AI in Spin Physics

SPIN2021

And the Future of Spin At Fermilab

Dustin Keller with the University of Virginia, October 22

SPIN2021 The 24th International Spin Symposium
Matsue, Japan
18-22 October 2021
Matsue, Shimane Prefecture, Japan

Fermilab

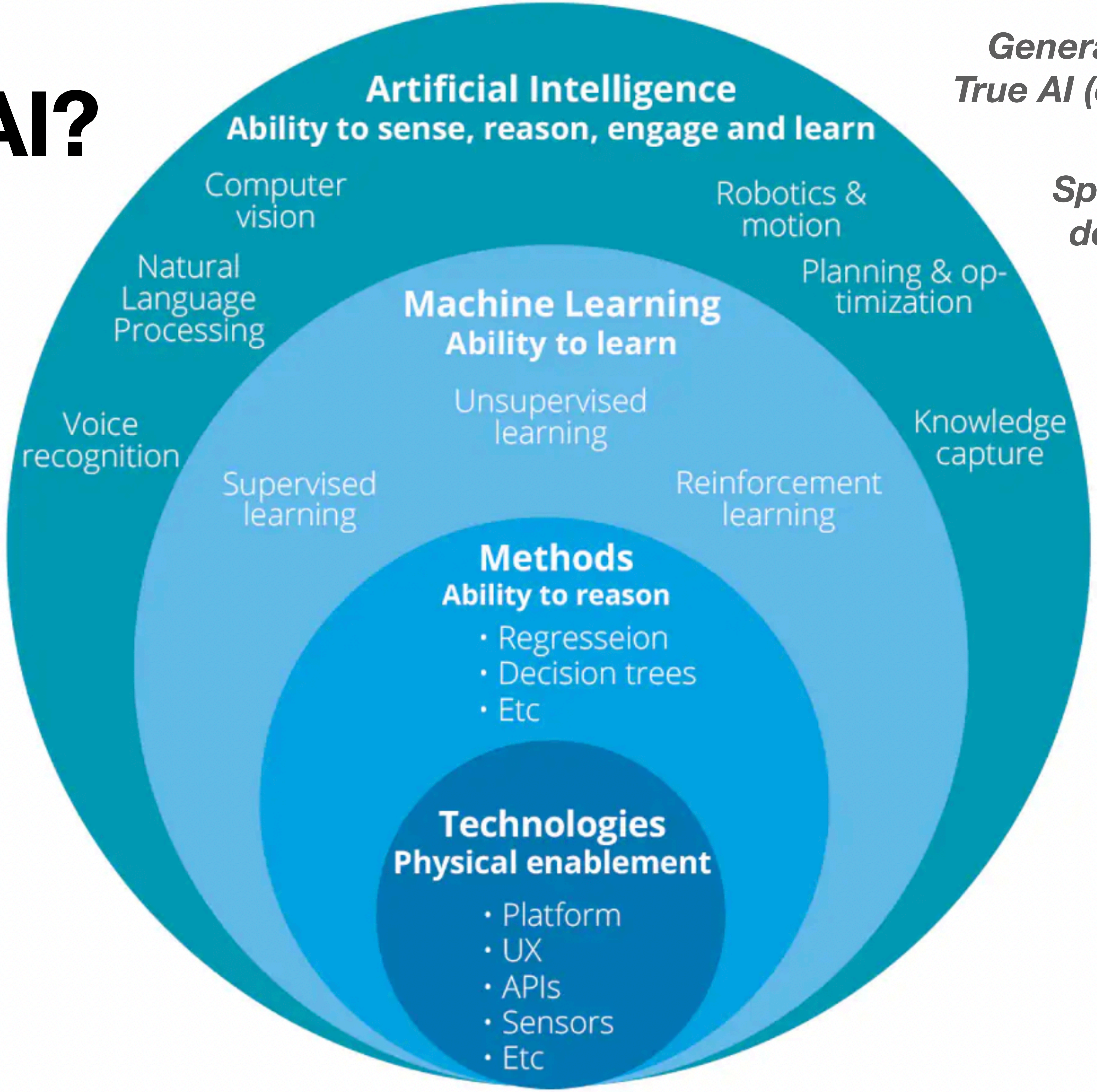
UVA - SPIN
PHYSICS GROUP

Artificial Intelligence and Spin Physics

and the future of Spin at Fermilab

- What is AI
- Some examples in Spin
- Where are things going
- A bit about gluons
- How does FNAL fit in

