The present and future science program at Jefferson Lab

LIGHT CONE 2019

Ecole Polytechnique, Palaiseau, France
16-20 SEPTEMBER 2019

QCD on the light-cone:

From hadrons to heavy ions

- CEBAF 12 GeV upgrade
- Science & Capabilities
- Recent highlights
- Light-cone physics
- Future projects
- JLab12 to EIC
- Summary

Jianwei Qiu

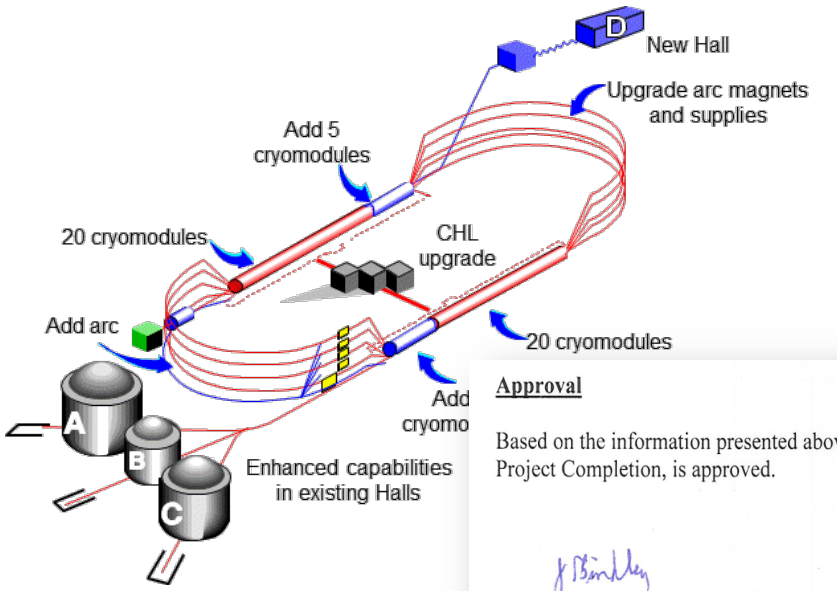
Theory Center

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

CEBAF 12 GeV Upgrade



Approval

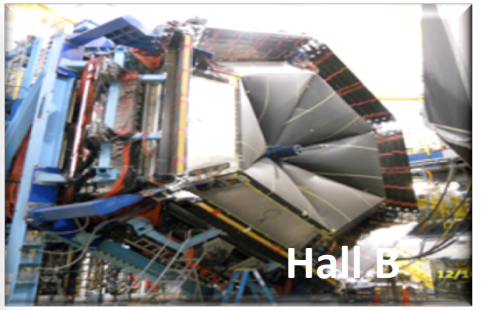
Based on the information presented above and at this review, Critical Decision 4, Approve Project Completion, is approved.

J Binkley — 9/27/17

Dr. J. Stephen Binkley
Deputy Director for Science Programs
Office of Science

Date

12 GeV CEBAF Upgrade CD-4B (CD-4) ESAAB Approval — Page 8



Project Completion Approved on September 27, 2017

All four Halls are in physics operations

JLab 12 GeV science era is here!

A critical step toward EIC!

A Lepton-Hadron Facility has the highest luminosity

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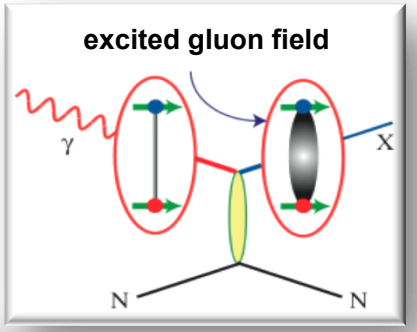
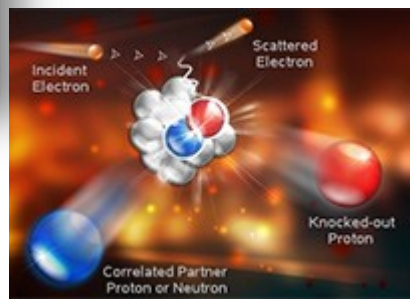
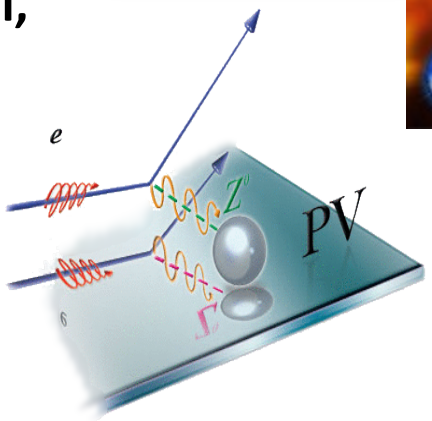
JLab12 Scientific Questions

- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?
- Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?
- What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?
- Can we discover evidence for physics beyond the standard model of particle physics?







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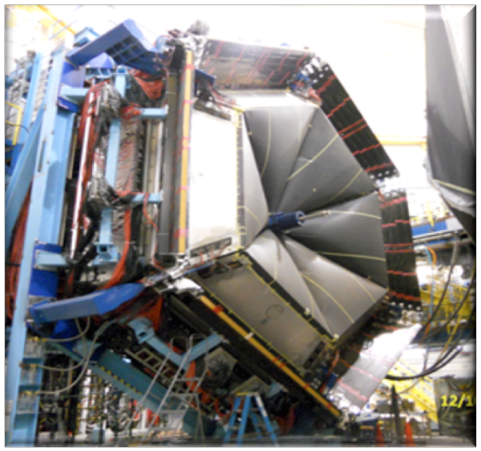
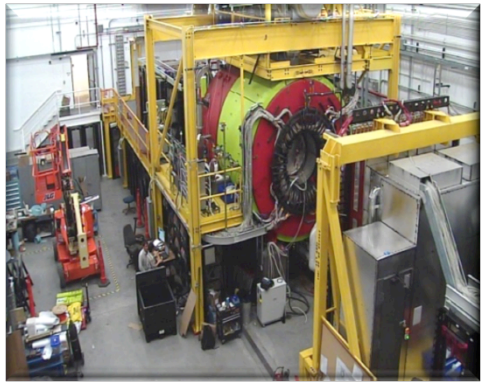
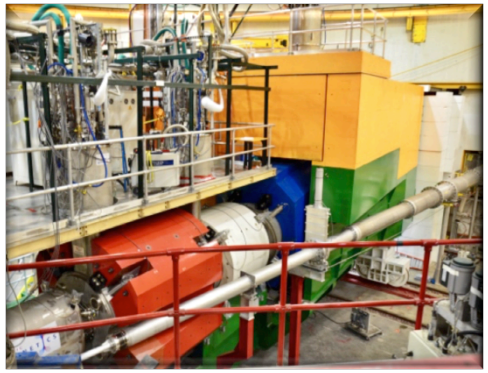
JLab12 Scientific Capabilities



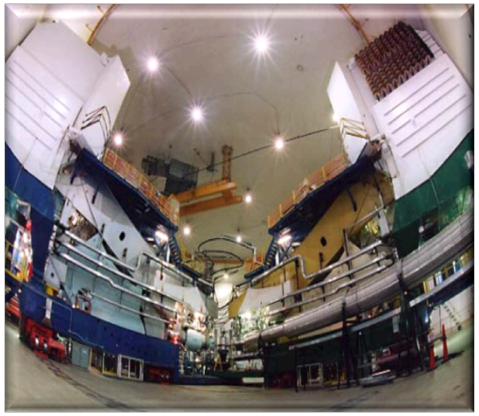
Hall D – exploring origin of confinement by studying exotic mesons



Hall B – understanding nucleon structure via generalized parton distributions (GPDs) and transverse momentum dependent distributions (TMDs)



Hall C – precision determination of valence quark properties in nucleons and nuclei



Hall A – short range correlations, form factors (SBS), hyper-nuclear physics, future new experiments (e.g., SoLID and MOLLER)

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Hall Status Snapshots – early results published in Nature

nature
International weekly journal of science

- *Precision measurement of the weak charge of the proton*, Qweak collaboration, *Nature* **557**, 207–211 (2018)
- *The pressure distribution inside the proton,* Burkert, Elouadrhiri, Girod, *Nature* **557**, 396-399 (2018)
- *Ultrafast Nucleons in Asymmetric Nuclei,* The CLAS Collaboration, *Nature* **560**, 617-621 (2018).
- *Modified structure of protons and neutrons in correlated pairs,* The CLAS Collaboration, *Nature* **566**, 354–358 (2019).

Also:

- *A glimpse of gluons through deeply virtual compton scattering on the proton*, Defurne et. al., *Nature Communications* **8**, 1408 (2017).
- *Novel electron scattering experiment finds a smaller proton radius*, PRad Collaboration, submitted to Nature (2019).

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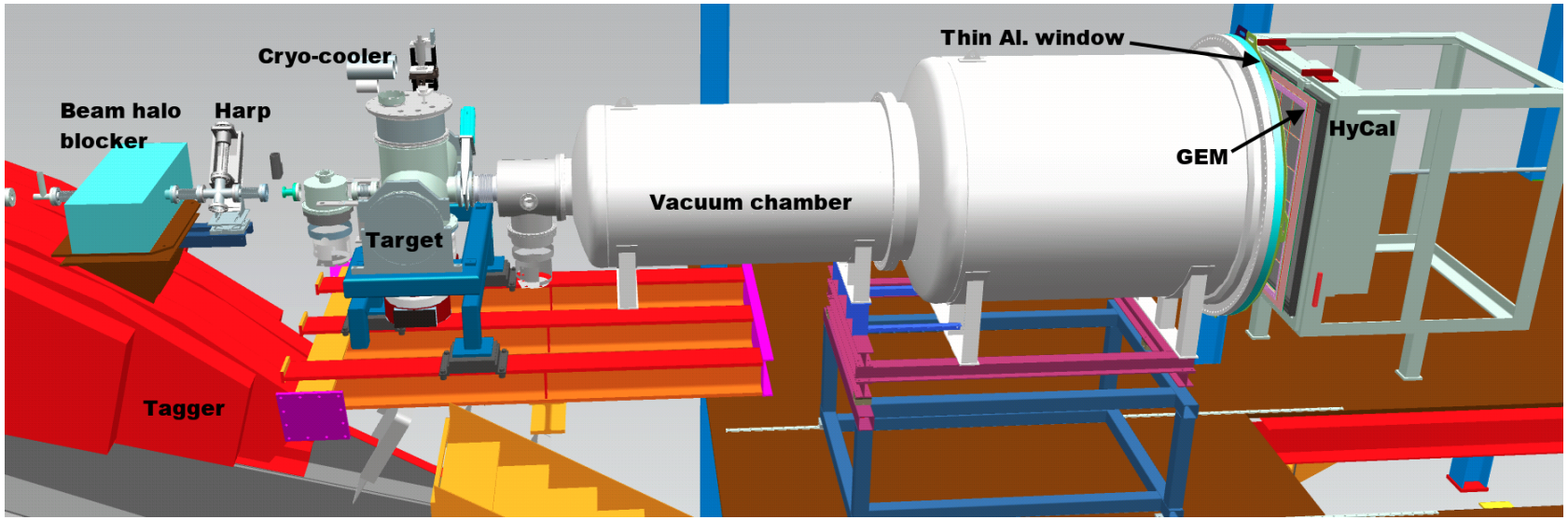
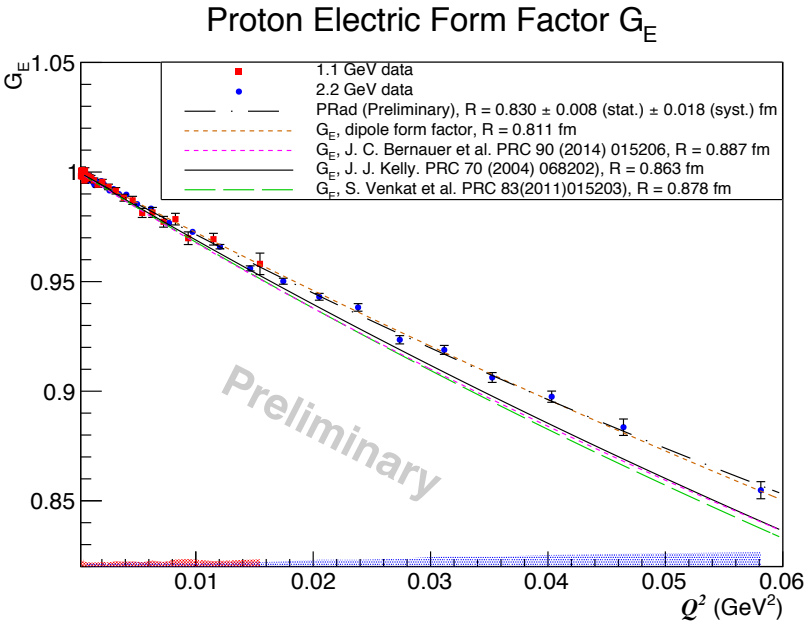
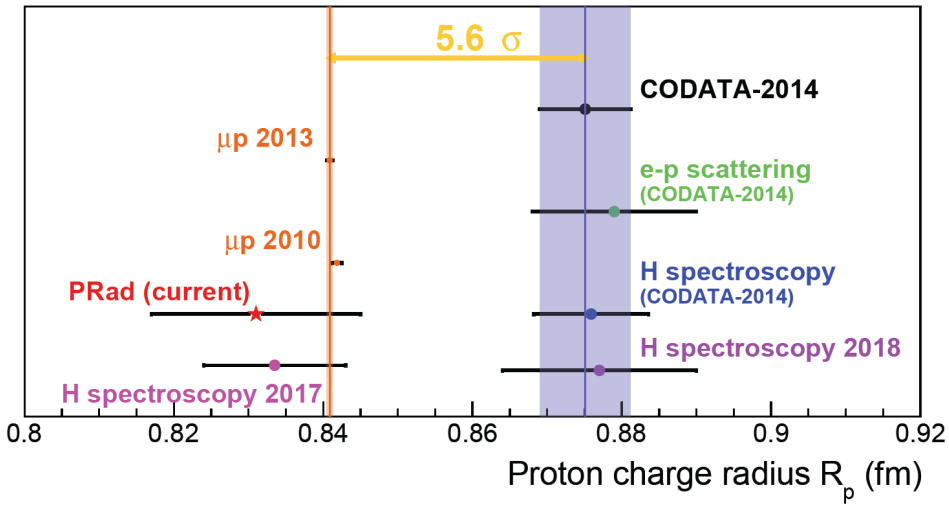
Hall B: PRAD – solving the proton charge radius puzzle







