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*Saverio D'Auria*

# Challenges of new detectors for high energy physics experiments

Istituto Nazionale di Fisica Nucleare

CVII Congresso della
SOCIETÀ ITALIANA DI FISICA
Italian Physical Society

# Contents

Mini-review of detector development in H.E.P. for accelerator based experiments, mostly addressed to non specialist

Not covering neutrino detectors

- Detectors in present experiment upgrades
- Challenges for future colliders
- Longer term developments

Focusing on charged particle tracking, calorimetry not included


## Abstract

Mini-review , indirizzata a non specialisti, dello sviluppo di rivelatori in Fisica delle alte energie, in esperimenti con acceleratori. Lo sviluppo di rivelatori per neutrini non è trattato, né la misura di energia delle particelle (calorimetria). I tre temi principali sono gli sviluppi di rivelatori attualmente in costruzione, le sfide per I nuovi collisionatori con sviluppi a lungo termine.

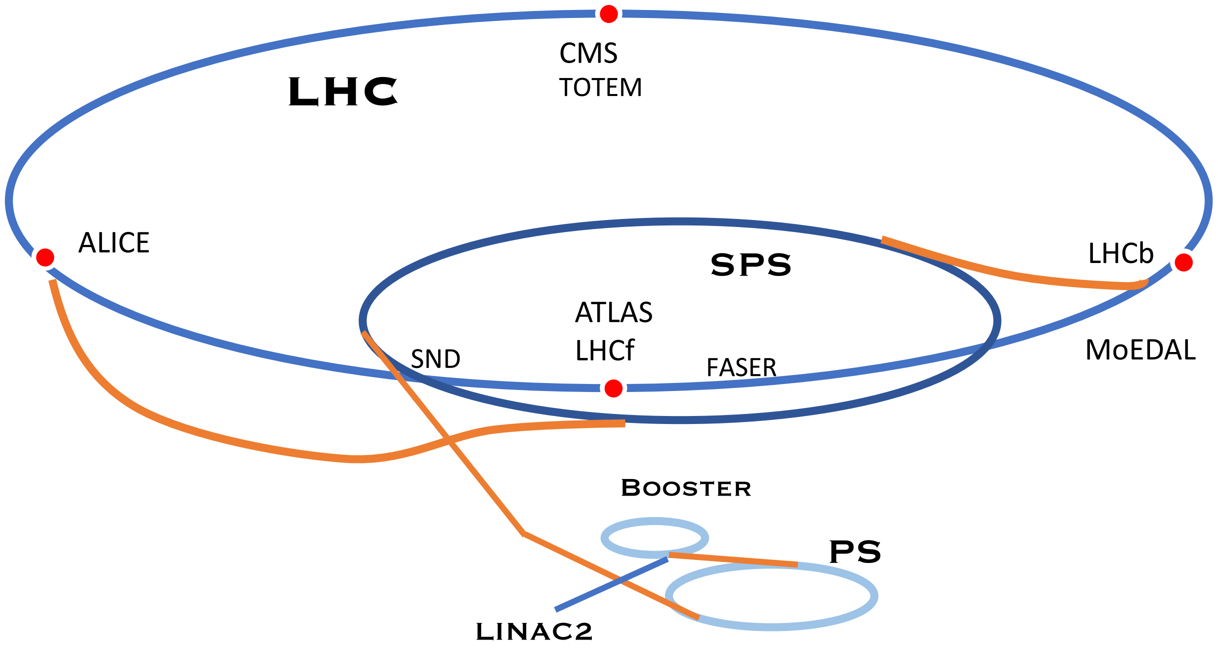
# Upgrades of present HEP experiments

Experiments being upgraded at accelerator(s)

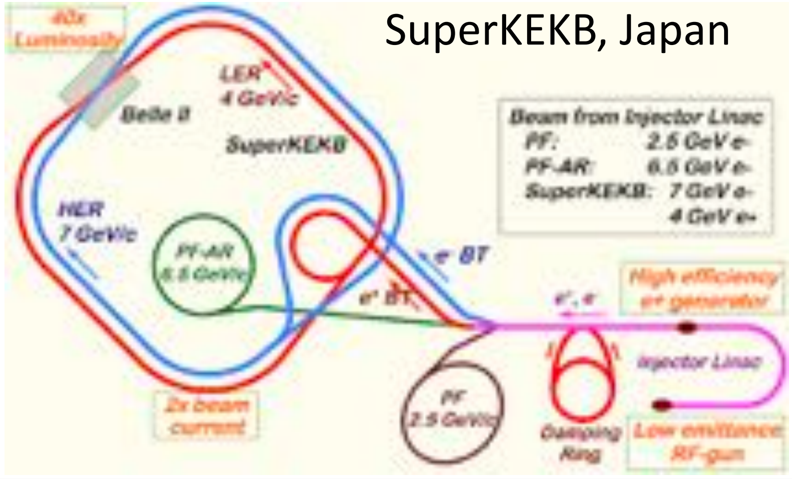
**LHC** : ALICE, LHCb, ATLAS, CMS, FASER, LHCf, MoEDAL, TOTEM, (SND $\nu$)

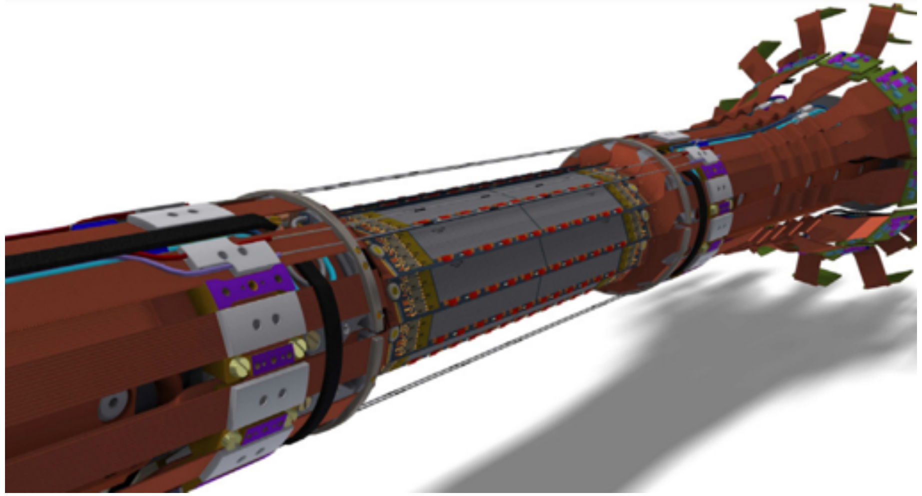
SuperKEK: Belle II is taking data now

Quick overview of main features




SuperKEKB, Japan



Belle II Pixel detector

# Timeline of approved upgrades

ALICE / LHCb upgrade installed now (2021) for LHC

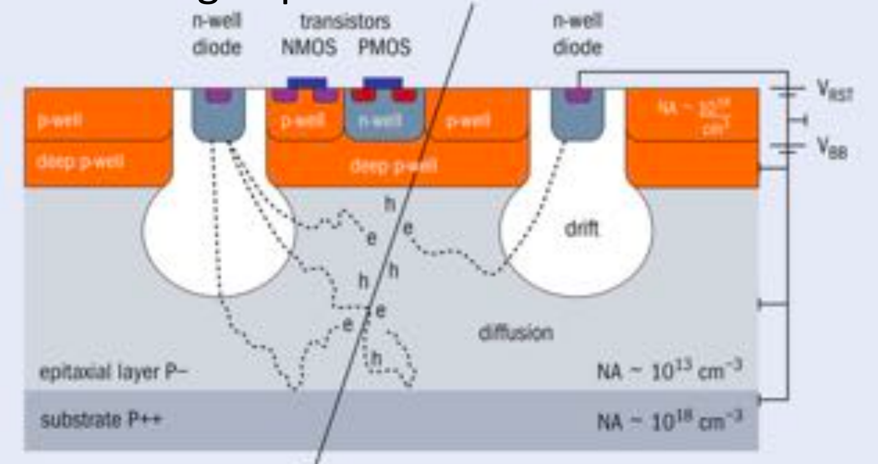
ATLAS/CMS: “phase 2” upgrade to be installed in ~2026 for HL-LHC

