ICHEP 2020 | PRAGUE

Detector R&D Summary

Paula Collins, CERN
August 5th, 2020

Timepix3 bumps, photograph courtesy S. Vahanen, ADVACAM

Introduction

This conference has seen exploitation of R&D for current experiments, implementation of R&D for future detectors and blue sky R&D driven by technological possibilities

R&D efforts are getting more and more coordinated and global, commonalities are being exploited

Rivera: Strategic R&D Programme on Technologies for future Experiments ← talk at this conference

"*Cutting Edge Science Relies on Cutting Edge Instrumentation*"
(Maxim Titov, ICORE meeting, 2017)

at the same time it has never been more true that

"*today, more than ever before, science holds the key to our survival as a planet and to our security and prosperity*"
(Barack Obama, 2009)

Prague: Where it all began

233 years ago, premiere of Don Giovanni took place at the Estates Theatre, Prague

- Mozart started writing the overture at 5 am on the morning of the premiere
- Completed just in time to ~~upload to indico~~ hand over to the scribes for copying out parts
- The Prague audience showed their great appreciation (not so popular elsewhere)

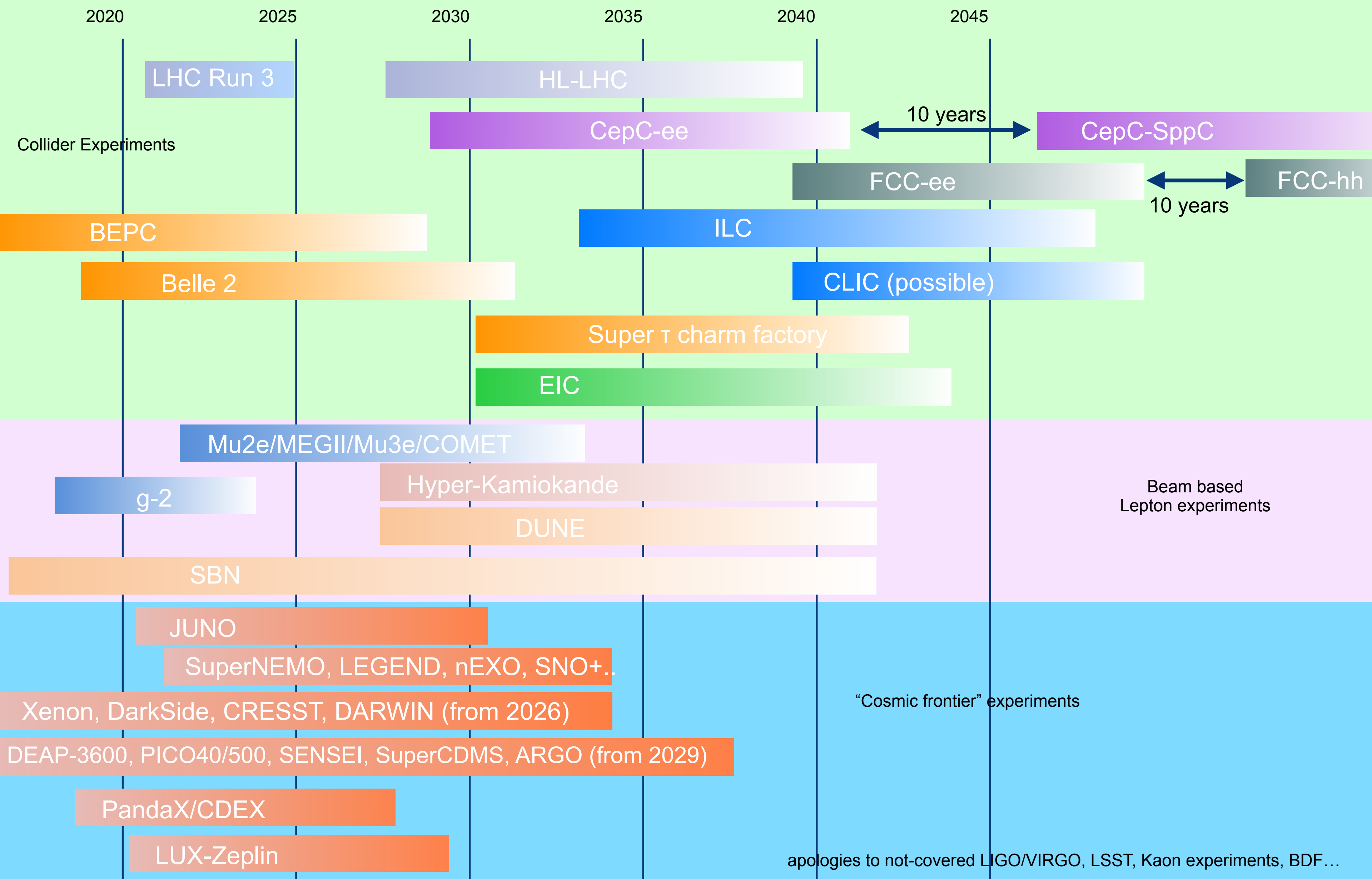

Neues Singspiel.
Im kaiserl. königl. National-Hof-Theater
wird heute Mittwoch den 7ten May 1788 aufgeführet:
(zum erstenmal)
IL DISSOLUTO PUNITO,
OSIA:
IL DON GIOVANNI.
Don Juan, oder: der bestrafte Bösewicht.
Ein Singspiel in zwey Aufzügen,
Die Musik ist vom Hrn. Wolfgang Mozart, Kapellmeister in wirkl. kaiserl. Diensten.
Der Anfang ist um 7 Uhr.

Leporello

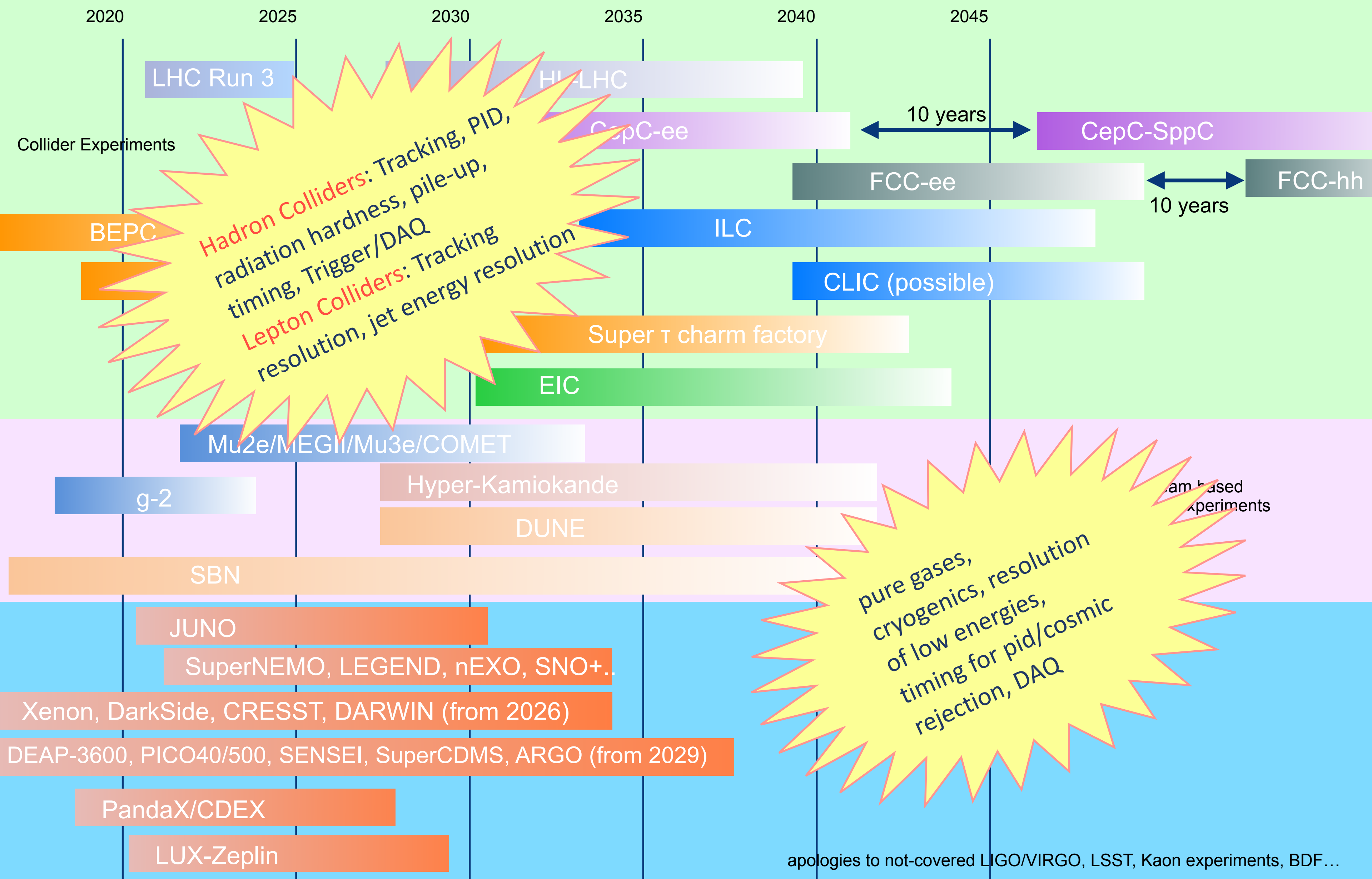
Very long list.
Parallel sessions

many beautiful presentations, which to pick?

Experimental roadmap (ICHEP 2020 examples…)



Experimental roadmap (ICHEP 2020 examples…)



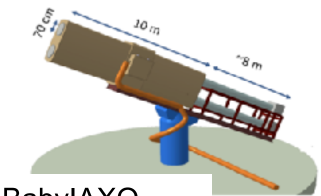
apologies to not-covered LIGO/VIRGO, LSST, Kaon experiments, BDF…

Just a few highlights

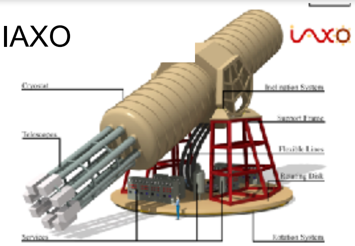
Lacarra: Axion search with BabyIAXO in view of IAXO

SUMICO

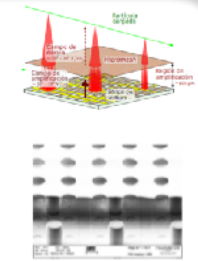
CAST



BabyIAXO



IAXO



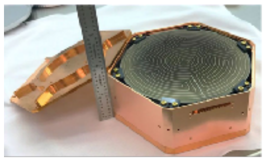
Generations of axion search helioscopes from 1992 through to 2020; many detector options considered

Kurinsky: Super CDMS searches for low mass particle dark matter

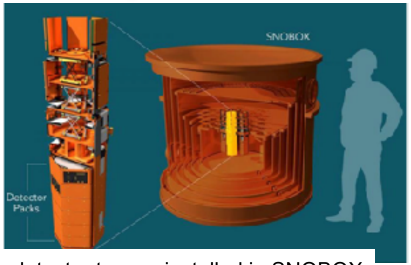
CDMS preparing with background measurements
Draw on electron recoil and Nuclear recoil experience from previous experiments

NEXUS @ FNAL

CUTE @ SNOLAB

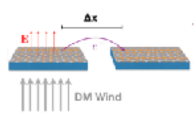


Silicon Germanium crystal detectors

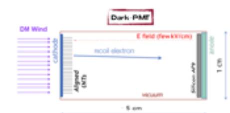


detector towers installed in SNOBOX

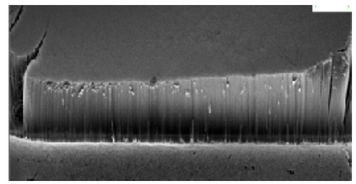
Pandolfi: Carbon Nanostructures for Directional LDM



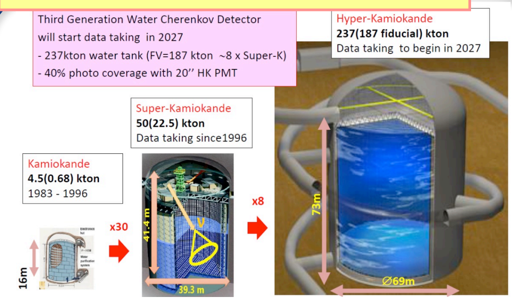
Graphene FETs



Dark photocathode of aligned nanotubes

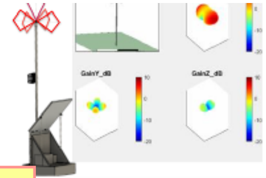


Rosa: Tasihiro: Zsoldos: Hyper-K PMT/OD



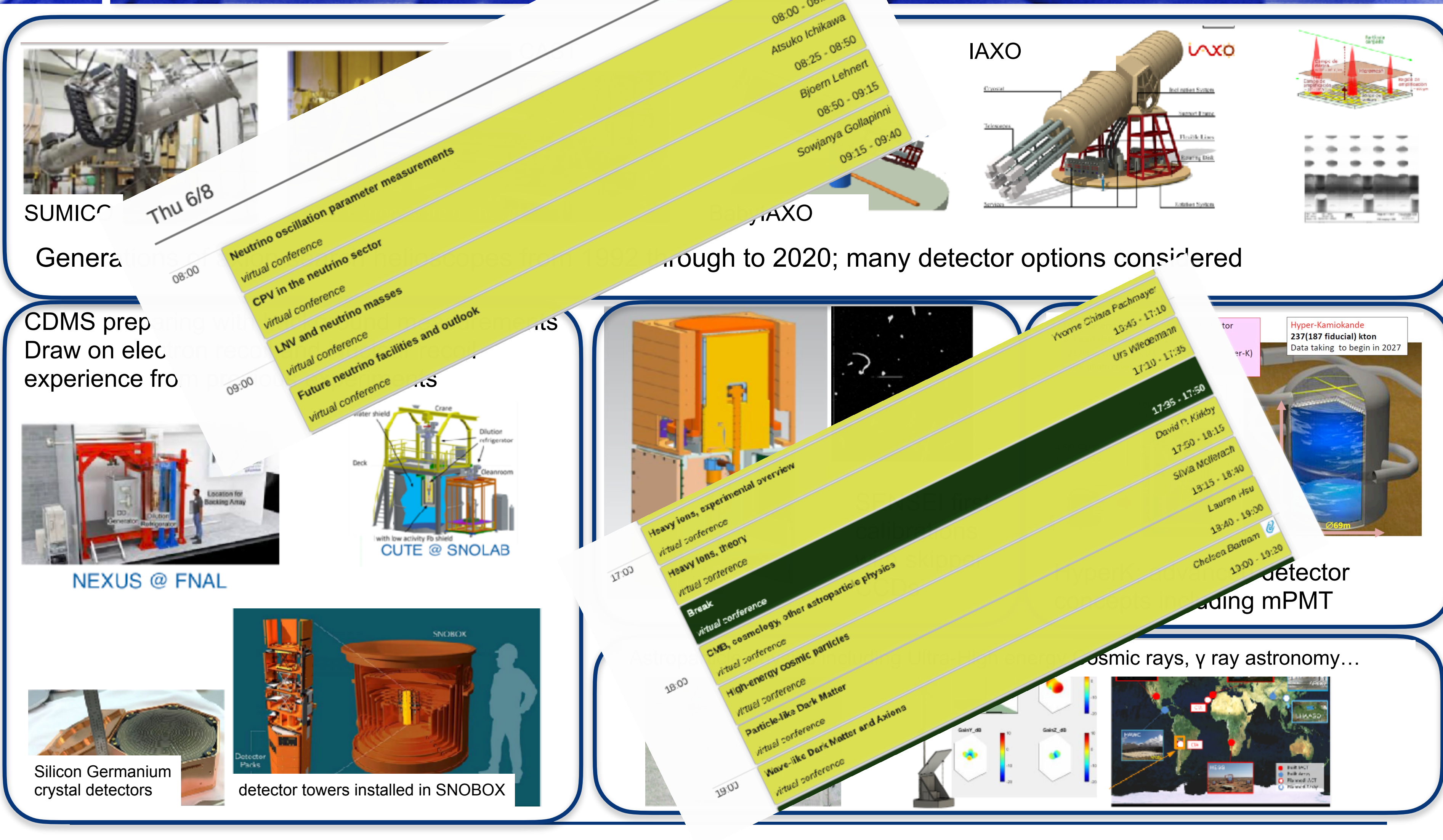
HyperK; advanced detector concepts including mPMT

Astroparticle physics including Ultra-High energy Cosmic rays, γ ray astronomy…



De Jong, Vicha: GRAND, SWGO, Pierre Auger

Just a few highlights



Lepton Collider Drivers

Low mass vertexing and tracking with low mass and high precision; (impact parameter resolution)

Precision needed also for calorimeters; adequate segmentation for particle flow

Beam parameters	ILC		CLIC			FCC-ee			CepC	
Energy(TeV)	0.25	0.5	0.38	1.5	3	0.091	0.24	0.36	0.091	0.24
Luminosity (x 10^{34} cm^{-2} s^{-1}) per IP	1.35	1.8	1.5	3.7	5.9	230	8.5	1.7	32	1.5
Bunch train frequency (Hz)	5		50							
Bunch separation (ns)	554		0.5			20	994	3000	25	680
Number of bunches / train - beam	1312		312	312		16640	393	48	12000	242

Supra-conducting solenoids 2-4 Tesla; sizes adapted to reach similar momentum precision

Outer tracking: Silicon or TP/DC options

Calorimetry: Dual and High Granulatiry options

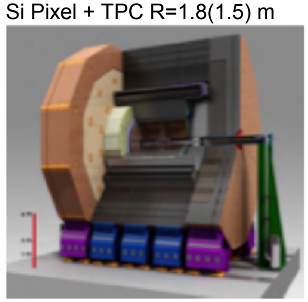
applicable to LHeC/FCCeh ;

Yamazaki: Updated LHeC

Tanabe: ILD Detector for International Linear Collider

ILD/ILC

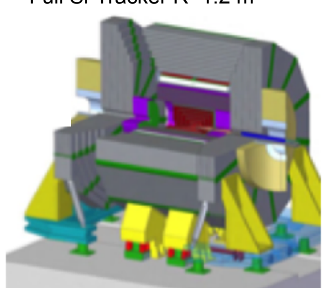
3.5(4) T solenoid, 8.8 x 8 m
Si Pixel + TPC R=1.8(1.5) m



White: The SiD detector

SiD/ILC

5T solenoid, 6.8 x 8 m
Full Si-Tracker R=1.2 m



Power Pulsing options

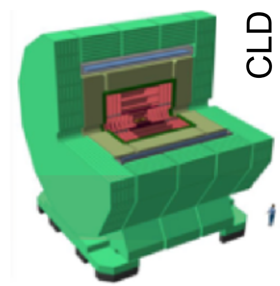
5T solenoid, 6.8 x 6 m
Full Si-Tracker R=1.5 m

CLICdet

Dort: Tracker R&D for CLIC

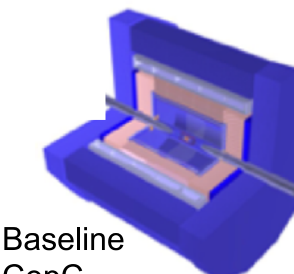
Roloff: CLD proposal

2T solenoid, 7.4 x 7.4 m
Full Si-Tracker R = 2m



CLD

3T solenoid, 6.4 x 7.8 m
Si Pixel + TPC R=1.8m

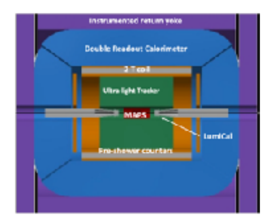


Baseline CepC

Ouyang: Hig res si sensors for CEPC vertex detector

Pre-shower/MPGD + Dual Calorimetry

2T solenoid, 4.2 x 6 m
Si Pixel + Drift Chamber R=2m

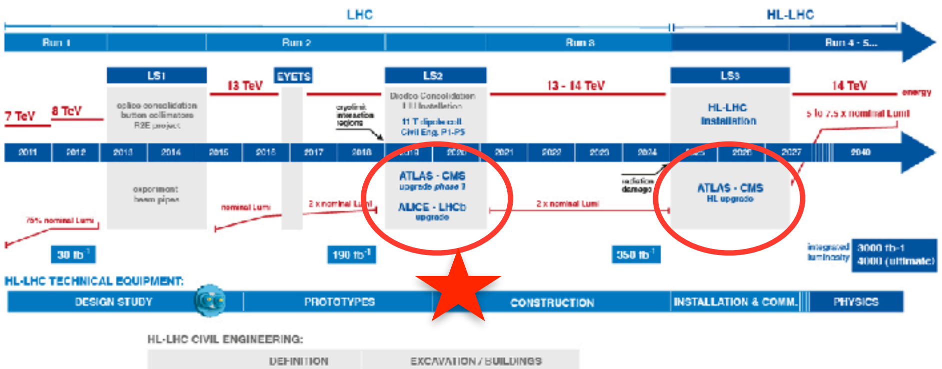


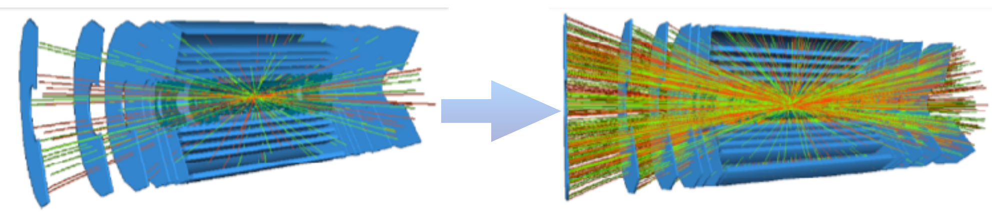
IDEA
FCC-ee / CepC

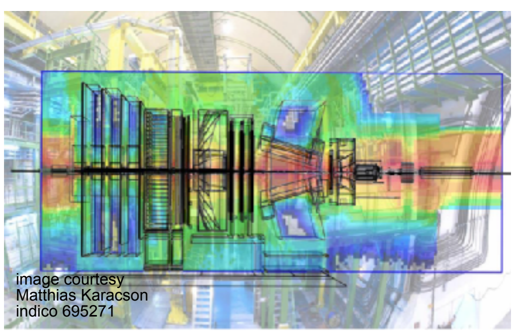
Bedeschi: IDEA for e+e- collider

The HL-LHC era is upon us

Svihra, Panebianco: Phase I LHCb and ALICE upgrades
Klein, Terzo, Sperlich, Evans, Rossi: Phase II upgrades
+ many more talks







Maintain Physics Performance in very high occupancy and pile up conditions

- combinatorial complexity and fake tracks
- mitigated by **granularity, high readout speed** and **trigger** innovations and where possible: **timing**

Operate with detector elements exposed to very high radiation doses

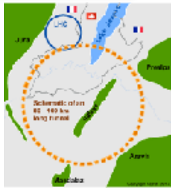
- **Radiation hardness** needed for all subdetectors

Control Systematics to match statistics

- **low material budget** hence creative solutions needed at mechanics level; support structures, cooling, power delivery, and **thin detectors** for innermost regions

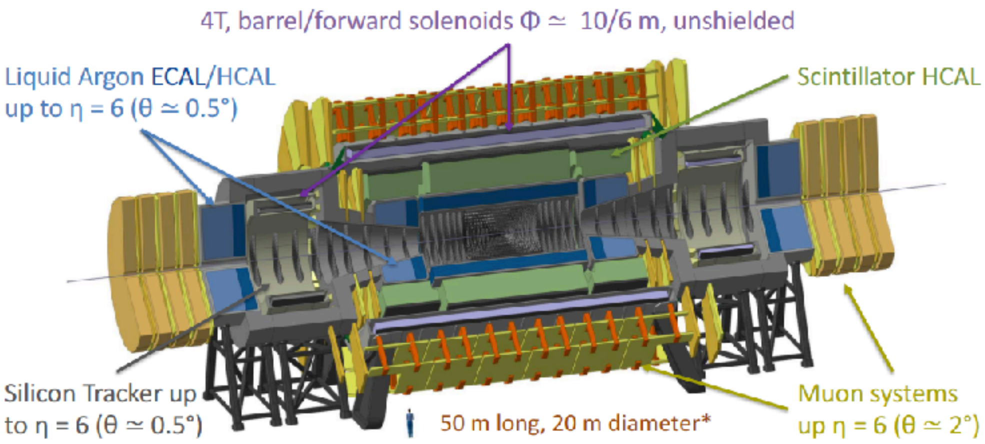
- **Cope with tremendous DAQ and data processing challenges**

Beyond HL-LHC: FCC-hh, SPPC



HL-LHC → FCC-hh ($L = 5 \times 10^{34} - 3 \times 10^{35}\ cm^{-2}s^{-1}$)

- E_{CM} ↗ x7
- L ↗ x6
- Ldt ↗ x10
- pile-up x 7 (μ = 1000) → timing !
- hit rates x 10
- data rates x 10
- radiation levels x 10-100
- Larger and stronger magnet
-



Christian Joram, VCI 2019

https://cds.cern.ch/record/2651300/files/CERN-ACC-2018-0058.pdf

Faltova: Design and performance studies of the calorimeter system for an FCC-hh experiment

Tracking

Neowise, seen from belvédère du Collet, 18/07/20
Reproduced with kind permission of J-P Lees

Tracking

e-e experiments target track P_T and Impact Parameter Resolutions ≃ /5 LHC

$\sigma(p_T)/p_T^2 \simeq 3 \times 10^{-5}$ GeV^{-1} (p ≤ 100 GeV)

$\sigma(d_0)/d_0 \simeq$ 2 / 3-5 / 10 - 20 μm (100/10/1 GeV at 90°)

R&D challenge

≃ 3 μm hit resolution with ≃ 0.2 % X_0 per layer (low multiple scattering) in pixel vertex detector

h-h experiments need similar detectors

Resolutions ≃ x 2 e-e (due to larger inner layer radius (rates/radiation) and mass (power/cooling)

R&D challenge

Hit rate readout capability ≃ 30 GHz/cm² in inner pixel layer

Current technology would not survive R < 30 cm for radiation tolerance

Neowise, seen from belvédère du Collet, 18/07/20
Reproduced with kind permission of J-P Lees

D. Contardo
EPS Det R&D 2019

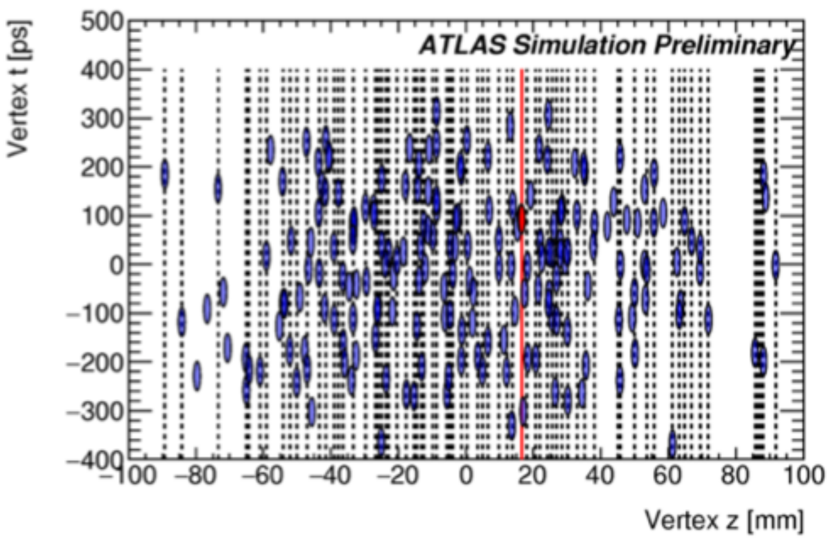
Timing for Tracking

Rizzi: A High-Granularity Timing Detector for ATLAS Phase II Upgrade

Evans: The LHCb VELO Upgrade Programme for HL running

1. Pileup mitigation with timing

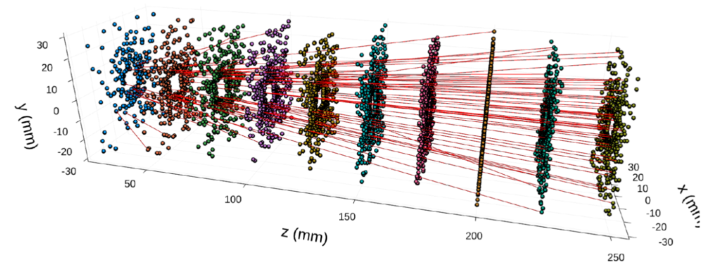
- ~200 collisions / bunch @ GPDs gives overlapping vertices and high pileup in forward
- Track to vertex assignment difficult with worse forward z_0 resolution
- Track resolution of < 50 ps
  - Distinguishes pileup from hard scatter tracks
  - Identifies overlapping vertices
  - allows Time Of Flight tagging and improves physics object reconstruction

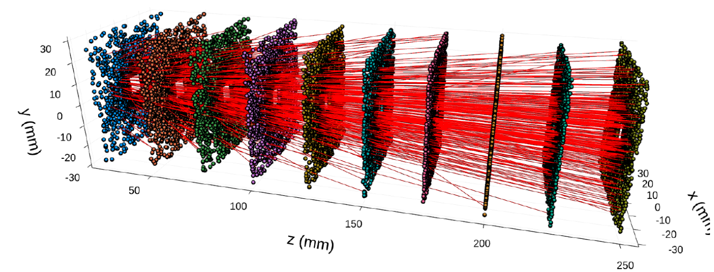


ATLAS HGTD, CMS barrel/endcap timing layers, ALICE silicon TOF for LS4

2. 4D tracking

- Challenging pattern recognition due to increased number of combinatorics and primary vertices e.g. LHCb UII
- Hit resolution of ~ 50 ps per track
  - recovers efficiency and resolution of reconstructed primary vertices
  - Resolves associations of secondary vertices and displaced tracks
  - Reduced combinatorics for gains in CPU usage, efficiency, ghost rate, control of systematic uncertainties..





