Experimental Investigations in QCD: sPHENIX, Jlab12 & the EIC

7th Workshop of the APS Topical Group on Hadronic Physics (GHP)

February 1-3, 2017

Thanks: Rolf Ent, Bob McKeown, Dave Morrison, Jianwei Qiu, Gunther Roland, Bob Tribble, Rik Yoshida for slides/ideas….

The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

http://science.energy.gov/np/reports

Recommendations:

Finish programs at existing & under construction facilities (**RHIC**, **JLab12**, NCLS, FRIB,…) & sustain a targeted program in fundamental symmetries & neutrino research

Invest in a ton-scale neutrino-less double beta decay experiment

Construct a high-energy high-luminosity polarized EIC with highest priority following the completion of FRIB.

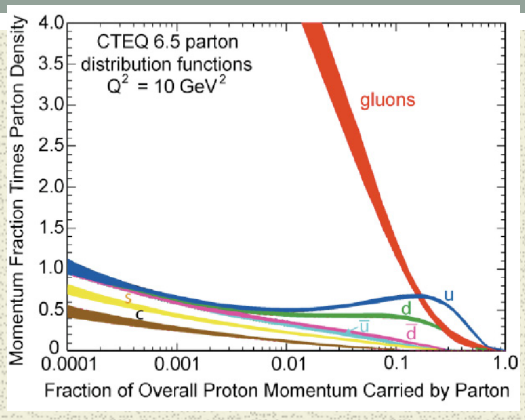
10 yrs

Invest in mid- and small-scale projects at universities and laboratories

Initiatives:

Theory & Computing

Detector & Accelerator R&D

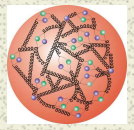


Connections: JLab & EIC

QCD radiation Dominate

Many-body Regime

Few-body Valence Regime

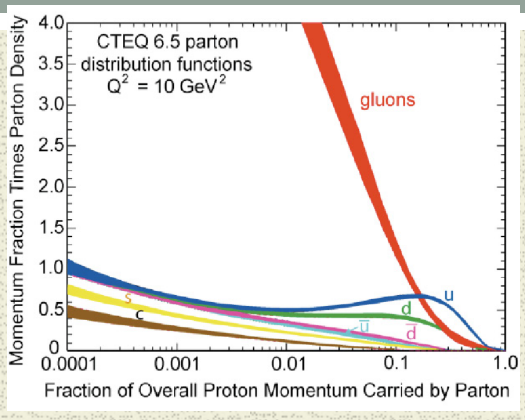


Shutter Speed:

10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 x (proton)

Energy

Jlab & EIC can probe the entire region and unravel the effects of QCD on the structure of nucleons and nuclei



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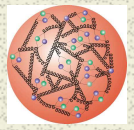

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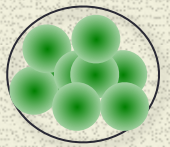
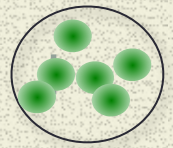
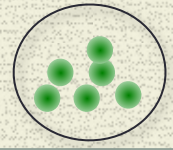






Shutter Speed:

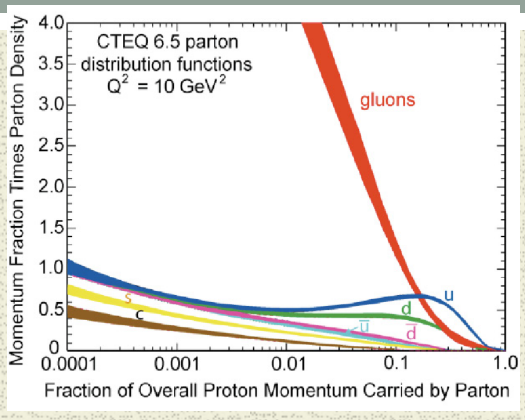
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 x (Nuclei)

Shadowing and Saturation Regime

Nucleon-Nucleon Interaction

Nuclear Modification of Nucleons

Jlab & EIC can probe the entire region and unravel the effects of QCD on the structure of nucleons and nuclei



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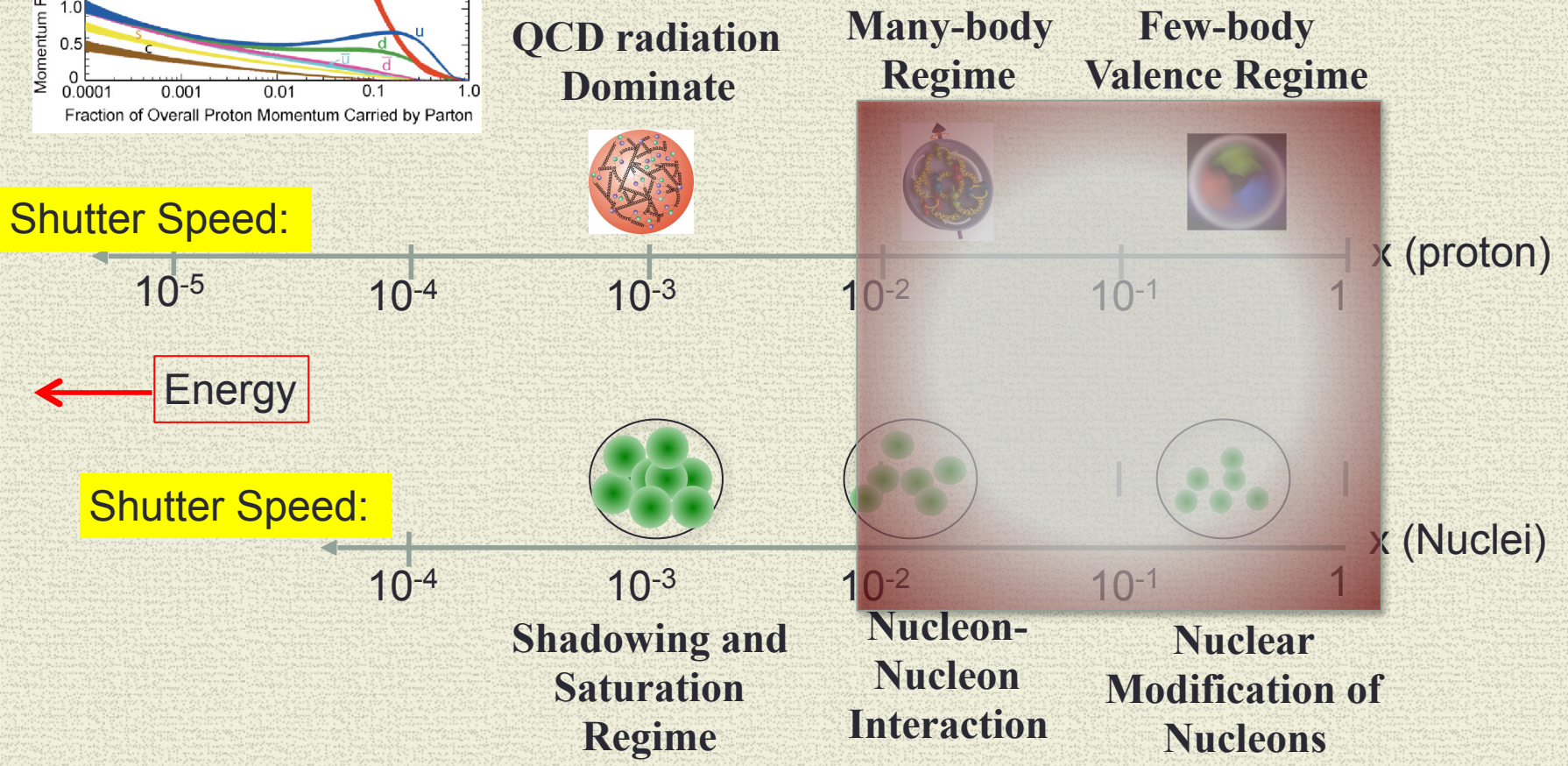
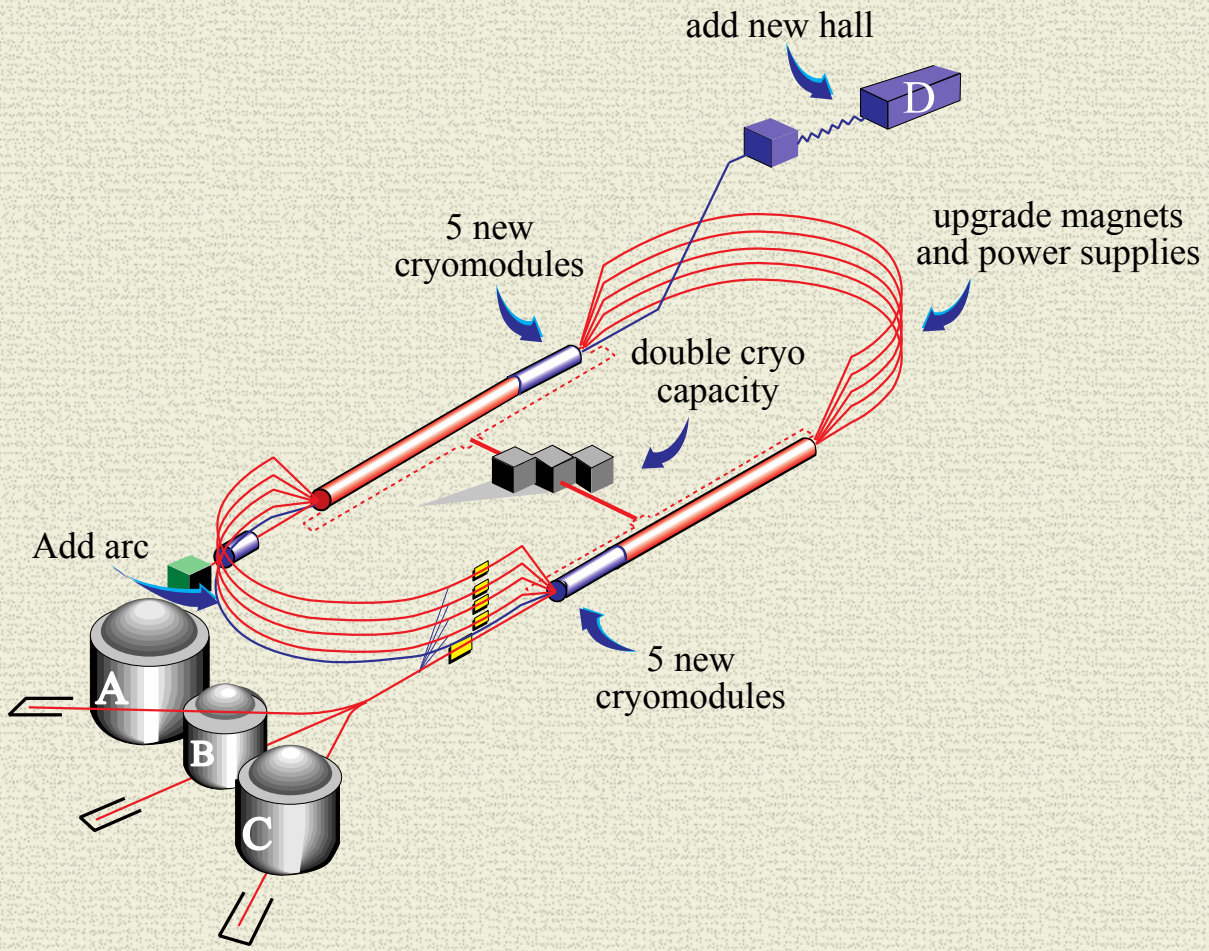


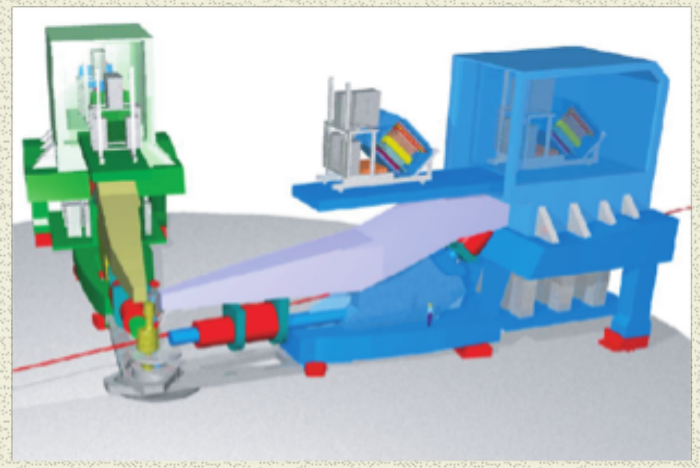
Jlab & EIC can probe the entire region and unravel the effects of QCD on the structure of nucleons and nuclei

