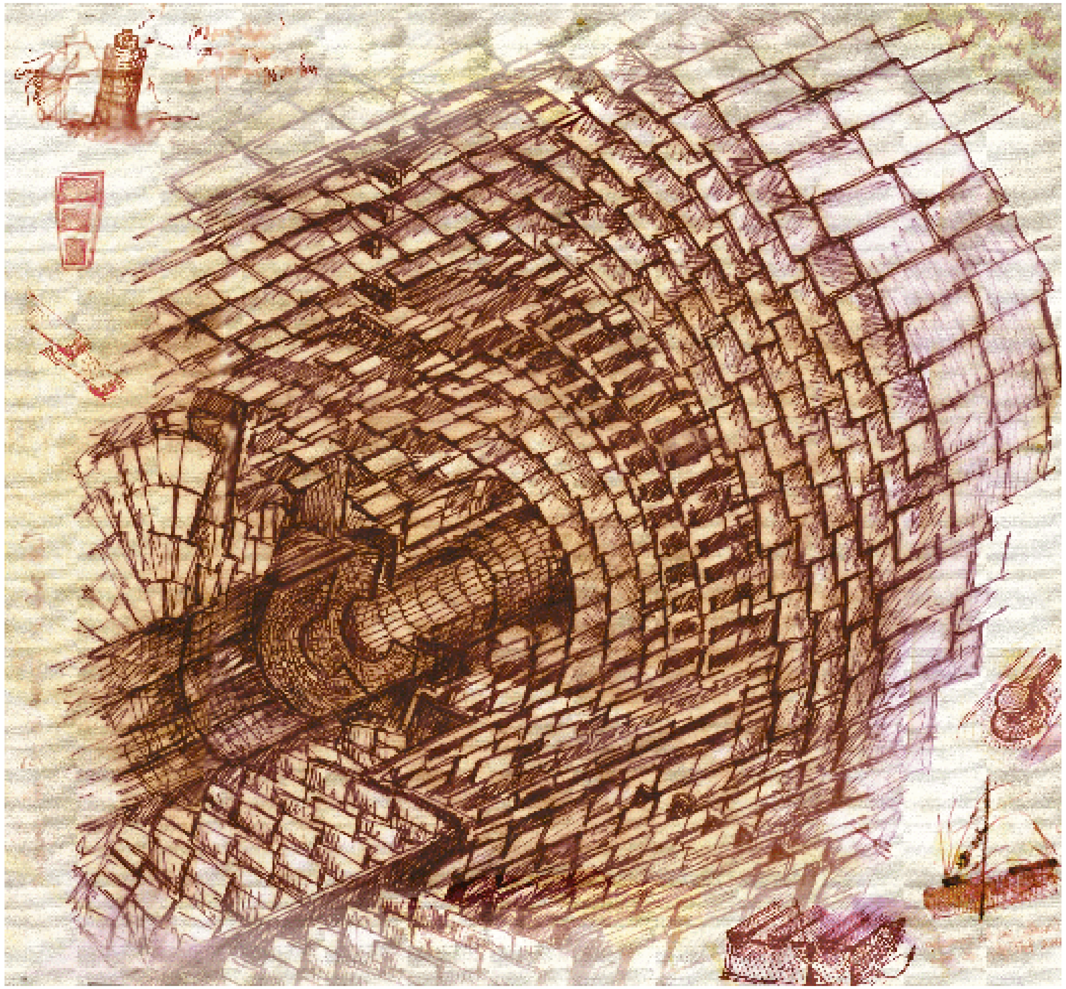
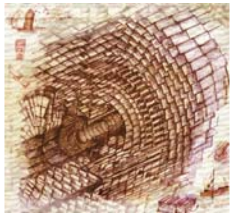
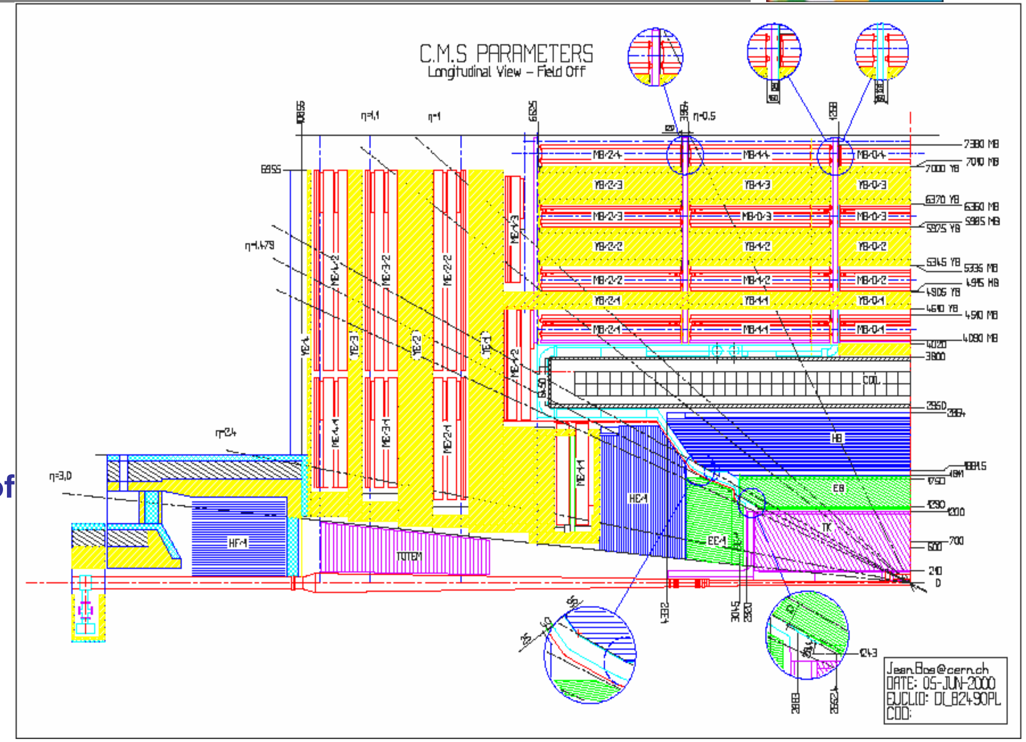
CMS SLHC Upgrade





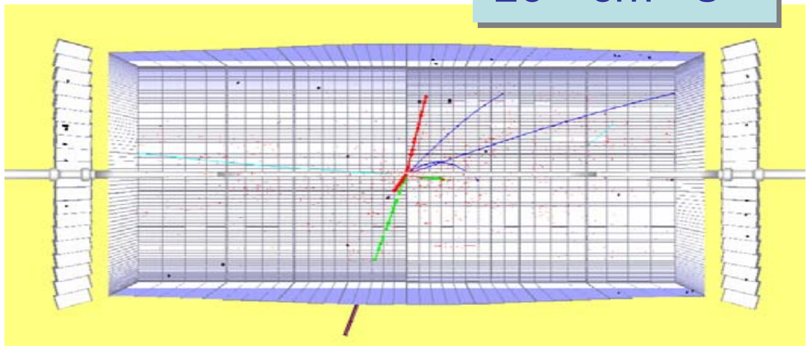
Calorimeters/Muons



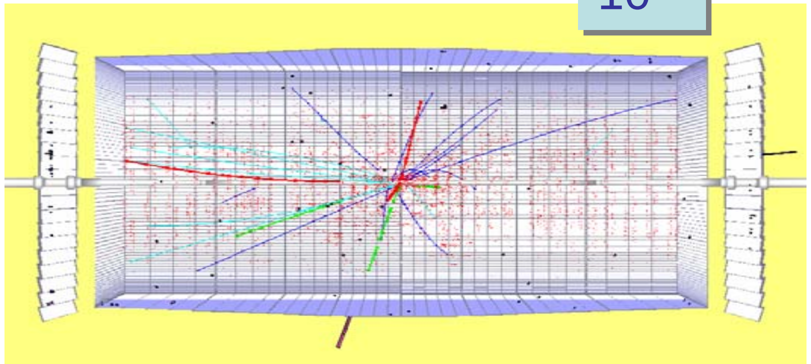
- **ECAL**
  - Crystal calorimeter electronics designed to operate in SLHC conditions
  - VPT in Endcap and Endcap crystals themselves may darken at SLHC
    - Very difficult to replace
- **HCAL**
  - HF at η > 2 will suffer from serious light loss
  - HF may be blocked by potential changes to the interaction region
  - This has a direct impact mainly in the case of looking for WW scattering
- **Both Calorimeters suffer degraded resolution at SLHC**
  - affects electron ID, Jet resolutions
- **MUON**
  - system front end electronics look fairly robust at SLHC
    - Cathode Strip Chambers/RPC Forward : Drift Tubes /RPC Barrel
- **Trigger electronics for the muon systems would most likely need to be replaced/updated**
  - Some Electronics is "less" radiation hard (FPGA)
  - Coping with higher rate/different bunch crossing frequency
  - May have to limit coverage in η (η > 2) due to radiation splash
    - This effect will be known better after first data taking, potential additional cost of chamber replacement

