Future Experimental Facilities and Detectors

Luciano Musa (CERN)

Hard Probes, 26 March

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Credits:

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Outline

① A-A Facilities/detectors for QGP studies at high energy density

- RHIC, HL-LHC, FCC-hh/SppC

② A-A Facilities/ detectors for QGP studies at high baryon density

- HIAF, JPARC, NICA, FAIR, SPS, RHIC-BES2

③ Future eA facilities/experiments for precision cold-QCD studies

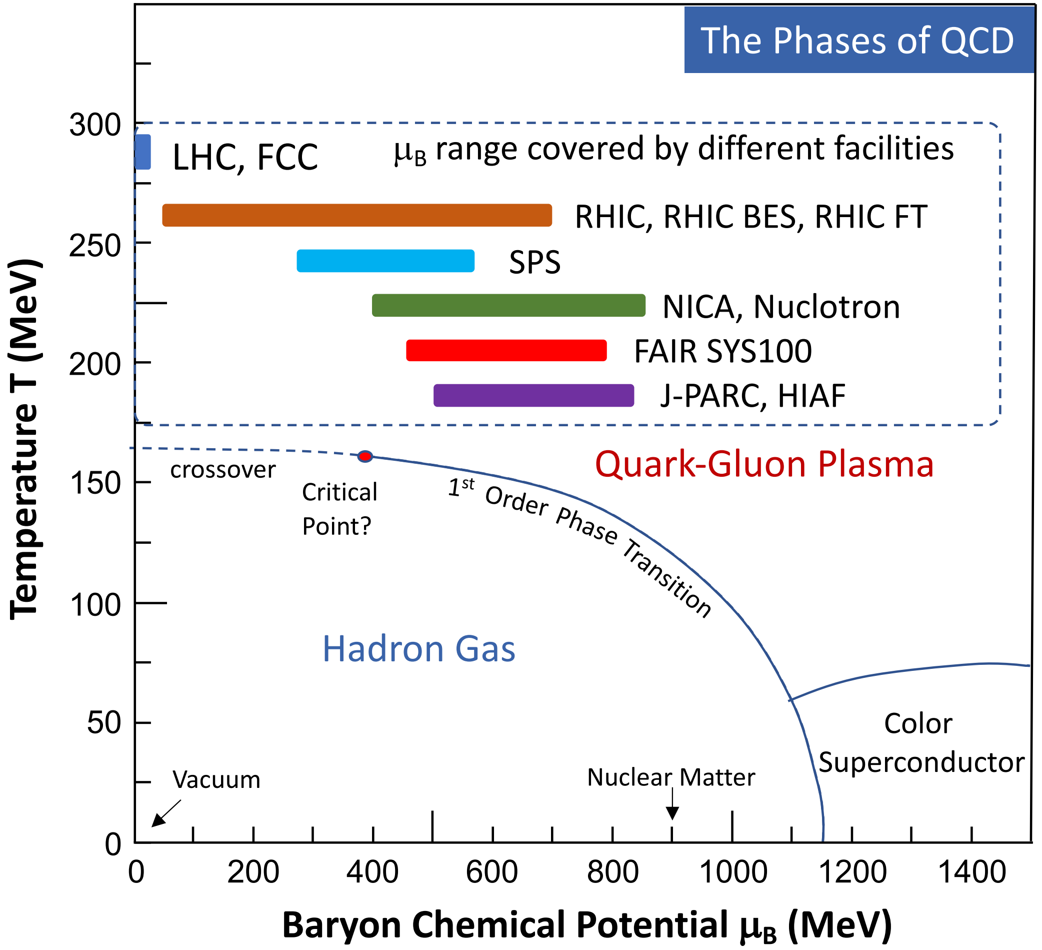
- EIC, LHeC, FCC-eH

◉ A few examples of novel detector technologies

- *will be introduced when discussing new facilities/detectors*

Future Landscape of AA Facilities

Future landscape of HI facilities



High energy collisions

- quantify properties of quark-gluon plasma and relate them 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 1^{st} order phase transition;
- Search for the Critical Endpoint (lQCD: $\mu_B > 300$, $T < 140$)
- QGP constituents at high μ_B → Neutron Star EOS

Future Landscape of AA Facilities

Future landscape of HI facilities

Future planned facilities push the frontiers

at higher/lower energy

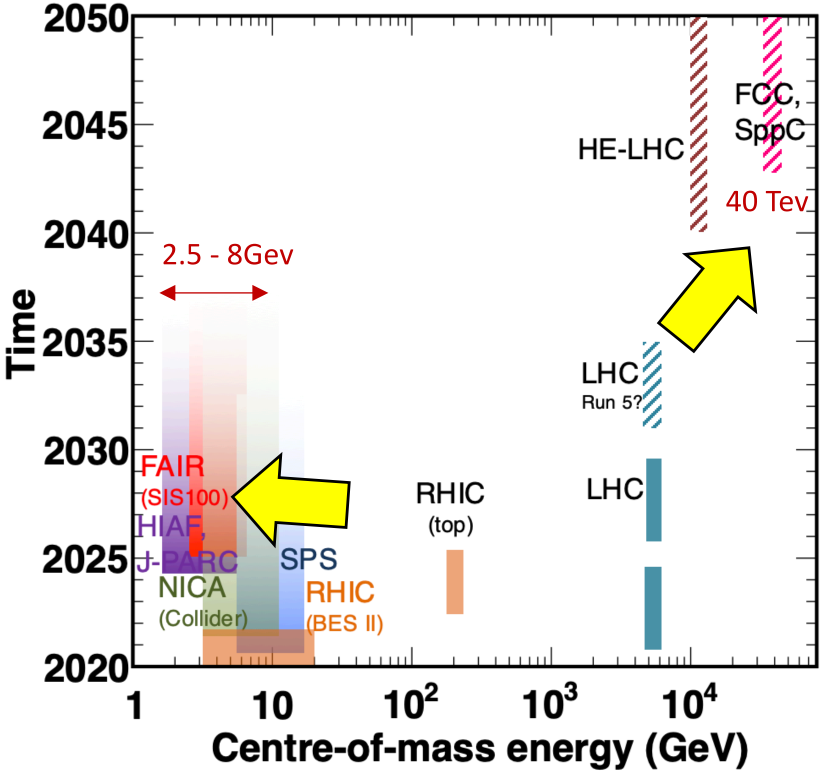


Figure from A. Dainese (QM2019)

and higher rates

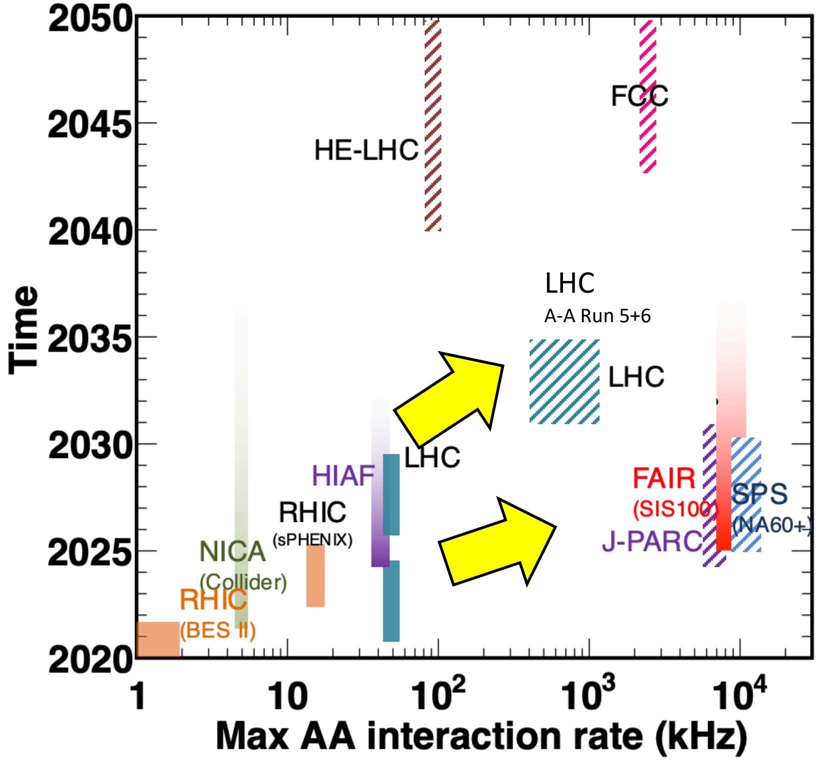


Figure from A. Dainese (QM2019)

High energy facilities

- RHIC: sPHENIX and STAR
- LHCC: ALICE, ATLAS, CMS, LHCb
- FCC-hh, SppC

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

Facility	RHIC	LHC/HL-LHC	SppC / FCC-hh
Timeline	→ 2025	→ 2041 (Runs 3 to 6)	> 2040?, > 2050?
Collision system	pp, d-Au, Au-Au	pp, p-Pb and Pb-Pb and lighter ions (e.g. ^{16}O, ^{129}Xe, ^{84}Kr, ^{40}Ar)	FCC: pp, p-Pb and Pb-Pb and lighter ions (e.g. ^{129}Xe, ^{84}Kr, ^{40}Ar)
$\sqrt{s_{NN}}$ (TeV)	0.2	5.5	39 (FCC)
Int. rate (kHZ)	~15 (Au-Au)	~50 (x 3-4 in Run5) for Pb-Pb	~2500 (FCC)
Experiments	sPHENIX, STAR	ALICE, ATLAS, CMS, LHCb HL-LHC, phase II of ATLAS and CMS phase II-b of ALICE and LHCb	up to four experiments

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams (arXiv: 1812.06772)

- High-precision measurement of macroscopic (long-wavelength) **QGP properties;**
- **Microscopic** parton **dynamics** underlying QGP properties;
- Parton densities in broad kinematic range and search for saturation;
- Collectivity across colliding systems, hot medium in small systems;

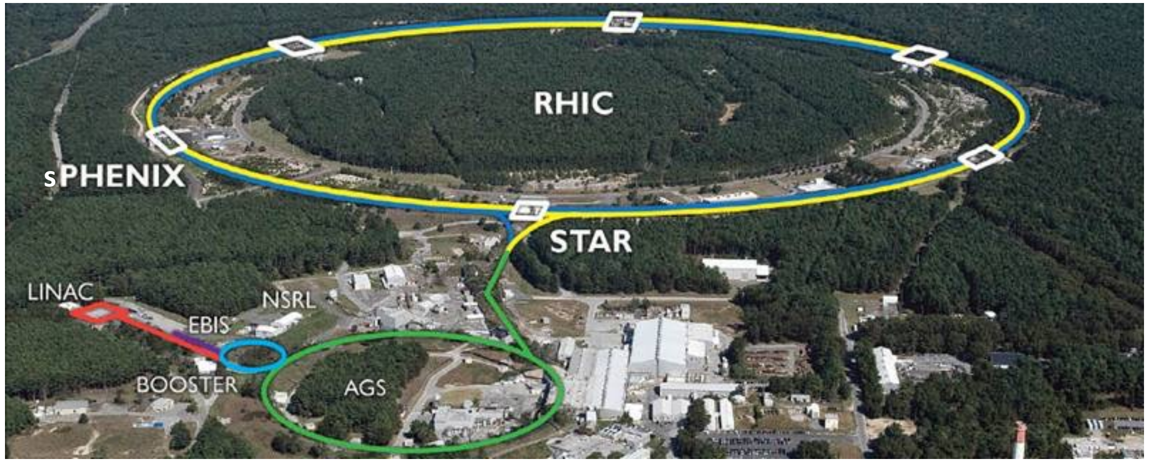
⇨ Complementarity of RHIC and LHC is crucial

FCC/SppC open completely new opportunities

Detectors:
high-precision, high interaction rates
⇨ thin, high-granularity, fast detectors

RHIC - sPHENIX

See also Megan Connors
Plenary VII, Thursday 16h:30

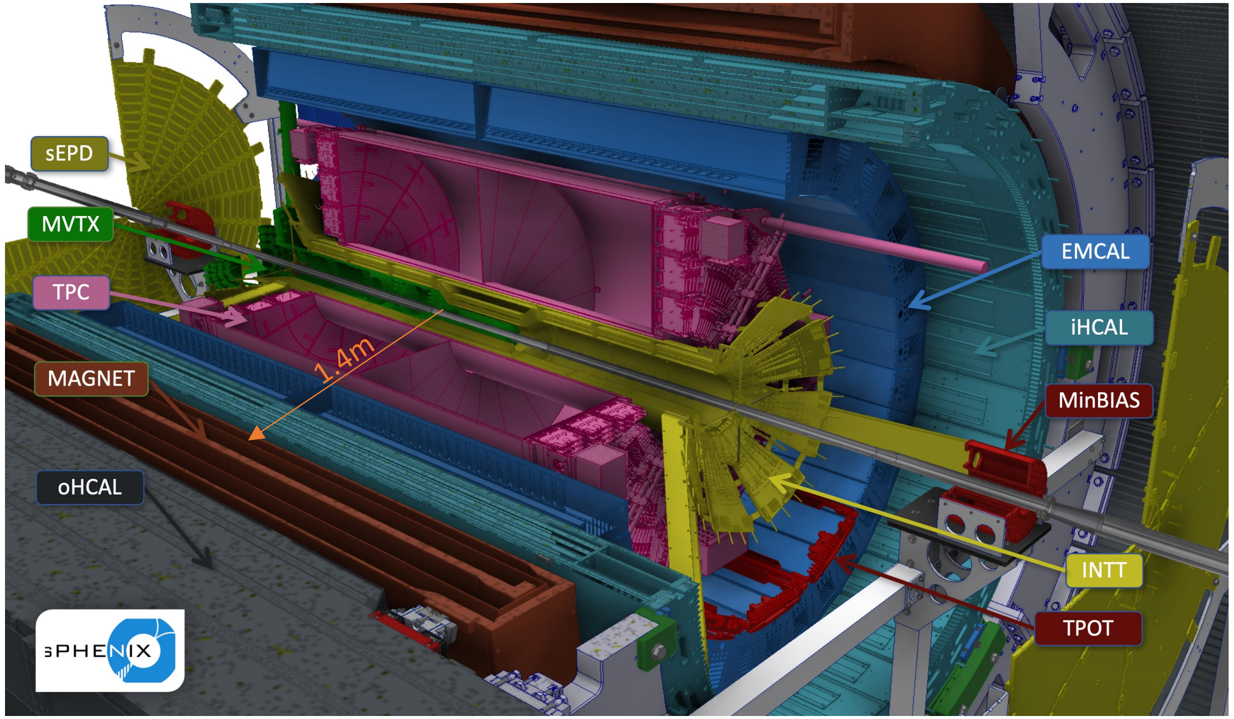


- 1.4 T superconducting solenoid (from BaBar)
- Hermetic coverage |η|<1.1
- Excellent vertexing
- High-precision tracking
- Large-acceptance Electromagnetic + Hadronic Calorimeter
- High data rates: 15 KHz for all subdetectors
- Trigger capability also with streaming readout

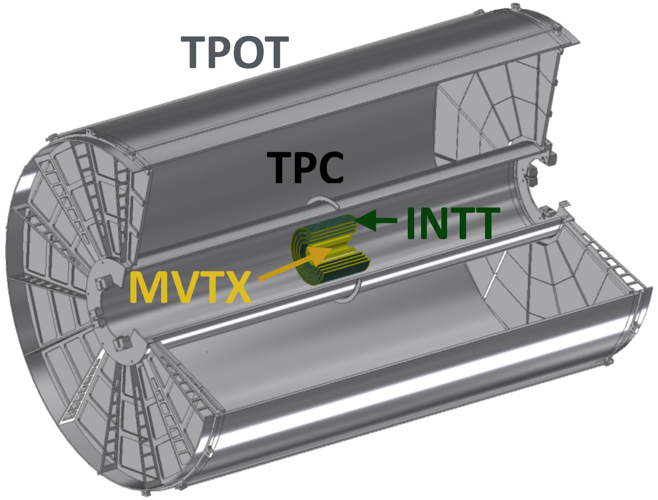
sPHENIX: a new state-of-the-art jet detector at RHIC (arXiv1207.6378)

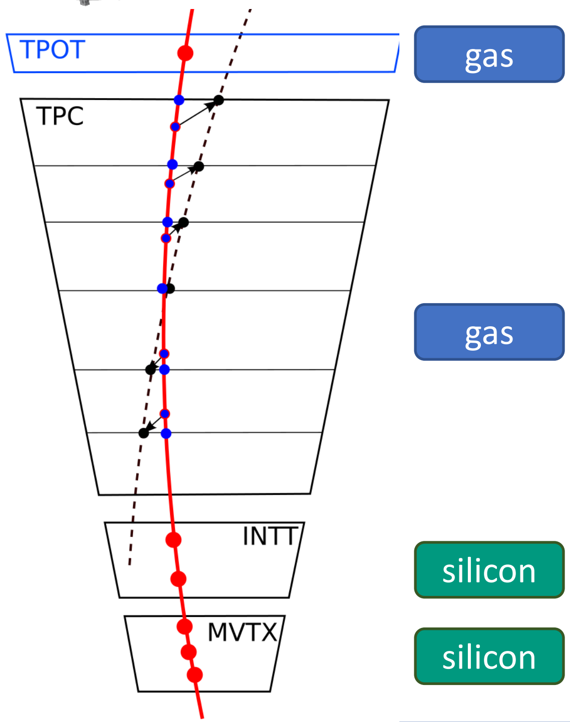
- proposed in 2010 (collaboration formed in 2016)
- installation completed in 2022
- first physics run in 2023

⇨ **focus on: jets, quarkonia and other rare process**



RHIC – sPHENIX Tracking Detectors





Vertexing: Micro-VerTeX detector (MVTX)

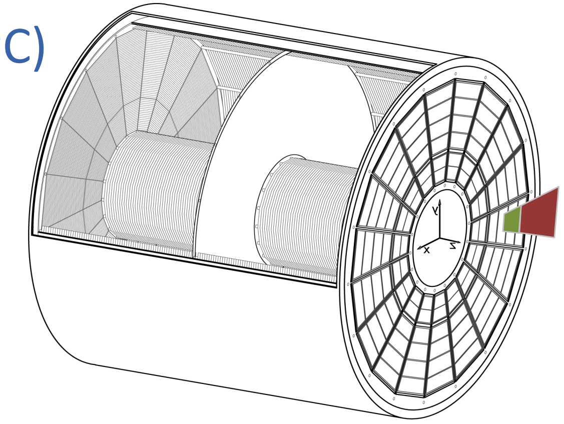
- based on ALICE ITS2 Inner Barrel
- 3 concentric layers instrumented with **M**onolithic **A**ctive **P**ixel **S**ensors (MAPS)
- radial extension: 2.5 – 4 cm radius
- spatial resolution: **5µm**; integration time ~**5µs**;

Timing: Intermediate Silicon Tracker (INTT)

- 4-layer Si strip intermediate tracker (7-10 cm radius)
- fast O(**100ns**) integration time

Momentum (& PID): Time Projection Chamber (TPC)

- compact; **gateless**, continuous readout (à la ALICE)
- quad GEM (Gas Electron Multiplier);
- 48 space points (30 – 78 cm)
- r-ϕ resolution **~ 150 µm**



Calibration: TPC Outer Tracker (TPOT)

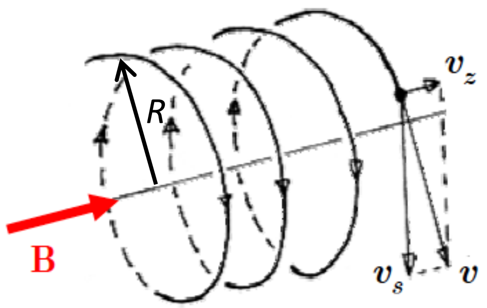
- 8 modules of Micromegas inserted between TPC and EMCal

Intermezzo – momentum measurement in a magnetic spectrometer

If a particle with mass m_0 and charge q traverses a magnetic field **B** with velocity v

Lorentz force $$\frac{d\bar{p}}{dt} = \bar{F} = q\bar{\upsilon} \times \bar{B}$$

In case of homogeneous magnetic field the trajectory is given by an helix



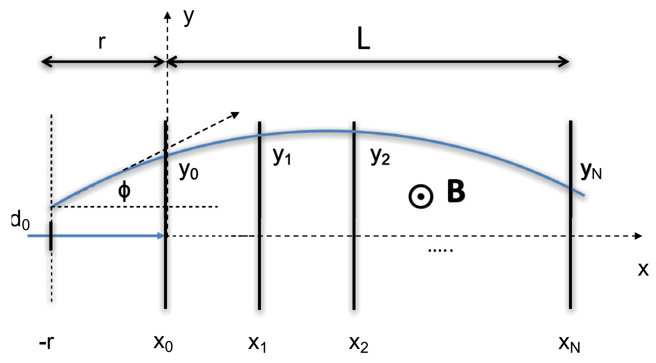
$$\frac{m\upsilon^2}{R} = q\upsilon B$$

$$R = \frac{m\upsilon}{qB}$$

$$p_T[GeV/c] = 0.3B[T] \cdot R[m]$$

Use several detector layers to measure the particle trajectory and determine its bending radius R

Assume N+1 detection layers, placed at x_0, x_1, x_N, measuring the y coordinate all with the same resolution

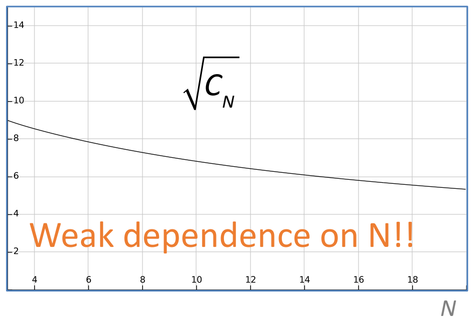


BL^2 = bending power

true if multiple-scattering is neglected

$$\frac{\delta p}{p} = \frac{p}{0.3BL^2}\sigma \cdot \sqrt{C_N}$$

$$C_N = \frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}$$

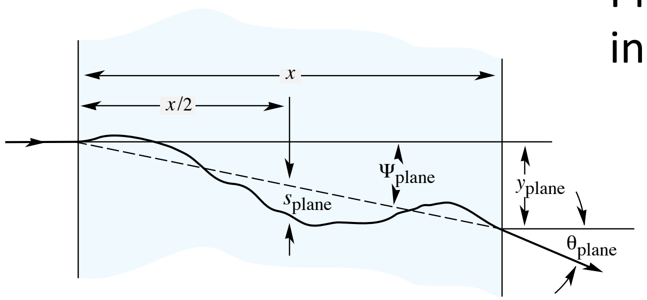


The relative error is:

- proportional to p
- inversely proportional to B
- inversely proportional to L^2
- proportional to the detector spatial resolution σ

Intermezzo – momentum measurement in a magnetic spectrometer

Statistical analysis of multiple coulomb collisions (Rutherford scattering at the nuclei of the detector material), gives:



Probability that a particle is deflected by an angle θ_p after travelling a distance x in the material is given by a (almost) Gaussian distribution with sigma of:

$$\langle \theta_p \rangle = \frac{0.0136}{\beta c p[GeV/c]} z_{particle} \sqrt{\frac{x}{X_0}} \cdot \left(1 + 0.038 \ln \frac{x}{X_0}\right)$$

X_0 ... Radiation length of the material
$Z_{particle}$ ... Charge of the particle
p ... Momentum of the particle

Contribution of multiple scattering to momentum resolution

$$\frac{\Delta p}{p} = \frac{N}{\sqrt{(N+1)(N-1)}} \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta BL} \sqrt{\frac{d_{tot}}{X_0}} \left(1 + 0.038 \ln \frac{d}{X_0}\right)$$

$d_{tot} = (N+1)d$ … total thickness of all detector layers

Z. Drasal, W. Riegler
NIM A 910 (2018) 127-132

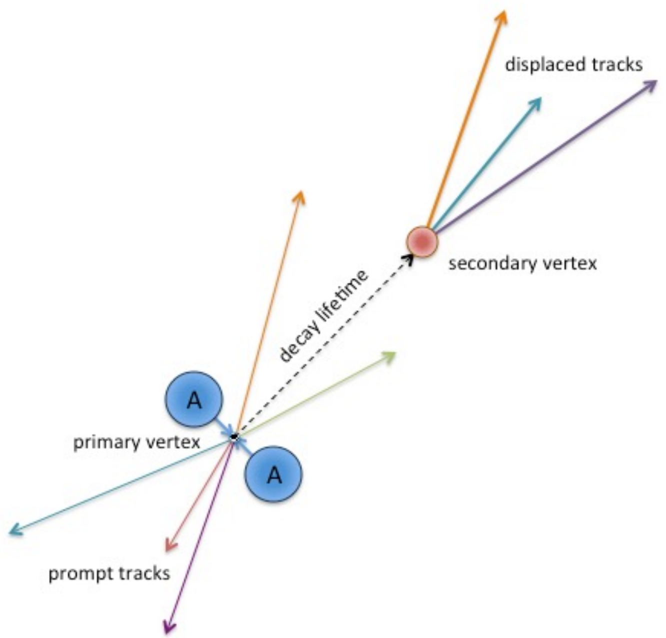
- Small d, i.e very thin detectors
- Large radiation length X_0 – i.e. low Z and low-density materials (Be, C, Al, …)

Note: Lateral displacement ε_p displacement is proportional to the thickness of the detector: usually can be neglected for thin detectors (for 300 μm silicon $\varepsilon_p \approx 0.01$ μm)

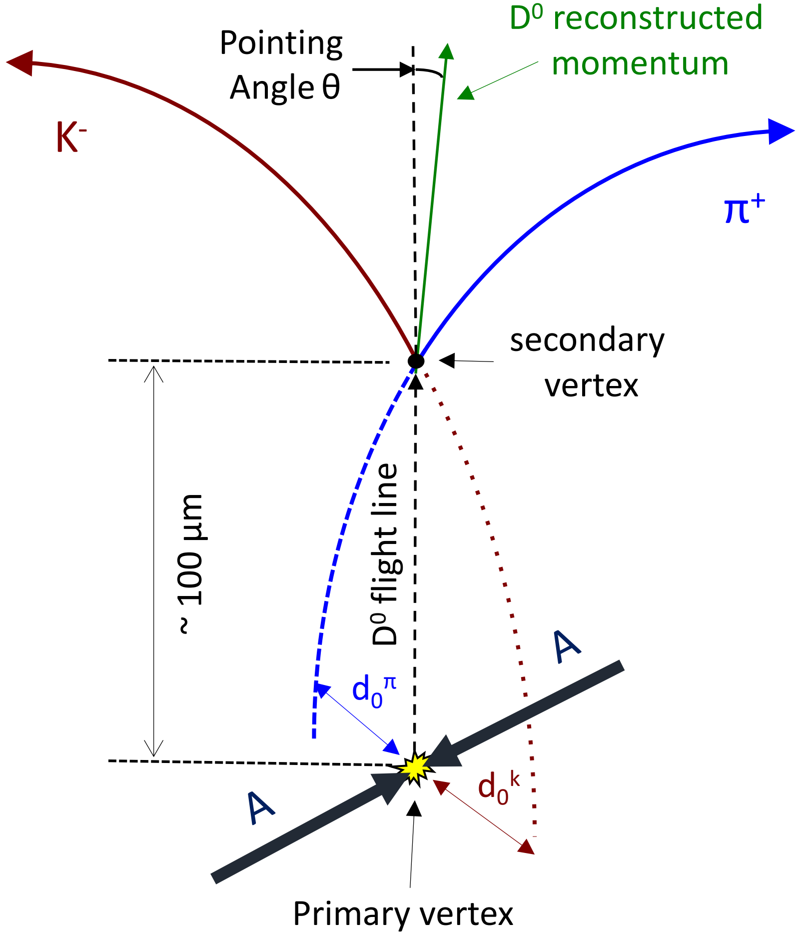
Intermezzo – secondary vertex resolution

Open charm

Particle	Decay Channel	cτ (μm)
D^0	$K^- \pi^+$ (3.8%)	123
D^+	$K^- \pi^+ \pi^+$ (9.5%)	312
D_s^+	$K^+ K^- \pi^+$ (5.2%)	150
Λ_c^+	$p K^- \pi^+$ (5.0%)	60



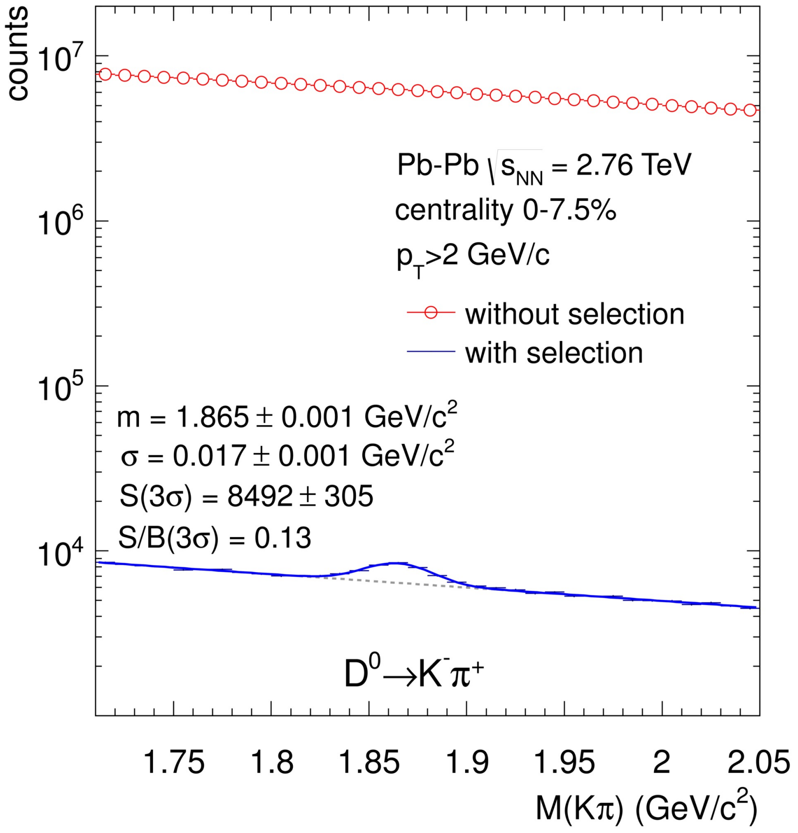
Example: D^0 meson



Analysis based on invariant mass, PID and decay topology

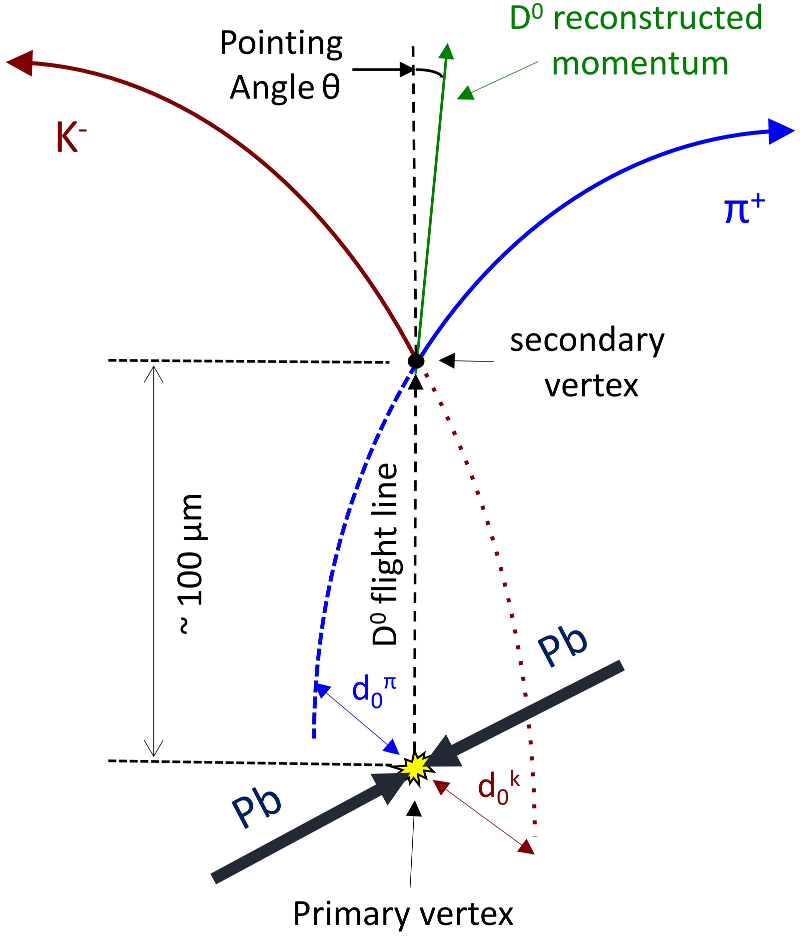
Intermezzo – secondary vertex resolution

ALICE, Int. J. Mod. Phys. A 29 (2014) 1430044



Invariant mass distribution of $K^-\pi^+$ pairs before and after applying selection criteria on the relation between the secondary (D^0 decay) and primary vertices

Example: D^0 meson



Analysis based on invariant mass, PID and <u>decay topology</u>

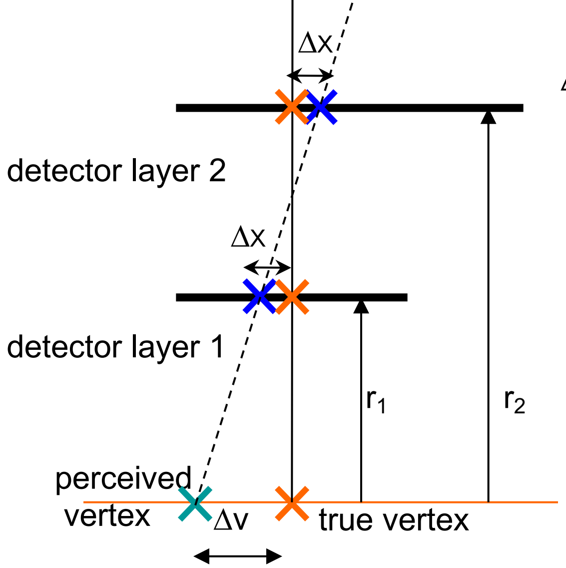
What determines the impact parameter resolution?