# Monolithic pixel detectors

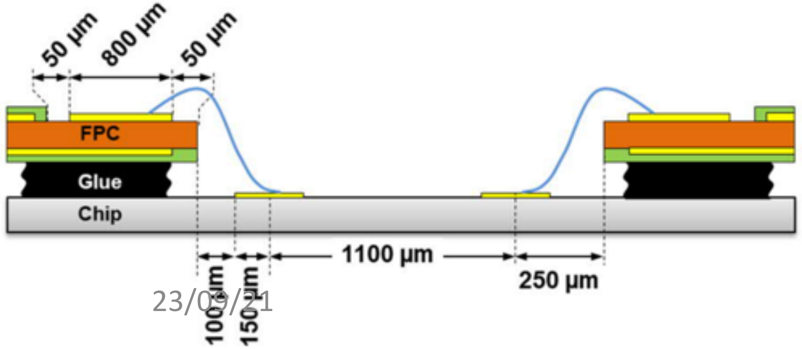
ALICE: upgrade (installed in 2021) using ALPIDE monolithic pixel ASIC

MAPS monolithic Active Pixel Sensor. Used in STAR@BNL (2015)

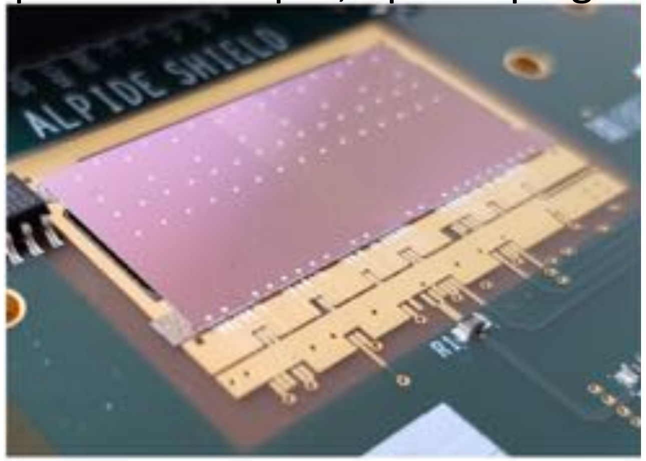
25µm p- epi layer on low resistivity CMOS wafer
Deep *p*-well around *n*-well diode, $C_{in}$ ~ 5 fF
Low voltage operation: drift with 1-7 V



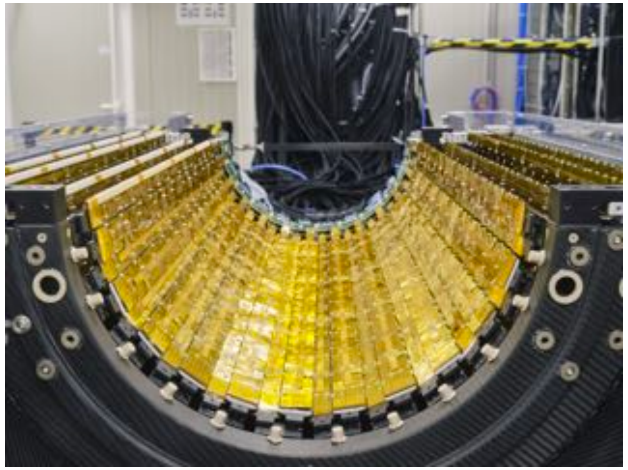

180 nm CMOS technology



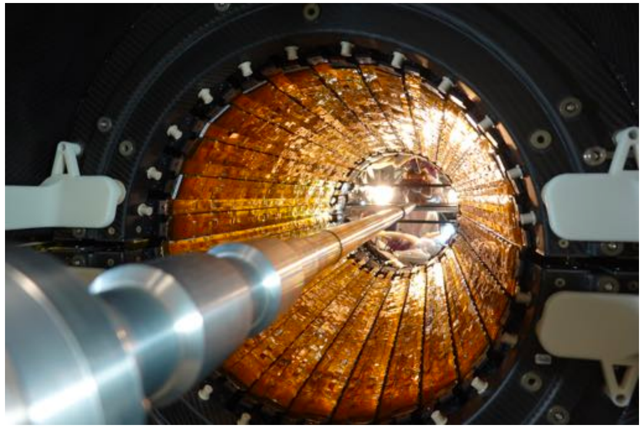

15 x 30 mm²
215 rows x 1024 columns,
pitch 29 x 27 µm; 2µs shaping




Noise 5 e⁻ ; Threshold 100 *e*⁻
Threshold variation 20 *e* RMS
PC board glued on chip front side
Wire bonding on active electronics
Through holes in printed circuts
Power 35 mW/cm²



10 m², 13 Gpixels for *p-Pb* and *Pb Pb* collisions



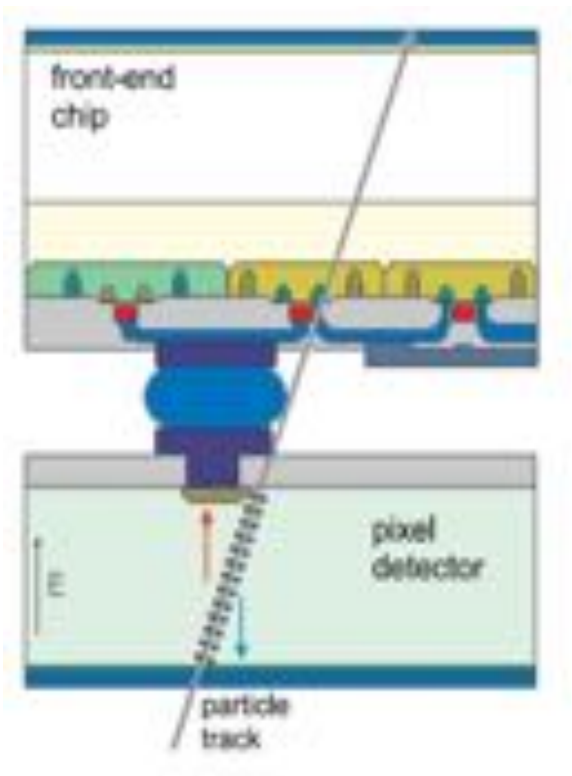
Installed around LHC beampipe at I.P.2

*ALICE collaboration*

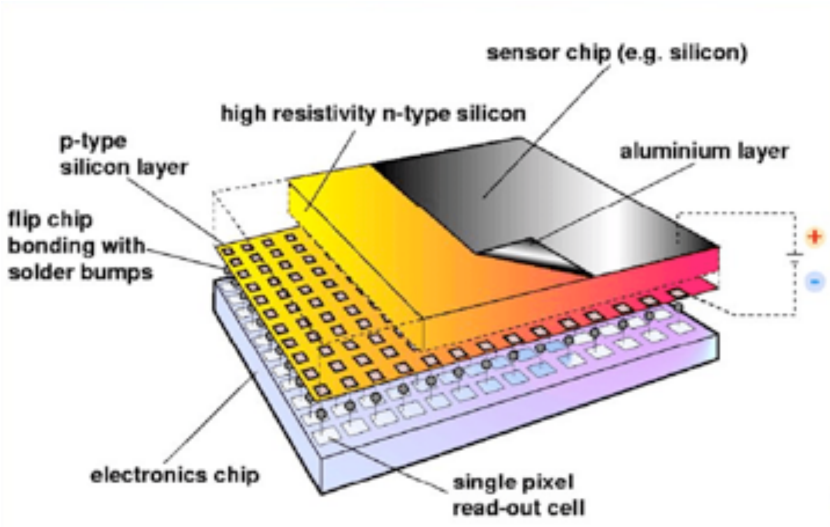
# Hybrid pixel detectors

**ATLAS & CMS**: “phase 2” upgraded detectors to be installed in 2025 for HL-LHC

Technology well established: pixel detectors designed in 1990’s still functioning through LHC run-3




