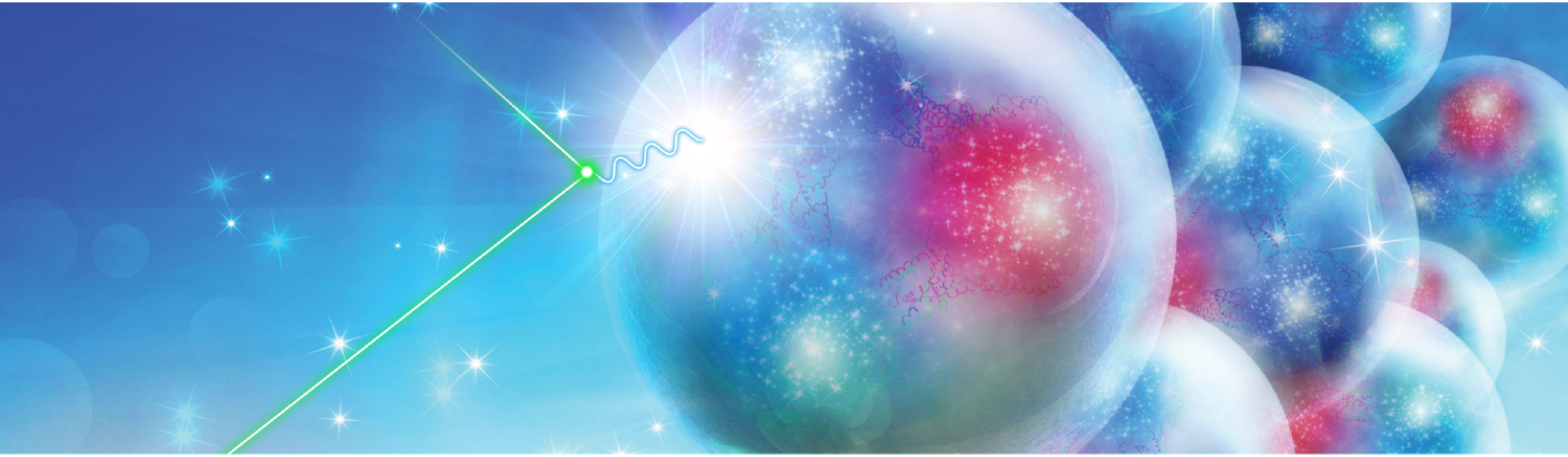


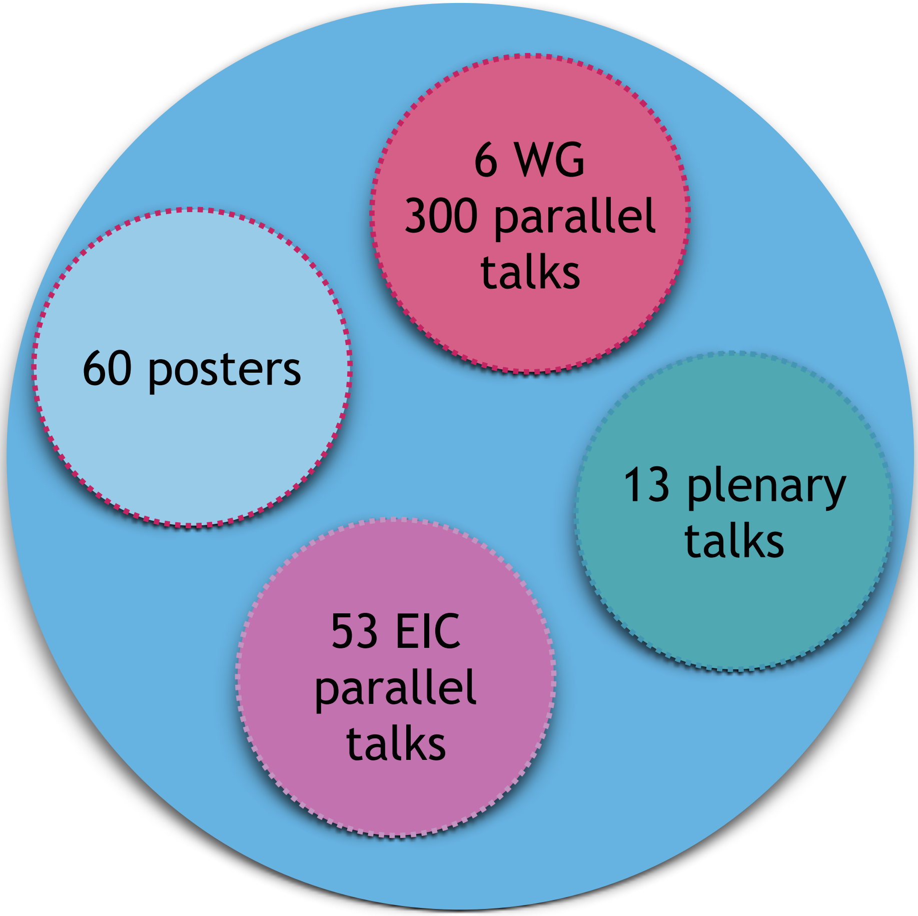
DIS 2022: highlights toward EIC

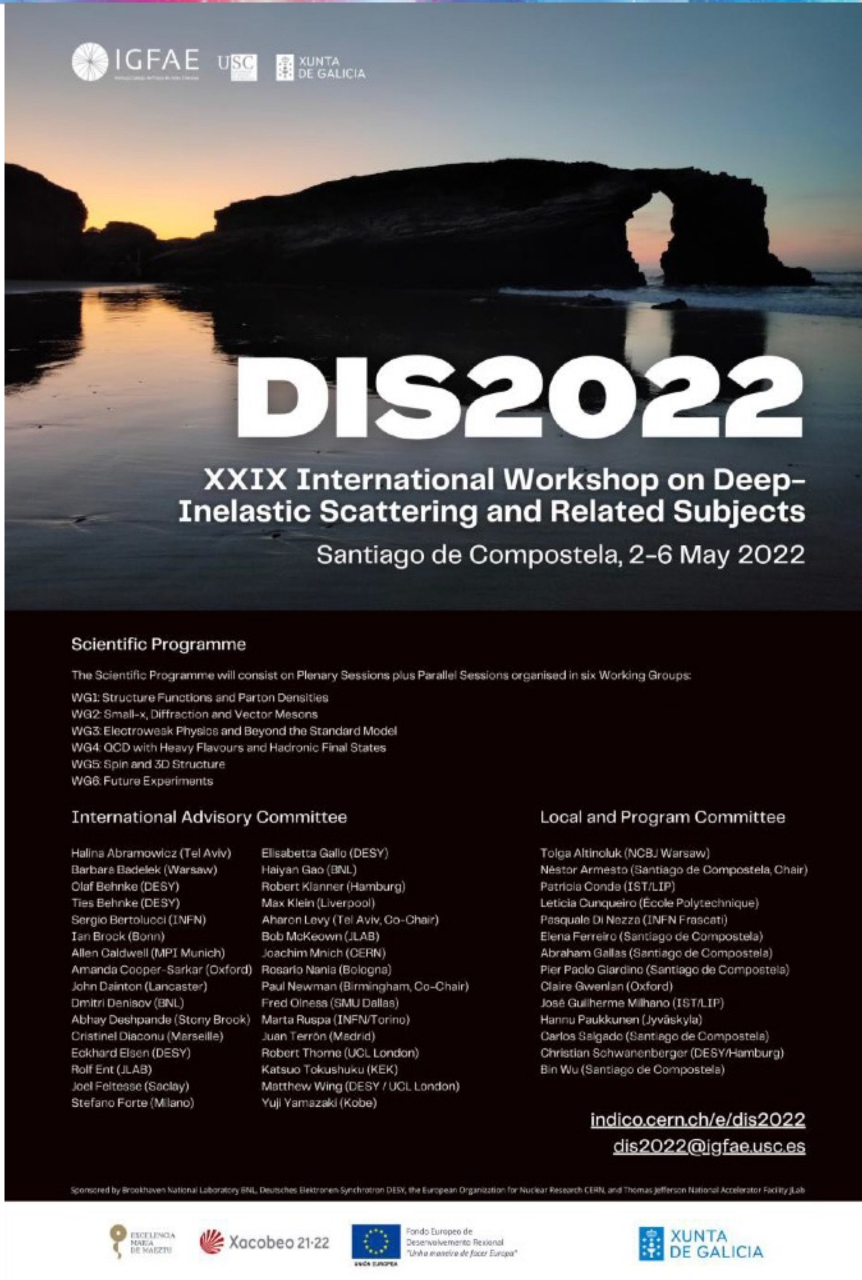
Giornata nazionale EIC_NET

Michela Chiosso (University of Torino and INFN)

30/06 - 01/07 2022
Catania

The conference





DIS: a unique microscope

Fundamentals of QCD in a clean environment

- Bjorken scaling
- QCD evolution & the rise of the gluon at HERA
- New regimes of QCD: saturation, CGC...
- Nuclear Theory: from models to first principles

A high-energy probe

- EW physics in DIS
- Precision SM parameters
- Higgs couplings
- BSM models

DIS: a unique microscope

A precise mapping of the proton/nuclei

- PDFs at high precision → crucial for hadron colliders
- HERA: high-precision at hadron colliders is possible
- Beyond PDFs: TMDs, 3D tomography...
- Mass/spin of the proton

DIS: a unique microscope

DIS in the big picture of HEP
Fabrizio Caola

``Interesting physics'' ≠ ``BSM''

… as any physicist not working on particle physics would tell you

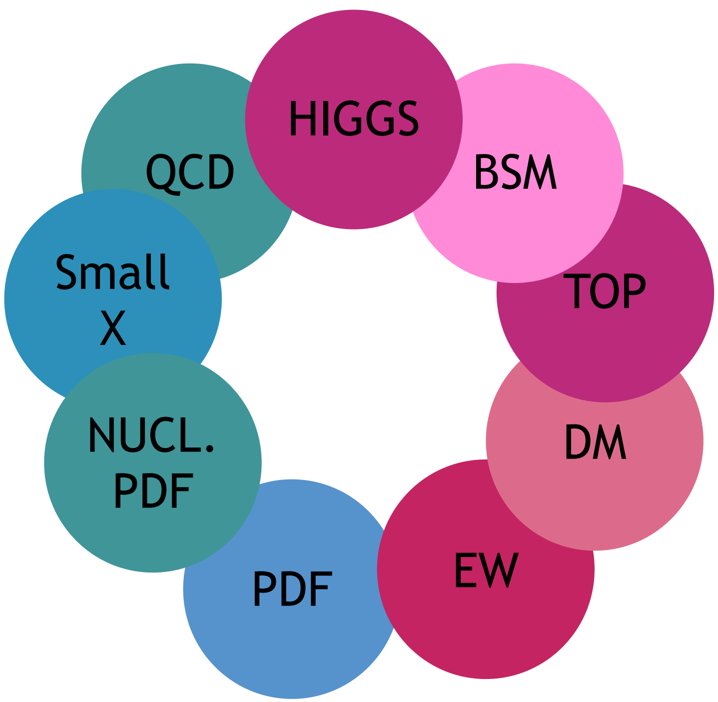
- If a collider can deliver new discoveries, that's of course great
- Looking at the future: the era of ``guaranteed new physics deliveries'' (like the Higgs for the LHC) may well be over
- But there is a rich set of unexplored areas in the SM that are worth pursuing

Many interesting open questions in QCD. For example

- Mass/spin proton/nuclei
- The structure of the proton [PDFs, TMDs, tomography…]
- Nuclear physics: from models to first principles
- QCD evolution and new phases of QCD (saturation, QGP…)
- …

Future DIS facilities (EIC, LHeC, FCC-eh) would shed light on these issues

Future Facilities



LHeC, FCC-eh

e+e- colliders (FCC-ee, CLIC, ILC)

