Transformative Measurements with Nuclei

EIC Physics with the ALERT Detector before the EIC

Whitney R. Armstrong

Argonne National Laboratory

July 21, 2017

Nuclear Physics and the ~~Nucleon~~ α Particle

From the **first textbook on nuclear physics**

"The general evidence on nuclei strongly supports the view that **the α particle is of primary importance as a unit of the structure of nuclei** in general and particularly of the heavier elements. It seems very possible that the greater part of the mass of heavy nuclei is due to **α particles which have an independent existence in the nuclear structure**."

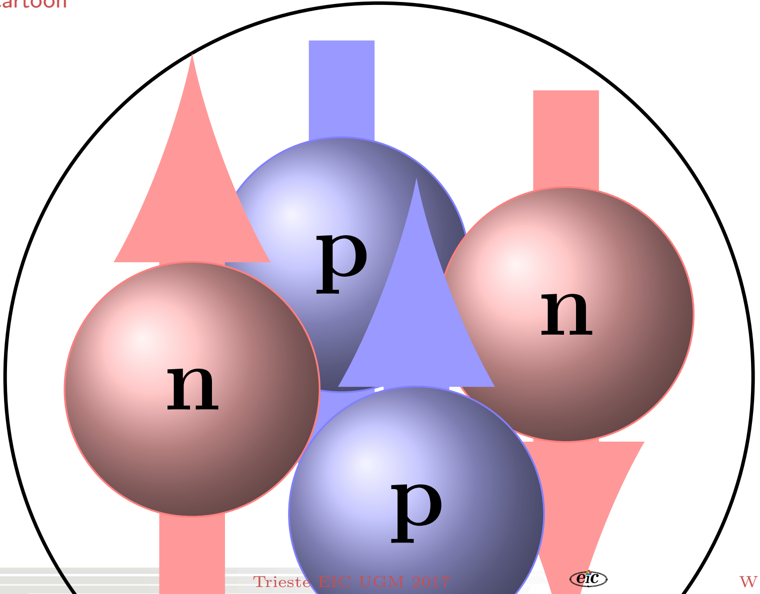
— Rutherford, Chadwick, and Ellis (1930)

Note: this is roughly **2 years before the discovery of the neutron.**

Knowledge of the basic (nucleonic) structure of the α (i.e. 2p+2n) **transformed our understanding of nuclei.**

The Partonic Structure of the α Particle

A cartoon



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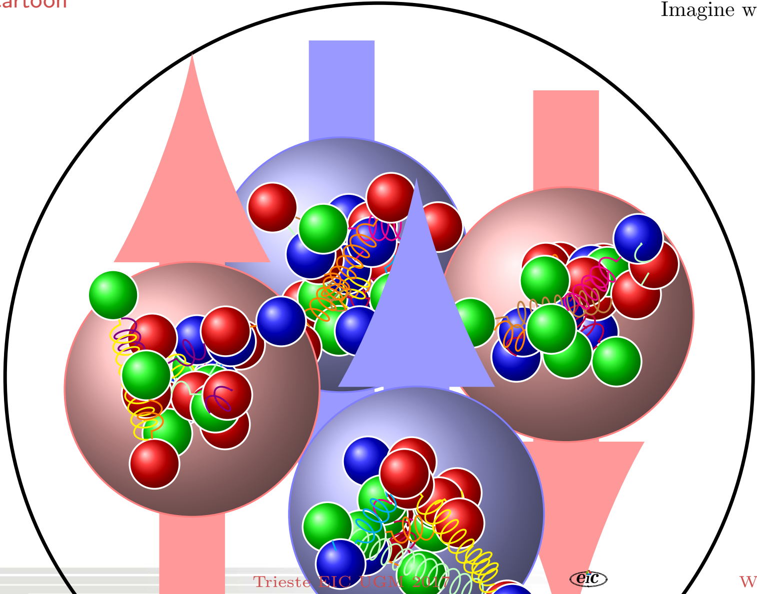

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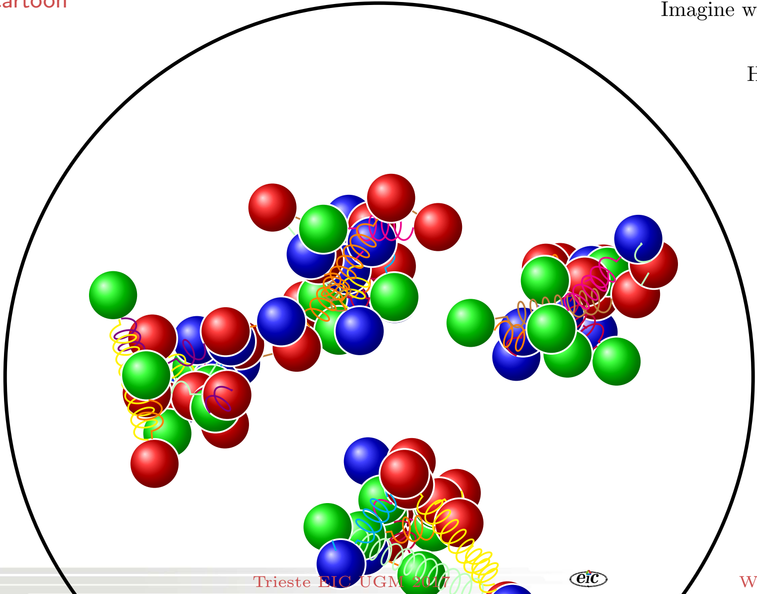

