Designing trackers for future colliders

the CMS Tracker for LH-LHC and future technologies

Stefano Mersi

2019-07-08

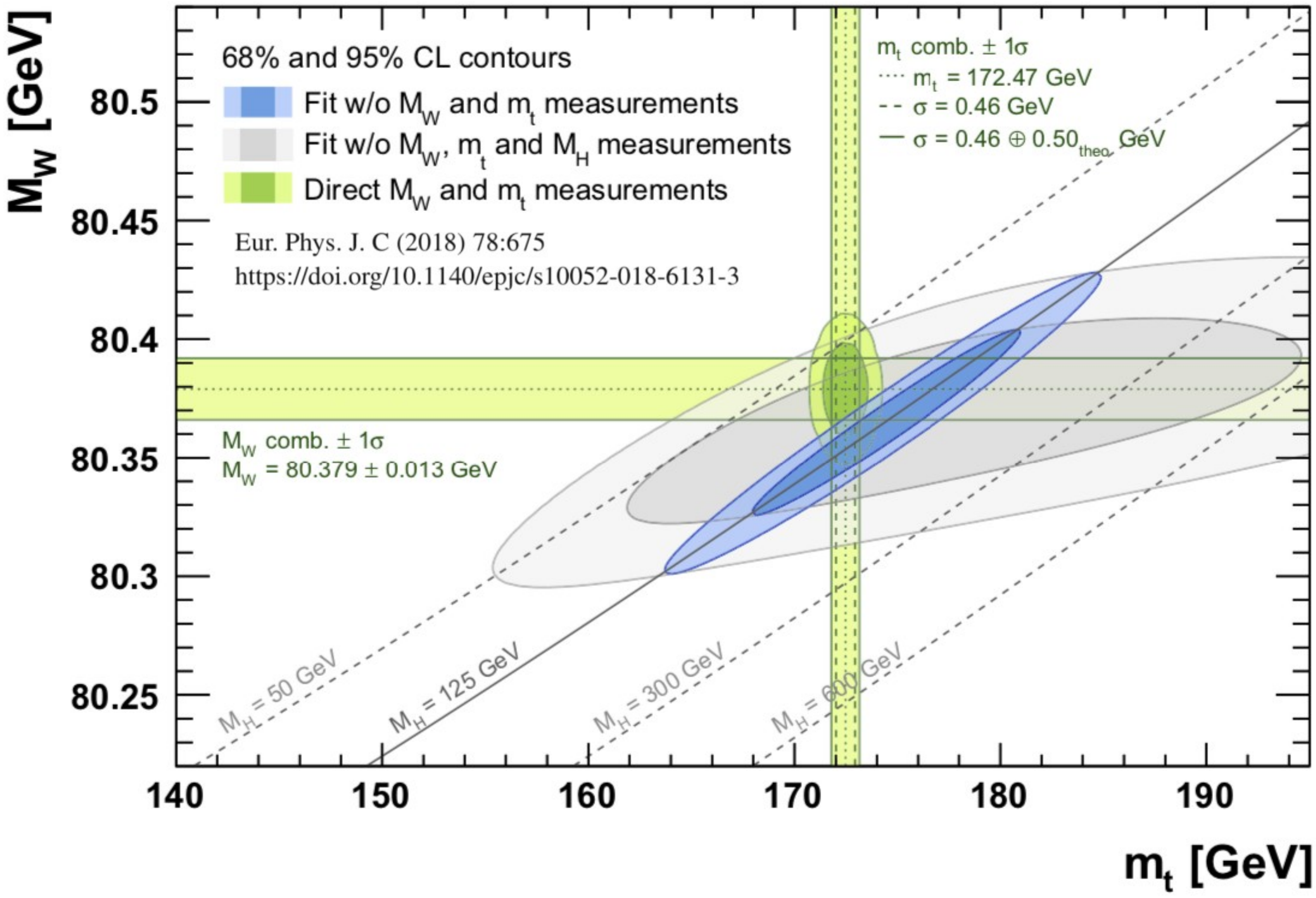
iWoRiD 2019 – Chania, Crete

We discovered the Higgs boson!

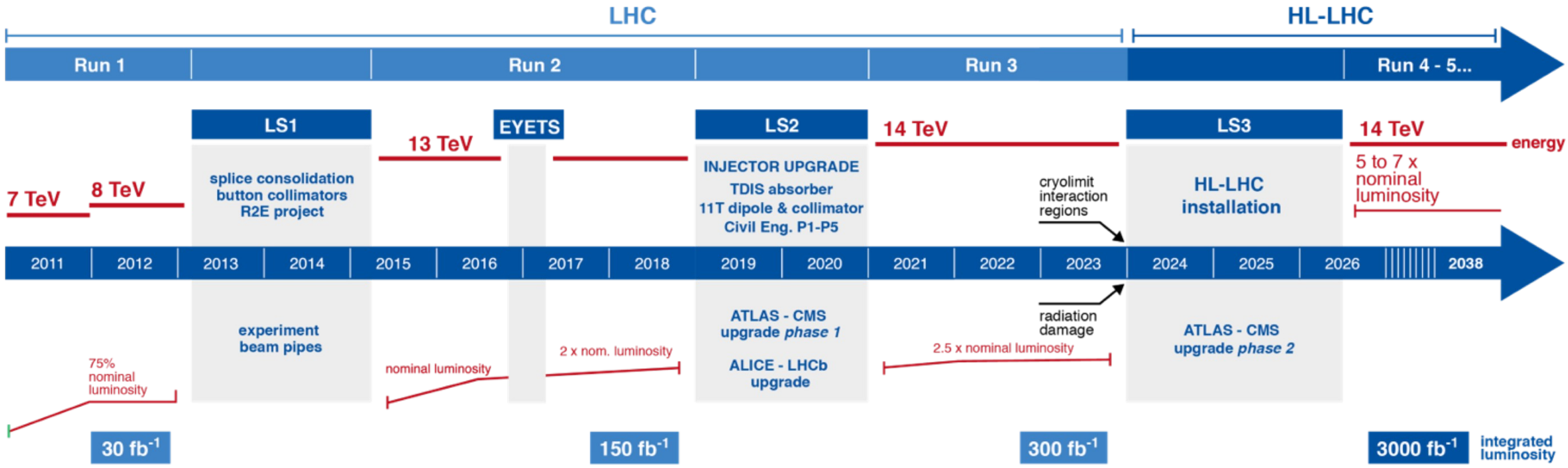
We discovered the Higgs boson!

The way forward: precision!

Just a single example:
resolving the slight tension between masses of W, top, and Higgs



HL-LHC is on its way



Future colliders – H factories

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

D. Schulte Higgs Factories, Granada 2019 5

D. Schulte
"Higgs Factories"
Open Symposium - Update of the European Strategy for Particle Physics – Grenada
12-17 May 2019

Luminosity & Pileup:

Collider	Luminosity	PU
$LHC_{Nominal}$	= 10 Hz/nb	→ 20
$LHC_{Current}$	= 20 Hz/nb	→ 40
HL-LHC	= 100 Hz/nb	→ 200
HE-LHC	≈ 250 Hz/nb	→ ~800
FCC-hh	≈ 300 Hz/nb	→ ~1000

https://indico.cern.ch/event/808335/contributions/3380835/attachments/1845110/3026939/Summary-Accelerators-Granada.pdf

Technology challenge

Upgrade in luminosity means:

- **Radiation hardness**
  - Radiation damage proportional in integrated **luminosity** at hadron colliders (ex. HL-LHC, 3000 fb^{-1}, 3 cm from beam spot)
  - Surface damage – mainly affects electronics measured with Total Ionization Dose (→ 1.25 GRad @ HL-LHC)
  - Bulk damage – mainly affects sensors → dark current → **power dissipation** measured in 1-MeV-neutron-equivalent (→ 2.2×10^{16} neq/cm^2)
- **Segmentation**
  - Needs to be proportional to the **Pile-Up**, to allow two-track separation → **power consumption**
  - Further improvements in the first layers (vertex reconstruction) also help tagging b mesons and τ leptons
- **Bandwidth**
  - Increase in **luminosity** also impact the readout bandwidth → **power consumption + readout links**

Front-end vs. detector performance

Power lines & readout links contribute to the detector **material budget**

Moreover power must be extracted via **cooling**, with adds more **material**

MORE power/material

Higher granularity

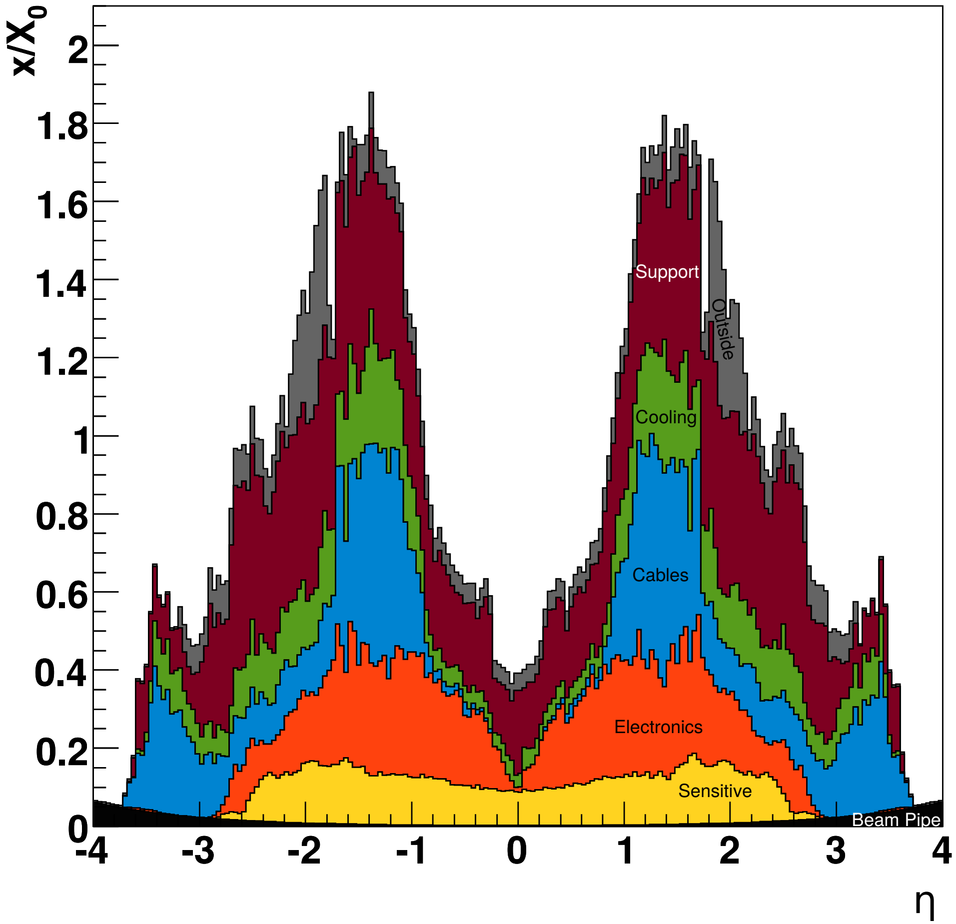
Higher radiation

Bandwidth

Material is mainly driven by power

- Material budget spent (~equally) in:
  - Support structures
  - Cooling lines (= power)
  - Power supply (& bias)
  - Auxiliary electronics
- Design low-power electronics

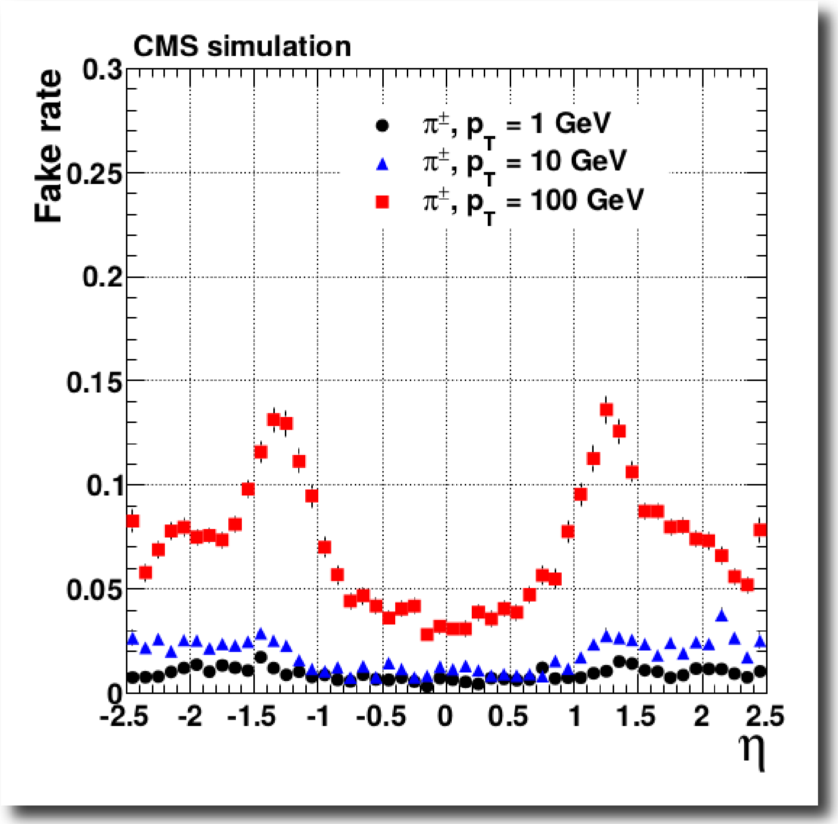
Current CMS Tracker

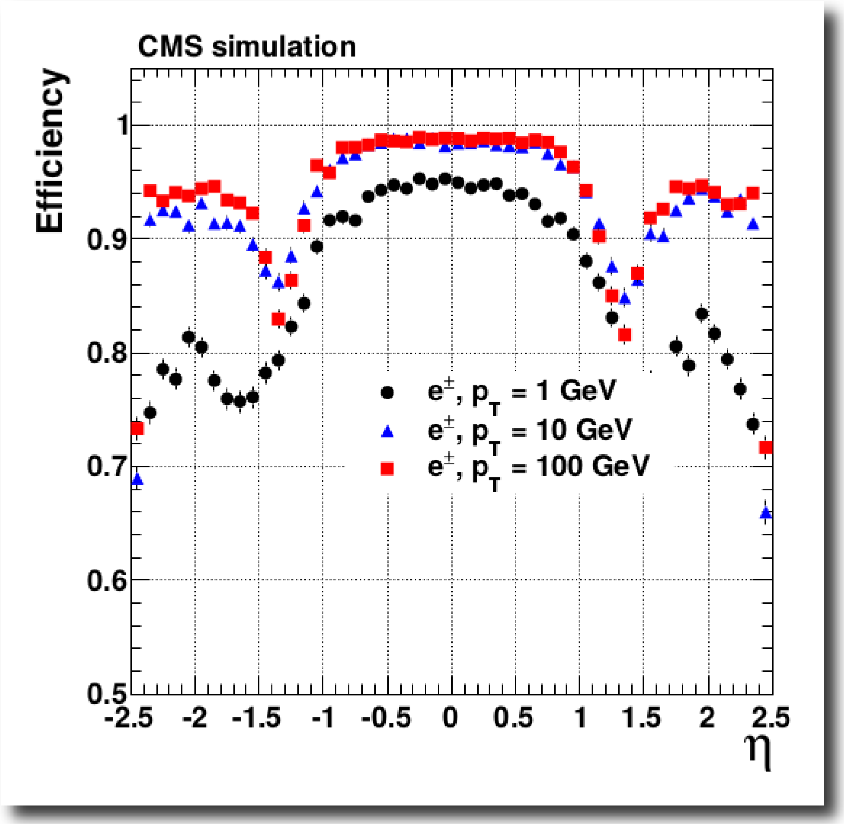


Material matters...

π and e tracking degraded in that region

Current CMS Tracker





Front-end vs. detector performance

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Higher radiation

Bandwidth

CMS Tracker for HL-LHC

Careful design…

DC-DC converters – serial power

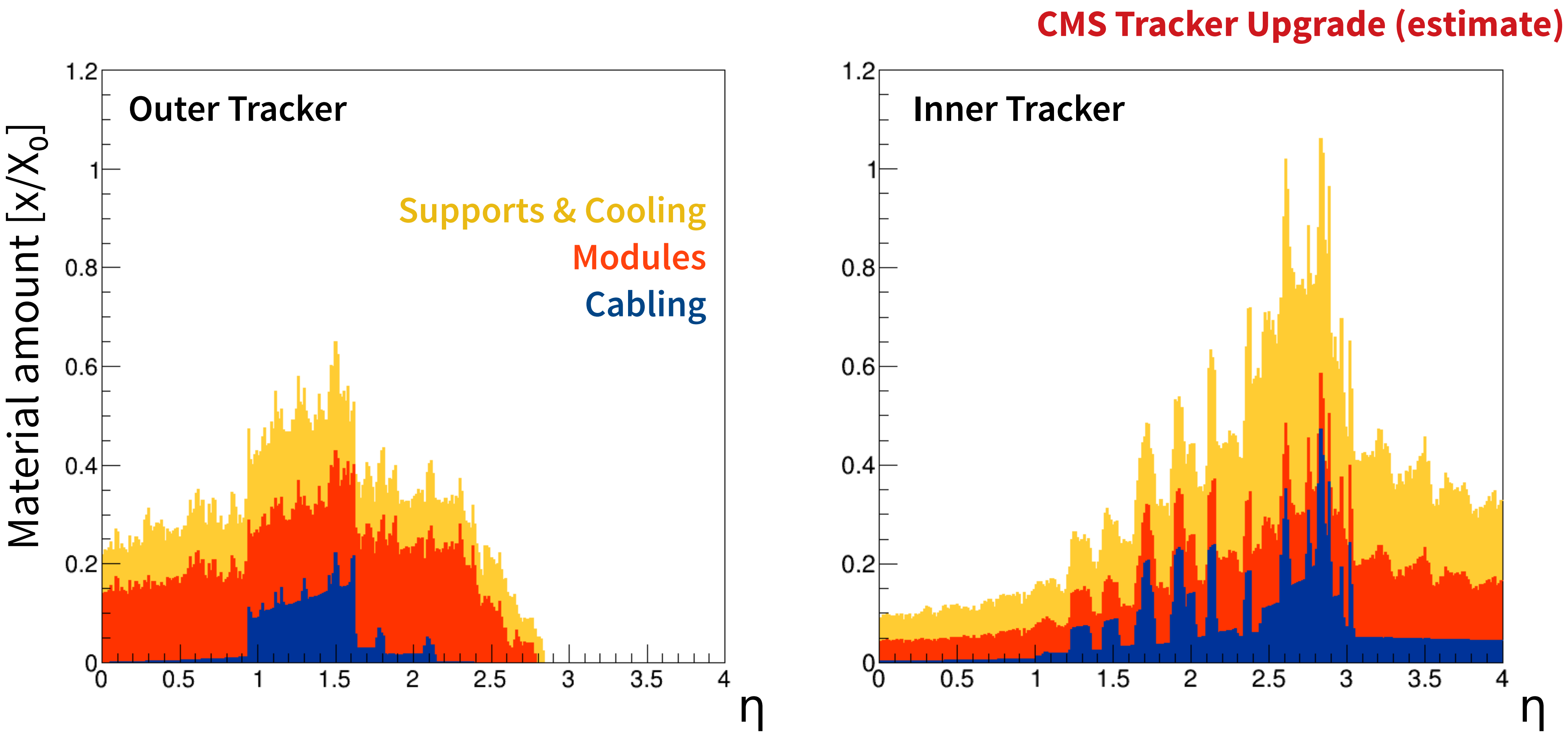
CO_2 cooling

Low-power GBT optical transmitters

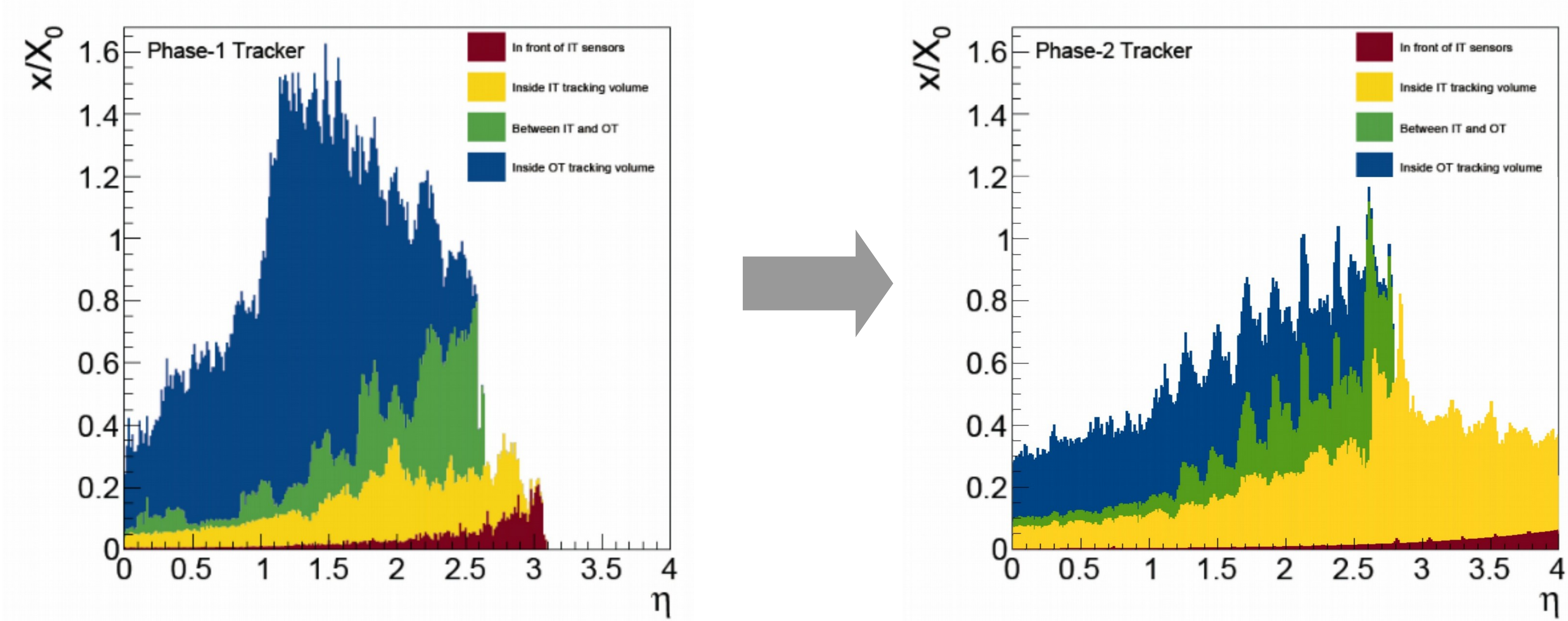
Careful choice of front-end features

Less layers in outer tracker

Tracker upgrade: material budget



Tracker for HL-LHC: less material!



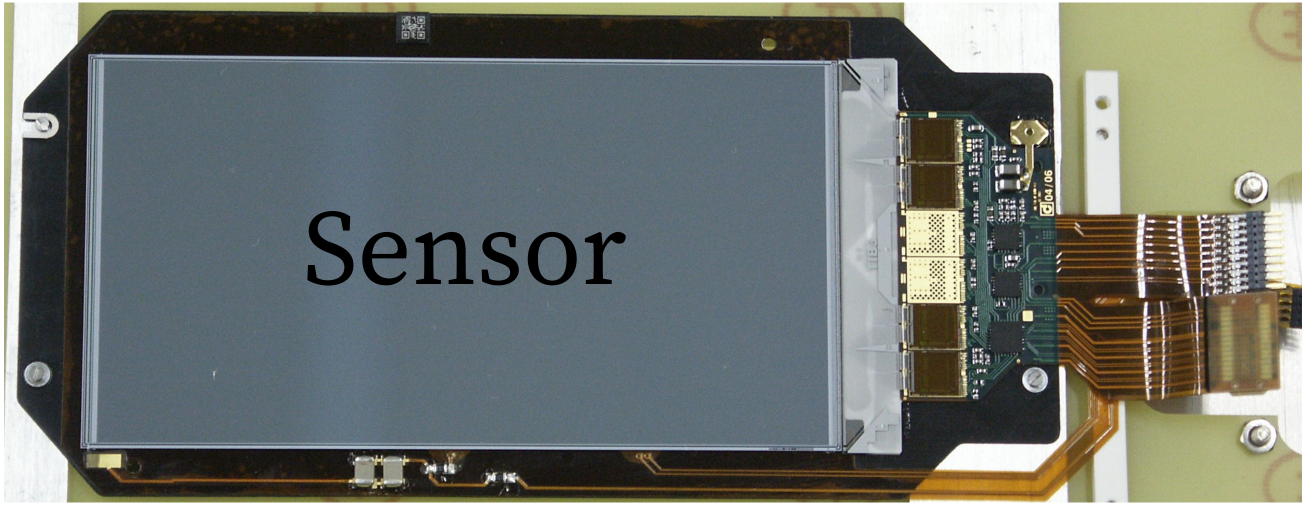
Material budget modeled from engineering drawings. Significant reduction in particular around $|\eta| = 1.5$ expected. Large reduction in Outer Tracker due to the integration of services in modules, not possible in the Inner Tracker

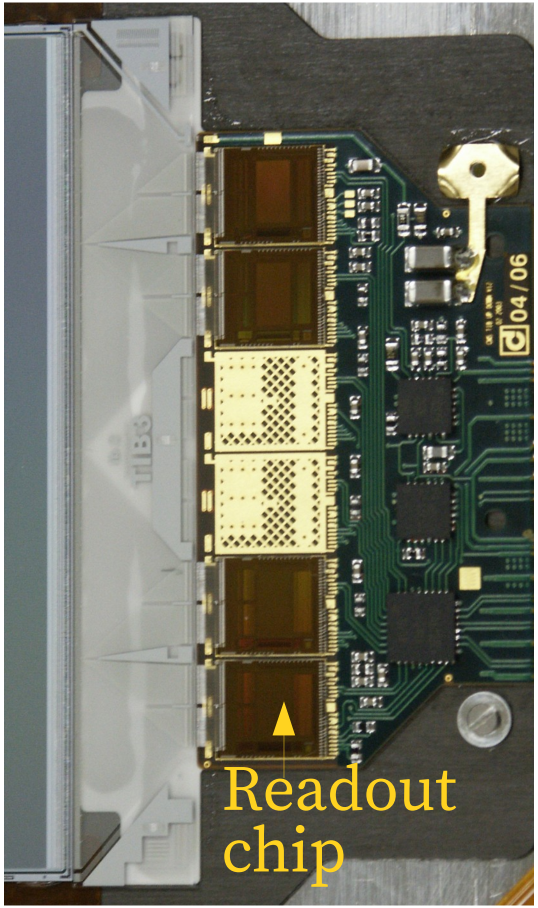
Current technologies
for Silicon Tracker detectors

Strip hybrid detectors

Ex: current tracker module

- With large sensors ~10×10 cm^2 (1 wafer)
- no dead material behind sensor
- x,y via two detectors 100 mrad





