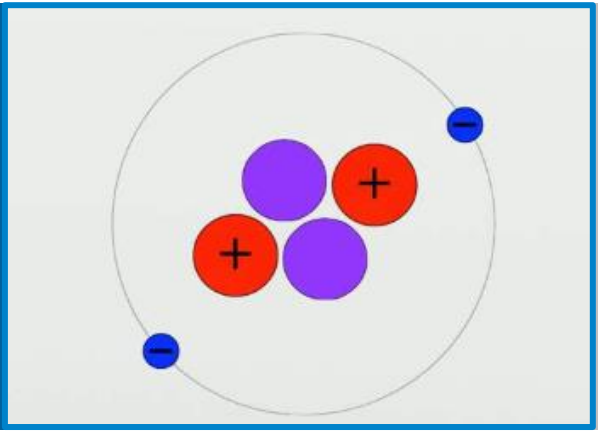
DIS2023: XXX International Workshop on
Deep-Inelastic Scattering and Related Subjects

Future Experiment of Coherent J/ψ Electro-production off Helium-4



Chao Peng (MEP Group, Argonne National Laboratory)

03/29/2023

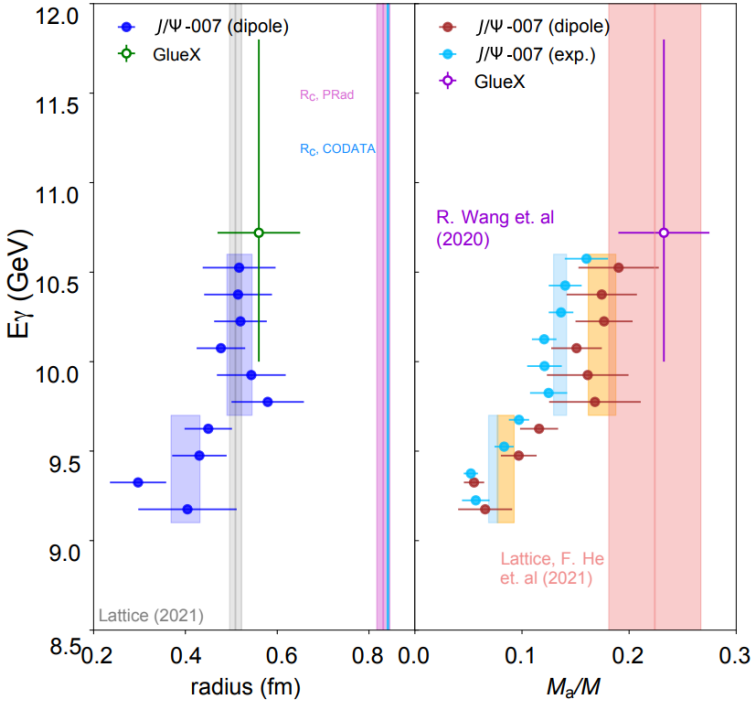
Nucleus and QCD

- Ground state of light nuclei can be well described in terms of hadronic degrees of freedom
  - Long range: nucleon-nucleon interaction mediated by light mesons
  - Intermediate range: multi-pions and heavier mesons
  - Short range: phenomenological repulsive part

- However, transition from hadronic description to quark-gluon description is puzzling
  - One of the critical goals in nuclear physics – understanding nucleus in terms of basic degrees of freedom in QCD
  - Explicit role of quarks and gluons in nuclei
  - Ab-initio calculations for light nuclei initiated, experimental input will be important

Matter Radii of Nucleons and Nucleus

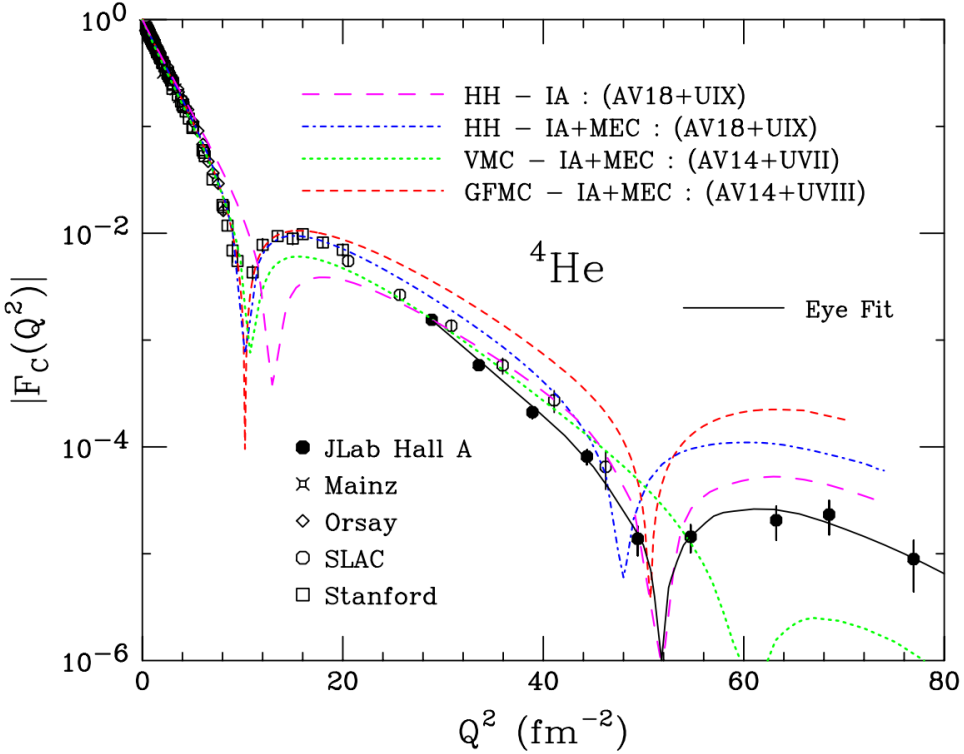
- Mass radius of the proton is notably smaller than the electric charge radius
  - Observed in J/ψ-007 experiment
  - Dipole fit result is shown, a variety of models was used
  - Active debate on the proper definition of r_M
- Mass radius of a light nuclei (^{4}He) is similarly interesting
  - Charge radius of a nuclei – average motion and dynamical properties
  - How about the mass radius?



