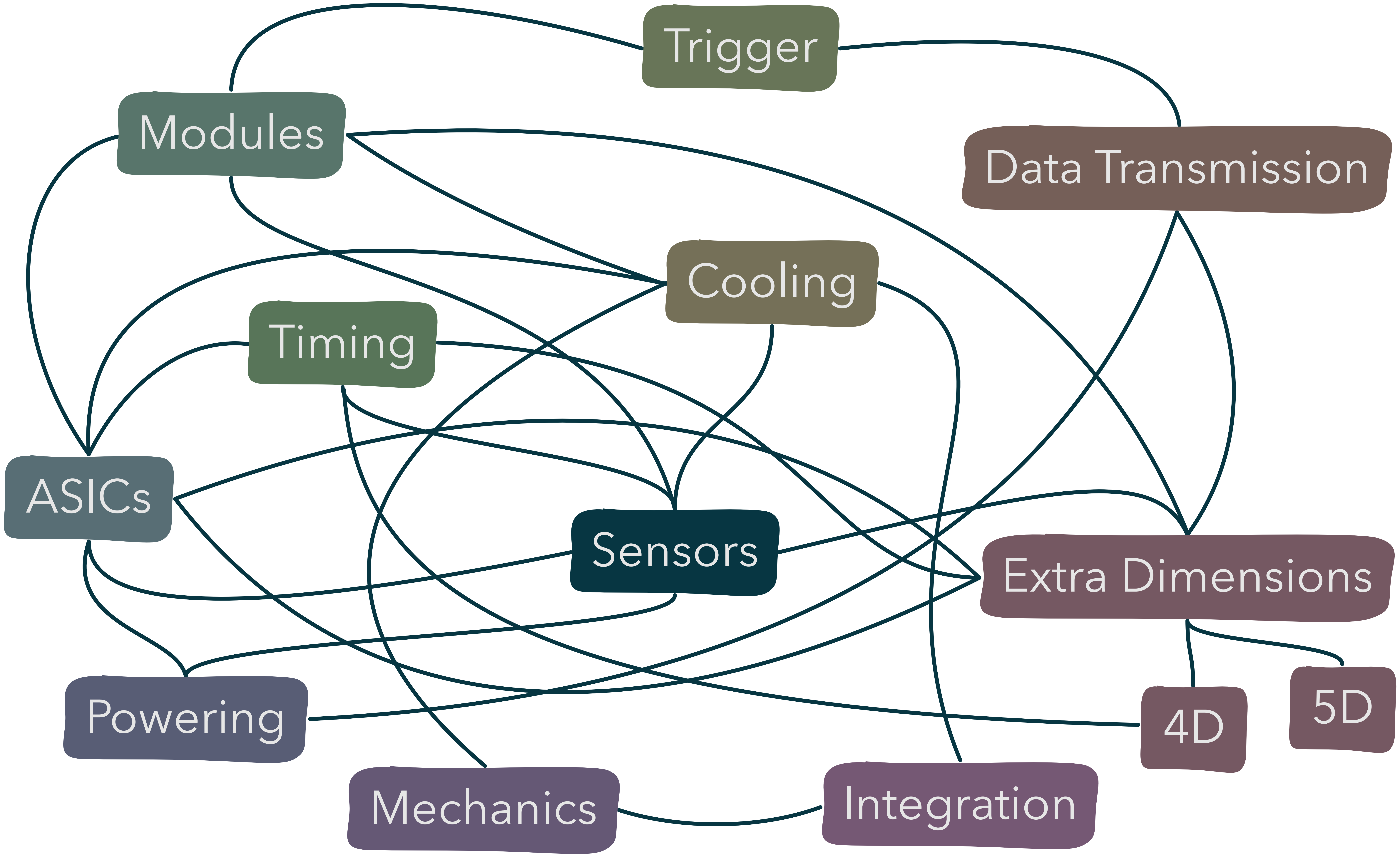
Current R&D and Future Trends in Silicon Detectors

Andreas Mussgiller

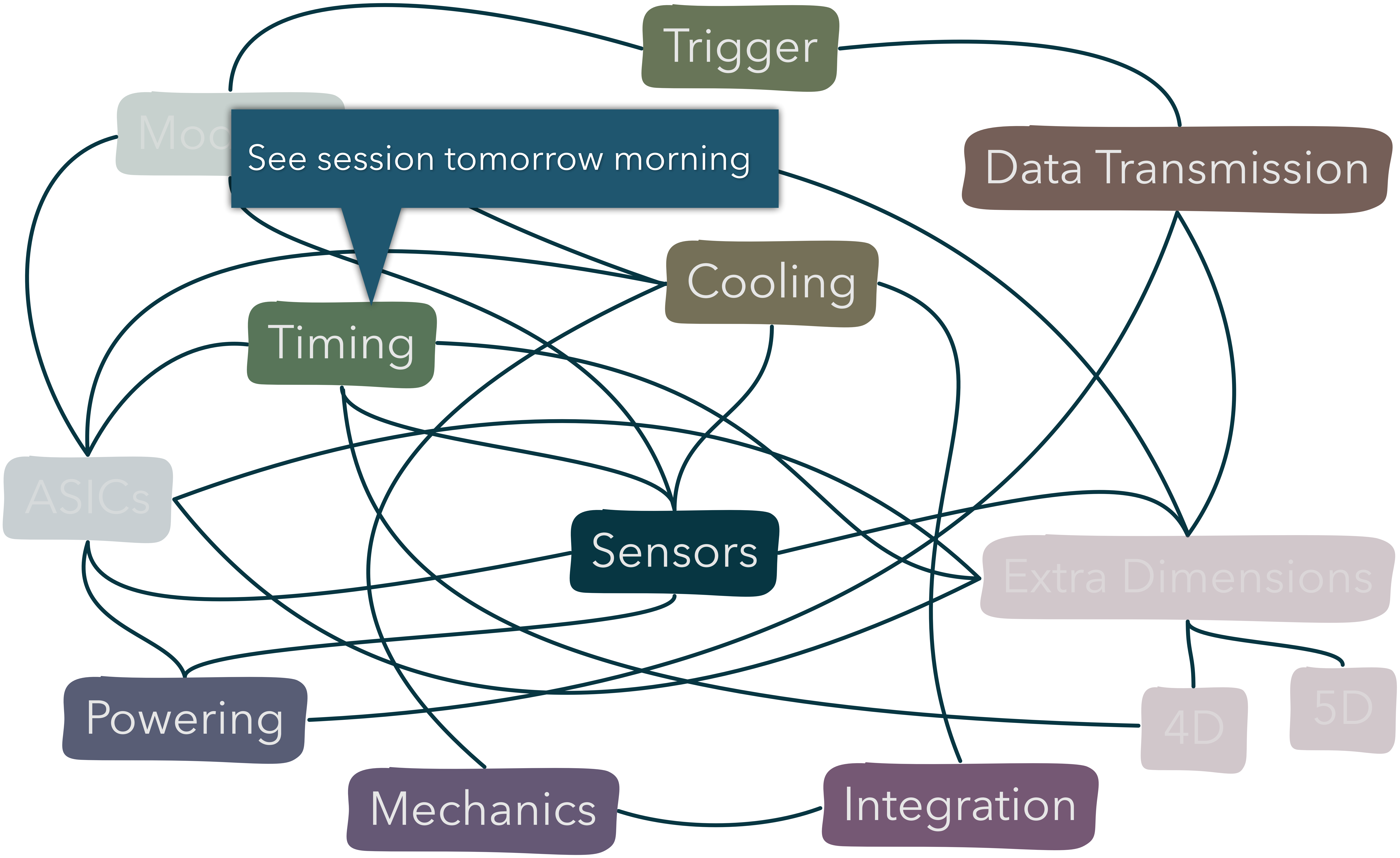
Instrumentation for Colliding Beam Physics (INSTR20)

25/02/2020

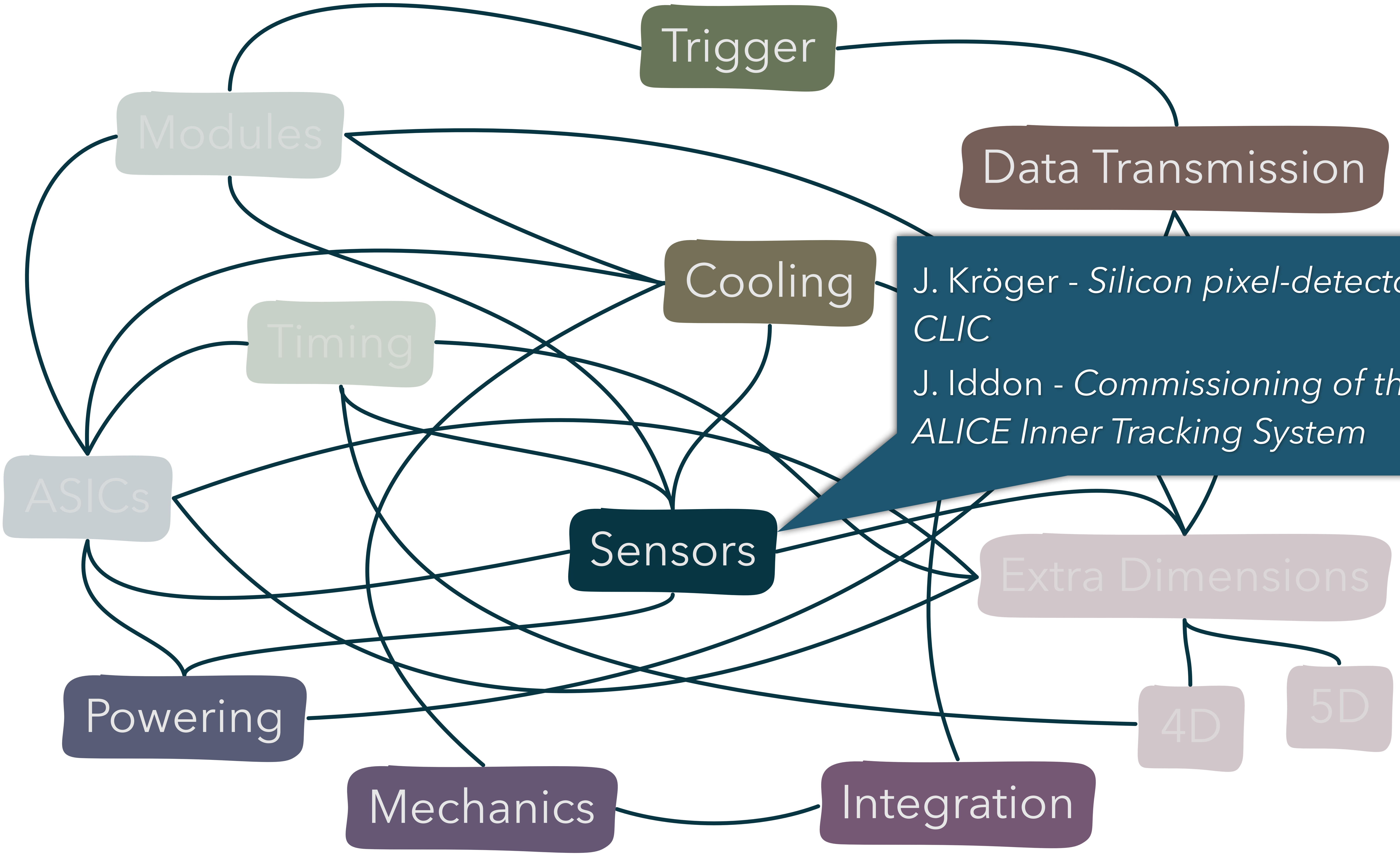
Outline


Trigger
Modules
Data Transmission
Cooling
Timing
ASICs
Sensors
Extra Dimensions
4D
5D
Powering
Mechanics
Integration

Outline


Trigger
See session tomorrow morning
Data Transmission
Cooling
Timing
ASICs
Sensors
Extra Dimensions
4D
5D
Powering
Mechanics
Integration

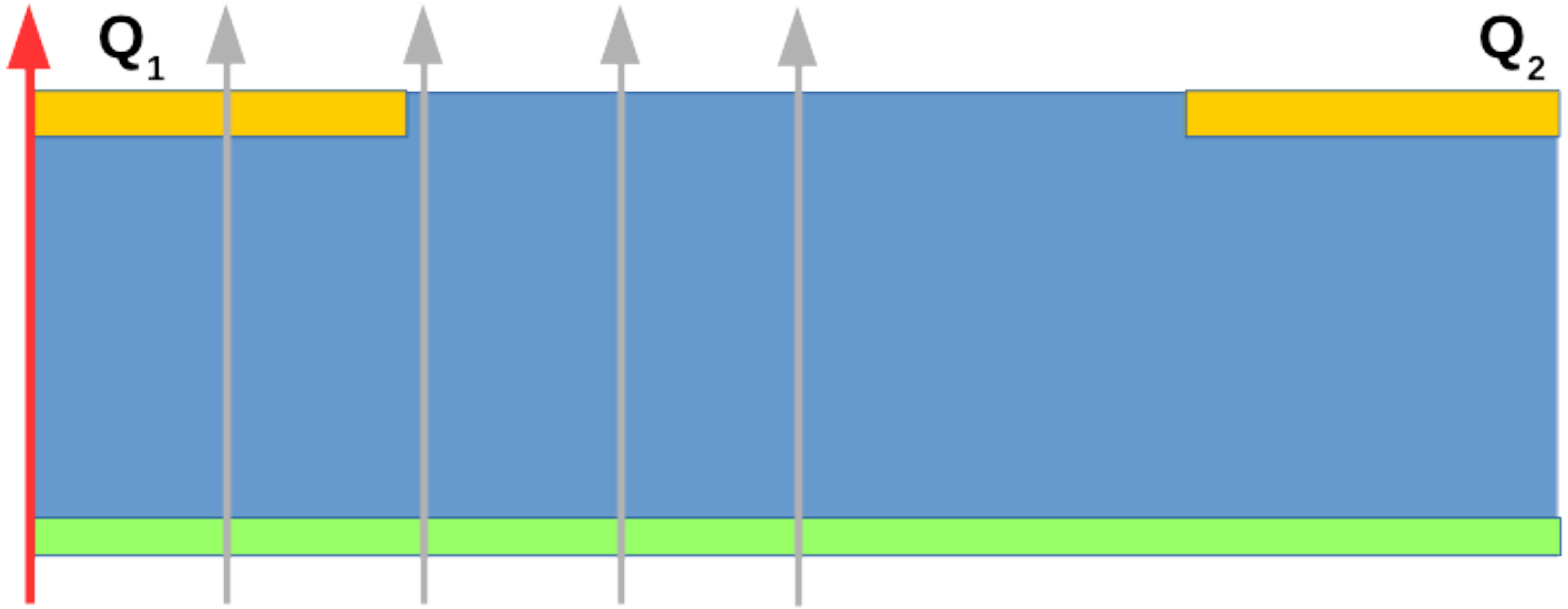
Outline



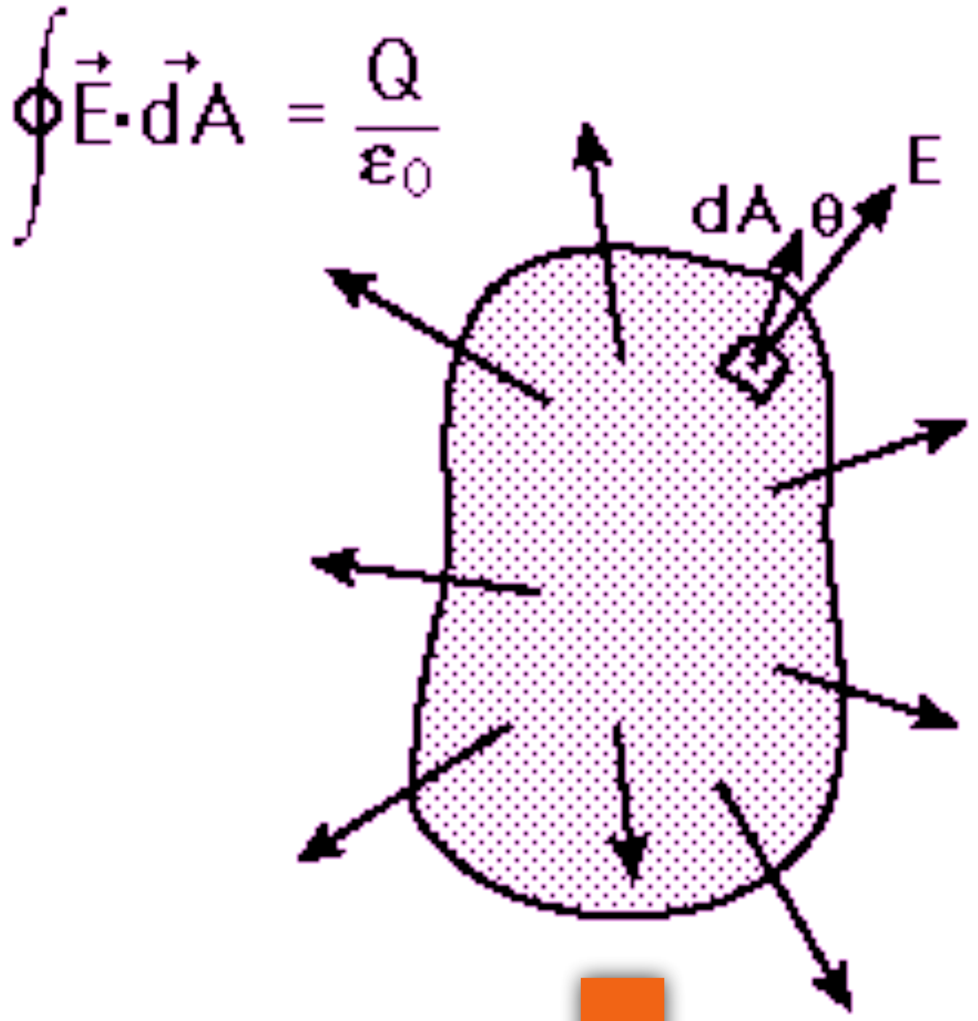
J. Kröger - *Silicon pixel-detector R&D for CLIC*

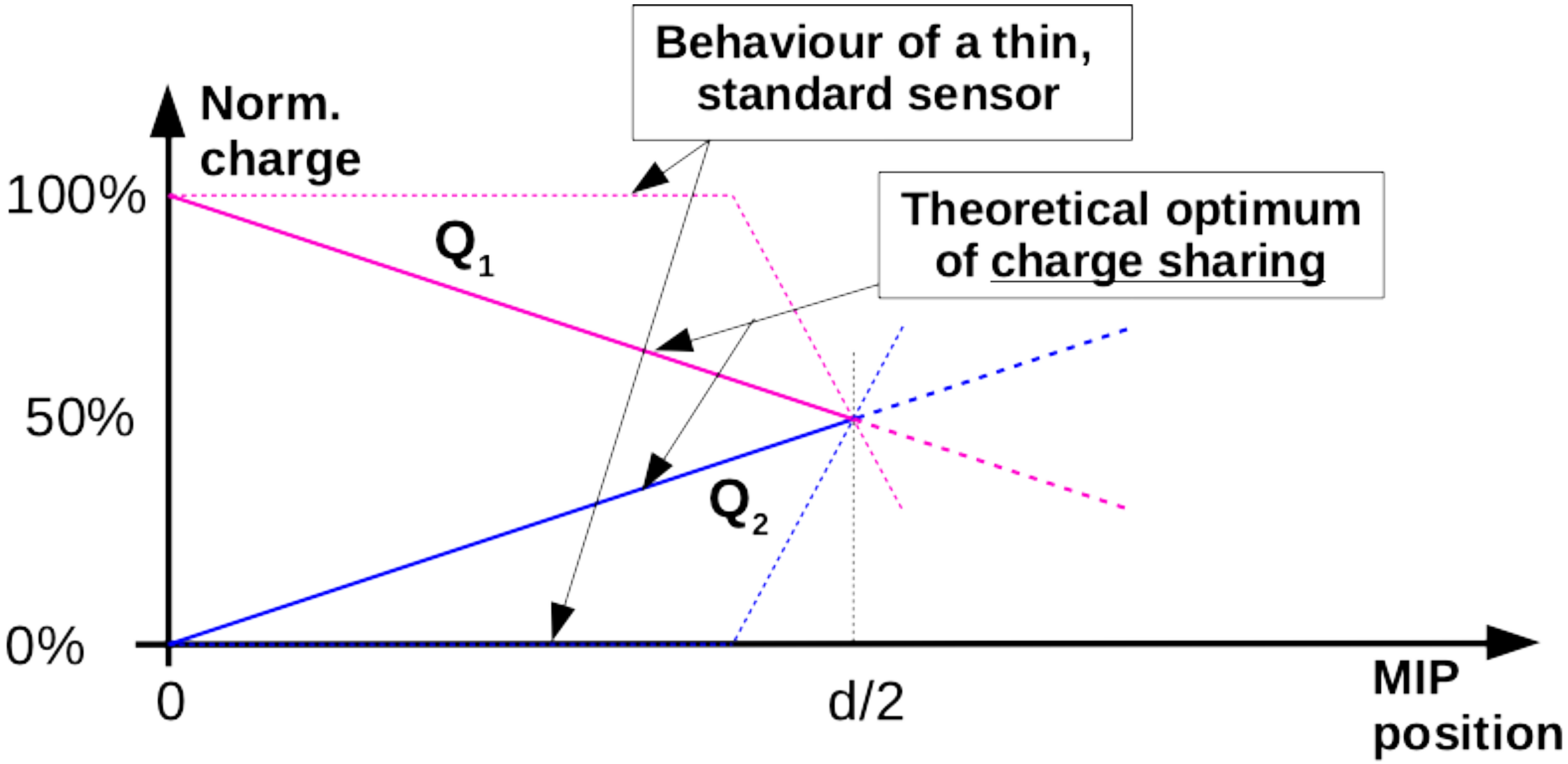
J. Iddon - *Commissioning of the New ALICE Inner Tracking System*

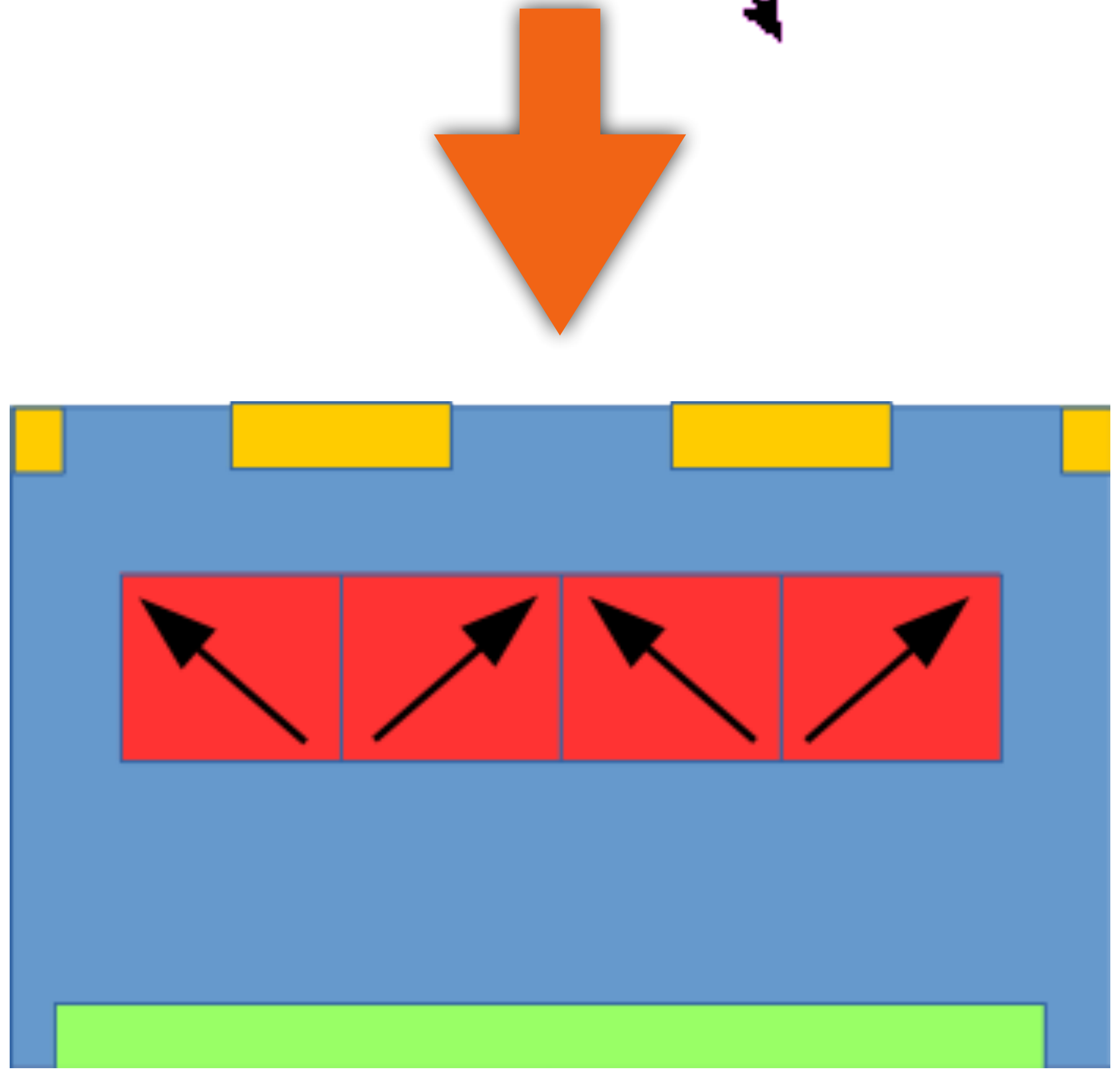
Position Resolution Revisited



Free charges follow field lines
➡ exploit Maxwell's 1st eq

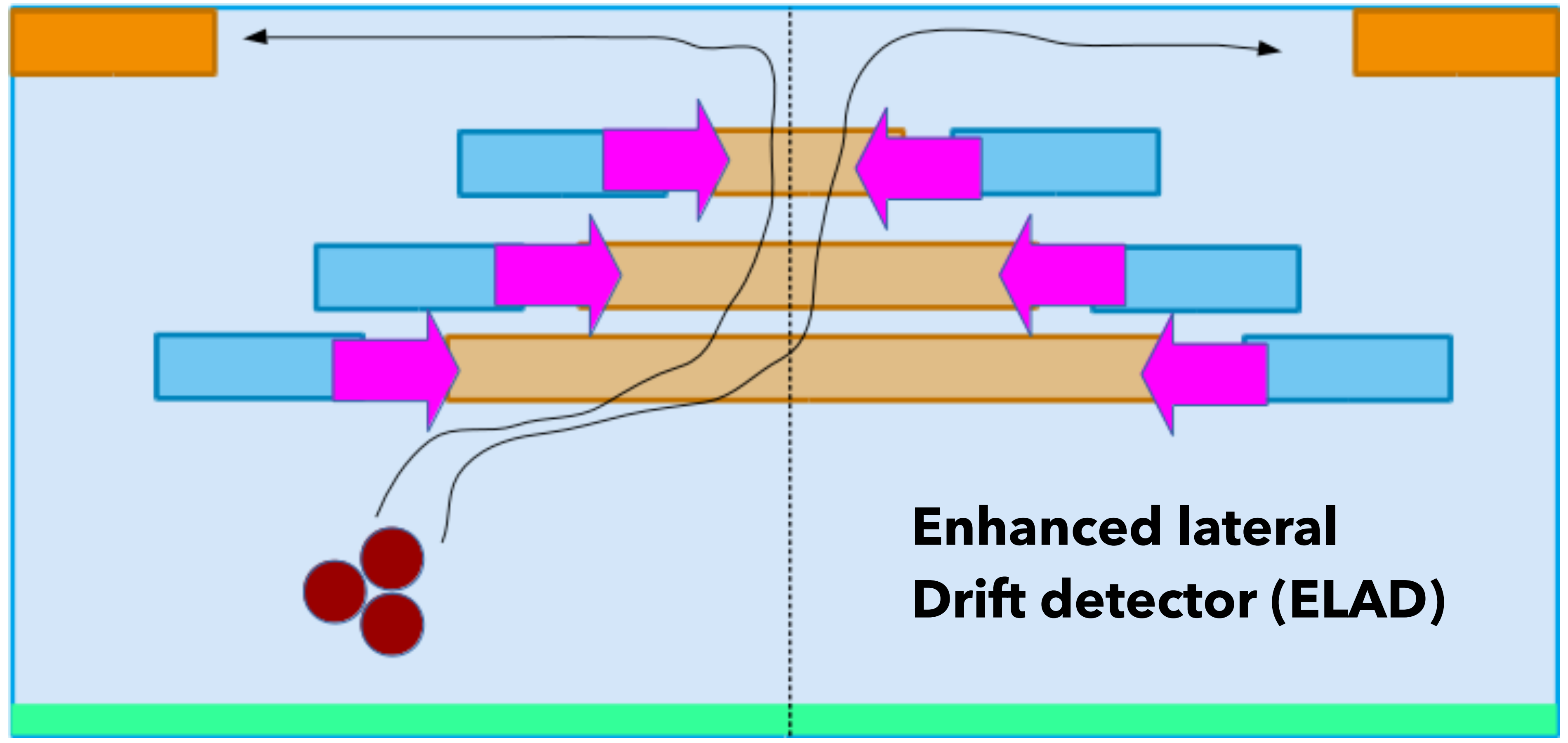


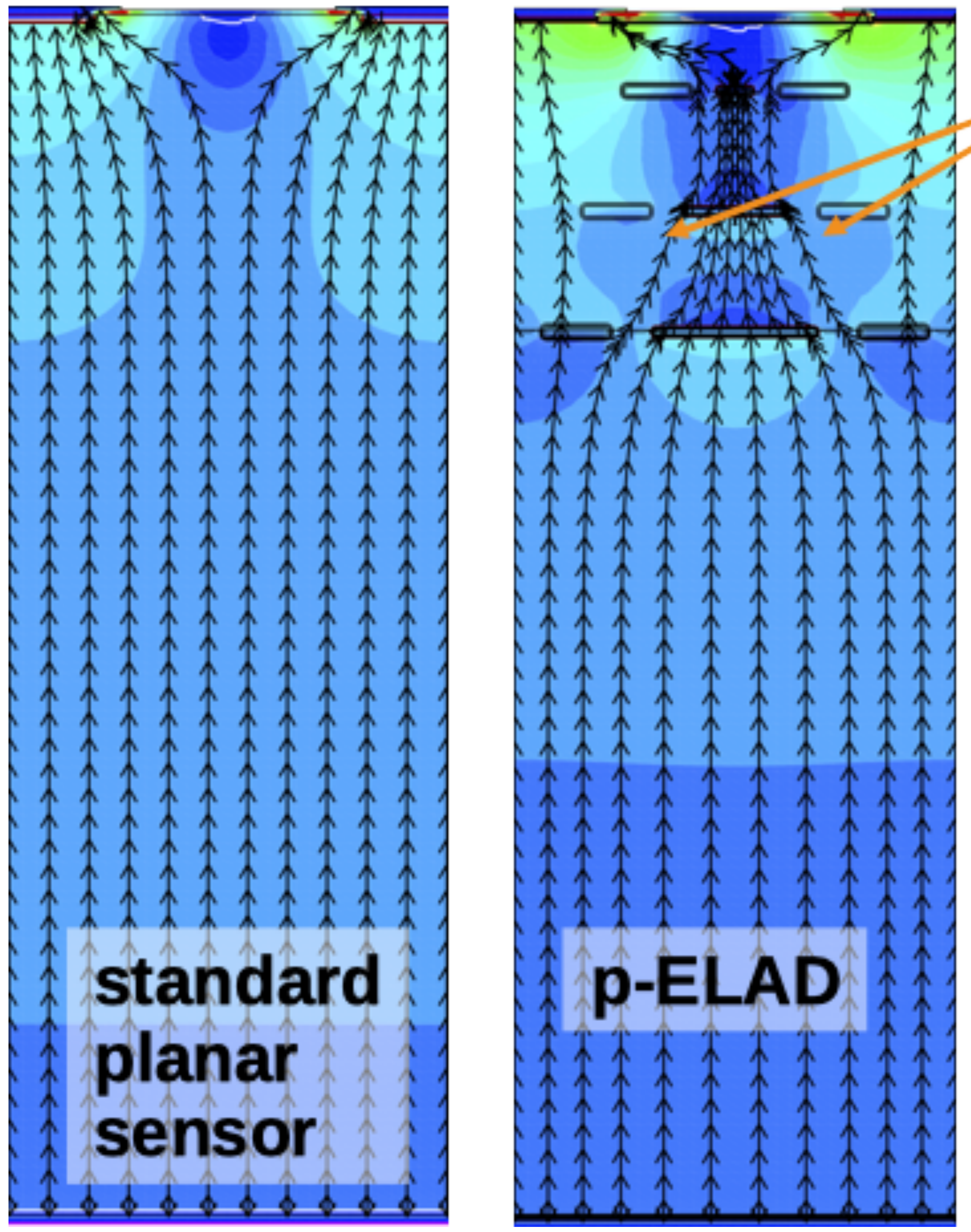




Concept of Enhanced Lateral Drift Detectors (ELAD)

