High Energy *Nuclear* / QCD Oriented Experiment

Zvi Citron
also for Sasha Milov and Igor Korover

אוניברסיטת בן-גוריון בנגב
جامعة بن غوريون في النقب
Ben-Gurion University of the Negev

What Questions Did We Ask ~~5~~ 6 Years Ago?

HEP Town Meeting

5 December 2018

Outstanding Questions in High-Density QCD and Heavy-Ions

- How do the properties of hadrons emerge from fundamental interactions?
- What are the contours of the QCD phase diagram?
  - Is there a first order phase transition? A critical point? [RHIC,NICA]
  - How does the strongly interacting QGP emerge from QCD? How (when) does it thermalize and equilibrate? [HL-LHC, RHIC, NICA]
- How do partons behave at high densities?
  - What are the initial relativistic nuclear states? [HL-LHC, EIC/LHeC]
  - Can we observe gluon saturation? [HL-LHC, EIC/LHeC]
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  - Can quasi-particles be observed in this deconfined liquid? [HL-LHC, RHIC]
  - Can actual medium response be observed? [HL-LHC, RHIC]
- Is hadron production the same in elementary collisions and nuclear collisions?

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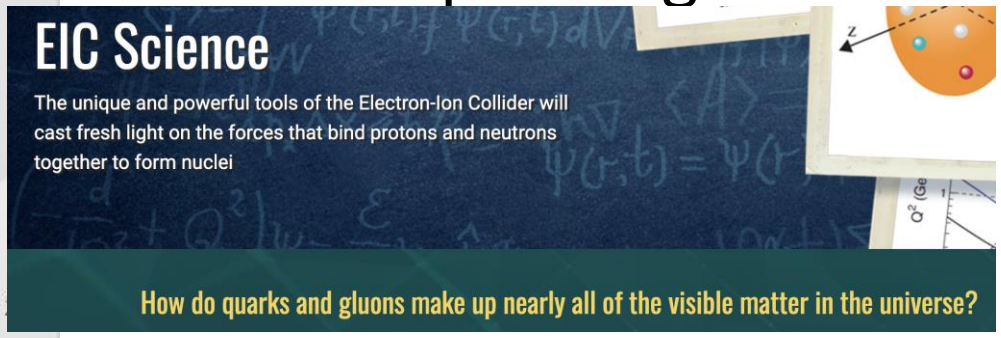
- Different phrasing but overlaps EIC goals



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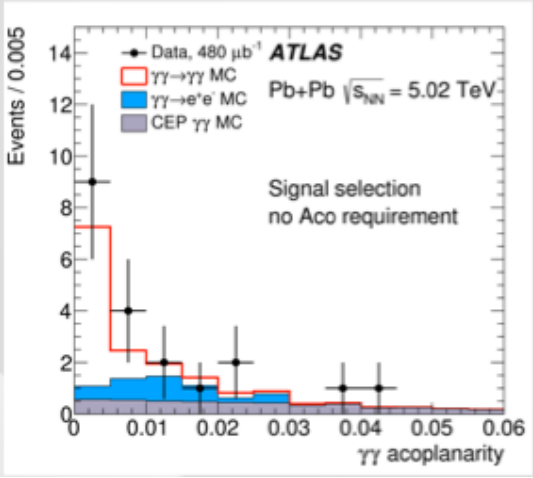
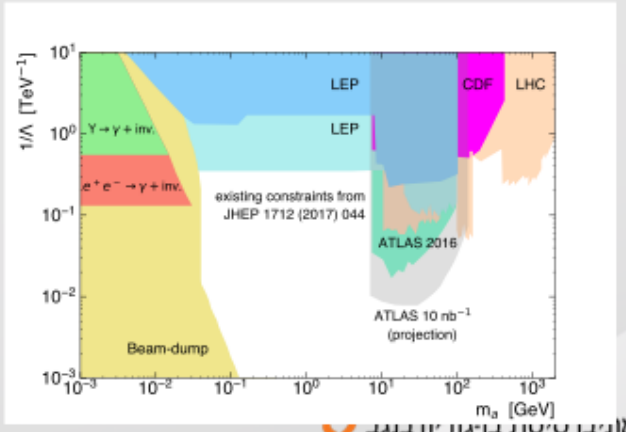
Maximal Utilization of HI Collisions

- HI collisions are a unique experiment, community's goal should be to maximize available physics
- E.g. LHC HI as as LPhotonC collider for light-by-light scattering
  - Interesting QED prediction!
  - Set limits for axion-like particles
- We should be thinking of ways to maximize HI programs





- Photon + photon/A/p program has blossomed - many results since then
- Overlaps with EIC
- Overlaps with LUXE

Current Experimental Activities

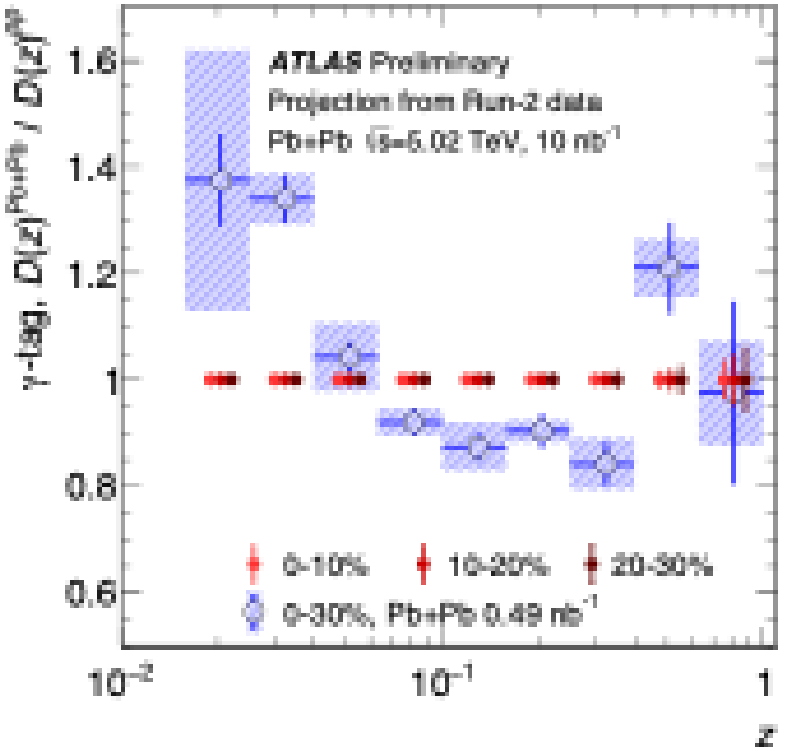
- ATLAS Heavy-Ion Program [ongoing]
  - Sasha (WIS) & Zvi (BGU)
- NA60+ @ SPS [future]
  - Sasha (WIS)
- ePIC @EIC [future]
  - Igor (TAU) & Zvi (BGU) & …

ATLAS Heavy Ion Program

- HI program includes but is **more than** Pb+Pb to study QGP
  - Remaining Run 3 and Run 4 will include O+O, p+O, p+Pb, and probably more
  - Weizsäcker-Williams photons come along for free
  - (Special pp runs)
- Heavy-Ion Program spans:
  - "Classic" RHI goal – create and study extremely hot & dense nuclear matter in AA collisions to learn about QCD
  - Cold nuclear matter, nuclear modifications to PDF primarily in p+A
  - "HI-style" analyses in analyses in smaller AA and pp, following Run 1 discovery of QGP-like flow, → a coherent picture from small to large collision systems?
  - Using the ion beam in the LHC as a photon beam to study photon-photon, e.g. LbyL, and photo-nuclear interactions.
- WIS & BGU are heavily involved in all of the above
- [Note that Run 4 upgrades especially ITk open a lot of doors]

ATLAS HI: QGP Physics; Jet Quenching

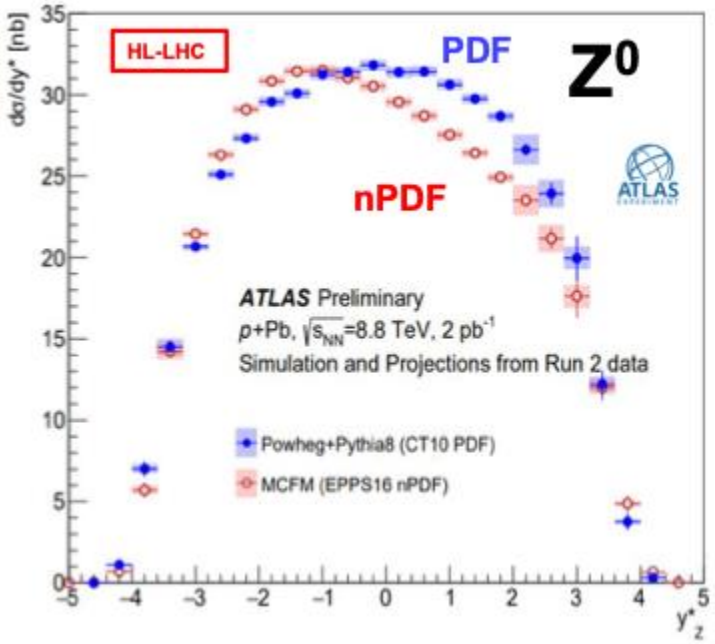
- The “classic” QGP experimental signature is jet-quenching, i.e. the energy loss of a jet to a QGP medium
- EW Boson + jet system provides a golden channel since the boson is not quenched
  - Rare - example of increased statistics enabling measurement improvement
  - (Sasha and others are thinking of creative new approaches beyond just statistical improvement)



Measure jet fragmentation function in PbPP and pp, and compare the two

ATLAS HI: nPDF Physics

- A lot left to do to constrain nuclear PDF
- p+A collisions are the natural place to study
  - Likely only Run 4



Measure EW bosons in p+Pb

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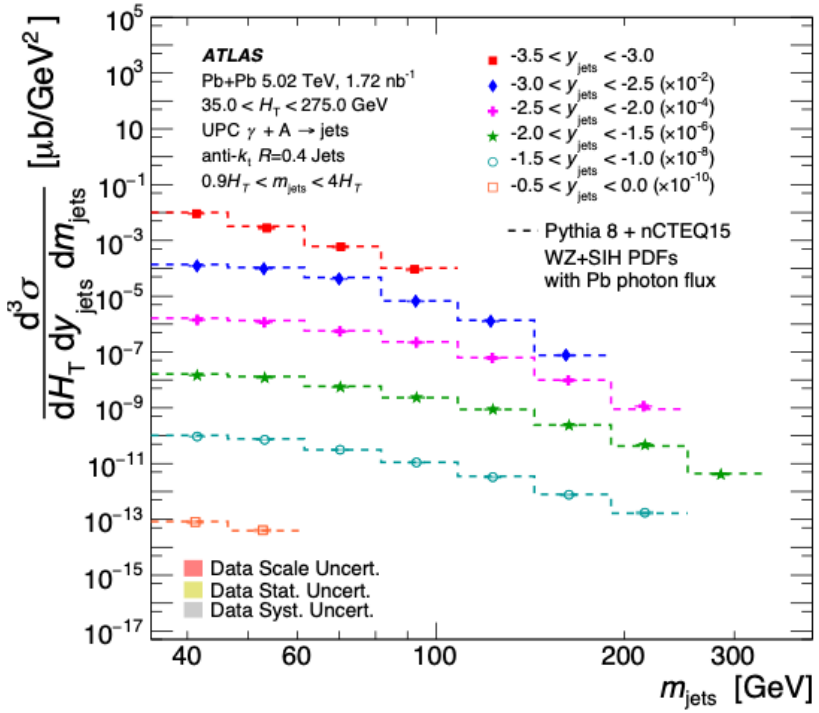
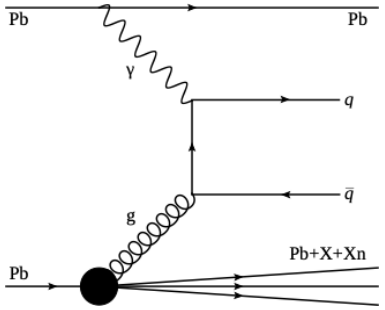
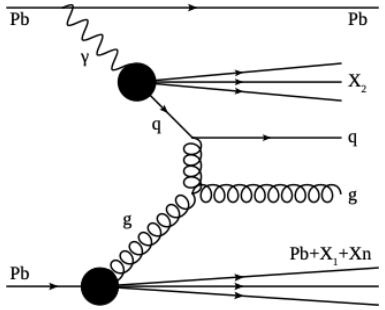
  - Likely only Run 4
- Photonuclear collisions also enable sensitivity







