EIC Physics in US

Zhongbo Kang
UCLA

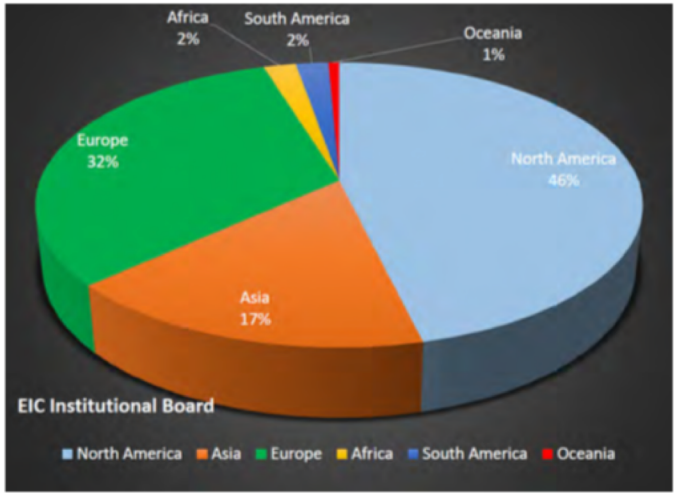
HADRON 2019 Conference
August 16 - 21, 2019

EIC Users Group keeps growing

The EIC Users Group: EICUG.ORG

Formally established in 2016
864 Ph.D. Members from 30 countries, 184 institutions

New:
Center for Frontiers in Nuclear Science (at Stony Brook/BNL)
EIC² at Jefferson Laboratory



EICUG Structures in place and active.

EIC UG Steering Committee (w/ European Representative)
EIC UG Institutional Board
EIC UG Speaker's Committee (w/European Rep.)

Task forces on:
-- Beam polarimetry
-- Luminosity measurement
-- Background studies
-- IR Design

Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016), Trieste (2017), CAU (2018), Paris (2019)**

Florida (2020), Poland (2021)

Courtesy of A. Deshpande

EIC Users Group keeps growing

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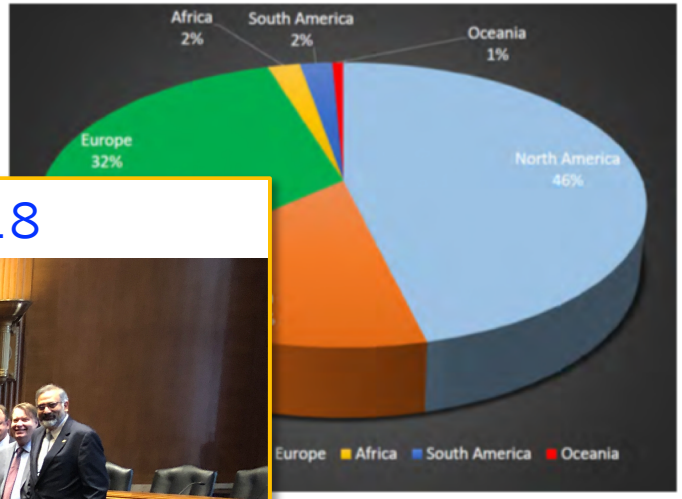

Capitol Hill visit, 12/04/2018

place and active.

mittee (w/ European Representative)
Board
mmittee (w/European Rep.)

ement

ny Brook (2014), Berkeley (2015), **ANL**
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Center for F

EIC² at Jefferson Laboratory

Courtesy of A. Deshpande

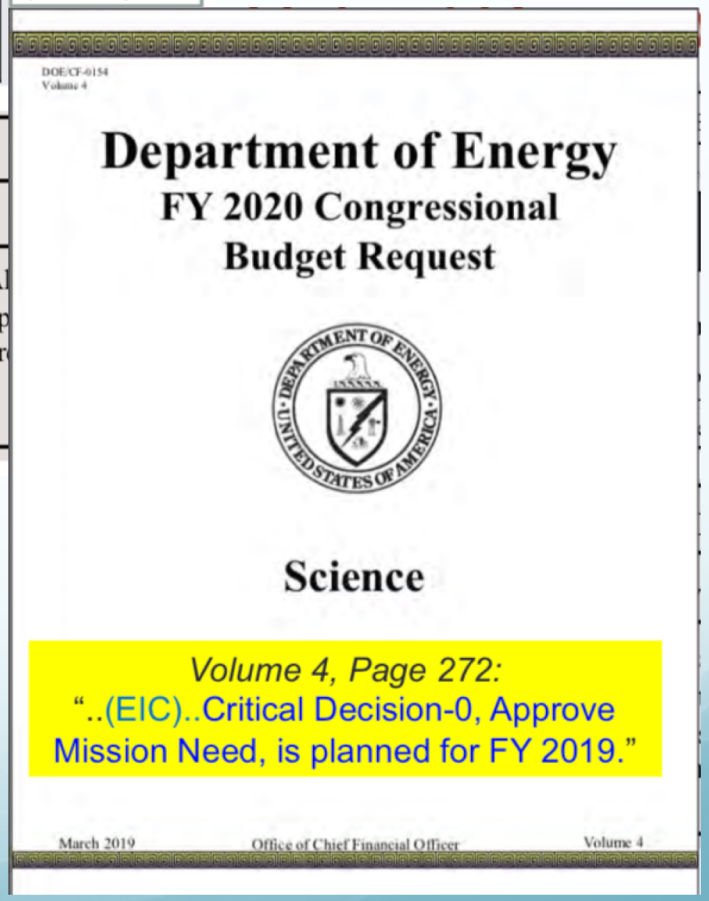
Critical Decision Process DOE

PROJECT ACQUISITION PROCESS AND CRITICAL DECISIONS					
Project Planning Phase		Project Execution Phase			Mission
Preconceptual Planning	Conceptual Design	Preliminary Design	Final Design	Construction	Operations
	CD-0 Approve Mission Need	**CD-1** Approve Preliminary Baseline Range	**CD-2** Approve Performance Baseline	**CD-3** Approve Start of Construction	**CD-4** Approve Start of Operations or Project Closeout

Expected Soon (2019)

Technical feasibility (~2030)

CD-0	CD-1	CD-2	CD-3	
Actions Authorized by Critical Decision Approval				
• Proceed with conceptual design using program funds • Request PED funding	• Allow expenditure of PED funds for design	• Establish baseline budget for construction • Continue design • Request construction funding	• Approve expenditure of funds for construction	• Al op pr


DOE/CF-0154
Volume 4

Department of Energy
FY 2020 Congressional Budget Request

Science

Volume 4, Page 272:
"..(EIC)..Critical Decision-0, Approve Mission Need, is planned for FY 2019."

March 2019 Office of Chief Financial Officer Volume 4

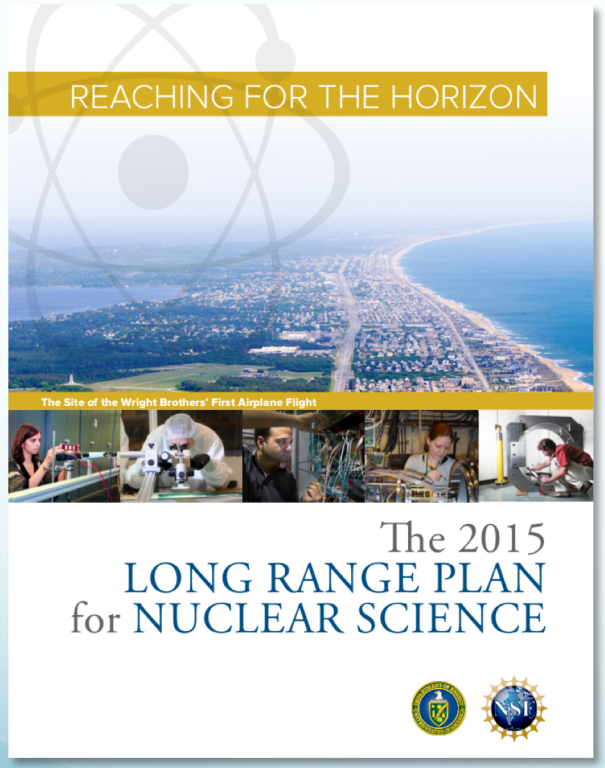
Courtesy of A. Deshpande

Outline

- Status of EIC
- EIC Physics: two major pillars and two minor pillars
  - Major 1: quantum tomography of protons and nuclei
  - Major 2: a new form of matter – color glass condensate
  - Minor 1: high energy QCD – jet physics in ep/eA collisions
  - Minor 2: beyond standard model physics – weak current/dark photon (among others)
- Summary

Justification of EIC

- The *Justification Phase* of the EIC has ended
- Finally we are entering the *Realization Phase* this year



Recommendation III

We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

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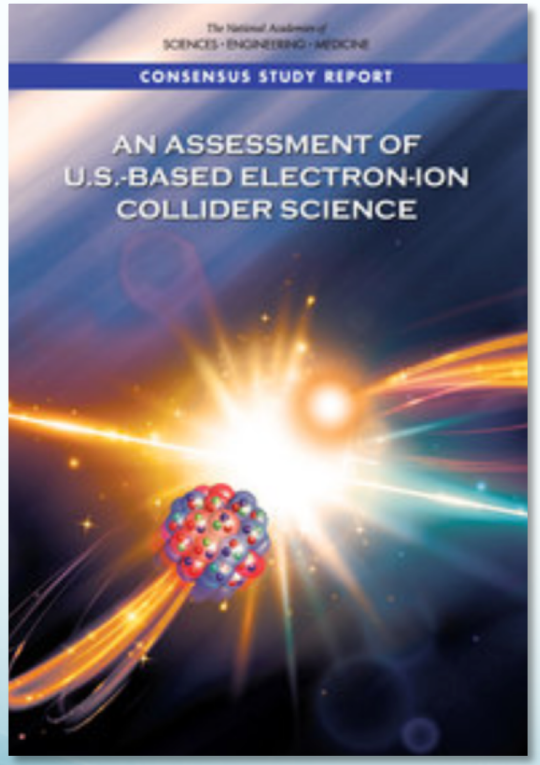


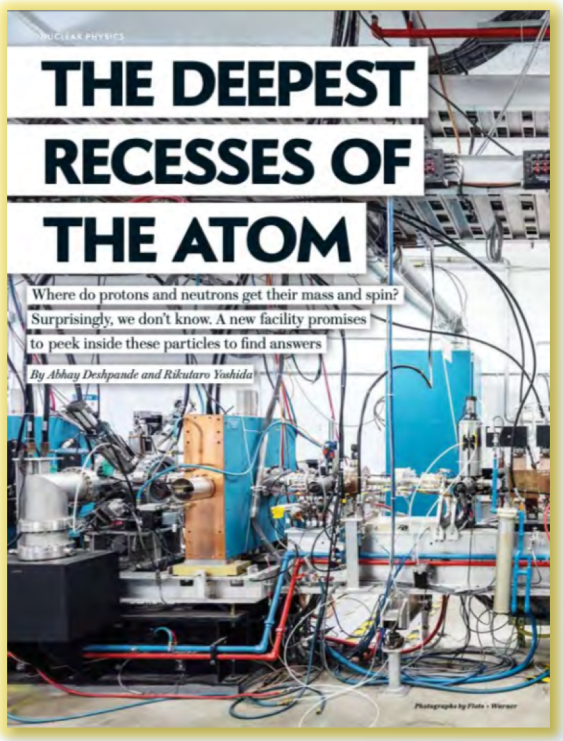
National Academy of Sciences Consensus Report on the Science Case for a U.S. based Electron-Ion Collider (July 2018)

