Future Facilities and Instrumentation
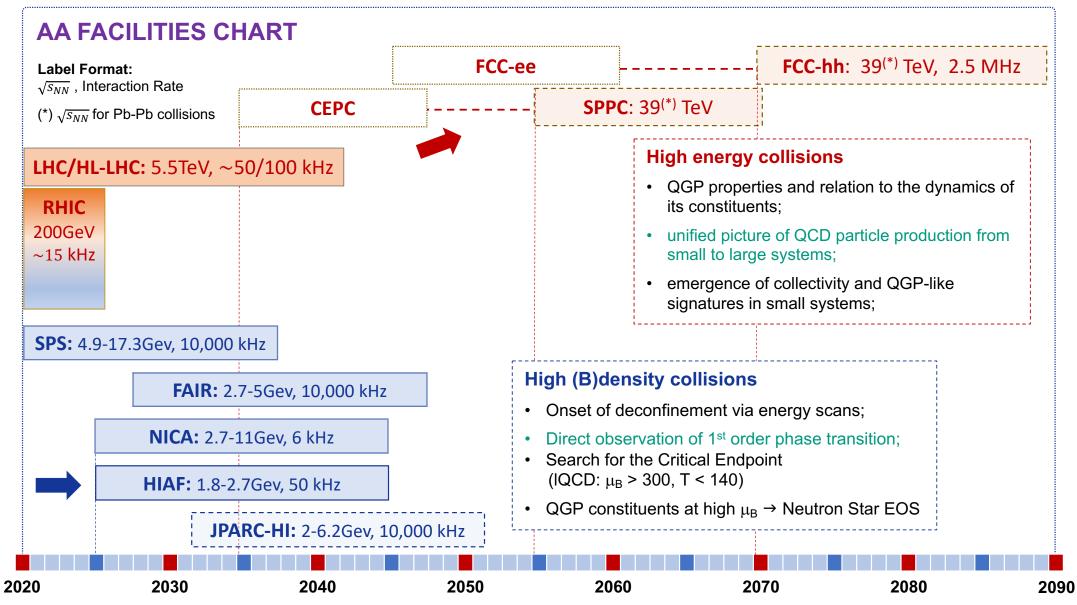
Luciano Musa (CERN)

Quark Matter 2023, Houston, 9 September 2023

The evolution of AA Facilities
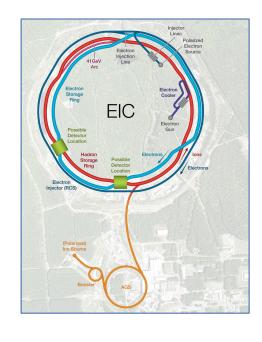
AA FACILITIES CHART

Label Format:
$\sqrt{s_{NN}}$, Interaction Rate

(*) $\sqrt{s_{NN}}$ for Pb-Pb collisions

FCC-ee

FCC-hh: 39$^{(*)}$ TeV, 2.5 MHz

CEPC

SPPC: 39$^{(*)}$ TeV

LHC/HL-LHC: 5.5TeV, ~50/100 kHz

RHIC
200GeV
~15 kHz

SPS: 4.9-17.3Gev, 10,000 kHz

FAIR: 2.7-5Gev, 10,000 kHz

NICA: 2.7-11Gev, 6 kHz

HIAF: 1.8-2.7Gev, 50 kHz

JPARC-HI: 2-6.2Gev, 10,000 kHz

High energy collisions

- QGP properties and relation to the dynamics of its constituents;
- unified picture of QCD particle production from small to large systems;
- emergence of collectivity and QGP-like signatures in small systems;

High (B)density collisions

- Onset of deconfinement via energy scans;
- Direct observation of 1st order phase transition;
- Search for the Critical Endpoint (lQCD: μ_B > 300, T < 140)
- QGP constituents at high μ_B → Neutron Star EOS

2020   2030   2040   2050   2060   2070   2080   2090

Future e-A colliders

e-p/A colliders for precision studies of cold-QCD

Facility	Years	E_{cm} (GeV)	Luminosity (10^{34} cm^{-2} s^{-1})	Ions	Polarization
EIC in US	> 2033	20–100 ➔ 140	0.2 – 3	p ➔ U	e, p, d, ^{3}He, Li
EicC in China	> 2032	16 – 34	0.1 -> 10	p ➔ Pb	e, p, light nuclei
LHeC	> 2035	200 - 1300	1	p ➔ Pb	e
FCC-eh	> 2070	3500	1.5	p ➔ Pb	e

EIC in the US is at an advanced stage of approval

EicC in China: CDR in 2023 (aim at approval @ 15th 5-year plan – 2026 ->)
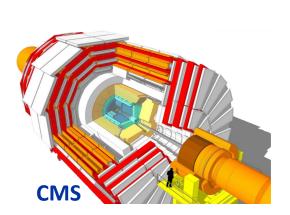
- Mass, spin and other emergent properties of nucleons from the dynamics of their constituents (quarks and gluons)

- Emergent properties of high-density gluon matter

- Nuclear structure
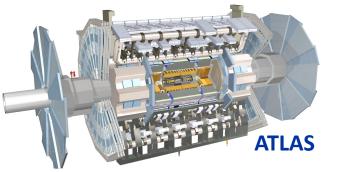
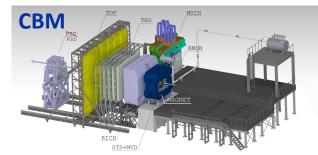explore QCD landscape over a large range of resolution (Q^2) and quark/gluon density (x^{-1})

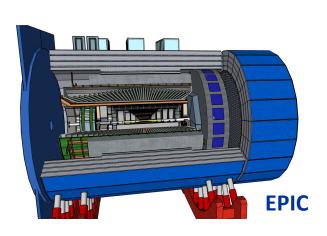# Advancing boundaries with innovative detectors
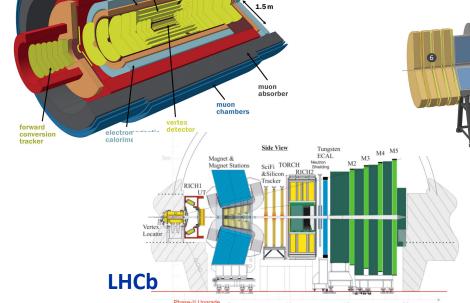
higher precision, faster and more intelligent

High-E AA Colliders: RHIC, LHC, SppC/FCC-hh

Facility	RHIC	LHC/HL-LHC	SppC / FCC-hh
Timeline	→ 2025	→ 2041 (Runs 3 to 6)	> 2035 / > 2070
Collision system	pp, d-Au, Au-Au	pp, p-Pb and A-A (Pb-Pb, ^{16}O, ^{129}Xe, ^{84}Kr, ^{40}Ar, ...)	FCC: pp, p-A and A-A (Pb-Pb, ^{129}Xe, ^{84}Kr, ^{40}Ar, ...)
$\sqrt{s_{NN}}$ (TeV)	0.2	5.5	~39
Int. rate (kHZ)	~15 (Au-Au)	≳50 (x 3-4 in Run5) for Pb-Pb	~2500 (FCC)
Experiments	sPHENIX, STAR	ALICE, ATLAS, CMS, LHCb phase II of ATLAS and CMS **phase II-b of ALICE and LHCb**	up to four experiments