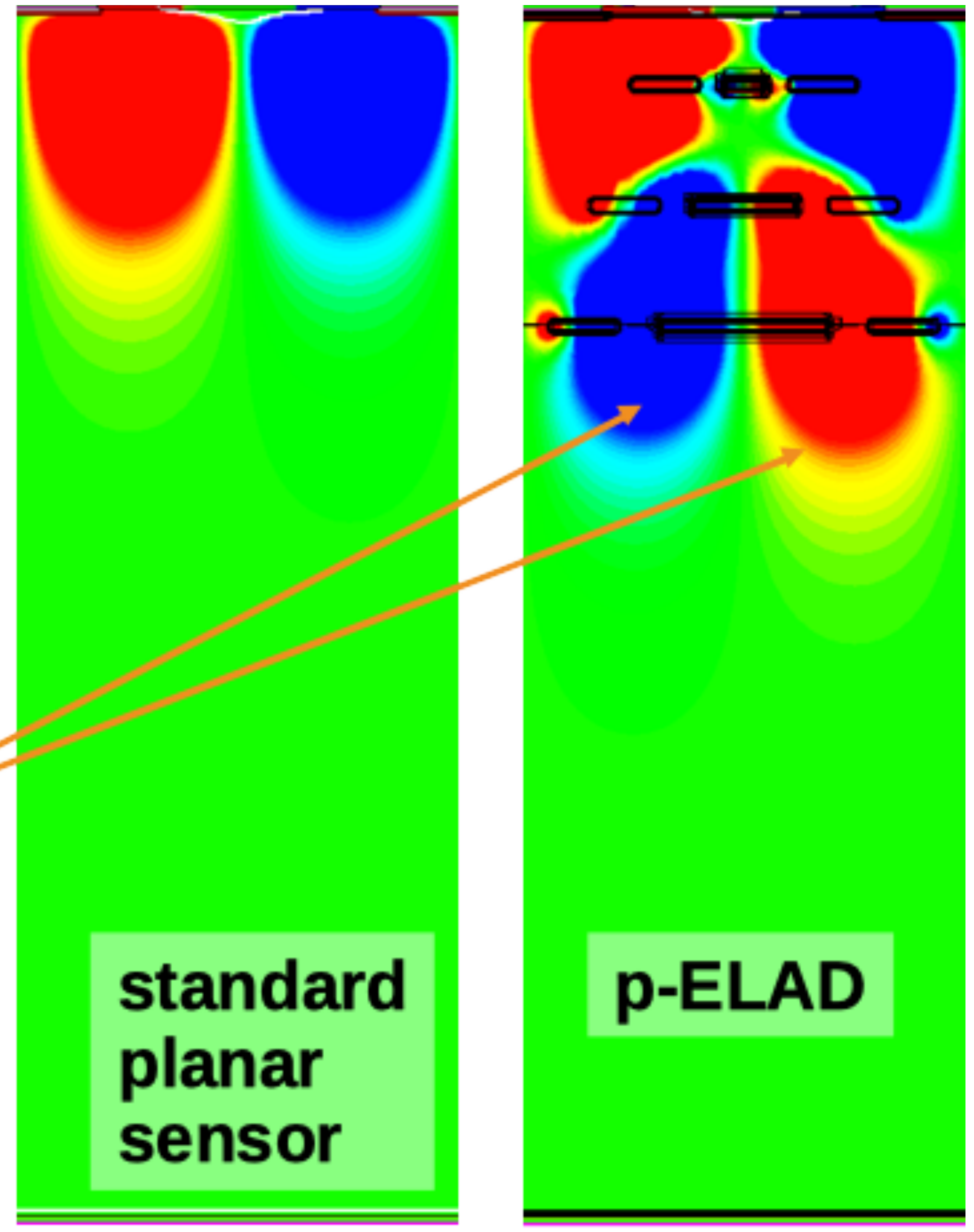
- Wanted: thin & fast & precise pixel detectors
- Reality: thin & fast translates to ~binary resolution
- Goal: reach theoretical limit of position resolution at given pitch, SNR and threshold
- How: linear charge sharing
- Solution: dedicated charge sharing mechanism by engineering the E-field
- Requires: layer-by-layer process combining epitaxy and ion beam implantation

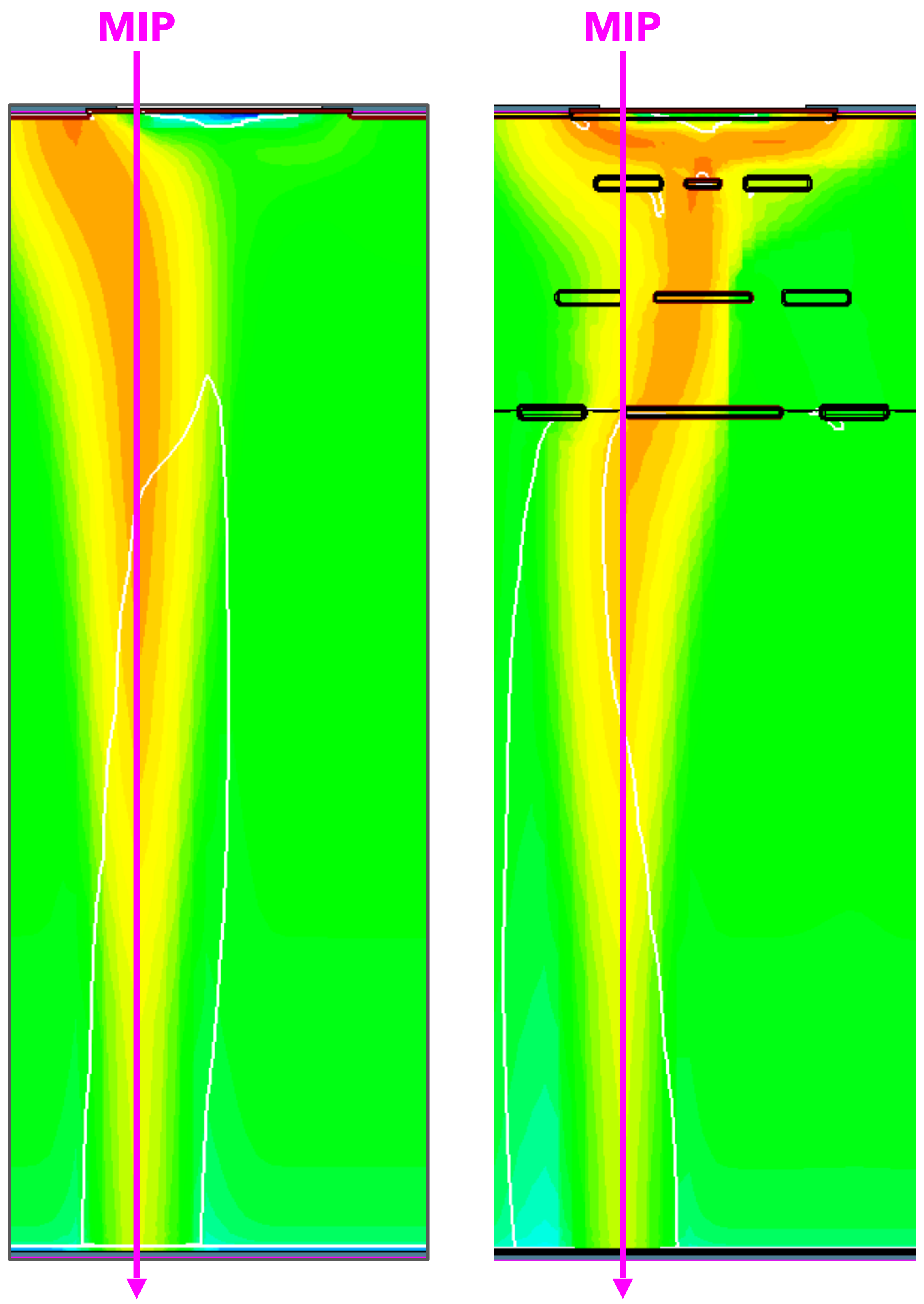




Electric field lines point to the centre!

Resulting field from deep implants.
Blue: e- move right
Red: e- move left

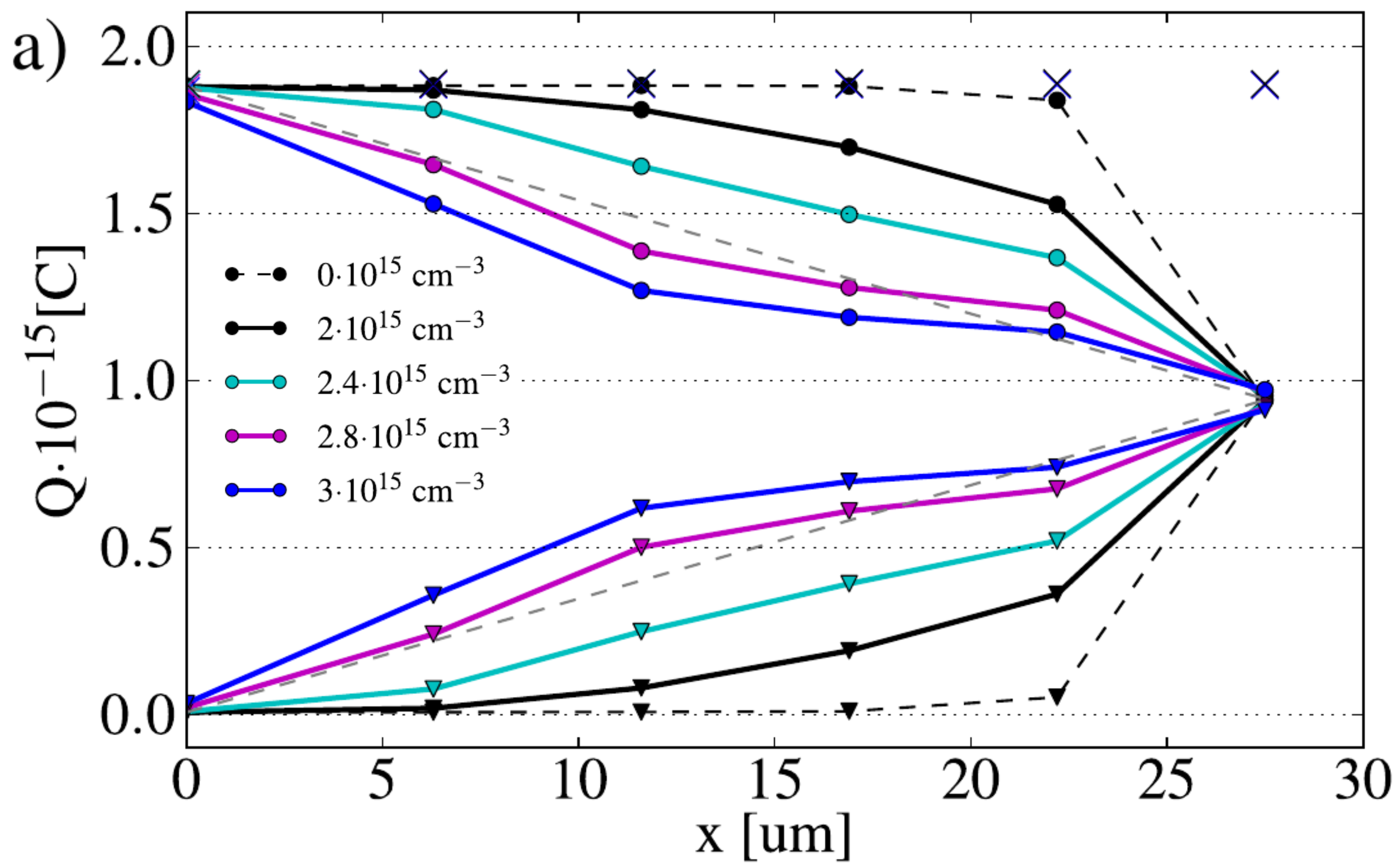




ELAD - TCAD / Detector Simulations

TCAD

Charge sharing vs. MIP position
n-ELAD @ 280 V

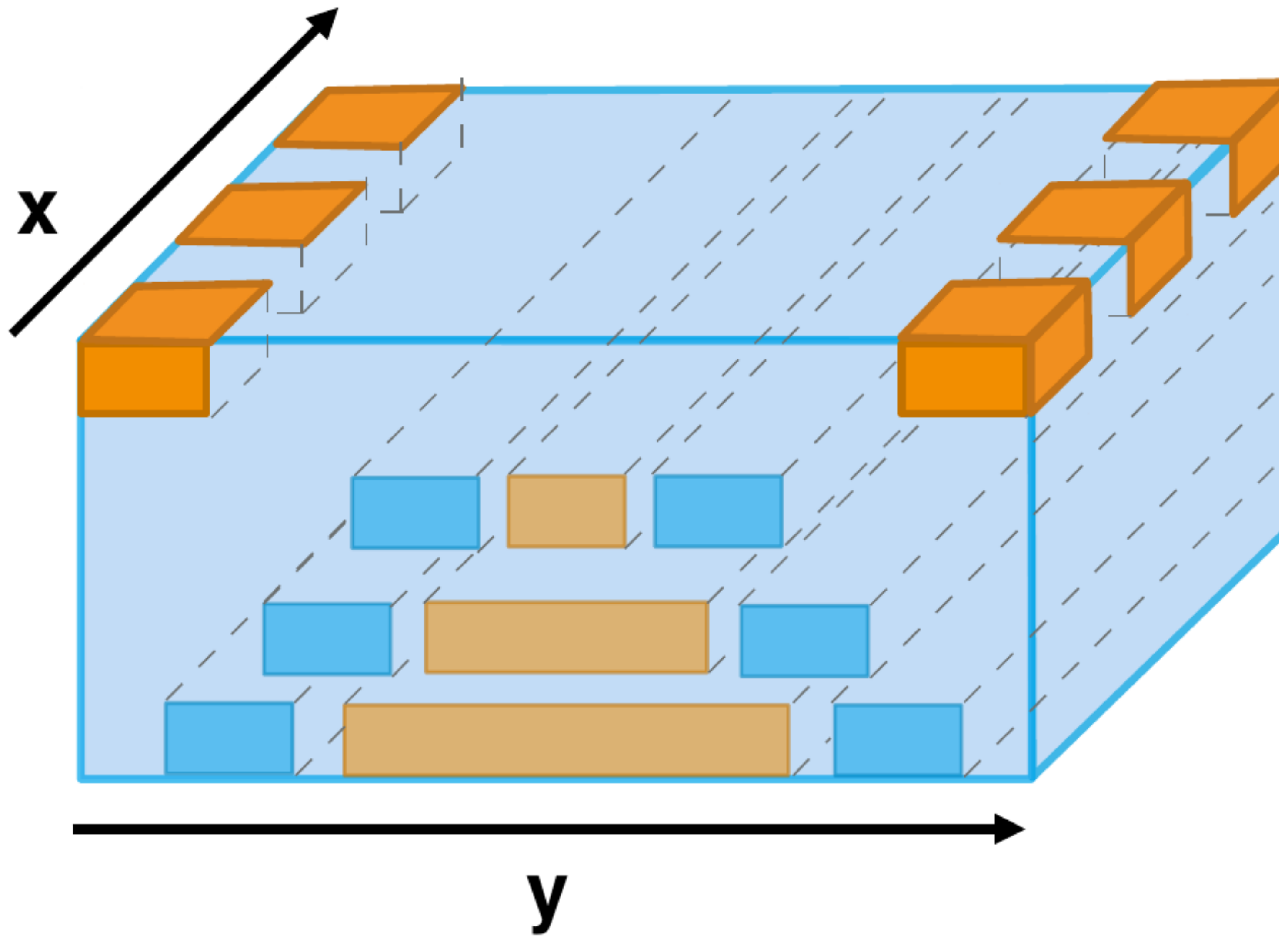


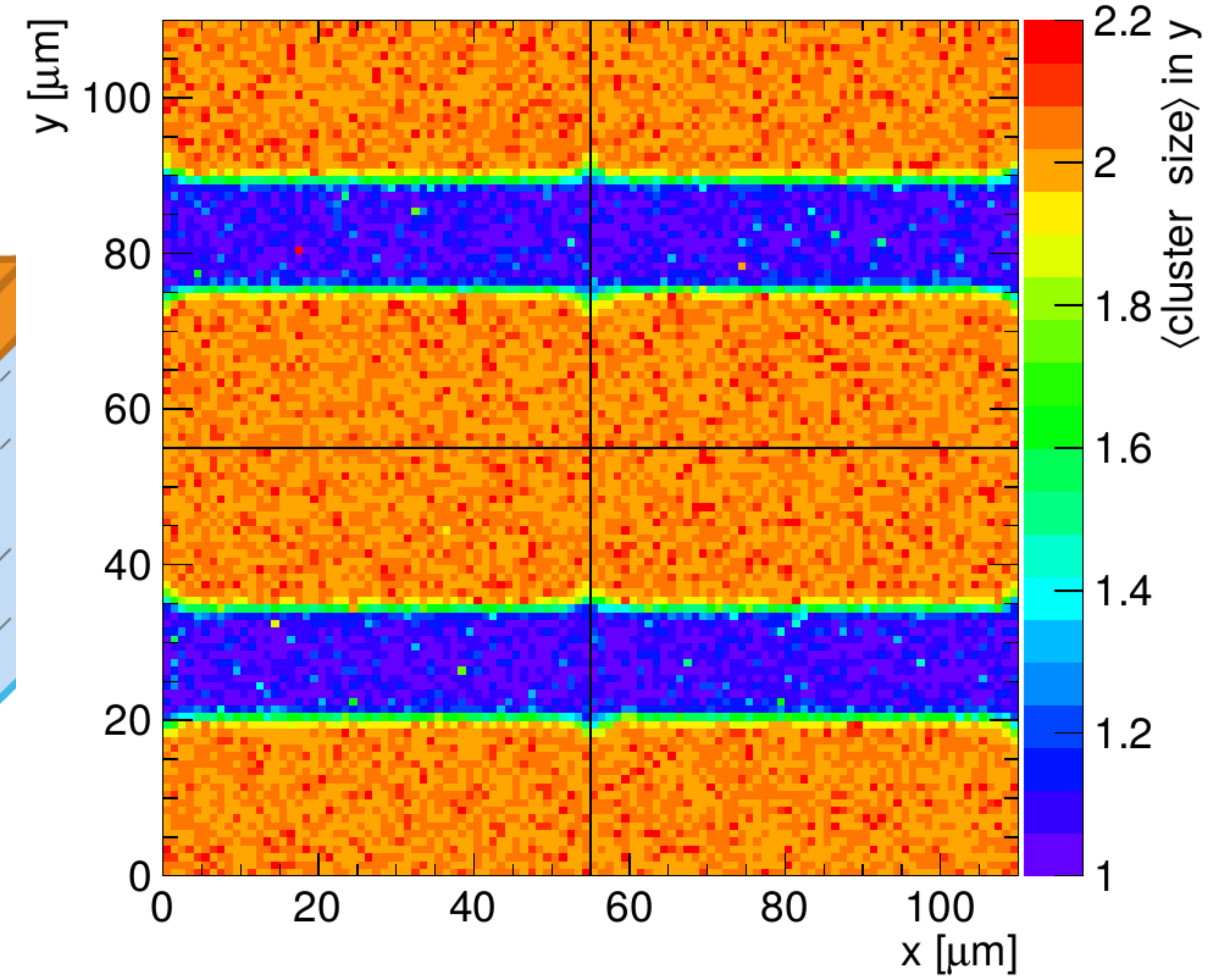
- ELAD design allows to tune charge sharing
- No charge loss (no low-field areas)
- Close to theoretical optimum

Patent granted: H. Jansen, DE102015116270B4
H. Jansen, Nucl. Instr. Meth. A 831 242 (2016)
A. Velyka, H. Jansen, TIPP 2017 proceedings

AllPix2

Study impact of buried implants on the spatial resolution
→ Final step of the optimisation scheme after TCAD
AllPix2: generic detector simulation framework
→ Monte Carlo particles from Geant4
→ Charge deposition
→ Charge drift/diffusion (import TCAD E-field)
→ Digitizer



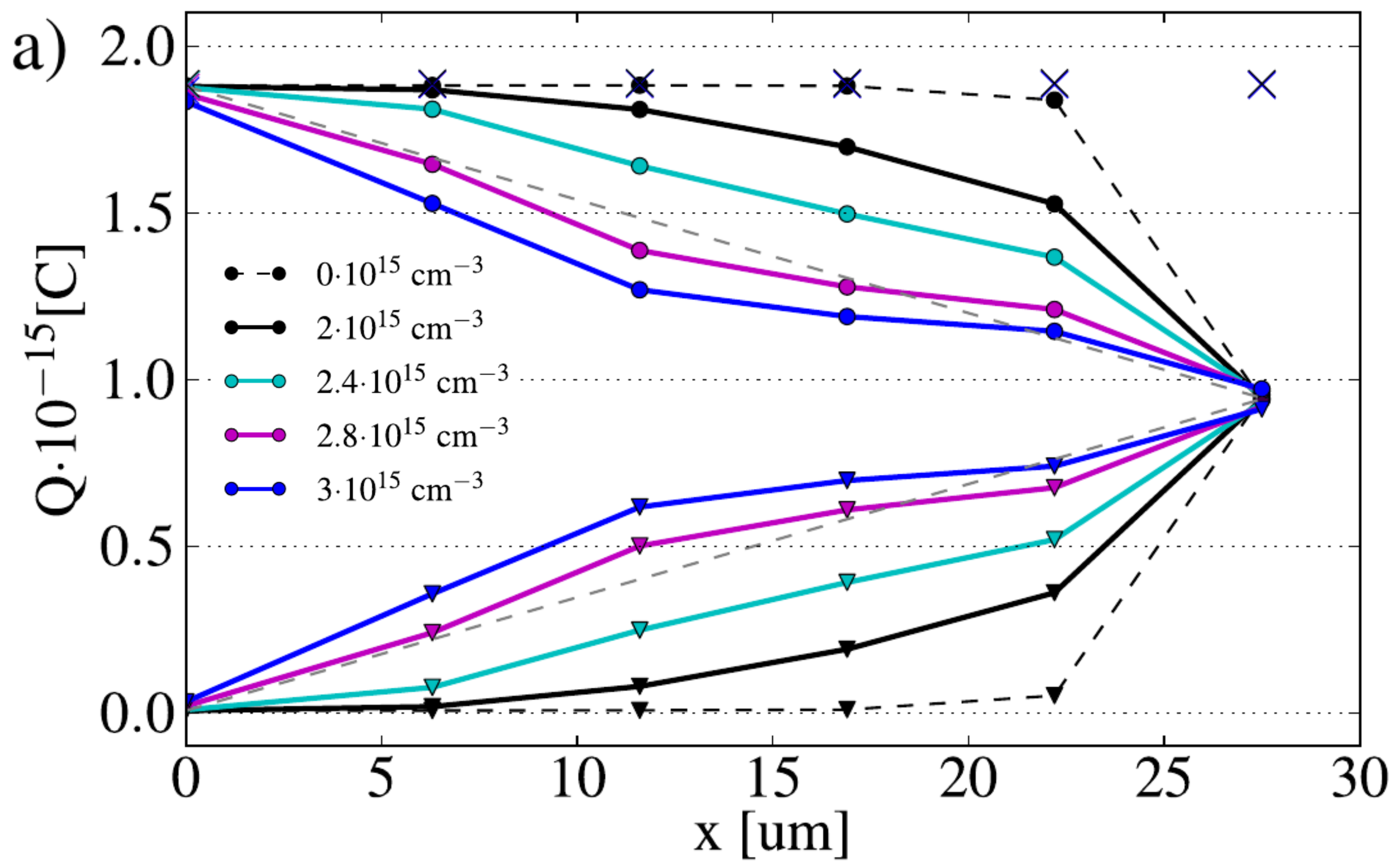


orange = clustersize 2
blue = clustersize 1
Improvement in resolution up to a factor 3!