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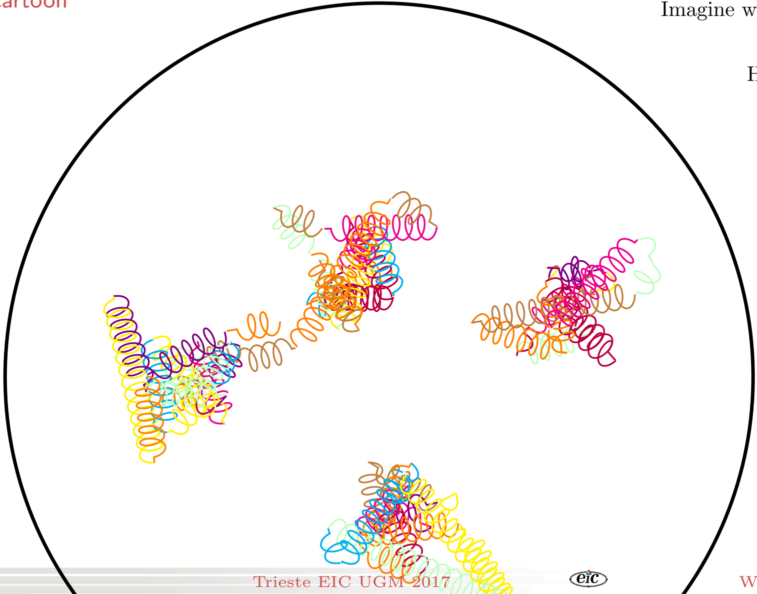

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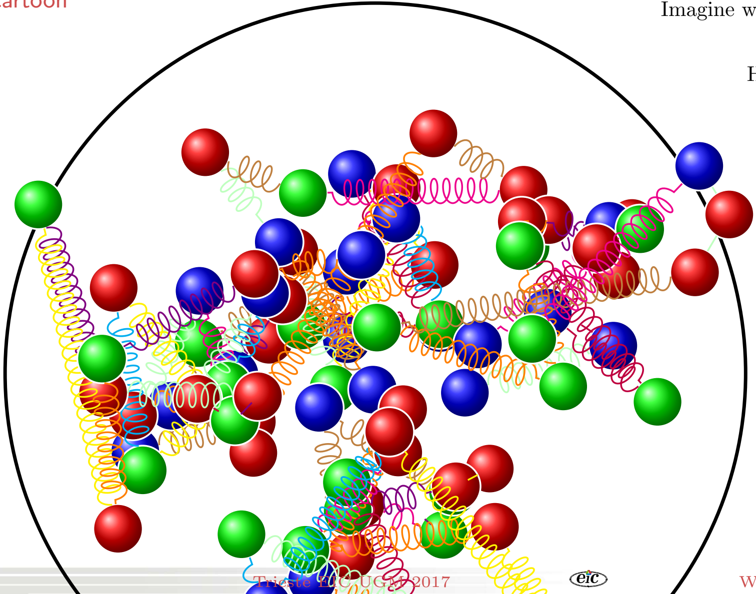

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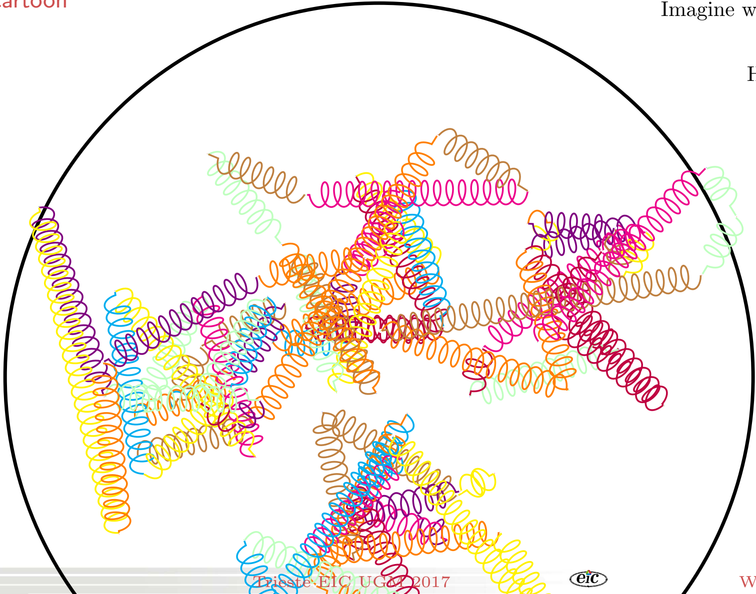

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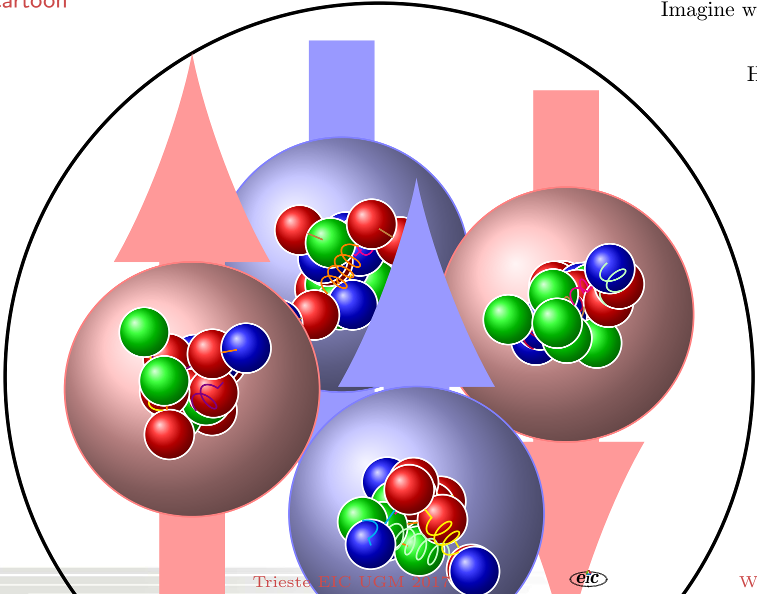

