Karlsruhe Institute of Technology

A New Pixel Detector for the CMS Experiment

Teilchenphysik-Kolloquium
Universität Heidelberg, May 8, 2012

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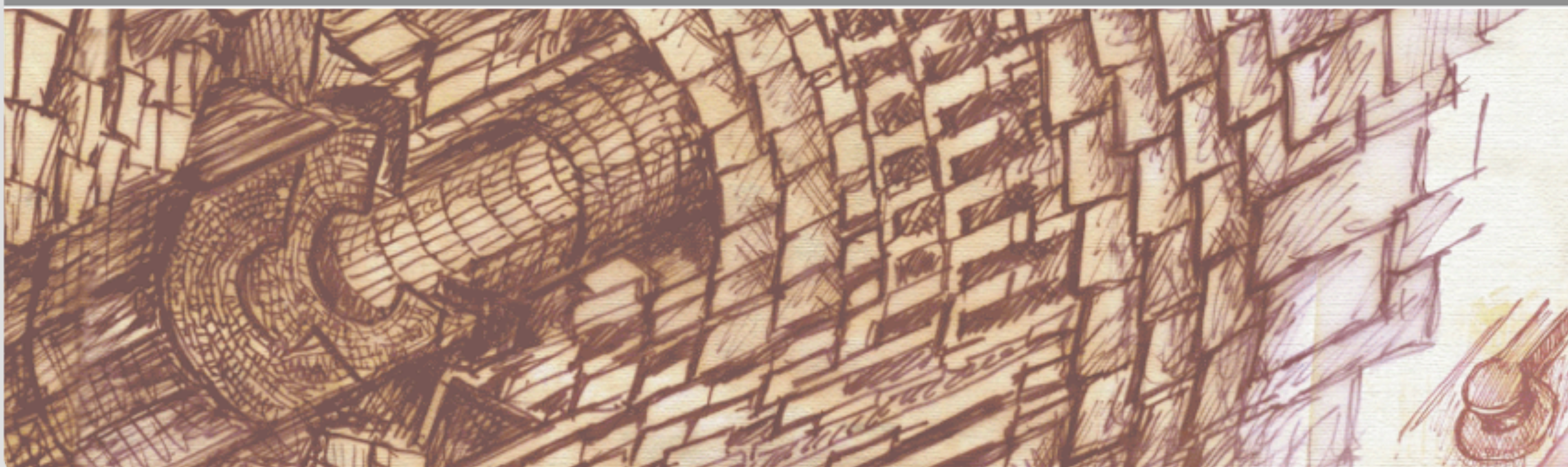

The Large Hadron Collider: Present and Future

Pixel Detectors for Collider Experiments

The CMS Pixel Detector

The CMS Phase 1 Pixel Upgrade

CMS Pixel Upgrade: Current Status and Plans

Ulrich Husemann
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The Large Hadron Collider: Present and Future

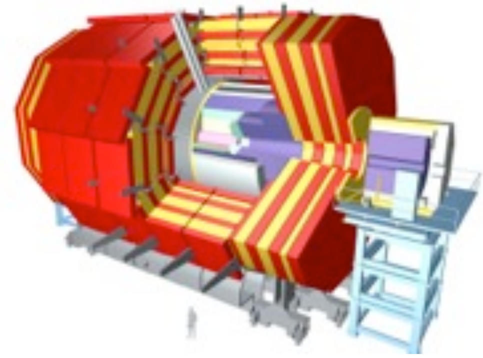
LHC – the Large Hadr

Lake Geneva

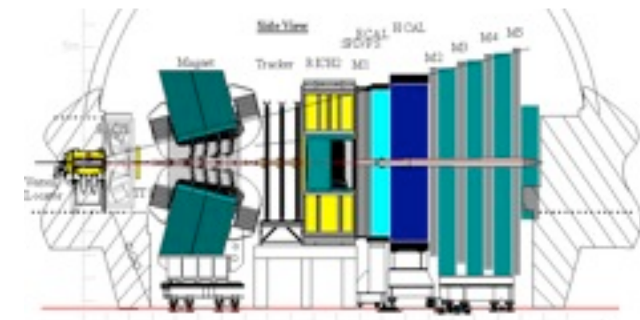
CERN accelerator complex,
about 100 m under ground
LHC circumference: ~27 km

LHC Accelerator:
proton-proton and
lead-lead collisions

CMS Experiment:
multi-purpose experiment



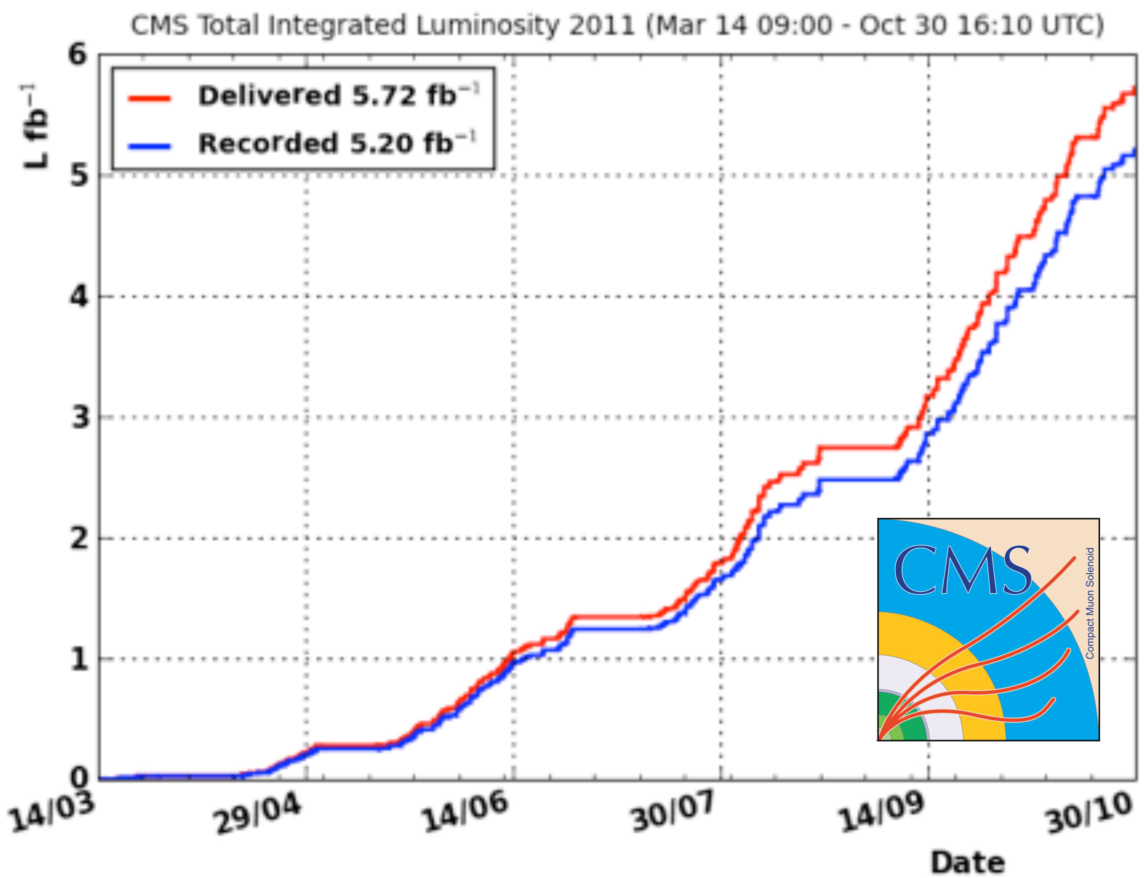
LHCb Experiment:
CP violation and B physics



ALICE Experiment:
heavy ion physics

ATLAS Experiment:
multi-purpose experiment

LHC Luminosities

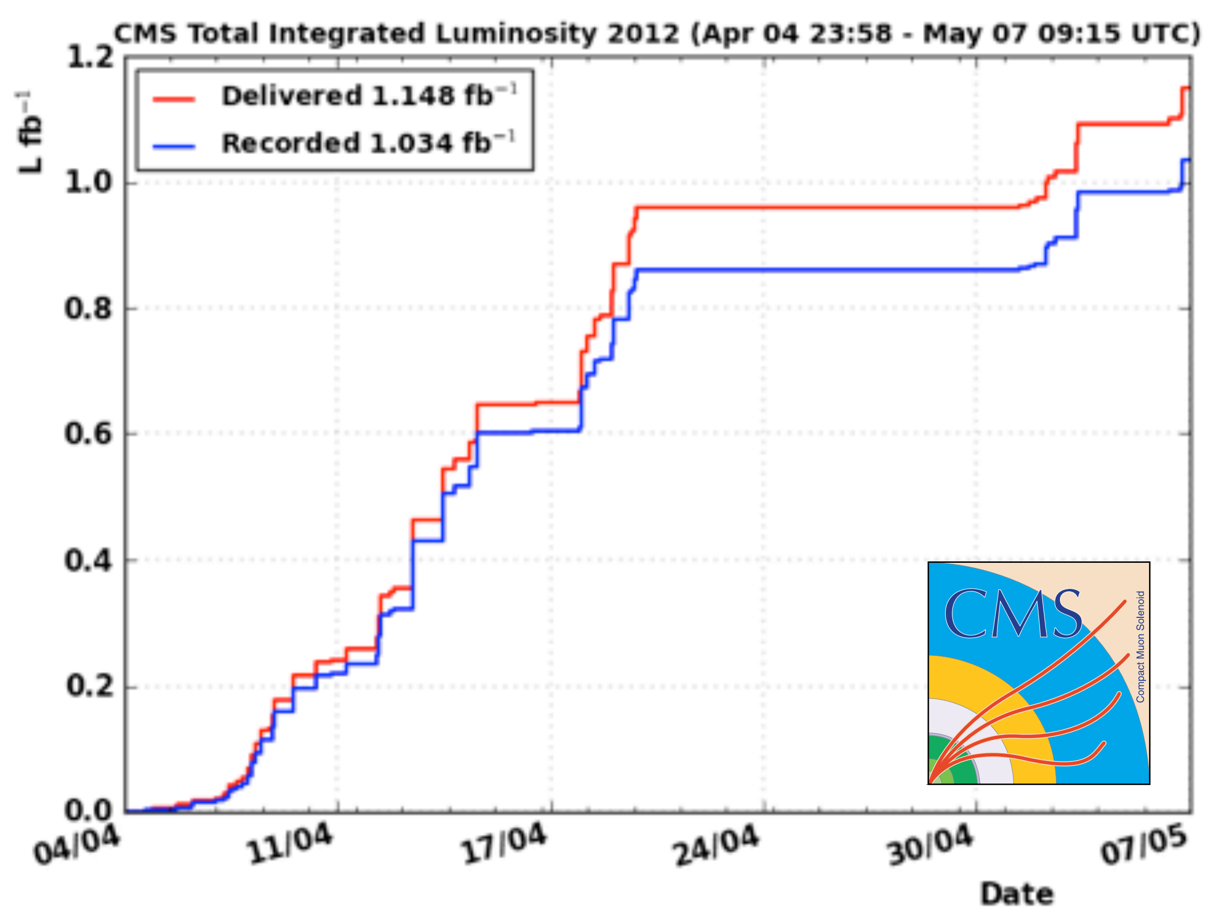


LHC 2010/2011: 7 TeV

- Record instantaneous lumi: 3.5×10^{33} cm^{-2} s^{-1}
- About 5 fb^{-1} (= 800,000 top pairs) per experiment
- Exceeding expectations

LHC 2012: 8 TeV

- Luminosity ramped up in record time
- Already >1 fb^{-1} delivered
- Expected for full year: 15–20 fb^{-1}



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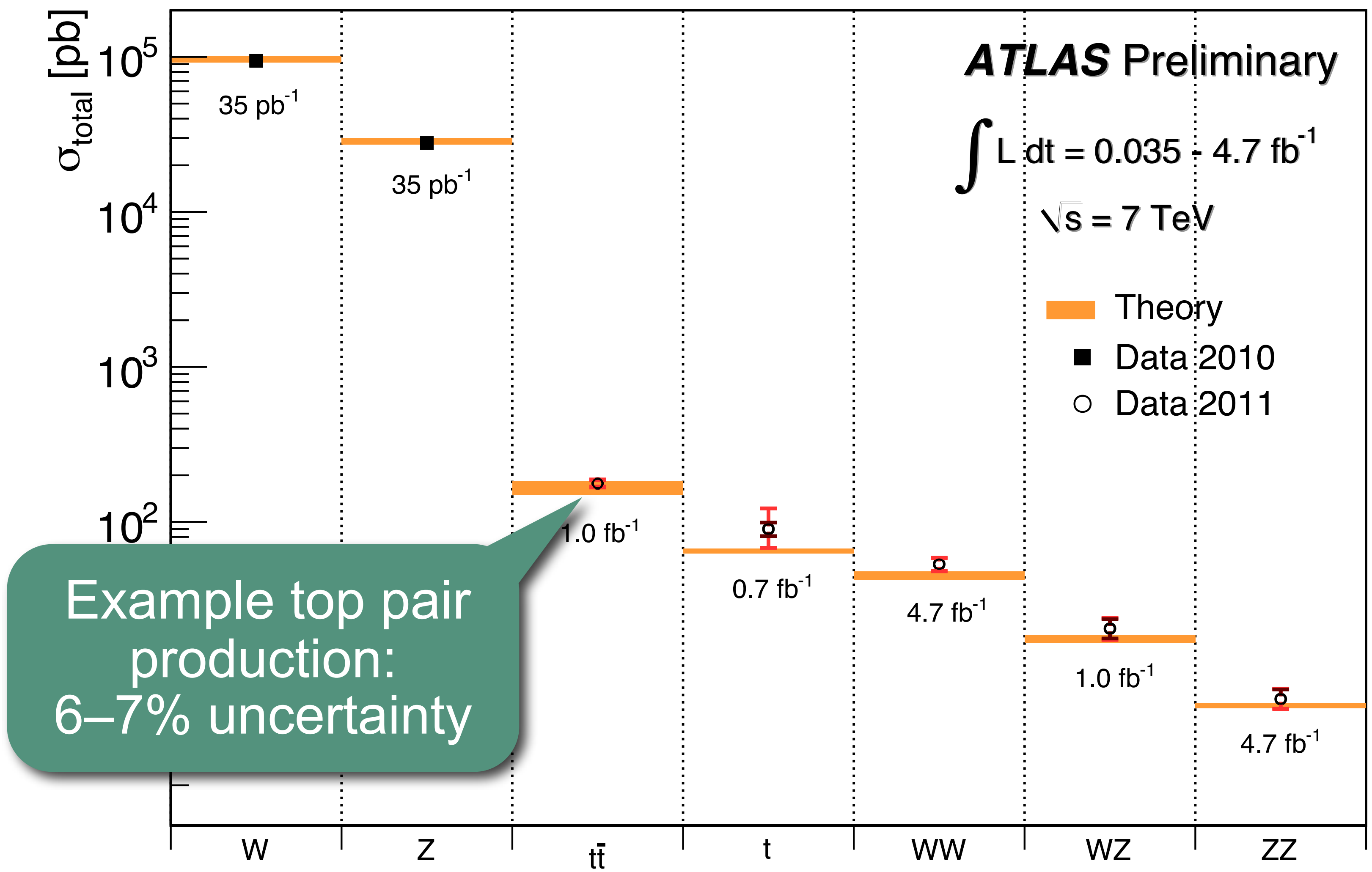
LHC Physics 2010/11: Rediscovery of the SM

- Precision measurements of W and Z bosons, top quarks, boson pairs, etc.
- Jump in center of mass energy (2 TeV → 7 TeV): many searches for physics beyond the standard model



[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots]

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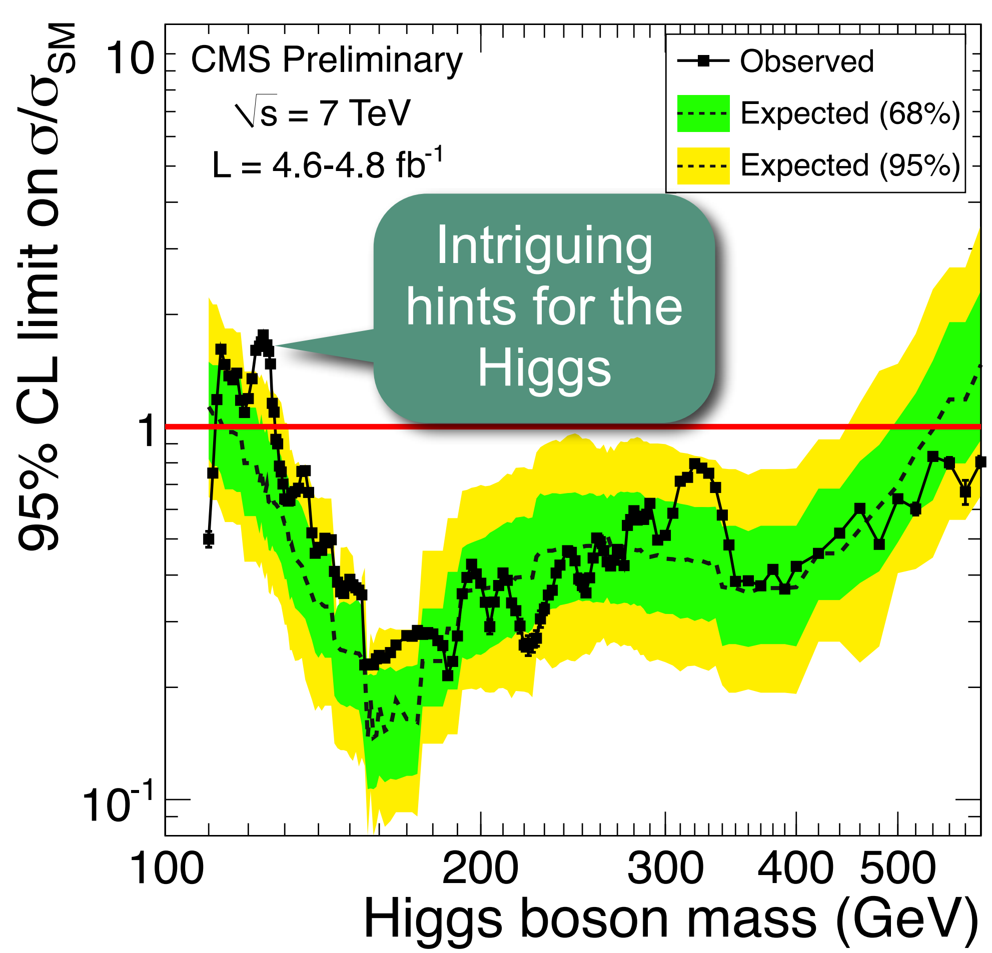
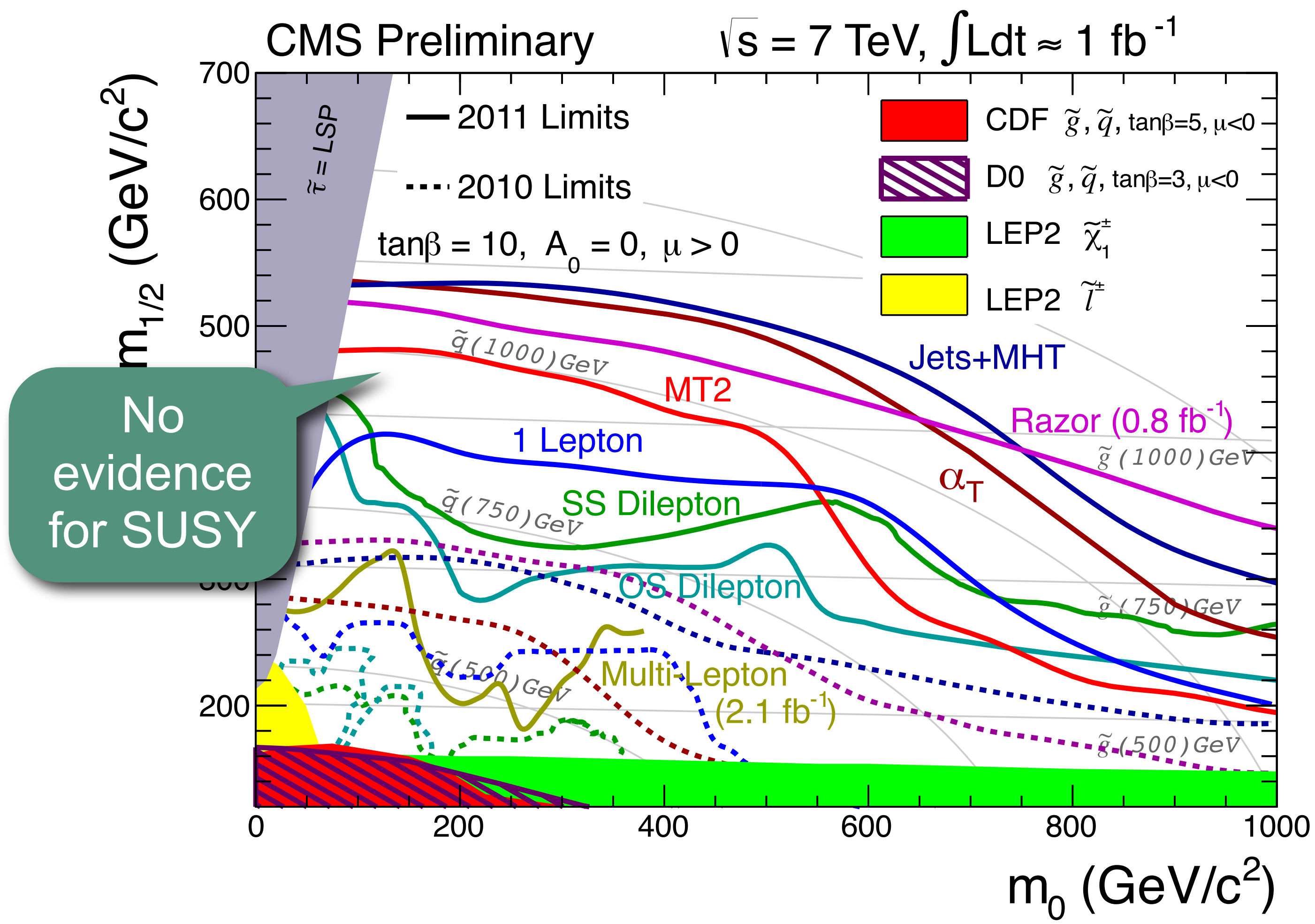
LHC Physics 2011/12: The Hunt for the Higgs

- 2011: Large increase in integrated luminosity: 35 pb^{-1} → 5 fb^{-1}
- 2012: Center of mass energy further increased: 7 TeV → 8 TeV
- Even more searches for new physics → no smoking gun yet…



[CMS-HIG-12-008]



[https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS]

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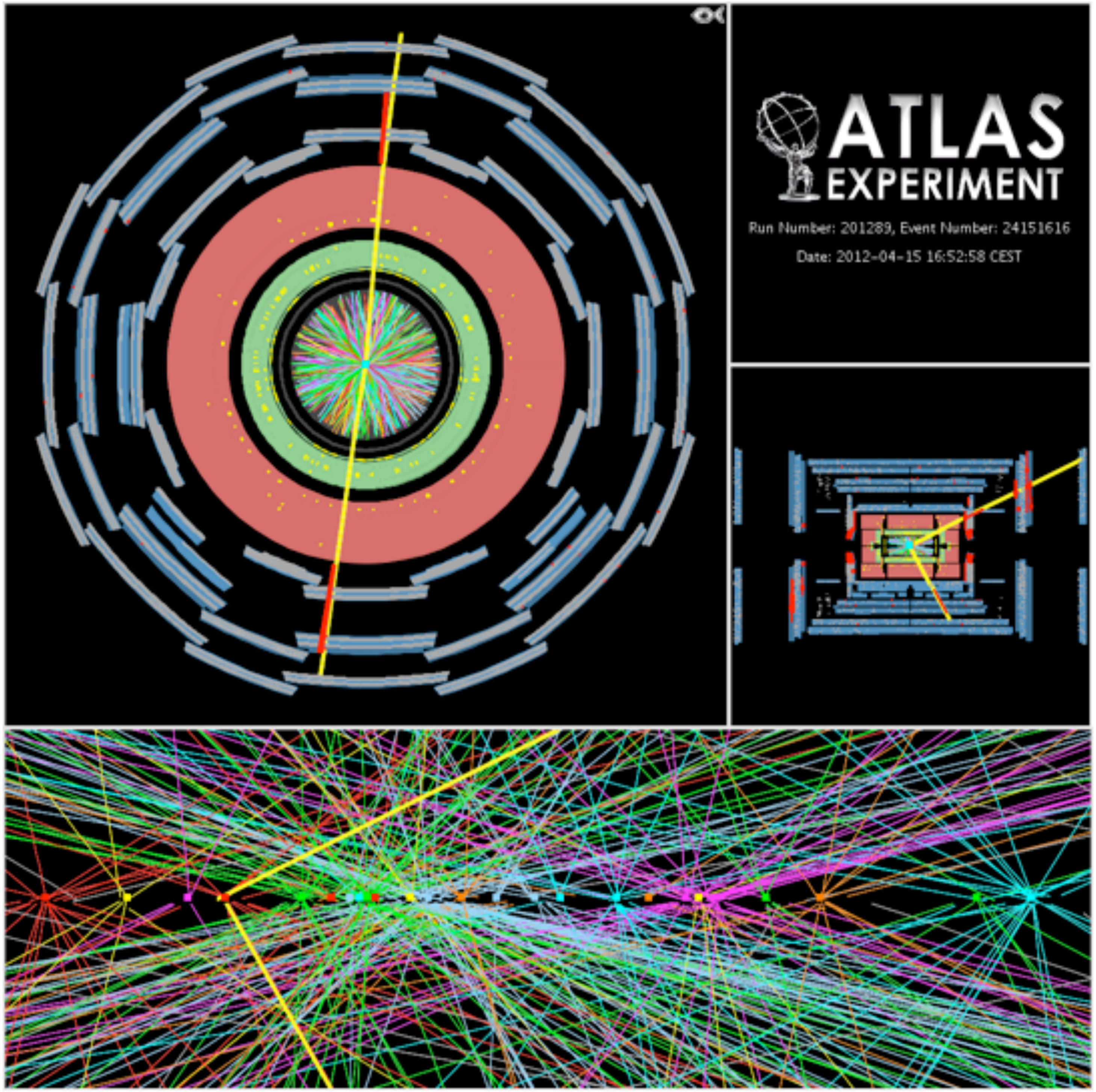
LHC Challenges Ahead