PRad R_p (current) = 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm

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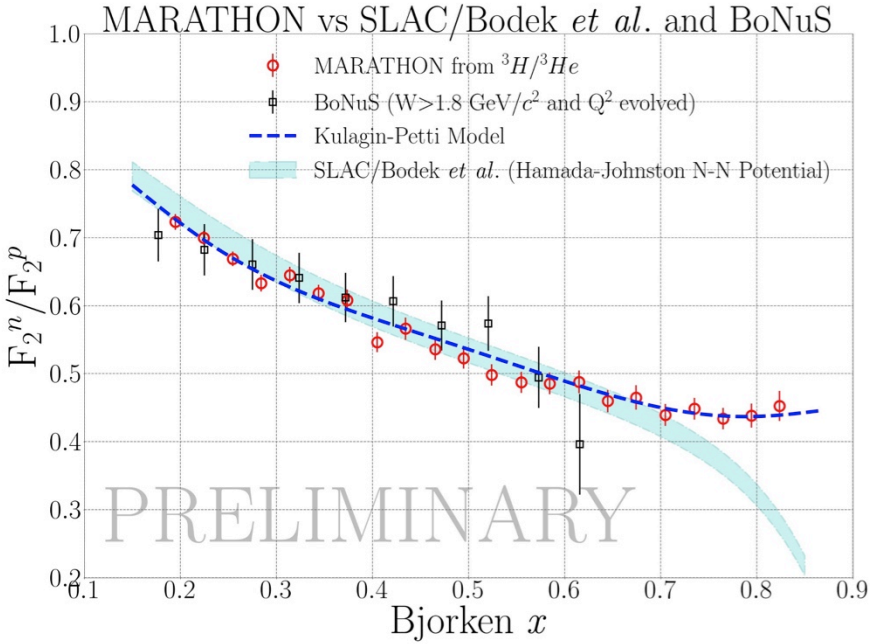
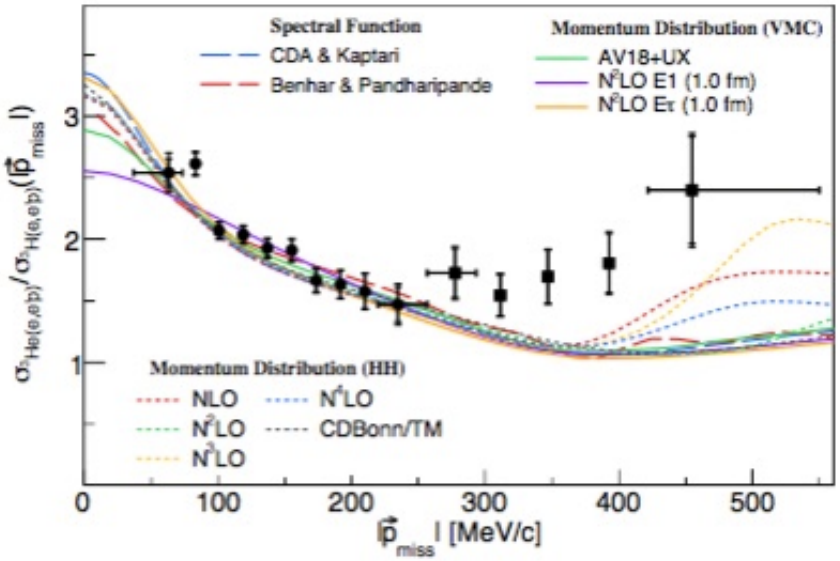
Hall A: Tritium (and Argon) – running completed

First tritium target used for electron scattering in three decades!

MARATHON preliminary results





JLAB-PHY-18-2656
SLAC-PUB-17200

First Measurement of the Ti(e,e')X Cross Section at Jefferson Lab

. Dai,[1] M. Murphy,[1] V. Pandey,[1,*] D. Abrams,[2] D. Nguyen,[2] B. Aljawrneh,[3] S. Alsalmi,[4] A. M. Ankowski,[1,5,†] J. Bane,[6] S. Barcus,[7] O. Benhar,[8] V. Bellini,[9] J. Bericic,[10] D. Biswas,[11] A. Camsonne,[10] J. Castellanos,[12] P. Chen,[10] M. E. Christy,[11] K. Craycraft,[6] R. Cruz-Torres,[13] D. Day,[2] S.-C. Dusa,[10] E. Fuchey,[14] T. Gautam,[11] . Giusti,[15] J. Gomez,[10] C. Gu,[2] T. Hague,[4] J.-O. Hansen,[10] F. Hauenstein,[16] D. W. Higinbotham,[10] C. Hyde,[16] C. M. Jen,[1] C. Keppel,[10] S. Li,[17] R. Lindgren,[18] H. Liu,[19] C. Mariani,[1] R. E. McClellan,[10] D. Meekins,[10] R. Michaels,[10] M. Mihovilovic,[20] M. Nycz,[4] L. Ou,[13] B. Pandey,[11] K. Park,[10] G. Perera,[18] A.J.R. Puckett,[14] S. Širca,[21,20] T. Su,[4] L. Tang,[11] Y. Tian,[22] N. Ton,[18] B. Wojtsekhowski,[10] S. Wood,[10] Z. Ye,[23] and J. Zhang[18]
(The Jefferson Lab Hall A Collaboration)

Short Range Correlation (e.e'p) publication *submitted*, arXiv:1902.06358v1

Phys. Rev. C 98 (2018) no.1, 014617
Phys.Rev. C 99 (2019) no.5, 054608
3rd publication submitted (arXiv:1908.01802)

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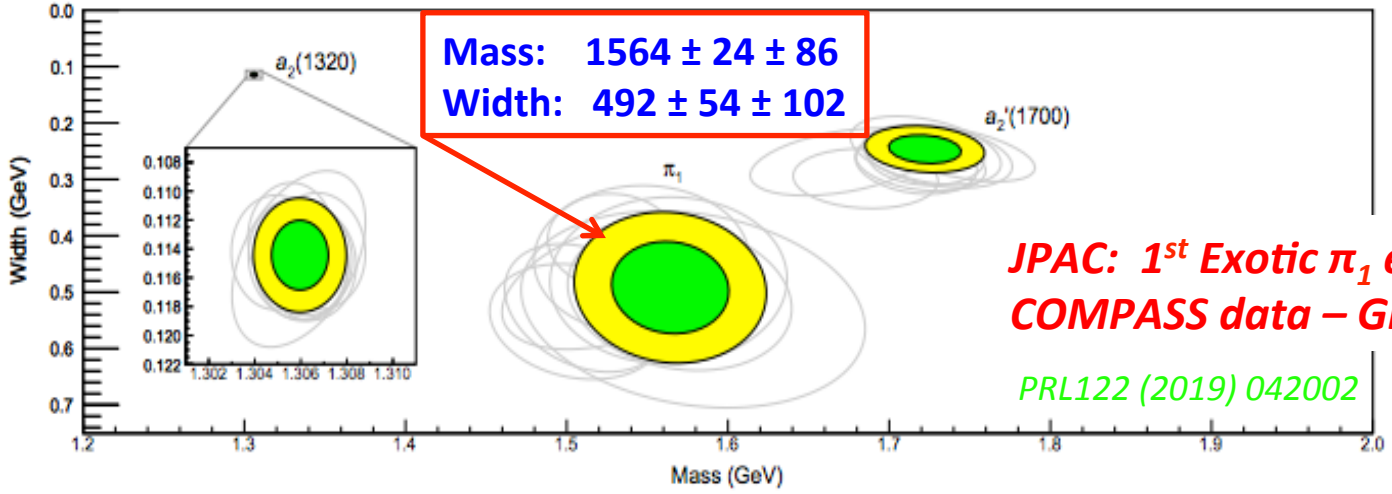
Hall D:

- **Hybrid meson – phase-one data taken:**

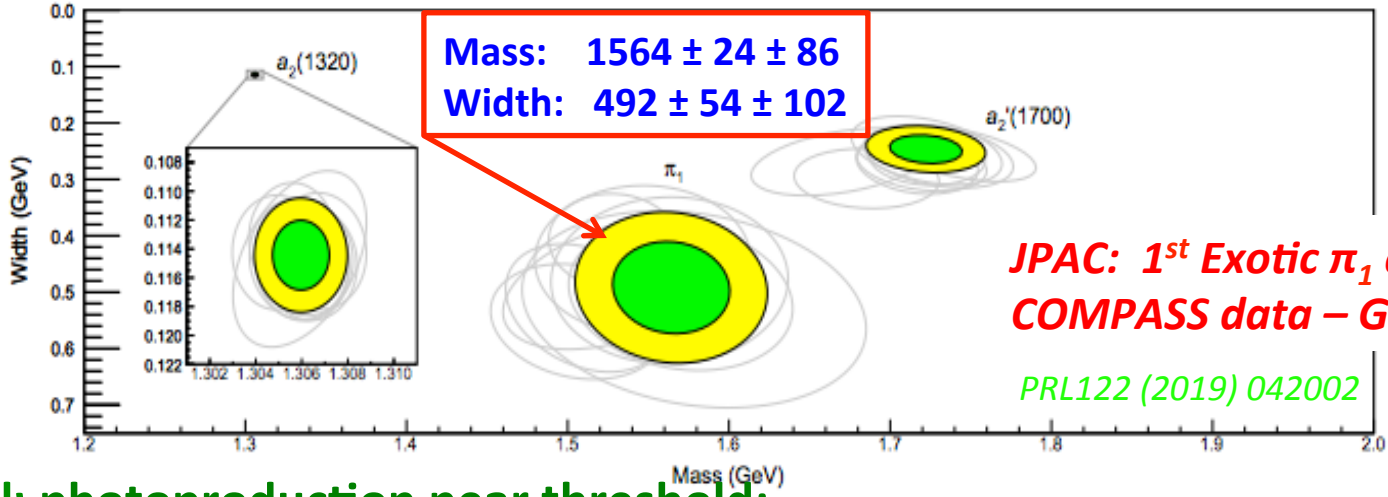


JPAC: 1st Exotic π_1 extracted from COMPASS data – GlueX data next!

PRL122 (2019) 042002

Hall D:

❑ Hybrid meson – phase-one data taken:



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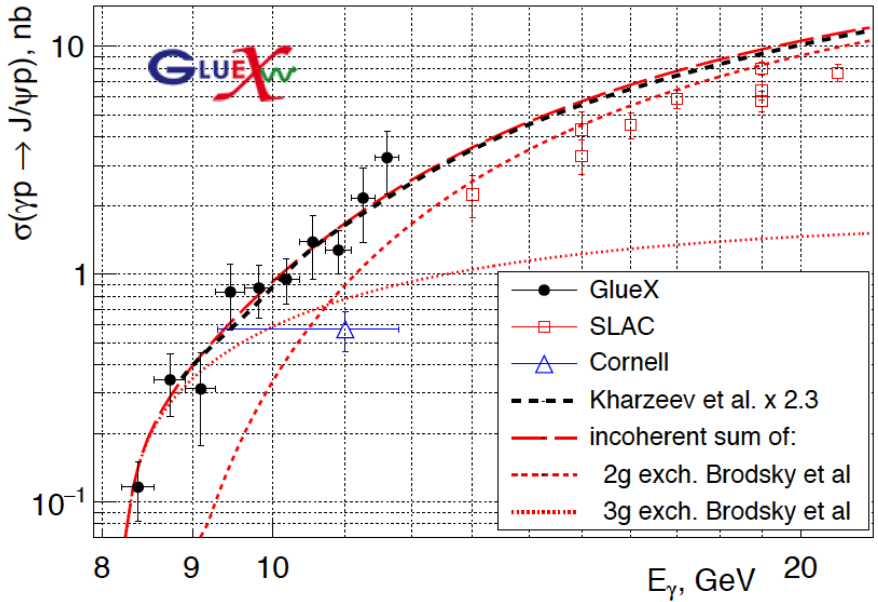
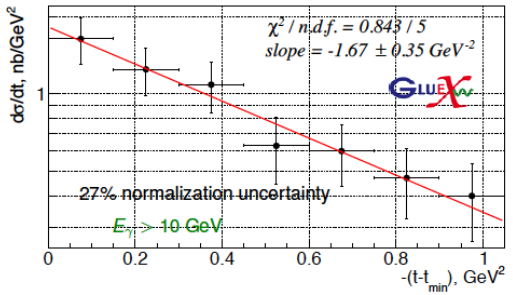
PRL122 (2019) 042002

❑ J/ψ photoproduction near threshold:





1-st measurement close to threshold

Cross section larger than expected from earlier results

PRL123 (2019) 072001; Editor's Suggestion

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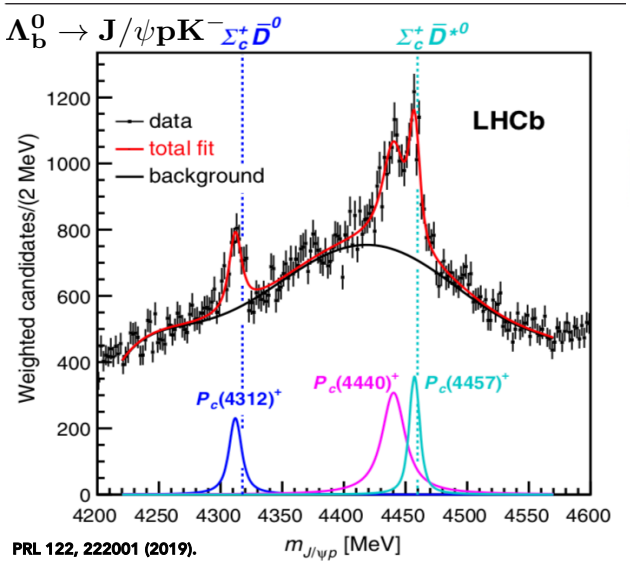
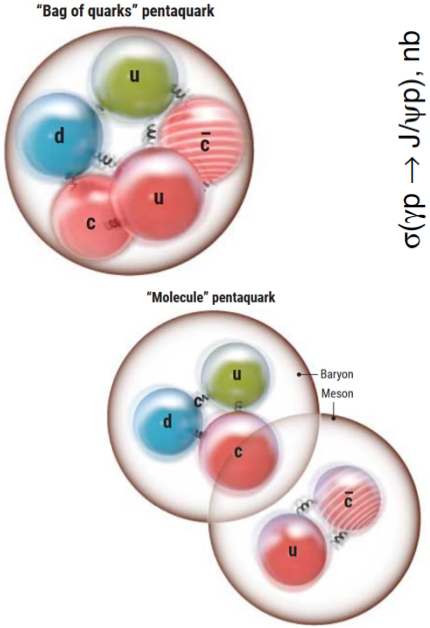
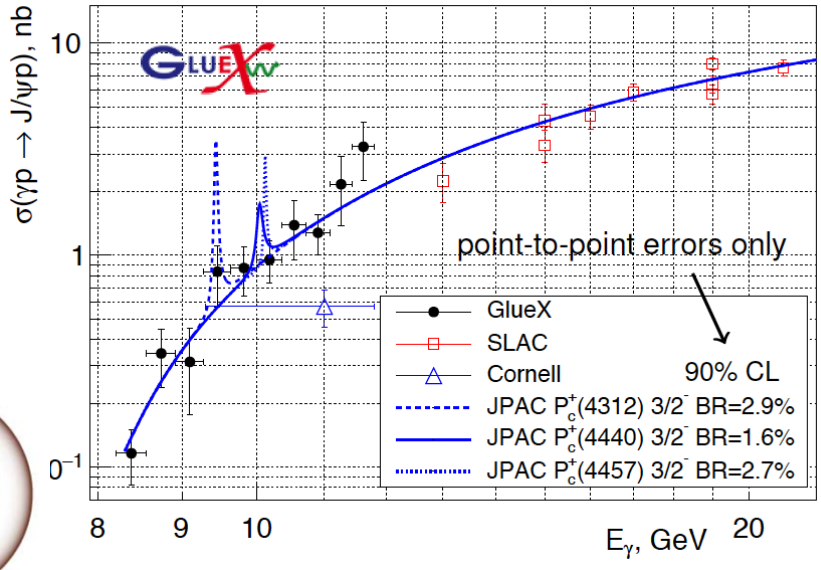
Hall C: J/ψ & LHC-b Charmonium Pentaquark







Explanations:

- Not a pentaquark but a molecule
- BR smaller than expected
  - Di-quarks?
  - Photo-production suppressed (Wang 1906.04044)

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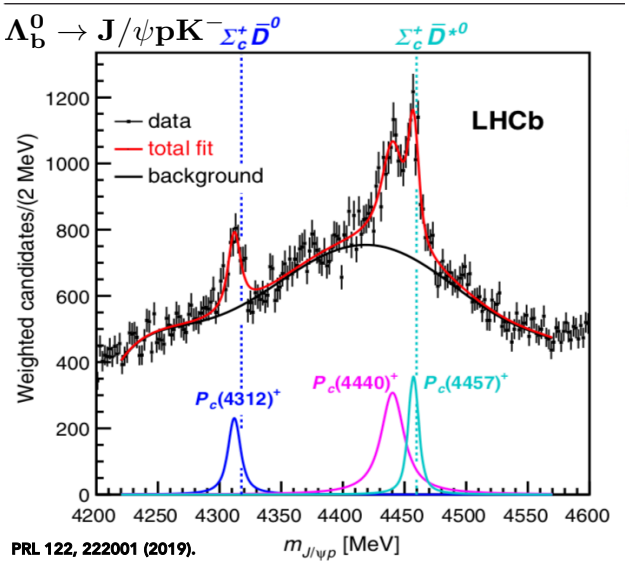
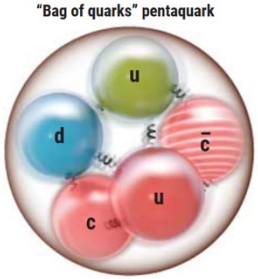
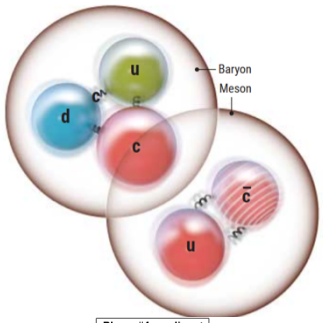
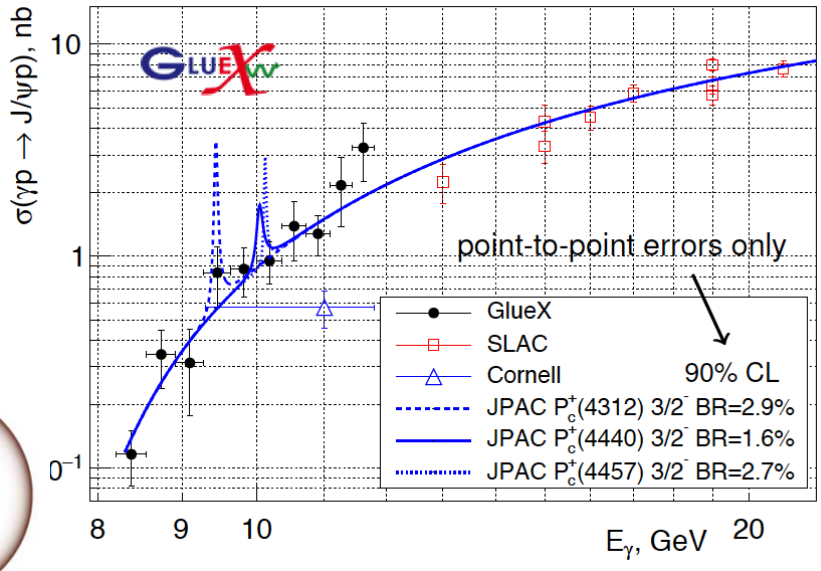
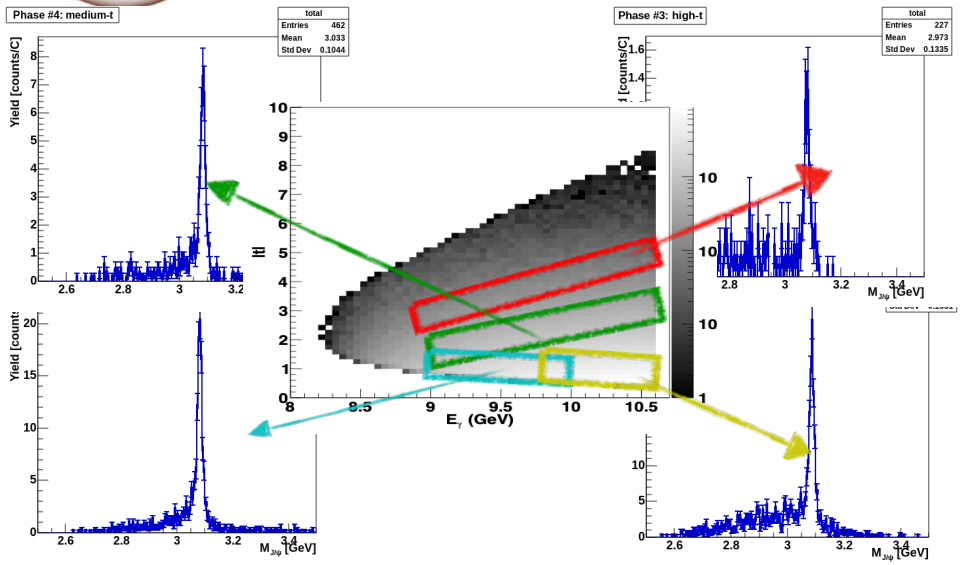
Hall C: J/ψ & LHC-b Charmonium Pentaquark











Explanations:

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→ Hall C J/Y photo-production experiment completed in 2019

- Largest data set of photoproduced J/ψ's (~2100)
- Absolute cross section ~5% precision; results soon

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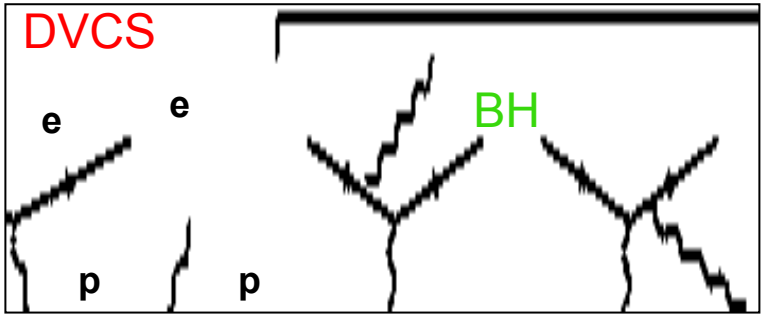
Hall A/B: towards the 3D structure of the proton

Simplest process: **e + p → e' + p + γ (DVCS)**

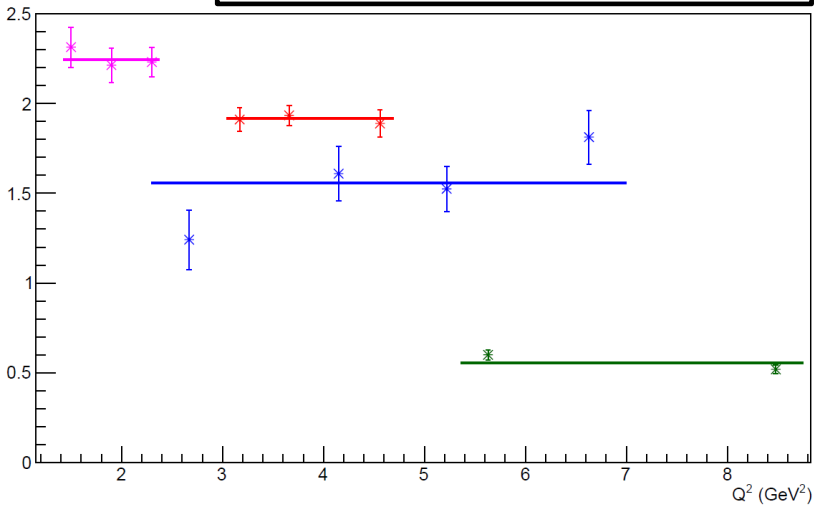


- **Polarized beam, unpolarized target:** $H(\xi,t)$
- **Unpolarized beam, long. polarized target:** $\tilde{H}(\xi,t)$
- **Unpolarized beam, transv. polarized target:** $E(\xi,t)$

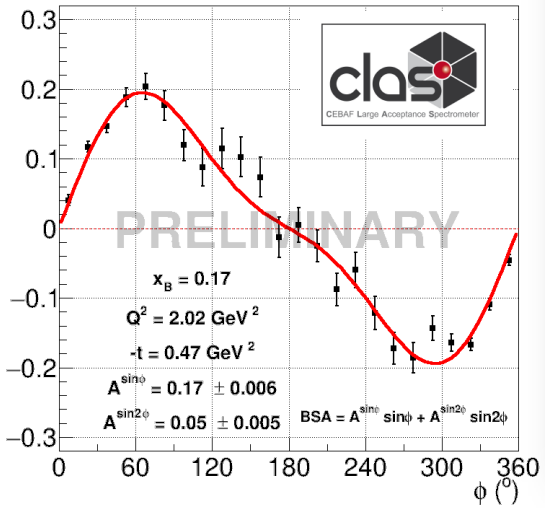
Hall A preliminary 12-GeV data for Compton form factor (over *limited* Q^2 range) agree with hard-scattering formalism

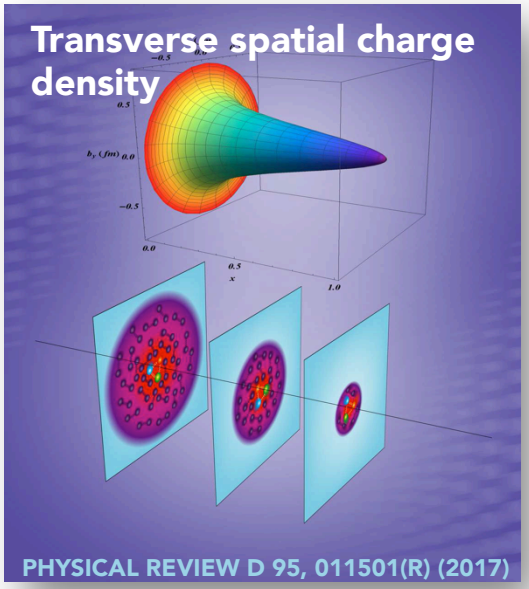
Hall B beam-spin asymmetry (BSA) and cross section data started for imaging studies in x, Q^2 and t

