Pixel 2014 - Niagara Falls, Canada

Pixel detector (sensors) for the CMS phase-II upgrade

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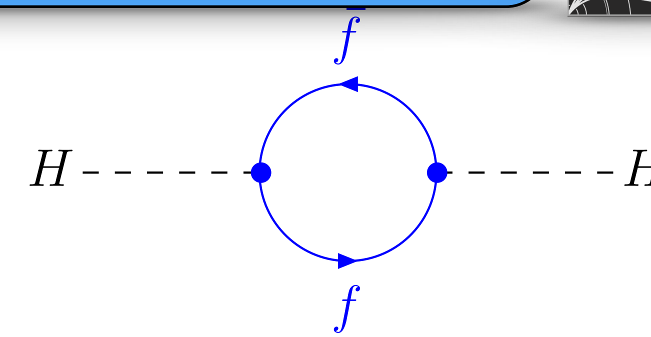
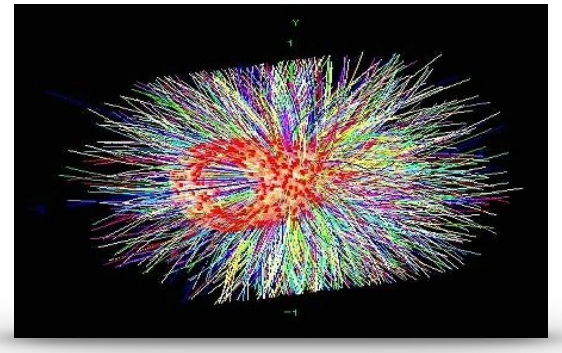
On behalf of the CMS collaboration

04/09/2014

Outline

- CMS pixel phase-II upgrade motivations





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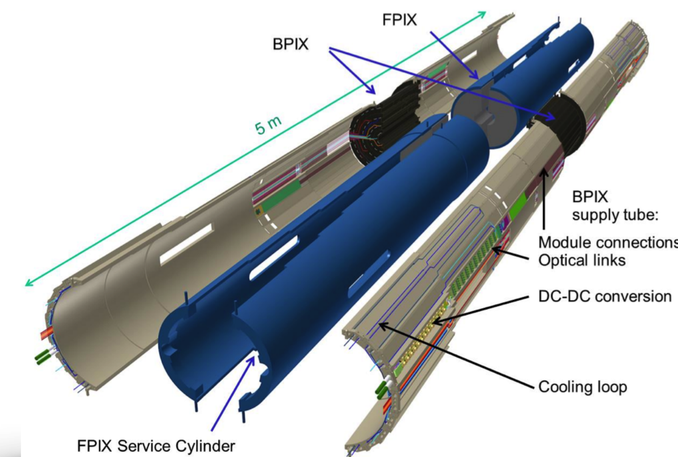

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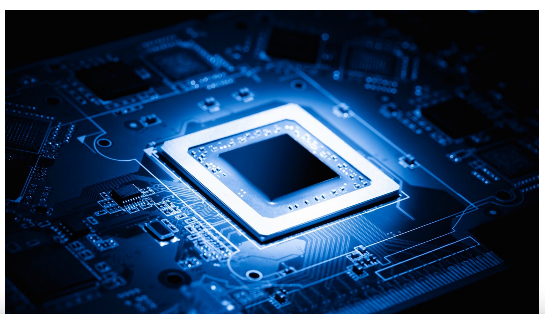

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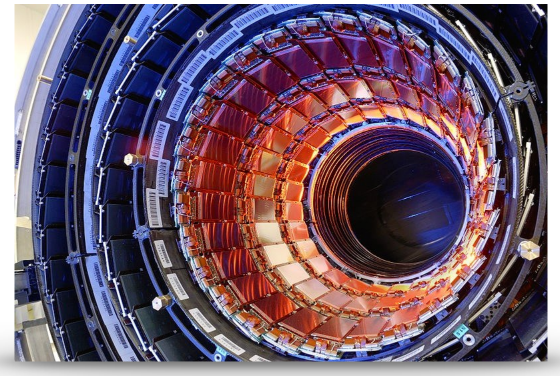

- Possible sensor choices

- Conclusions

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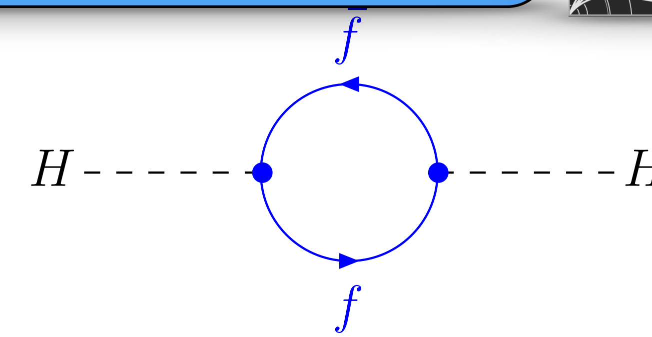

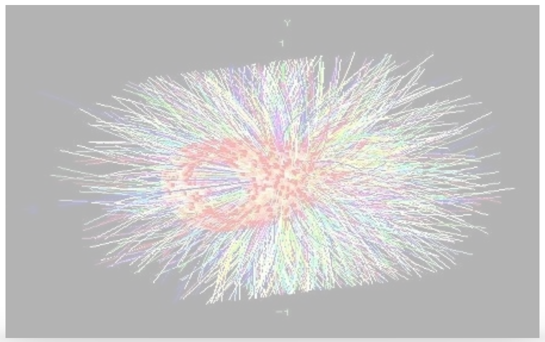

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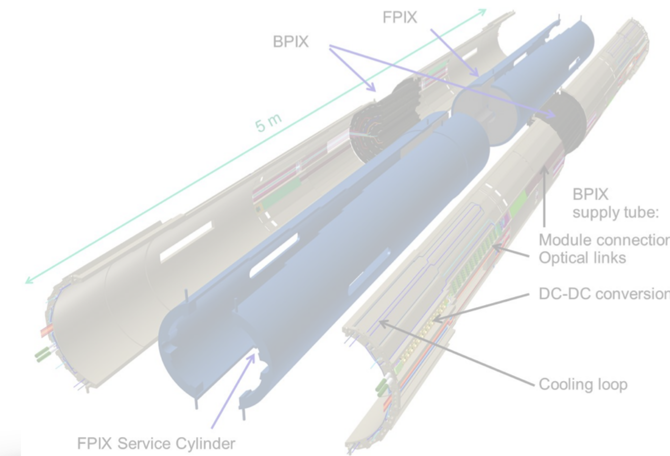

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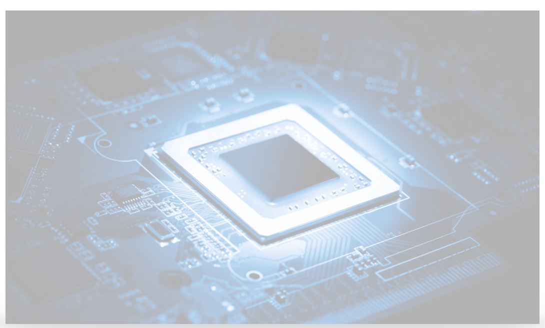

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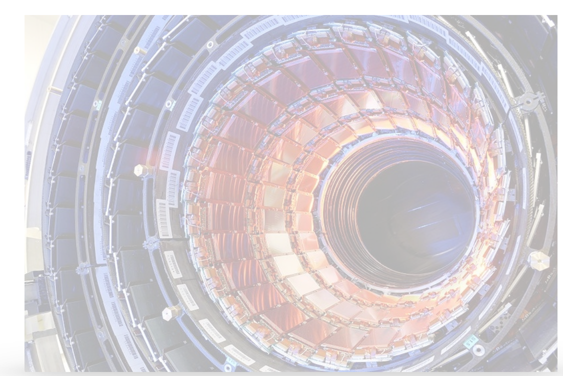

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Phase-II upgrade motivations

Major achievement of LHC: Higgs discovery in 2012 !

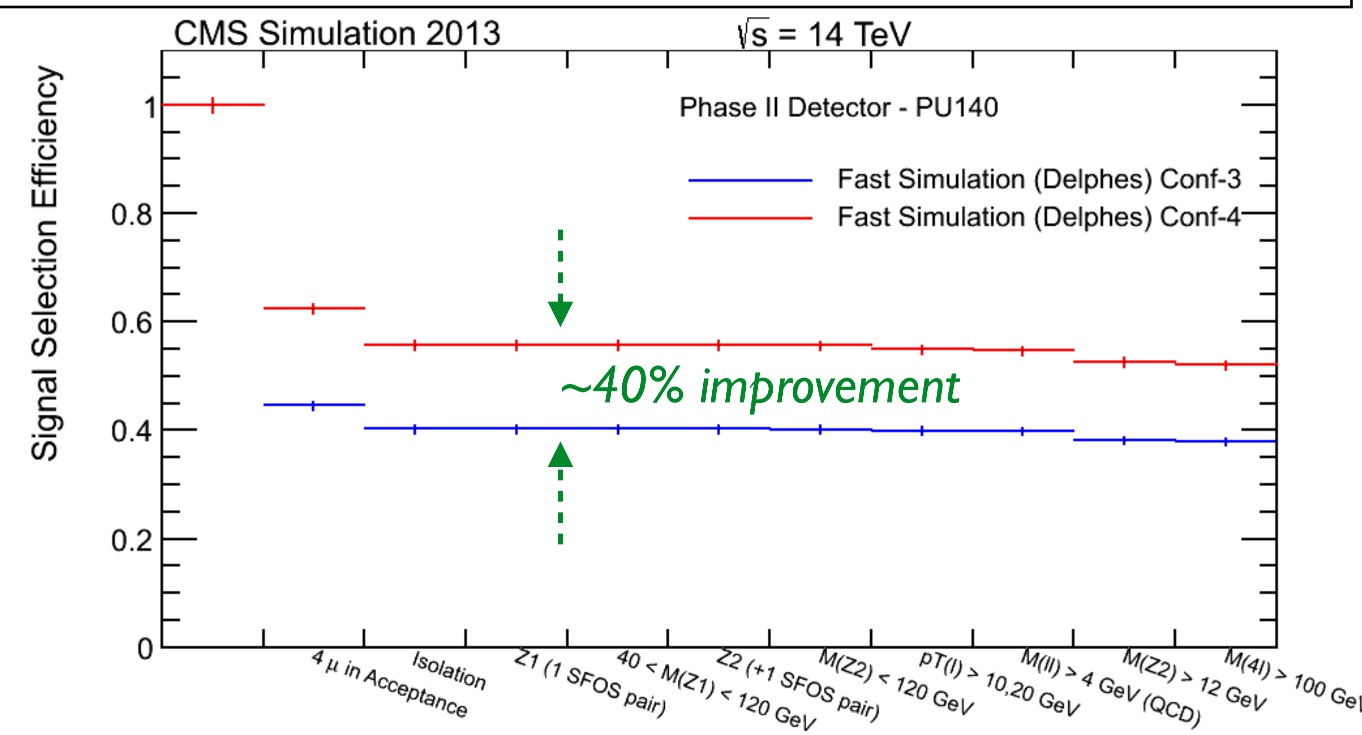
That's not the whole story, there are other questions that need to be answered

- Need to investigate the entire Higgs sector
  - Higgs coupling and property measurements
  - Di-Higgs searches with the aim of Higgs self coupling measurement
  - Vector Boson Scattering (VBS) measurements (*crucial forward tagging jets*)
- Standard Model (SM) measurements
  - Precision measurements (*e.g.* m_W, $\sin\theta_W$, α_s)
  - Search for rare SM processes, enhanced by BSM (*e.g.* $B_{s,d} \rightarrow \mu\mu$)
  - Differential measurements of W, Z, di-boson, Top

All these measurements require a lot of data

Efficiency cut flow for $H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$

- **Conf-3:** sub-detectors have same **angular acceptance** as **current version**, but central tracking detector and the forward electromagnetic calorimeters are replaced and improved
- **Conf-4:** tracking, electromagnetic and hadronic calorimetry, and muon detector, are **increased in acceptance up to $\eta \approx 4$**



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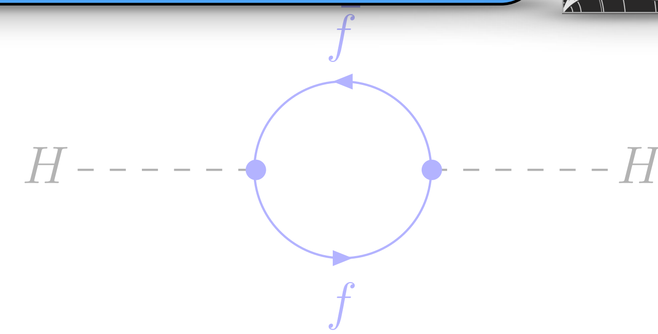

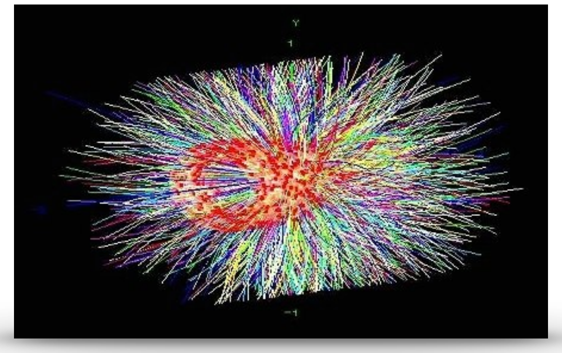

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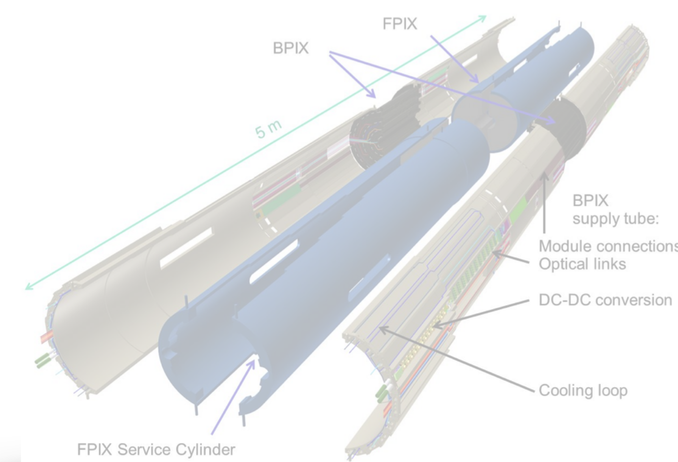

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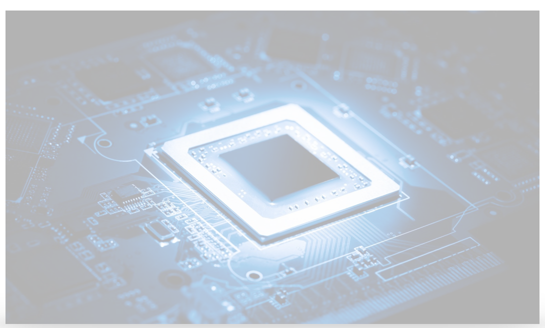

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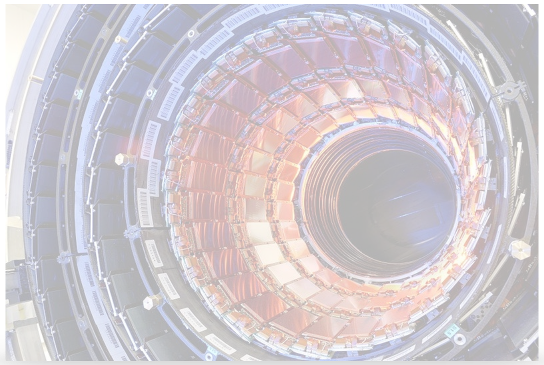

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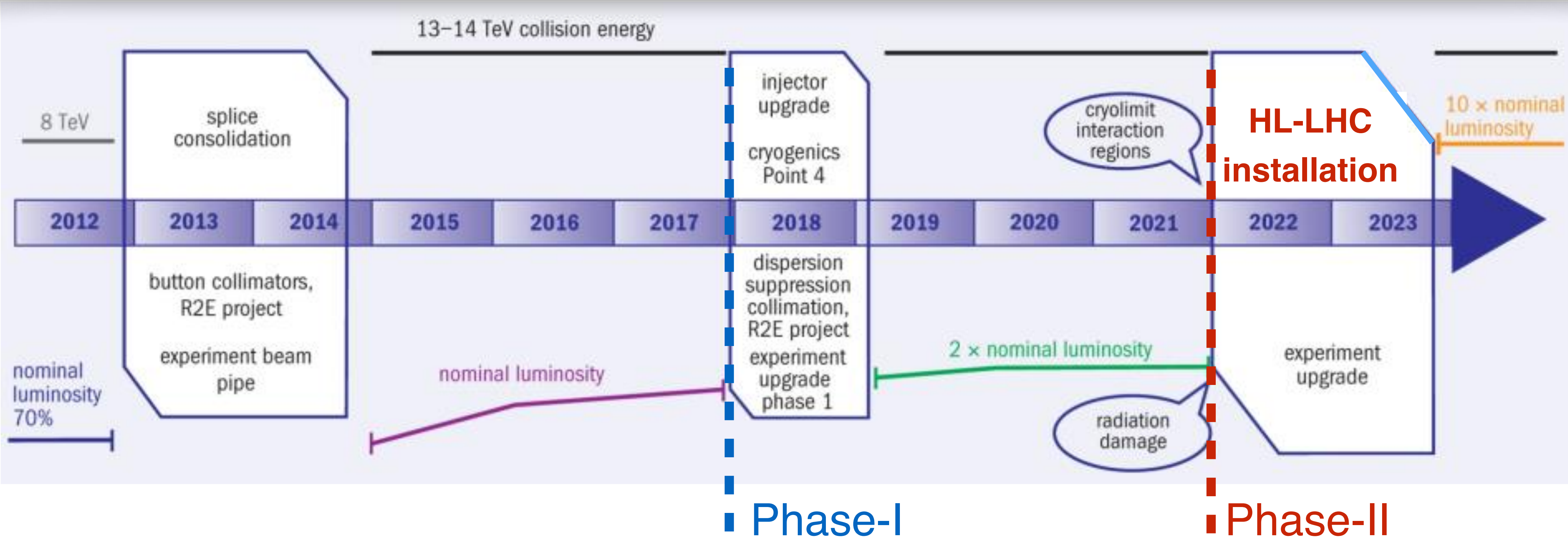
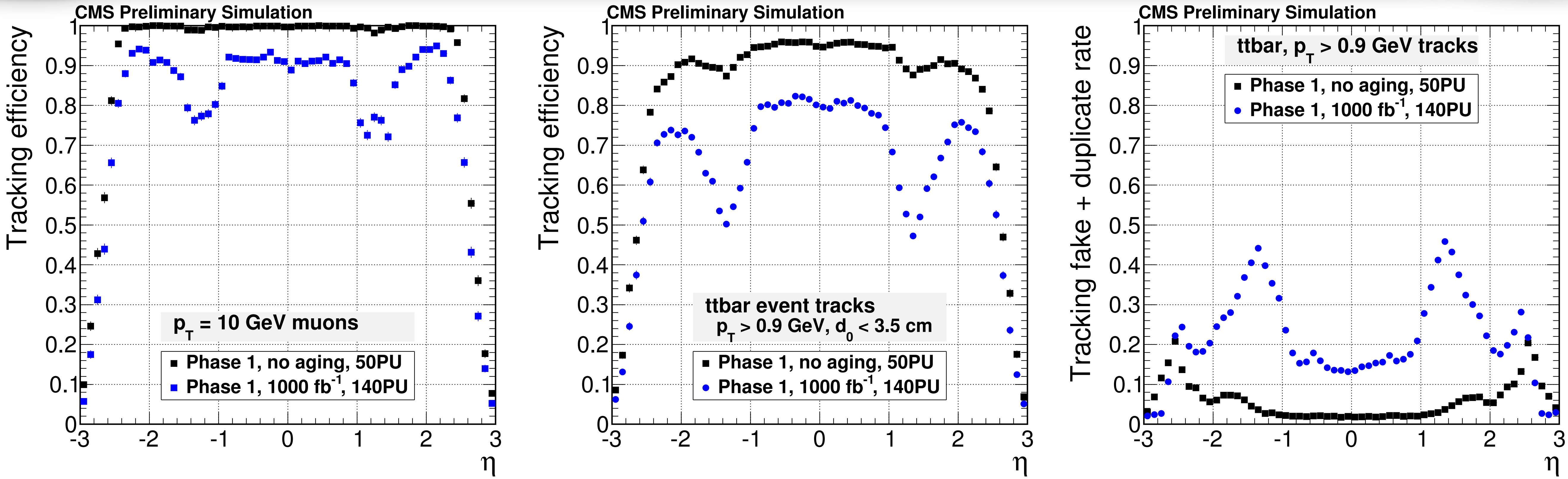


High Luminosity (HL) - LHC: upgrade damaged low-β triplets and install crab-cavities to optimise bunch overlap

- Energy = 14 TeV
- L_{inst} = 5x10^{34} cm^{-2} s^{-1} (➜ *~10 times now*)
- L_y = ~300 fb^{-1} / year (L_{total} ~ **3000 fb^{-1}** in 10 years)
- 25 ns bunch spacing
- <PileUp> = **140** (➜ *now 25*)
- Radiation @30 mm from IP: **2x10^{16} n_{eq} / cm^2** (➜ *~10 times phase-I*)
- Dose @30 mm from IP: **10 MGy** (1 Grad)
- Hit rate: **~2 GHz / cm^2** (➜ *~10-20 times now*)

Huge R&D is required to cope with harsh environment

Pixel detector operating conditions



Overall tracking performance degradation with ageing

- After 500 fb^{-1} **impact parameter** degradation of more than **50%**
- <PU> = 140 imply an irreducible **data loss** of **~7%**

Effects on the physics program

- Efficiency loss diminishes effectiveness of high-p_T lepton isolation, and degrades jet energy and missing transverse energy resolutions
- Fake tracks causes biases and resolution degradation in jet energy measurements, increases background levels, and adversely affects high-p_T lepton isolation criteria

Outline

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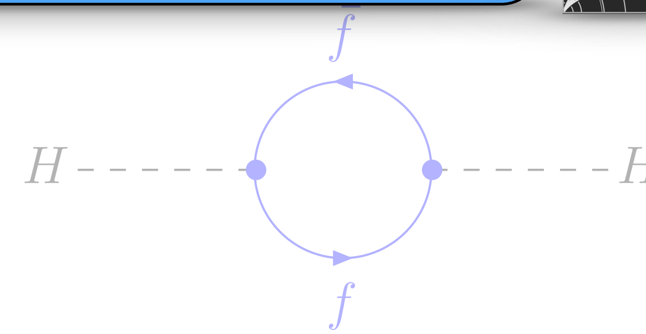

