Abhay Deshpande
July 6-7, 2023
CFNS Workshop on e-A Physics

EIC next 10 + years to start of operations

These are my personal (various) thoughts to initiate discussion within the EICUG community – and this workshop.

They are based on experience over many years at RHIC and discussions with experts on each topic

EIC first physics collisions and beyond

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

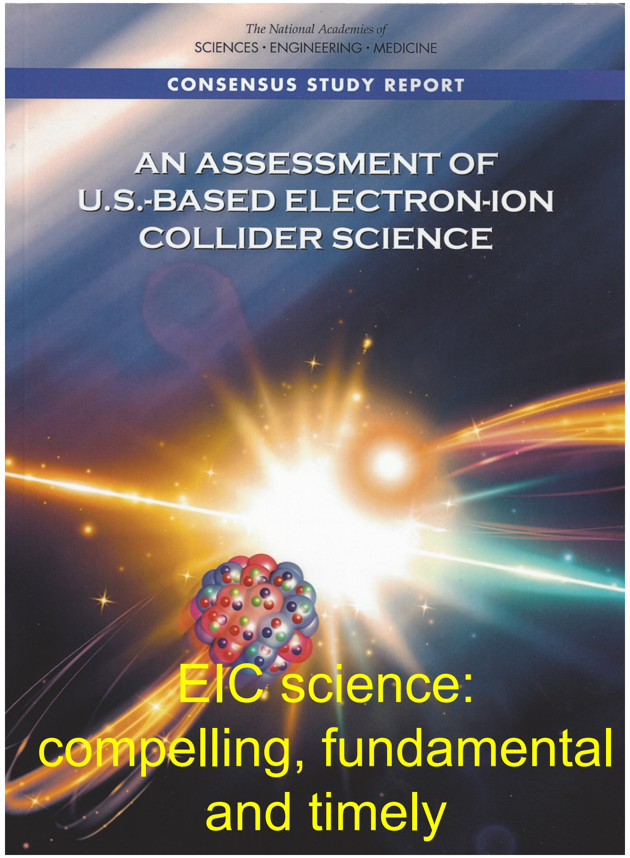
   How would the EIC Operations evolve? – Historical precedent and experience
3. Is “theory” ready to meet EIC data?
4. Ultimate Success of EIC ➔ A second detector

   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



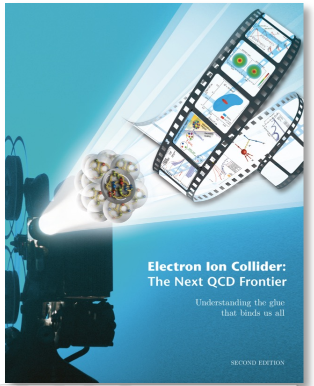
EIC science: compelling, fundamental and timely

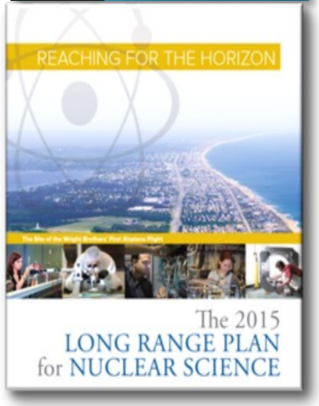
Physics of EIC

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

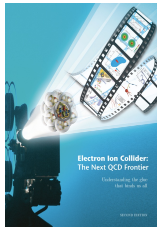
Machine Design Parameters:

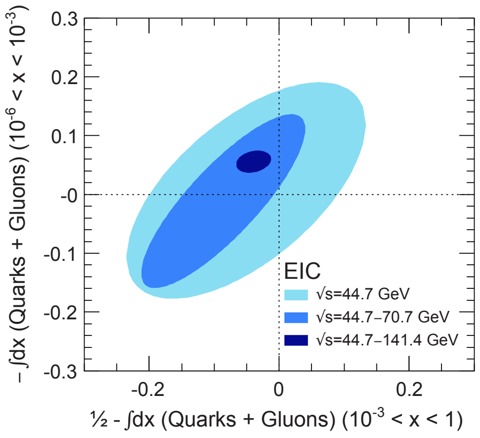
- High luminosity: up to 10^{33}-10^{34} $cm^{-2}sec^{-1}$
  - a factor ~100-1000 times HERA
- Broad range in center-of-mass energy: ~20-140 GeV
- Polarized beams e-, p, and light ion beams with flexible spin patterns/orientation
- Broad range in hadron species: protons…. Uranium
- Up to two detectors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