12 GeV Upgrade of the CEBAF @ JLab

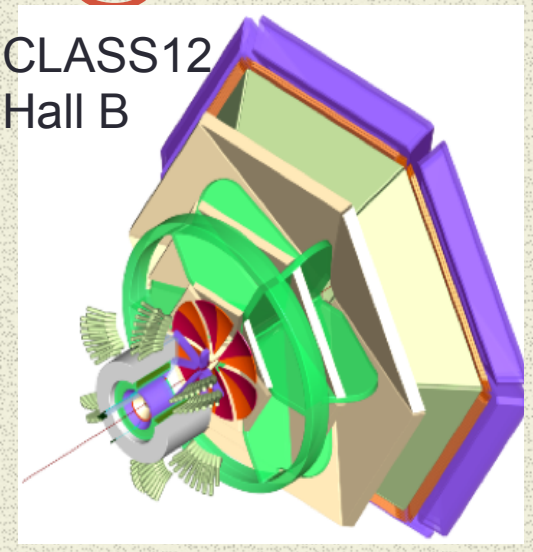


12 GeV Upgrade of the CEBAF @ JLab

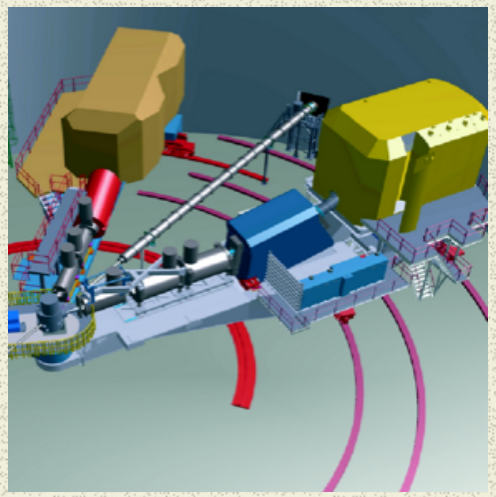
High Resolution Spectrometer Hall A



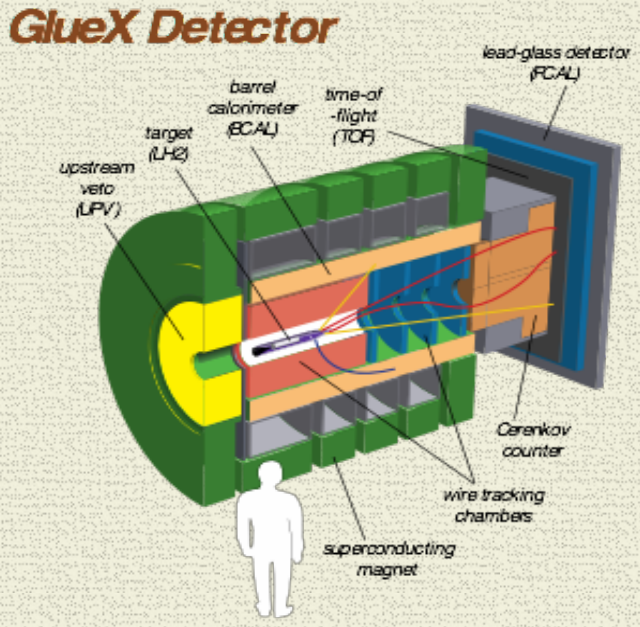
CLASS12
Hall B



Hall C
SHMS

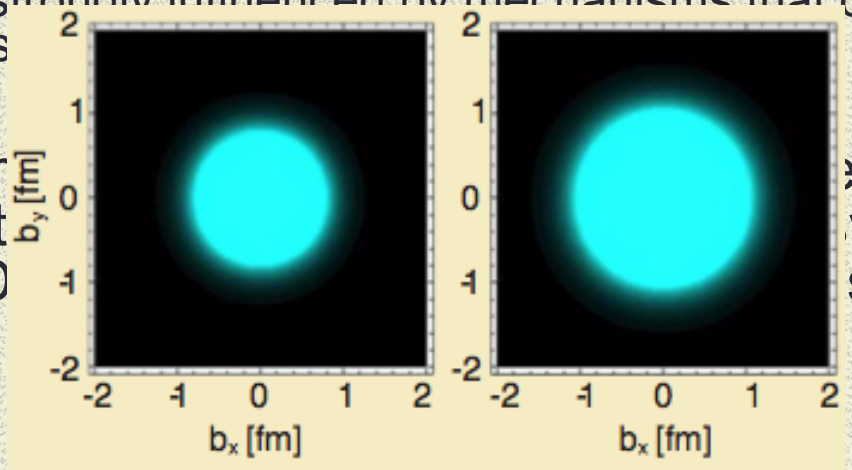


GlueX
Hall D



Science of 12 GeV Upgrade

- The 12 GeV Beam ideal for studying the dynamics of valence quarks that determine the quantum numbers of hadrons
  - The dynamics is strongly influenced by mechanisms that develop mass in QCD, dynamical s
- We now have firr ework to measure correlat verse position to reconstruct 3D space images of a proton



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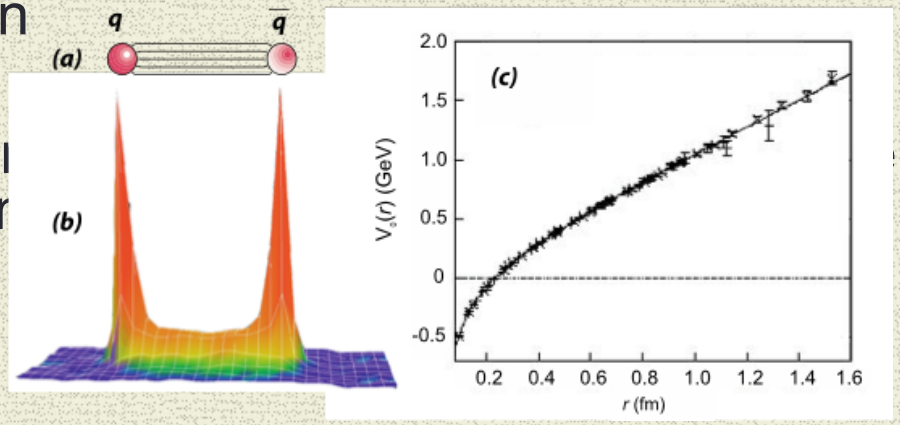
- Search for … the particle's quantum …



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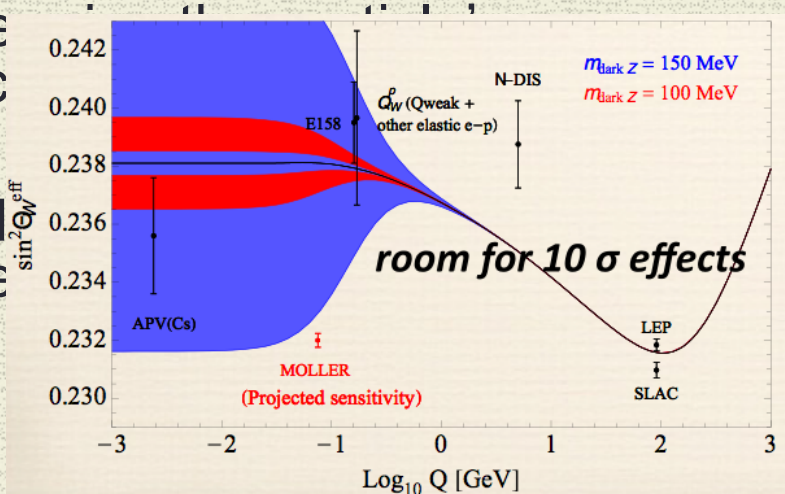
- Additional instrumentation in Hall-A (M… enable precision measurements challe… Standard Model



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- Search for particles where gluons determine the particle's quantum number (Hall-D): QCD exotica…
- Additional instrumentation in Hall-A (MOLLER & SoLID) will enable precision measurements challenging the limits of the Standard Model

12 GeV Upgrade Project

- Total Project Cost $338M
- Estimate to Complete $4M
- Project Scope **~99% Complete**
  - Doubling Accelerator Energy – **Done**
  - New Experimental Hall D and beamline – **Done**
  - Civil Construction including utilities – **Done**
  - Upgrade to Experimental Halls B & C – **~98% Complete**
    - Hall B & C Detectors **Done**
- October 2016 DOE Office of Project Assessment Review:
  - Schedule pressure on Solenoid delivery and commissioning
  - Project was complimented for aggressive issues management
  - Plan to demonstrate full project scope (except solenoid) in Spring 2017 was strongly endorsed.

    → Halls B & C Key Performance Parameter Runs this Spring

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  - New
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    - H

Big Picture:

JLab12 Is basically ready!

Operating the machine is critical!

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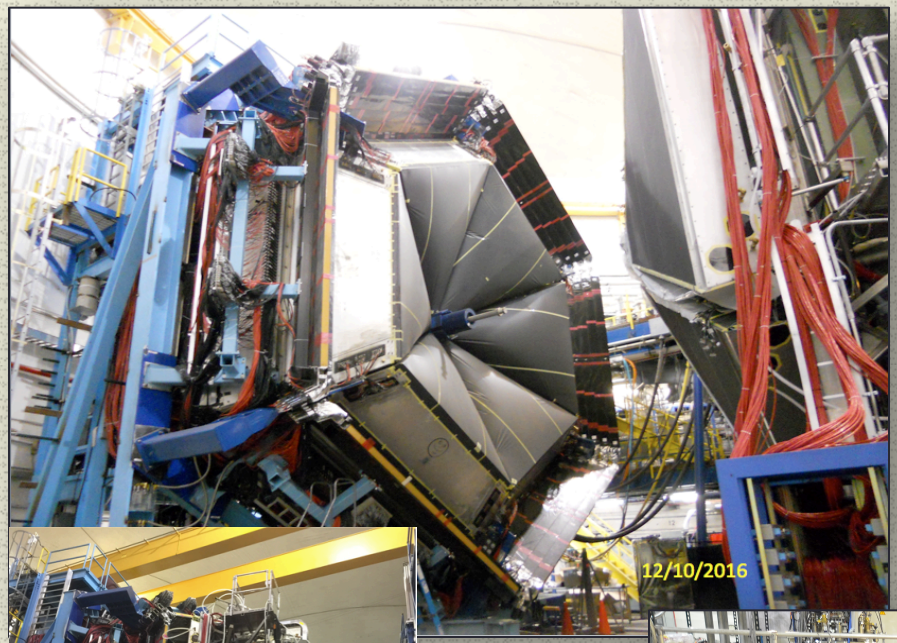
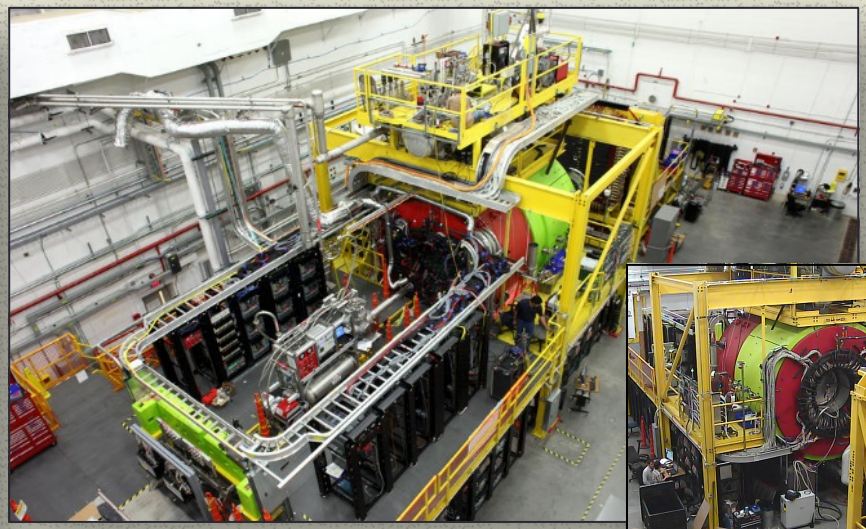
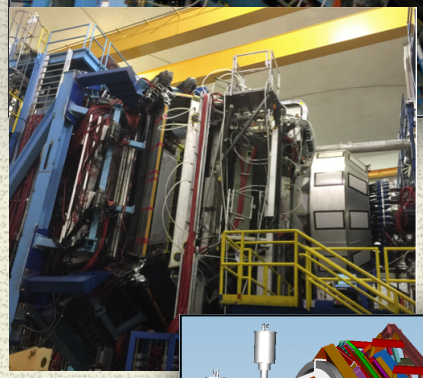
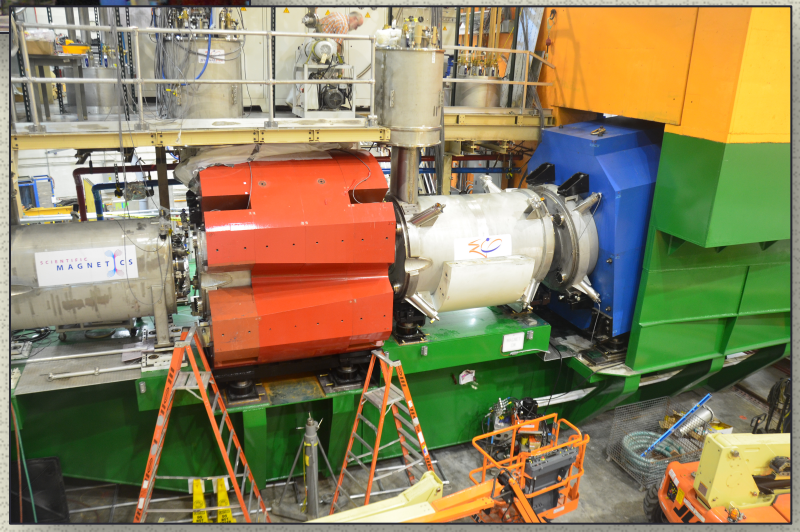
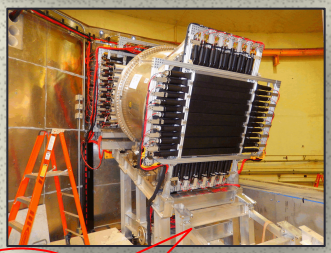
12 GeV Upgrade Project – Halls B, C and D

