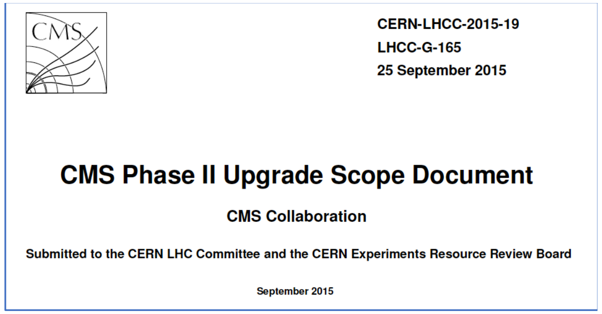
Technologies and design solutions for tracking (in 4D) at high pileup

HL-LHC and beyond

Outline

- What we (= CMS) have invented / learned / understood from the developments for HL-LHC
    - And what we will learn in the remaining 2-3 years of developments
- What others have invented (selected topics)
- Other new technologies on the horizon (… or beyond…)
- What will be useful in the far future, in extreme pileup conditions?
- Some intermediate targets?

Scope of the Upgraded Tracker



CERN-LHCC-2015-19
LHCC-G-165
25 September 2015

CMS Phase II Upgrade Scope Document

CMS Collaboration

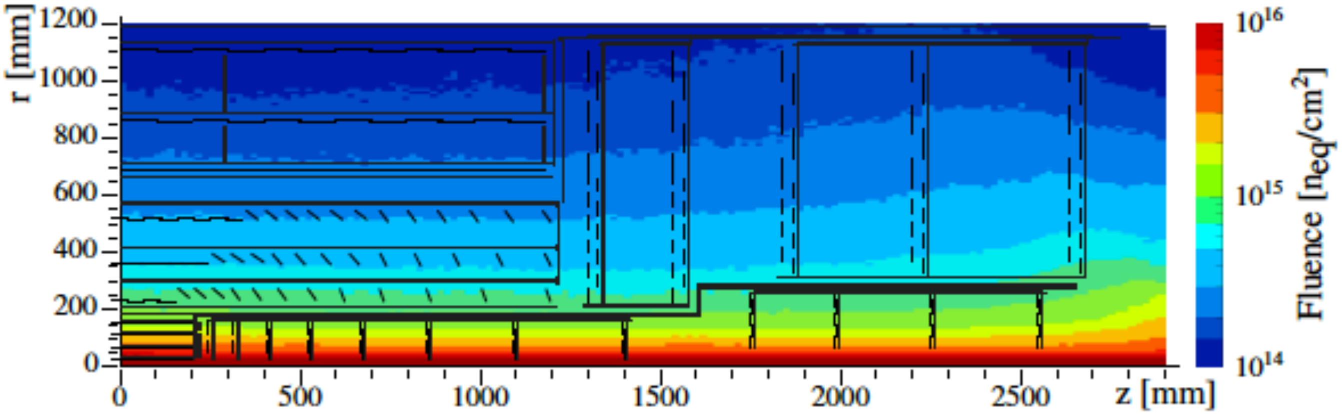
Submitted to the CERN LHC Committee and the CERN Experiments Resource Review Board

September 2015

- In a nutshell, the main enhancements of the Upgraded Tracker are:

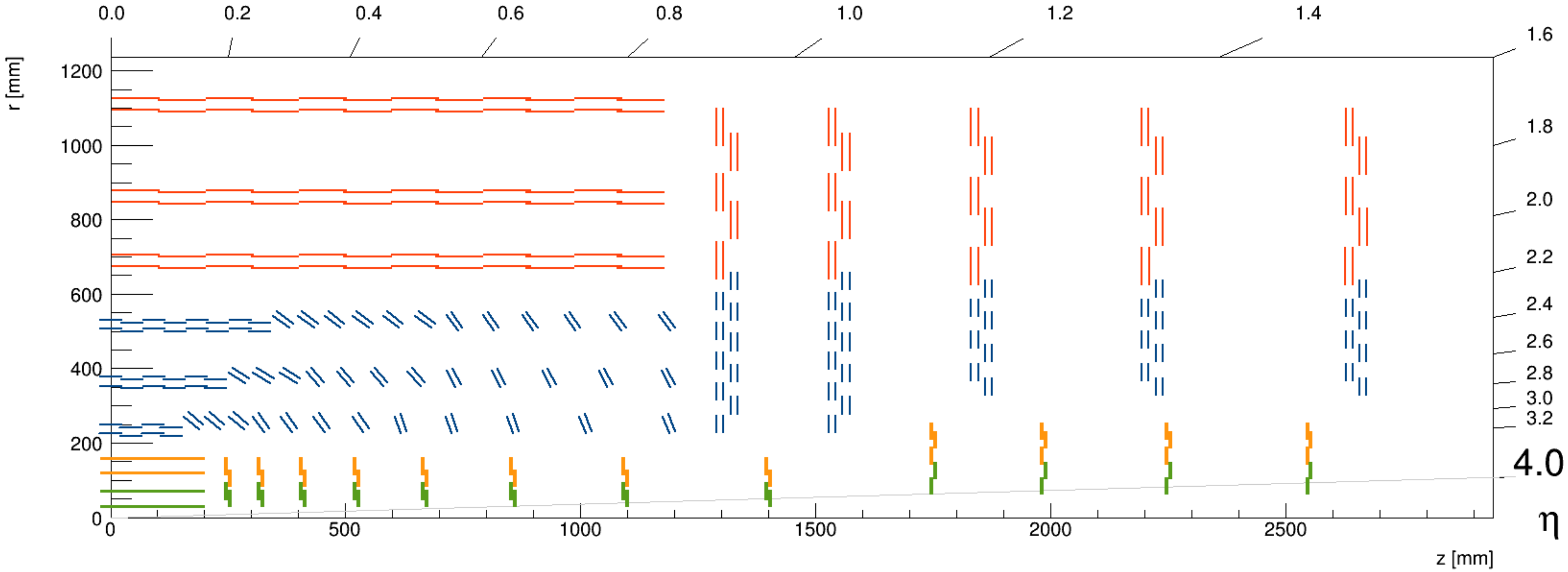
- Increased radiation tolerance to survive beyond 3000 fb^{-1} (plus margin)
  - With the possible exception of the layer/ring 1
- Increased granularity to enable fast and efficient pattern recognition up to 200 PU
  - Interplay with computing time
- Contribute tracking information to CMS L1 trigger decision, to enable effective event selection up to 200 PU
  - New trigger operation parameters: **Latency** 3.2 $\mu s \longrightarrow$ 12.5 μs, **Accept rate** 100 kHz $\longrightarrow$ 750 kHz
- Extend rapidity acceptance up to $\eta \approx 4$
  - Cover the peak production region of jets from Vector Boson Fusion and Vector Boson Scattering
  - Mitigate assignment of charged tracks to wrong vertices at high PU, affecting jet reconstruction and missing E_T

Radiation tolerance



Radiation levels depend essentially on R, not much on z

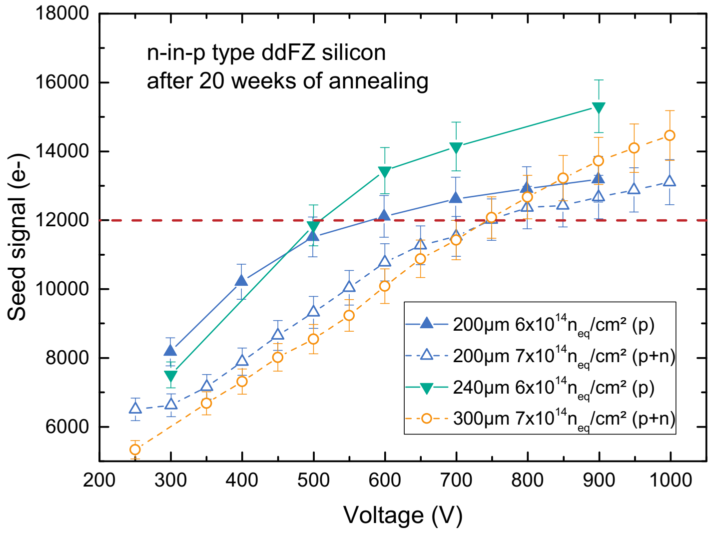
- The target is ~ 10× present tracker
  - **i.e. about 10^{15} neq/cm^2 for the Outer Tracker, > 2×10^{16} for the innermost pixel layer**
- Challenging for silicon sensors and electronics (notably in the pixel region)
- *Unprecedented levels!*

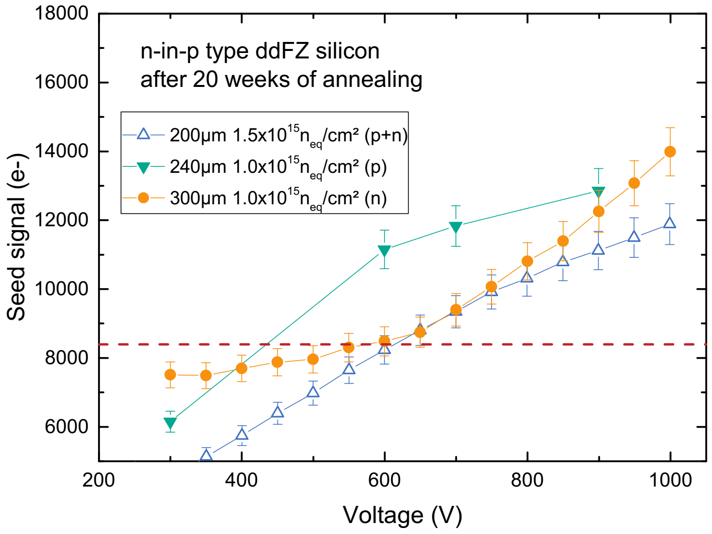

0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
4.0
η
r [mm]
1200
1000
800
600
400
200
0
0
500
1000
1500
2000
2500
z [mm]

Sensors for Outer Tracker

- After heavy irradiation (~10^{15}) charge from 320 µm thick sensors drops down to the same level as 200 µm
  - More trapping
  - In 200 µm the leakage current is smaller, and can be operated at smaller V_{bias}: mitigate requirement on cooling!
- In p-in-n sensors observed spurious signals (random non-gaussian noise, a.k.a. **R**andom **G**host **H**its)

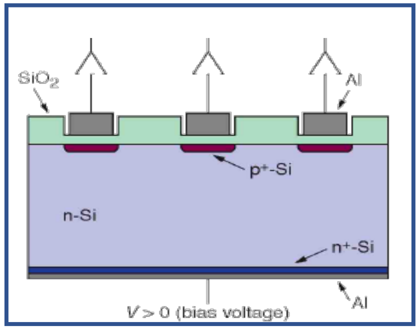
N.B. Typically 25000 e- from a non-irradiated sensors 320 µm thick

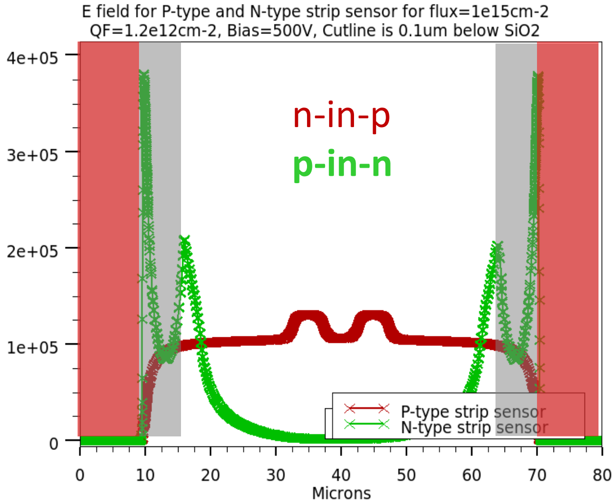




Understanding RGH

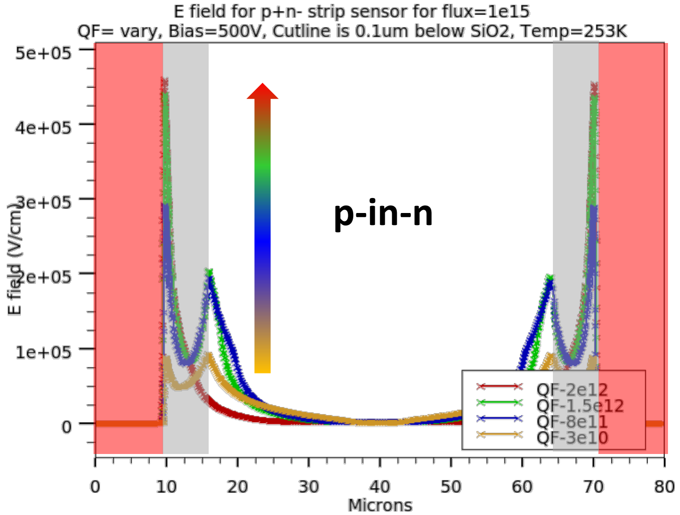
- T-CAD simulations show higher electric fields at the strip edges for irradiated p-in-n sensors than for n-in-p sensors
  - Suggests the occurrence of “micro-discharges” in p-in-n
- Increasing oxide charge…
  - increases max. electric fields in p-in-n, reduces max. electric fields in n-in-p
  - Observation: rate of RGHs are smaller for neutron than for proton irradiation
    - less ionization, less surface damage





$F=1\mathrm{x}10^{15}\mathrm{cm}^{-2}$; $Q_F = 1.2\mathrm{x}10^{12}\mathrm{cm}^{-2}$;
U = 500 V; **5-trap model (Silvaco)**

strip doping
aluminum

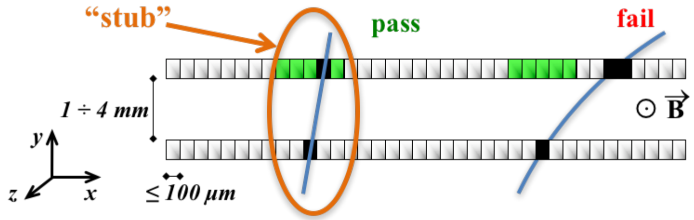


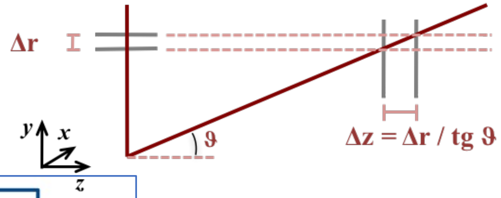
Outer Tracker sensors: conclusion

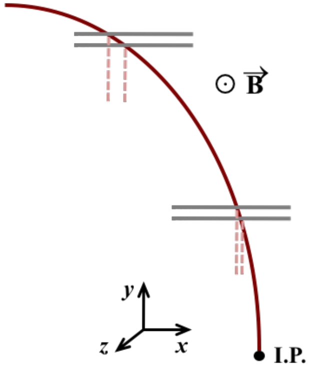
Basic R&D finished: the main properties of the sensors are defined

- Polarity
  - n-in-p is the selected option, as it offers robust performance
    - i.e. graceful degradation after heavy irradiation
- Material
  - MCz or FZ
    - MCz seems to have better annealing behaviour: allows for long annealing times with no adverse effects
      - Could be (eventually) operated at lower V_{bias} mitigating the requirements on the cooling
- Thickness
  - About 240 μm thickness seems to be the optimal value
    - Fine-tuning of thickness has a significant impact on longevity
    - Sufficient charge, good annealing behaviour, lower I_{dark} and V_{bias}

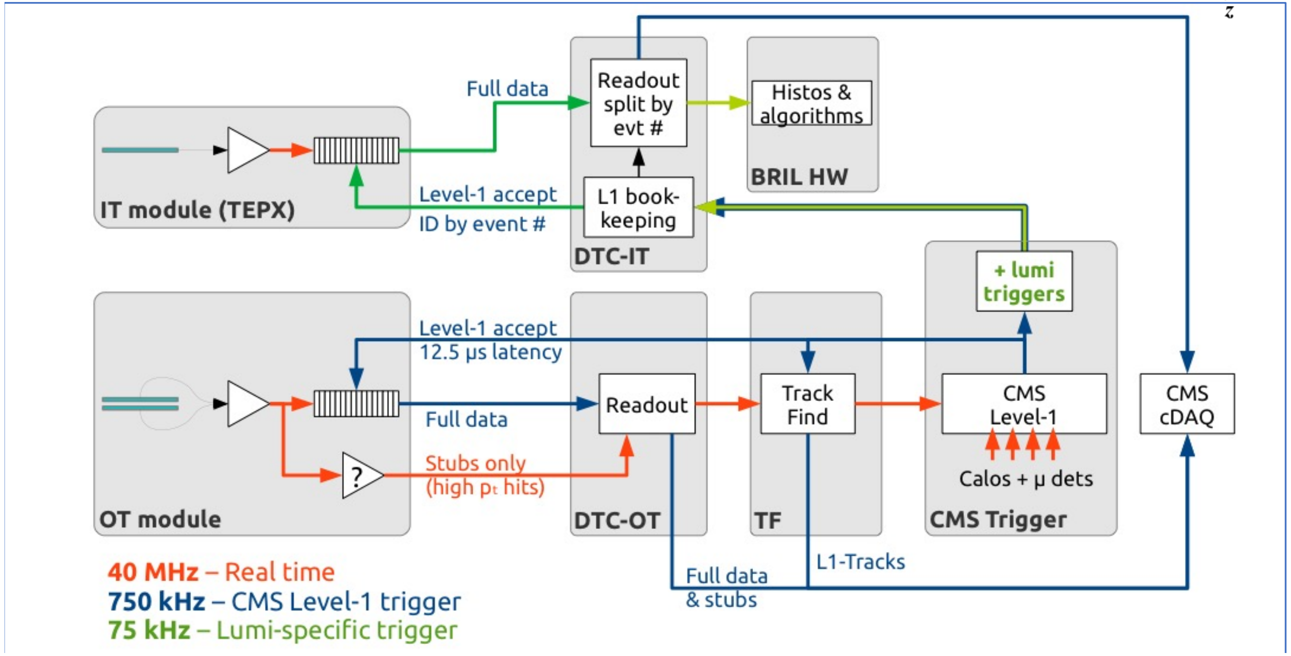
Outer Tracker input to Level-1 trigger: p_T modules





