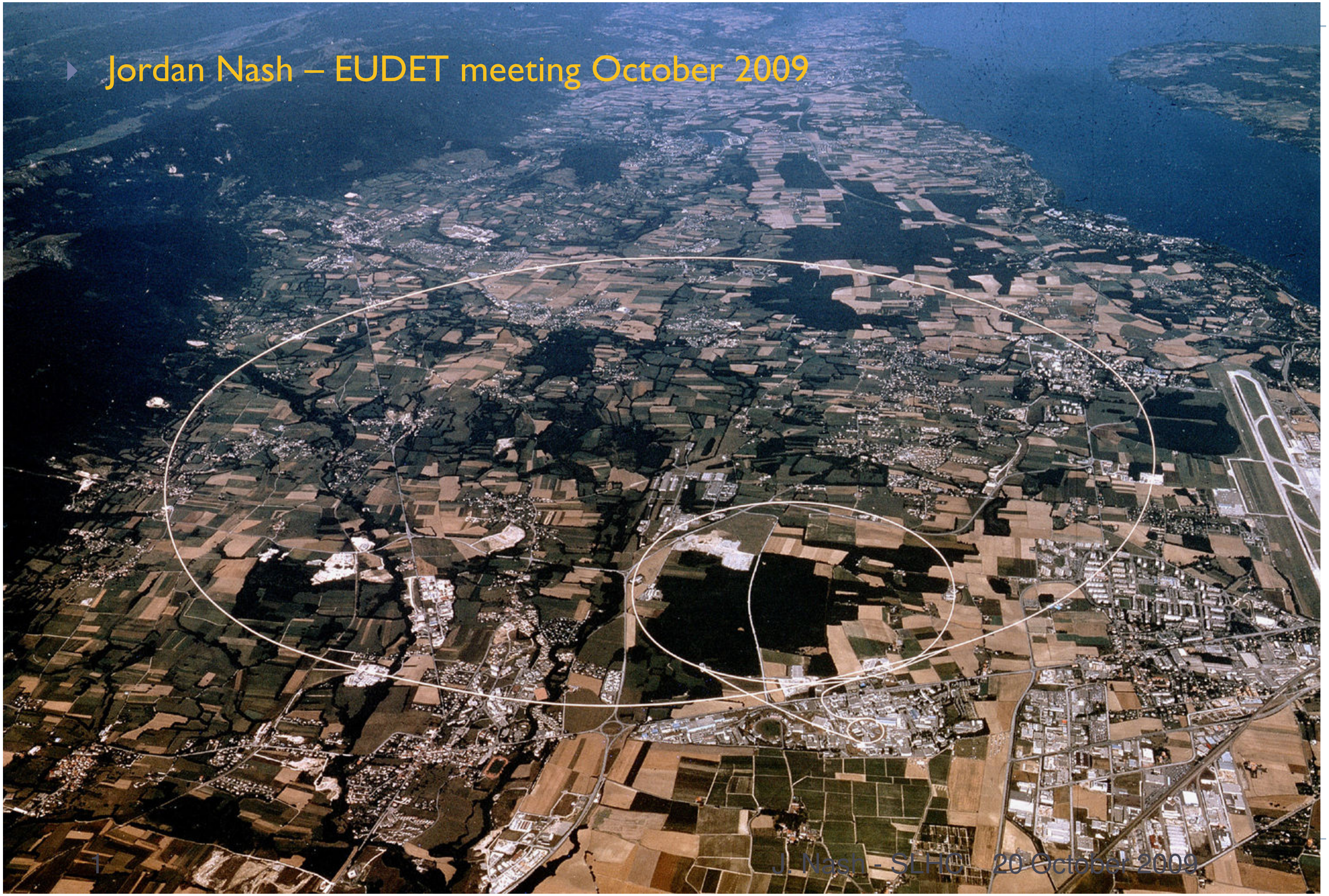
The “Super” LHC



- Jordan Nash – EUDET meeting October 2009

R/D Challenges for the SLHC

- Why a “Super” LHC
  - Potential Physics motivations
  - Implications for the detectors
- Upgrades to the Detectors

SLHC is about the maximizing the output of LHC physics

- We should be led by getting the best physics out of any upgraded machine/detector
  - Not by the highest peak luminosity
  - Even maximum integrated luminosity may not be the most important metric
  - Issues
    - Integrated luminosity
    - Backgrounds
    - Acceptance
    - Pile-up

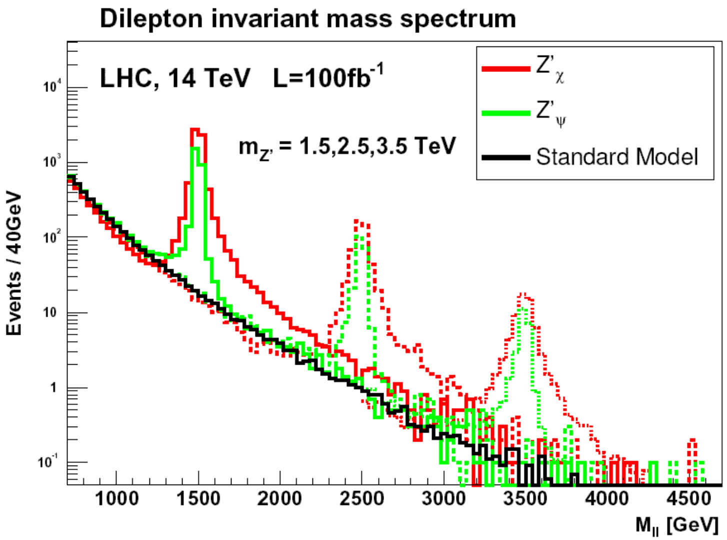
Some Physics themes

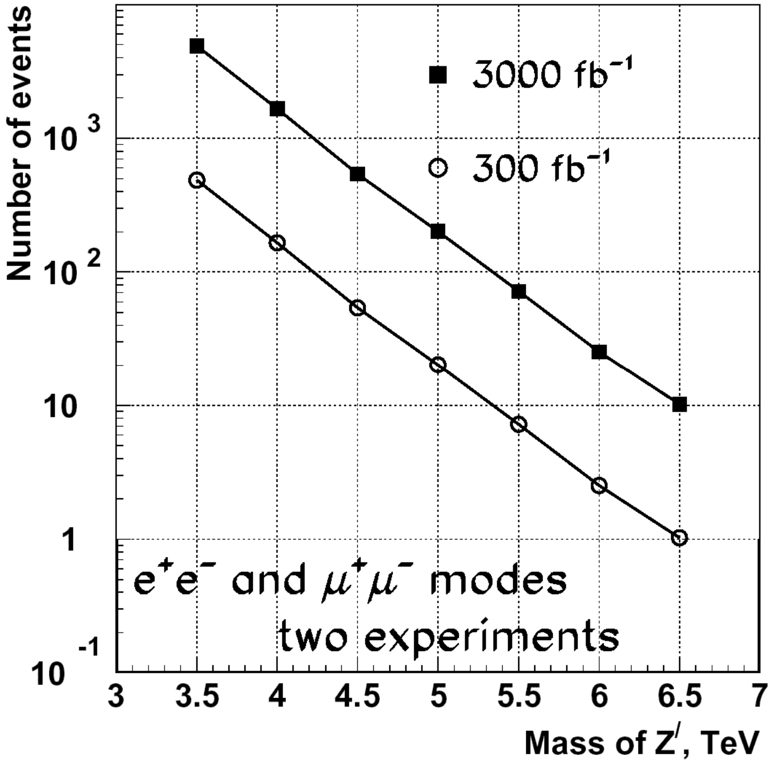
- Different physics channels require different conditions
- Three main directions for Phase II
  - Damn the torpedos - FULL Luminosity
  - Maximum of *quality* luminosity
    - Luminosity leveling?
  - Forward acceptance
- We won't know which is the most important until we have first data from the LHC
  - Important not to eliminate a physics opportunity until we are sure it makes sense to do so
  - We have to be ready to build detectors for any of these scenarios

SLHC Physics: Extra gauge bosons

- SLHC extends reach for Z'
  - Cross sections fall with E
  - SLHC gives access to higher E
- Good electron resolution required (including understanding saturation)

Just give us the Integrated Luminosity!



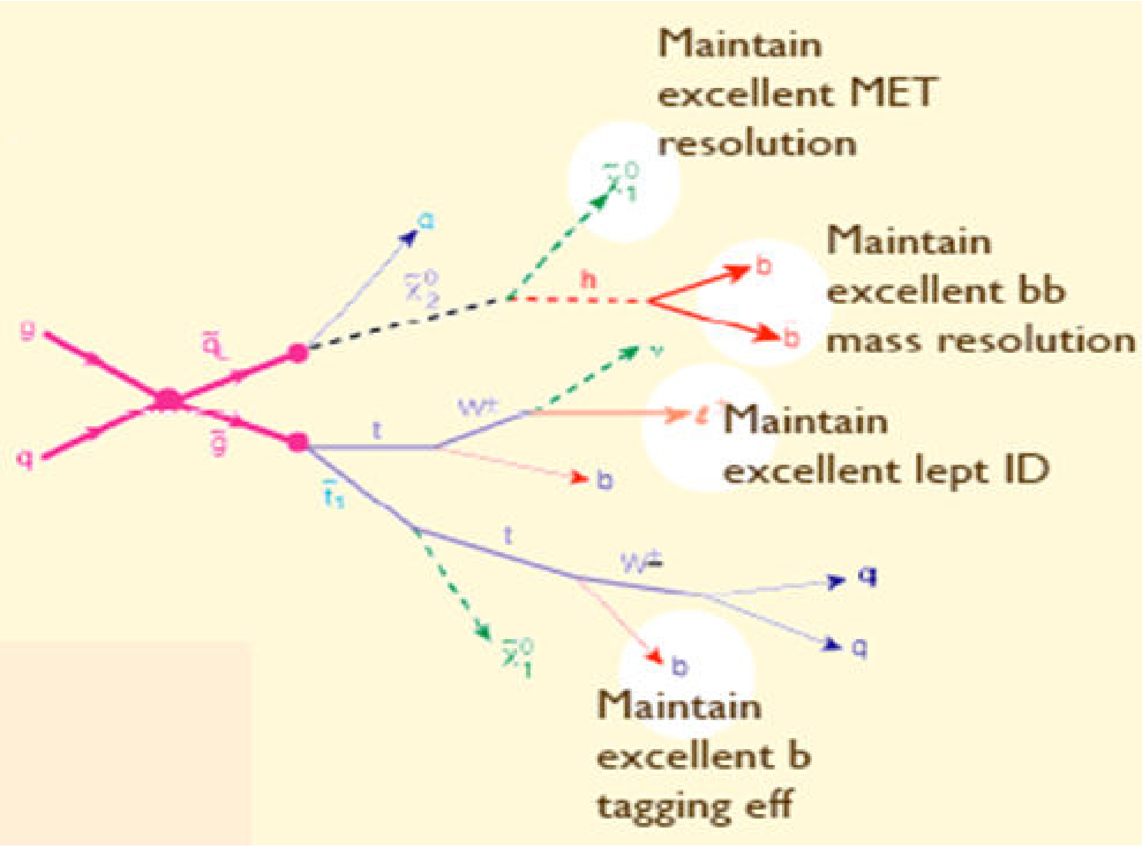


Z' mass (TeV)	1	2	3	4	5	6
$\sigma(Z' \to e^+e^-)(fb)$	512	23.9	2.5	0.38	0.08	0.026
$\Gamma_{Z'}$ (GeV)	30.6	62.4	94.2	126.1	158.0	190.0

SUSY searches - measurements

Here we need a lot of Integrated Luminosity, but needs to be high quality. Lower pile-up may be important.

- SLHC statistics will be vital in reaching understanding of complicated SUSY channels
  - Sparticles seen, but statistics for reconstruction limited at LHC
- Performance of the detector here is vital
  - B-tagging
  - Lepton id



Maintain excellent MET resolution

Maintain excellent bb mass resolution

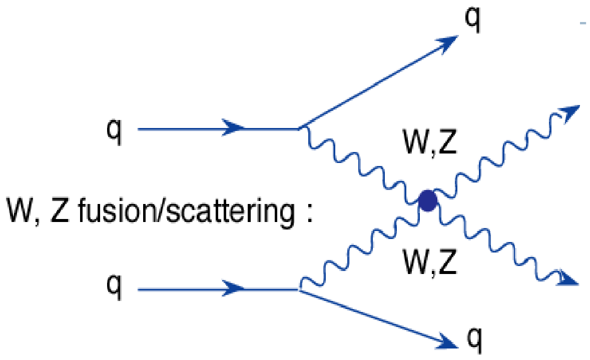
Maintain excellent lept ID

Maintain excellent b tagging eff

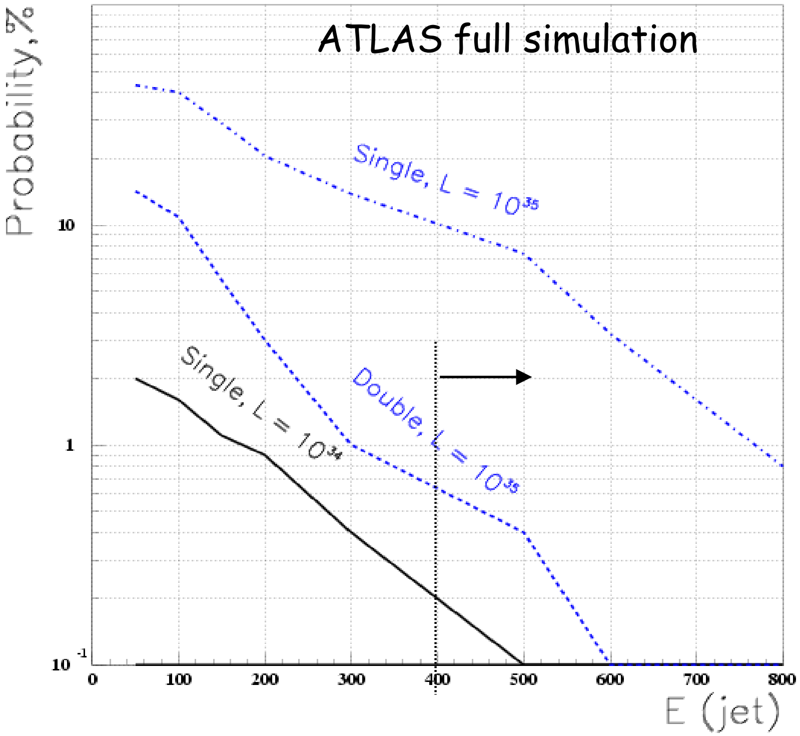
What if no Higgs is found?