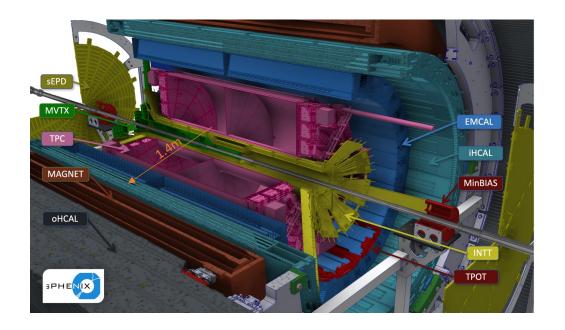An Upgrade Proposal from the PHENIX Collaboration (arXiv:1501.06197)

Physics opportunities for high-density QCD at the LHC with HI and p beams in Runs 3-4 (arXiv: 1812.06772)

ALICE 3 – A next generation HI experiment at the LHC (arXiv:2211.0249)

FCC/SppC open new opportunities (CYRM-2022-002, CEPC-SPPC CDR)
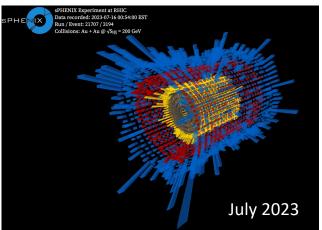
RHIC - sPHENIX

- 1.4 T superconducting solenoid
- Hermetic coverage $|\eta| < 1.1$
- Excellent vertexing (CMOS pixels)
- High-precision tracking
- Large-acceptance ECal + HCal
- High data rates: 15 KHz
- Trigger capability also with streaming readout

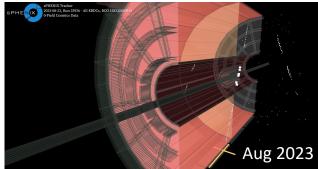sPHENIX: new state-of-the-art jet detector (arXiv1207.6378)

⇨ **focus on jets, quarkonia and other rare processes**

- installation completed and commissioning in 2023
- first physics run in 2024

July 2023

June 2023

Aug 2023

LHC long-term programme

LHC is starting the (HI) high-luminosity era (x6 luminosity)
⇨ start of first (long) Pb-Pb run imminent!

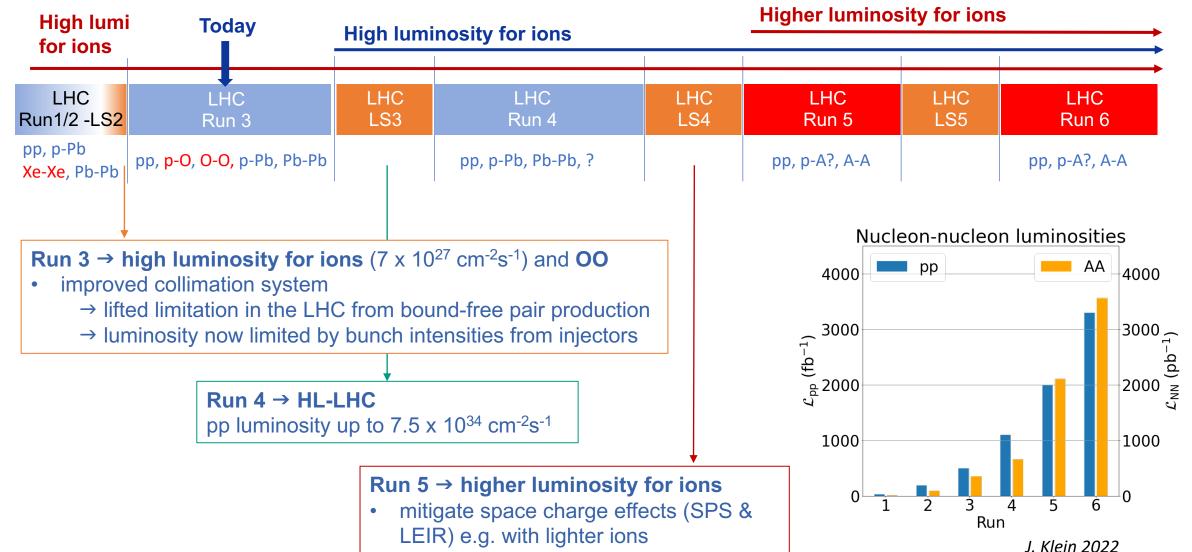Upgrades of the accelerator and the experiments planned for installation in **2026-2028**

- HL-LHC (pp): x O(10) wrt to LHC design luminosity
- major upgrades of **ATLAS** and **CMS**
- small upgrades of **ALICE** and **LHCb**

Planned for **2033-2034**: completely **new ALICE** (ALICE 3) and **new LHCb** (LHCb-II)

High lumi for ions		Today				High luminosity for ions								Higher luminosity for ions							
LHC LS2		LHC Run 3				LHC LS3			LHC Run 4				LHC LS4		LHC Run 5			LHC LS5		LHC Run 6	
2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041

LHC programme

High lumi for ions

Today

High luminosity for ions

Higher luminosity for ions

LHC Run1/2 -LS2	LHC Run 3	LHC LS3	LHC Run 4	LHC LS4	LHC Run 5	LHC LS5	LHC Run 6

pp, p-Pb
Xe-Xe, Pb-Pb

pp, p-O, O-O, p-Pb, Pb-Pb

pp, p-Pb, Pb-Pb, ?

pp, p-A?, A-A

pp, p-A?, A-A

Run 3 → high luminosity for ions (7×10^{27} cm^{-2}s^{-1}) and **OO**
- improved collimation system
  - → lifted limitation in the LHC from bound-free pair production
  - → luminosity now limited by bunch intensities from injectors

Run 4 → HL-LHC
pp luminosity up to 7.5×10^{34} cm^{-2}s^{-1}

Run 5 → higher luminosity for ions
- mitigate space charge effects (SPS & LEIR) e.g. with lighter ions

Nucleon-nucleon luminosities

J. Klein 2022

High-rate challenges

Extreme interaction and particle rates: PU ≈ 200 (8×10^9 event/s), particle rate up to 3GHz/cm^2

⇨ Higher granularity and resolution (especially in the silicon trackers)

⇨ Track or hit high-precision timestamping ("4D tracking")

⇨ extreme rad-hard (@ 30 mm, after 3000 fb^{-1}): NIEL ≈ 2×10^{16} n / cm^2 TID ≈ 12 MGy

⇨ Extreme data throughput: unprecedented challenges for trigger and online data processing

LHC Bunch Crossing 1ns Clip

from Chris Tully, Princeton University, HCP Summer School 2016

CMS Simulation			
<μ>	4D Merged Vertex Fraction	3D Merged Vertex Fraction	Ratio of 3D/4D
50	0.5%	3.3%	6.6
200	1.5%	13.4%	8.9

from Chris Tully, Princeton University, HCP Summer School 2016

HL-LHC ⇨ ATLAS and CMS upgrades
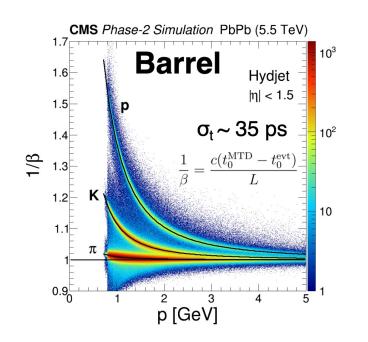
- Larger tracker acceptance: from $|\eta| < 2.5$ to $|\eta| < 4$
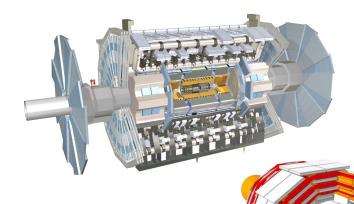
- Timing detectors for pile-up rejection:
  - $2.5 < |\eta| < 5$ for ATLAS
  - $|\eta| < 4$ for CMS (TOF PID)