- High luminosity comes at a price: pileup
- LHC design luminosities
  - 2808 proton bunches per beam, 25 ns spacing
  - Instantaneous luminosities up to 10^{34} cm^{-2} s^{-1}
  - Up to 25 simultaneous proton-proton collisions per bunch crossing (“pileup”)
- Pileup 2012:
  - 1380 bunches per beam with 50 ns bunch spacing
  - Already now: 25–32 pileup vertices

Z → μμ with 25 Pileup Vertices



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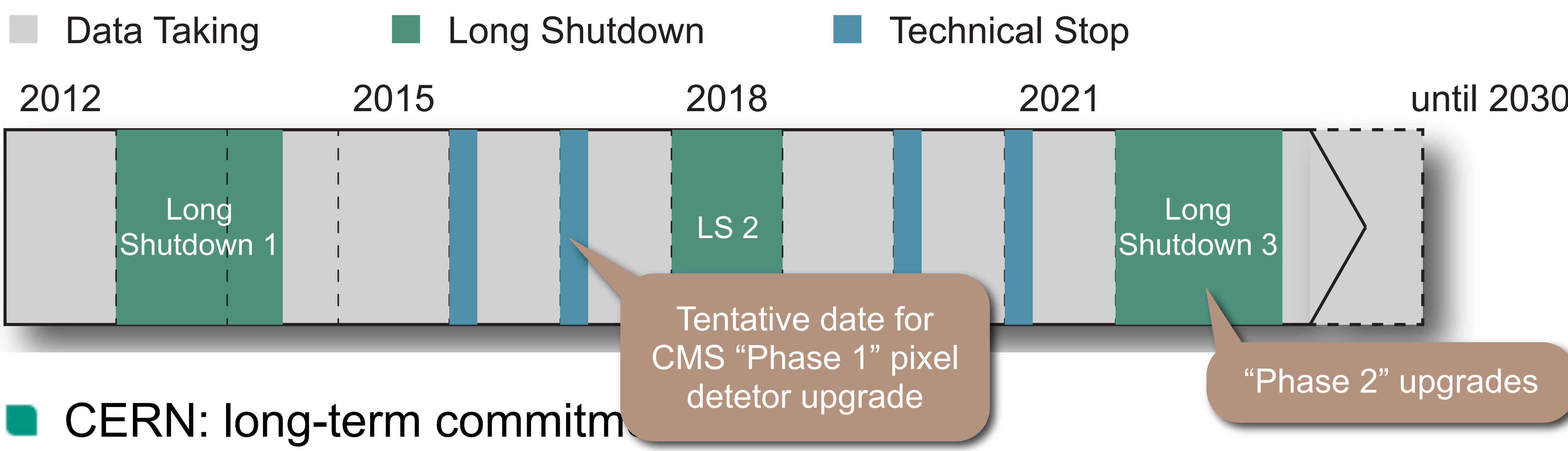
LHC Long Term Plan



- CERN: long-term commitment
  - Goal: deliver 3000 fb^{-1} of integrated luminosity by 2030
    → at least 5× increase in instantaneous luminosity
  - Detectors must be upgraded: current detectors suffer from aging and radiation damage, keep similar performance, improve radiation hardness at high luminosity
- According to current planning: three long LHC shutdowns for upgrades
  - 2013/14: LHC center of mass energy to 13–14 TeV
  - 2018: several machine upgrades
  - After 2022: start of high-luminosity phase of the LHC (HL-LHC)

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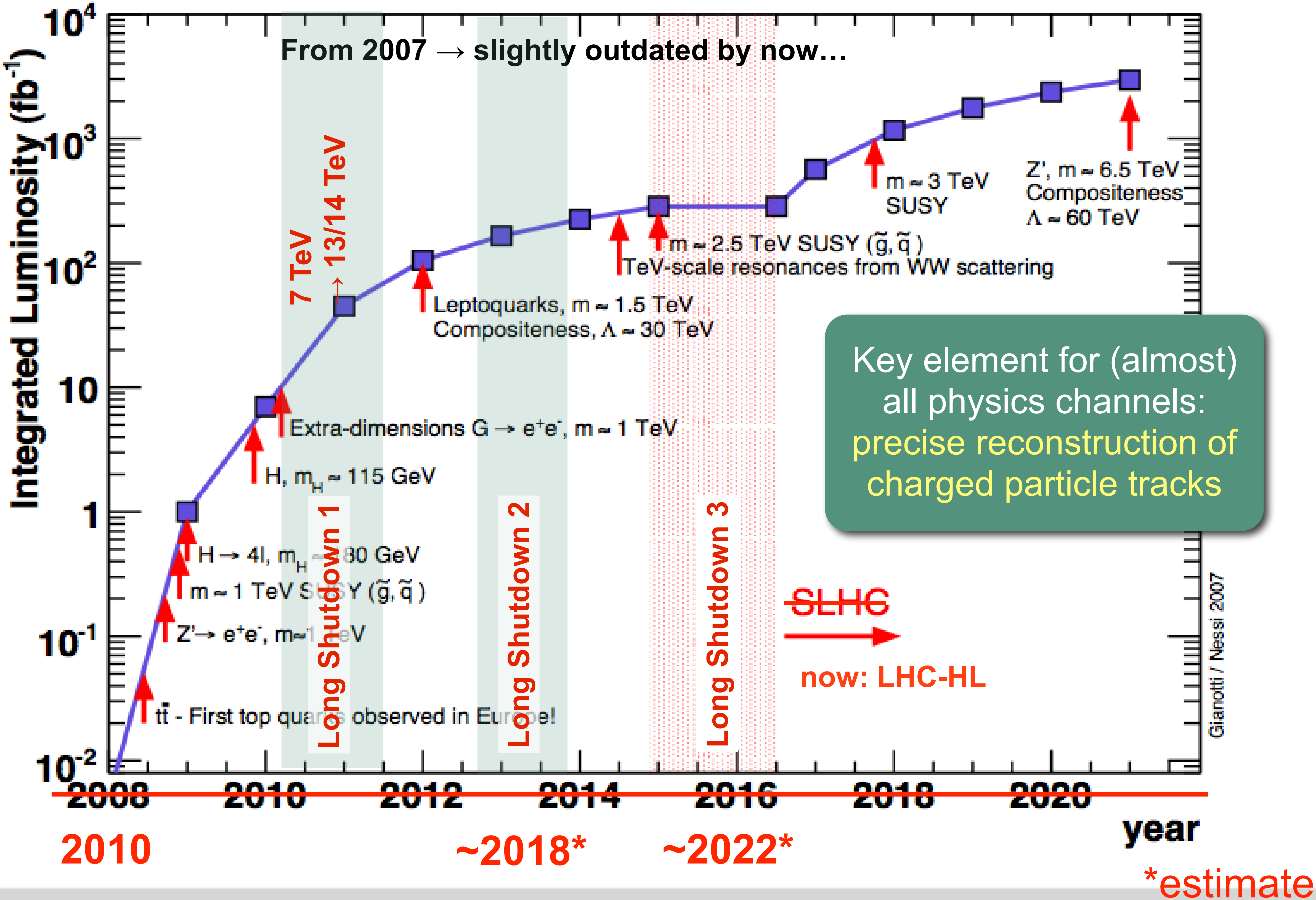
LHC High Luminosity Upgrade: Physics Case



Key element for (almost) all physics channels: precise reconstruction of charged particle tracks

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Pixel Detectors for Collider Experiments

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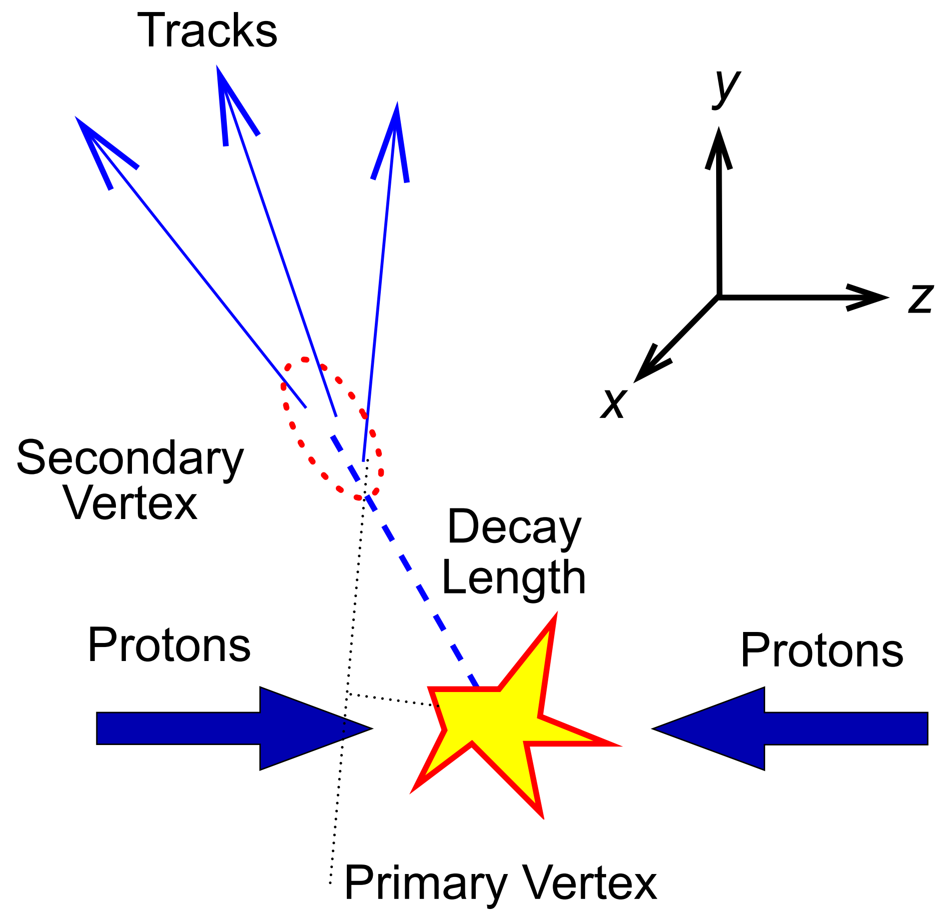
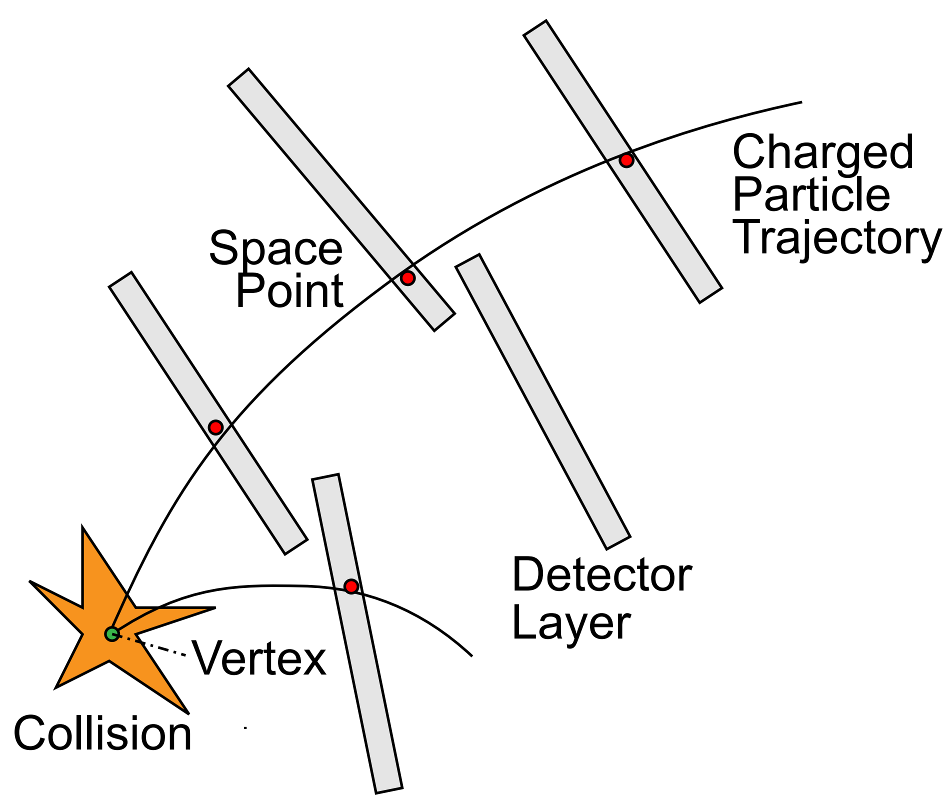
Tracking, Vertexing, and B-Tagging

- Tracking & vertexing
  - Charged particle tracking at small distances (~5 cm) from collision point: precise reconstruction of vertices
  - Charged particle tracking at large distances (~1 m): precise momentum measurement

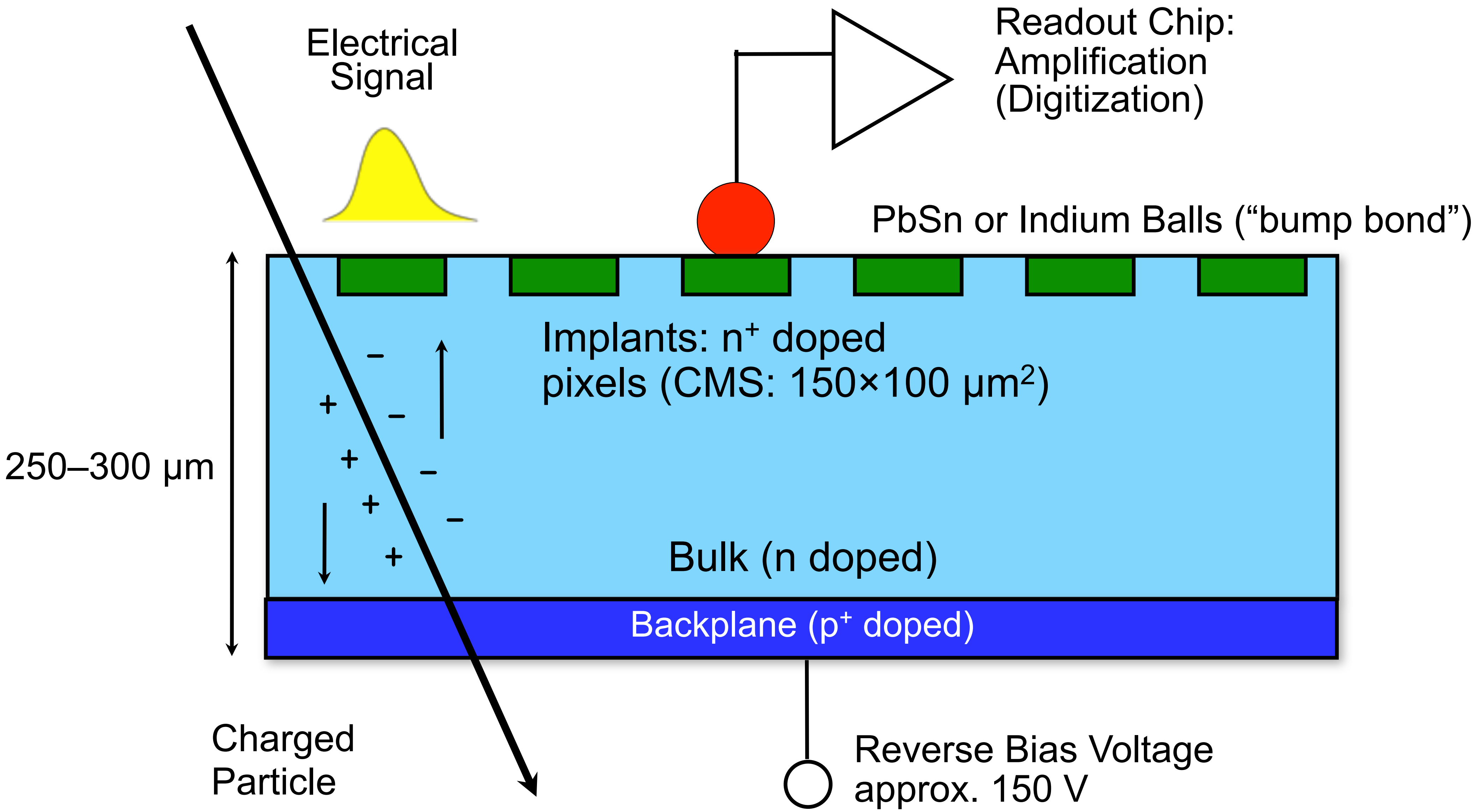




- B-tagging:
  - Identify hadrons with b-quarks via their long lifetimes (picoseconds)
  - Parts of the tracks from B hadron decays: large impact parameters and/or displaced secondary vertex

LHC Choice for Tracking Detectors: Silicon

- Innermost part of the tracking detectors: silicon hybrid pixel detectors
  - Detector = semiconductor diode with *pn* junction in reverse bias → depletion zone
  - Charged particles ionize detector material → electron/hole pairs induce signal



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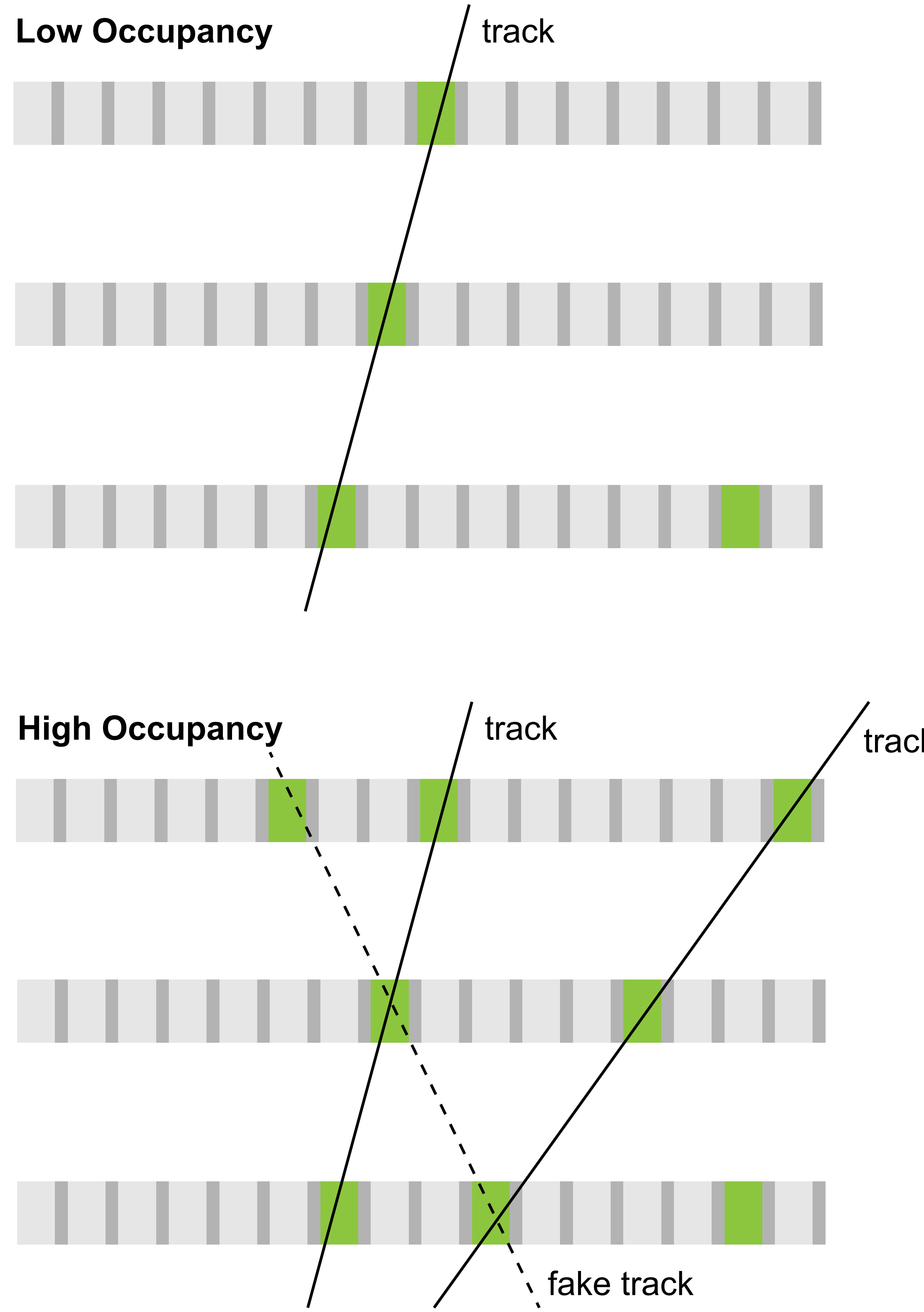
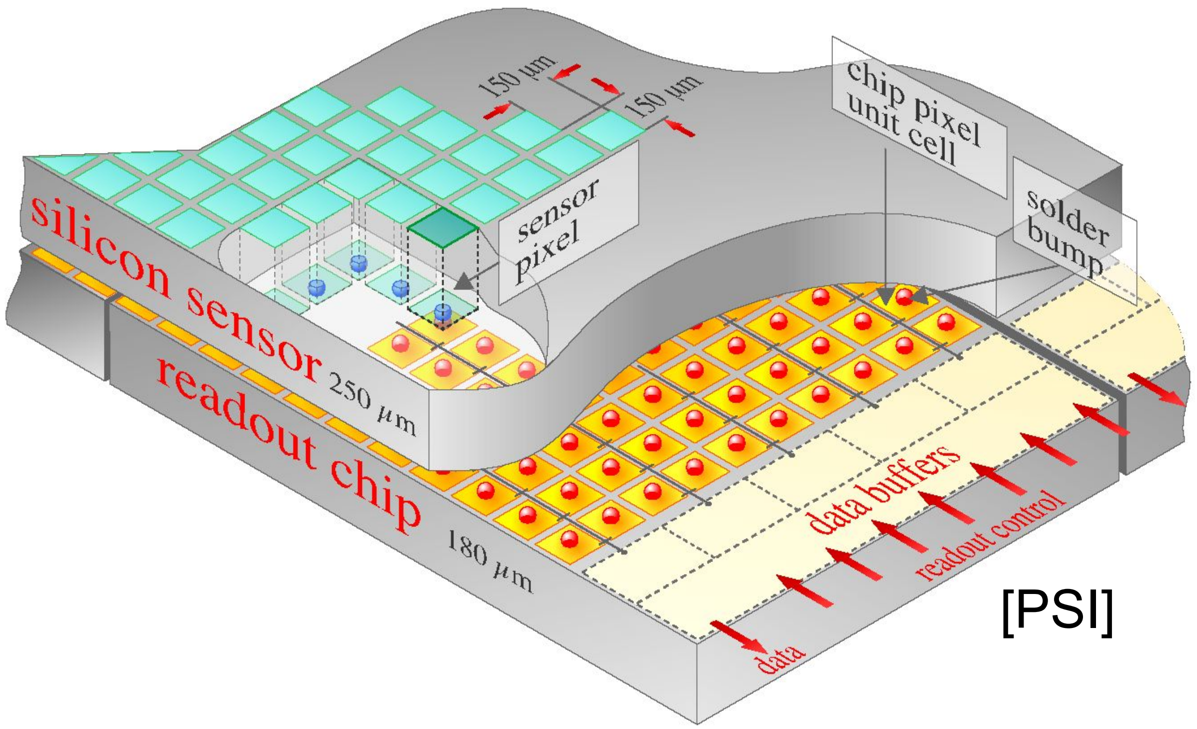
Tracking and Vertexing: Why Pixels?