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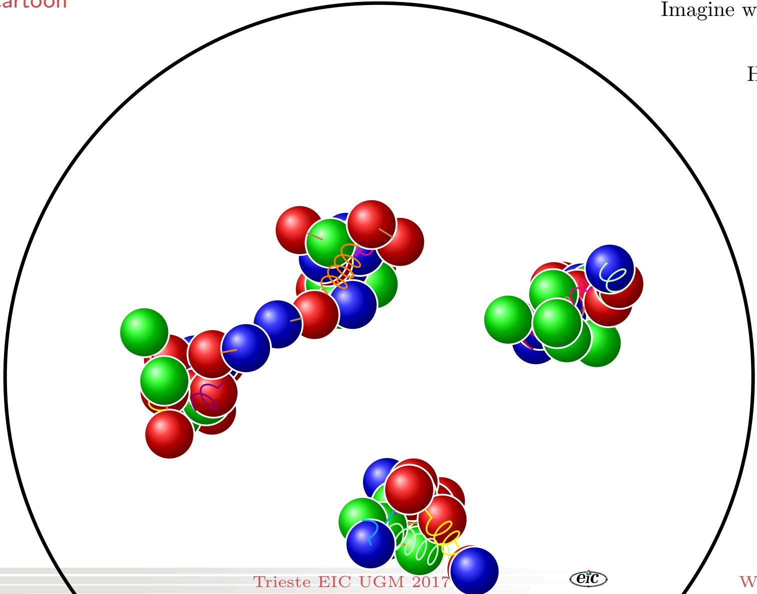

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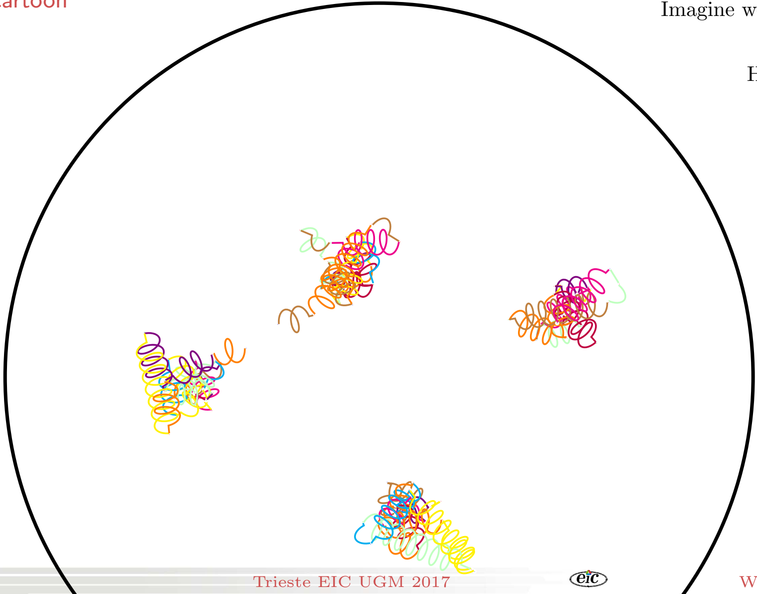

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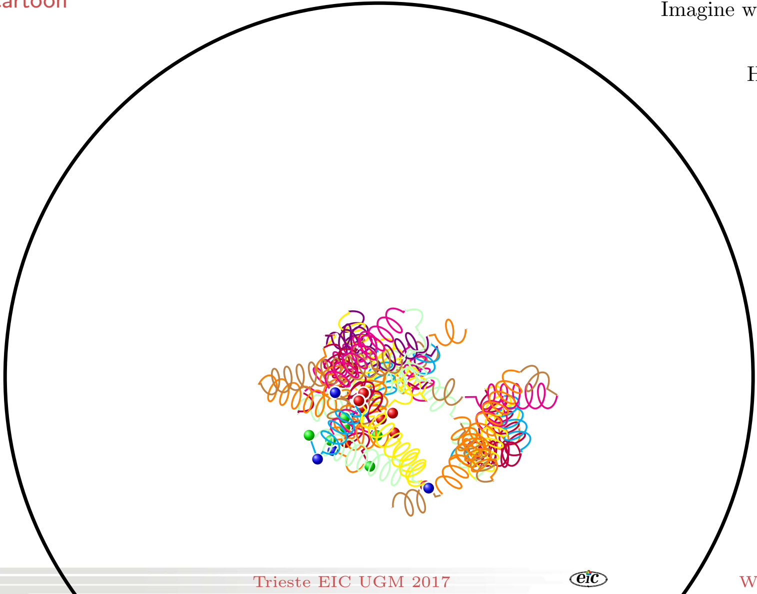

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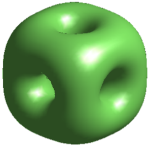
Nuclear Physics and the α Particle

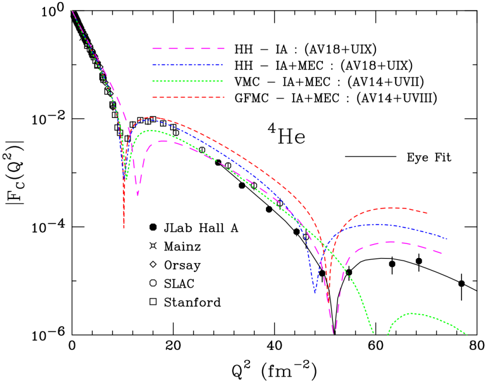
Some things we know.