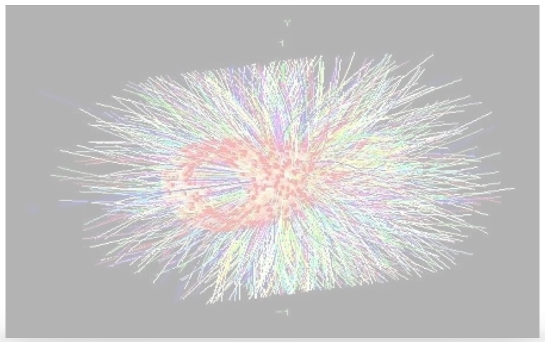

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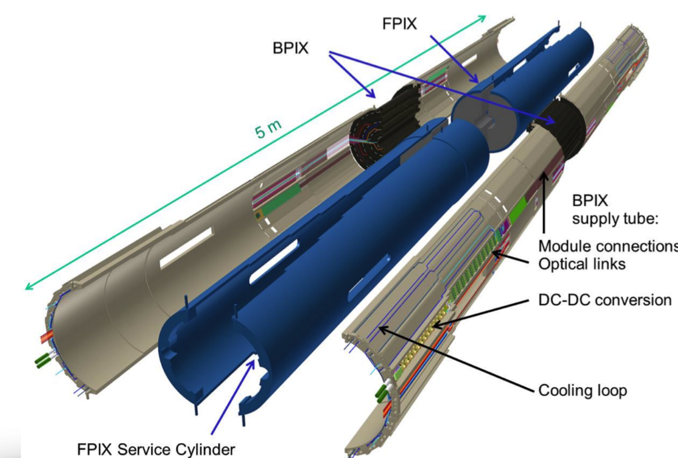

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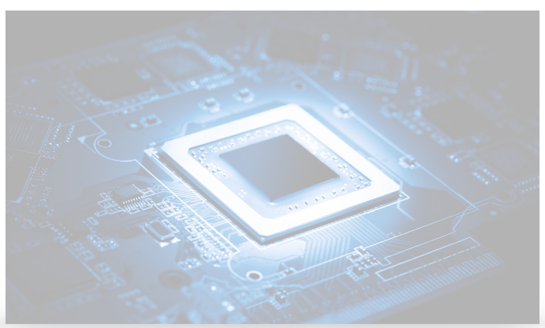

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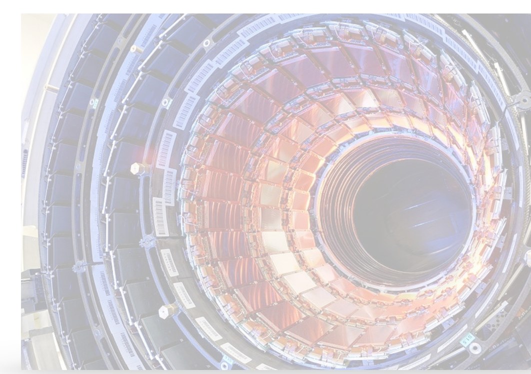

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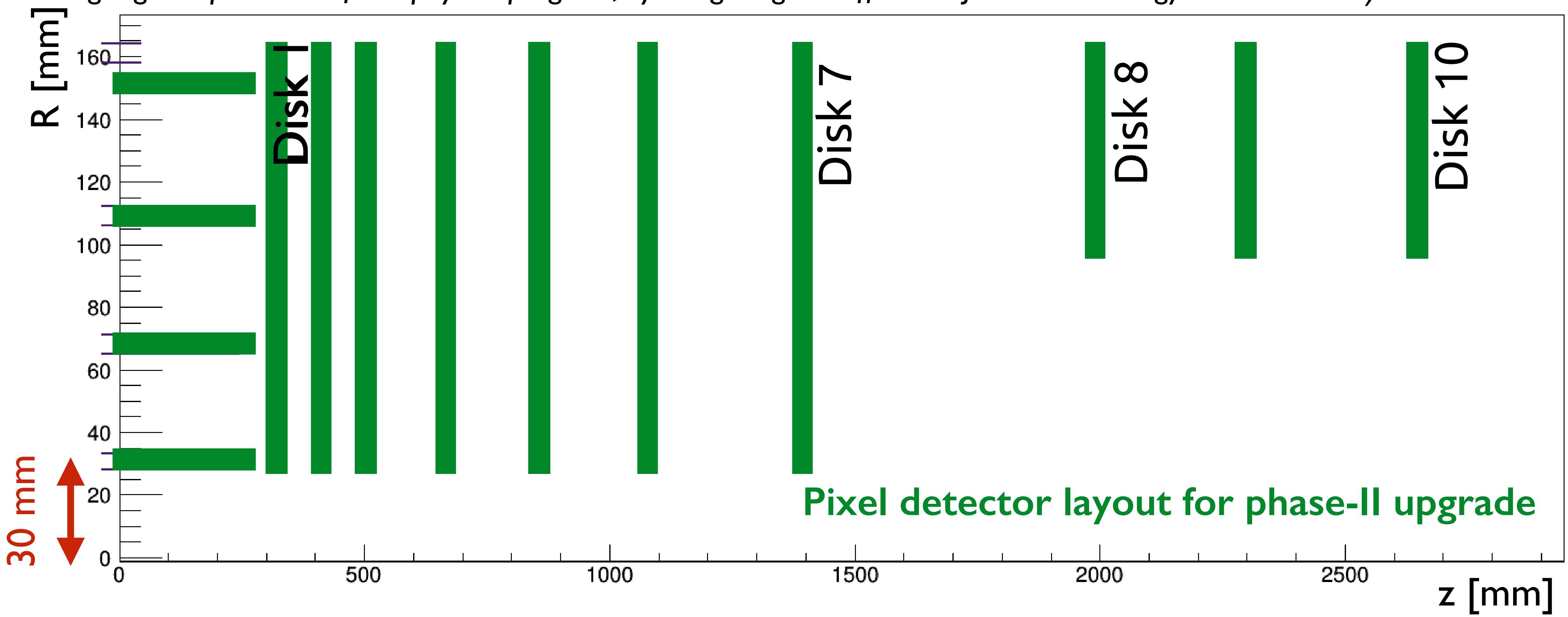
Pixel detector layout choices

Pixel detector layout for phase-II upgrade

- Improve resolution at high-p_T and improve two-track separation ➜ increase granularity (*present tracker has degraded track finding performance in high-energy jets due to hit merging in the pixel detector*)
- Improve resolution at low-p_T and reduce secondary interactions ➜ reduce material
- Increase forward acceptance (*to cover peak production region of jets from Vector Boson Fusion and and VBS, among highest priorities of the physics program, by mitigating PU effects in jet-ID and energy measurement*)



4 barrel layers (➜ *3 layers now*)

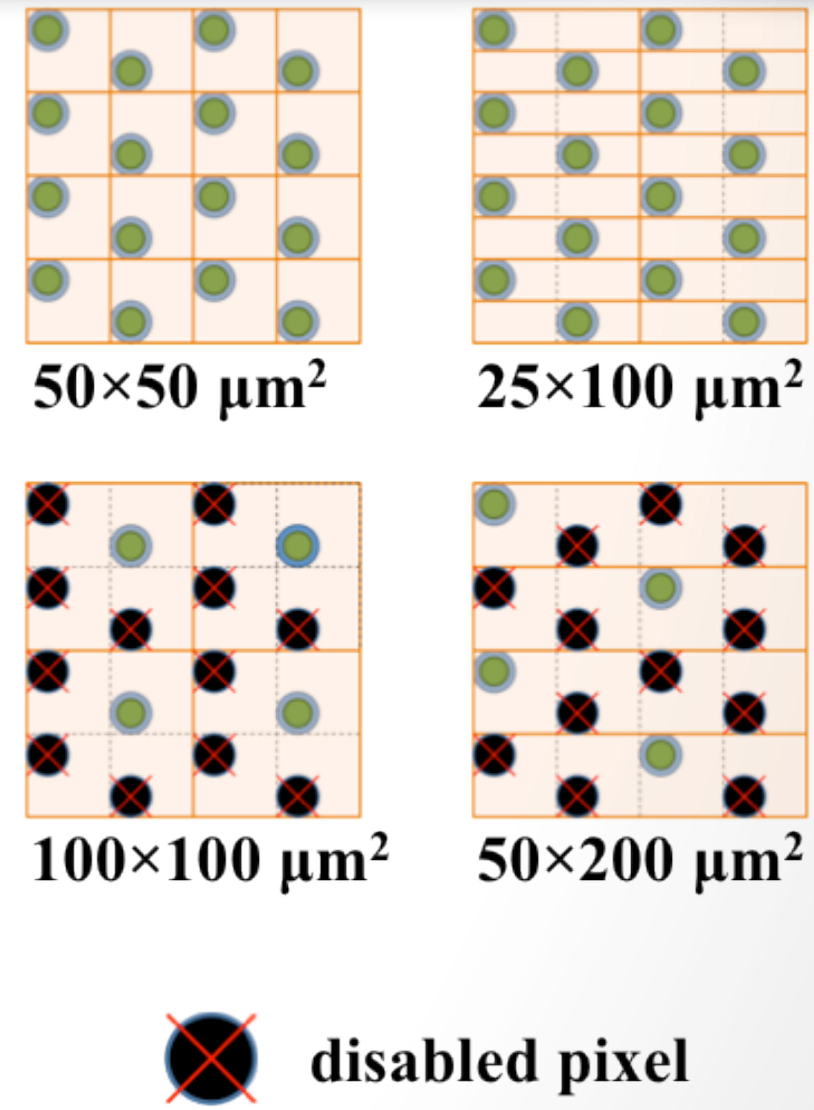
10+10 forward disks, coverage up to $\eta \approx 4$ (➜ *2+2 disks now, up to $\eta \approx 2.4$*)

Preserve the ease-of-access of current detector (*possibility to replace degraded parts over technical stops*)

Basic pixel detector design concepts

Readout chip

- Candidate technology: **65 nm** CMOS (*RD-53 cross collaboration Atlas-CMS for development*)
- Cell size: **50x50 µm²** or **25x100 µm²** (*aim large chip ~20x20 mm²*)
- Staggered bumps:
  - possibility to switch off 1/2 or 3/4 pixels (*e.g. outer regions with pixels of 100x100 µm² or 50x200 µm²*)



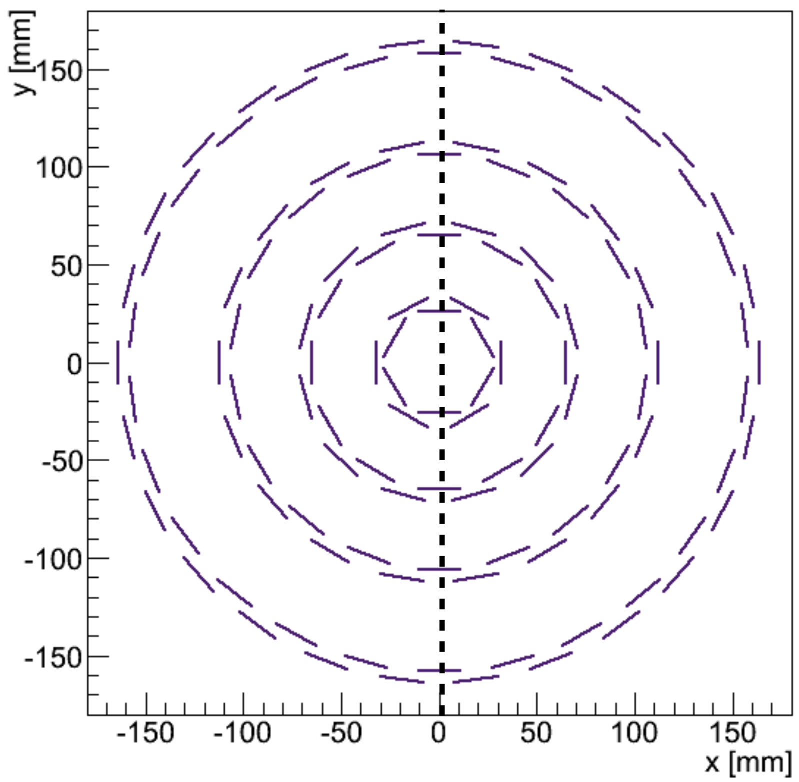
Sensors

- Favoured technology: **planar Silicon**
  - Define suitable n-in-p process and design (*more cost effective than present n-in-n because single sided process*)
  - Thin thickness
  - Requires robust spark rejection material
- Alternative/complementary for innermost layer: **3D Silicon**
  - Define suitable number of electrode columns
  - Define suitable electrode geometry and sensor thickness
  - Address production issues (*e.g. yield and cost*)

Total active area: ~ 4 m²
(➜ ~1.5 times phase-I)

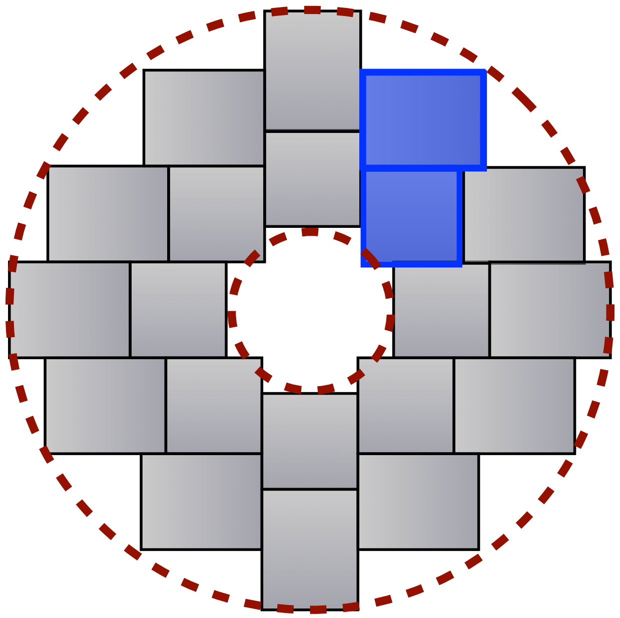
Pixel detector layout studies

Barrel geometry: two module types with 4x2 or 4x1 chips and no projective hole at z = 0

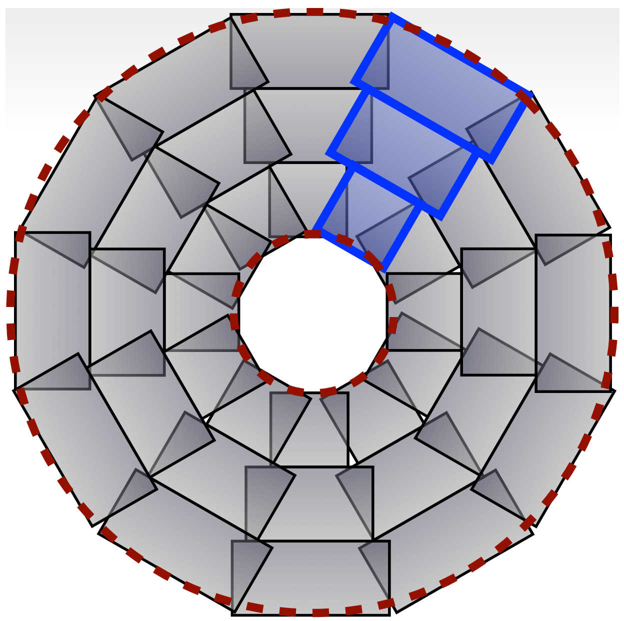


Forward geometry: two possible coverage schemes are being considered

Tile



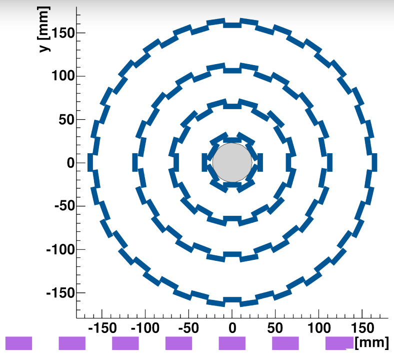
Petals

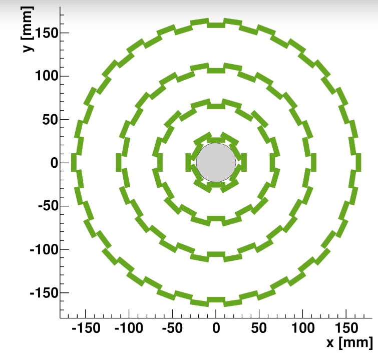


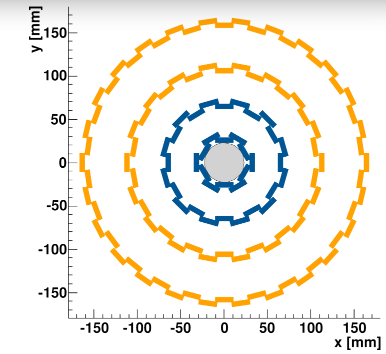
Geometry	Coverage	Overlap	#modules	#chips
Tile	89%	12%	26	160
Petals	98%	45%	44	232

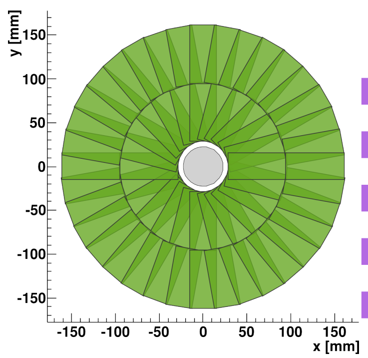
- Numbers are per disk
- Tile modules 4x2, 4x1, 2x2
- Petals modules 4x2, 2x1
- Chip size 21x23 mm^2 active area

Pixel detector layout studies







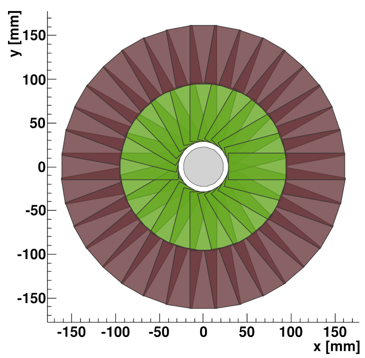


1 BPIX 25x100
FPIX 50x50
~1x10⁹ pixels

~~**2** BPIX 50x50
FPIX 50x50~~

Too much d_0 degradation

3 Inner BPIX 25x100
Outer BPIX 50x200
FPIX 50x50

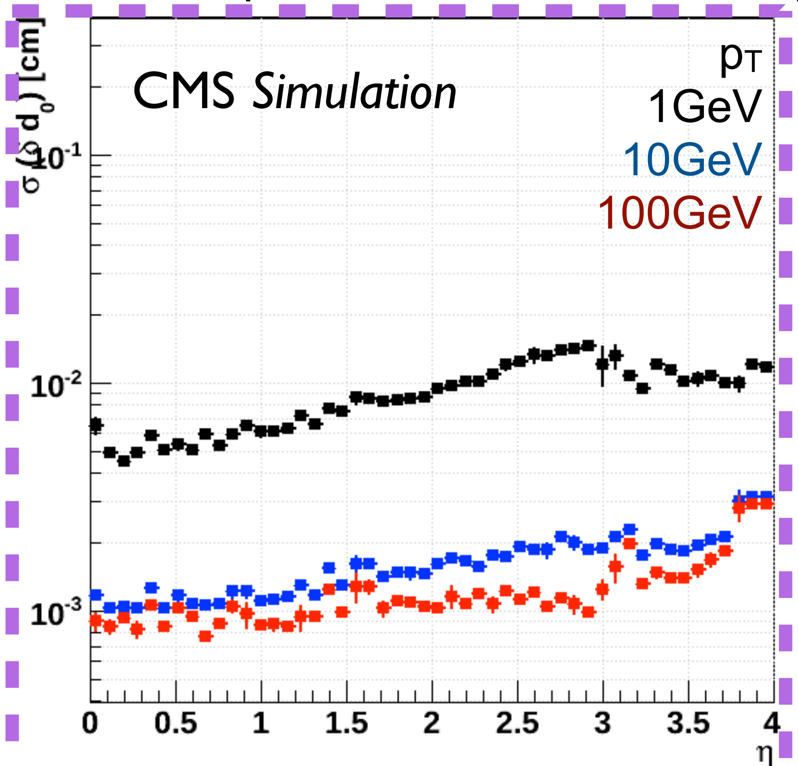


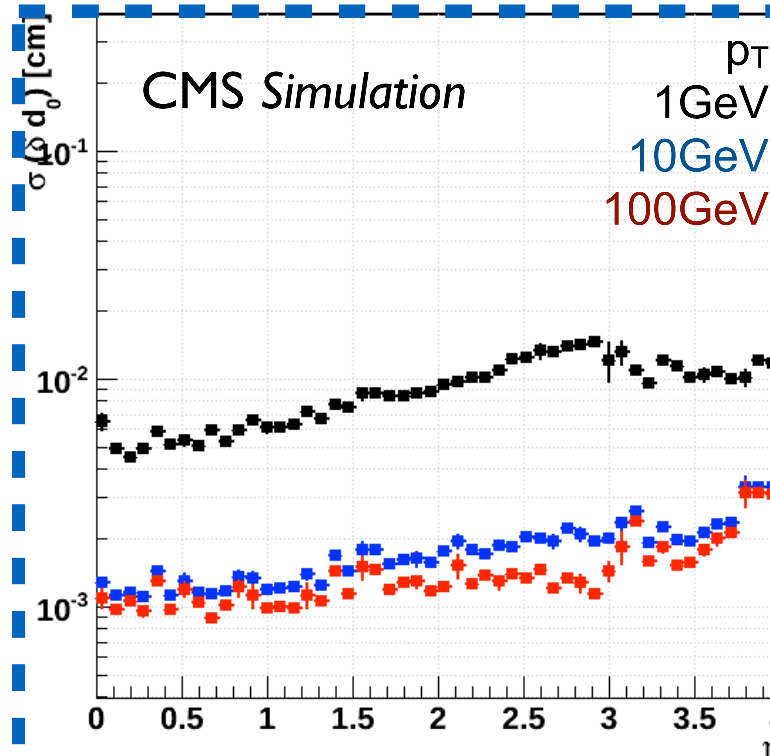
4 BPIX 25x100
Inner FPIX 50x50
Outer FPIX 100x100

5 Inner BPIX 25x100
Outer BPIX 50x200
Inner FPIX 50x50
Outer FPIX 100x100

Pixel cell size studies

- Too much d_0 degradation with pure squared pixels in BPIX
- Two extreme configurations, #1 and #5, have comparable tracking performance
- Configuration #5 has ~1/2 channels of #1





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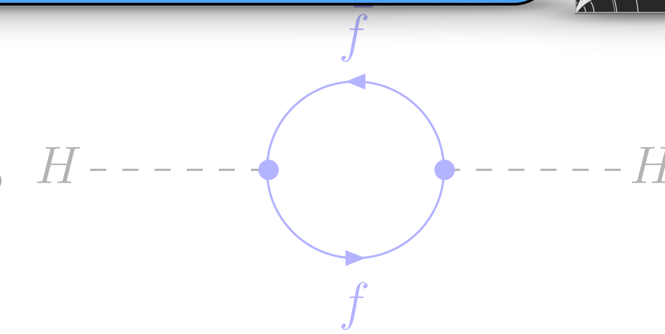

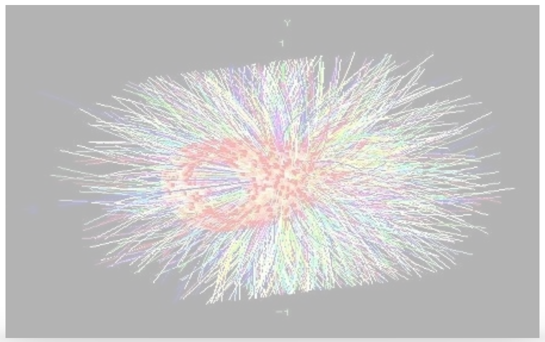

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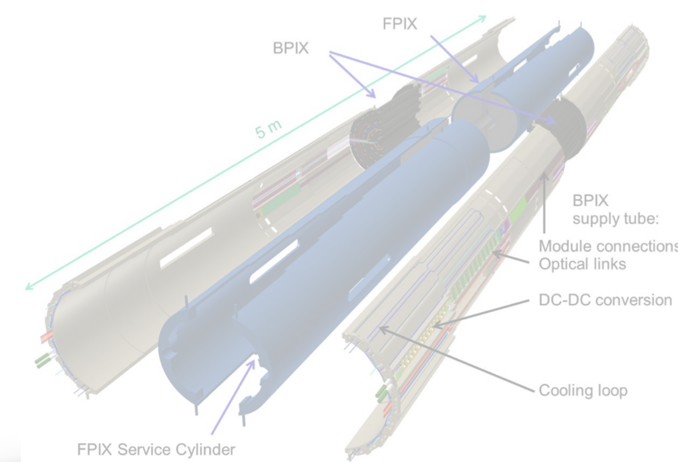

