The 2015 U.S. Nuclear Science Long Range Plan

Berndt Mueller
BNL/Duke

7th Workshop on
Hadron Physics in China
DKU August 3-7, 2015

BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Long Range Plan Charge to NSAC

U.S. Department of Energy
and the
National Science Foundation

Dr. Donald Geesaman
Chair
DOE/NSF Nuclear Science Advisory Committee
Argonne National Laboratory
9800 South Cass Avenue
Argonne, Illinois 60439

Dear Dr. Geesaman:

This letter requests that the Department of Energy (DOE)/National Science Foundation (NSF) Nuclear Science Advisory Committee (NSAC) conduct a new study of the opportunities and priorities for United States nuclear physics research and recommend a long range plan that will provide a framework for coordinated advancement of the Nation's nuclear science research programs over the next decade. This exercise should exclude the DOE Isotope Program managed by the DOE Office of Science's Office of Nuclear Physics, for which a dedicated strategic planning exercise will be convened.

Charge to NSAC (ctd.)

The new NSAC Long Range Plan (LRP) should articulate the scope and the scientific challenges of nuclear physics today, what progress has been made since the last LRP, and the impacts of these accomplishments both within and outside of the field. It should identify and prioritize the most compelling scientific opportunities for the U.S. program to pursue over the next decade and articulate their scientific impact. A national coordinated strategy for the use of existing and planned capabilities, both domestic and international, and the rationale for new investments should be articulated. To be most helpful, the LRP should indicate what resources and funding levels would be required (including construction of new facilities, mid-scale instrumentation, and Major Items of Equipment) to maintain a world-leadership position in nuclear physics research and what the impacts are and priorities should be if the funding available provides for constant level of effort from the FY 2015 President's Budget Request into the out-years (FY 2016-2025), with constant level of effort defined using the published OMB inflators for FY 2016 through FY 2025. A key element of the new NSAC LRP should be the Program's sustainability under the budget scenarios considered.

The extent, benefits, impacts and opportunities of international coordination and collaborations afforded by current and planned major facilities and experiments in the U.S. and other countries, and of interagency coordination and collaboration in cross-cutting scientific opportunities identified in studies involving different scientific disciplines should be specifically addressed and articulated in the report. The scientific

Charge to NSAC (ctd.)

impacts of synergies with neighboring research disciplines and further opportunities for mutually beneficial interactions with outside disciplines, should be discussed.

In the development of previous LRP's, the Division of Nuclear Physics of the American Physical Society (DNP/APS) was instrumental in obtaining broad community input by organizing town meetings of different nuclear physics sub-disciplines. The Division of Nuclear Chemistry and Technology of the American Chemical Society (DNC&T/ACS) was also involved. We encourage NSAC to exploit this method of obtaining widespread input again, and to further engage both the DNP/APS and DNC&T/ACS in laying out the broader issues of contributions of nuclear science research to society.

Please submit your report to DOE and NSF by October 2015. The agencies very much appreciate NSAC's willingness to undertake this task. NSAC's previous LRP's have played a critical role in shaping the Nation's nuclear science research effort. Based on NSAC's laudable efforts in the past, we look forward to a new plan that can be used to chart a vital and forefront scientific program into the next decade.

Sincerely,

Patricia M. Dehmer
Acting Director
Office of Science

F. Fleming Crim
Assistant Director
Directorate for Mathematical
and Physical Sciences

2014-15 LRP Schedule

- Charge delivered at 24 April 2014 NSAC Meeting
- LRP Working Group formed with ~60 members including several international members.
- Community organization this summer
- DNP town meetings in the July-September 2014
- Joint APS-DNP-JPS Meeting Oct 7-11, 2014 in Hawai'i
- Community white papers due by end of January 2015
- Resolution meeting of the Long Range Plan Working Group during 16-20 April 2015 in Kitty Hawk, NC
- Report writing April-June 2015
- Draft report sent to "wise women and men"
- LRP final report due to NSAC and DOE/NSF in October 2015

Town Meetings

- Computational Theory: July 14-15, Washington, DC
- Education and Innovation: Early August, MSU
- Nuclear Structure and Astrophysics: August 21-23, TAMU
- Joint QCD: September 13-15, Temple Univ.
- Fundamental Symmetries: Sept 28-29, Chicago

See http://www.aps.org/units/dnp/meetings/town.cfm

Conveners of town meetings and members of white paper writing groups selected by DNP.

LRP Resolution Meeting

- 16-20 April 2015 in Kitty Hawk, NC
- Presentations on
  - Town Meeting / White Papers
  - Facilities (CEBAF, RHIC, ATLAS, FRIB)
  - Proposed facilities (EIC)
  - Initiatives (new experiments)
  - Community issues (education, etc.)
  - International context
- Budget discussion
- Discussion of recommendations
  - Recommendations will become public when report is sent to NSAC in October 2015
- See Don Geesaman's talk at IUPAP WG.9 Conference:
  - http://www.triumf.info/hosted/iupap/icnp/nsspresentations/2015/NSS_North_America.pptx

“Cold” QCD

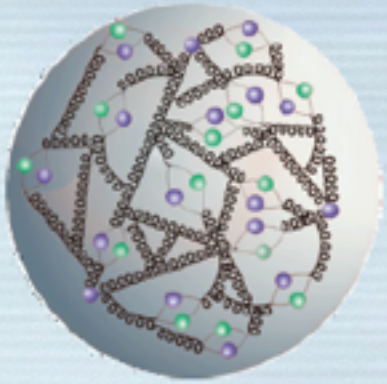
QCD: Important Questions

- What is confinement, and how is it related to the dynamic breaking of chiral symmetry, and the origin of 98% of the visible mass in the Universe?
- What are spatial and momentum distributions of the quarks and gluons in the nucleon, and what are the dynamics that are responsible?
- What can spectroscopy, including gluonic excitations, tell us about strongly interacting matter.
- How do the properties of nuclei and the strong force emerge from our understanding of QCD?

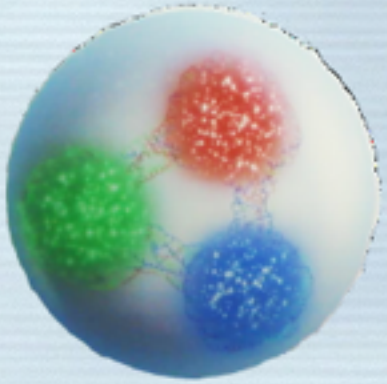
Looking further down the road .....

QCD is the only strongly-coupled theory given to us by Nature.
What does it teach us about the physical universe as a whole?

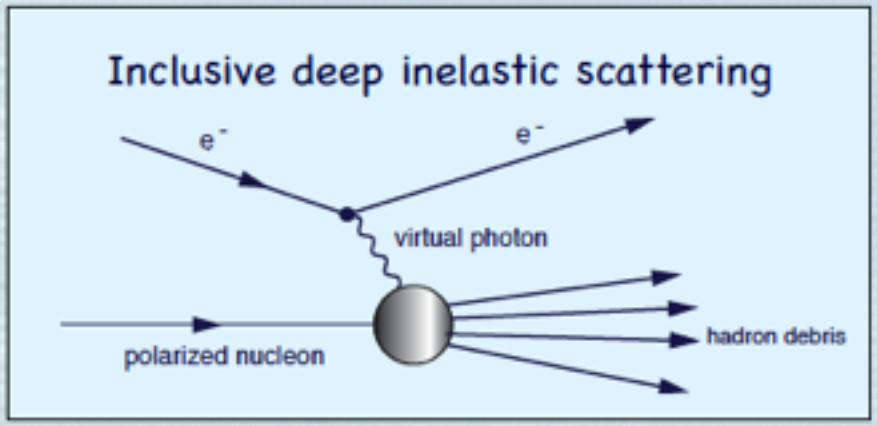
Deep Inelastic Scattering is somewhat like having a camera, with Bjorken-x being the shutter speed

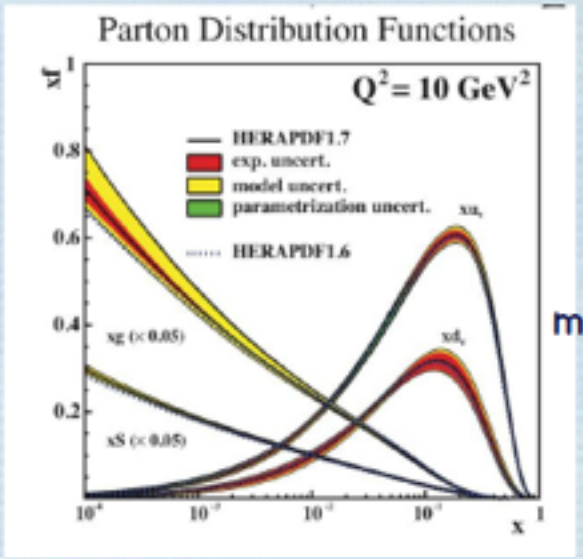


With x_{Bj} ~small
the things you hit are small:
short exposure time



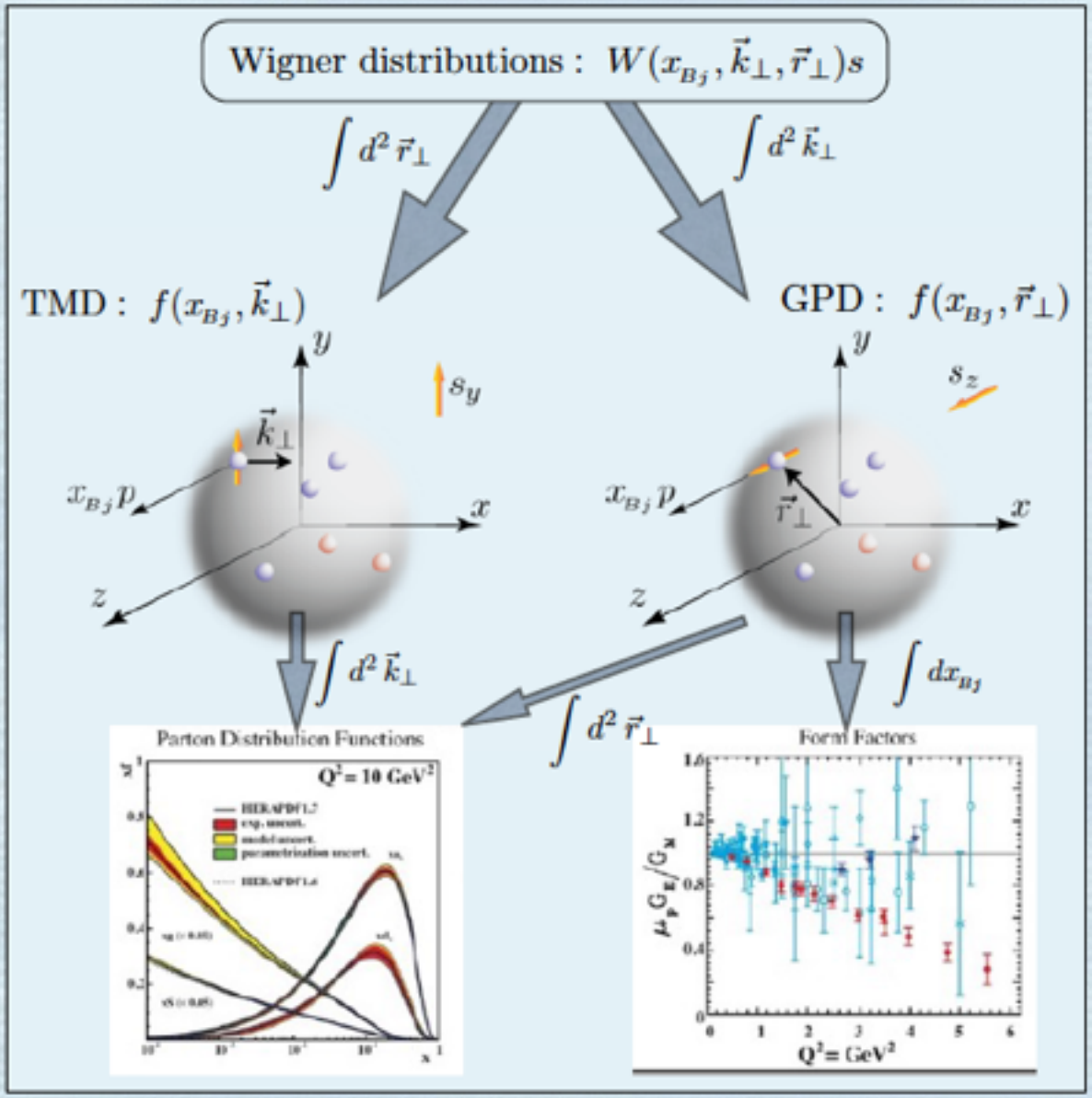
With x_{Bj} ~0.3
the things you hit are big:
long exposure time





Longitudinal
(1-Dimensional)
momentum distribution
functions

Multi-dimensional Parton Distribution Functions



The Wigner distribution contains the complete single-particle information about a quantum system

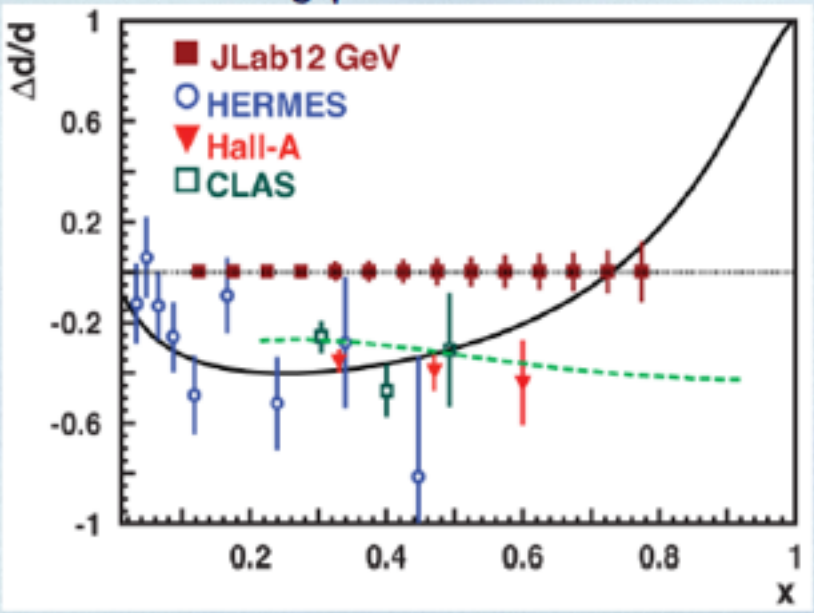
Two new types of PDFs emerge:

- Transverse-Momentum-Dependent (TMD) PDFs
  - confined motion in nucleon
  - Measured in semi-inclusive DIS
- Generalized Parton Distribution Functions (GPDs)
  - spatial imaging of nucleon
  - measured in exclusive reactions.

