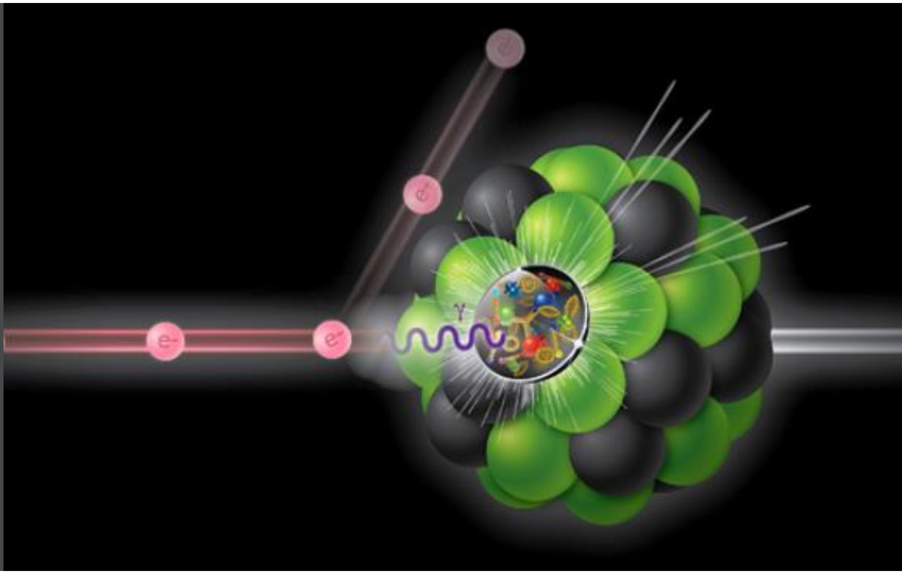
CHALLENGES IN BUILDING A DETECTOR FOR THE ELECTRON-ION COLLIDER



Electron – Ion Deep-Inelastic Scattering

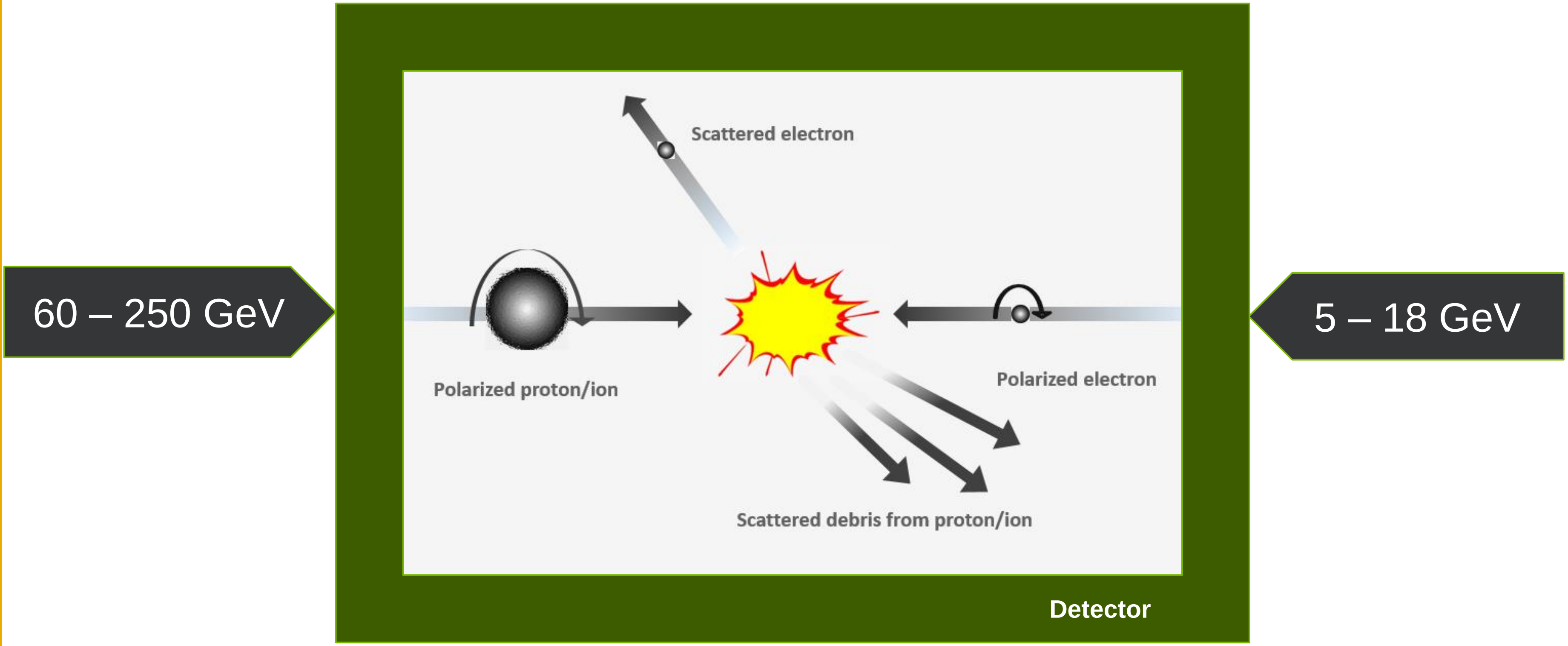
JOSÉ REPOND

Wednesday March 28th, 2018
Intersections between Nuclear Physics and Quantum Information
Argonne National Laboratory

What is the EIC – Electron-Ion Collider?

