CMS upgrade plans and CERN participation
(with tracker bias)

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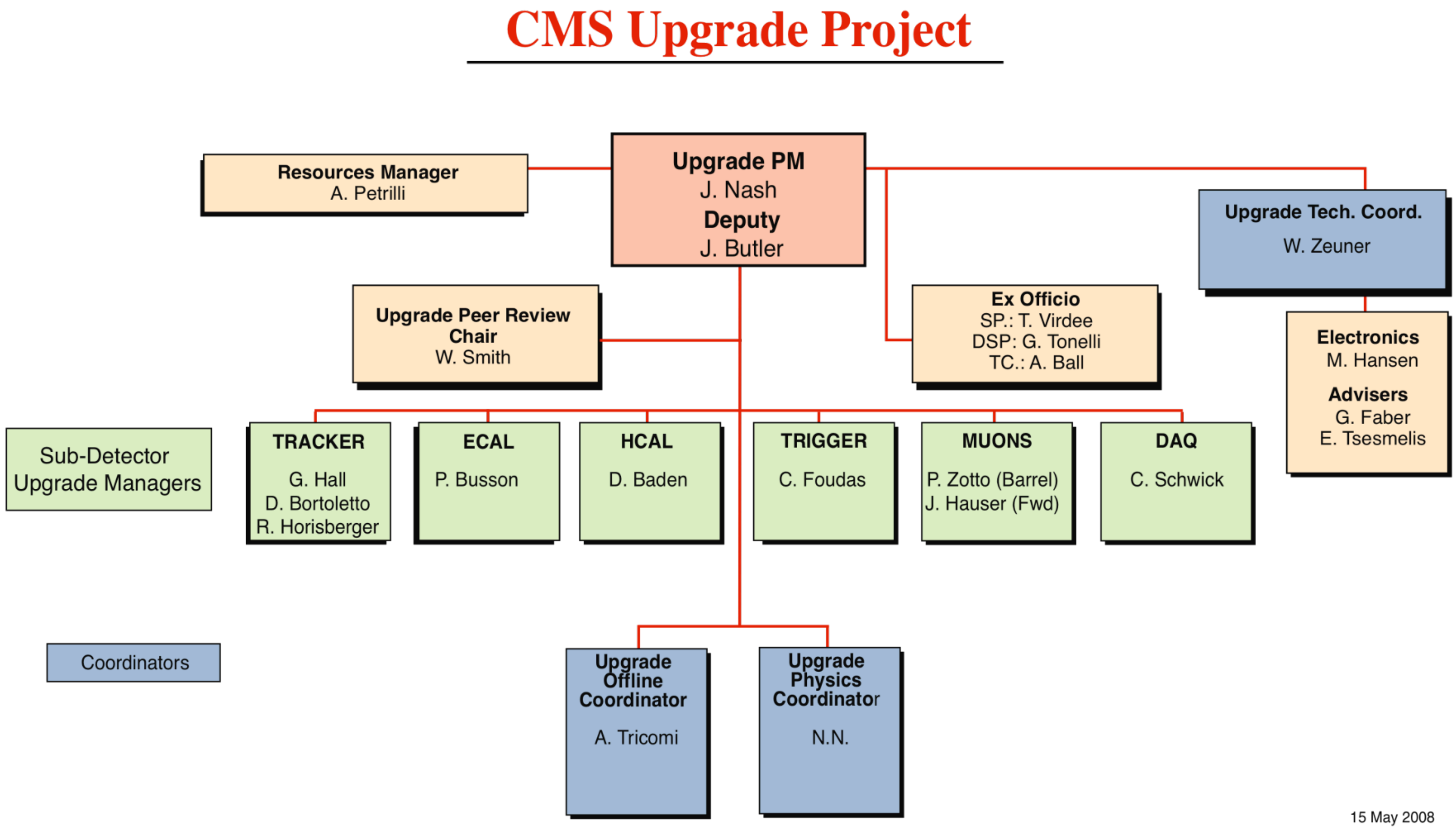
Outline

- Brief reminder about LHC upgrade
- Brief reminder about CMS Tracker
- "Phase I" upgrades
  - Pixel detector
  - Others: BCM, CSC, RPC, HCAL electronics,Trigger
- "Phase II" upgrades
  - Trigger and tracker
  - Open issues in forward electromagnetic calorimetry
- A few details about 3 specific R&D projects

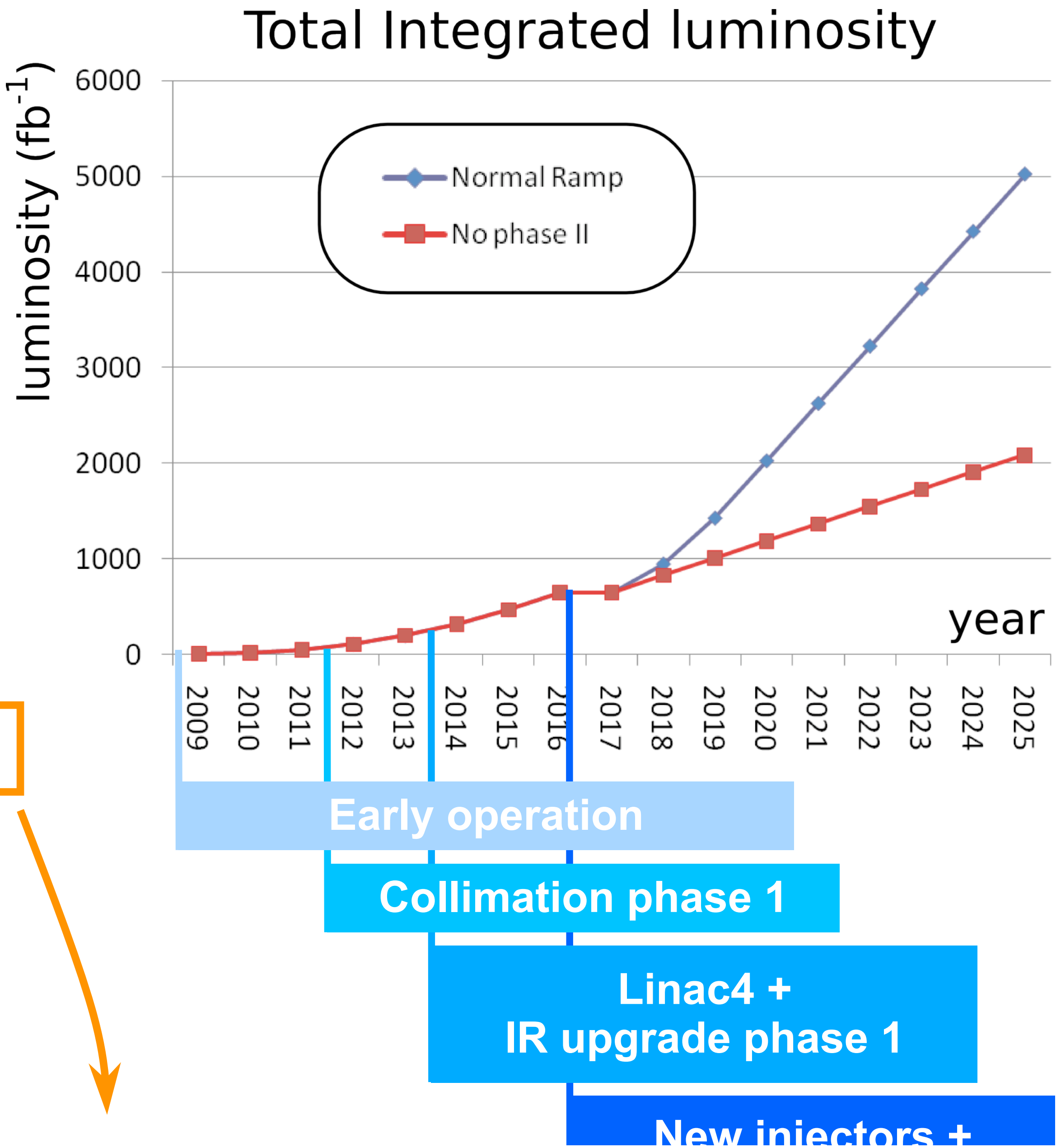
CMS Upgrade Organization



SuperLHC: brief reminder

	LHC	SLHC (Phase 2)
peak luminosity	10^{34} cm^{-2} s^{-1}	10^{35} cm^{-2} s^{-1}
integrated luminosity (max)	100 fb^{-1}/year	1000 fb^{-1}/year
c.m. energy	14 TeV	14 TeV
bunch crossing interval	25 ns	50 ns (?)
# pp events / crossing	~20	~400
# particles in tracker	~1 000	~20 000

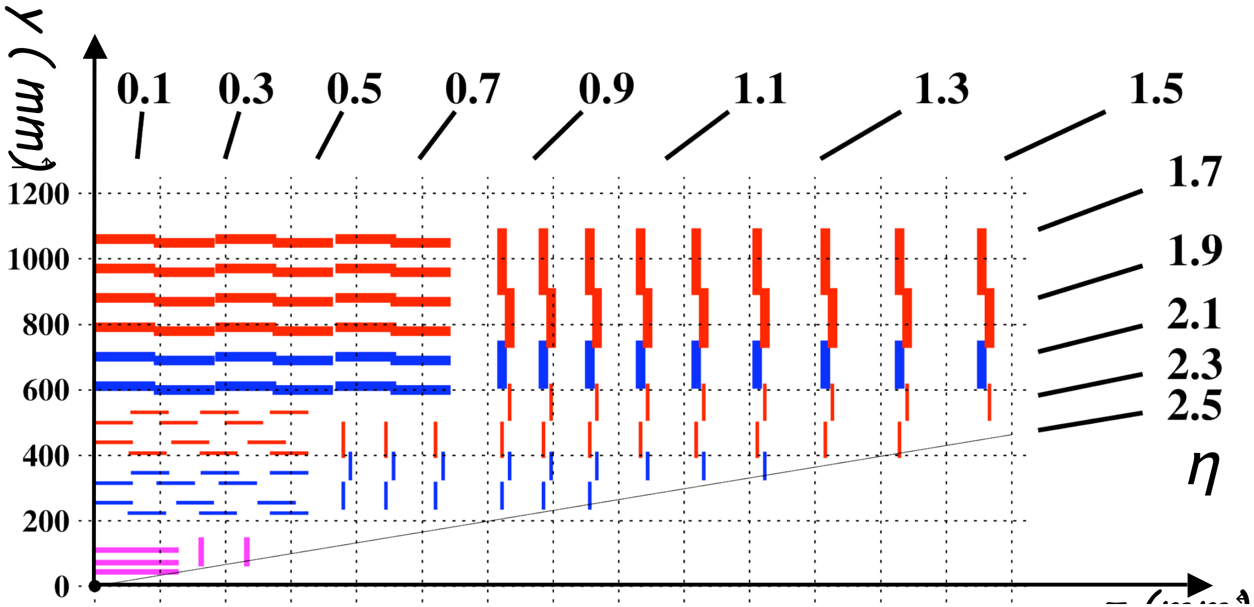
Year	Peak Lumi (x 10^{34})	Annual Integrated (fb^{-1})	Total Integrated (fb^{-1})
2009	0.1	6	6
2010	0.2	12	18
2011	0.5	30	48
2012	1	60	108
2013	1.5	90	198
2014	2	120	318
2015	2.5	150	468
2016	3	180	648
2017	3	0	648
2018	5	300	948
2019	8	420	1428
2020	10	540	2028
2021	10	600	2628
2022	"	"	"



Current Tracker system

- 3 silicon pixel layers
  - Quickly removable for beam pipe bakeout or replacement
- 10 silicon micro-strip layers
  - 4 double sided
  - 6 single sided
  - End-caps matching