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

Reaching out to the public

Scientific American (2015)
The glue that binds us

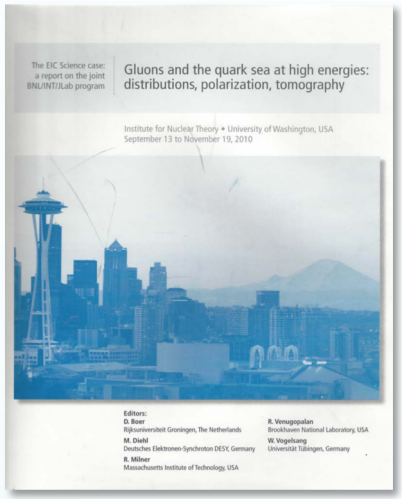
CERN Courier (2018)
Aschenauer, Ent

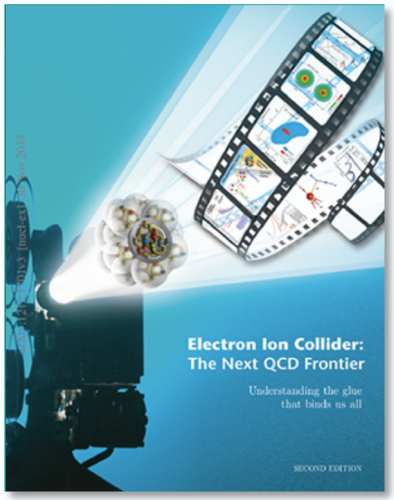


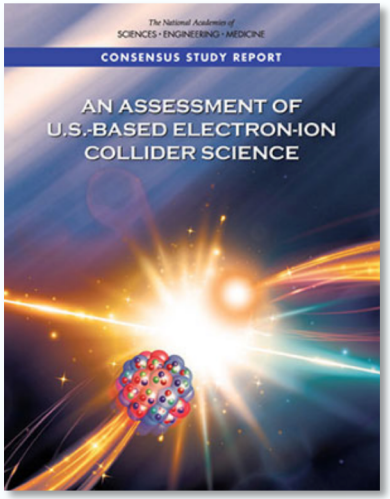
Scientific American (2019)
Deshpande, Yoshida

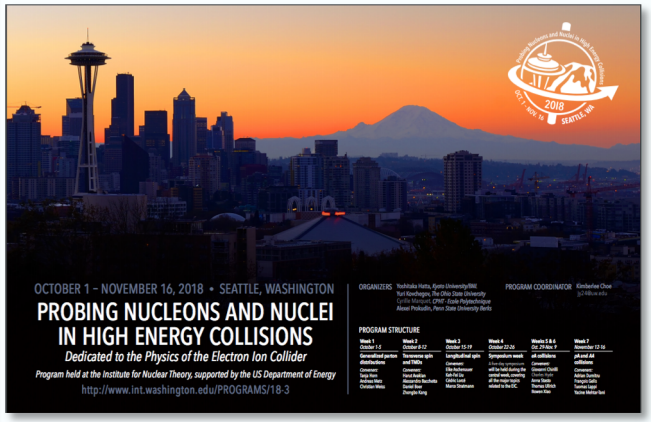
EIC Scientific Studies

- EIC physics continues being developed in the community









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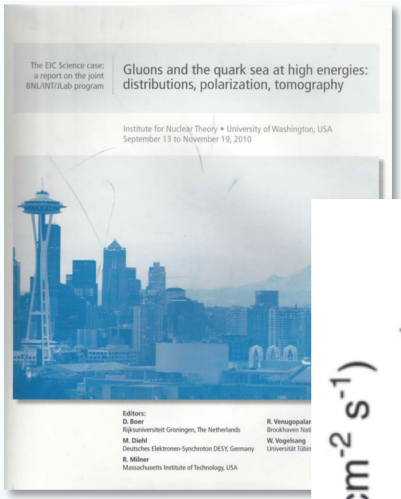
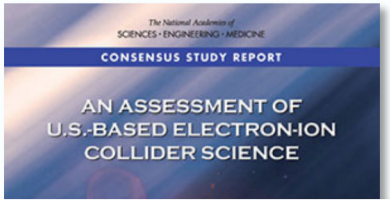
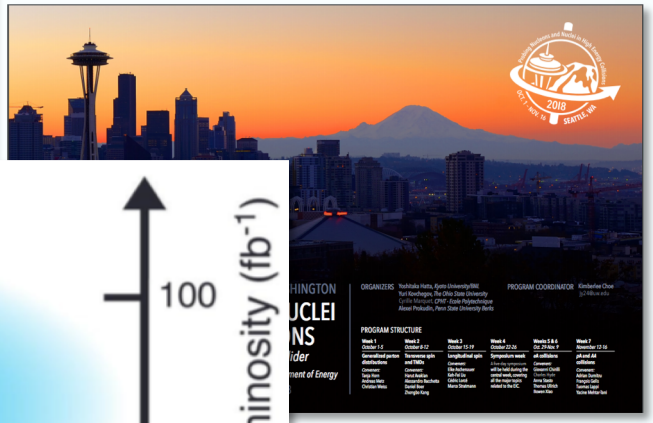
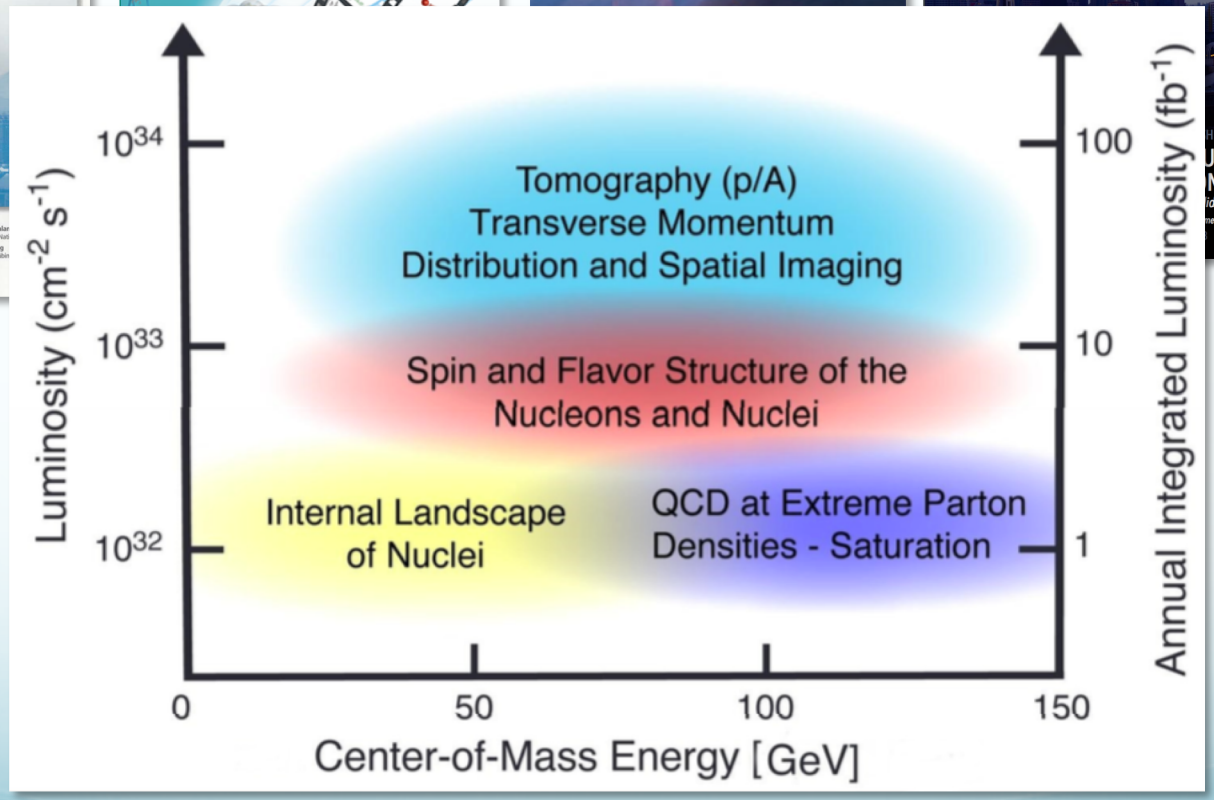




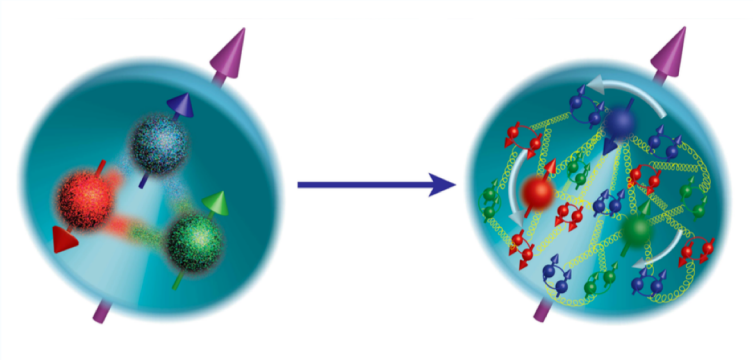




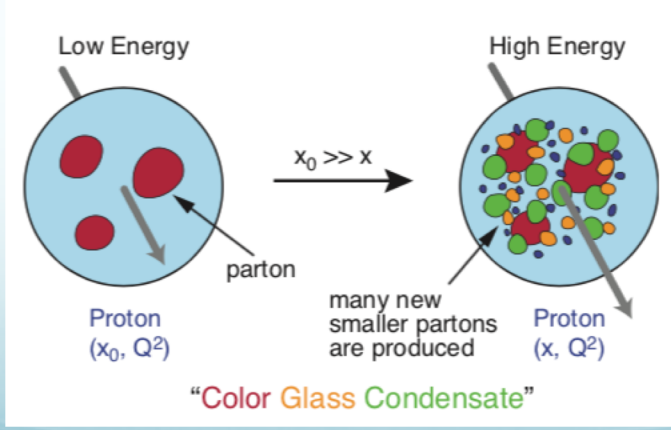
EIC Science Pillars: major ones

- Two major pillars
  - actively developed and developing at the moment (EIC white paper)