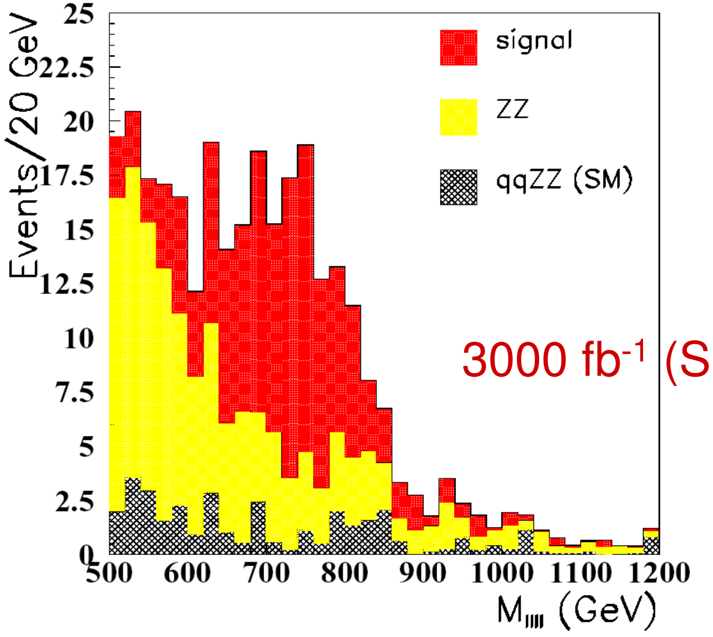
Forward tagging is essential

- Will need to look at WW scattering
  - Some mechanism required to avoid unitarity violation
- Forward Jet Tagging Essential



Fake fwd jet tag (|η| > 2) probability from pile-up (preliminary ...)



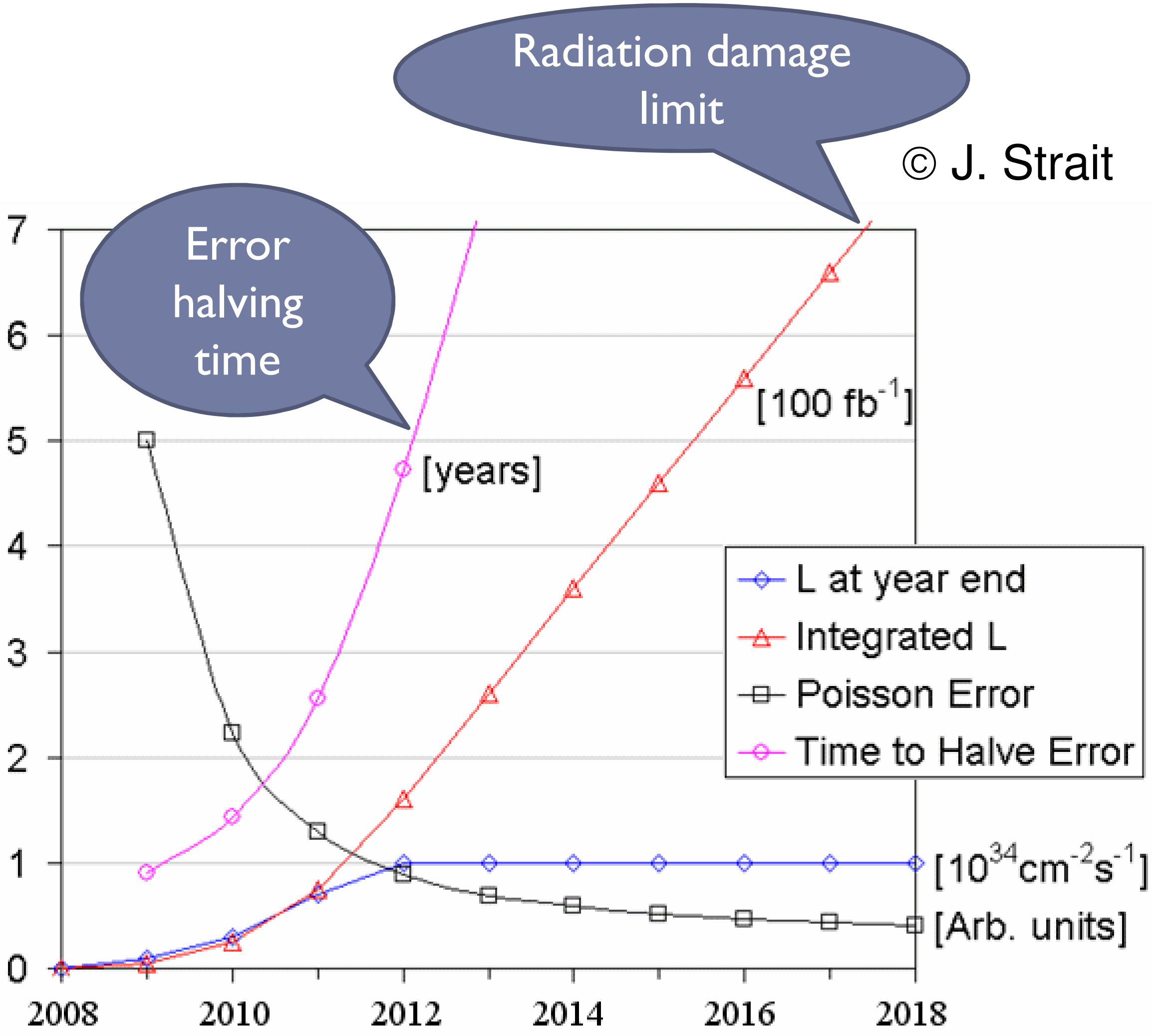


3000 fb^{-1} (SLHC)

Practical reasons to upgrade the LHC

- Hardware ageing
  - Machine elements
  - Detector elements
- Foreseeable luminosity evolution

⇒ a major luminosity upgrade in ~2017 (SLHC)



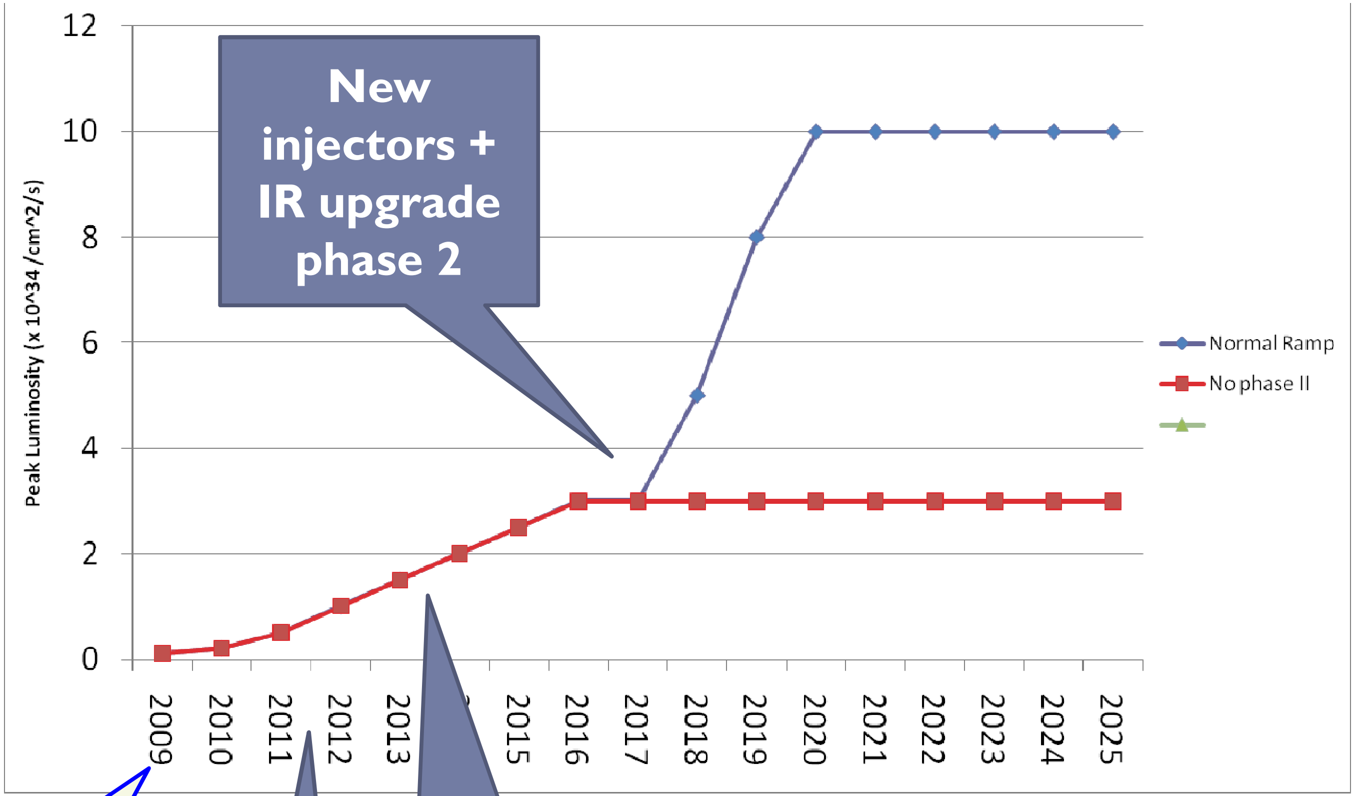
Radiation damage limit

Error halving time

© J. Strait

parameter	symbol	nominal	ultimate	ph. I	**ES**	**FCC**	**LE**	**LPA**
transverse emittance	ε [μm]	3.75	3.75		**3.75**	**3.75**	**1.0**	**3.75**
protons per bunch	N_b [10^{11}]	1.15	1.7		**1.7**	**1.7**	**1.7**	**4.9**
bunch spacing	Δt [ns]	25	25		**25**	**25**	**25**	**50**
beam current	I [A]	0.58	0.86		**0.86**	**0.86**	**0.86**	**1.22**
longitudinal profile		Gauss	Gauss		**Gauss**	**Gauss**	**Gauss**	**Flat**
rms bunch length	σ_z [cm]	7.55	7.55		**7.55**	**7.55**	**7.55**	**11.8**
beta* at IP1&5	β* [m]	0.55	0.5	0.3	**0.08**	**0.08**	**0.1**	**0.25**
full crossing angle	θ_c [μrad]	285	315	410	**0**	**0**	**311**	**381**
Piwinski angle	$\phi=\theta_c\sigma_z/(2^*\sigma_x^*)$	0.64	0.75	1.26	**0**	**0**	**3.2**	**2.0**
geometric reduction		0.84	0.80	0.62	**0.77**	**0.77**	**0.30**	**0.48**
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	2.3	3.0	**14.0**	**14.0**	**16.3**	**11.9**
peak events per #ing		19	44	57	**266**	**266**	**310**	**452**
initial lumi lifetime	τ_L [h]	22	14	11	**2.2**	**2.2**	**2.0**	**4.0**
effective luminosity ($T_{turnaround}$=10 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	0.46	0.91	1.07	**2.3**	**2.3**	**2.5**	**2.7**
	$T_{run,opt}$ [h]	21.2	17.0	14.9	**6.9**	**6.9**	**6.4**	**9.0**
effective luminosity ($T_{turnaround}$=5 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	0.56	1.15	1.38	**3.4**	**3.4**	**3.7**	**3.7**
	$T_{run,opt}$ [h]	15.0	12.0	10.5	**4.9**	**4.9**	**4.5**	**6.3**
e-c heat SEY=1.4(1.3)	P [W/m]	1.1 (0.4)	1.0 (0.6)		**1.0 (0.6)**	**1.0 (0.6)**	**1.0 (0.6)**	**0.4 (0.1)**
SR heat load 4.6-20 K	P_{SR} [W/m]	0.17	0.25		**0.25**	**0.25**	**0.25**	**0.36**
image current heat	P_{IC} [W/m]	0.15	0.33		**0.33**	**0.33**	**0.33**	**0.78**
gas-s. 100 h τ_b	P_{gas} [W/m]	0.04	0.06		**0.06**	**0.06**	**0.06**	**0.09**
extent luminous region	σ_l [cm]	4.5	4.3	3.3	**5.3**	**5.3**	**1.6**	**4.2**
comment		nominal	ultimate		**D0+CC**	**crab**		**wire com.**