ELAD - TCAD / Detector Simulations

TCAD

Charge sharing vs. MIP position
n-ELAD @ 280 V



- ELAD design allows to tune charge sharing
- No charge loss (no low-field areas)
- Close to theoretical optimum

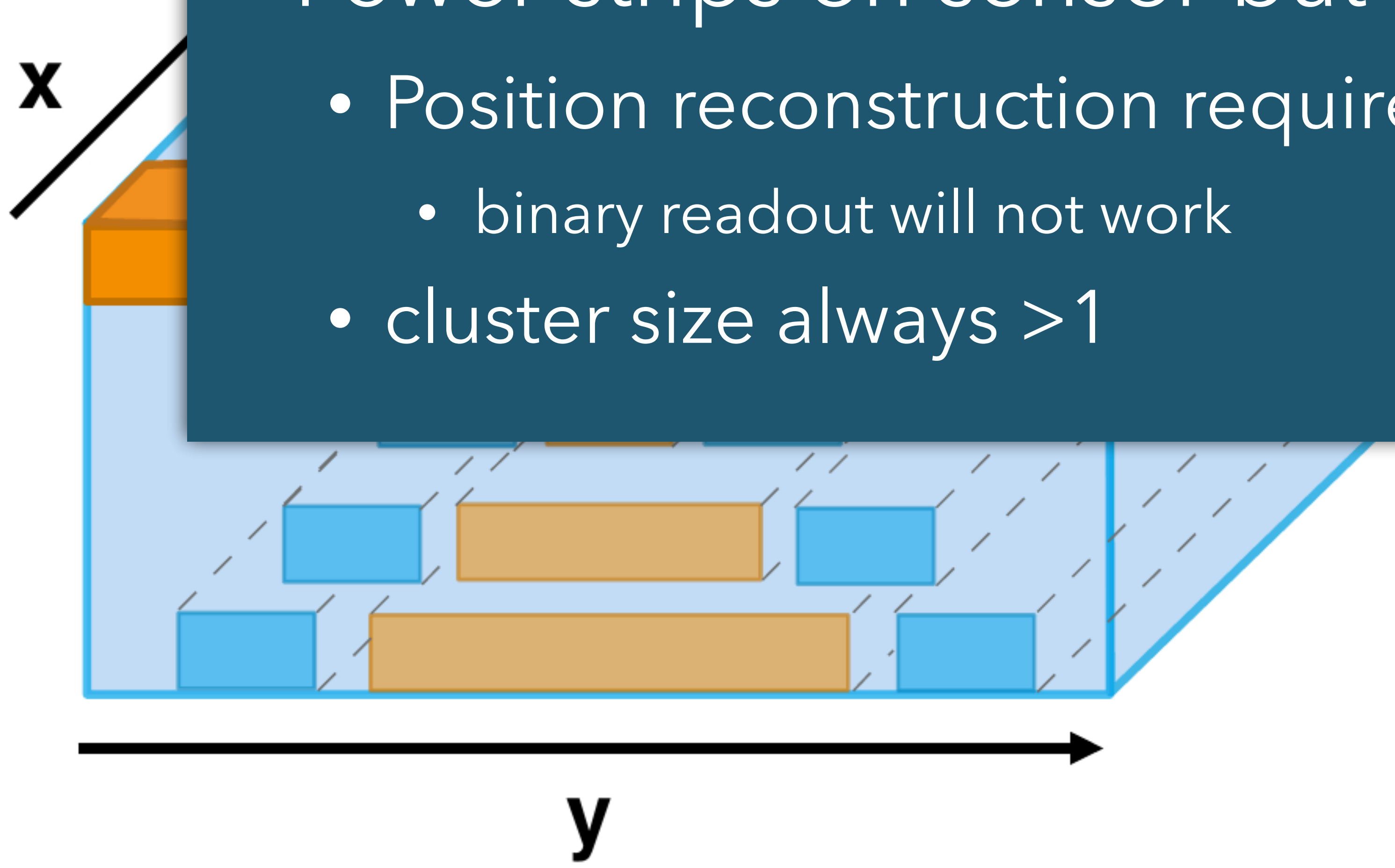
Patent granted: H. Jansen, DE102015116270B4
H. Jansen, Nucl. Instr. Meth. A 831 242 (2016)
A. Velyka, H. Jansen, TIPP 2017 proceedings

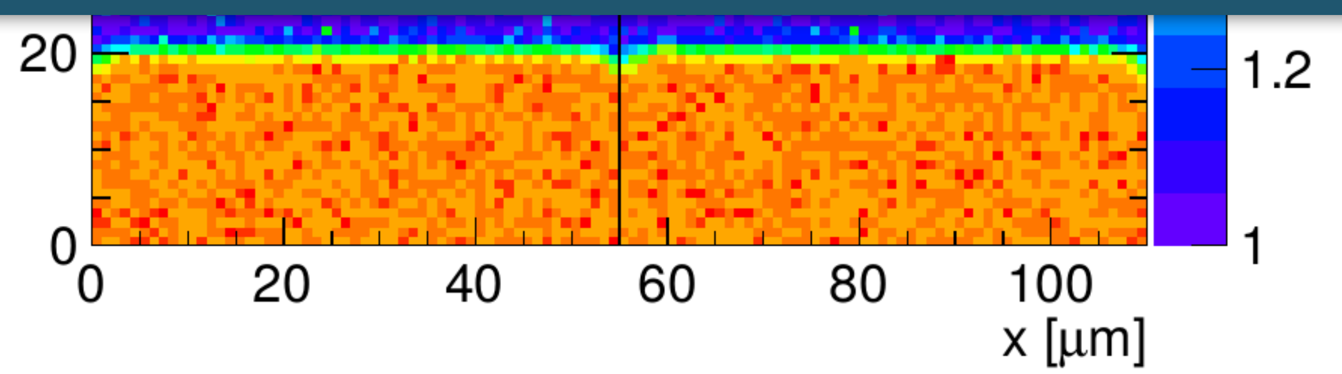
AllPix2

Study impact of buried implants on the spatial resolution
→ Final step of the optimisation scheme after TCAD
AllPix2: generic detector simulation framework

However…

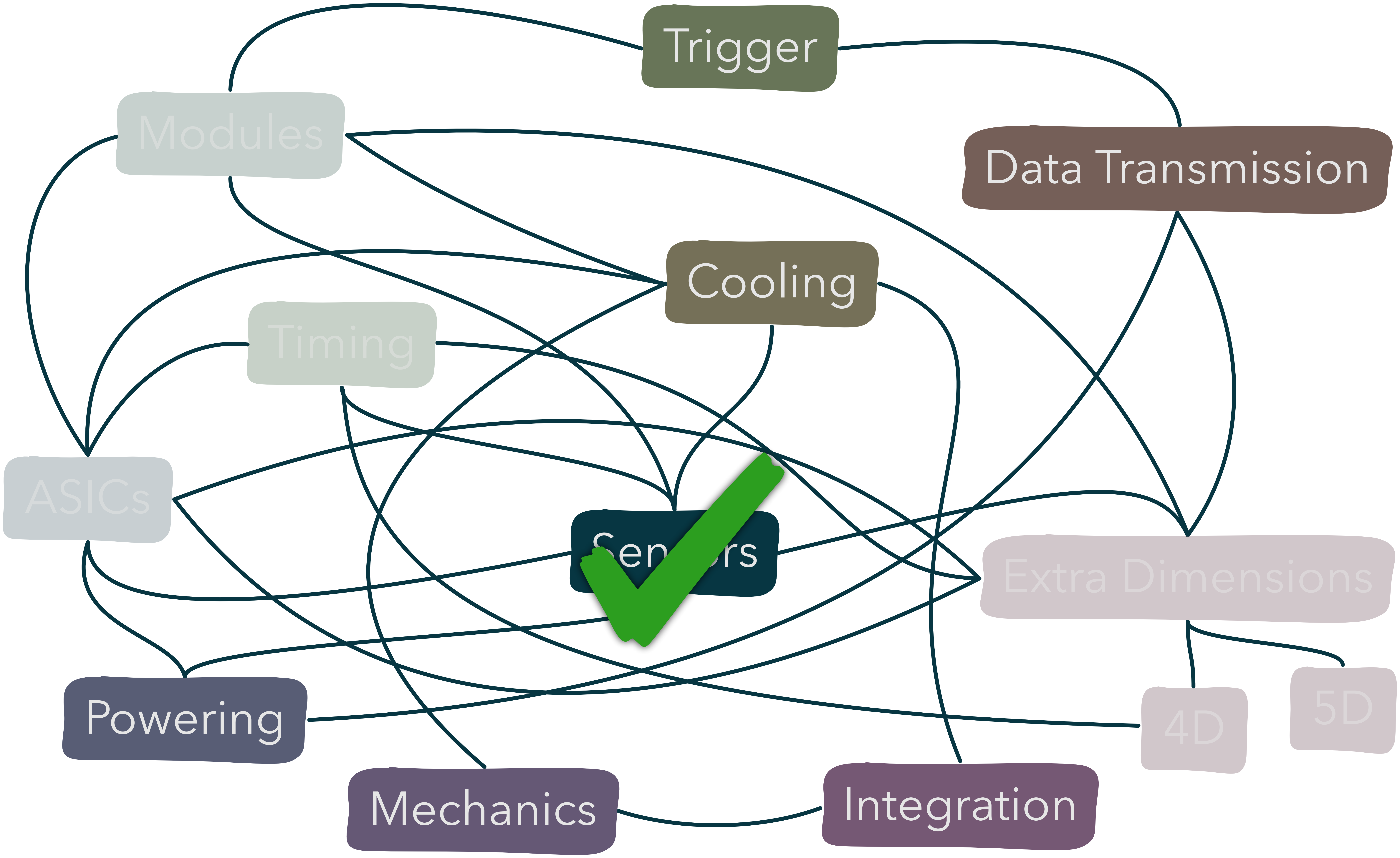
- Irradiation will change deep implant doping concentration
  - charge sharing probably changes with irradiation
  - to be checked with first prototype sensors
  - ELADs might not be suitable for hh machines
- Fewer strips on sensor but more data per cluster
  - Position reconstruction requires amplitude information
    - binary readout will not work
  - cluster size always >1





orange = clustersize 2
blue = clustersize 1
Improvement in resolution up to a factor 3!

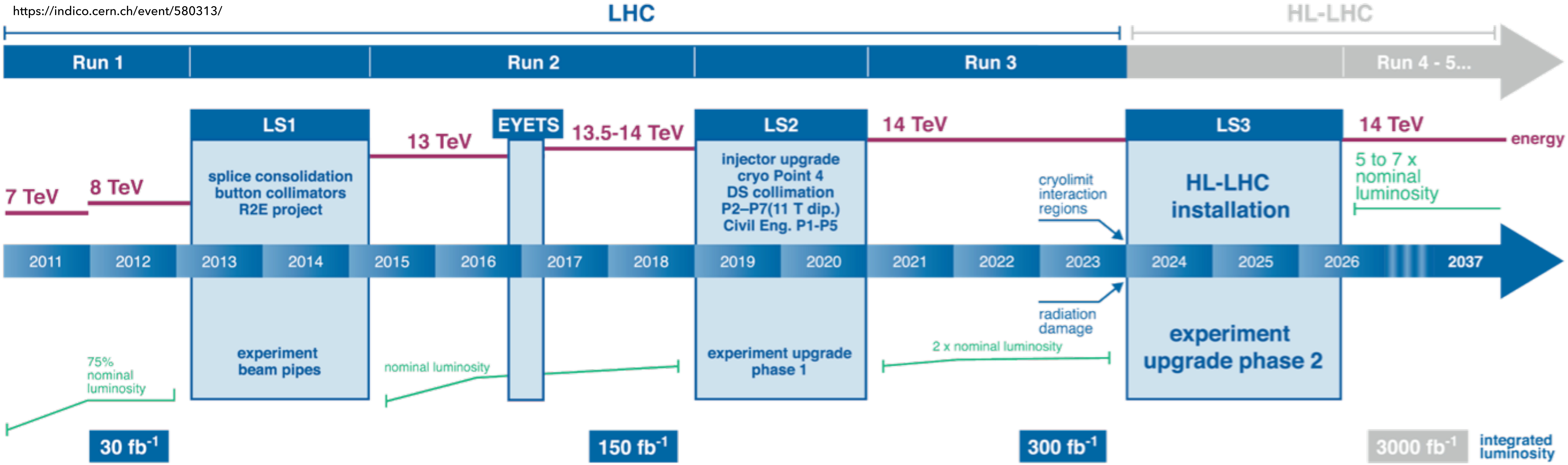
Outline



Trigger
Modules
Data Transmission
Cooling
Timing
ASICs
Sensors
Extra Dimensions
Powering
4D
5D
Mechanics
Integration

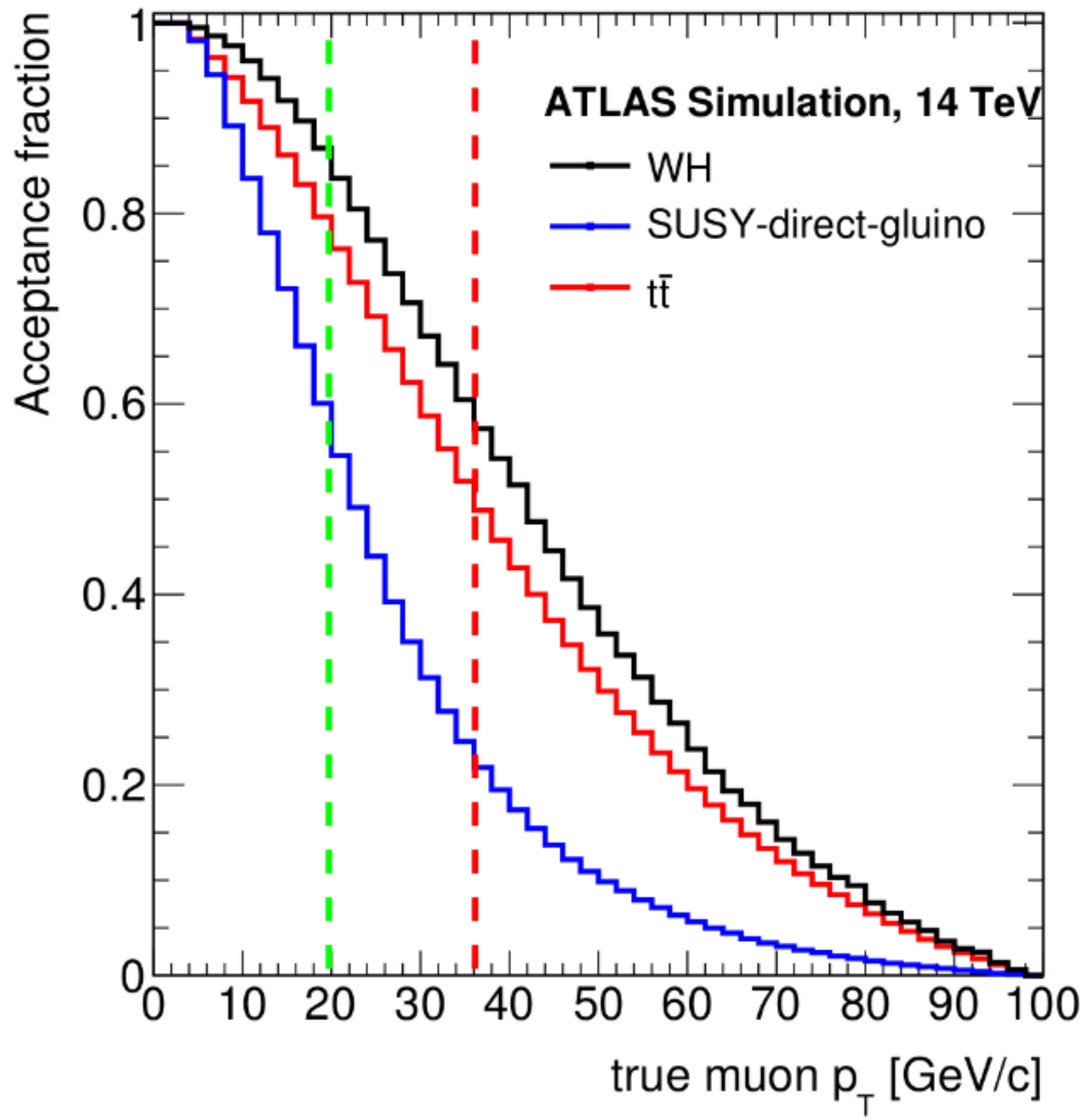
High-Luminosity LHC

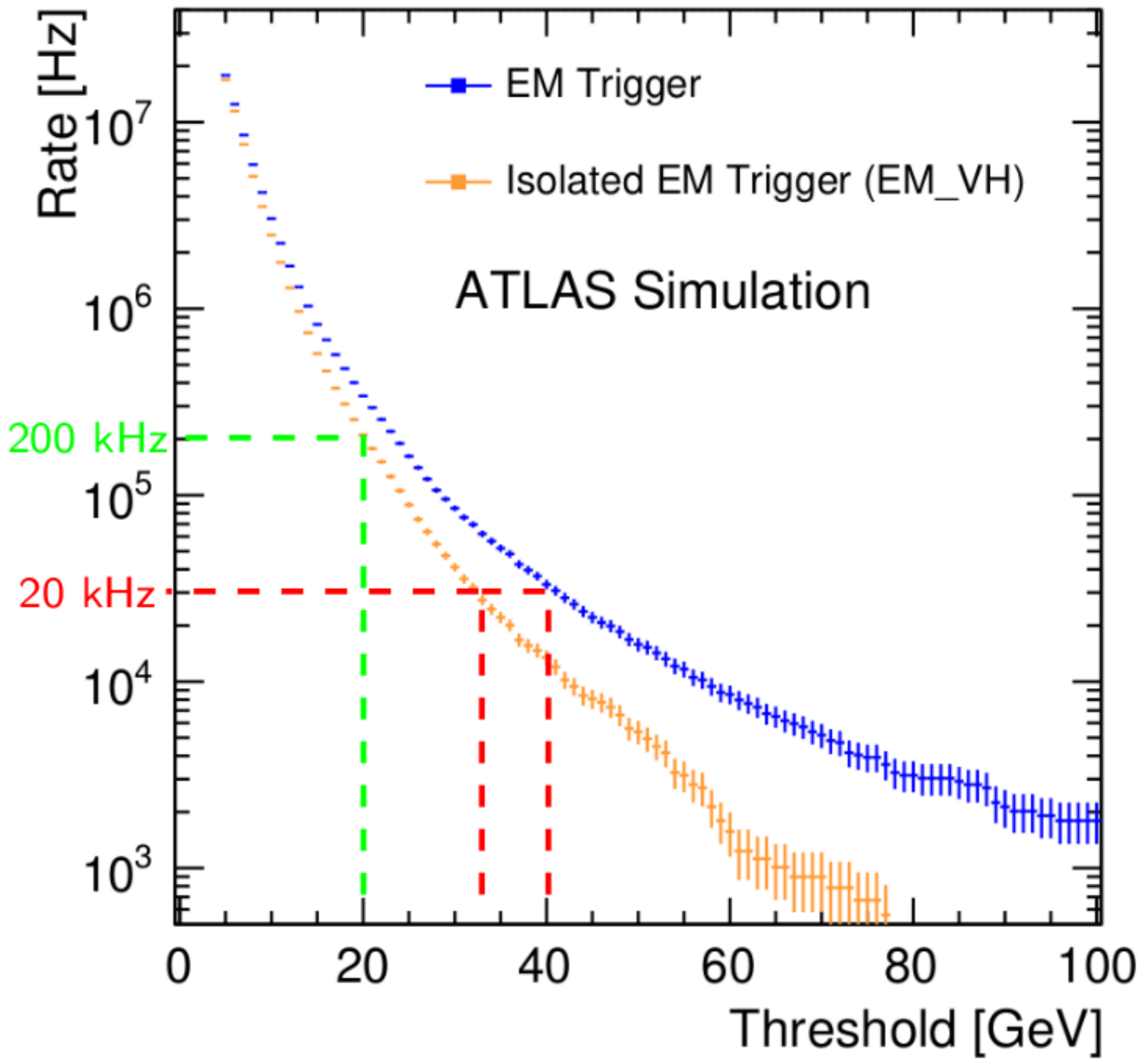
Frédérick Bordry, Chamonix Workshop 2017
https://indico.cern.ch/event/580313/



- Exploit full potential of LHC and to collect up to 4000 fb^{-1}
  - Upgrades of accelerator and detectors are necessary to reach this ambitious goal
  - Primary motivation of all upgrades is to maximise physics reach, which drives the design choices for the detector upgrades
- Future trackers have to deal with
  - higher radiation levels ➡ sensor & electronics design, cooling
  - pile up of up to 200 at $7.5 \times 10^{34}\ cm^{-2}s^{-1}$ ➡ higher bandwidth, use of tracker information at early trigger stage
  - higher track density ➡ increased granularity
- LS3 will start 2025 as we heard yesterday

Triggering at HL-LHC

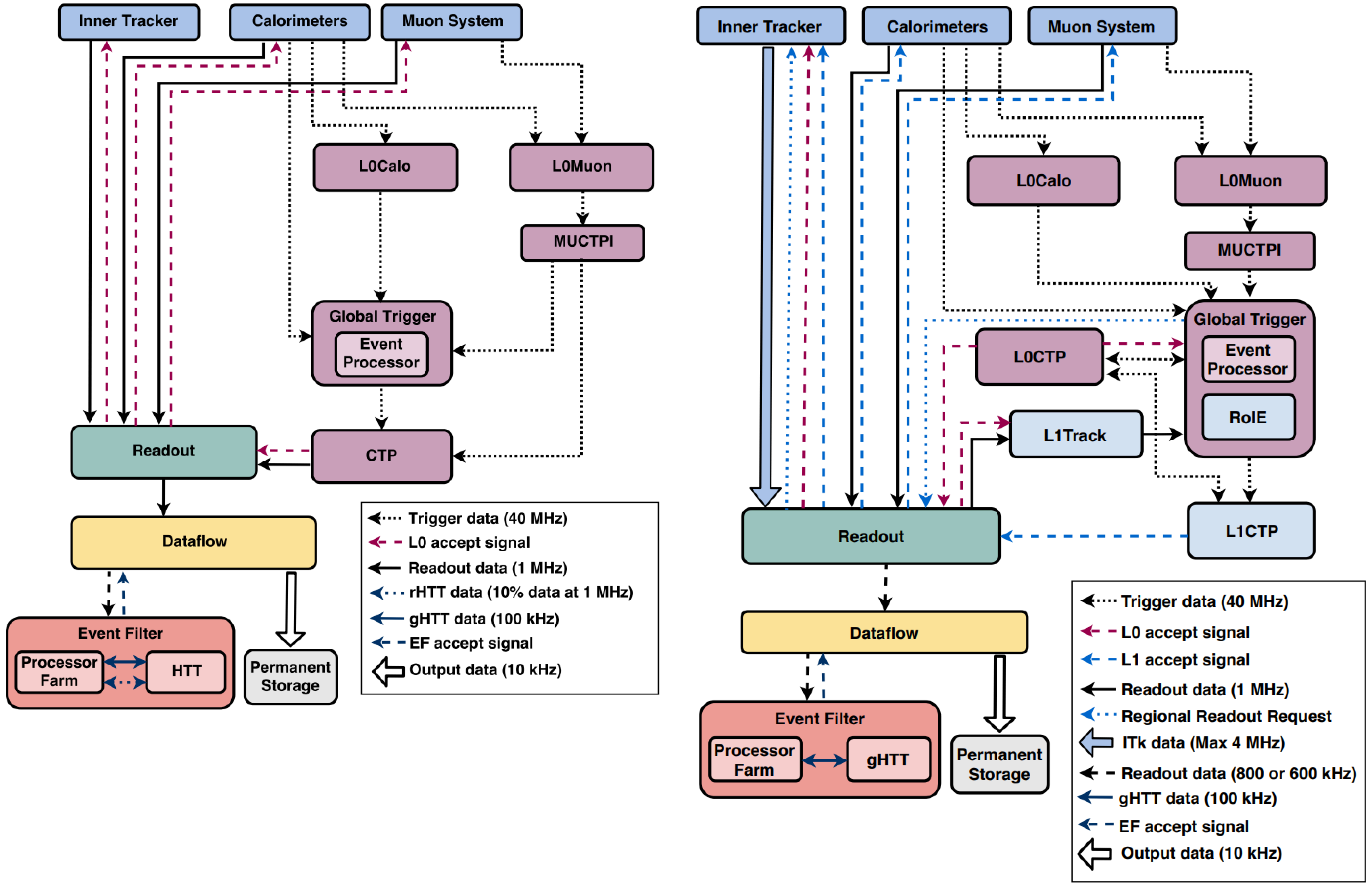




- Increasing the trigger pT threshold to lower the rate would limit the physics reach
- Trigger has to become ‚smarter' ➟ use tracker information in an early trigger stage

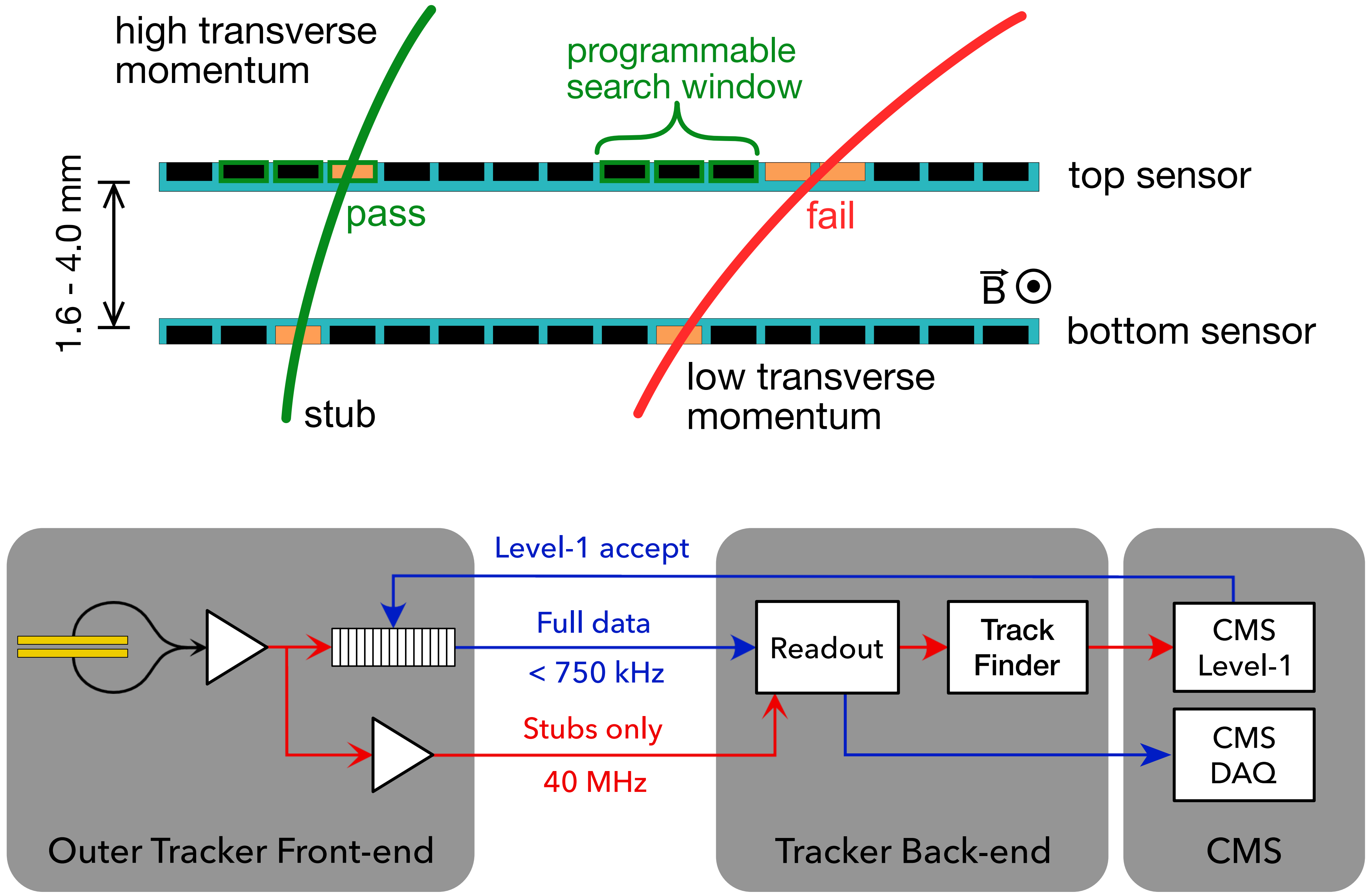
Track Trigger Implementations

ATLAS



- Level-0 (L0): Muon and Calo trigger
- Two options:
  - L0 only, full detector readout and regional tracking in Event Filter
  - L0 and L1-Track
    - L0 initiates regional readout
    - regional data is used in track trigger