- Spin-0 $\rightarrow$ Only charge form factor
- Tightly bound system $\rightarrow$ smaller radius than ^{3}H and ^{3}He.
- Diffractive Minimum $\rightarrow$ nucleon clumps make diffraction grating



Skyrme Model

Karliner, et.al., J.Phys. G43 (2016) no.5, 055104



(Camsonne, et.al., PRL.112. 132503)

Hadron Tomography

The basic strategies using electron beams

Hadron Tomography

The basic strategies using electron beams

- Deep-Inelastic Scattering (DIS)
  $\rightarrow$ **1D** - Longitudinal parton momentum distribution
- Elastic Scattering
  $\rightarrow$ **2D** - Transverse charge distribution integrated over all x
- Deeply Virtual Compton Scattering (DVCS)
  $\rightarrow$ **3D** - Transverse **quark** distribution at fixed x
- Deeply Virtual Meson Production (DVMP)
  $\rightarrow$ **3D** - Transverse **gluon** distribution at fixed x

x = fraction of hadron's LC momentum carried by parton

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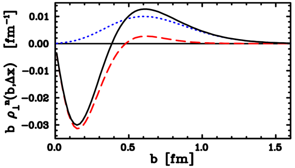
Key insight - G. Miller

FT is 2D (not 3D) yielding **transverse** charge distributions.

$$\rho_\perp(b_\perp) = \int \frac{d^2q}{(2\pi)^2} e^{i\boldsymbol{q}\cdot\boldsymbol{b}_\perp} F_1(Q^2)$$

As $x \to 1$:

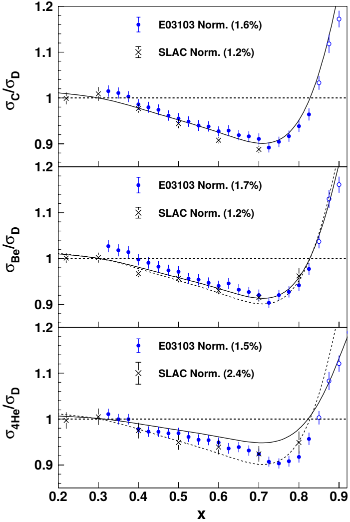
- proton - all momentum carried by u-quark at center (positive)
- neutron - all momentum carried by d-quark at center (negative)



Miller and Arrington, Phys.Rev. C78 (2008) 032201

neutron $x > 0.23$ is the dashed, $x < 0.23$ is dotted

EMC Effect



J. Seely et al. Phys.Rev.Lett. 103 (2009) 202301

EMC Effect in DIS

- Is structure function modified?
- Significant even in ^{4}He!
- Origin of effect remains unclear

The oldest and most important nuclear effect is still puzzling.

The ALERT Experiments

A comprehensive program to study nuclear effects

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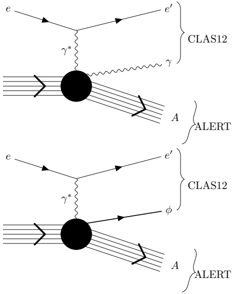
Coherent Processes on ^{4}He

- $^4\mathrm{He}(e, e'\ ^4\mathrm{He}\ \gamma)$
- $^4\mathrm{He}(e, e'\ ^4\mathrm{He}\ \phi)$

Explores the partonic structure of ^{4}He



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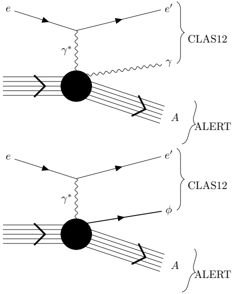
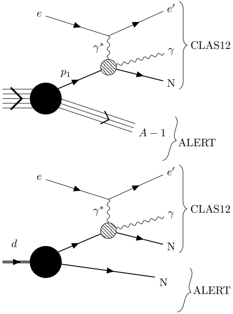


Incoherent processes on ^{4}He and ^{2}H

- $^4\mathrm{He}(e, e'\gamma\, p + {}^3\mathrm{H})$
- $^4\mathrm{He}(e, e'\gamma + {}^3\mathrm{He})n$
- $^2\mathrm{H}(e, e'\gamma\ + p)n$

Identify medium modified nucleons



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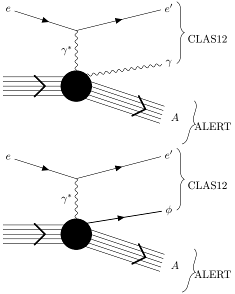

Incoherent processes on ^{4}He and ^{2}H

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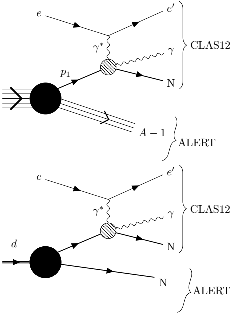
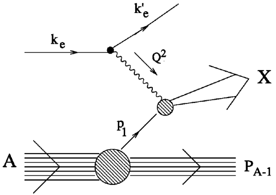


