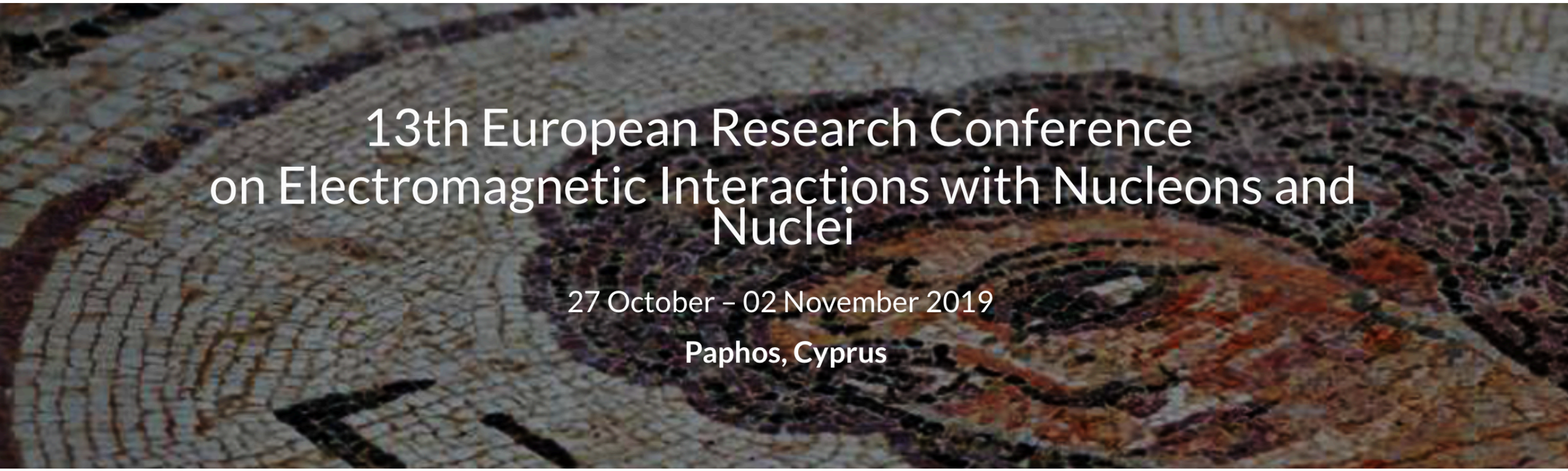
Direction in Hadron Physics (Exp.)

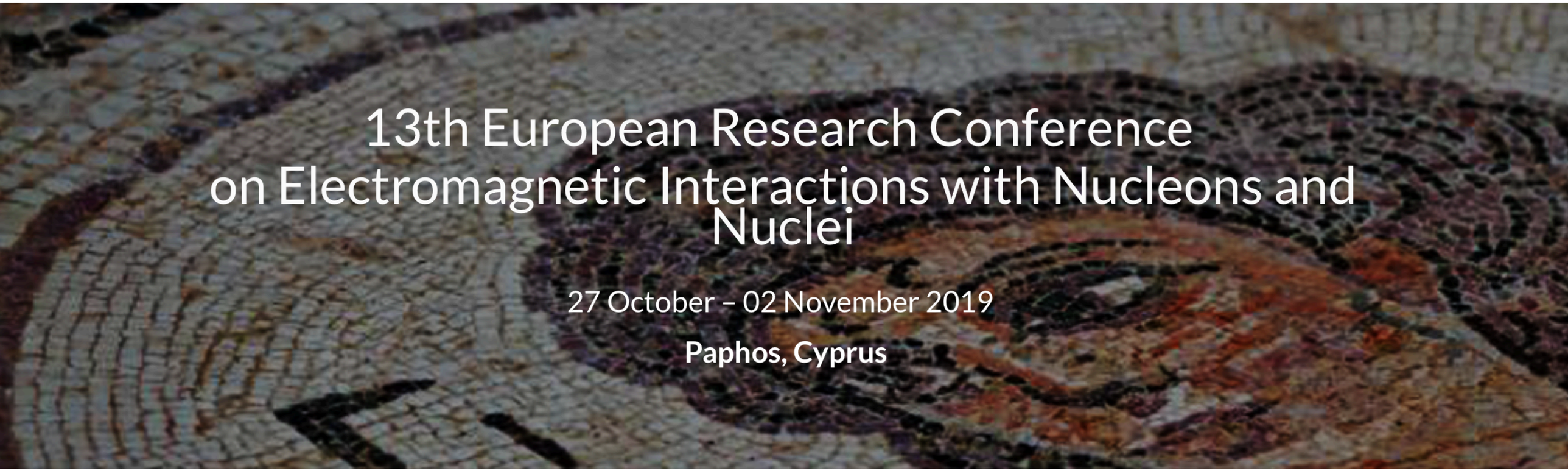


Ernst Sichtermann
Lawrence Berkeley National Laboratory

Office of Science
U.S. Department of Energy

BERKELEY LAB

Direction(s) in Hadron Physics (Exp.)



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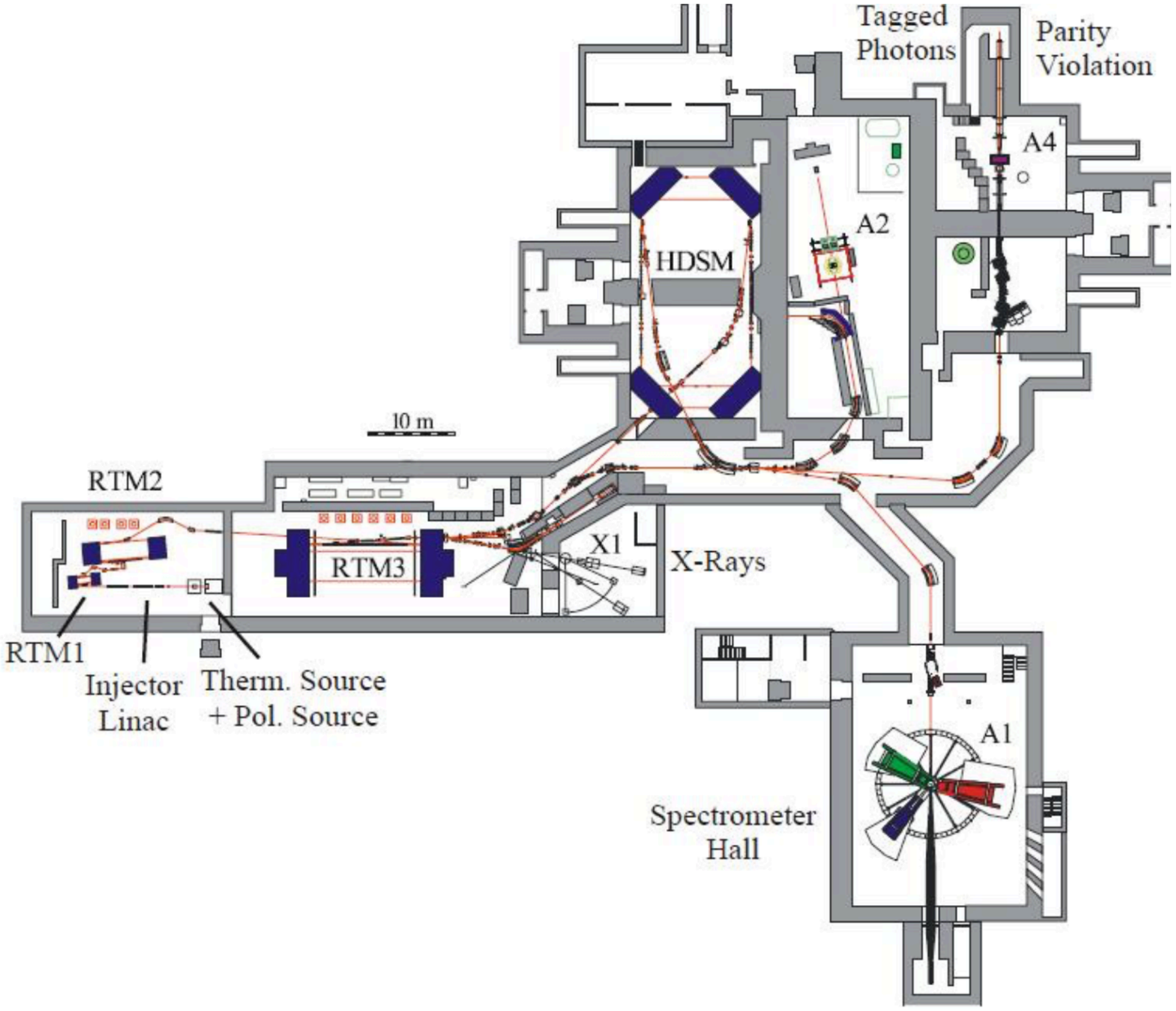
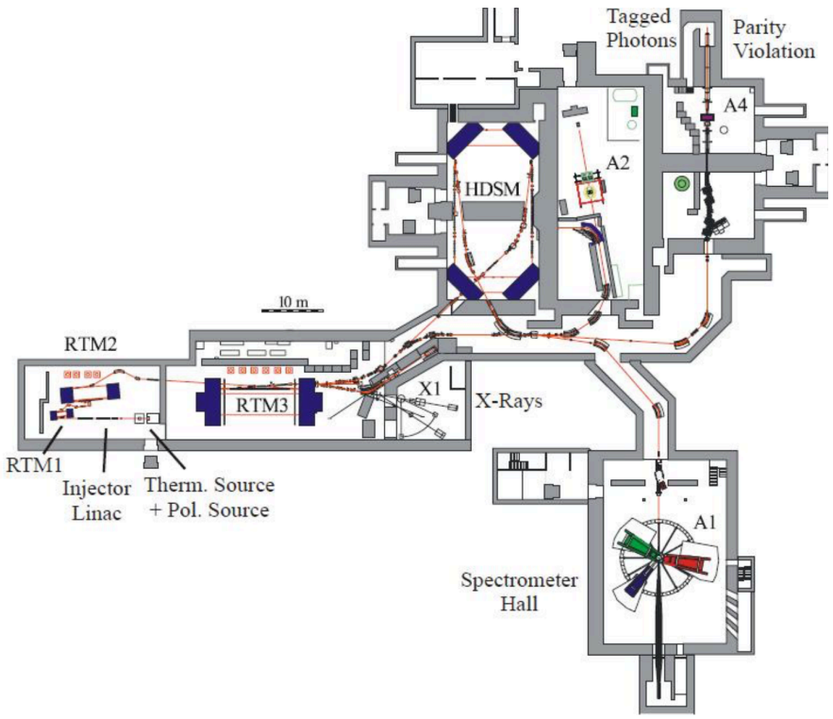
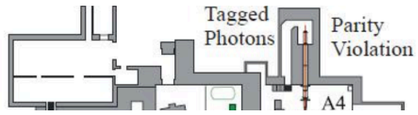
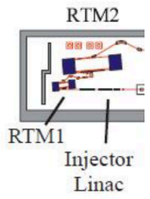
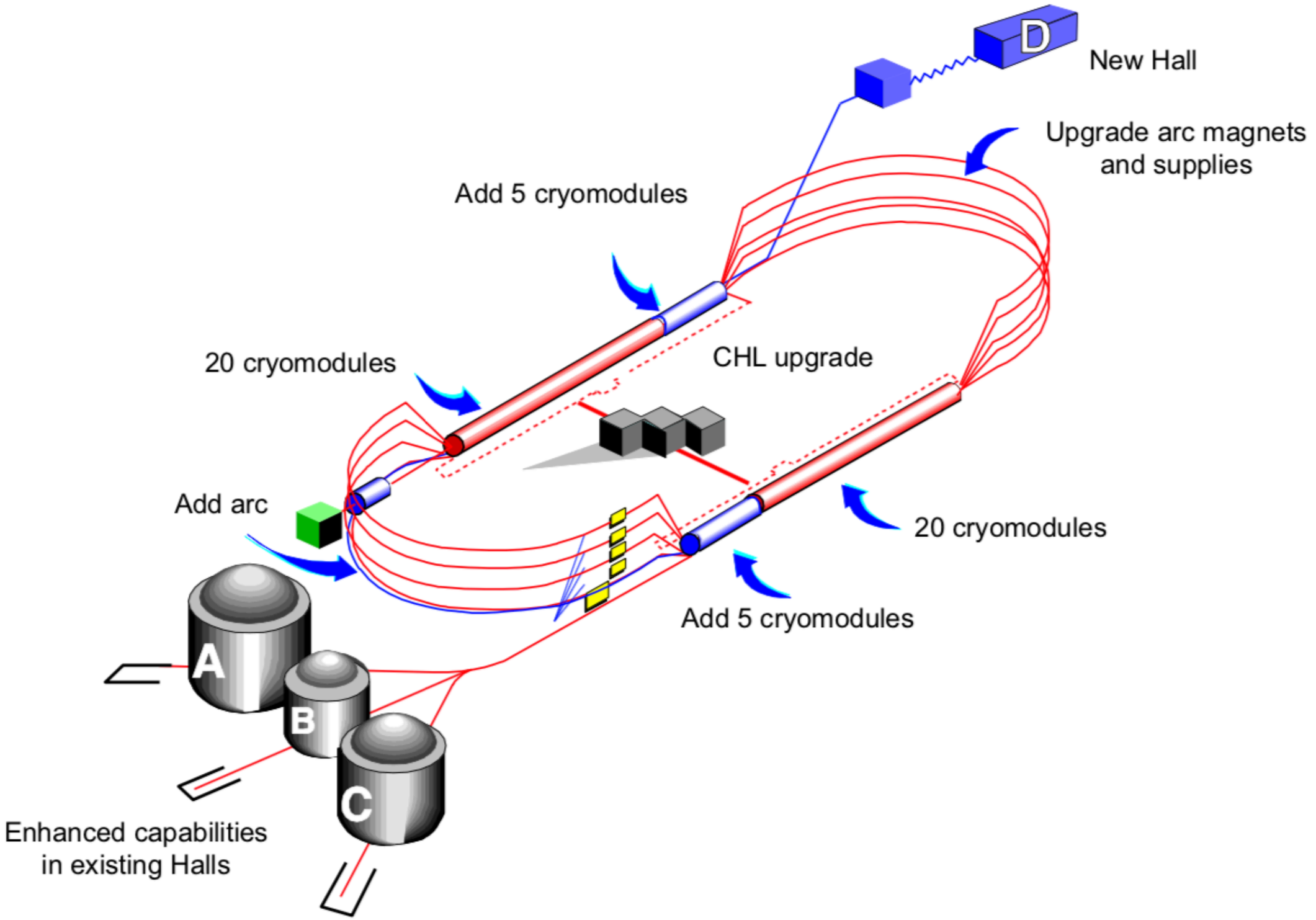


Mainz Microtron, 1.6 GeV high-intensity polarized electron beams


Tagged
Photons
Parity
Violation
A4
A2
HDSM
10 m
RTM2
RTM3
X1
X-Rays
RTM1
Injector
Linac
Therm. Source
+ Pol. Source
A1
Spectrometer
Hall

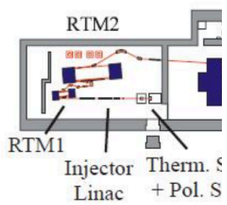


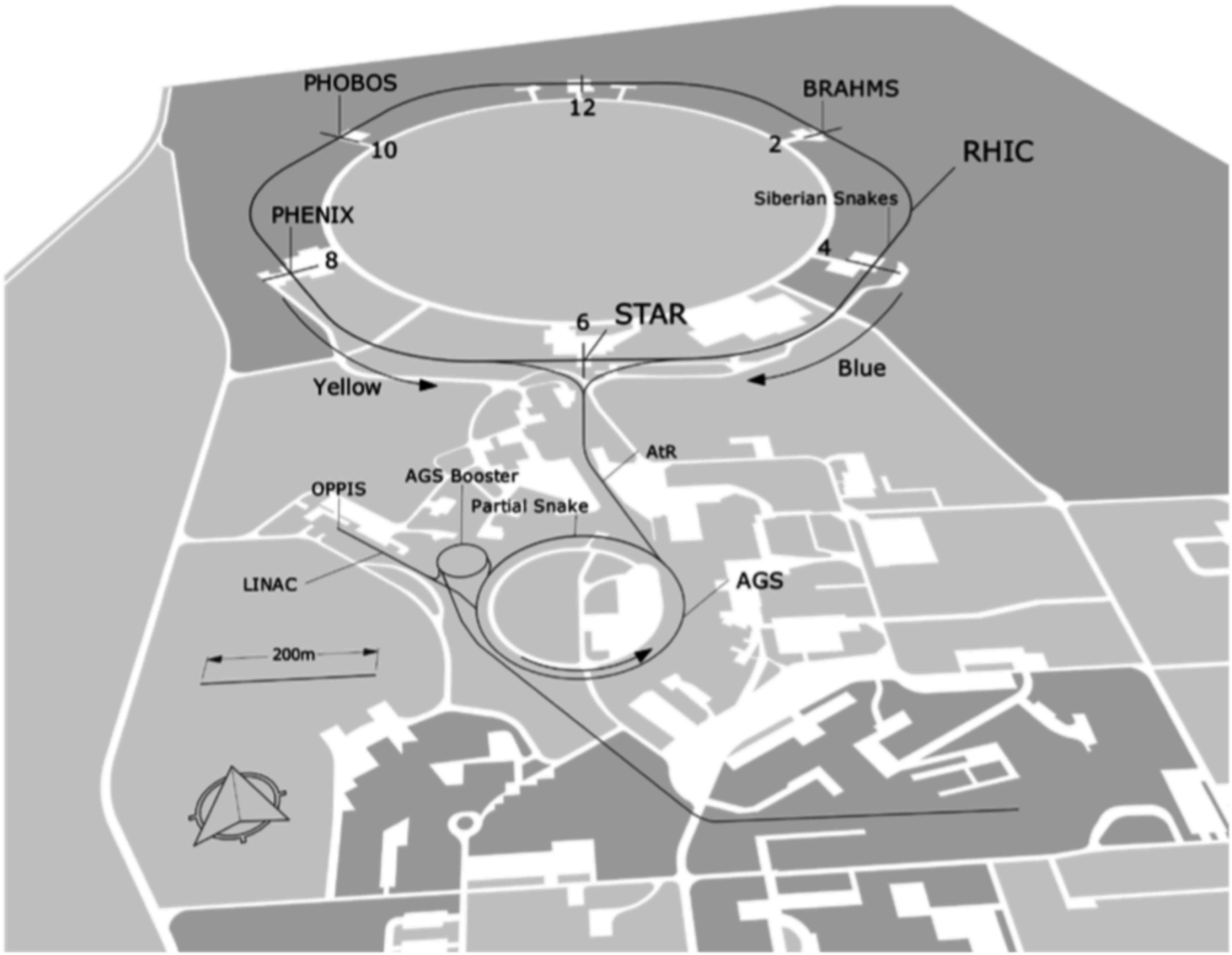




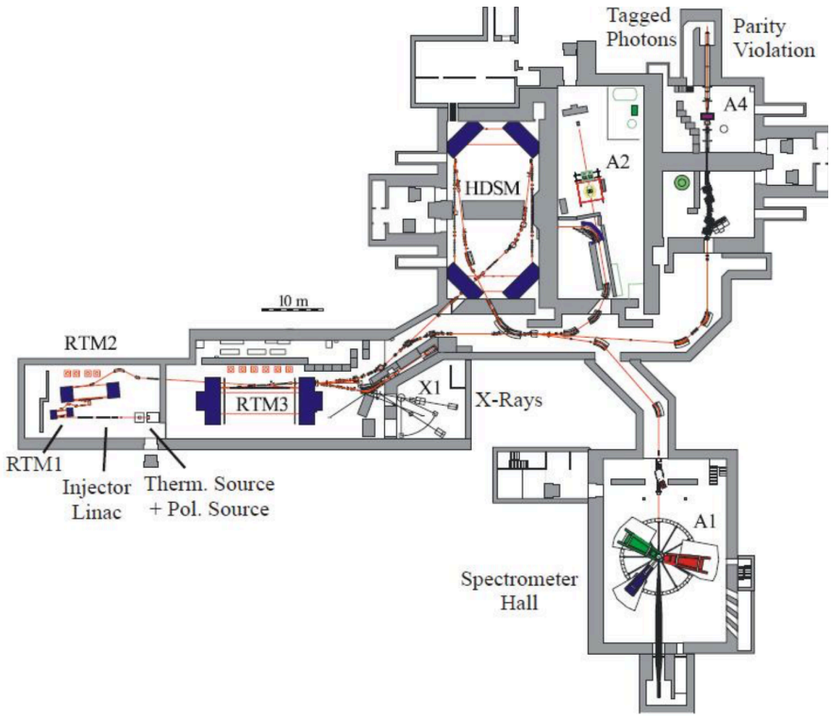
Jefferson Lab, 12 GeV high intensity polarized electron beam

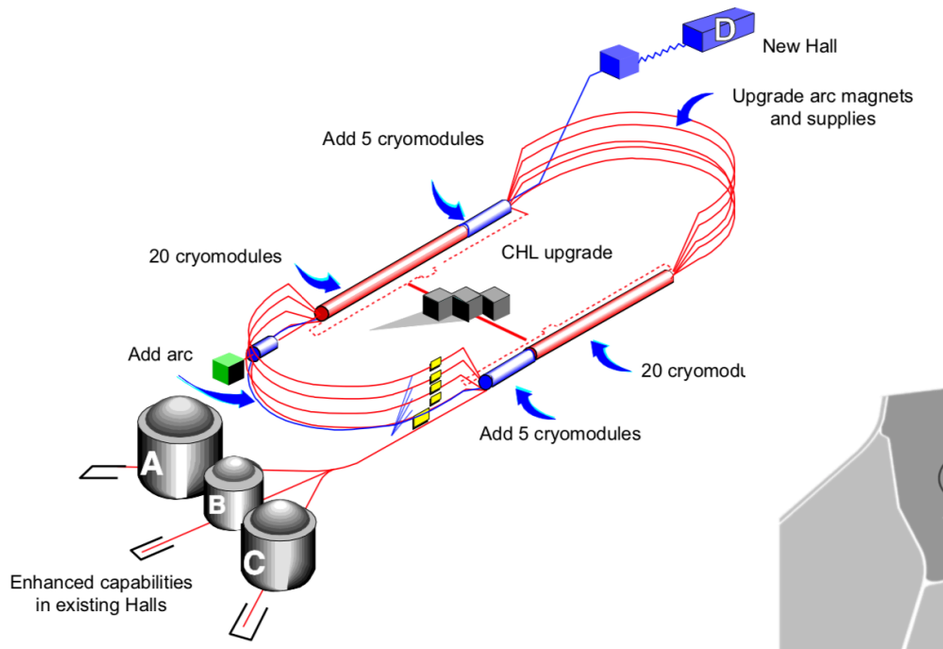
the world's only polarized proton collider…



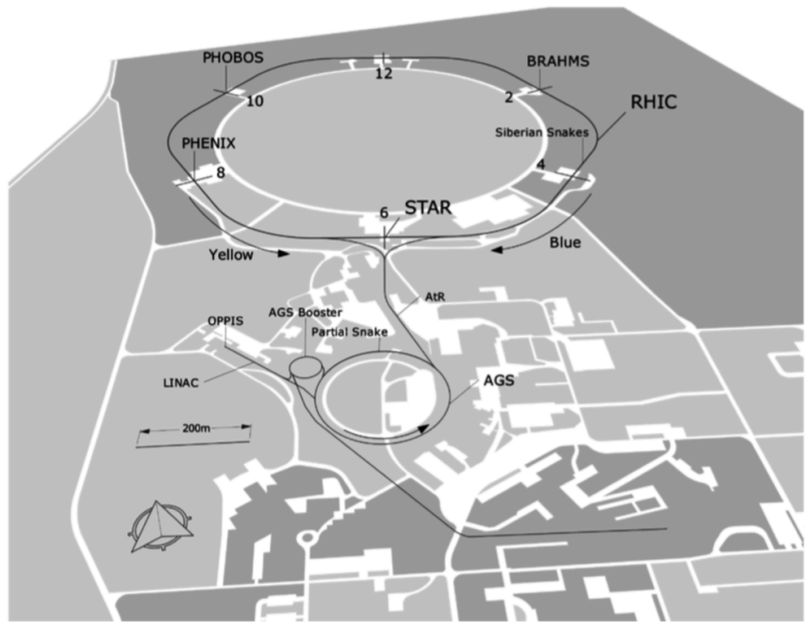


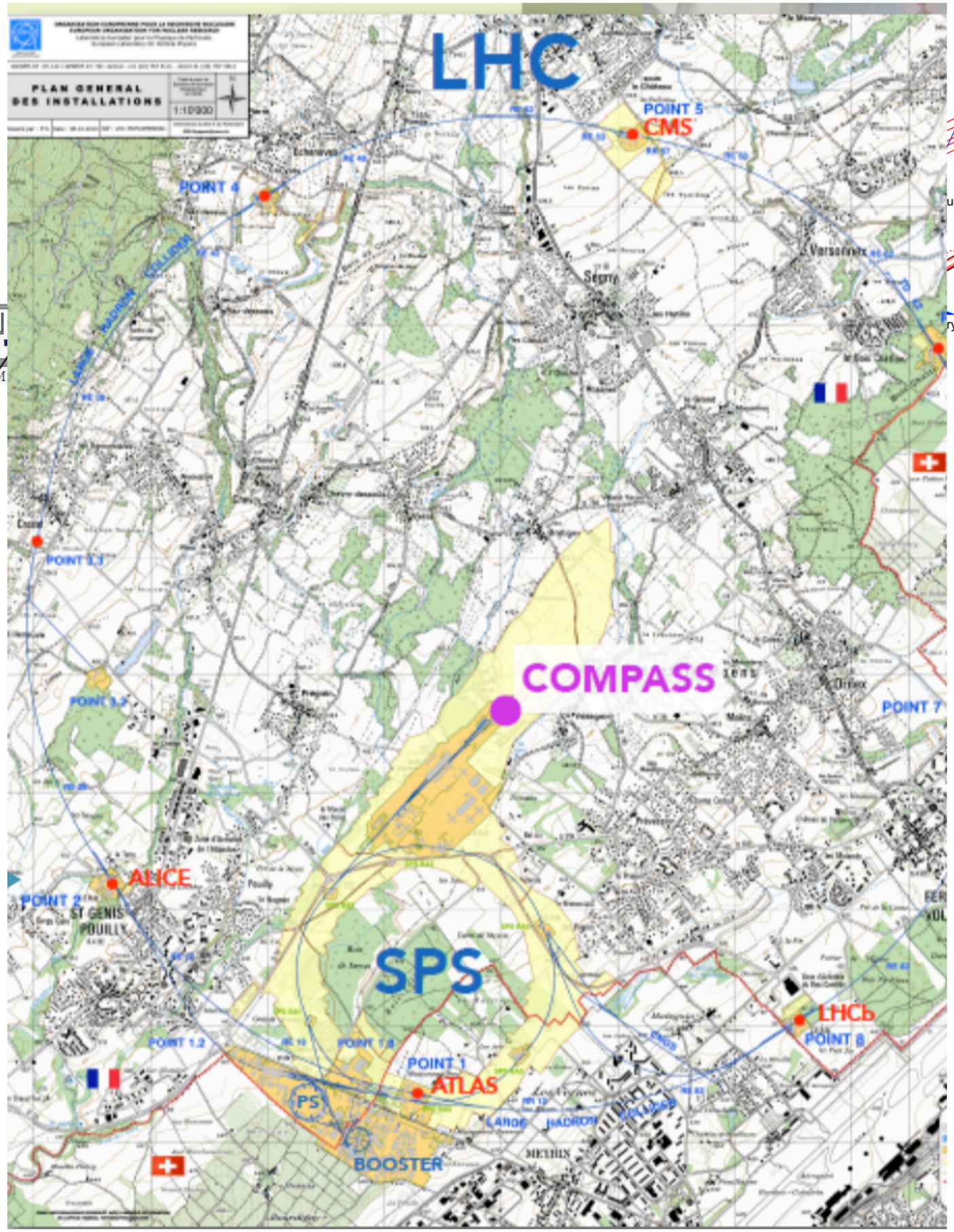
Relativistic Heavy Ion Collider, up to 510 GeV polarized proton-proton collider

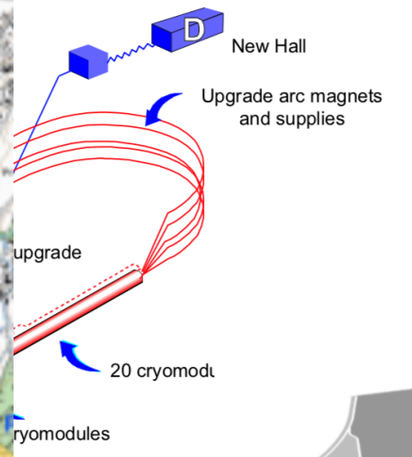




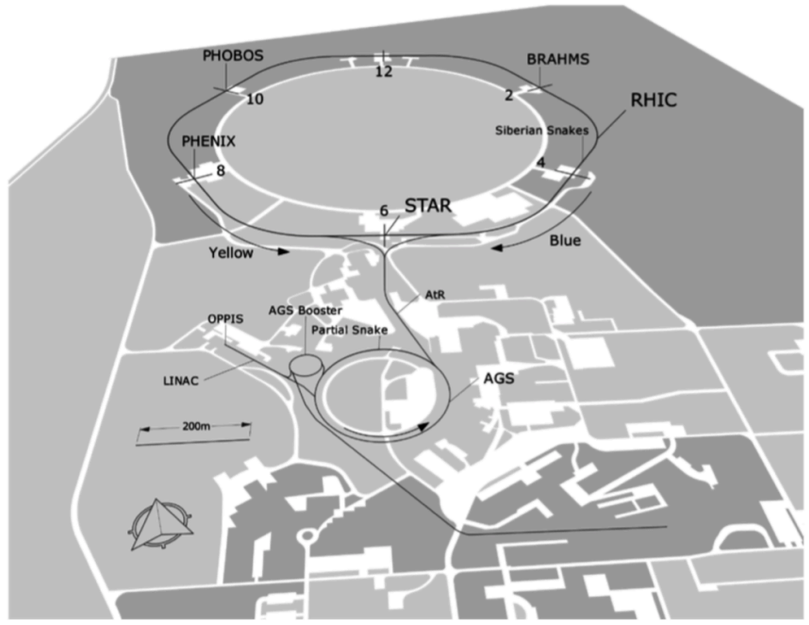
the world's only polarized proton collider…





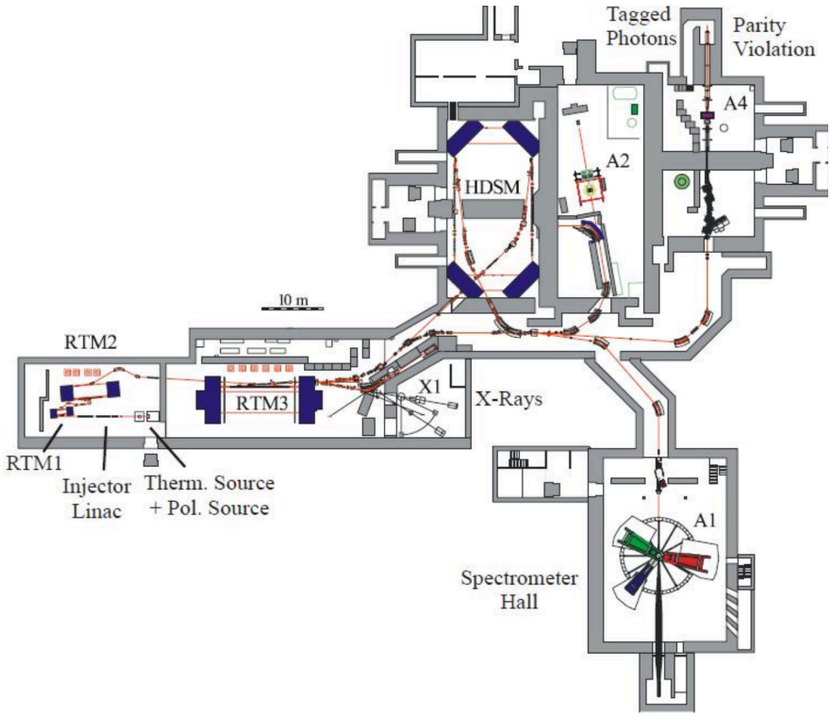


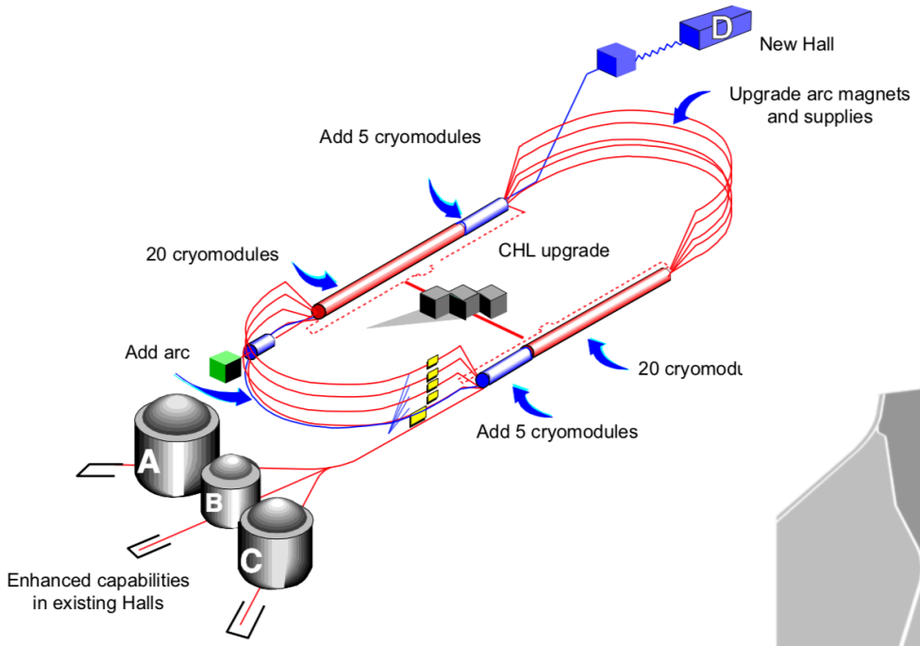
the world's only polarized proton collider…



