EIC next 10+ years to start of operations

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October 16, 2023

Discussion in the CFNS Fellows Gathering @ Stony Brook

These are my personal thoughts, not “the opinion” of the EIC Project (though they should be ;-))

From now until first physics collisions

1. EIC Project (1 machine + 1 detector) timeline & criticality of its success
2. Some thoughts on EIC early operations & planning

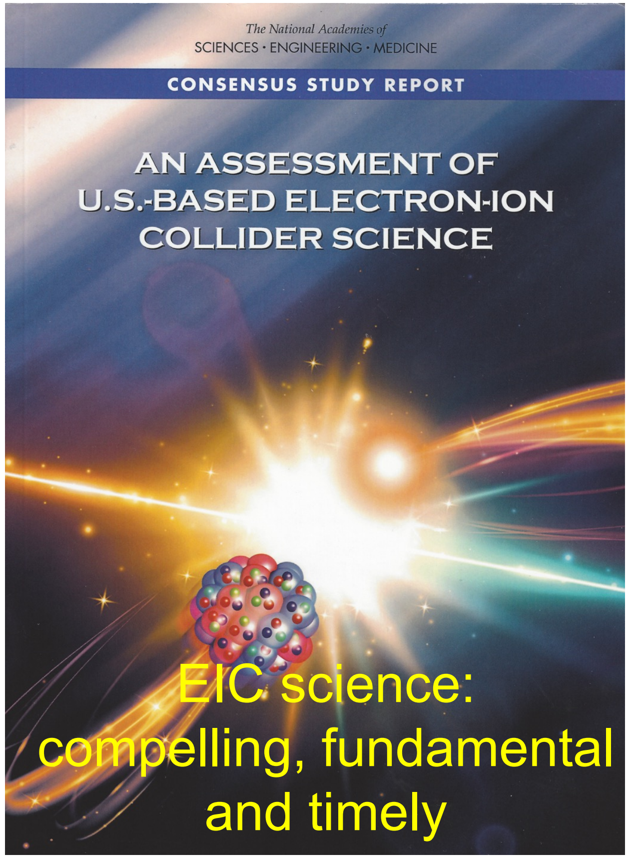
   How would the EIC Operations evolve? – Historical precedent and experience
3. Is "theory" ready to meet EIC data?
4. Ultimate Success of EIC ➔ A second detector

   Expansion of EIC Science Scope for ePIC & science scope for Detector 2

Item 1:
EIC project and its timeline

National Academy of Science, Engineering and Medicine

Assessment July 2018

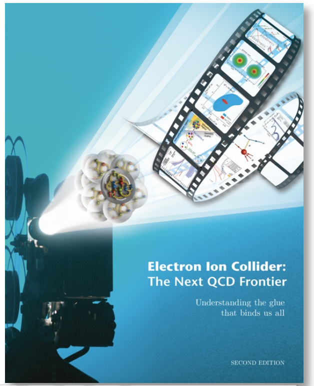


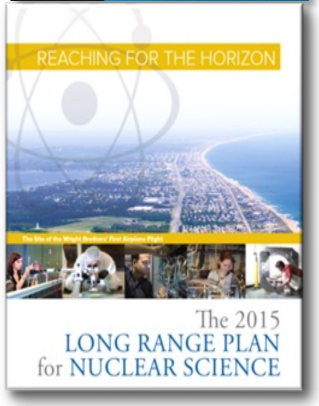
Physics of EIC

- Emergence of Spin
- Emergence of Mass
- Physics of high-density gluon fields

Machine Design Parameters:

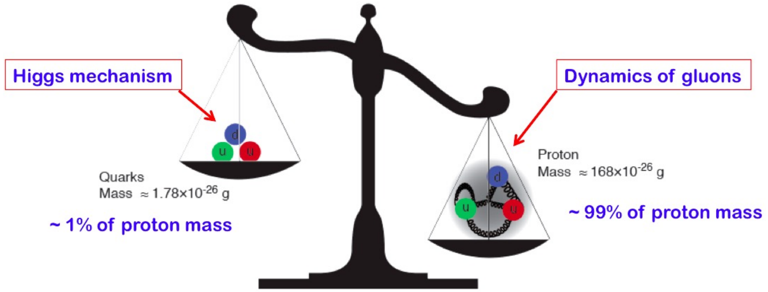
- High luminosity: up to 10^{33}-10^{34} $cm^{-2}sec^{-1}$
  - a factor ~100-1000 times HERA
- Broad range in center-of-mass energy: ~20-140 GeV
- Polarized beams e-, p, and light ion beams with flexible spin patterns/orientation
- Broad range in hadron species: protons…. Uranium
- Up to two detectors well-integrated detector(s) into the machine lattice



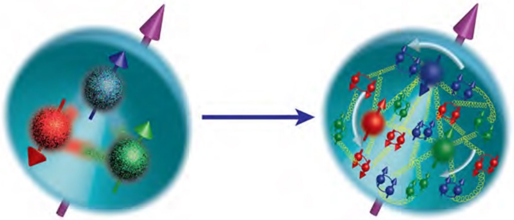


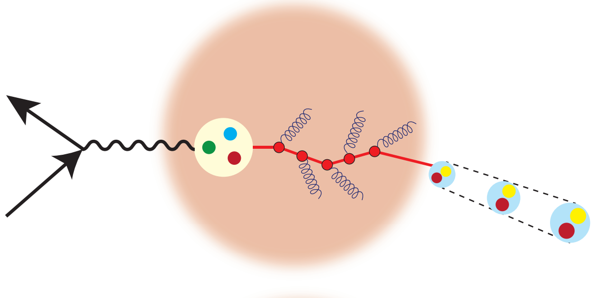
EIC Physics at-a-Glance

Eur. Phys. J. A 52 (2016) 9, 268 arXiv:1212.1701 (nucl-ex)

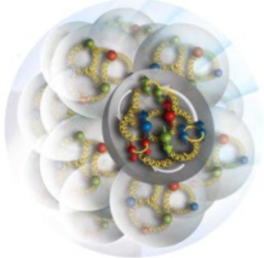


How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties (mass & spin) emerge from their interactions?

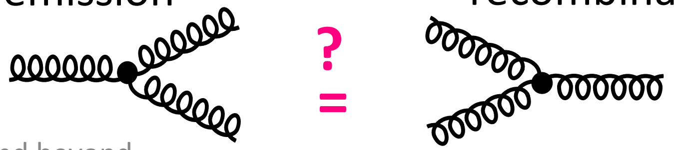




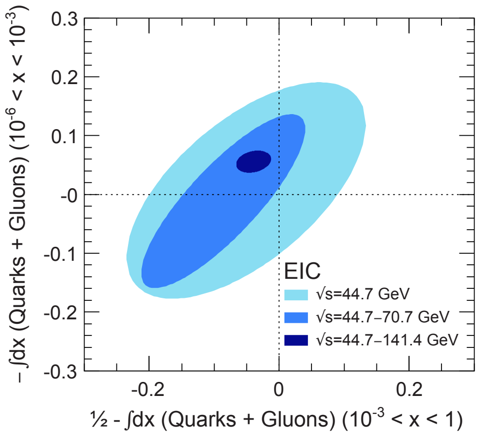
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

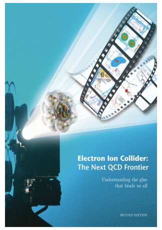


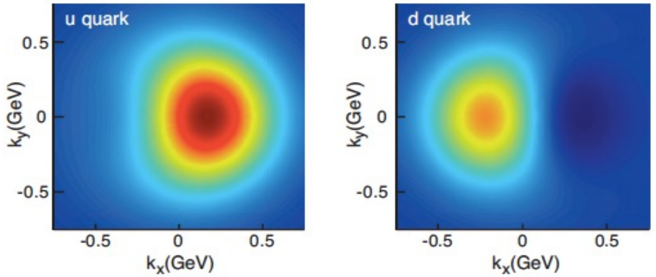
How does a dense nuclear environment affect the quark- and gluon- distributions? What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