- Endcap calorimeter higher granularity

- Muon ID up to $|\eta| < 2.8$ • HL-ZDC

- Trigger and DAQ improvements

CMS *Phase-2 Simulation* PbPb (5.5 TeV)

Barrel

Hydjet
$|\eta| < 1.5$

$\sigma_t \sim 35$ ps

$$\frac{1}{\beta} = \frac{c(t_0^{\mathrm{MTD}} - t_0^{\mathrm{evt}})}{L}$$

MIP Timing Detector (MTD)
- barrel: LYSO + SiPMs
- endcaps: LGADs
- $\sigma_{\mathrm{TOF}} \approx$ **30ps**

CMS BW for MB events: 2018: 6GB/s (8.8 kHz)   Run3: 17 GB/s (25 kHz)   Run4: 51GB/s (> 50kHz)
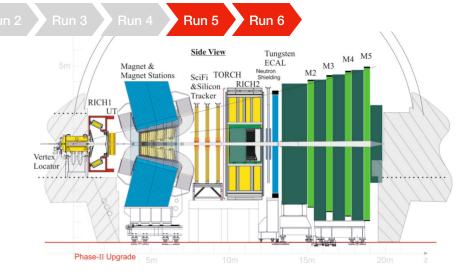
LHCb Phase II Upgrade

LHCb-PUB-2022-012

Upgrade II

- L_{peak} = 1.5x10^{34} cm^{-2} s^{-1}

- L_{int} ≈ 300fb-1 during Run 5 & 6
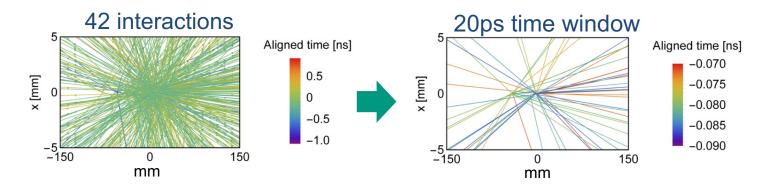
General purpose flavour physics facility … but also a general purpose **heavy-ion experiment** for pA and AA in forward rapidity

- no centrality limitations for AA   48 interactions
- excellent vertexing and PID

Targeting same performance
in Run 3, but with pile-up ~4

20ps time window
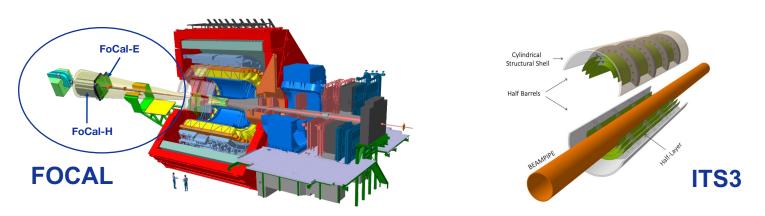
Key ingredients: granularity, f   radiation hardness

Fixed Target: possible extension with polarized gas target, solid target

Single Pixel V$_{bias}$ = −150V - 2.5e^{6}neq/cm^2

ALICE Phase II Upgrade
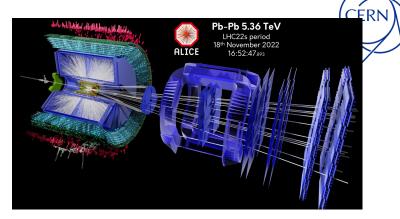
Major ALICE upgrade in LS2 (**ALICE 2**) for Run 3 & Run 4

continuous readout (all events @50kHz) + x3 improved vertexing
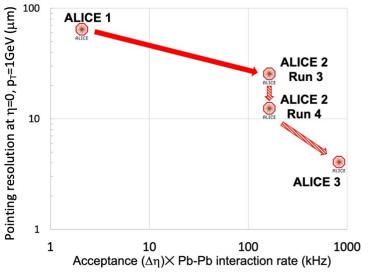
Intermidiate (narrow scope) upgrades in LS3 (**ALICE 2.1**)

FOCAL

ITS3

• Letter of Intent for **ALICE 3** (LoI Mar '22)

2010-2012		2015-2018		2022-2025		2029-2032		2035-2037		
Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

ALICE 1   phase I upg   **ALICE 2**   **Phase IIb Upg**   **ALICE 3**

ALICE 3: an all-silicon detector

high-efficiency for reconstruction of (multi-)HF hadrons and of low-mass dielectrons
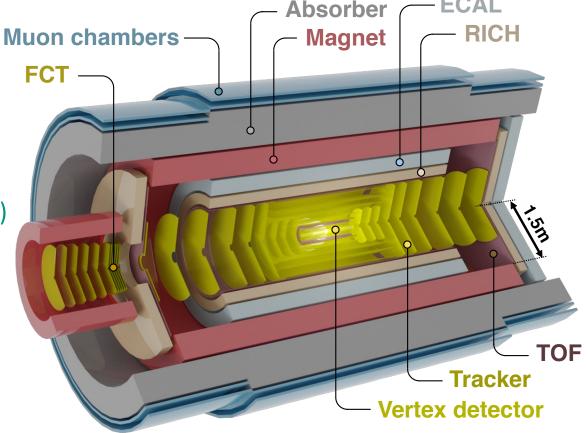
vertexing inside the beampipe with unprecedentedly low material budget

large acceptance with excellent coverage down to low p_T

excellent particle ID (muons, electrons, photons, hadrons)

⇨ **Vertexing precision**: 10μm at $p_T = 200$ MeV

⇨ **Acceptance**: $|\eta| < 4$ (with particle ID)

⇨ **A-A (pp) rates:** up to 1 MHz (25 MHz)
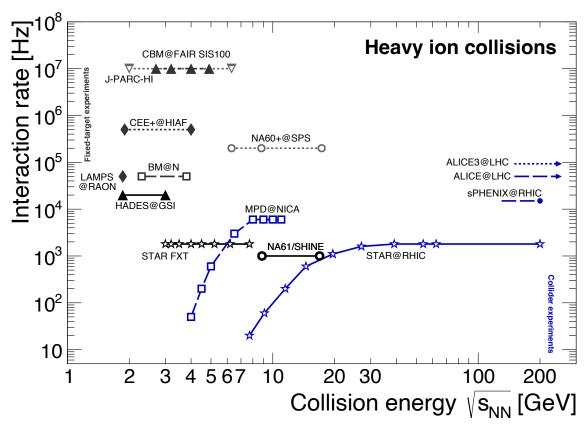
⇨ **novel technologies: MAPS, CMOS LGAD, combined TOF+RICH**

Muon chambers · FCT · Absorber · Magnet · ECAL · RICH · 1.5m · TOF · Tracker · Vertex detector

High baryon density facilities

Systematic exploration of high μ_B region

T. Galatyuk, NPA 982 (2019), update Aug 2023 (GitHub link)

Experimental approach

- probe with highest precision different regions of the QCD matter phase diagram

Observables

- Flavour production (multi-strange, charm)
- Dileptons (emissivity of matter)
- e-by-e correlations and fluctuations
- collective effects