Hybrid pixel detector
Radiation sensor and
Front-end ASIC electronics
in separate crystals



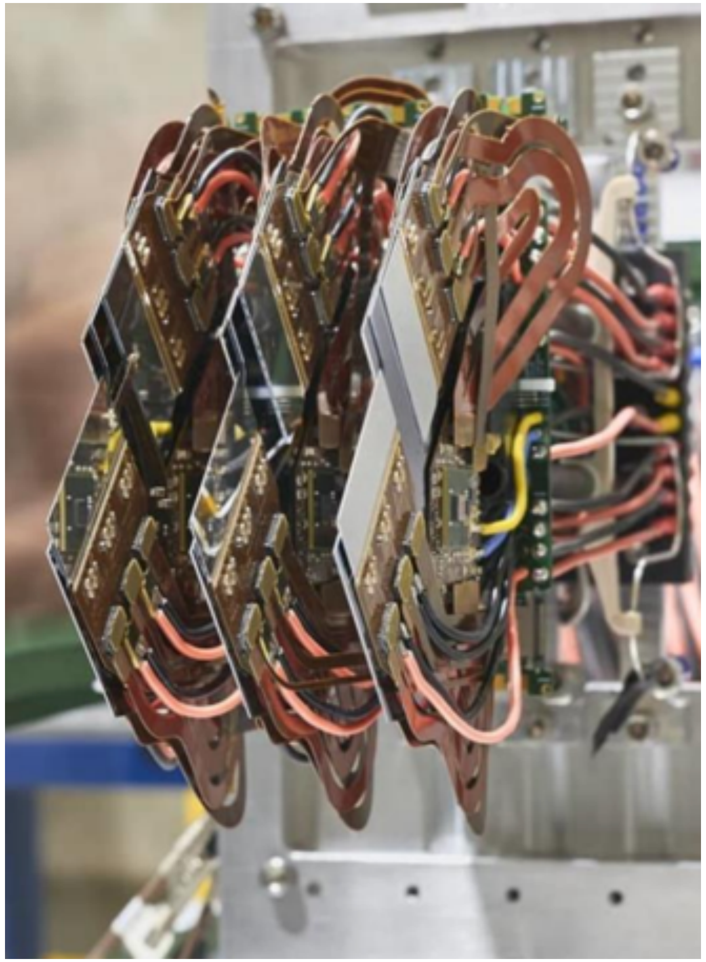

**Challenges:**

- 8x higher hit, trigger, dose (SEU) rate,
- 10x higher design max fluence,
- 3 x higher spatial resolution
  - CMS 100 x 150 → 50 x 50 µm
  - ATLAS 50 x 250 → 50 x 50 µm
- larger surface,
  - CMS 1 $m^2$ →4.9 $m^2$
  - ATLAS 2.9 $m^2$ → 13 $m^2$
- lower temperature
  - Atlas $C_3F_8$ → $CO_2$ -25°C → –35°C
- Thinner material (100 + 100 µm)

# Hybrid pixel detectors

**LHCb**: has replaced strips with hybrid pixels ASIC VeloPix based on TimePix3: 256 x 256 pixels 55 x 55 μm$^2$

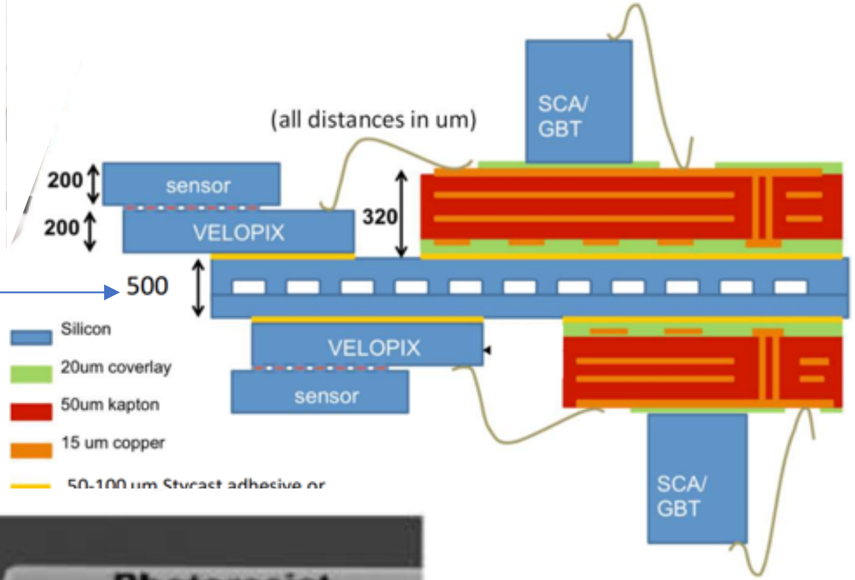
Being installed at IP (Sept. 2021)



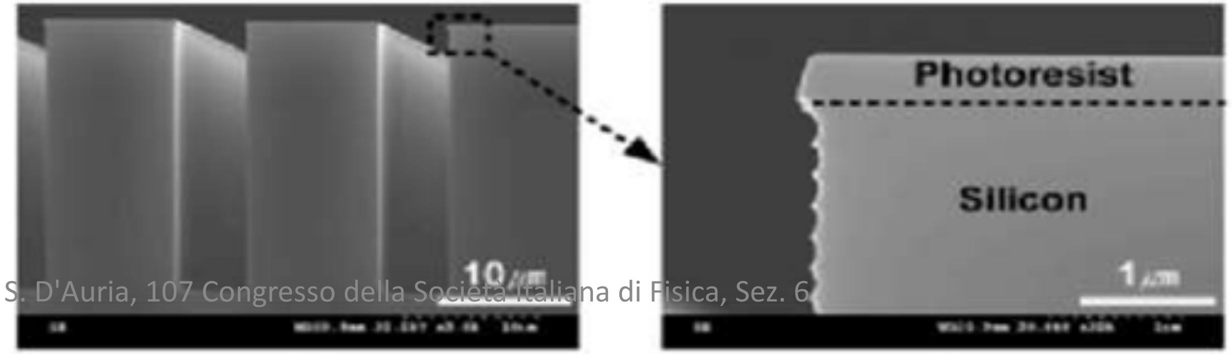
**Technical Challenges:**

- Readout rate at 40 MHz
- Cooling: low mass 1.6 kW at -25°C
- 41MPix
- High fluence $8 \times 10^{15}$ n eq. in Si