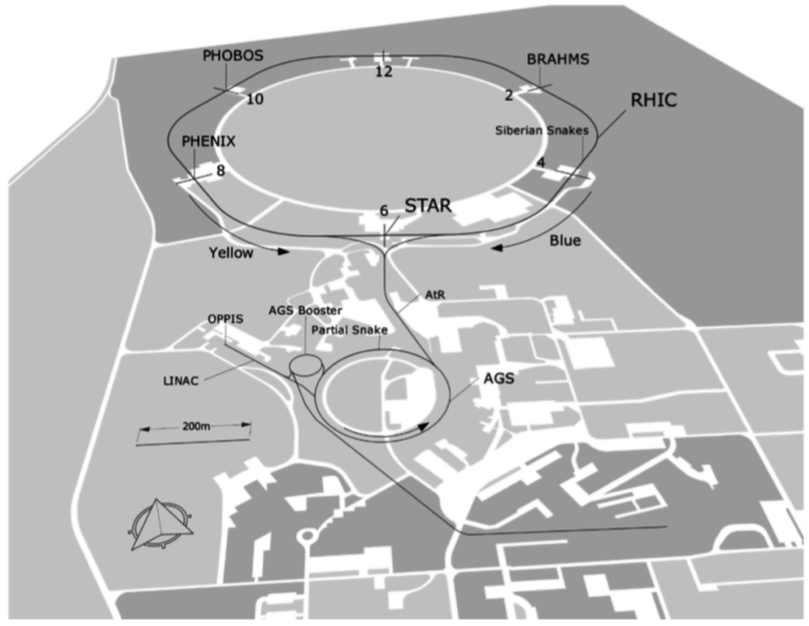
CERN, M2 200 GeV muon beams
190 GeV hadron beams

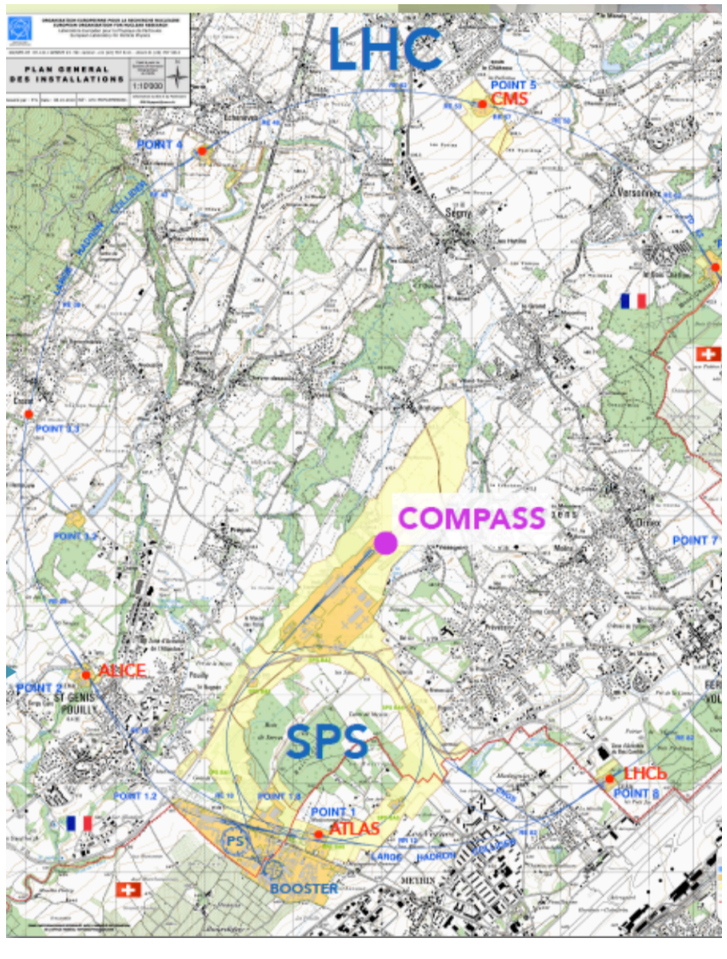
BEPC-II, up to 4.6 GeV electron-positron collider



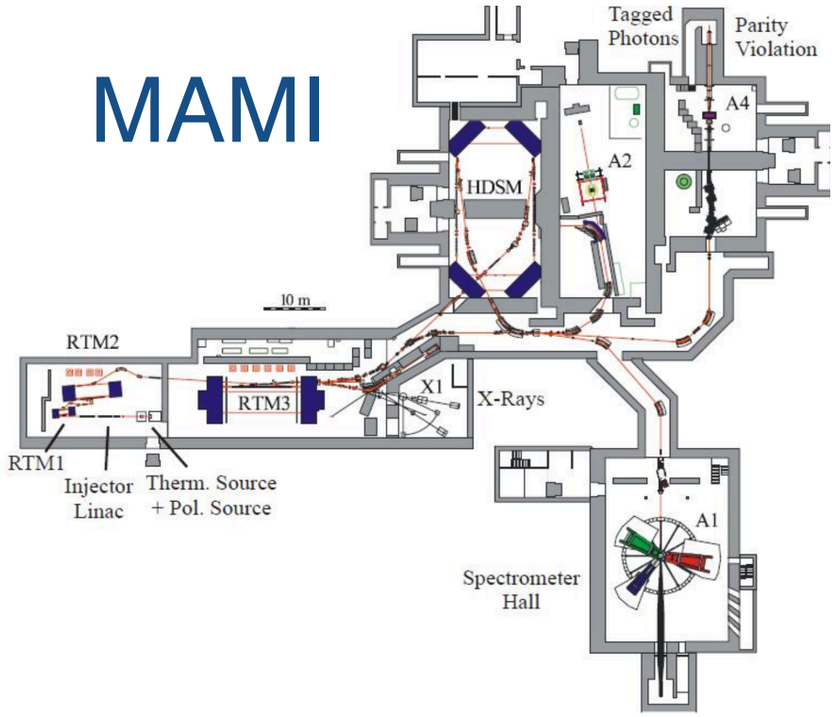


the world's only polarized proton collider…

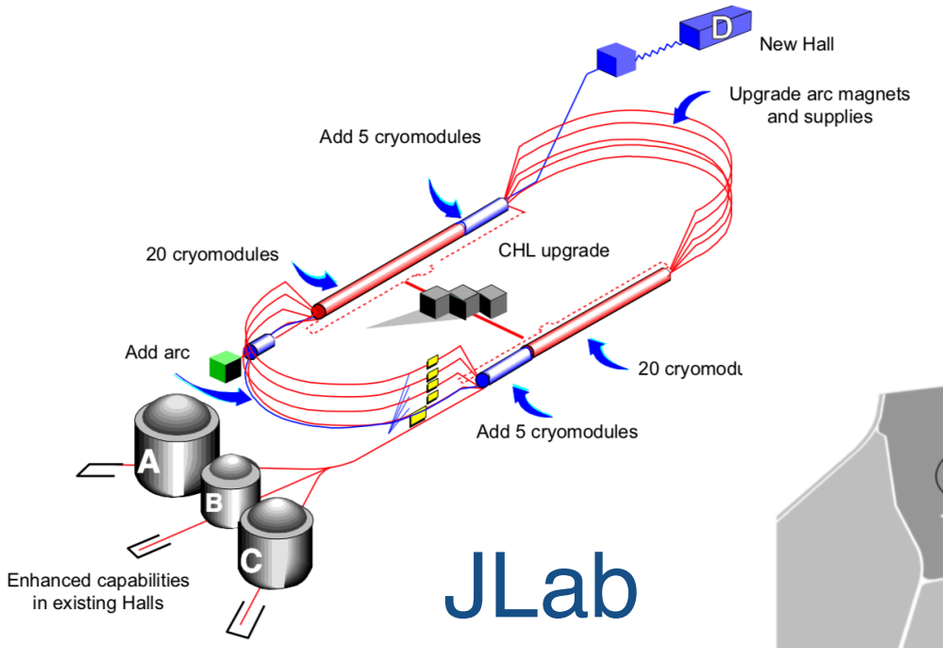




MAMI

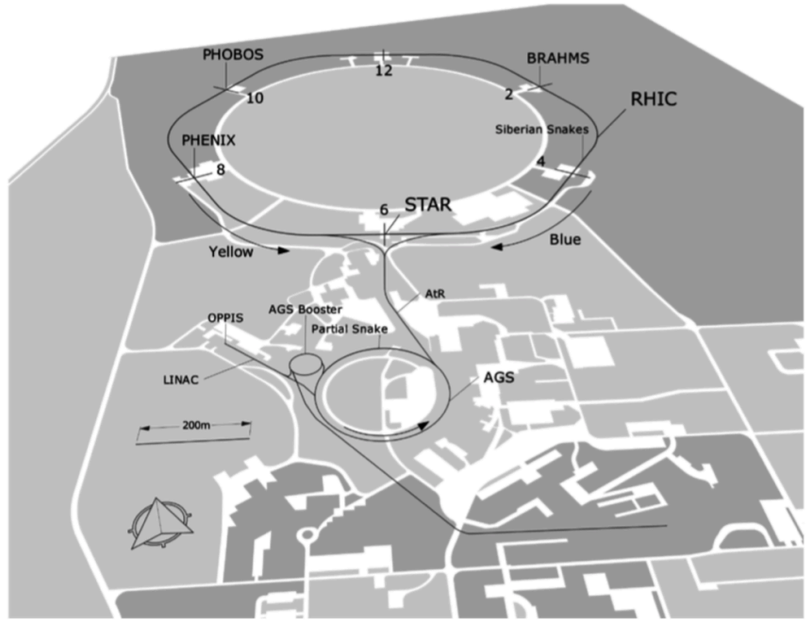


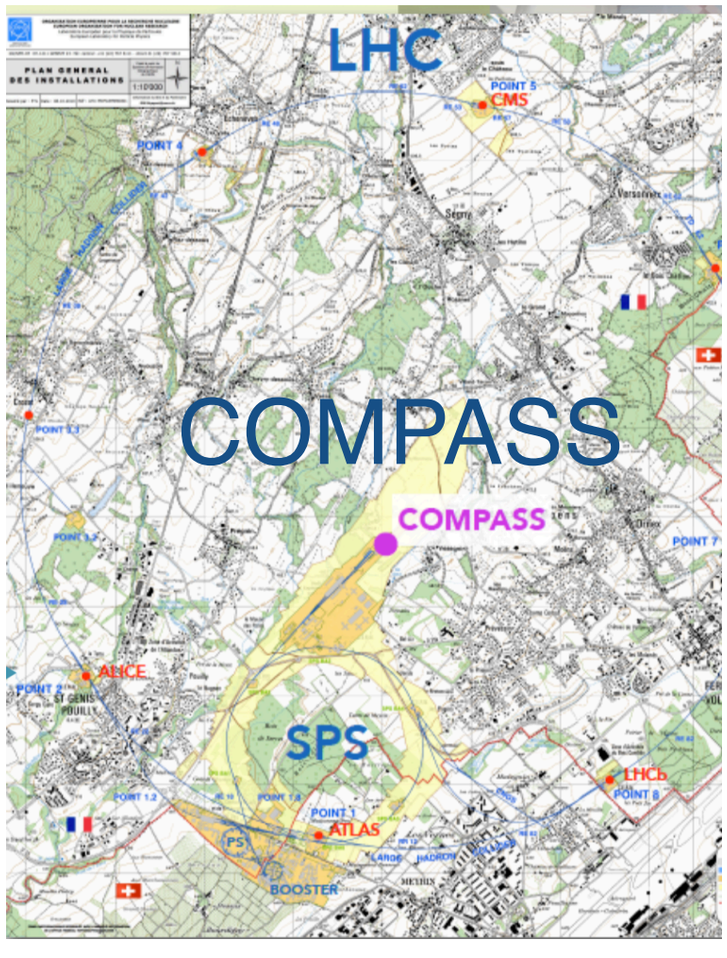
JLab



RHIC

the world's only polarized proton collider…

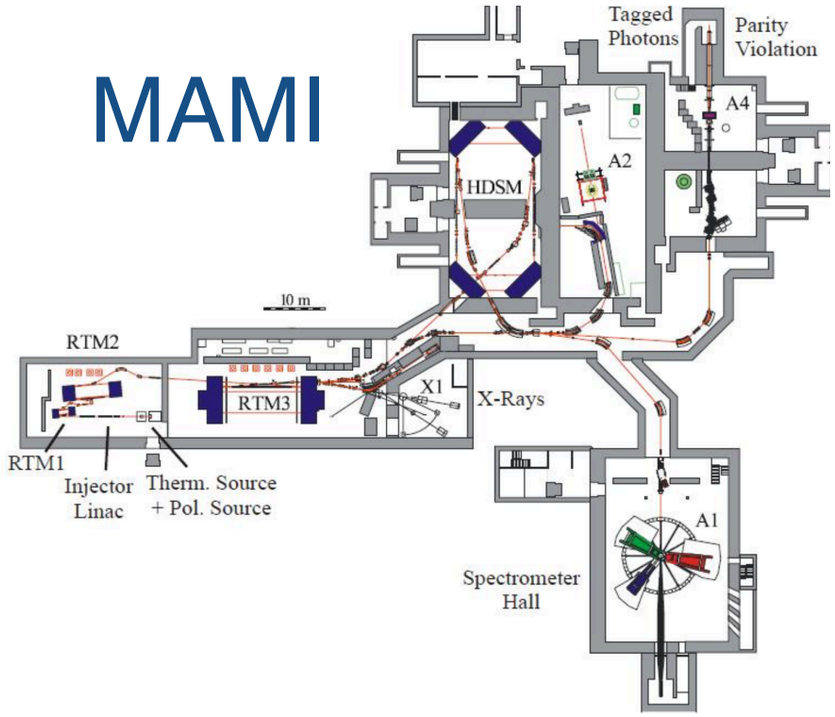




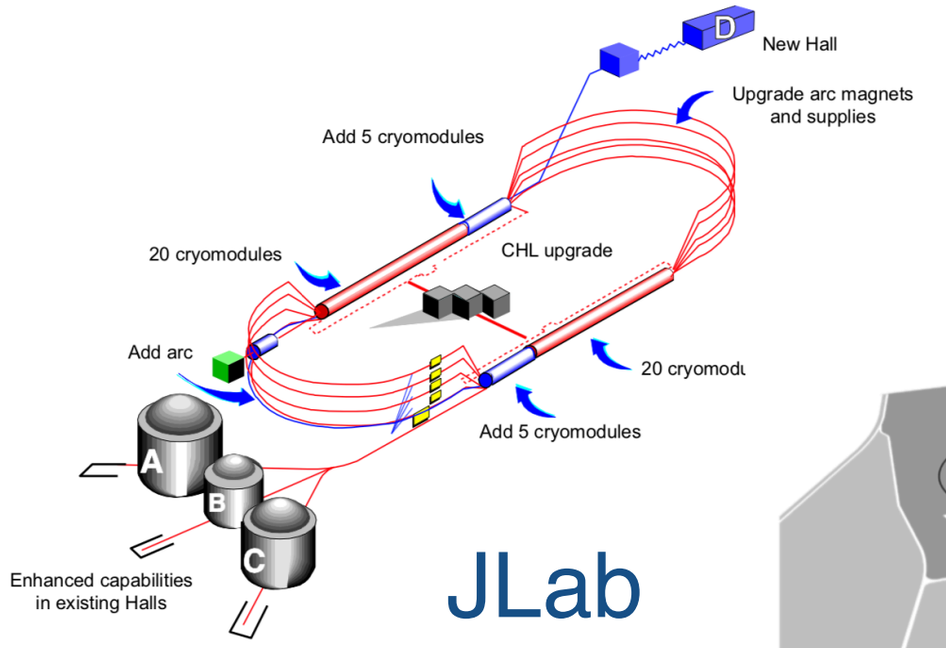
COMPASS

BES-III

MAMI



JLab



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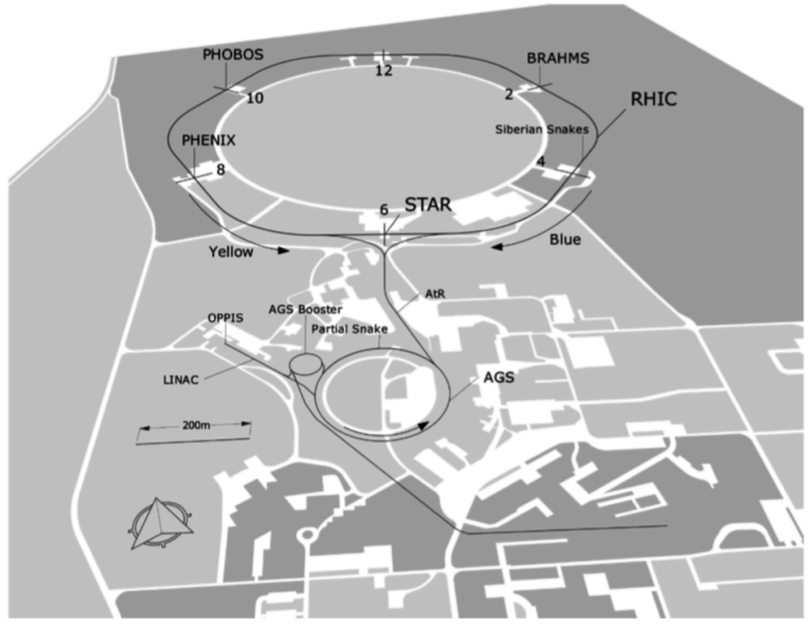
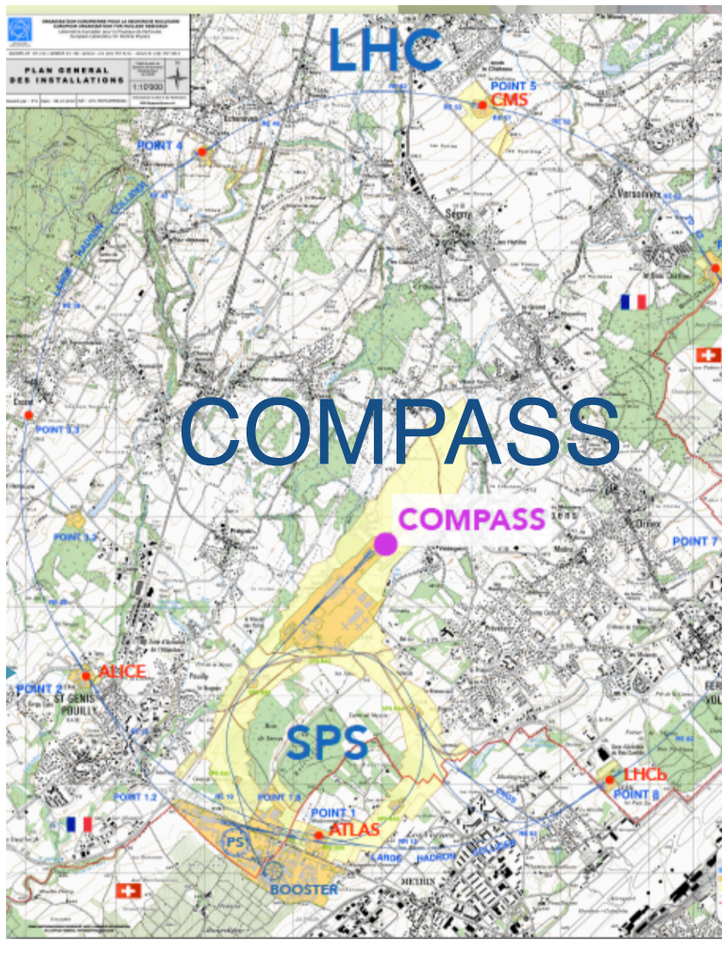
the world's only polarized proton collider…





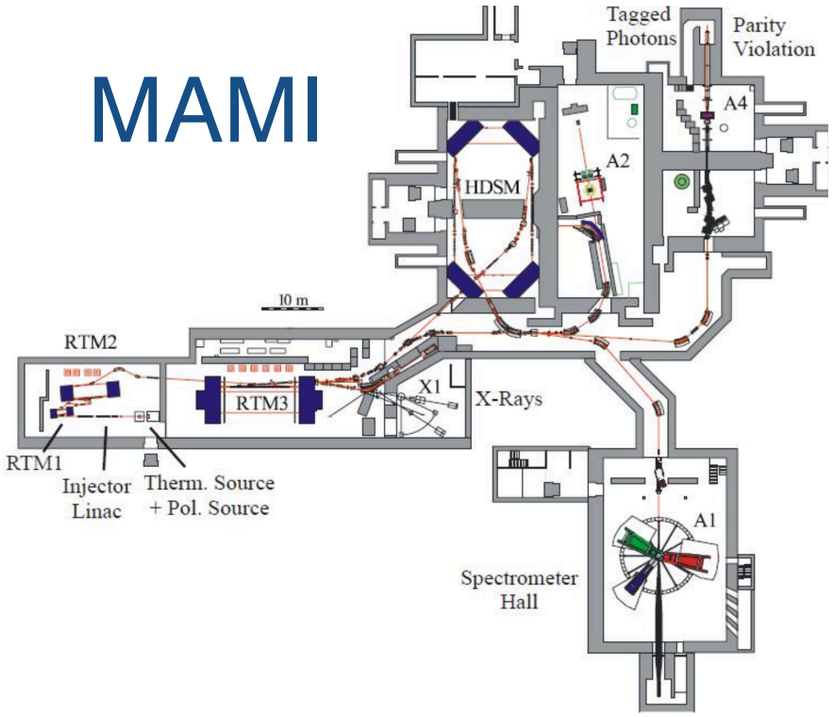
COMPASS

BES-III

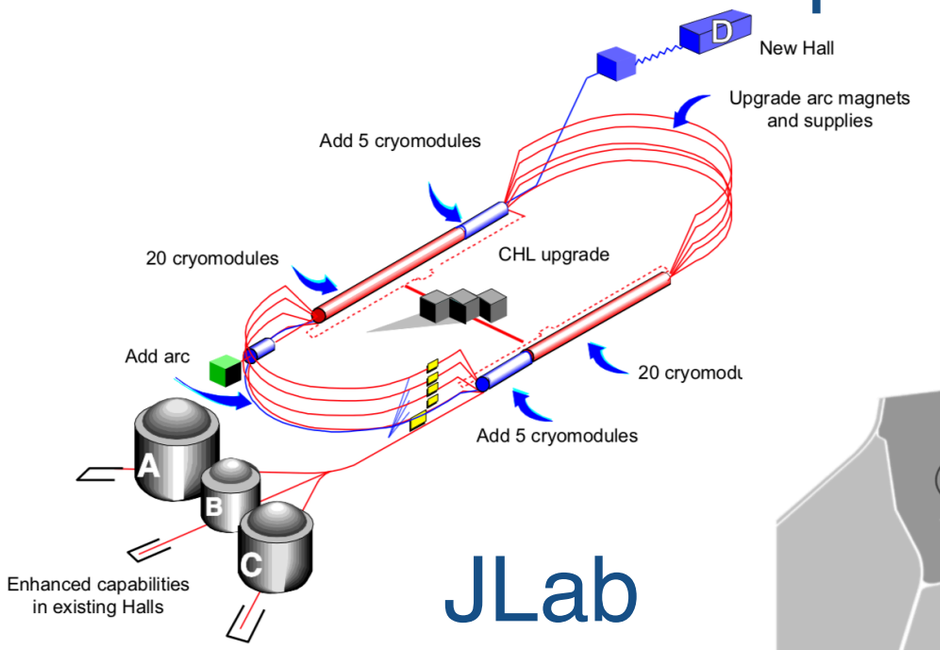
+ …

World Wide Interest and Complementarity

MAMI



JLab



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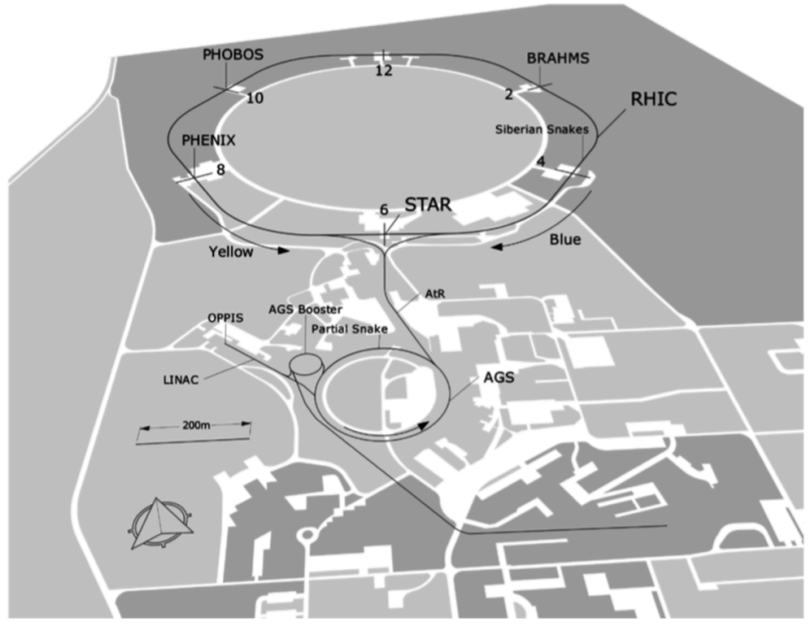
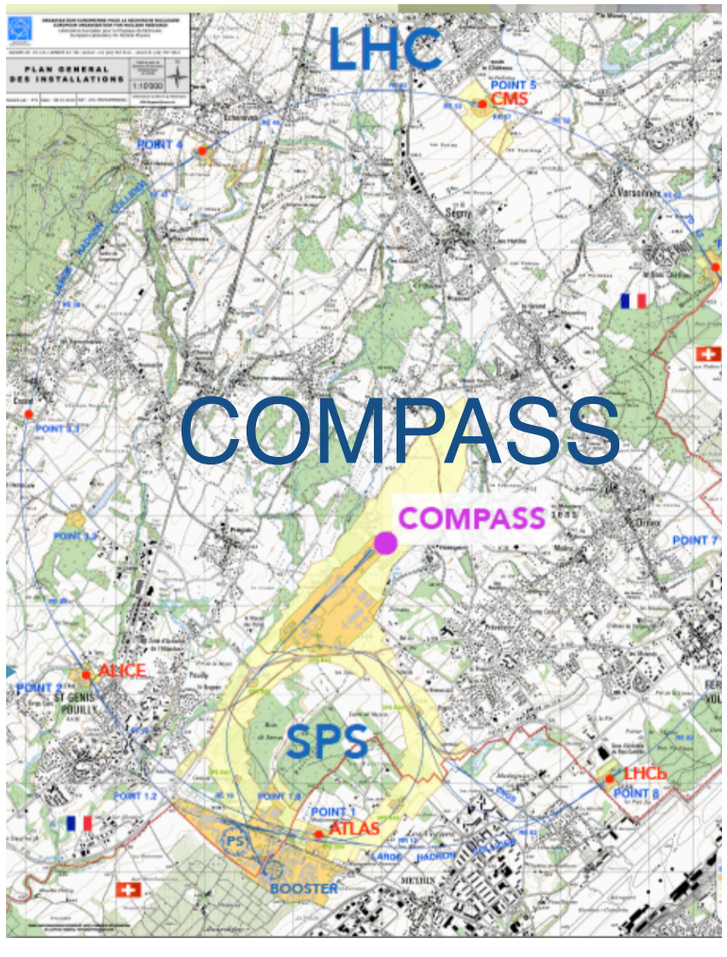
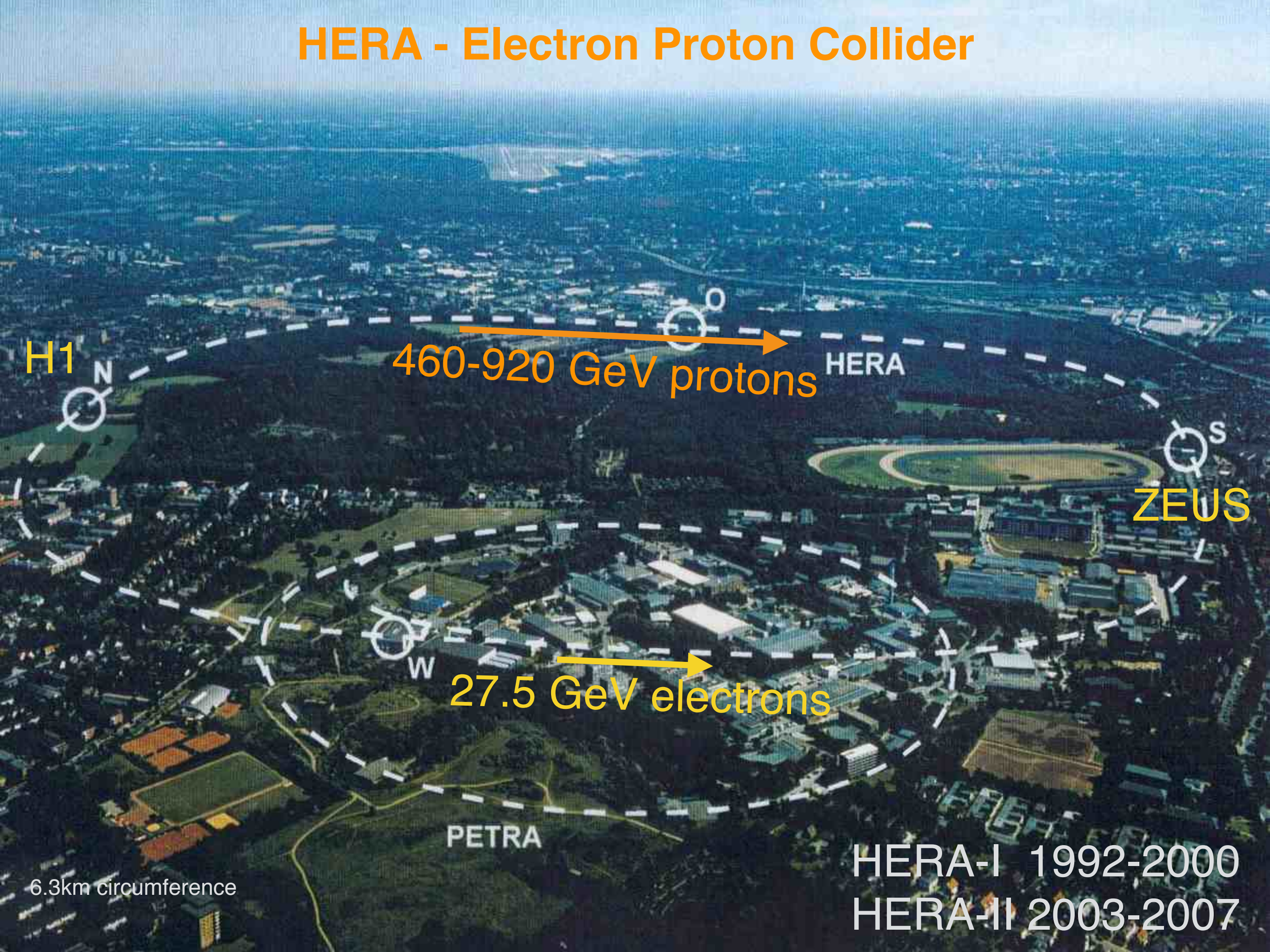