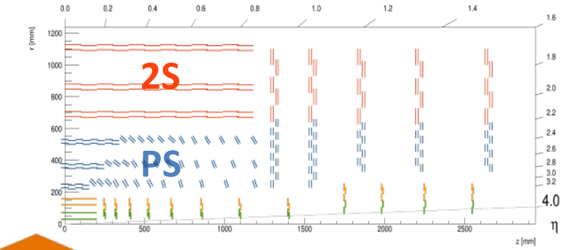


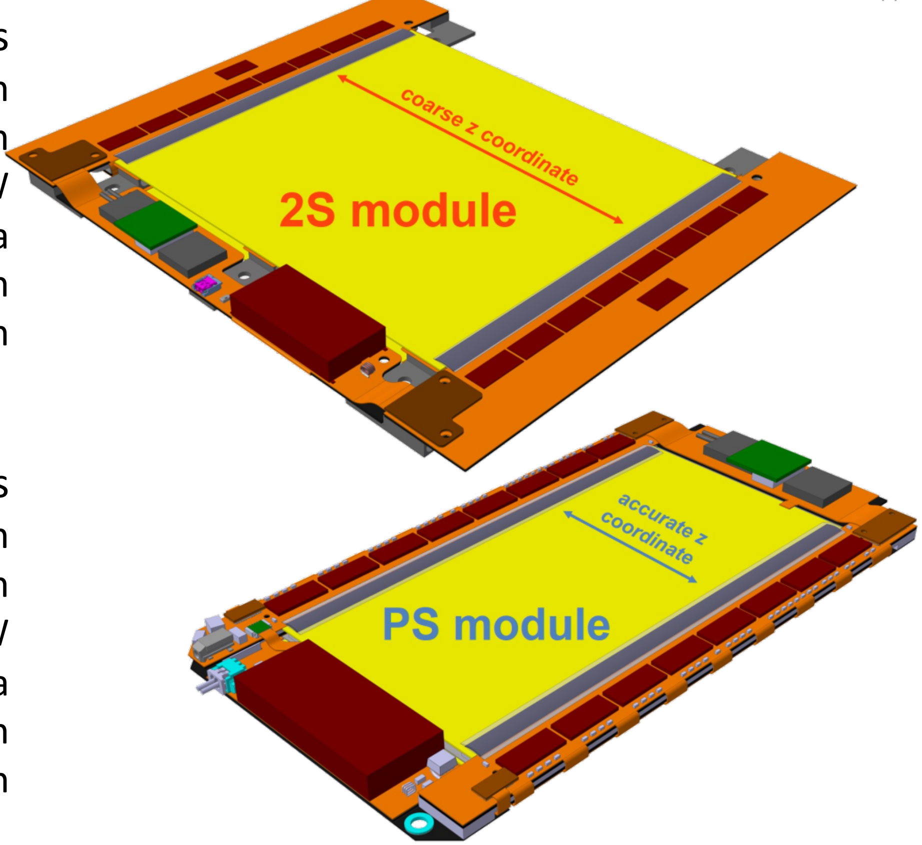
- ➢ Optimize selection window and/or sensors spacing
  - ⦿ To obtain, as much as possible, consistent p_T selection through the tracking volume
- ➢ The concept works down to a certain radius
  - ⦿ 20÷25 cm with the CMS Bfield and a realistic 100 μm pitch



➢ **No room for stereo strips!!**

p_T modules





2 Strip sensors

2 × 1016 Strips: ~ 5 cm × 90 µm

2 × 1016 Strips: ~ 5 cm × 90 µm

P ~ 5.4 W

~ 2 × 90 cm^2 active area

For R > 60 cm

Spacing 1.8 mm and 4.0 mm

`

Pixel + **S**trip sensors

2 × 960 Strips: ~ 2.5 cm × 100 µm

32 × 960 Pixels: ~ 1.5 mm × 100 µm

P ~ 7 .8 W

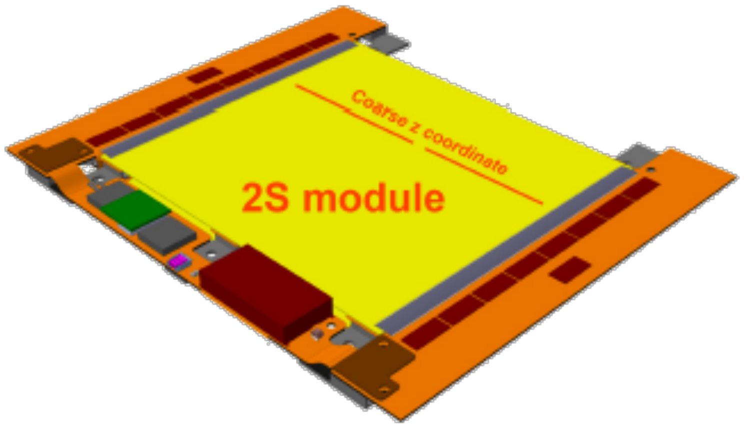
~ 2 × 45 cm^2 active area

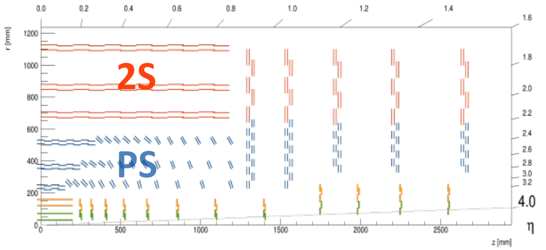
For r > 20 cm

Spacing 1.6 mm, 2.6 mm and 4.0 mm

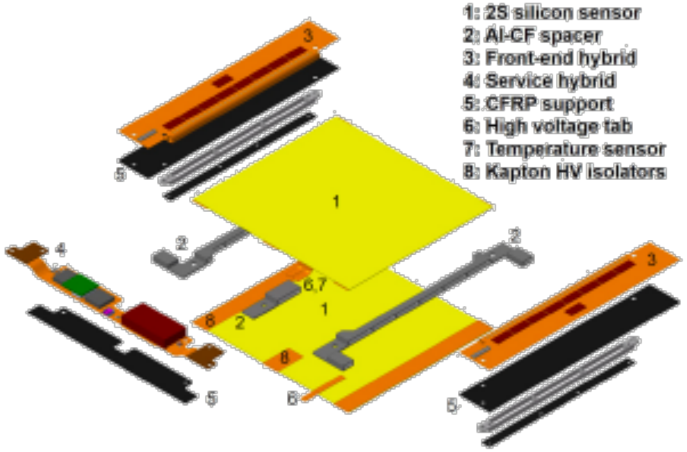
Operate sensors at about –20°C with cooling set point at –30°C

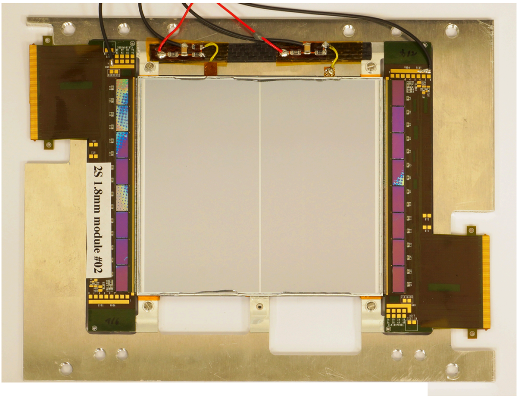
2S module

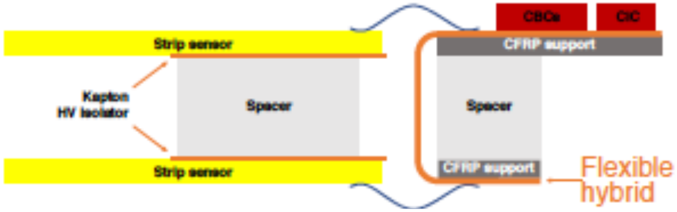




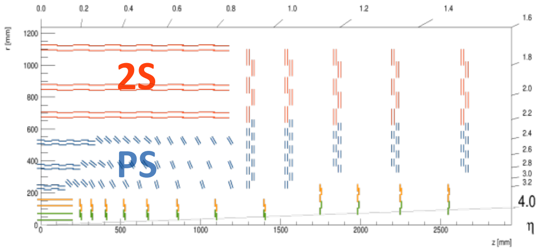
- Read out from the edges, to avoid difficult / expensive TSV technologies
- Flex hybrid circuit collects signals from both sensors
    - Supports wirebonding to sensors and bump-bonding of readout ASICs
    - Complex routing and high-density of lines
    - 8 CBC, 1016 channels per sensor per end
- The sensors has 90 μm pitch – at the limit of the hybrid technology!

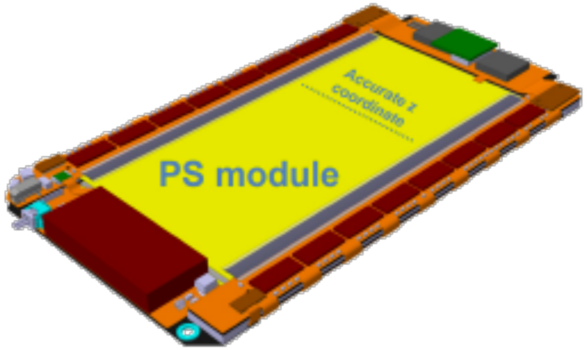




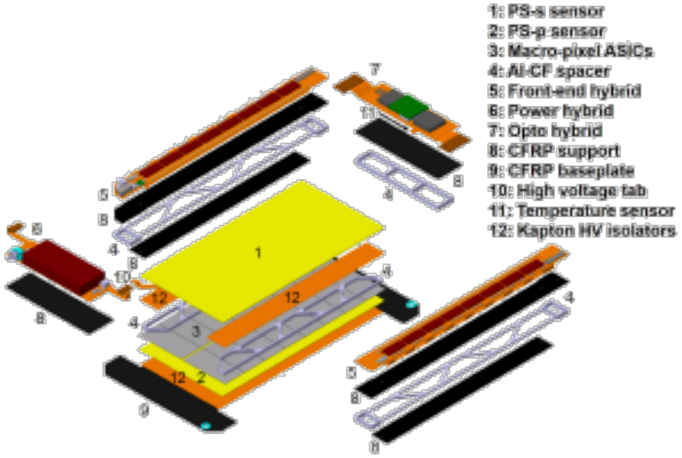


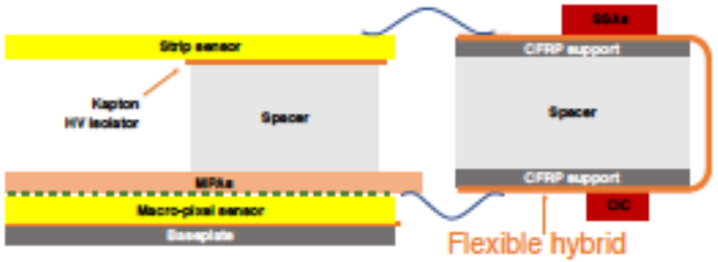
PS module





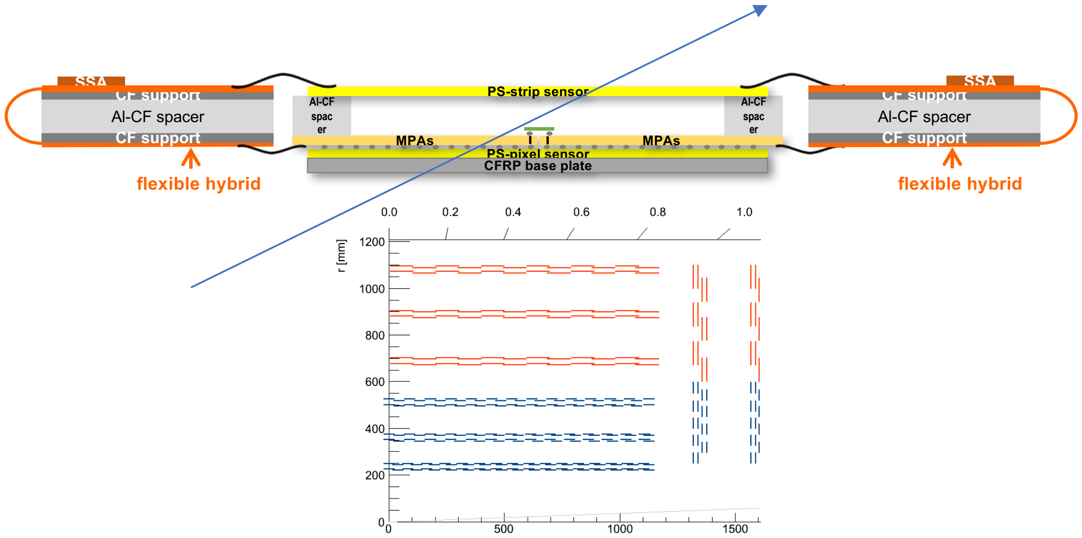
- Size limited to ½ 6” wafer
  - Cover the length with 2 chips – connect from the sides
  - 25 mm long strips required at low radii anyway
- Hard limit at 100 μm pitch in order to use large-volume (inexpensive) bump-bonding
  - N.B. 25 m^2 of Macro-Pixel Sensors
- Segmentation in z is a compromise between z_0 resolution and power dissipation
- Deploy down to ~20 cm to achieve reasonable z_0 resolution in L1 tracking
  - Also much less expensive and power-hungry than pixel modules!!

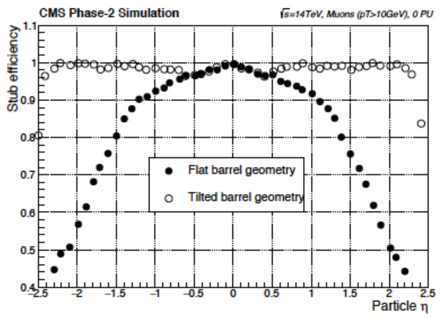


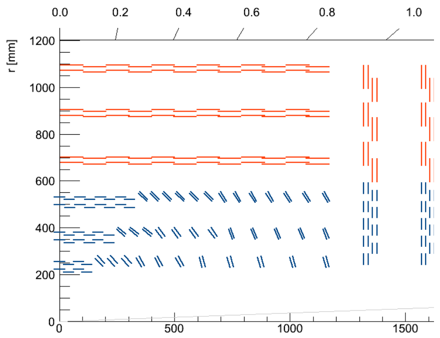


A new standard in hybrid circuits!