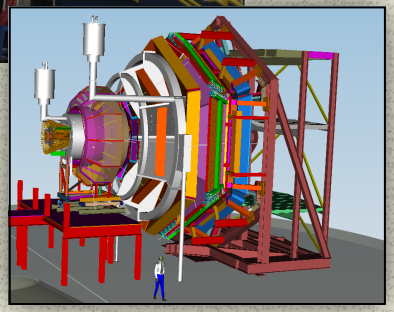


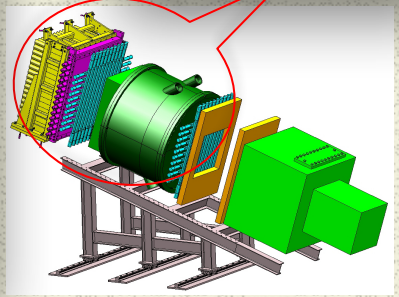








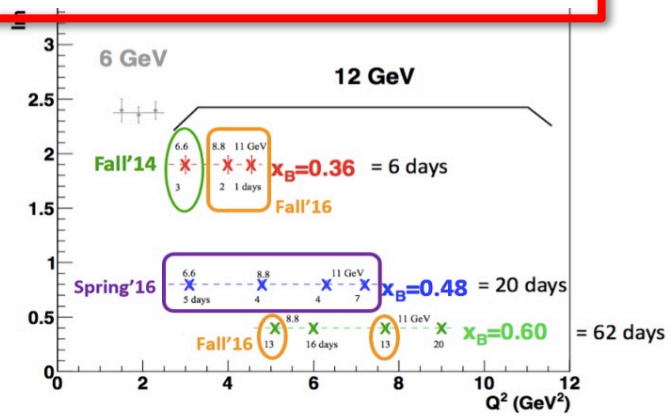


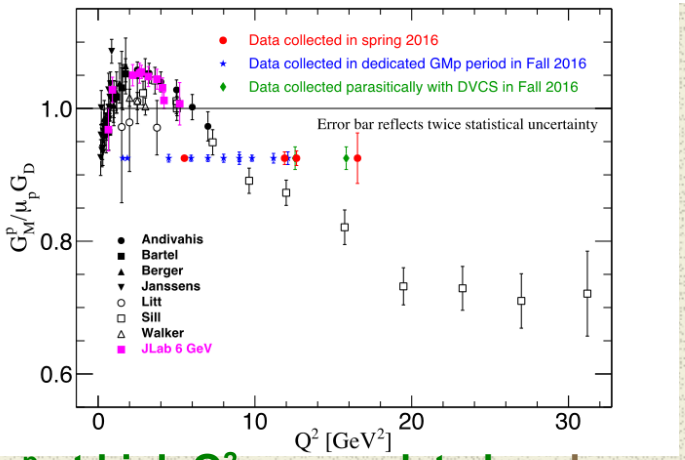


Hall A Recent Accomplishments & 12 GeV Plans

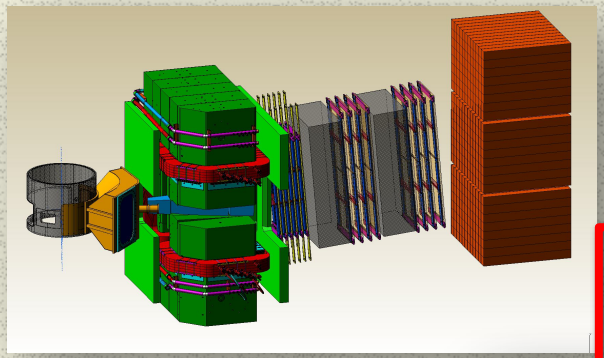
Flagship: form factors, future new experiments (e.g., SoLID and MOLLER)

Scaling tests of the DVCS cross section – scheduled (first) phase completed





G_M^p at high Q^2 – completed; reduce uncertainties on SBS form factor program

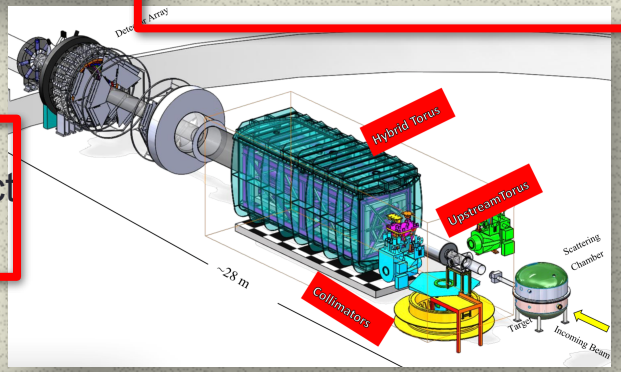


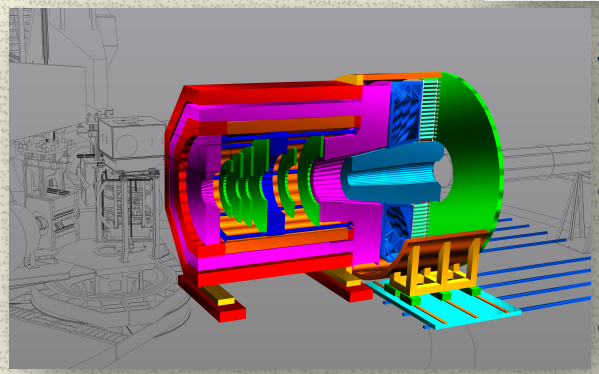
Super Big Bite (SBS) Spectrometer

- High Q^2 form factors
- and other (SIDIS, TDIS)
- **DOE Project completing Feb. 1st!**

MOLLER Experiment

- Precision standard model test
- **CD-0 approved,** project paused due to budget uncertainties





SoLID

- Large acceptance and luminosity
- 8 approved experiments (TMDs, GPDs, J/Psi, PVDIS,…)
- CLEO-II cryostat @ JLab

Hall B Accomplishments & 12 GeV Plans

Flagship: nucleon structure via generalized parton distributions

Flow of physics from *CLAS* > 180 pubs in refereed journals & > 200 Ph.D. theses completed (and 35 more in progress)

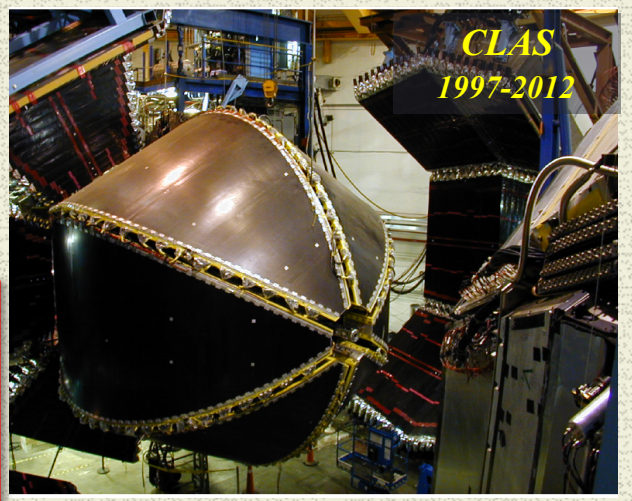
Experiments PRad to measure proton radius (completed) and HPS to search for evidence of dark matter (A' boson).

Basic science program at 12 GeV > 15 years of experiments
- Tomography of the proton & confinement
- Spectroscopy & structure of the nucleon
- Strong interaction & hadronization in nuclei

Building new detector system *CLAS12* for science at 12 GeV
- Many state-of-the art detection systems for tracking and particle identification
- Torus magnet (complete) & Solenoid magnet

International collaboration (> 45 institutions) preparing run
- 4 complex detectors built by European institutions

Ready now to demonstrate key performance parameters, Full commissioning of *CLAS12* in the fall of 2017.



Hall C Recent Accomplishments & 12 GeV Plans

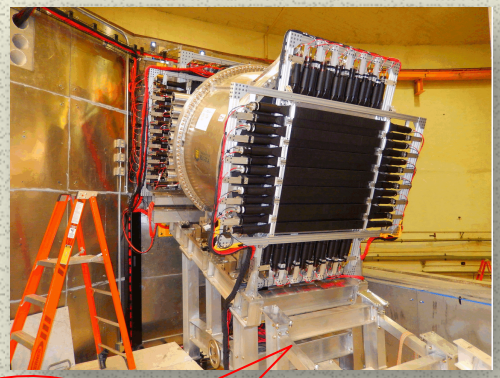
Flagship **– precision determination of valence quark properties in nucleons/nuclei**

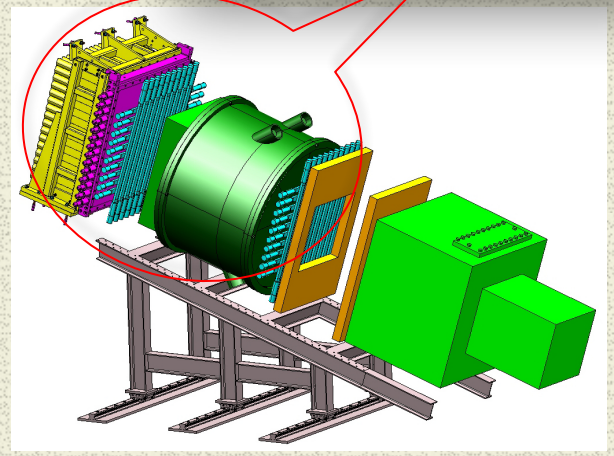
12 GeV Upgrade: New SHMS

- **User-built (and nearly completely user-funded) detector package**
- Highest momentum measurement capability in 12 GeV era
- **All equipment on site**, preparing to demonstrate **Key Performance Parameters *this Spring***
- **Initial physics program starting this year** :

  will commission with (parts of) 7 experiments:

  High x structure functions, color transparency, SIDIS program, Kaon form factor feasibility



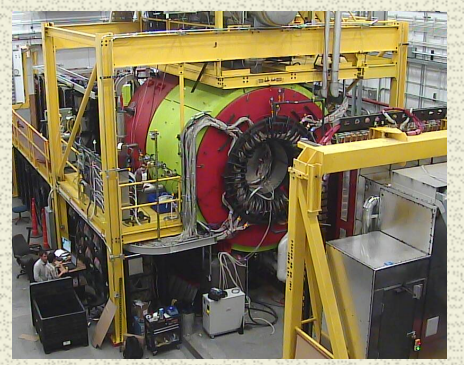


12 GeV science builds on high precision 6 GeV program

Spin-dependent and spin-averaged structure functions, pion and kaon form factor, formalism validation for GPDs and TMDs for charged and neutral particles (with NPS), Compton scattering, relation between short-range correlations and parton dynamics.

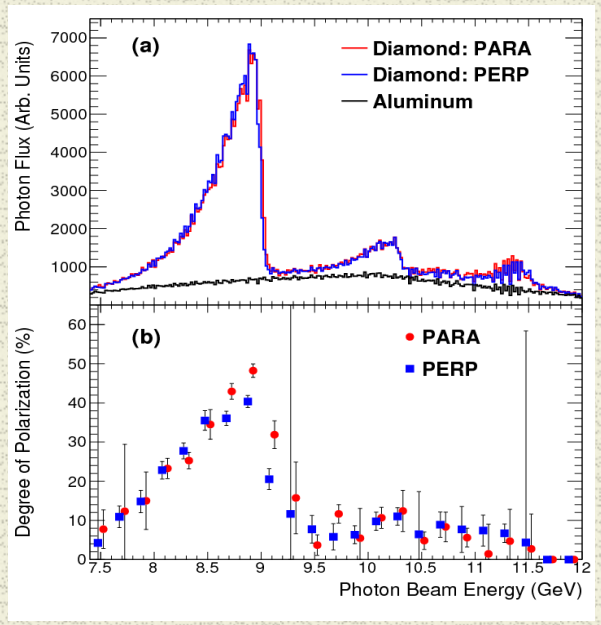
Hall D Recent Accomplishments & 12 GeV Plans

Flagship – exploring origin of confinement by studying exotic mesons (GlueX experiment)



- Engineering run Spring 2016: All the systems were operational
  - Commissioning complete
  - 3 weeks of data: useful for "early physics"
- Test run Fall 2016: 1 week for DAQ and beam tests and tuning
  - Ready for 1-st physics run in Spring 2017!
- Data analysis well advanced: **1-st paper submitted to PRL!**

γp→pπ⁰ ,η
beam asymmetry
$d\sigma/d\varphi \sim P\Sigma\cos(2(\varphi-\varphi_o))$



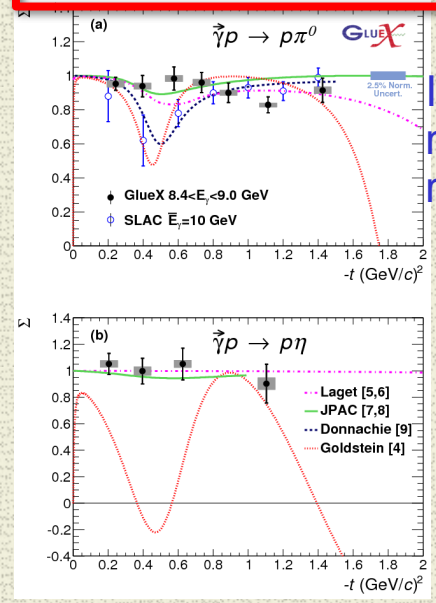
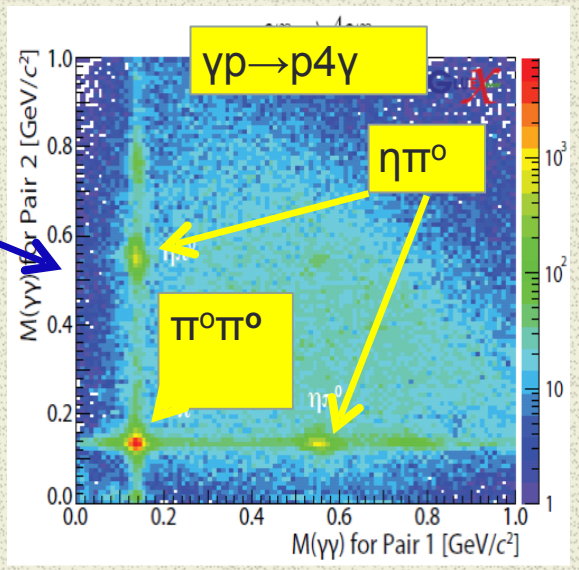
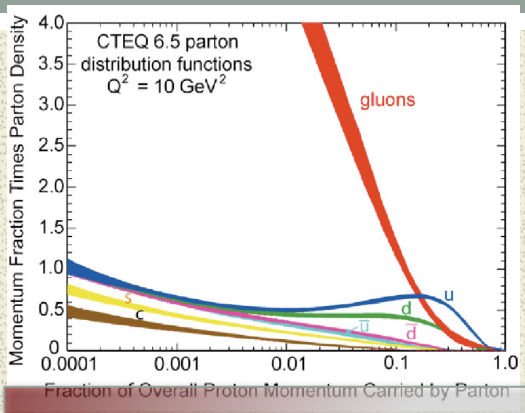
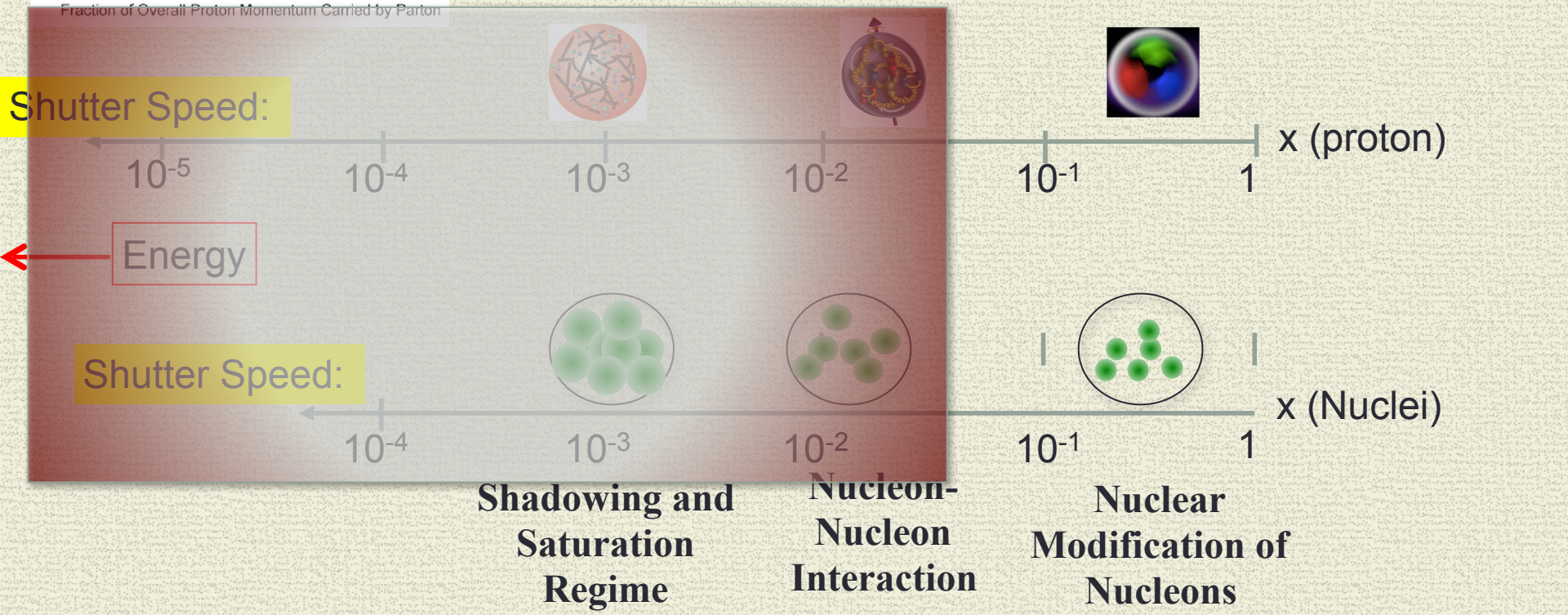