EIC, EICc

Muon collider

Fix target experiments at CERN

JLAB experiments

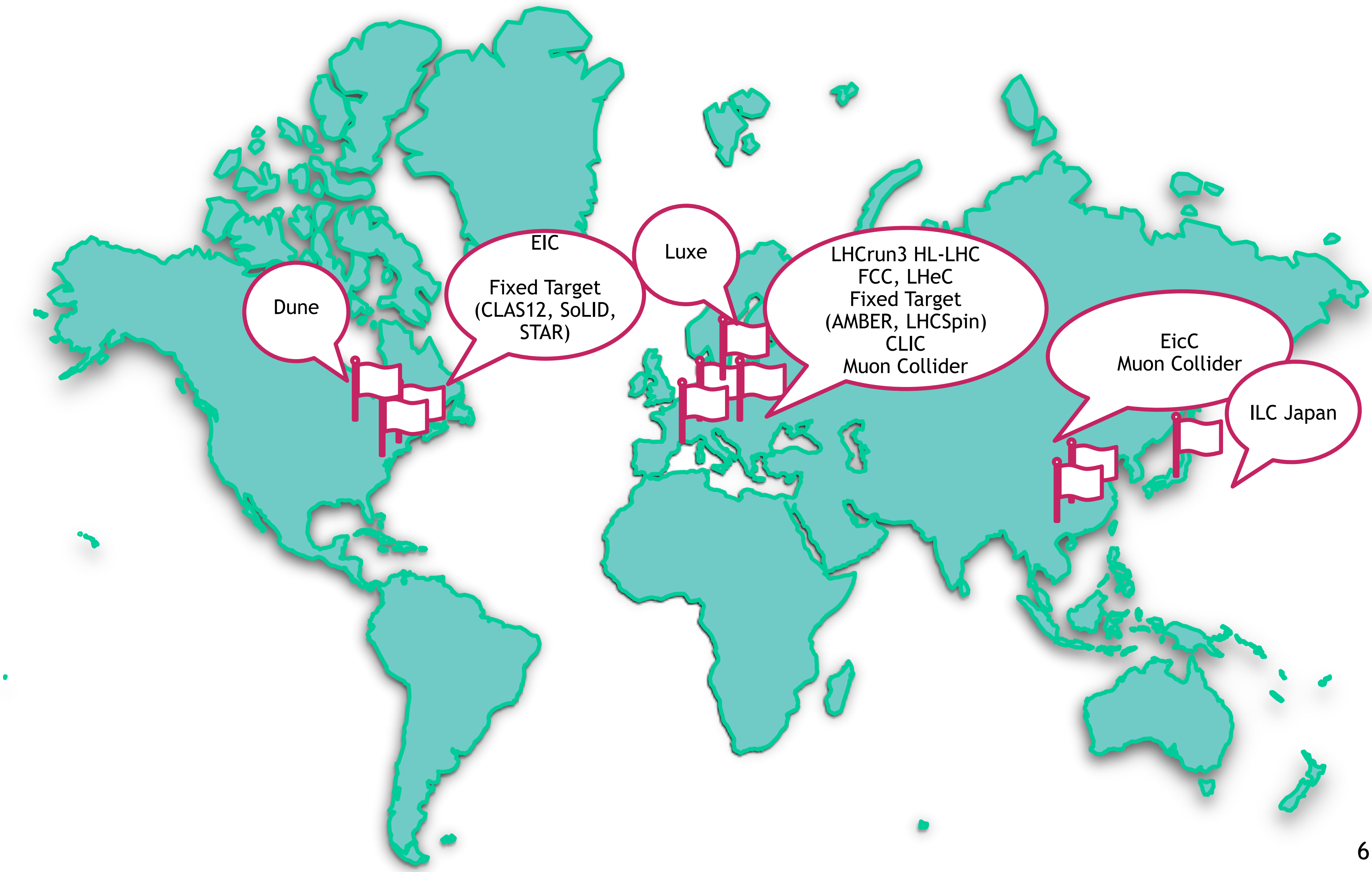
Neutrinos experiments

Dark Matter searches

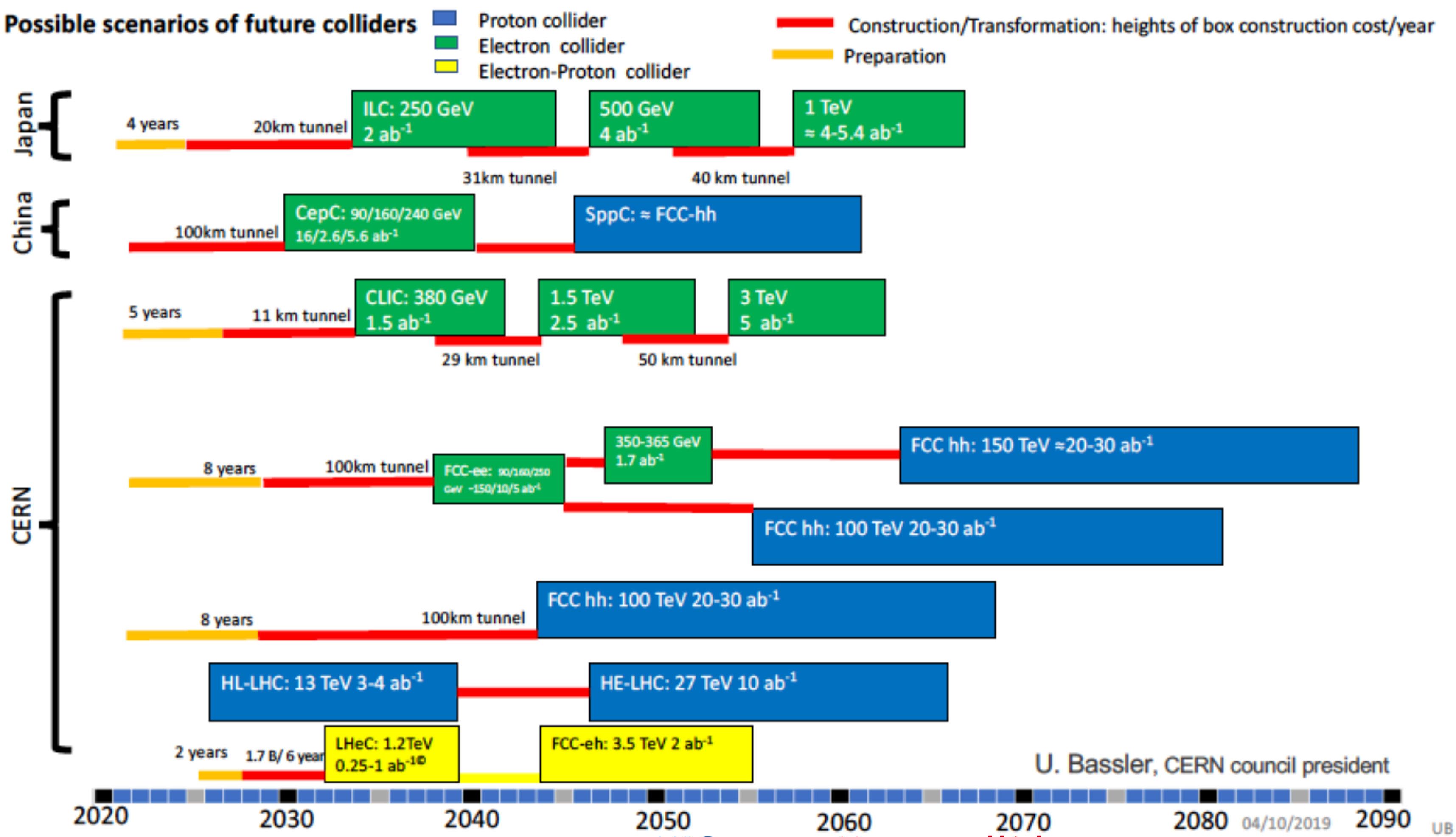
Other future experiments and upgrades

New Analysis Methods

Future Facilities



Timeline of Future Colliders



EIC

MIC

Muon collider

LHeC: installation during **LS4**;

concurrent operation through LHC **Runs 5/6**; and period of **dedicated running**, arXiv:1810.13022

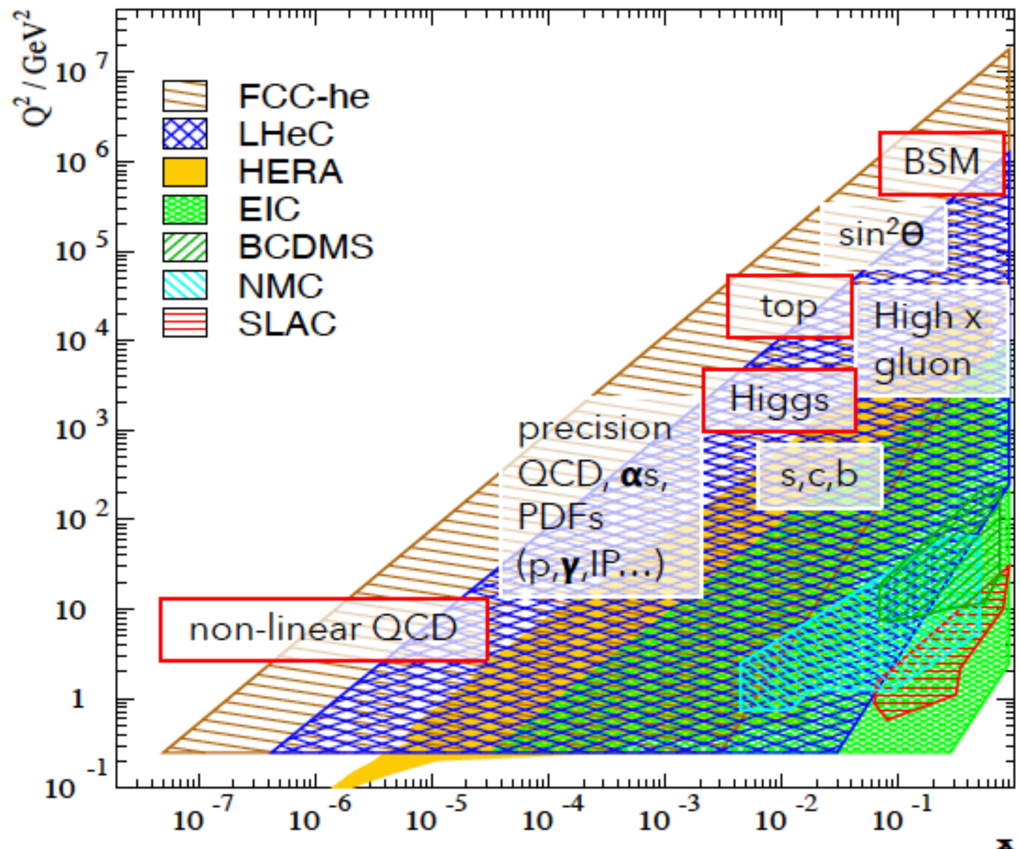
Physics with Energy Frontier DIS

opportunity for unprecedented increase in DIS kinematic reach;

×1000 increase in lumi. cf. HERA

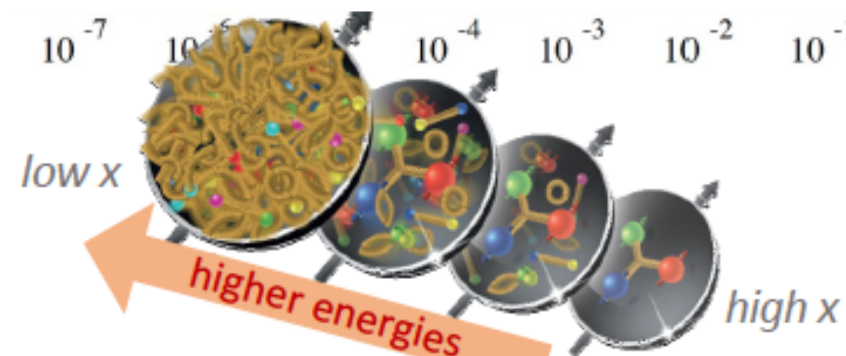
completely resolve all proton pdfs,
sensitivity to $x \to 1$, and exploration of small x regime;

extensive additional physics programme ×15/120 extension in Q2,1/x reach vs HERA Physics with Energy Frontier



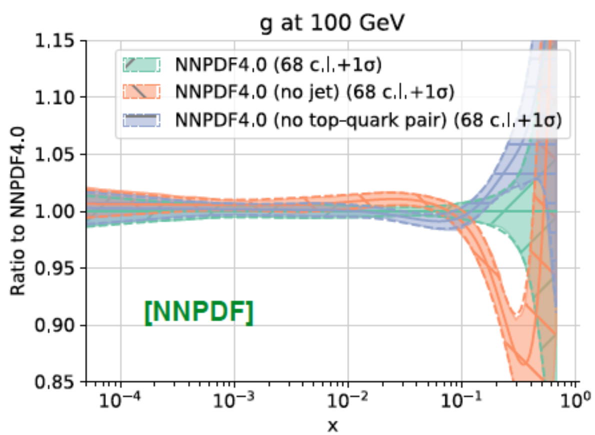
Ultimate Questions and Challenges in QCD

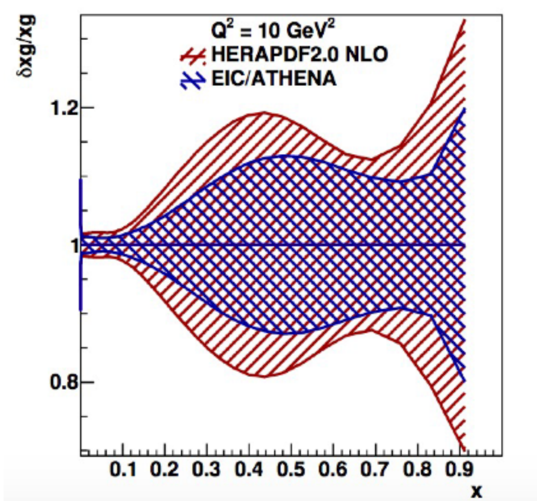
Pillars of EIC Physics:
How does the spin of proton arise? (Spin puzzle)
What are the emergent properties of dense gluon system?
How does proton mass arise?