Valence quark distributions at 12 GeV

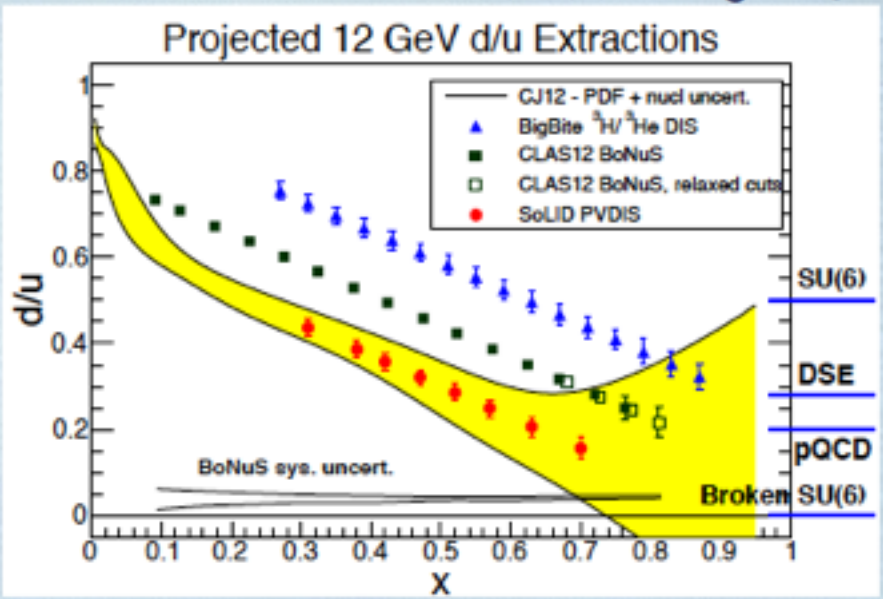
(examples)

Spin-structure studies showing d-quark polarization determined using polarized DIS



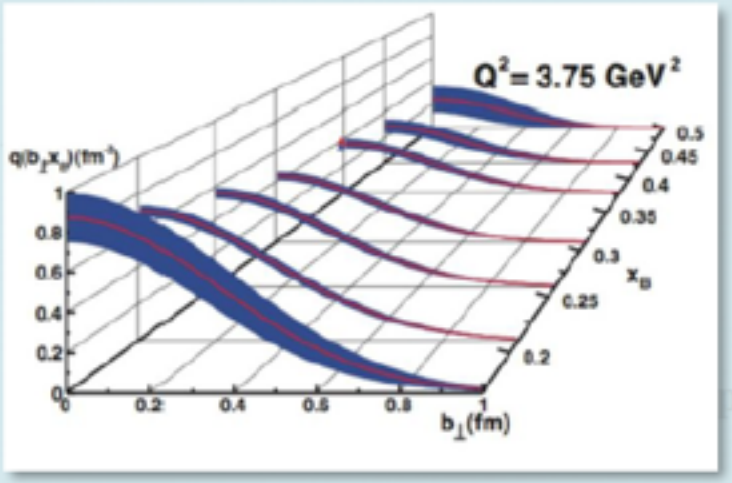
Red points are measurements from Hall A (combined with proton data).

Projected errors on ratio of unpolarized structure functions d(x)/u(x) at high x_{Bj}

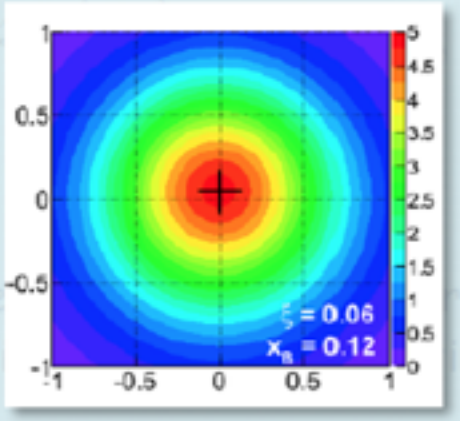


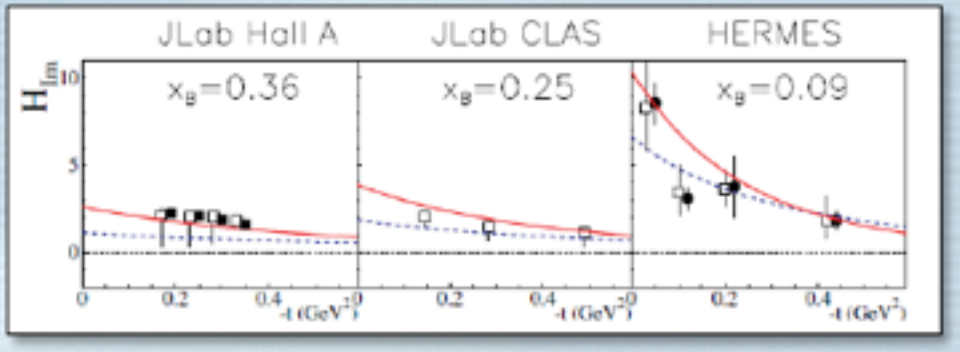
- d/u is calculable using several approaches.
- Can be measure in three ways!
  - Comparing DIS from ^{3}He and ^{3}H.
  - Spectator tagging using BoNuS in CLAS 12.
  - Using PVDIS in SoLID

Generalized Parton Distributions using DVCS and imaging

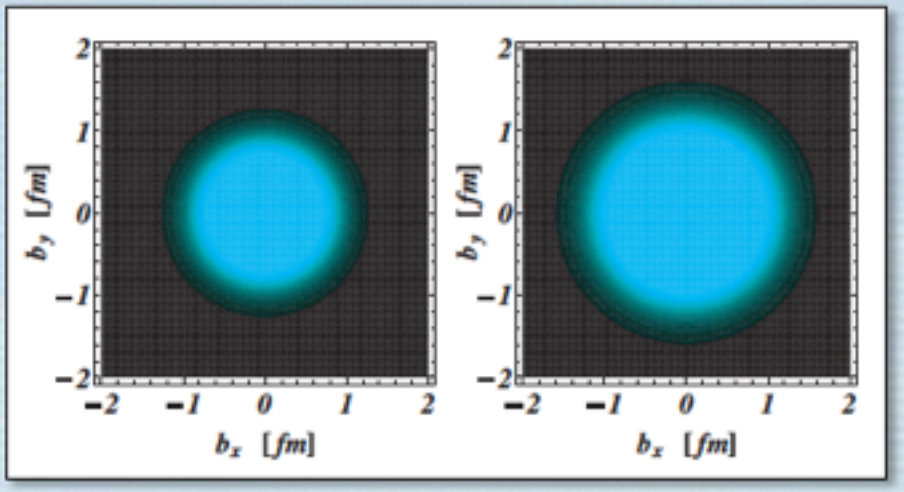


Examples of what can be done following the 12 GeV upgrade.

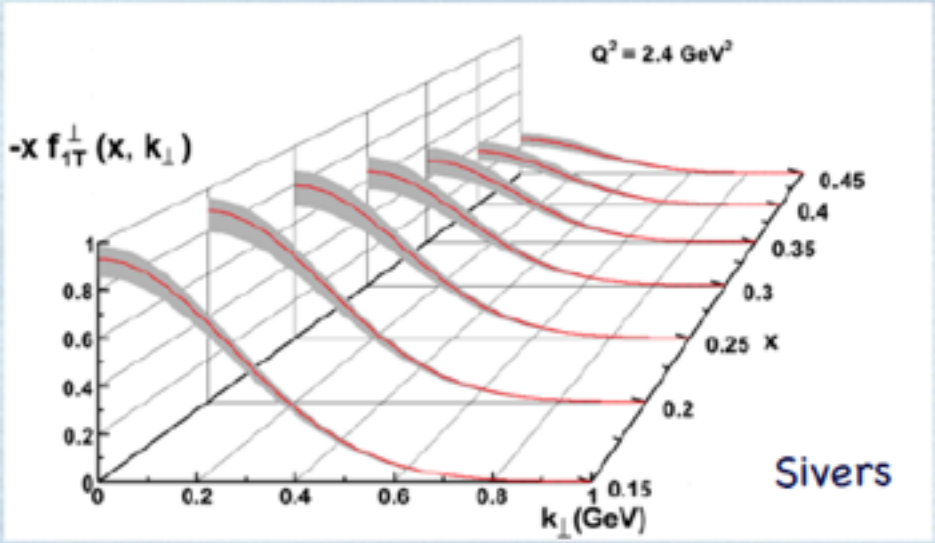




Different local fits
VGG model
KM10 global fit on the world data ranging from H1,ZEUS to HERMES, JLab

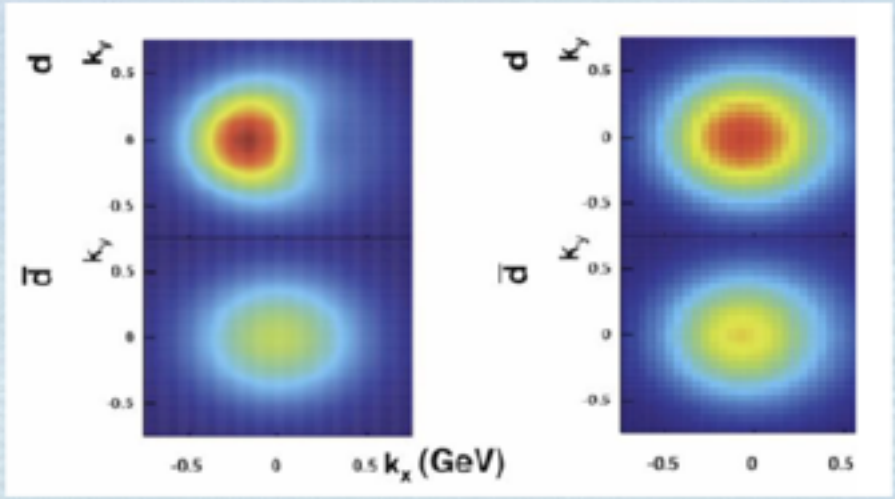


Examples of TMDs:
Sivers function measurements at 12 GeV

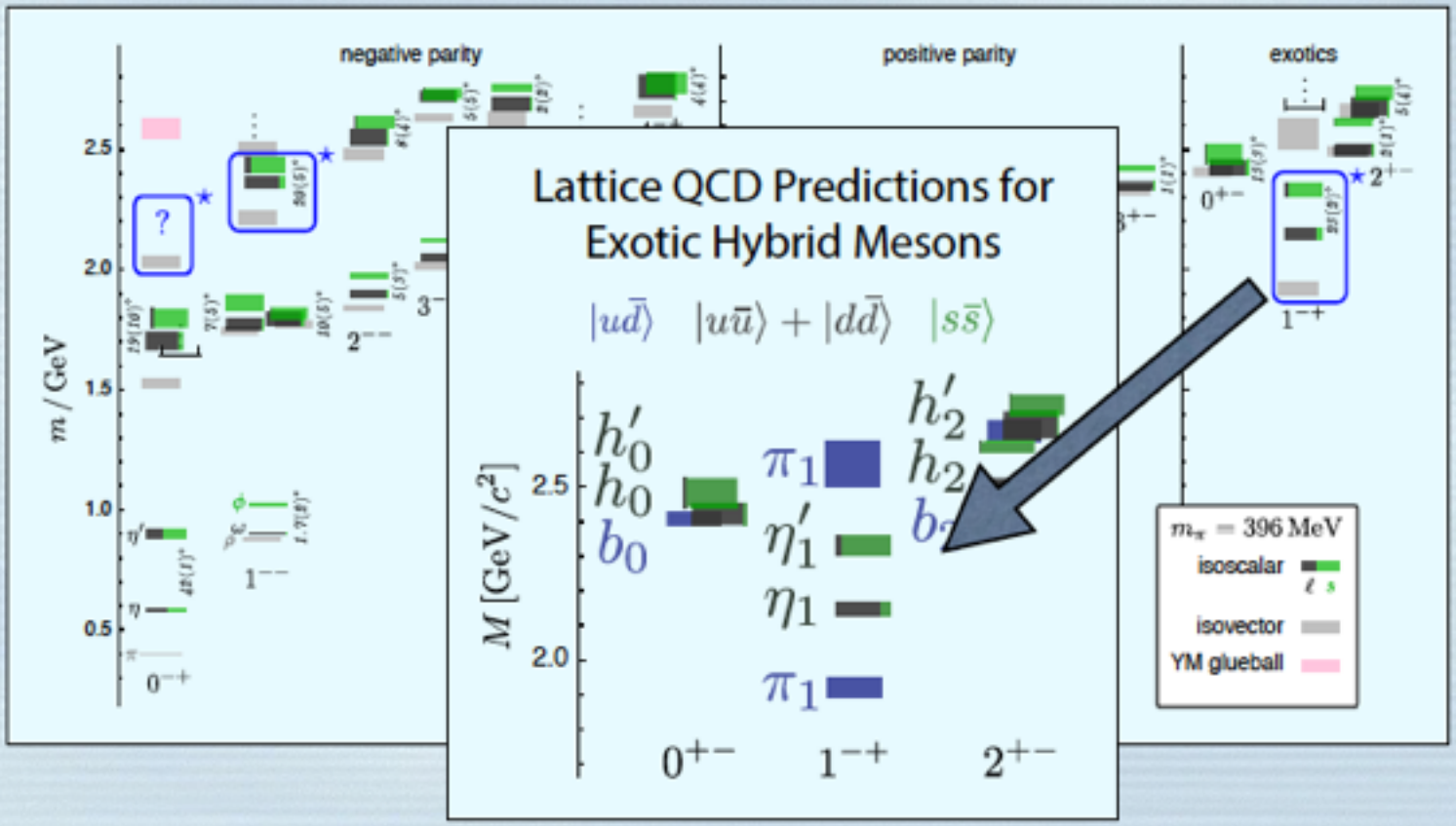


- Measured using by observing single-spin asymmetries in semi-inclusive deep inelastic scattering.
- Example of projected errors shown at left for transversely polarized nucleon