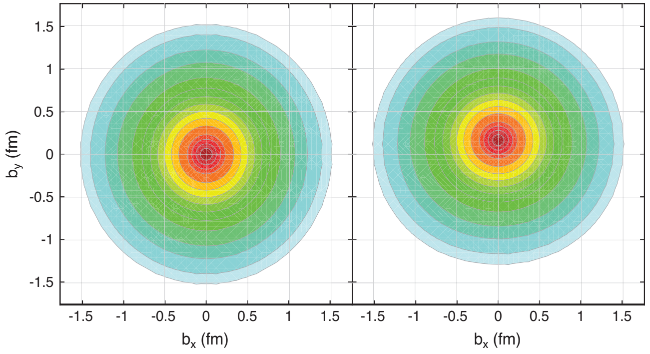


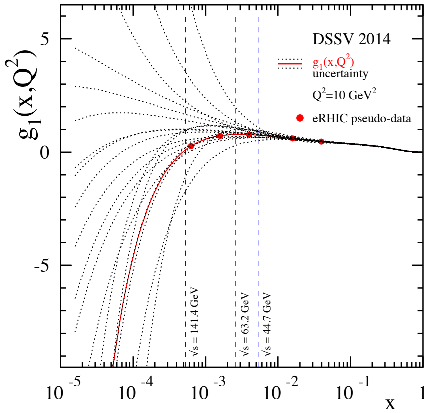
EIC science highlights

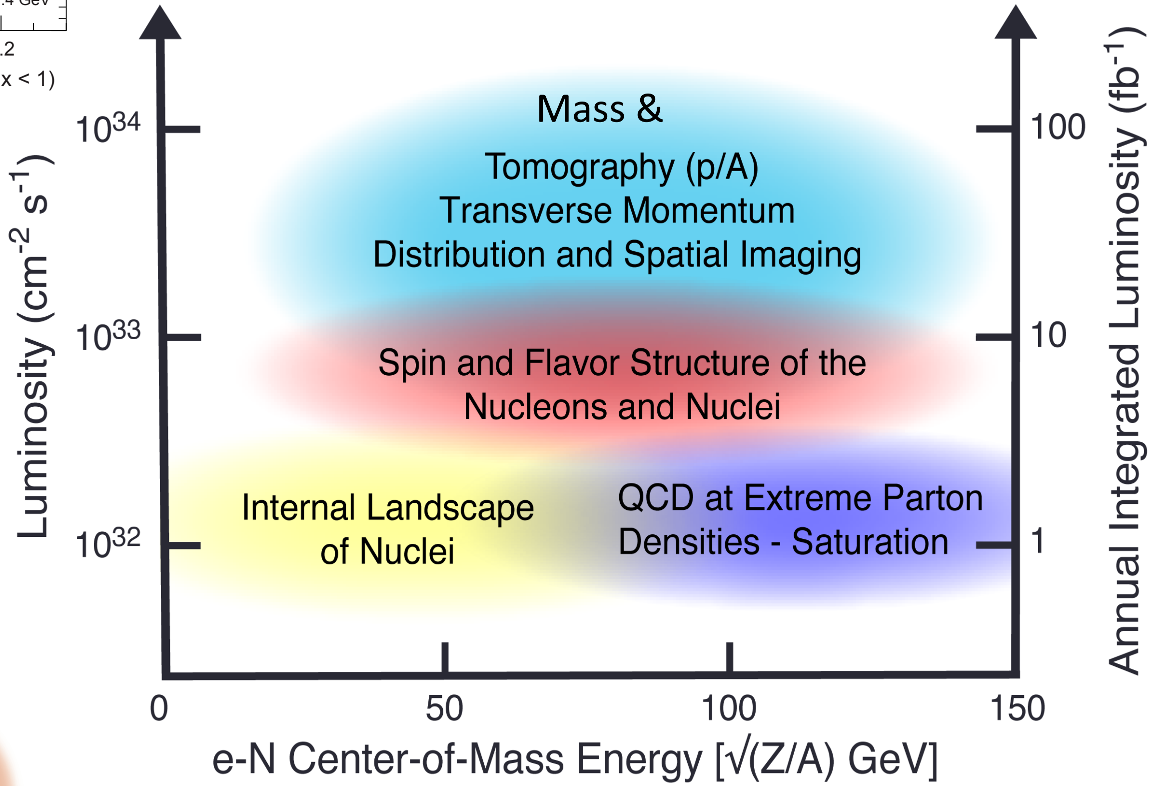


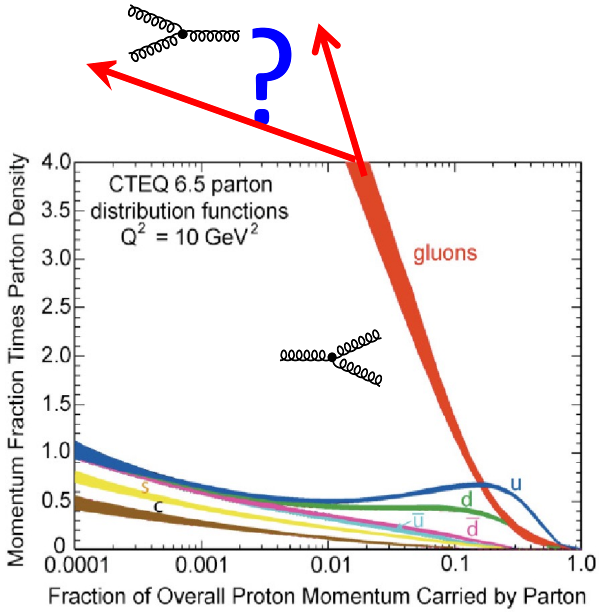


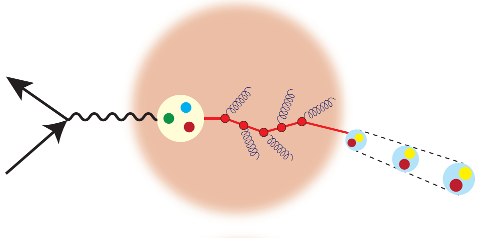




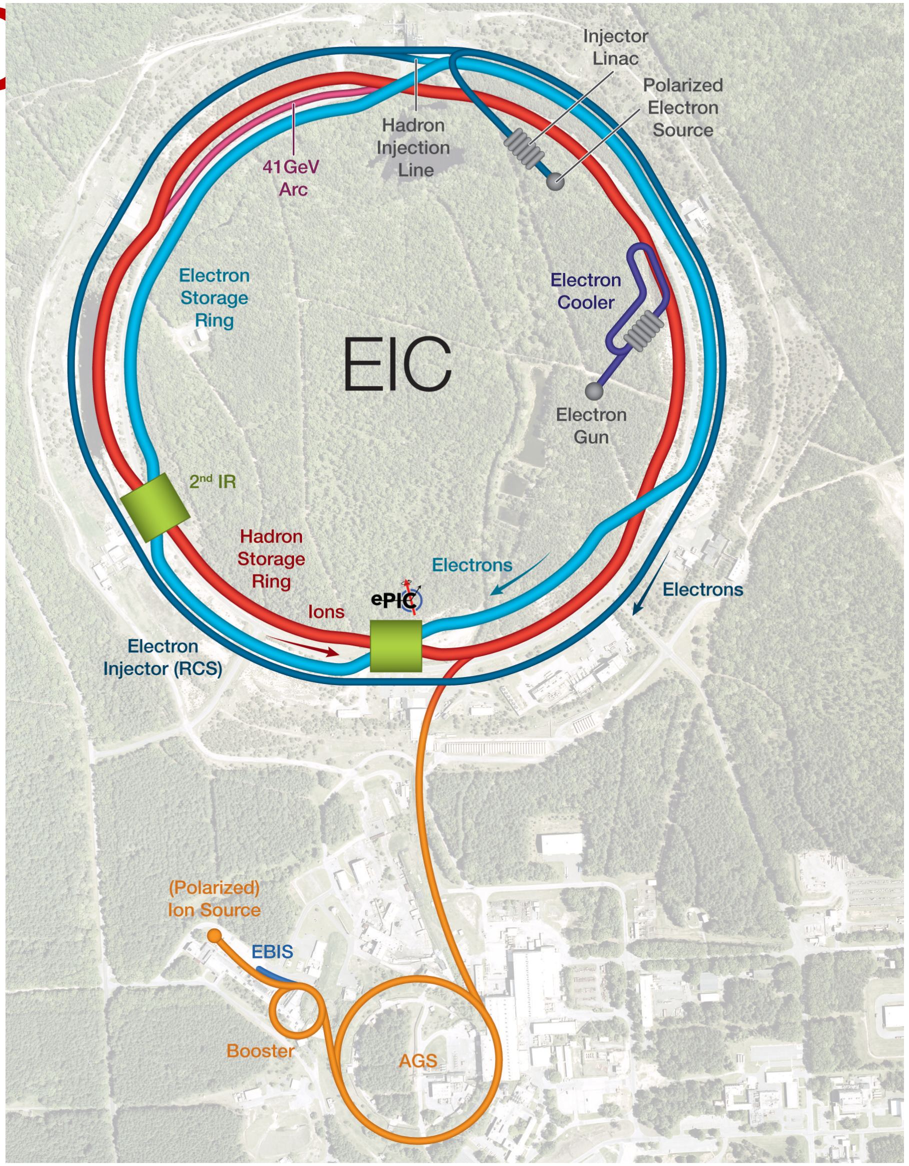




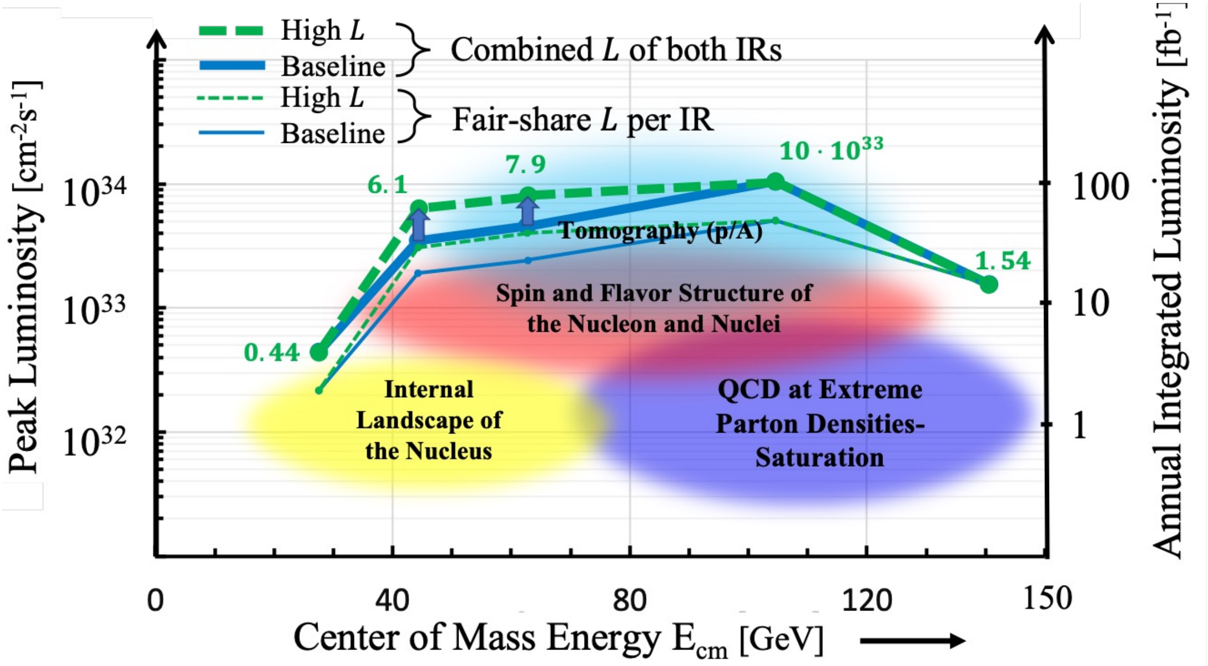




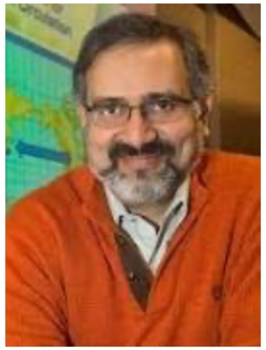
EIC Accelerator D



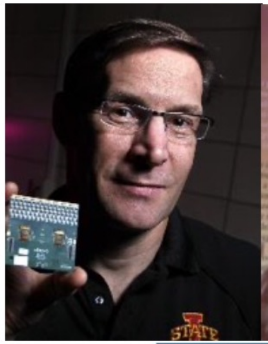
Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!







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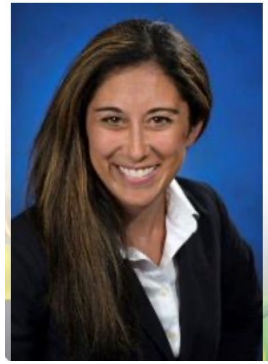
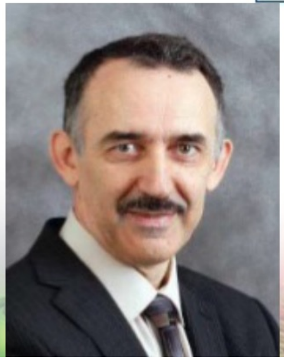
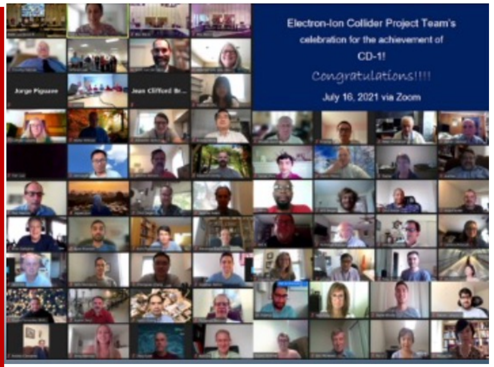
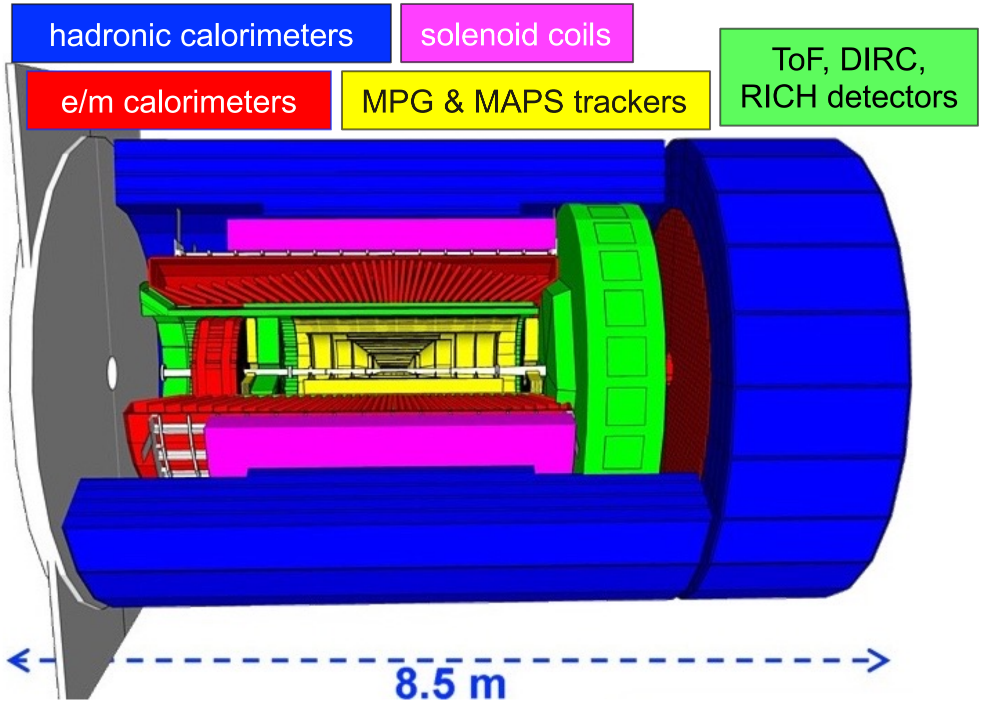
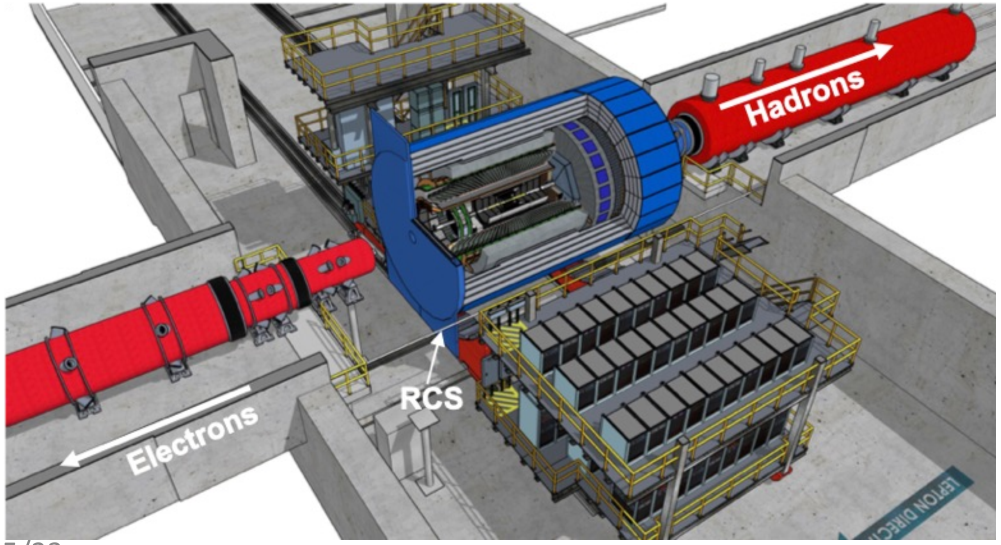