DIS on ^{4}He and ^{2}H : Tagged EMC Effect

- $^4\mathrm{He}(e, e'{+}^3\mathrm{H})\mathrm{X}$ (proton DIS)
- $^4\mathrm{He}(e, e'{+}^3\mathrm{He})\mathrm{X}$ (neutron DIS)
- $^2\mathrm{H}(e, e'\ + p)\mathrm{X}$ (neutron DIS)

Test FSI and rescaling models

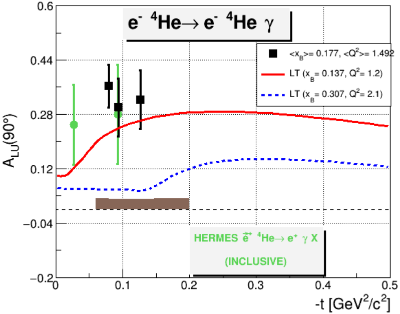


And many more channels for free

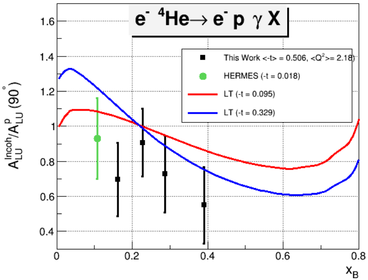
Previous Experiment: CLAS EG6

Coherent and incoherent DVCS results

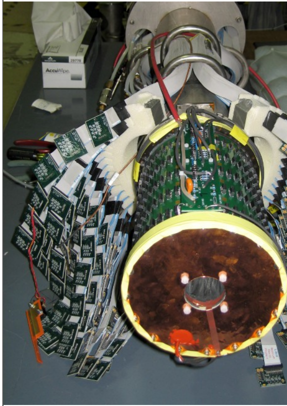
M.Hattawy's EG6 analysis



First exclusive coherent DVCS measurement on ^{4}He



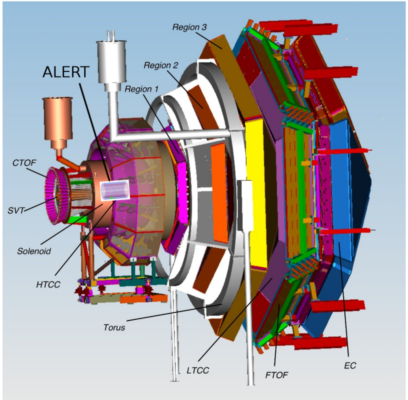
Incoherent DVCS measurement plagued by kinematic uncertainties
$\rightarrow$ need to tag spectators



ALERT Run Group

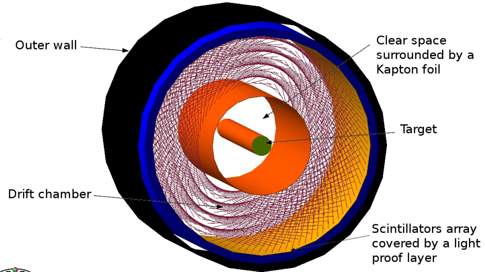
CLAS12 + ALERT detector

- Use CLAS12 to detect scattered electron, e', and forward scattered hadrons.
- A low energy recoil tracker (ALERT) will detect the spectator recoil or coherently scattered nucleus

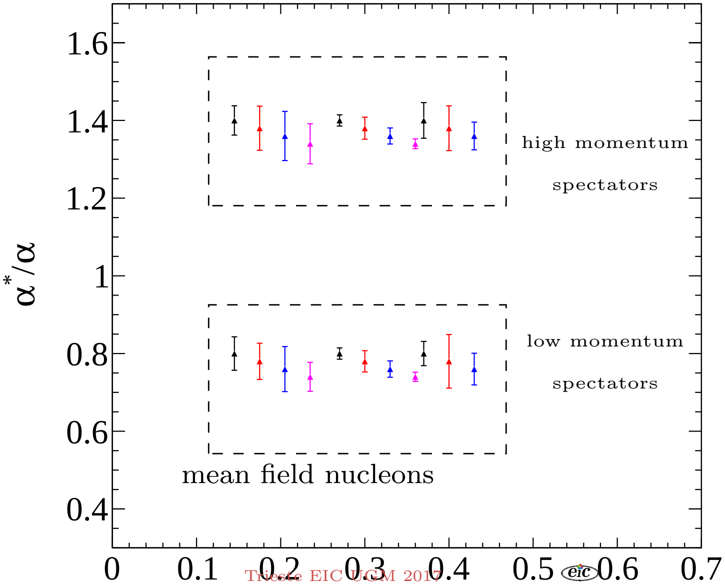


ALERT requirements

- Identify light ions: H, ^{2}H, ^{3}H, ^{3}He, and ^{4}He
- Detect the **lowest momentum** possible (close to beamline)
- Handle **high rates**
- Provide **independent trigger**
- Survive high radiation environment $\rightarrow$ **high luminosity**



Projected Results: Off-forward EMC Ratio



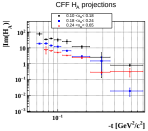
Colors indicate the different t bins which are shifted horizontally for clarity

Separated mean field nucleon EMC Effect and SRC nucleon EMC Effect

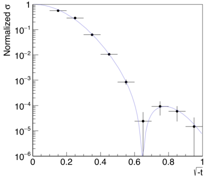
^{4}He Transverse Quark and Gluon Densities