Proton and Nuclear Collinear PDFs

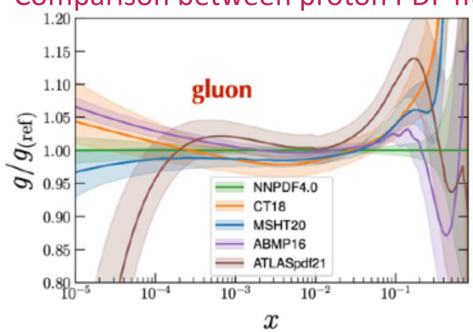
- ✦ Global analyses of PDFs prove our understanding of QCD and of the nucleon structure
- ✦ Key inputs for precision programs at hadron colliders, e.g., precision EW measurements, searches for new physics BSM
- ✦LHC delivers plenty of PDF sensitive data with high statistics and with theory evaluated almost all at NNLO; some of the N3LO calculations are already available; however, an advance on the treatment of the LHC experimental systematics and methodologies of PDF determinations can be crucial
- ✦ LHC-independent inputs on PDFs, from DIS experiments or lattice QCD simulation with improved precisions, are highly valuable

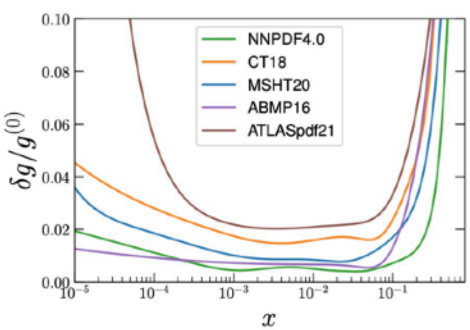


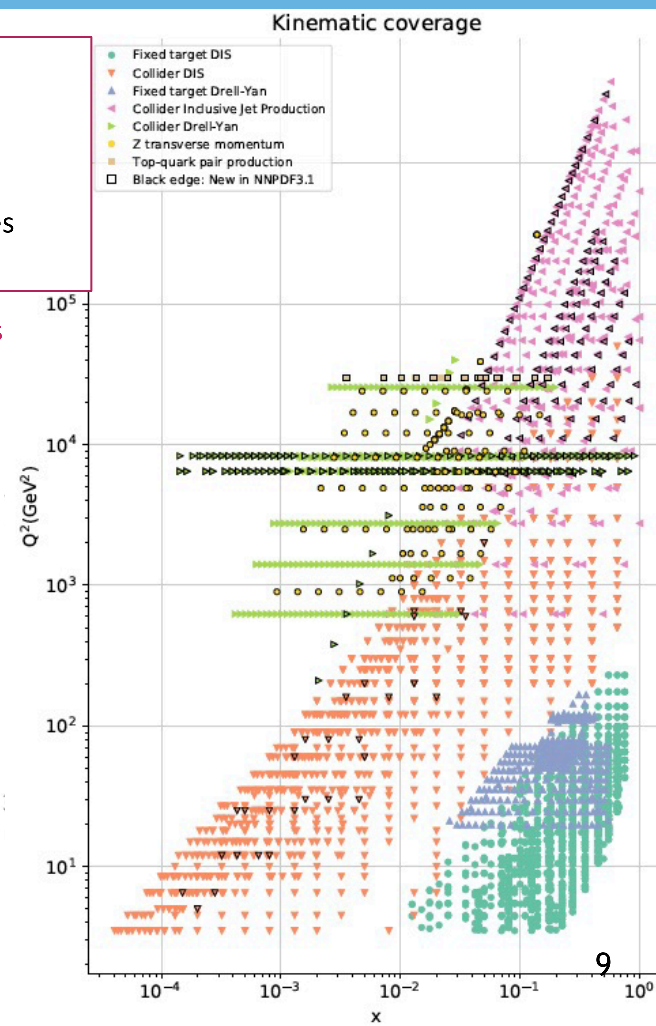


Global fits constrain high x region with fixed-target (eA) DIS + PDF-sensitive LHC data
improves precision, but adds theoretical complexity, requiring increased tolerances where there are tensions

Comparison between proton PDF fits







Proton and Nuclear Collinear PDFs

Paul Newman

input to collinear parton densities with wide-ranging impact:

- eA measurements in the low x region for the first time

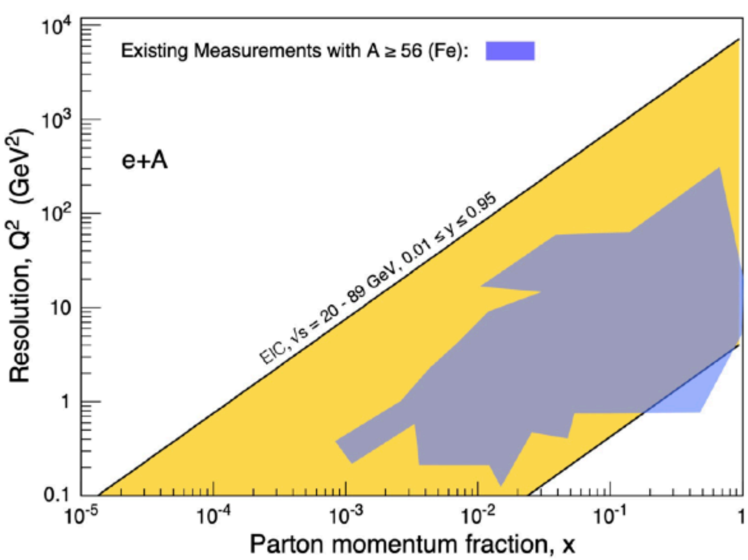
Knowledge of nuclear PDFs (especially gluon) in the low x region
 Key to EIC physics programme of exploring new strong interaction dynamics in densely packed gluon systems

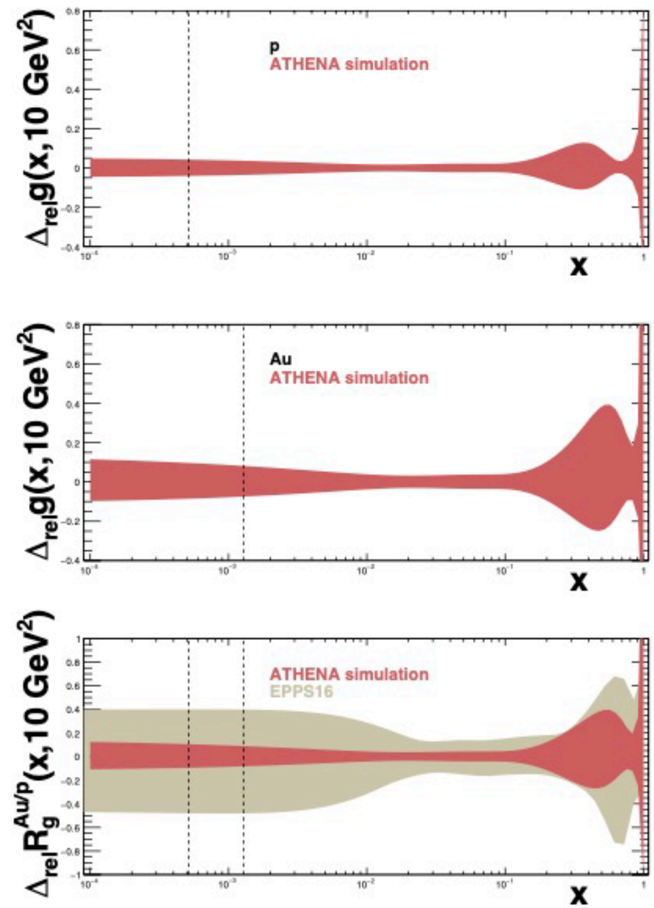
- Precise ep data in large x region covering wide range of large(ish) Q2:

Precision on all proton PDF species from an experimentally and theoretically cleaner DIS-only extraction
Key to optimizing sensitivity to new BSM physics near to kinematic limit at the LHC and elsewhere

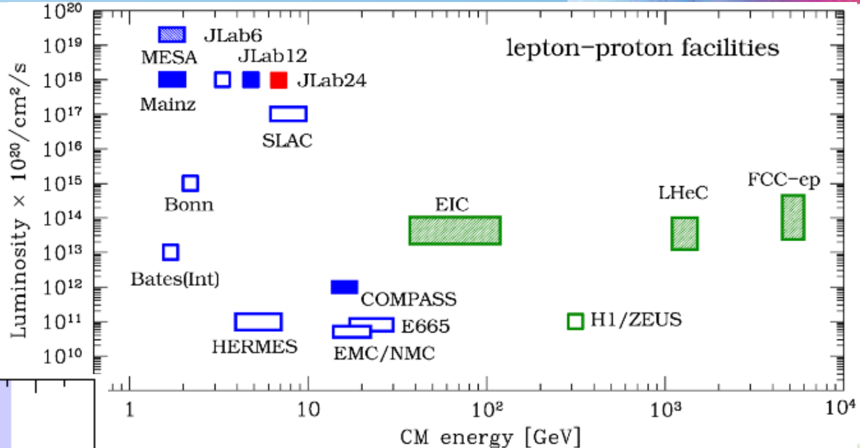
EIC will be world's first …
 - eA collider
- High lumi ep Collider
- Polarised target collider

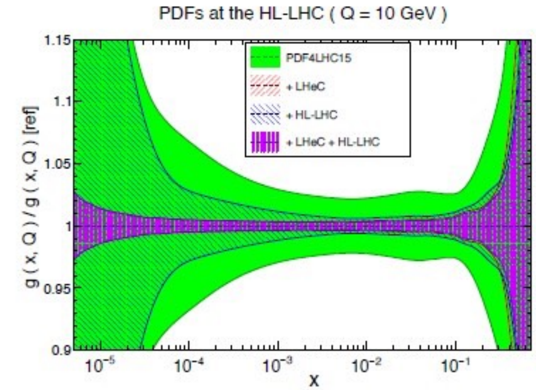
explore potential EIC impact on our knowledge of unpolarised collinear eA and ep parton densities.

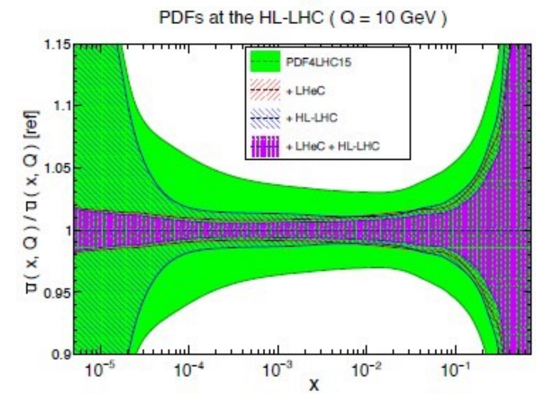


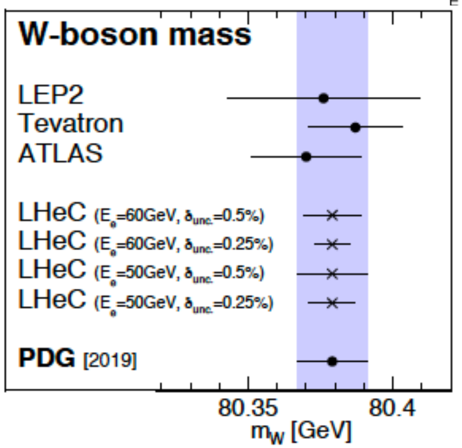


From PDFs to precision EW measurements

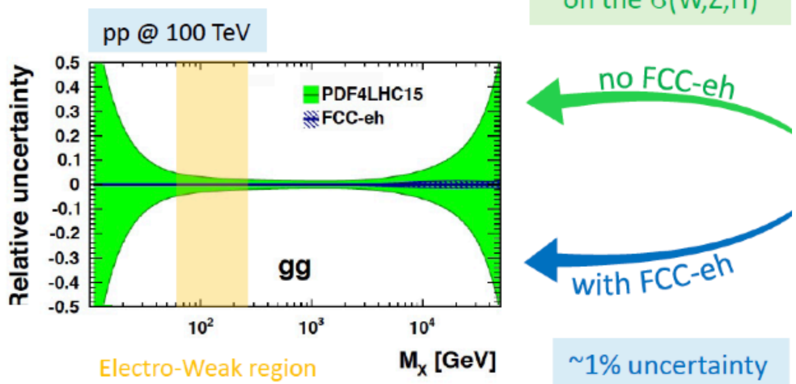




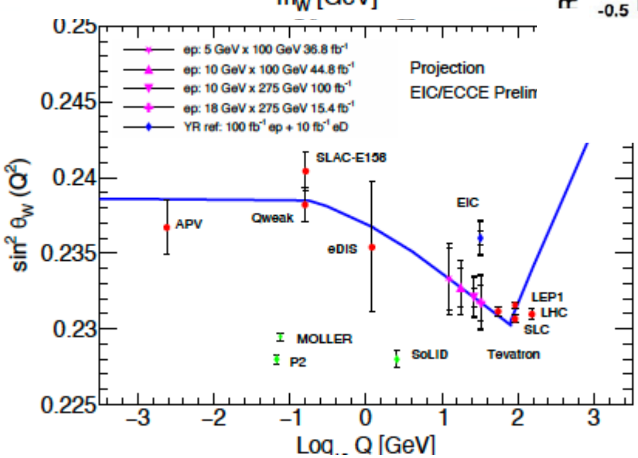




~5-7% uncertainty on the σ(W,Z,H)



~1% uncertainty on the σ(W,Z,H)



@ HL-LHC W mass precision measurement uses dedicated dataset at low <mu>

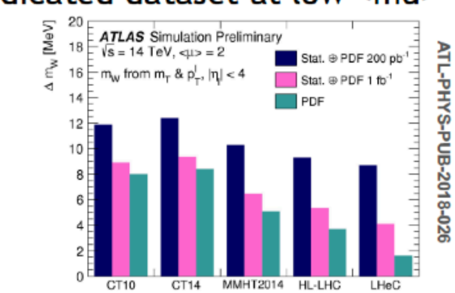
→ exploit the extended leptonic coverage

→ LHeC will provide additional precision through PDF

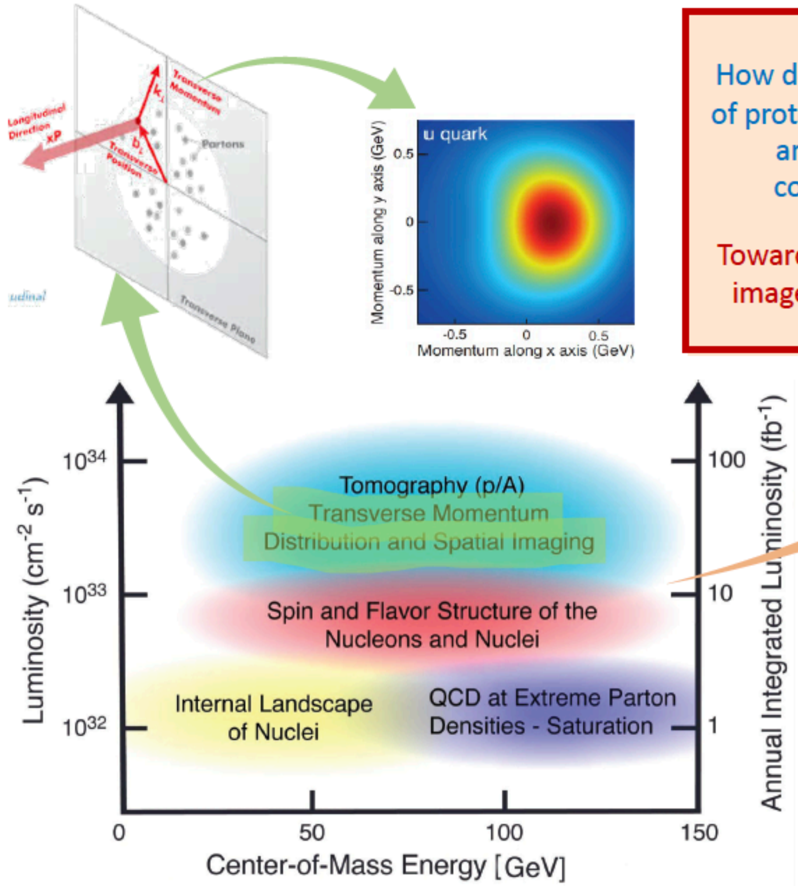
Δm_W = ±6 MeV (with reduced PDF unc from HL LHC)