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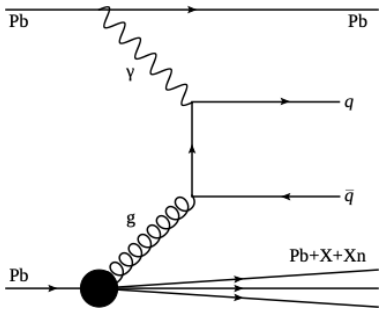
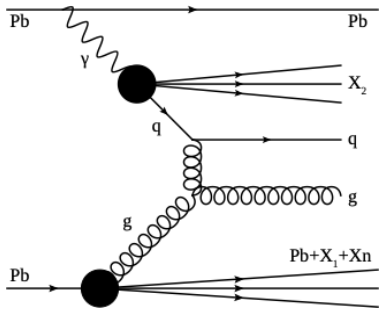
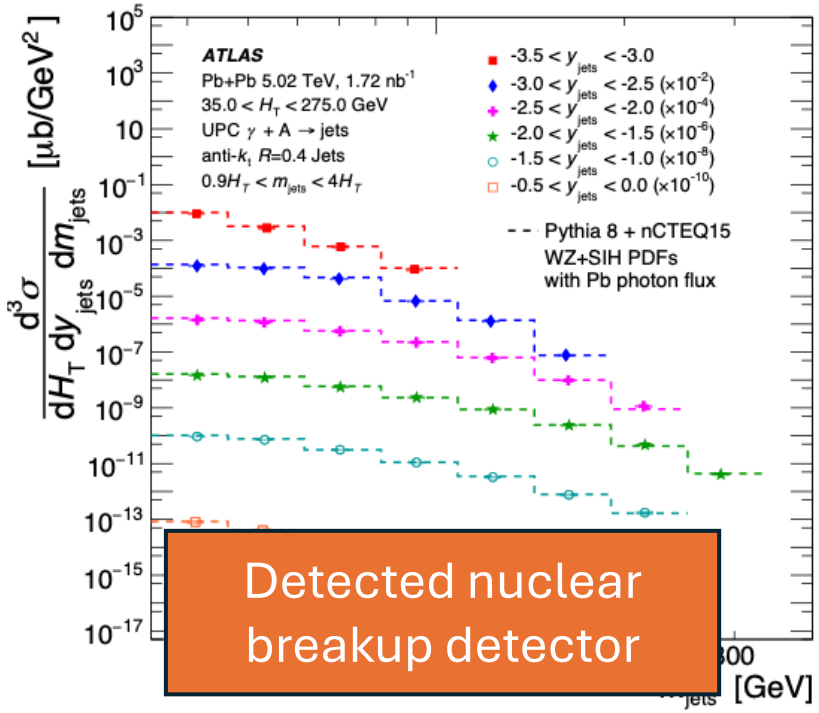
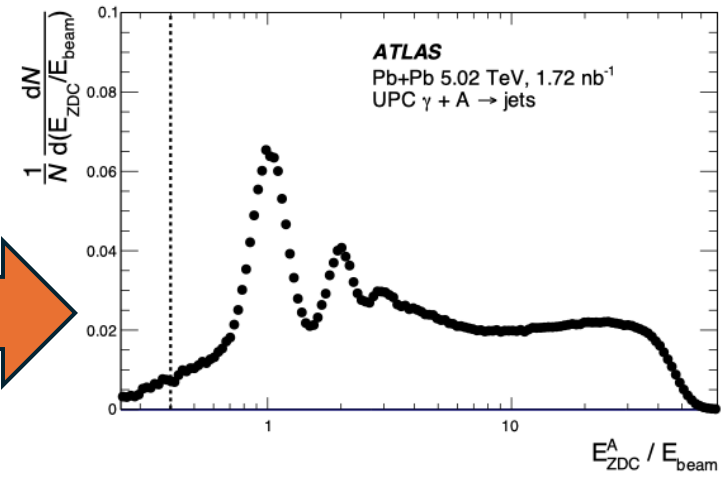




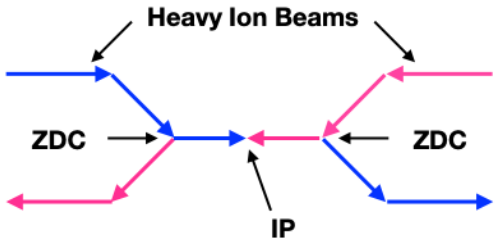


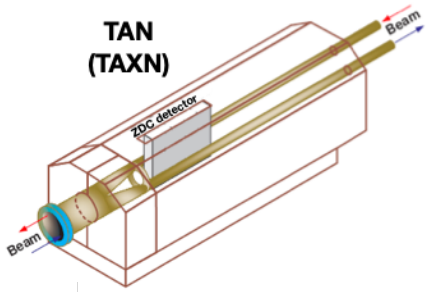
Detected nuclear breakup detector

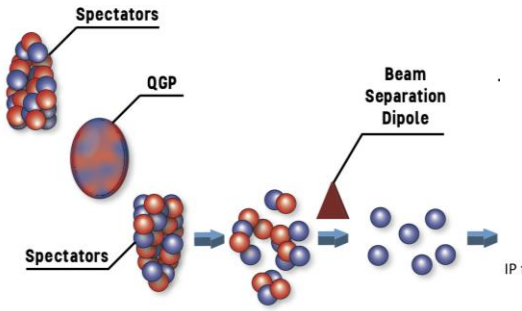


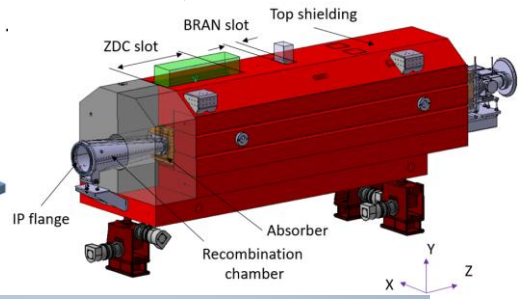
Zero Degree Calorimeter

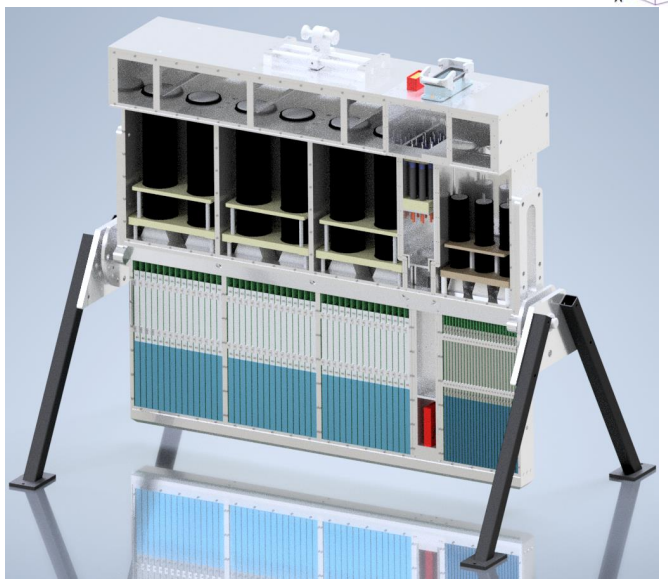
- The ZDC is an HI oriented detector
  - Basic use case is measuring spectator neutrons which are remnants of ion
  - Radiation exposure is too high during full (pp) luminosity
- Located downstream from IP, neutrals reach it, charged swept away by magnet











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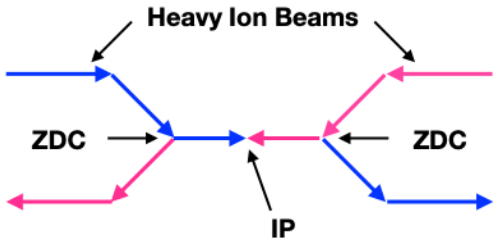
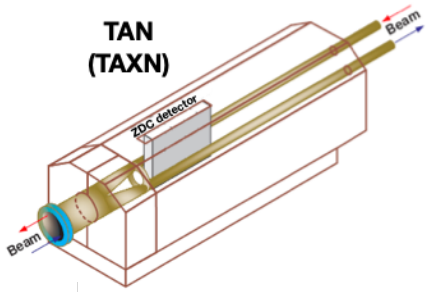
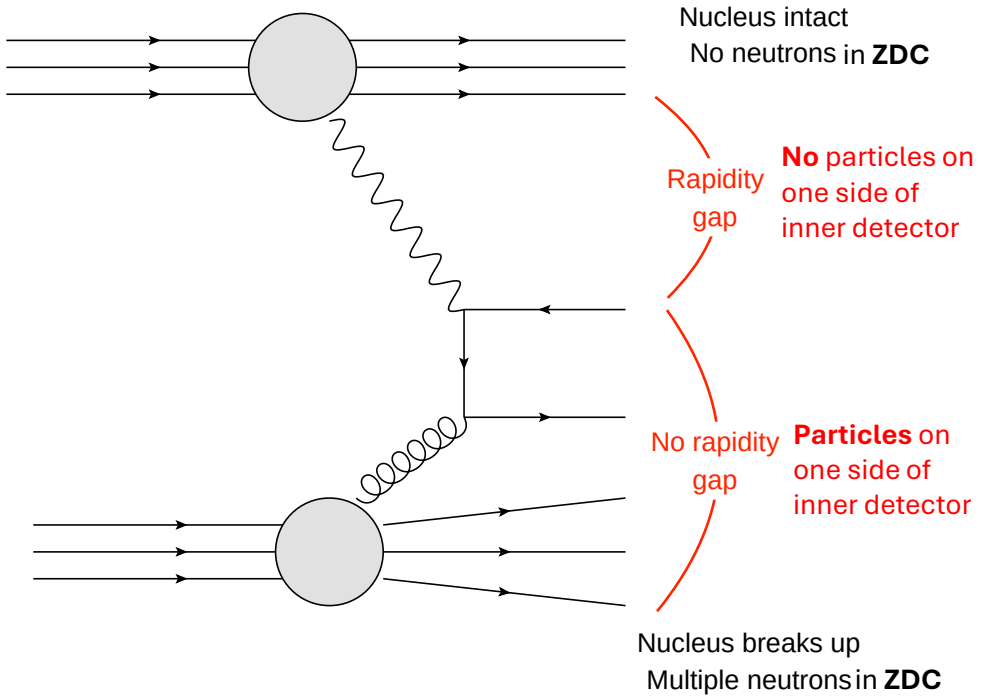