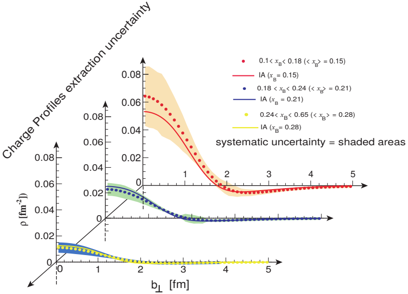
Coherent scattering on ^{4}He

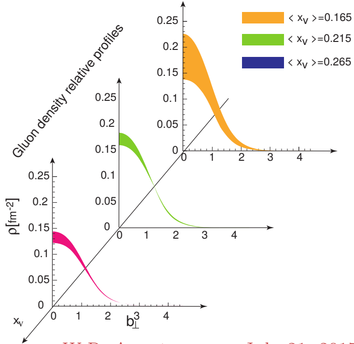
DVCS



ϕ Production







Quark and gluon radii apparent!

At $x > 0.2$ is the diffractive minimum at the same t value?
Is it washed out at low-x by the sea?

New Directions and Ideas

The α particle and the structure of light nuclei

What is the partonic structure of the ground state of ^{12}C and the Hoyle State?

α-cluster model

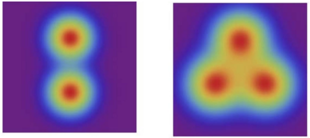
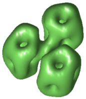


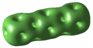
Figure 1 Charge density of ^{8}Be and ^{12}C in ACM.

Della Rocca and Iachello, in progress

Skyrme Model

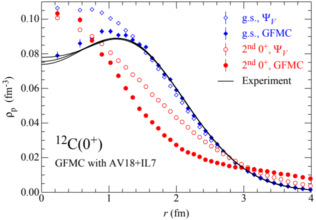


Ground State



Hoyle State?

Karliner, et.al., J.Phys. G43 (2016) no.5, 055104



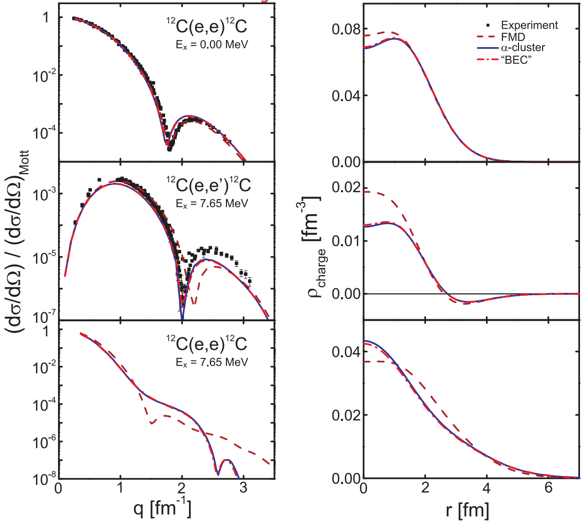
Carlson, et.al., Rev.Mod.Phys. 87 (2015) 1067

- **QCD dynamically generates the mass** of 98% of the visible universe, i.e., QCD generates the mass of all atomic nuclei (See talk by C. Roberts)
- **The Hoyle State** of ^{12}C is **critically important for nucleosynthesis**.
- **^{12}C is most important ingredient for life on Earth!**

How to directly study the partonic structure of the Hoyle state?

- Targets of 2_{nd} 0^+ state ^{12}C do not exist.
- Cannot scatter directly from Hoyle state.

Hard Exclusive processes on nuclei have the ability to probe nuclear structure in terms of quarks and gluons through extractions of transition GPDs (e.g. through the ground-state to Hoyle state transition GPD).

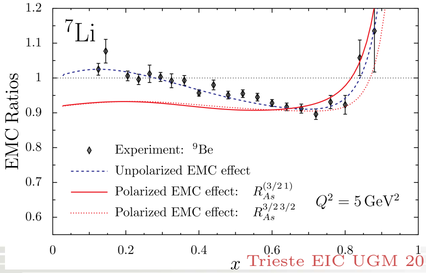


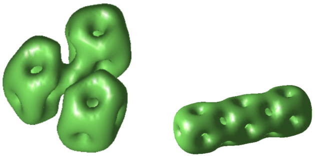
Chernykh, et.al., PRL. 98 (2007) 032501

Nuclear Physics ~~at~~ before an EIC

Looking to the near future and to the EIC

- Can we measure the transverse quark and gluon distributions in ^{12}C?
  - Detecting the recoil ^{12}C is very difficult! $\rightarrow$ need a new detector technology





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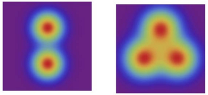

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(Della Rocca, Iachello in progress)

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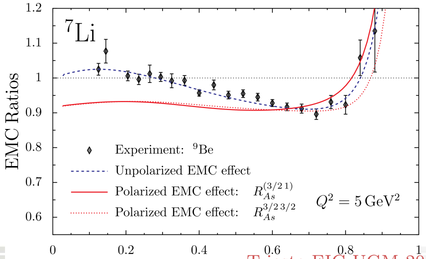
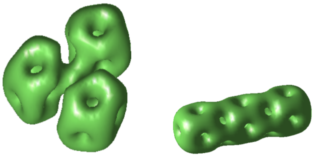
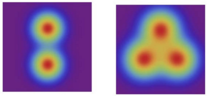




Carlson, et al., Rev.Mod.Phys. 87 (2015) 1067



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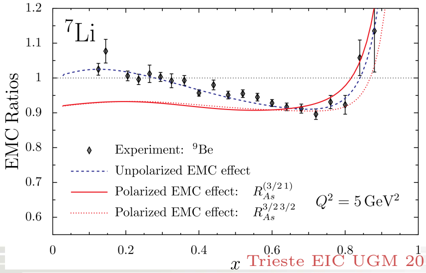
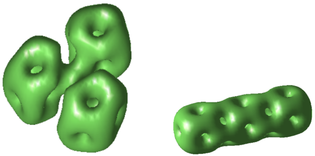
- Can we measure the **quark and gluon distributions of the neutron in inside ^{13}C?**
  - Hard to detect neutron and nearly impossible to detect spectator ^{12}C with a fixed target but very possible with an EIC!
  - Can we polarize ^{13}C at an EIC? Is there a polarized EMC effect of the bound neutron?