Amplitude of hel-dep x-section



DVCS raw BSA





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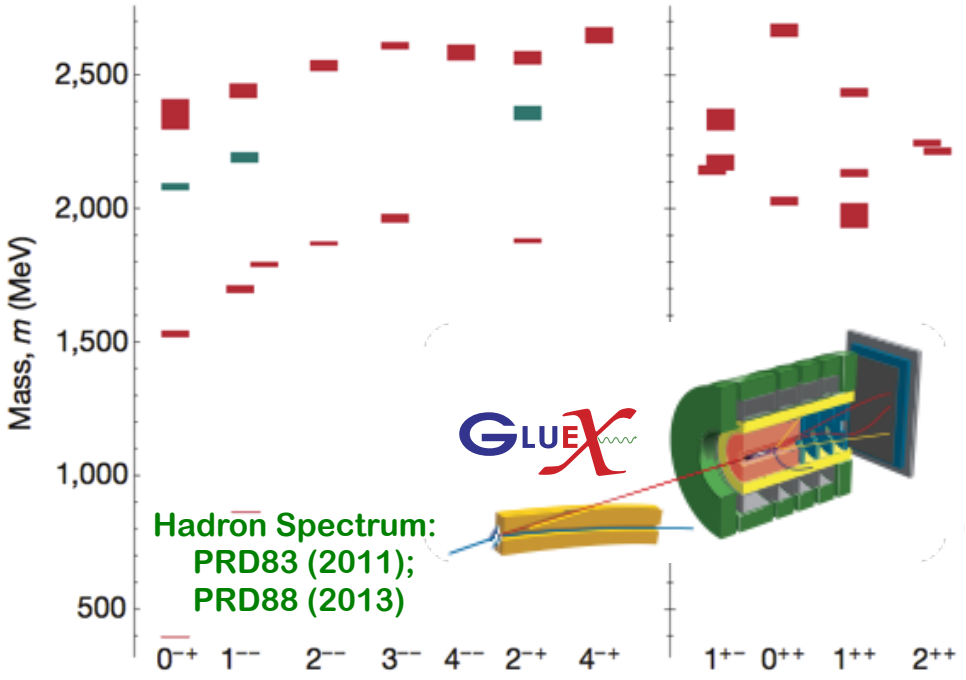
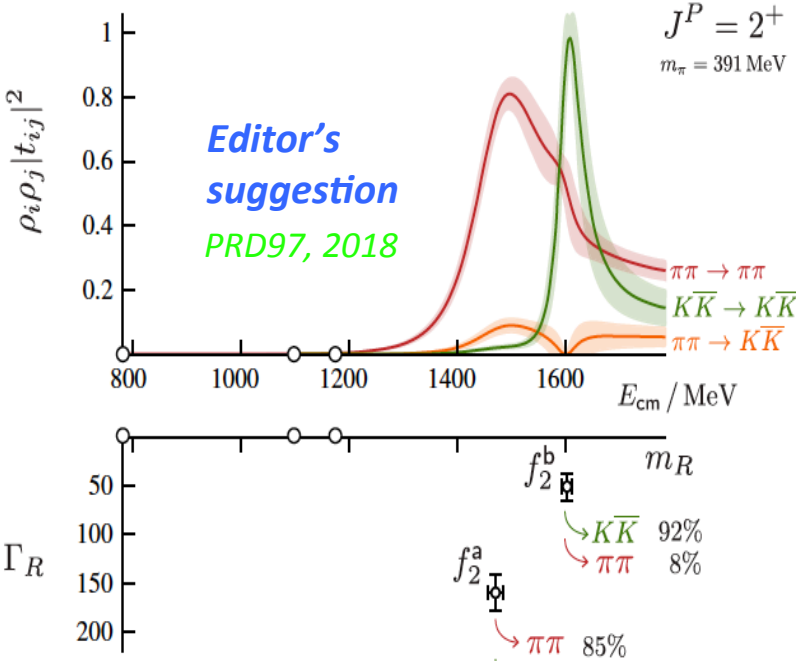
LQCD – beyond the mass spectrum

- ✧ GlueX looking for exotic hybrid mesons in photoproduction
- ✧ Might appear as enhancement in πππ ~ πρ, πσ, πf0(980)…

Light quark meson + "exotics" & "hybrids" spectrum





Motivation in GlueX PID upgrade proposal

GlueX actively calibrating in this channel

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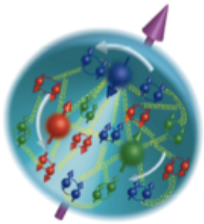
LQCD/PQCD – hadron/nuclear structure

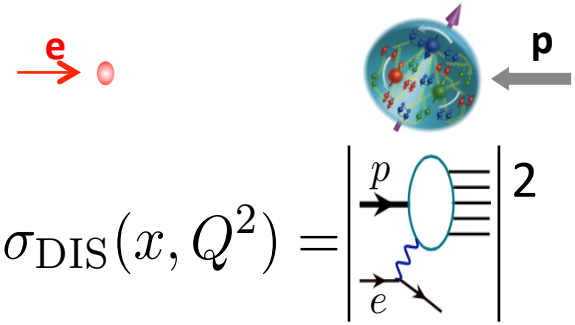
- **No "still picture" for hadron's partonic structure:**



Quarks and gluons are moving relativistically, color is fully entangled!

Partonic structure = "Quantum Probabilities": $\langle P,S|\mathcal{O}(\overline{\psi},\psi,A^{\mu})|P,S\rangle$

- **High energy probes see partons on the light-cone:**



$$\sigma_{\rm DIS}(x,Q^2) =$$

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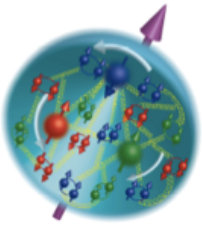

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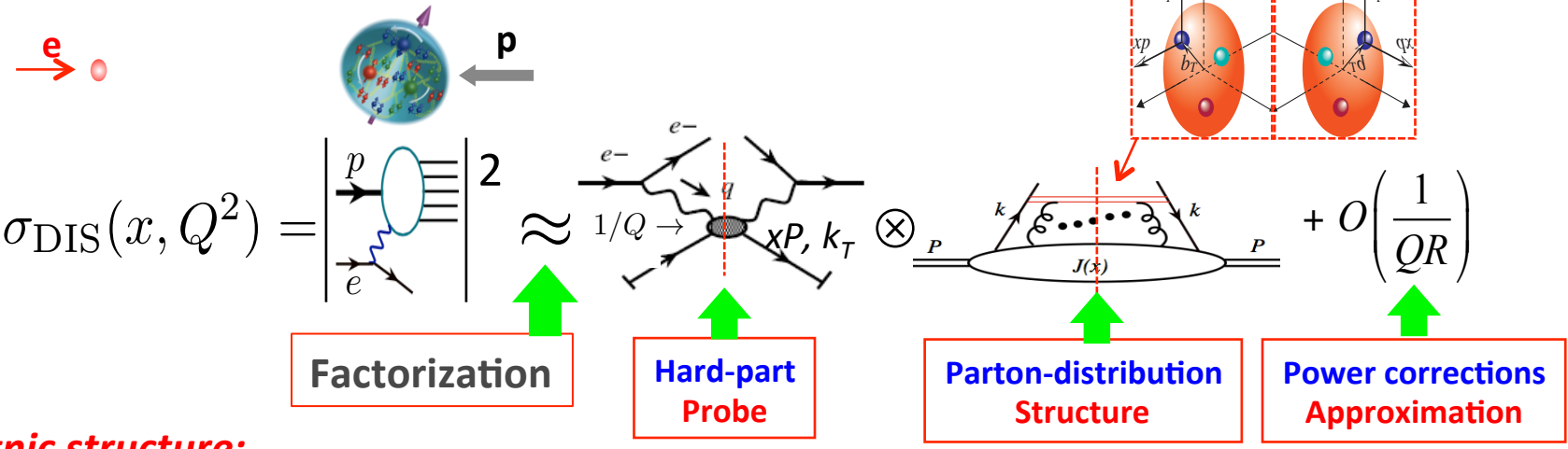
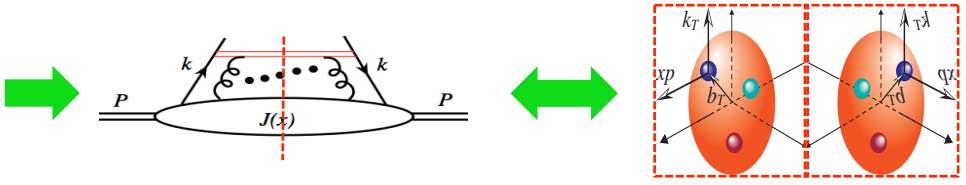
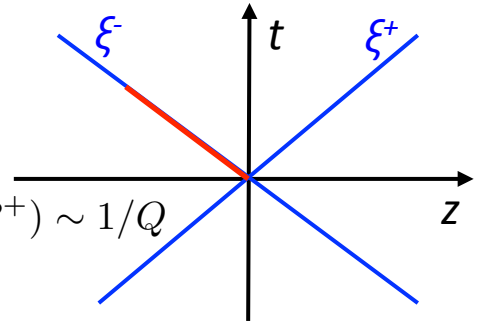


Partnic structure:



$$f_q(x,\mu^2) \equiv \int \frac{dP^+\xi^-}{2\pi} e^{-ixP^+\xi^-} \times \langle P|\overline{\psi}(\xi^-)\frac{\gamma^+}{2P^+}\exp\left\{-ig\int_0^{\xi^-} d\eta^- A^+(\eta^-)\right\}\psi(0)|P\rangle$$



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LQCD/PQCD – hadron/nuclear structure

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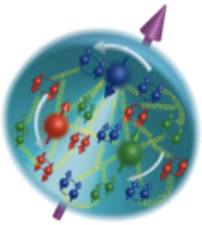

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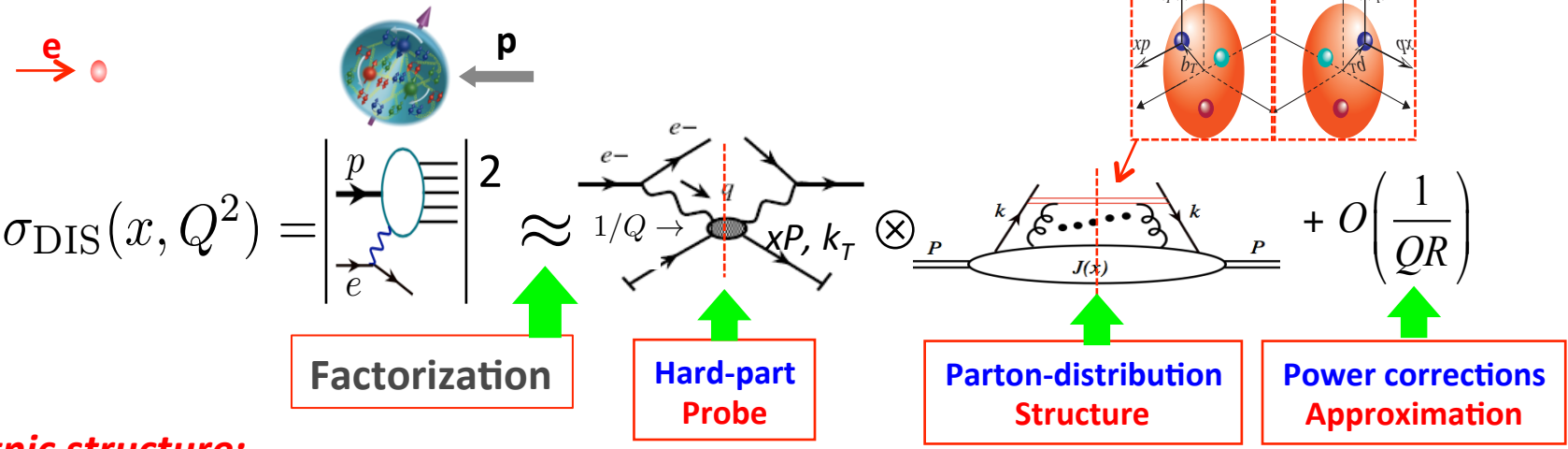
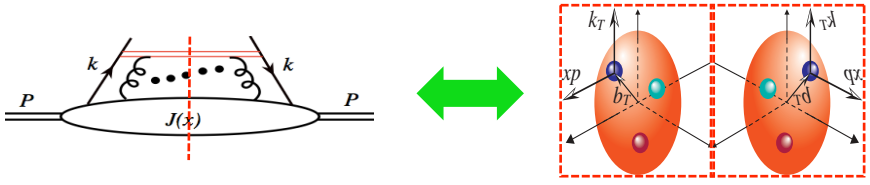
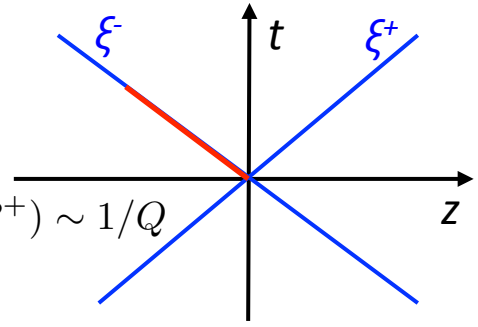


Partnic structure:



$$f_q(x,\mu^2) \equiv \int \frac{dP^+\xi^-}{2\pi} e^{-ixP^+\xi^-}$$

$$\times \langle P|\overline{\psi}(\xi^-)\frac{\gamma^+}{2P^+}\exp\left\{-ig\int_0^{\xi^-} d\eta^- A^+(\eta^-)\right\}\psi(0)|P\rangle$$



LQCD – "Wrong" time!

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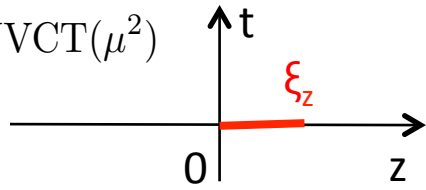
LQCD/PQCD – hadron/nuclear structure

Ji, arXiv:1305.1539

❑ New idea – quasi-PDFs:

$$\tilde{q}(x,\mu^2,P_z) \equiv \int \frac{d\xi_z}{4\pi} e^{-ixP_z\xi_z} \langle P|\overline{\psi}(\xi_z)\gamma_z \exp\left\{-ig\int_0^{\xi_z} d\eta_z A_z(\eta_z)\right\}\psi(0)|P\rangle + \mathrm{UVCT}(\mu^2)$$

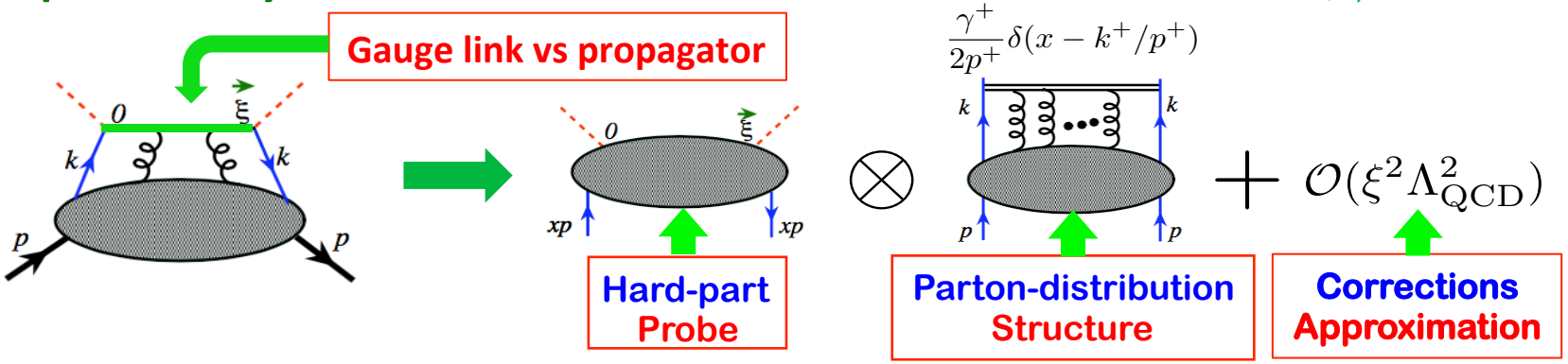


No longer boost invariant + power divergent, …

Key observation: $(0,z) \longrightarrow (0^+,\xi^-)$ when $P_z \to \infty$

❑ Complementary idea – "lattice cross section":