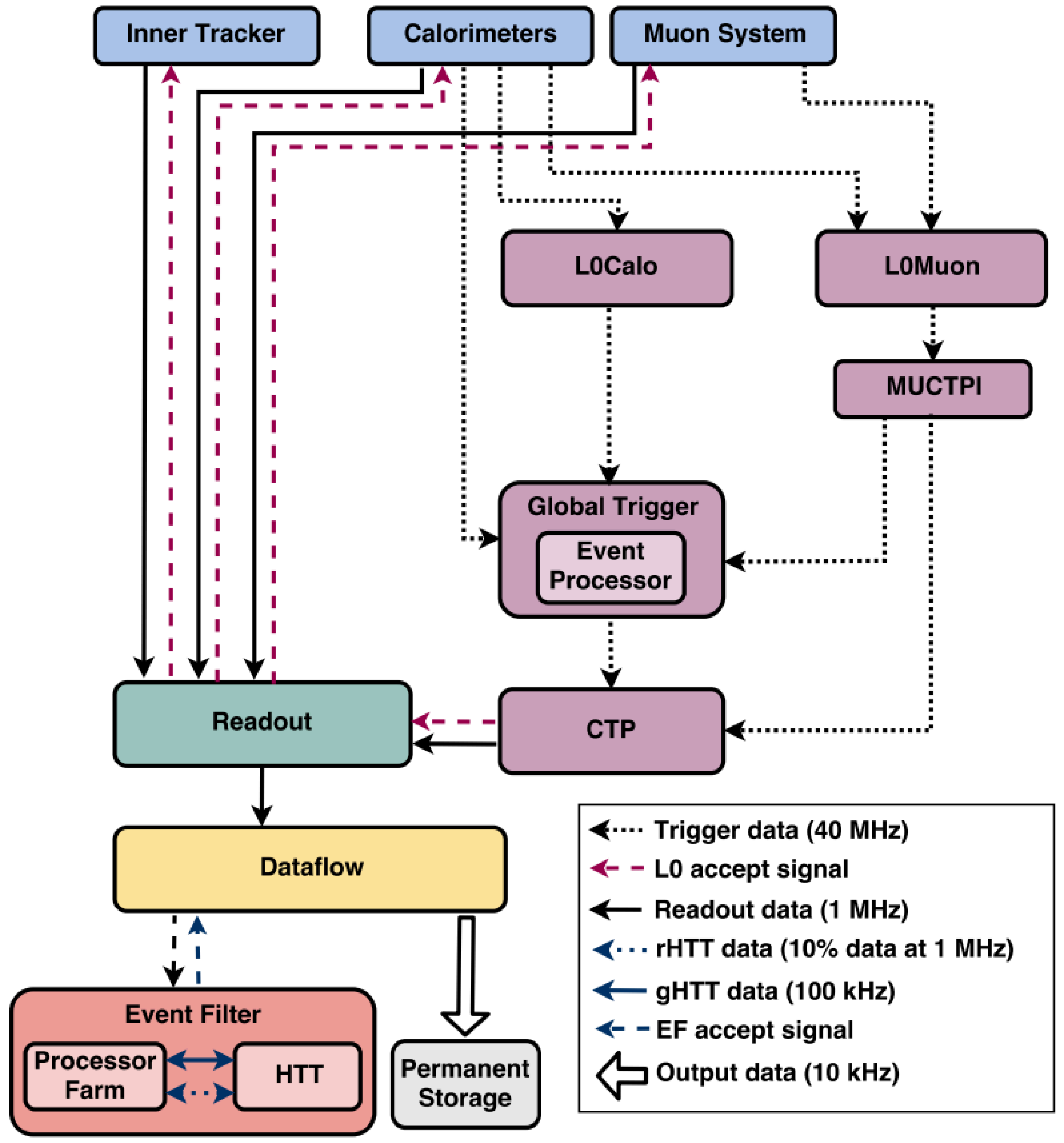
CMS

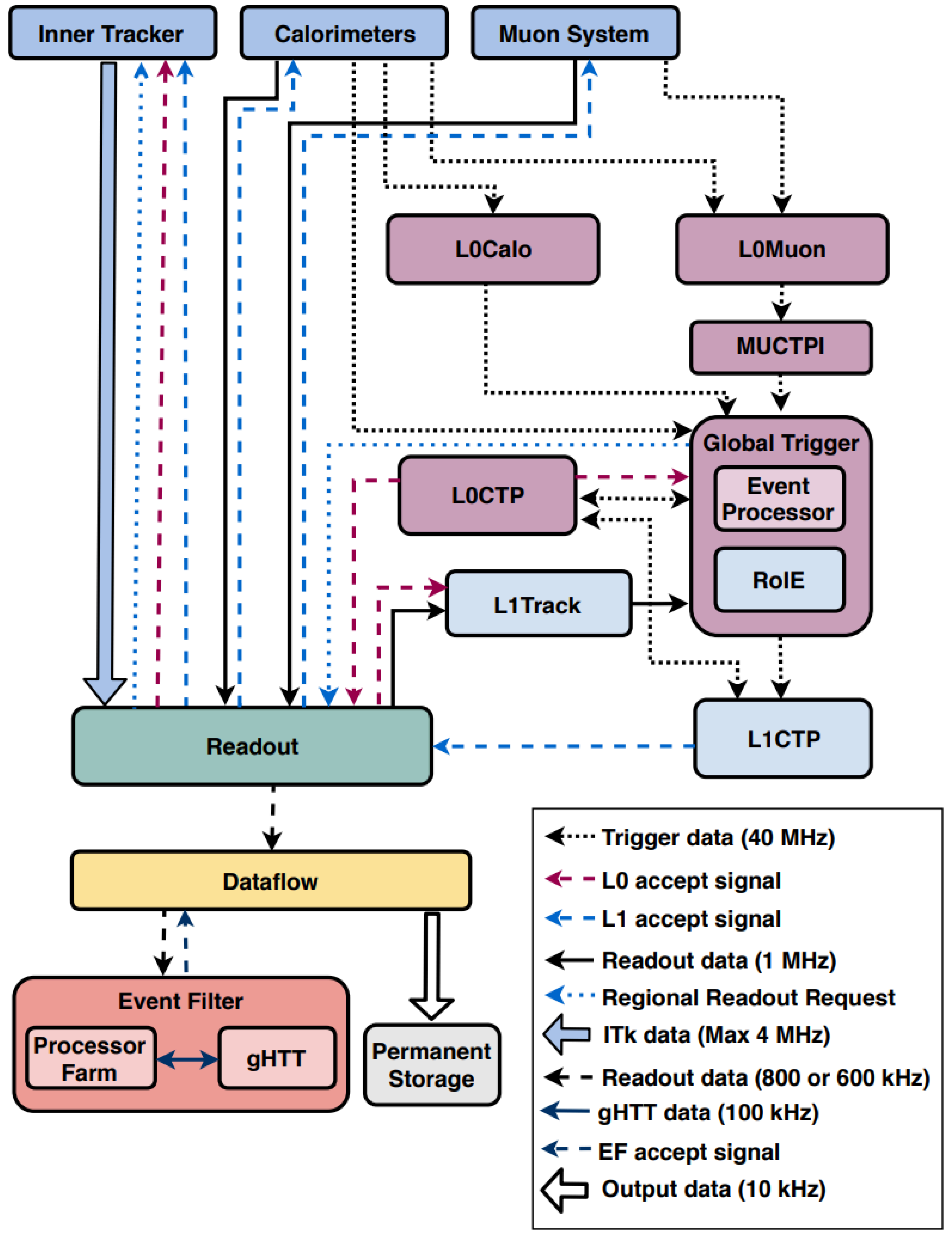


- Modules consist of two closely spaced sensors for local pT discrimination
- Minimalistic information for high-pT tracks is transferred to track trigger at 40 MHz
- Information from Track Trigger is used in Level-1 trigger

Track Trigger Implementations

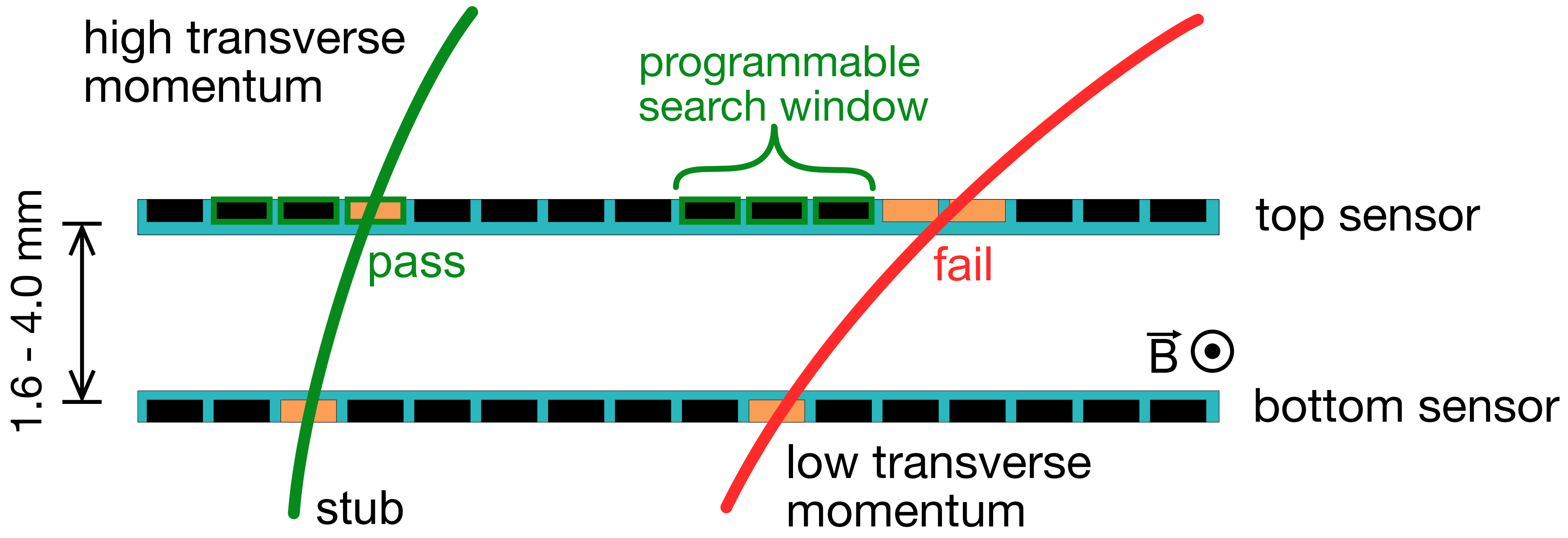
ATLAS

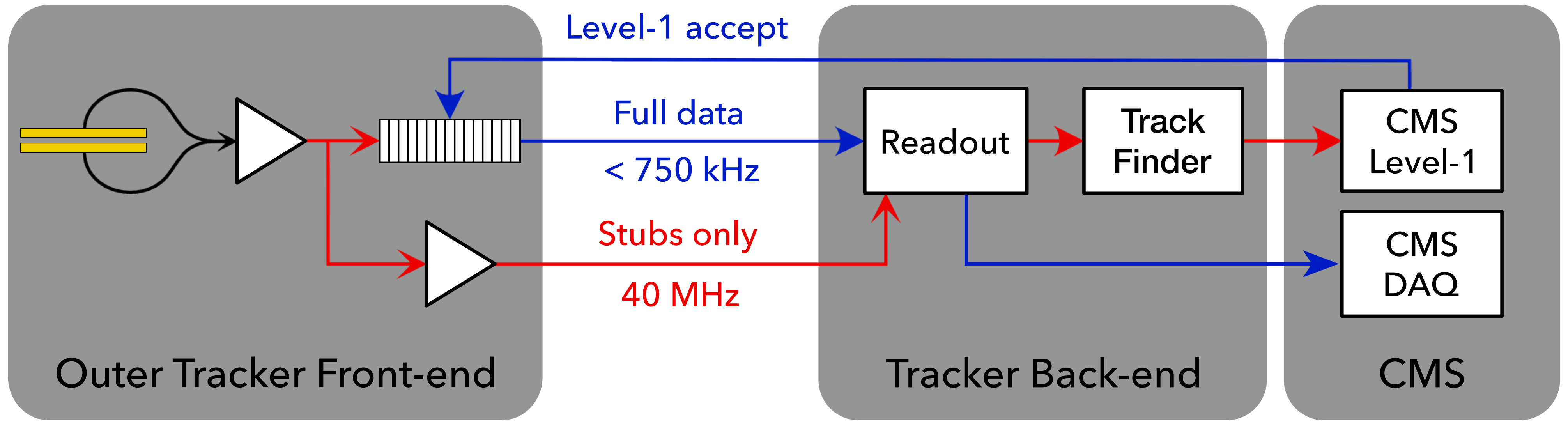




- Level-0 (L0): Muon and Calo trigger
- Two options:
  - L0 only, full detector readout and regional tracking in Event Filter
  - L0 and L1-Track
    - L0 initiates regional readout
    - regional data is used in track trigger

CMS

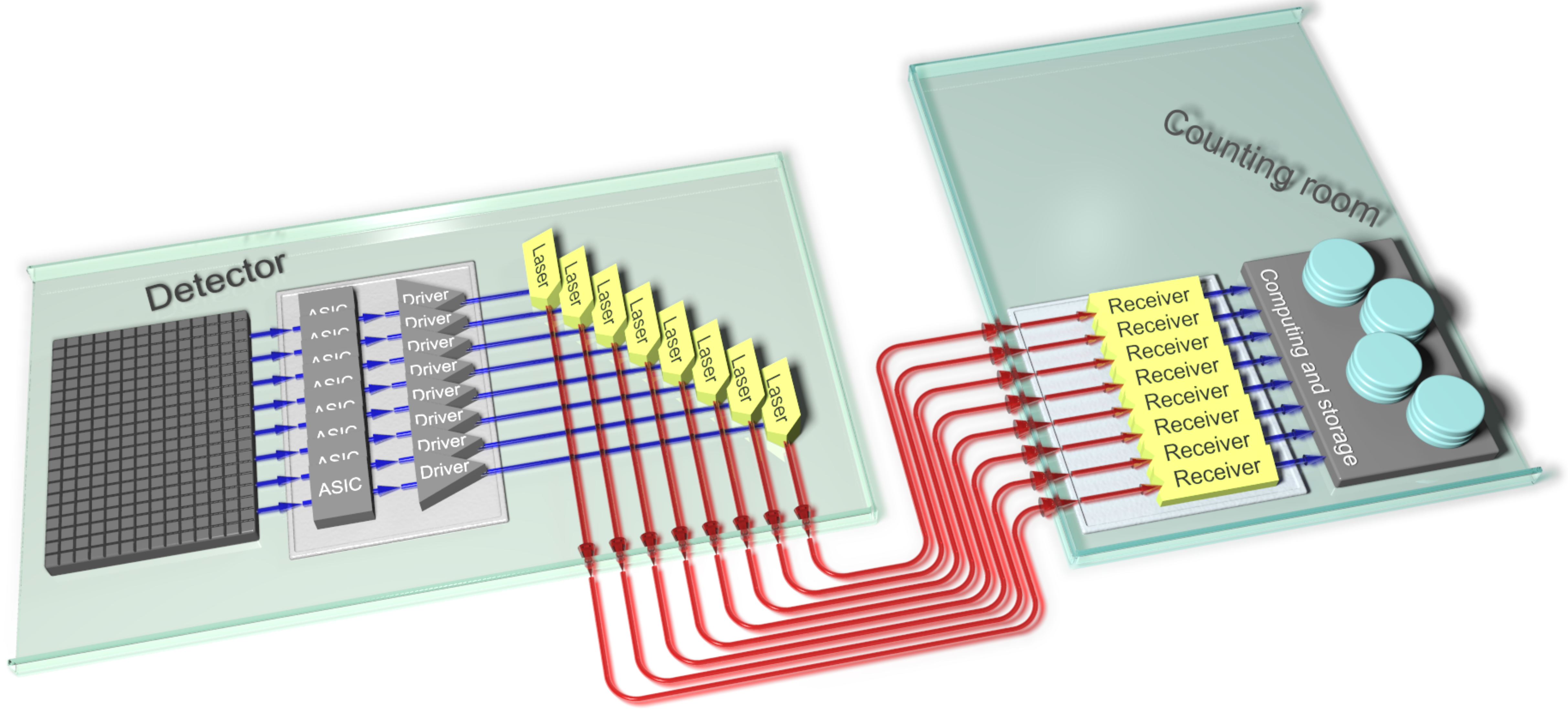




- Modules consist of two closely spaced sensors for local pT discrimination
- Min... tra...
- Information from Track Trigger is used in Level-1 trigger

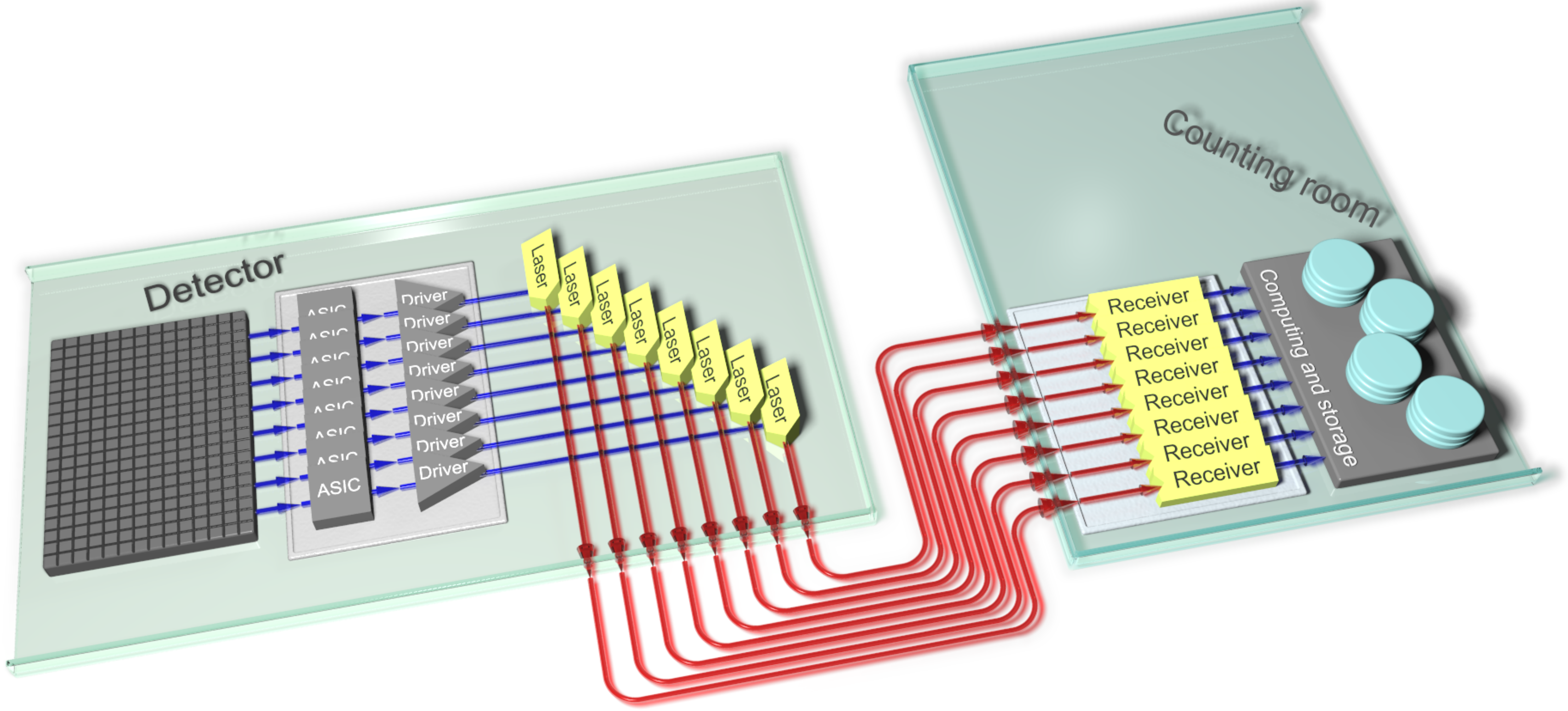
M. Jeitler - *The Phase-2 Upgrade of the Hardware Trigger of CMS at the LHC*

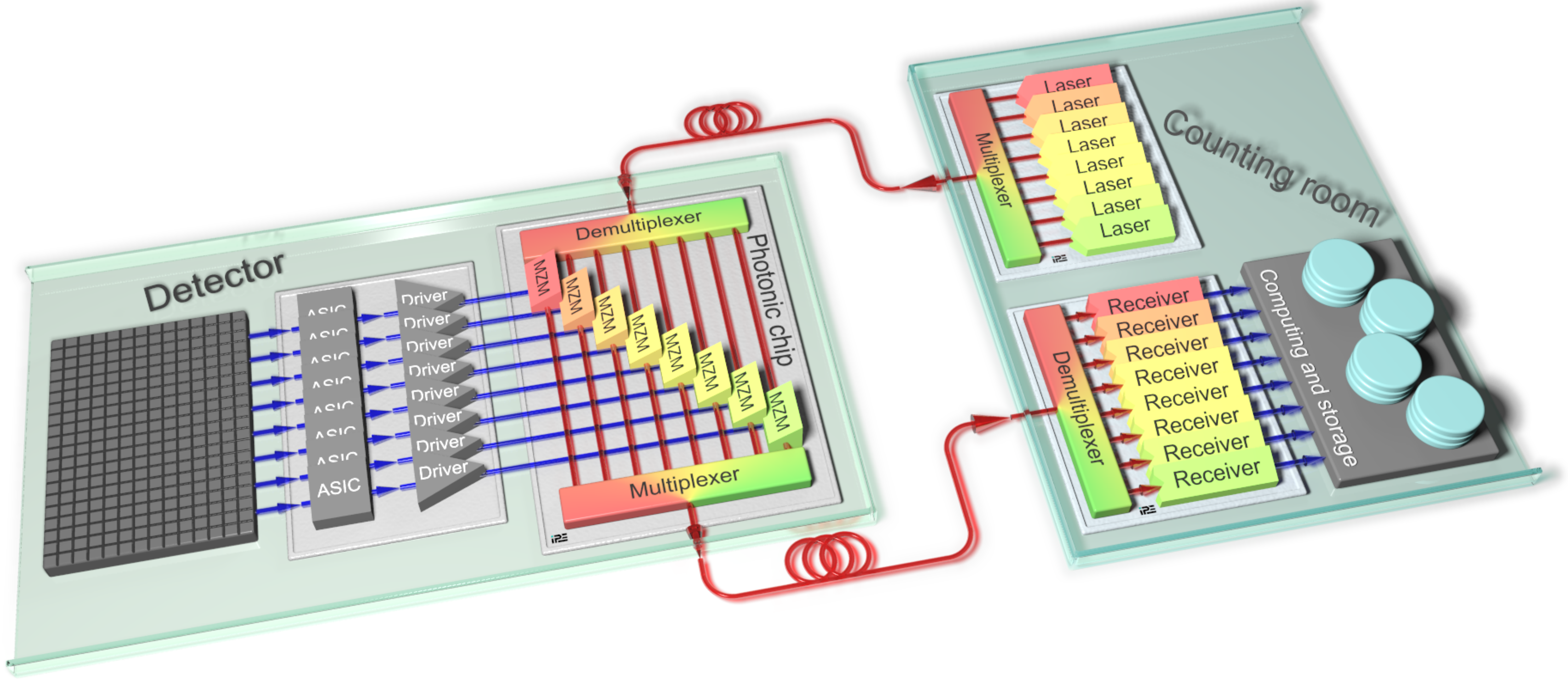
The Future of Optical Links



- Current link implementation based on vertical cavity surface emitting lasers (VCSEL)
  - Information is encoded by varying the laser current
  - bandwidth limited to 10 Gbit/s per fibre
    - faster prototypes are under development but
  - only one modulated signal per fibre
  - radiation tolerance of the VCSEL is an issue

The Future of Optical Links





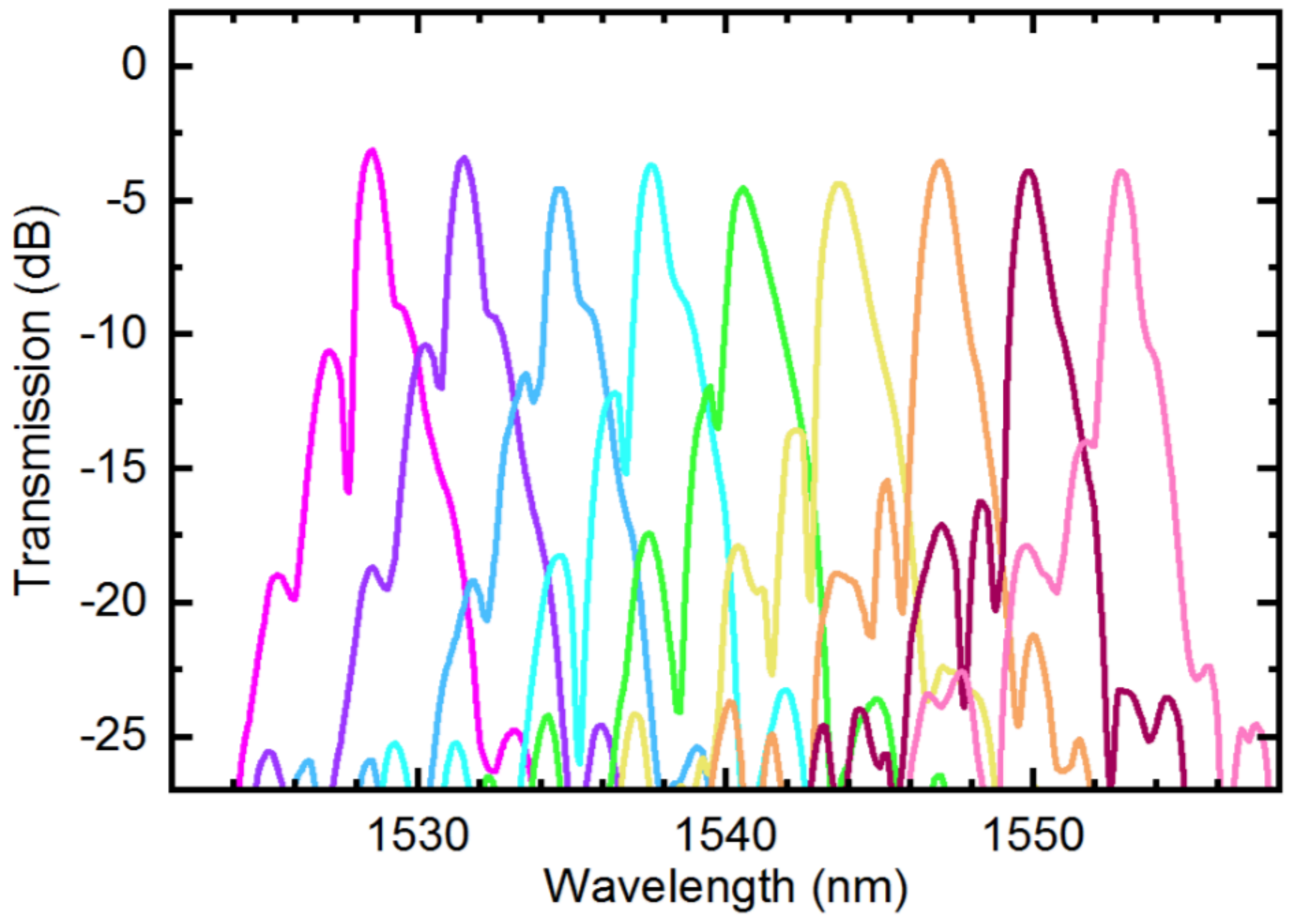
Y. Zheng et al. (2019 JINST 14 P08021)

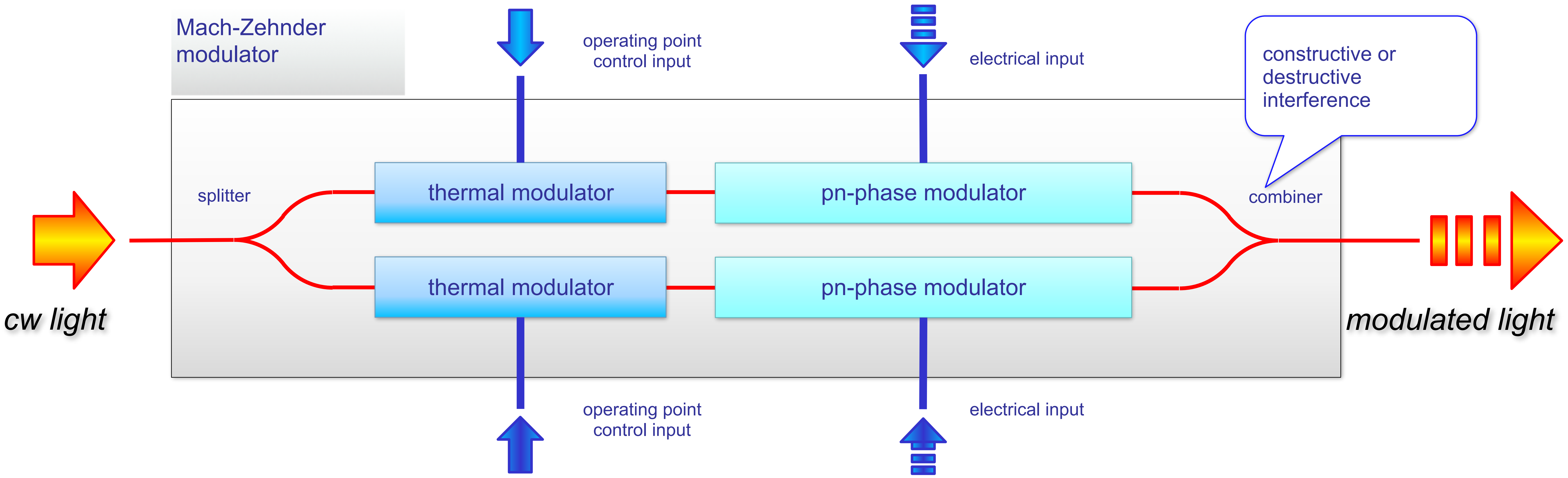
- Current link implementation based on vertical cavity surface emitting lasers (VCSEL)
  - Information is encoded by varying the laser current
  - bandwidth limited to 10 Gbit/s per fibre
    - faster prototypes are under development but
  - only one modulated signal per fibre
  - radiation tolerance of the VCSEL is an issue

- Even higher bandwidth requirements in future detectors expected
- Could be addressed by silicon photonics and Wavelength Division Multiplexing (WDM) technology
  - optical multiplexer combine light from stabilized lasers
  - optical carriers are separated by wavelength through Echelle grating demultiplexer in the front end
  - individual optical carriers are modulated by Mach-Zehnder modulators (MZMs)
  - modulated optical signals are multiplexed by second Echelle grating and transmitted to the back end