Vertex projection from two points: a simplified approach (telescope equation)

e.g. ALICE vertex detector ➡ pointing resolution ≈ (5 ⊕ 22GeV/p·c) μm

From detector position error | From Coulomb scattering

1. Gluckstern R.L., "Uncertainties in track momentum and direction, due to multiple scattering and measurement errors NIM 24 p. 381 (1963)"



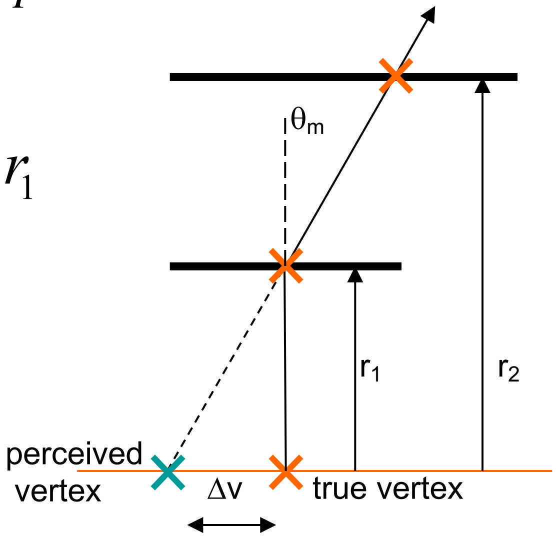
$$\Delta v = \Delta x \bullet \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$

first pixel layer

$$X / X_0 = 0.3\%$$

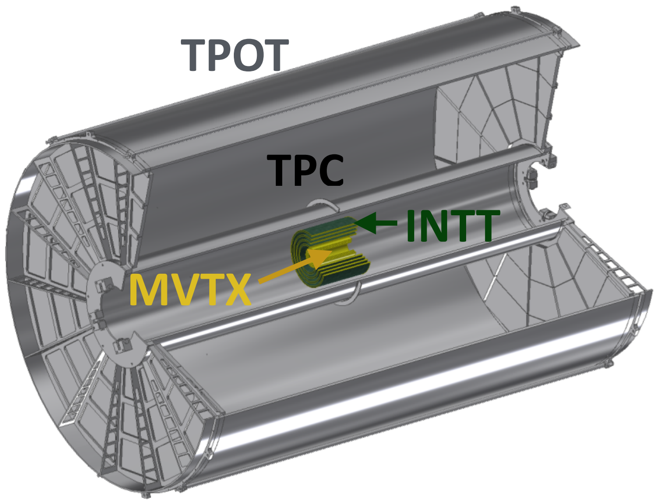
$$\theta_m = \frac{13.6 Mev}{\beta \cdot c \cdot p} \cdot \sqrt{X / X_0}$$

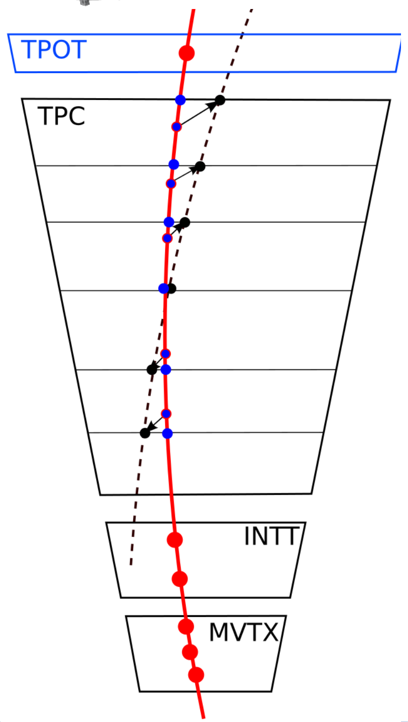
$$\Delta v = \theta_m \cdot r_1$$

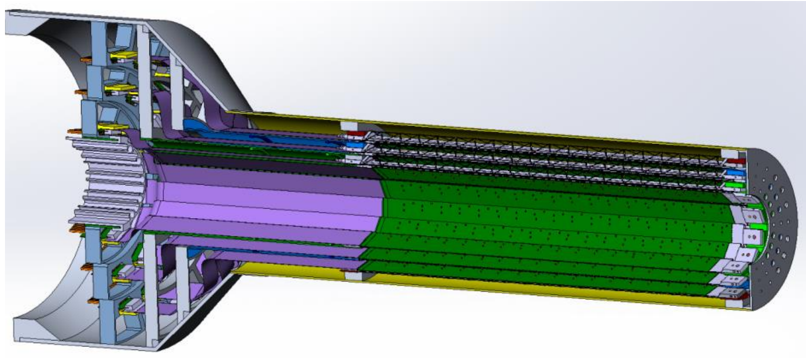


for a more general and rigorous discussion see: Gluckstern R.L., NIM 24 p. 381 (1963), Z. Drasal, W. Riegler NIM A 910 (2018) 127-132

RHIC – sPHENIX Tracking Detectors

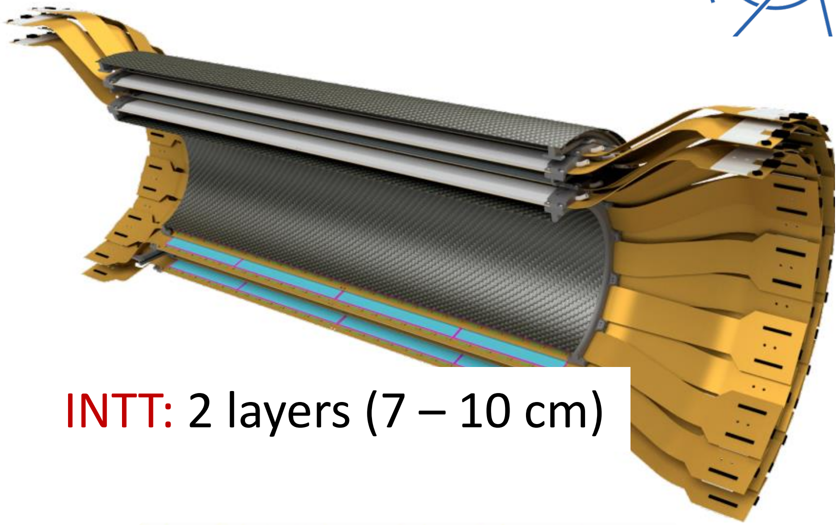




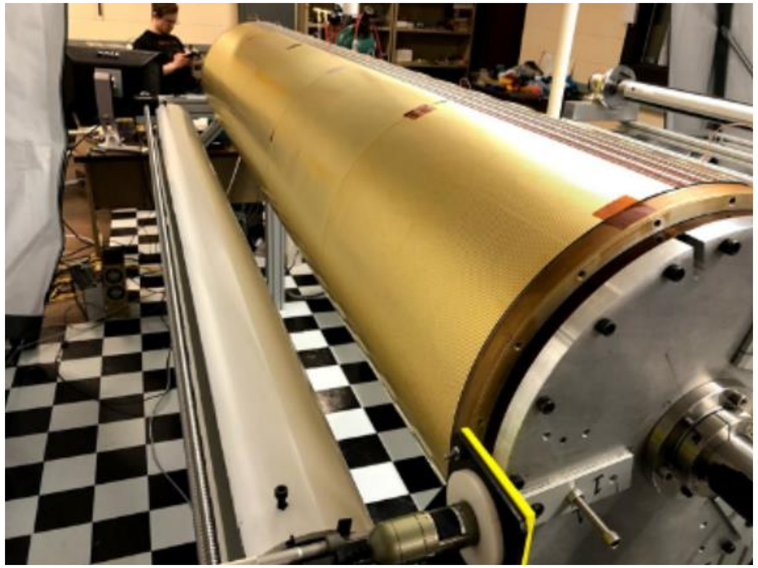


MVTX: 3 layers (2.5 – 4 cm)

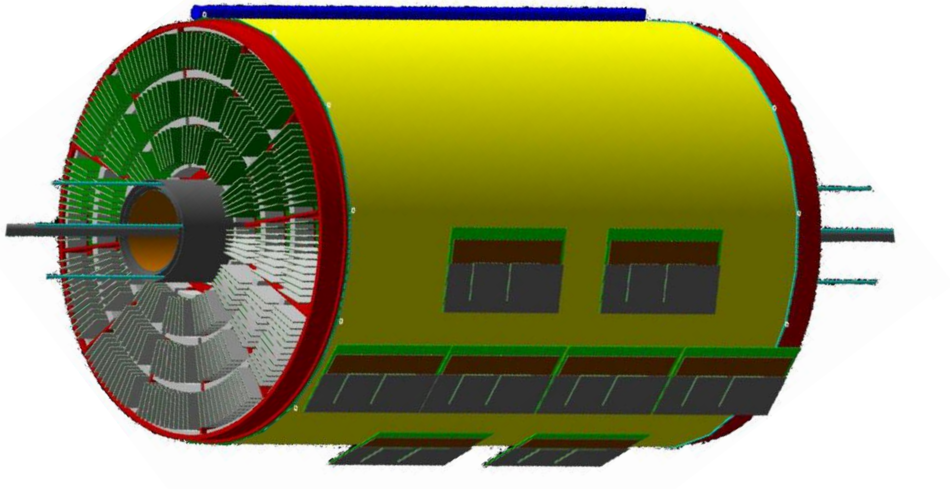
$X/X_0 \sim 0.3\%$/layer, $\sigma \sim 5\mu m$



INTT: 2 layers (7 – 10 cm)

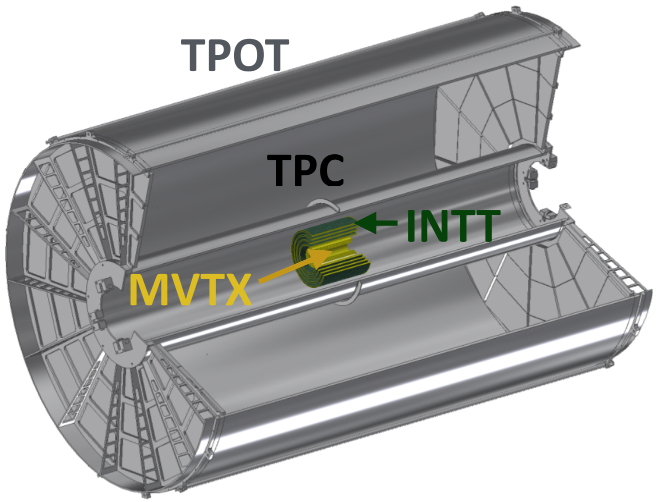


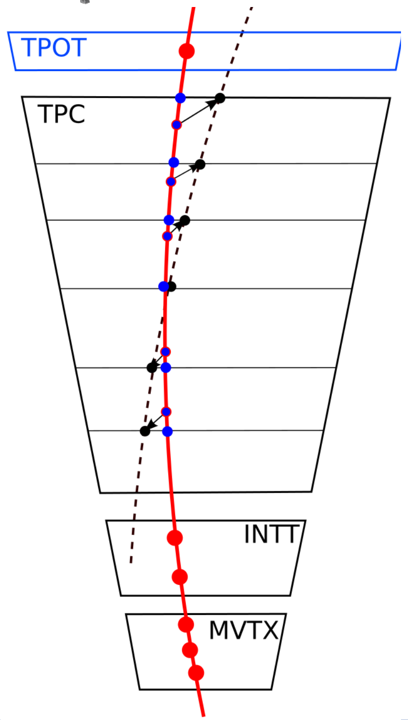
TPC: 48 pad rows (30 – 78 cm)

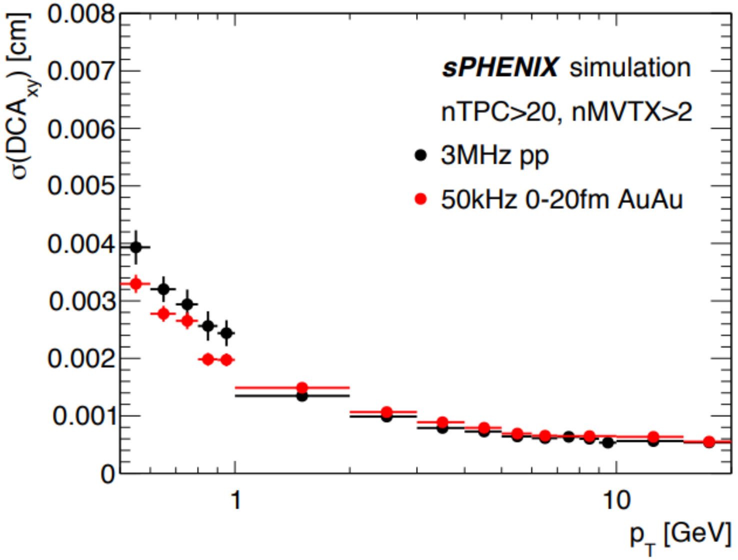


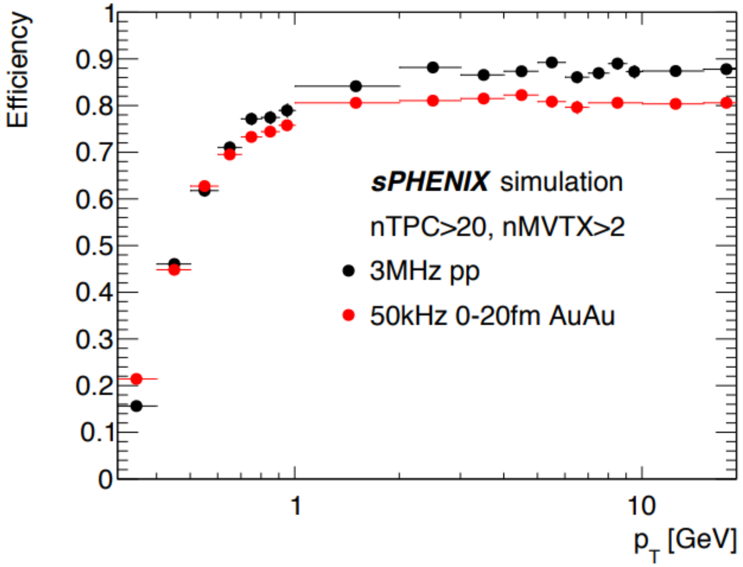
TPC + TPOT: 1 space point @ 90cm

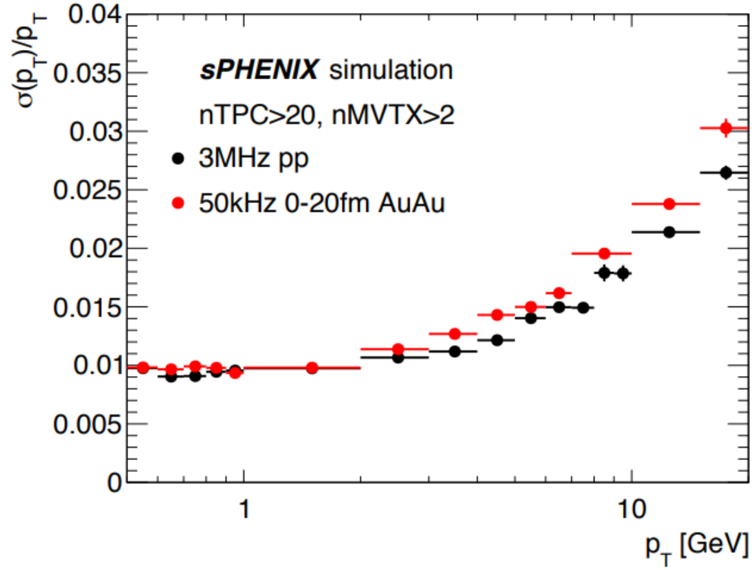
RHIC – sPHENIX Tracking Detectors











- DCA resolution in rϕ, z < 40 μm for p_T>0.5 GeV
  ➪ crucial for open heavy-flavour
- Eff. ~80% for p_T> 1 GeV/c
- p_T resolution < 2% for pT < 10Gev/c
  ➪ important to measure rare processes and separation of Y states;

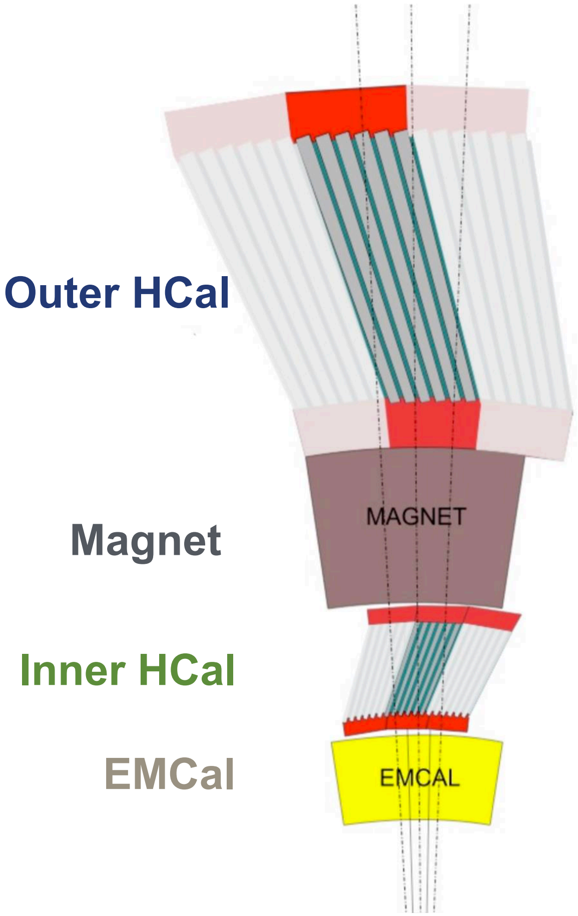
RHIC – sPHENIX Calorimeters

Electromagnetic + Hadronic Calorimeter system: $|\eta|<1.1$ and full 2π azimuthal coverage

EMCal + Hcal: measure total electromagnetic and hadronic energy of jets (10 – 50 GeV/c^2)

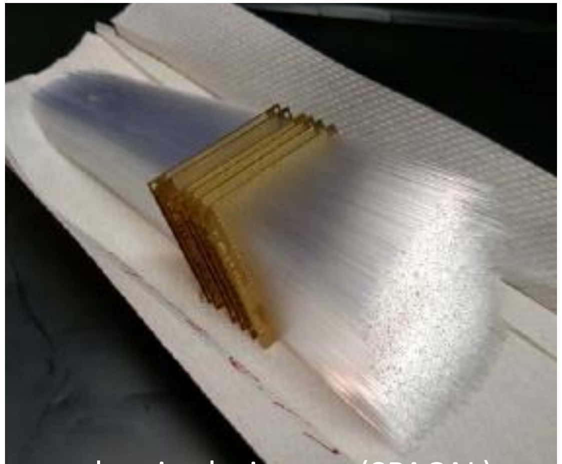
EMCal to identify photons, electons and positrons
- γ used to tag energy of opposing jets
- e to study HQ suppression and to tag HF jets

Small Molière radius and fine segmentation to reduce influence of underlying event background



EMCal: tungsten-scintillating fibre sampling calorimeter (SPACAL type)

absorber: mix of epoxy and tungsten powder



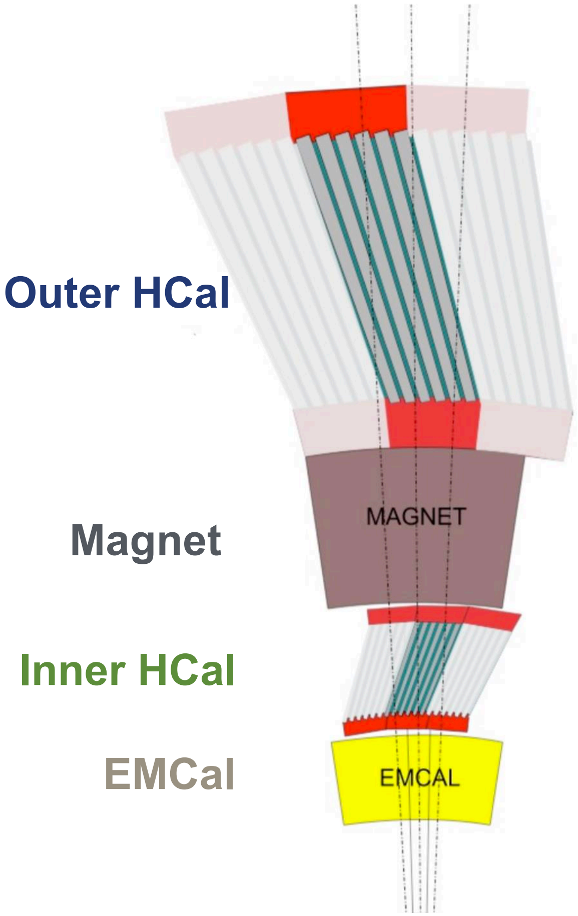
spaghetti calorimeter (SPACAL)

- R_M = 2.3 cm, X_0 = 7mm;
- 20 X_0, Tower size: $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ ($\approx 2.5 \times 2.5 \times 14\ cm^3$)
- Light collection: Silicon PhotoMultipliers (SiPM)
- Resolution: $16\%/\sqrt{E} \oplus 5\%$

RHIC – sPHENIX Calorimeters

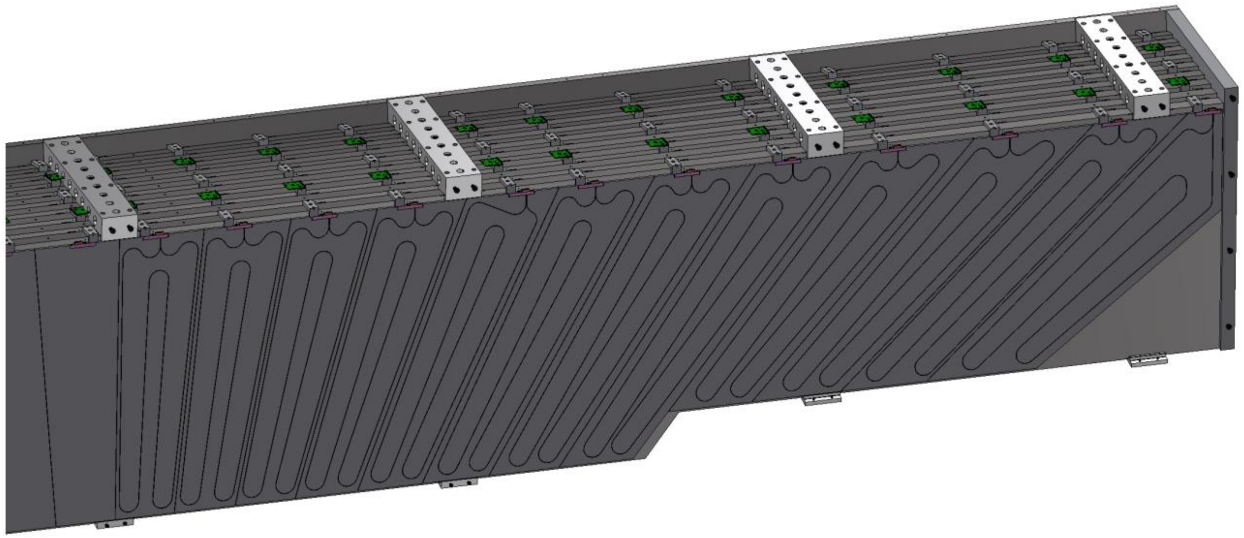
Electromagnetic + Hadronic Calorimeter system: |η|<1.1 and full 2π azimuthal coverage

EMCal + Hcal: measure total electromagnetic and hadronic energy of jets (10 – 50 GeV/c^2)



Inner HCal: Al absorber plates and scintillat. tiles with embedded WLS fibers

Outer HCal: as Inner Hcal but with steel as absorber

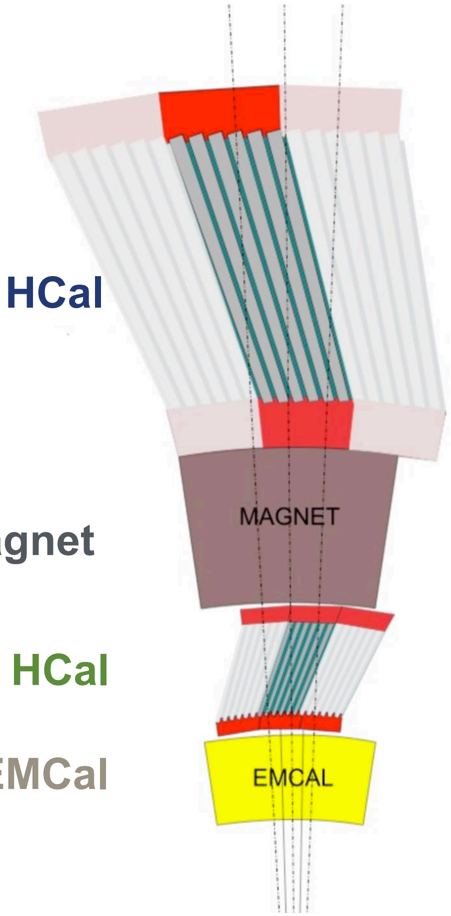


- 18 X_0, 4.9λ_{int}, Tower size: $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- Silicon Photomultipliers (SiPM) used for light collection
- Resolution: $88\%/\sqrt{E} \oplus 12\%$

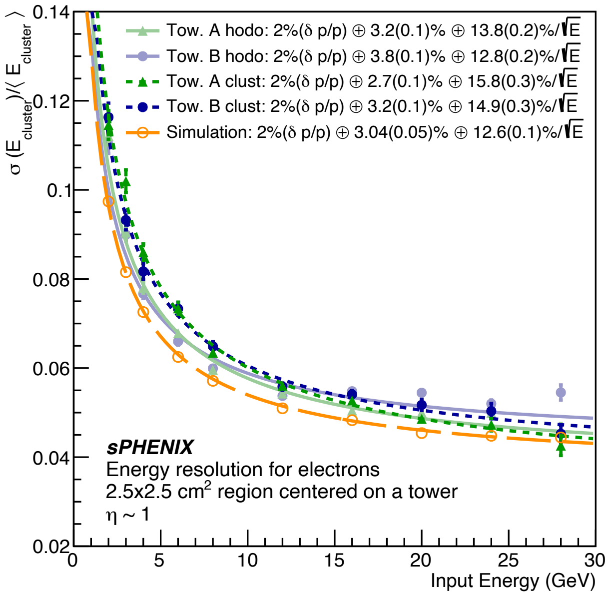
RHIC – sPHENIX Calorimeters

Electromagnetic + Hadronic Calorimeter system: |η|<1.1 and full 2π azimuthal coverage

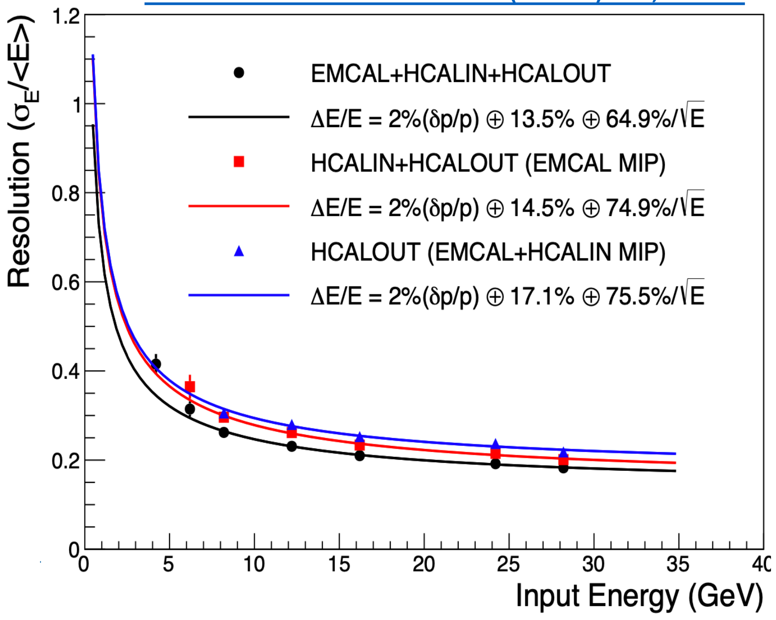
EMCal + Hcal: measure total electromagnetic and hadronic energy of jets (10 – 50 GeV/c²)



arXiv:2003.13685



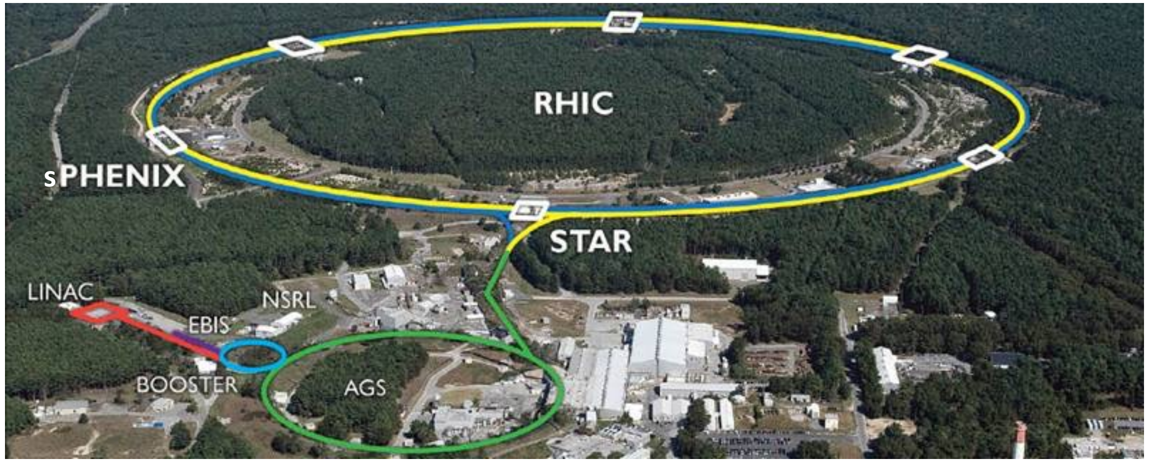
IEEE Trans. Nucl. Sci. 65 (2018) 12, 2901



First detector at RHIC to employ hadronic calorimetry to enable full jet reconstruction at mid rapidity

RHIC – STAR Experiment

See also Megan Connors
Plenary VII, Thursday 16h:30



New STAR detector capabilities developed for BES programme (and for Run 2022)

- Inner TPC upgrade (higher granularity
- Forward tracking and calorimetry in $2.8 < \eta < 4.2$
- Event Plane Detector

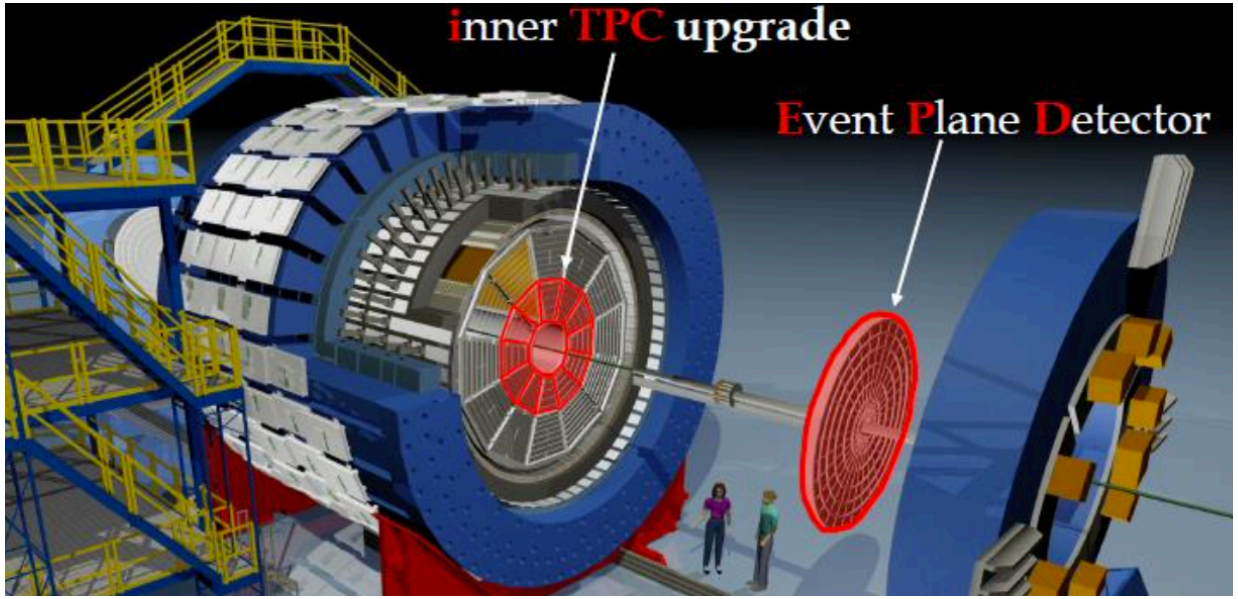
Au–Au and d-Au in 2023 – 2025

Forward photons (and charged hadrons)

- nPDFs, small-x with p-Au, longitudinal dynamics

Running at 1.4 kHz

- 4B Au-Au events / year



LHC programme

See also David Chinellato
Plenary VII, Thursday 16h:55

Overview

LHC has started the high-luminosity era (for HI)

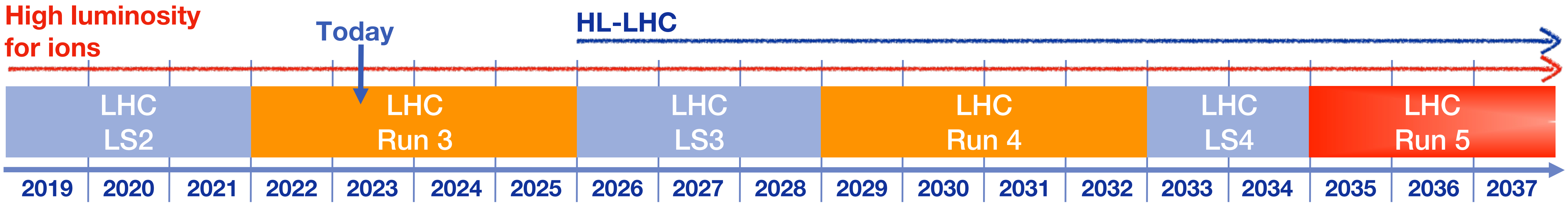
Further upgrades of the accelerator and the experiments in LS3

- HL-LHC (pp): x O(10) wrt to LHC design luminosity
- major upgrades of ATLAS and CMS (Phase II)
- small upgrades of ALICE (ITS3, FOCal) and LHCb

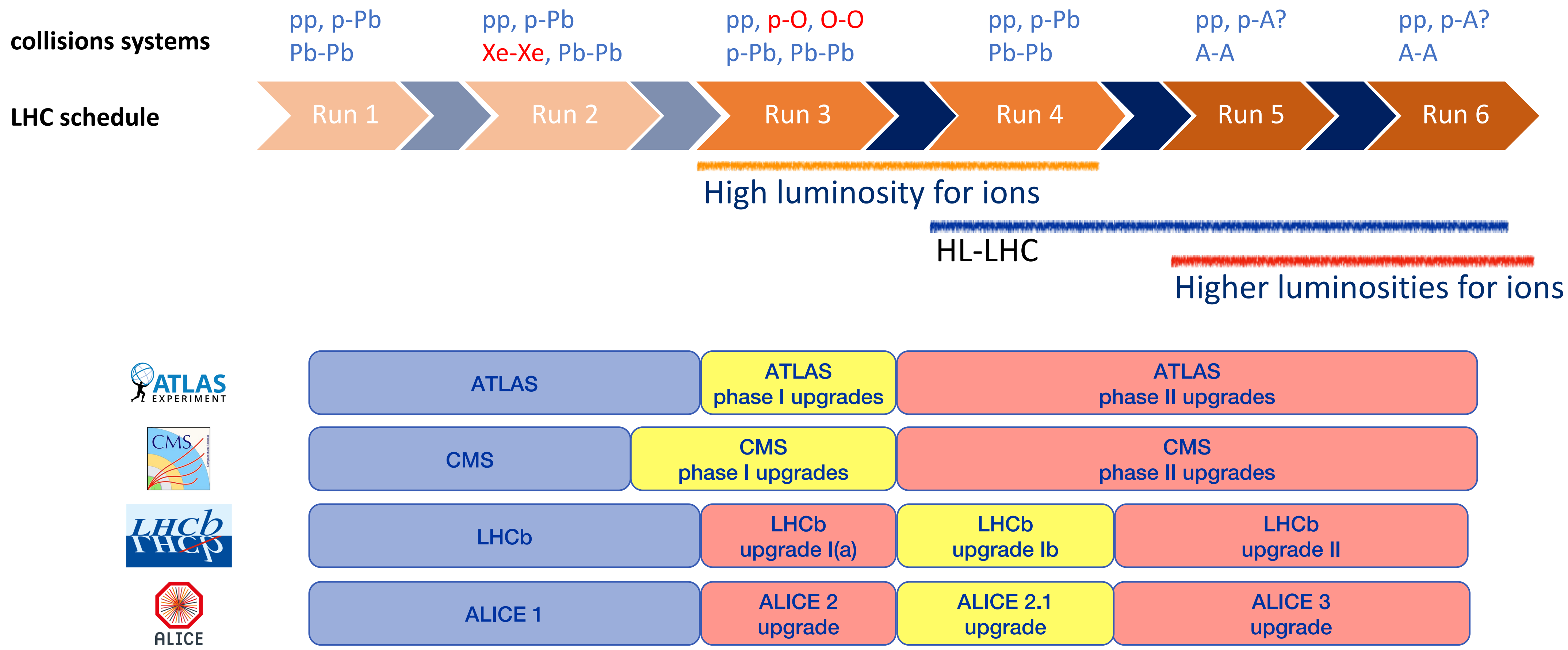
European Particle Physics Strategy Update recommends **full exploitation of the LHC,** incl. heavy-ion programme

- planned for LS4: completely new ALICE (ALICE 3) and LHCb (LHCb-II) - Phase IIb upgrades

The upgrades open very promising opportunities for heavy-ion physics at the different timescales



LHC programme



→ evolution of LHC and the experiments

intermediate upgrade | major upgrade

LHC programme

HL- LHC (pp): L_{int} up to $7.5\times10^{34}cm^{-2}s^{-1}$

Extreme interaction rate conditions: pileup (PU) up to 200 (**8×10^{9} event/s**) ➪ track timestamping ("4D tracking")