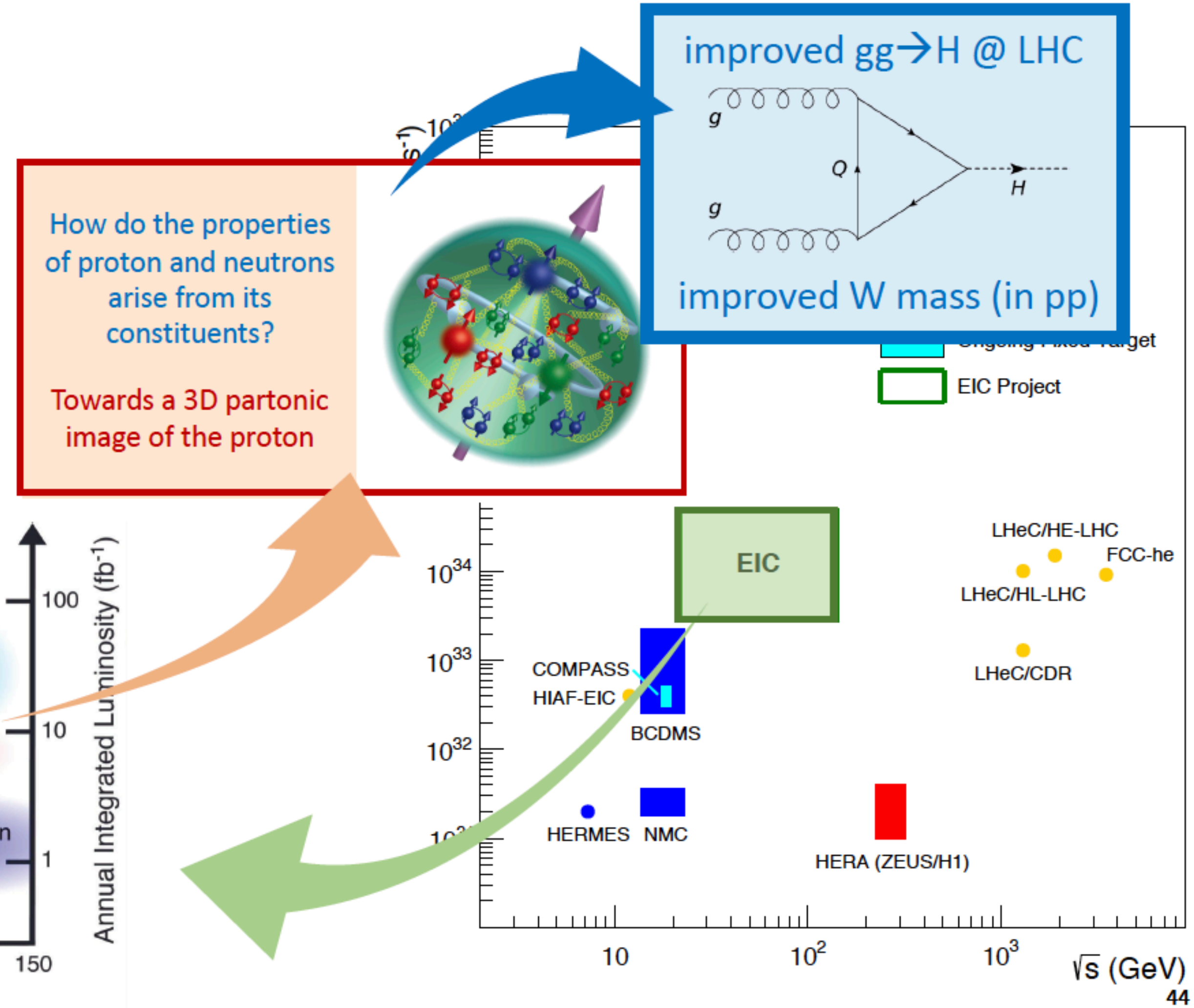
Δm_W = ±2 MeV (with improved PDF from LHeC)

M_W and M_Z (as well as m_{Top}) will be measurable unprecedent precision independently at the **LHeC**



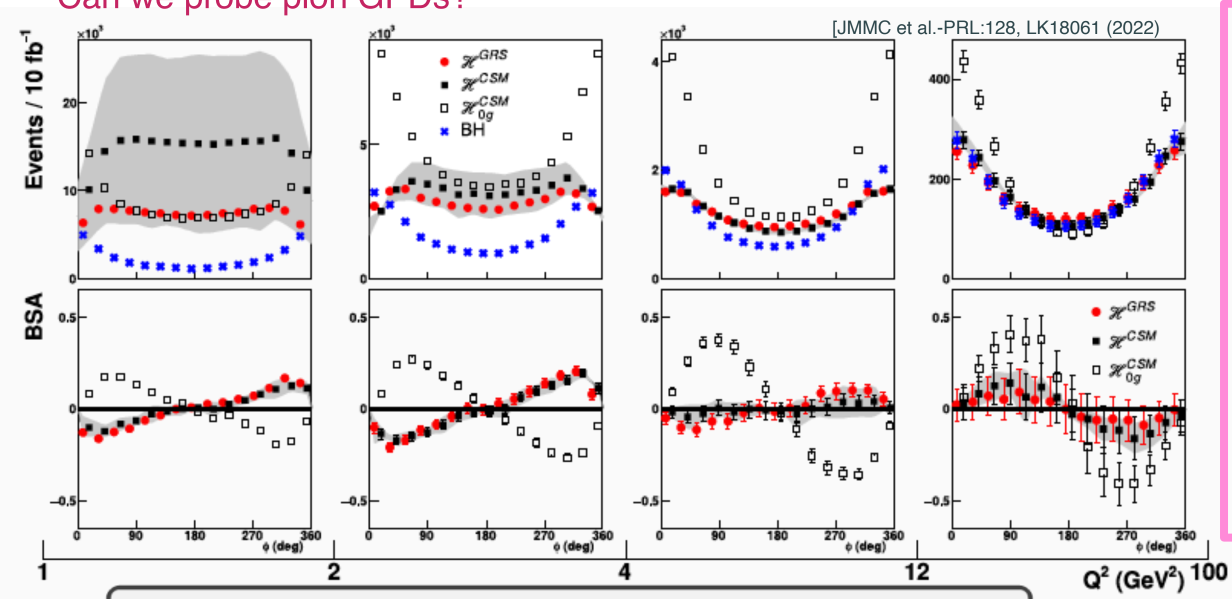
The Future of DIS
Jorgen D'Hondt





3D structure and spin physics @ EIC

Can we probe pion GPDs?



- **Signal expected at EIC kinematics**
- **Gluon-quark "destructive interference"**
- **Gluon dominance: Beam spin asymmetry sign change**

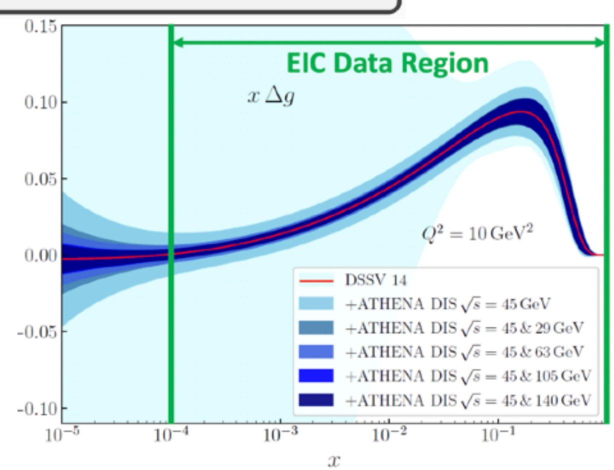
The 3D structure of pions at future electron-ion colliders
Jose Manuel Morgado Chávez

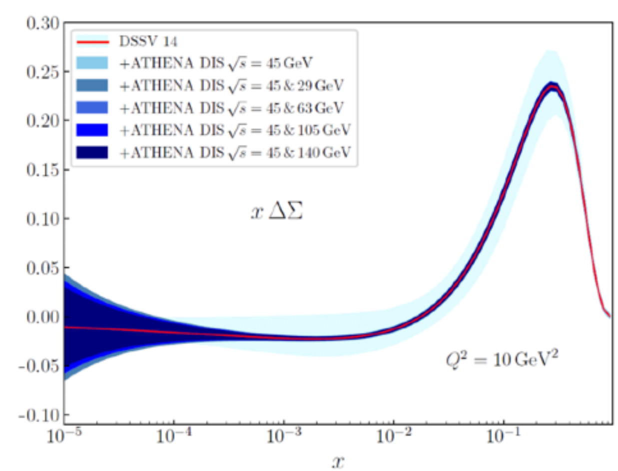
Probing the origin of nucleon spin with ECCE
Tyler Kutz

Probing nucleon spin structure with inclusive DIS at EIC-ATHENA
Barak Schmookler

Exploring the origin of the EMC effect with electron-deuteron DIS and spectator nucleon tagging at EIC
Zhoudunming Tu

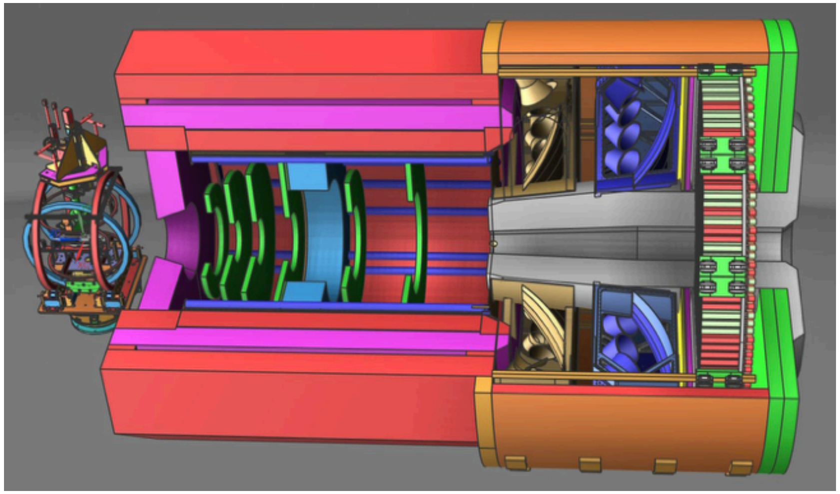
Analyses by the DSSV and the JAM collaborations show that inclusive electron-proton scattering at the EIC will constrain the polarized gluon PDF to a remarkable degree





JLAB future experiments

SoLID



The Future of CEBAF
Reza Kazimi

Deeply virtual Compton scattering with polarized positrons : perspectives for Jefferson Lab
Silvia Niccolai

Measurement of Lepton-Charge Asymmetry Using a Positron Beam at Jefferson Lab
Xiaochao Zheng

3D Nucleon Structure with SoLID
Chao Peng

CLAS12 luminosity upgrade and future physics opportunities
Stepan Stepanyan

	Present Design	Possible	Challenges
Luminosity increase	Hall A & C @11GeV Total < 85 μA (< 82 μA Each dump limit)	Hall A & C @11GeV Total < 140 μA (< 82 μA Each dump limit)	▪ RF Beam Loading ▪ Dump Cooling ▪ BBU Instability
Positron option	Not Yet an Option	>100 nA Unpolarized Or >10 nA Polarized e+	▪ Target Design ▪ e+ Collection ▪ Beam dynamics, Injector and Main ▪ High Intensity e- Beam (~1 mA) Need ▪ Production Energy Choice and Design ▪ Gaining Experience
Energy increase	Up to 11 GeV to A, B, or C 12 GeV to D	20 – 24 GeV	▪ Scaling Up FFA Optics to Several GeVs ▪ Dump Cooling & Enviro. Evaluation ▪ Injector Energy increase ~ factor 4. ▪ BBU instability

The Future of CEBAF - Reza Kazimi (*DIS2022 May 3*) 23 Jefferson Lab

DVCS with polarized positrons beam at JLab

The important of beam-charge asymmetry for DVCS was highlighted by the pioneering HERMES experiment
Disposing of a polarized positron/electron beams at JLab → new observables = different sensitivities to GPDs
Beam Charge Asymmetries proposed to be measured at **CLAS12**:
The unpolarized beam charge asymmetry A^C_{UU}, which is sensitive to the **real part of the CFF** → D-term, forces in the proton
The polarized beam charge asymmetry A^C_{LU}, which is sensitive to the **imaginary part of the CFF**
The neutral beam spin asymmetry A^0_{LU}, which is sensitive to **higher-twist effects**

σ: polarization independent CS
$\tilde{\sigma}$: polarization dependent CS

New GPD Observables @ JLab

Physics goal: beam-charge asymmetry for DVCS with polarised electrons and positrons → **separation of DVCS and DVCS-BH interference amplitudes, sensitivity to real part of GPDs**

$$A^C_{UU} = \frac{(Y^+_+ + Y^+_-) - (Y^-_+ + Y^-_-)}{Y^+_+ + Y^+_- + Y^-_+ + Y^-_-} = \frac{\sigma_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

$$A^C_{LU} = \frac{(Y^+_+ - Y^+_-) - (Y^-_+ - Y^-_-)}{Y^+_+ + Y^+_- + Y^-_+ + Y^-_-} = \frac{\tilde{\sigma}_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

$$A^0_{LU} = \frac{(Y^+_+ + Y^-_+) - (Y^+_- + Y^-_-)}{Y^+_+ + Y^+_- + Y^-_+ + Y^-_-} = \frac{\tilde{\sigma}_{DVCS}}{\sigma_{BH} + \sigma_{DVCS}}$$

$$A^C_{LU} \neq A^{\pm}_{LU} = \frac{\pm(\tilde{\sigma}_{INT} \pm \tilde{\sigma}_{DVCS})}{\sigma_{BH} + \sigma_{DVCS} \pm \sigma_{INT}}$$

PEPPo(**P**olarized **E**lectrons for **P**olarized **Po**sitrons) => ***demonstrate feasibility***of using bremsstrahlung radiation of **MeV energy Polarized Electrons** for production of **Polarized Positrons**.