Illustration for multi-particle reconstruction



Connections: JLab & EIC



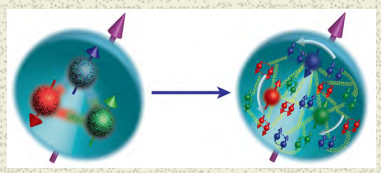


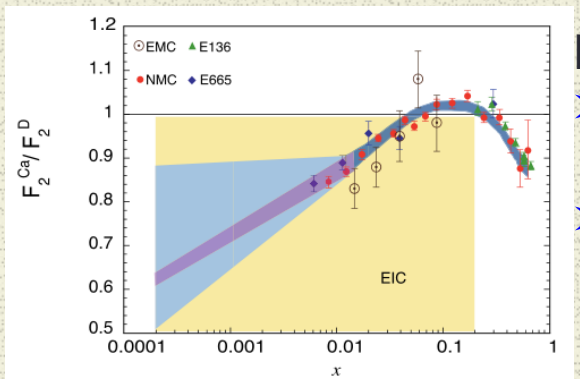
Jlab & EIC can probe the entire region and unravel the effects of QCD on the structure of nucleons and nuclei

EIC is required to investigate with precision, the dynamics of quarks & gluons and their role in structure & interactions in visible matter:

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

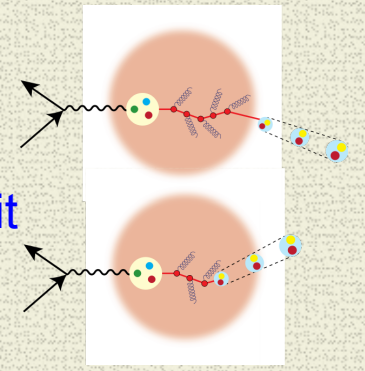
How do the nucleon properties ***emerge*** from these distributions?



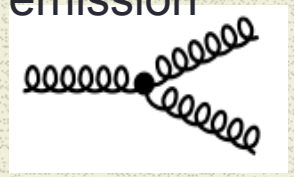


How does the **nuclear environment** affect:

- the space and momentum distributions of quarks and gluons and their interactions?
- the passage of quarks and gluons through it and how are the hadronic final states formed?



gluon emission



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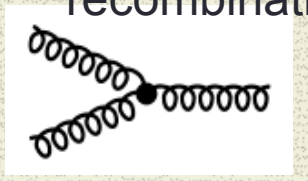
gluon recombination



What happens to the **gluon density in nuclei at high energy?** Does it saturate, giving rise to a gluonic matter of universal properties in all nuclei including protons? Do the gluons remain confined within the nucleons inside nuclei?

The Electron Ion Collider

Two options of realization!

For e-N collisions at the EIC:

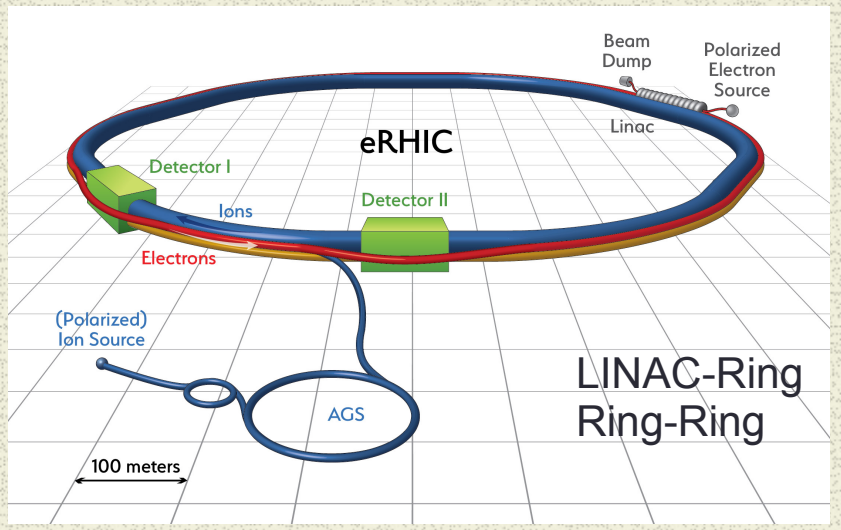
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

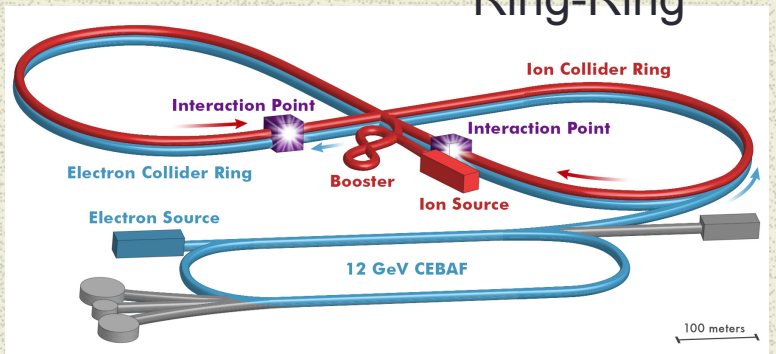
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure

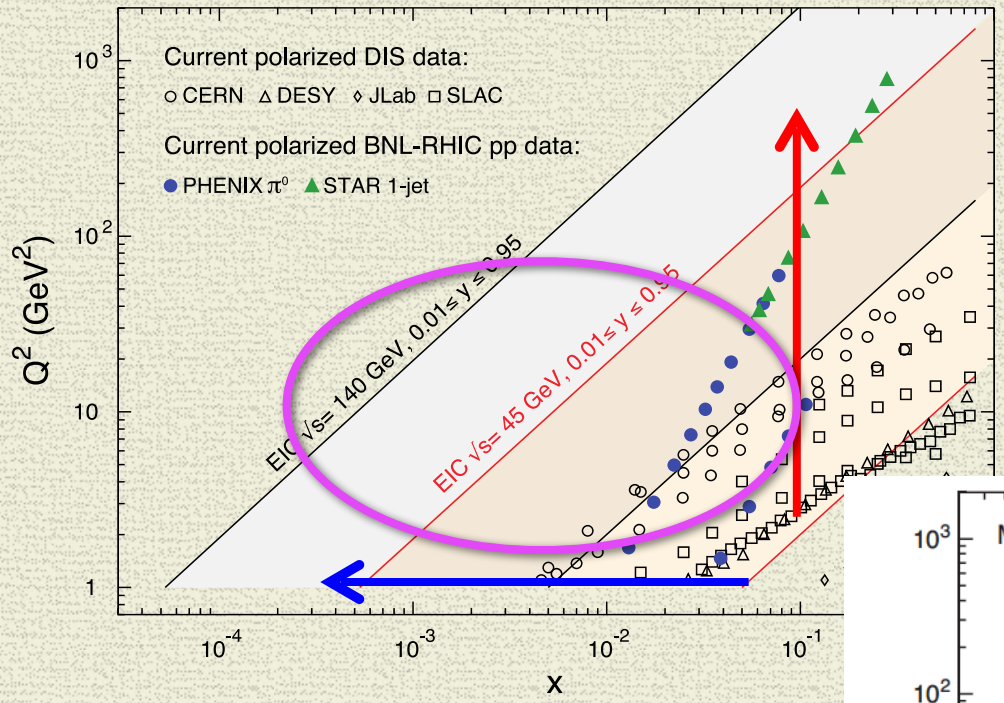


Not to scale

Ring-Ring



EIC: Kinematic reach & properties

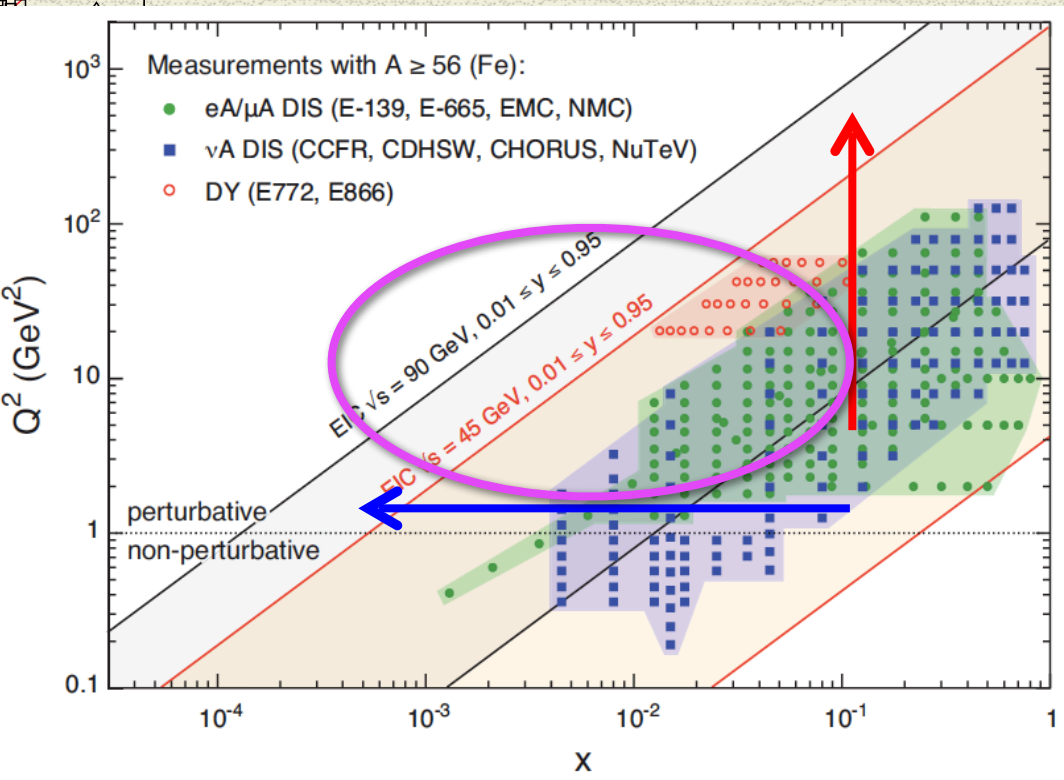


For e-N collisions at the EIC:

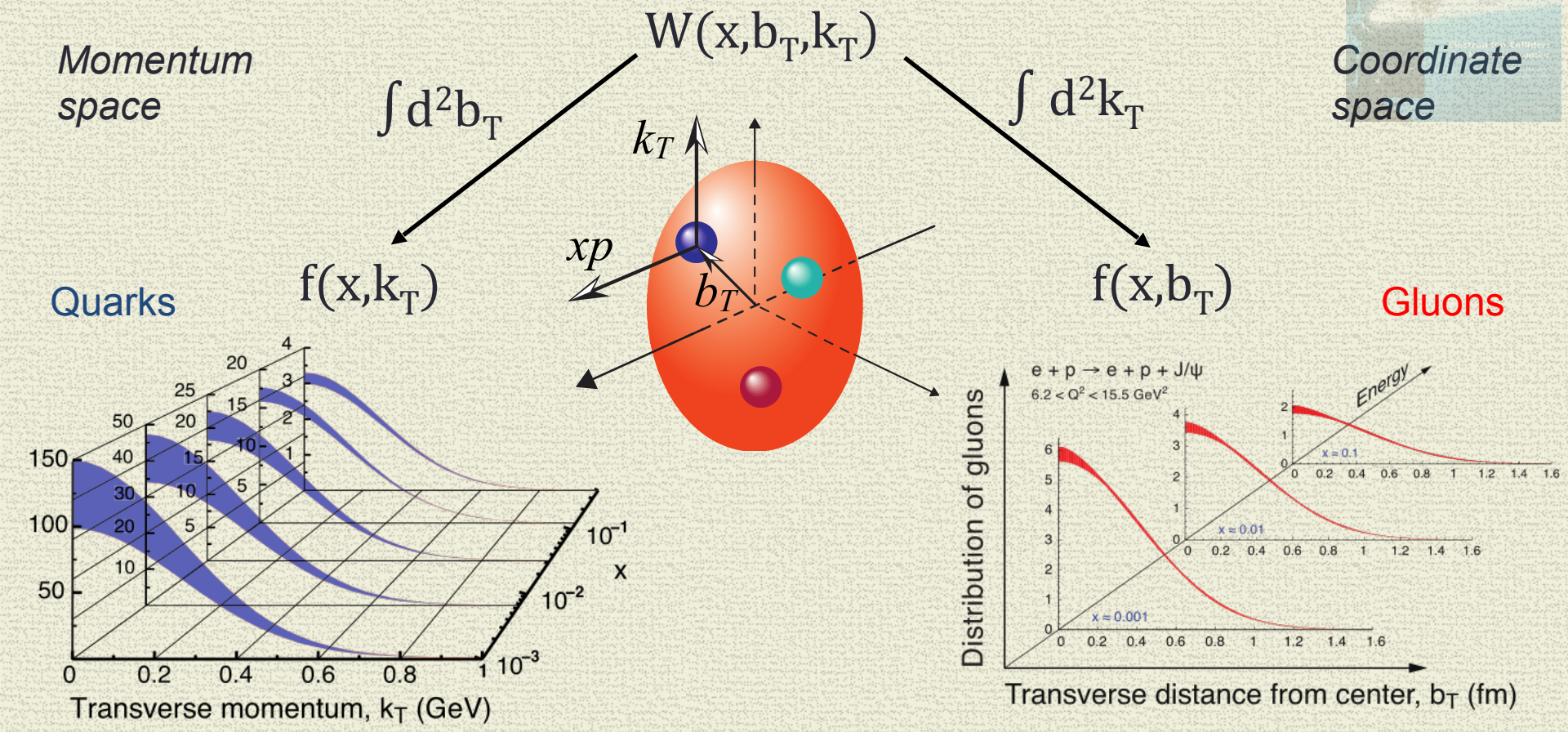
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

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)



3-Dimensional Imaging Quarks and Gluons



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

Spin-dependent 2D (transverse spatial) + 1D (longitudinal momentum) coordinate space images from exclusive scattering

3-Dimensional Imaging Quarks and Gluons

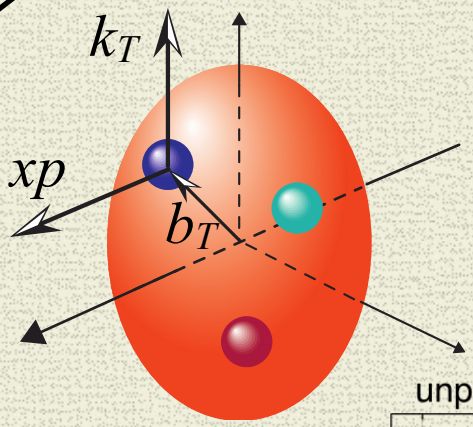
Momentum space

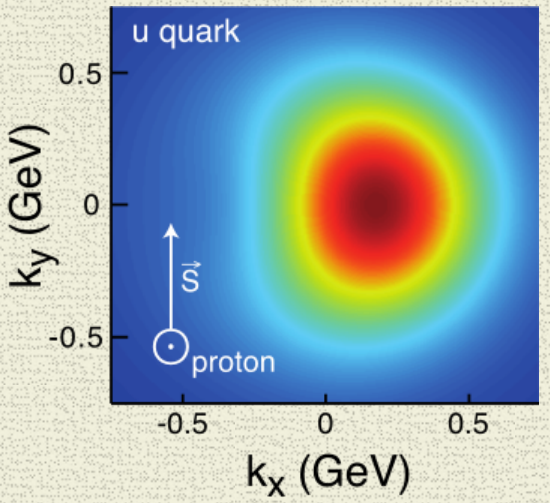
$W(x,b_T,k_T)$

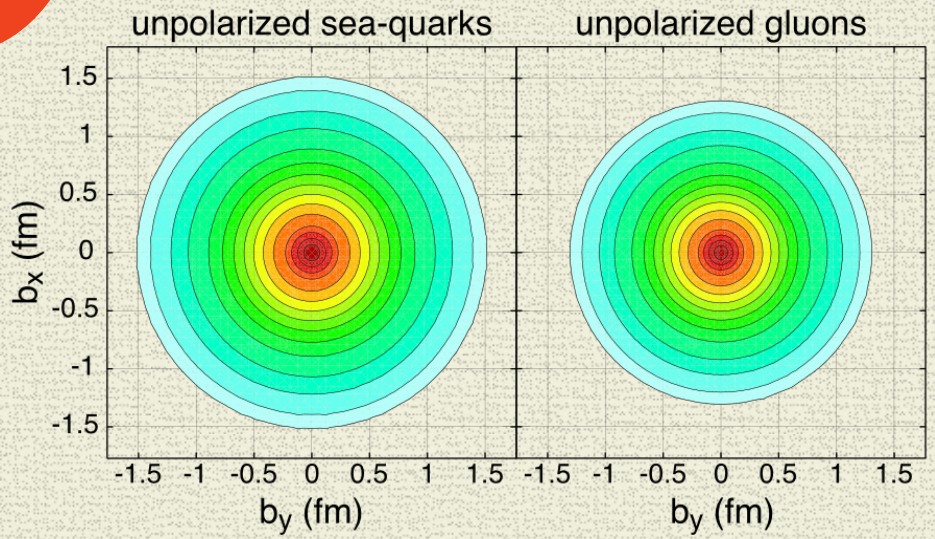
$\int d^2b_T$ $\int d^2k_T$

Coordinate space

$f(x,k_T)$ $f(x,b_T)$

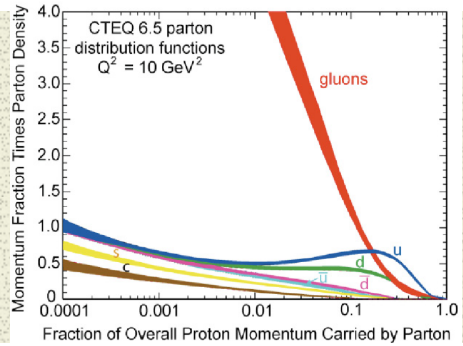




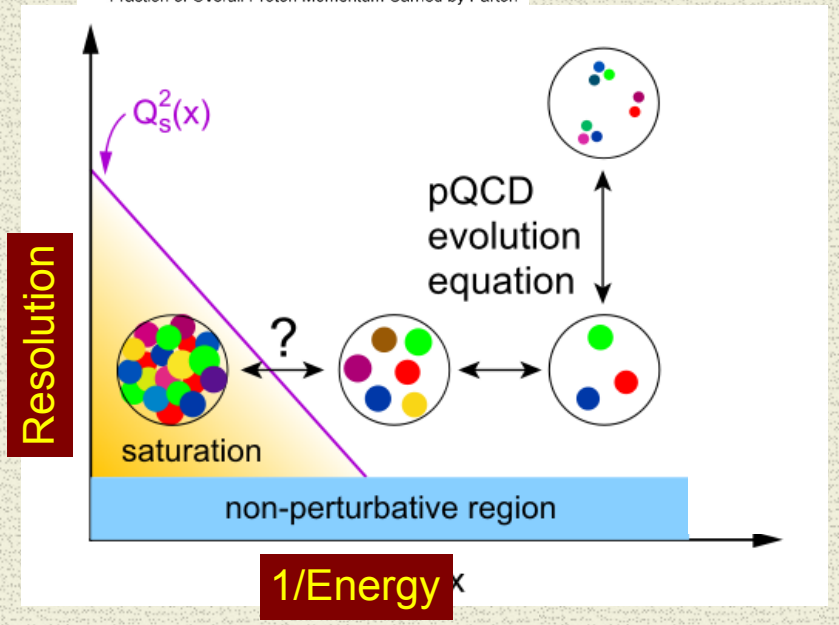


Position r X Momentum p → Orbital Motion of Partons

→ *Directly comparable with Lattice QCD Calculations*



What do we learn from low-x studies?



What tames the low-x rise?

- New evolution eqn.s @ low x & moderate Q^2
- Saturation Scale $Q_S(x)$ where gluon emission and recombination comparable

gluon emission = gluon recombination

At Q_S

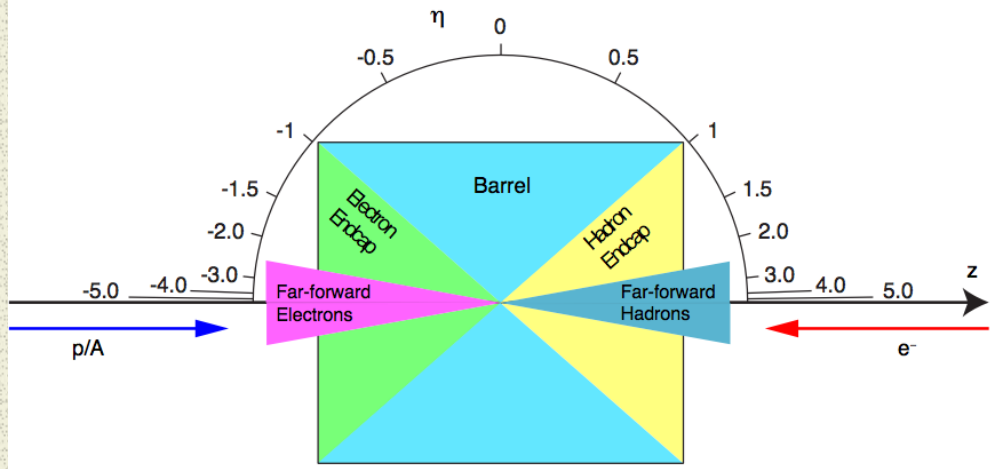
First observation of gluon recombination effects in nuclei:
➔leading to a *collective* gluonic system!
First observation of g-g recombination in *different* nuclei
→ Is this a universal property?
→ Is the Color Glass Condensate the correct effective theory?

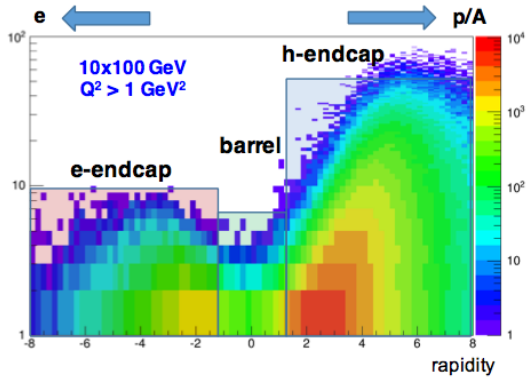
EIC Detector Concepts

Requirement are mostly site-independent with some slight differences in the forward region (IR integration)

In Short:

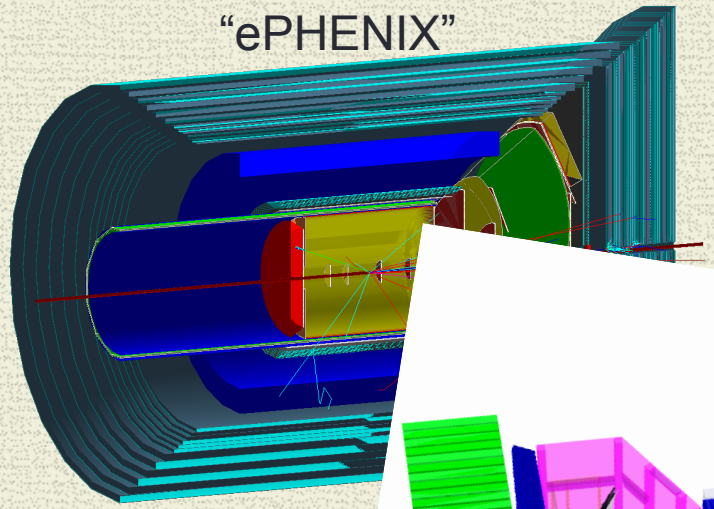
- Hermetic detector, low mass inner tracking, good PID (e and π/K/p) in wide range, calorimetry
- Moderate radiation hardness requirements, low pile-up, low multiplicity