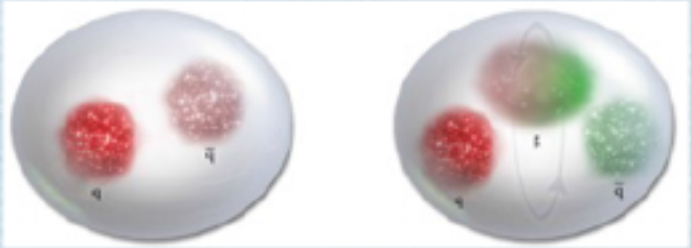
Down-quark momentum tomography using the Sivers function at x = 0.1. The tomography possible in the 6 GeV era, while non-zero, cannot resolve the dipole deformation that will be possible in upcoming studies.



QCD predicts mesons with gluonic excitations… now they are seen on the lattice

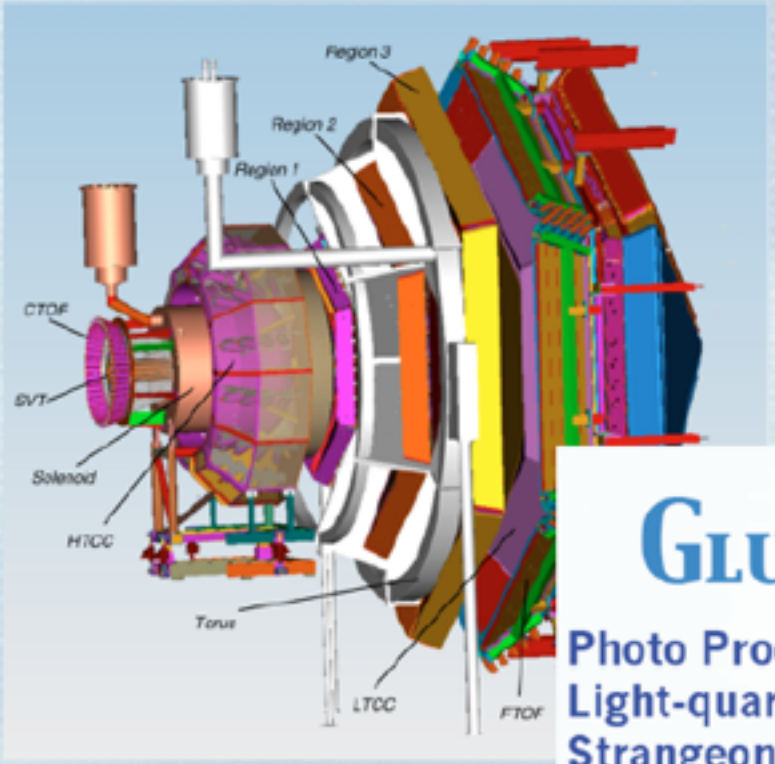


Conventional meson , with a composed of a q and a qbar.



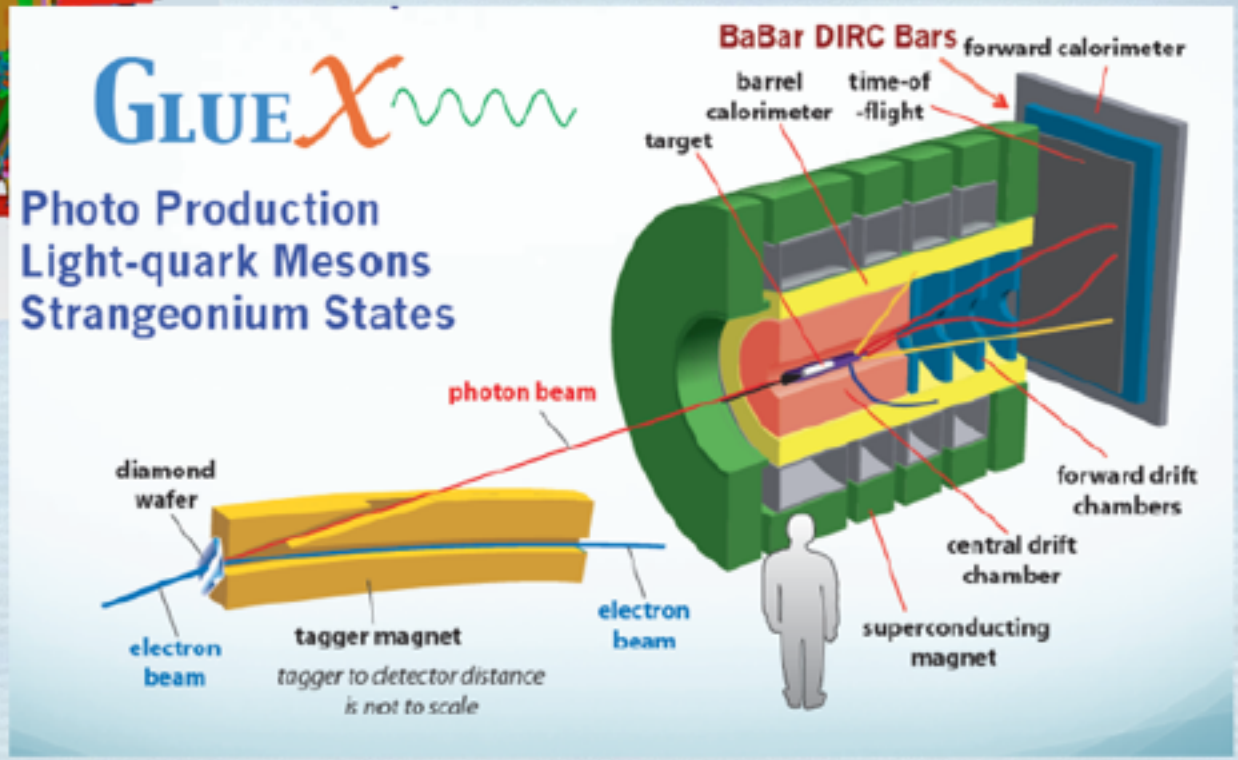
LQCD studies indicate the lowest-lying hybrid is likely composed of quarks in an S state and a "constituent gluon" in a P-state.

Searches for hybrids with JLab at 12 GeV



- CLAS 12 in Hall B.
- Quasi-real photo-production of light-quark mesons.

- GlueX in the new Hall D.
- Apparatus is optimized to detect hybrid mesons.
- Commissioning of the detector is underway!



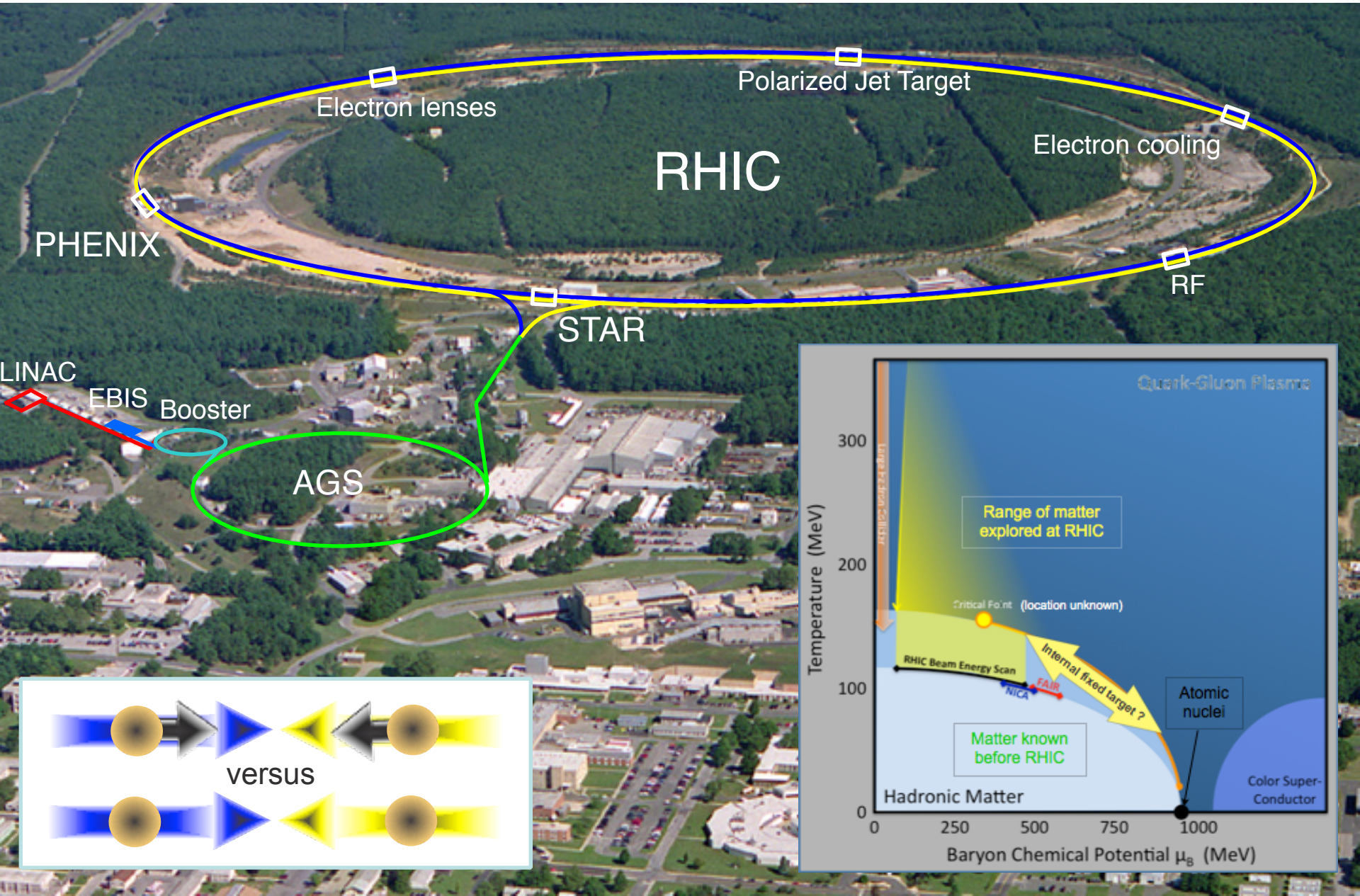
Recommendations from QCD and Hadron Physics

- **Recommendation 1:** Our highest priority recommendation is the completion of construction and robust operation of the 12 GeV CEBAF facility at Jefferson Lab, along with targeted instrumentation investments such as the MOLLER and SoLID projects, to fully realize its scientific potential.

- **Recommendation 2:** A high luminosity, high-energy polarized Electron Ion Collider (EIC) is the highest priority of the U.S. NP QCD community for future new construction. (***voted jointly with Phases of QCD community***)

“Hot” QCD

Completing the RHIC Scientific Mission



New Questions

- Do the initial conditions for the hydrodynamic expansion contain unambiguous information about saturated gluon fields in nuclei?
- What is the smallest collision system that behaves collectively?
- What does the QCD phase diagram look like? Does it contain a critical point in the HG-QGP transition region? Does the HG-QGP transition become a first-order phase transition for large μ_B?
- What is the structure of the strongly coupled QGP at varying length scales? What makes it a liquid?
- What do Upsilon states tell us about quark deconfinement and hadronization?
- What do transversely polarized protons tell us about the coupled spin-momentum dynamics of QCD at different scales?