- Resolution and material budget
  - Small pixels → high hit resolution → high track and vertex resolution
  - Material budget: 3D space point with a single detector layer
- Tracking advantages of highly segmented detectors
  - Low hit occupancy (= fraction of bunch crossings in which a pixel is hit) → low hit combinatorics
  - "Track seed" from region with smallest probability for wrong assignment of hits to tracks

Rule of thumb: tracking works for occupancies of 1% or less



Silicon Pixel Detectors – A Brief History



[PSI]

Hybrid Pixel Detectors

- Silicon sensor and readout chip: separate devices
- Readout chip: one circuit per pixel
- Interconnects: solder bumps

- First ideas for a hybrid pixel detector
  - Gaalema (1984): first pixelated X-ray detector (Hughes Aircraft Co.) …
  - … followed by first serious work on hybrid pixel detectors for particle physics at CERN, SLAC, LBNL
- Late 1980ies: pixel detectors = tracking option for SSC and LHC
  - CERN: R&D Collaboration (RD19)
  - First small scale applications: fixed target and LEP
- Today: ALICE, ATLAS, and CMS use hybrid pixel detectors

For a historical review see:
E. Heijne, NIM A465 (2001) 1

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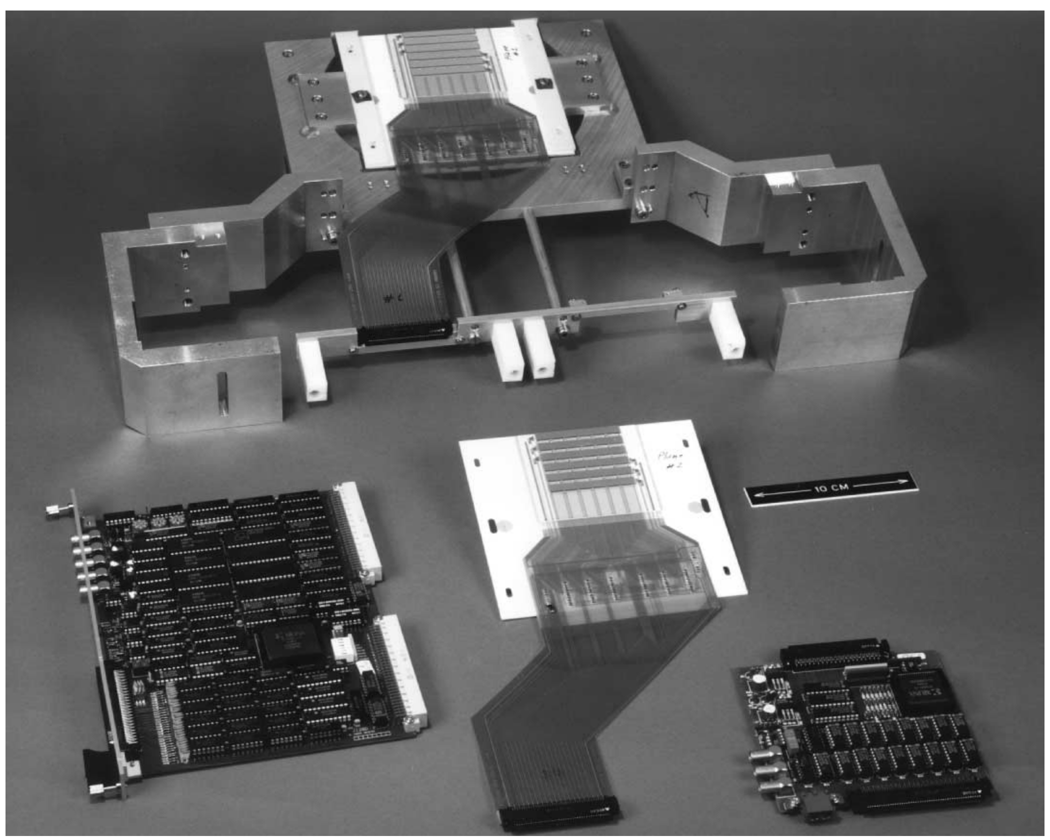
First Experience: Heavy Ion Pixel Telescope

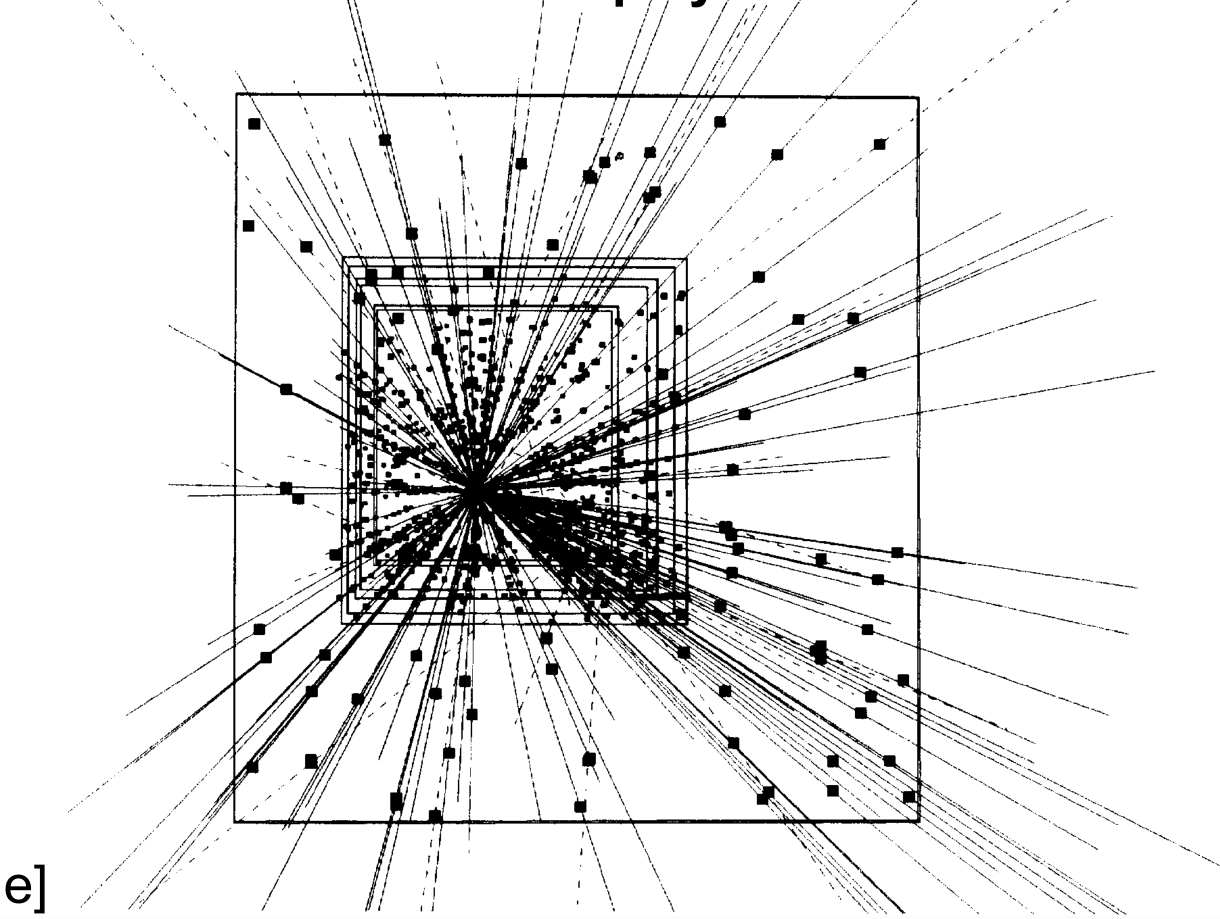
- First use case at CERN: WA94/WA97/NA57 fixed target experiments – strangeness production in heavy ion collisions (Pb)
- Occupancy similar to LHC, but much smaller rate
- Pixel telescope: 7 layers parallel, 500,000 channels total

Omega2 Pixel Array and Readout Electronics



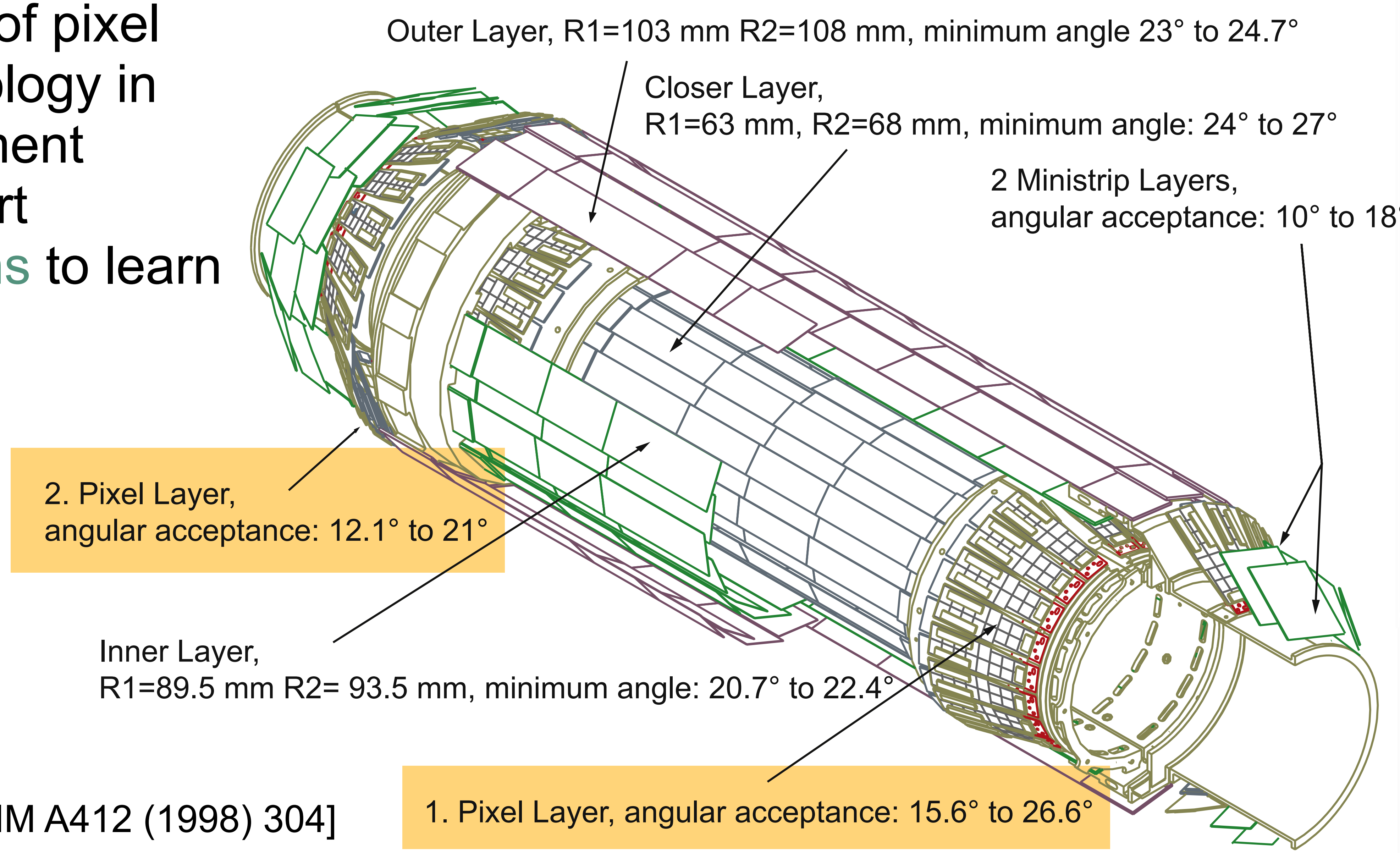
[Heijne]

Event Display



First Long-Term Test: DELPHI

- Upgrade of DELPHI micro-vertex detector for LEP2: two pixel layers in very forward region
- Long term test of pixel detector technology in collider experiment before LHC start
→ many lessons to learn



[NIM A412 (1998) 304]

The CMS Pixel Detector

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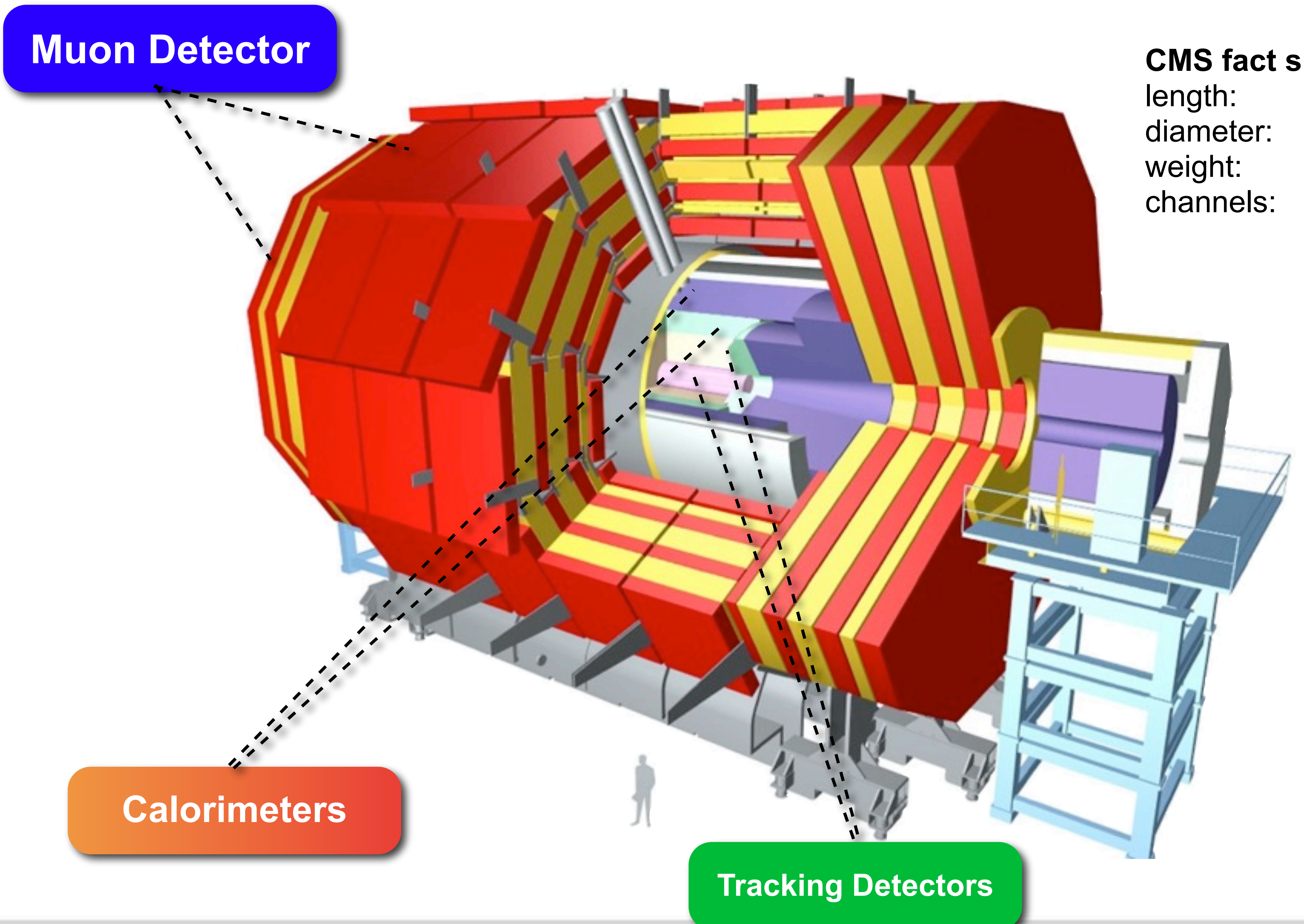
CMS – Compact Muon Solenoid



CMS fact sheet

length:	21 m
diameter:	15 m
weight:	14 ktons
channels:	80 M

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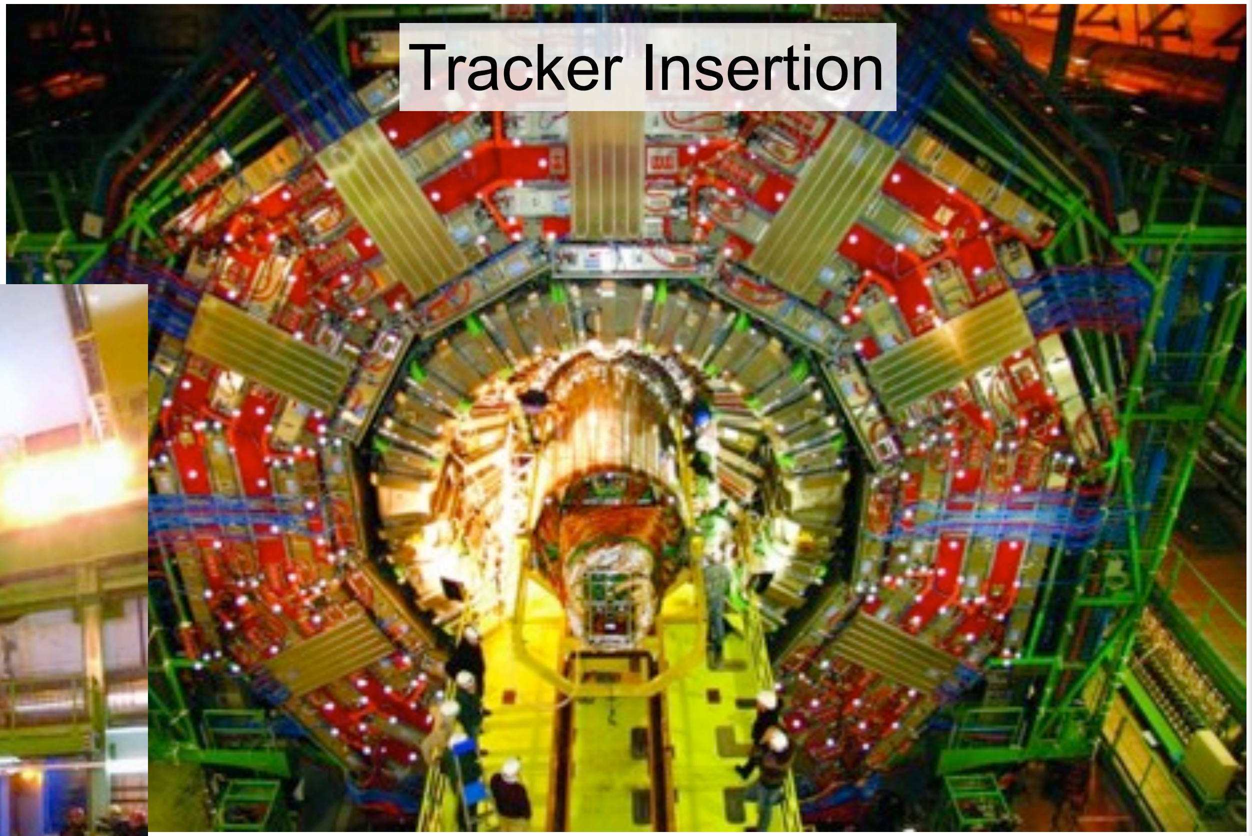
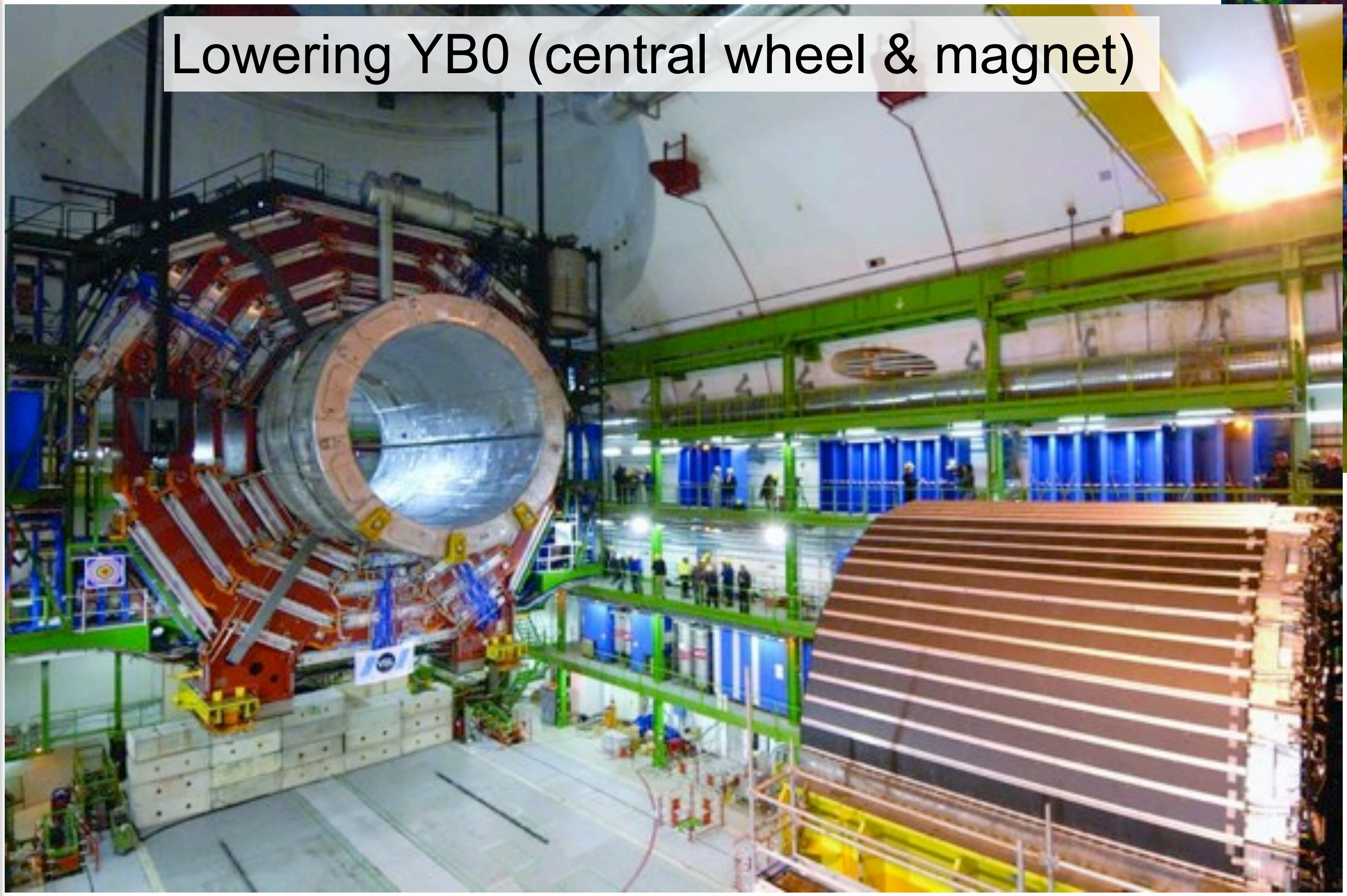
CMS Photo Gallery





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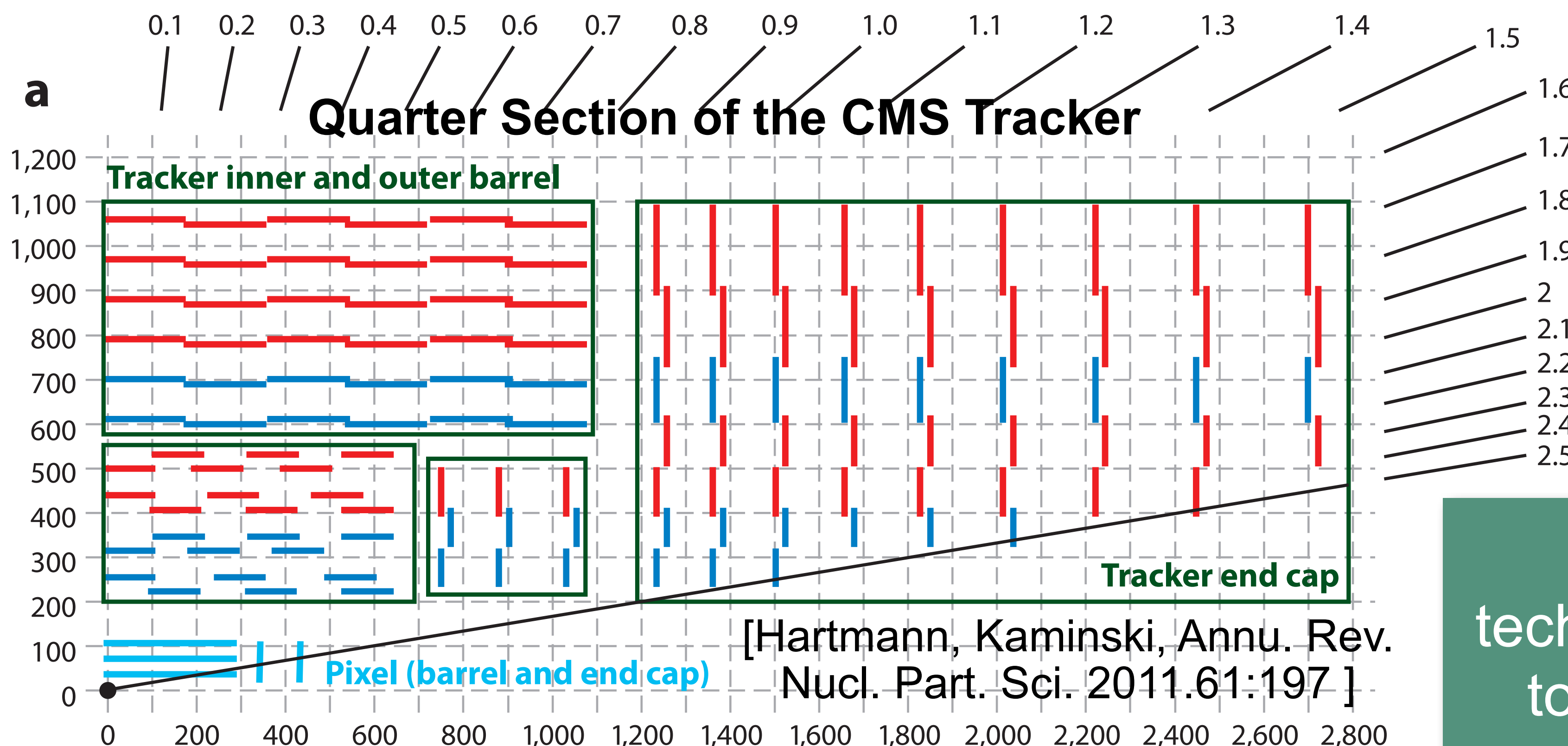
CMS Tracker Design



[Hartmann, Kaminski, Annu. Rev. Nucl. Part. Sci. 2011.61:197]

Note time scales: pixel technology choice dates back to CMS Tracker Technical Design Report 1998

- General CMS tracker design
  - Large all-silicon tracker, > 200 m^2 of active area
  - High magnetic field (3.8 T) → excellent momentum resolution
- Pixel detector design considerations in CMS
  - Small radii (4–11 cm) → excellent impact parameter resolution, low cost
  - High magnetic field → exploit charge sharing through Lorentz drift