Silicon wafer as capillary for CO2
Evaporative cooling




Deep Reactive Ion Etching
Silicon-Silicon bonding



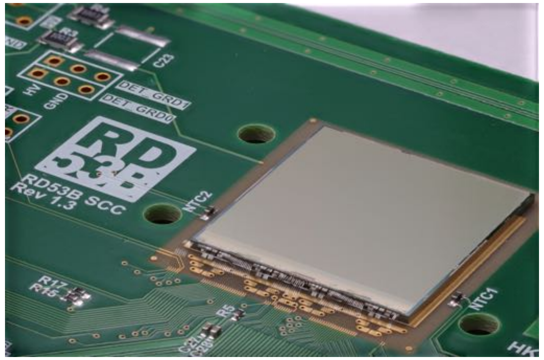

*J Buytaert, VELO grpup, July 2019*

# Hybrid pixel detectors

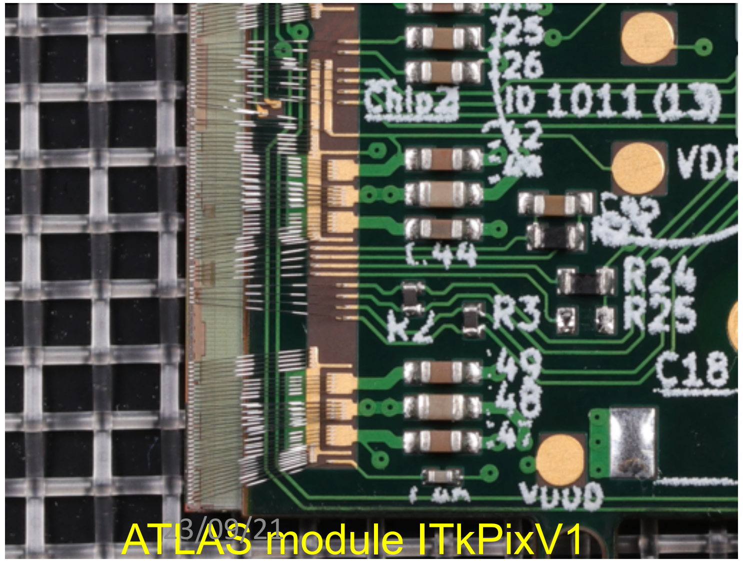
## ATLAS/CMS: "phase 2" pixel upgrade layout

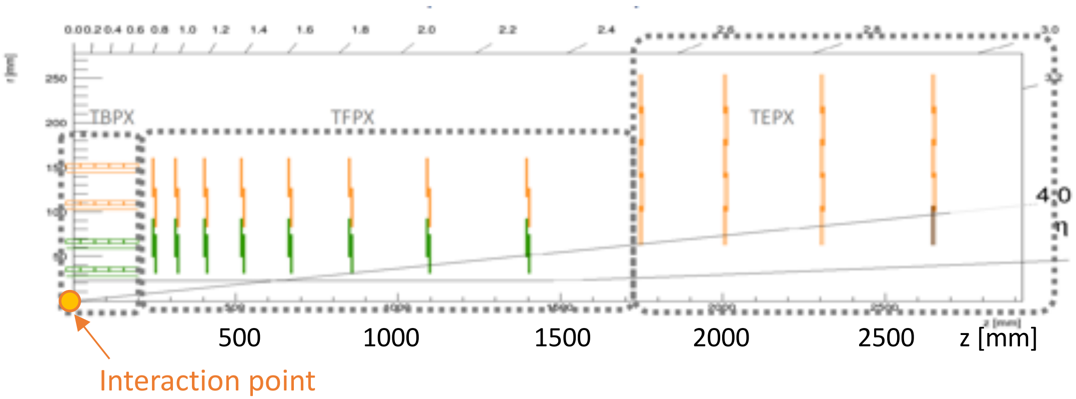
Using very similar readout chip
main differences in analog part

ATLAS (ITkPix): 400×384 pixels, differential FE
CMS (CROC): 432×336 pixels, linear FE

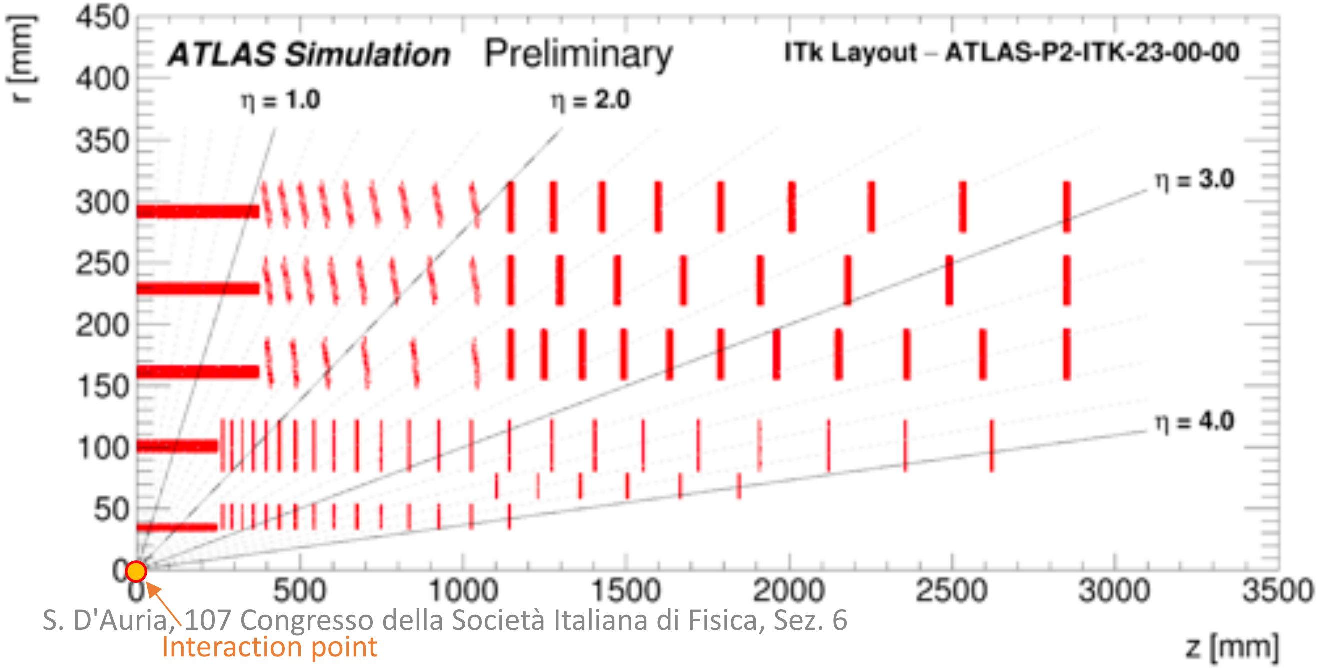



ASIC
ITkPixV1
20 x 21 mm2




CMS layout
2 Gpix




ATLAS
Layout
5.2 Gpix

# Adding time coordinate

Pile-up is severe at HL-LHC.

ATLAS upgrade: add High Granularity Timing Detector (HGTD) uses Low Gain Avalanche Diodes (LGAD) at $-30$°C with $CO_2$ cooling.

Pile-up: number of p-p interactions in the same bunch crossing

Aim at 20 ps time resolution to discriminate origin of track: hard interaction or ”other” non-interesting interactions.