Strip hybrid detecto

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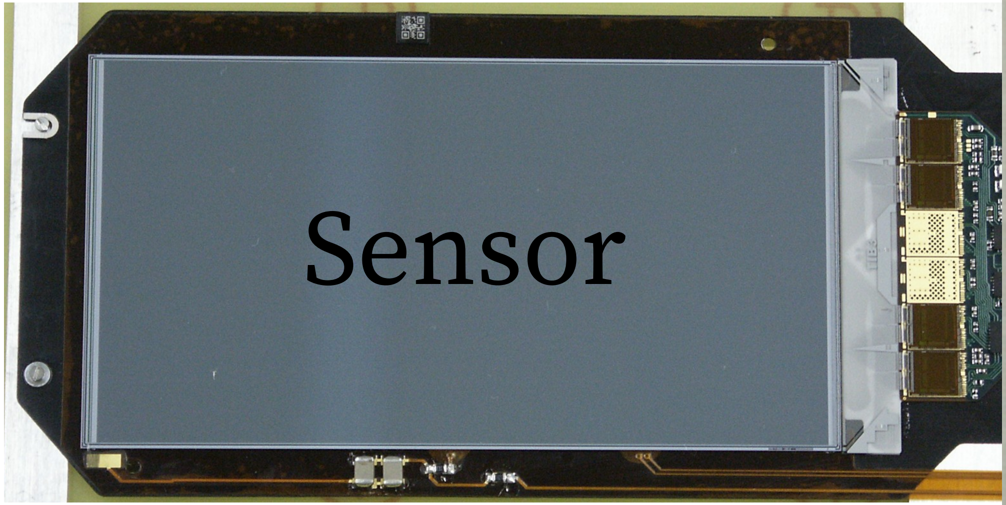
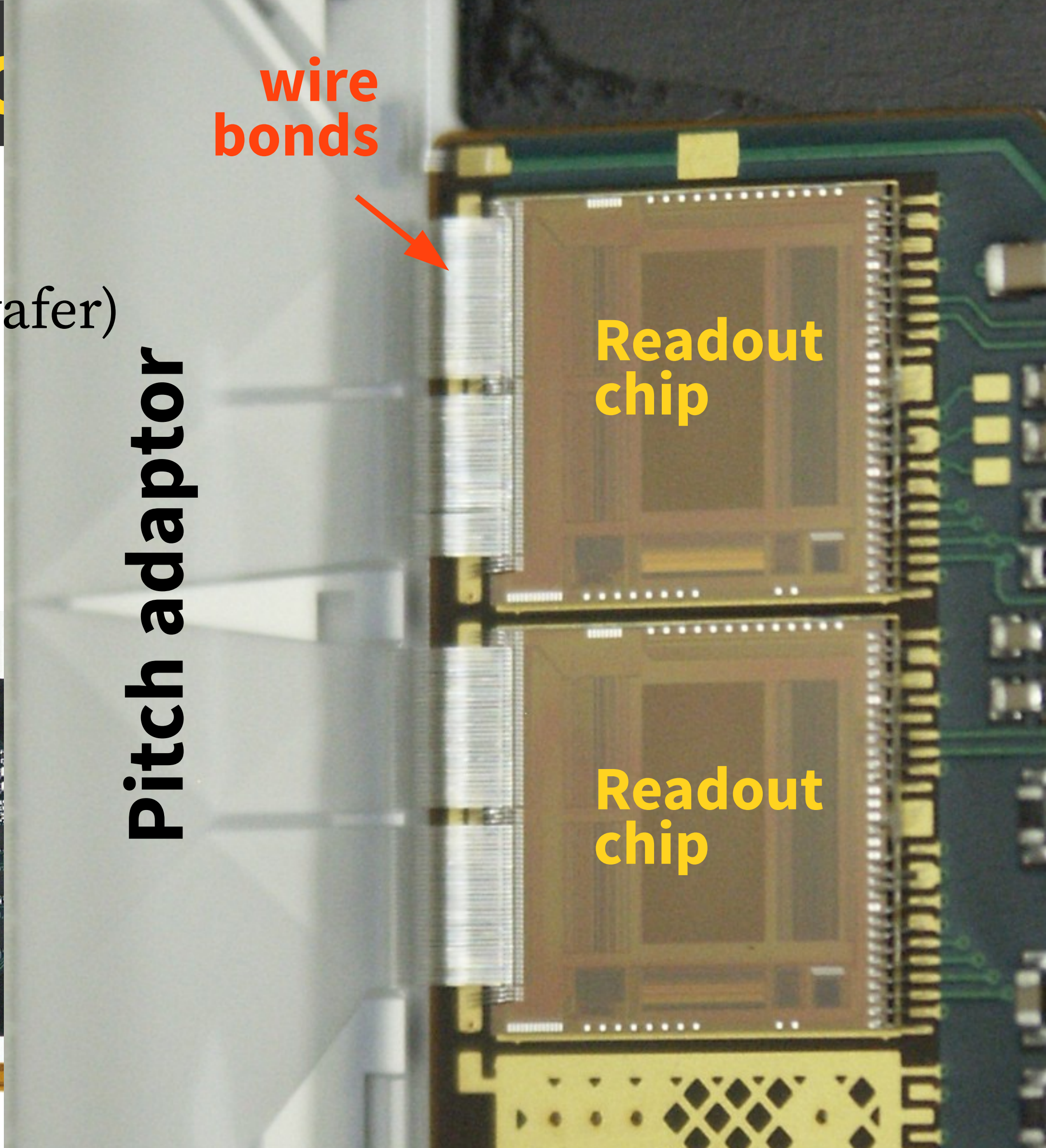
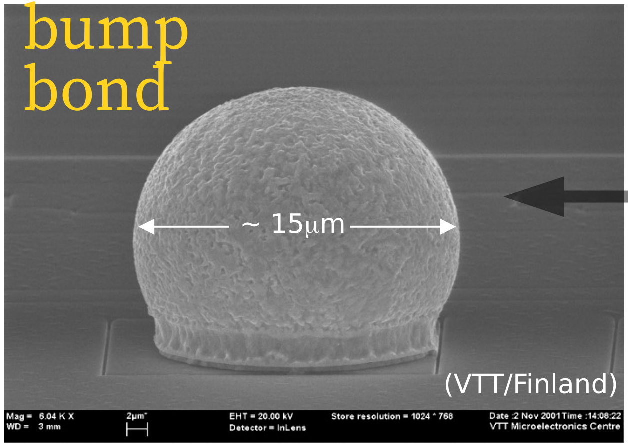
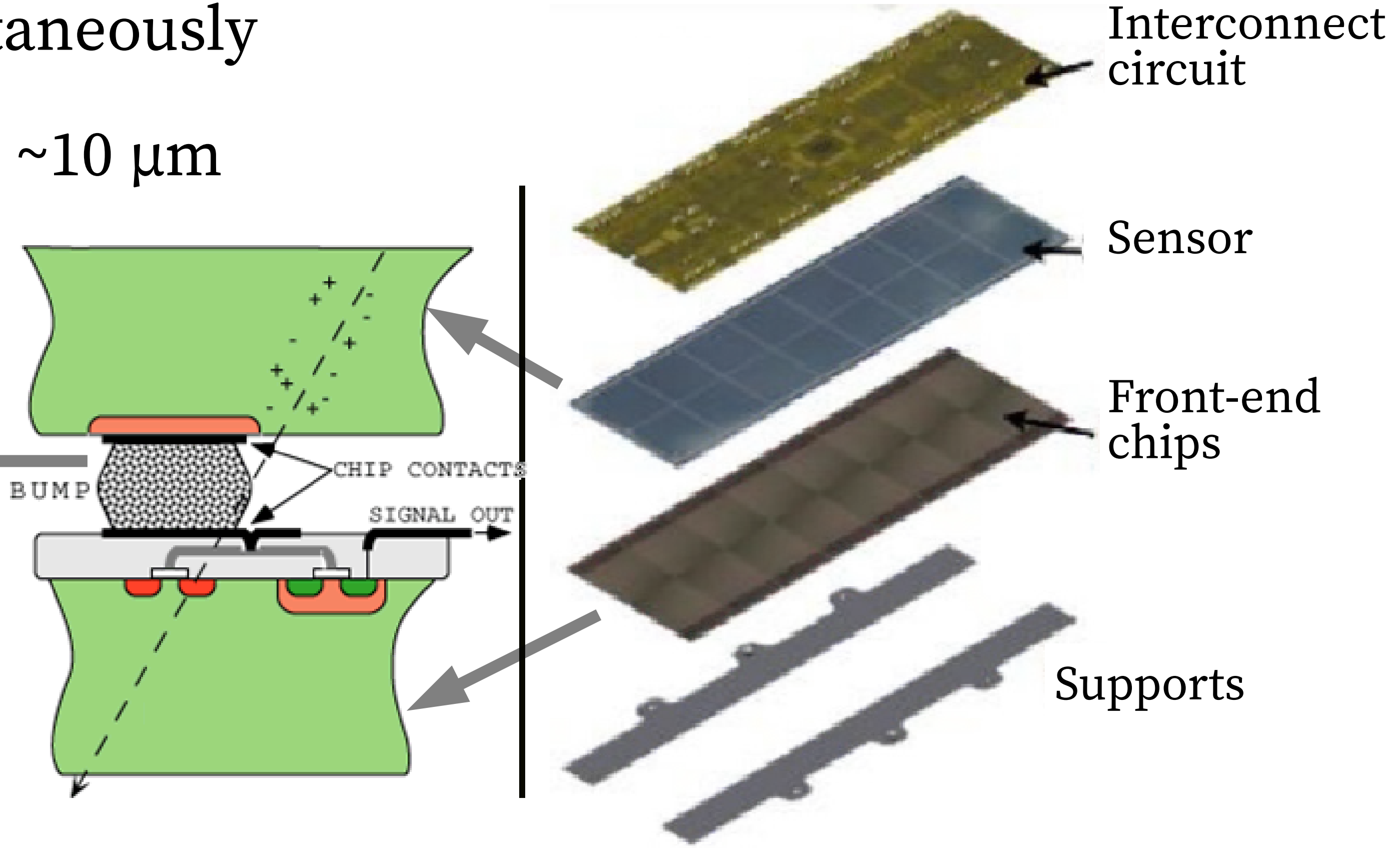




Strip hybrid detectors

- Front-end electronics right behind the sensor
- x,y measured simultaneously
- Single hit resolution ~10 μm

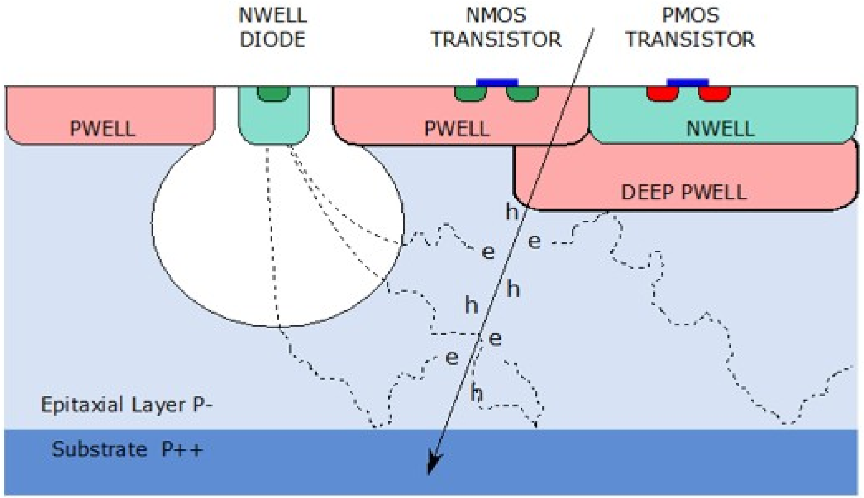




MAPS detectors

Monolithic Active Pixel Sensors

- **Advantages:**
  - Integration of sensor and front-end
  - Very thin detectors (low material budget!)
- **Main limitations:**
  - Slow readout
  - Radiation hardness
- **Notable applications:**
  - **Alice** (LHC – CERN): ALPIDE
  - **Star** (RHIC – Brookhaven): Ultimate-2



Charge collection by diffusion – not by drift

CMS Tracker upgrade for HL-LHC

CMS Tracker upgrade for HL-LHC

Completely obliterating two fundamental components: mechanics & DAQ

Total tracker replacement

Radiation tolerance up to **∫L.dt = 3000 fb^{-1}**	**Operating cold** (-20°C) +50% margin in Outer Tracker **Inner tracker can be extracted**
Pile up **200** Occupancy **< %**	**Increase granularity**
Longer latency → **12.5 μs**	Larger front-end **buffers**
Higher L1A rate → **> 750 kHz**	**Bandwidth!**
Improve two-track separation to resolve tracks in high pT jets	**Increase granularity**
Improve resolution at low p_T Reduce secondary interactions	**Reduce amount of material**
Increase **forward acceptance**	Mostly through **pixel layout**
Contribute to L1-trigger	**Real-time efficient tracking** **40 MHz output for L1**

Detector layout & summary

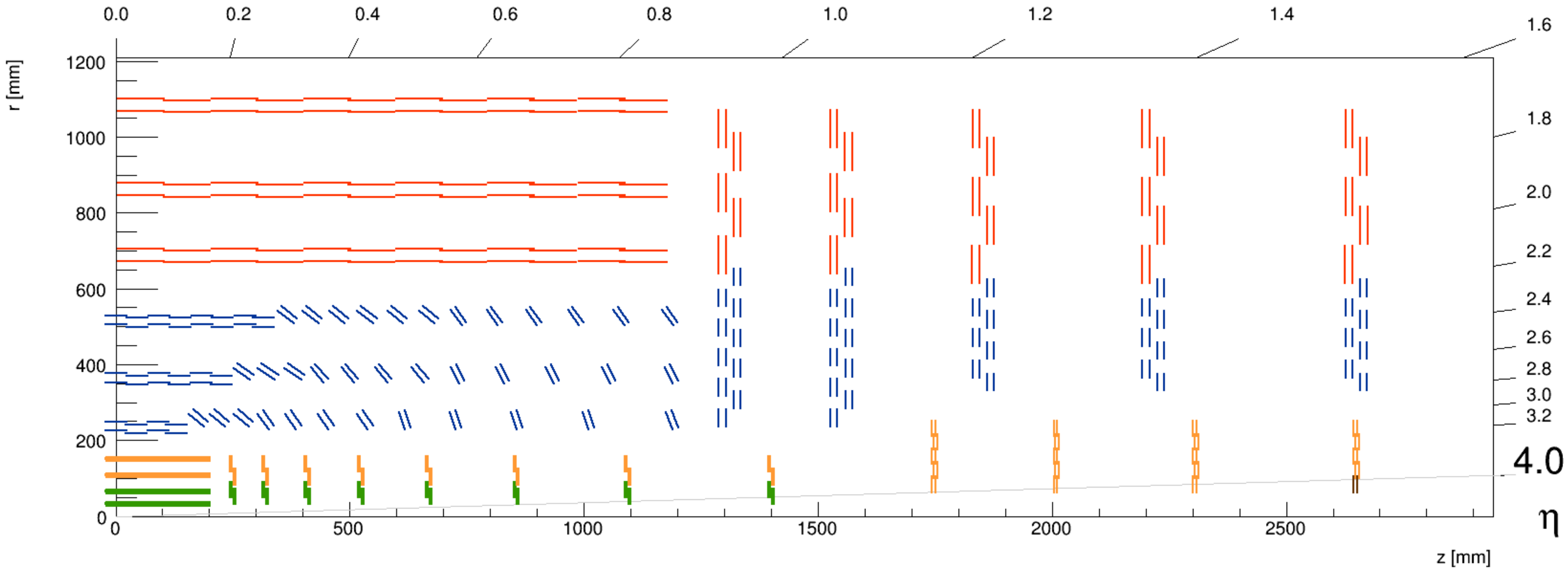
Outer Tracker

Current		HL-LHC
~200 m^2	Silicon surface	~190 m^2
9.3 M	Strips	42.0 M
–	MacroPixels	173 M
15 148	Modules	13 296
100 kHz	readout rate	750 kHz /40 MHz

Inner Tracker

Current		HL-LHC
~1 m^2	Silicon surface	4.9 m^2
66 M	Pixels	2.0 G
1440	Modules	4352
100 kHz	readout rate	750 kHz

CMS Tracker layout: hybrid technology



2 types of Outer Tracker:

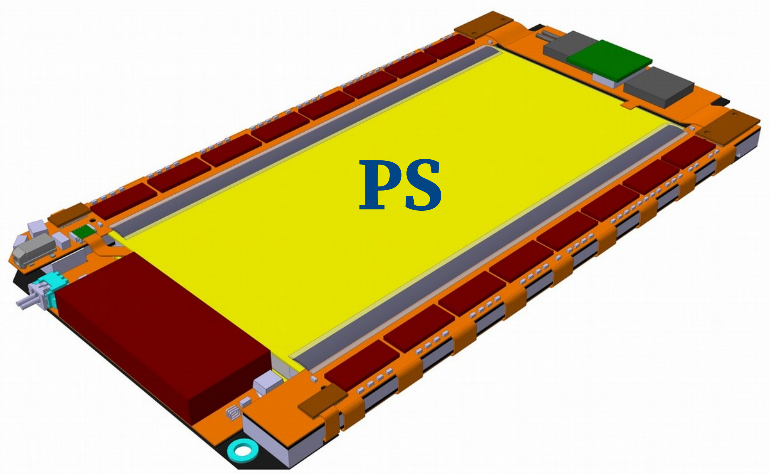
- 2S (Strip-Strip sensor modules)
- PS (macro-Pixel Strip sensor modules)

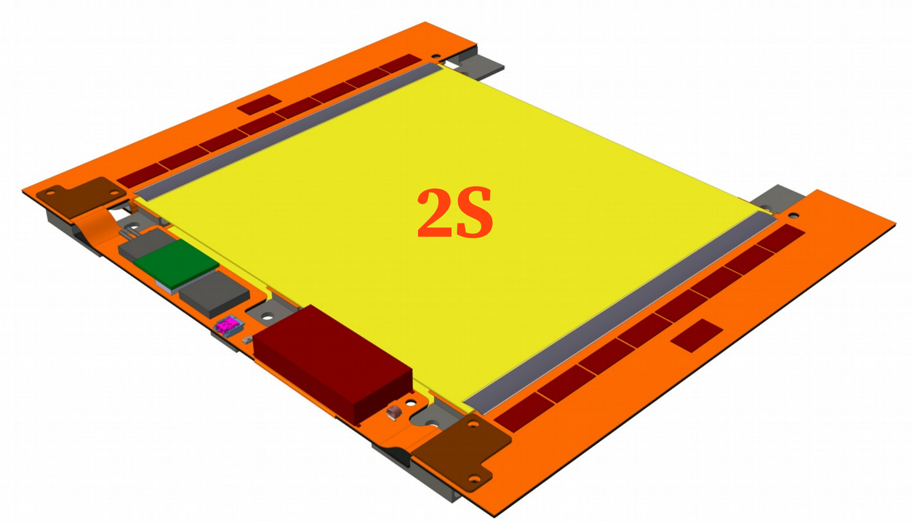
2 types of Inner Tracker modules

- 2×2 Pixel Chip modules
- 2×1 Pixel Chip modules

Outer Tracker modules

2 detecting surfaces each
All services are integrated on the module:
- DC/DC power converter
- Optical transceiver





Will be described in much greater detail in the **following talk by Basil Schneider**

CMS chip comparison (+ 1 MAPS)

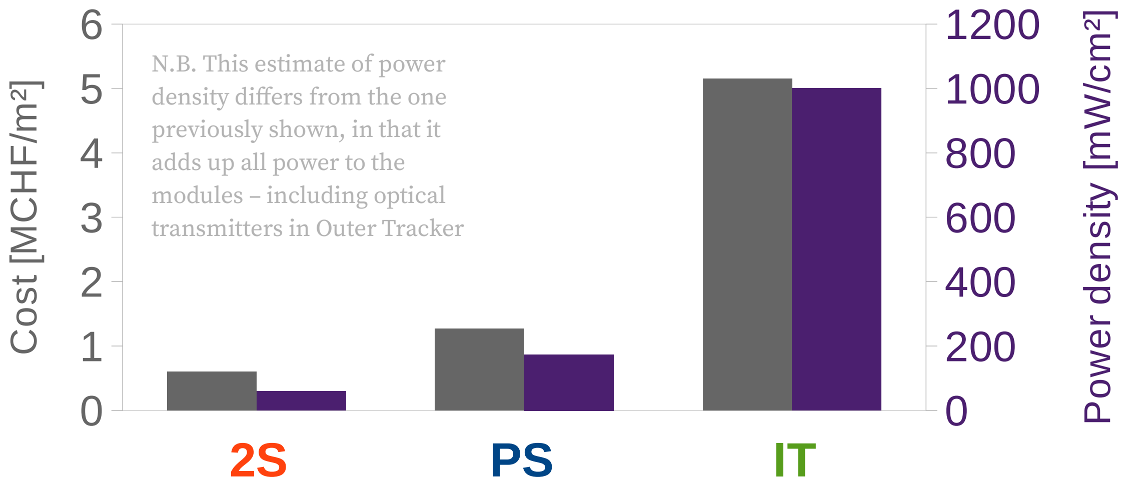
Detector type	Detector type	Chip	Technology [nm]	Channels	Density [cm^{-2}]	Power/Channel [µW/ch]	Power density [mW/cm²]
CMS HL-LHC	**Hybrid Pixel**	**CROC**	**65**	**292 000**	**40 000**	**10**	**384**
CMS HL-LHC	Hybrid **Macro-pixel**	**MPA**	**65**	**1 920**	**682**	**100**	**68**
CMS HL-LHC	Hybrid **Strip**	**SSA**	**65**	**120**	**43**	**1000**	**43**
CMS HL-LHC	Hybrid **Strip**	**CBC**	**130**	**127**	**22**	**1000**	**22**
ALICE Tk	MAPS	Alpide	180	524 288	127 551	0.31	40

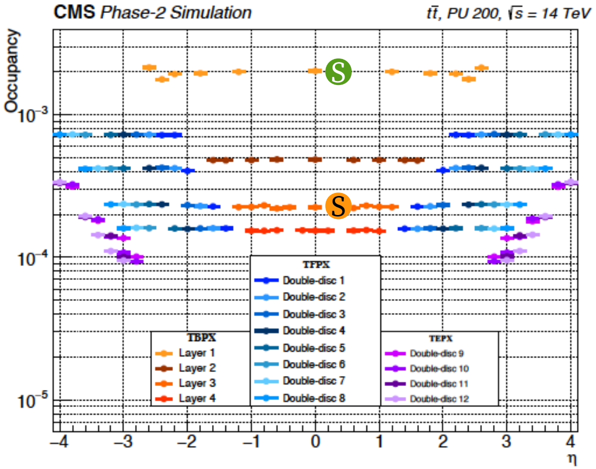
Detector type	Pitch x [µm]	Pitch y [µm]	Interconnection	Signal	Integration time [ns]	Trigger rate [kHz]
CMS HL-LHC	**50**	**50**	**Custom bump bonding**	**4-bit TOT**	**25**	**750**
CMS HL-LHC	**100**	**1 466**	**C4 bump bonding**	**1-bit ADC**	**25**	**750**
CMS HL-LHC	**100**	**23 471**	**Wire-bonding**	**2-bit ADC**	**25**	**750**
CMS HL-LHC	**90**	**50 249**	**Wire-bonding**	**1-bit ADC**	**25**	**750**
ALICE Tk	28	28	Integrated	1-bit ADC	10 000	100

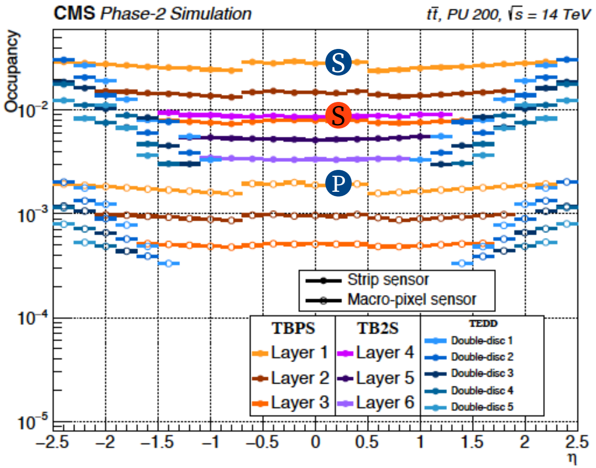
PS: technology tuned for the need

PS modules provide three layers of unambiguous 3D coordinates

- An asset for pattern recognition
- Granularity well matched to intermediate radii
- A much more cost effective solution than extending the IT to larger radii / more layers
- Having developed three different systems pays off!

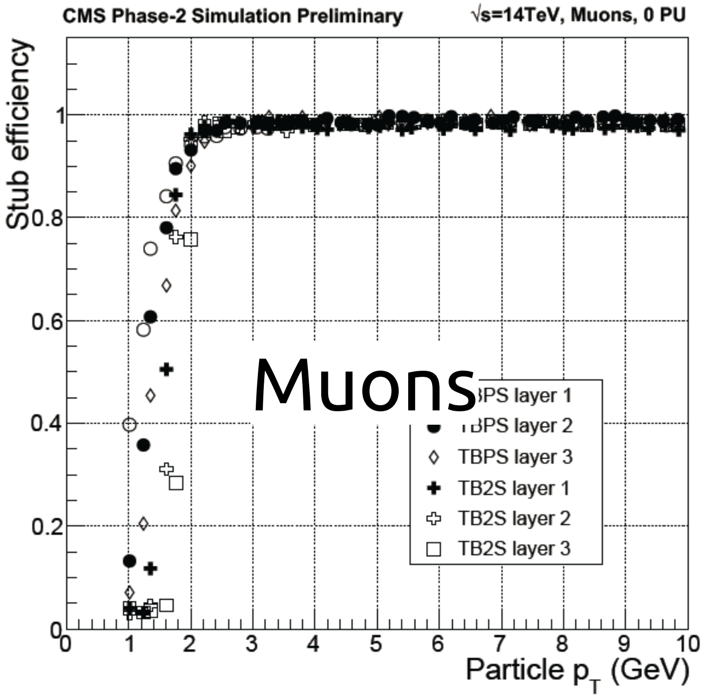




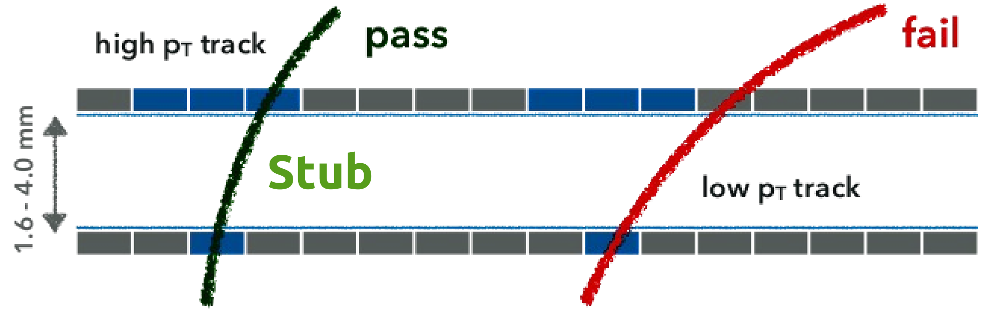


Outer Tracker modules → trigger

- Comparison of hits in closely spaced silicon sensors
- Selection of hit pairs belonging to tracks with pT ≳ 2 GeV
- On-module real-time data reduction by factors 10-100
- Hit pairs ("stubs") are sent to back-end, tracks are formed
- After reception of L1 trigger decision, whole event is read out (at up to 750kHz)
- **An asset for pattern recognition in high pile-up: to be kept in mind**

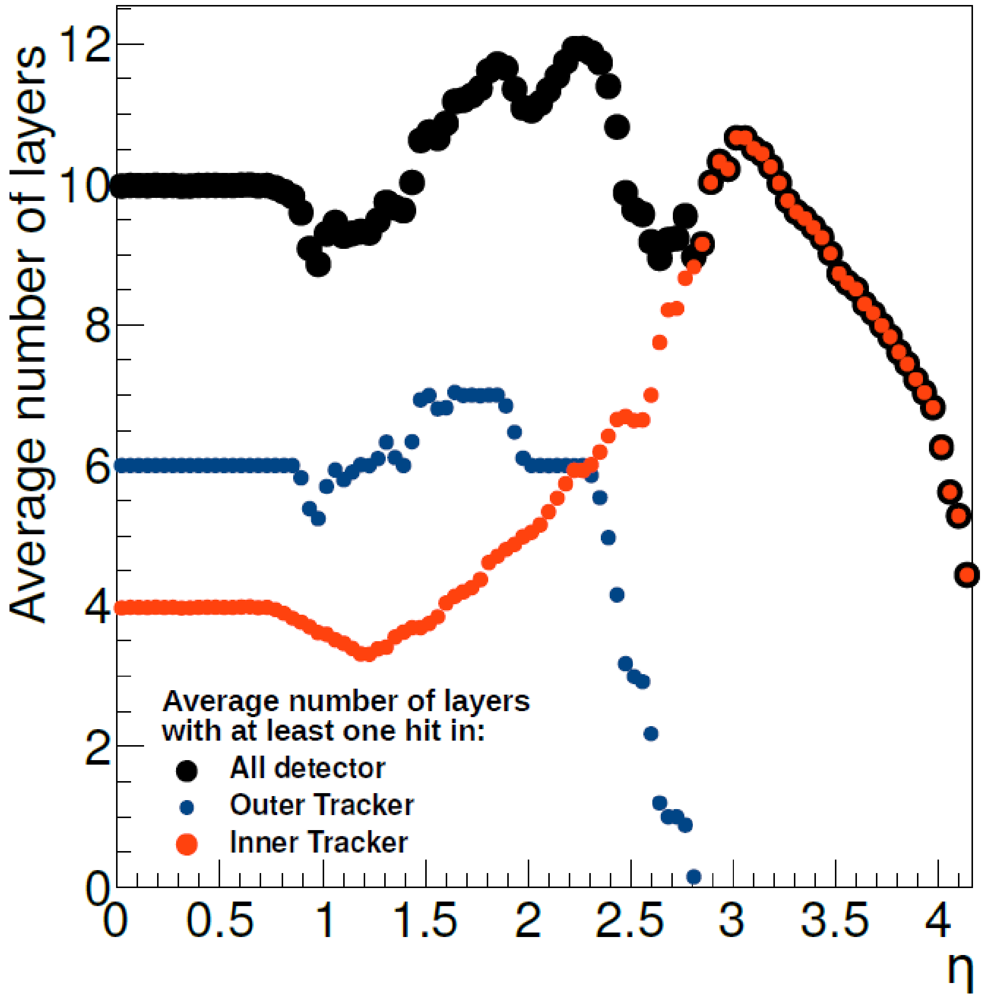


Thanks to CMS 3.8 T magnetic field!