CMS from LHC to SLHC

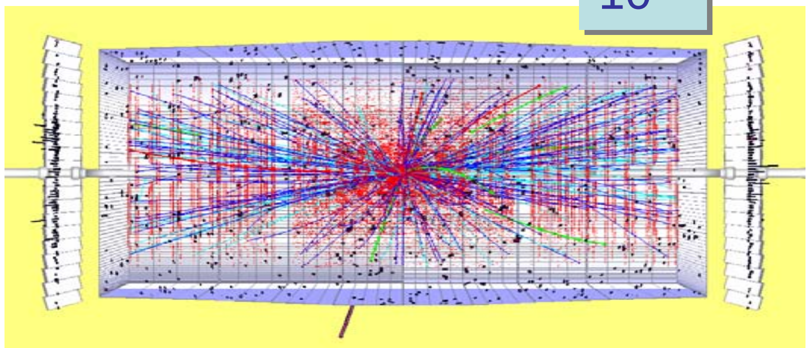
10^{32} cm^{-2} s^{-1}



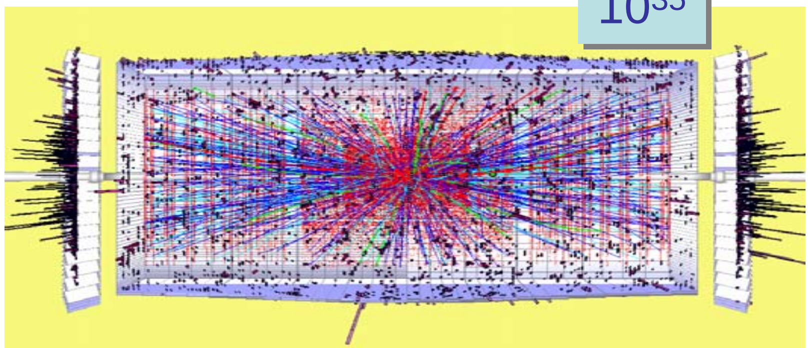
10^{33}



10^{34}

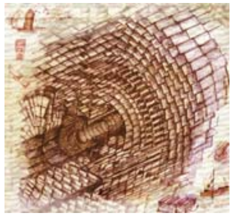


10^{35}



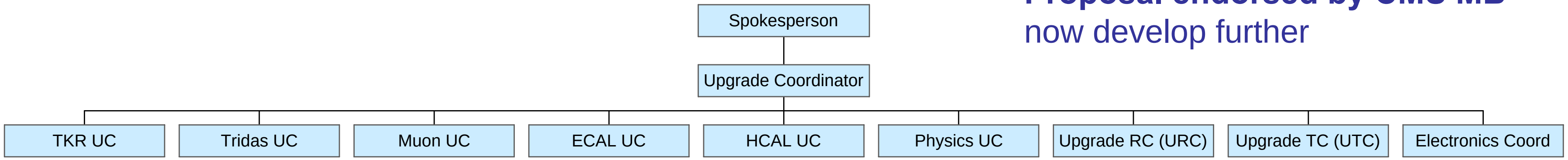
I. Osborne

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



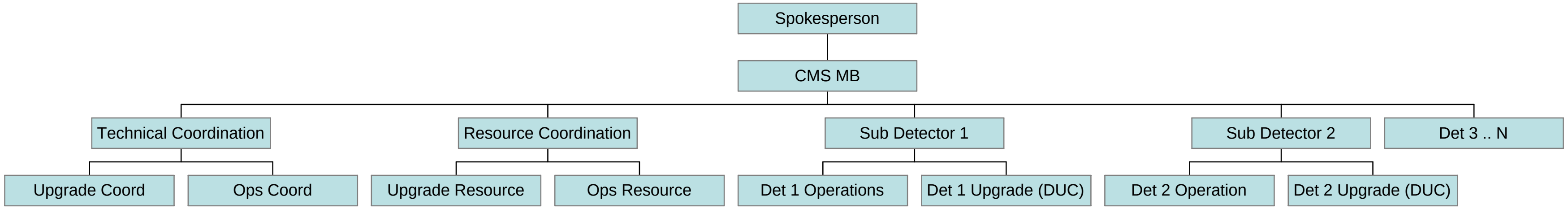
SLHC Upgrades

Upgrade Management Team

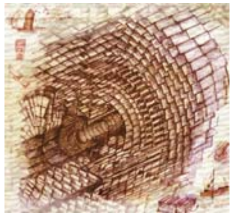


Proposal endorsed by CMS MB
now develop further

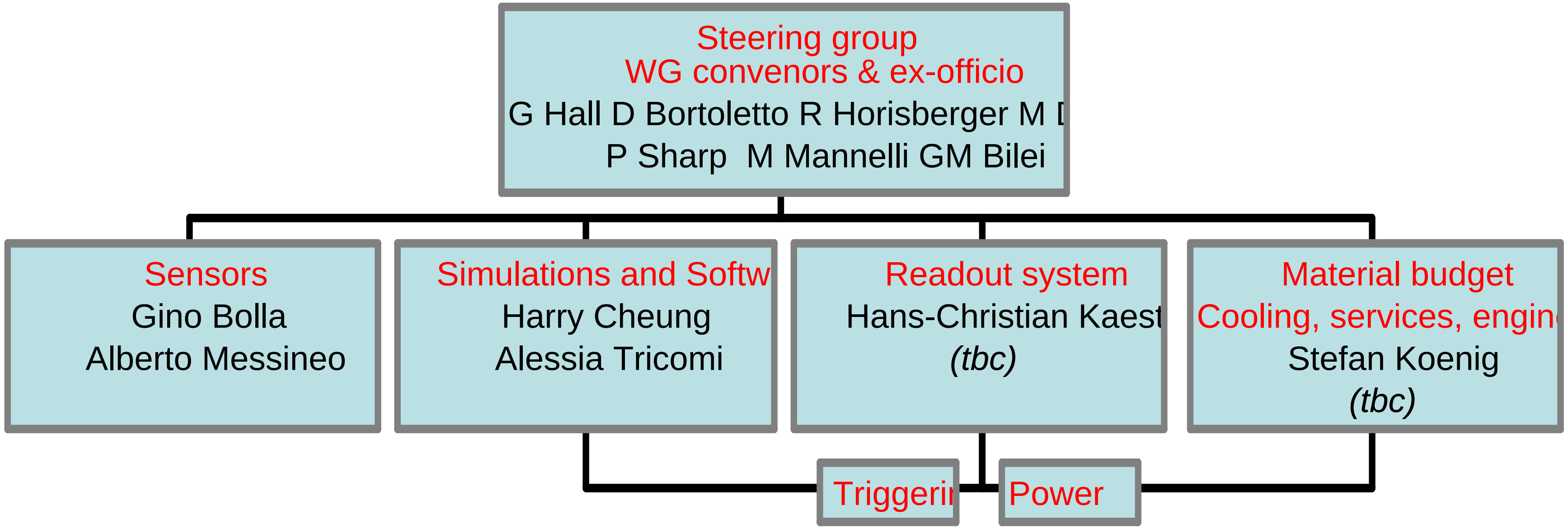
Enlarged CMS Management Team



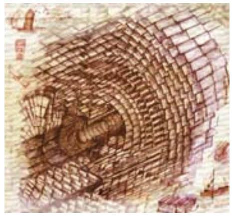
Upgrade PM or Co-ordinator (Wide Remit acting as CMS advocate of the upgrade)
Work with sub-detectors to ensure upgrade resources are adequate and balanced wrt operations and to help integrate new groups in Upgrade effort
Look at global upgrade issues (e.g. material budget, interaction with machine, physics capability)
Ensure R&D is appropriate and focused



Status of Working Groups



- **Goal: two convenors/WG to share load and help overcome the geographic dispersion**
- **WGs, with Steering Group, should define programme and milestones**

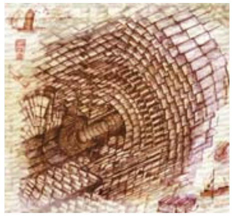


The challenge…

- Build a replacement tracker for $\mathcal{L} = 10^{35}$ cm^{-2}.s^{-1} with equal or better performance, AND L1 Trigger Capability

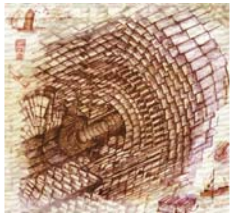
- To do so, solve several <u>very</u> difficult problems
  - deliver power - probably requiring greater currents
  - develop sensors to tolerate radiation fluences ~10x larger than LHC
  - construct readout systems which can also contribute to the L1 trigger using tracker data
  - …and so on…

- It is probably as difficult a challenge as the original LHC detectors were in 1990
  - or possibly harder…



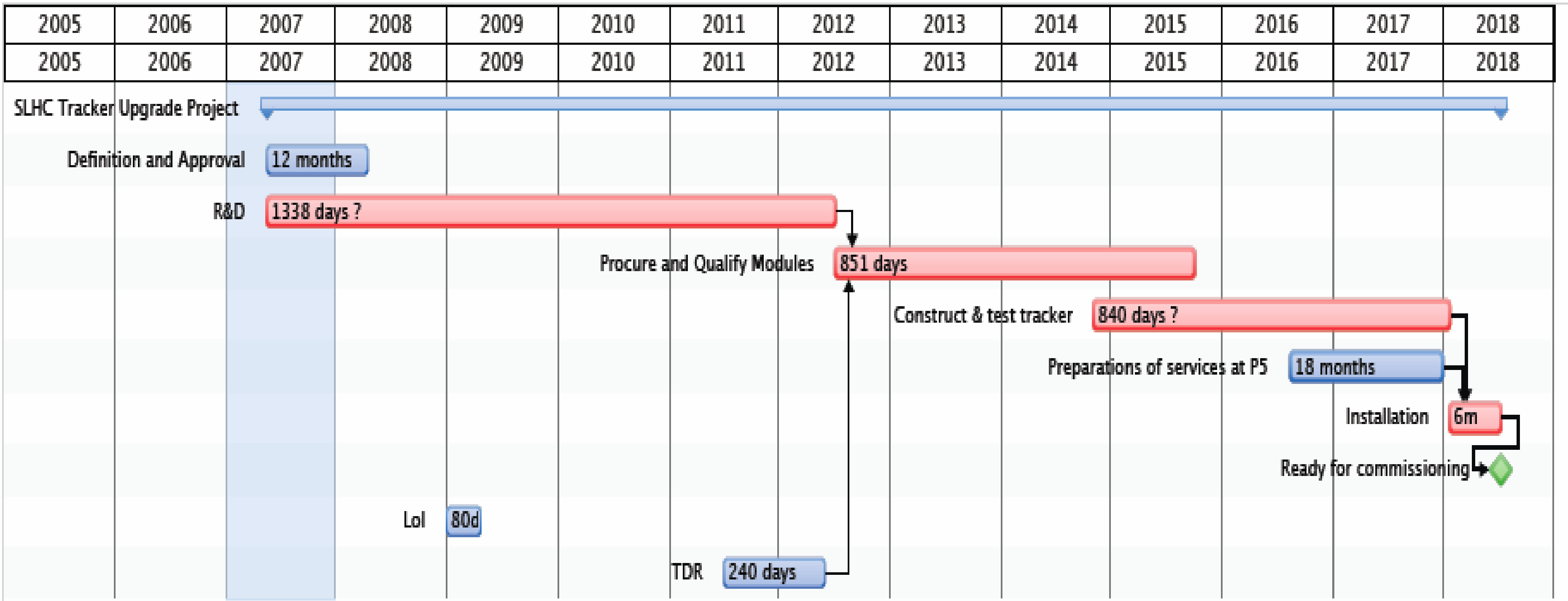
Planning an Upgrade Project

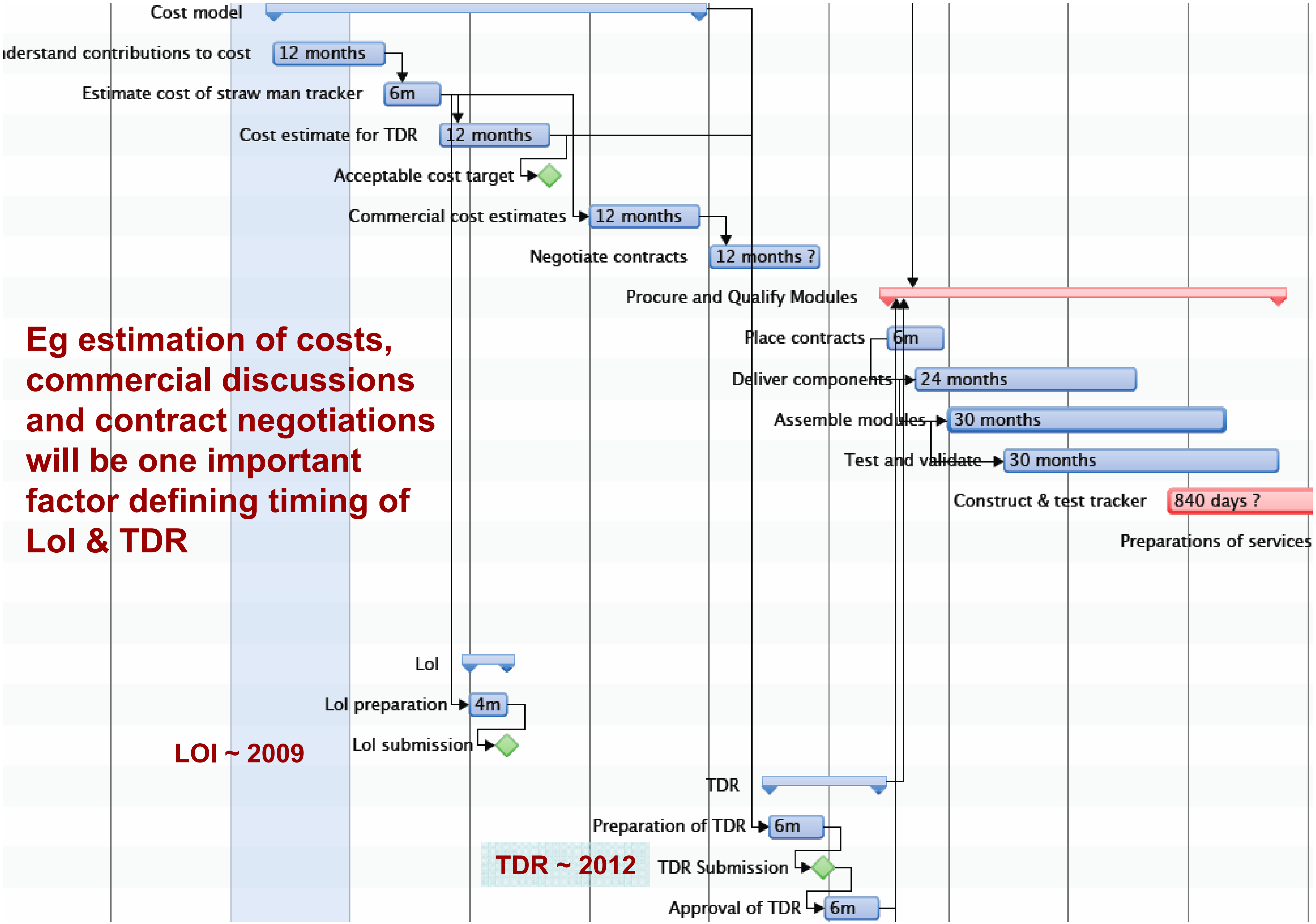
- **To define the project scope we need (to iterate to establish)**
  - …some idea of timescale
  - …assessment of resources expected to be available, and those needed
    - Including - importantly- likely effort
    - with time profile
- **Planning assumption: ~10 years - from now - to operational upgraded tracker, with possible breakdown:**
  - 5 years R&D
  - 2 years Qualification
  - 3 years Construction
  - 6 months Installation and Ready for Commissioning
- **NB experience tells us that system approach and attention to QA are important considerations from a very early stage**