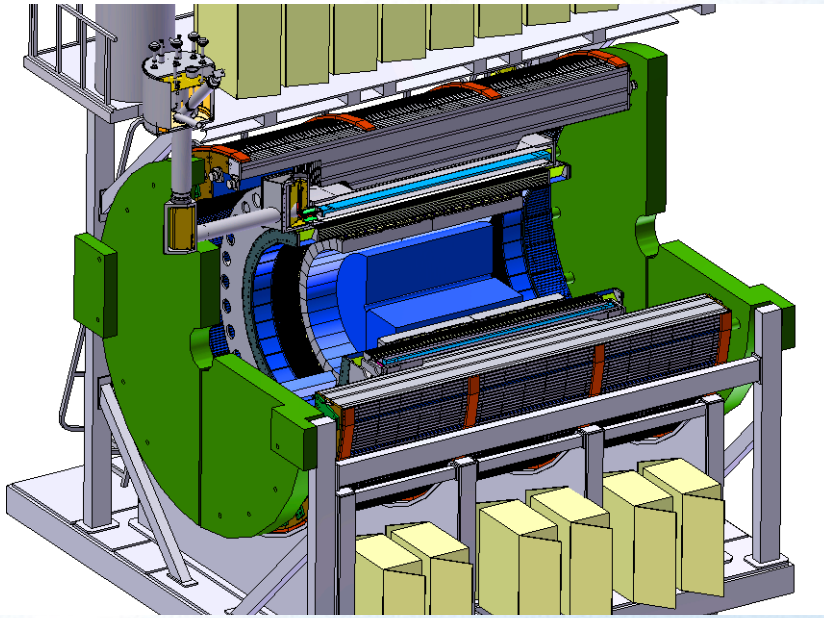
Completing the RHIC science mission

Status: RHIC-II configuration is complete

- Vertex detectors in STAR (HFT) and PHENIX
- Luminosity reaches 25x design luminosity

Plan: Complete RHIC mission in 3 campaigns:

- **2014–17: Heavy flavor probes of the QGP using the micro-vertex detectors; Transverse spin physics**
- *2018: Install low energy e-cooling*
- **2019/20: High precision scan of the QCD phase diagram & search for critical point**
- *Install sPHENIX*
- **Probe QGP with precision measurements of jet quenching and Upsilon suppression**
- **Spin physics and initial conditions at forward rapidities with p+p and p+A collisions ?**
- *Transition to eRHIC*



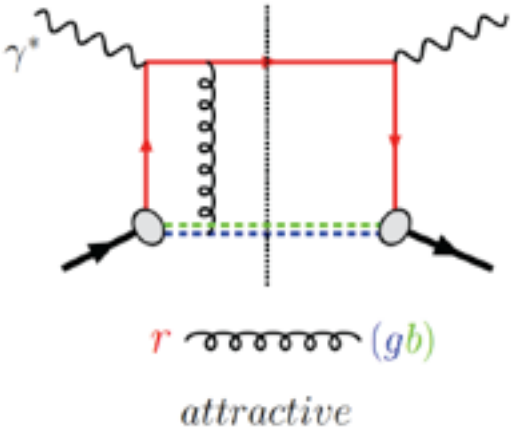
RHIC remains a unique discovery facility

Transverse polarized p+p collisions

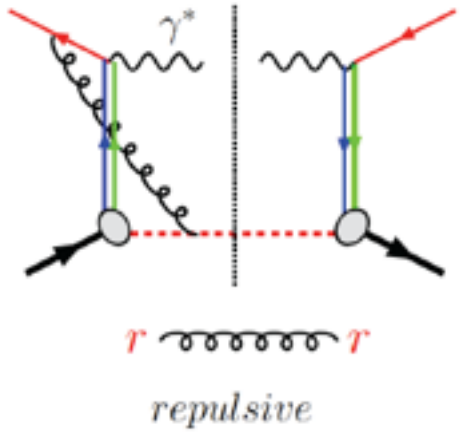
Access the dynamic structure of protons:

→ **Test and confirm QCD structure of color spin interactions**
- → **Non-universality of transverse momentum dependent functions**
- → **$Sivers_{DIS} = -Sivers_{pp}$**
  - → **Observable: A_N for Drell-Yan and $W^{+/-}$ production**

DIS:
γq-scattering attractive



pp:
qqbar-anhilation repulsive



→ **Test scale evolution of transverse momentum dependent functions**
- → **Observable: compare magnitude of A_N for Drell-Yan and $W^{+/-}$**

Scale: DY: $Q^2 \sim 16$ GeV^2 $W^{+/-}$: $Q^2 \sim 6400$ GeV^2

Transverse polarized p+p collisions

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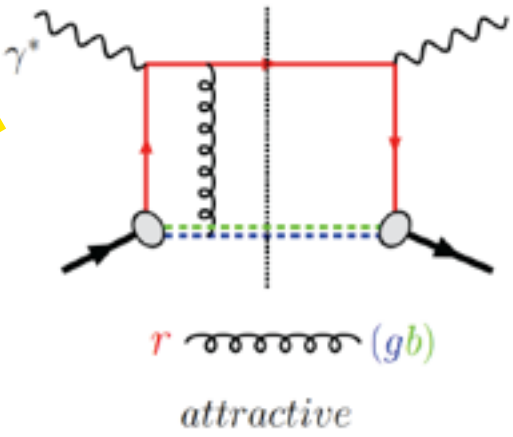
Achieves NP Performance Milestone HP13 in Run 17?

DIS:
γq-scattering attractive



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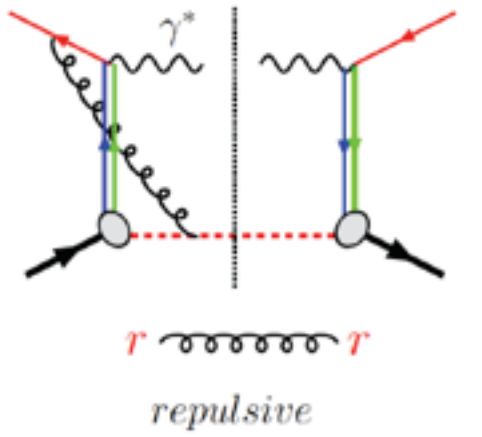

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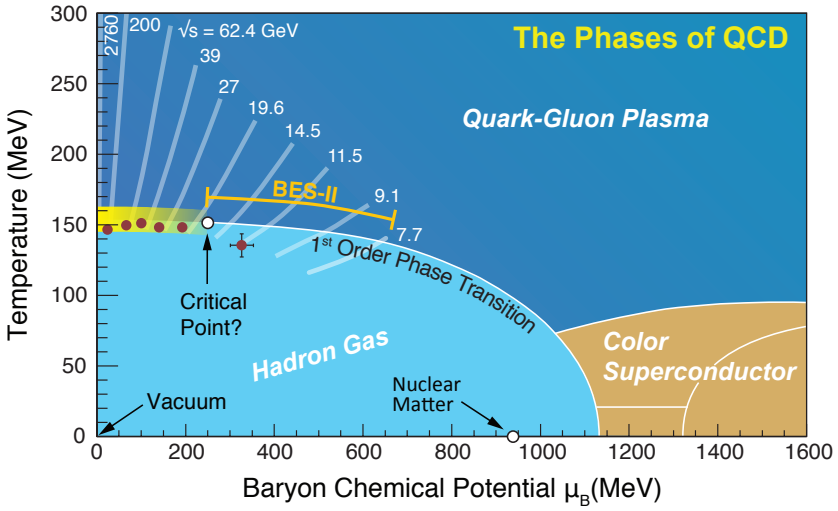
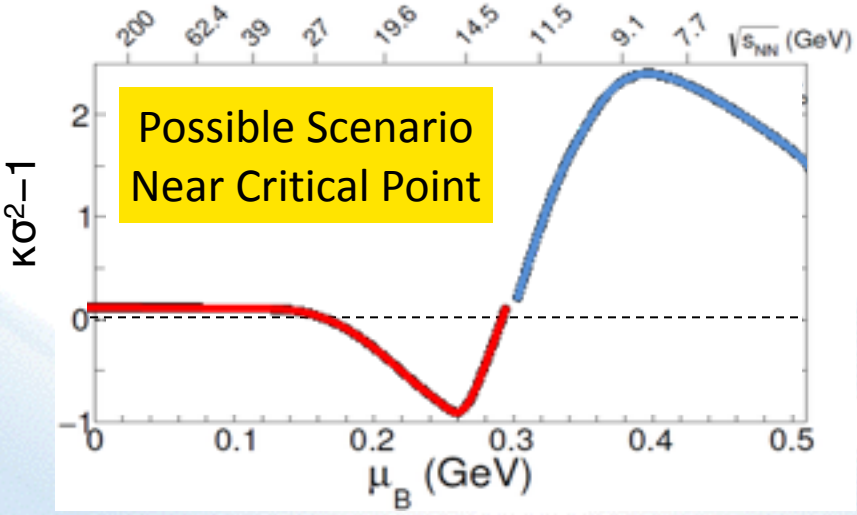
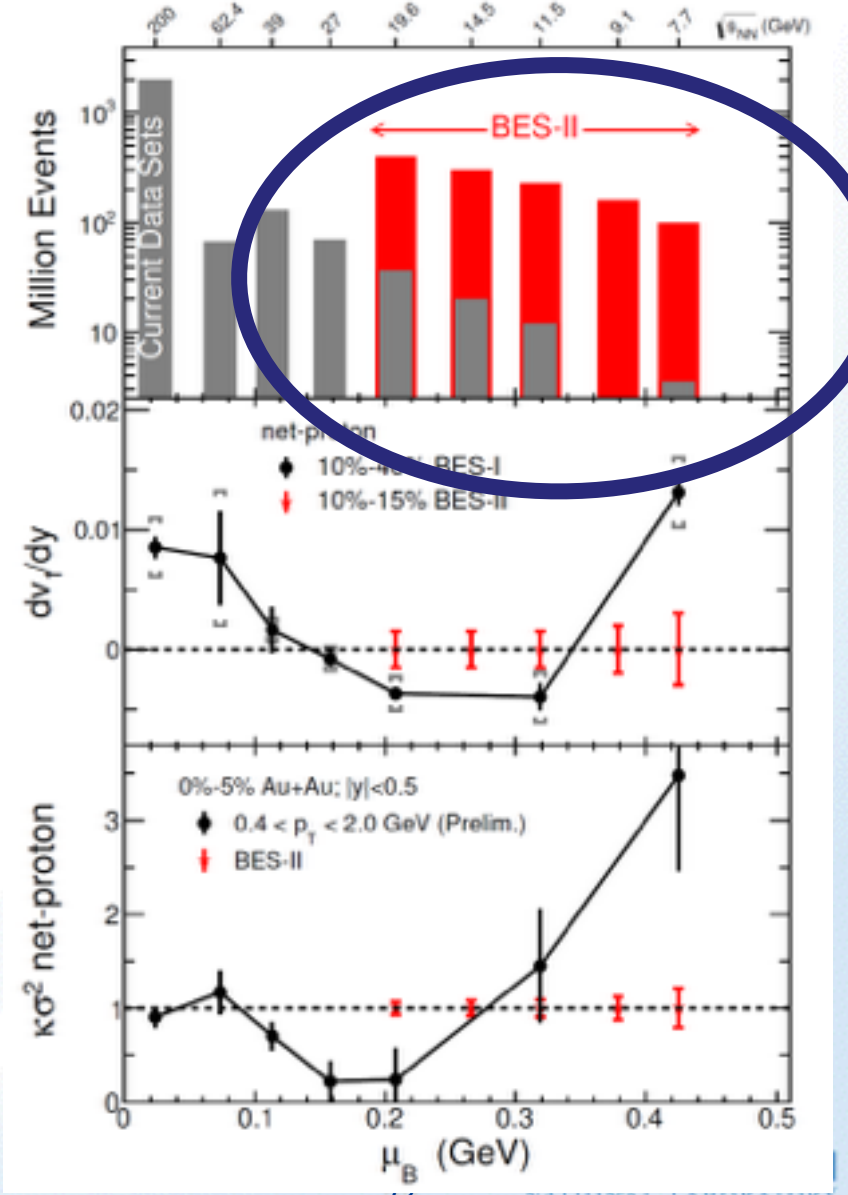
Toward critical fluctuations

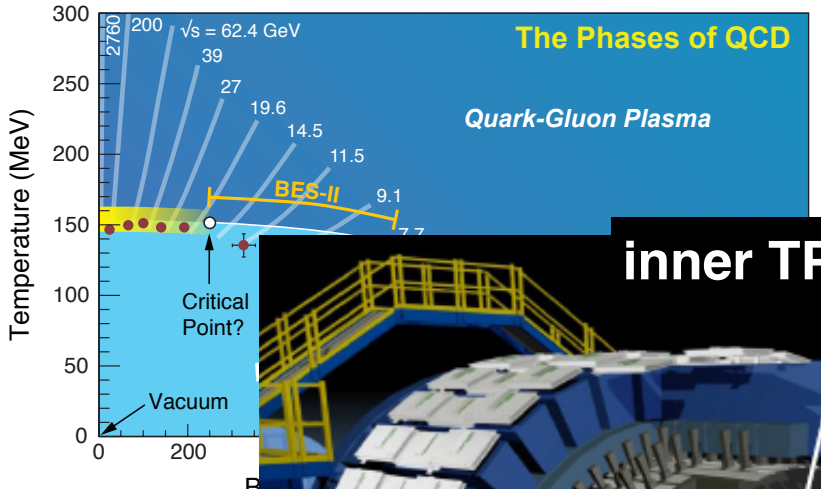


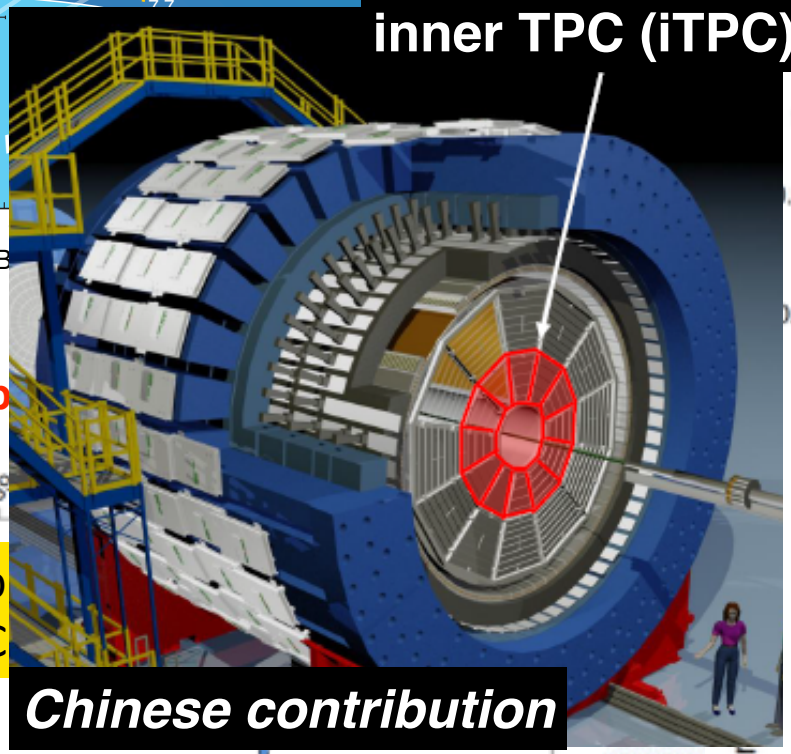
Model independent structure of net baryon number kurtosis