BES-III

+ …

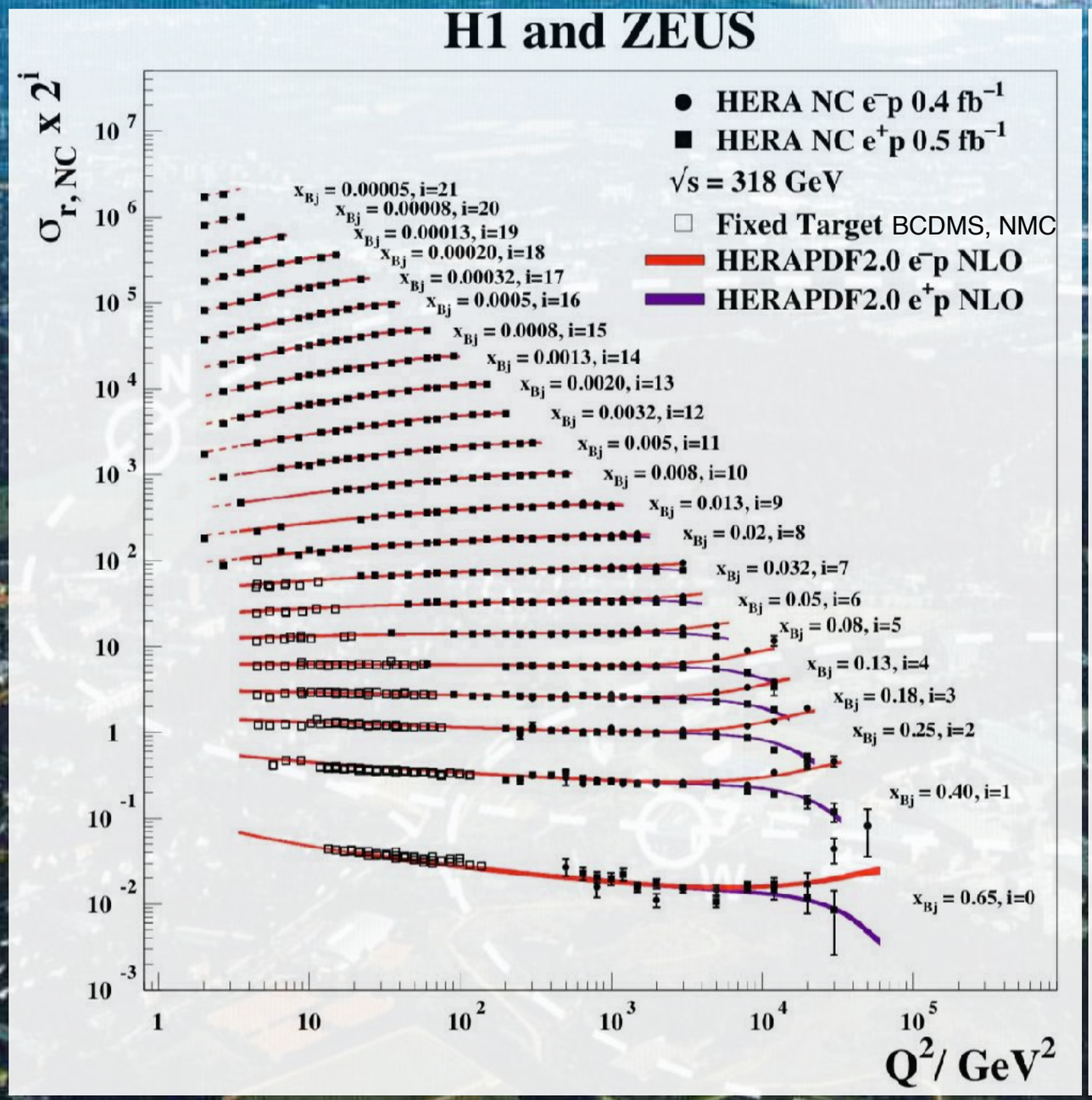
HERA - Electron Proton Collider



HERA-I 1992-2000
HERA-II 2003-2007

HERA's Legacy

H1 and ZEUS Coll., EPJ C75 (2015) 580

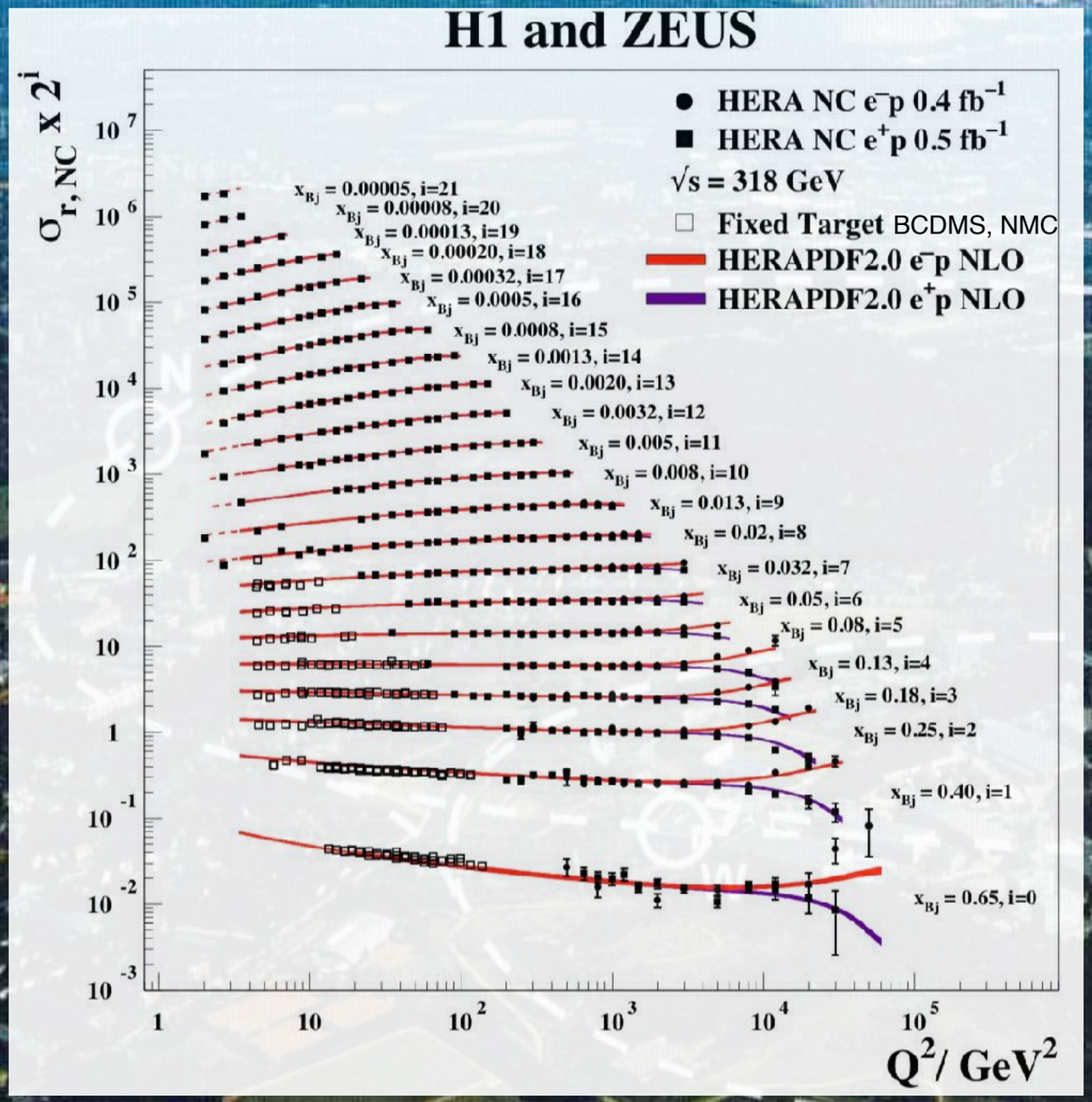


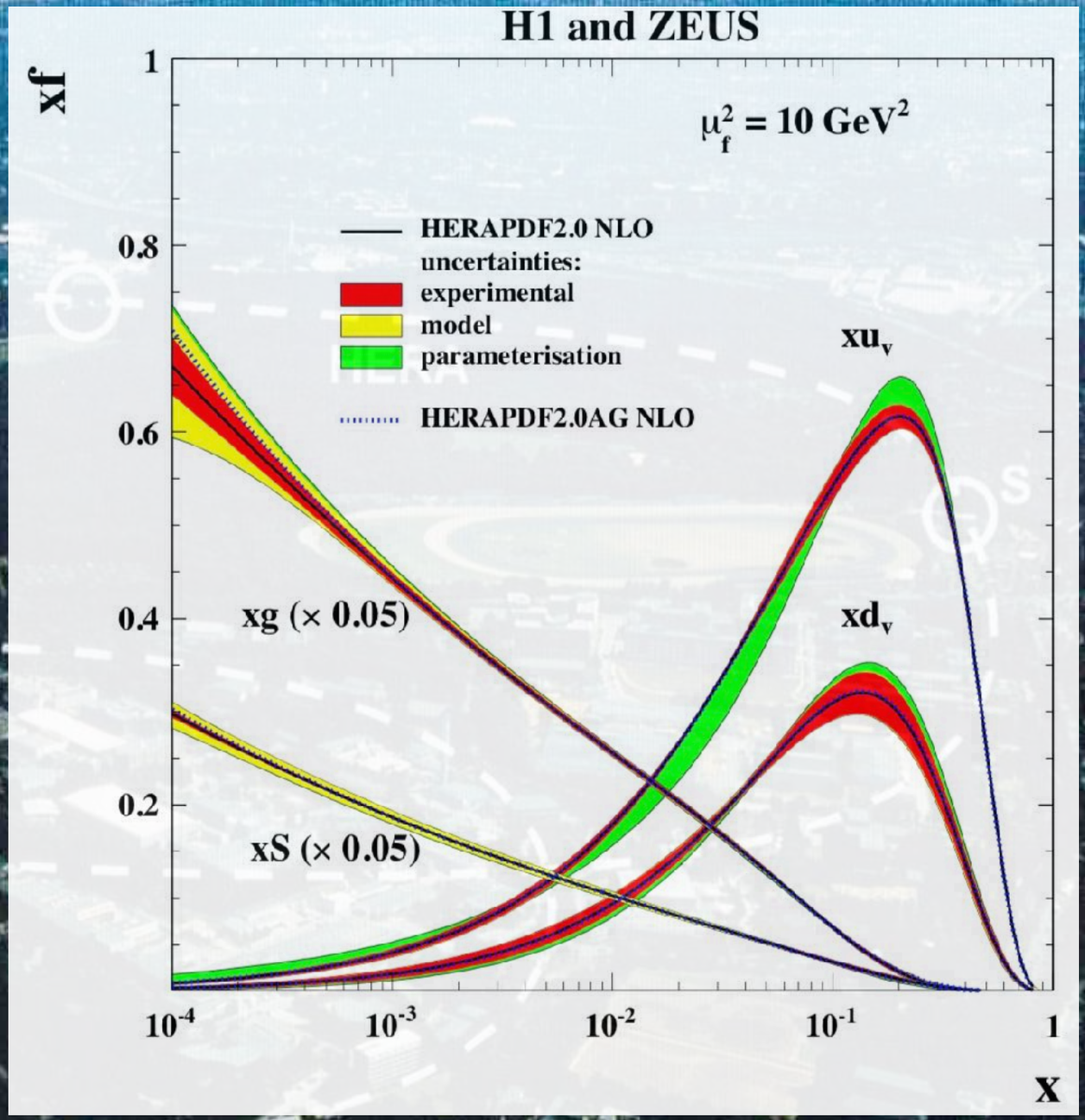
A lot in this plot:

- covers about five orders of magnitude in *x* and Q^2,
- consistency of fixed-target data and HERA data,
- scaling at $x \sim 0.1$ and violations elsewhere,
- strong rise of gluon density,
- E.W. interference at high Q^2,
- crucial input to "PDF fits"

HERA's Legacy

H1 and ZEUS Coll., EPJ C75 (2015) 580

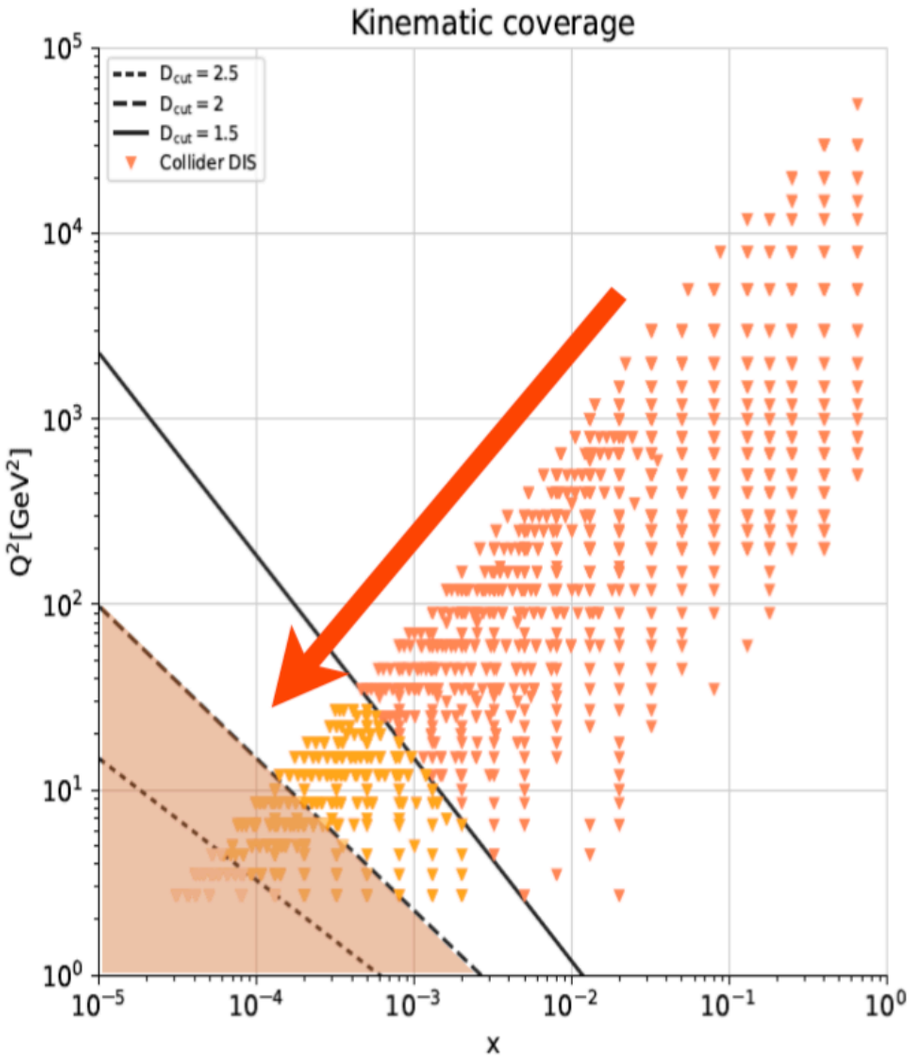


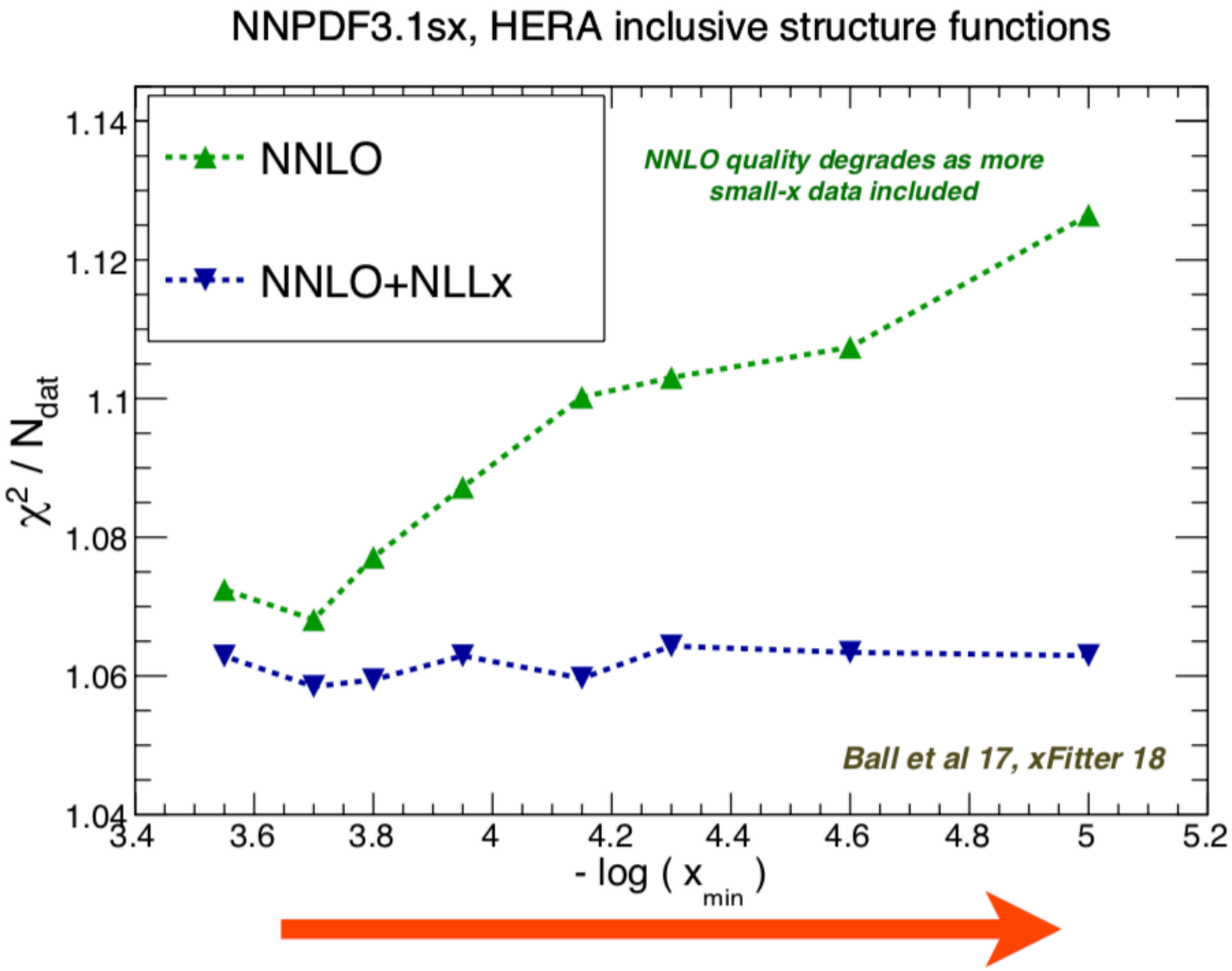


Vast body of *precision* measurements over a wide kinematic range,
Exquisite insight in high-energy proton structure and QCD dynamics.

Evidence for BFKL dynamics

NNPDF3.1 fits based on **fixed order** (NNLO) and **small-*x* resumed** (NNLO+NLLx) theory





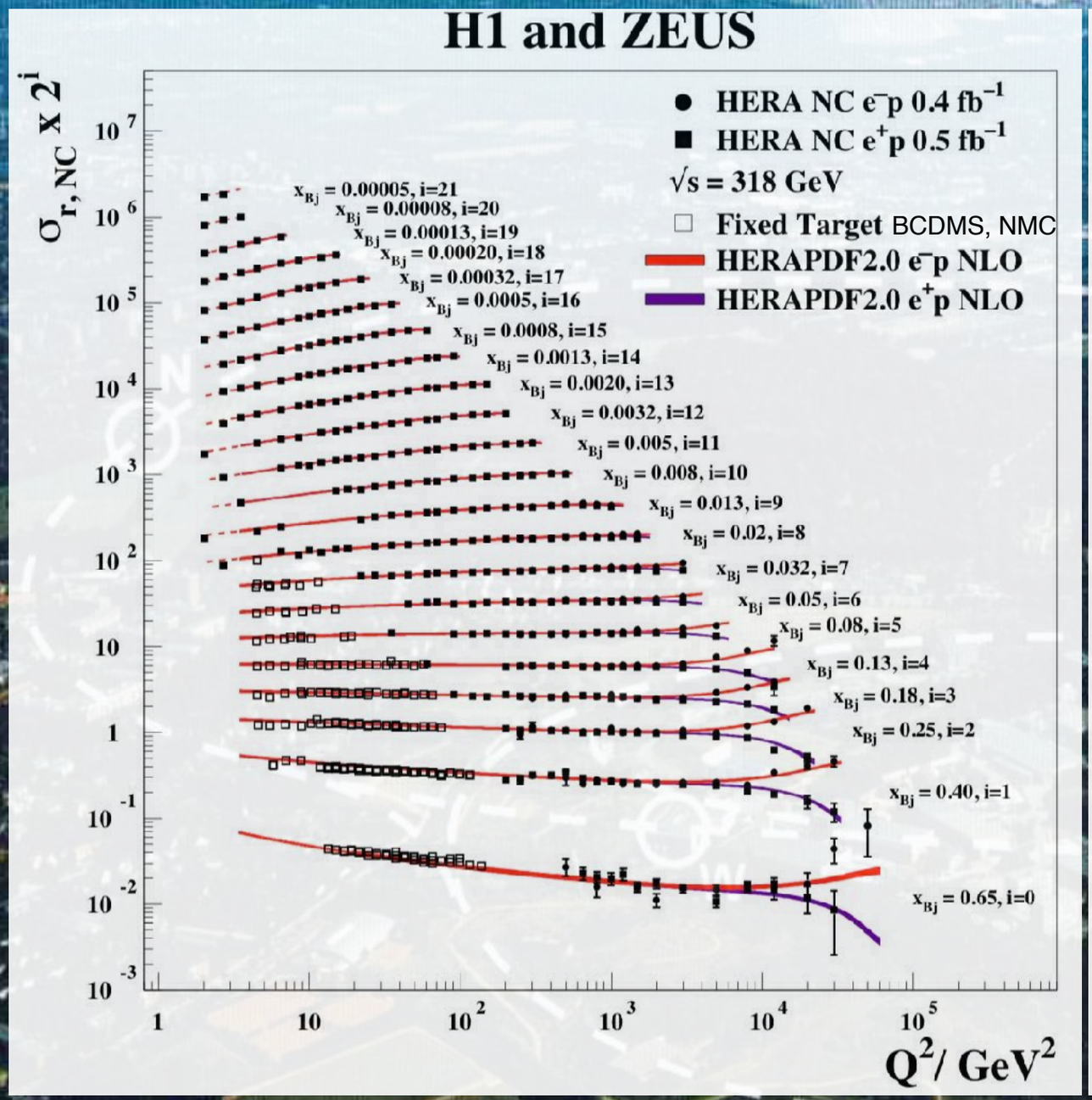
Monitor the **fit quality** as one includes more data from the **small-*x* region**

Best description of **small-*x* HERA data** only possible with **BFKL effects!**

From Juan Rojo at DIS 2019, see Tuomas Lappi's talk. Certainly motivates complementary studies.

HERA's Legacy

H1 and ZEUS Coll., EPJ C75 (2015) 580



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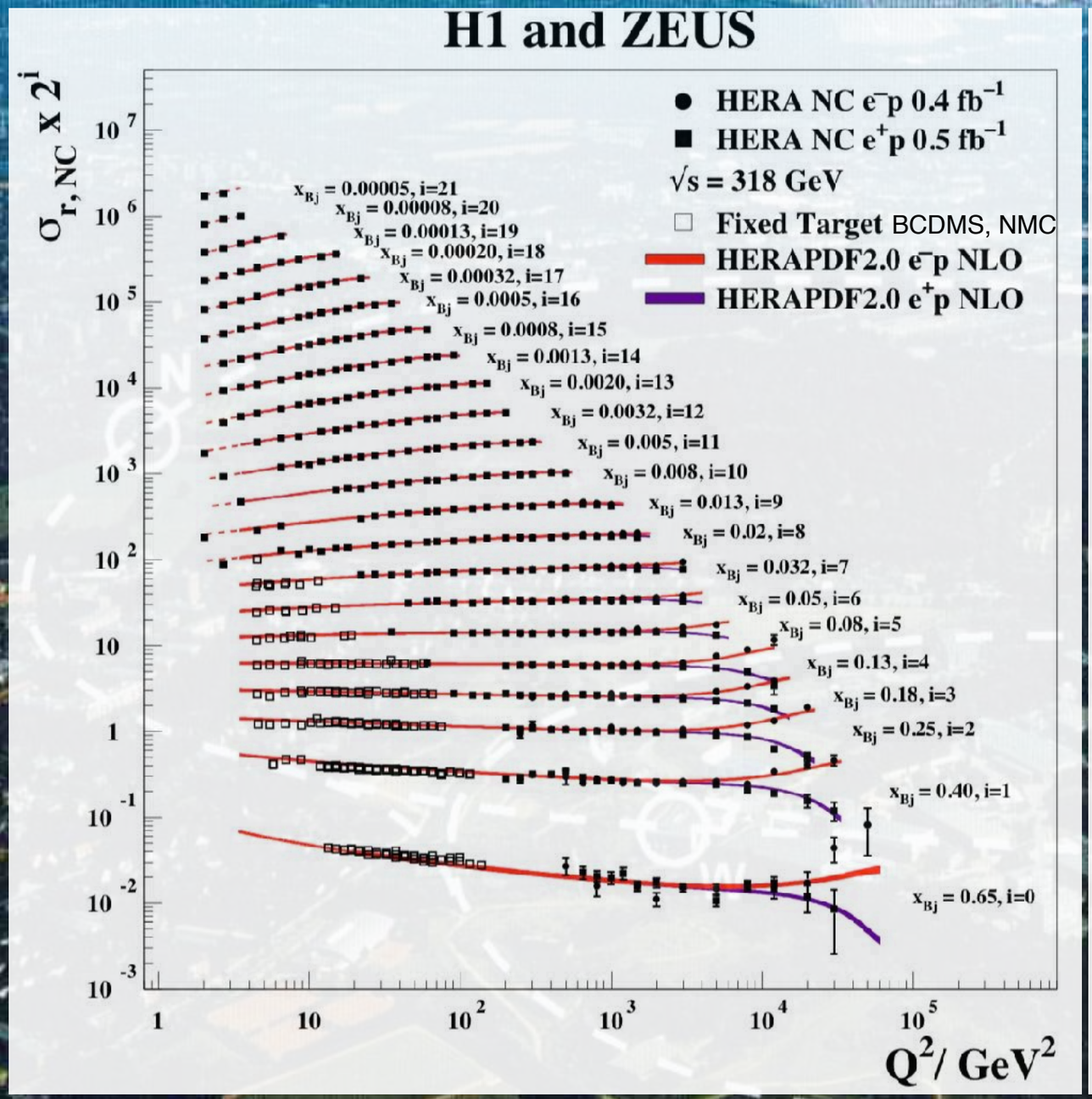
HERA's Legacy

H1 and ZEUS Coll., EPJ C75 (2015) 580

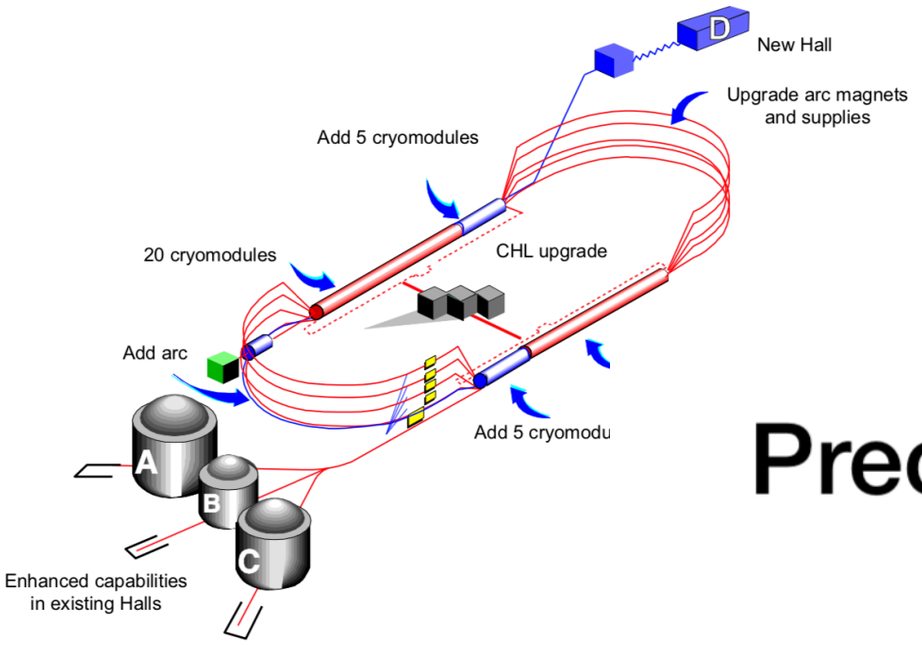


Lots missing as well

- higher and lower *x*,
- ion beams,
- proton and ion polarization,
- identified hadron SIDIS,
- transverse mom. dependence,
- exclusive channels,
- diffraction,
- …

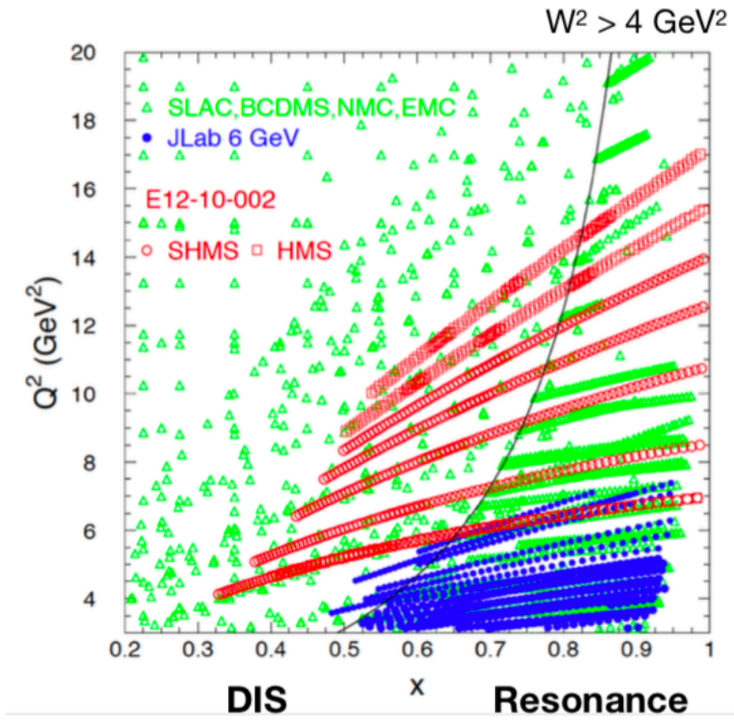
Strong motivation for ongoing programs,
Further improvement is *presently* coming from LHC itself.

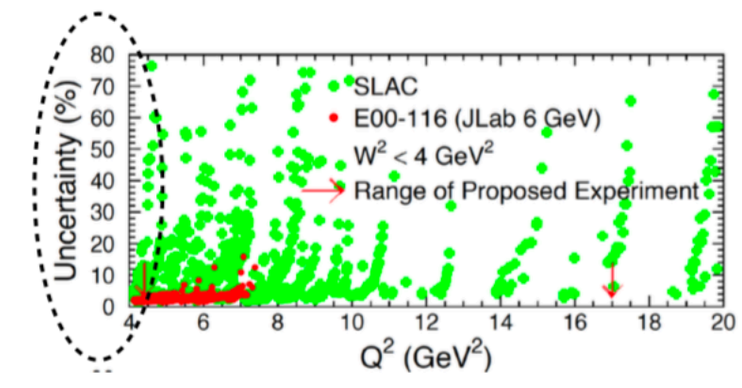
See talks by Fred Olness and Lucian Harland-Lang.