B. Duran et al. [J/ψ-007], arXiv:2207.05212

Diffractive Minima of ^{4}He

- Two diffractive minima observed from charge form factor of ^{4}He
  - Bound nucleons distributing their charge in the nucleus
  - First diffractive minimum - charged quarks forming clumps
- What about the gluonic gravitational form factor of ^{4}He?
  - Will there be gluonic clumps?
  - Same position (Q^2) of the possible diffractive minimum?
  - A probe to gluonic structure and a measurement over wide t



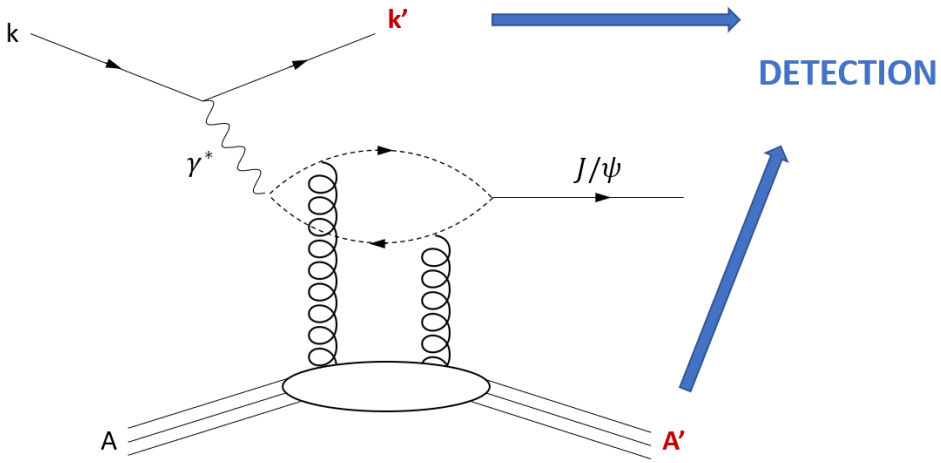
A. Camsonne, PRL 112, 132503 (2014)

Coherent J/ψ Electro-production

- J/ψ production
  - Multiple gluonic exchange
  - A direct probe to the gluonic structure

- Detection of scattered electron and **recoil ^{4}He** from J/ψ electro-production
  - Reconstruct missing mass
  - Determine virtual photon four-momentum
  - Explicit ground state recoil target detection – removal of incoherent backgrounds
  - Additional detection of J/ψ decay can further suppress single e/π backgrounds

- Recoil ^{4}He detection is critical
  - A promising candidate – nanowire recoil detector