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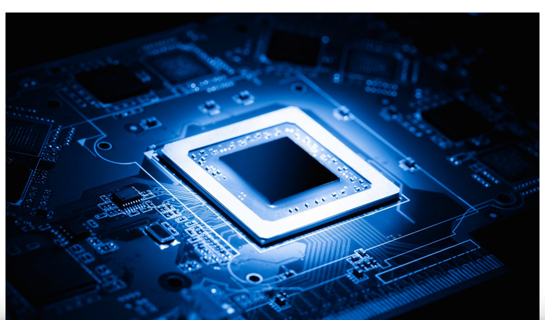
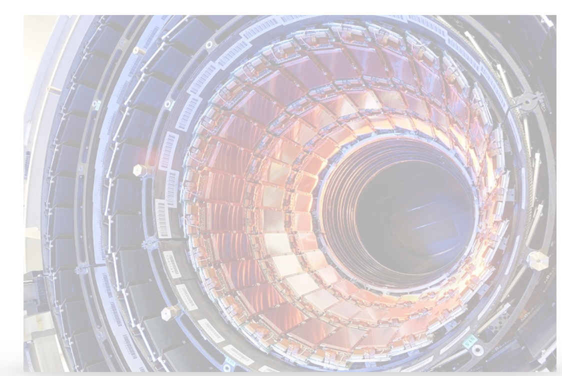


- **Readout chip specifications**

- Possible sensor choices



- Conclusions

Pixel readout chip specifications

Extremely challenging requirements

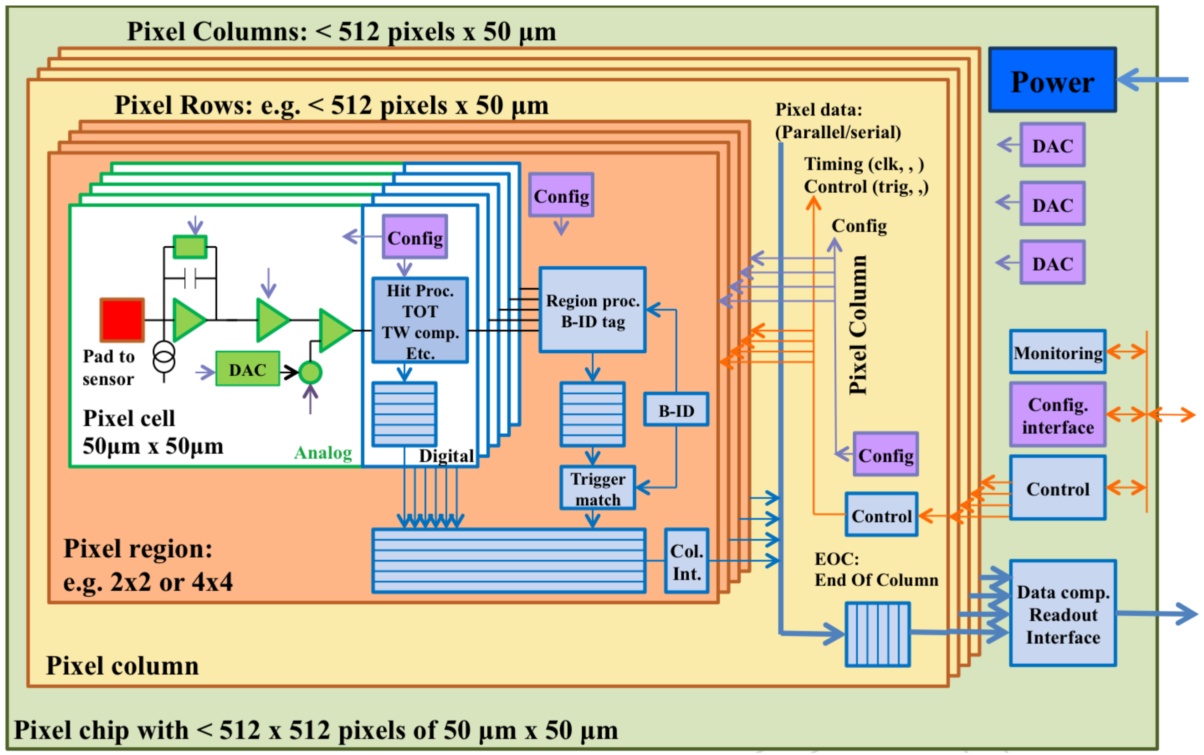
Generation	Present	Phase-I	Phase-II
Pixel size	100x150 μm^2	100x150 μm^2	50x50 (25x100) μm^2
Sensor	2D, 300 μm	2D, 300 μm	thin 2D, 3D
Chip size	8x10 mm^2	8x10 mm^2	**> 20x20 mm^2**
Transistors	1.3x10^6	?	**~10^9**
Hit rate	100 MHz / cm^2	400 MHz / cm^2	**~2 GHz / cm^2**
Hit memory per chip	0.1 Mb	1 Mb	~16 Mb
Trigger rate	100 kHz	100 kHz	**~1-2 MHz**
Trigger latency	3.2 μs	3.2 μs	~12 μs
Readout rate	40 Mb/s	400 Mb/s	~2 Gb/s
Radiation	15 Mrad, r = 42 mm, L = 150 fb^−1	120 Mrad, r = 29 mm, L = 500 fb^−1	**1 Grad, r = 30 mm, L = 3000 fb^−1**
Technology	250 nm	250 nm	**65 nm**
Architecture	Analog	Digital	Digital
Buffer location	End Of Column	End Of Column	Pixel
Power	~0.15 W / cm^2	~0.15 W / cm^2	**~0.3 - 0.5 W / cm^2**

See talk from Maurice GARCIA-SCIVERES: "RD-53 Progress on High Rate Pixel Readout chip"

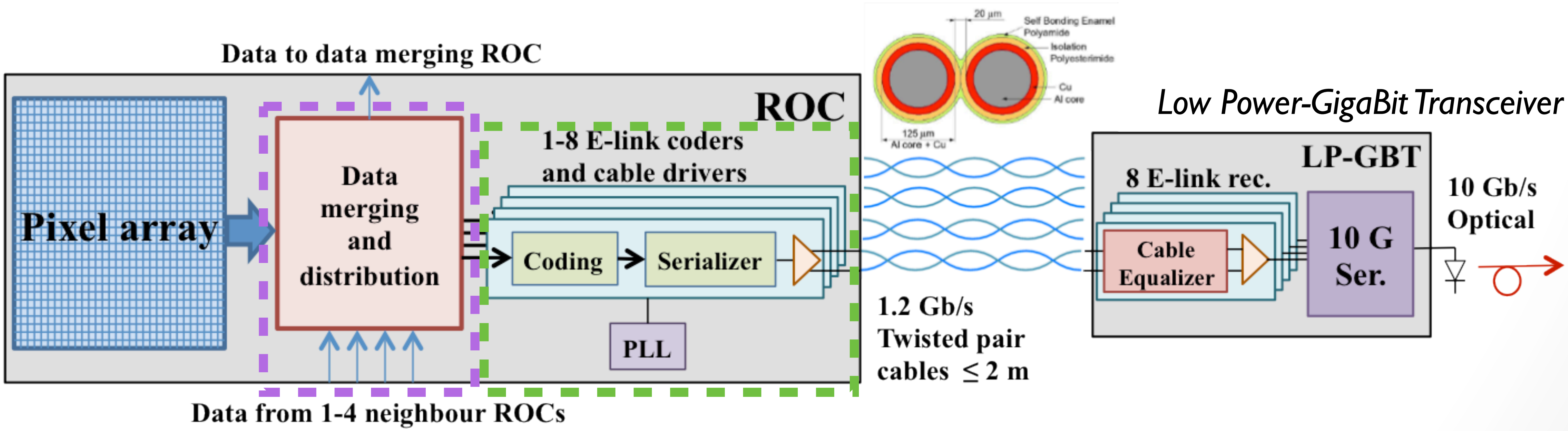
Mauro Dinardo, Universita` degli Studi di Milano Bicocca and INFN

Pixel readout chip and data link specifications

Readout chip architecture



- Possibility to tune bias currents of analogue front-end to account for different sensor choices
- Digital hit processing, including trigger latency buffer, implemented in ***pixel regions*** (*e.g. 2x2 or 4x4 pixels*) followed by data merging, formatting and readout after the first level trigger accept (*the price of local digital processing is that digital noise injection into the front end must be controlled, and clocks and trigger signals must be distributed throughout the pixel matrix*)

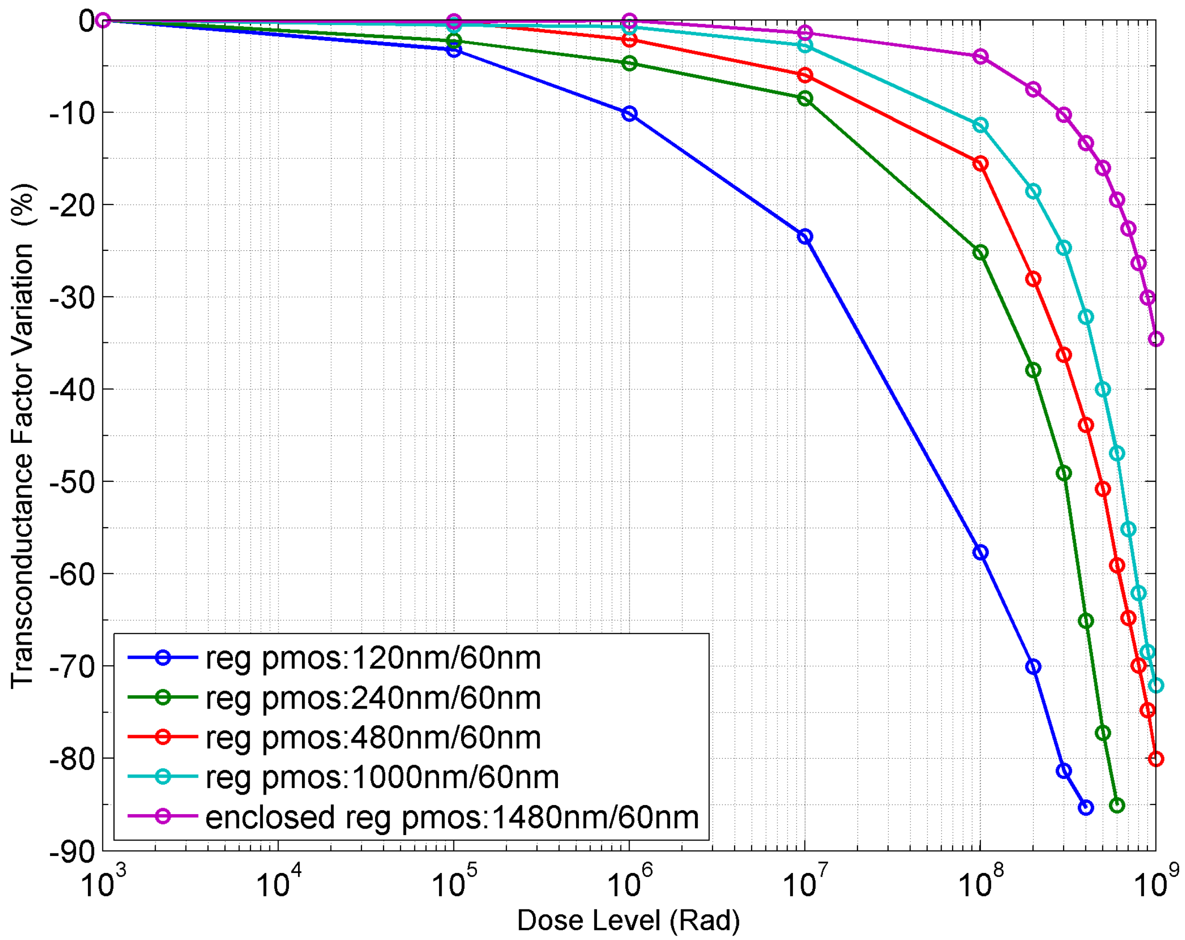


The chip will also implement data merging functionality (from 2 or even 4 chips in the innermost region)

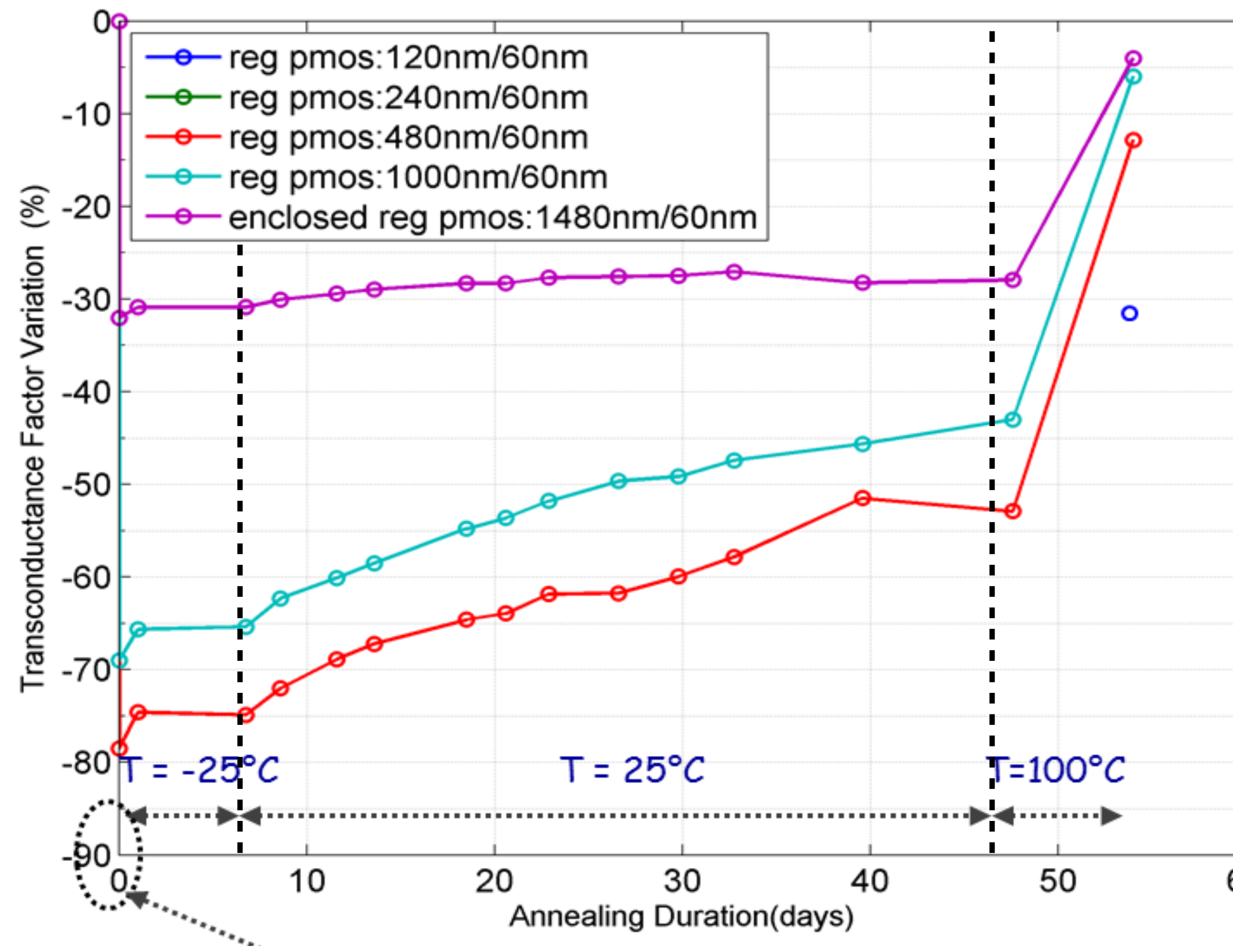
The chip should provide up to 8 data output e-links of 1.3 Gb/s

Radiation hardness of 65 nm CMOS technology

Transconductance factor variation vs. dose



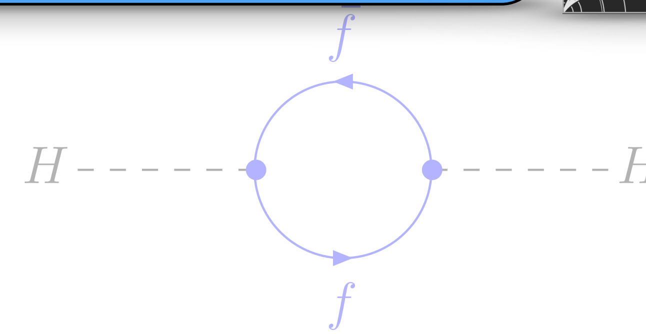
Transconductance factor variation vs. annealing time



RD-53 collaboration

See talk from Mohsine MENOUNI: "RD53 investigation of CMOS radiation hardness up to 1 Grad"

- Among other effects, PMOS-FETs (especially minimum size ones) show **large transconductance degradation vs. dose** (*becomes very steep at dose > 100 Mrad*)
- Damage mechanisms have yet to be fully understood
- It appears that some of the radiation damage in the chip could be **annealed with high temperatures** ➜ possibly define plausible annealing scenarios during detector maintenance to optimise longevity of sensors and electronics (*detailed evaluation of annealing effects on sensor performance*)



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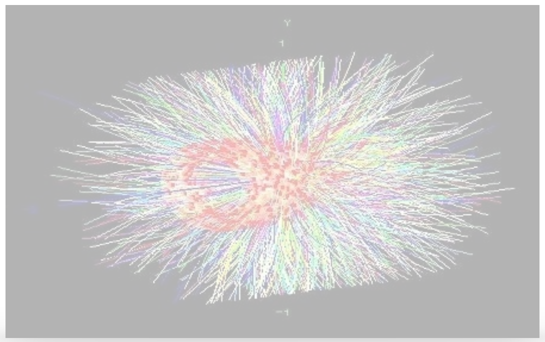

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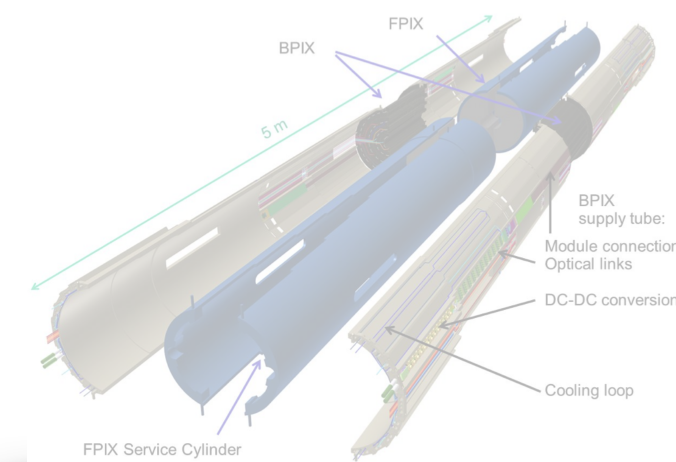

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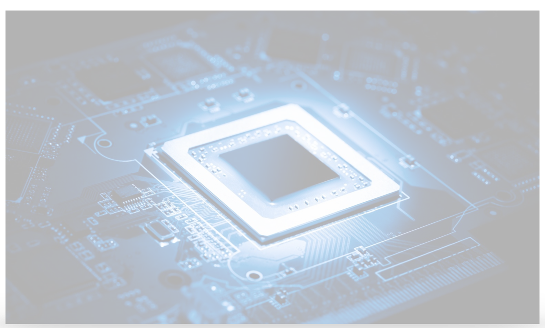

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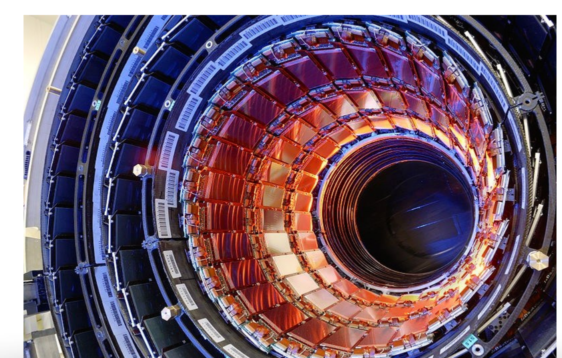

- Possible sensor choices
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Possible sensor choices

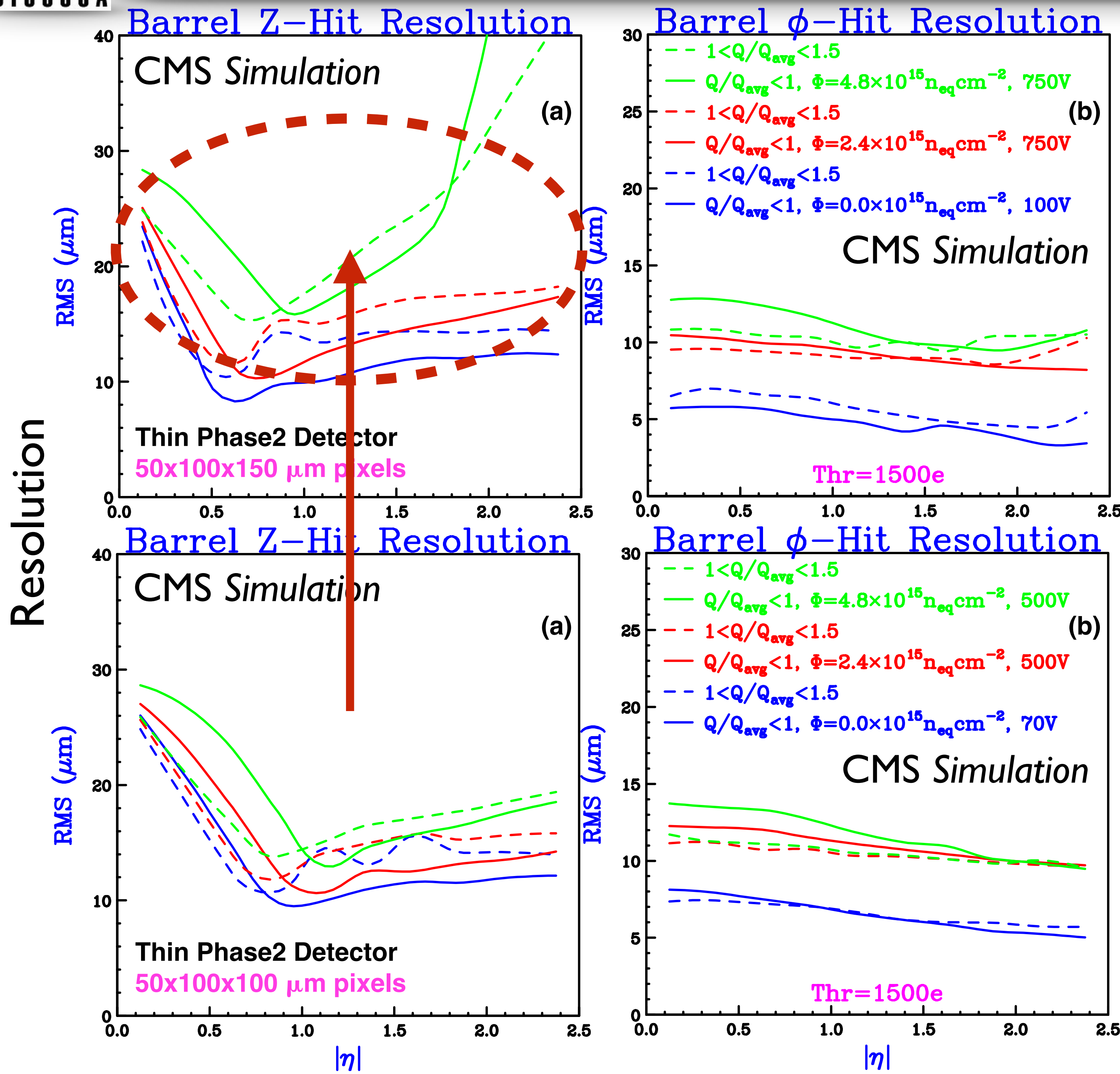
Planar Silicon n-in-p we need to define

- Sensor thickness
- Sensor process (*FZ, MCz, EPI*)
- Spark rejection material
- Pixel isolation and bias scheme