Fix target experiment at CERN

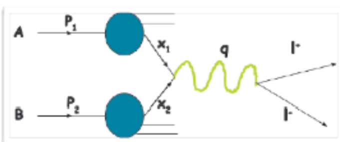
AMBER
Apparatus for Meson and Baryon Experimental Research

- The AMBER experiment at the CERN M2 beamline is a new “QCD Facility” to investigate the Emergence of Hadron Mass
- AMBER phase-I was approved in December 2020, for measurements on
  - Proton radius from muon-proton elastic scattering
  - Pion structure from pion-induced Drell-Yan and Charmonium production
  - Antiproton cross-sections – input for Dark Matter searches

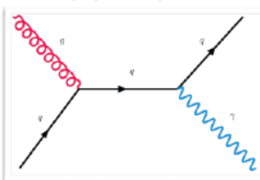
https://amber.web.cern.ch/

Experimental access @AMBER (with pion and kaon beams):

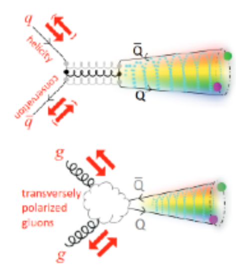
- Drell-Yan



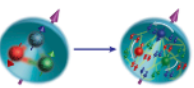
- Prompt-photon production



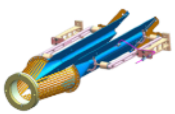
- Charmonium production



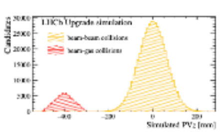
- The planned upgrade of the M2 beamline will provide radio-frequency separated hadron beams.
- High purity kaon beams are being proposed for a phase-II of AMBER:
  - Kaon structure from kaon-induced Drell-Yan and Charmonium production
  - Gluon content in the kaon from direct-photon production
  - Light meson spectroscopy using kaon beams
  - Kaon charge radius from elastic kaon-electron scattering



First spin-physics program at LHC



Unpolarised physics program



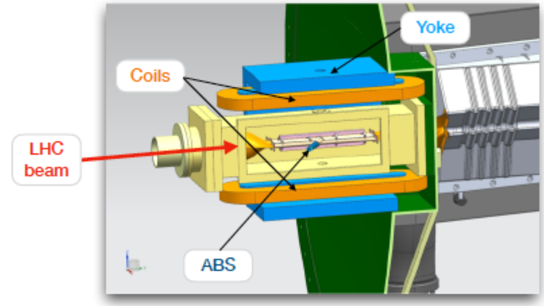
Run in parallel with collider mode

LHCspin

Extending the fixed-target program in Run4

LHC + LHCb + transverse polarised target $H^{\uparrow}, D^{\uparrow}$

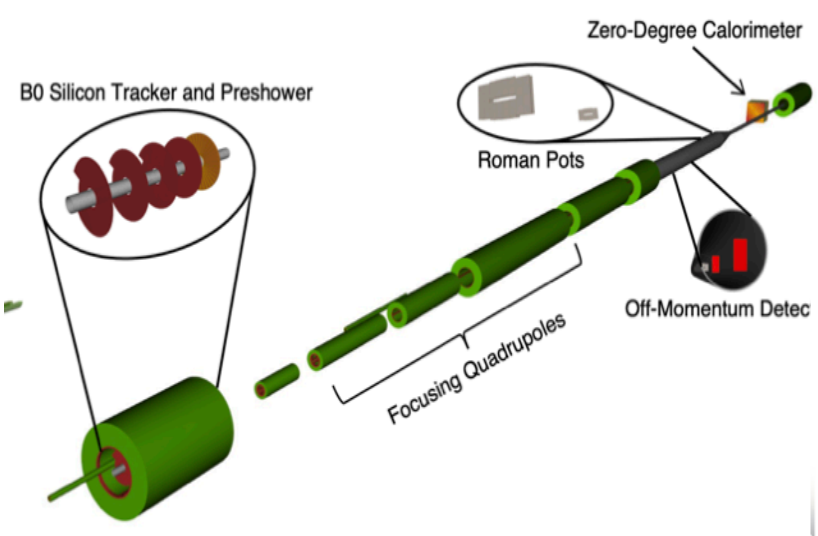
Unique kinematic conditions



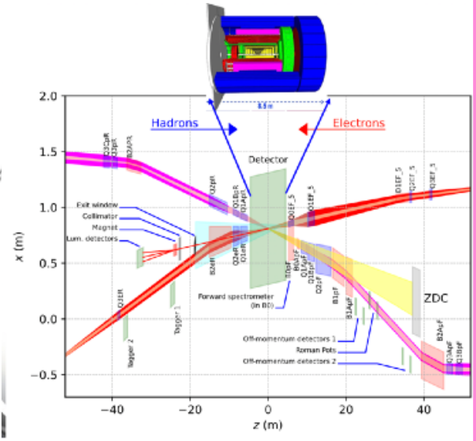
Target Cell

- Almost same position of the SMOG2 cell (L = 20 cm, D = 1 cm)
- Inject both unpolarised and **polarised gas** (only way to bring polarised physics at LHC)
- $P \simeq 85\,\%$ achieved at HERMES

EIC Far-Forward

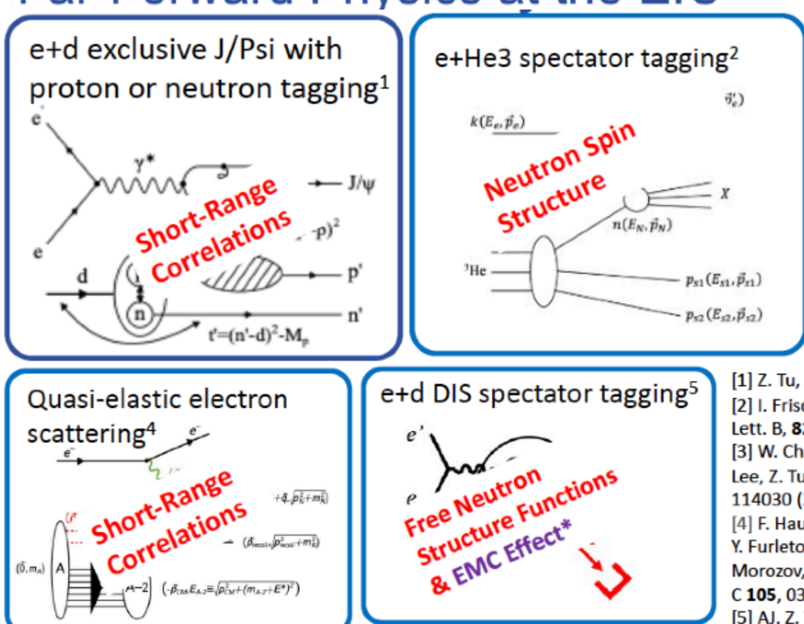


Far-forward/ backward area at EIC : +/-40m

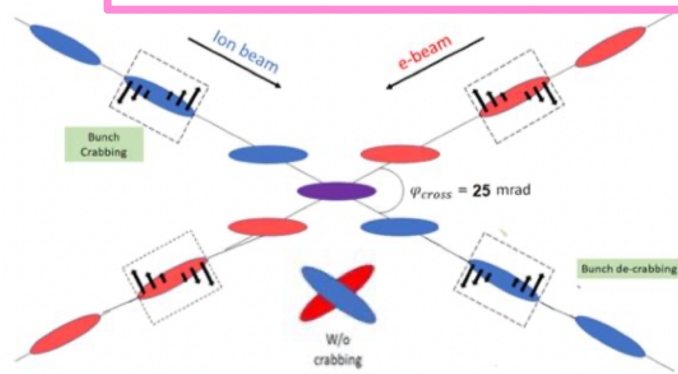


Far-Forward Detector Instrumentation for the ATHENA Collaboration at the EIC
Alex Jentsch
Coherent Deep Virtual Compton Scattering on ^{4}He with CORE@EIC
Andrey Kim
Incorporating Critical Beam Effects into Physics and Detector Simulations for the Electron-Ion Collider
Brian Page
Study of exotic nuclei made easy – a potentially novel topic for physics at the EIC
Brynna Moran

Far-Forward Physics at the EIC



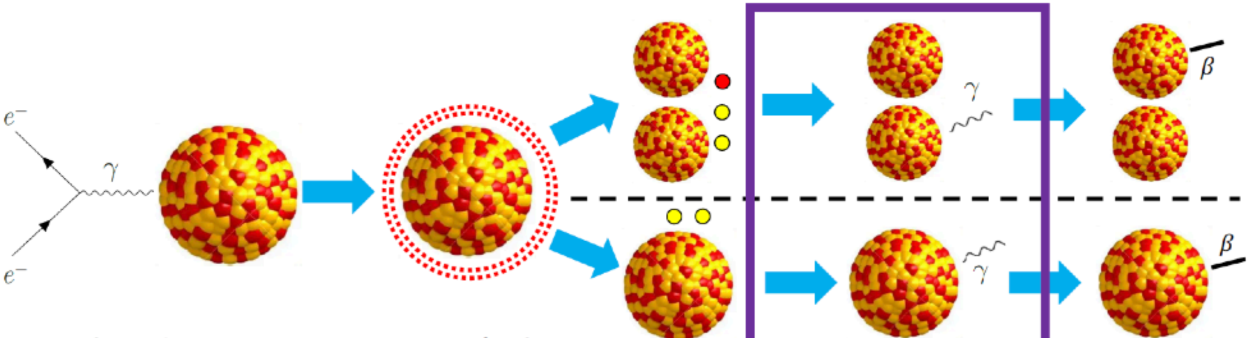
[1] Z. Tu, AJ, et al., Phys. Lett. B **811,** 135877 (2020)
[2] I. Friscic, D. Nguyen, J. R. Pybus, AJ, *et al.,* Phys. Lett. B, **823**, 136726 (2021)
[3] W. Chang, E.C. Aschenauer, M. D. Baker, AJ, J.H. Lee, Z. Tu, Z. Yin, and L. Zheng, Phys. Rev. D **104**, 114030 (2021)
[4] F. Hauenstein, AJ, J. R. Pybus, A. Kiral, M. D. Bake Y. Furletova, O. Hen, D. W. Higinbotham, C. Hyde, V. Morozov, D. Romanov, and L. B. Weinstein, Phys. Rev C **105**, 034001 (2022)
[5] AJ, Z. Tu, and C. Weiss, Phys. Rev. C **104**, 065205 (2021) **(Editor's Suggestion)**



Simulating Beam Effects in PYTHIA
- Collision Vertex
- Beam Momenta
- Final State Particle Distributions

EIC Far-Forward

Isotope production at the EIC



Ground State isotopes energy: ~105-110 GeV/nucleon
⇒ Gamma value: ~100
⇒ Time dilation allows direct detection for short lived decay particles

Isotopes in ground state and decay photons

This is primarily where the EIC could potentially contribute

5/04/2022 6

- We have shown that the EIC has the potential to produce exotic nuclei.
- These nuclei can be detected and identified using the proposed optics of the second interaction point with its secondary focus.
- Studying the level structure of the produced isotopes will be possible through the detection of the de-excitation photons.

Motivating Questions

- Would the high-energy electron-heavy nucleus scattering of the future EIC have the capability to produce exotic nuclei?
- Can we go on to detect and correctly identify the produced exotic nuclei?
- Can we also study the level structure of the nuclei by detecting the decay photons? What requirements does this place on the far forward detection area?

Advantages of EIC in Rare Isotope Studies:

- High energy collisions

-Survey-type experiment

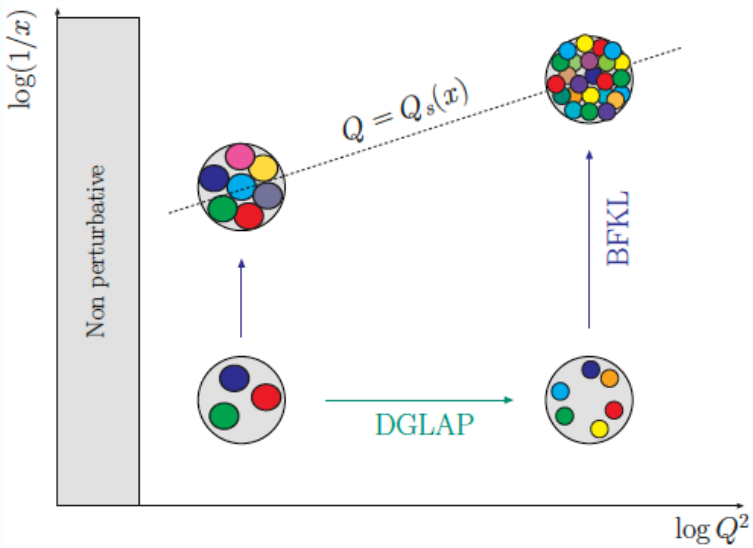
2 Interaction Regions: IR6 and IR8

2022 EIC Detector Proposal Advisory Panel report cites these types of studies when discussing potential future experiments.