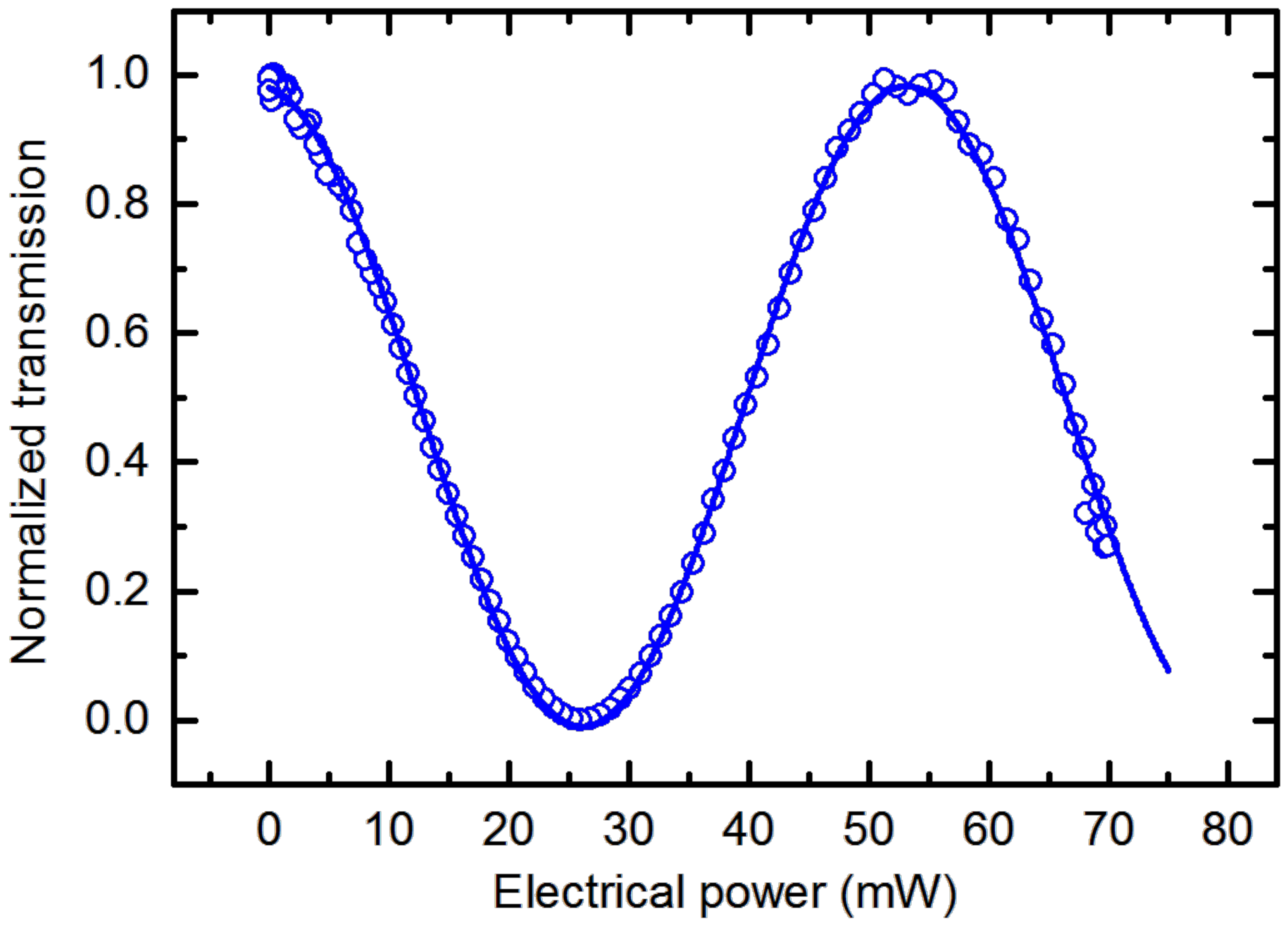
The Future of Optical Links

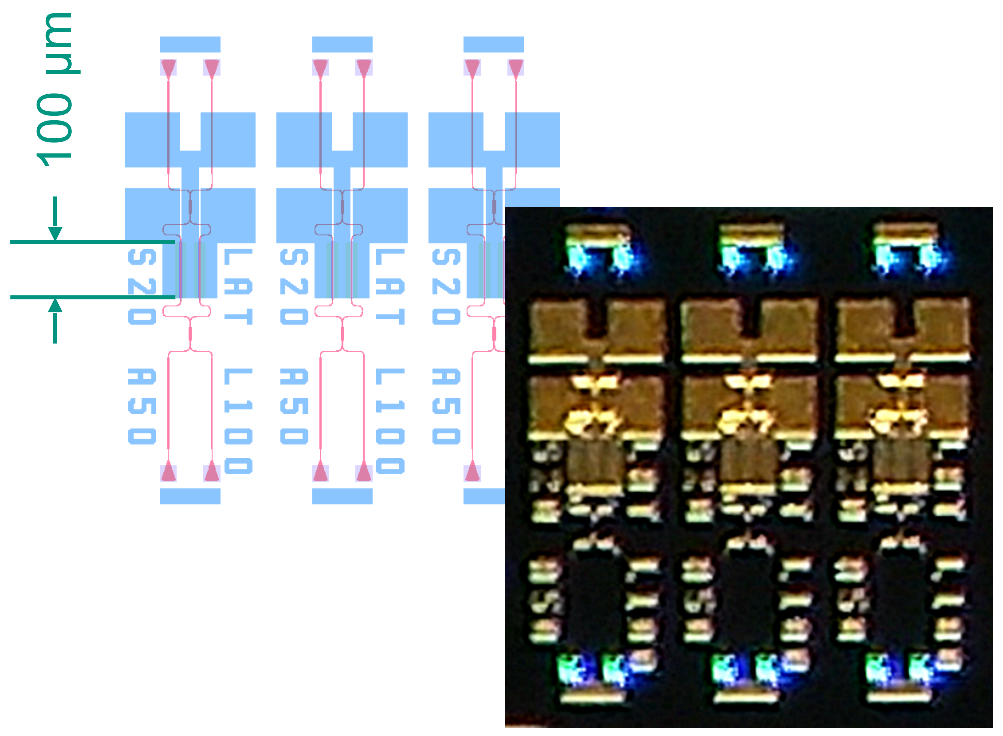
Output of 1x9 Demultiplexer





Performance of Thermal Modulator





- Length of thermal modulator is only 100 µm
- 2π-shift at ≈ 58 mW
- Potential to reduce power needed for data transmission
  - no laser diodes in front-end

Y. Zheng et al. (2019 JINST 14 P08021)

Powering Schemes

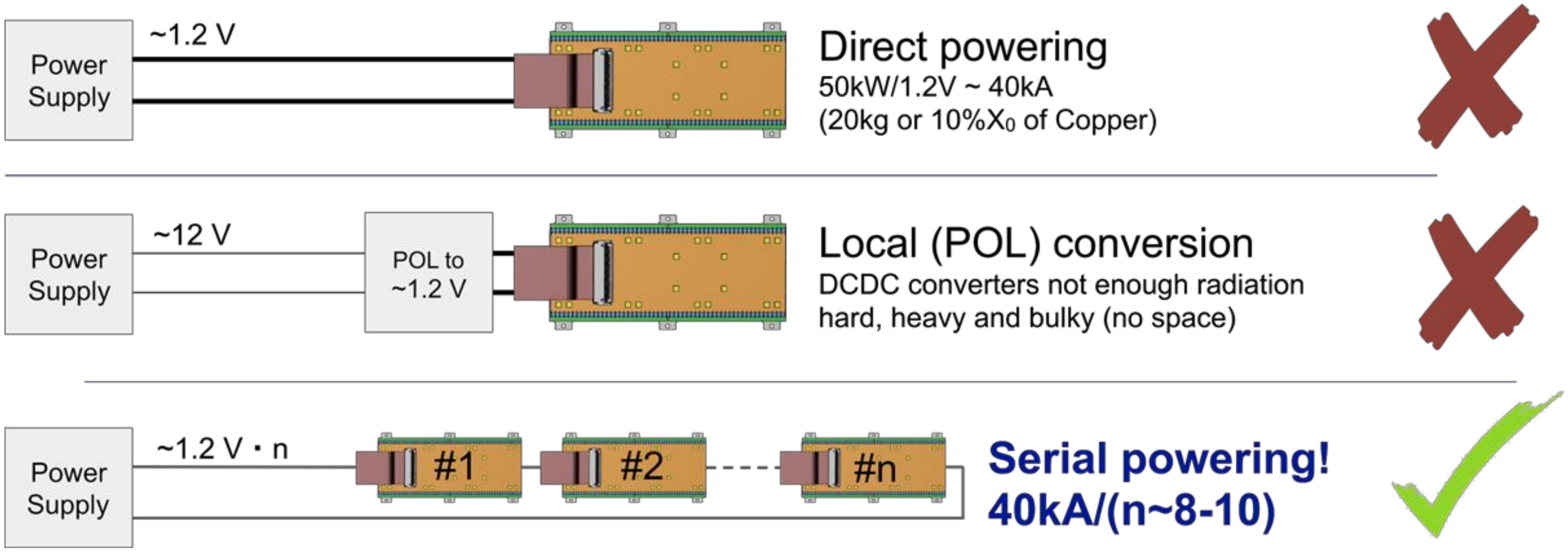
- DC-DC powering widely accepted in HEP as a viable powering scheme
- Serial powering will be used in Phase-2 pixel detectors
  - space constraints
  - material budget

Certainly not complete
Many simplifications

Experiment	Sub-detector	What	How	Where
CMS	Outer Tracker	Strip modules, LpGBT, VTRx+	DC-DC	Front-end
	Phase-1 pixel	Pixel modules	DC-DC	Patch panel
	Phase-2 pixel	LpGBT, VTRx+	DC-DC	Patch panel
		Pixel modules	Serial	
	Endcap calorimeter	Silicon modules, LpGBT, VTRx+	DC-DC	Patch panel or front-end
	Barrel calorimeter	Crystal ADC	DC-DC	Front-end
	Muon system (GEM)	Chambers	DC-DC	Front-end
	Timing detector	Readout, LpGBt, VTRx+	DC-DC	Front-end
ATLAS	Strips	Strip modules, LpGBT, VTRx	DC-DC	Front-end
	Phase-2 pixel	LpGBT, VTRx+	DC-DC	Patch panel
		Pixel modules	Serial	
	Tile calorimeter	Electronics	DC-DC	Patch panel
	Liquid argon calorimeter	Electronics	DC-DC	Front-end
	Muon micromegas	GBTx, VTRx	DC-DC	Front-end
LHCb	Velo	Pixel modules, GBTx	DC-DC	Patch panel
	Fiber tracker	Fiber modules, GBTx, FPGA	DC-DC	Front-end
ALICE	Pixels	Pixel modules	DC-DC	Front-end
Belle 2	SVD	Silicon modules	DC-DC	Patch panel

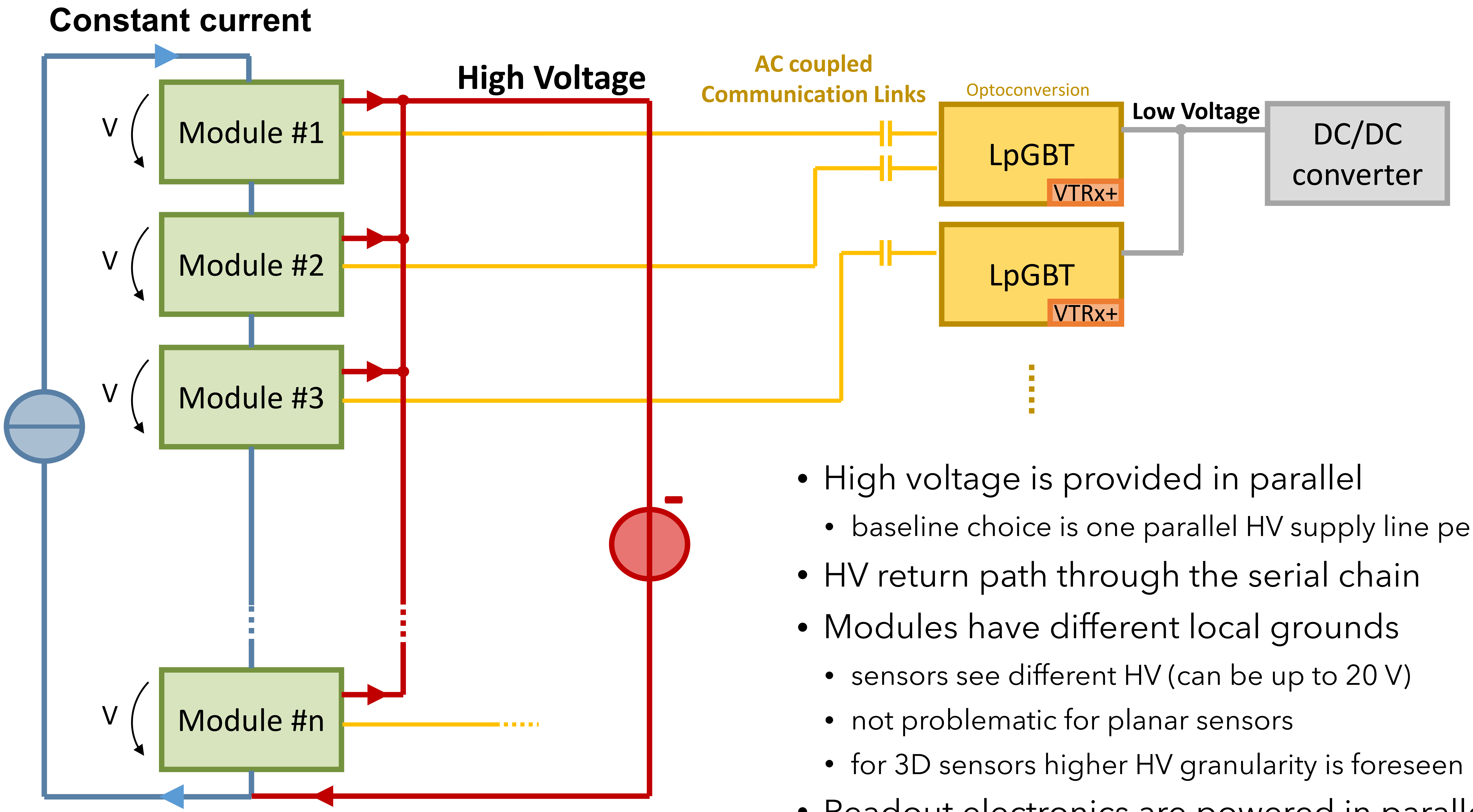
K. Klein (Aachen), D. Koukola (CERN), P. Luukka (Helsinki)

Serial Powering for ATLAS & CMS Phase-2 Pixels



- Numbers on this slide are for CMS, values for ATLAS are very similar
- Estimated power consumption of CMS Phase-2 Pixels is 50 kW
  - direct powering would result in substantial losses in cables and increase in mass due to cables
  - DC-DC converters are not radiation hard enough and there is no space for them anyway
- Serial powering is a viable solution
  - all the elements in a chain see the same current by construction
  - voltage is equally shared if all elements represent the very same and constant load, which is maintained by a Shunt LDO in the ROC
- However: three different powering/supply schemes mixed in a single system

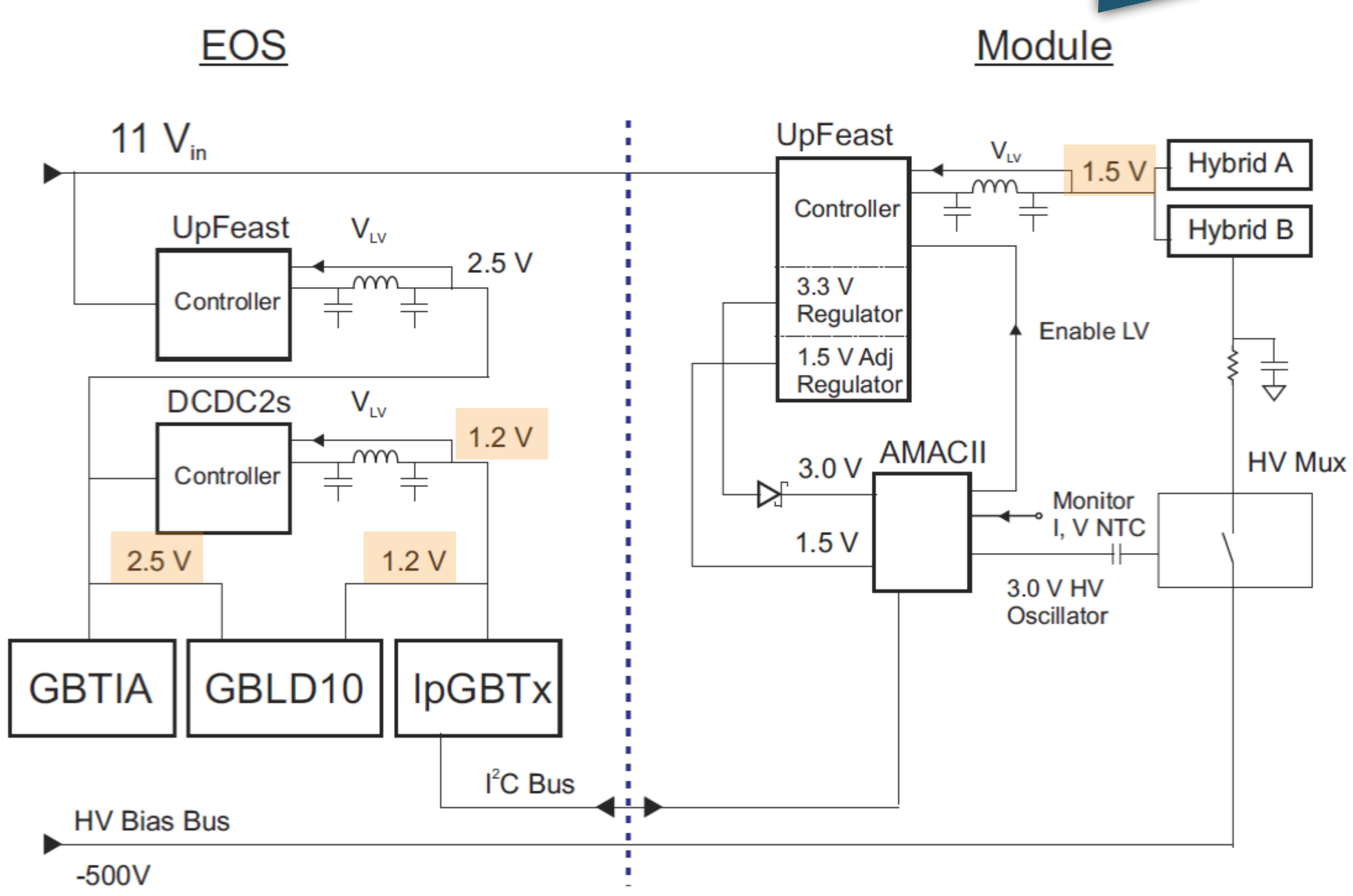
Serial Powering for ATLAS & CMS Phase-2 Pixels



- High voltage is provided in parallel
  - baseline choice is one parallel HV supply line per serial chain
- HV return path through the serial chain
- Modules have different local grounds
  - sensors see different HV (can be up to 20 V)
  - not problematic for planar sensors
  - for 3D sensors higher HV granularity is foreseen
- Readout electronics are powered in parallel with DC-DC converters
  - AC coupling of front-end ASICs required

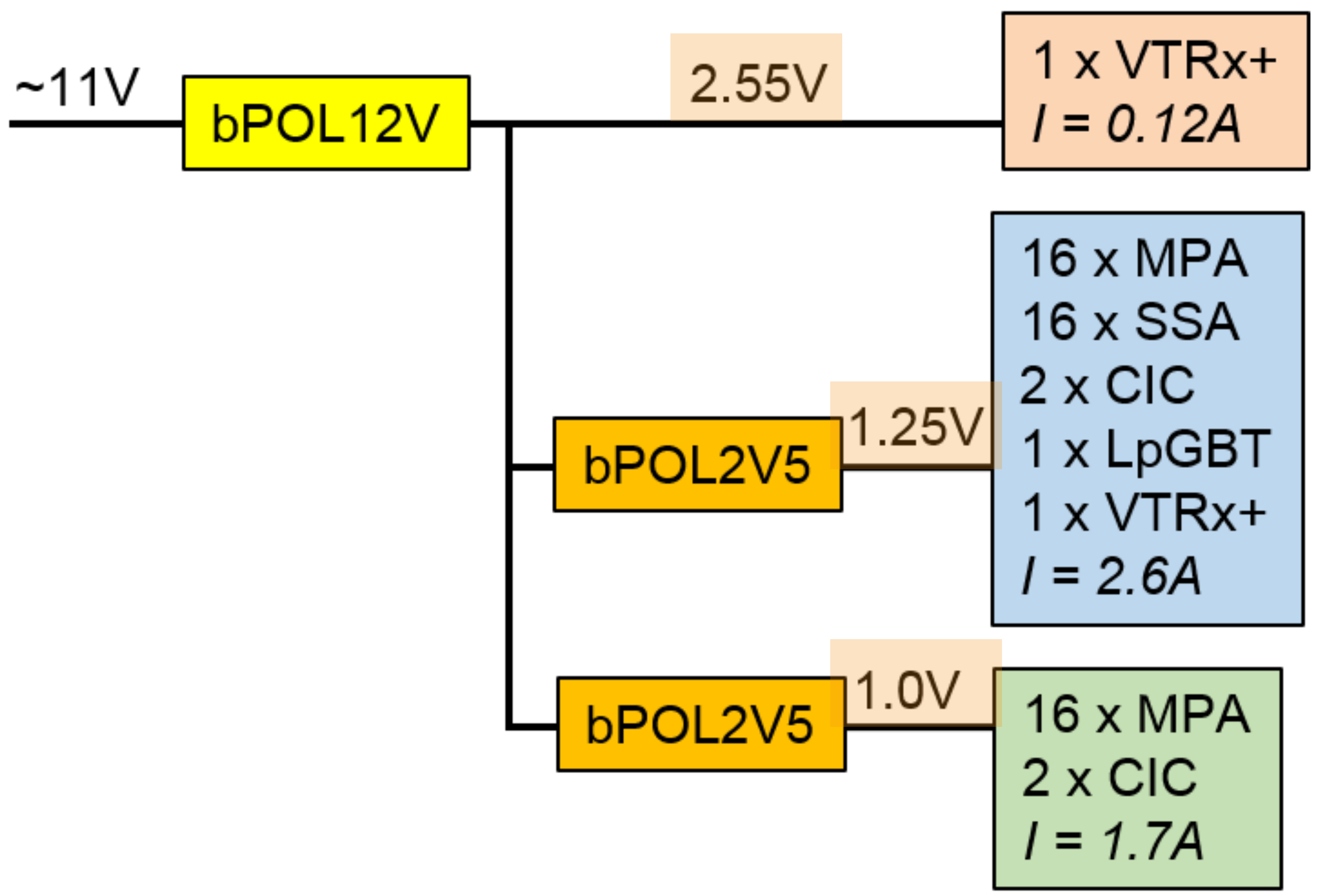
DC-DC Low Voltage Powering Schemes

	ATLAS	CMS
Supply voltages	1.5 V for ROCs	1.25 V and 1.0 V for ROCs
	2.55 V for VTRx+	2.55 V for VTRx+
	1.25 V for LpGBT, VTRx+, ...	1.25 V for LpGBT, VTRx+
Number of modules	17 888	13 296
Total front-end power	70kW	85kW



2 stages on end of sub-structure (EOS)

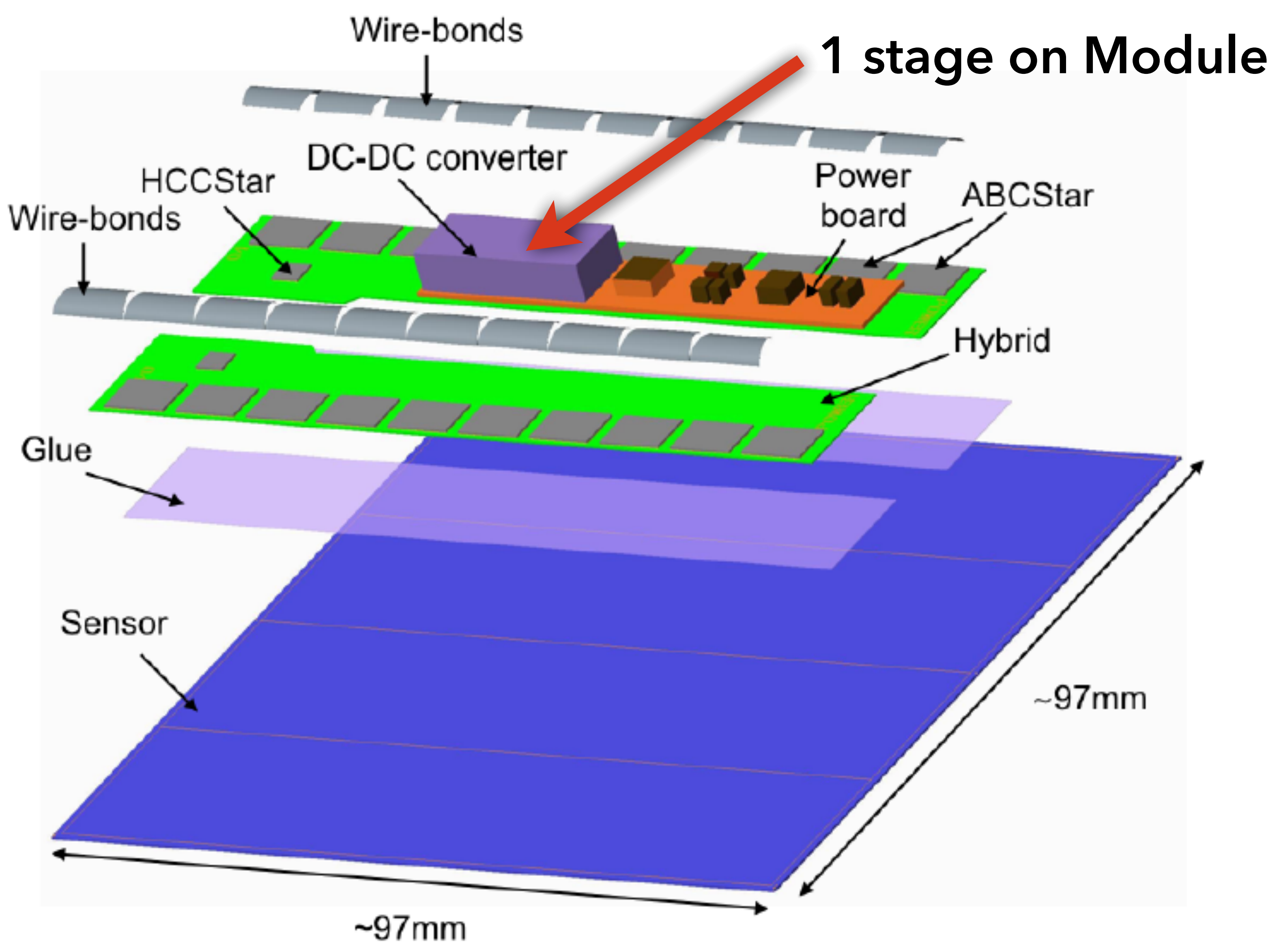
1 stage on module

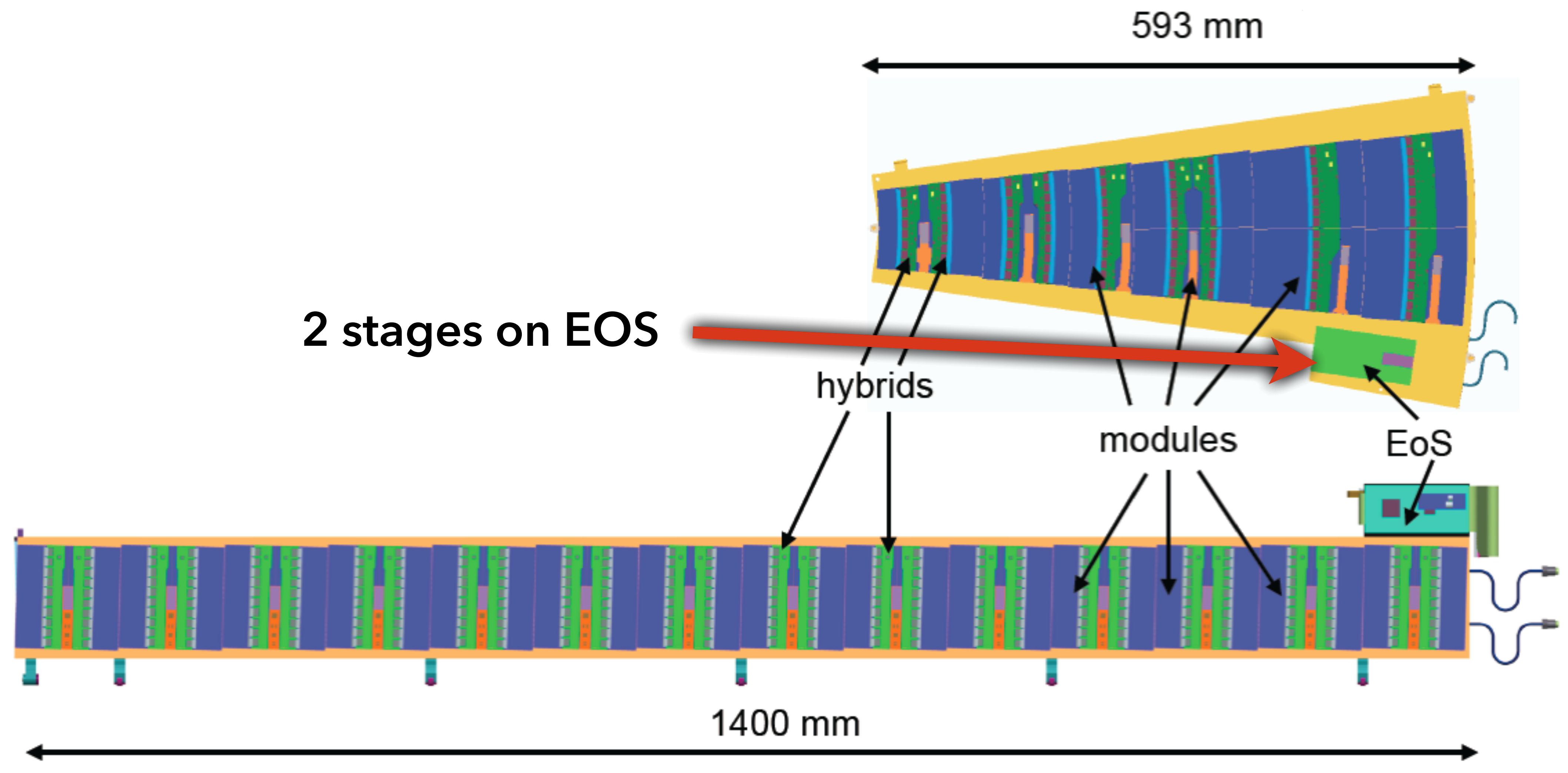


2 or 3 stages on module depending on module type

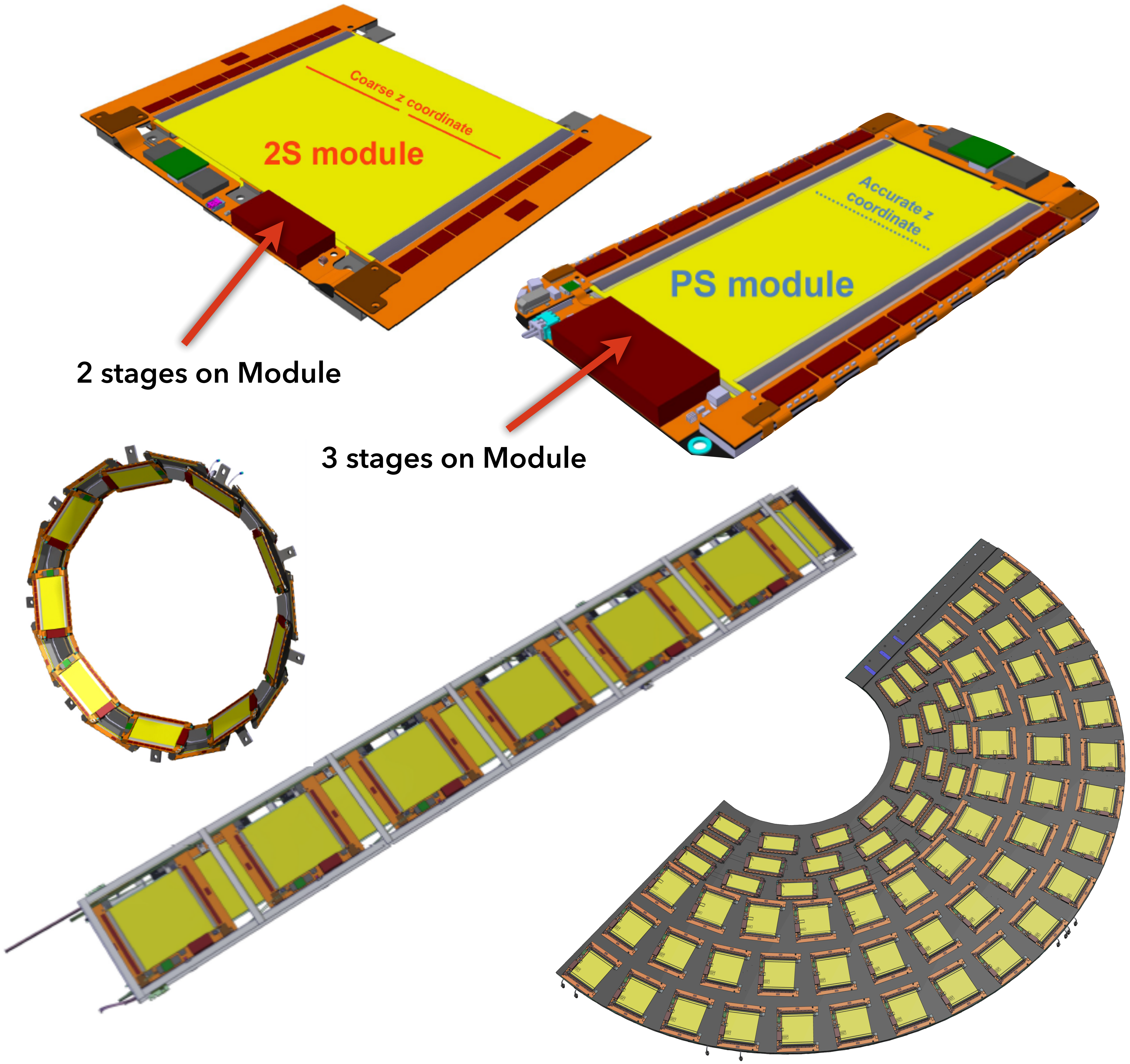
DC-DC Low Voltage Powering Implementation