❖ Quantum Tomography of protons and nuclei



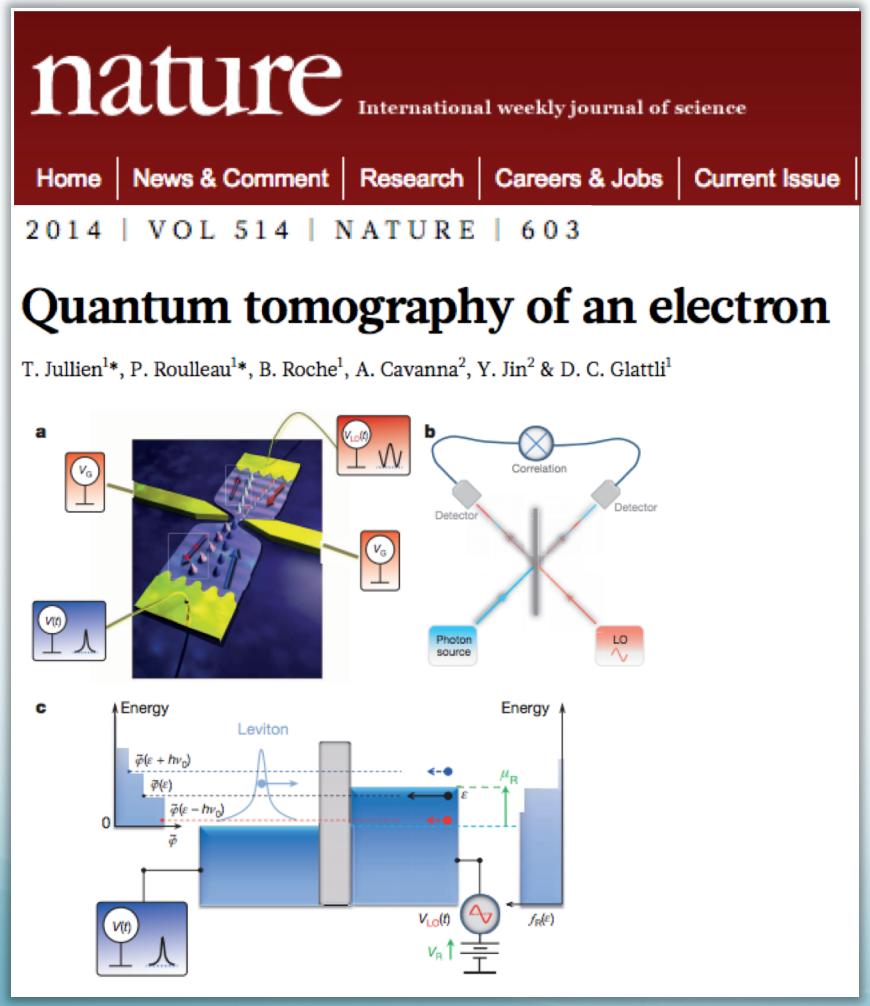
❖ A new form of matter - color glass condensate



major pillar: quantum tomography of nucleons and nuclei

Quantum Tomography

- Usually people in AMO or condensed matter physics, material science talks about quantum tomography



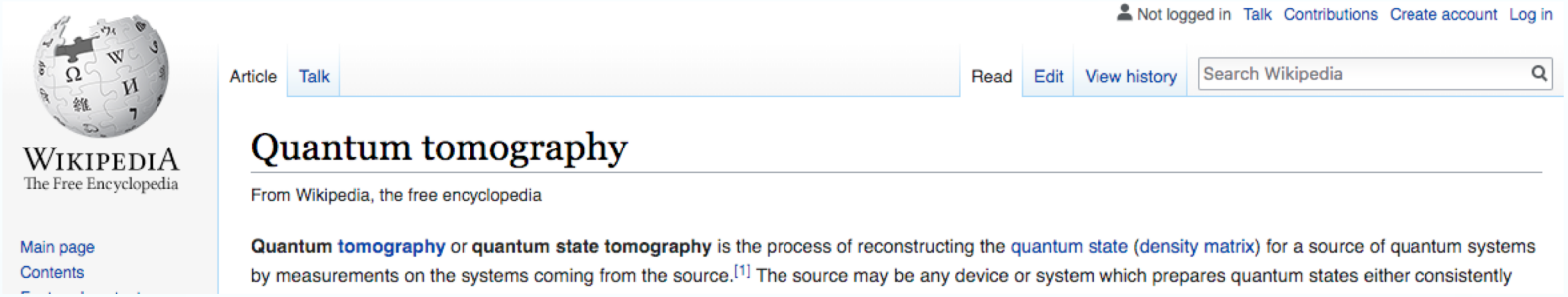
Complete knowledge of a quantum state as given by a wavefunction $|\psi\rangle$

allows the prediction of the probability of all possible measurement outcomes

A crucial step in quantum mechanics

Wikipedia

- Quantum tomography is the process of reconstructing the quantum state for a source of quantum systems by measurements on the systems coming from the source



- Wigner function W(p, r): contains needed information of the quantum state

Phase-space distribution and Wigner function

- The state of a classical particle is specified by its momentum and position (p, r) – phase-space
- In quantum physics, because of uncertainty principle, such phase-space distributions seem useless, ...
- A quantum version of such a phase-space distribution
  - Wigner, 1932

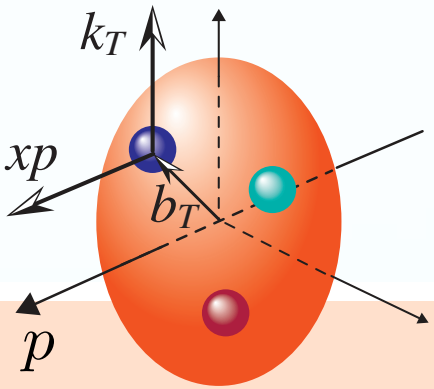
$$W(p,r) = \int dy\, e^{ip\cdot y}\, \psi^*\left(r + \frac{y}{2}\right)\, \psi\left(r - \frac{y}{2}\right)$$

  - Integrate over r (p), one gets the momentum (coordinate) probability density
  - Not positive definite in general (only in classical limit)
  - Contains information about a quantum system

X. Ji, 2003

Unified view: internal landscape

- Wigner distributions: a quantum version of phase-space distribution



5D

$W(x,b_T,k_T)$
Wigner Distributions

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

3D

Fourier trf.
$b_T \leftrightarrow \Delta$

$\xi = 0$

$f(x,k_T)$
transverse momentum distributions (TMDs)
semi–inclusive processes

$f(x,b_T)$
impact parameter distributions

$H(x,0,t)$
$t=-\Delta^2$

$H(x,\xi,t)$
generalized parton distributions (GPDs)
exclusive processes

1D

$\int d^2k_T$ $\int d^2b_T$ $\int dx$ $\int dx x^{n-1}$

$f(x)$
parton densities
inclusive and semi–inclusive processes

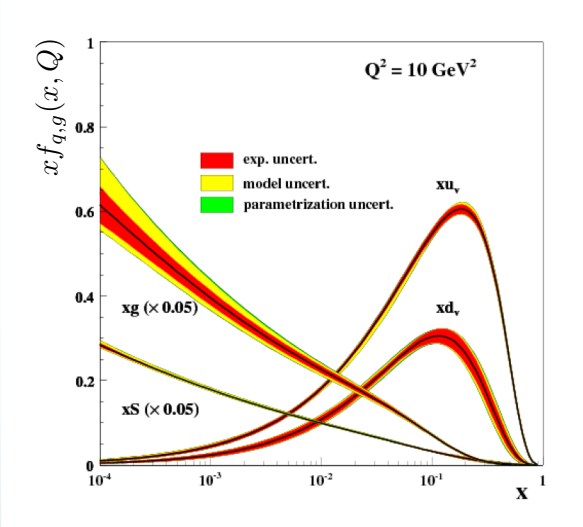
$F_1(t)$
form factors
elastic scattering

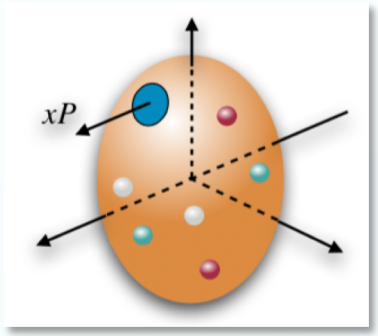
$A_{n,0}(t)+4\xi A_{n,2}(t)+....$
generalized form factors
lattice calculations

Now 3D structure

- 1D: 30+ years study, but no correlation at all
- Proton 3D structure: both longitudinal + transverse

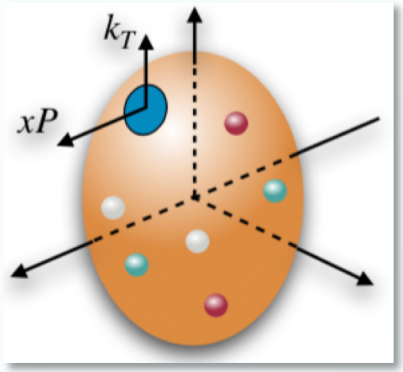
Transverse Momentum Dependent parton distributions (TMDs)





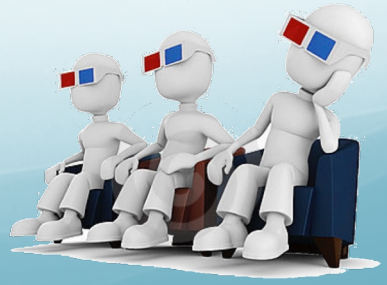
$f(x)$

Longitudinal motion only



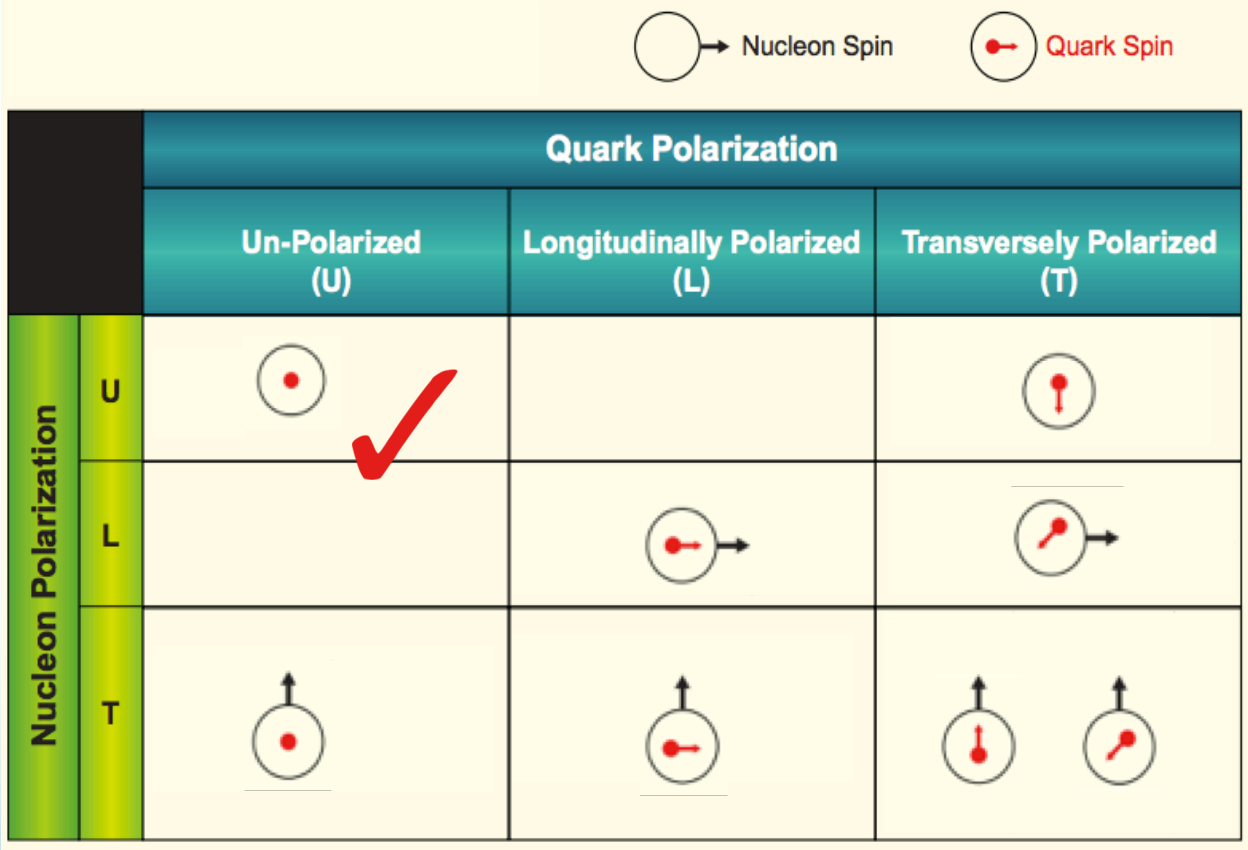
$f(x, k_T)$

Longitudinal + transverse motion



TMDs: much richer structure

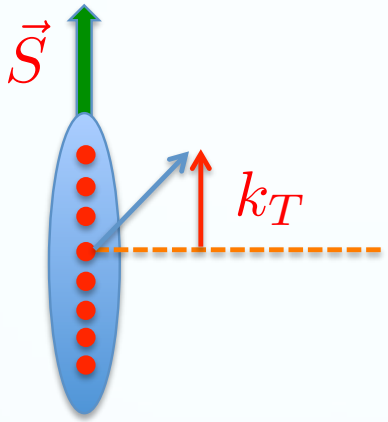
- Quark: 8 TMDs in high energy limit
  - Quantum correlations: spin-spin, spin-orbital, orbital motion, quantum phase interference, …