Petrillo: Development of the CMS MTD Endcap Timing Layer for HL-LHC

Timing for Tracking

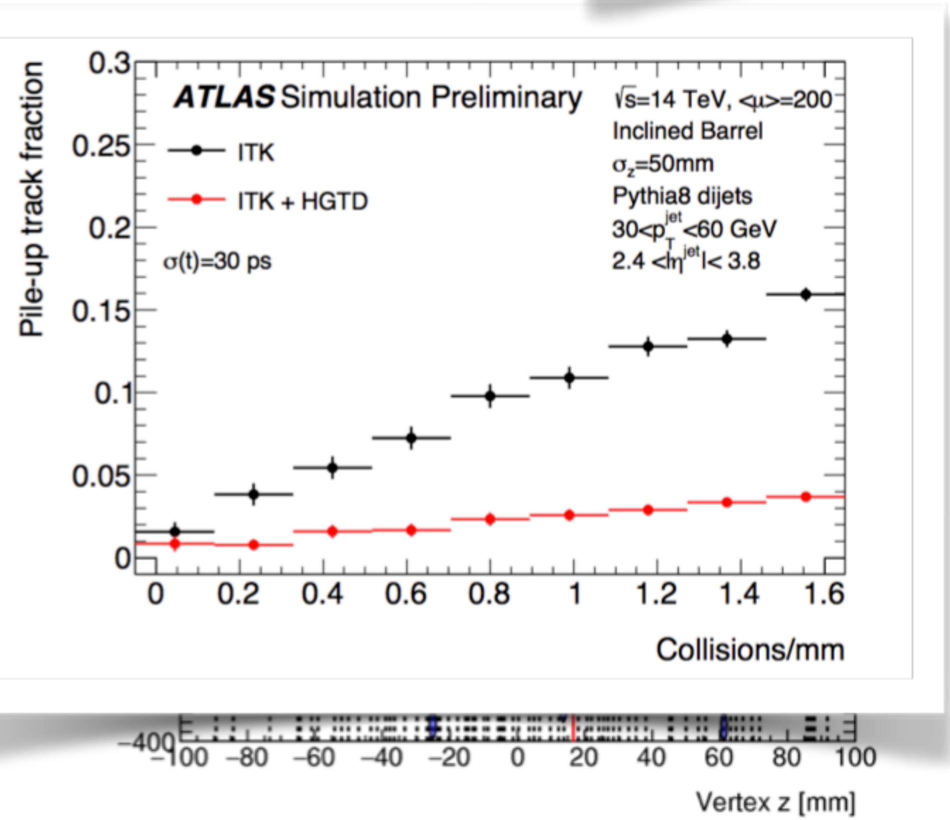
1. Pileup mitigation with timing

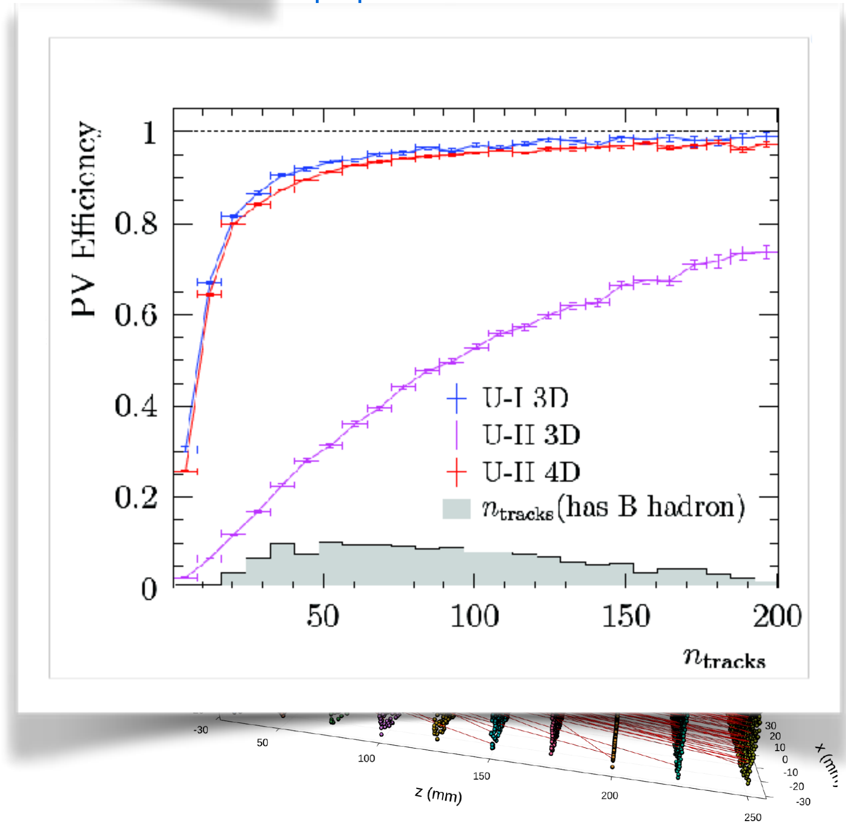
2. 4D tracking

Examples of Physics Gains

- ~200 collisions / bunch @ GPDs gi
  vertices and high pileup in forward
- Track to vertex assignment difficult with worse forward z_0

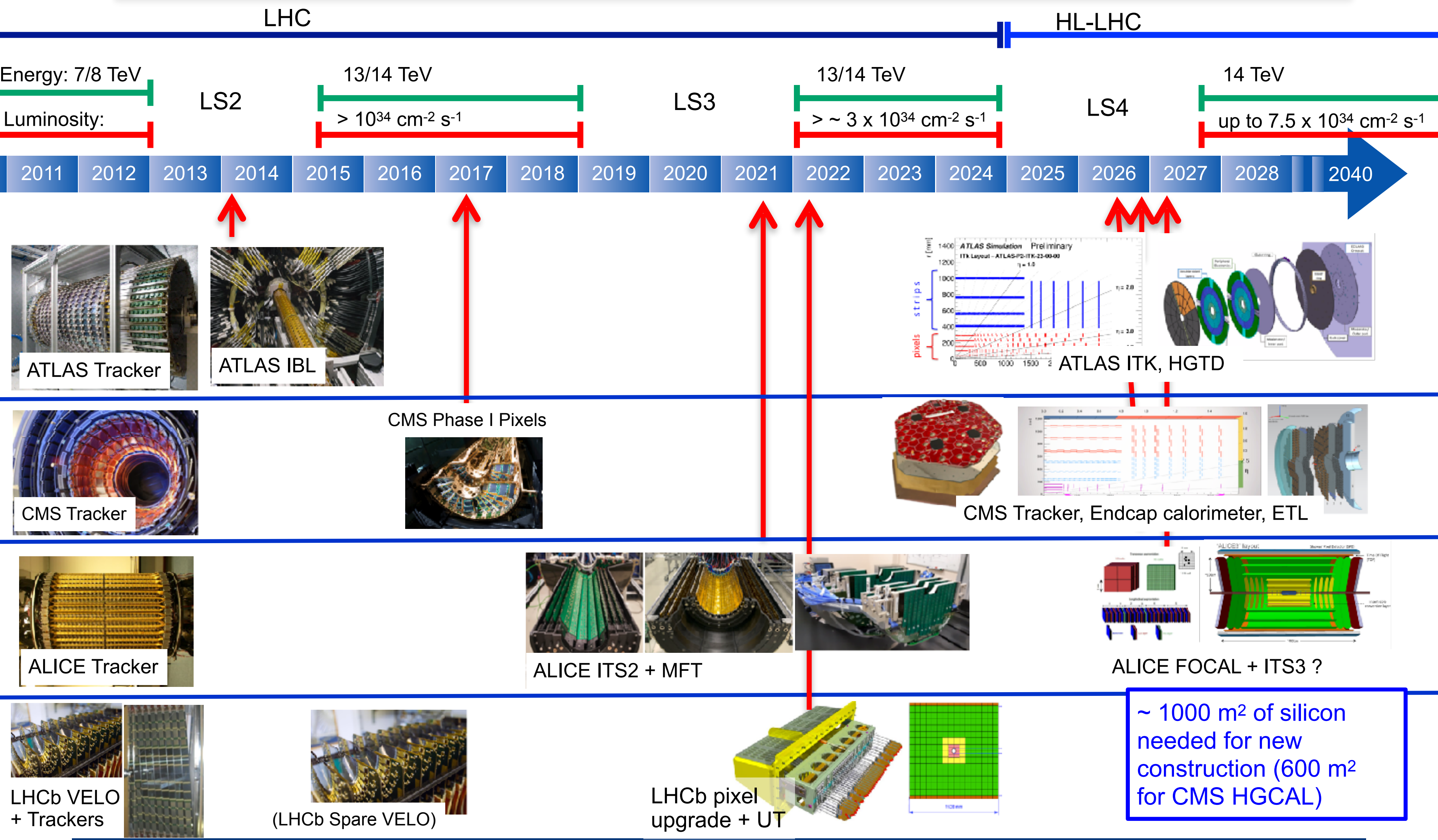
- n recognition due to increased number of
  primary vertices e.g. LHCb
- Hit resolution of ~ 50 ps per track





ATLAS HGTD, CMS barrel/endcap timing layers, ALICE silicon TOF for LS4

Silicon @ the LHC present and future



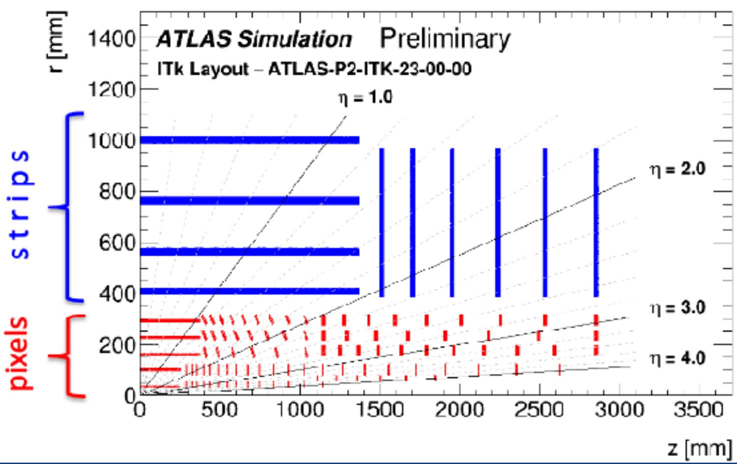
adapted from P. Collins, ECFA HL-LHC workshop, 2014

ATLAS and CMS trackers for HL-LHC

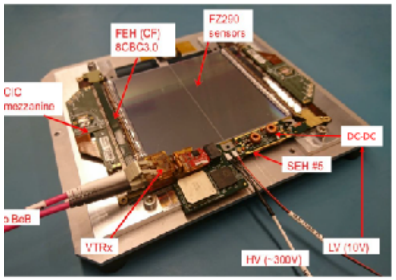
Terzo: ATLAS ITK Pixel Detector Overview: Terzo
Sperlich: ATLAS ITK Strip Detector system for the Phase II LHC Upgrade

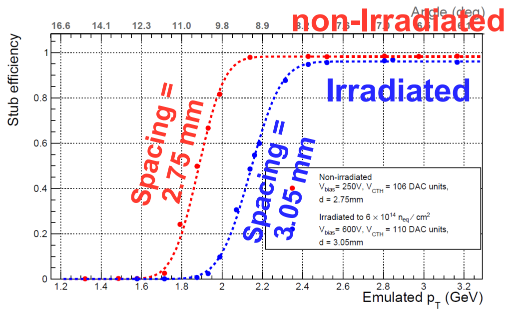
Klein: CMS Tracker Upgrade for the High Luminosity LHC
Hart: Level-1 Track Finding at CMS for the HL-LHC
Pasztor: Precision Luminosity Measurement with CMS

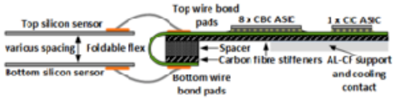
ATLAS; 165/12.7 m² strips/pixels



CMS: 200/4.7 m² strips/pixels



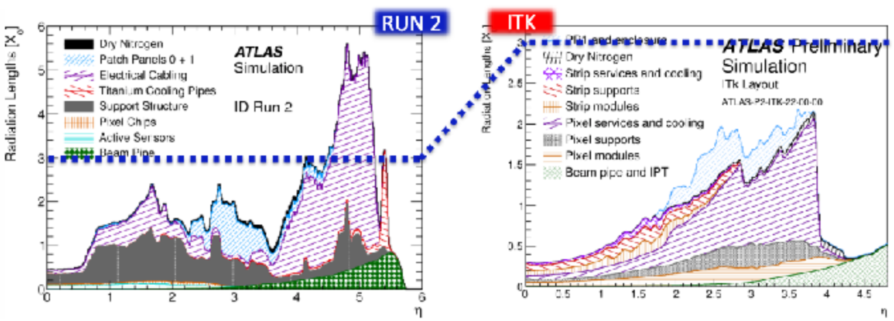




Use of Tracking Information at L1 Trigger
Major role in luminometry in Phase-2

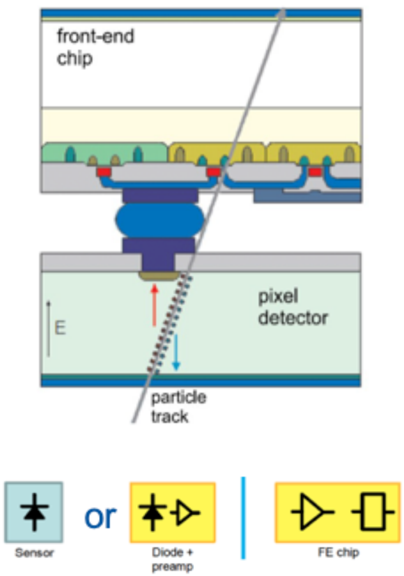
Lots of common development and technologies

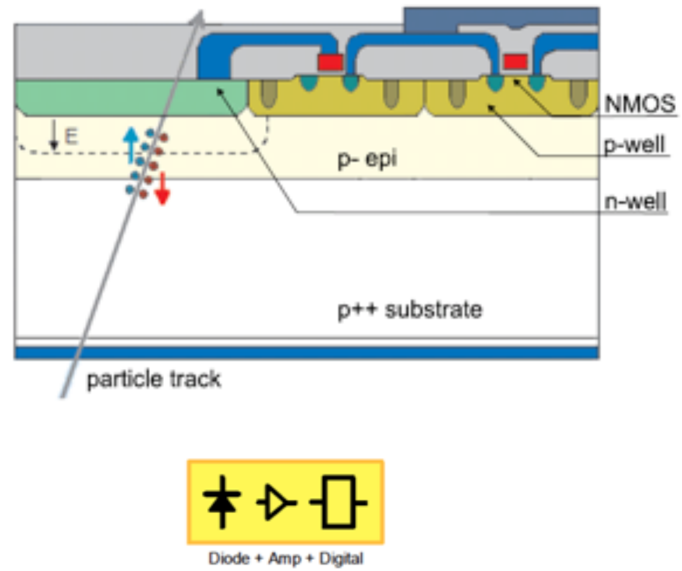
- Pixel chips based on common 65 nm CMOS RD53 development
- Planar n-in-p sensors
- 3D sensors for innermost layers; option of MAPS for outermost pixel layer (ATLAS)
- CO_2 cooling
- Serial powering
- LpGBT



Significant material reduction

Hybrid & Monolithic Silicon Detectors



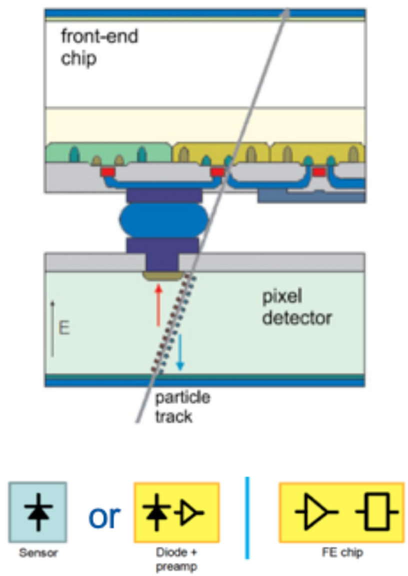


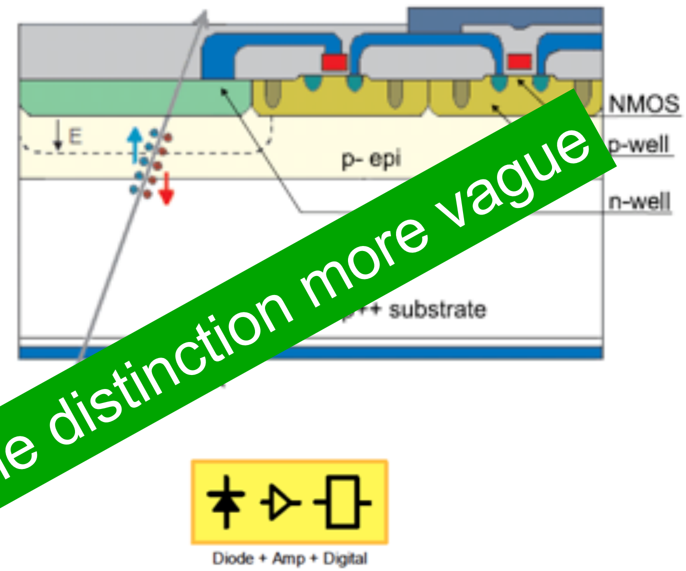
- Large majority of presently installed systems
- Separately optimise sensor and FE-chip
- fine pitch bump bonding to connect sensor and readout chip
- 100% fill factor easily obtained
- complex signal processing in chip; high rate capability; rad hard chips and sensors
- Spin off from HEP developments e.g. spectral

- charge generation volume integrated into the ASIC
- thin monolithic CMOS sensor, on-chip digital readout architecture
- allows very thin sensors
- High volume and large wafers open possibility for large area
- potential for better power-performance ratio
- Saves cost and complexity of bump bonding

P. Riedler

Hybrid & Monolithic Silicon Detectors





New Technologies make the distinction more vague

- Large majority of presently ins ns
- Separately optimise se -chip
- fine pitch bump b nnect sensor and readout chip
- 100% fill factor asily obtained
- Spin off from HEP developments e.g. spectral photon counting chips

- charge generation volume integrated into the basic
- thin monolithic CMOS sensor, on-chip digital readout architecture
- allows very thin sensors
- High volume and large wafers open possibility for large area
- potential for better power-performance ratio
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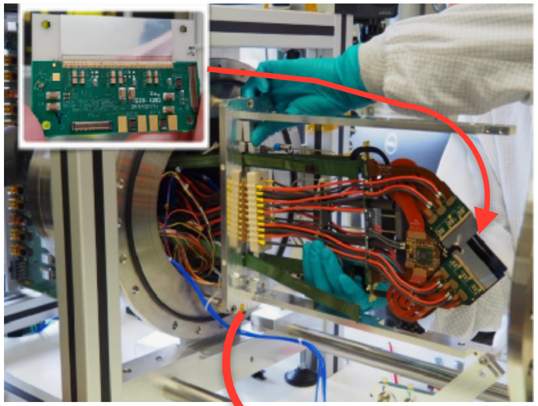
P. Riedler

Hybrid Sensors - State of the Art

Svihra: The LHCb VELO Upgrade I



LHCb hybrid silicon pixel modules for Phase I upgrade (Run3/4)

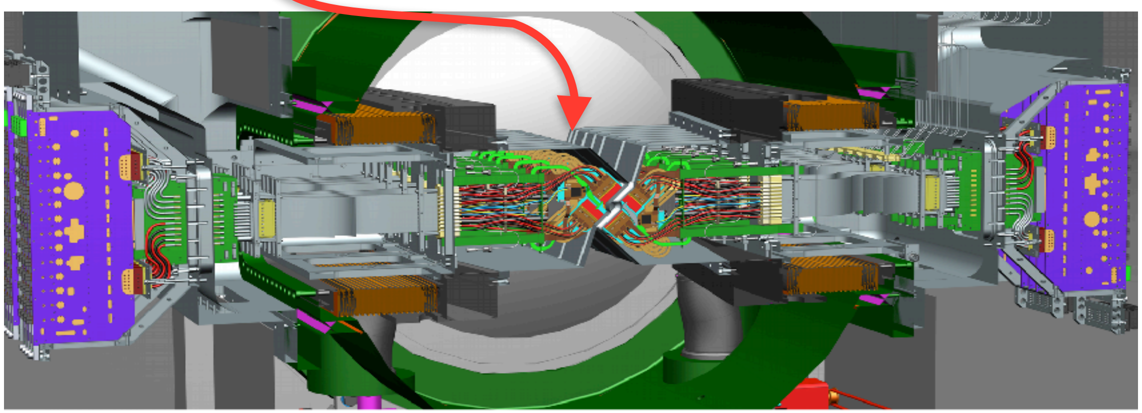
55 x 55 μm pixels

VeloPix ASIC in 130 nm CMOS

Triggerless binary readout @ 40 MHz

>20 Gb/s/ASIC

40M pixels

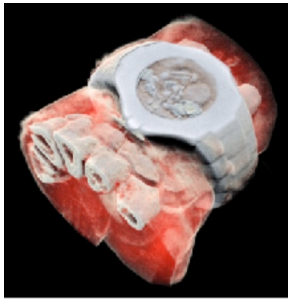


VELO mounted within a secondary vacuum in the primary LHC vacuum

Innermost pixel just 5.1 mm from the beam, need to bias to ~ 1kV

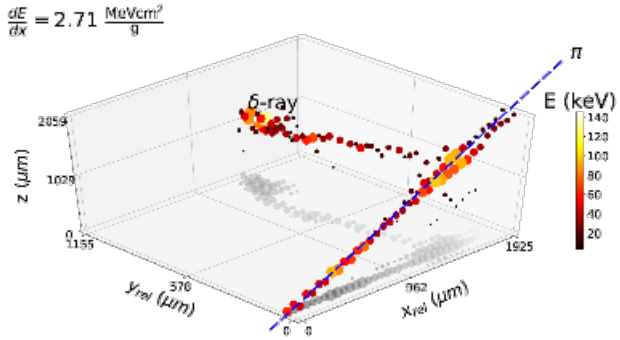
VELO moves in after stable beams declared

Widespread application in X-ray/ neutron imaging - medicine/ synchrotron/space



Mars bio imaging

40 GeV/c pion tracks accompanied by δ-rays in 2 mm thick CdTe sensor:



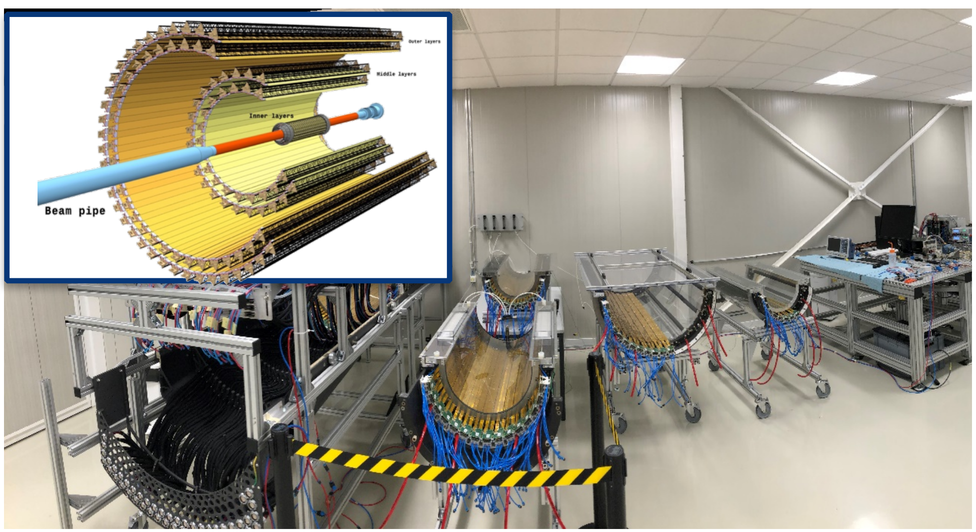
Bergman: Timepix3 as solid state detector

Monolithic Sensors - State of the Art

Panebianco: ALICE upgrades for Run3

CMOS monolithic active pixel sensors for ALICE ITS (Run 3)

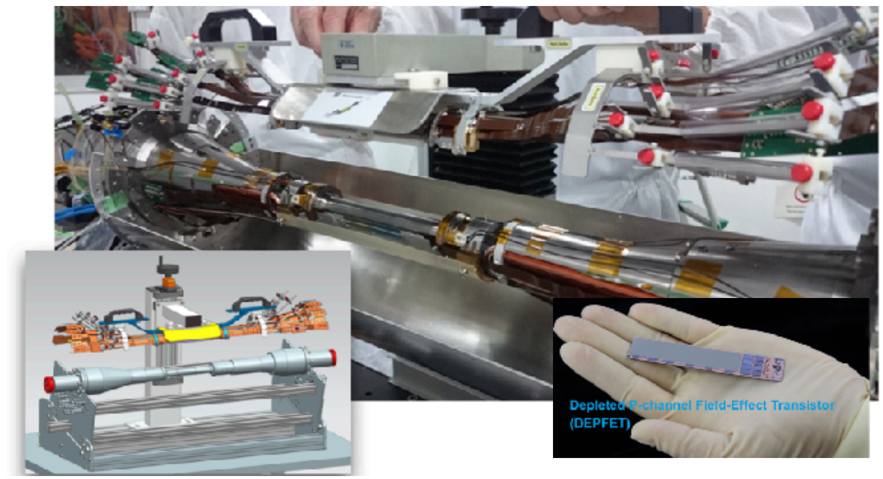
- TowerJazz 180 nm technology; on-chip digital readout architecture
- 27 x 29 μm² pixels
- High resistivity epi layer + moderate reverse bias → rad hard to TID 2.7 Mrad
- 0.3% X_0/layer (IB), 0.8% X_0/layer (OB)