Planned facility for Nuclear Physics

Collision of (polarized) electrons and (polarized) protons/ions



Beam crossings every 2.1 ns → Very high luminosity = 10^{34} $cm^{-2}s^{-1}$

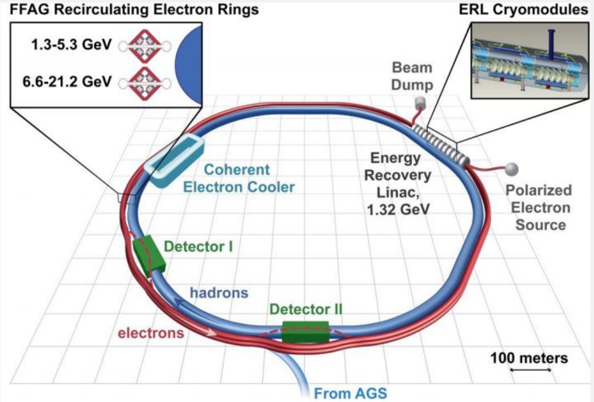
Where will the EIC be? What will it look like?

2 machines needed: an electron machine and a proton/ion machine
Beams stored in storage rings, collide at interaction points

Two national laboratories with part of the equipment

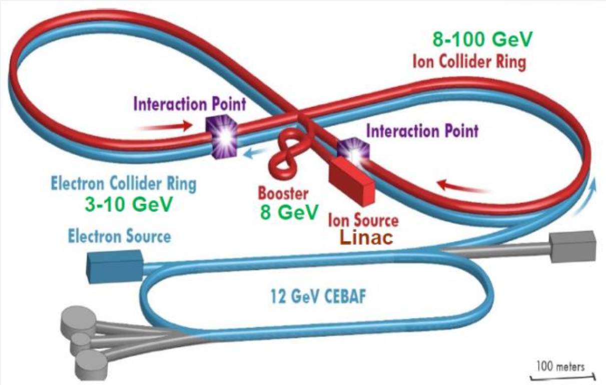
BROOKHAVEN NATIONAL LABORATORY

Has a **proton/ion machine** (RHIC)
Needs an **electron ring**



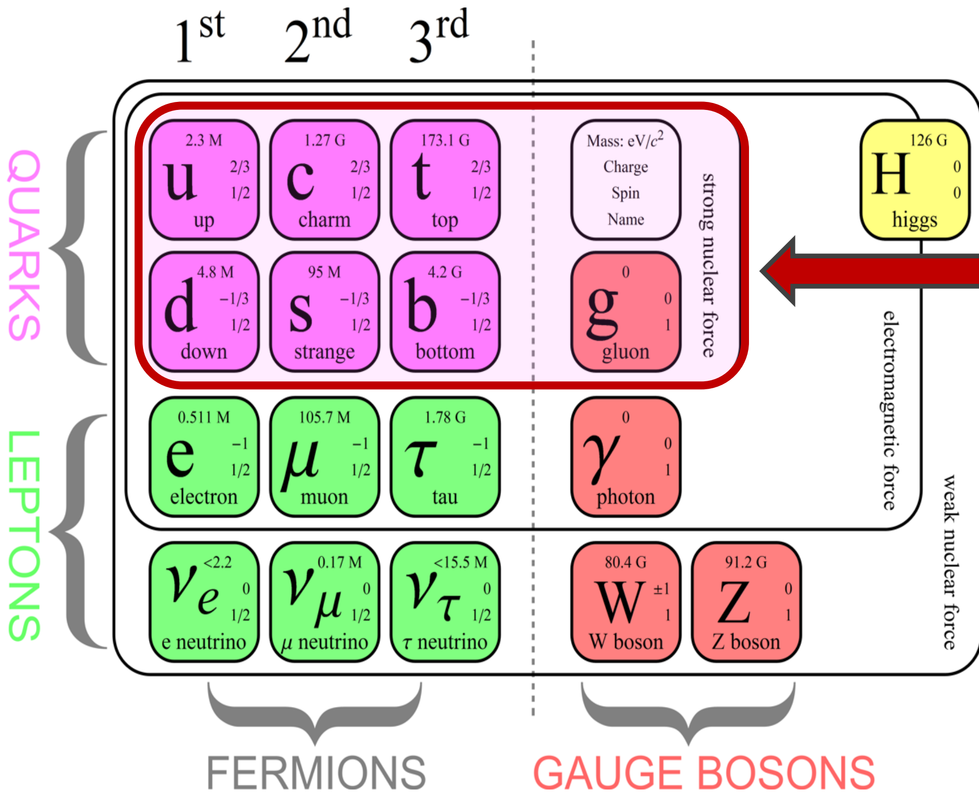
Jefferson Lab

Has an **electron machine** (CEBAF)
Needs a **proton/ion machine**



Site selection in the next few years

Excursion I: Standard Model of Particle Physics



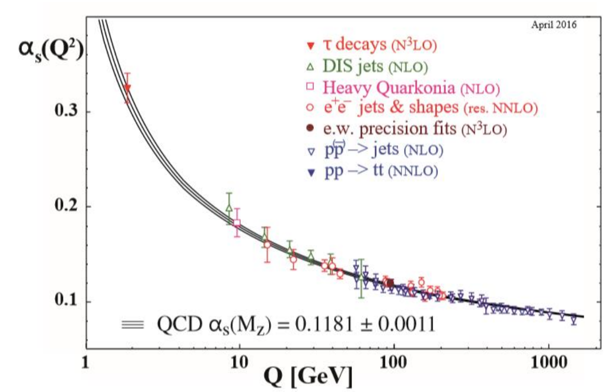
Emphasis of the Electron-Ion Collider

Strong force described by

Quantum Chromodynamics (QCD)

- High-energy part/short distances

  Exact calculations (perturbative)
  Tested in countless experiments



- Low-energy part/long distances

  Large coupling (non-perturbative)
  More difficult to calculate