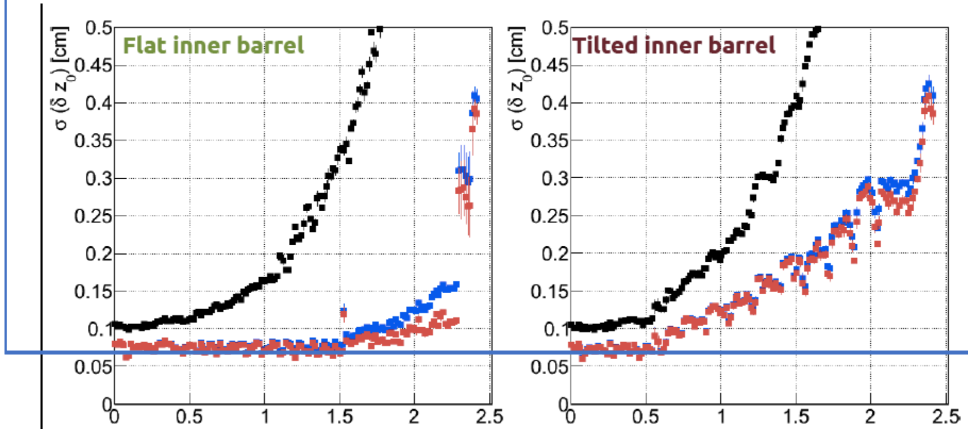
Tilted geometry vs flat with TSVs





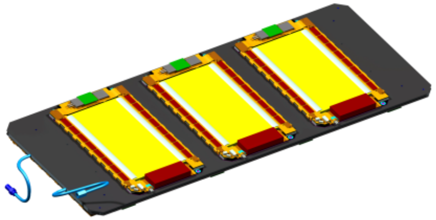


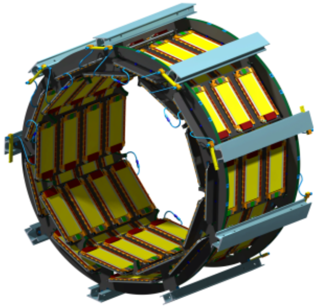
- TSVs expensive and risky (quality, yield)

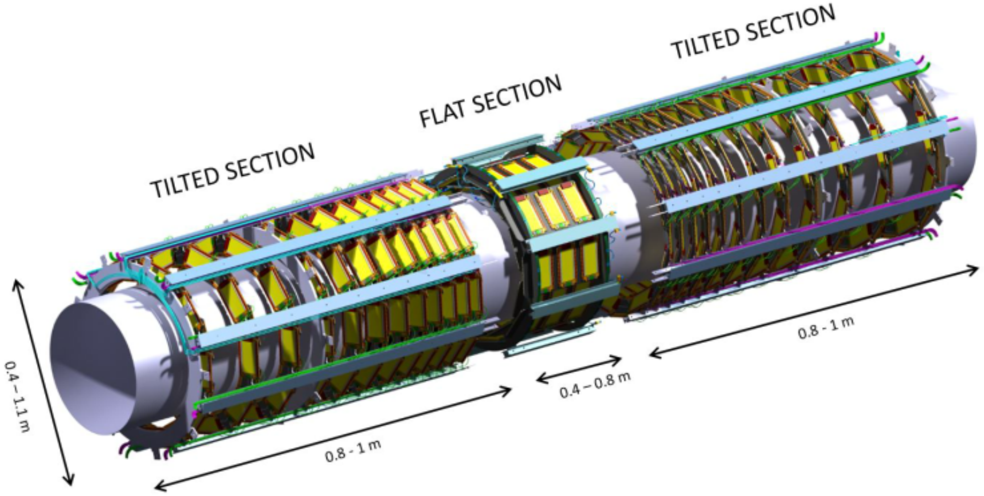


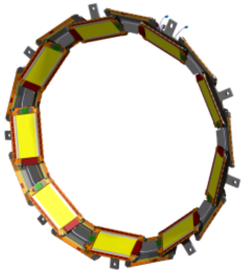
- Tilted mechanics more difficult and more expensive, likely heavier
- Degraded z_0 resolution for L1 tracks
- Large reduction in number of PS modules (≈1200) ⟹ mass reduction, **large cost saving (≳ 4 MCHF)**

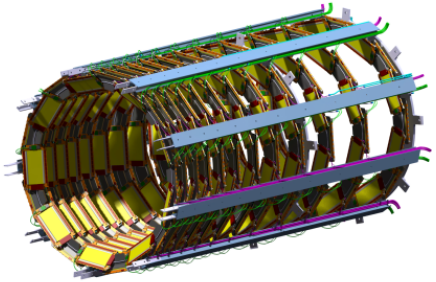
Small penalty in performance for L1 tracks
Large cost saving and less risks

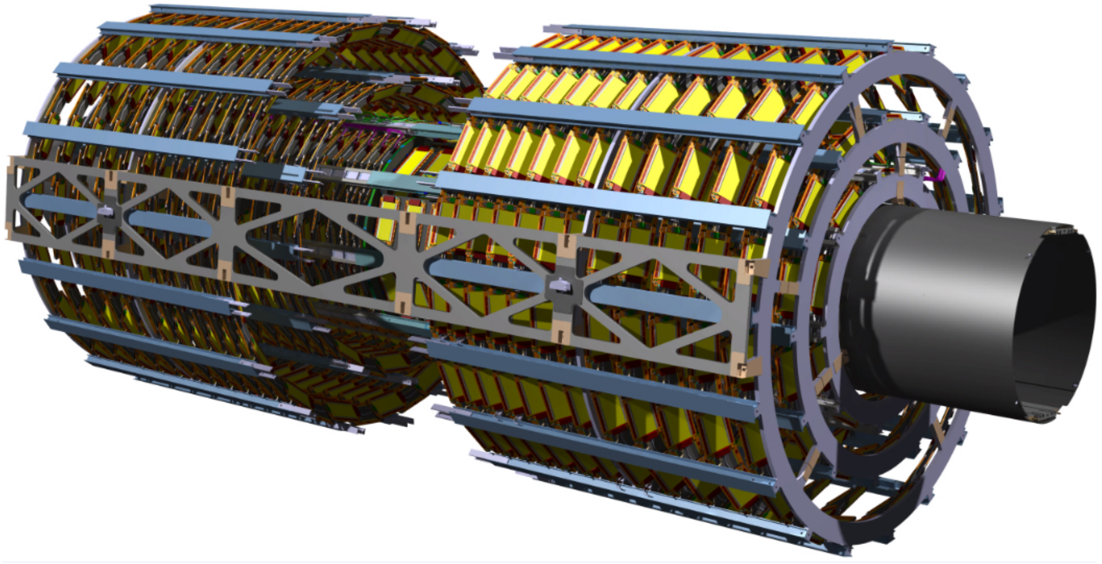





TILTED SECTION
FLAT SECTION
TILTED SECTION
0.4 – 1.1 m
0.8 - 1 m
0.4 – 0.8 m
0.8 - 1 m



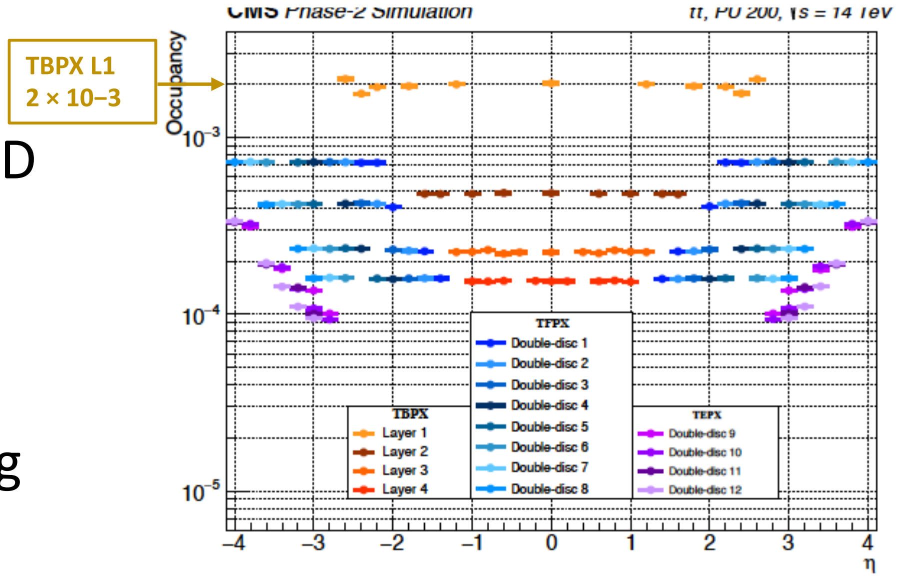


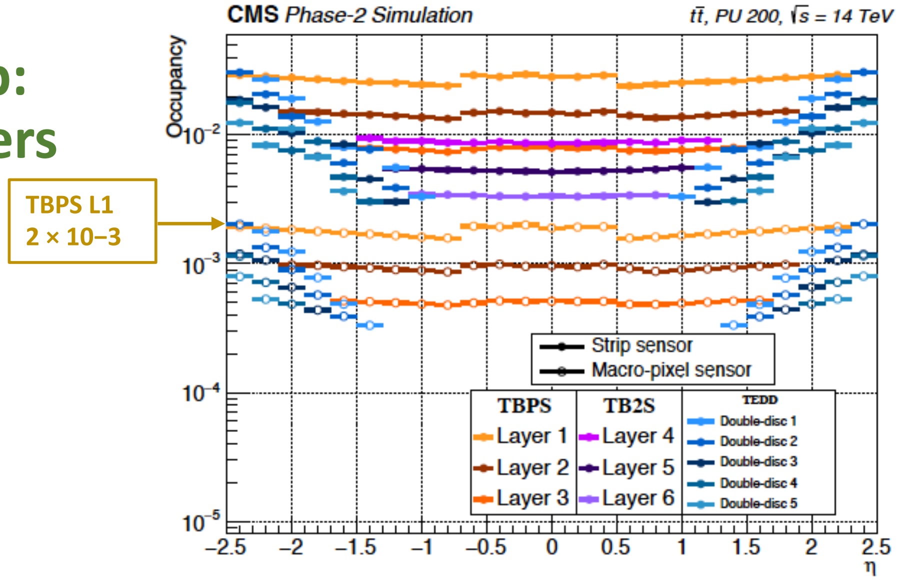


Additional considerations

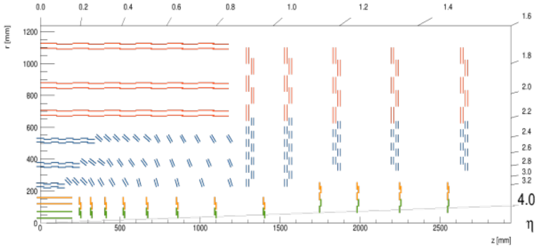
- PS modules provide three layers of unambiguous 3D coordinates (plus p_T info)
  - An asset for pattern recognition
- Granularity well matched to intermediate radii
- A much more cost effective solution than extending the IT to larger radii / more layers
- Having developed three different systems pays off!
- **p_T modules are an asset for tracking in high pileup: a design solution to keep in mind for future trackers**

	2S system	*PS system*	*IT system*
Cost (MCHF / m²)	0.60	1.27	5.15
Cost ratios		PS/2S = 2.1	IT/PS = 4.1
Power density (W / cm²)	0.060	0.173	1.0
Power ratios		PS/2S = 2.9	IT/PS = 5.8





Inner Tracker



Enhanced radiation tolerance → thinner silicon sensors → less charge available
Possibly 3D sensors in the inner regions

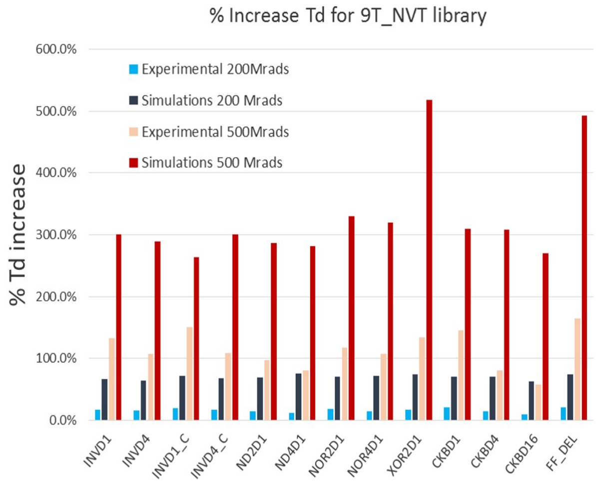
Improved two-track separation for high-energy jets

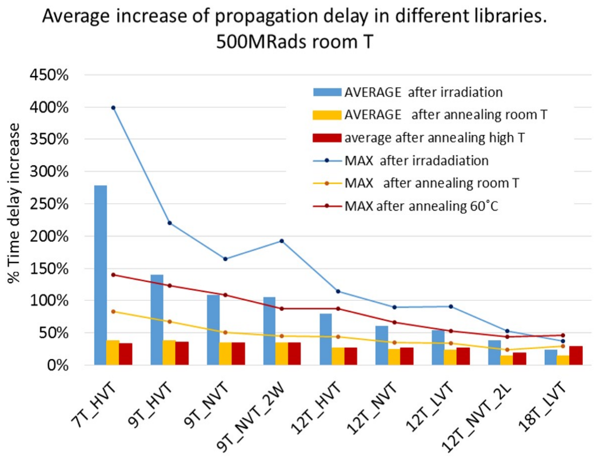
Readout chip with small cell-size, low detection threshold, and huge data rate capability

25 PU	⟹	200 PU		× 8 hit rates (3.2 HGz / cm^2 in the first layer)
3.2 μs	⟹	12.8 μs L1 latency	×4 ×8	× 32 size of buffers
100 kHz	⟹	750kHz L1 rate	×7.5 ×8	× 60 bandwidth from front end
300 fb^{-1}	⟹	3000 fb^{-1}		× 10 radiation tolerance (also for sensors)

Technology: 65 nm CMOS
Cell size 25×100 μm^2 (×6 smaller than phase-1 detector)
Common development with ATLAS in RD53

Radiation qualification of 65nm CMOS



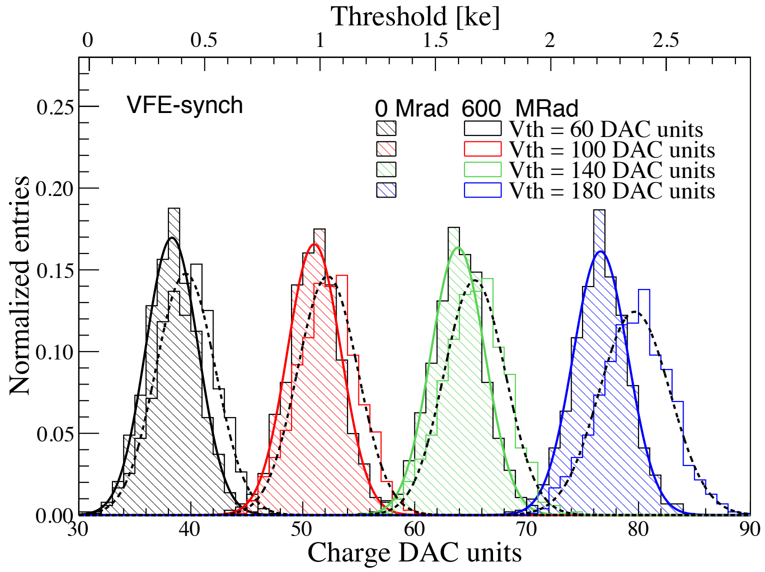


Thorough studies of radiation degradation vs T & bias conditions

Results reproduced (qualitatively) by rad damage effective model

Excellent results from small-size demonstrators

Eagerly awaiting results from large-size demonstrator RD53A!

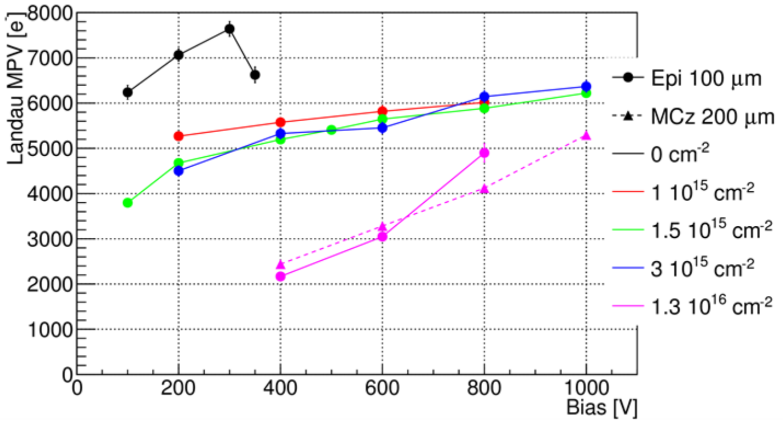


Sensors R&D ongoing

Pixel structures only tested to about 2E15

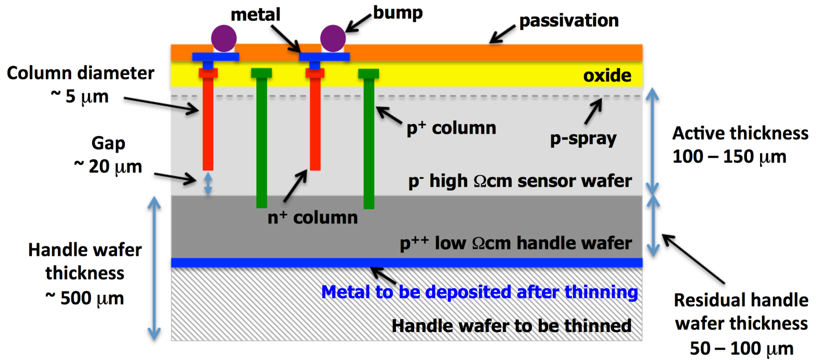
Higher fluences explored with strip sensors or test structures

Hints that optimal thickness should be around 150 µm

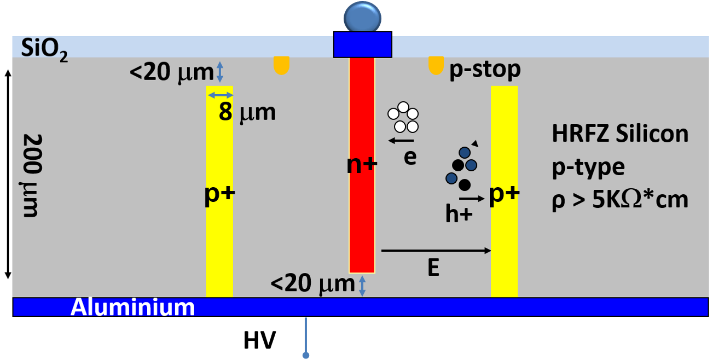


The 1E16 range is very challenging!