Using the proton as a QCD "laboratory"

Sivers function: a spin-momentum correlation

- Sivers function: unpolarized quark distribution inside a transversely polarized proton

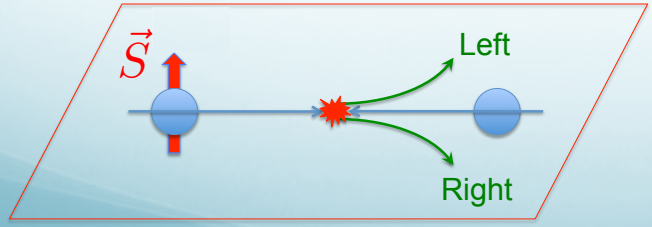


$$\vec{S} \cdot (\hat{p} \times \mathbf{k}_T)$$

Sivers function

Sivers effect

left-right asymmetry



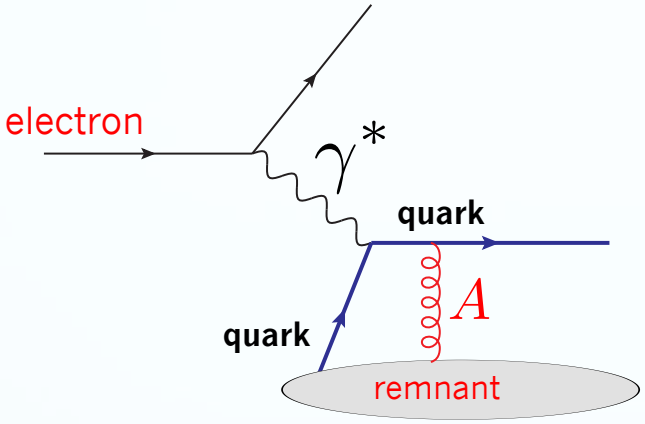
Look closer

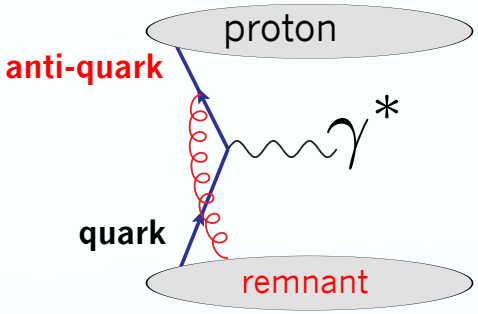
- ✓ **Naïve time-reversal-odd**: recall momentum and spin change sign under T
- ✓ **Forbidden?**: such a correlation is forbidden in QCD, unless there is a phase

Recall: $\hat{T}\psi(t) \rightarrow \psi^*(-t)$

Quantum mechanical phase

- Quark passes through a color gauge field, generated by the remnant of the proton, it will accumulate a phase





DIS: after the interaction
final state

Drell-Yan: before the interaction
initial state

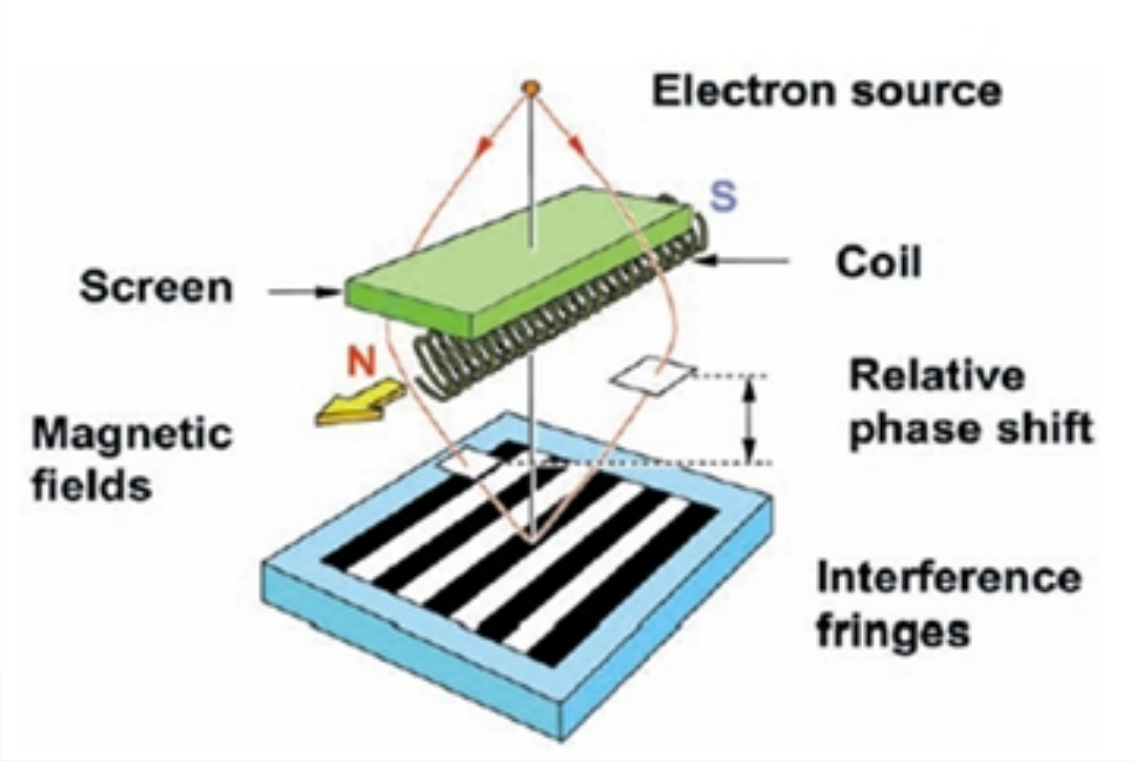
$$e^{i\phi} \qquad \phi = g_s \int_{\text{path}} dr \cdot A$$

$$\text{Sivers function}\big|_{\text{DIS}} = (-)\,\text{Sivers function}\big|_{\text{DY}}$$

Collins 02, Boer-Mulders-Pijlman 03, Collins-Metz 04, Kang, Qiu, PRL 09, ...

Sivers effect: QCD version of Aharonov-Bohm effect

- Pure quantum effect: different paths lead to interference

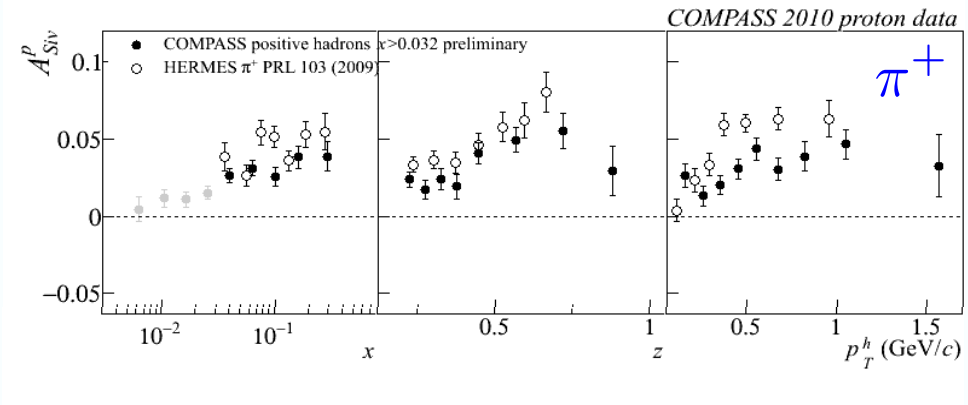


- Physics today, September 2009

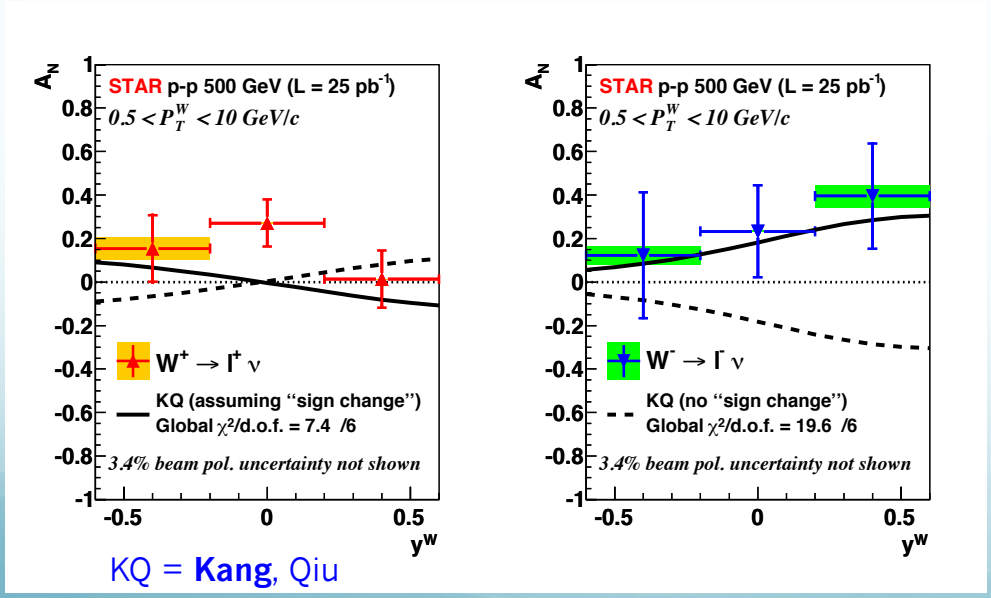
$$\Psi = \Psi_1 \, e^{i\phi_1} + \Psi_2 \, e^{i\phi_2} \qquad \phi_i = e \int_{\text{path i}} d\vec{r} \cdot \vec{A}$$