μ-Strip tracker	Pixels
~210 m^2 of silicon 9.3M channels	~1 m^2 of silicon 66M channels
73k APV25s 38k optical links 440 FEDs	16k ROCs 2k optical links 40 FEDs
16 module types 300-500 μm	8 module types 300 μm
~33kW	~3.6kW

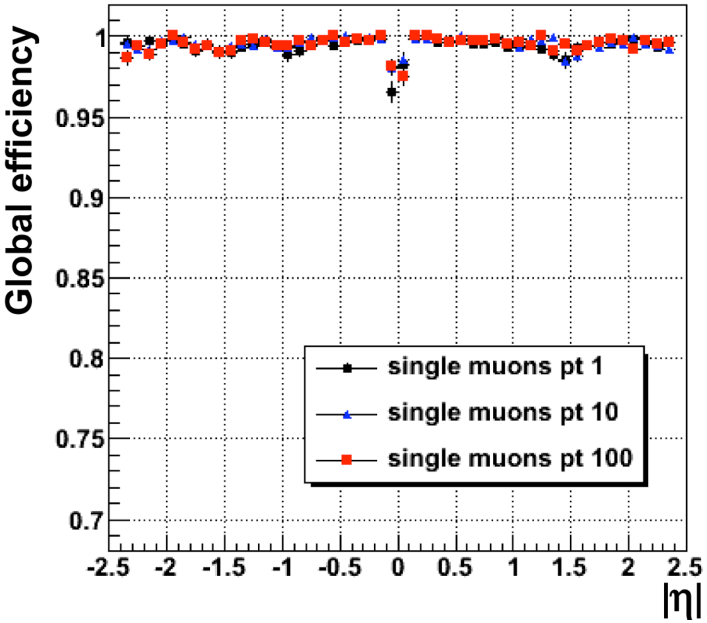


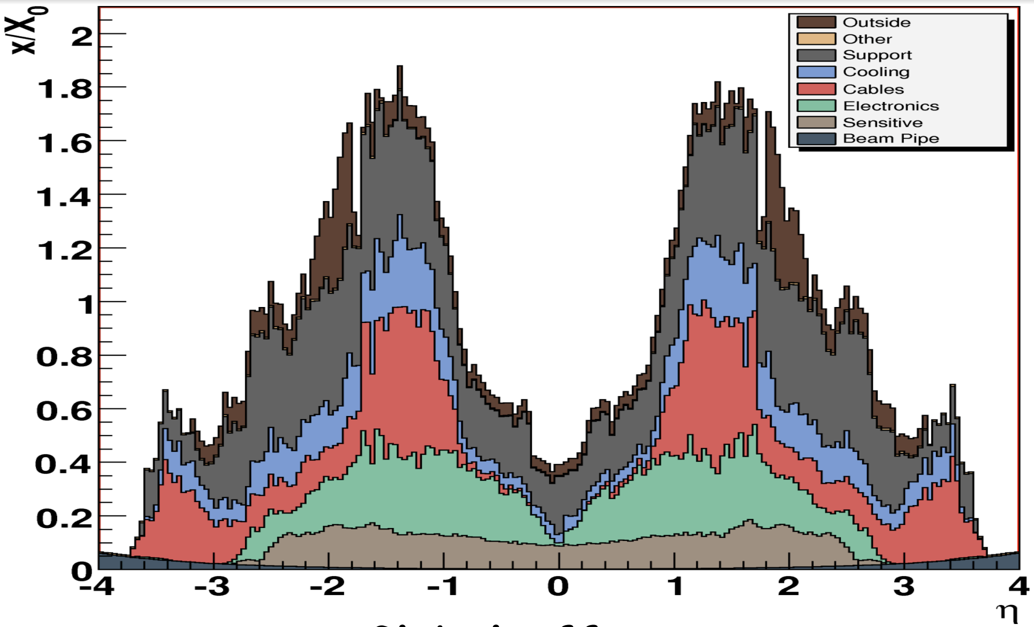
Occupancy @ 10^{34}

Pixels: 10^{-4}
Inner Strips: 3×10^{-2}
Outer Strips: 10^{-2}

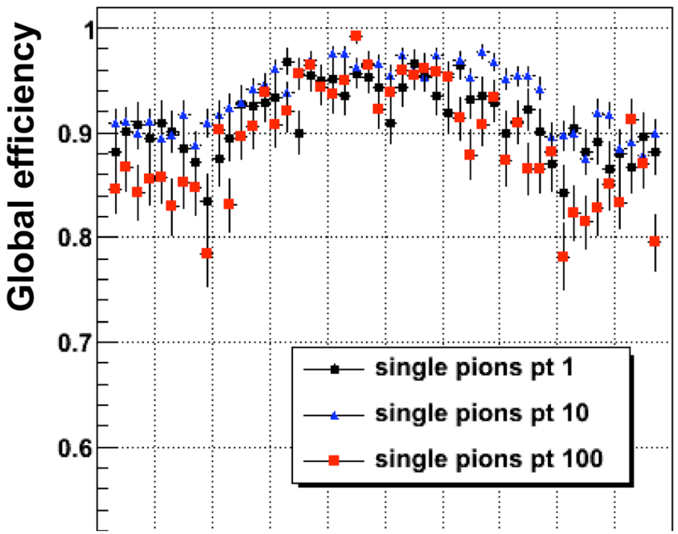
Tracker performance: limited by material

μ track finding efficiency

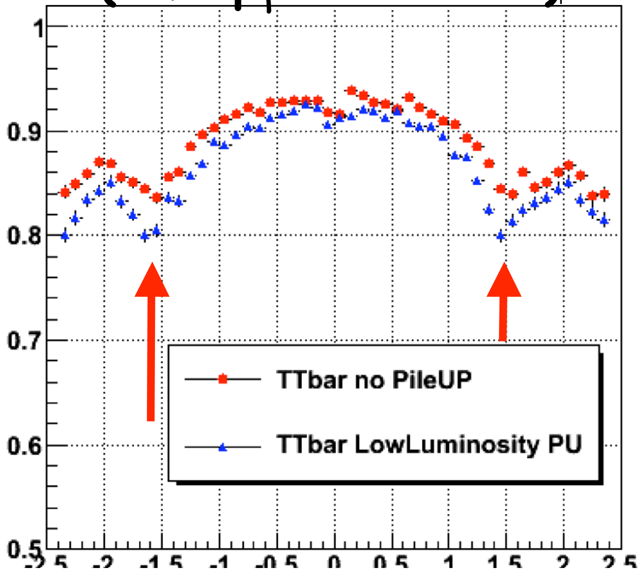




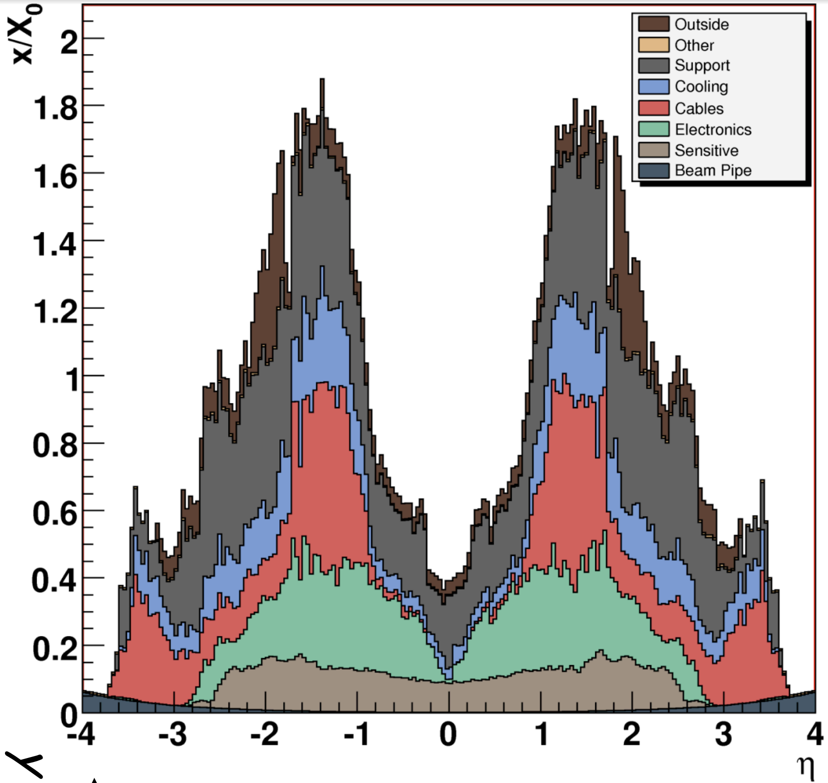
π track finding efficiency



Global efficiency (sim. p_T > 0.9 GeV)

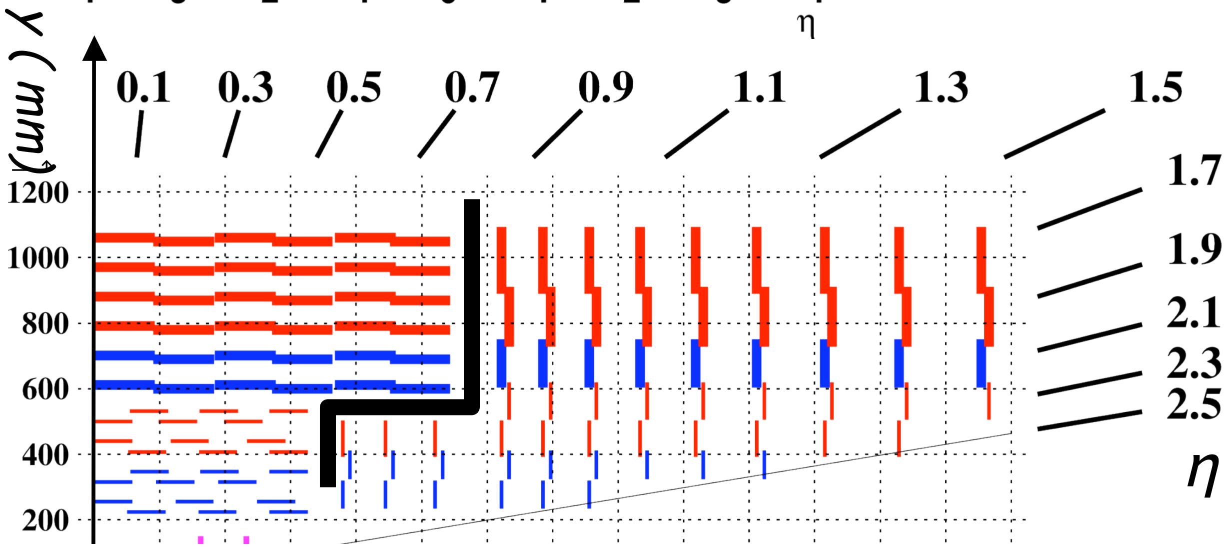


Tracker material



Large peak around η=1.5 dominated by services inside the TK volume

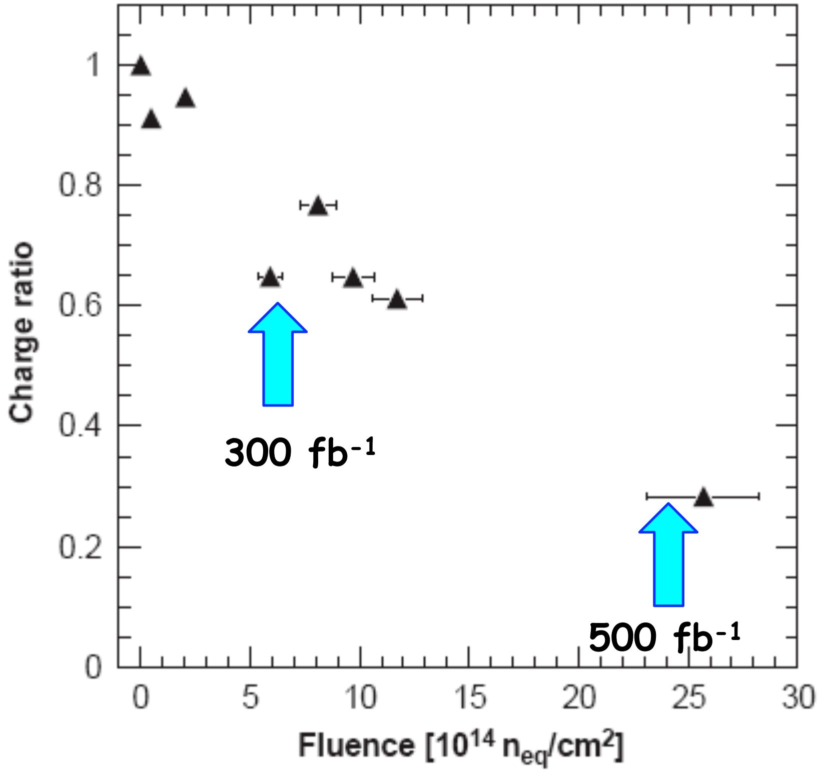
Driven by amount of current and power absorbed by FE electronics