Jim Yeck



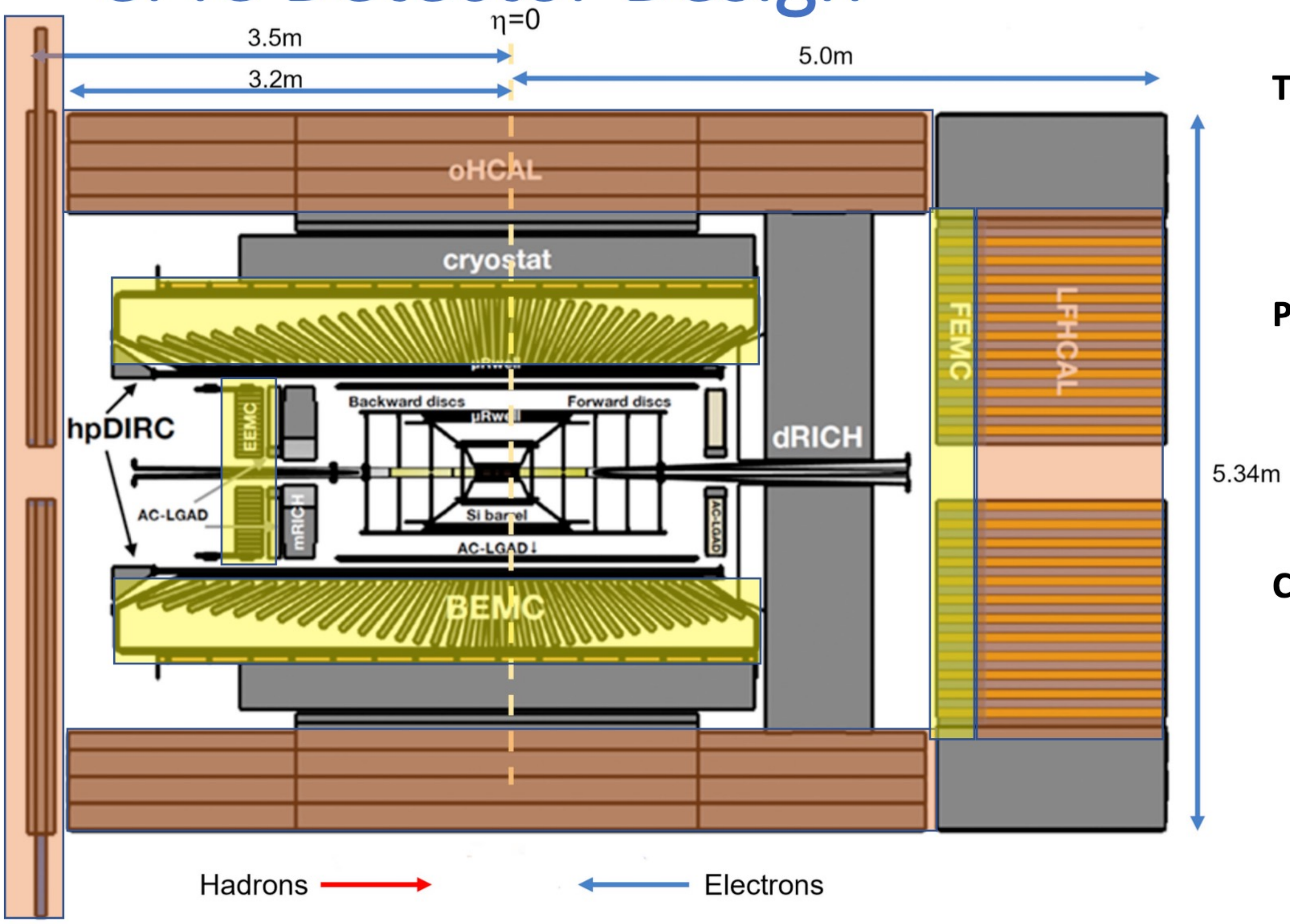


EIC Management team working with the EICUG to realize EPIC

Detector requirements:

- Large rapidity ($-4 < \eta < 4$) coverage; and far beyond
  - Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
    → Integration into IR from the beginning critical
    Many ancillary detector along the beam lines: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, ….
- High precision low mass tracking
  - small (μ-vertex Silicon) and large radius (gas-based) tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EM-calorimetry
- High performance PID to separate e, π, K, p on track level
  - good e/h separation critical for scattered electron ID
- Maximum scientific flexibility
  - Streaming DAQ → integrating AI/ML
- Excellent control of systematics
  - luminosity monitor, electron & hadron Polarimetry

ePIC Detector Design



Tracking:

- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

PID:

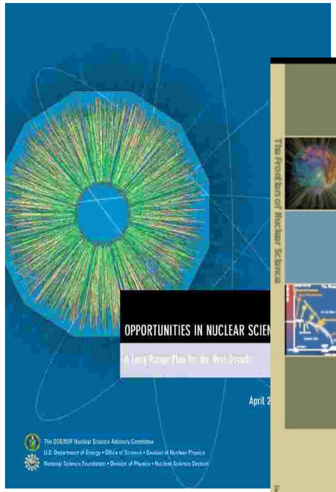
- hpDIRC
- ~~mRICH~~/pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

Calorimetry:

- ~~SciGlass~~/Imaging Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

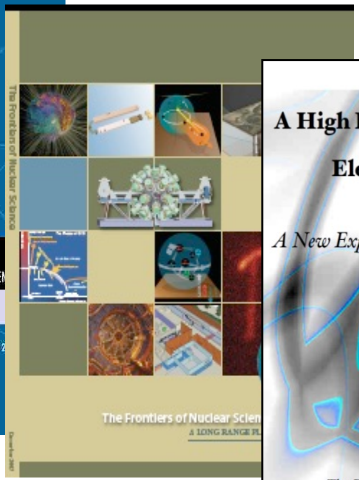
The Scientific Foundation for an EIC was Built Over Two Decades

2002



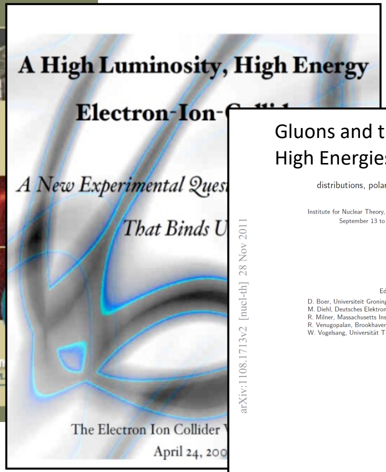
"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

2007



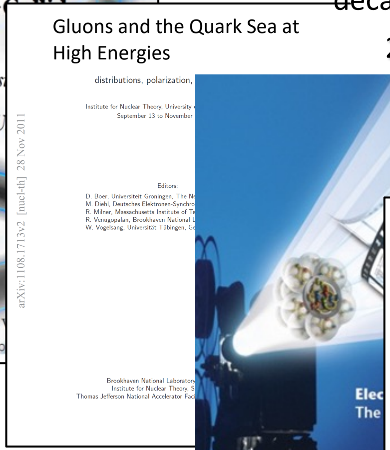
"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

2009



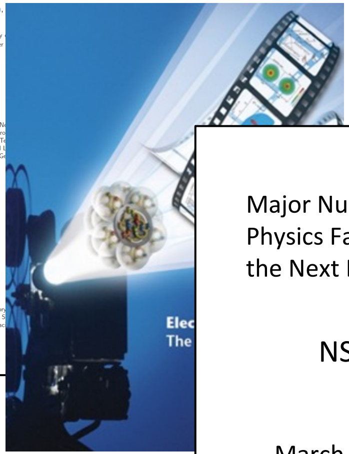
"..a new dedicated facility will be essential for answering some of the most central questions."

2010



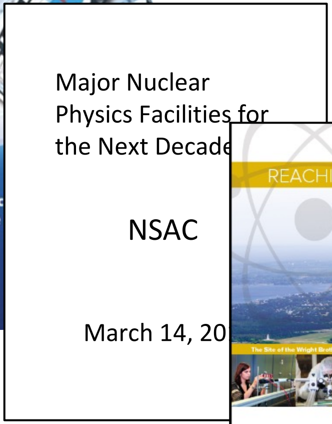
"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

2012



Electron-Ion Collider..*absolutely central* to the nuclear science program of the next decade.

2013



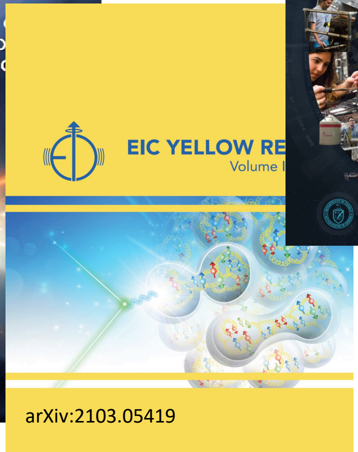
2015

"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

2018

The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

2021



Science Requirements and Detector Concepts for the EIC – Drives the requirements of EIC detectors

2023

Build expeditiously

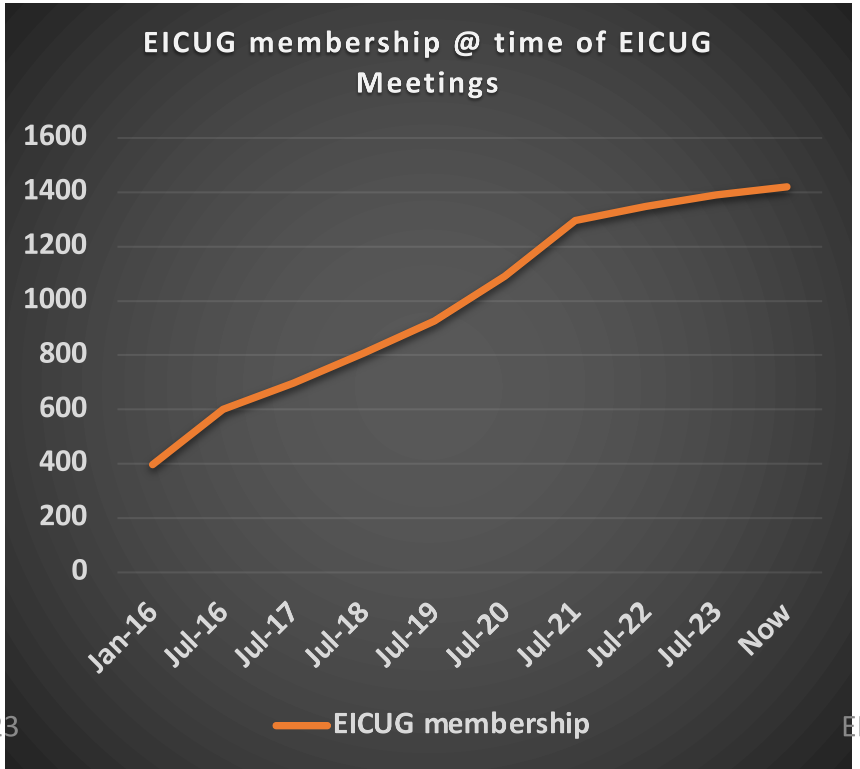
Worldwide Interest in EIC

The EIC User Group:
https://eicug.github.io/

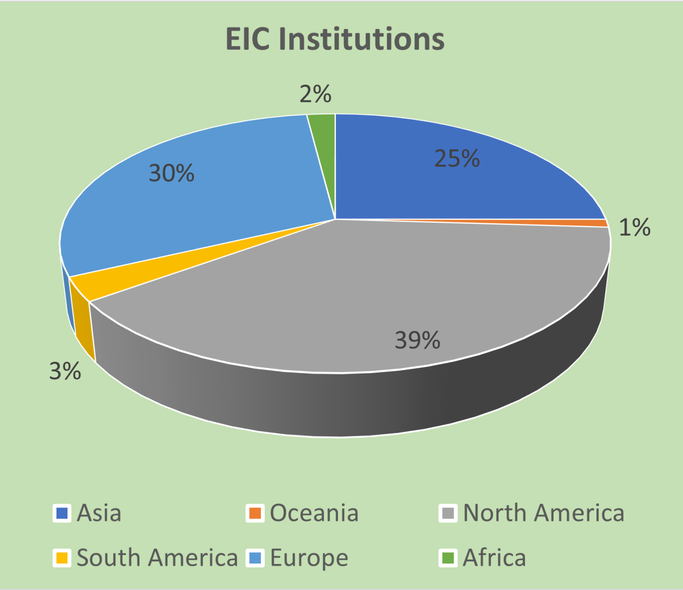
Formed 2016 –
- **1417 collaborators,**
- **37 countries,**
- **285 institutions**

as of October 02, 2023.

