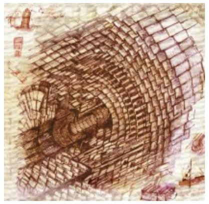

The Upgrade of the CMS Tracker for Super-LHC

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For the CMS Tracker Collaboration

9th International Conference on Large Scale Applications and Radiation Hardness of Semiconductor Detectors

Florence, October 2nd, 2009

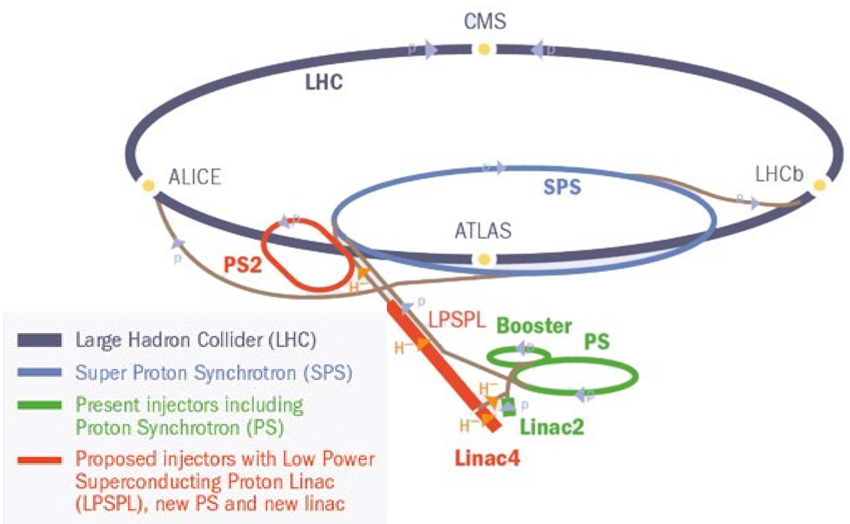
The Super-LHC (SLHC)

	LHC	SLHC Phase-1	SLHC Phase-2
Peak luminosity	10^{34}cm^{-2}s^{-1}	2-3 x 10^{34}cm^{-2}s^{-1}	10^{35}cm^{-2}s^{-1}
Integrated luminosity	≈ 50fb^{-1}/y	≈ 100-200fb^{-1}/y	≈ 500fb^{-1}/y
Start-up	2009 = t_0	t_0 + 4-5 years	t_0 + 10 years

Needs upgrade of LHC injector chain and interaction regions (IR):

Phase-1 (civil engineering started):
- Linac2 (50MeV) → Linac4 (160MeV)

Phase-2 (approval expected for 2011):
- Booster (1.4GeV) → LPSPL (4GeV)
- PS (25GeV) → PS2 (50GeV)
- enhancements to SPS (450GeV)

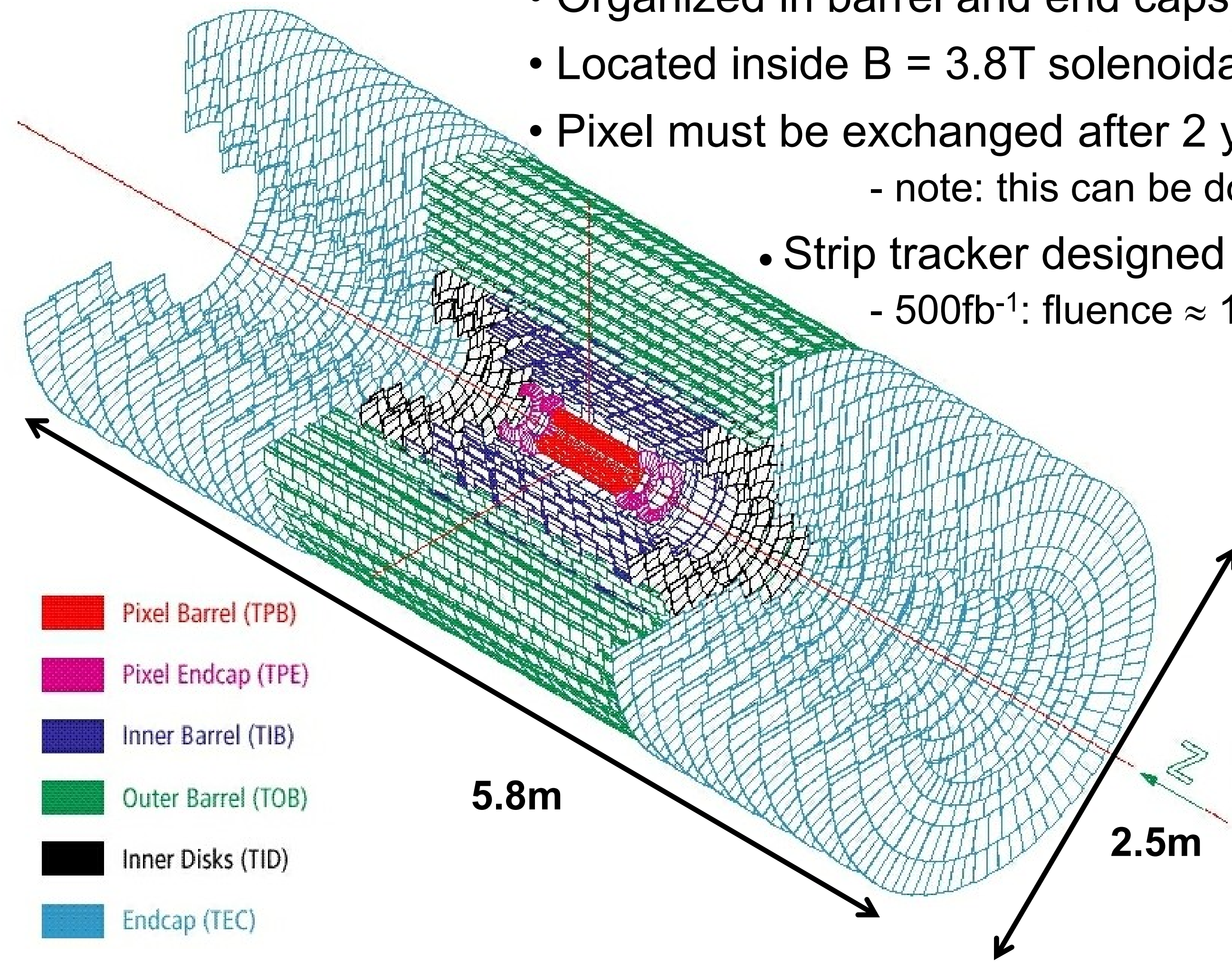


Motivations:

- Physics
- Radiation damage to LHC components (IR quadrupoles) and detectors
- Age of LHC injector chain (1959-1978)

The Current CMS Tracker

- **Silicon pixel detector and silicon micro-strip tracker**
- Organized in barrel and end caps
- Located inside B = 3.8T solenoidal field
- Pixel must be exchanged after 2 years at design luminosity
  - note: this can be done in standard shutdowns
- Strip tracker designed to withstand 10 LHC-years
  - $500 fb^{-1}$: fluence $\approx 1.6 \cdot 10^{14} n_{eq}/cm^2$, dose $\approx$ 70kGy



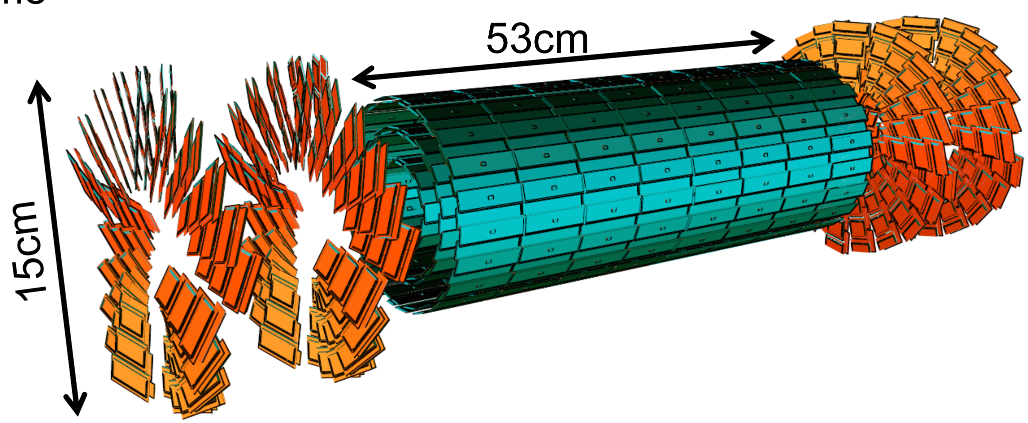
Phase-1 Pixel Upgrade

- Strip tracker stays untouched
- **Pixel detector will be exchanged due to radiation damage**
- **Changes to Pixel detector layout**
  - Four barrel layers at 3.9, 6.8, 10.9, **16.0** cm
  - Three forward disks per side

Talk by H-C. Kästli

- **Technological improvements, no radical changes**
  - Binary-coded sparsified serial readout at 160/320MHz
  - Modifications to periphery of PSI46 ROC: ADC, increased depth of buffers, ...
  - New, lightweight mechanics
  - Evaporative CO_2 cooling system instead of monophase C_6F_{14}
  - DC-DC conversion powering scheme
  - ...