Developing also 3D sensors for ultimate rad tolerance (target 1st barrel layer and 1st ring in forward)



Single sided process at FBK



Double sided process at CNM

Expect to collect all the answers in the next two years

Possibly a kind of final word about radiation tolerance of silicon sensors??

Another key ingredient: serial powering

Requirements for current distribution are unprecedented

Future pixel detector will consume ~50 kW @ 1V
To be compared with present detector 9 kW @ 2.5 V

One order magnitude higher current

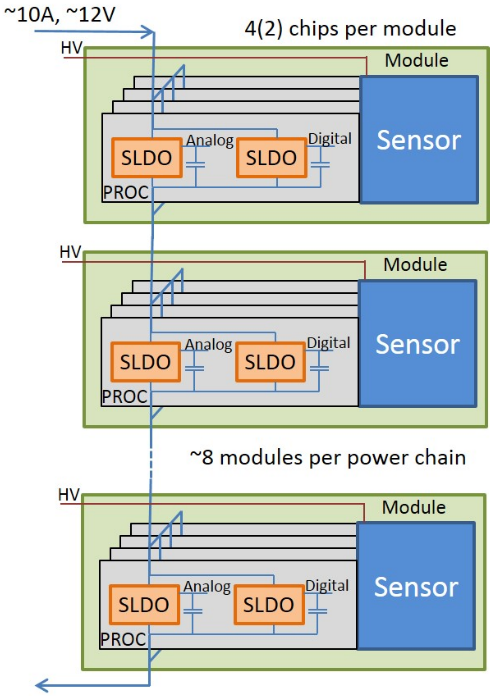
In serial distribution current flows through several (~10) FE modules

Modules in the power chain have different reference ground!

Very challenging system issues!

N.B. HV distribution is parallel

Never attemped in a large-scale detector!

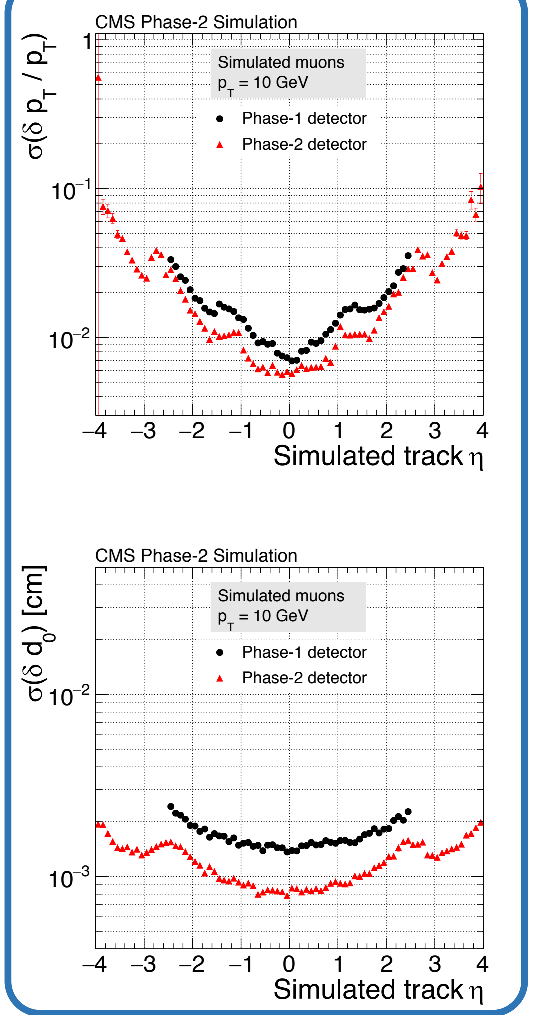


Common ATLAS/CMS development

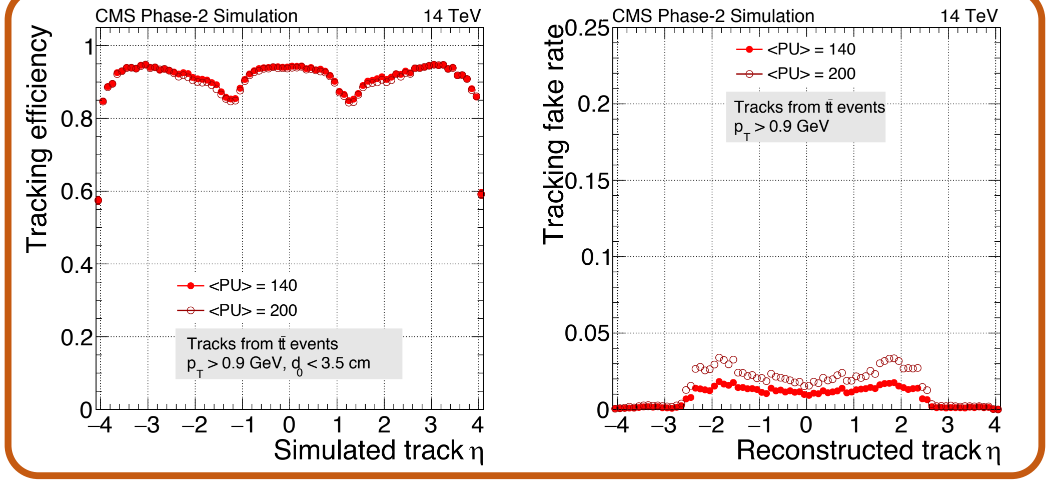
Will set a new standard in HEP detector design (… especially if we make it work!)

Performance highlights

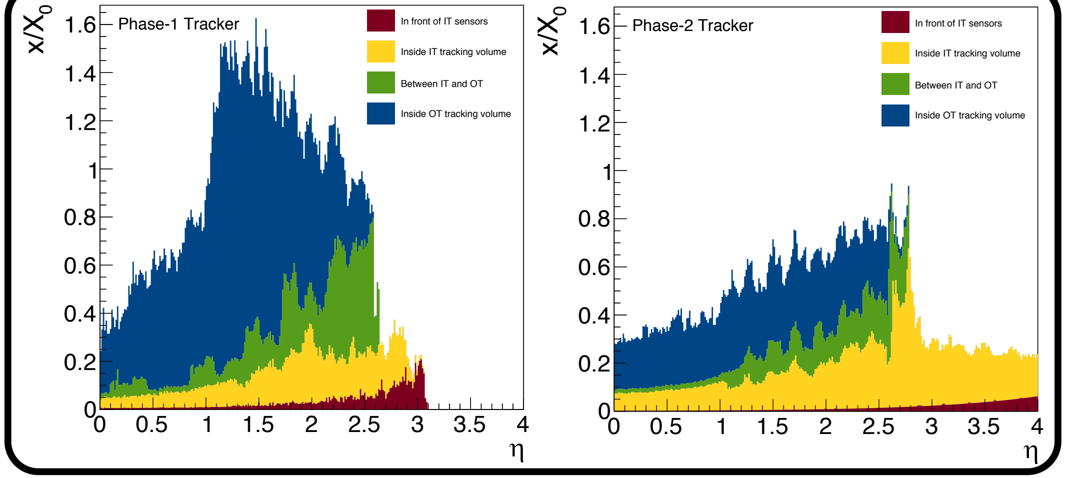
Improved resolution



Robust track finding performance

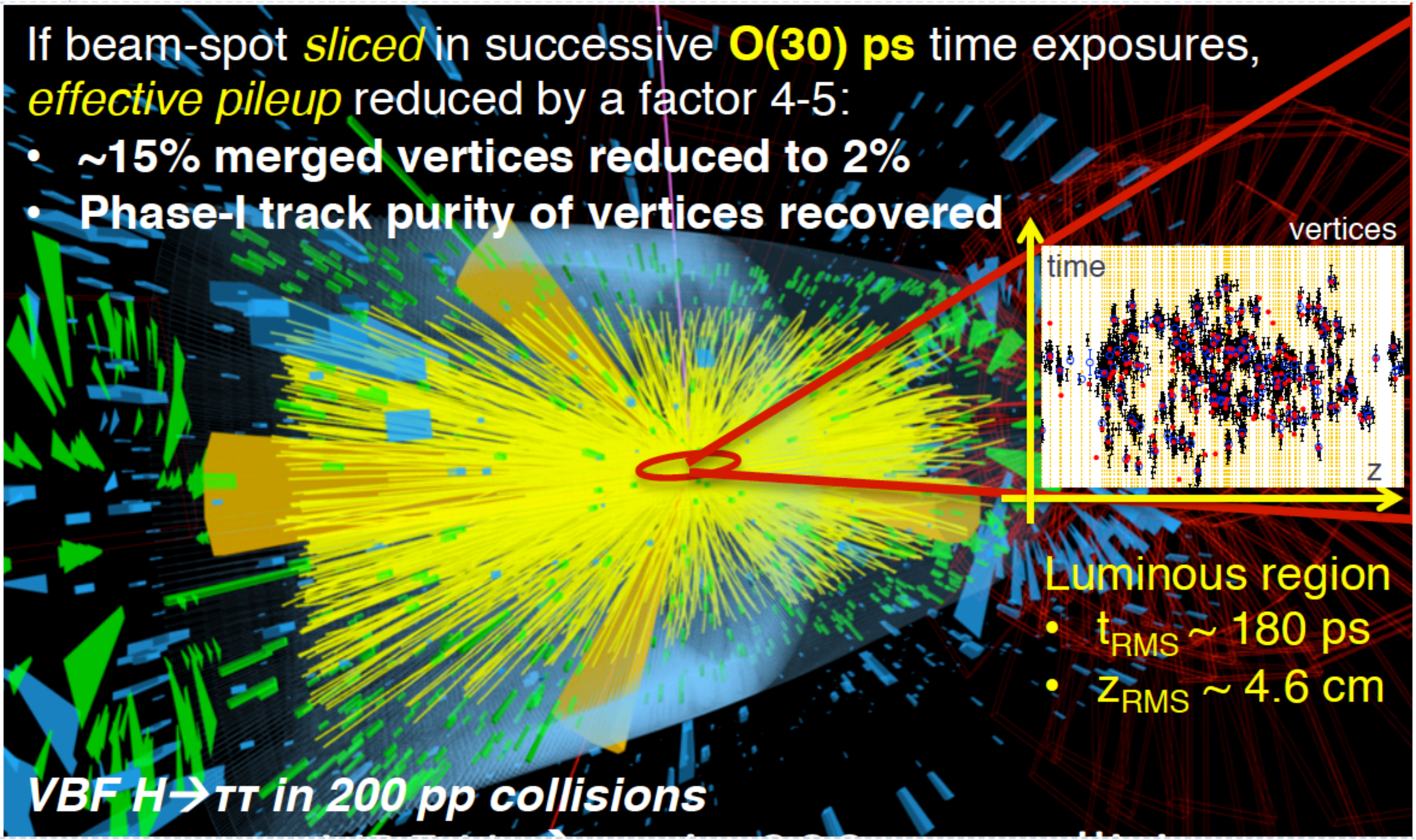


Less material



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

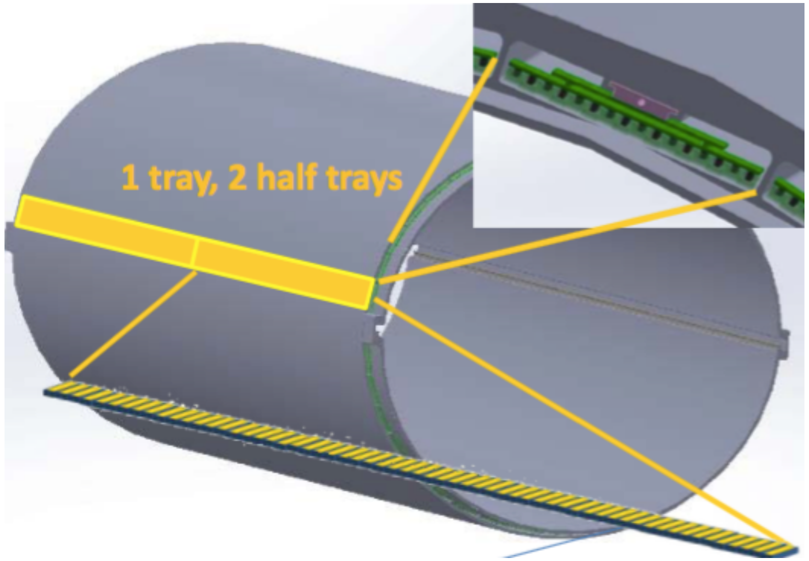
- **~15% merged vertices reduced to 2%**
- **Phase-I track purity of vertices recovered**