Small-x physics: beyond standard evolution

Small-x physics extremely interesting in its own merit.

QCD in a new regime



- A lot of recent progress towards making predictions more precise and accurate → see B. Xiao's talk
- Effects larger in pA, $A^{1/3}$ enhancement of the saturation scale
- Also can be studied from diffraction, in a relative clean fashion [see E. Iancu's talk]

Can we study the onset of saturation and its connection to (resummed) DGLAP with as little modelling as possible, in a clean (=protons, perturbative) setting?

What you should know about UPC

- **Ultraperipheral collisions are providing a new physics program based on γγ, γ+Pb and γ+p collisions**
  - Sit "alongside" the hadronic HI (QGP) physics program at RHIC and the LHC
  - Clean environment allowing precise measurements
- **Results being shown at DIS include**
  - Dileptons (ee, μμ, ττ) - photon luminosity, geometric dependence of photon fluxes
  - Impact of linear photon polarization
  - BSM searches with ττ & γγ final states - already competitive with previous searches, and much more Run 3/4 data coming
  - Vector mesons - parton structure and spatial imaging
  - Photonuclear jets - measurements of nPDFs, studies of gluon polarization
  - Collectivity in hadronic photonuclear final states
- **Excellent synergies between RHIC & LHC**
- **Previews of the EIC physics program in the decade before EIC!**

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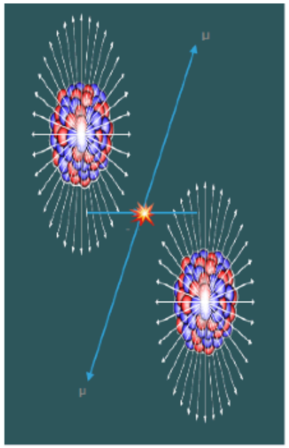
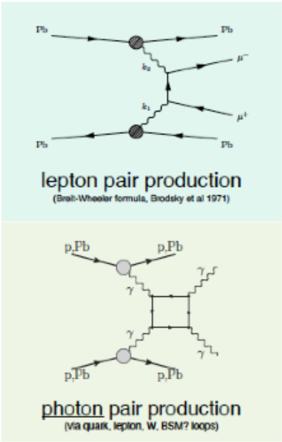
Exclusive γγ processes



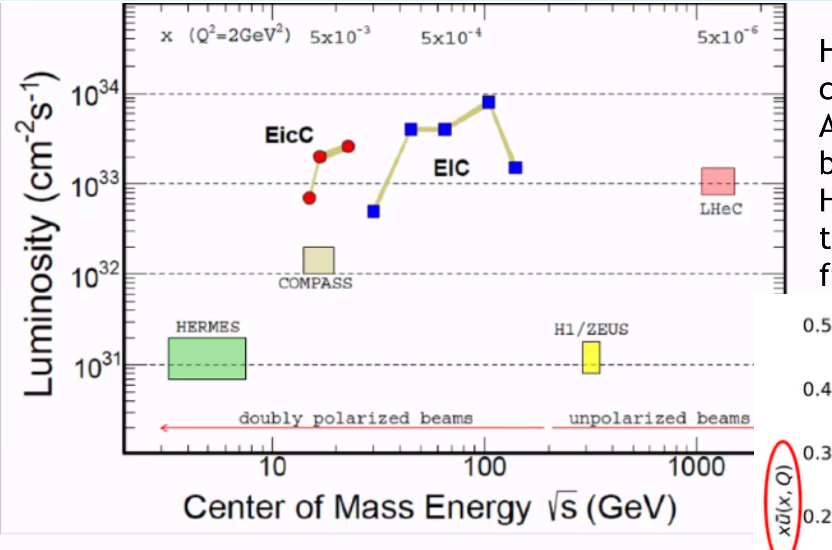


γγ "luminosity"
lepton decays

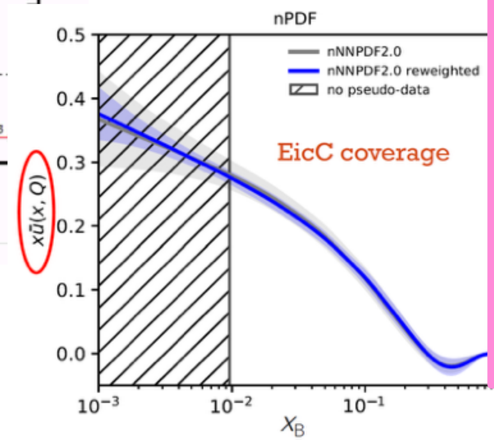
rare QED processes
BSM physics

Heavy ion collisions are excellent QED & BSM laboratories!

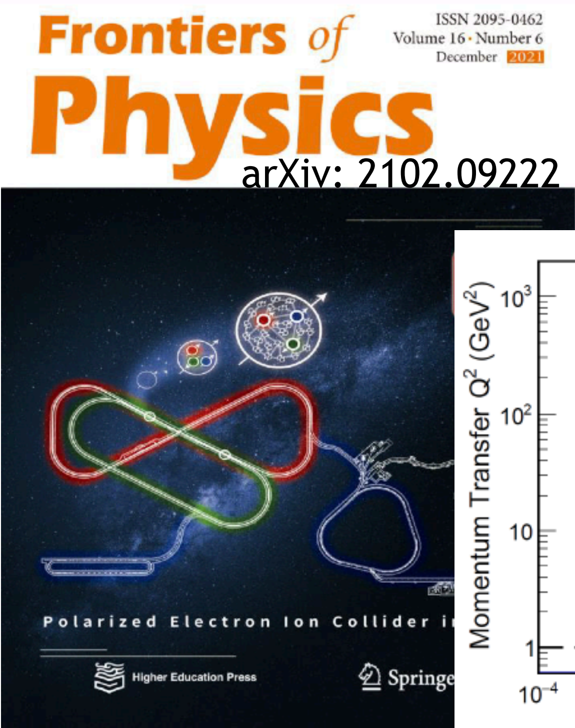
EIC and EIcC



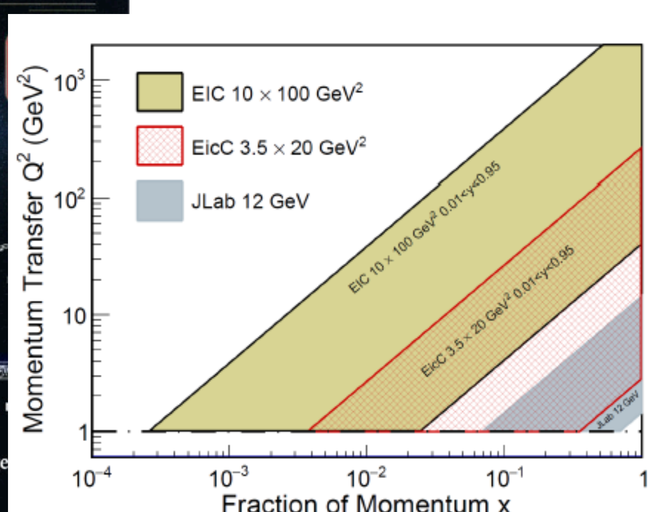
HIAF construction is near complement
Aiming to finish EicC CDR by 2023
Hope to get support in the next 5-year-plan and first collision in 2032



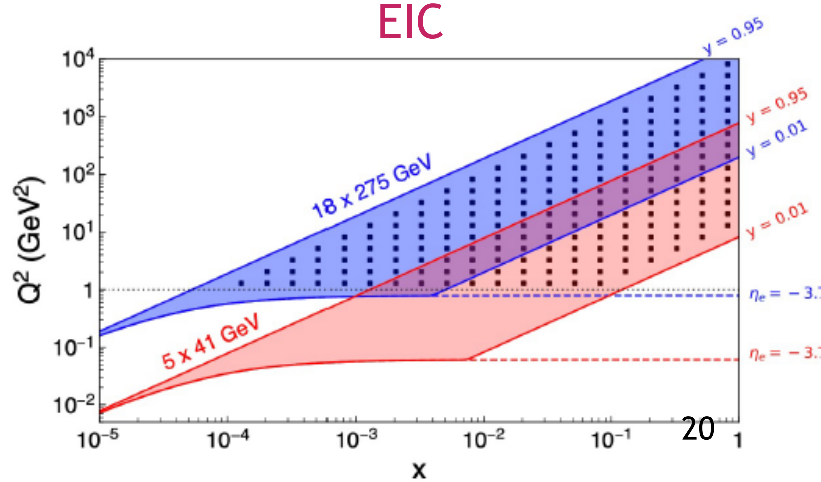
SIDIS reconstruction and observables at EIC with ATHENA
Connor Pecar
Exclusive Lepton Pairs at the Electron-Ion Collider
Krzysztof Piotrzkowski
Study of SIDIS observables with the Athena Detector
Duane Byer
Proton and Nuclear Collinear Parton Densities at the Electron Ion Collider using simulated ATHENA Data
Paul Richard Newman
Overview of Electron-ion collider in China
Jinlong Zhang



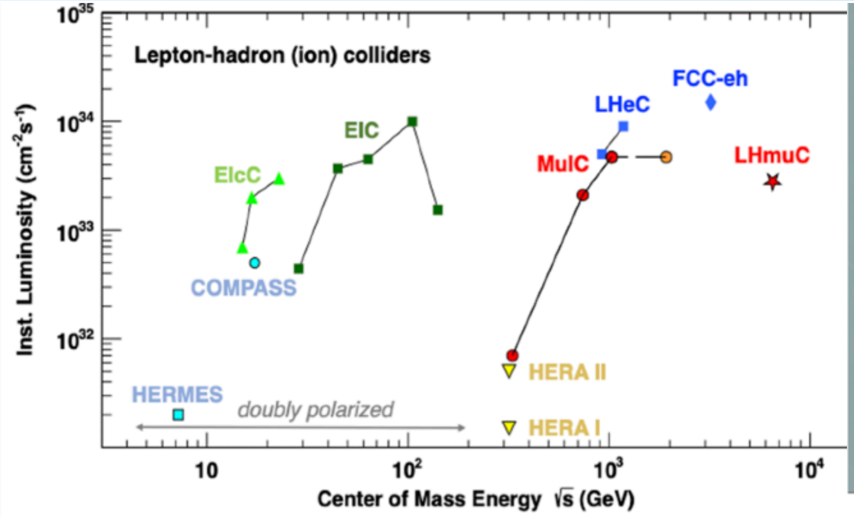
arXiv: 2102.09222

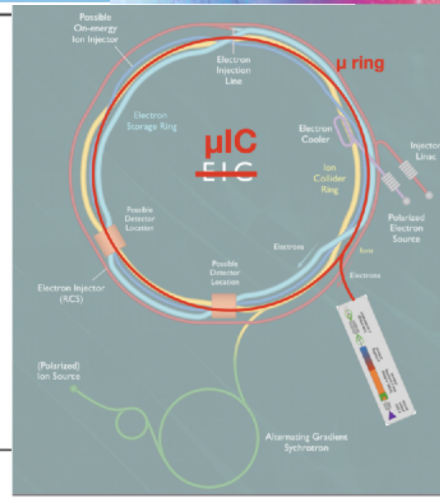


EIC



Muon Colliders

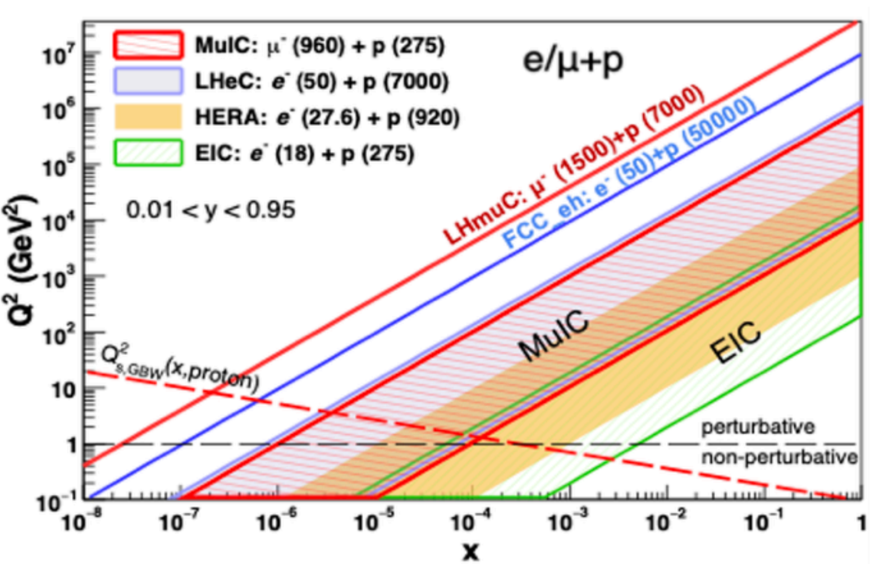




The Physics Potential of a TeV Muon-Ion Collider
Darin Acosta

A Future Muon-Ion Collider at Brookhaven National Laboratory
Ethan Cline

Detector design for a multi-TeV muon collider
Nazar Bartosik



multi-TeV Muon Collider facility

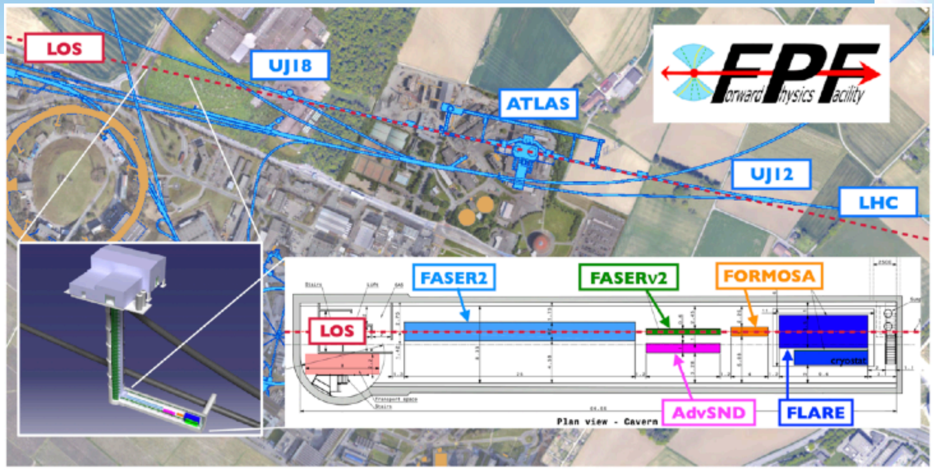
The extensive physics program at a Muon Collider requires a multipurpose detector
↳ **the latest design of the CLIC experiment taken as a starting point** *(e^+e^- collider)*