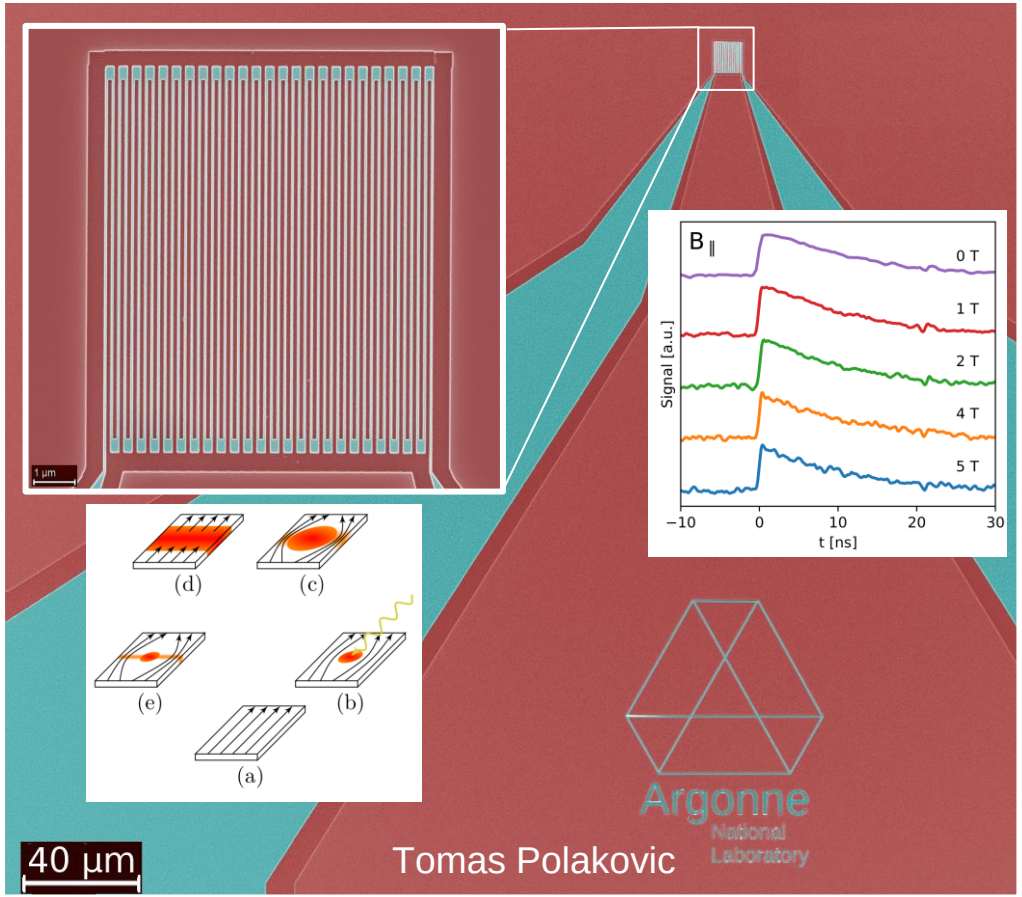
2-gluon exchange diagram

Superconducting Nanowire Detectors

Construction and Operation

- Thin film ~10nm NbN film with T_c=15 K [1]
- Meandering 100nm wire fills pixel area
- After etching device has T_c~ 5 K
- Current biased: I_b~ 15 - 20 µA

- Very Low timing jitter (current record of 3 ps)
- Reset times can be as low as 5-10 ns (potentially <1 ns in the future)
- Pixels on the order of 10x10 µm^2 to 30x30 µm^2
- Operates at LHe temperatures (T < 5K)
- Operation in magnetic fields up to ~6T [2]
- Photon detection efficiencies >90%
- Expected to very radiation hard
- Can be fabricated with different geometry or pixel dimensions



Ongoing R&D at Argonne

[1] APL Materials 6, 076107 (2018)
[2] Nucl.Instrum.Meth.A 959 (2020) 163543
[3] Nanomaterials 2020, 10, 1198

Superconducting Nanowire Recoil Detector

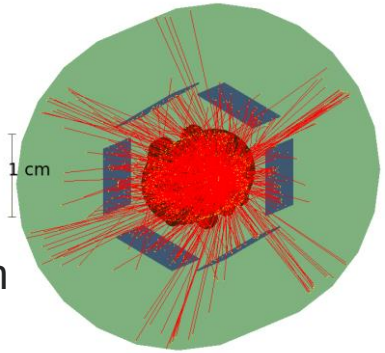
Two possible modes of detection

Scintillation photon detector

- LHe EUV scintillation detected by sparse array of photon detectors
- LHe transparent to own scintillation
- Photons from recoil directly detected by SC nanowires

Pro: Easy fabrication
- sparse array of photon detectors

Con: PID and kinetic energy resolution

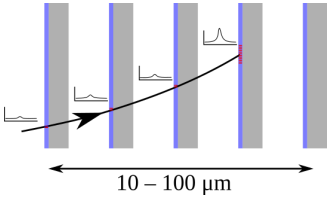


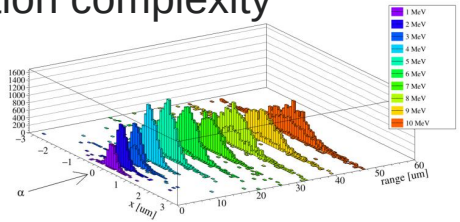
Recoil telescope array

- Directly detect recoils in range telescope
- Use wire size - energy threshold correlation for PID and energy reconstruction