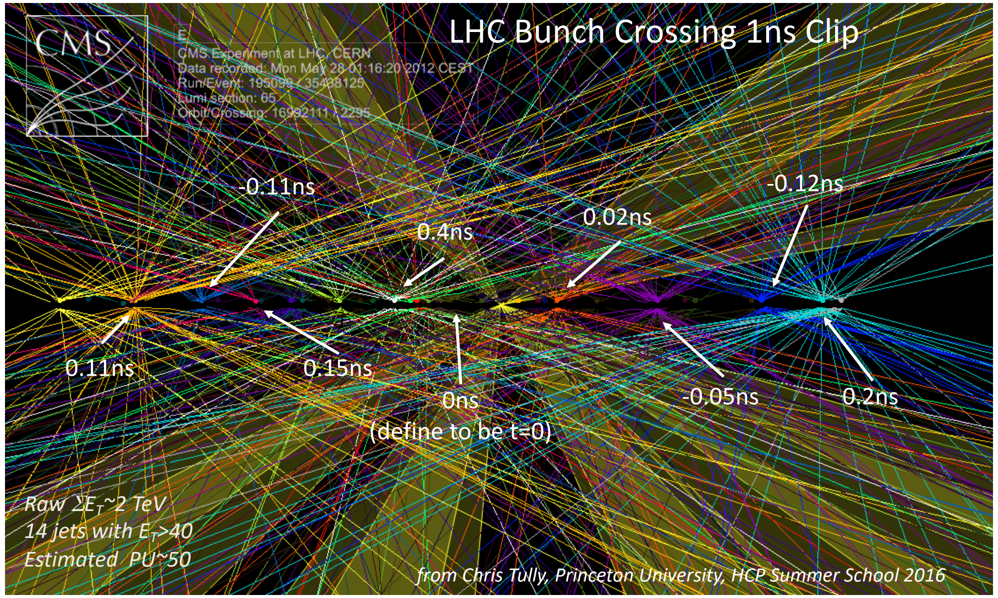
Extreme particle rates: up to $3GHz/cm^{2}$

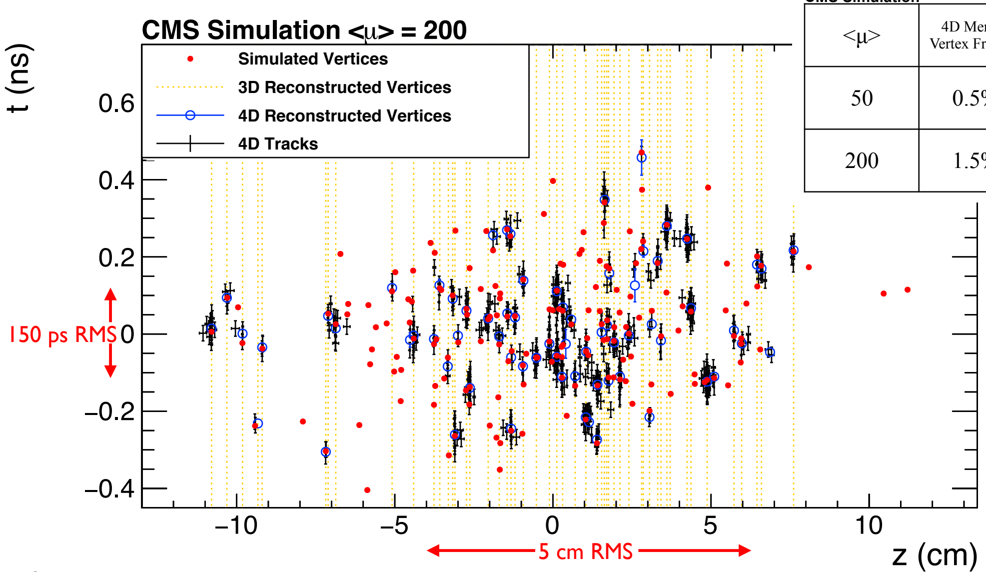
➪ Higher detector granularity (especially in the silicon trackers)

➪ extreme radiation load - radiation levels for 1^{st} pixel layer (≈ 30 mm), after 3000 fb^{-1}

Non-ionizing energy loss (NIEL), $\Phi_{eq} \approx 2 \times 10^{16}$ / cm^{2} Ionizing energy loss (IEL), Dose ≈ 12 MGy

Extreme data throughput ➪ unprecedented challenges at the trigger level and online data processing





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

LHC – ATLAS Phase II Upgrade

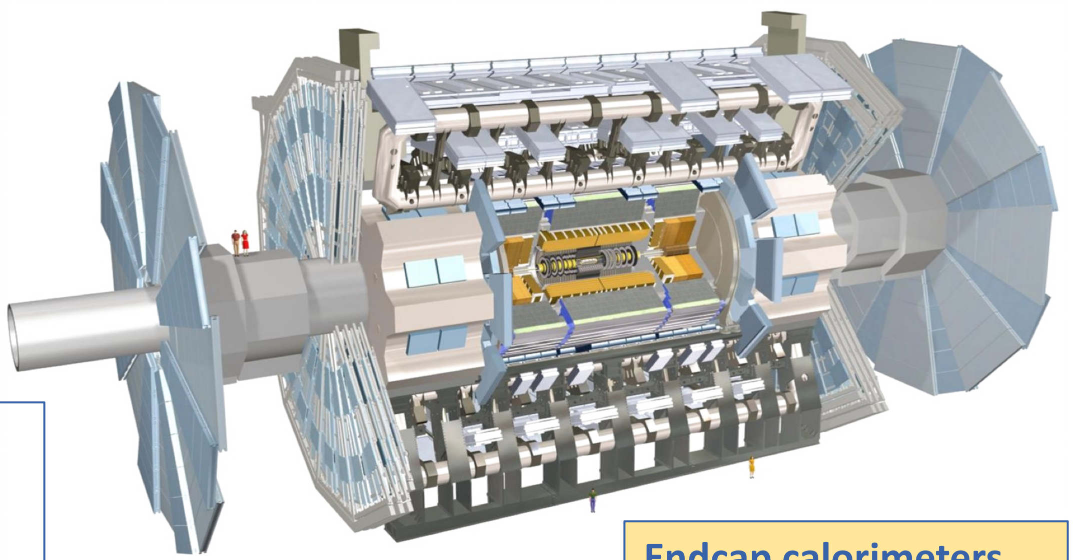
Lar Calorimeter
- **Segmented super-cells**:
  shower-shape discrimination at trigger level

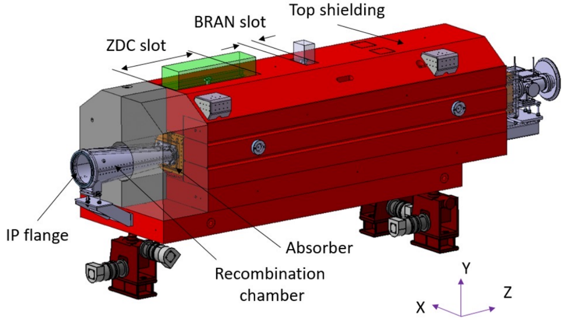
Trigger and DAQ
- **L1 and HLT improvements**
- Further upgrades

Electronics upgrades

Luminosity Detectors

Forward timing detector
- based on Low-Gain Avalanche Diodes (**LGADs**)
- PID with $\sigma_{TOF} \approx 35ps$





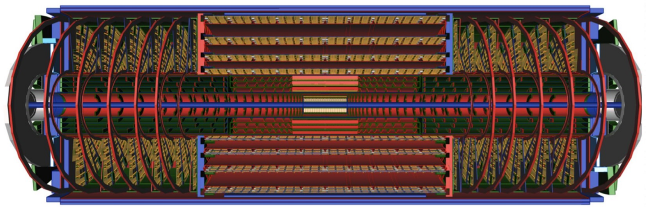
HL-ZDC
- JZCaP (jointly with CMS)
- increase radiation hardness
- Reaction plane detector

Muon system
- **New Small Wheels installed in LS2**
  g sTGC + Micromegas
- New muon chambers

Endcap calorimeters
- higher granularity

- Extended tracker acceptance to $|\eta| < 4$
- Time-of-flight PID $2.5 < |\eta| < 4$
- Endcap calorimeters with higher granularity

New Inner Tracker (ITk)
- hybrid silicon pixel and strip detectors
- extended coverage up to $|\eta| < 4$

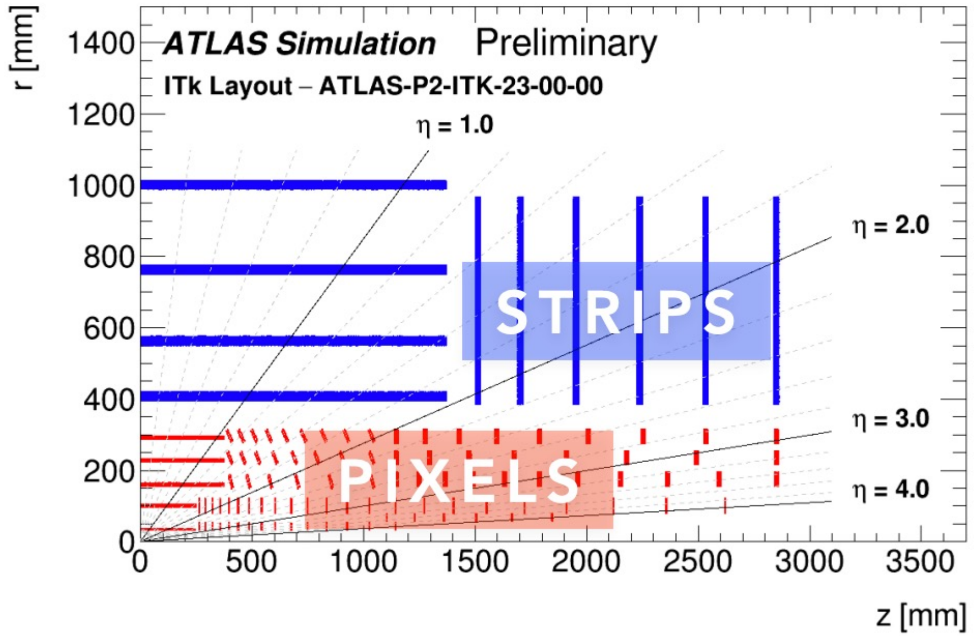


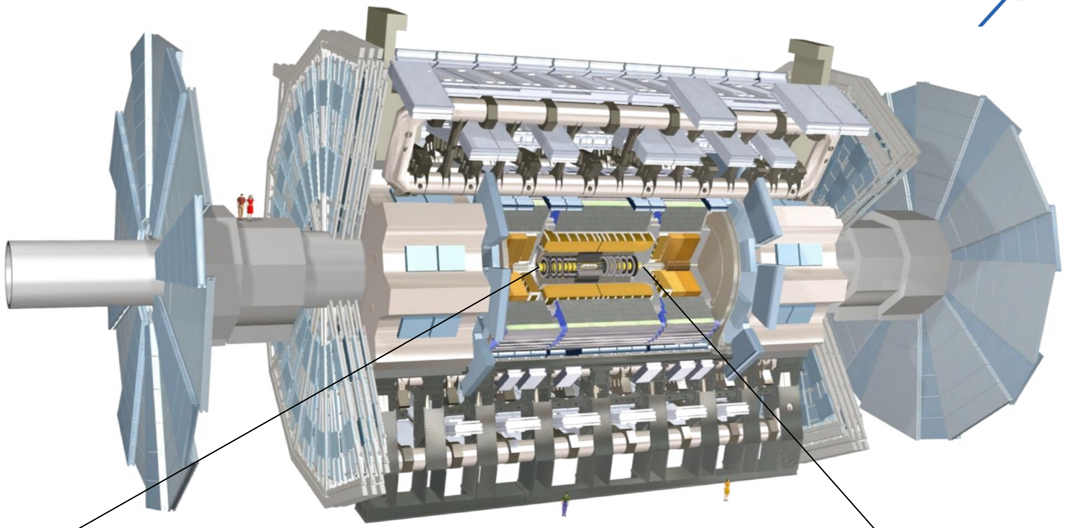
Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6

LHC – ATLAS Phase II Upgrade

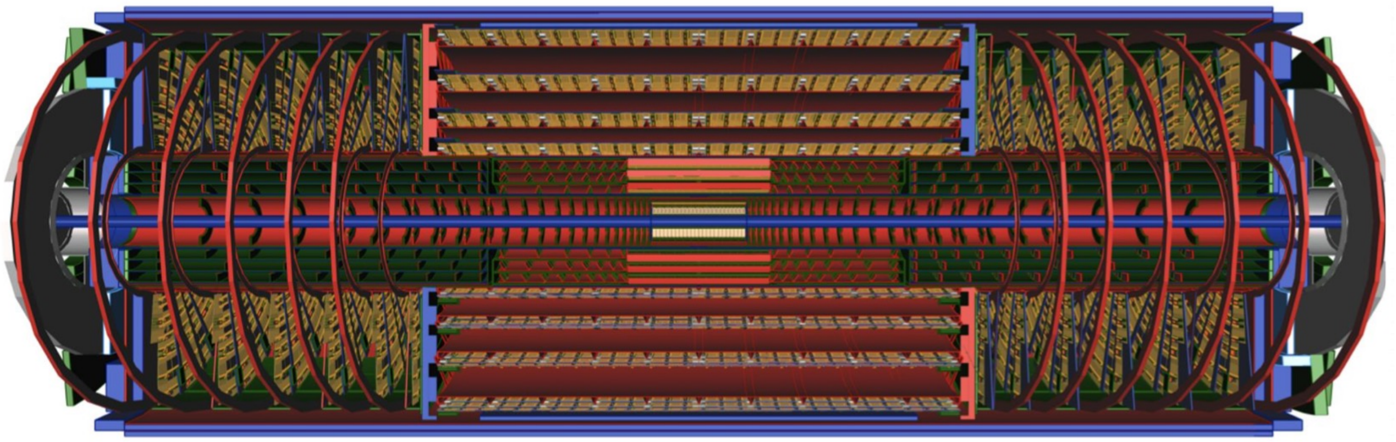
Phase II upgrades will bring benefits for heavy-ion physics

- silicon-based inner tracker with wider η coverage
- high-granularity timing detector (forward) provides time of flight





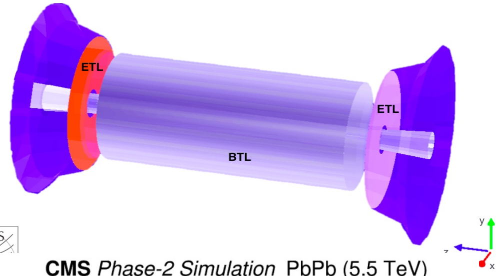
~200 m^2 of silicon

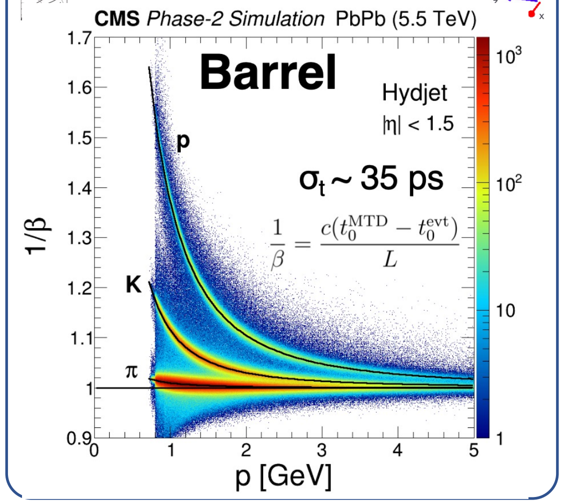


Run 1 Run 2 Run 3 Run 4 Run 5 Run 6

LHC – CMS Phase II Upgrade

Timing Detector
- barrel: LYSO + SiPMs
- endcaps: LGADs
- $\sigma_{TOF} \approx$ 30ps

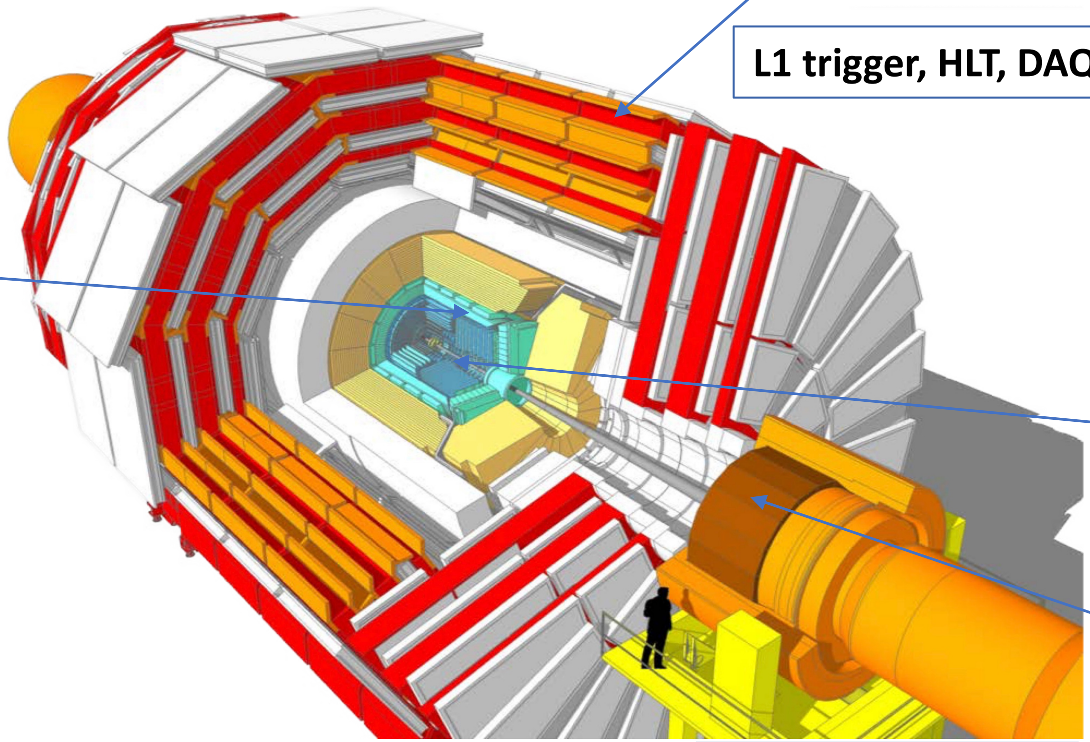




Luminosity Detectors

New Readout for Muon System

L1 trigger, HLT, DAQ



HL-ZDC
- JZCaP (jointly with ATLAS)
- increase radiation hardness
- Reaction plane detector

New Tracker
- inner: hybrid silicon pixels extended
- outer: hybrid silicon pixels + strips

Endcap calorimeter
- high-granularity Ecal + HCal → 4d showers ($\sigma_t \approx$ 20ps)

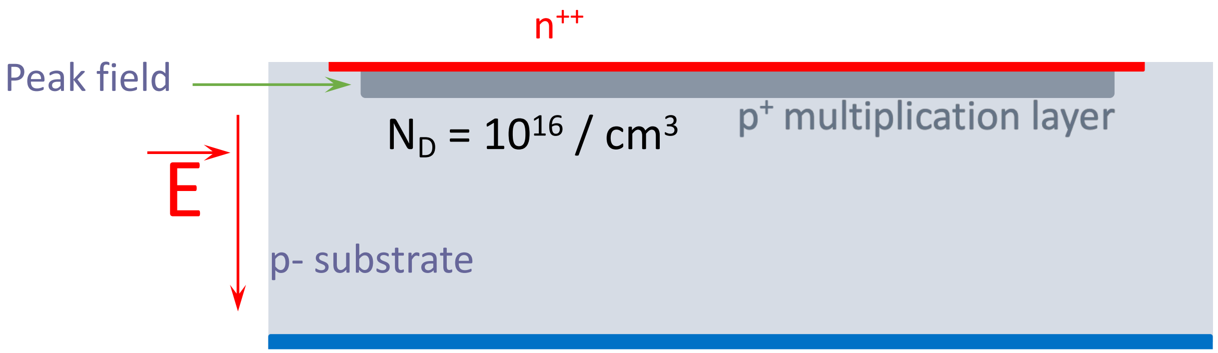
Hcal: HPD → SiPMs

- Charged particle tracking up to |η| < 4, muons up to |η| < 3
- Time-of-flight PID up to |η| < 3
- high-precision vertexing, wide coverage calorimetry

Forward Muon system
- All GEM chambers
- New frontend electronics for CSC endcaps

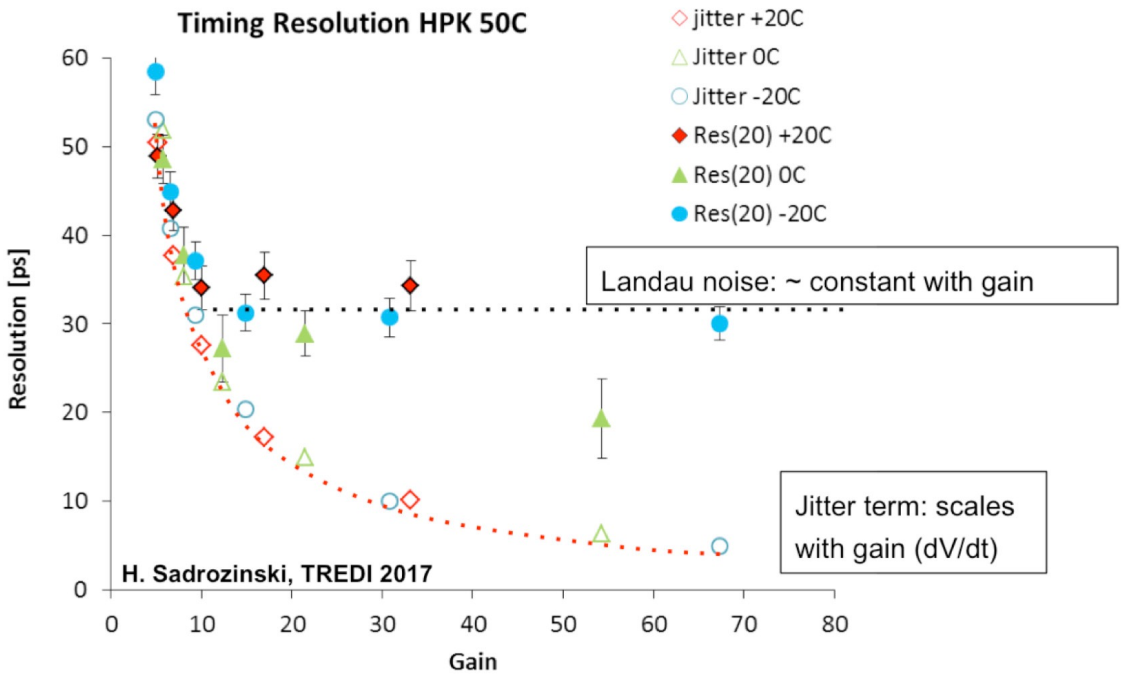
Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6

Low Gain Avalanche Detectors (LGAD)



H. Sadrozinski et al.,NIM A730 (2013) 226-231, NIM A831 (2016) 18-23

N. Cartiglia et al. NIM A796 (2015) 141-148, NIM A845 (2017) 47-51



Charge multiplication

- in silicon sensors happens for E ~ 300kV/cm
- Electrons (to less extent holes) acquire sufficient kinetic energy to generate additional e-h pairs

A field of 300kV/cm is obtained by implanting an appropriate charge density that locally generates high fields (N_D~10^{16}/cm^3)

The gain has an exponential dependence on the electric field and the path length in the high field

- Jitter term continues to decrease with gain
- Timing resolution plateaus to Landau noise value
- Thickness 50 microns

LHC – LHCb Phase IIb Upgrade

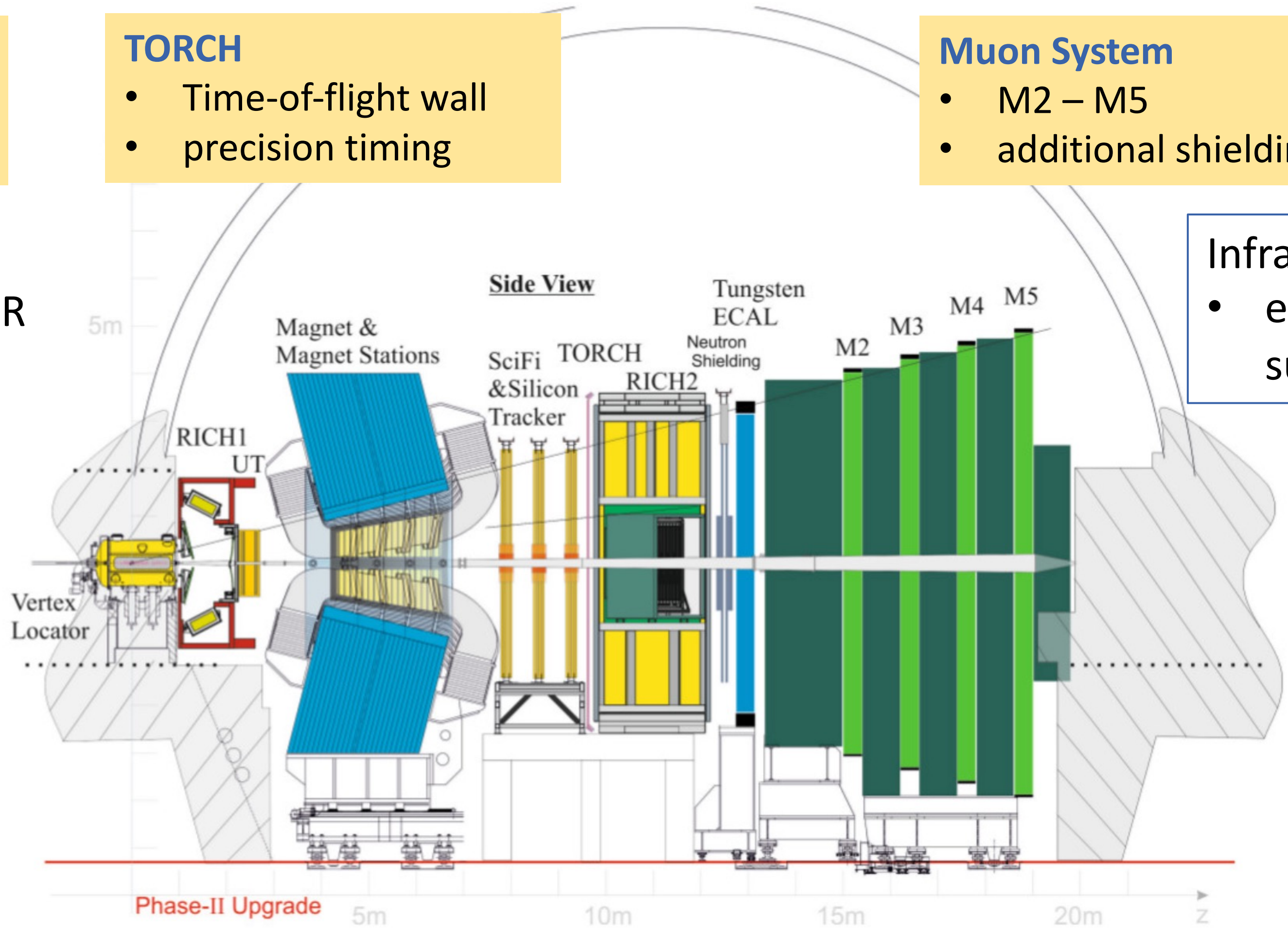
RICH
- RICH1 and RICH2
- precision timing

TORCH
- Time-of-flight wall
- precision timing

Muon System
- M2 – M5
- additional shielding (instead of Hcal)

Infrastructure
- engineering, mechanical support, shielding

LHCb – II Framework TDR
LHCb-PUB-2022-012



Vertex Locator (VELO)
- New VELO
- precision timing (4D tracking)

Tracking
- new Upstream Tracker (timing)
- Mighty Tracker (SciFi + silicon)
- Magnet stations (possibly) → p_T below 5 GeV/c

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

- No centrality limitations for AA
- excellent vertexing and PID capabilities

Calorimeters
- SPACAL or Shashilik
- precision timing

Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6

LHC – LHCb Phase IIb Upgrade

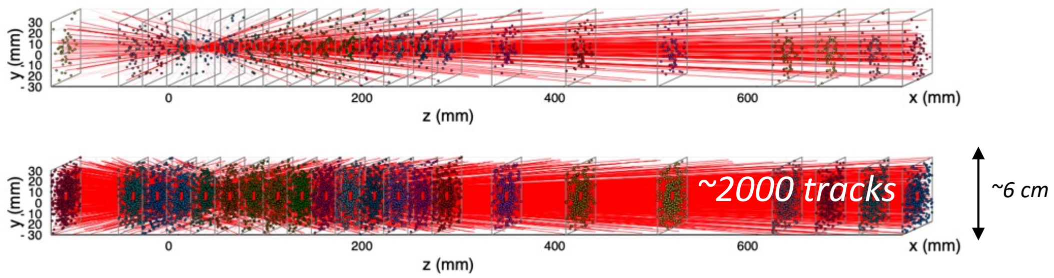
Vertex Locator – truly 4D tracking

- High-precision time tagging of space-points
- Ensures similar performance to Upgrade I
  ~50ps, 50μm^2
- Extreme lifetime fluence: 6x10^{16} n_{eq}/cm^2
- 3D sensors, 15ps LGAD & thin planar also studied

Run 3: pile-up ~6

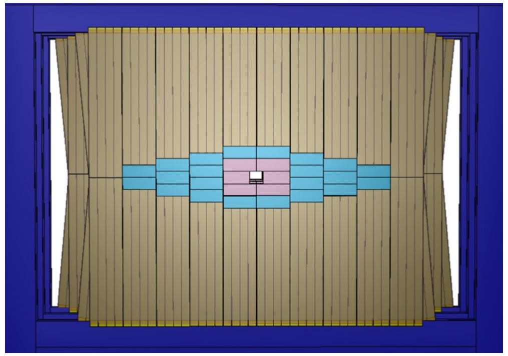
Upgrade II: pile-up ~42

VErtex LOcator (VELO)



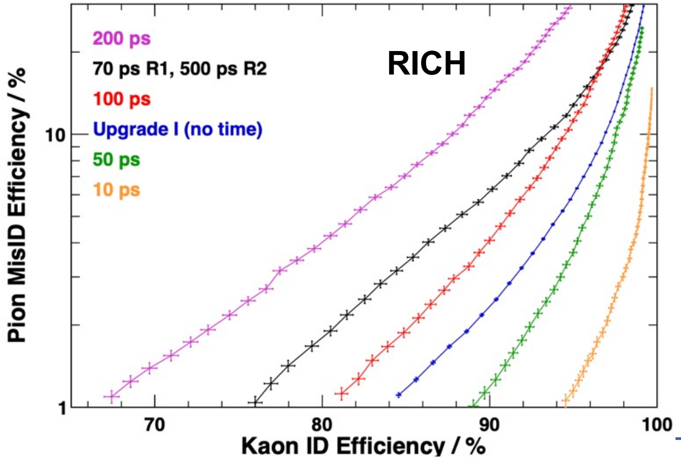
Upper Tracker – MAPS + Scintillating fibres

- Monolithic Active Pixels Sensors (MightyPix) in the inner region:
  50 x 150μm^2, 3x10^{15} n_{eq} / cm^2;
- Scintillating fibres in the outer region
  radiation-hard fibres, cryogenic cooling, micro-lens enhanced SiPMs



Hadron ID key to LHCb physics programme

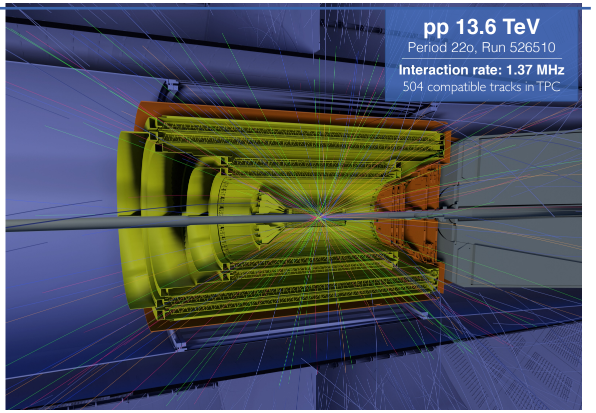
- Precision timing crucial for Upgrade II performance:
  - RICH: Time-stamping each photon with **σ_t few tens ps**
  - TORCH: **10-15ps** time resolution per track



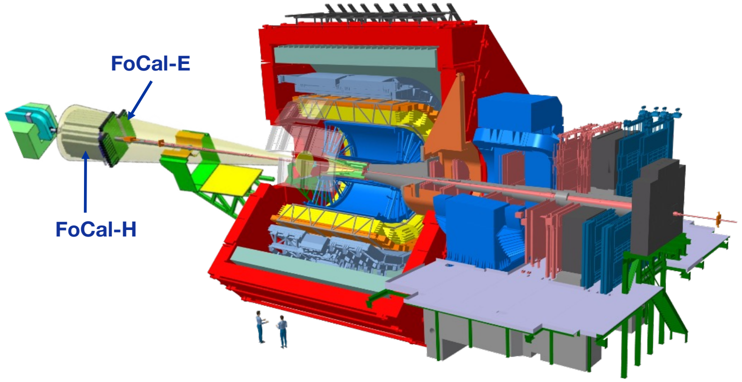
Run 1 | Run 2 | Run 3 | Run 4 | Run 5 | Run 6

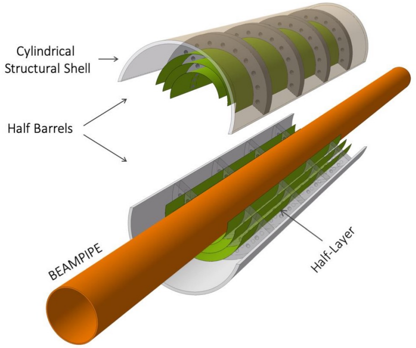
LHC - ALICE Phase IIb upgrade

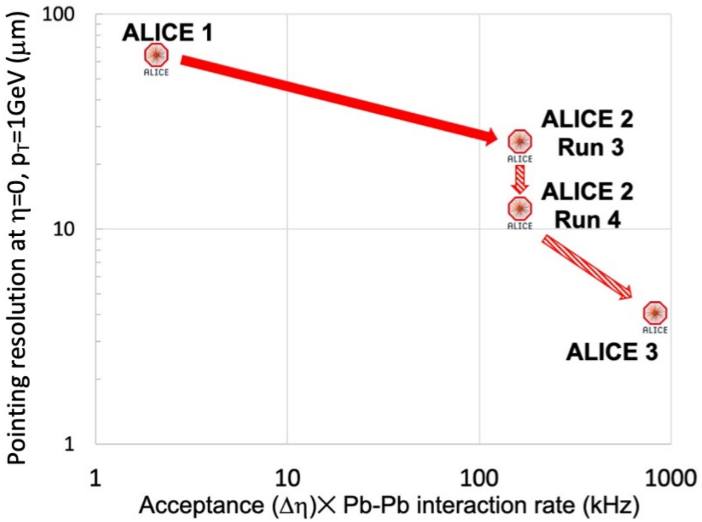
- Major ALICE upgrade in LS2 (**ALICE 2**) for Run 3 & Run 4



- Intermidiate (narrow scope) upgrades in LS3 (ALICE 2.1)







- 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

LHC - ALICE Phase IIb upgrade

Detector Overview

high-efficiency for reconstruction of (multi-)HF hadrons and of low-mass dielectrons

vertexing close to the beam with unprecedentedly low material budget

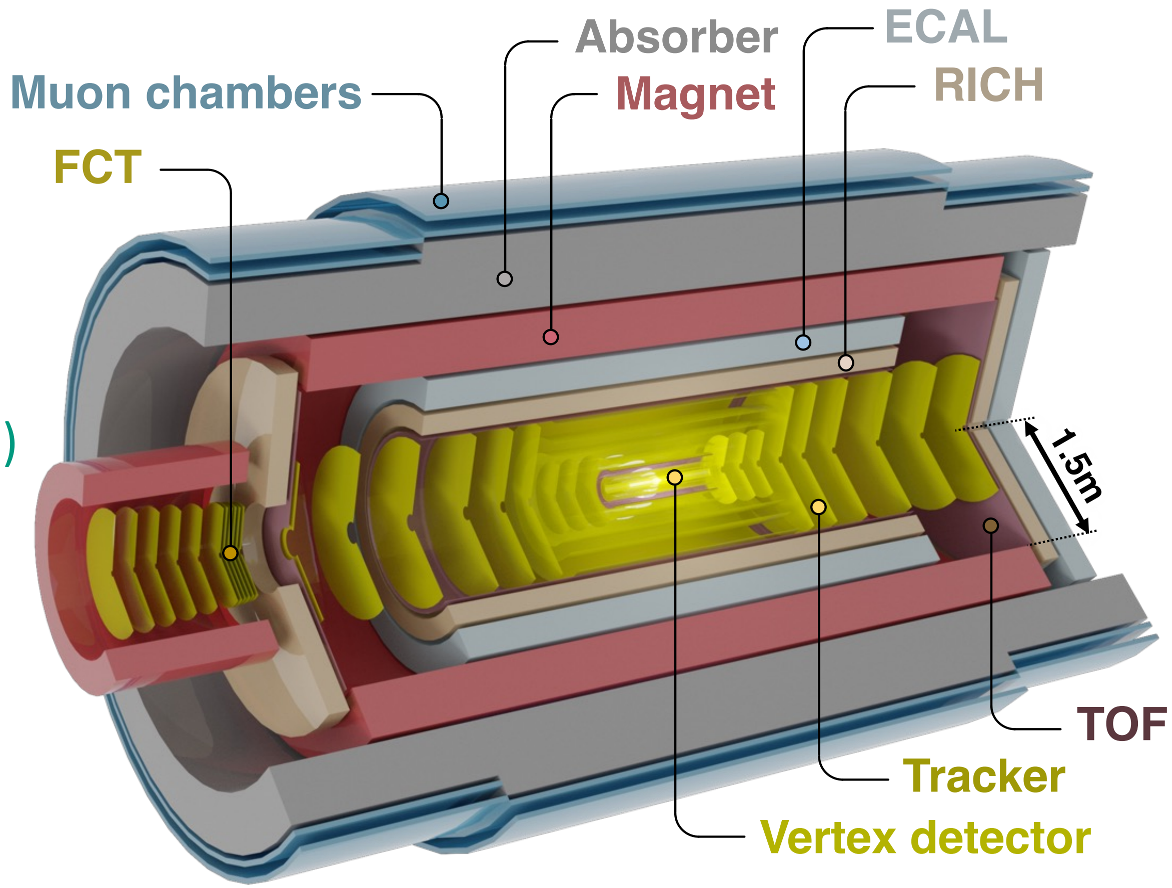
large acceptance with excellent coverage down to low p_T