Scenario for Peak luminosity…



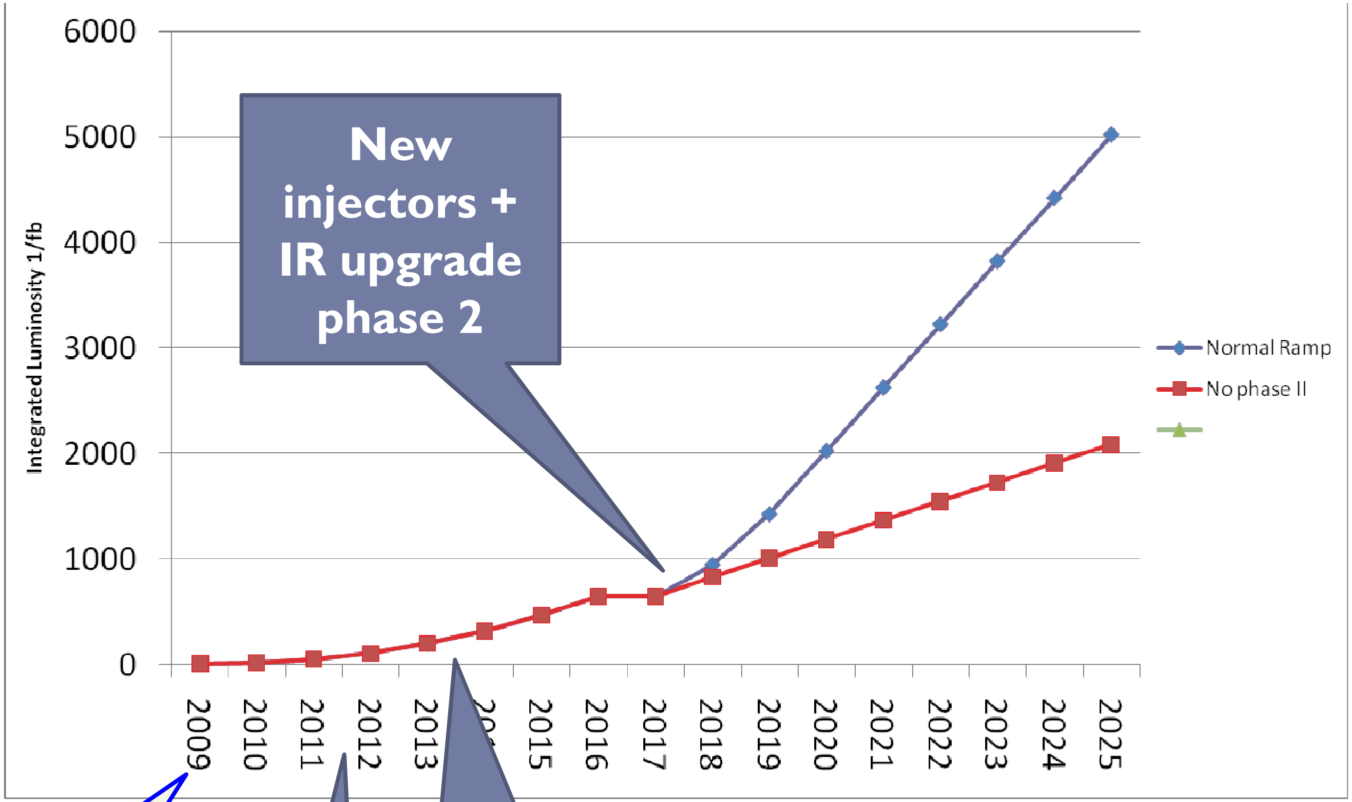
New injectors + IR upgrade phase 2

Linac4 + IR upgrade phase I

Collimation phase 2

Early operation

Integrated luminosity…



New injectors + IR upgrade phase 2

Early operation

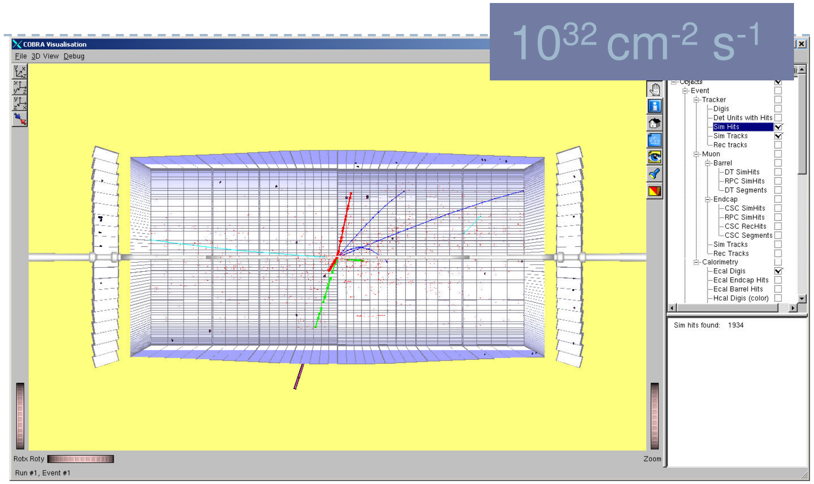
Collimation phase 2

Linac4 + IR upgrade phase I

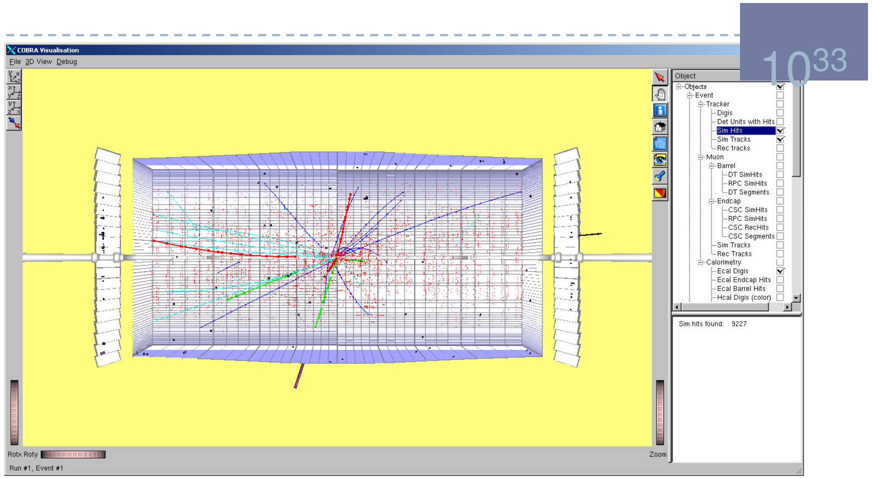
What are the key timescales/issues?

- Phase 1
  - How well do detector components handle the increasing luminosity?
    - Both instantaneous and integrated effects
  - What detector elements will need replacement/modification to cope?
    - Detectors will record >500 fb^{-1}, can they withstand this?
- Phase 2
  - What detector elements will need replacement?
  - What do machine plans imply for interaction regions
  - Is there a requirement for a long shutdown?
    - How long – 18 Months? (1 Full calendar year without beam +)
    - When – sometime after the middle of the next decade
      - Developing and building new tracking detectors will take many years
      - We have to plan this now in order to have any chance of running detectors with high luminosity
    - ATLAS and CMS have to agree on the dates
      - No sense in having two long shutdowns
      - Reach 700 fb^{-1}(potential limit)
        - Likely >2017

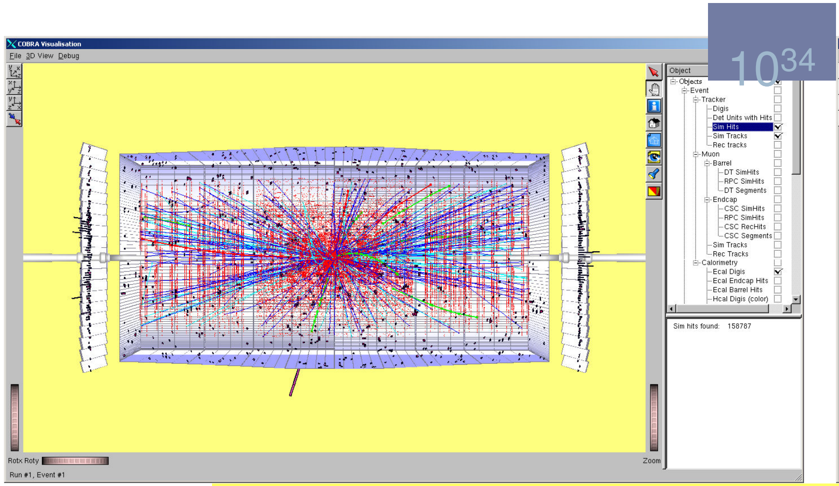
Detector Challenges
CMS from LHC to SLHC


10^{32} cm^{-2} s^{-1}

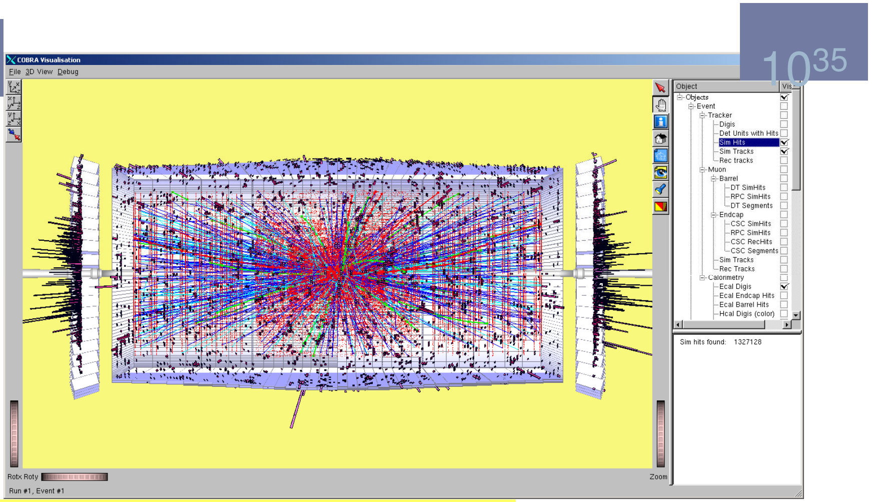
Sim hits found: 1934


10^{33}

Sim hits found: 9227


10^{34}

Sim hits found: 158787


10^{35}

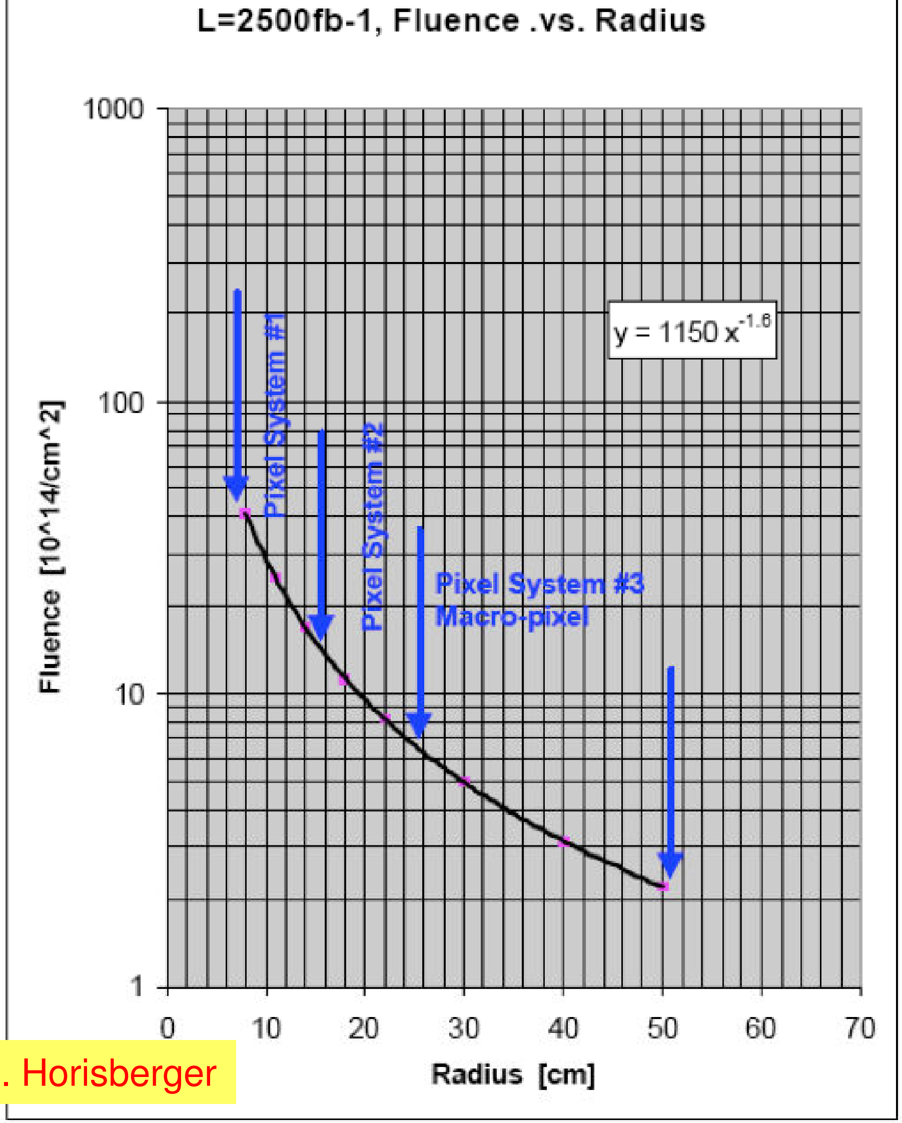
Sim hits found: 1327128

The tracker is the key detector which will require upgrading for SLHC Phase 2

I. Osborne

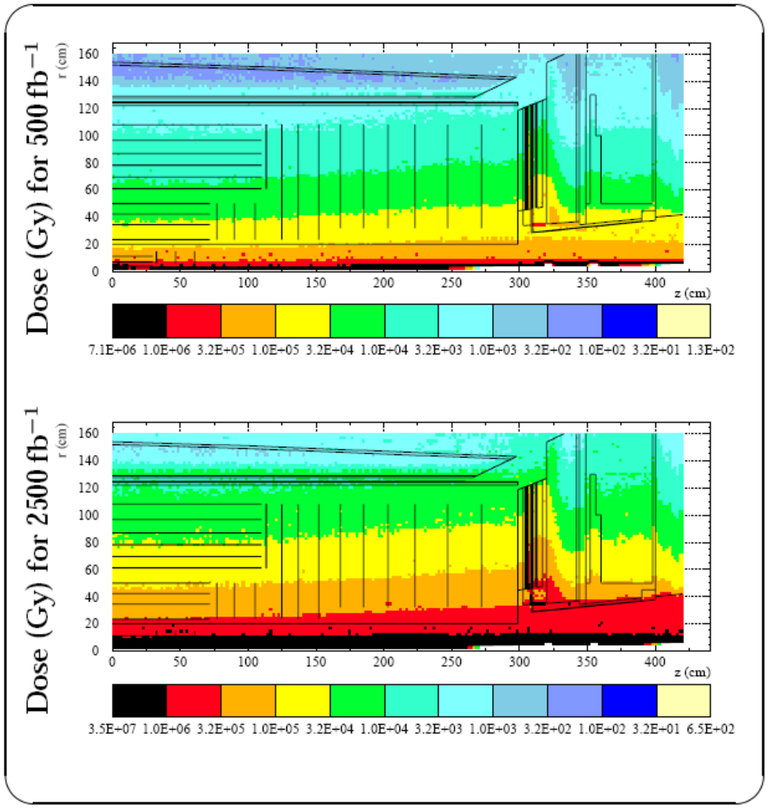
Radiation environment for trackers

Except for the very innermost layers many current technologies should survive SLHC



R. Horisberger

Radiation Dose in Inner Detectors



M. Huhtinen *SLHC Electronics Workshop 26 February 2004* 3

Phase I issues for tracking

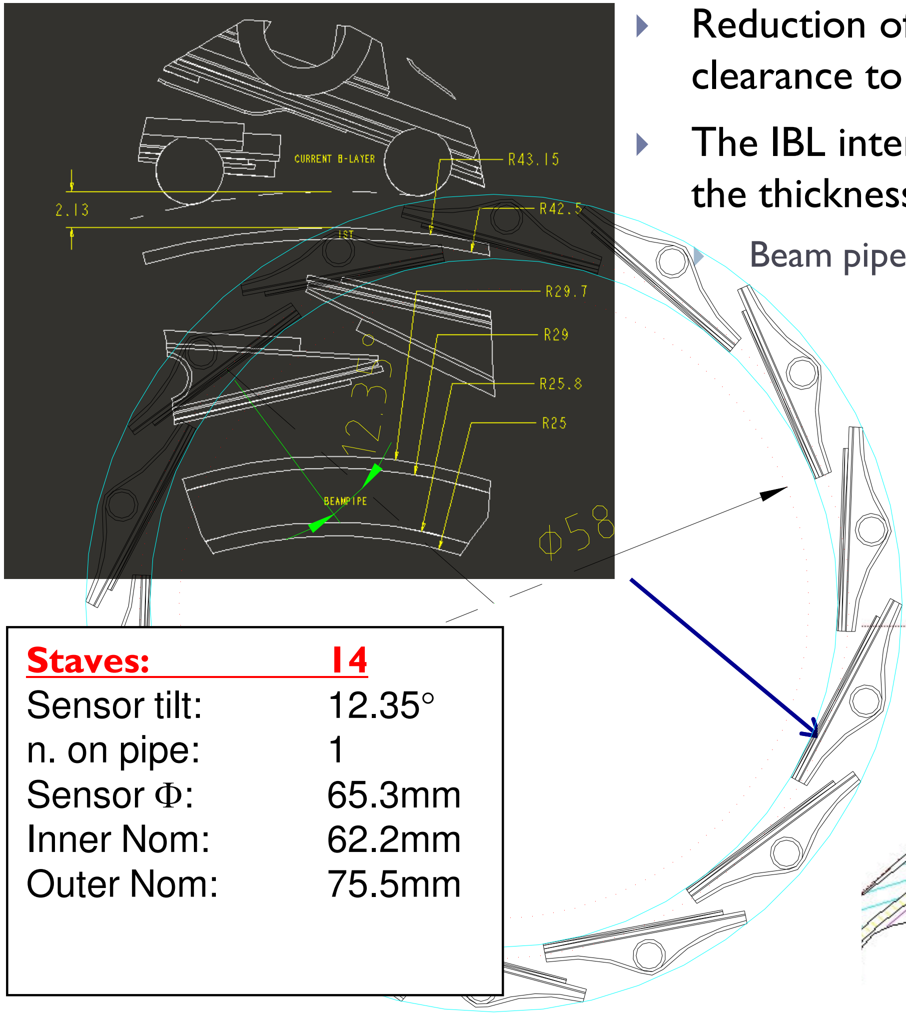
- Rough estimate of pixel layer lifetimes

  4cm layer should survive a minimum of 200fb^{-1}
- Will have to replace the pixel detector during phase I
  - How often?
  - How much to replace?
  - New features
- CMS: Looking at reducing the material in the replacement pixel detector, and potentially adding a fourth layer
- ATLAS: Can't remove the current pixel detector, will remove beampipe, and then insert new beampipe with an inner layer attached
- Outer trackers looks robust to survive Phase I