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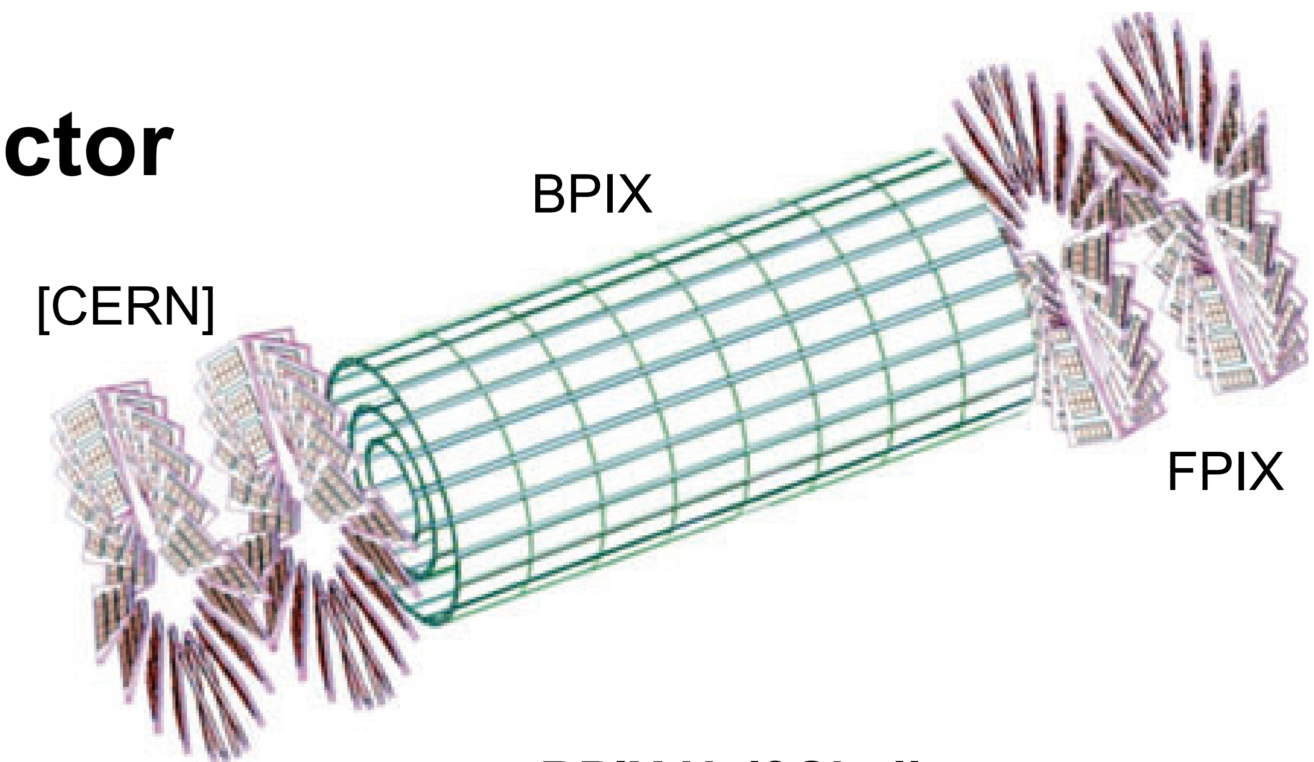
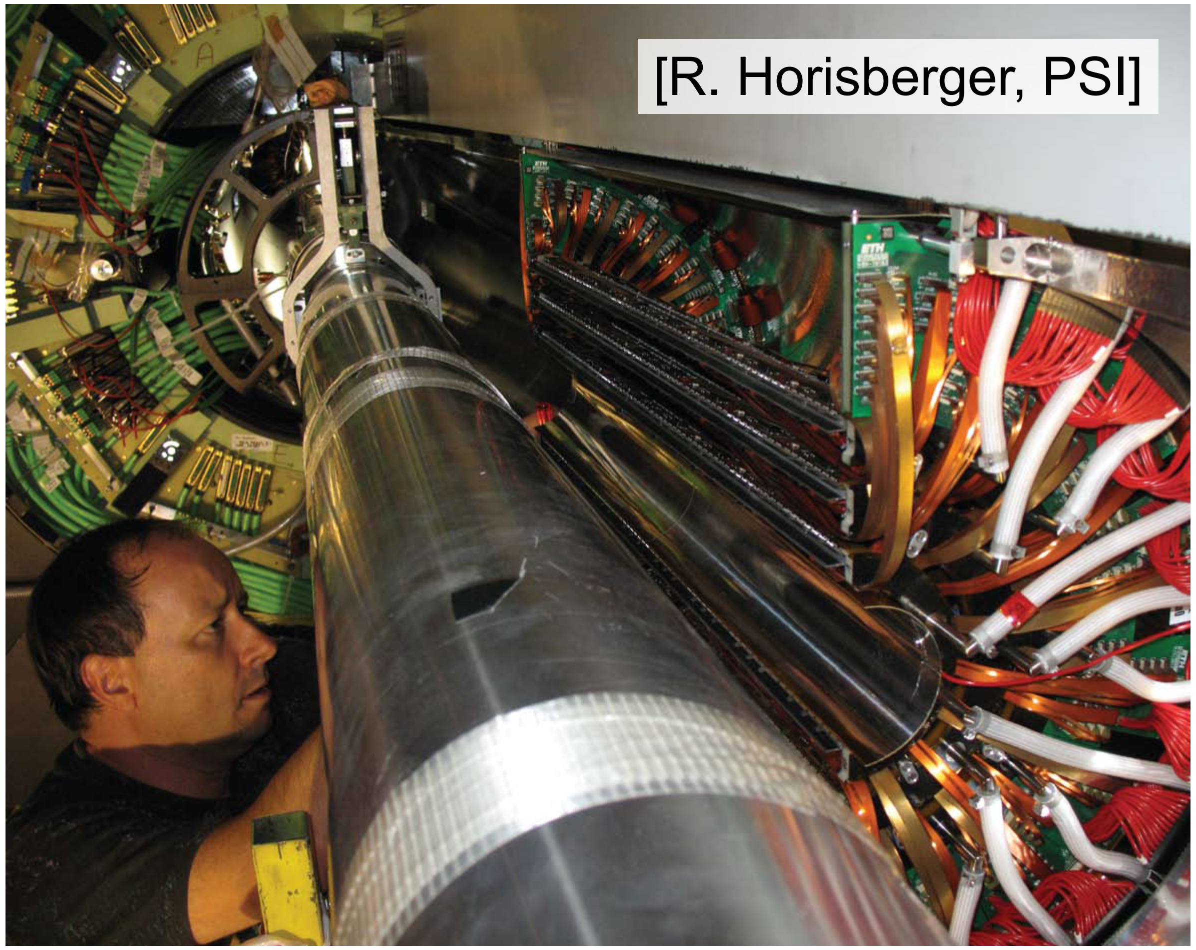
The Current CMS Pixel Detector

- Separated into barrel and forward pixel detectors
  - BPIX: three layers
  - FPIX: two times two disks
- Mechanics:
  - Light-weight and modular
  - "Easy" installation/removal



BPIX Half Shell

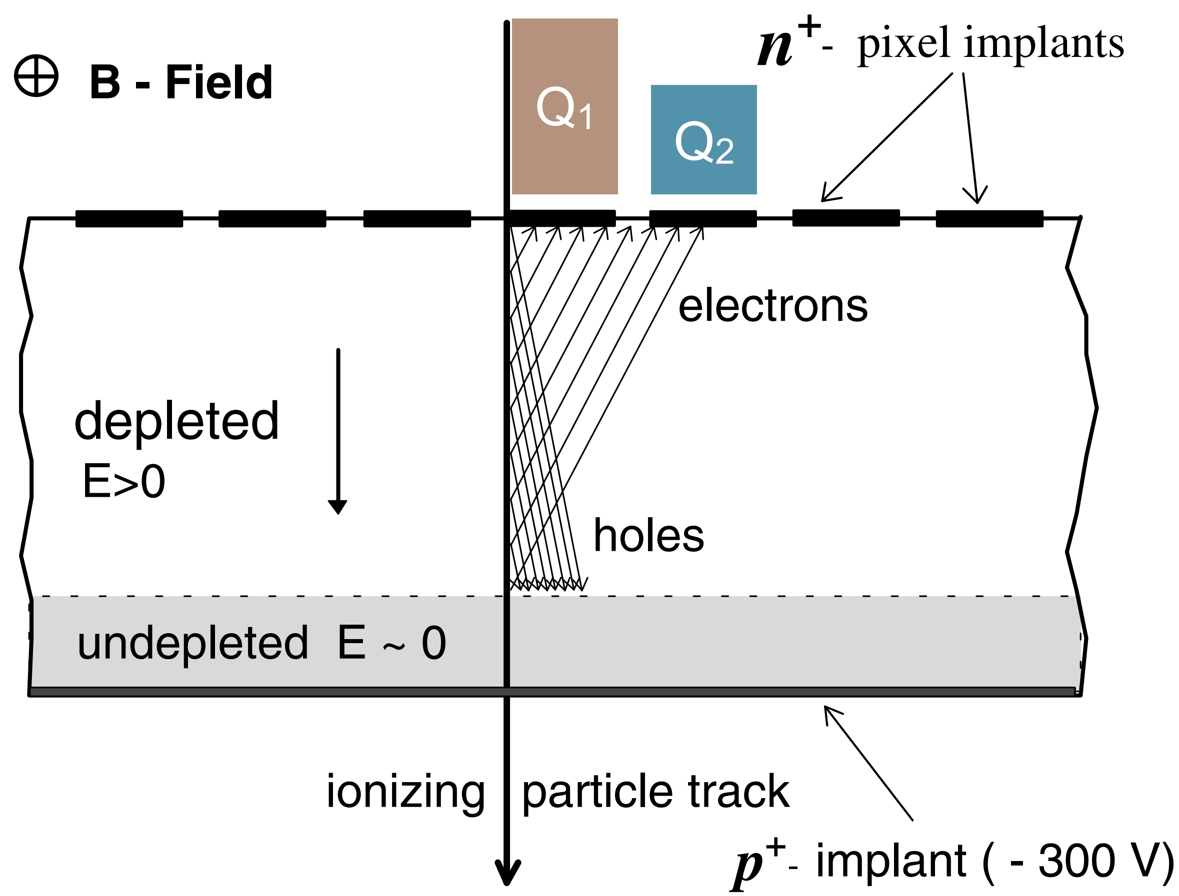


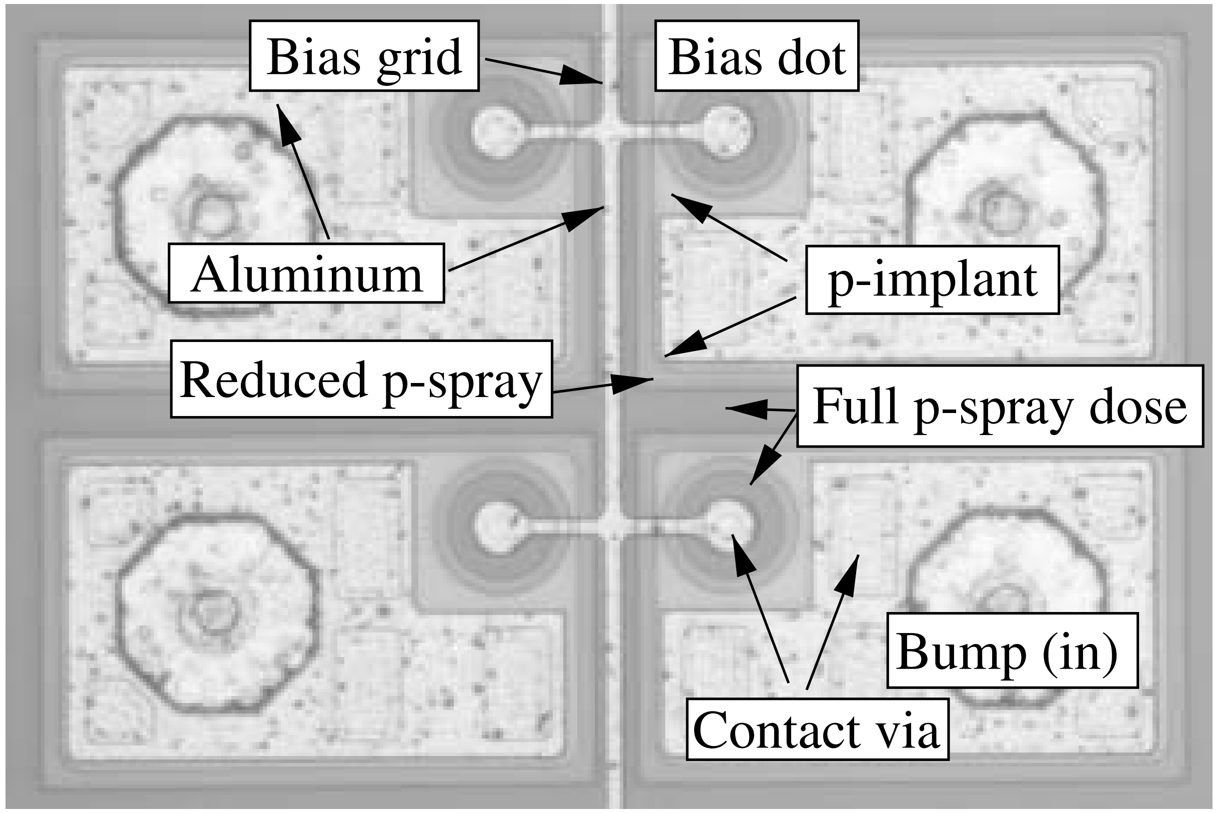
FPIX Half Disk

Pixel Sensor: Precision Through Sharing

Current sensor technology sufficient for Phase 1 upgrade

- CiS n^+-in-n sensor → collect electrons
- Improve hit resolution by charge sharing:
  - Almost quadratic pixels: 100x150 μm^2 → similar resolution in rφ and z
  - Exploit strong electron Lorentz drift in 3.8 T magnetic field
  - Most accurate measurement of pulse height: analog readout

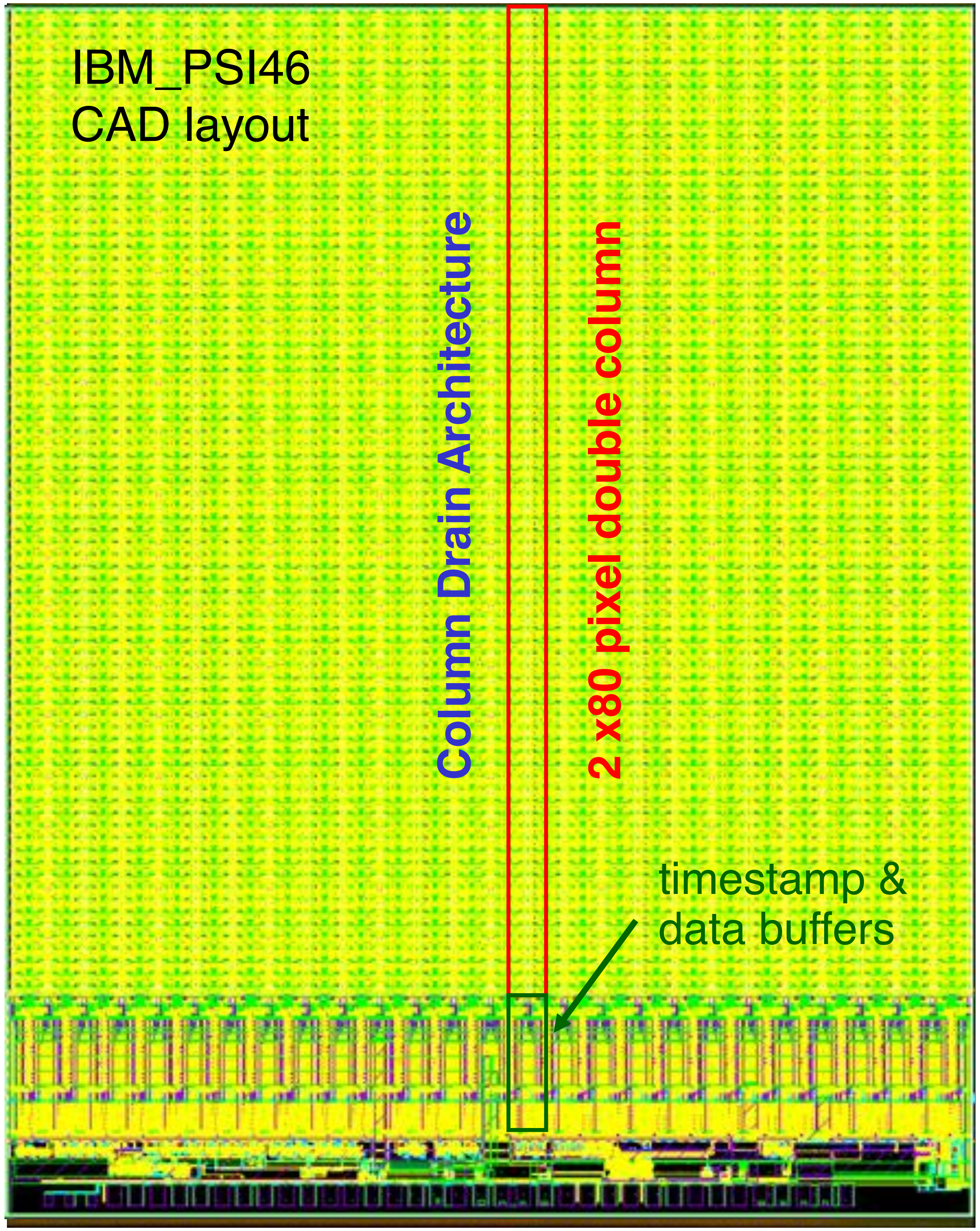




[W. Erdmann,Int. J .Mod. Phys. A25 (2010) 1315]

The PSI46 Readout Chip

- Chip features
  - 250 nm IBM process
  - Area: 7.9 mm × 9.8 mm, five metal layers
  - Analog readout at 40 MHz
- Basic layout
  - Pixel array: 52 columns, 80 pixel unit cells in each column
  - Periphery: transfer and store pixel hits, trigger timestamp
- Discriminator threshold: <2500 electrons



Readout by double column and buffer sizes: serious rate limitations above 10^{34} cm^{-2} s^{-1} at 50 ns bunch spacing (100 MHz/cm^2)→ upgrade required!

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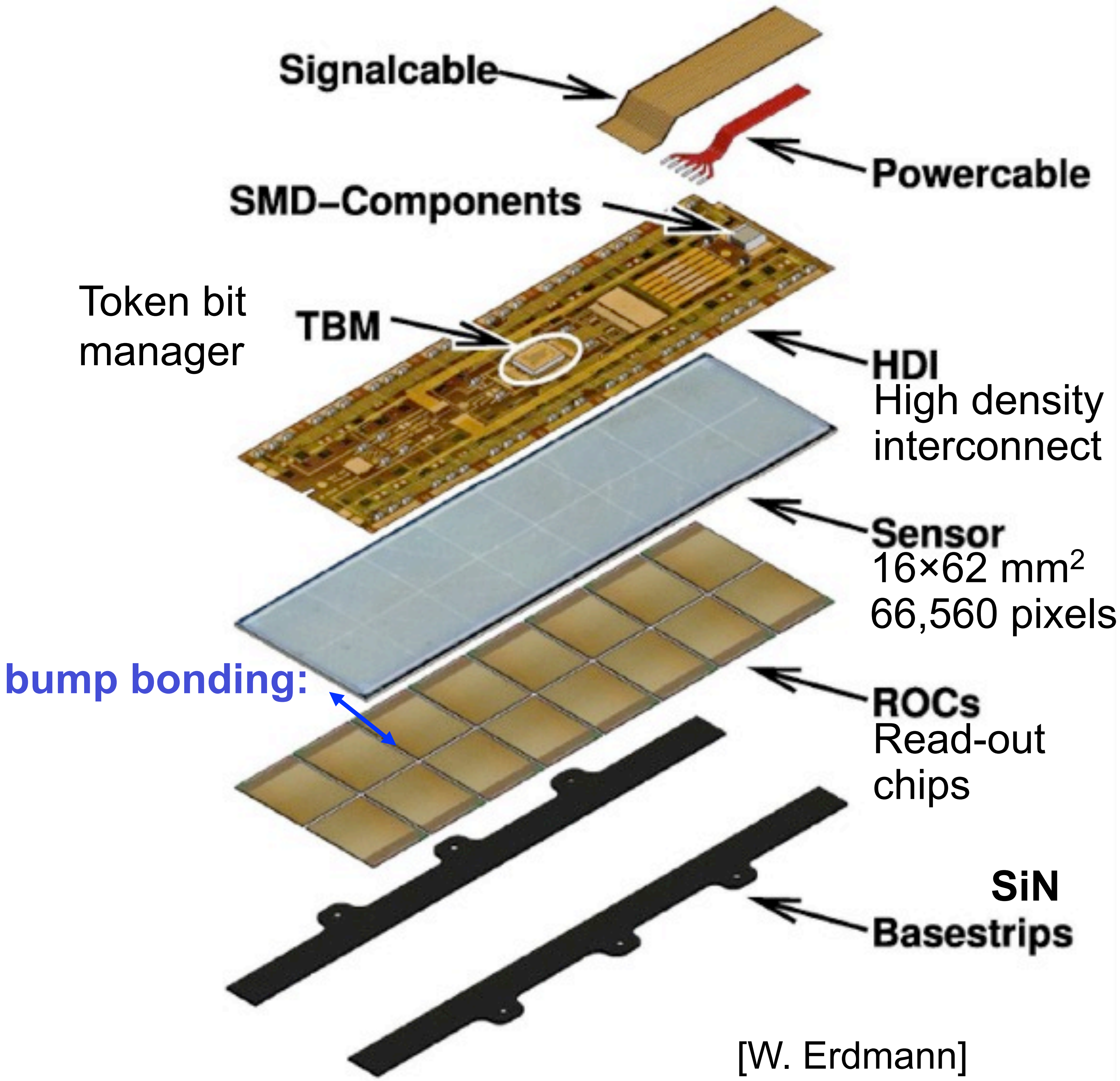
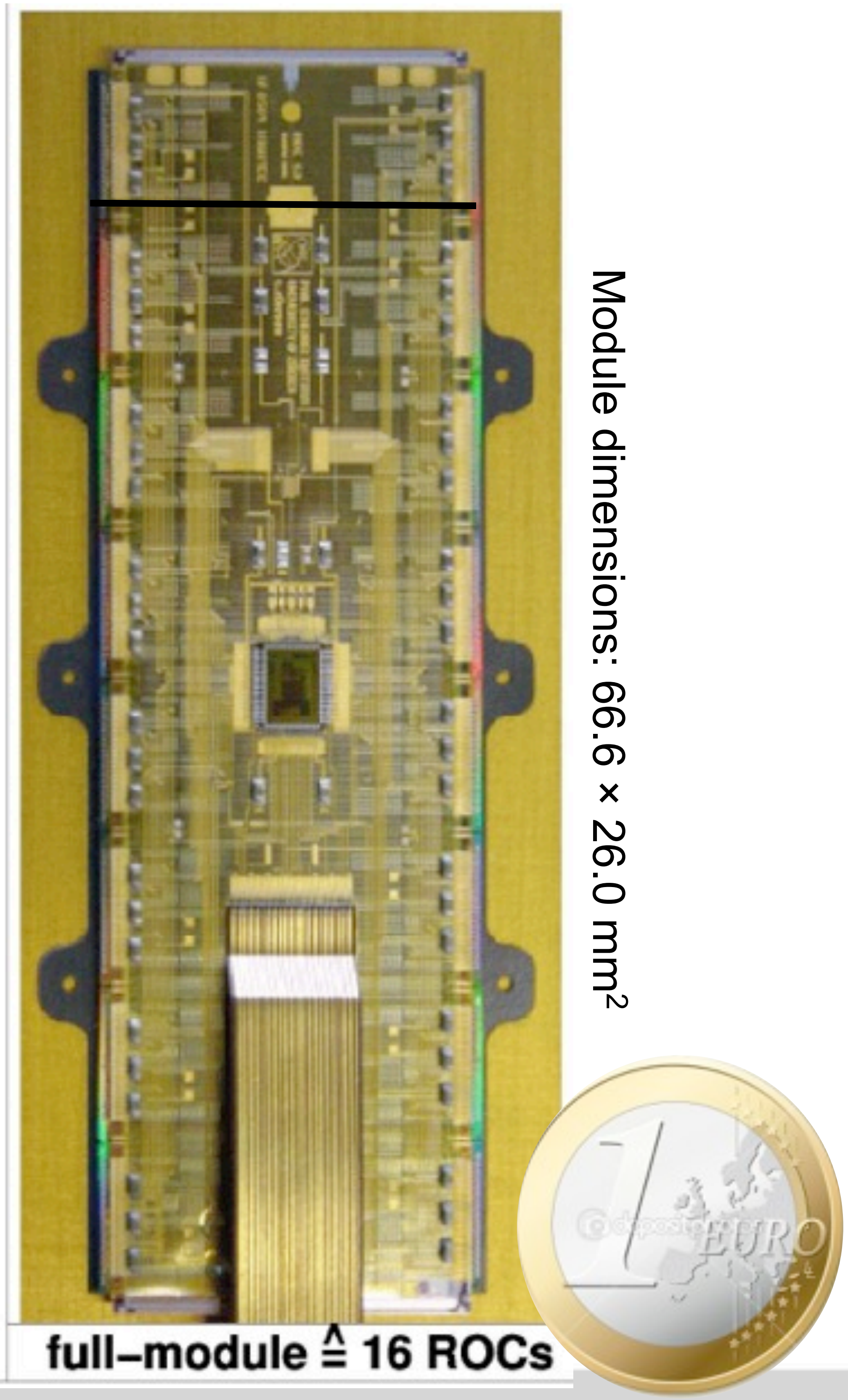
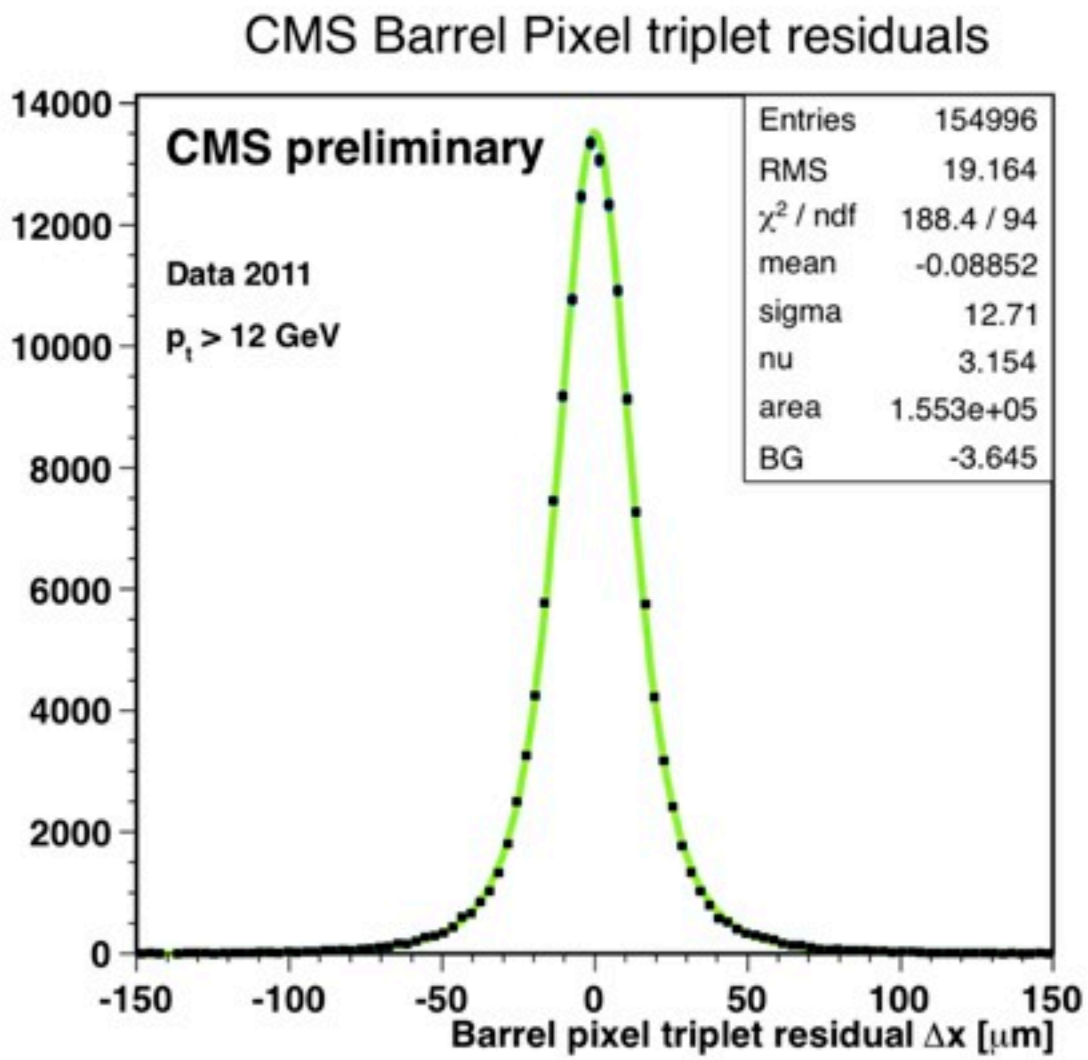
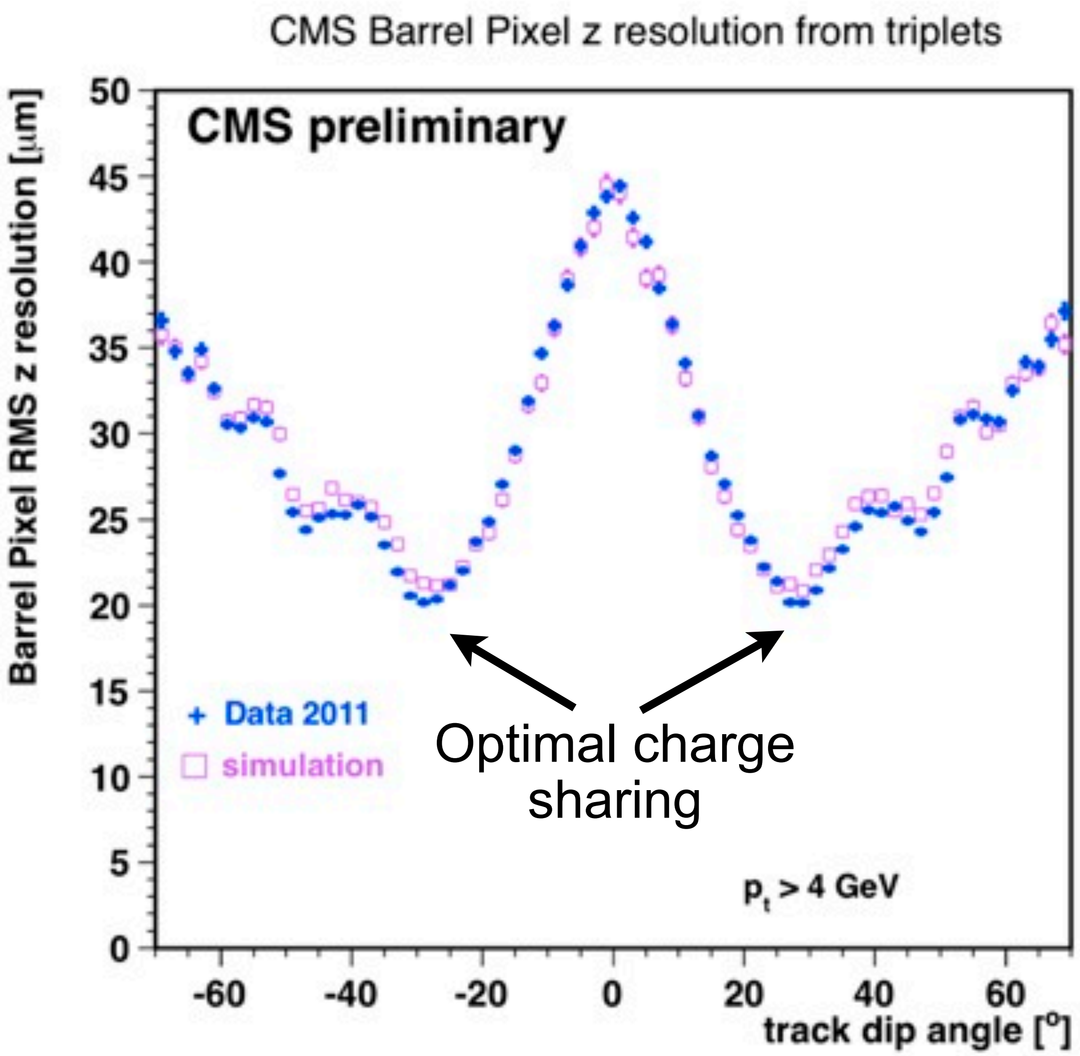
CMS Barrel Pixel Module