3D Silicon we need to define

- Number of columns per cell
- Column size ➜ sensor thickness
- Pad position
- Production process: single/double sided

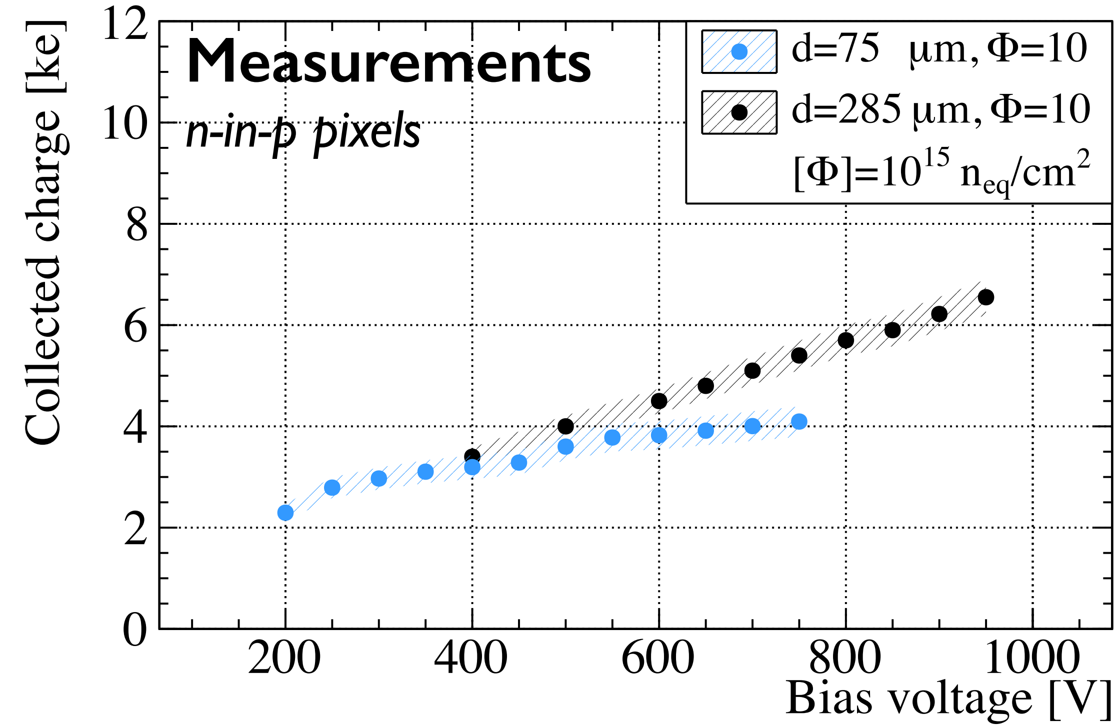
Thin planar Silicon sensors: thin thickness



Thin planar sensors advantages

- Higher fields with same bias ➜ shorter drift time ➜ less trapping ➜ ultimately, better radiation hardness
- Reduced full-depletion voltage
- Smaller clusters ➜ reduction of merged clusters in dense jets

At very **high fluences** **thick** and **thin planar** sensors **give similar charge**

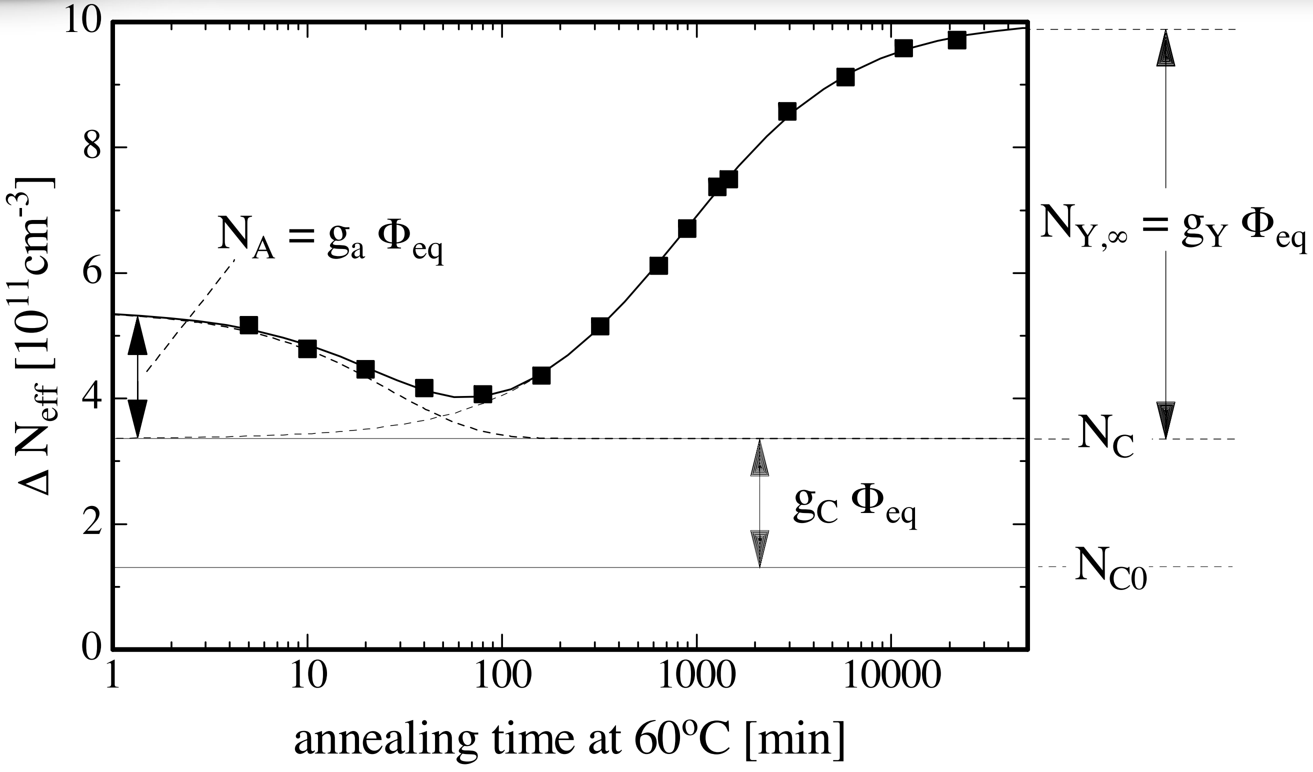


S. Terzo, 21st RD50 Workshop, CERN, 2012

Assumptions

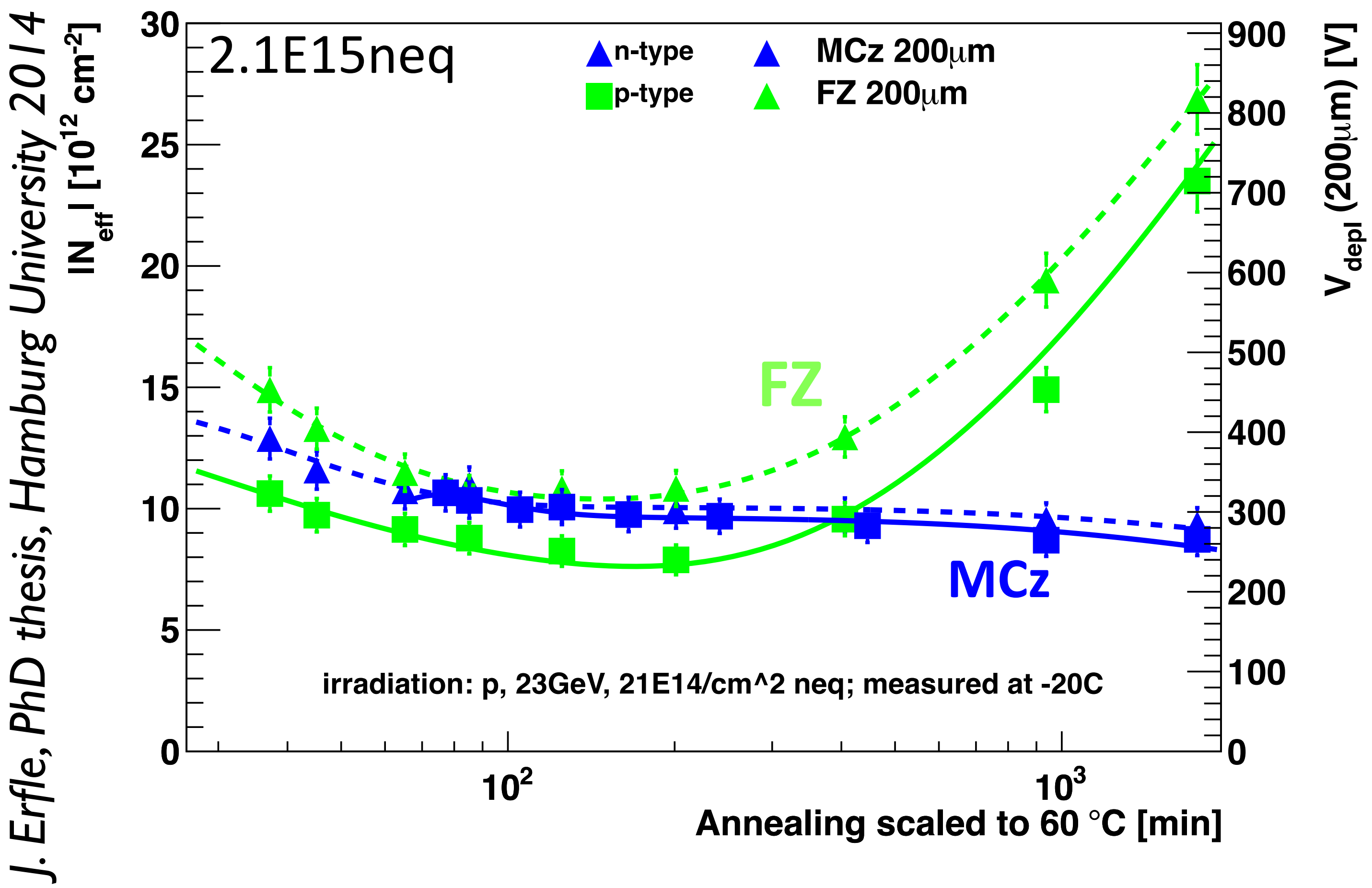
- Noise 150 e^- and other readout and calibration effects are small
- Extrapolate DOFZ irradiated Silicon model, tuned on data up to 1.2×10^{15} n_{eq} / cm^2, to larger fluence, 4.8×10^{15} n_{eq} / cm^2
- Average E-fields of 50 kV / cm can be achieved

Thin planar Silicon sensors: different processes



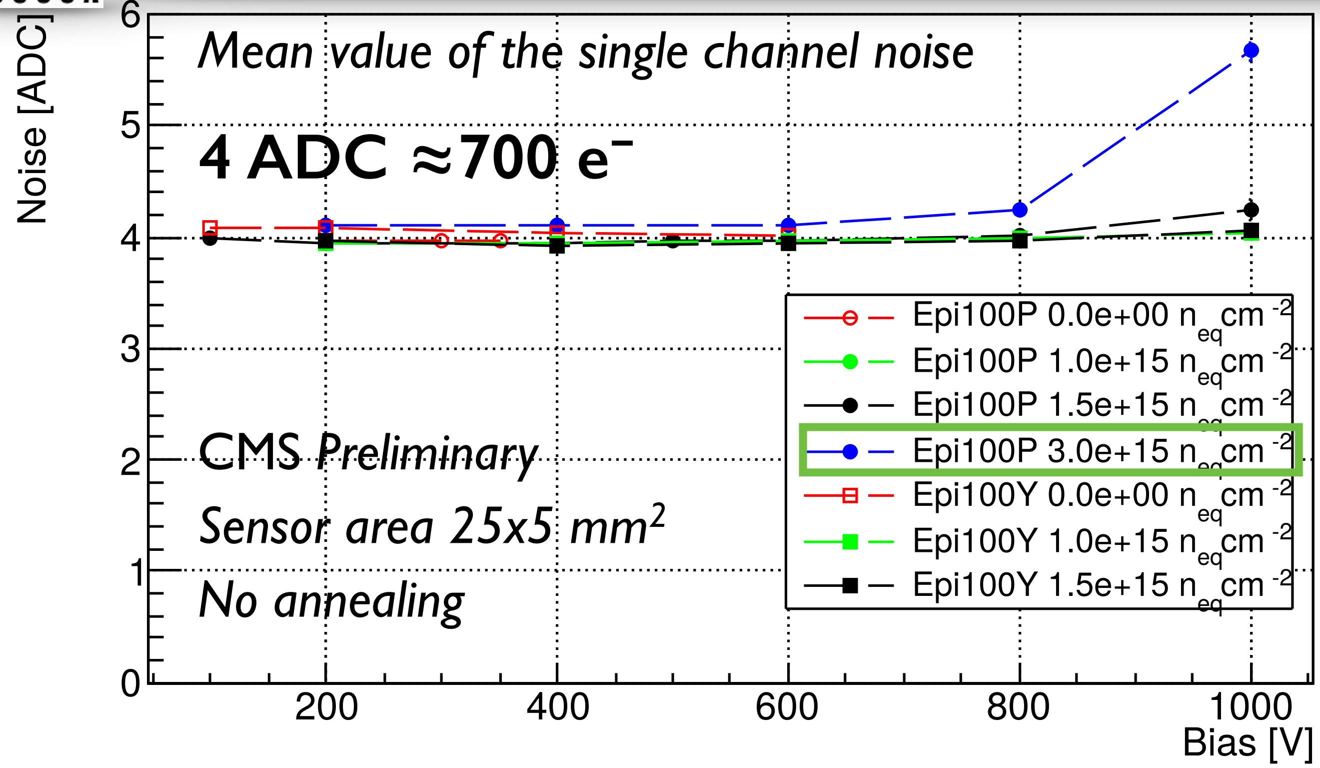
Usual annealing behaviour of Silicon after irradiation: beneficial annealing and reverse annealing

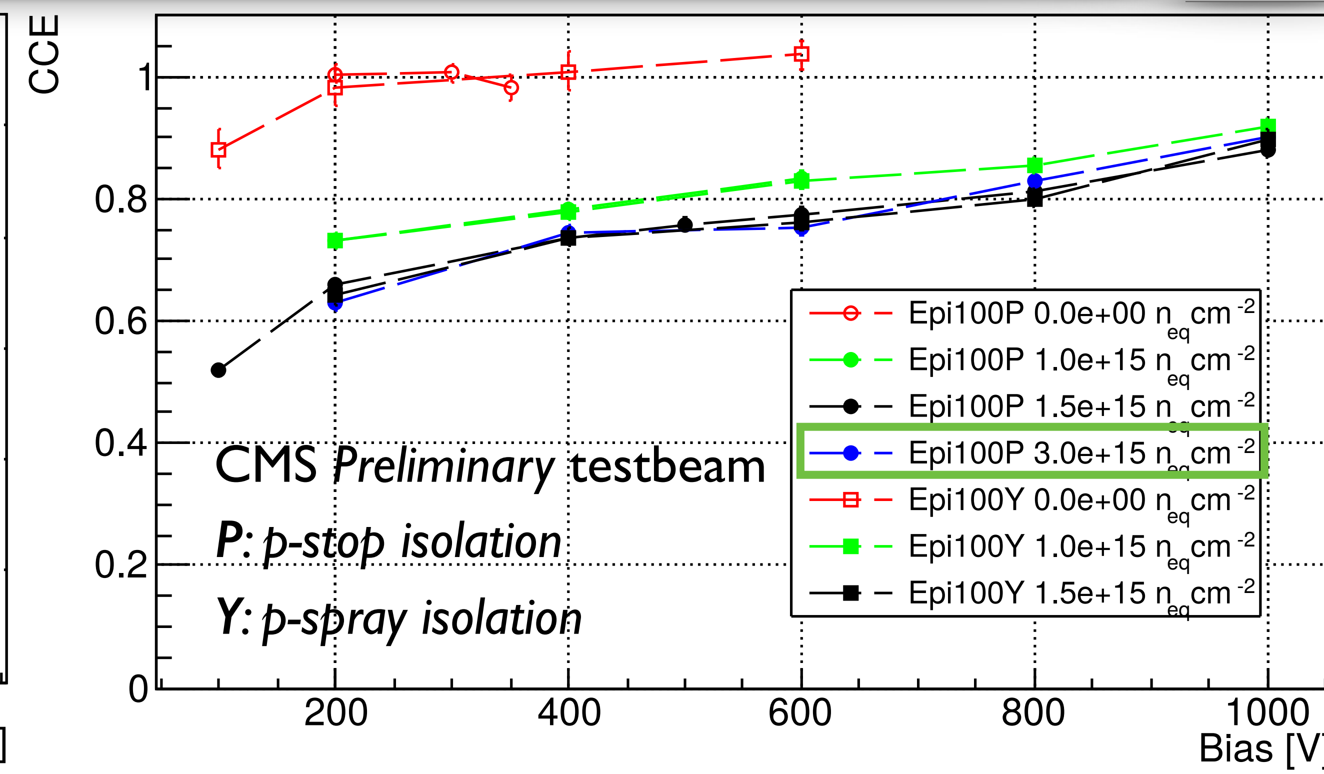
$V_{depl} \approx q_0 / (2\varepsilon_0\varepsilon_r)\ |N_{eff}|\ d^2$

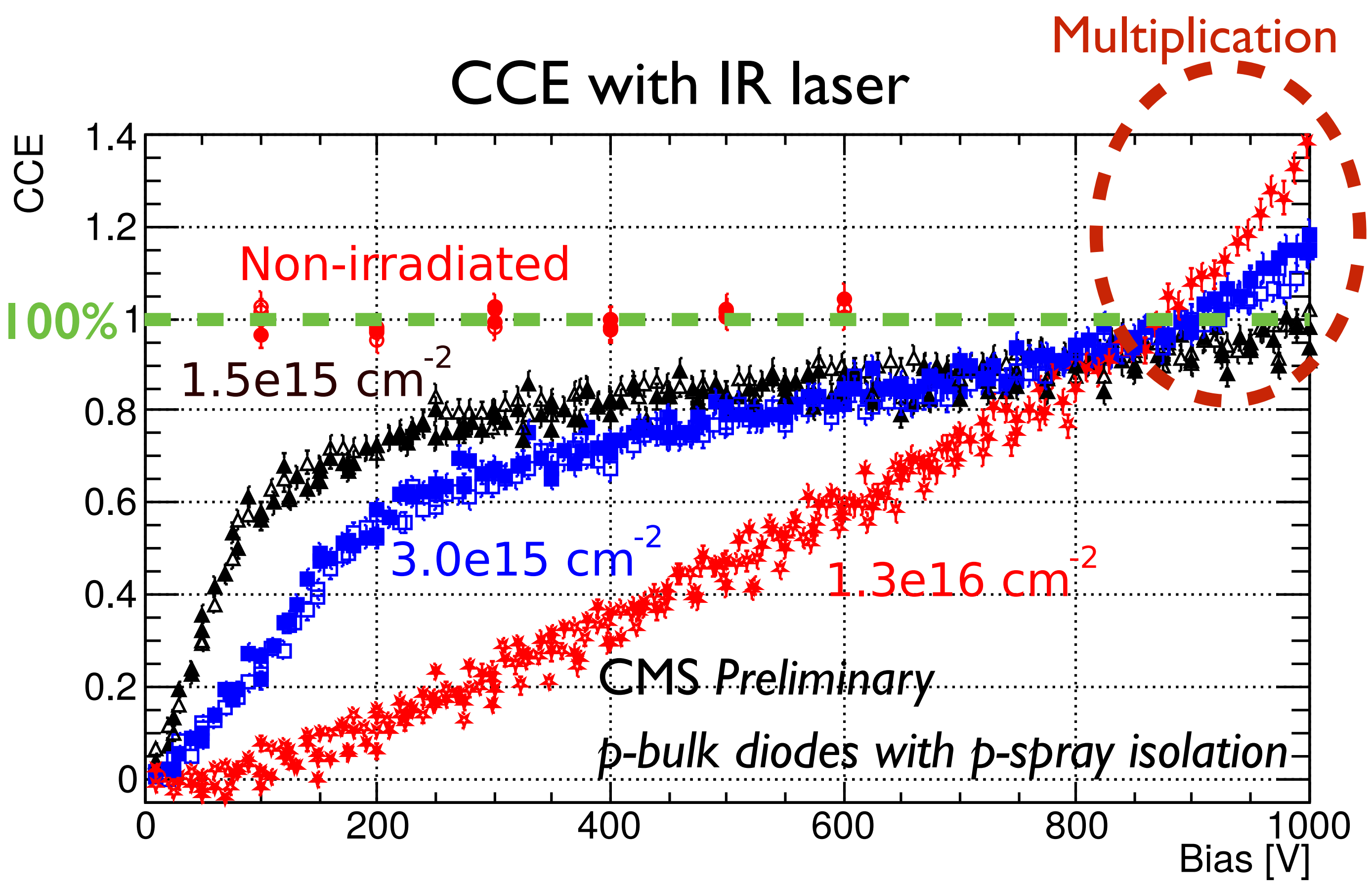


- MCz is much more stable in time than FZ
- With MCz longer warm periods are possible ➜ might impact readout chip operations / annealing
- But price for MCz is expected to be higher than FZ

Thin planar Silicon sensors: EPI Silicon performances







n-in-p EPI strip sensors (*100 μm thick, 80 μm pitch*)