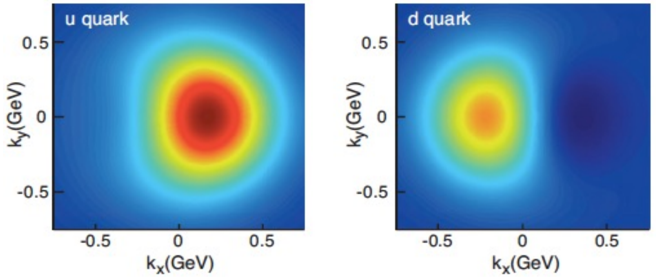


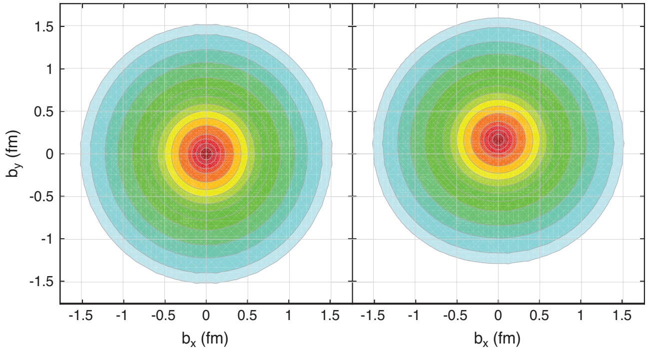


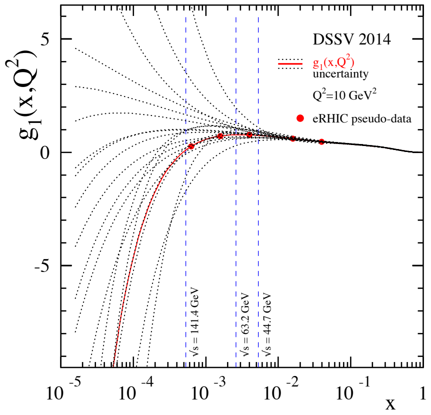
EIC science highlights

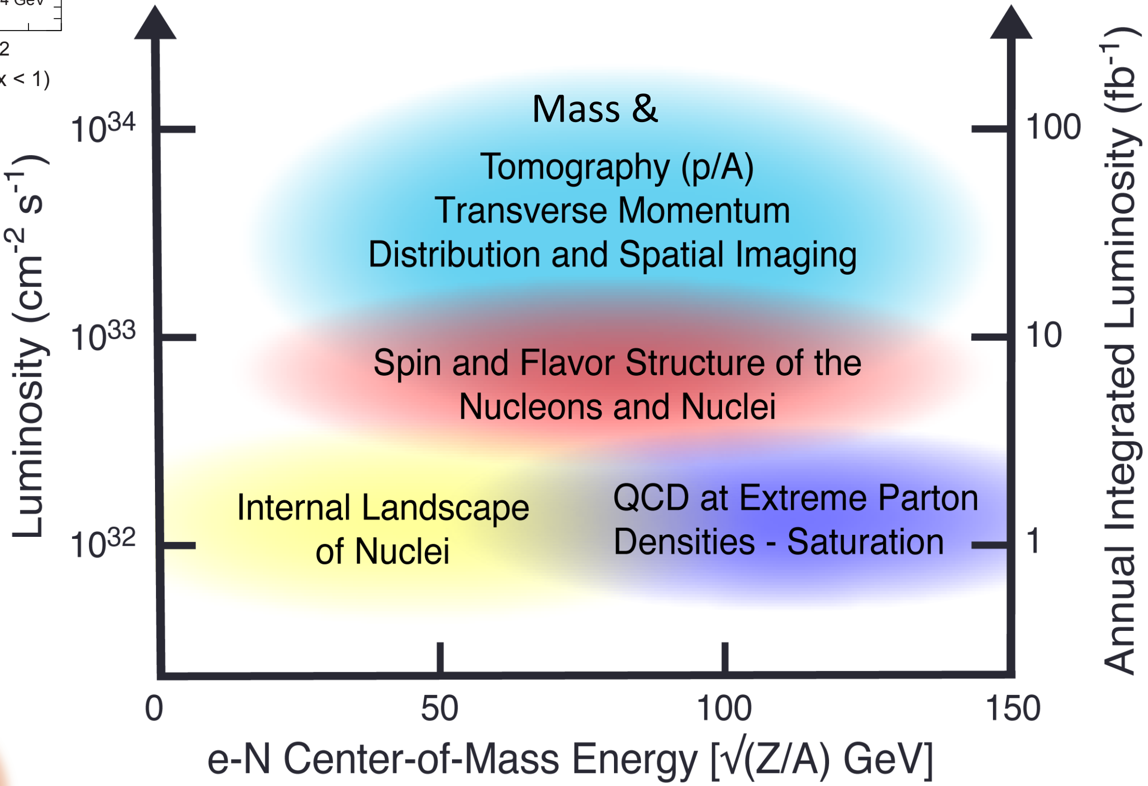


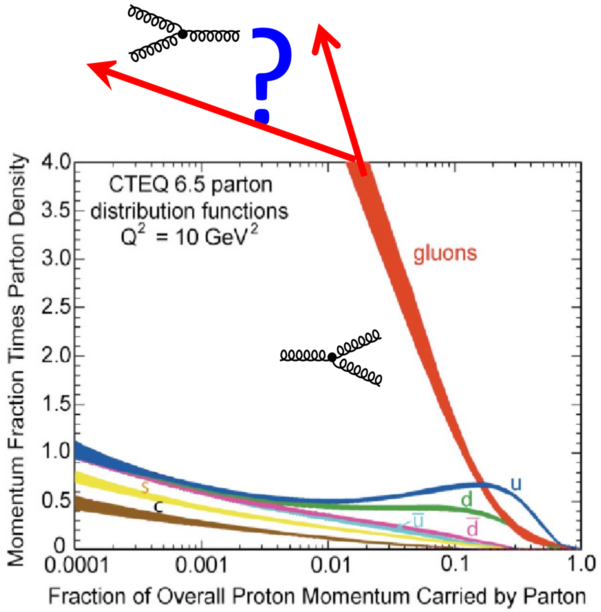


