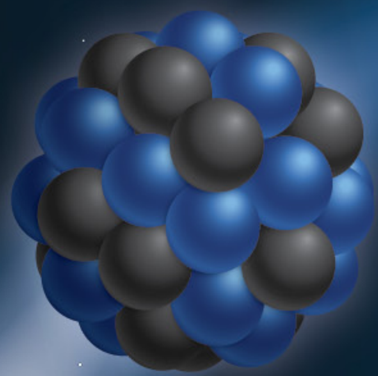
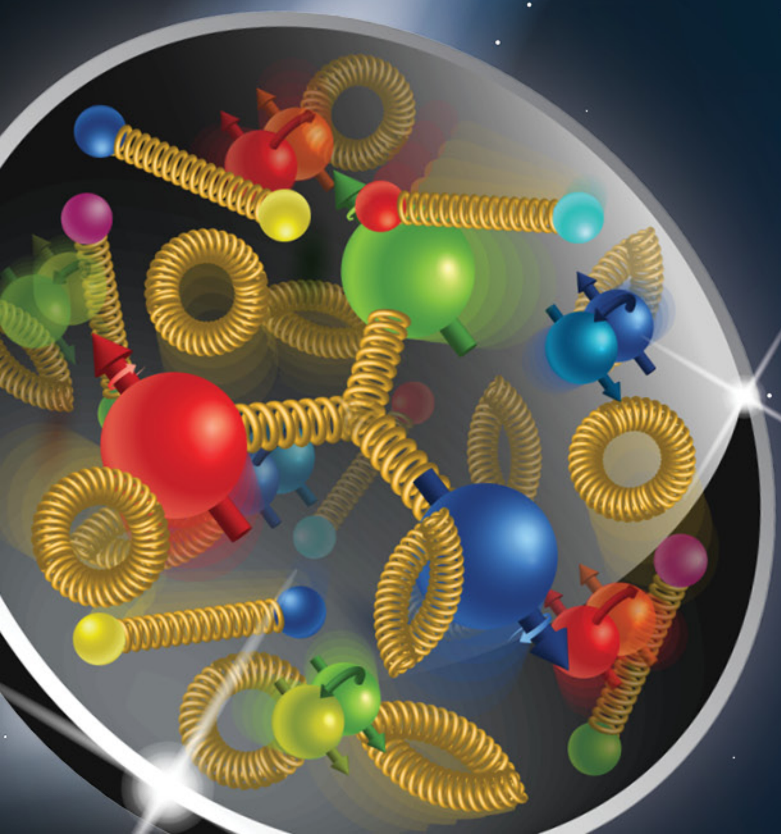




EIC Science

Y.Furletova (JLAB)

RHIC & AGS

Annual Users' Meeting 2020

Thanks to E.C. Aschenauer (BNL), R. Ent (JLab)
and EIC UG community

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY   Jefferson Lab   U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- ❑ Introduction
- ❑ EIC accelerator
- ❑ EIC physics
- ❑ EIC UG activity
- ❑ Summary

" EIC HF Overview " Ivan Vitev
"EIC Cold QCD Future Physics Program" Andreas Metz
"Jet Measurements at the EIC" Felix Ringer

Introduction

2002 Long-range plan (LRP)

2010 INT Workshop

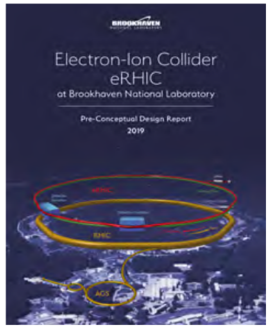
2012 White Paper

2015 Long-range plan

2018 NAS review

2019 Two accelerator proposals

eRHIC(BNL) JLEIC (JLAB)



January 9, 2020

DOE CD-0 and Site selection

Work towards CD-1

Time

Now

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

January 9, 2020

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory will provide crucial infrastructure for the new Electron Ion Collider. + ENLARGE

WASHINGTON, D.C. – Today, the U.S. Department of Energy (DOE) announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

EICUG Yellow Book (physics/ detector)

Our Mission

- ❑ **Where did we come from?**

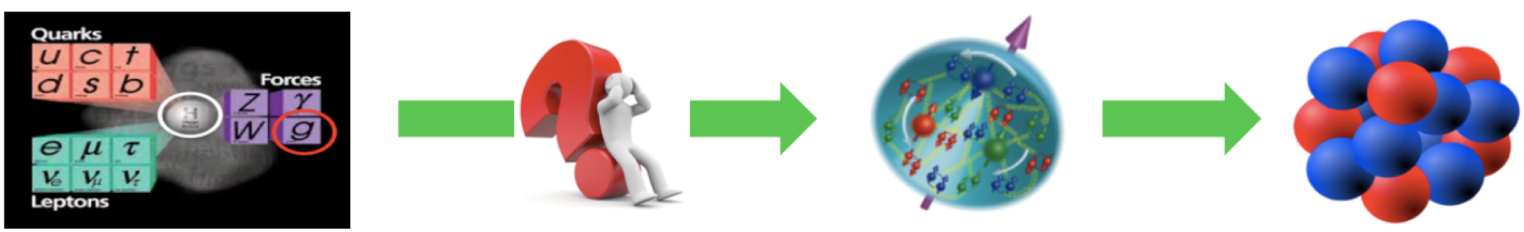
Global Time: →

How did hadrons are emerged from the energy, the quarks and gluons?

- ❑ **What are we made of?**

What is the internal structure and dynamics of hadrons?

- ❑ **What holds us together?**



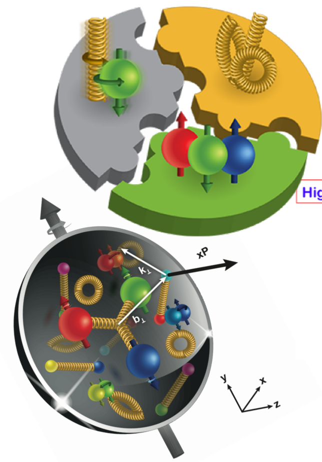
How does the glue bind us all?

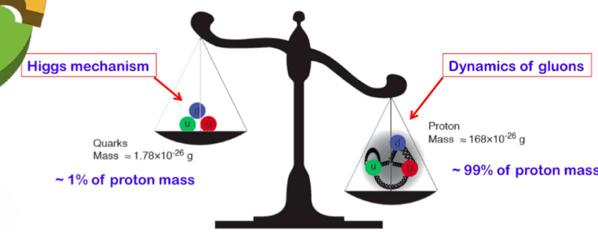
Jianwei Qiu (DIS2018)

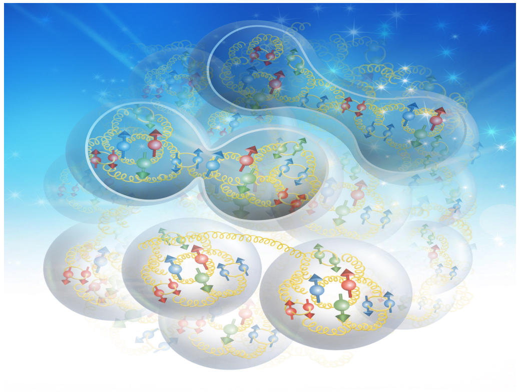
EIC physics

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?







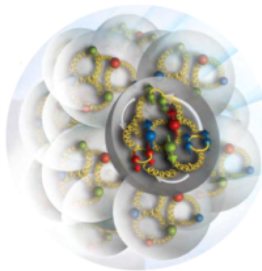
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

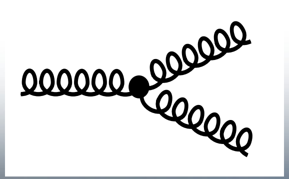
How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

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?

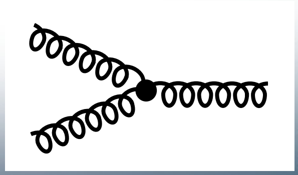


gluon emission

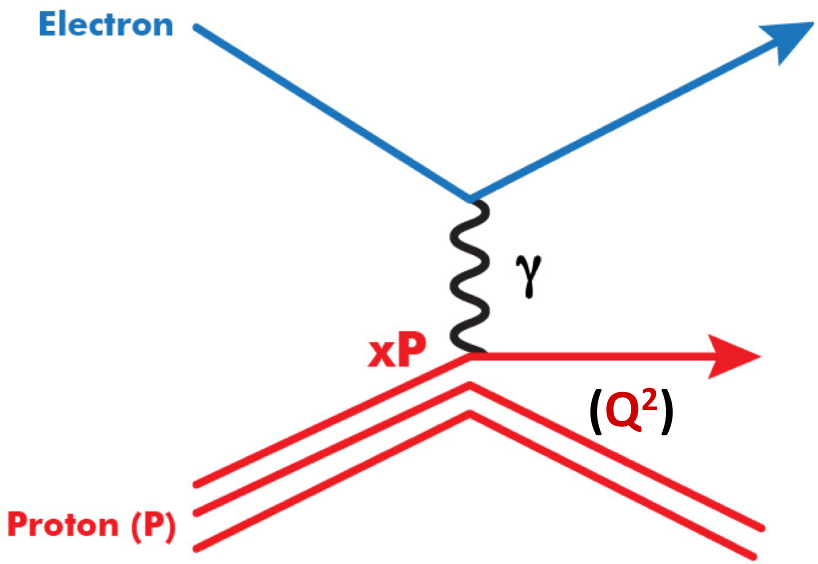


?
=

gluon recombination



Deep inelastic scattering

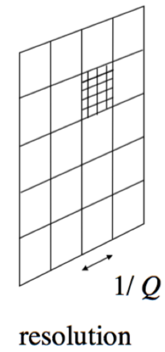


Q^2=-q^2 : 4-momentum transfer squared

x (0<x<1) - fraction of proton momentum carried by the struck quark

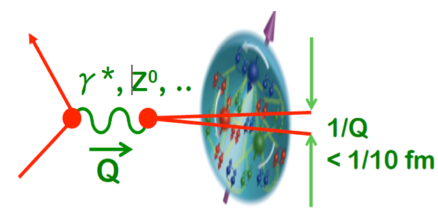
y (0<y<1)=(Ee-Ee')/Ee - fractional energy transfer

Ability to change **Q^2** changes the resolution scale

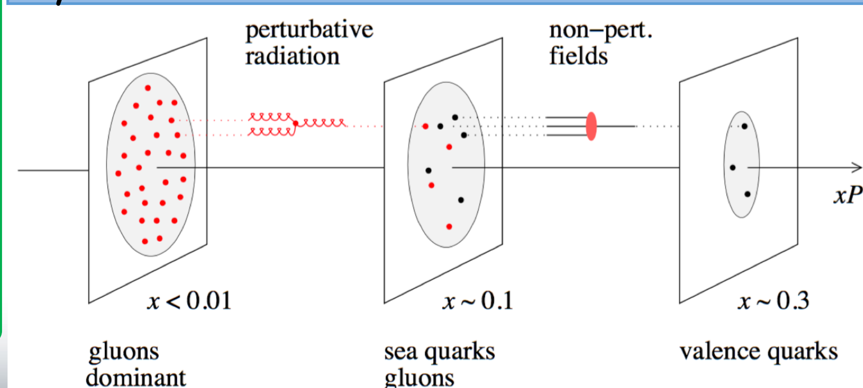


Q^2 = 400 GeV^2

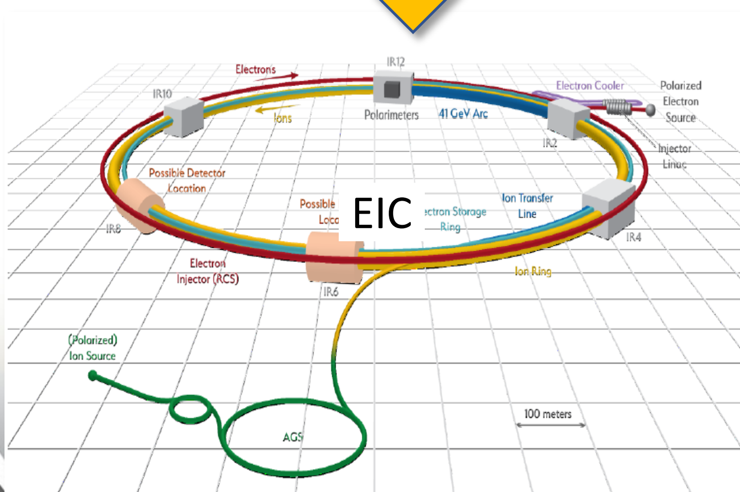
=> 1/Q = 0.01 fm



Ability to change **x** projects out different configurations where different dynamics dominate



From RHIC to EIC



Design based on **existing** RHIC,
RHIC is well maintained, operating at its peak

Hadron storage ring 40-275 GeV (existing)
- Many bunches
- Bright beam emittance
- Need strong cooling **or** frequent injections

Electron storage ring (2.5–18 GeV (new))
- Many bunches,
- Large beam current (2.5 A) ➔ 10 MW S.R. power

Electron rapid cycling synchrotron (new)
- 1-2 Hz
- Spin transparent due to high periodicity

High luminosity interaction region(s) (new)
- L = $10^{34}cm^{-2}s^{-1}$
- Superconducting magnets
- 25 mrad Crossing angle with crab cavities
- Spin Rotators (longitudinal spin)
- Forward hadron instrumentation
- Up to 2 interaction regions