Todays' Pixel Detector:
- 66 million pixels, 1m^2 of silicon
- Cell size: 100µm (rϕ) x 150µm (z)
- n$^+$-in-n sensors



Phase-2 Tracker Upgrade

Most subdetectors of CMS are expected to survive and perform well at SLHC

$\Rightarrow$ upgrades of trigger electronics and DAQ “only“

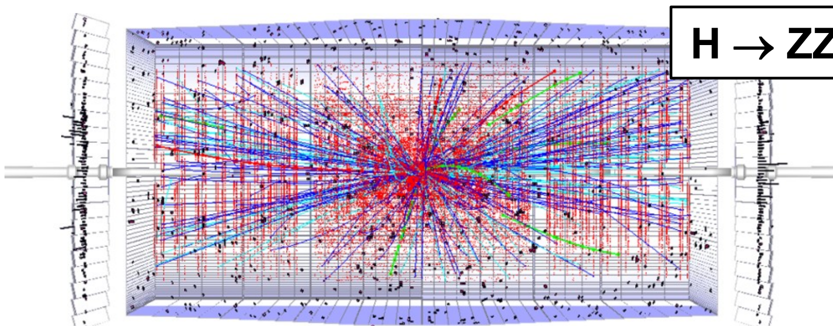
Exception: The Silicon Tracker

- Need to adapt to **SLHC radiation level**, in particular silicon sensors
  - For 3000 fb^{-1} at r = 4 (22) cm: fluence ≈ 19 (1) x 10^{15} cm^{-2} & dose ≈ 5 (0.4) MGy
- Pile-up increases from ~ 20 events to 300-400 events per bunch crossing

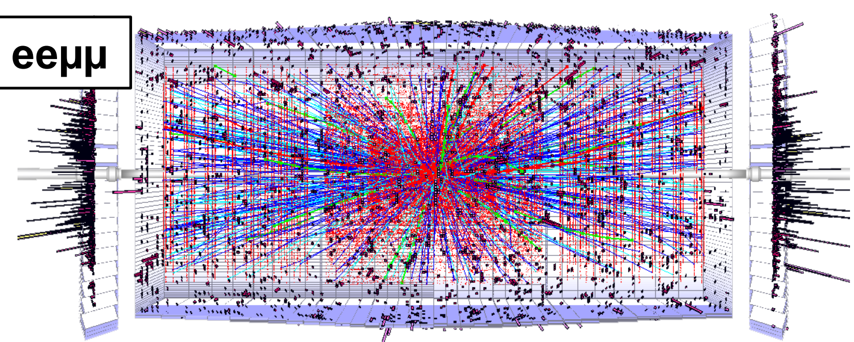
  $\Rightarrow$ up to 20 000 particles in the tracker

  $\Rightarrow$ **higher granularity needed** to keep occupancy at 1% level
- Keep L1 trigger frequency at 100kHz $\Rightarrow$ **tracker data must be fed into L1 trigger**

H → ZZ → eeμμ



20 pile-up events, corresp. to $10^{34} cm^{-2}s^{-1}$



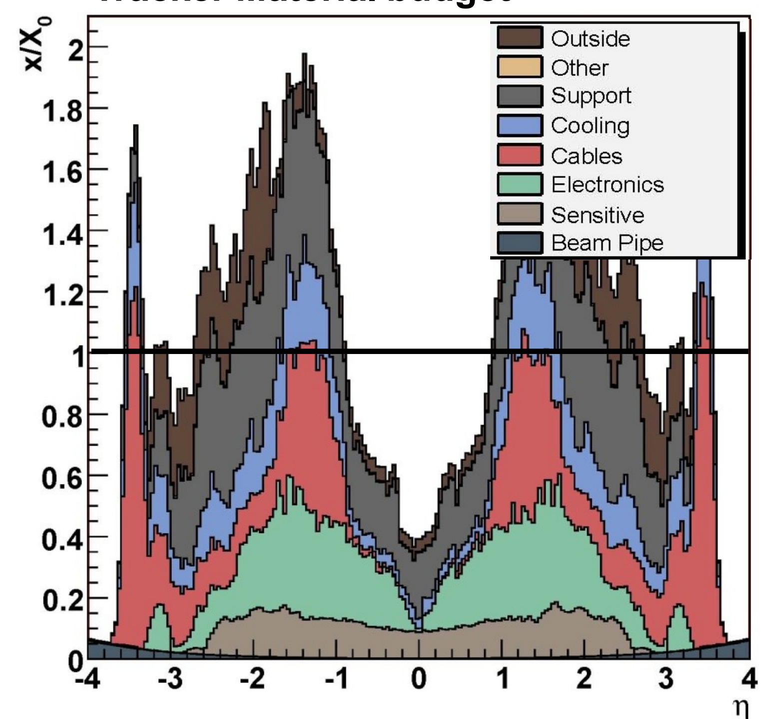
200 pile-up events, corresp. to < $10^{35} cm^{-2}s^{-1}$

Physics Requirements

- To fully exploit SLHC potential, performance must be preserved, if not improved
- Maintain tracking and vertexing performance, in a more challenging environment
- Excellent instrument → (expected) intrinsic spatial & p_T resolutions seem adequate

- However, detector suffers from its own **material**
  - multiple scattering (→ spatial resolution), Bremsstrahlung (→ energy resolution), photon conversions, hadronic interactions (→ detection efficiencies)
  - this drives many R&D areas (more details later)
    - ✓ novel powering and cooling systems
    - ✓ reduced redundancy in layout
    - ✓ power savings in layout & electronics (today: pixels ~ 3.6kW/m^2, strips ~ 0.2kW/m^2)