[Current is worse than power i.e. more copper than cooling]

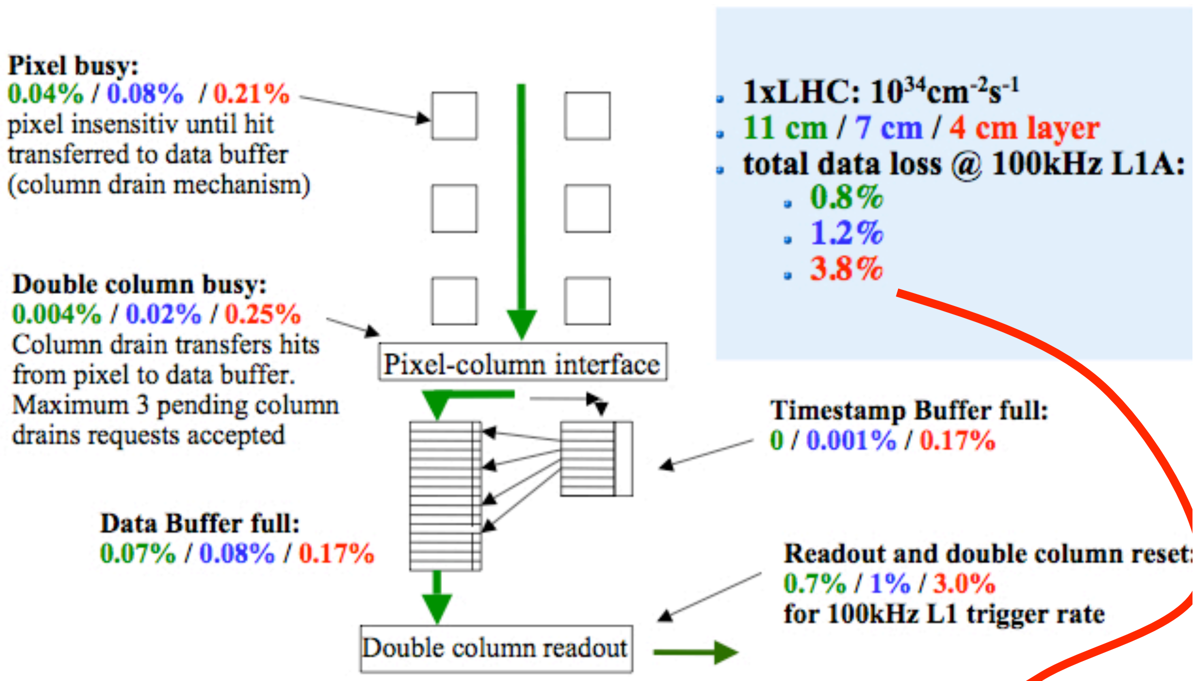
Limitations of pixel detector

Radiation damage of n-on-n sensors
Designed to survive ~300 fb^{-1}



Readout system originally conceived for 7cm @10^{34}

Already marginal at 4cm



Total dead time increases to 16% @ 2x10^{34}

Options for pixel upgrade

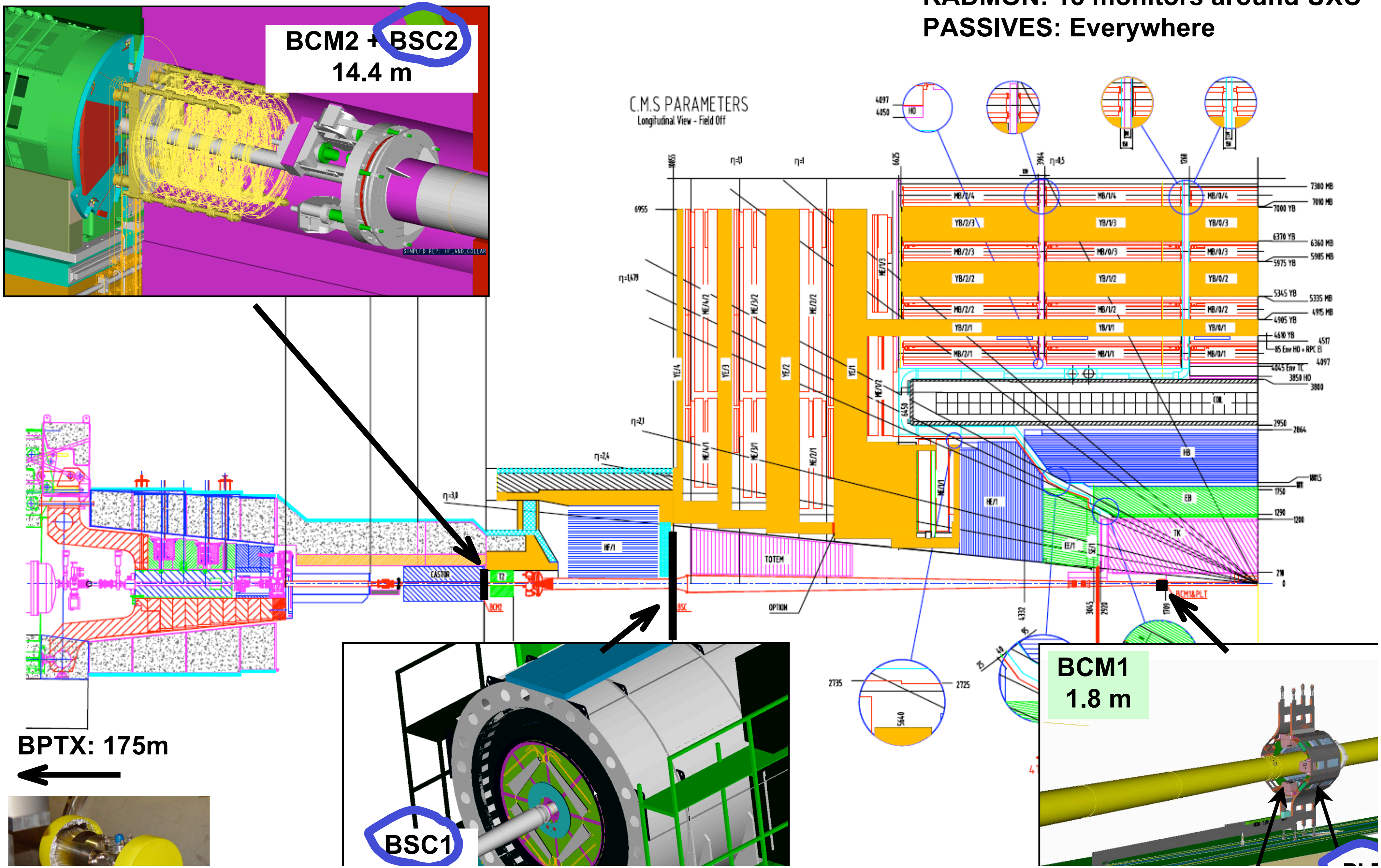
- Three barrel layers (as now) and three disks for endcap
  - Benefit of third disk not demonstrated (or quantified)
- Sensors with p-type bulk, more rad-hard
  - Submission with HPK, expected delivery early next year
- Double size of readout buffers
  - Relatively minor modification, feasible for phase I, but reduces data loss from 16% to 10% only (@ 2×10^{34}) [options for deeper modifications under study]
- Improvements in mechanics and electronics design
  - Optimize design and choice of components (notably μ-twisted pair cables instead of kapton cables in the barrel) to reduce passive material in the rapidity acceptance
- Two-phase CO_2 cooling
  - Should help reducing the amount of material. Not impossible for phase I. Prototype system in view of phase II. CERN involved (more later).
- Evaluate 3-d sensors for innermost layer at 4cm
  - Needs dedicated readout. Unlikely for phase I.
- Readout chip in 130 nm technology
  - Could bring substantial improvements (reduction of data loss and power)
  - Needs substantial R&D. Unlikely for phase I.
- Fourth barrel layer (+ reoptimized endcaps?)
  - Needs CO_2 cooling AND novel powering method AND high speed link, to comply with constraints on services. Unlikely for phase I.
  - For phase II a global re-optimization of pixel geometry could also be envisaged. (Different barrel length? Barrel only??)

Phase I pixel upgrade: remarks

- Collaboration between PSI (barrel) and consortium of US Institutes (forward) - same as for present detector
  - More coherence between the two continents would be very beneficial…
- Based on official LHC operation/upgrade schedule, aiming at detector ready for installation at the end of 2012
  - Is it the good choice?
- CERN involved only through the R&D on CO_2 cooling
  - Many Institutes suddenly interested in CO_2 cooling (FNAL, Purdue, PSI, Aachen I, Lyon, Karlsruhe), and I bet more will come up…
  - Important in view of future installation, commissioning and operation (… and troubleshooting…) that CERN keep control of this item

Diagram of Location of BRM+PLT Subsystems

RADMON: 18 monitors around UXC
PASSIVES: Everywhere



Pixel Luminosity Telescope

Total length 9 cm, located at r ~ 5 cm, z +- 1.7 m

Diamond pixels bump-bonded to CMS pixel ROC

Expected to deliver:

- measurement of luminosity
- measurement of interaction point centroid
- identification of beam in abort gap
- measurement of beam halo

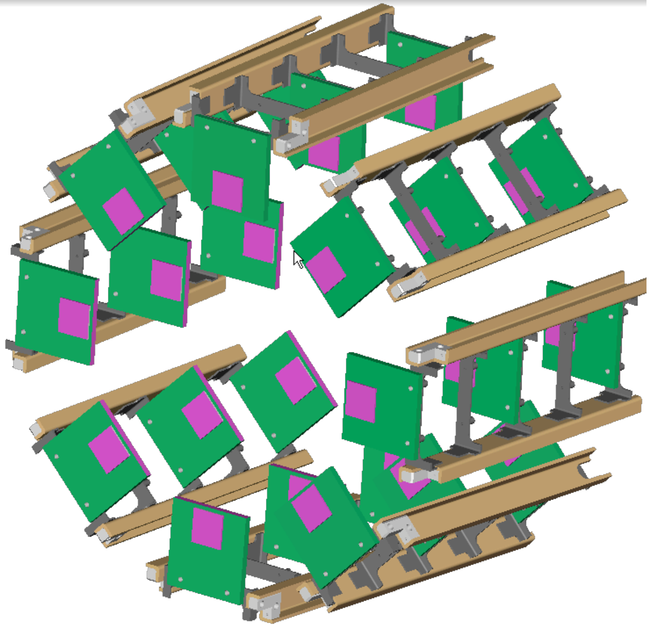
Technical review this December

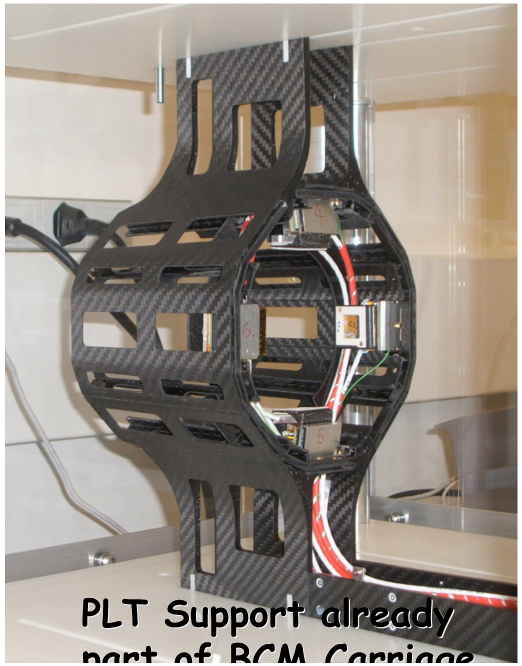
Small prototype installed this or next shutdown