Pro: Excellent energy reconstruction

Con: Higher fabrication complexity

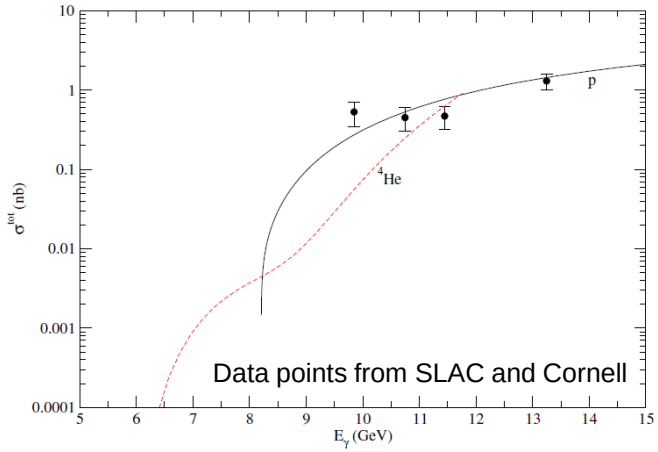


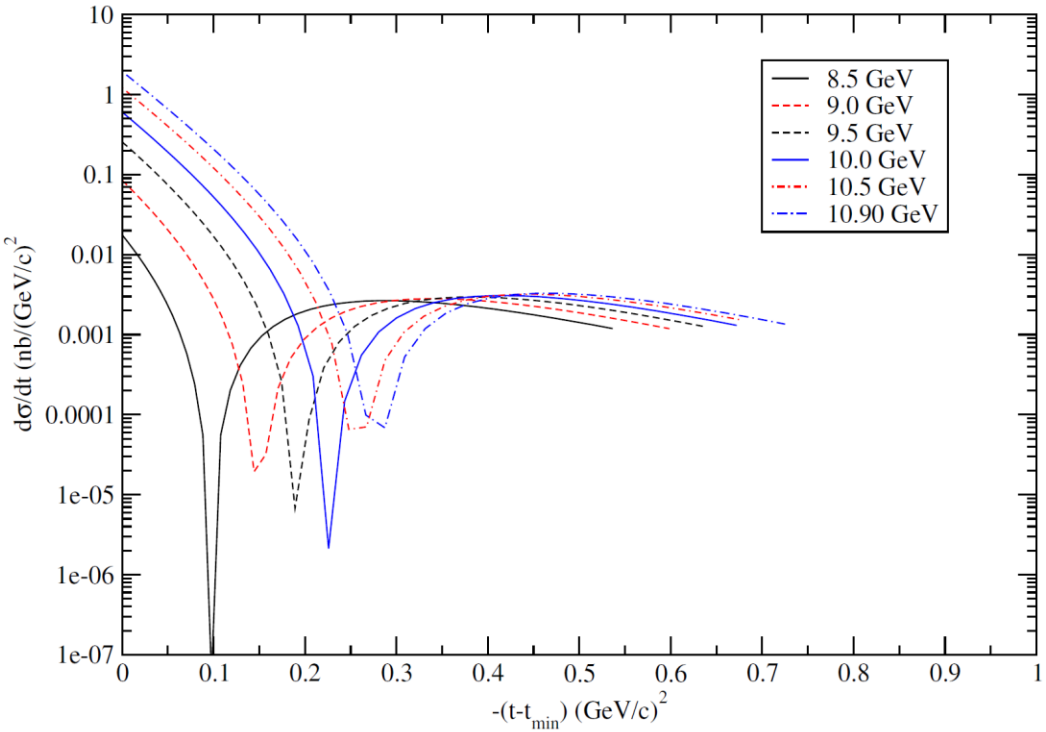


Cross Section Estimates

- Photo-production cross section
  - $\gamma + {}^4He \rightarrow J/\psi + {}^4He$
  - Pomeron-Exchange Model

Y.-s. Oh and T. S. H. Lee
Phys. Rev., vol. C66, p. 045201, 2002.
J.-J. Wu and T. S. H. Lee
Phys. Rev., vol. C86, p. 065203, 2012.





Calculations from H. Lee

Cross Section Estimates

- Electro-production
  - $e + 4He \rightarrow e' + {}^4He + J/\psi$
  - Estimated with Vector Dominance model

M. Adams et al.
Z. Phys. C, vol. 74, pp. 237–261, 1997.

$$\sigma_{el}(Q^2) = \int_{-t_{max}}^{t_{min}} dt \frac{d\sigma(t, Q^2)}{dt} \cdot \left(\frac{M_{J/\psi}^2}{Q^2 + M_{J/\psi}^2} \right)^m \cdot (1 + \varepsilon R(Q^2))$$

  - m = 2.575

M. Tytgat,
Ph.D. dissertation, Hamburg U., 2001.

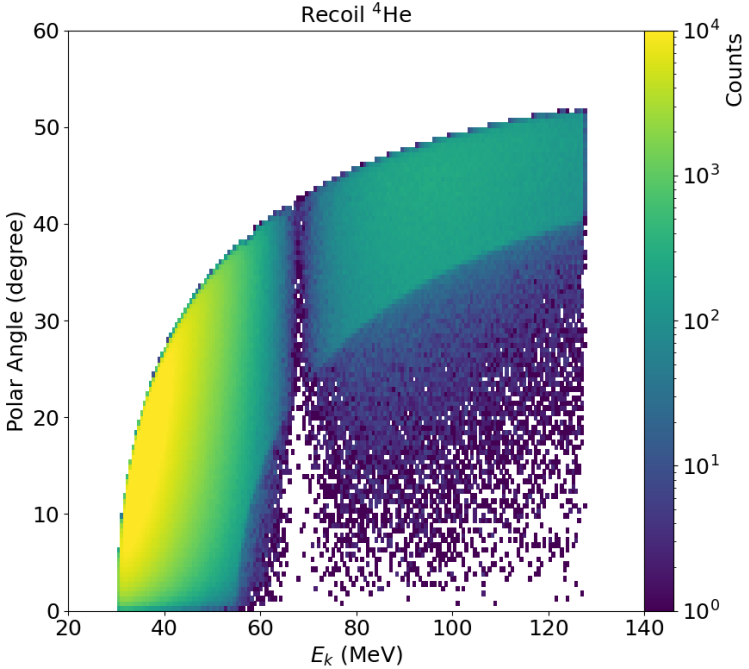
$$R(Q^2) = \left(\frac{cM_{J/\psi}^2 + Q^2}{cM_{J/\psi}^2} \right)^n - 1$$