Same electronics reads two sensors

Detector layout & summary



Tracker performance must be **robust against** (unavoidable) **losses of modules**

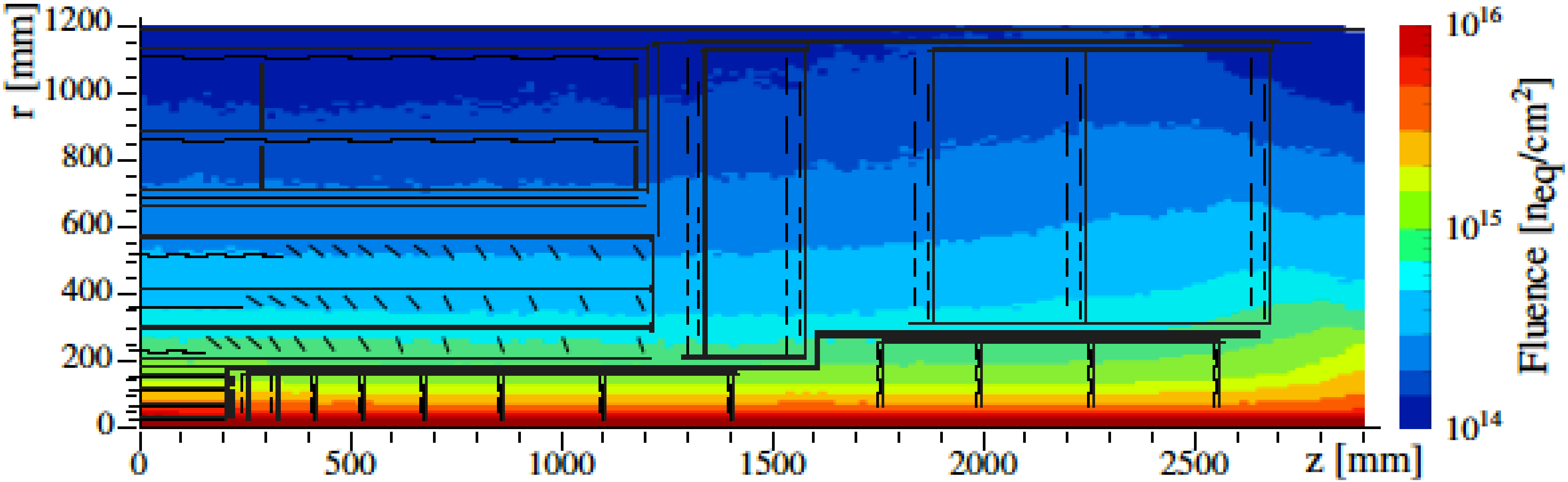
Outer Tracker:

- **6 layers**
- Robust track finding at L1 in the rapidity acceptance **|η| < 2.4**

Inner Tracker:

- **Central region: 4 layers** (as in Phase-1 upgrade)
- ensures robustness for pixel-based track seeding
- good track finding performance, down to very low pT
- **Forward part:**
  > 8 layers (6 layers)
  → **|η| ~ 3.5** (~4.0)

Total fluence neq/cm²



The target is ~ 10× present tracker

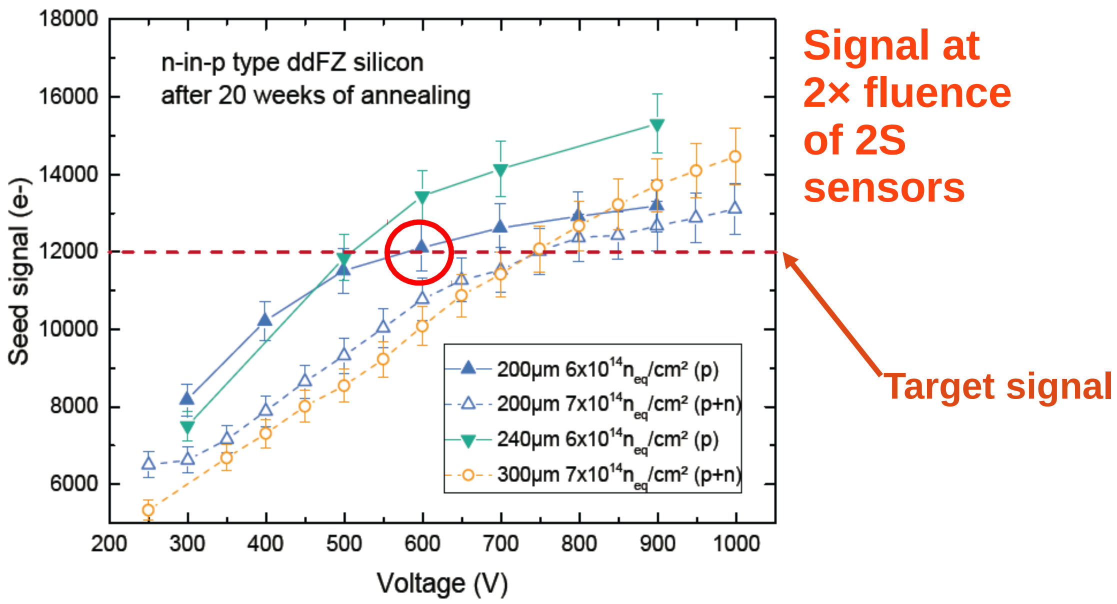
i.e. about 10^{15} neq/cm² for the Outer Tracker, > 2×10^{16} for the innermost pixel layer

→ Challenging for silicon sensors and electronics (notably in the pixel region)

→ **Unprecedented levels!**

Outer Tracker sensors

- 3 types of sensors: **2S**, **PS-s** (strips), **PS-p** (macro-pixels)
- Extensive R&D program with sensors from a single vendor
  - n-in-p type 6“ wafers, 600V nominal bias voltage (possibility to increase to 800V to boost signal)
  - final choice of thickness this summer also depending on thermal performance, robustness, cost
- **Required signal** charge for **200 µm** at **600V** at **nominal fluence** (+margin)



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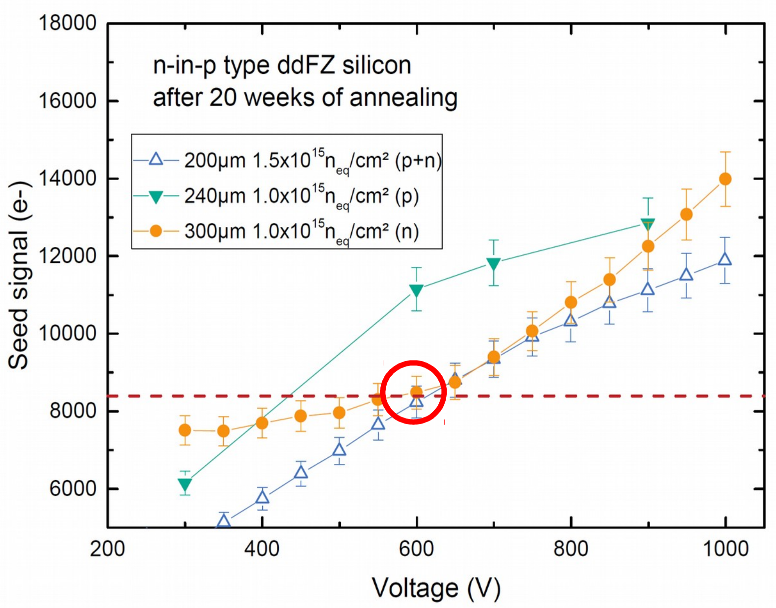
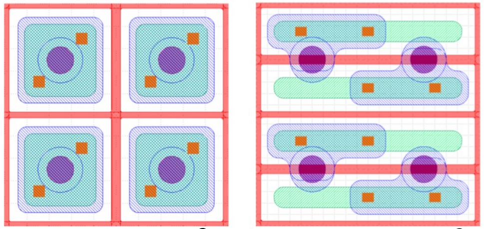


Signal at 1.5× fluence of PS sensors

Target signal

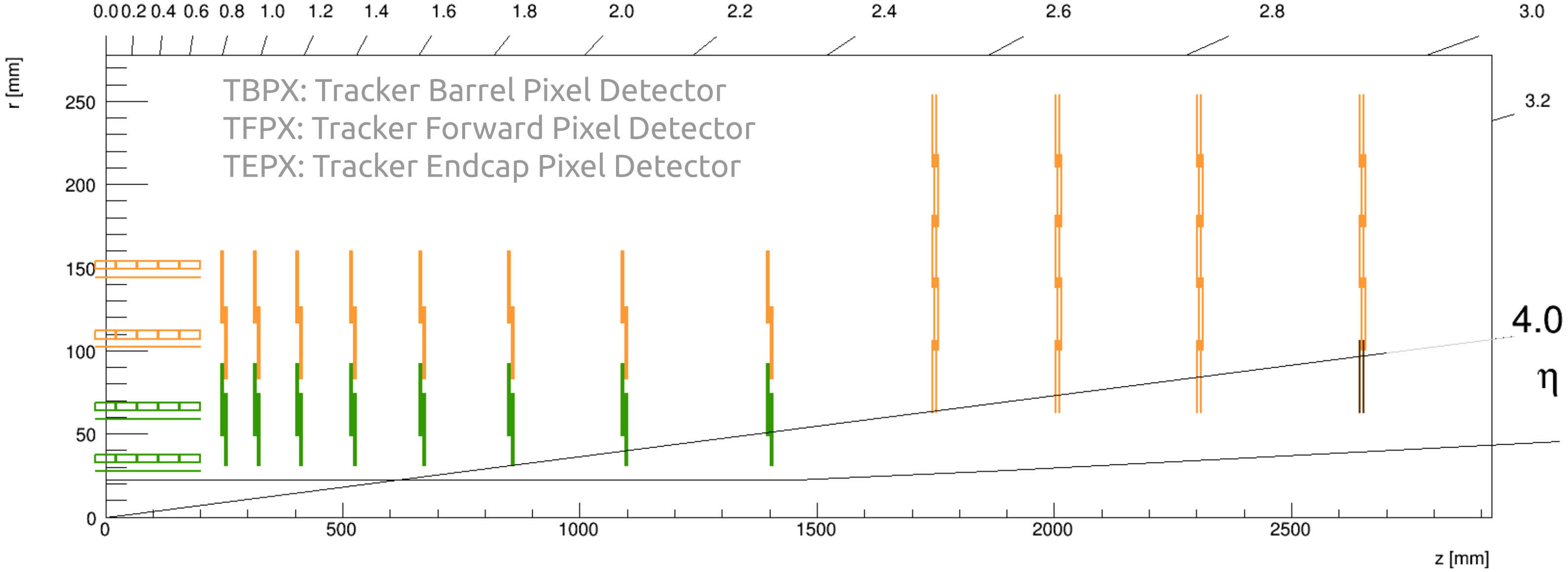
Inner Tracker layout

- Classic hybrid pixel detector
- Narrow pitch and high granularity **50×50** or **25×100 µm²** cell size
- Pseudorapidity **coverage to η ~ 4**
- Unprecedented radiation (**2.3×10¹⁶ neq/cm²**, **1.2 GRad**) & hit rates (**3 GHz/cm²**)
- **Extractable** – potential to exchange degraded parts
- Contribution to **real time luminosity** measurement (TEPX)



50×50 µm² 25×100 µm²

÷6 smaller than current detector

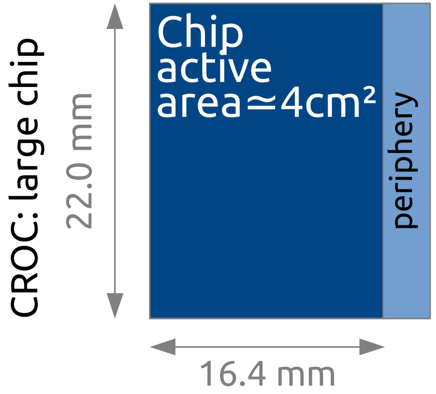


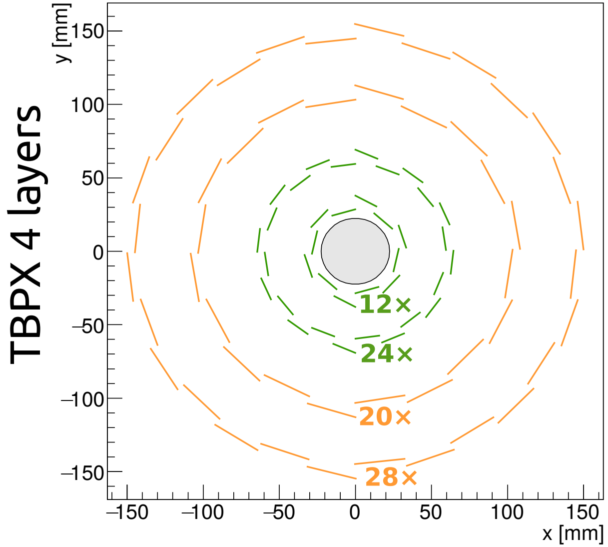
Inner Tracker layout

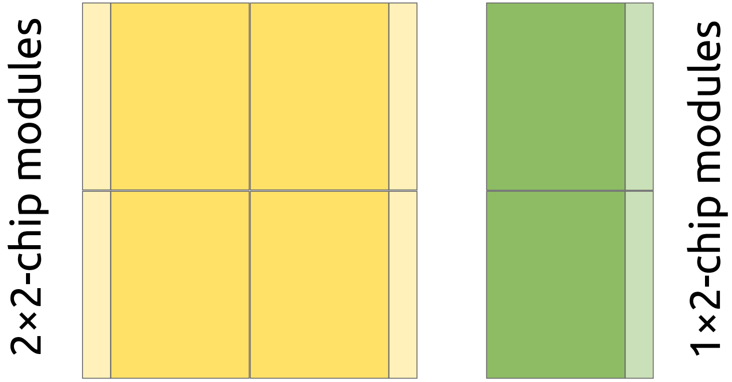
Like current detector: ladder built with modules on planar surfaces

(small gap between consecutive modules
 but no projective gap at $\eta = 0$)

- **1×2-chip modules** for Layer 1-2 ladders
- **2×2-chip modules** in Layers 3-4 convenient
  (gives a 2-fold reduction # cooling pipes)







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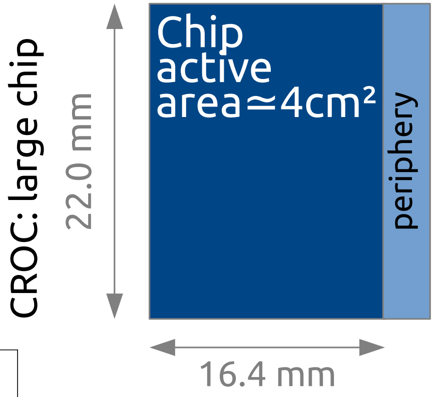
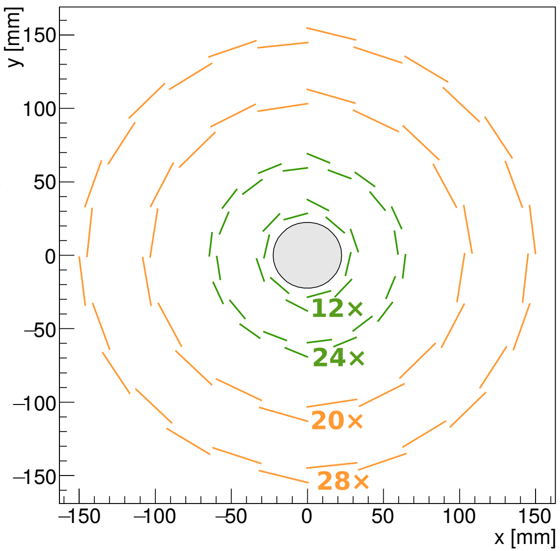
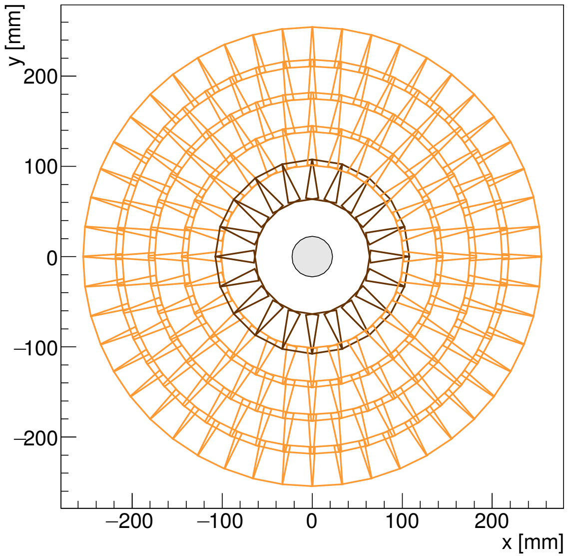
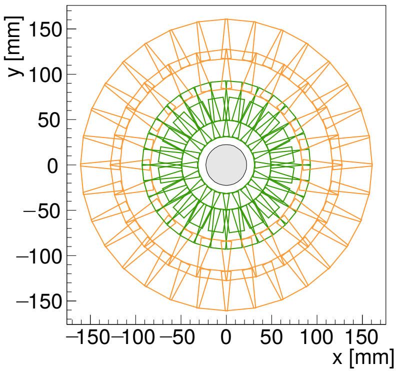


TBPX 4 layers



TEPX 4 disks





TFPX 8 disks

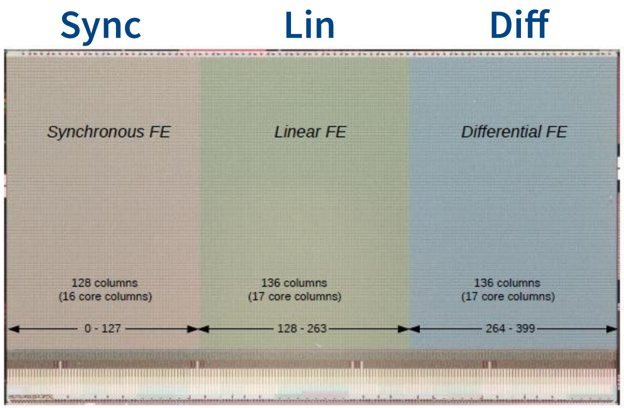
Inner Tracker ASIC

Developed by RD53 collaboration: 19 institutes – CMS+ATLAS

RD53A ROC Chip 65 nm CMOS successful demonstrator – used to develop Sensors, Modules and System

- 20×12 mm^2 (~½ of final size)
- 3-in-1 different Front-End architectures — accurate review process CMS (& Atlas) made their choice for the final chip

CMS final chip: CROC (submission Apr '20)



Phase-1		HL-LHC
Rate **400 MHz/cm²**	× 8	Rate **3.2 GHz/cm²**
L1 rate **100 kHz**	× 7.5	L1 rate **750 kHz**
Latency **3.2 µs**	× 4	Latency **12.8 µs**
Radiation **~100 Mrad**	× 10	Radiation **~1.2 Grad**

×60 Bandwidth

×32 Buffers

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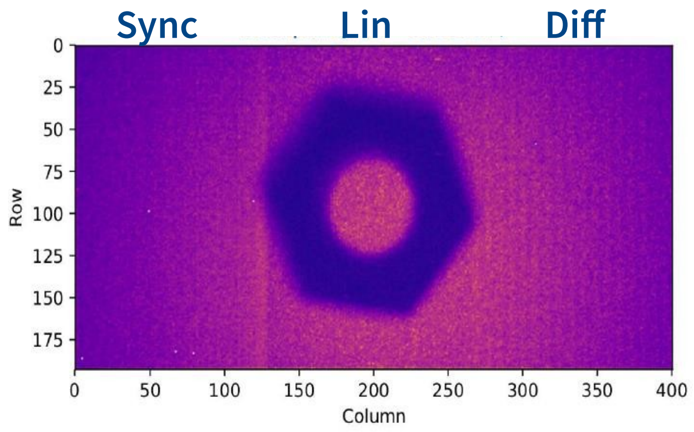

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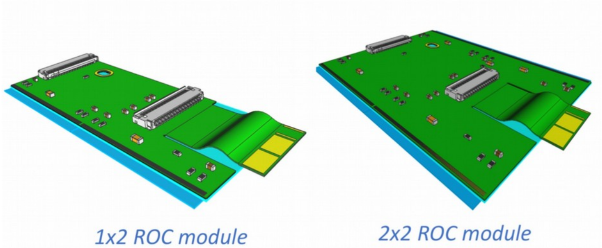
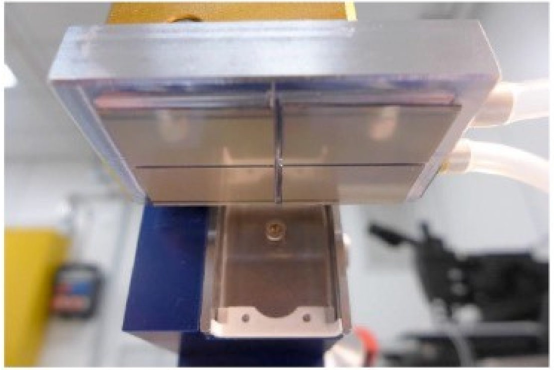
Inner Tracker modules

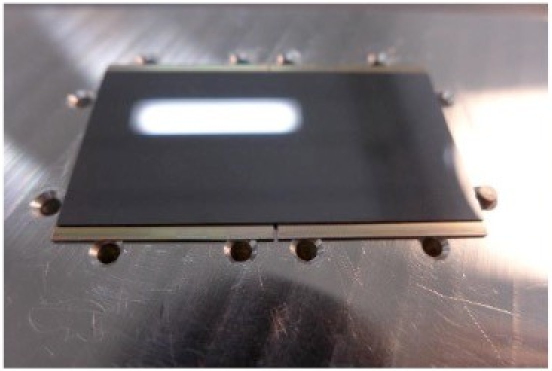


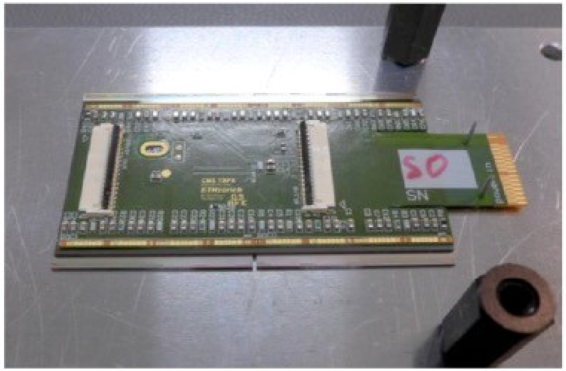
	TBPX	TFPX	TEPX	Total
1×2 modules	324	832	0	1156
2×2 modules	432	896	1408	2736
Sensors	756	1728	1408	3892
Pixel chips	2376	5248	5632	13256
Pixels [$\times 10^6$]	347	767	823	1937
Silicon area [m^2]	0.87	1.92	2.06	4.84

Module design

- Design similar to current detector, but
- HDI contains only passive components (routing of signals, power, bias)
- Development of module design, assembly tools and procedures ongoing







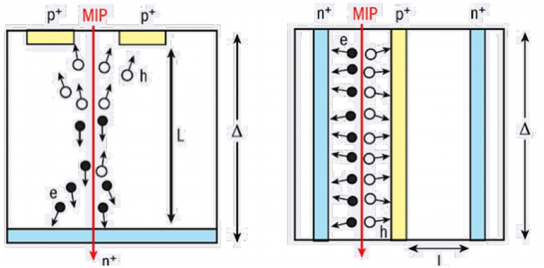
Inner Tracker Sensors

Planar (traditional) vs. **3D** (shorter drift, lower bias V)

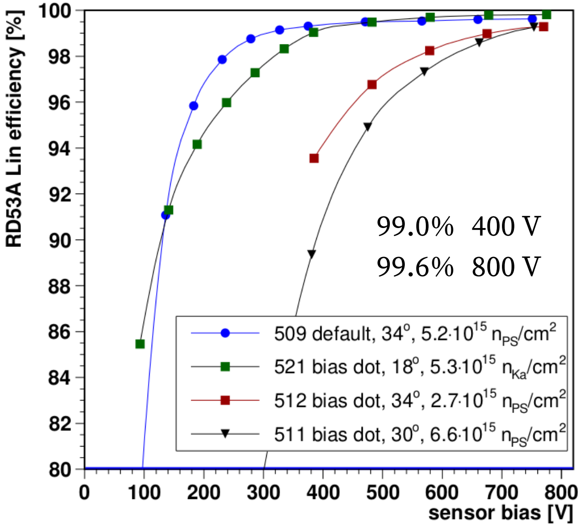
Rad-hard chip needed to study sensors at same dose! RD53A boosted this activity!