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

⇨ **Vertexing precision x 3**: 10μm at p_T = 200 MeV

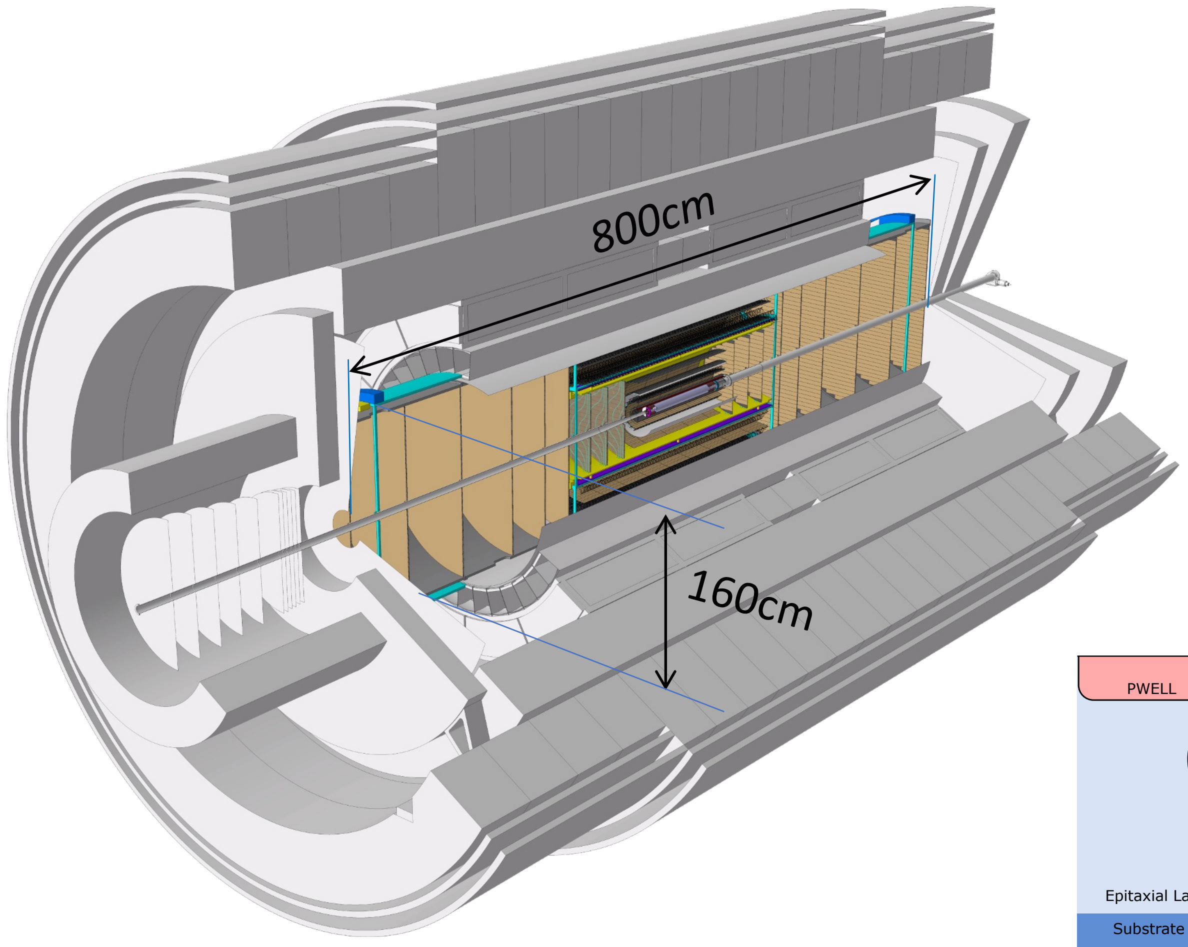
⇨ **Acceptance x 4.5**: |η| < 4 (with particle ID)

⇨ **A-A rate x 5 (pp x 25)**



⇨ novel technologies: MAPS, CMOS LGAD, combined TOF+RICH

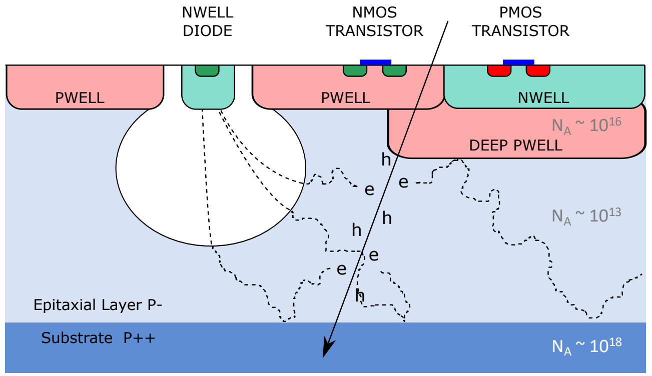
ALICE 3 – Outer Tracker

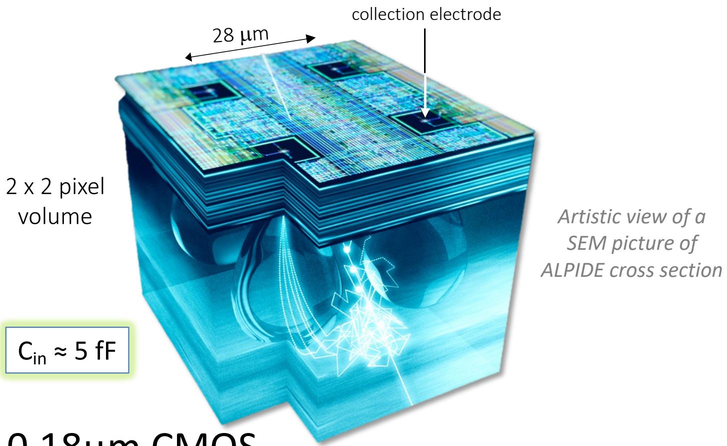


60 m^2 silicon pixel detector

based on CMOS Active Pixel Sensor (APS) technology

- large coverage: $\pm 4\eta$
- high-spatial resolution: $\sigma_{pos} \approx 5\mu m$
- very low material budget: X/X_0 (total) $\lesssim 10\%$
- low power: $\approx$ 20 mW/cm^2



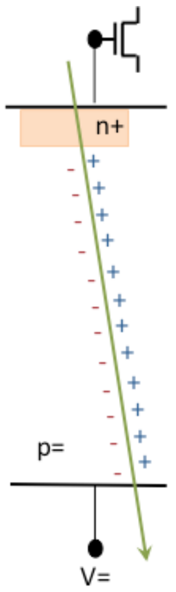


ALICE ITS2 CMOS Pixel Sensor (ALPIDE) - 0.18μm CMOS

⇨ build on experience with ITS2 and ITS3, use CMOS technology with smaller feature-size transistors (65nm)

Low-capacitance pixel sensors

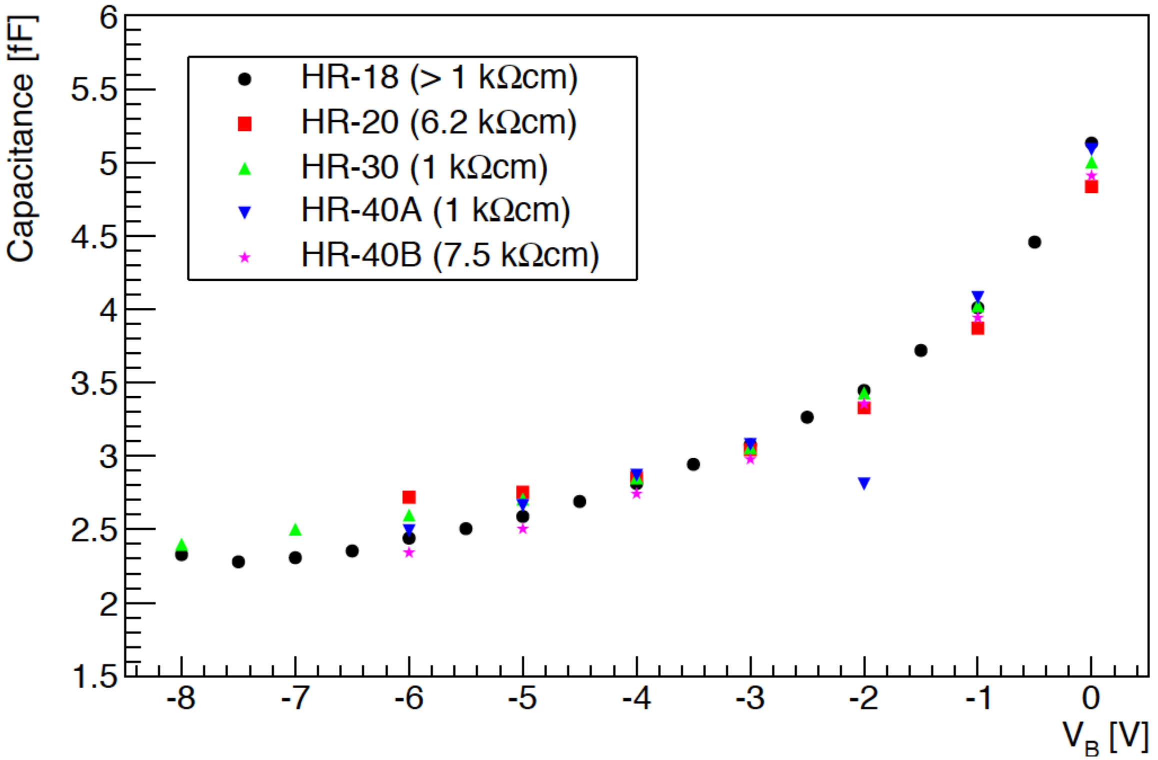
Low capacitance ➔ large S/N at low power



NWELL DIODE output signal = Q /C

- Minimize spread of charge over many pixels
- minimize capacitance:
  - ➡ small diode surface
  - ➡ large depletion volume

Explorer chip (ALICE R&D)



☞ Silicon strip capacitance: > 10 pF (~1.5 pF / cm)

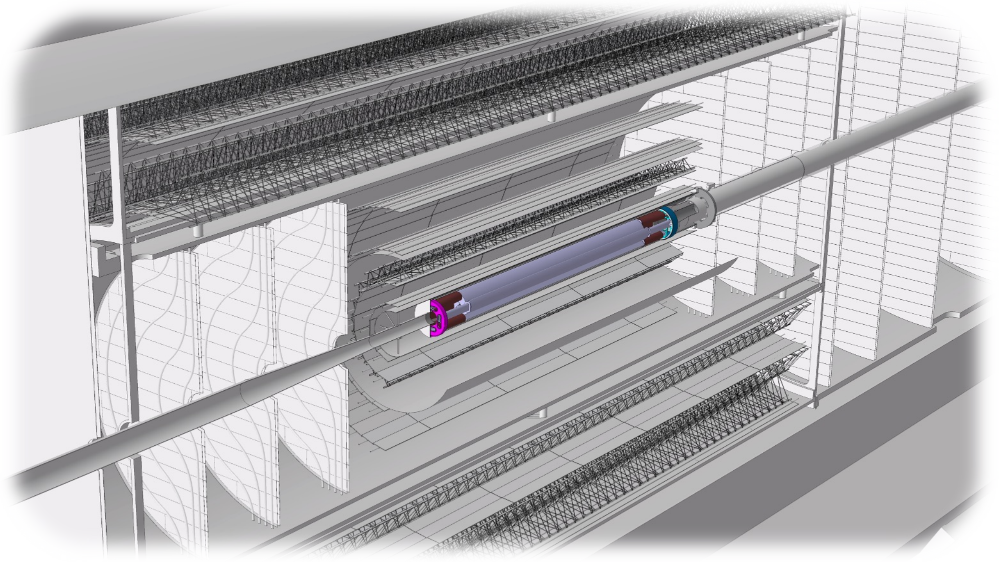
☞ Hybrid pixel capacitance: ~300 fF

☞ MAPS "small electrode" pixel capacitance: < 5 fF

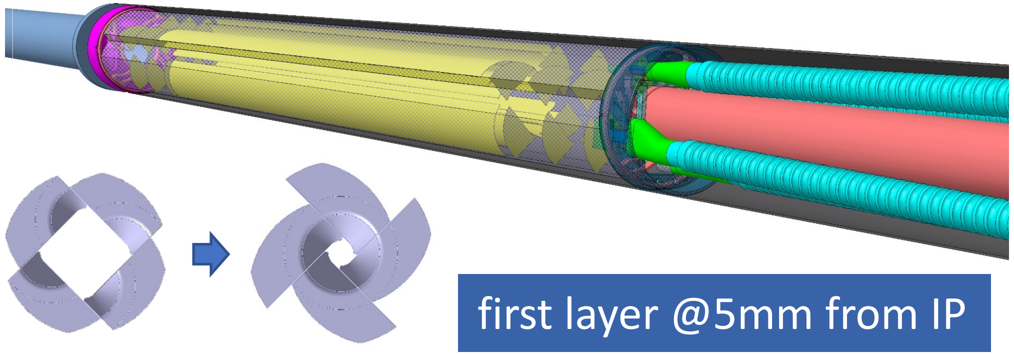
C_d = 1fF: 1300 e^- ➔ 200mV (digital signal)

ALICE 3 – Vertex Detector

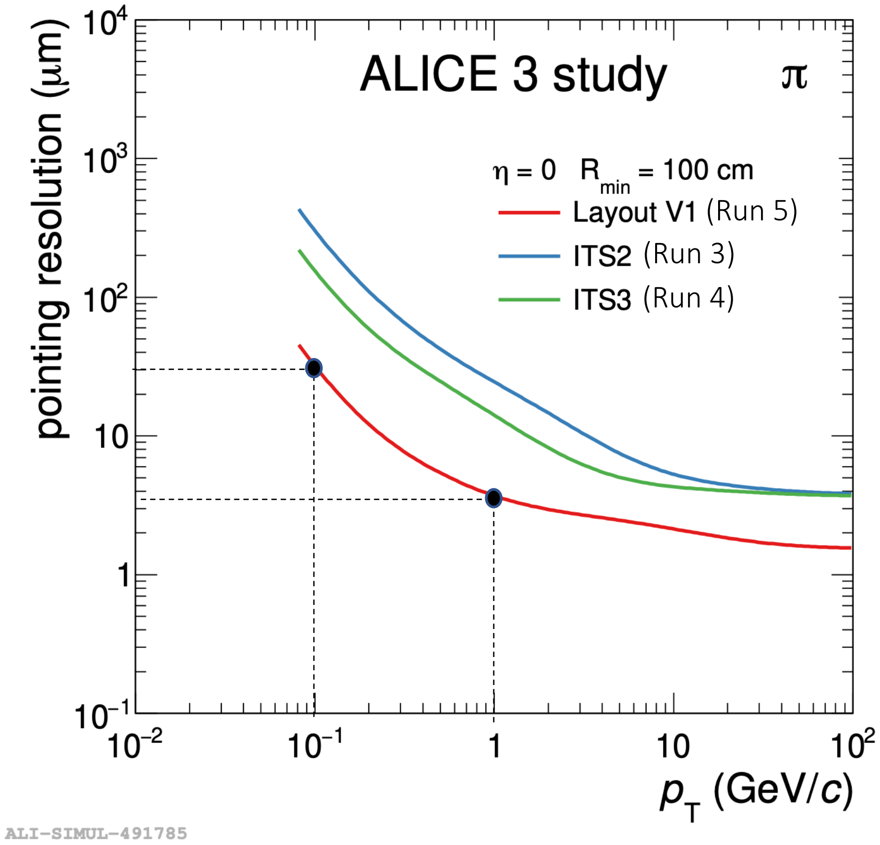
retractable vertex detector concept inside beampipe



rotary petals in secondary vacuum



first layer @5mm from IP



pointing resolution

~ few μm at 1 GeV/c, 30 μm at 100 MeV

→ critical for HF measurements and dileptons

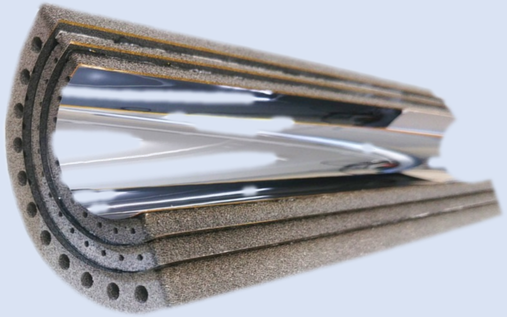
ALICE 3 – Vertex Detector

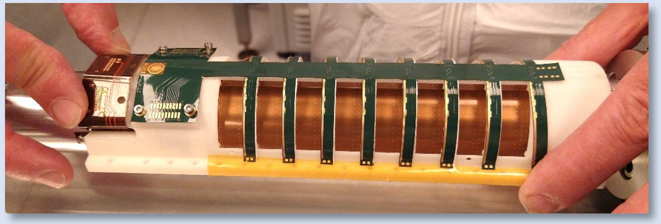
unprecedented performance

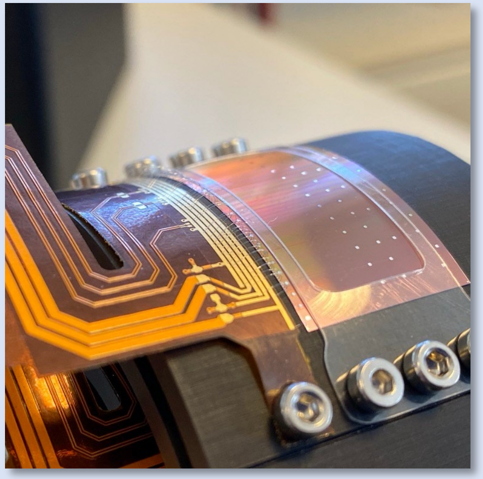
wafer-size, ultra-thin, curved, CMOS APS sensor

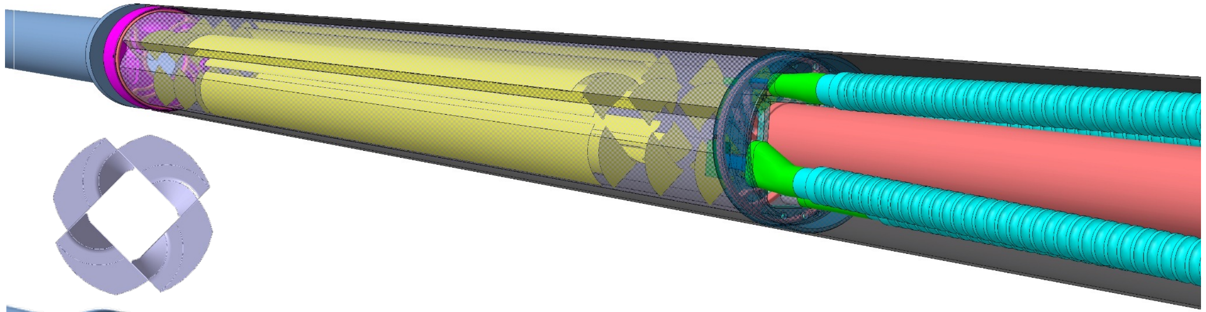
- 5mm radial distance from interaction point (inside beampipe, retractable configuration)
- unprecedented spatial resolution: $\sigma_{pos} \approx 2.5\ \mu m$
- … and material budget $\approx 0.1\%\ X_0$ / layer

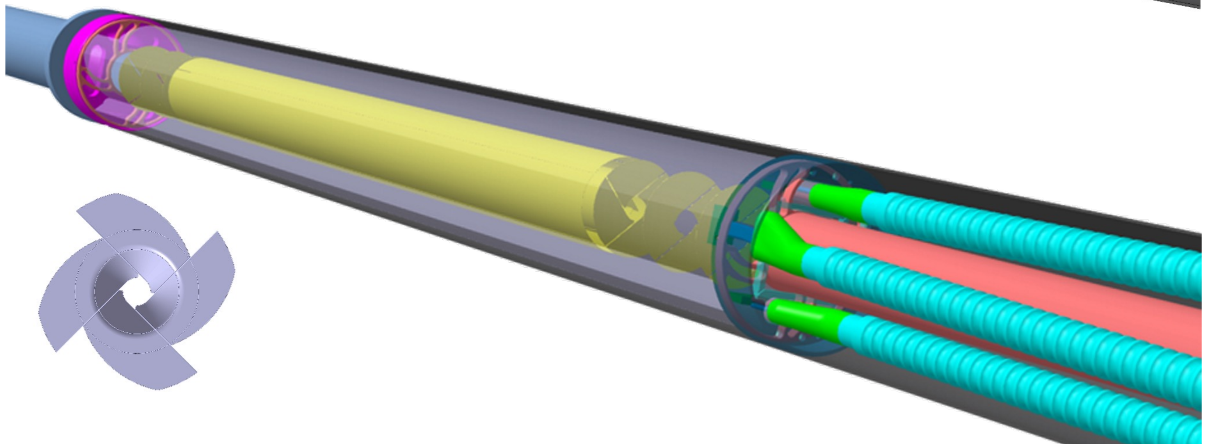
ITS3 R&D







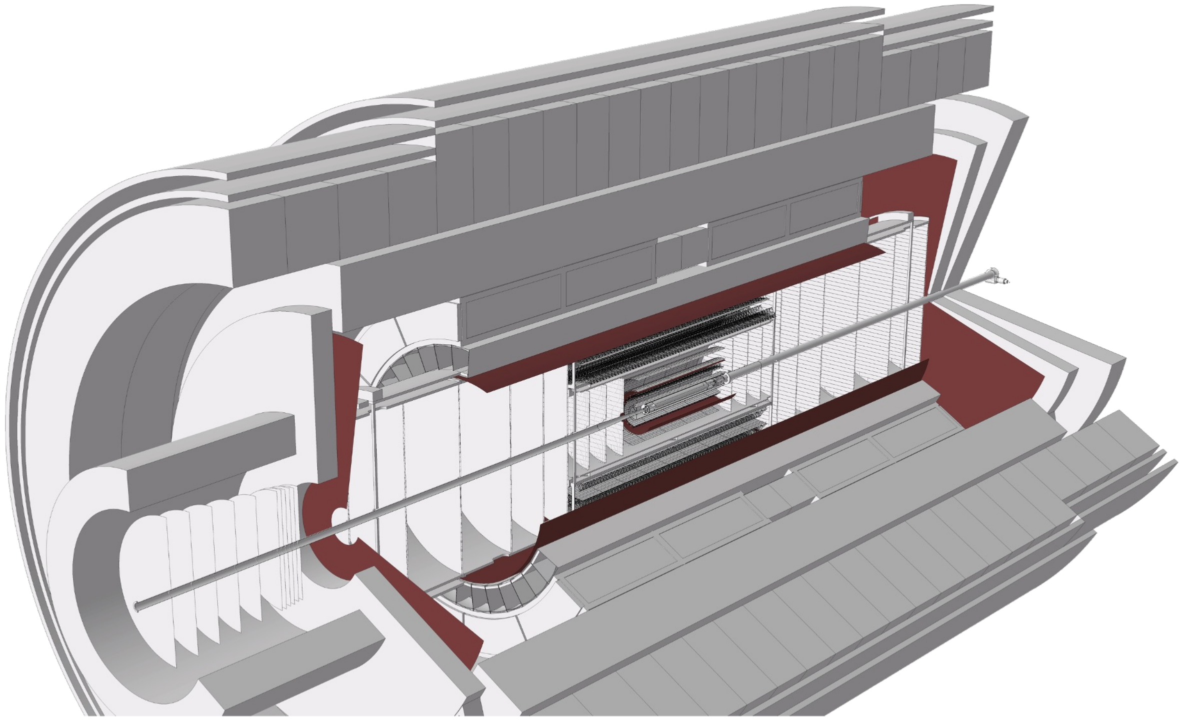




R&D on

- wafers-sized, curved sensors (**same as for ITS3**)
- **advanced mechanics and cooling for integration inside beampipe** (rotary petals, matching beampipe parameters, feed-through for services)

ALICE 3 – Time Of Flight



Barrel TOF ($|\eta| < 1.75$)

- Outer TOF radius = 85cm
  surface: $30m^2$, pitch: 5 mm
- Inner TOF, radius = 19 cm
  surface: $1.5m^2$, pitch: 1 mm

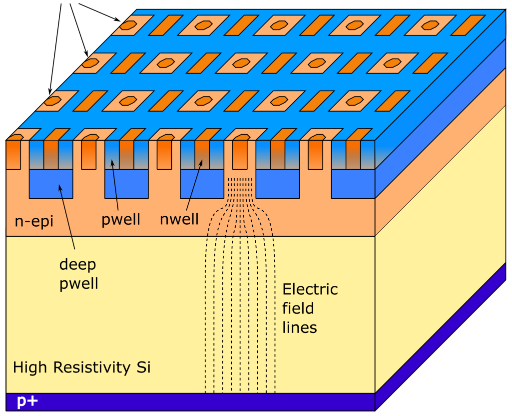
$\sigma_{TOF} \lesssim 20ps$

Forward TOF ($1.75 < |\eta| < 4$)

- Inner radius = 15 cm, Outer radius = 150 cm
  surface = $14m^2$, pitch = 1mm to 5mm

Two R&D lines

- **CMOS LGAD (baseline):** main R&D line in ALICE
  - ➪ integration of sensor and readout in a single chip
  - ➪ easier system integration and significant cost reduction
- Conventional LGADs (fallback): R&D line in ALICE with very thin sensors



ARCADIA MAPS

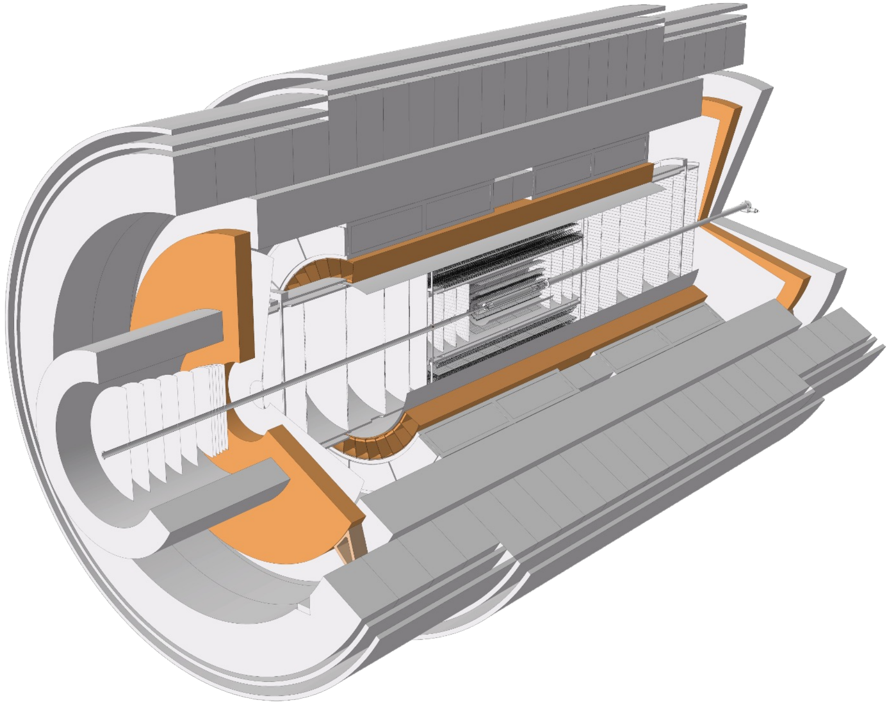
ALICE 3 – RICH

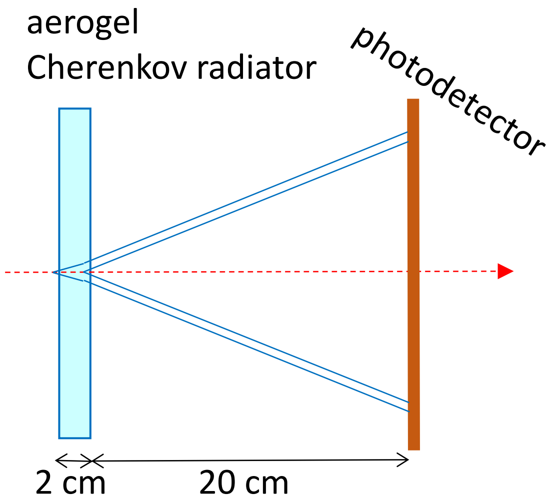
Barrel RICH ($|\eta| < 1.75$)

- radius= 0.9m, length= 5.6m
- photon detection area = 39 m^2
- pixel size = 3 x 3 mm^2

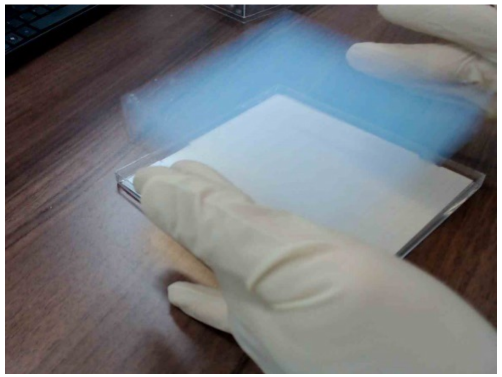
Forward RICH ($1.75 < |\eta| < 4$)

- photon detection area = 14 m^2





silica aerogel



refractive index n ≈ 1.03

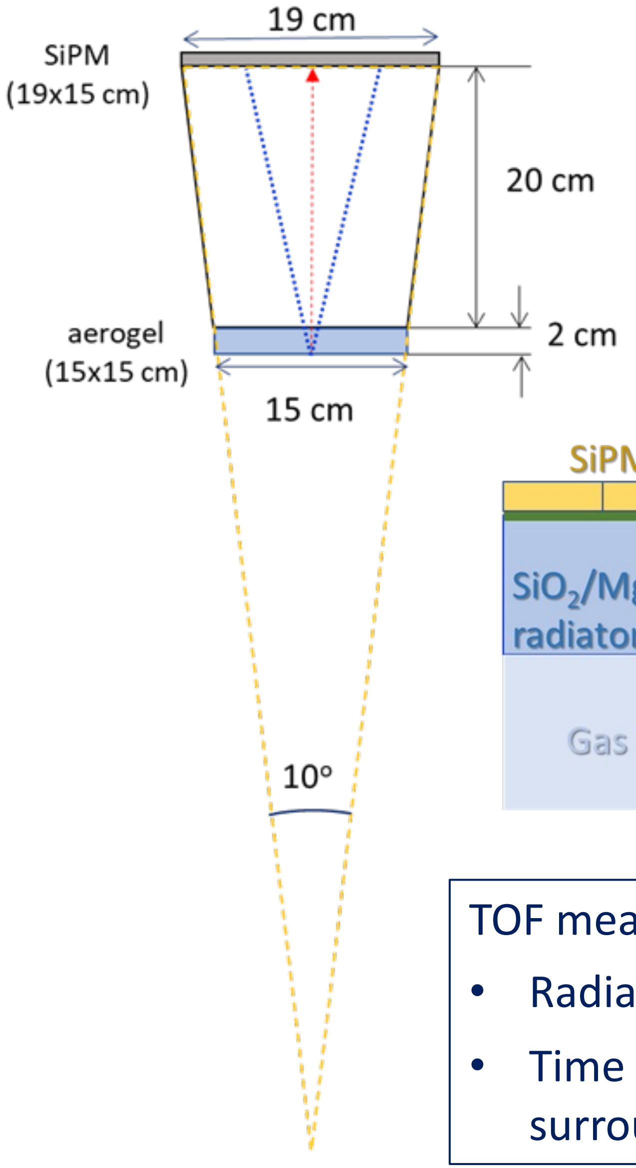
R&D focuses on photodetection

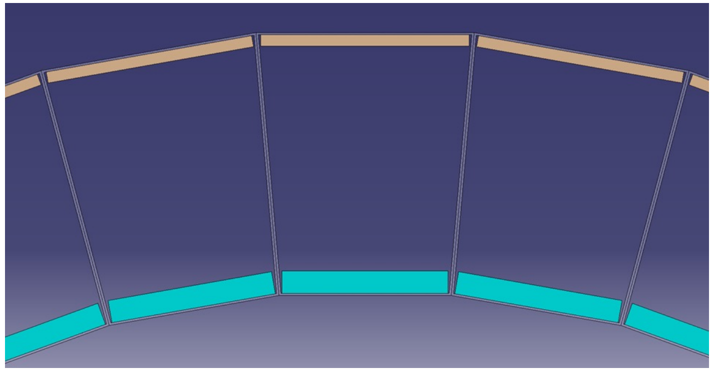
path towards monolithic photon sensors (digital SiPM)

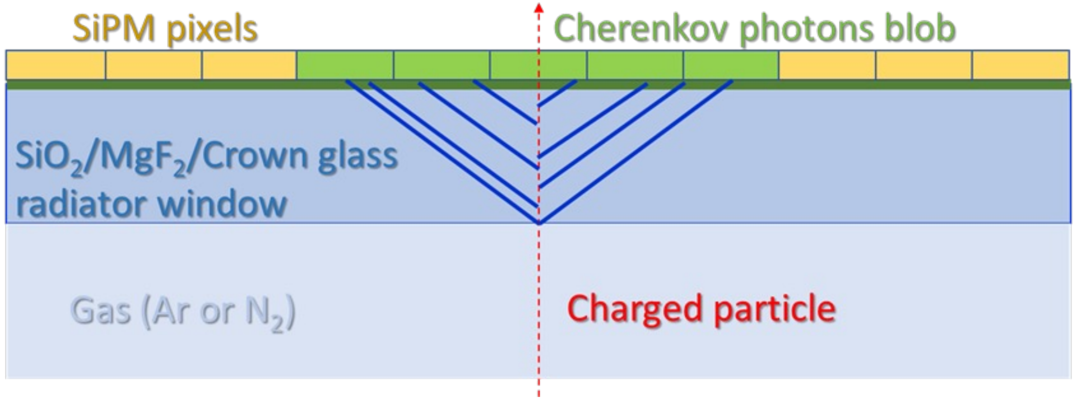
➩ massive R&D in industry for CMOS imaging sensor based single-photon avalanche diodes (SPADs)

Conservative plan: hybrid photon sensors with commercial (analogue) SiPMs and external readout chip

ALICE 3 – RICH + TOF combined in a single detector?