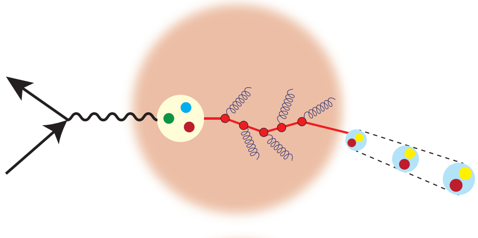




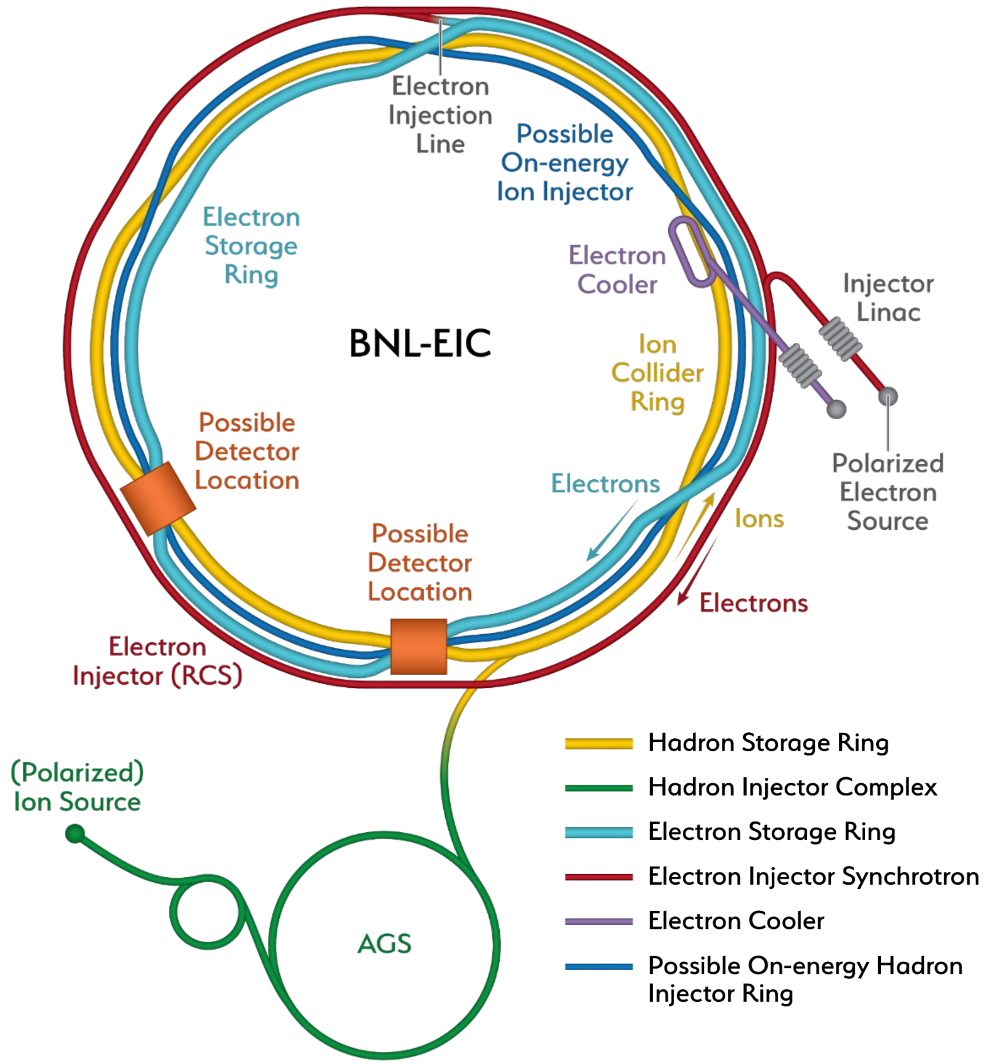




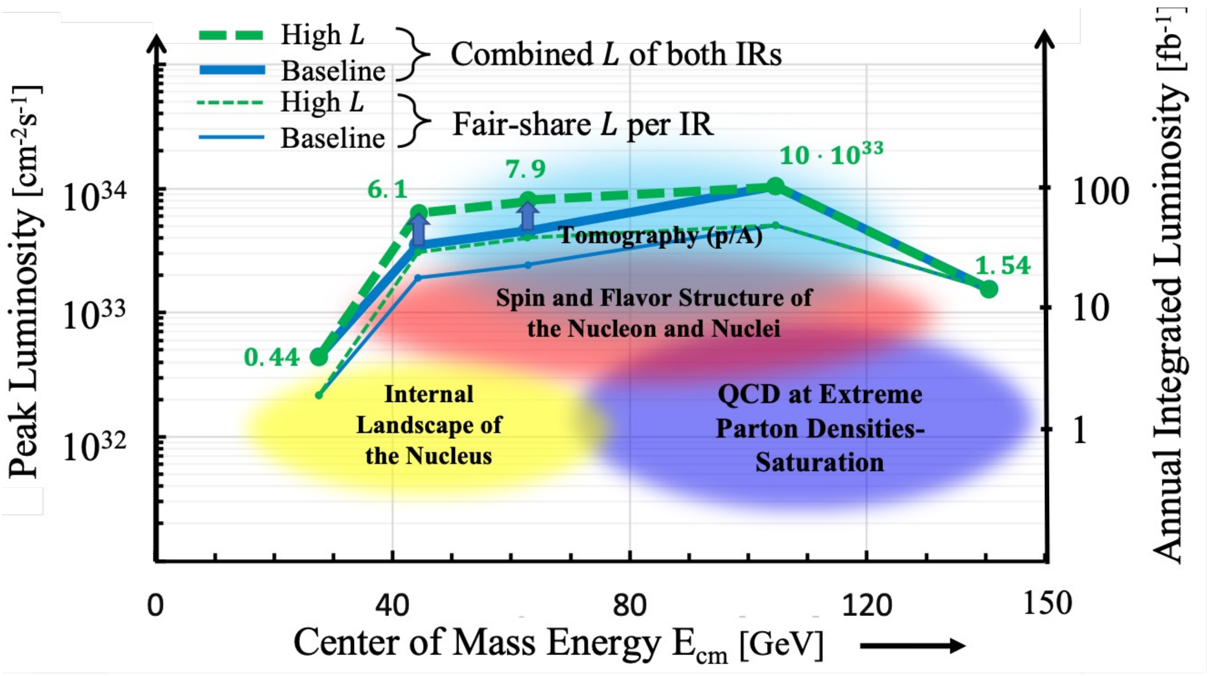




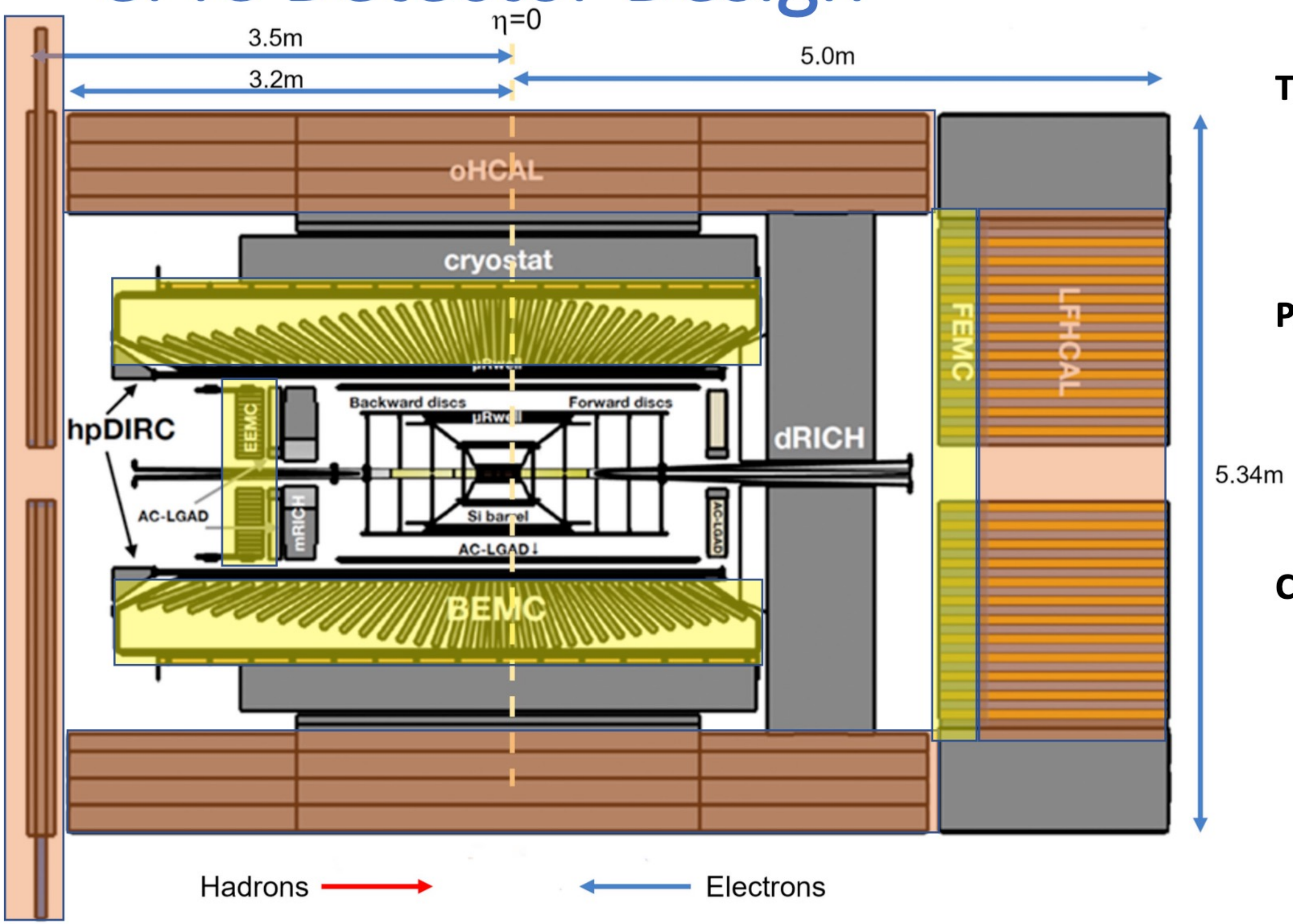
EIC Accelerator Design



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!