CMS Pixel Performance





[https://twiki.cern.ch/twiki/bin/view/CMSPublic/DPGResultsTRK]

- Single hit efficiency: >99%, measured rφ resolution: 13 μm
- Data taking efficiency: 97% of pixel channels operational, 99% uptime

The CMS Phase 1 Pixel Upgrade

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General Phase 1 Pixel Upgrade Strategy

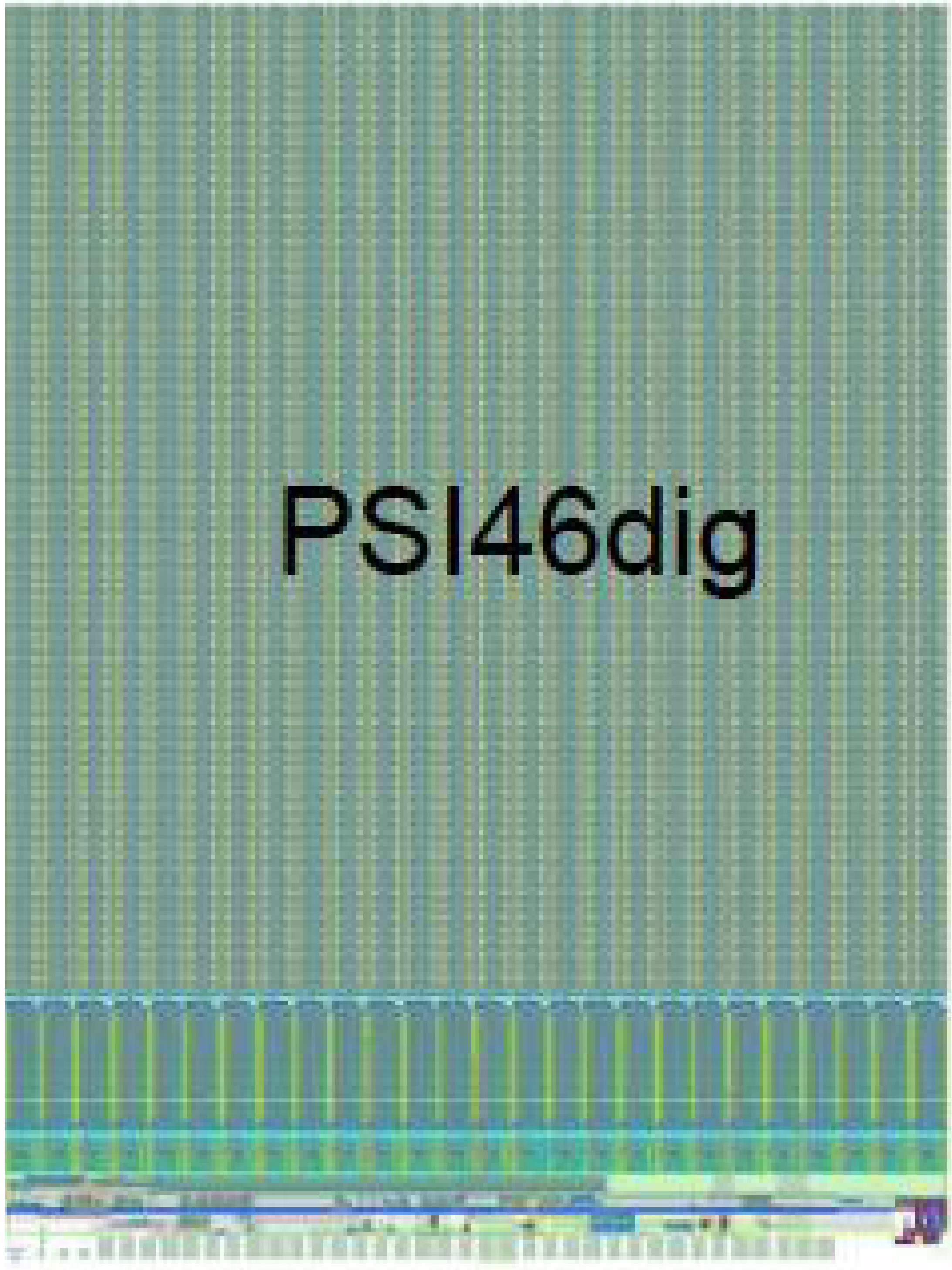
Goal: similar pixel performance in much harsher environment

Modification	Impact
New digital readout chip	Front-end electronics ready for high rates
More layers: 3→4 barrel layers, 2×2→2×3 forward disks	More 3D pixel space points, more tracking redundancy
Smaller radius of innermost layer	Improved impact parameter resolution (key to excellent B-tagging at high pileup)
Improved mechanics, cooling, and powering	Reduced material budget: less multiple scattering, fewer photon conversion

New CMS Pixel Readout Chip

Karlsruhe Institute of Technology

- Goal: overcome rate limitations of current readout chip ($100\ MHz/cm^2 \rightarrow 250\ MHz/cm^2$)
- Strategy: modest evolution of current chip (staying at 250 nm)
- First chip iteration:
  - Digital readout: 8-bit ADC for pulse height
  - 6th metal layer → reduce cross-talk, lower threshold
  - Larger buffers for data and time stamps
  - First version received from foundry, some minor issues, in testing phase
- Second chip iteration:
  - Improved column drain architecture
  - Submission planned in late 2012



[B. Meier et al., PSI]

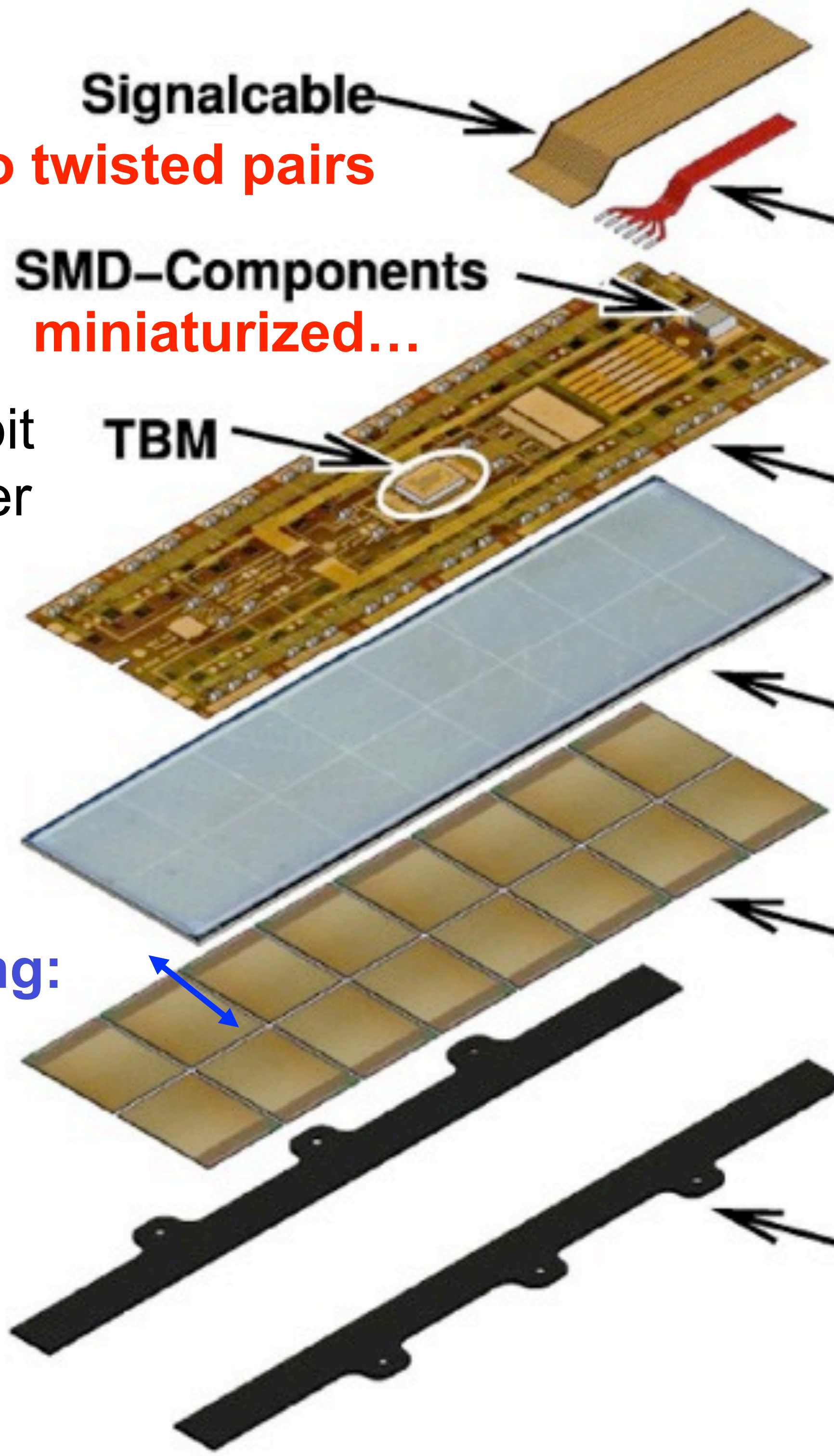
Upgraded Barrel Pixel Module

upgrade: micro twisted pairs

miniaturized…

Token bit manager

bump bonding:

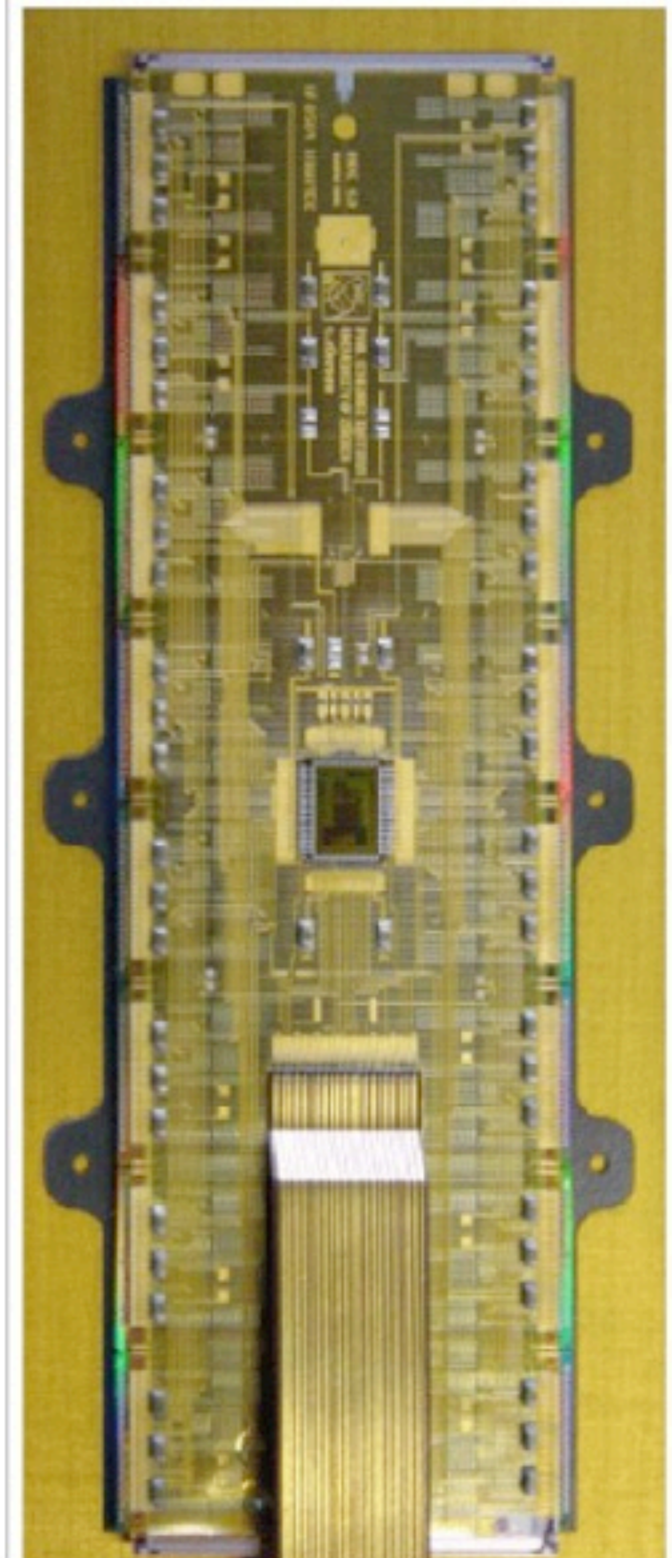


High density interconnect

16×62 mm^2
66,560 pixels

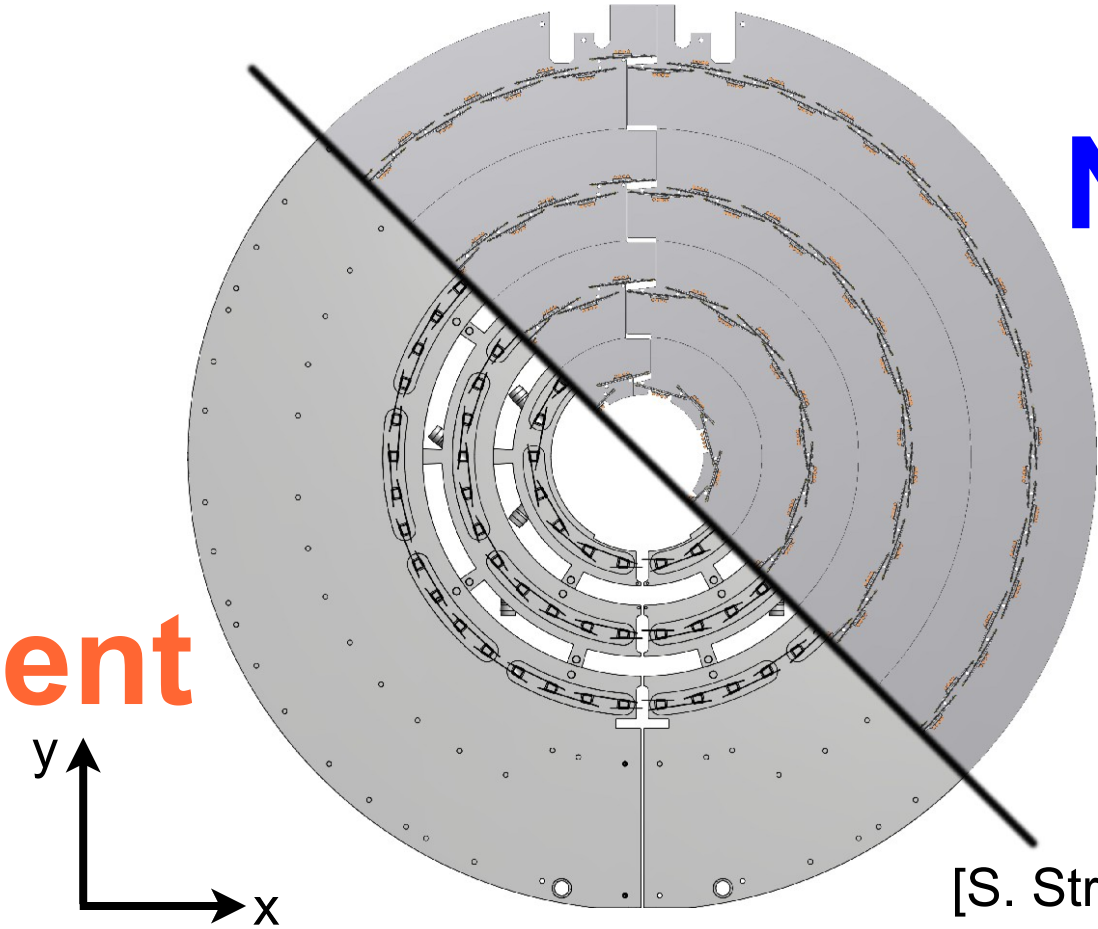
new digital readout chip

[G. Steinbrück after W. Erdmann]



full–module ≙ 16 ROCs

Changes to Barrel Pixel Detector Mechanics



Present	New
3 Sensor Layers (768 Modules)	4 Sensor Layers (1184 Modules)
Lightweight Mechanics	Ultra-Lightweight Mechanics
C_6F_{14} Cooling	CO_2 Cooling
Support Tube with Readout/Control Electronics	Lightweight Support Tube, Electronics moved to $\|\eta\|>2.2$