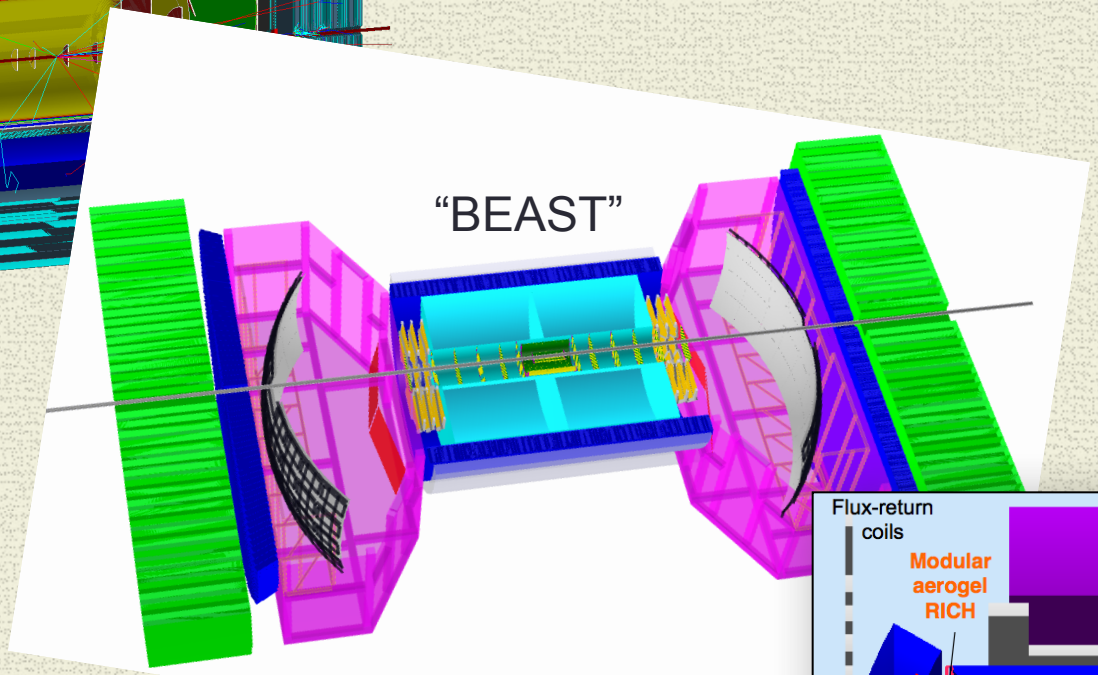


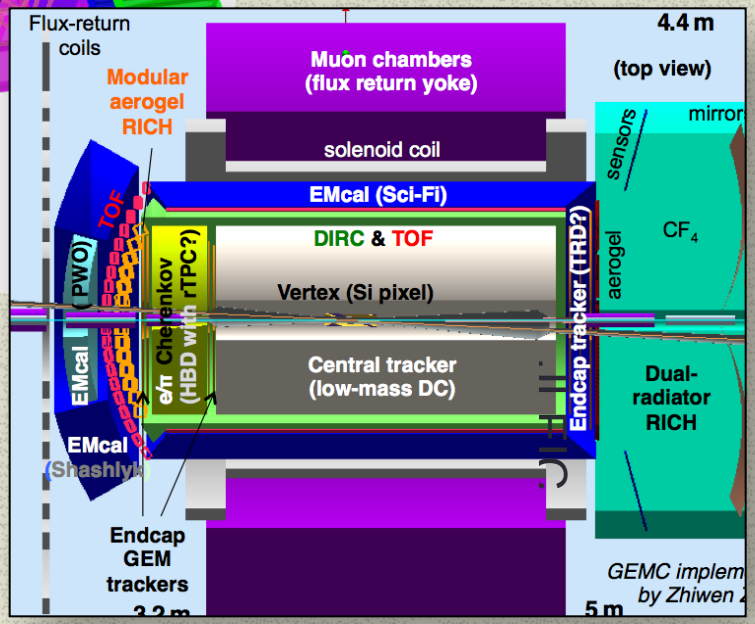


Curtesey of Thomas Ullrich

EIC Detector Concepts







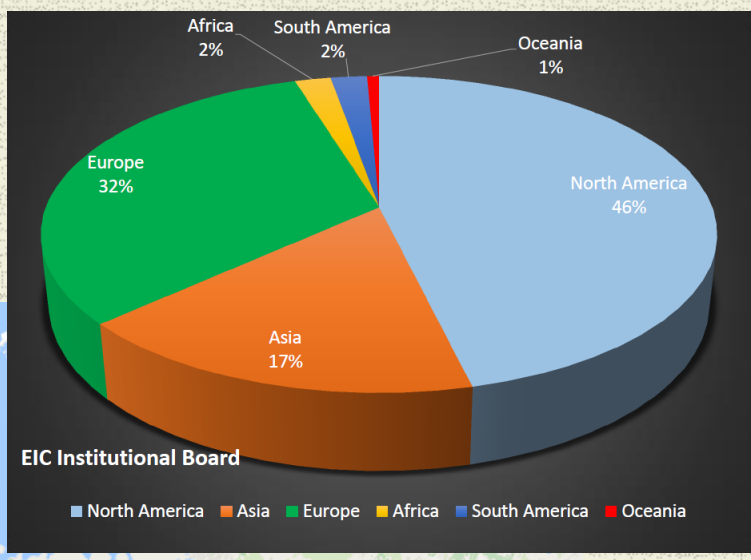
Other ideas from the Users Group are welcome! (essential!)

The EIC Users Group: EICUG.ORG

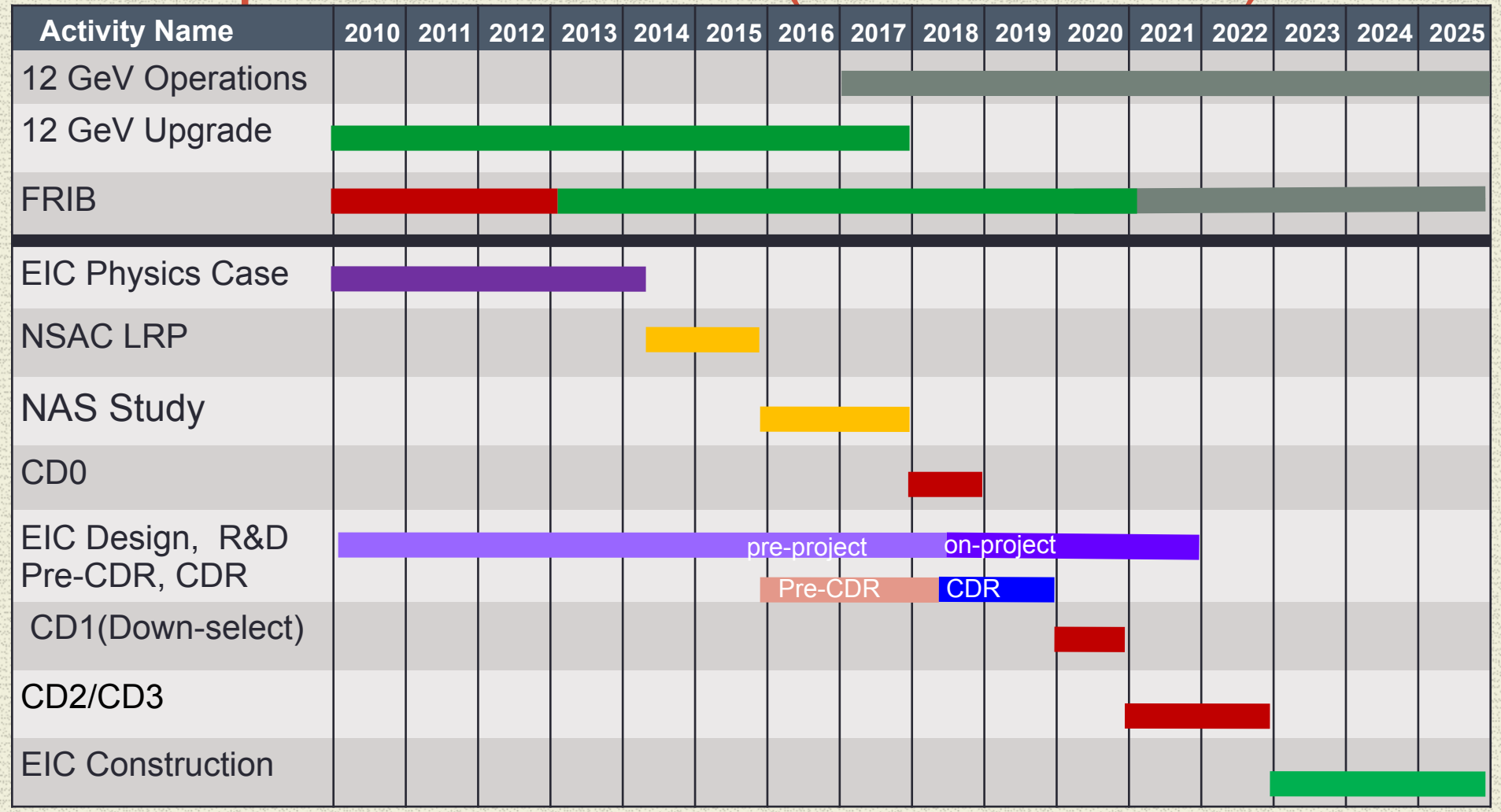
(no students included as of yet)

670 collaborators, 28 countries, 150 institutions... (December, 2016)

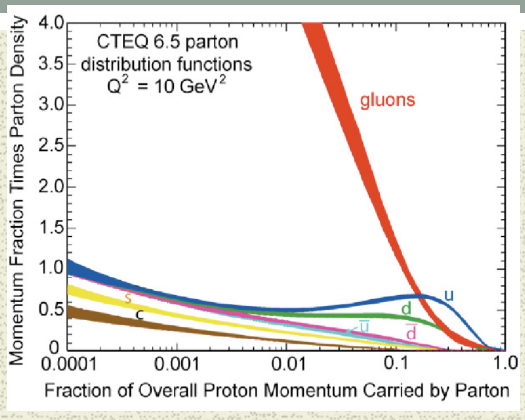
Map of institution's locations



JLEIC possible timeline (eRHIC similar)

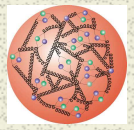


CD0 = DOE "Mission Need" statement; **CD1** = design choice and site selection
CD2/CD3 = establish project baseline cost and schedule
update: 1/13/17



Connections: JLab & EIC

QCD radiation Dominate | **Many-body Regime** | **Few-body Valence Regime**

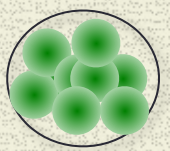
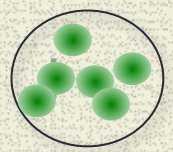
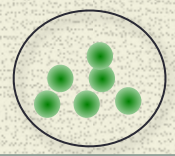


Shutter Speed:

10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 x (proton)

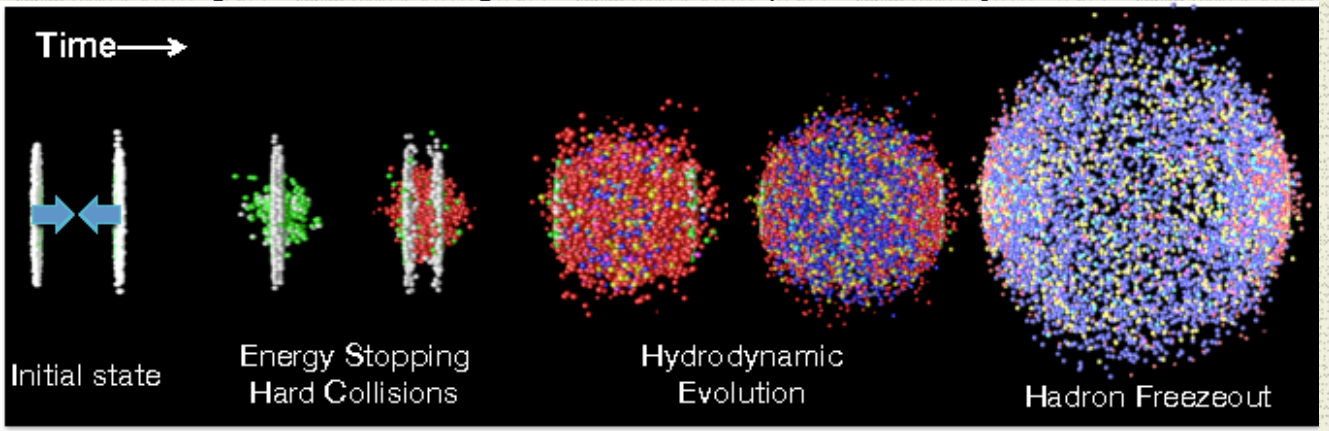
Energy

Shutter

10^{-4} x (Nuclei)

Jlab & EIC can



Science questions to be addressed by sPHENIX

- Hadronic matter under conditions of extreme temperature (net baryon density) transitions to a new state of matter: QGP. → Lattice QCD at zero net baryon density estimates the transition should occur at 170 MeV.
- QGP is expected to have dominated the first six microseconds of the early universe
- Collisions of heavy ions at RHIC have created temperatures of ~300 MeV, and recently LHC has indicated measuring temperatures ~420+ MeV
- While we do not doubt RHIC and LHC make the QGP in the heavy ion collisions, much remains ununderstood about this newly discovered state of matter

Science questions to be addressed by sPHENIX

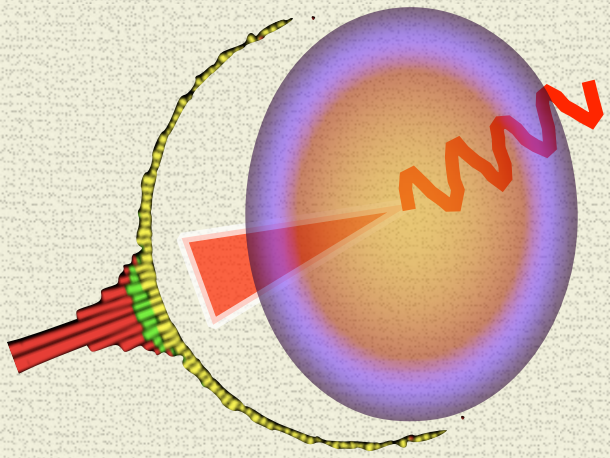
- How does a partonic shower develop and propagate in the quark-gluon plasma?
- How does one reconcile the observed strongly coupled quark-gluon plasma with the asymptotically free theory of quarks and gluons?
- What are the dynamical changes in the quark-gluon plasma in terms of quasiparticles and excitations as a function of temperature?
- How sharp is the transition of the quark-gluon plasma from the most strongly coupled regime near T_c to a weakly coupled system of partons known to emerge at asymptotically high temperatures?