ATLAS: IBL Layout and New Beam Pipe

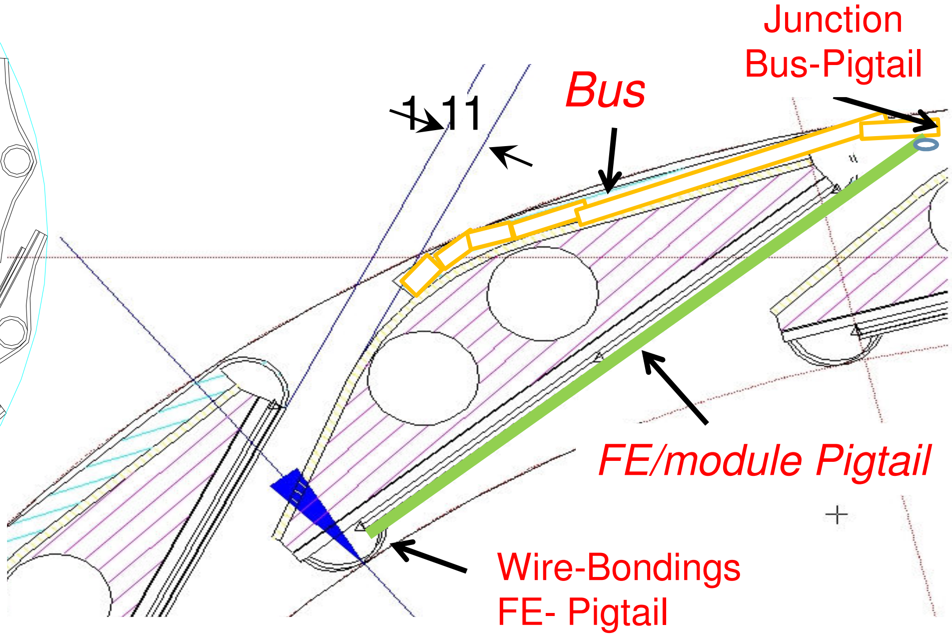
- Several layouts under study: 14 staves at R_{min}=~3.1 cm
  - *Single and double staves – One or two (redundant) cooling channels*

- Reduction of beam-pipe (ID from 29R to 25R) allows enough clearance to fit the IBL
- The IBL internal envelope is defined by the new beam pipe and by the thickness of the insulation required during the bakeout.
  - Beam pipe ID= 50, thickness = 0.8 mm, Insulation =4 mm



Staves:	**14**
Sensor tilt:	12.35°
n. on pipe:	1
Sensor Φ:	65.3mm
Inner Nom:	62.2mm
Outer Nom:	75.5mm

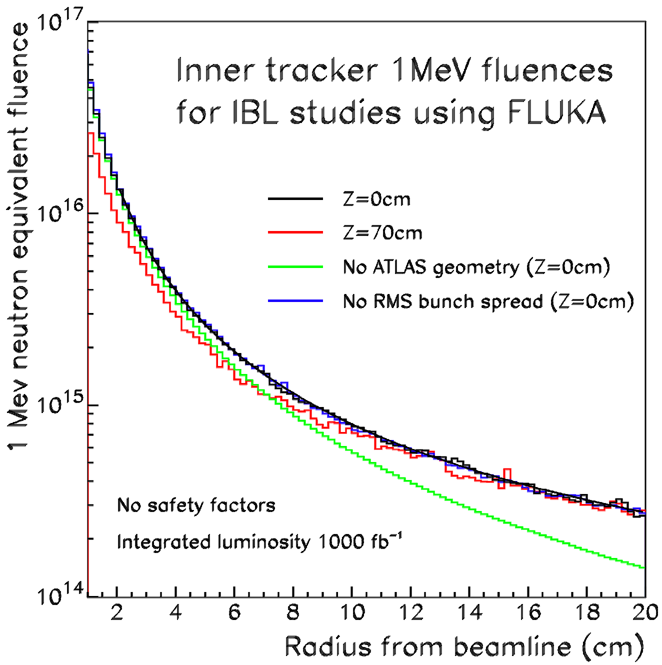
Inverted turbine



Credits: N. Hartman et al.

Requirements for Sensors/Electronics (G. Darbo)

- Requirements for IBL
  - IBL design **Peak Luminosity** = 3x10^{34} cm^{-2}s^{-1} → New FE-I4, higher hit rate
  - Integrated Luminosity seen by IBL = 550 fb^{-1}
  - Total NIEL dose = 2.4 x 10^{15} ± 30% (σ_{pp}) ± 50% (damage factor) = 4.7 x 10^{15} n_{eq}/cm^2 → more rad-hard sensors
  - Total radiation dose > 200 Mrad
- ATLAS Pixel Sensor/FE-I3 designed for 10^{15} n_{eq}/cm^2 / 50 Mrad



Ref. Ian Dawson – ATLAS Upgrade Week (Feb.09)

- Fit made for 2 < r < 20 cm for L=1000fb^{-1}

$$\Phi(r) = \left(\frac{493}{r^2} + \frac{25}{r}\right) \times 10^{14}$$

- Gives for IBL @ 3.7 cm (550 fb^{-1}):

√$_{1MeV}$=2.4x10^{15} (1.2 MGy)

- Safety factors not included in the computation (pp event generator: 30%, damage factor for 1 MeV fluences: 50%)

Sensor: 3D, Planar, Diamond (G. Darbo)

- IBL sensor developments coming from ATLAS R&D efforts – IBL define specification and requirements for the sensors:
    - ATLAS 3D Sensor Collaboration (16 Institutes and 4 processing facilities):

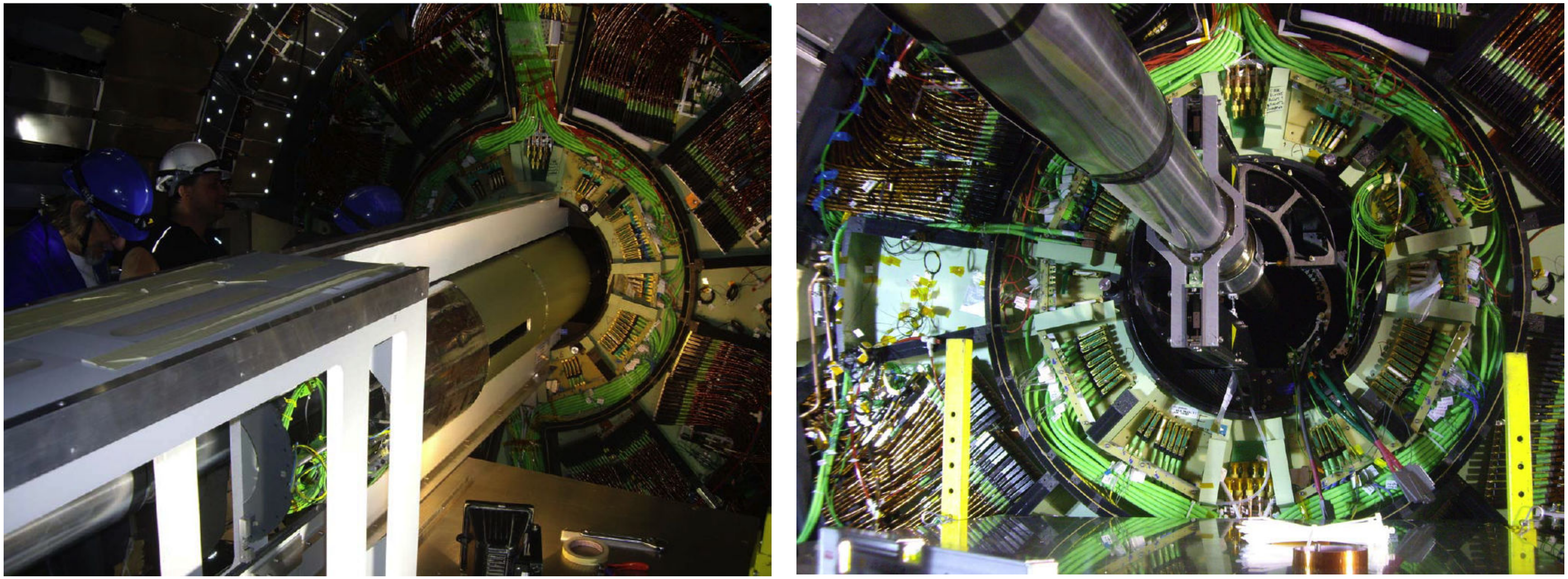
      Bergen, Bonn, CERN, Cosenza, Freiburg, Genova, Glasgow, Hawaii, LBNL, Manchester, New Mexico, Oslo, Prague, SLAC, Stony Brook, Udine - Processing Facilities: CNM Barcelona, FBK-IRST (Trento), SINTEF/Stanford
    - ATLAS Planar Pixel Sensor R&D Collaboration (16 Institutes)

      Bonn, Berlin, DESY, Dortmund, MPP & HLL Munich, Udine, KEK, CNM Barcelona, Liverpool, LBNL, LPNHE, New Mexico, Orsay, Prague, Santa Cruz.
    - ATLAS Diamond R&D Collaboration (6 Institutes, 2 vendors):

      Bonn, Carleton, CERN, Ljubljana, Ohio State, Toronto

- Bring the 3 sensor technologies to the prototype phase for IBL

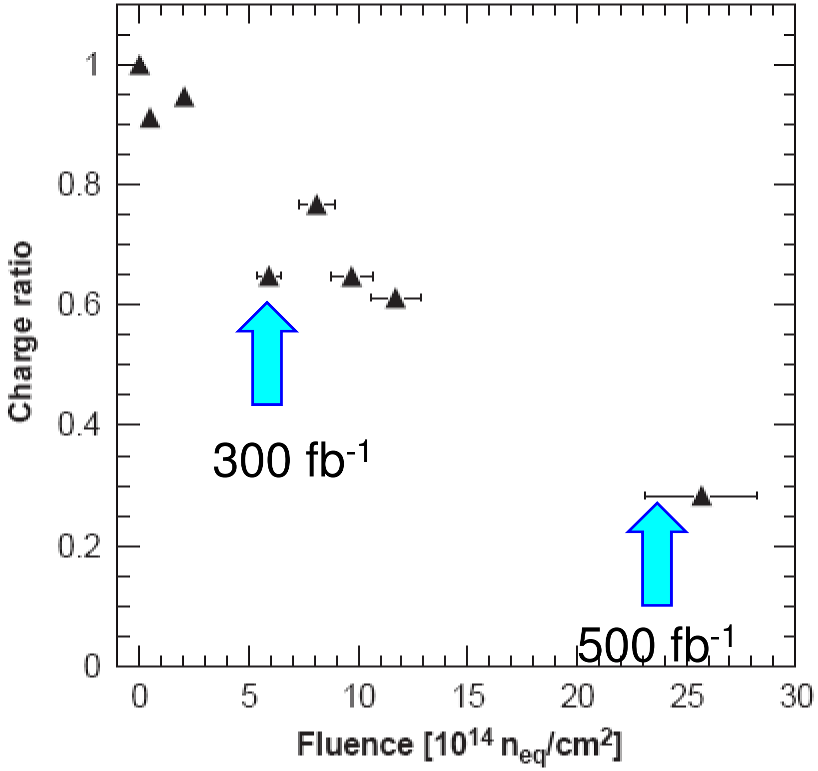
Fast insertion of CMS Pixel system

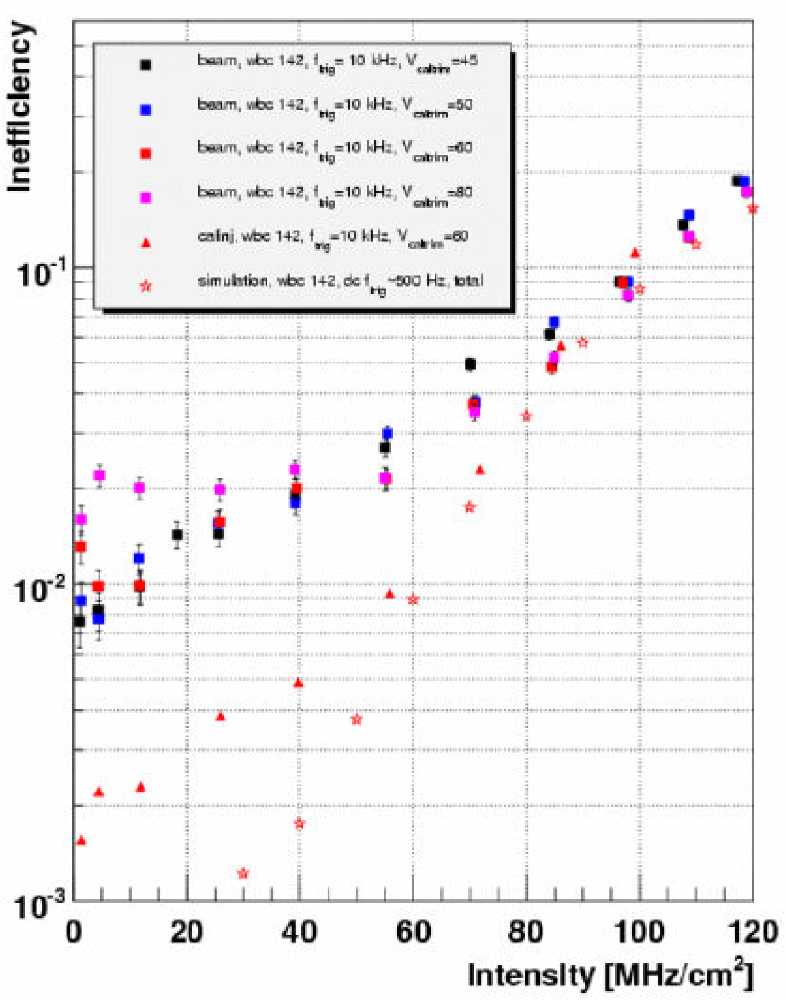


Insertion of the Pixel was done in a few hours

Limitations in Phase 1

- Radiation damage due to integrated luminosity.
  - Sensors designed to survive $6\times10^{14} n_{eq}/cm^2$ (~ 300 fb^{-1}).
  - n-on-n sensors degrade gradually at large fluences