  Interactions described by models or on the lattice
  Much less explored

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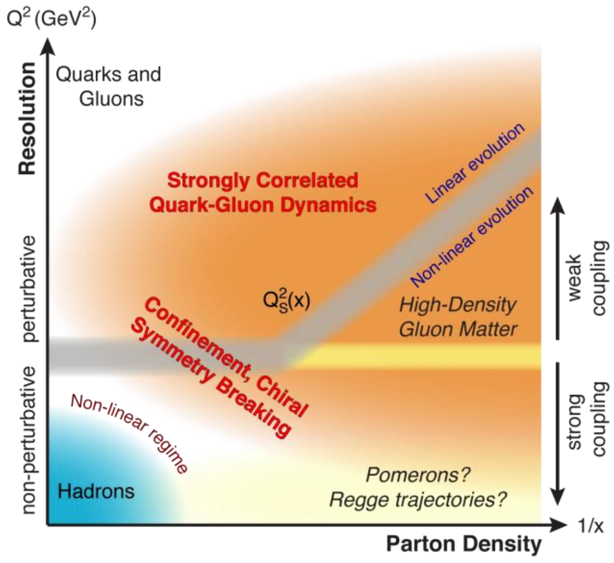
What will the EIC do?

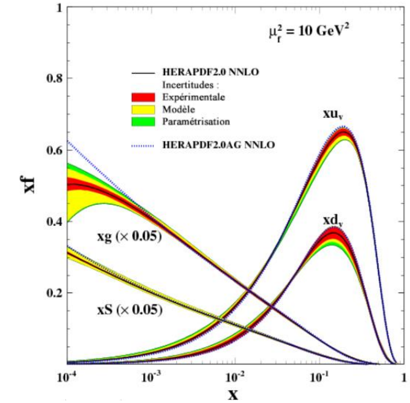
Study all aspects of Quantum Chromodynamics

Questions to be addressed by the EIC

Where is the glue in the nucleon?
Where is the glue in the nucleus?
What makes the spin of the nucleon?
What confines hadrons to be colorless?
Does the gluon density saturate at low-x?
Is there intrinsic charm in the nucleon?
How is the mass of the nucleon generated?
Many more questions…



Example I: Tomography of the nucleon

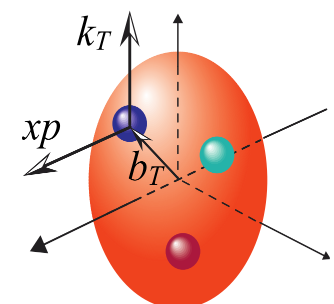


- We have very good knowledge of the parton content of the proton
  ↳ u,d,sea quarks and gluons

  → As a function of the longitudinal momentum $x = E_{parton}/E_{proton}$

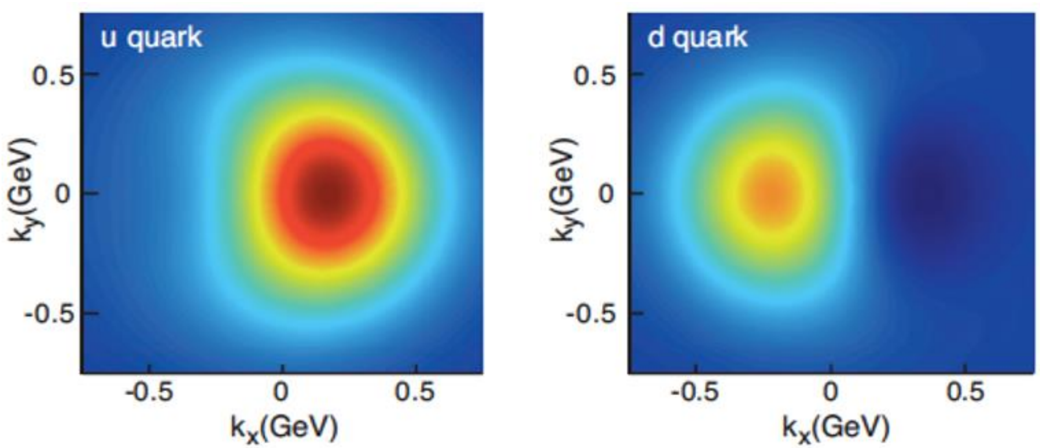
- The EIC will investigate the parton content of the proton/nucleus as a function of

  Transverse position b_T
  Transverse momentum k_T



- Quark flavor separation requires excellent **particle identification**

  → Separation of pions, kaons, and protons (electrons and muons are easy!)