ePIC Detector Design

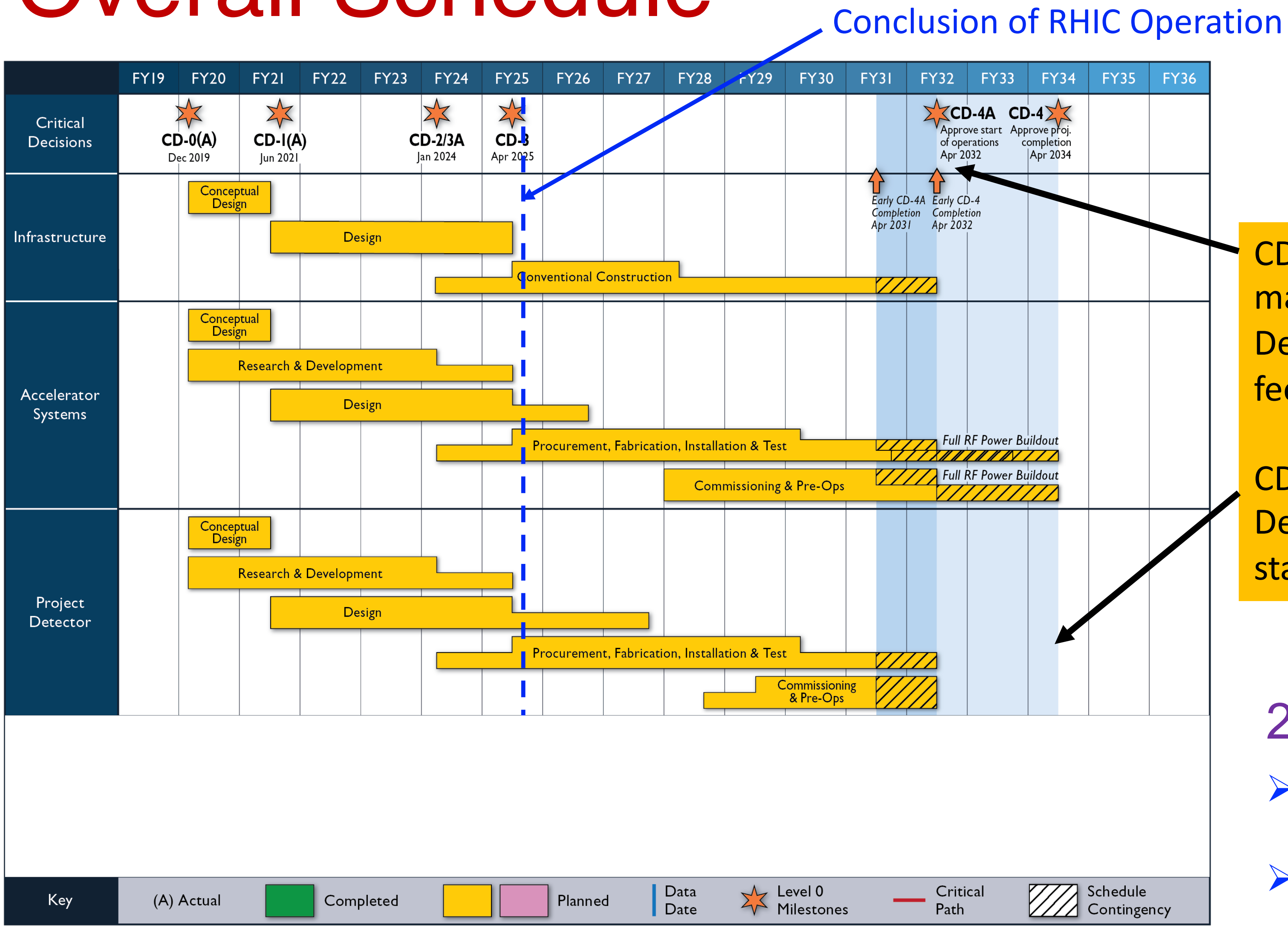


Tracking:
- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

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)

Overall Schedule



CD4A early finish, collisions begin for machine tuning
Detector 1 needs to be ready to give feedback.

CD4 Machine delivers for physics
Detector 1 should be fully functional to start physics

2nd Detector and IR

- Current assumption realization trailing ~3 – 5 years behind Detector-1
- focus on complementary IR/physics & technologies

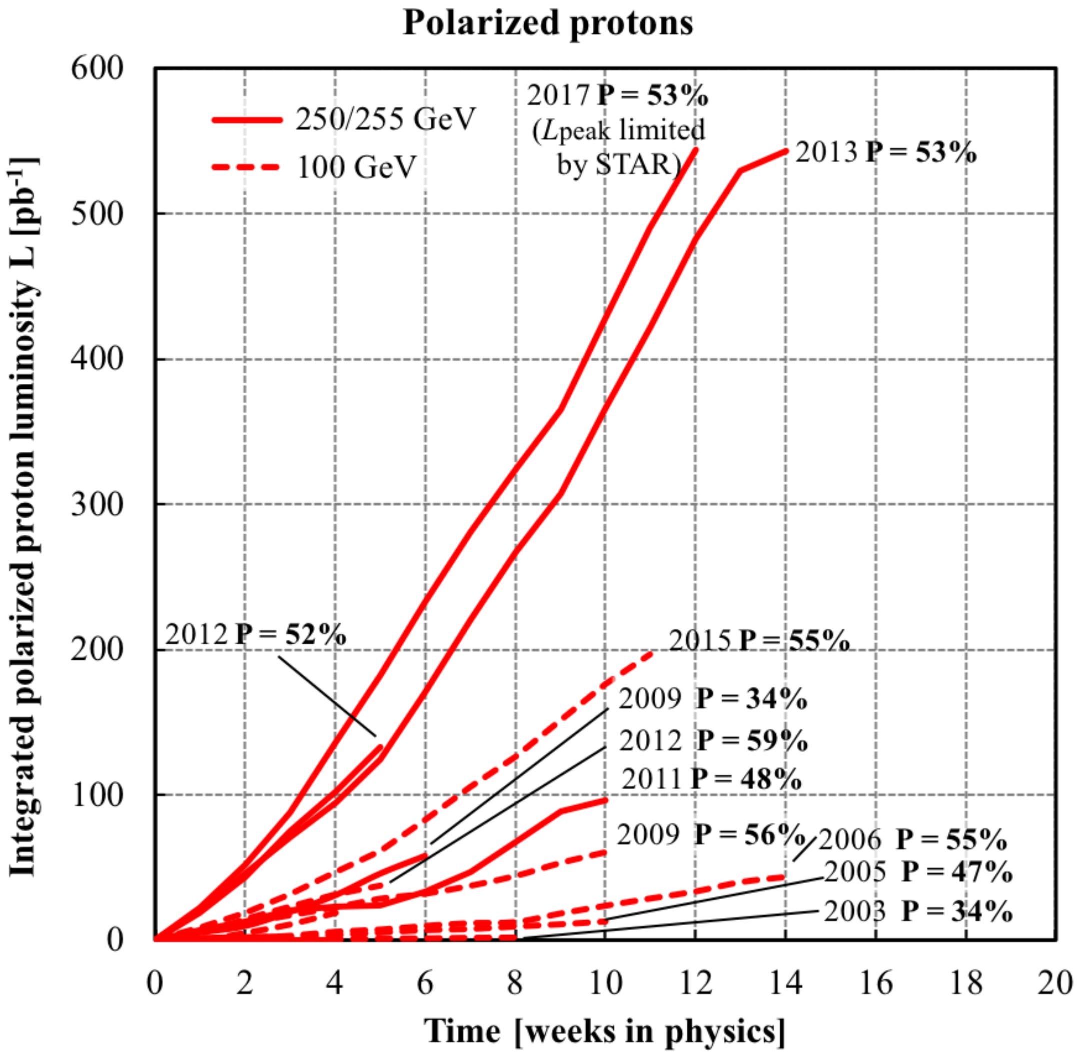
Eventually the guidance will come from the CAD annually via EIC-PAC