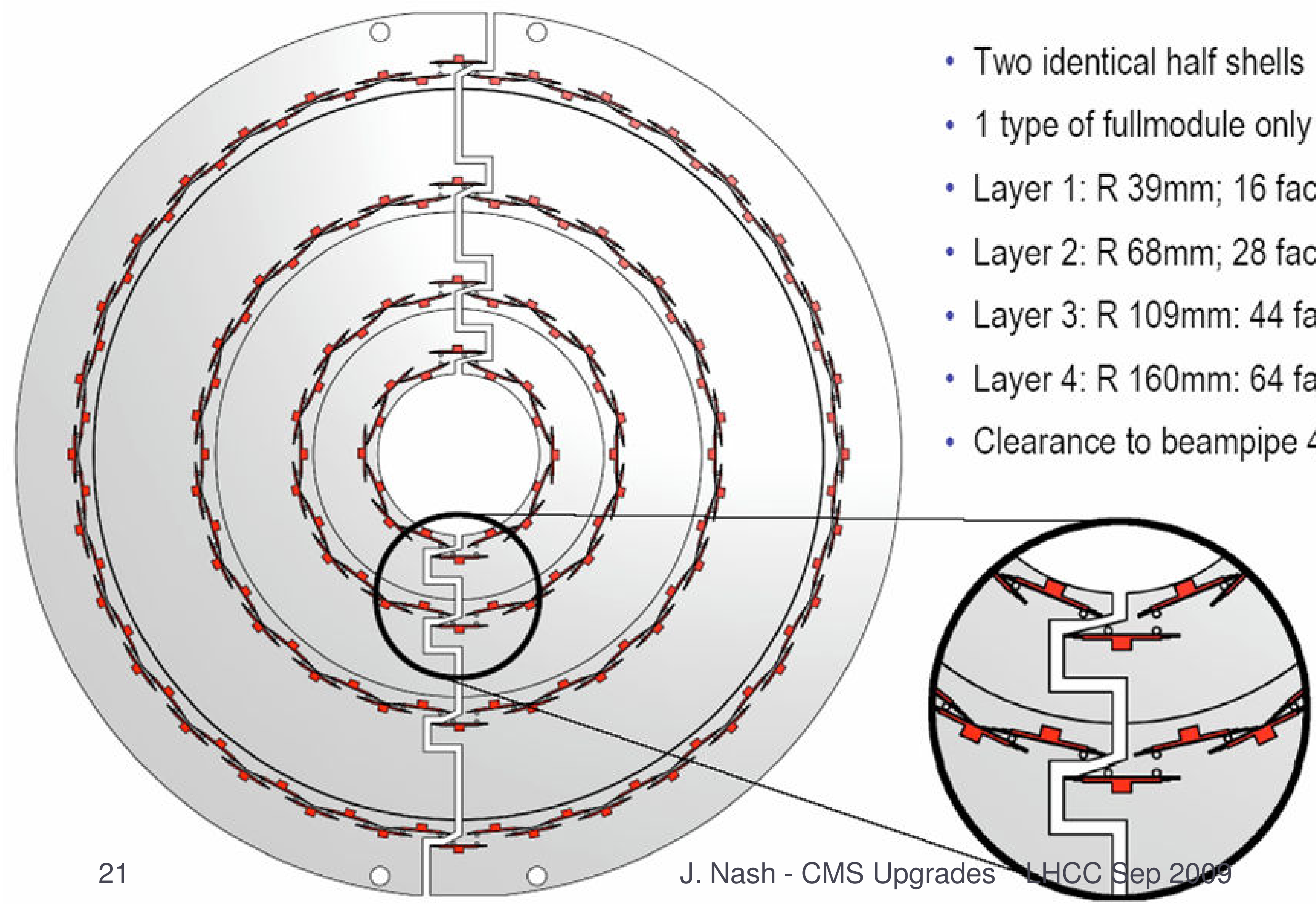




Dead time will rise to ~12% due to increase in peak luminosity

CMS BPIX Upgrade Phase 1 (2013)

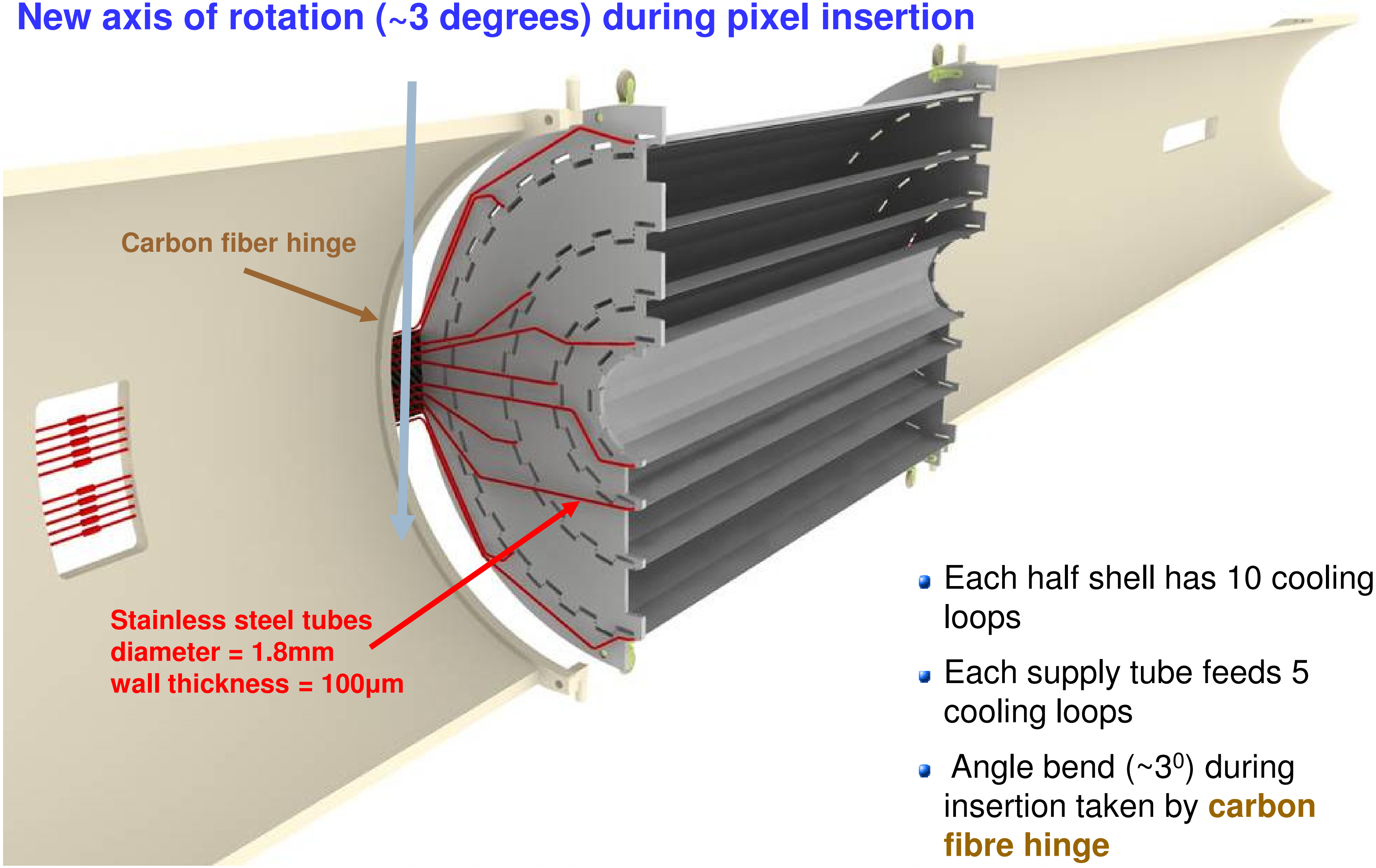
→ **1216 modules**
(1.6 x present BPIX)



- Two identical half shells
- 1 type of fullmodule only
- Layer 1: R 39mm; 16 faces
- Layer 2: R 68mm; 28 faces
- Layer 3: R 109mm: 44 faces
- Layer 4: R 160mm: 64 faces
- Clearance to beampipe 4mm

Inertion of BPIX – Supplytube System with new CO2 Cooling

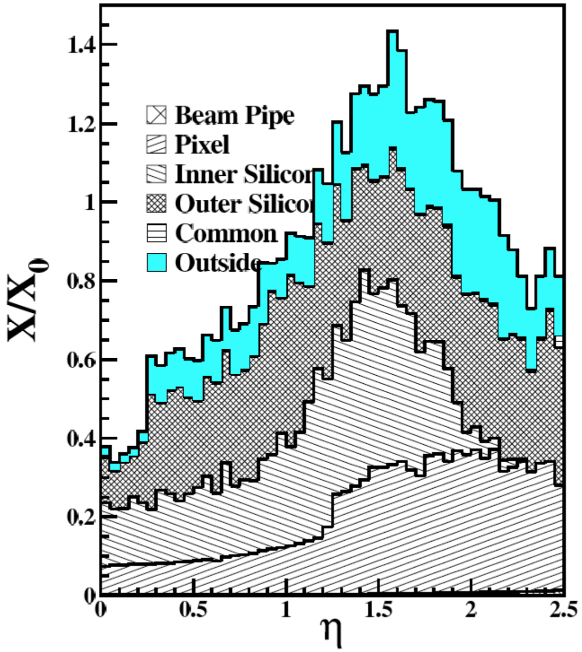
New axis of rotation (~3 degrees) during pixel insertion



- Each half shell has 10 cooling loops
- Each supply tube feeds 5 cooling loops
- Angle bend (~3^0) during insertion taken by **carbon fibre hinge**

Key issues for tracker upgrades (Not just more channels!)

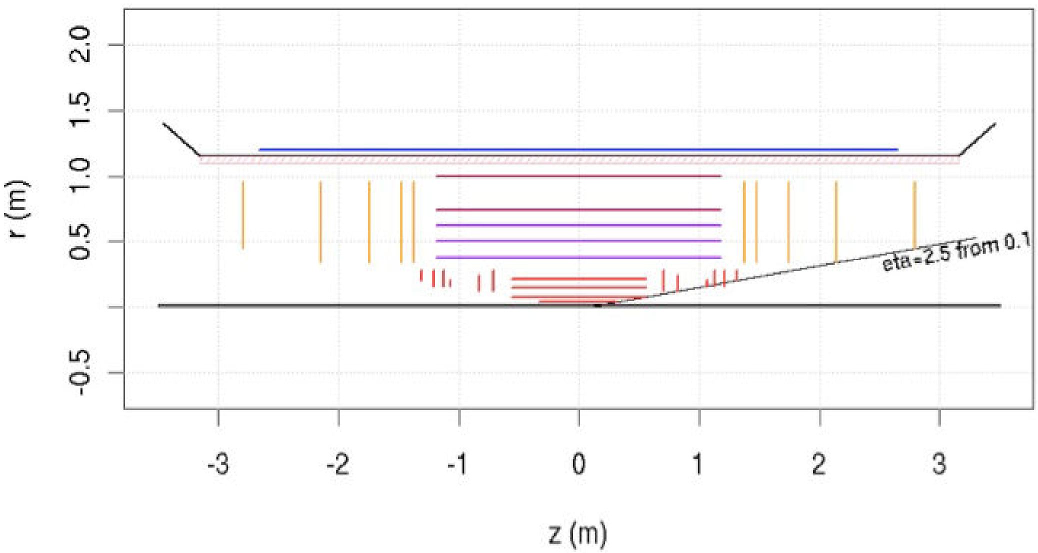
- Power
  - How to get current needed to the electronics
  - More complicated front ends, more channels may want more power
    - DC-DC converters, Serial powering
- Material Budget
  - Can we build a better/lighter trackers?

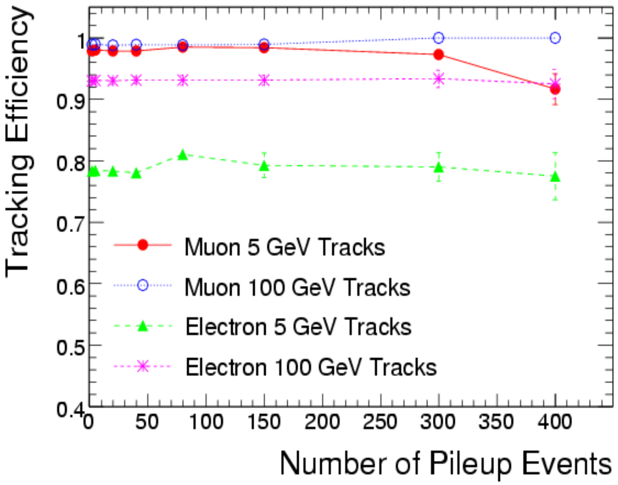


From CMS Physics TDR Vol 1 (LHCC 2006-001)

ATLAS ID layout for simulation and engineering

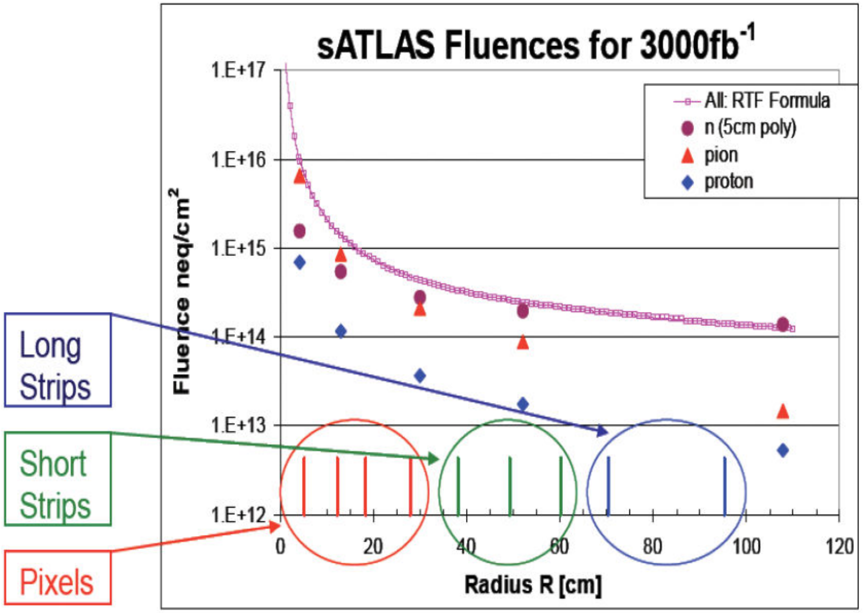
Full semiconductors solution : strips (~160m^2) and pixels, organized in staves !
Patter recognition efficiency being optimized (14 hits system)!





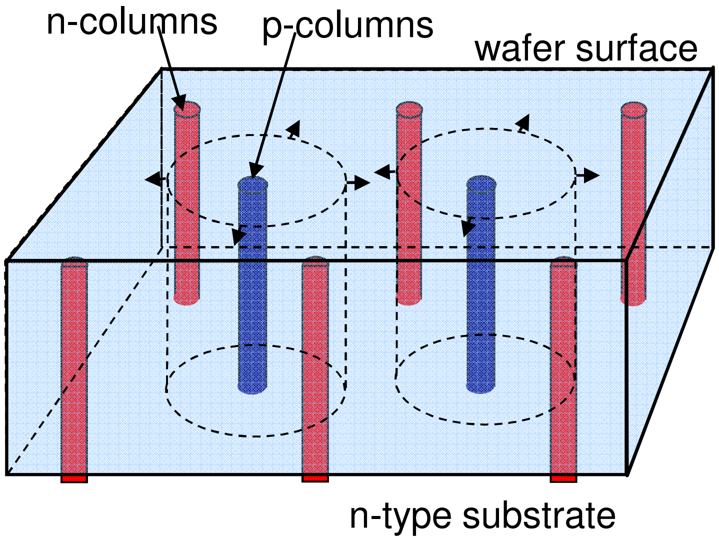
- ✓ *More granularity for similar occupancy at higher luminosity*
- ✓ *The crucial point is to reduce as much as possible the material budget*

Choice of the sensor technology still in the R&D phase

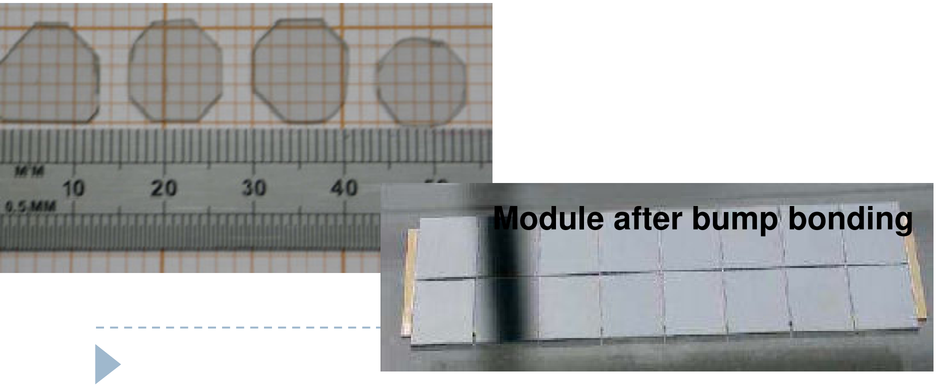


While in the strips region, the existing Si planar technology (n-in-p) will probably be OK from the point of view of radiation (tested ~10^{15}n/cm^2), the solutions for the innermost layers might need to be different or revisited !