Proton TMD's – predicted quark densities versus transverse momentum. Proton polarized in the y-direction.

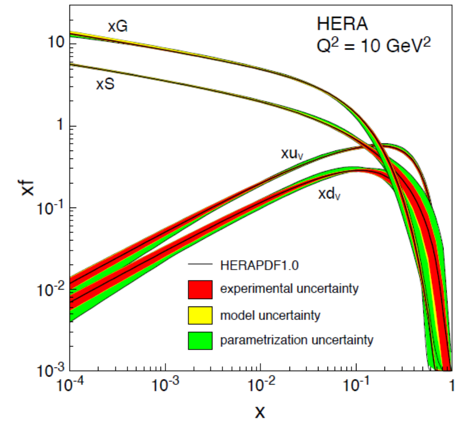
Example II: Saturation of the gluon density?

Gluon density g(x) increases with decreasing $x = E_g/E_{proton}$

If unchecked -> violation of unitarity: cross-section must remain finite

→ g(x) has to saturate (turn over) at some point!

No clear evidence/indication that this is happening from previous experiments (HERA)



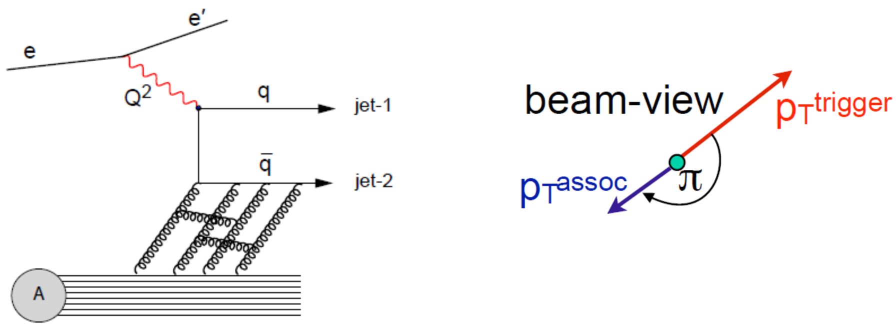
How to observe saturation of the gluon density?

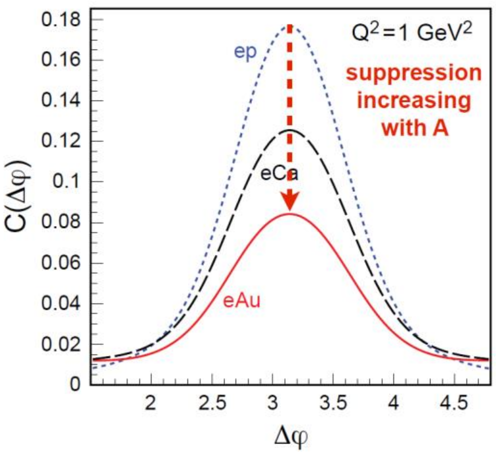
Can only observe in the perturbative regime, i.e. where $Q^2 > 1\ GeV^2$ (α_S reasonably small)

Effect significantly enhanced in nuclei: saturation scale $Q^2_S \propto A^{1/3}$

→ Look for deviations from predictions based on linear (DGLAP) evolution

→ Di-hadron/jet angular correlations $\Delta\varphi$





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Current status of the EIC

The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

We recommend a high-energy high-luminosity polarized Electron Ion Collider as the **highest priority** for new facility construction following the completion of FRIB.

We recommend **vigorous detector and accelerator R&D** in support of the neutrinoless double beta decay program and the Electron Ion Collider

EIC User Group

Established in 2016, now counting more than 900 members

Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

Established Accelerator R&D priorities in February 13, 2017 report

Review by the National Academy of Sciences

Started in early 2017
Duration: 18 months

To be followed by CD0 (expected in FY 2019)

Overview – Argonne's EIC Activities

Argonne involved in all aspects of the planned project

- Accelerator design/developments
- Theory calculations/predictions
- Physics/detector simulations
- Detector R&D
- Computing

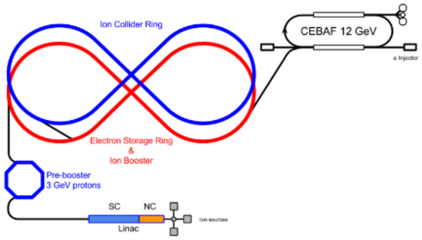
Challenges

The emphasis of this talk

Challenges of the EIC: Accelerator

High luminosity: $\mathcal{L} \sim 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

2 – 3 orders of magnitude higher than HERA (ep collider: 1992 – 2007)
→ High beam currents (both electron and hadron)
→ Ion beam cooling (requirements beyond state-of-the-art!)