Sivers asymmetry from SIDIS and W

- Sivers asymmetry has been measured in DIS process

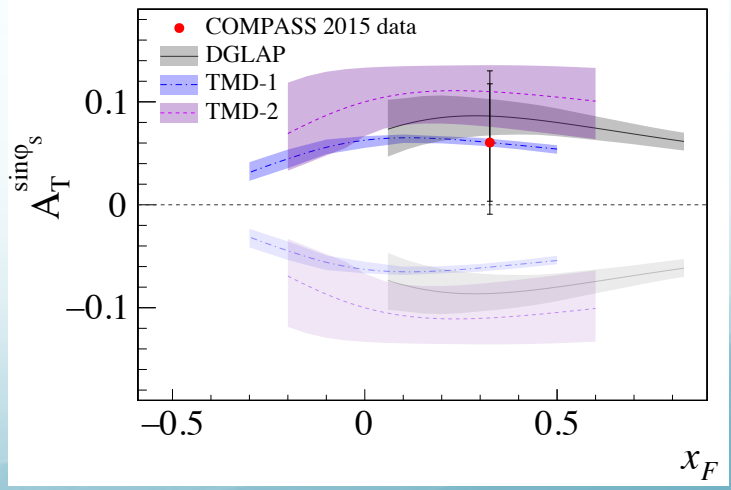


- Predictions comparison with DY/W



KQ = **Kang**, Qiu

Echevarria, **Kang**, et.al., 2014
COMPASS, PRL, 2017



STAR, PRL, 2016

Sivers asymmetry from SIDIS and W

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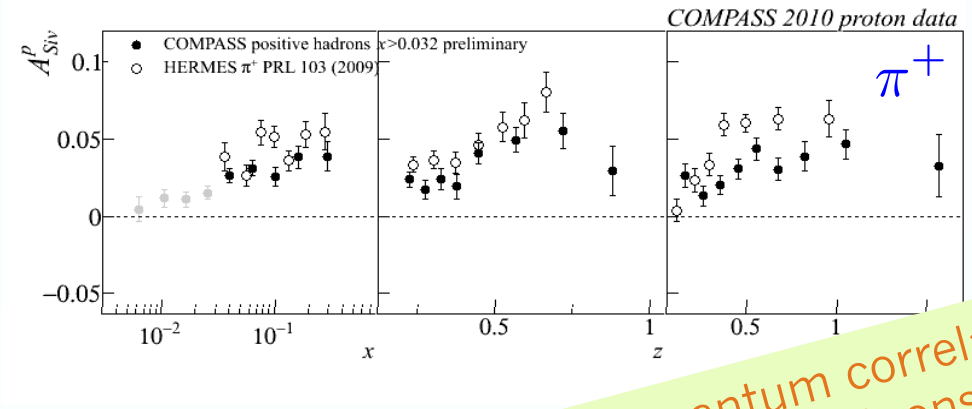
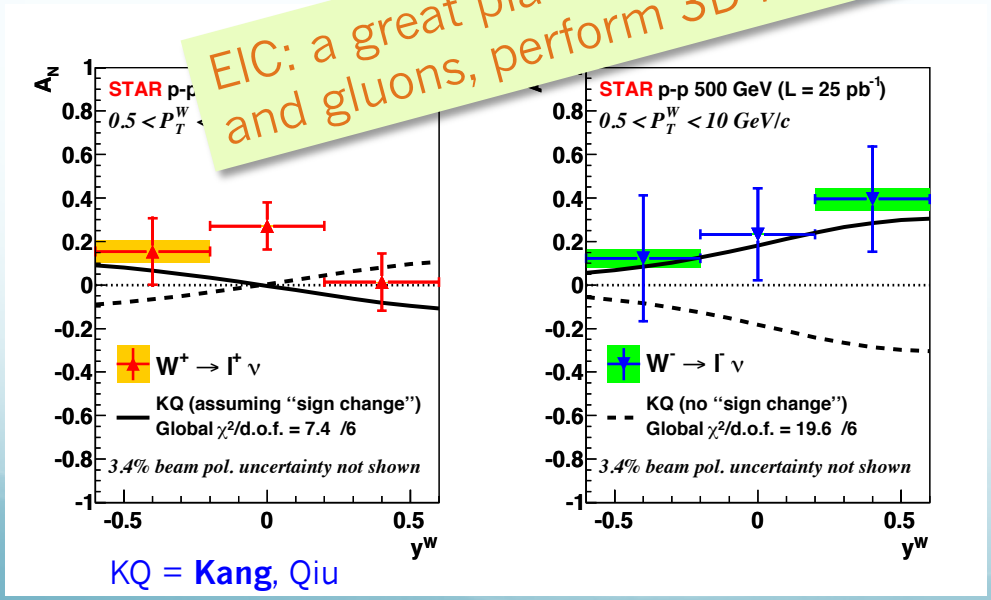


- Predictions compari

EIC: a great place to study quantum correlations for both quarks and gluons, perform 3D imaging of gluons in particular



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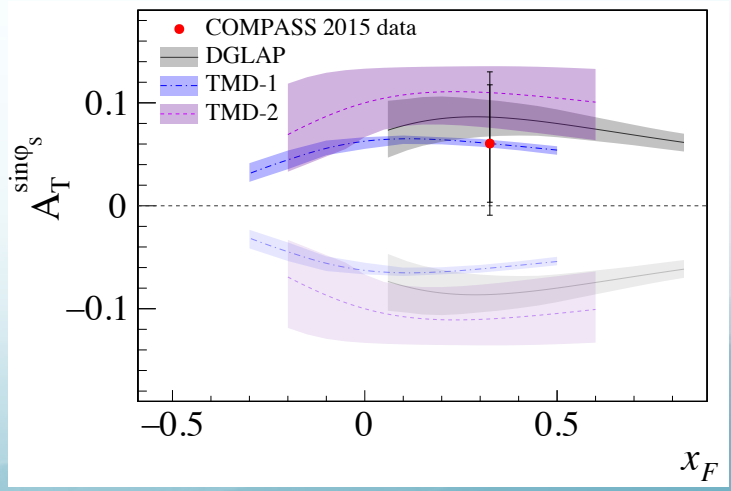


EIC: wider kinematic range

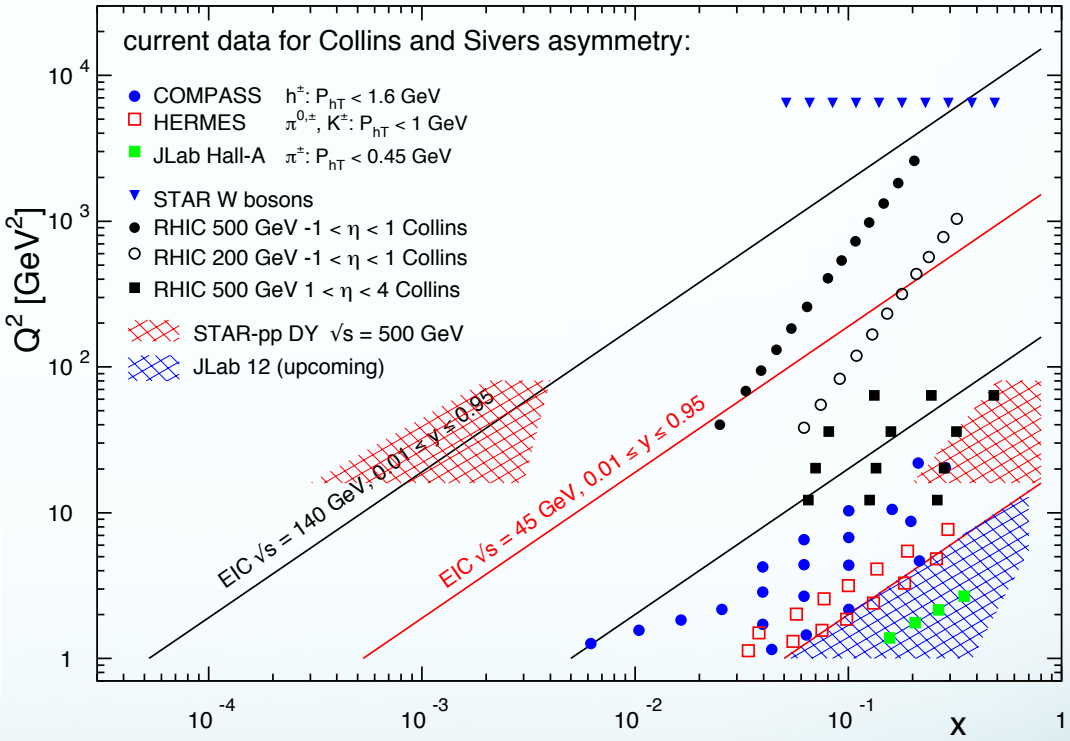
For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity $L_{ep} \sim 10^{33\text{-}34}$ 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

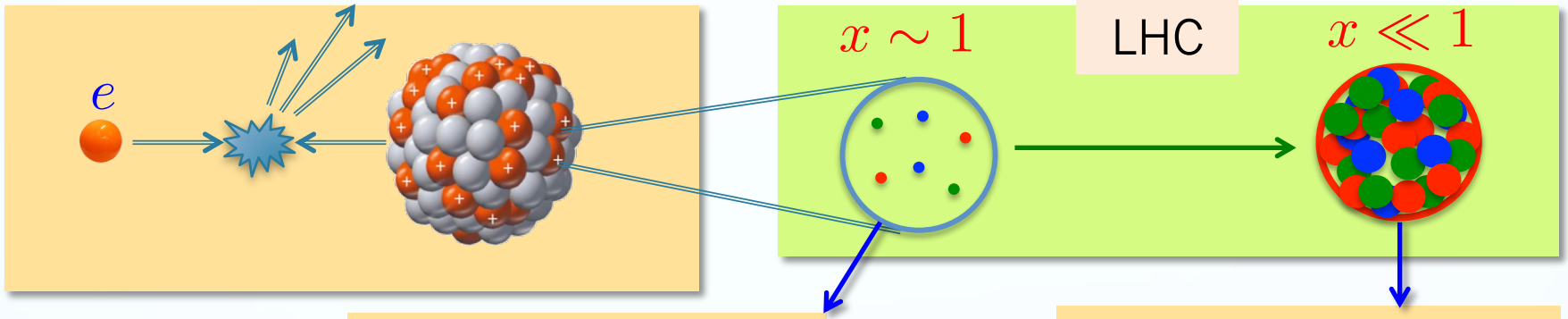
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider



major pillar: a new form of matter
color glass condensate

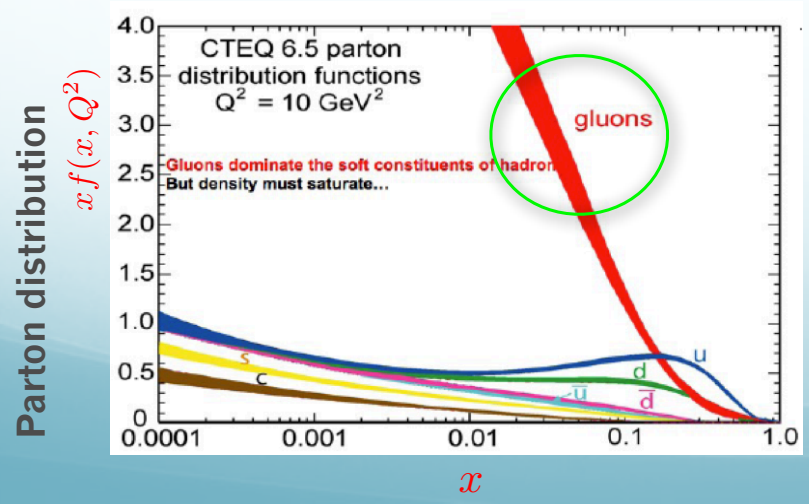
QCD structure of nucleons/nuclei revealed by high energy scattering