CMS has both options open. **So far:**

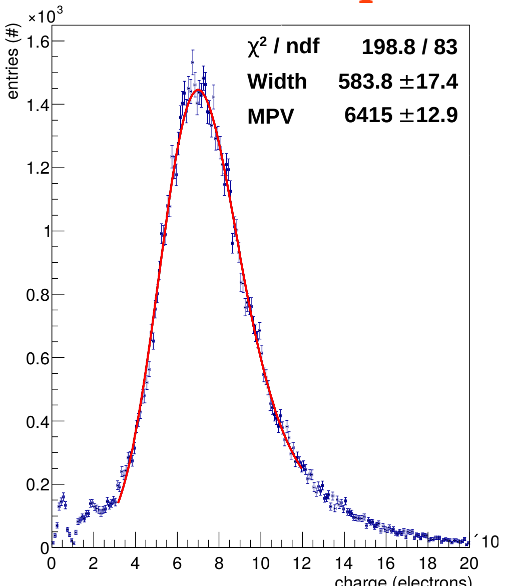
- **Planar** sensors proven to fluence larger than **Layer 2**
- **3D** sensors proven to **~½ fluence of Layer 1** (10^{16} neq/cm^2)

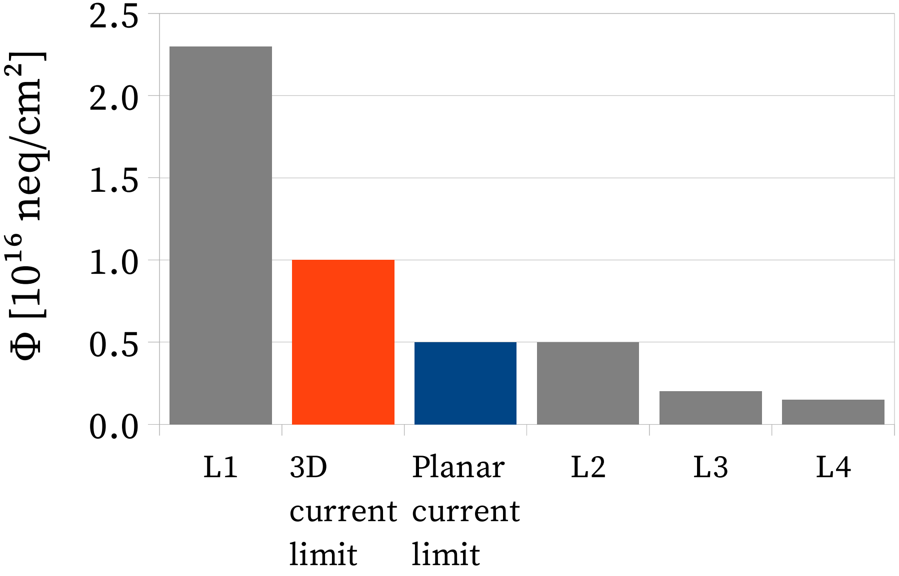


$\Phi > 5\times10^{15}$ neq/cm^2

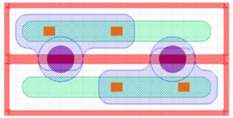
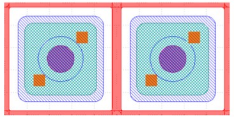


$\Phi = 1\times10^{16}$ neq/cm^2

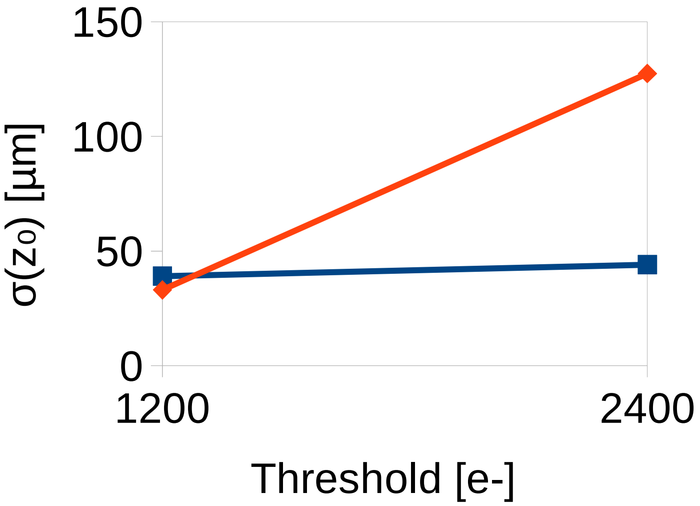


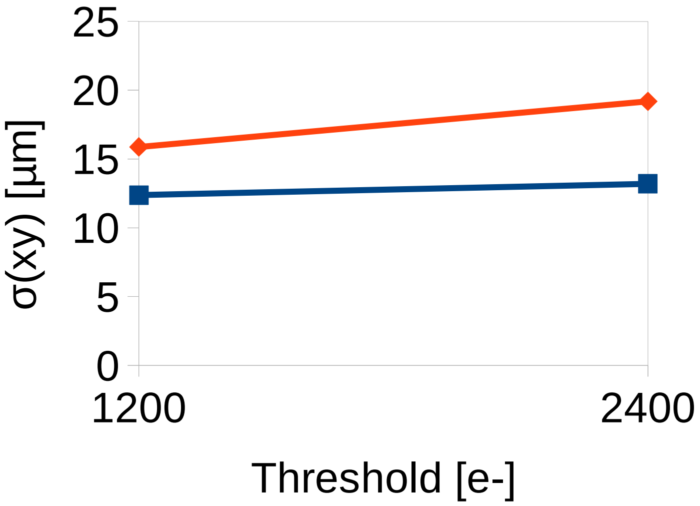


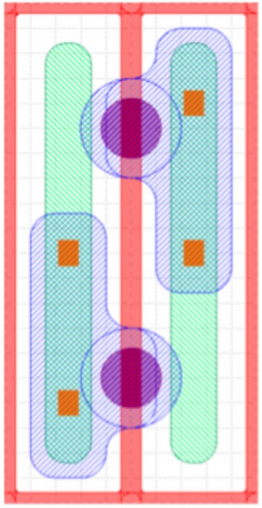
Inner Tracker Sensors

25×100 μm² preferrable to **50×50 μm²** according to MC simulation







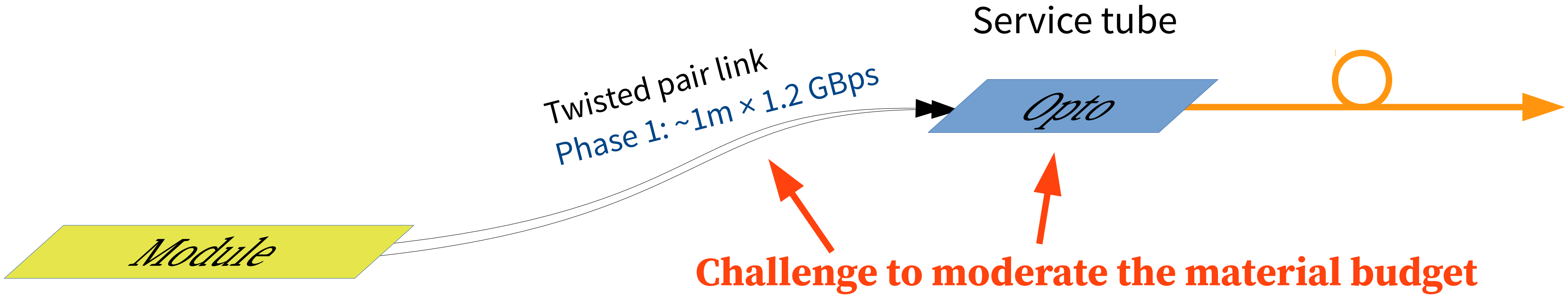
Cross-talk effect measured (≳10%) with planar 25×100 due to coupling with the RD53A bump pattern (50×50) – Modified design to mitigate effect included in ongoing production at FBK

Inner Tracker data links

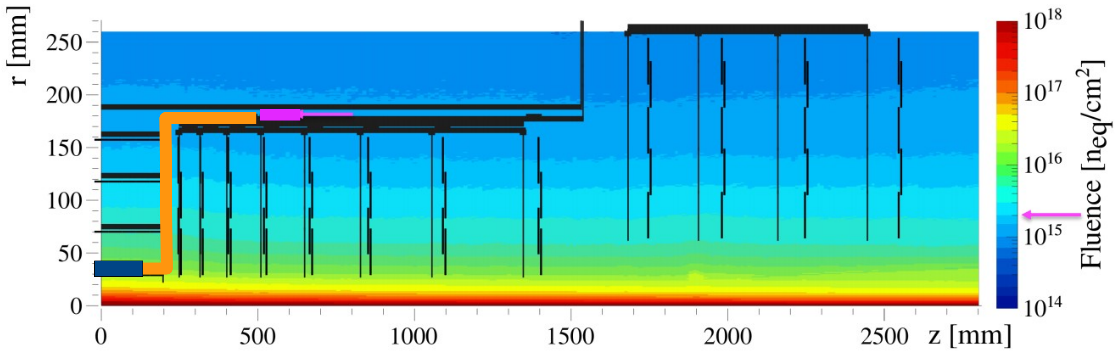
Optical on-board readout not possible:

- Radiation hardness of opto components
- Space on the modules

→ **Electrical links to opto links O(1m)**



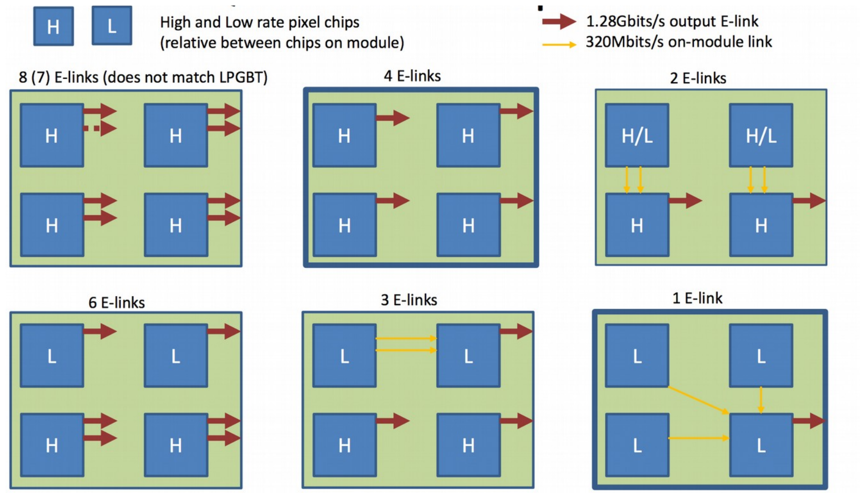
Inner Tracker data links



opto/electrical conversion

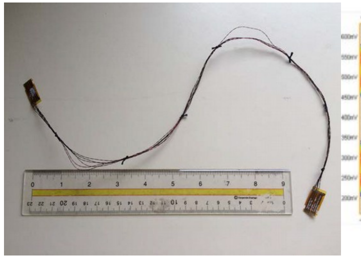
Optoelectronics limits
(1×10^{15} n/cm^2 fluence, 100 Mrad)

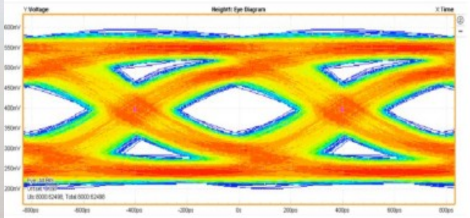
on-module data aggregation



e-links

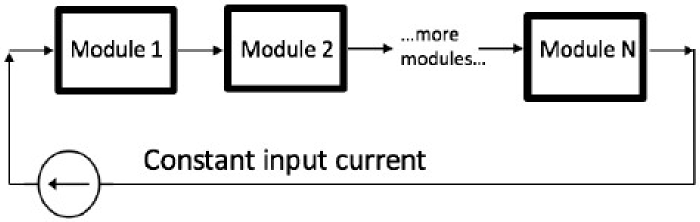
~7k readout + 4k control
differential electrical links
link selection ongoing



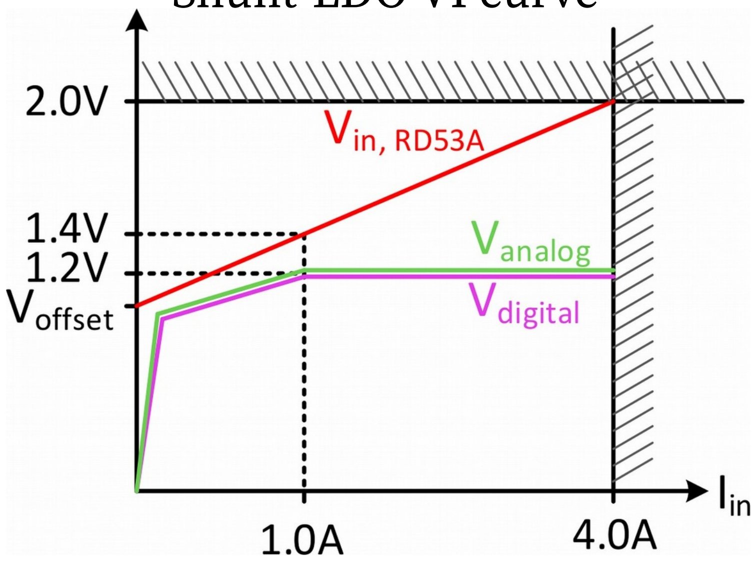


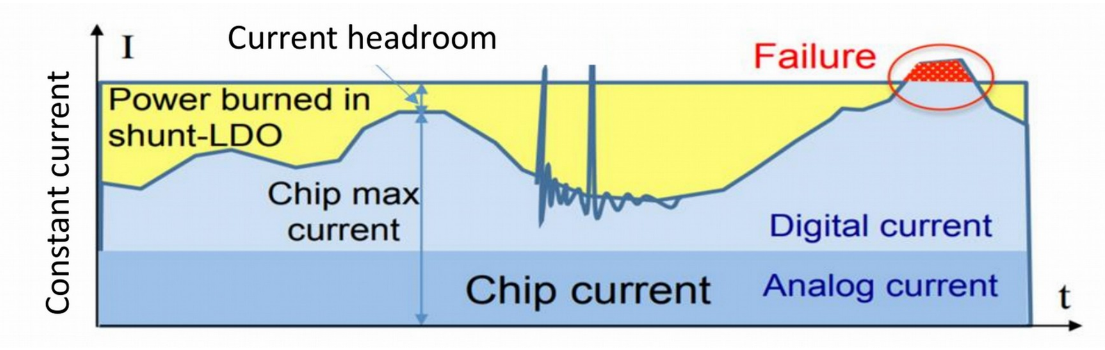
Inner Tracker serial power

- Serial powering is the only viable solution for the IT system ~50 kW on-detector power
  - Low mass- Integrated on-chip solution - Radiation hard - Not sensitive to voltage drops- Low noise Operation
- I_{in} constant, enough I_{in} to satisfy highest I load. Any extra current gets **burnt by shunts**.
- Up to 11 modules in series – chips on module in parallel

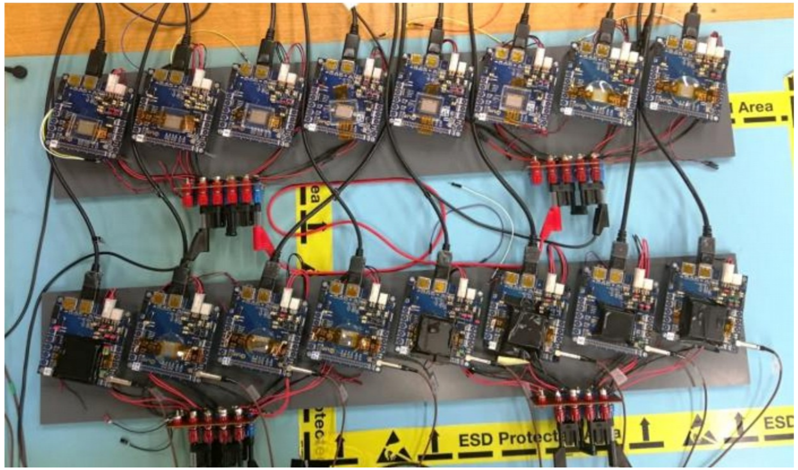


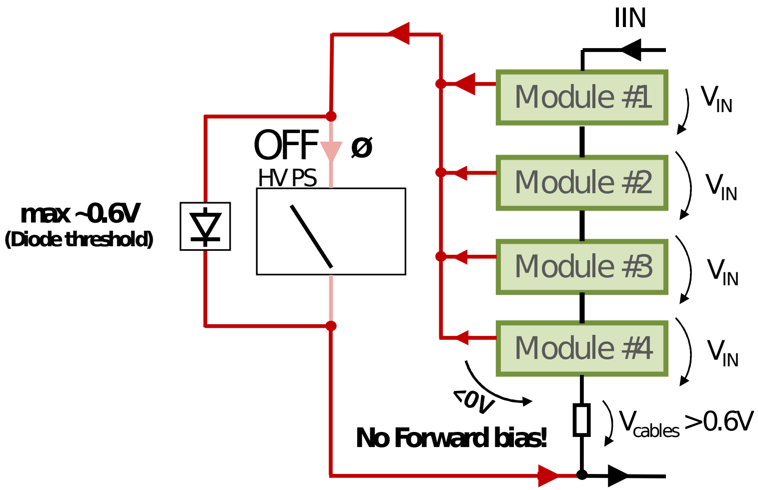
Shunt-LDO VI curve





Inner Tracker serial power





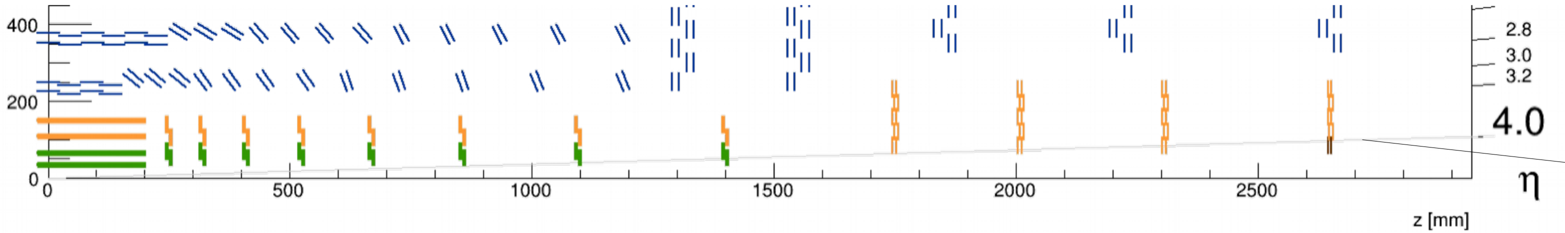
First serial power tests based on single chips externally connected

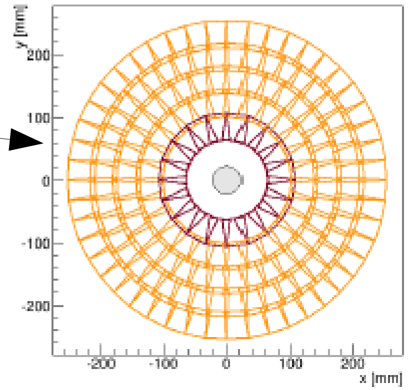
- Modules in series – chips on module in parallel

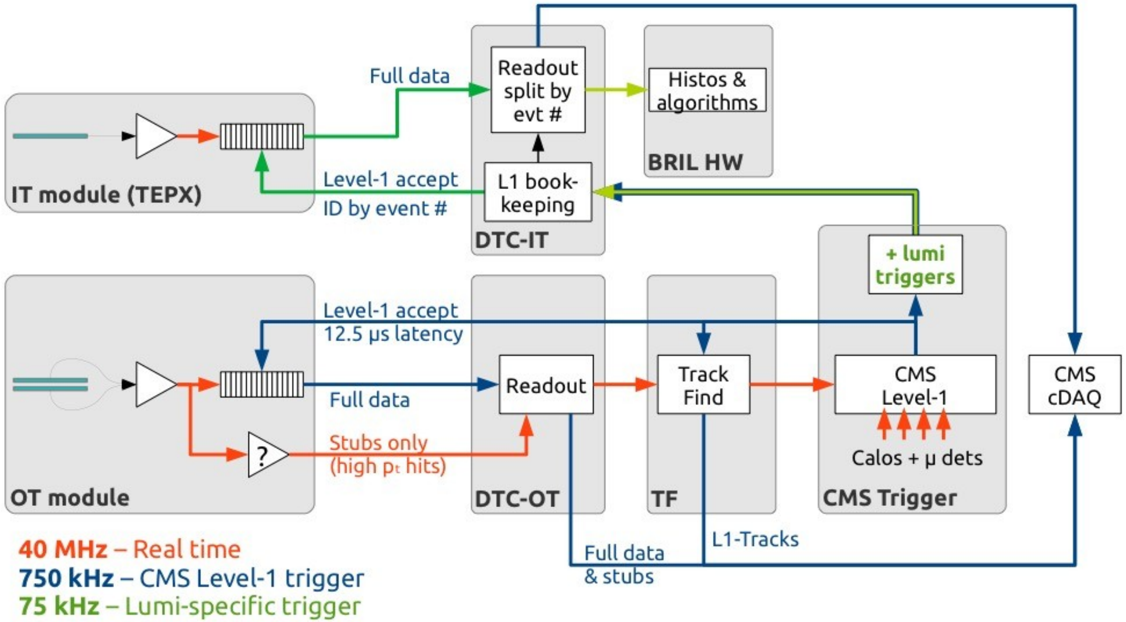
HV Distribution defined (for planar sensors) and tested

- Different local ground on each module
- Up to 20V difference in one chain
- Can generate **forward bias** of sensors when HV =0 (need bypass when off)

Extension disk double as luminometer



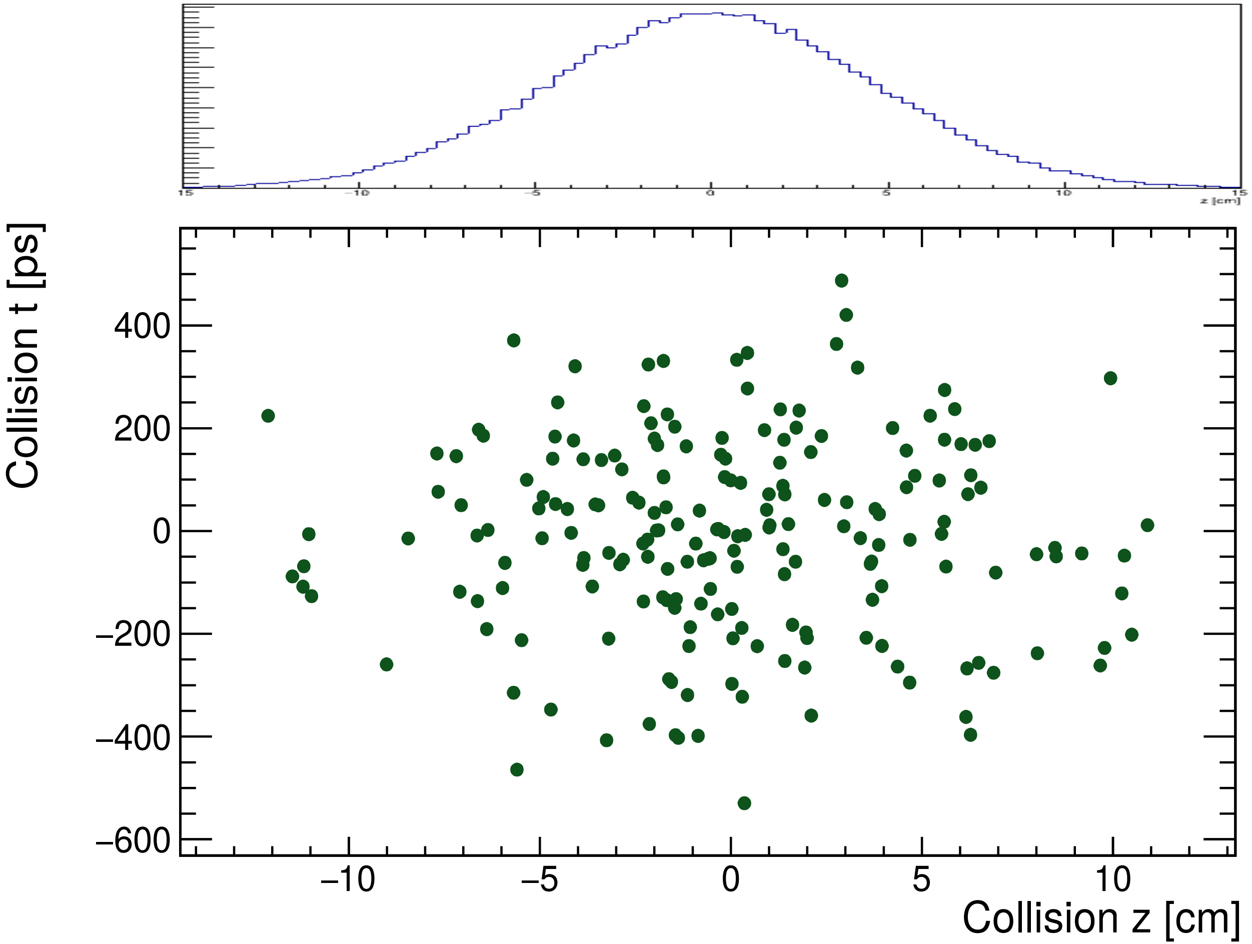




Lumi triggers (75 kHz) are added in the back-end
Large & powerful luminometer.
No extra requirement for the front-end system
1 st ring of the last disk beyond acceptance
Fully dedicated background monitor
(With separate readout and control)

Pile-up mitigation with timing (futuristic, but on its way!)