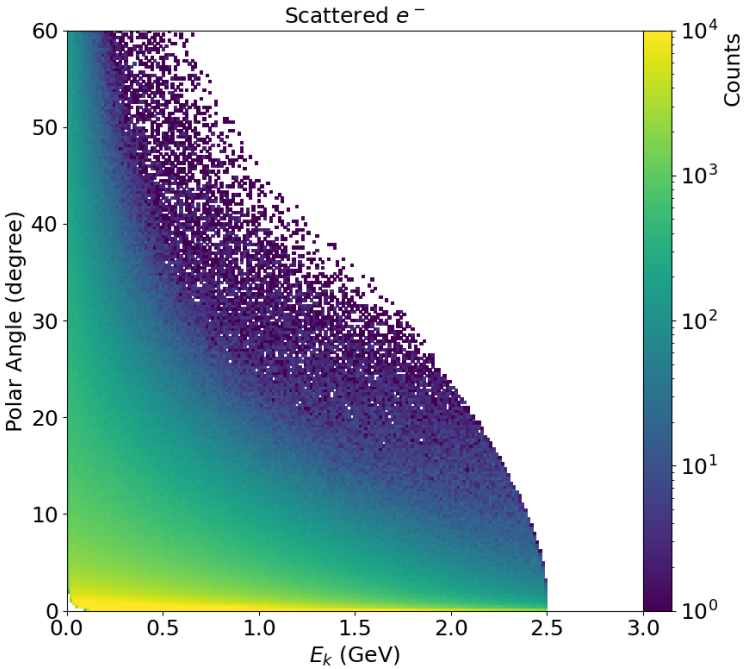
  - c = 2.164, n = 2.131

R. Fiore, L. Jenkovszky, V. Magas, S. Melis, and A. Prokudin
Phys. Rev. D, vol. 80, p. 116001, 2009.

Angle and Kinetic Energy Distributions

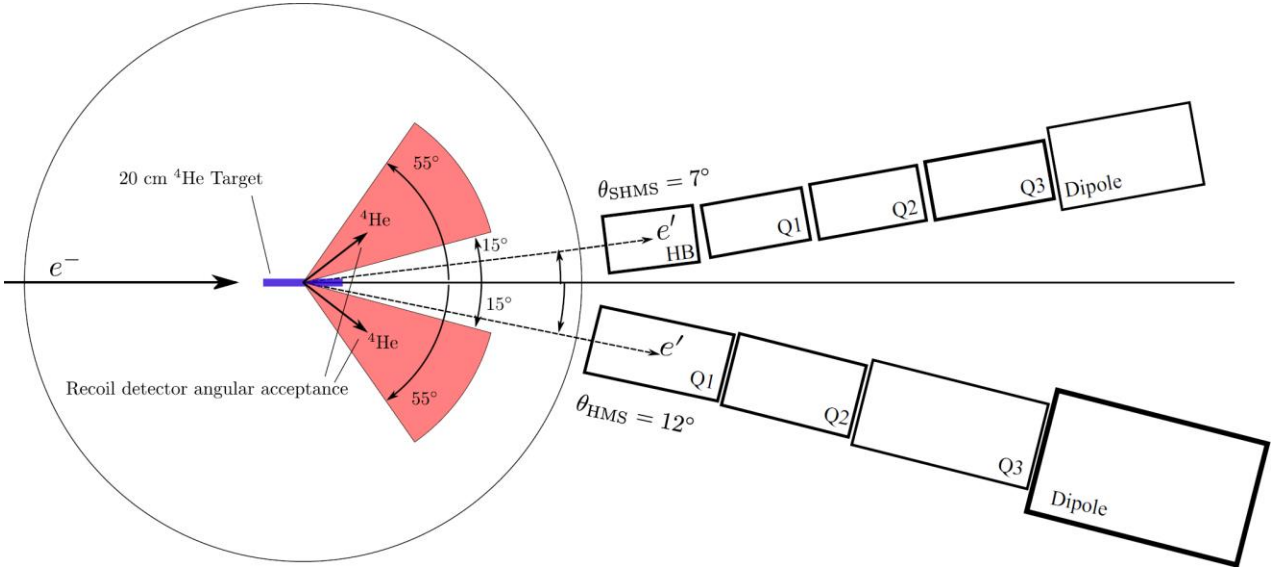
- Angle and kinetic energy distributions are obtained with the cross-section estimation (E_{beam} = 11 GeV)
  - For high rates, focus on the forward-angle and low-momentum region