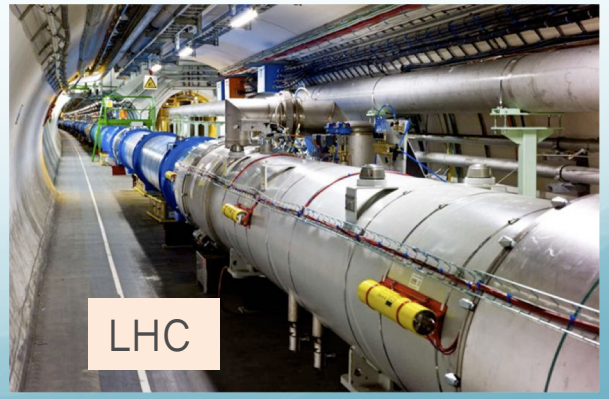
$$x = \frac{\text{parton (gluon) longitudinal momentum}}{\text{proton longitudinal momentum}}$$



- A dilute system
- Probes interact independently

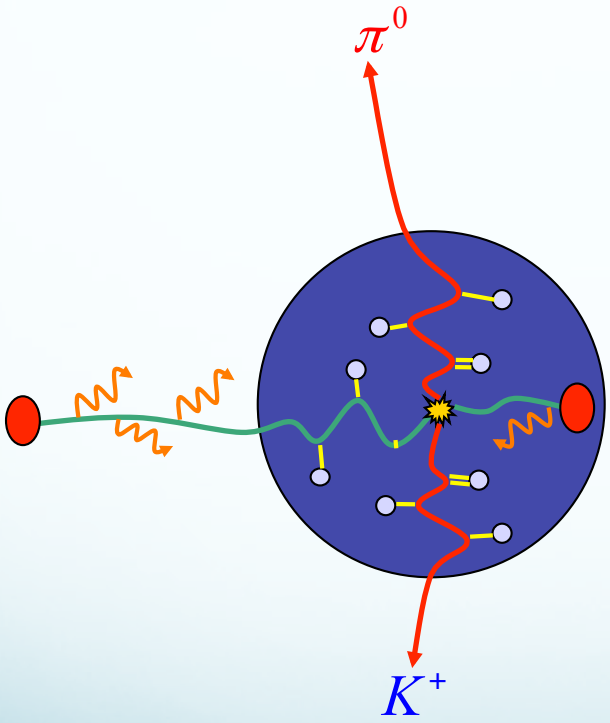
- A dense system
- Probes interact coherently

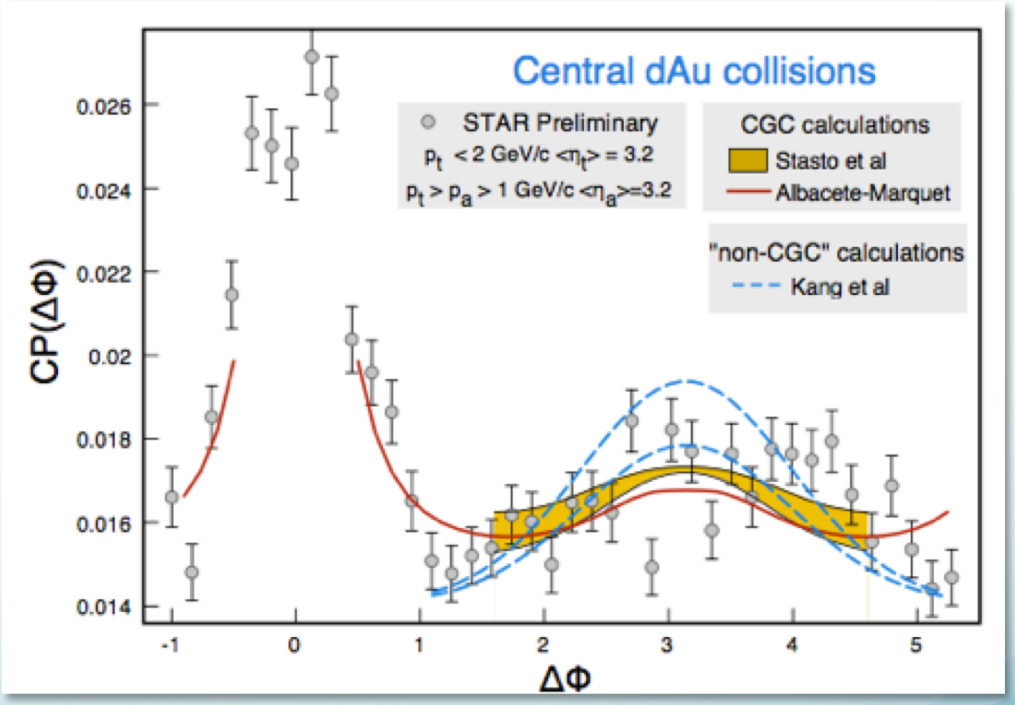




Early hints on gluon saturation

- Strong multiple scattering with the dense gluon system of the nucleus leads to broadening and suppression of away side
  - Different formalisms would lead to similar predictions

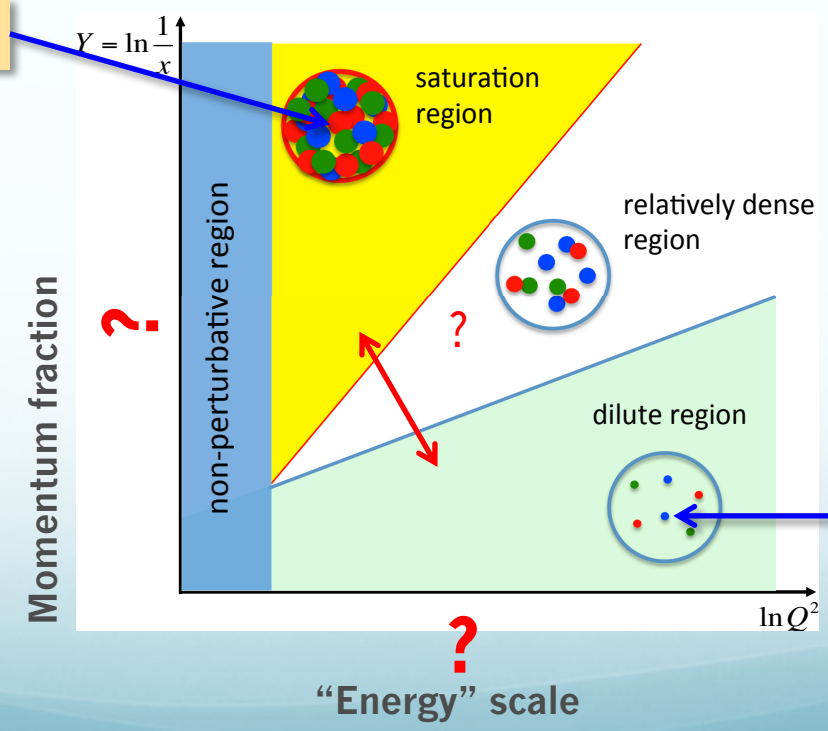




QCD phase diagram

- Where and how does the transition from a dilute parton system to a coherent dense gluon-dominated state occur?
- What are the properties of such a dense gluon regime?

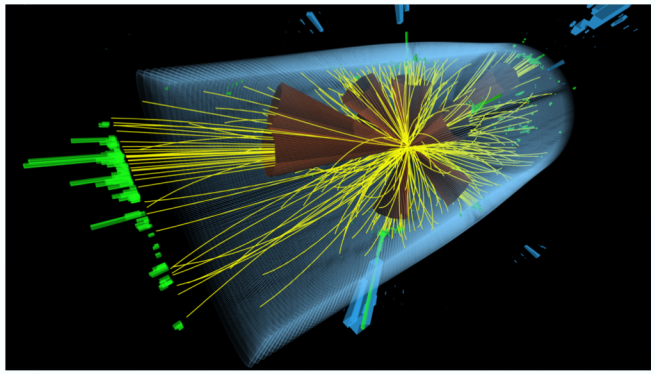
EIC would figure out



Historically very successful, factorization, perturbative QCD

EIC Science Pillars: minor ones

- Two minor pillars
  - Under active development (beyond EIC white paper)
    - ❖ High energy QCD: e.g., jets, jet substructure in ep/eA collisions



    - ❖ Beyond Standard Model Physics: e.g., charged lepton flavor violation (related to Majorana neutrino), weak neutral current coupling, dark photon, …

minor pillar: High energy QCD (jets)

Purposes of jet/QCD studies in DIS

- I: Studying QCD/jets to probe
  - Fundamental parameters of QCD: strong coupling constant
  - Parton structure of proton
  - Signature for BSM physics

NNLO + resummation

- II: Studying QCD/jets to probe QCD medium
  - Cold nuclear matter in e+A collisions
  - Hot quark-gluon plasma in A+A collisions

NLO + resummation is probably sufficient at the moment

First e+A jet measurements are still yet to come at EIC

Too many effects need to be taken into account in A+A

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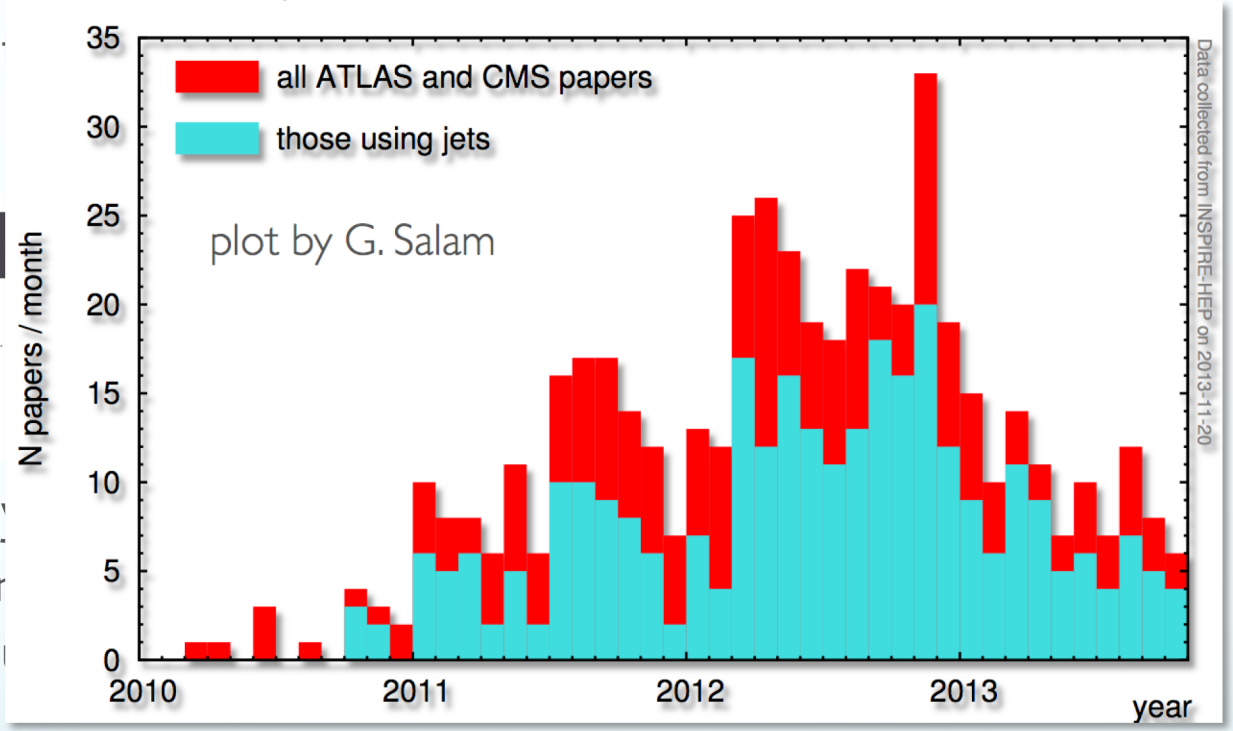