Mueller: The pixel vertex detector at Belle II

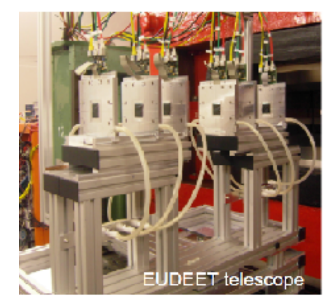
DEPFET pixel detector running now at Belle II

- 50 x 55-85 μm² pixels, 20 μs rolling shutter
- 0.21% X0 per layer, 2 self supporting layers



EUDET telescope family

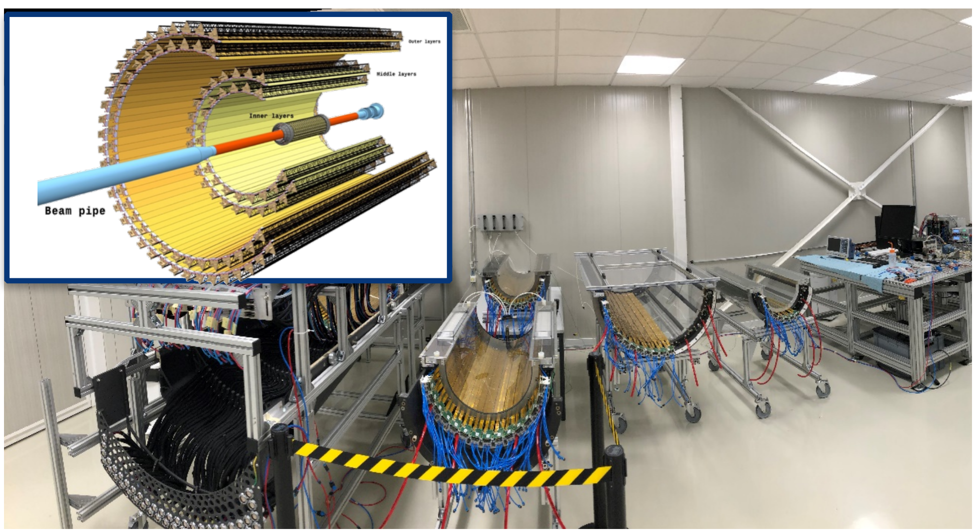
- Born from MIMOSA developments
- 2 μm precision beam tracking at DESY testbeam
- easy DUT integration
- serving community since 2009



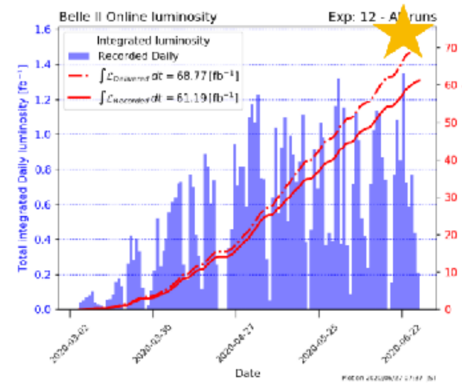
Monolithic Sensors - State of the Art

CMOS monolithic active pixel sensors for ALICE ITS (Run 3)

- TowerJazz 180 nm technology; on-chip digital readout architecture
- 27 x 29 μm^2 pixels
- High resistivity eps layer + moderate reverse bias → rad hard to TID 2.7 Mrad
- 0.3% X_0/layer (IB), 0.8% X_0/layer (OB)

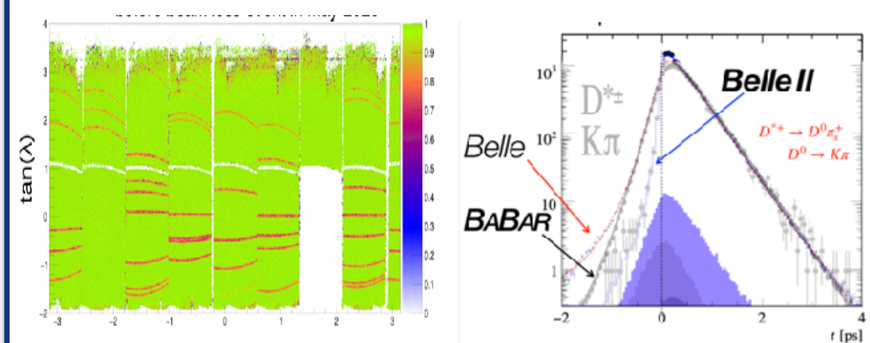


Mueller: The pixel vertex detector at Belle II



Depfets operated at a world record luminosity of 2.4 x 10^{34} cm^2 s^{-1}

With excellent efficiency and a factor 2 improvement on Belle resolution



- easy DUT integration
- serving community since 2009

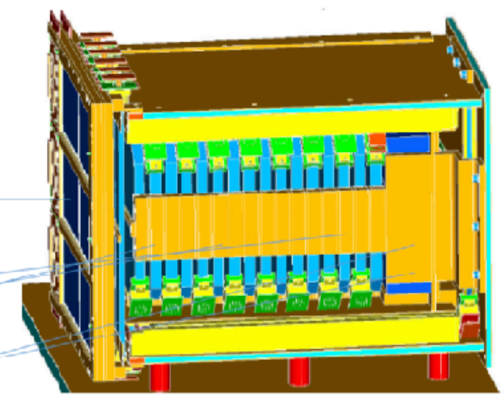
Monolithic Sensors - State of the Art

CI
se

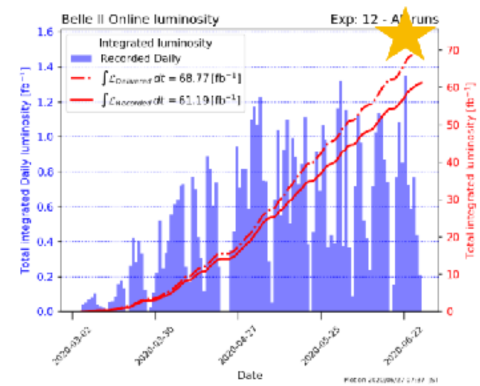
ALPIDE based tracker for space

Zuccon: ALPIDE pixel detector for tracking in space

- Silicon tracker
  Trigger planes
- Plastic scintillator planes
- LYSO cubes
- Veto counters



Mueller: The pixel vertex detector at Belle II



Depfets operated at a world record luminosity of 2.4 x 10^{34} cm^2 s^{-1}

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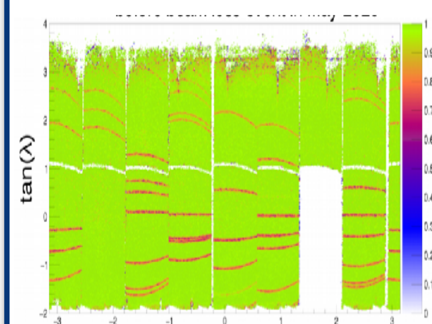

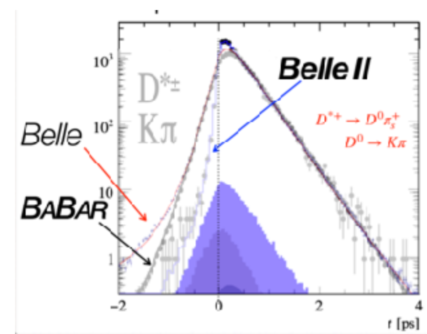

- easy DUT integration
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Monolithic Sensors - State of the Art

CM
se

ALPIDE based tracker for space

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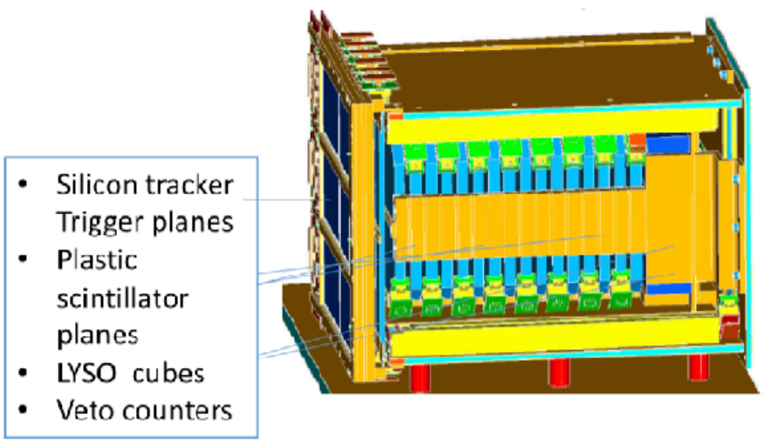
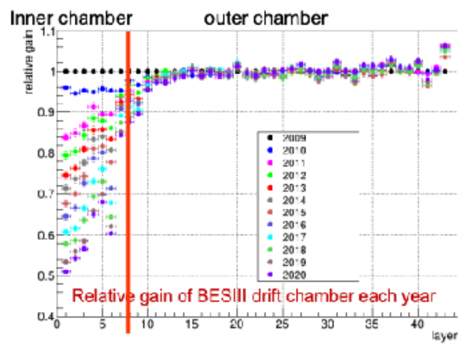
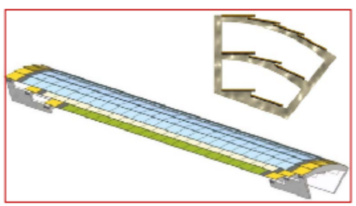
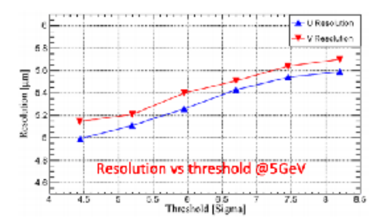


Dong: Study of a MAPS detector prototype for the upgrade of the BESIII inner tracker



10 Mimosa28 chips thinned to 50 μm
Flex cable, carbon fiber mechanical support 0.37 % X_0 /layer





achieved 5 μm resolution in testbeam
(self constructed telescope)

- easy DUT integration
- serving community since 2009

Hybrid/Monolithic R&D

high rate, radiation hardness, timing, packaging

Sensor engineering for radiation hardness (3d, diamond..) and timing O(10) ps (planar, LGADs, 3d…)

ASIC engineering for ultimate bandwidth, timestamps, high density logic, power, packaging (TSVs..)

CMOS modified process for radiation tolerance, faster and higher rate readout, and timing

sensor optimisation 3D, LGAD…

fine pitch bonding, alternative interconnection low material

SoI process Si/ASIC wafers connected through Insulator Oxide layer

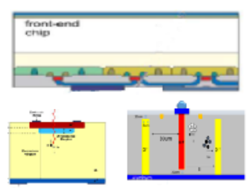
Capacitive Coupling of HV CMOS design to ASIC through insulating glue

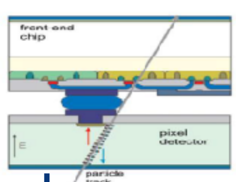
DMAPS large electrodes

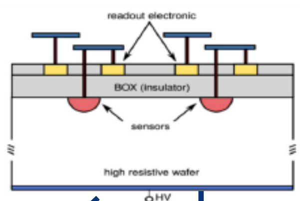
DMAPS small electrodes

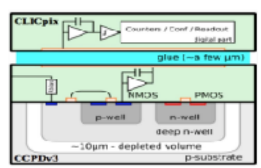
with faster and higher rate readout capabilities

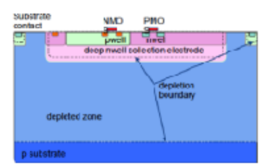
ultimate timing; SiGe BiCMOS, SPAD..

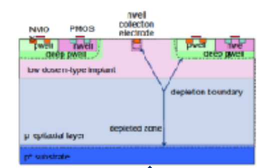


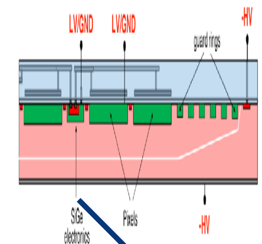












“Hybrid” “Monolithic”

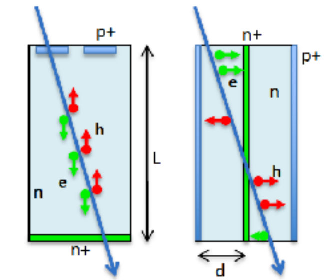
adapted from D. Contardo EPS Det R&D 2019

addition of gain layer for ultimate timing

Hybrid sensors - going 3(4)d

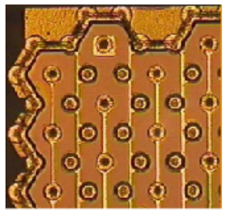
Aiming for unprecedented radiation hardness and the possible addition of timing down to 10's of ps

Already running for ATLAS (b-layer), AFP, CMS CT-PPS

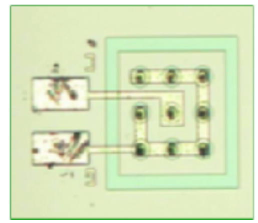


Planar sensor 3D sensor

S. Parker et al., IEEE TNS 58 (2) (2011) 404



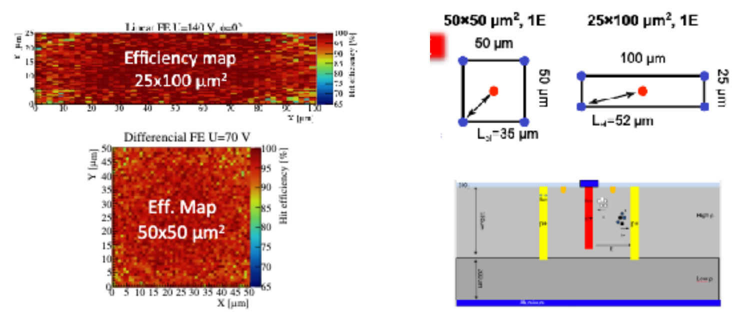
G. Kramberger et al., NIMA 934 (2019), 26



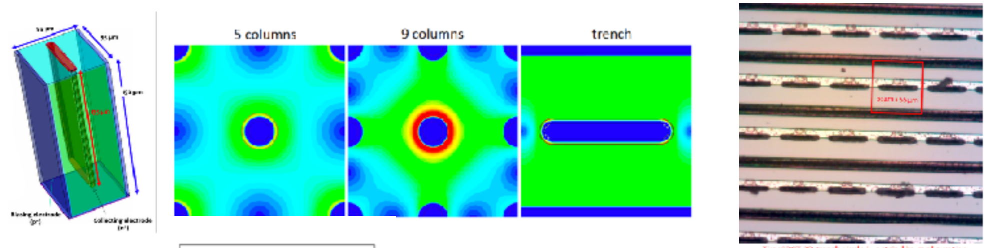
Phase-2 ATLAS ITK Pixel Upgrade : Terzo

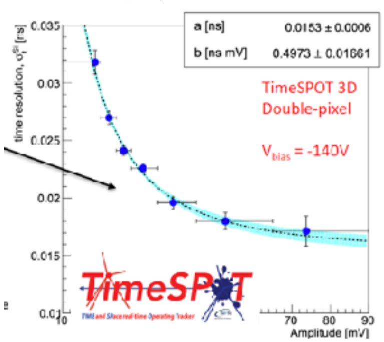
New single sided technology; electrodes etched from same side

Radiation hard to 1 x 10^{16} n_{eq}/cm^2 at <= 140V



Timespot collaboration approach; optimised 3D sensor design





Time resolutions achieved:

Global: 20 ps

Intrinsic: 15 ps

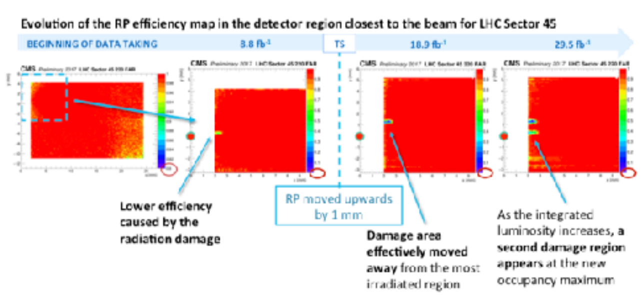
Large (10 mip) laser signals:

sub ps resolution!

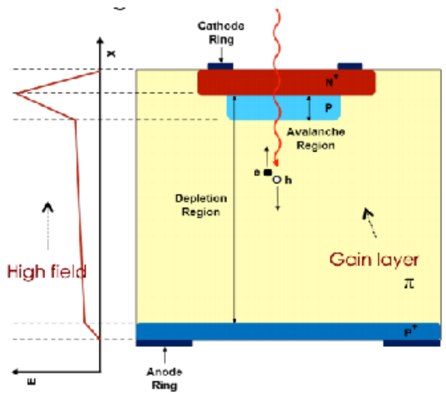
Solano - PPS performance and upgrade

Proof that it is possible to operate a near-beam spectrometer at the LHC in high-lumi data taking

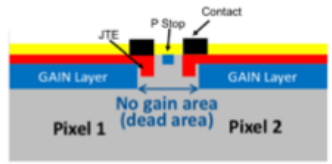
Radiation damage mitigated by moving detector slightly during technical stops

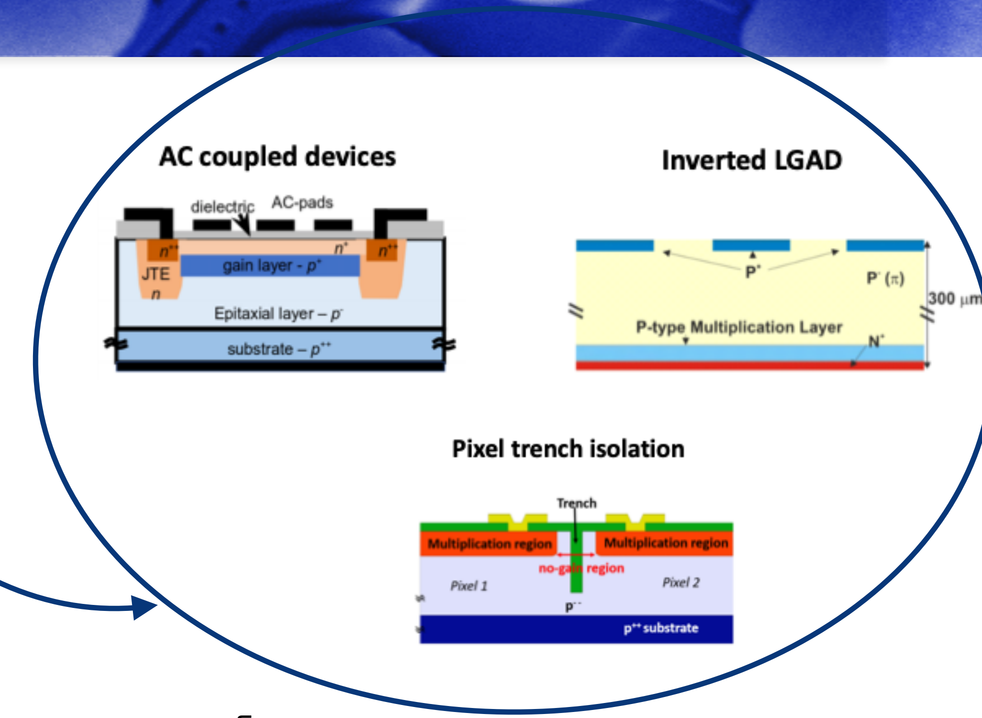


LGAD sensors



standard design





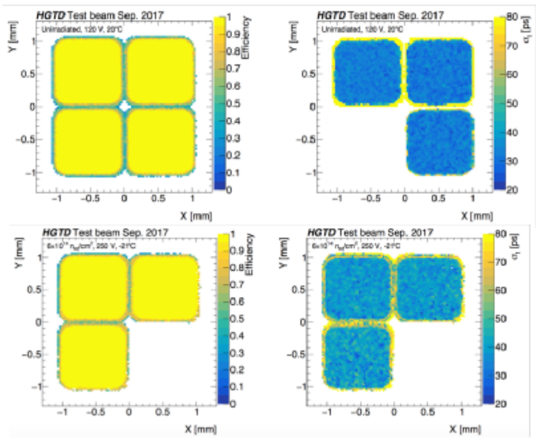
Low Gain Avalanche Detectors

- Silicon sensors with internal gain, developed at CNM barcelona
- Extra, highly doped p layer added just below p-n junction of a PIN diode
- Avalanche multiplication of electrons to create additional electron-hole pairs
- Precise timing capabilities
- electron collecting: signal dominated by hole drift

Degradation of gain with irradiation (temperature important)

hard to reduce pixel size due to “LGAD fill factor” issue

prototype sensors (here from ATLAS) show excellent efficiency and time resolution, before and after irradiation



LGADs for ATLAS and CMS timing layers

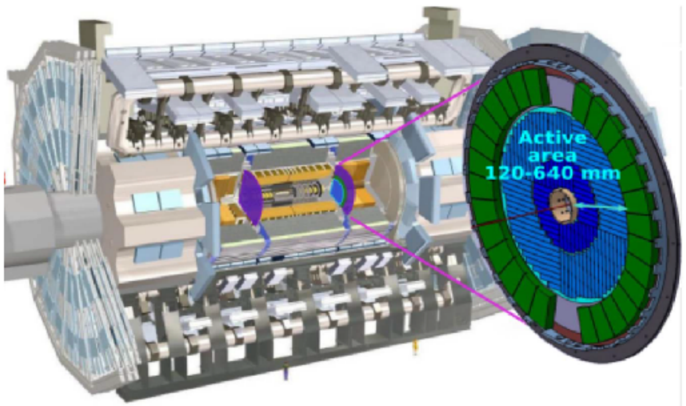
Rizzi: A High-Granularity Timing Detector for ATLAS Phase II Upgrade

Petrillo: Development of the CMS MTD Endcap Timing Layer for HL-LHC

ATLAS High Granularity Timing Detector

CMS Endcap Timing detectors

Both equipped with LGADS with 1.3 x 1.3 mm^2 pads targeting < 50 ps resolution



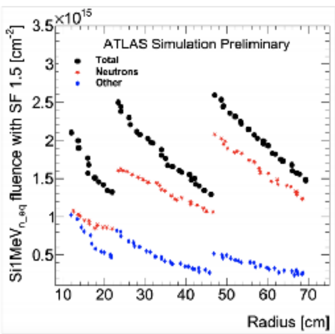
Two double sided layers in front of Calorimeter endcap

covers: $2.4 < \eta < 4.0$ with 12 cm < R < 64 cm @ z = 3.5 m

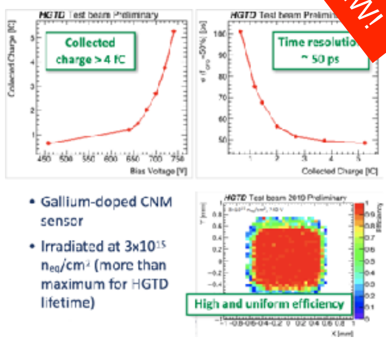
3 rings are replaced 4/2/0 times to maintain fluence < 2.5×10^{15} n_{eq}/cm^2

2(3) hits per track for R> (<) 30 cm

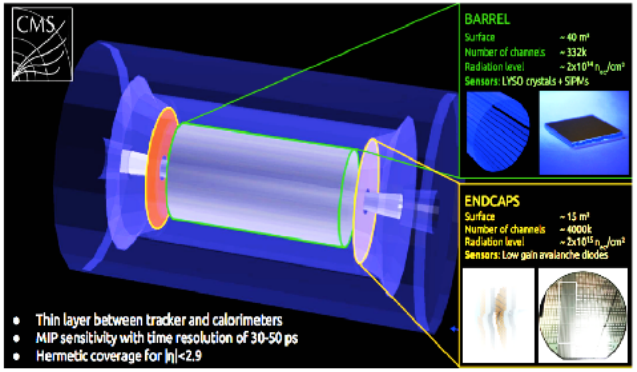
ToA and ToT from ALTIROC



NEW!



Post irradiation:
4 fC and 50 ps achieved!

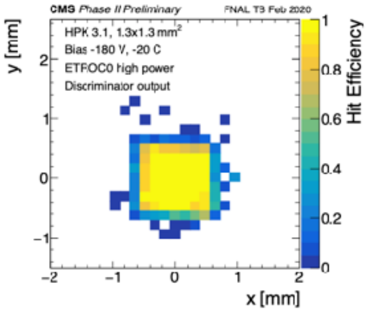


Two double sided layers in front of Calorimeter endcaps; hermeticity with BTL

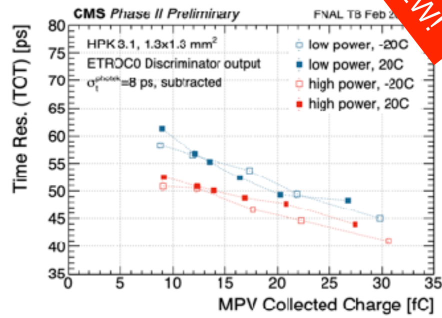
fluence < 1.7×10^{15} n_{eq}/cm^2

covers: $1.6 < \eta < 3.0$ with 0.31 < R < 1.2 @ z = 3 m

ToA and ToT with single TDC from ETROC readout



NEW!



Pre irradiation
40-50 ps after discriminator
with full efficiency!

LGADs for ATLAS and CMS timing layers

Rizzi: A High-Granularity Timing Detector for ATLAS Phase II Upgrade

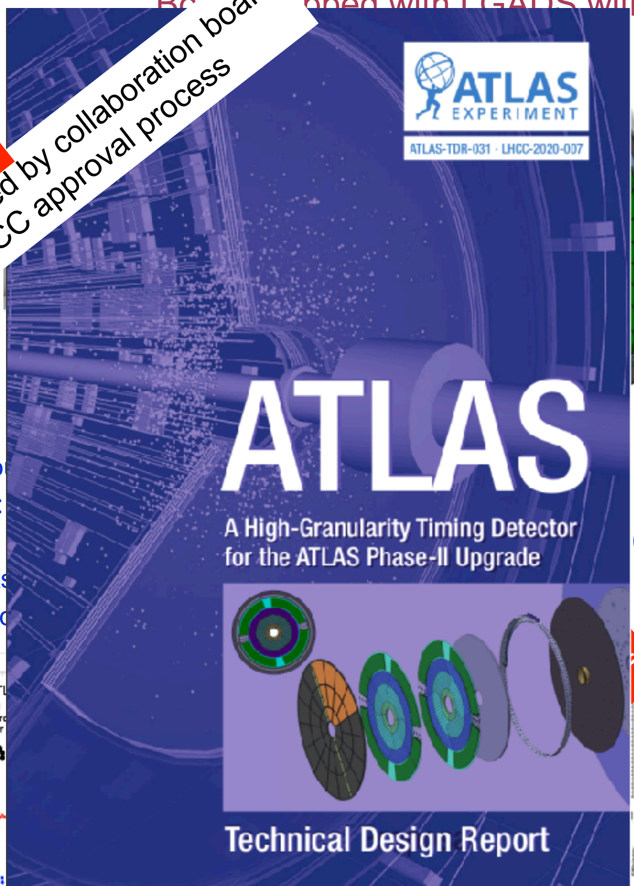
Petrillo: Development of the CMS MTD Endcap Timing Layer for HL-LHC

ATLAS High Granularity Timing Detector

CMS Endcap Timing detectors

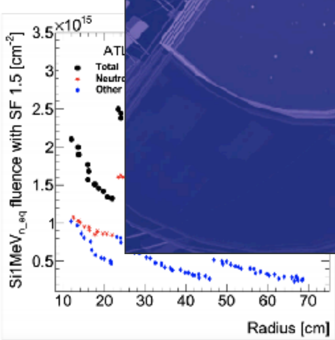
Bo… …pped with LGADS with 1.3 x 1.3 mm² pad

NEW! approved by collaboration board in LHCC approval process



Two do…
covers:…
3 rings…
2(3) hits…
ToA and…

…0¹⁵ n_{eq}/cm²

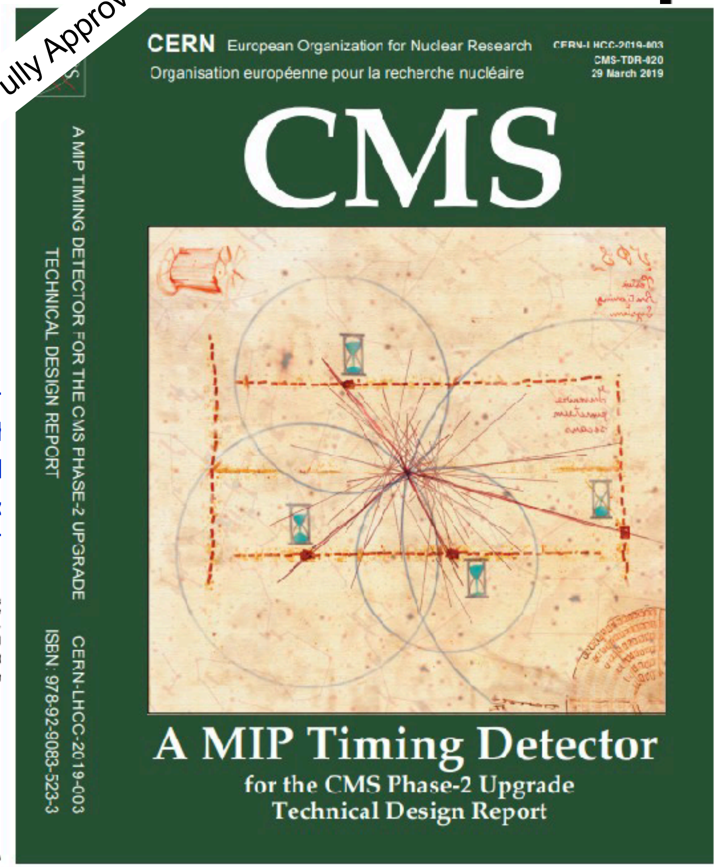


n_{eq}/cm² (more than maximum for HGTD lifetime)

High and uniform efficiency

Post irradiation: 4 fC and 50 ps achieved!

