# LHC Upgrades

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# Overview

- Motives for upgrades
- Requirements for machine
- Timing
- Changes to the experiments
  - limited time, so selected “highlights”
  - omitting ALICE (apologies!)
- There is now a lot of material on upgrade plans
  - talks, proposals, official documents,… available for consultation

# Motives for upgrades

- No shortage of physics yet to be discovered
  - when it is, the detailed ATLAS/CMS objectives should be much more precise
  - meanwhile strongest arguments are for increasing sensitivity by adding statistics
  - LHCb hopes to characterise NP by (greater) precision measurements
- LHC operational conditions becoming clearer
  - about half the integrated luminosity to 2020 will be delivered at twice the design value, possibly with 50ns bunch spacing
  - detectors were not designed for this (remember LHC was a challenge!)
- Age and experience go together
  - real detectors will be imperfect and may degrade
  - technology is constantly improving and performance can be enhanced
- Profit from the huge investment over more than two decades
  - obvious that future developments will be equally lengthy and challenging

# Physics goals of sLHC

**Main ATLAS Physics goals:**

Higgs discovery: Mass and understanding electro-weak symmetry breaking

Unification of forces, gravity, SUper SYmmetry, extra dimensions

New forces (W', Z')

Flavour: why 3 families, neutrino mass, dark matter

Whatever is discovered at the LHC will need a lot of data to understand exactly what has been discovered: characterising the discoveries.
In addition, the sLHC can extend the discovery potential, to higher masses or lower cross-sections.
While the LHC aims at ~300 $fb^{-1}$ per experiment, the sLHC aims for 3000 $fb^{-1}$ of data, opening up new possibilities for channels limited by statistics at the LHC

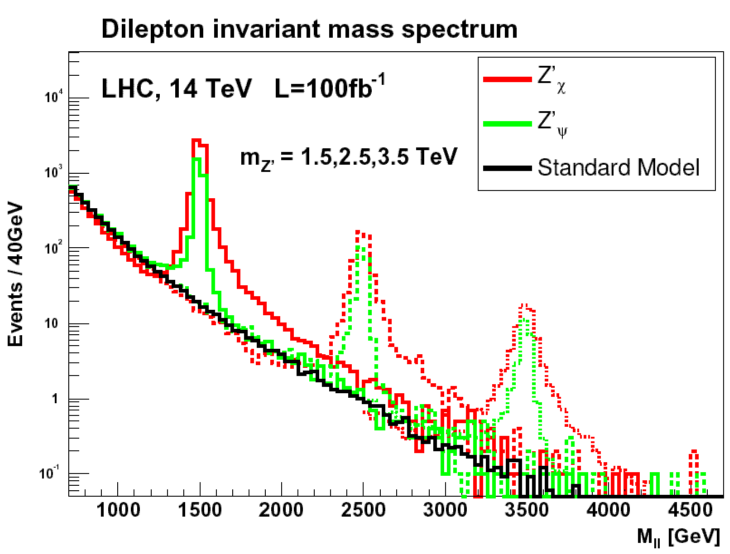
There are many measurements where extending the LHC data set is important, including:

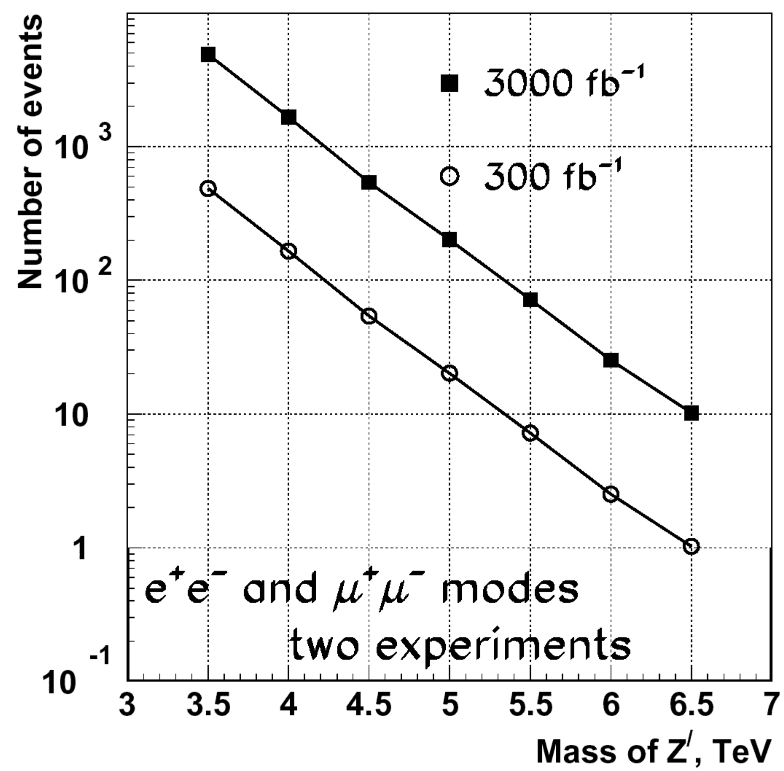
1. Higgs couplings
2. Triple gauge-boson couplings
3. Vector boson fusion at ~1 TeV
4. SUSY – discovery or spectroscopy
5. New forces: W', Z' to higher limits

# 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!



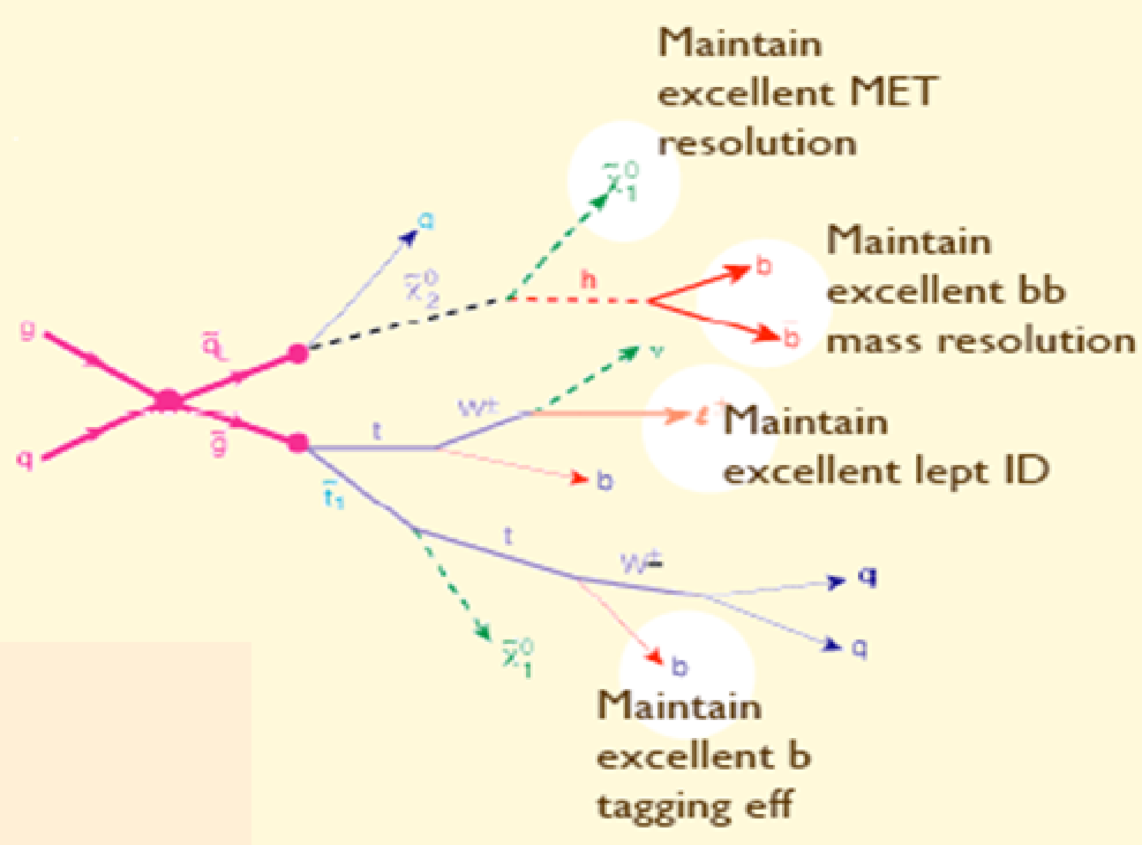




| $Z'$ mass (TeV) | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $\sigma(Z' \to e^+e^-)(fb)$ | 512 | 23.9 | 2.5 | 0.38 | 0.08 | 0.026 |
| $\Gamma_{Z'}$ (GeV) | 30.6 | 62.4 | 94.2 | 126.1 | 158.0 | 190.0 |

# SUSY searches - measurements

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

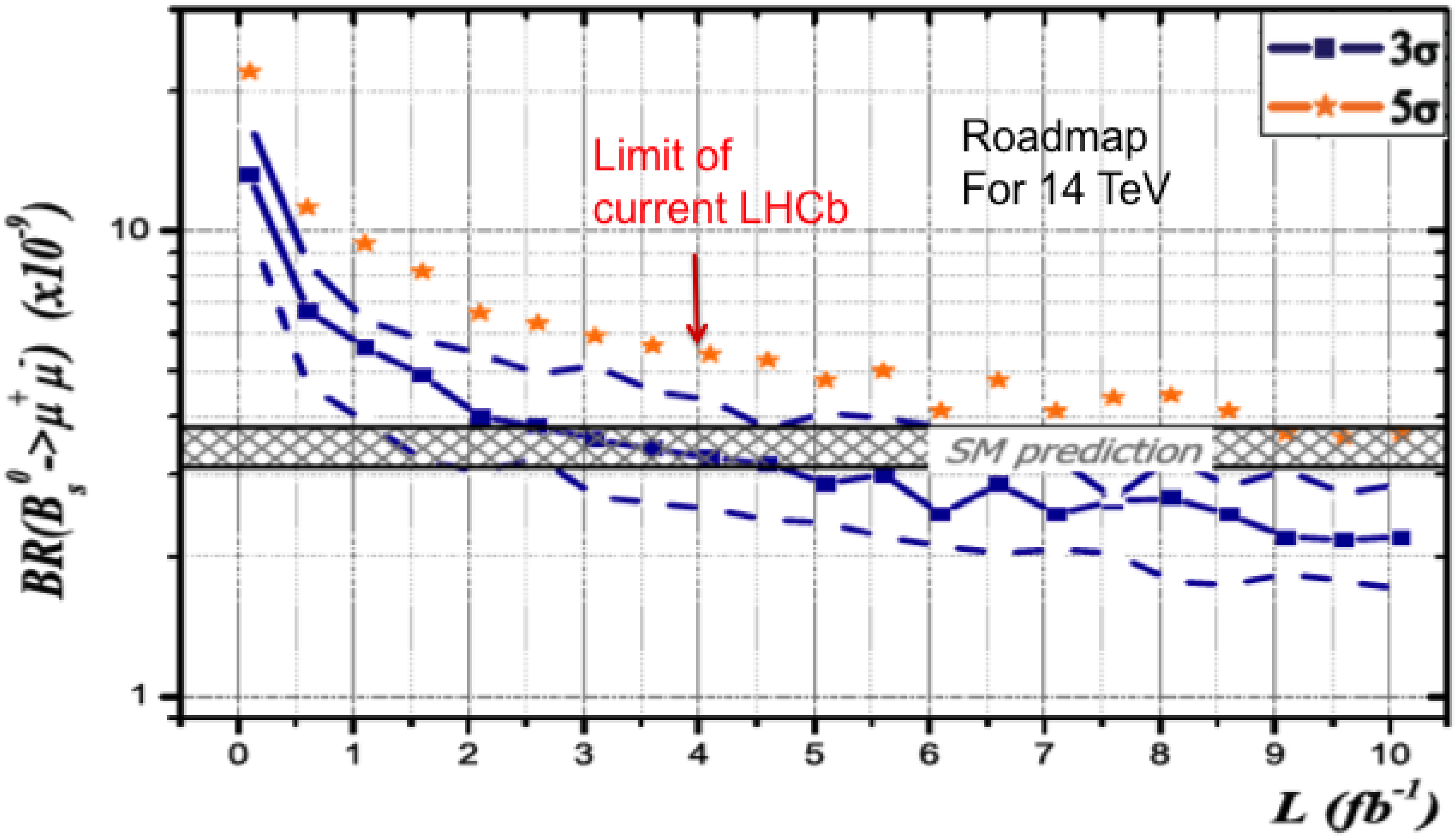
- SLHC statistics will be vital in reaching understanding of complicated SUSY channels
  - Sparticles seen, but statistics for reconstruction limited at LHC
- Performance of the detector here is vital
  - B-tagging
  - Lepton id