LGAD as macro- hybrid pixels

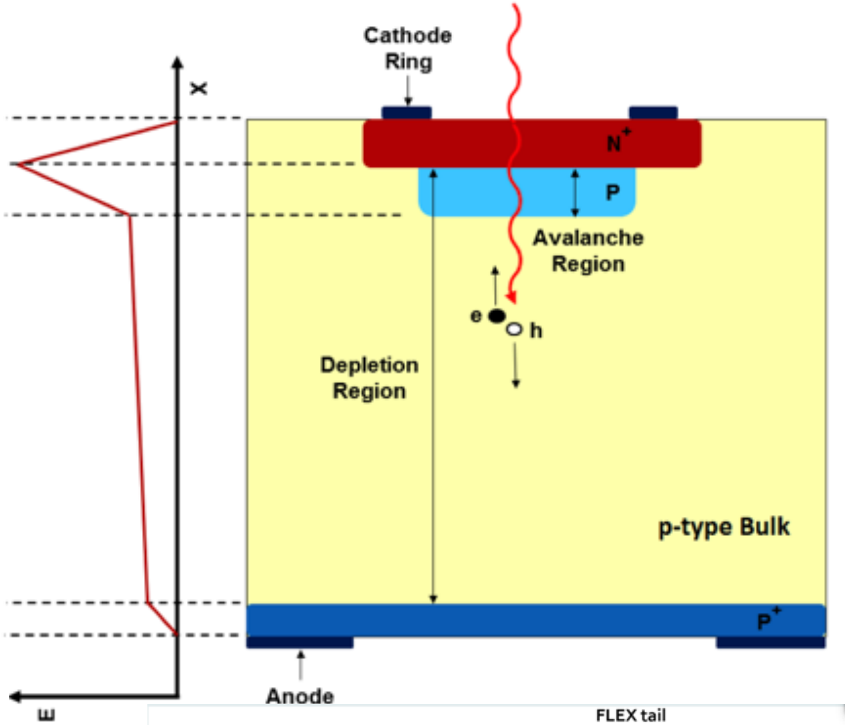
ASIC readout “ALTIROC” bump bonded to LGAD, 15 x 15 = 225 channels

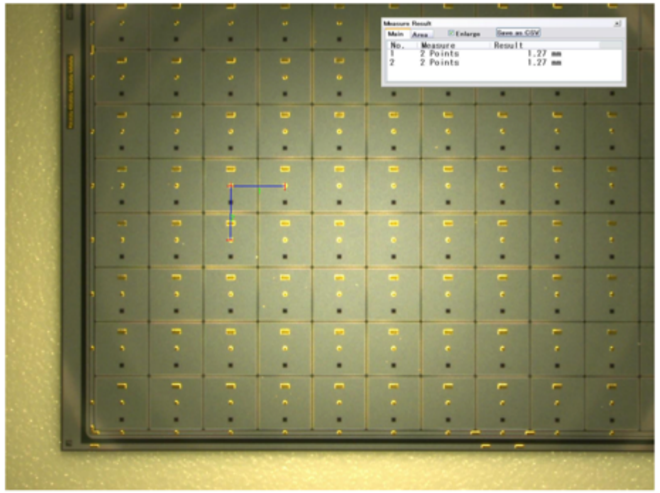
Present design 2 ASICS per LGAD sensor ( 21 x 40 mm )

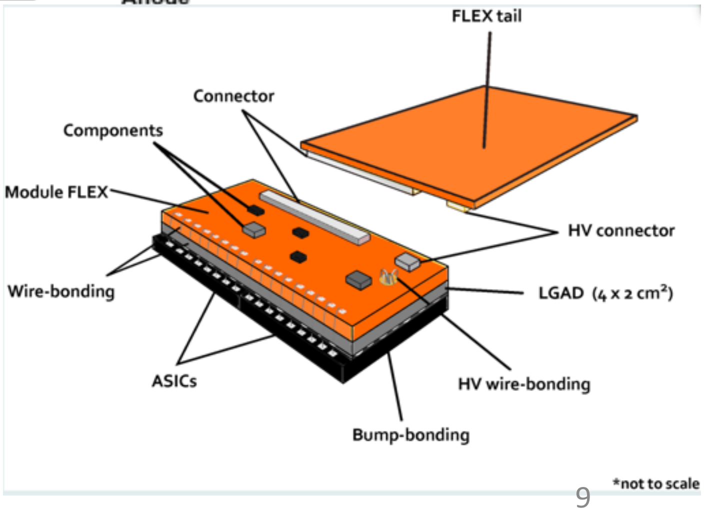
Macro-pads 1300 x 1300 μm$^2$

Challenges:

- large area, ~ 5 m$^2$
- Precise timing
- Sensitivity to background radiation
- Radiation resistance








*HGTD Tech Des. Rep.*

# Detector challenges for hadron colliders

- Radiation hardness
- Cost and Reliability
- Time resolution
- Power dissipation
- Services: power, cooling

**Ideal tracking detector is**

- Extremely thin to reduce multiple scattering, and give a point-like measurement of position
- Radiation resistant
- Low cost and reliable
- Has *pico seconds* signal rise time
- Consumes almost no power
- Is cooled by air
- Has wireless data connection to DAQ

# Radiation Hardness

## By design, in electronics

Smaller structures are less likely to be hit by radiation: present ASICS 65 nm CMOS, down to 28 nm

Shielding with implants transistors from one another, various design libraries being tested

Redundant design

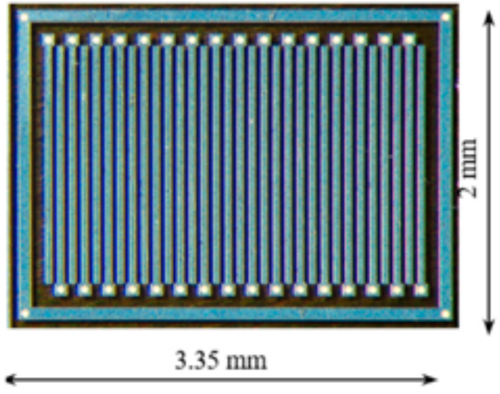
## Material

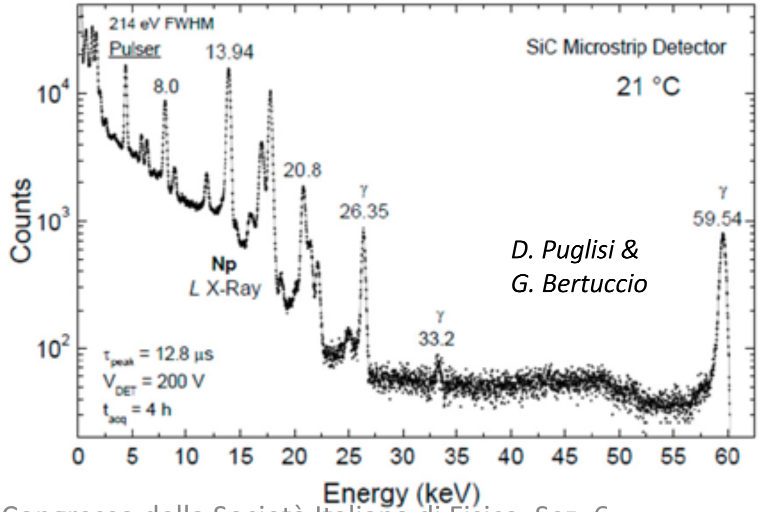
Silicon is excellent till $2\times10^{16}$ neutrons/cm$^2$ (1MeV equivalent in Si)  Can we push this limit?