Possible timescale

- **Mixture of bottom-up & top-down plan**
- **Sample of major activities broken down to try to see implications and interconnections**
- **Allowance for some easily overlooked items**
  - **Eg cost estimates, placing contracts, develop test equipment, service preparations…**

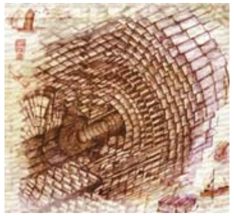




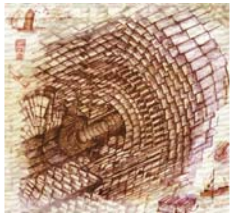
Eg estimation of costs, commercial discussions and contract negotiations will be one important factor defining timing of LoI & TDR

LOI ~ 2009

TDR ~ 2012



Sensor Technology Issues



Radiation Levels
from Tracker TDR (Mikka Huhtinen)

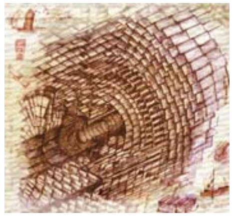
- **The charged hadron fluence has a strong radial dependance; the neutral hadron fluence, in particular above about 60cm has little radial dependence**

- **For radii below 60cm, the fluence is dominated by charged pions; at about 70cm, the fluence of charged pions and neutral hadrons are approximately equal**
  - **This motivated the TIB/TOB thin/thick sensor transition**

- **There is factor of almost 6 reduction in total fluence going from 22cm to 58cm radius**

- **There is a further factor of about 2 in going from 58cm to 115cm radius**

- **The fluence at 4cm radius is almost 20 times higher than at 22cm radius**



Scope of this Discussion: Outer Tracker

- **The region of the inner-most Pixel Layers is fundamentally challenging at the SLHC, especially for the Sensor Technology**
  => one may speculate as to the most promising way forward

- **If Limited in Scope (1 ~ 2 Layers)**
  - **"Exotic" Radiation Hard Technology**
  - **Replaceable layers with ~ Standard Technology**
  - **? …**

- **If more Extended in Scope (3 ~ 4 Layers)**
  - **"Semi-Standard" Radiation Hard Technology**

- **Here focus on Outer Tracker**
  - **Assume boundary between inner-most Pixel Layers and Outer Tracker is somewhere between 20 ~ 40cm**
  - **In any future baseline layout, Outer Tracker and inner-most Pixel Layers will have to make a coherent Tracking System**

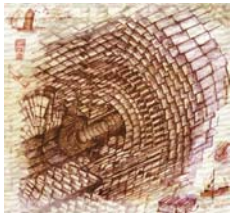
Performance & Manufacturability

- For the Outer Tracker Sensors,

- Performance is Fundamental
  - Charge Collection Efficiency
  - Input Capacitance
    - Noise & FE Read-Out Power
  - Bias Voltage, Leakage Current
    - Sensor Power Dissipation & Cooling requirements

- Very Large Scale & Excellent Quality Manufacturability is Essential

- Aim for Single Sensor Technology for Outer Tracker
  - May play a role in defining Radial Boundary between Outer Tracker and Inner-most Pixel Layers

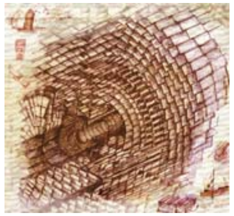


Radiation Levels from Tracker TDR (Mikka Huhtinen)

- At the SLHC, the fluence at the innermost radius of TIB (22cm) will be about half as much as at the innermost Pixel layer at full LHC luminosity
- At the SLHC, the fluence at the innermost (outermost) radius of the TOB will be about 2.5 (1.1) times higher than at innermost radius of TIB at full LHC luminosity
- For the region above 22cm, currently occupied by the Strip Tracker, a program of measurements is proposed, addressing

Thin Single-Sided p-on-n vs n-on-p sensors on FZ vs MCZ

- Based on results obtained, can understand if possible to extrapolate towards innermost vertex / b - layers



Proposed Program of work for Thin Single-Sided Sensors

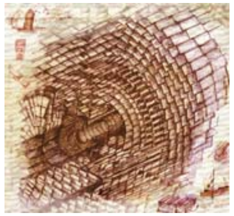
- **Extend previous work to substrate thickness less than or equal the pitch**
  - Strip capacitance (back-plane, inter-strip & total)
  - Critical fields, depletion and and break-down voltage
  - Sensor functionality (charge collection efficiency etc)
  - As function of pitch, w/p, metal overhang, substrate thickness

- **Extend previous studies from LHC to SLHC fluence**

- **Extend previous studies to include MCZ and Epitaxial substrates**

- **Extend previous studies to include n-on-p (n-on-n)**

- **Re-produce complementary sets of measurements and simulation**



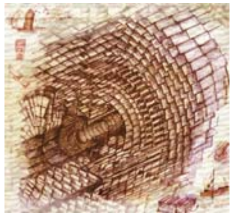
Program of work with HPK
Thin Single-Sided Sensors

- The CMS Tracker partnership with HPK played a central role in the success of the Strip Tracker
  - R&D, device characteristics studies, large scale / high quality production
- Continue to build on this for the SLHC

Fabrication Technology for Thin Single-Sided Sensors

- Thickness > 200um
  - Thin Wafer (FZ & MCZ)
- Thickness > 100um
  - Carrier Substrate (FZ & MCZ)
- Thickness < 100um
  - Epitaxial

- High density (pixel) sensor to FE connection and module assembly
  - High volume, low cost bump bonding
    - (SOI)
  - Extend packaging techniques from complex commercial devices

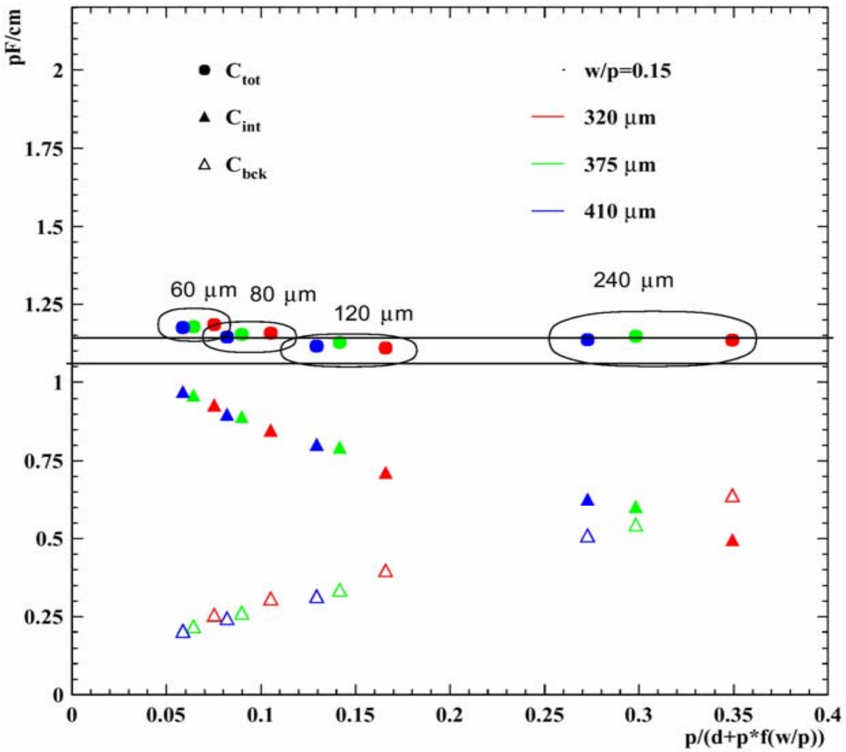


The Silicon Sensors
Electrical characteristics of strip detectors

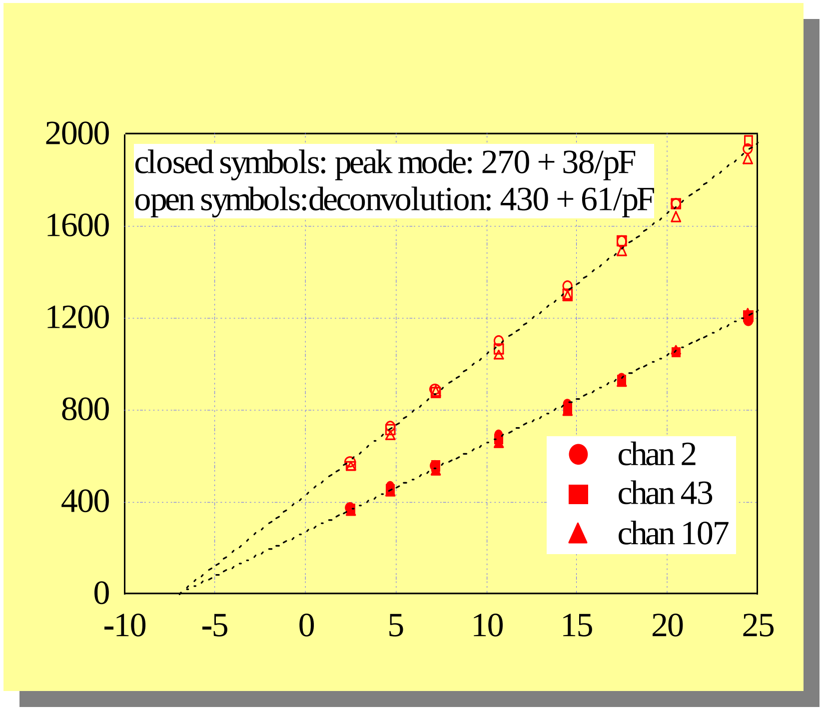
Total Strip capacitance is the main contribution to electronic noise