LHCb

# $B_s \to \mu^+\mu^-$ Roadmap

- Will take Upgrade to reach SM sensitivity



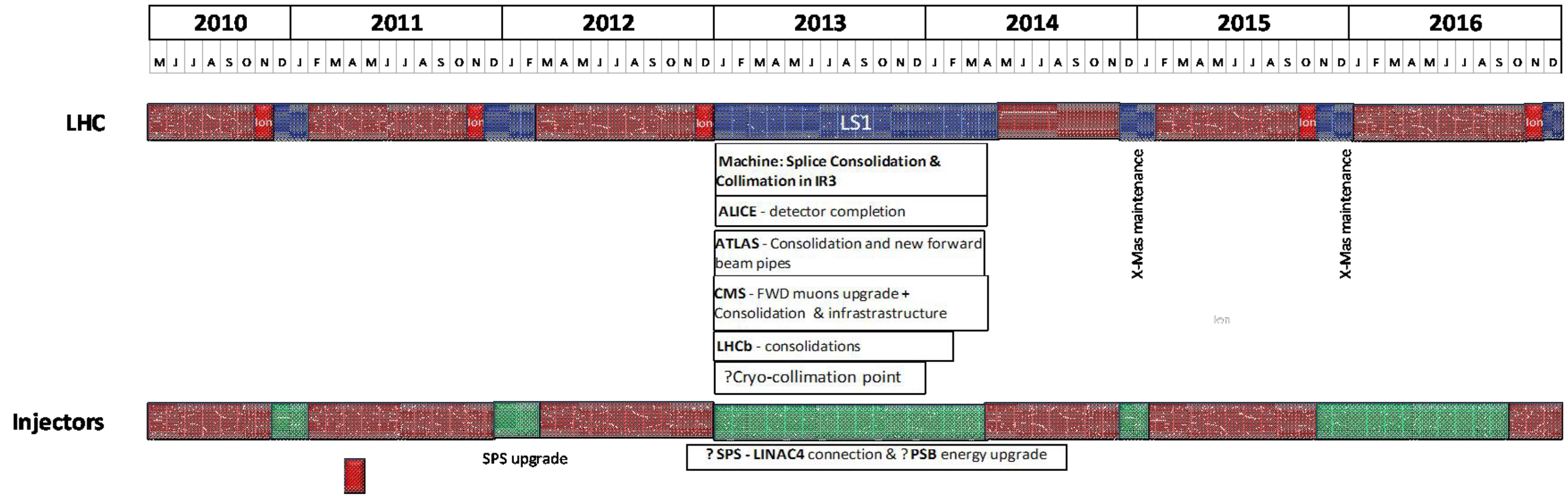

- Reach SM sensitivity and beyond with Upgrade

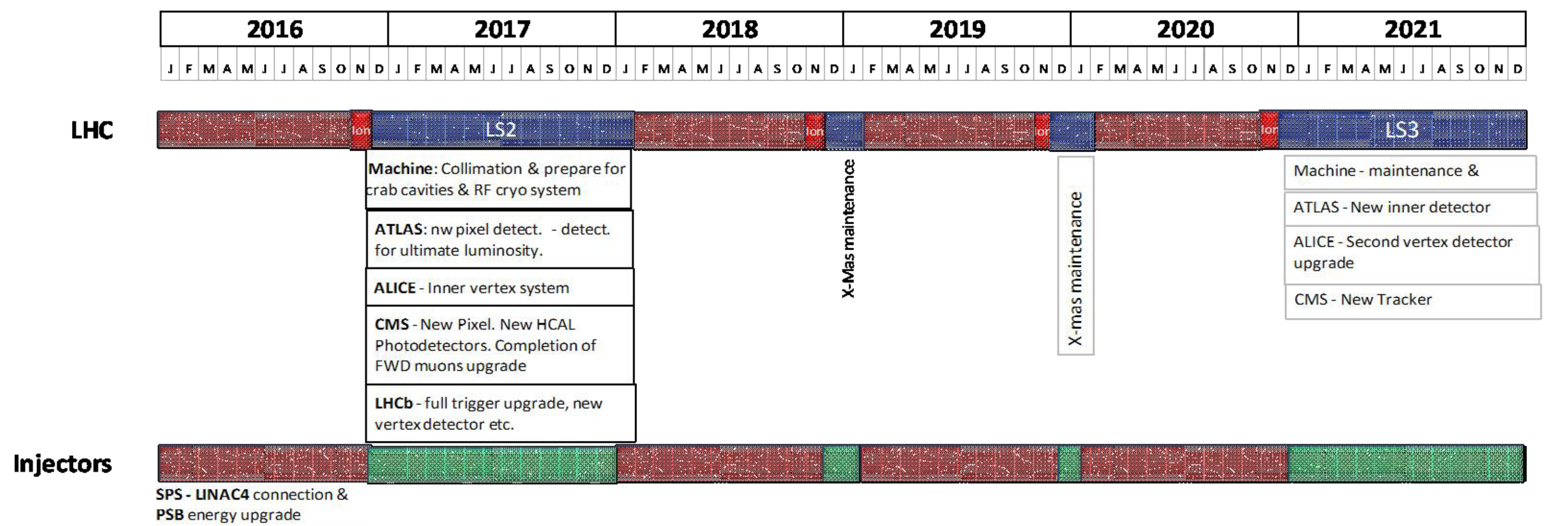
# Objectives for the accelerator

- Increase the energy and luminosity to the design values
  - should be achieved after 2013 shutdown
- Further increase the luminosity to about twice design level
  - following a second shutdown around 2017
- Still some uncertainties about how this will be achieved
  - 25ns or 50ns bunch spacing? $N_p$/bunch, electron cloud, no. bunches, …
  - what new machine challenges remain to be overcome?
  - imperfections and reliability
- but now building on very promising early performance demonstrating how well the LHC design is delivering
  - emittances, $\beta^*$, steady progress in extending performance
- Long term goal, after 2021
  - Run to ~2030 and provide 3000 $fb^{-1}$ with ~$5 \times 10^{34}$ $cm^2 s^{-1}$ levelled luminosity

# Draft 10 year plan

[Outcome Chamonix 2011 presented @ LMC 81 - draft]



# Summary Performance Reach:

## Performance Reach of the LHC

-Existing LHC & injectors can reach nominal performance with 25ns and 50ns beams: $L = 1\ 10^{34}\ cm^{-2}\ sec^{-1}$

-Small emittance option with 50ns operation can reach:

$L = 1.7\ 10^{34}\ cm^{-2}\ sec^{-1}$

@ half nominal total beam current for 50ns beam option

-Nominal machine with LINAC4 and 50ns operation can reach:

$L = 2.5\ 10^{34}\ cm^{-2}\ sec^{-1}$

with approximately nominal total beam current

-Full upgrade can reach:

$L \geq 5\ 10^{34}\ cm^{-2}\ sec^{-1}$

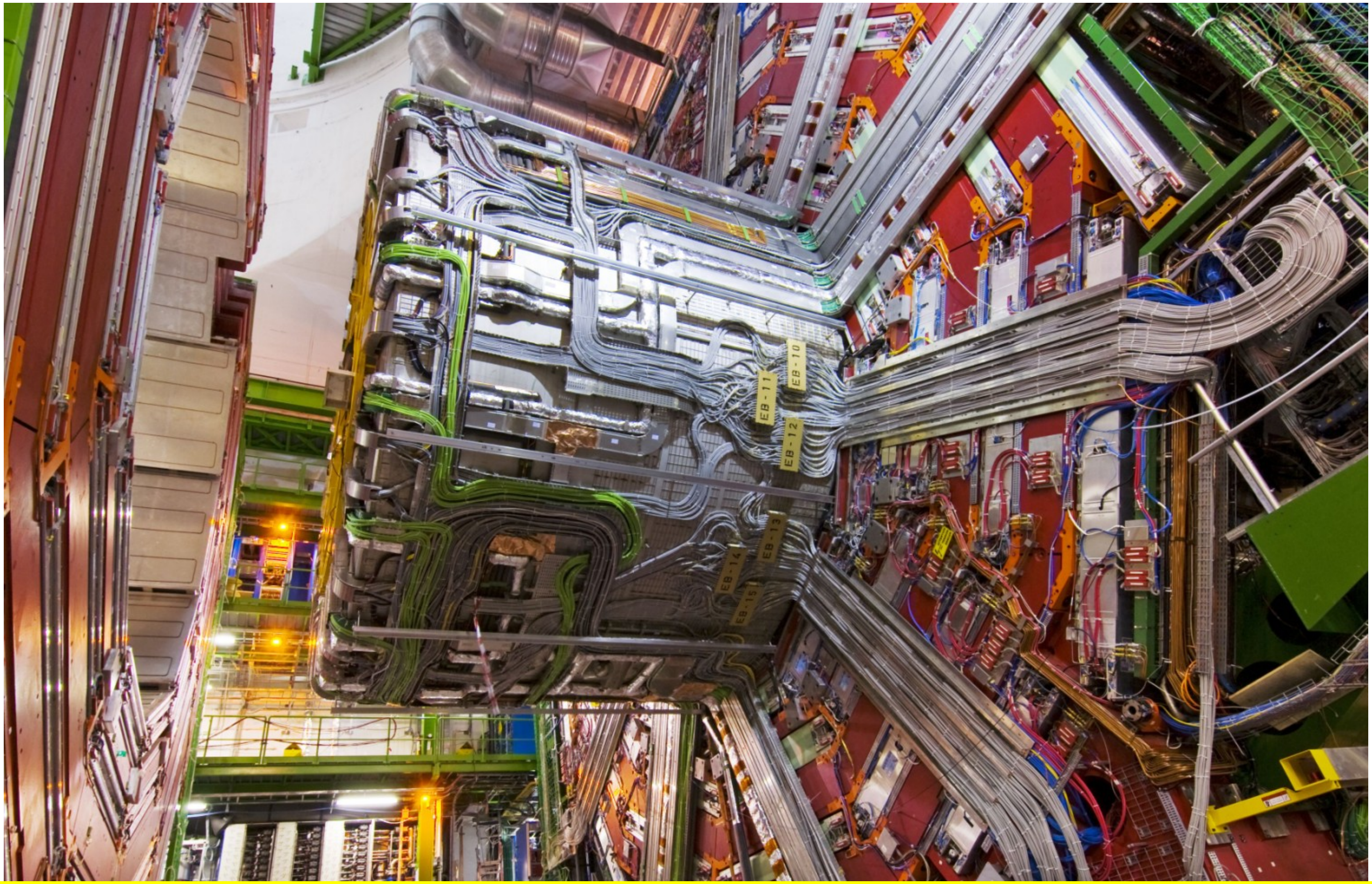
with geometric reduction factor!

➔ CC & LRBB wires are ideal tool for leveling!

# Implications for the experiments

- In this decade pile-up could be x2, or even x4 at 50ns, worse than designed for
  - experiments are just beginning to encounter multiple events/crossing
  - tracking performance, calorimeter isolation for trigger, forward detectors
- Next decade requirements
  - higher granularity
  - greater radiation tolerance
  - improvements to trigger to constrain L1 rate
  - rejuvenation of accessible detector components, eg electronics
  - longevity of existing detector systems which can't change much
- Constraints
  - experiments can't be rebuilt and not complete freedom to adapt
  - eg L1 latency, energy deposited in LAr, access to interior of experiments

# Example of a constraint: CMS YB0




Power cables, optical fibres, cooling pipes on surface of solenoid vacuum tank. Major restrictions on access to interior and VERY long time needed if services were to be dismantled and redone.

# Schedule

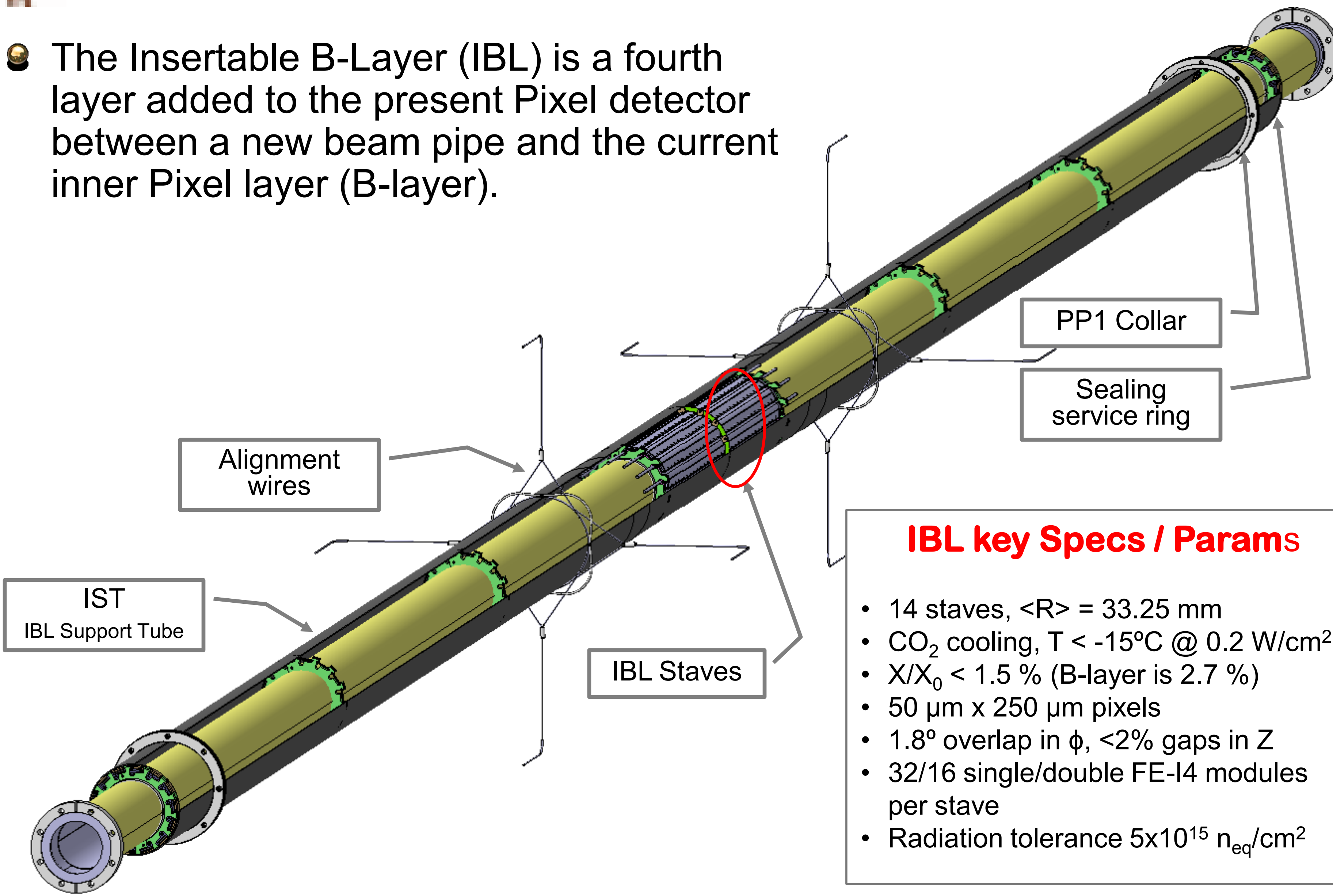
- Three main steps for CMS and ATLAS
- 2013 shutdown
  - mainly consolidation for high luminosity & 14 TeV, esp muon systems
  - possible installation of new beampipe(s) and ATLAS inner pixel layer
- 2017 shutdown
  - completion of any high lumi consolidation
  - new beampipes, reducing radius – if not done earlier
  - CMS pixel replacement, L1 trigger upgrade, HCAL photosensors, DAQ,…
  - ATLAS forward calorimeter, muon upgrades, DAQ,…
- 2021
  - replace tracking detectors with new systems
  - trigger upgrades
  - other improvements to muons, calorimeters, electronics, DAQ

# Pixel detector upgrades

- Being so close to the beam, radiation damage was expected to degrade innermost layers within first decade
  - CMS pixels are removable to permit replacement or repair
- Exceeding L= $10^{34}$ degrades performance
  - buffer depth of inner layers is limited, which leads to inefficiency
- ATLAS
  - insert inner layer with smaller pixels, aiming for 2013
  - choose between 3D silicon, planar silicon or diamond pixel sensors
  - new 130nm FE ROC is at an advanced stage
- CMS
  - replace whole detector with more layers but less material in 2017
  - new cooling, power and data links required
  - extend buffers in ROC but keep existing design (0.25μm CMOS)

# IBL Detector

- The Insertable B-Layer (IBL) is a fourth layer added to the present Pixel detector between a new beam pipe and the current inner Pixel layer (B-layer).