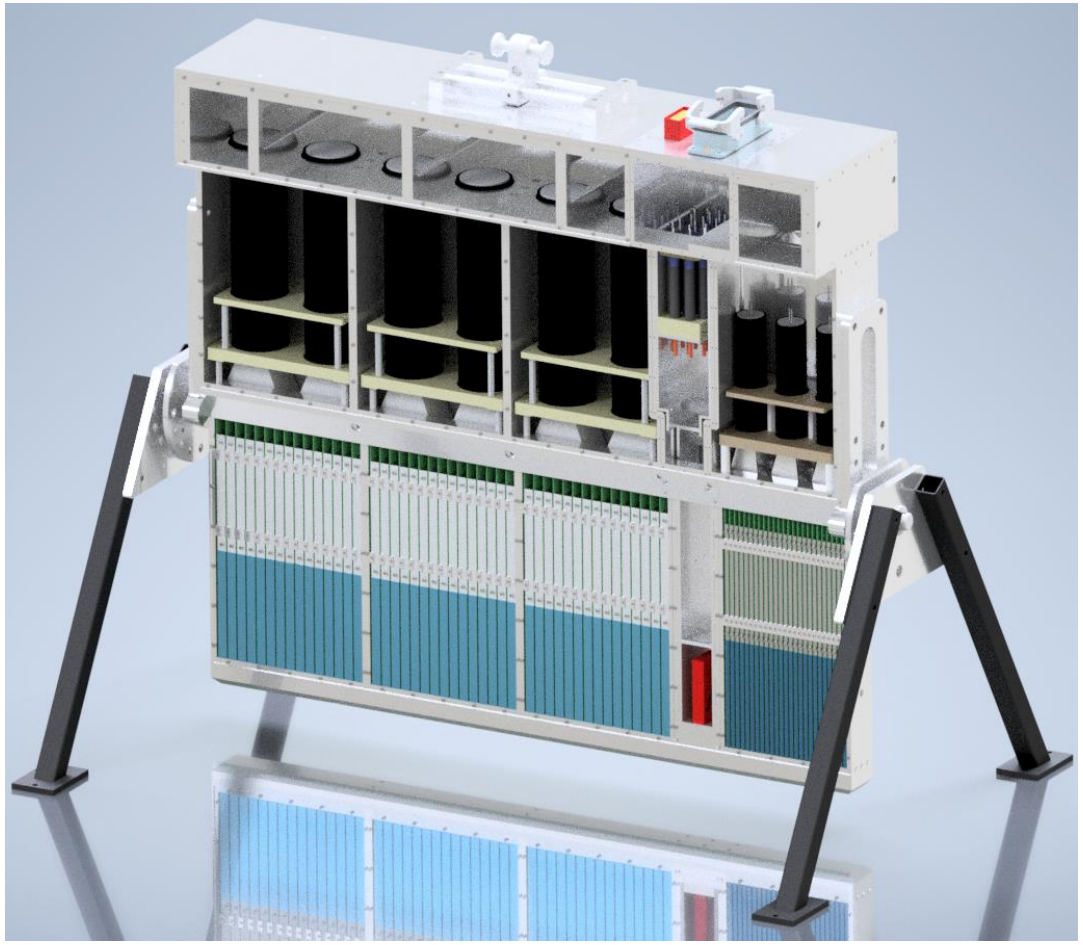


- As a trigger, key detector for entire HI program
- Also key detector (trigger and offline) for ‘photon physics’ program



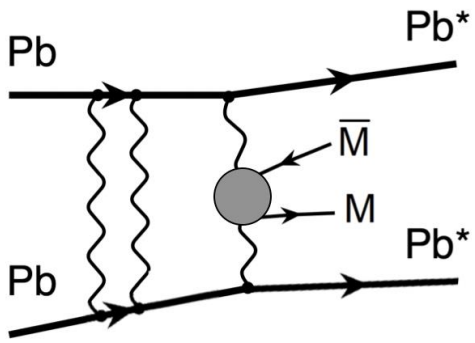
ATLAS ZDC → JZCaP HL-ZDC

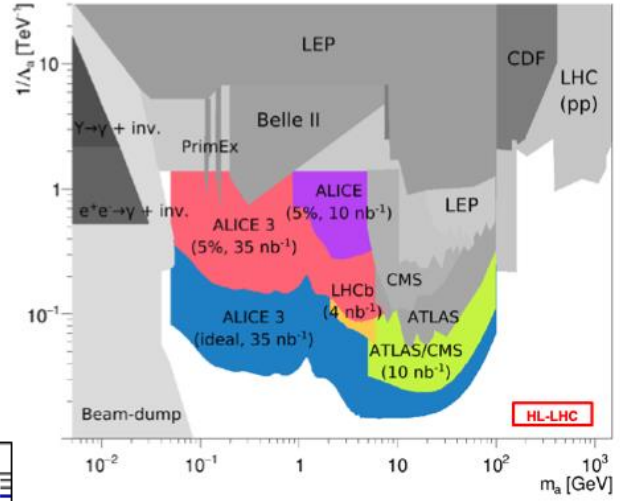
- All new detector for HL-LHC
- The **J**oint **Z**dc **Ca**lorimeter **P**roject (JZCaP) is a combined ATLAS-CMS effort to develop an improved ZDC for both experiments
- Accommodates Run 4 beam optics

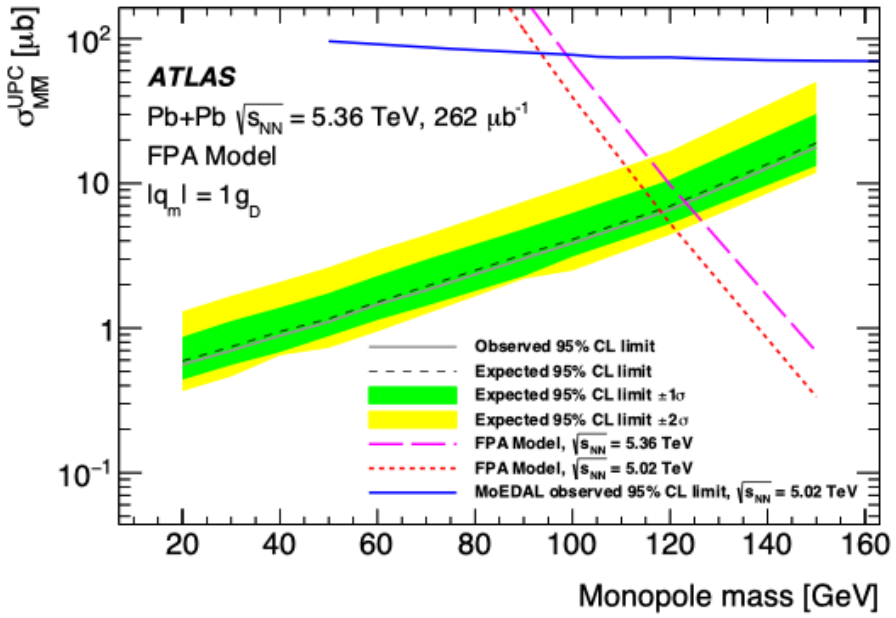


ATLAS HI: Photo-photo and photonuclear

- Once we're making these 'ultra-peripheral collision' measurements there is a lot to measure
- And p+A as p+γ gives sensitivity to proton …

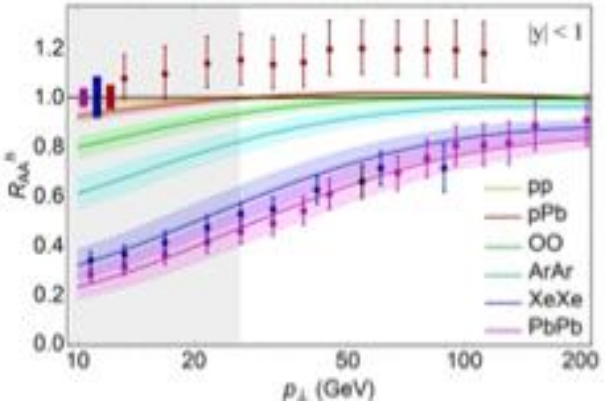




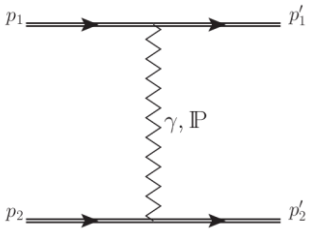


ATLAS HI: Small systems

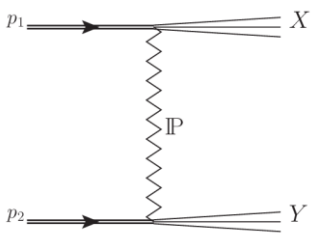
- Oxygen-oxygen collisions could connect between QGP signatures in PbPb, and QGP-like (!) signatures in pp

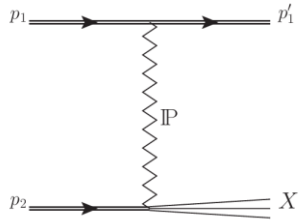


ATLAS not-HI: QCD

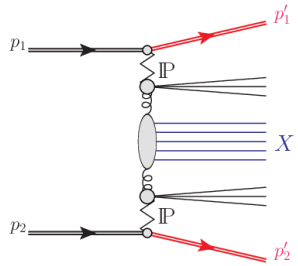


Elastic scattering

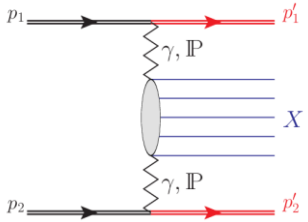




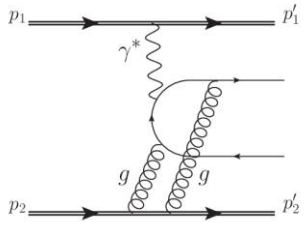
Single/double diffractive dissociation



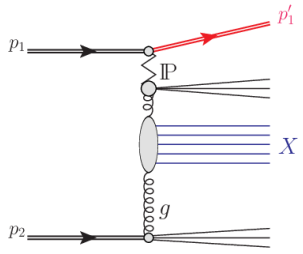
Double pomeron exchange



Central exclusive production



Exclusive photoproduction



Single-diffraction with central system

NA60+

The project is part of the CERN Physics Beyond Collider Initiative

LoI (arXiv:2212.14452) discussed with SPSC in February 2023

Expect a proposal in Spring 2025

The aim is to take data in 2029/30, after LHC LS3

7 years running with Pb beam: one beam energy per year

proton beams for reference for dedicated p-A studies

Sasha (WIS) playing a major role

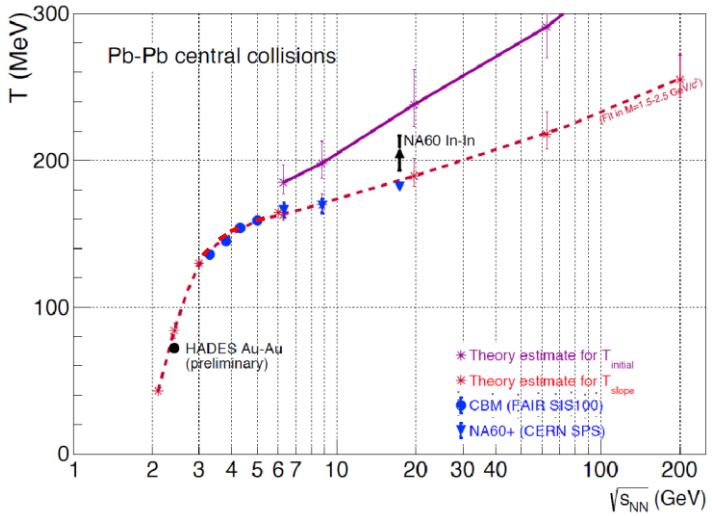
https://na60plus.ca.infn.it/

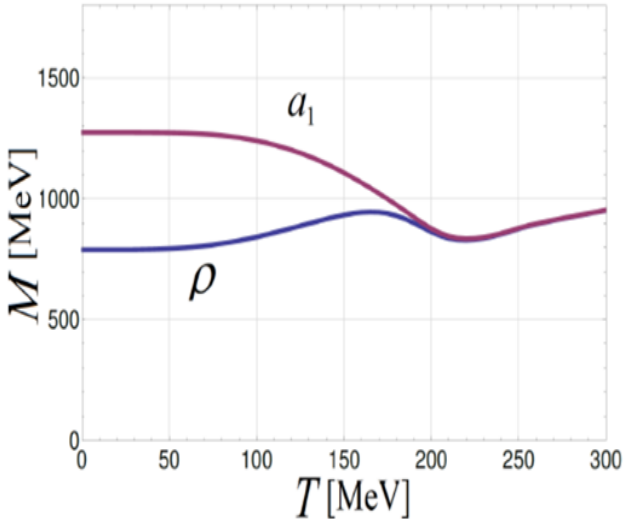
Physics program of NA60+

Caloric curve of QGP

thermal dimuons temperature vs $\sqrt{s_{NN}}$

Rapp and v.Hees, PLB753(2016) 586
T. Galatyuk et al., EPJA52(2016) 131





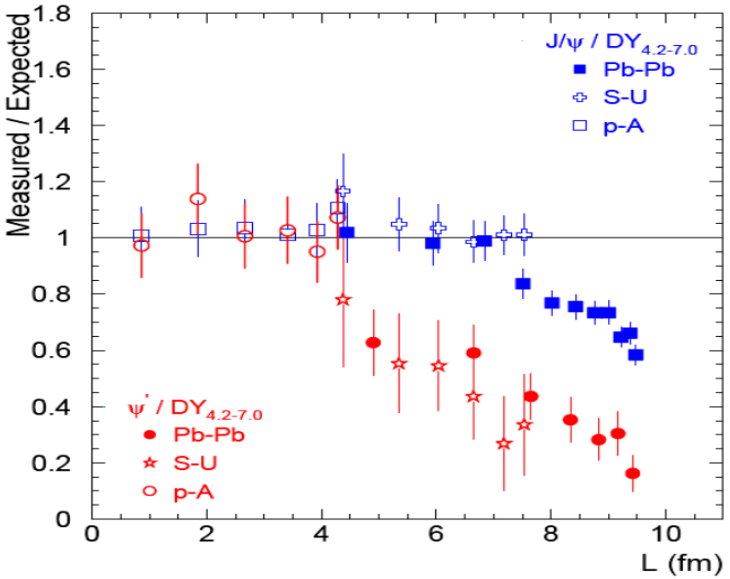
Chiral symmetry restoration via ρ-a_1 mixing in the dimuon channel