ATLAS



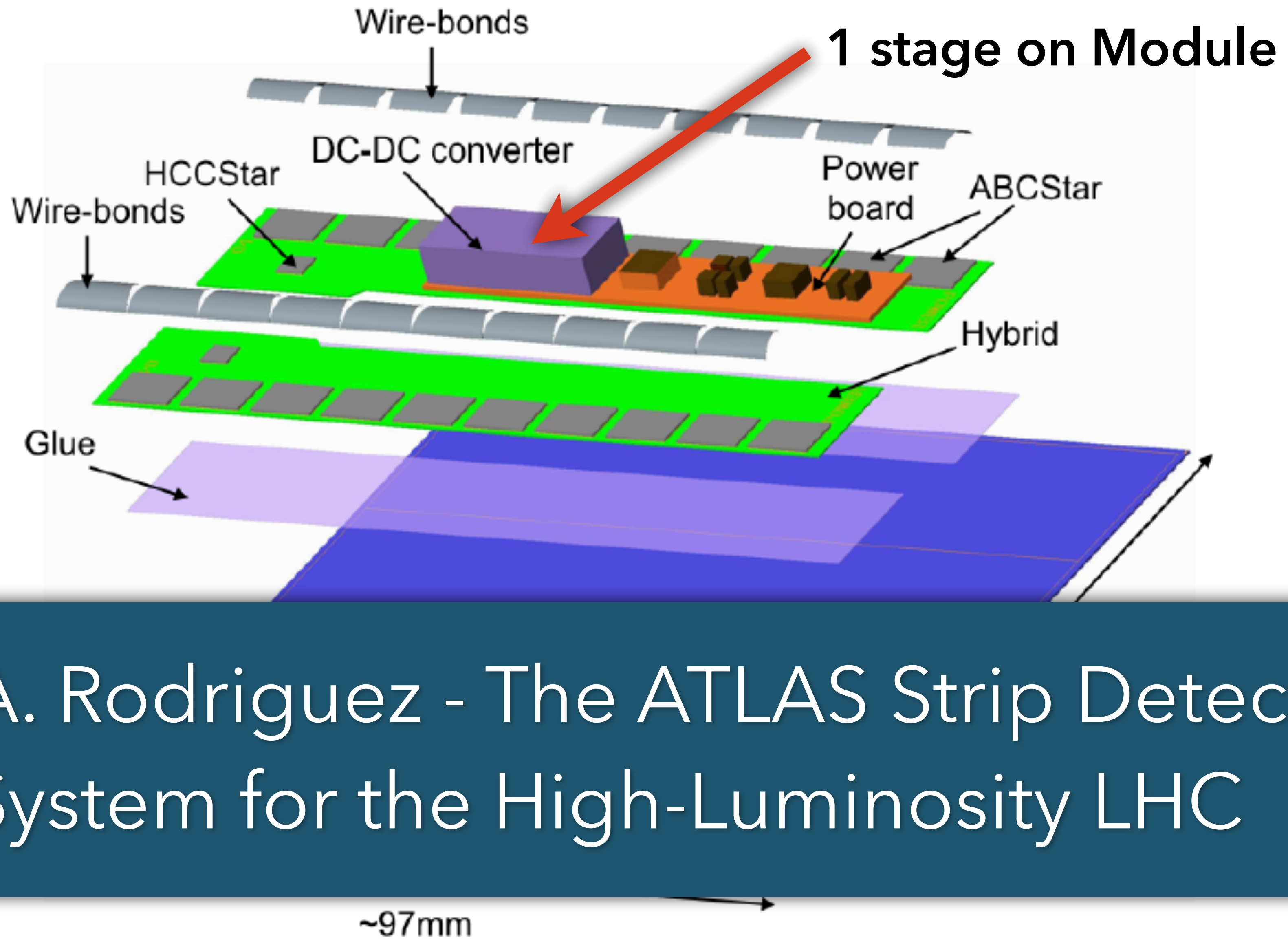


CMS

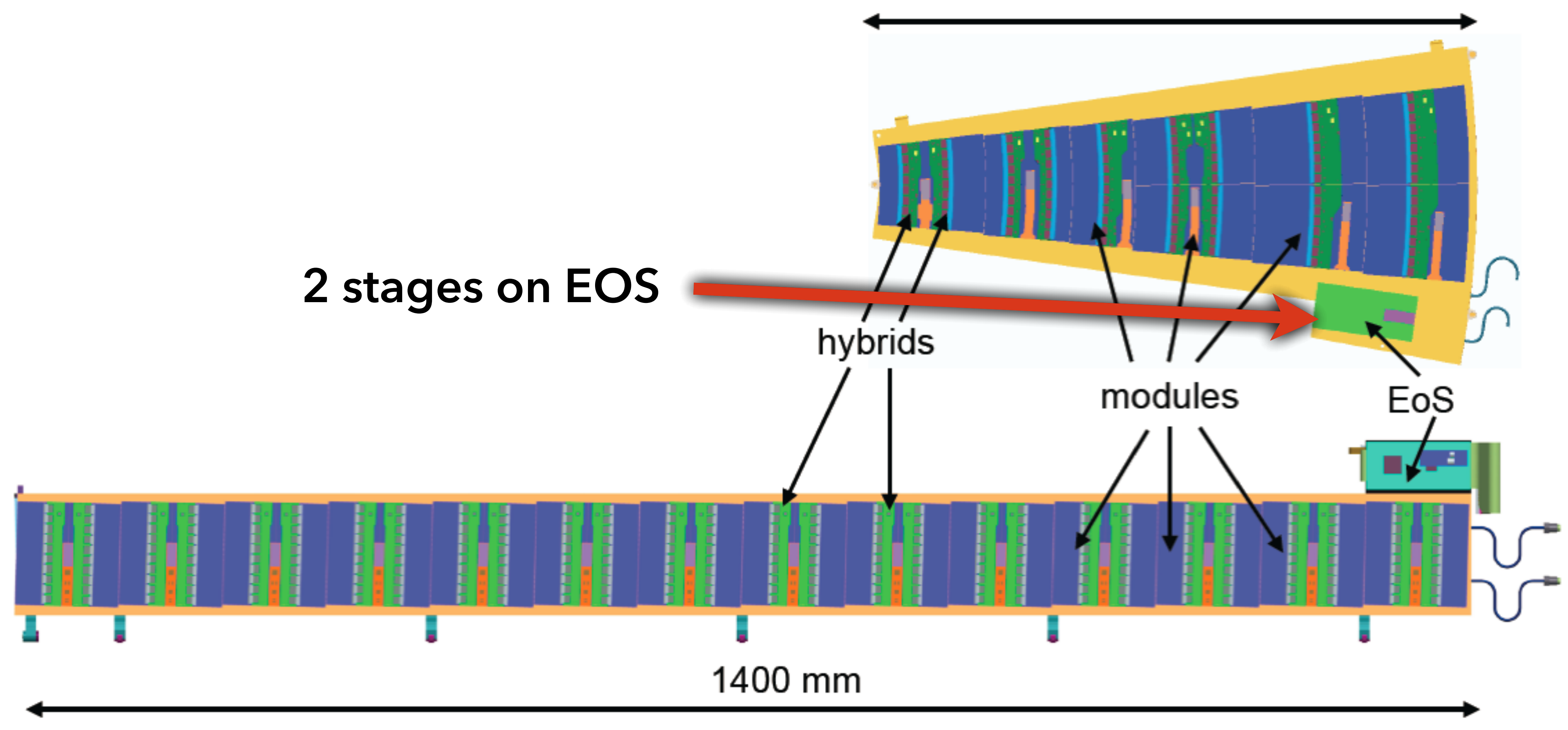


DC-DC Low Voltage Powering Implementation

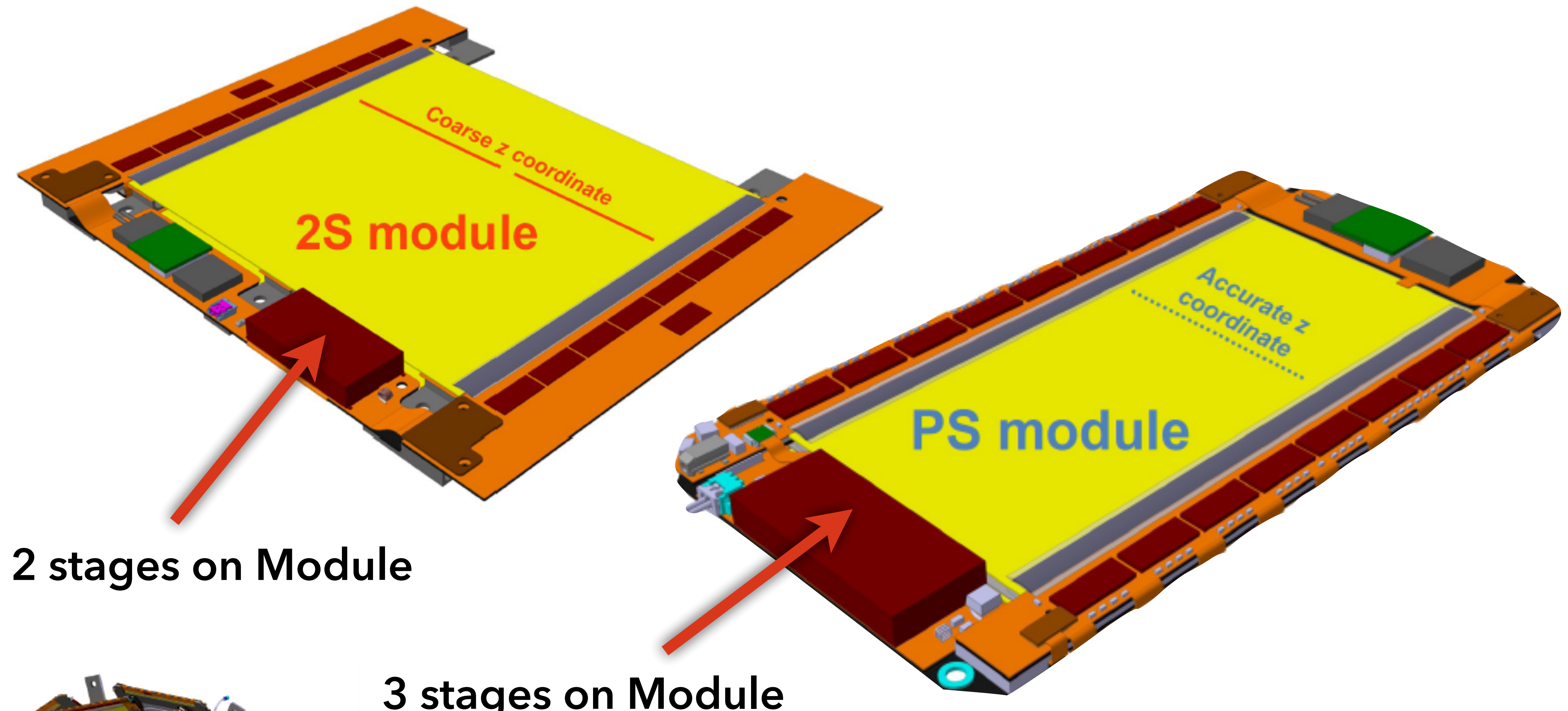
ATLAS

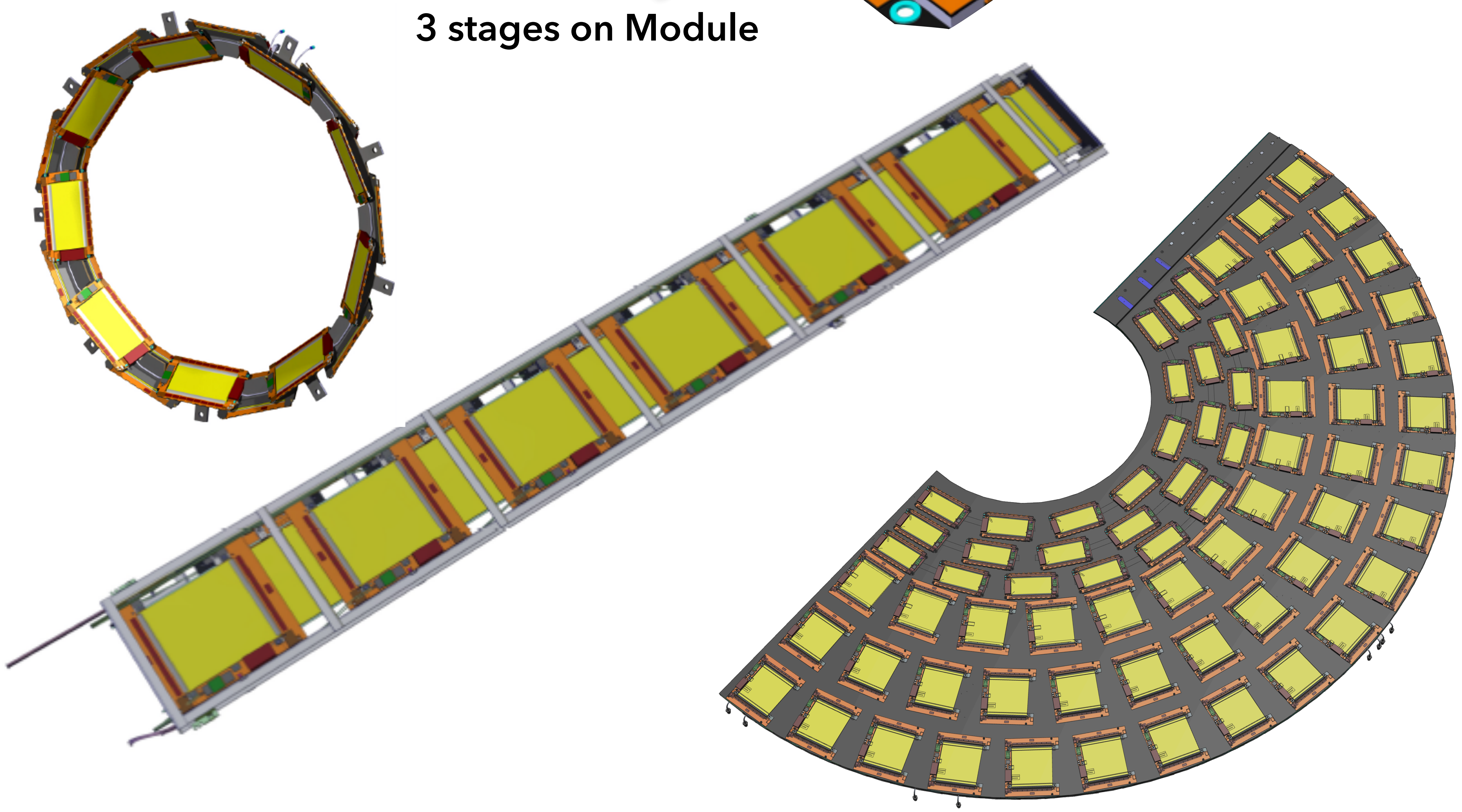


A. Rodriguez - The ATLAS Strip Detector System for the High-Luminosity LHC



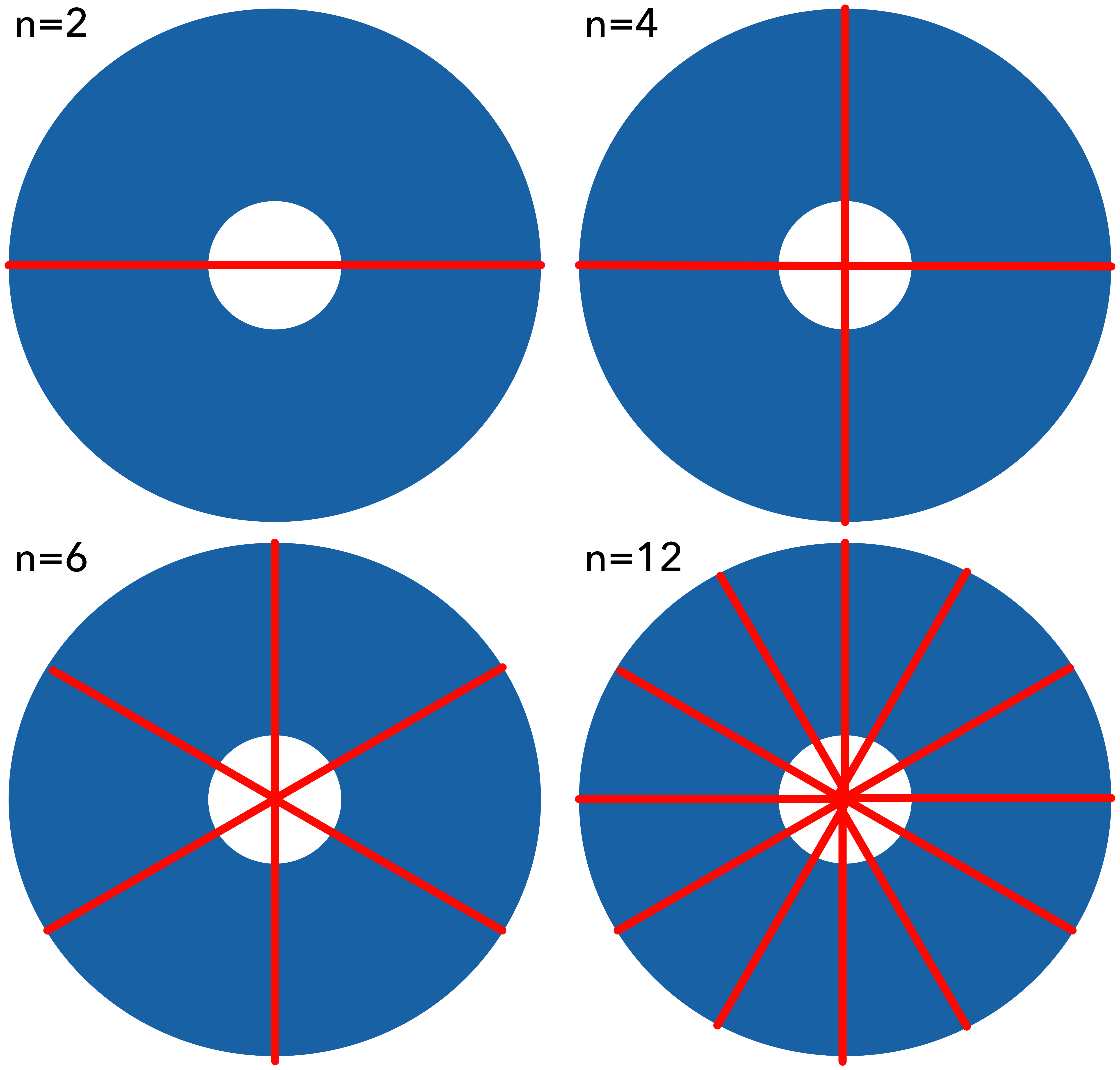
CMS





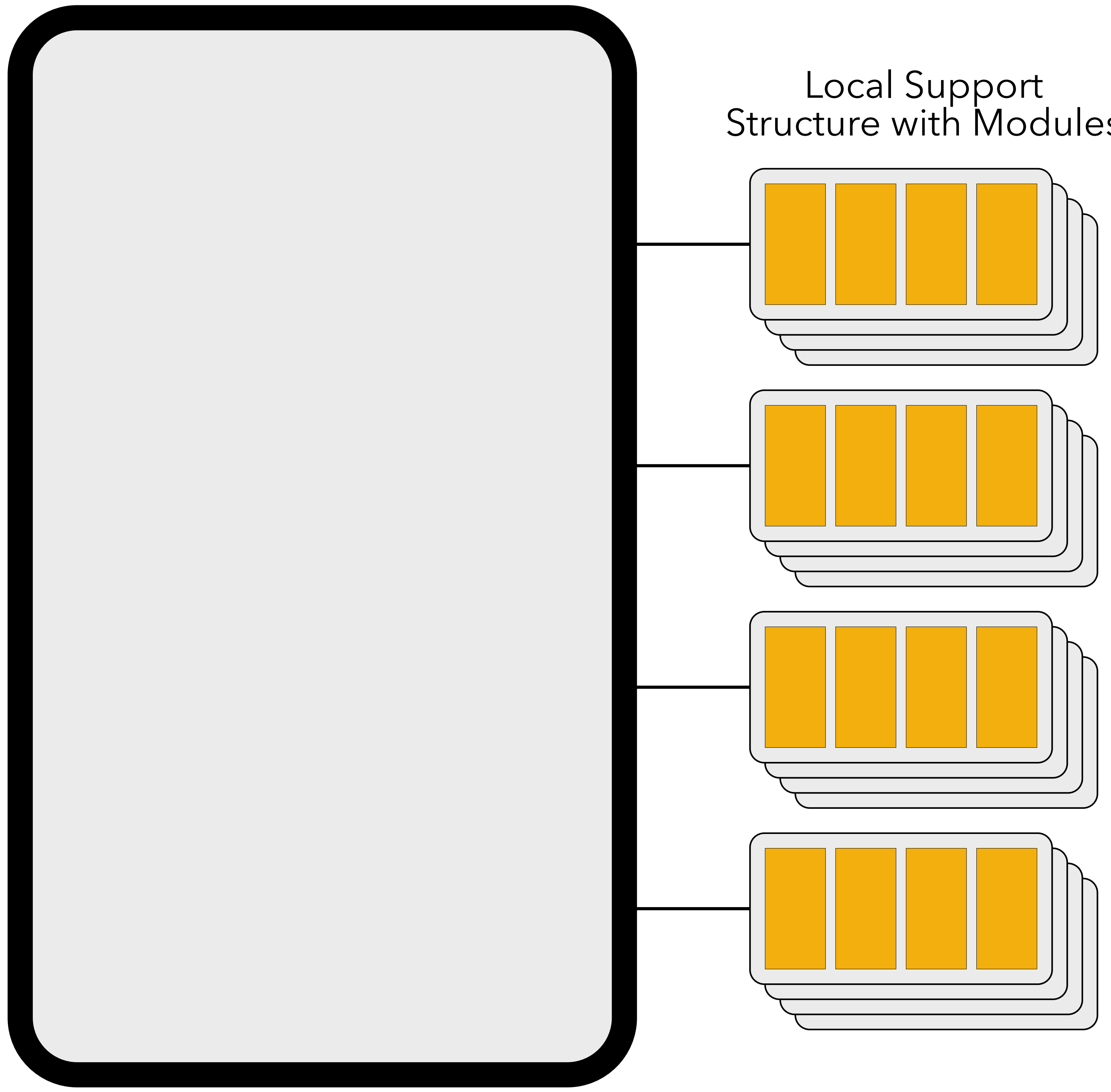
ATLAS & CMS End Caps - A Conceptual Comparison

- A single disk support structure would be ideal in terms of overlaps
- With a diameter of over 2 m this becomes a tricky business
  - production requires really special/large autoclaves and machines
  - large number of modules per structure is challenging from a handling point of view
- Divide structure in **n** parts
  - number of modules per ring must be dividable by **n**
    - more overlaps ➟ additional mass
  - handling becomes easier with increasing **n**
- **n = 2** and **n = 4**: still fairly large in terms of handling
- **n > 6**: overlaps become an issue
  - transition to wedge-shaped sensors needed



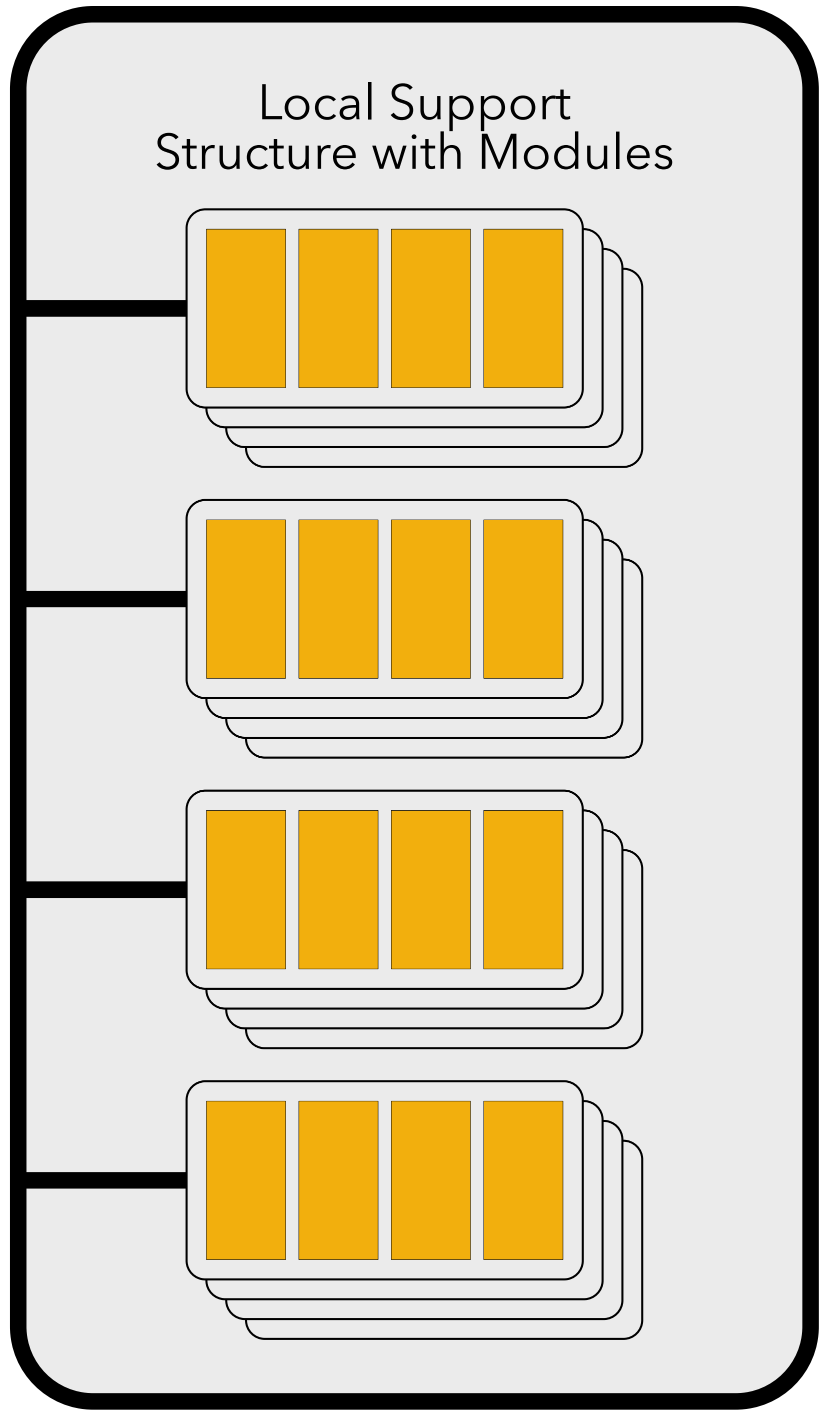
ATLAS & CMS End Caps - A Conceptual Comparison