Start of the 12 GeV program at JLab,

Precision F_2 measurement at large x





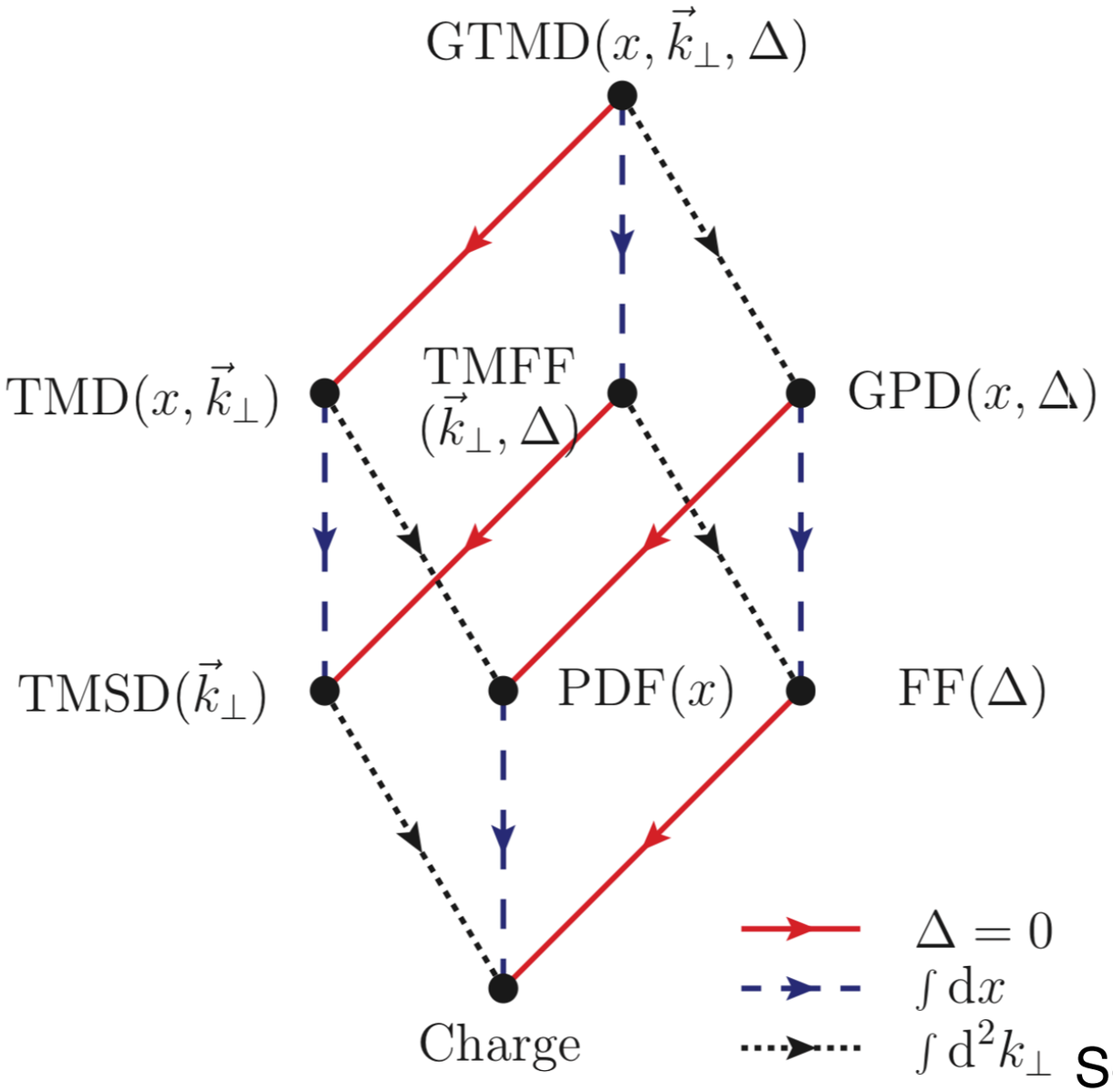
- SLAC data - limited statistics, mostly low Q^2
  - -> JLab 12 GeV can extend Q^2 coverage with high precision
- Inclusive H(e,e') and D(e,e') measurements at Hall C
- New data taken in 2018 - extended x and Q2 coverage
- Extend quark-hadron duality studies from 6 GeV experiment (E00-116)

S.P. Malace *et al*., Phys. Rev. C 80 035207 (2009)

S.P. Malace et al., Phys.Rev.Lett. 104 (2010) 102001

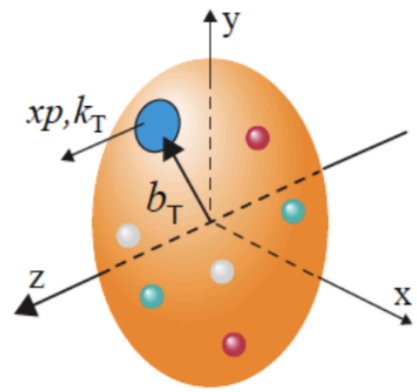
From: Sanghua Park's talk yesterday.

Imagine, imaging!



What is the 2D confined transverse motion of quarks and gluons inside a proton?

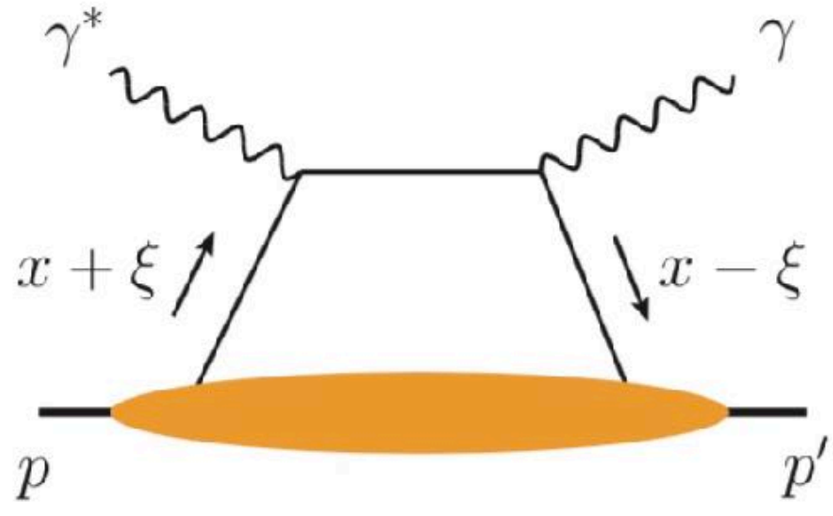
How to identify universal proton structure properties from measured k_T-dependence?



How does the confined motion ong with x, Q^2?

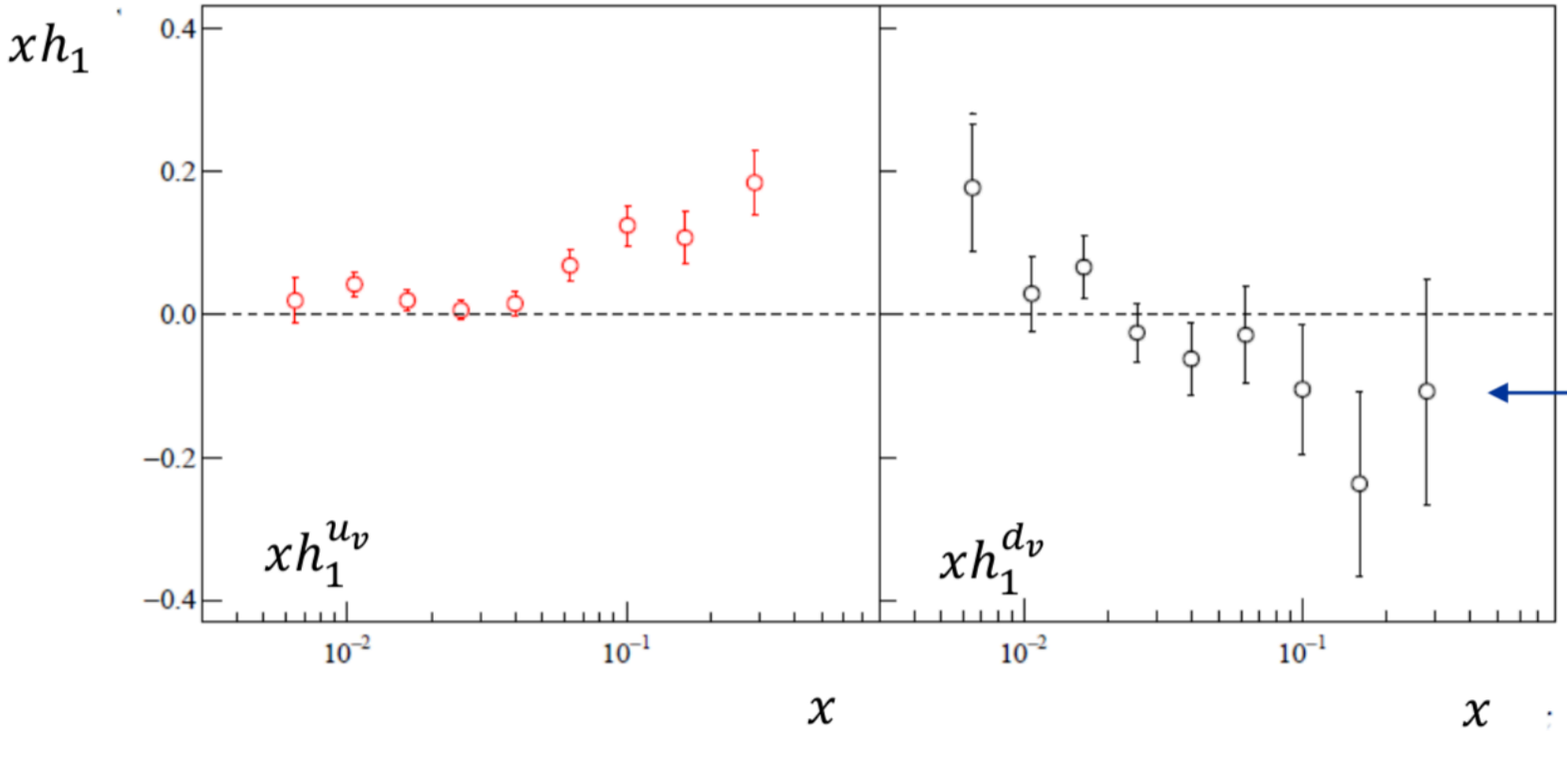
Can we extract QCD color force responsible for the confined motion?

How is the motion correlated with macroscopic proton properties, as well as microscopic parton properties, such as the spin?



See e.g. Daria Sokhan and Alexei Prokudin's talks

Continuation of COMPASS program

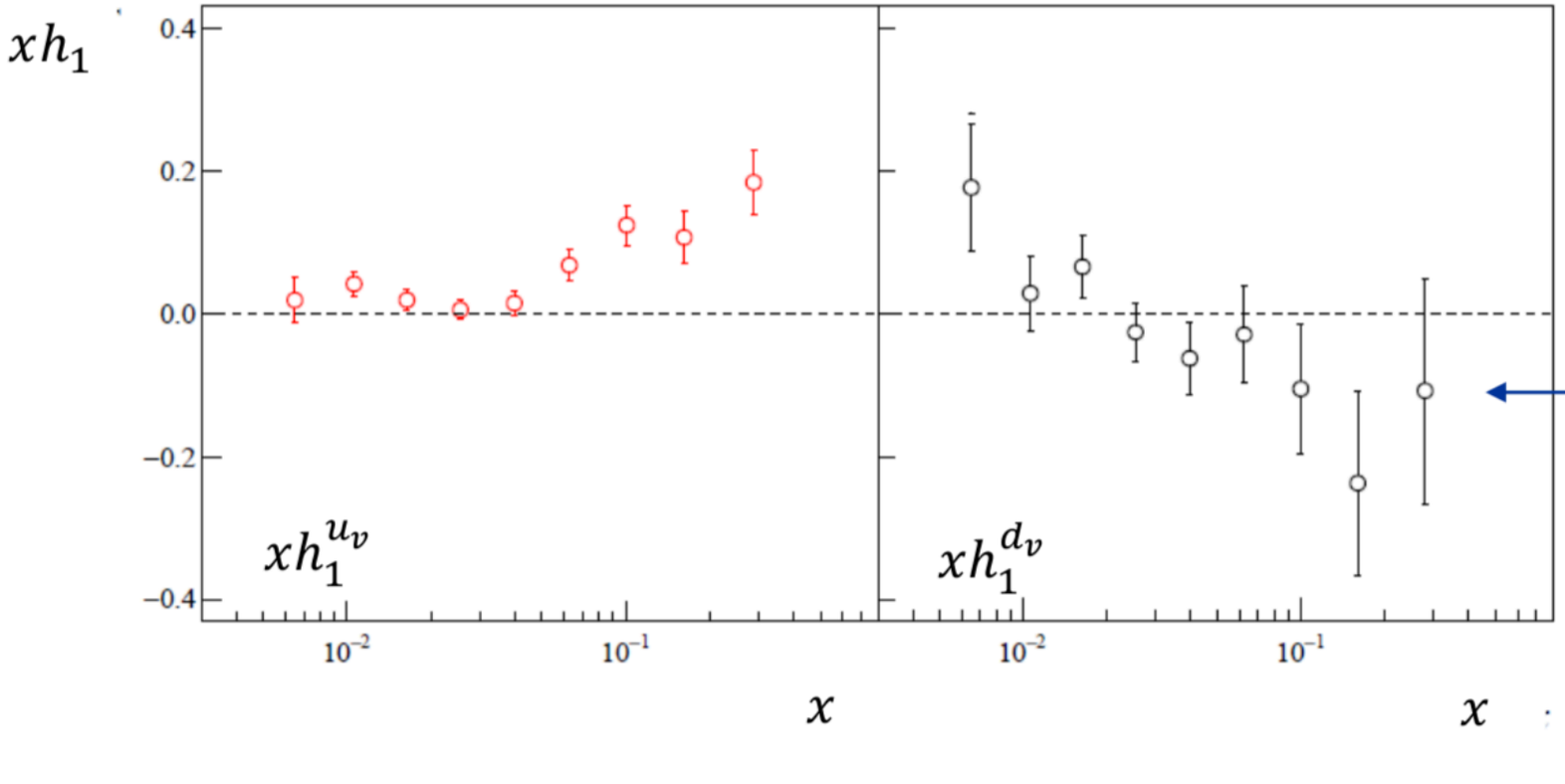


present

PRD 91(2015) 014034
from COMPASS p, d and e+e- data
we have followed the method in for all the transversity extraction

See Anna Martin, DIS 2019

Transversity - prior work from COMPASS



present

PRD 91(2015) 014034
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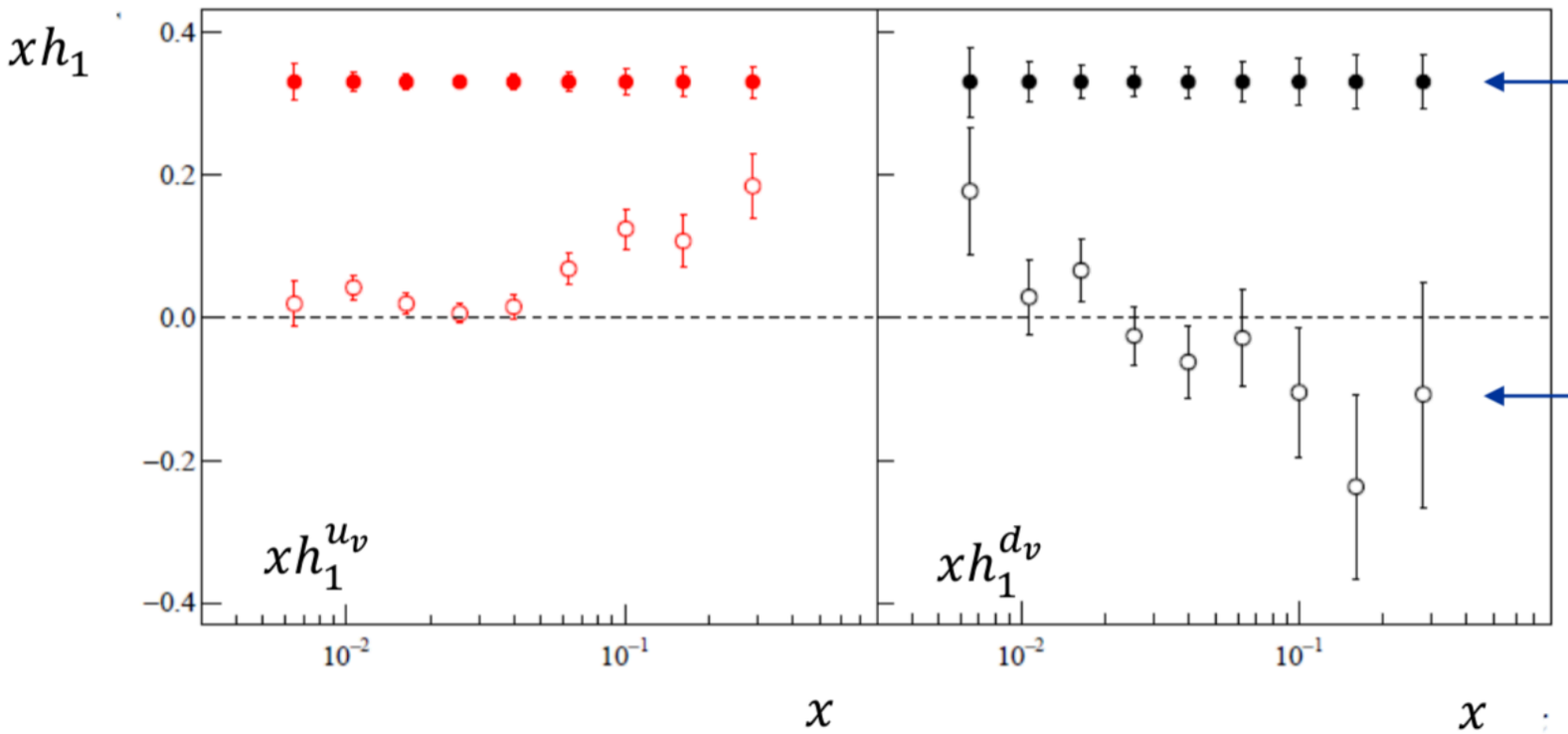
we have followed the method in for all the transversity extraction

See Anna Martin, DIS 2019

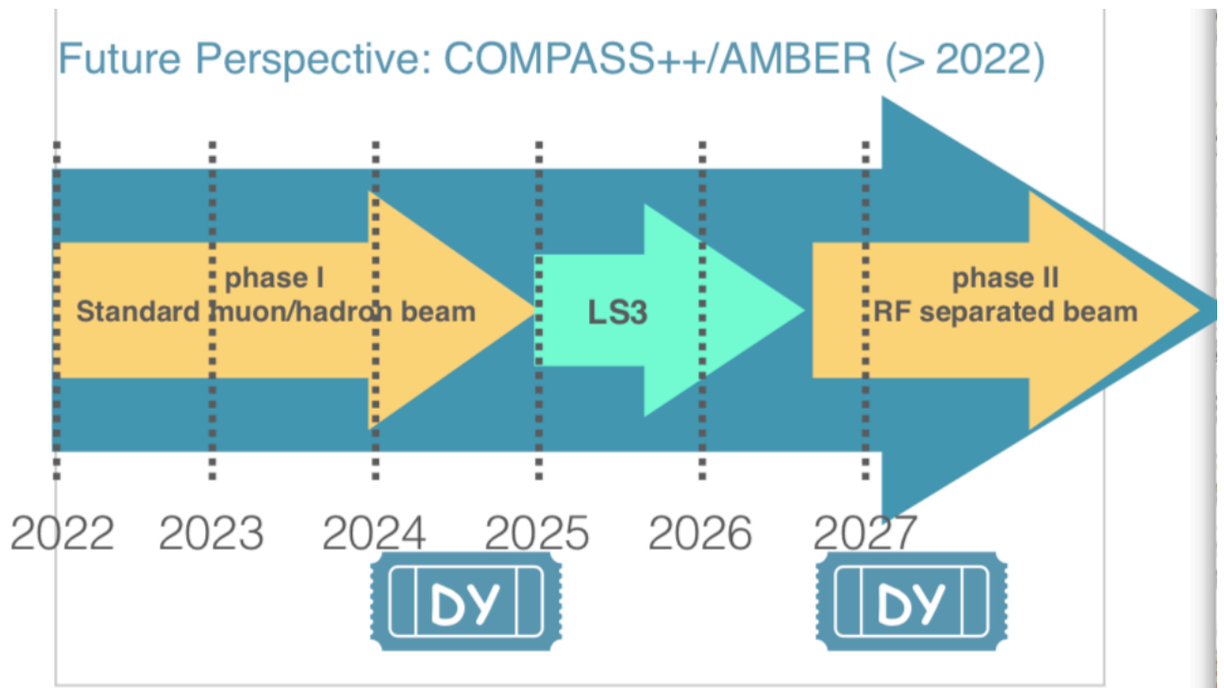
Transversity - COMPASS future



projected

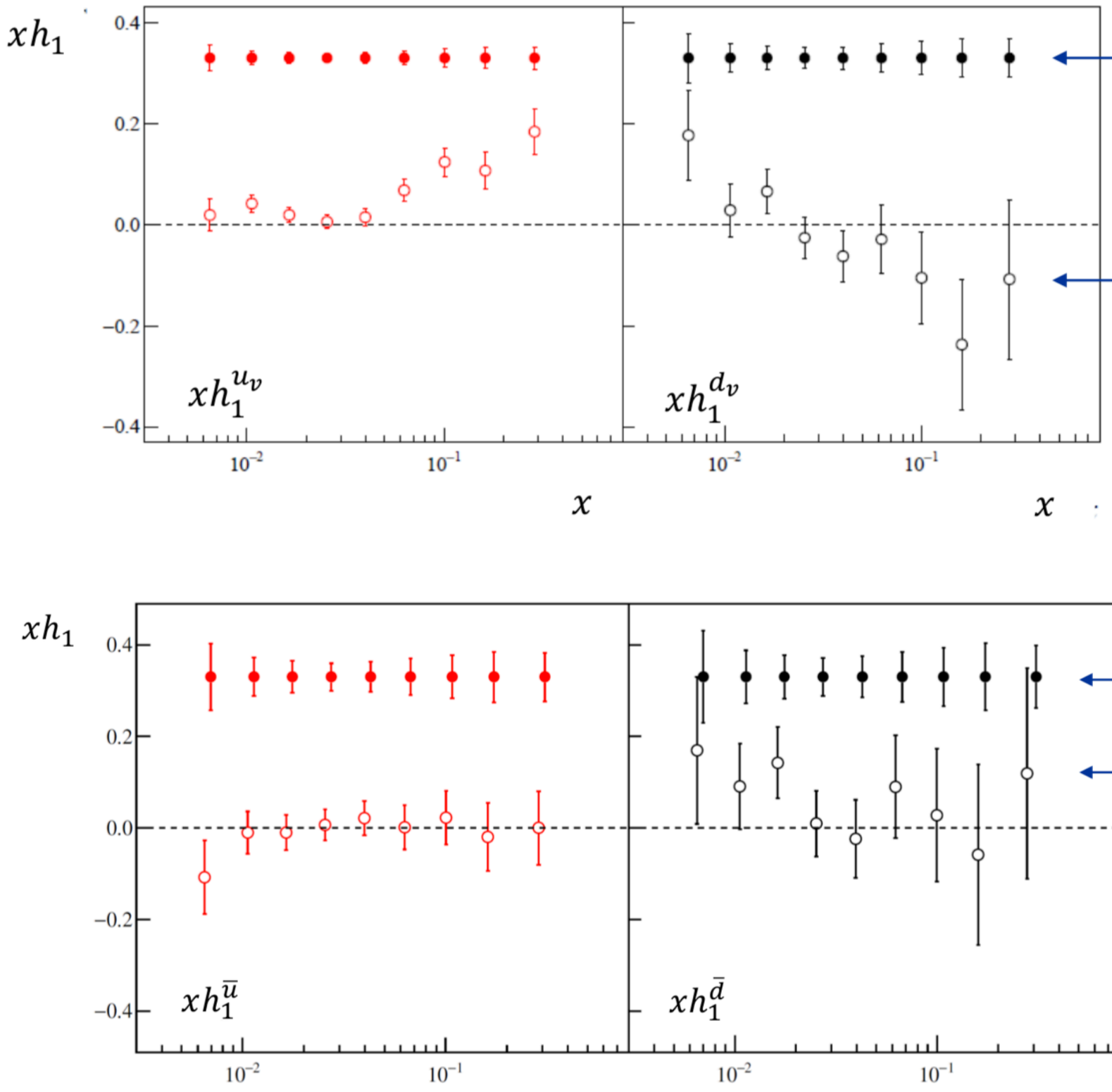
present

PRD 91(2015) 014034
from COMPASS p, d and e+e- data
we have followed the method in for all the transversity extraction



See Anna Martin, DIS 2019

Transversity - COMPASS future



projected

present

PRD 91(2015) 014034
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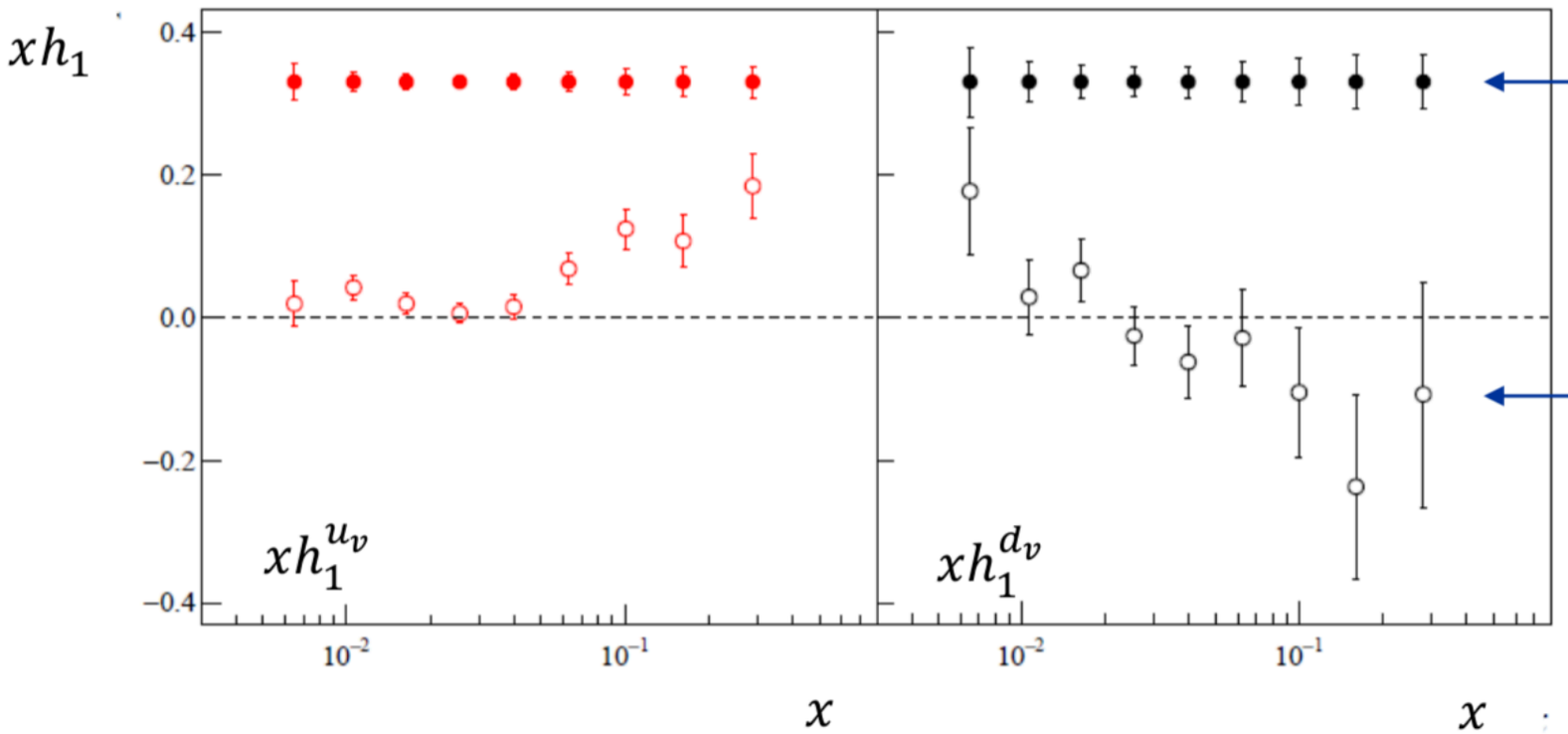
projected

present

See Anna Martin, DIS 2019

Transversity - COMPASS future



projected

present

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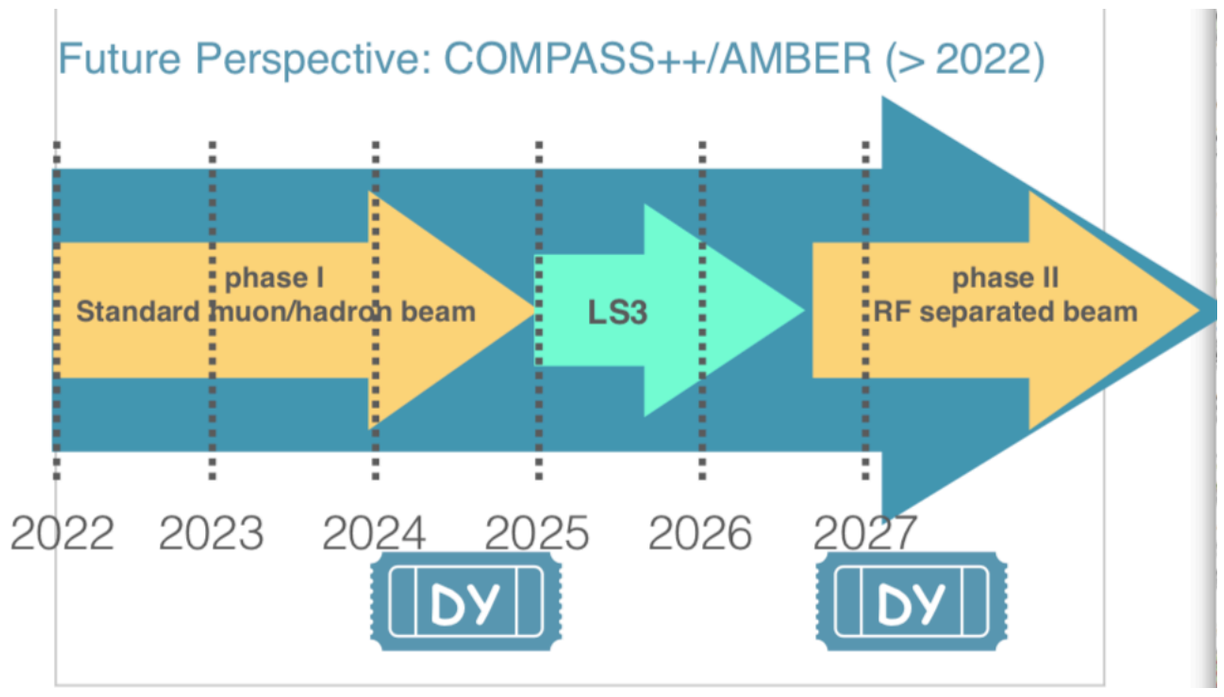
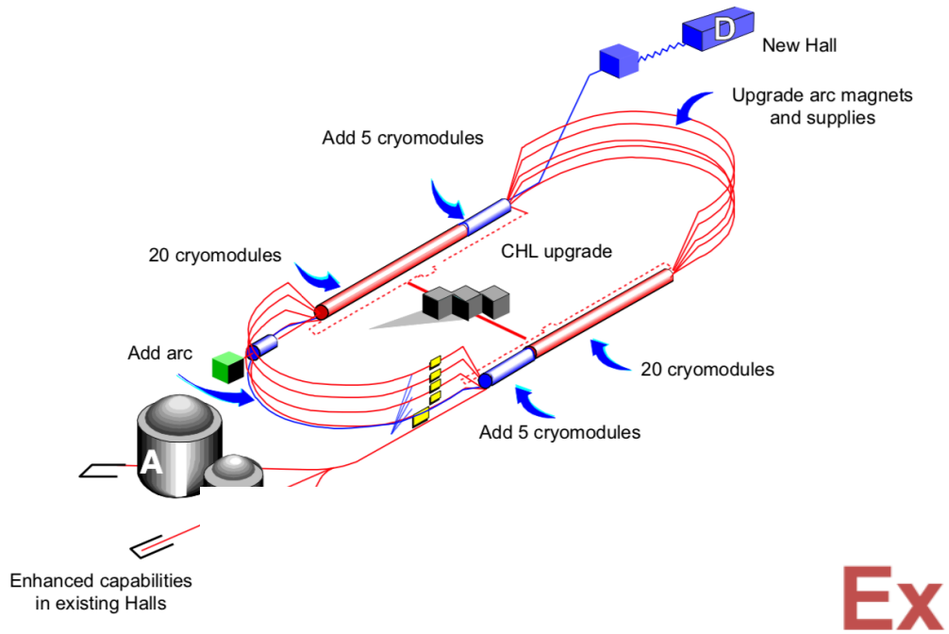
from COMPASS p, d and e+e- data
we have followed the method in for all the transversity extraction



See Anna Martin, DIS 2019

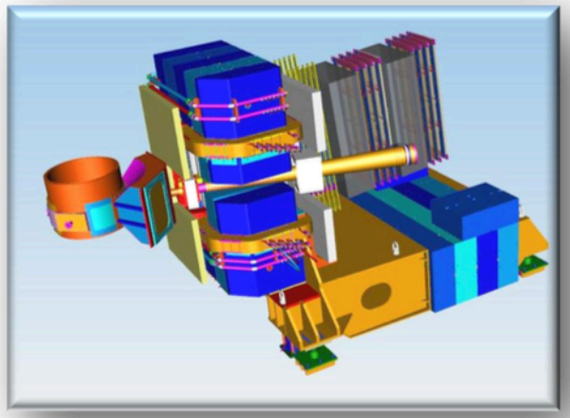
Michele Chioso, yesterday
Bernard Ketzer, yesterday



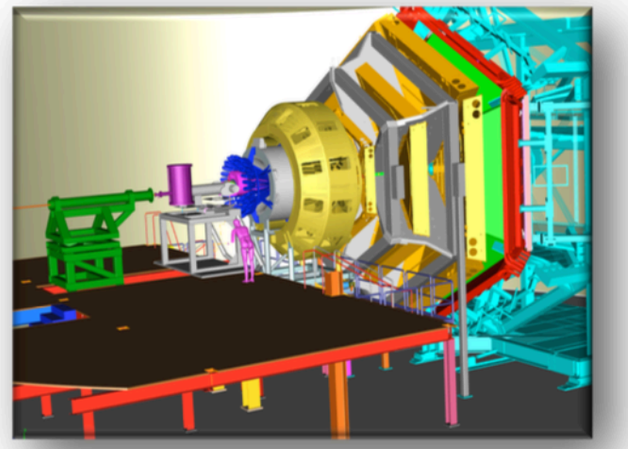
Start of the 12 GeV program at JLab,

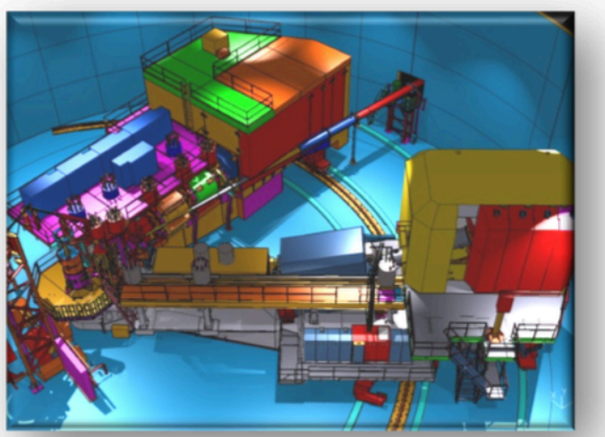
Experimental Capabilities

Hall A
Existing HRS magnetic focusing spectrometers + Big Bite + new, large acceptance Super Big Bite