Ma and Qiu, arXiv:1404.6860



Jefferson Lab

LQCD/PQCD – hadron/nuclear structure

Ji, arXiv:1305.1539

❑ New idea – quasi-PDFs:

$$\tilde{q}(x,\mu^2,P_z) \equiv \int \frac{d\xi_z}{4\pi} e^{-ixP_z\xi_z} \langle P|\overline{\psi}(\xi_z)\gamma_z \exp\left\{-ig\int_0^{\xi_z} d\eta_z A_z(\eta_z)\right\}\psi(0)|P\rangle + \mathrm{UVCT}(\mu^2)$$

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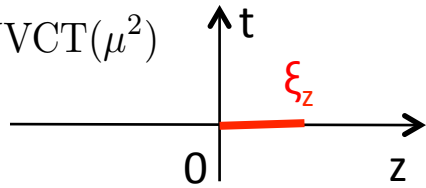

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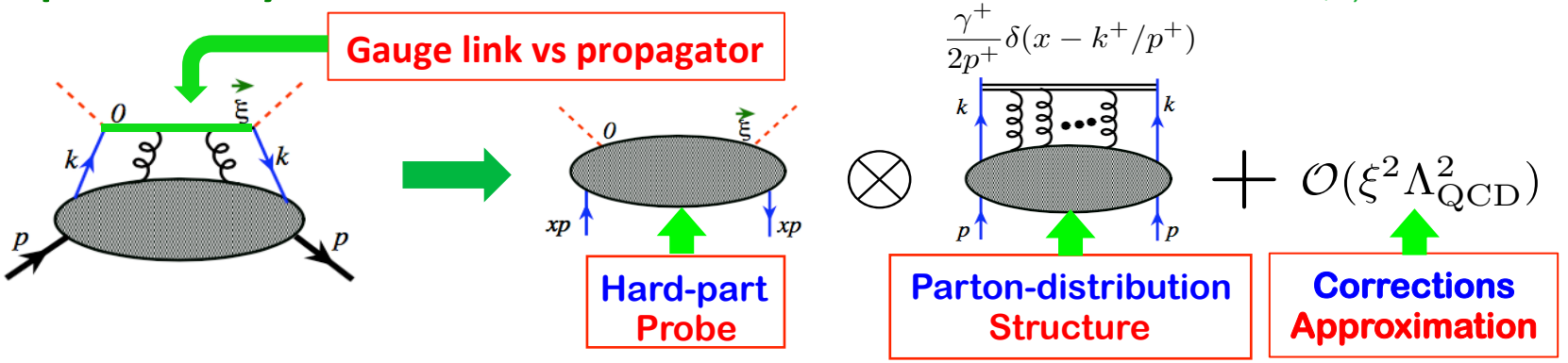


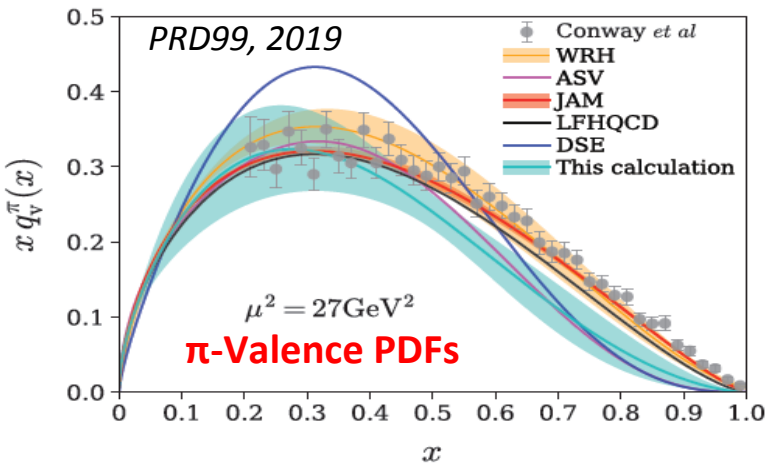
❑ Tremendous potentials:

Access to large-x region, …

Neutron PDFs, … (no free neutron target!)

Meson PDFs, such as pion, kaon, …

More direct access to parton flavor, …



1st LQCD calculation of pion valence PDFs!

LQCD/PQCD/EXP – hadron/nuclear structure

❑ Predictive power of QCD – Universality & Global analyses::

arXiv:1905.03788
Submitted to PRL

No modern detector can see quarks and gluons in isolation!

- lepton-hadron reactions (COMPASS, JLab, **EIC**)

$$\sigma^{\rm EXP}_{l+P\to l+H+X} = C_{l+k\to l+k+X} \otimes {\rm PDF}_P \otimes {\rm FF}_H$$

- hadron-hadron reactions (LHC)

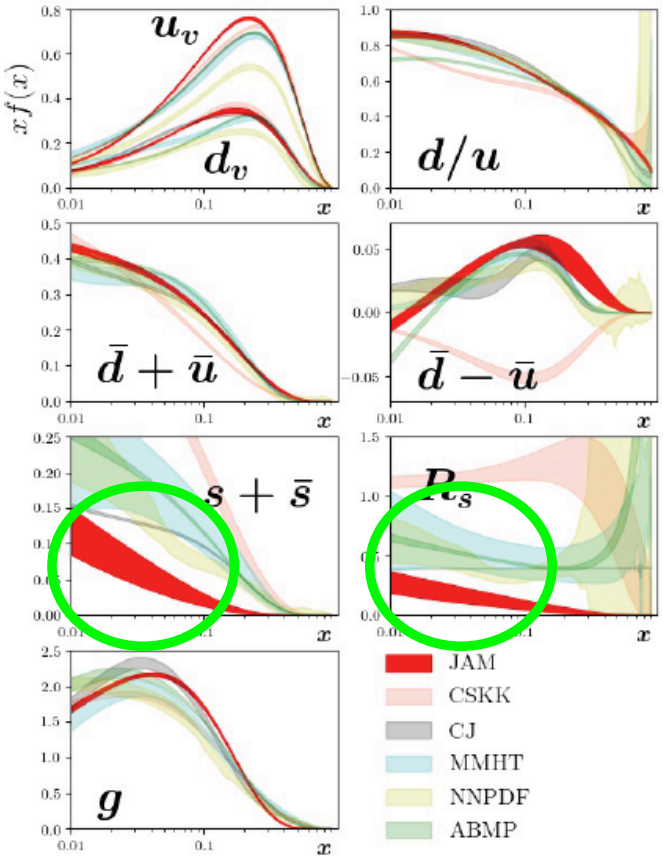
$$\sigma^{\rm EXP}_{P+P\to l+\bar{l}+X} = C_{k+k\to l+\bar{l}+X} \otimes {\rm PDF}_P \otimes {\rm PDF}_P$$

- lepton-lepton reactions (Belle)

$$\sigma^{\rm EXP}_{l+\bar{l}\to H+X} = C_{l+\bar{l}\to k+X} \otimes {\rm FF}_H$$

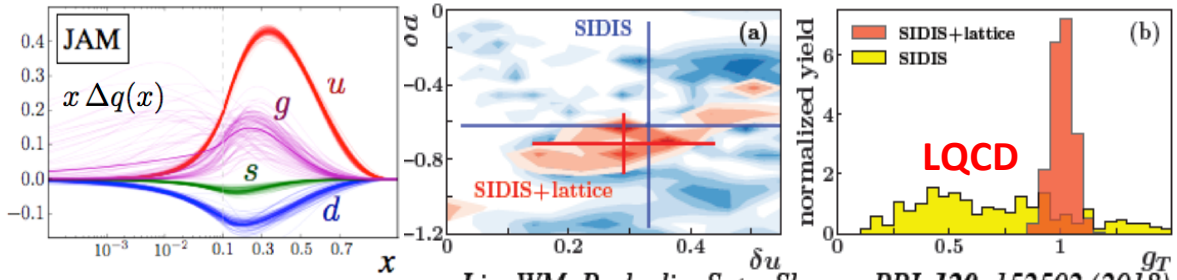
- ✓ DIS (p, d)
- ✓ DY (pp, pd)
- ✓ SIA $(\pi^{\pm}, K^{\pm})$
- ✓ SIDIS $(\pi^{\pm}, K^{\pm})$

Simultaneous fit



Strange quark suppression!

❑ Role of precise lattice data:



Lin, WM, Prokudin, Sato, Shows, PRL 120, 152502 (2018)

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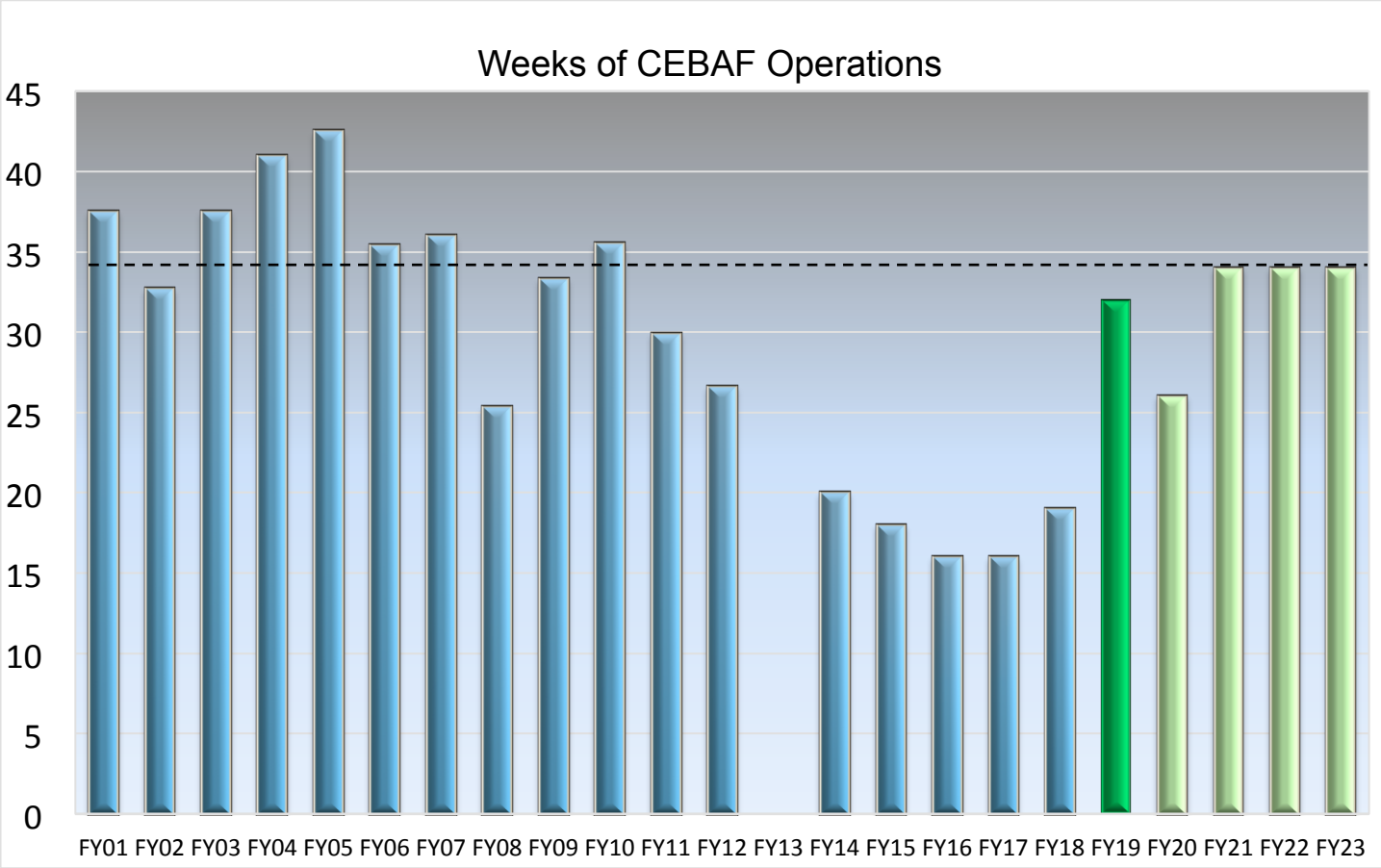
Future: CEBAF is approaching optimal weeks of operation



- **On-track for > 30 weeks of operation in FY19**
- **FY20 operations planning incorporates installation of replacement 2K Cold Box**
- **Working towards optimal 34 weeks of reliable operations**

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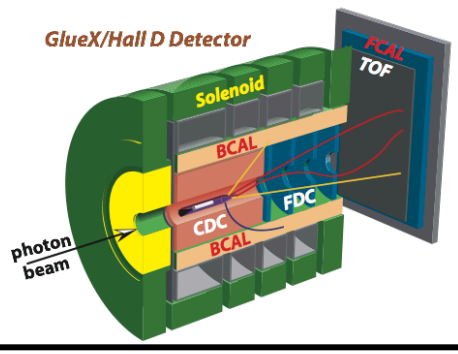
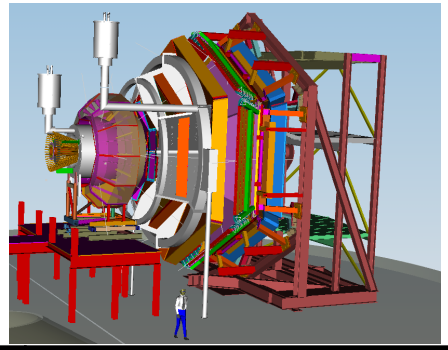
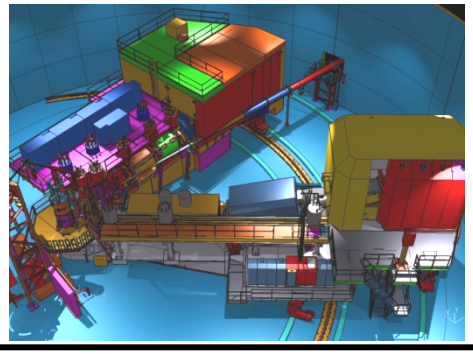
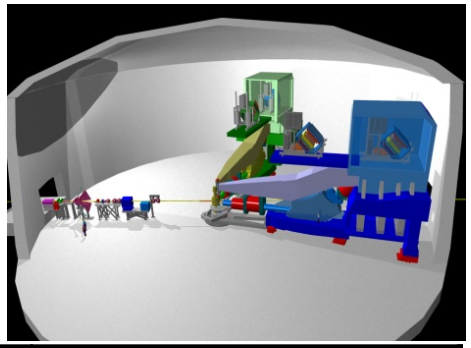
Detector Requirements – Complementarity, Hall A for MIE