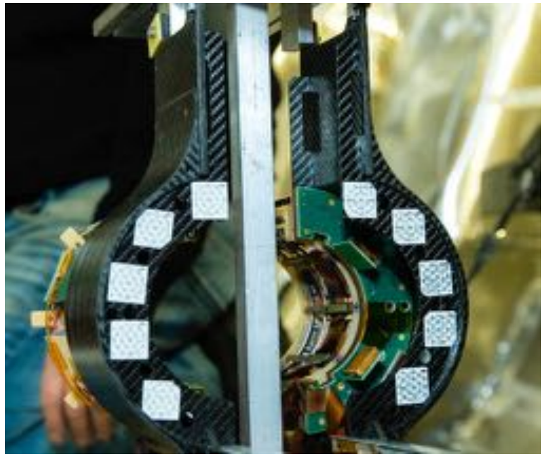
Diamond  used in beam monitoring at LHC and at SuperKEKB

Silicon Carbide: large bandgap, large production due to white LED. IV-IV semiconductor, deep traps from interstitials?

SiC detectors



CMS Beam conditions monitor diamond

# Monolithic pixels for rad-hardness

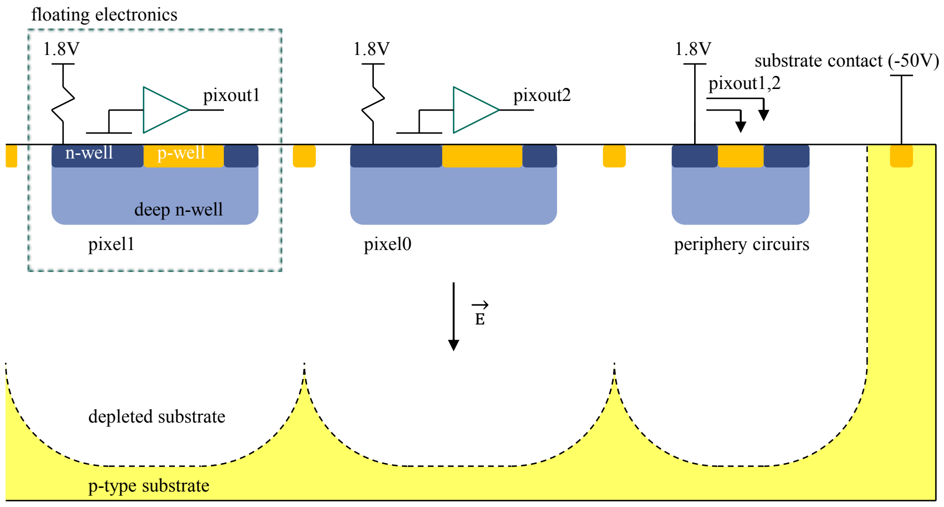
Monolithic detectors for rad-hard environment

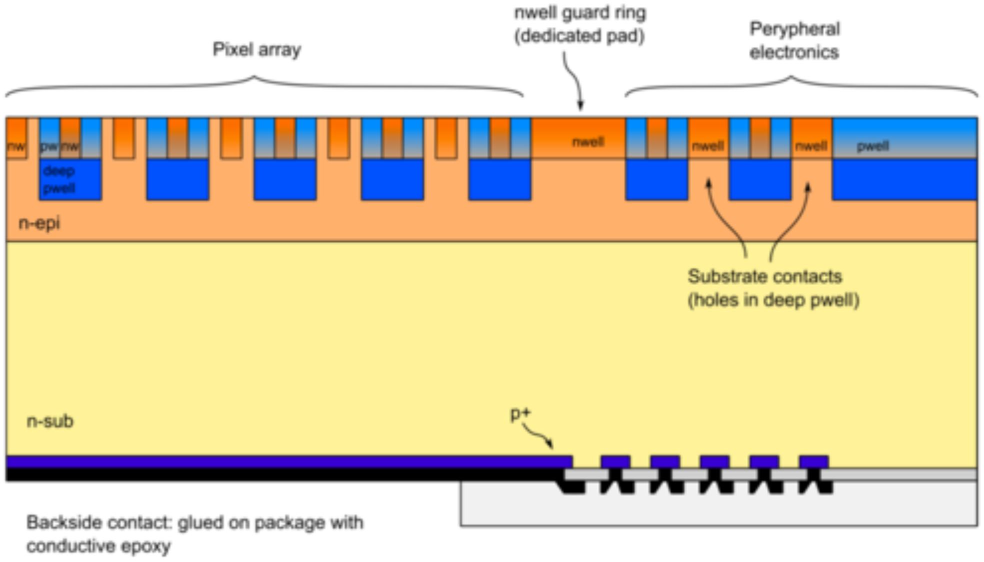
“Standard” CMOS design, push the limit to Rad Hardness using full depletion

DMAPS Depleted Monolithic Active Pixel Sensor. ATLASPIX chip

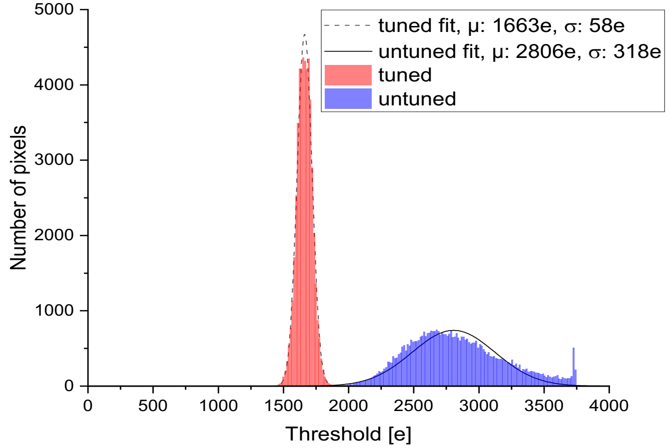
30 μm depletion using CMOS design on (almost) low resistivity 300 Ω cm p-type substrate. 10 x more bias than ALPIDE (50 V) but full depletion. 50 x 150 μm matrix implemented.