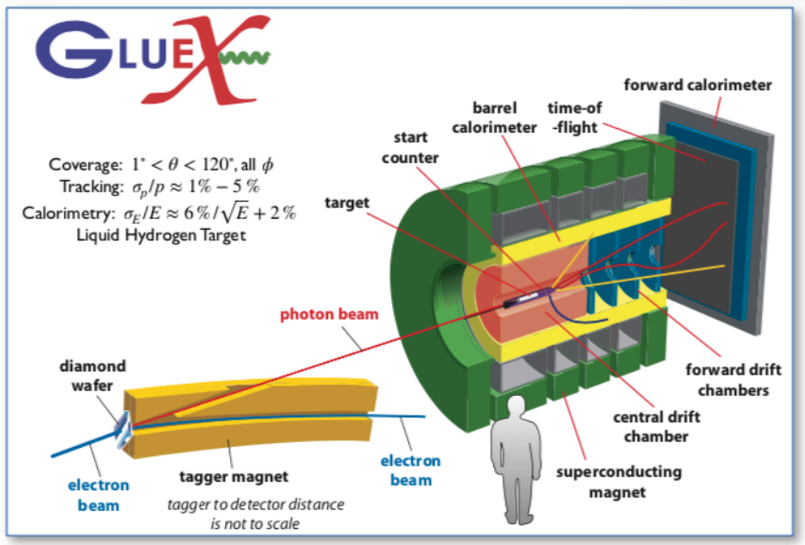


Hall B
New CLAS12, large acceptance spectrometer
→ Good hadron PID
→ Simultaneous measurement of broad phase space



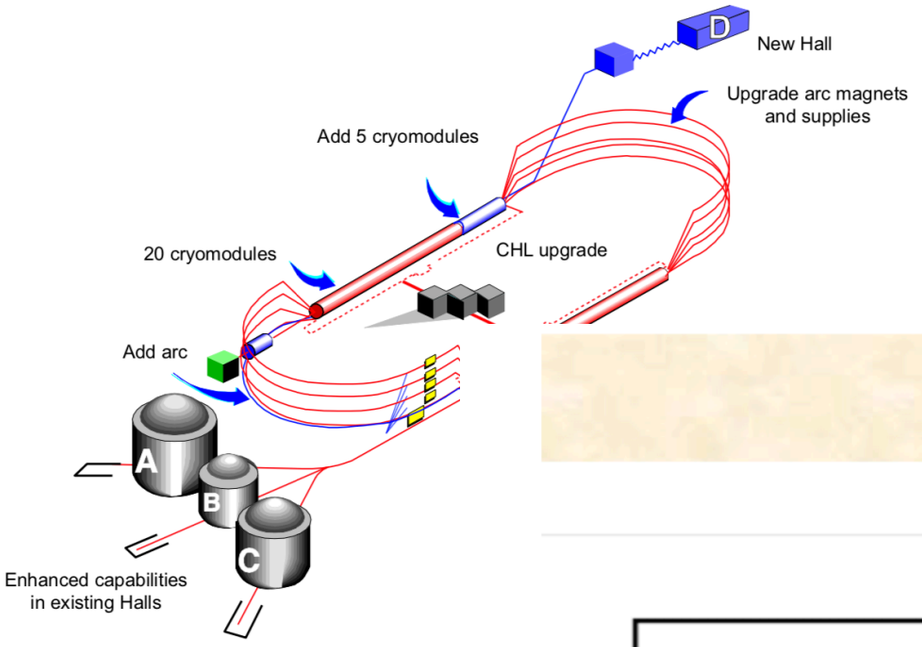


Hall C
HMS + new SHMS magnetic focusing spectrometers
→ Precision cross sections, LT separations



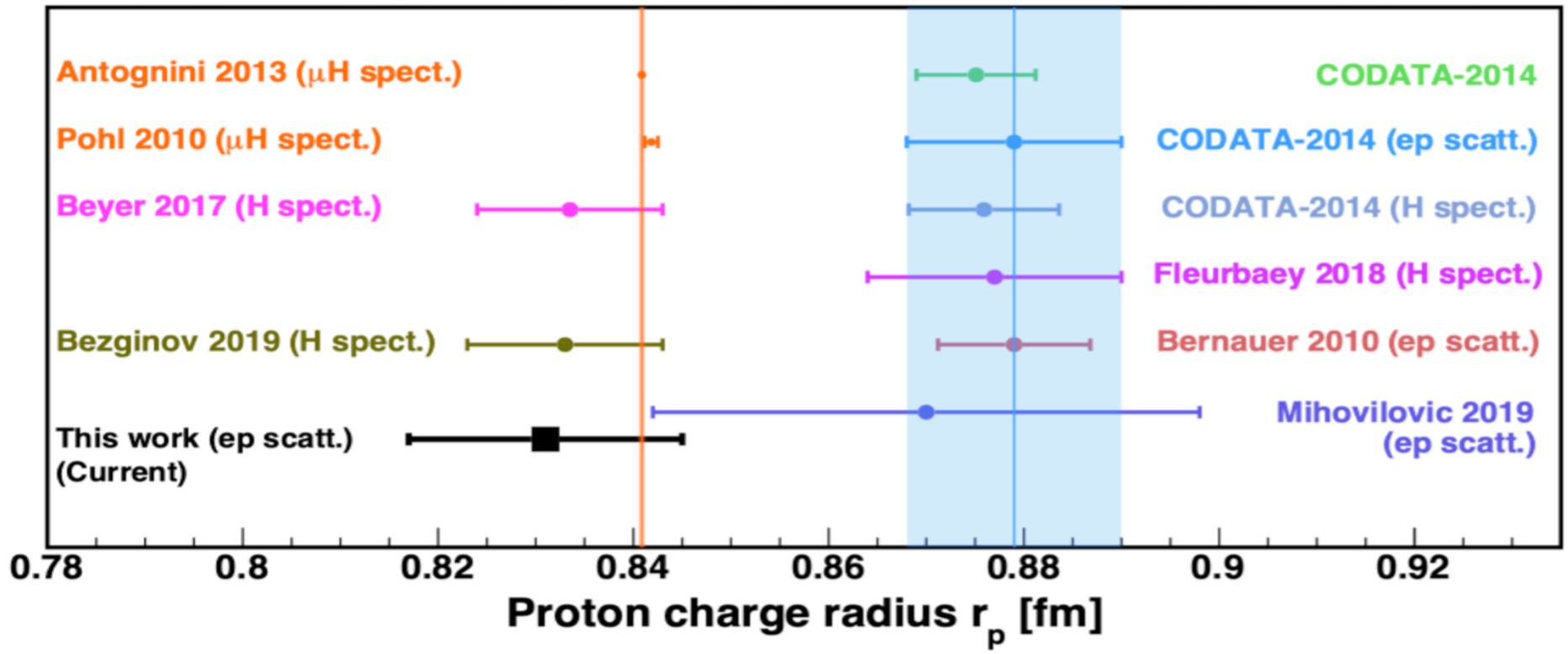
Hall D
GlueX large acceptance spectrometer
→ Total event reconstruction for meson spectroscopy

From: Dave Gaskell's talk.



Start of the 12 GeV program at JLab,

Proton Radius from PRad



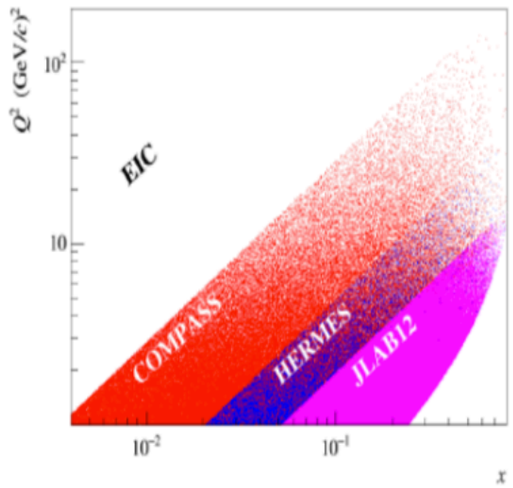
Prad result:
R_p = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm

Nature paper in print: will come out on Nov 7

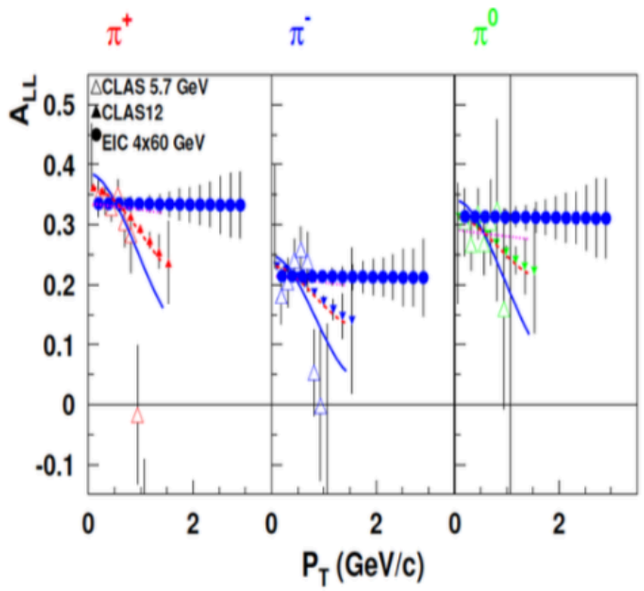
55

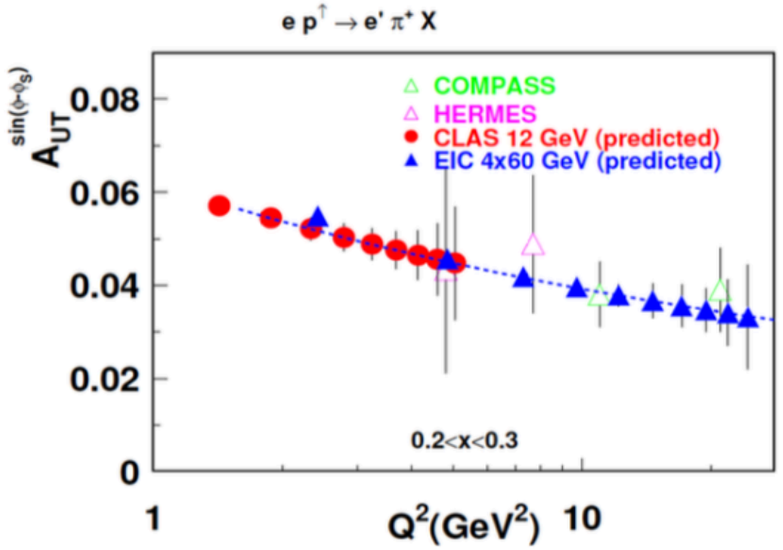
From: Nilanga Liyanage's talk on Thursday

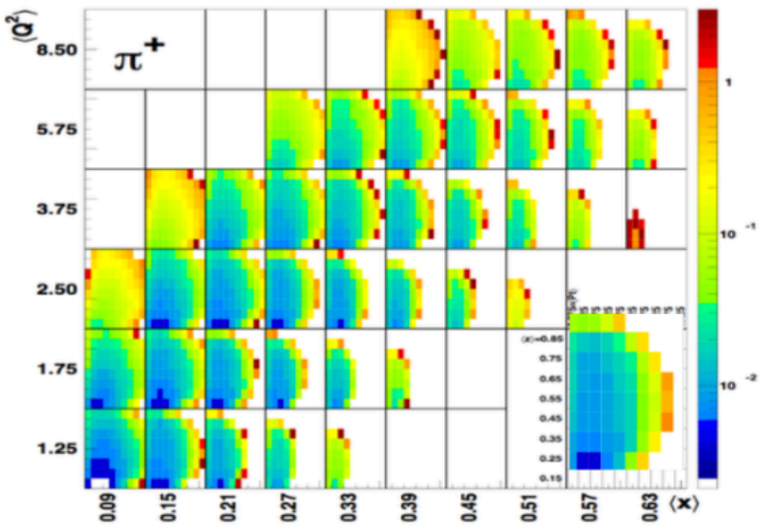
CLAS12: Evolution and k_T-dependence of TMDs



CLAS12 kinematical coverage





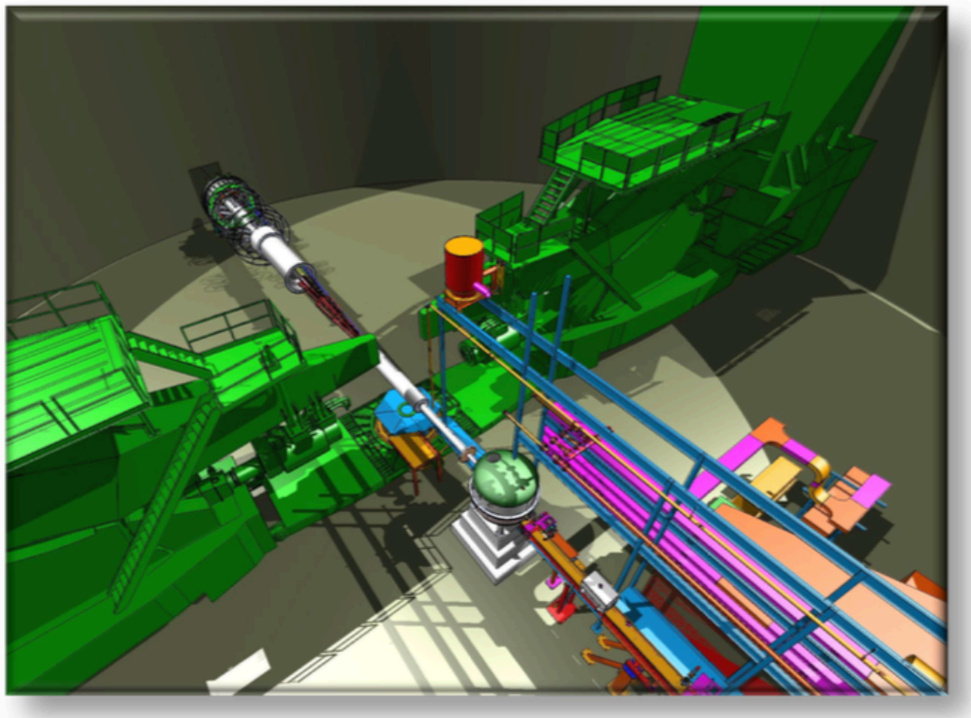


k_T-dependence of $g_1(x, k_T)$

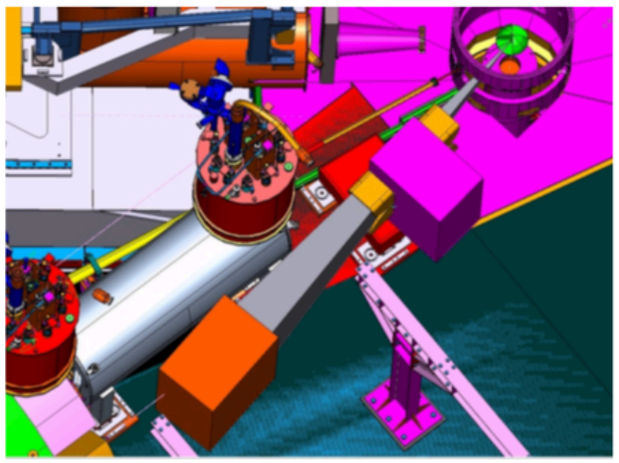
Q^2-dependence of Sivers, $f_1^{\perp}(x, k_T)$

- Large acceptance of CLAS12 allows studies of P_T and Q^2-dependence of SSAs in a wide kinematic range
- Comparison of JLab12 data with HERMES, COMPASS (and EIC) will pin down transverse momentum dependence and the non-trivial Q^2 evolution of TMD PDFs in general, and Sivers function in particular.

12 GeV program at JLab - near and longer-term upgrades



MOLLER spectrometer (Hall A)
→ Measurement of PV in *ee* scattering



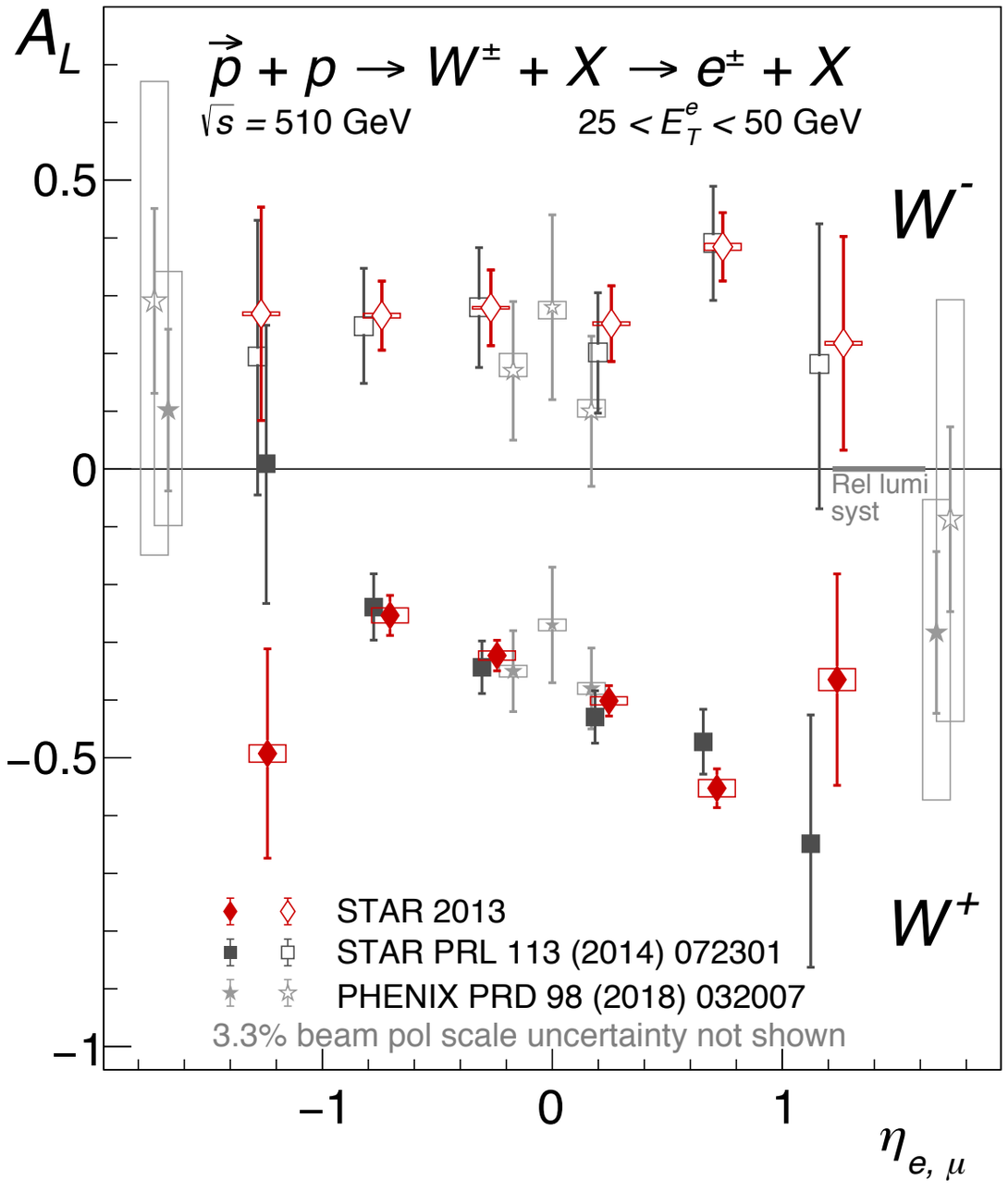
Neutral Particle Spectrometer (Hall C)
→ DVCS
→ π^0 in exclusive, SIDIS reactions
→ Wide angle Compton scattering

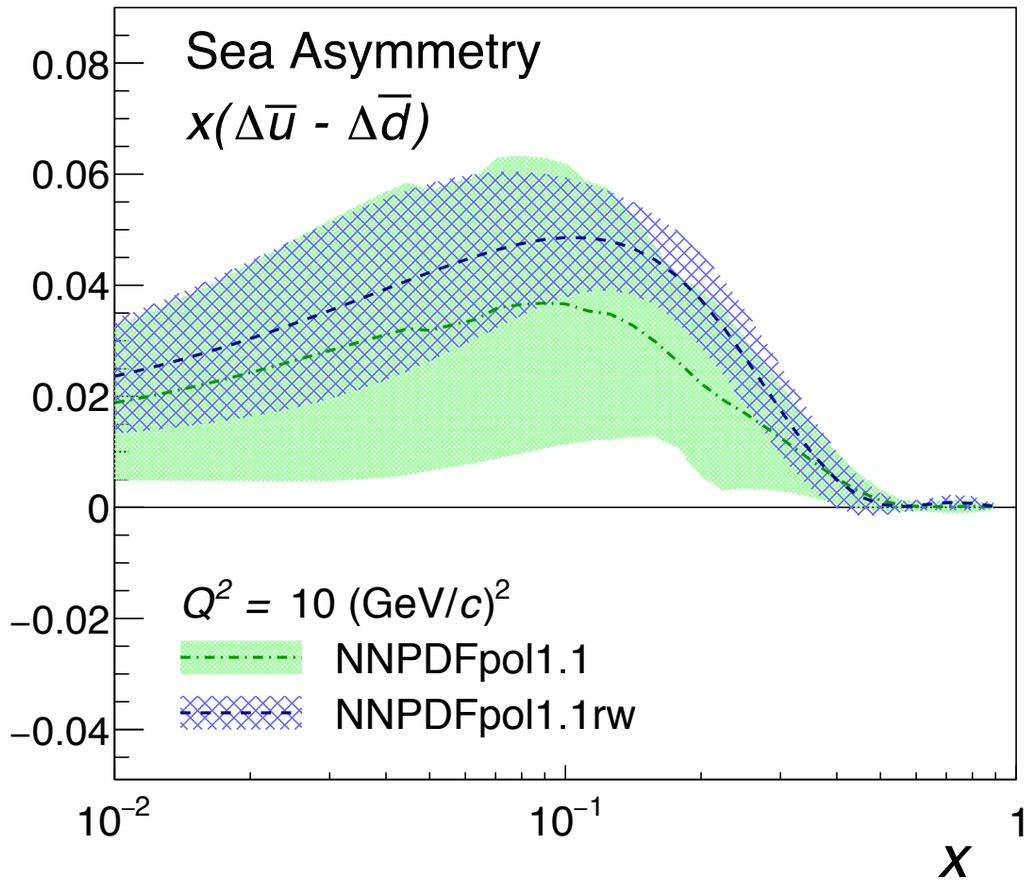
Solenoidal Large Intensity Device (SoLID)
→ Parity violation in DIS
→ SIDIS with unpolarized/polarized target

Jefferson Lab

c.f. Krishna Kumar's talk

RHIC





From Renee Fatemi's talk

To come: analysis from watershed 2017 transversely polarized run

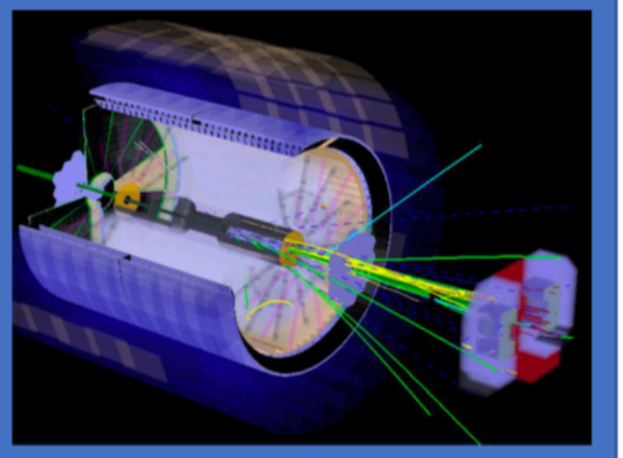
RHIC

sPHENIX, a heavy-ion motivated experiment, is being constructed

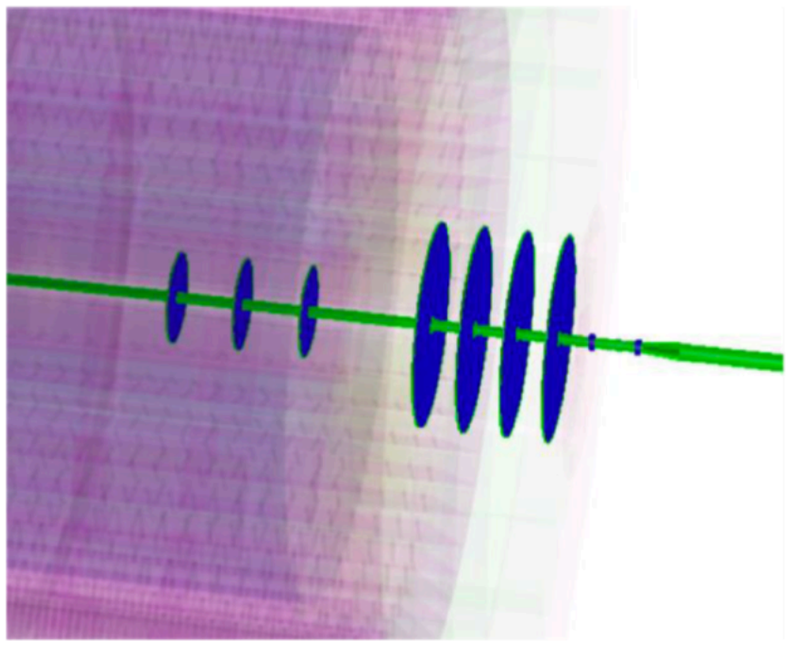
STAR is realizing a forward acceptance upgrade

STAR Forward ($2.5 < \eta < 4$) Upgrade in 2021

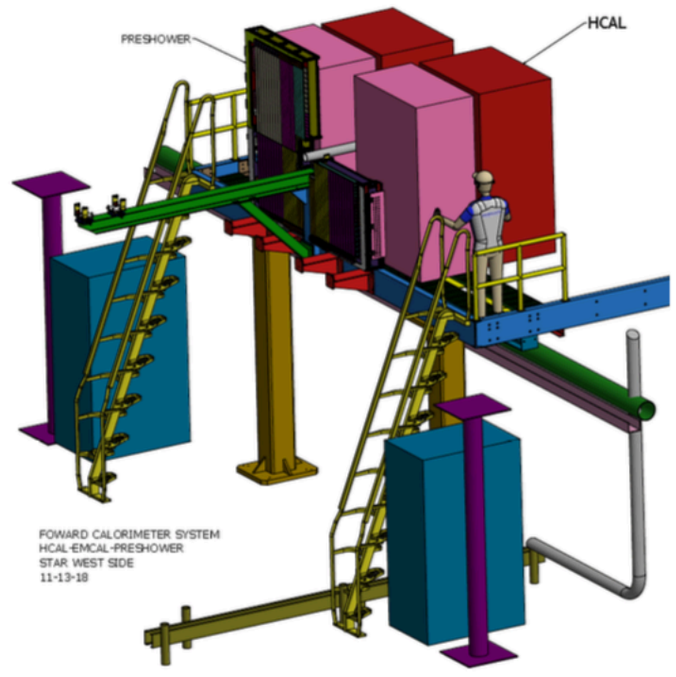
The STAR Forward Calorimeter and Forward Tracking System



A Tale of Initial State:
From Nucleon to Nuclei



- **3 Silicon microstrip disks**
- **4 small Thin Gap Chambers**



- **EM calorimeter: 18 X_0 PbSc**
- **Had. calorimeter: 4.5λ FeSc**
- **Pre/Post-shower: Scintillator**

STAR Forward Physics Program (2021-2025)
$\Delta g(x)$ at low x, TMDs at low and high x
Signature and A-dependence of saturation
Initial state & hadronization in nucl. collisions

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~60%/√E	---
Tracking	charge separation photon suppression	0.2<p_T<2 GeV/c with 20-30% 1/p_T

Proposal: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0648

RHIC

sPHENIX, a heavy-ion motivated experiment, is being constructed

STAR is realizing a forward acceptance upgrade

	Year	√s (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Potential running	2021/22	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	ECal+HCal+Tracking
	2021/22	$\overrightarrow{p}\overrightarrow{p}$ @ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/gamma-jets at $\eta > 1$	ECal+HCal
In parallel with sPHENIX running	2023-25	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	Subprocess driving the large A_N at high x_F and h	A_N for charged hadrons and flavor enhanced jets	ECal+HCal+Tracking
		$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	initial state and hadronization in nuclear collisions signatures for Saturation	R_{pAu} direct photons and DY Dihadron, g-jet, h-jet, diffraction	ECal+HCal+Tracking
		$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence for Saturation	R_{pAl}: direct photons and DY Dihadrons, g-jet, h-jet, diffraction	ECal+HCal+Tracking

Electron Ion Collider Initiatives

Past

Possible Future

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	17	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-3}	
ion	p	p, Pb, …	p - Pb	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
L [$cm^{-2}s^{-1}$]	2×10^{31}	1×10^{34}	5×10^{33}	10^{33} - 10^{34}
Interaction Points	2	1	1	2
Timeline	1992 - 2007	post ALICE	> 2028	> 2028

High-Energy Physics

Nuclear Physics

Representative though not complete, c.f. ENC, HE-LHeC, PEPIC, VHEeP, FCC-eh

Electron Ion Collider Initiatives

Approach: combine strengths
use existing investments (risk, cost),
pursue luminosity;100x - 1000x HERA
nuclei and *polarization*,
optimized instrumentation.