Polarization of ions

Sources exist for protons and deuterium, but not for other light nuclei
→ How to maintain the polarization?

Interaction region design and synchronization for different collision energies

Electrons 5 – 18 GeV ↔ protons/ions 60 – 250 GeV

Background suppression

EIC: combination of electron and hadron machine
Synchrotron radiation from electrons → reduced vacuum → proton/ion – gas events
→ Design of masks, vacuum system

Challenges of the EIC: Theory: 3D Imaging of Nuclei

The EIC needs realistic predictions for the 3D densities of quarks/gluons in nuclei

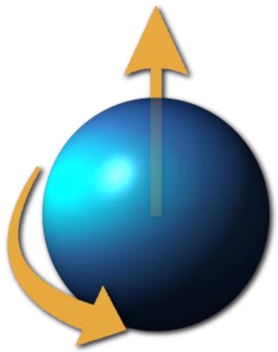
- We are performing such a calculation, the first of its kind
- The calculations are done using a relativistic contact model
- The calculations are completely compatible with relativity, which is necessary for symmetries and conservation laws to be observed

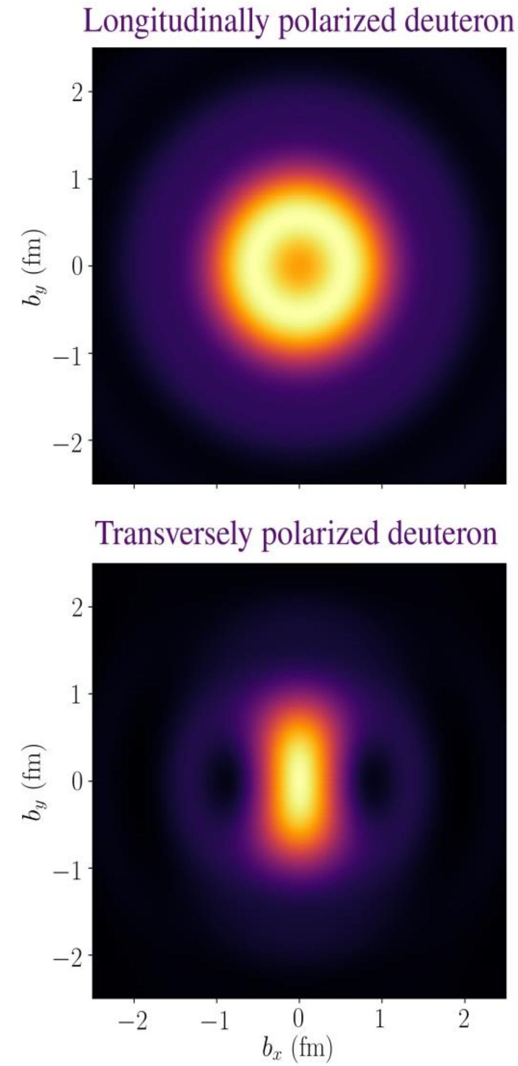
Emphasis is being put on polarized ions

- A polarized ion is spinning in a specific direction
- This special polarization direction allows more detailed structures to be seen (pictures →)
- These calculations will strengthen the physics of the EIC

Computing challenges

- Managing large data files and integration with event generators





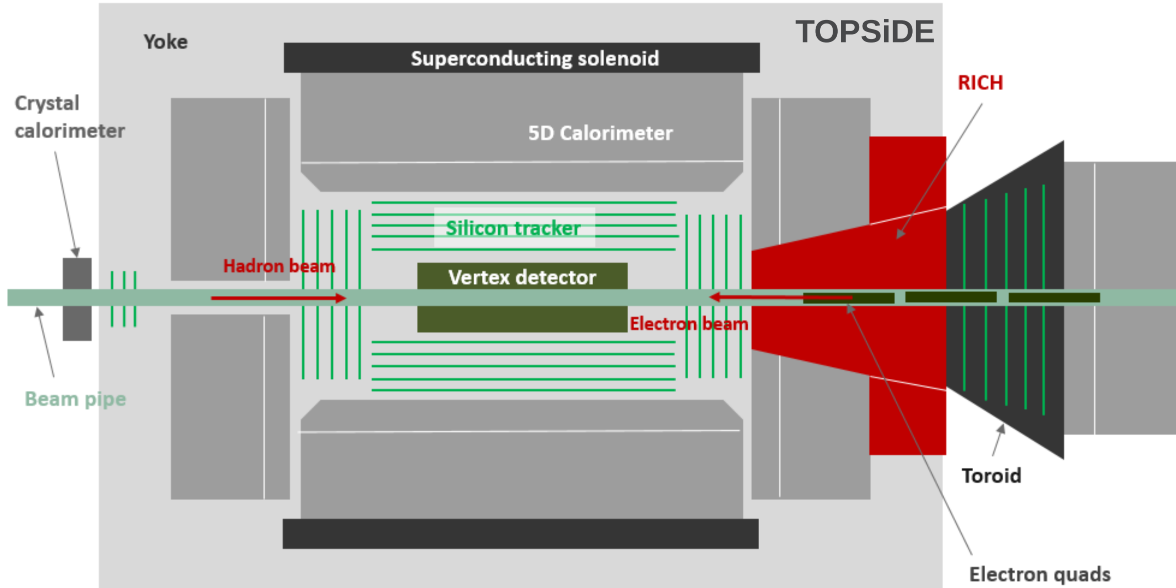
Excursion II: The Argonne Concept of an EIC Detector