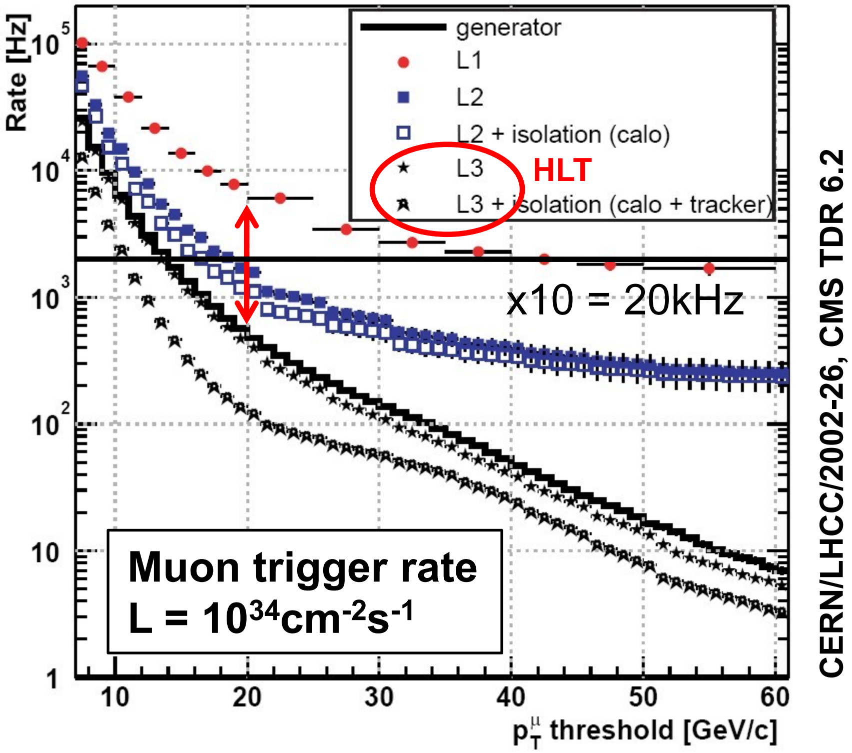
Tracker Material budget

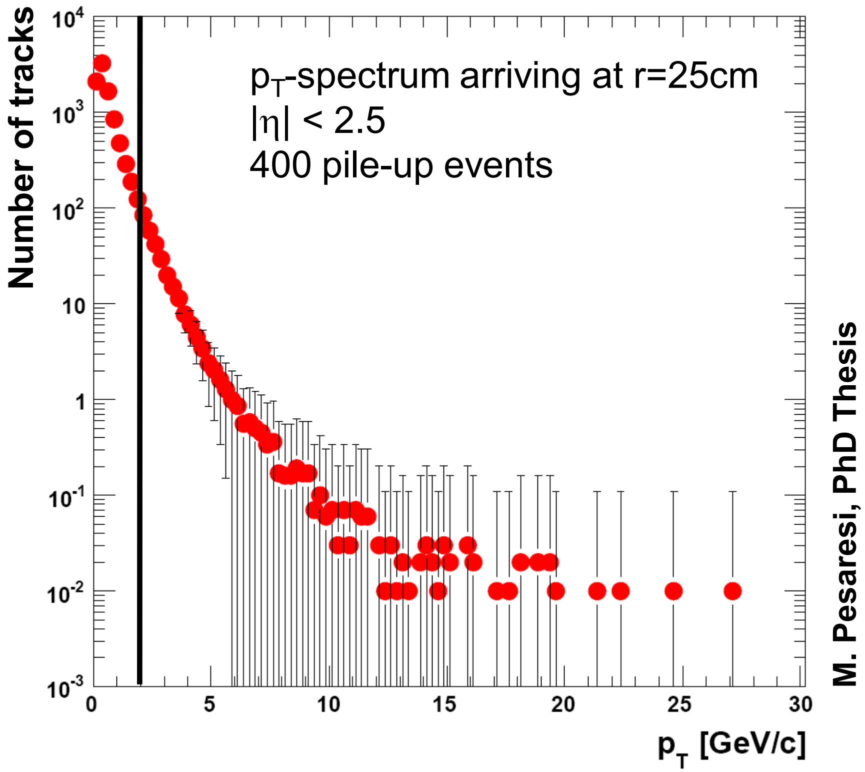


Track Trigger

- Currently, tracker information is used only in High Level Trigger (HLT)
- Reduction of L1-trigger rate by increasing thresholds not feasible (+ lose physics)
- Tracker info helps: improved p_T-resolution, e^- matching, isolation, primary vertex identification
- Cannot read out full tracker data within latency (6.4µs)

⇒ **Identify "high-p_T" tracks** (~ 5% for p_T < 2-3GeV) **and ship this data out only**



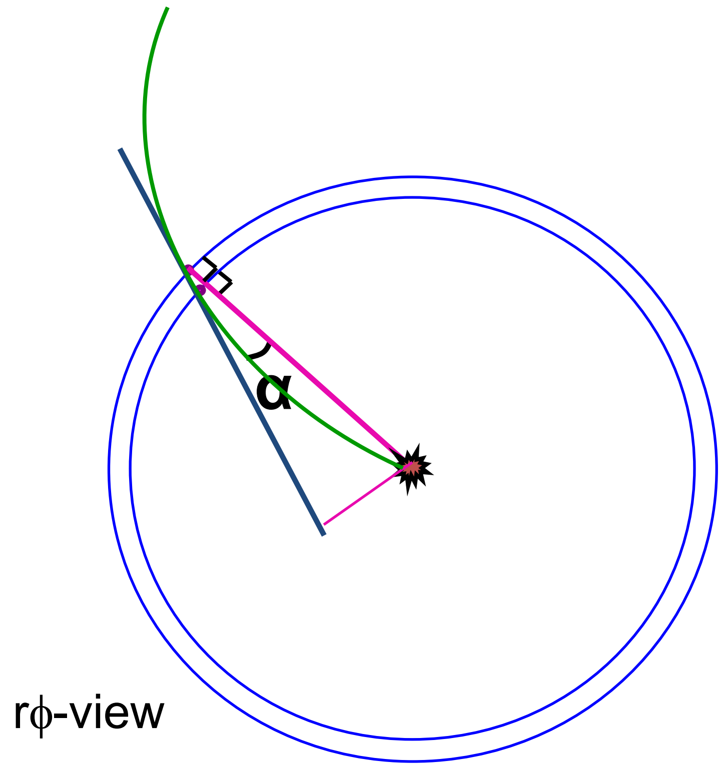


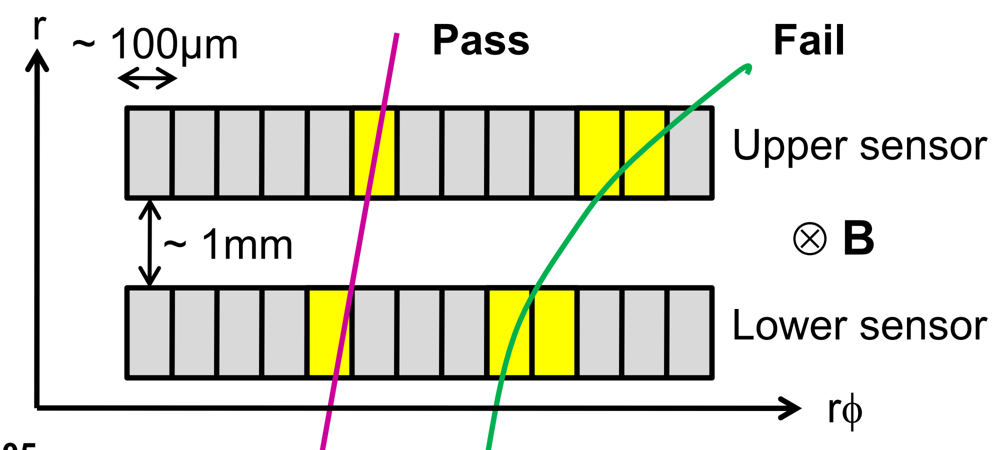
Suggestion #1: Stacked Layers

- High-p_T tracks are more straight $\Rightarrow$ compare hit patterns in close layers ("stacks")
- Needs pixelated detector layers

Pros:
- Compatible with thin sensors (mass!)
- Provides z-information $\rightarrow$ vertex identification

Cons:
- p_T-layers will have high power consumption
- ... will be costly
- ... will be massive
- Correlation logic must take into account tilt, alignment, Lorenz angle etc.





J. Jones, G. Hall, C. Foudas and A. Rose, LECC 2005

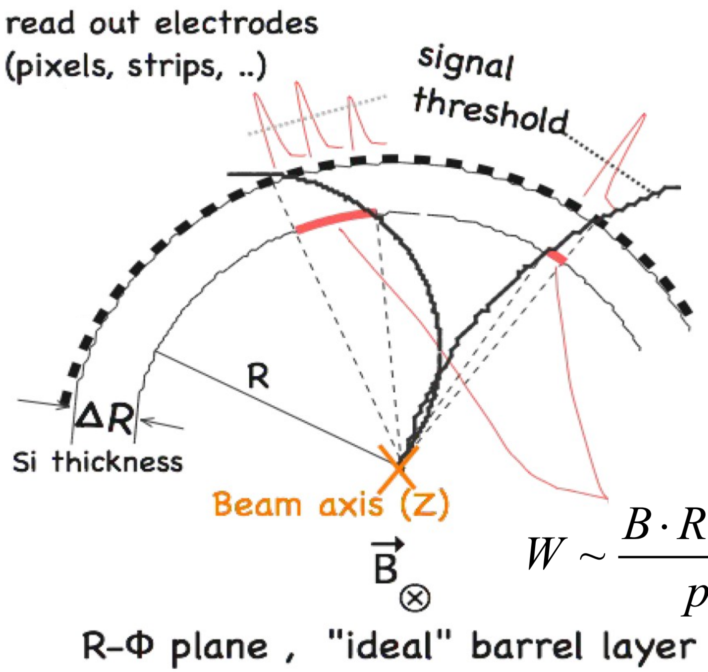
Suggestion #2: Cluster Width

- Discrimate on-chip between low and high-p_T tracks based on cluster width
- Tracks within ϕ-slices are reconstructed off-detector in FPGAs (e.g. Associative Memory chip) for L1

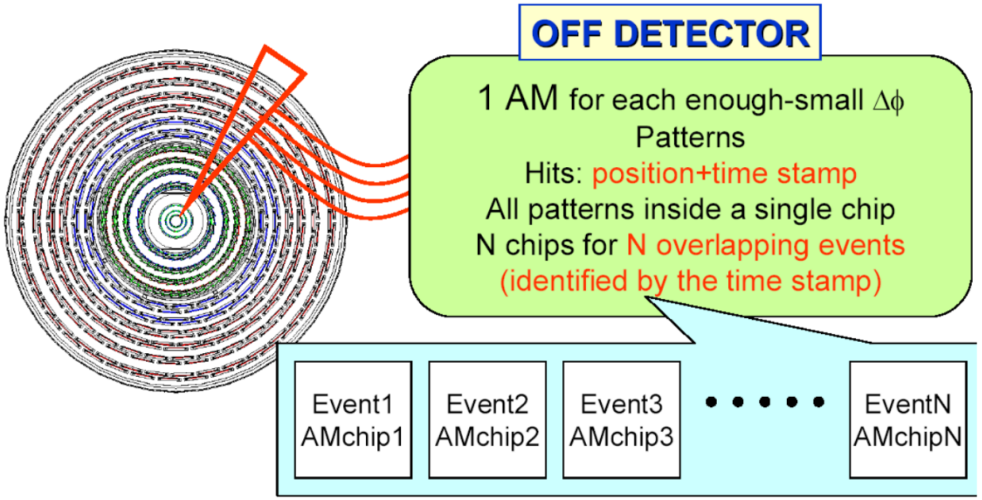
Pros:
– Can use “classic“ strip modules (low power, cost)
– No correlation between modules needed $\rightarrow$ simple

Cons:
– Requires certain radius and sensor thickness
– No z information $\Rightarrow$ no vertex finding
– Background from secondary interactions?