$2.5 < \sqrt{s_{NN}} < 8$ Gev – key region for 1st order phase transition and Critical Point search
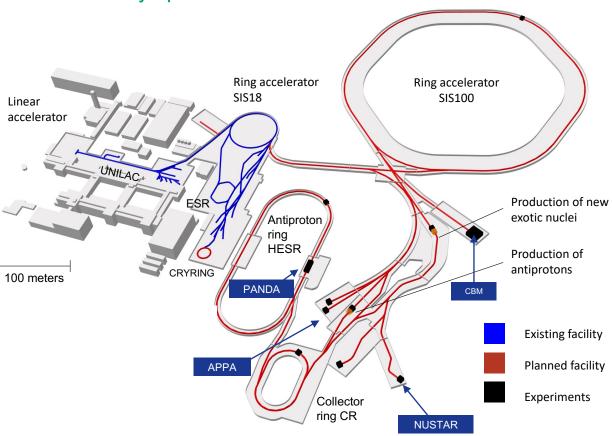
Facilities: BNL-RHIC, CERN-SPS, FAIR-SIS100, JINR-NICA, J-PARC, HIAF

FAIR Facility

FAIR (Facility for Antiproton and Ion Research in Europe)

- Ion beams up 11 AGeV
  - ⇨ cme for Au-Au up to 4.9 AGeV

- Ion intensity up to 10^9/s

Linear accelerator

UNILAC

ESR

CRYRING

Antiproton ring HESR

PANDA

APPA

Collector ring CR

NUSTAR

Ring accelerator SIS18

Ring accelerator SIS100

100 meters

Production of new exotic nuclei

Production of antiprotons

CBM

Existing facility

Planned facility

Experiments

Four Pillars

- **CBM – Compressed Baryonic Matter**

- NUSTAR – Nuclear Struc, Astroph., Reac.
- PANDA – Antiproton Annihilation
- APPA – Atomic, Plasma Physics and Appl.
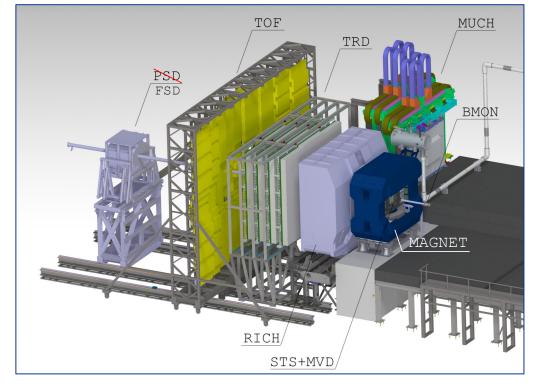
Modularized Start Version (MSV)

FAIR 2028: will feature a large part of the programe (First Sicence +), including **CBM**

CBM Experiment

TOF
TRD
MUCH
PSD
FSD
BMON
MAGNET
RICH
STS+MVD

CBM Cavern

CBM Building
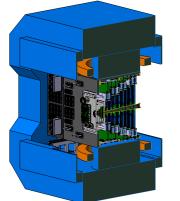
Hadrons, dielectrons and dimuons, charm

Interaction rates up to 10MHz ($\sqrt{s_{NN}}$: 2.7 – 5 GeV)
dead-time free continuous readout, online event selection
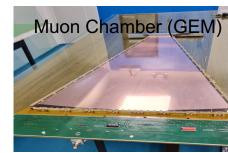
2028: commissioning with SIS100 beam

MVD: MIMOSIS

STS: Si STRIPS

eTOF@STAR (MRPC)

TRD

Muon Chamber (GEM)

NA60+ Experiment
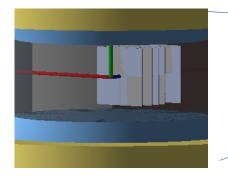
Beam energy scan ($\sqrt{s_{NN}}$: 6.3 – 17.3 GeV) for precision studies of: hard processes, electromagnetic

Roadmap
- Technical proposal: **2024-2025**
- Constr. & Installation: **2026-2028**
- Data taking: **2029 - 2037**
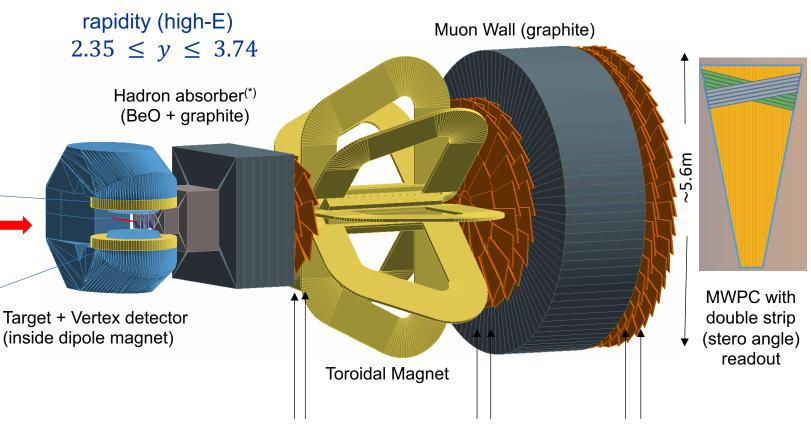
EoI in 2019 https://cds.cern.ch/record/2673280
LoI in 2022 CERN-SPSC-2022-036 ; SPSC-I-259

follows design of NA60 but with better-performing detectors

rapidity (high-E)
$2.35 \leq y \leq 3.74$

Muon Wall (graphite)

Hadron absorber[(*)]
(BeO + graphite)

~5.6m

MWPC with double strip (stero angle) readout

Target + Vertex detector (inside dipole magnet)

Toroidal Magnet
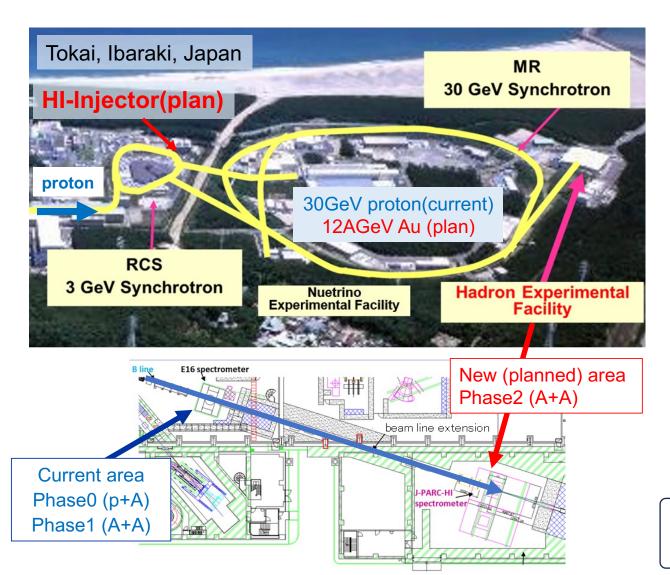
Muon Spectrometer (6 stations) on rails to adjust position depending on energy

5-plane vertex detector based on MAPS (ALICE ITS3)
- Spatial resolution: 5μm
- X/X₀: 0.1% /plane

X/X_0: 0.1% /plane

Muon tracking stations: MPGD (GEM, MicroMeagas) or **MWPC** (baseline) with total active area $100 m^2$, spatial resolution (radial direction) $\sim 200 \mu m$, max particle flux $\sim$ kHz/cm^2

J-PARC-HI Project

J-PARC-HI

fixed target A+A experiment with high intensity HI beam

Phase 0: $\sim 10^{10}$ Hz 30GeV p beam vetor meson via dielectron decay
current status: commissioning