Toward critical fluctuations



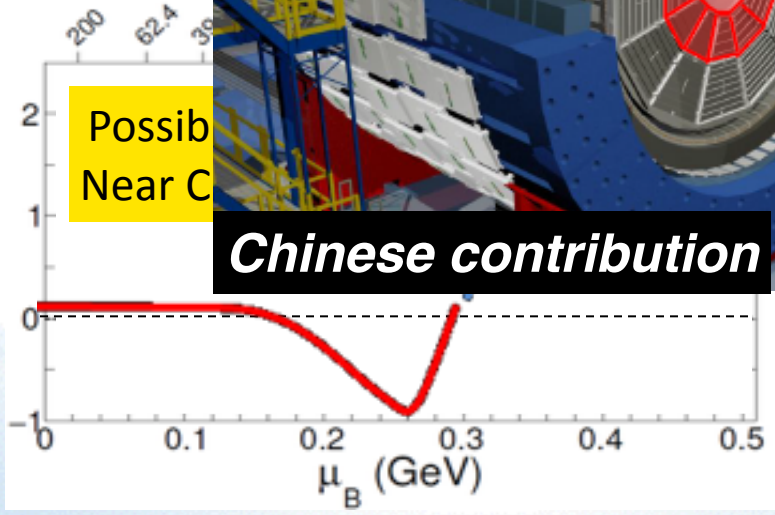


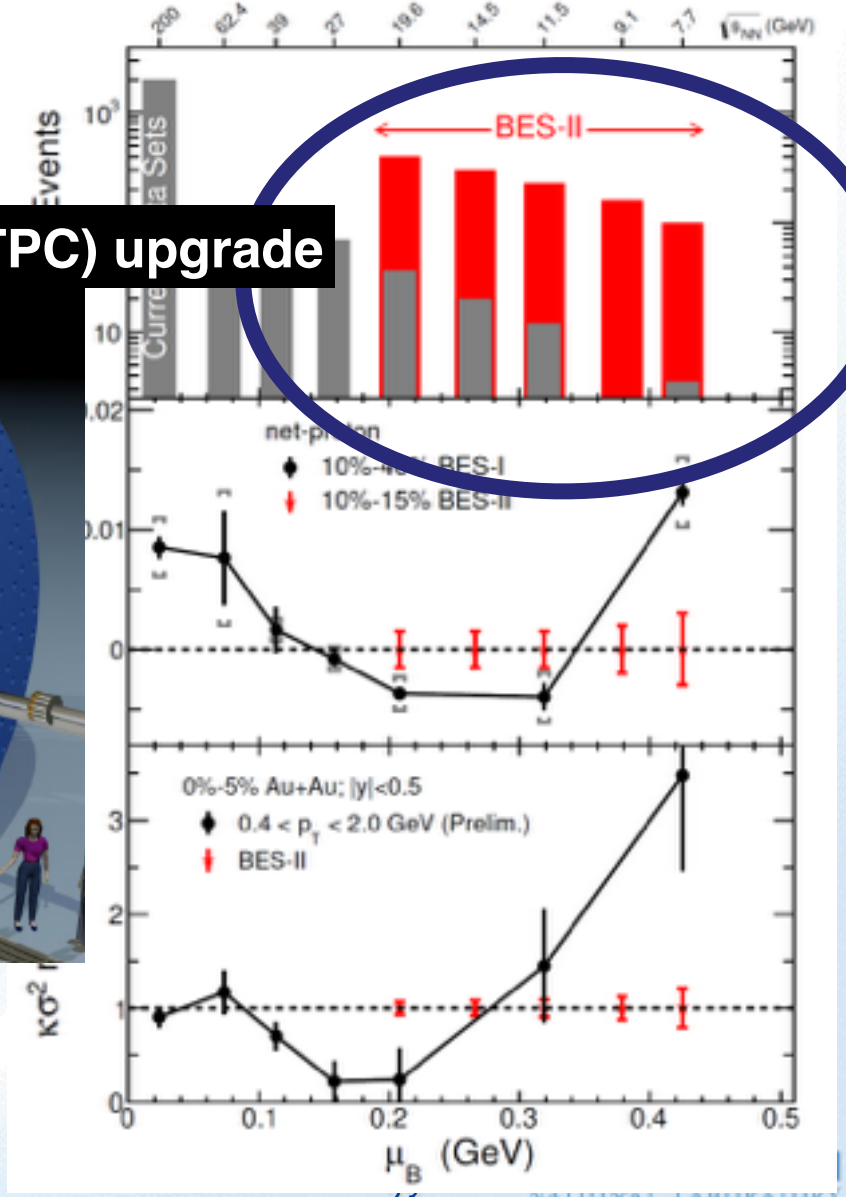
inner TPC (iTPC) upgrade

Model
net b

Possib
Near C

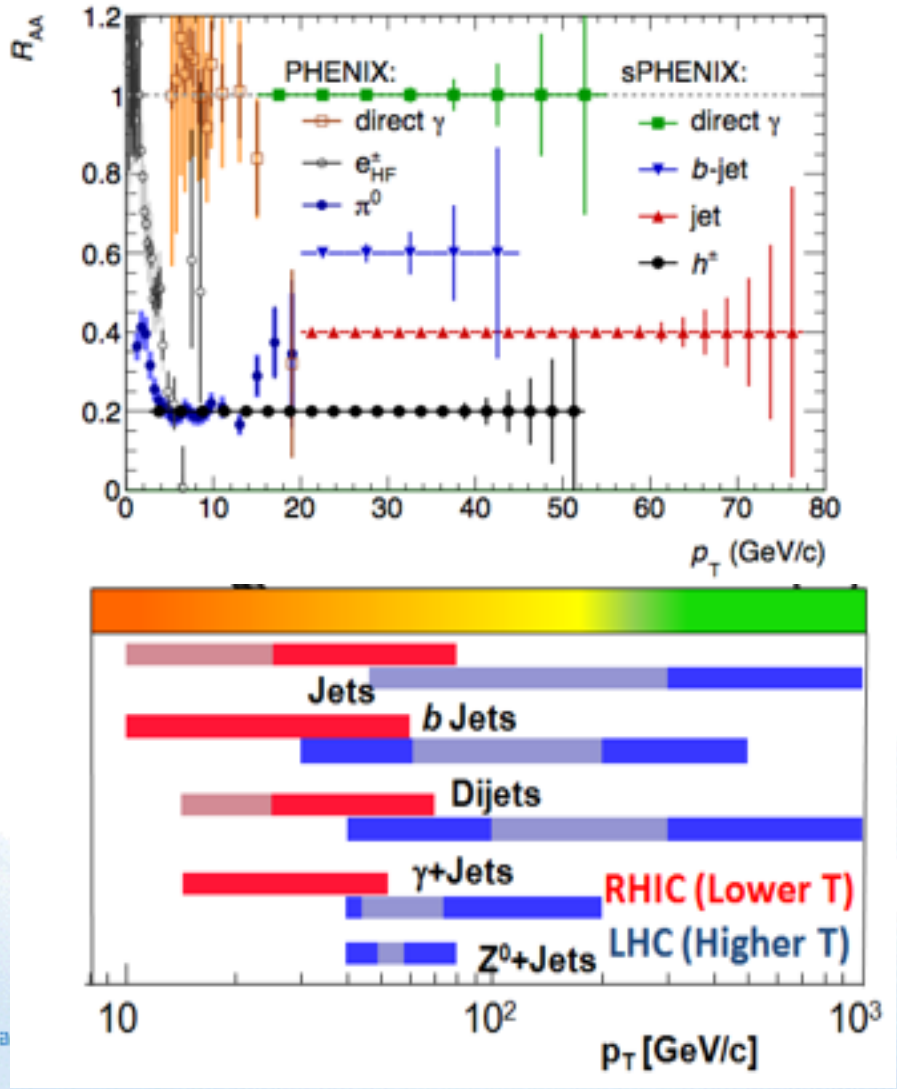
Chinese contribution



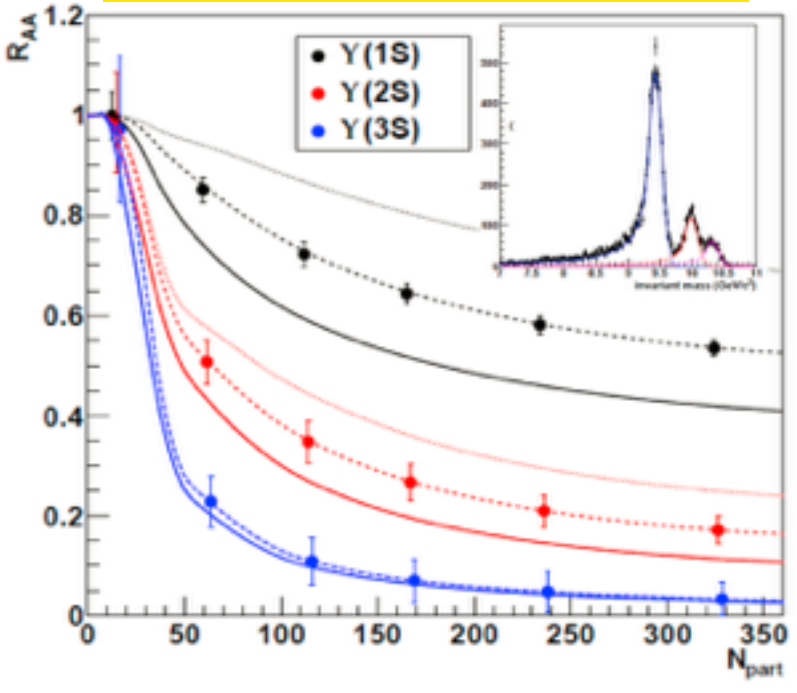


Jets & Upsilon: sPHENIX reach

Complete calorimetric jet spectroscopy



High precision Upsilon spectroscopy



Kinematic overlap between RHIC and LHC provides critical tests for theoretical frameworks

Hot QCD Recommendations

Recommendation 1:

As our highest priority we recommend a program to complete the search for the critical point in the QCD phase diagram and to exploit the newly realized potential of exploring the QGP's structure at multiple length scales with jets at RHIC and LHC energies. This requires

- **implementation of new capabilities of the RHIC facility (a state-of-the-art jet detector such as sPHENIX and luminosity upgrades for running at low energies) needed to complete its scientific mission,**
- **continued strong U.S. participation in the LHC heavy-ion program, and**
- **strong investment in a broad range of theoretical efforts employing various analytical and computational methods.**

Recommendation 2:

A high luminosity, high-energy polarized Electron Ion Collider (EIC) is the U.S. QCD Community's highest priority for future construction.

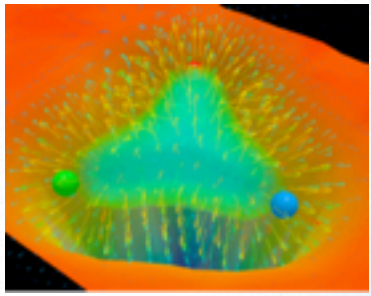
Electron Ion Collider: The next QCD frontier

Understanding the Glue that Binds Us All

Role of gluons in hadron & nuclear structure

- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons:

  Without gluons, there would be no nucleons, no atomic nuclei… no visible world!



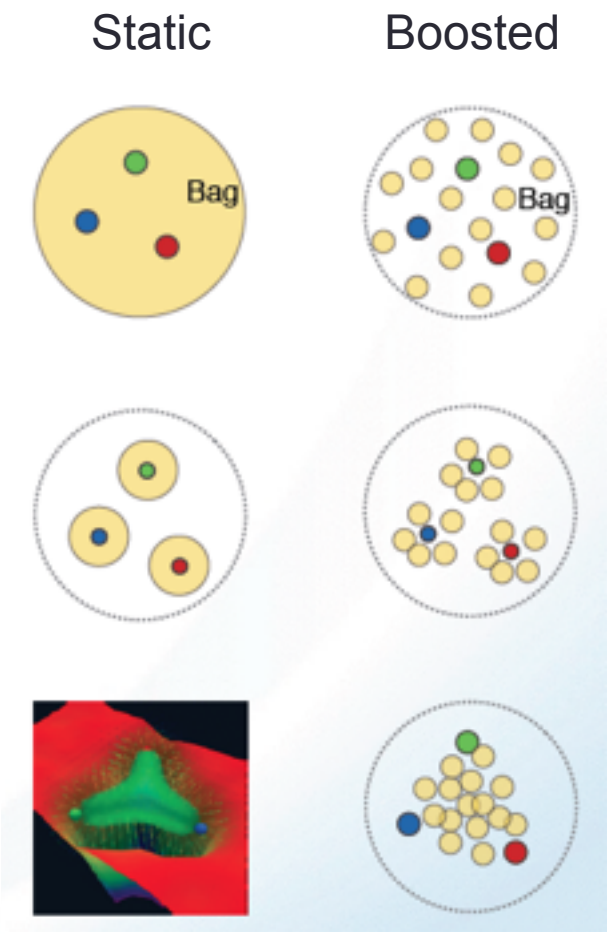
- Gluons carry ~50% the proton's momentum, ?% of the nucleon's spin, and determine the transverse momentum of quarks

- The quark-gluon origin of the nucleon-nucleon forces in nuclei is not understood

- Lattice QCD presently cannot address dynamical properties of hadrons

- **EIC will provide experimental insight and guidance crucial for a complete understanding of *how* hadrons & nuclei emerge from quarks and gluons**

What does a proton look like?