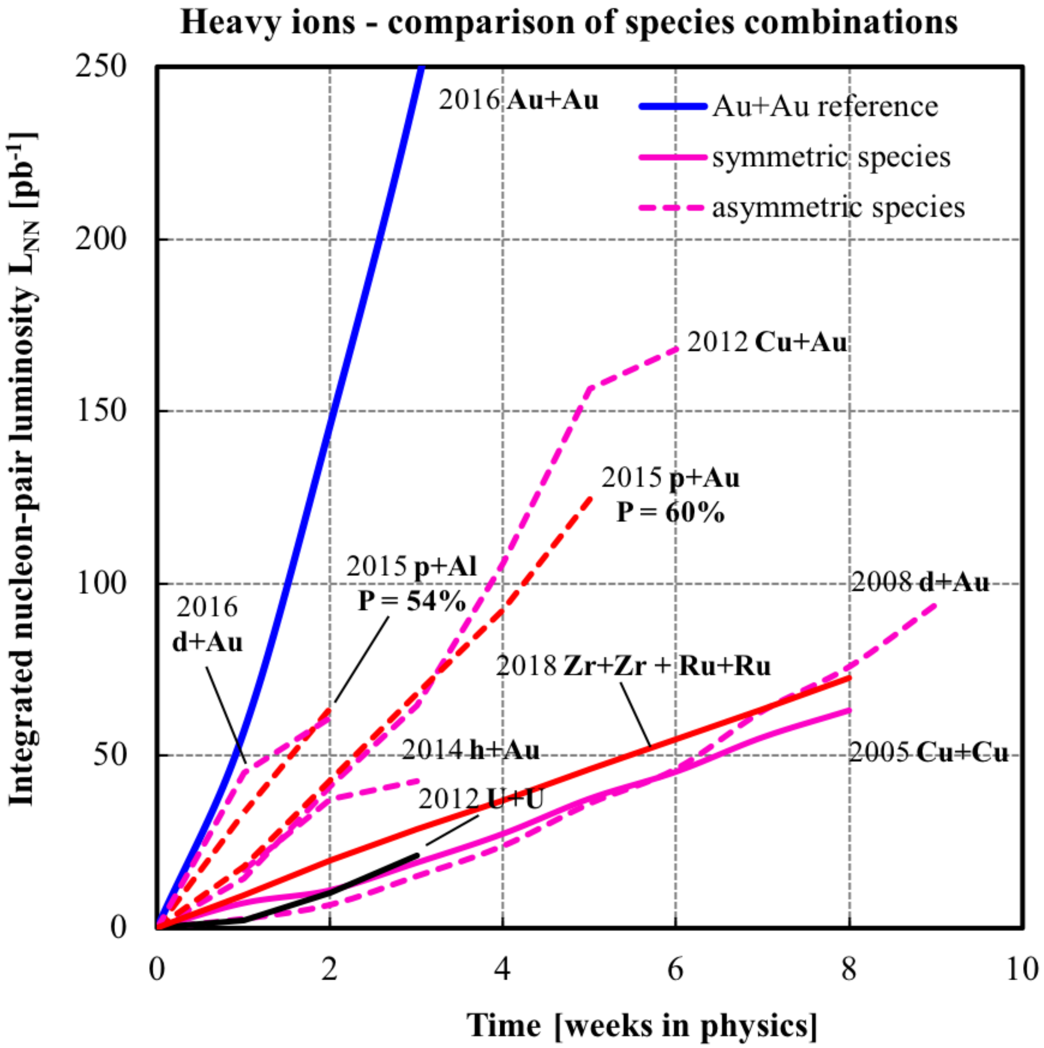
- Based on early operational experience of EIC and
- development of each subcomponent of the EIC including various novel components like
  - crab cavities
  - Beam cooling components….

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 development from EIC/CAD – we should be able to make more concrete proposals for early running – energy, species and physics goals/outcomes.

Lessons: @RHIC Polarized protons harder than nuclei





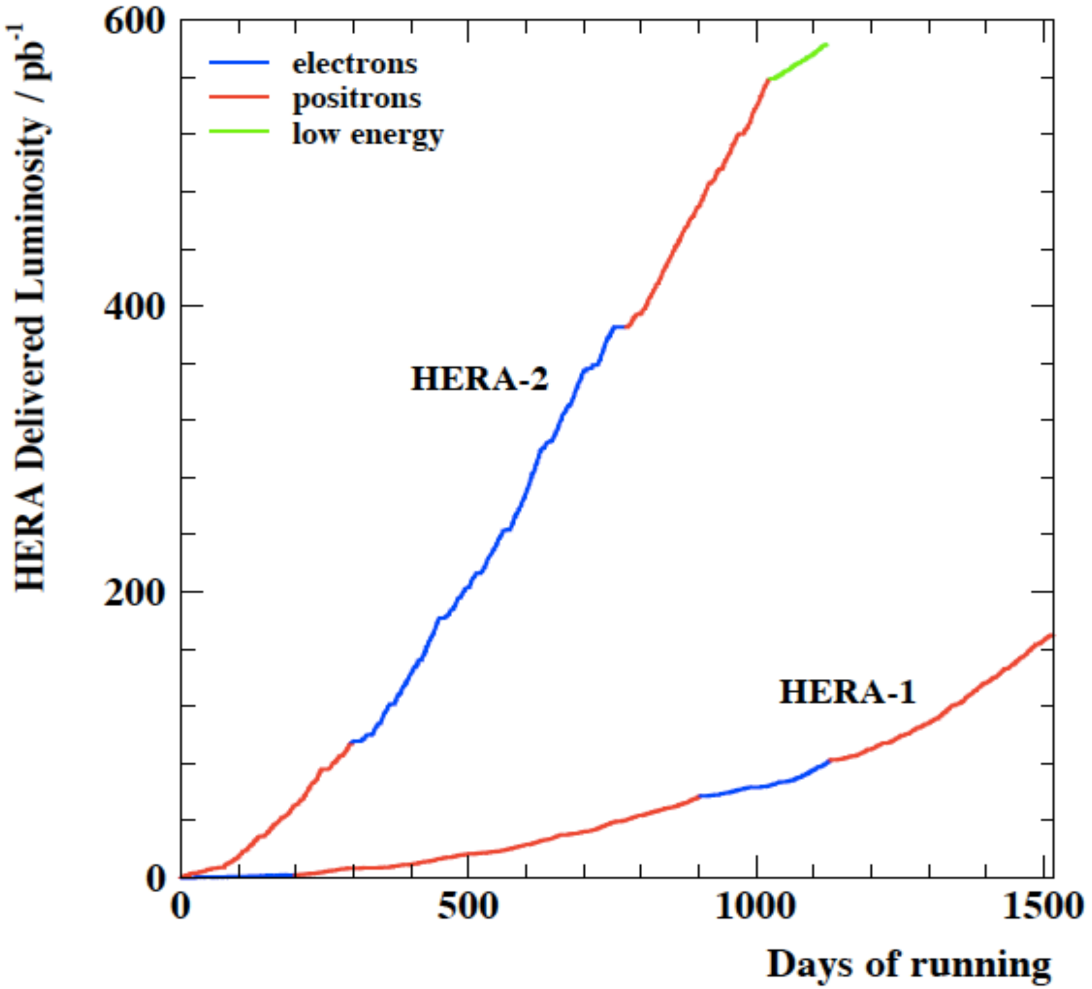
Historical Precedence and lessons:

HERA Experience and lessons: (see the EIC/eRHIC CDR)

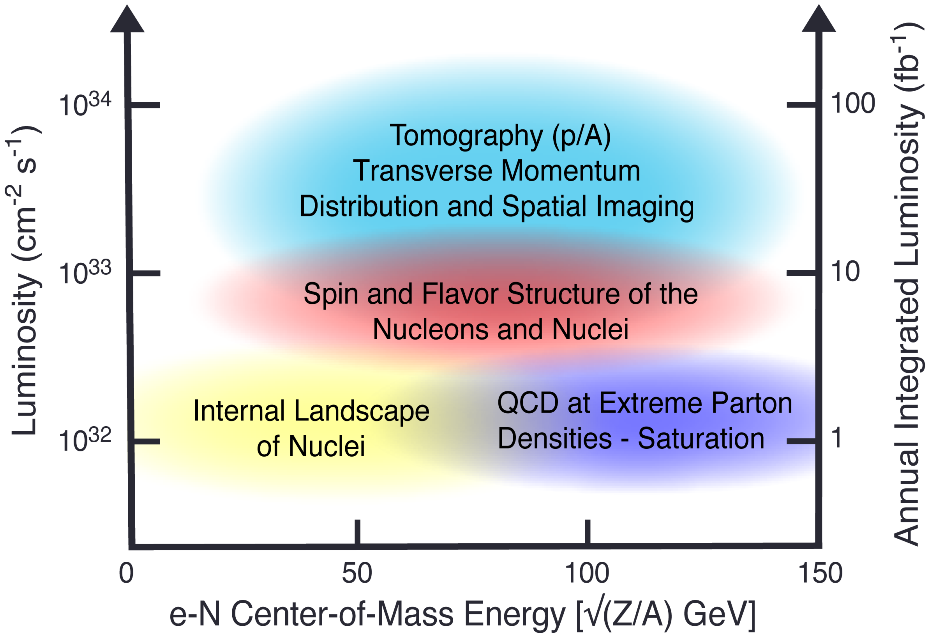
- IR & machine at EIC designed based on lessons at HERA
- HERA highest luminosity ~ 5 x 10^{31} $cm^{-2}sec^{-1}$

Based on those lessons:

- Start of the machine carefully, slow – avoid haste and accidents
- Luminosity development…. beam cooling, frequent beam injection..
  - At EIC new components for the machine: crab-cavity – impact on polarization? Experimental verification?
- Development of polarization (both beams and luminosity) will take time
  - early R&D investments in R&D paid-off at RHIC, follow the model
- Light ion polarization, measurement, T/L spin orientation confirmation



Guiding principle



- Items in the EIC White Paper and supported by NAS ➔ CD0 critical items will get early priority.
- Quick progress on these will become engines of support for more and sustained running of the EIC
- High luminosity and high polarization (in both beams) will take some time 3-5 years

Preliminary thoughts

Time on this slide starts at CD4

I would hope to see about 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 years, and 10^{34} in ~5+ years at 10 x 250 GeV polarized proton operation. (Starting with 50% & ending 70% polarized beams)

- 18 GeV e beam will be experimented with before CD4 (after CD4A) if RF is ready but not "operated for physics" 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.

These coupled with the fact that we would like fast physics results:

- I think we will run e-A physics 10 x 100 GeV beams at the beginning, with highest possible luminosity and
- run at least three nuclei in early (3 years).
- In those years, ample time would be given to develop polarization and luminosity for e-p.

Start EIC physics program hence be:

Begin with electron-Nucleus/Ion Physics: Intermediate energy and high energy operation with different nuclei

- 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, 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 beams should be polarized) ➔ we should be ready to utilize what we/ePIC 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 in the end.

Operational thoughts further….

$L_{e\text{-}p}$~ 10^{33} cm^{-2} sec^{-1} luminosity ➔ ~ 20 fb^{-1}/year including 70% accelerator & detector efficiency

EIC White Paper and Yellow Report assumed these luminosities and hardly any measurement (other than a few in TMDs and GPDs) required more.

- Transverse spin measurements needing only proton (or light ion) beam polarization should be easier to achieve than double longitudinal spin measurements with high e-polarization
- Everyone's favorite measurement will be start happening after the 2^{nd} year with polarized beams and unpolarized nuclear beams.
- If light ion physics needs more (I have seen some plots), we need to make the case strong with details.

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:

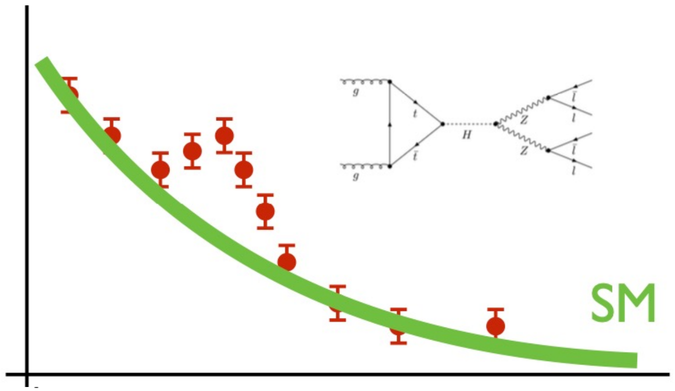
"A Case for an EIC Theory Alliance: Theoretical Challenges of the EIC", R. Abir et al. arXiv: 2305.14572v1

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

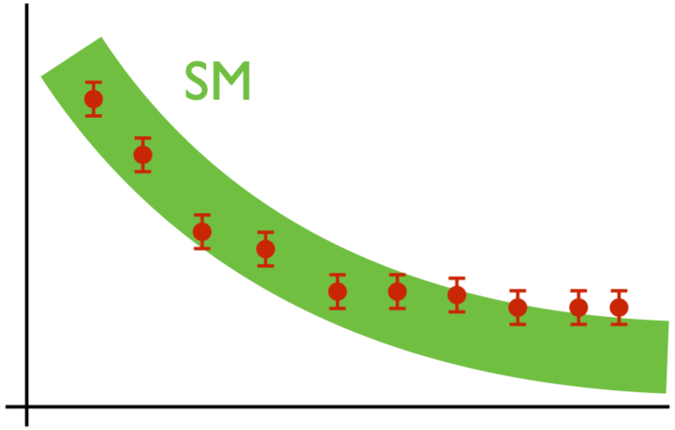
Anticipated precision at the LHC drove higher precision calculations in theory

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



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

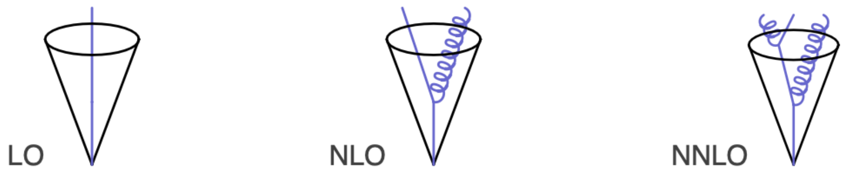
- Most likely look for "new interactions"
- Small deviations from SM : PRECISION
- EFT description / BSM model