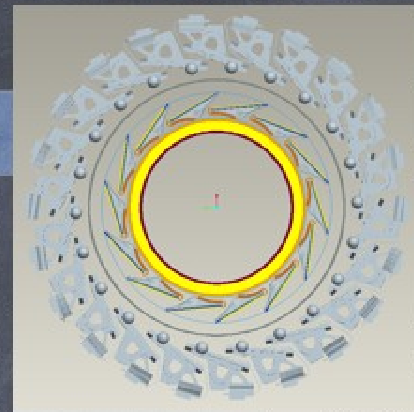


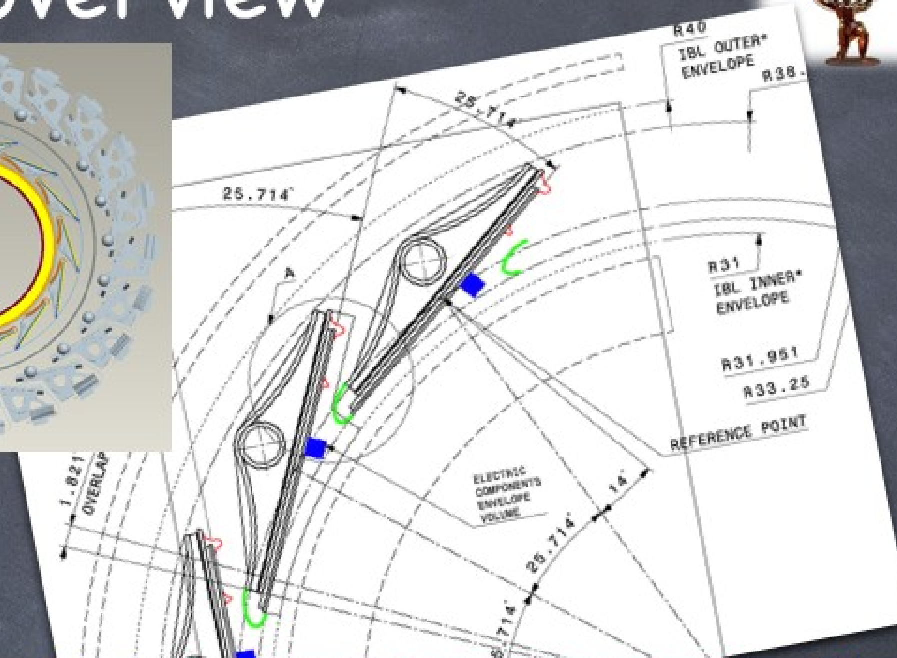

**IBL key Specs / Params**

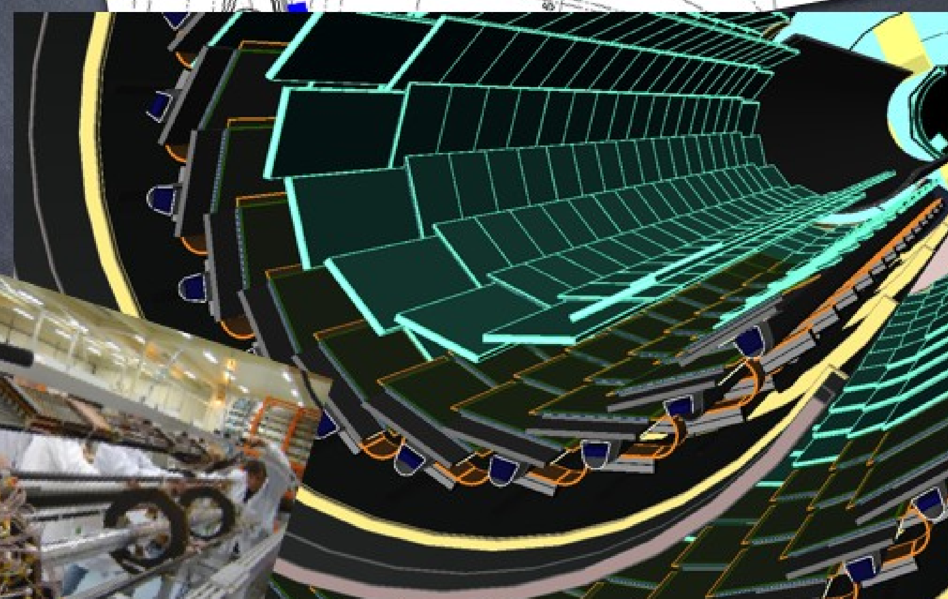
- 14 staves, <R> = 33.25 mm
- $CO_2$ cooling, T < -15ºC @ 0.2 W/cm$^2$
- $X/X_0$ < 1.5 % (B-layer is 2.7 %)
- 50 µm x 250 µm pixels
- 1.8º overlap in $\phi$, <2% gaps in Z
- 32/16 single/double FE-I4 modules per stave
- Radiation tolerance $5\times10^{15}$ $n_{eq}$/cm$^2$

# System overview

| | Value | Units |
|---|---|---|
| Number of staves | 14 | |
| Stave length | 706 | mm |
| Modules per stave | 16 | |
| Pixel size (phi, z) | 50×250 | $\mu m^2$ |
| Module active size | 40.8×20.4 | $mm^2$ |
| Coverage in η | $\eta < 3.0$ | degree |
| IBL nominal radius | 33.25 | mm |
| IBL outer envelope | 38.3 | mm |
| IBL inner envelope | 31.0 | mm |
| Stave tilt angle | 14 | degree |
| Sensor thickness: | | |
| Planar silicon | 150÷250 | $\mu m$ |
| 3D silicon | 230 | $\mu m$ |
| Diamond | 400÷600 | $\mu m$ |
| Radiation length at z=0 | 1.54 | % of $X_0$ |



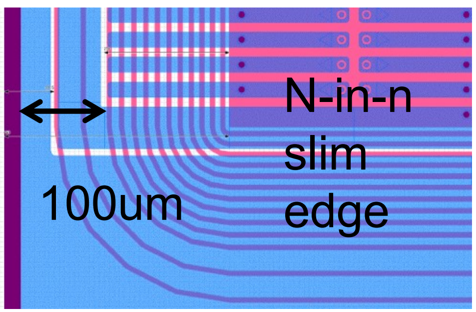


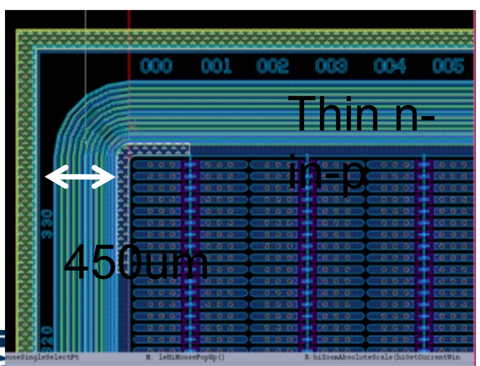



# Sensor technologies for IBL

## Planar silicon

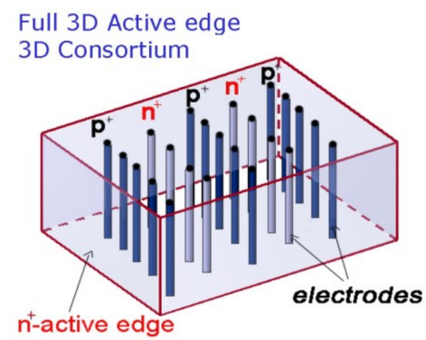
- Slim edge n-in-n
- Thin n-in-p
- Prototyping with CiS, HLL, HPK

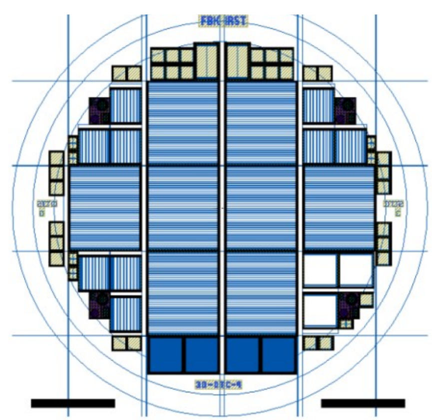



## 3D silicon

- Active edge single sided and double sided
- Prototyping with CNM, Sintef/SLAC, FBK



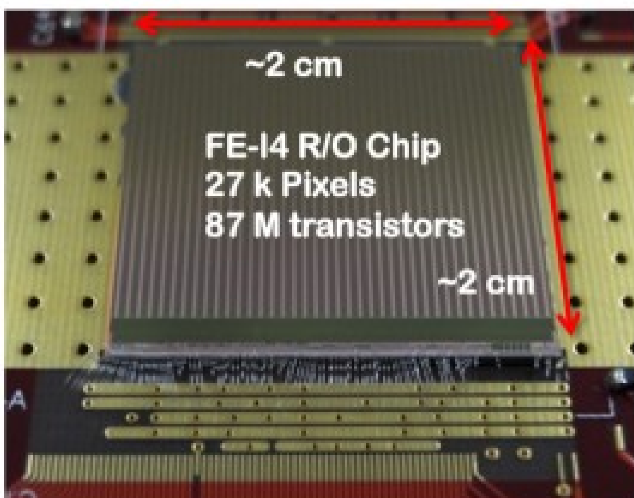
# Motivation for Speed-up

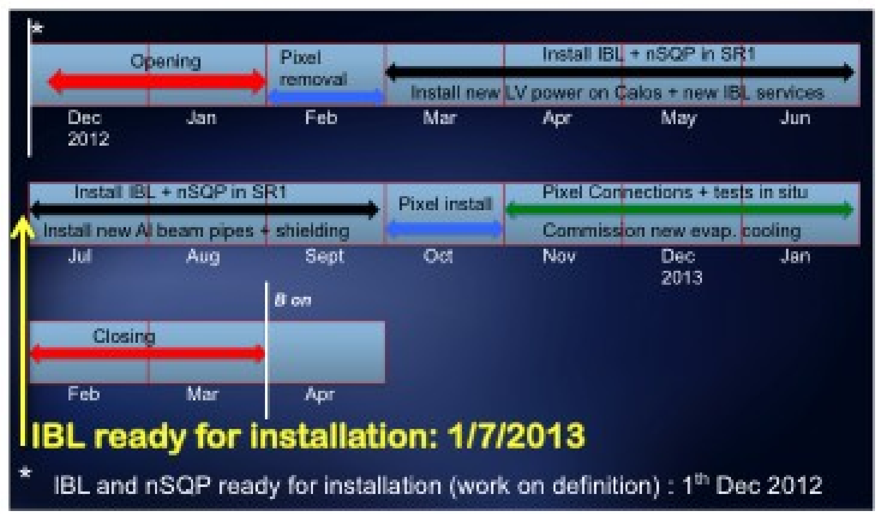
- *FE-I4 success push up optimism:*
  - First version of the chip is quite successful, planar sensor with FE-I4 measured on test beam at DESY, 3D sensors with FE-I4 just start testing.

- *LHC shutdown schedule:*
  - Machine has moved LHC next shutdown into 2013/14. phase I shutdown delayed (2017 or later)
  - Installation in 2013 simplified by low activation of beam pipe.

- *nSQP project*
  - If Pixel detector is brought to surface IBL installation is further simplified.

- *Physics profit earlier of better tracking performance.*

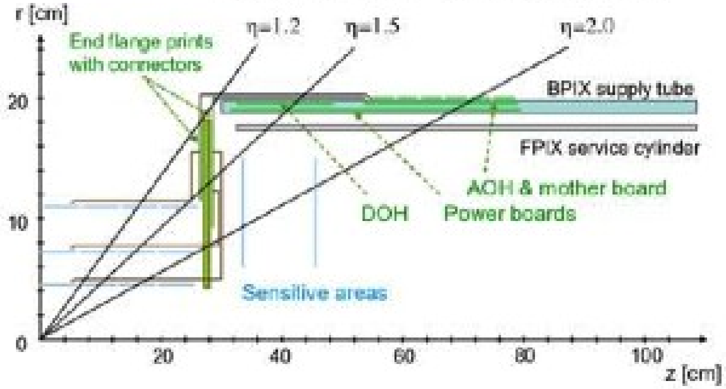


# Shift material budget out of tracking region

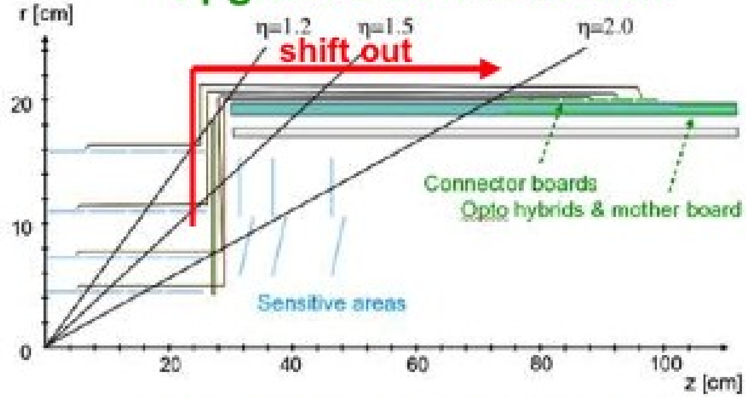
R Horisberger

## Current BPIX Services

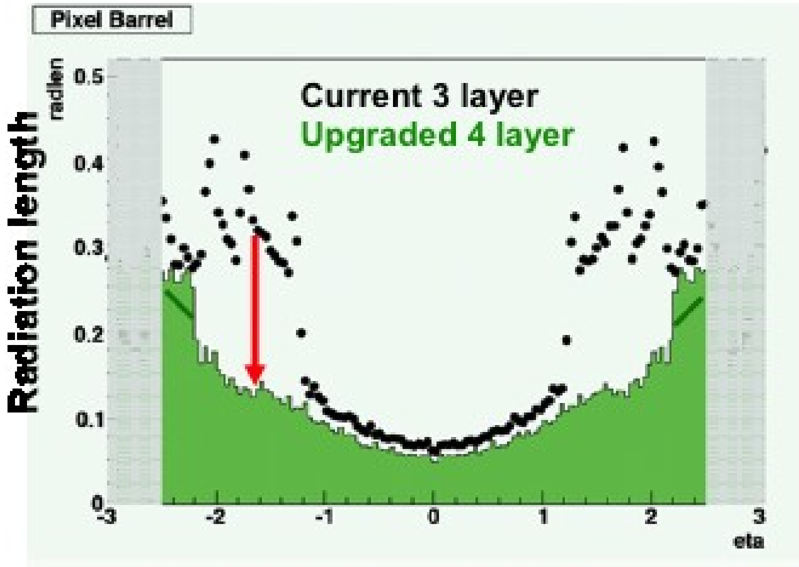


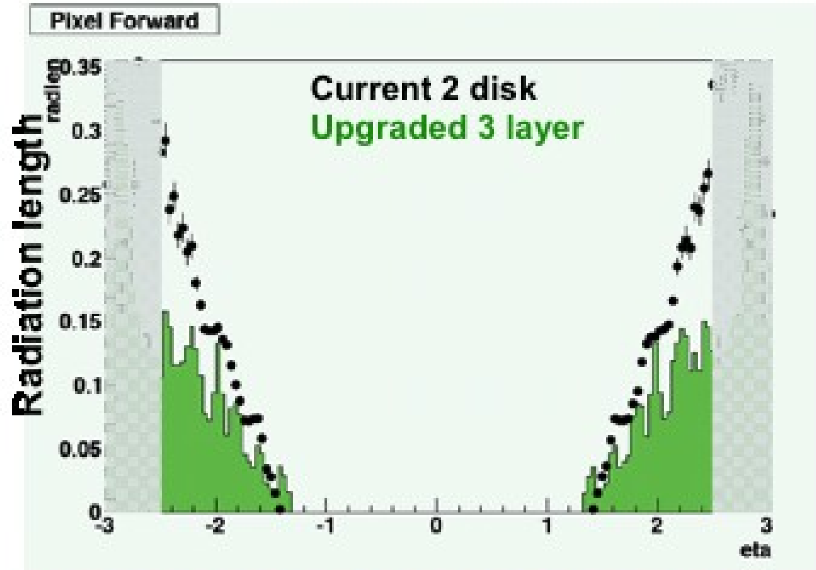

η<2.2 : weight = 16.9 Kg (3 layer)

## Upgraded BPIX Services



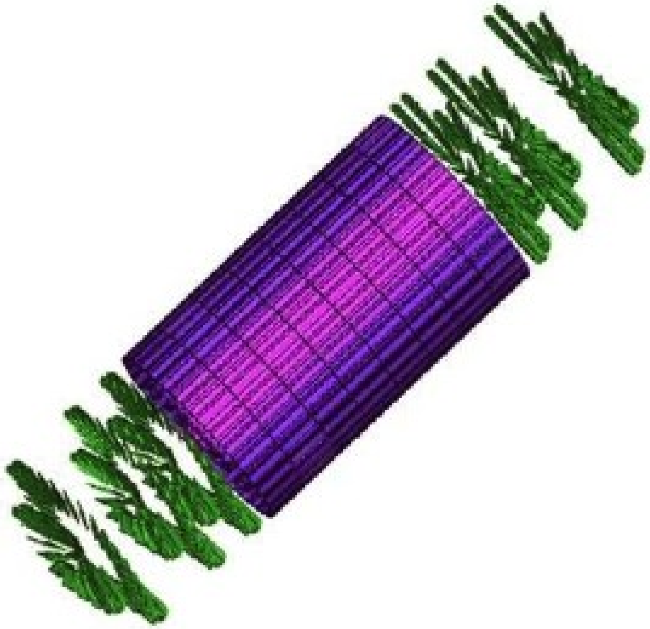

η<2.2 : weight = 6.5 Kg (4 layer)