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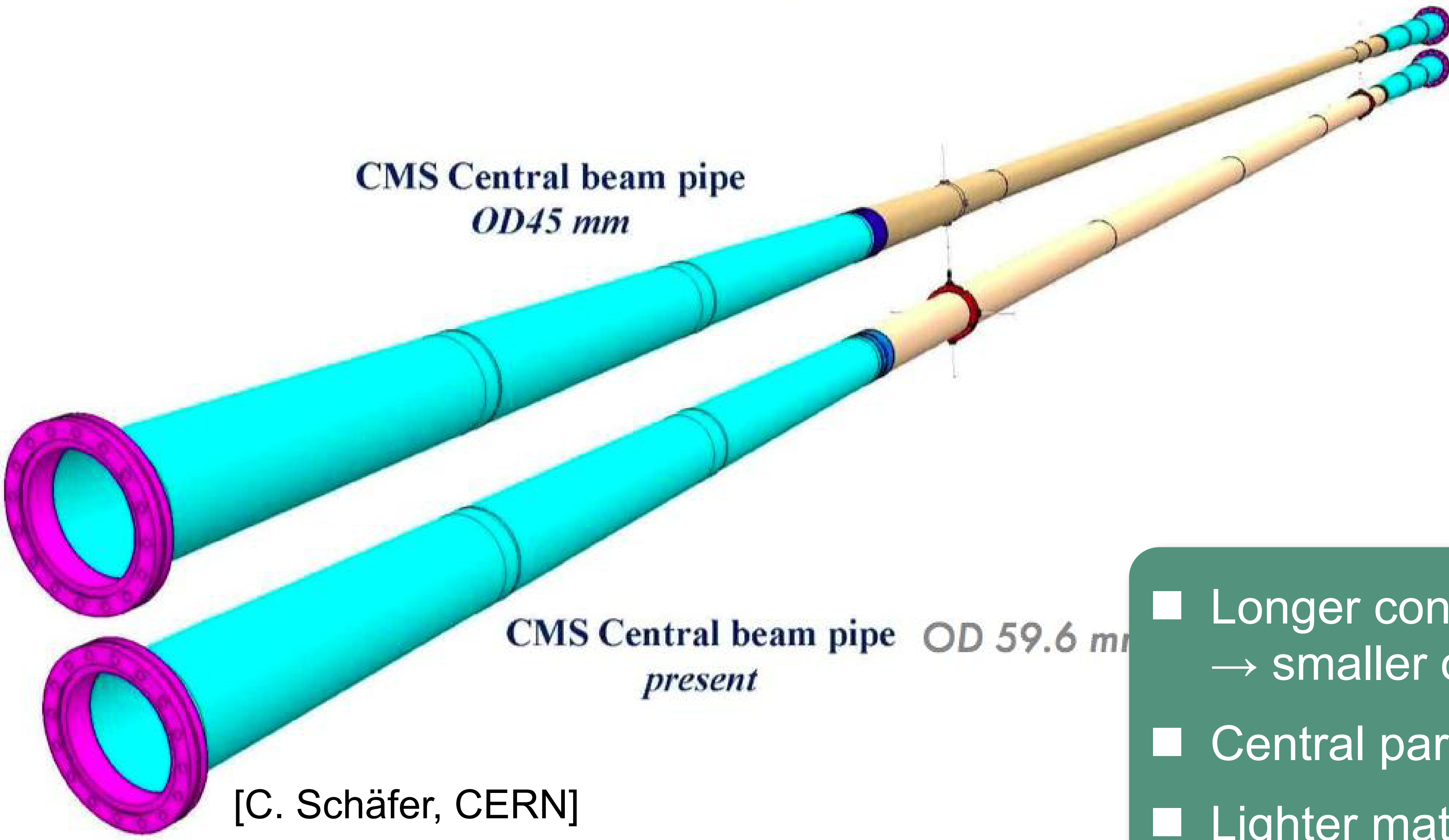
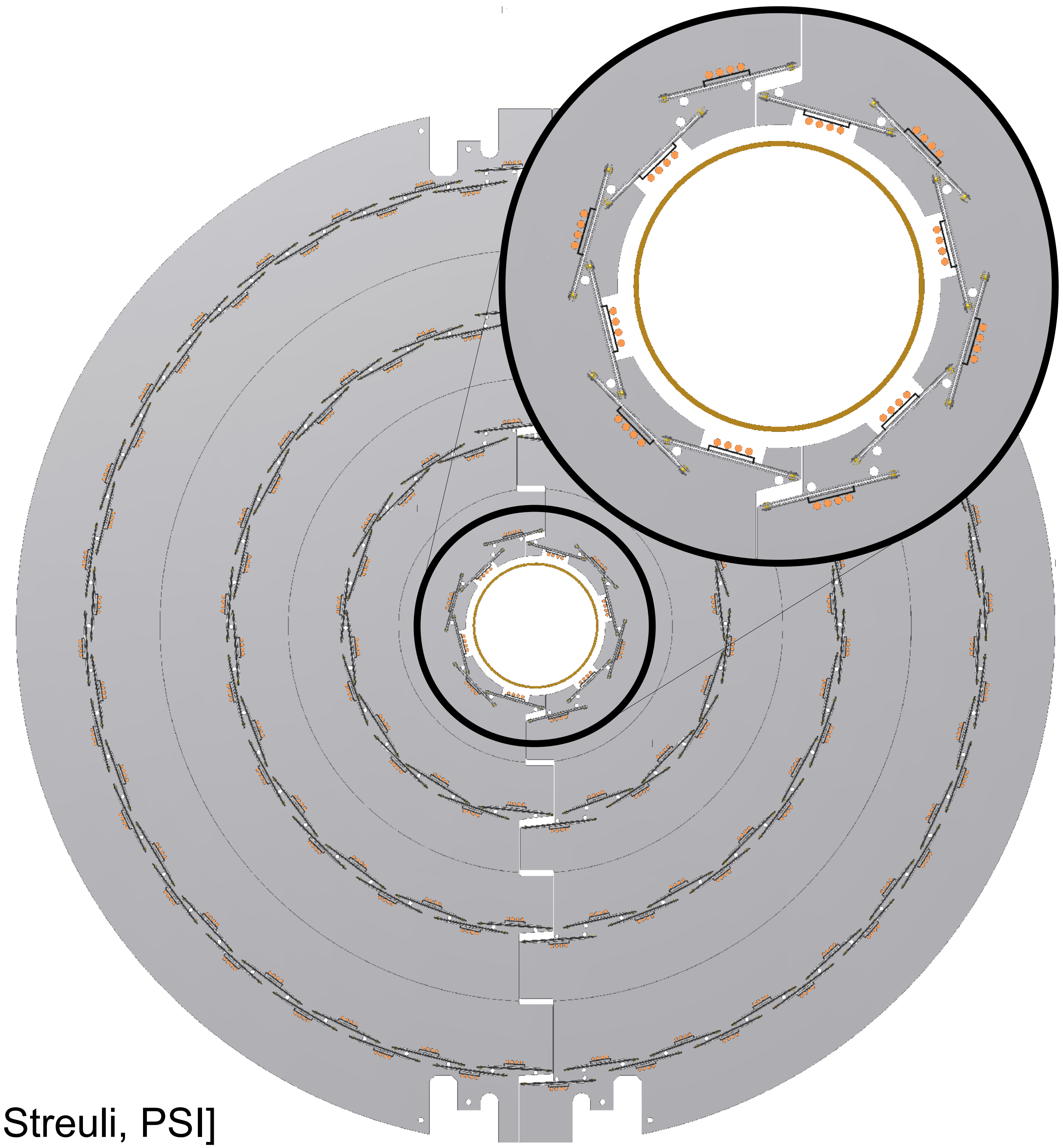
New Central Beam Pipe



[C. Schäfer, CERN]

- Longer conical section → smaller outer diameter
- Central part: 0.8 mm beryllium
- Lighter material in outer part: AlBe instead of stainless steel
- Installation in Long Shutdown 1 (2013/2014) → flexible scheduling of pixel installation

New Four-Layer Barrel Pixel Detector

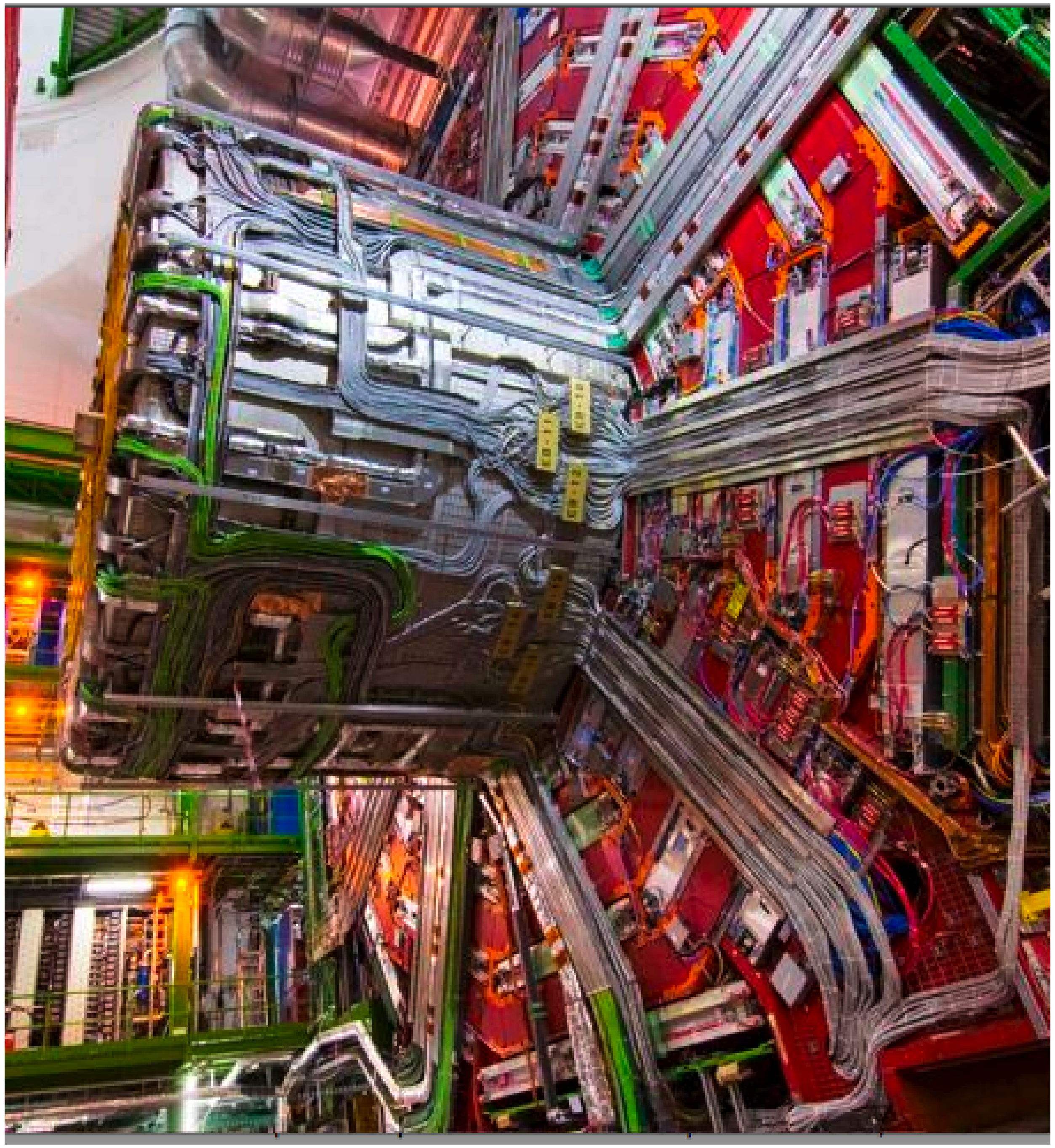


[S. Streuli, PSI]

- Two identical half-shells
- Layer positions:
  1. R = 29 mm, 12 faces
  2. R = 68 mm, 28 faces
  3. R = 109 mm, 44 faces
  4. R = 160 mm, 64 faces
- Innermost layer:
  - Radius reduced from 44 mm to 29 mm
  - 2.5 mm clearance to new beam pipe (outer diameter: 45 mm)
- New outermost layer: additional 3D space point at 160 mm

Pixel Services

- Detector "services" = all cables, pipes, optical fibers
- Most pixel services are "buried" deep in CMS detector
  - Must reuse existing power cables, optical fibers, cooling lines
  - But: need to supply power, cooling and readout to 1.9 times more readout chips
- Cooling solution: CO_2
- Powering solution: "high-voltage" power lines & DC-DC conversion
- Readout solution: 40 MHz analog readout → 320 MHz digital readout



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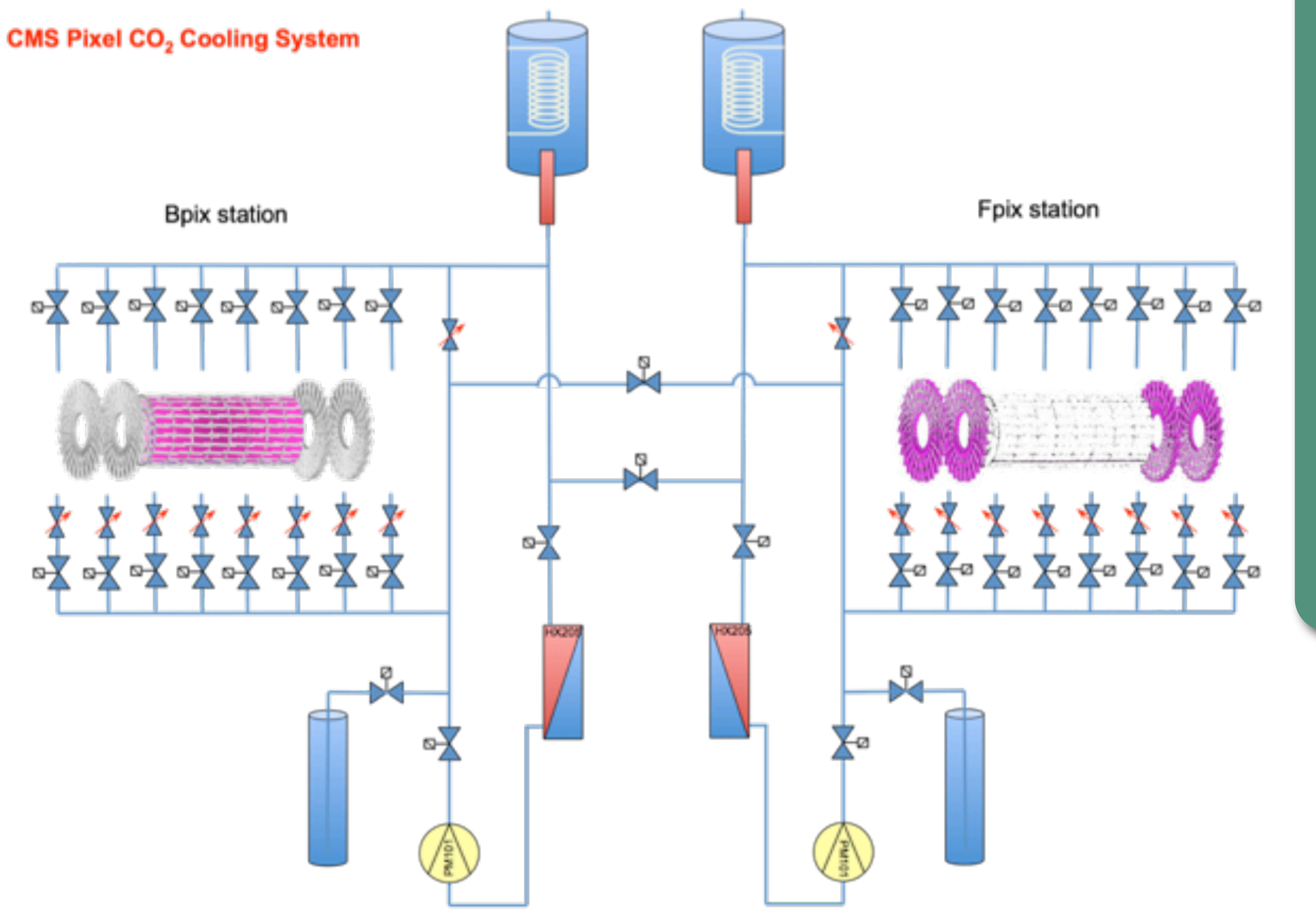
CO_2 Cooling



[H. Postema, B. Verlaat, CERN]

Advantages of CO_2 cooling:

- Large latent heat, low viscosity, low coolant mass
- High pressure → small tubing
- Radiation hard, non-corrosive, non-toxic

Implementation à la LHCb/ AMS: 2PACL (two-phase accumulator controlled loop)

Two redundant systems for barrel and forward pixels

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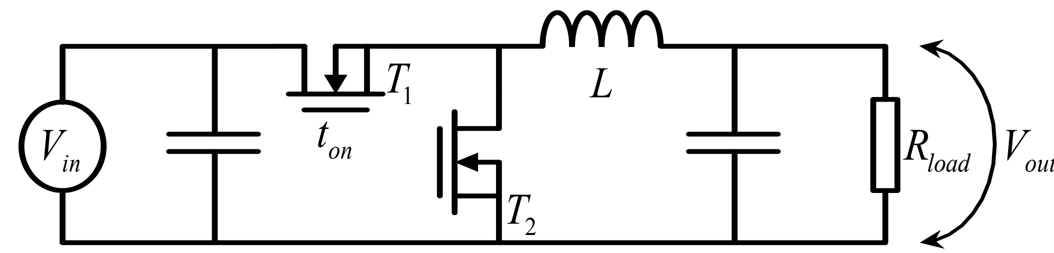
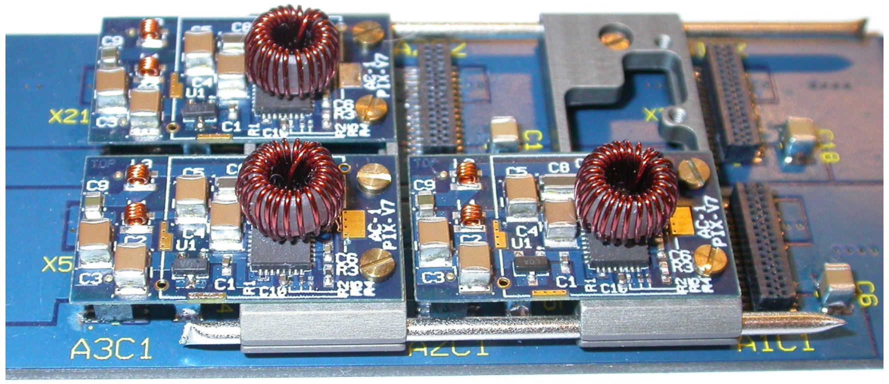
DC-DC Conversion

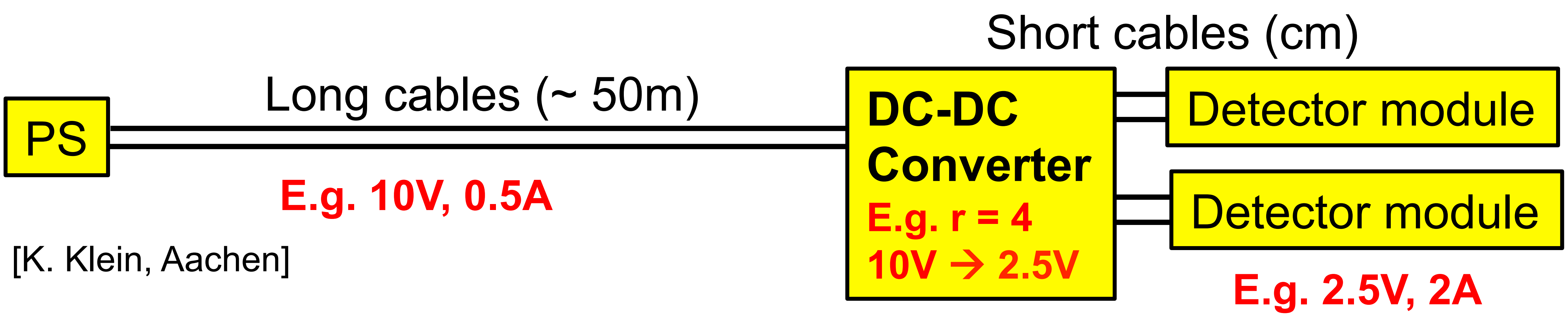
- Power dissipation in the pixel detector
  - Front-end: digital and analog voltage
  - Leakage current through sensors due to radiation damage
  - Ohmic losses in cables
- Local down-conversion of voltages
  - AMIS*x* ASIC (CERN): buck converter
  - Radiation hard, 80% conversion efficiency
  - Small power supply modification needed

Buck Converter Schematic



DC-DC Converter PCB



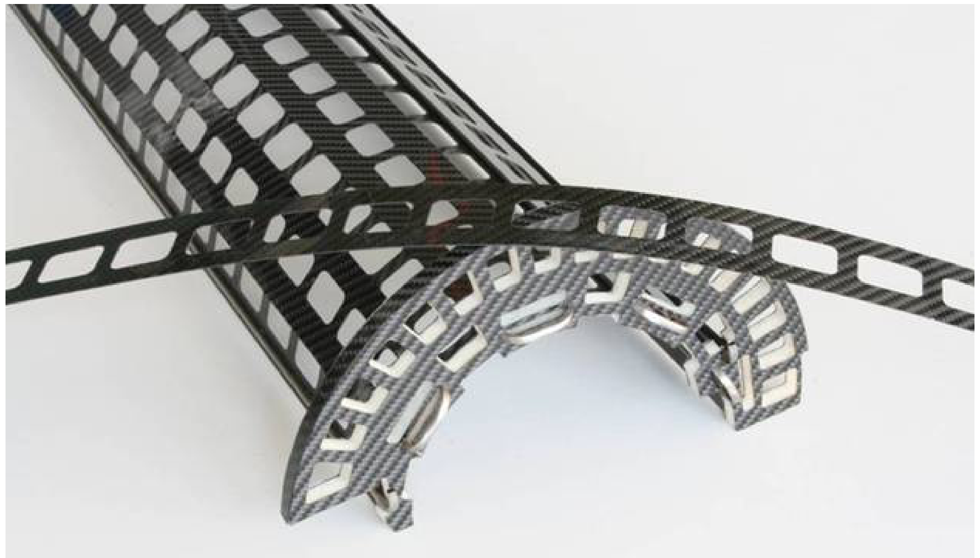


[K. Klein, Aachen]

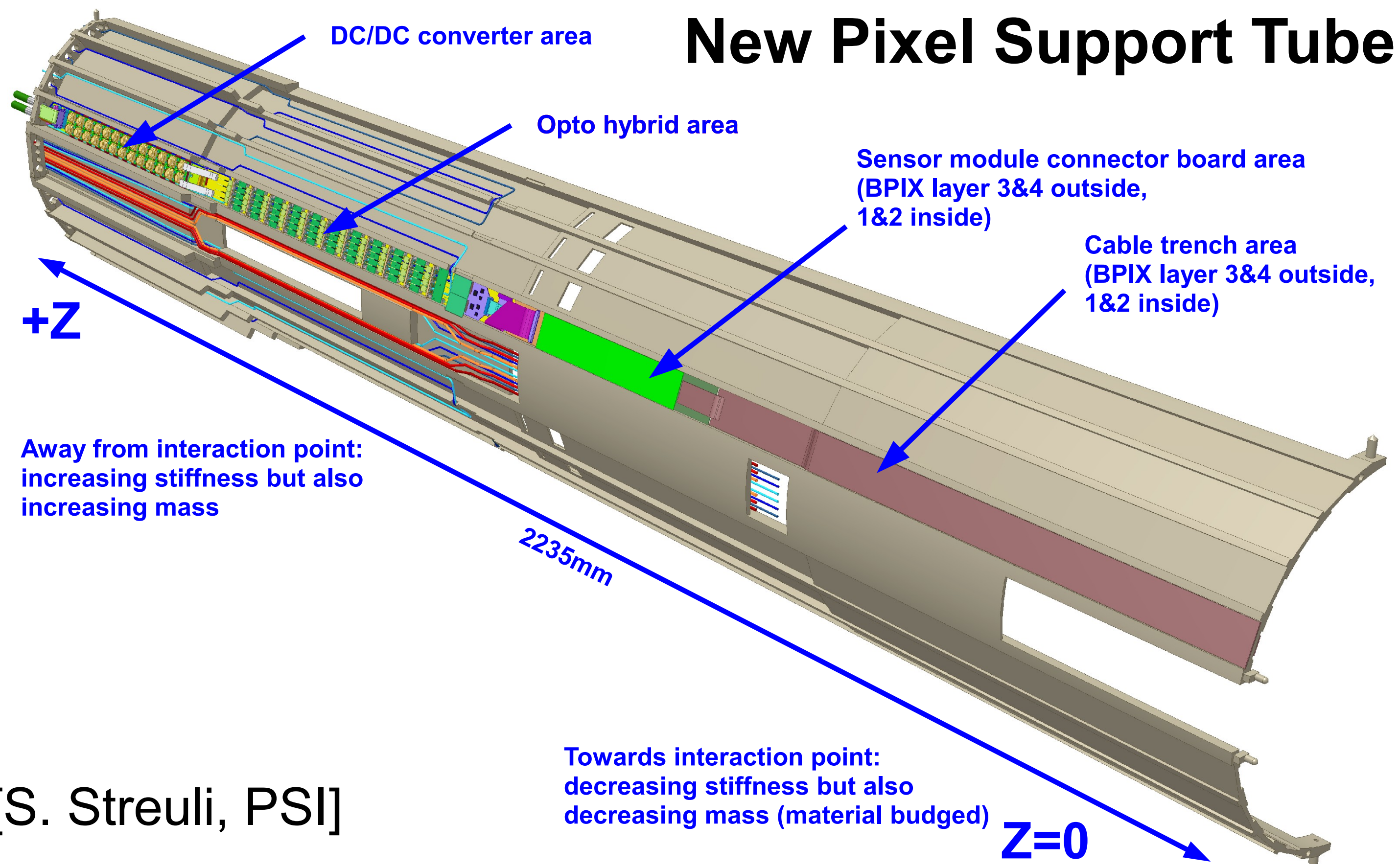
Ultra-Light Mechanics and Support Tube

Mechanical structure

- Airex foam and carbon fiber
- CO_2 cooling integrated
- Mass of layer #1: 59 g including coolant → 30% reduction

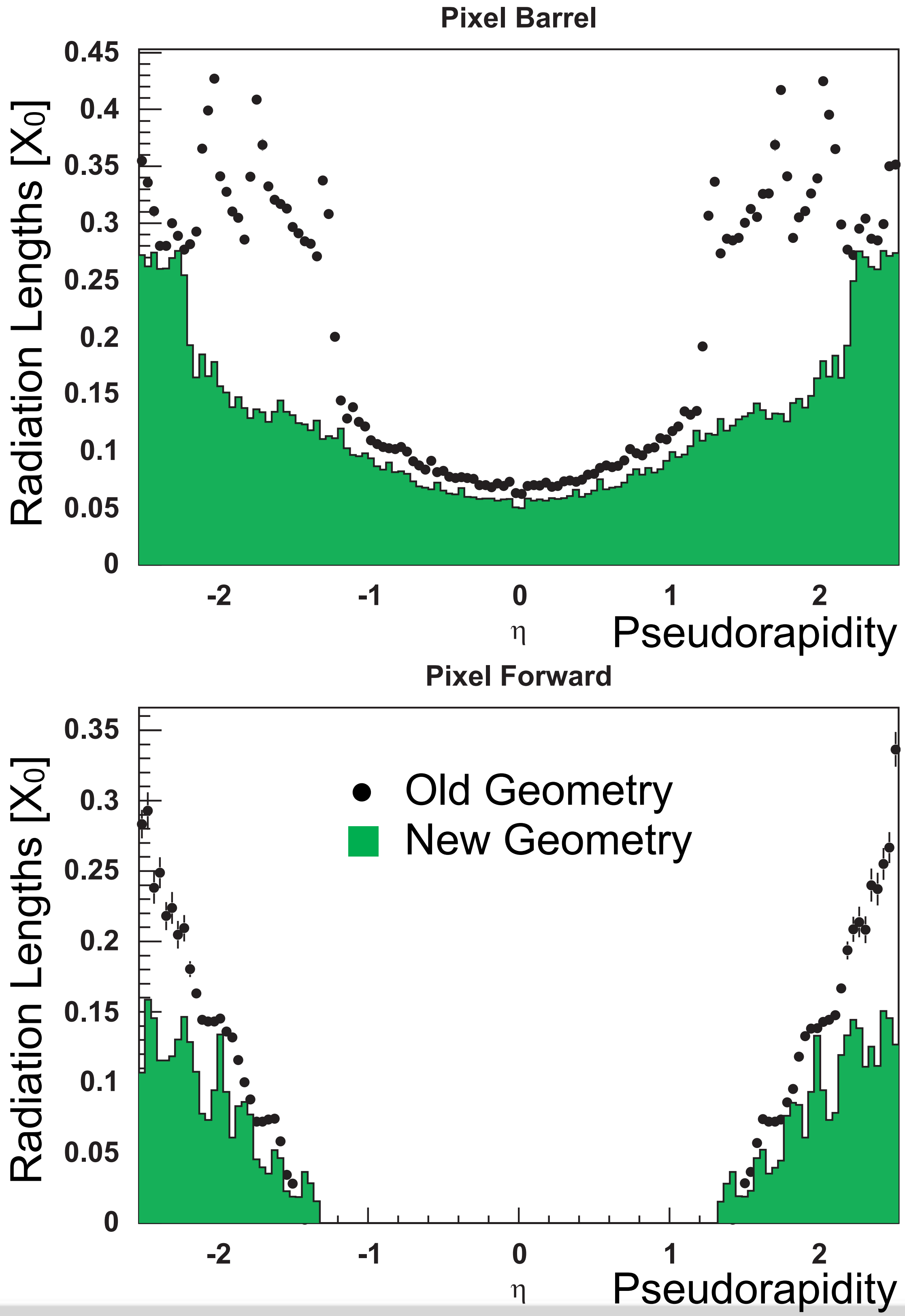


[S. Streuli, PSI]