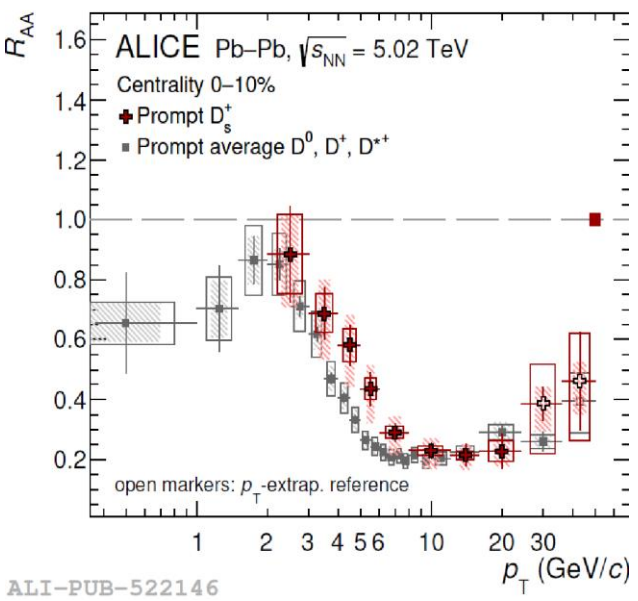
C. Jung et al., PRD 95 (2017) 036020

Suppression of charmonium vs . $\sqrt{s_{NN}}$ in dimuon decay channel

$c\bar{c}$ melting in QGP

NA50, PLB 477 (2000) 28
NA50, EPJC49 (2007) 559

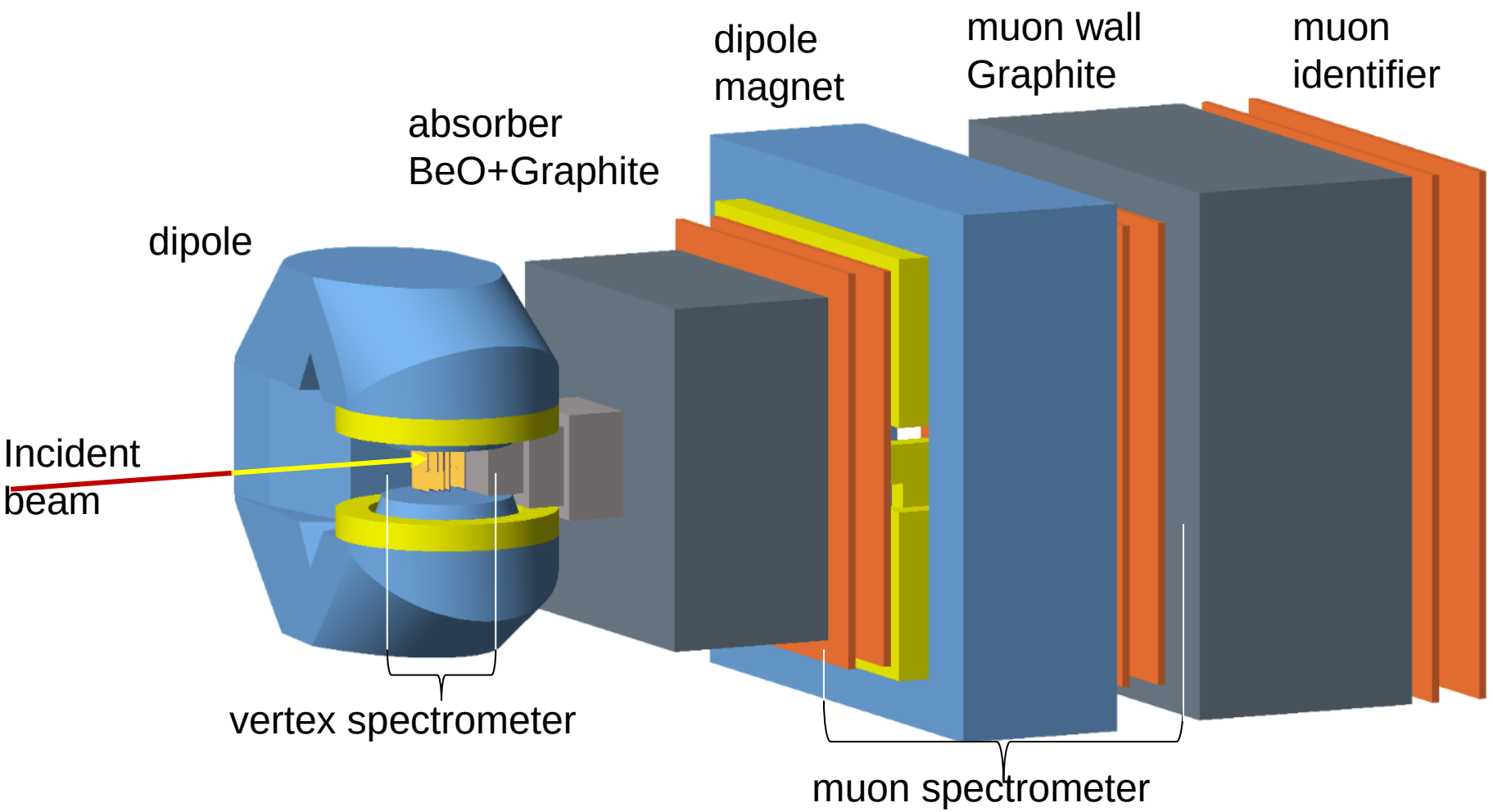




Hadronic decays of open HF to measure QGP transport coefficients and charm hadronization

ALICE, PLB 827 (2022) 136986

NA60+ setup



NA60+ is a ‘classic’ muon experiment consisting of two spectrometers:

Vertex spectrometer is based on MOSS technology, developed for ALICE upgrade

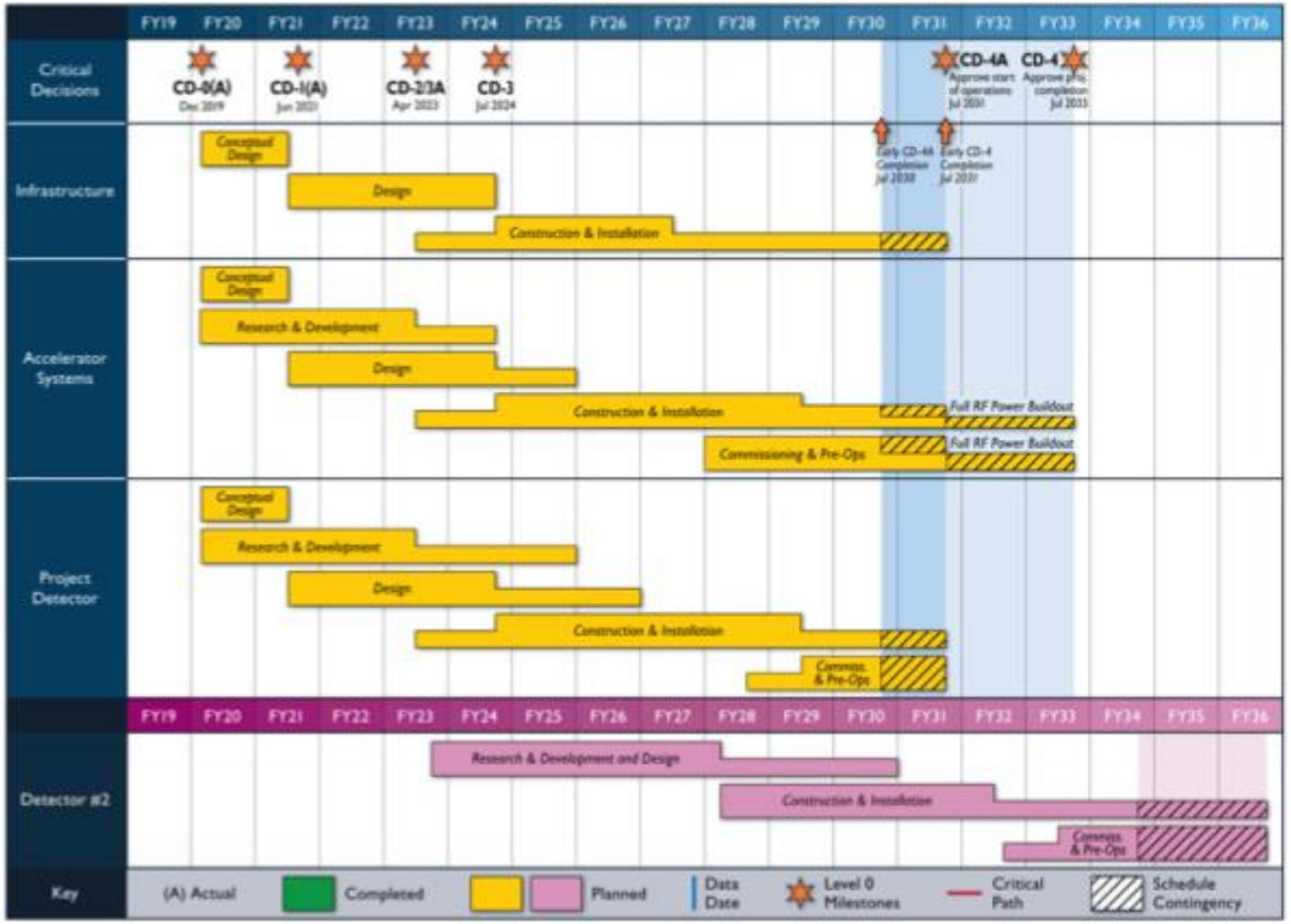
Muons spectrometer uses well-established MWPC

The MNP33 magnet (currently part of NA62) identifies all key elements for the new facility

Proposal in 1st half of 2025

The Electron Ion Collider

- EIC is the next major US collider facility
- Scheduled for collisions in 2031/32 and physics in 2033/34
- (Only) ePIC detector/collaboration for day 1