Pile-up mitigation: timing



Simplified model:

Collisions:

$\sigma_z = 4.6$ cm

$\sigma_t = 180$ ps

Measurements:

$\Delta z = 40\ \mu m$

$\Delta t = 30$ ps

Probabilty of vertex merging:

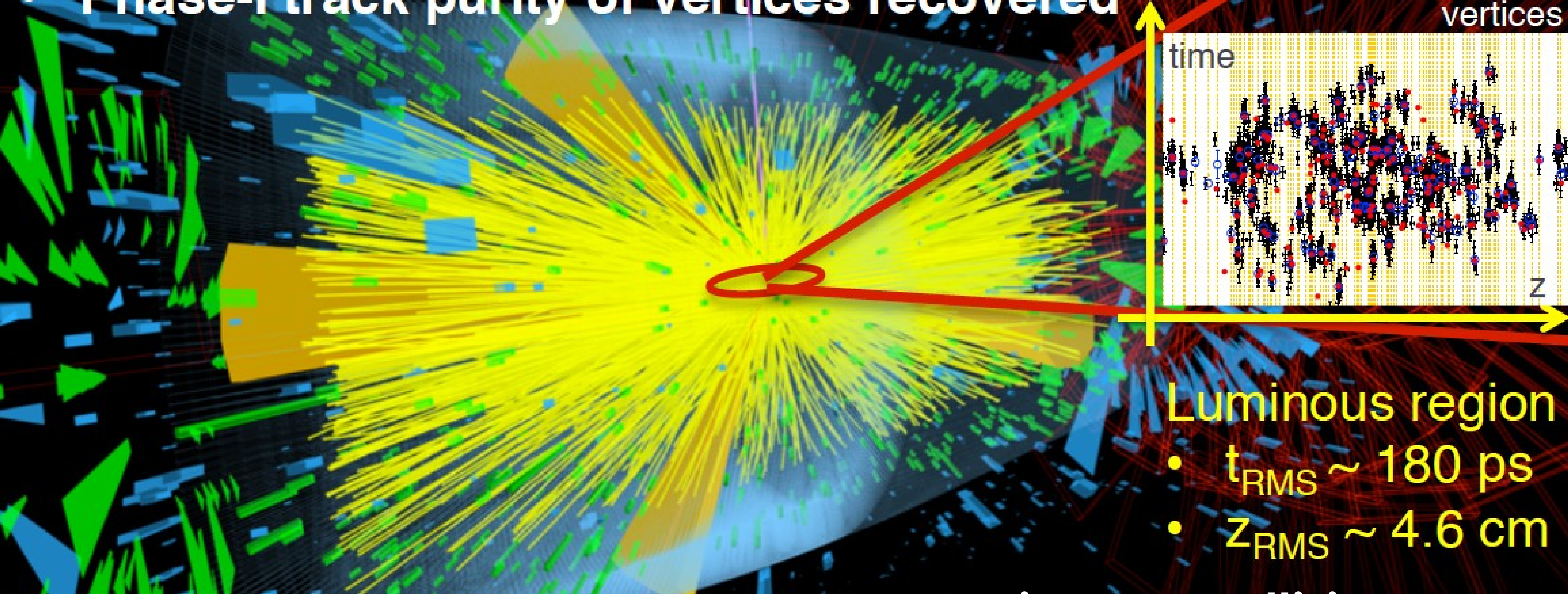
z-only matching: **10%**

z+t matching: **2%**

÷5 reduction of extra vertices from timing resolution

If beam-spot *sliced* in successive **O(30) ps** time exposures, *effective pileup* reduced by a factor 4-5:

- **~15% merged vertices reduced to 2%**
- **Phase-I track purity of vertices recovered**



VBF H-ττ in 200 pp collisions

Dedicated timing detector

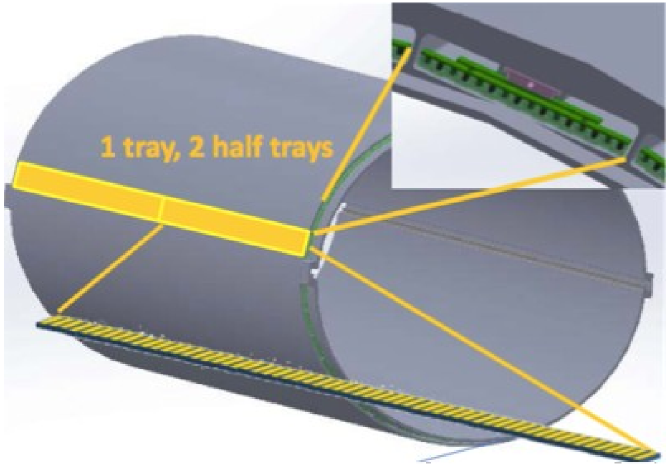
Hermetic coverage up to $|\eta| = 3$

Barrel

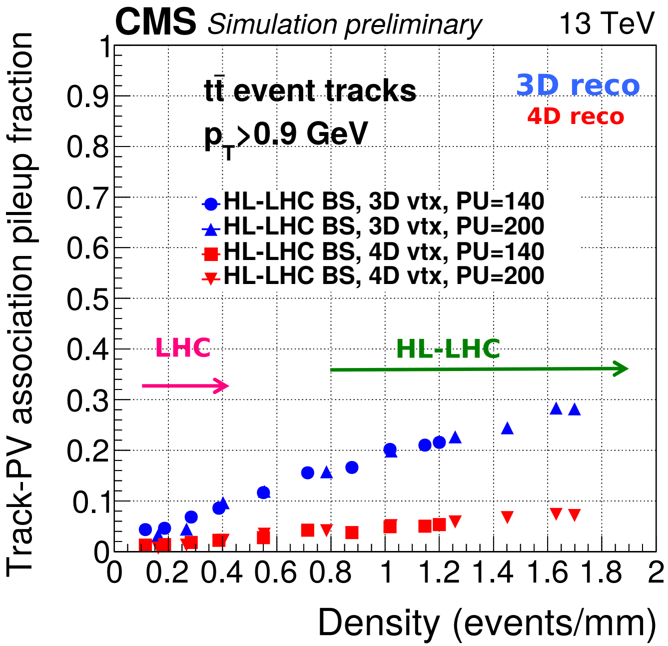
LYSO Crystals + SiPM embedded in the Tracker tube

Ready before Tracker integration

Maintain performance at 2×10^{14} neq/cm^2



The factor ÷5 in vertex merging coming from 3D→ 4D vertex reconstruction compensates the ×5 in pile-up from LHC to HL-LHC

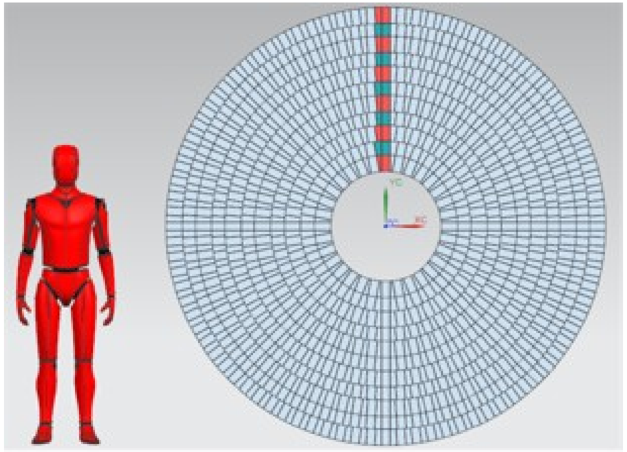


Endcap

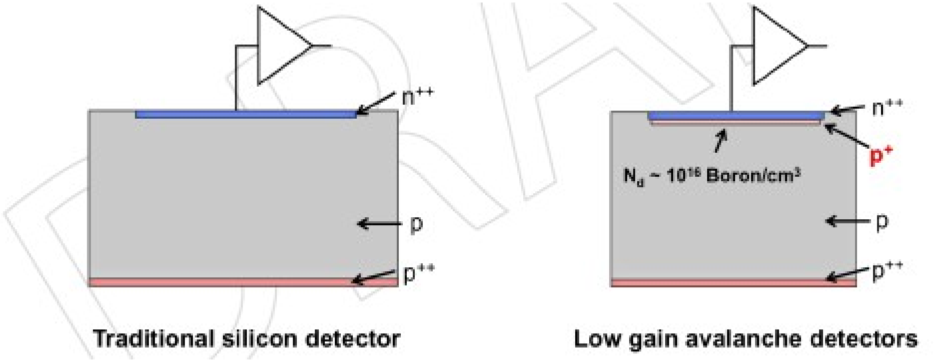
LGAD Si detectors

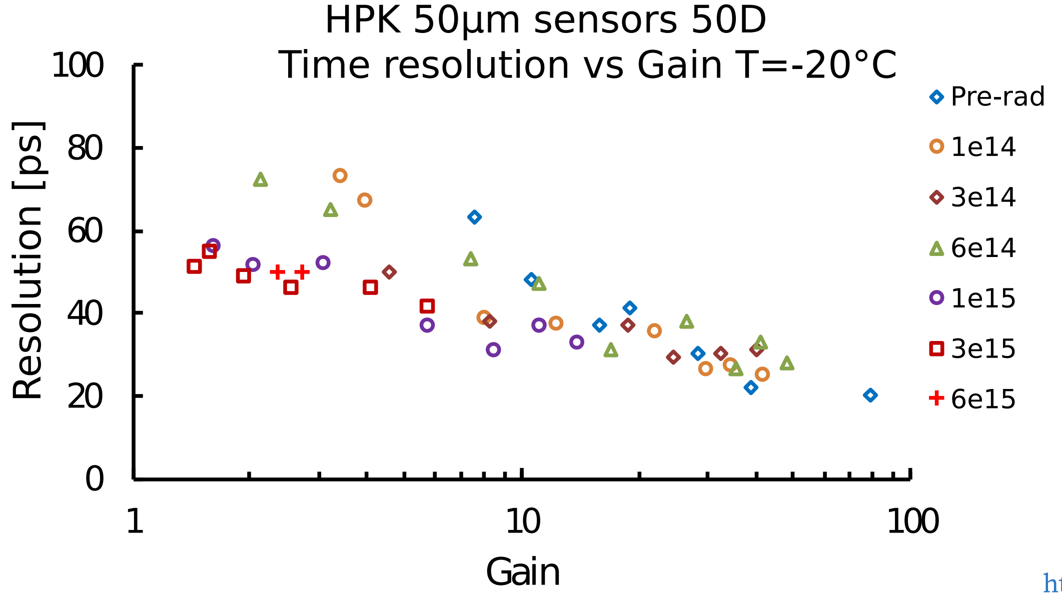
In front of the calorimeter

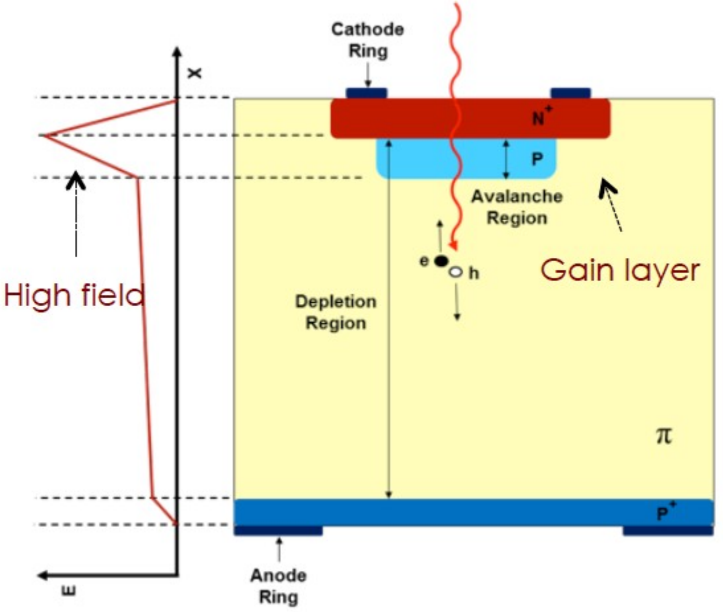
Low-gain Silicon detectors



LGAD detectors for endcap timing







Expected timing performance:

30~50 ps after irradiation

3 mm² pad size (limit for C)

6 m² total instrumented surface

https://arxiv.org/pdf/1810.00350.pdf

Future technologies
for Silicon Tracker detectors
(at high luminosoty)?

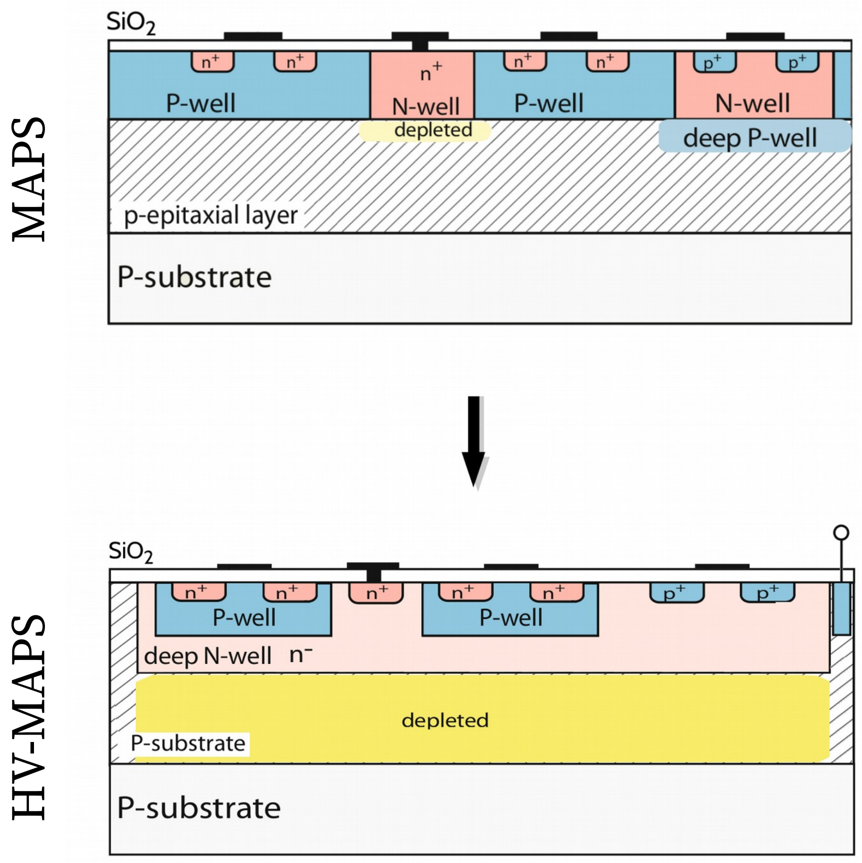
HV-CMOS

An evolution of the MAPS concept:

- integrate transistors into diode ("smart diode", full fill factor)
- deep N-well shields low voltage devices
- HV required (based on HV-CMOS)
- fully or partially depleted sensor
- full CMOS

Main advantages:

- Epi layer fully depleted: charge collection by drift
- Collection time ~1 ns

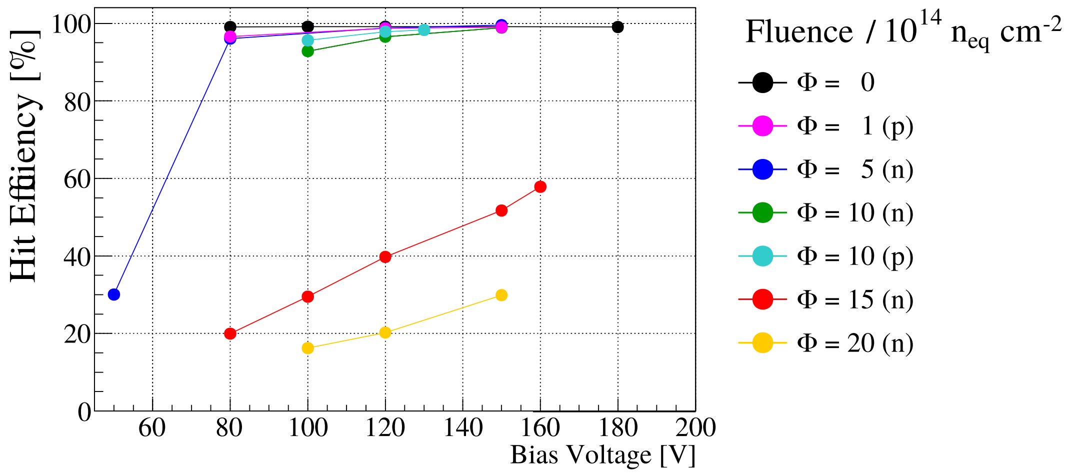


Christof Sauer

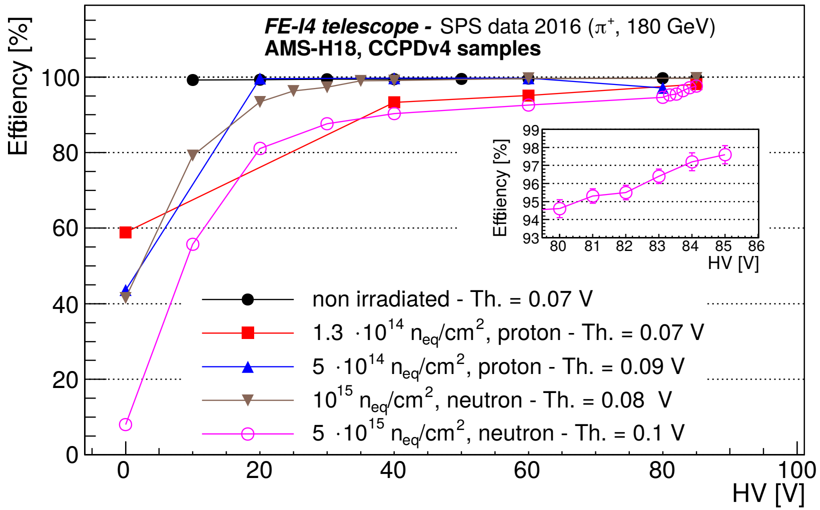
HV-CMOS: Atlas R&D

Atlas researched HV-CMOS for HL-LHC – several prototypes

Irradiation results with H35DEMO chip [1]
Combining sensor + front-end



Irradiated ams H18 HV-CMOS pixel sensor
Coupled to a standard FE-I4 [2]

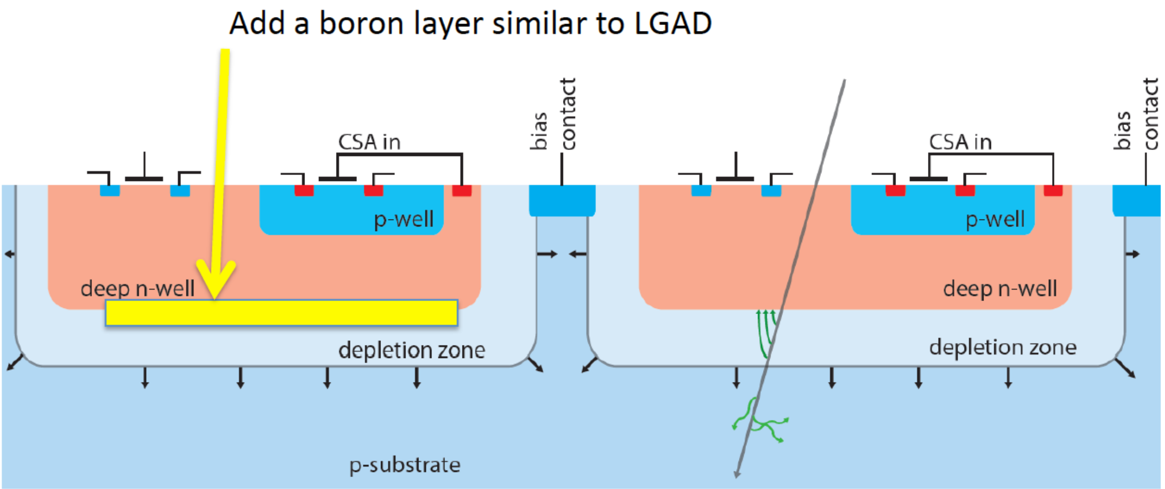


Same production cost as CMS PS system
No advantage for performance
The technology is **very appealing**
Radiation hardness may be further improved

[1] https://arxiv.org/abs/1811.07817
[2] https://arxiv.org/pdf/1611.02669

Future developments?

Fast-timing HV-CMOS?



The HV-CMOS structure could be in principle modified to insert an avalanche layer to increase the timing performance, as in the LGAD detectors.

Thin-film detectors?

Thin films is an existing technology currently used in popular applications, like solar cells, LCD – possible application to reduce the material budget?

Silicon Photonics

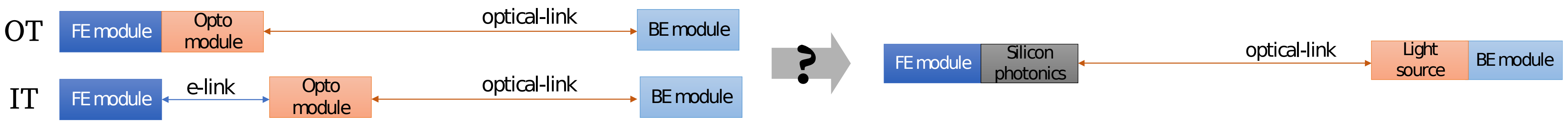
The issue:

- placing optical links on the detector crucial to reduce material
- not for Inner Tracker, because of lack of space and radiation tolerance of current technology

These limitations could be overcome by the use of Silicon Photonics, integrating the optical link directly into the front-ends.

Principle:

- Silicon is transparent in 1.3 – 1.6 μm
- Modulators can be built as reverse-biased pn junctions
- Advantages:
  - Radiation resistance potentially as good as Si-sensors and CMOS electronics
  - Possibility of co-integration with readout electronics: **less material in links**
  - Detector only modulates light, with the light source far from radiation: **less power/material**

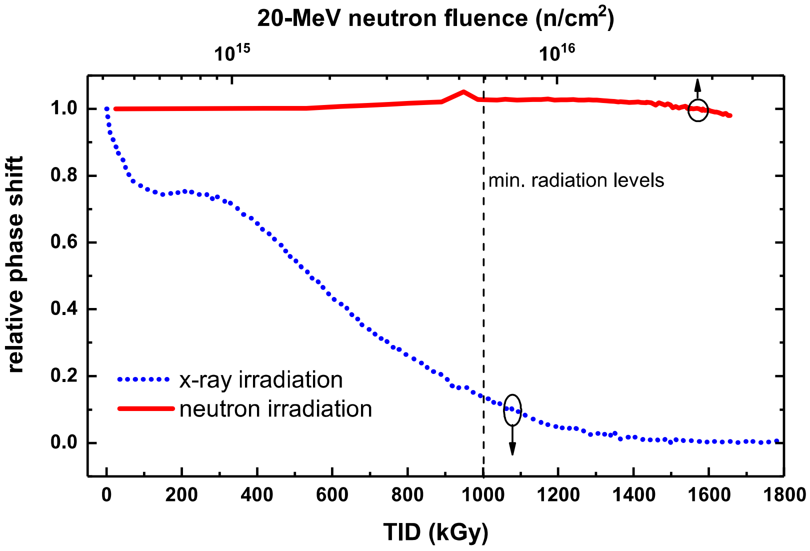


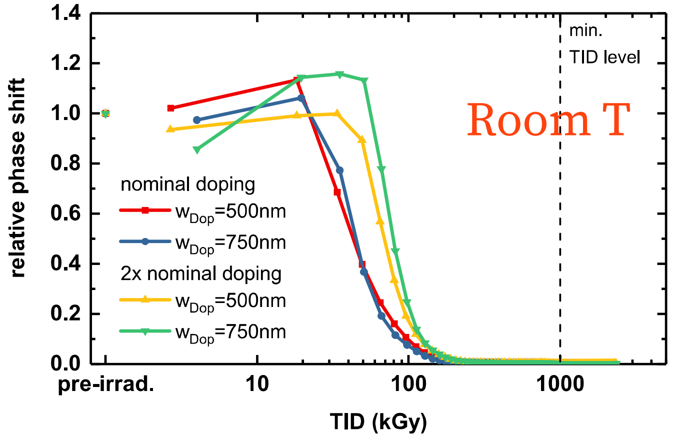
Silicon Photonics

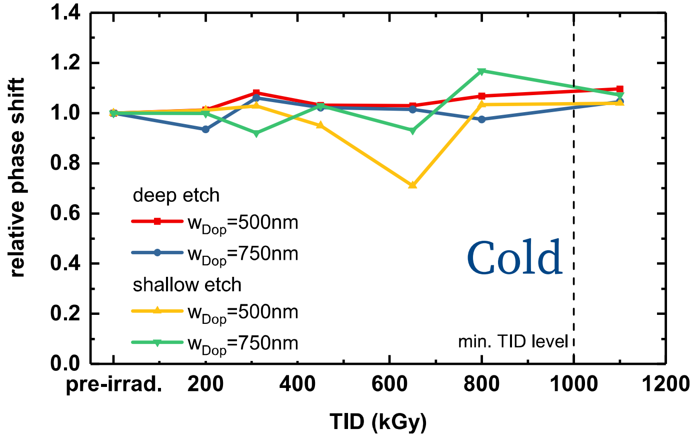
Intriguing results:

- Robust against neutron irradiation (bulk damage)
- x-ray irradiation mitigated if cold (-30 °C)

Damage of photodiodes need also to be under control for a bi-directional link, but **may open new avenues**!



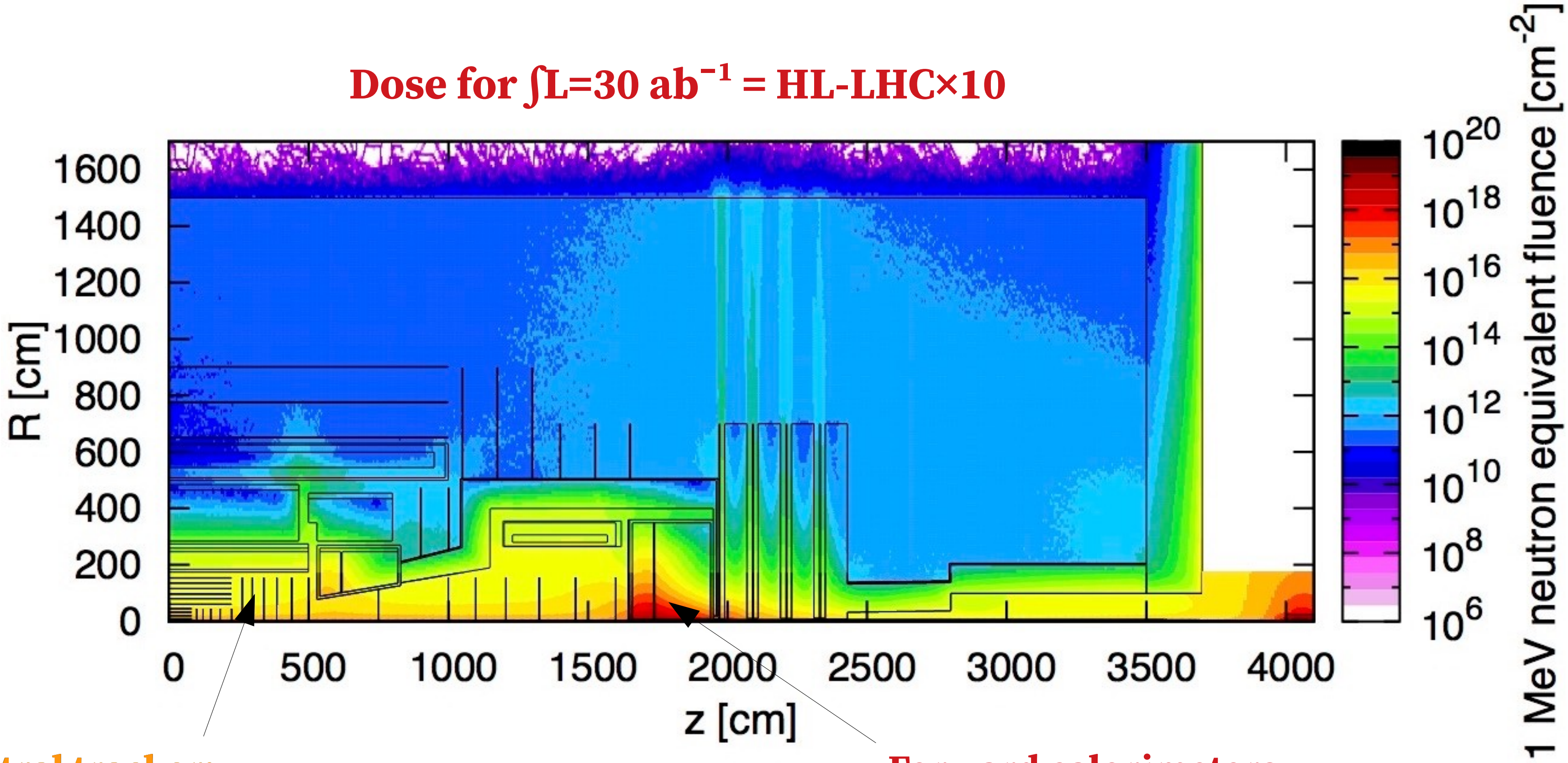




IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 11, NOVEMBER 2017

FCC-hh total dose

Dose for ∫L=30 ab^{-1} = HL-LHC×10



Central tracker:
first IB layer (2.5 cm): ~5-6 $10^{17}/cm^2$
external part: ~5 $10^{15}/cm^2$

Forward calorimeters
maximum at ~5 $10^{18}/cm^2$ for both ECAL/HCAL
$10^{16}/cm^2$ at r=2 m!

FCC-hh: which technologies?

Tracking 1000 Pile-Up: which technologies?

- Outer layers — ~10^{15}: LGAD and HVCMOS promising
  - LGAD: timing will be very useful to tame pile-up
  - HV-CMOS: low cost for large surfaces – easy mass production
- Intermediated layer — ~10^{16} standard Si best option
- Innermost layers — ~10^{16}/year ← no solution for silicon here
  - More than one replacement per year not reasonable
  - Maybe need to consider more creative solutions here!