Phase1: 12 AGeV Au beam, $\sim 10^8$ Hz, dielectrons

Phase2
- 12 AGeV Au beam, $\sim 10^{11}$Hz(!)
- multiple probes
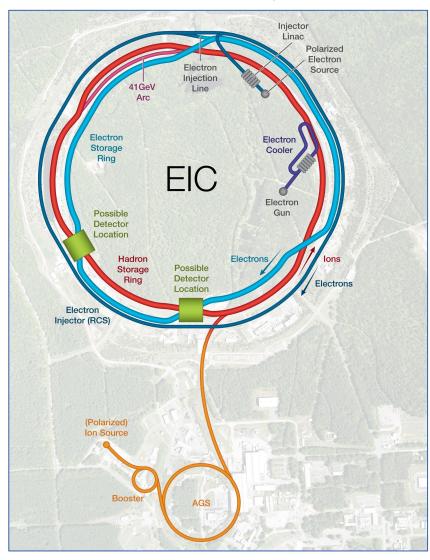
Pending funding approval by KEK and JAEA, Phase 1 could start in 2031/2032

The Electron Ion Collider (EIC)

Electron Ion Collider Scope

- High Luminosity: $10^{33} - 10^{34}$ cm^{-2} sec^{-1}, 10 – 100 fb^{-1}/year

- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV

- Highly Polarized Beams: 70%

- Large Ion Species Range: protons – Uranium

> Similar but more challenging than the FCC-ee (2x e$^-$ current)

p: 41 GeV, 100 to 275 GeV → p/A beam ⟶ e beam ← e: 5 GeV to 18 GeV

Accelerator system
Construction phase [(*)] : 2026 – 2030   Science Phase: 2035

Detector #1 (Project Detector)
Construction phase: 2024 – 2031

Detector #2
Construction phase: 2028 – 2034
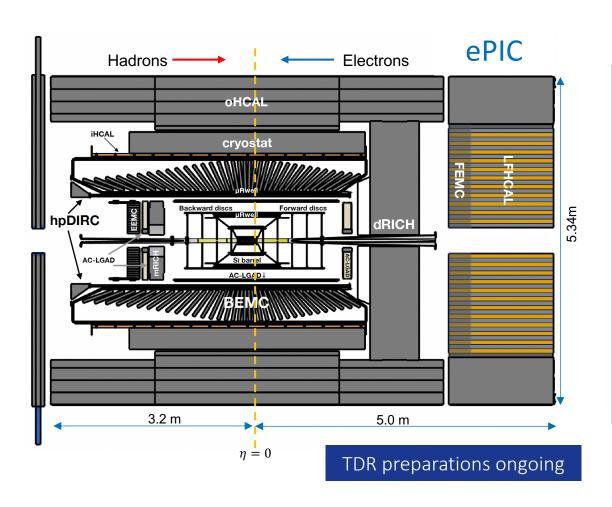
[(*)] *Construction: procurement, fabrication, installation, test*

EPIC - EIC First Detector

- 2020 – 2021: EICUG Yellow Report

- Mar 2021: call for proposals

- Mar 2022: **ECCE** chosen <u>as reference</u> design for detector 1

- July 2022: ePIC Collaboration

ePIC

TDR preparations ongoing
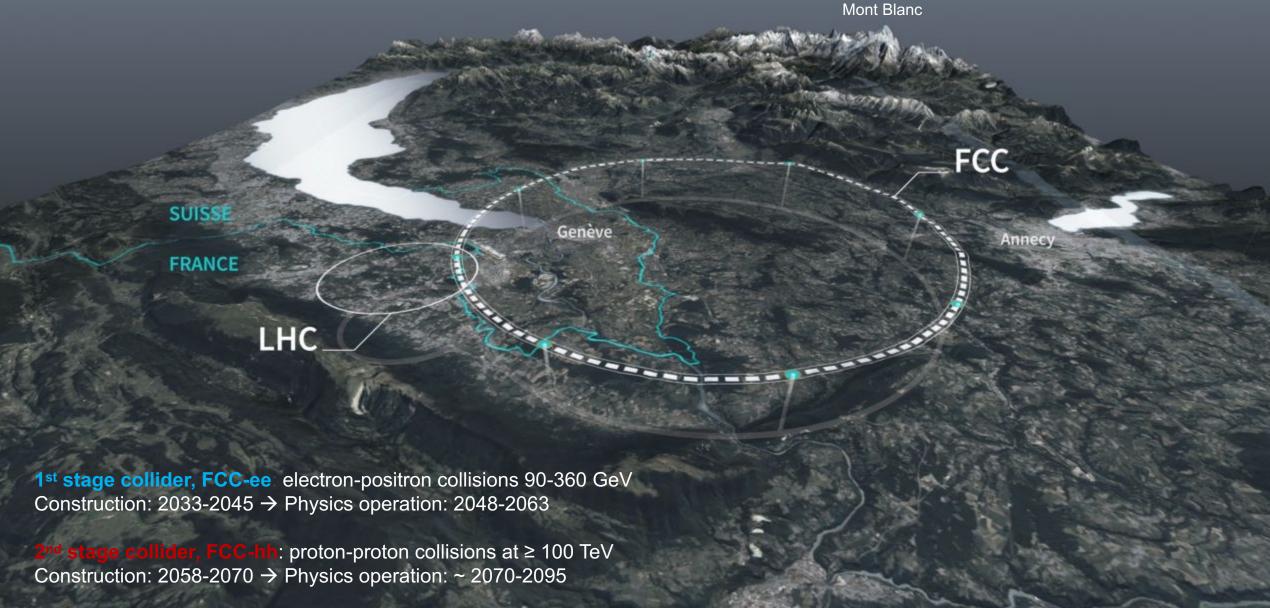
- Large rapidity ($-4 < \eta < 4$) coverage

- High precision low mass tracking
  - new 1.7T magnet, MAPS + MPGD

- Electromagnetic and Hadronic Calorimetry
  - e-side: $PbWO_4$ EMCal   h-side: finely segmented
  - barrel: imaging EMCal   outer barrel HCal

- High performance PID to separate π, K, p on track level
  - also need good e/π separation for scattered electron
  - AC-LGAD TOF, pfRICH, hpDIRC, dRICH

- Many other ancillary detectors integrated in the beam line: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter

Integration into Interaction Region ($\pm$40m) is critical

The Future Circular Collider (FCC)
A new 91 km tunnel to host multiple colliders

Mont Blanc

FCC

SUISSE

FRANCE

Genève

Annecy

LHC

1st stage collider, FCC-ee: electron-positron collisions 90-360 GeV
Construction: 2033-2045 → Physics operation: 2048-2063

2nd stage collider, FCC-hh: proton-proton collisions at ≥ 100 TeV
Construction: 2058-2070 → Physics operation: ~ 2070-2095
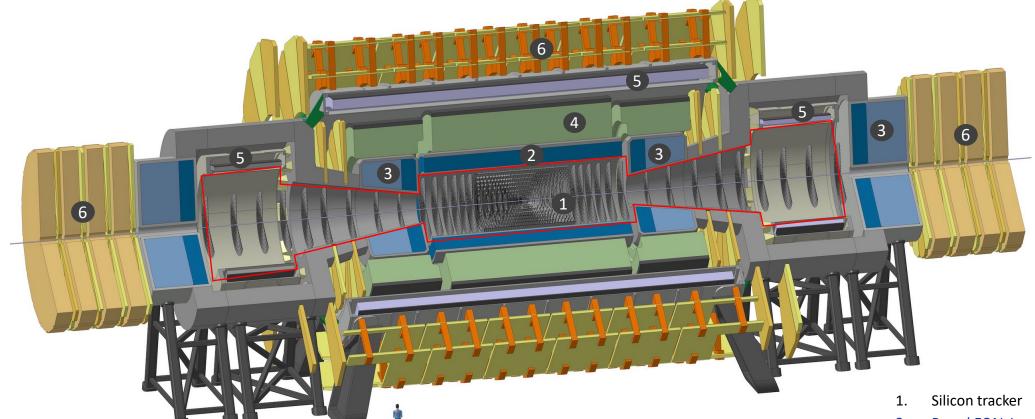
FCC-hh reference detector