	HERA @ DESY	LHeC @ CERN	EIC in China	EIC in U.S.
$\sqrt{s_{ep}}$ [GeV]	320	200 - 1300	17	20 - 100 (140)
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-3}	
ion	p	p, Pb, …	p - Pb	p - U
polarization	-	-	p, light nuclei	p, d, ^{3}He, Li
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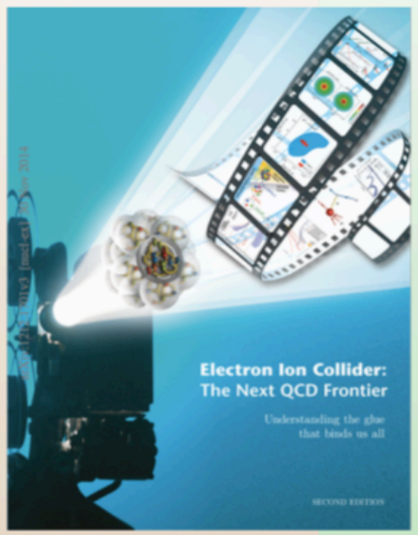
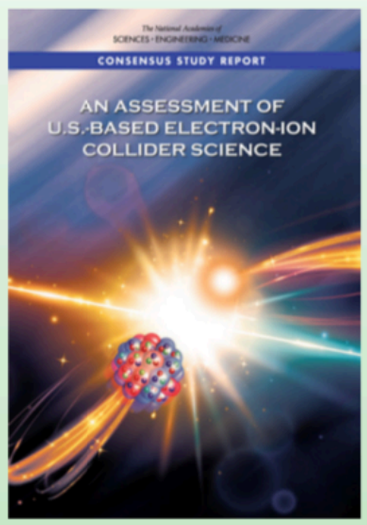
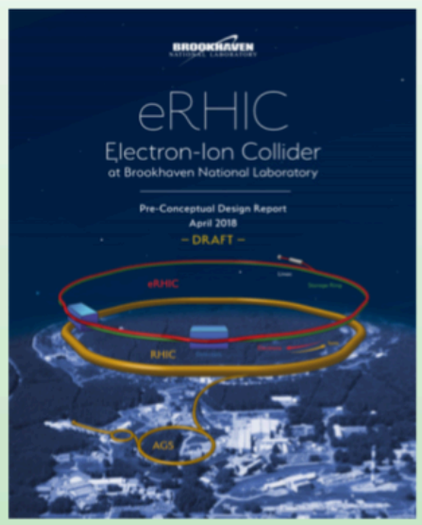
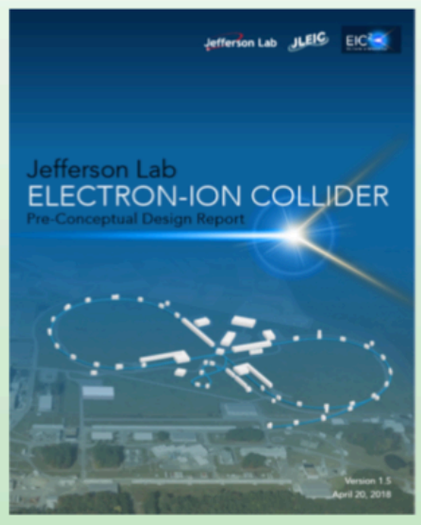
Timeline	1992 - 2007	post ALICE	> 2028	> 2028

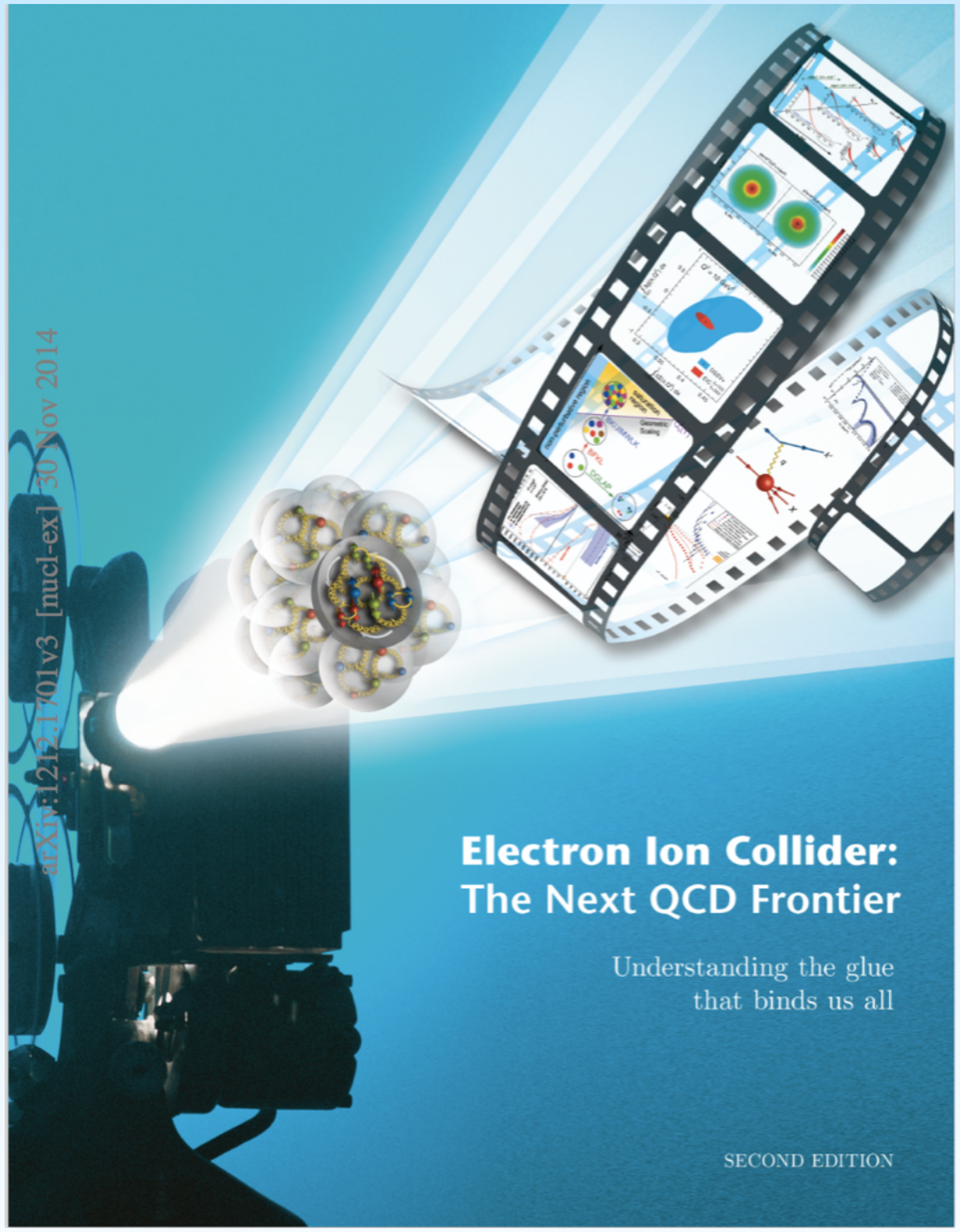








U.S. EIC Capabilities



Eur. Phys. J. A52 (2016) no.9, 268 - 644 citations

See also Rept.Prog.Phys. 82 (2019) 024301

- *A collider to provide kinematic reach well into the gluon dominated regime,*

- *Electron beams provide the unmatched precision of the electromagnetic interaction as a probe,*

- *Polarized nucleon beams to determine the correlations of sea quark and gluon distributions with the nucleon spin,*

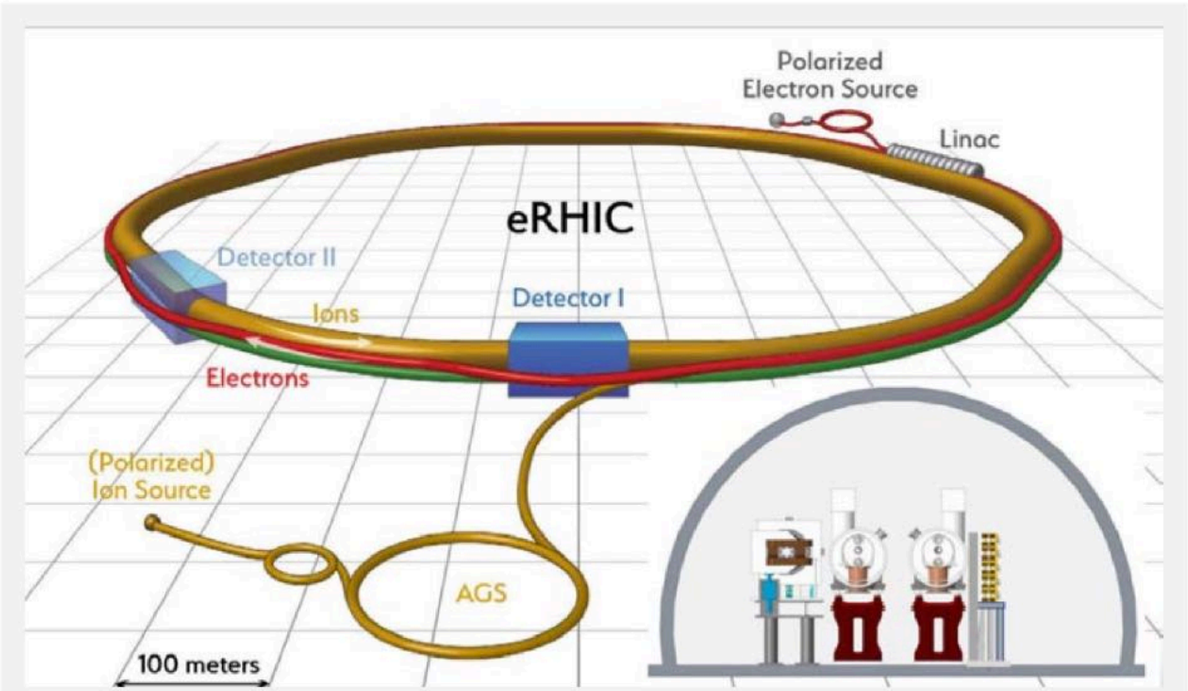
- *Heavy Ion beams to access the gluon-saturated regime and as a precise dial to study propagation of color charges in nuclear matter.*

- *Facility concepts at RHIC and at Jefferson Laboratory, re-use of existing, significant investment.*

U.S.-based EIC - Two Facility Concepts

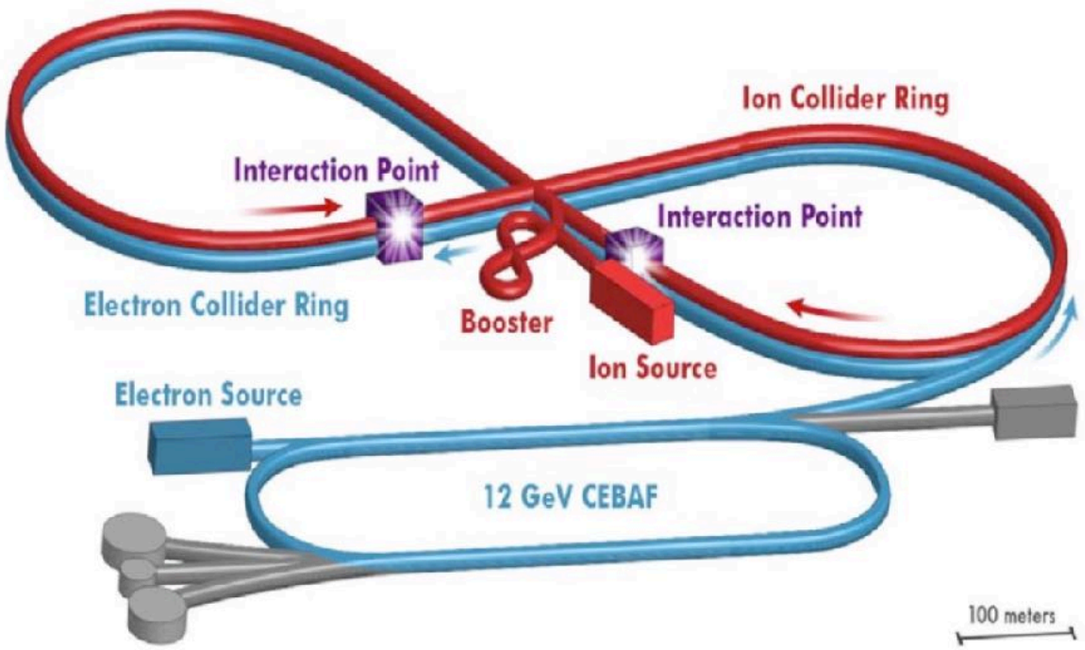
eRHIC (as presented in the W.P.):

- re-use RHIC hadron beam,
- new electron storage ring,
- 5 - 18 GeV e energy,
- Heavy Ions up to 100 GeV/u
- $\sqrt{s}$ up to 93 GeV
- L ~ 0.4×10^{34} $cm^{-2}s^{-1}$/A base design,
  1.0×10^{34} $cm^{-2}s^{-1}$/A w. strong cooling



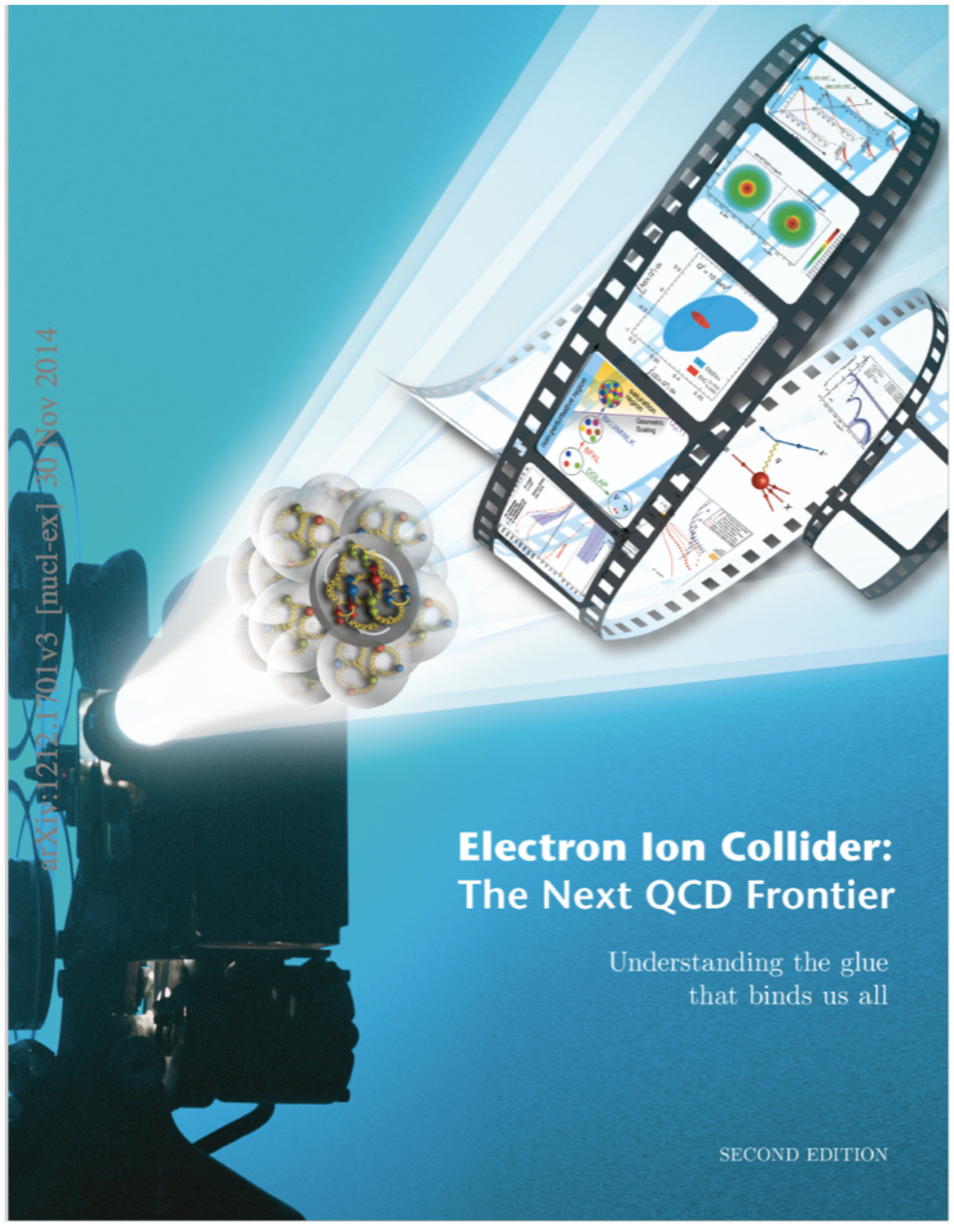
JLEIC (as presented in W.P.):

- re-use CEBAF 12 GeV electron beam facility,
- new hadron injector,
- new figure-8 collider configuration,
- 3-10 GeV electron energy,
- 12-40 GeV/u Heavy Ion energy, upgradable (ion arc dipole)
- L ~10^{34} $cm^{-2}s^{-1}$/A



Science cases by themselves!

U.S. EIC Science Case



Eur. Phys. J. A52 (2016) no.9, 268 - 644 citations

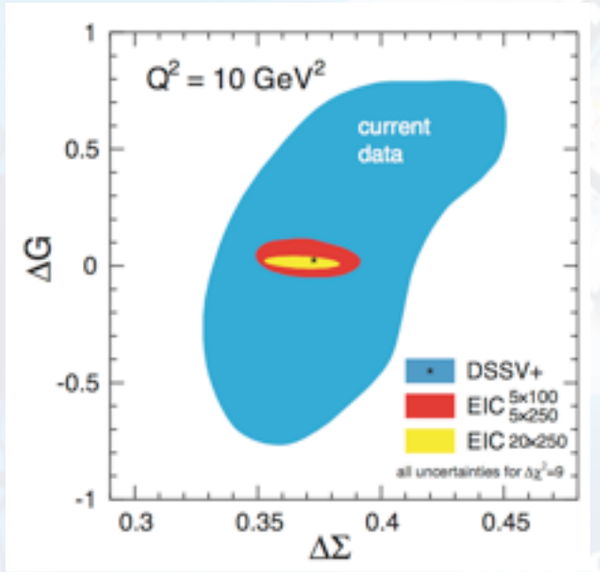
See also Rept.Prog.Phys. 82 (2019) 024301

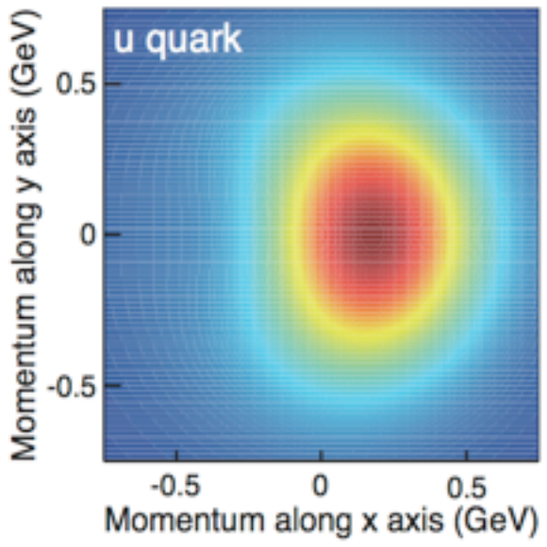
Organized around four themes:

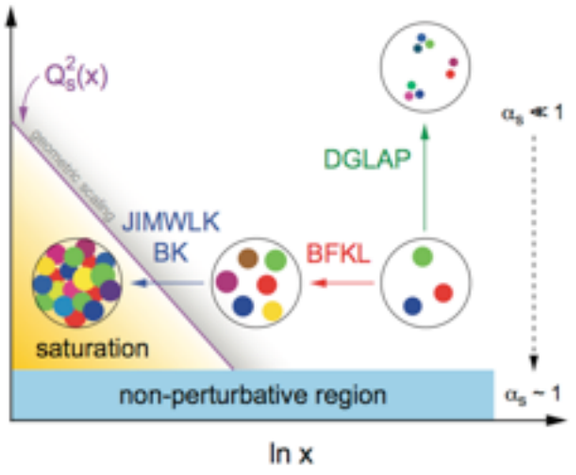
- *Proton spin,*
  quark and gluon helicity distributions, orbital motion
- *Imaging of nucleons and nuclei*
  TMDs, GPDs, Wigner functions
- *Saturation*
  Non-linear evolution, Color-glass condensate,
- *Hadronization and fragmentation,*
  in-medium propagation,attenuation

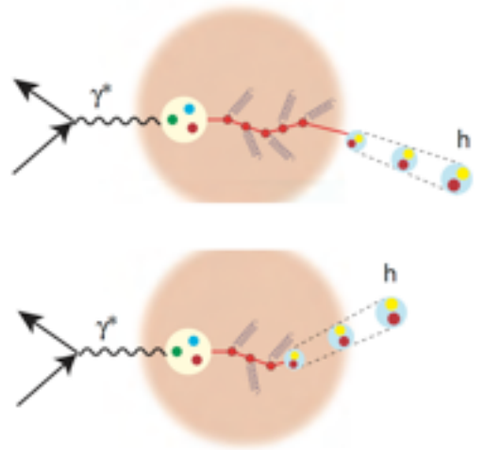
Identified measurements and impact.

U.S.-based EIC - Core Science





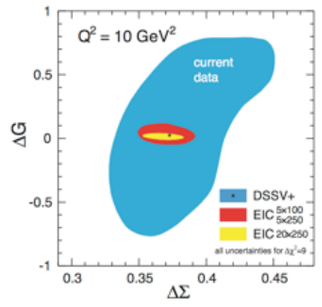




Nuclear Physics enabled by EIC **accelerator** energy, intensity, polarization, and species, **experiment** capabilities,

theory

U.S.-based EIC - Proton Spin



Current polarized DIS data:

○ CERN △ DESY ◊ JLab □ SLAC

Current polarized BNL-RHIC pp data:

● PHENIX π^0 ▲ STAR 1-jet

EIC √s= 140 GeV, 0.01≤ y ≤ 0.95

EIC √s= 45 GeV, 0.01≤ y ≤ 0.95

Q^2 (GeV^2)

10^3

10^2

10

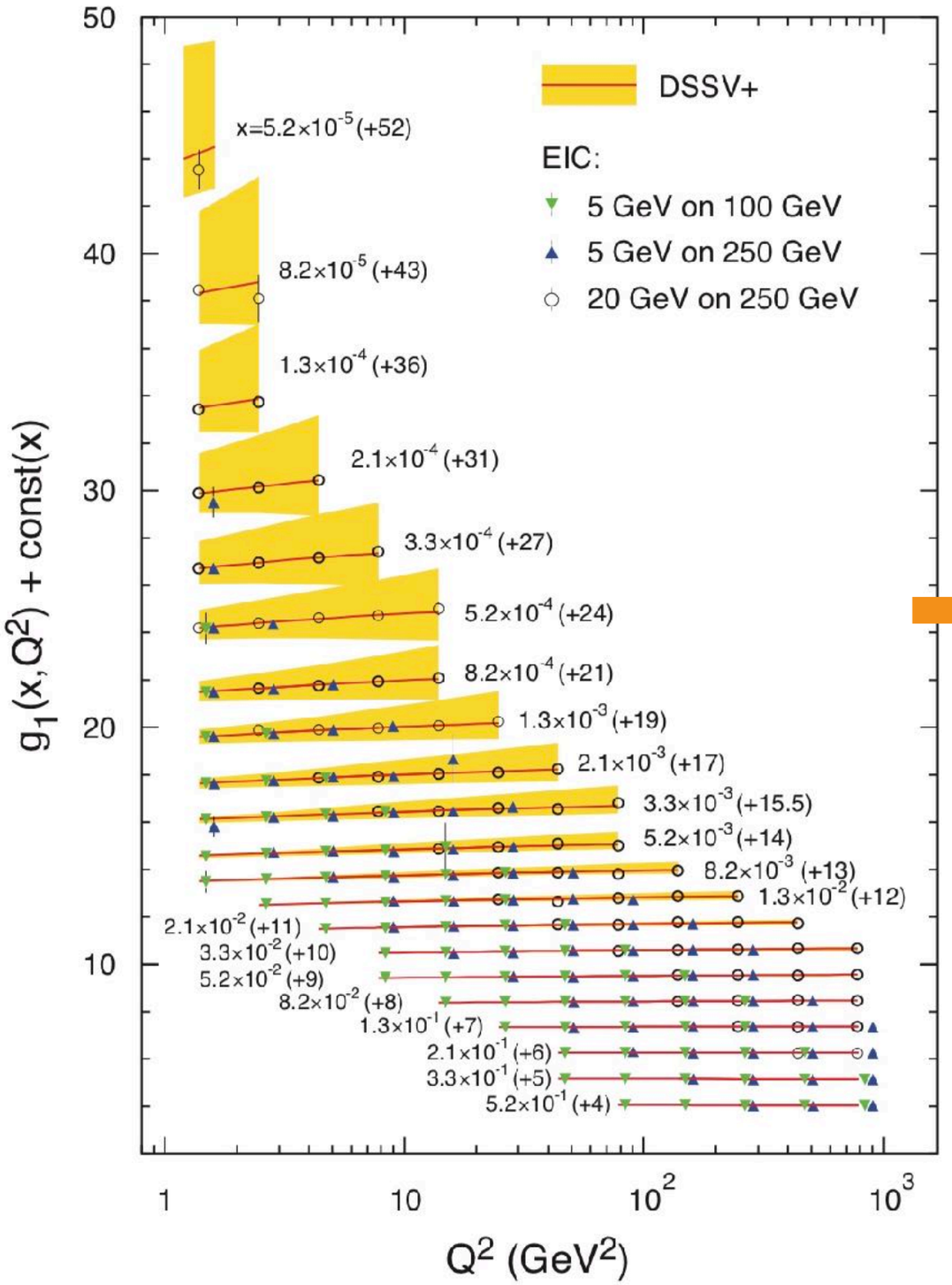
1

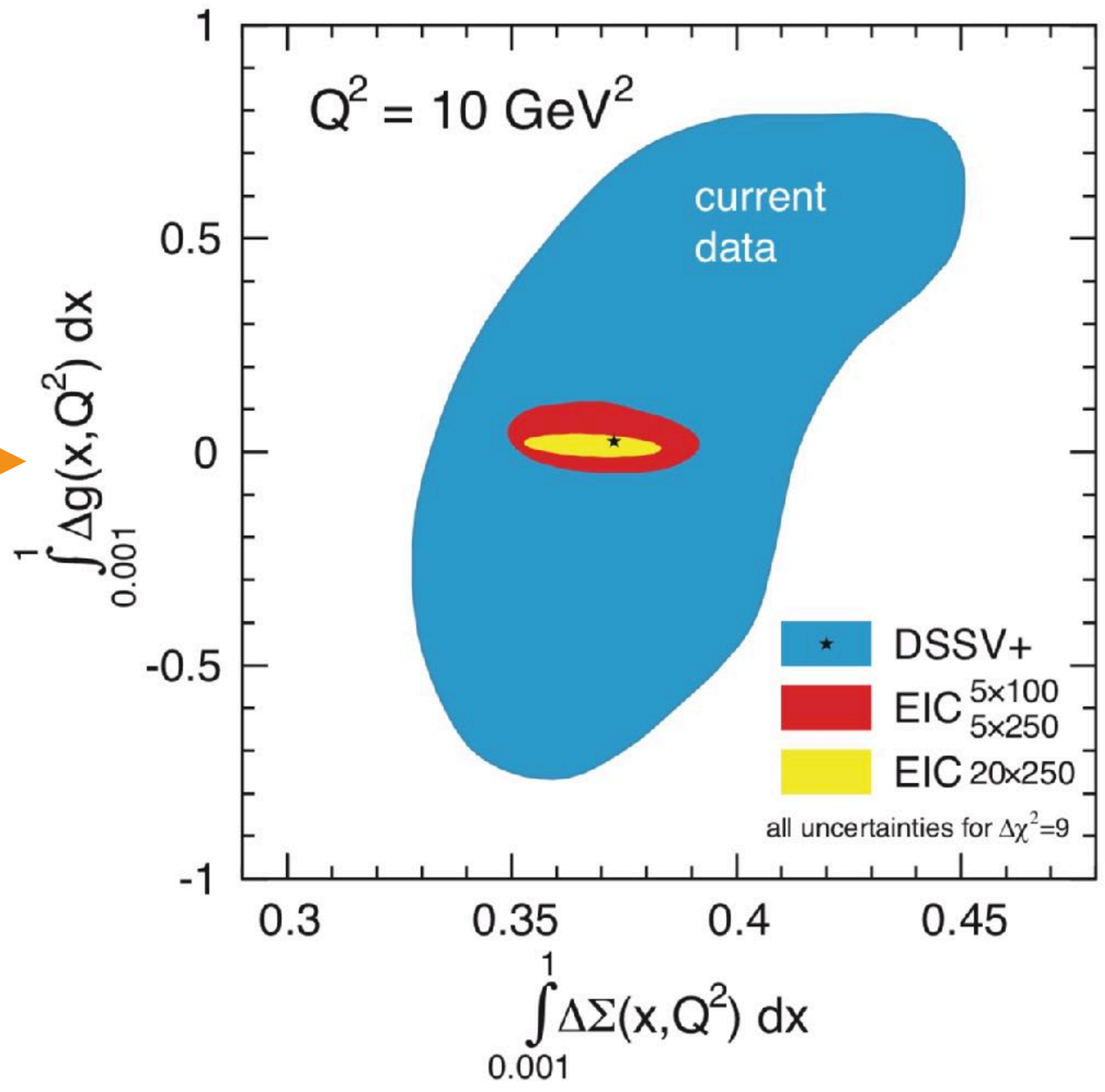
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1

x

Two orders in *x* and Q^2 compared to existing data; few, if any, alternatives.

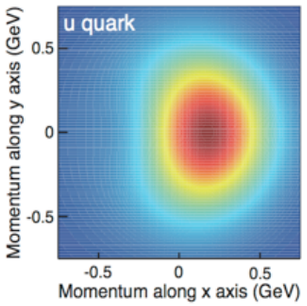
U.S.-based EIC - Proton Spin

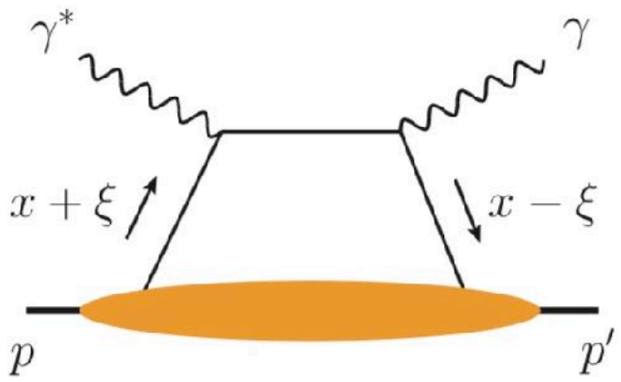


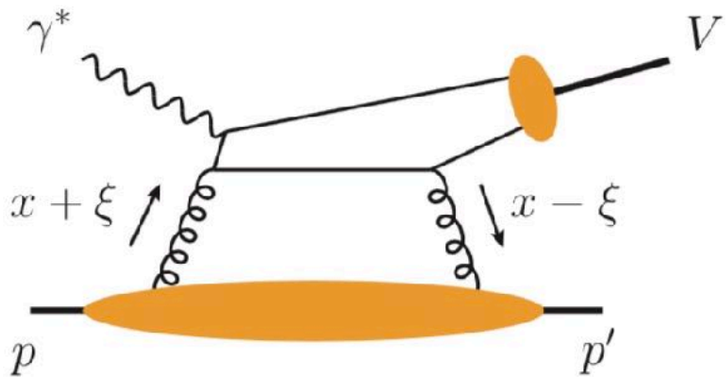


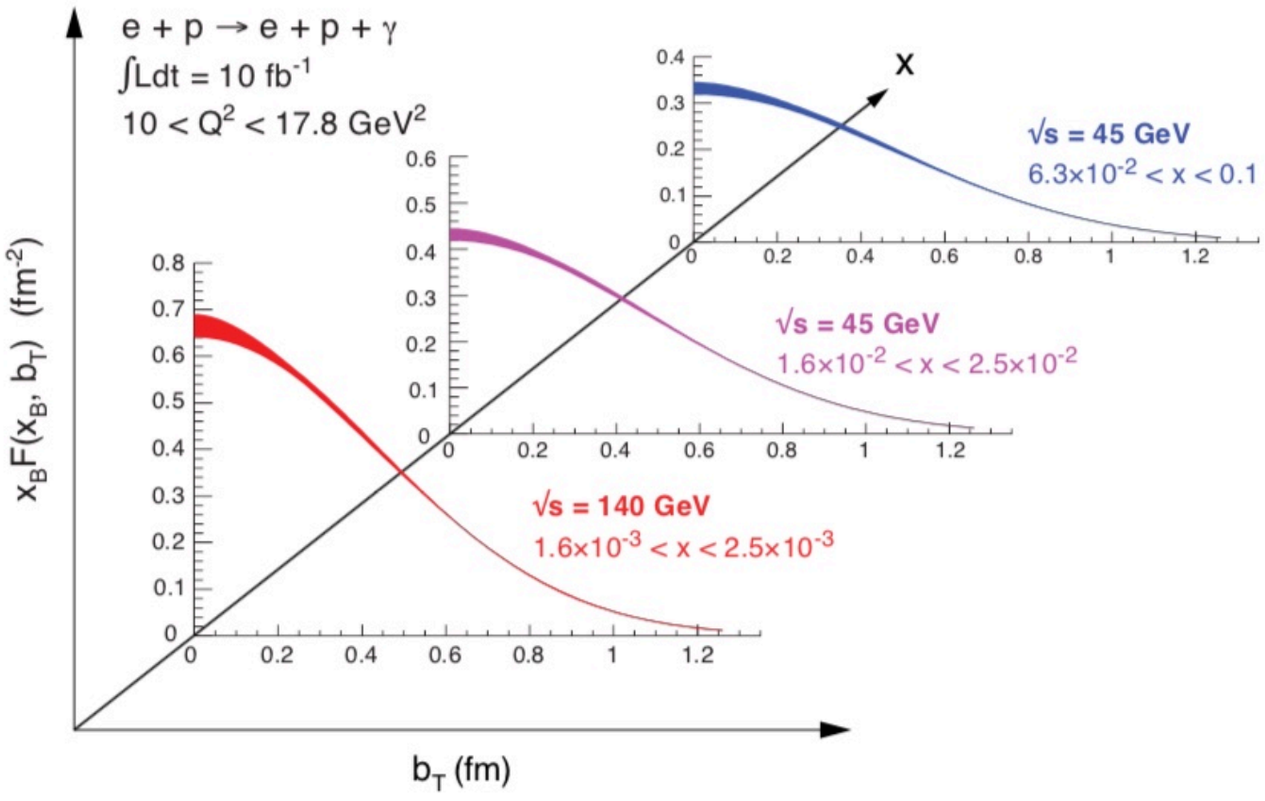
Conclusive insights in quark and gluon helicity from inclusive measurements, and orbital momentum by subtraction (!)