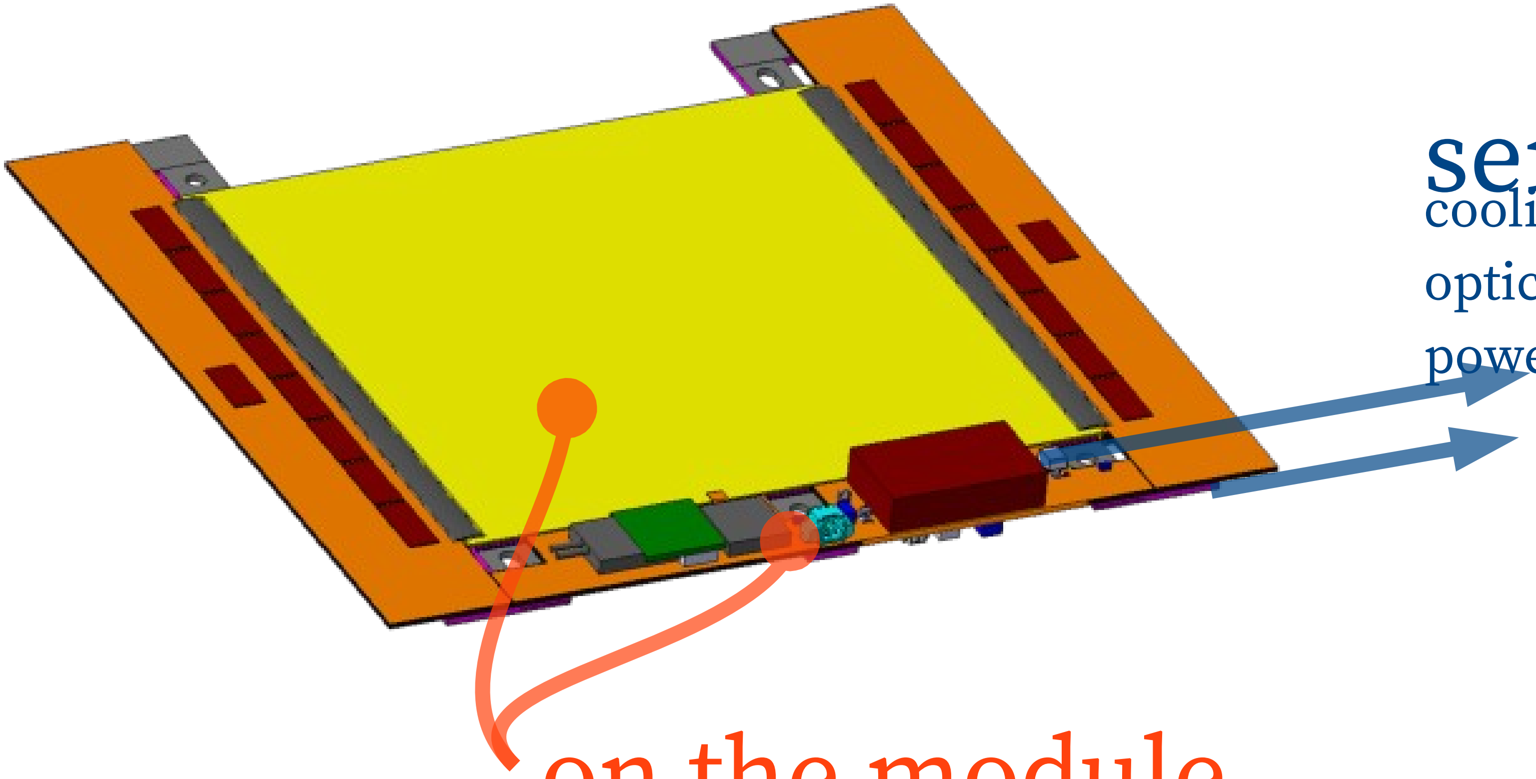
Known optimal solutions

- Powering: serial (will be "standard")
- Readout links: silicon photonics (if R&D confirms this solution)
- pT modules → also tracking information at Level-1 in all layers (esp. with timing @ L1!)


That's all Folks!

Bonus:
Evaluating the impact of design options on detector performance

tkLayout material estimation



services

cooling pipes

optical fibres

power cables

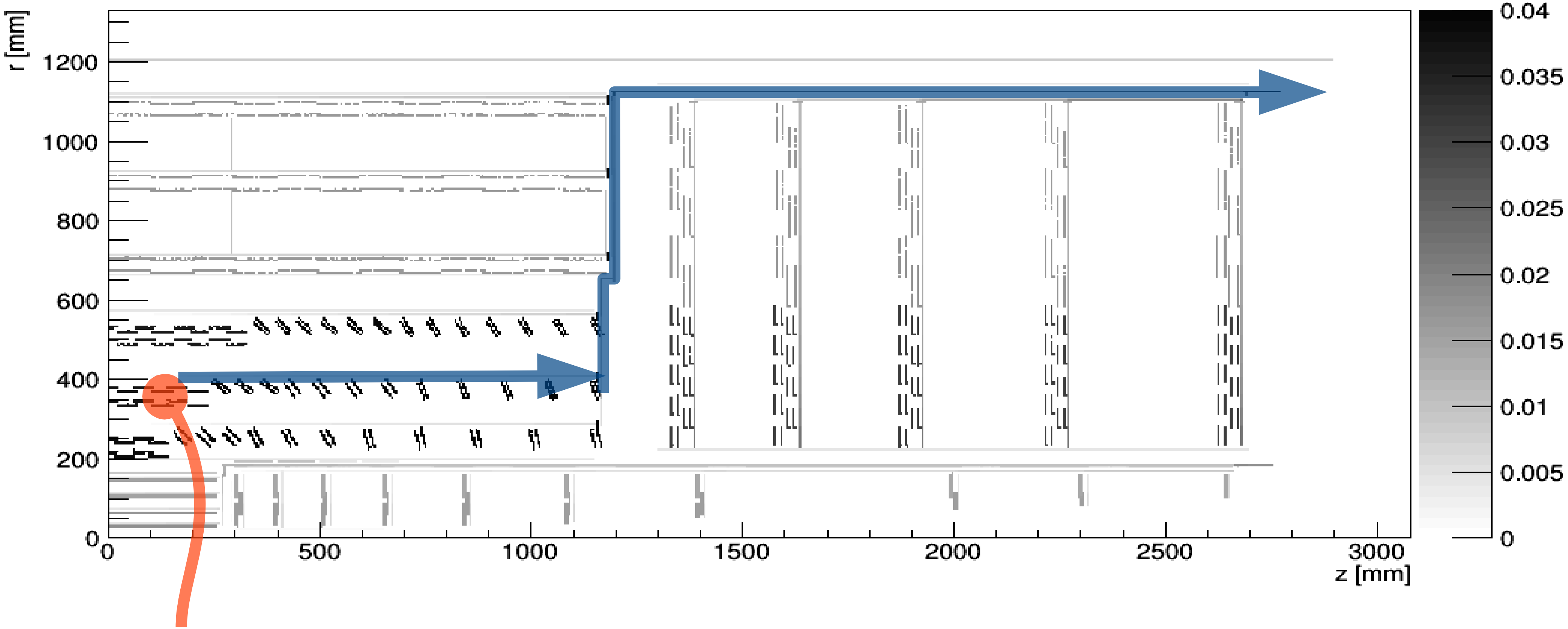
on the module

sensor

hybrids & ASICs

cooling contacts

tkLayout material estimation



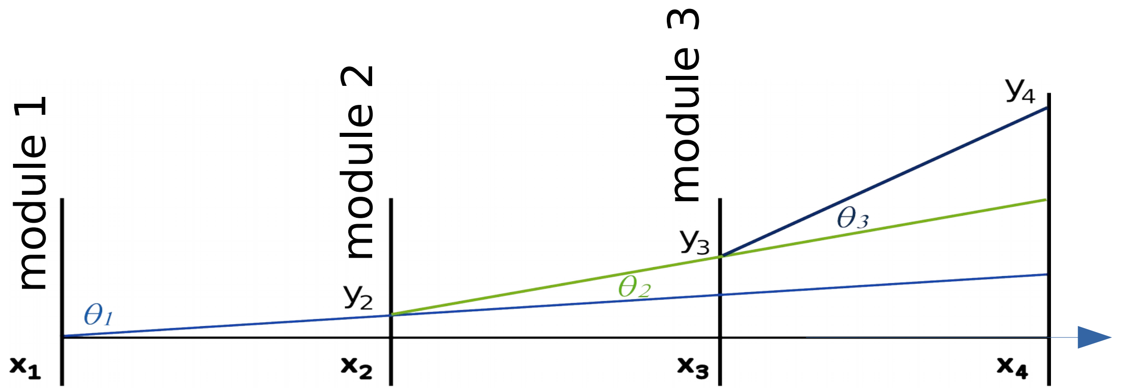
Material on active elements

+

Material for services automatically routed

tkLayout μ resolution estimation

- A priori error estimation
  - No Monte Carlo
  - No fit actually done

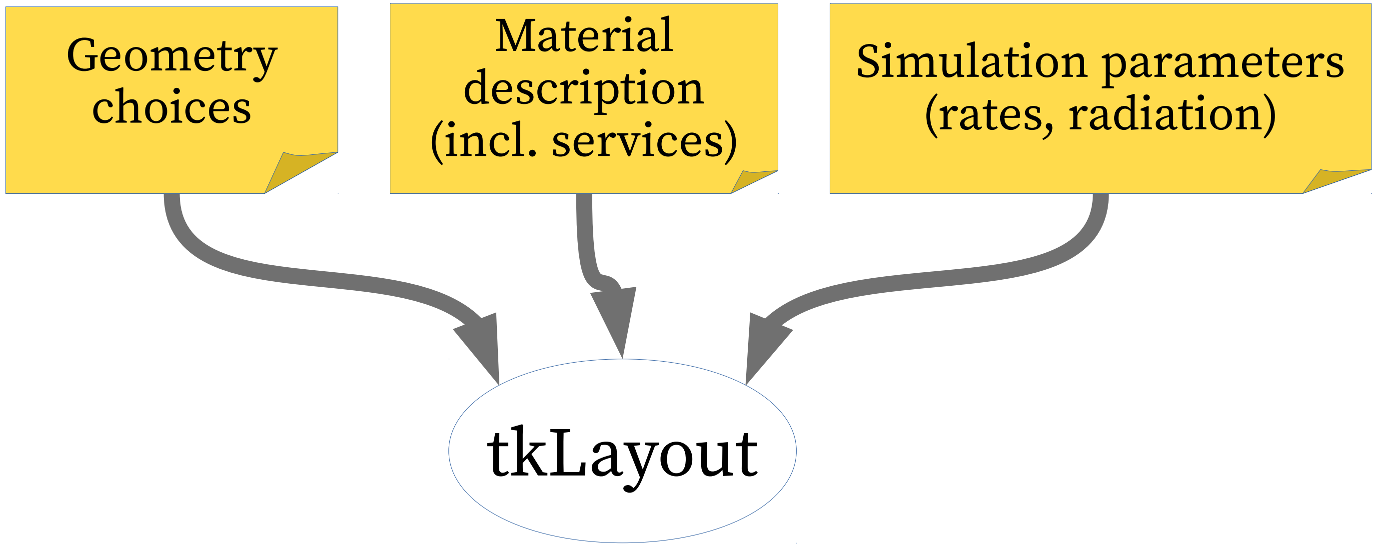


- Error propagation to estimate resolution of track parameters
  - **Intrinsic resolution** of the measurement point
  - **Multiple scattering** treated as a (correlated) measurement error

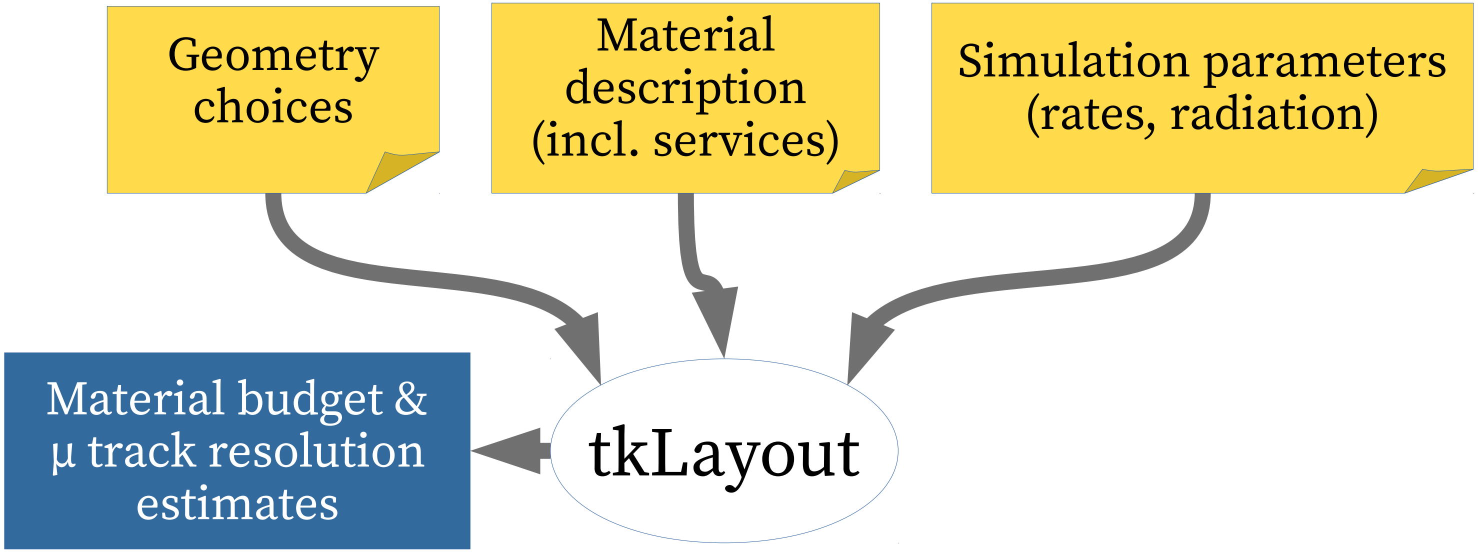
$$\boldsymbol{\sigma_n^2} = \left\{ \frac{p^2}{12}, \; f\left(\text{angle of incidence}\right) \right\}$$

$$\boldsymbol{\sigma_{n,m}} = \langle y_n y_m \rangle = \sum_{i=1}^{n-1} (x_m - x_i)(x_n - x_i) \langle \theta_i^2 \rangle$$