EIC capabilities

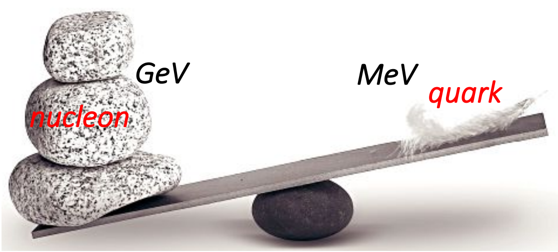
- ✓ DIS facility
- ✓ Nuclear beams A = 2–208
- ✓ CM energy $\sqrt{s}$ (eN) ~ 20–140 GeV
- ✓ Luminosity L ~ 10^{34} cm^{-2} s^{-1}
- ✓ polarized lepton & hadron beams (up to 70%)
- ✓ Next generation of detectors

⟺

- ➢ control of the kinematic
- ➢ first eA collider in the world !
- ➢ wide coverage for Q^2, x_B ; Include non-perturbative, perturbative and transition regimes. overlap with existing measurements
- ➢ high precision physics; rare processes; various measurements/configurations: (different ions, different center of mass energies, different polarizations)
- ➢ Spin properties and spin dependences
- ➢ final states

Mass of the Proton, Pion, Kaon

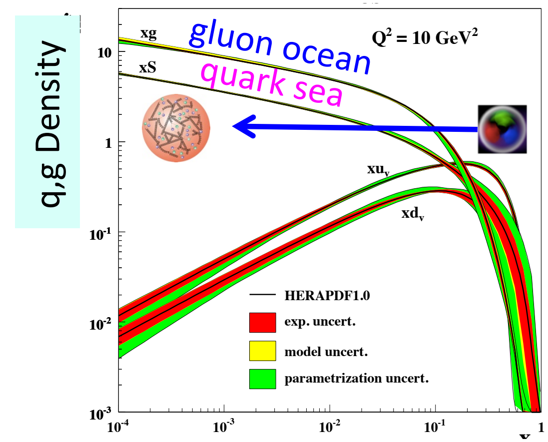
Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions.



Proton

Quark structure: uud
Mass ~ 940 MeV (~1 GeV)
Most of mass generated by dynamics.

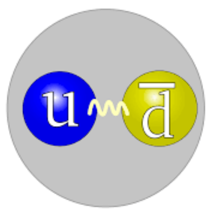
Gluon rise discovered by HERA e-p



Fraction of overall proton momentum carried by q,g

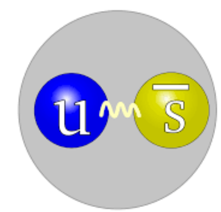
Pion

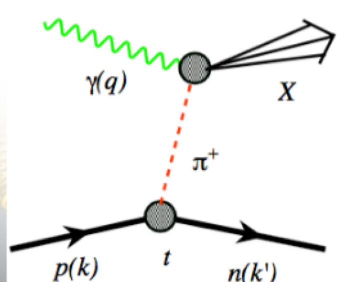
Quark structure: ud
Mass ~ 140 MeV
Exists only if mass is dynamically generated.
Empty or full of gluons?



Kaon

Quark structure: us
Mass ~ 490 MeV
Boundary between emergent- and Higgs-mass mechanisms.
More or less gluons than in pion?





For the proton the EIC will allow determination of an important term contributing to the proton mass, the so-called "QCD trace anomaly"

For the pion and the kaon the EIC will allow determination of the quark and gluon contributions to mass with the Sullivan process.

The Spin of the Proton

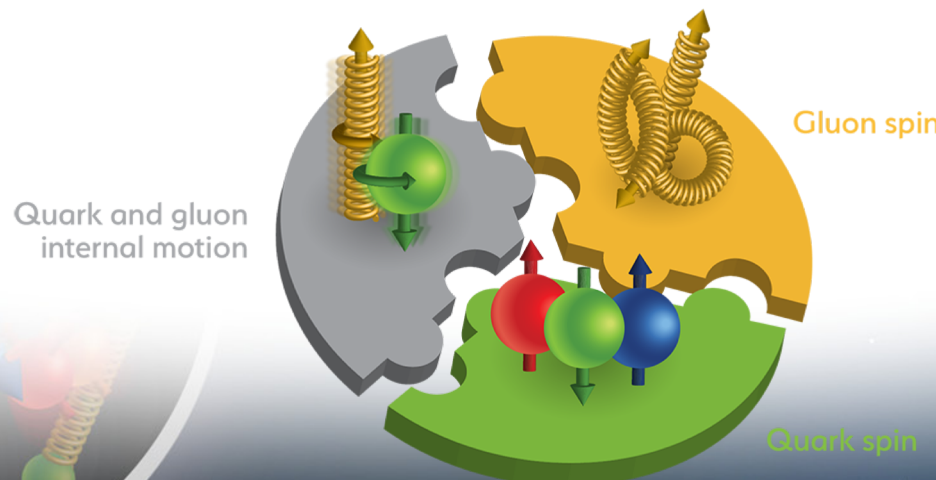
SPIN is one of the fundamental properties of matter
all elementary particles, but the Higgs carry spin
Spin cannot be explained by a static picture of the proton

It is more than the number $\frac{1}{2}$! It is the interplay between the intrinsic properties and interactions of quarks and gluons

What do we know:

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}\right| J^z_{QCD} \left| P,\frac{1}{2}\right\rangle = \overbrace{\frac{1}{2}\int_0^1 dx\Delta\Sigma(x,Q^2)}^{\text{total quark spin}} + \overbrace{\int_0^1 dx\Delta G(x,Q^2)}^{\text{gluon spin}} + \overbrace{\int_0^1 dx(\sum_q L_q^z + L_g^z)}^{\text{angular momentum}}$$

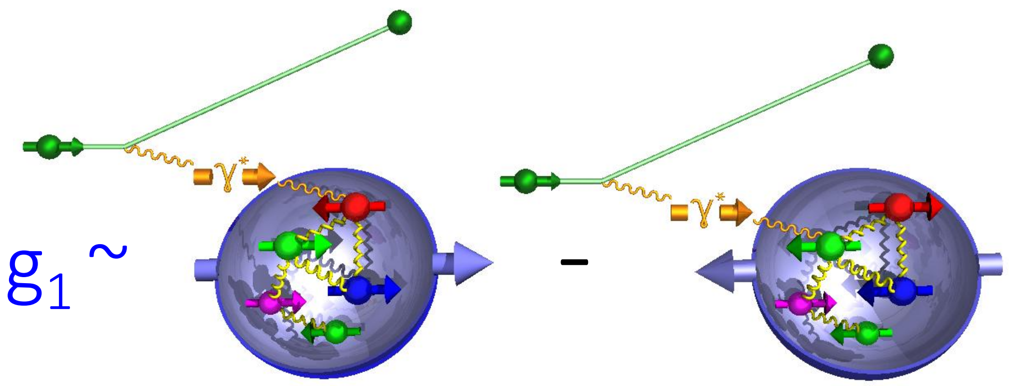
~ 30% ~ 40% ~?

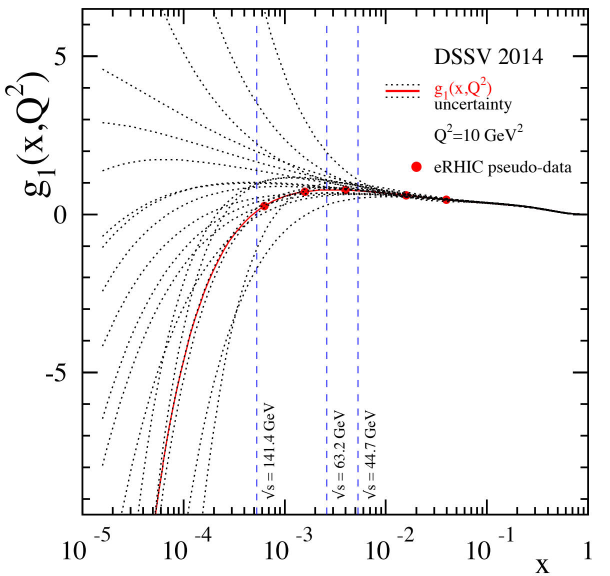


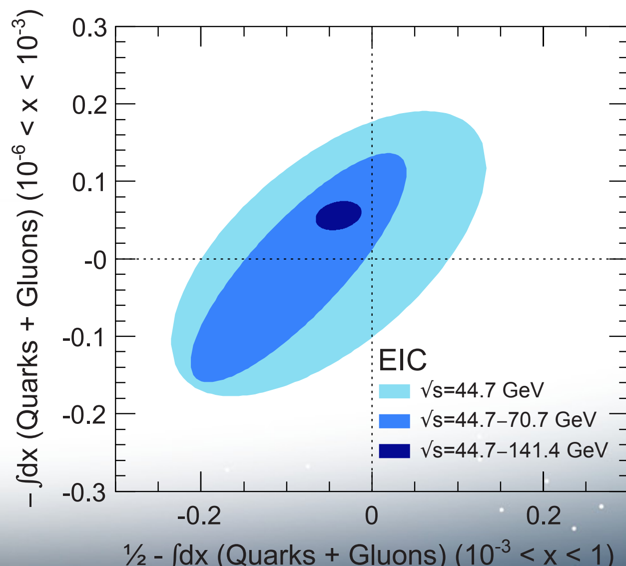
EMC found:
$\Delta\Sigma = 0.12 \pm 0.17$ ~ 30%

The Spin of the Proton

The current knowledge about g_1 as function of x at Q^2=10 GeV^2







quark contribution:

The integral of g_1 over x from 0 to 1

gluon contribution:

$dg_1(x,Q^2)/dlnQ^2 \rightarrow \Delta g(x,Q^2)$

3-Dimentional imaging

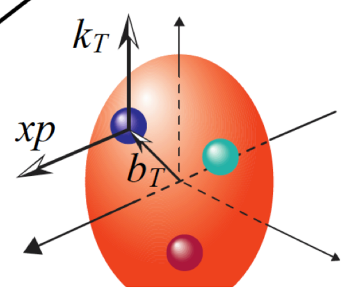
Wigner functions $W(x,b_T,k_T)$

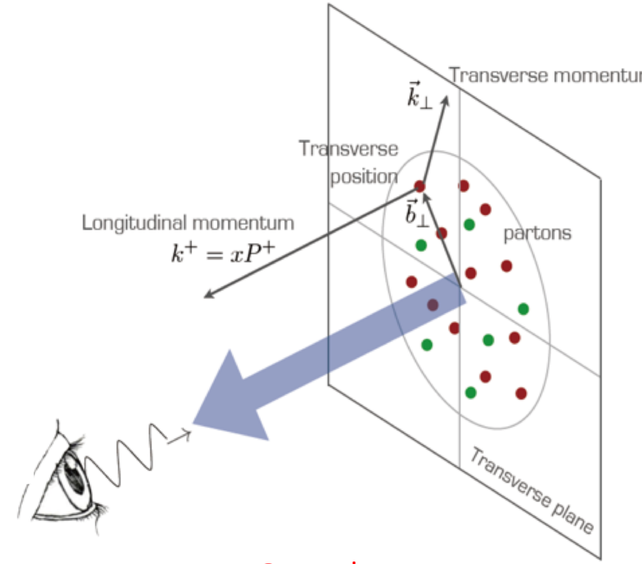
offer unprecedented insight into confinement and chiral symmetry breaking.

$$W(x,b_T,k_T)$$

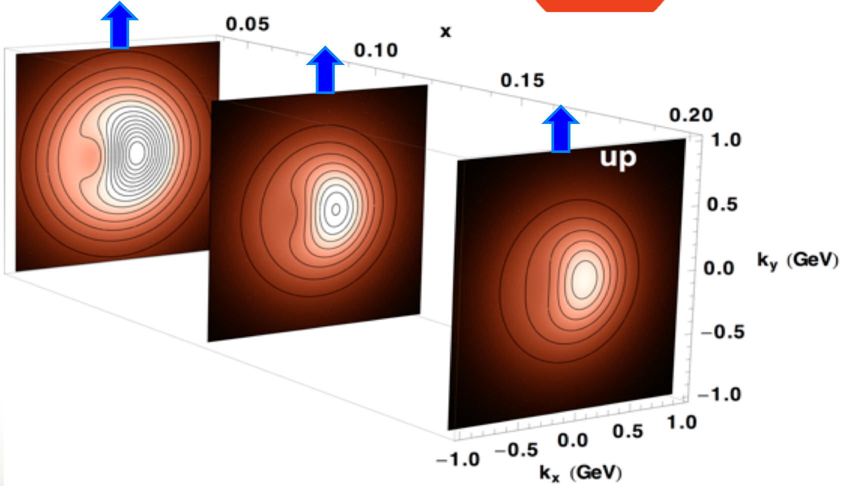
Momentum space $\int d^2b_T$ → $f(x,k_T)$