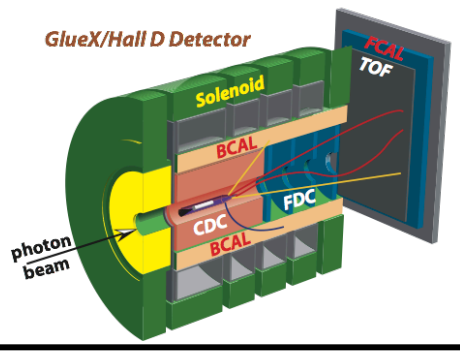


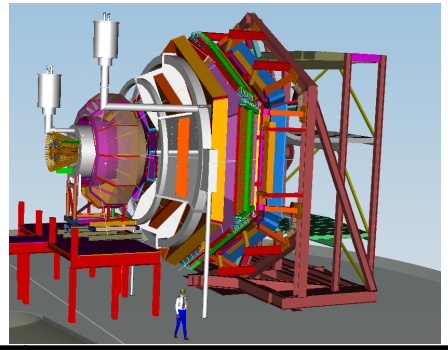


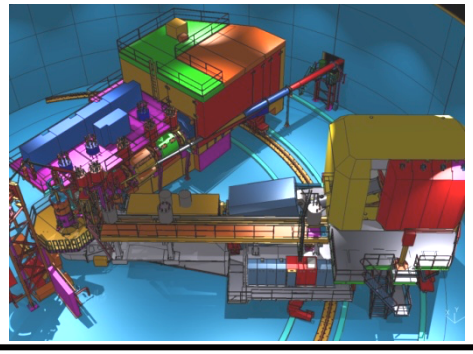


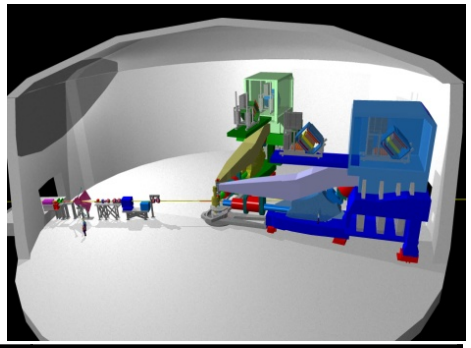
Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	custom installations
polarized photons	hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent momentum resolution	
high multiplicity reconstruction		luminosity up to 10^{38}	
particle ID			

Detector Requirements – Complementarity, Hall A for MIE









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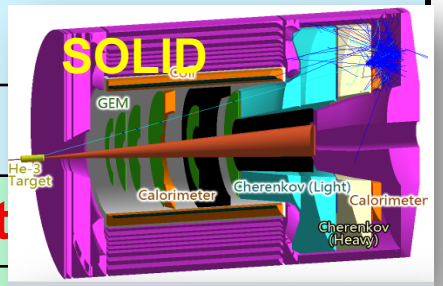
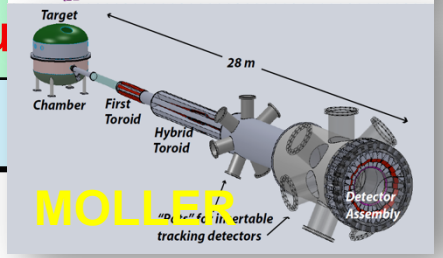
particle ID			

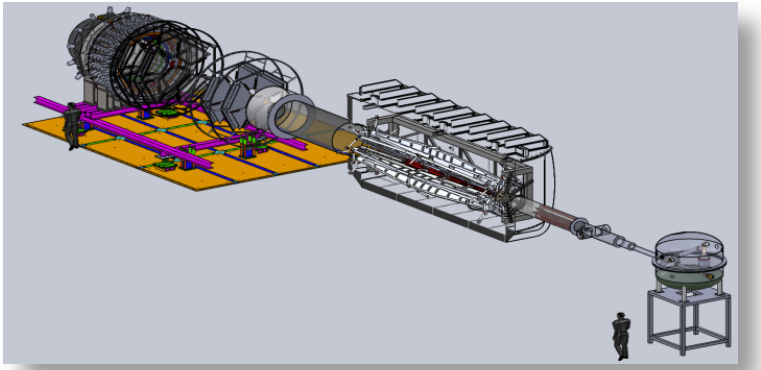




Future: Moving ahead on MOLLER and SoLID

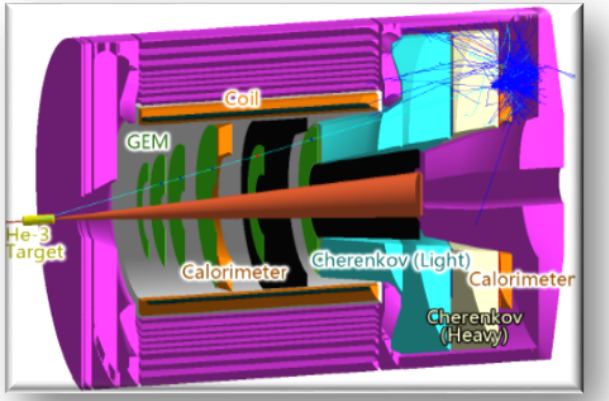
MOLLER

- Proposed experiment in 2010
- Opportunity with 12 GeV Upgrade to Search for New Physics at mass scales beyond LHC
- CD-0 approved January 2017, project paused
- Project underway
  - Established project team
  - Director's Review held April 2019
- Funding
  - FY20 start in President's Budget Request
  - House appropriations includes $2.5M



SoLID

- Solenoidal Large Intensity Device – new multipurpose detector facility for Hall A
- Science focus on nucleon-imaging: important prerequisite science for EIC
- Produced a "Pre Conceptual Design Report"
- Director's Review scheduled Sept: verify cost estimate and technical readiness
- Proposal will be submitted to ONP, with request for a Science Review



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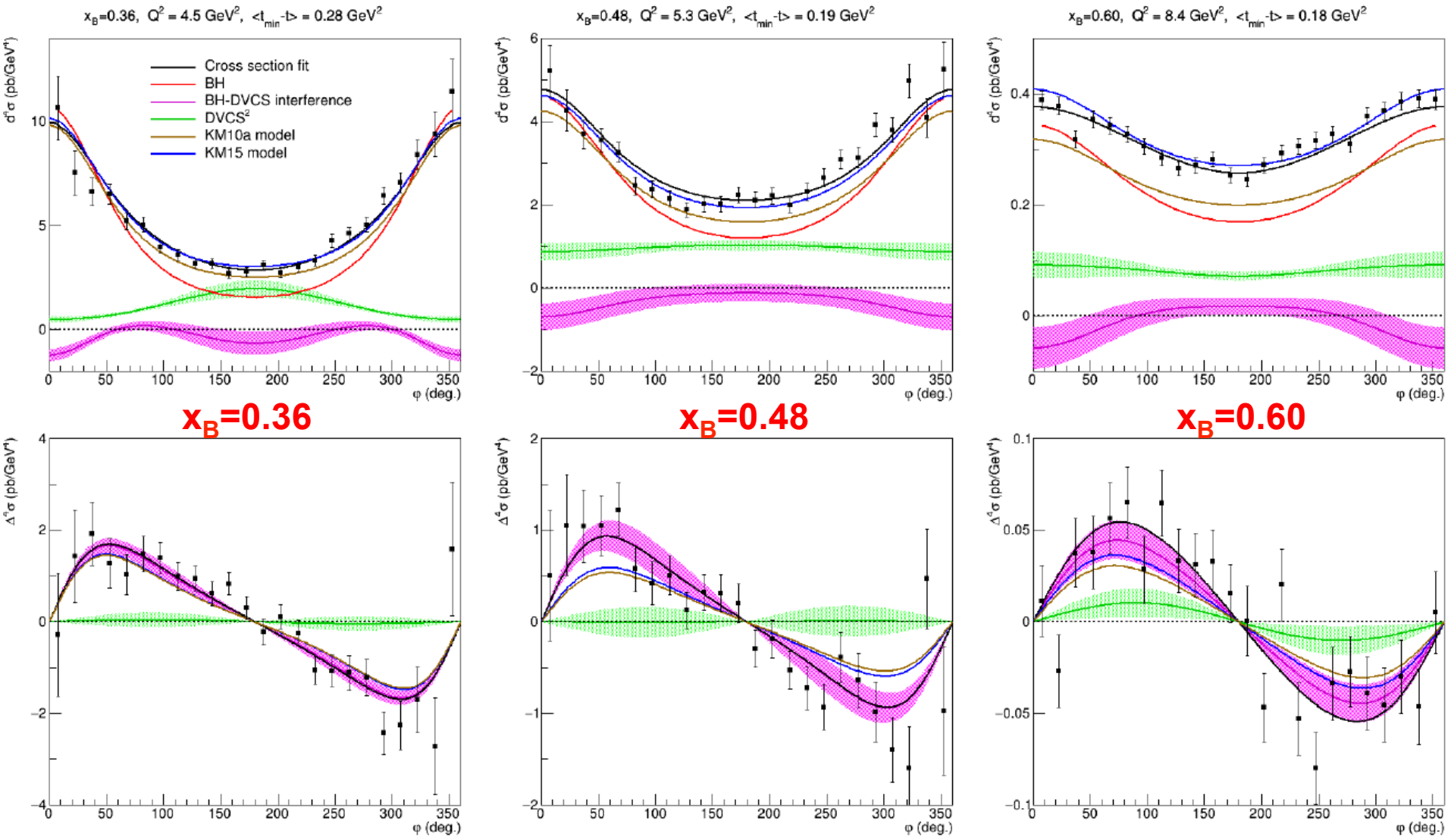
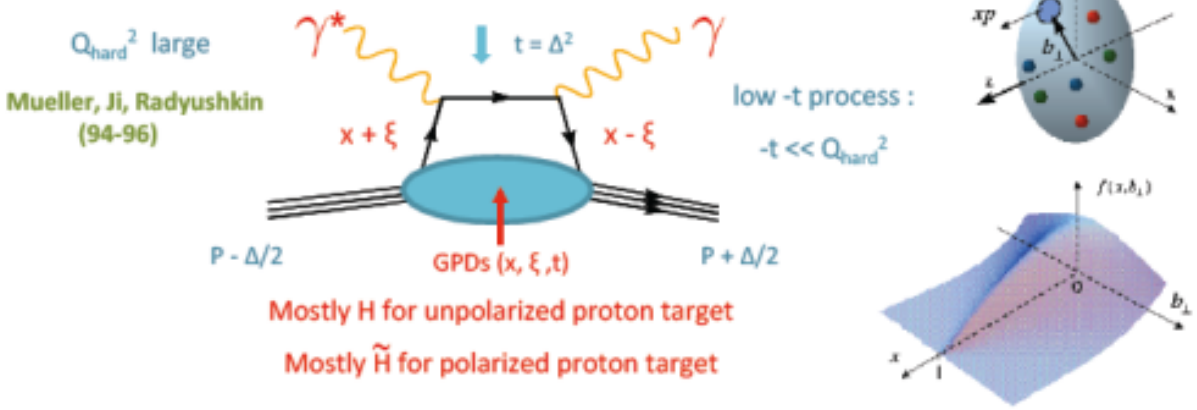
E12-06-114 DVCS/Hall A Experiment at 11 GeV

Sample of cross-section results:



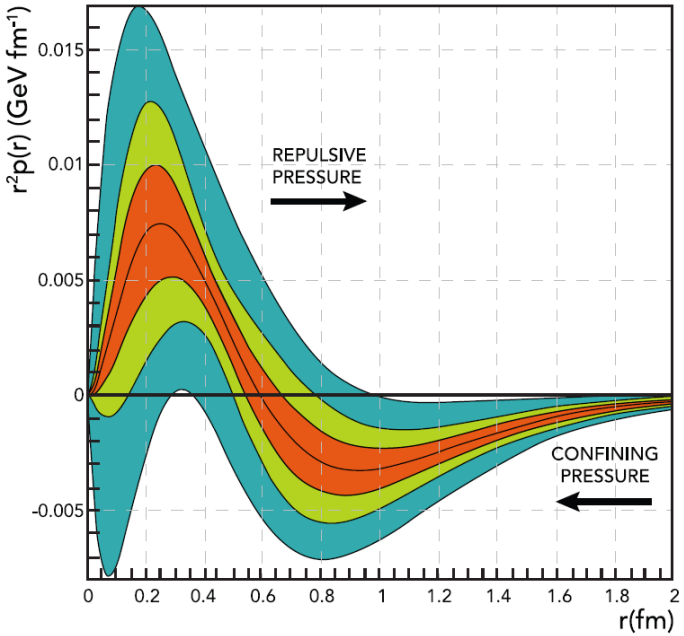
Jefferson Lab

Deeply Virtual Compton Scattering @ 11 GeV



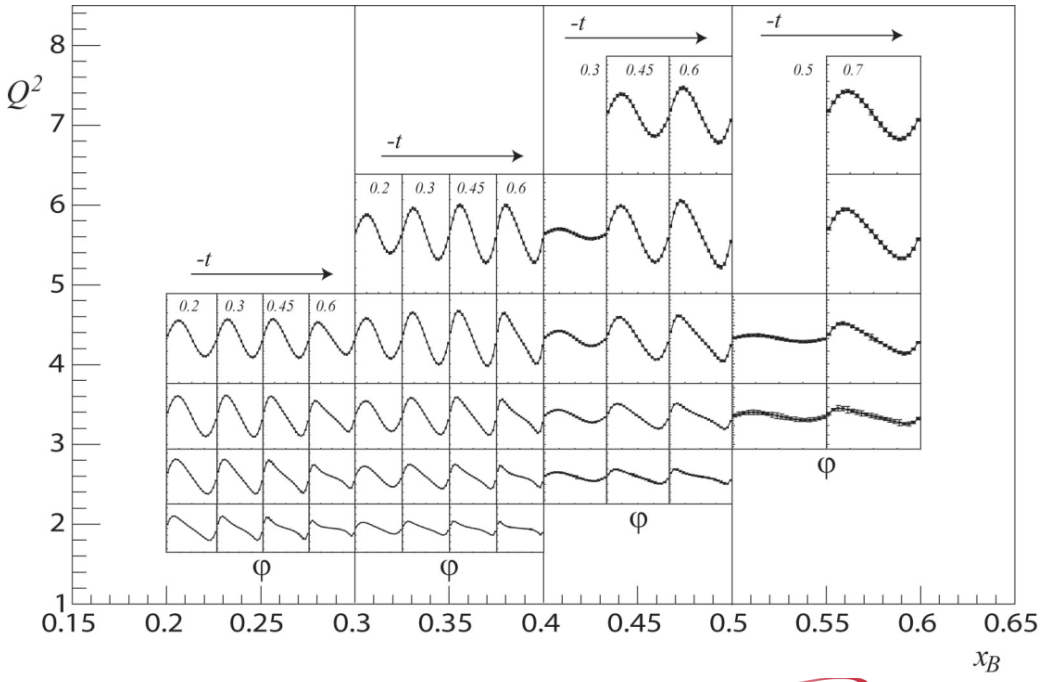
Hall A DVCS scaling check completed

Hall B DVCS on H 50% complete



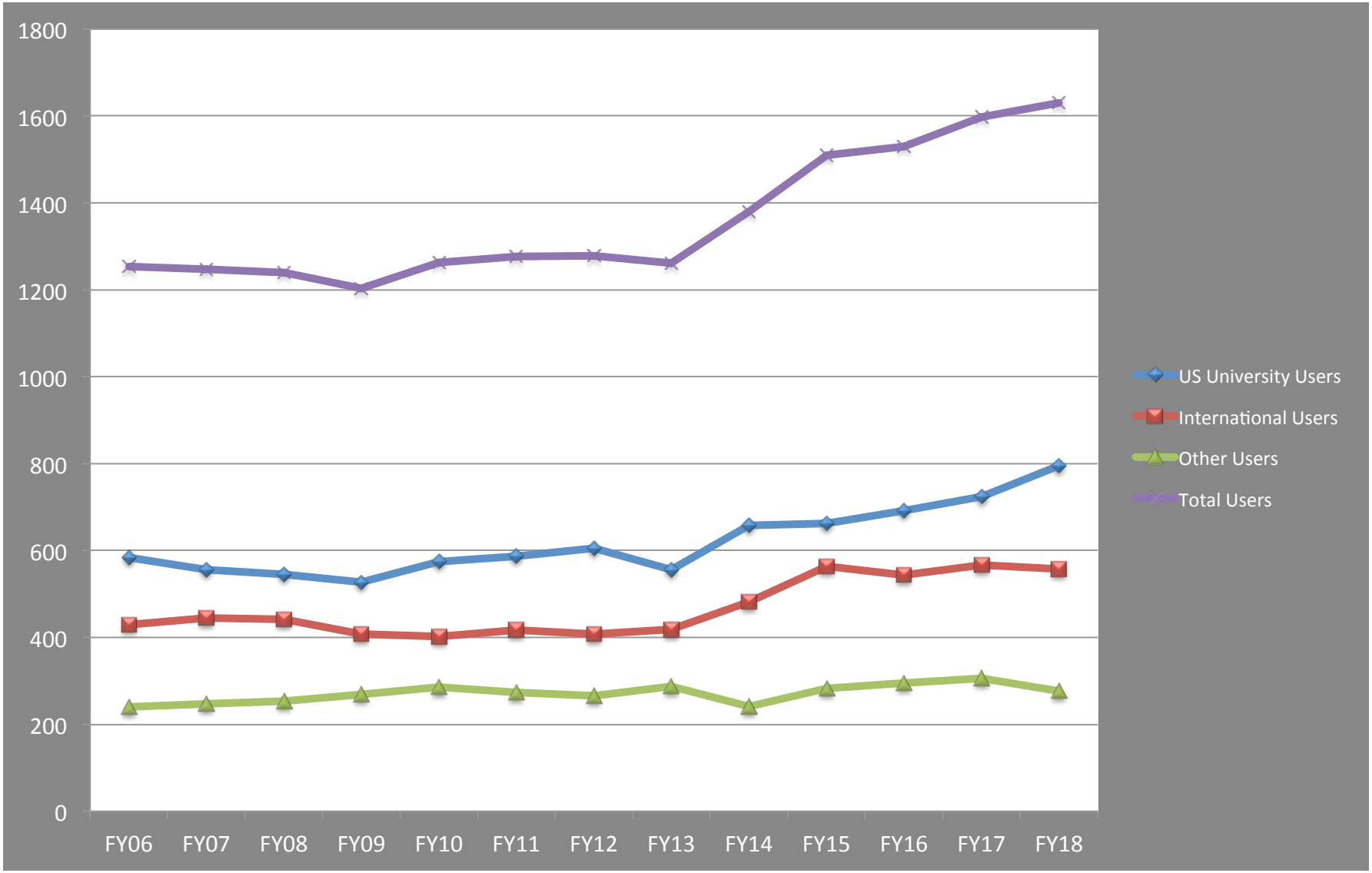
Nature **557**, 396-399 (2018)

CLAS12 (projected)



Jefferson Lab

Jefferson Lab's user community continues to grow



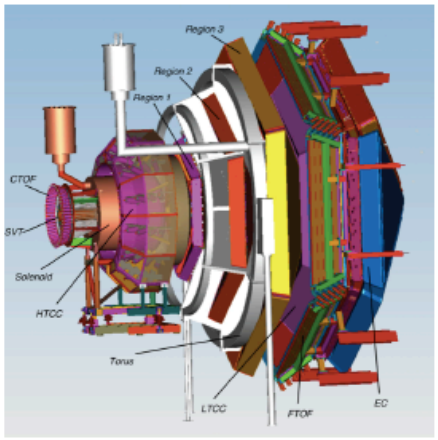
Future: Approved experiments – PAC days (after PAC47)

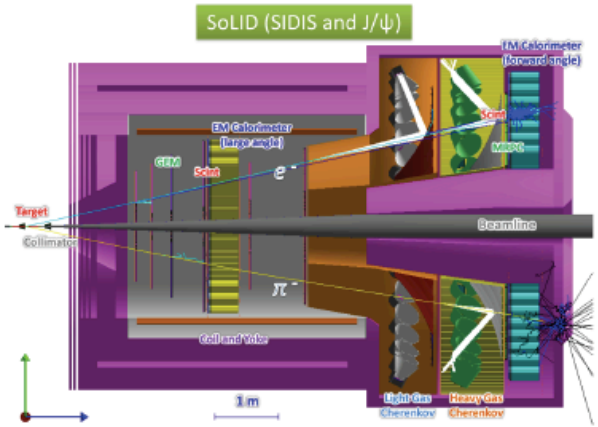
Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD	0	219	11	540	0	**770**
The transverse structure of the hadrons	150.5	85	146	25	0	**406.5**
The longitudinal structure of the hadrons	42	230	211	0	0	**483**
The 3D structure of the hadrons	359	872	196	0	0	**1427**
Hadrons and cold nuclear matter	220	275	205	15	14	**729**
Low-energy tests of the Standard Model and Fundamental Symmetries	547	180	0	79	60	**866**
Total Days	**1318.5**	**1861**	**769**	**659**	**74**	**4681.5**
Total Days - Without SoLID	**844.5**	**1861**	**769**	**659**	**28**	**4161.5**
Total Approved Run Group Days (includes MIE)	**1318.5**	**1026**	**726**	**459**	**74**	**3603.5**
Total Approved Run Group Days (without SoLID)	**844.5**	**1026**	**726**	**459**	**28**	**3083.5**
Total Days Completed	**176.5**	**191**	**118.0**	**138**	**0**	**623.5**
Total Days Remaining	**668**	**835**	**608**	**306**	**28**	**2460**

A Decade of Experiments!

Jefferson Lab

Center for Nuclear Femtography:

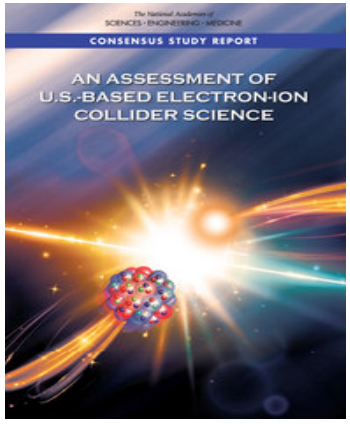




Lattice QCD

DVCS

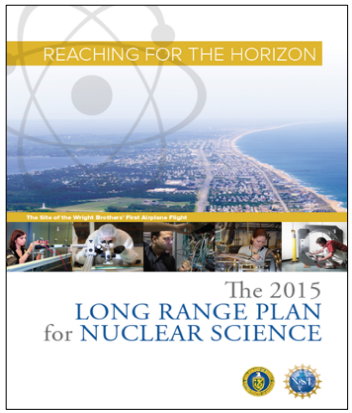
SIDIS

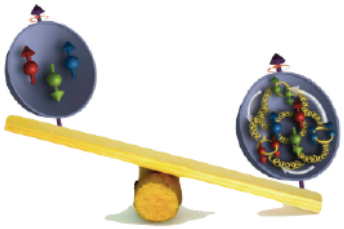


Imaging the Quarks

Electron-Ion Collider

Imaging the Gluons





Understand the glue that binds us all:
The Next QCD Frontier in Nuclear Physics

CENTER for NUCLEAR FEMTOGRAPHY

Jefferson Lab

What EIC can do, but, HERA & other colliders cannot do?

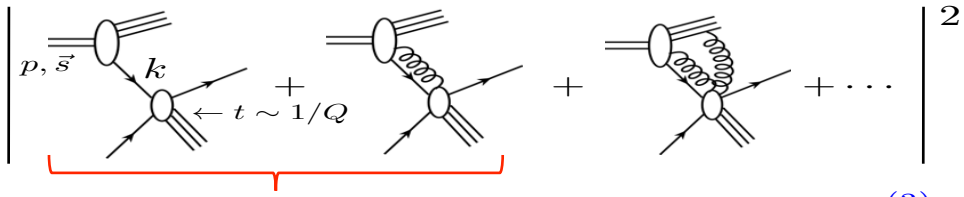
- **What is so special about the Lepton-Hadron Collider?**

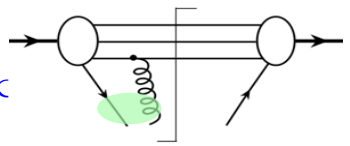
  Hit the proton with a well-controlled hard probe without breaking it!

- **Quantum imaging:**
  - **HERA discovered: 15% of e-p events is diffractive – Proton not broken!**
  - **US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!***

- **Quantum interference & entanglement – dual role of hadron spin:**
  - **US-EIC: Highly polarized beams – *Origin of hadron property: Spin, …***

    Direct access to chromo-quantum interference!

$\sigma(Q,\vec{s}) \propto$ 

$\sigma(s) - \sigma(-s)$ ➡ **Quantum interference** ➡ $T^{(3)}(x,x) \propto$ 

- **Nonlinear quantum dynamics – dual role of nuclei:**
  - **US-EIC: Light-to-heavy nuclear beams – *Origin of nuclear force, …***

    Catch the transition from chromo-quantum fluctuation

    to chromo-condensate of gluons, …

    Emergence of hadrons (femtometer size detector!),

    – "a new controllable knob" – Atomic weight of nuclei

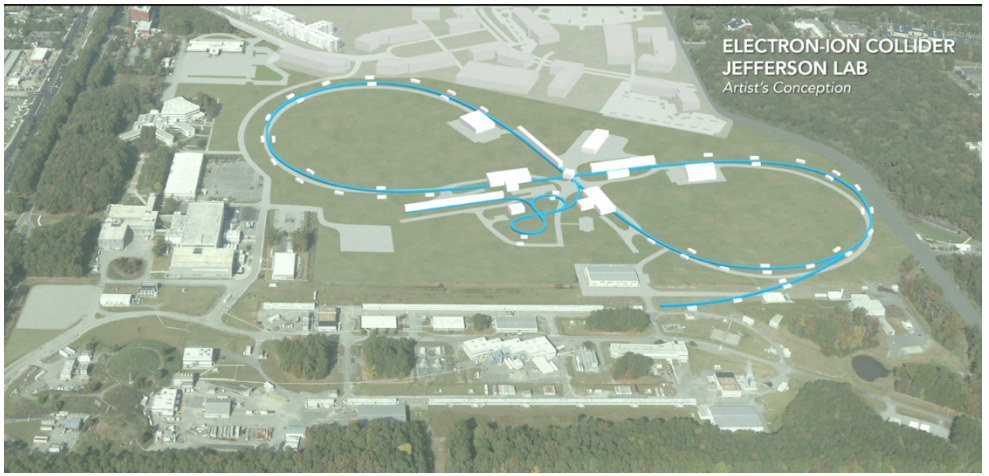
Jefferson Lab

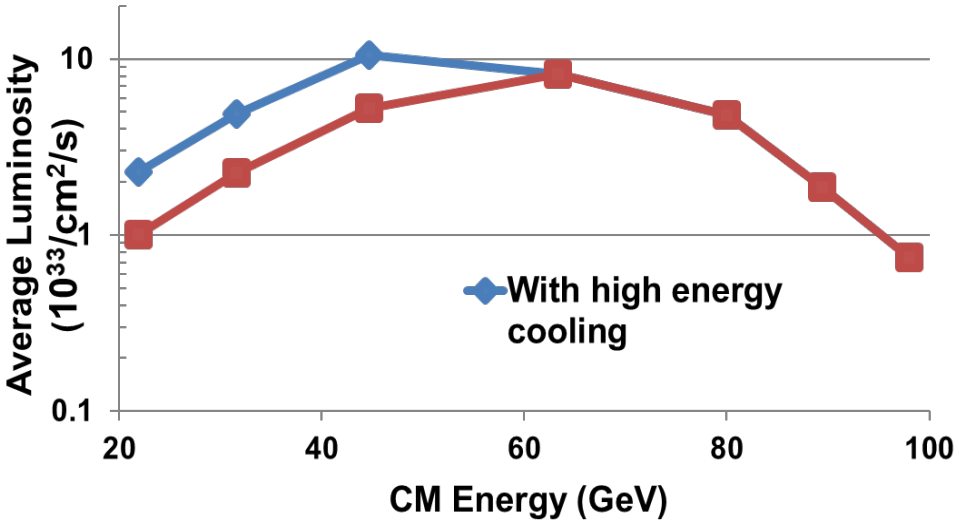
Electron Ion Collider at Jefferson Lab

JLab EIC Figure 8 Concept

- High Polarization (including deuterons)
- High Luminosity
- Energy Range: √s : 20 to 100-140 GeV (magnet technology choice)
- Low technical risk for white paper goals
- Flexible timeframe for construction consistent w/running 12 GeV CEBAF
- High performance, low-risk
- Cost effective operations

