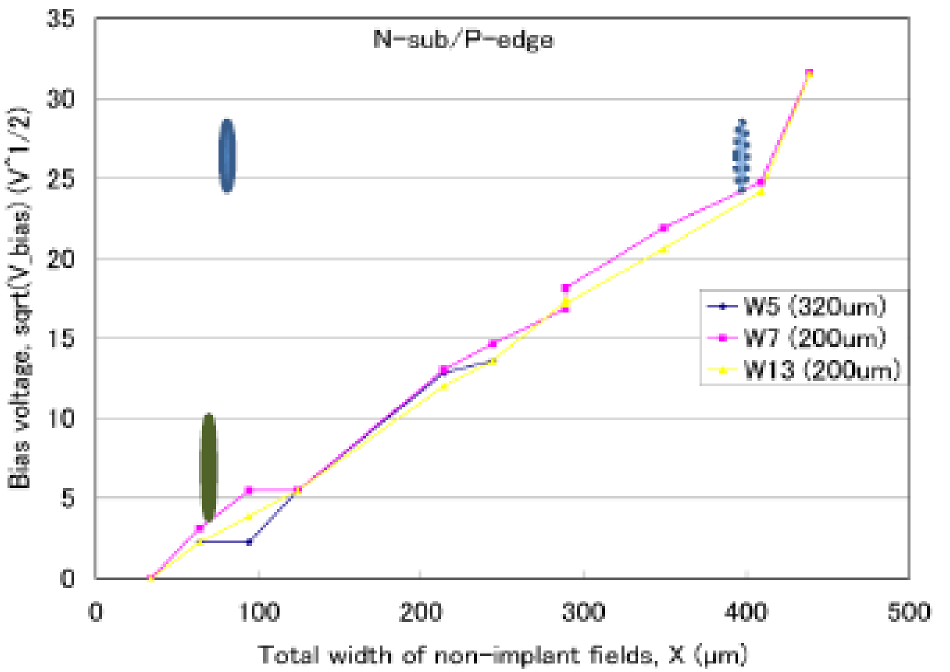
141.08 350.70 167.17

Pre-irradiation

Comparison with Nobu's presentation

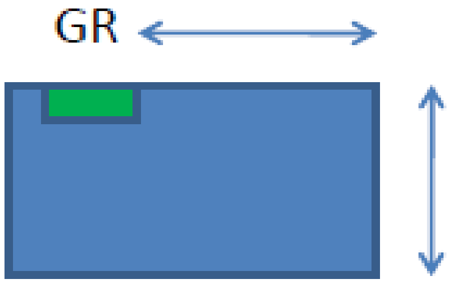
- Nobu showed a very interesting presentation during the last meeting.
- Observed the max bias voltage to depend *only on (horizontal) unimplanted distance to the edge implant, not number of GRs.*