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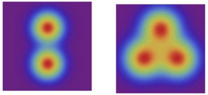

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Summary

- The ALERT Run Group physics is a precursor to EIC physics
- The EIC has tremendous transformative potential
- Studying QCD in nuclei presents an opportunity to transform our current understanding of nuclear matter

After all ...

Electron Ion Collider: The Next QCD Frontier
"Understanding the glue that binds us all"

Pushing Requirements for EIC Machine and Detector

Luminosity 10^{35}
Polarized Ions
Tagging
Excited State tagging!

Backup Slides

ALERT Design

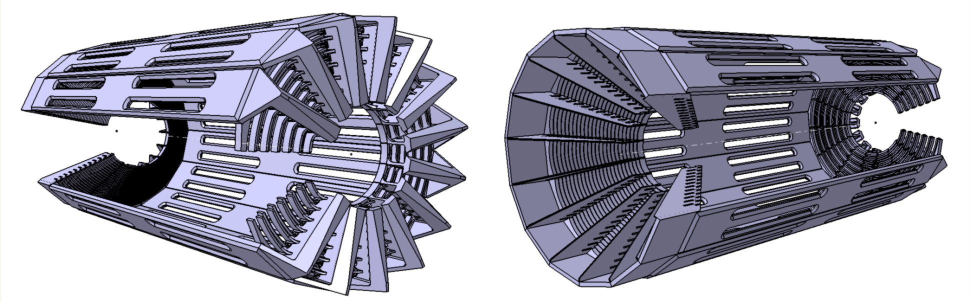
Basic Design

- Detector will surround a $\sim$3 atm gas target cell which is 6 mm in radius and constructed with 25 μm kapton walls
- Hyperbolic drift chamber with 10° stereo angle.
- Outer scintillator hodoscope for PID

Drift Chamber Design

- 2 mm wire separation
- 10° stereo angle
- Minimize material (windows/walls)
- Detects $\theta \sim 30°$ to 170°

Ongoing work led by IPN Orsay



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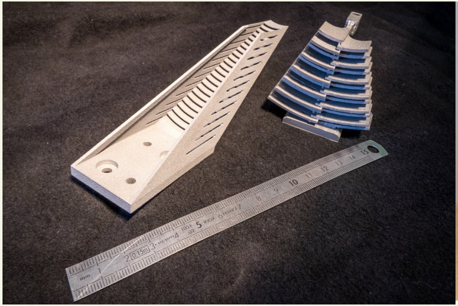


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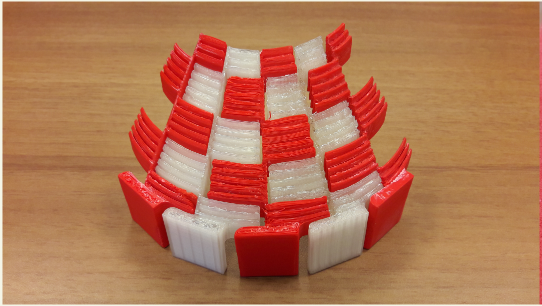
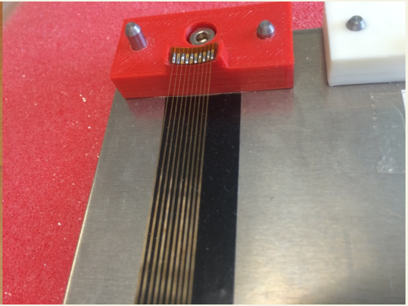
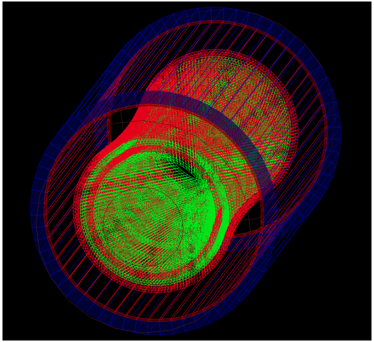




ALERT Design

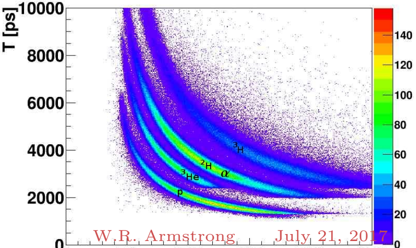
Scintillator Hodoscope Design

- 2 cylindrical layers ∼30 cm long
  1. Inner layer (thin) strips - 2 mm × 9 mm × 30 cm
     SiPM connected to each end of the strip
  2. Outer layer (thick) cells - 2 cm × 9 mm × 3 cm
     Segmented along beam axis (10 outer per 1 inner layer)
     SiPM readout attached to outer surface
- Good time resolution → need fast scint, fast SiPMs with good resolution, and small segmentation of scintillator cells.
- ^{4}He and ^{3}He dominate the signals coming from inner layer
- ^{1}H, ^{2}H, and ^{3}H will typically make it to the second layer depositing most of their energy.