Fully Approved



x [mm]

MPV Collected Charge [fC]

Pre irradiation 40-50 ps after discriminator with full efficiency!

LGADs for ATLAS and CMS timing layers

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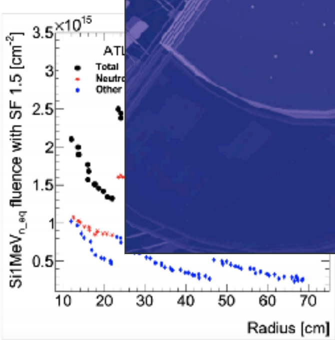
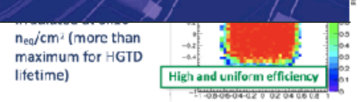
Bo… …pped with LGADS with 1.3 x 1.3 mm² pad

NEW! approved by collaboration board in LHCC approval process

Two do… covers: 3 rings 2(3) hits ToA and…

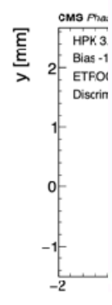


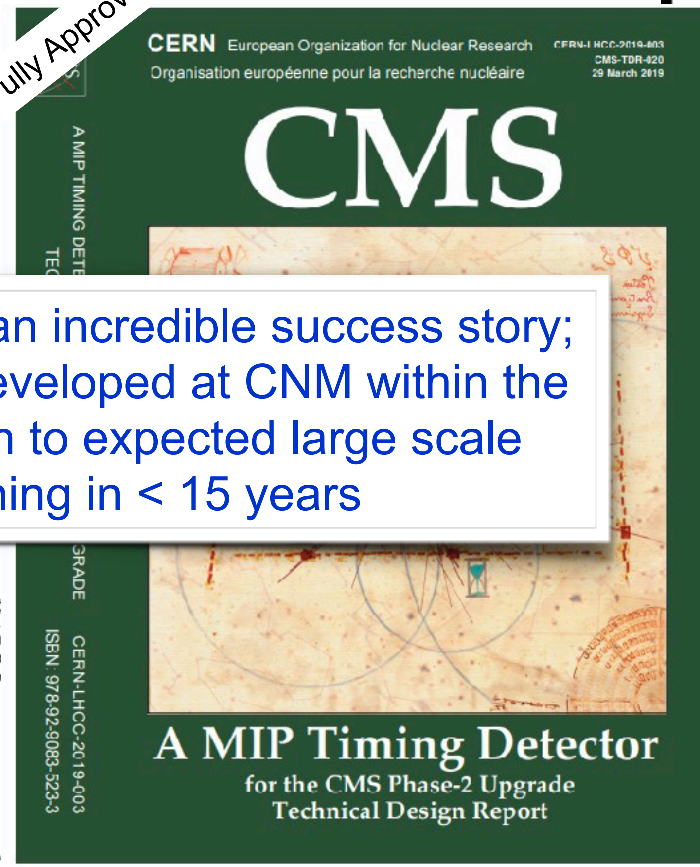


Post irradiation: 4 fC and 50 ps achieved!

CMS Endcap Timing detectors

Fully Approved





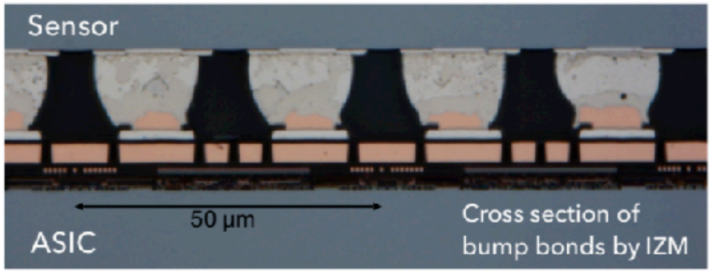
MPV Collected Charge [fC]

Pre irradiation 40-50 ps after discriminator with full efficiency!

LGADs are shaping up to be an incredible success story; from novel concept (2010), developed at CNM within the RD50 collaboration, through to expected large scale installation and running in < 15 years

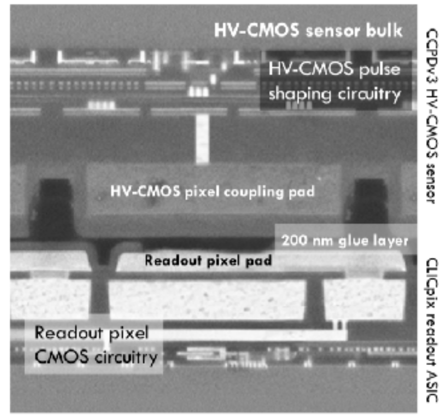
Putting it together: Hybridization

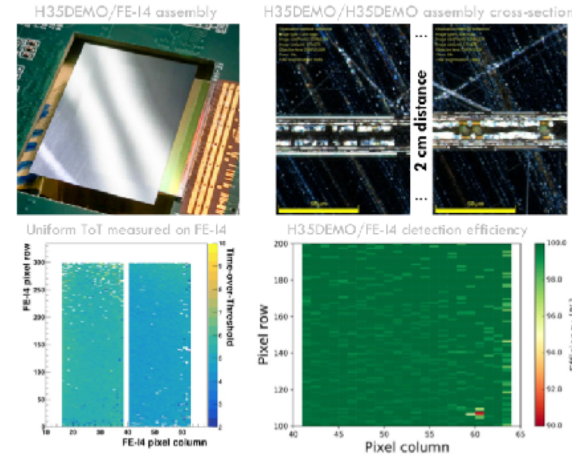
Dort: Silicon Vertex and Tracker R&D for CLIC



- Challenging single-chip bump-bonding process with pixel pitch of 25 µm performed by IZM
- Interconnect yield of up to 99.6% found in laboratory testing (test-pulse, source, etc.)

JINST, 15(03), C03045





Signal processing shared between sensor and ROC

allows capacitive transfer of signal between HV-CMOS sensor and ROC through a thin, non conductive glue layer

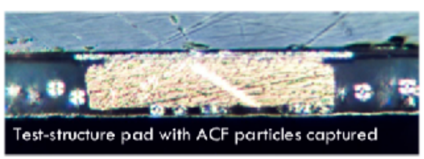
Successful CCPD assembly

100 nm gap difference; 5 µrad parallelism

Uniform signal coupling and efficiency > 99%

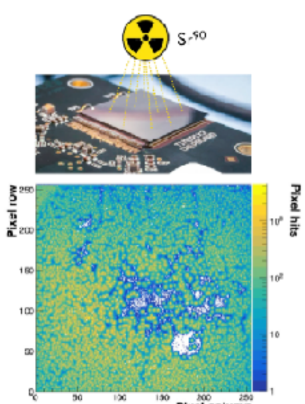
Bonding with Anisotropic Conductive Film

Industry standard but challenge going to HEP pixel sizes

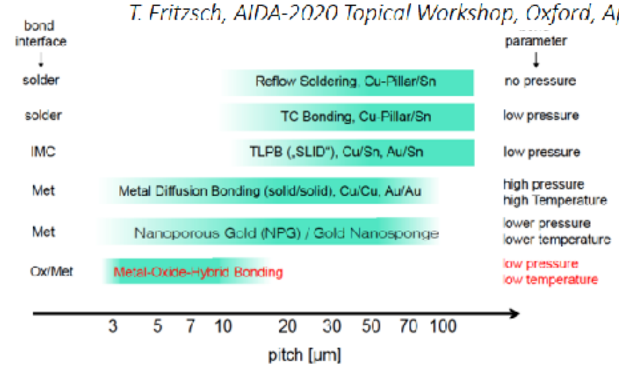


Successful manufacture of first Timepix3-pixel sensor with ACF hybridization

path to 3d integration



T. Fritzsch, AIDA-2020 Topical Workshop, Oxford, April 2019



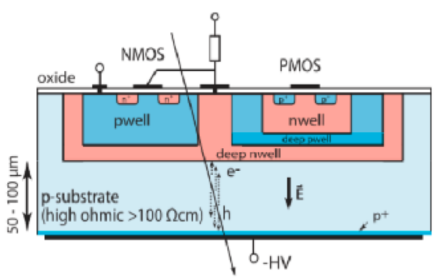
Towards Radhard Maps

Advances in commercial CMOS technologies combined with dedicated designs allowed significant progress from STAR to ALICE to ATLAS in areas like radiation hardness, response time, and hit rates

Strong interest for R&D to fully exploit potential of MAPS in future trackers

High granularity, low material budget and power, large area at reduced cost (cf hybrid)

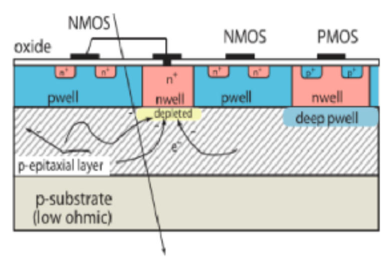
Large electrodes



- Electronics in collection well
- No or little low field regions
- High resistivity substrate
- Large signal
- Short drift path for high radiation hardness

- Larger sensor capacitance → higher noise and slower @ given power
- Potential cross talk between digital and analog section

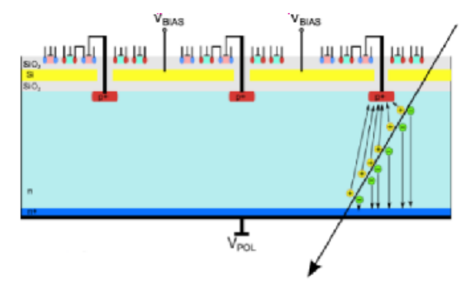
Small electrodes



- Electronics outside collection well
- low resistivity substrate
- Small capacitance, for high SNR and potentially fast signals but worse behaviour far from electrode
- Separate analog and digital electronic

- Large drift path → need process modification to usual CMOS processes for radiation hardness

"Buried" electrodes (SoI)



- Electronics and sensor in separate layer
- Can use thick or thin high resistivity material and HV (>200V)

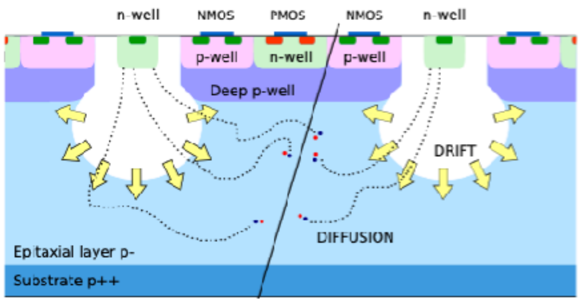
- Special design/processing to overcome radiation induced charge up of oxides

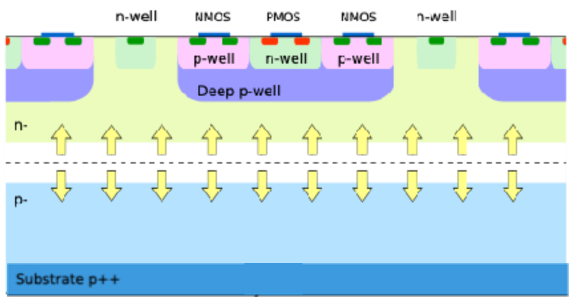
Towards Radhard Maps

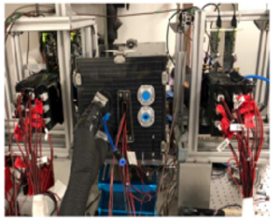
Sanches: Radiation hard monolithic CMOS sensors with small electrodes for HL-LHC and beyond

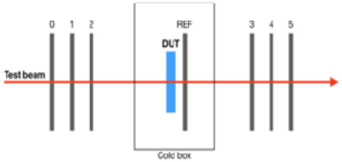
From ALPIDE to MALTA/Monopix: Modified Tower Jazz 180 nm process

- Malta (JINST 12 (2017) P06008) designed as a radiation hard high speed monolithic CMOS sensor for ATLAS
- uniform n-implant blanket in epitaxial layer gives lateral depletion right through to to small input capacitance electrode









MALTA Telescope @ the SPS

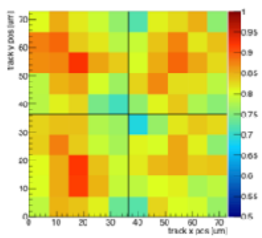
Chip showed good performance

Additional refinements(arXiv 1909.11987) gave additional improvements

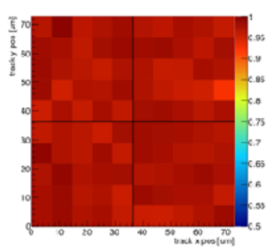
- n- implant gaps/extra deep p wells to improve charge collection at pixel edges and corners

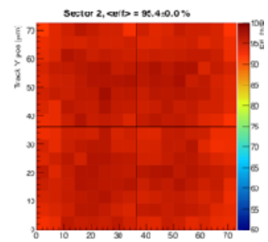
Most recent step; move to Cz to enable high depletion depth and high operational voltage

Also implemented in CLICTD
- extended efficiency crucial for future ultrathin sensors arXiv:2004.02537

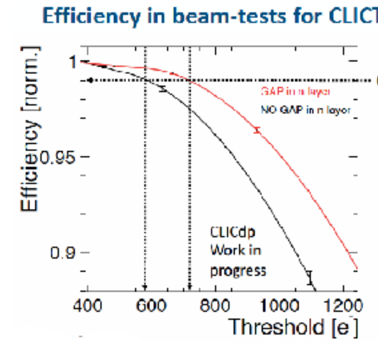


in-pixel efficiency after 1×10^{15} 1 MeV n_{eq}/cm^2
← before and after → design changes





Malta-Cz after
2×10^{15} 1 MeV n_{eq}/cm^2
@ threshold = 226 e^-



MAPS for ALICE ITS3

Rossi: ALICE Upgrade for LHC Run 4 & Beyond

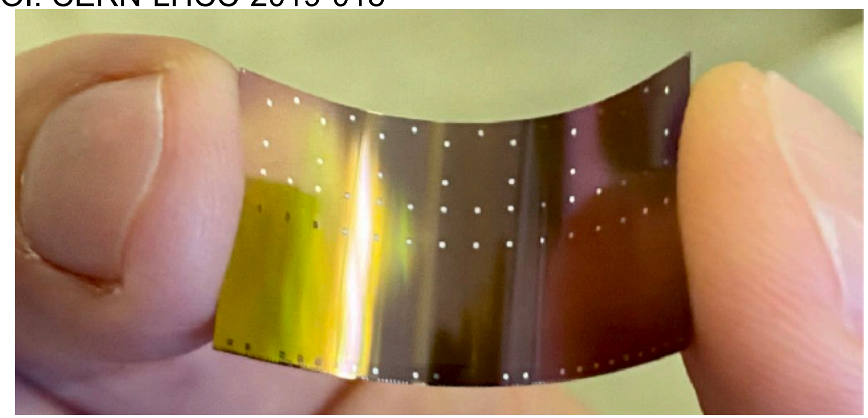
Fully cylindrical, (almost) mass-less Inner Barrel proposed for installation in LS3

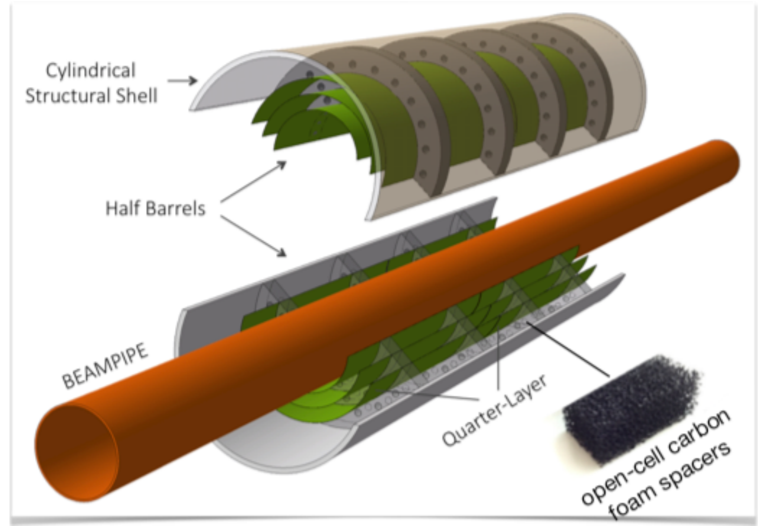
New beam pipe with IR = 16 mm, ΔR = 0.5 mm (0.14% X0)

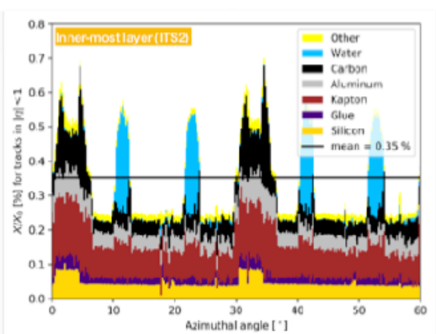
Three cylindrical, wafer-sized layers based on curved ultra-thin sensors; 20-40 μm, x/X0 < 0.02-0.04% per layer

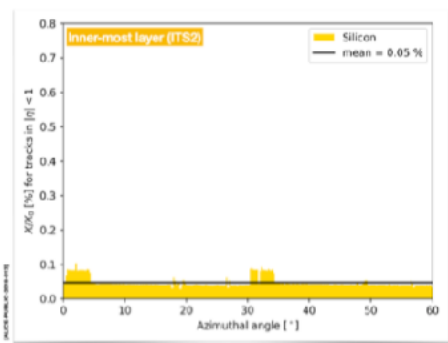
Material budget reduced to the bare minimum

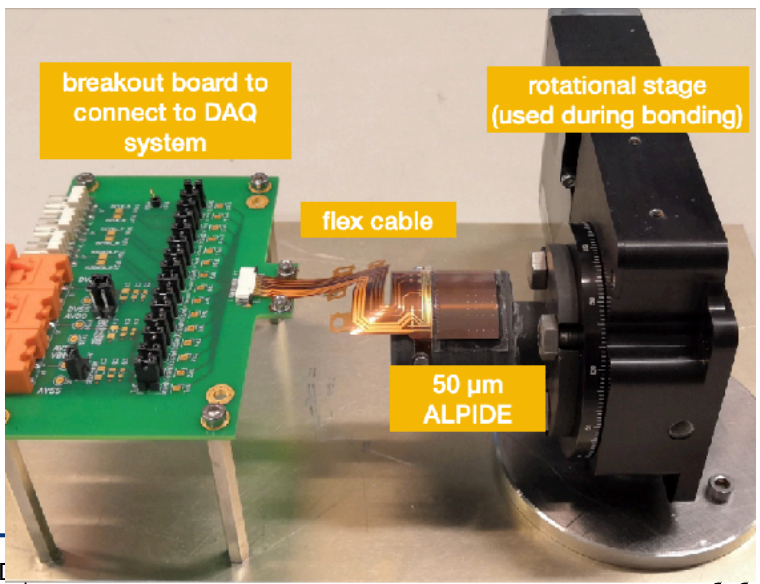
LOI: CERN-LHCC-2019-018











MAPS for next generation ep Detector: FCC-eh and LHeC

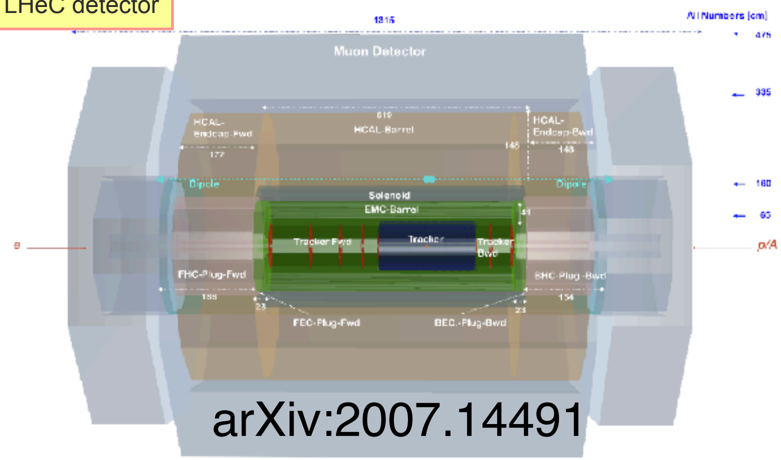
LHeC: 50 GeV ERL × 7 TeV (p)

- CDR 2012 – update last week
- Physics: PDFs, Higgs, top, BSM…
  - Optimised accelerator and IP
  - Technology: fwd calorimeter, tracking
- HV-CMOS based central tracker
  - Radiation 1/1000 of LHC, no pile-up
  - integrated readout electronics

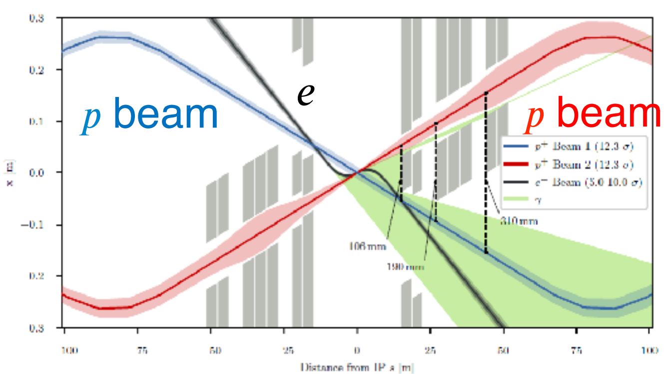
FCC-eh: 60 GeV ERL × 50 TeV

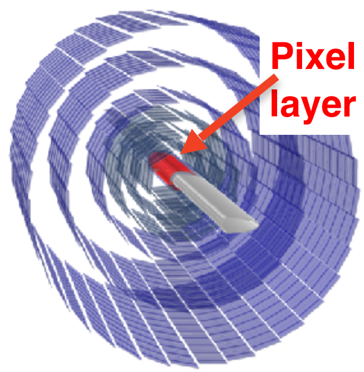
- Large acceptance tracking, taggers. Forward calorimetry extended $\sim \ln E_p$

Yamazaki: The Updated LHeC detector

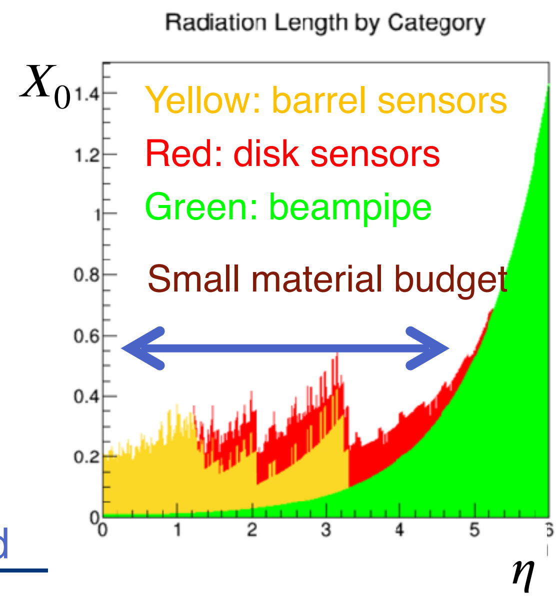


3-beam Interaction Region – new design





Elliptic pipe, 1or 2 pixel layers, perhaps bended



CMOS future @ ILD/FCC/CepC

Physics driven requirements — **Running constraints** — **Sensor specifications**

$\sigma_{s.p.}$ 2.8um → Small pixel ~16 μm

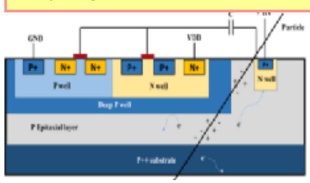
Material budget 0.15% X_0/layer → Thinning to 50 μm

→ Air cooling → low power 50 mW/cm²

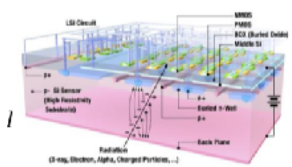
r of Inner most layer 16mm → beam-related background → fast readout ~1 μs

→ radiation damage → radiation tolerance ≤3.4 Mrad/ year ≤6.2×10¹²n ... /(cm² year)

Ouyang: Development of high res low power Silicon pixel sensors for CepC

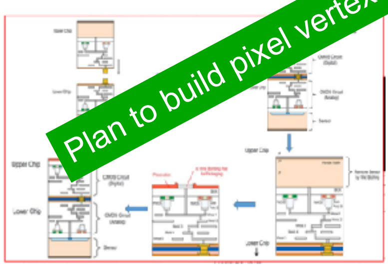


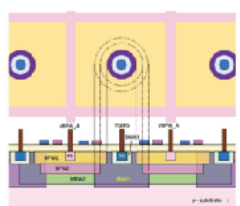
CMOS pixel sensor
- *TowerJazz CIS 0.18 μm process*
- *Quadruple well process*
- *Thick (~20 μm) epitaxial layer*
- *with high resistivity (≥1 kΩ•cm)*



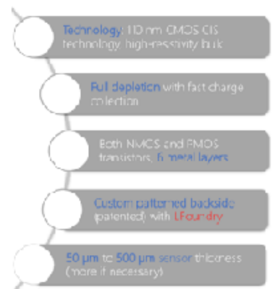
SOI pixel sensor
- *LAPIS 0.2 μm pro...*
- *High resistiv... ≥1 kΩ•cm)*
- *D... ...yers available ...g and backside ...cess*

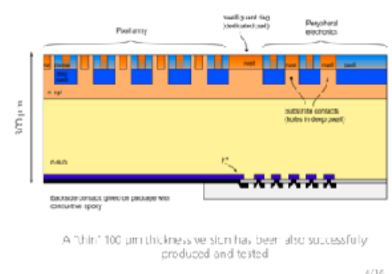
Plan to build pixel vertex detector prototype in next 3 years





Giubilato: ARCADIA, Innovative low-power large area MAPS for HEP and applied science



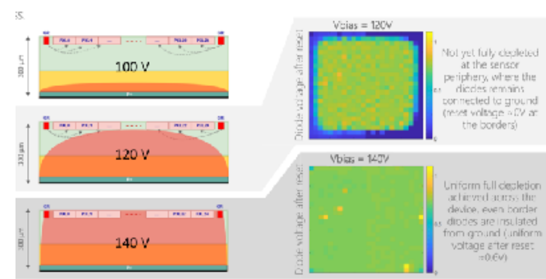


...nned depleted doide ...ocess → reduction of surface leakage by 2 orders

depleted charge collection electrode → reduction of diode capacitance

Lateral electric field → improved charge collection efficiency

AC-coupling to amplifier → allows bias voltage



SoI based 3D integration is coming

Ultra light self supported layers with stitching CMOS sensors

CMOS future @ ILD/FCC/CepC

Physics driven requirements | **Running constraints** | **Sensor specifications**

- $\sigma_{s.p.}$ 2.8um → Small pixel ~16 μm
- Material budget 0.15% X_0/layer → Thinning to 50 μm
  - → Air cooling → low power 50 mW/cm²
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  - → radiation damage → radiation tolerance ≤3.4 Mrad/year, ≤6.2×10¹²n_eq/(cm² year)

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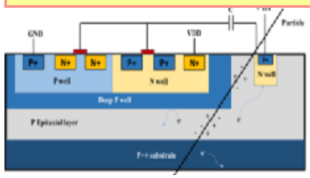

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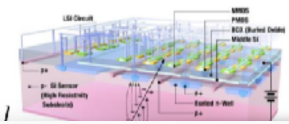
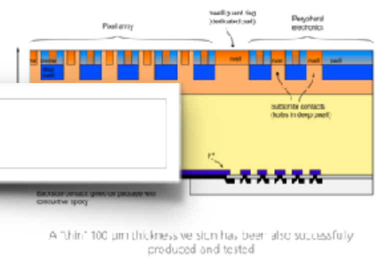


- *High resistiv... kΩ•cm)*
- *D... ...yers available ...g and backside ...cess*



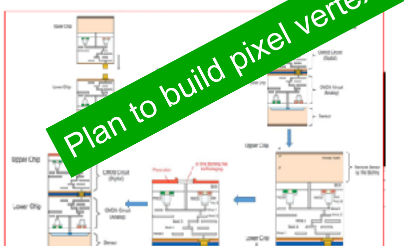
A bright future for monolithics!

surface leakage by 2 orders

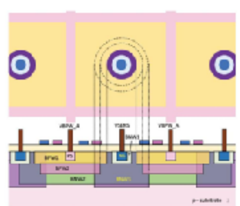
depleted charge collection electrode → reduction of diode capacitance

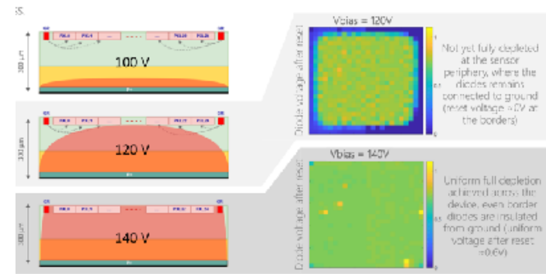
Lateral electric field → improved charge collection efficiency

AC-coupling to amplifier → allows bias voltage



Plan to build pixel vertex detector prototype in next ...