Coordinate space $\int d^2k_T$ → $f(x,b_T)$

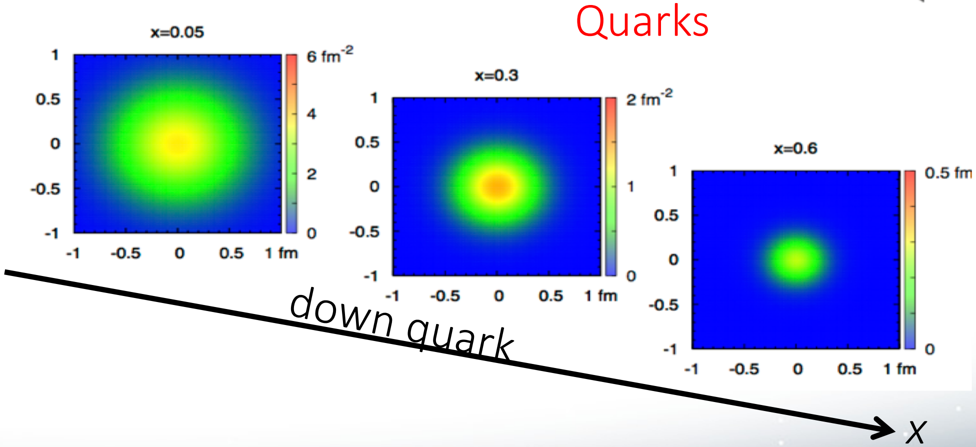




Quarks



Quarks



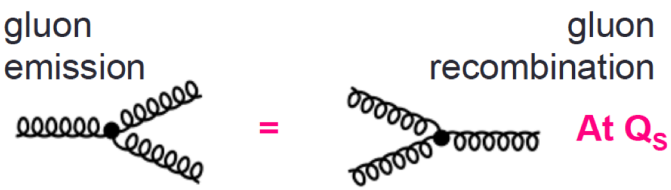
Spin-dependent 3D momentum space images from semi-inclusive scattering

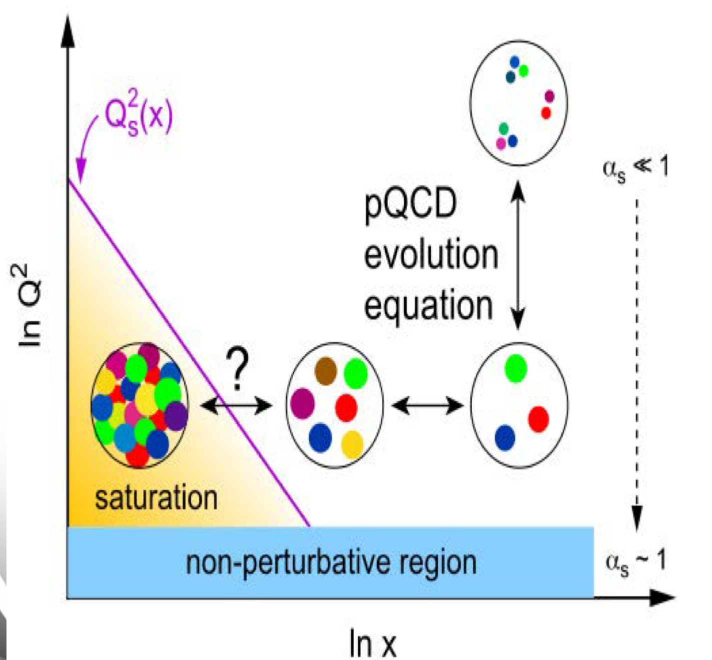
Spin-dependent 2+1D coordinate space images from exclusive scattering

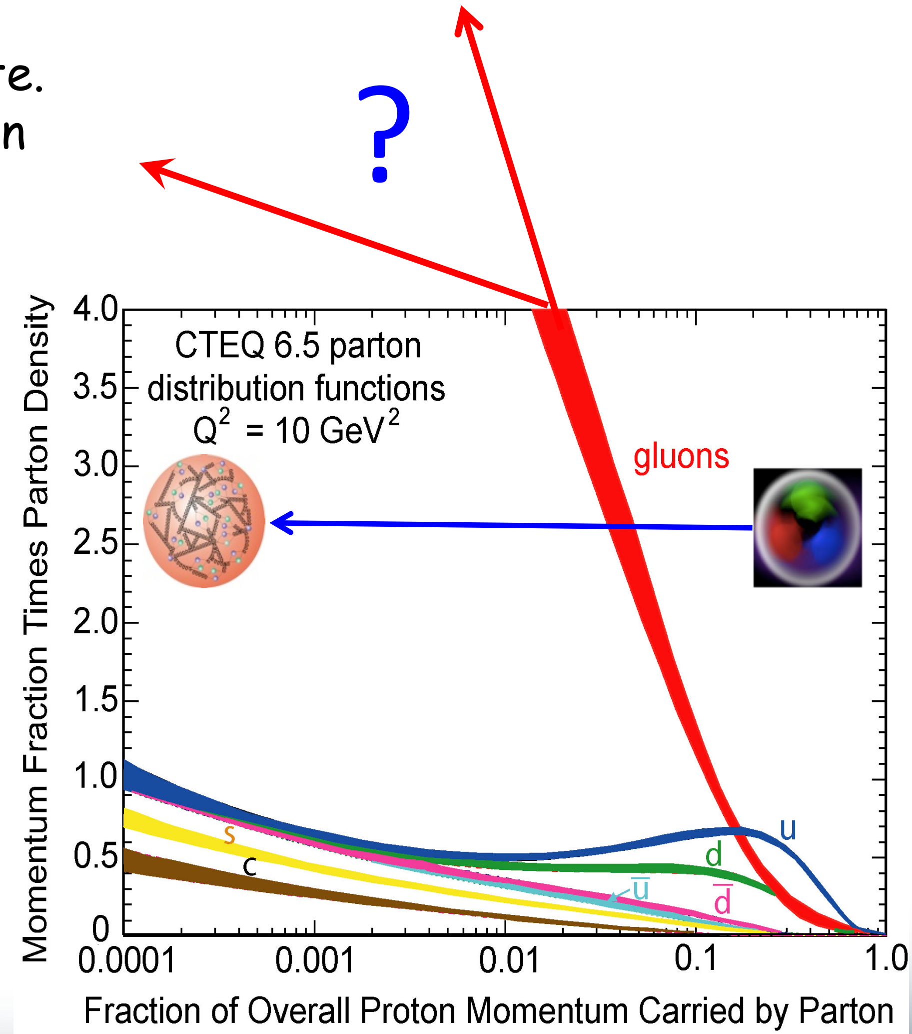
Extreme Parton Densities

Low-x

At very low x, cross-section will saturate.
could be investigated in transition region



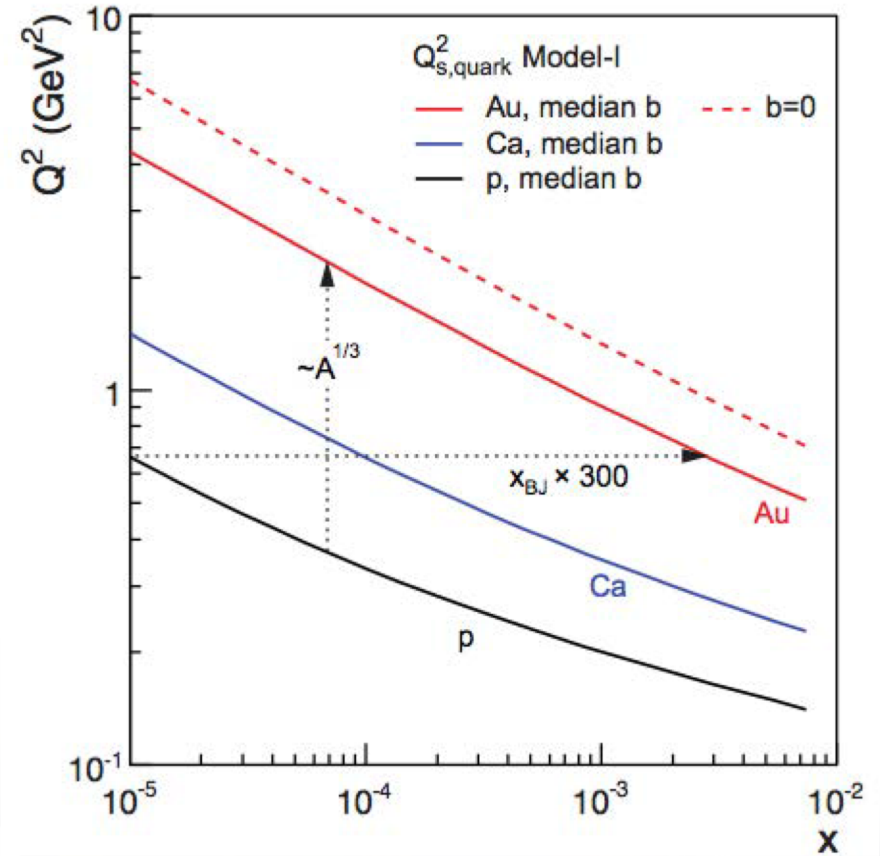




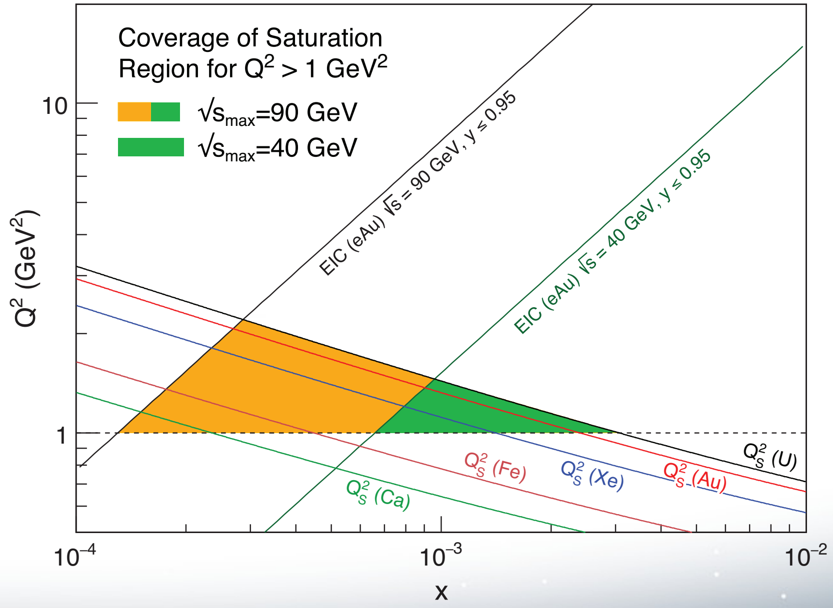
Extreme Parton Densities

Low-x

Saturation regime reached at significantly lower energy in nuclei



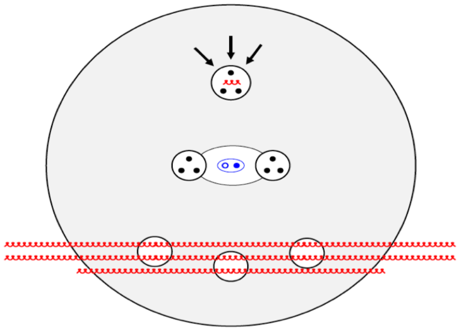
EIC will allow to unambiguously map the transition from a non-saturated to saturated regime



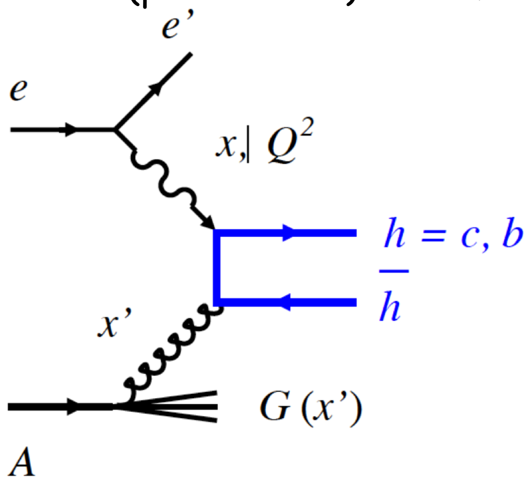
Gluon density and nucleon interactions

High-x

Nucleon interactions

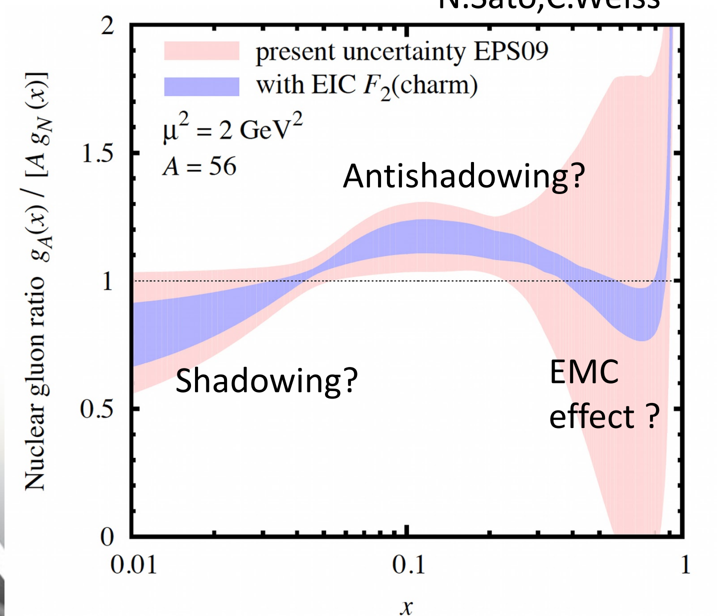


Boson (photon or Z) Gluon Fusion (BGF)



Heavy quark production probes large-x' gluons "almost locally" at $x'_{glue} \geq x_{BJ}\,(1+4m_h^2/Q^2)$

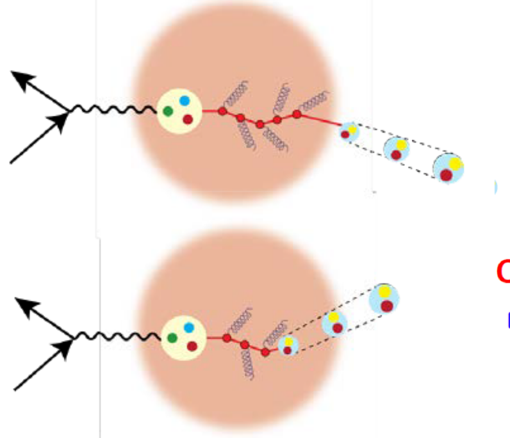
N.Sato,C.Weiss

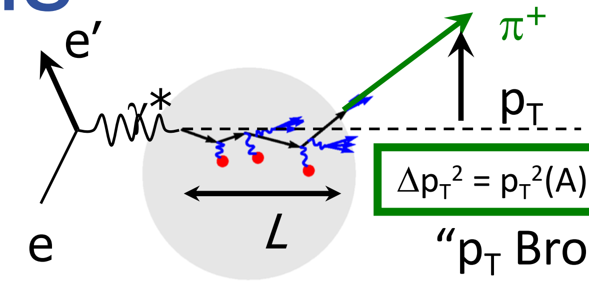


- x > 0.3 "EMC effect"
  Modified single-nucleon structure? Non-nucleonic degrees of freedom?
- x ~ 0.1 "Antishadowing"
  QCD structure of pairwise NN interaction, exchange mechanisms
- x < 0.01 "Shadowing"
  QM interference, collective gluon fields

Emergence of hadrons

(colored) quark passing through cold QCD matter emerges as color-neutral hadron.