It is a function of w/p only, Independent of pitch and thickness

Ctot ~ 1.2pF/cm for w/p = 0.25

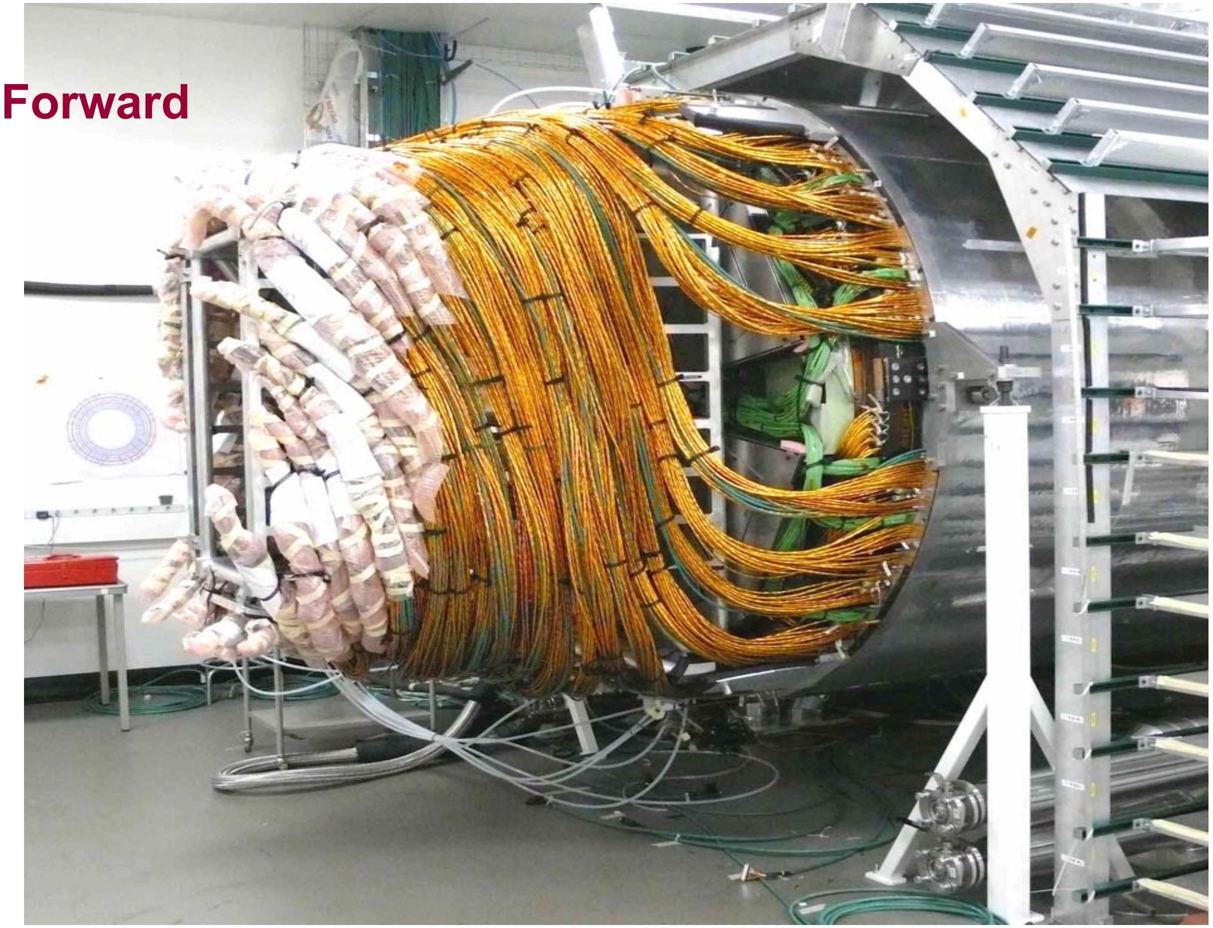


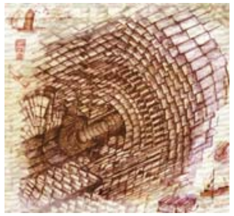
Noise ~ 430e- + 75e- * strip length cm



CMS SLHC Tracker
Ideas & Progress towards a Straw Man Layout

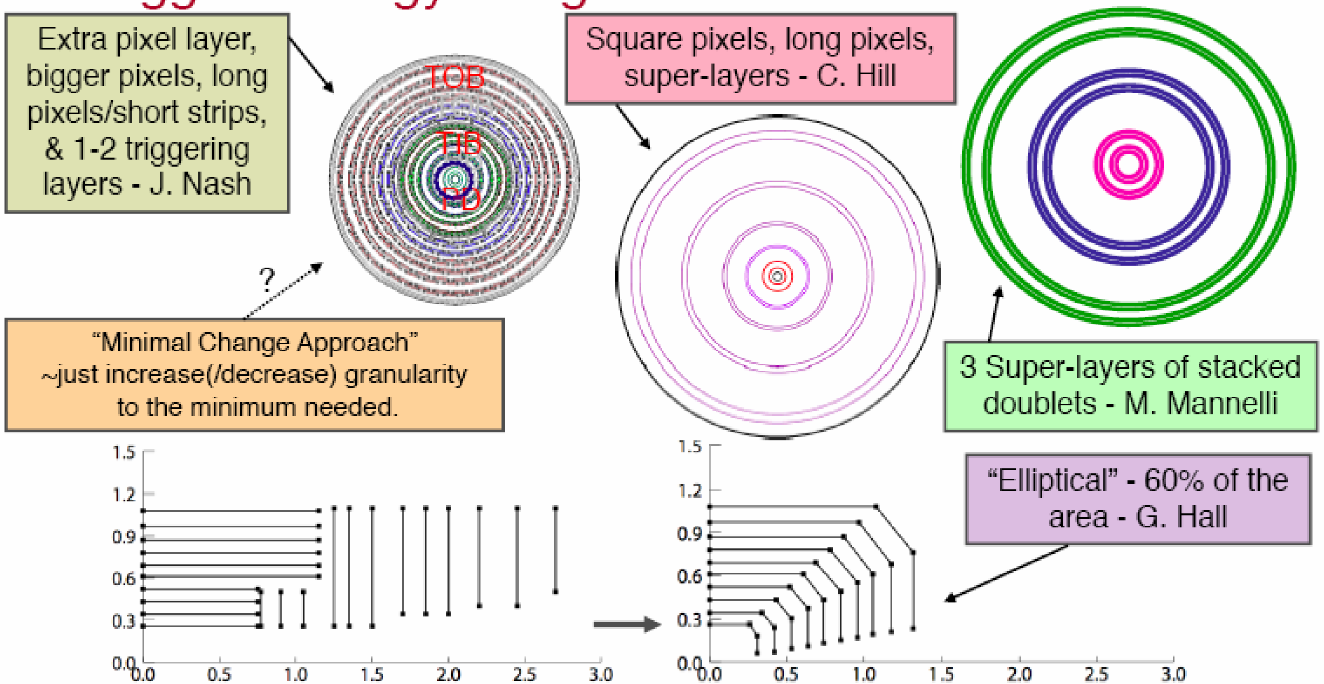
- **Build on Success of Present CMS Tracker**
- **To make a Large Step Forward**

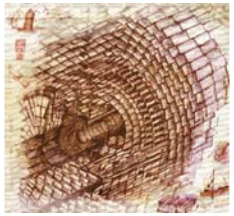




CMS SLHC Tracker
Ideas & Progress towards a Straw Man Layout

- **Broad ranging discussion**
  - **First, Explore alternative ideas and approaches**
  - **Then, Focus on most promising ones**
    - No single strawman tracking system or tracking trigger strategy/design





CMS SLHC Tracker
Ideas & Progress towards a Straw Man Layout

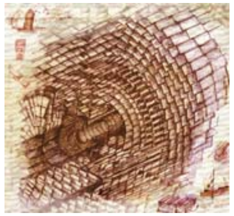
- **Briefly recall Required Functionality**
- **Highlight Three sets of Ideas concerning:**

Local Occupancy Reduction / Hit Discrimination

Granularity vs Power Consumption

Material Budget Minimization

- **Show Example Straw Man layout as Framework for Further Studies**
- **Illustrate how this Framework helps to Direct and Focus different Lines of Activity**

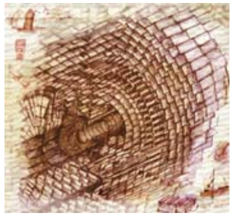


Material Budget Minimization

The present CMS Silicon Strip Tracker is extremely effective

- **The performance limiting factor is NOT intrinsic precision, and most likely will NOT be our ability to align etc.**
- **The performance limiting factor is the Material Budget of the Tracker**
- **This also limits the performance of the CMS ECAL**
- **There is much to gained if we can lower the material budget, AS WELL AS achieving the performance requirements just mentioned**

Material Budget Minimization



Required Functionality

- **Fast, Robust, Efficient, High Resolution Tracking**

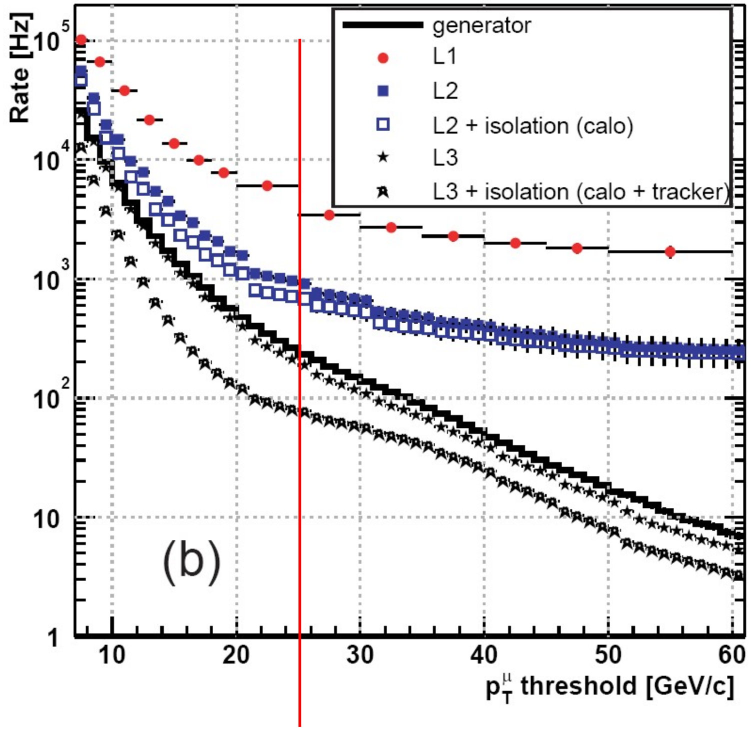
- **HLT Capability:**
  - The present CMS Tracker will be used in the HLT, immediately after the hardware Level-1 Trigger, to select Physics Objects and Event Topology with much better Resolution, Efficiency & Background Rejection
    - High Pt muons, electrons, b-jets, tau-jets, Missing ET, etc.

- **Level 1 Trigger Capability:**
  - Must keep ~ same L1 Trigger rate, despite 10 time higher event rate, 10 ~ 20 times higher occupancy, without sacrificing Efficiency and Background Rejection
  - Just raising thresholds will not work AND is NOT desirable: scale is set by Physics

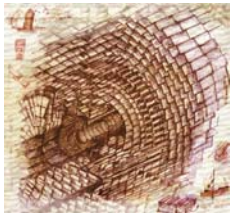
At SLHC need to transfer use of the Tracker from HLT to Level-1 Trigger

Required Functionality

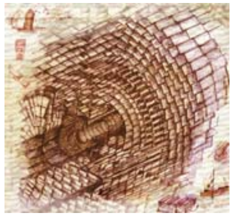
- **Confirmation of Isolated High-pt μ Candidates**
  - **Fast, Efficient & Clean Tracking**
  - **Excellent Pt resolution**
- **Increased Rejection of fake e/γ Candidates**
  - **Match with Track at Vertex**
- **Rejection of Uncorrelated Combinations, from different primary vertex**
  - **Match with Tracks at Vertex**
- **…**