G. Barbagli, F. Palla and G. Parrini, TWEPP2007

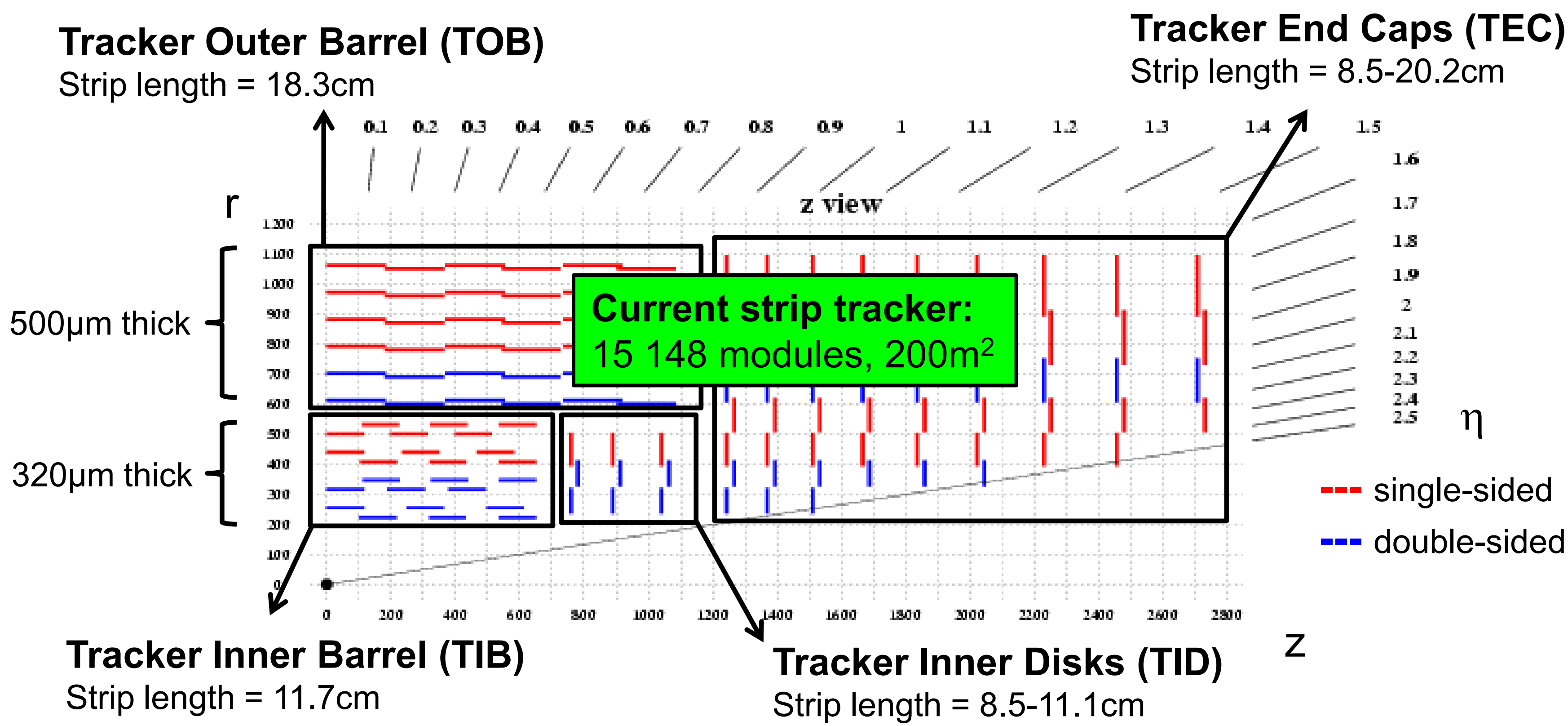


$$W \sim \frac{B \cdot R \cdot \Delta R}{p_T}$$



Outer Tracker Layout

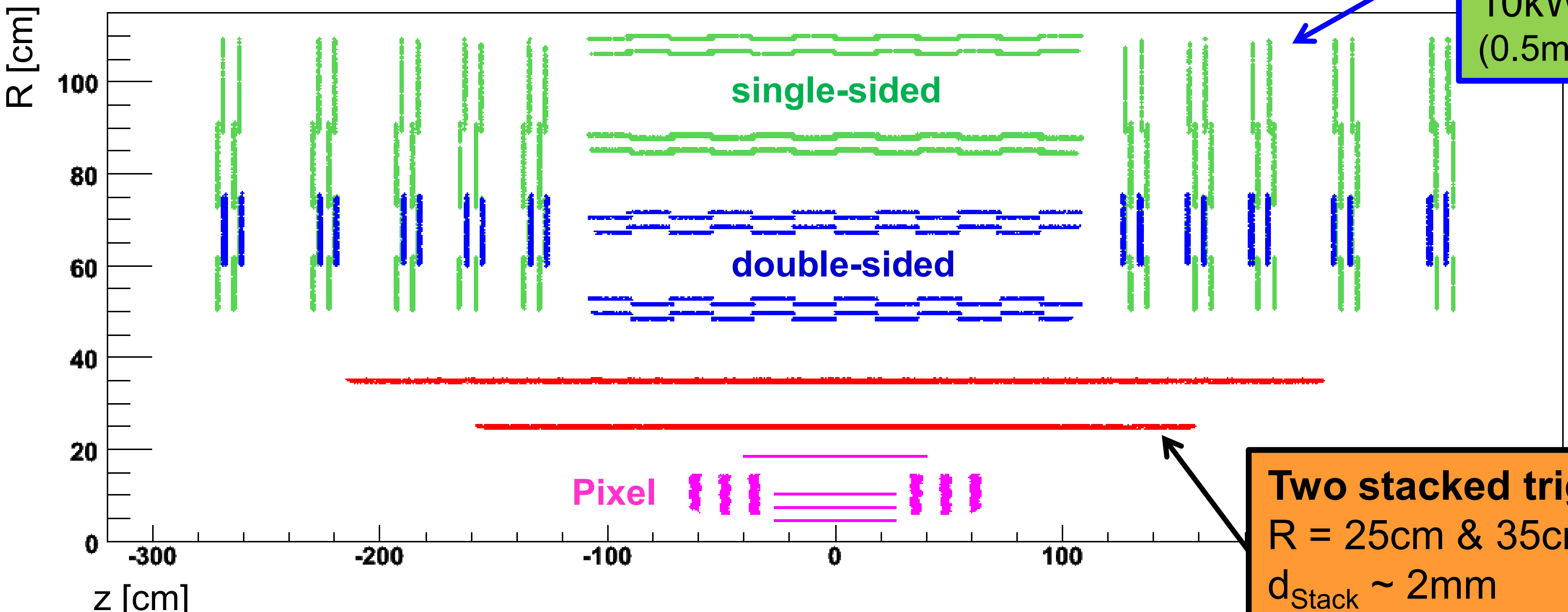
- Current layout with 10 barrel layers guarantees robust and redundant tracking
- Define future layout based on **systematic detector simulations** (big task!)
- **Two “strawman“ layouts with p_T-layers** have cristallized and are being studied



Strawman #1: The Hybrid Layout

- Minimalistic trigger configuration combined with "classical" outer tracker
- Two types of modules needed (some details later)

Numbers are indicative only!