Luminous region
- $t_{RMS} \sim 180$ ps
- $z_{RMS} \sim 4.6$ cm

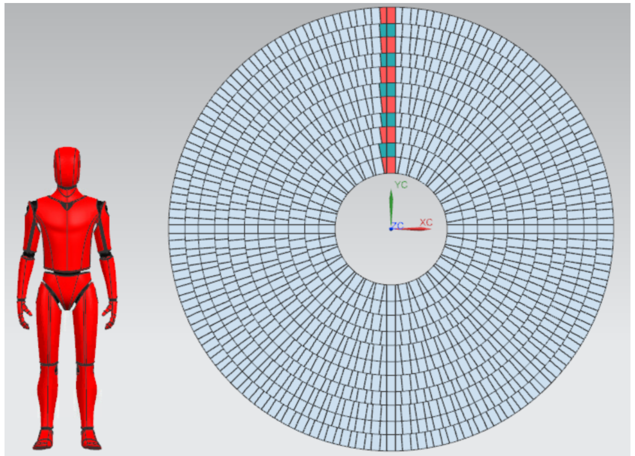
VBF H→ττ in 200 pp collisions

Barrel Timing Layer
Outside Tracker
LYSO + SiPM

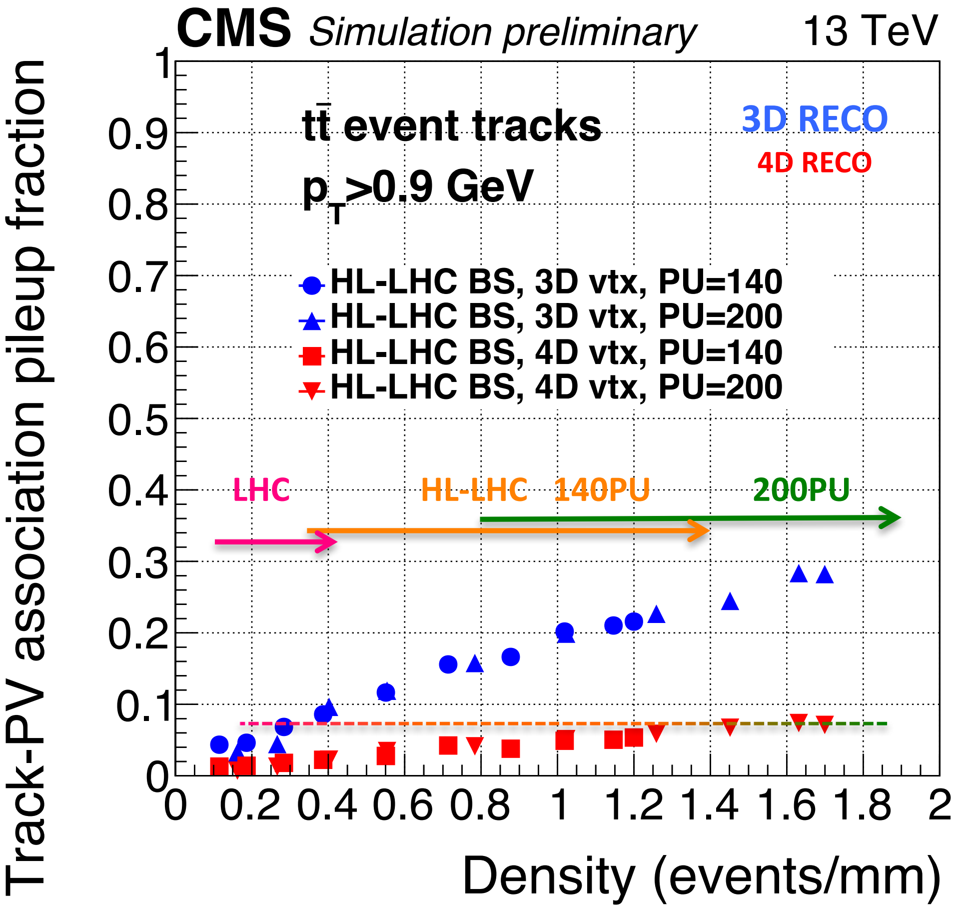


Large coverage for vertexing in 4D

Endcap Timing Layer
On HGCal nose
Low Gain Silicon detectors



Track-vertex association – with track timing

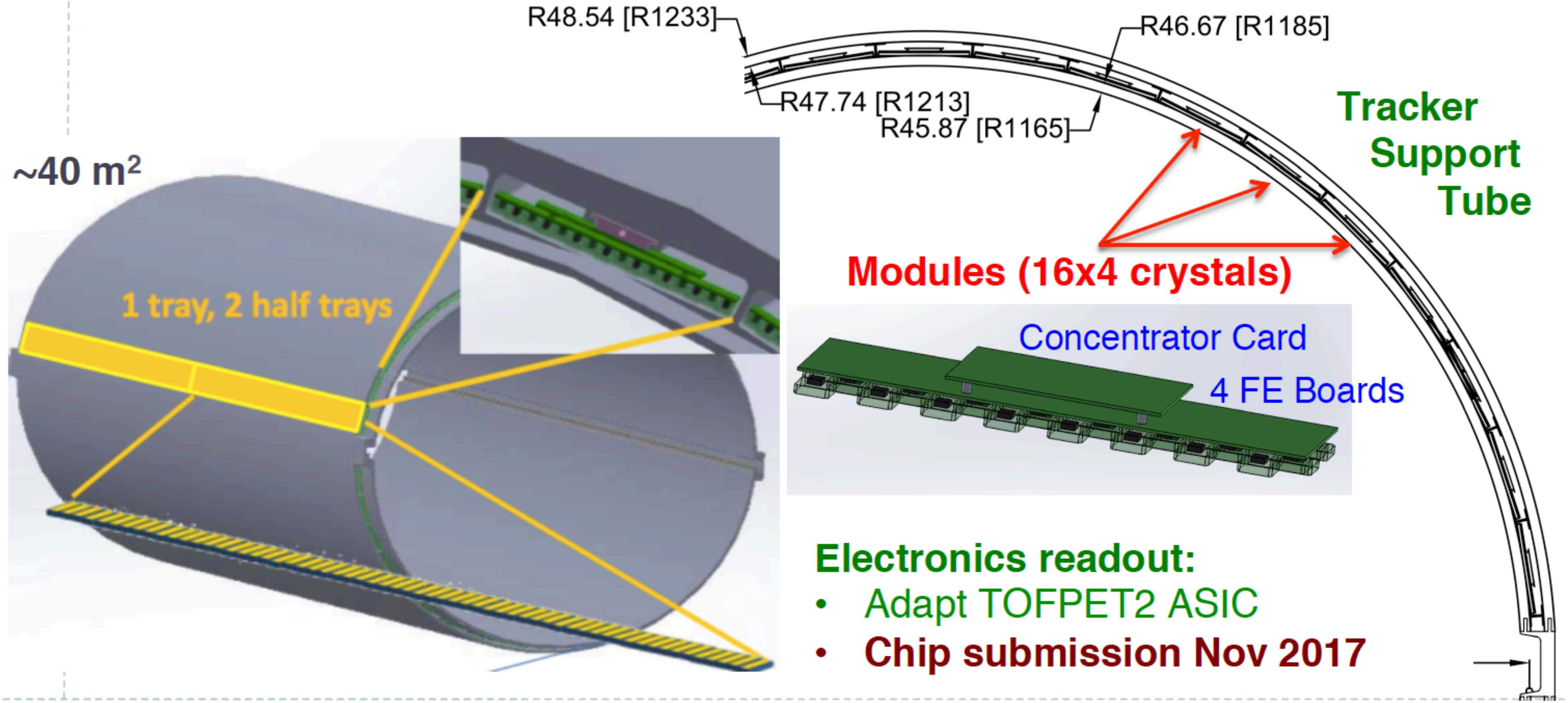


- With timing, 'effective vertex density' down to LHC level !
  1. Cleaner isolation cones
  2. Improved primary and secondary vertex reconstruction
  3. Improved jet and p_T^{miss} reconstruction

- Boost performance of several observables
- **Bottom line: 20÷30% enhanced statistical power in most physics channels!**

LYSO crystals + SiPM embedded in the Tracker tube

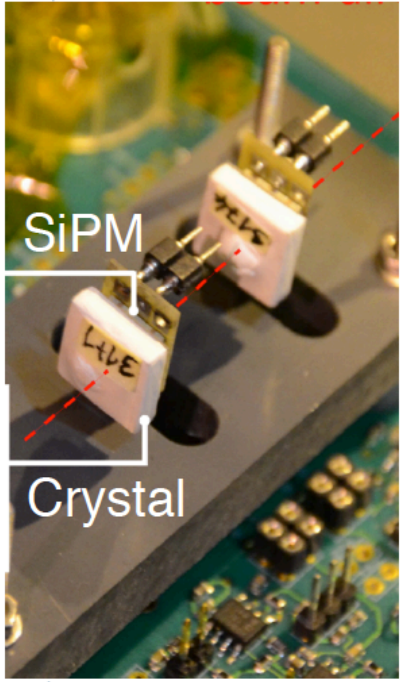
- Ready before TK integration (mid 2022)
- Maintain performance at radiation level **2×10^{14} n_{eq}/cm^2**

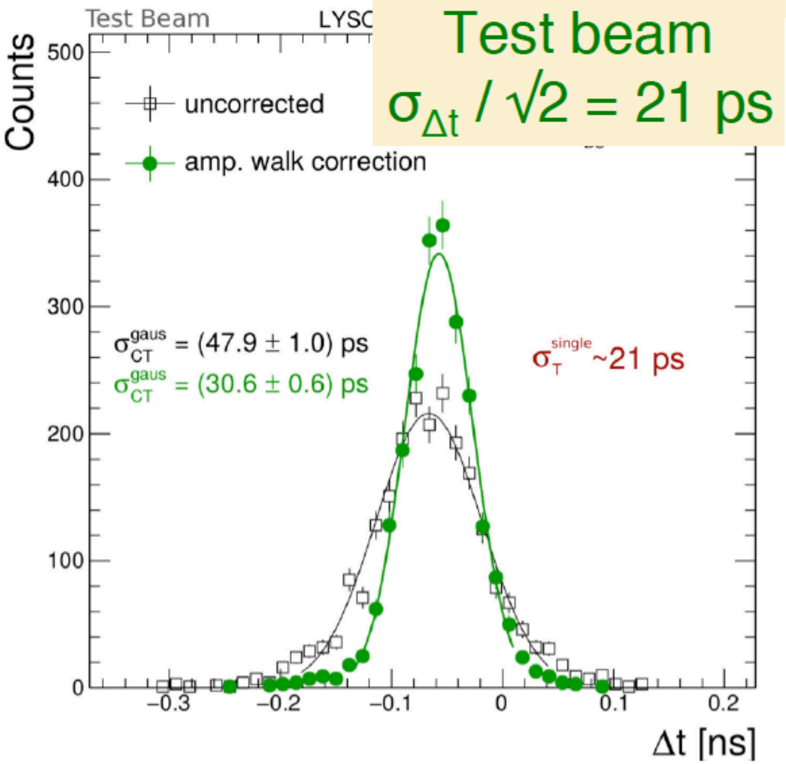


Electronics readout:

- Adapt TOFPET2 ASIC
- **Chip submission Nov 2017**

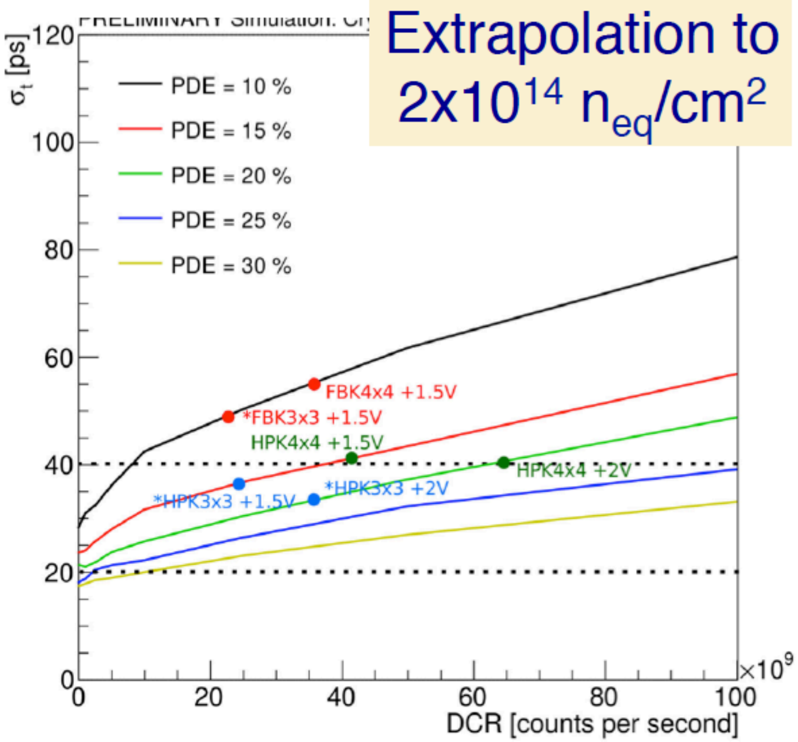
- **Nominal geometry: 12 x12 mm^2 (~ 3 mm thick) + 4x4 mm^2 SiPMs**
- **Production-like geometry qualified in test beams**
- **Good radiation hardness of production-ready SiPMs**
  - Operate SiPMs at ~ –30 ^{0}C (limit self-heating and dark rate)





Test beam

$\sigma_{\Delta t} / \sqrt{2}$ = 21 ps



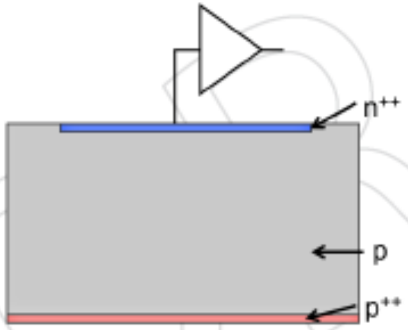
Extrapolation to
2x10^{14} n$_{eq}$/cm^2

Silicon detectors with embedded low-gain layer

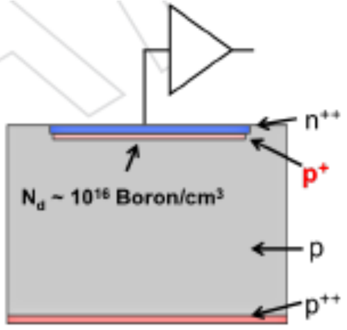
Produce fast-rising signals for precision timing

With suitable readout chip and clock distribution

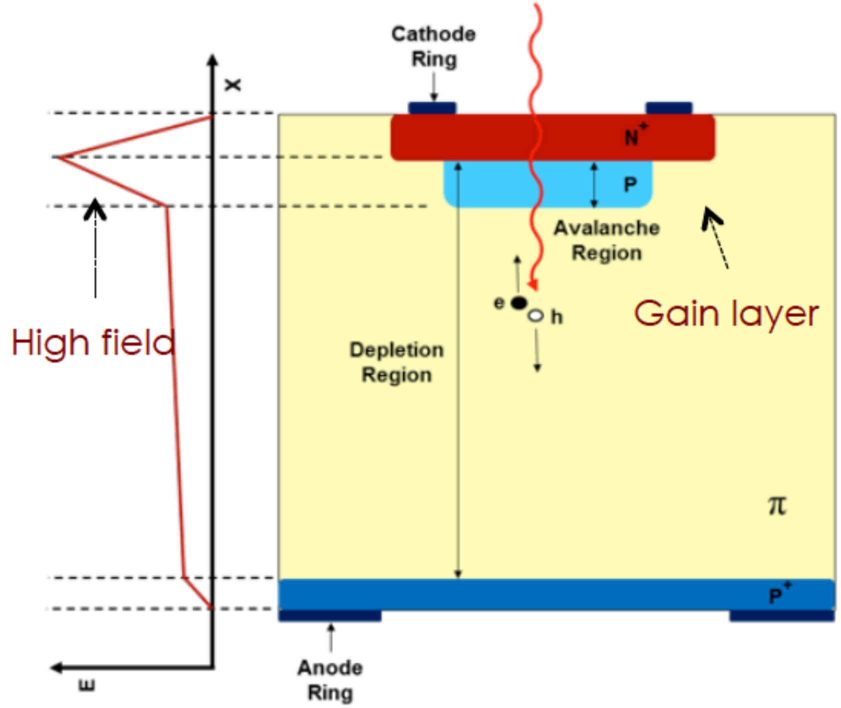
Radiation tolerance is more difficult than for ”standard” sensors



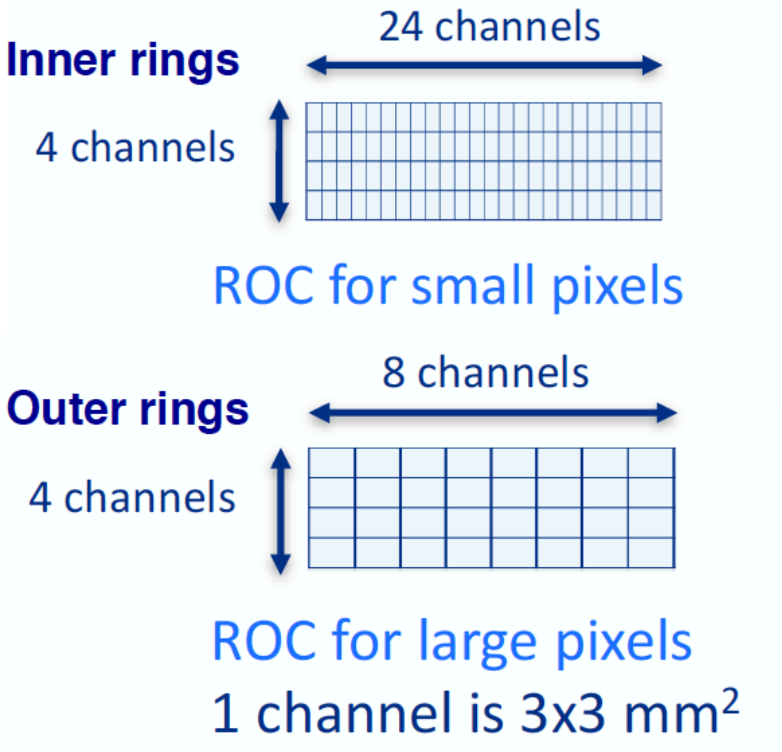
Traditional silicon detector



Low gain avalanche detectors



- **Nominal geometry: 4.8 x 9.6 cm^2 modules with 1x3 mm^2 pads**
  - 16 ASICs bump-bonded to sensors
  - 3:1 ganging in the TDC at small η (3x3 mm^2 granularity)
- **Single pads shown to have $\sigma_t \leq 50$ ps up to 10^{15} n_{eq}/cm^2**
- **Readout ASIC in development**
  - Simulation underway – prototype runs 2018 and 2019