Factor ~ 100 reduction
For same Pt threshold



- <u>**Local Occupancy Reduction**</u>

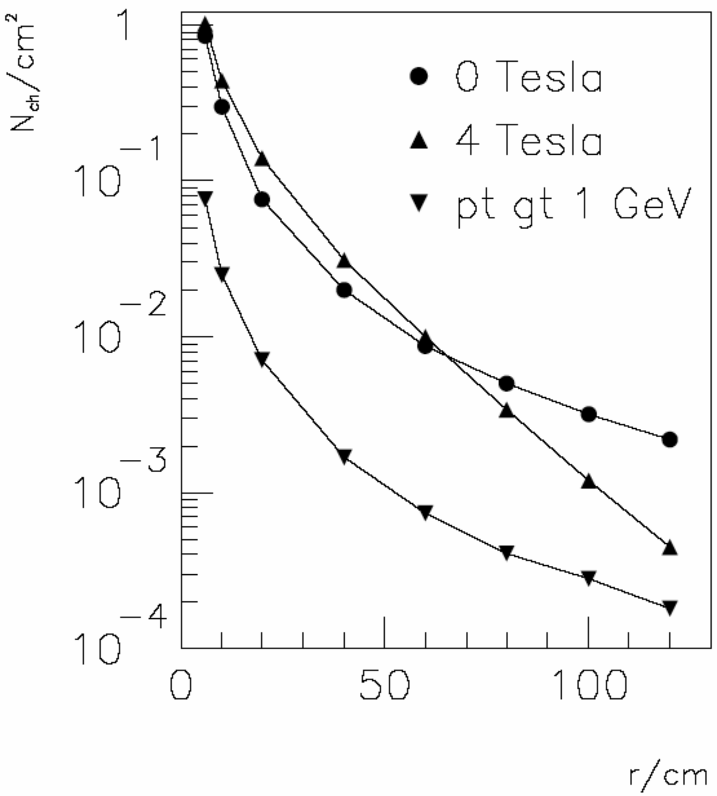


Local Occupancy Reduction

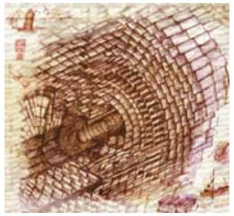
- **The CMS Tracker produces vast amounts of information for each L1 Triggered event**
- **Current Strip Tracker rate for full read-out of 100KHz L1 accepted events ~ 1'000GHz of analogue strip information**
- **It is implausible to access the Full Information at 10^{35} Luminosity & 20(40)MHz crossing rate, as input to the L1 Trigger Decision**
- **Even assuming Local Zero-Suppression need ~ Factor 100 Reduction to maintain Band-width at L1 ~ same as with Present Tracker Read-Out**

<u>Local Occupancy Reduction</u>

Local Occupancy Reduction



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



Local Occupancy Reduction

Possible Strategy: Local Pt Discrimination

- **Only read-out hits from tracks above a certain Pt threshold**
  - Applying a 1 GeV Pt threshold would reduce read-out hits by ~ factor 10
  - Tracks below 1 GeV Pt are usually not very interesting, especially in the early phases of event selection

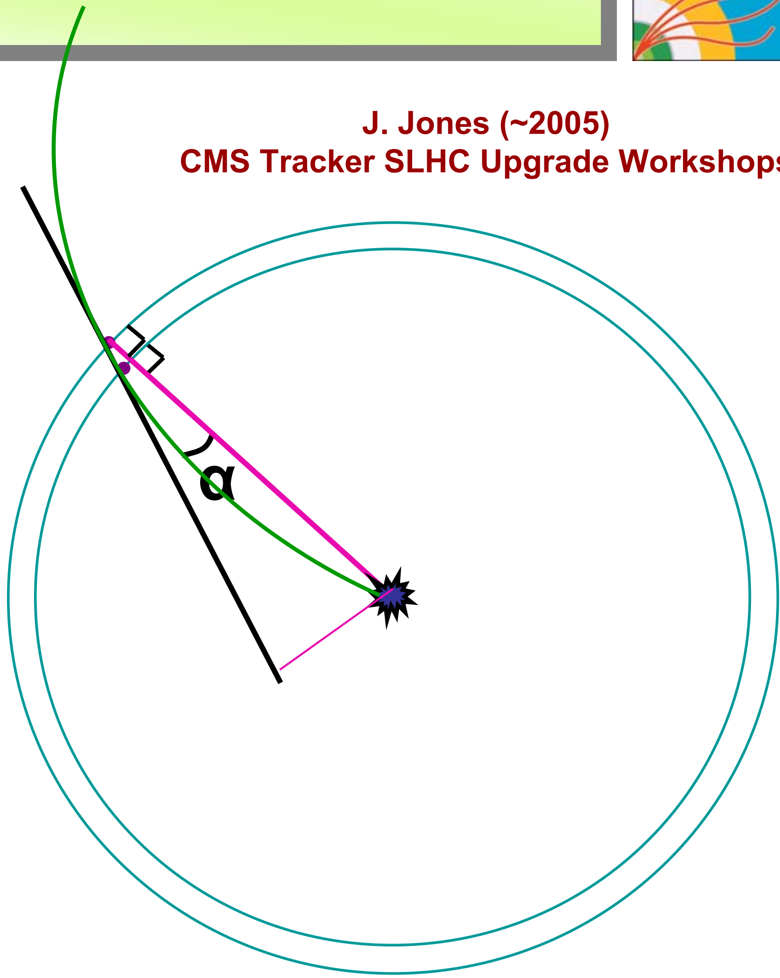
- **For Level 1 Triggering purposes, need also to identity (muon) tracks above 10 ~ 20 GeV**
  - Applying a 10GeV Pt threshold would further reduce read-out hits by 3~4 Orders of Magnitude

- **Consider a hierarchical scheme for Local Pt Discrimination**
  - Residual Rate dominated by fakes
    - Requires detailed study
    - Assume Factor > 10 * 10 Reduction is Achievable

Local Occupancy Reduction

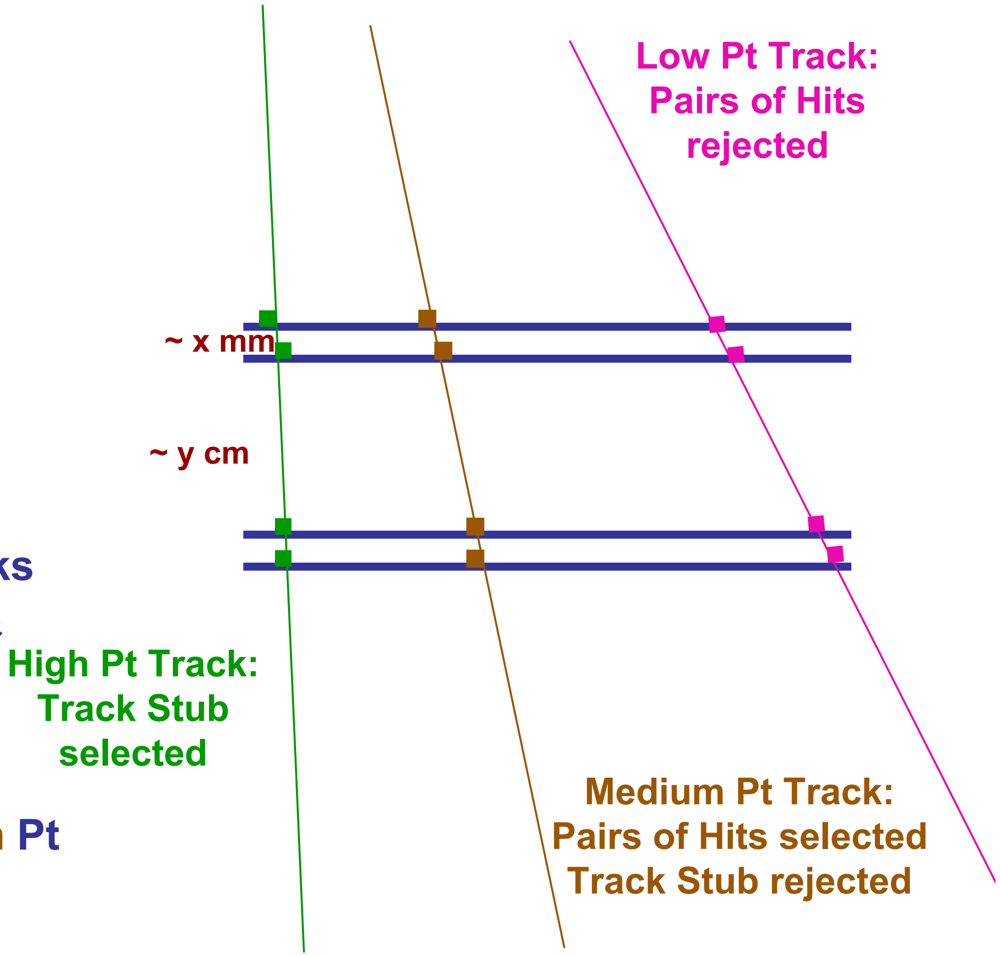
- **Pairs of Sensor Planes, for local Pt measurement**
- **High Pt tracks point towards the origin, low Pt tracks point away from the origin**
- **Use a Pair of Sensor Planes, at ~ mm distance**
  - **Pairs of Hits provide Vector, that measure angle of track with respect to the origin**
  - **Note: angle proportional to hit pair radius**
- **Keep only Vectors corresponding to high Pt Tracks**

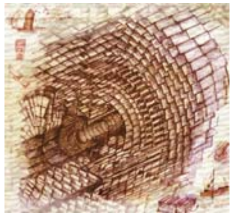
J. Jones (~2005)
CMS Tracker SLHC Upgrade Workshops



Local Occupancy Reduction

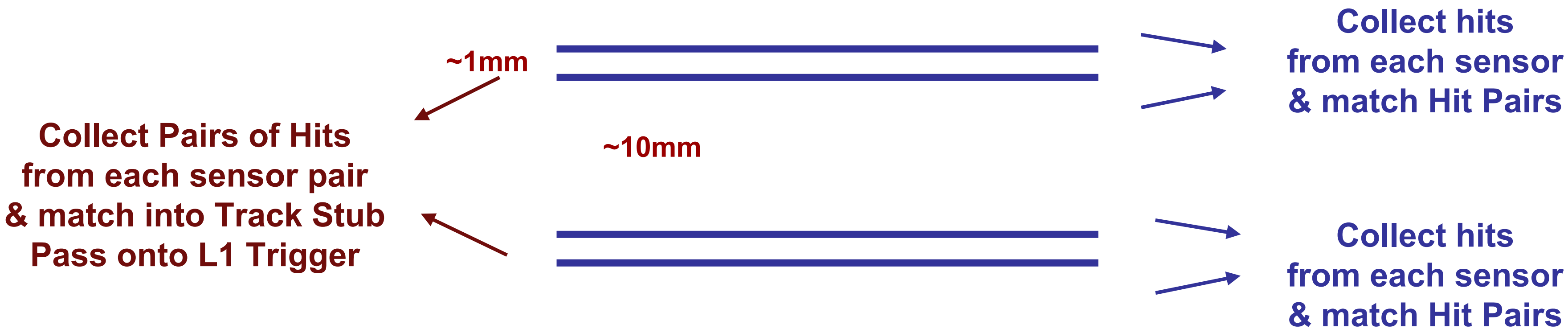
- Stacks of 2 Sensor Pairs, at ~ cm distance
  - Redundancy
  - Track Stub provides higher resolution local Pt measurement
- Two level data reduction
- Each Sensor Pair
  - Rejects Hit Pairs from low Pt tracks
  - Accepts Hit Pairs from medium & high Pt track
- The Stack of Sensor Pairs
  - Rejects Track Stubs from medium Pt tracks
  - Accepts Track Stubs from high Pt tracks





Local Occupancy Reduction

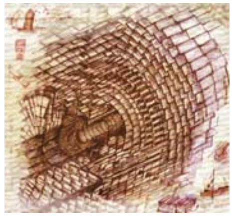
Local Information Gathering, and Processing Hierarchy



- Collect hits from each Sensor in a Pair
  - Match into Hit Pairs
  - Retain Hit Pairs from medium & high Pt Tracks

- Collect Hit Pairs from each Sensor Pair in a Super-Layer
  - Match into Track Stubs
  - Retain Track Stubs from high Pt Tracks
  - Pass onto L1 Trigger

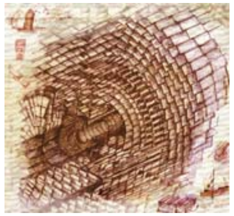
- **Granularity vs Power Consumption**



Granularity vs Power Consumption

- **The CMS Silicon Strip Tracker is extremely effective because:**
  - **Fine strip pitch, from 80um to 200um**
    - each hit has high resolution and track parameters are rapidly constrained
  - **Strip length, from 10cm to 20cm results in cell size ~ 0.5mm^2**
    - occupancy ~ 2% or less at 10^{34}
  - **Pattern recognition converges ~ unambiguously with first few hits => fast**
- **At SLHC occupancy 10~20 times higher**
  - **Strip length in range 1 ~ 2cm to maintain low occupancy**
    - **Short Strips**
  - **Pixel length in range 1~2mm => reduce occupancy, 3D info => 3D Tracking**
    - **Long Pixels**