EIC - DVCS, DVMP, and Imaging

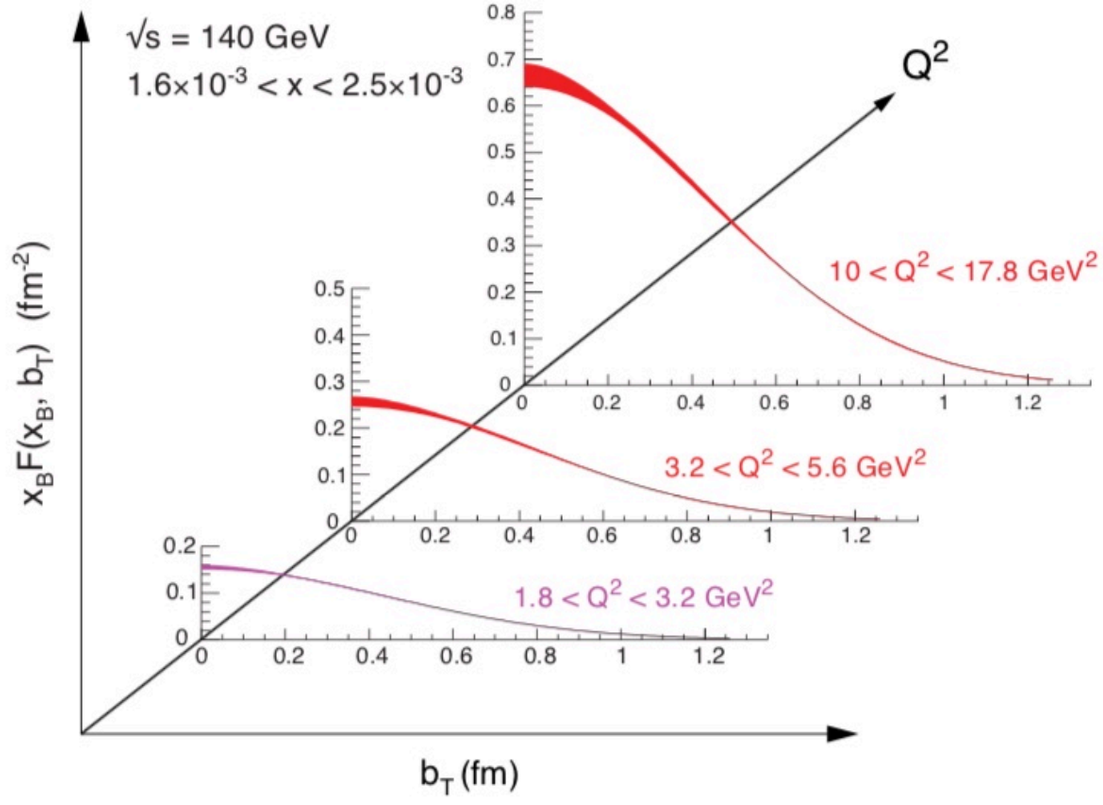






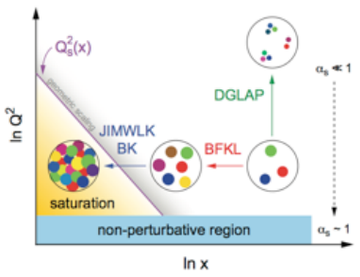


x-dependence at fixed Q^2



Q^2-dependence at fixed x

U.S.-based EIC - The Nuclear Landscape



Measurements with A ≥ 56 (Fe):
- eA/μA DIS (E-139, E-665, EMC, NMC)
- νA DIS (CCFR, CDHSW, CHORUS, NuTeV)
- DY (E772, E866)

eRHIC √s = 78 GeV, 0.01 ≤ y ≤ 0.95

Q_s^2 Au

Ca

p

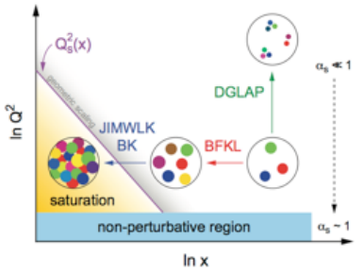
Q^2 (GeV^2)

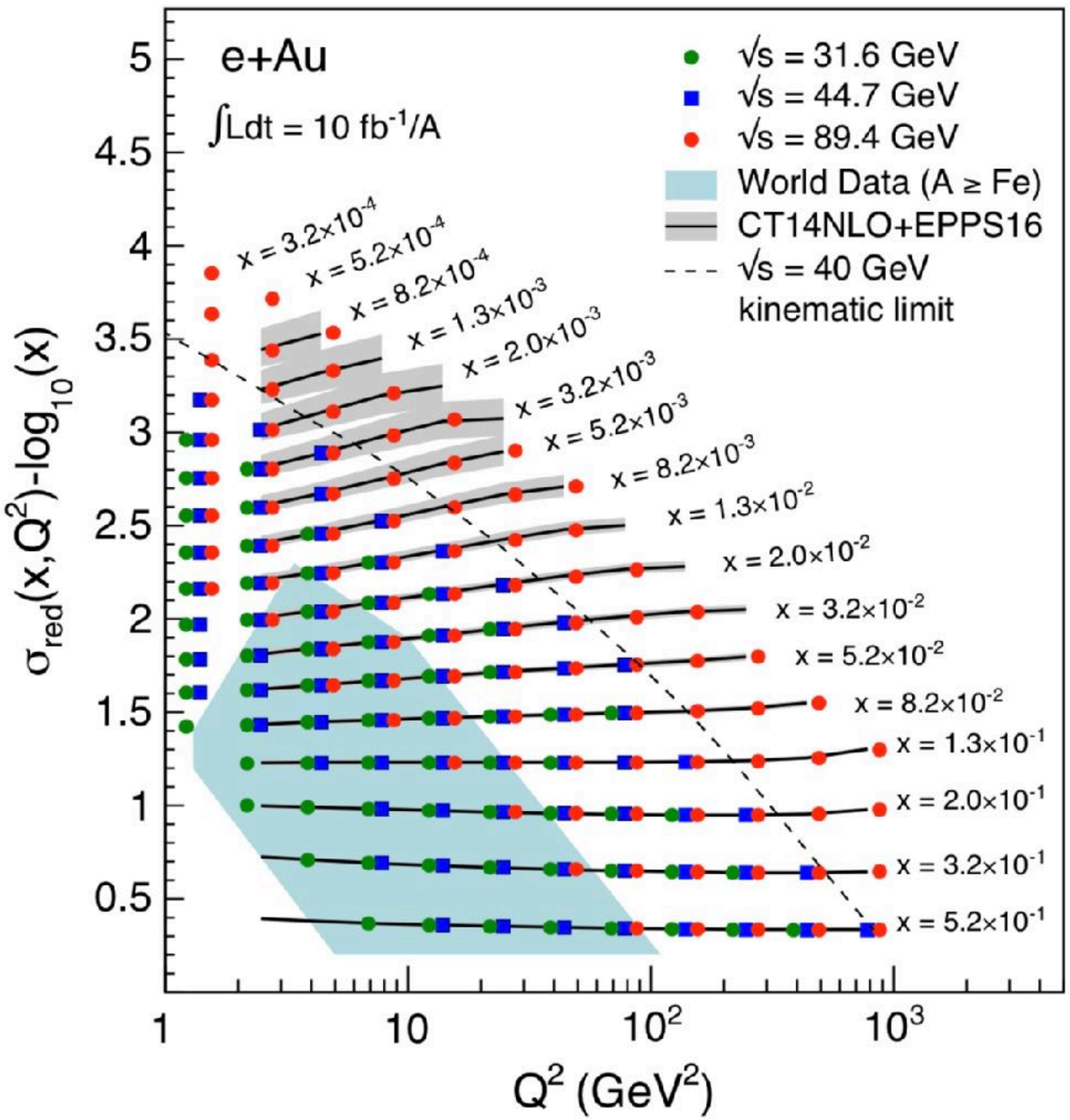
x

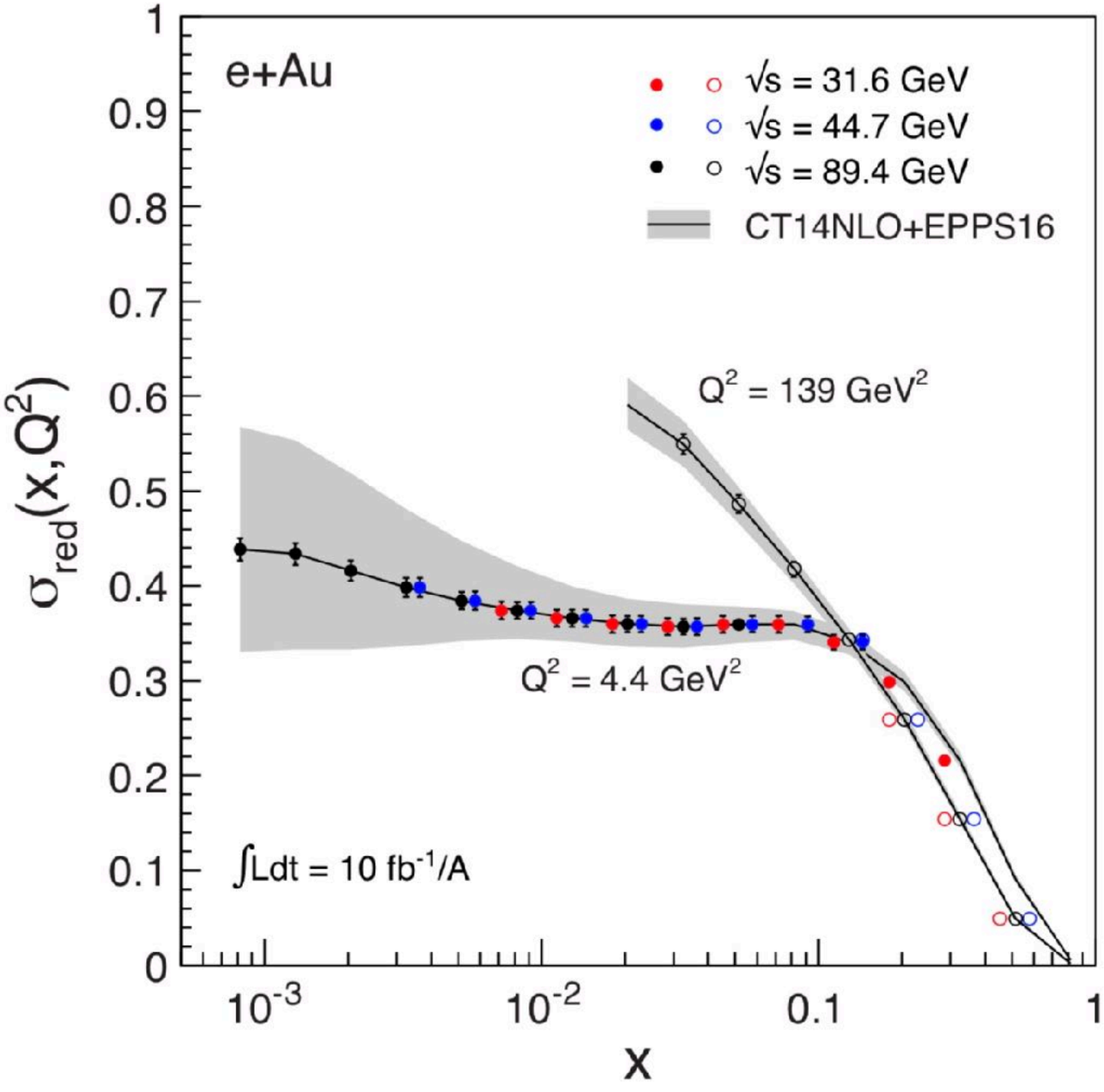
Complementarity with ongoing and future RHIC and LHC measurements, neutrino physics, cosmic ray physics, …

LHeC, if it will be realized, will further extend the kinematic coverage.

U.S.-based EIC - The Nuclear Landscape

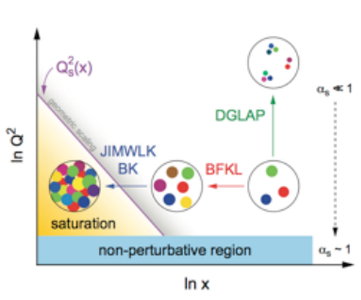




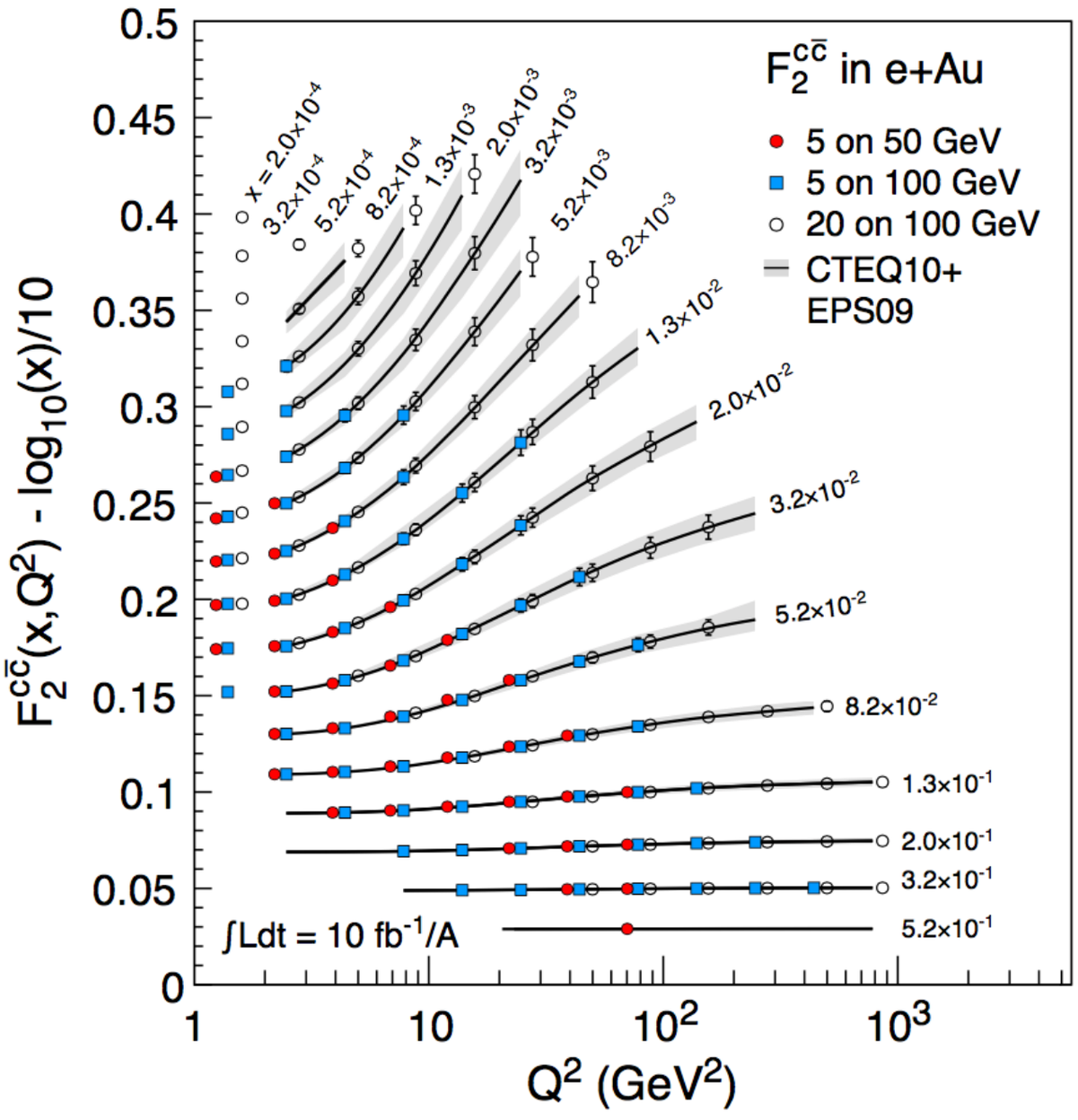


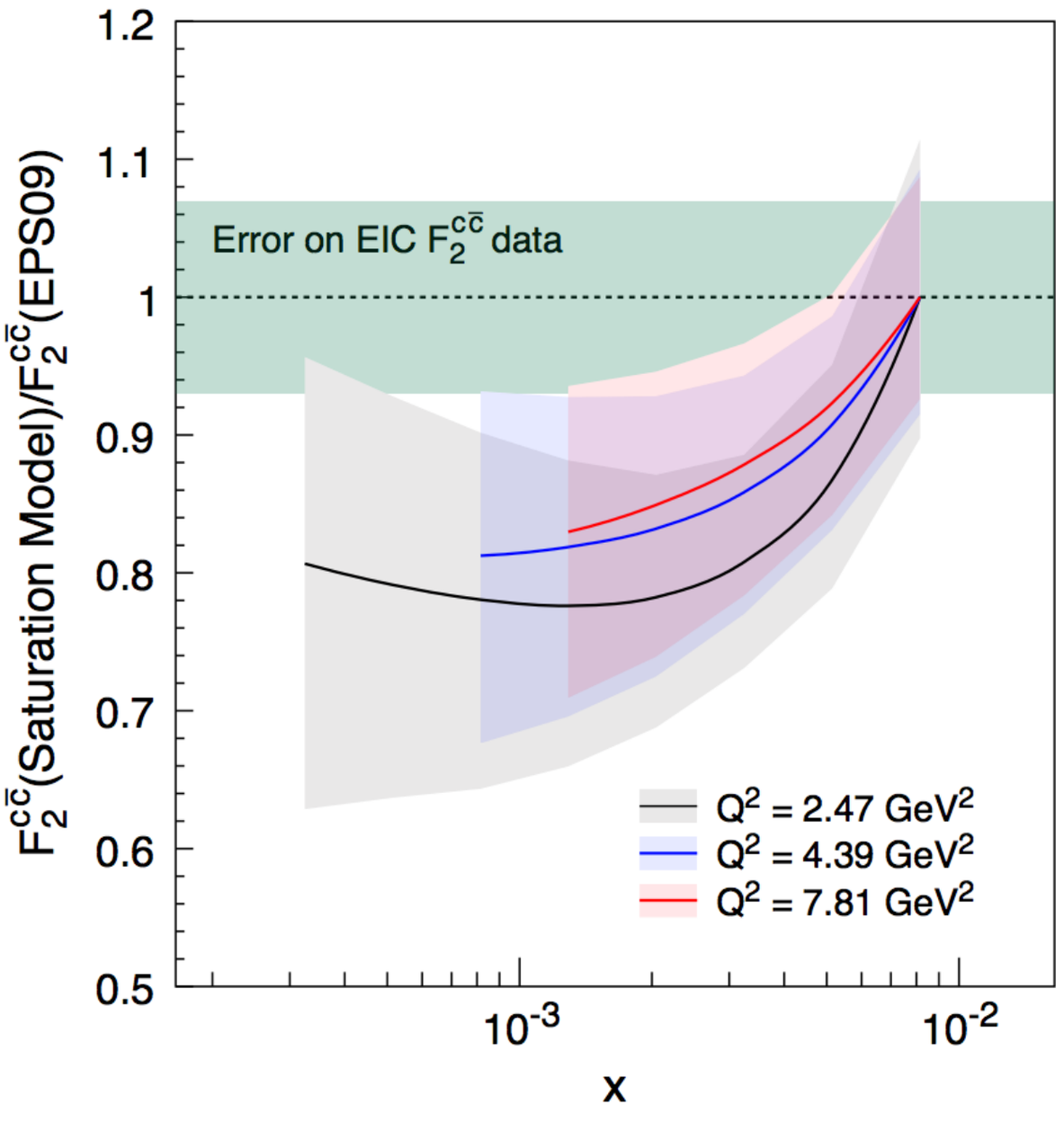
$$\sigma_{\text{reduced}} = F_2(x,Q^2) - \frac{y}{1+(1-y)^2} F_L(x,Q^2)$$

Impactful baseline inclusive measurements.



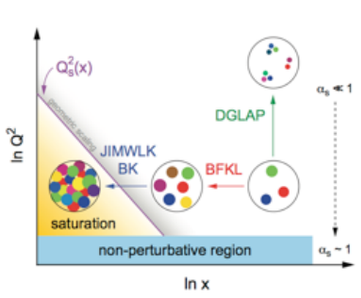
EIC - Saturation from within the PDF?

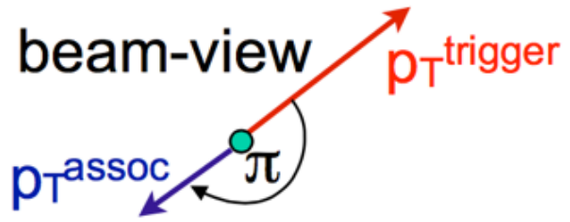


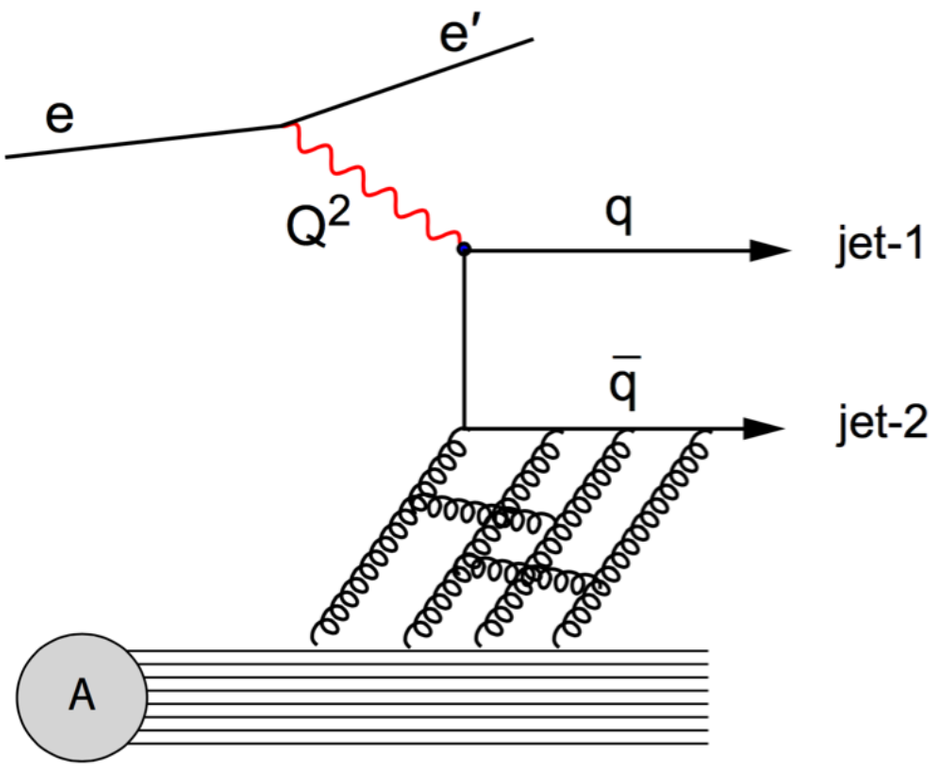


Improbable **and** ***certainly no substitute*** **for thinking** ***outside*** **the PDF!**

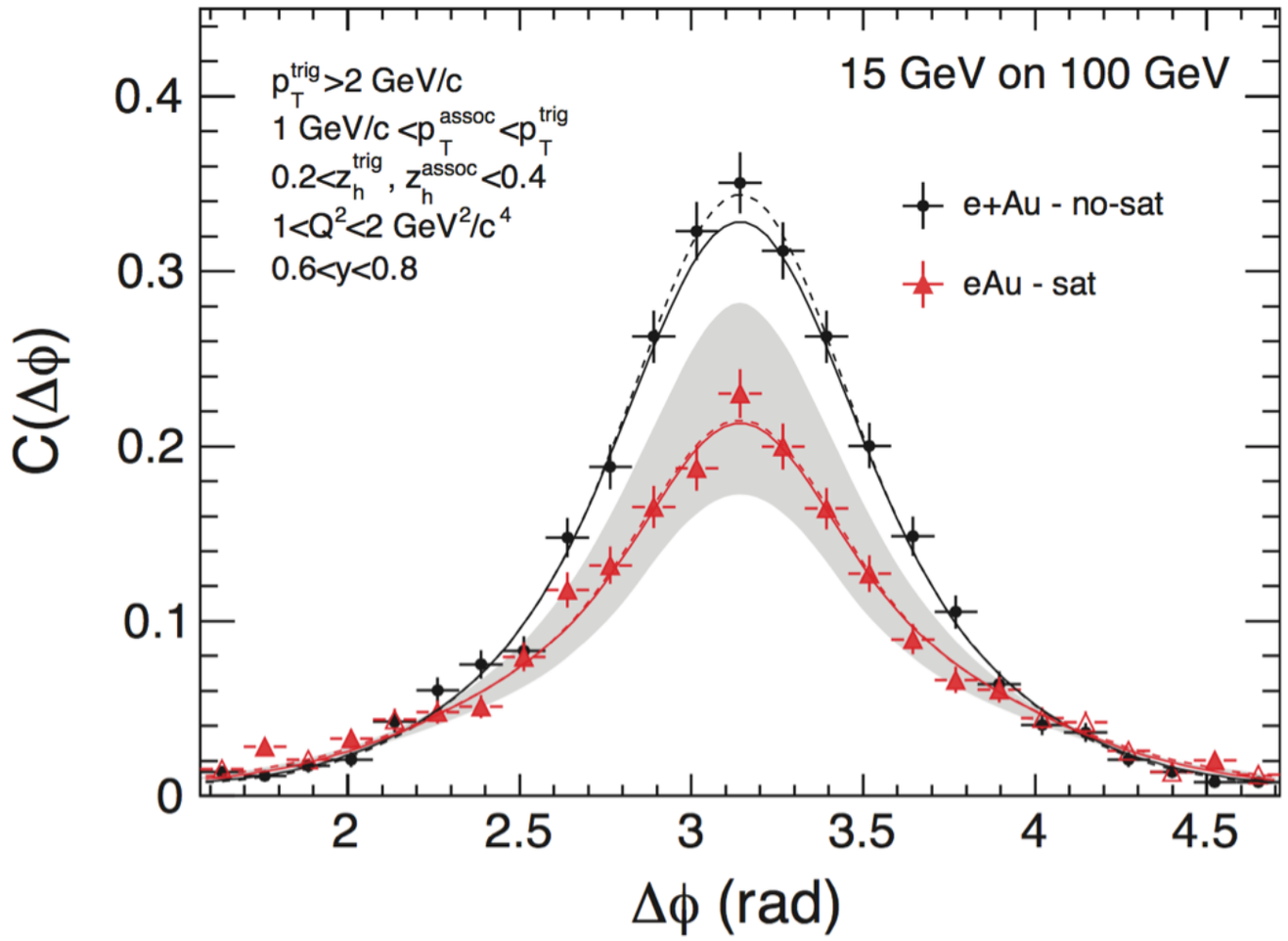
EIC - Dihadrons to probe Saturation







Dominguez, Xiao, Yuan (2011)

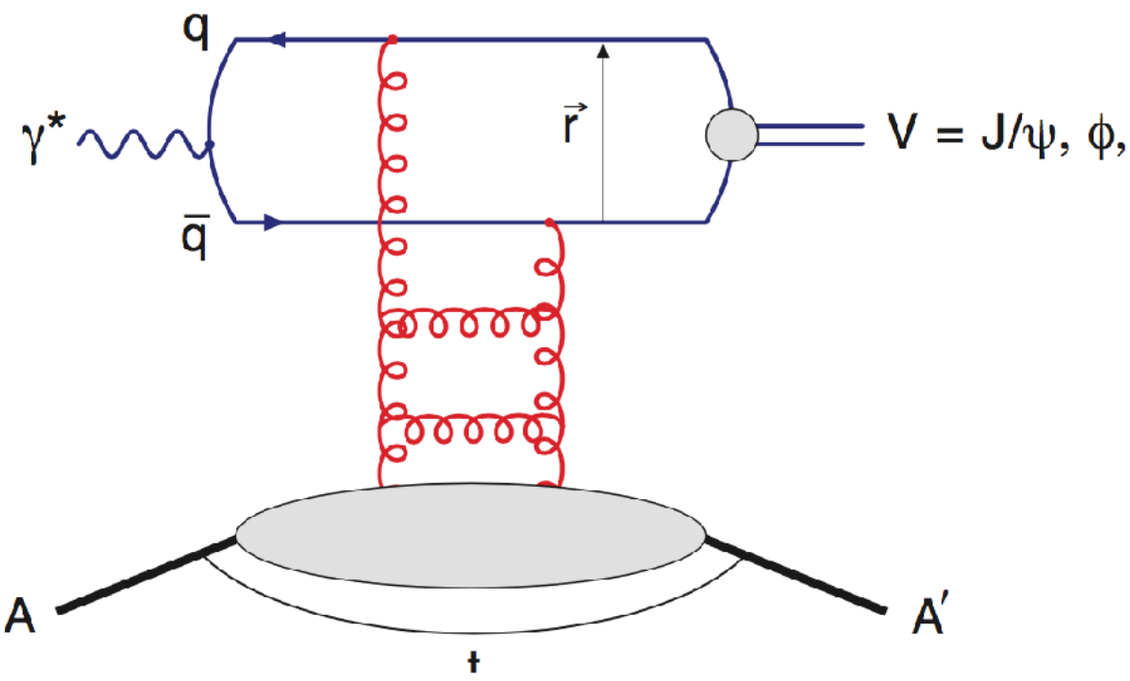


Zheng et al (2014)

Suppression of back-to-back hadron or jet correlation directly probes the (un-)saturated gluon distributions in nuclei,

EIC - Exclusive Vector Mesons to probe Saturation

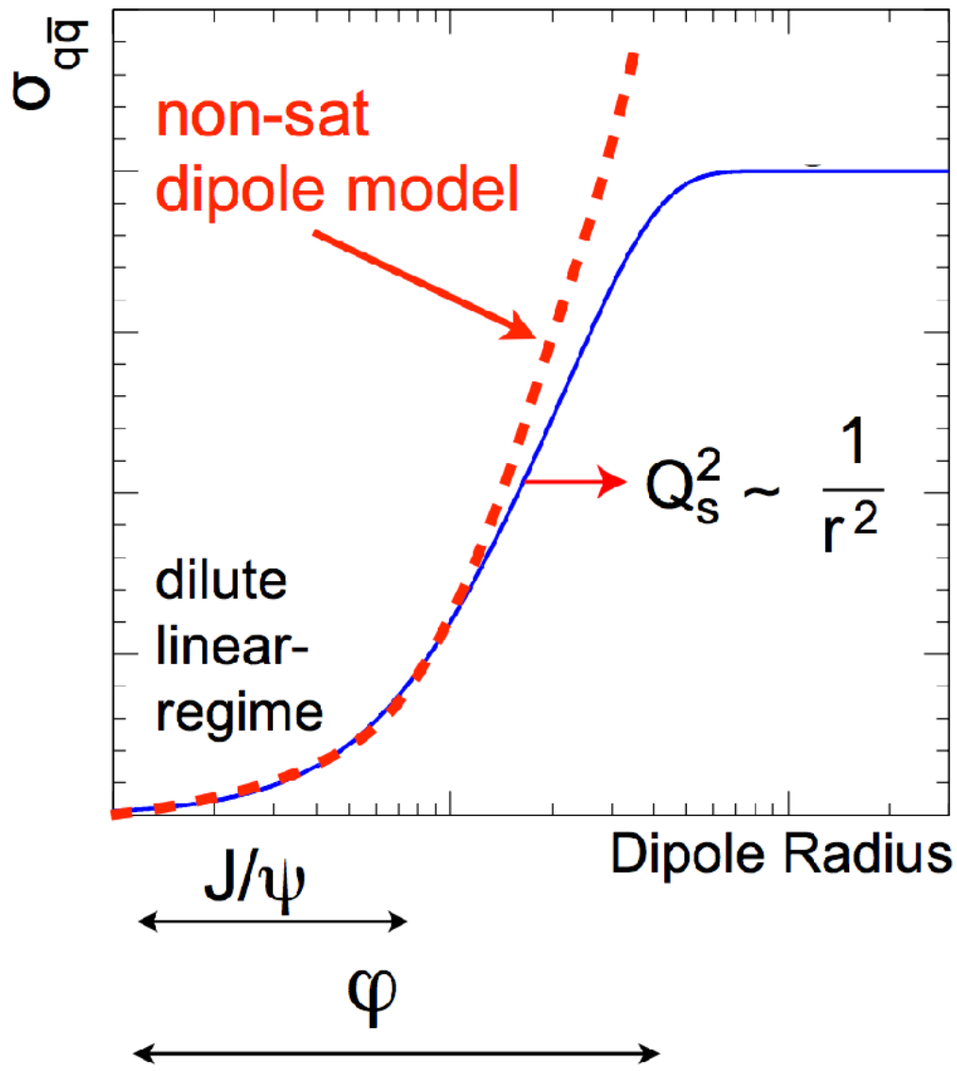
$$t = (p_A - p_{A'})^2 = (p_{\mathrm{VM}} + p_{e'} - p_e)^2$$