The Electron Ion Collider

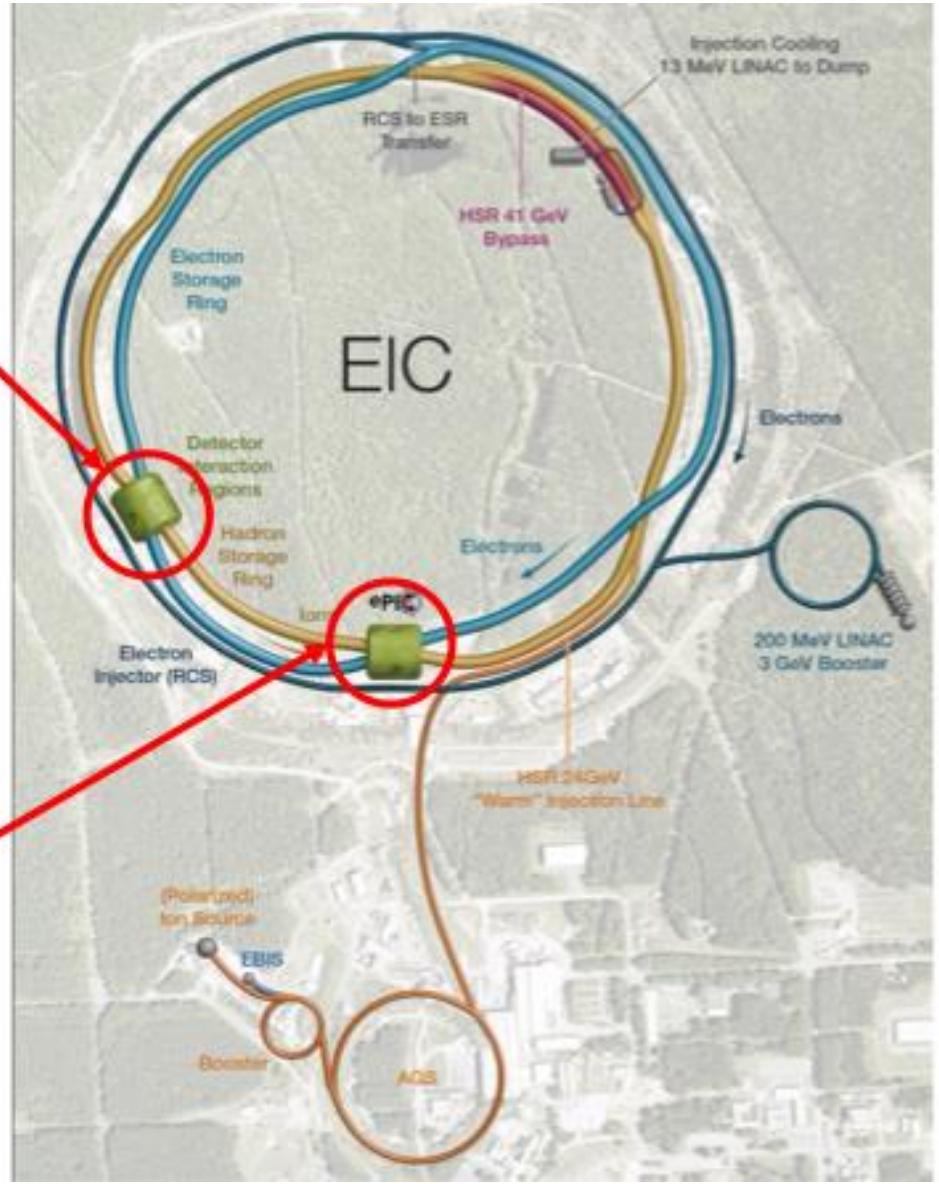
- Electrons: 5 - 18 GeV
- Protons: 41, 100 – 275 GeV
- Polarization > 70%

What is new/different?:

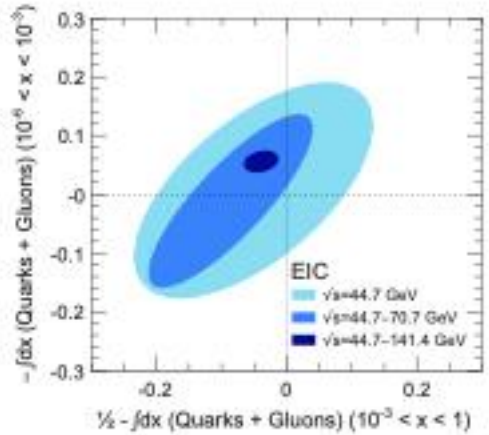
- A factor of 100 - 1000 higher luminosity than HERA → **more statistics, higher precision!**
- Both electrons and protons / light nuclei polarized → **spin-dependent observables!**
- Nuclear beams: d to U → **heavy-nuclei provide access to novel studies in QCD!**