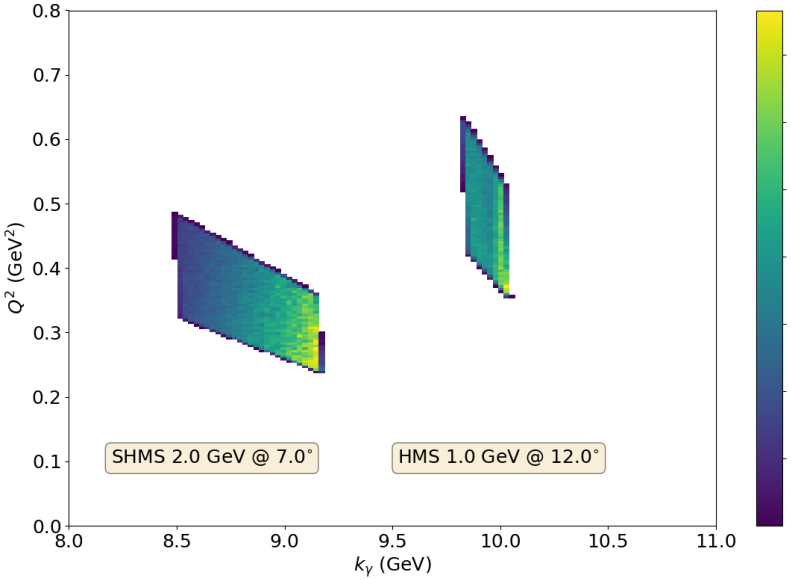
Possible Schematic of the Measurement

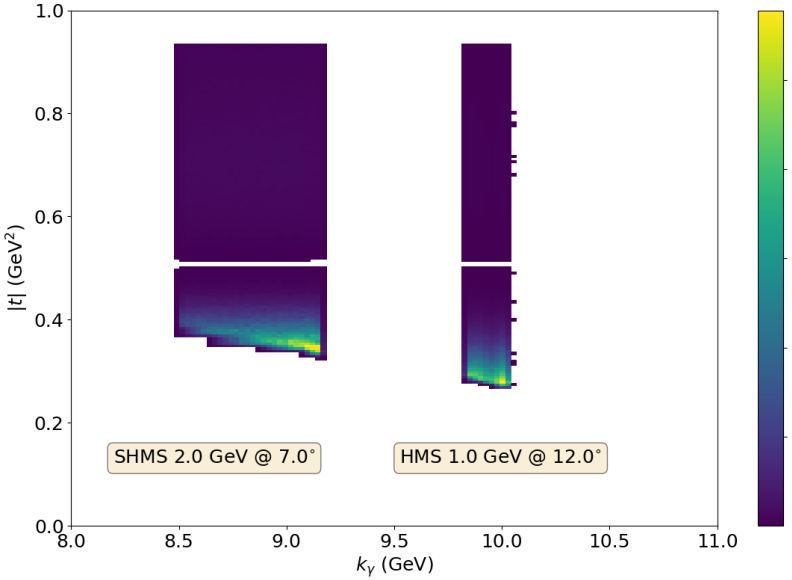
- Explored with existing electron facility (JLab) and detectors (HMS & SHMS at Hall C)
  - Detection of scattered electron and recoil ^{4}He
  - Simple simulation for signals, full simulations with backgrounds (mainly elas. rad. tail) are ongoing
  - Considering other detectors/facilities in full simulations (CLAS/SoLID at JLab, ePIC at EIC)
  - Detection of lepton pairs from J/ψ decay possible in large acceptance detectors



Simulation – Kinematic Coverage

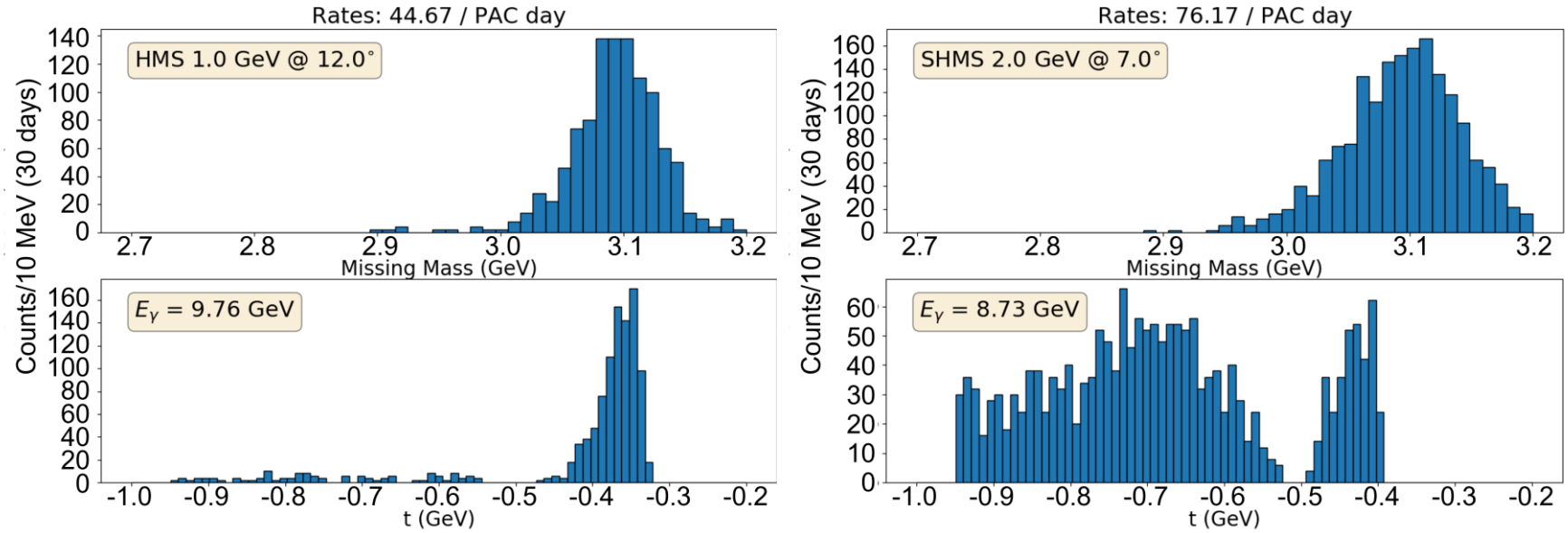
- The experimental setting focuses on the forward-angle and low-momentum region
  - HMS: central momentum 1.0 GeV/c at an angle of 12.0˚
  - SHMS: central momentum 2.0 GeV/c at an angle of 7.0˚