LHC experiments have demonstrated the great power of the Particle Flow approach
which relies on high-granularity calorimeter data and high-quality track reconstruction

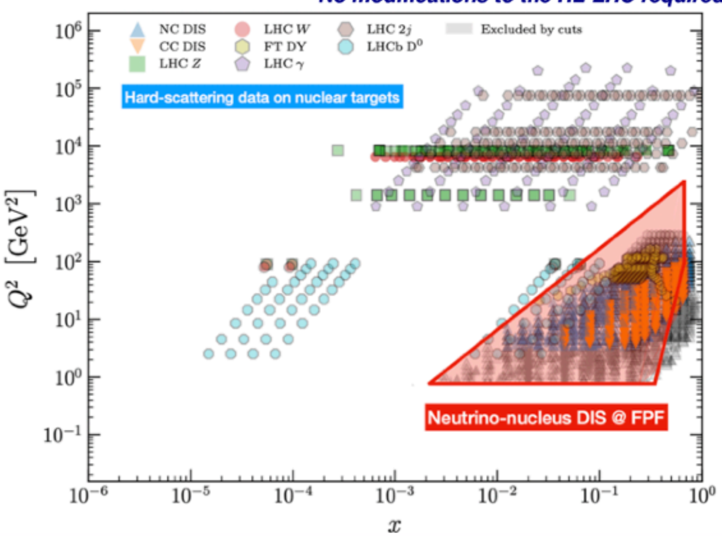
The main components of the baseline detector:

- **Tungsten nozzles** extending over 6cm → 6m from the interaction point (IP)
- **All-silicon tracker** with double-layer structure in the Vertex Detector
- **High-granularity sampling calorimeters**
  - **ECAL** 40 layers of **W + Si**
  - **HCAL** 60 layers of **Fe + scintillator + SiPM**
- **Superconducting solenoid:** B = 3.57T magnetic field
- **Muon spectrometer:** 7 layers of **Fe + RPC**

Neutrinos Experiments



No modifications to the HL-LHC required!



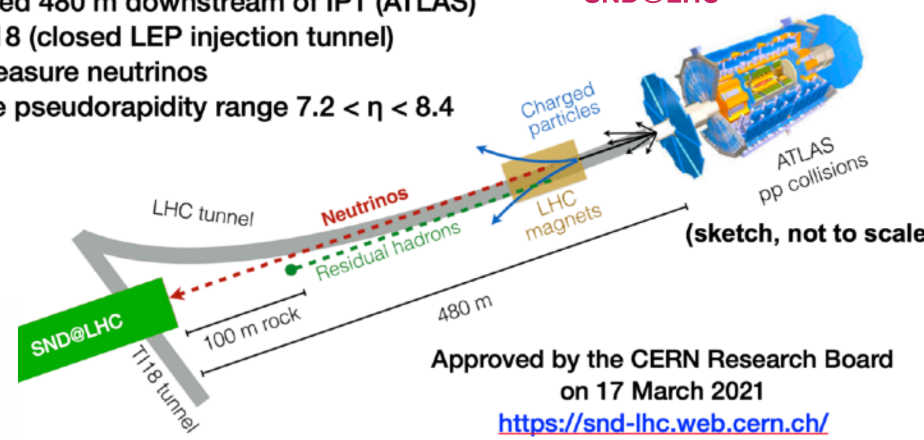
Scattering and Neutrino Detector at the LHC
Marco Dallavalle

Deep-inelastic scattering with TeV neutrinos at the Forward Physics Facility
Juan Rojo

Precision measurements of (anti)neutrinos interactions with the SAND detector at the DUNE near site
Gabriele Sirri

Probing Free Nucleons with (Anti)neutrinos
Riccardo Petti

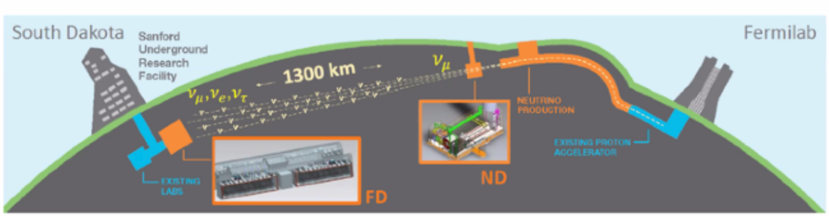
Stand-alone experiment,
located 480 m downstream of IP1 (ATLAS)
in TI18 (closed LEP injection tunnel)
to measure neutrinos
in the pseudorapidity range 7.2 < η < 8.4



Approved by the CERN Research Board on 17 March 2021
https://snd-lhc.web.cern.ch/
to take data in 2022-2025

2

DUNE: Deep Underground Neutrino Experiment



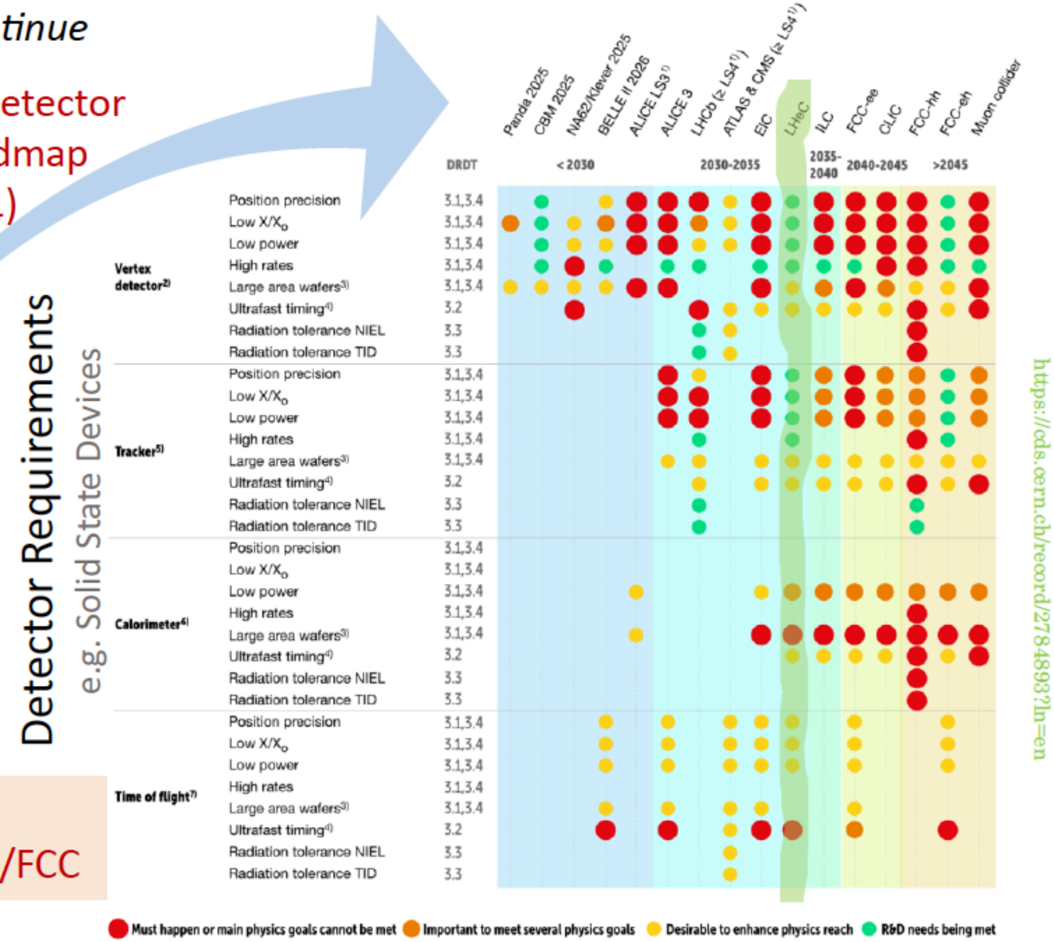
Make the invisible visible – Detector R&D for DIS

Dedicated detector R&D efforts are to continue

Major challenges:
- Tracking & Vertexing
- 1^{o} close to the beamline
- High-resolution calorimetry

European Detector R&D Roadmap (2021)

Synergies with many other major projects, potentially as stepping stones



Potentially one detector for a joint DIS and Heavy-Ion program @ HL-LHC/FCC

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Summary

We have a very rich, diverse and challenging Physics Program for the next decades

The EIC community can give a very valuable contribution

Which interests, expertises and possible contributions from the EIC_net community?

Time to discuss…

Phenomenology of pion GPDs: Sullivan process

Question: *Can we access pion's GPDs through experiment?*
[D.Amrath at al.-EPJC:179(58)2008]

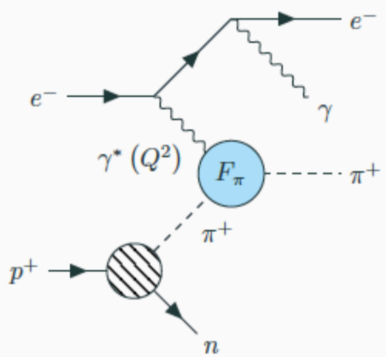
Sullivan process [J.D.Sullivan-PRD:1732(5)1972]

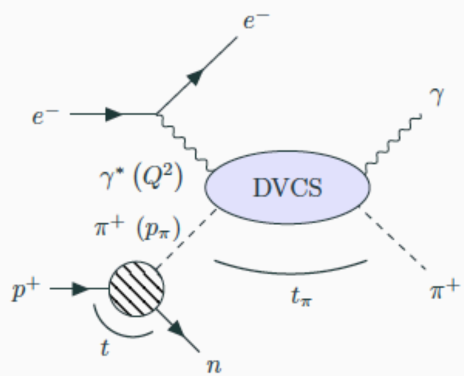
Deep inelastic electron-proton scattering with πn fixed final states.

One-pion-exchange approximation: [D.Amrath et al.-EPJC:179(58)2008]

- $|t|^{\text{Max.}} = 0.6\,\text{GeV}^2$
- Factorization: $\sigma_L^{\gamma^*} >> \sigma_\perp^{\gamma^*}$

} Met at EIC [EICYR:phys.ins-det/2103.05419]



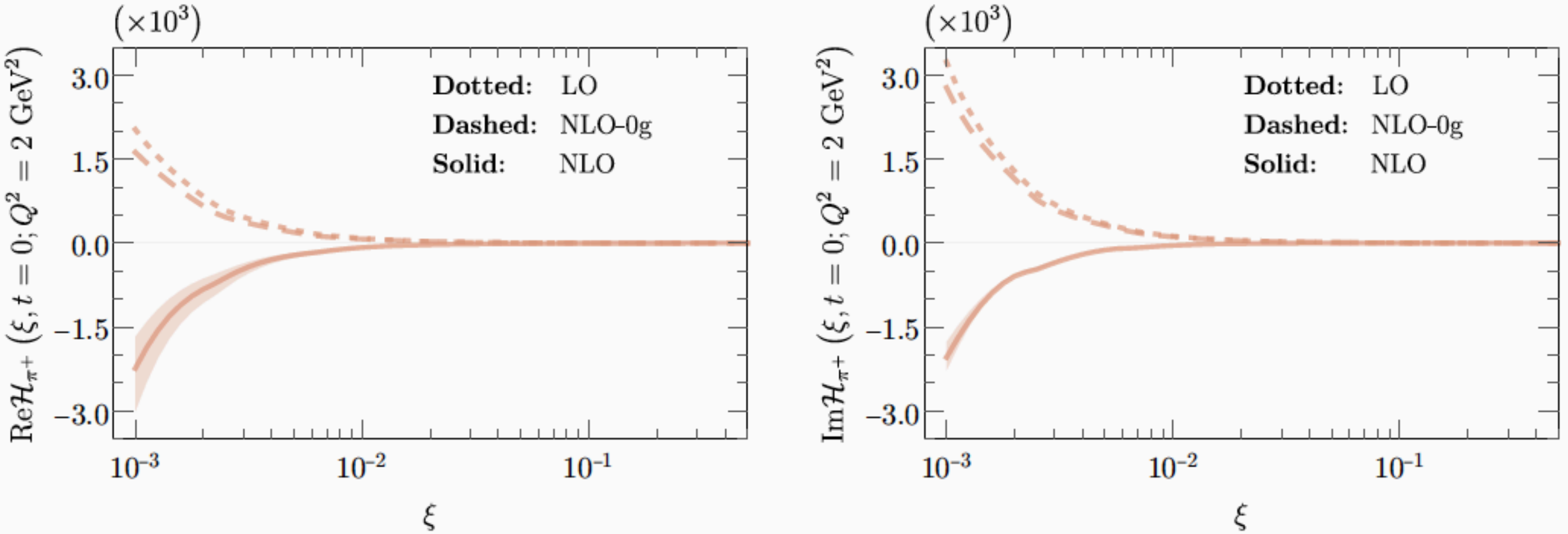


DVCS amplitudes are parametrized by hadron GPDs.
[X.Ji-PRD:7114(55)1997]

Employed for EFFs.
[G.M.Huber at al.-PRC:045203(78)2008]

Can we probe DVCS contribution through experiment?
[D.Amrath at al.-EPJC:179(58)2008]

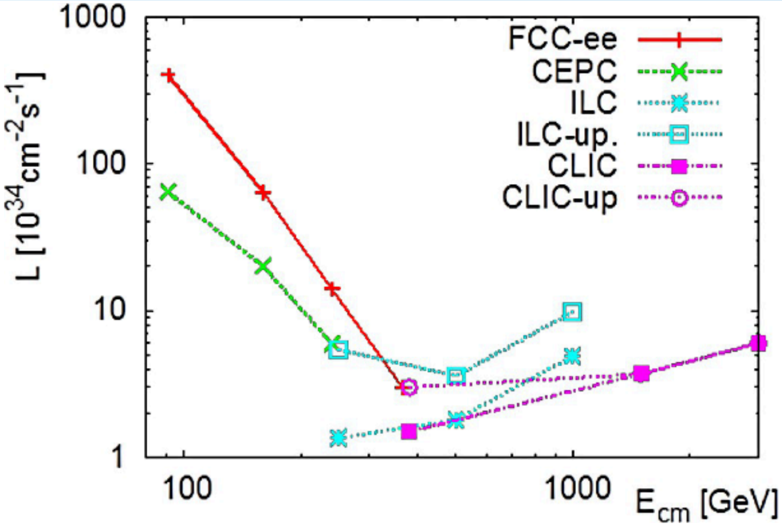
Phenomenology of pion GPDs: Compton Form Factors



- Small effect of NLO corrections to quark amplitudes.
- Dominant effect of gluons.