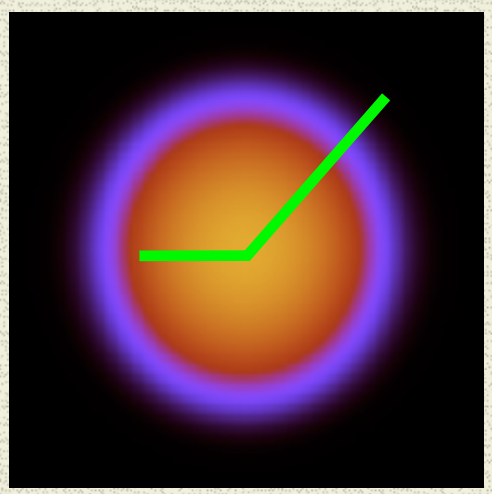
Jets, di-jets, heavy quarks and quarkonium states are Planned as future precision probes of QGP in the sPHENIX detector

Multi-scale probes of QGP

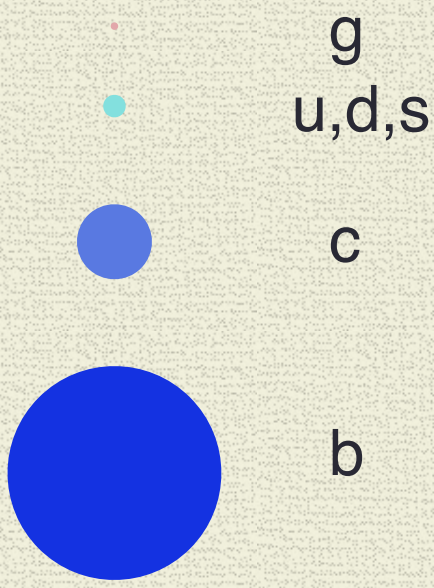
Three key approaches to study
QGP structure at multiple scales

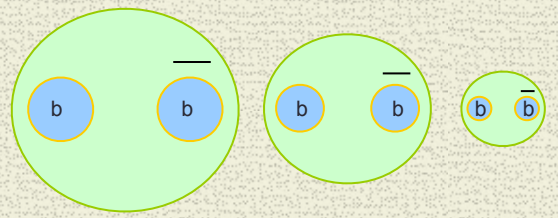
Jets and jet structure





Parton mass/flavor



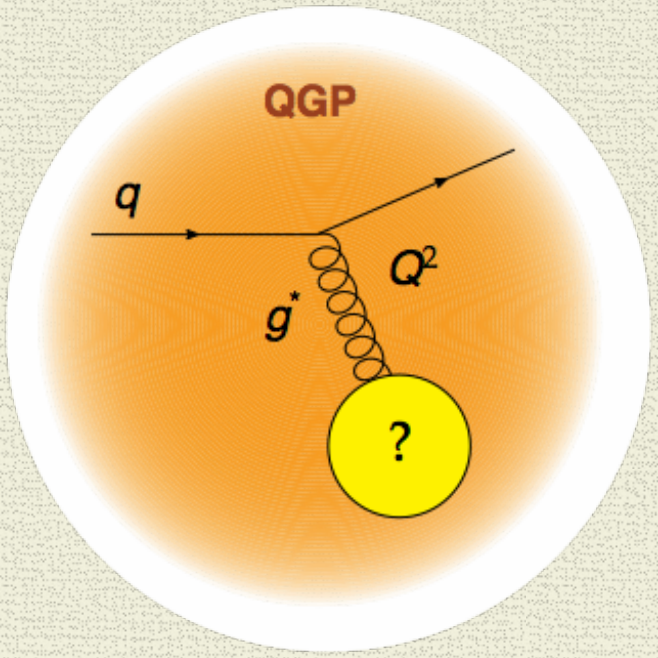


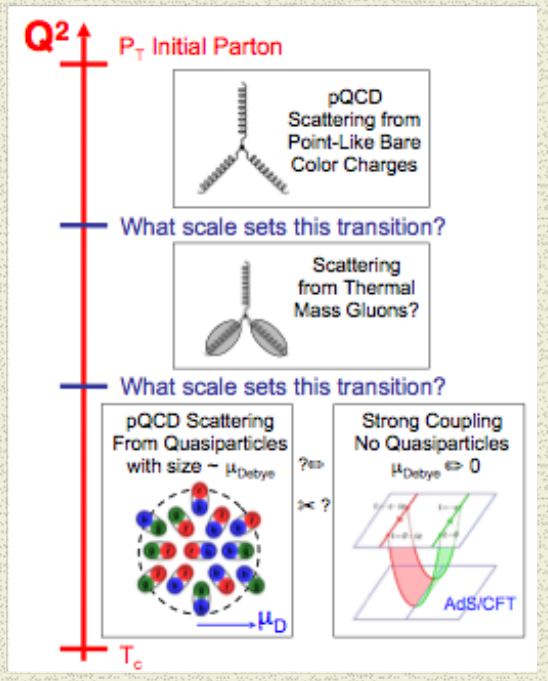
Y(3s) *Y(2s)* *Y(1s)*

Upsilon spectroscopy

Probing the QGP:

What controls do we have?



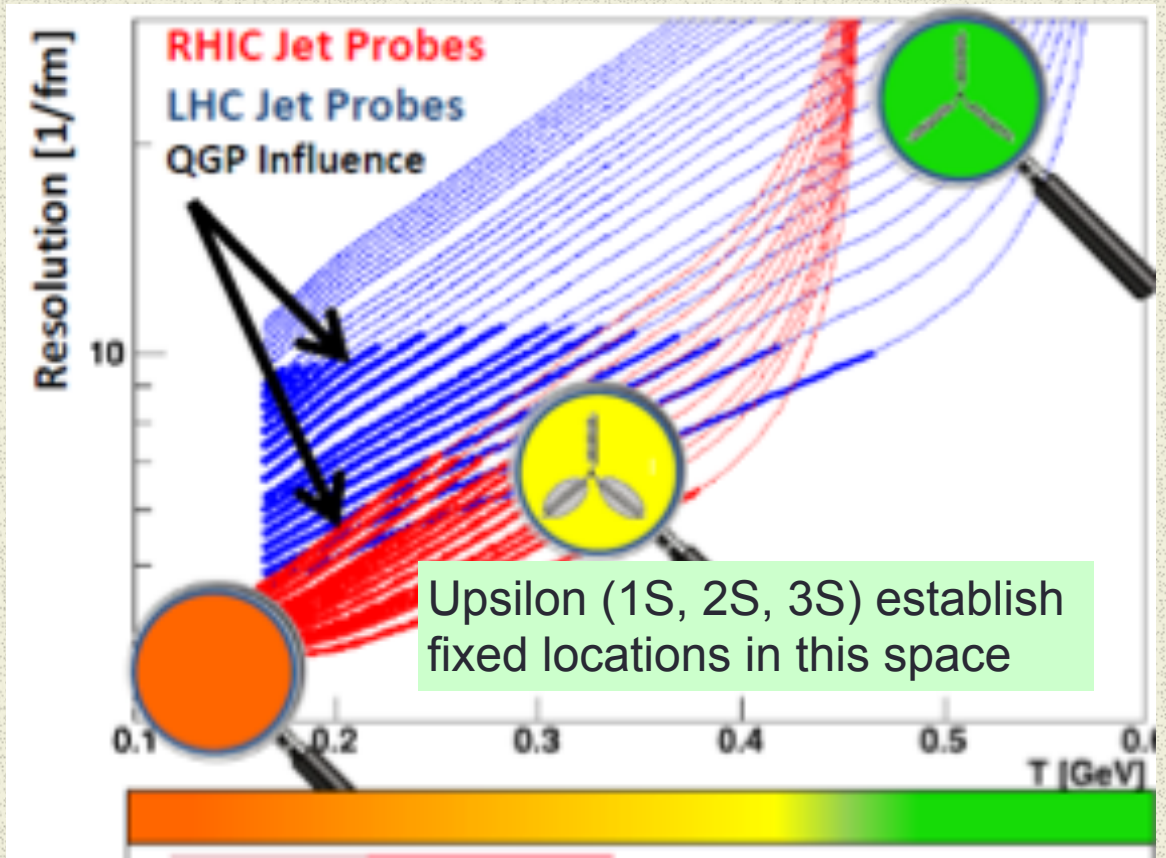


Probing the QGP:

What controls do we have?

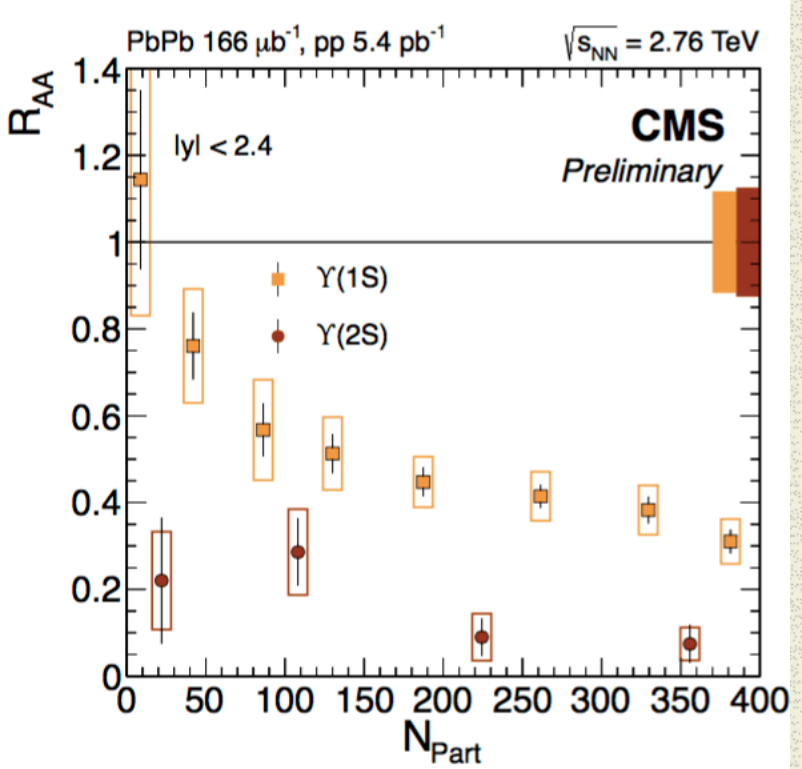
RHIC & LHC: Evolving probe in an evolving medium

M. Habich, et al., EPJC, 75:15 (2015)



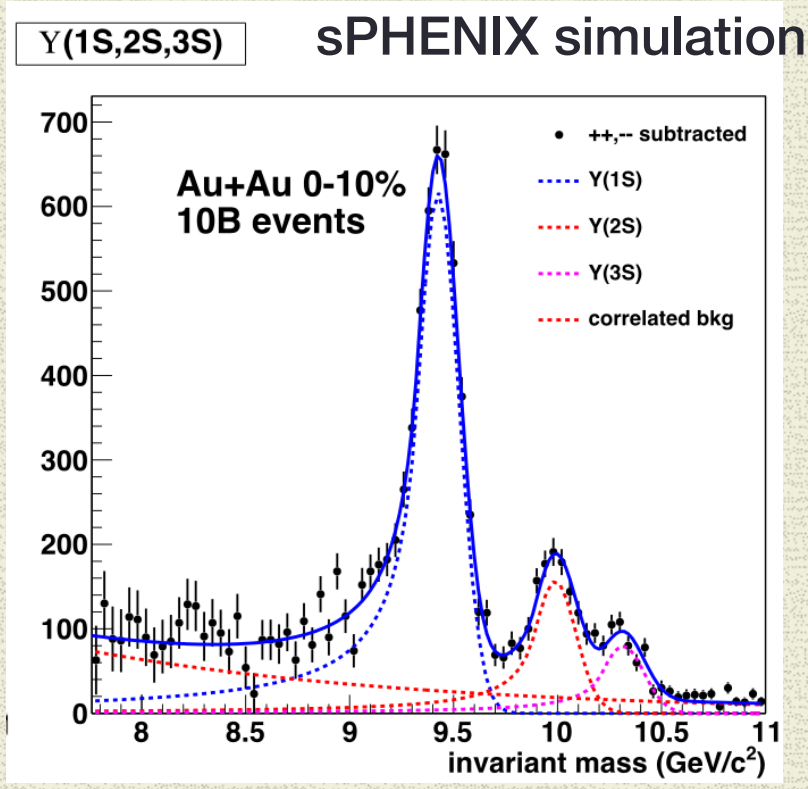
Initial hard scattering virtual parton virtuality (1/fm) vs. local temperature of the QGP

Physics drives detector requirements: Y(ns)