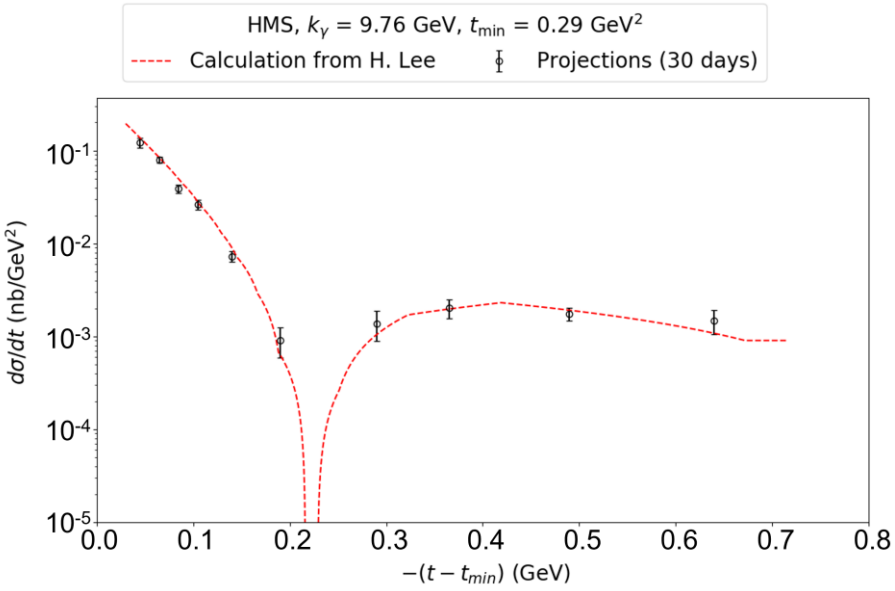
Simulation – Kinematic Variables Reconstruction

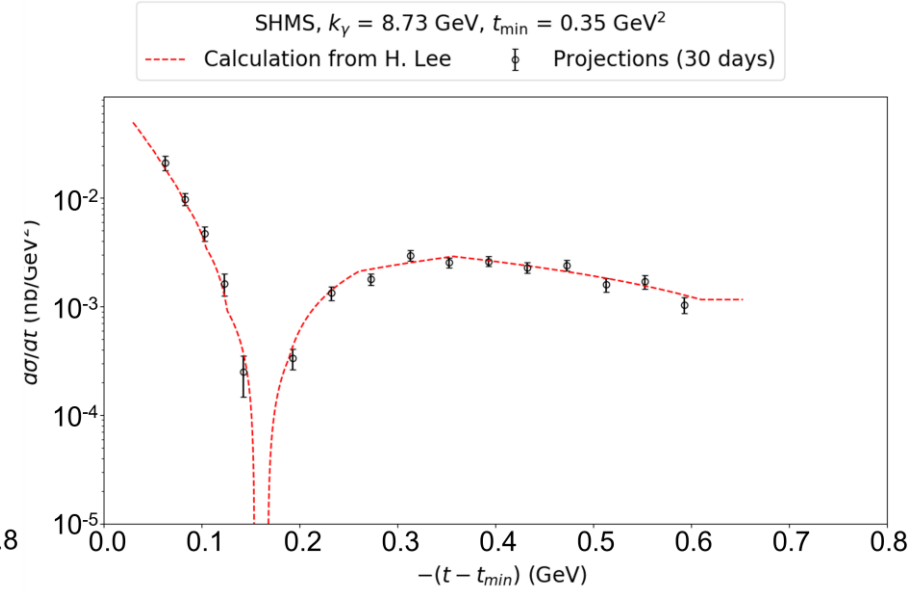
- Explored with existing electron facility (JLab) and detectors (HMS & SHMS at Hall C)
  - Detection of scattered electron and recoil ^{4}He
  - Kinetic energy resolution for recoil ^{4}He ~25 keV, angular resolution ~50 mrad
  - HMS (SHMS), momentum resolution ~0.1% (0.2%), angular resolution ~1 mrad (2 mrad)



Simulation – Projected Signals

- Simulated signals with reconstructed events in tagging detector and HMS & SHMS
  - Enough statistics for the diffractive minima with 30 days of beam time (E = 11 GeV, I = 50 uA)





Summary

This work is supported in part by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

- Coherent electro-production of J/ψ off a ^{4}He target offers a unique opportunity
  - Explore the gluonic component of its matter distribution
  - Scan for the possible diffractive minima

- Such a measurement seems feasible at the existing electron beam facilities
  - Enough statistics with ~30 days beamtime at Hall C, JLab
  - Require a novel tagging detector – development of nanowire recoil detector
  - Ongoing full simulations with physical and coincidental backgrounds
  - Ongoing simulations with large-acceptance detectors and future facilities/detectors

- A possible future experiment to probe the gluonic structure of ^{4}He at JLab and EIC

Thank you!

Backup Slides

HMS and SHMS

- Low angle and low momenta from HMS & SHMS, it may change according to the practical limit

TABLE I: The basic parameters of the HMS, SOS and SHMS spectrometers.