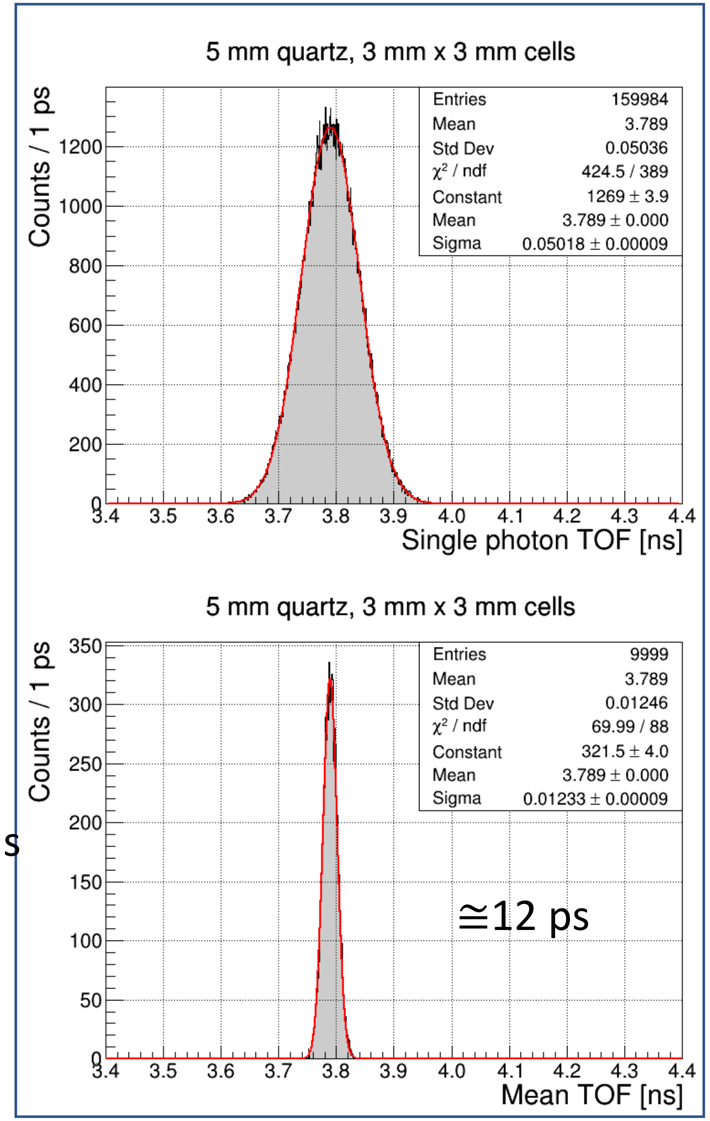




simulations

Single photon

Avg. all photons



TOF measurement in RICH SiPM layer

- Radiator window in front of photosensor (w/o gap)
- Time information from Cherenkov photon cluster surrounding the MIP

FCC-hh / SppC

CERN Future Circular Collider (FCC)

European Science Policy

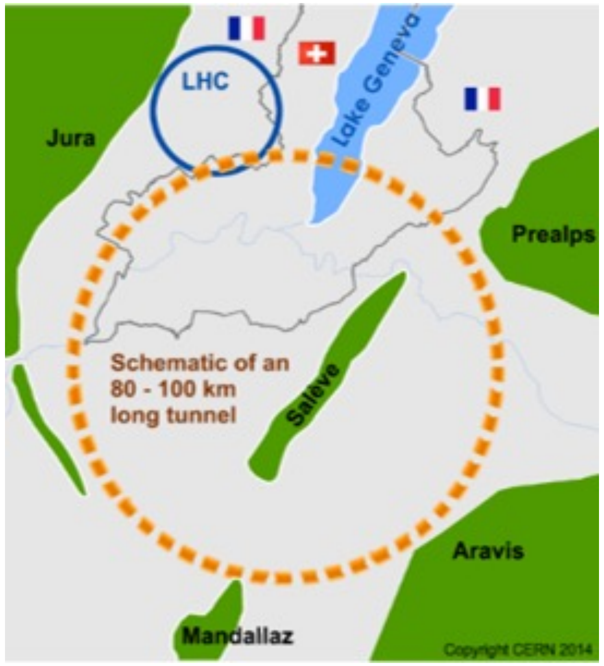
Recommendations of the 2020 update of the European Strategy for Particle Physics (ESPP):

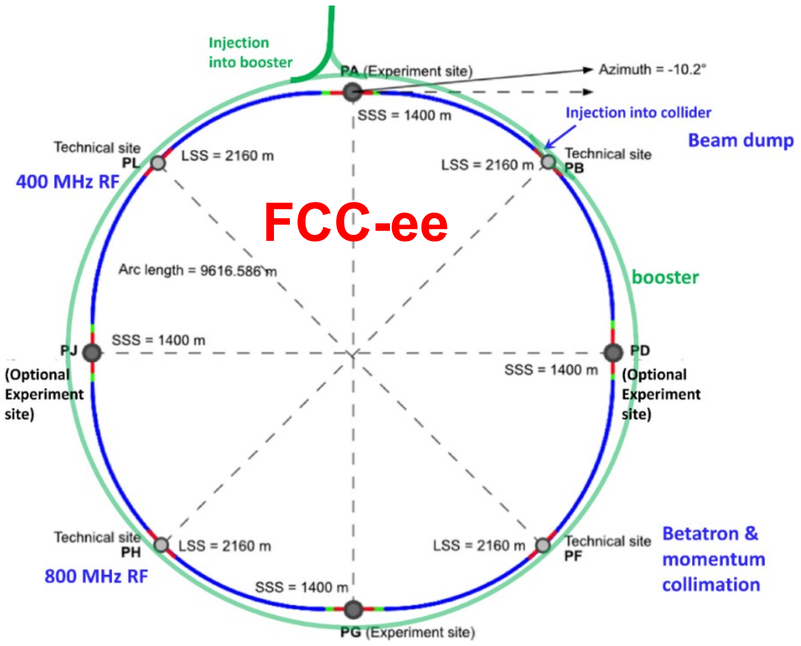
- Full exploitation of the high-luminosity LHC upgrade (HL-LHC)
- An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy.
- Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least **100 TeV** and with an electron-positron Higgs and electroweak factory as a possible first stage.
- FCC Feasibility Study is one of the main recommendations of the 2020 update of the European Strategy for Particle Physics

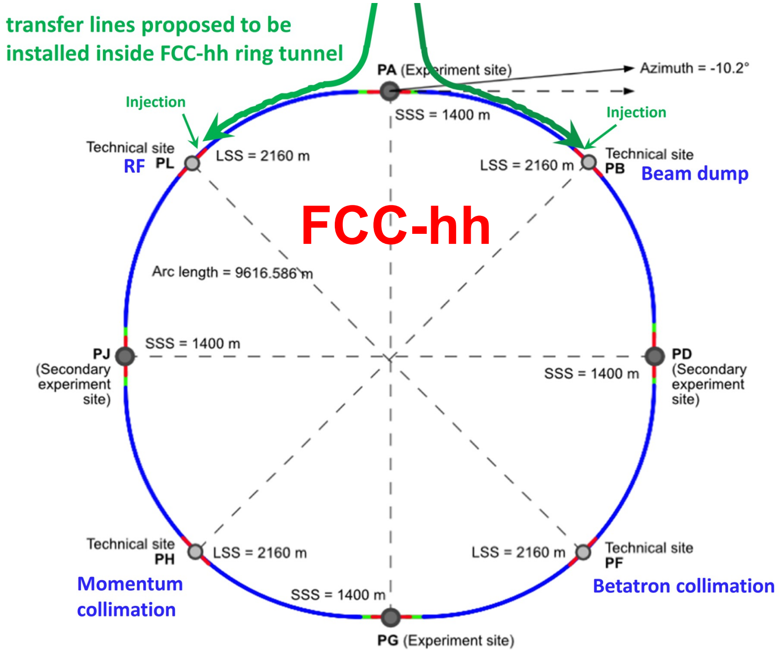
CERN Future Circular Collider (FCC)

Indicative FCC long-term program maximizing physics opportunities

- Stage 1: FCC-ee (Z, W, H, $t\bar{t}$), as Higgs, electroweak & top factory at highest luminosities
- Stage 2: FCC-hh (cme ~ 100 TeV), as natural continuation at energy frontier, **with ion and eh options**
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure





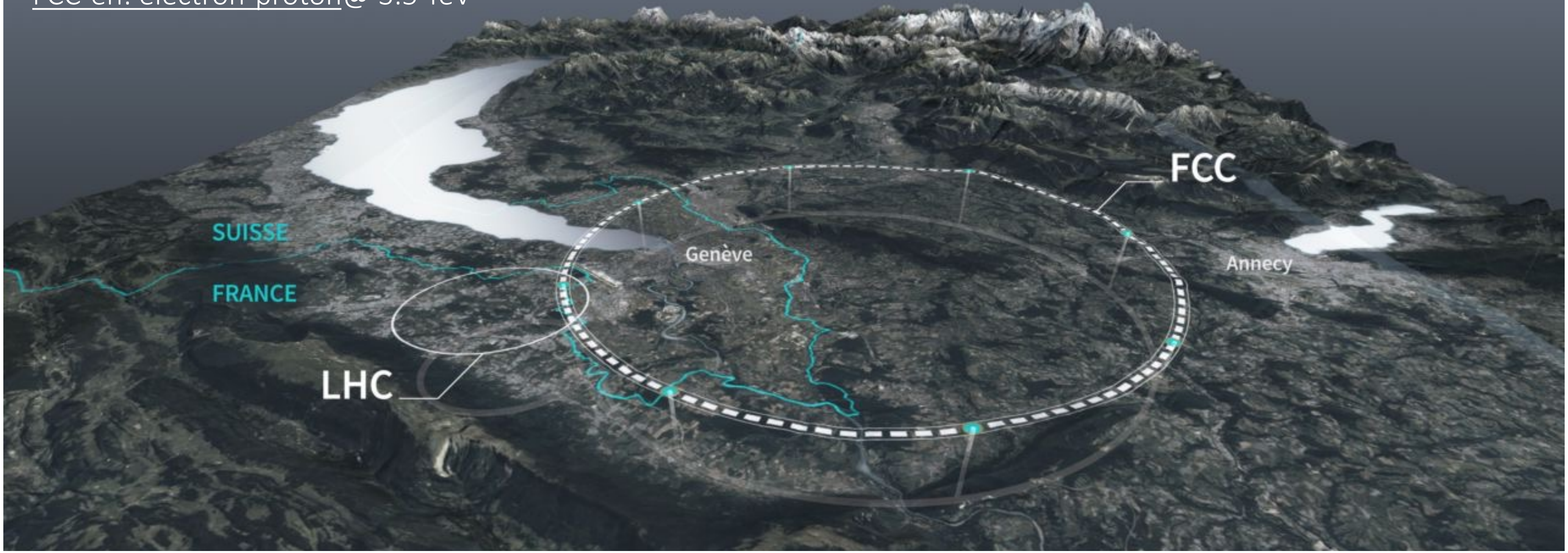


2020 - 2040 | **2045 - 2060** | **2065 - 2090**

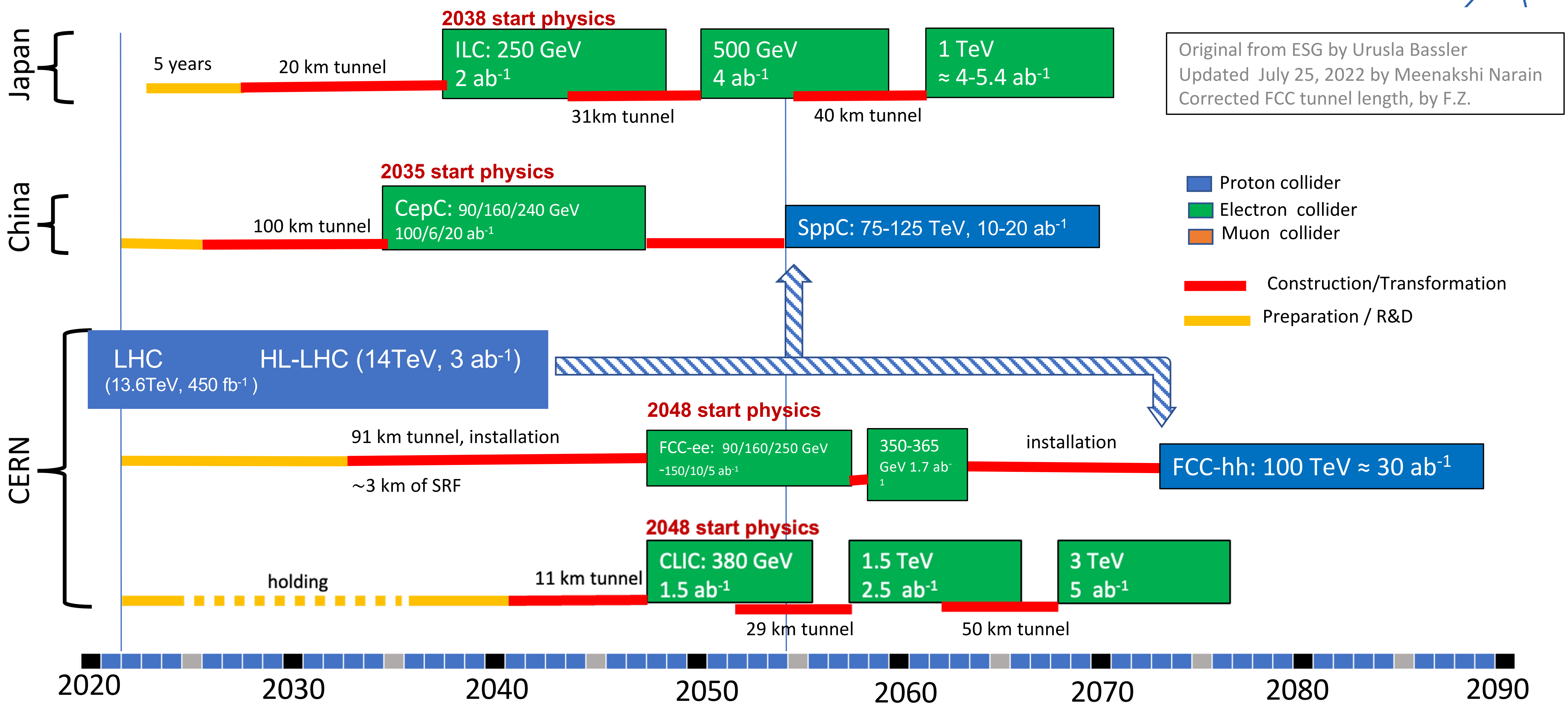
⇨ **a similar two-stage project CepC/SppC is under study in China**

CERN Future Circular Collider (FCC)

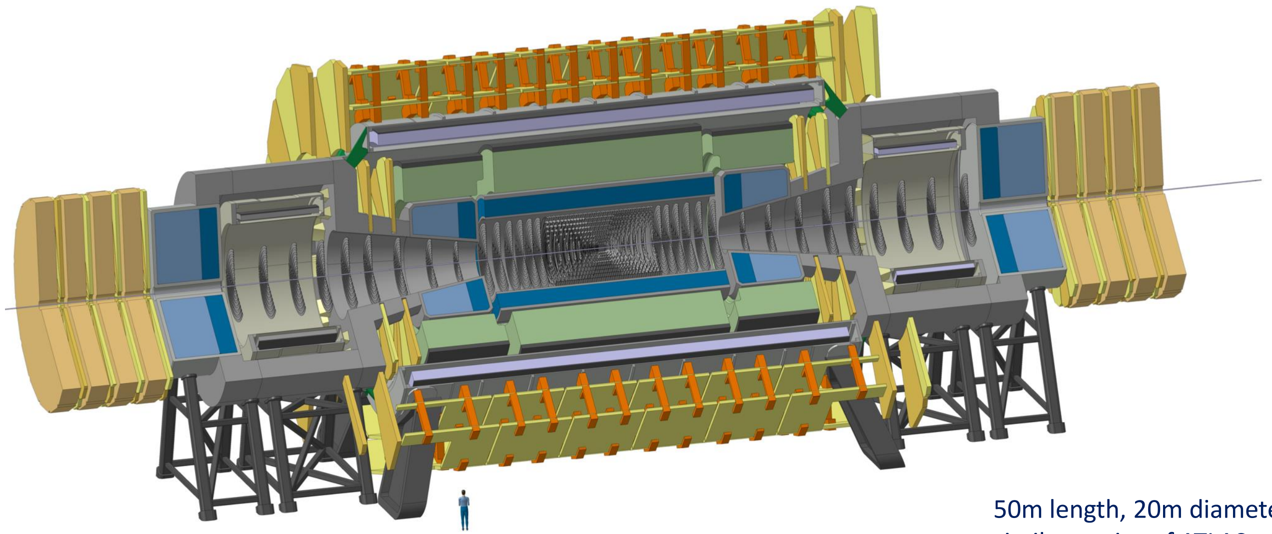
A new 91 km tunnel to host multiple colliders
100 – 300 m under ground, 8 surface sites
FCC-ee: electron-positron @ 91, 160, 240, 365 GeV
FCC-hh: proton-proton @ 100 TeV, and heavy-ions (e.g. Pb-Pb @ 39 TeV)
FCC-eh: electron-proton@ 3.5 TeV



Indicative scenarios for FCC and other future colliders

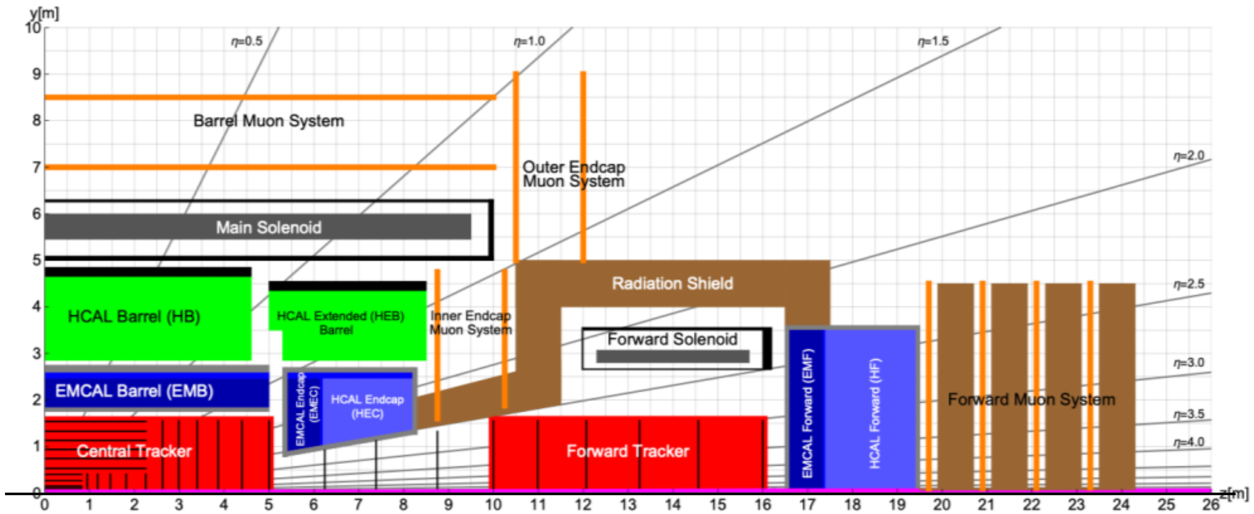


FCC-hh reference detector



50m length, 20m diameter
similar to size of ATLAS

- Central solenoid (4T) + two forward solenoids (4T)
- Silicon Tracker (400 m^2) covering $|\eta| < 6$
- ECAL & HCAL , 4 x granularity of ATLAS/CMS
- Muon system à la ATLAS



Same detector for heavy ions?

- pp with pile-up of 1000 more challanging than Pb-Pb environment;
- Excellent performance for hard probes also in HI collisions;
- Coverage for forward measurments up to $|\eta| < 6$
- Operation with reduced field would give access to low-p_T obesravables
- Silicon timing layers for pile-up rejection could be used for hadron PID

Unique studies of the QGP at the FCC

FCC-hh HI performance

- Pb-Pb $\sqrt{s_{NN}} = 39$ TeV;
- L_{int} > 100 nb^{-1} /month (projections for full LHC programme, Run 1 to 6, ~50nb^{-1})
- QGP properties (from LHC to FCC): volume x2, energy density x3, initial T_0 up to 0.8-1 Gev

Physics opportunities (some examples)

arXiv:1605.01389v3

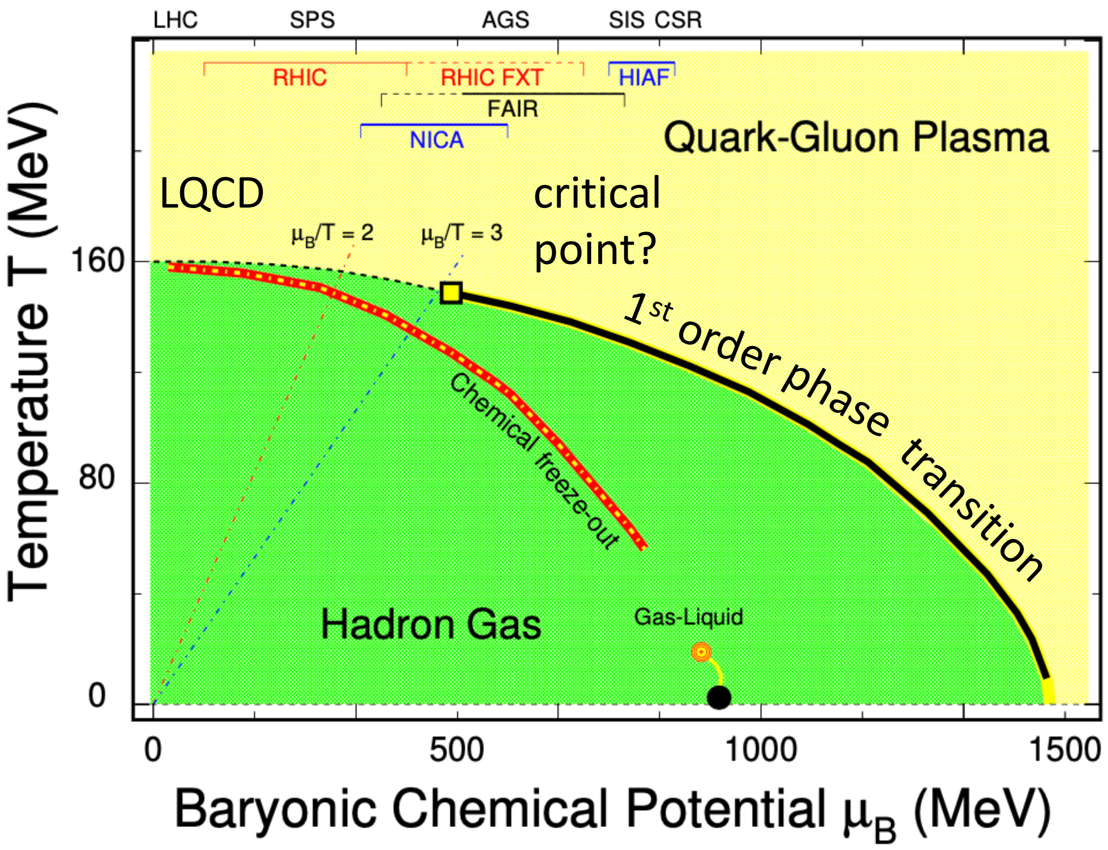
- Unique studeis of the Quark-Gluon Plasma
  - Larger temperature → thermal production of charm [1,2], Υ(1S) melting [3]
  - Larger $\sqrt{s}$ and L_{int} → new hard observables, e.g. top [4,5], Higgs [6,7] to characterize the QGP
- Unique studies of high-density intial state
  - Access to saturation region (down to x < 10^{-6}) with perturbative probes, e.g. forward-*y* di-jets [8]
  - Access to [small-x, large-Q^2] region with top, W, Z

[1] C.M. Ko, Y. Liu, JPG43 (2016) no. 12, 125108
[2] K. Zhou et al., PLB758 (2016) 434
[3] A. Andronic et al., based on JPG38 (2011) 124081
[4] D. d'Enterria et al., PLB746 (2015) 64
[5] Appolinario, Mihano, Salam, Salgado, PRL 120 (2018) 23, 232301
[6] D. d'Enterria, C. Loizides, arXiv:1809.06832
[7] D. d'Enterria, arXiv:1701.08047
[8] C. Marquet et al., based on JHEP 1612 (2016) 034

Future High Baryon Density facilities and detectors

Future high baryon density facilities

Systematic exploration of high μ_B region



Experimental approach

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

Observables

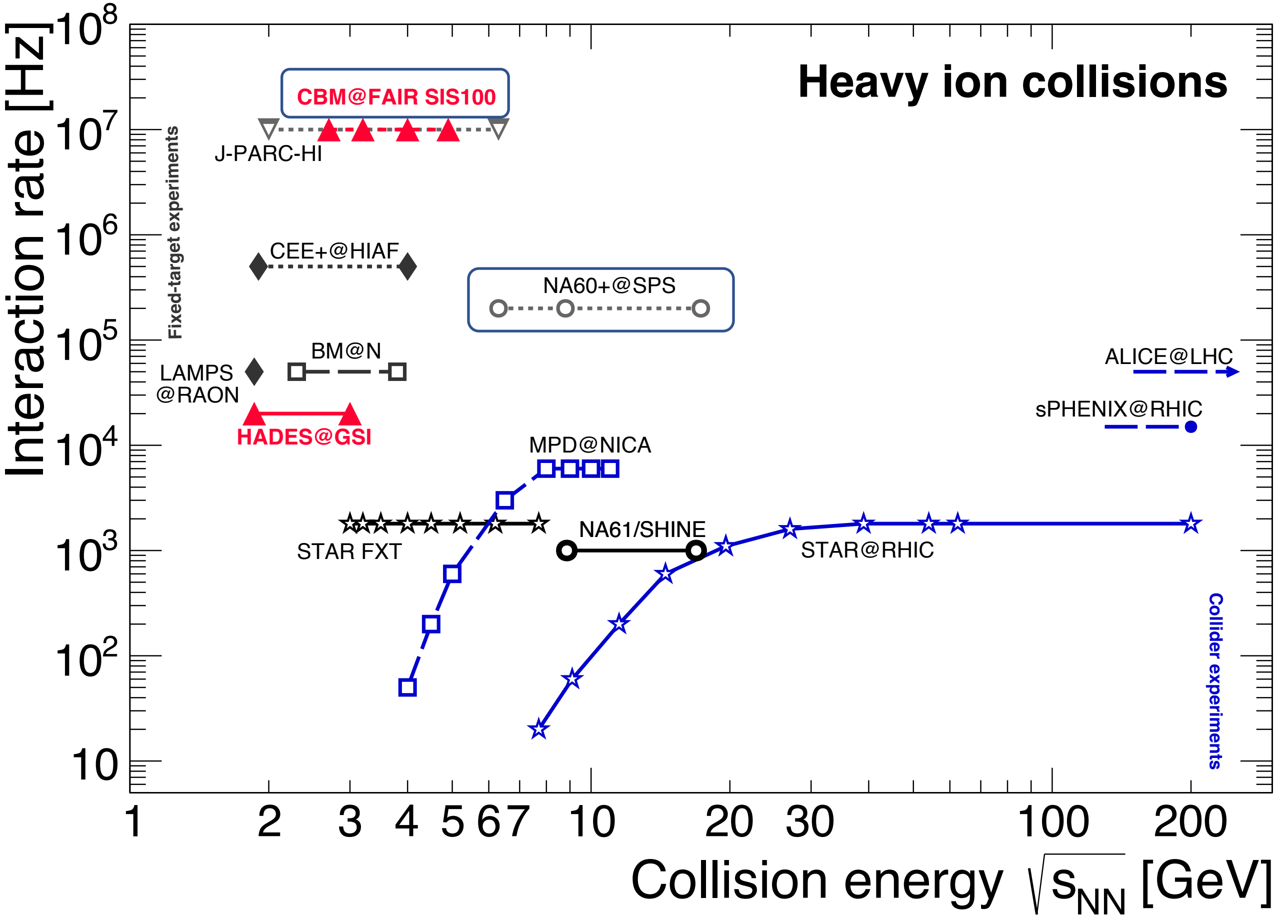
- Flavour production (multi-strange, charm)
- Dileptons (emissivity of matter)
- e-by-e correlations and fluctuations
- collective effects

$2.5 < \sqrt{s_{NN}} < 8$Gev – key region for 1st order phase transition and Critical Point search

Facilities: BNL-RHIC, CERN-SPS, FAIR-SIS, JINR-NICA, J-PARC, HIAF

Future high baryon density experiments

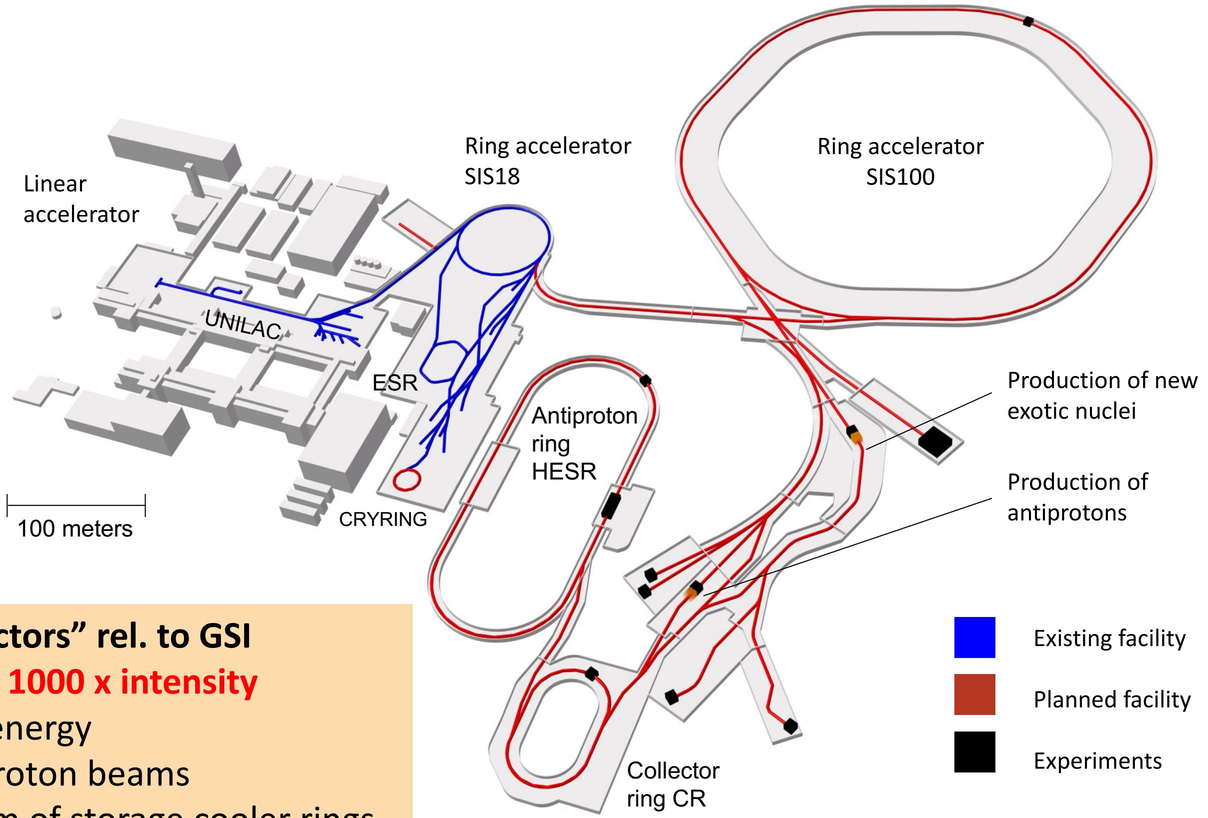
Systematic exploration of high μ_B region



T. Galatyuk, NPA 982 (2019), update 2022 (GitHub link)

Compressed Baryonic Matter (CBM) Experiment @ FAIR Facility

FAIR (Facility for Antiproton and Ion Research in Europe)

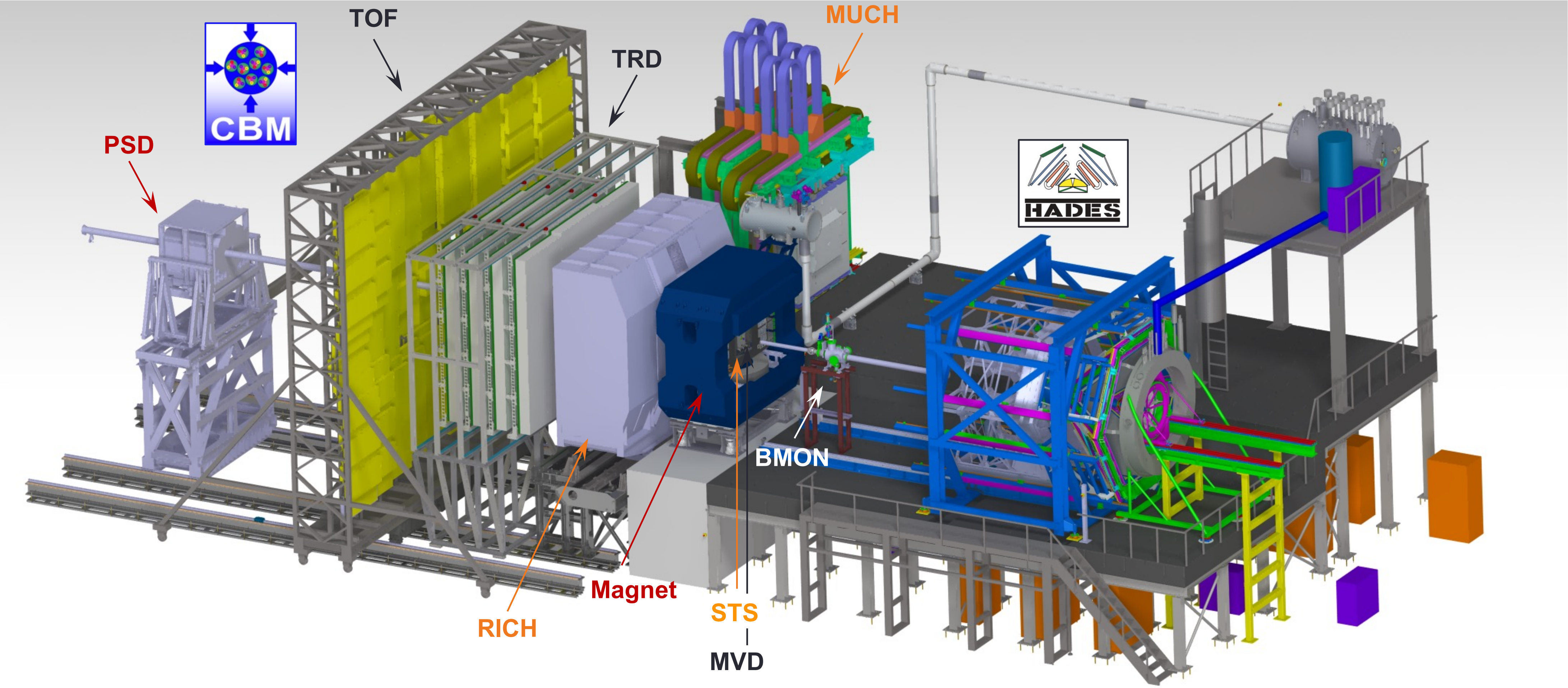


"Gain factors" rel. to GSI
- **100 – 1000 x intensity**
- 10 x energy
- antiproton beams
- system of storage cooler rings

- 1.1 km circumference (17m underground)
- Can accelerate ions of all natural elements
- Superconducting magnets (-269 °C)
- Ion beams up to kinetic energy of 11 AGeV
  ⇨ cm energy for Au-Au up to 4.9 AGeV
- Ion intensity up to 10^9/s

The four experiment Pillars
- NUSTAR – Nuclear Structure Astrophysics and Reactions
- PANDA – Antiproton Annihilation at Darmstadt
- CBM – Compressed Baryonic Matter
- APPA – Atomic, Plasma Physicis and Applications

Compressed Baryonic Matter (CBM) Experiment

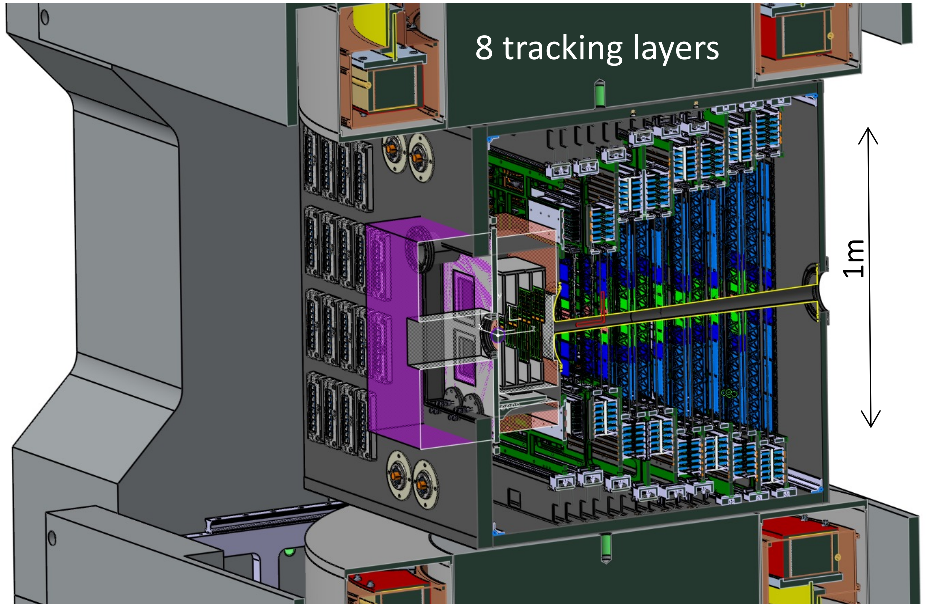


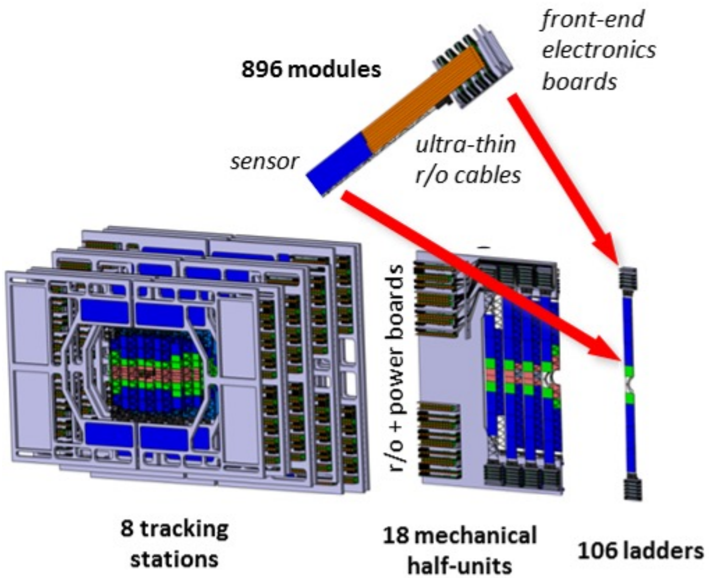
Micro-**V**ertex **D**etector (**MVD**) and **S**ilicon **T**racking **D**etector (**STS**) inside a Superconductive Dipole Magnet (**Magnet**)