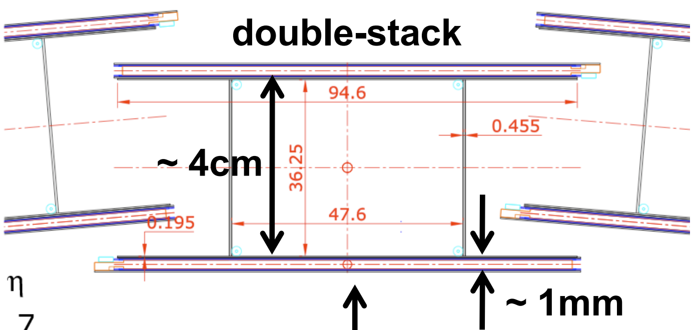
Tracking layers
2.5/5.0cm strips
85m² active area
10kW FE-power
(0.5mW/strip)

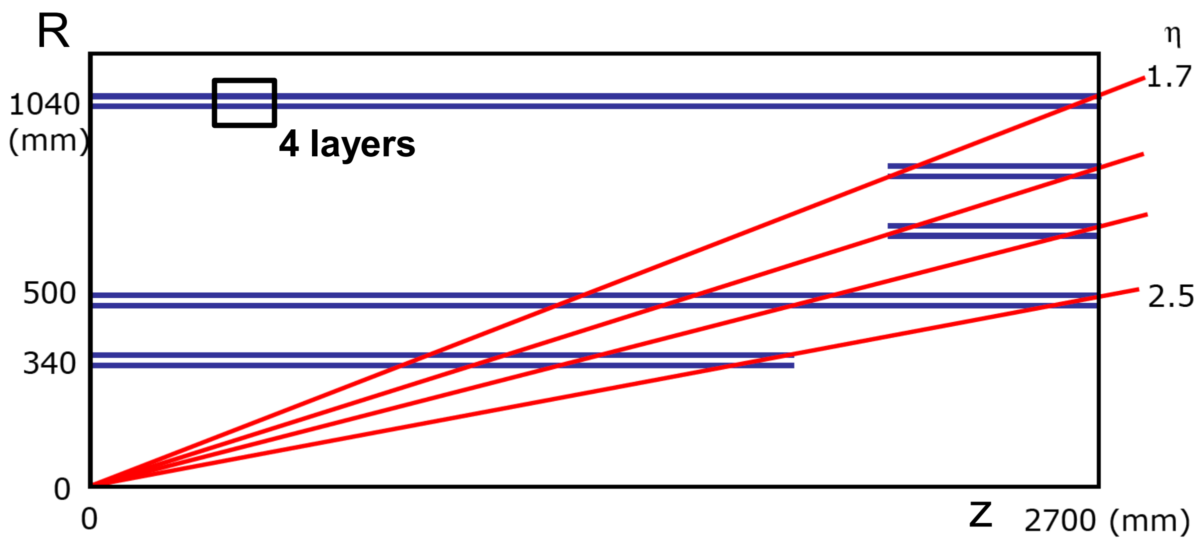
Two stacked trigger layers
R = 25cm & 35cm
d_{Stack} ~ 2mm
~ 100µm x 2.5mm (z) pixels
27m² active area
12kW FE-power (0.1mW/pixel)

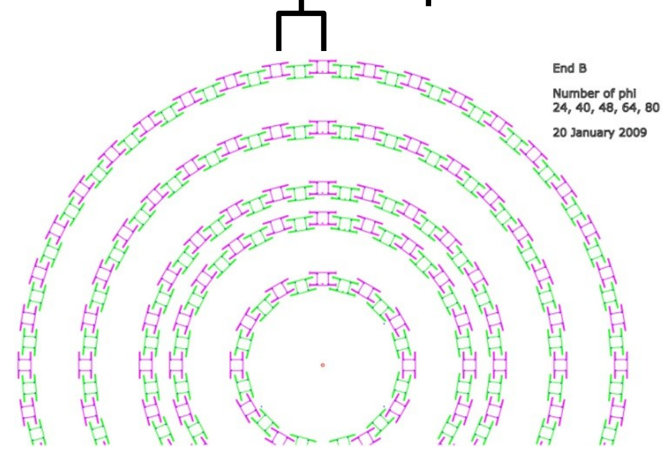
Strawman #2: Long Barrel Double-Stack Layout

- 3 + 2 stacked layers organized as 5 double-stacks (= 12 sensor layers at $\eta = 0$)
- All-pixel tracker: ~ 300m^2 active area with ~ 100µm x 1mm pixels
- Estimated FE-power consumption: O(100kW)
- Data volume and cost higher than for Hybrid Layout

Numbers are indicative only!



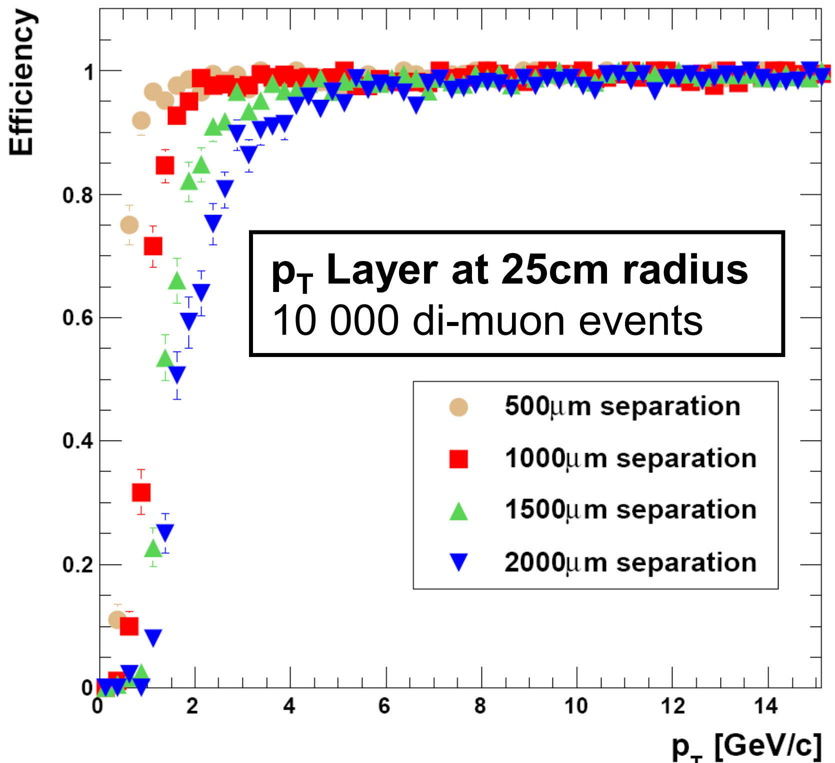




Simulations Results (Example)

- Sensor separation defines p_T cut (for fixed search window)
- Transition region (i.e. efficiency between 0% and 100%) broadens with separation

Untilted sensors (no comp. of Lorenz angle)



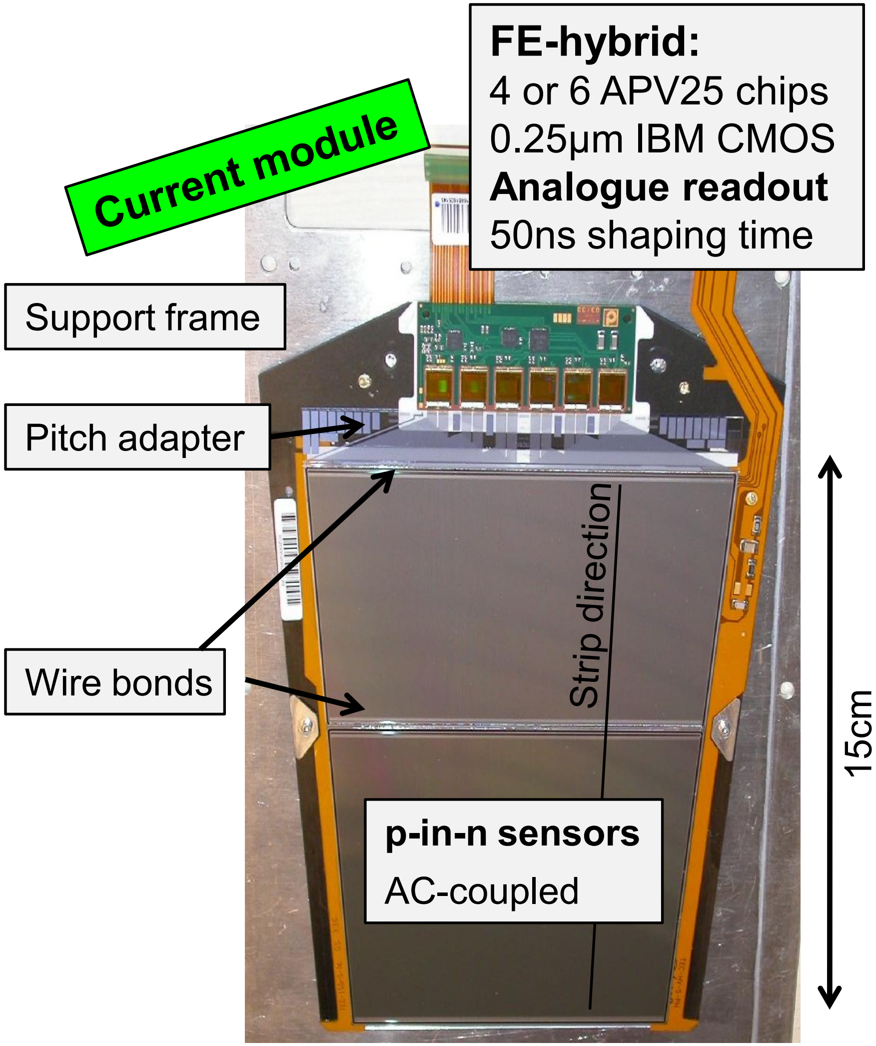
Separation [µm]	Efficiency for p_T > 2GeV [%]	Fakes [%]	Reduction factor
500	99.4	2.7	9.2
1000	**99.2**	**6.6**	**22.0**
1500	98.6	16.3	37.0
2000	97.1	23.3	54.4