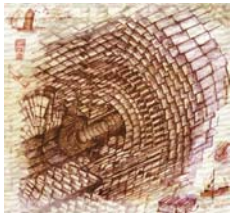
Finer Granularity, Increased Channel Count



Granularity vs Power Consumption

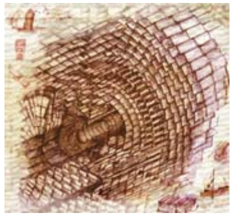
- **The Tracker Material Budget is strongly driven by**
  - **Large Power Dissipation, and need for Efficient Cooling (~33kW)**
  - **Large Current requirements (~20kA)**

<u>Lower Power Dissipation and Current Consumption</u>



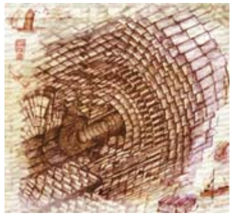
Granularity vs Power Consumption
Short Strips vs Long Pixels

- **Cost and Manufacturability are a Key Input**
- **Implications on System, Read-Out Architecture etc.**
- **Comparative Performance Studies are Important Guidance**
- **Reliable projections of Power Dissipation/cm^2 are a Fundamental Input**
- **Short Strips vs Long Pixels**
  - **Extrapolate from Strip Tracker APV25 to reduced capacitance short strips**
  - **Extrapolate from Pixel ROC to larger capacitance long pixel**
  - **Compare: Power, Material, Cost, Feasibility, Performance**
- **Pursue both approaches until these points are sufficiently well understood to draw some conclusions**



Granularity vs Power Consumption
Power Consumption for Long Pixel Tracker

- **Power Dissipation of Present CMS Pixel FE Chip ~ 30uW/channel**
  - **30uW / 15'000um^2 ~ 2kW/m^2 for current LHC Pixel**
  - **Compare to ~ 125W/m^2 for present LHC Strip Tracker ~ 16 * Power Density**
    - **Nb 6'666 pixel / cm^2 vs 4.5 strip / cm^2 => 1'500 higher channel density**
- **Assume SLHC Pixel size ~ 120um * 2.0mm ~ 0.24mm^2**
  - **This implies ~ 4M Channels / m^2**
- **Assume Power / Pixel of SLHC chip = LHC Pixel chip**
  - **This results in ~ 125W/m^2 ~ present Strip Tracker Power Density**
- **Assume Total Sensitive Area is ~ 210m^2**
  - **Implies ~ 850M Channels… "Giga Tracker"**

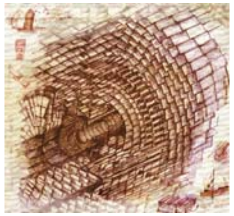


Granularity vs Power Consumption
Power Consumption for Long Pixel Tracker

- **Plausible SLHC 0.13um Long Pixel FE Chip Power Dissipation ~ 20uW/channel**
  - Private communication Roland Horisberger
- **IF True, this would:**
  - Result in ~ 85W/m^2 FE Chip Density
  - result in Total FE Chip Power Dissipation ~ 17kW (vs 26kW)
  - leave head room for additional power dissipation (L1 Trigger, etc)
  - open possibility for reduction of overall Power Budget
- **The Power consumption extrapolations shown here are speculative**
  - But Interesting, and worth pursuing until reliable conclusions can be drawn

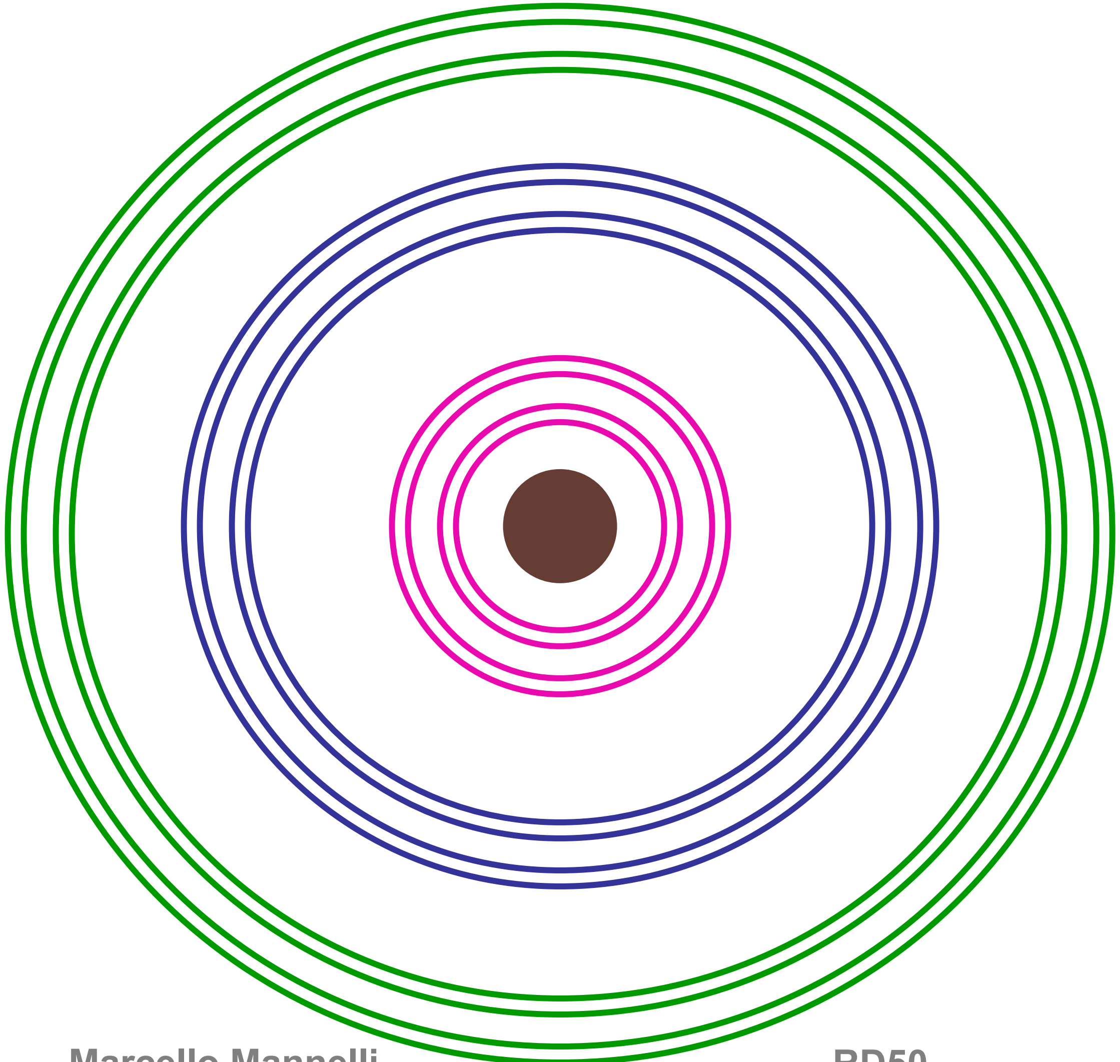
Example Straw Man Layout

- **Example Straw Man Layout**



CMS SLHC Tracker
Example Straw Man Layout

Straw-man Layout Example

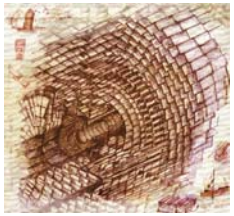


12 Measurement Layers

Organized in 3 Super-Layers

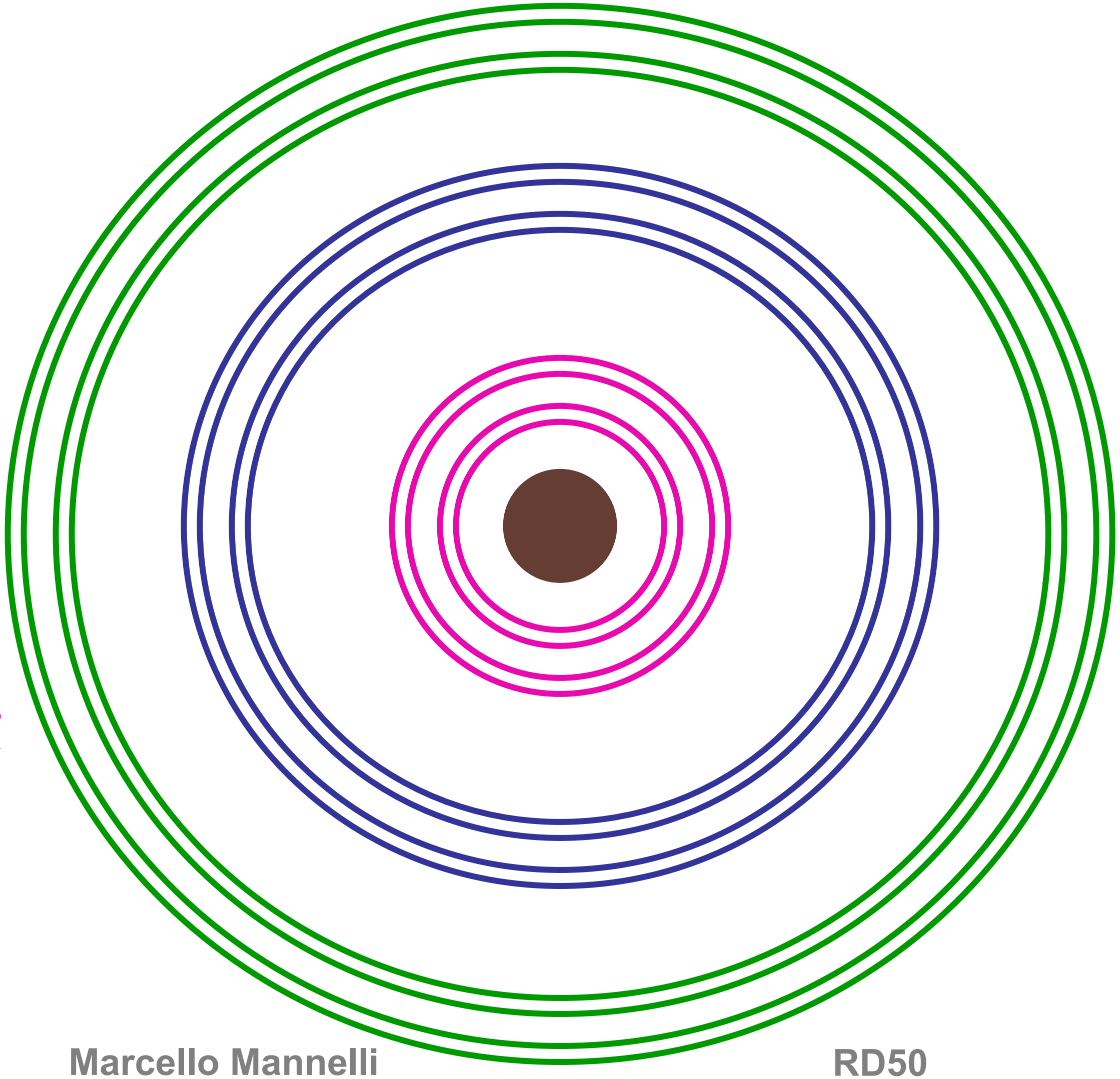
Each Super-Layer consists of a Stack of 2 Sensor Pairs
(4 measurement layers / Super-Layer)

- **Inner Super-Layer ~ 20~40cm (Geometry of Inner Vtx layers?)**
- **Middle Super-Layer ~ 60cm**
- **Outer Super-Layer ~ 100cm**