3D silicon : 250 μm have been tested , high eff.
~ 10^{16} p,n/cm^2, S/N ~ 60



Diamond : low leakage, radiation hard, low capacitance, heat spreader … but lower signal … and difficult to mass produce



Reducing tracker mass

- Look at how the trackers are powered
  - Copper is a lot of the material
  - Deliver power at a higher voltage
  - Local voltage reduction
    - DC-DC Conversion
    - Serial Powering
- High speed data links – reduce power for more channels
  - Common R/D project - versatile link
- $C0_2$ cooling

DC-DC Conversion for the Tracker Upgrade

A novel powering scheme will be needed ⇒ review process to narrow down options.

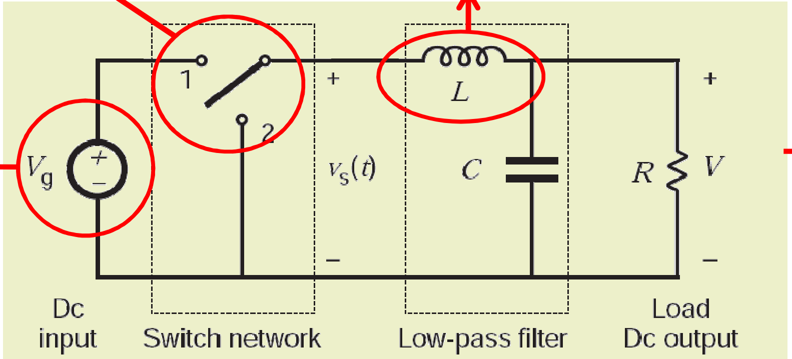
The CMS tracker has chosen **DC-DC conversion as baseline solution**, and maintains Serial Powering as back-up. Reverting to back-up must remain possible.

V_{in} (e.g. 10V)
Cable loss red. by $1/r^2$

DC-DC Converter
Conversion ratio r = 2 - 10
$r = V_{in}/V_{out} = I_{out}/I_{in}$

V_{out} (e.g. 1.2V)

"Buck converter": few components, efficiency ~ 80%, high currents, high r



Switching noise

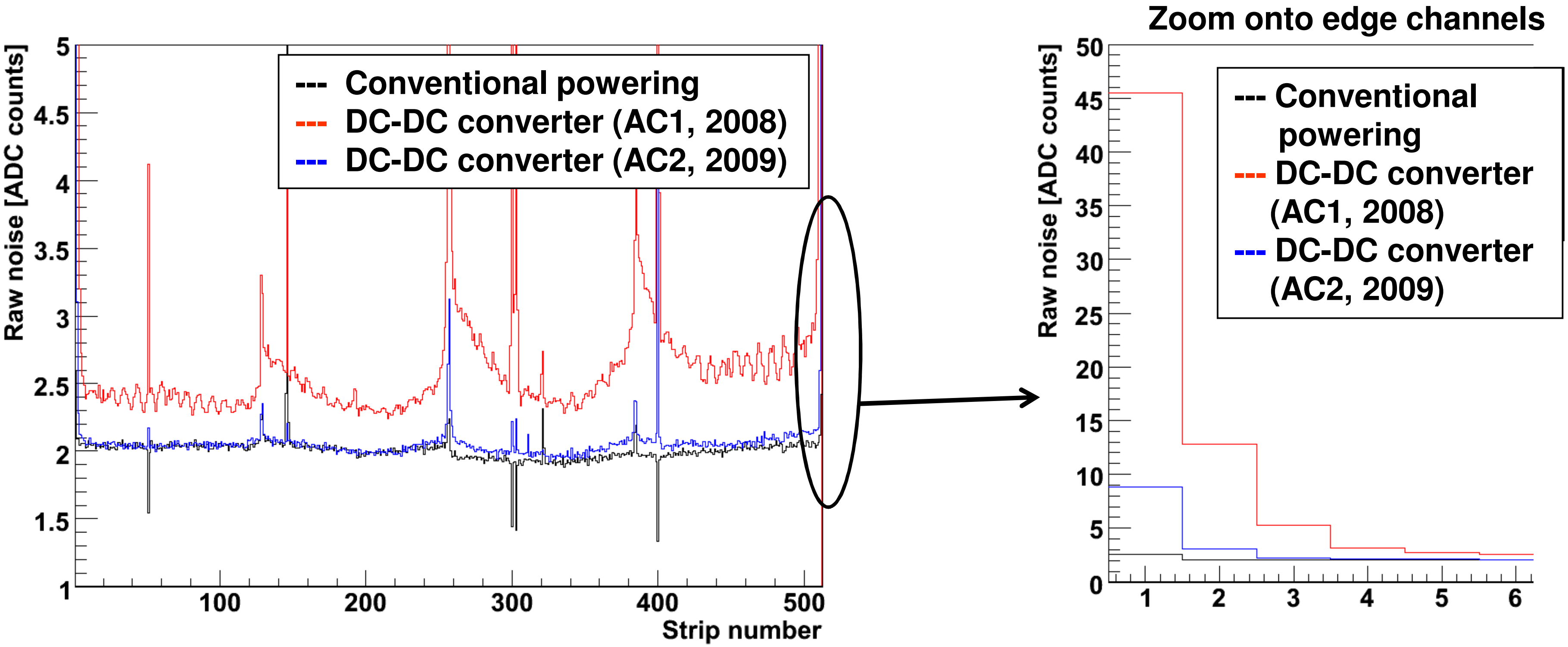
Ferrites saturate for B > ~2T
⇒ air-core inductor needed

- bulky
- radiates noise

HV-tolerant semi-conductor technology needed
→ radiation-hardness
(22cm & 3000fb^{-1}:
Fluence ~ 10^{15}/cm^2
Dose ~ 1MGy)

- Efficiency
- Material budget
- Space constraints

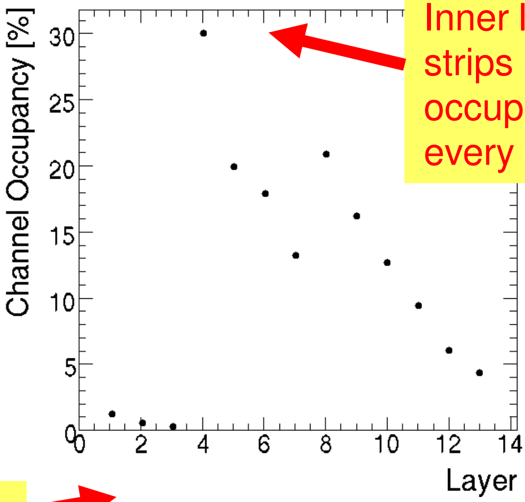
Silicon Strip Module Noise



- Raw noise: RMS of fluctuation around pedestal value
- Edge channels are particularly sensitive (explanation in back-up slides)
- Large increase with previous generation of boards (**AC1**), in particular on edge strips; both conductive (ripple) and radiative (inductor) contributions (TWEPP08)

Tracking with 500 min Bias events

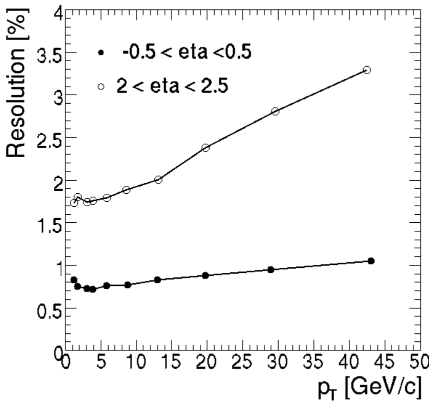
- Study of current CMS tracker for Heavy Ion events
- Track density very similar to 50ns running
  - $dn^{ch}/d\eta$/crossing ≈ 3000
  - Tracker occupancy very high
  - Need more pixel layers/shorter strips
- Tracking possible
  - When tracks are found they are well measured
  - Efficiency and fake rate suffer
  - CPU Intensive



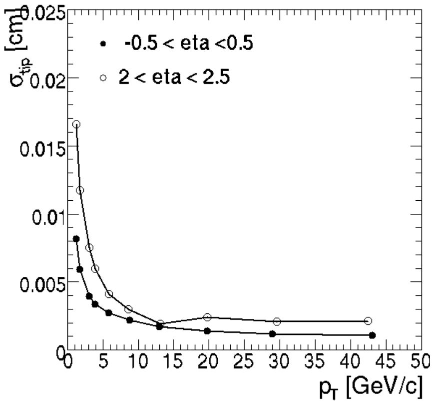
Inner layers of strips reach 30% occupancy on every xing!

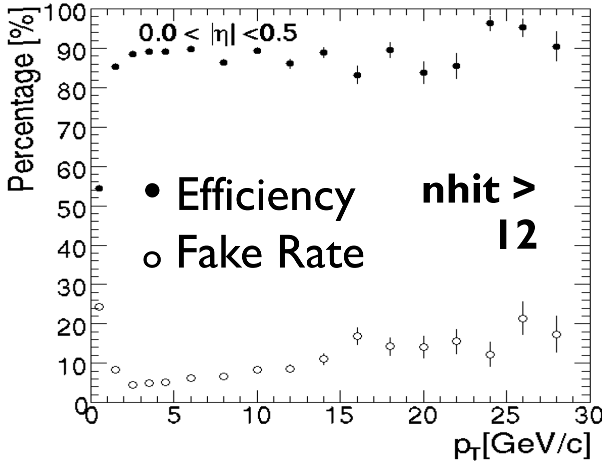
Pixel layers

Momentum Resolution



Transverse Impact Parameter Resolution



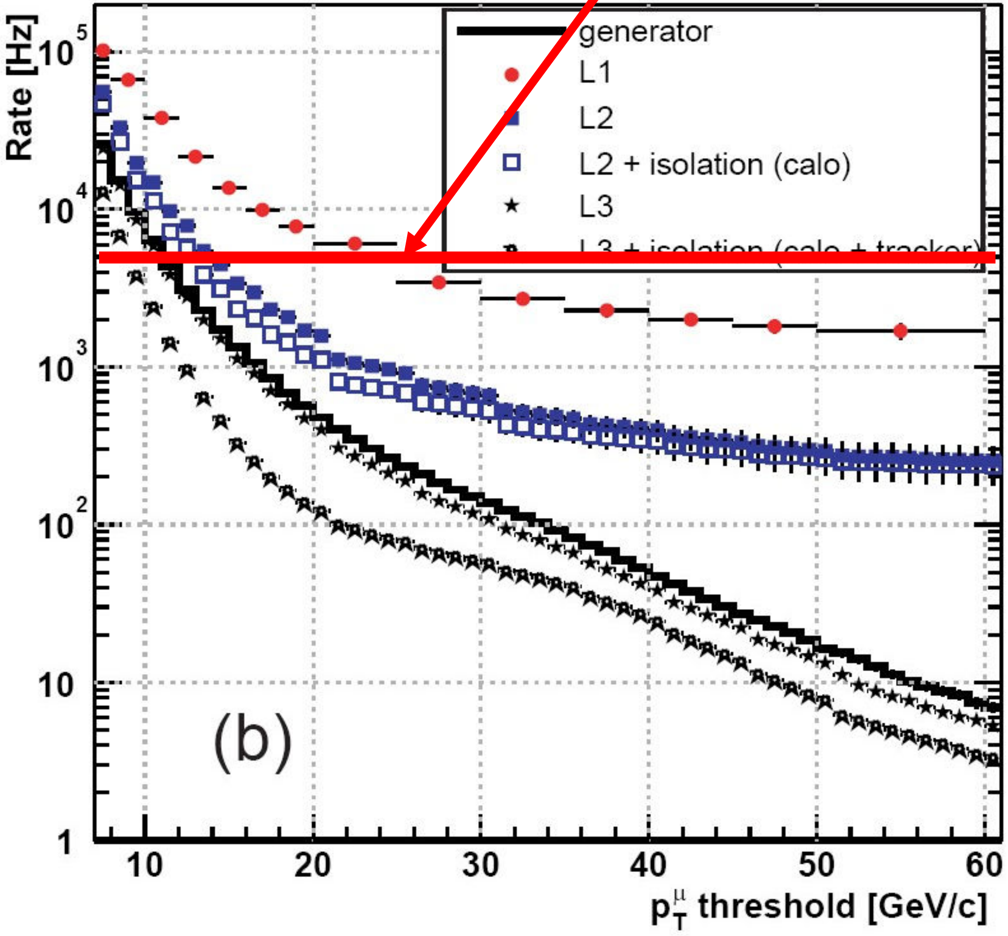


C. Roland

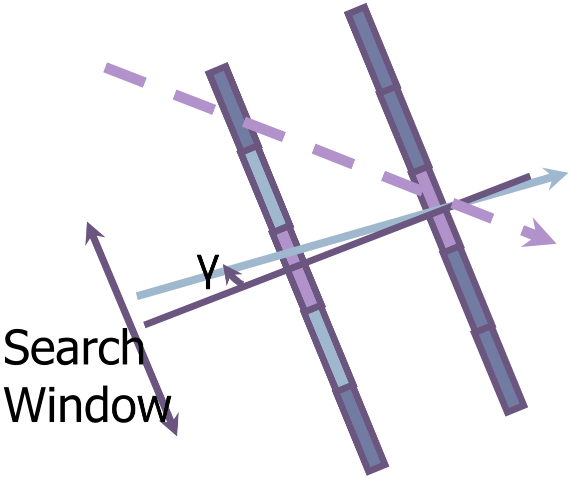
Level 1 Trigger

Level 1 Trigger has no discrimination for $P_T >$ ~ 20 GeV/c

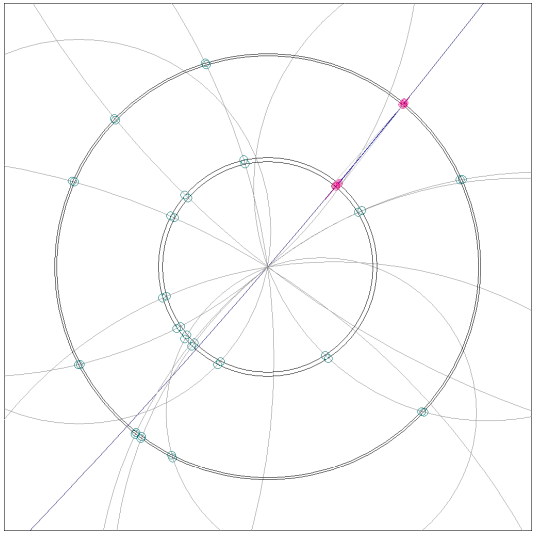
- The trigger/daq system of CMS will require an upgrade to cope with the higher occupancies and data rates at SLHC
- One of the key issues for CMS is the requirement to include some element of tracking in the Level I Trigger
    - One example: There may not be enough rejection power using the muon and calorimeter triggers to handle the higher luminosity conditions at SLHC
- Adding tracking information at Level I gives the ability to adjust P_T thresholds
- Single electron trigger rate also suffers
    - *Isolation criteria are insufficient to reduce rate at* $\mathcal{L} = 10^{35}\ cm^{-2}.s^{-1}$