Strong International Participation.



Annual EICUG meeting
2016 UC Berkeley, CA
2016 Argonne, IL
2017 Trieste, Italy
2018 CUA, Washington, DC
2019 Paris, France
2020 FIU, Miami, FL
2021 VUU, VA & UCR, CA
2022 Stony Brook U, NY
2023 Warsaw, Poland
2024 Lehigh U, PA



Physics @ the US EIC beyond the EIC's core science

Of HEP/LHC-HI interest to Snowmass 2021 (EF 05, 06, and 07 and possibly also EF 04)

New Studies with proton or neutron target:

- Impact of precision measurements of unpolarized PDFs at high x/Q^2, on LHC-Upgrade results(?)
- Precision calculation of α_S : higher order pQCD calculations, twist 3
- Heavy quark and quarkonia (c, b quarks) studies with **100-1000 times lumi of HERA and with polarization**
- Polarized light nuclei in the EIC

Physics with nucleons and nuclear targets:

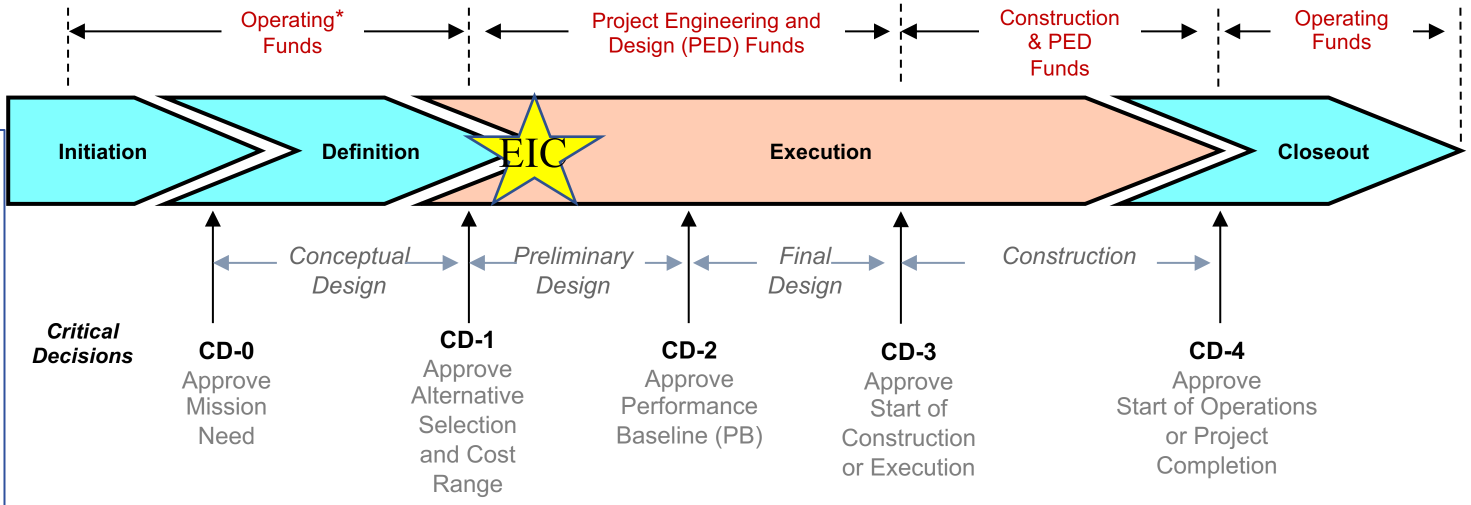
- Quark Exotica: 4,5,6 quark systems…? Much interest after recent **LHCb** led results.
- Physic of and with jets with EIC as a precision QCD machine:
  - Jets as probe of nuclear matter & Internal structure of jets : novel new observables, energy variability
  - Entanglement, entropy, connections to fragmentation, hadronization and confinement

Precision electroweak and BSM physics:

- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation
- LHC-EIC Synergies & complementarity

Study of universality: e-p/A vs. p-A, d-A, A-A at RHIC and LHC

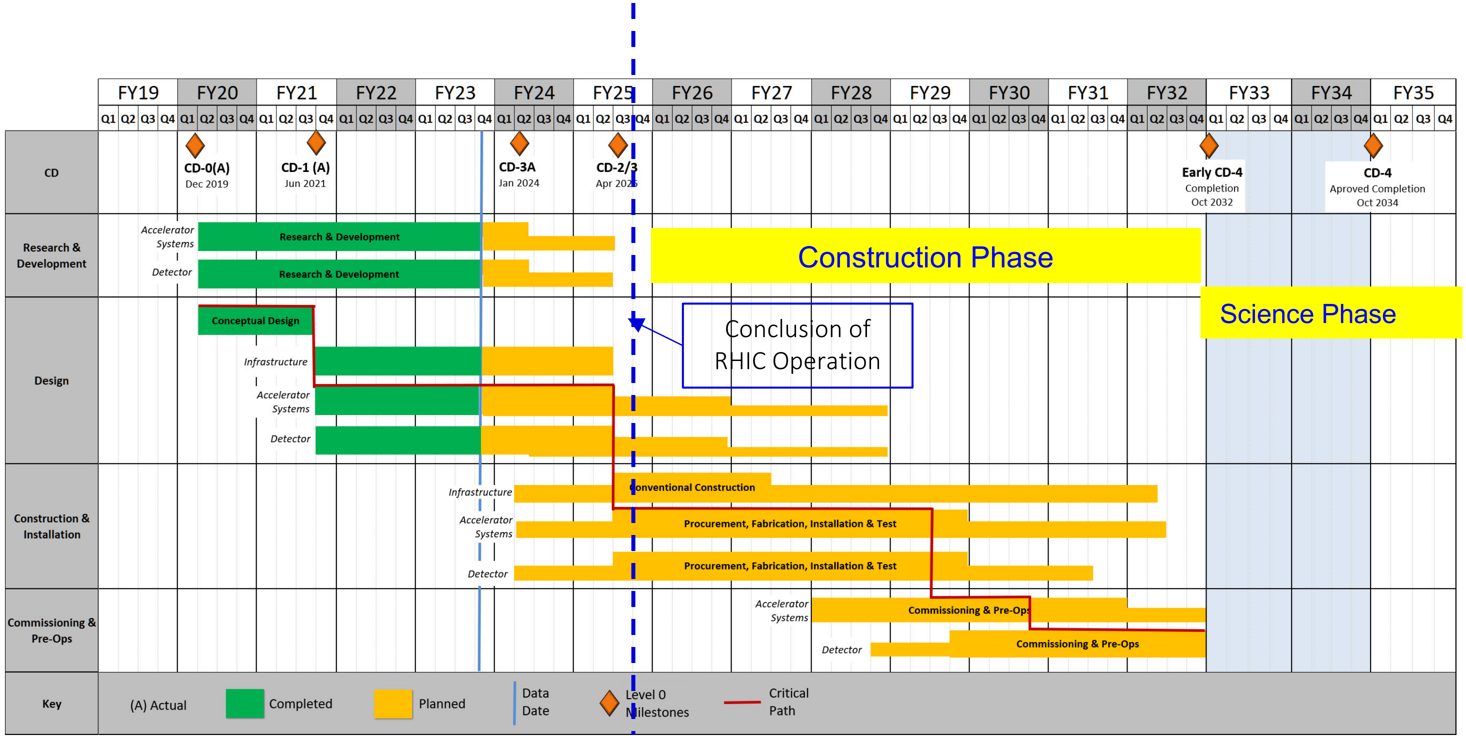
Timeline:



EIC Critical Decision Plan

CD-0/Site Selection	December 2019 ✓
CD-1	June 2021 ✓
CD-3A	**January 2024**
CD-2/3	**April 2025**
CD-4A	October 2032
CD-4	**October 2034**

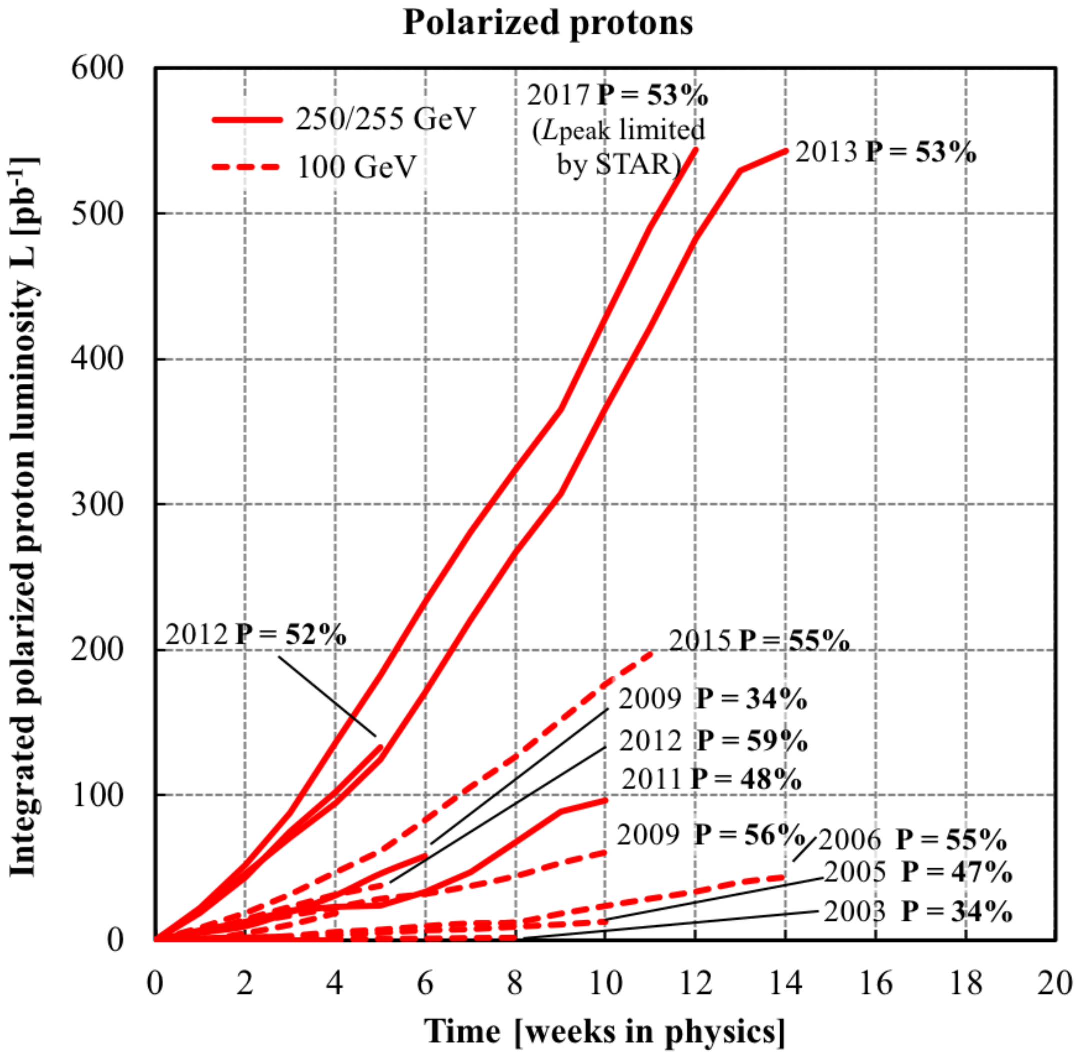
CD-3A: (review mid-November)
Define Baseline:
technologies, Scope, Cost & Schedule
Long Lead Procurement (LLP) items
Design Maturity: ~90%
Plan is tracked through EVMS
& Change control process
Start of construction for LLPs