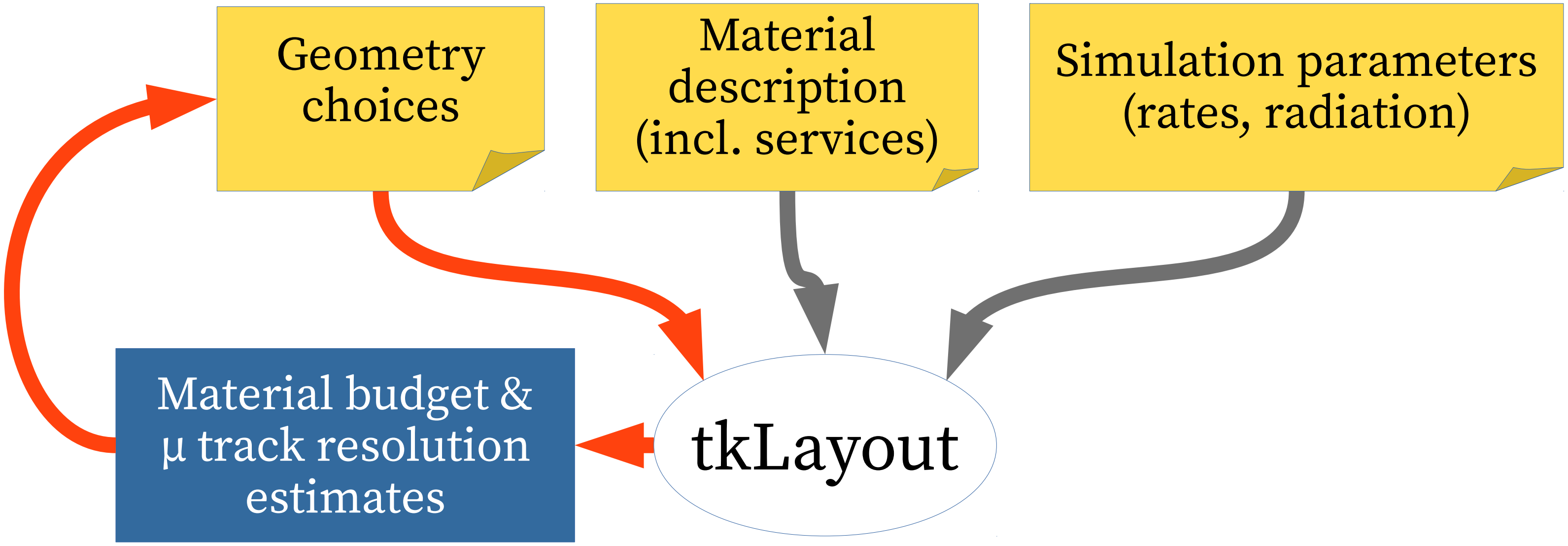
Design optimization work-flow



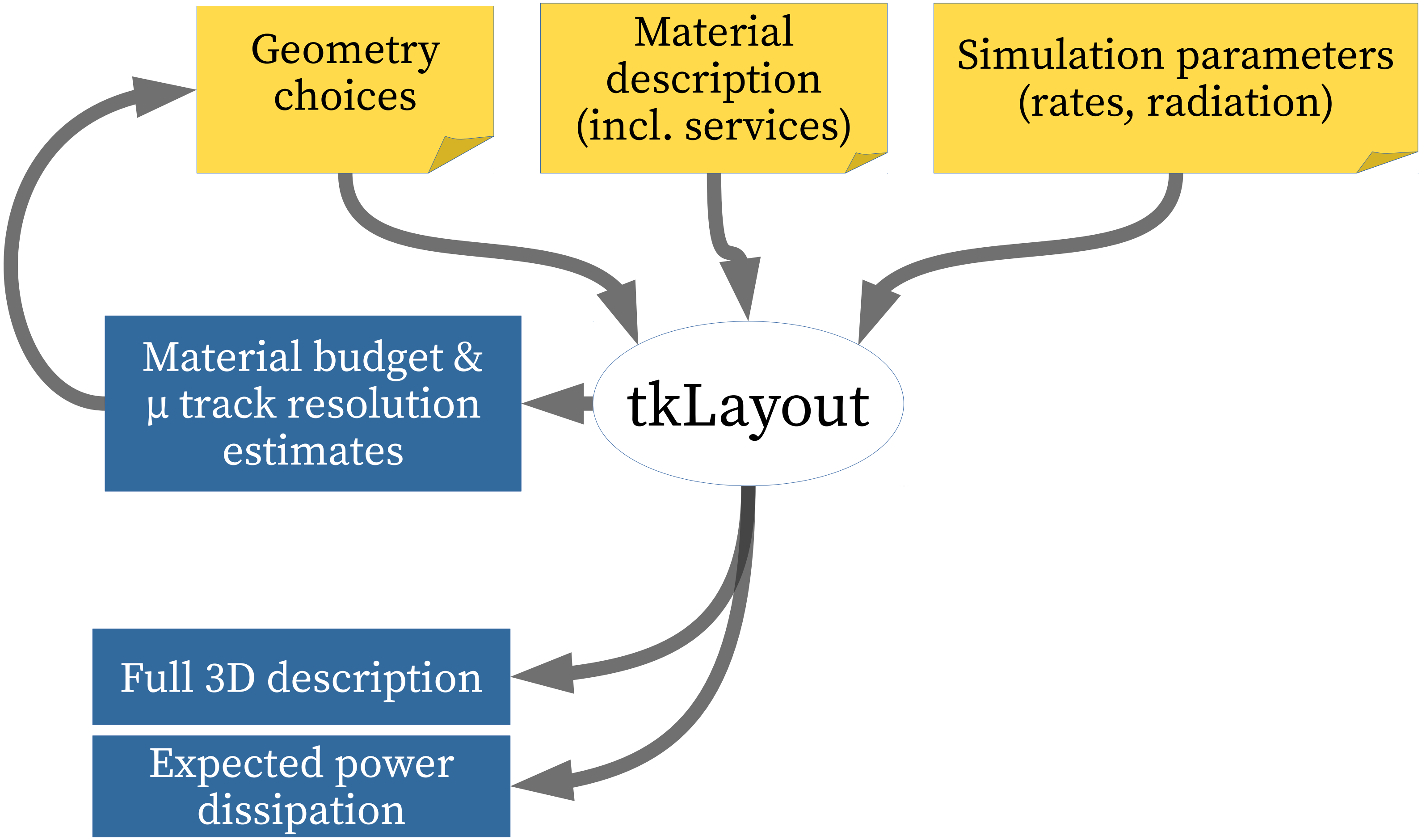
Design optimization work-flow



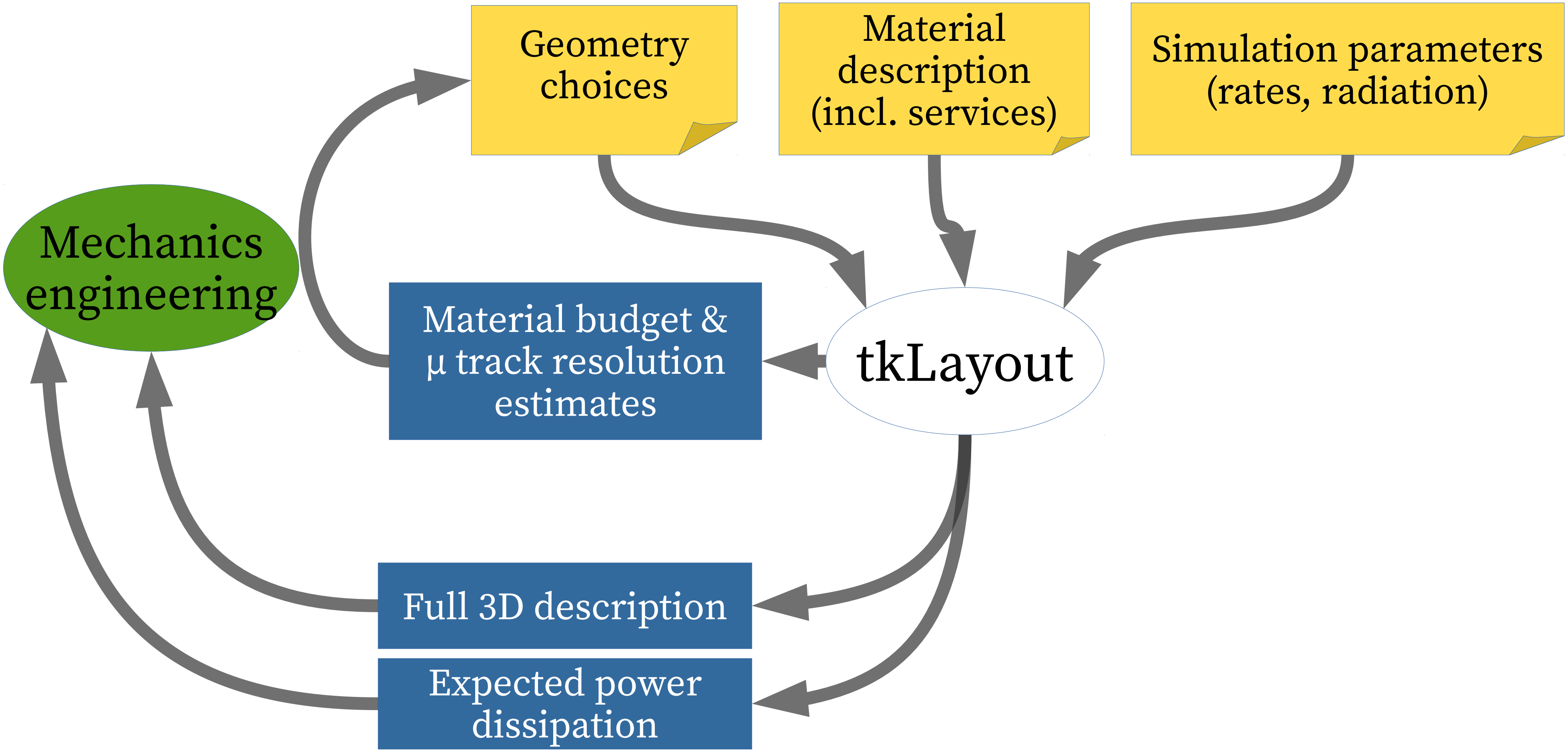
Design optimization work-flow



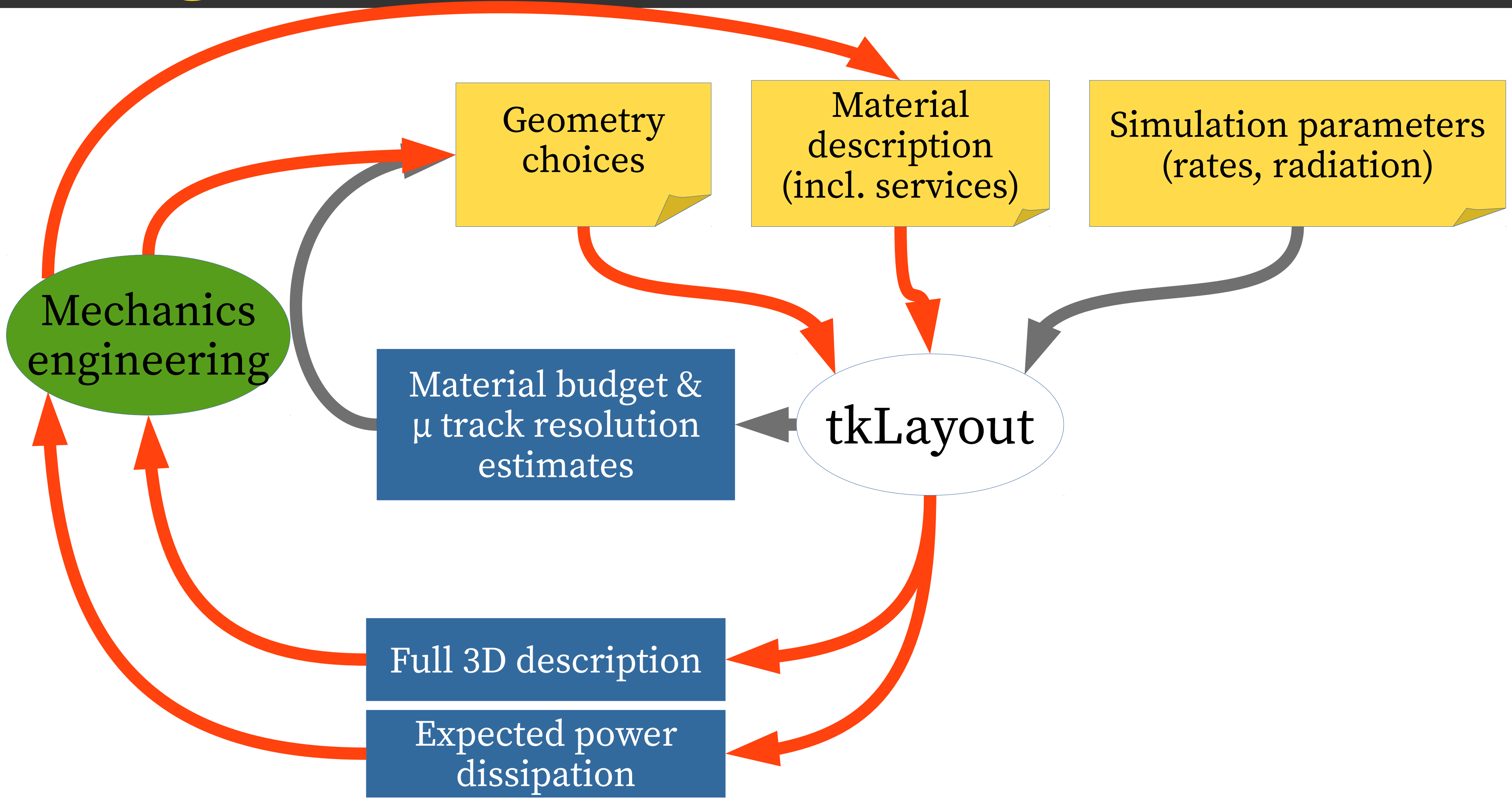
Design optimization work-flow



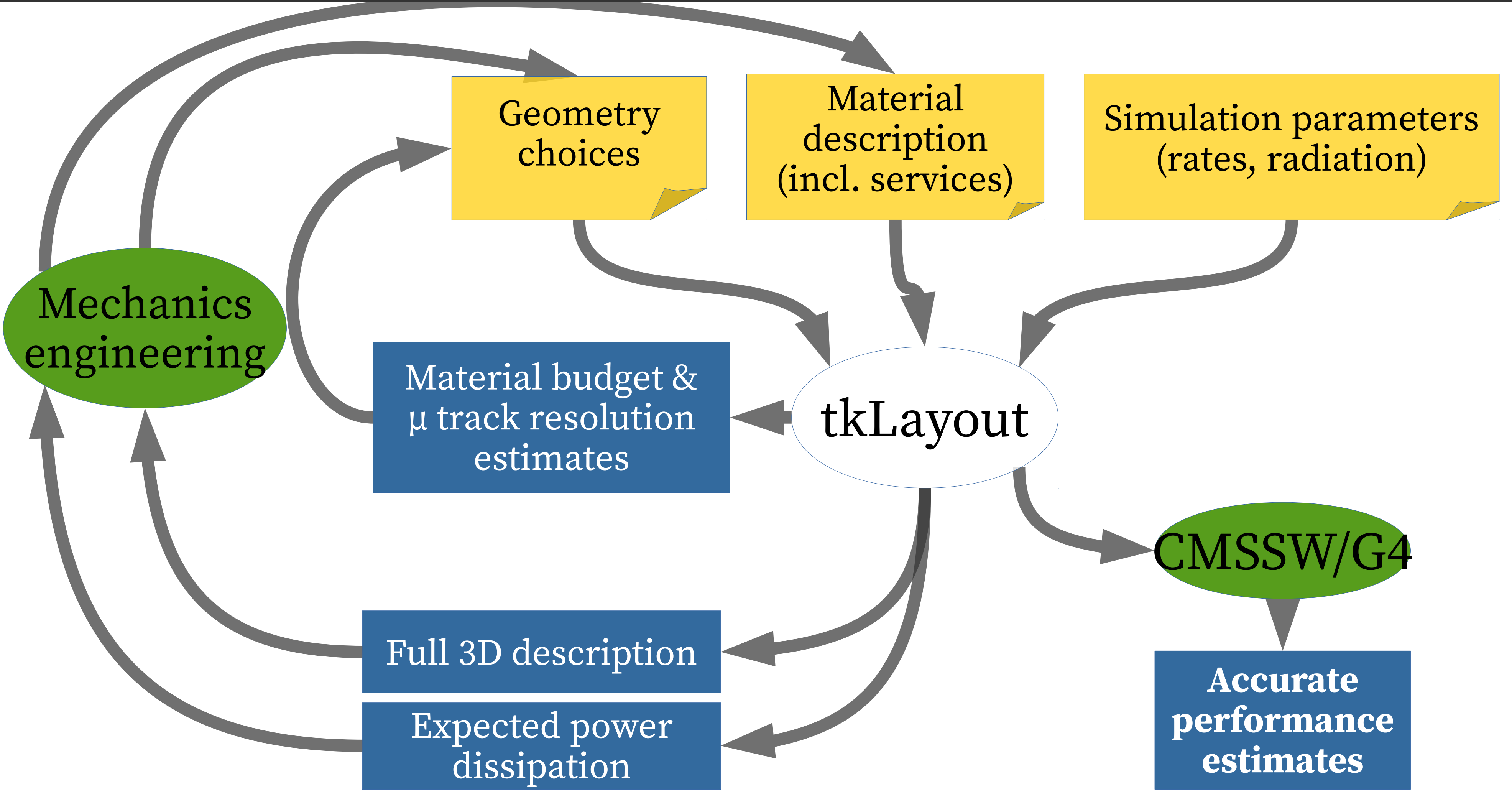
Design optimization work-flow



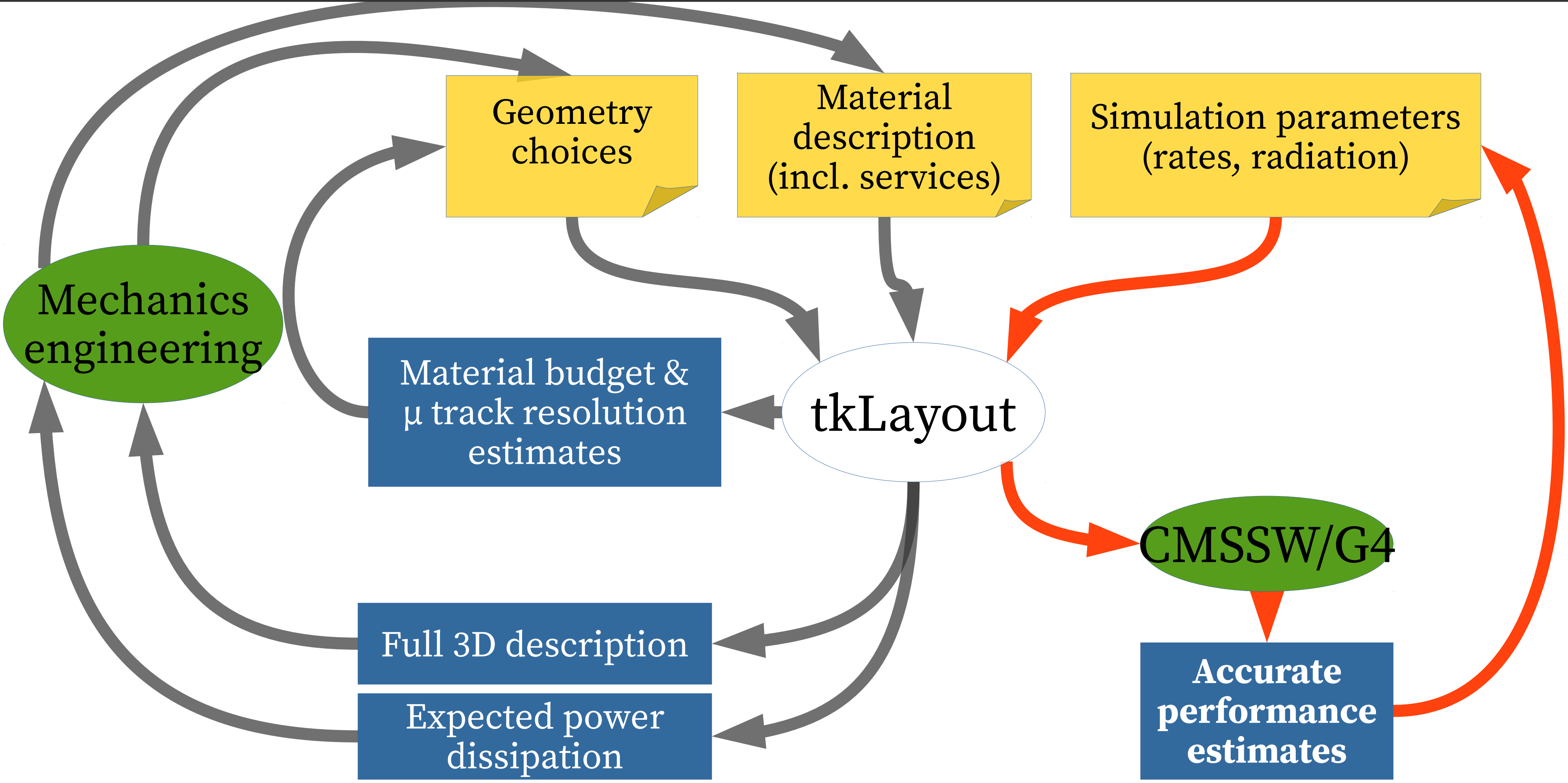
Design optimization work-flow



Design optimization work-flow

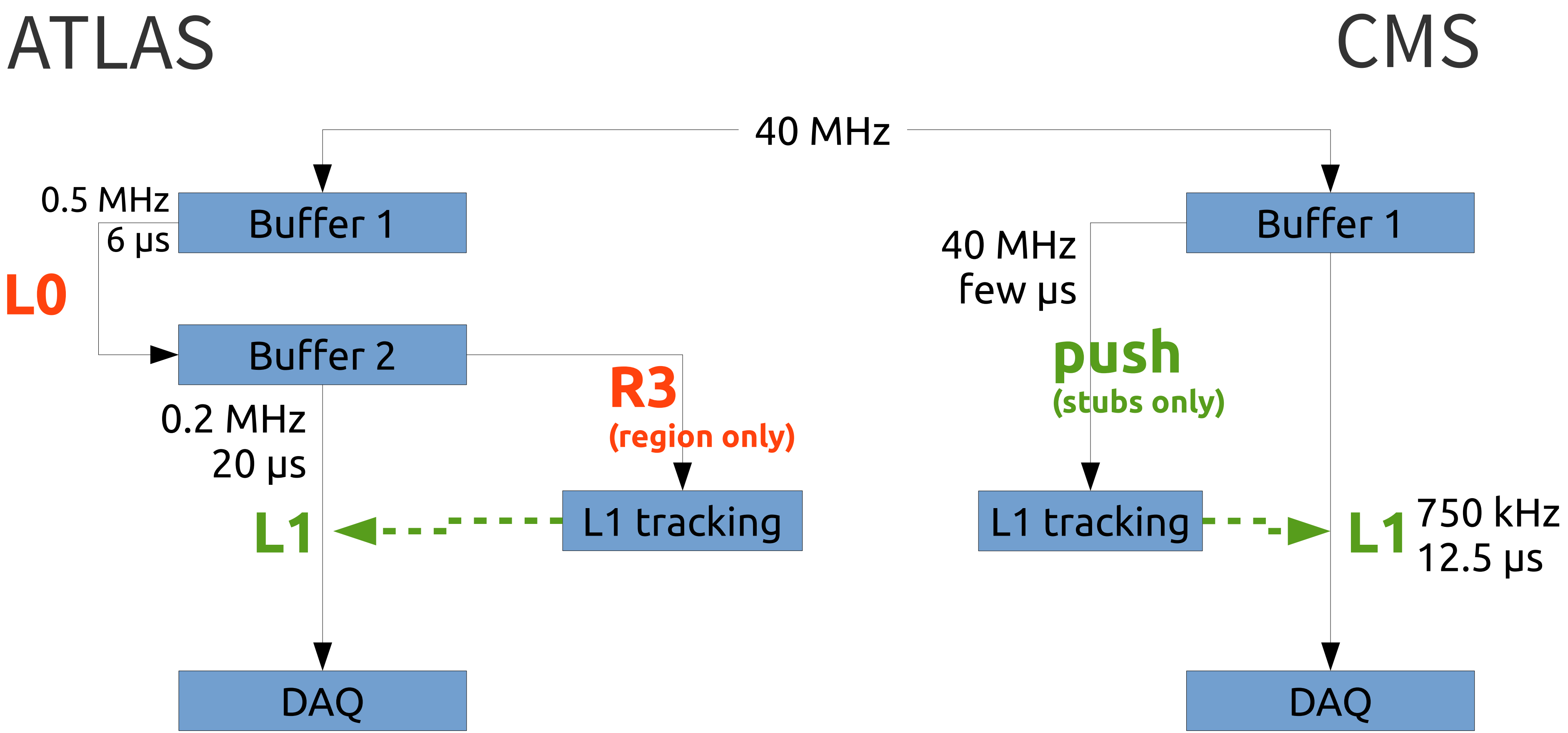


Design optimization work-flow

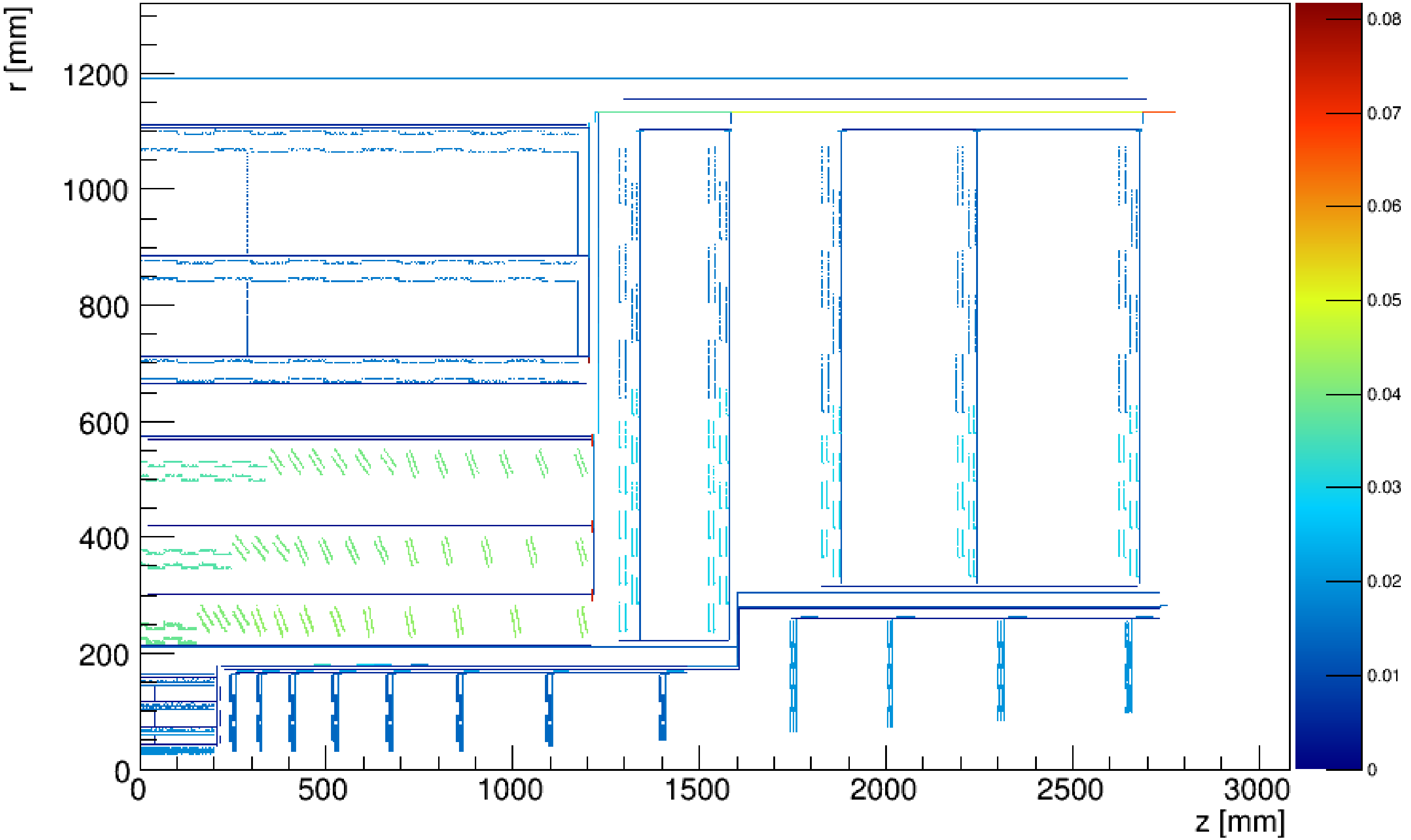


Backup

DAQ architectures

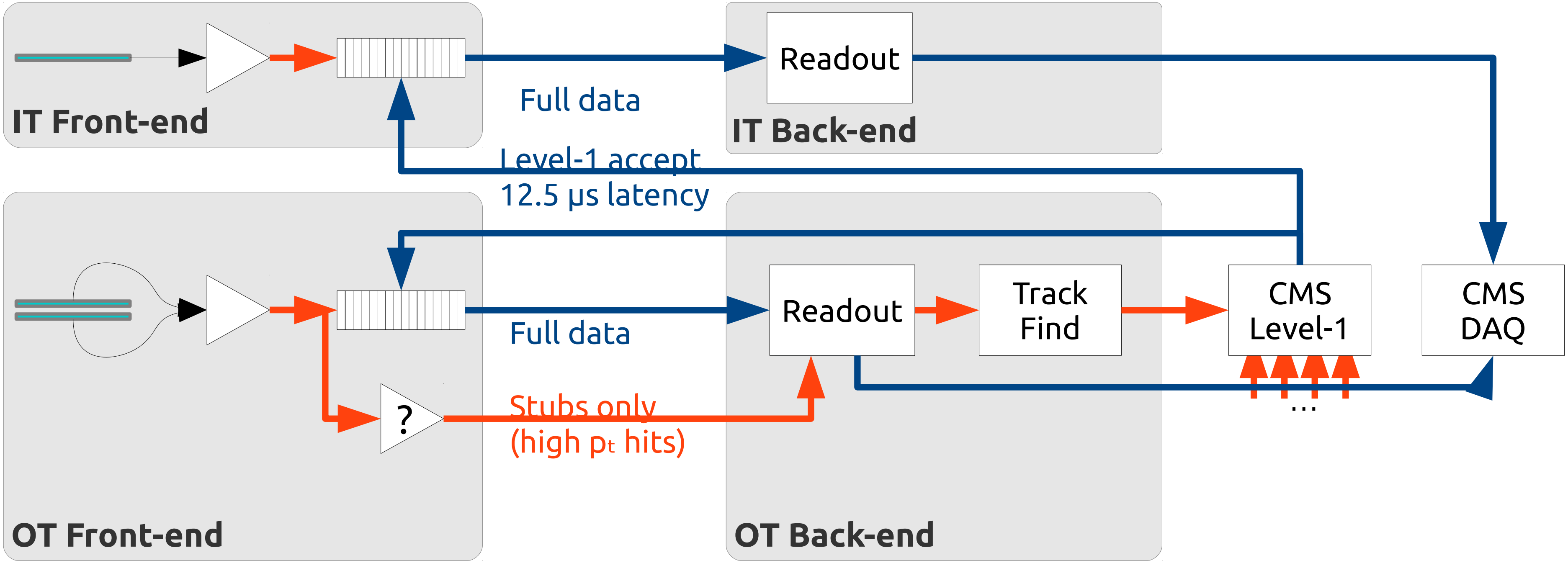


Material budget



Readout scheme

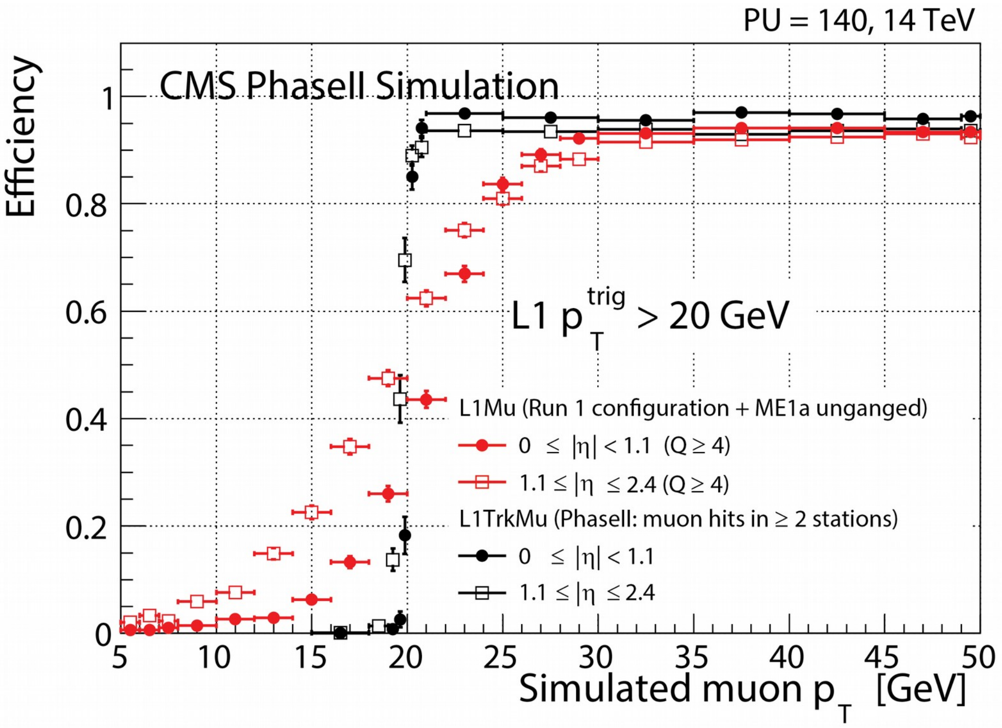
- Level-1 “stubs” from OT are processed in the back-end
- Form Level-1 tracks, pT above ~ 2 GeV contributing to CMS Level-1 trigger
- Pixel and Outer tracker are readout at 750 kHz with 12.5 μs latency

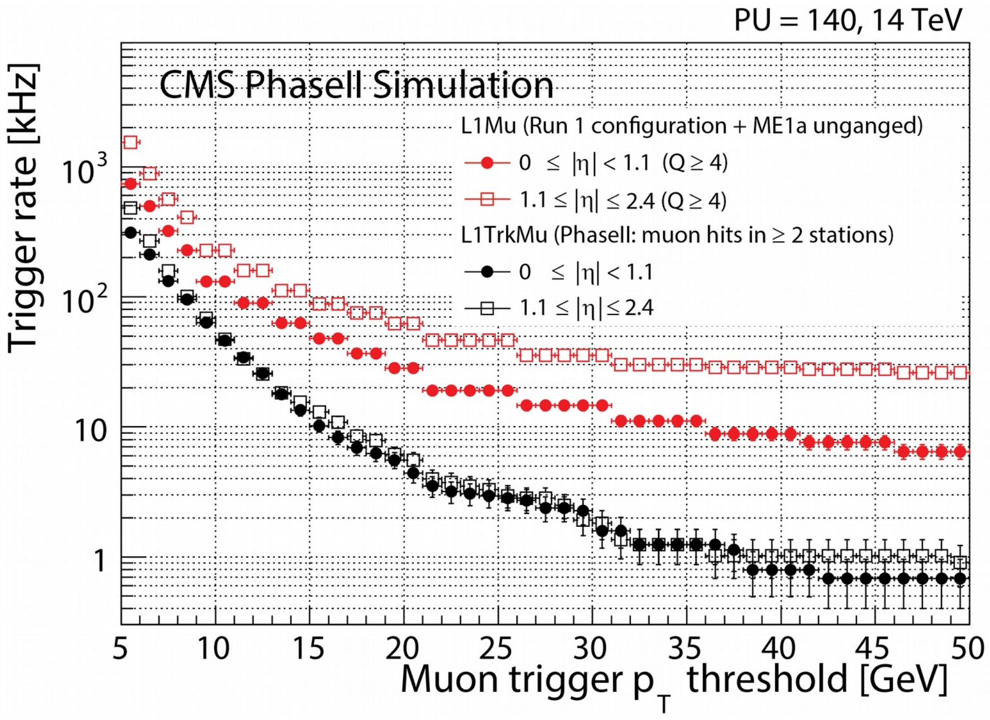


40 MHz – Real time **750 kHz** – CMS Level-1 trigger

The trigger challenge at HL-LHC

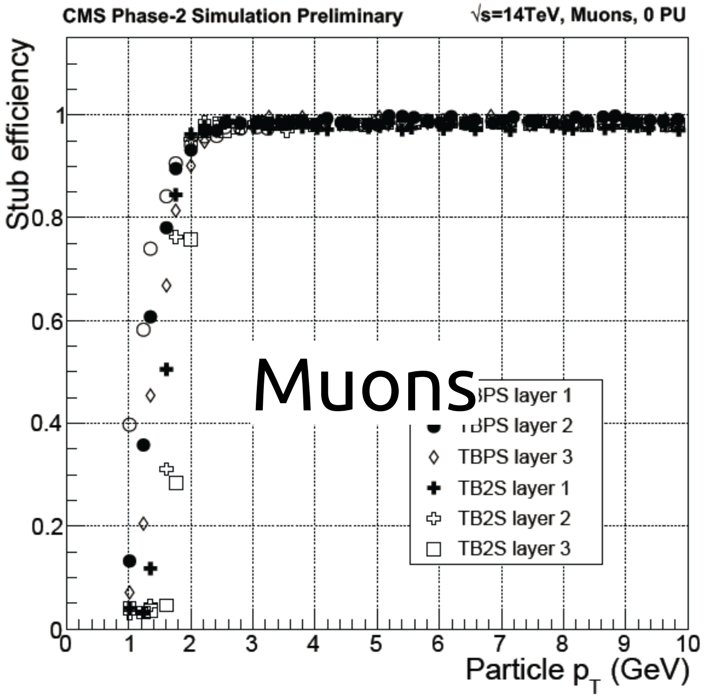
- High rates → more pileup → algorithms become inefficient
- Target **L1 trigger rate: 750 kHz**, **L1 trigger latency = 12.5 µs**
- Tracker information at L1 highly beneficial for L1 trigger performance:
  - Sharper turn-ons, **lower rates**, vertex discrimination, new variables (isolation, invariant mass)



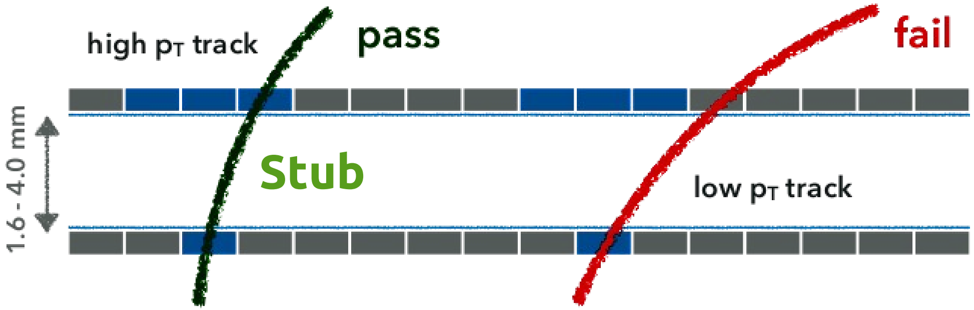


Solution to the trigger challenge

- Design of Outer Tracker driven by implementation of track finding for L1 (layout, modules)
- Exploits pT-dependent bending of tracks in strong CMS magnetic field
- Comparison of hit patterns in closely spaced silicon sensors
- Selection of hit pairs belonging to tracks with pT ≳ 2 GeV
- Data reduction by factors 10-100
- Done on-module, at 40MHz
- Hit pairs ("stubs") are sent to back-end, tracks are formed
- Tracks are combined in CMS L1 trigger system with calorimeter and muon information
- After reception of L1 trigger decision, whole event is read out (at up to 750kHz)
- **An asset for pattern recognition in high pile-up: to be kept in mind**



Thanks to CMS 3.8 T magnetic field!