Basic Operating Principles

- By design, ALERT is blind to minimum-ionizing particles (where the threshold can be tuned through the gas or electronically)
- For coherent processes where the cross sections are low, so we will compensate by running at the highest possible luminosity with a high threshold, hence, we will cut out all the high energy particles.



n-DVCS as sensitive probe of medium modifications

Observes a modified SF and modified FF in one measurement

$$A^{\sin\phi}_{LU,n} \propto \mathrm{Im}(F_1^n \mathcal{H}^n - \frac{t}{4M^2} F_2^n \mathcal{E}^n + \frac{x_B}{2}(F_1 + F_2)^n \tilde{\mathcal{H}}^n)$$

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- First term $\rightarrow$ suppressed by F_1^n
- Second term $\rightarrow$ Ji's sum rule (quark OAM) $J_q = \int dx\, x\big[H_q(x,\xi,t=0) + E_q(x,\xi,t=0)\big]/2$

Ji, Phys.Rev.Lett. 78 (1997) 610-613

- Third term $\rightarrow$ polarized EMC Effect?

Cloët, et.al., Phys.Rev.Lett. 95 (2005) 052302

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Connection to polarized EMC Effect

The third term above is

$$\mathrm{Im}\left((F_1 + F_2)^n \tilde{\mathcal{H}}^n\right) = G_M^n(t)\, \mathrm{Im}(\tilde{\mathcal{H}}^n(\xi,\xi,t))$$

The ratio in the forward limit looks like

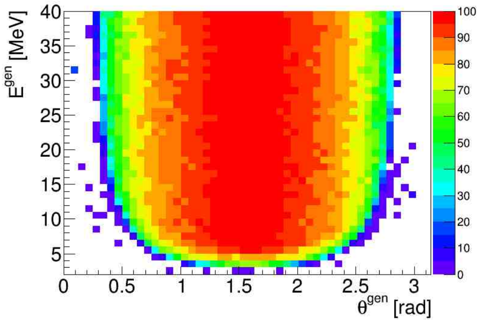
$$\frac{\text{bound } n}{\text{quasi-free } n} \longrightarrow \frac{\mu_{n^*}}{\mu_n} \frac{g_1^{n^*}(x)}{g_1^n(x)},$$

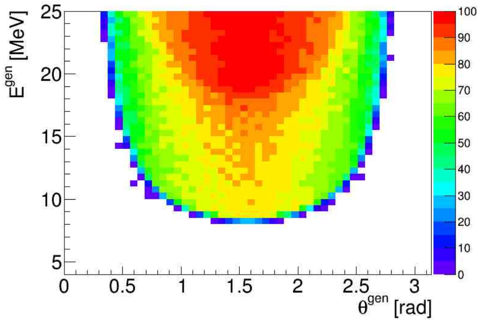
Clearly n-DVCS with nuclei presents a uniquely sensitive measure of medium modifications

ALERT Simulation

Full Geant4 Simulation

- Acceptances minimum momenta: 70 MeV/c for protons, 240 MeV/c for ^{4}He





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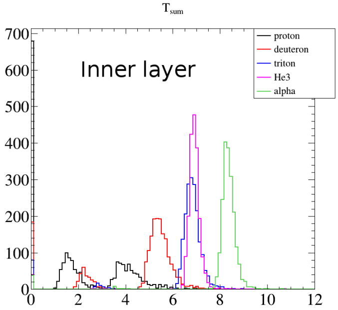
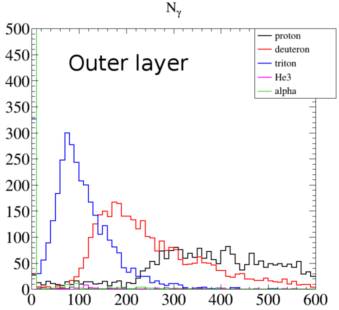
- Detailed scintillator photon yields and timing information $\rightarrow$ optimize geometry to provide the best PID





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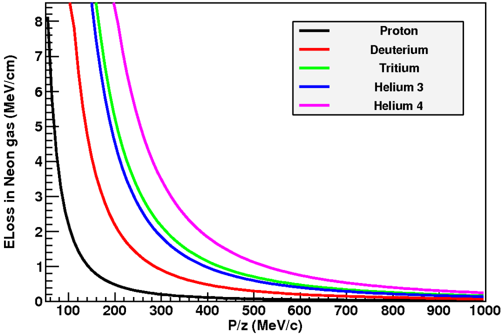

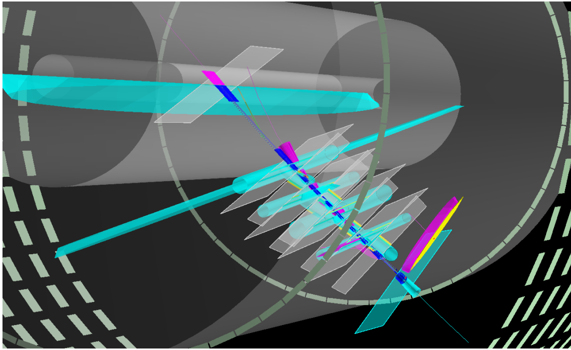

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- DC hit occupancies simulated - can operate comfortably at nominal CLAS12 luminosity