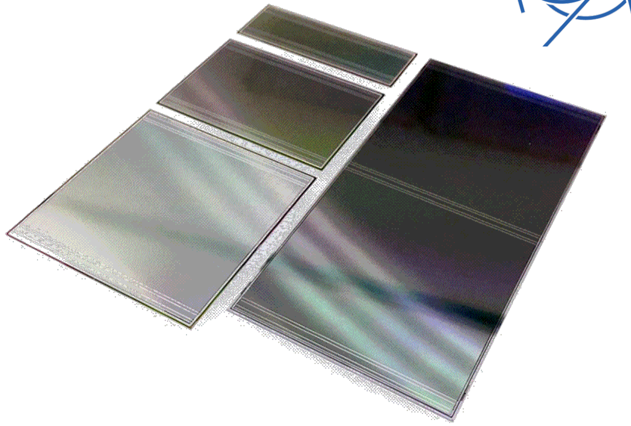
MUon **CH**amber (**MUCH**) or **R**ing **I**mage **CH**erenkov (**RICH**), **T**ransition **R**adiation **D**etector (**TRD**), **T**ime **O**f **F**light (**TOF**)

Projectile **S**pectator **D**etector (**PSD**), **B**eam **MON**itoring (**BMON**) and T_0 system

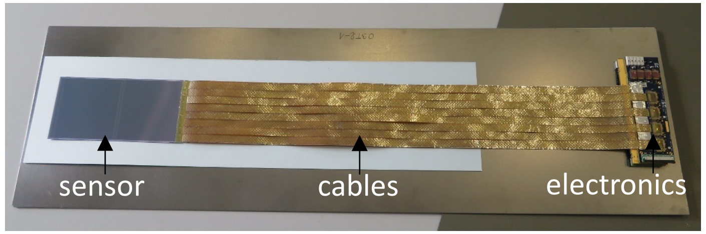
CBM – Silicon Tracker System



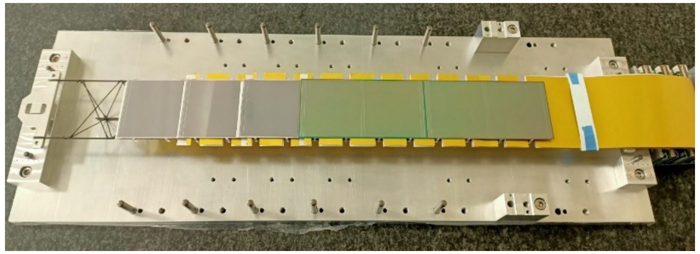




double-sided, 320 μm thick, 1024 strips per side at 58 μm pitch, 7.5 deg angle front/back



module

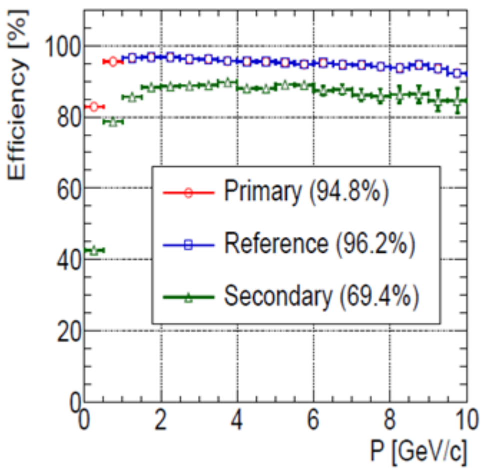


ladder prototype

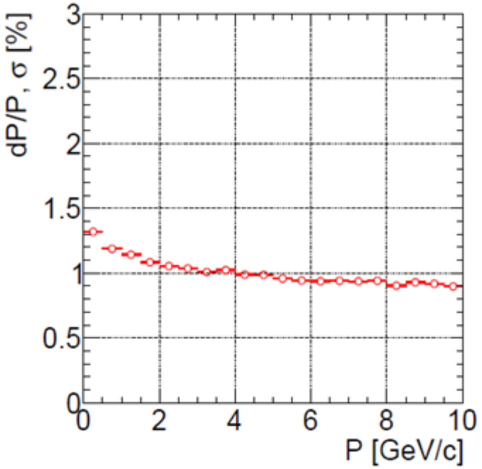
Main requirements

- $\frac{\sigma_p}{p} \lesssim 1\%$ @1GeV/c
- $X/X_0 \lesssim 1\%$
- Tr. Eff. (primary) ≳ 95%

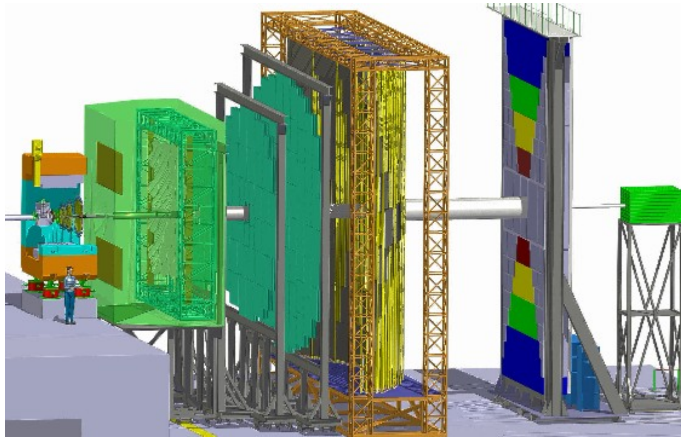
Tracking efficiency



Momentum resolution



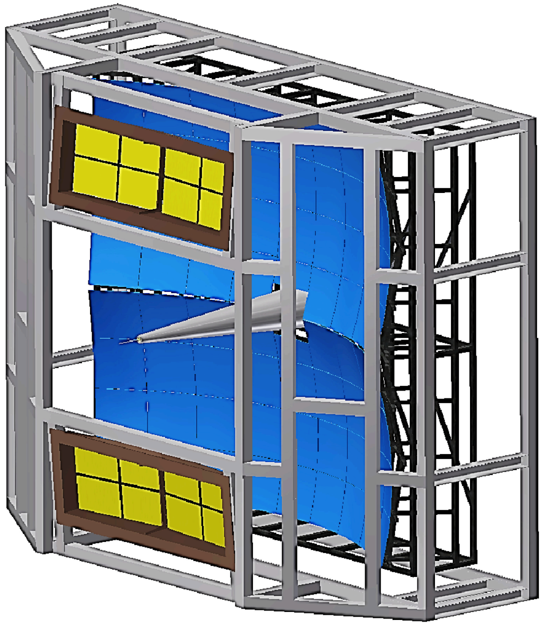
CBM – electron ID with RICH



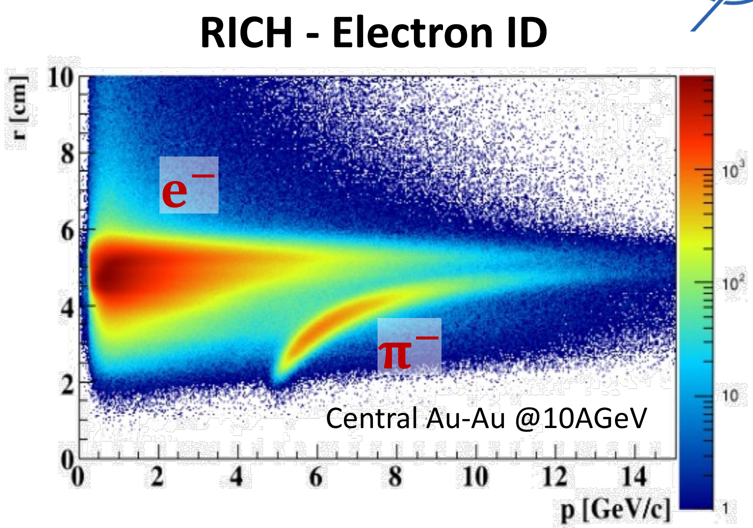
Identification of electrons from lowest momenta up to 8-10 GeV/c

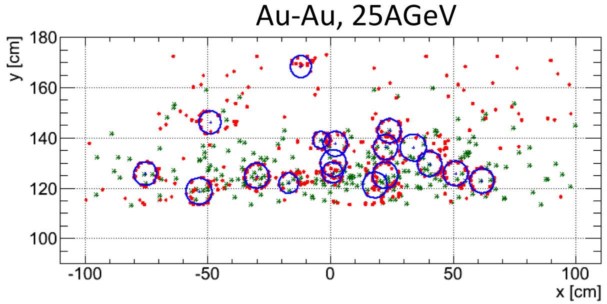
➪ dielectron spectrum
➪ photons via γ conversion pairs

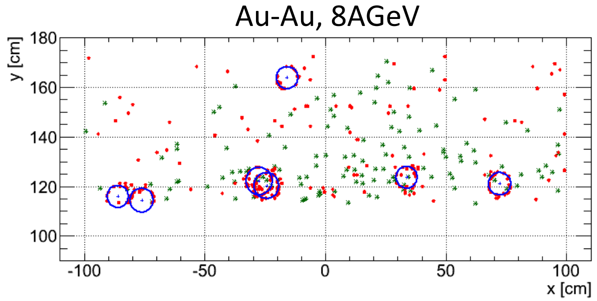
Whole detector can be moved out to allow the insertion of the MUCH detector for a complementary measurement of dileptons in the dimuon channel



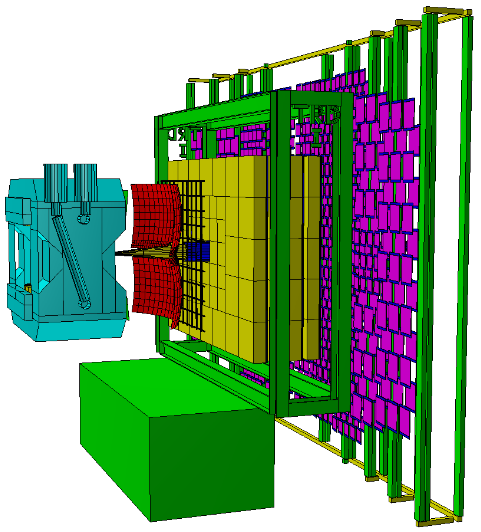
- Gaseous (CO_2) RICH detector
- Cherenkov rings focused on photon detector array by spherical glass mirrors (Al reflective, MgF_2 protective)
- Photon detection: multi-anode PMs



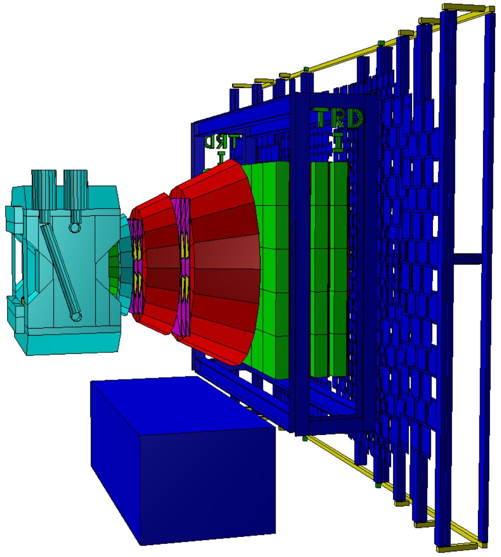




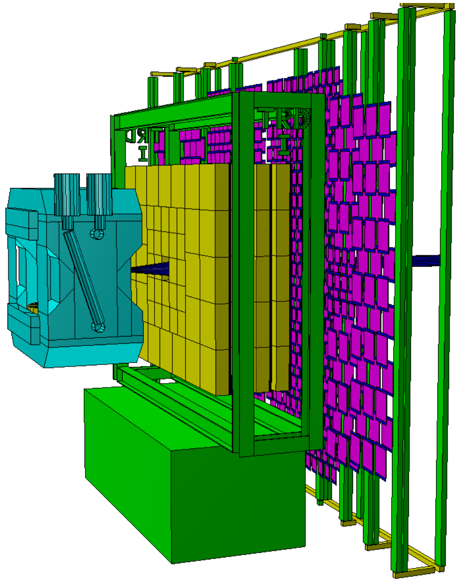
CBM – PID (&tracking) with TRD



measurement of electrons

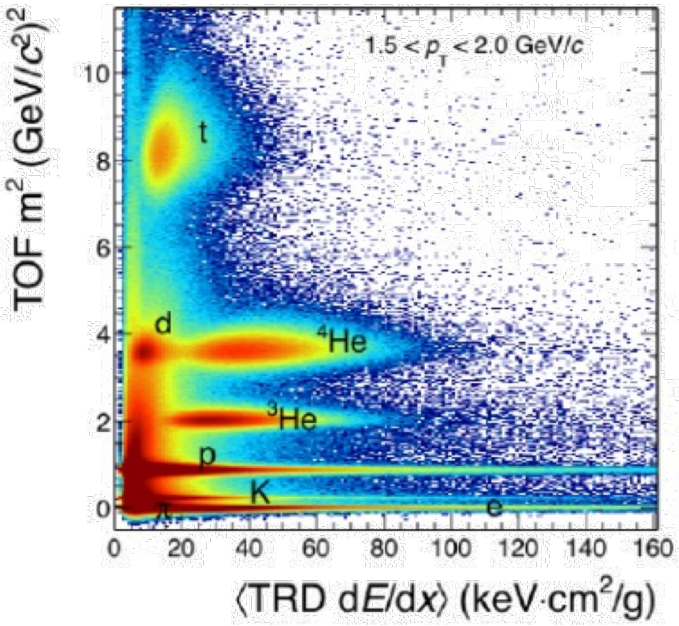


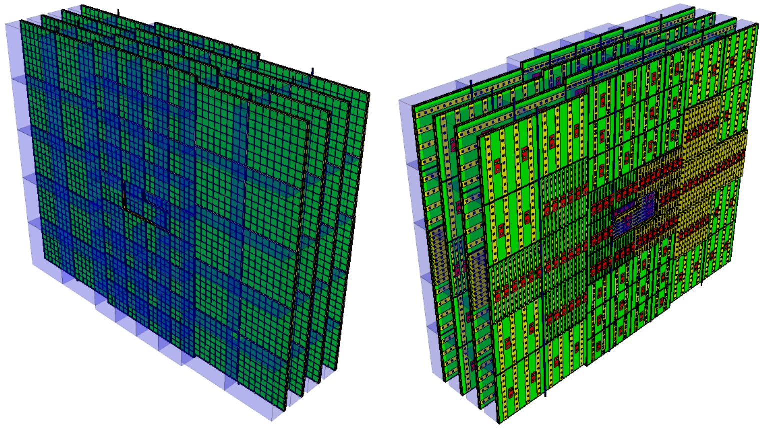
measurement of muons



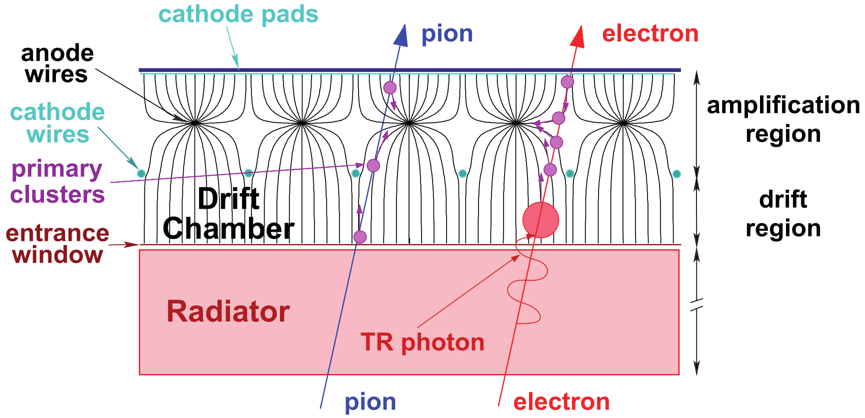
measurement of hadrons

Central Au-Au @10AGeV





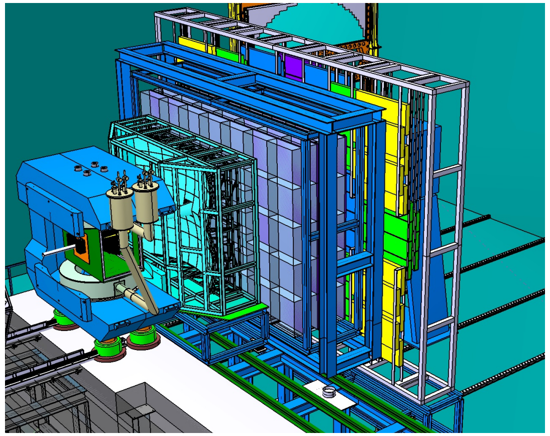
Four layers: radiator side (left), ROC + electronics right)



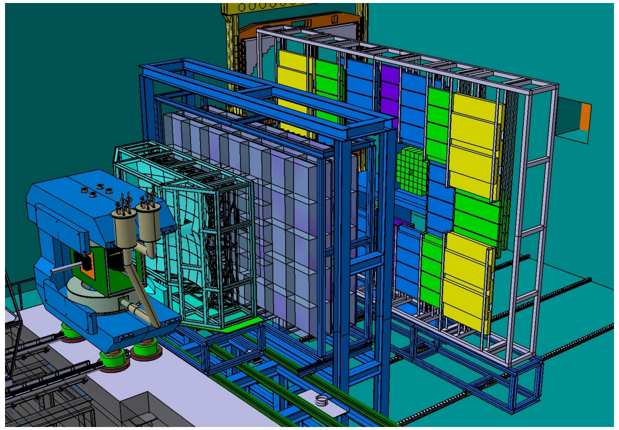
TRD + ToF -
Electron, Light Nuclei,
Heavy Fragments

Clear separation between pions and electrons, and light nuclei

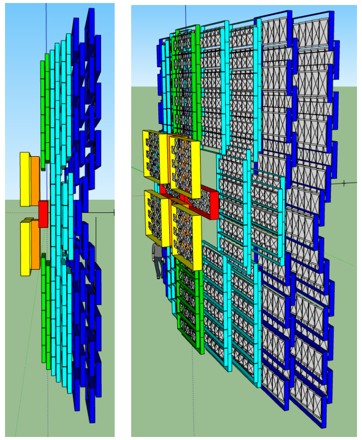
CBM – PID with TOF detector



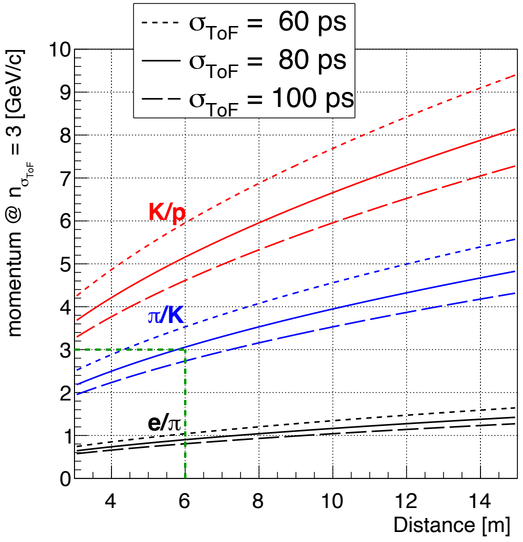
TOF @6m

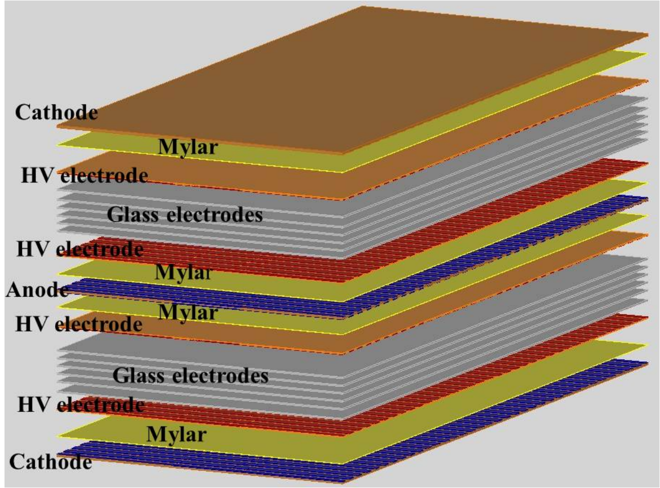


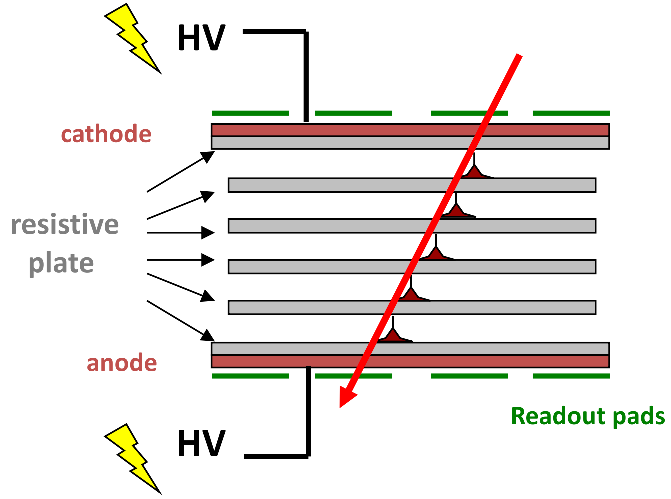
TOF @10m



TOF Wall

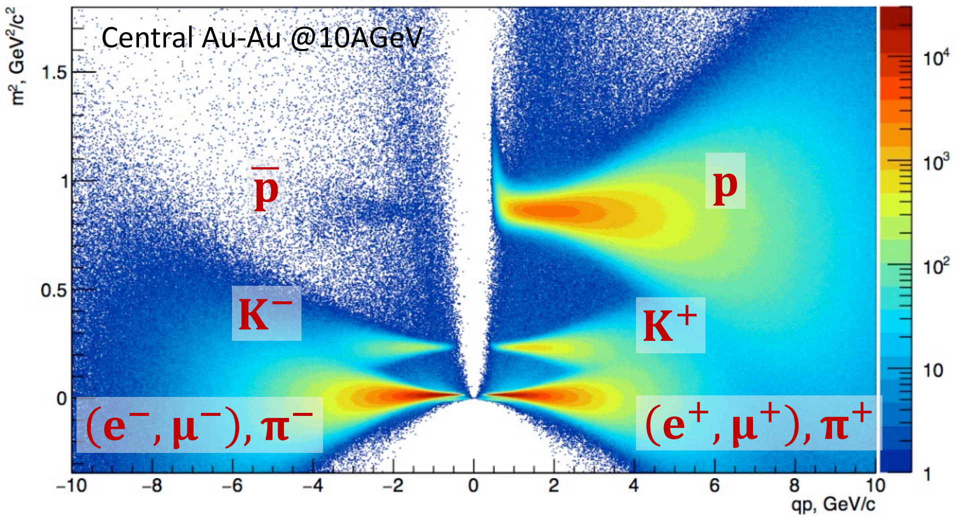






Multigap Resistive Plate Chamber

ToF - Hadron Identification



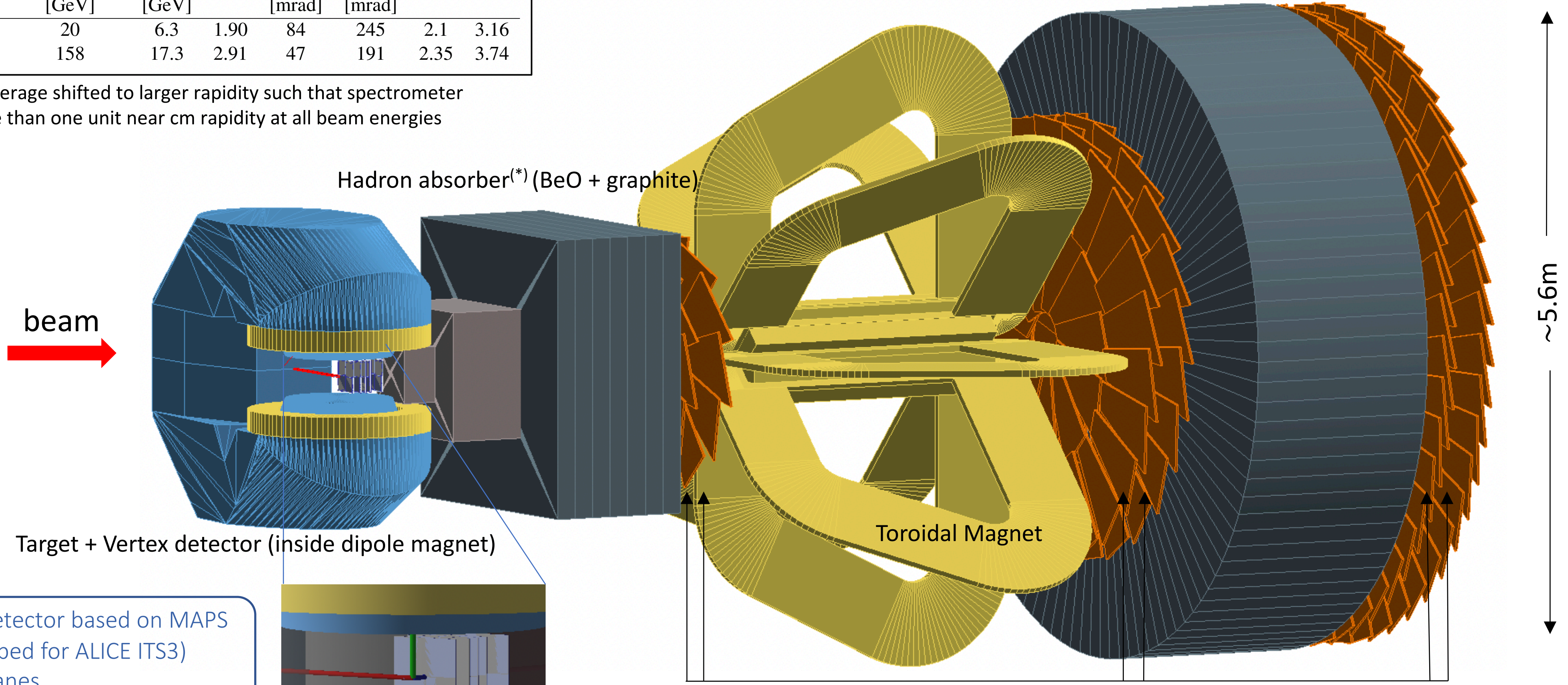
Clear separation between charged protons, pions and kaons

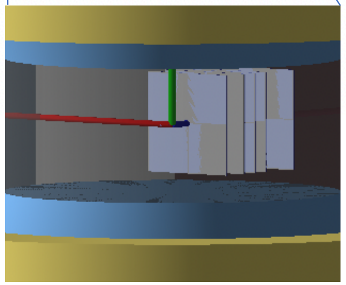
High μ_B experiments - NA60+

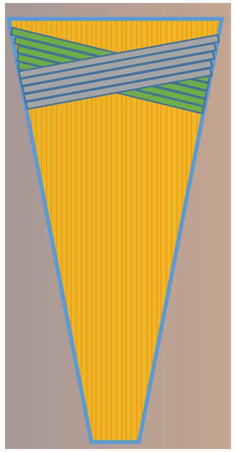
NA60+ Detector (closely follows design of NA60 but with better-performing detector technologies)

configuration	beam energy [GeV]	$\sqrt{s_{NN}}$ [GeV]	y_{cm}	θ_{min} [mrad]	θ_{max} [mrad]	y_{min}	y_{max}
low energy	20	6.3	1.90	84	245	2.1	3.16
high energy	158	17.3	2.91	47	191	2.35	3.74

Rapidity coverage shifted to larger rapidity such that spectrometer covers more than one unit near cm rapidity at all beam energies







MWPC with double strip (stero angle) readout

Vertex detector based on MAPS (developped for ALICE ITS3)

- 5 planes
- Total area: ~$0.5 m^2$
- X/X_0: 0.1% /plane
- Spatial resolution: 5μm

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

(*) At very large rapidities (η>4.2), outside the spectrometer aceptance, a high-density plug stops non-interacting beam ions and spectator nucleons

e-A Colliders

Future e-A colliders

Several e-p/A collider facilities proposed in China, Europe and US

Facility	Years	E_{cm} (GeV)	Luminosity (10^{34} cm^{-2} s^{-1})	Ions	Polarization
EIC in US	> 2035	20 - 140	0.2 – 3	p → U	e, p, d, ^{3}He, Li
EIC in China(**)	> 2030	16 – 34	1 -> 100	p → Pb	e, p, light nuclei
LHeC(*)	> 2030	200 - 1300	1	p → Pb	e
FCC-eh(*)	> 2050	3500	1.5	p → Pb	e

EIC in the US is the only project at an advanced stage of approval

- It will be located at BNL (alternative and cost range, Critical Decision 1, 2021)
- Performance baseline (Critical Decision 2) expected in Jan 2024

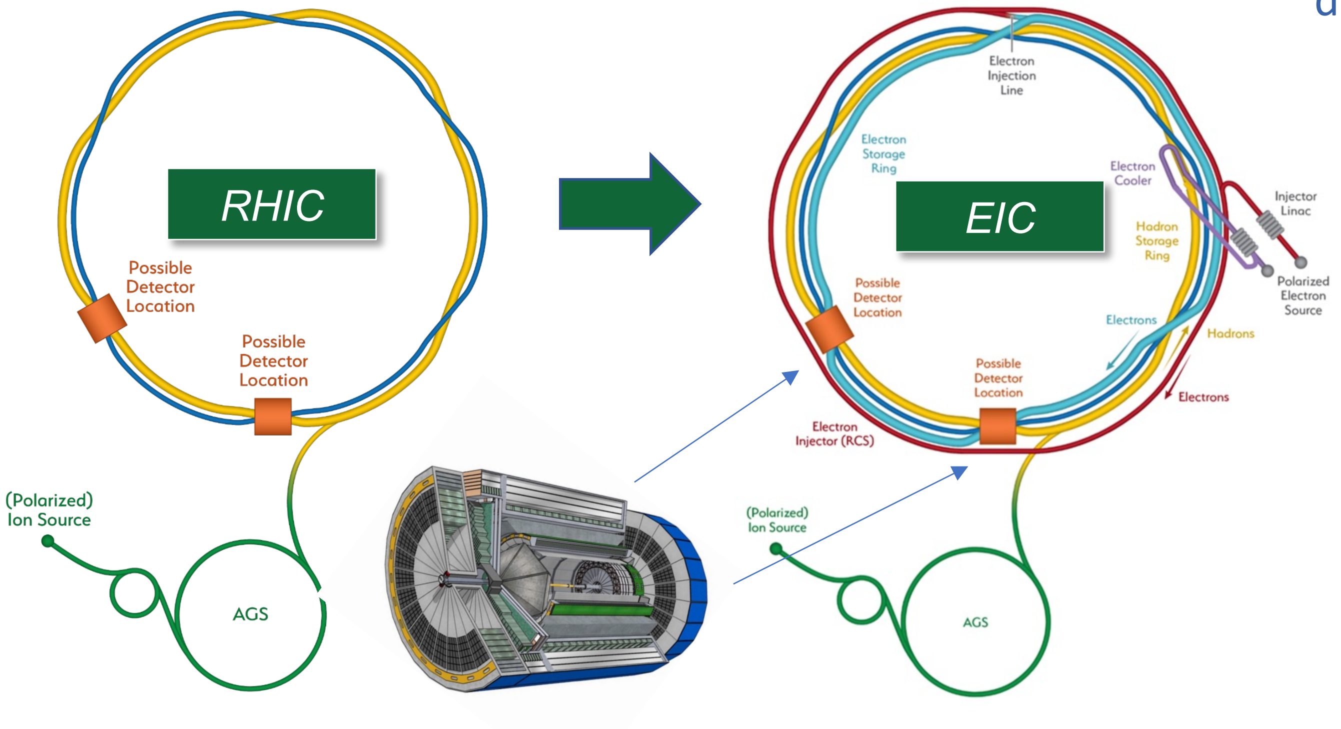
- Mass, spin and other emergent properties of nucleons from the dynamics of their constituents (quarks and gluons)
- Emergent properties of high-density gluon matter
- Nuclear structure

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

(*) LHeC/FCC-eh presented in additional material (slides 71 – 76) (**) not discussed here

The Electron Ion Collider (EIC) at BNL

Electron Ion Collider (preliminary) Scope

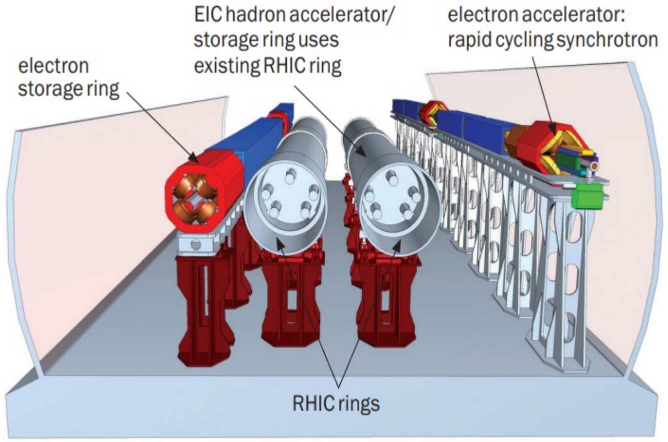


Utilize (& modify) existing operational hadron collider:
E_p: **40 … 275 GeV**

Add electron storage ring (E_e: **4 … 18 GeV**), cooling in existing RHIC tunnel and electron injector.

Two interaction regions

Current plan has the RHIC facility shutting down in 2025 and being modified for the EIC

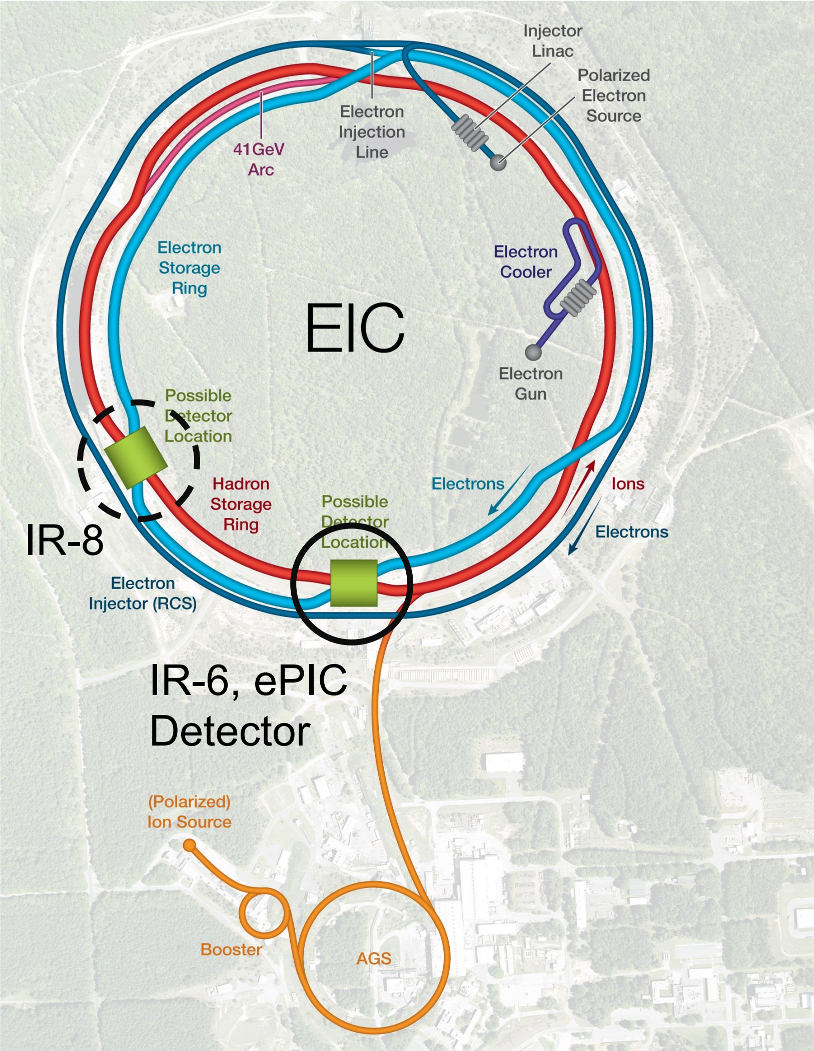


New systems include

- Polarized electron source,
- Injector linac,
- Electron cooler complex,
- Rapid Cycling Synchrotron(RCS)
- Electron storage ring (ESR),
- Capability for implementing 2 IRs
- Infrastructure improvements.