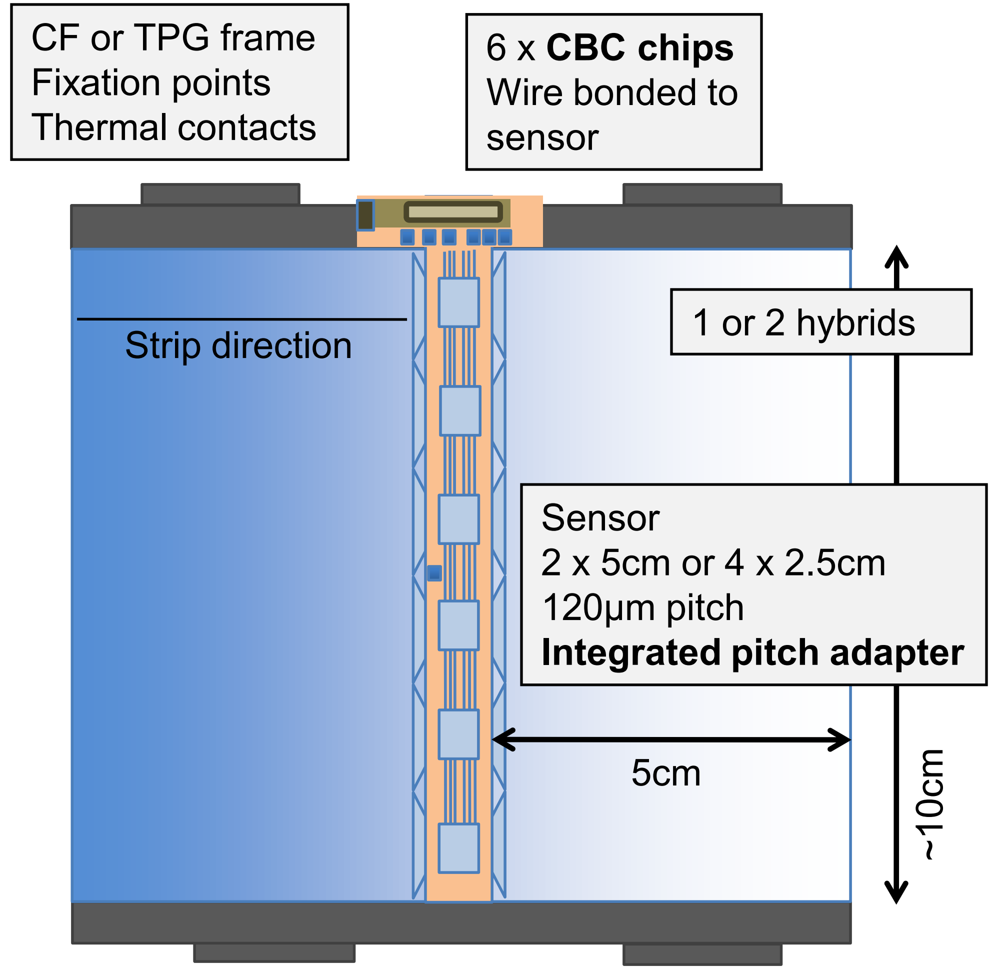
Row search window (ϕ) = 3 pixels
Column search window (z) = 2 pixels at 0.5mm; 3 pixels at 1mm - 2mm

M. Pesaresi, PhD Thesis, Development of a new Silicon Tracker at CMS for Super-LHC

Outer Tracker Module (First Ideas)

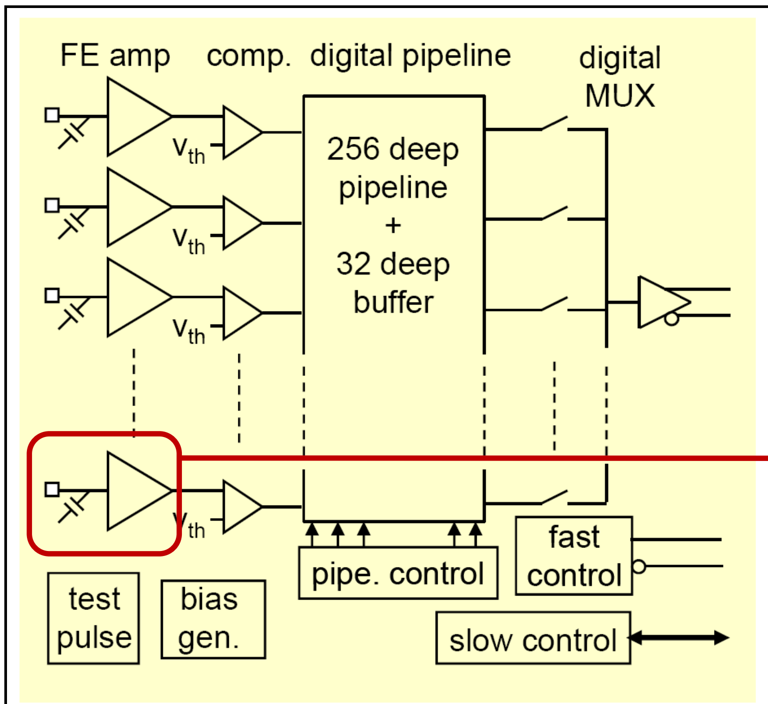
Design not decided. Finite Element analysis of mechanical & thermal properties started.



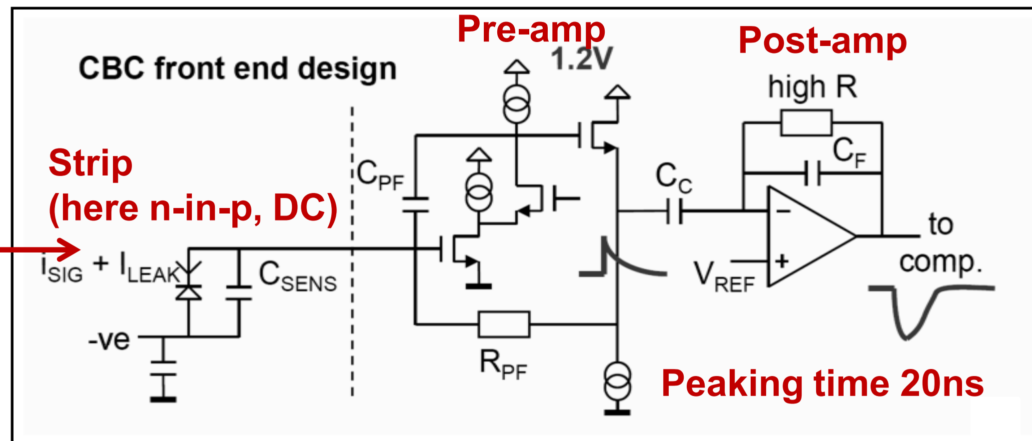


Outer Tracker Readout Chip

- Proposed successor of APV25: **“CMS Binary Chip (CBC)“ in 130nm CMOS**
- **Binary unsparsified readout:** lowest power; synchronous; constant data volume
- Power per channel ~ 0.5mW (simulation for C_{sensor} = 5pF)
- Compatible with both signal polarities, DC & AC coupling
- Challenges: noise immunity, fewer diagnostics, binary position resolution