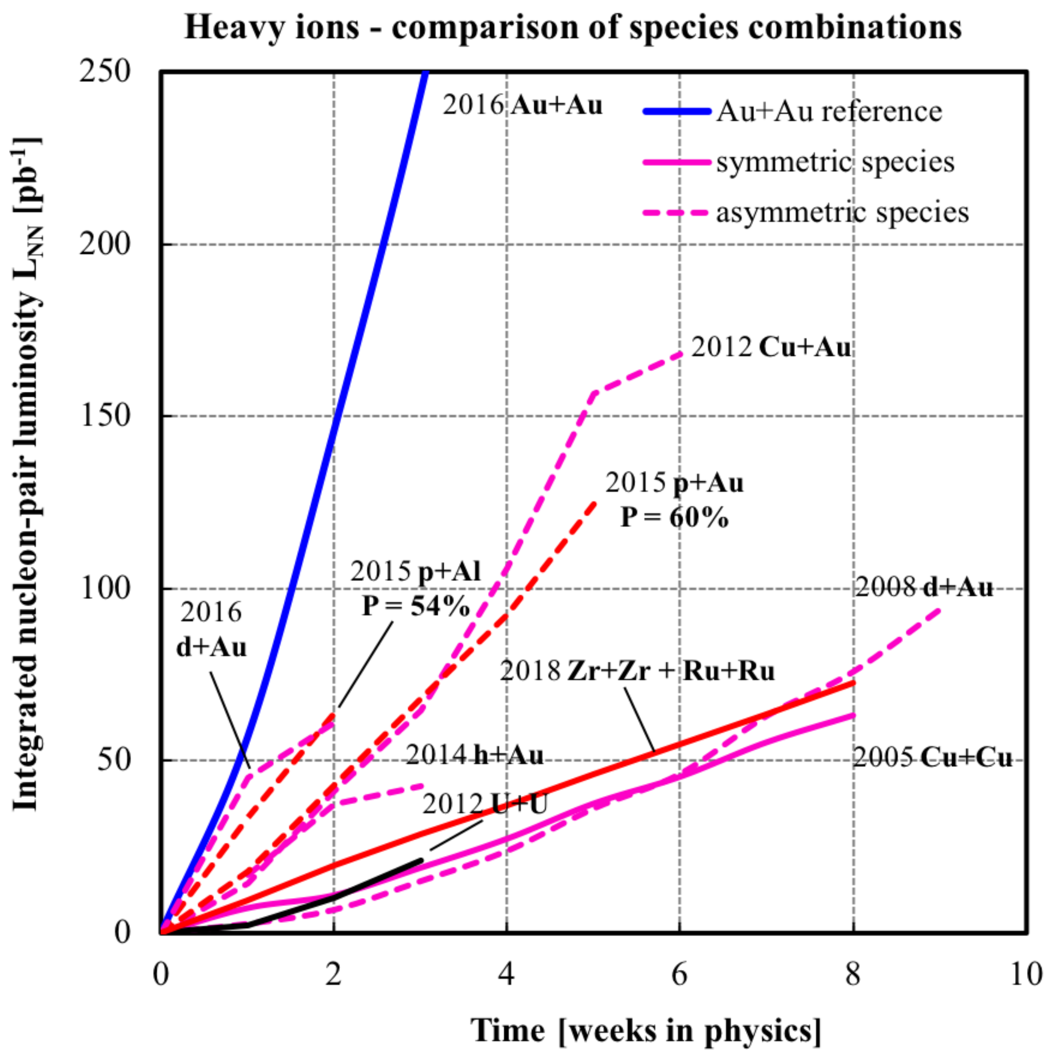


Item 2:
Transition to operation:
Operations planning

Start with lowest possible luminosity to build confidence in the machine in order to avoid accidental damage to the detector components and the machine itself. As we go forward and we get some explicit guidance on luminosity rise from EIC/CAD – we should be able to make more concrete proposals for early running – energy, species and physics goals/outcomes.

@RHIC Polarized protons harder than nuclei





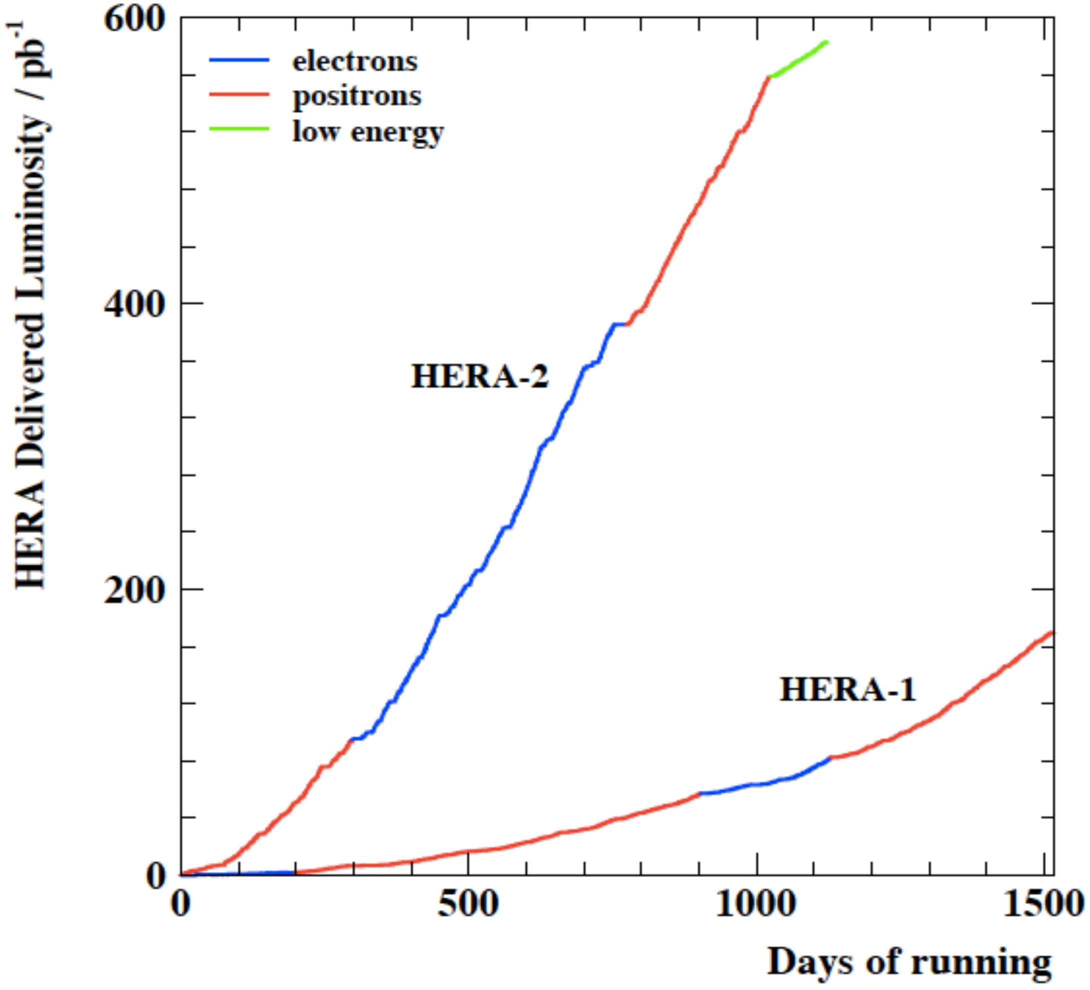
Historical Precedence:

HERA Experience:

- HERA highest luminosity ~ 5 x 10^{31} $cm^{-2}sec^{-1}$

HERA & RHIC lessons:

- Start of the machine slow and deliberate
- Development of polarization (both beams along with luminosity) will take time but early investments pay-off



Preliminary thoughts & estimates

Time on this slide starts at CD4

We should (hope to) see ~1 x 10^{32}cm^{-2}sec^{-1} in the 1st year (already twice the maximum reached at HERA), and reach ~10^{33} in ~2-3 years, and 10^{34} in ~5+ years at 10 x 250 GeV polarized proton operation.

18 GeV e beam will be experimented with before CD4 if RF is ready but not for "physics operation" until about 3-5 years into the program.

I expect polarization of electron and proton would be harder to achieve compared to e-A luminosity.

We would like to show fast physics results ➔

- e-A physics 10 x 100 GeV beams at the beginning with highest luminosity possible
- run at least two nuclei in the first two years
- ample time would be given to develop polarization and luminosity for e-p

Start EIC physics program hence *could* be:

Begin with electron-Nucleus/Ion Physics:

Intermediate/high energy operations with different nuclei leading to:

- Search for saturation from inclusive to sem-inclusive ➔ F_2^A, disappearance of jet
- Interactions in color with nuclear matter: with multiple nuclear sized targets; study of jet production and its interaction with nuclear matter, study jet internal structure, hadronization
- With luminosity increase: exclusive diffraction in e-A to establish saturation
- Comparison runs of e-p should be expected at moderate luminosity (not for polarization) but we should be ready to utilize what we get **for inclusive & start semi-inclusive spin physics**

Allow ample **time for luminosity and polarization development. In RHIC era, significant time of *p-p* was given to R&D.** This philosophy gave high returns later in the program.

Operational thoughts further….

10^{33} luminosity ➔ 20 fb^{-1}/year including 70% accelerator & detector efficiency

White paper and Yellow Report hence assumed those luminosities and hardly any measurement showed more luminosity in e-p-equivalent would be needed.

- It is hence my guess that physics with polarized beams will start happening after the 2nd year with.
- Transverse spin measurements needing only proton beam polarization should be easier to achieve than double longitudinal spin measurements with high e-polarization

Item 3:
Is theory ready for EIC to start?