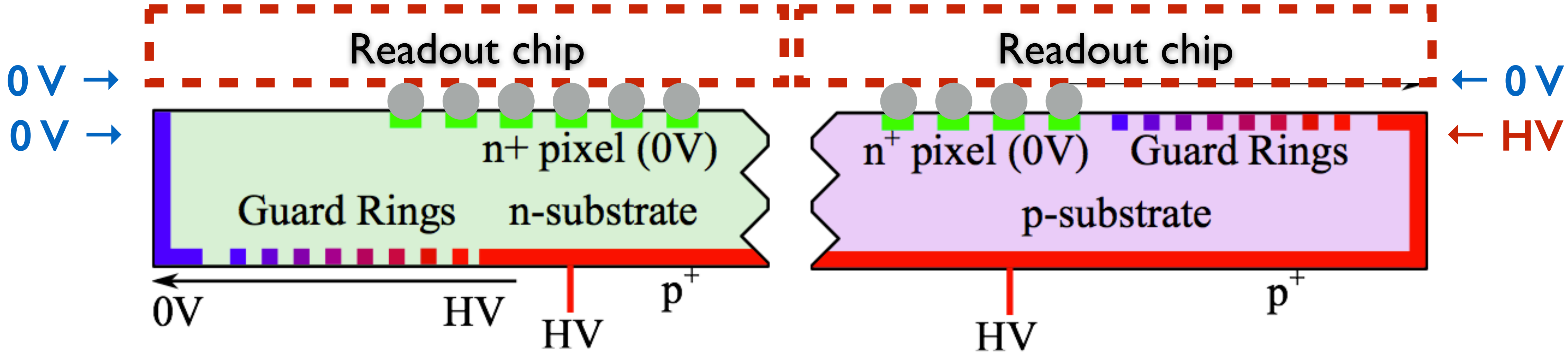
- **Irradiated: −20°C (chip at ~ +9°C)**
- **Non-irradiated: +20°C (chip at ~ +24°C)**

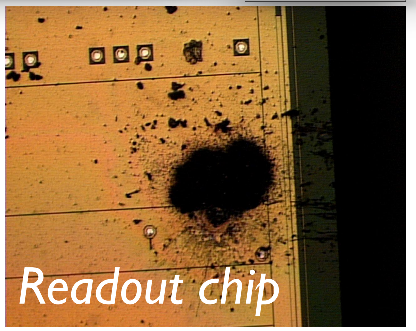
- Testbeam data are in agreement with measurements on diodes

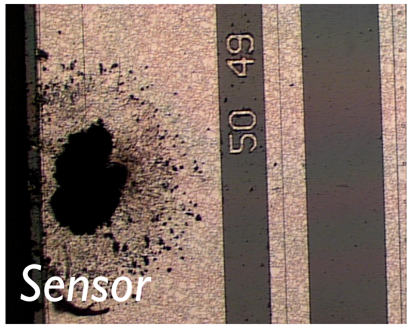
- High-bias / low-temperature are needed

See poster from Matteo CENTIS VIGNALI: "Characterisation of thin irradiated epitaxial silicon sensors for the CMS phase II pixel upgrade"

Thin planar Silicon sensors: spark rejection material

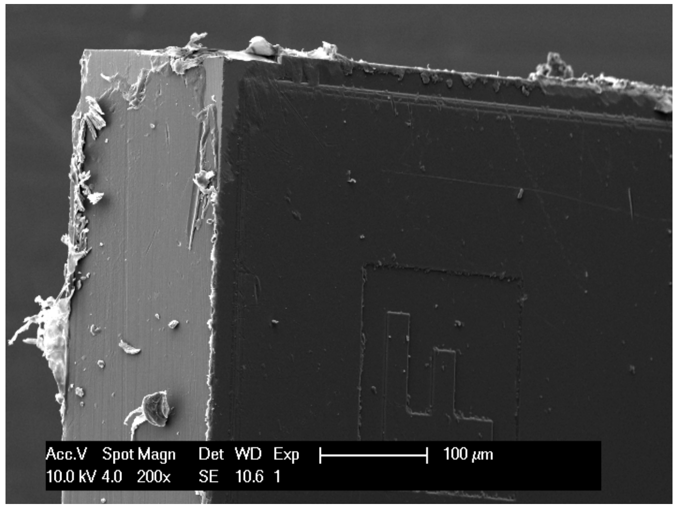






Possible solutions

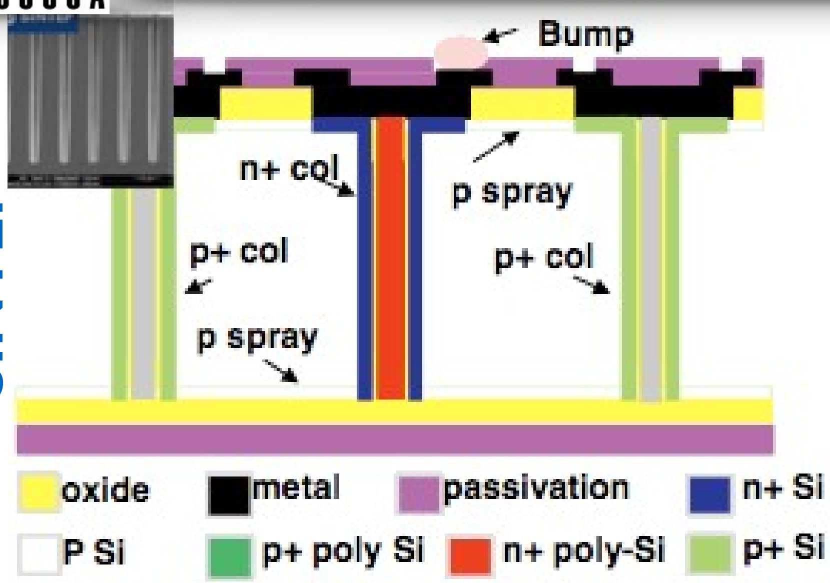
- Parylene-N (*5-10 μm, deposited all over the module*)
  - no sparking up to 1000 V
  - no effect of irradiation (*1x10*^{16} *n*$_{eq}$ */ cm*^{2})
  - good passivation
  - concerns about protection of bond pads during module manufacturing
- BenzoCycloButene (*3 μm, lithography needed*)
  - no sparking up to 1000 V
  - can be deposited before bump bonding at IZM
  - need to prove radiation resistance

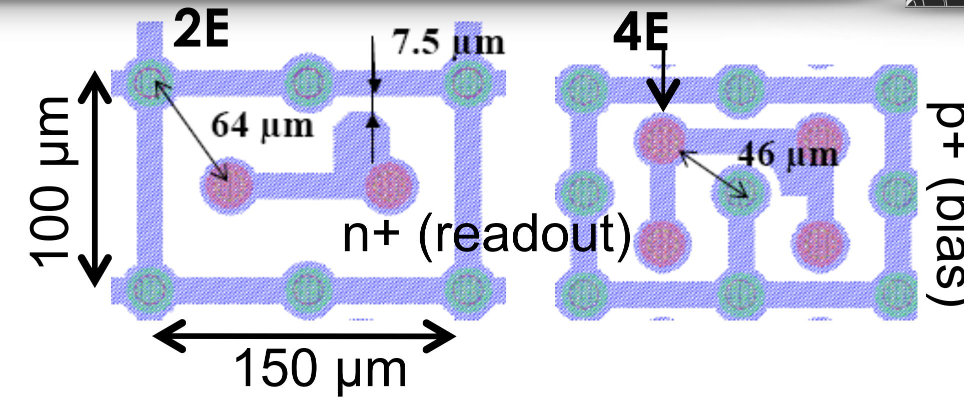


Uniform 2 μm Parylene coating
Scanning Electron Microscope image

Silicon 3D sensors: different processes

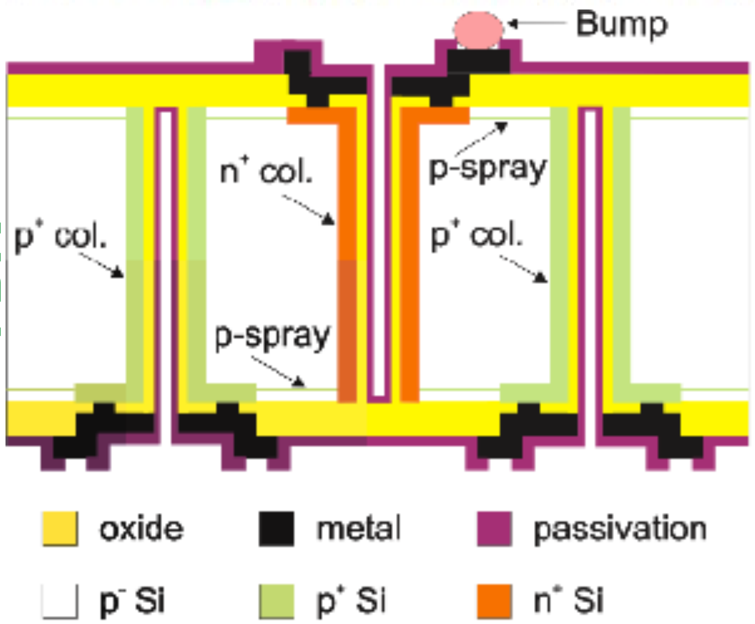
SINTEF

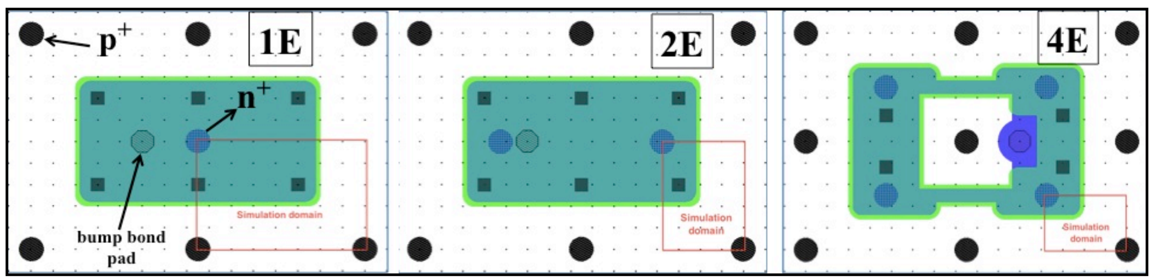




- Single-sided process
- Passing-through columns
- Active edges (*support wafer required*)

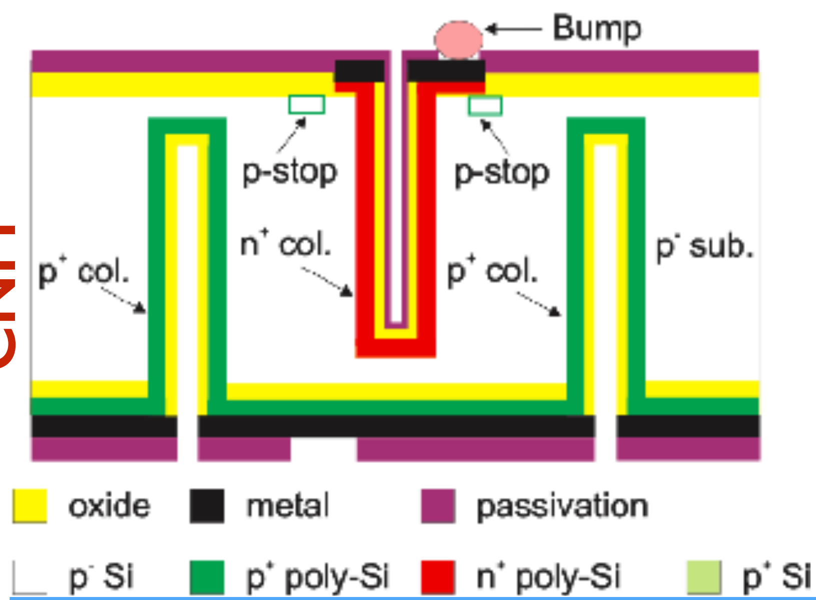
FBK





- Double-sided process
- Passing-through columns (*full*)
- Slim edges (*200 µm*)

CNM



- Double-sided process
- Passing-through columns (*partial*)
- Slim edges (*200 µm*)

Silicon 3D sensors: different processes

FBK Atlas08	[Φ = 0] charge	[Φ = 7x10^14 neq / cm^2] charge	charge loss	[Φ = 0] S/N	[Φ = 7x10^14 neq / cm^2] S/N
1E	14.3 ke–	8.2 ke–	43%	66	33
2E	14.8 ke–	10.5 ke–	29%	55	38
4E	**14.2 ke–**	**11.8 ke–**	**17%**	**36**	**32**
SINTEF					
2E	17.2 ke–	12.9 ke–	25%	60	28

Laboratory and testbeam results from 200 µm thick FBK Atlas08 batch and SINTEF (*active edge ~ 20 µm*)

Silicon 3D sensors: different processes

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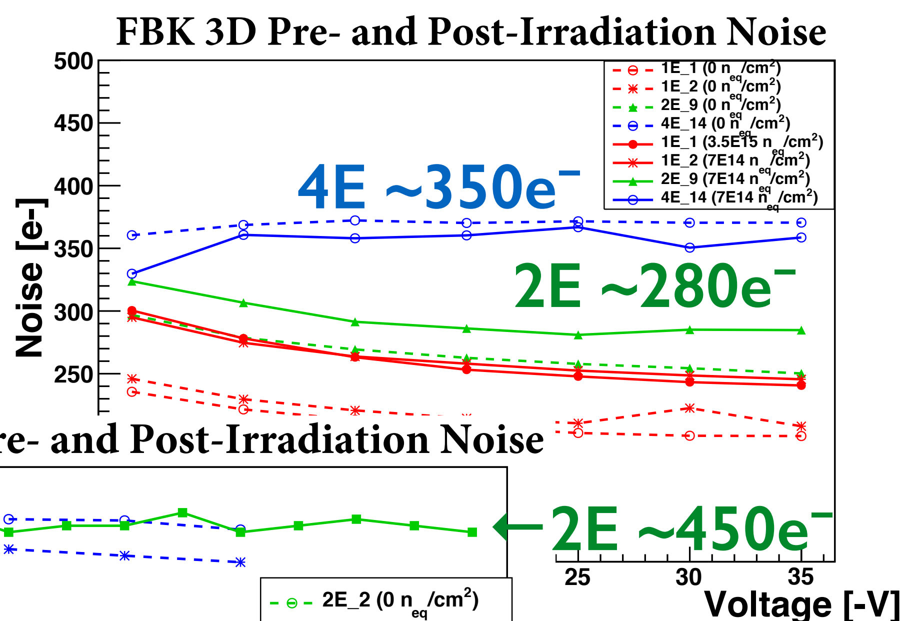
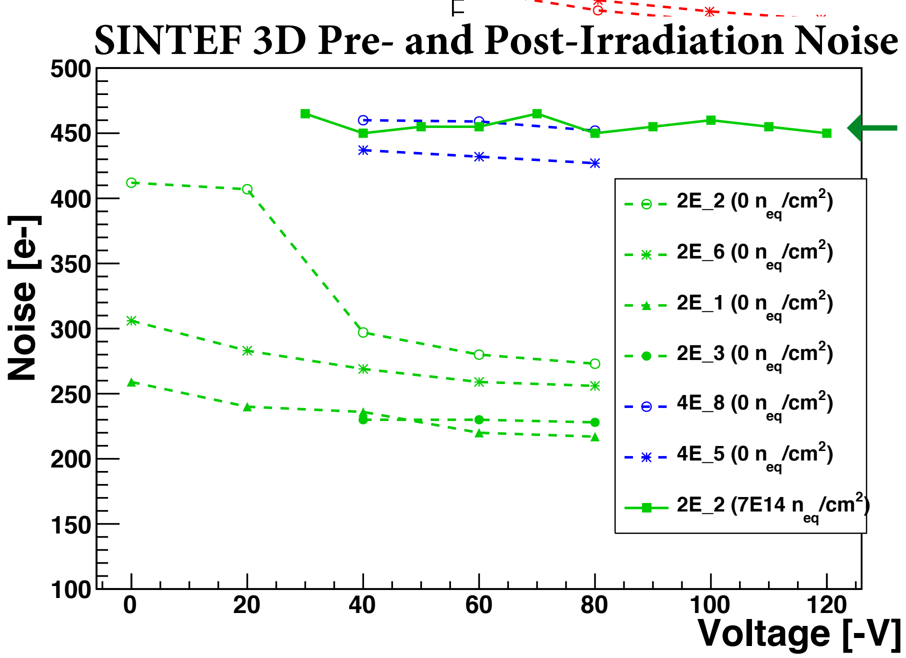
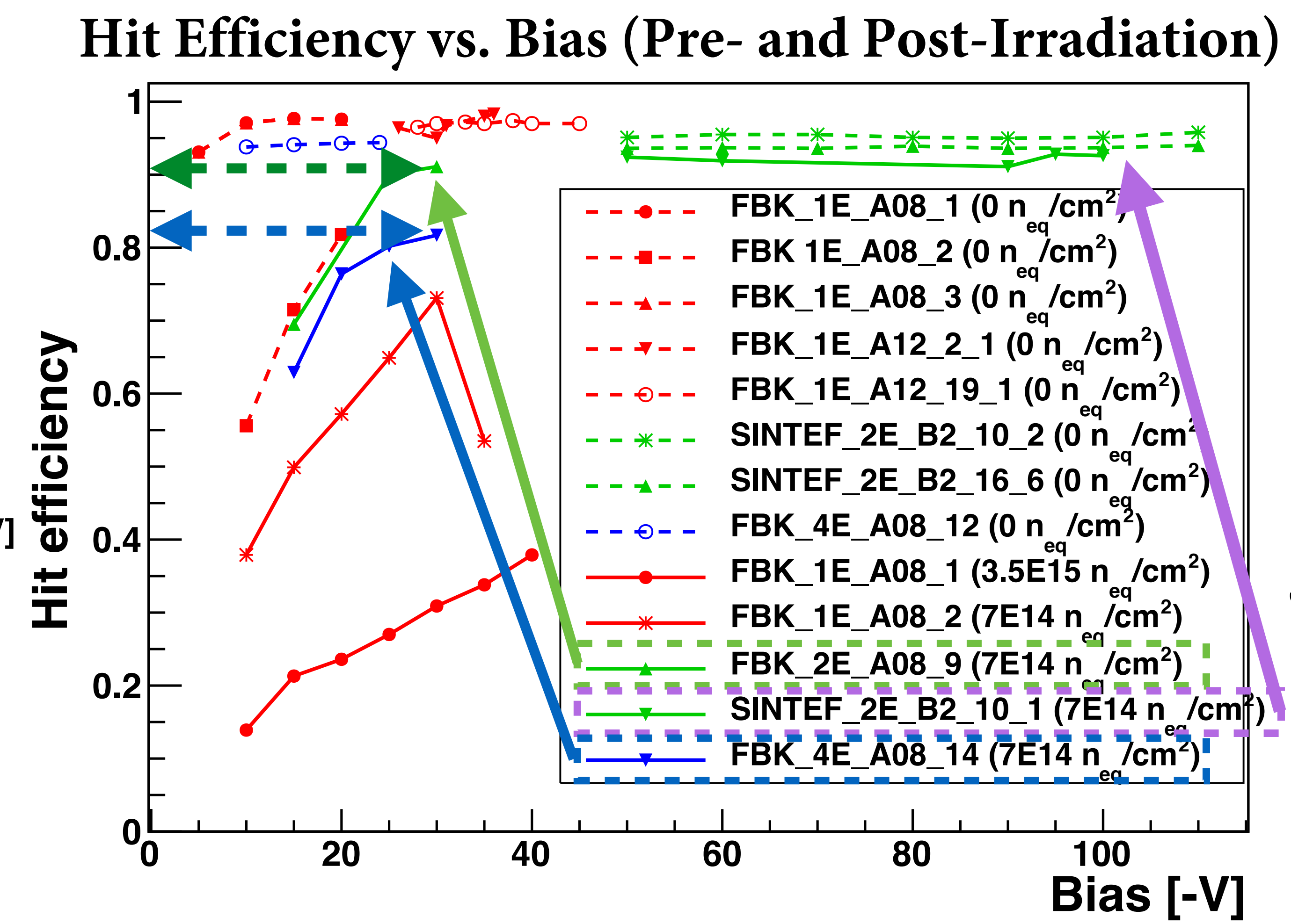