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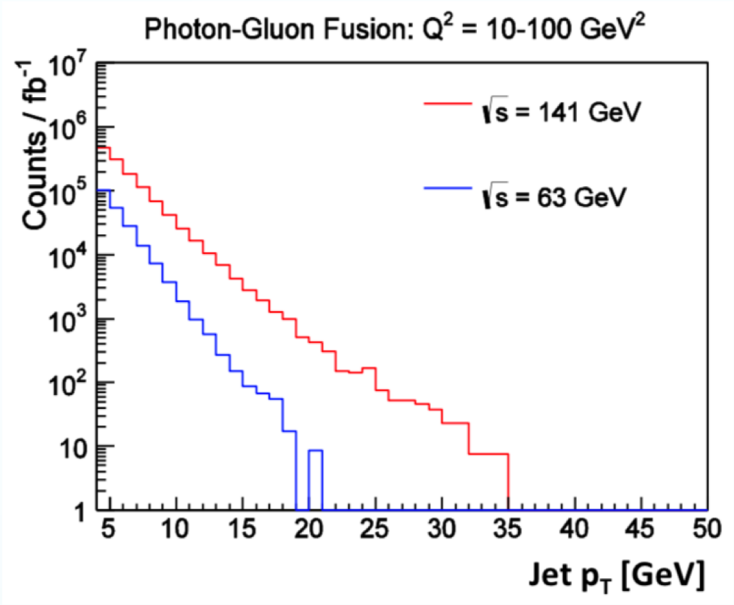
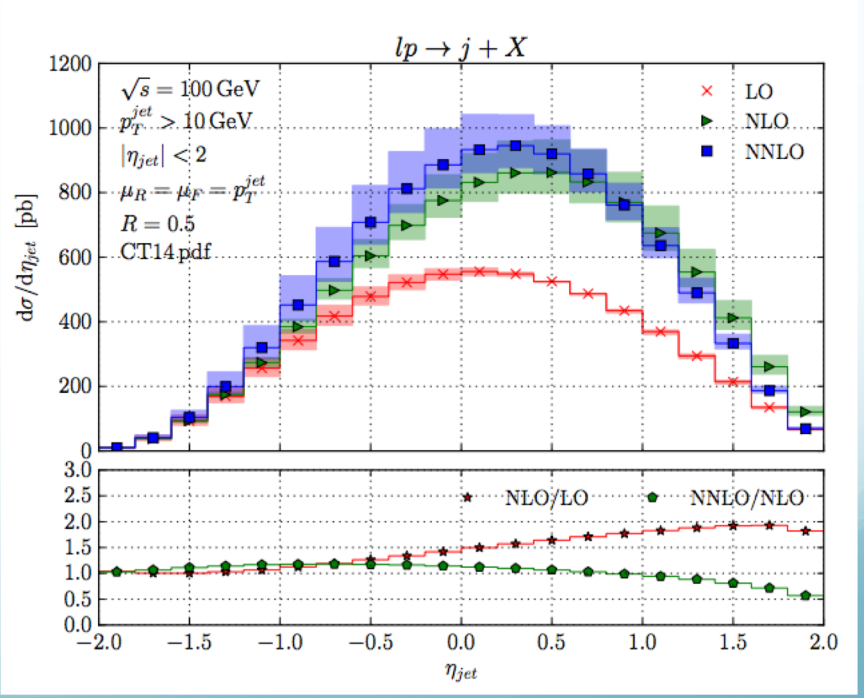
Jet physics is promising at EIC

- Plots from EIC team at BNL

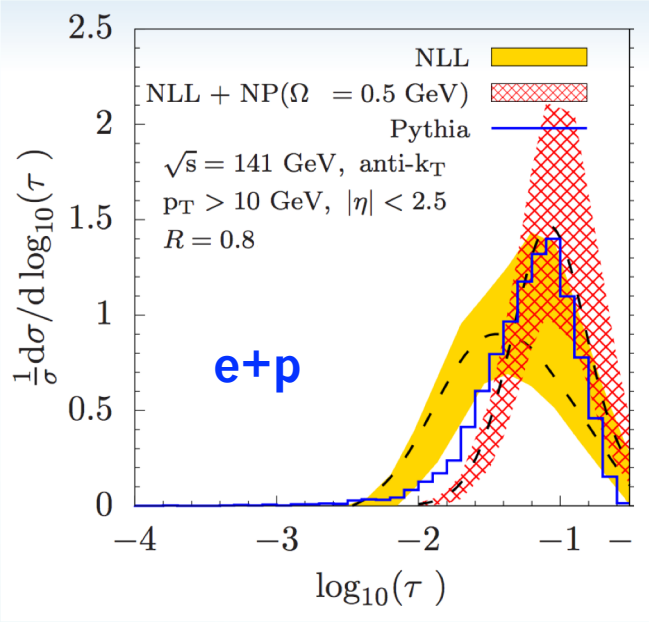


Theory at NNLO, Abelof-Boughezal-Liu-Petriello, 2018

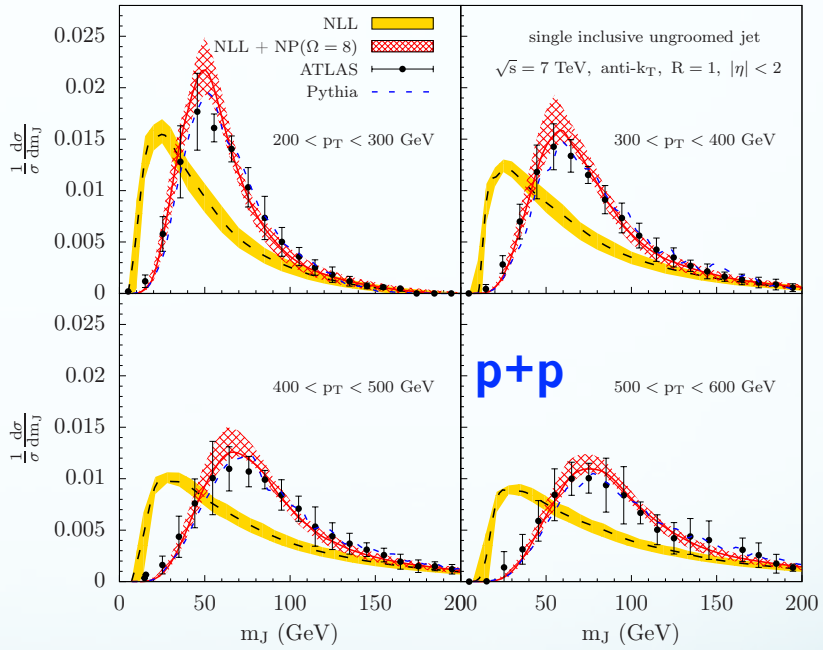


Jet at EIC: cleaner environment

- Computation and comparison with event generator
  - e+A collision is much cleaner environment, likely the main non-perturbative contribution is hadronization effects



Kyle Lee, with help from B. Page, E. Aschenauer



Kang, Lee, Liu, Ringer, JHEP, 2018

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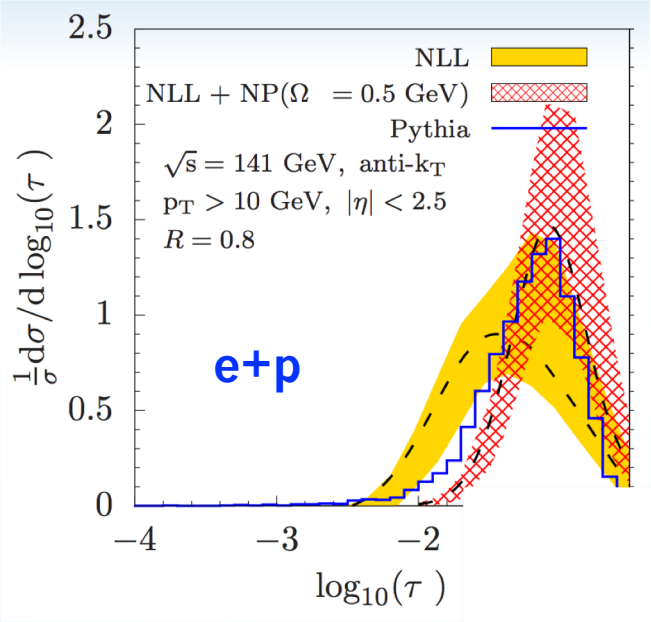
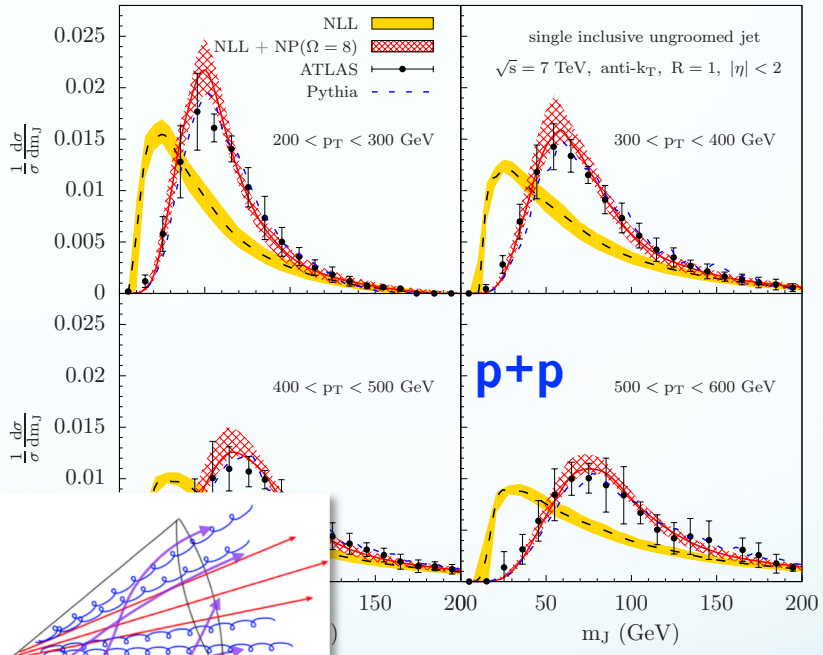
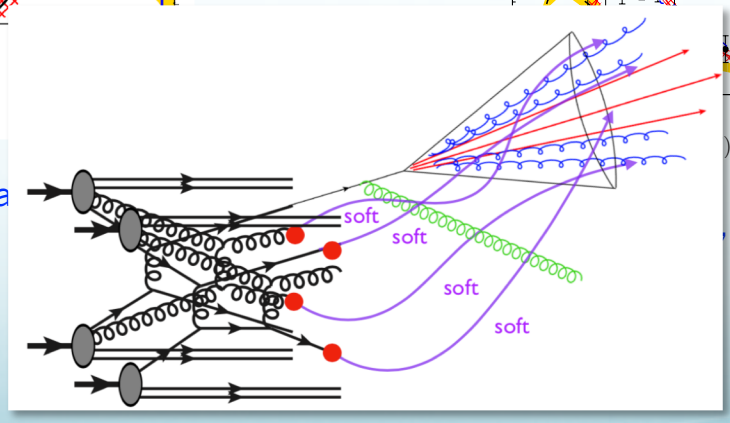