SoI based 3D integration is coming

Ultra light self supported layers with stitching CMOS sensors

Gaseous Detectors

Gaseous Detectors

Gas detector remain key technology for radiation detection in particle physics experiments

- efficient, low mass, relatively cheap, relatively easy to build and radiation hard detector solutions
- Intrinsically provide amplification of signal by gas amplification (less on-detector electronic) thus excellent single particle sensitivity

Future developments centre around

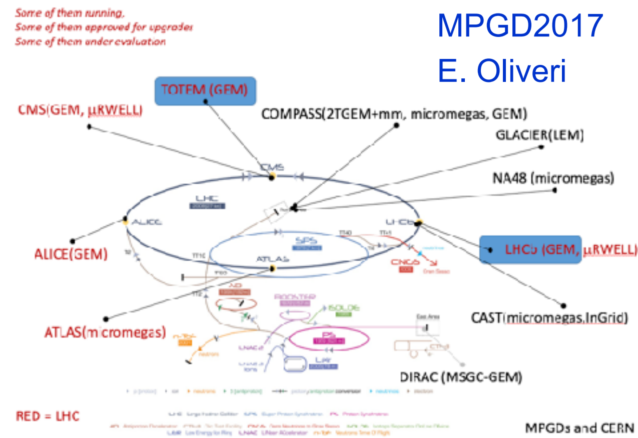
- large area gas based detector systems - Industrialisation, performance scaling
- Understanding of the underlying physics processes and materials (gases, simulations, electronics)
- Replacement of greenhouse gases
- Timing a key issue for future experiments

adapted from D. Contardo
EPS Det R&D 2019

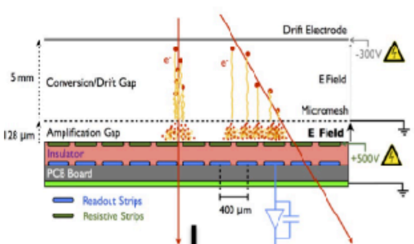
Micro Pattern Gas Detectors: State of the Art

- PCB photolithography progress allows high granularity and rate capability devices
- Several designs adjusted to requirements for muon detection and TPC/RICH readout
- MPGDs have been chosen for all LHC upgrades
- Successful accomplishment of LHC Upgrades will help to disseminate MPGD technologies even more widely

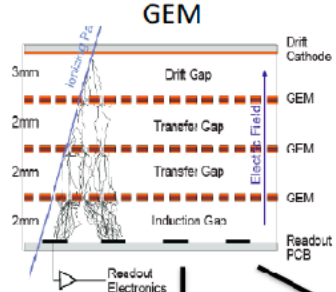
MPGD2017
E. Oliveri



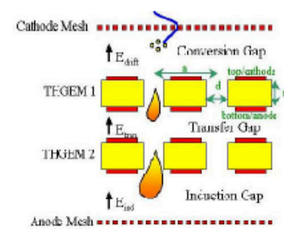
MicroMegas (MM)



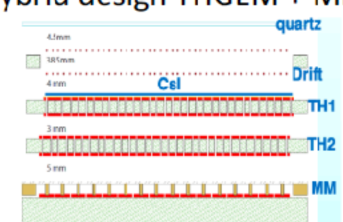
GEM



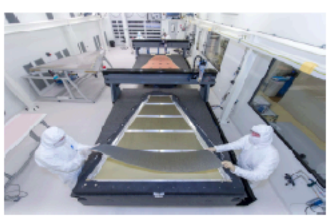
THGEM



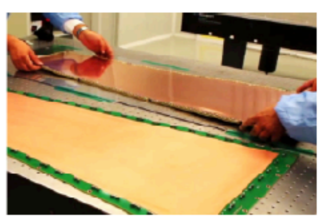
Hybrid design THGEM + MM



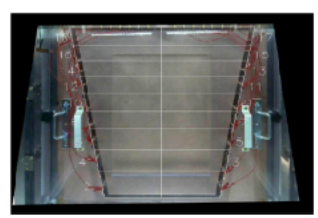
ATLAS new small wheels



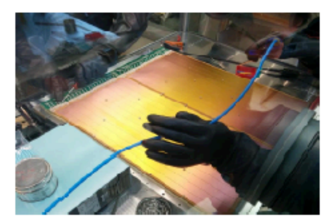
CMS GEM



ALICE TPC upgrade



COMPASS RICH



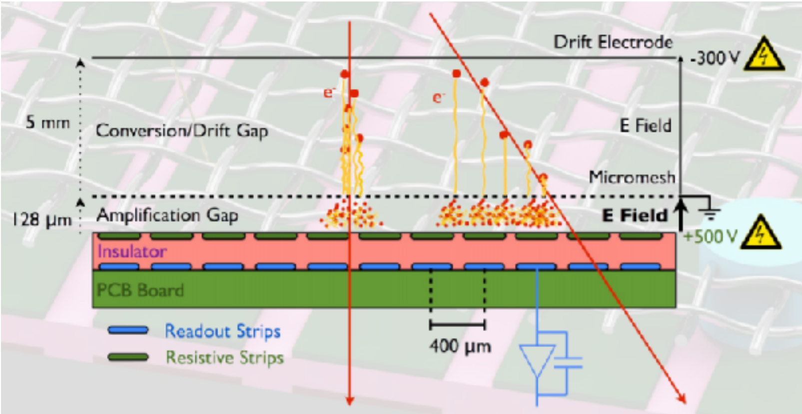
adapted from D. Contardo
EPS Det R&D 2019

ATLAS New Small Wheel

To be installed in LS2.

Total area: 2500 m² !

Resistive bulk μ–megas technology

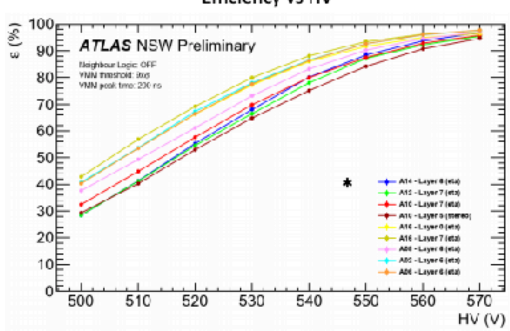


Installation Fixation on NSW A

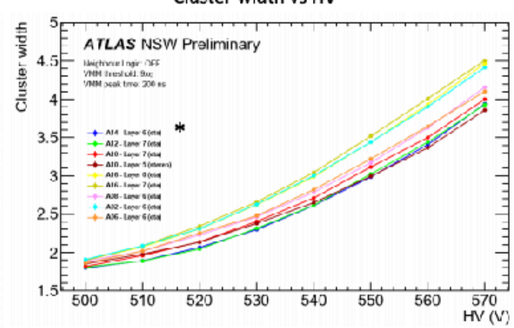
- Average layer efficiency of all sectors built so far exceeds 90%
- Successful accomplishment of NSW side C in time depends on international restrictions due to Covid-19

Largest μ–Megas chambers ever built (?)

Efficiency vs HV



Cluster width vs HV



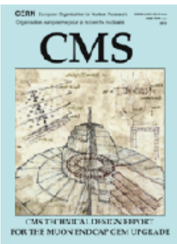
Manisha: Geometrical Alignment for ATLAS NSW
Maeda: ATLAS Level-1 Endcap Muon Trigger for Run-3
Cieri : Upgrade of the ATLAS μ Trigger for HL-LHC
Vafeidis : Integration and commissioning of ATLAS NSW
Bolanos : Cosmic results with Micromegas sectors for NSW

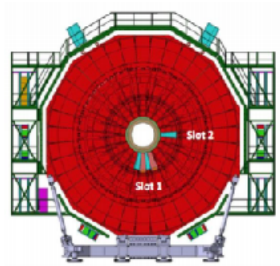
Naseri: Small-Strip TGC and electronics for NSW
Higuchi : The ATLAS muon trigger design/performance
Kitsaki: The ATLAS NWS simulation & reconstruction software
Pezzotti: Irradiation and Gas Studies for NSW
Fassouliotis: Large size Micromegas for NSW

Upgrade of the CMS Muon system with GEM detectors

Mocellin: Commissioning and Prospects of first CMS GEM Station
Fasanella: The CMS Muon Spectrometer Upgrade

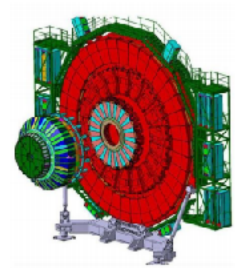
RUN 2
2017-2018





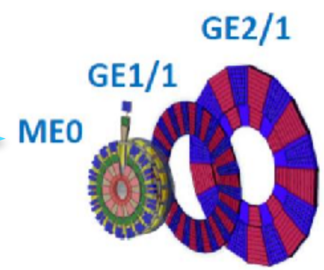
Slice test
Demonstration of GEMs in CMS

Long Shutdown 2
NOW



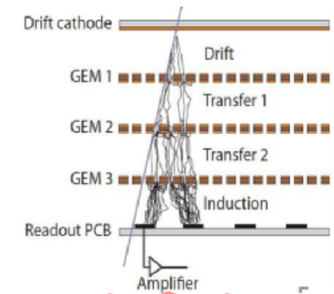
GE1/1 installation

Year End Technical Stops and Long Shutdown 3
2022-2026



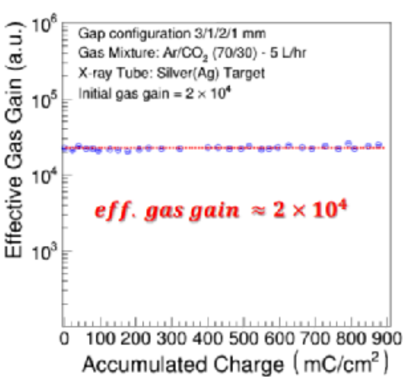
Installation of ME0 and GE2/1
GEMs stations by the end of LS3

Triple GEM technology



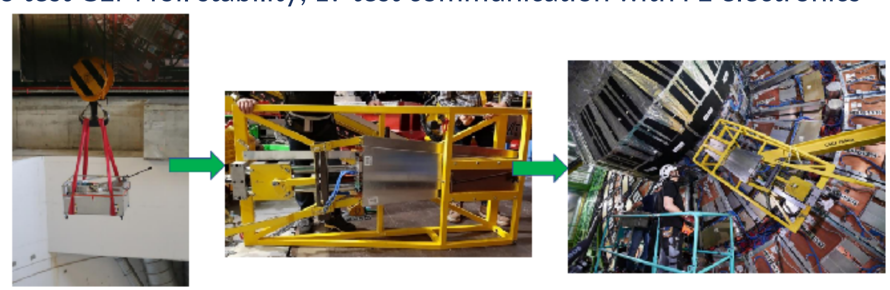
Largest GEM chambers ever built and first Phase II upgrade detectors!

- 72 Super Chambers (145 m2) to be installed during LS2 5 chambers already successfully operated in CMS since 2017/2018.
- Much more to come in LS3.



Longevity Studies at GIF++ facility and with dedicated X-ray source demonstrated full lifetime with safety factor 3.

- 36/36 Super Chambers installed in negative endcap
- Installation ongoing on positive endcap 10/36 already installed!
- HV to test GEM foil stability; LV test communication with FE electronics



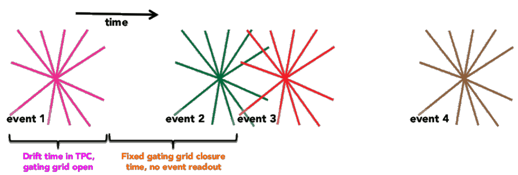
Validated Super Chambers lowered to CMS experimetal cavern

GEM Super Chamber mounted in the installation jig

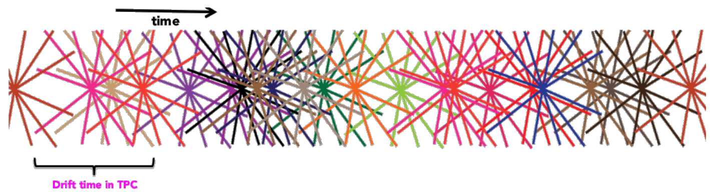
GEM Super Chamber installed on the nose of CMS experiment

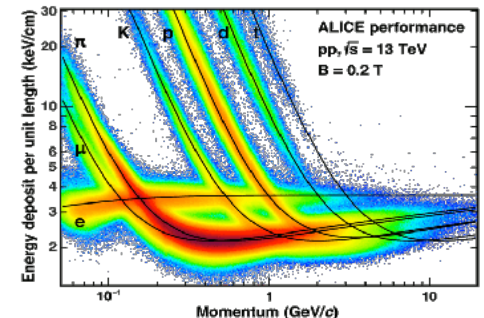
ALICE TPC Upgrade

RUN 1&2: Gated operation



RUN3: Continuous operation



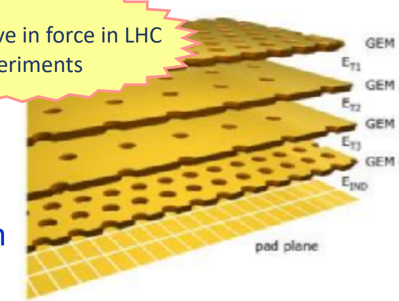


ALICE TPC: Gorgeous performance in Run 1&2, now upgraded for continuous readout at 50 kHz Pb-Pb collisions

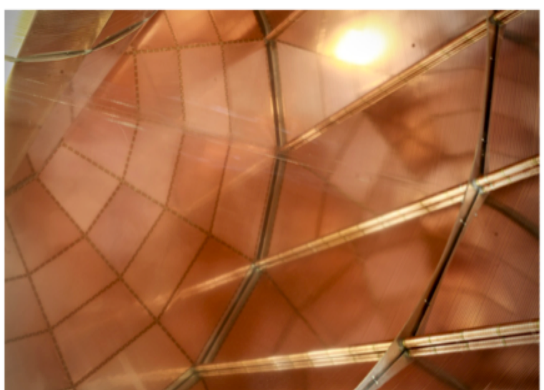
Solution: 4-GEM staggered hole readout

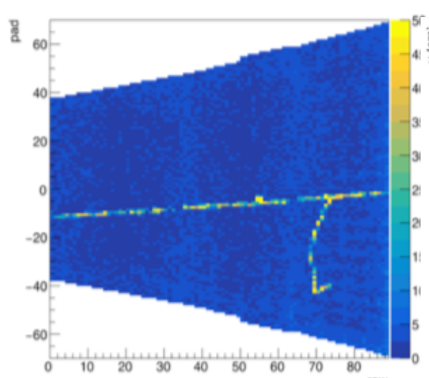
- 50 um polyamide foils with a 5 um copper cladding on both sides
- Hexagonal hole pattern with a standard pitch of 140 um
- provide ion back flow of less than 1%

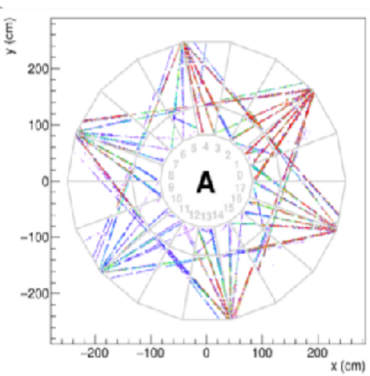
MPGDs arrive in force in LHC experiments

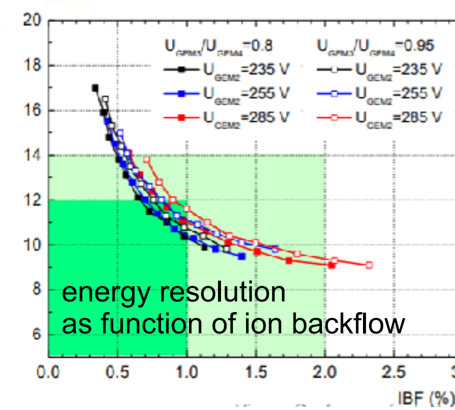


All chambers installed and precommissioning ongoing with laser, cosmic runs and X ray irradiation
Re-installation in ALICE cavern foreseen for August 2020









ALICE TPC Upgrade

RUN 1&2: Gated operation

RUN3: Continuous operation

ALIC

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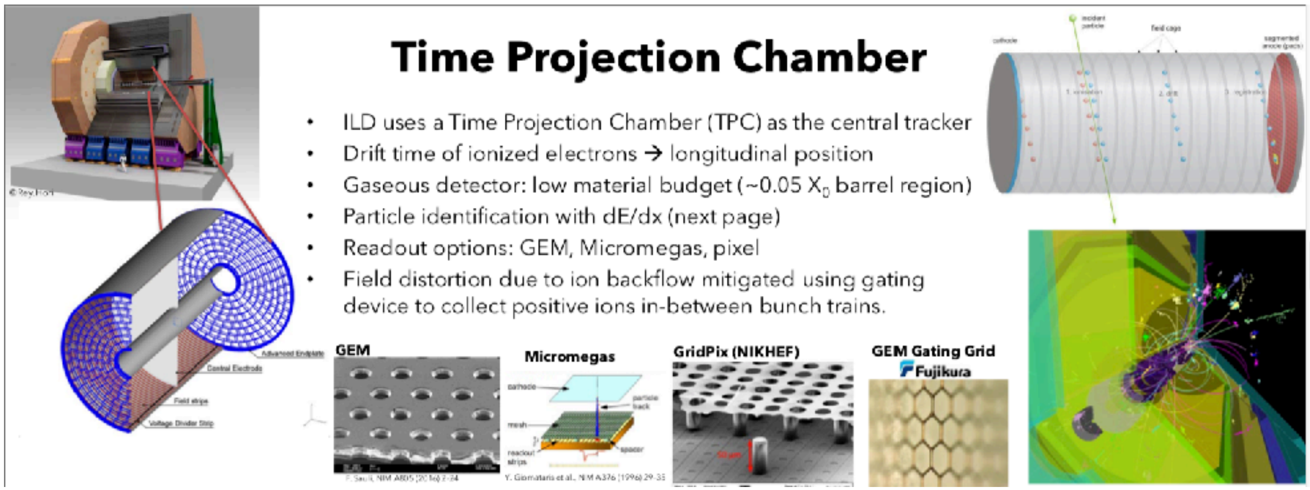
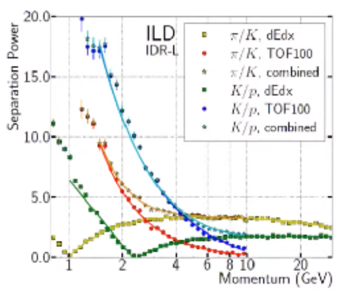
Re-ins

Tanabe: ILD Detector for International Linear Collider



GEMs, Micromegas and pixel readout also considered for the ILD TPC



Combination with ECAL time-of-flight (100 ps) can improve particle identification and eliminate blind spots

Panebianco: ALICE Upgrades for Run 3

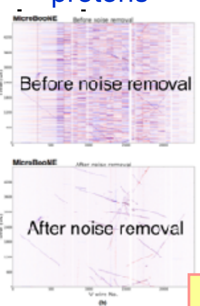
LArTPC for Neutrino/Dark Matter Physics

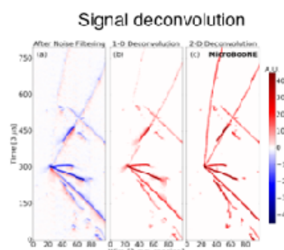
Single Phase

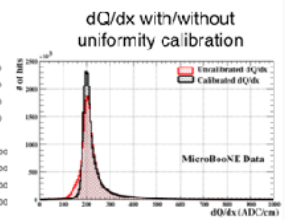
MicroBoone LArTPC

Operating since 2015: ultimate in calibration

- Noise filtering, Wire response modelling, signal deconvolution
- Space charge effects and E field calibrations
  - data driven correction maps with UV laser and cosmic ray data
- Charge and energy calibration with crossing muons and protons

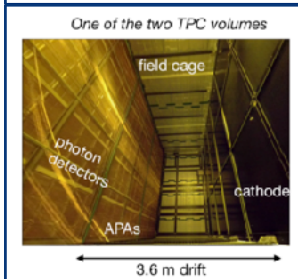


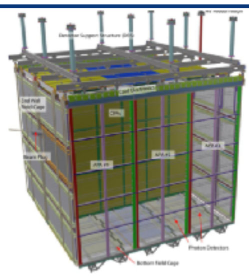




Sharankova : The microboone experiment

ProtoDUNE-SP





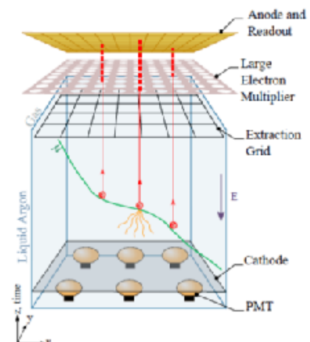
11m x 10m x 11m
→DUNE Module
14m x 14m x 62 m
17.000 ton LAr

Two drift volumes separated by a central cathode

- 500V/cm E field
- wire plane anode plane assemblies
- photon detection with 3 technologies based on WLS + SiPM

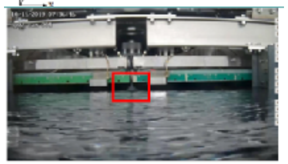
Bordoni : Construction, Installation and Operation of Protodune-SP

Dual Phase

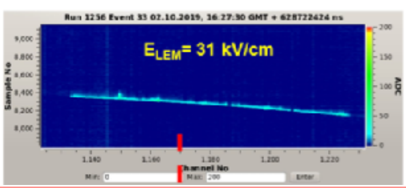


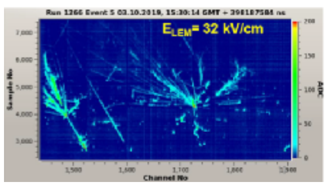
ProtoDUNE- DP

- PMTs detect scintillation light at the bottom
- Electrons drifted vertically
- Electrons extracted from liquid into gas phase
- Charge signal amplified in LEM holes and readout at the top in two directions
- Challenge: instrument large surface with small, planar, gap



bubbles removed with high pressure cycling





muon tracks and hadronic interactions

Eurin: ProtoDUNE Dual Phase: Design, Construction, Results

Ar extracted from **CO_2** wells in **Colorado**

Further purified via a **cryogenic distillation** column at **Fermilab**

Rignanese: DarkSide-20K and the Direct DM search with LAr

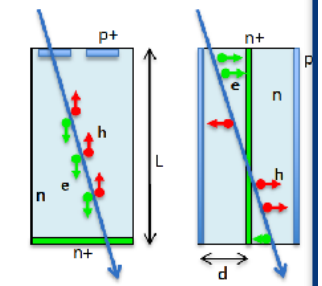
Hybrid sensors - going 3(4)d

Aiming for unprecedented radiation hardness and the possible addition of timing down to 10's of ps

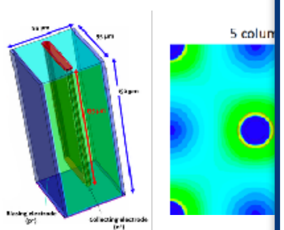
Already running f…

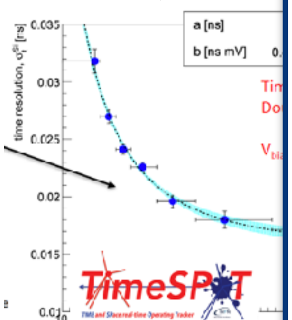
…erzo

…/;
…e side
…$_q$/cm^2 at <= 140V



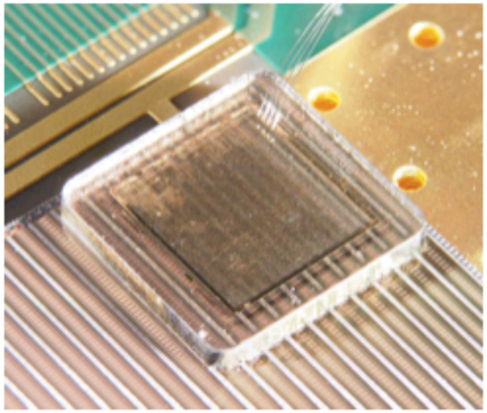
Timespot collabora…

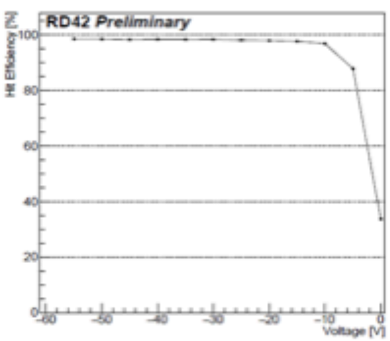


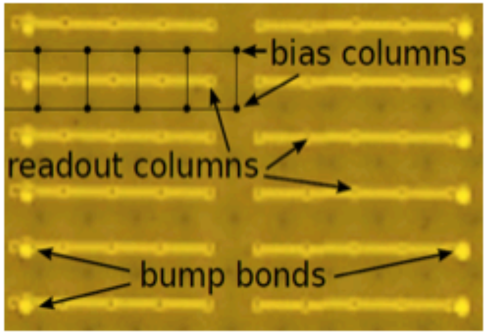


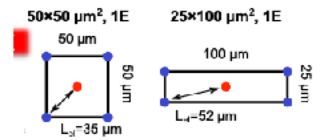
Kagan: New beam test results of 3D pixel detectors
Trischuk: Latest results on Radiation Tolerance of Diamond Pixel & Pad detectors