Detector ready 09/10 or 10/11 shutdown

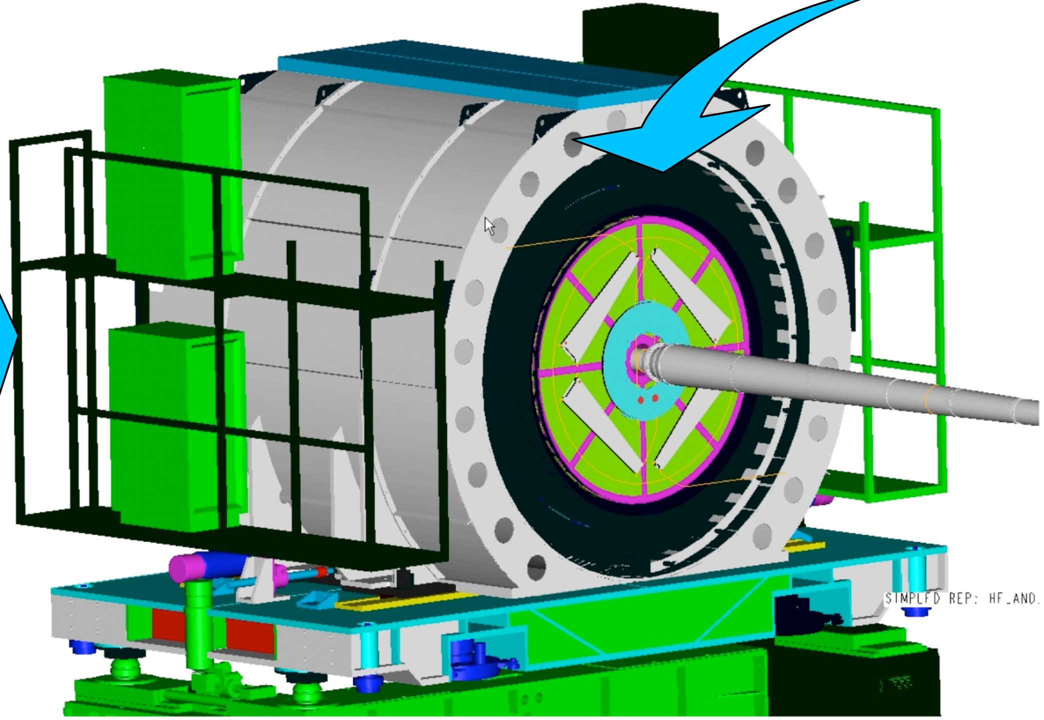
US project.

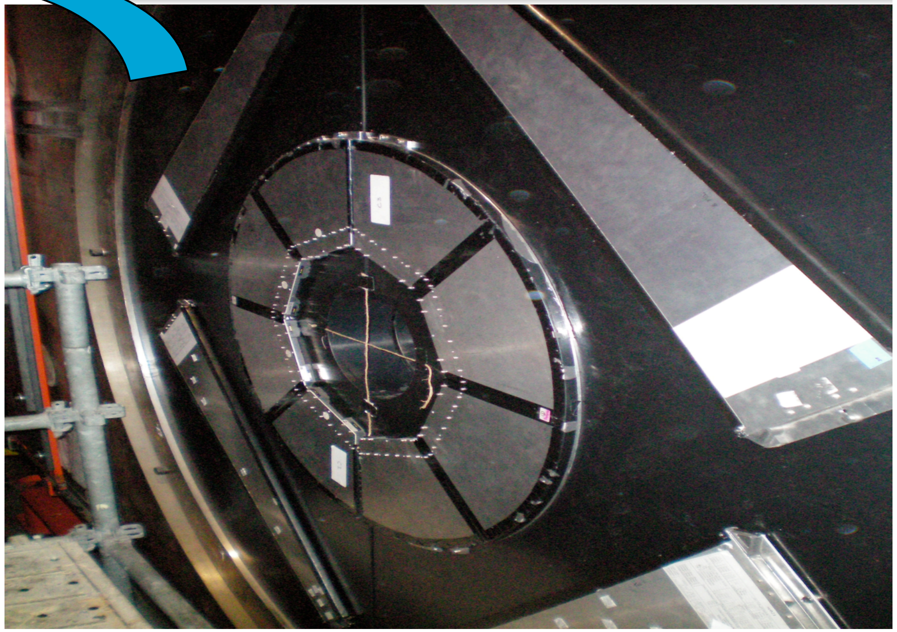
CERN will provide engineering support for integration.

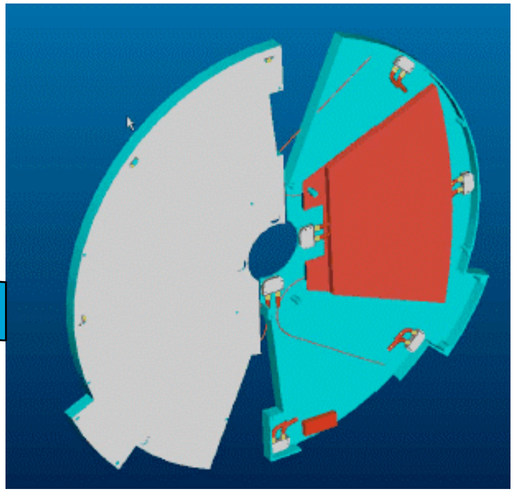




Beam Scintillation Counters





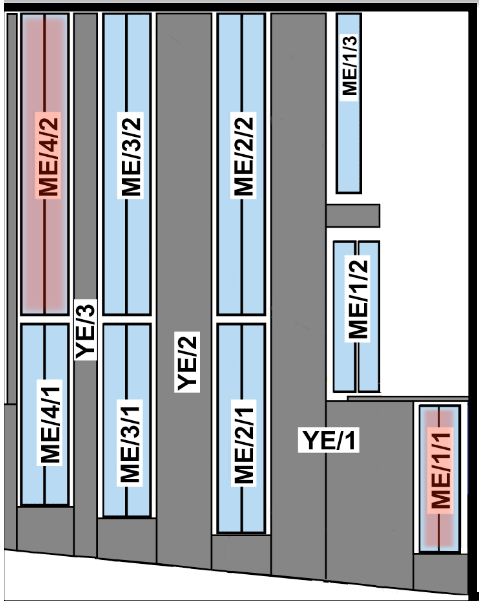


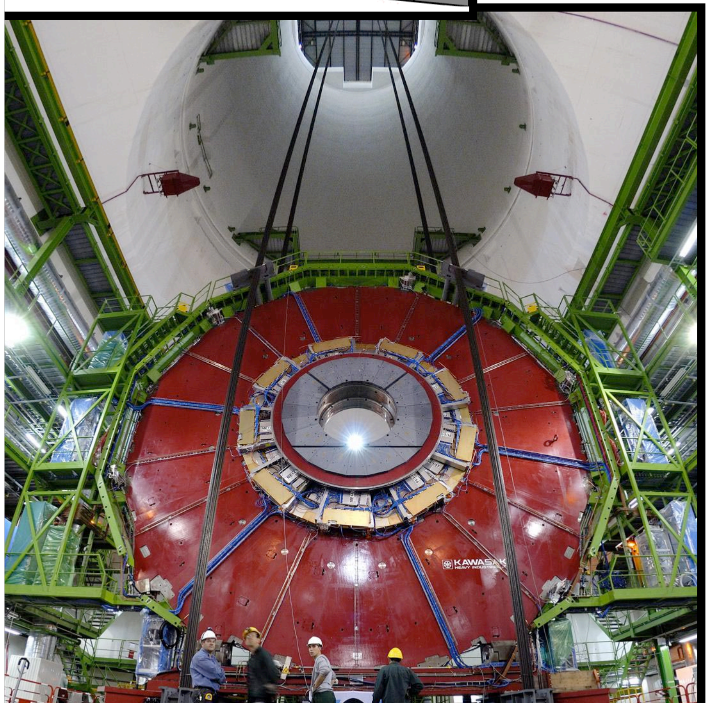
1.2m^2 of plastic scintillation panels on HF front faces
+ 2 additional tiles at ±14.36m (36 channels total)

Beam halo monitoring + trigger
Time resolution 3ns
Expected lifetime ~ 1 - 2 years
Needs replacement / upgrade

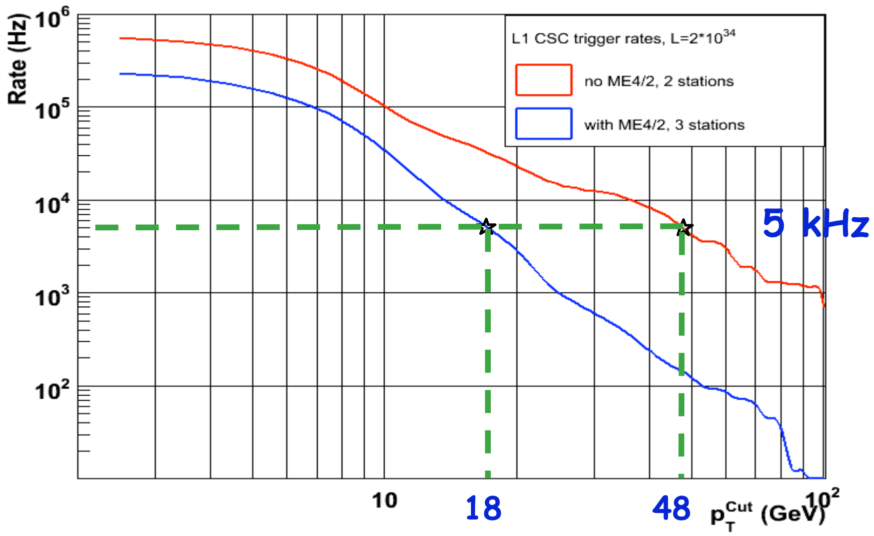
Options still to be investigated (Quartz? Plus diamond?)
Likely involvement of CERN (to be defined)

Endcap CSC stations ME/4/2 and ME/1/1





- **ME/4/2 chambers to be built (72)**
  - Improve performance and robustness of trigger and μ reconstruction
  - Particularly relevant at higher luminosity
- **ME/1/1 electronics upgrade**
  - New faster digital cards for ME/1/1 to cope with high particle rates
  - Upgrade also back-end electronics
  - Reuse current ME/1/1 electronics for ME/4/2 (two projects coupled)