Inner rings

24 channels

4 channels

ROC for small pixels

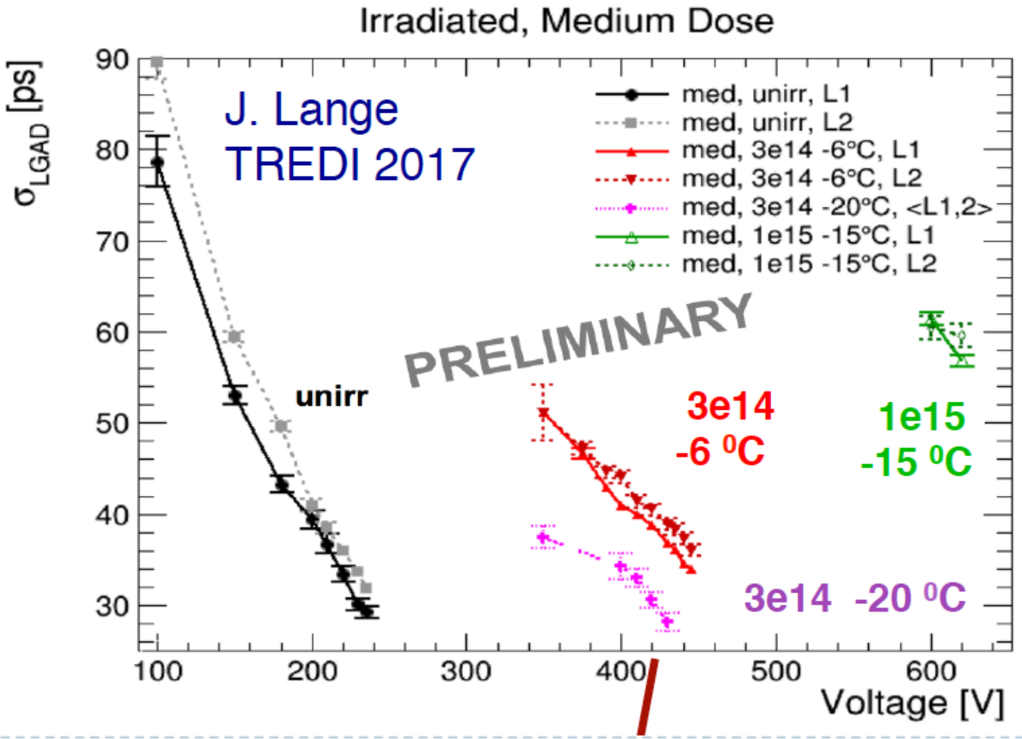
Outer rings

8 channels

4 channels

ROC for large pixels

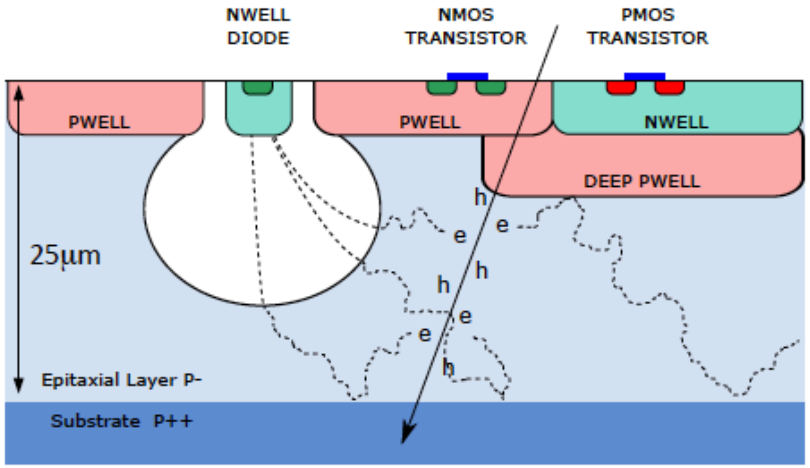
1 channel is 3x3 mm^2



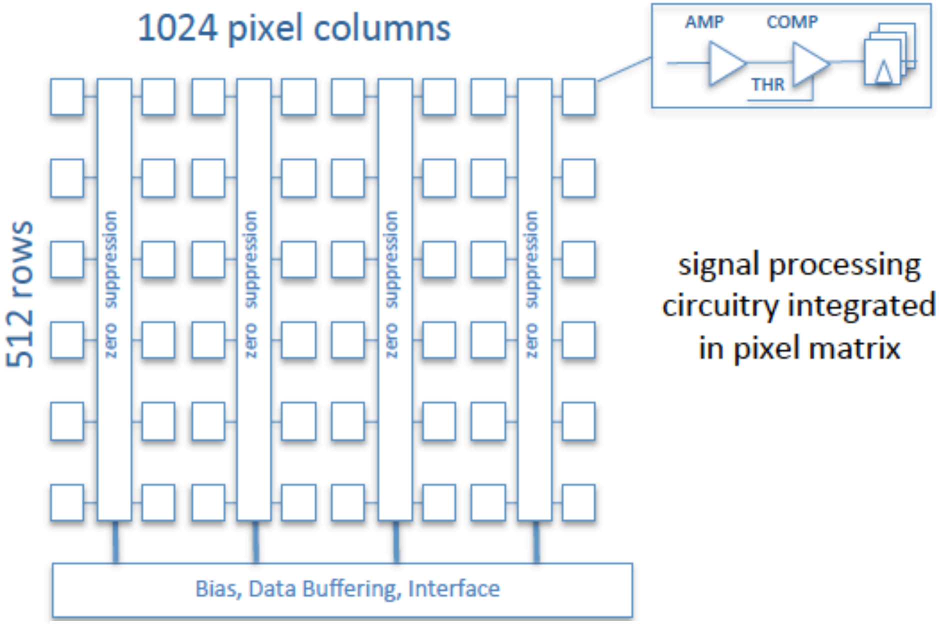
The Others

Other LHC detectors and other new technologies

HV CMOS in ALICE

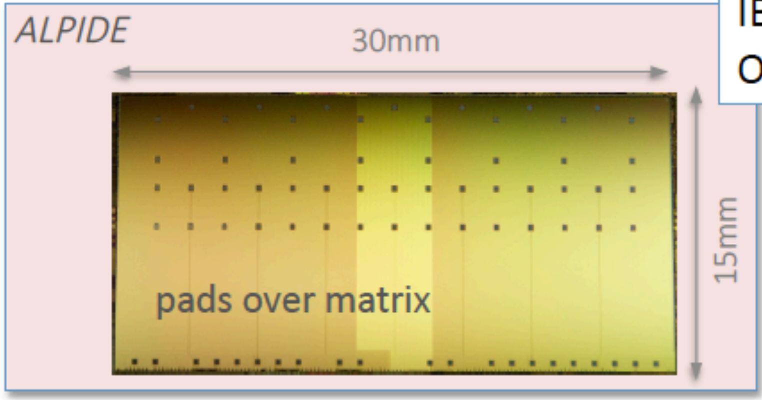


CMOS 180nm

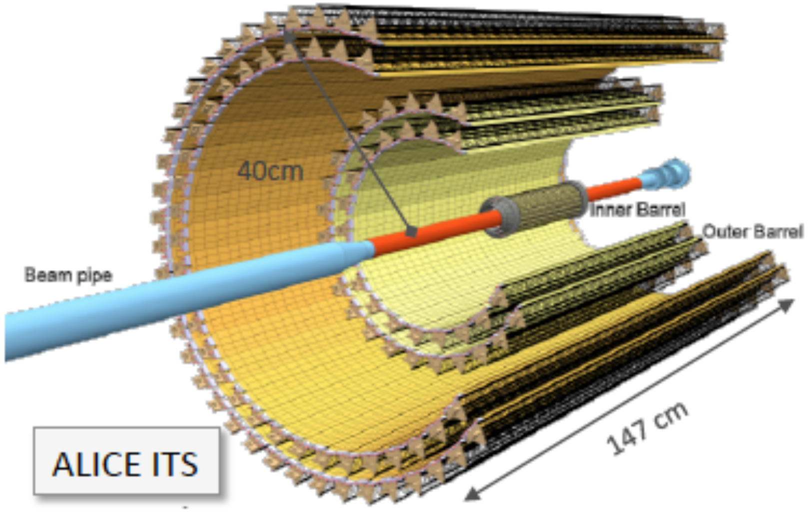


signal processing
circuitry integrated
in pixel matrix

pixel capacitance 2.5 fF (@ V_{bb} = -3 V) ⇨ MIP signal ~ 50mV



IB: 50µm thick
OB: 100µm thick

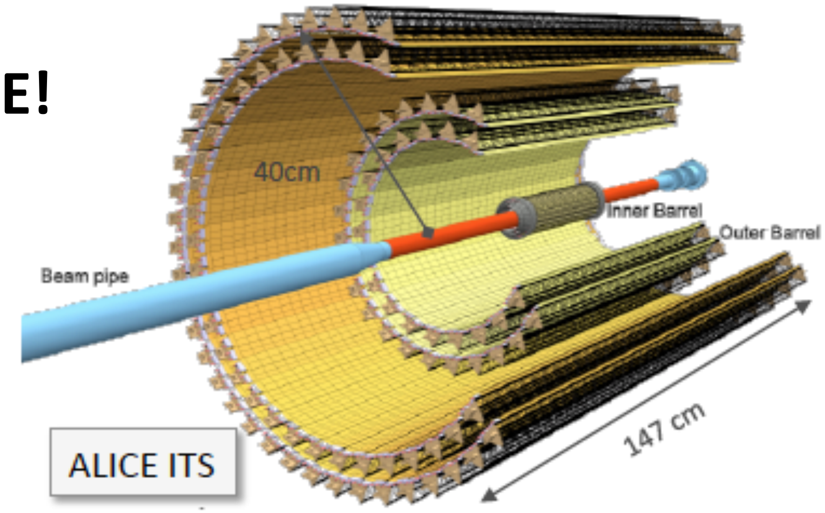


HV CMOS in ALICE

No bump-bonding
Less mass
Less cost (…maybe)

Lower radiation tolerance and rate capabilities

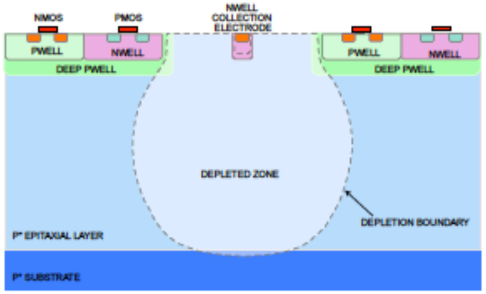
Ideal solution for a best-quality tracker for ALICE!



HV CMOS in ATLAS?!?

- Reduces charge collection time (<1ns)
- Enhances radiation hardness (~10^{15} n / cm^2)

The process modification requires a single additional process mask with no changes on the sensor and circuit layout



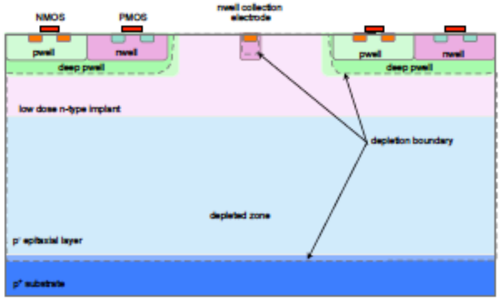
Vertical full depletion

Lateral partial depletion

Collection time < 30ns (V_{bb}=-3V)

Suitable for up to 10^{14} n/cm^2

Foundry Standard Process



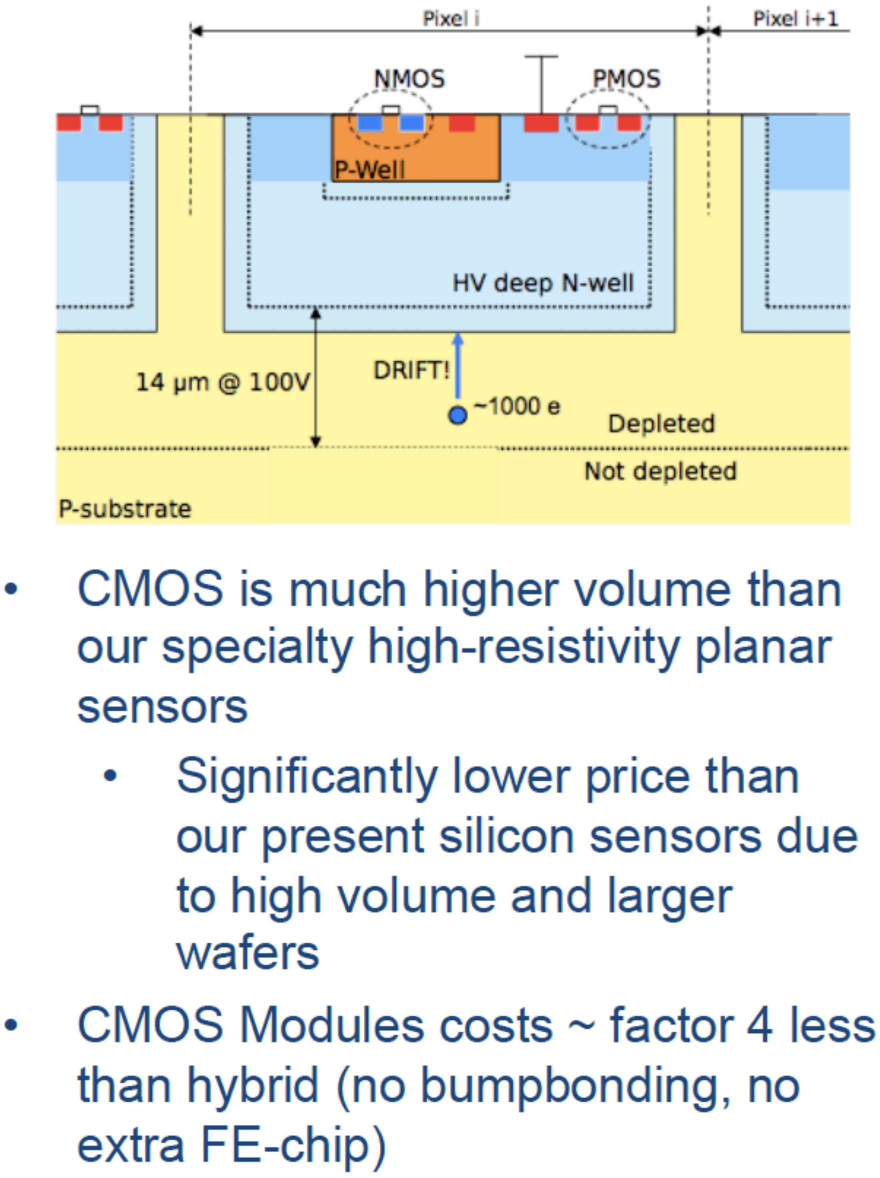
Epi-layer fully depleted

Collection time < 1ns

Operational for up to 10^{15} n/cm^2

Modified process CERN/Tower

	ALICE ITS	ATLAS Outer Pixel	ATLAS Inner Pixel
NIEL [n_{eq}/cm^2]	10^{13}	10^{15}	10^{16}
TID	<1Mrad	80 Mrad	2x500Mrad
Response Time [ns]	2000	25	25
Hit rate [MHz/cm^2]	10 + SF	100-200	2000



- CMOS is much higher volume than our specialty high-resistivity planar sensors
  - Significantly lower price than our present silicon sensors due to high volume and larger wafers
- CMOS Modules costs ~ factor 4 less than hybrid (no bumpbonding, no extra FE-chip)

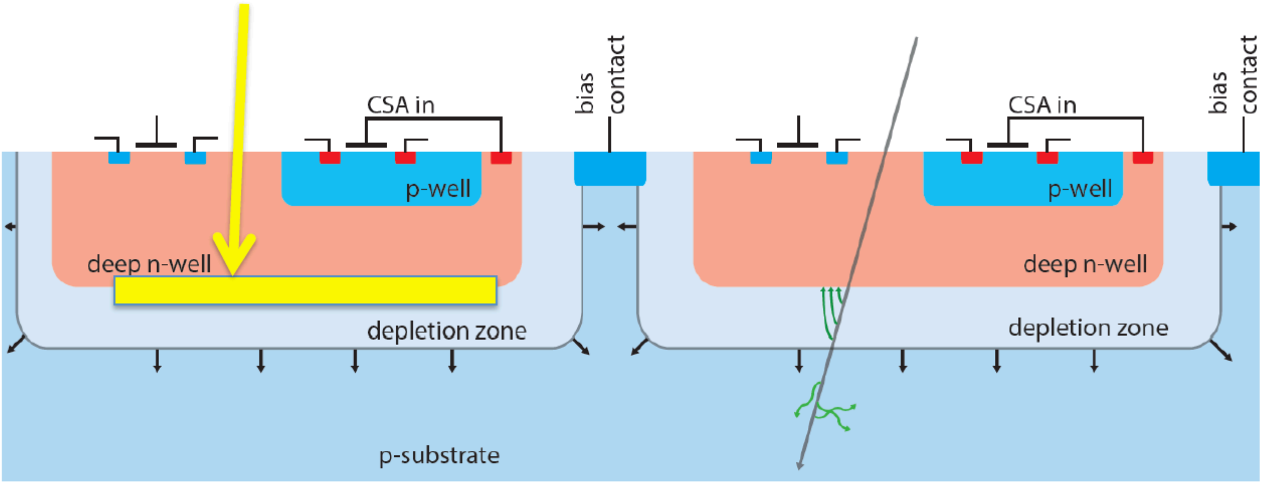
⟵ From an ATLAS slide

Same cost as our PS system
(not counting the development cost!)

No advantage for performance

The technology is very appealing
Especially if it's used where it is useful!

Futuristic silicon



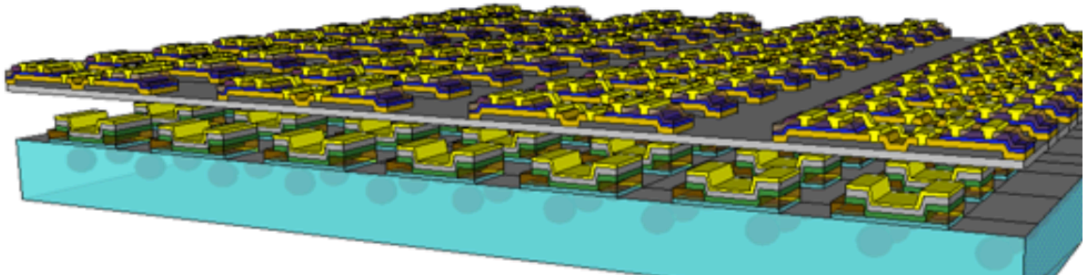
Add a boron layer similar to LGAD

Fast timing HV CMOS ??

Thin film particle detectors ????