$\Delta p_T^2 = p_T^2(A) - p_T^2(^2H)$

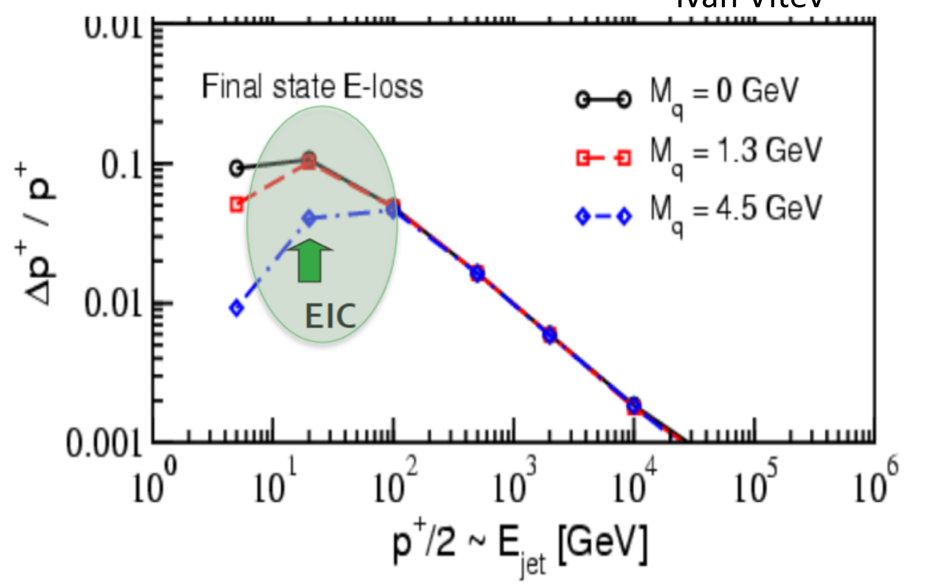
"p_T Broadening"

$$\nu = \frac{Q^2}{2mx}$$

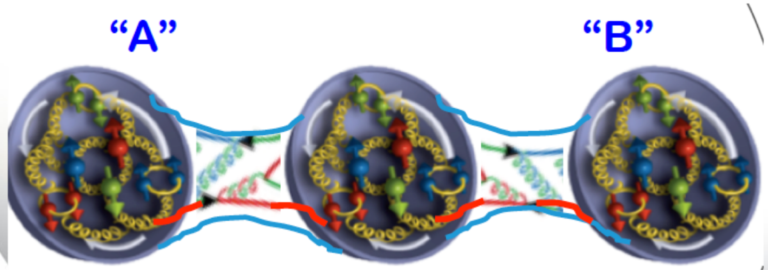
Control of ν and medium length!

Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter: Connect to energy loss in Hot QCD

Ivan Vitev

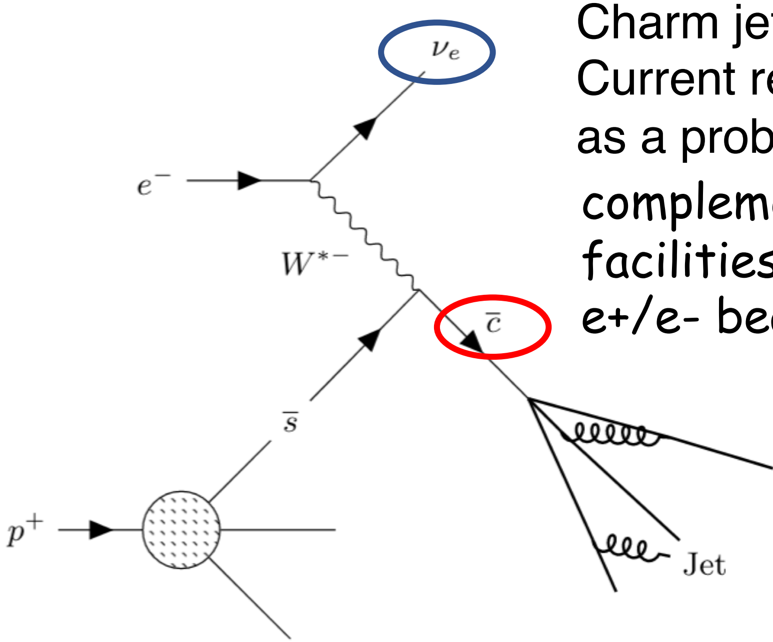


➢ What does a nucleus look like?
Does the color of "A" know the color of "B"



Need the collider energy of EIC and its control on parton kinematics!

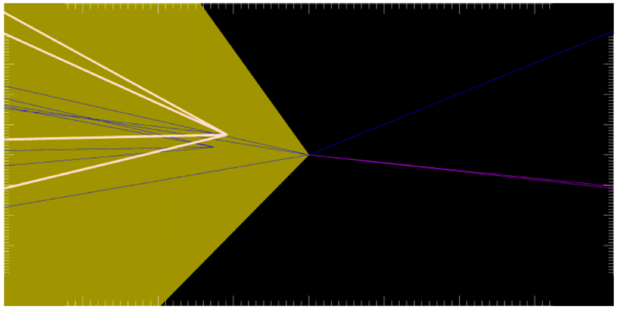
Electroweak physics at EIC

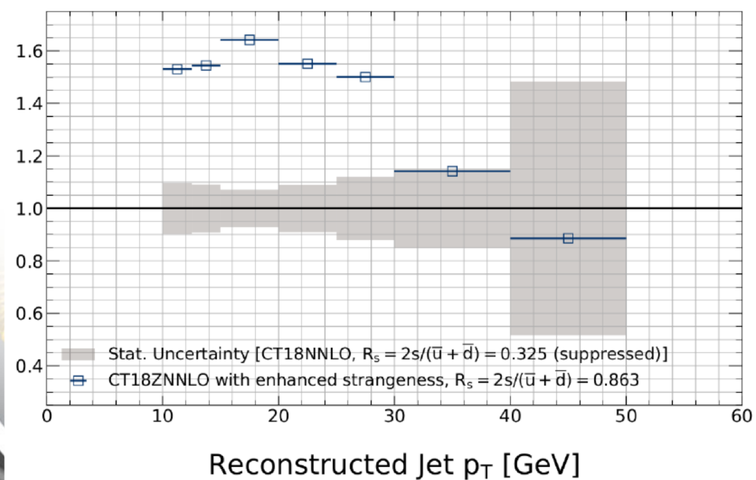


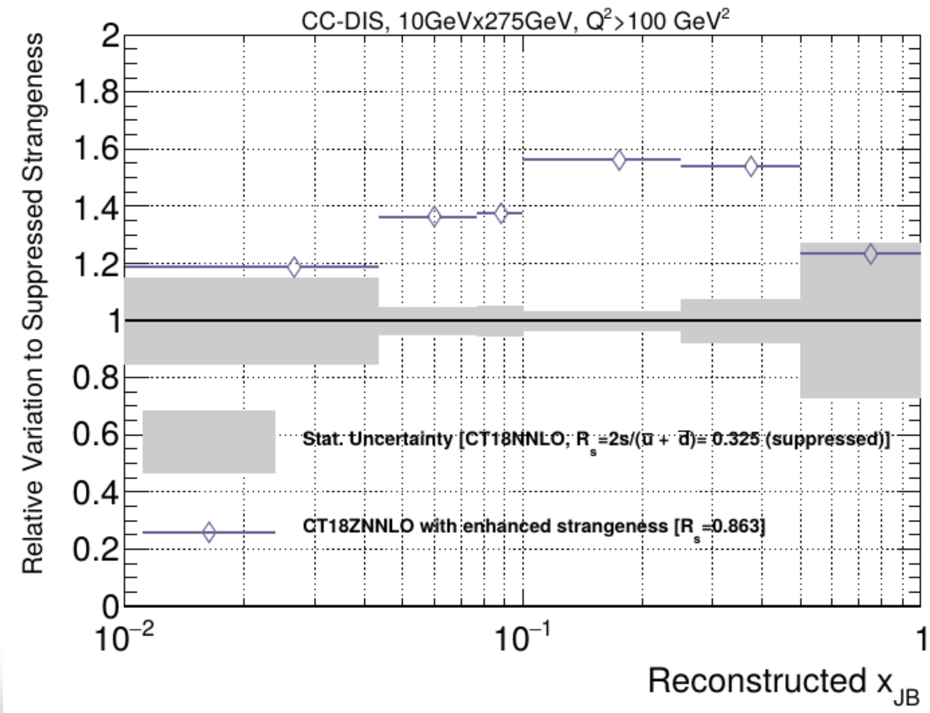
Charm jets in the Charged Current reactions as a probe for strangeness

complementary to neutrino facilities (νN).

e+/e- beams => s/s-bar

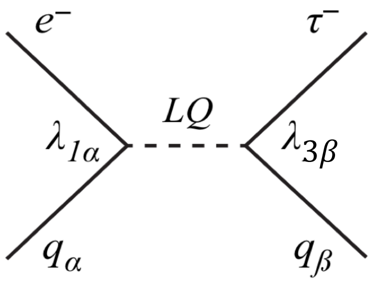


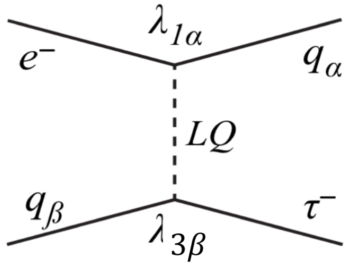




M. Arratia, Y.Furletova,T. J. Hobbs, F. Olness and S. Sekula

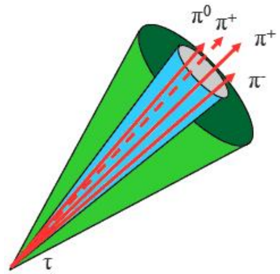
Charged Lepton Flavor Violation

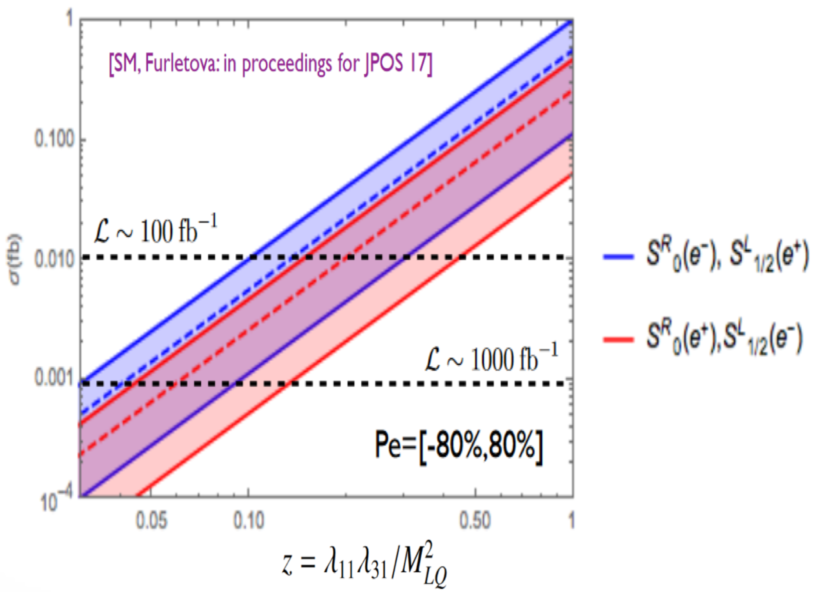




via Leptoquark or parity-violation ,...