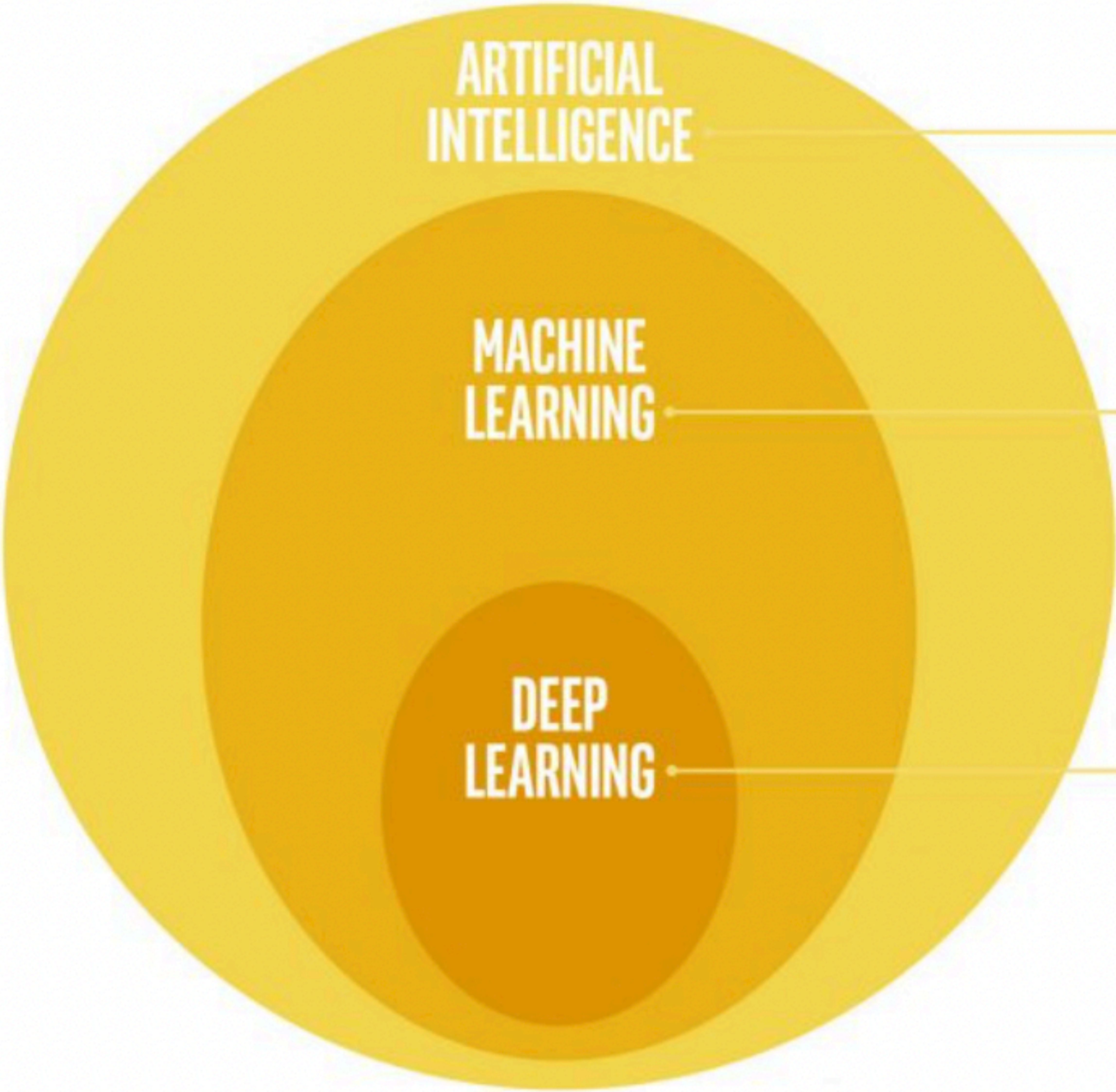
What is AI?