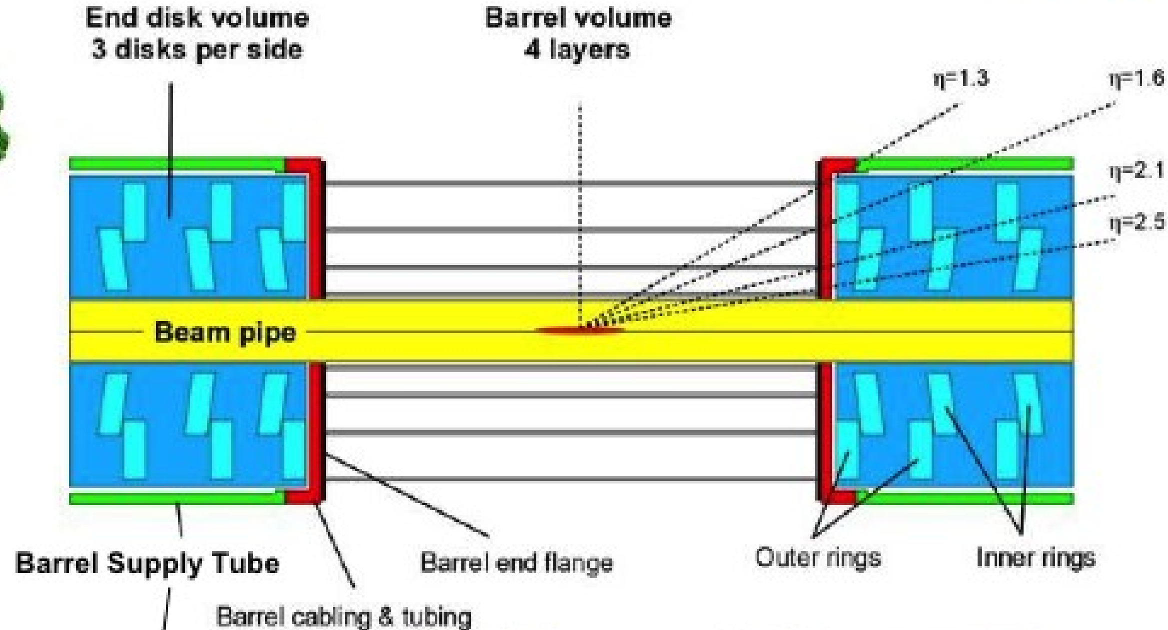


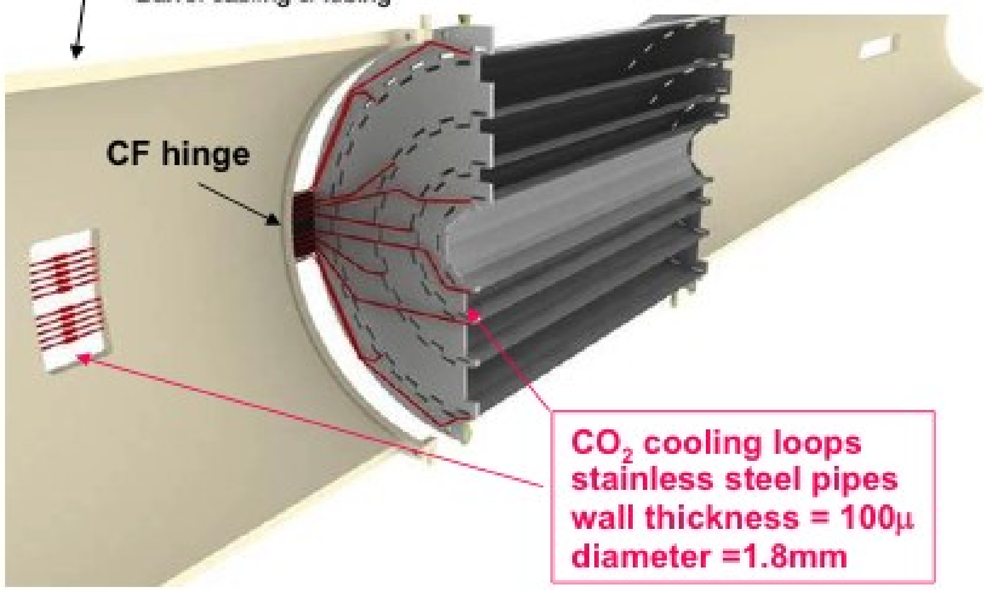

η ~1.5 : γ-conversion for H→ γγ from 22% to 11% for new 4 Layer Pixel System

# BPIX / FPIX Envelope Definition & Insertion into CMS

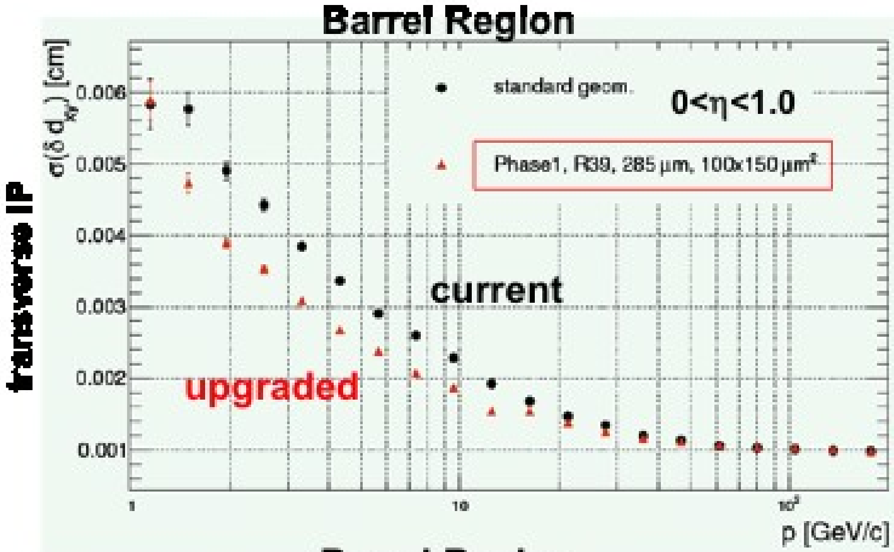


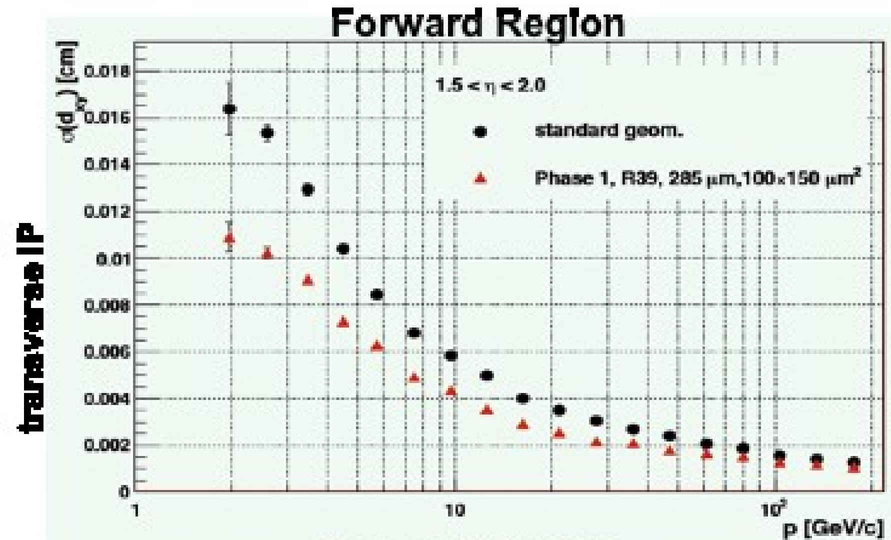


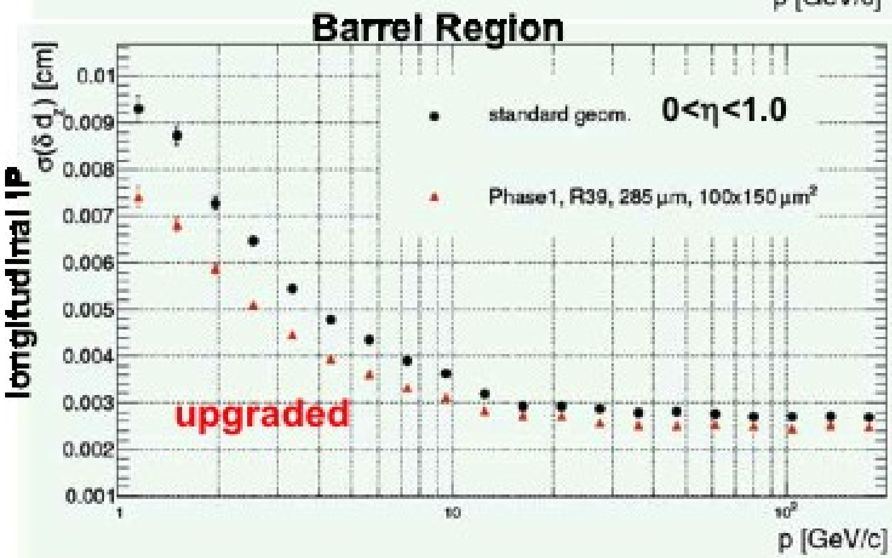

**Insertion of new system verified**

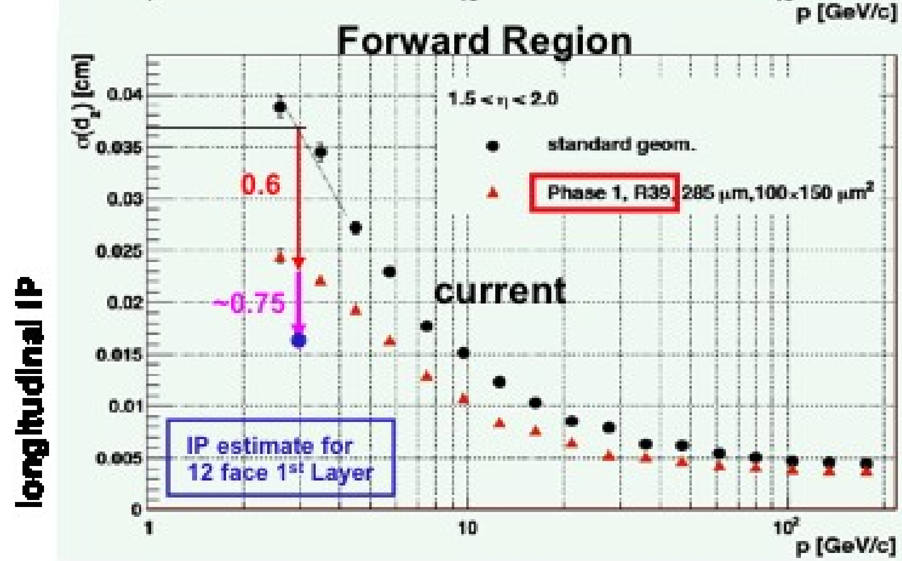


# Impact Parameter of old / new Pixel System



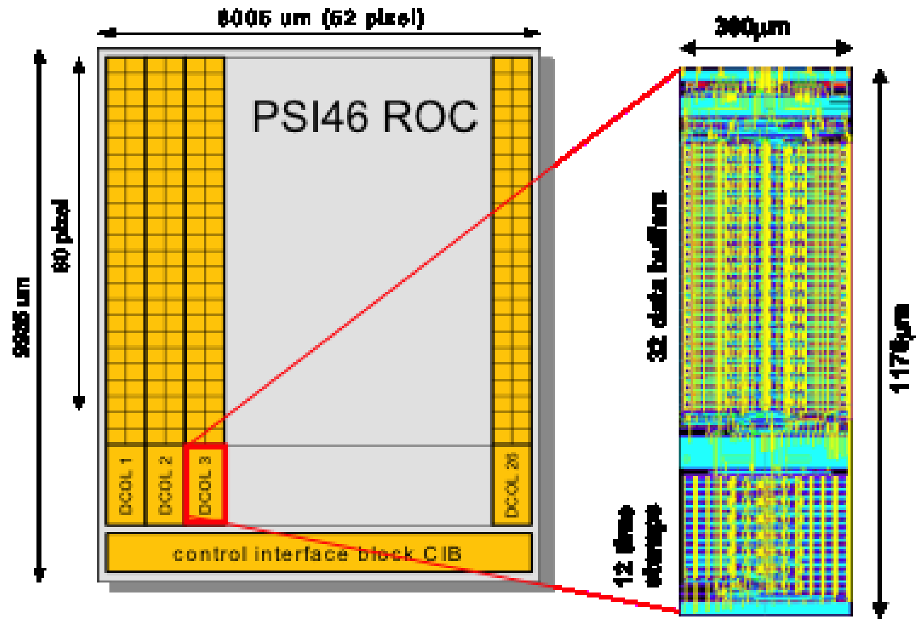




Beam pipe r<23mm : 16 faces to 12 faces → reduce MS term by ~0.75 → total 0.75x0.6 = 0.45 !

# Upgrade of Pixel Readout Chain




**Present ROC for 1st Layer:**

| Luminosity | bx-spacing | Data Loss |
|---|---|---|
| $1\times10^{34}cm^{-2}s^{-1}$ | 25nsec | 4% |
| | 50nsec | 16% |
| $2\times10^{34}cm^{-2}s^{-1}$ | 25nsec | 15% |
| | 50nsec | ~50% |

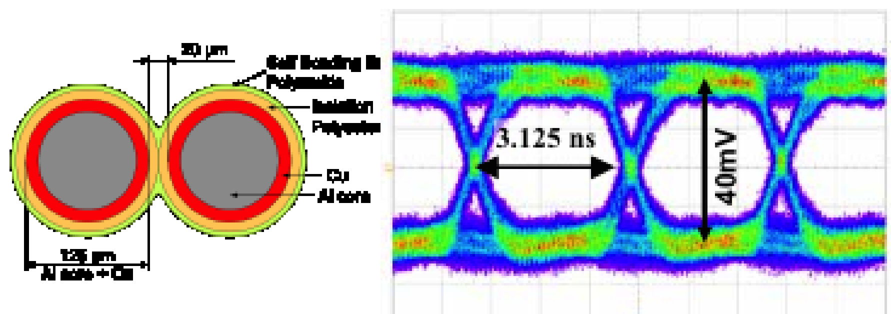
50nsec operation of LHC was not planned in original ROC architecture in 1998.

**Data losses removed by ROC changes:**

| | Status |
|---|---|
| 1) Increase depth of | |
| - data buffer 32 → 80 | done |
| - timestamps 12 → 24 | done |
| 2) add readout buffer | done |
| 3) 160Mbit/sec serial binary data out | now |
| 4) deal with PKAM events → DAQ resync | |

**µ-twisted CCA pair** (Copper-Cladded Aluminum)

- 1m long low mass link at 320MHz , chips done !