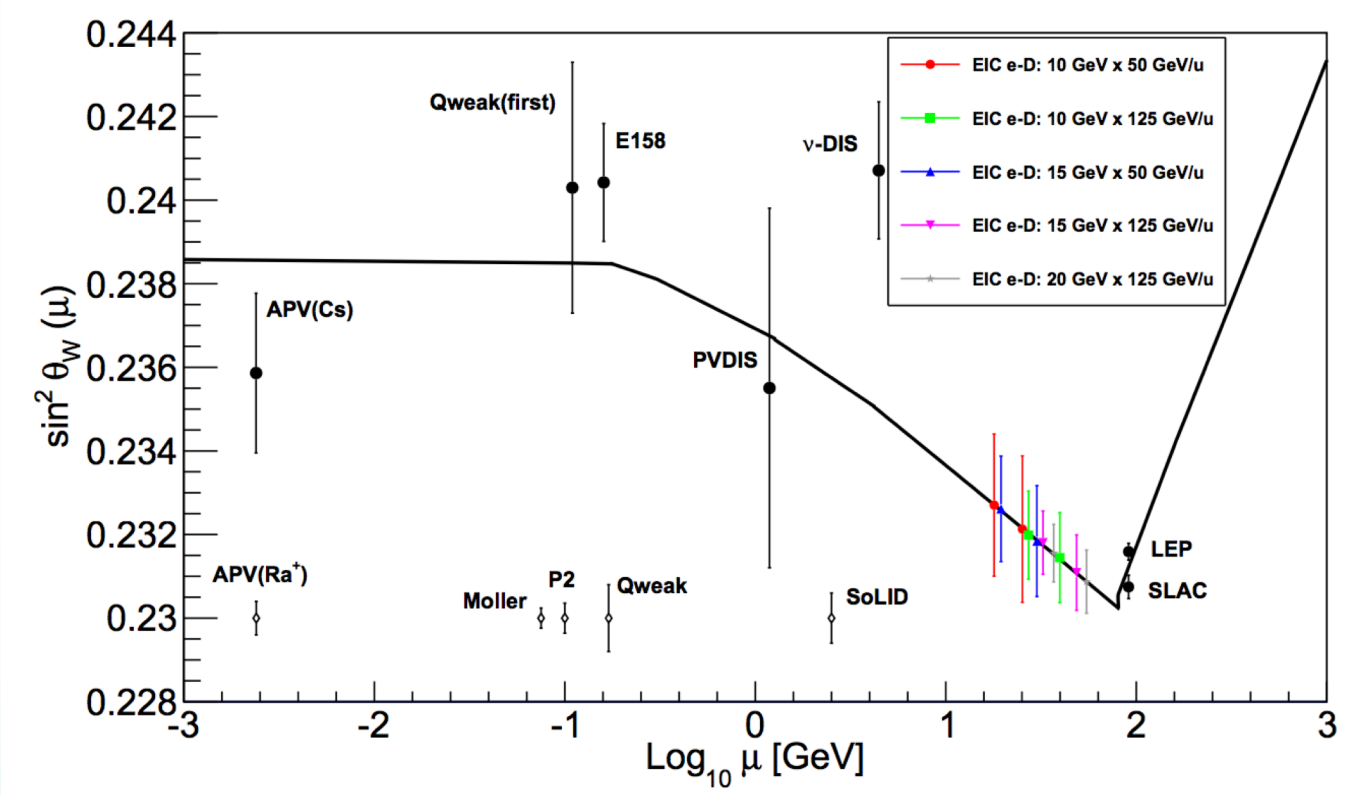
Kyle Lee, with help from B. Pa

, Liu, Ringer, JHEP, 2018

minor pillar: BSM Physics

The Weinberg angle

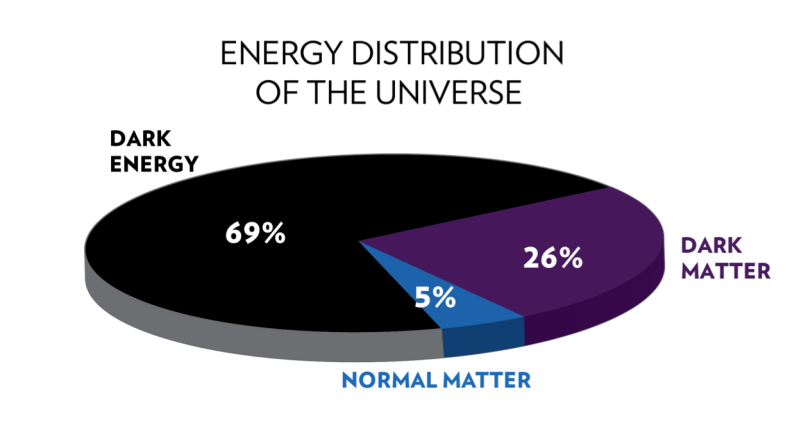
- The weak mixing angle or Weinberg angle



Zhao, Deshpande, Huang, Kumar, Riordan, EPJA, 2017

Dark matter at EIC

- Dark matter exist (observed via gravity)



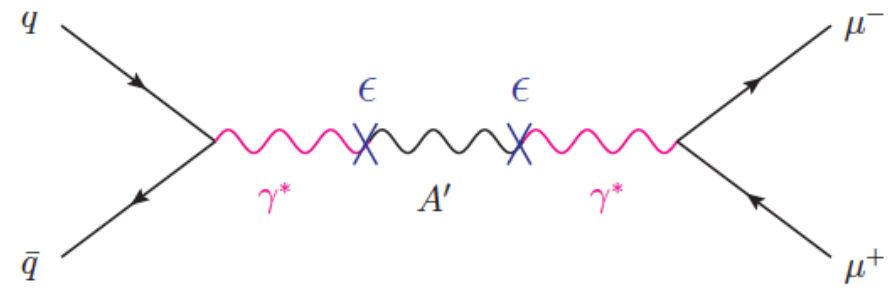
- How to look for dark matter
  - Three "portals" to dark sectors

Vector Portal	$\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$	Most visible	Dark photons
Higgs Portal	$\epsilon_h \lvert h\rvert^2 \lvert\phi\rvert^2$	exotic rare Higgs decays rare meson decays	
Neutrino Portal	$\epsilon_\nu (hL)\psi$	not-so-sterile neutrinos	

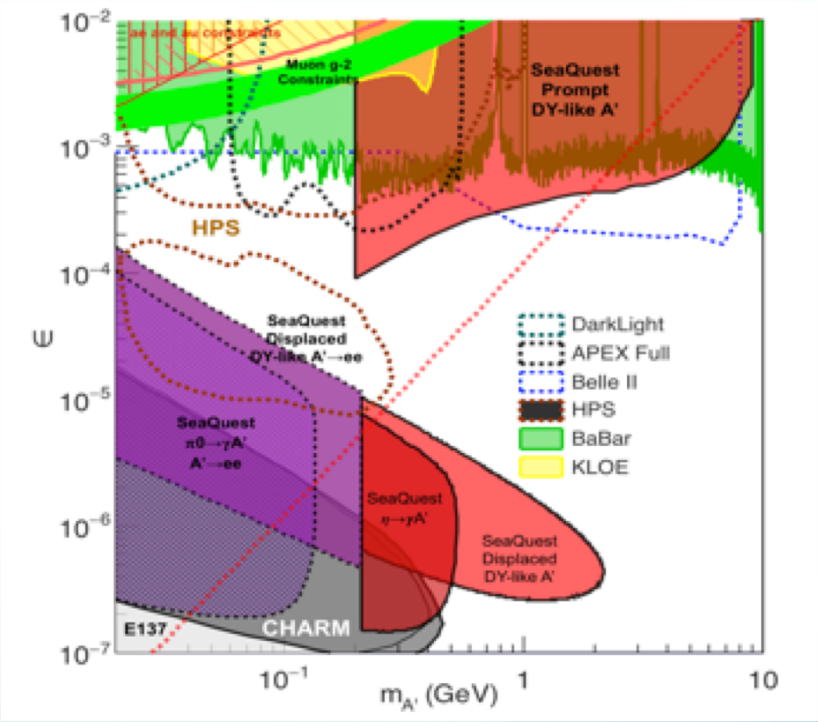
Dark photon search

- Dark photon at Fermilab via SeaQuest
  - Drell-Yan type process to search for dark photon in p+A collisions

Highlighted at an overview talk by N. Toro at "Dark Interactions 2016"
See also: Berlin, Gori, Schuster, Toro, PRD, 2018



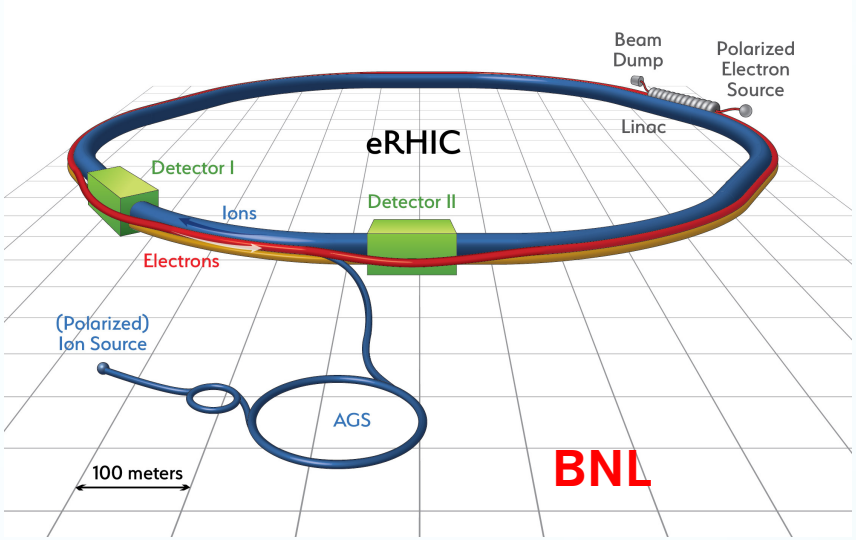
- Dark photon search at EIC
  - R. Milner (DarkLight spokesperson)
  - Significant interest among collaboration

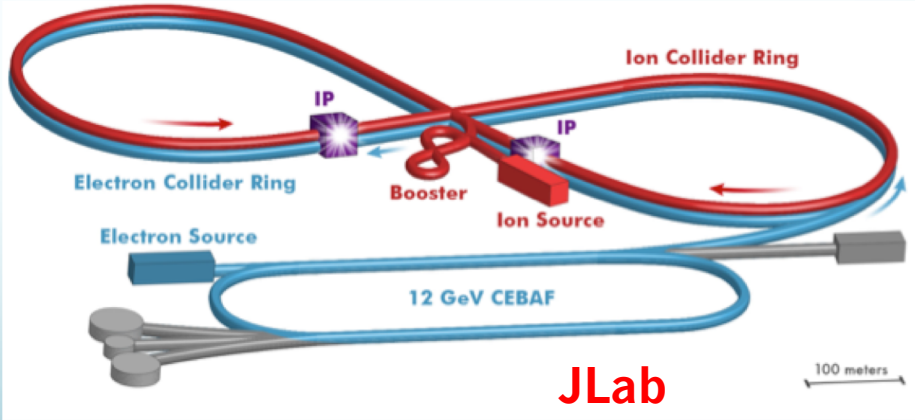


M. Liu, K. Liu, et.al., 2016

EIC designs: BNL and JLab

- Variable CM energies: 20 – 100 GeV
  Upgradable to 140 GeV
- Collision luminosity: $10^{33\text{-}34}$ $cm^{-2}s^{-1}$
- Polarized (~70%) electrons, protons, and light nuclei





Summary

Electron Ion Collider (EIC) is the next QCD frontier

Exciting physics opportunities ahead of us

Thank you!