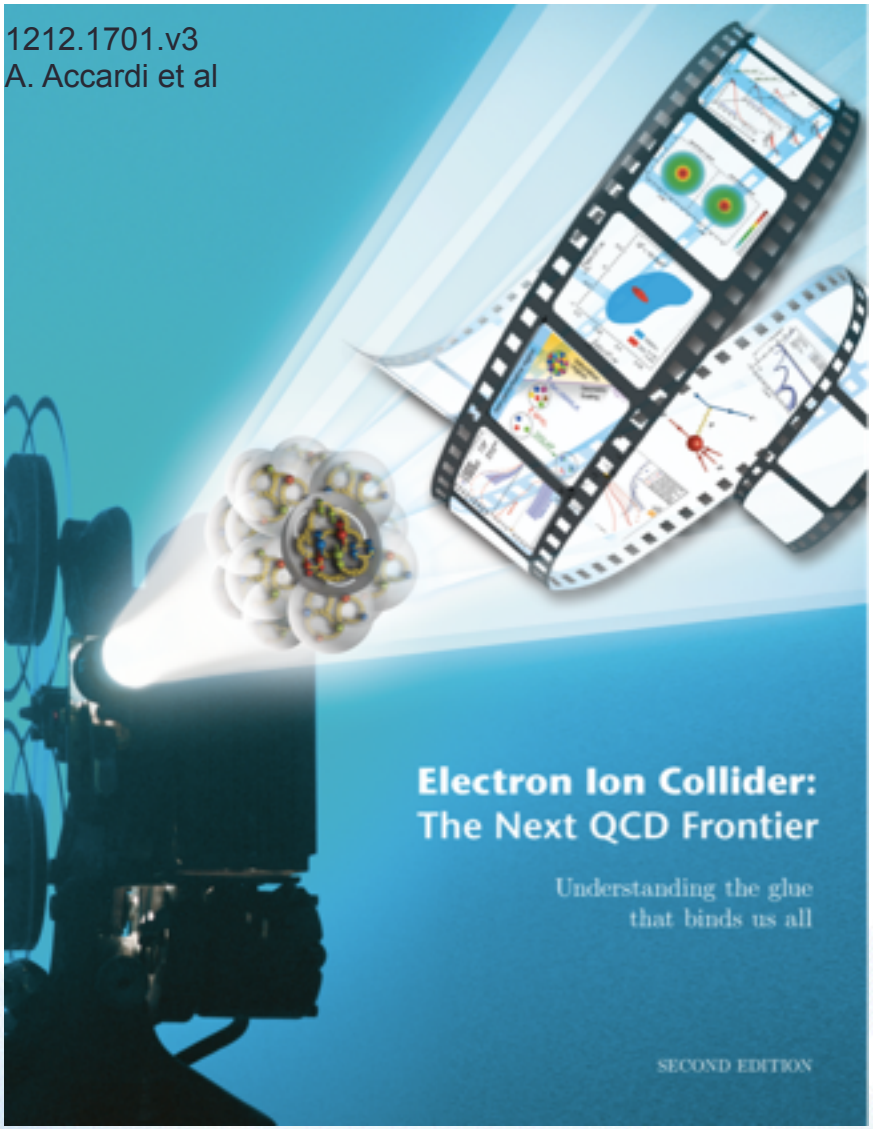
Bag Model: Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge Radius

Constituent Quark Model: Gluons and sea quarks hide inside massive quarks.
Gluon radius ~ Charge Radius

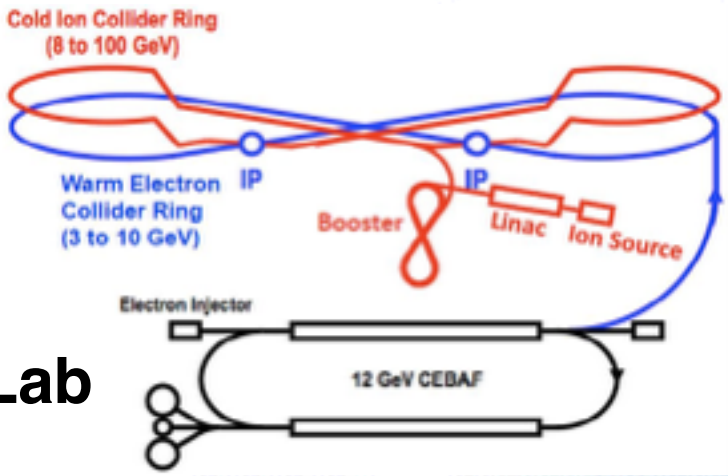
Lattice Gauge theory (with slow moving quarks), gluons in between quarks:
Gluon radius < Charge Radius

Need transverse images of the quarks and gluons in protons

Electron Ion Collider



Two proposals for realizing the science case

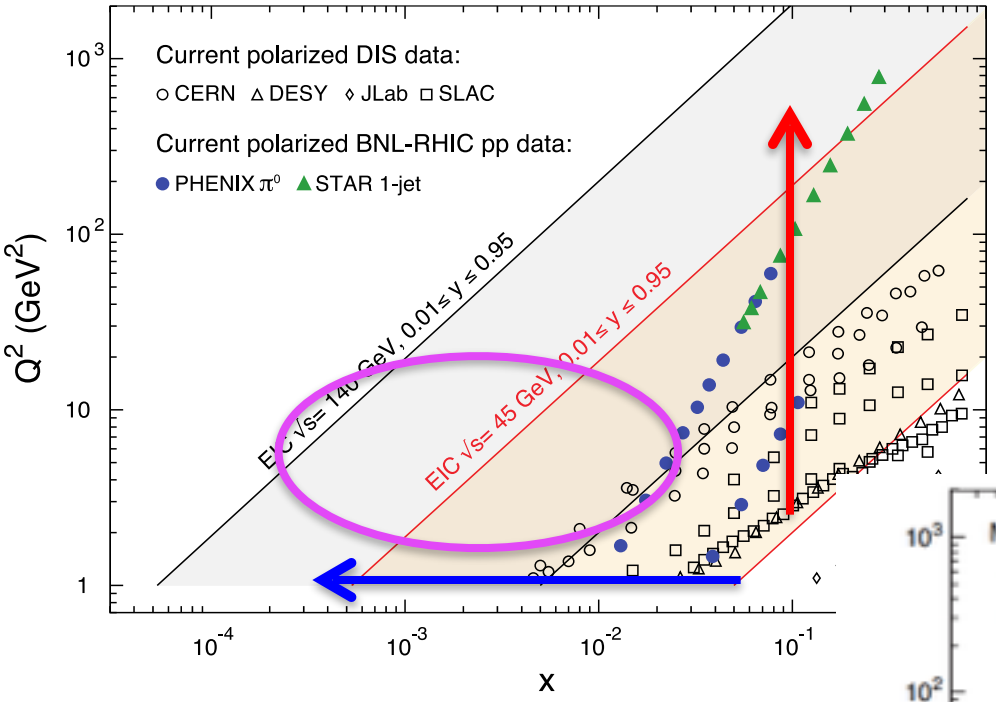


JLab

AGS

BNL

US EIC: Kinematic reach & properties

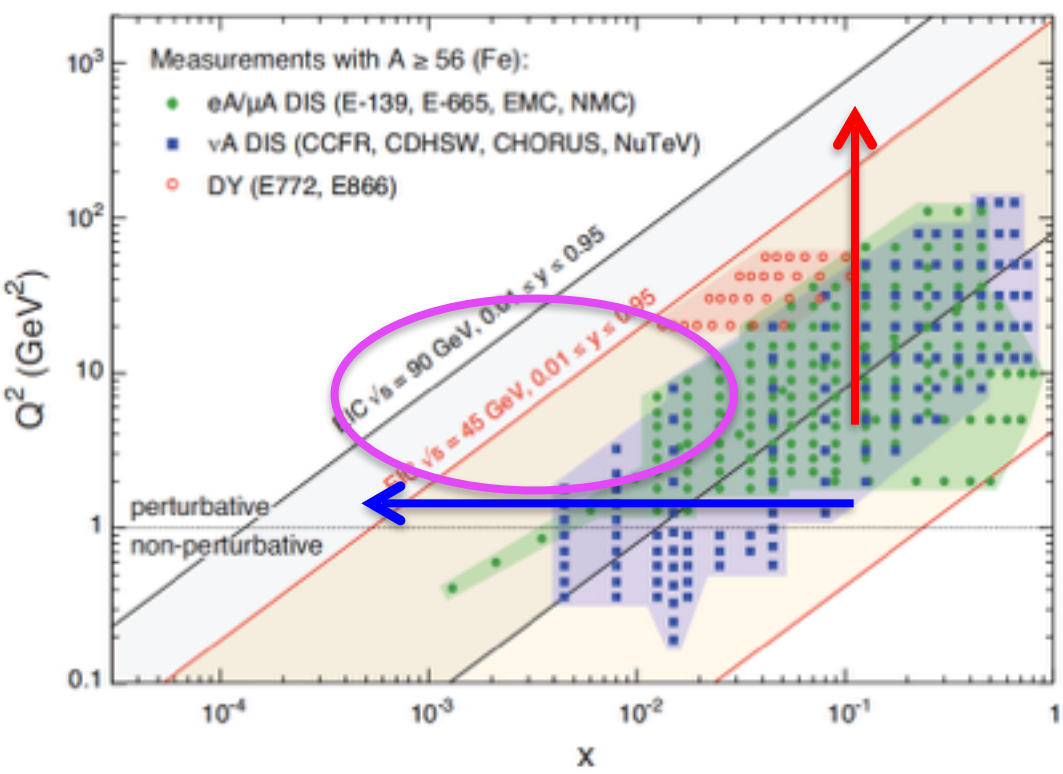


For e-N collisions at the EIC:

- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Lum. per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities



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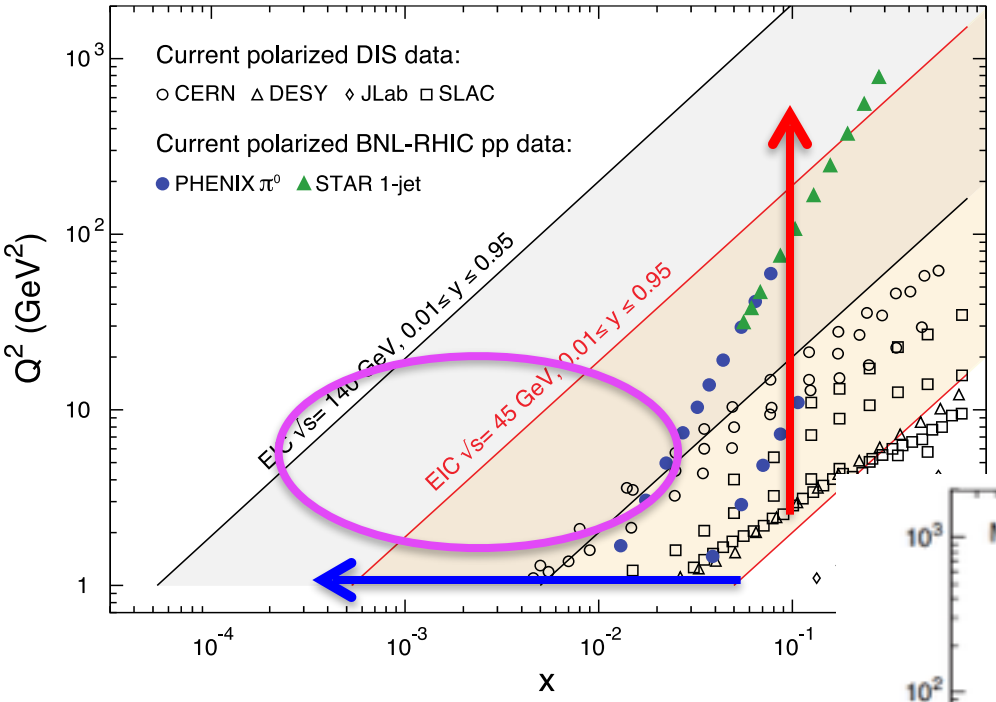