***n* > 2**



- Local supports with modules are inserted into mechanical super structure
- Super structure has to carry full load
- Integration is straight forward
- In ATLAS: n = 16

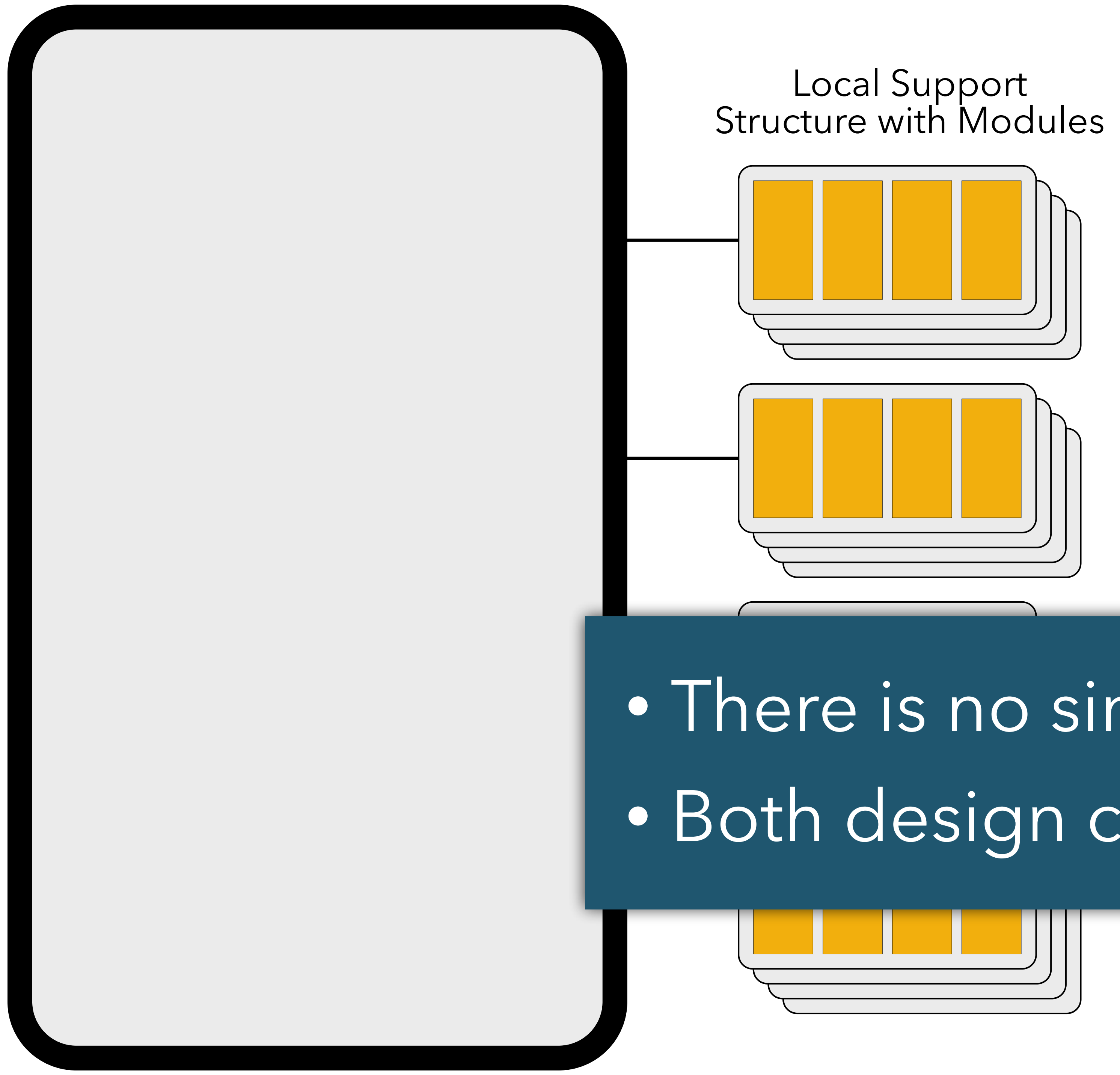
***n* = 2**



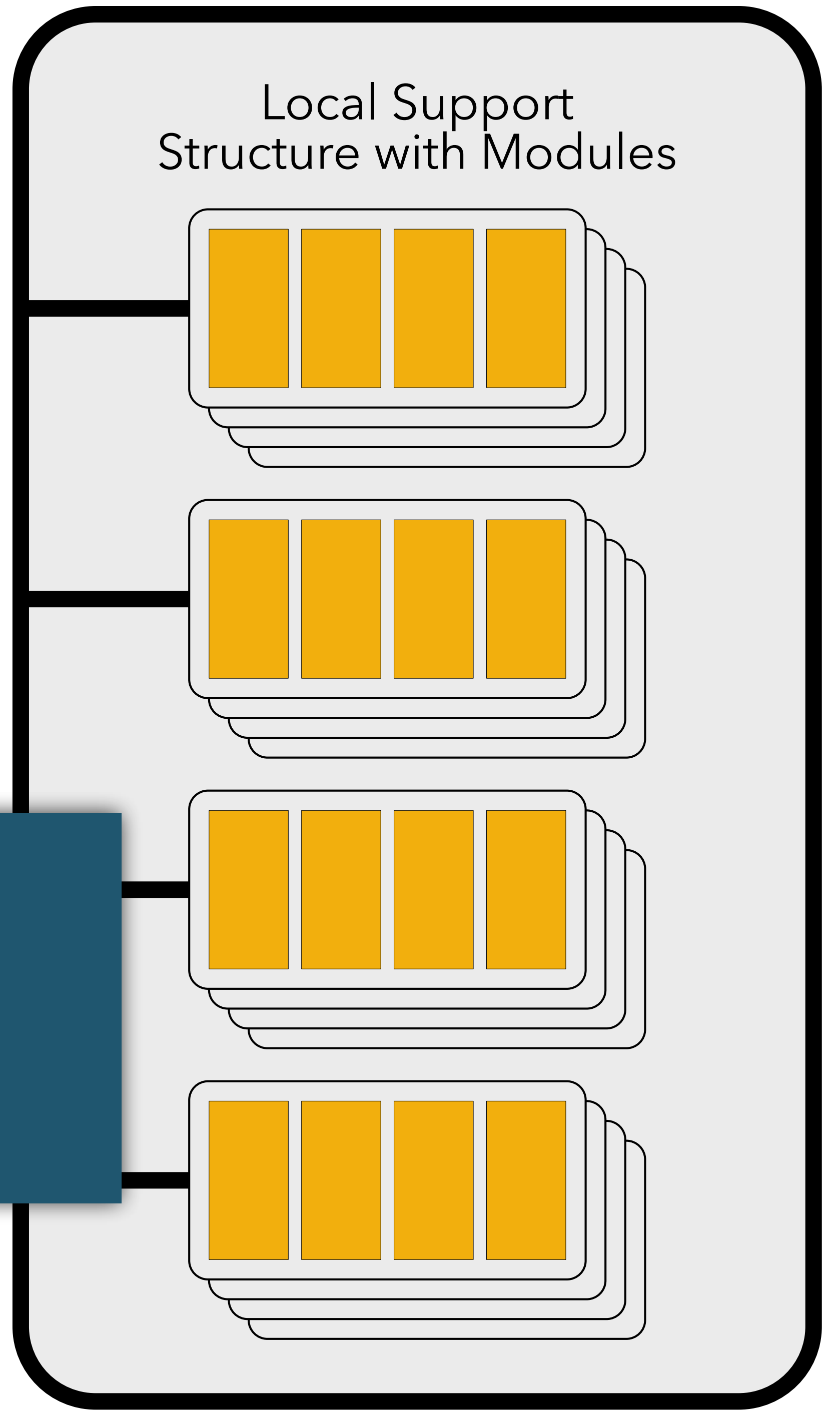
- Local supports are integral part of mechanical design
  - Load is shared among all mechanical components
  - Super structure can be lighter
- Mechanically stable object only exists after last integration & assembly step
- In CMS: n = 2

ATLAS & CMS End Caps - A Conceptual Comparison

n > 2



n = 2



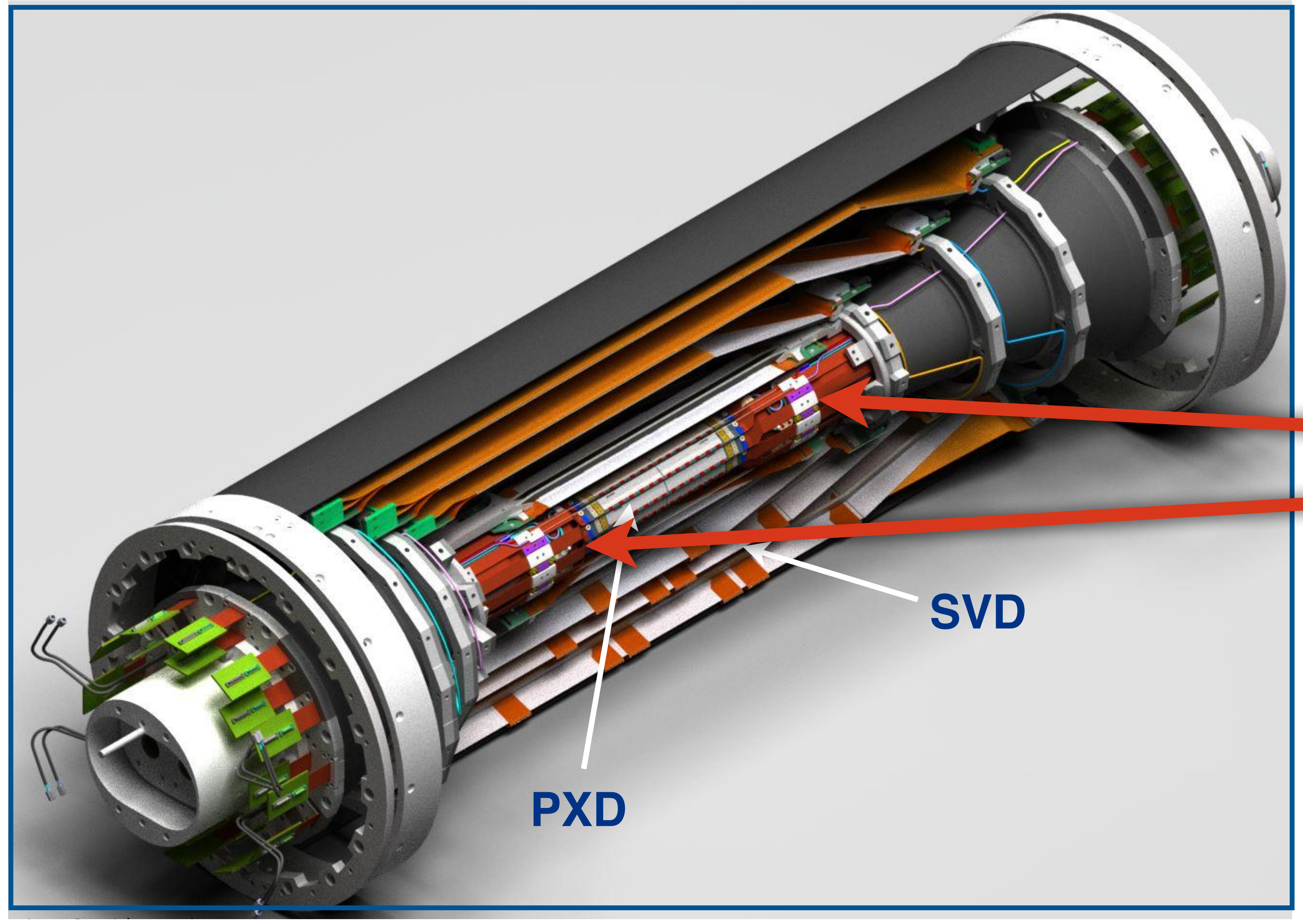
- There is no single best solution
- Both design choices have their pros and cons

- Local supports with modules are inserted into mechanical super structure
- Super structure has to carry full load
- Integration is straight forward
- In ATLAS: n = 16

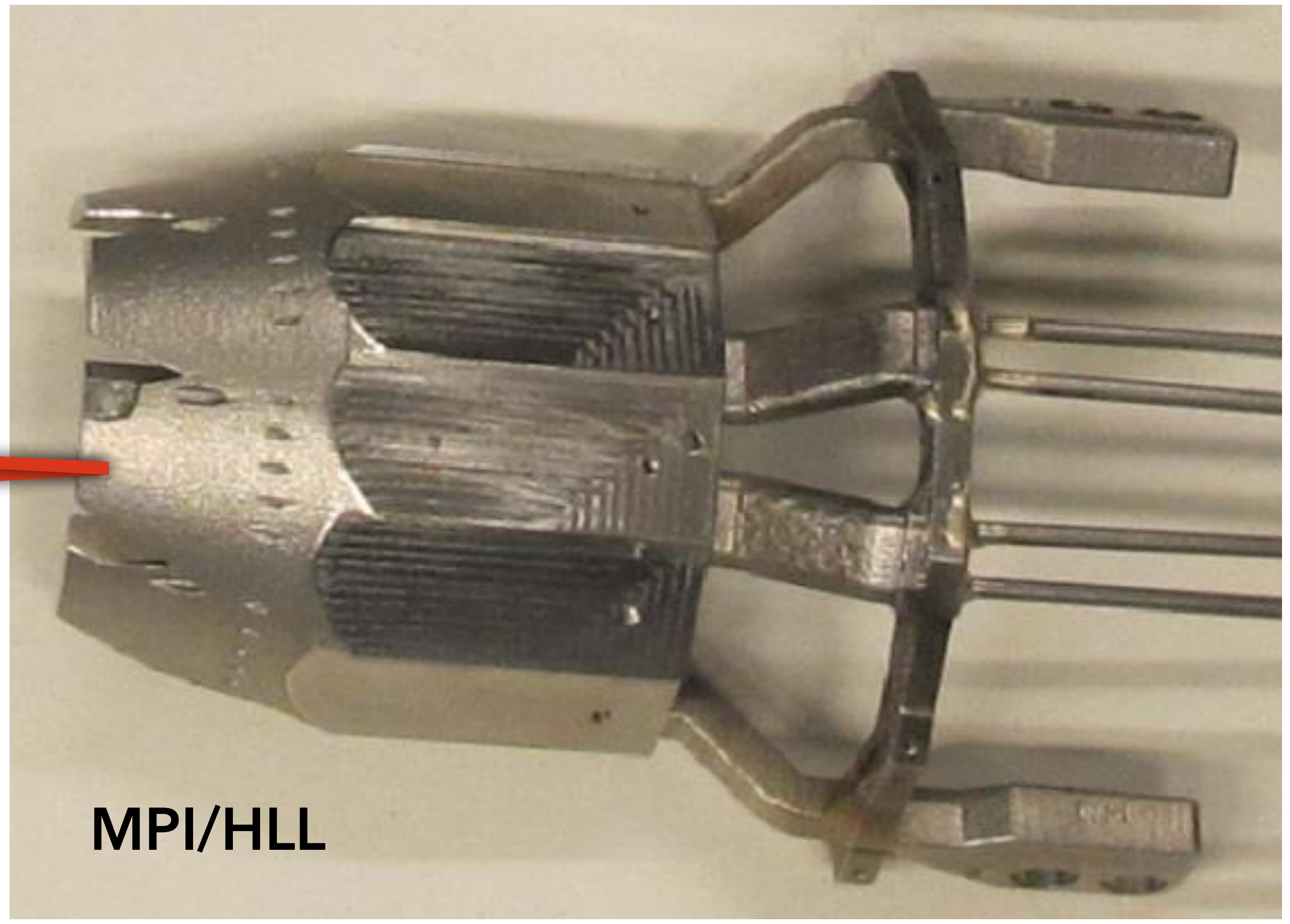
- Local supports are integral part of mechanical design
  - Load is shared among all mechanical components
  - Super structure can be lighter
- Mechanically stable object only exists after last integration & assembly step
- In CMS: n = 2

Mechanics & Cooling Continued

Belle II PXD & SVD



PXD Support and Cooling Block (SCB)

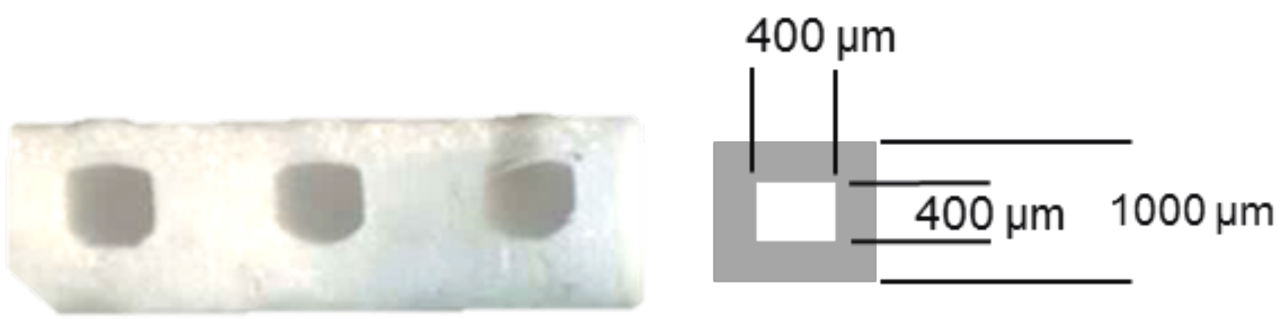


- Belle II PXD Support and Cooling Block (SCB) printed in stainless steel
  - integrated CO_2 and N_2 channels
  - outside acceptance
- potential of additive manufacturing has to be exploited also inside trackers

stainless steel printed on cooling pipe with 2.5 mm OD and 150 µm wall thickness

3D printed ceramic

➟ Engineering for CTE compatibility

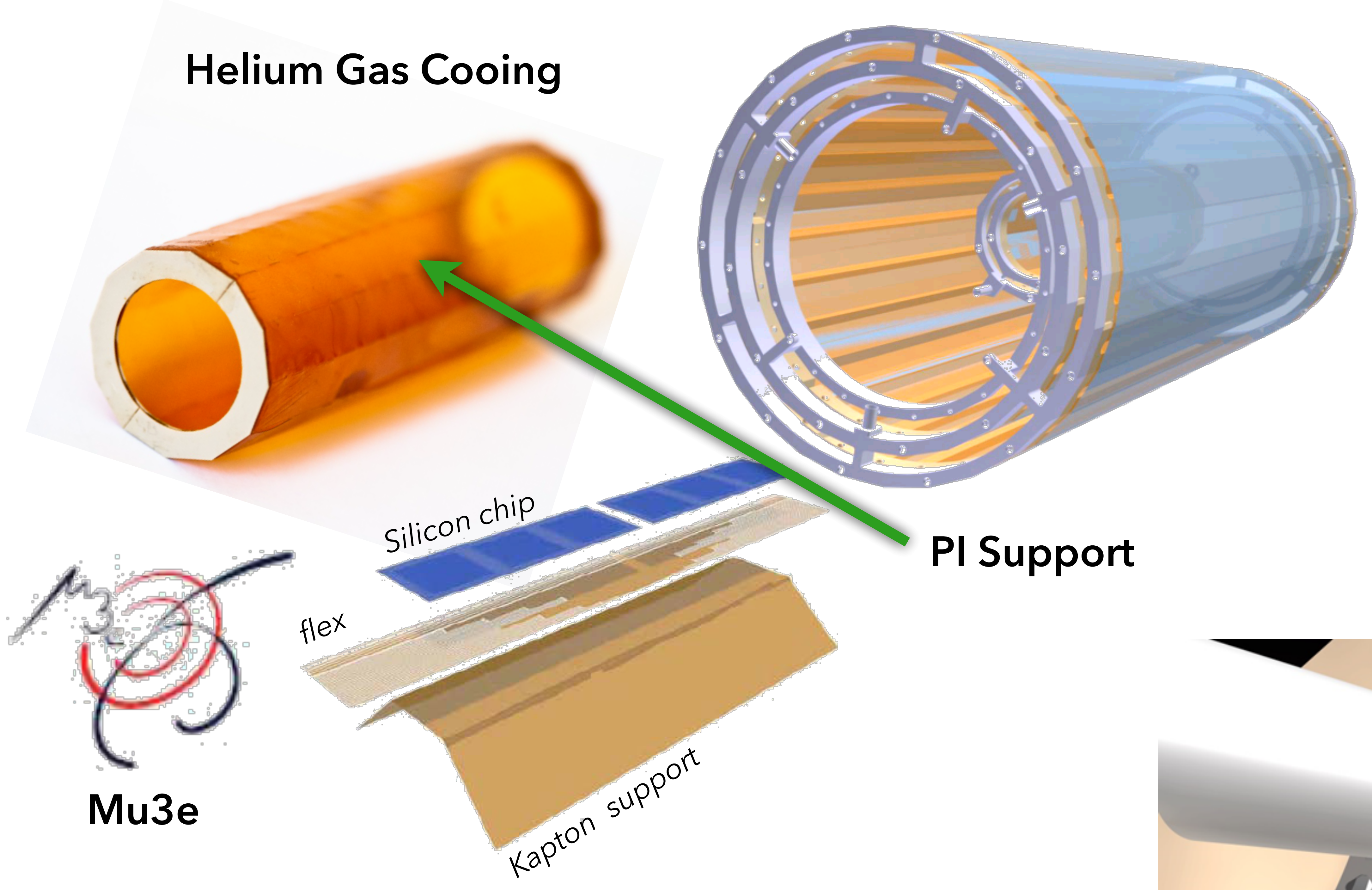


CERN EP-DT & 3D Ceram

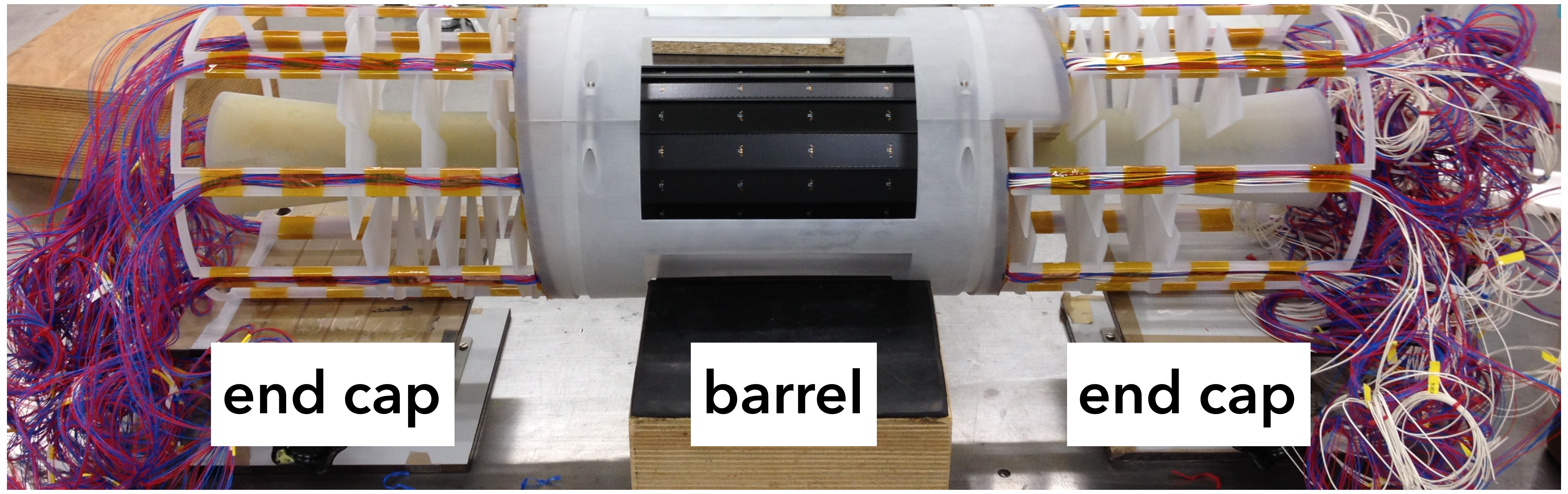
C. Gargiulo, A. Onnela (CERN)