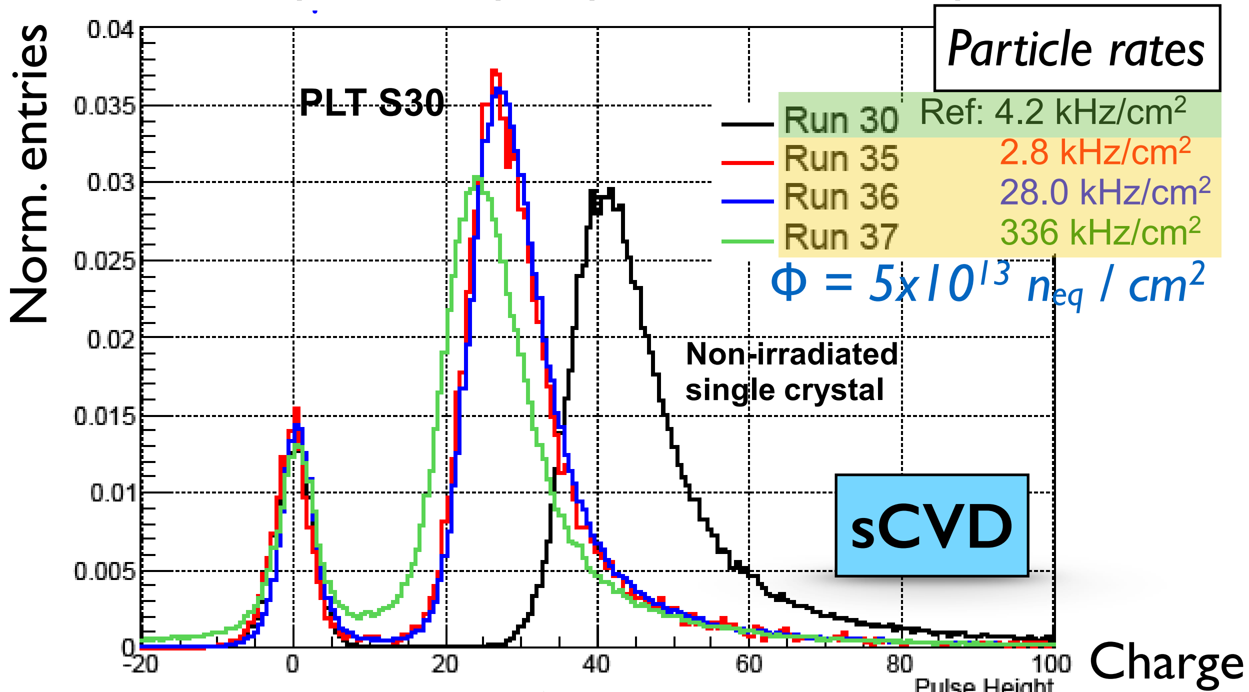


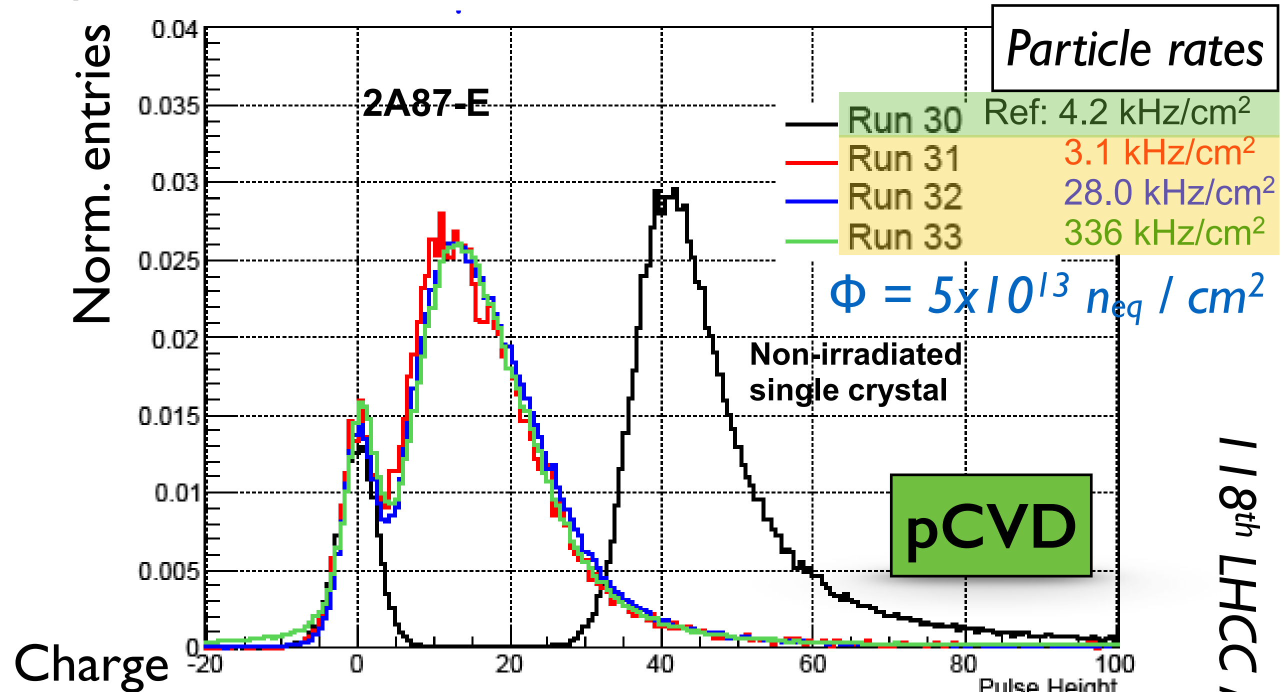
M Bubna et al 2014 JINST 9 C07019

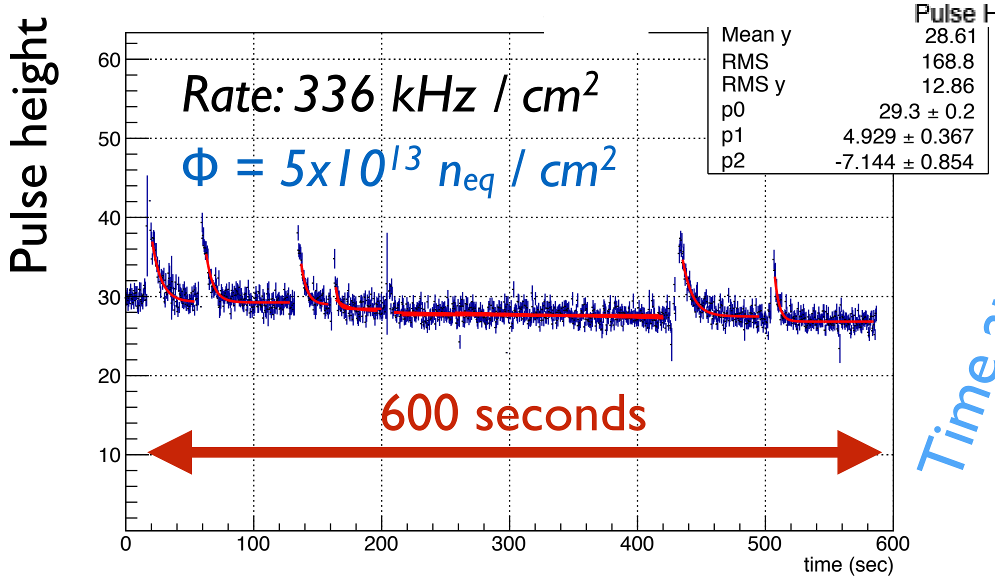
Diamond sensors: polarisation effects

Several problems have still to be overcome

- **Polarisation effects**
- Availability of diamond material in sufficient quantity and quality (*different collection length in samples coming from same production, influence of surface treatment on detector properties, scarceness of diamond material*)
- Improved radiation hardness with respect to Silicon is still to be demonstrated
- Reliable interconnection of diamonds to readout chips on production scale
- No plausible perspective for mass production ➜ no reliable price estimate

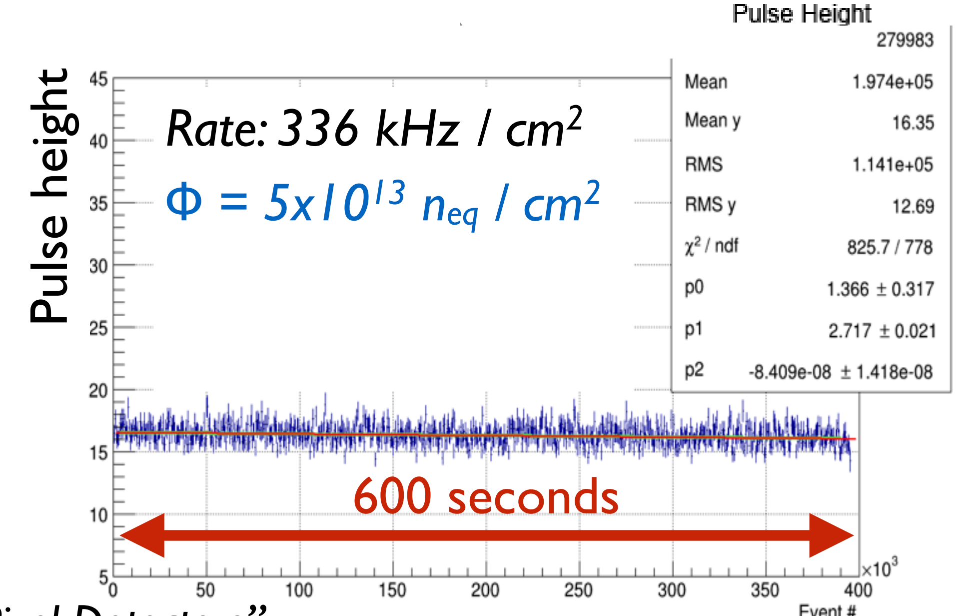






Time and rate dependance

No time nor rate dependance

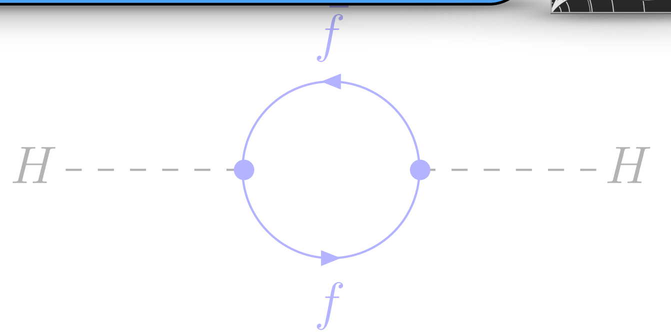


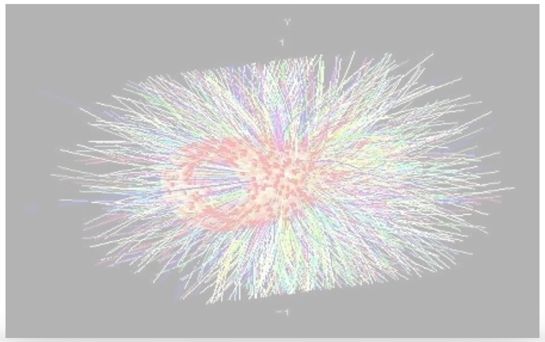
118th LHCC Meeting

 See talk from Rainer WALLNY: "Results from the Pilot Runs and Beam Tests of Diamond Pixel Detectors"

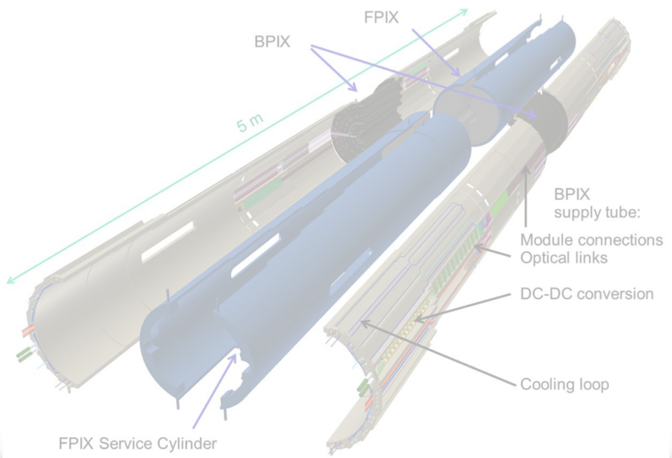
Outline

- CMS pixel phase-II upgrade motivations

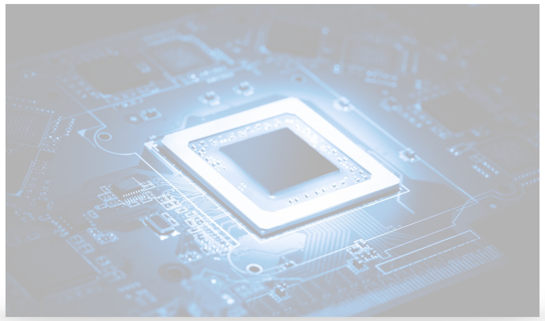




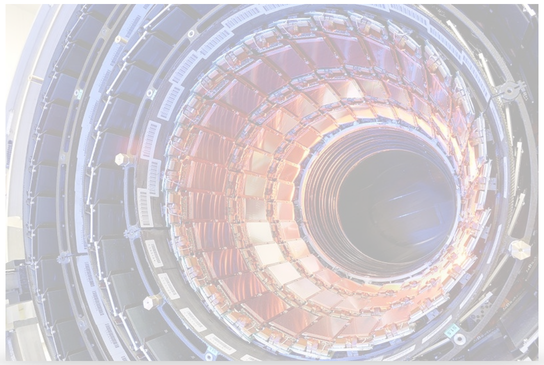
- Detector operating conditions



- Detector layout choices



- Readout chip specifications



- Possible sensor choices
- Conclusions

Conclusions

- **Pixel detector operating conditions during phase-II are extremely challenging**
  - <PileUp> = **140**
  - Radiation @30 mm from IP: **$2x10^{16}$ n_{eq} / cm^2**
  - Dose @30 mm from IP: **10 MGy** (1 Grad)
  - Hit rate: **~2 GHz / cm^2**

- Final **general detector layout** and geometry is almost defined

- **Readout chip development** (*Atlas-CMS collaboration*): 65 nm candidate technology ➜ need to demonstrate radiation hardness up to foreseen 10 years operation at HL-LHC

- **Sensor development**: Silicon thin planar n-in-p (and/or Silicon 3D for innermost layer) candidate technology ➜ need to define sensor process, bias isolation geometry, thickness, electrode geometry

- Still a lot of exciting work ahead (hopefully) leading to future physics discoveries !

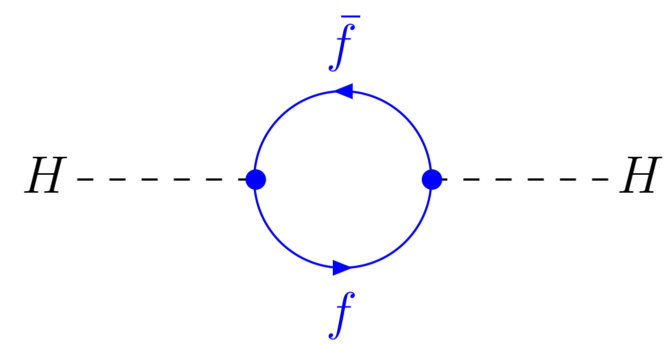
Backup

Phase-II upgrade motivations

Major achievement of HLC: Higgs discovery in 2012 !

That's not the whole story, there are other questions that need to be answered:

- What's the origin of Higgs mass correction-fine tuning ?
- How do we incorporate gravity ?
- Why such a puzzling spectrum of fermion masses and mixings ?
- What is the nature of Dark Matter ?
- Is there are new sources of CP violation ?



What's the origin of Higgs mass correction-fine tuning ?

- $M^2_H = M^2_{H,0} + \delta M^2_H$ → *quadratically divergent*
- From fermion loops:

  $\delta M^2_{H,f}$ at $\Lambda = M_{Plank}$ is $\mathbf{\delta M^2_{H,f} \approx 10^{35}\ GeV^2}$

$$\delta M^2_{H,f} = -\frac{\lambda_f^2}{8\pi^2}[\Lambda^2 - m_f^2 \ln\frac{\Lambda^2}{m_f^2}] + \ldots$$

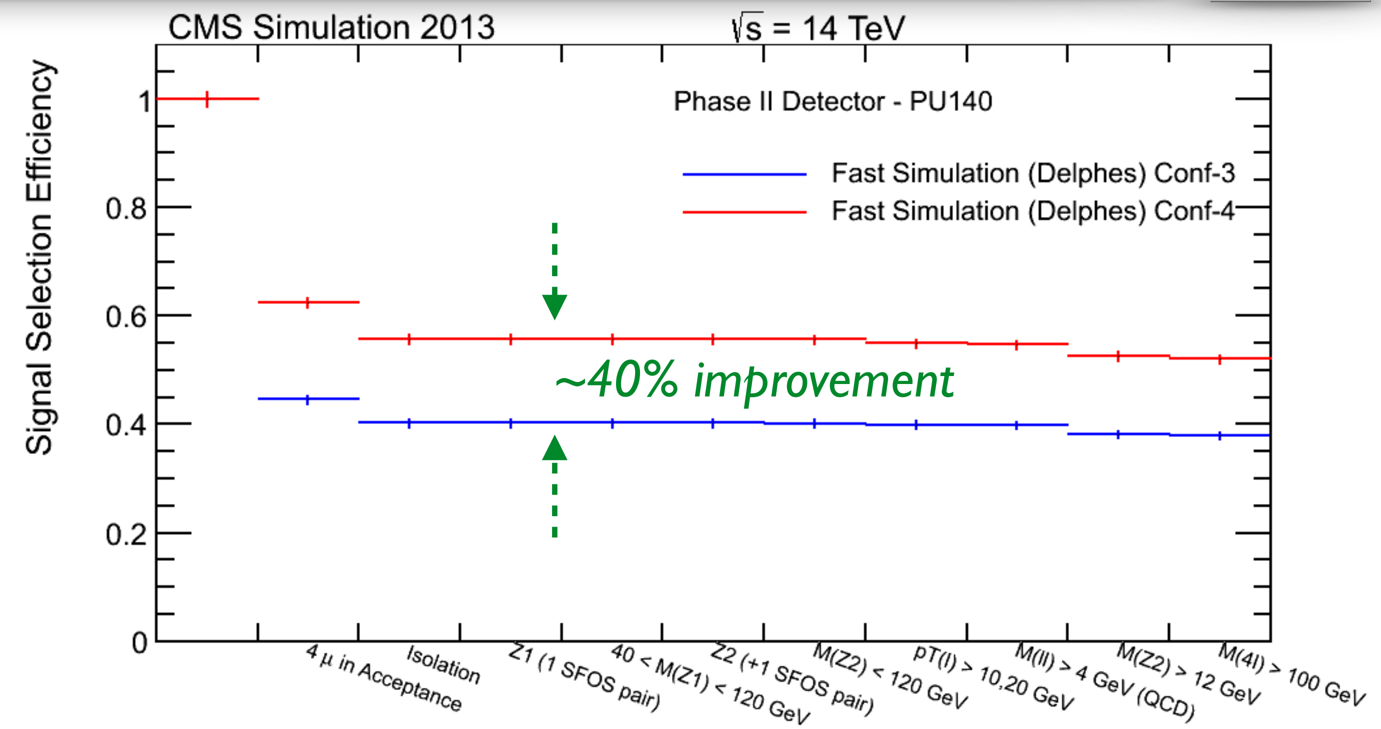
An Higgs mass of M_H = 126 GeV requires an *adjustment* between the tree-level mass $M^2_{H,0}$ and $\delta M^2_{H,f}$ of **1/10^31** !

There must be a mechanism that cancel out the *adjustment* ➜ precision measurements of Higgs sector should unveil such a mechanism

Phase-II upgrade motivations: some examples

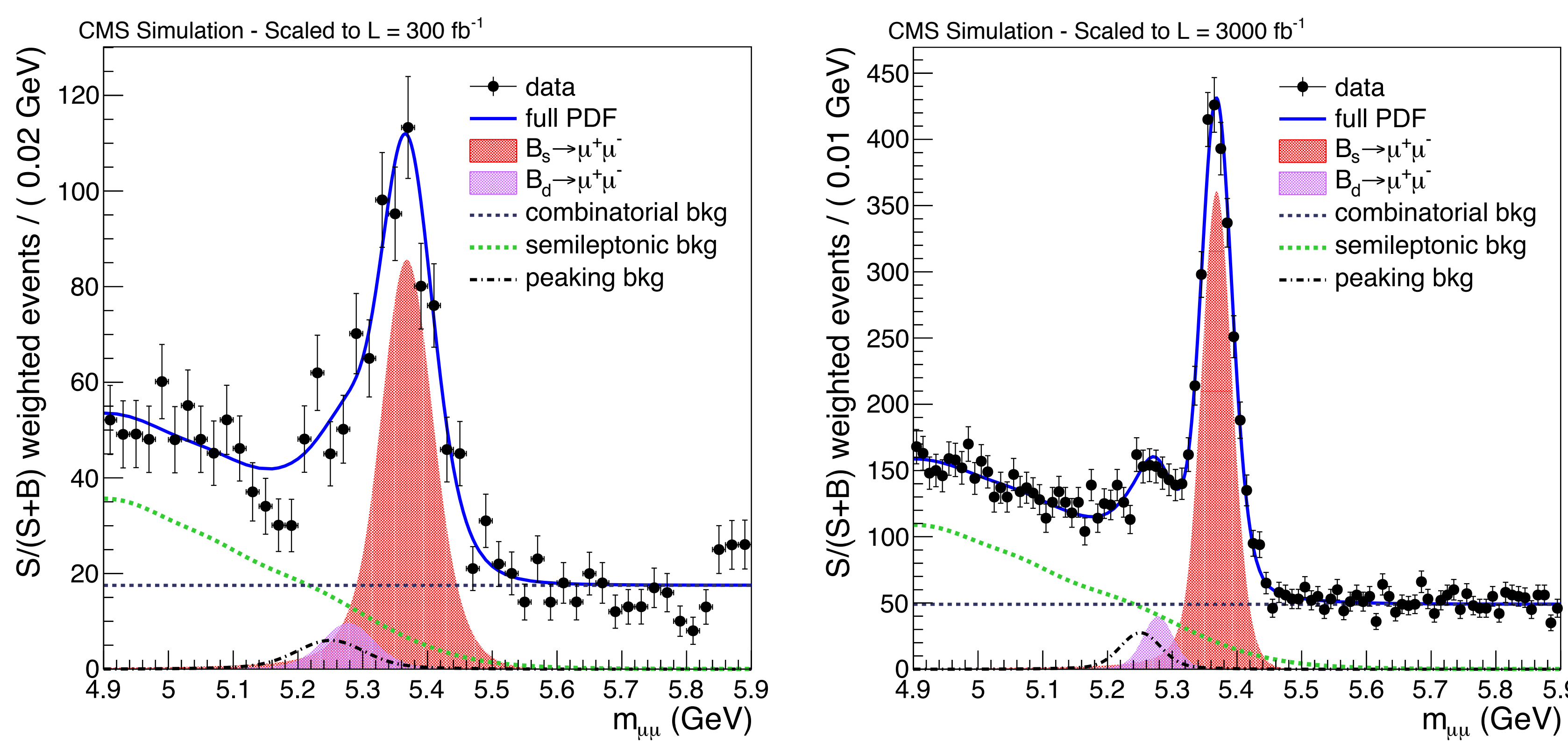
Efficiency cut flow for $H \to ZZ \to \mu\mu\mu\mu$

- **Conf-3:** sub-detectors have same **angular acceptance** as **current version**, but central tracking detector and the forward electromagnetic calorimeters are replaced and improved
- **Conf-4:** tracking, electromagnetic and hadronic calorimetry, and muon detector, are **increased in acceptance up to $\eta \approx 4$**

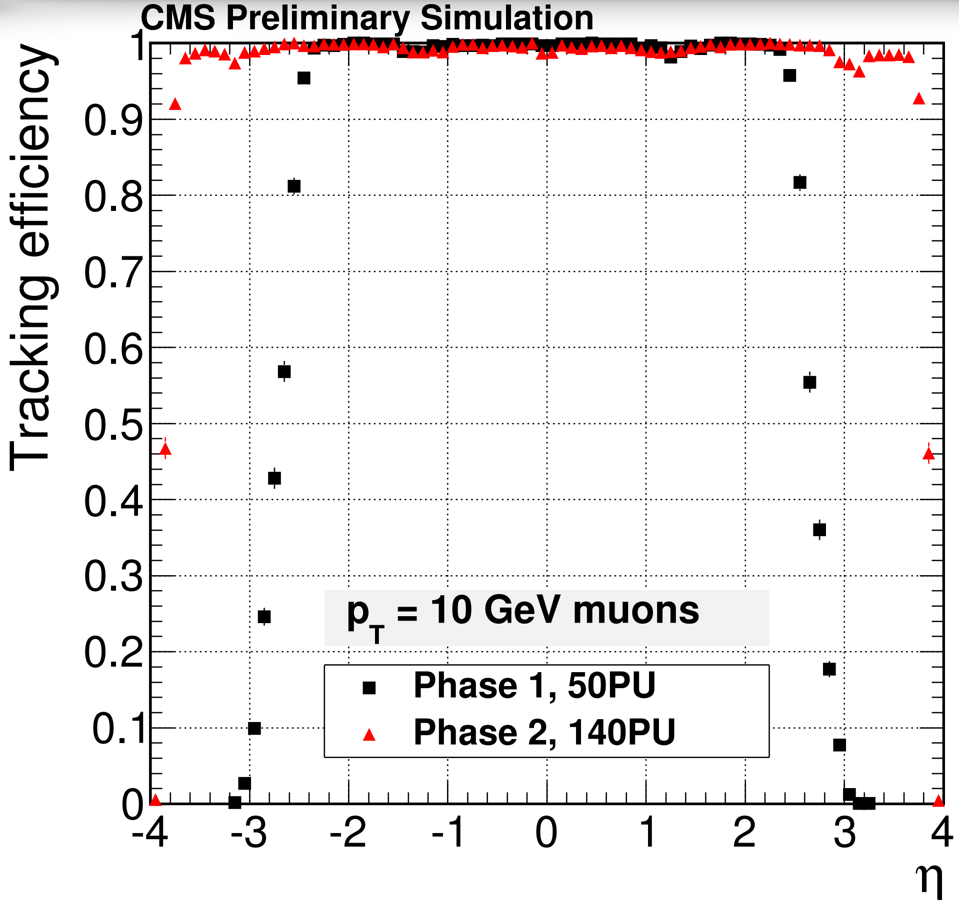


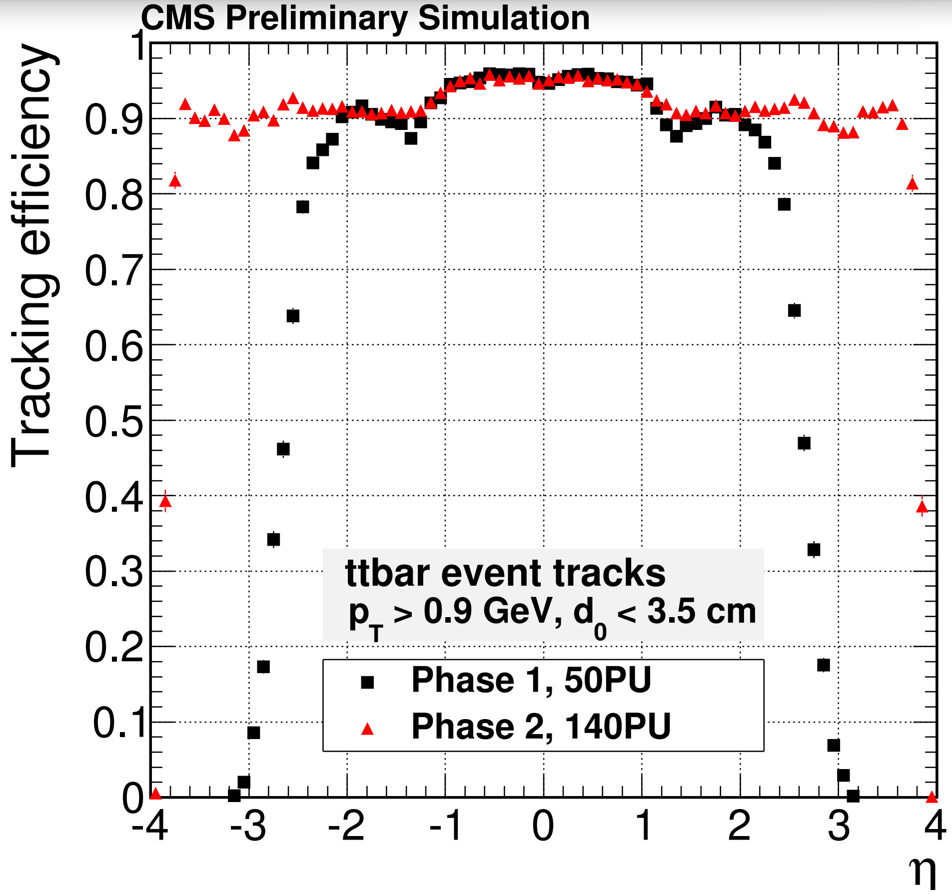
$B_{s/d} \to \mu\mu$ mass resolution for 300 fb^{-1} and 3000 fb^{-1}