Silicon Tracker (400 m^2) covering |η| < 6

Solenoid magnets: **B = 4T**

50m long, 20m diameter
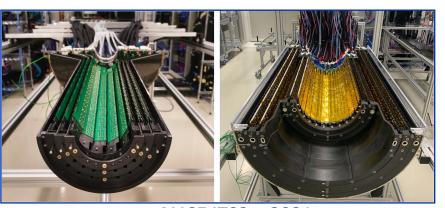
1. Silicon tracker
2. Barrel ECAL Lar
3. Endap and forward HCAL/ECAL Lar
4. Barrel HCAL Fe/Sci
5. Central Solenoid (>10m diameter) + two forward solenoids
6. Muon system

CMOS sensors in the realm of HI experiments
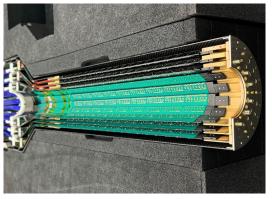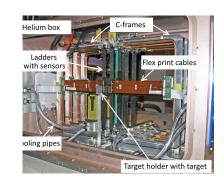
STAR HFT – 2014
ULTIMATE

ALICE ITS2 – 2021
ALPIDE

sPHENIX MVTX - 2023
ALPIDE
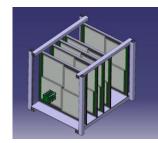
NA61 prototype
ALPIDE
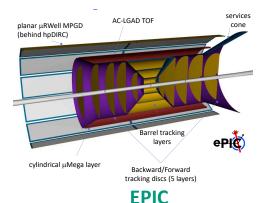
CBM MVTX – 2027
MIMOSIS
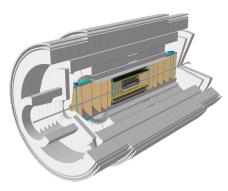
ALICE ITS3 – 2028
"Wafer-scale MOS"

NA60+ - 2028
(based on ALICE ITS3)

EPIC
(based on ALICE ITS3)

ALICE3
next generation

State-of-the-art CMOS Active Pixel Sensors
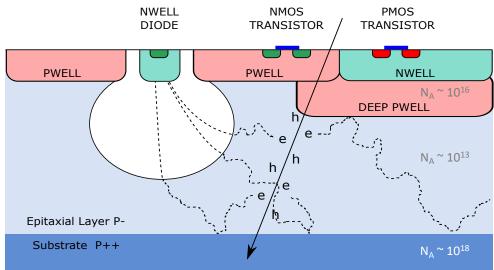
ALPIDE Sensors for ALICE ITS and MFT
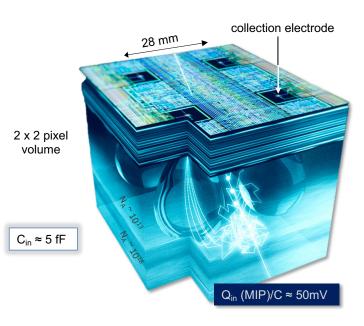
Based on CMOS technology 180nm

- **10 m²** active silicon area
- **12.5 G-pixels**
- **50 μm** thin sensor
- Spatial resolution **~5μm**
- Max particle rate ~ **100 MHz /cm²**

- Detection layer: high-resistivity (> 1kΩ cm) epi layer (25µm)
- Very small collection diodes (2 µm diameter) ⇨ low capacitance (~fF)
- Reverse bias voltage to substrate (contact from the top)
- CMOS circuitry within active area

Evolution of CMOS APS for HEP

full depletion of the sensitive layer combined with a low capacitance electrode

CERN & Tower

Contents lists available at ScienceDirect
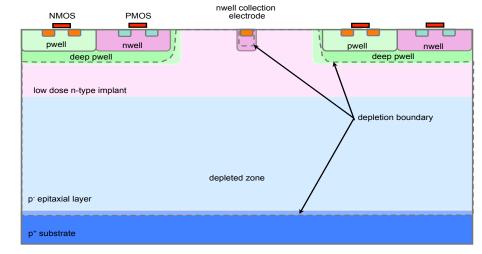
Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

A process modification for CMOS monolithic active pixel sensors for enhanced depletion, timing performance and radiation tolerance

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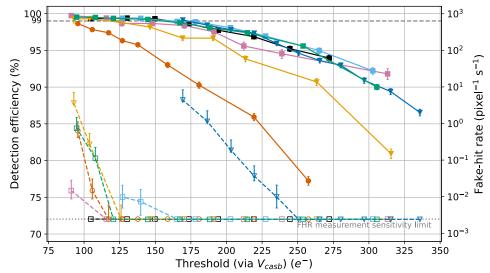
First studied with **180nm**
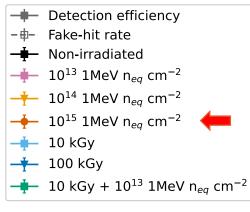
an even better performance with **65nm**

Fully depleted sensor
- charge collection time $\ll 1 ns$
- capacitance $\approx 1fF$
- operational up to 10^{15} n_{eq} /cm^2
- Time res.: 67 ps (w/o corrections)

Operated at room temperature!

doi:10.48550/arXiv.2212.08621

Wafer-size curved sensors

Nearly massless truly cylindrical detectors

TPSCo ISC 65nm CMOS Imaging
300mm wafers + stitching

300mm wafers

TPSCo ISC 65nm
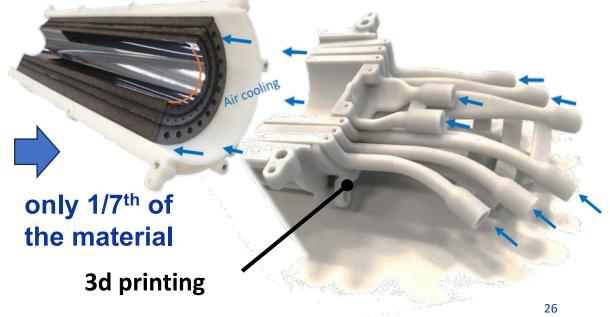
afer-size

services outside
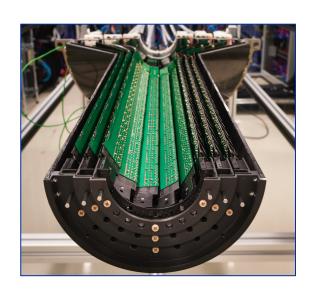
thin (<50μm CMOS can be curled)

2×9 ALPIDEs
30, 40, 50 μm

6 cm

14 cm

Air cooling

only 1/7th of the material

3d printing
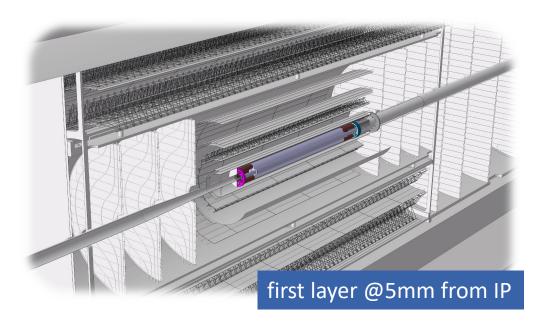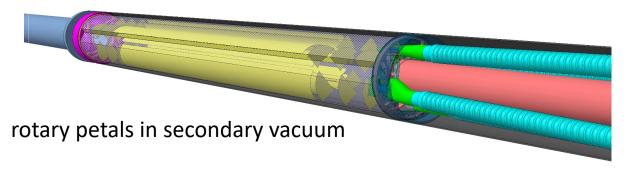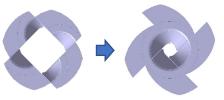
Retractable vertex detector inside beampipe