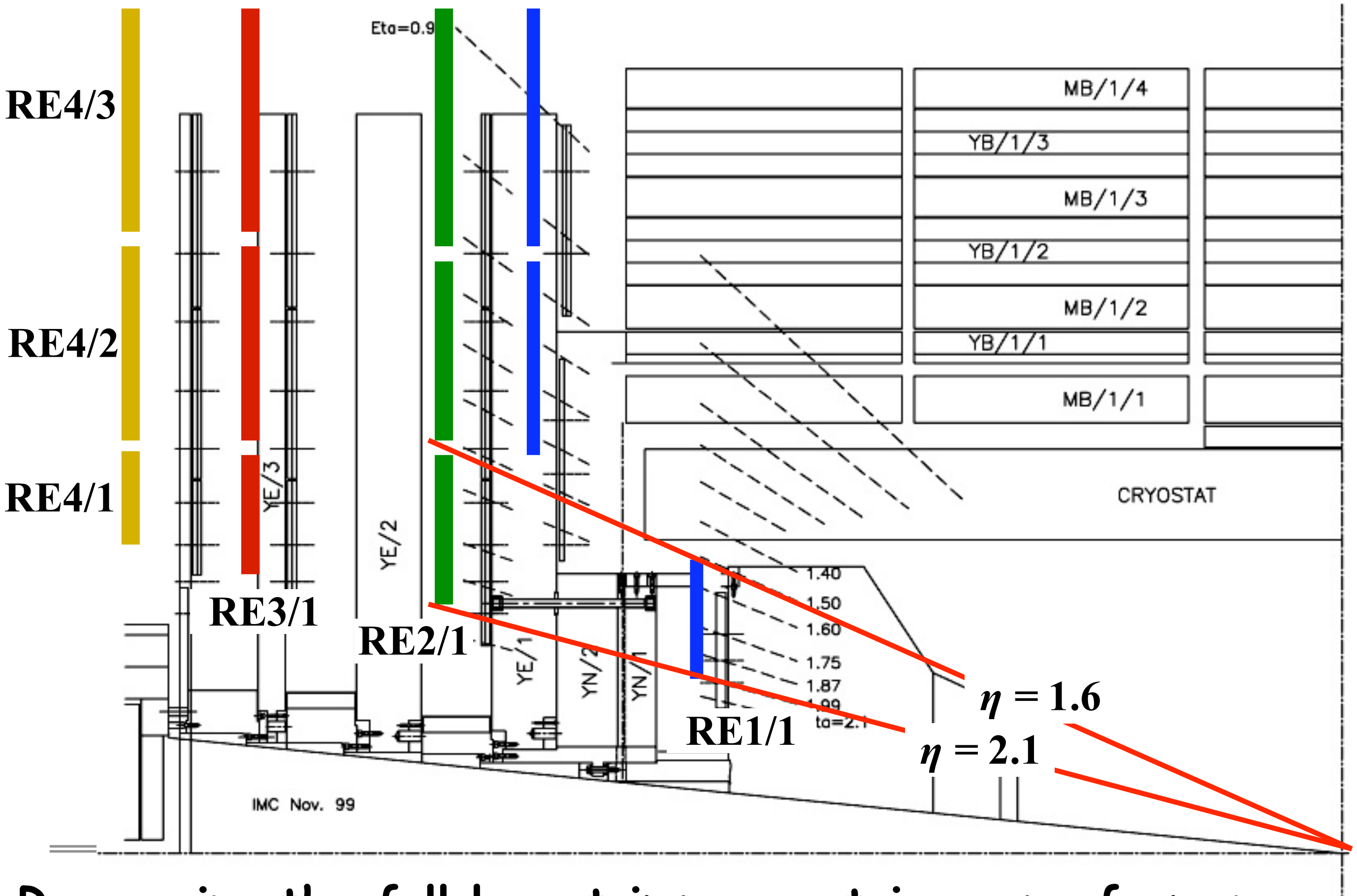


Both are US projects

CERN to provide (as usual) support for reception, testing, installation and commissioning

Forward RPC at startup

	RE1/1	RE1/2	RE1/3	RE2/1	RE2/2	RE2/3	RE3/1	RE3/2	RE3/3	RE4/1	RE4/2	RE4/3
N of chambers	36*2	36*2	36*2	18*2	36*2	36*2	18*2	36*2	36*2	18*2	36*2	36*2



High η region not foreseen at startup

4th station staged for financial reasons

Recovering the full layout improves trigger performance

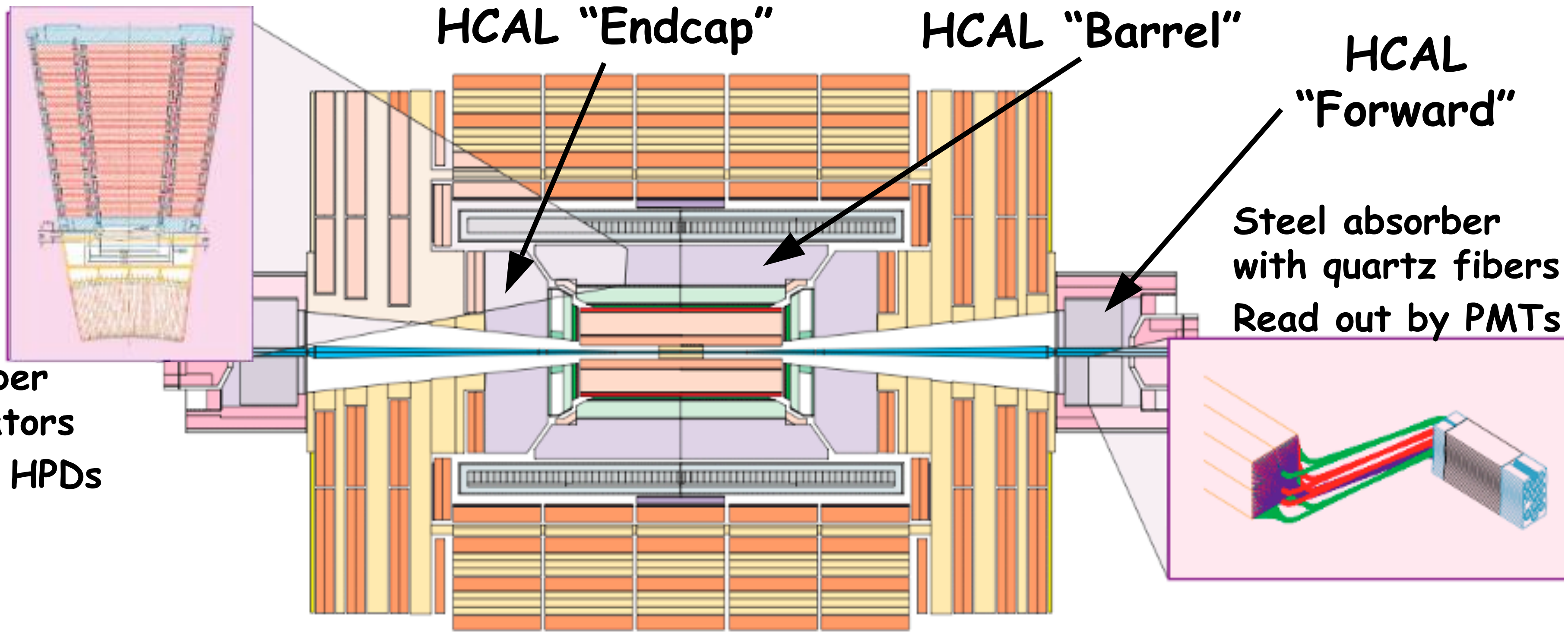
Upgrade plan still not clear

Forward RPC upgrade plans

1. Restore 4^{th} station at low η (RE4/2+RE4/3)
   - Move 2^{nd} station to position 4
   - Install double chambers in position 2, with AND/OR capability for enhanced trigger performance
   - Schedule: 2011?
   - Resources from China, India, Korea, Pakistan, Belgium, CERN
   - CERN involvement still to be defined

2. Upgrade of high-η region
   - More R&D needed to certify suitability for higher rates (ageing tests ongoing - gas recirculation/filtering)
   - Current detectors (almost certainly) not adequate for 10^{35} - may need different technology?
   - First upgrade around 2013, and one more later???

HCAL limitations



HB/HE

- Light from all layers in a tower added optically
  - No way to correct for higher radiation damage in inner layers
  - No way to vary weighting in separate layers to improve linearity and resolution
- HPDs are very noisy

HF

- PMTs not sufficiently radiation hard
  - Expect degradation at high luminosity
- No timing capability
  - Problem with non beam-related bkg
- Affected by charged particle rates at high luminosity

HCAL readout upgrade

Plan: Replace HPDs (HB/HE) and PMTs (HF) with "Silicon Photo Multipliers" (array's of APDs)

- Advantages:
  - Higher quantum efficiency, higher gain, much less noise, high linearity
  - Radiation hard
- Solve automatically noise and radiation damage issue
- Allow increase in segmentation and add timing
- Should make HCAL adequate also for SLHC

Study underway for 3-4 years to investigate use of SiPM in HO
(HO = few barrel layers located outside coil - serve as tail catcher and contribute to μ trigger)
HPD gain not OK for this location (muon signal too small)

No problem identified - plan to implement in HO in 2010

Schedule for full upgrade in HB/HE/HF not completely clear (…to me)

Level-1 Trigger from 2×10^{34} to 10^{35}

- Occupancy
  - Degraded performance of algorithms
    - Electrons: reduced rejection at fixed efficiency from isolation
    - Muons: increased background rates from accidental coincidences
- Trigger Rates
  - Need to hold max L1 rate at 100 kHz
    - Avoid rebuilding front end electronics/readouts where possible
  - Implies raising E_T thresholds on electrons, photons, muons, jets… or use new information
- ⇒ new information from use of more fine-grained information from calorimeter & forward muon triggers & improved algorithms exploiting this new information ("Phase I")
- Add information from Tracker later on ("Phase II")
- Strategy: define asap Tracker information to design compliant trigger architecture

Trigger and tracker

- The trigger upgrade is a vast project - mostly US (no details in this talk)

- The plan is:
  - Define project in 2010
  - Test prototypes in 2011
  - Construction in 2012
  - Deploy for 2013 data taking

- Serious implications for the Tracker upgrade
  - Current wisdom is that calo isolation cuts (even with improved granularity) and muon Pt measurements cannot provide sufficient rate reduction [Compelling evidence promised for FNAL workshop in 2 weeks] ⇒ Need information from the Tracker
  - Sending out data from the TK (even a fraction of it) at 40 MHz is a major issue
  - Will degrade the quality of the detector as a Tracking device

Upgrade Phase II: a new strip tracker

Goals:

- Maintain tracking performance in higher density environment
- Provide information for LV1 trigger

Higher occupancy

- Change sensor design: higher granularity (shorter strips - help also to reduce noise from capacitance, and leakage current per channel)

Higher radiation levels

- Optimize choice of sensor material
- ASICs: profit from deep sub-micron technology