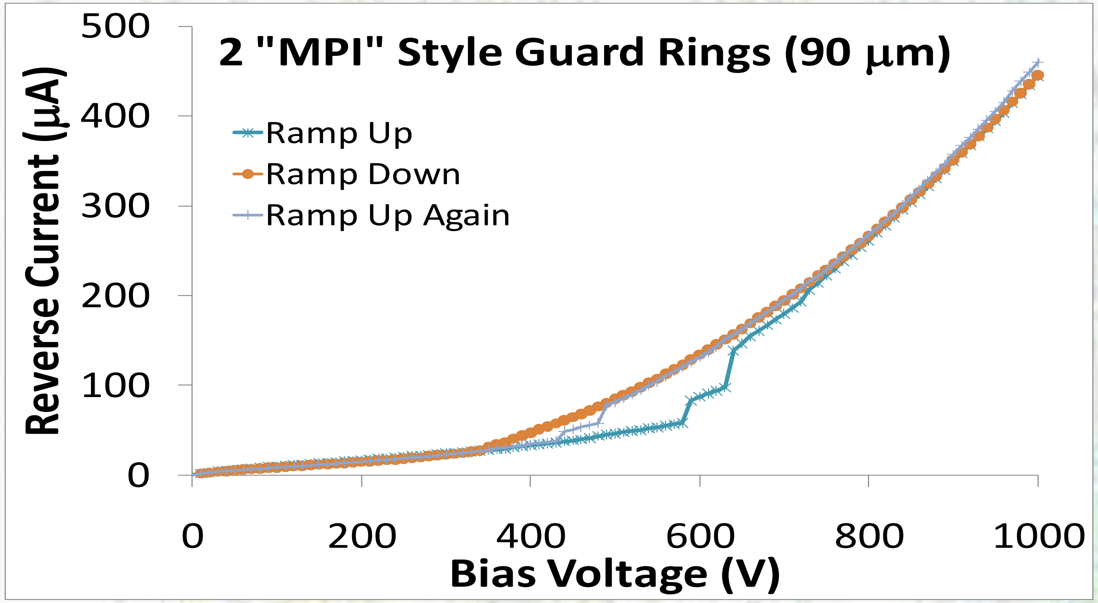
Non-implanted edge

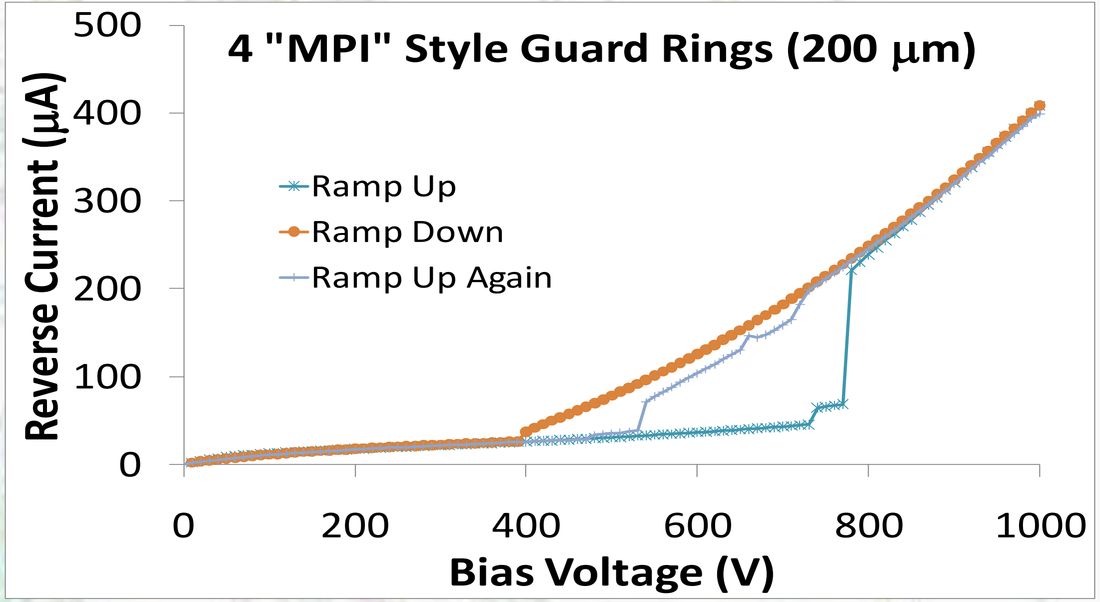
Plots are from Nobu's presentation at 6th PPS meeting.

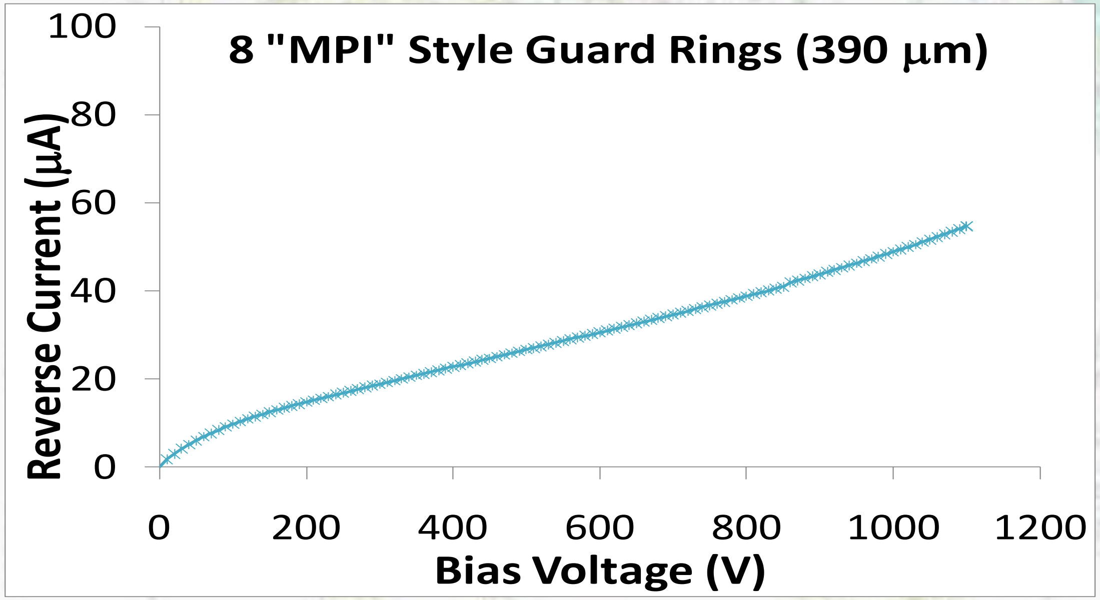


- Best examples of p-type (green, 70 um) and n-type (blue, 78 um) extend above the very uniform dependence.
- Without edge implant, and with resistive edge, we have a different distance at play: depth matters (e.g. same point at the distance of 400 um detector thickness).

Slim Edges After 4×10^{15} n$_{eq}$ cm^{-2}


2 "MPI" Style Guard Rings (90 μm)


4 "MPI" Style Guard Rings (200 μm)


8 "MPI" Style Guard Rings (390 μm)

Diodes tested after irradiation

- 390 μm will hold 1100 V
- Thinner structures show breakdown before 1000 V
  - It isn’t clear if due to narrow edge
  - Or due to dicing cutting through outer guard ring due to miss alignment