Greatly benefitted from Daniel deFlorian's recent talk at DIS2023 and also input from Werner Vogelsang and a recent White Paper submitted to the NSAC Long Range Planning process:

"A Case for an EIC Theory Alliance: Theoretical Challenges of the EIC", R. Abir et al. arXiv: 2305.14572v1

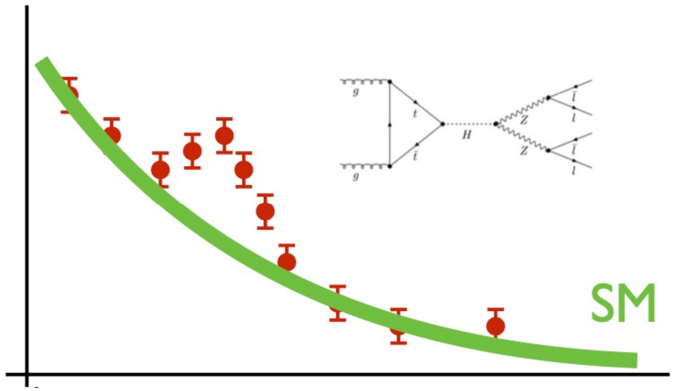
Based on: CFNS/Stony Brook & CFNS/MIT Workshops in 2022:

1) Precision QCD for e-p at the EIC and 2)Theory for EIC in the Next Decade

Fig. from de Florian

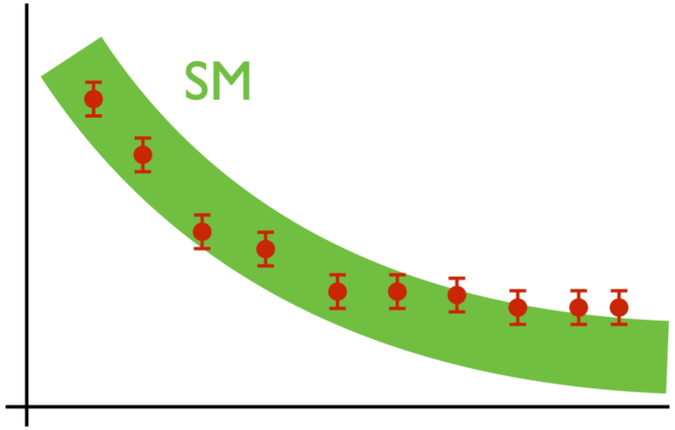
Anticipated precision at the LHC drove higher precision calculations in theory

- Still plenty of room for new discoveries : two main scenarios



- Search for (and find) new states
- Resonance needs “descriptive” TH

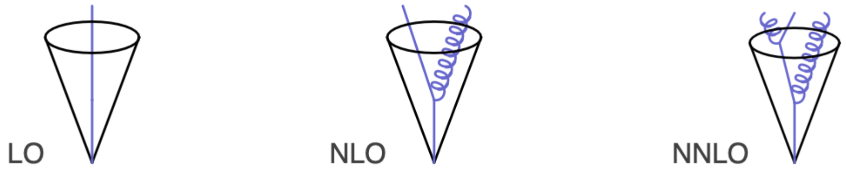
- Most likely look for “new interactions”
- Small deviations from SM : PRECISION
- EFT description / BSM model



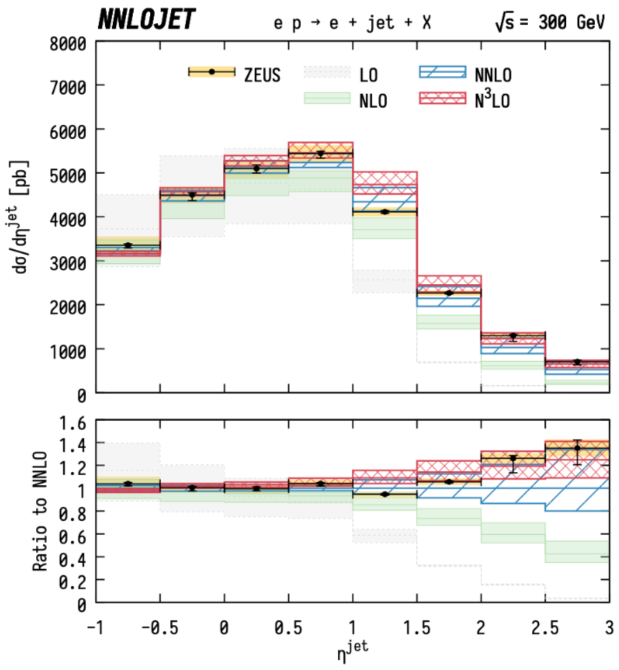
Theory uncertainties HAD to be reduced

Why higher order corrections?

- Large Corrections $\alpha_s \sim 0.1$
- Better TH/EXP matching



- Accurate Theoretical Predictions Scale dependence reduced



- DIS Single jet production at N3LO

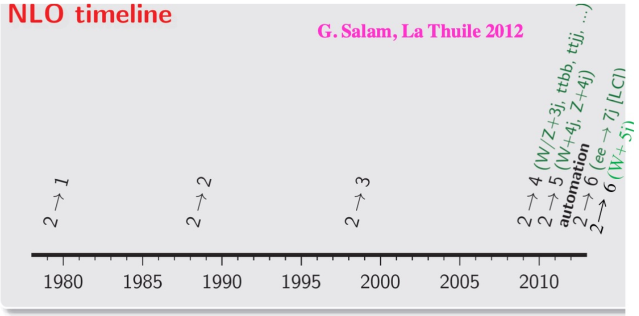
Currie, Gehrmann, Glover, Huss, Niehues, Vogt (2018)

- uncertainties still larger than experimental errors (HERA)

Recall, EIC luminosity will be at least 100 (if not 1000) times larger than HERA

Clearly theory precisions needs to be visited immediately.

The NLO ~~revolution~~ ~~standard~~ automation



- Final goal: Really automatic NLO calculations **zero cost for humans**
- Apart from very large multiplicities and loop induced processes automatic NLO "conceptually" solved
  - in a few years a number of codes

HELAC-NLO, Rocket, BlackHat+SHERPA, GoSam+SHERPA/MADGRAPH, NJet+SHERPA, Madgraph5-aMC@NLO, RECOLA, OpenLoops+SHERPA..

- Uncertainties, EW corrections, masses, matching to PS, etc

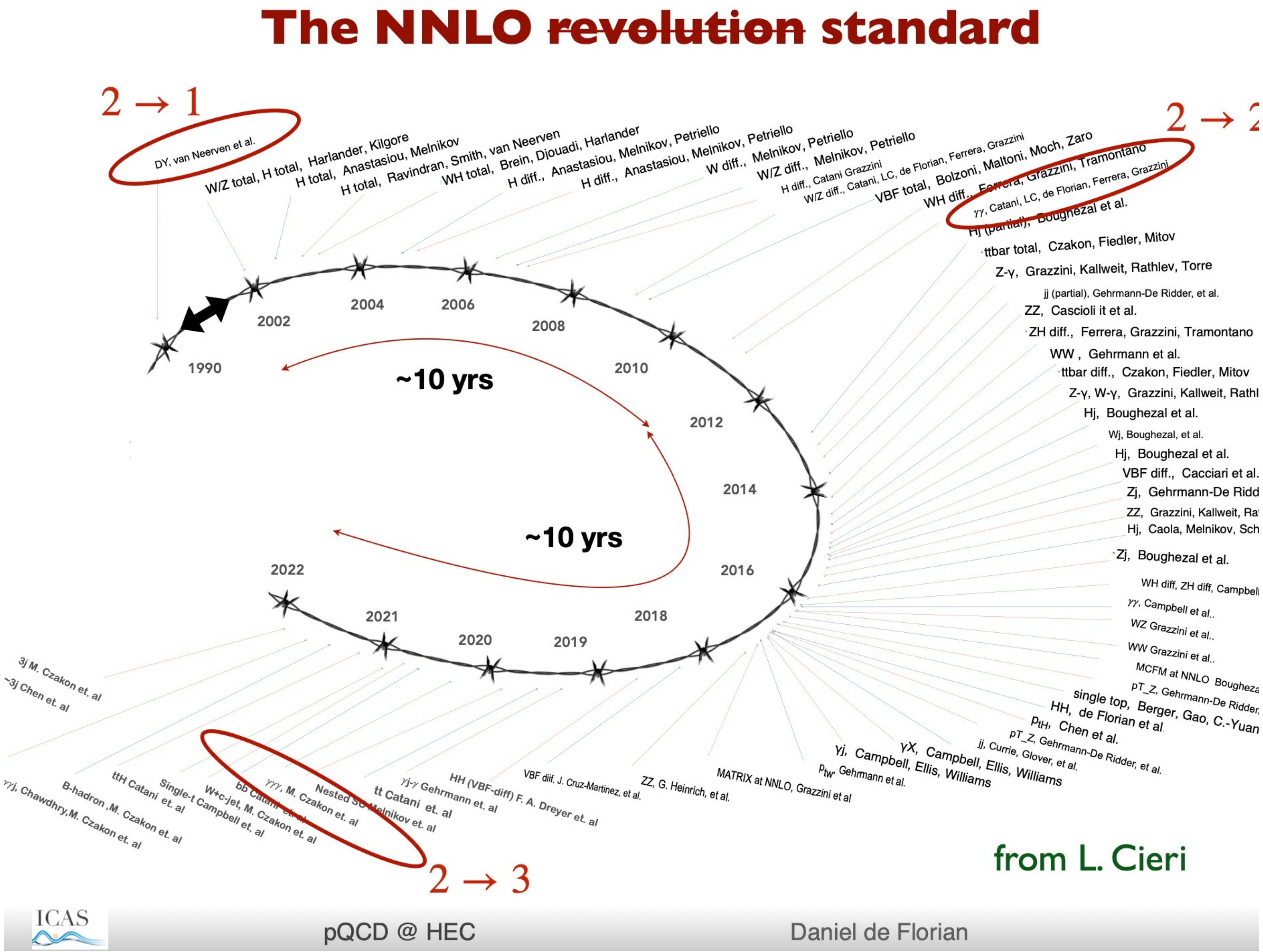
Automation at NLO already used and demonstrated.

Modern version: with ChatGPT LO tested(?) (Joke!)

LO can (almost) be done by chatGPT

Can you write a Fortran 77 code that computes the DIS cross section at LO using LHAPDFs? Please work in a 5-flavor scheme and using the latest set of CTEQ to make Joey Huston happy

```sql
Sample Fortran 77 code to compute the DIS cross section at LO using LHAPD
in a 5-flavor scheme and neglecting the contribution from the photon PDF

implicit none

Declare the input variables
real*8 x, q2, y, s, tau, pdf, sigma
integer flavor, nset, ievtnum
character*255 pdffile

Declare the LHAPDF functions
external initpdfset, evolvepdf, alphaspdf, endpdfset

Set the input kinematics
x = 0.1d0
q2 = 10.d0**6
y = 0.5d0
s = q2 / x / y
tau = a2 / s
Set the LHAPDF set and initialize it
pdffile = 'cteq66'
call initpdfset(nset,pdffile,0)

Compute the LO partonic cross section for each flavor
sigma = 0.d0
do flavor = 1, 5
   pdf = evolvepdf(x, q2, flavor) / x   ! divide by x to get the PDF for t
   sigma = sigma + alpha_em**2 / (2.d0 * s * q2) * pdf * &
          ((4.d0 / 9.d0 + 16.d0 / 27.d0 * delta(flavor,2)) * (1.d0 + (1.
           (4.d0 / 27.d0 * delta(flavor,2)) * (1.d0 + y**2))
end do

Compute the DIS cross section by convolving with the PDF of the proton
sigma = sigma * 3.d0 / 2.d0 / x / q2 / (1.d0 - y)
```



New Standard at LHC is NNLO

But it took 20 years from 1990's to 2020's for all processes to be calculate & tested

DIS23 MICHIGAN STATE UNIVERSITY @EIC

E. Aschenauer DIS23

- Inclusive DIS known at N3LO Vermaseren, Vogt. Moch (2005)
- Quark kernels almost known at N3LO Falcioni, Herzog, Moch
- Steps toward N4LO (first moments): N4LO DIS+evolutic
  Moch, Ruijl, Ueda, Vermaseren, Vogt (2022) **A. Pelloni DIS23**
- DIS Single jet production at N3LO Currie, Gehrmann, Glover, H
- What about other less inclusive observables?
- In many cases legacy calculations from HERA (missing pol
- Some hard to find (needed for validation), some wrong (D
- Need to reach level of LHC calculations and account for
- Set **new standards** for EIC

ICAS pQCD @ HEC Daniel de Florian

Need to gather TH community for precision at EIC

EIC Wishlist

Precision QCD predictions for *ep* physics at the EIC
CFNS August 2022

Regarding DATA

- Measure cross-sections instead of ratios for a more dedicate analysi
- Release both QED corrected and uncorrected data
- Develop method for unbinned cross-sections

Regarding PDFs, FFs and more distributions

- Replication of PDF4LHC and HERA efforts for EIC : PDF4EIC
- Perform Global NNLO analysis of polarized PDFs
- Impact of QED corrections to polarized PDFS
- Perform Global analysis of DVCS
- Generate threshold resummed PDFS and FFs
- New set of photon PDFs (existing are outdated)

Regarding Perturbative corrections (QCD/QED)

- Jets in DIS: matched NNLO + q_T resummation
- DIS with QED/EW corrections
- Calculations for dihadron production

Regarding Theoretical Issues

- Discuss (non)Universality of TMDs
- Search for ideal observables to measure Wigner distribution
- Role of lattice in PDFs (in two slides!)
- Studies for Lambda polarization at EIC
- N^*, Δ electro-couplings at $Q^2 > \text{GeV}^2$
- Proton structure functions in transition regime → DIS
- Dipole and quadrupole amplitudes

Precision QCD predictions for *ep* physics at the EIC (II)

https://indico.bnl.gov/e/qcd4eic

CFNS (StonyBrook)
18-22 September 2023

Conclusions

- Amazing progress in fixed order calculations during the last two decades
  Automation of NLO **Driven by LHC**
  Several NNLO processes $2 \to 2$ and already a few $2 \to 3$ ✓
  Even N³LO for simpler kinematics and first set of splitting functions
  Account for QED/EW effects
- But… Reaching new bottlenecks
- $2 \to 3$ (Massive) 2-loop amplitudes complicated beyond leading color
- Real radiation far from trivial (numerical infrared treatment)
- N^3LO beyond Drell-Yan like processes will require significant developments
- Need a more rigorous treatment of TH uncertainties
- **From LHC to EIC**
  - By the time EIC starts taking data ~N^3LO might be the new standard!