Thin Films: thin layers of materials ranging from nm to µm

- Current popular applications
  - solar cells
  - LCD screens
- Thin Films for Particle Detectors:
  - Thin Film Diodes + Thin Film Transistors



Remarks

HV CMOS and LGAD, combine and add functionalities in a piece of silicon, respectively

HV CMOS is interesting to realize low mass detectors operating at low/intermediate rates
Possibly in future for large-surface implementation in not too-high rates (if indeed low cost / good yield is achieved)

LGAD is very interesting for high pileup environment, but not for use in the highest density regions

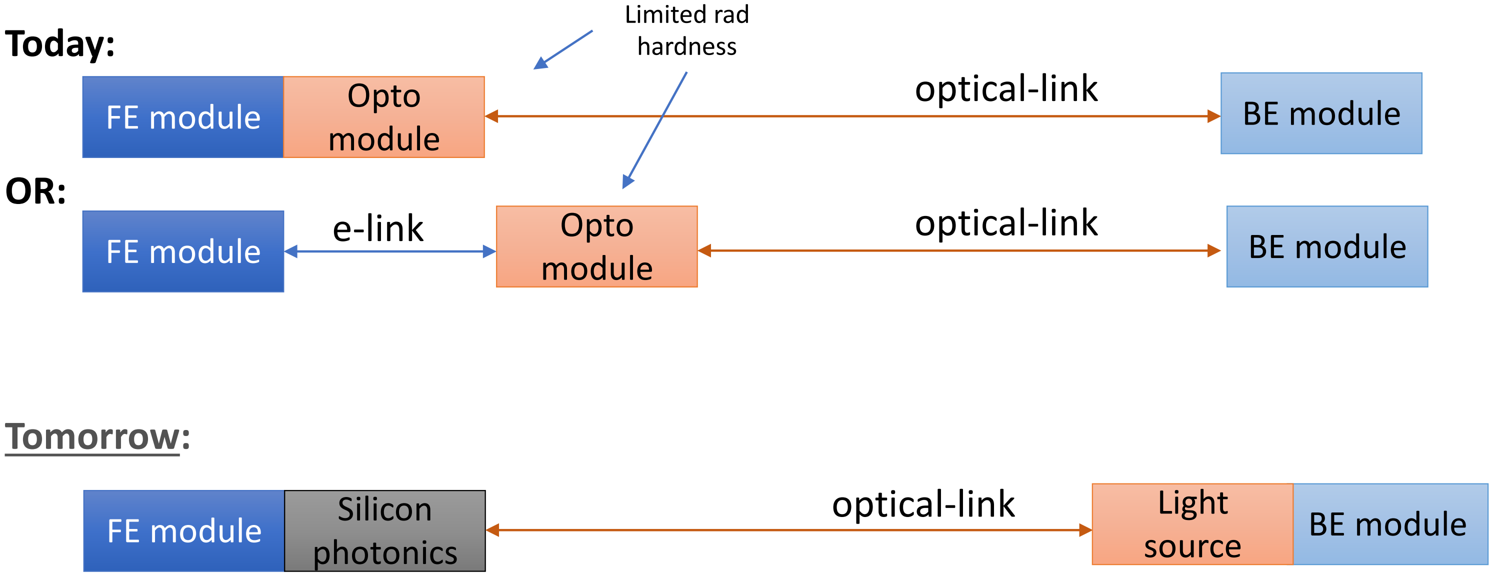
None of the two developments (nor any other I know of) improves on rad tolerance of traditional sensors
… on the contrary!

With the R&D planned in the next two years we may say a final word about radiation tolerance of silicon sensors…!

Silicon photonics

Use silicon as optical medium (transparent in the 1.3 – 1.6 µm range)
Modulators can be realized as reverse-biased PN junctions

- *Radiation resistance potentially as good as Si-sensors and CMOS electronics*
- *Possibility of co-integration with readout electronics*
- *Place light source in the back-end*



Today:

FE module | Opto module | optical-link | BE module

Limited rad hardness

OR:

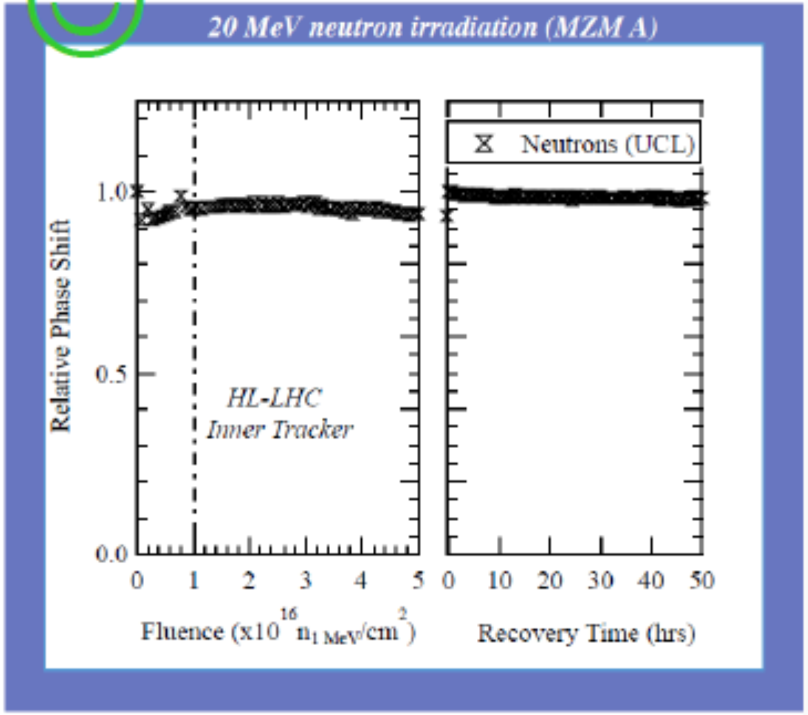
FE module | e-link | Opto module | optical-link | BE module

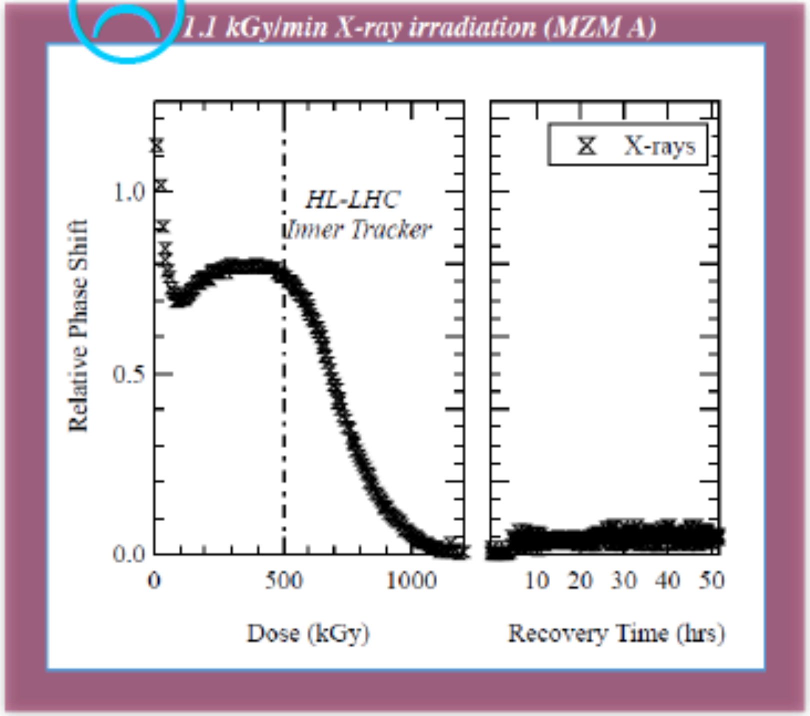
<u>Tomorrow</u>:

FE module | Silicon photonics | optical-link | Light source | BE module

From 2016: radiation testing of Mach-Zender modulators

- neutron irradiation
- X-ray irradiation


20 MeV neutron irradiation (MZM A)


1.1 kGy/min X-ray irradiation (MZM A)

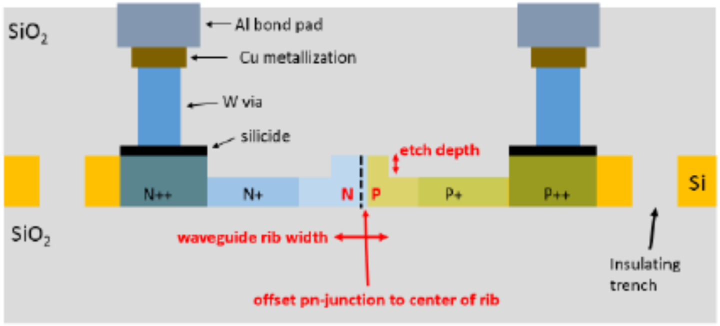
Intriguing results!

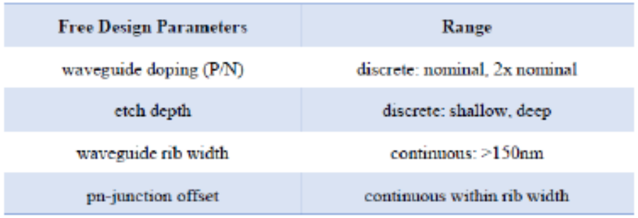
Hint: effect from charge trapping in oxide layers, but no effect from bulk damage!

Can it be improved further with custom designs?

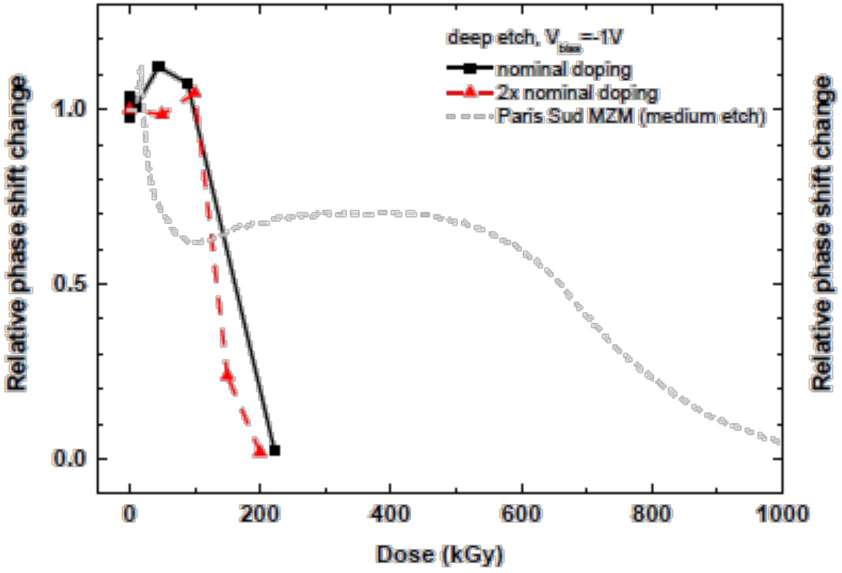
Large improvement obtained by varying design parameters!

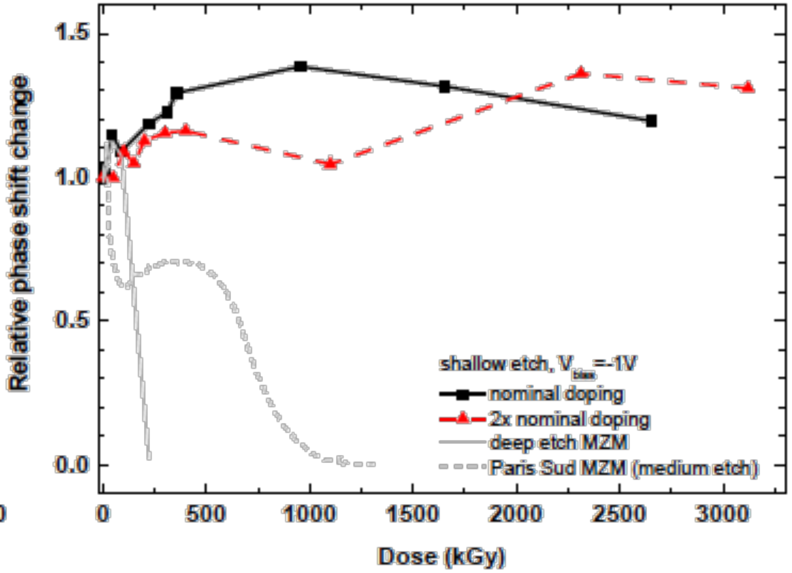
Cross-section through a typical MZM phase shifter with lateral pn-junction





Free Design Parameters	Range
waveguide doping (P/N)	discrete: nominal, 2x nominal
etch depth	discrete: shallow, deep
waveguide rib width	continuous: >150nm
pn-junction offset	continuous within rib width





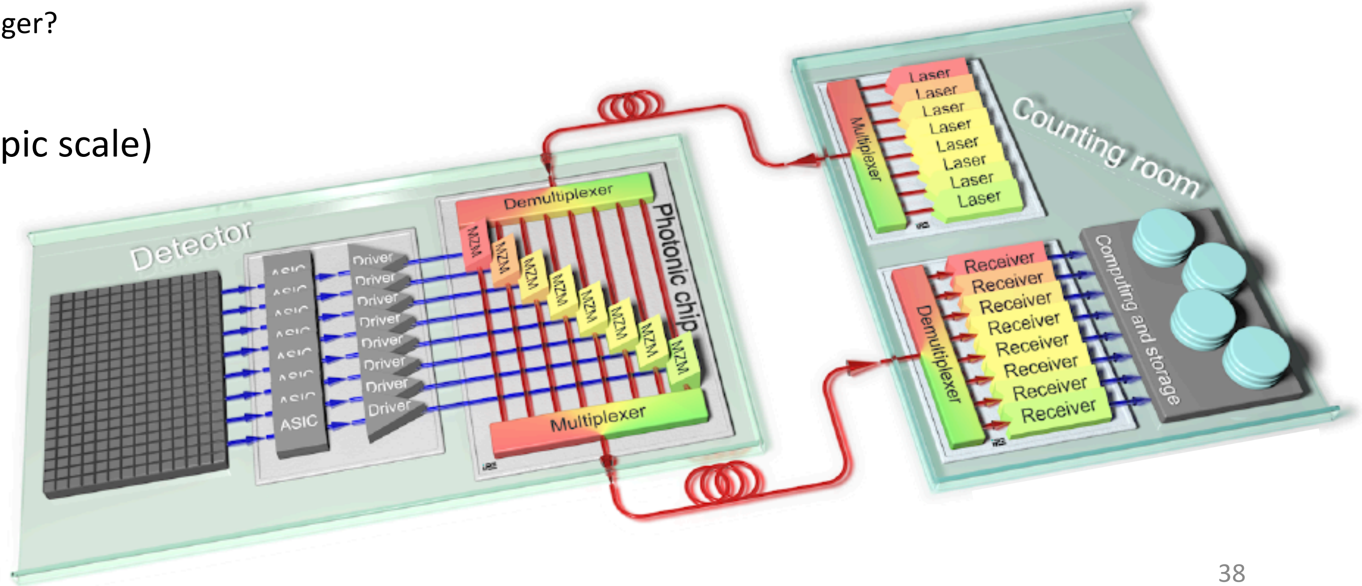
Silicon photonics: outlook

Large R&D program needed to develop solutions adapted to HEP

- ➢ Crucial aspects are packaging and connectivity
- ➢ Learn how to optimally use these devices in system design

May open new horizons for future trackers (and particle detectors in general)

- ○ Large bandwidth from the front-end
  - Trackers more regularly used in L1 trigger?
- ○ Extreme radiation hardness
- ○ Avoid electrical links (on macroscopic scale)
- ○ Reduction of mass and power



Power and data links: beyond future…

Draft: 06/04/2017

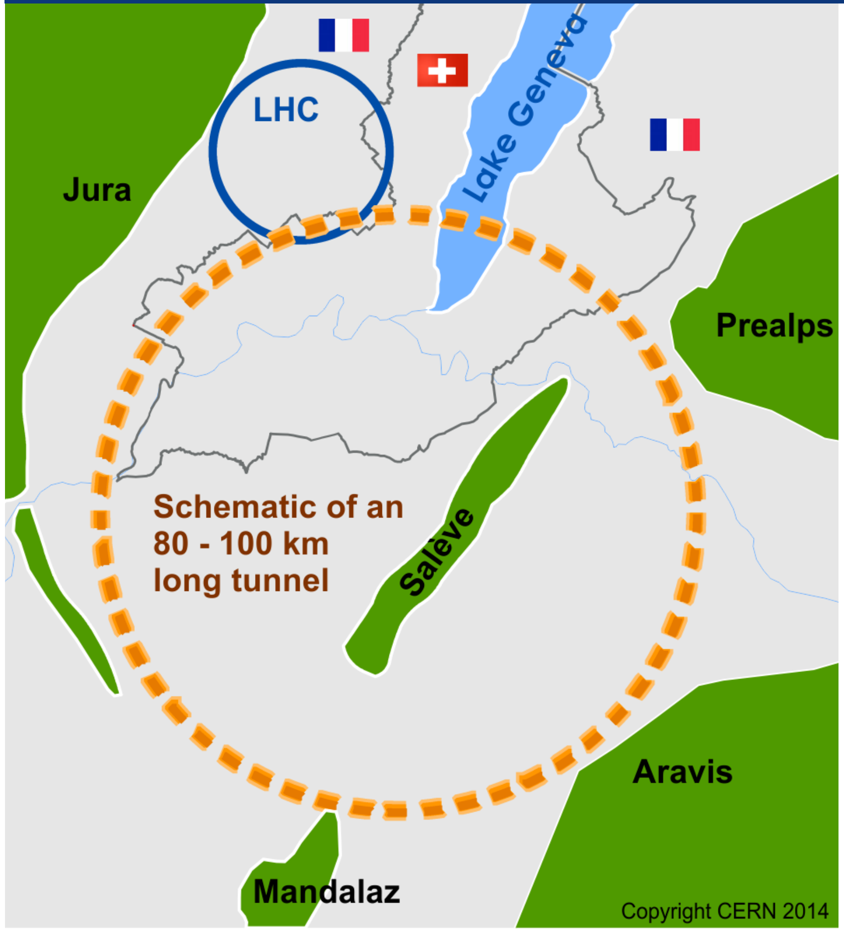
- Technical Proposal -

DEVELOPMENT OF WIRELESS TECHNIQUES IN DATA AND POWER TRANSMISSION APPLICATION FOR PARTICLE-PHYSICS DETECTORS

- WADAPT -

Wireless Allowing Data And Power Transmission

Scope of FCC Study



International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
- → main emphasis, defining infrastructure requirements
- **~16 T ⇒ 100 TeV *pp* in 100 km**