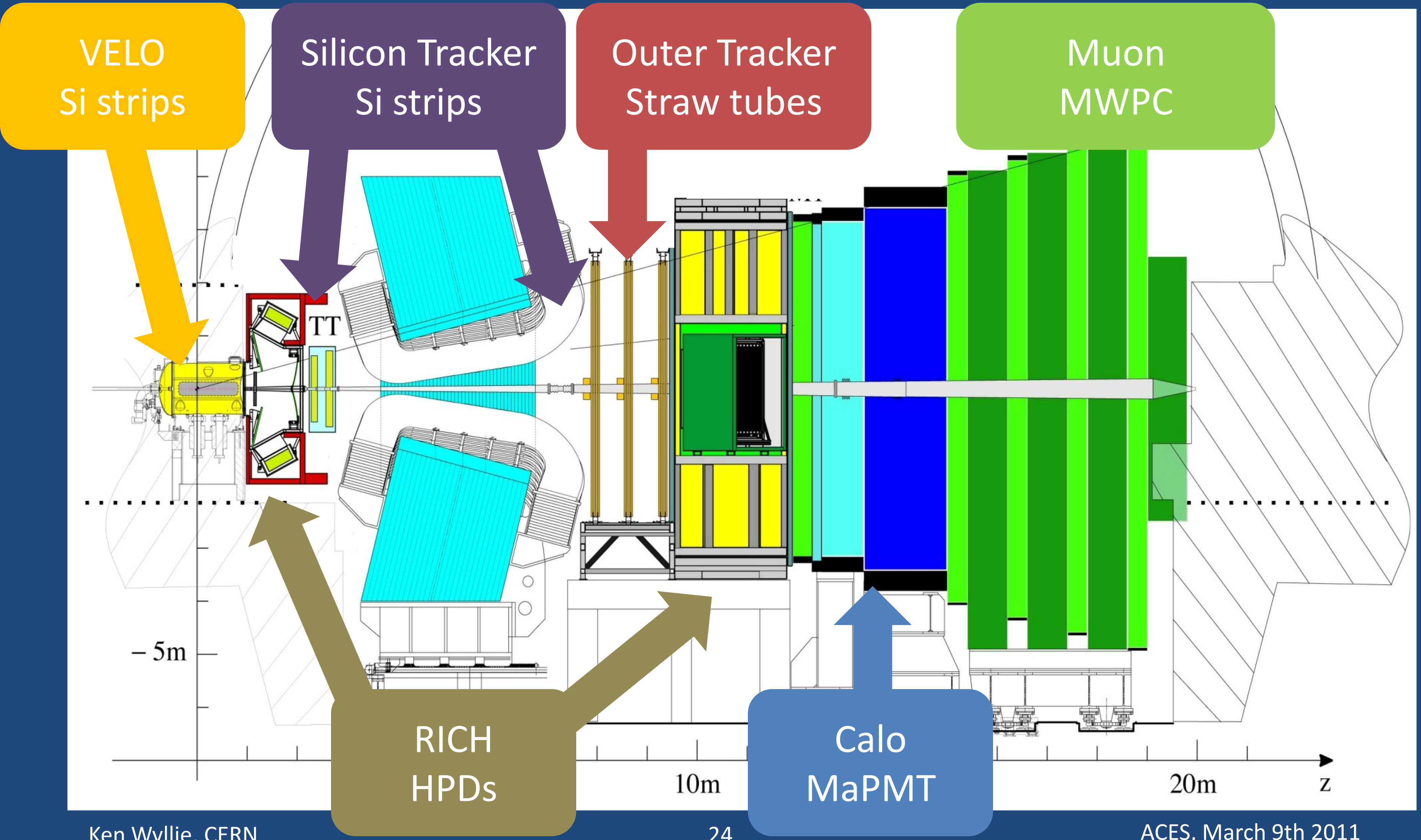
# Other changes in Phase I 2017 include…

- LHCb
  - present limit of 1fb$^{-1}$/y can be increased to 5 fb$^{-1}$/y
  - read out all data at 40MHz and generate trigger off-detector
    - trigger decision can be more sophisticated using data from all sub-detectors
  - upgrade significant detector elements, especially VELO

- ATLAS trigger
  - add tracking information in L2 hardware processing

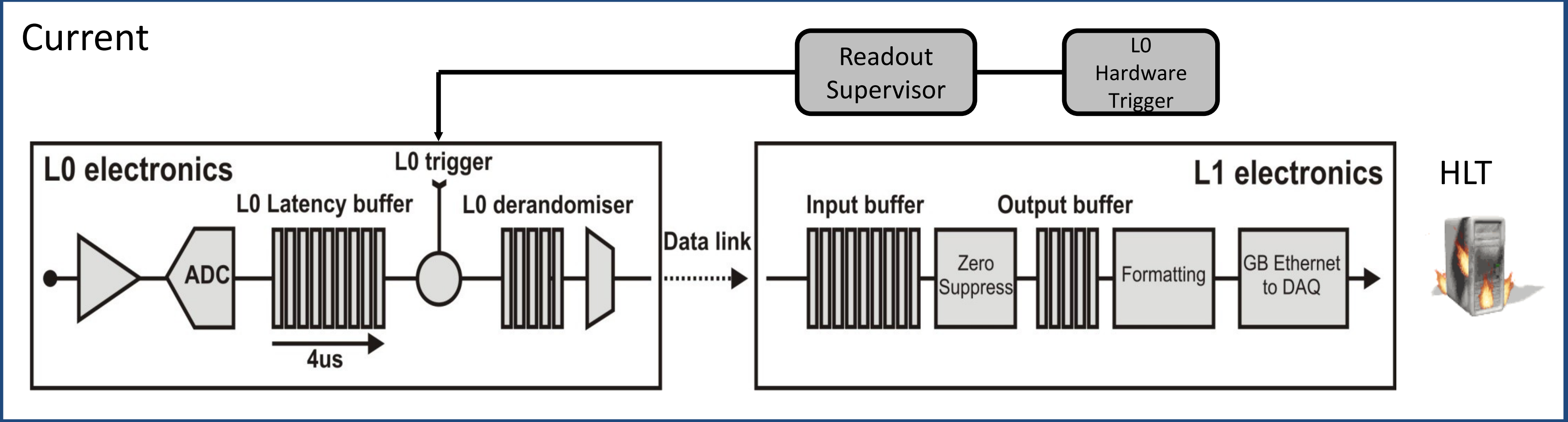
- CMS L1 trigger
  - improve isolation selection in calorimeters
  - architecture may be foundation for future tracking trigger

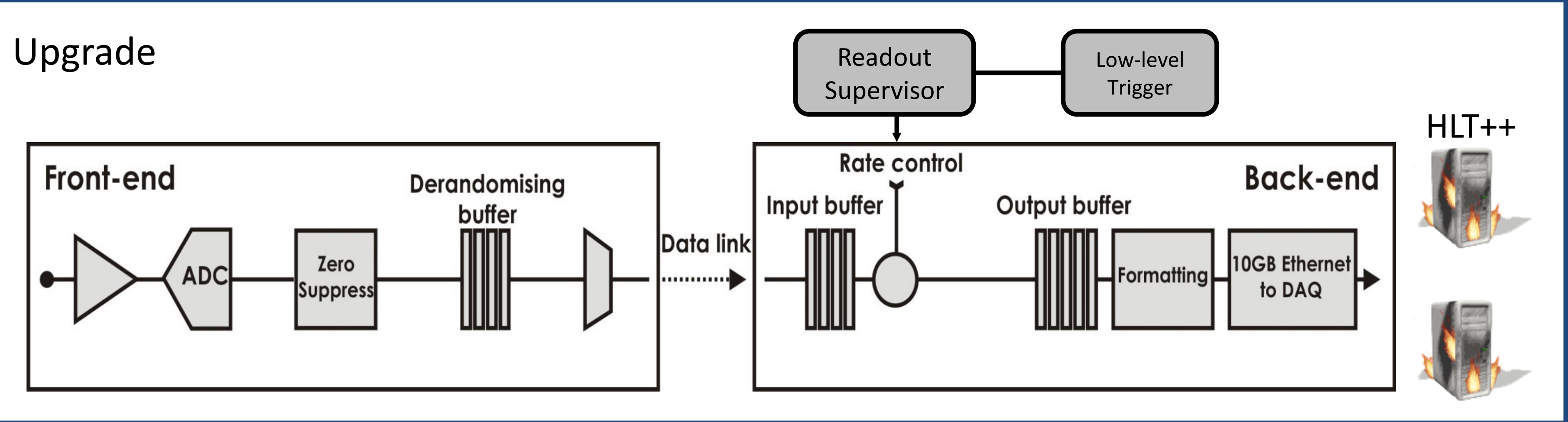
# LHCb sub-systems



# Electronics architecture

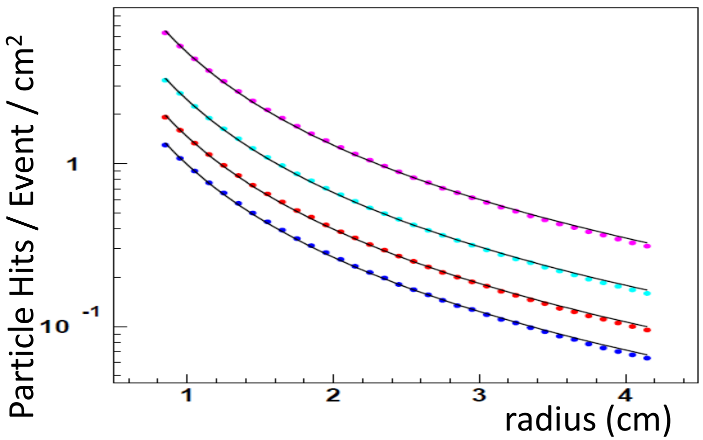
## Front-end electronics: transmit data from every 25ns BX



# VELO upgrade data rate challenge

- Electronics has to digitise, zero suppress and transmit event data at 40 MHz
- By pixel standards the occupancy of the VELO is miniscule, but the data rate is HUGE
- 1 chip has to transmit 10-20 Gbit / second
- Our current granularity, occupancies = ok but FE electronics and DAQ are not



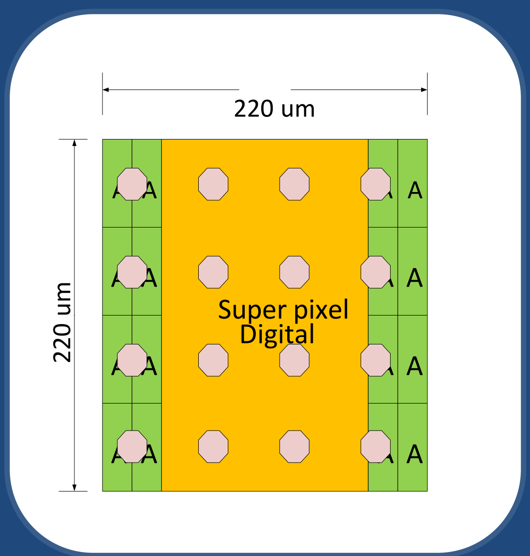

| Luminosity ($cm^{-2}s^{-1}$) | $2.10^{32}$ Current | $5.10^{32}$ | $10.10^{32}$ Phase 1 | $20.10^{32}$ Phase 2 |
|---|---|---|---|---|
| A= | 0.98 | 1.46 | 2.46 | 4.80 |

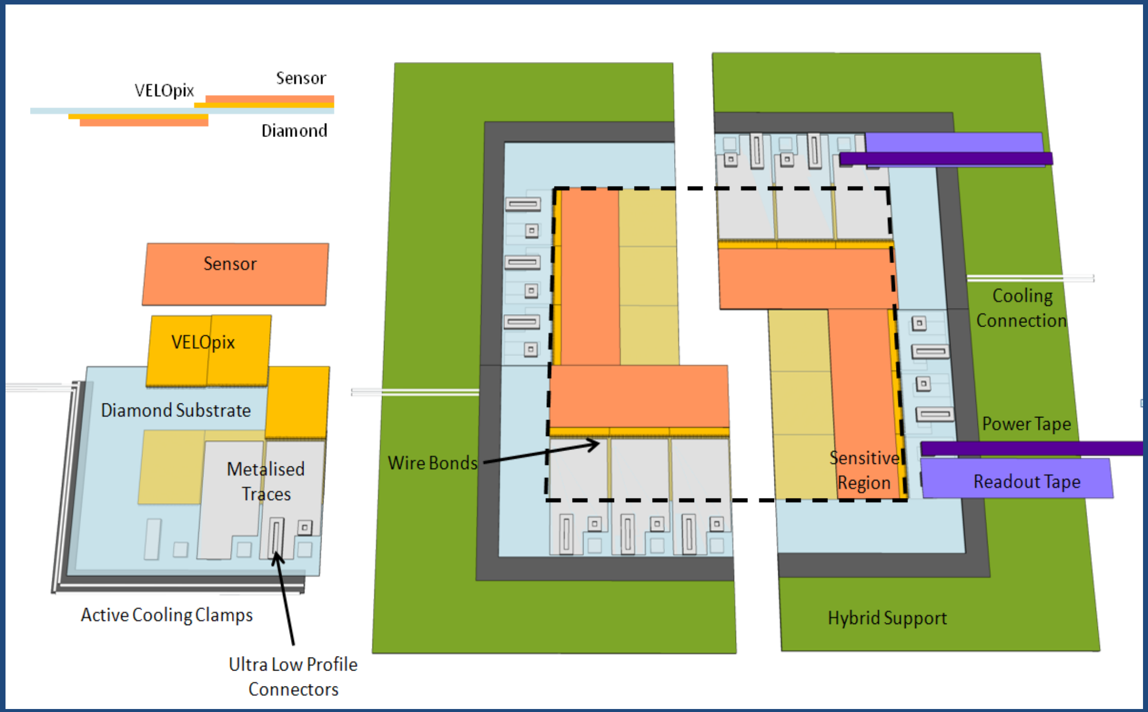
# VELO

## Pixel (baseline) option

### VeloPix chip: 256 x 256 array, 55 x 55 μm pixels

- Strong overlap with TimePix2 (under design)
- 3 or 4 bits TOT
- Architecture to minimise bandwidth (hottest chip = 12 Gbit/s)
- Serial readout

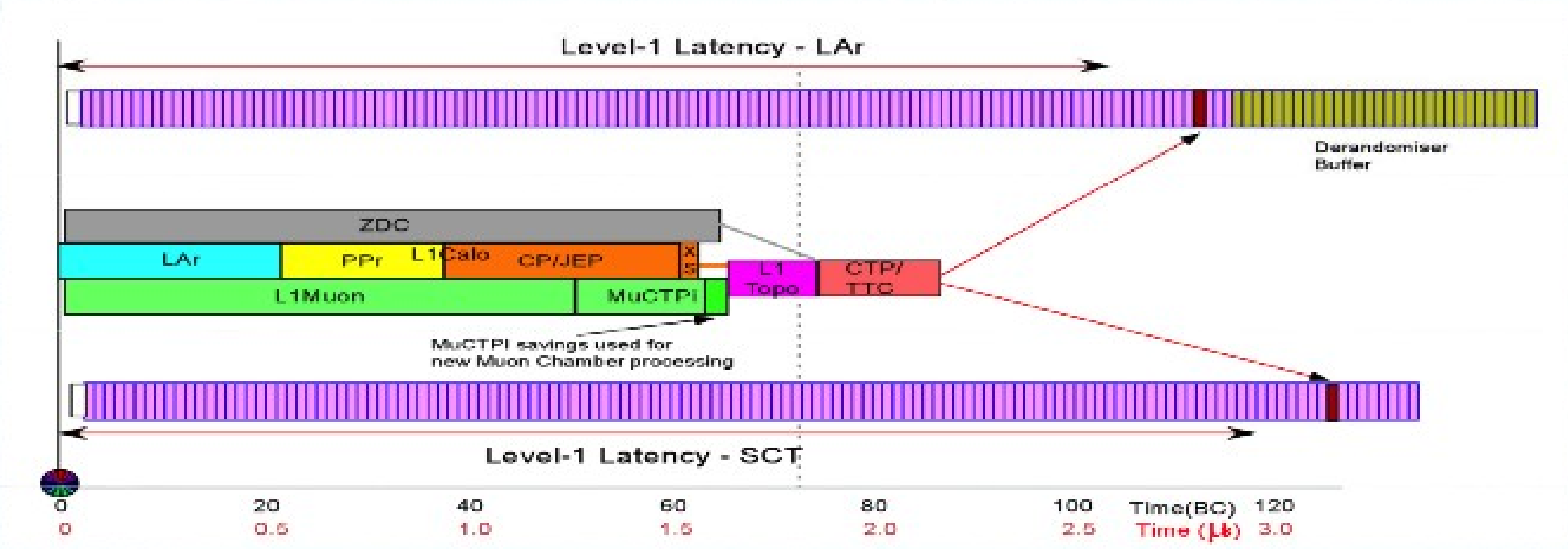



Ken Wyllie, CERN

# Trigger Improvements

- Detailed studies of system latency show scope for L1 improvements and additional functionality: $E_T^{miss}$, topological trigger combining multiple trigger objects