The Electron Ion Collider (EIC) at BNL

Electron Ion Collider (preliminary) Scope



Project Design Goals

- High Luminosity: L= $10^{33} - 10^{34}$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
- Large Detector Acceptance and Good Background Conditions

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

The Electron Ion Collider (EIC) at BNL

Detector Integration Challenge of the EIC

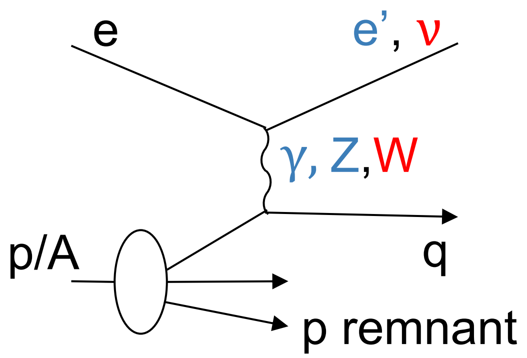
EIC Physics demands ~100% acceptance for all final state particles (including particles associated with initial ion)

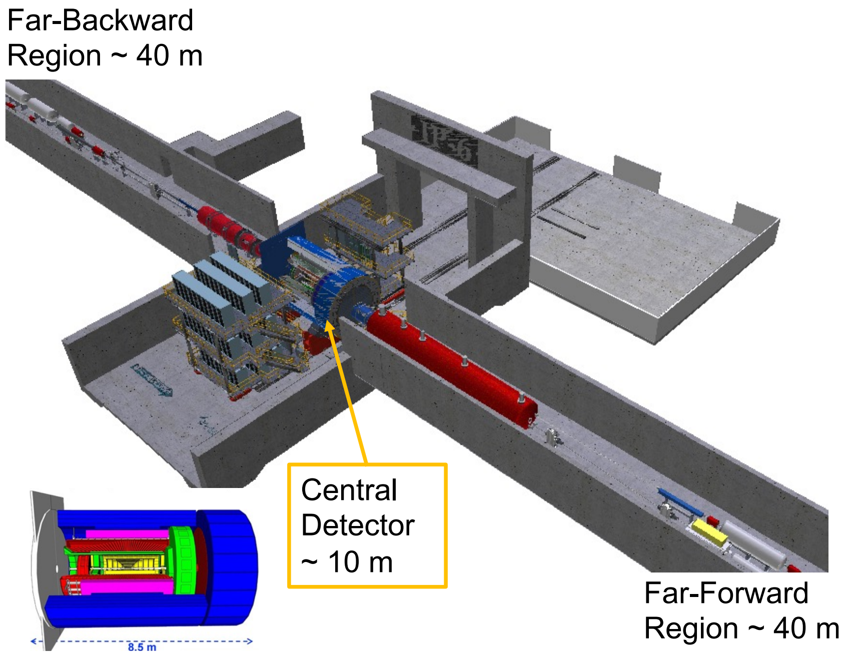
All particles count!

Ion remnant is particularly challenging

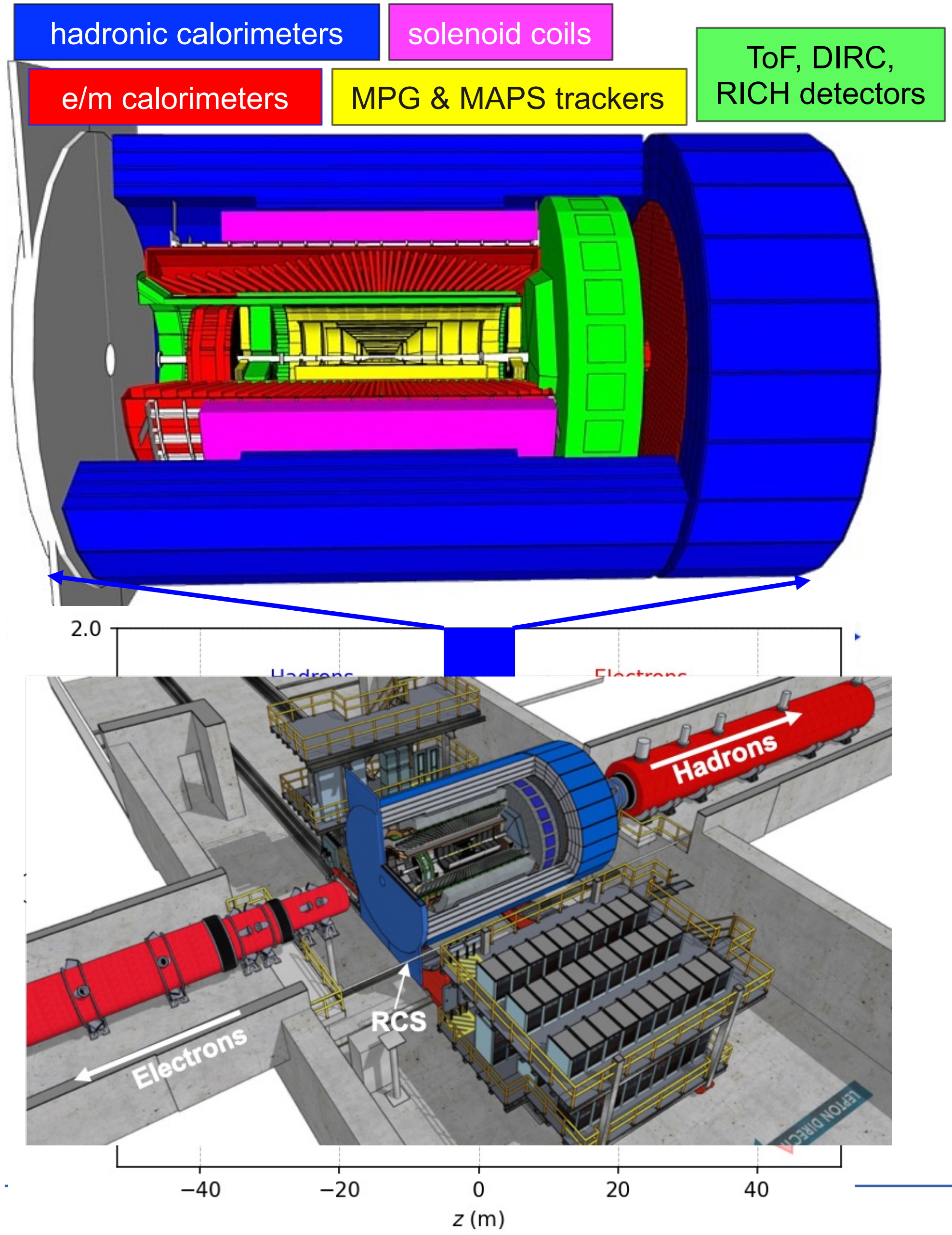
Many particles with $\beta \approx 1$, but in the far-forward region @30m distance also many particles with $\beta \sim 0.5 \rightarrow \Delta t = 200$ ns

Highly integrated (and complex) detector and interaction region scheme





The Electron Ion Collider (EIC) at BNL



EIC General Purpose Detector: ePIC

Overall Detector Requirements

- Large rapidity ($-4 < \eta < 4$) coverage;
  and far beyond in especially far-forward detector regions
- High precision low mass tracking
  - small (μ-vertex) and large radius tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EM-calorimetry
- High performance PID to separate π, K, p on track level
  - also need good e/π separation for scattered electron
- Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
  - Many ancillary detector integrated in the beam line: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, ….
- High control of systematics
  - luminosity monitor, electron & hadron Polarimetry

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

The Electron Ion Collider (EIC) at BNL

Radius/Distance from IP

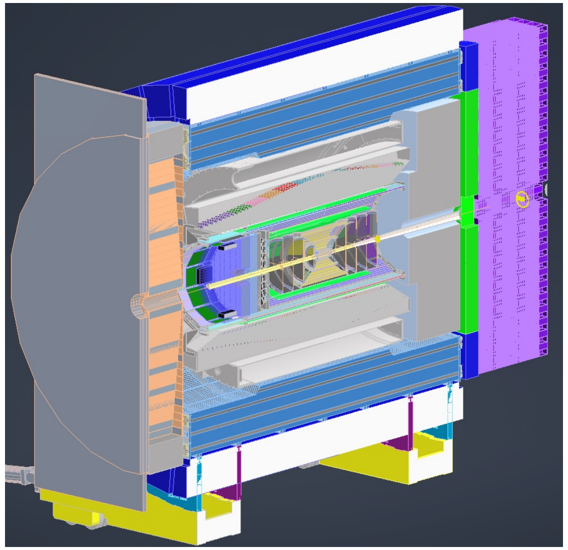
Vertex detector → Identify primary and secondary vertices,
Low material budget: 0.05% X/X_0 per layer; High spatial resolution: 10 μm pitch MAPS

Central tracker → Measure charged track momenta
MAPS – tracking layers in combination with micro pattern gas detectors
MPGD: μ-RWell or MicroMegas

electron and hadron endcap tracker → Measure charged track momenta
MAPS – disks in combination with micro pattern gas detectors

Particle Identification → pion, kaon, proton separation on track level
RICH detectors (modular and dual radiator RICH, DIRC) & **Time-of-Flight**
high resolution timing detectors (LAPPS, LGAD) 10 – 30 ps; novel photon sensors: MCP-PMT/LAPPD

Electromagnetic calorimeter → Measure photons (E, angle), identify electrons
$PbWO_4$ Crystals (backward), W/SciFi Spacal (forward)
Barrel: **Pb/SciFi+imaging part or new Scintillating** glass → cost effective



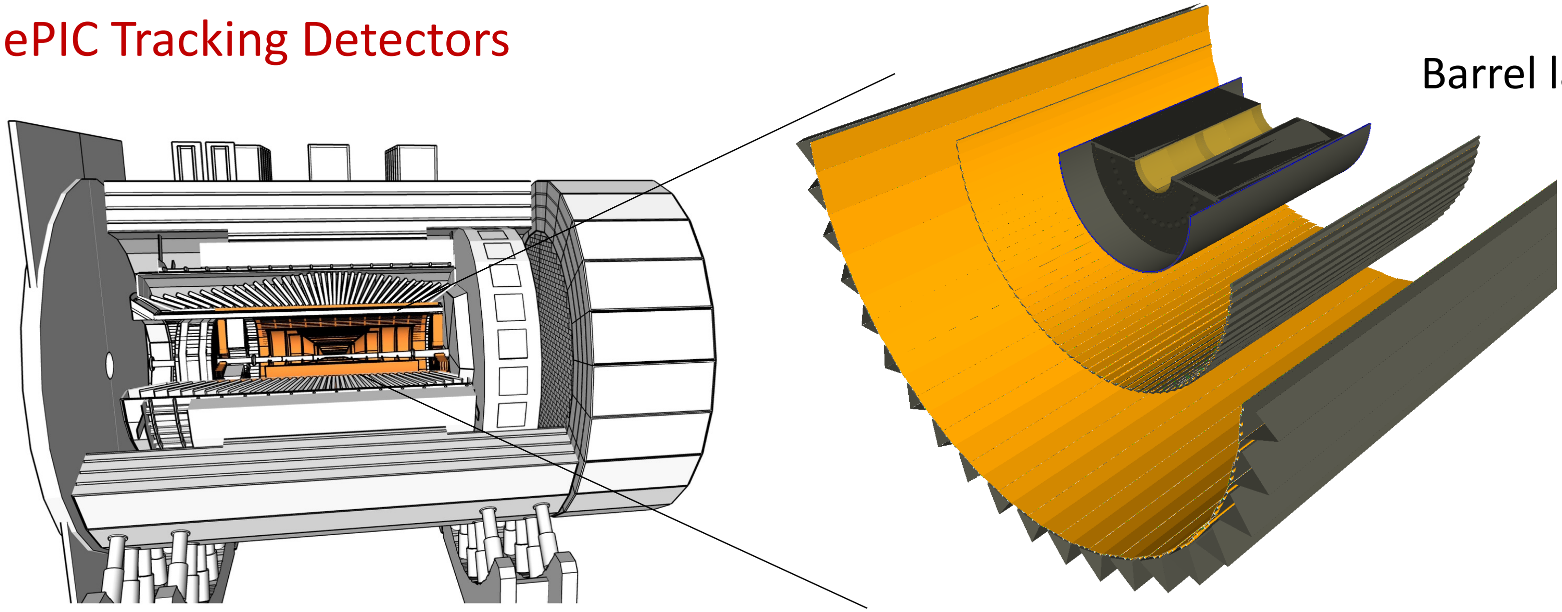
Hadron calorimeter → Measure charged hadrons, neutrons and K_L^0
challenge achieve ~50%/√E + 10% for low E hadrons (<E> ~ 20 GeV)
Fe/Sc sandwich with longitudinal segmentation

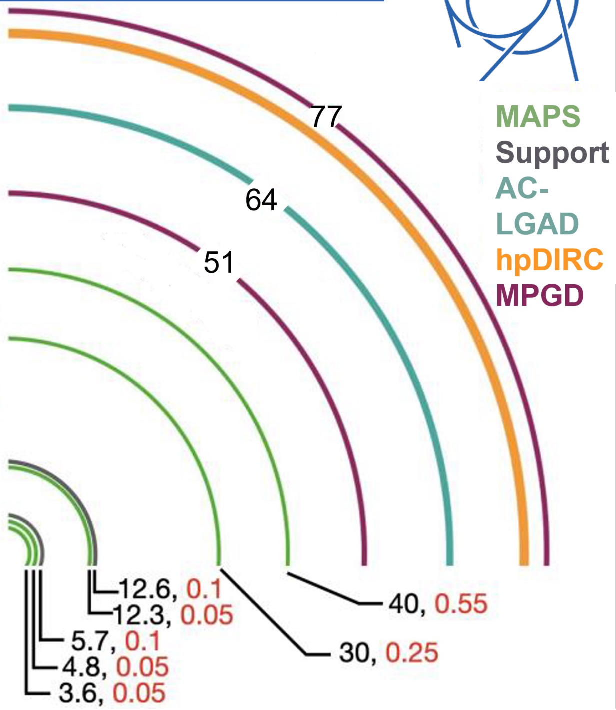
Very forward and backward detectors → scattered particles under very small angles
Silicon tracking layers in lepton and hadron beam vacuum
Zero – degree high resolution electromagnetic and hadronic calorimeter

DAQ & Readout Electronics: trigger-less / streaming DAQ

The Electron Ion Collider (EIC) at BNL

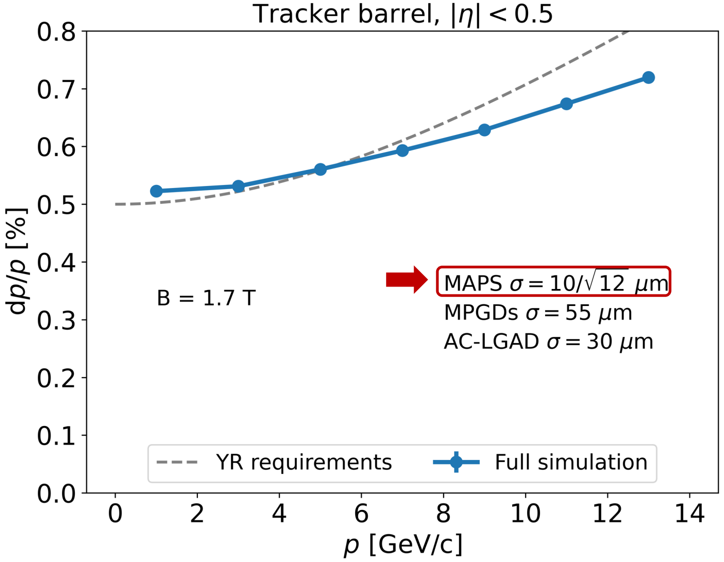
ePIC Tracking Detectors





Black numbers are radii in cm

Red numbers are material in % X0



- Si Tracker based on MAPS
- Five layers in barrel, supplemented by MPGDs for pattern recognition
- Five discs in forward/backward directions (+MPGD in forward)

MAPS based on ALICE ITS3 developments

The Electron Ion Collider (EIC) at BNL

ePIC – Particle Identification (PID)

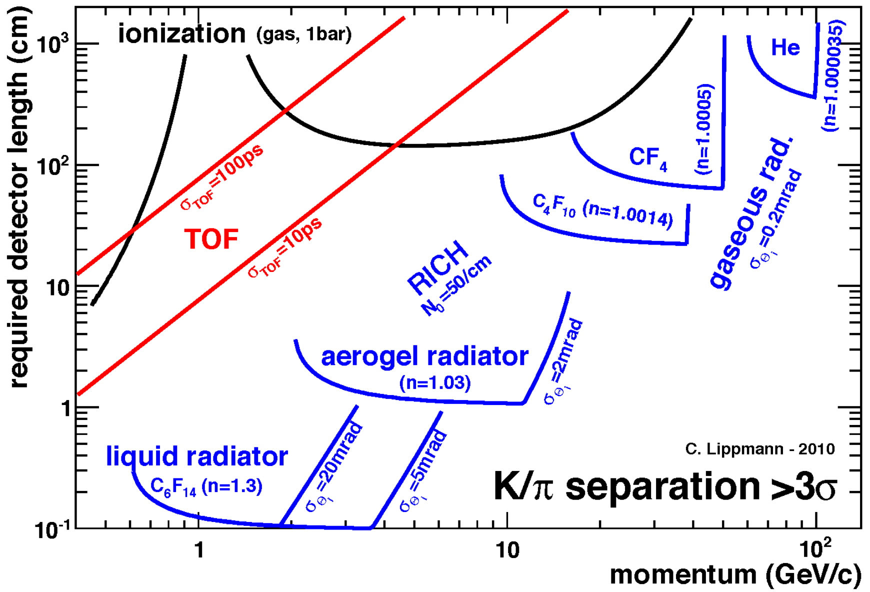
General strategy to separate:

- electrons from photons → 4π coverage in tracking
- electrons from charged hadrons → mostly provided by calorimetry
- charged pions, kaons and protons from each other → Cherenkov detectors
- Cherenkov detectors complemented by other technologies at lower momenta → Time-of-flight or dE/dx

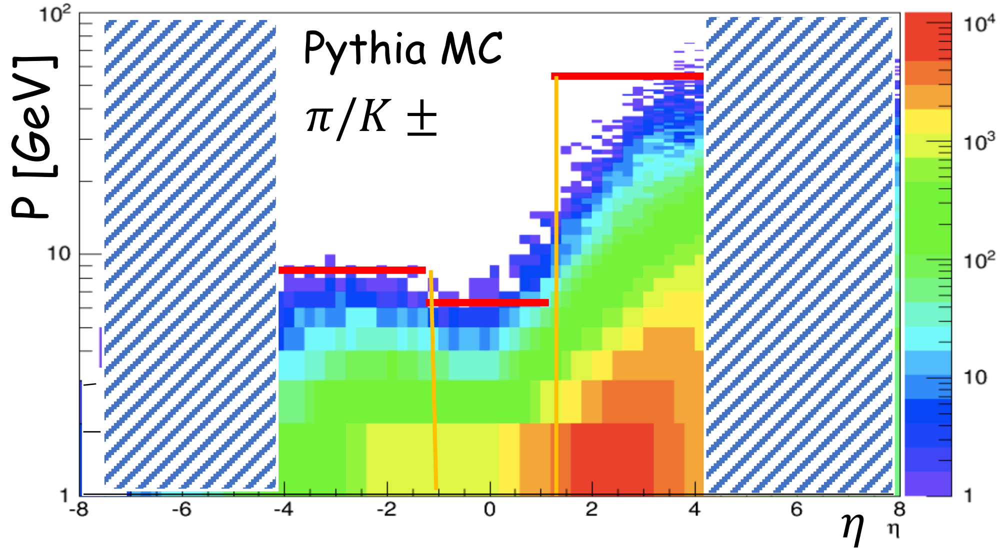
Physics requirements

Rapidity (η)	π/K/p and π^0/γ	e/h	Min p_T (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c

Need more than one technology to cover the entire momentum ranges at different rapidities



Projections for PID detector performance

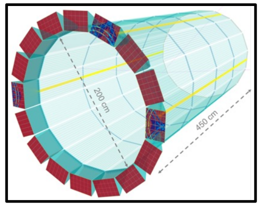


The Electron Ion Collider (EIC) at BNL

ePIC – Hadron ID

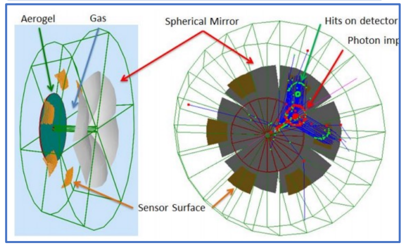
Barrel

DIRC = Detection of internally Reflected Cherenkov light

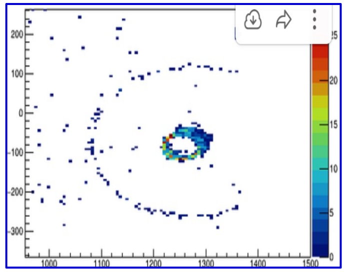


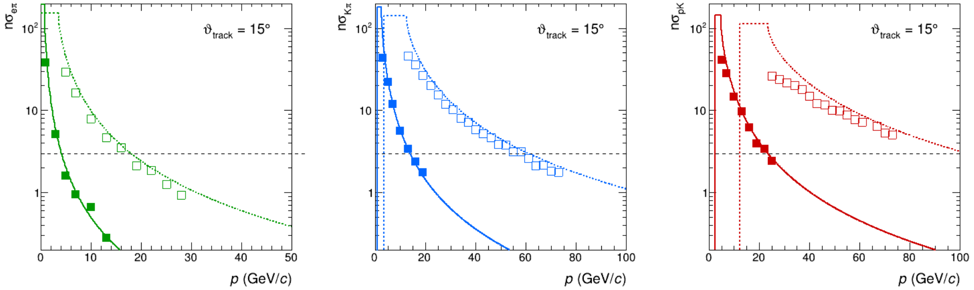
hpDIRC (High Performance DIRC)
- Quartz bar radiator → Reuse of BaBAR DIRC bars
- light detection with MCP-PMTs
- Fully focused
- p/K 3σ sep. at 6 GeV/c

Forward Endcap



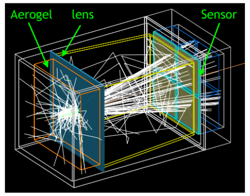
dRICH (dual RICH)
- Aerogel and C-F gas radiators
- Full momentum range
- Sensor: Si PMs(TBC)
- p/K 3σ sep. at 50 GeV/c





HP-RICH (high pressure RICH)
- Eco-friendly alternative for dRICH
- Ar @ 3. 5 bar ↔ C_4F_{10} @ 1 bar
- Ar @ 2 bar ↔ CF_4 @ 1 bar

Backward Endcap

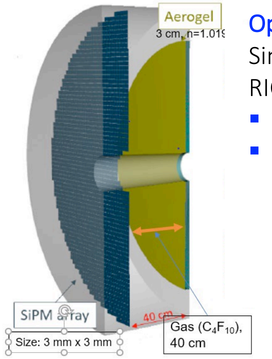


Geant4 Simulation

With realistic material optical properties

Option-1:

mRICH (Modular RICH)
- Aerogel Cherenkov Det.
- Focused by Fresnel lens
- e, pi, K, p
- Sensor: SiPMs/ LAPPDs
- Adaptable to includeTOF
- p/K 3σ sep. at 10 GeV/c



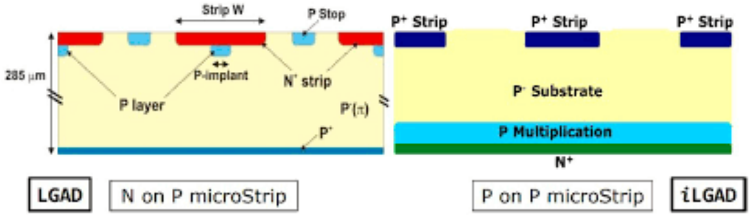
Option-2:

Single volume proximity focusing aerogel RICH with long proximity gap (~30 cm)
- Sensor: LAPPDs → includeTOF
- p/K 3σ sep. at 10 GeV/c

Everywhere

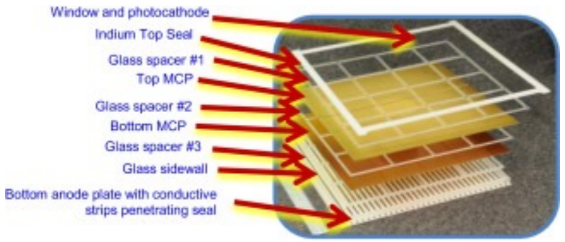
TOF with short lever arm

AC-LGAD (Low Gain Avalanche Detector)
- Silicon Avalanche, 20-35 psec
- Accurate space point for tracking
- Relevant also to central barrel
- R&D, PED by International consortium HEP & NP



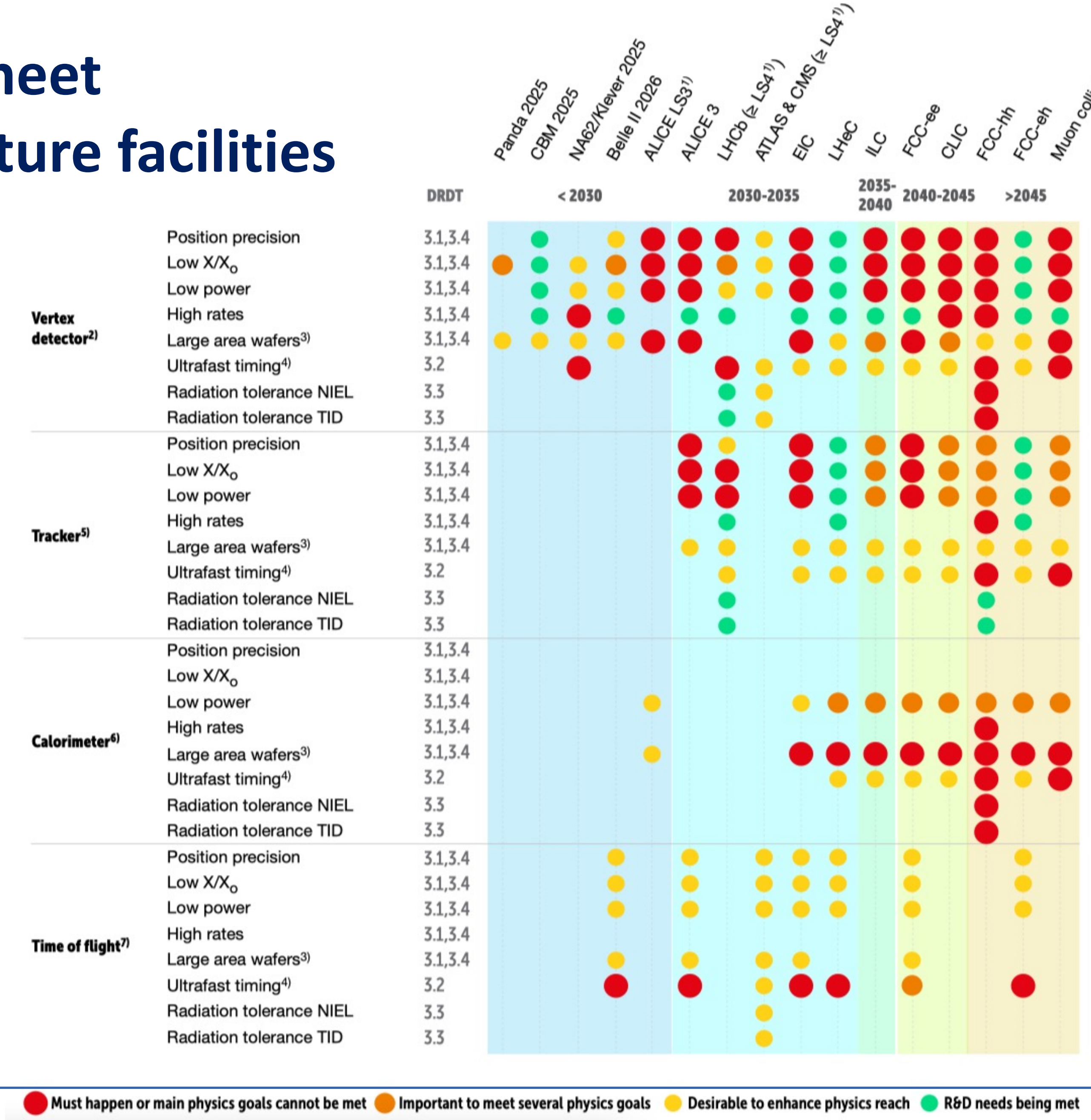
LAPPD (Large Area psec Photon Detector)
- MCP, Cherenkov in window
- 5-10 psec

→ supported by DOE SBIR program



Robust R&D programme to meet detector requirements for future facilities

ECFA Detector R&D Roadmap
the case of **“solid state detectors“**

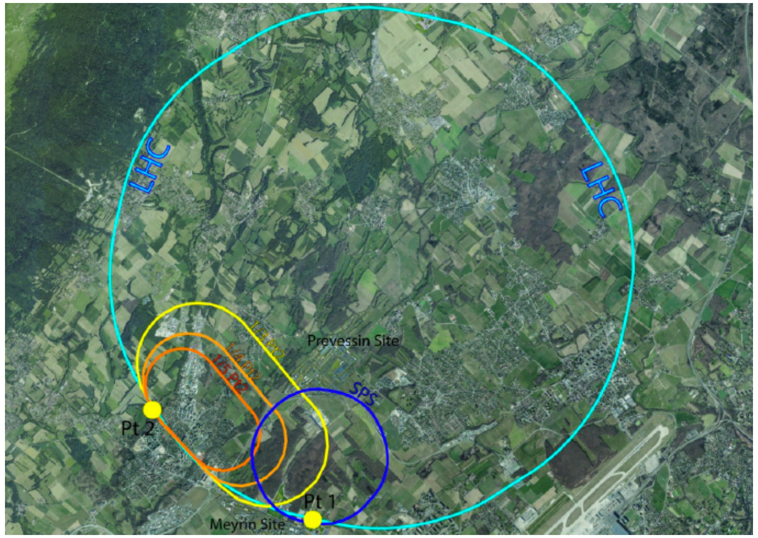


https://cds.cern.ch/record/2784893

Additional Material

Hadron-Electron Collisions at the LHC and FCC

LHeC, PERLE and FCC-eh



50 x 7000 GeV^2: 1.2 TeV ep collider

Operation: 2035+, Cost O(1) BCHF

CDR (2012): 1206.2913 J.Phys.G

Upgrade to 10^{34} cm^{-2}s^{-1}, for Higgs, BSM

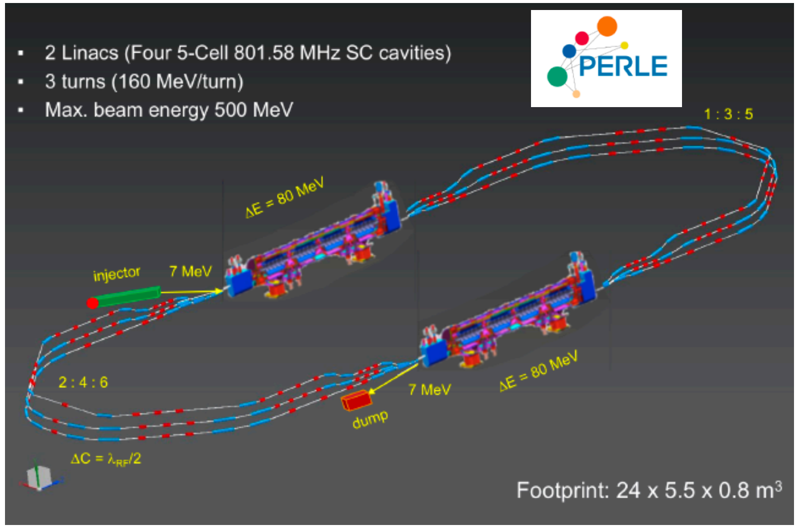
CERN-ACC-Note-2018-0084 (ESSP)

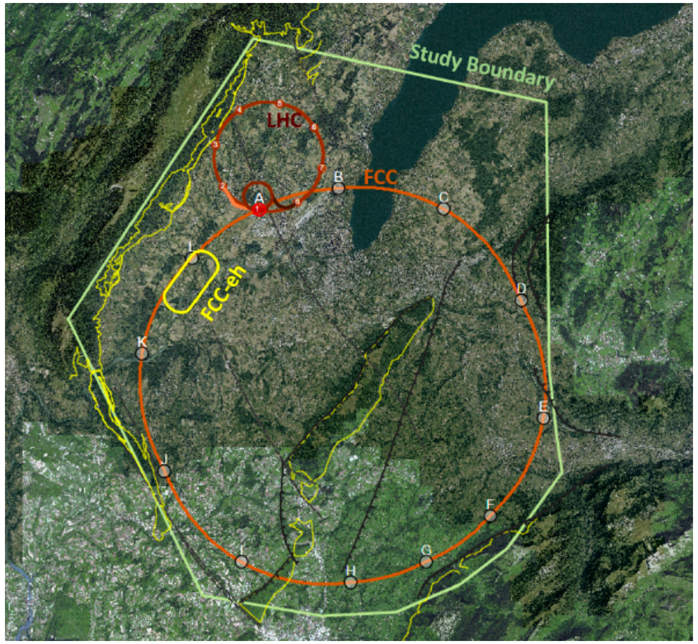
Update **CDR published in 2020**
arXiv:2007.14491, subm J.Phys.G

Powerful **ERL** for Experiments @ Orsay
CDR: 1705.08783 J. Phys.G
CERN-ACC-Note-2018-0084 (ESSP)

Operation: 2025+, Cost: O(20) Meuro

LHeC ERL Parameters and Configuration
I_e = 20mA, 802 MHz SRF, 3 turns ⇨
E_e=500 MeV a first 10 MW ERL facility





60 x 50000 GeV^2: 3.5 TeV ep collider

Operation: 2050+
Cost$_{(of\ ep)}$ O(1-2) BCHF

Concurrent operation with FCC-hh

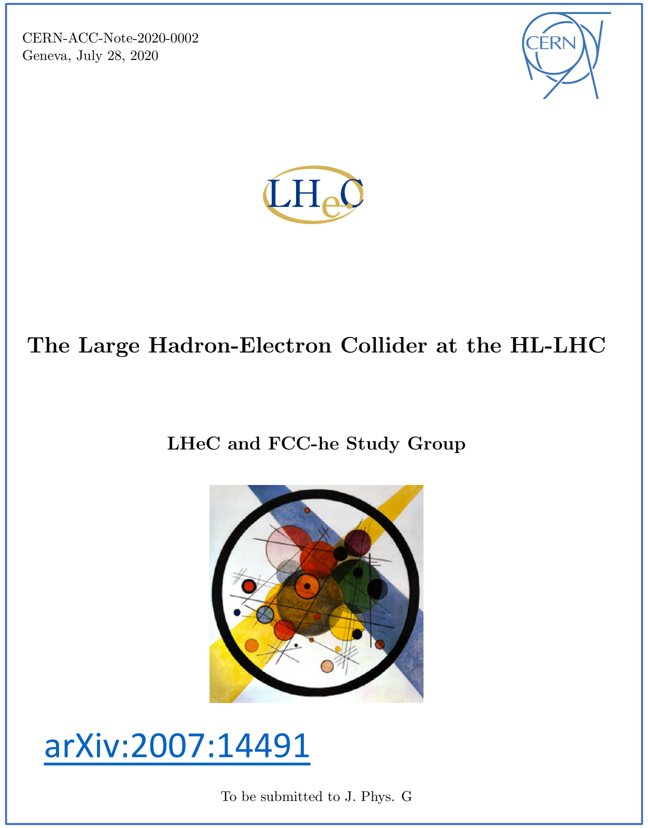
FCC CDR:
Eur.Phys.J.ST 228 (2019) 6, 474 Physics
Eur. Phys.J.ST 228 (2019) 4, 755 FCC-hh/eh