"IP-8" – Eventual Second Detector

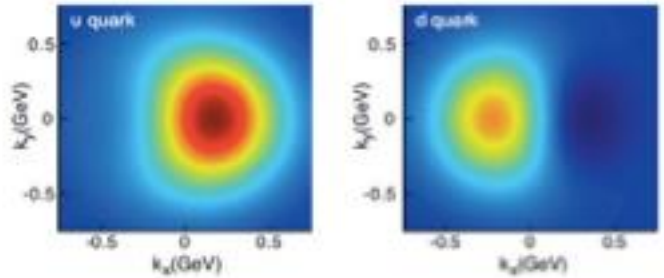
"IP-6" – ePIC Detector

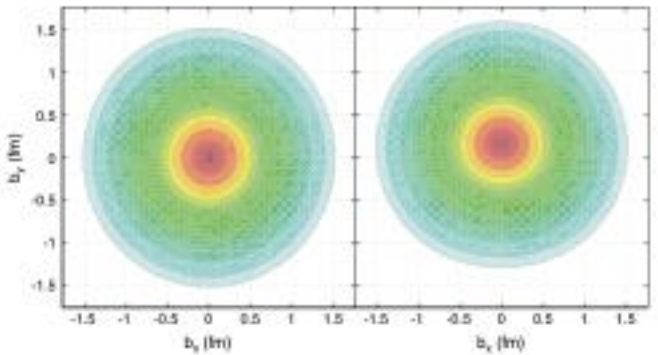


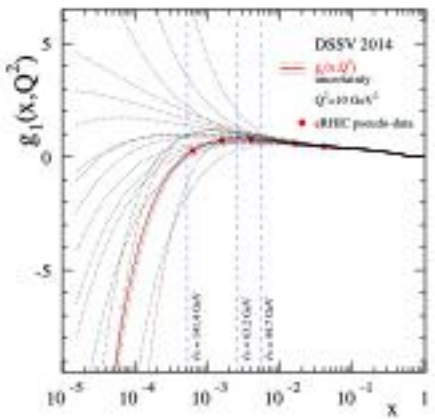
Credit A. Jentsch

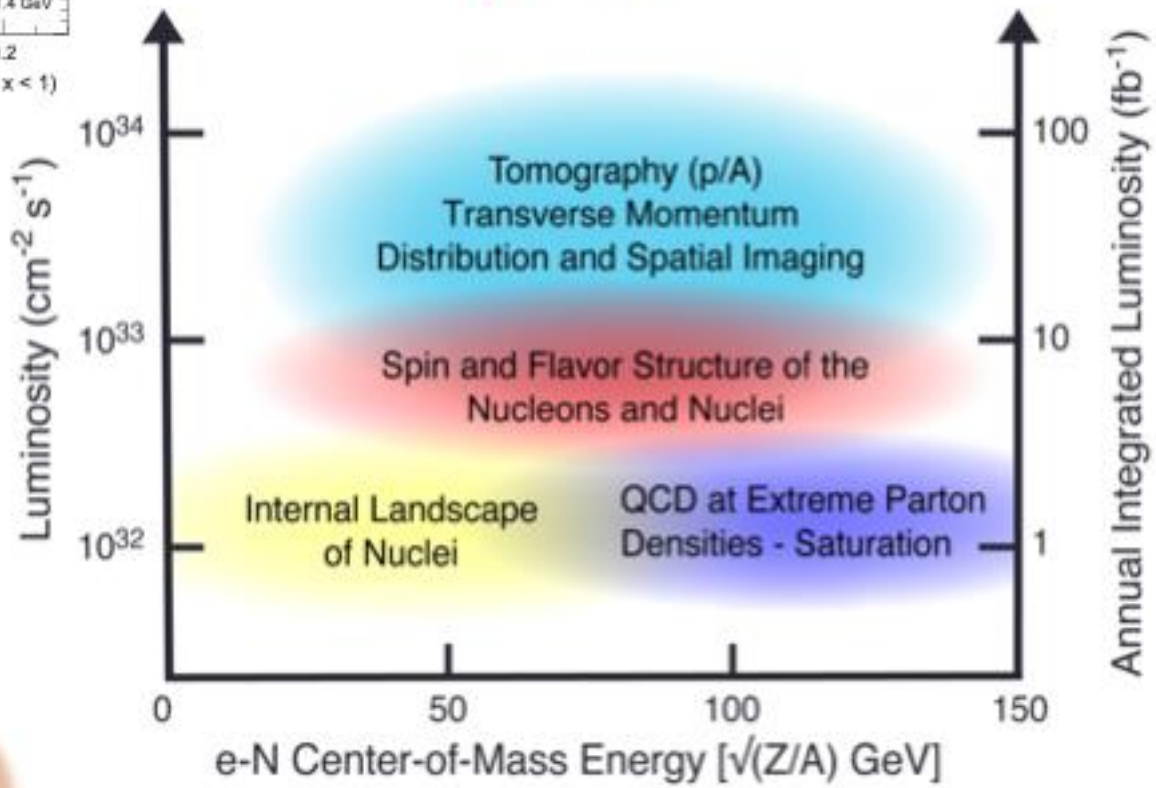


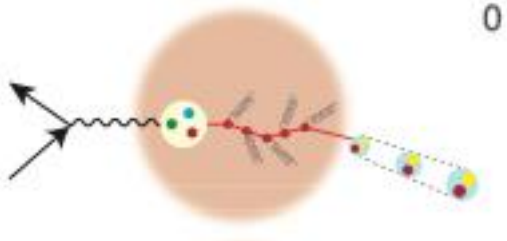
EIC science highlights

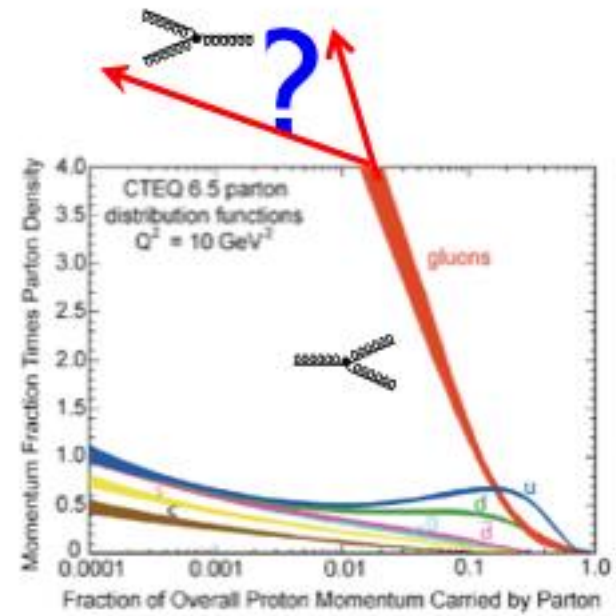






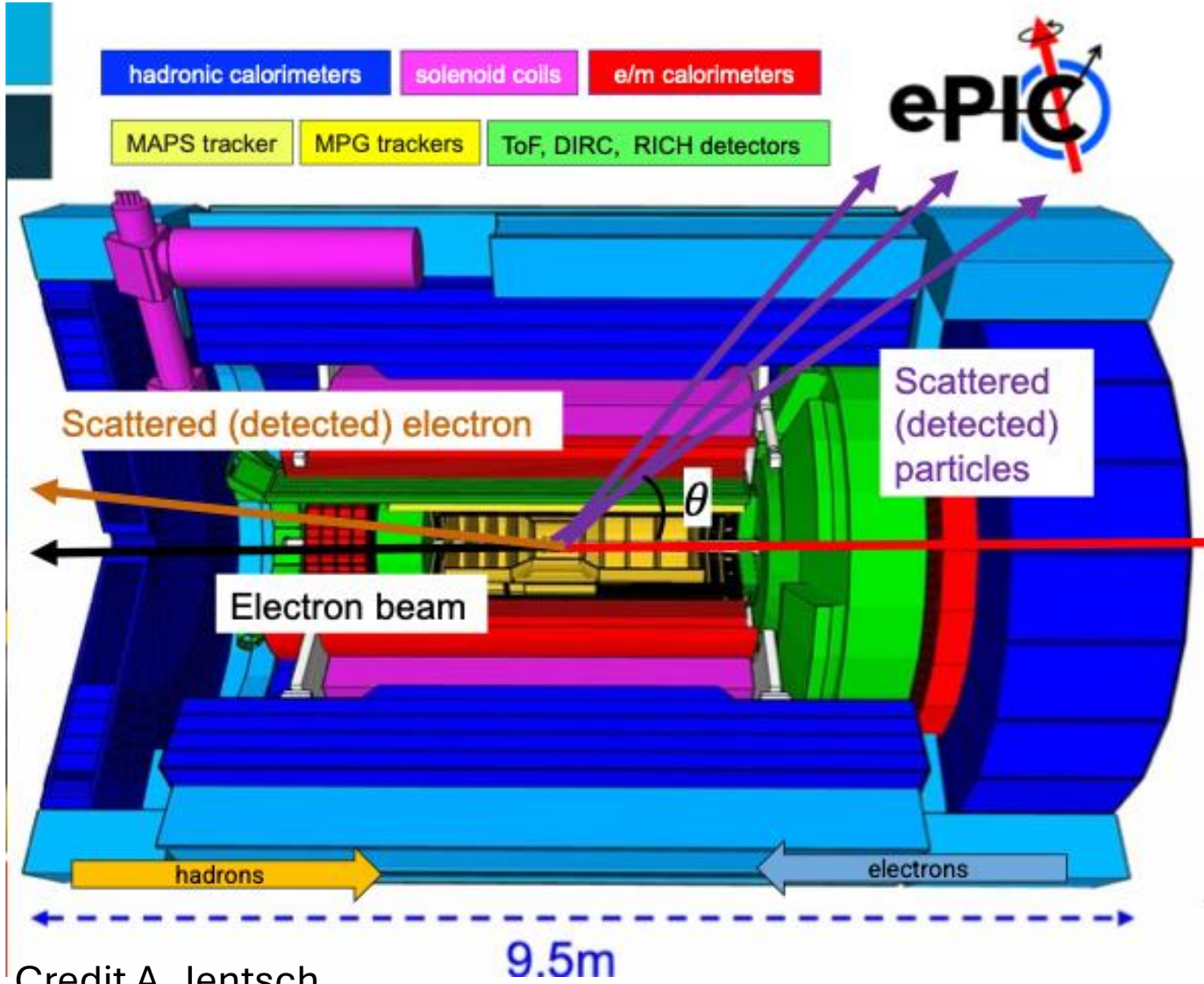






Credit A. Deshpande

ePIC @ EIC



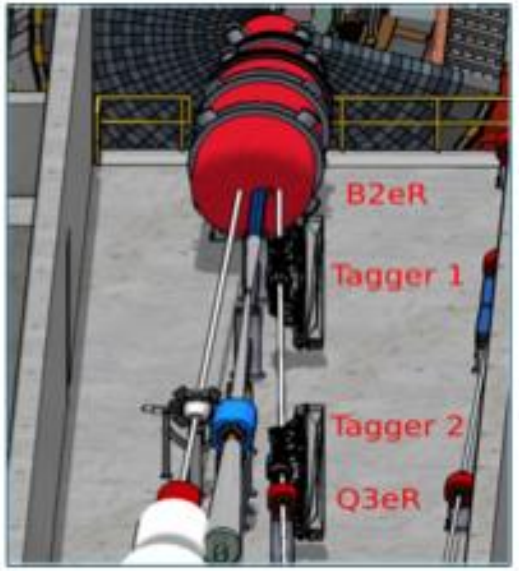
Overall detector requirements:

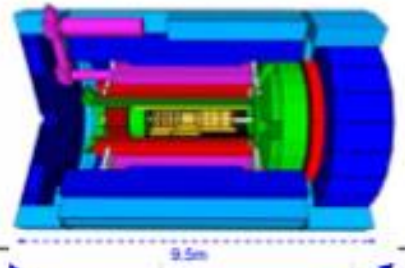
- Large rapidity ($-3.5 < h < 3.5$) coverage; and far beyond in far-forward/far-backward detector regions.
- Necessity for:
  - High-resolution tracking.
  - EM and hadronic calorimetry.
  - PID over a very broad momentum range.

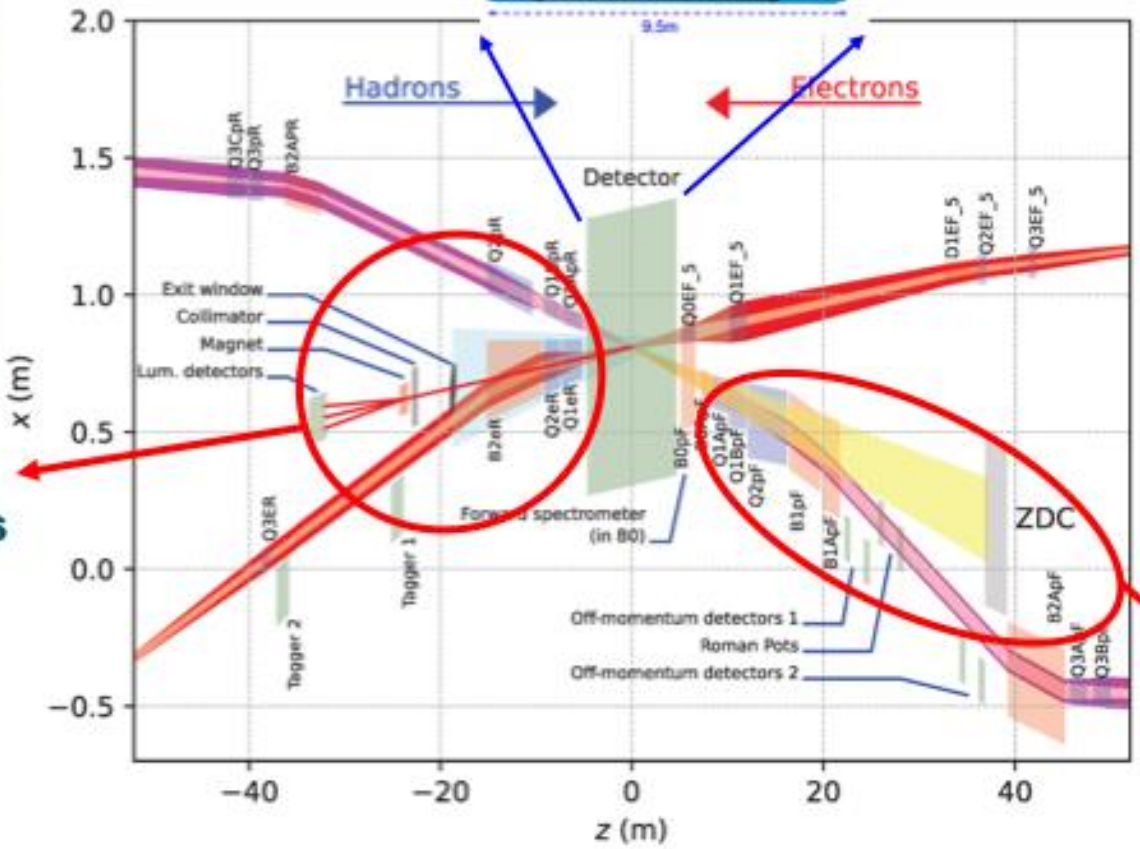
Proton/nucleus beam

Credit A. Jentsch

ePIC @ EIC

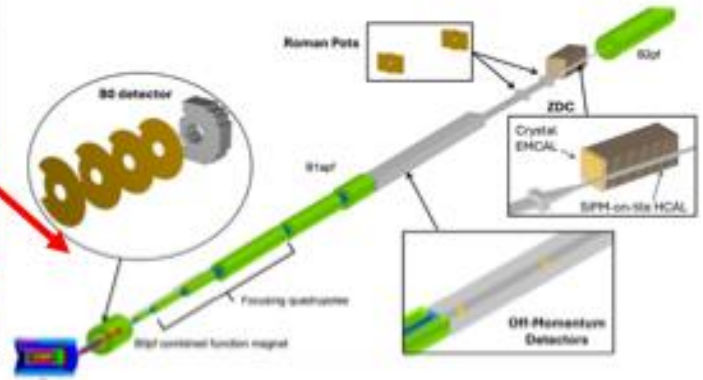






Far-Forward Detectors

- B0 spectrometer and EMCAL.
- Roman pots and off-momentum detectors.
- Zero-degree calorimeter.



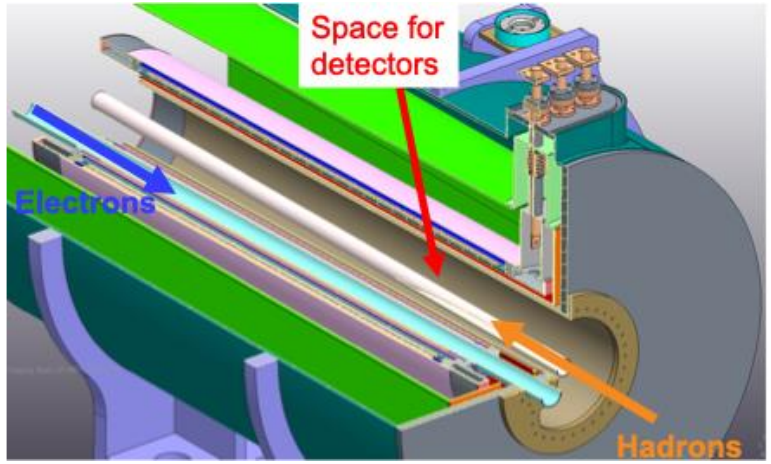
Far-Backward Detectors

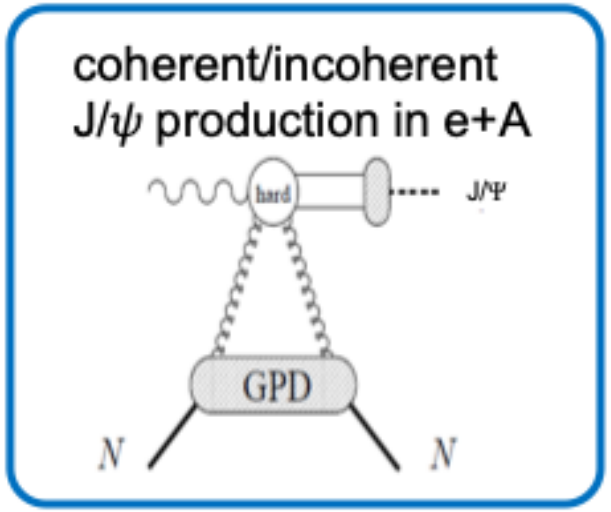
- Luminosity monitor
- Low-Q^2 Tagging Detectors

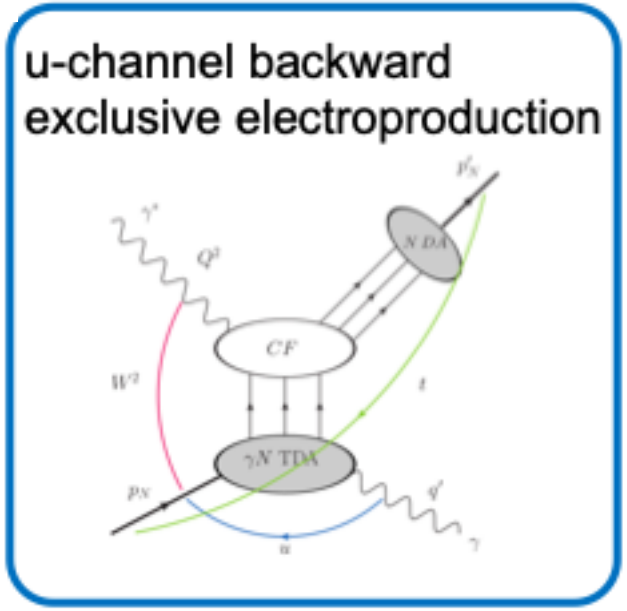
Credit A. Jentsch

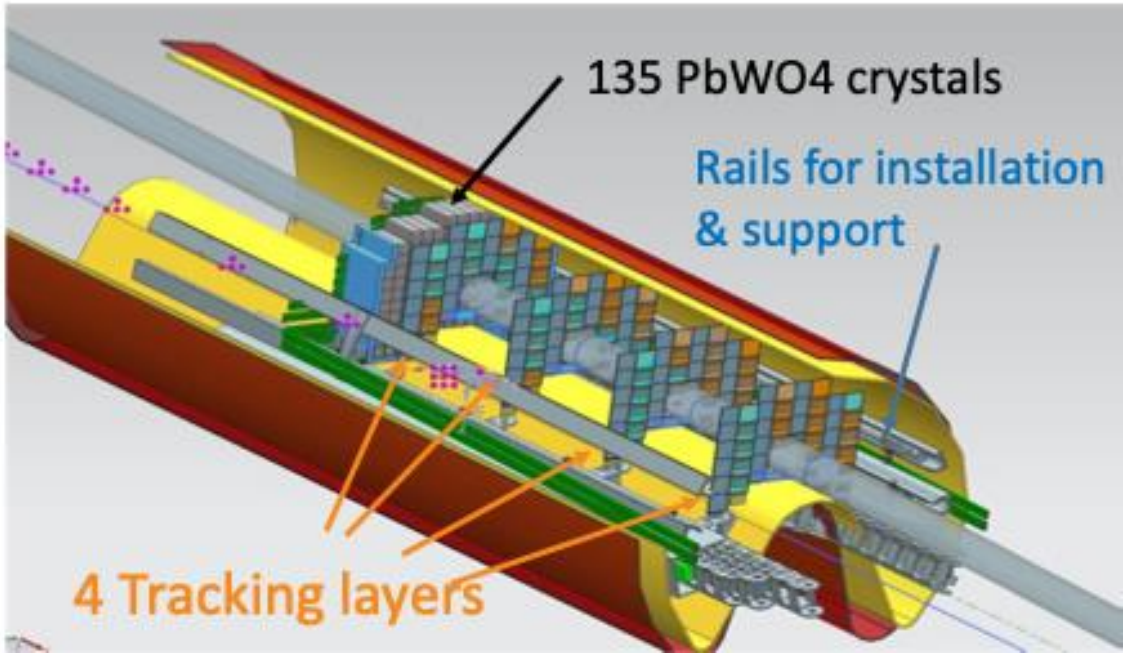
B Detectors

- Israeli responsibility for forward B0 detectors
- EM Calo using PbWO + SiPM
- Si Tracker using AC-LGADs









ePIC @ EIC

- There is a very broad physics program (likely reaching hep-ex)
- Israeli participation from the ground floor
- Overlap with HL-LHC in time and (some) physics
- Recognized CERN experiment FWIW