5D Concept

Energy E

Position x,y,z

Time t



Salient features

- 4π detector (hermetic coverage)
- Multi-purpose detector (no need for another specialized detector)
- Mostly based on silicon sensors (tracker, electromagnetic calorimeter)
- **Each particle measured individually** (optimized for Particle Flow Algorithms)
- **Particle identification** (pion-kaon separation) performed by Time-of-Flight (tracker and calorimeter)
- Imaging calorimetry (tens of millions of readout channels)
- Coil on the outside (not to degrade calorimetric measurements)
- Toroid in the forward direction (to obtain a momentum measurement)
- Special detectors in the forward direction (Ring Imaging Cerenkov for Particle ID, debris taggers)

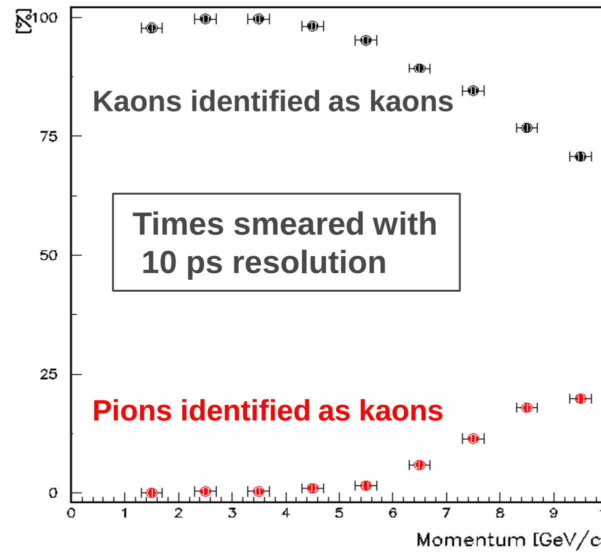
Challenges of the EIC: Central detector

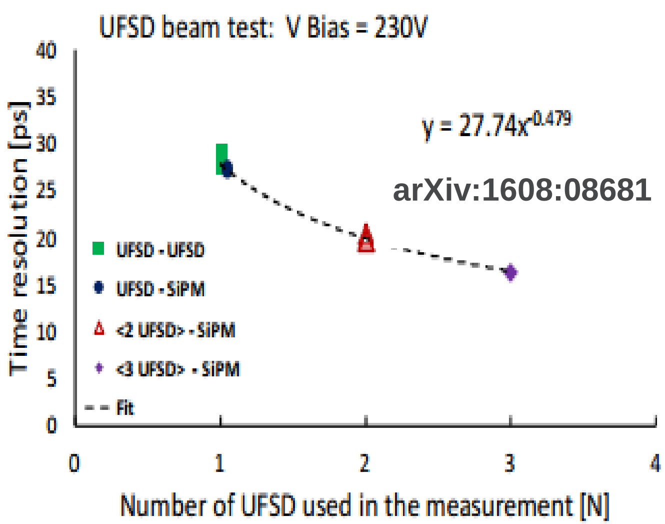
Ultra-fast Silicon Detectors

Needed for particle identification (time-of-flight)
Simulation study showed that a time resolution of the order of σ_{time} ~ 10 ps is needed

To date resolutions of σ_{time} = 27 ps have been achieved with the LGAD technology

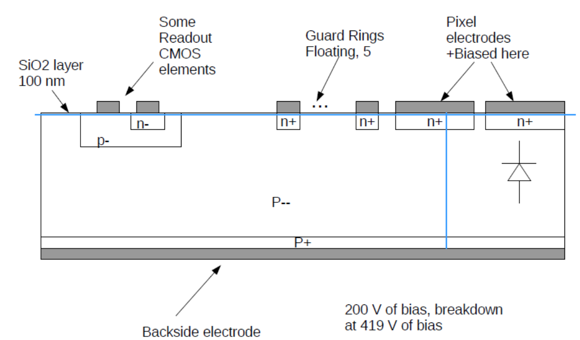
→ Amplification layer forces electrons to drift (and not just diffuse)