Concepts:Tracking Trigger



High momentum tracks are straighter so pixels line up



Pairs of stacked layers can give a P_T measurement

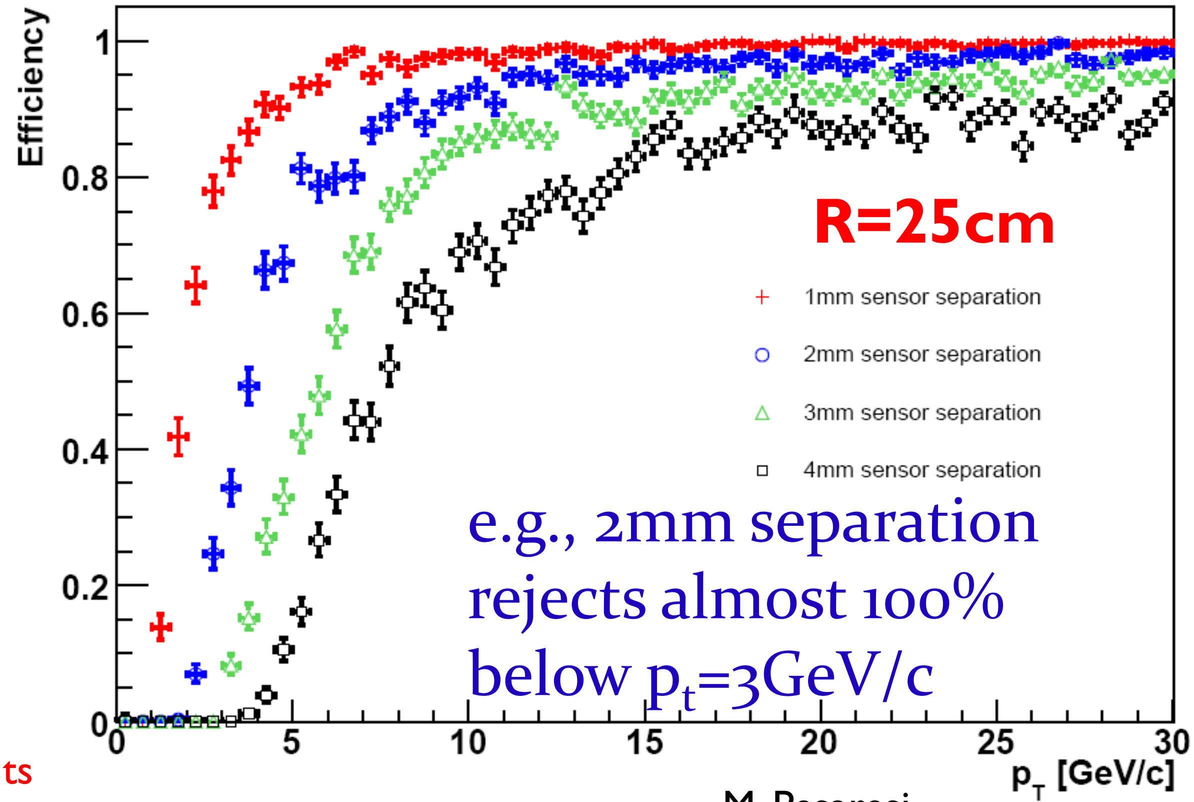
Geometrical p_T-cut - J. Jones, A. Rose, C. Foudas LECC 2005

- Why not use the inner tracking devices in the trigger?
  - Number of hits in tracking devices on each trigger is enormous
  - Impossible to get all the data out in order to form a trigger
  - How to correlate information internally in order to form segments?
- Topic requiring substantial R&D
  - "Stacked" layers which can measure p_T of track segments locally
    - Two layers about 1mm apart that could communicate
  - Cluster width may also be a handle

Stacked layers

- At fixed detector pitch sensor separation determine the effective p_t cut

- Increasing separation →
  - higher p_t selection
  - broader transition region
  - Reduced high p_t efficiency (more combinatorial)



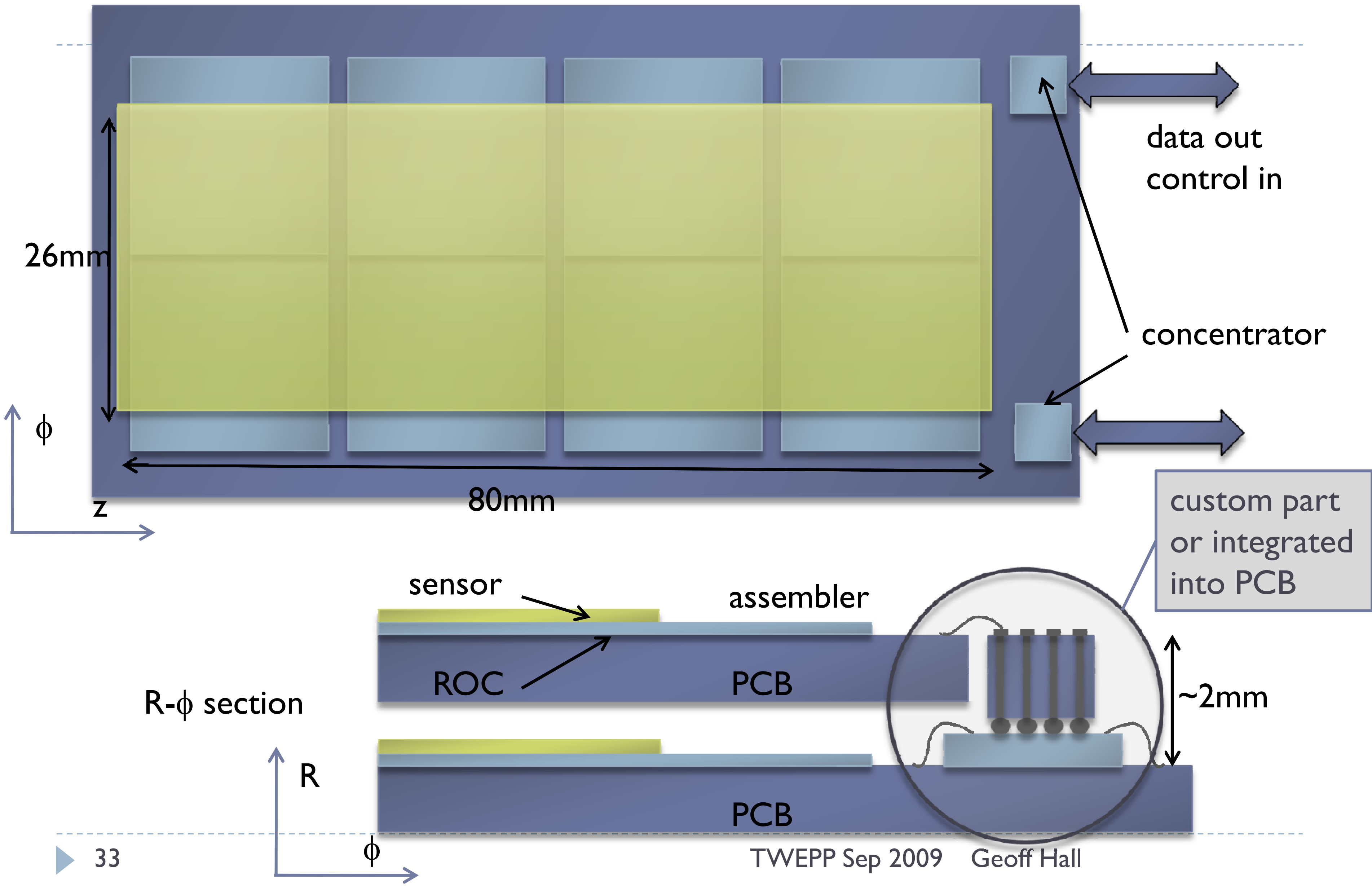
R=25cm

e.g., 2mm separation rejects almost 100% below p_t=3GeV/c

M. Pesaresi

Performance of a stacked layer at R = 25cm 10,000 di-muon events with smearing

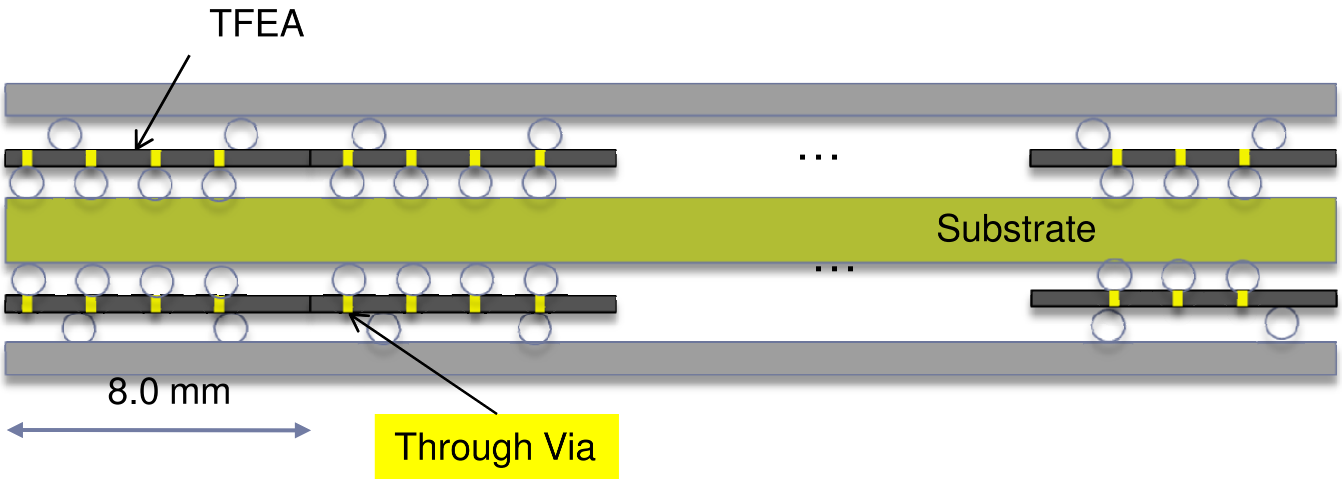
Module schematic



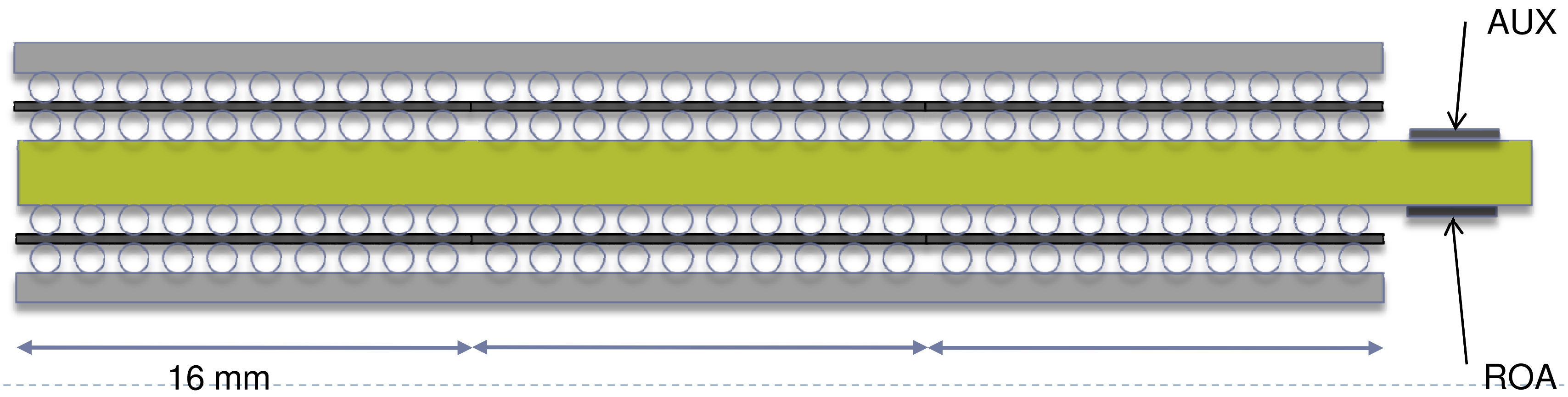
Double bump assembly

A Marchioro

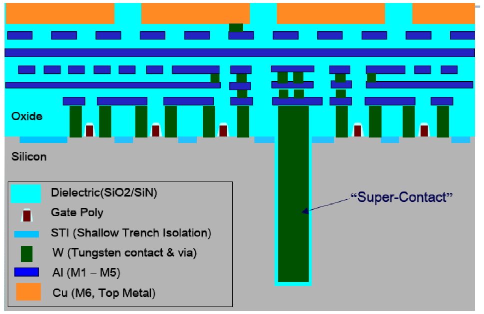
- Such techniques are becoming available
  - eg for high density non-volatile memories and telecom applications



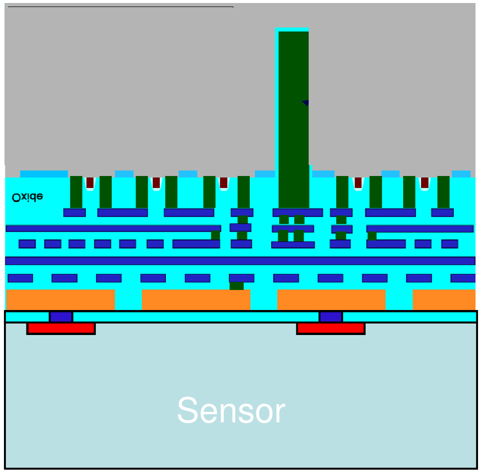
Sensor	250um
C4	100 um
ASIC	100 um
C4	100 um
Substrate	700 um
C4	100 um
ASIC	100um
C4	100 um
Sensor	250 um