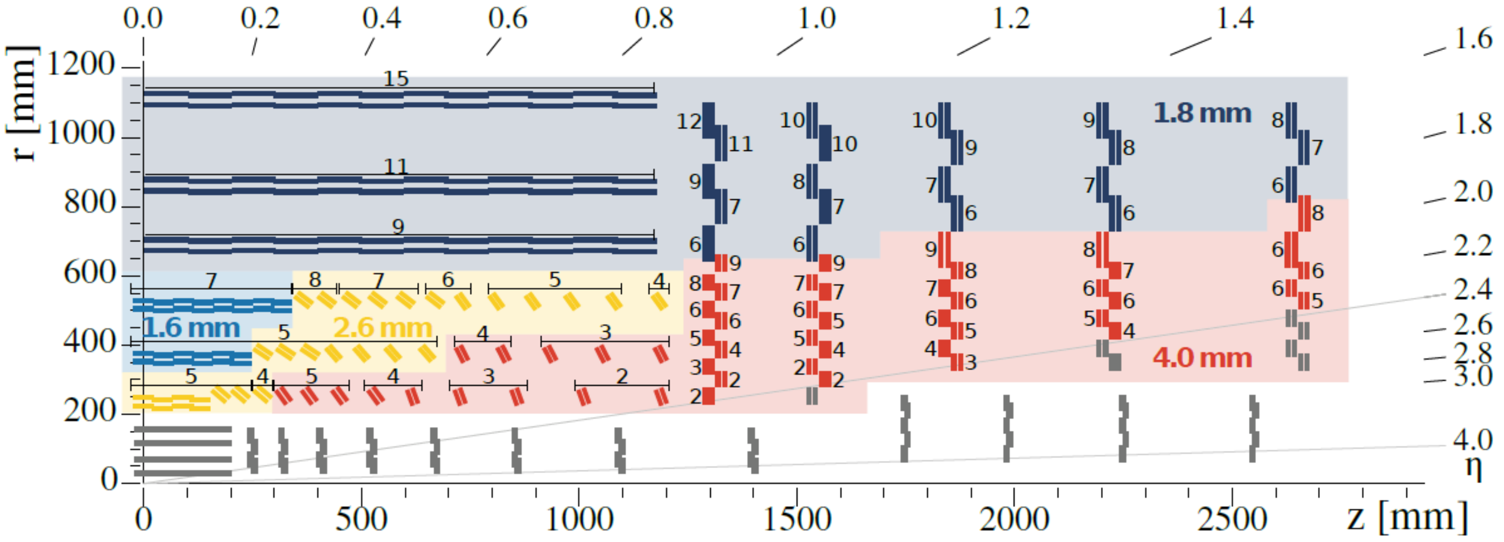


Same electronics reads two sensors

Outer Tracker modules

- pT discrimination depends on acceptance window & sensor separation
- Acceptance window is programmable (both width and position)
  - Large spacing ↔ large window needed
  - Large spacing → good pT resolution
  - Large window → more accidentals
- Small windows preferred in inner layers
- Five sensor variants needed

Module type and variant		TBPS	TB2S	TEDD	Total per variant	Total per type
2S	1.8 mm	0	4464	2792	7256	**7680**
	4.0 mm	0	0	424	424	
PS	1.6 mm	826	0	0	826	**5616**
	2.6 mm	1462	0	0	1462	
	4.0 mm	584	0	2744	3328	
Total		**2872**	**4464**	**5960**	**13296**	



Colors=spacings

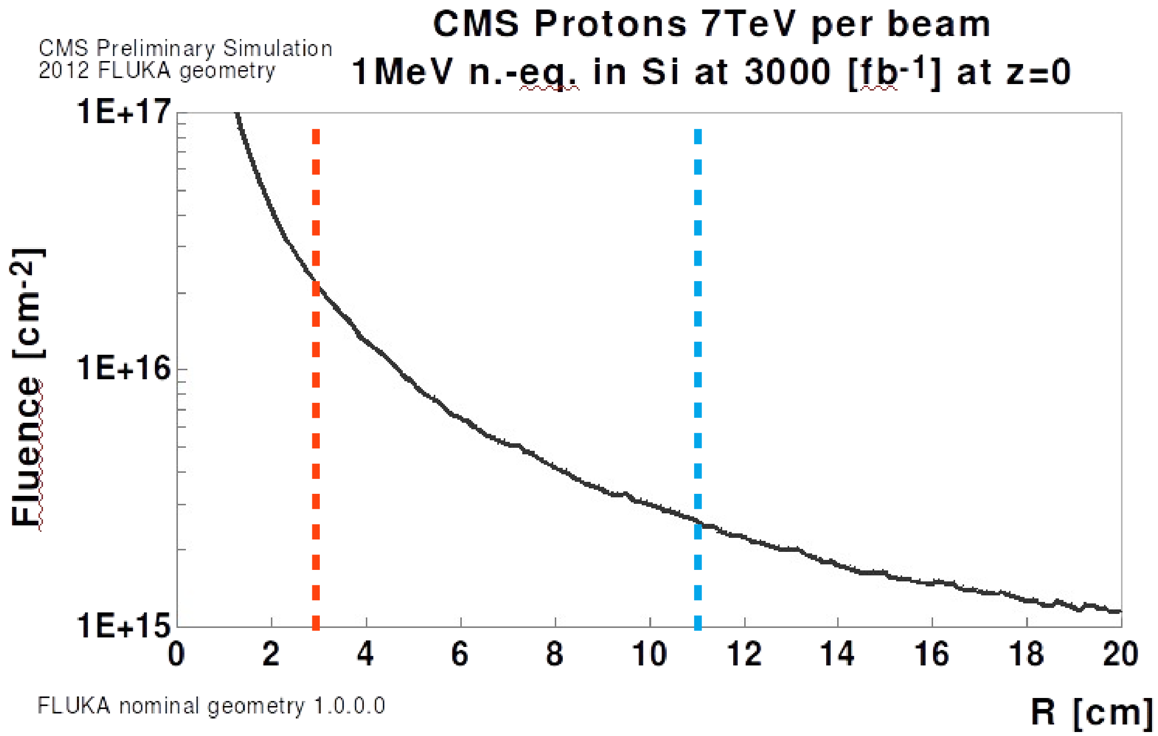
Numbers= acceptance windows

Inner Tracker sensors

Hadron fluence varies strongly with r

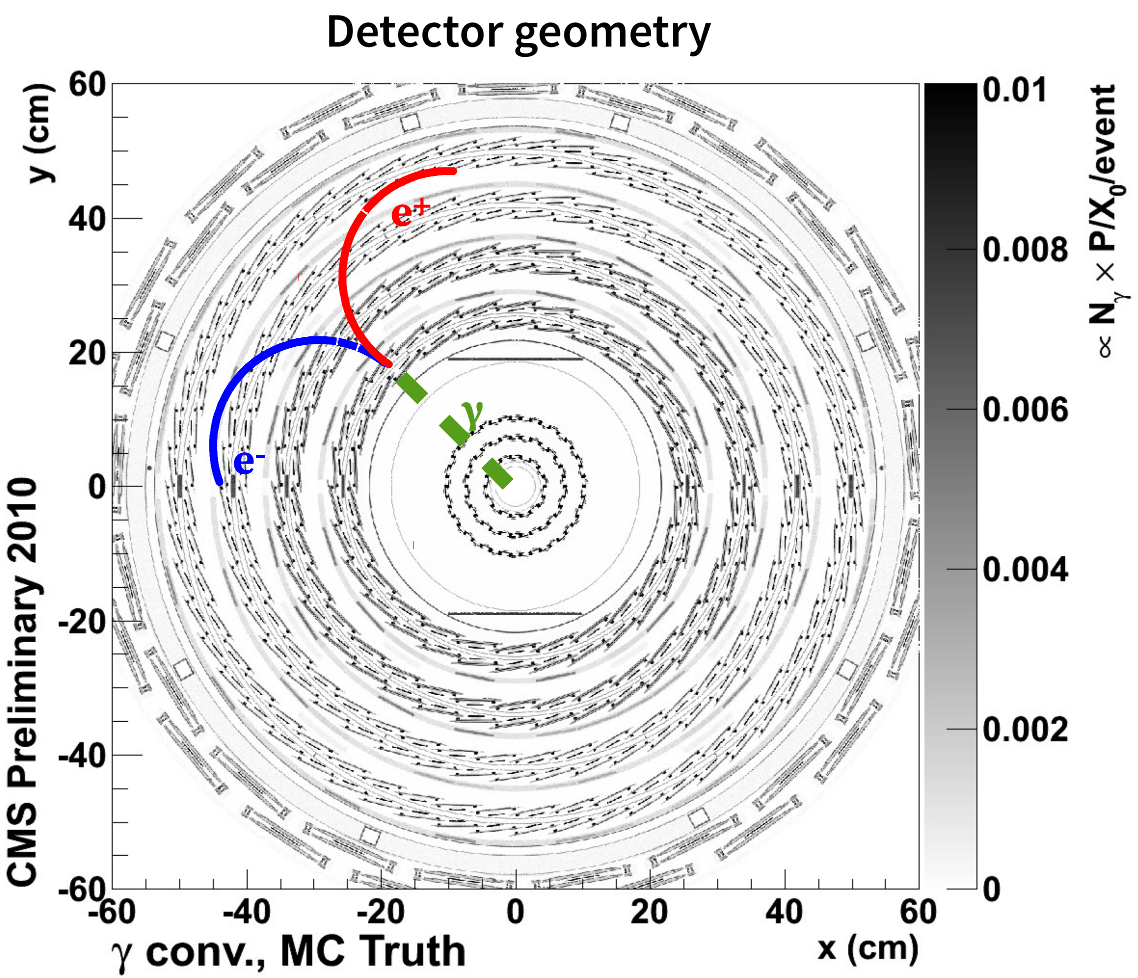
After 3000 fb^{-1}

- 2×10^{16} n_{eq} cm^{-2} @ r=3 cm
- 3×10^{15} n_{eq} cm^{-2} @ r=11 cm



Material budget: γ tomography

Current CMS Tracker



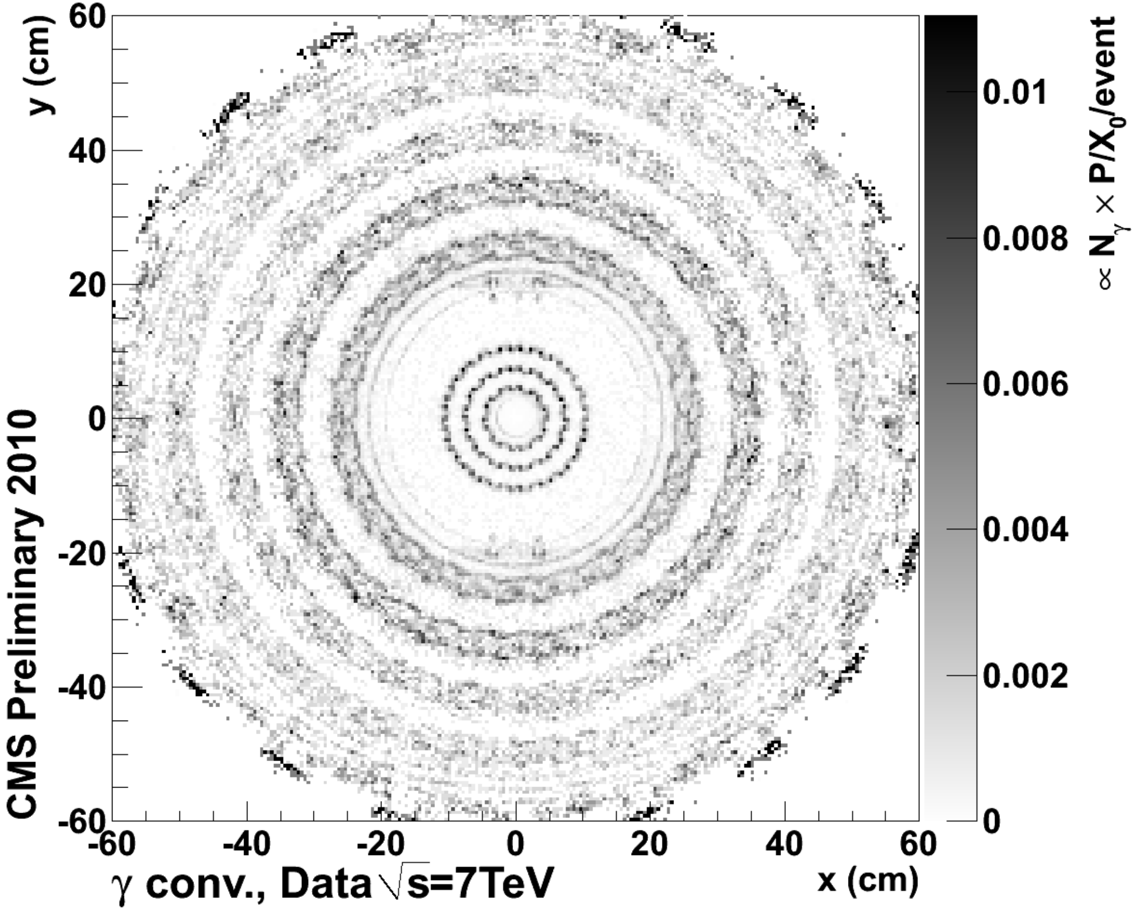
CMS-PAS-TRK-10-003

Material budget: γ tomography

Current CMS Tracker

Every straw
is visible

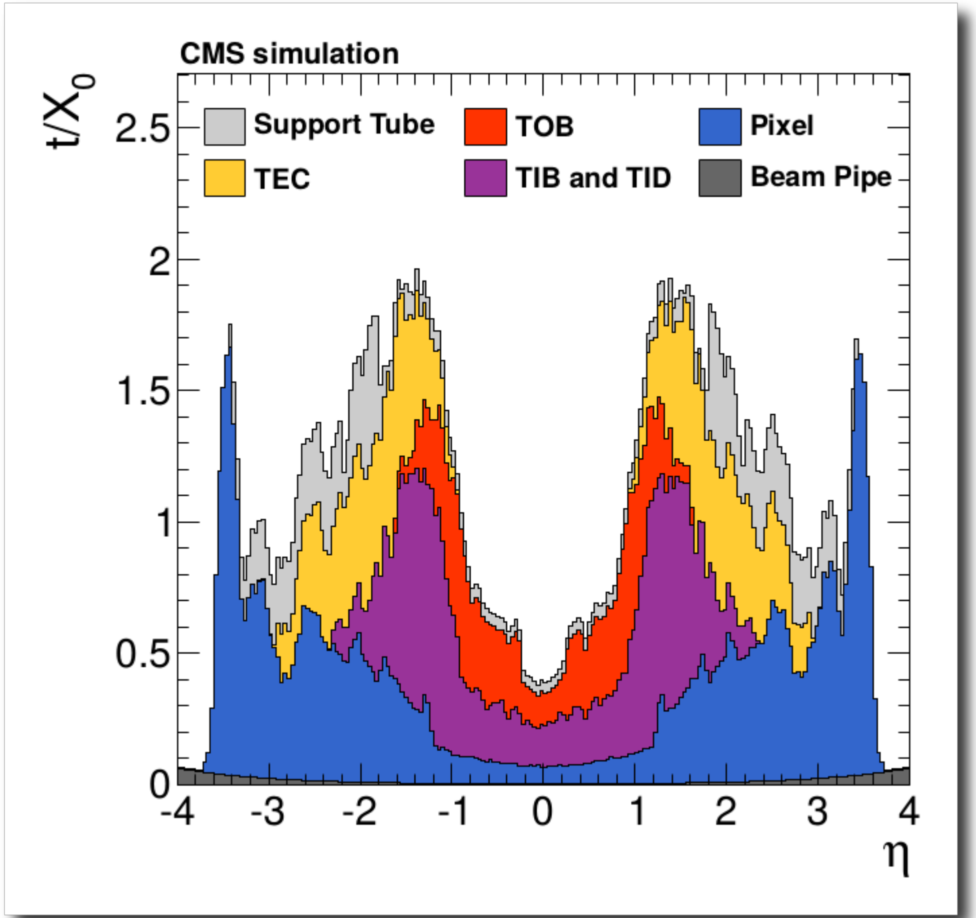
Data analysis



CMS-PAS-TRK-10-003

Material matters...

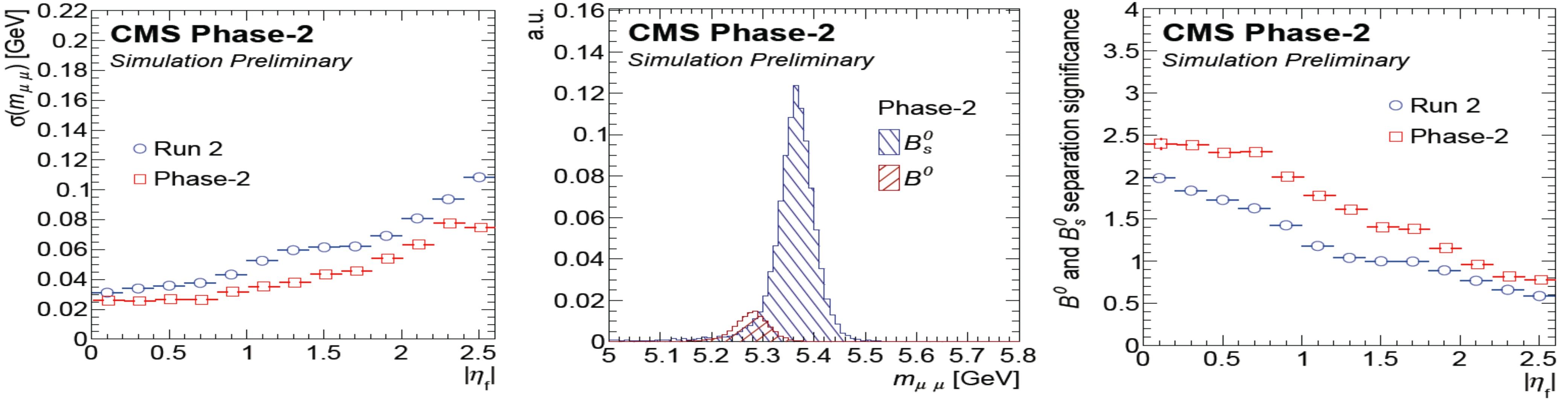
Current CMS Tracker



…allows improved resolution

$B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

- FCNC: low branching fractions in standard model: sensitive to new physics
- B candidates formed from two oppositely charged muon candidates with pT > 4 GeV for |η| < 1.4, and pT > 2GeV for |η| > 1.4
- Profits from tracker momentum resolution and use of tracking information at L1 trigger: significant gains in mass resolution and peak separation significance wrt Run 2



Contribution to the L1-Trigger

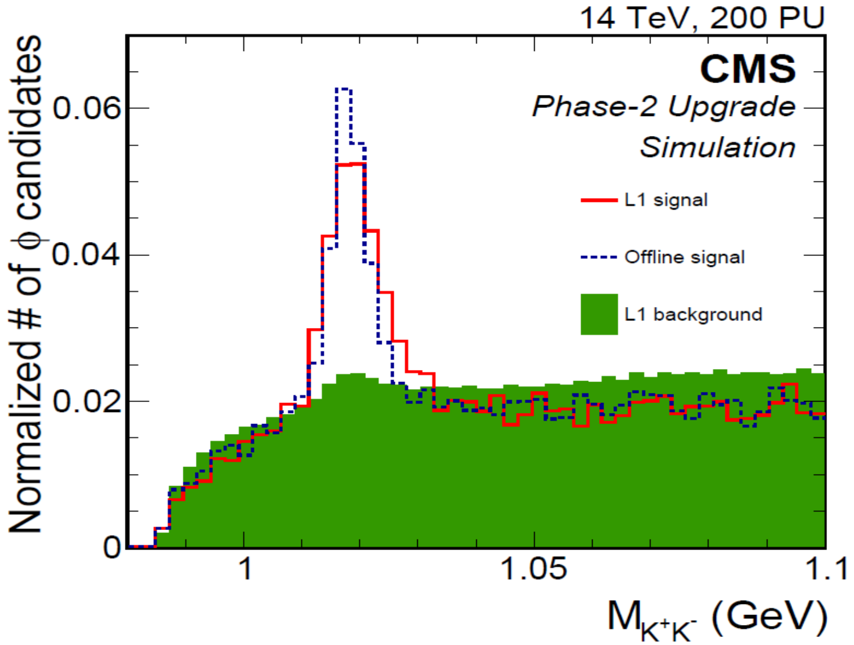
New feature of CMS Tracker for HL-LHC

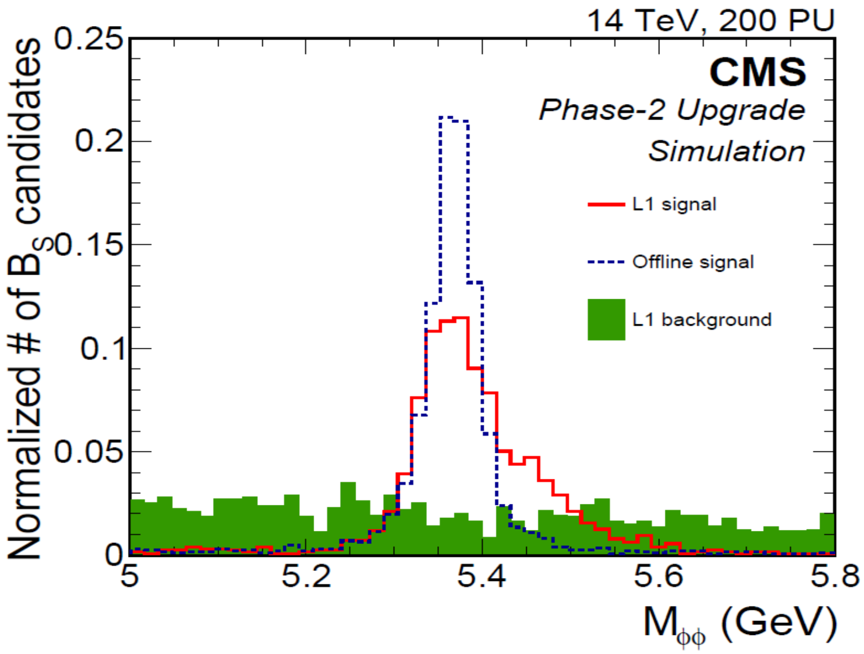
- Tracking information available at L1 trigger
- Trigger can be based on tracks formed at bunch-crossing rate
- Allows selection of specific processes @40 MHz

Selection of rare processes @L1

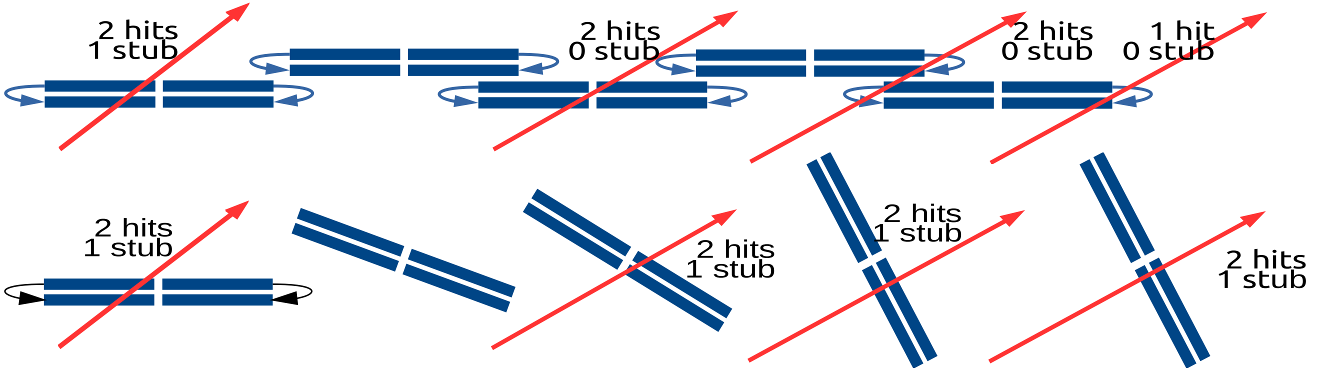
$B^0_s \rightarrow \Phi\Phi \rightarrow 4K$

- FCNC: forbidden at tree level in standard model, loop contributions from heavy particles
- Sensitive to new physics, and CP violating phase in CKM matrix
- Challenge: reconstruct (trigger & offilne) tracks from low momentum particles
- B_s candidates formed at L1 trigger!
- Analyses not possible without low thresholds in L1 track finder





Hermetic coverage with tilted barrel

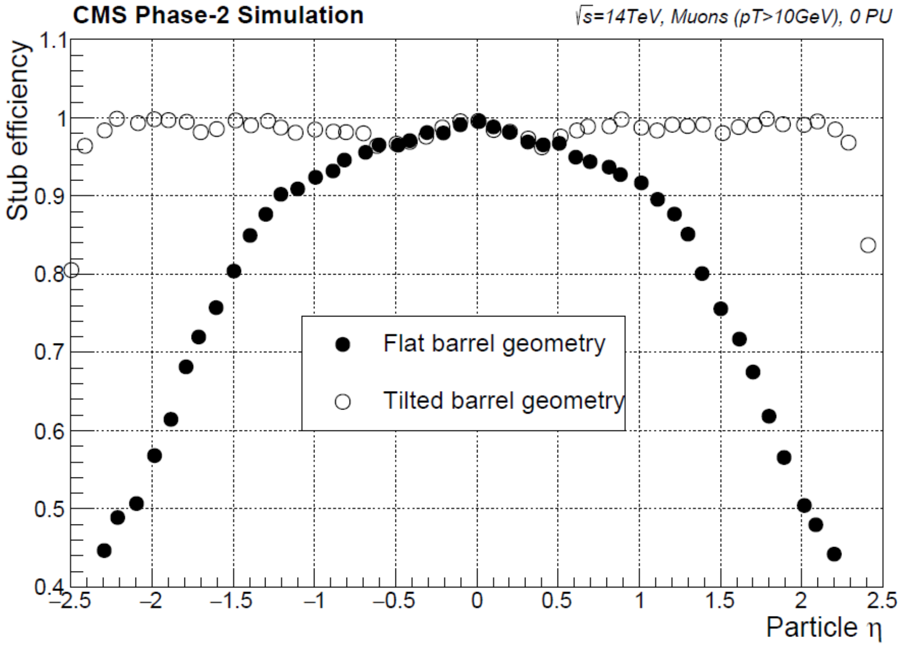


Flat barrel

Tilted barrel

Optimal coverage

Less modules needed (material!)



Tilted barrel

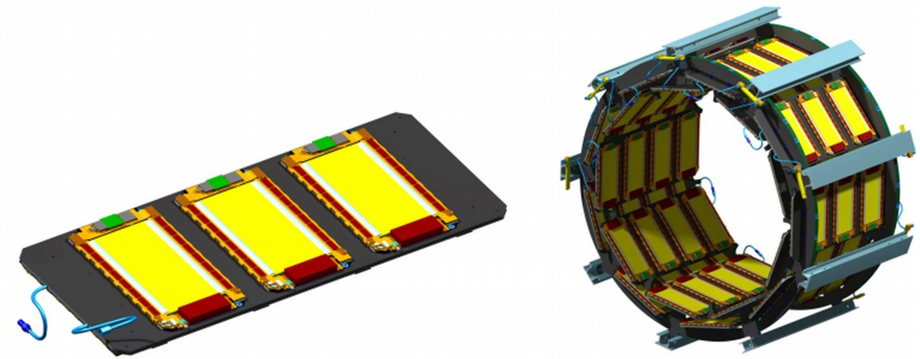


Figure 3.27: A TBPS layer 1 plank and the layer 1 central flat section with its 18 planks.

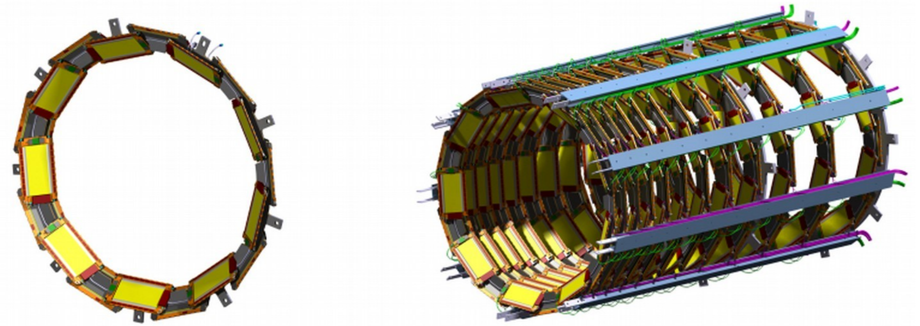
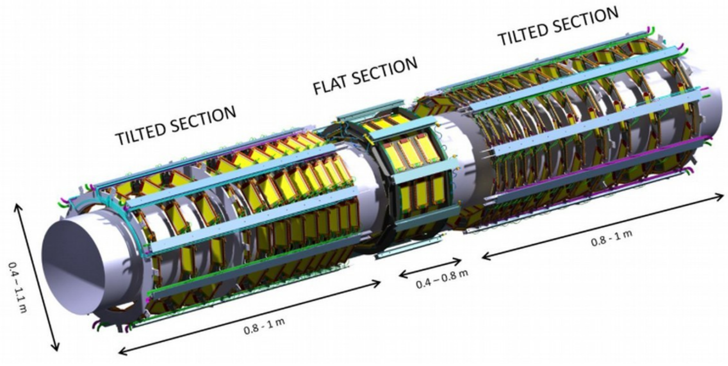


Figure 3.28: A TBPS layer 1 ring and one of the two layer 1 tilted sections.



Current technology limit

Even with a large effort in material budget reduction, the material amount in the detector is affected by the high power density of pixels and the separation between front-end and optical transmitters (with their own power lines, cooling, etc.)

The current limit of 10^{16} neq/cm^2 and 1.2 Grad is probably a hard one for current sensors and chips

Future technologies to overcome mass and radiation tolerance:

- A research in radiation tolerant HV-CMOS MAPS detector was performed by ATLAS – technology probably not mature for HL-LHC
- An improvement could come if optical links could be directly coupled to the front-ends, through Silicon Photonics