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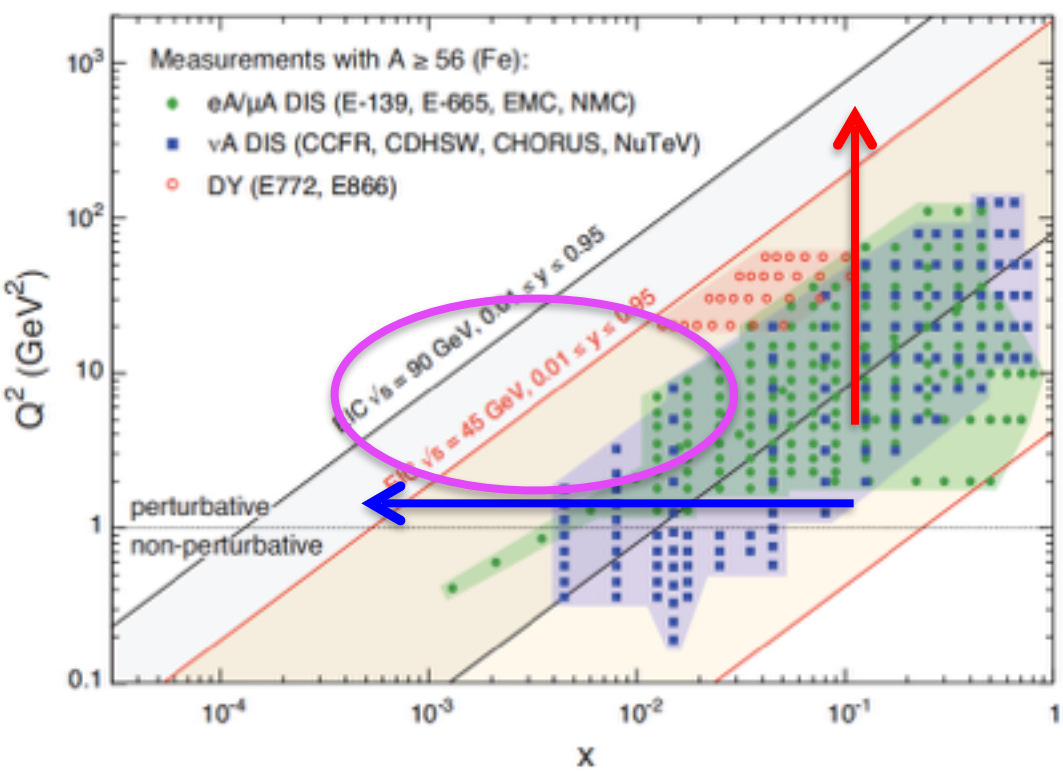
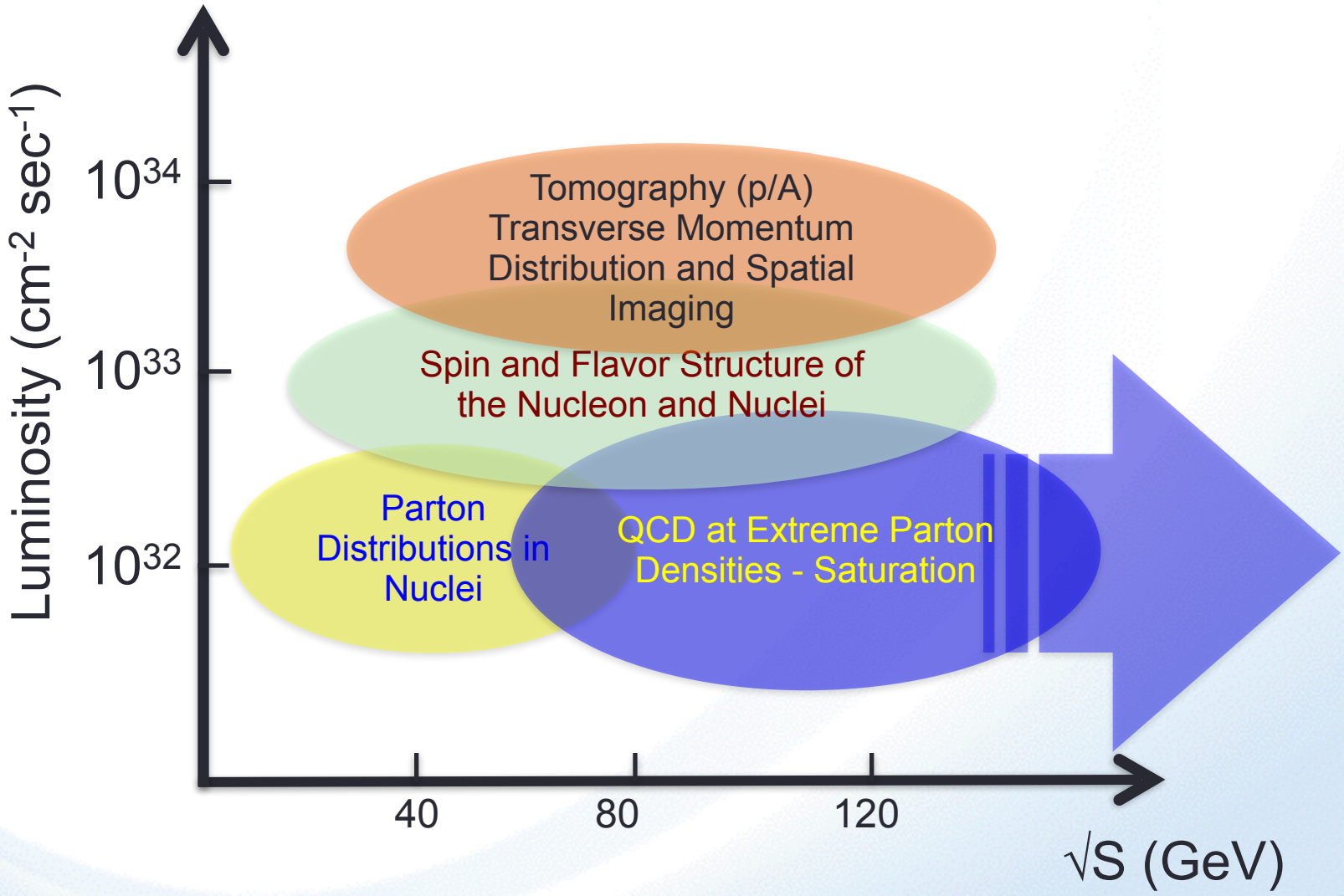
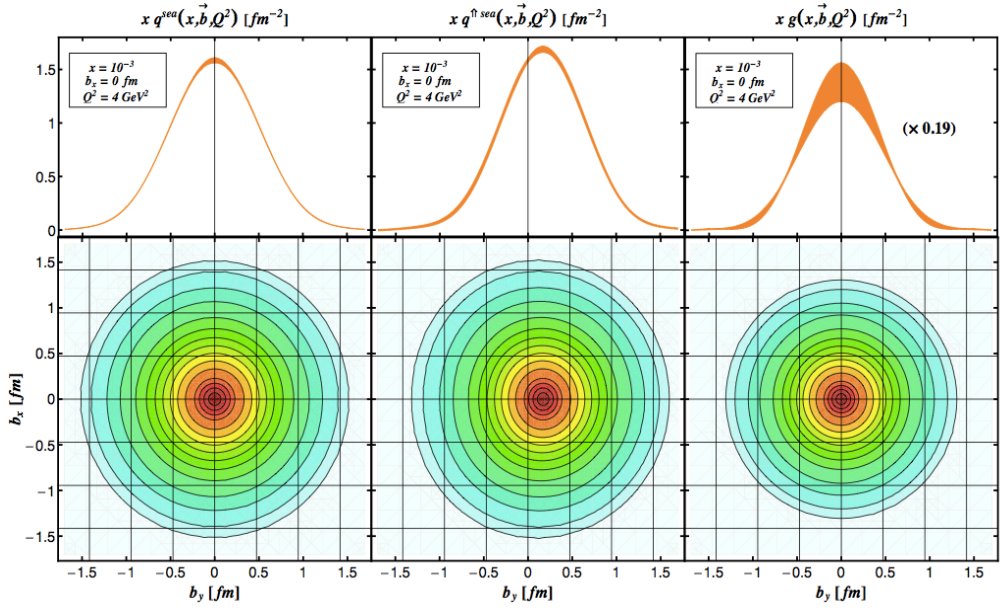
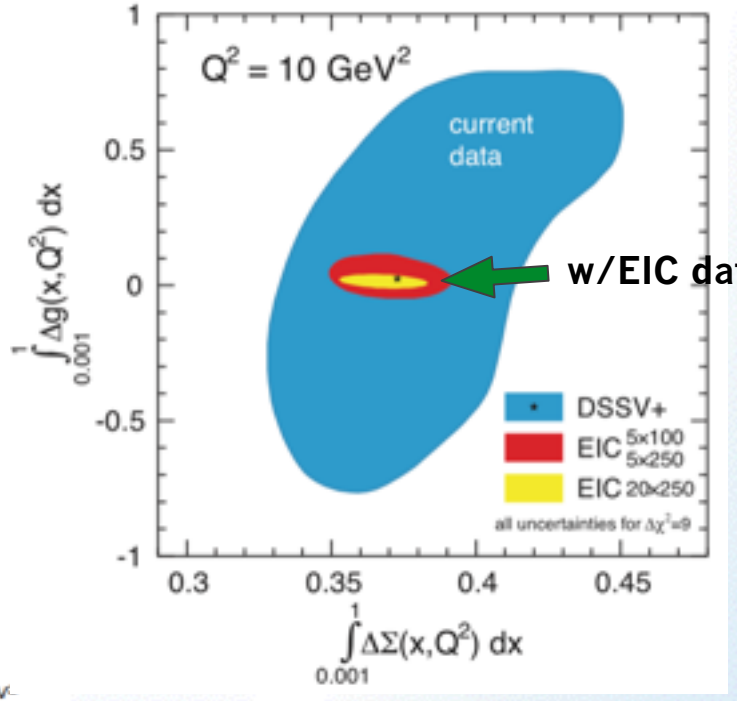


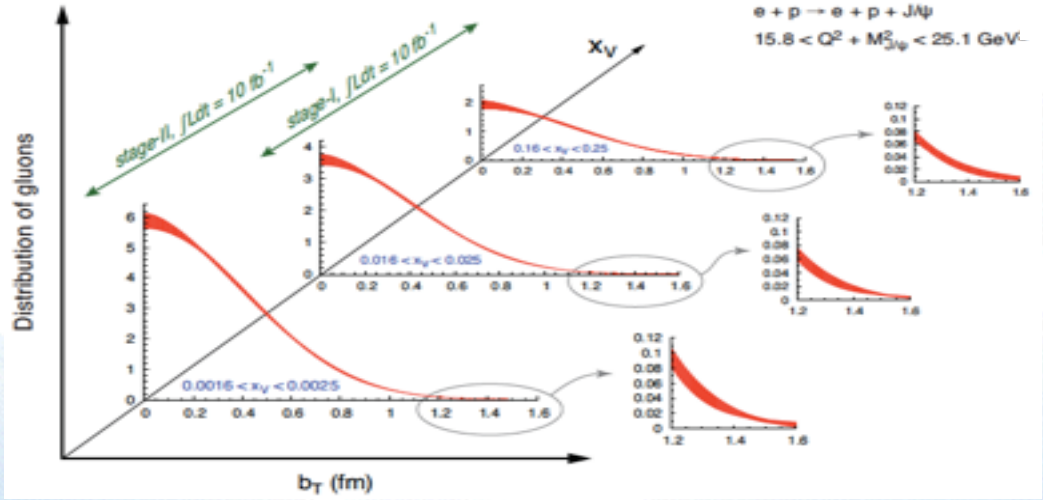
Physics vs. Luminosity & Energy

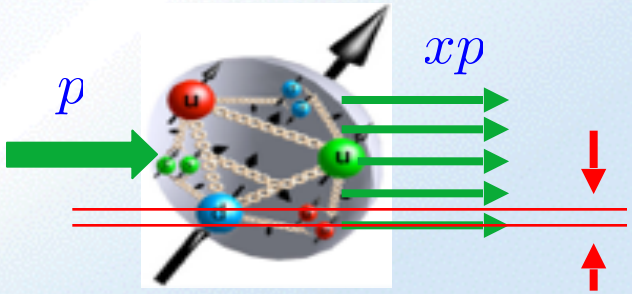


Exquisite precision









EIC: Why now?

- A set of ***compelling physics questions about the gluon's role in nucleons and nuclei*** has been formulated
- ***Measurements that provide answers*** to those compelling questions about have been identified
- ***Powerful formalisms*** that connect the measurements to rigorously defined properties of QCD structure & dynamics of the nucleons and nuclei have been developed
- Based on the accelerator R&D since the 2007 LRP, technical designs of an EIC re-using existing facility infrastructure now exist

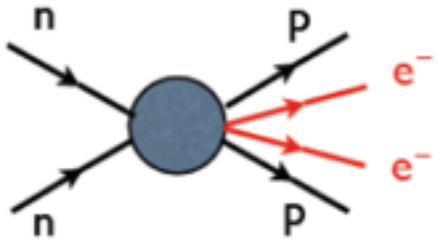
Joint Recommendation

We recommend a high-energy, high-luminosity polarized Electron-Ion Collider (EIC) as the highest priority for new facility construction, following the completion of FRIB. The EIC will enable three-dimensional imaging of the internal landscape of nucleons and nuclei with unprecedented resolution to reveal the roles of abundant gluons and sea quarks, and exploration of a new QCD frontier where a universal form of gluon matter with characteristic collective behavior is predicted to dominate nuclear dynamics.