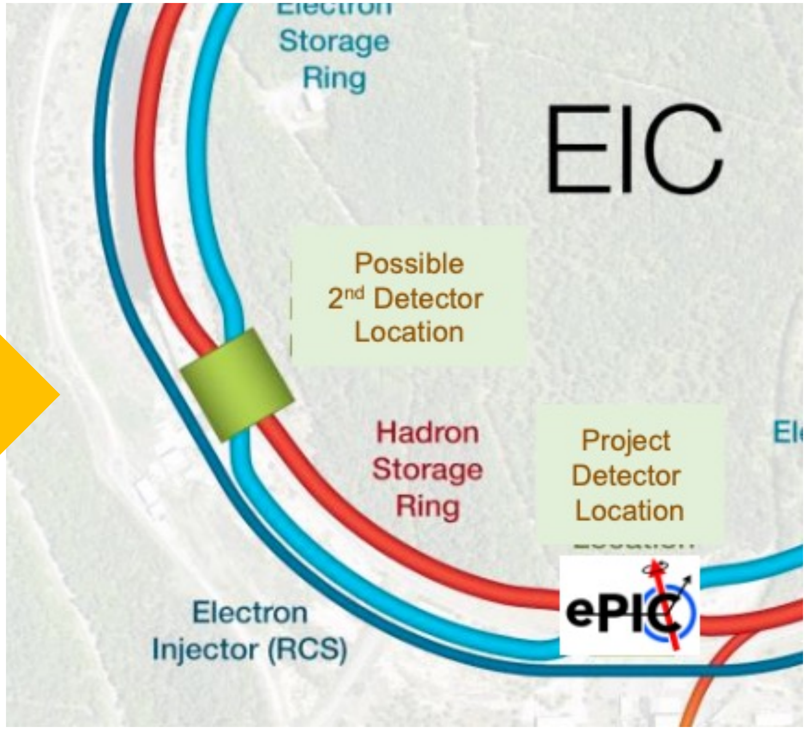
ICAS pQCD @ HEC Daniel de Florian 24

An enormous thrust in precision calculations in Theory including already emerging precision in Lattice QCD is needed in the next ~10 years before or around the same time the EIC data will become available

While EIC project (machine and 1st detector) have to succeed….

I think we have everything we need to sow the seeds for a 2nd detector

The 2nd detector



NSAC documents talk about possibly ~4 detectors

NAS Report: planning for up to 2 well-integrated detectors

EICUG desires 2 Detectors

EIC Project has 1 Machine, 1 IR and ~1 Detector

without negating the possibility of the 2nd IR/Detector

Two documents: with overlapping arguments

Ent and Milner et al for the EICUG SC

JLAB-PHY-23-3761

Motivation for Two Detectors at a Particle Physics Collider

Paul D. Grannis* and Hugh E. Montgomery†
(Dated: March 27, 2023)

It is generally accepted that it is preferable to build two general purpose detectors at any given collider facility. We reinforce this point by discussing a number of aspects and particular instances in which this has been important. The examples are taken mainly, but not exclusively, from experience at the Tevatron collider.

arXiv: 2303.08228v2 March 24, 20234

Case for two detectors being made from **Nuclear** and **Particle** Physics

History: Discoveries established with **more than one** detectors in Nuclear Science

- Discovery of gluon : TASSO, JADE, Mark J, and PLUTO @ DESY
- H1 and ZEUS at Rise of F_2 and hence the gluon dominance at low-x
- BRAHMS, PHOBOS, PHENIX and STAR Discovery and establishing the existence of Quark Gluon Plasma
- Measurements at DESY and JLab eventually led to “parton imaging”

- EMC/CERN discovered and then SMC/CERN and EXXX/SLAC established nucleon spin crisis (low-x) & EMC discovered and then NMC/CERN & E865/FNAL established nuclear effects on nucleon PDFs (also low-x)

Two detectors (independent cross checks) builds trust in novel discoveries and prevents historical mistakes

Building Trust

- Quark Gluon Plasma: RHIC Experiments
- Discovery of Top Quark D0/CDF
- Discovery of Higgs Boson: ATLAS and CMS
- Gravitational Waves: LIGO and VIRGO
- Neutrino oscillations

Mistakes or misinterpretations:

- Cold fusion
- 17 KeV neutrinos in Tritium
- Superluminal neutrinos
- Leptoquarks
- Pentaquarks from 2000’s

Vision for the 2nd detector: C²C

- Complementary (IR, detector technologies & design)
  - Continue to explore complementary ready and not-yet-ready technologies
  - Generic detector R&D program – Run through Jlab
- Complementary (physics)
  - A significant list of physics topics exists (some-exclusive to 2nd IR, some-overlapping): drill down and see which of those can *develop into strong pillars of science for the 2nd detector.*
  - New physics developing around the world: we need to monitor constantly
- Complementary (people)
  - New non-US/outside groups who may bring new interests & funding in future
  - New US groups – other than those with significant responsibilities in ePIC

Potential Physics topics beyond Core EPIC detector's mandate exist

Focus first on Physics beyond the EIC's core (CD0) science

(there will be others: some overlapping, some exclusive due to different IR design)

Physics with nucleons and nuclear targets:

- Quark **Exotica**: 4,5,6 quark systems…? Much interest after recent **LHCb** led results.
- **Nuclear Fragments** from light and heavy nuclei : e-A – Connecting to low energy nuclear physics (exotic nuclei), studying the shapes of nuclei and their nternal substructure; entanglement, entropy, fragmentation, hadronization and such phenomena

New Studies with proton or neutron target: (mostly overlapping?)

- Impact of precision measurements of unpolarized PDFs at high x/Q^2, on LHC-Upgrade results(?)
- Precision calculation of α_S : higher order pQCD calculations, twist 3
- Heavy quark and quarkonia (c, b quarks) studies with 1000 times lumi of HERA (and polarization)

Precision electroweak and BSM physics:

- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation
- LHC-EIC Synergies & complementarity: (**muon detectors** were of particular interest)

EIC Science from the perspective of High Energy Physicists

arXiv:2203.13199v1 [hep-ph] 24 March 2022

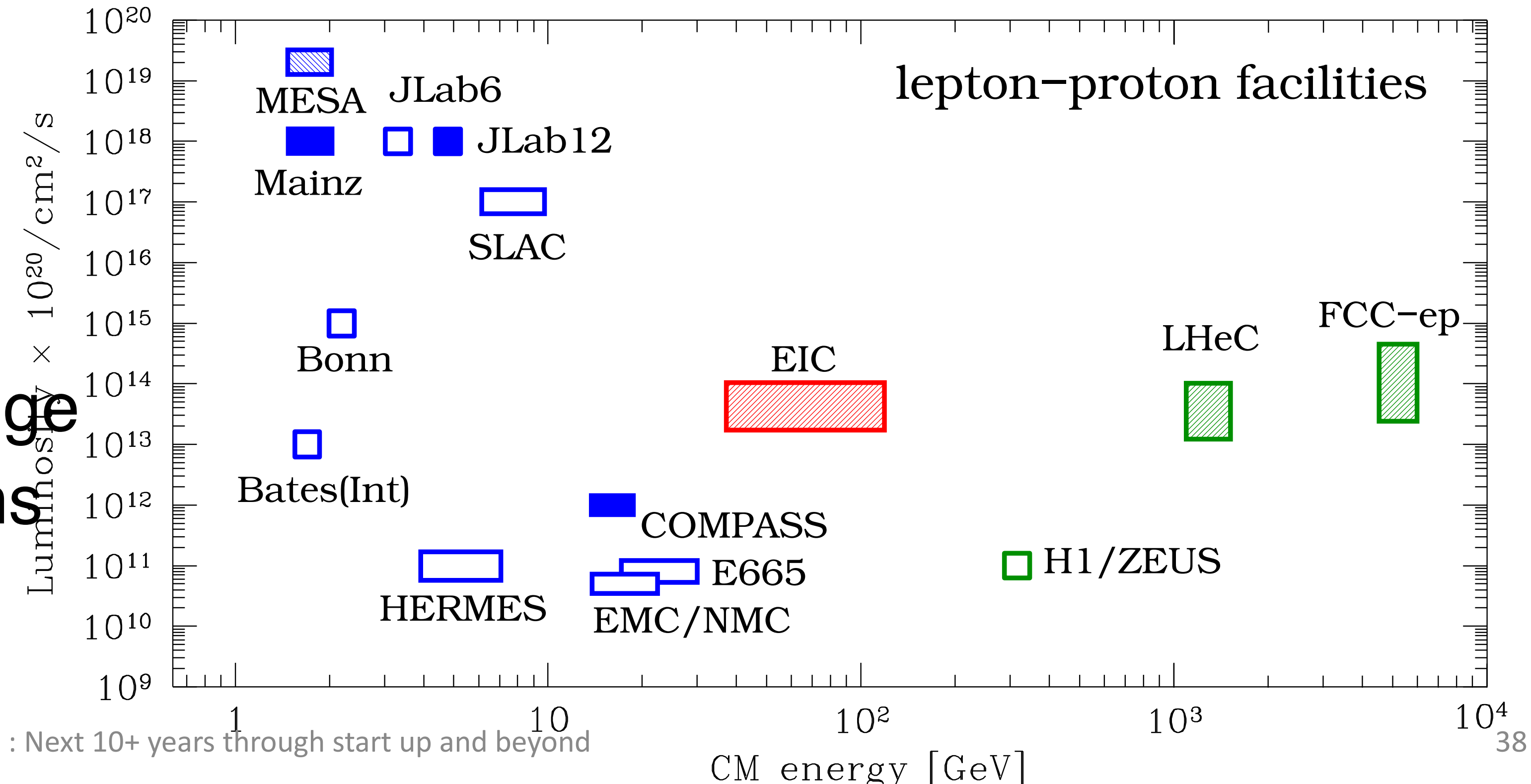
Snowmass 2021 White Paper: Electron Ion Collider for High Energy Physics