Considerably lower the cost of sensors



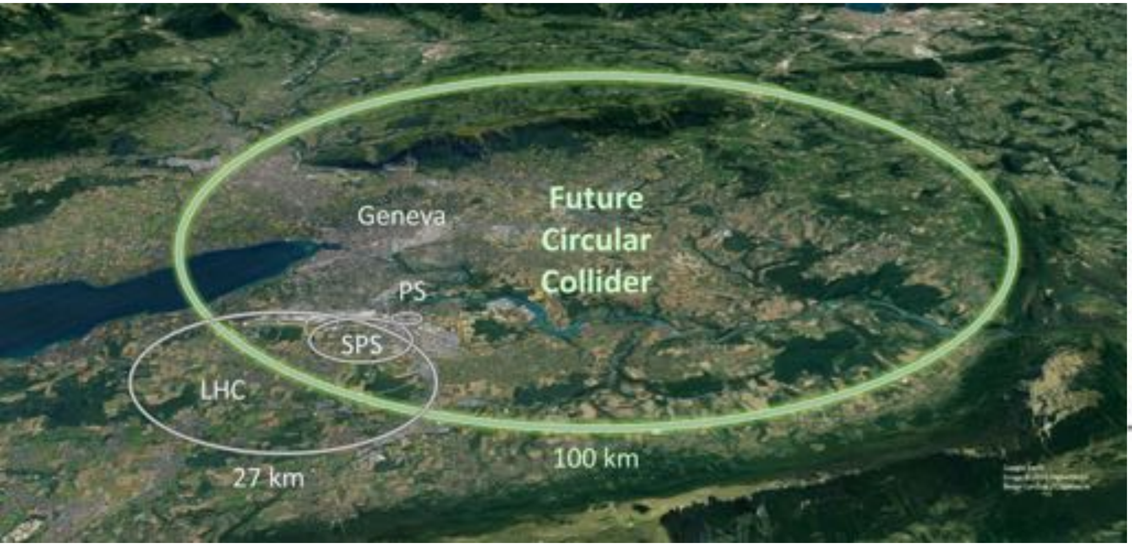

ARCADIA sensor
110 nm CMOS,
double side
technology

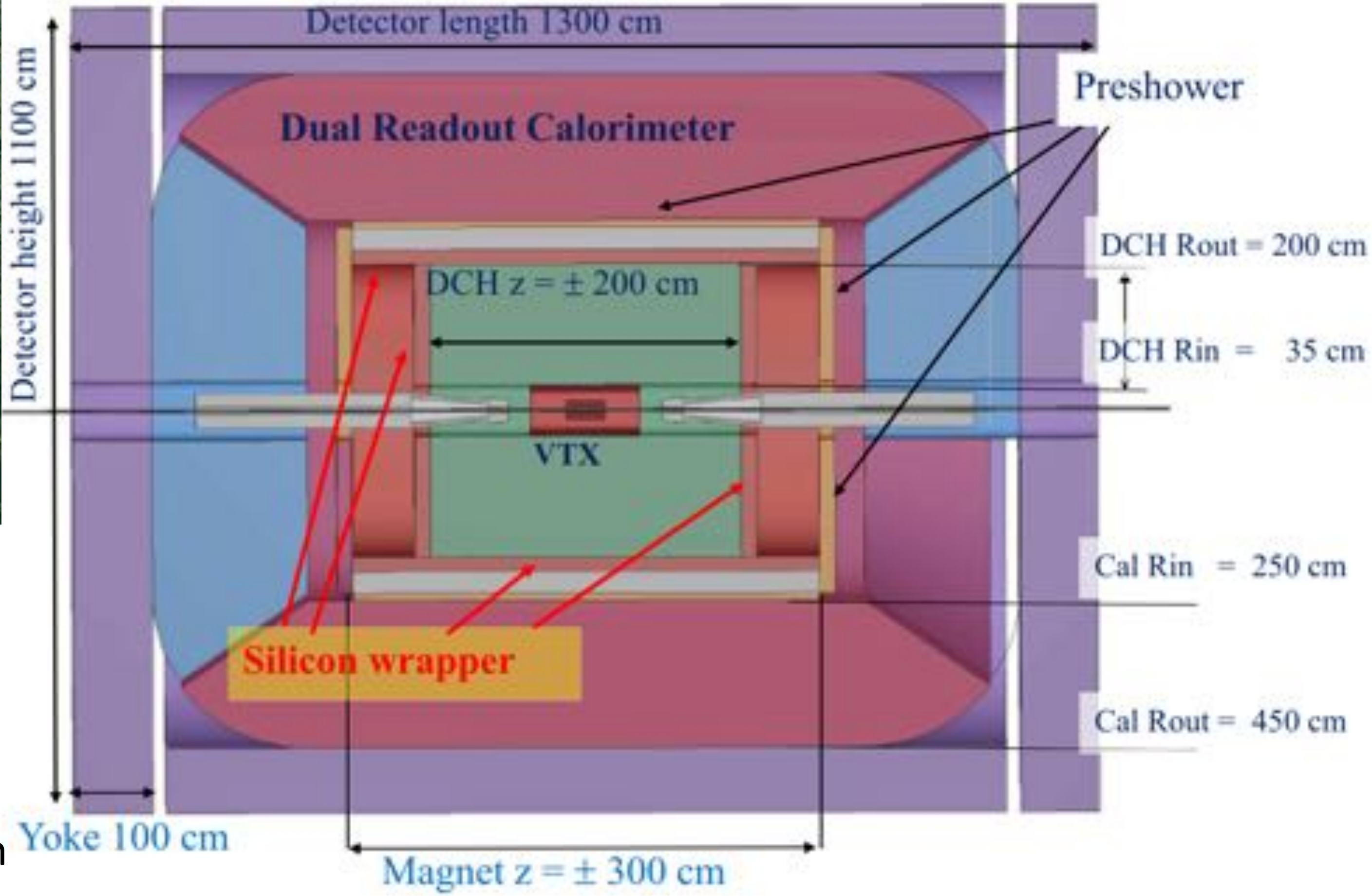



*A. Andreazza*

# Detectors at future colliders

## Future Circular Collider ($e^+e^-$) : 100 km ring




97.75 km circumference

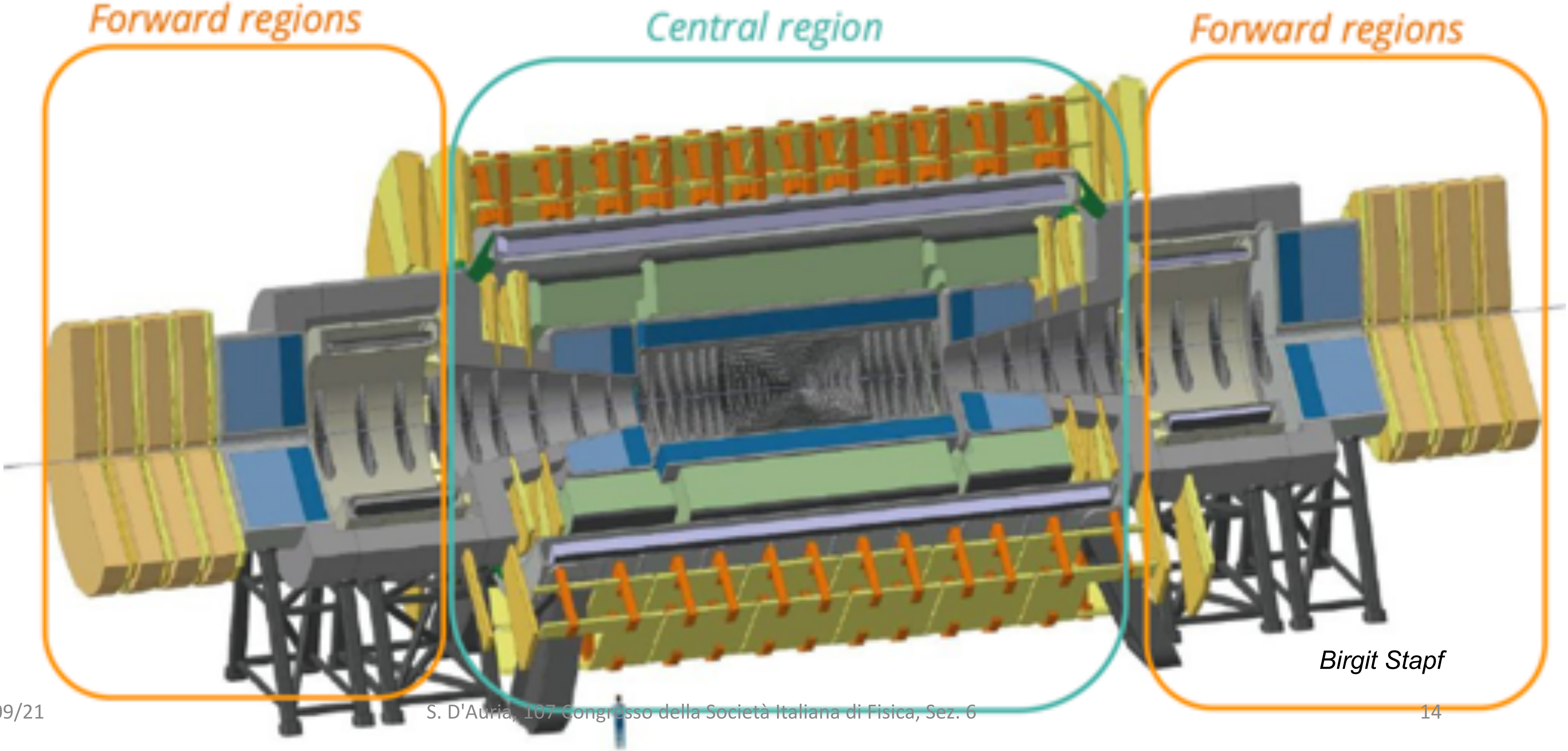
Initially an electron-positron collider will be installed in the tunnel
maximum beam energy 200 GeV
tuned at the resonance of top -- anti-top pair production