[S. Streuli, PSI]

Impact on Material Budget

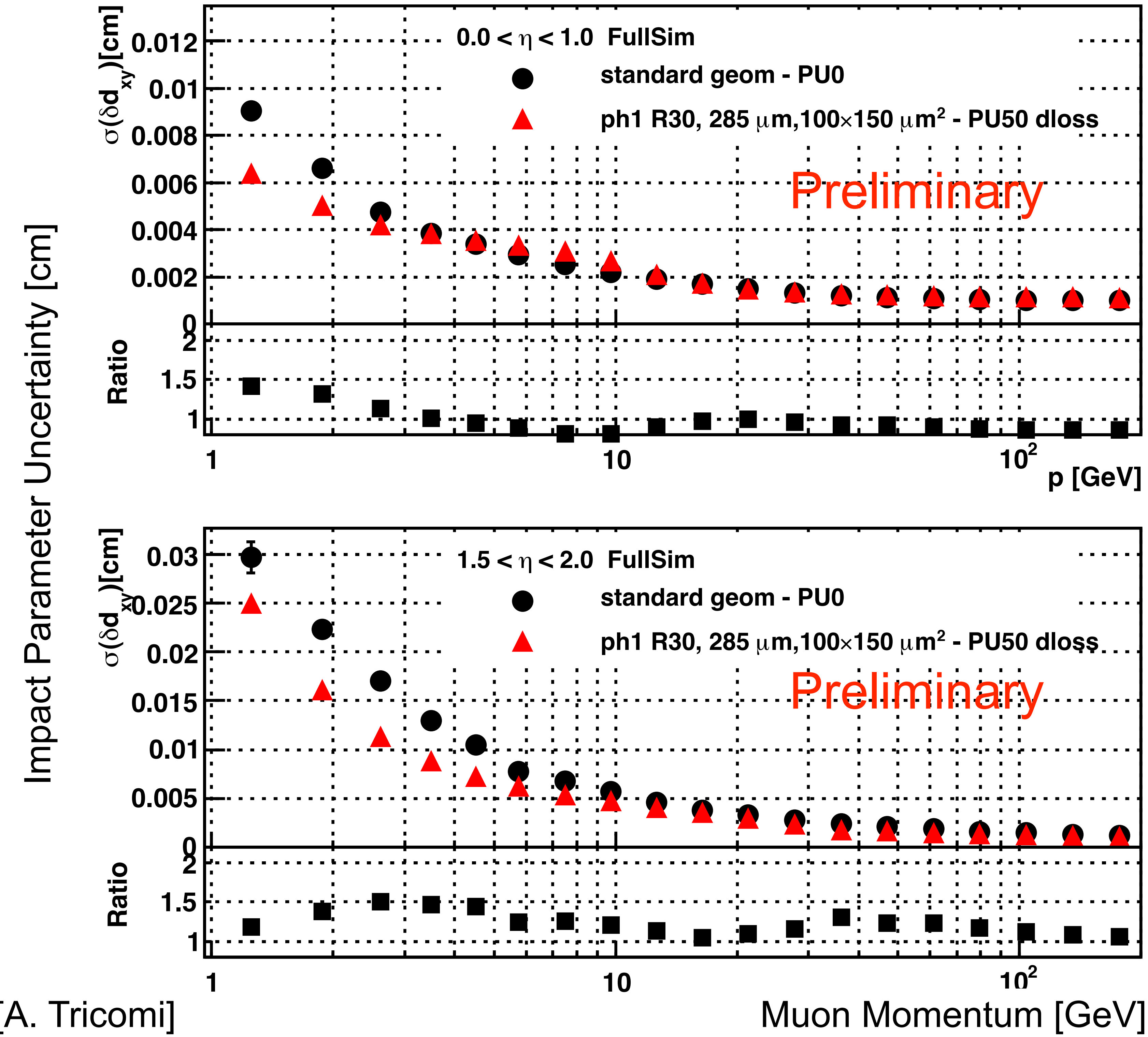


[A. Bean, NIM A650 (2011) 41]

- Central part (|η|<1.1): new four-layer detector with less material than old three-layer detector
- Forward part: shifting of services on support tube further outward

Significant reduction of material budget

Impact on Tracking: Transverse Impact Parameter



[A. Tricomi]

● Old Geometry (no pileup)

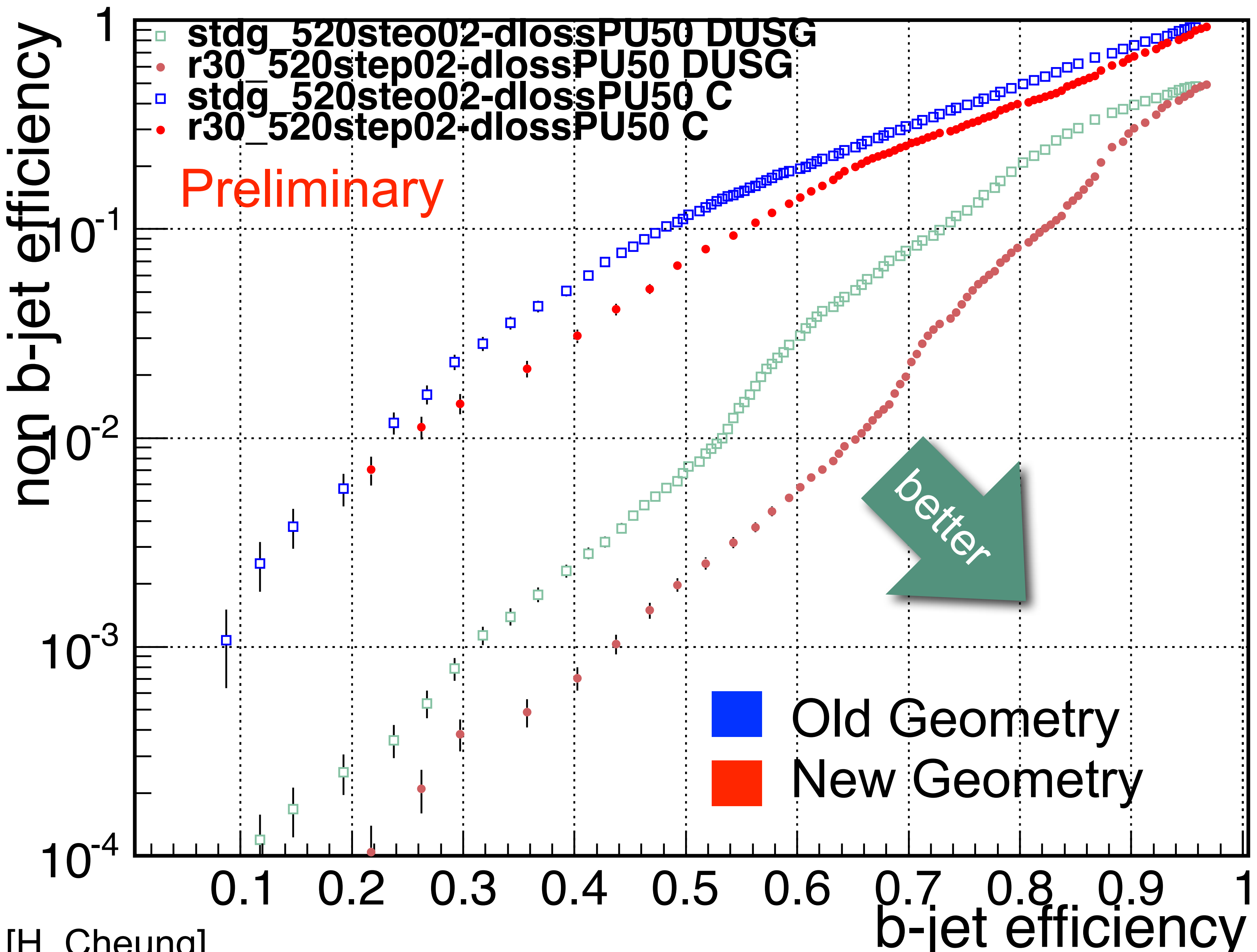
▲ New Geometry (50 pileup vertices)

Upgraded pixel detector at 50 pileup vertices:

- As powerful as current detector at no pileup
- Better resolution for low momenta

Impact on B-Tagging: Compare ROC Curves

CMS Combined Secondary Vertex Tagger @ 50 Pileup Vertices



[H. Cheung]

Upgraded detector: significantly better b-tagging performance at high pileup

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CMS Pixel Upgrade: Current Status and Plans

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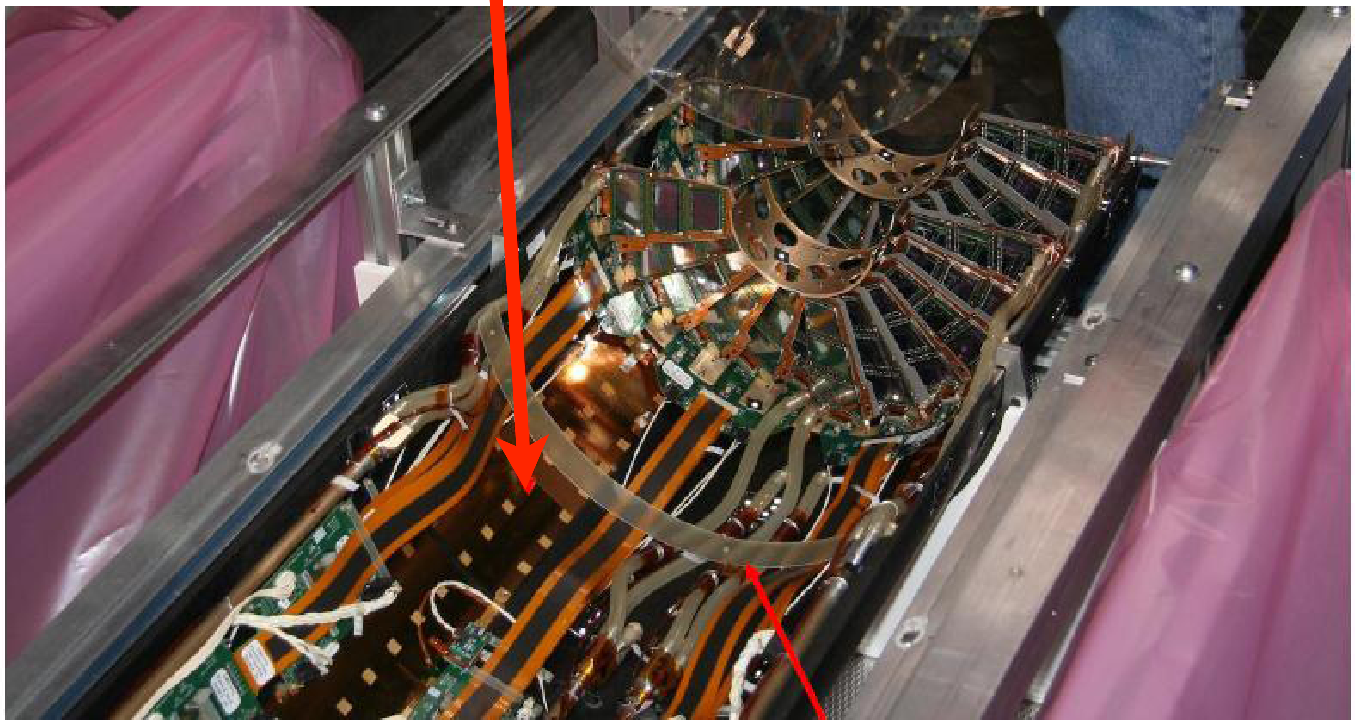
Pixel Project Status and Planning

- Immediate plans
  - Technical Design Report (Summer 2012): technology choices and physics case
  - Qualification of new components, especially new readout chip
  - Late 2012: ramp-up of barrel pixel module production lines
    → pre-series of all "ingredients": sensor, readout chip, HDI, cables, …
- Install new beam pipe during Long Shutdown 1 (LS 1)
- "Pilot blade" project (LS 1)
  - Install upgraded pixel modules at location foreseen for the third forward disk
  - in-situ test of the full chain

Space for Pilot Blade



[S. Kwan et al.]

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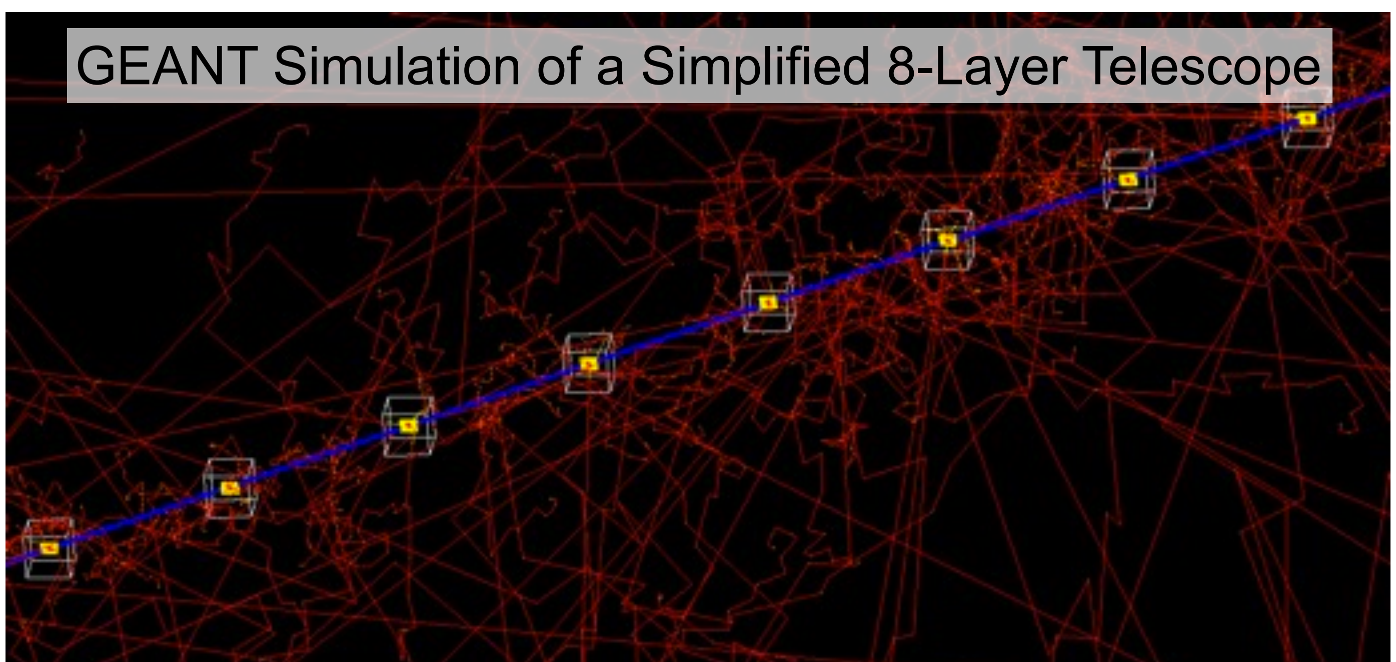
Module Production: BPIX Layer 4 in Germany

- Plans for distributed barrel pixel module production → more logistics (current detector: PSI only)
  - Layers 1 and 2: Swiss consortium (PSI, ETH Zürich, U Zürich)
  - Layer 3: Italy/CERN/Taiwan/Finland
  - Layer 4: German consortium (DESY, U Hamburg, KIT, RWTH Aachen)

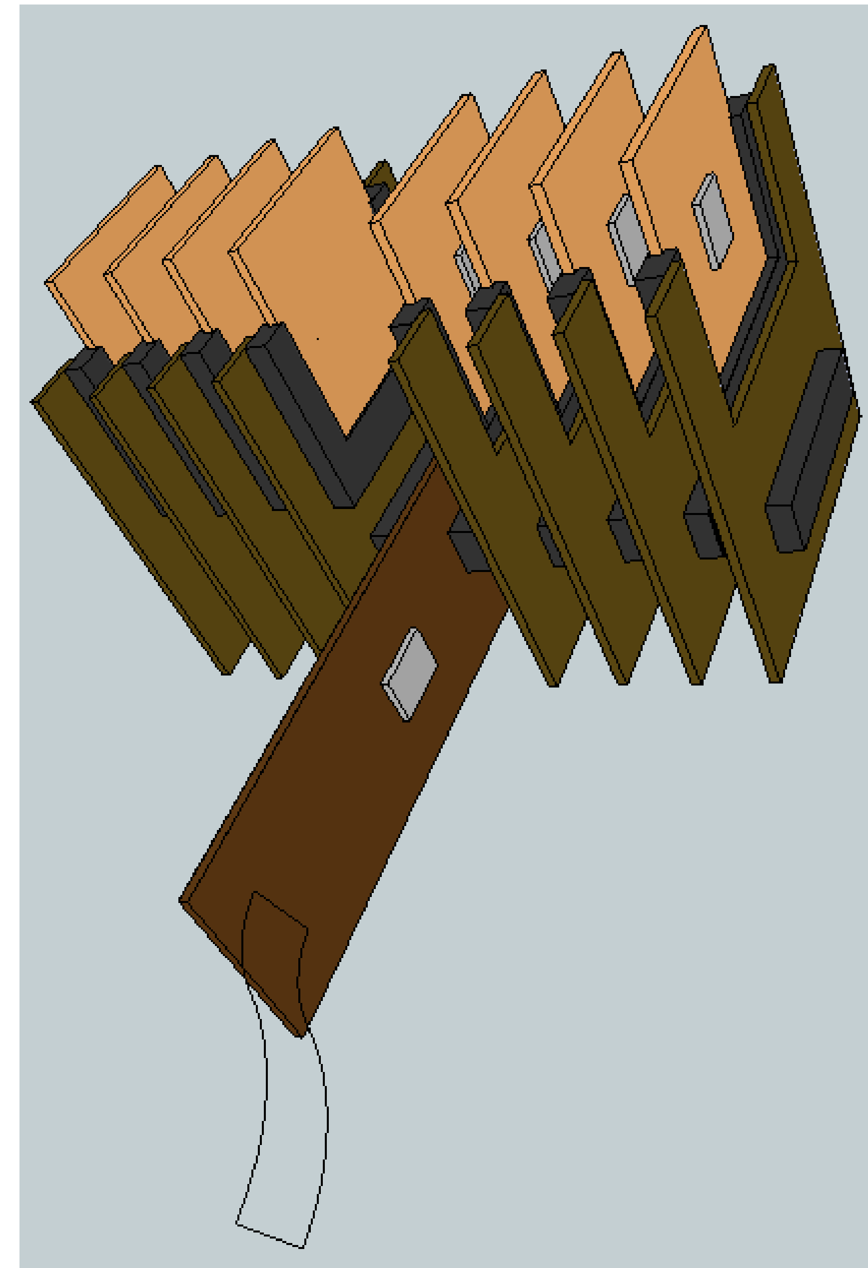
- German consortium
  - Two production lines, 350 modules each: UHH/DESY and KIT/RWTH
  - Sharing development effort for precision tools, testing equipment, …
  - Macro-assembly of Layer 4 at DESY
  - Investigations into cost-effective in-house bump bonding (DESY, KIT)
  - Various test-beam studies (DESY, KIT)

High-Rate Beam Tests

- New pixel chip designed for high hit rates (200 MHz/cm^2)
  → test high-rate performance a.s.a.p
- High-rate beam test:
  - 8-layer pixel telescope with single-chip modules
  - CERN H4IRRAD high rate test beam
  - KIT: trigger firmware, tracking and simulation software (based on EuDet telescope software)

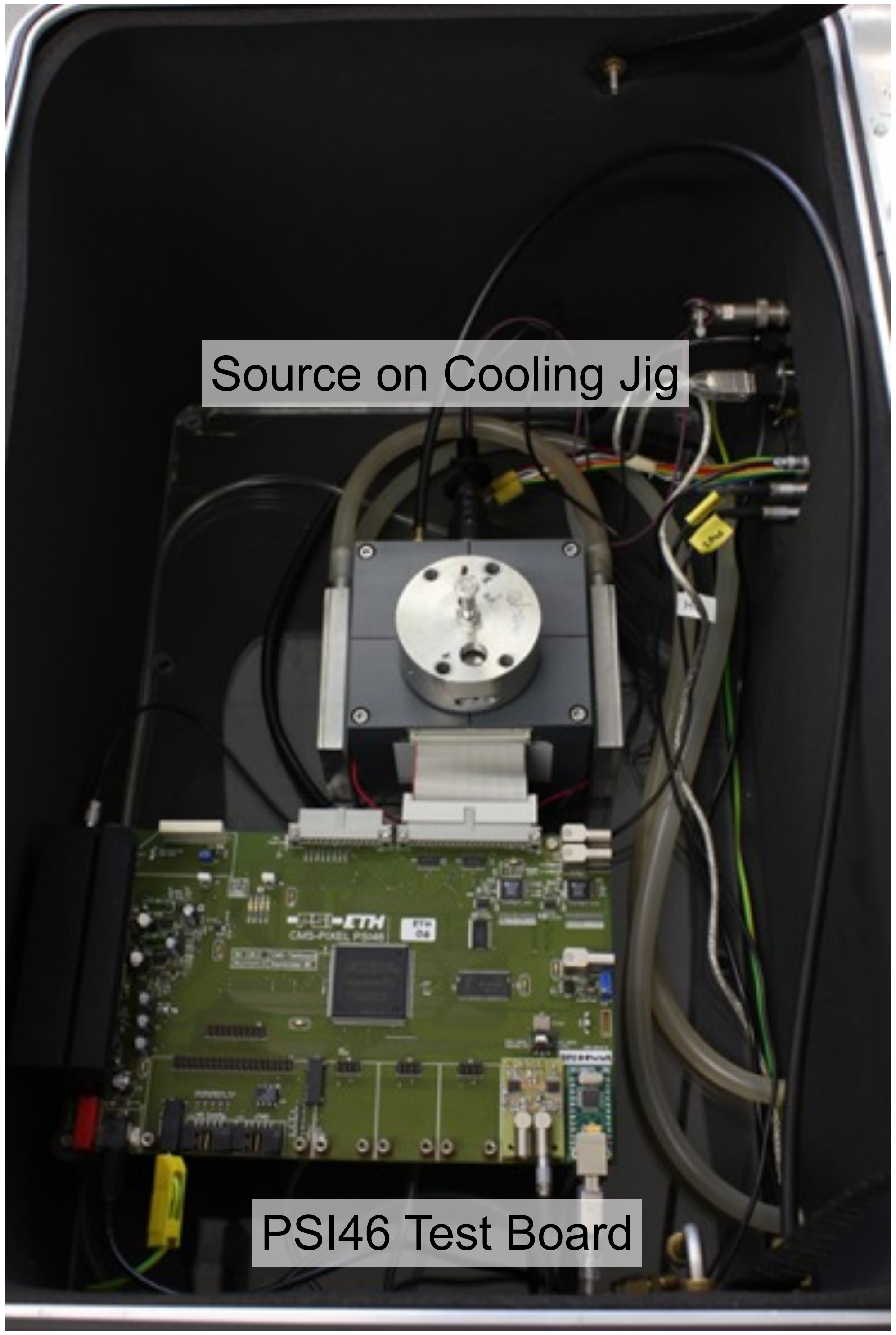


[R.-S. Lu, NTU]