Tau-Jets

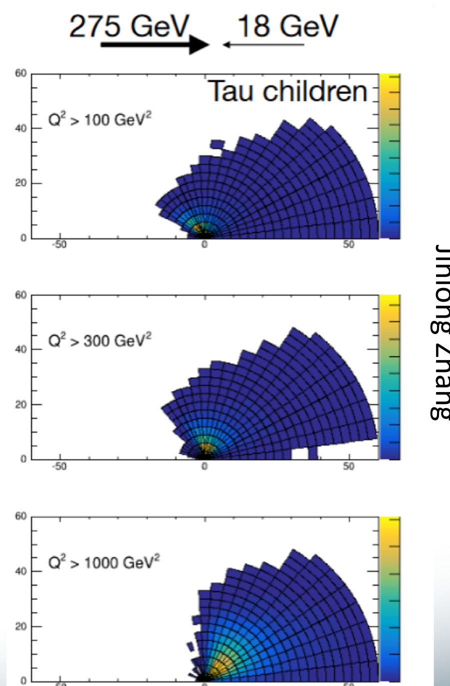




Tau decay mode and branching ratio

- **3-prong** **15.21 (0.06)%**
  - $\pi^-\pi^+\pi^-\nu_\tau$ 9.31 (0.05)%
  - $\pi^-\pi^+\pi^-\pi^0\nu_\tau$ 4.62 (0.05)%
  - others (kaon, etc) 1.28%
- **1-prong** **84.58 (0.06)%**
  - $\mu^-\bar{\nu}_\mu\nu_\tau$ 17.39 (0.04)%
  - $e^-\bar{\nu}_e\nu_\tau$ 17.82 (0.04)%
  - $\pi^-\nu_\tau$ 10.82 (0.05)%
  - $\pi^-\pi^0\nu_\tau$ 25.49 (0.09)%
  - $\pi^-2\pi^0\nu_\tau$ 9.26 (0.10)%
  - $\pi^-3\pi^0\nu_\tau$ 1.04 (0.07)%
  - others (kaon, etc) 3.24%
- others 0.21%

- **Tau vertex displaced at cm level**
  - 3-prong tau jet; decay topology important for τ jet ID
  - 1-prong: recovering higher branching ratios; but background control is much more demanding

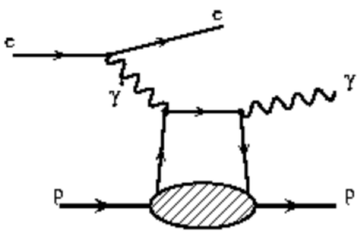


Angle for theta, radius for momentum

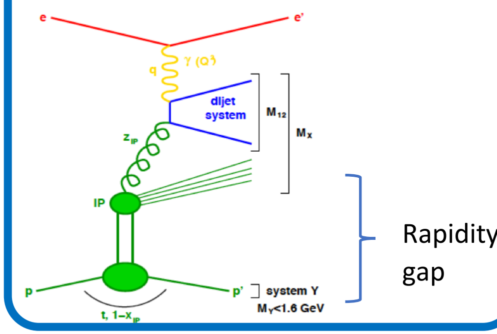
- Current limits set by HERA sitting at sensitivities of a few fb. The high luminosity of the EIC will gain us 2 orders of magnitude
- Polarization, electron/positron beam, proton vs deuteron

Far-forward physics at EIC

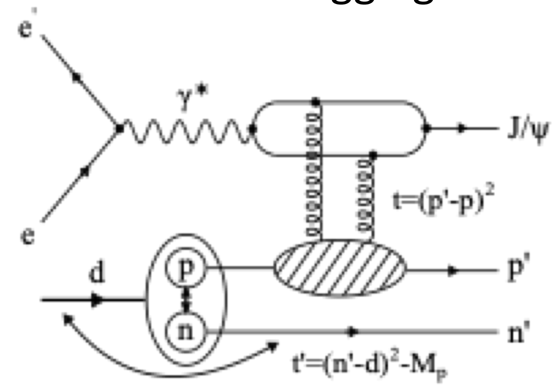
- e+p DVCS events with proton tagging



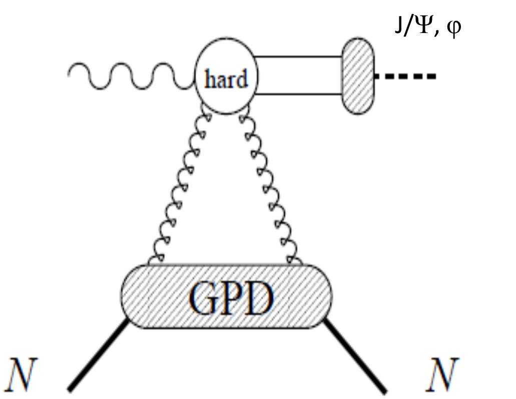
- Diffraction



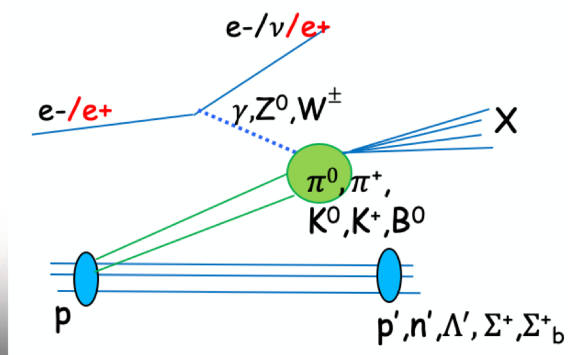
e+d exclusive J/Psi events with proton or neutron tagging



- Saturation (coherent/incoherent J/ψ production)



- Meson structure:
  - with neutron tagging (ep→ (π) →e' n X) .
  - Lambda decays ($\Lambda \rightarrow p\pi^-$ and $\Lambda \rightarrow n\pi^0$)



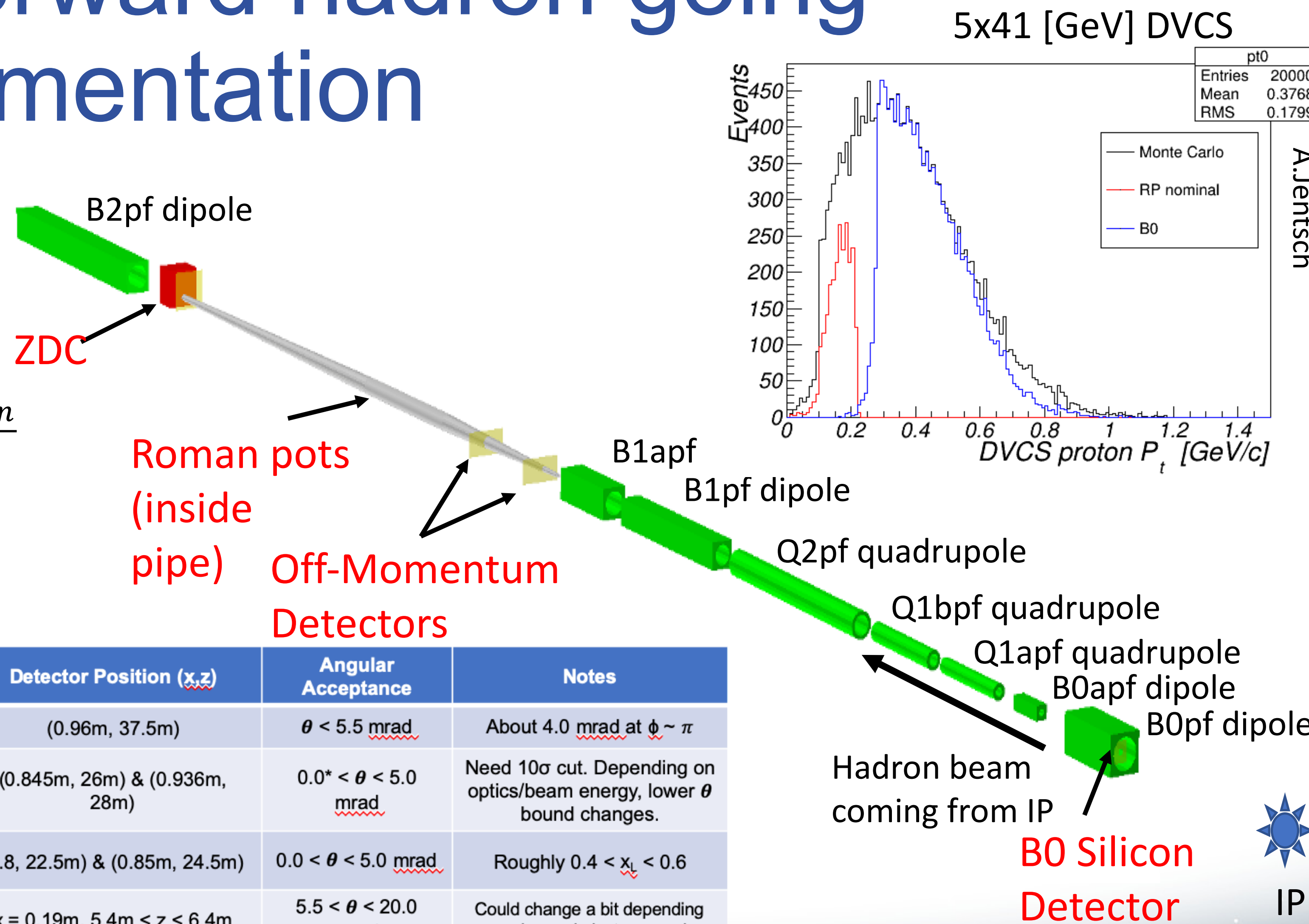
e+He3 with spectator proton tagging.

e+He4 coherent He4 tagging.

e+Au events with neutron tagging to veto breakup and photon acceptance.

….

Far-forward hadron going instrumentation

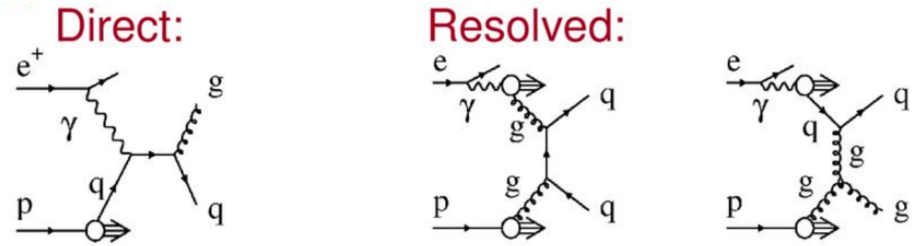


$$x_L = \frac{p_{z,nucleon}}{p_{z,beam}}$$

Detector	Detector Position (x,z)	Angular Acceptance	Notes
ZDC	(0.96m, 37.5m)	θ < 5.5 mrad	About 4.0 mrad at $\phi \sim \pi$
Roman Pots (2 stations)	(0.845m, 26m) & (0.936m, 28m)	0.0* < θ < 5.0 mrad	Need 10σ cut. Depending on optics/beam energy, lower θ bound changes.
Off-Momentum Detectors	(0.8, 22.5m) & (0.85m, 24.5m)	0.0 < θ < 5.0 mrad	Roughly 0.4 < x_L < 0.6
B0 Sensors (4 layers, evenly spaced)	x = 0.19m, 5.4m < z < 6.4m	5.5 < θ < 20.0 mrad	Could change a bit depending on pipe and electron quad.

Needs an integration with accelerator at the early stage of the IR design

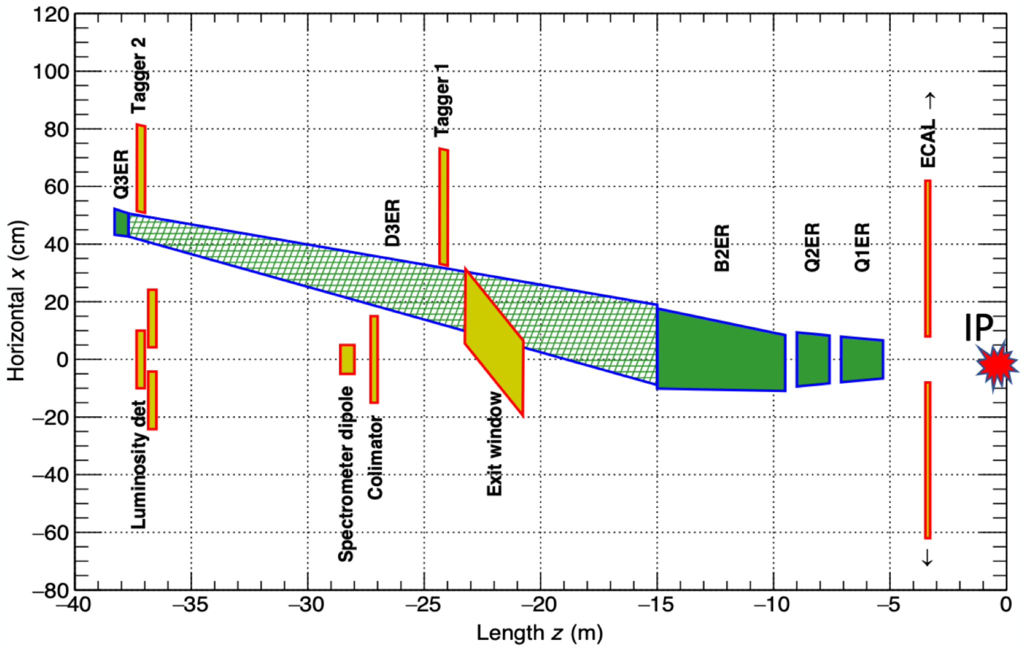
Photoproduction

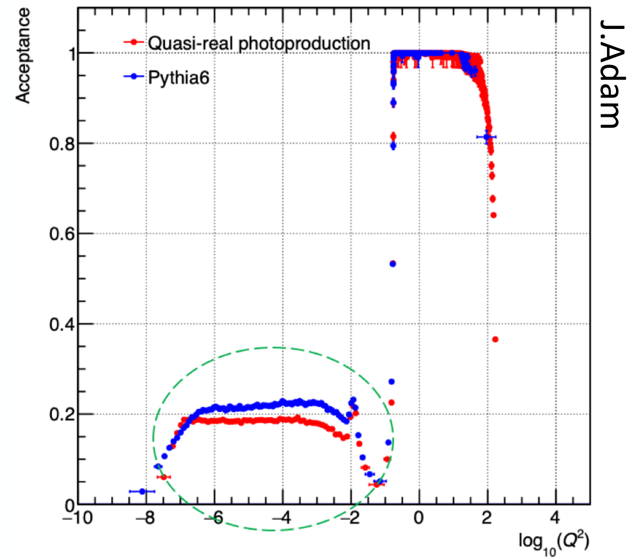


- ✓ Most events ep event at EIC are photoproduction (cross section ~ $1/Q^4$)
- ✓ Exchange photon is almost real at Q^2 ~0 (DIS Q^2>1GeV)