Courtesy of M. Klein (HK Conference, 19.01.2021)

Hadron-Electron Collisions at the LHC and FCC

Physics with Energy Frontier DIS

Published in 2020


CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

LHeC

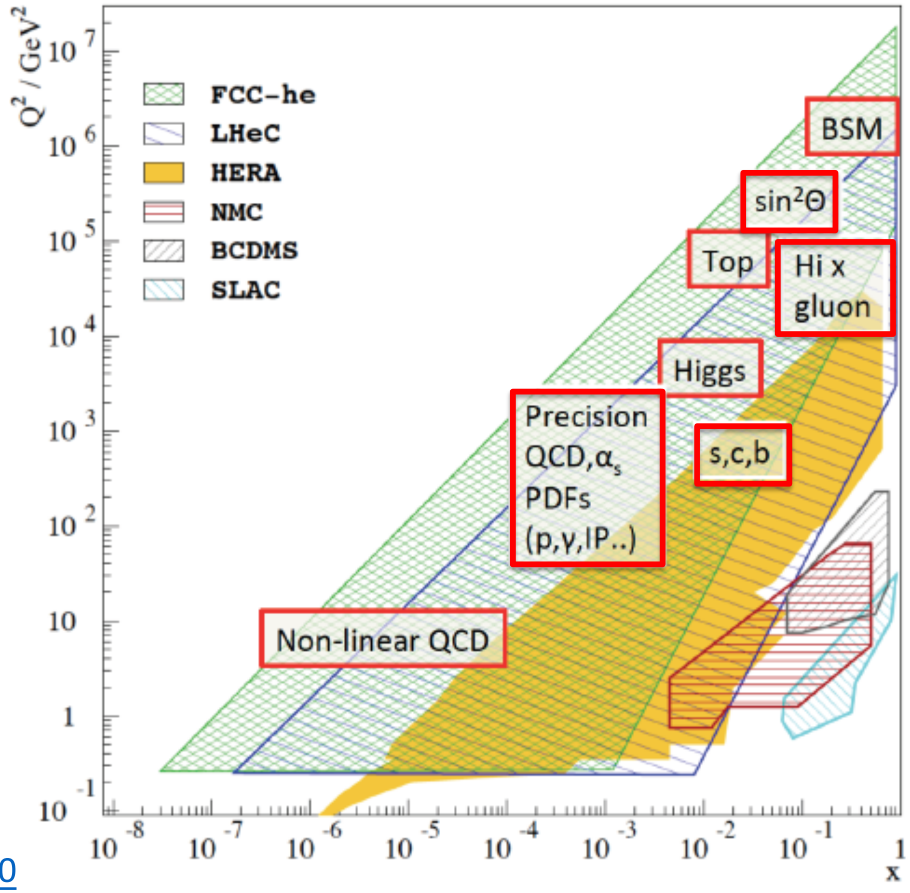
The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

arXiv:2007:14491

To be submitted to J. Phys. G

5 page summary: ECFA Newsletter Nr. 5, Aug 20



Raison(s) d'être of ep/eA at the energy frontier

Cleanest High Resolution Microscope: QCD discovery

Empowering the LHC/FCC Search Programme

Trasnformation of LHCC/FCChh into high precision Higgs facility

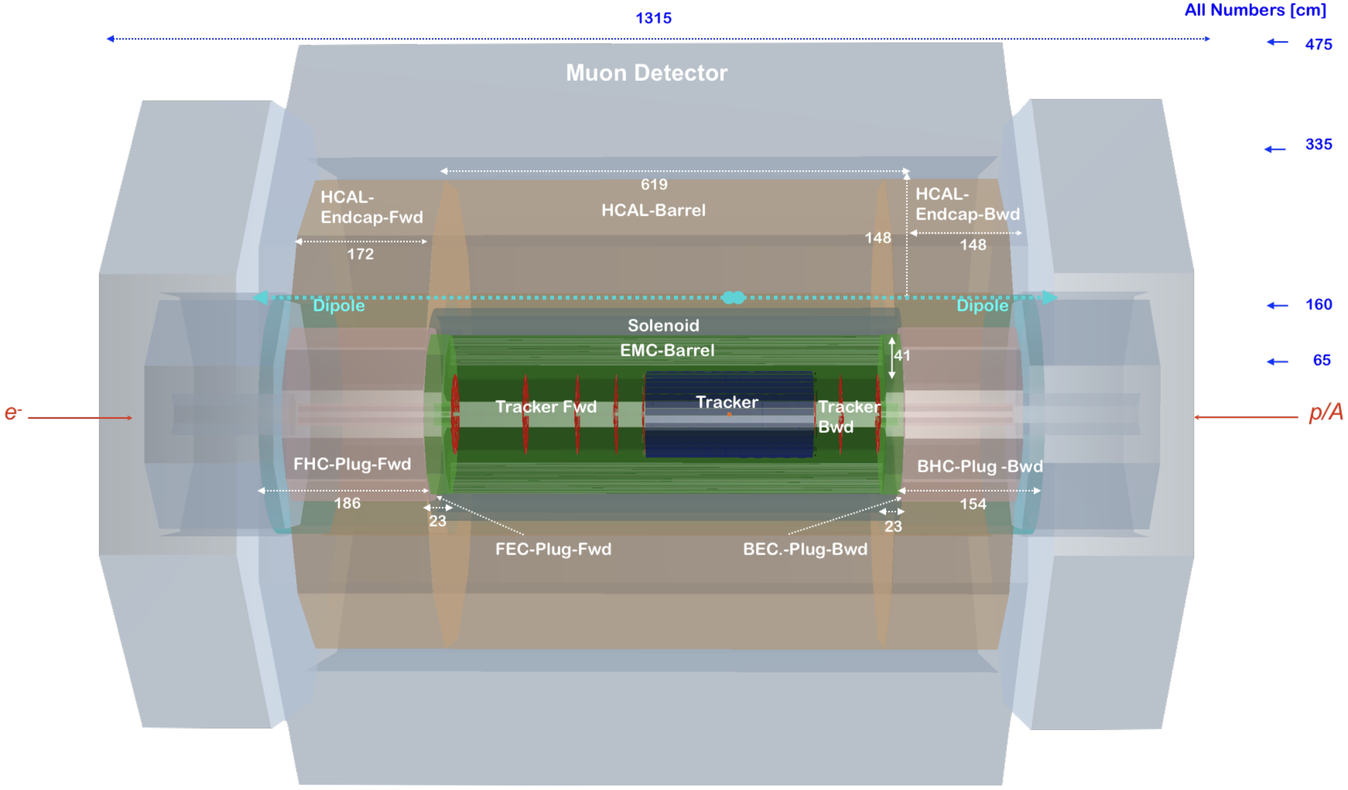
Discovery (top, H, heavy ν's)

A unique Nuclear Physics Facility

Courtesy of M. Klein (HK Conference, 19.01.2021), slides 3-4

Hadron-Electron Collisions at the LHC and FCC

LHeC Detector Design 7/2020



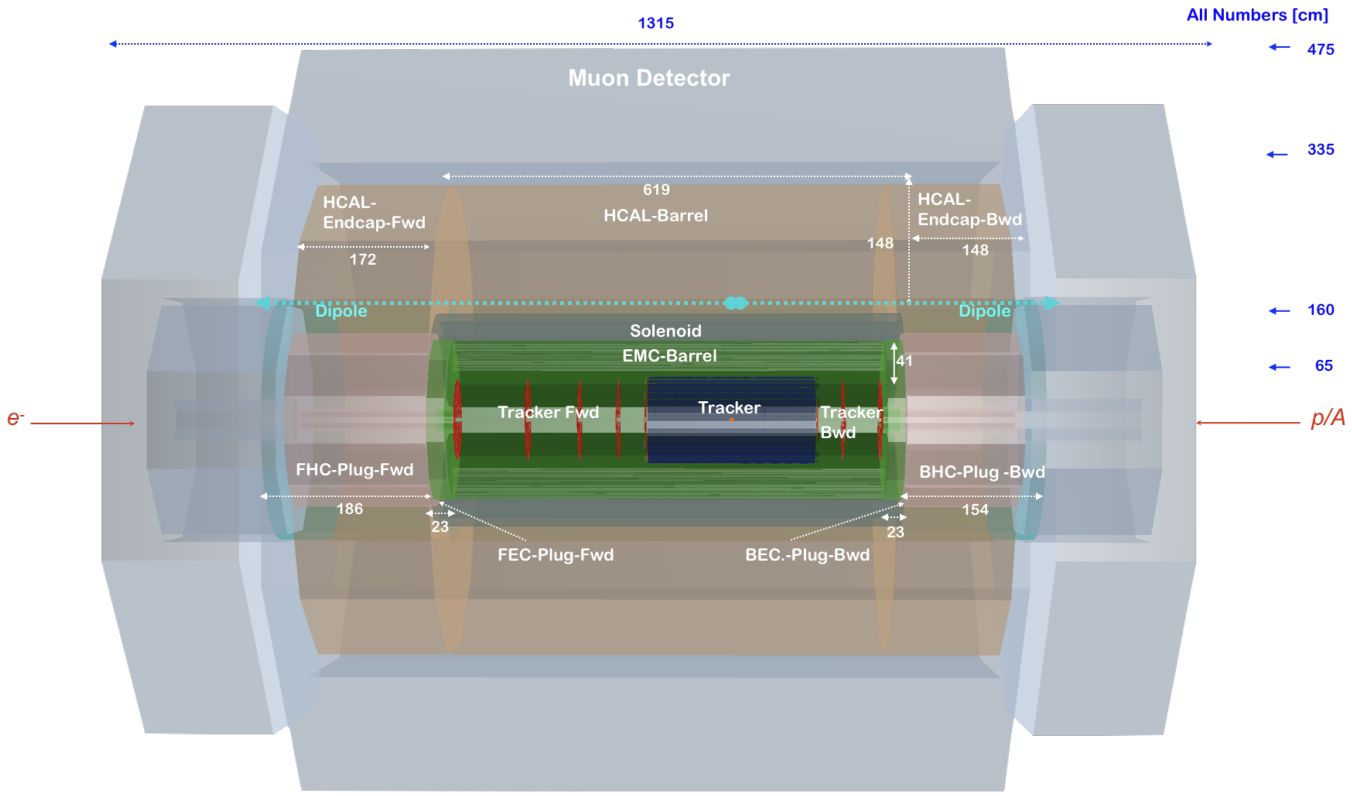
Current design leans heavily on HL-LHC technologies
But they are over-spec'ed for radiation hardness

General detector requirements

- **High-resolution tracking system**
  - primary and secondary vertex resolution down to small angles
  - precise p_T measurement and matching to calorimeter
- **Full coverage calorimetry**
  - Electron energy 10%/√E calibr. 0.1%
  - Hadronic energy 10%/√E calibr. 1%
  - Tagging of backward scattered electrons and photons
  - Tagging of forward scattered photons, neutrons and deuterons
- **Full coverage muon system**
  - Tagging and combination with tracking, no independent p measurement

Hadron-Electron Collisions at the LHC and FCC

LHeC Detector Design 7/2020



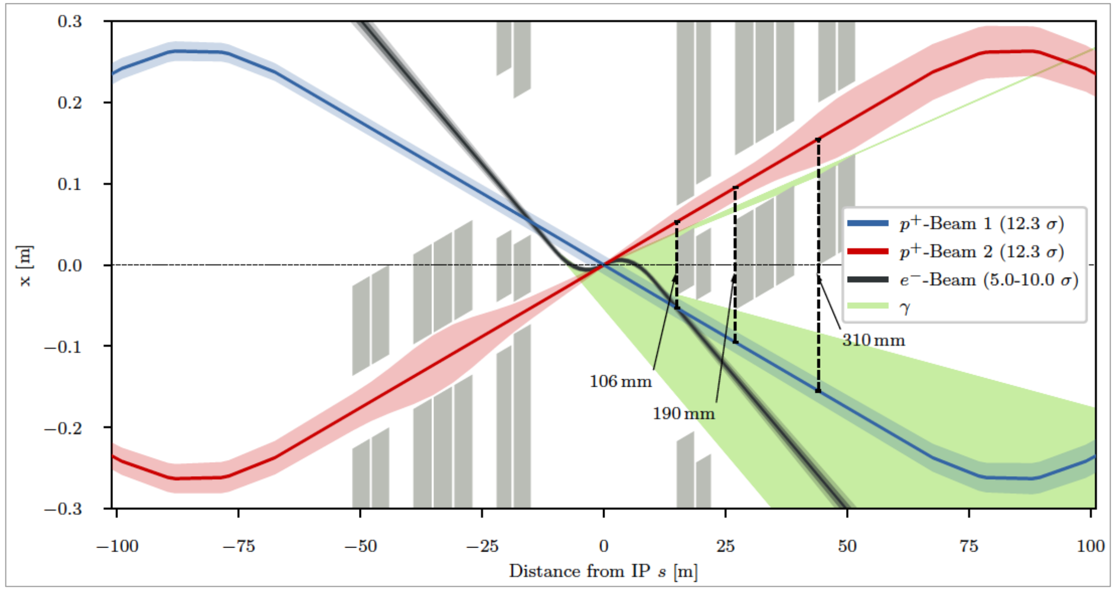
Key elements to the detector design

- LHeC will run simultaneously with the LHC ⇨ 3 beam IR with compatible optics
- Modular for assembly above ground and rapid installation
- No pileup
- Low radiation wrt pp
- Tracker radius: 60 cm
- Magnetic field: B = 3.5T
- Length x Diameter = 13 x 9 m^2

Chalanging technology aspects related to the design of the interaction region

Hadron-Electron Collisions at the LHC and FCC

Synchronous ep/pp operation



Head-on collisions: large synchrotron radiation fan from outgoing e-beam ➪ Eliptical beampipe accomodates synchrotron fan

Complex magnet configuration

- Solenoid Detector Magnet (3.5T)
- Dual dipole magnets (0.15 – 0.3 T) throughout detector region (|z| < 14m)
  - to guide e-beam in and out
  - bend e-beam into head-on collision with p-beam
  - Safely extract the distorted e-beam
- 3.5T superconducting NbTi/Cu solenoid in 4.6K liquid helium cryostat

2T scaled up to 3.5T

H. Ten Kate (1st CERN EP-R&D Workshop)

Baseline design concept relies on present technology for detector magnets

Solenoid and dipoles have a common support cylinder in a single cryostat; free bore of 1.8m; extending along the detector with a length of 10m

New ideas on thin magnets (cf. E. Perez at FCC workshop) and R&D programe for FCC relevant for LHeC

FCC-eh – The Large Hadron-Electron Collider at the FCC

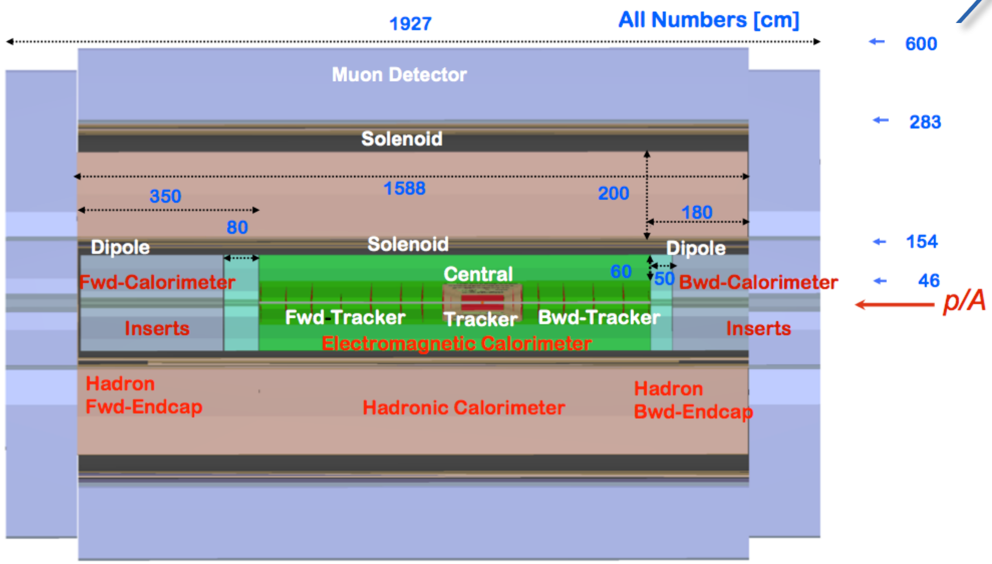
FCC-eh – The Large Hadron-Electron Collider at the FCC

Similar schemes in collision with protons of 7 TeV (**LHeC**), 13 TeV (**HE-LHeC**) and 50 TeV (**FCC-eh**)

Detector scales in size by up to ln (50/7) ~2

Double Solenoid + Dipole

Even larger tracking region to retain 1^0 performance



R&D Needs for LHeC and FCC-eh

- Current (baseline) proposal based on detecor technologies for HL-LHC and FCC-hh ⇨ no (need for) dedicated R&D
- **Detector performance/cost optimization will benefit singificantly from R&D in several areas:**
  - High-resolution, low-power MAPS for vertex and inner tracking layers (low radiation envinronment)
  - Low-power & low(er) cost silicon sensors and module assembly for (large surface) outer tracker
  - Progress on ECal technologies, in particular remove need for cryogenics
  - R&D on thin magnet technologies

LHC programme

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
collisions systems	pp, p-Pb Pb-Pb	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
LHC schedule	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6

Run 3 → high luminosity for ions (7 x 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

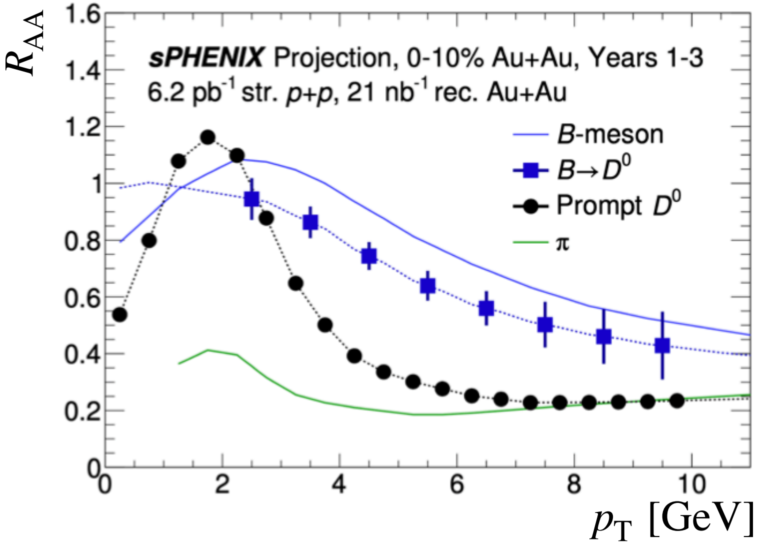
pp luminosity up to 7.5 x 10^{34} $cm^{-2}s^{-1}$

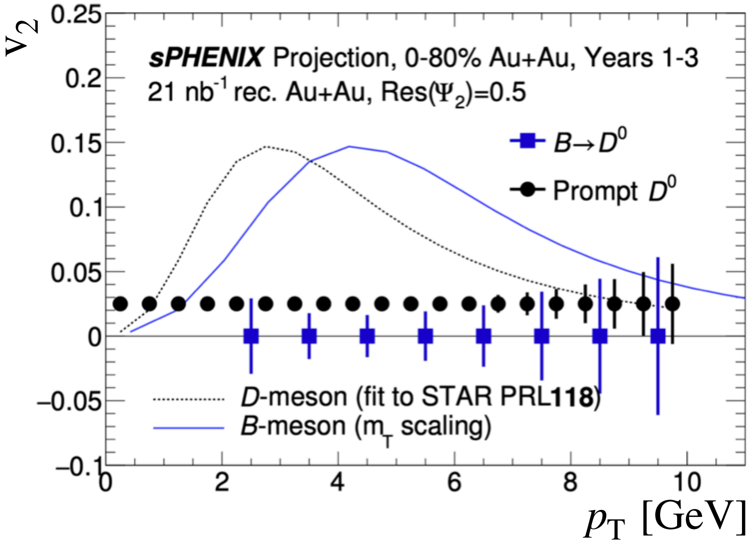
Run 5 → higher luminosity for ions

- **mitigate space charge effects (SPS & LEIR)** e.g. with lighter ions

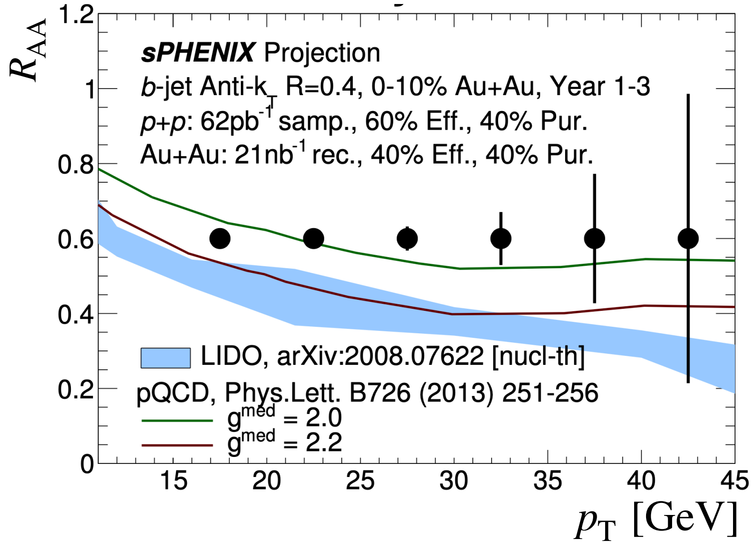
RHIC – sPHENIX physics performance projections

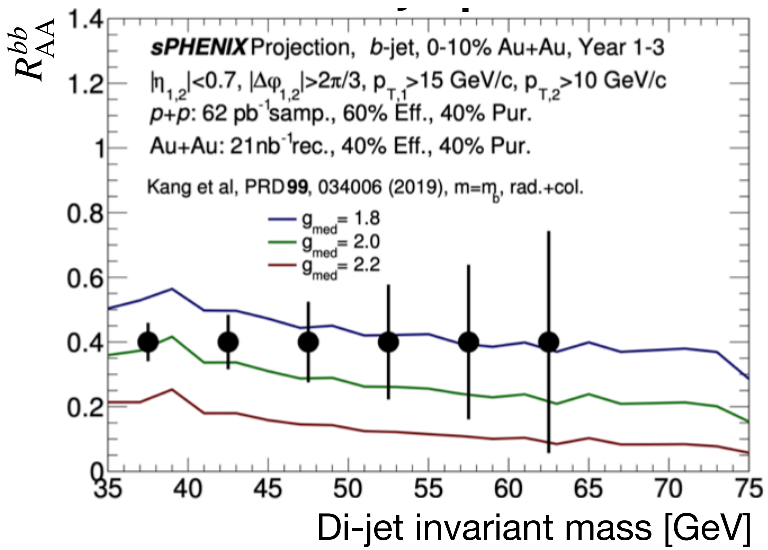
Heavy Flavour

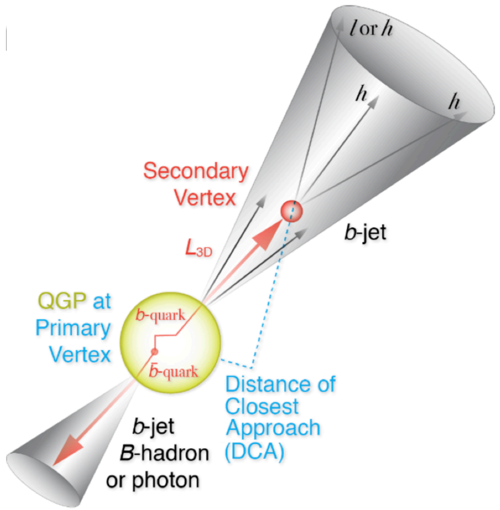




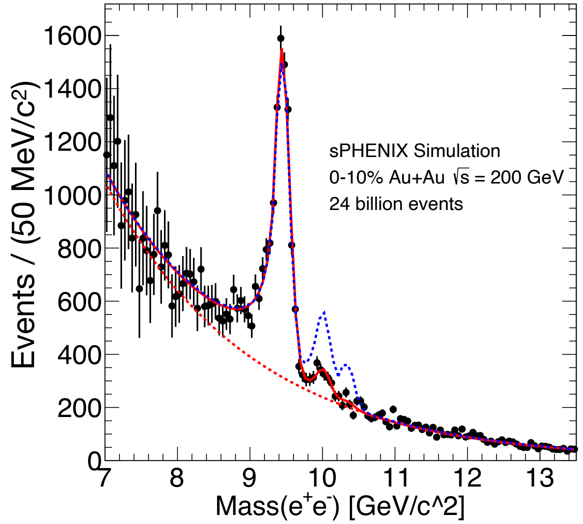
b-jet and b-jet pair







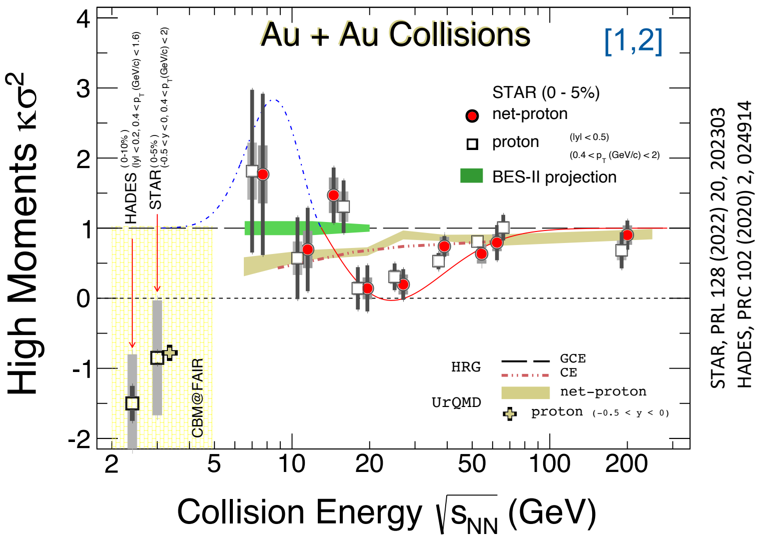
Υ physics



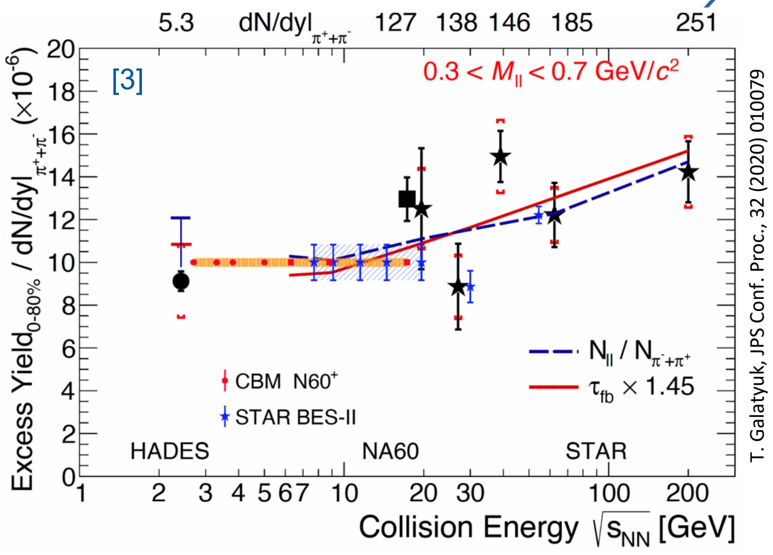
Compressed Baryonic Matter (CBM) Experiment

CBM Scientific objectives (a selection)

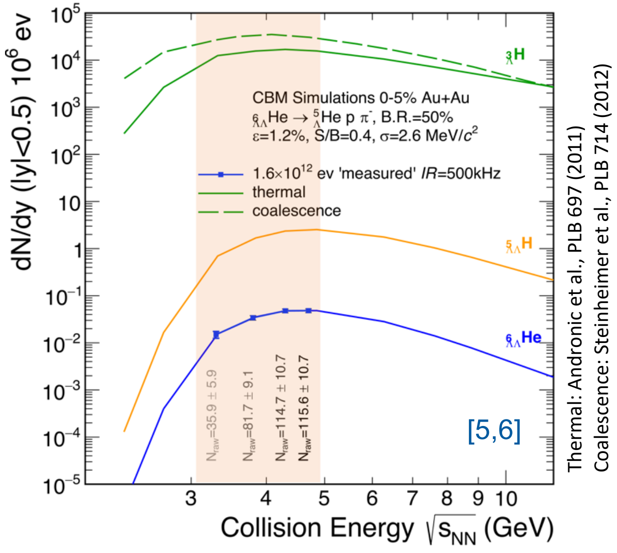
Criticality



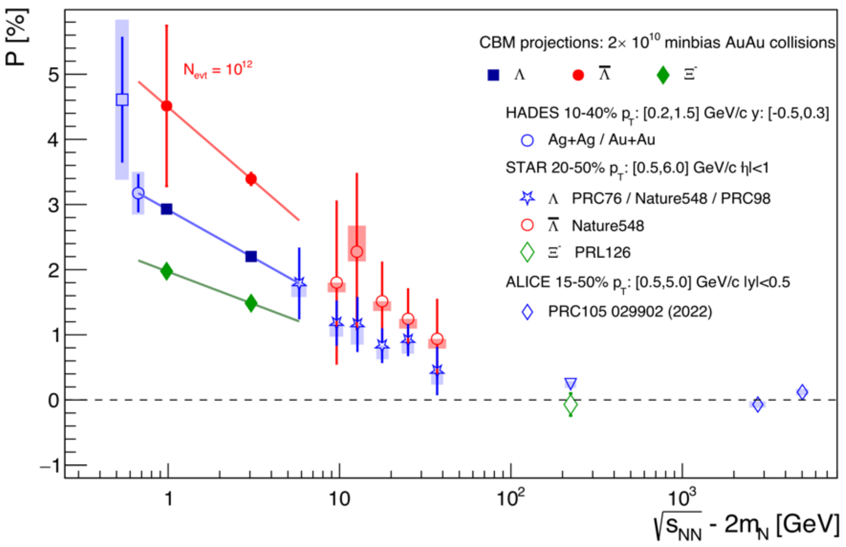
Emmissivity



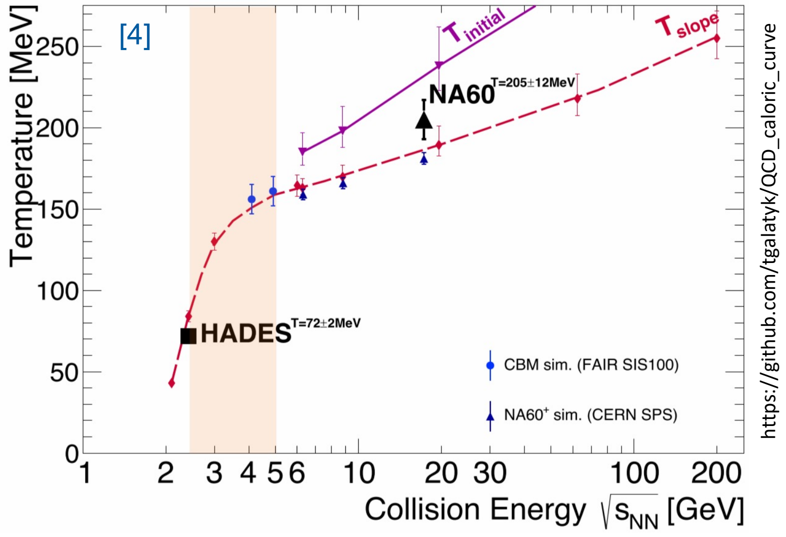
Hypernuclei



Vorticity



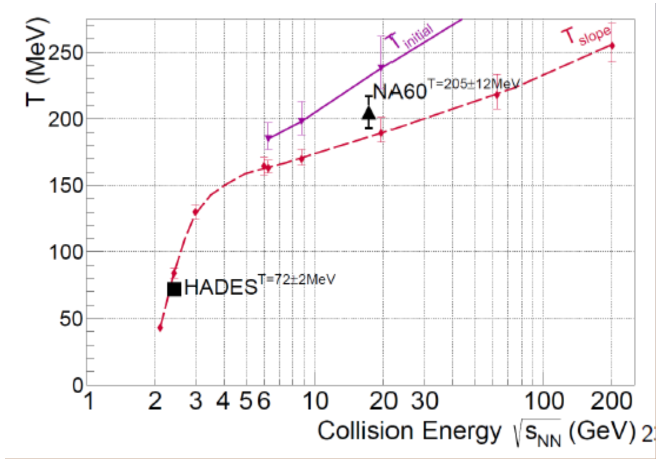
Calotic Curve



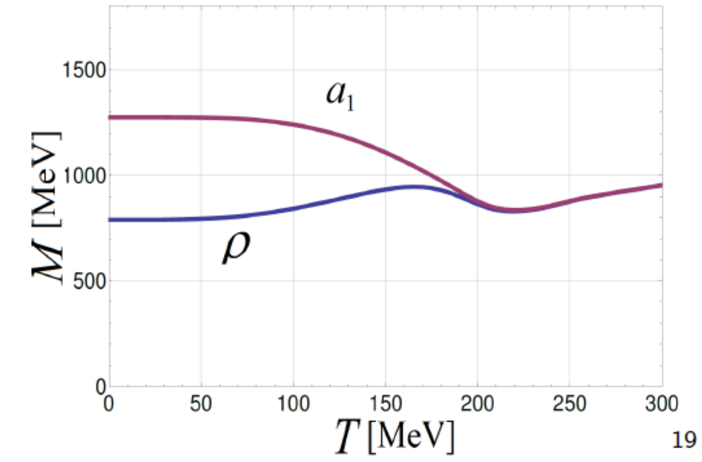
High μ_B experiments - NA60+

Scientific pillars of the proposed NA60+ experiment:

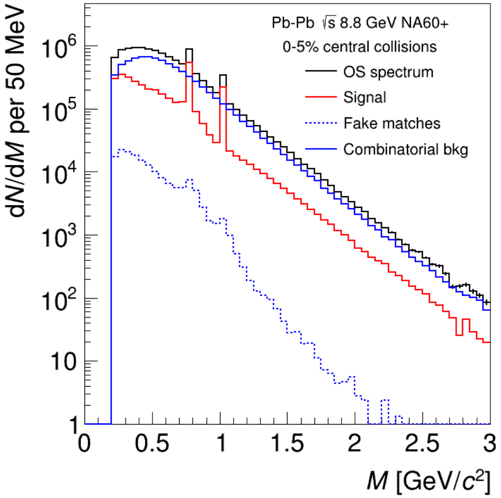
- Measurement of thermal dimuons from QGP/hadronic phase ⇨ caloric curve for first order transition
  ⇨ extract temperature via fit $\frac{dN}{dM} \propto M^{3/2} e^{-M/T_s}$, possible flattening in $\sqrt{s}$–dependence of T_s
- $\rho - a_1$ modifications: chiral symmetry restoration
  ⇨ full chiral $\rho - a_1$ mixing → dimuon enhancement in the region 1 < M < 1.4 GeV/c²

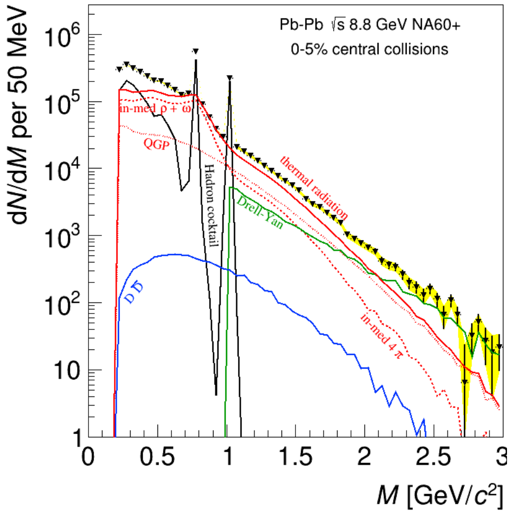


HADES, Nature Phys. 15(2019) 1040
NA60, EPJC 61(2009) 711



C. Jung et al., PRD 95 (2017) 036020





Letter of Intent: the NA60+ experiment (arXiv:2212.14452v1)

- And much more: e.g. quarkonium suppression (signal of deconfinement), hadronic decays of charmed mesons/baryons (QGP transport coefficients)