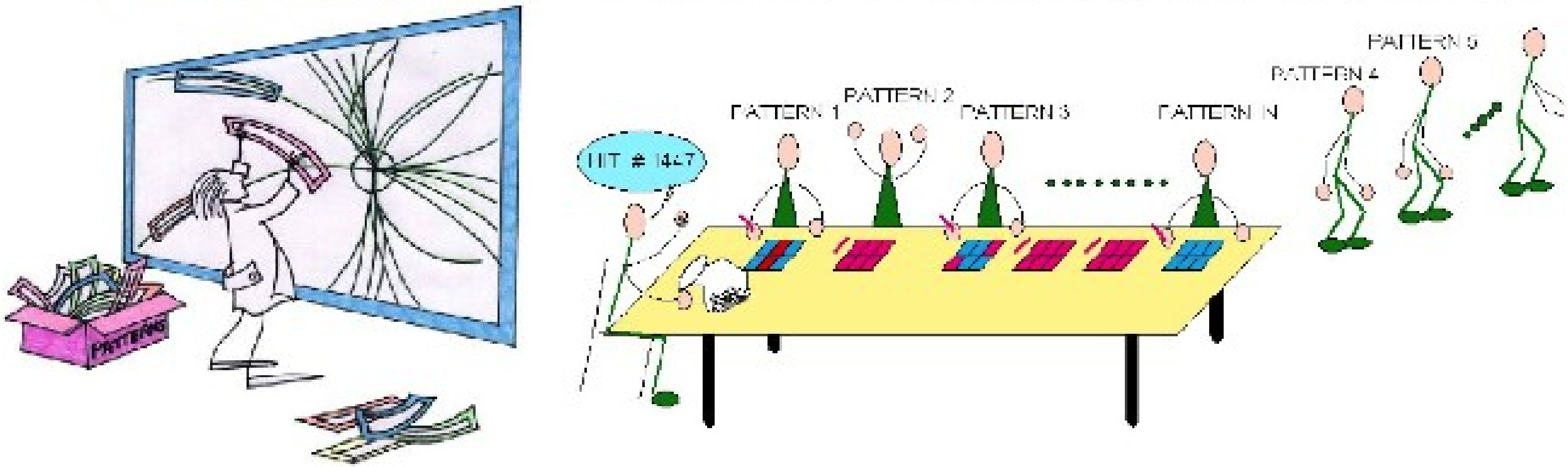



- L2 improvements: include FTK to improve efficiencies combine tracks early with trigger objects
- Explore new technologies for HLT (eg GPUs)

# Level-2 fast track finder, FTK (before the SD)

## Two time-consuming stages in tracking

- **Pattern recognition – find track candidates with enough Si hits**



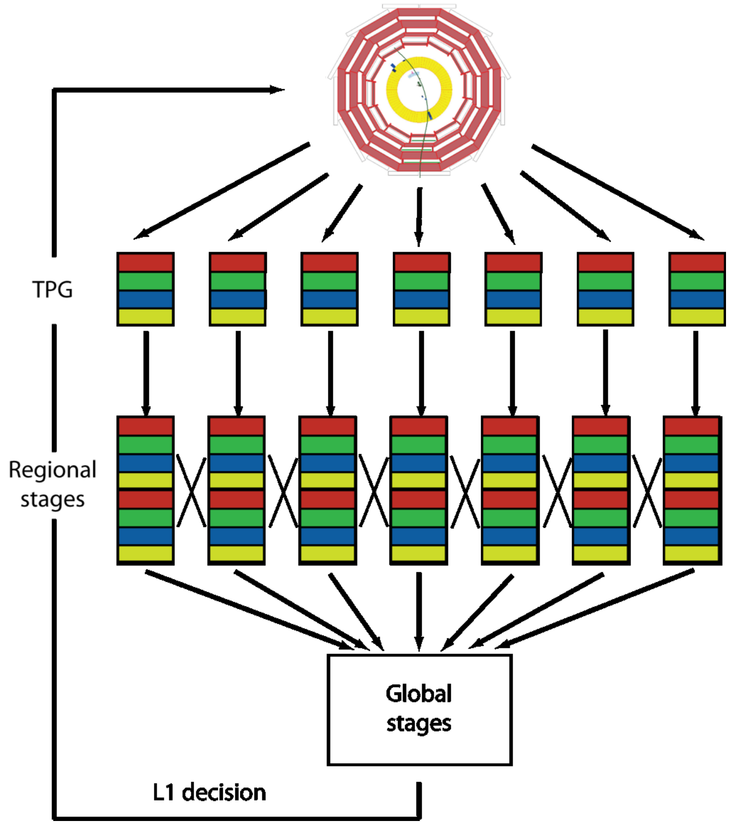

  - **$10^9$ prestored patterns simultaneously see each silicon hit leaving the detector at full speed.**
- **Track fitting – precise helix parameter & $\chi^2$ determination**
  - **Equations linear in local hit coordinates give near offline resolution:**

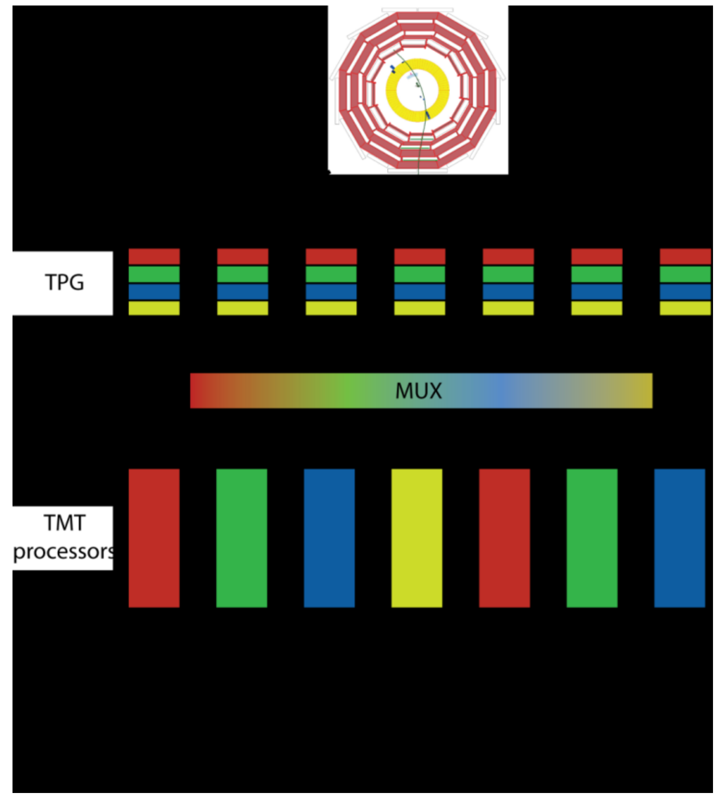
$$p_i = \sum_{j=1}^{14} a_{ij} x_j + b_i$$ ***a* & *b* are prestored constants; VERY fast in FPGA**

# Key Principles of the Upgrade

- Hold the Level 1 Accept Rate at 100kHz
  - (plus side) Avoids as much as possible rebuilding front end and readout electronics
  - (minus side) Puts more pressure on the DAQ to deal with increased data size
- Employ full granularity of detectors in trigger
  - (0.087 x 0.087 in $\eta - \phi$)
- Rely on powerful modern FPGAs with huge processing and I/O capability to implement more sophisticated algorithms
- Use state of the art telecom technology to support increased bandwidth requirements
  - Also will achieve some hardware standardization

# CMS Time-Multiplexed Trigger: Concept

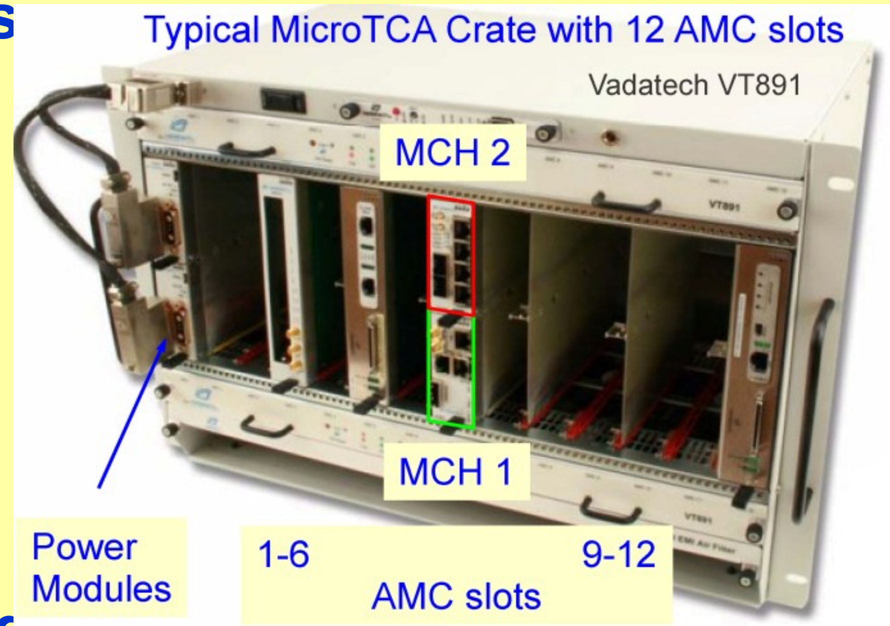



- The key problems of triggering remain the same as in 1995
  - Concentration of dataflow into a single processor
  - Limitations on algorithms due to internal bandwidth limits
  - Understanding and optimising what is going on

# CMS Upgrade Architecture: μTCA

- **Advanced Telecommunications Computing Architecture ATCA**
- **μTCA derived from AMC std.**
  - Advanced Mezzanine Card
  - Up to 12 AMC slots
    - *10-11 Processing modules*
    - 1-2 Controller Modules
    - 10 GB/s point-to-point links
- **Dramatic increase in computing power and I/O.**
- **Possible to built a trigger based on a single μTCA card → reduce**
  - Complexity
  - Maintenance + Manpower costs



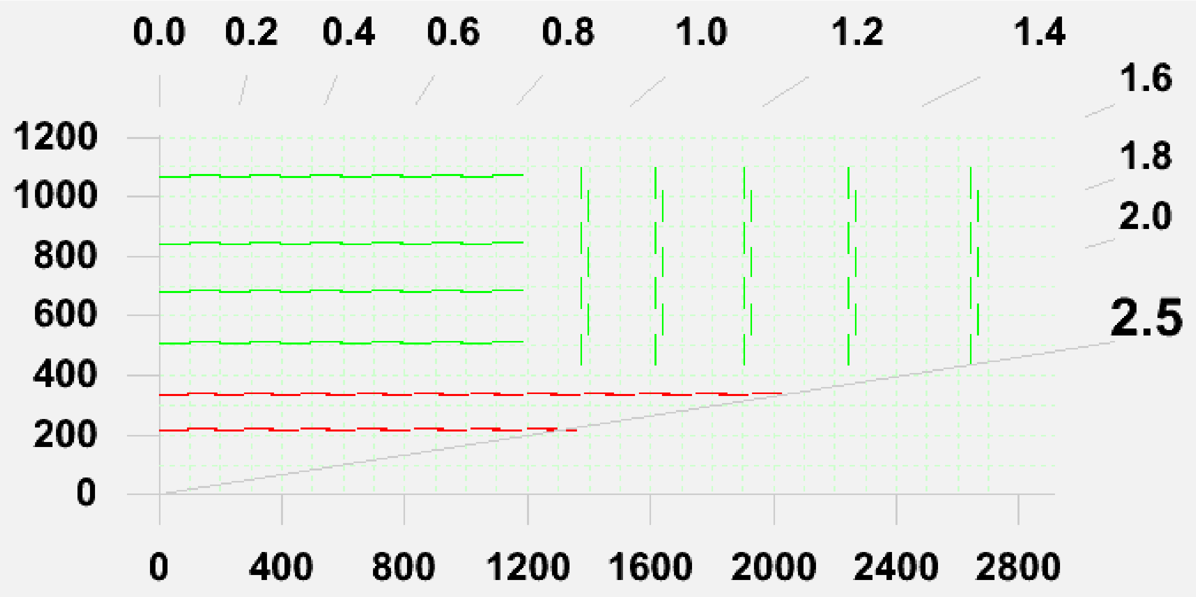

Single Module μTCA card 75x180

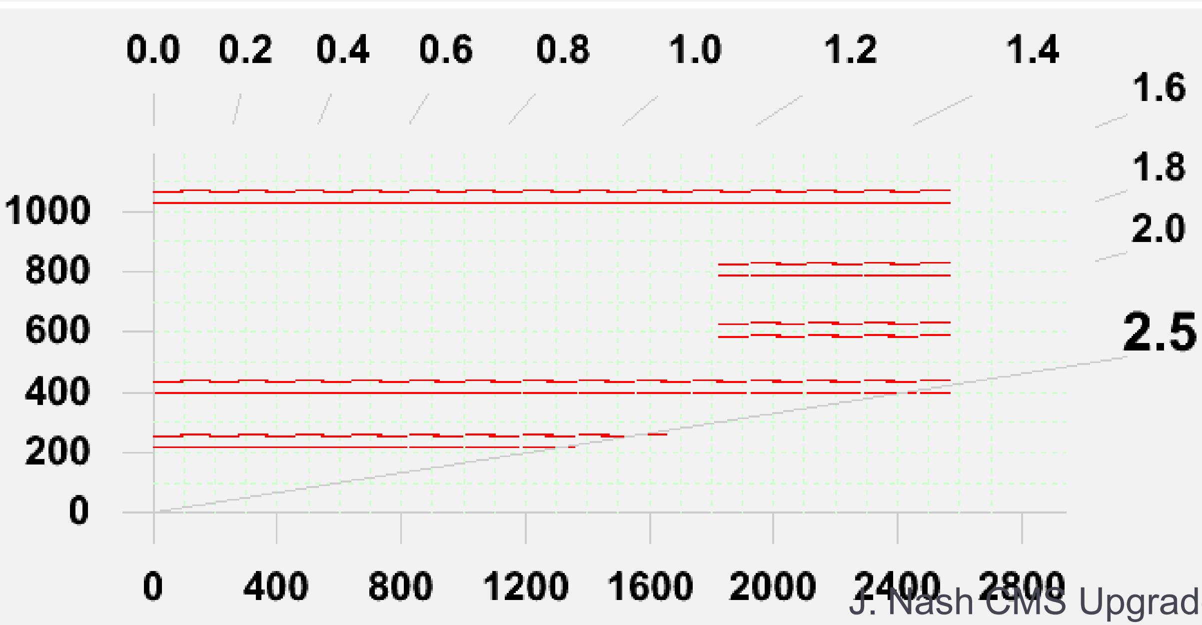

CMS GCT Matrix Card 75x180 mm (2009)