Resolved contribution:

- ➢ γ hadronic structure
- ➢ Constrain gluonic contributions





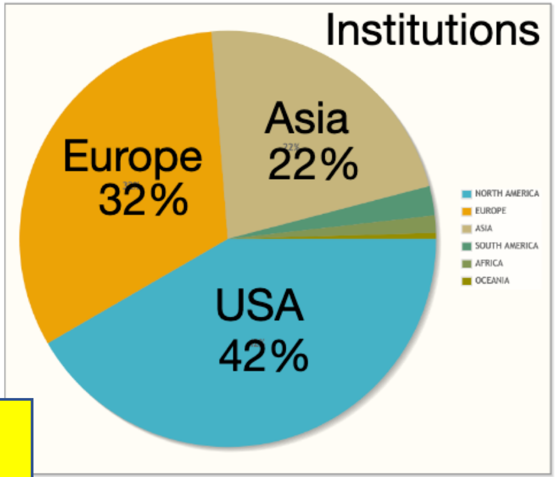
❑ Q^2 acceptance up to ~10^{-6}

- ➢ This area is designed to provide coverage for the low-Q^2 events (photoproduction)
- ➢ Need space for the luminosity detector (ep -> epg bremsstrahlung photons)

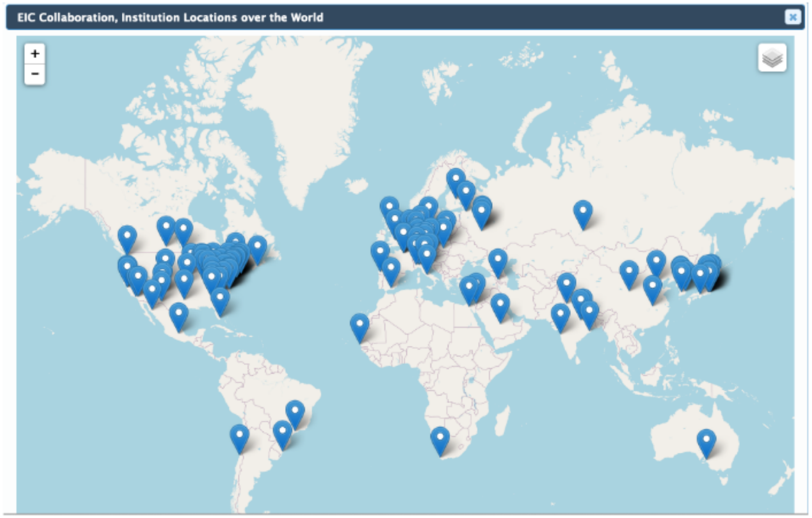
EICUG status

www.eicug.org

- EICUG organization established in 2016
- EICUG **now**: **1073** members
  - **645** Exp. scientists
  - **273** Th. scientists
  - **147** Accel. scientists
  - **3** Support
  - **5** Other
- EICUG **now**: **221** institutions from **31** countries in **6** world regions



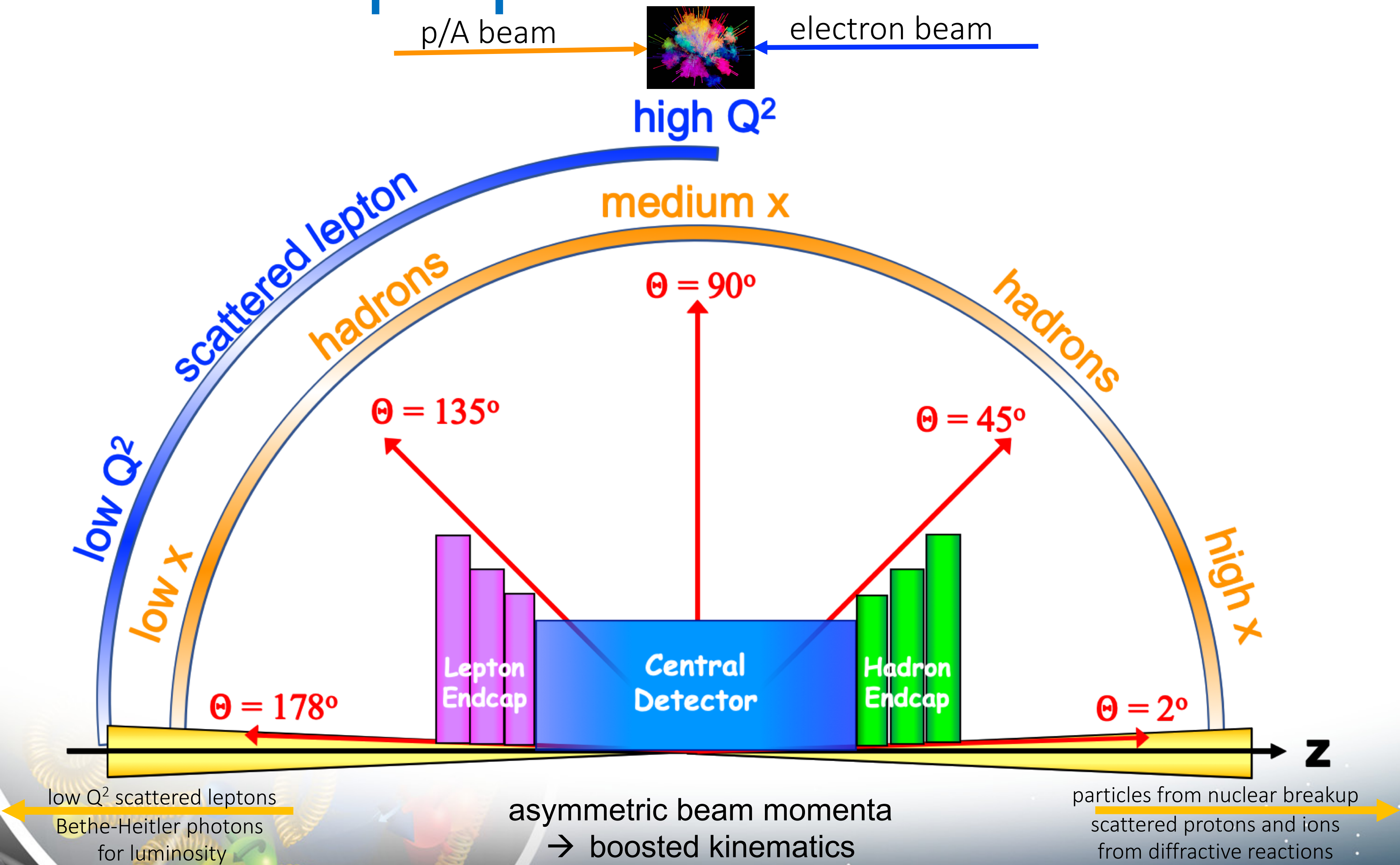
- EICUG now: world map



EICUG Yellow Book (physics/ detector)

2

General purpose EIC Detector

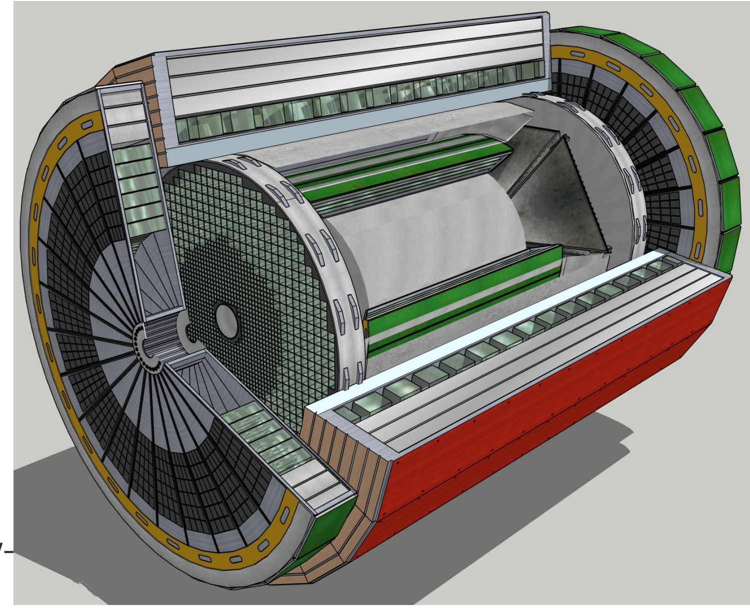


asymmetric beam momenta
→ boosted kinematics
Endcaps important

Any general purpose EIC Detector is complex

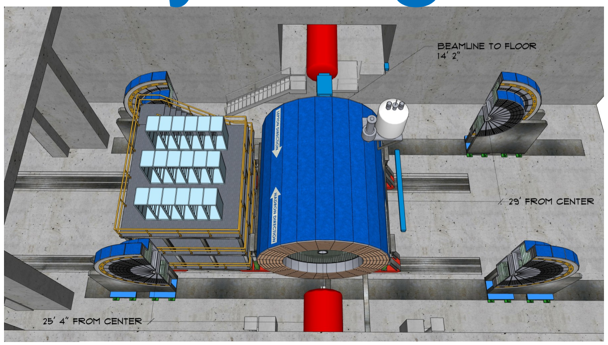
Overall detector requirements:

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



Integration into the Interaction Region is critical

Integration with accelerator at the early stage of the design

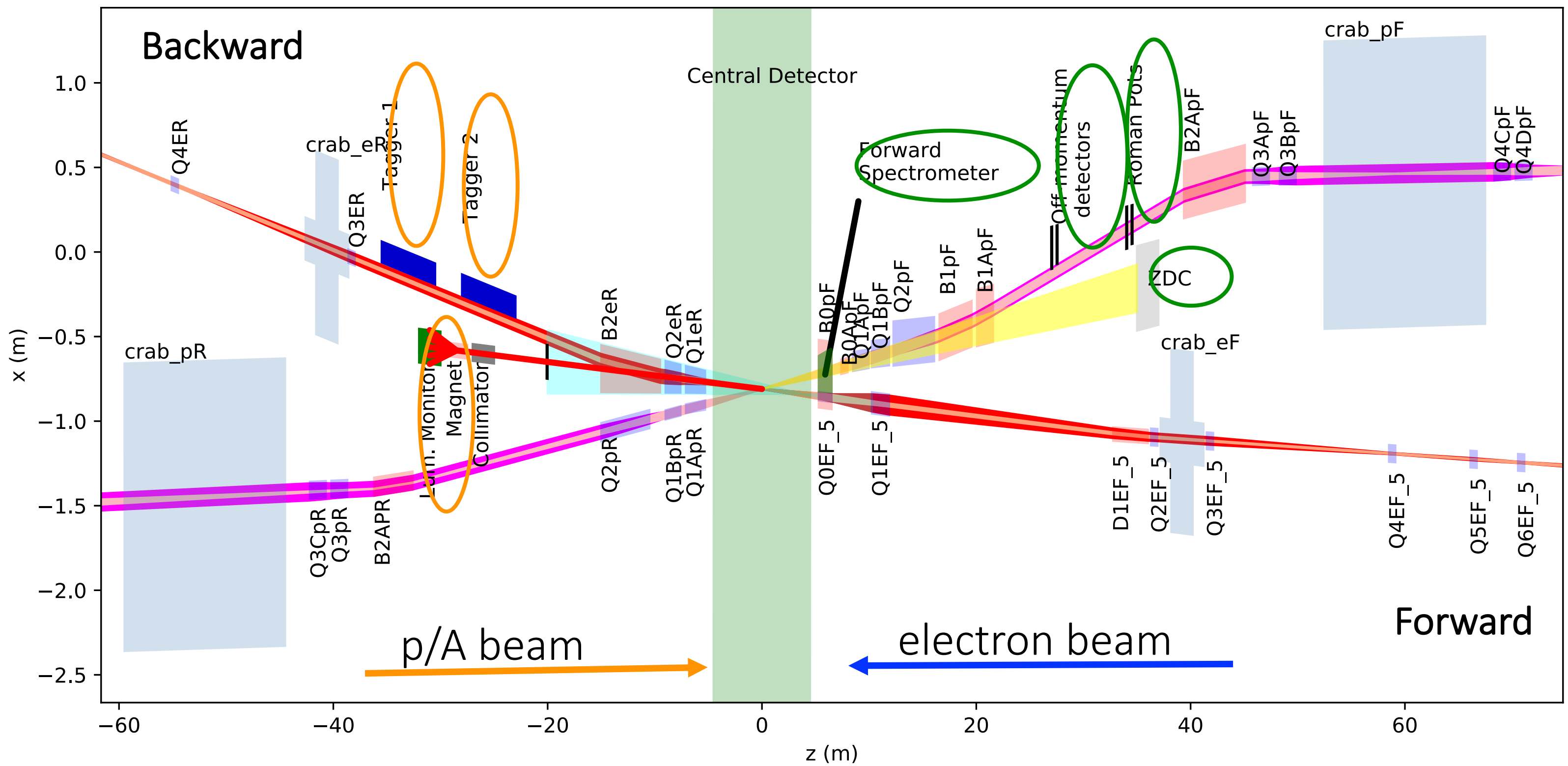


Total size detector: ~75m

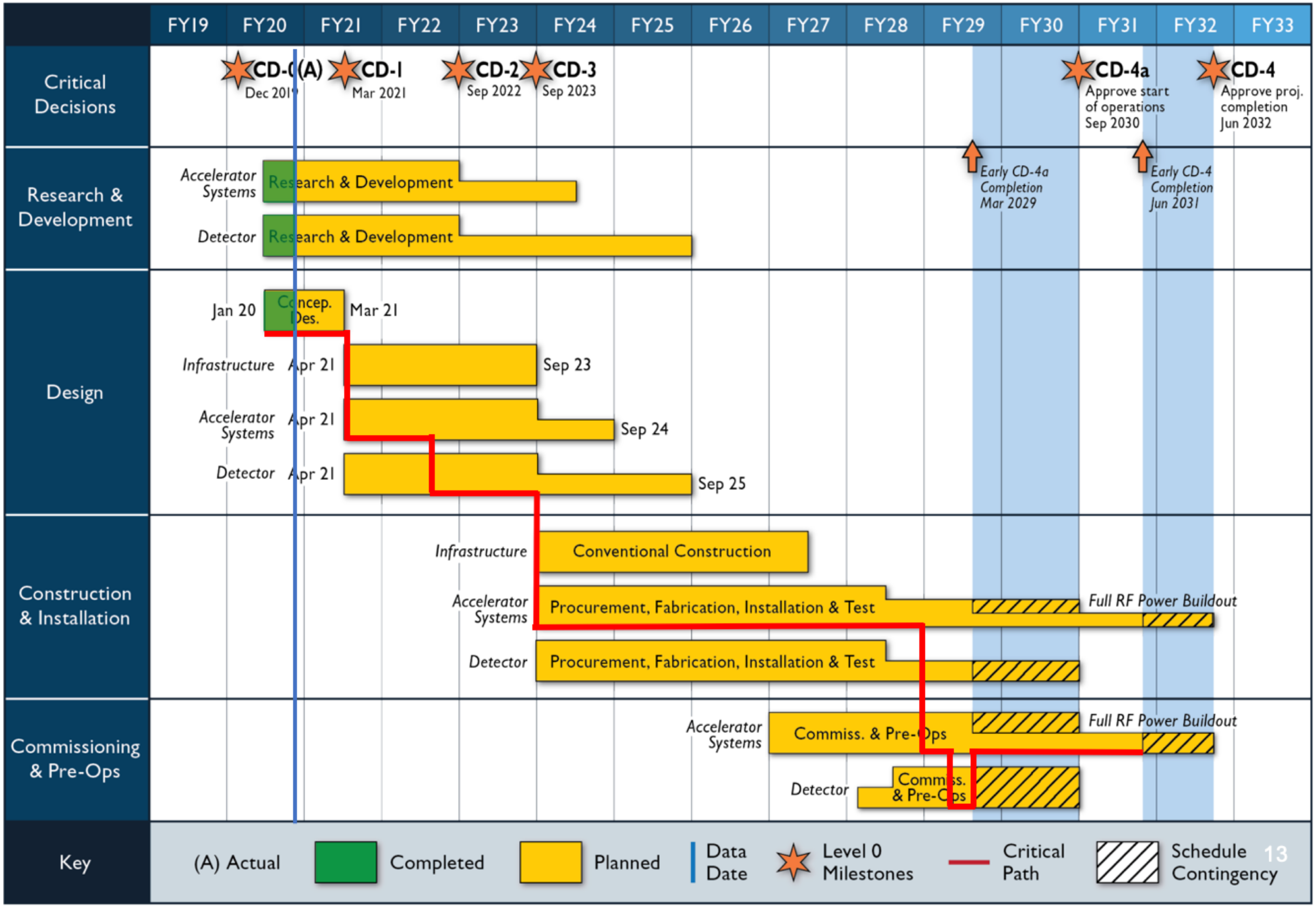
Central detector: ~10m

Backward electron detection: ~35m

Forward hadron spectrometer: ~40m



Schedule


FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26 FY27 FY28 FY29 FY30 FY31 FY32 FY33
Critical Decisions
CD-0 (A) Dec 2019
CD-1 Mar 2021
CD-2 Sep 2022
CD-3 Sep 2023
CD-4a Approve start of operations Sep 2030
CD-4 Approve proj. completion Jun 2032
Research & Development
Accelerator Systems
Research & Development
Detector
Research & Development
Early CD-4a Completion Mar 2029
Early CD-4 Completion Jun 2031
Design
Jan 20
Concep. Des.
Mar 21
Infrastructure
Apr 21
Sep 23
Accelerator Systems
Apr 21
Sep 24
Detector
Apr 21
Sep 25
Construction & Installation
Infrastructure
Conventional Construction
Accelerator Systems
Procurement, Fabrication, Installation & Test
Full RF Power Buildout
Detector
Procurement, Fabrication, Installation & Test
Commissioning & Pre-Ops
Accelerator Systems
Commiss. & Pre-Ops
Full RF Power Buildout
Detector
Commiss. & Pre-Ops
Key
(A) Actual
Completed
Planned
Data Date
Level 0 Milestones
Critical Path
Schedule Contingency

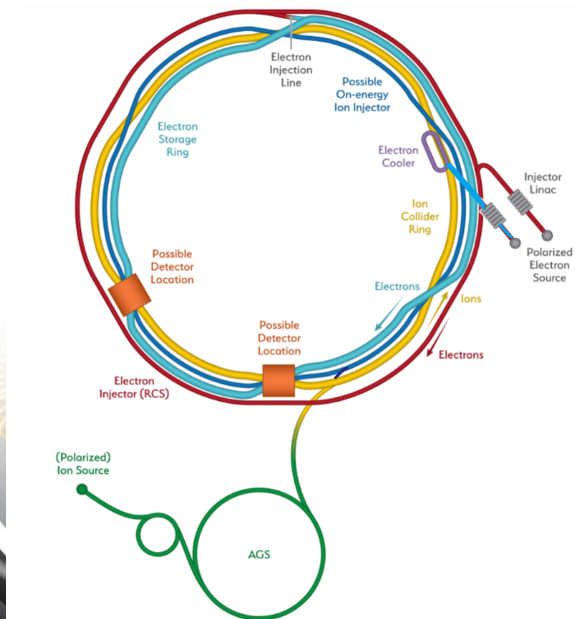
Conclusion

- Physics of nucleon and nuclear structure must drive the accelerator and detector design.
- Theory developments will allow to obtain the answers to the big questions discussed
- Detector technologies will allow for a high resolution EIC detector with a wide acceptance, particle identification and machine integration for far-forward areas.
- **Machine parameters**, **interaction region** and **detector design** must go hand in hand, paying close attention to the emerging **physics program** of the EIC (a good collaboration among Accelerator Physicists, Experimentalists, and Theoreticians)

EIC UG

RHIC UG

JLAB UG

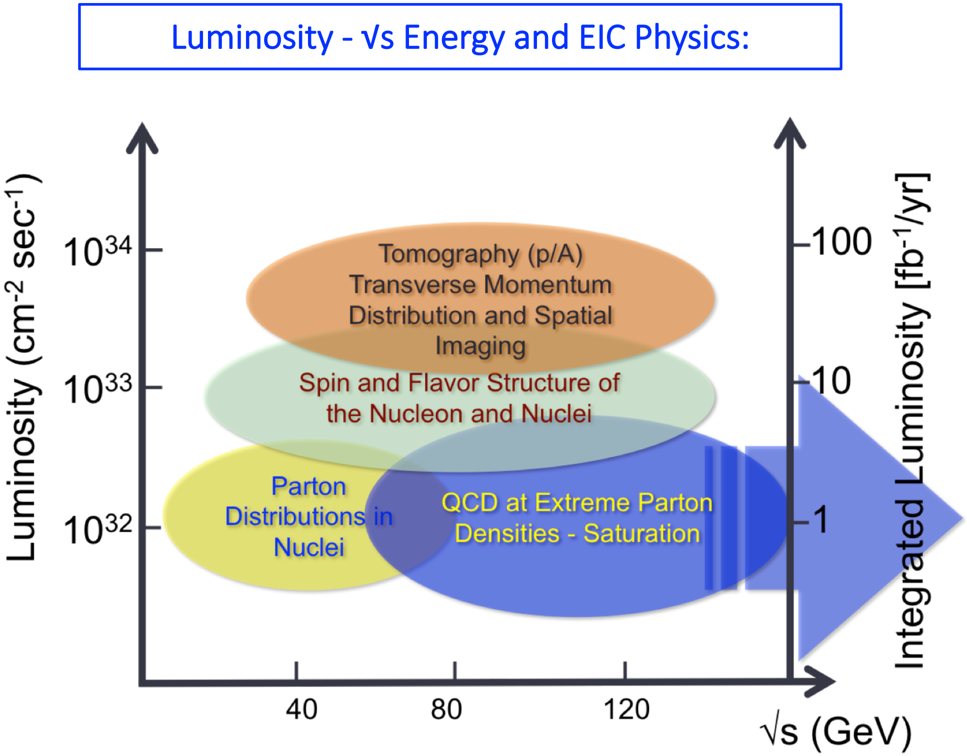


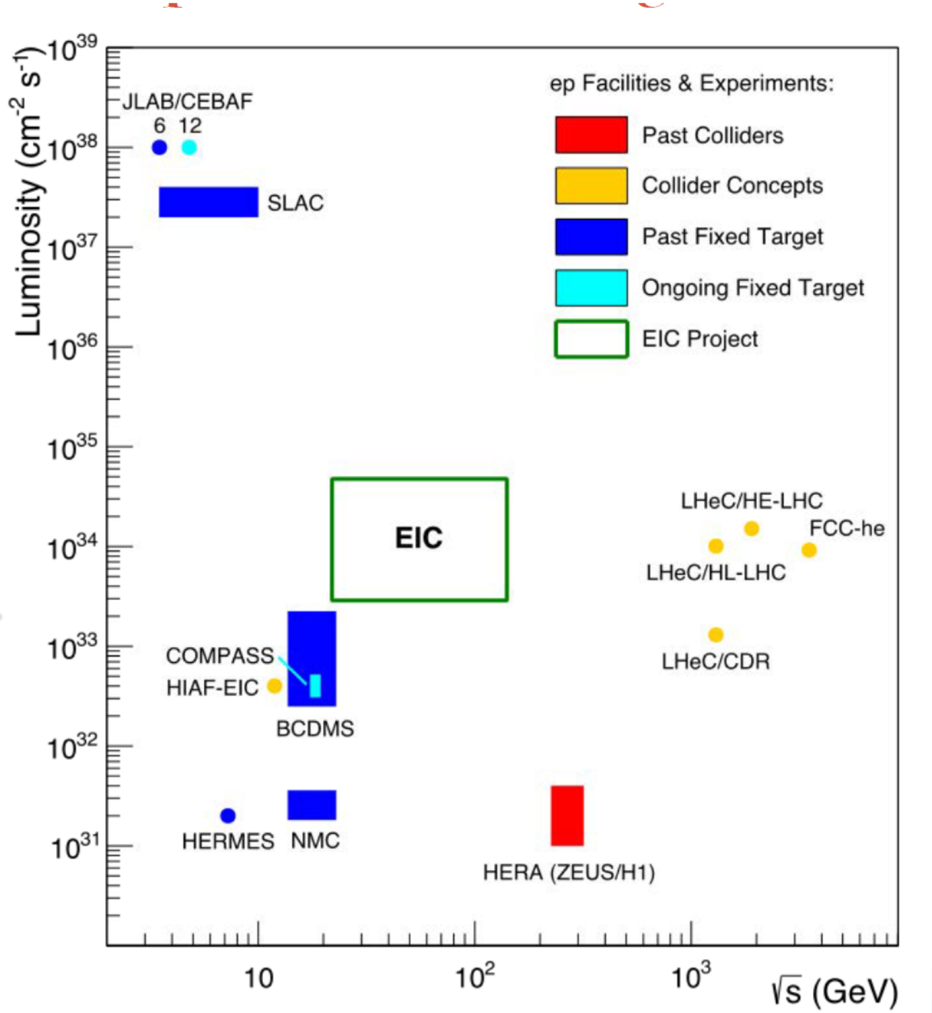
EIC

Thank you!