- ATLAS 3D pixel prototype
  - (50 µm x 50 µm 3D cells)
- 5 cells (5 x 1) ganged together
  - with surface metallisation
- Beam Test efficiency > 99%



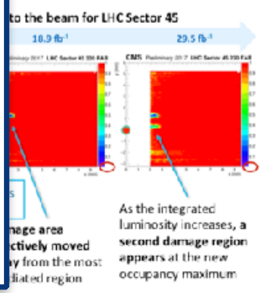






…near-beam spectrometer at

…ing detector slightly during

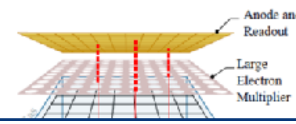


~~LArTPC~~ LXe for Neutrino/Dark Matter Physics

Single Phase

MicroBoone LArTPC

Operating since 2015: ultimate in calibration



Dual Phase

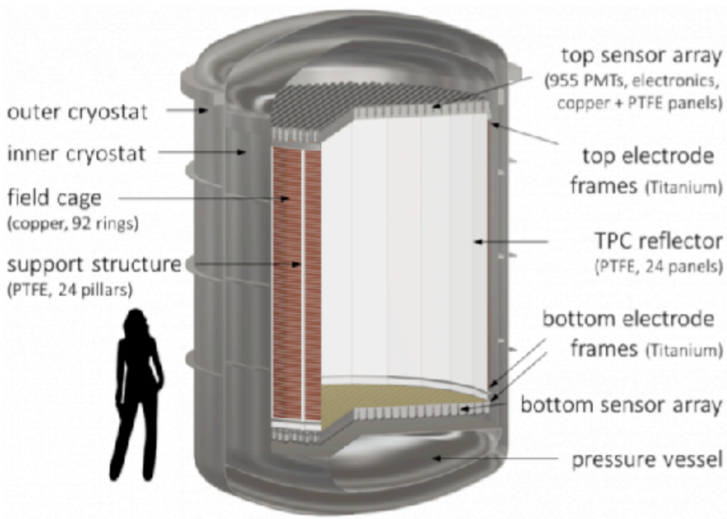
ProtoDUNE- DP

- PMTs detect scintillation light at the

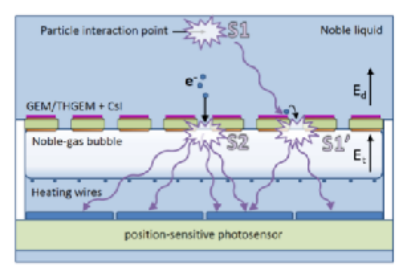
Giovanni: The DARWIN experiment: the ultimate detector for direct dark matter search

WEIZMANN INSTITUTE OF SCIENCE

NYU ABU DHABI



- Dual-phase Time Projection Chamber (TPC)
- Two photo/charge sensor arrays (top and bottom)
- Low-background double-wall cryostat
- Outer shield filled with water (12 m diameter)
- Neutron/Muon Veto



Largest LXe target ever

Readout: 4” cryogenic triple-THGEM GPM with reflective CsI

- photon detection with 3 technologies based on WLS + SiPM

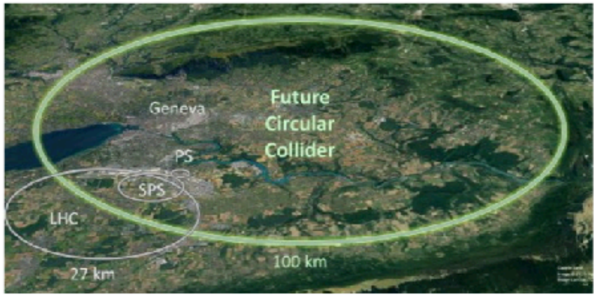
Bordoni : Construction, Installation and Operation of Protodune-SP

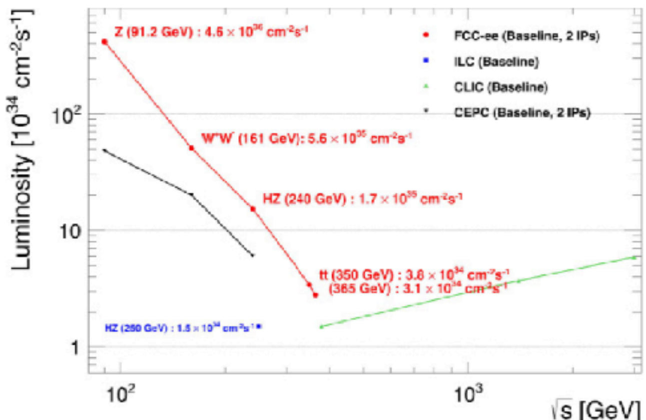
Rignanese: DarkSide-20K and the Direct DM search with LAr

IDEA drift chamber

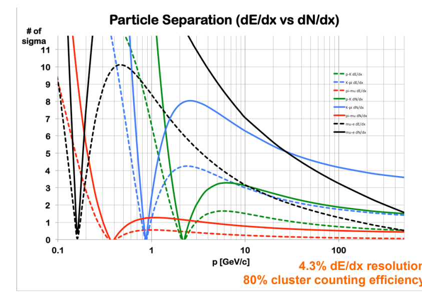
Targetted for FCC-ee

Blondel: Circular and linear e+e- colliders, another story of complementarity
Bedeschi: A detector concept proposal for a circular e+e- collider
Tassielli: A proposal of a drift chamber for the IDEA experiment



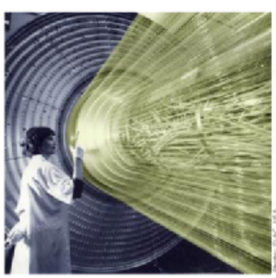


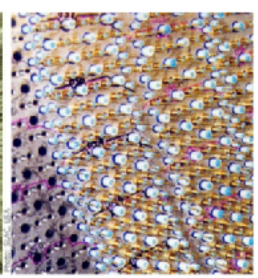
- State of the art momentum and angular resolution for charged particles
- B field limited to ~2T to contain vertical emittance at Z pole → large tracking radius needed
- High transparency required given typical momenta Z, H decays
- Particle ID is a valuable additional ability

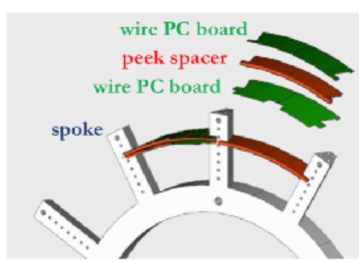


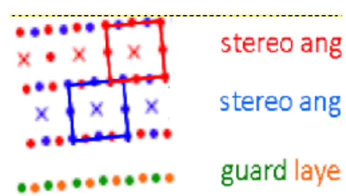
The IDEA drift chamber:

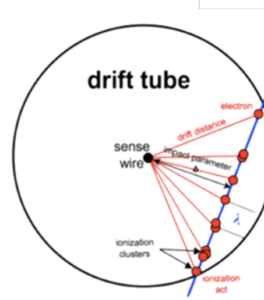
- meshed stereo wire cages: field to sense wire ratio 5:1
- Wire net created by + and - orientation generates a more uniform equipotential surface
- Very challenging construction based on MEG II solution
- Global principle of separating wire support from gas enclosure allows low mass construction
- "cluster counting" possible with addition of timing to count number of ionisation acts → PID
- Complemented by silicon layer wrapped around outside of chamber and potential TOF to plug momentum gap

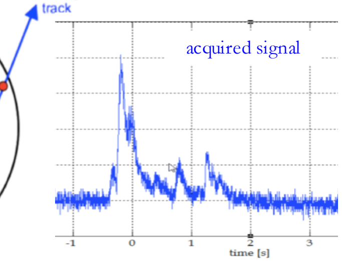










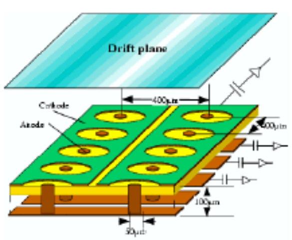


Micro Pattern Gas Detectors: Future

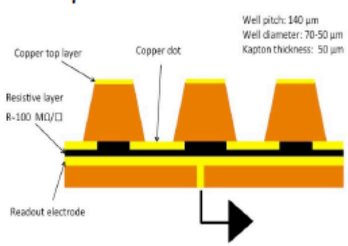
- Single amplification stage designs (μPIC, μResistive-Well/Resistive-Plate-Well)
  - Ease fabrication, resistive layer with new material (e.g. DLC) to improve rate capability > MHz
- Picosecond devices with radiator and radiation tolerant photocathodes
- Fabrication process for large scale detectors and transfer to industry
  - 3d printing, dry plasma ink jet printing (developed for flexible devices)
  - Monolithic CMOS production of MM design InGrid demonstrator - considered for ILD TPC
- New gas mixtures without Greenhouse gases

30-50 μm precision

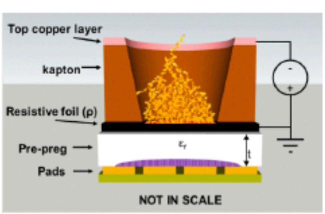
μPIC



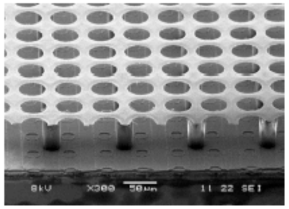
μ-Resistive-Well



Resistive-Plate-Well

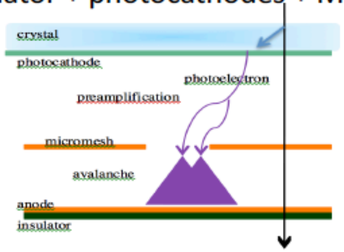


InGrid CMOS MM



25 ps achieved

Radiator + photocathodes + MM



- CERN RD51 : http://rd51-public.web.cern.ch/rd51-public/

D. Contardo
EPS Det R&D 2019

Light Detection

Light Detection

Time of flight / MIP timing / RICH / single photon detection R&D challenges

- Noise rates and cross talk must be kept low
- Rate capability must be sufficiently high
- Single photon timing target for TOF/DIRC/TORCH/Mip timing ~ 40-70 ps
- Operation in magnetic field
- strong synergy with scintillating device R&D

Light detection for calorimetry / particle flow for h-h and e-e

- Speed, noise, high granularity (2-3 orders of magnitude) all crucial
- Very large systems installed within minimal space

Many families of photon detectors!

Vacuum based
- PMTs
- MaPMTs
- Hybrid PMTs
- MCP-PMT
- HAPD
- LAPPDs

Solid State
- Silicon based (MPPC, CCD)
- Silicon PMs

Gaseous
- Photosensitive (TMAE/TEA)
- MWPC/MPGD + CsI

Superconducting
- Transition Edge
- Kinetic Inductance

For an excellent summary see

adapted from D. Contardo
EPS Det R&D 2019

Photon detection for PID - State of the art

Pillars of particle ID: Cherenkov radiation, dE/dx, Transition Radiation, TOF :

RICHes with focalisation

- Extended radiator (gas)
- Mandatory for high momenta

SELEX, OMEGA, DELPHI, SLD-CRID, HeraB, HERMES, COMPASS, LHCB, NA62, EIC

RICHes with Proximity focusing

- Thin radiator (liquid, solid, aerogel)
- Low momenta

STAR, ALICE HMPID, HERMES, CLEO III, CLAS12, EIC,

DIRCs

- Quartz as radiator and light guide
- Low momenta

Babar DIRC: derivatives BELLE II TOP, Panda & EIC (focusing DIRC), LHCb TORCH

Time Of Flight detectors

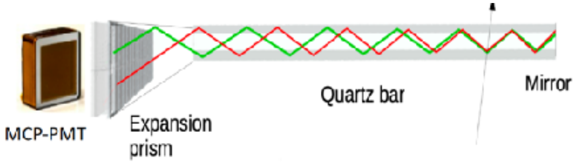
- use prompt Cherenkov light
- fast gas detector

ALICE, BES III

Belle II Time of Propagation RICH (TOP)

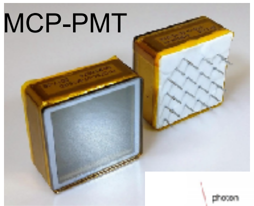
~ 90 ps resolution in barrel + focusing Aerogel RICH in forward region

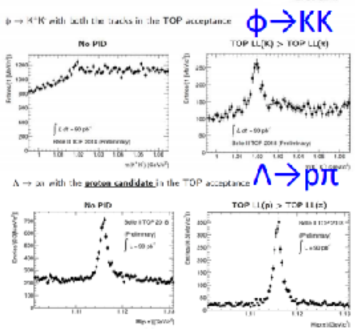
Belle II Barrel PID: A DIRC derivate:

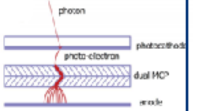


Installed between drift chamber and calorimeter

- Single photon efficiency
- < 100 ps SPTR
- few mm spatial resolution
- operation in 1.5T B field



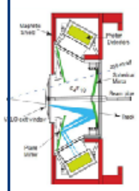


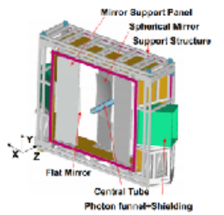


TOP in full commissioning, calibration and operation!

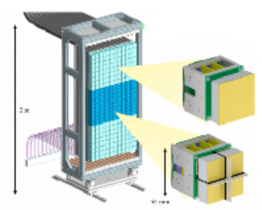
Running Experience and performance of the Novel TOP Barrel PID Detector in the Belle II Experiment : Hartbrich

LHCb Run 1 RICHes





LHCb Run 3 upgrade



New photon detectors MaPMTs Hamamatsu R13743 (H12700) and R13742 (R11265)

New electronics at 40 MZ readout rate

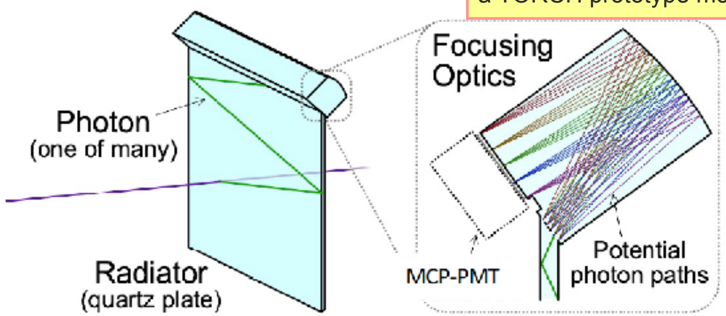
New optics layout for RICH1

The LHCb RICH Upgrade: Minzoni

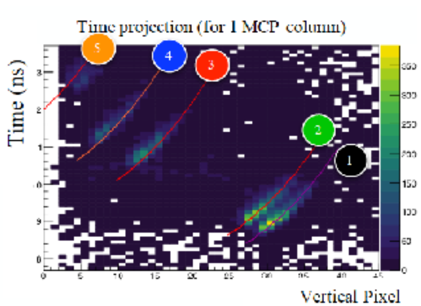
Photon detection for PID - Future

TORCH for LHCb Run 4/5

Kreps: Testbeam performance of a TORCH prototype module



- Prompt production of cherenkov light in quartz bars
- Cherenkov photons travel to detector plane via total internal reflection and cylindrical focusing block
- 70 ps per photon →15 ps per track
- Photons detected by square micro channel plate PMTs; resolution improved by charge sharing

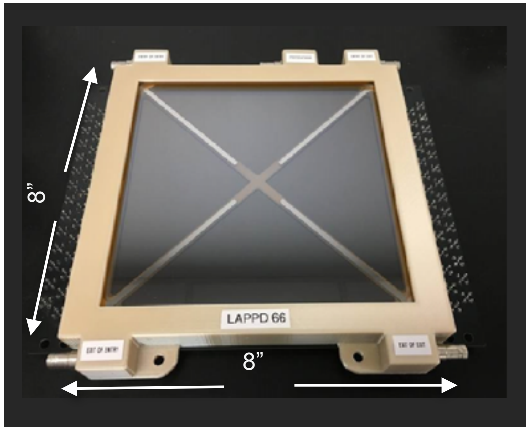


Test beam results:

- patterns seen for different orders of reflection
- Best resolution of 70 ps for 18 cm drift
- 100 ps for 111 cm drift
- Very close to required performance!

Large Area Picosecond Photodetector (LAPPD™)

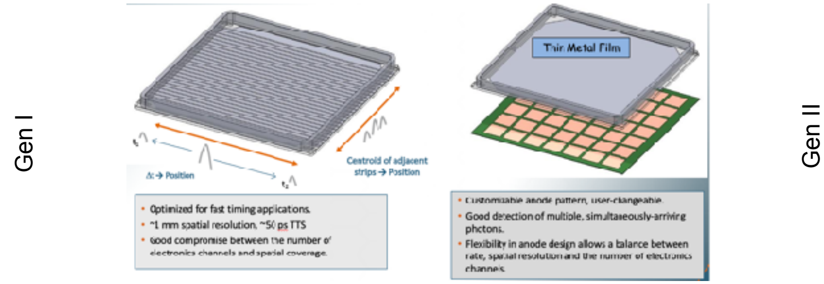
Option for the Future?



- Timing resolution < 55 ps
- Position sensitivity 3 x 3 mm or better
- High gain - mid 10^6 or higher for single PE
- 92% open area
- Blue-sensitive photocathode: Potassium-sodium-Antimony (K_2NaSb)

Large Area Picosecond Photodetector (LAPPD) : Foley

Time and position measurement of photons and mips



De Rosa: A multi-PMT photodetector system for the Hyper-Kamiokande Experiment

See also: Qian: MCP based large area pmts for neutrino detector

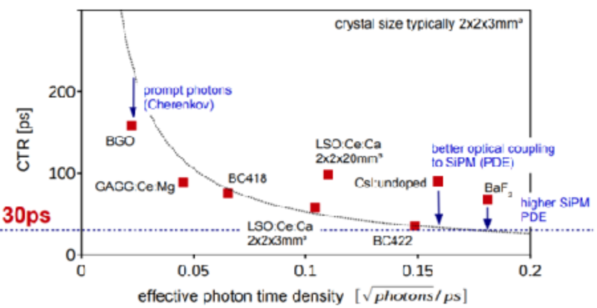
SiPMs for Tracking & PID - State of the Art

SiPMs - a commercial product used in several imaging applications outside HEP: PET, LIDAR..

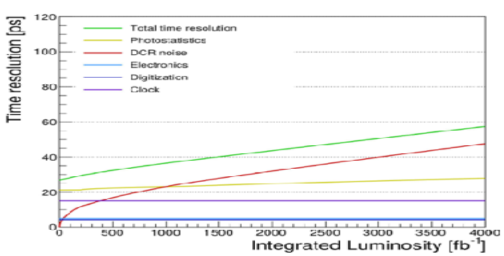
Proton tomography imaging for cancer treatment: Giubilato

Many developments in material/process/design to improve PDE, QE, DCR, radiation hardness

Recent developments in CMOS process to integrate digital electronics



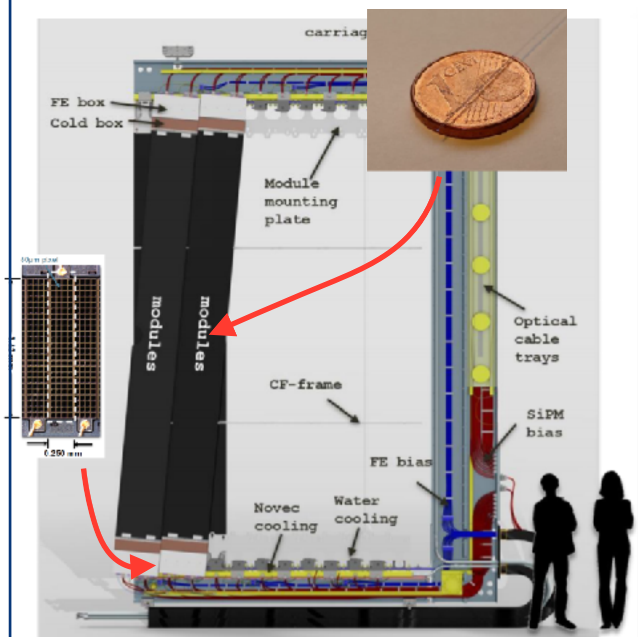
Stefan Gundacker, Experimental advances in photon detection time resolution limits of SiPMs and scintillator based detectors, VCI 2019

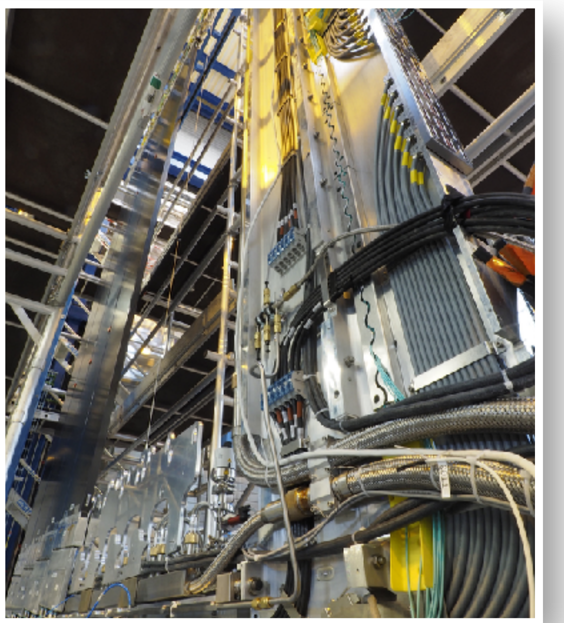


CMS: Time resolution evolution with irradiation

LHCb SciFi installation for Run 3 -

a detector which can only be built thanks to SiPMs!

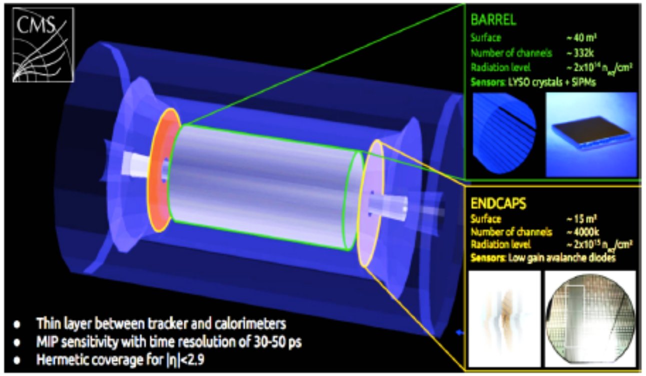




128 modules (0.5 x 5 m^2) arranged in 3 stations × 4 layers (XUVX)
11,000 km of 0.25 μm fibres, 524 channels
< 100 μm resolution over a total active surface of ~ 340 m
SiPMs cooled to -40^{o}C and readout by custom PACIFIC chip
1% X_0 per layer and 40 MHz readout

4-D CsI calorimeter for KOTO : Kotera

SiPMs for Tracking & PID - future

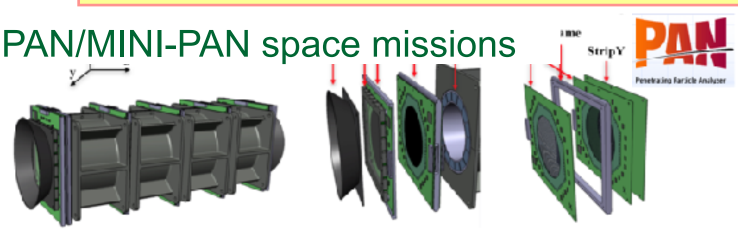


CMS Barrel Timing Layer in Tracker volume

- LYSO bars 56 x 3 x 3 mm³ readout at both ends with 3 x 3 mm² SiPM
- 350 kchannels, 40 m²

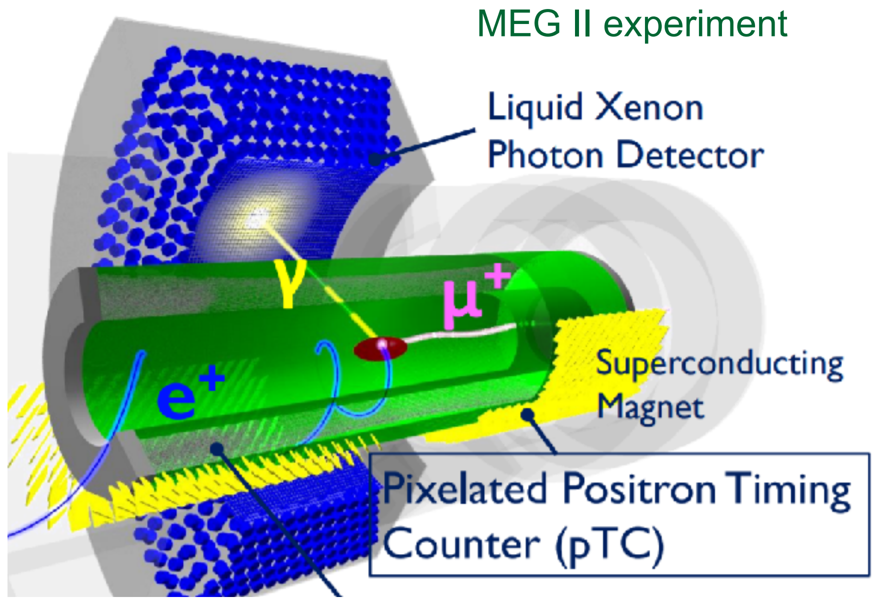
Lu: Precision timing with the CMS MTD Barrel Timing Layer

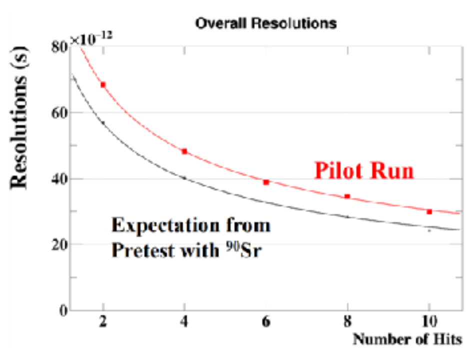
PAN/MINI-PAN space missions



- Builds on principles/technologies demonstrated by AMS, PAMELA
- Light weight (20kg) low power (20W) spectrometer with permanent magnet
- TOF module: 3 mm scintillator, readout on all sides by SiPM (<100 ps)

Wu: Development of a Penetrating particle Analyser for high energy radiation measurements in space





pTC consists of fast plastic scintillator tiles with 2 x 6 SiPM readout. Positron hits on average 8.8 tiles

From pilot run (2017): Required timing resolution of 40 ps can be achieved.