Rapid disappearance of Y(2s), Y(3s) in peripheral events is puzzling

➜Statistics, statistics, statistics…



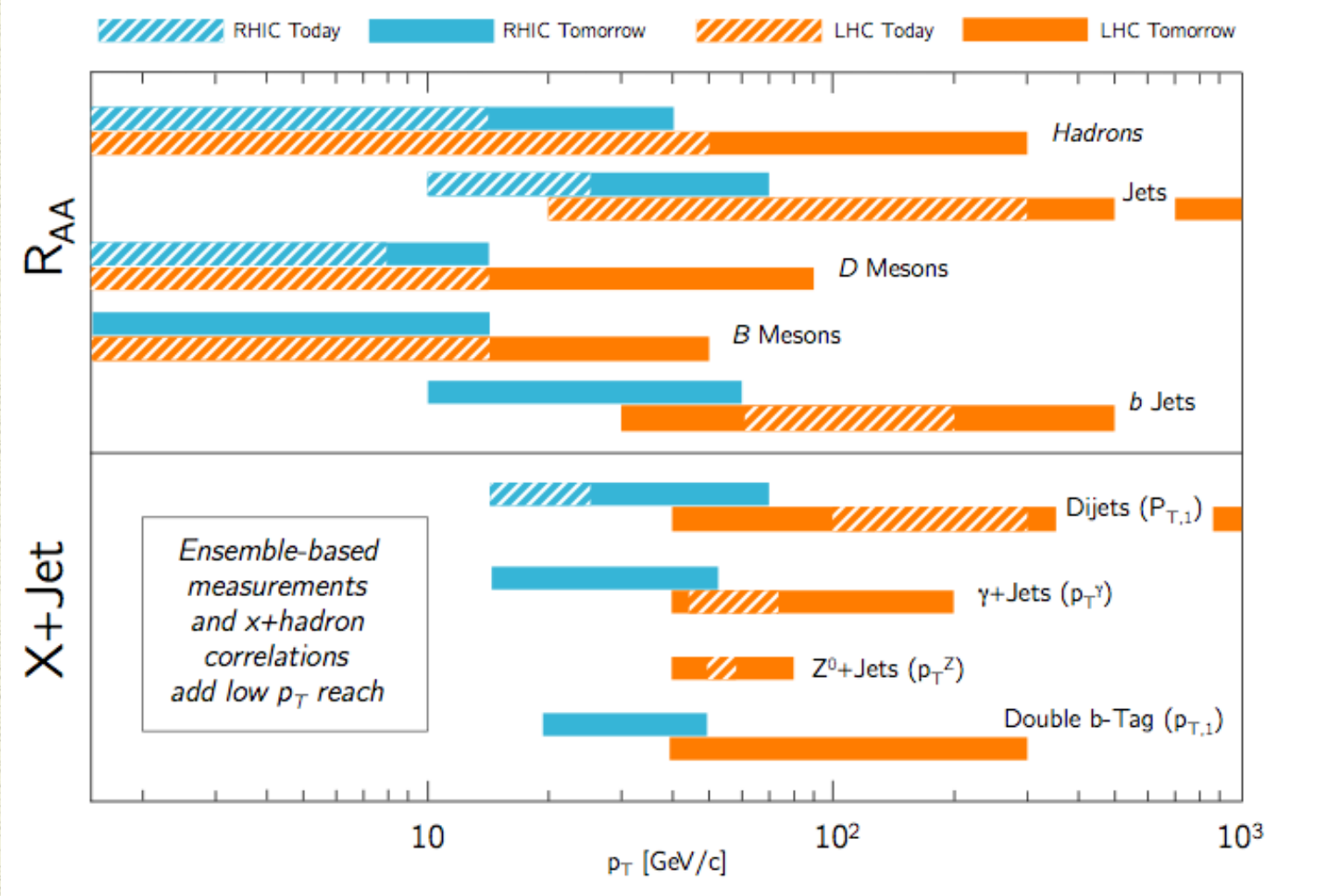
Count every Y delivered

➜ high rate, large acceptance

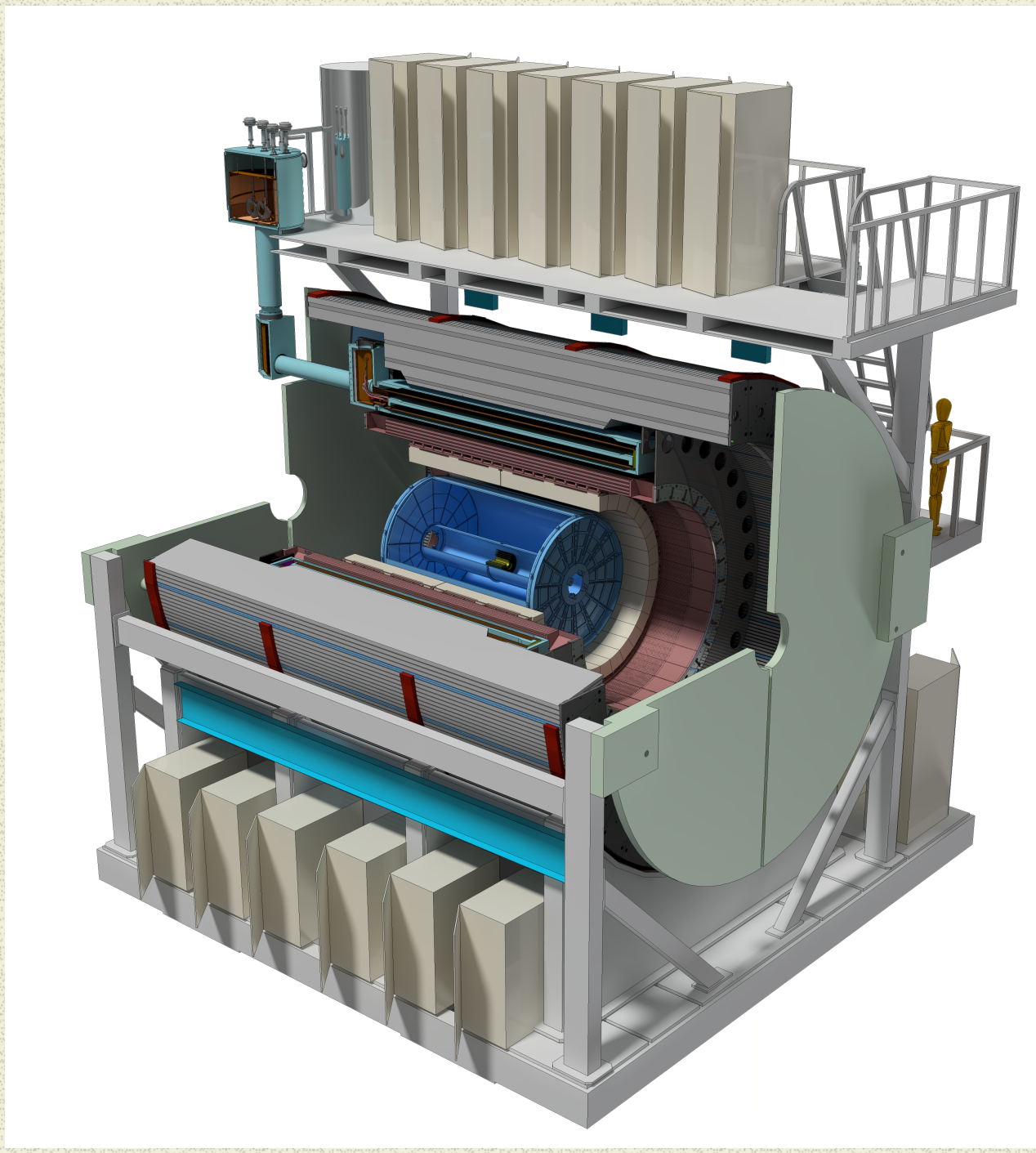
Make every Y count

➜ excellent momentum resolution

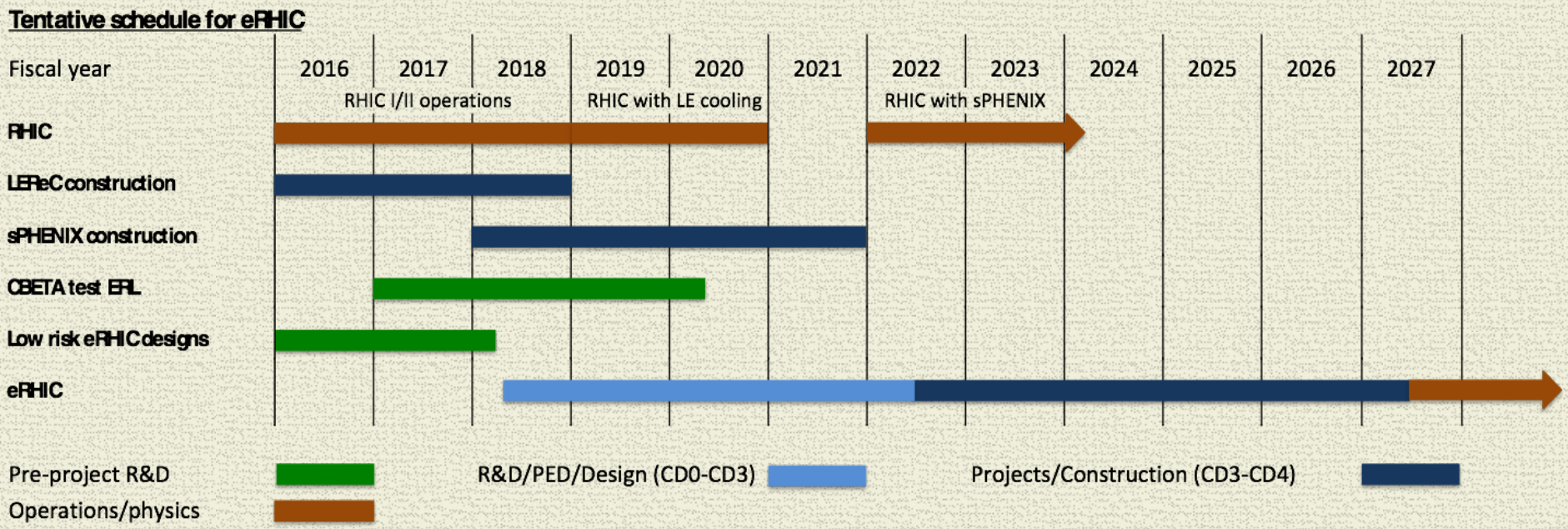
Physics drives detector requirements: RHIC ⊕ LHC



- Currently 62 institutions, 235 scientists, engineers, postdocs and students
- Became official project (CD-0 granted by DOE) September 2016
- Anticipating a DOE CD-1 review early summer 2017
- Construction completes spring 2021
- First data taking run 2022



Tentative schedule for RHIC and eRHIC



RHIC Operations:

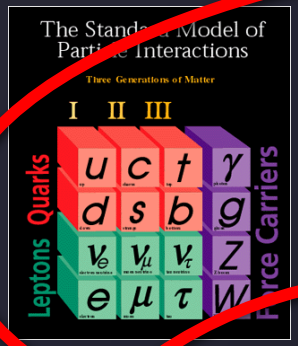
- 2017/18: two more RHIC Runs 17 and 18 with eLens and 56 MHz
- Low Energy RHIC electron Cooling (installation in 2018) for RHIC Runs 19 and 20 (Beam Energy Scan II)
- sPHENIX construction (final installation during 2021) for two RHIC Runs 22 and 23

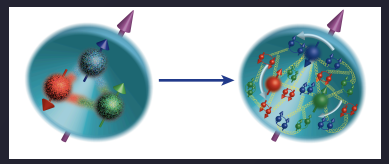
RHIC → EIC/eRHIC

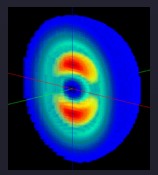
- Low risk design (pCDR) complete by 2018
- High priority eRHIC R&D items complete by 2019
- eRHIC: mission need (CD-0 in 2018?), alternative selection (CD-1 in 2019?), project baseline (CD-2 in 2020?), construction start (CD-3 in 2022?), installation (2024 – 2026?) and start of operation (CD-4 in 2027?)

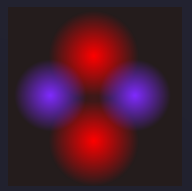
21st Century Nuclear Science:

Probing nuclear matter in all Its forms & exploring their potential for applications

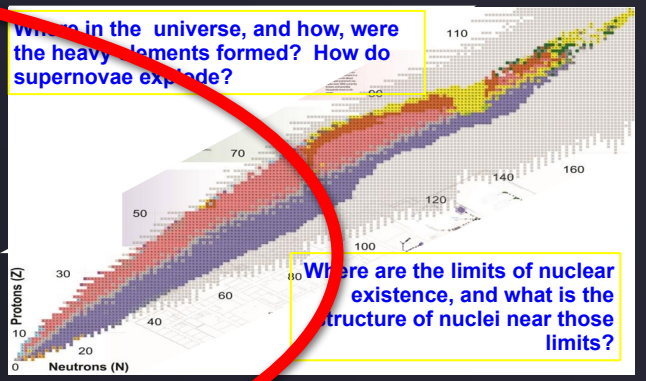


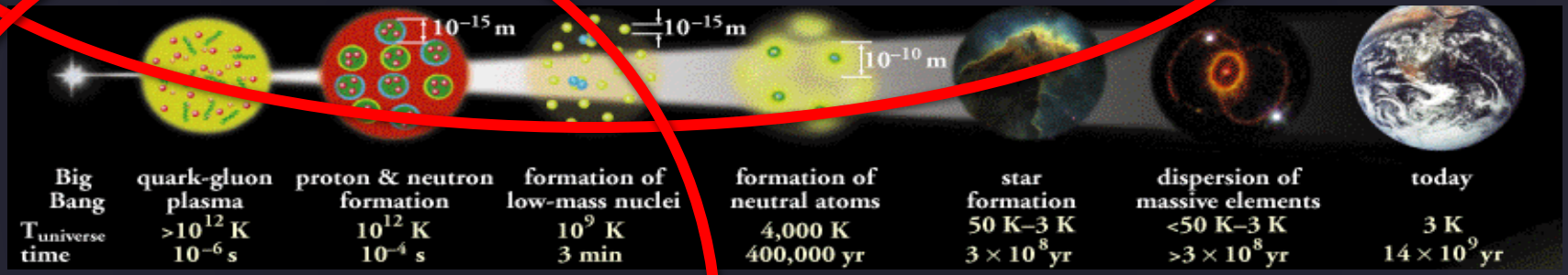




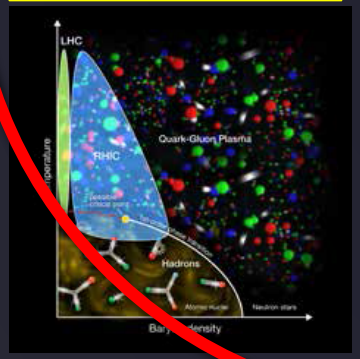


How are the properties of protons and neutrons, and the force between them, built up from quarks, antiquarks and gluons? What is the mechanism by which these fundamental particles materialize as hadrons?

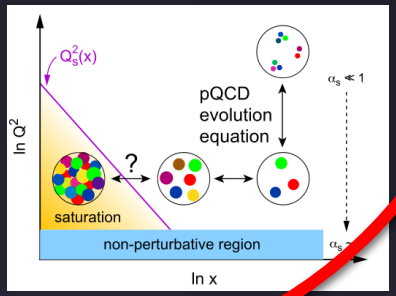




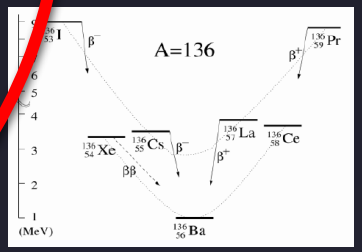
What is the nature of the different phases of nuclear matter through which the universe has evolved?



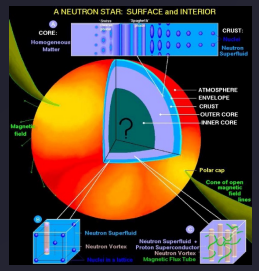
Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?



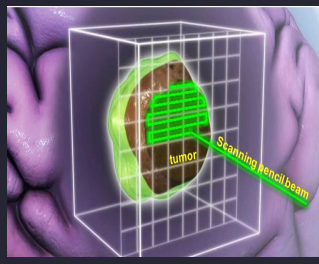
How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?



How are the nuclear building blocks manifested in the internal structure of compact stellar objects, like neutron stars?



How can technologies developed for basic nuclear physics research be adapted to address society's needs?



Summary

- The physics of sPHENIX, JLab12 & the EIC is at the heart of understanding the visible matter in terms of the theory of Strong Interactions.

- The NSAC Long Range Plan (LRP) 2015 put them all on very high pedestal.
  - JLab12 construction is about to be completed, transitioning to operations and upgrades (MOLLER, SoLID and such)…
  - sPHENIX received a CD0 and expects to start construction in 2019 and opereational after 2022 for about three years
  - EIC designs are being developed (accelerator and detector concepts) CD0 expected in 2018/19, CD4 some time 2025+