HVCMOS (cheaper!) not explored yet

Initiated simulations
Next step insertion of amplification layer

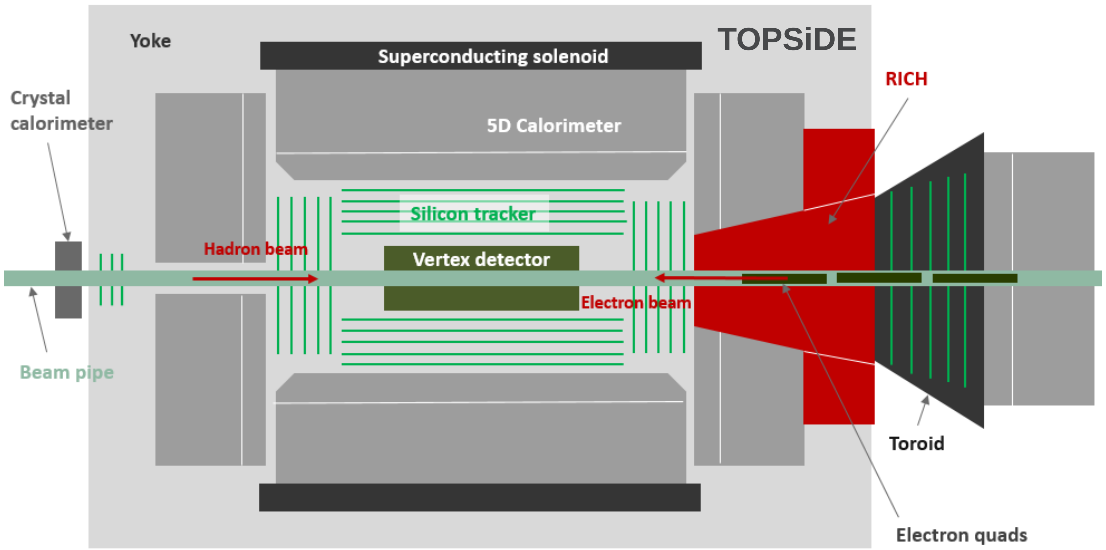


Challenges of the EIC: Central detector

Magnets

Large central magnet with a field of ~2.5 Tesla
Forward magnet (dipole or toroid)

→ Interference? Field in the area of the RICH?



Cerenkov detector

Needed in the forward direction to identify particles with high momenta (10 – 50 GeV/c)
Only known technology is a gaseous Ring Imaging Cherenkov counter

→ How to collect the light? Interference with magnetic fields?

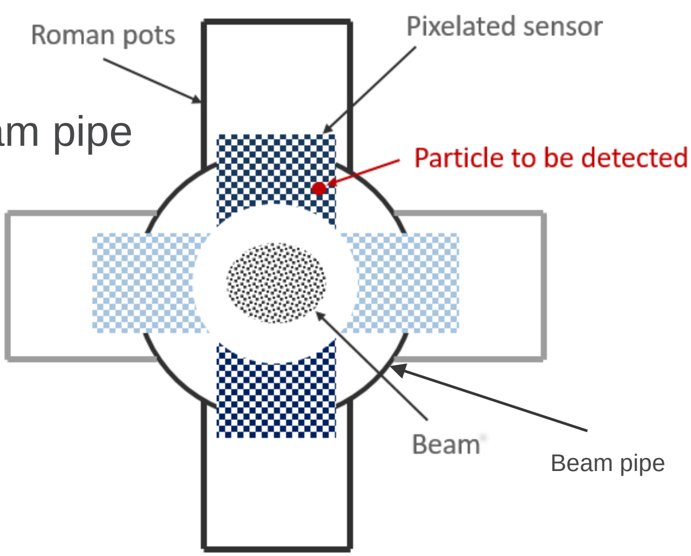
Challenges of the EIC: Forward detector

Breakup of the proton/ion

Creates debris into the forward cone
All particles (protons, neutrons, photons, nuclei) need to be identified and measured
These particles have momenta lower than the colliding protons/ions

Technique

Use storage ring dipole magnets as analyzers
Insert position sensitive detectors downstream into the beam pipe
Measure positions, reconstruct tracks → momentum
Measure time-of-flight → particle ID

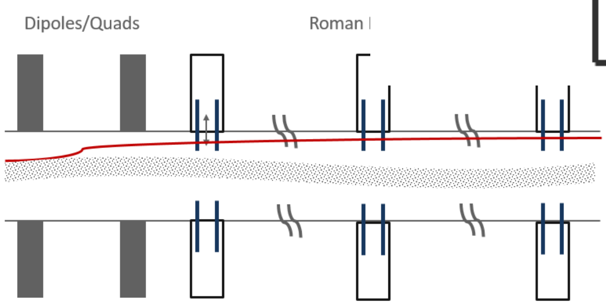


Challenge

Radiation hard sensors handling high particle rates
Providing excellent timing

Options

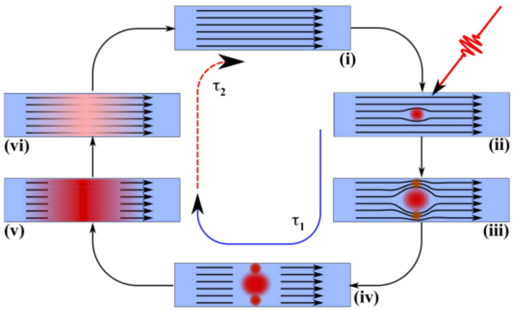
Silicon strip detectors
Superconductive nanowire detectors



Excursion III: Superconductive Nanowires

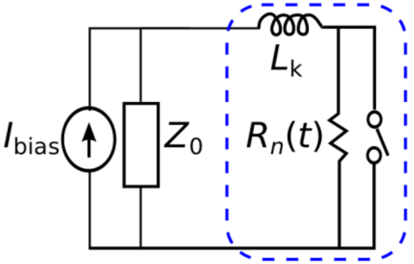
Principle of operation

(i) Thin, superconductive wire biased just below the critical current
(ii) A traversing particle heats the wire
(iii-v) The wire becomes normal conductive
(vi) The wire recovers and becomes superconductive again