BSM search in rare muon decay : the MEG II experiment

Moresalchi: The Mu2e electromagnetic calorimeter

Calorimetry

Calorimetry

e-e colliders: High Granularity Calorimeter

Calice concept: fine longitudinal segmentation and transverse granularity for 3D shower topology and Particle-Flow reconstruction (Ejet = E_{track} (~ 75%) + Eγ (~15%) + E_{h0} (~ 10%))

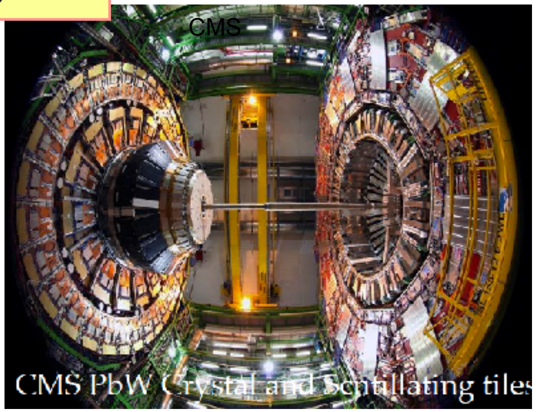
Jet energy resolution 4-3% (> 50-100 GeV for W/Z to jets separation, ~/5 LHC

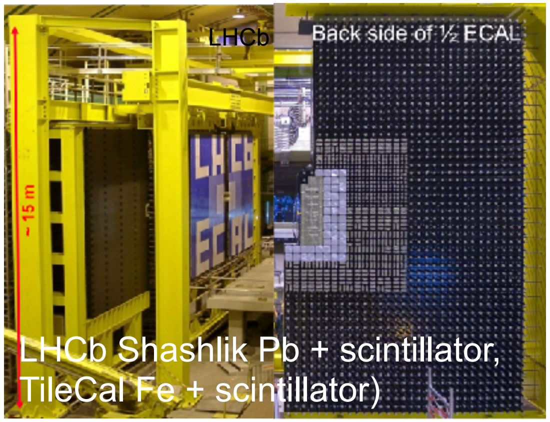
hh collider: add efficient rejection of collision pile-up

ILD HGC configuration	Electromagnetic section	Hadronic section options	
Active Layer/Absorber	Si / W	Scint. tile + SiPM /Steel	Glass RPC / Steel
Number of layers	30	48	48
Cell size (cm x cm)	0.5 x 0.5	3 x 3	1 x 1
Readout	analog	analog	semi-digital
Depth number of X_0/Λ_{int}	24 X_0	5 Λ_{int}	5 Λ_{int}
Number of channels ($x10^6$)	100	8	70
Total area	2500	7000	7000

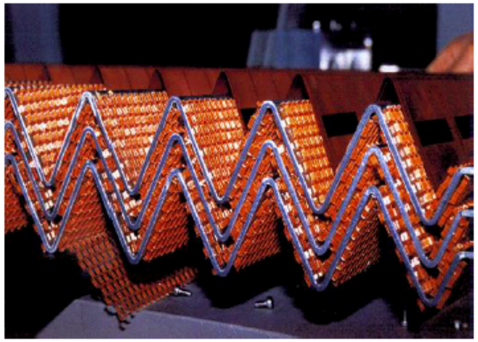
Calorimetry: State of the art

Martinez: Development of ATLAS LAr Calo Readout Electronics for HL-LHC
Moayedi: Upgrade of ATLAS Hadronic Tile Calorimeter for HL-LHC





4 main technologies: LAr, scintillators, crystals (tiles or fibers), Silicon sensors



2 main concepts:

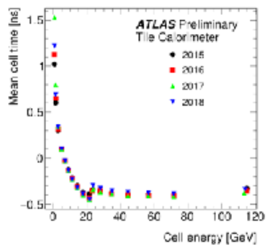
Homogeneous crystals (CsI, LYSO)
- best possible resolution
- applications in PET, homeland security

Sampling
- Imaging: Particle flow Algorithm
- Dream: Dual readout
- Sampling with Crystals shashlik

Calorimetry: State of the art

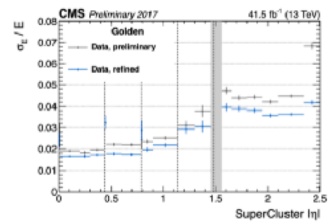
ATLAS

Harkusha: Performance of ATLAS tile calorimeter
Strizenec: LAr Calo commisioining for LHC Run-3



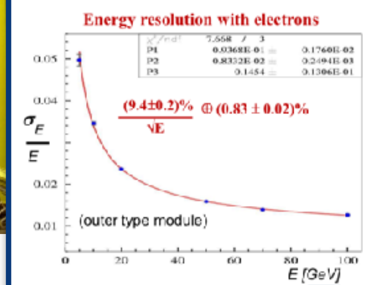
CMS

Konstantinov:
Soldi: Precision calorimetry at high luminosity

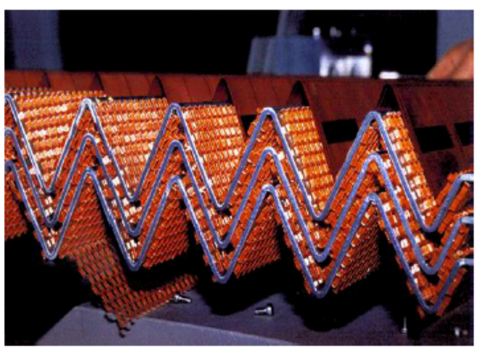


LHCb

Pili: Performance of the LHCb detector in Run2



4 main technologies: LAr, scintillators, crystals (tiles or fibers), Silicon sensors



2 main concepts:

Homogeneous crystals (CsI, LYSO)
- best possible resolution
- applications in PET, homeland security

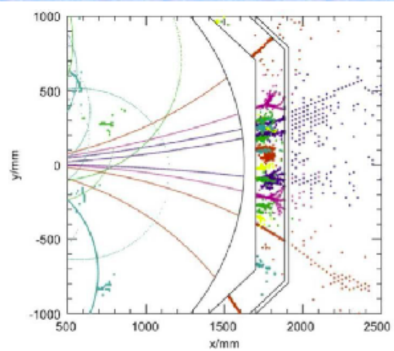
Sampling
- Imaging: Particle flow Algorithm
- Dream: Dual readout
- Sampling with Crystals shashlik

Particle Flow calorimetry

Boudry: Ultra-Granular Calorimeters for Higgs factories

CALICE collaboration : Development and study of finely segmented/imaging calorimeters

- Applicable for e+e- Higgs factories
- Multi-layer measurements of shower signal to allow precise ToF estimate of e/γ/h0
- New handle to mitigate pile-up of neutral particles

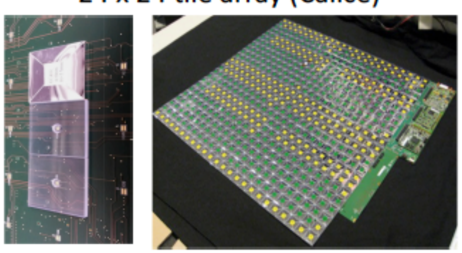


Imaging Calorimetry → high granularity (in 4D) and efficient software(PFA)

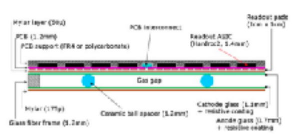
- Energy share in a typical jet: 60 % charged hadrons; 30 % photons (from $\pi 0$) 10 % neutral hadrons (mainly n, K_L)
- ParticleFlow Concept
  - Tracking for charged particles
  - ECAL for photons ($\pi 0$)
  - Neutral hadrons from HCAL
- Issues: double-counting, wrong association

ILC and CMS scintillating tiles + SiPM
- SiPM packaging for cooling performance
- radiation tolerance of organic scintillators O(1) MRad and SiPMs ~ 5×10^{13} n_{eq}/cm2

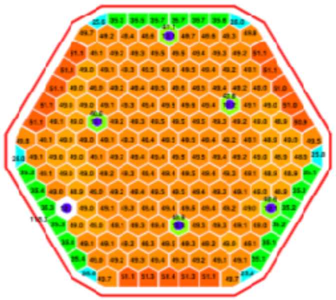
3 x 3 cm² scintillating tiles + SiPMs
24 x 24 tile array (Calice)



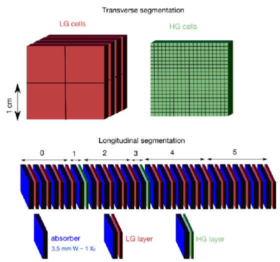
SemiDigital HCAL
-RPC as sensitive element
particle counting with 3 energy thresholds



Silicon tungsten ECAL
CMS Si-HGC
- 8” wafer sensors
- complex ASIC in 130 nm technology with 50 ps precision timing
- compactness of sensitive volume



CMOS monolithic sensors
- allow particle counting
- Focal project



Body Level One

CMS High Granularity Calorimeter for /HL-LHC

Mans: The CMS Phase 2 High Granularity 5D calorimeter
Zhang: Paving the way to reconstruct 5D HGCAL information

CMS endcap region:

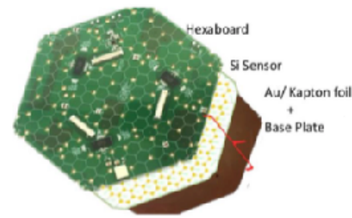
- PbWO4 crystal transmission loss due to radiation damage
- Worsening energy resolution due to increased pileup

- Build a fine segmented 'particle flow' calorimeter, ECAL + HCAL combined.
- Use Si sensors as long as radiation and particle flow requires, then switch to cheaper scintillator tiles + SiPM (à la CALICE).
  - CE-E: Si, Cu, CuW,Pb absorbers, 28 layers, 25 X0 & ~1.3λ
  - CE-H: steel absorbers, 22 layers, ~8.5λ

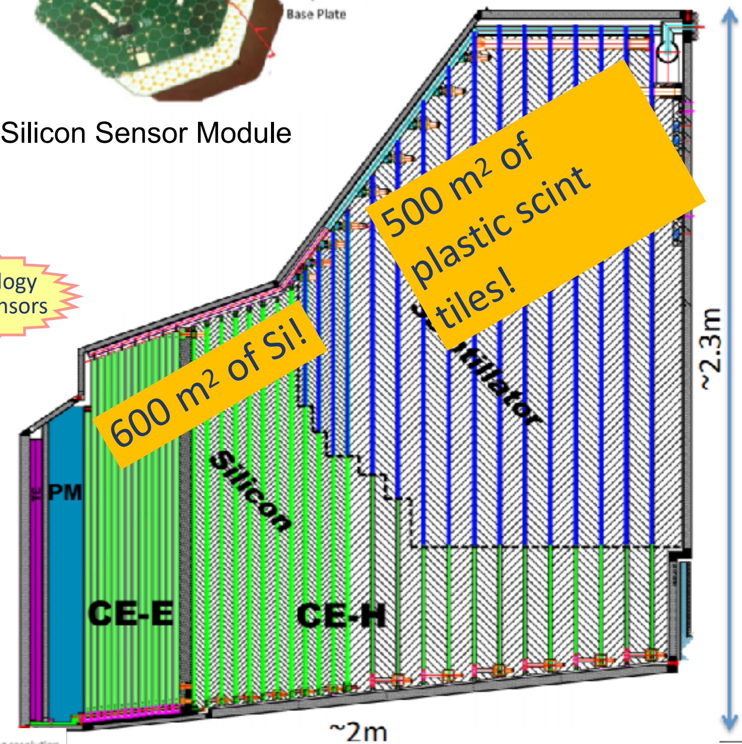
First use of 8" technology for large scale HEP sensors

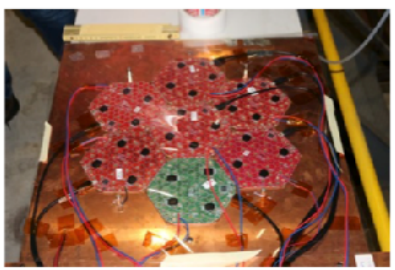
- Si pad sensors from 8" wafers. Different sensor geometries and thicknesses (300, 200, 120 μm) to get best radiation hardness.

215 ton/endcap,
full system at -30^{o}C!



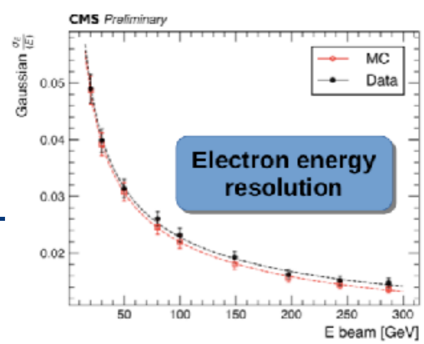
Silicon Sensor Module

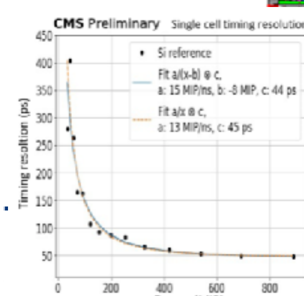




New Testbeam results

- 28 EM layers, 12 silicon HAD layers, 39 scintillator layers from CALICE AHCAL

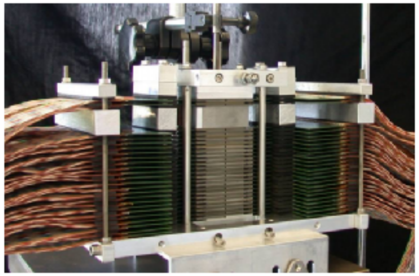




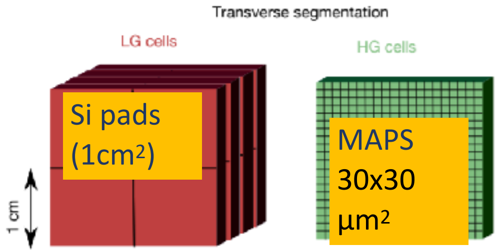
ALICE FoCal - a step further

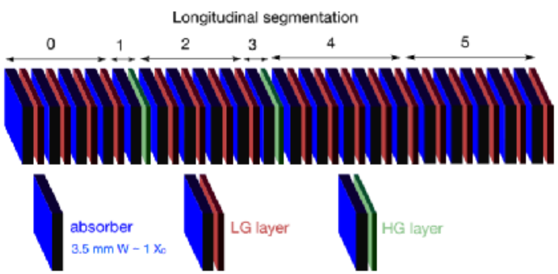
Rossi: ALICE Upgrade for LHC Run 4 & Beyond

Performance published in JINST 13 (2018) P01014



Motivation: Measure Parton Density Functions (PDF) at low parton momentum fraction by measuring the yield of direct photons at forward rapidities → Need highly granular readout and a small Molière radius





LoI: CERN-LHCC-2020-009

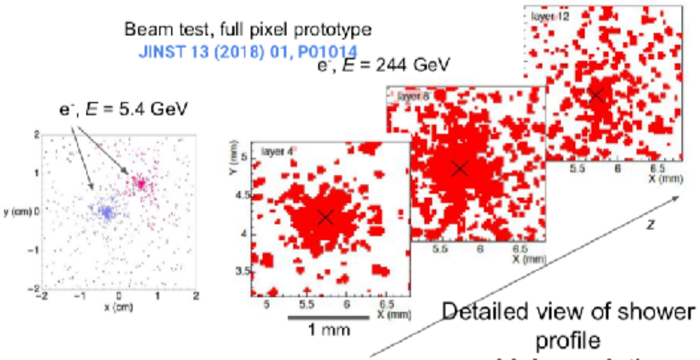
Full detector

- 1 m^2 surface

- FoCal-E: High granularity Si-W sampling calorimeter → direct γ,π^0
- FoCal-H: Pb-Sc sampling calorimeter for photon isolation and jets

Digital ECAL prototype:

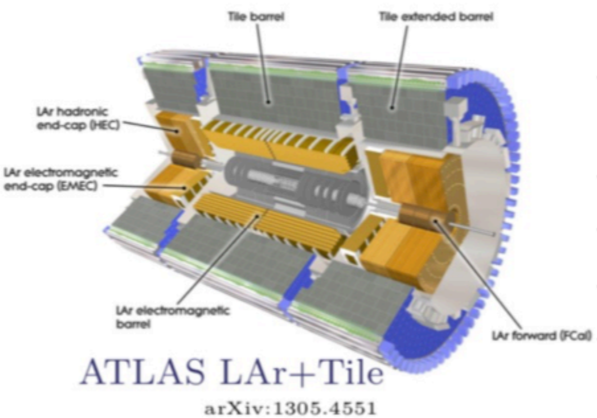
- number of pixels above threshol ~ deposited energy
- Monolithic Active Pixel Sensors (MAPS) PHASE2/MIMOSA23 wit a pixel size: 30x30 µm2
- 24 layers of 4 sensors each: activ area 4x4 cm2 , 39 M pixels
- 3 mm W absorber for 0.97 X0 pe layer R_M ~ 11 mm

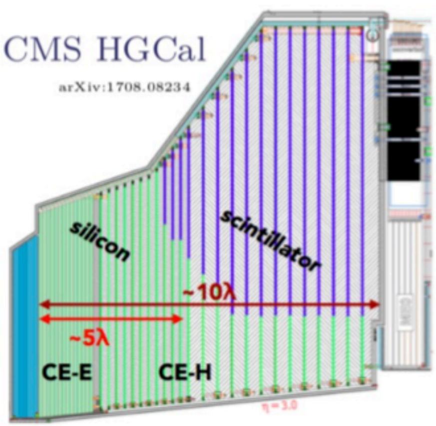


Borysova: Development and performance of compace LumiCal prototype calorimeter for future linear collier experiments

FCC-hh - SpcC collider calorimeters

Faltova: Design and performance studies of the calorimeter system for an FCC-hh experiment

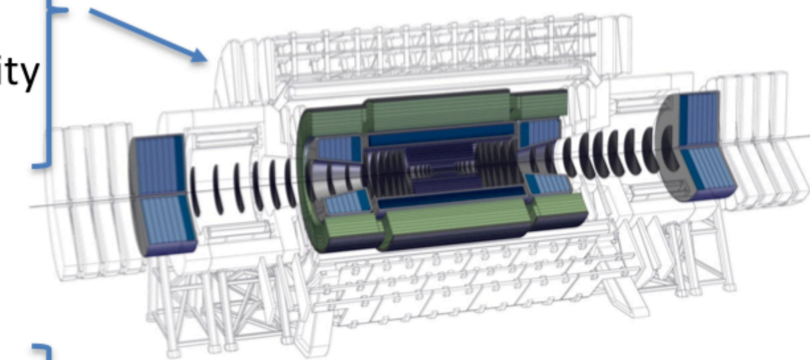




- Good instrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

- High granularity
  - → Pile-up rejection
  - → Particle flow
  - → 3D/4D/5D imaging

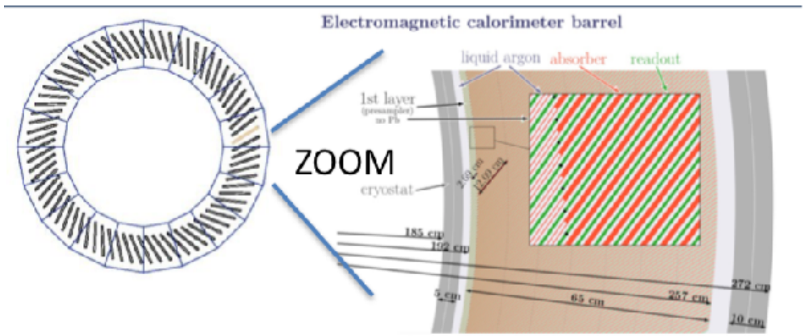
FCC-hh Calorimetry



FCC-hh - SpcC collider calorimeters

Faltova: Design and performance studies of the calorimeter system for an FCC-hh experiment

ECAL

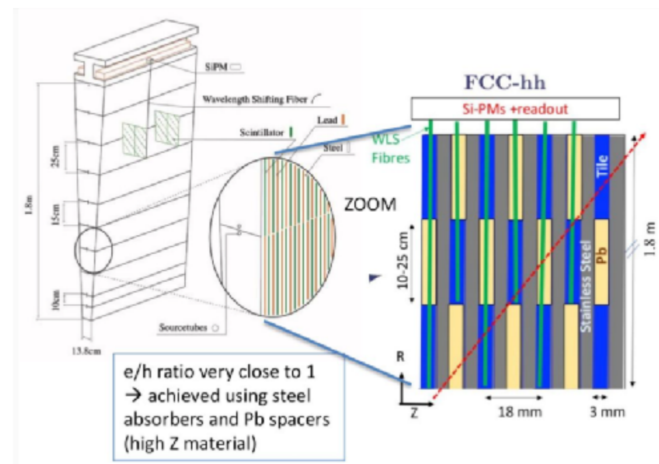


Liquid Argon calorimeter: Unique technology that can sustain expected radiation up to 5 x 10^{18} n_{eq}/cm^2 and 500 Grad; finer longitudinal and lateral granularity needed for FCC-hh

- Straight inclined structure design with 8 longitudinal segmentation Δη x Δφ ~ 0.01(0.025) x 0.01(0.025) / 10 ATLAS
- Engineering challenge to develop multilayer PCB electrodes, and high density feedthrough for readout outside the cold volume
- Interest in low mass composite cryostat
- target order 30 ps time resolution to cut down pileup

Silicon HGC could be an alternative up to η ~ 2.5

Barrel HCAL



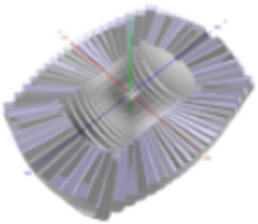
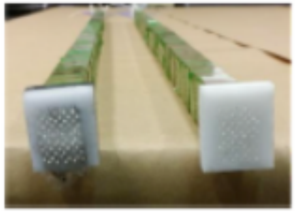
ATLAS type with scintillating tiles - steel absorbers

- High granularity Δη x Δφ = 0.025 0.025
- 10 instead of 3 longitudinal layers for a total of 0.3M channels
- WLS and SiPM readout for speed/noise/compactness

Other calorimetry R&D

Boudry: Ultra-Granular Calorimeters for Higgs factories

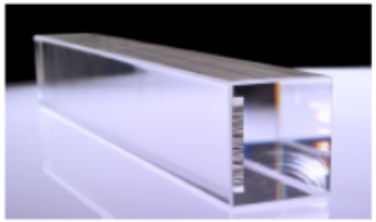
- IDEA proposal for FCC-ee and CepC
  - Dual Readout Calorimeter, based on DREAM/RD52 concept
    - 1 mm fibers Scint.*/Cerenkov with 1.5 mm pitch in PB or Cu absorber readout with SiPMs
    - 10^8 fibers 2m long (assembly challenge)
    - Longitudinal segmentation options:
      - staggered ≠ length fibers, precise timing measurement

32 + 32 scint./cerenkov fibers protoype
$\sigma(E)/E \simeq 10(30)\%/\sqrt{E} + 1\%$ for e/γ(π)

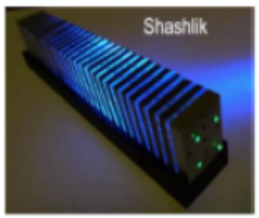
CMS homogenous $PbWO_4$ crystals + APDs

- FE ASIC ≃ 50 ps for 25 GeV



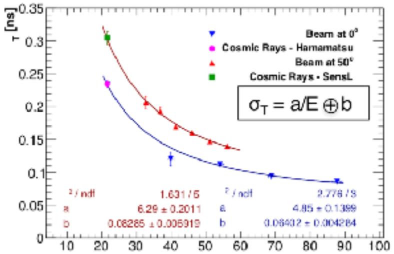
LHCb Phase-2 upgrade sampling electromagnetic crystal calorimeter

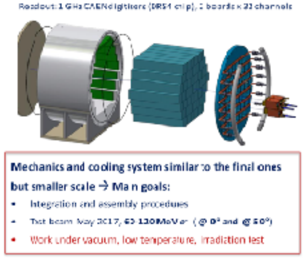
- ≃ 300 Mrad, ≃ 50 ps

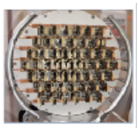


Mu2e EMCAL crystal calorimeter

- Use of 674 CsI crystals, each readout by 2 SiPMs
- Assembly ongoing; covid delay for installation
- Excellent Energy and Time response

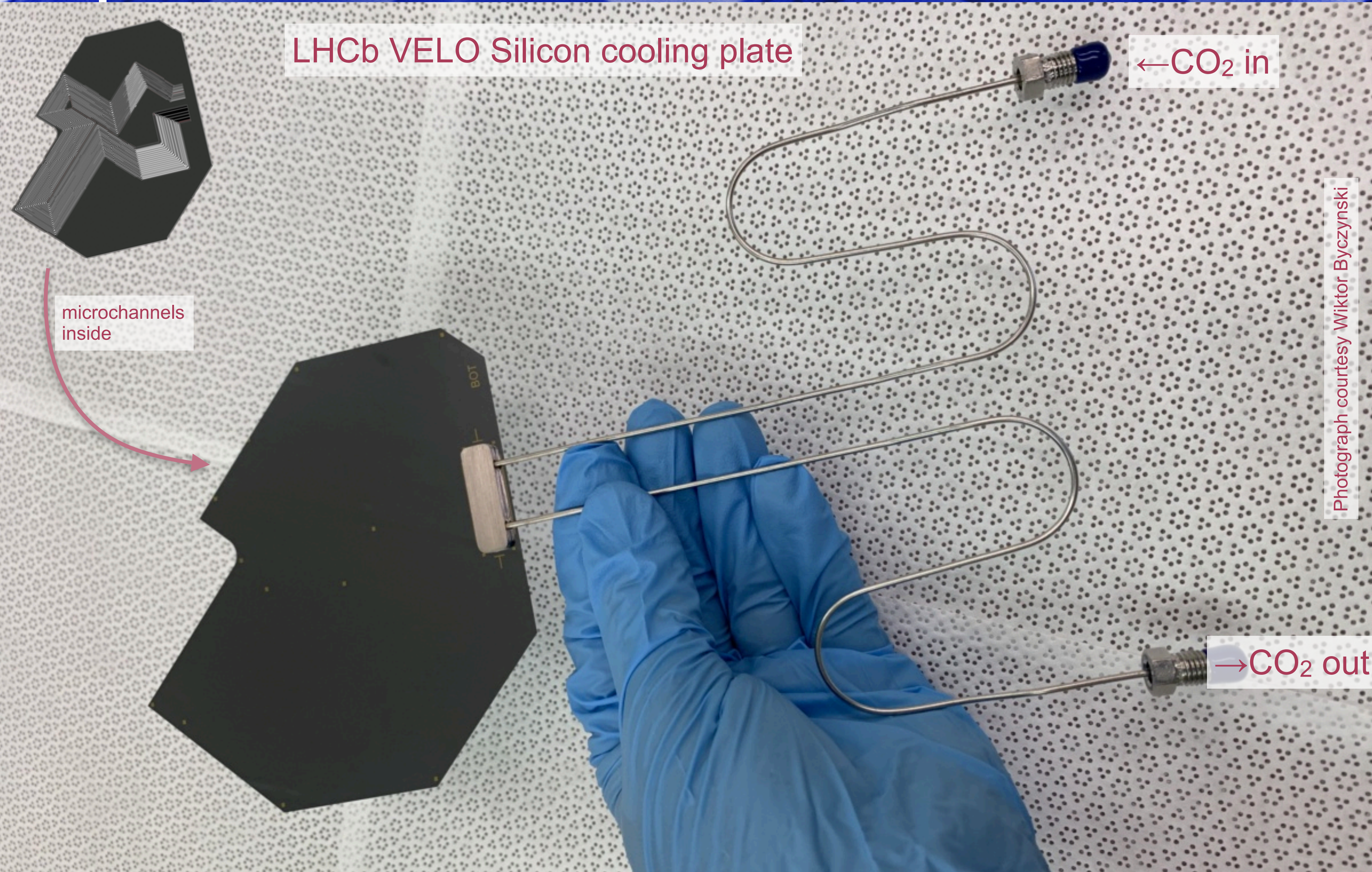







Morescalchi: Status of the Mu2e crystal calorimeter

Mechanics, Cooling, Integration



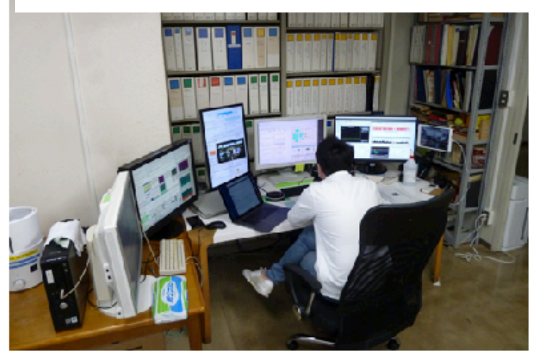
Delivering Physics in pandemic

CMS Gems

LHCb foil installation with remote technical support

ATLAS LAr, a new control room

Belle II, BESIII continued operations as scheduled, in spite of heavy load on local shifters (here the corner of a coffee room converted to remote BCG shift room)