ALICE 3 vertex detector

rotary petals in secondary vacuum

first layer @5mm from IP
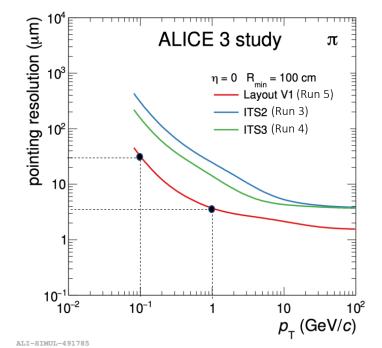
J.D. Bjorken in a 1985 paper on Ξ_{cc} and Ω_{ccc} measurements:

My guess for the resolution requirement is (ideally) a few microns(!!) in the transverse direction and perhaps 200 microns in the longitudinal.
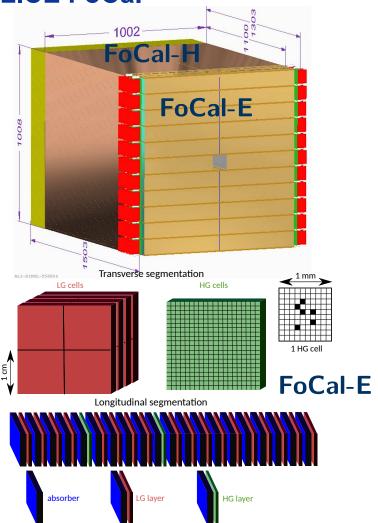
AIP Conference Proceedings 132, 390 (1985)
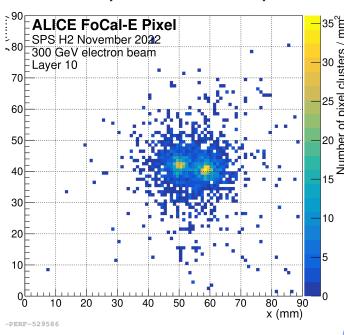
pointing resolution:~ few µm at 1 GeV/c, 30 µm at 100 MeV

ALICE 3 study π

$\eta = 0$ $R_{min} = 100$ cm
— Layout V1 (Run 5)
— ITS2 (Run 3)
— ITS3 (Run 4)

pointing resolution (µm)

p_T (GeV/c)

ALI-SIMUL-491785

CMOS Pixel Sensors for imaging calorimeters

ALICE FoCal
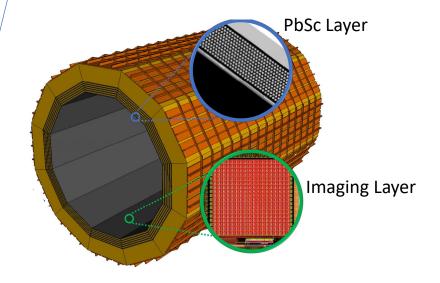
Shower separation in FoCal-E pixels

Similar approach is also considered for the EPIC BECAL

Pixel layers (ALPIDE) interleaved with Si PAD

Particle Identification

PID continues to be a trademark of HI facilities

- FAIR / CBM: RICH, TOF, TRD, Muon ID
- LHC / ALICE 3: RICH, TOF, Muon ID
- EIC / EPIC: DIRC, RICH, TOF, Calorimetry

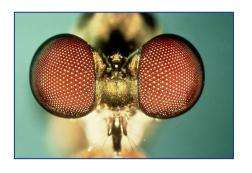⇨ important also for future e^+e^- facilities

Novel developments & trends

Time of Flight: AC-LGAD, CMOS with gain layer, SiPM

RICH:

- "biomimetic" approach to arrange optical elements to focus light into sensors
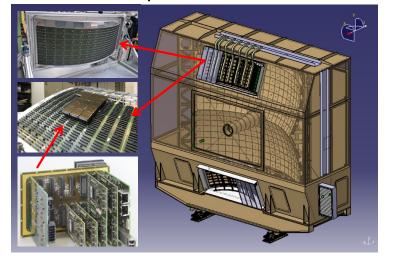- photon sensors: 2.5 and 3D SiPM, LAPPD

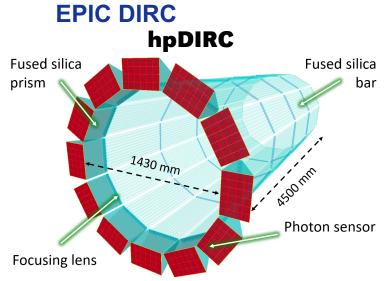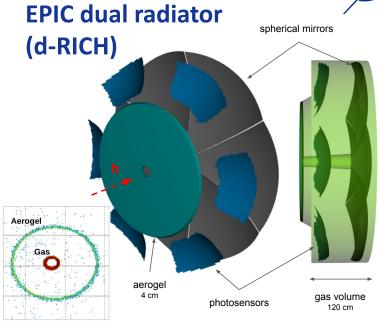Cherenkov Angle and ToF measurement with one detector

Cherenkov light detectors

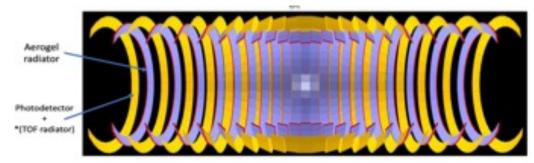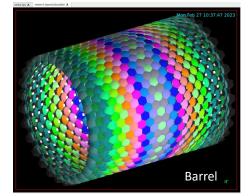## CBM RICH
CO_2 radiator, spherical mirrors, MAPMT

EPIC DIRC

hpDIRC

Fused silica prism

Fused silica bar

1430 mm

Focusing lens

adv___ced optics

EPIC dual radiator (d-RICH)

spherical mirrors

Aerogel

Gas

photosensors

120 cm
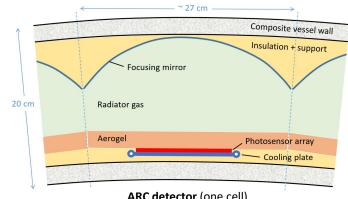
ALICE 3 - proximity focused (aerogel) RICH with projective geometry

Aerogel radiator

Photodetector + "(TOF radiator)"

better quality image

ARC detector

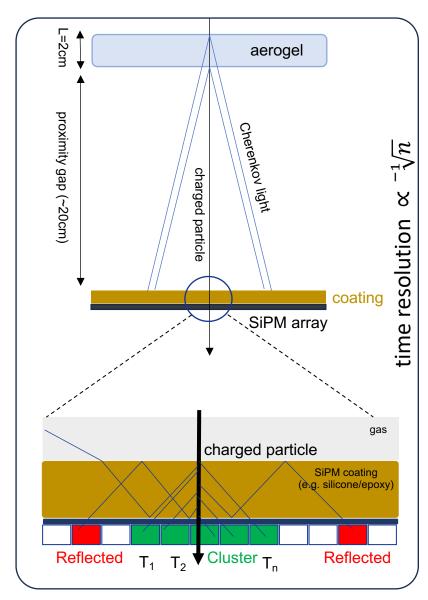## LHCb & FCC-ee) ("biomimetic" approach) - tile the plane with separate cells, each with its own mirror, sensor array

Barrel

~ 27 cm

Composite vessel wall

Insulation + support

Focusing mirror

20 cm

Radiator gas

Aerogel

Photosensor array

Cooling plate

ARC detector (one cell)

Cherenkov Angle and ToF with one detector

Cherenkov light for T(...)
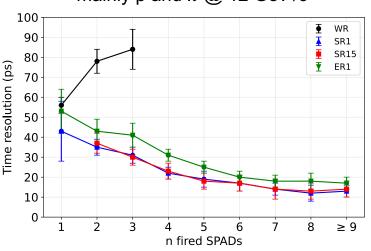
Time resolution improve(...)