- **~100 km tunnel infrastructure** in Geneva area, site specific

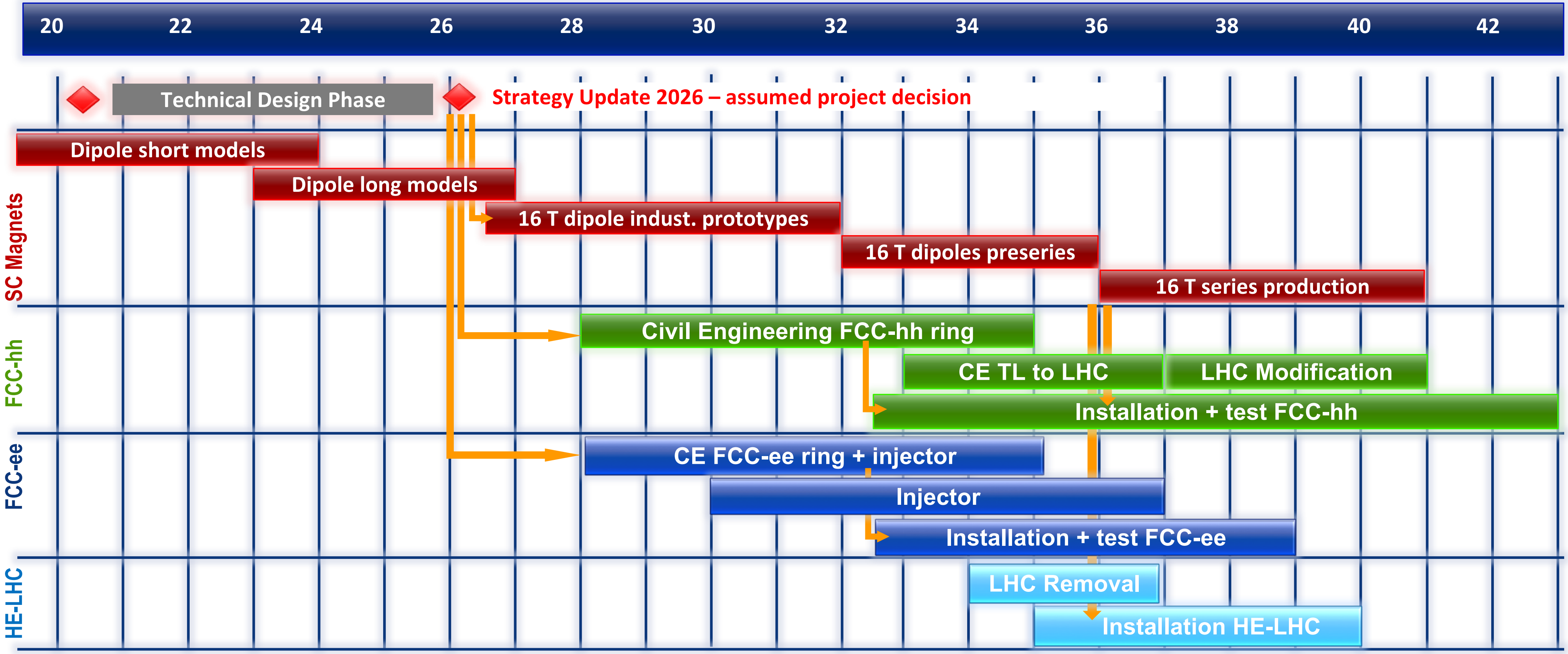
- ***e^+e^-* collider (*FCC-ee*)** as potential first step

- ***p-e* (*FCC-he*) option,** integration one IP, e from ERL

- **HE-LHC** with *FCC-hh* technology (LHC Ring 8→16T, 14→28TeV)

- **CDR for end 2018**

Draft Schedule Considerations



20 22 24 26 28 30 32 34 36 38 40 42

Technical Design Phase

Strategy Update 2026 – assumed project decision

SC Magnets

Dipole short models

Dipole long models

16 T dipole indust. prototypes

16 T dipoles preseries

16 T series production

FCC-hh

Civil Engineering FCC-hh ring

CE TL to LHC

LHC Modification

Installation + test FCC-hh

FCC-ee

CE FCC-ee ring + injector

Injector

Installation + test FCC-ee

HE-LHC

LHC Removal

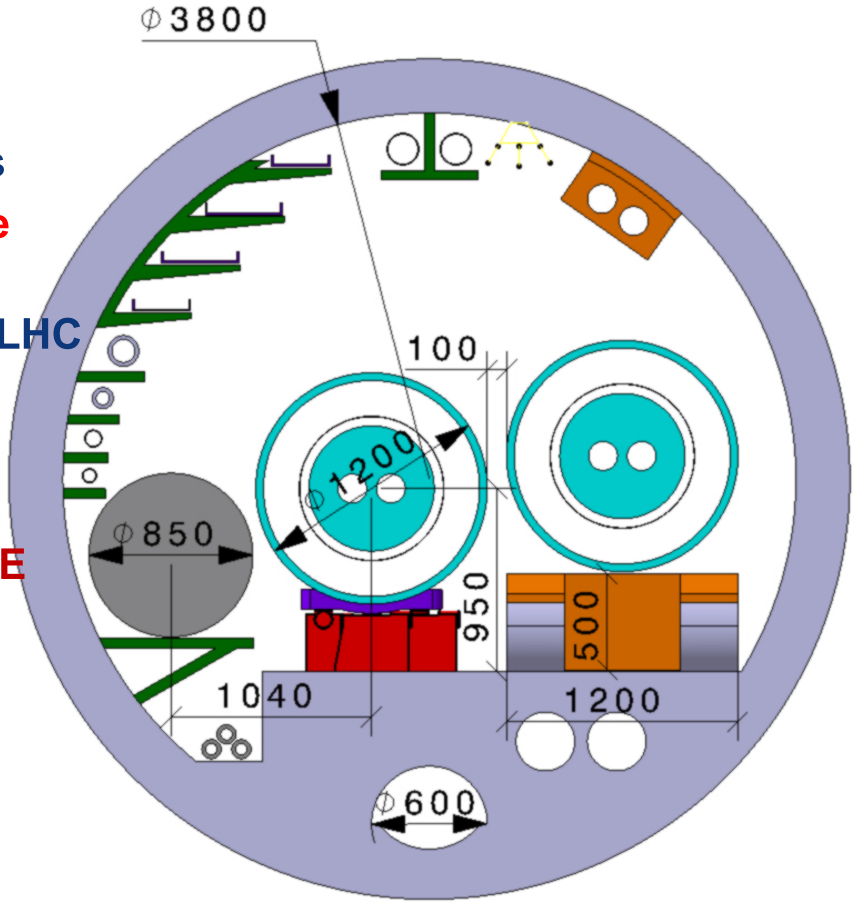
Installation HE-LHC

HE-LHC integration aspects

Working hypothesis for HE LHC design:

No major CE modifications on machine tunnel and caverns

- Similar geometry and layout as LHC machine and experiments
- **Maximum magnet cryostat external diameter compatible with LHC tunnel ~1200 mm**
- **Classical 16 T cryostat design based on LHC approach gives ~1500 mm diameter!**



Strategy: develop a single 16 T magnet, compatible with both HE LHC and FCC-hh requirements:

- **Allow stray-field and/or cryostat as return-yoke**
- **Optimization of inter-beam distance (compactness)**

→ Smaller diam. also relevant for FCC-hh cost optimization

FCC-pp collider parameters

parameter	FCC-hh		HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100		27	14	14
dipole field [T]	16		16	8.33	8.33
circumference [km]	97.75		26.7	26.7	26.7
beam current [A]	0.5		1.12	1.12	0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	2.2	1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25	25
synchr. rad. power / ring [kW]	2400		101	7.3	3.6
SR power / length [W/m/ap.]	28.4		4.6	0.33	0.17
long. emit. damping time [h]	0.54		1.8	12.9	12.9
beta* [m]	1.1	0.3	0.25	0.20	0.55
normalized emittance [μm]	2.2 (0.4)		2.5 (0.5)	2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	25	5	1
events/bunch crossing	170	1000 (200)	~800 (160)	135	27
stored energy/beam [GJ]	8.4		1.3	0.7	0.36

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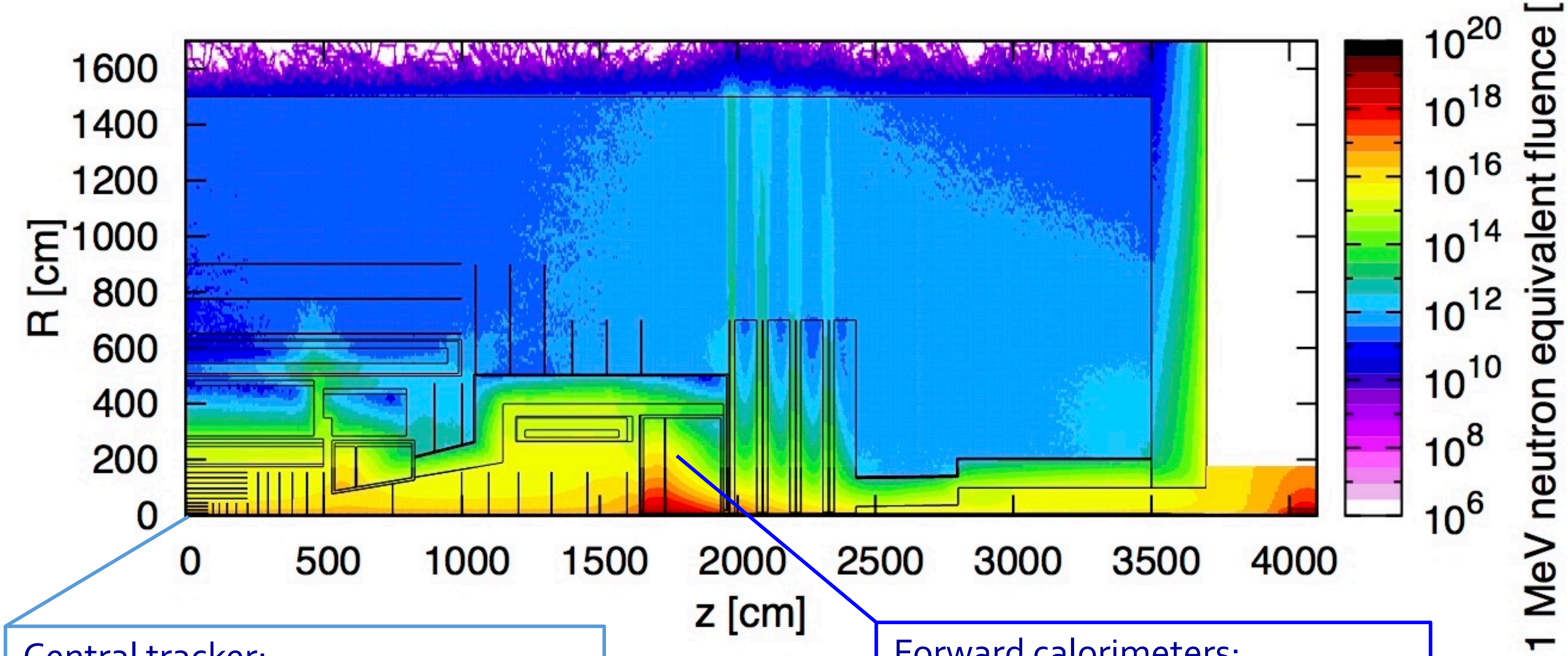
1 MeV neutron equivalent fluence for 30ab^{-1}



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 the EM and the HAD-calo
- ○ 10^{16} cm^{-2} at R=2 m

Technologies for Tracking at ⟶ 1000 pileup

- **Outer layers - a few 10^{15}:** LGAD and HVCMOS promising
  - LGAD: timing will be precious
  - HVCMOS: low cost for large surfaces – easy mass production
    - Both combined?
- **Intermediated layers - a few 10^{16}**: standard Si sensors still the option
  - With readout chips in advanced technologies
- **Innermost layers - a few 10^{16}** ***per year***: is this silicon???
  - More than one replacement per year is going to be very unpractical…
  - Stay tuned for the results of the next two years
  - Maybe need to consider more creative solutions here!

- **Readout links: silicon photonics**
- **p_T modules (useful at all stages!)**
- **Tracking information at Level-1**
  - ✓ (e.g. everything from outer layers, stubs from intermediate layers)
- **Serial powering**

From a meeting of the CERN EP department on future R&D:

We should formulate the needs for an FCC detector, but place the detector R&D inside the existing CERN programs e.g.

- Change of ATLAS CMS pixels during the HL-LHC period
- Possible further upgrades of ATLAS, CMS during HL-LHC period
- LHCb PhaseII upgrade, ALICE PhaseII upgrade
- Fixed target experiments (existing, Ship …)

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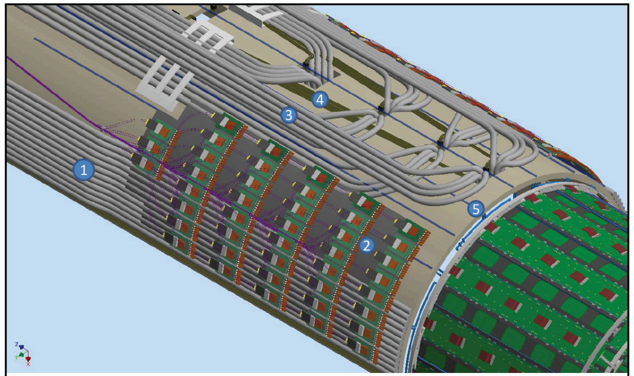
Pixel phase-3?

Technologies for pixel phase-3

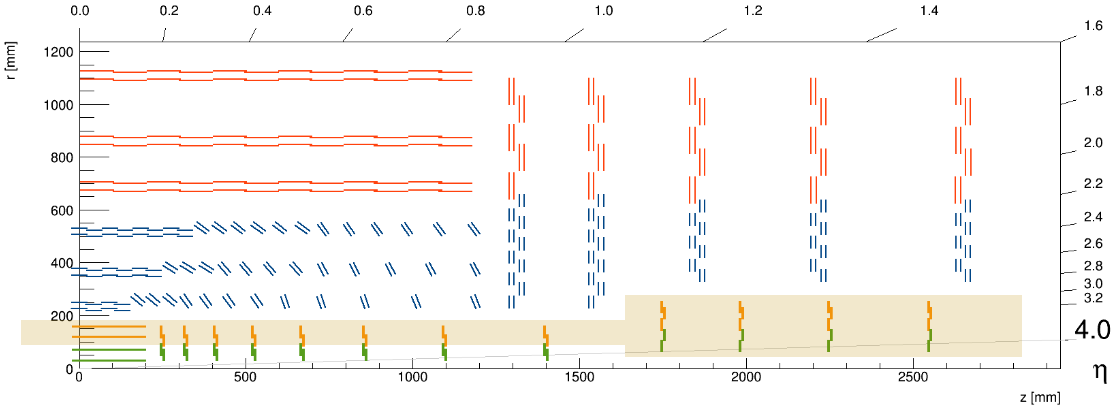
- **Silicon photonics**
  - Get rid of lpGBT boards and DC/DC converters
  - All functionalities integrated in (serially powered) modules
  - Reduce complexity and remove mass from service cylinders
  - Rad hard enough for layer 1? Timescale?

- **More advanced ASIC technology**
  - Reduce power (by a large factor)



1: TBPX power bundle scheme. 2: TBPX port card mount. 3: TFPX first 4 double-dee power bundle scheme. 4: TFPX cooling tube routing. 5: TBPX cooling tube routing.

Technologies for pixel phase-3



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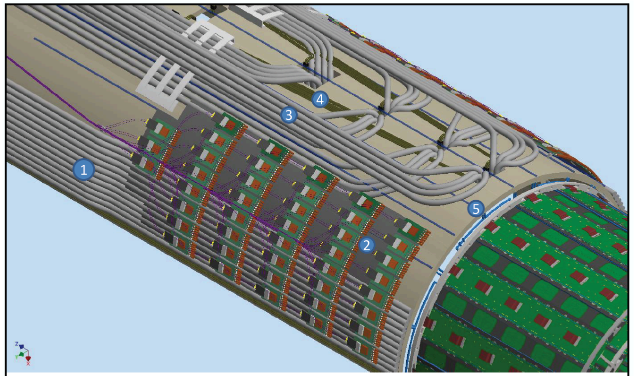

1: TBPX power bundle scheme. 2: TBPX port card mount. 3: TFPX first 4 double-dee power bundle scheme. 4: TFPX cooling tube routing. 5: TBPX cooling tube routing.

- **More advanced ASIC technology**
  - Reduce power (by a large factor)

- **Maybe LGAD for more timing layers?**
  - Extend acceptance of timing measurements in rapidity and p_T
  - Rad hard enough?
  - High granularity? Tracking performance? Power?

Concluding:

… all that might be very fancy, but now we have to build the phase-2 upgrades!