Backup

Past, existing and proposed DIS facilities



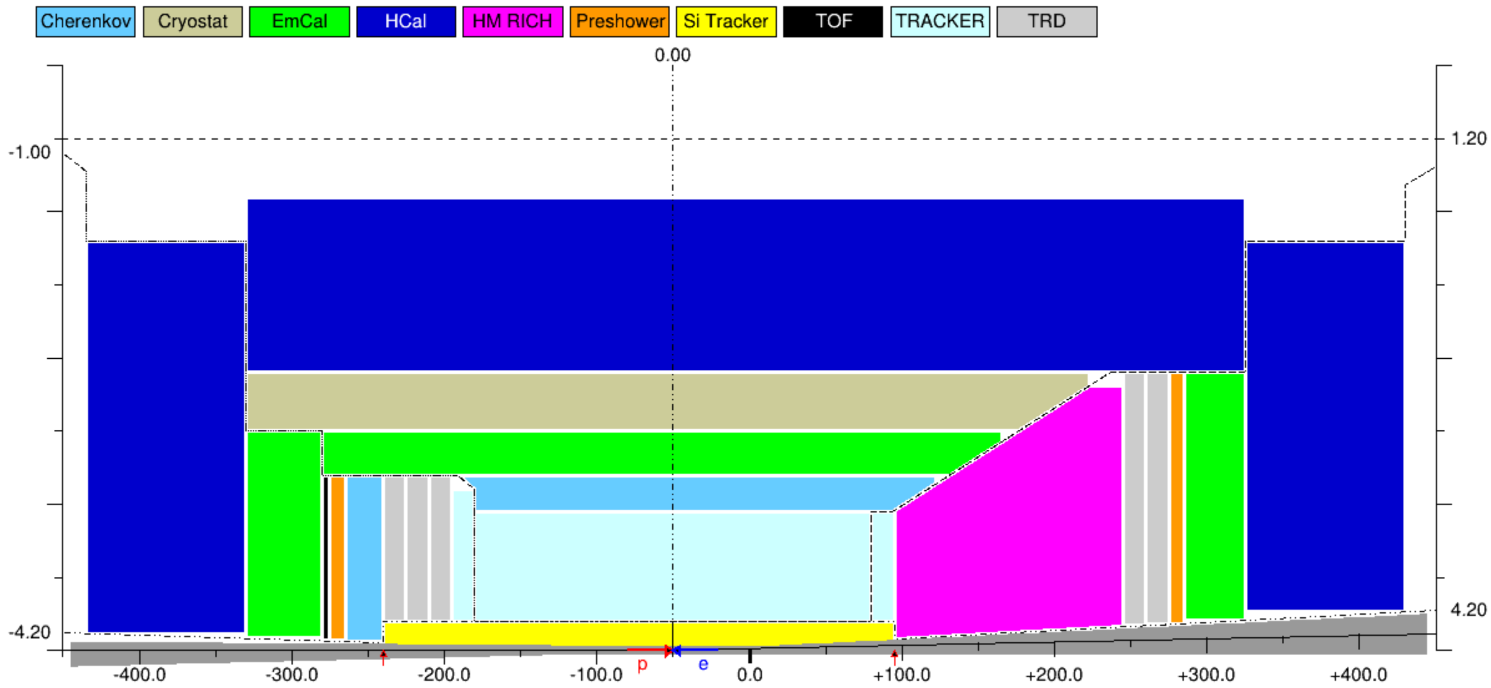


IR-related physics requirements

Table 8.1: Summary of the requirements from the physics program on the overall IR design.

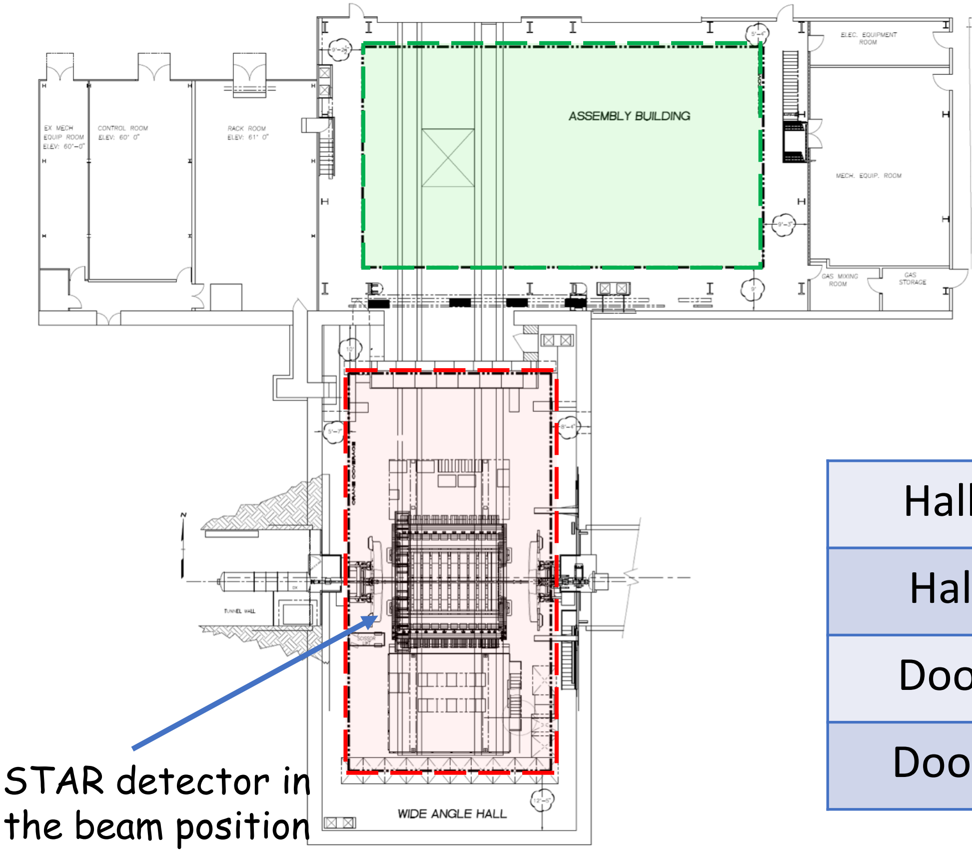
	Hadron	Lepton
Machine element free region	$\pm 4.5\,\mathrm{m}$ main detector beam elements $< 1.5^{o}$ in main detector volume	
Beam Pipe	Low mass material, i.e. Beryllium	
Integration of detectors	Local Polarimeter	
Zero Degree Calorimeter	$40\,\mathrm{cm} \times 40\,\mathrm{cm} \times 1\,\mathrm{m}\ @s = 30\,\mathrm{m}$	
scattered proton/neutron acc. all energies for e+p	Proton: $0.18\,\mathrm{GeV/c} < p_T < 1.3\,\mathrm{GeV/c}$ $0.5 < x_L < 1 (x_L = E'_p / E_{Beam})$ Neutron: $p_T < 1.3\,\mathrm{GeV/c}$	
scattered proton/neutron acc. all energies for e+A	Proton and Neutron: $\theta < 6\,\mathrm{mrad}$ (for $\sqrt{s} = 50\,\mathrm{GeV}$) $\theta < 4\,\mathrm{mrad}$ (for $\sqrt{s} = 100\,\mathrm{GeV}$)	
Luminosity	Relative Luminosity: $R = L^{++/--} / L^{+-/-+} < 10^{-4}$	
		γ acceptance: $\pm 1\,\mathrm{mrad}$ $\rightarrow \delta L / L < 1\%$
Low Q^2-Tagger		Acceptance: $Q^2 < 0.1\,\mathrm{GeV}^2$

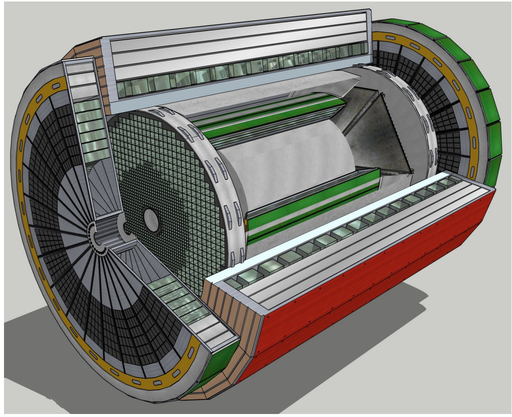
EIC central detector outline



- ~4π hermetic coverage in tracking, particle ID and calorimetry with the polar angle acceptance only limited by the beam pipe
- Low material budget in the acceptance (at the level of 3-5% X/X_0):
  - To minimize multiple Coulomb scattering for the low-momenta particles
  - To minimize bremsstrahlung in front of the e/m calorimeters
- Need to integrate the support structures, services and cabling
- Start thinking about the assembly, installation and maintenance

Central detector installation in IP6

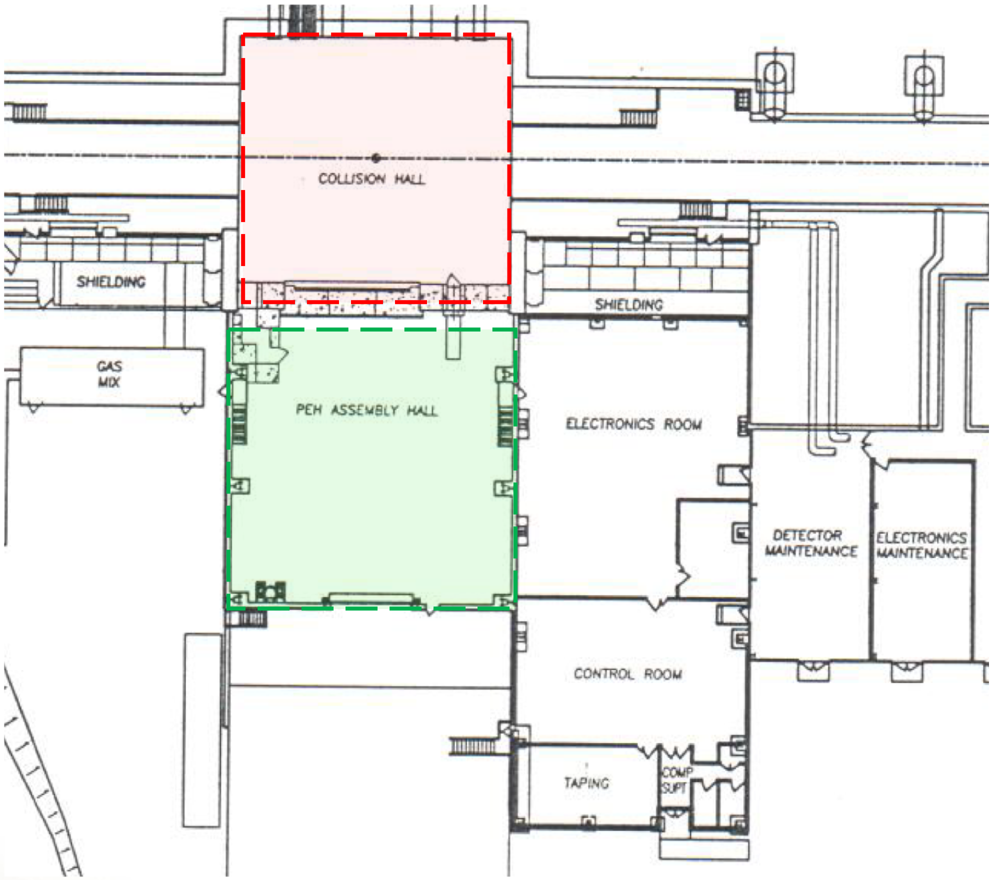


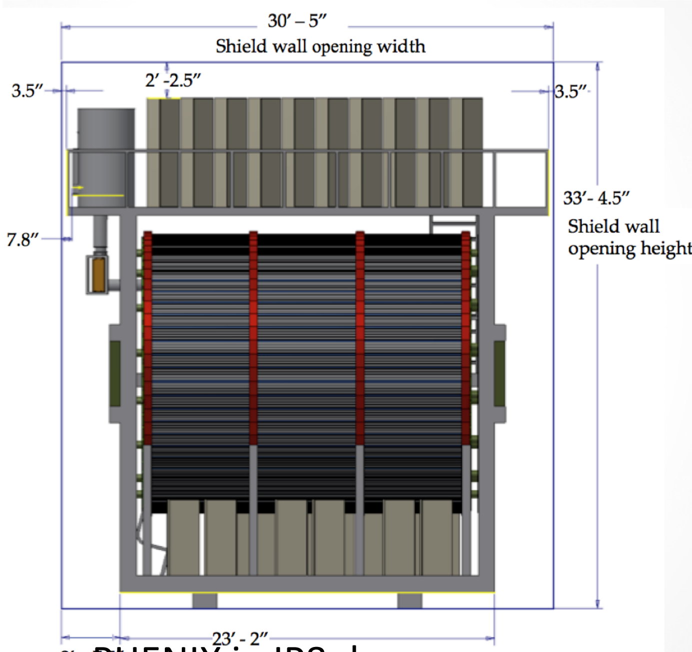


Hall length	~3200 cm
Hall width	~1615 cm
Door width	823 cm
Door height	823 cm

- Limited space along the beam line (the final focusing quads are placed as close to the IP as possible in order to maximize the luminosity)
- Barrel part of the main detector is designed to fit through the door
- Use large assembly hall for the long detector maintenance

Central detector installation in IP8





sPHENIX in IP8 doorway

Hall length	~1740 cm
Hall width	~1860 cm
Door width	927 cm
Door height	1017 cm

- Very small exp. hall
- Large doorway