- Single SiPM σ_T improv(...)

  Weighted average of s(...)
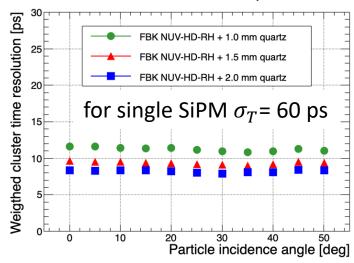
(...)ngle SPAD dark counts

Tests at the CERN PS (prelim.)

mainly p and π @ 12 Gev /c

simulation for 5 GeV/c pions

for single SiPM σ_T = 60 ps

Time resolution 10-20 ps

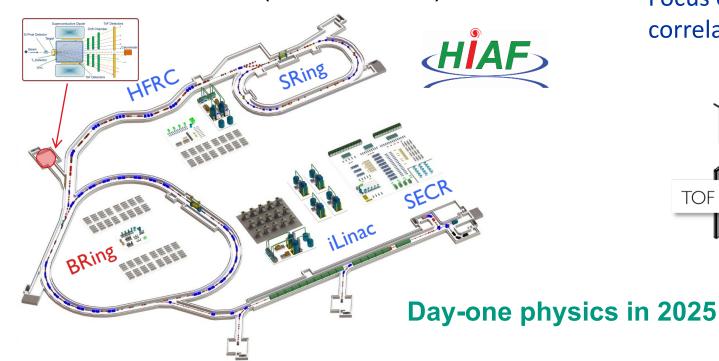for number of fired pixels ≥ 6 (> 90% of events!)

Conclusions

- Landscape of AA and eA facilities in the short and long-term, will span a wide energy spectrum and at increasingly higher intensities

- The new facilities and detectors offer remarkable opportunities for conducting comprehensive investigations into hot and dense quark matter as well as cold QCD matter.

- These advancements call for higher precision, faster, and more sophisticated detector technologies

- Detector technology innovation will remain a driving force behind the advancement of our research

- Close collaboration with industrial partners essential to access and effectively leverage the most advanced technologies

CEE @ the High Intensity Accelerator Facility (HIAF)

New campus in Huizhou (Guangdong) under construction (2018 – 2025)
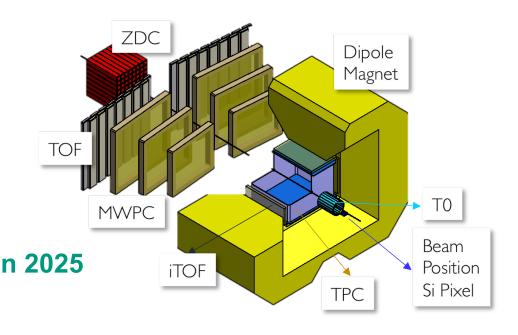

Day-one physics in 2025

S. Ruan NIM A 892 (2018)   J.C. Yang et al., NIM B 317 (2013)

High-intensity synchrotron Booster Ring (569 m)
- Extraction energy: 0.2-0.8 GeV / u
- Operation period: 3-10 s, Intensity (^{238}U) ~10^{11}/pulse

CSR External-targe Experiment

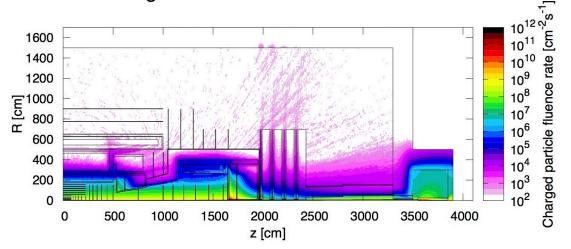Focus on event-by-event fluctuations and correlations hadron production and flow

Hadron spectrometer
- acceptance: 2° – 90°
- interaction rates: > 100 kHz
- free- streaming DAQ
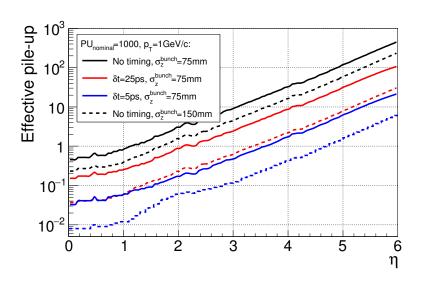
Meeting Tomorrow's Demands: Innovations Needed

Assuming $L = 30 \cdot 10^{-4}\ cm^{-2}s^{-1}$ and $30\ ab^{-1}$

First tracker layer (R = 2.5 cm)

- Particle flux: **20 GHz cm^{-2}**

- Data throughput: **0.3 Tbit s^{-1} cm^{-2}**

- Fluency: **5.5 x 10^{17} 1Mev N$_{eq}$ cm^{-2}**

FCC-hh nominal average pile-up:

O(1000) = **5-7 x HL-LHC** = **33 x LHC**

- **4D vertexing** with additional track **time-stamp** is essential!

- Yet, very challenging beyond $|\eta| > 4$ even for $\delta t = 5 - 10 ps$

Present technologies cannot sustain these values up to R = 40cm ⇨ novel detectors needed!

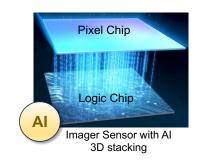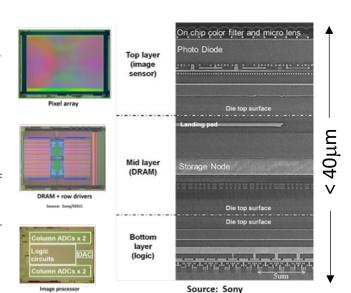# Advanced on-chip signal processing ("edge processing")

In recent years, attempts to integrate AI in imagers

Despite of a low-performance eye-lens and limited bandwidth to the brain, the human visual system generates stunning images with a low-power, sparse and asynchronous stream of digital spike events

SONY – IMX500, May 2020

Image sensor equipped with AI processing functionality

12 M pixel, 1.55μm pitch, 5.6 x 5.6 mm^2

Pixel Chip
Logic Chip
AI
Imager Sensor with AI
3D stacking

Industry's first 3-layer Stacked CMOS Image Sensor with DRAM for Smartphones (presented at ISSCC, Feb 2017)

Pixel array

DRAM + row drivers
Source: Sony/ISSCC

Column ADCs x 2
Logic circuits
DAC
Column ADCs x 2
Image processor

On chip color filter and micro lens
Photo Diode
Top layer (image sensor)
Die top surface
Landing pad
Mid layer (DRAM)
Storage Node
Die top surface
Die top surface
Bottom layer (logic)
5um
Source: Sony

< 40μm

Modern **3D hybrid stacking** technology with multiple layers (Imager, DRAM, logic processor)

➡ integrate sophisticated digital processing, including **AI** (the pixel sensor as first layer of AI)

➡ several layers for measurement of space (small pixels, no time) and time coordinates (larger pixels, fast timing)