General AI: Full AI, Strong AI, True AI (designed to do anything)

Specialized AI: Designed to do just one task very well

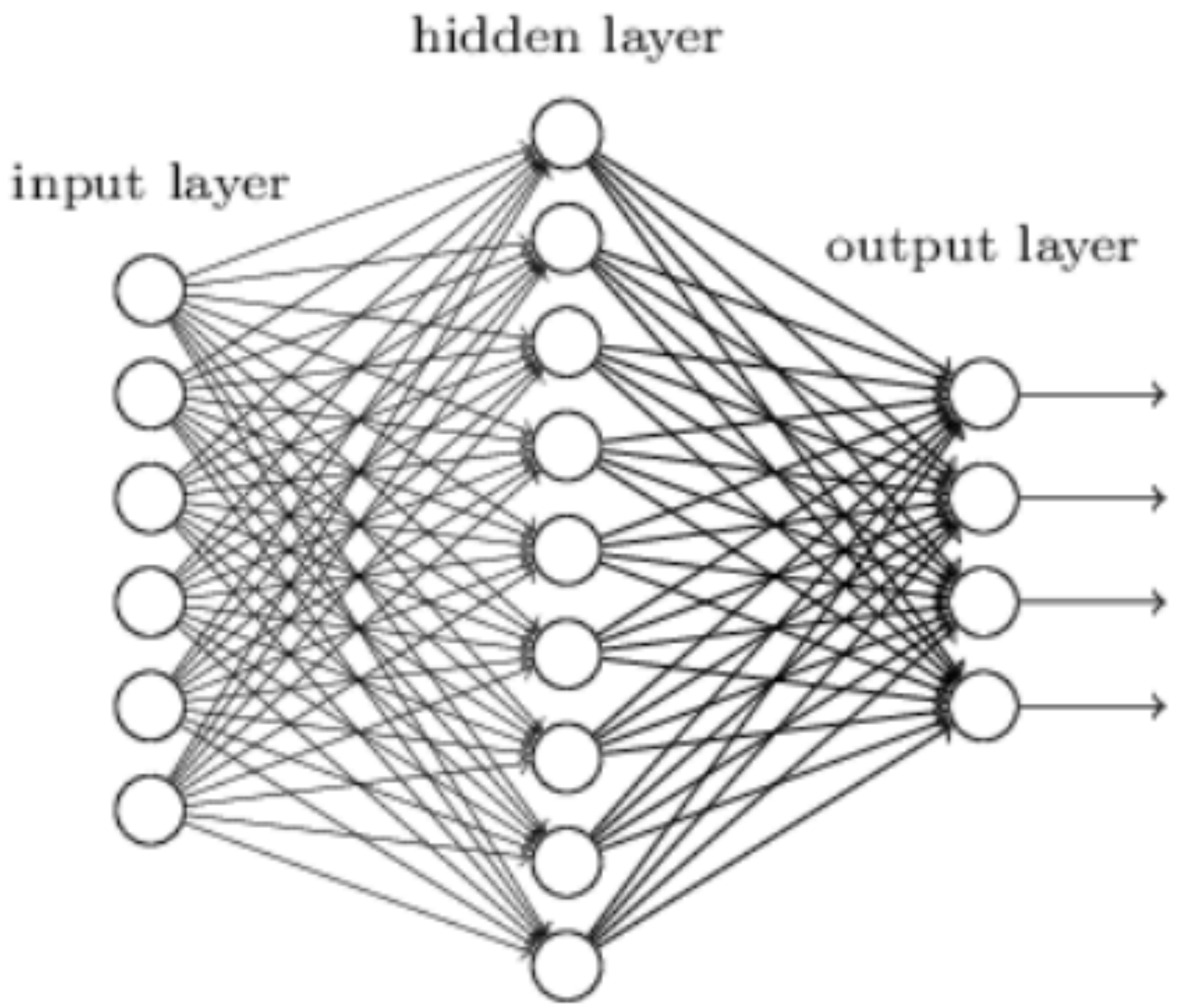
ARTIFICIAL INTELLIGENCE TERMS



- **AI** is an umbrella term for machines capable of perception, logic, and learning.
- **Machine learning** employs algorithms that learn from data to make predictions or decisions, and whose performance improves when exposed to more data over time.
- **Deep learning** uses many-layered neural networks to build algorithms that find the best way to perform tasks on their own, based on vast sets of data.