Constraint: reuse (most of power) cables, cooling pipes, optical fibres

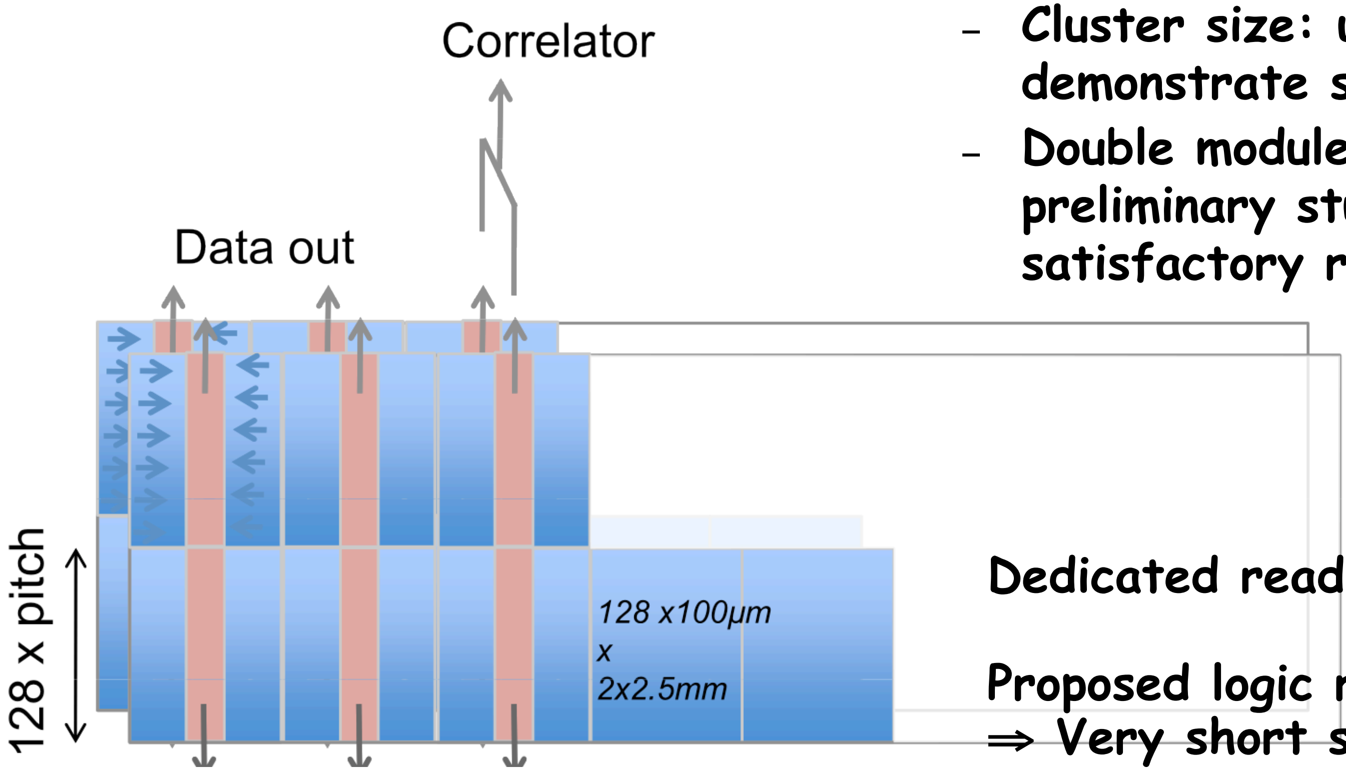
- Max. current in cables limited: requires novel powering schemes (a must!)
- Need high-speed links to push data through same fibers

Reduce material amount

- Deep submicron technology helps moderating the power dissipation (but not much the current)
- CO_2 two-phase cooling may help (and even be mandatory, depending on cooling requirements)
- Optimize layout of detector and services to minimize material in the Tracking

Trigger info from Tracker

- Initial thoughts of a full "trigger tracker" now much less popular
  - Links are power hungry, connectivity between distant layers a nightmare
- Current approach:
  - Develop a data-reduction method from individual modules (p_T cut)
  - Populate with "p_T modules" one or two layers, read out at 40 MHz, and check if needed trigger performance can be achieved



- Methods for data reduction
  - Cluster size: under study, but difficult to demonstrate sufficient reduction
  - Double modules with chip-to-chip correlator: preliminary studies seem to show that satisfactory reduction can be achieved

Dedicated readout (e.g. no memory)

Proposed logic requires ≤ 1 hit per chip
⇒ Very short strips (~ 2 mm @ 20 cm)

Sensors and detectors R&D

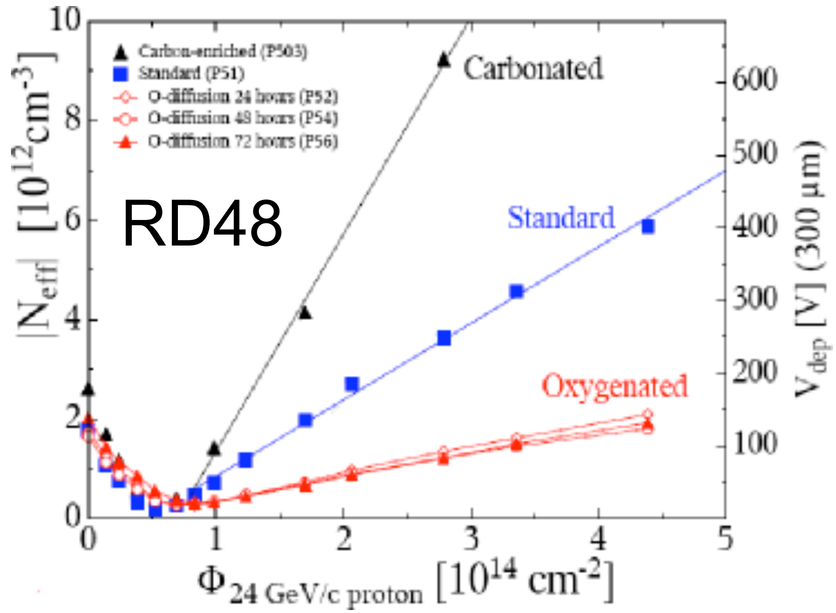
- Based on long and exhaustive R&D work of RD48 / RD50

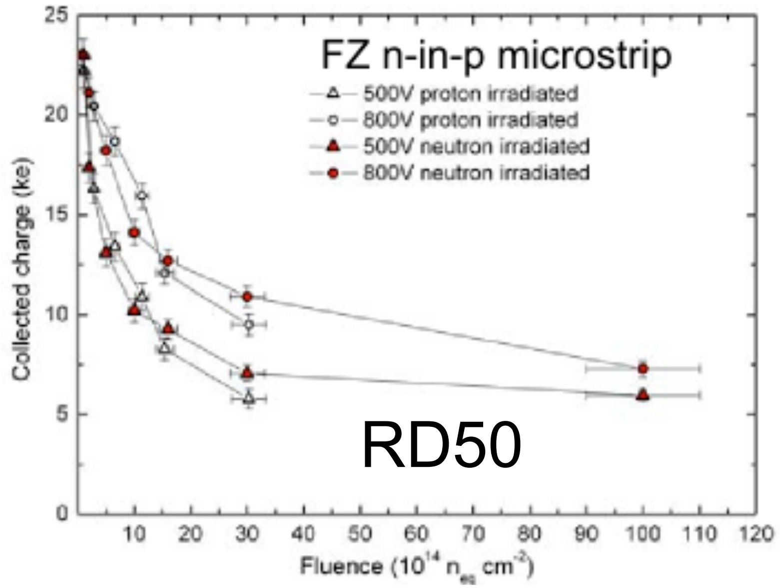
- Oxygenated materials have shown smaller V_{fd} increase after irradiation with charged hardons

- **Option of p-type bulk**
  - Charge collection less affected by irradiation (depleted zone on strip side)
  - No sign of reverse annealing
  - Can work under-depleted. Thinner sensors (lower noise electronics / shorter strips)
  - Electron readout - larger Lorentz angle (but OK with thinner sensors)

- **CCE studies showed good signal after very high radiation fluence**

- Except perhaps for first pixel layer



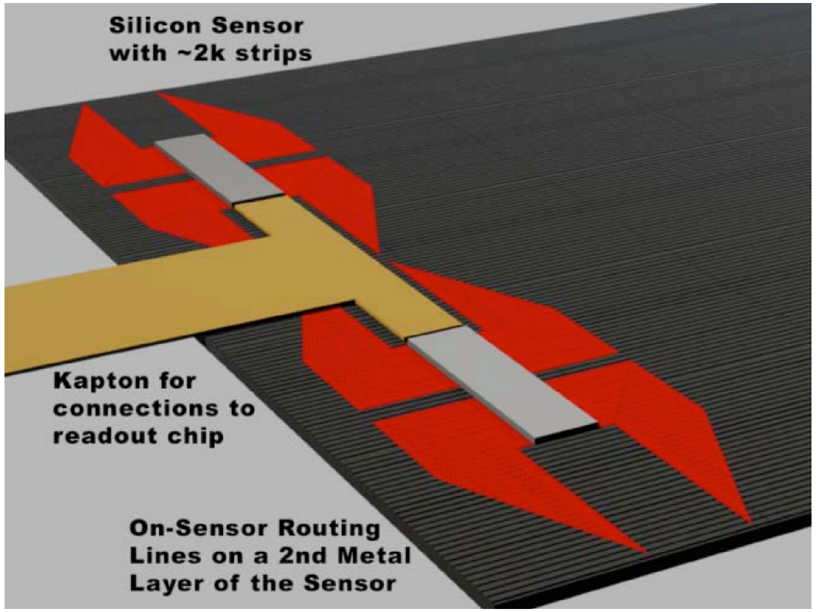


Sensor R&D (II)

Goal: identify one sensor type in planar technology for the outer region (possibly p-MCz) and one more pixelated for the inner tracker

Special routing for large sensors with short strips

- double metal layers?
- bump bonding?



A few CMS-specific R&D proposals submitted to management. Notably:

R&D for thin Sensors with HPK (M. Mannelli)

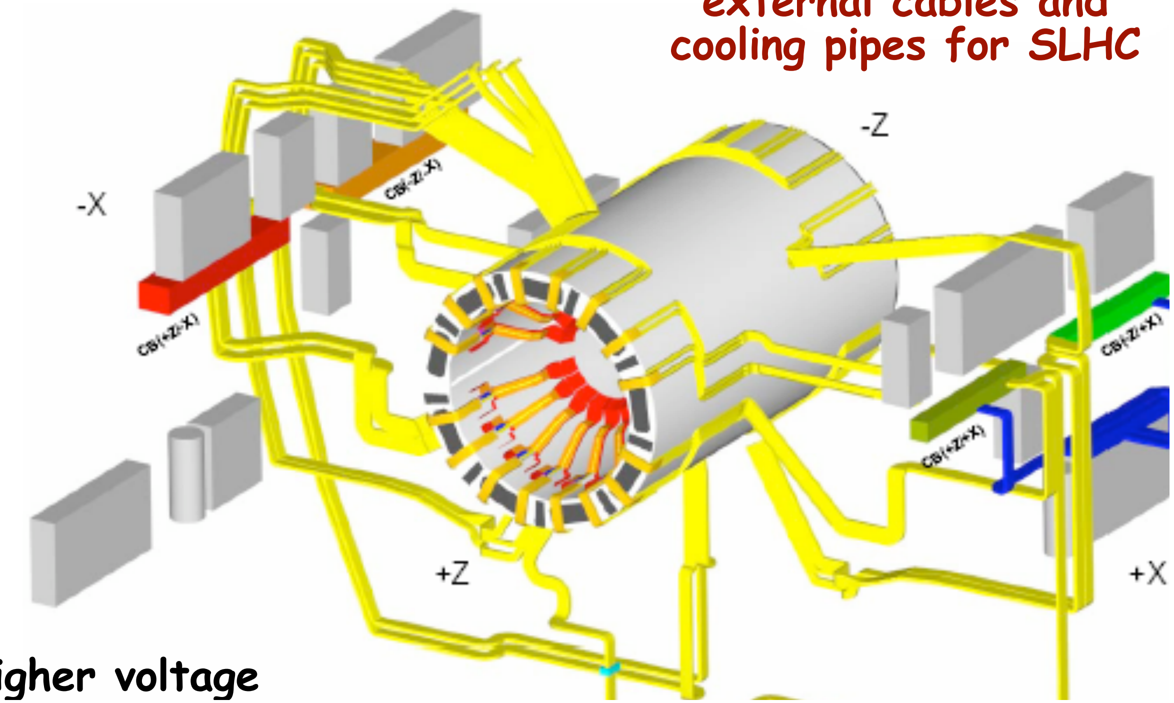
Several strips and pixel geometries on several different substrates