# Detectors at future colliders

Later proton-proton (hh) collider in the same tunnel: beam energy 50 TeV

10400 “bunches” of protons, 8.3 GJ beam energy stored.  Detectors at 2 interaction points

**FCC hh**



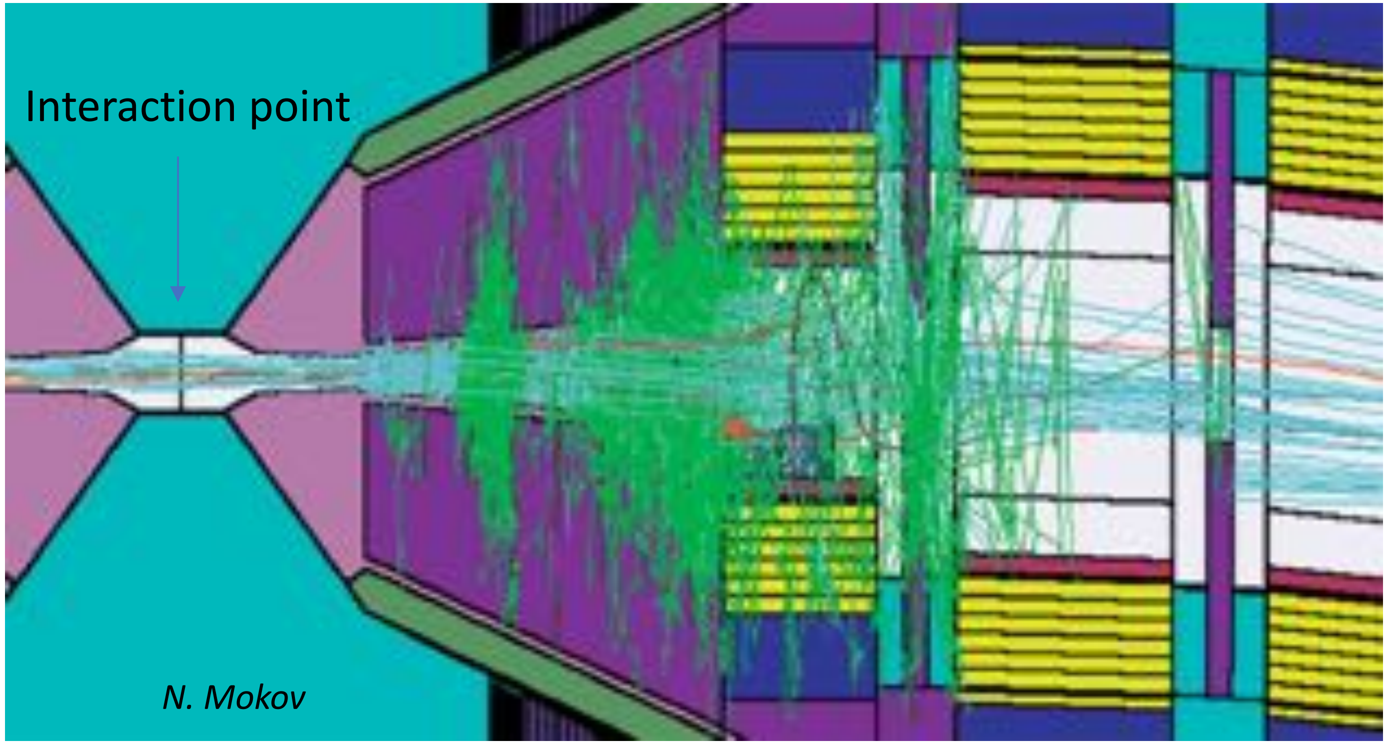
# Experiment layout

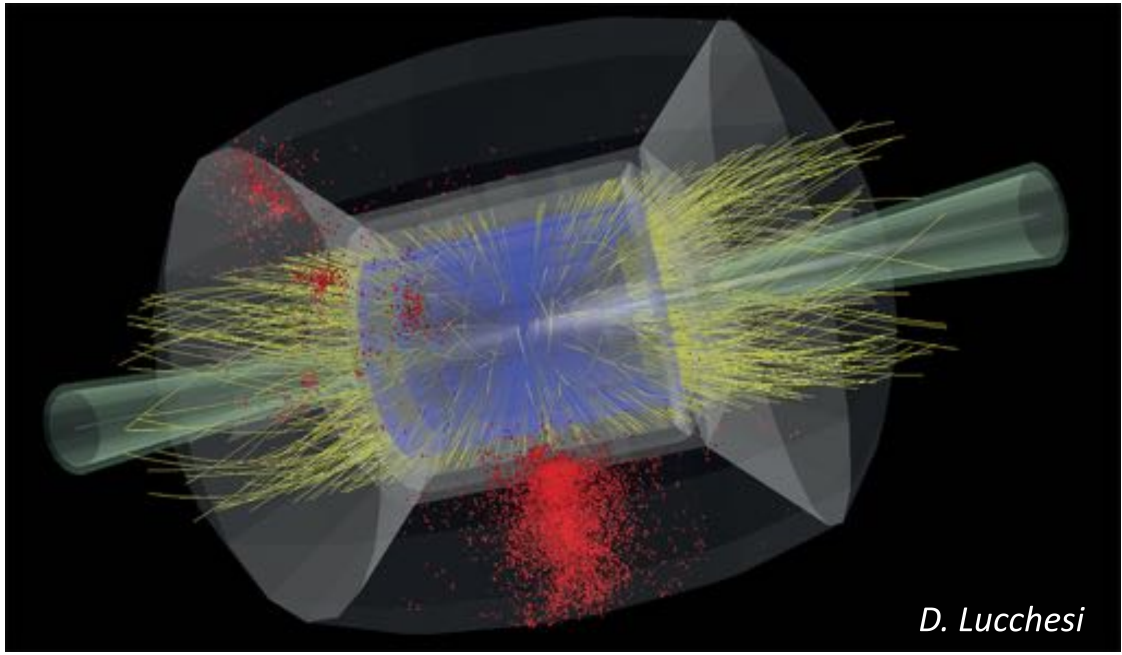
## Muon-muon collider

Tracking detector requirements same as for *hh*  but

Expect large occupancy form muon decays and beam induced background.

Require <u>good timing</u> (150 ps) to disentangle physics hits.



# Conclusions

Present HEP experiments are upgrading the existing detectors, replacing large fraction of charged particle trackers

New technologies are being used

Typical path: R&D → small-size detector for physics →use in large scale HEP

Monolithic pixel are an ~~emerging~~ established technology being used in 10 $m^2$ Alice@LHC (low lumi interaction point); conservative approach not to use in high lumi, but viable lower cost solution for upcoming future collider experiments: FCC (ee) and FCC (hh)

Thin detectors, $\mathcal{O}$30 µm, fast charge signal, low level of multiple scattering, curved crystals

Time resolution essential for disentangle pile up: internal gain allows , $\mathcal{O}$ 25 ps time resolution

Features: industrial production; large availability of detectors;

**plenty of space for synergy with other field to provide detectors suitable for other applications**

# Grazie per l'attenzione

***Thank you !***

***for your attention***
***and***
***for your questions***