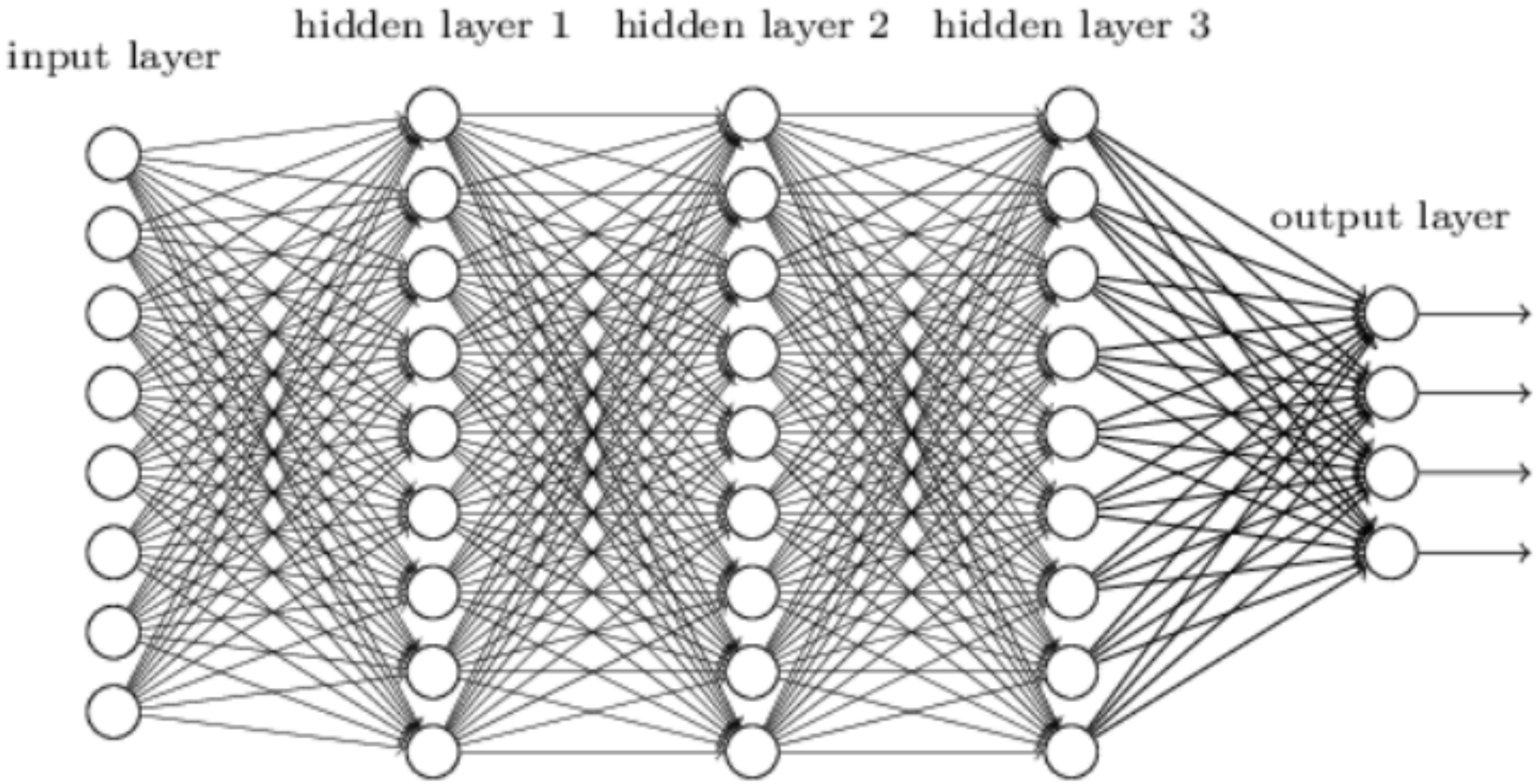
Basic Neural Network

"Non-deep" feedforward
neural network