Logic continuation of the successful sensor procurement of the current TK

Power delivery (I)

- Smaller feature size will result in smaller FE supply voltage (1.2 V @ 0.13 µm)
- Power per channel decreases (2.7 µW/ch → 0.5 µW/ch)
- N of channels will increase, because of higher occupancy (but not more than needed!)
- Total readout power expected to be ~25-35kW
  - about as present system so larger currents at front-end
- Today:
  - $P_{Front\text{-}end} \approx$ 33kW
  - $P_{cables} \approx$ 20 kW
  - $I_{cables} \approx$ 15 kA
- Example:
  - Same power, current ×2
  - Voltage drop ×2
  - Power in cables ×4: 80 kW
- Conclusion:
  - Mandatory to bring in current at higher voltage

Not feasible to replace external cables and cooling pipes for SLHC



Power delivery (II)

Two main approaches considered:

(i) Serial powering
(ii) DC-DC converters

Both can solve the problem - if they work - and help reduce the material
They have different disadvantages

Serial powering

- Complicated system issues:
  - Modules at different voltages
  - Difficult to implement different supply voltages (e.g. FE chips and optical link)
  - A variety of issues in case of malfunctioning of a module (or at startup)

DC-DC converters

- Radiation hardness needs to be demonstrated
  - Potential showstopper
- A number of other smaller drawbacks
  - Notably noise (switching noise or radiated noise) - needs some added shielding and careful system studies

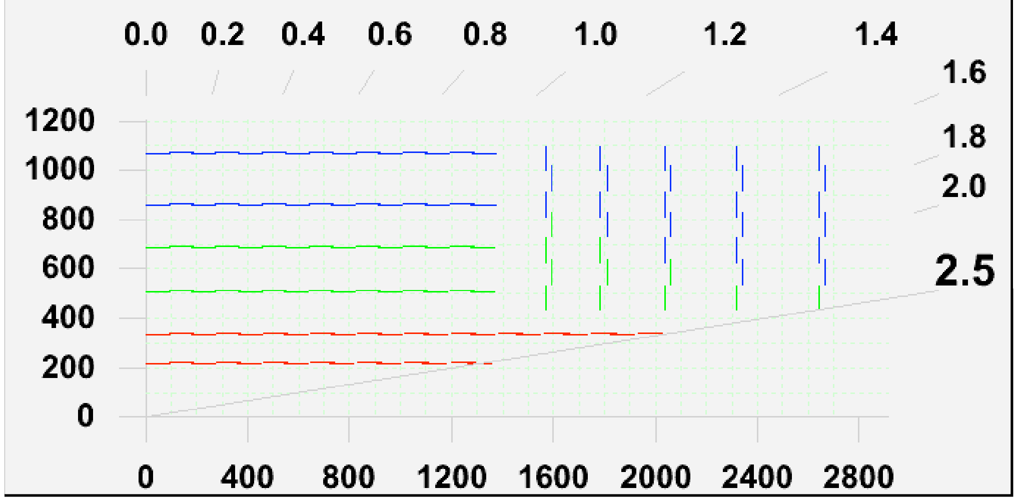
Still no clear path (perhaps slight bias towards DC-DC converters)

Some possible layouts

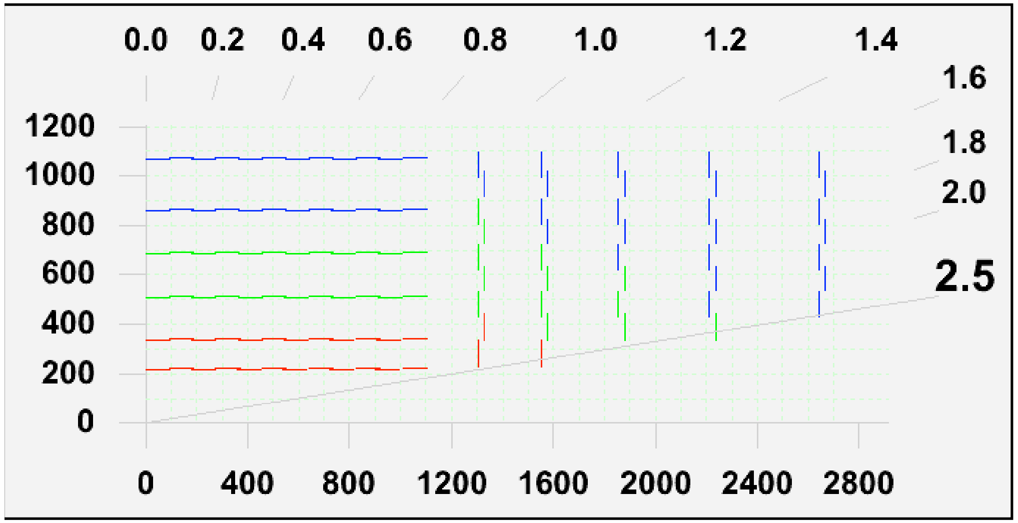
- After early "Strawmen" used in the simulation, a more systematic approach to the study of the detector geometry has now started (CERN initiative)

First exercise. Assumptions.

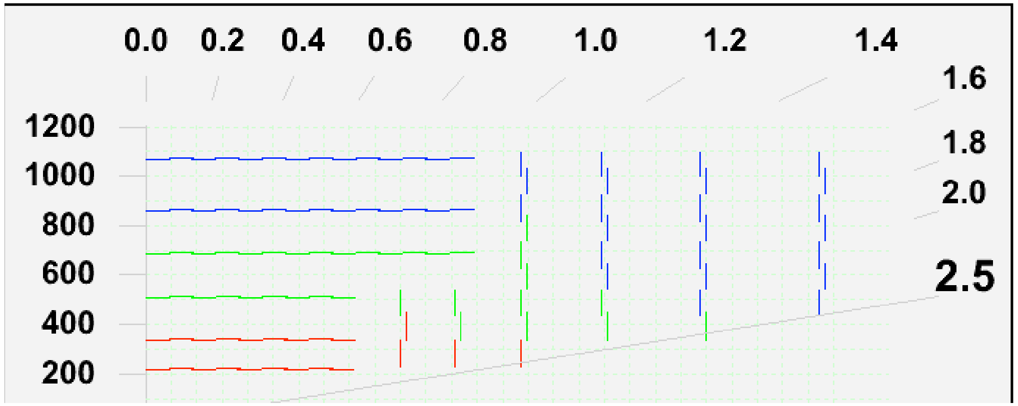
- Four pixel barrel layers (not shown - geometry not yet studied)
- Two "Pt" layers for the trigger as innermost strip layers
  - Insufficient? Sufficient? Overdone?
- Two DS layers
  - Really needed after 4 pixel + 2 "striplet"?
- Two SS layers
  - 10 layers in total (13 in today's Tracker). Educated guess to verify.
- Pt modules: 200.0 CFH/cm^2 - Strip modules: 40.0 CHF/cm^2
- Pt modules: 0.30 mW/chan - Strip modules: 0.70 mW/chan




```
 Pt            Strip
 26.9 m²     122.1 m²
154.2 M ch    19.9 M ch
 46.2 kW      13.9 kW
Overall pwr       60.1 kW
Overall cost    102.7 Mchf
```




```
 Pt            Strip
 19.0 m²     108.1 m²
111.2 M ch    18.8 M ch
 33.4 kW      13.2 kW
Overall pwr       46.6 kW
Overall cost      81.3 Mchf
```




```
 Pt            Strip
 15.8 m²     106.3 m²
 91.6 M ch    19.0 M ch
 27.5 kW      13.3 kW
Overall pwr       40.8 kW
Overall cost      74.1 Mchf
```

More advantageous routing of services

Better efficiency (less channels, power

Tracker final considerations

- Providing trigger info is a formidable challenge
  - and requirements are still not fully understood
- Readout architecture still not defined
- Reducing the material budget will be very difficult with such requirements
- Novel powering scheme is mandatory
- Novel cooling technology perhaps also
- (Compared to the above, sensors look almost easy…)

<u>Considerations on schedule</u>

Present Tracker:

- Layout frozen on Apr 00 (readout electronics defined,conceptual design of modules, etc..)
- Started engineering design of all the parts…
- … tracker successfully installed in Dec 07 (Δt = 7.6 years)
- No lack of resources, and not many holidays…

Upgrade:

- In official schedule long shutdown starts end 16: Δt = 8.0 years from today!
- Where is the mistake??

A few words about ECAL

No significant problem expected in the barrel

Issues in the forward:
- Preshower not rad-hard enough for SLHC - will die
- Crystals and VPTs will have significantly degraded performance
- EE will be activated (estimate that in the inner region 10h ⇔ 1yr allowed dose)

To be noted that:
- Full replacement of EE easily generates a 100 MCHF project (… one more…)
- No straightforward solution available
- Activation may be a showstopper

To make a sensible plan need thorough study of performance of heavily irradiated supercrystals on test beam (planned)

Possible options

If the EE performance is still useful (or cannot be replaced because of activation), the space (~15 cm) of the preshower can be used for a new detector that optimize the combined performance

Possibly, some additional space can be taken from the TK endcap (to optimize overall TK+ES+EE performance)

If EE needs to be replaced and can be replaced, there is a new calorimeter to be invented, and all options are open (… and a lot of resources need to be found)

⇒ **Focus on collecting conclusive data to predict EE performance**

Common projects (list)

The Versatile Link Common Project PH-ESE (F. Vasey et al)
Development of a general purpose optical link for all data transmission
White paper WP3

GBT: Gigabit Bidirectional Trigger and data link PH-ESE (A. Marchioro et al)
Single integrated high-speed link for Timing, Trigger, Slow Control and Data
Complementary to the Versatile Link.
White paper WP3

New power distribution schemes PH-ESE (F. Faccio et al)
White paper WP2 and SLHC-PP WP8
(CMS-specific R&D project by Aachen)

Development of rad-hard semiconductor detectors PH-DT (M. Moll et al)
R&D carried out within the RD50 Collaboration
White paper WP4

WP1 - qualification of deep sub-micron technologies

WP6 - quality assurance and interconnect technologies

WP5 - study of radiation environment (some activity starting)

A bit more on three specific projects

1. R&D on rad-hard environmental sensors
2. Cooling R&D for the upgrade(s) of the CMS Tracker
3. Monolithic detectors for upgraded Tracker

R&D on rad-hard environmental sensors (I)

Draft R&D proposal existing since a while - not yet finalized because of lack of time.

Monitoring of T & RH in the TK volume will be (even more) relevant at SLHC
Increase of radiation levels requires re-qualification of sensors
Developments of customized RH sensors may be needed

T measurements at LHC:

Radiation hardness of T sensors was not a big issue (side effect: a full zoology of sensors used in the different subsystems, causing unnecessary complications in the monitoring and control systems)

T measurements at SLHC:

Likely still not a big problem.

Goal: systematic studies of radiation hardness of commercial *Resistance Temperature Detectors* to identify *one* device to be used in the Tracking systems (study evolution of calibration with irradiation and *during* irradiation on statistically significant samples).

R&D on rad-hard environmental sensors (II)

RH measurements at LHC:

Research for rad-hard, magnetic field tolerant, small-size RH sensors carried out within the CMS SST project; one (and only one!) candidate identified and qualified: HMX2000, "just in time" wrt to TK construction; no sufficient time to address issues related to production and construction (test and calibration of all sensors before integration, etc…); sensor with very small output and non-trivial calibration.

RH measurements at SLHC:

The HMX2000 likely will not survive SLHC doses, and may also not survive market fluctuations. Probably a good idea to develop a sensor in house (possibly with better characteristics), together with needed "test and calibration kit".

Some ideas existing, but no work done yet.
Scope for collaboration with other experiments and DT.