Fulfills White Paper, NAS Requirements





PreCDR complete
E_{CM} 65→100GeV in progress

Jefferson Lab

Electron Ion Collider at Jefferson Lab

JLab EIC Figure 8 Concept

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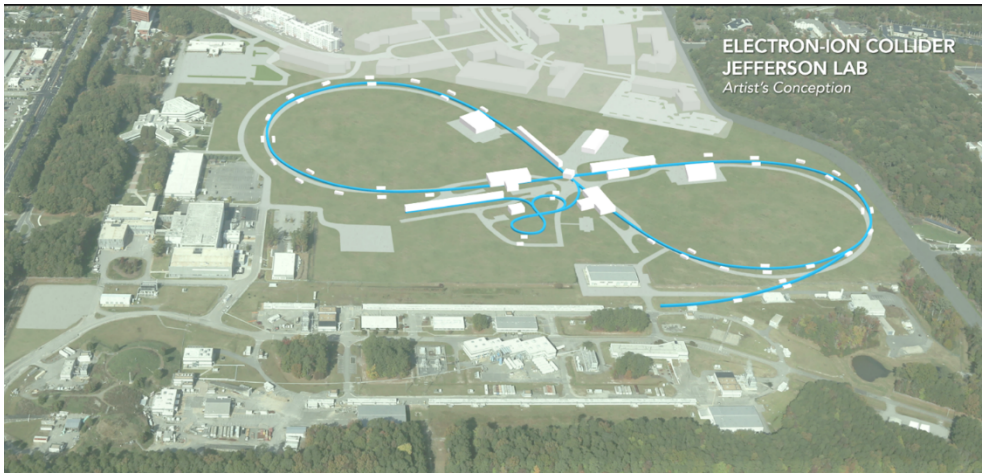
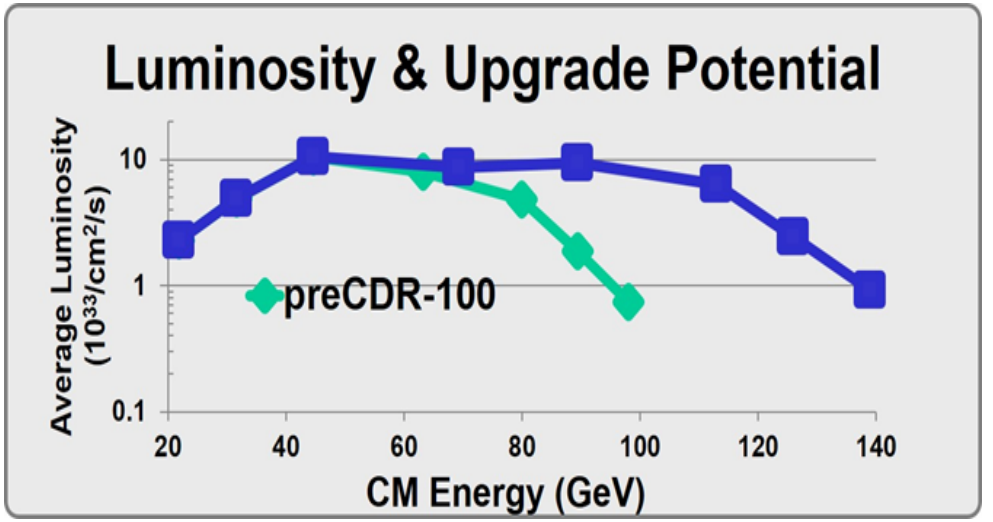


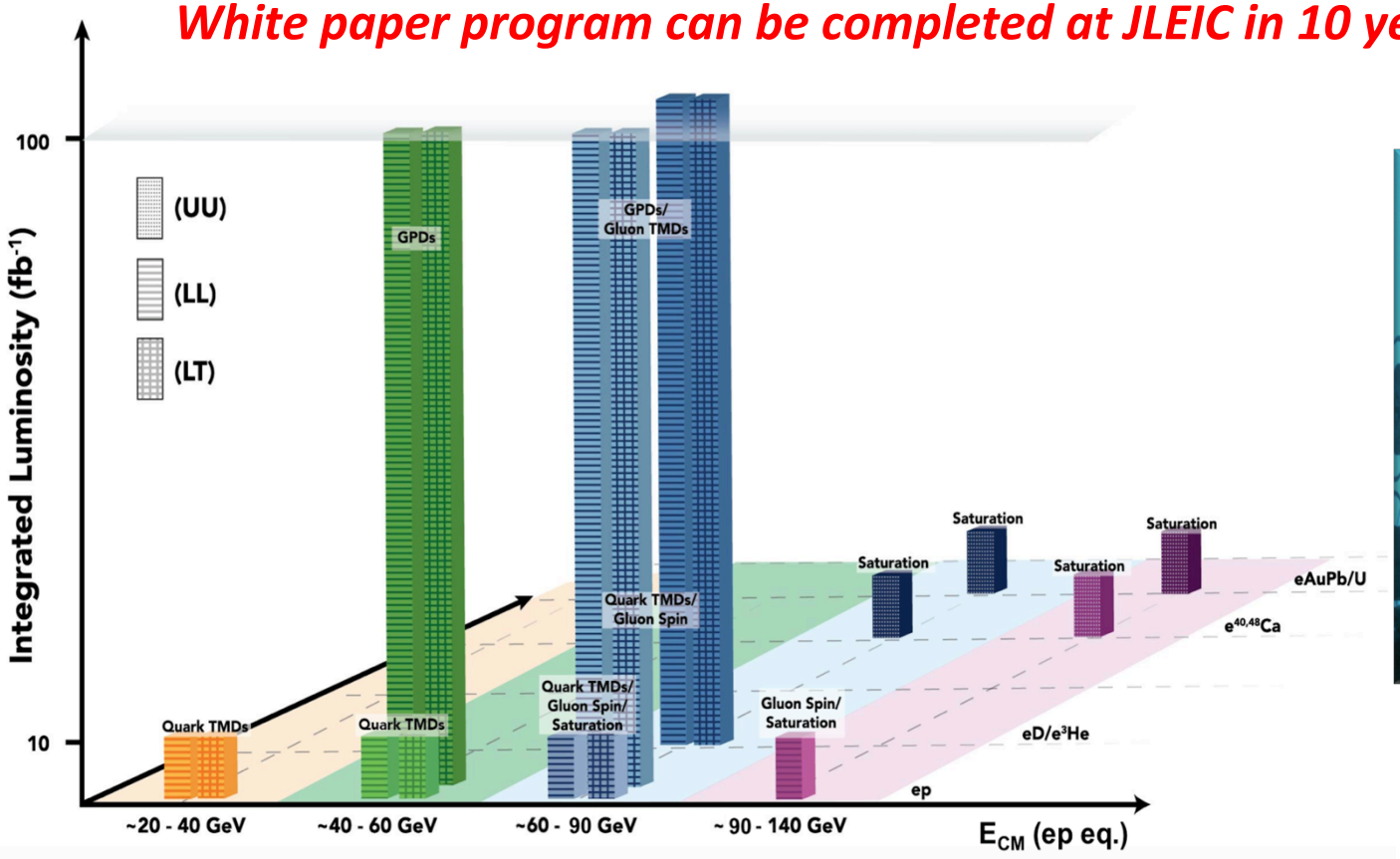


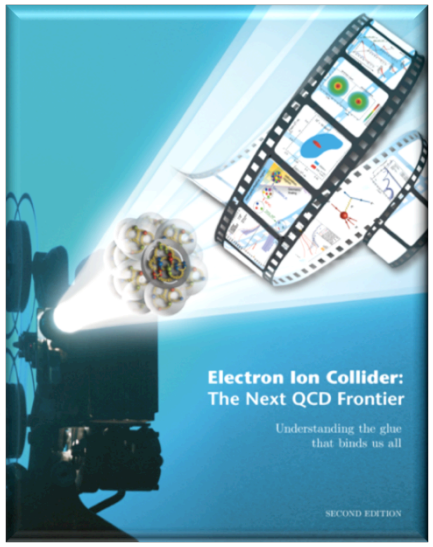
PreCDR complete
E_{CM} 65→100GeV in progress

Jefferson Lab

White Paper Science Goals Require > 700 fb^{-1}

White paper program can be completed at JLEIC in 10 years





- The total integrated luminosity to complete whitepaper program is 710 fb^{-1}
- At L_{avg} = 10^{34} cm^{-2}s^{-1} this program requires 7 years of operatio
- At 10^{33} cm^{-2}s^{-1} it requires 70 years to complete

- Construction of JLEIC will not interfere with on-going fixed-target JLab program
- JLEIC + fixed target = unique lepton-hadron facility in the world

Jefferson Lab

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.**

T. Hallman – DOE Nuclear Physics
EICUG meeting, July 2019

Summary

- The 12 GeV science program at JLab is underway
  - F Hall operation is now routine
  - A broad program of 79 approved experiments with many opportunities for is planned
  - Initial science results are already being reported
  - Tehory/experiment/IT are closely integrated
  - JLab user community continues to grow > 1600
- Future equipment projects
  - MOLLER: Passed CD0 – funds starting to flow
  - SoLID: Had Director's review – prepare for DOE science review
- EIC status continues to develop
  - FY20 DOE budget language
  - JLEIC design continues to be improved

Thank you!

Hall Status Snapshots – beginning of 12 GeV Era

Hall A

- Two publications from Argon Spectral Function experiment, one submitted
- First paper from Tritium series of experiments submitted
- Near-final results presented at User Group Meeting for three experiments
  - DVCS experiment – results consistent with expected Q^2 dependence!
  - Proton Magnetic Form Factor – prerequisite for SBS science program
  - Ratio of $^3H/^3He$ at large Bjorken-x

Hall B

- Heavy Photon Search experiment has article based on engineering data
- Proton Radius experiment has final results, article submitted to Nature
- Calibration of various Run-Group Data in excellent shape
- On for production run (initial goal of production analysis: 20% of data)

Hall C

- Near-final results presented at User Group Meeting for three experiments
  - Color Transparency
  - Deuteron Electrodisintegration at High (missing momentum) P_m
  - Inclusive structure function results for H and D targets

Hall D

- Making excellent use of supercomputing facilities like NERSC
- 1st publication in 2017, recent J/Ψ paper in PRL, η' paper submitted, more in pipeline
- PWA analysis preparations done

Highlights: QCD and Hadron Structure

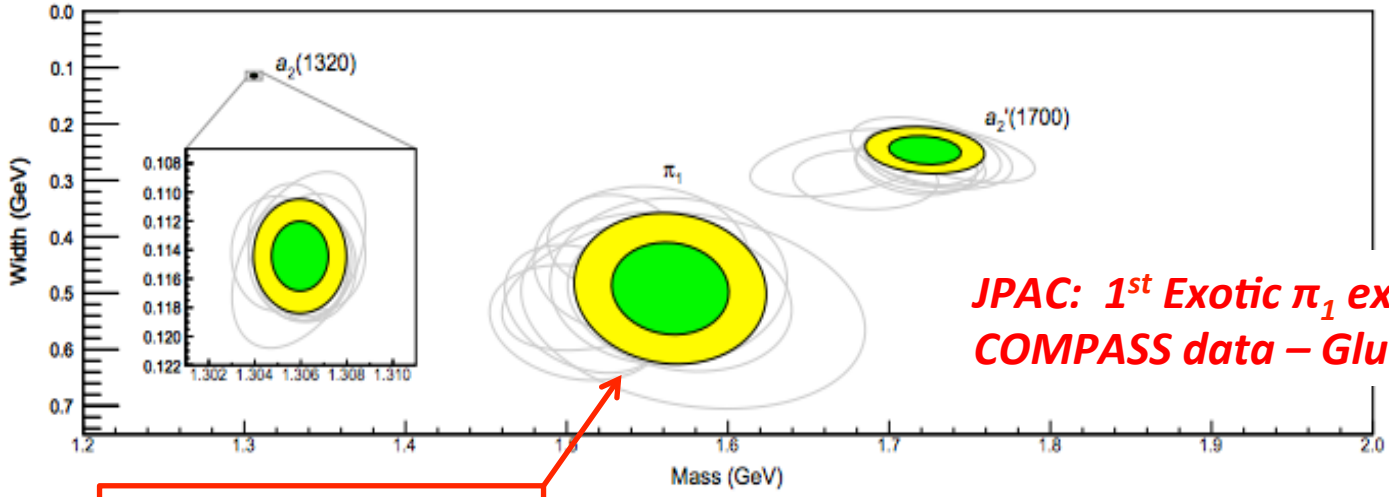
❑ Hadron Spectroscopy - JPAC:

PRL122 (2019) 042002

"Determination of the Pole Position of the Lightest Hybrid Meson Candidate"

Exotics in $\eta^{(\prime)}\pi$ – led to the 1st Exotic π_1

- ✧ **For the first time pole parameters of the exotic π_1 resonance were extracted using a coupled channel fit to COMPASS $\eta^{(\prime)}\pi$ P- and D-waves**
- ✧ **Results compatible with the existence of a single π_1 meson, which solves a longstanding puzzle about two different $\pi_1(1400)$ and $\pi_1(1600)$, decaying separately into $\eta\pi$ and $\eta'\pi$**



Mass: 1564 ± 24 ± 86
Width: 492 ± 54 ± 102

JPAC: 1st Exotic π_1 extracted from COMPASS data – GlueX data next!

Jefferson Lab