R. Abdul Khalek,[1] U. D'Alesio,[2,3] Miguel Arratia,[4,5,*] A. Bacchetta,[6] M. Battaglieri,[7,1] M. Begel,[8] M. Boglione,[9] R. Boughezal,[10] Renaud Boussarie,[11,*] G. Bozzi,[12,3] S. V. Chekanov,[10] F. G. Celiberto,[13,14,15] G. Chirilli,[16] T. Cridge,[17] R. Cruz-Torres,[18] R. Corliss,[19,20] C. Cotton,[21] H. Davoudiasl,[8] A. Deshpande,[8,19] Xin Dong,[18,*] A. Emmert,[21] S. Fazio,[8] S. Forte,[22] Yulia Furletova,[1,*] Ciprian Gal,[23,20,*] Claire Gwenlan,[24,*] V. Guzey,[25] L. A. Harland-Lang,[26] I. Helenius,[27,28] M. Hentschinski,[29] Timothy J. Hobbs,[30,31,*] S. Höche,[32] T.-J. Hou,[33] Y. Ji,[18] X. Jing,[34] M. Kelsey,[35,18] M. Klasen,[36] Zhong-Bo Kang,[37,38,20,*] Y. V. Kovchegov,[39] K.S. Kumar,[40] Tuomas Lappi,[27,28,*] K. Lee,[41,42] Yen-Jie Lee,[43,44,*] H.-T. Li,[45,46,47] X. Li,[48] H.-W. Lin,[49] H. Liu,[40] Z. L. Liu,[50] S. Liuti,[21] C. Lorcé,[51] E. Lunghi,[52] R. Marcarelli,[53] S. Magill,[54] Y. Makris,[55] S. Mantry,[56] W. Melnitchouk,[1] C. Mezrag,[57] S. Moch,[58] H. Moutarde,[57] Swagato Mukherjee,[8,†] F. Murgia,[3] B. Nachman,[59,60] P. M. Nadolsky,[61] J.D. Nam,[62] D. Neill,[63] E.T. Neill,[53] E. Nocera,[64] M. Nycz,[21] F. Olness,[61] F. Petriello,[46,47] D. Pitonyak,[65] S. Plätzer,[66] Stefan Prestel,[67,*] Alexei Prokudin,[68,1,*] J. Qiu,[1] M. Radici,[6] S. Radhakrishnan,[69,18] A. Sadofyev,[70] J. Rojo,[71,72] F. Ringer,[73,19] Farid Salazar,[37,38,74,75,*] N. Sato,[1] Björn Schenke,[8,*] Sören Schlichting,[76,*] P. Schweitzer,[77] S. J. Sekula,[78,*] D. Y. Shao,[79] N. Sherrill,[80] E. Sichtermann,[18] A. Signori,[6] K. Şimşek,[81] A. Simonelli,[9] P. Sznajder,[82] K. Tezgin,[83] R. S. Thorne,[17] A. Tricoli,[8] R. Venugopalan,[8] A. Vladimirov,[84] Alessandro Vicini,[22,*] Ivan Vitev,[85,*] D. Wiegand,[86] C.-P. Wong,[48] K. Xie,[87] M. Zaccheddu,[2,3] Y. Zhao,[88] J. Zhang,[89] X. Zheng,[21] and P. Zurita[84]

EIC’s versatility, resolving power and intensity (luminosity) open new windows of opportunity to address some of the crucial and fundamental scientific questions in particle physics. The paper summarizes the EIC physics from the perspective of the HEP community participating in Snowmass 2021

- Beyond the Standard Model Physics at the EIC
- Tomography (1,3,5 d PDFs) of Hadrons and Nuclei at the EIC
- Jets at EIC
- Heavy Flavors at EIC
- Small-x Physics at the EIC

- High luminosity wide CM range
- Polarized e, p, and ion beams
- All nuclei



Detector technologies EIC & LHC:

Potential for overlap and collaboration: Many EIC collaborators already part of RD51 (and family) at CERN & vice-versa.

- MAPS μVertex for primary/secondary vtx: barrel & end-caps (ALICE ITS3)
- Micro Pattern Gas Detectors: large rapidity, spatial resolution ~100 μm
- Electromagnetic Calorimetry for kinematic reconstruction, precise energy measurements e, γ; e/π & π^0/γ separation. Various technologies at various locations:
  - W/SciFi w/o PMT, PbWO4, SiGlass; AstroPix & Pb/SciFi
  - High resolution Crystal Cal for e-endcap
  - Barrel EMCal 6 layers AstroPix and Pb/SciFi
- Particle Identification – extremely important for most EIC physics
  - K/pi separation over a wide range 1-20 GeV/c
  - Hadron ID: hpDIRC in Barrel, forward EndCap: duel RICH, backward Endcap: modular RICH or pF RICH, also TOF for short lever arm : LGAD, LAPPD
- Streaming Readout

Complementary detectors : 1 + 1 > 2

More than one detectors with different acceptances, optimizations and technologies:
Redundancy, cross-calibration and independent validation of important results

- Complementary acceptance -- confirming or refuting discoveries – studying from different “point of views”
- Complementary Technologies – multiple examples of systematic uncertainties improvement due to different Particle ID, Calorimetry, Tracking, magnetic field strengths and orientations.
  - H1/ZEUS, PHENIX/STAR, CDF/D0 and ATLAS/CMS vs. LHCb
  - Very important because most measurements at the EIC expected to be systematics limited
- Impact of different perspectives that different collaborators bring to the same problem.
  - Complementary analyses strategies build confidence in conclusions
- Complementary Science would add a very significant weight to to the argument for the 2nd detector

Path forward 2nd Detector:
Focused workshops and detector studies on new physics topics:

✓Look at **complementary detector technologies** (to ePIC) and attract groups that are experts in them to the EICUG

✓Focused discussions on **new physics topics** (not just listed in this talk but also beyond) to try to make a unique case complementary to ePIC/EIC White Paper

✓**Build community** – new groups/faces/resources needed to contribute and become part of new detector effort

Resources:

Generic detector R&D – supported by DOE administered from JLab

Center for Frontiers in Nuclear Science @ Stony Brook (& EIC – Theory Institute at BNL) and the EIC^2 at JLab

Summary

1. EIC Project (1 machine + 1 detector) timeline & criticality of its success

   Consolidate the collaboration, science and detector : Its success is paramount

2. Some thoughts on EIC early operations & planning

   – Historical precedent and early operational experience: inclusive – to – exclusive, e-A to polarized e-p/A

3. Is “theory” ready to meet EIC data? NO

4. Ultimate Success of EIC ➔ Physics with a second detector : $(\text{Complementarity})^3$ – physics, detector and people.

Message to CFNS Fellows: You can be leaders in all of this!

- EIC project's path is well understood. Its success is paramount. Your input and leadership will be paramount in EIC's success and EIC assure a great career for all of you!
- Tremendous developments in THOERY are needed in the next 10 years for EIC's success
- 2nd detector is essential for completing the Vision of EIC
  - C^3 : Complementary physics, technology and people
  - Series of workshops, outreach and critical evaluation

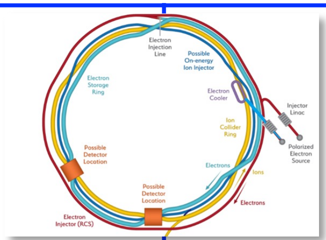
I look forward to discussions and ideas….

Thank you

Opportunity for complementary detector designs for different IRs exists!

Complementarity for 1st-IR & 2nd-IR

	1st IR (IP-6) ePIC	2nd IR (IP-8)
Geometry:	ring inside to outside tunnel and assembly hall are larger Tunnel: ⃠ 7m +/- 140m	ring outside to inside tunnel and assembly hall are smaller Tunnel: ⃠ 6.3m to 60m then 5.3m
Crossing Angle:	25 mrad	35 mrad secondary focus



different blind spots
different forward detectors and acceptances
different acceptance of central detector

Luminosity:

More luminosity at lower E_{CM} ?
Optimize Doublet focusing FDD vs. FDF
→ impact of far forward p_T acceptance

Experiment:

1.7 Tesla or 3 (?) Tesla
different subdetector technologies

EIC Design Parameters

Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

eRHIC Hadron Polarization

Measured RHIC Results:

- Proton Source Polarization 83 %
- Polarization at extraction from AGS 70%
- Polarization at RHIC collision energy 60%

Planned near term improvements:

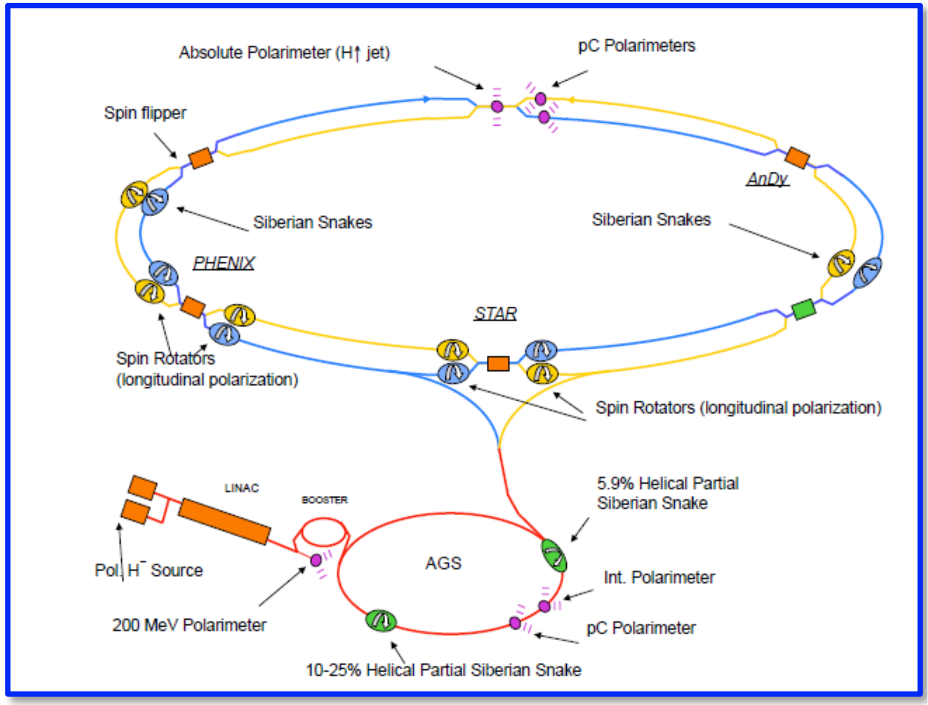
AGS: Stronger snake, skew quadrupoles, increased injection energy
➔expect 80% at extraction of AGS
RHIC: Add 2 snakes to 4 existing no/reduce polarization loss
➔ expect 80% in Polarization in RHIC and EIC
Expected simulations results benchmarked against RHIC operations

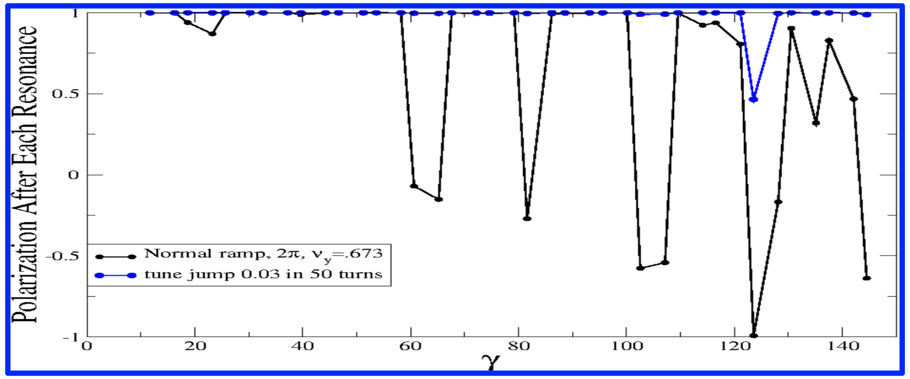
^{3}He in eRHIC with six snakes

Achieved 85% polarization in 3He ion source
Polarization preserved with 6 snakes for up to twice the design emittance

Deuterons in eRHIC:

Requires tune jumps in the AGS, then
benchmarked simulation show 100% Spin transparency
No polarization **loss** expected in the EIC hadron ring





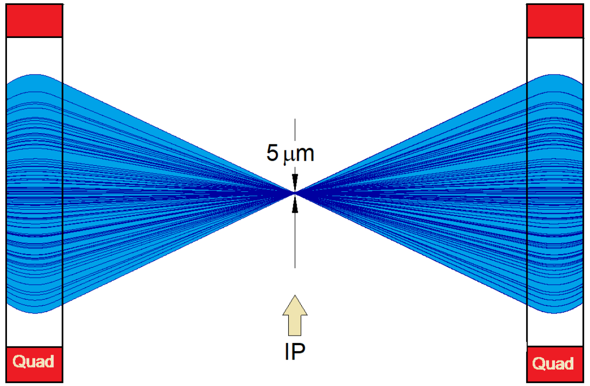
EIC achieves high luminosity $L = 10^{34}\ cm^{-2}s^{-1}$

- **Large bunch charges** $N_e \leq 1.7 \cdot 10^{11}$, $N_p \leq 0.69 \cdot 10^{11}$

- **Many bunches,** n_b=1160
  - crossing angle collision geometry
  - large total beam currents
  - limited by installed RF power of 10 MW

- **Small beam size** at collision point achieved by
  - small emittance, requiring either:
    - strong hadron cooling to prevent emittance growth
      or frequent hadron injection
  - and strong focusing at interaction point (small β_y)
  - flat beams $\sigma_x/\sigma_y \approx 10$

Strong focusing β_y =5 cm



- **Strong, but previously demonstrated beam-beam interactions**

  $\Delta\nu_p = 0.01$ demonstrated in RHIC

  $\Delta\nu_e = 0.1$ demonstrated in HERA, B-factories