Building a Trigger module with 3D

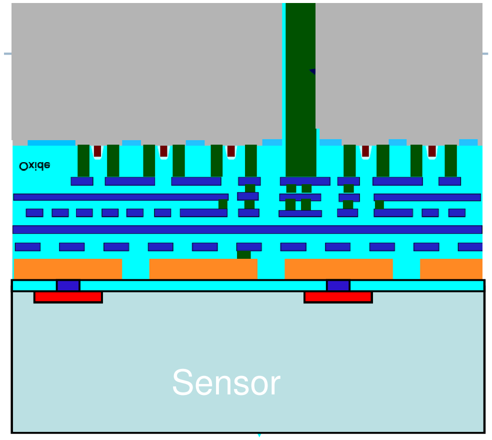


Readout IC wafer with TSV from foundry

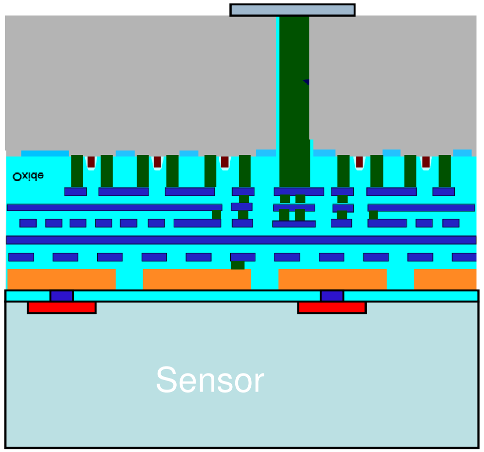


DBI bond

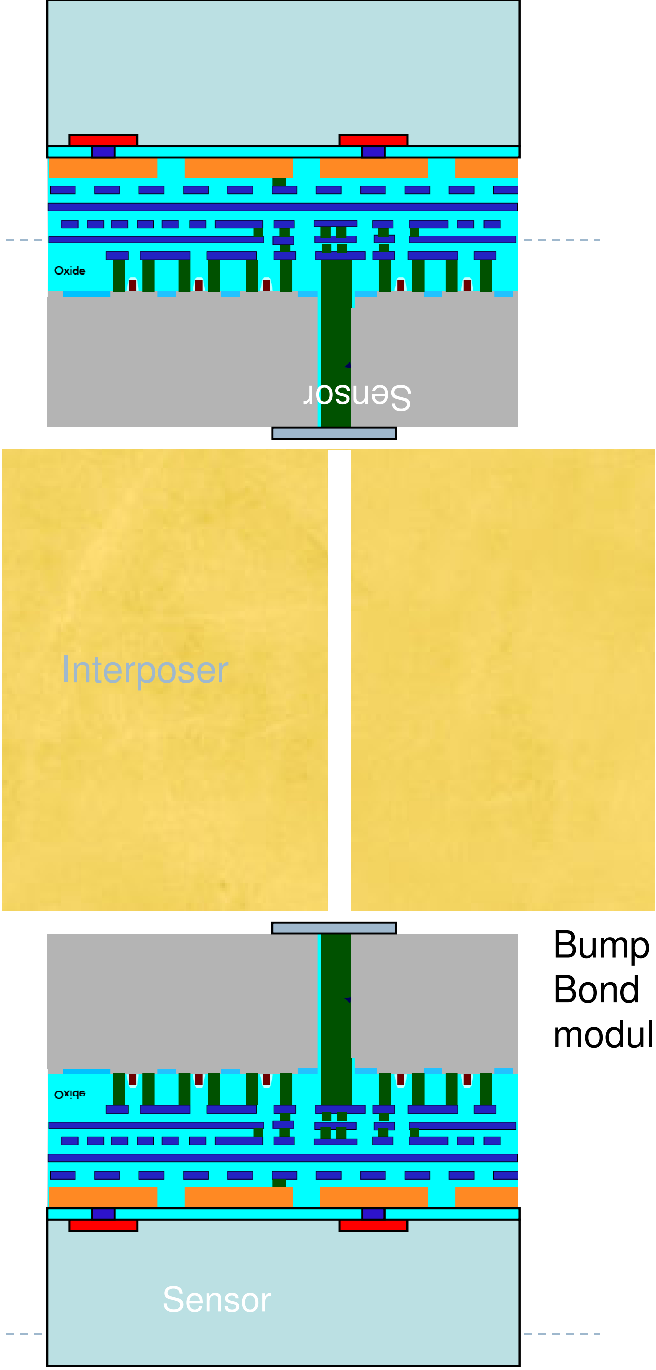
Oxide bond diced ROIC to sensor Wafer.



Thin to expose TSV



Contact lithography provides
Access to topside pads for vertical data path



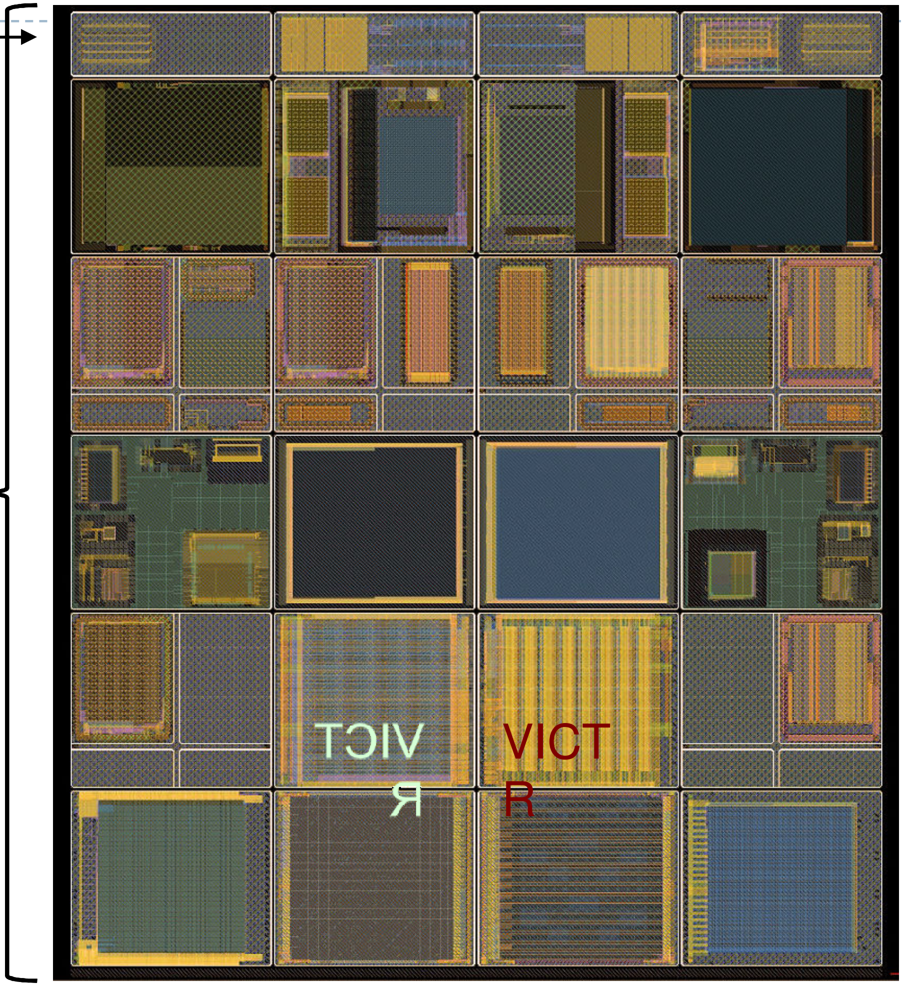
Bump Bond module

Test, assemble module with interposer

Final Reticule

Test chips:
TX, TY
2.0 x 6.3 mm

Subreticules:
A, B, C, D, E, F, G, H, I, J
5.5 x 6.3 mm

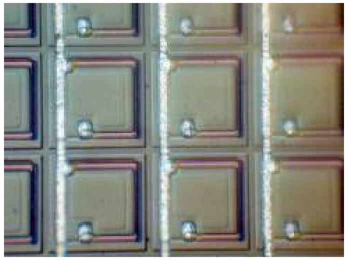


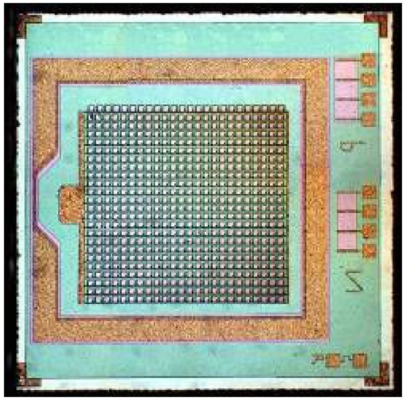
← Top tiers → ← Bottom Tiers →

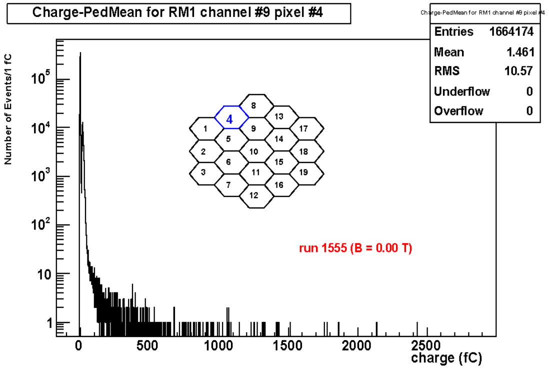
Notice Symmetry about vertical center line

CMS Hadron Calorimetry - SiPMs

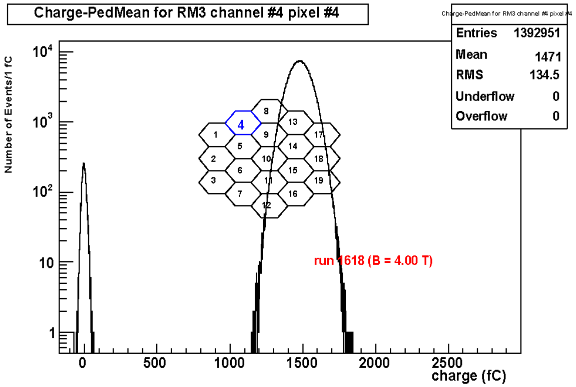
- Array of avalanche photo diodes (“digital” photon detection)
  - Array can be 0.5x0.5 up to 5.0x5.0 mm^2
  - Pixel size can be 10 up to 100μ
- All APDs connect to a single output
  - Signal = sum of all cells
- Advantages over HPDs:
  - 28% QE (x2 higher) and 10^6 gain (x500 higher)
  - More light (40 pe/GeV), less photostatistics broadening
  - Very high gain can be used to give timing shaping/filtering







HPD



SiPM

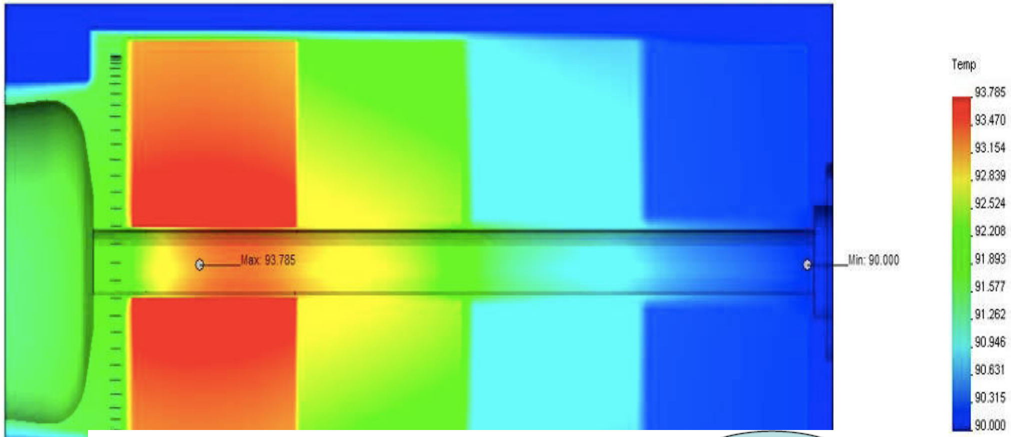
ATLAS Lar Calorimeters (forward) will need a major rework

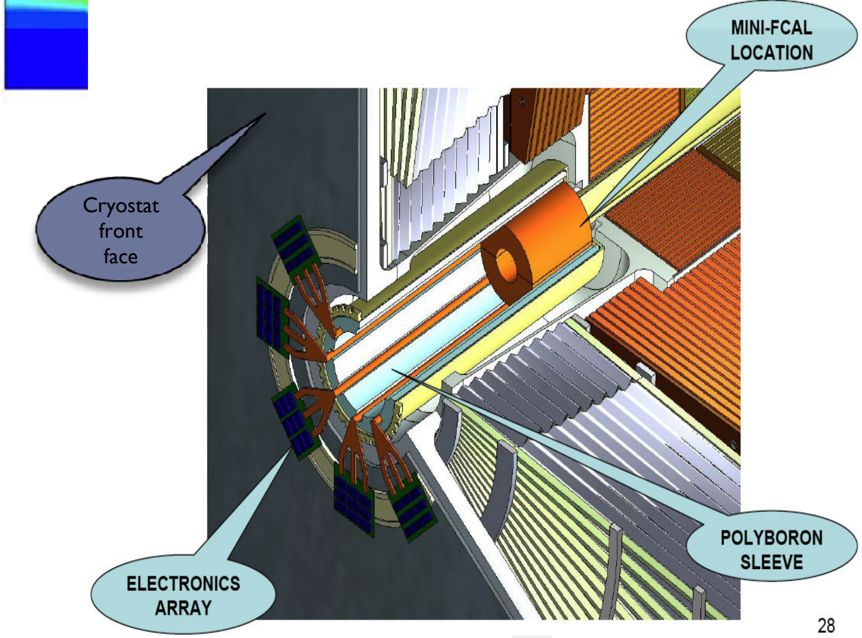
Studies and tests under way; if these show that action is needed, two solutions are considered:

- Warm calorimeter in front of current calorimeter (diamond technology?)

-Open cryostat, insert complete new FCAL with smaller gaps and more cooling power

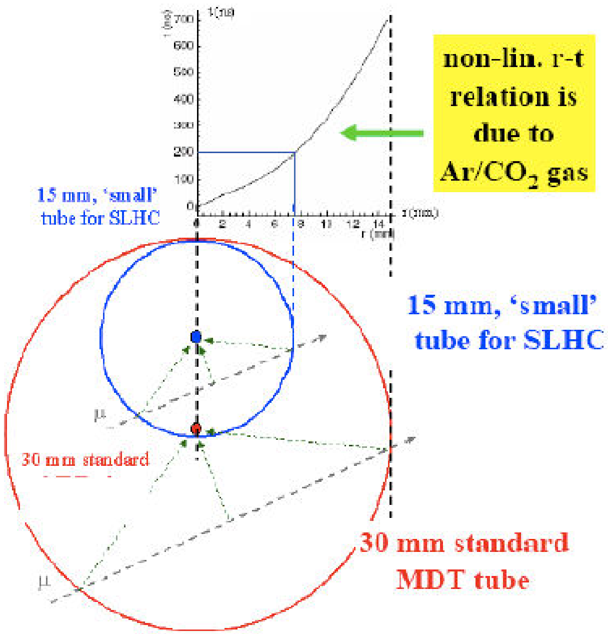
All this will require a major shutdown of about 15 months to operate in the experimental cavern

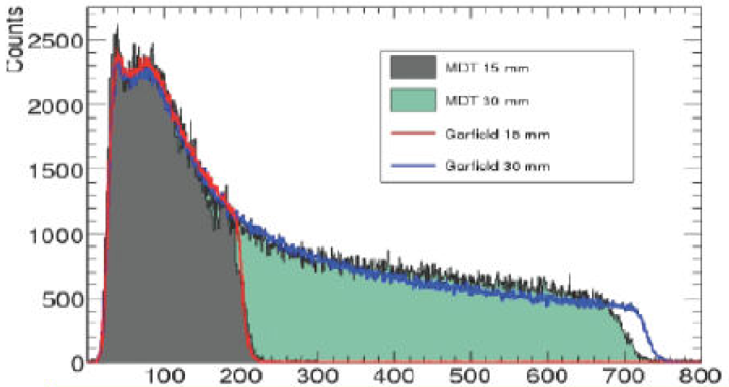




ATLAS Muons

Small-tube MDTs





drift time spectr. w. large and small tubes

Smaller tubes provide reduced channel cross section (x 1/2) (reduced occupancy)
shorter pulse, shorter maximum charge collection time (x 1/3),
reduced space charge (~ R^{-3} = 1/8) (affecting chamber resolution at large *r*)

18 July 2009 S. Palestini 16

Conclusions

- Increasing the luminosity of the LHC will provide a series of difficult R/D challenges to the LHC collaborations
- The communities are actively pursuing the key R/D
  - Maturity varies from nearly complete designs for phase I detector upgrades to very early concept development for phase 2 detectors
- Some of the problems are still not obvious how to solve
  - New technologies/techniques need to be developed.