Cooling R&D for the upgrade(s) of the CMS Tracker

Proposal submitted to CMS management and approved

1. Cooling methods
2. Cooling pipework and joining techniques

Study two-phase CO_2 cooling, inspired to the LHCB VELO system (by NIKHEF)

Attractive features compared to present system:

♦ Cooling fluid: cheap, environmental friendly, light
♦ Suitable for micro channels: low viscosity, high latent heat, high heat transfer coefficient
♦ Potential for reducing the size of pipes (e.g. 1 mm diameter, 50÷100 μm wall thickness)
♦ Potential for greatly reducing the n of independent cooling lines

→ Potential for significant reduction of material
(especially in the pixel detector, and in some regions of the outer tracker)
→ Possibility to cope with enhanced power dissipation (if it cannot be avoided)
⇒ Optimization of cooling method goes together with optimization of pipework and thermal contacts

Cooling R&D plans

Pipework and thermal contacts recognized as issues requiring common R&D and one optimized choice finally adopted for the whole detector, as they significantly affect the detector performance (through the amount of material involved, and the cooling performance achieved).

The first goal is to produce a conceptual design for a CO_2 cooling plant plus pipework and thermal contact for the first pixel upgrade, having addressed and solved all issues concerning the integration in CMS.

Testing and quality assurance procedures of cooling circuits are integrated in the conception of of the system.

Two groups active at CERN

Cryolab.
General study of properties of microchannels, derivation of engineering rules.

CMX + DT.
Start collecting data on a simple setup, to be evolved step by step.
Study CMS constraints and integration issues.

Problem: this activity is not covered by any WP, and it is very difficult to support it

Six other Institutes have started (or are starting) activities in this field

Strategically it would be very important that we keep control of the developments

Monolithic detectors for upgraded Tracker

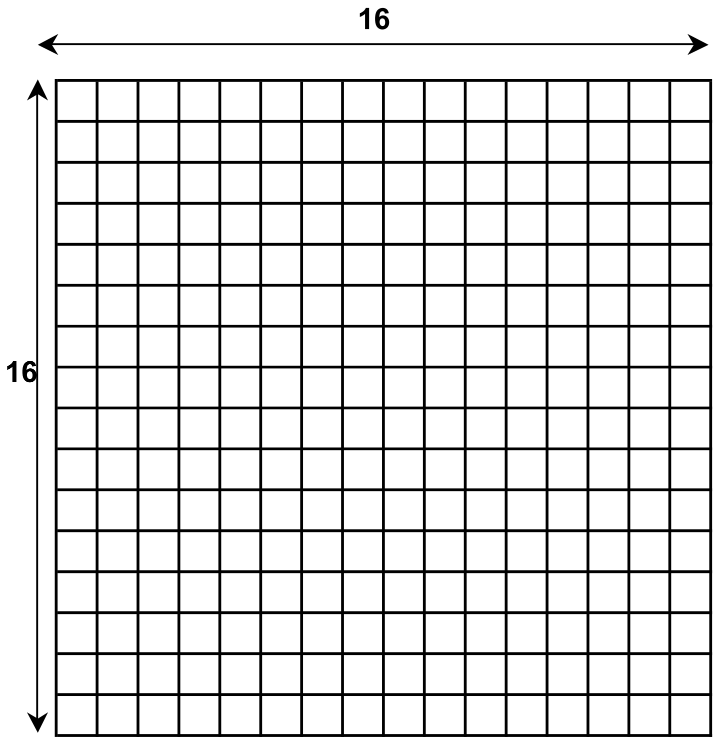
Motivations:

- expected increase in luminosity at SLHC requires enhanced granularity in the TK
- generation of trigger primitives requires even higher granularity
  (at least following the ideas proposed so far)
- theory says that *in principle* analogue power per unit surface can be *smaller* if the readout is more segmented
  (but the really tricky issue is to get the data out, or perform the data reduction in the front end)

Idea of studying an "all pixel" option has been put forward before.
Integrated approach (expected benefits):

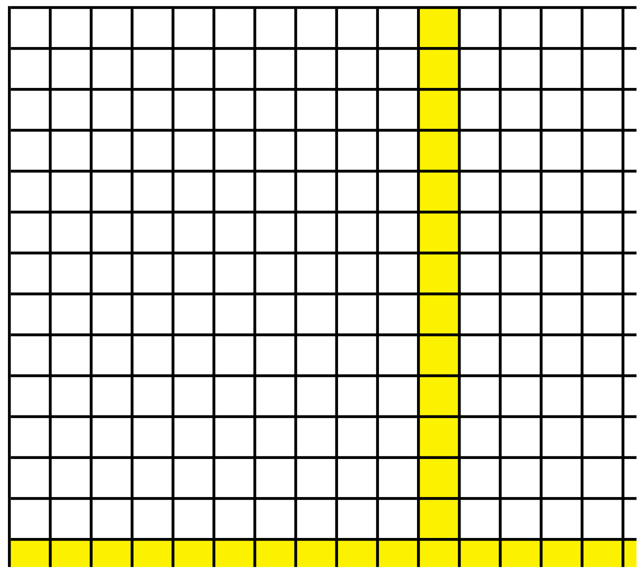
- cost per unit surface (in production) *smaller* than for normal silicon detectors
- readout electronics already integrated
- connection simplified
- lower capacitance of charge collection electrodes -> less analogue power / unit surface
- advanced CMOS technology (90 nm) allows industrial production of devices on substrates with doping levels suitable for particle detection
- in principle even more radiation hard than normal silicon detectors

Monolithic detectors for upgraded Tracker



Possible strategy:
- cells of 100 μm x 100 μm (or similar)
- do not distribute clock to single cells
- individual cells send current signal out to the periphery
- use metal lines as capacitors

Granularity correct for current pixel region.
At larger radii, need to reduce data at the periphery….



Efficient processing of data in the front-end and data transmission remain challenges (esp. for trigger)

Monolithic detectors: perspectives

Radically new approach!

- Attractive potential benefits… but need to be demonstrated!
- Large development cost (1-2 MCHF), dominated by engineering run of full demonstrator
- Needs a few man-years of circuits design and simulation, then test development and testing (not impossible to find)
- Interest expressed by the Strasbourg group; will be supported by IN2P3
- Goal is to demonstrate the detector in a timescale of ~2 years

- Nicely orthogonal to (almost) everybody's plans…
- Certainly a lot of inertia to abandon the traditional approach
- Need to progress fast to gain credibility as a realistic option for SLHC

Conclusions

- Plan of construction/upgrade work of CMS for the coming 4-5 years reasonably well defined (with some small grey areas to be clarified)
  - ⇒ One of the key challenges is the development of a CO_2 cooling system for the pixel upgrade

- The upgrade of the CMS detector for 10^{35} is a very big challenge
  - ⇒ Several activities have started
  - ⇒ So far many questions, very few answers

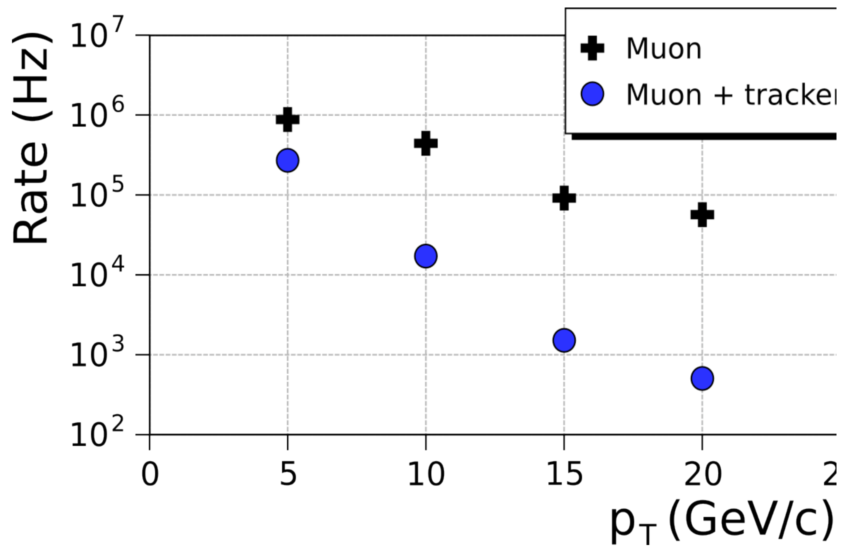
- Two outstanding open points with large implications:
  - ⇒ Define contribution of Tracker to L1 trigger
  - ⇒ Performance of the EE at SLHC

Tracking information in L1 trigger

- Goals
  - Confirmation of isolated high-p_T muons
  - Reduce fake e/γ candidate
    - by matching with inner track/vertex
  - Signature of high-p_T particles close to/in jets
    - helps identifying taus and bs

Muon L1 rate at

$L = 1 \times 10^{35}\ cm^{-2}\ s^{-1}$



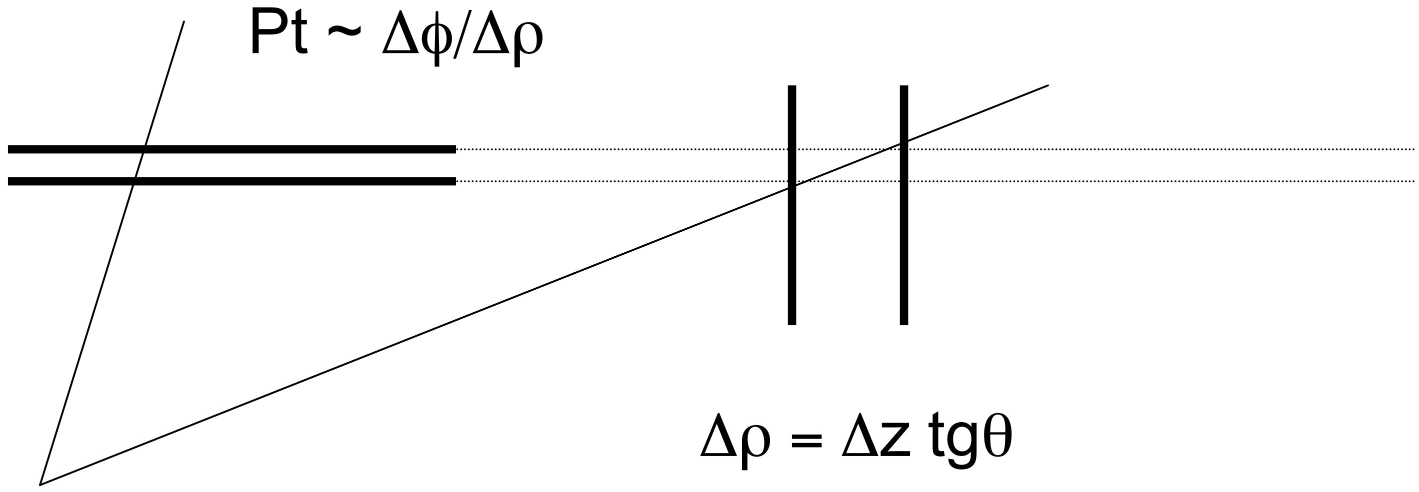
- Approach
  - Reduce data volume by applying p_T cuts
  - Time constraints (~μs) do not allow complete tracking
- Techniques
  - Cluster width: low momentum tracks have larger cluster
  - Closely spaced “trigger layers”

difference in hit positions: larger lever, better resolution

Pt modules in forward

The principle still works:

Need to measure $\Delta\phi/\Delta\rho$
In wedge-shaped detectors strips measure $\phi/\Delta\rho$
In a pair Δz translates to $\Delta\rho$ (with small spread within a detector)
But with a fairly large scaling factor (~5)



So a spacing of 2 mm in the barrel translates to ~1 cm in the forward
Possibly feasible with an external correlator?
Not feasible through wirebonds