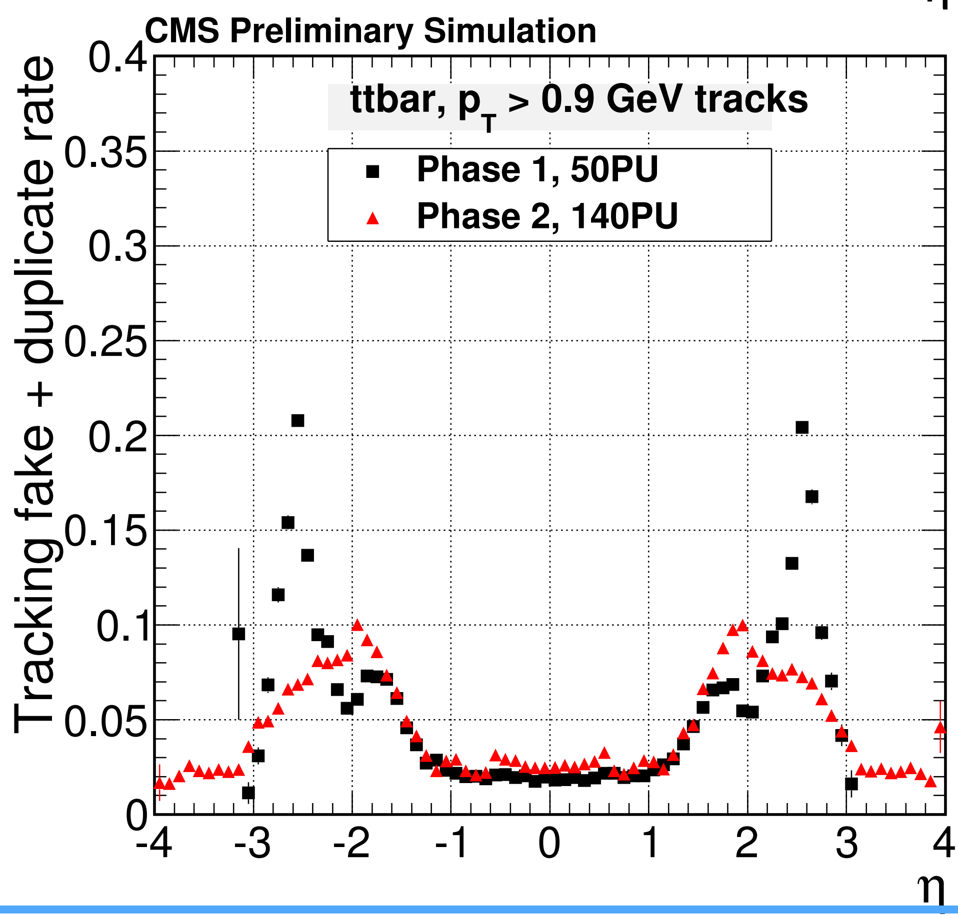
- Improvement in mass resolution for the 3000 fb^{-1} projection expected from improved inner tracking system and by removing end-cap candidates

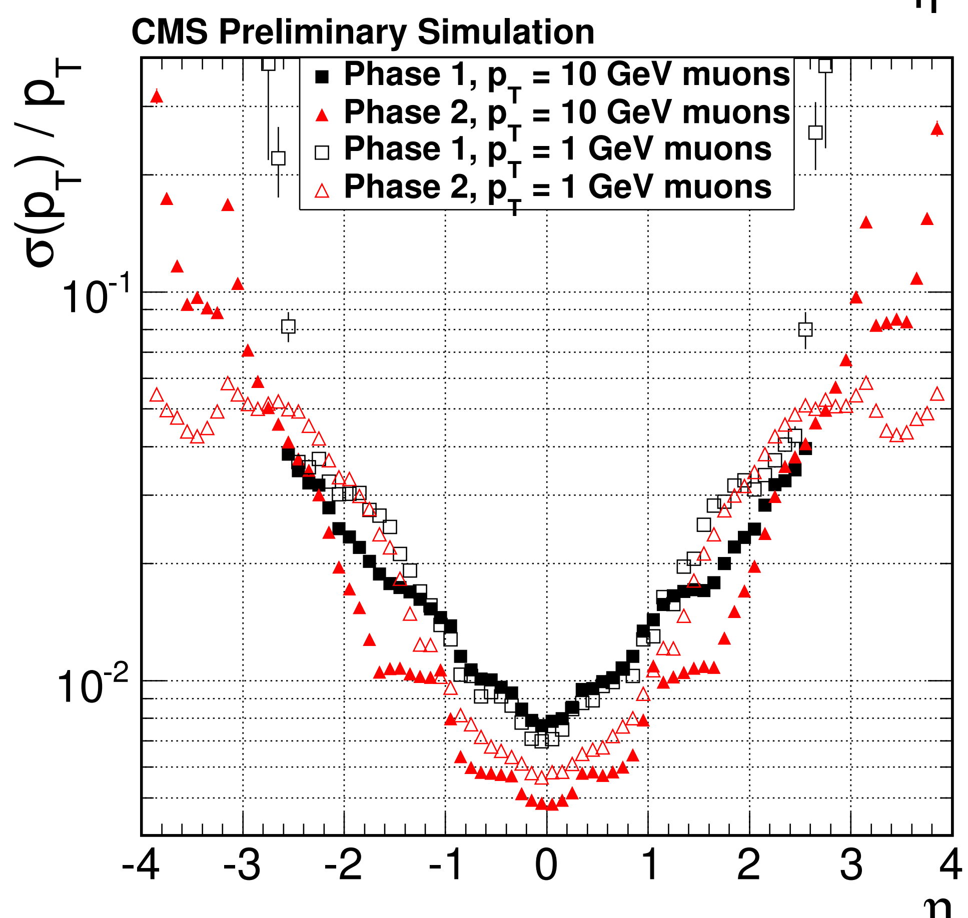


Phase-II tracking performance

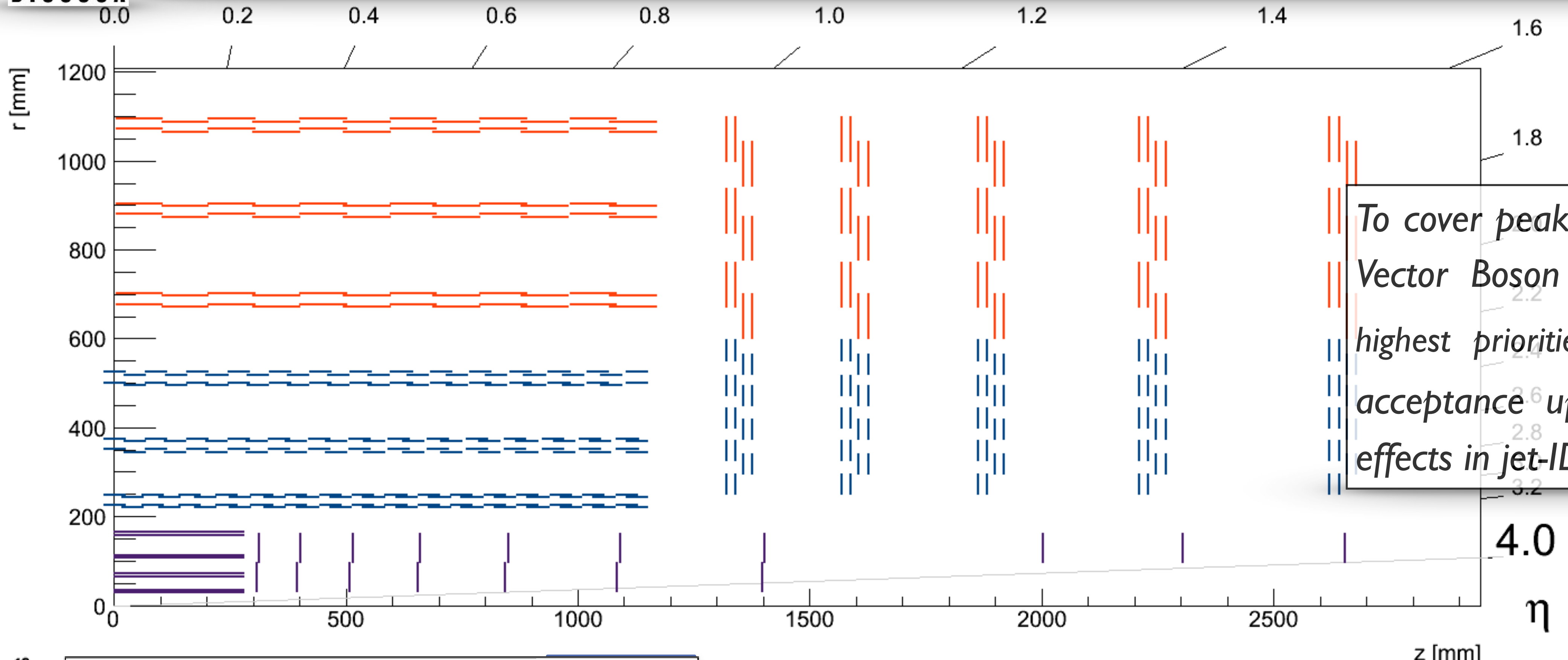




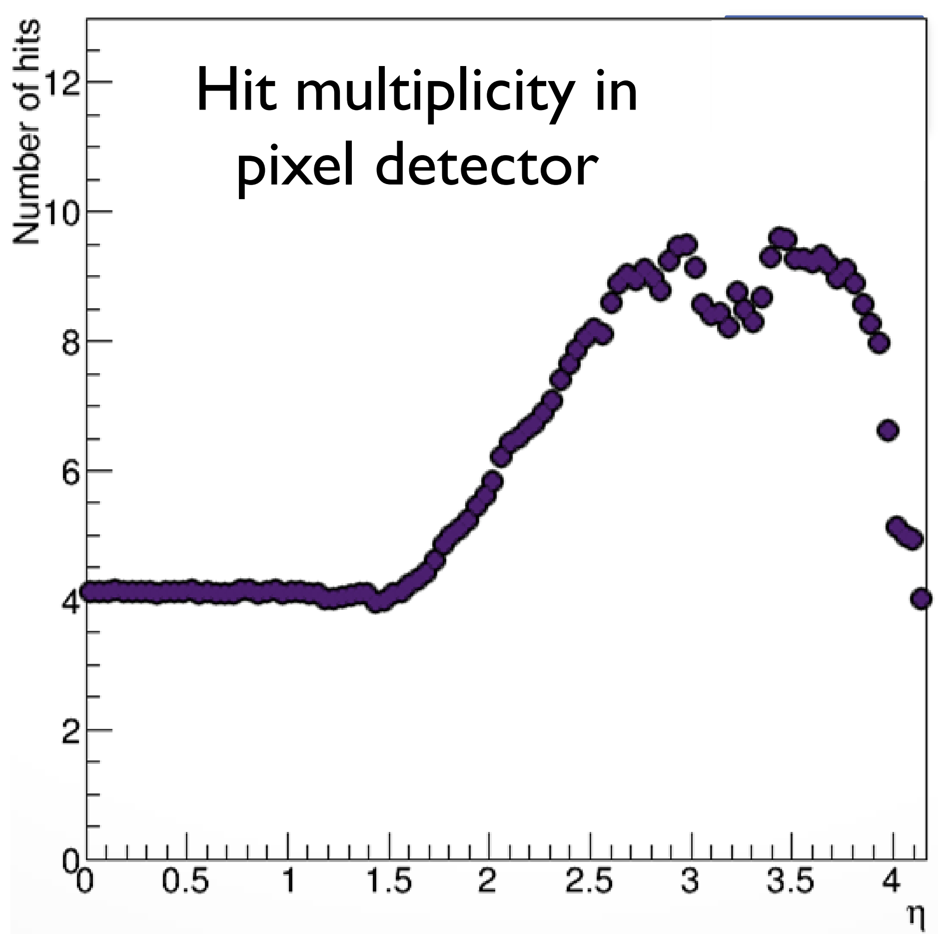


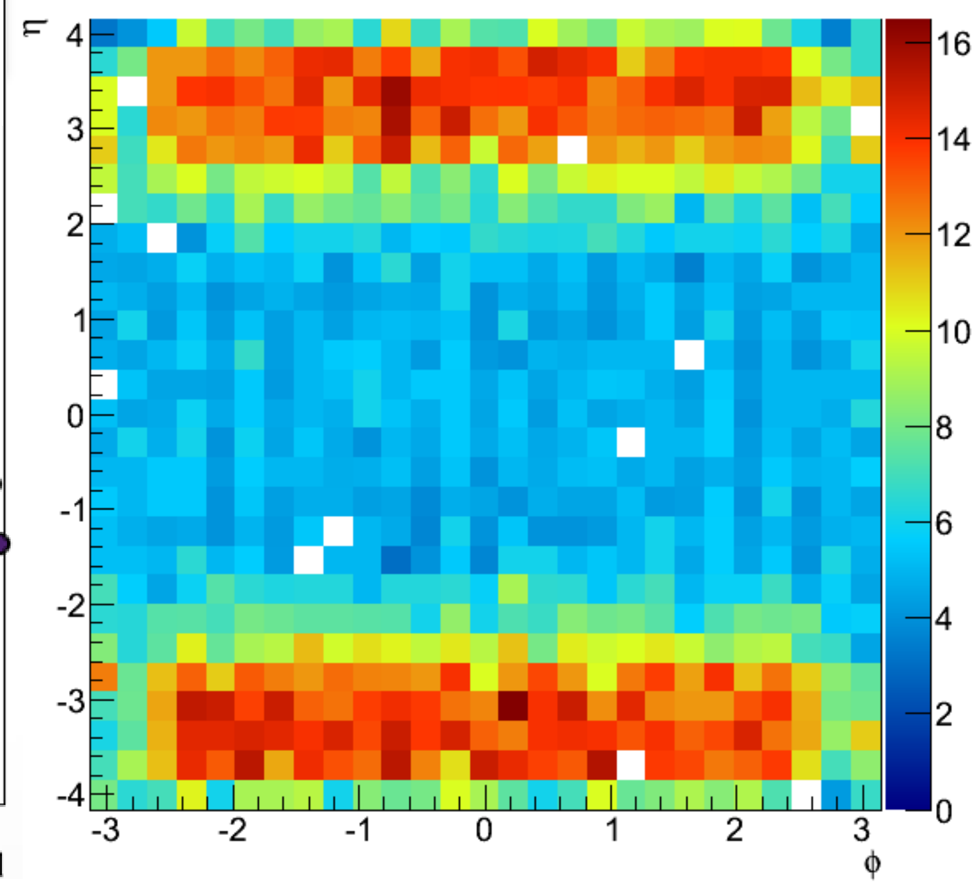


Forward pixel acceptance studies



To cover peak production region of jets from Vector Boson Fusion and and VBS (among highest priorities of the physics program) ➜ acceptance up to **η** *≈ 4, to mitigate PU effects in jet-ID and energy measurement*





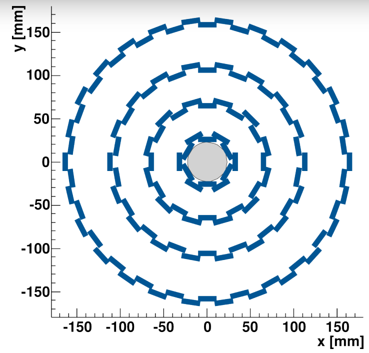
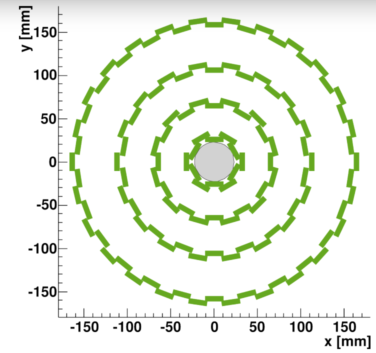
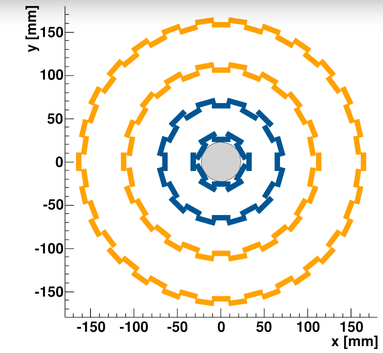
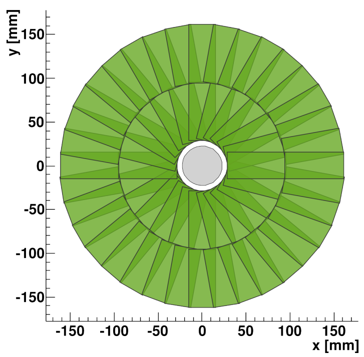
Barrel

- pixel size: 50x50 and 100x100 μm^2
- modules with 4x2 and 4x1 chips

Forward

- pixel size: 50x50 and 100x100 μm^2
- modules with 2x2 and 2x1 chips

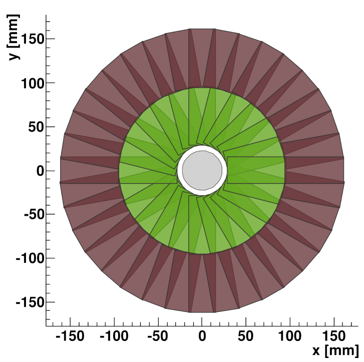
Pixel detector layout studies

1 BPIX 25x100
FPIX 50x50

2 BPIX 50x50
FPIX 50x50

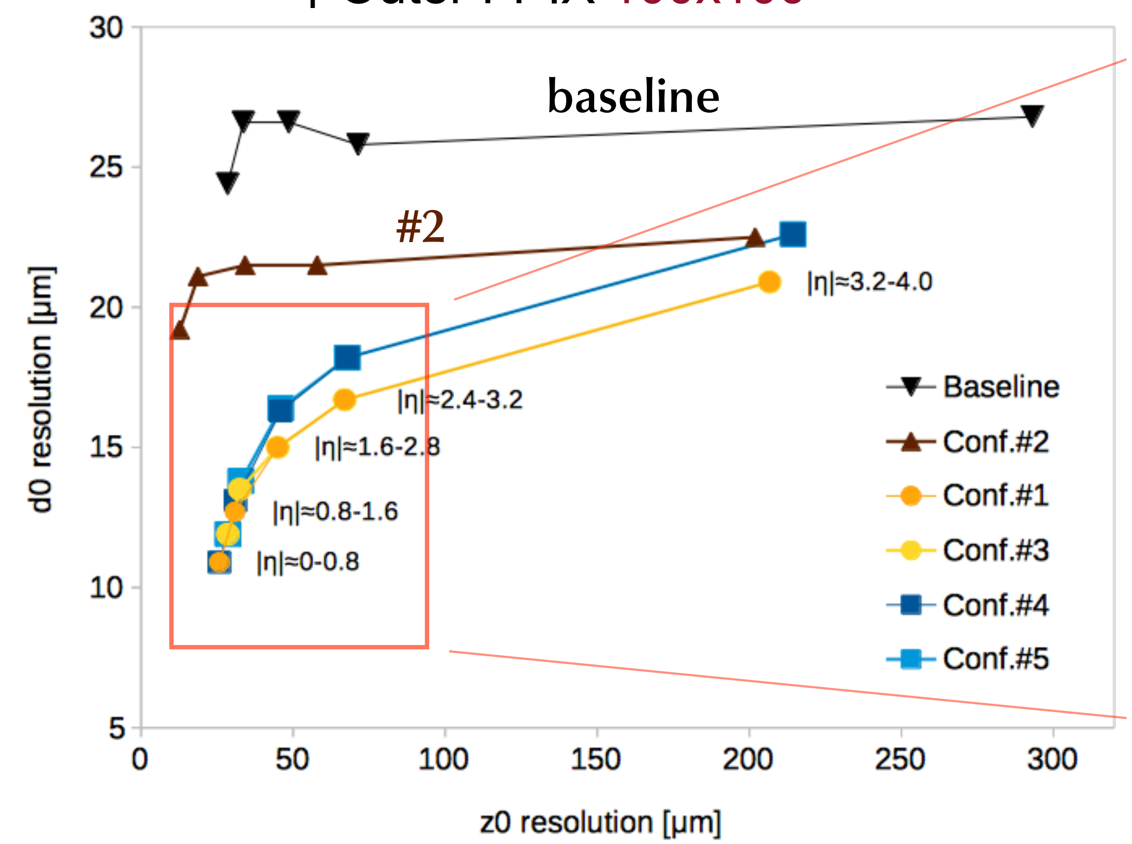
3 Inner BPIX 25x100
Outer BPIX 50x200
FPIX 50x50