Design being finalized, layouting has started
Expected for Spring 2010

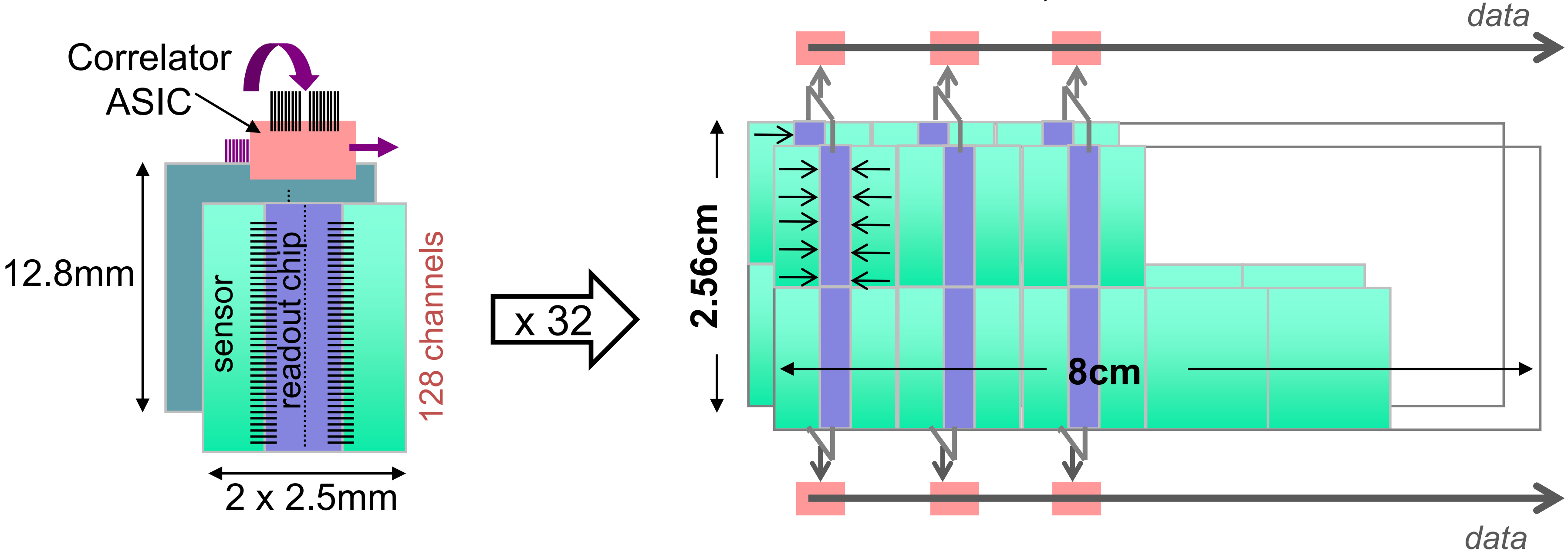


M. Raymond and G. Hall, TWEPP2008

Trigger Module Proposal #1: pT-Module

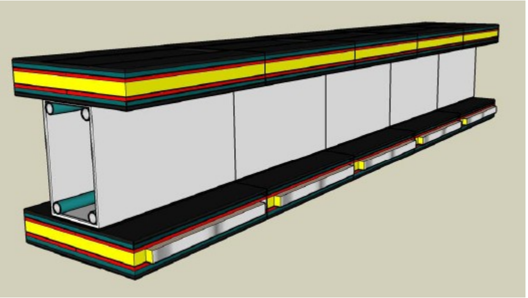
- **Two stacked sensors** a 2.56cm x 8cm with 2.5mm x 100µm pixels
- Read-out chips for 2 x 128 columns, coarse pitch bump-bonding to sensor
- Hits are transferred to chip edge (0.5% occupancy, 10bit bus @ 40MHz)
- Hit patterns & address of stacked sensors are compared in **correlator ASIC**
- Rough FE-Power estimate: 100µW per pixel (~ doubles if link power included)
- Stress on **easy prototyping** to assess soon feasibility of concept in test beams

G. Hall, TWEPP2009

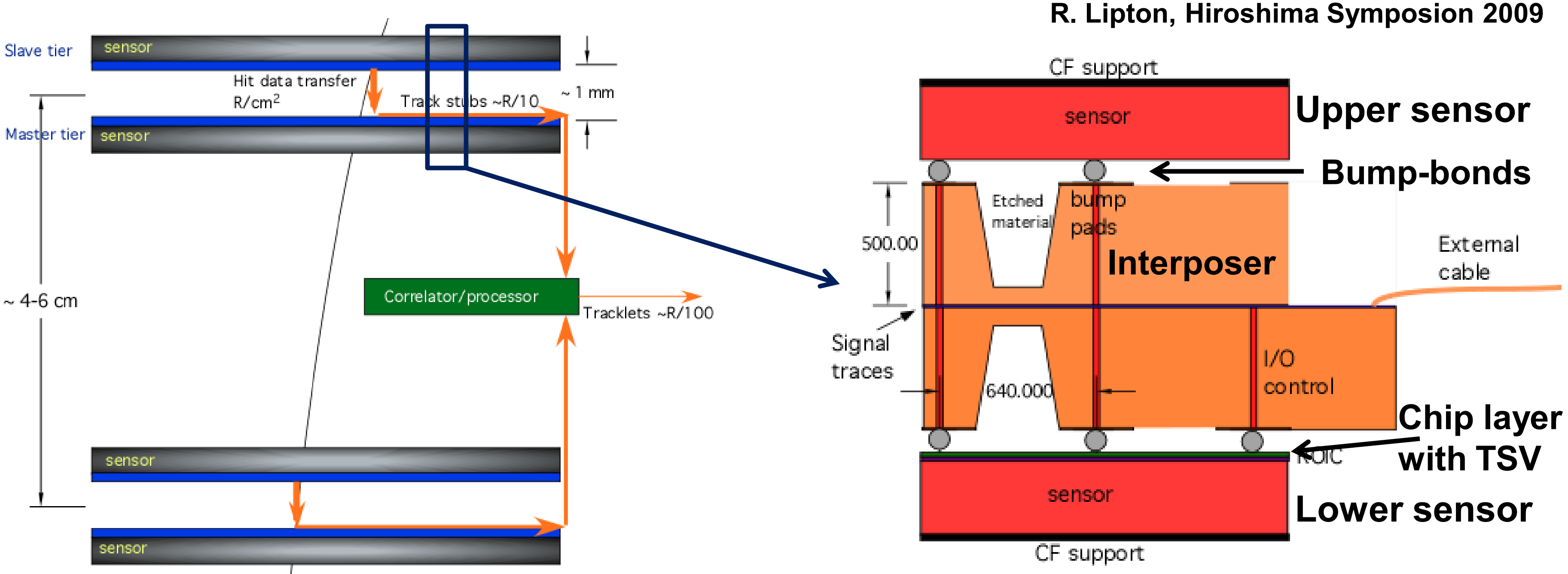


Trigger Module Prop. #2: Vertically Integrated Module

- Stacked modules with 85cm^2 a 100µm x 1mm pixels
- Data not transferred to edge, but **direct communication of stacked sensors through vias in “interposer“ layer**
- **3D electronics integration** with **Through-Silicon-Vias**
- Large power and band width requirements
- New exciting technologies; feasibility yet to be proven