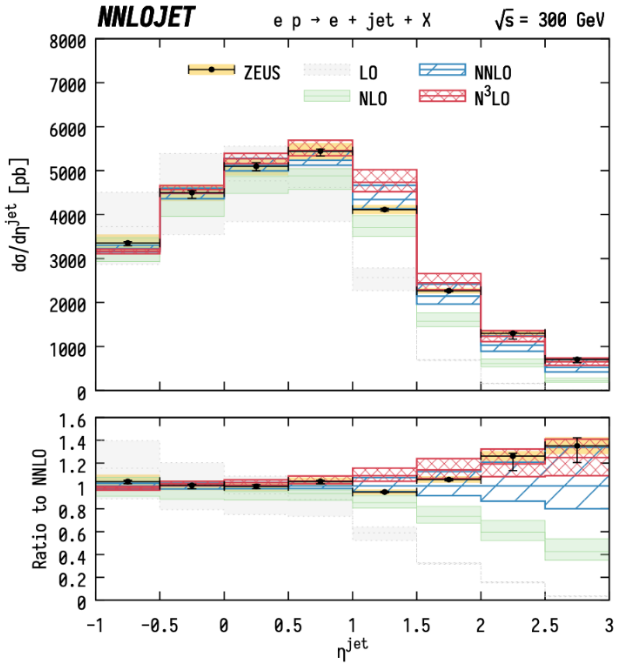
Theory uncertainties HAD to be reduced

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

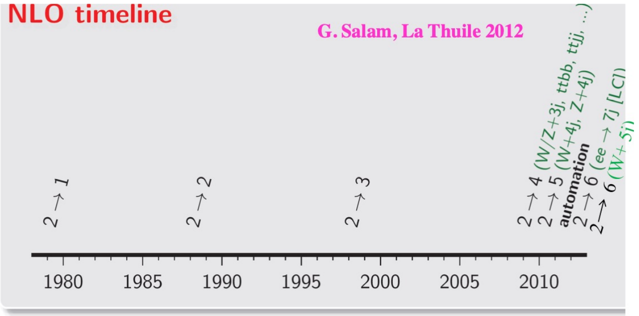
Currie, Gehrmann, Glover, Huss, Niehues, Vogt (2018)

- 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.

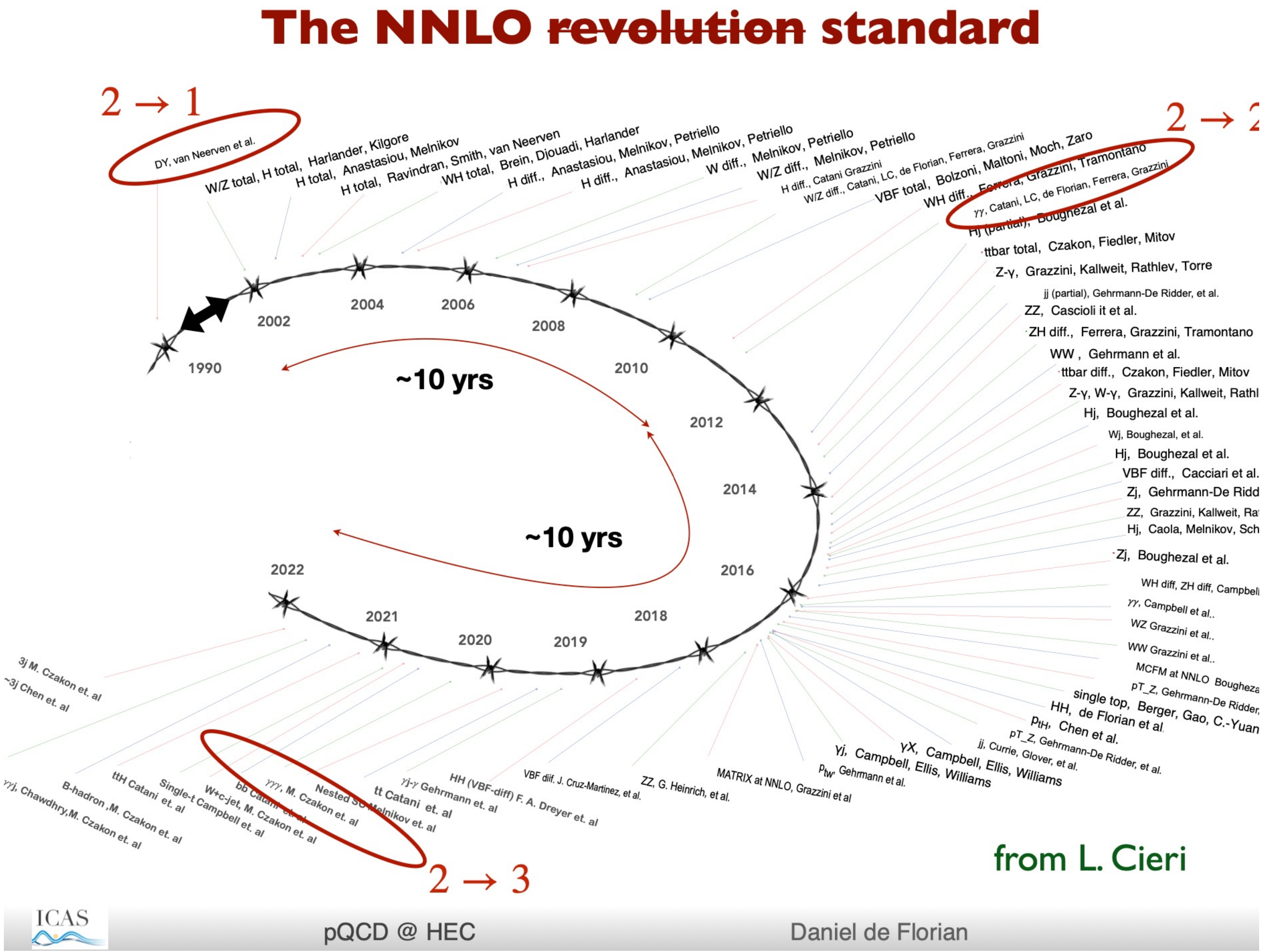
Modern version: with ChatGPT LO tested(?) (Joke!)