CMS SLHC Tracker
Example Straw Man Layout

Straw-man Layout Example



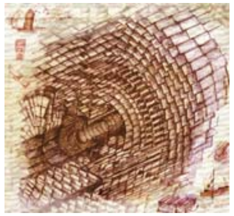
12 Measurement Layers

Organized in 3 Super-Layers

Each Super-Layer consists of a Stack of 2 Sensor Pairs
(4 measurement layers / Super-Layer)

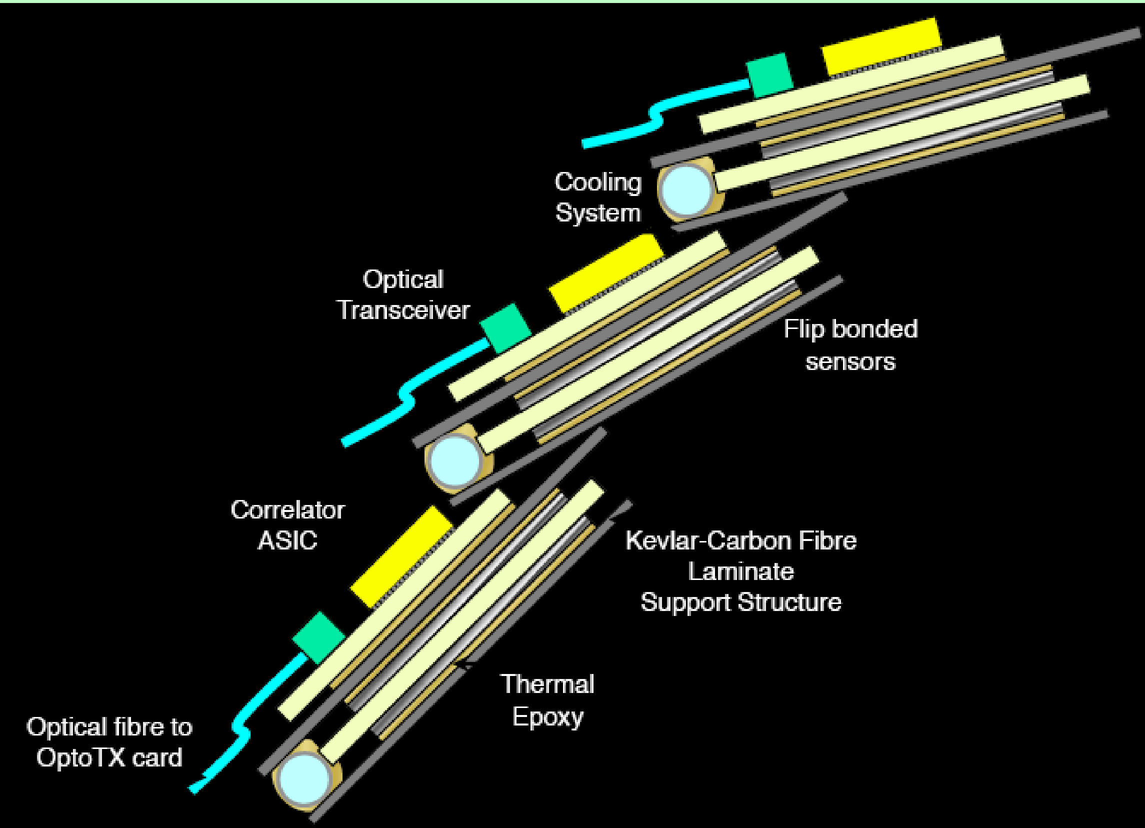
Can search for high Pt Track Stubs Independently in each Super-Layer

Can Combine Super-Layer to ensure High Efficiency & Low Fake rate



CMS SLHC Tracker
Example Straw Man Layout

Conceptual Design

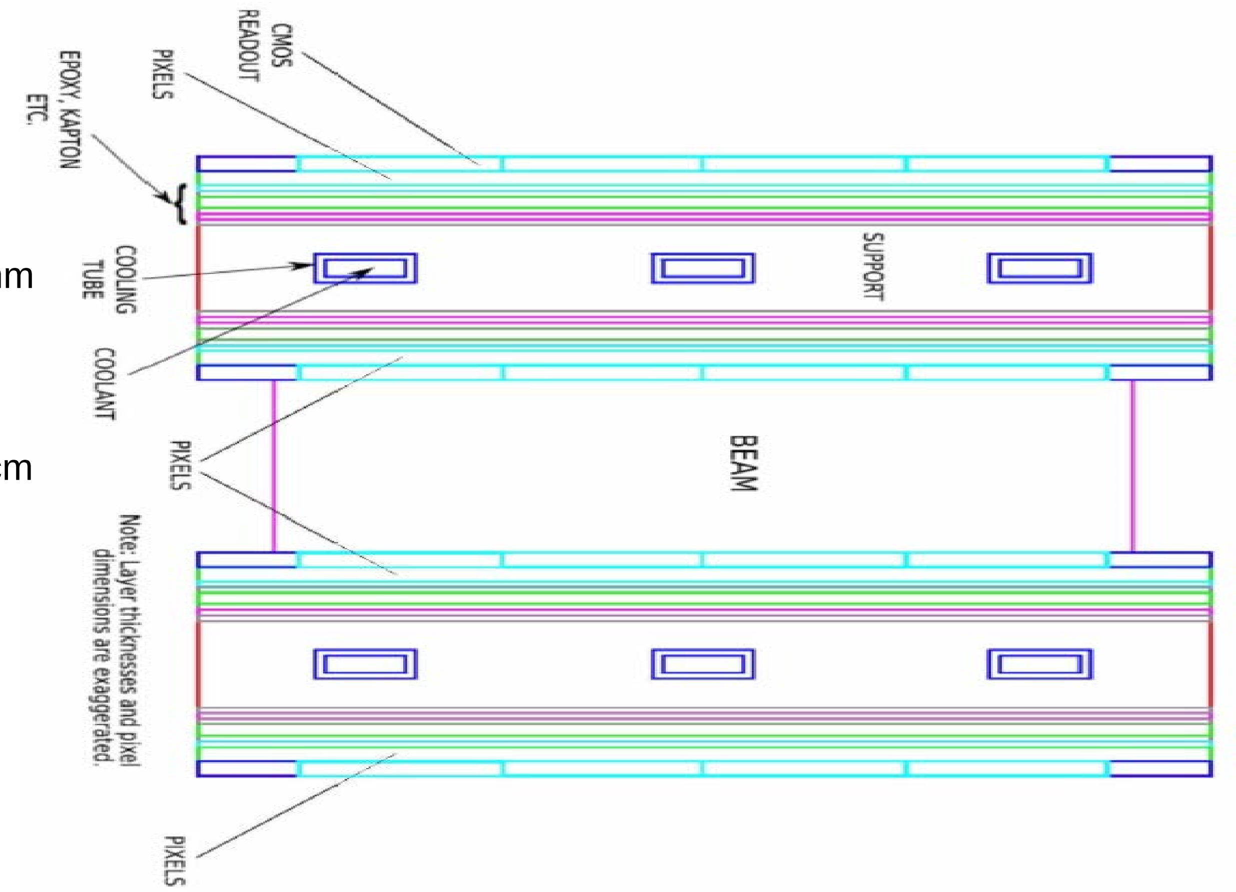


17.7.2007 John Jones (john.jones@cern.ch) 10

CMS SLHC Tracker
Example Straw Man Layout

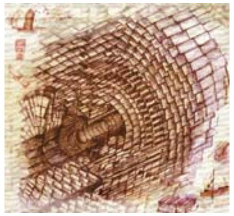
~ 2mm

~ 4 cm



Roberto Rossin
SWG 11 Sep 2007

Aspect ratio
NOT to scale



CMS SLHC Tracker
Example Straw Man Layout

Stack of Sensor Pairs provide opportunity for shared mechanics and services

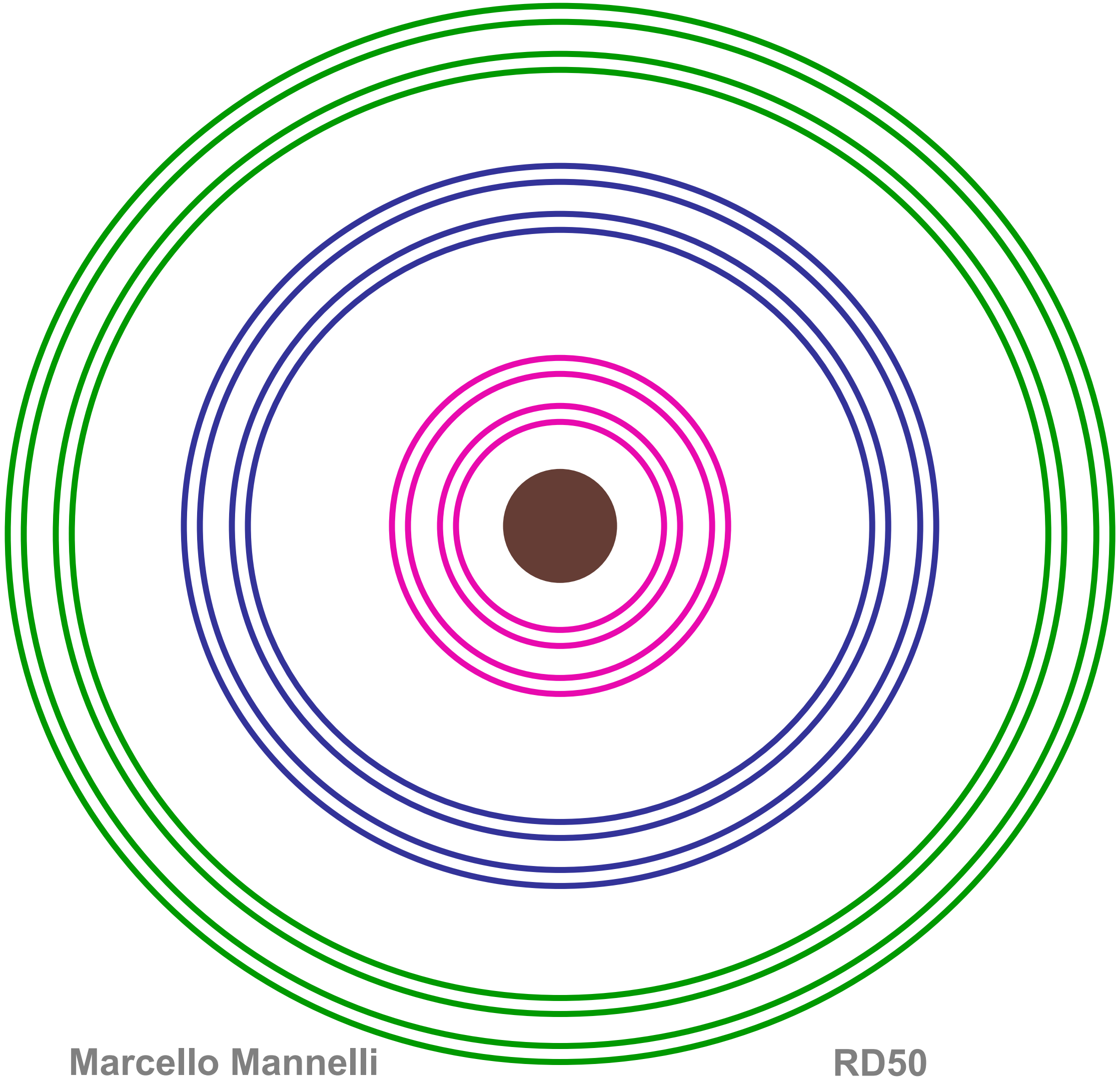
A Double-Sided ROD = 2 hits
For 1.5 * X0 of Single-Sided ROD

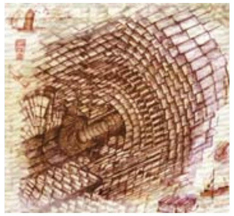
6 Layers of Double Modules = 12 hits
For 9 * X0 of Single Module layer

Current Tracker = 14 hits
For 12 * X0 of Single Module layer
(If all “TOB - Like”)

Stacking Doublets onto Beams could allow to further reduce X0 with respect to RODs?