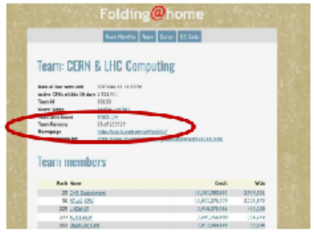
Foods and drinks

Examples of HEP labs efforts against COVID at local and international level

Computing resources to support COVID research

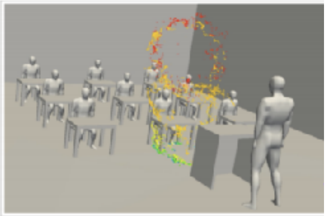
CERN open-access repository (Zenodo) used to store and share pandemic's data

Folding@Home: CERN ranking improved from 2600 to 23 (out of > 250,000 teams) in ~ 2 months



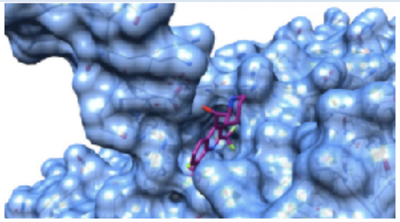
Desy: 10% of computing power provided for corona

Wide range of simulation programs running at IPNS to support COVID



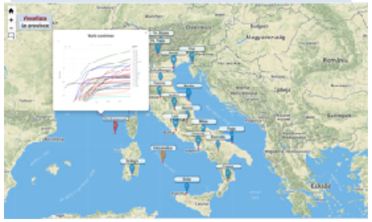
教室における飛沫飛散シミュレーションの例
（京都工芸繊維大学 山川提供）

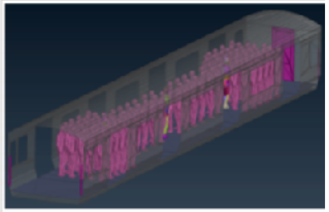
Sibylla Biotec focus ACE2 protein; INFN provides computing support for this and for Exscalate4CoV



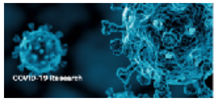
Fermilab/Brookhaven computing clusters for Open Science Grid Modelling virus - drug interactions

INFN: communication and analysis covid19.infn.it





通勤列車モデル



IPNS

… and many more…

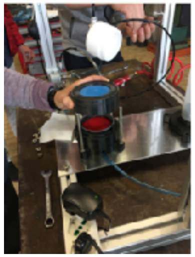
Facemasks, PPE


Près de 3 000 masques en tissu fabriqués par des bénévoles

Indvidual initiatives

INFN: 3D printing of the Charlotte Valve convert full face snorkelling masks into ventilatory support equipment

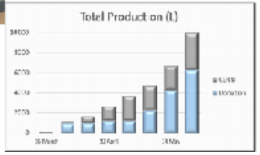
Facemasks distributed by DESY



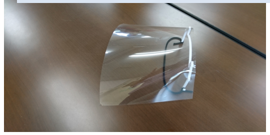
COVID lab INFN for analysis of tissue characteristics

CERN

> 10 ton of sanitising gel and > 15000 face shields produced at low cost (80% of both donated)



KEK mech eng face shields



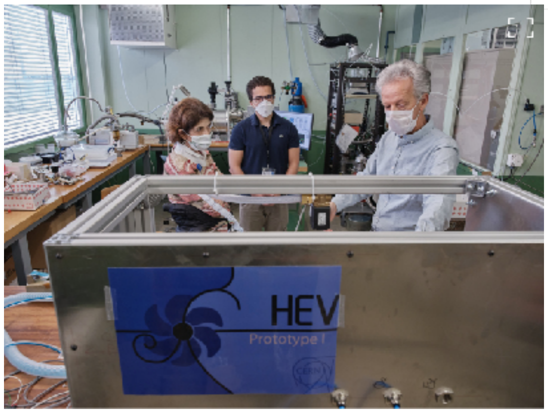
masks donated to KEK by chinese colleagues

Examples of HEP labs efforts against COVID at local and international level

Ventilatory Support for COVID-19 patients
- drawing on Detector R&D expertise in HEP, gas handling & controls
- international collaborations formed across multiple labs and with biomedical engineering and clinical partners
- address the worldwide need

HEV: Initiative from LHCb; high quality, low-cost, adaptable to low income settings

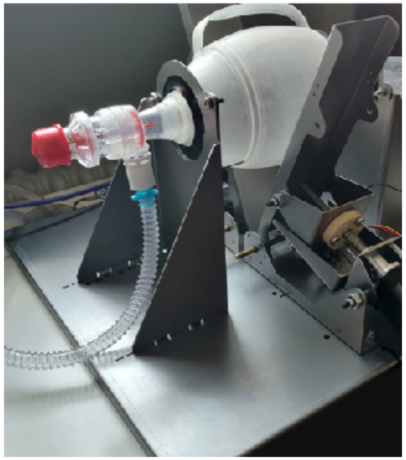
hev.web.cern.ch



mvm.care

MVM: Initiative from GADM research project; optimised to permit large-scale production in short time and limited cost; FDA emergency use authorisation

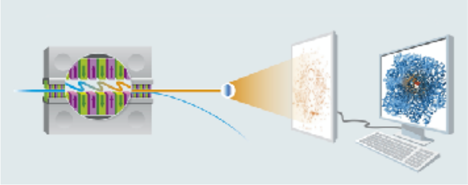
OpenBreath: Scaleable low cost ventilator based on bag valve mask, very low cost, functional, fully open source, aimed at low income settings

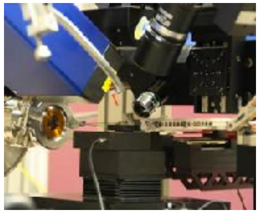


openbreath.it

X-ray synchrotron radiation

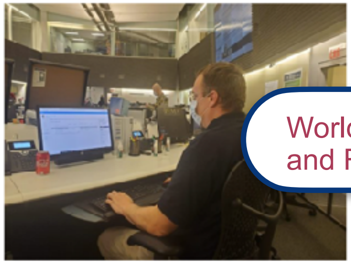
DESY/Brookhaven; X-ray structural analysis



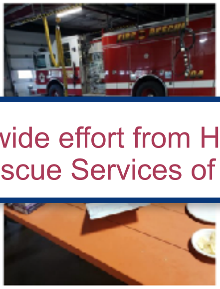


Use of Petra III Xrays to investigate drug delivery

World wide effort from Health, Fire and Rescue Services of all labs



Keenan Newton is on call at the Illinois State Emergency Operations Center. Photo: Rusty Tanton, Illinois Emergency State Agency



Lieutenant Steve Hernandez of the Fermilab Fire Department reviews information passed to him from previous shifts. Photo: Chuck Kuhn

The CERN Fire and Rescue Service at the time of COVID-19

The END

Thanks for a fascinating conference and special thanks (in chronological order) to

Maxim Titov and Petra Riedler,

Christian Joram, Eurin Guillame, Fabiola Gianotti, Neville Harnew, Roger Forty, Yutaka Ushiroda, Vit Vorobel, Marcel Demarteau, Archana Sharma, Silvia Scorza, Thomas Schwetz-Mangold, Kazu Akiba, Alain Blondel, Jochen Klein, Heinz Pernegger, Marco van Leeuwen, Giovanni Tassielli, Massi Ferro-Luzzi, William Trischuk, Jianglai Liu, Peter Svihra, Guy Wilkinson and to the many, many speakers who emailed me with additional information about their talks

Backup

Body Level One

Body Level One

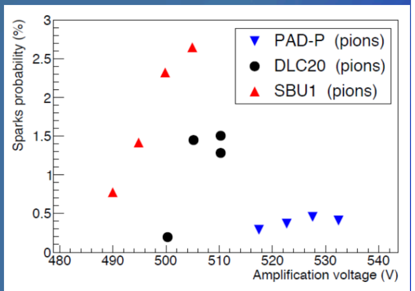
Body Level One

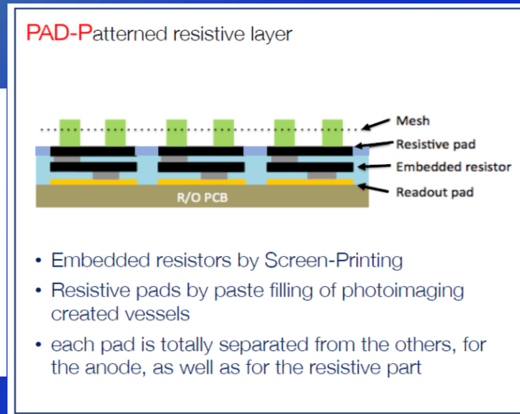
Body Level One

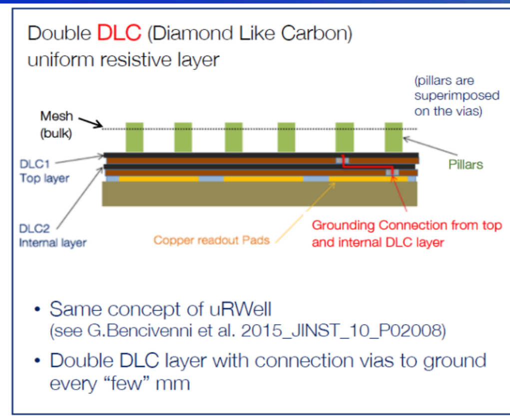
R&D on Resistive MM and μWELL for High-Rate Applications

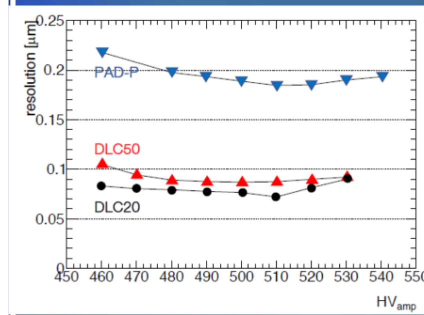
Pixelated Restitive MM Studies for high rates (~10's MHz/cm^2):

M. Iodice





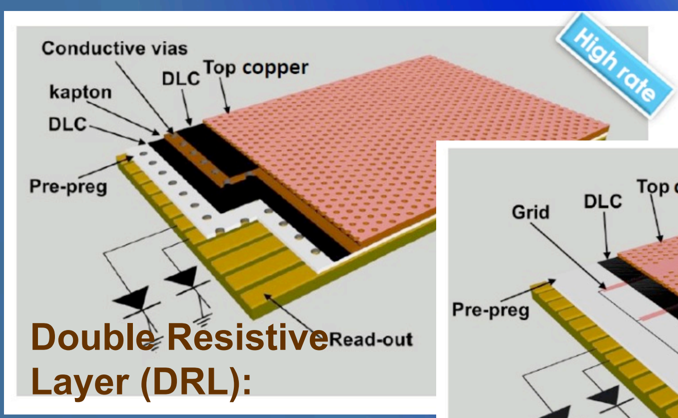


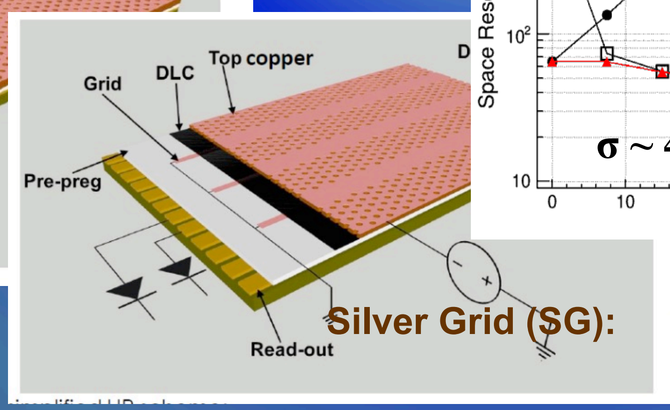


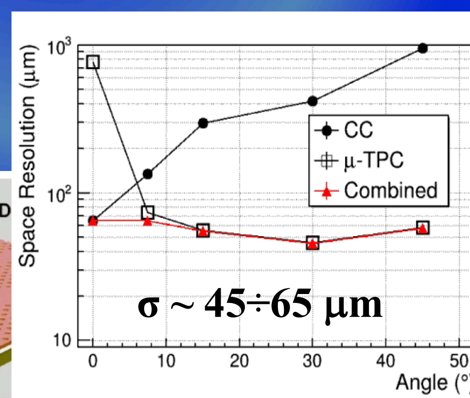
- **Quite significant charging-up that nevertheless saturate at $\mathcal{O}$(1MHz/cm2)**
- **Degraded performance on energy and spatial resolution compared to DLC**
- Best performance with the "low resistivity" DLC (~20 MW/□) and with fine network of grounding vias(~6 mm)
- Robustness not yet at the level of PAD-P à the DLC-SBU technique promising but not yet conclusive

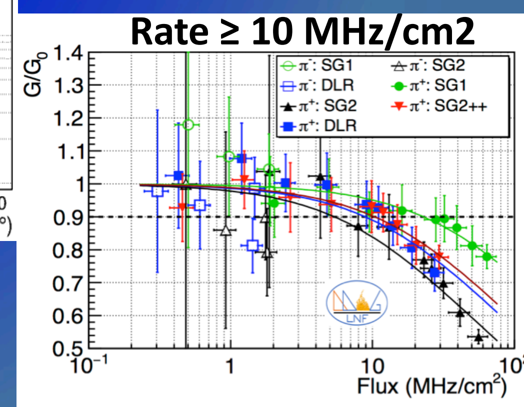
μWELL Studies for high rates (~10's MHz/cm2):

M. Giovanetti









Mechanics and Integration

Minimize material budget of pipework

Advanced powering schemes

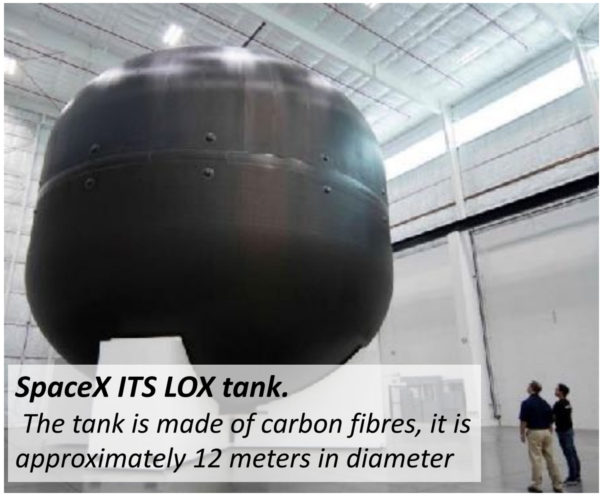
Advanced materials and integration

Heat management integrated in the detector design

simple air cooling may be possible for future lepton collider, or liquid for more complex geometry

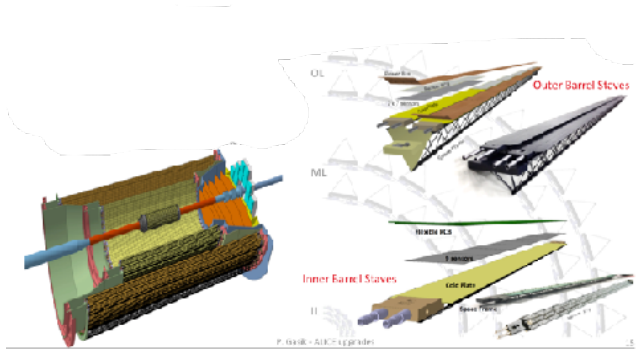
Future hadron collider; more powerful cooling and lower temperature

→CO_2/N_2O are promising coolants, which are in addition environmentally -friendly

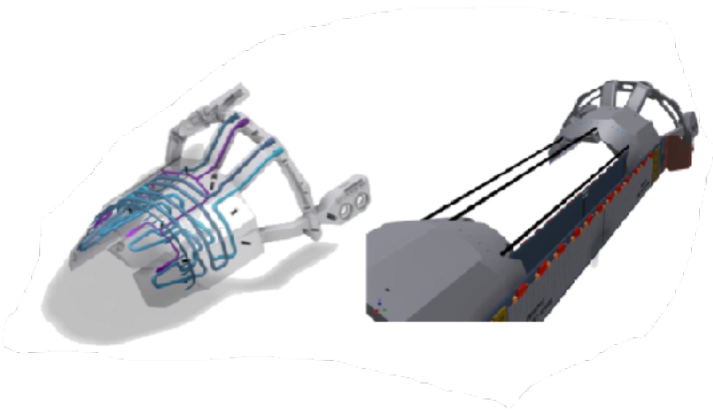


SpaceX ITS LOX tank.
The tank is made of carbon fibres, it is approximately 12 meters in diameter

ALICE advanced low mass stave supports



Belle II PXD support and cooling block (SCB) printed in stainless steel showing potential of additive manufacturing



Physics in society - greenhouse gases

GHGs like R134a ($C_2H_2F_4$), CF_4, SF6, C_4F_{10}, … are used by several particle detector systems at the LHC experiments

Use of greenhouse gases in the LHC

Four R&D lines for optimizing the use of gases
Different strategies can be combined together

Topic of high importance

- **Optimization of current technologies**: Gas recirculation; Careful operation; Leak fixing wherever possible
- **Gas Recuperation**: Recuperation of used gas
- **Abatement**: Destruction of GHGs (unsatisfactory fallback solution)
- **Alternative Gases**: New eco-friendly gases HFOs, …

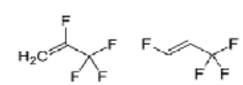
Gas	GWP - 100 years
$C_2H_2F_4$	1430
CF_4	7390
SF_6	22800

EU ’F-gas’ regulations limit their use and have an impact on their price and availability.

R134a

- By volume, R134a, is the dominant gas at CERN (RPC)
- A prototype separation plant was able to separate off R134a from RPC exhaust at perfect quality, such that it can be reinjected.
- Alternative candidate gases are available, but require lots of studies.

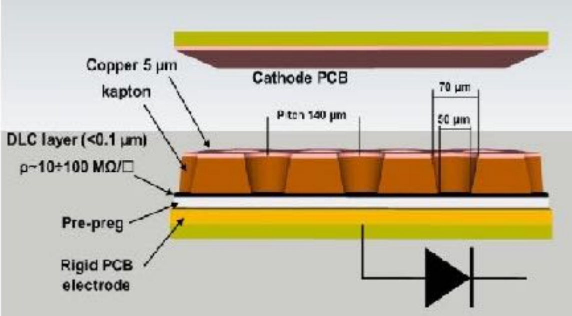
Mandelli: Performance studies of RPC with environmentally friendly gasses
Guida: Strategies for reducing the use of greenhouse gases from particle detector operation at the CERN LHC experiments



HFO1234yf ($C_3H_2F_4$) ODP 0 GWP 4
HFO1234ze ($C_3H_2F_4$) ODP 0 GWP 6

The μ-RWELL technology

The μ-RWELL



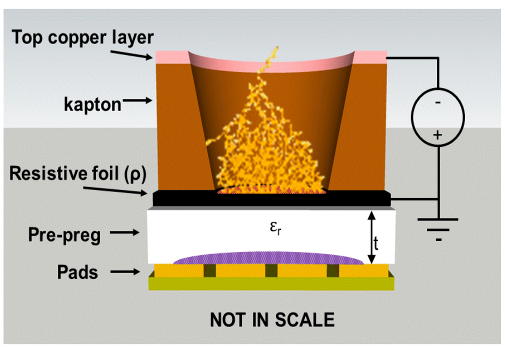
The μ-RWELL_PCB is realized by coupling:

1. a WELL patterned Apical® foil acting as amplification stage
2. a resistive layer for discharge suppression
3. a standard readout PCB

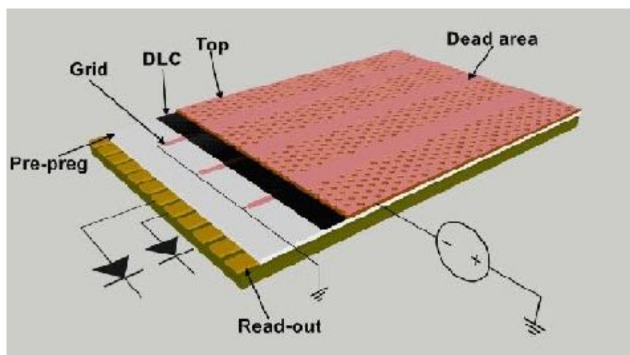
Promising MGPD technology.

Fully industrial process.
Tech. transf. to ELTOS (IT).

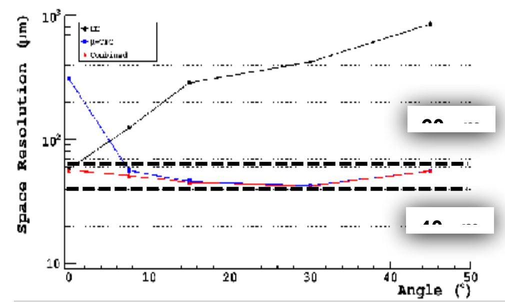
The principle of operation



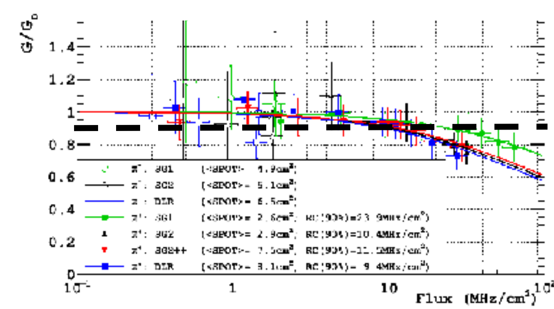
The SG high rate



Space resolution w/uTPC



Rate capability ~10 MHz/cm^2



Gain ~ 10^4

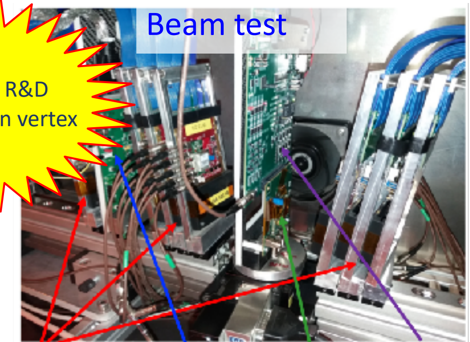
σ_t ~ 5.7 ns

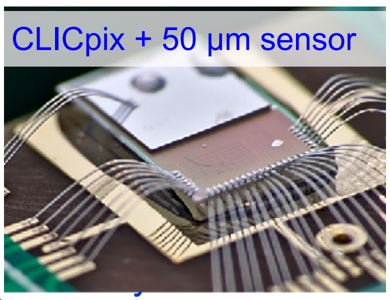
CLIC Vertex/Tracker R&D

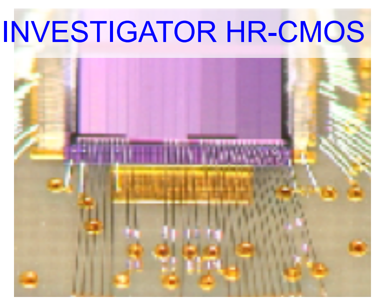
Sensor + readout technologies

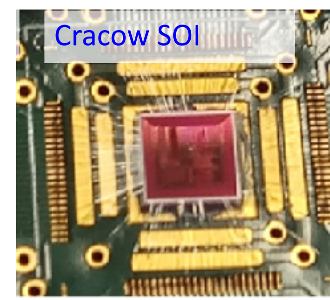
Sensor + readout technology	Currently considered for
Bump-bonded Hybrid planar sensors	Vertex
Capacitively coupled HV-CMOS sensors	Vertex
Monolithic HV-CMOS sensors	Tracker
Monolithic HR-CMOS sensor	Tracker
Monolithic SOI sensors	Vertex, Tracker

Broad and innovative R&D program on vertex detectors

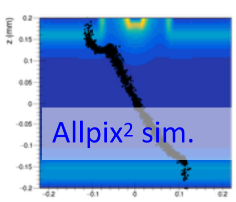


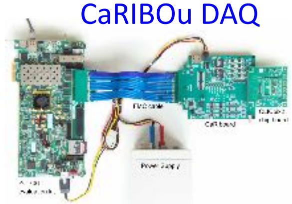




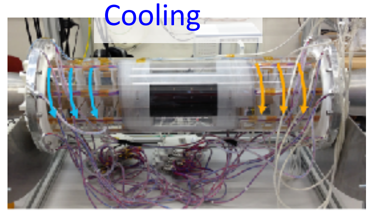


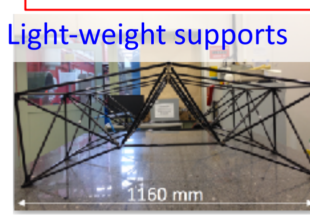
Simulation/Characterisation

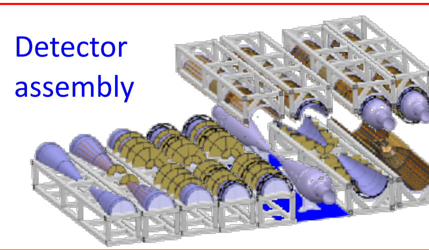




Detector integration



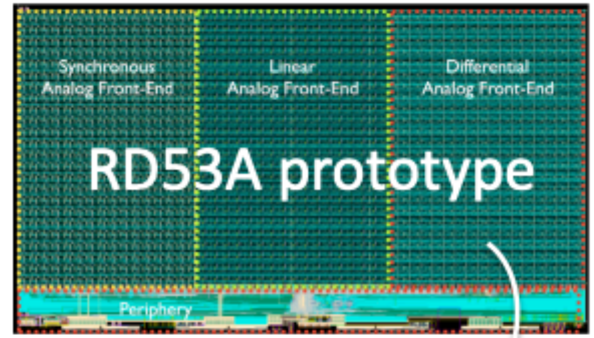




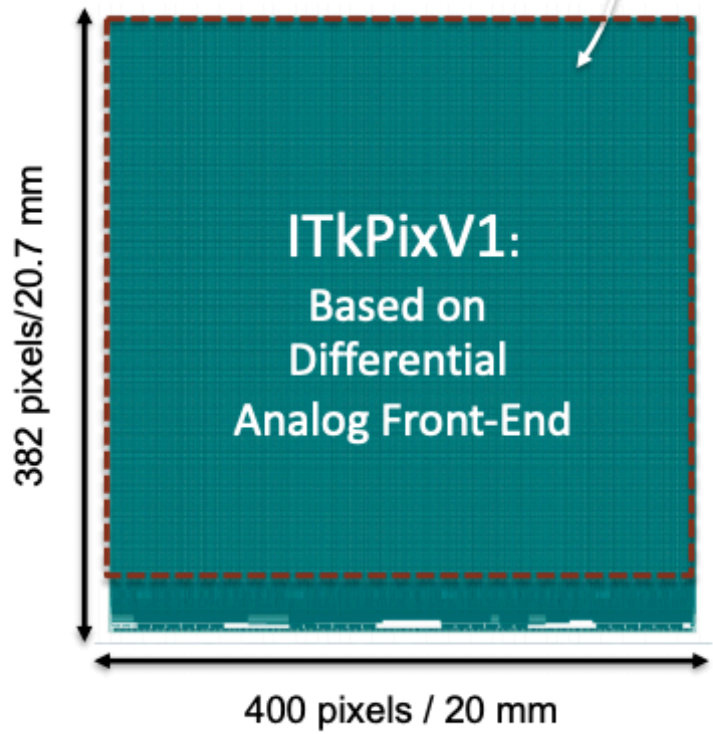
- Challenging requirements lead to extensive detector R&D program
- ~10 institutes active in vertex/tracker R&D
- Collaboration with ATLAS, ALICE, LHCb, Mu3e, AIDA-2020

A new Front End chip

- **Present RD53A large prototype in 65 nm**
  - Common ATLAS and CMS R&D
  - Small pixel size: 50 x 50 μm^2
  - Three different Analog Front End (FE)
  - Integrated shuntLDO regulators for serial powering



- **Full size chip ITkPixV1**
  - Produced in 65 nm technology
  - Radiation hard > 5 MGy (10^{16} $n_{eq}cm^{-2}$)
    - Single Event Effects (SEE) hardened
  - In time threshold < 1 ke
  - Trigger rate: 1 MHz
  - High hit rate: 3 GHz/cm^2
  - Improved shuntLDO design for serial powering
  - Data format including compression
  - Command forwarding



First ITkPixV1 chips ready for module assembly