Other Nuclear Subfields

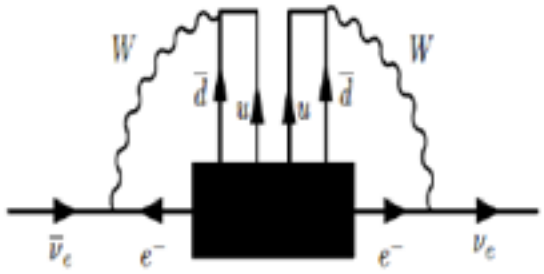
Fundamental Symmetries

Neutrinoless double beta decay



Observation of NLDBD would be direct evidence of new physics, with far-reaching implications:

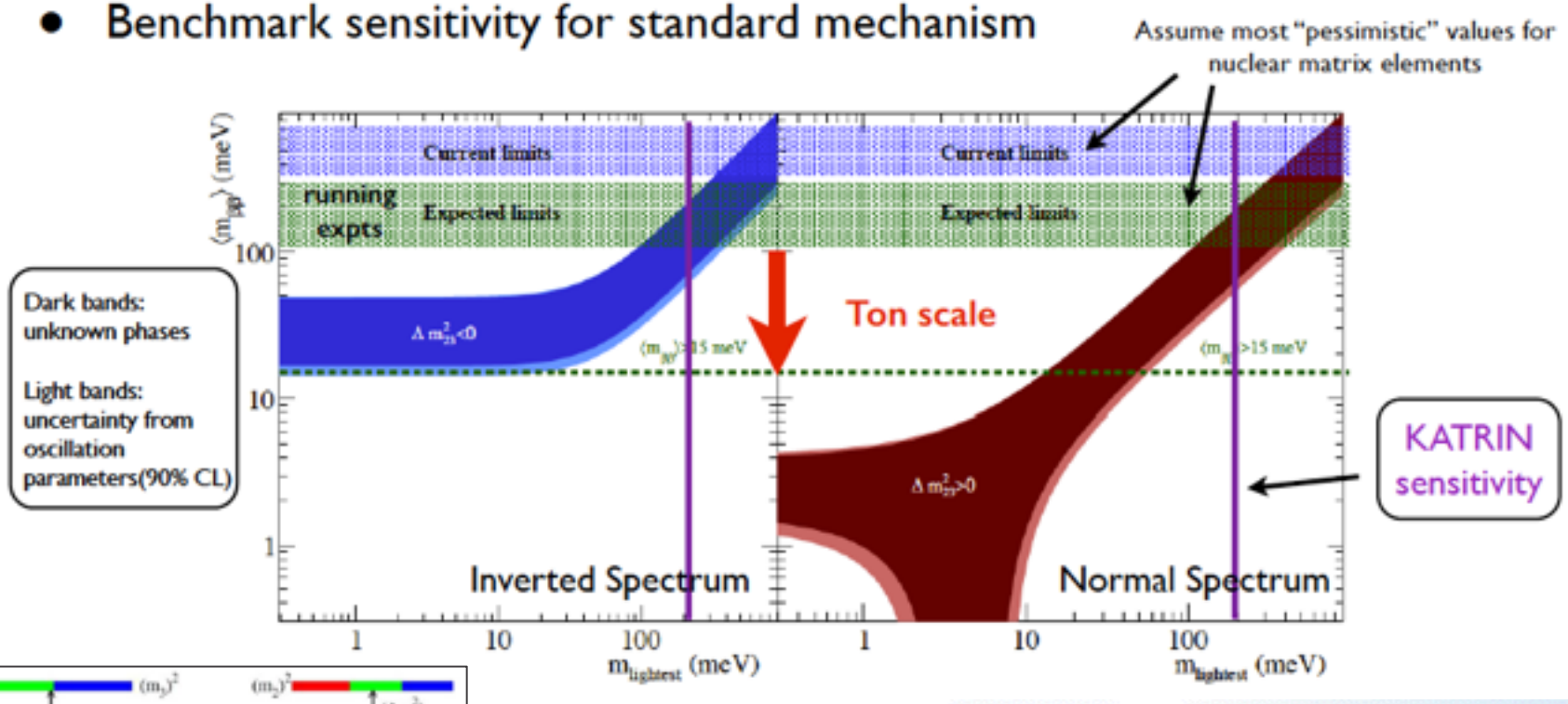
- Demonstrate that neutrinos are Majorana fermions
- Shed light on the mechanism of neutrino mass generation

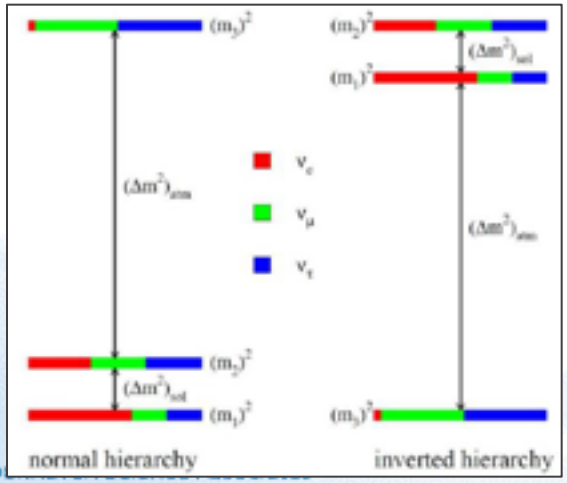


- Probe a key ingredient (LNV) needed to generate the cosmic baryon asymmetry via "leptogenesis"

Neutrino masses

- Benchmark sensitivity for standard mechanism





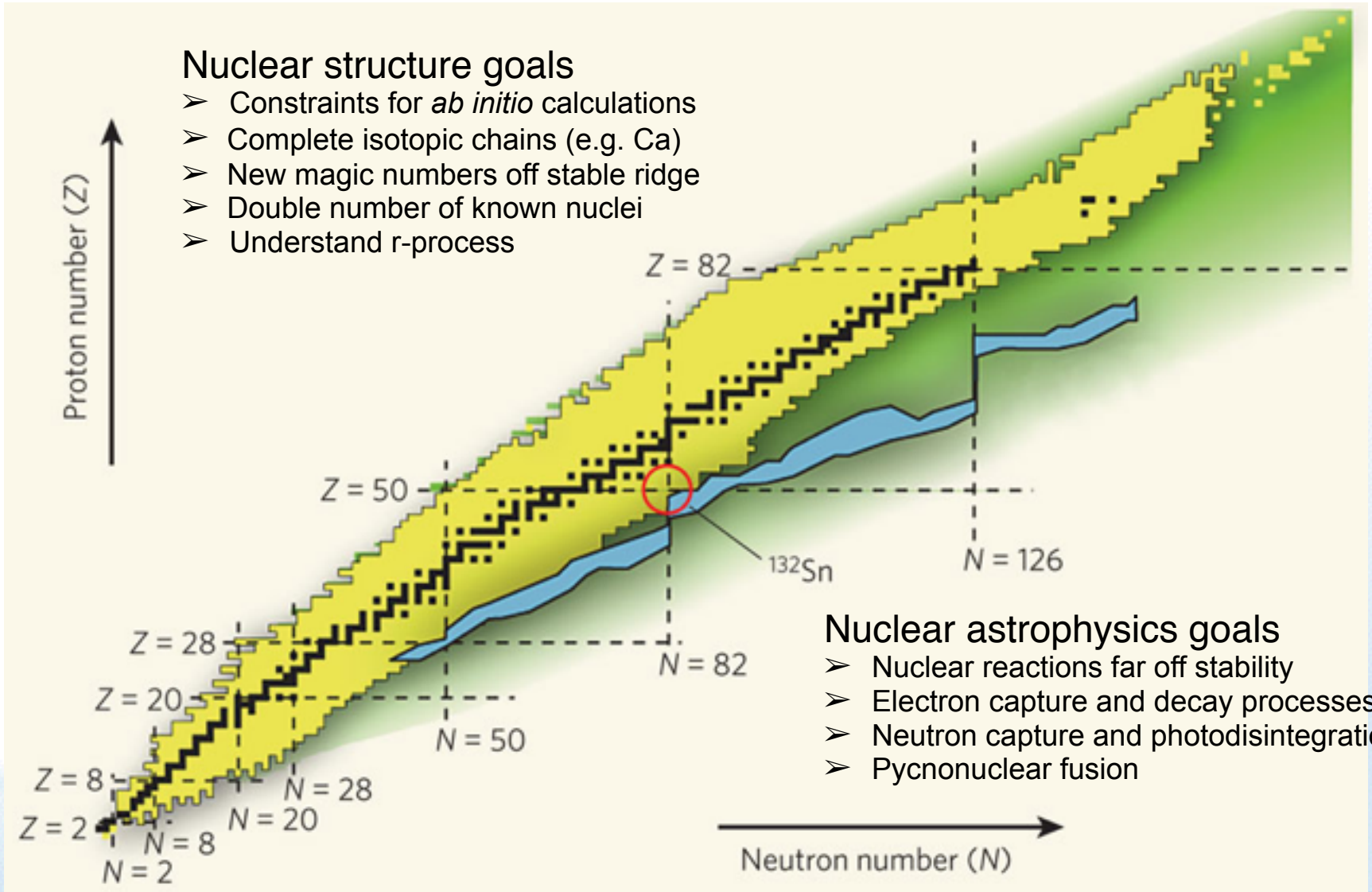
- Next generation experiments are moving forward to improve sensitivity by factor ~100.
- The field is rapidly approaching readiness to proceed with tonne scale experiments led by U.S. scientists.

Fund. Symmetries & Neutrinos

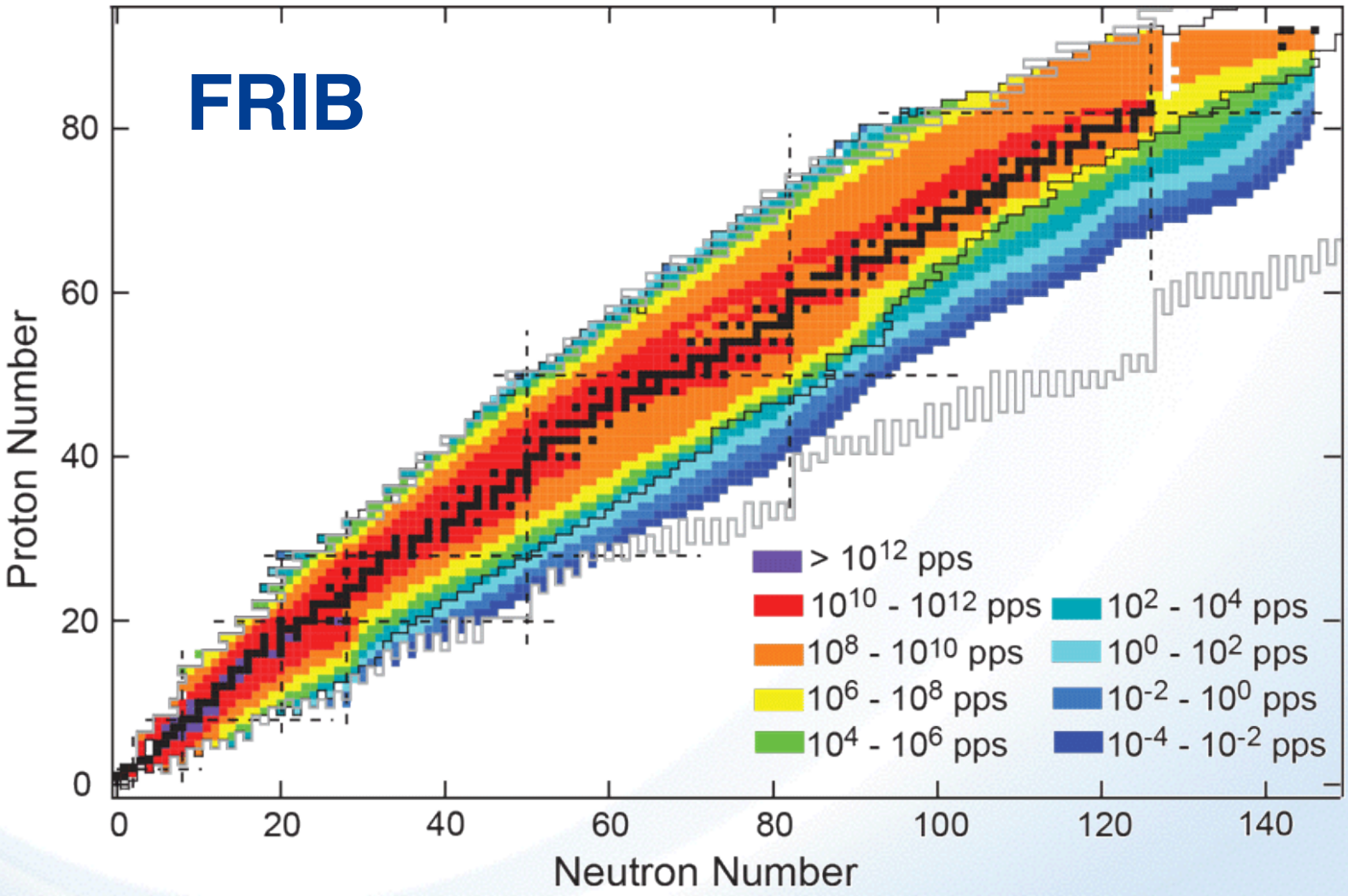
Recommendation

We recommend an enhanced and sustained program of experiments and theory in fundamental symmetries and neutrinos designed to determine neutrino properties, search for yet unseen violation of time reversal invariance and lepton number conservation, and reveal interactions beyond the Standard Model. Construction and deployment of a U.S.-led tonne-scale neutrinoless double beta-decay experiment is a vital component of this program.

Nuclear structure / astrophysics



Rare isotope production



Nuclear Structure / Astrophysics

Joint recommendations:

1. **The highest priority in low-energy nuclear physics and nuclear astro-physics is the timely completion of the Facility for Rare Isotope Beams (FRIB) and the initiation of its full science program.**

2. **We recommend appropriate support for operations and planned upgrades at ATLAS, NSCL, and university-based laboratories, as well as for the utilization of these and other facilities, for continued scientific leadership. Strong support for research groups is essential.**

3. **We recommend targeted major instrumentation and accelerator investments to realize the discovery potential of our field.**

Summary

- Broad community support for a vigorous exploitation of the investments made as a result of the 2007 Long Range Plan:
  - CEBAF 12 GeV
  - RHIC II
  - New instrumentation at ATLAS
  - Completion of FRIB
- Broad consensus that an EIC is the future facility for QCD research in nuclear physics
- Broad support for experiment(s) capable of discovering neutrinoless double beta decay
- Necessity of vigorous R&D on EIC and NLDBD
- Broad support for continued investments in nuclear theory, esp. for collaborative and computational research
- Stay tuned for official recommendations