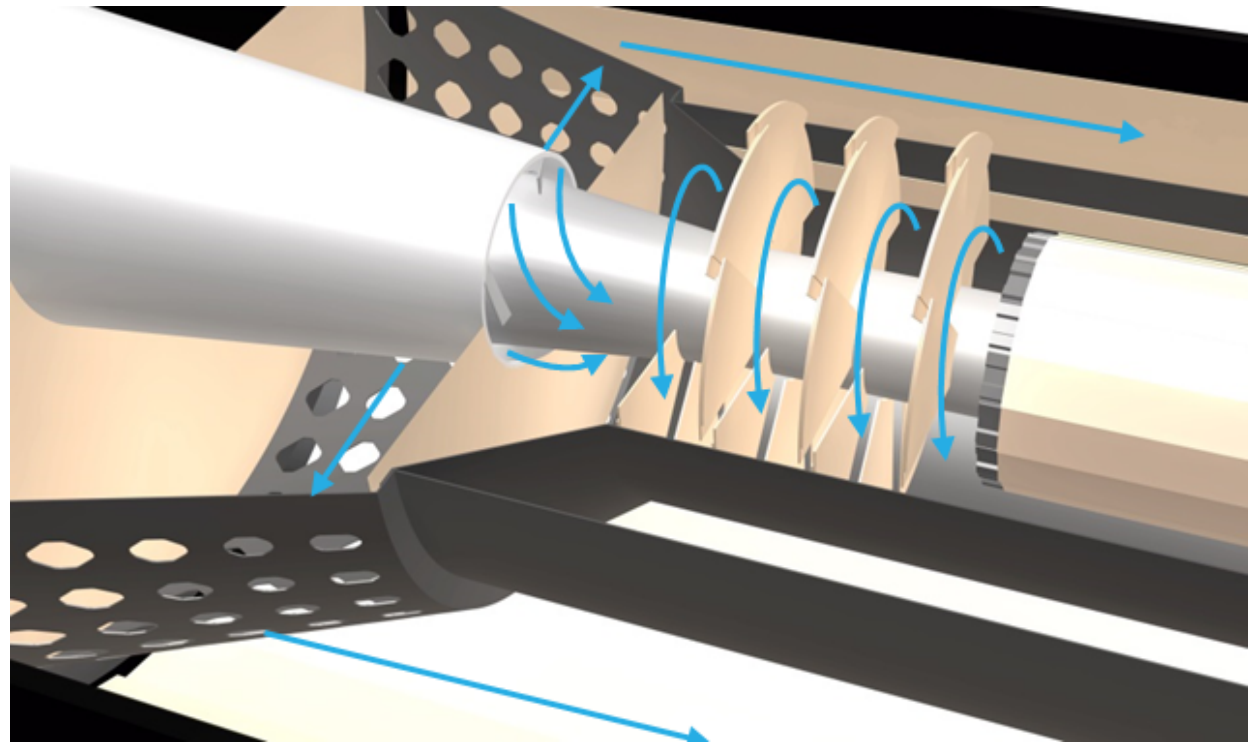
Mechanics & Cooling Continued

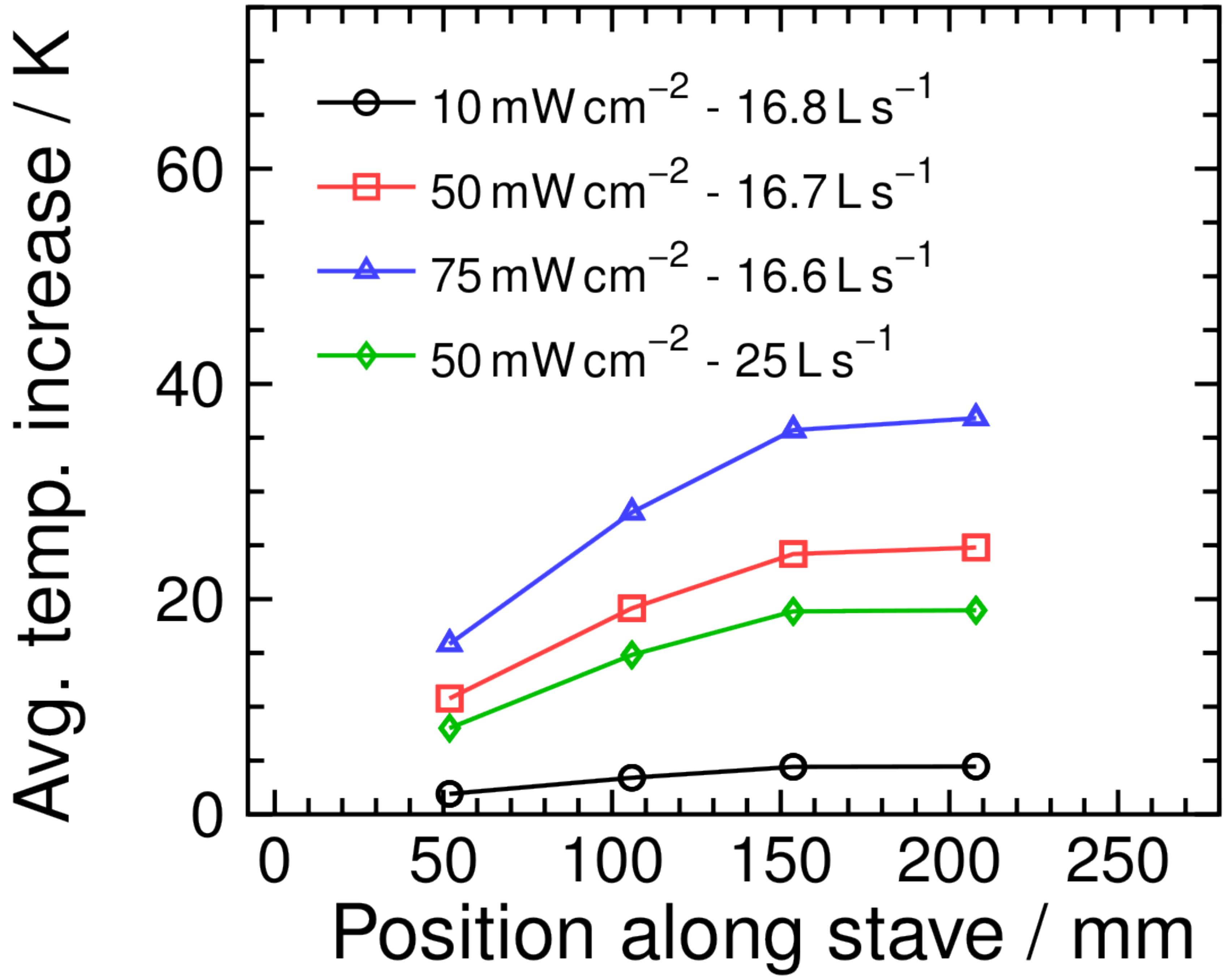
Helium Gas Cooing



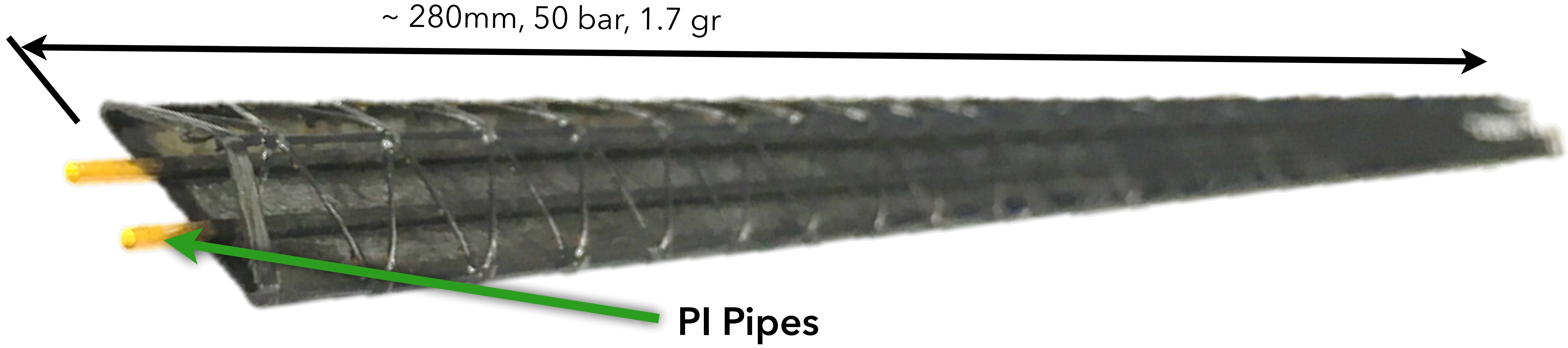
CLICdet Vertex Forced Air Cooling





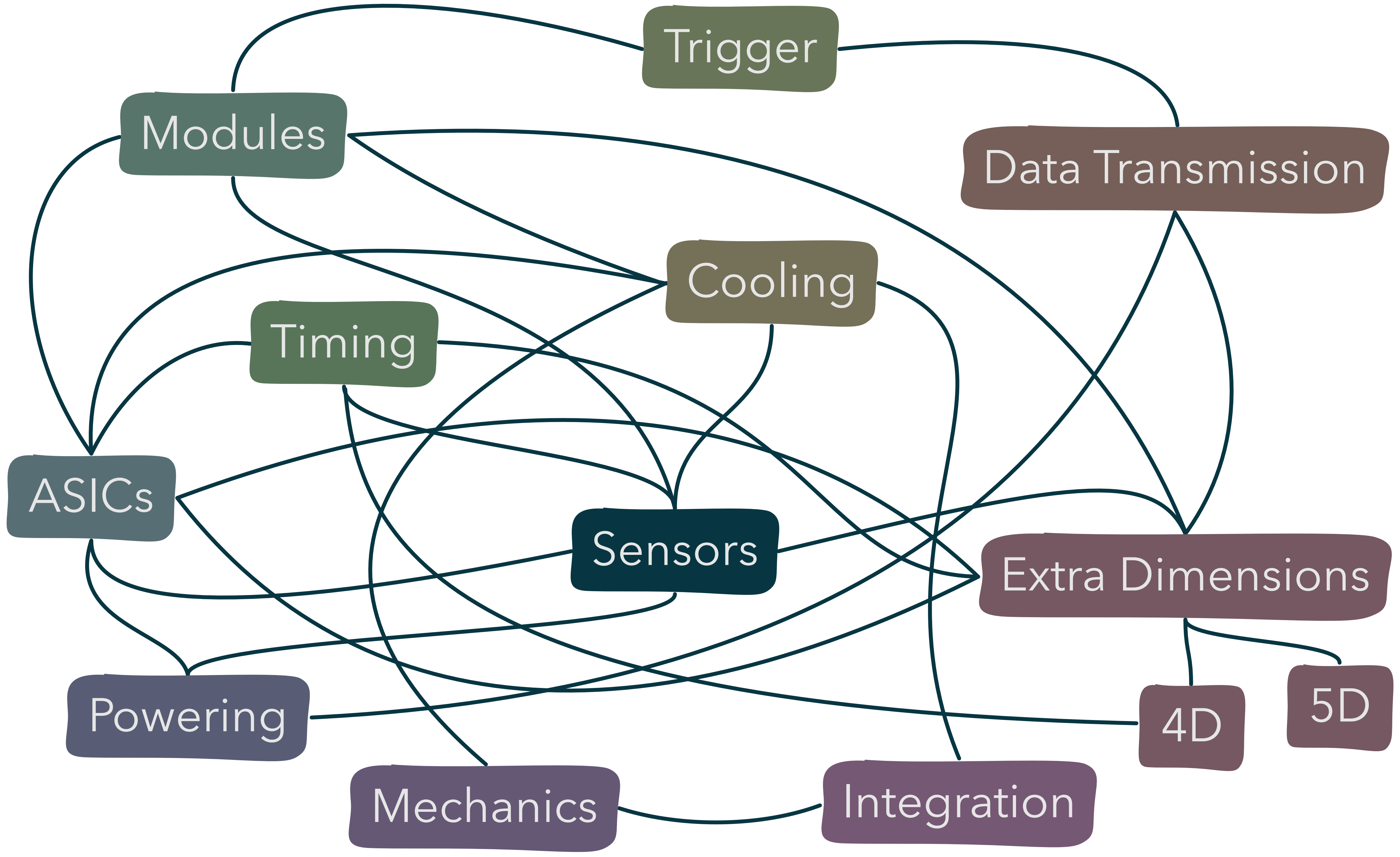


ALICE ITS2 Stave

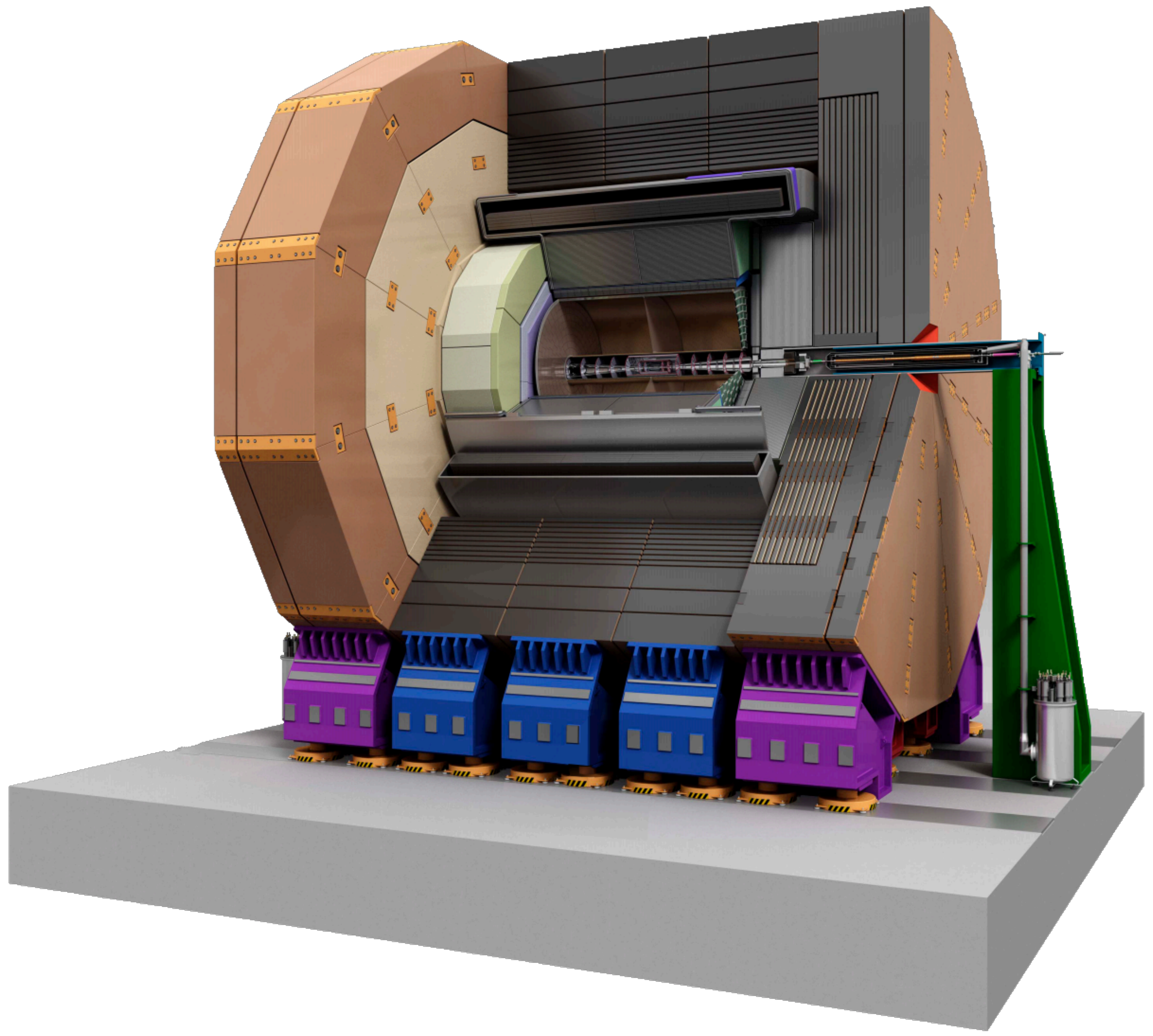


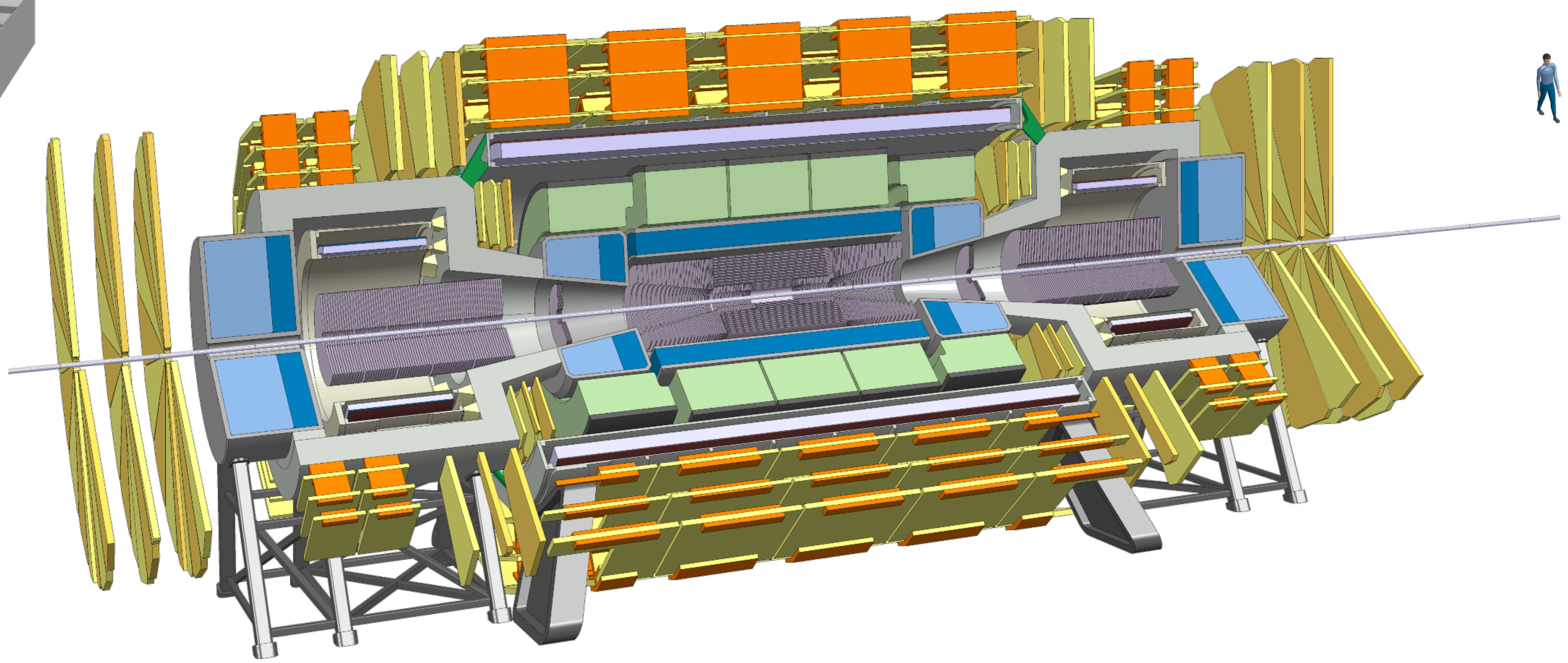
C. Gargiulo, A. Onnela (CERN)

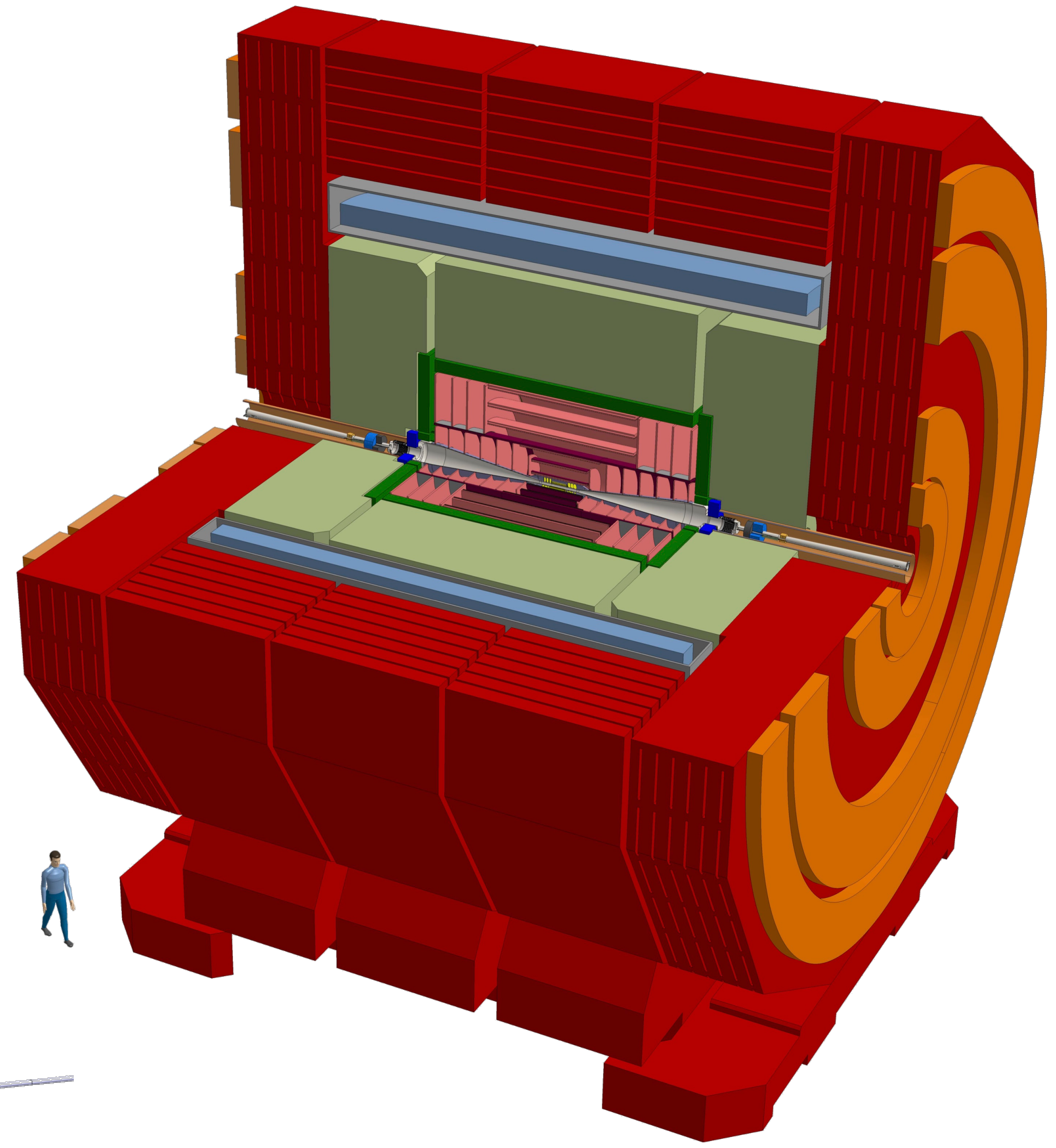
Summary



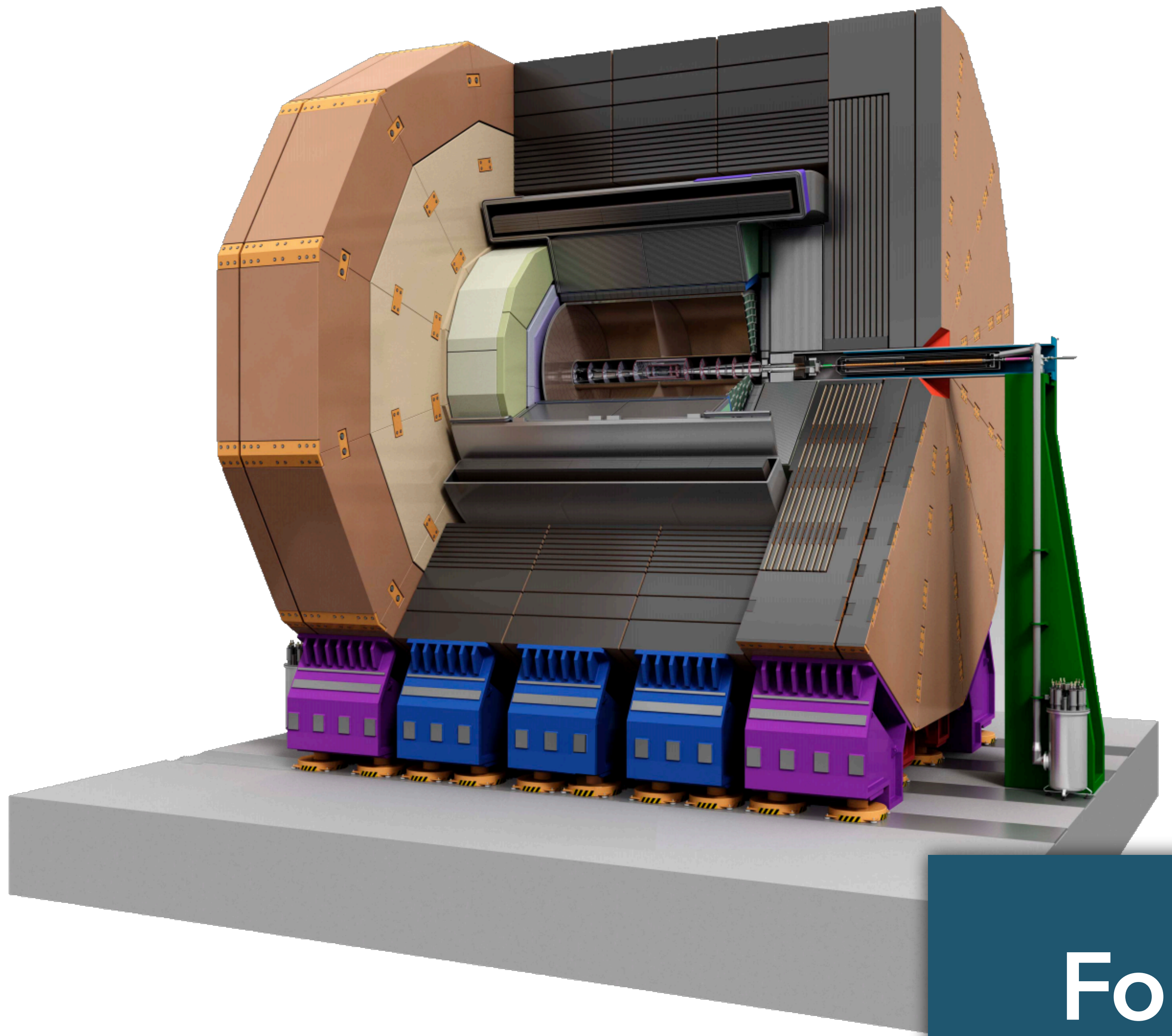
Trigger
Modules
Data Transmission
Cooling
Timing
ASICs
Sensors
Extra Dimensions
Powering
4D
5D
Mechanics
Integration

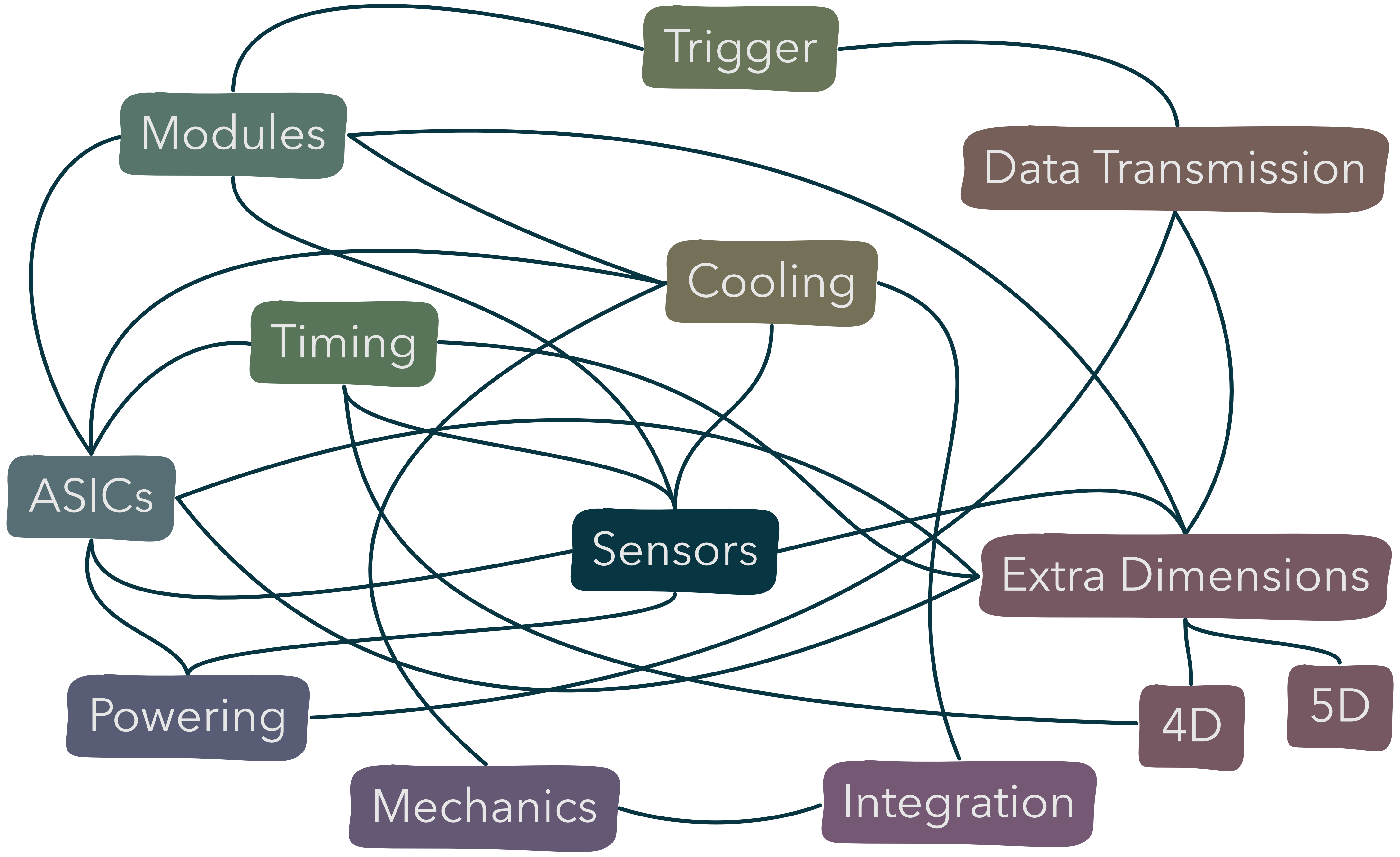


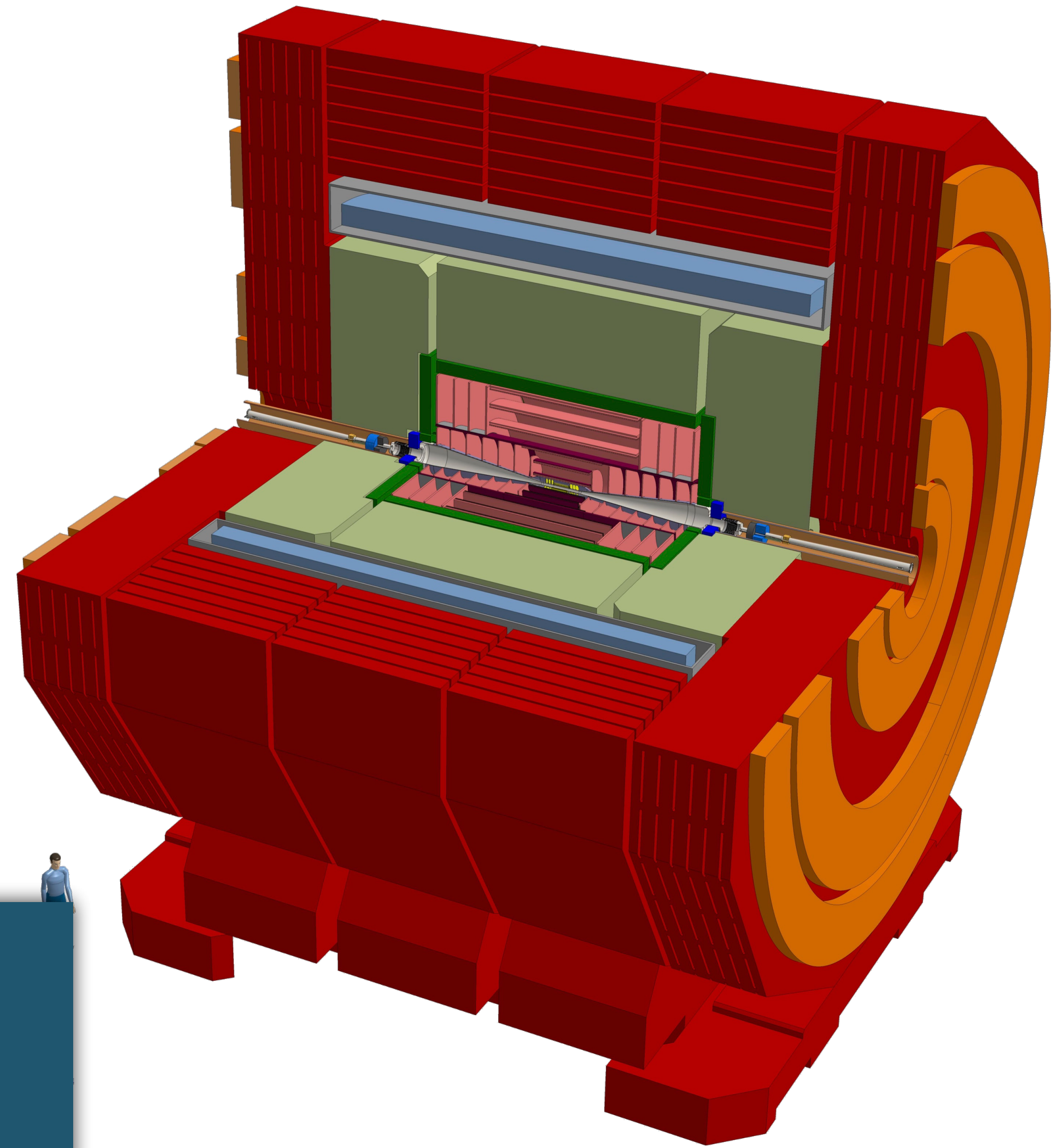




Summary







Forum on Tracking Detector Mechanics 2020

25-27 May 2020

INFN - LNF Frascati