# 2021: Phase II

- ATLAS and CMS will insert completely new trackers
  - yet to be fully defined
  - technologies to achieve the radiation tolerance and performance are still under development
    - many challenges and promising ideas, some of which will be developed during Phase I (CO2 cooling, DC-DC & serial powering, advanced links…)
    - but must not sacrifice performance – conflicts between power and material needs care
- L1 trigger will be a particular challenge
  - consensus seems to have emerged that tracking information will be needed
  - new types of module are needed – but time is short

# CMS – Studies of new tracker layouts

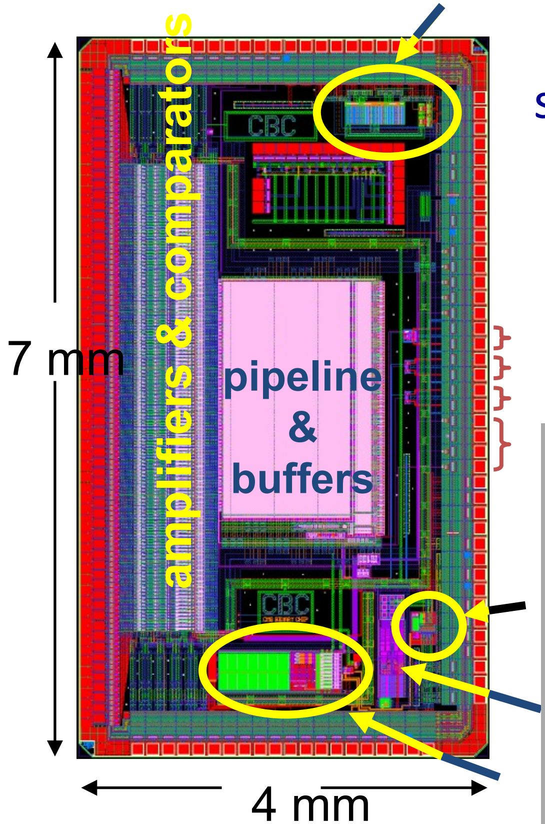


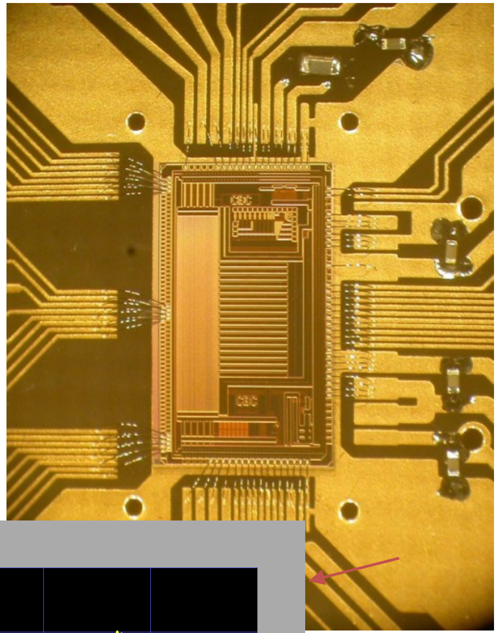

- Studying several potential layouts for a new outer tracker
- Want to increase granularity as well as minimize material in future tracker
- Need to understand how many triggering layers (in red at left), and where they need to be located in order to provide adequate triggering capability
- No final decision on layout of tracker until final requirements determined

# CBC: CMS Binary Chip for outer tracker

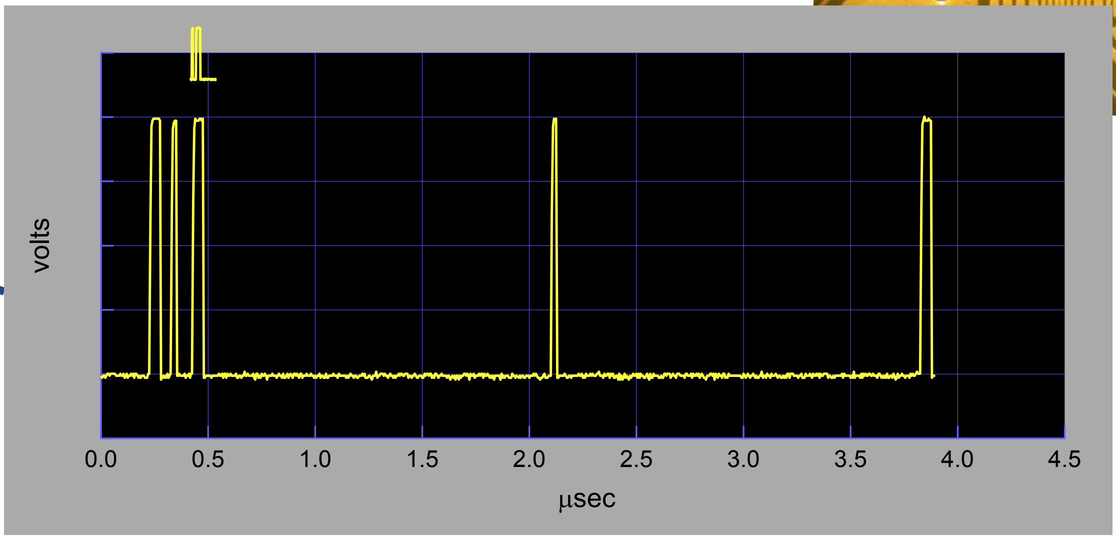
- New 130nm ASIC, descended from APV25 philosophy
  - now working and module prototyping beginning




studies to include trigger functions

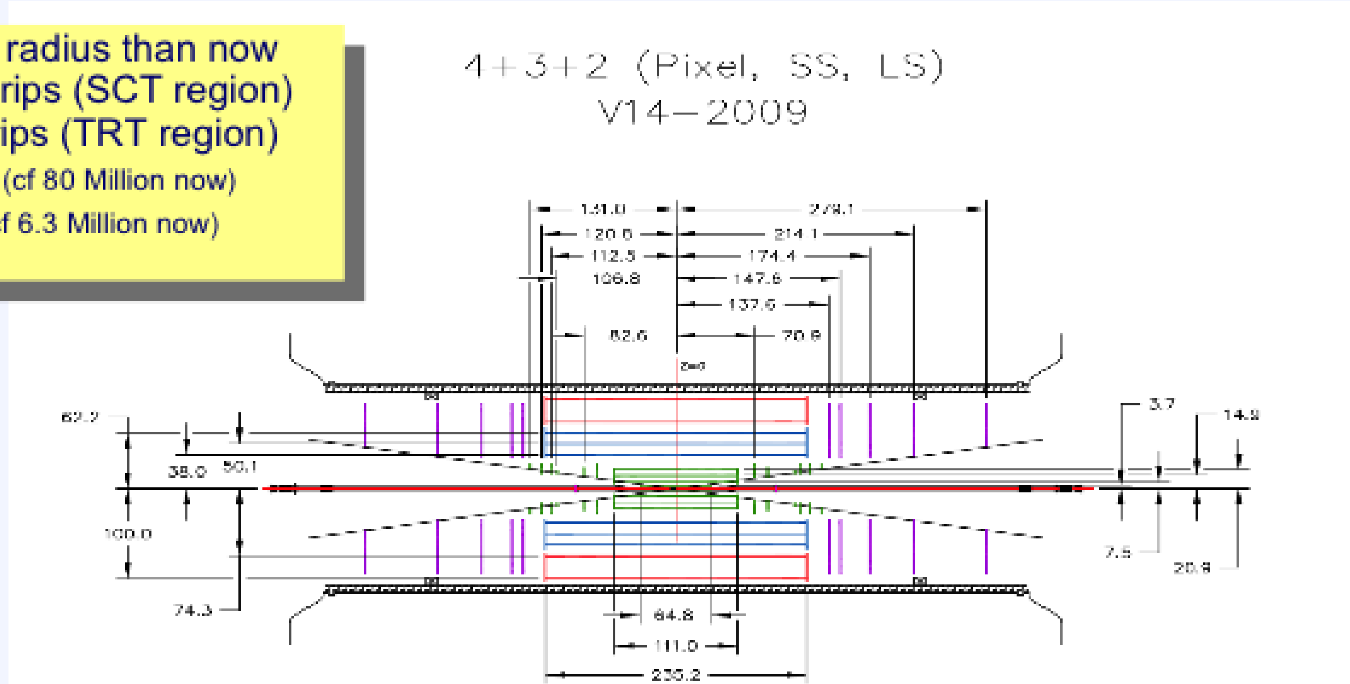


2 consecutive data frames (2 headers)
1 fC signal injected on one channel

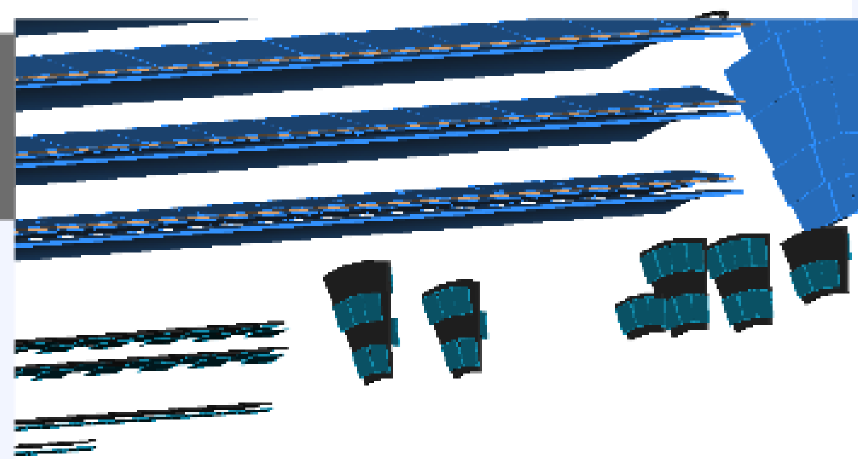


# Strawman Layout of New ATLAS Inner Tracker

4 layers of pixels to larger radius than now
3 double-layers of short strips (SCT region)
2 double-layers of long strips (TRT region)
Approx. 400 Million pixels (cf 80 Million now)
Approx. 45 Million strips (cf 6.3 Million now)



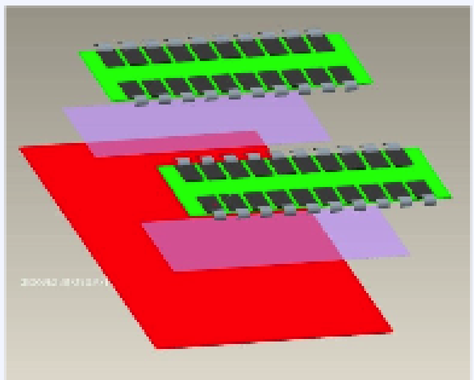

Implemented in Geant, including realistic service material, to study performance and look at optimisations

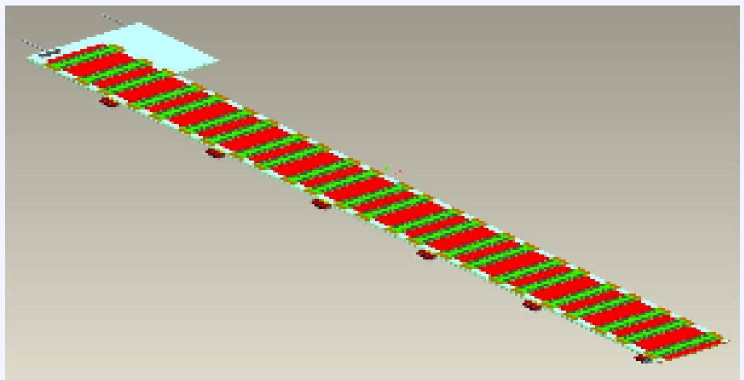


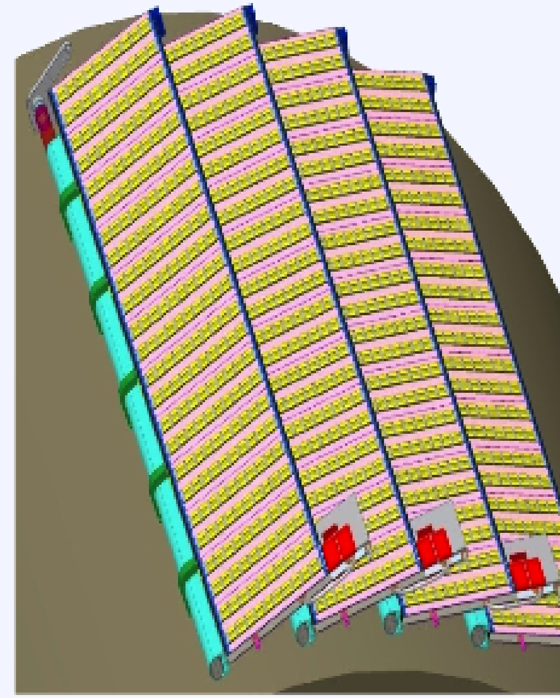
Inner Tracker Sub-committee set up to further improve on this: number of layers, length of barrel, conical end-caps, maintenance

# Microstrips: Modules and staves

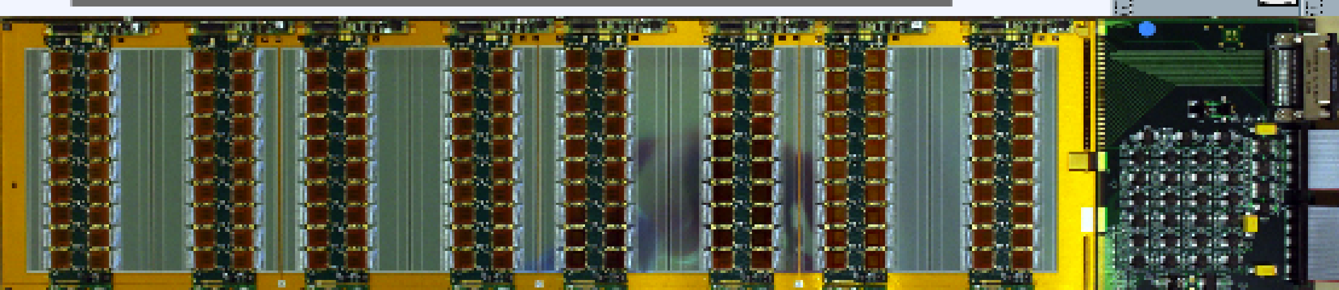
Hybrid with front-end chips glued directly to sensor
Sensor glued to cooled mechanical support - "Stave"
Staves arranged in cylinders
Stave can reduce material and helps assembly schedule by avoiding bottle-neck at module mounting on cylinders

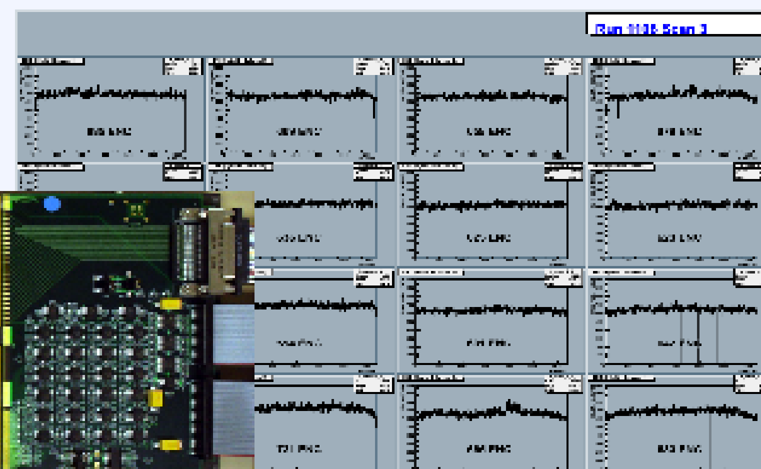


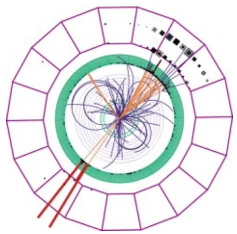




Mini-stave built: very good and uniform front end performance (noise, gain, pedestal, threshold); low dead channel count







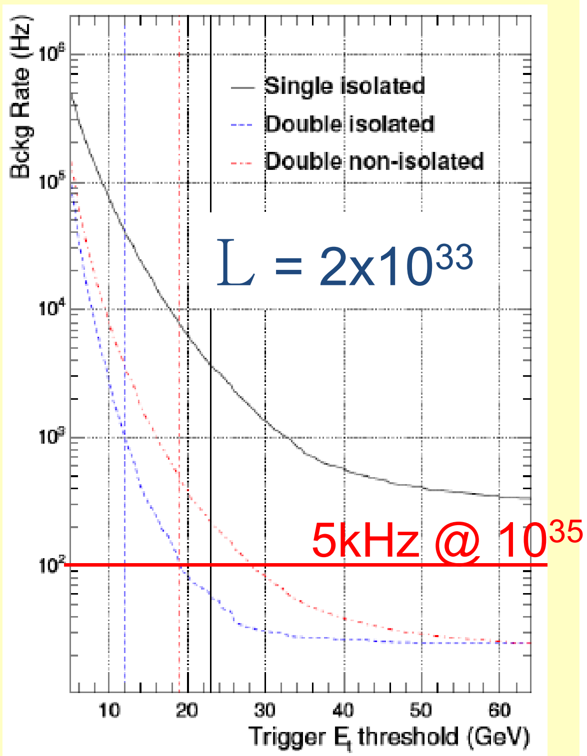
# Why tracker input to L1 trigger?