CERN-DG-RB-2024-527
Minutes-248
25 March 2024

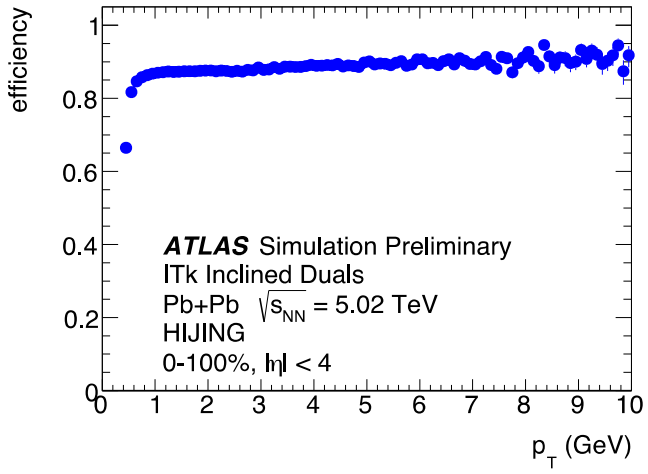
6.2 **ePIC** is the first experiment proposed at the future electron-ion collider (EIC) at BNL (US). It is designed for research on strong interactions in regions complementary to existing facilities (e.g. ALICE and the North Area experiments). The DoE review process is underway, with a combined CD2/CD3 stage (construction start) expected in mid-2025, and data taking from 2030 on. DoE funding is linked to the review process, and commitments by other funding agencies are being made. There are 43 collaborators from CERN Member States, and synergies with CERN for detector technology, DAQ and computing. A dedicated agreement is being negotiated concerning the ALICE ITS3 technology that is of interest for ePIC, with two engineers from the collaboration to be based at CERN. The REC recommends that recognition be granted, on the understanding that, as for any other RE, it shall not imply granting of test-beam time, which will need to be applied for separately. **The Research Board granted Recognized Experiment status to ePIC as RE47 for an initial period of three years.**

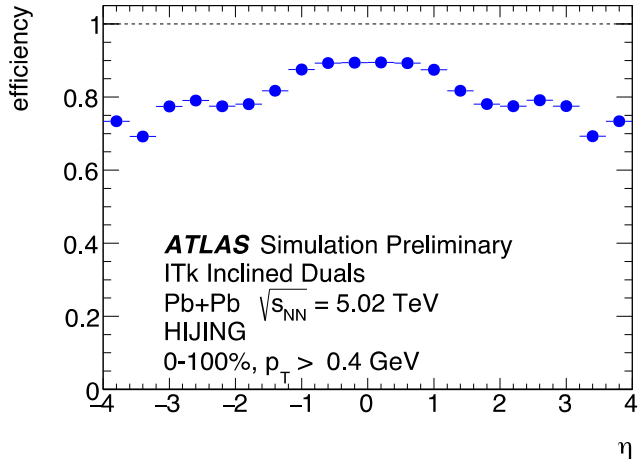
Some Bottomish Lines

- HI, maybe better HI+, is an active and successful part of the LHC program including “bread and butter” QGP studies but also much more
- Continued support into and throughout HL-LHC
  - More than just accumulating statistics in Run 4
  - Also NA60+ @ SPS during Run 4
  - Run 5 still TBD
- EIC is an opportunity which lends itself to synergies with HL-LHC, and hep generally

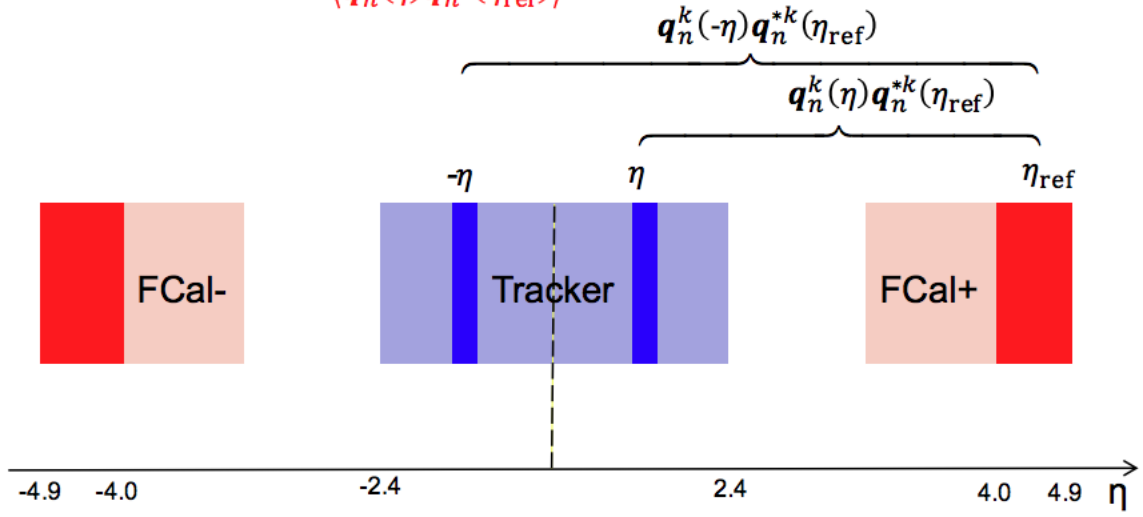
Extra Information

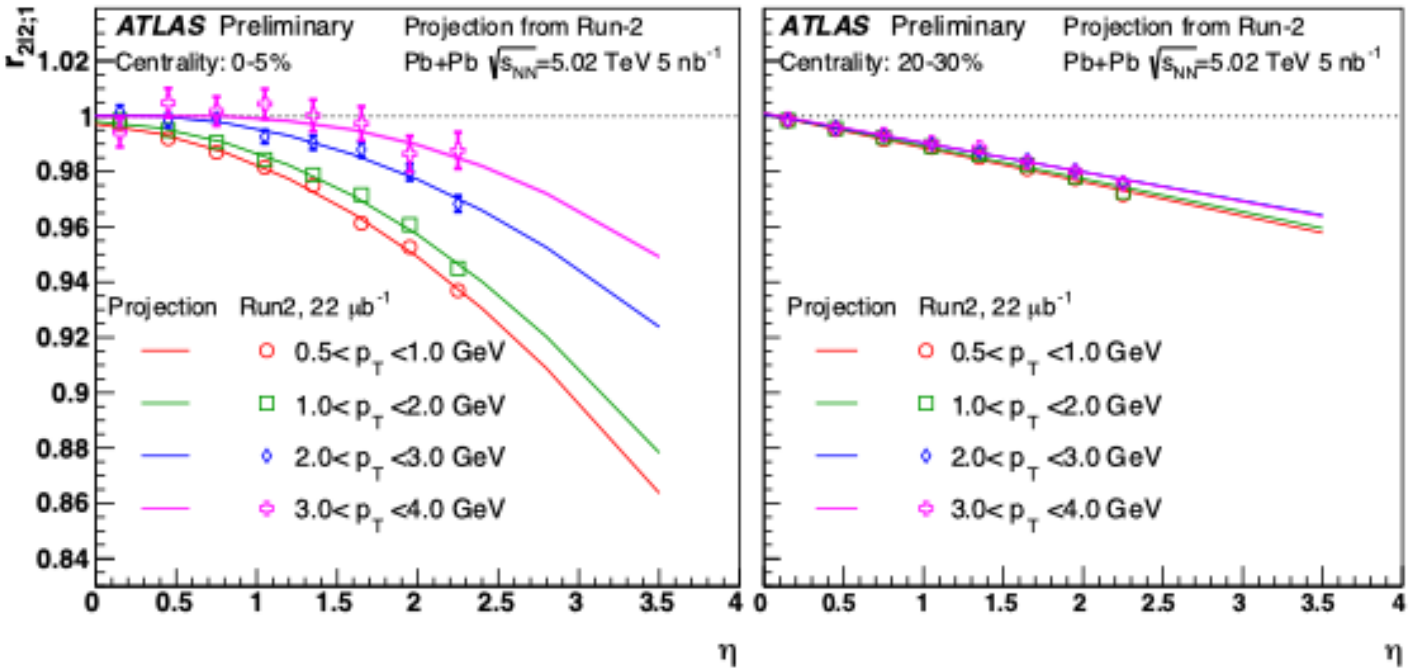
ITk in Run 4 HI





(a) $r_{n|n;k}(\eta) = \frac{\langle q_n^k(-\eta) q_n^{*k}(\eta_{ref}) \rangle}{\langle q_n^k(\eta) q_n^{*k}(\eta_{ref}) \rangle}$





WIS group NA60+ activity

WIS group is responsible for the muon spectrometer detectors

The technological choice is the MWPC with strip readout.

The main considerations leading to this choice are

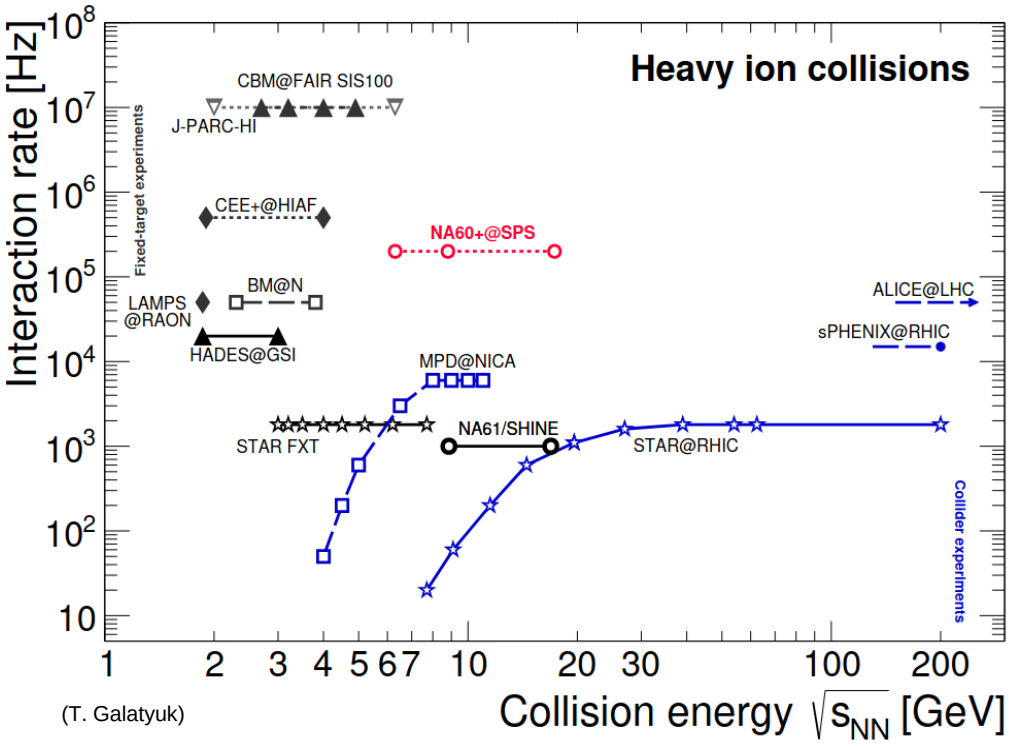
- Physics requirements: 200 um resolution and 10^4 cm^{-2} rate are well within the reach
- MWPC is a well-established and reliable technology, the WIS has much experience in
- Low production and maintenance costs, significant for ~100m^2 detector coverage