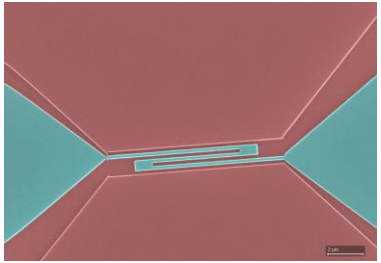
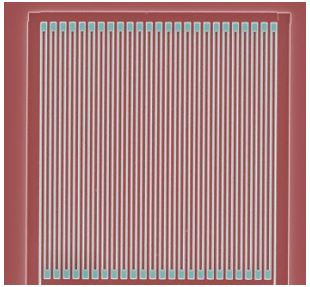
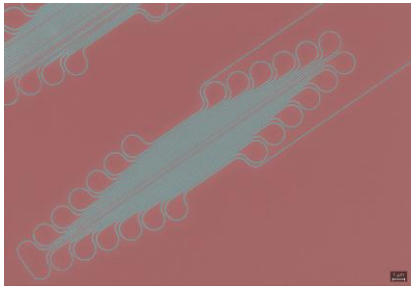
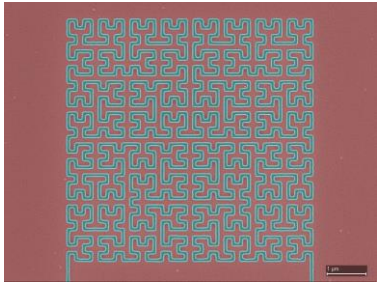
Parameter	HMS	SOS	SHMS
Momentum Range (GeV/c)	0.5-7.3	0.3-1.7	1.5-11.0
Momentum Acceptance (%)	± 10	± 20	-10 - +22
Momentum resolution (%)	0.10-0.15	<0.1	0.03-0.08
Horiz. Angl. Accept.(mrad)	± 32	± 40	± 18
Vert. Angl. Accept. (mrad)	± 85	± 70	± 50
Solid angle (msr)	8.1	9.0	> 4.5
Maximum scattering angle	$\leq 80^o$	$\leq 168.4^o$	$\leq 40^o$
Minimum scattering angle	$\geq 10.5^o$	$\geq 13.3^o$	$\geq 5.5^o$
Horiz. Angl. res. (mrad)	0.8	0.5	0.5-1.2
Vertical Angl. res. (mrad)	1.0	1.0	0.3-1.1
Vertex Reconstr. res. (cm)	0.3	2-3	0.1-0.3

arXiv:1204.6413

SNSPD Properties and Characteristics

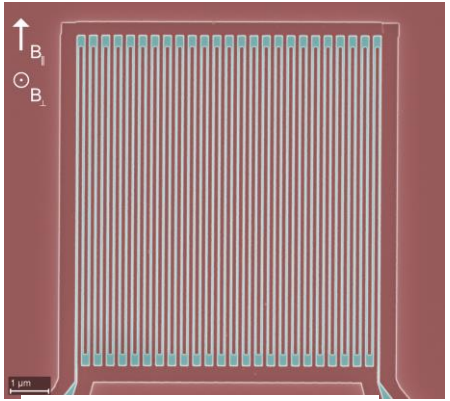
Quick Summary

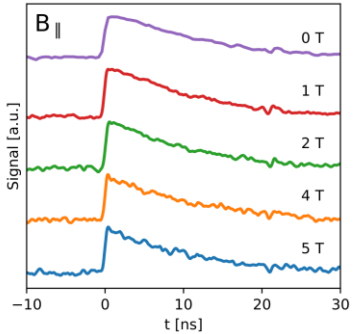
- Photon energy thresholds as low as ~100 meV
- Timing jitter 20–40 ps easily achieved (current record of 3 ps)
- Reset times can be as low as 5-10 ns (potentially <1 ns in the future)
- Pixels on the order of 10x10 μm^2 to 30x30 μm^2
- Fast, granular, high-rate pixel detector → low occupancies
- Conveniently operates at LHe temperatures (T < 5K)
- Photon detection efficiencies >90%
- Expected to very radiation hard (more on this later)
- Can be fabricated with different geometry or pixel dimensions

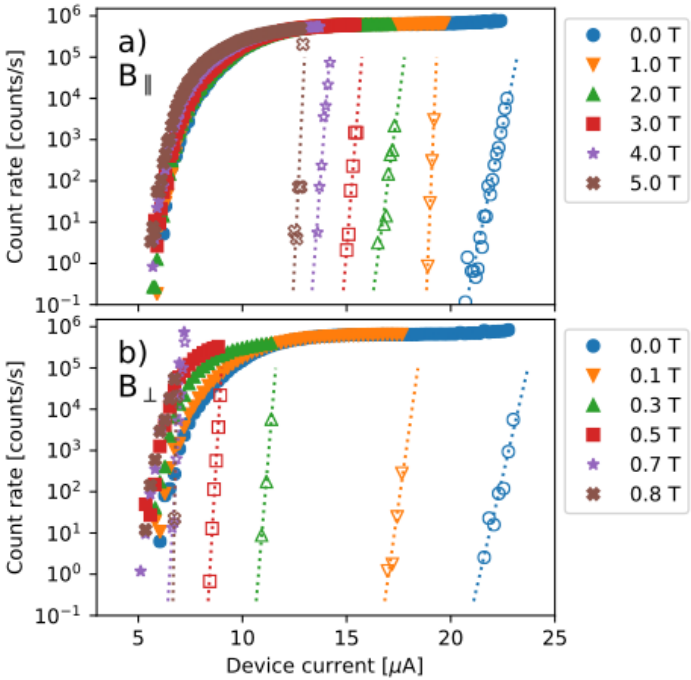





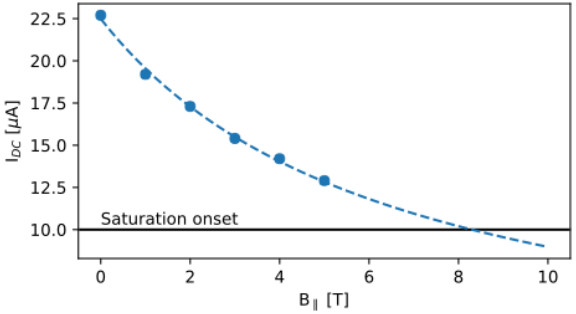
Slide Courtesy of W. Armstrong

Strong Magnetic fields and high rates









Can operate on strong magnetic fields with nearly zero dark count

Fixed Target Experiments

Superconducting Nanowire Particle Detectors

- Micro Range Telescope for Active LHe Target
- Recoil $^3H/^3He$ tagger for incoherent processes