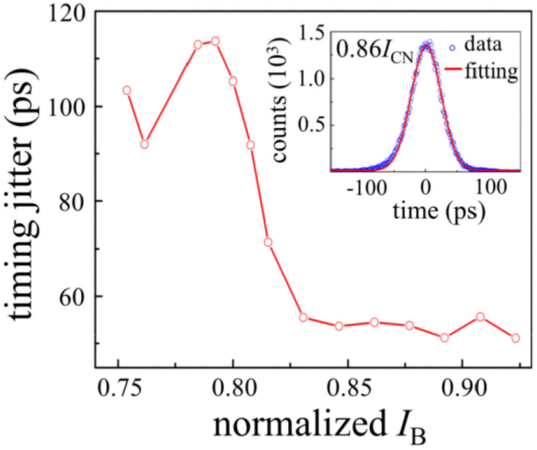
Detection technique

Measure change in bias current
Detector insensitive while normal conductive → single particle counter



Characteristics

Good efficiency, up to 50%
Fast signals, good timing resolution → down to tens of picosecond
Spatial segmentation → (almost) anything is possible



Forward debris detector

Good candidate? → We will find out…

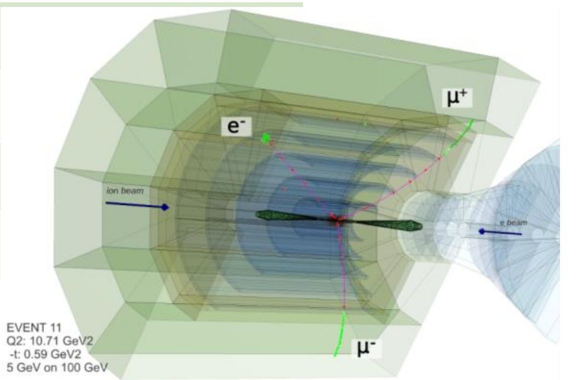
Excursion IV: Simulating the detector response

Benefits of simulations

Estimate the performance of various detector concepts/designs
Estimate the measurement precision to be achieved
Optimize the detector concept/design

Simulation tool chain

Task	Tool
Generate collision events	Lepto, PYTHIA8, Milou….
Transport of particles through matter	GEANT4
Digitizing the response (making it look like real data)	Digitizer, e.g. RPC_sim
Reconstruct tracks	Genfind, Genfit…
Reconstruct particles	Pandora PFA
Depository for events	HepSim
Analyze events	Root
Event display	



Assembled, but further being developed

Challenges of the EIC: Simulations

Data model

Needed to link tools, factorize the tasks, foster collaborations…
Easily maintainable model

Done

Detector geometry

Unified, parametrized description → one source for all tools

Done

Digitizers

Silicon sensors
RPC pads (HCAL)
Cerenkov (light collection)

Ongoing/challenging

Generic tracking

Independent of details of geometry
Changes in geometry do not require retuning

Almost done

Generic particle reconstruction

Independent of geometry

Ongoing/Challenging

Challenges of the EIC: Computing

Computing for the next decade: Argonne's EIC HUB

Hub provides critical organization to

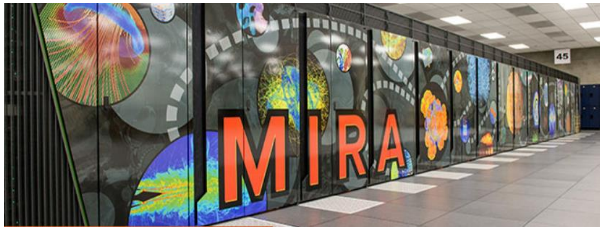
- Exploit fully current computing **resources**
- Develop sophisticated, **novel algorithms**
  (parallel algorithms, deep learning, neutral nets…)
- Position ourselves for the use of **next generation** computing
  (Exa-scale and/or quantum computing)

Challenges

Orchestrate the many moving parts of computing related to the EIC

Data management, job execution, version control, bench marking…

Develop a **dynamic front-end user interface** which can be used for the next decade by the entire EIC community
(Collaboration with CELS has started)



Position Argonne as leaders in computing for the EIC

Conclusions

The EIC and QIS

QIS and colliding beam experiments?

Not aware of any overlap/cross-fertilization

EIC theoretical calculations and QIS?

Can quantum simulators be used for QCD calculations, which in turn might be relevant for the EIC? → **Adam Freese's talk**

Fast timing and QIS?

At the moment, hedging our bets on ultra-fast silicon detectors (UFSDs)
Are there other sensors, which can be used in trackers, calorimeters?

- Boundary condition I: cooling requires a cryostat (inert material -> to be avoided)
- Boundary condition II: sensor needs to measure times (to 10 ps) and deposited energy
- Boundary condition III: sensor needs to be finely segmentated

Forward debris detection and QIS?

Possibility of using nanowires
(these are quantum devices in the sense that they are either superconducting or not)
Can the cooling cope with the high particle rates?