Integration into the experiment

- MWPCs are being developed by WIS, the second prototype was tested in November
- Electronics is being developed in USTC, Hefei, the first version produced
- Data acquisition in collaboration with INFN Cagliari, work is starting
- Reconstruction and simulations in collaboration with INFN Torino, work is starting

Uniqueness of NA60+

The NA60+ program needs a large luminosity to search for rare QGP probes



This luminosity can be collected with Pb+Pb interaction rates $>10^5\ s^{-1}$, reachable with $10^6\ s^{-1}$ beam intensity in a fixed target environment

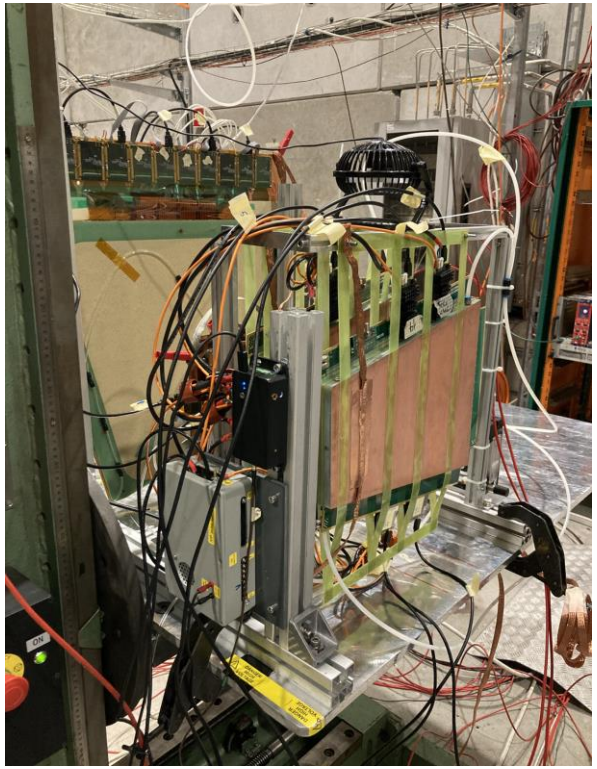
NA60+ is unique for energy coverage and interaction rate in the heavy-ion landscape

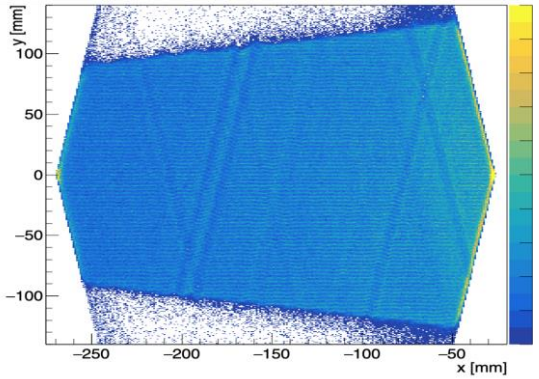
NA60+ is complementary to experiments accessing different (hadronic) observables in the same energy range (STAR BES, NICA, NA61) and similar observables in a lower energy range (CBM)

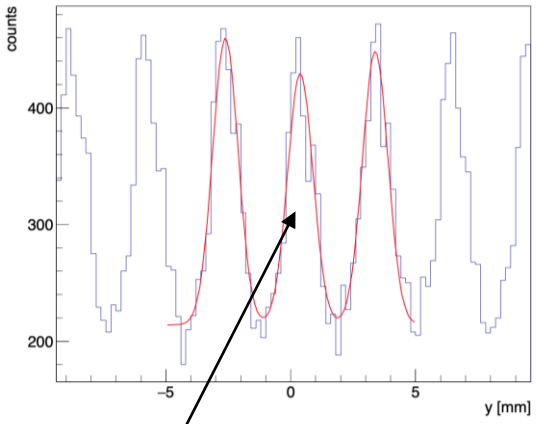
First prototype

MWPC with strip readout satisfies NA60+ requirements. The readout is based on a VMM3a chip

Prototype 1: Test beam at CERN in fall 2023



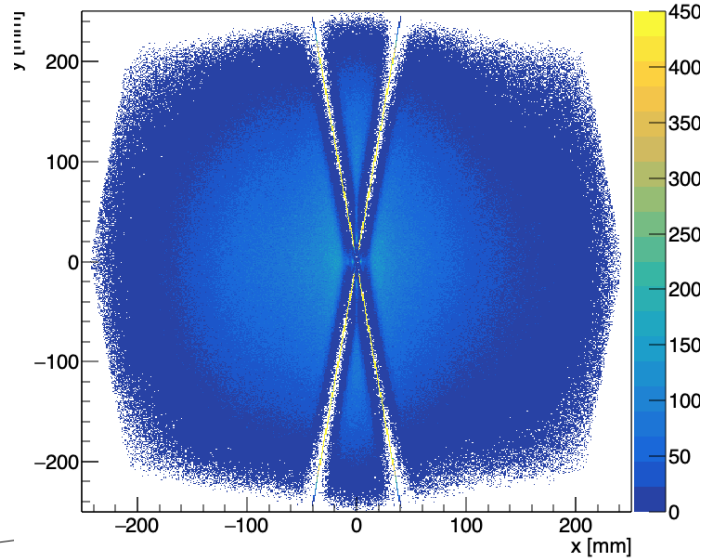


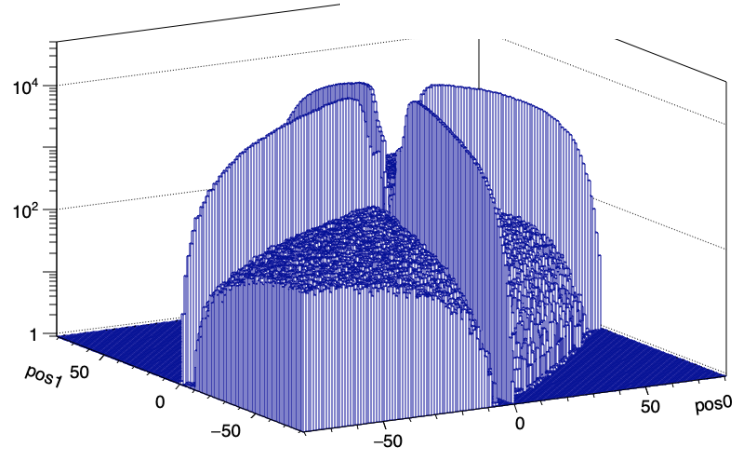


$\sigma_x < 0.1$ mm, $\sigma_y = 0.51$ mm

Uncovered problems in SRS vmm-sdat package related to DHR

Which has been fixed

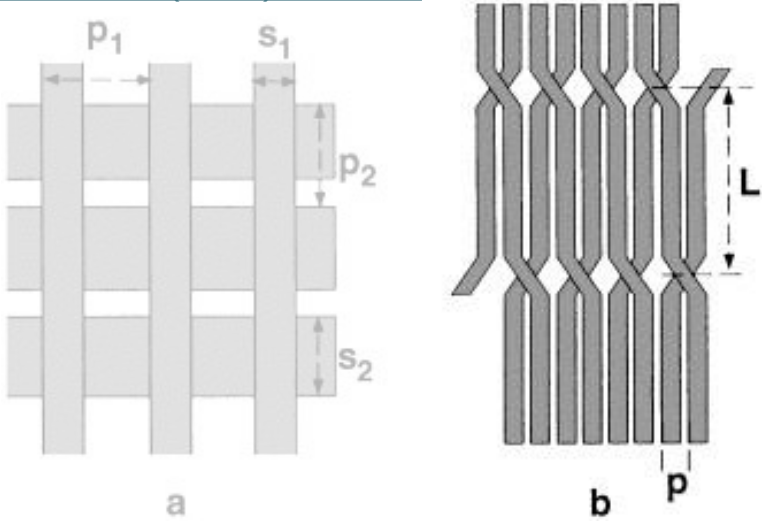


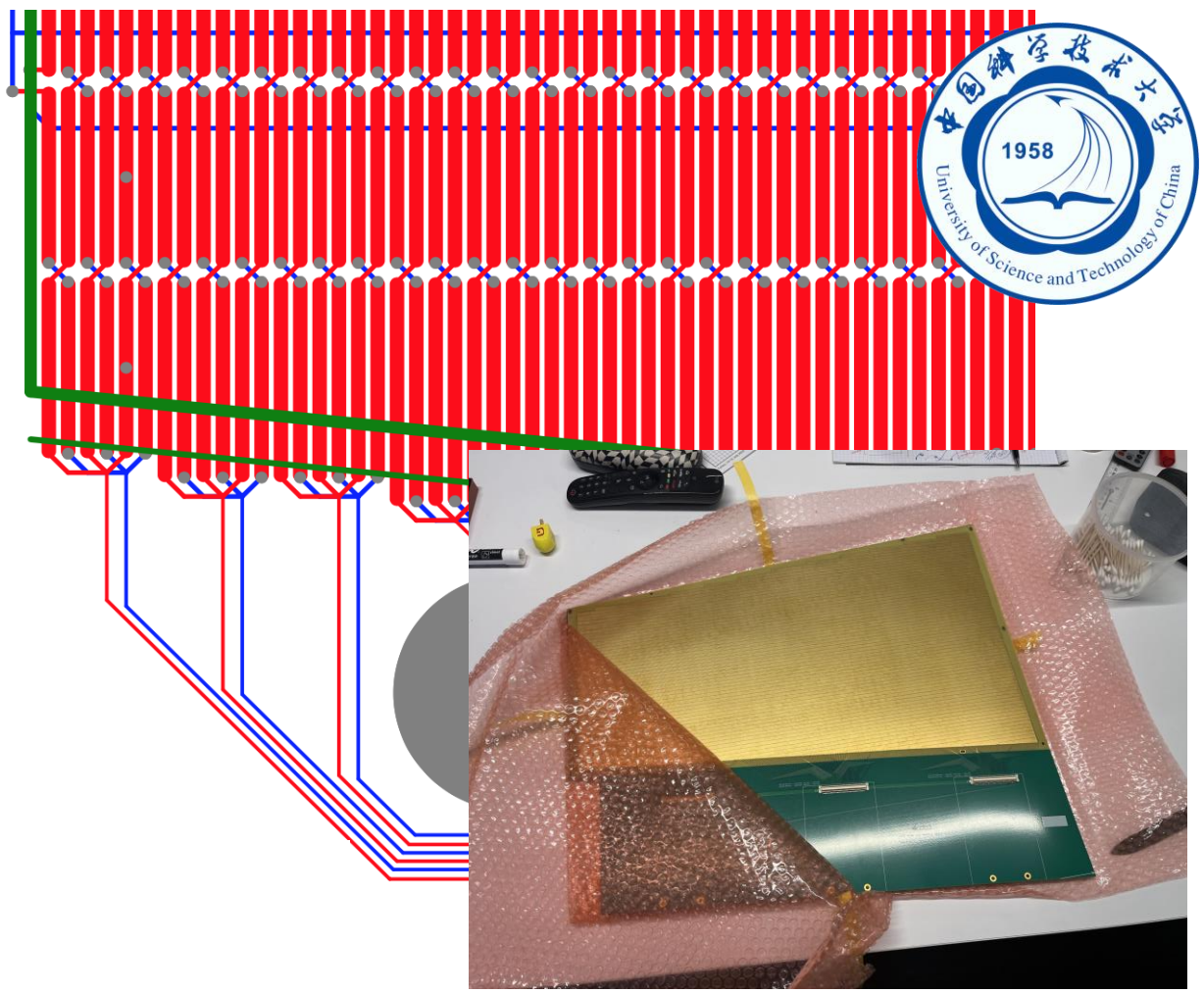


Second prototype

Prototype 2: Test beam at CERN in Nov 2024

NIMA 425 (1999) 254-261





Single-sided strip readout better suited for VMM-based electronics with optimized geometry

Near-final electronics (USTS, Hefei group)

Additional test to optimize the electronic channels