4 BPIX 25x100
Inner FPIX 50x50
Outer FPIX 100x100

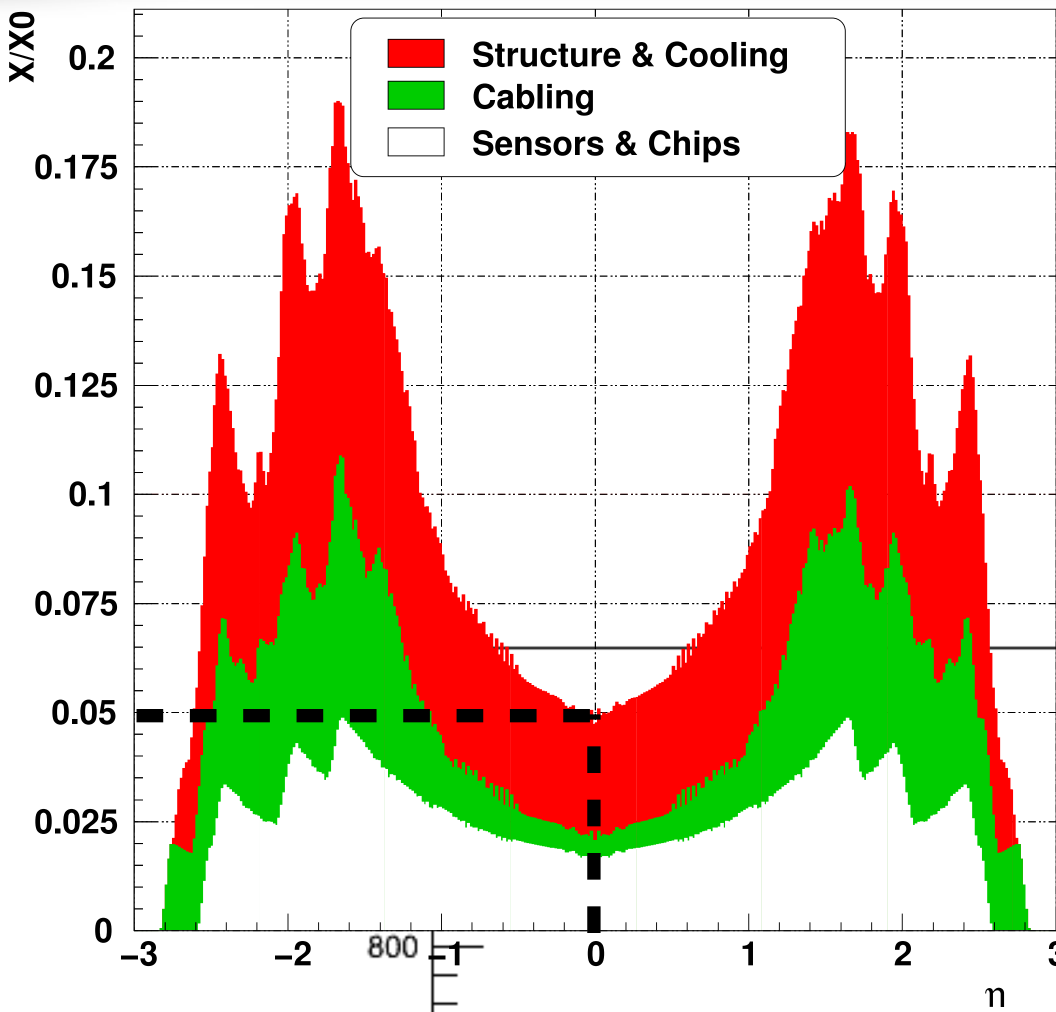
5 Inner BPIX 25x100
Outer BPIX 50x200
Inner FPIX 50x50
Outer FPIX 100x100

Petal configurations with mixed pixel sizes show better tracking performance than **Petal #2** and **baseline** (phase-I) geometries



Radiation environment characteristics

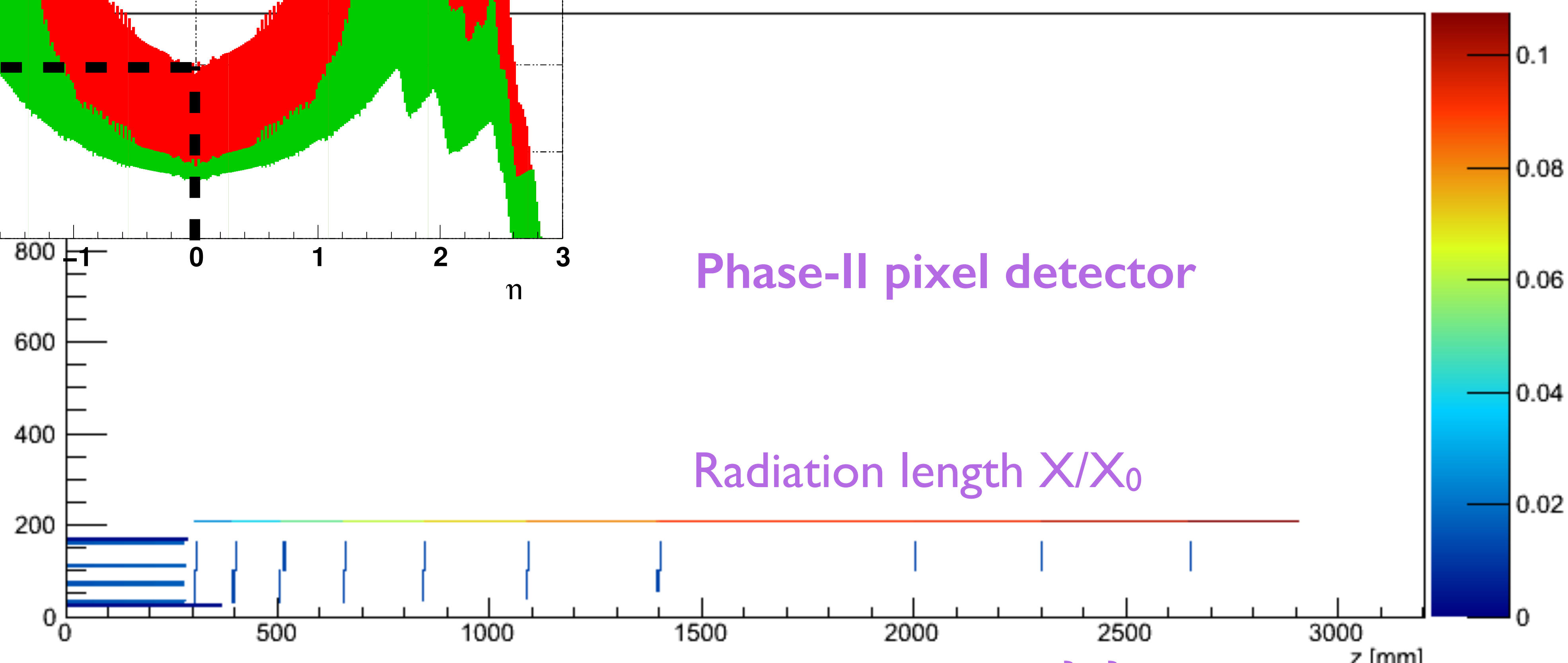
Radiation length for the present pixel detector



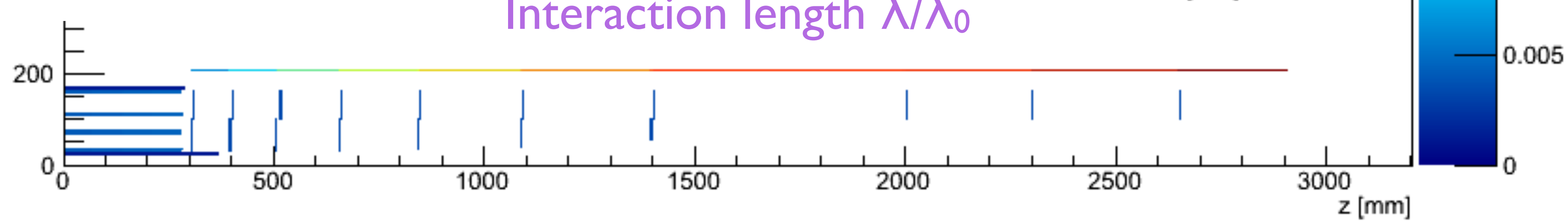
The foreseen phase-II pixel detector will be "lighter" than the present one

Phase-II pixel detector

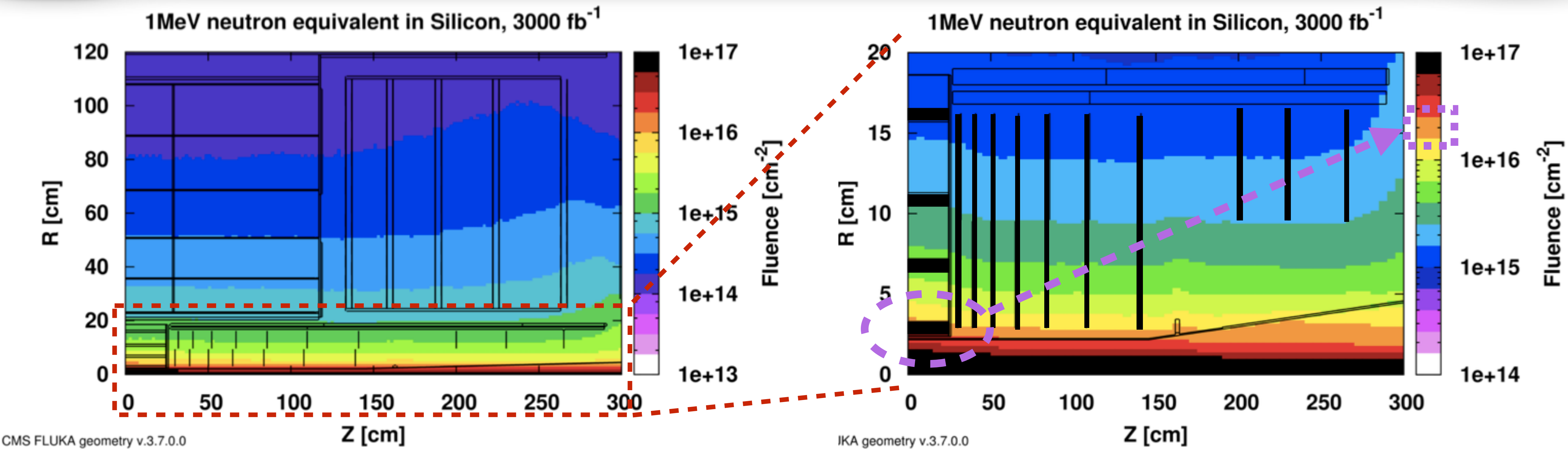
Radiation length X/X_0



Interaction length λ/λ_0



Possible sensor choices



Radiation fluence after 3000 fb^{-1} in the tracker (left) and zoom in the pixel (right)

Posible sensors technologies

- Favoured technology: planar Silicon
  - Define suitable n-in-p process and design (*more cost effective than present n-in-n because single sided process*)
  - Thin thickness
  - Requires robust spark rejection material
- Alternative/complementary for innermost layer: 3D Silicon
  - Define suitable sensor thickness and electrode geometry
  - Address production issues (*e.g. yield and cost*)

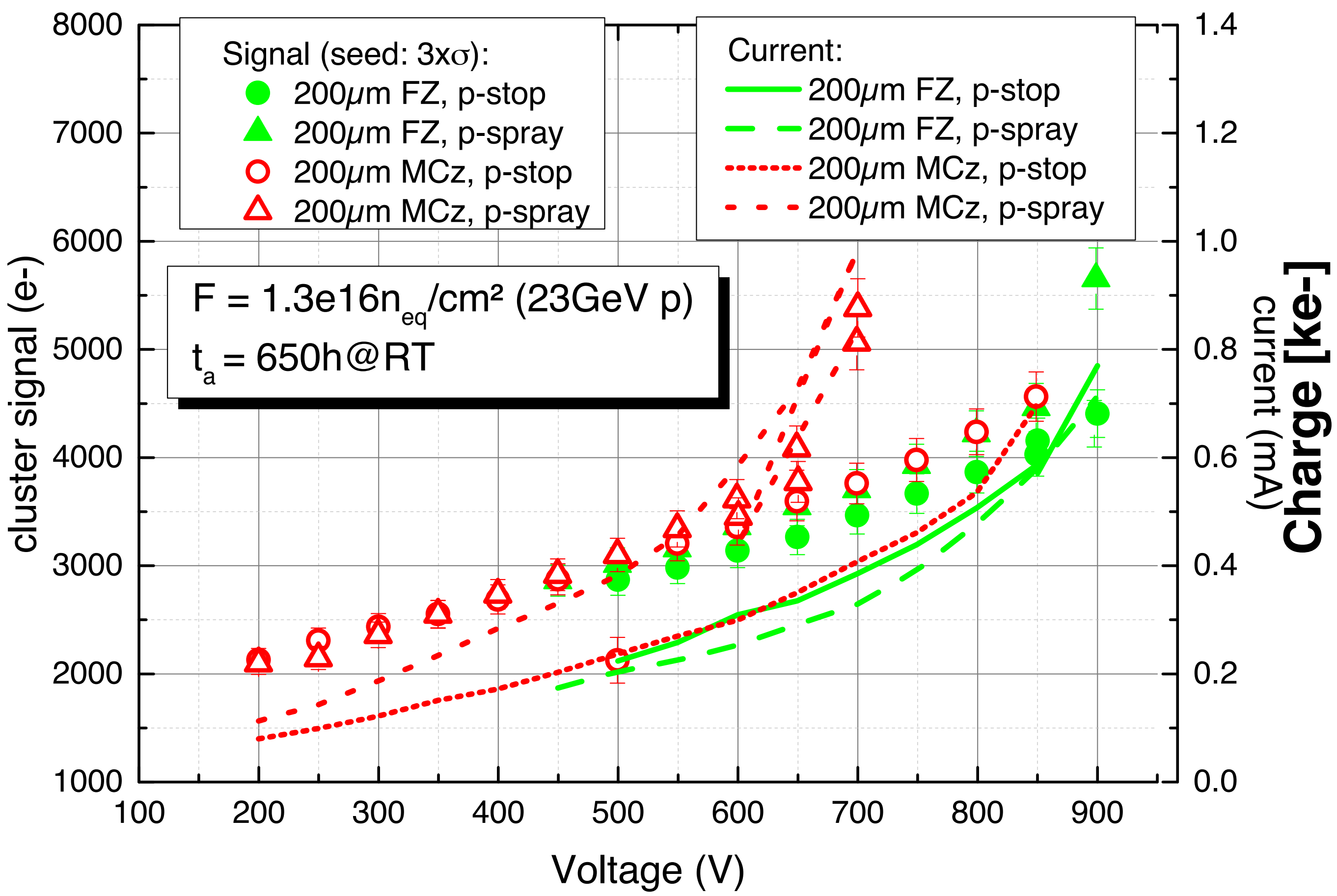
Possible sensor choices

Planar n-in-p need to define

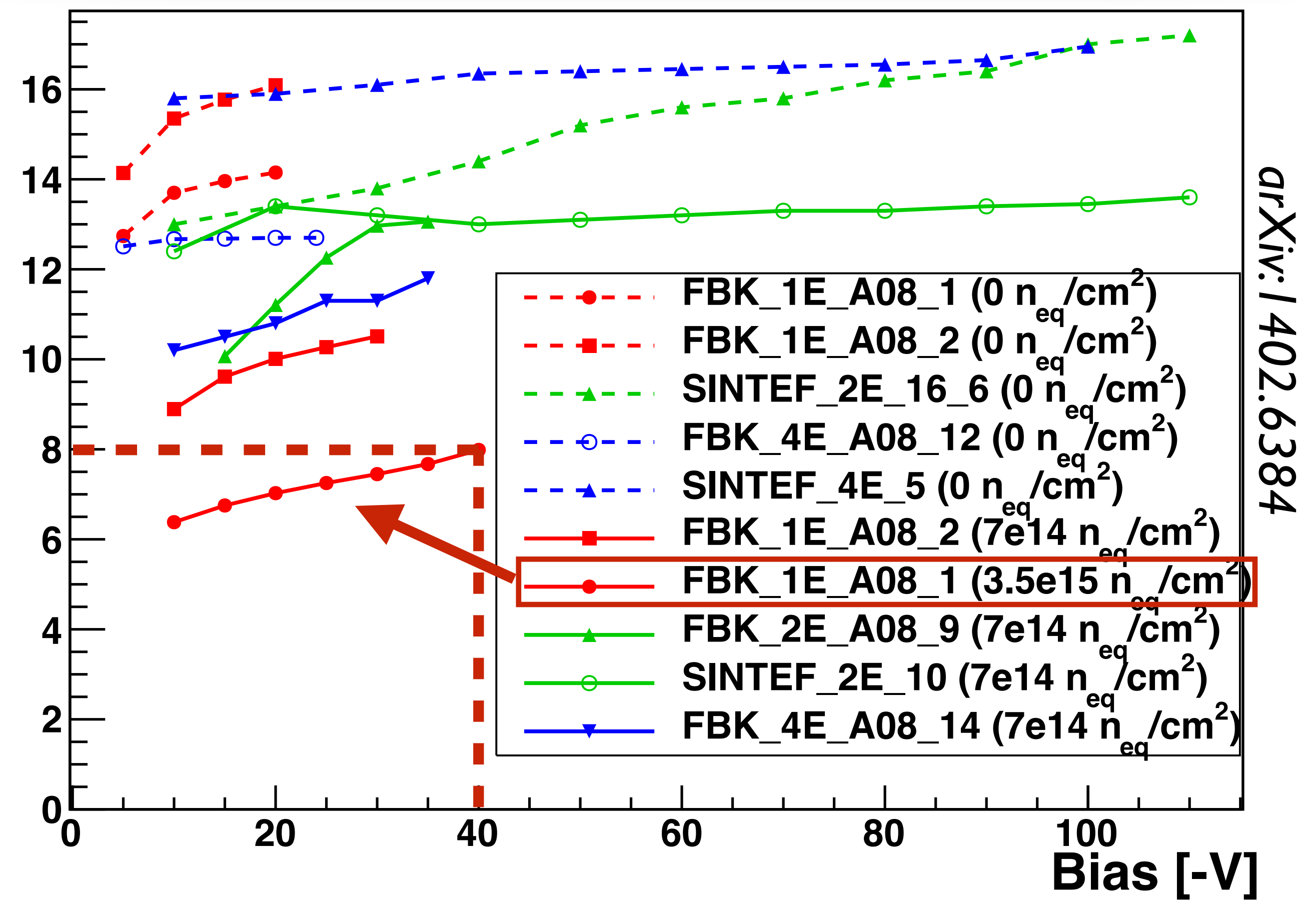
- Sensor thickness
- Sensor process (*FZ, MCz, EPI*)
- Spark rejection material
- Pixel isolation and bias scheme

Silicon 3D need to define

- Number of columns per cell
- Column size ➜ sensor thickness
- Pad position
- Production process: single/double sided



Signal charge and leakage current in planar n-in-p Silicon strip structures in different processes and isolations (*irradiation* 1.3×10^{16} n_{eq} / cm^2)



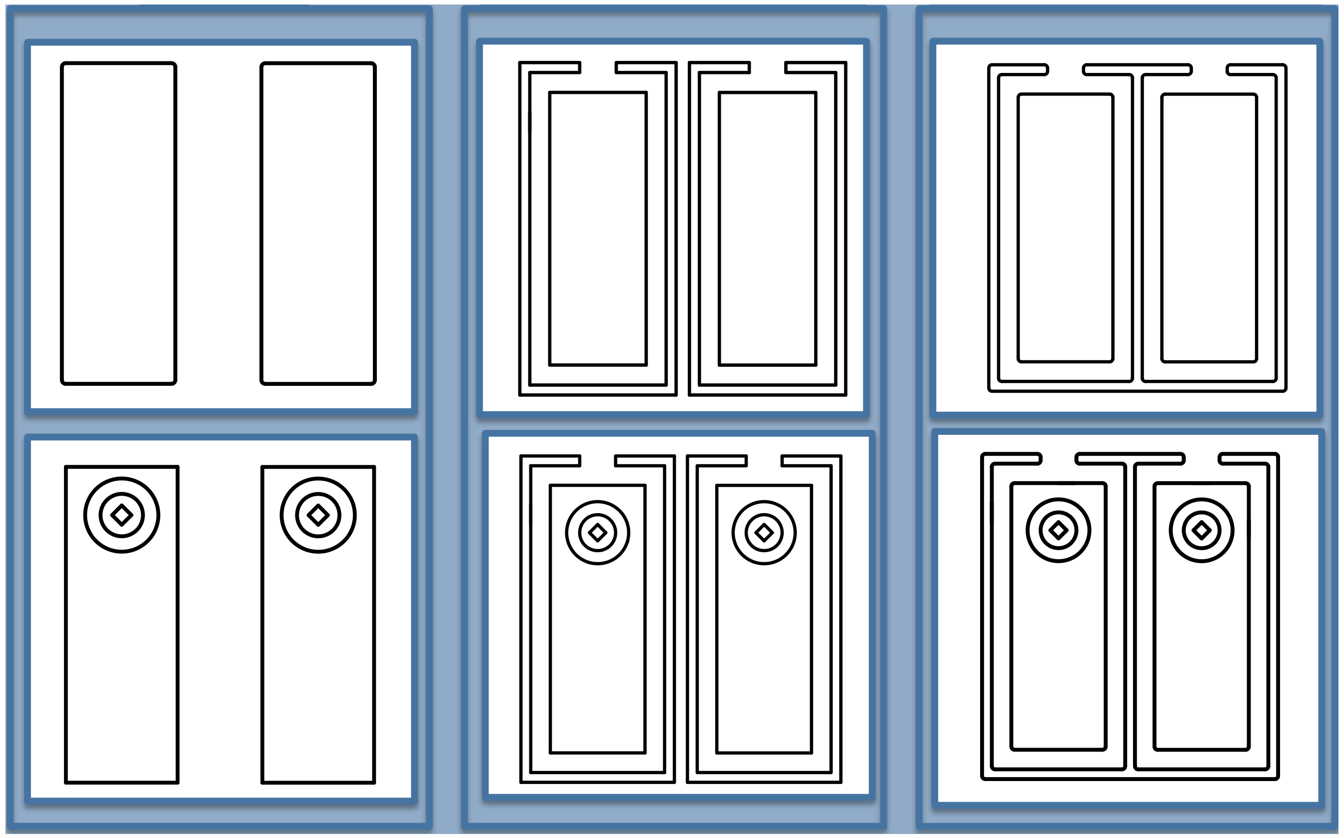
Signal charge in 3D n-in-p Silicon pixel structures from different vendors and with different column configurations (*before and after irradiation up to* 3.5×10^{15} n_{eq} / cm^2)

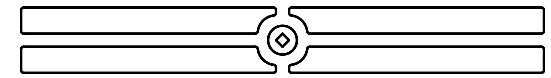
Thin planar Silicon sensors: isolation and bias scheme

p-spray | Individual p-stop | Common p-stop

no bias scheme

punch-through





p-spray with common punch through

Forward PIXel preliminary measurements on EPI and FZ designs (*non irradiated*)

- EPI FPIX 50 um with larger implants FPIXE have smaller breakdown (~350 V) compared to larger gap pixel FPIXF layouts (~500 V)
- FZ FPIX 120 um with larger gap pixel FPIXF have smaller breakdown (~380 V) compared to larger implants FPIXE layouts (~600 V)

Barrel PIXel preliminary measurements on EPI and FZ designs (*non irradiated*)

- EPI BPIX 50 μm with p-spray isolation and different gap sizes (BPIXA - BPIXD) show breakdown at ~550 - 600 V
- EPI BPIX 100 μm with p-spray isolation and different gap sizes (BPIXA - BPIXD) show a breakdown > 1100 V
- Leakage current of both EPI BPIX 50 μm and 100 μm sensors becomes noisy after 450 V - 500 V
- FZ BPIX 120 μm with p-spray isolation and different gap sizes (BPIXA - BPIXD) show a breakdown > 1100 V