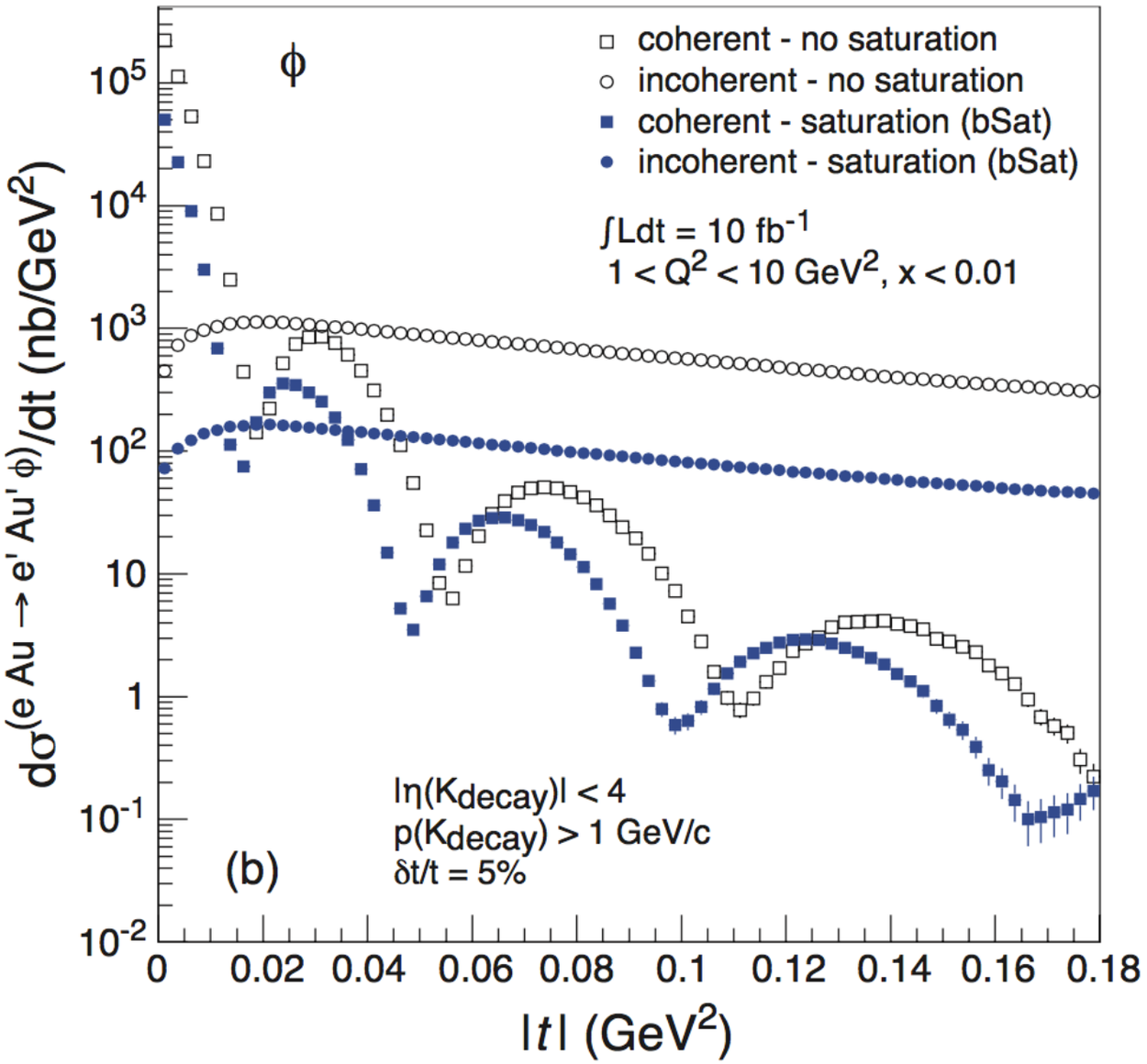
Nucleus escapes down the beampipe

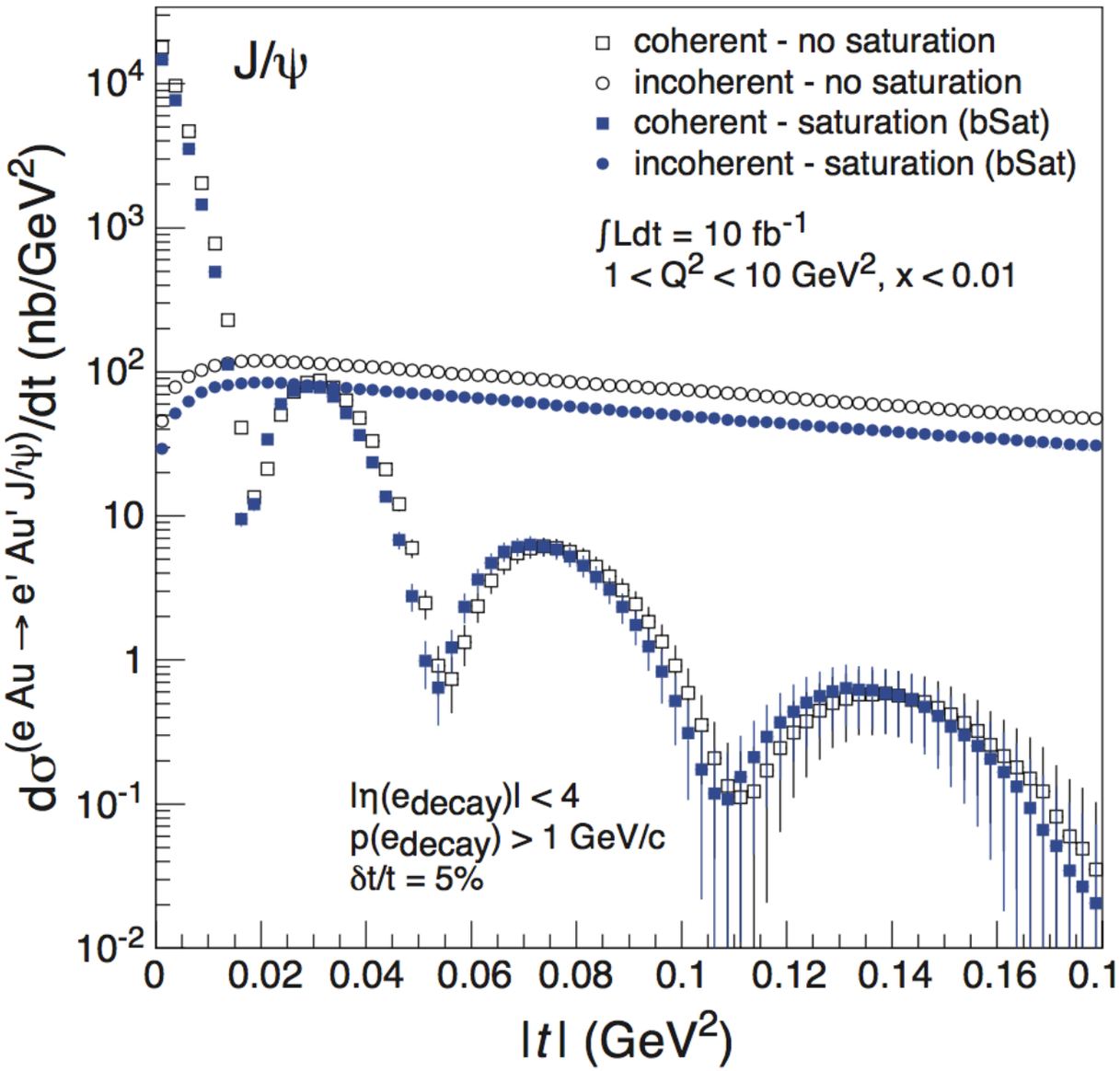
(In)coherence tagged with ZDC

Dipole Cross-Section:



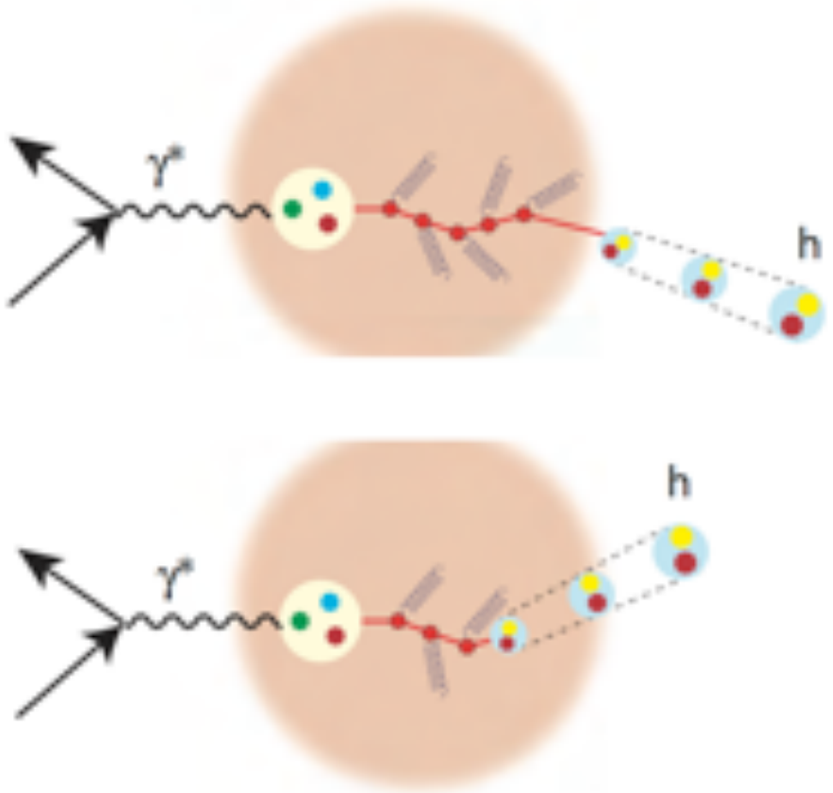
EIC - Exclusive Vector Mesons to probe Saturation





Exclusive vector meson production is key to (all) imaging, as is deeply virtual Compton scattering

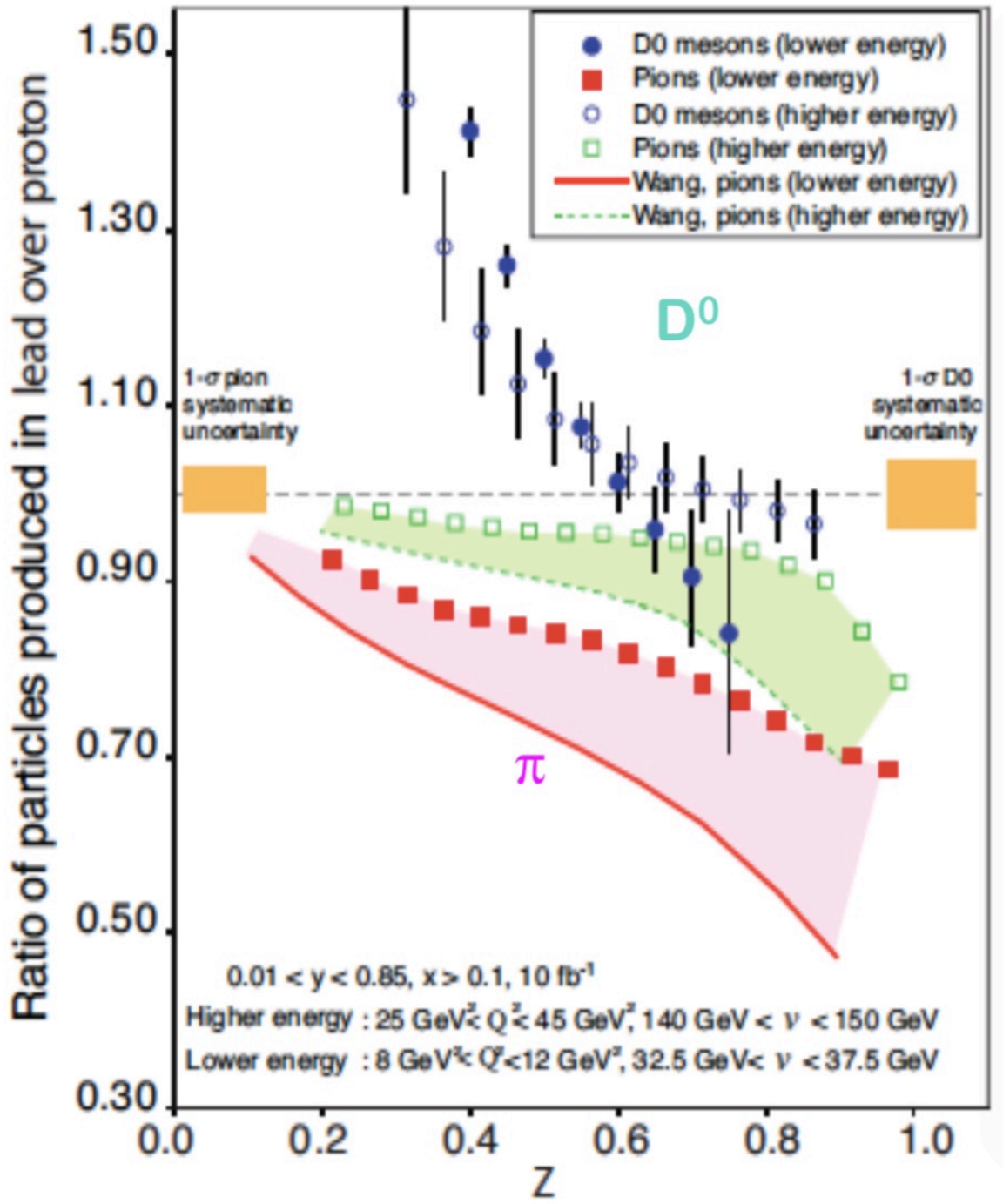
EIC - SIDIS to study Emergence of Hadrons



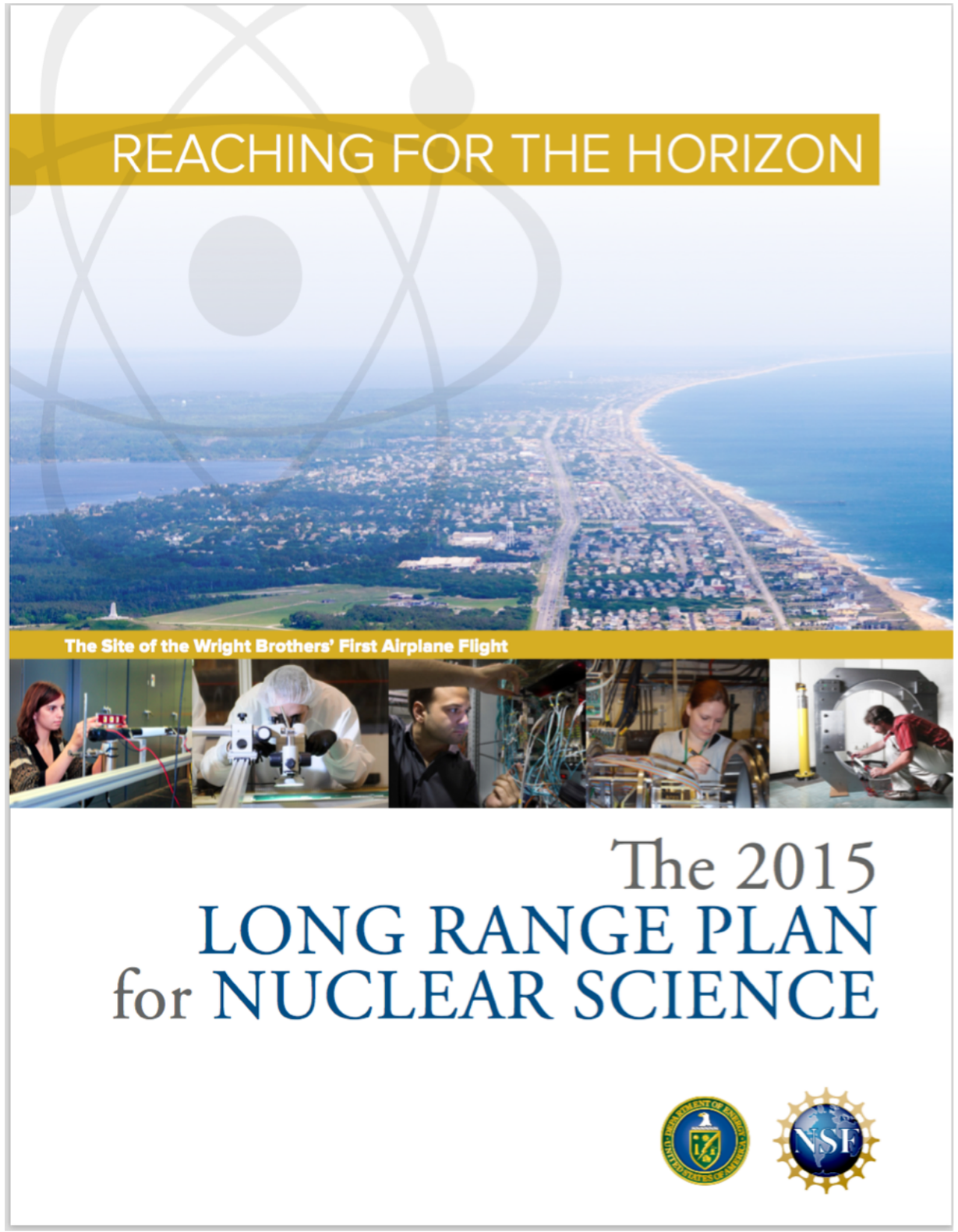
Control of $\nu = \dfrac{Q^2}{2mx}$ and

medium length

Study mass-dependence via charmed hadrons.



Status of U.S.-based EIC



RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

RECOMMENDATION II

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

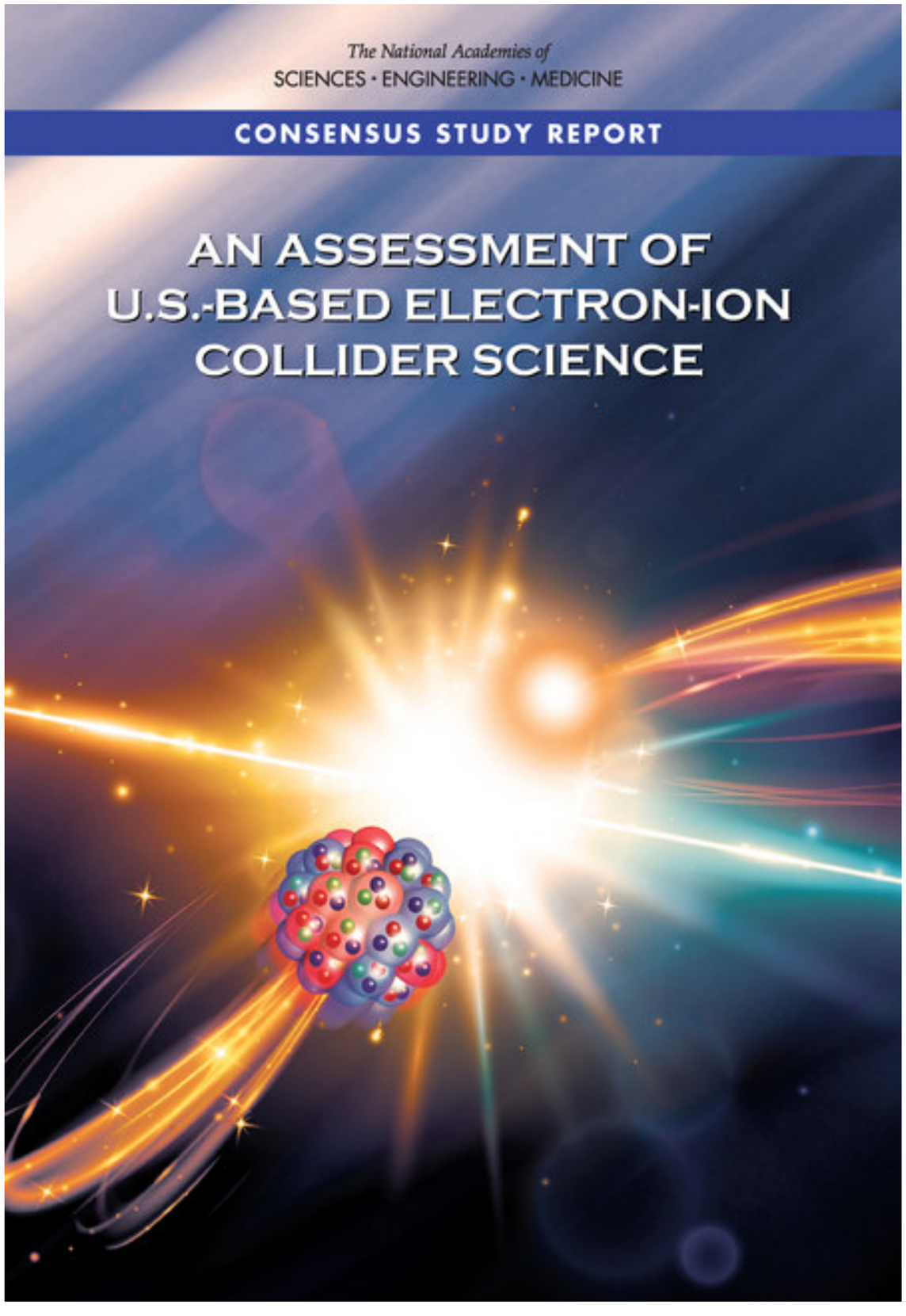
RECOMMENDATION III

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB. [Q3 FY22]

RECOMMENDATION IV

We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

Status of U.S.-based EIC



The committee *unanimously* finds that the science that can be addressed by an EIC is *compelling, fundamental, and timely.*

The *unanimous* conclusion of the Committee is that an EIC, as envisioned in this report, would be a *unique facility in the world that would boost the U.S. STEM workforce and help maintain U.S. scientific leadership in nuclear physics.*

The project is strongly supported by the nuclear physics community.

The technological benefits of meeting the accelerator challenges are enormous, both for basic science and for applied areas that use accelerators, including material science and medicine.

U.S.-based EIC - Closing Comments

Four central nuclear physics themes:

- nucleon spin,
- imaging in nucleon and nuclei,
- gluon-dense matter / saturation,
- hadronization and fragmentation

U.S.-based Electron-Ion Collider is strongly endorsed in the 2015 Long Range Plan for Nuclear Physics,

2018 NAS Science Assessment:

"EIC is compelling, fundamental, and timely"

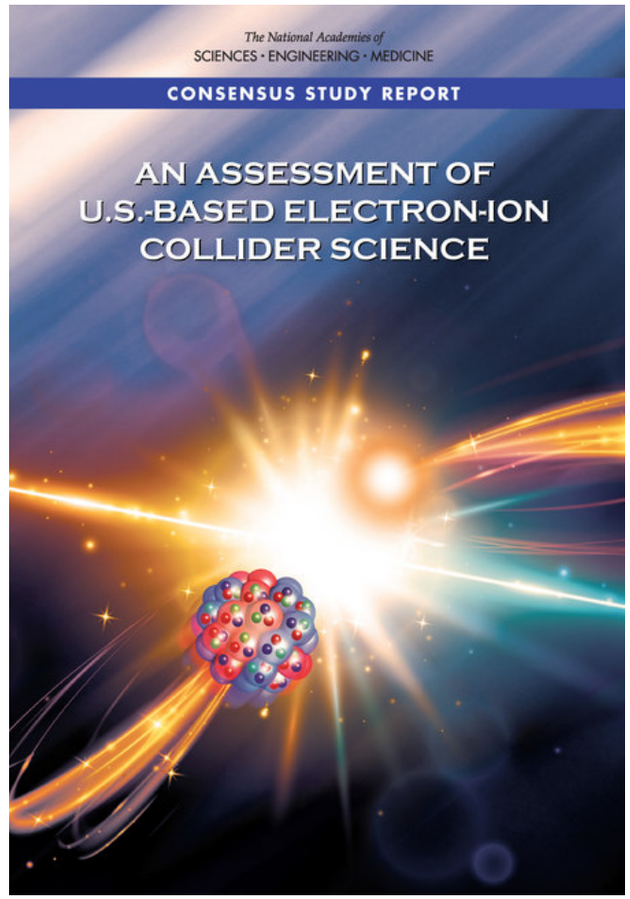
Science case: theory, experiment, *and* accelerator,

U.S. Department of Energy and both candidate host-laboratories are working together towards realizing the *project*,

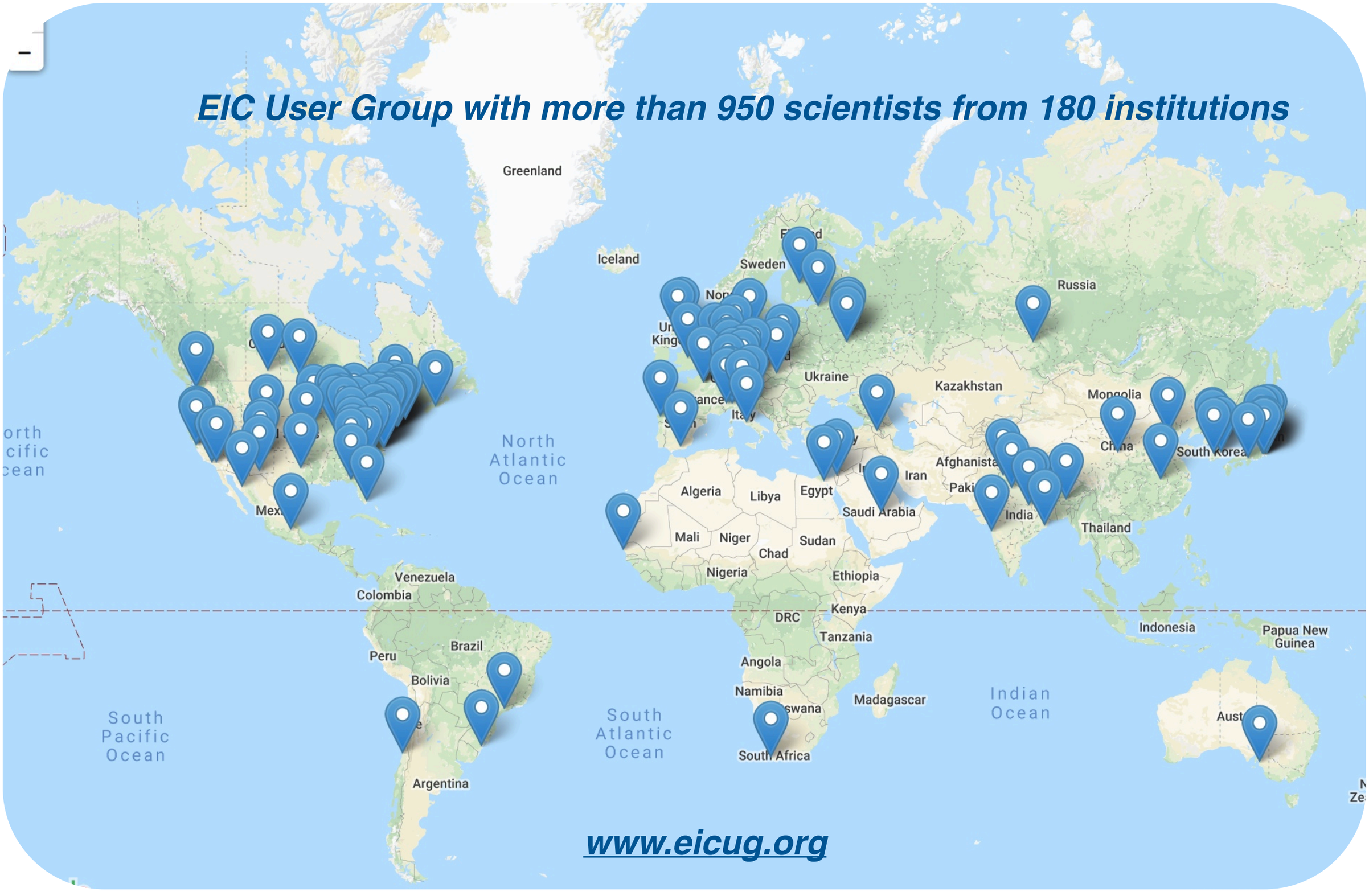
Cost review complete, site selection ongoing,

NP budget has an overall positive (recent) past and outlook,

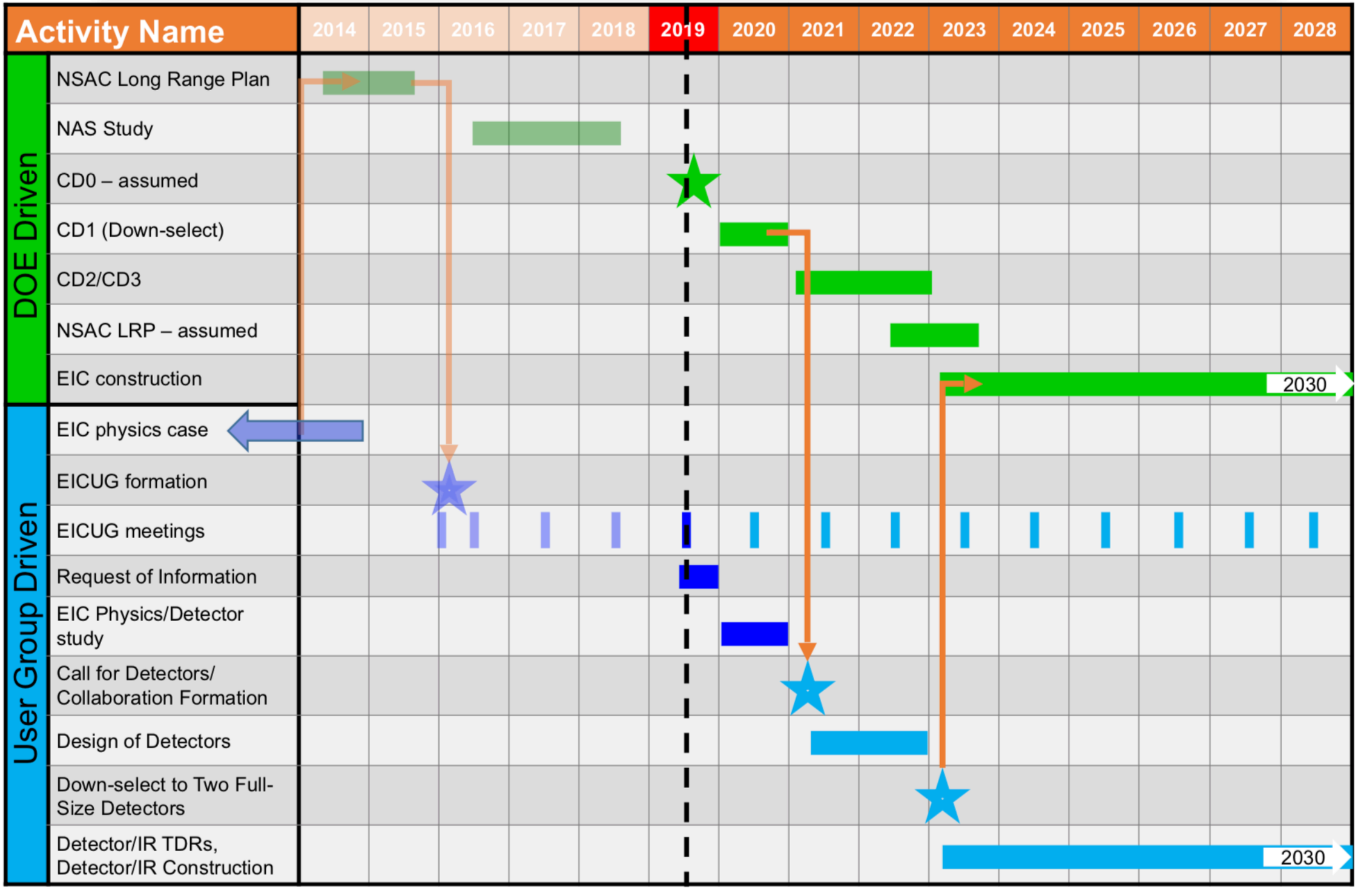
The EIC User Group, eicug.org, welcomes new collaborators;
About to embark on a 12-18 month physics and detector conceptual development study.



Status of U.S.-based EIC



EICUG Timeline



Current Status and Path forward of EIC

The “wickets” are substantially aligned for a major step forward on the EIC

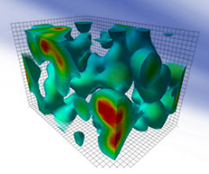
- A Mission Need Statement for an EIC has been approved by DOE
- An Independent Cost Review (ICR) Exercise mandated by DOE rules for projects of the projected scope of the EIC is very far along
- DOE is moving forward with a request for CD-0 (approve Mission Need)
- DOE has organized a panel to assess options for siting and consideration of “best value” between the two proposed concepts
- The Deputy Secretary is the Acquisition Executive for this level of DOE Investment
- **The FY 2020 President’s Request includes $ 1.5 million OPC. The FY 2020 House Mark includes $ 10 million OPC and $ 1 million TEC.**

From Tim Hallman’s talk at the EICUG meeting in Paris this Summer.

My understanding: Internal Cost Review complete, site-selection in progress,
Some timelines will be sooner than many have internalized.

Physics and Detector Conceptual Development Study

- **Initiated by the EICUG SC. Rolf Ent and Thomas Ullrich will lead this effort.**
- **Purpose**
  - Advance state of documented physics studies and detector concepts in preparation for the EIC.
  - Provide basis for further development of concepts for experimental equipment best suited for science needs, including complementarity of two detectors
  - Input towards future Technical Design Reports (TDRs)
- **Approach**
  - Two WG: *Physics* requirement and *Detector* concepts - 4 conveners each
  - Several sub-groups each, ~2 conveners/sub-group
  - Time limited effort: ~1 year
- **Meetings**
  - December 12-13, 2019, MIT: Kick-off organizational meeting
  - Workshops
    - March 19-21, 2020, Temple U., Philadelphia
    - May 22-24, 2020, U. of Pavia, Pavia, Italy
    - September 17-19, 2020, CUA, Washington D.C.
    - November 19-21, 2020, UCB, Berkeley, CA



It is essential, EIC activities in DOE seem to proceed fast.
Let’s get going !!!