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 Copy code

```
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 $Q^2 > \mathrm{GeV}^2$
- Proton structure functions in transition regime $\to$ 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

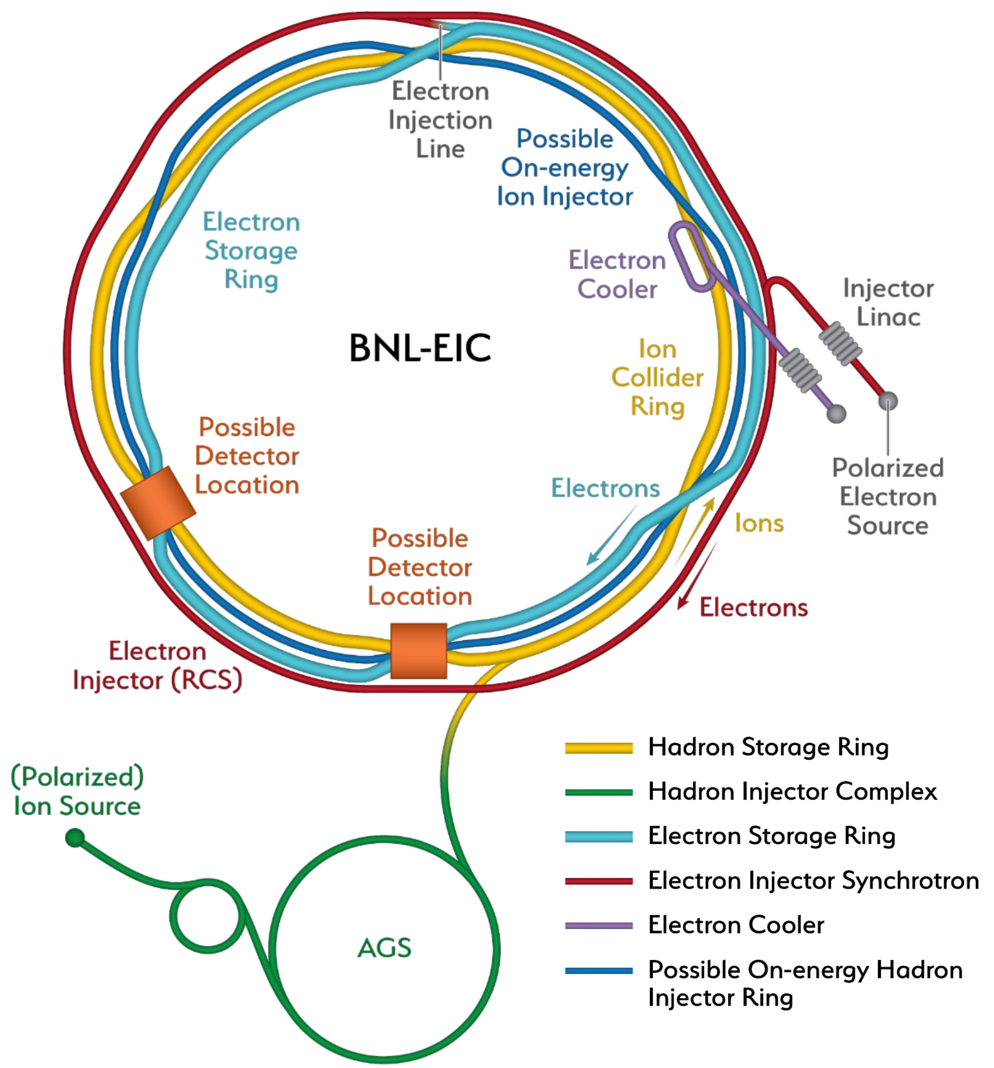
- Amazing progress in fixed order calculations during the last two decades
  - Automation of NLO **Driven by LHC**
  - Several NNLO processes $2 \to 2$ and already a few $2 \to 3$ ✓
  - Even N³LO for simpler kinematics and first set of splitting functions
  - Account for QED/EW effects
- But… Reaching new bottlenecks
- $2 \to 3$ (Massive) 2-loop amplitudes complicated beyond leading color
- Real radiation far from trivial (numerical infrared treatment)
- N³LO 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 ~N³LO might be the new standard!

ICAS pQCD @ HEC Daniel de Florian 24

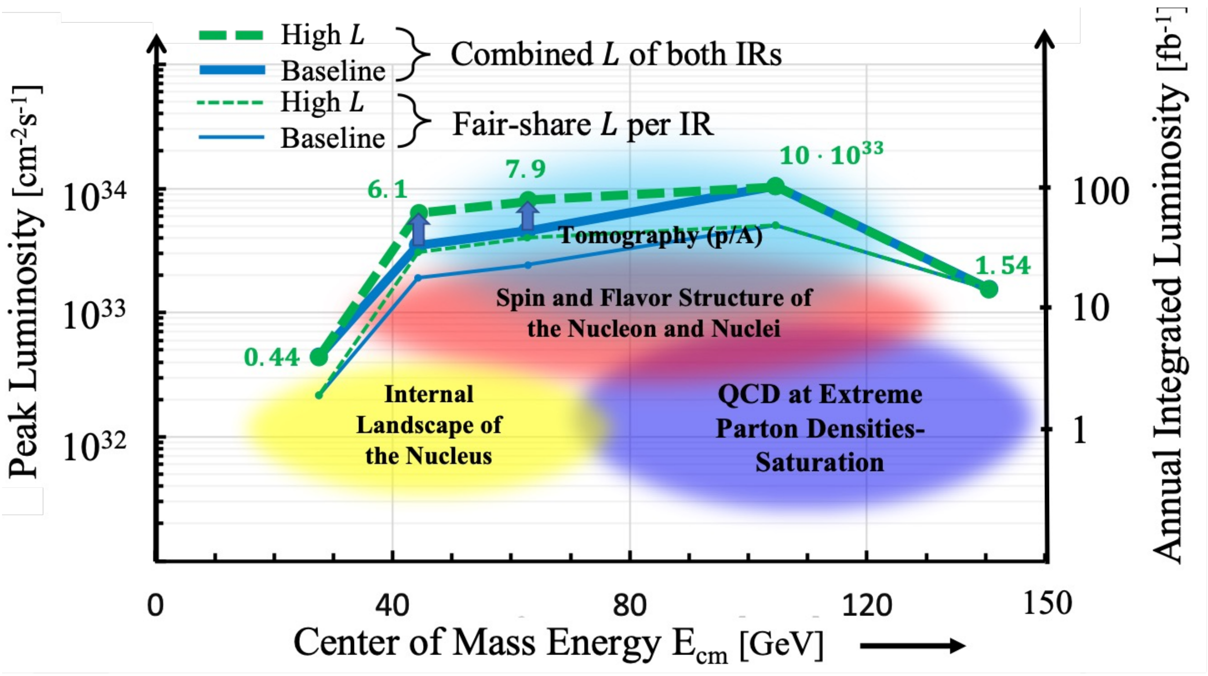
An enormous thrust in precision calculations in Theory including already emerging precision in Lattice QCD is needed in the next ~10 years before or around the same time the EIC data will become available

Item 4:
EIC would be incomplete without the 2^{nd} IR and a detector

EIC Accelerator Design



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!



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

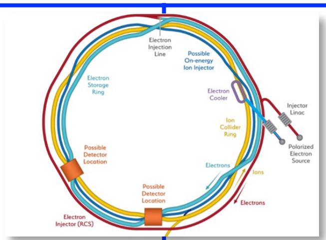
While EIC project (machine and 1st detector) have to succeed….

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

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	ring outside to inside
	tunnel and assembly hall are larger Tunnel: ⃠ 7m +/- 140m	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

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)

Vision for the 2nd detector: C^3

- 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 (some-exclusive to 2nd IR, some-overlapping) exists: 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

Center for Frontiers in Nuclear Science

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)

Remarks:

- EIC project's path is well understood. Its success is paramount.
- 2^{nd} detector is essential for completing the Vision of EIC
  - C^3 : Complementary physics, technology and people
- It is time to march forward developing a design and case for the 2^{nd} detector: Detailed studies through series of workshops, outreach and critical evaluation for each developing argument ➔ Plan an INT-Program in ~2025 like we had in 2010

I look forward to discussions on any and all fronts for the 2^{nd} detector development.

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.

Thank you