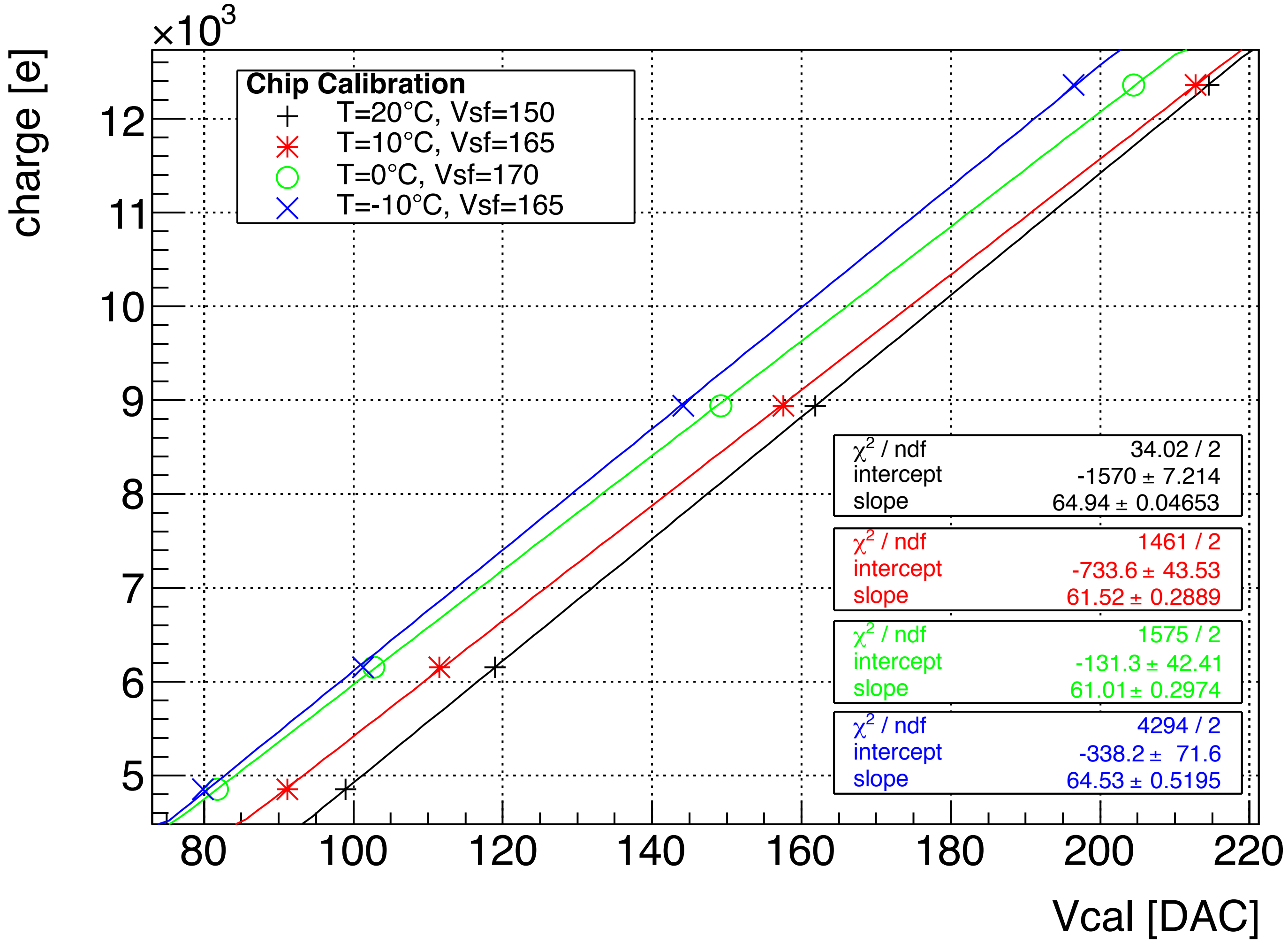


[K. Harder, RAL]

Module Calibration with Am Source

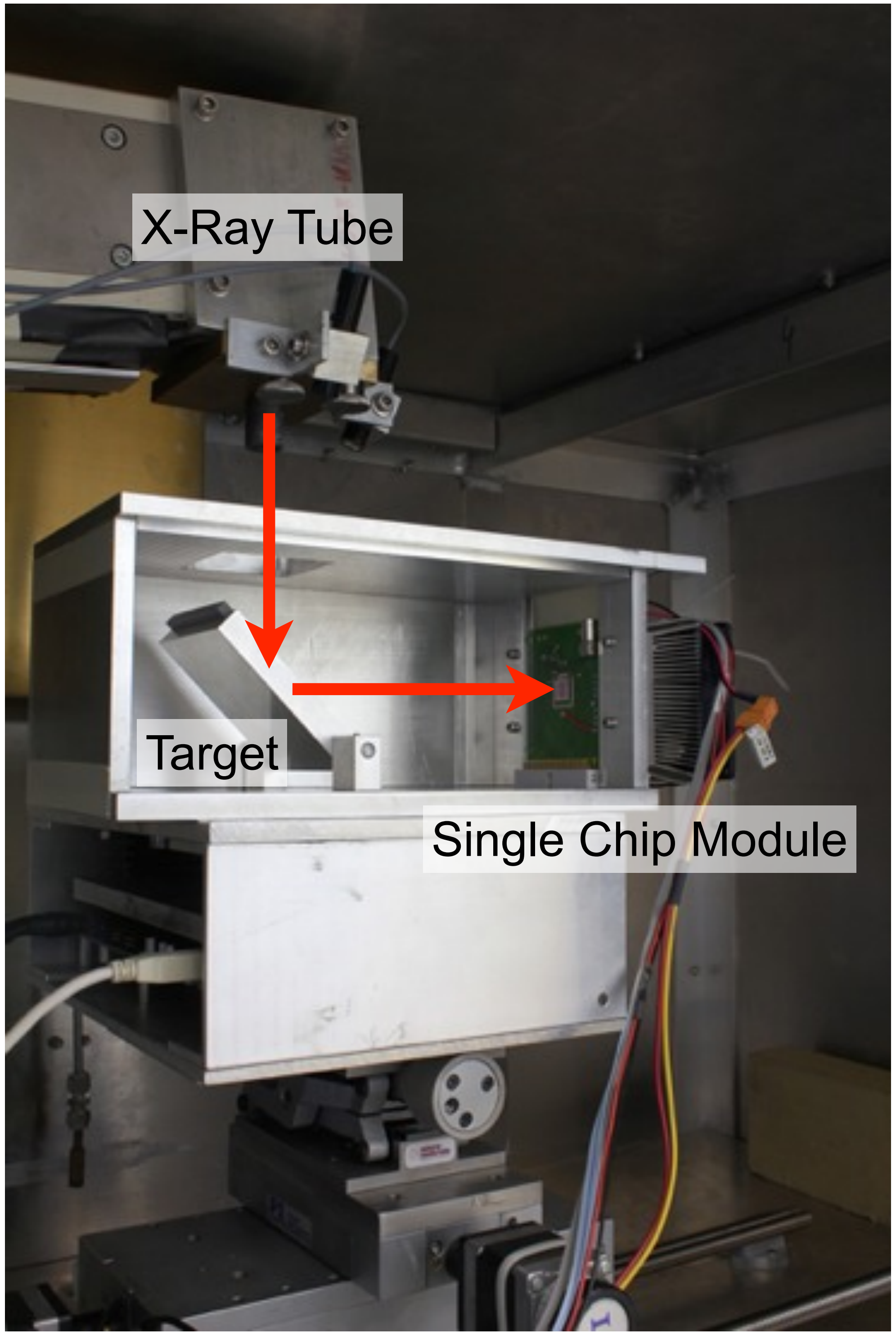


- Pixel module calibration
  - Pulse height: linear with energy at all temperatures → precise charge sharing
  - Defined energy: characteristic X-rays

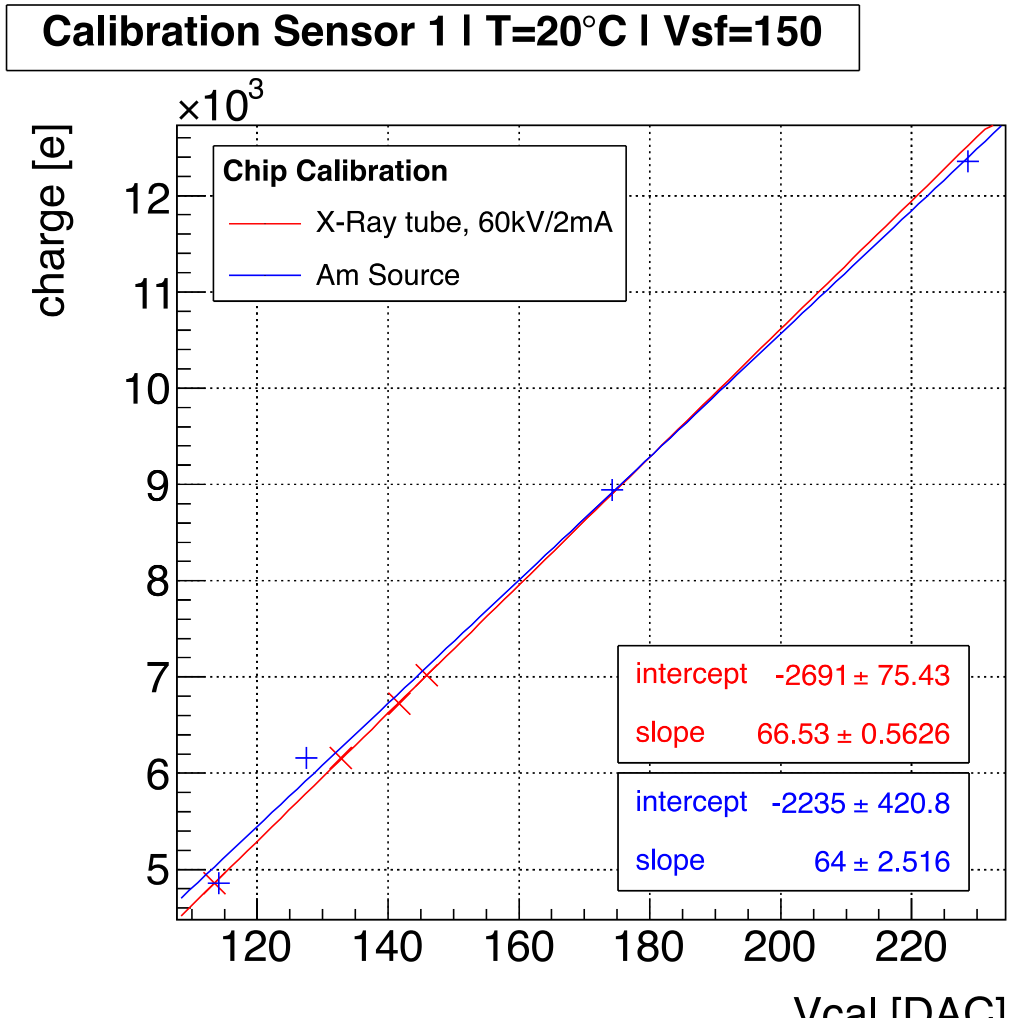


[T. Barvich, S. Heindl, J. Hoß, Th. Weiler, KIT]

Module Calibration with X-Ray Tube



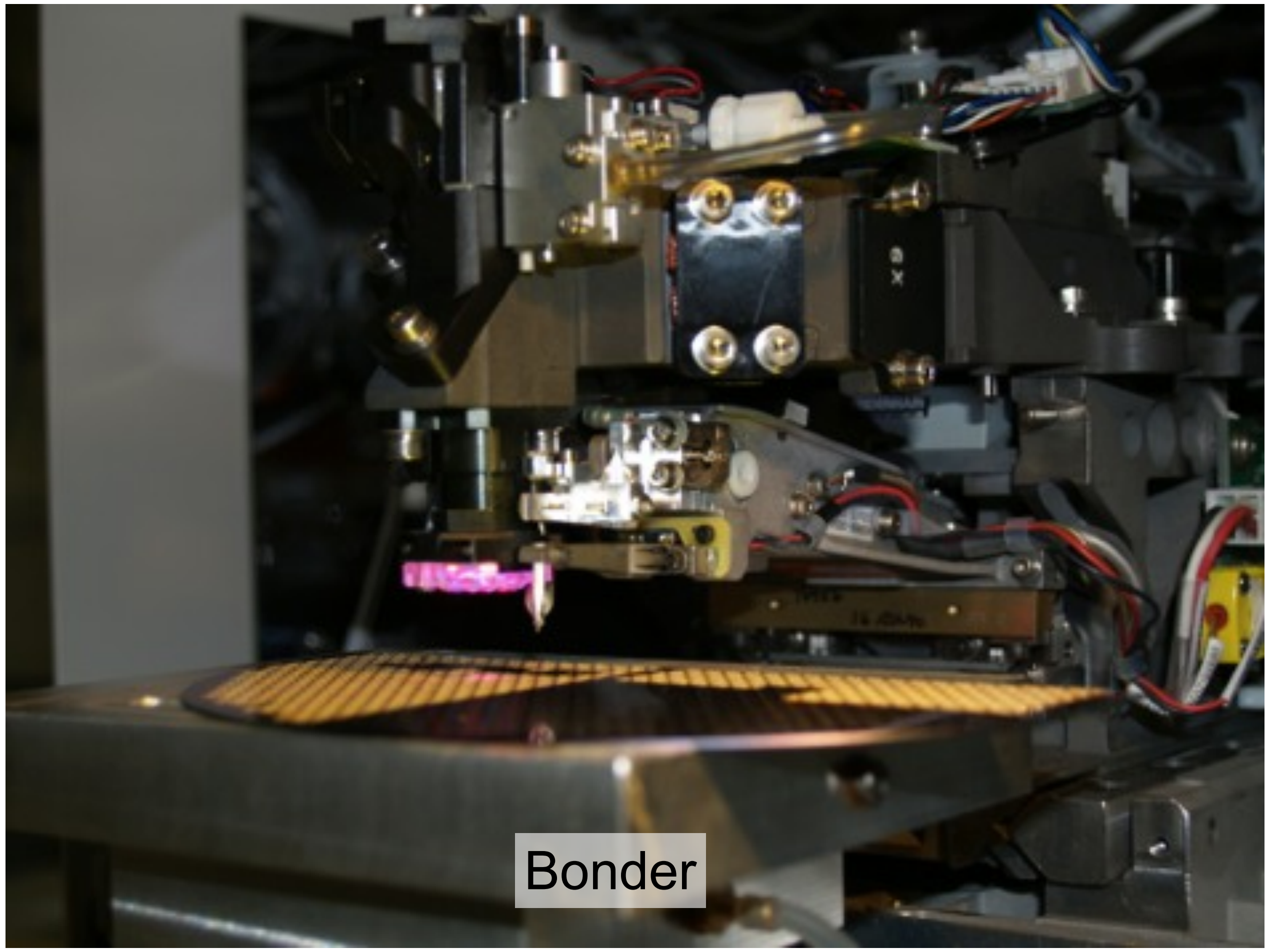
- Pixel module calibration
  - Pulse height: linear with energy at all temperatures → precise charge sharing
  - Defined energy: characteristic X-rays

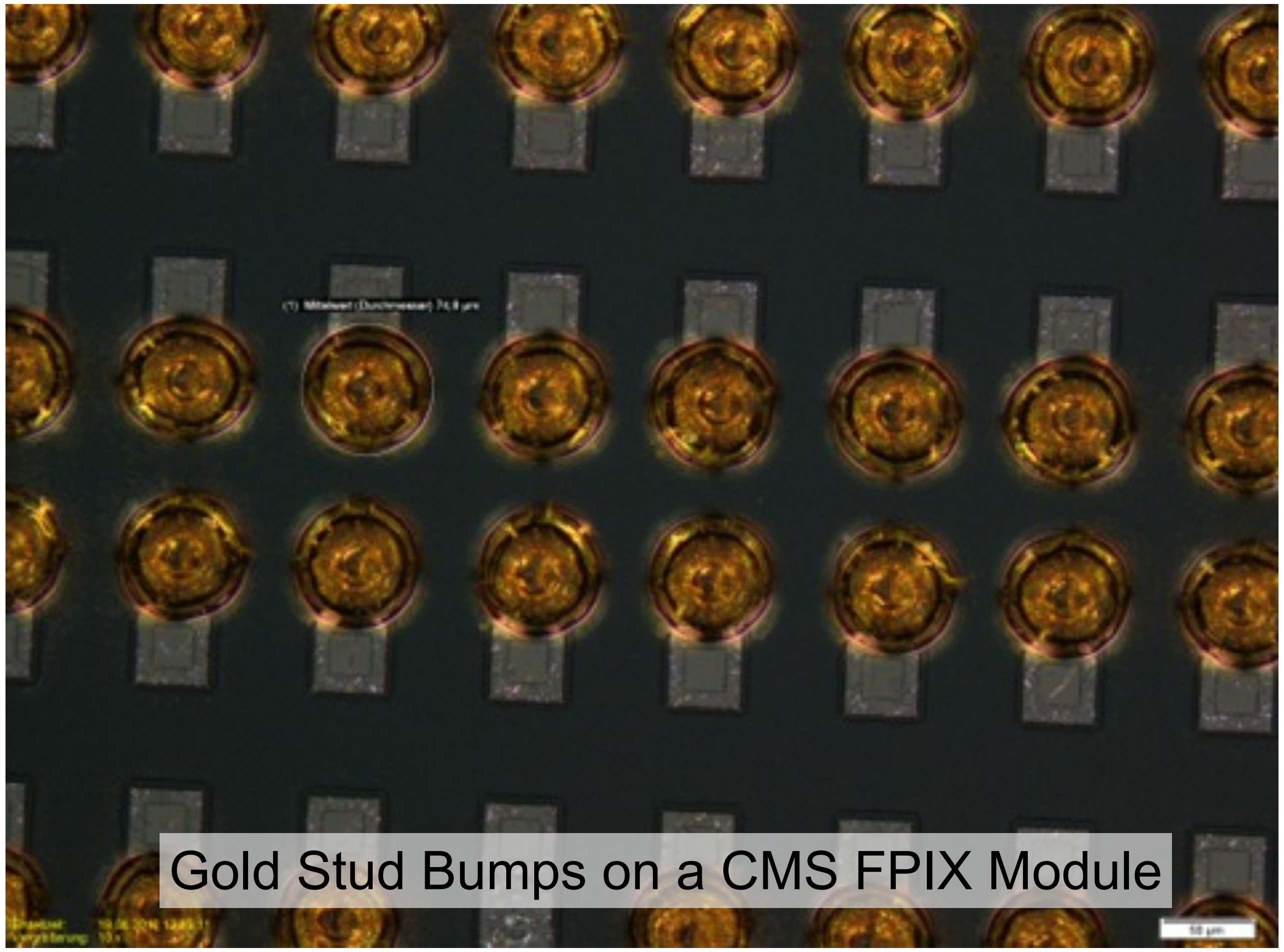


[T. Barvich, S. Heindl, J. Hoß, Th. Weiler, KIT]

Evaluation of Bump Bonding Options

- Bump bonding: most cost-intensive step in module production
- DESY and KIT (Institute for Data Processing and Electronics): in-house options for (part of) bump bonding process
- Currently investigating flip-chipping and gold-stud bumping

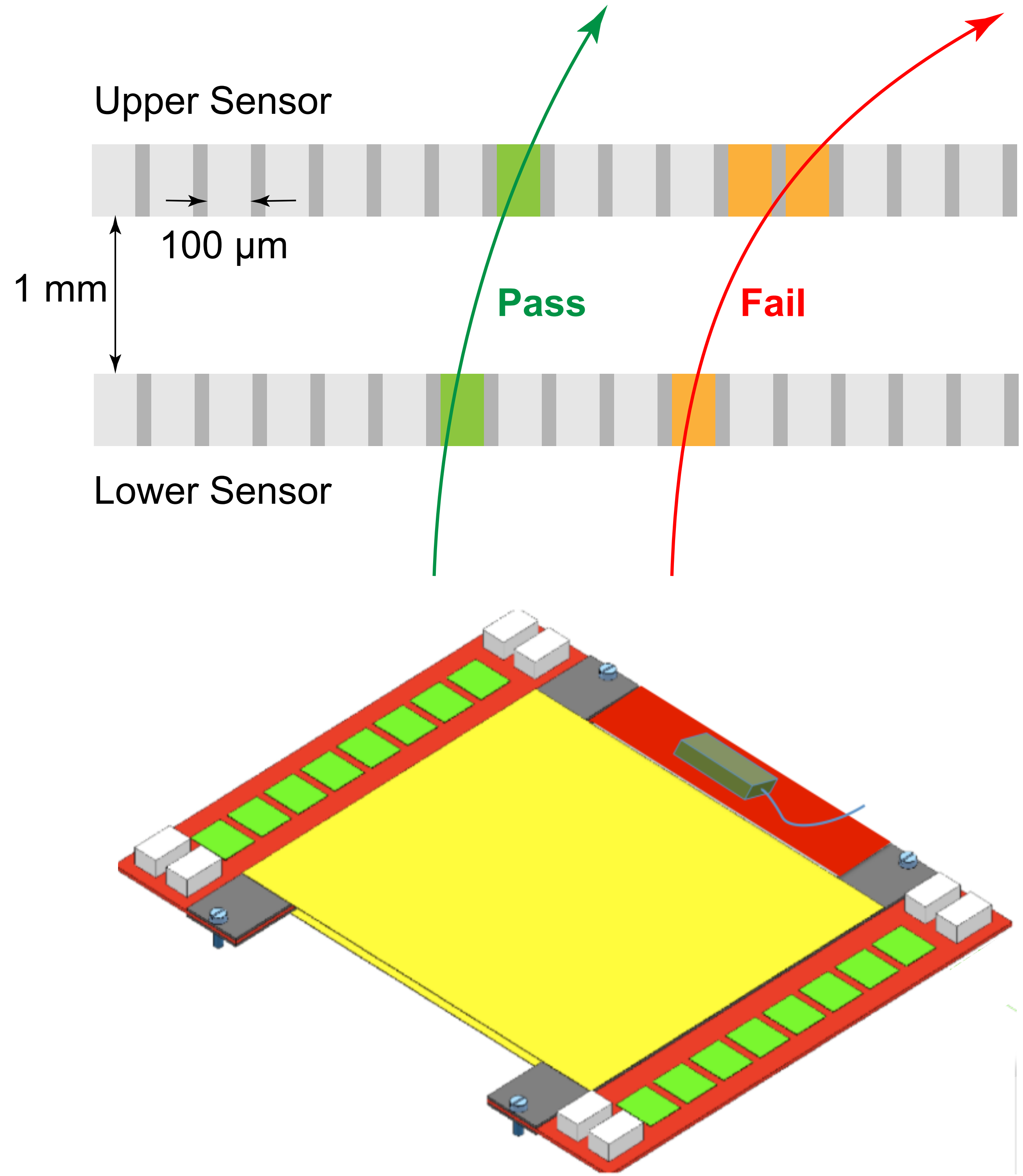




[Th. Blank, M. Caselle, S. Heitz, B. Leyrer, KIT]

The CMS Tracker Beyond 2020

- Long Shutdown 3 (2021): preparation for High-Luminosity LHC
  - ATLAS and CMS: complete replacement of tracker
  - Challenge: trigger on interesting physics → keep thresholds for key triggers low
  - CMS: exploit tracking information in the early trigger stages
- Novel concept: p_T modules
  - Goal: suppression of low-p_T tracks (< 1–2 GeV) for the trigger
  - Idea (R. Horisberger): local coincidence of two sandwiched silicon detector layers (strips + strips or strips + pixels)



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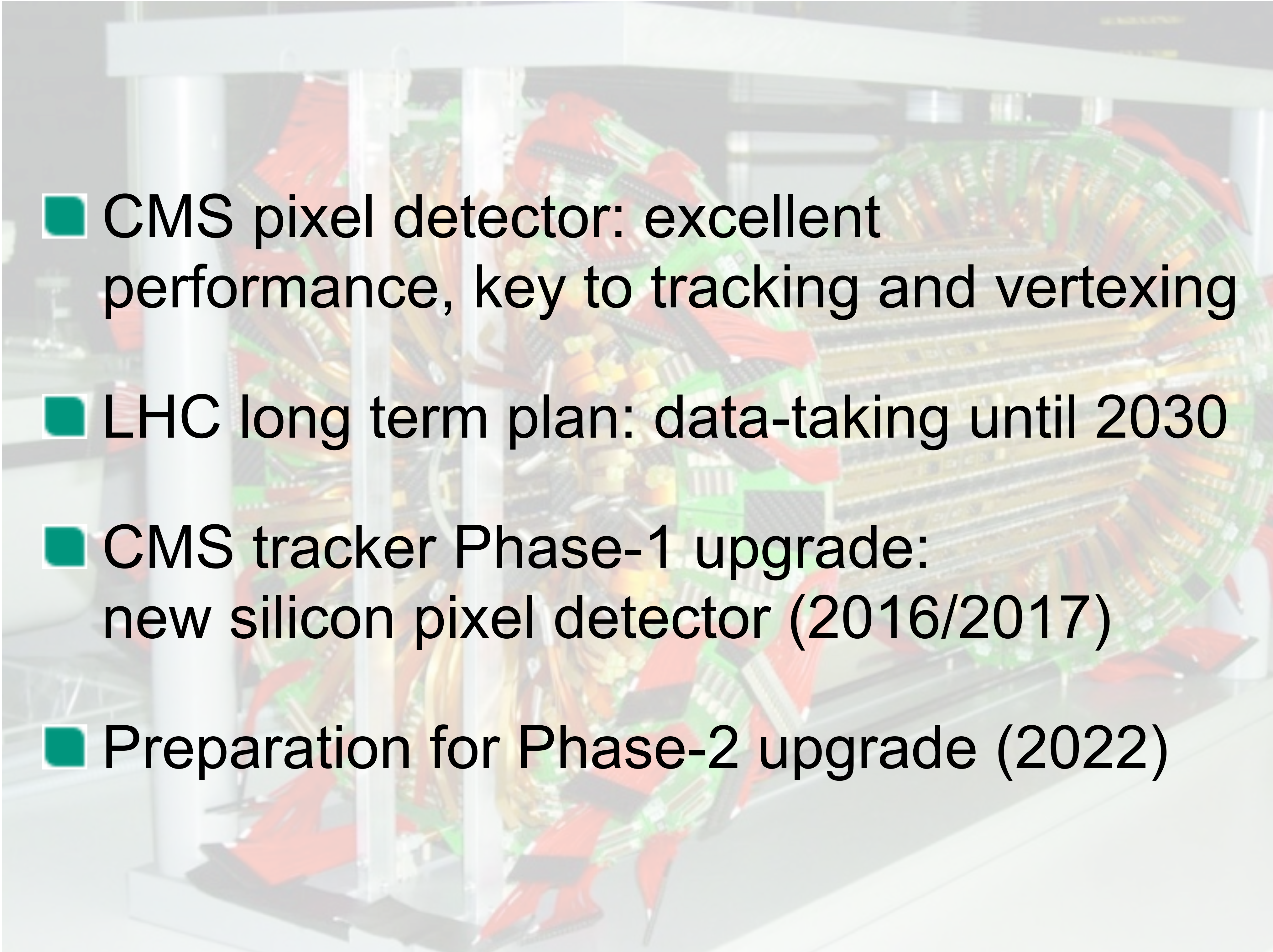
Conclusions



- CMS pixel detector: excellent performance, key to tracking and vertexing
- LHC long term plan: data-taking until 2030
- CMS tracker Phase-1 upgrade: new silicon pixel detector (2016/2017)
- Preparation for Phase-2 upgrade (2022)

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