=> May be useful approach for reducing Material Budget, independent of Local Occupancy Reduction scheme





Extension of Straw-man Layout in the End-Caps ?

- **Extend Local Pt discrimination & Triggering Capability to End-Caps**
- **Provide homogeneous response, until loss of lever arm due to Tracker Acceptance**
- **Keep it “Simple”: Minimize number of variants**
  - **Use same module as Central Barrel**

Simulation and Performance Issues

Basic Things to Vary

•Cell Geometry:

Pitch 80~120~160um
Length 1~2~4mm/1~2~4cm
Sensor Thickness 60~100~200um

•Sensor Pair Geometry

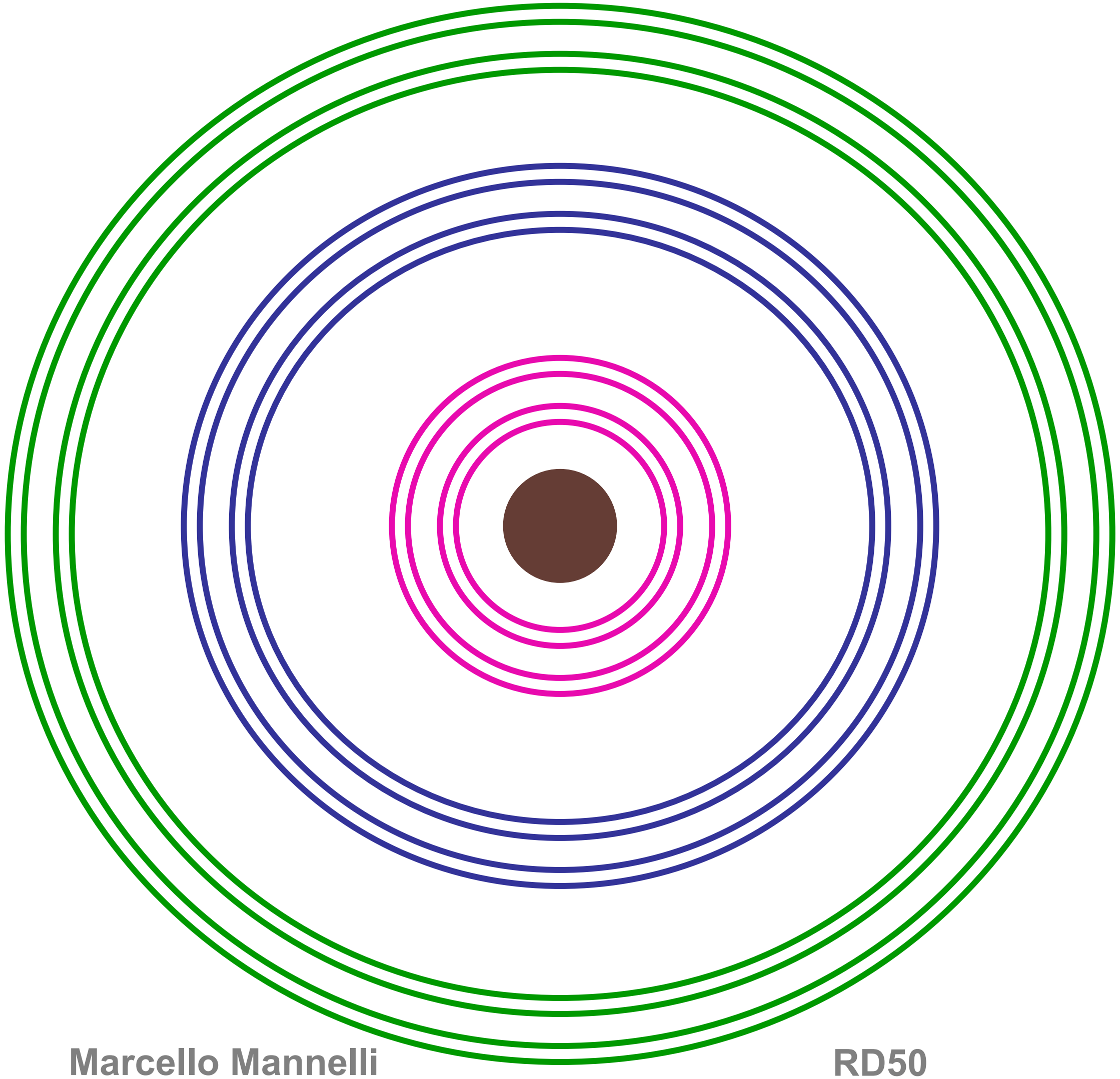
D ~ 1~2~4mm,
Align Transverse 20~200um,
Align Radial 50~200um

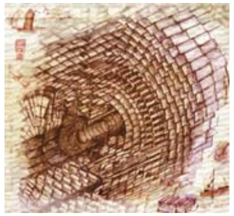
•Stack of Sensor Pairs:

D ~ 20~40~80mm, 160mm ?
Align Transverse 100~400um,
Align Radial 100~1000um

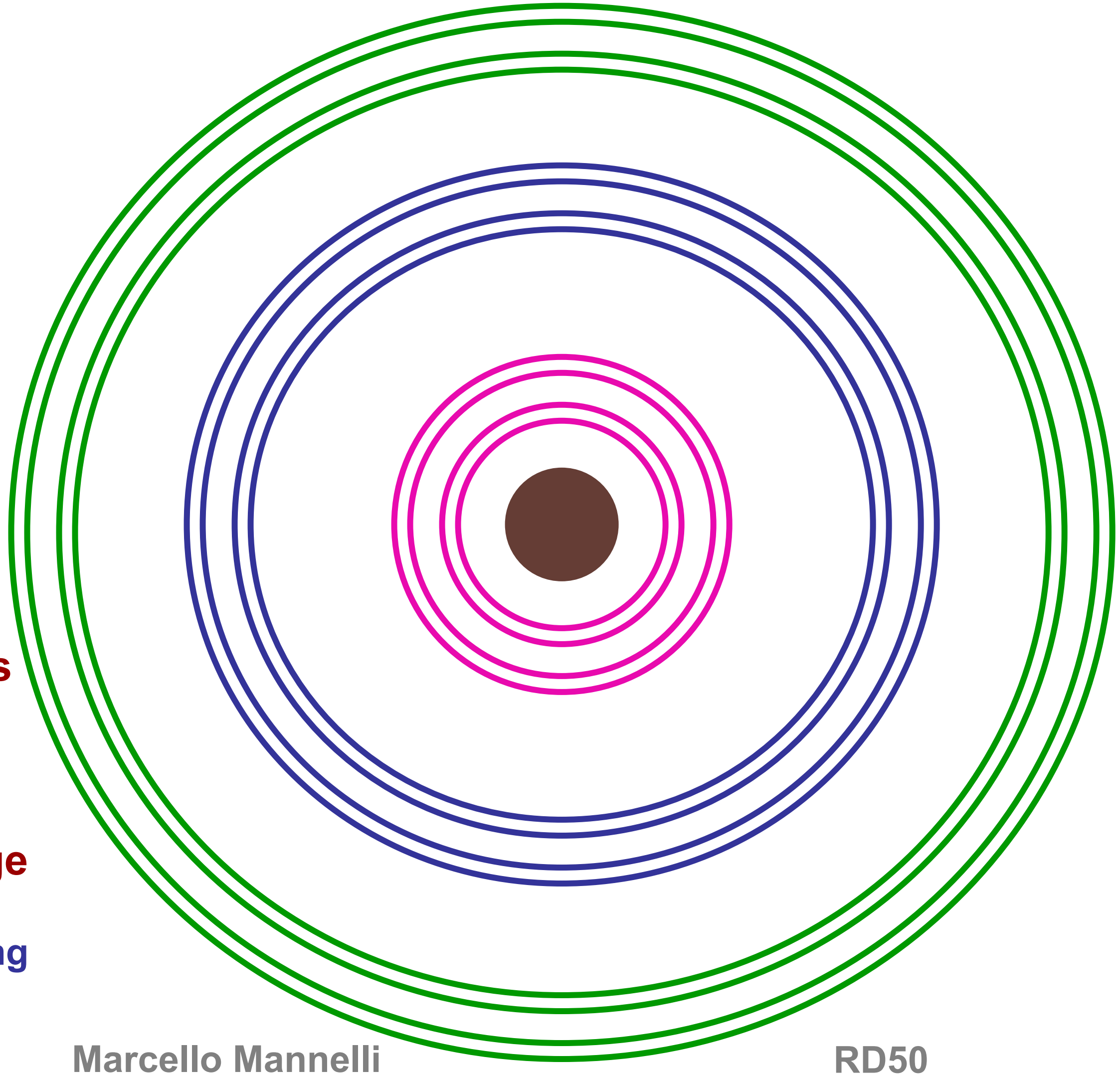
•Radial Positions

20~30~40cm, 50~60~70cm, ~100cm



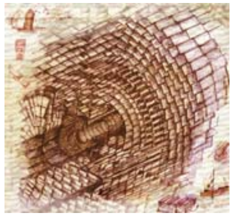


Simulation and Performance Issues



Basic Things to Check

- Track Quality
- Hit Pair Pt Resolution
- Track Stub Pt Resolution
- Fake Rate & Efficiency if require
  - Single Hit Efficiency: 95%~99.5%
  - 4/4 hits in sensor pair
  - 1/3 vs 2/3 Track Stubs
- Min radius at which scheme works effectively
- All the above varying the design parameters over the plausible range
  - Eg. Effect of cell geometry on resolution, occupancy and resulting effect on fake rate & efficiency



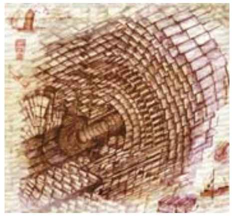
Conclusions

- **The present CMS Tracker will be a powerful tool for LHC Physics**

- **“Novel” approach:**
  - **Tracking with “few” high quality hits, in High Occupancy environment**

- **Technology extrapolation, at “large” radii:**
  - **Very Large Scale Deployment of Radiation Hard Strip Sensors, with Low Power Density, Low Mass, and Low Cost**
    - **when proposed, the Strip Tracker represented ~ 2 Order of magnitude extrapolation from existing devices**

- **Technology extrapolation, at “small” radii:**
  - **Large Scale Deployment of Very Radiation Hard Pixels, with Low Power, and acceptable cost**



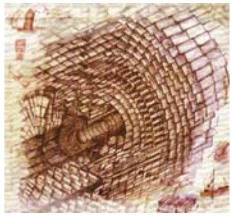
Conclusions

- **The CMS SLHC Tracker will be based on the present experience**
  - **but is required to provide Tracking and L1 Trigger capability in 10~20 times higher occupancy & radiation environment, and should be lighter**

- **“Novel” approach:**
  - **Extend Tracking with “few” high quality hits to include local Occupancy Reduction & Pt Discrimination, in Very High Occupancy environment**

- **Technology extrapolation, at “large” radii:**
  - **Very Large Scale deployment of Very Radiation Hard Long Pixels (Short Strips), with Lower Power Density, Lower Mass, and Low Cost**

- **Technology extrapolation, at “small” radii:**
  - **Large Scale Deployment of Extremely Radiation Hard Pixels, with Lower Power Density, and Acceptable Cost**



Conclusions

- **The Function of the Straw Man is to Illustrate the New Underlying Ideas for a CMS SLHC Tracker, with L1 Trigger capability**
  - **The Example Straw-man Layout shown here is Deliberately Extreme**
  - **It is intended to highlight the Potential AND the Pitfalls of the basic approach, to allow informed decisions down the line**

- **And to Provide a Framework to help Direct and Focus different Lines of Activity**
  - **Performance Studies**
  - **Sensors / Front-End Read-Out / Module Functionality & Design**
  - **Mechanics / Cooling and Services Integration**
  - **Data Reduction and Data Transmission**
  - **Power Distribution**
  - **Etc….**

- **On the way to a Base-Line Layout**