Gluon dominance makes essential at least NLO accuracy in any phenomenlogical analysis of DVCS at an EIC.

e+e- collider:
FCC-ee, CEPC, ILC, CLIC



QCD at FCC-ee
Eduardo Ploerer

Unique QCD precision studies accessible at FCC-ee (CEPC, ILC):

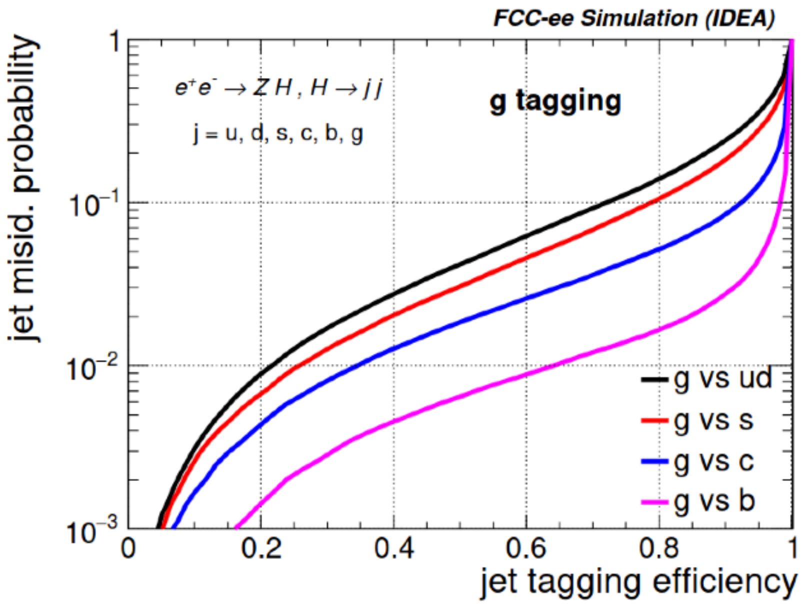
NnLO+NnLL jet substructure

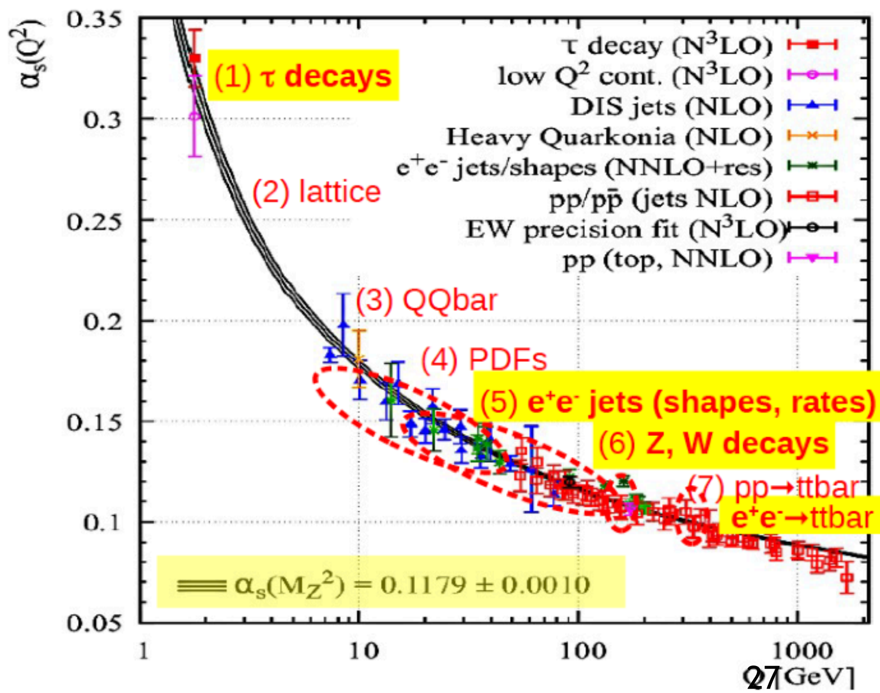
<1% control of colour reconnection

High-precision hadronization

Per-mille a_s via hadronic Z,W,t decays, evt shapes...

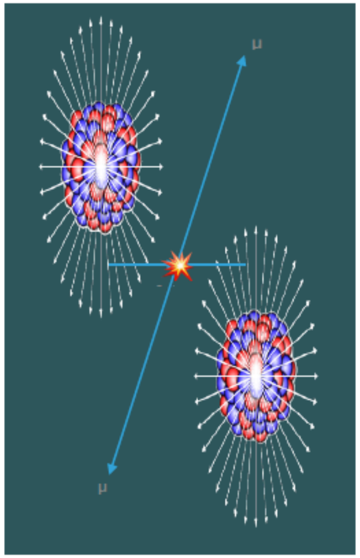
Quark-gluon discrimination

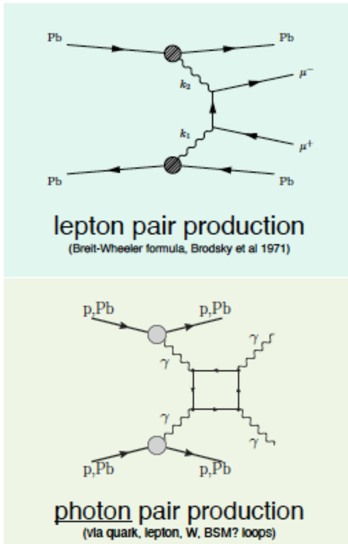




UPC at heavy ion colliders

Exclusive γγ processes



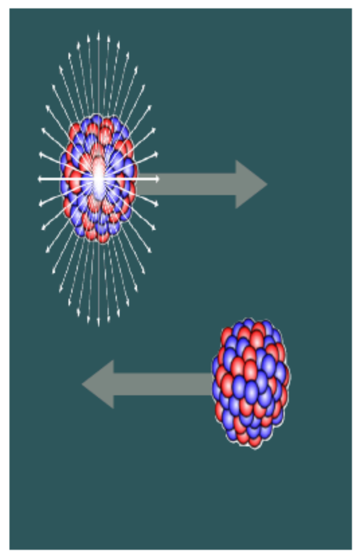


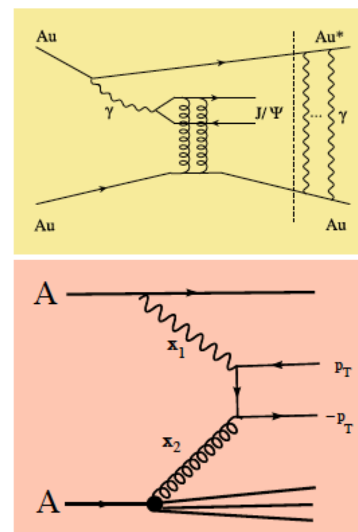
γγ "luminosity"
lepton decays

rare QED processes
BSM physics

Heavy ion collisions are excellent QED & BSM laboratories

Photonuclear processes



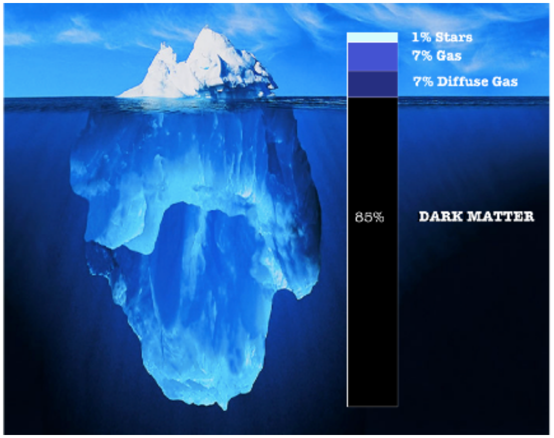


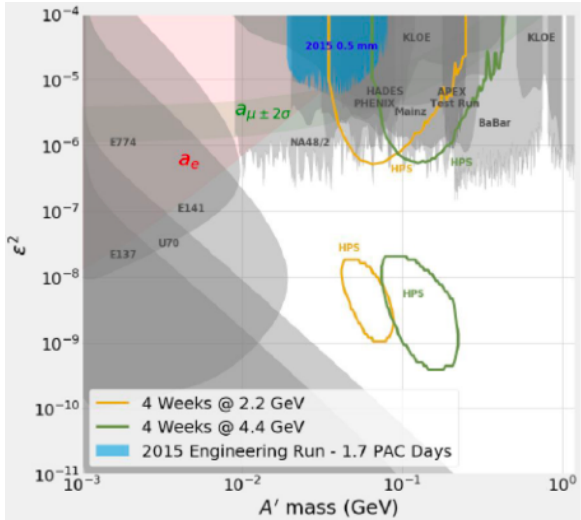
"exclusive"/elastic
vector meson production
nuclear geometry
nuclear PDFs/GPDs
parton saturation?

inelastic hadron and
jet production:
nuclear PDFs
parton saturation?

Photonuclear processes provide similar capabilities to ep/eA machines!

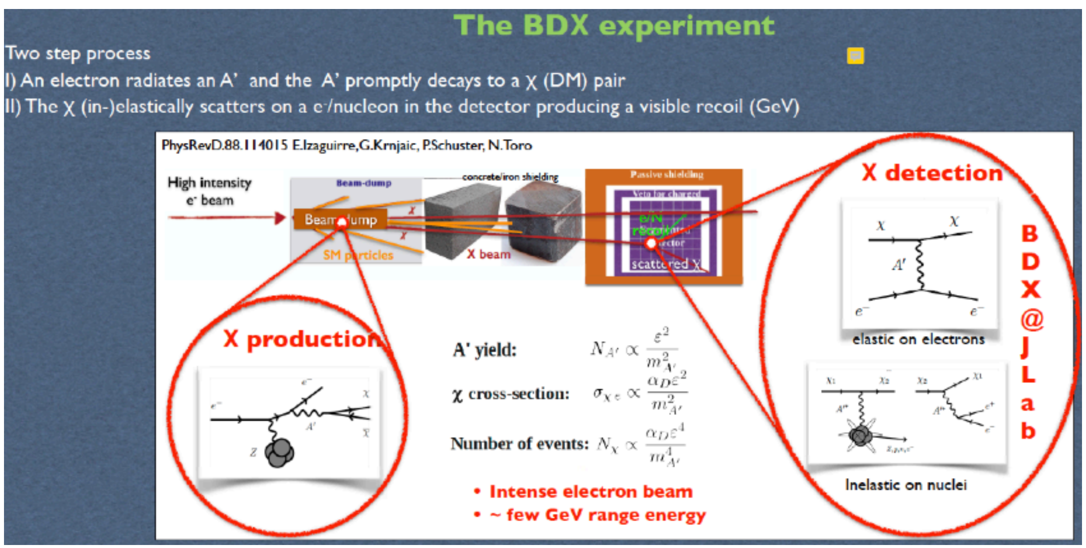
Dark Matter searches





Dark Sector searches at the intensity frontier
Marco Battaglieri
Dark matter production with light mediator exchange at future e+e- colliders
Aleksander Zarnecki

@nJLab BDX experiment

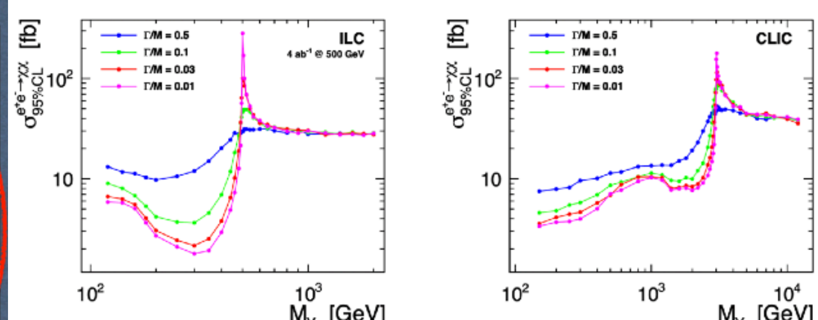


@ ILC and CLIC

Future e+e− colliders: complementary option for DM searches.

New framework for mono-photon analysis developed

Combined limits for Vector mediator



Radiation suppressed for narrow mediator with $M_Y \sim \sqrt{s} \Rightarrow$ weaker limits