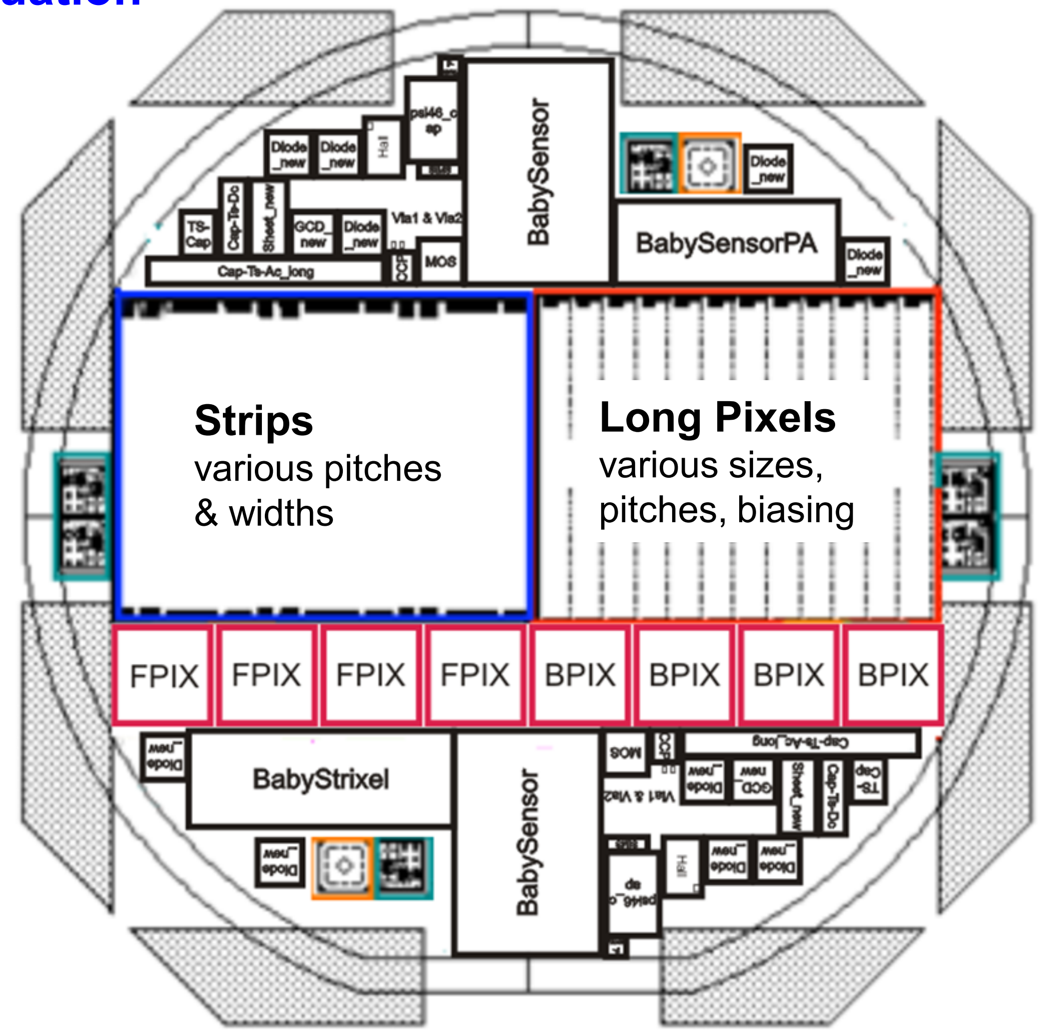


R. Lipton, Hiroshima Symposion 2009



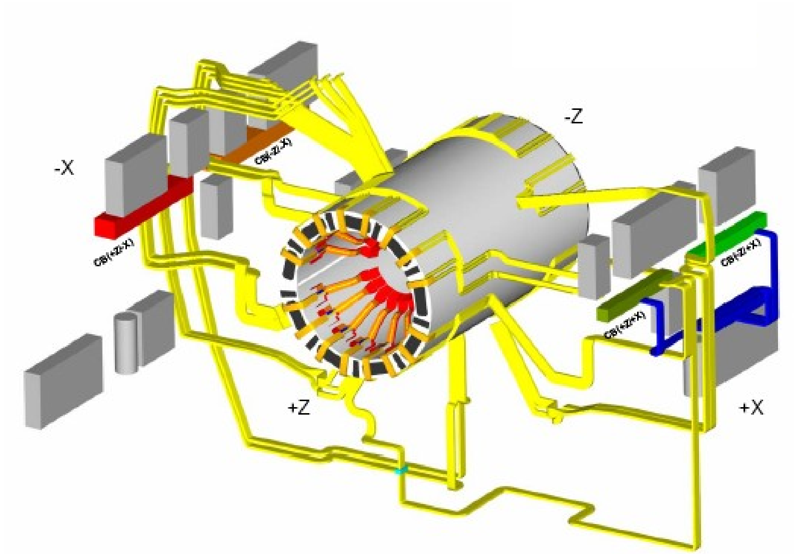
Sensor R&D for Phase-2

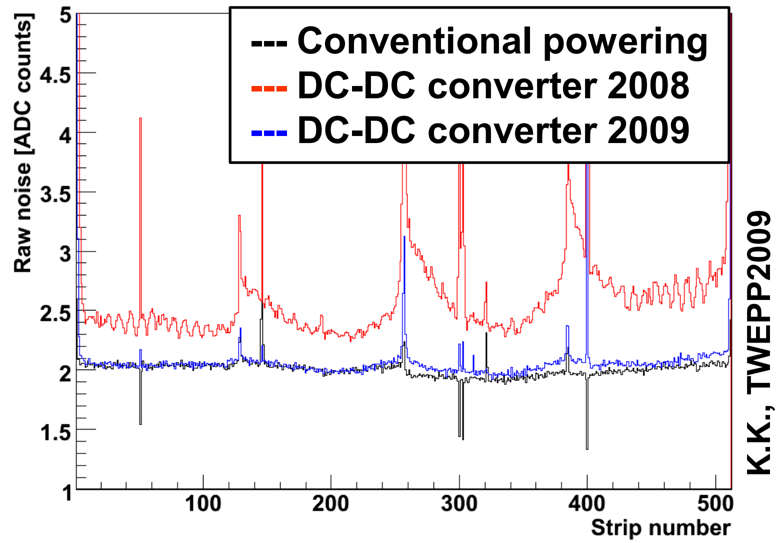
- **R&D with HPK for technology evaluation**
- Wafers with multi-geometry pixel & strip areas, test structures, etc.
- **Huge phase space** to be explored:
  - p-in-n-FZ (100µm, 200µm, 300µm)
  - p-in-n-MCz (200µm)
  - n-in-p-FZ (100µm, 200µm, 300µm)
  - n-in-p-MCz (200µm)
  - p-in-n EPI (75µm, 100µm)
  - n-in-p EPI (75µm, 100µm)
  - for n-in-p: p-spray and p-stop
  - additional double metal layer for integrated pitch adapter
- Extensive irradiation (p, n) and testing campaign being set up



Power & Cooling

- Tracker services (pipes, fibres, cables) follow complicated routes; exchange not practicable (impact on ECAL...) ⇒ major constraint for the Upgrade
- Plan to move from monophase C_6F_{14} cooling to **two-phase CO_2 cooling**
  - Evaporates at high pressure → low vapour volume → thin pipes
  - High latent heat → lower sensor temperatures can be reached
- Might need more power than today, at higher current → larger cables losses ~ I^2 ⇒ move to a **DC-DC conversion powering scheme**
  - Bring power into detector at higher voltage but lower current ⇒ lower cable losses
  - Switching devices with air-core inductors → R&D to minimize noise





Summary

Phase-1: Exchange of pixel detector

- 4 layers + 3 disks
- Improved detector: read-out, CO_2 cooling, DC-DC conversion, lower material budget

Phase-2: Exchange of whole tracker

- Track trigger requirement drives detector design
- Try to improve performance by saving material

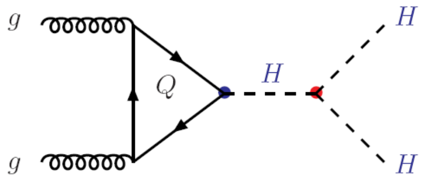
- A lot of R&D ongoing: sensors, readout chips, DC-DC conversion, CO_2 cooling, ...
- Several suggestions for overall layout and module design exist
- Need to explore them better before convergence can be reached
- Aim for Technical Design Reports for Phase-1/2 in 2010/2012

Back-up Slides

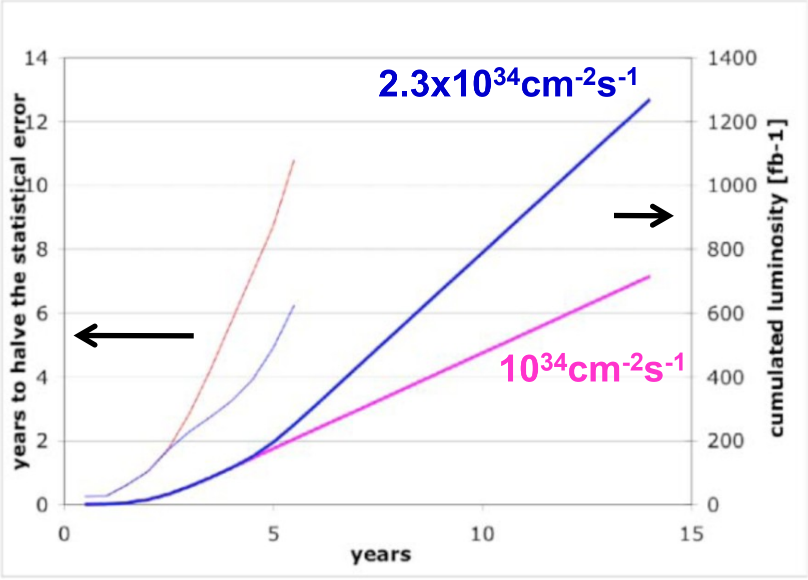
Physics Potential of the SLHC

Higher statistics improves accuracy and extends discovery reach by ~ 20-25%:

- **Higgs physics**
  - Rare decays; 25% error on Higgs self-coupling (M_H=200GeV)



- **Super-Symmetry**
  - Discovery reach for squarks & gluinos extends from 2.5TeV to 3TeV
- **Exotica**
  - Discovery reach for new gauge bosons (Z': 5.3TeV → 6.5TeV), KK excitations etc.
- **Electroweak physics**
  - E.g. factor 2-3 higher accuracy for triple & quartic gauge boson couplings
- ...
- + simply reduce time to half statistical error!



W. Scandale, EPAC 2006