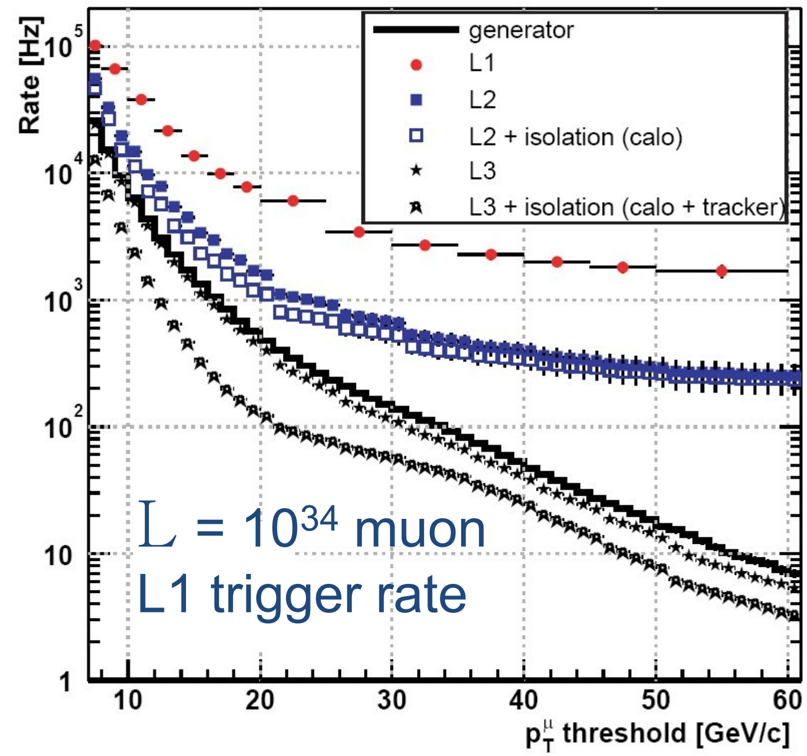
- Single *μ, e and jet* L1 trigger rates will greatly exceed 100kHz
  - Tracker data appears to be only extra info capable of improving selectivity
    - can increase latency, to 6.4μs, but must maintain 100kHz for compatibility

Single electron trigger rate

$\langle p_T \rangle \approx$ few GeV/bx/trigger tower

*Isolation criteria alone are insufficient to reduce rate at $\mathcal{L}$= $10^{35}$ cm$^{-2}$.s$^{-1}$*



# The track-trigger challenge

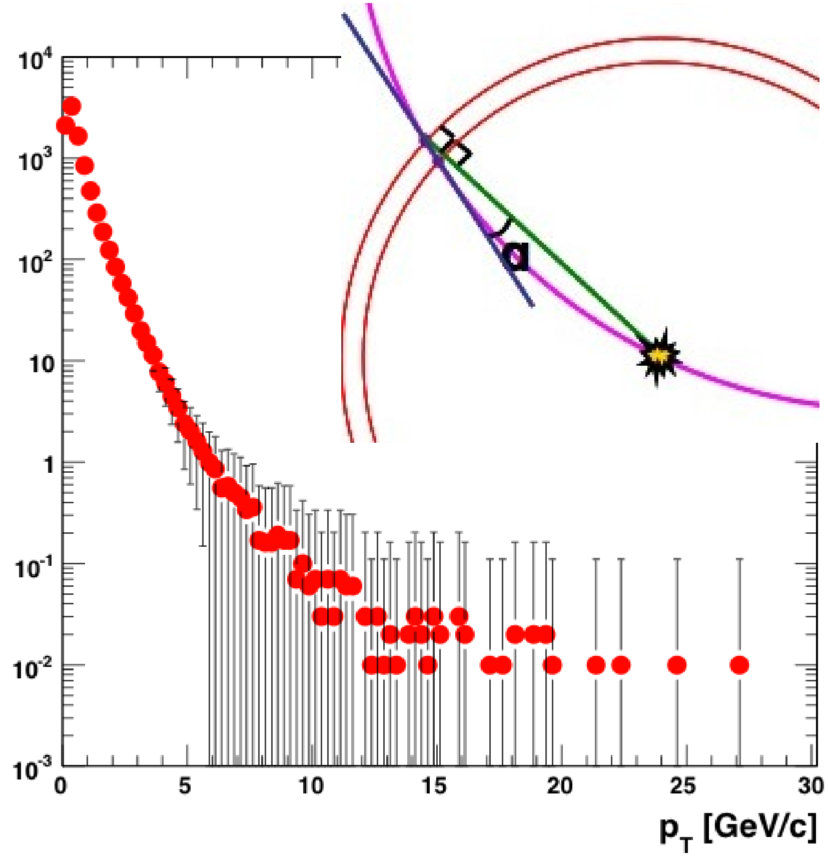
- Impossible to transfer all data off-detector for decision logic
  - for most of detector, at least

- Large fraction of low $p_T$ tracks
  - not useful for trigger
  - conceptually simple to measure
  - hit density means high combinatorials

- Possible solution by correlating information from two closely spaced radial layers

  several ideas for how to do this

  but a big challenge to implement and demonstrate in next few years



# Track Trigger at L1

Several ideas for implementing a track trigger at L1.
Wanted: high-PT (~20 GeV) leptons.

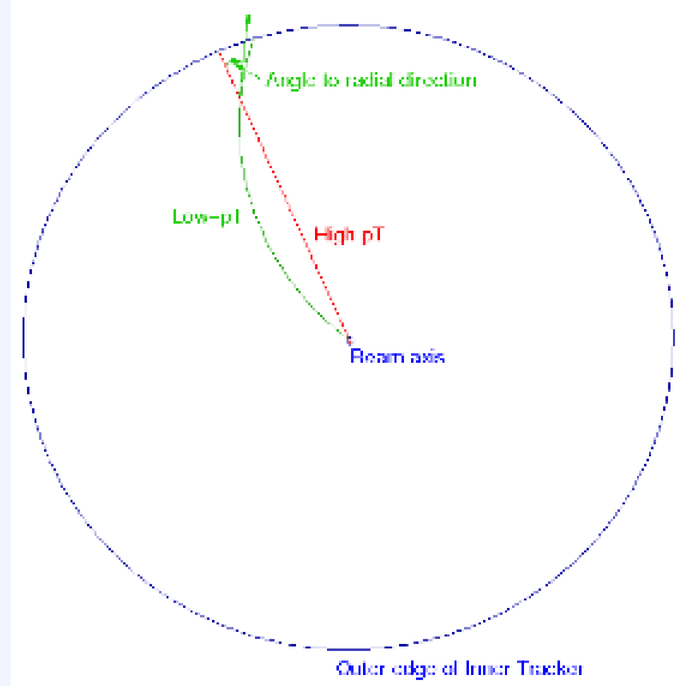
ATLAS EM calo has good identification, allowing a two-stage trigger approach:

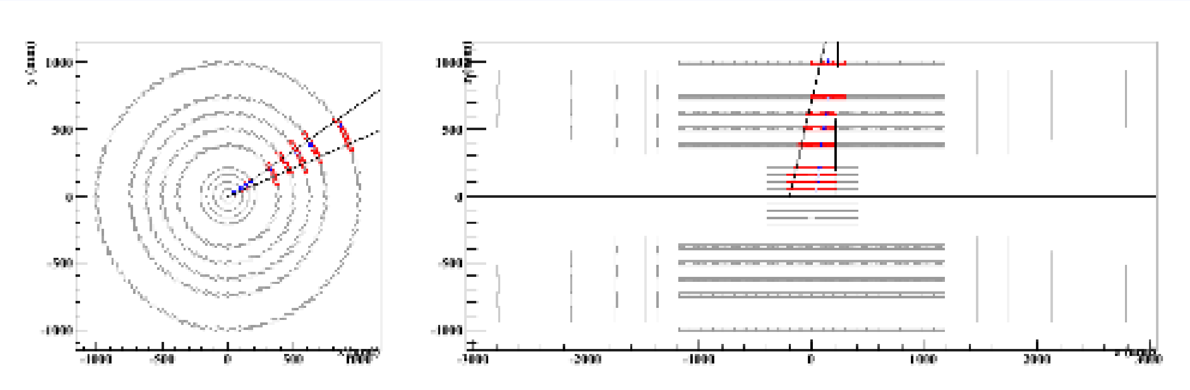
Calorimeter or muon system identifies a candidate high-PT lepton and gives region-of-interest

Inner tracker modules in that region are read-out, and hardware track finders confirm presence of track with matching momentum

RoI is a few % of modules so small increase in bandwidth needs --> very little increase in material

Needs additional data stream in FE chip and a lot more study, but encouraging so far



Alternatively, measure track angle to radial direction at outer edge of inner tracker - look for near radial tracks

Either with paired silicon layers or GasPix detector with 10 mm drift gap

# Summary

- Too much material to do justice to
  - much has been omitted
- LHC is a huge data mine and improvements to the detectors will ensure it will be delivering physics for two decades
- Many of the changes are extremely challenging
- They will need all the ingenuity of the next generation of physicists to accomplish successfully
- The rewards will be immense

# BACKUP MATERIAL

# Options for Leveling:

- CRAB cavities

  -New technology not yet demonstrated for hadron storage rings

- Wires for long range beam-beam compensation:

  -New technology not yet demonstrated for hadron storage rings with long range beam-beam interactions

- Operation with offsets at the IP:

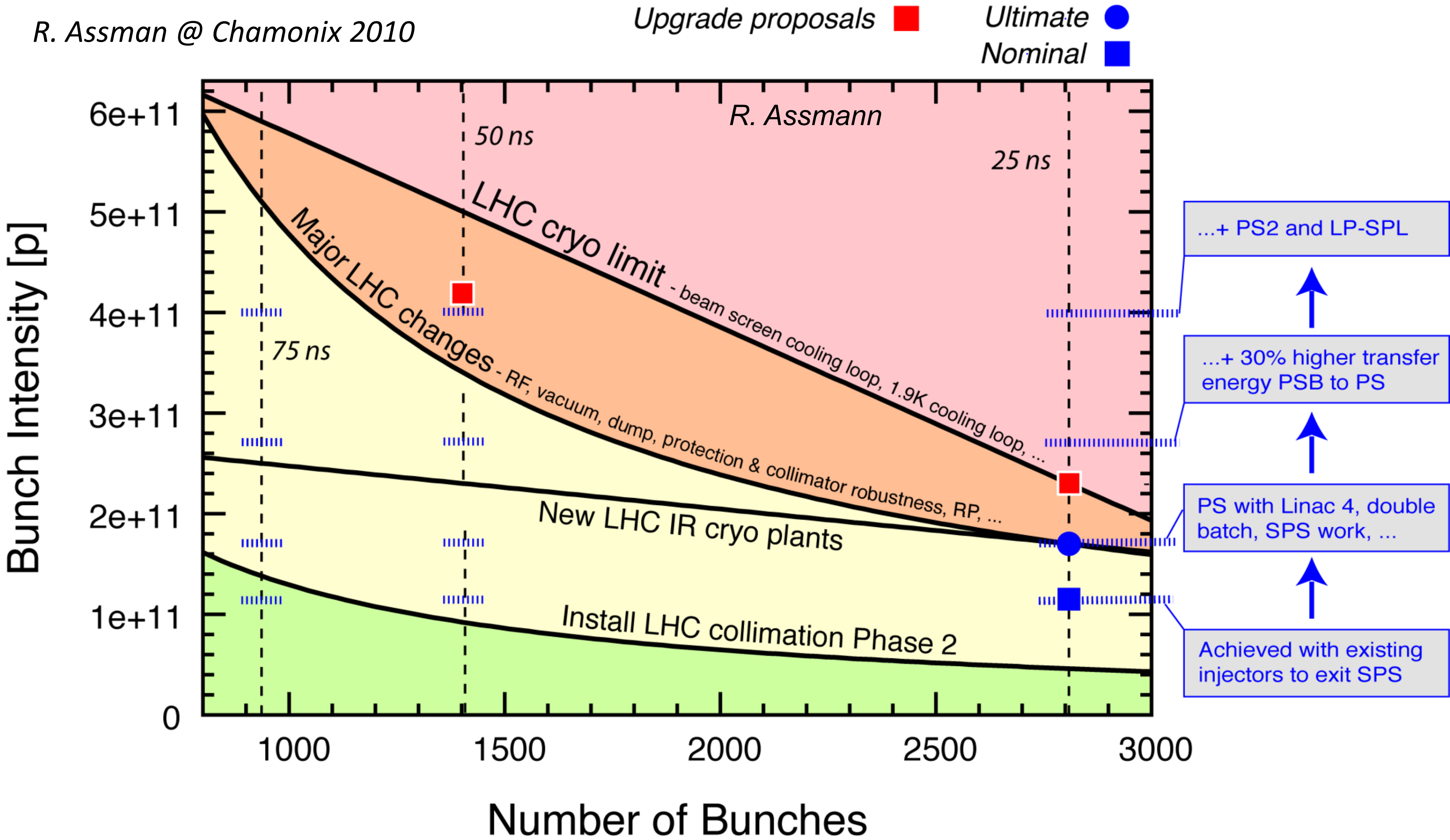
  -Has been difficult in other machines

- Dynamic optics change during physics collisions:

  -Has never been done so far in a collider plus complication of crossing angle in common beam pipes for the LHC

# Summary of LHC Intensity Limits (7 TeV)

*R. Assman @ Chamonix 2010*




**Ideal scenario: no imperfections included!** Note: Some assumptions and conditions apply…