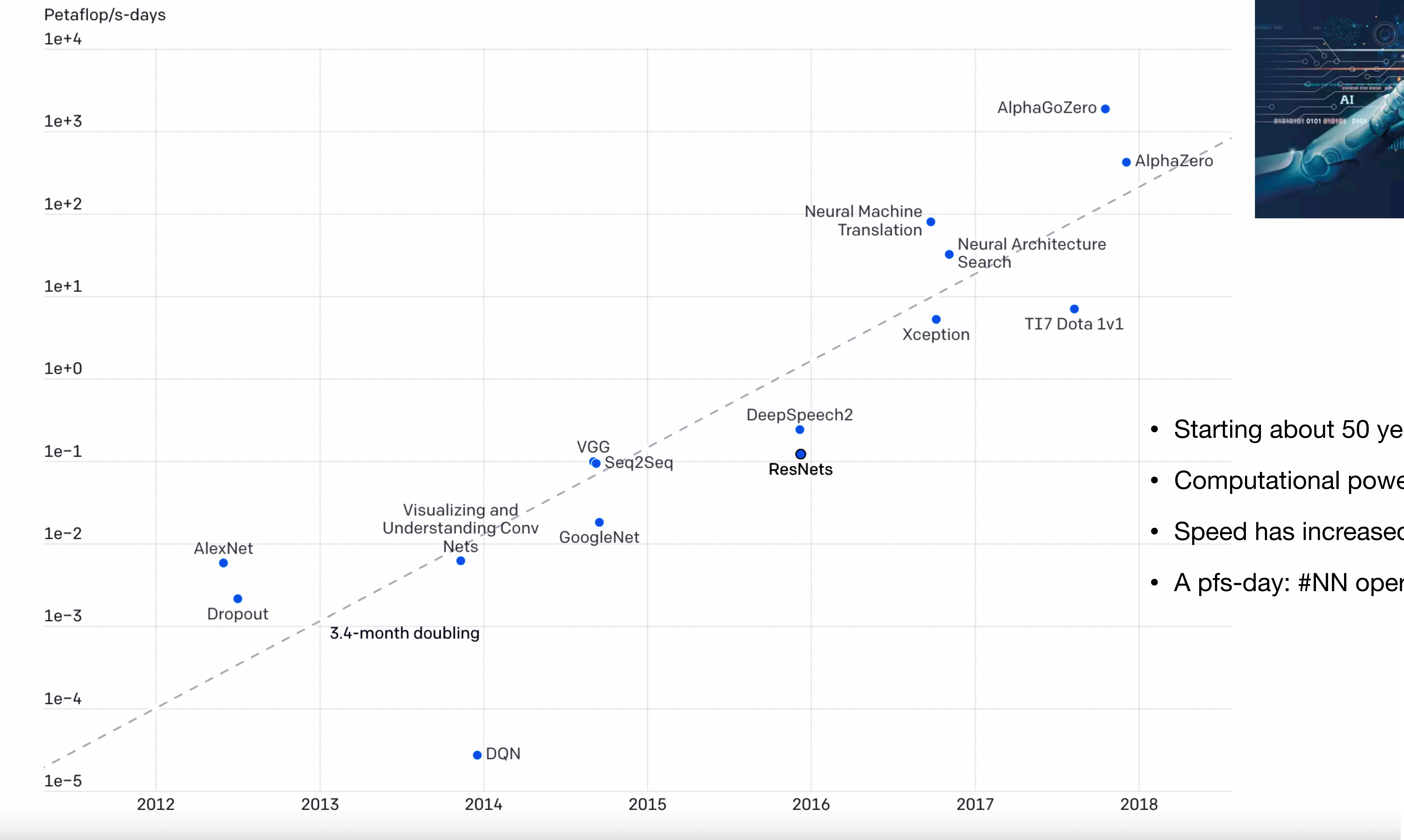


Perceptron Concept

Deep neural network



Evolution Timeline



R. Kurzweil

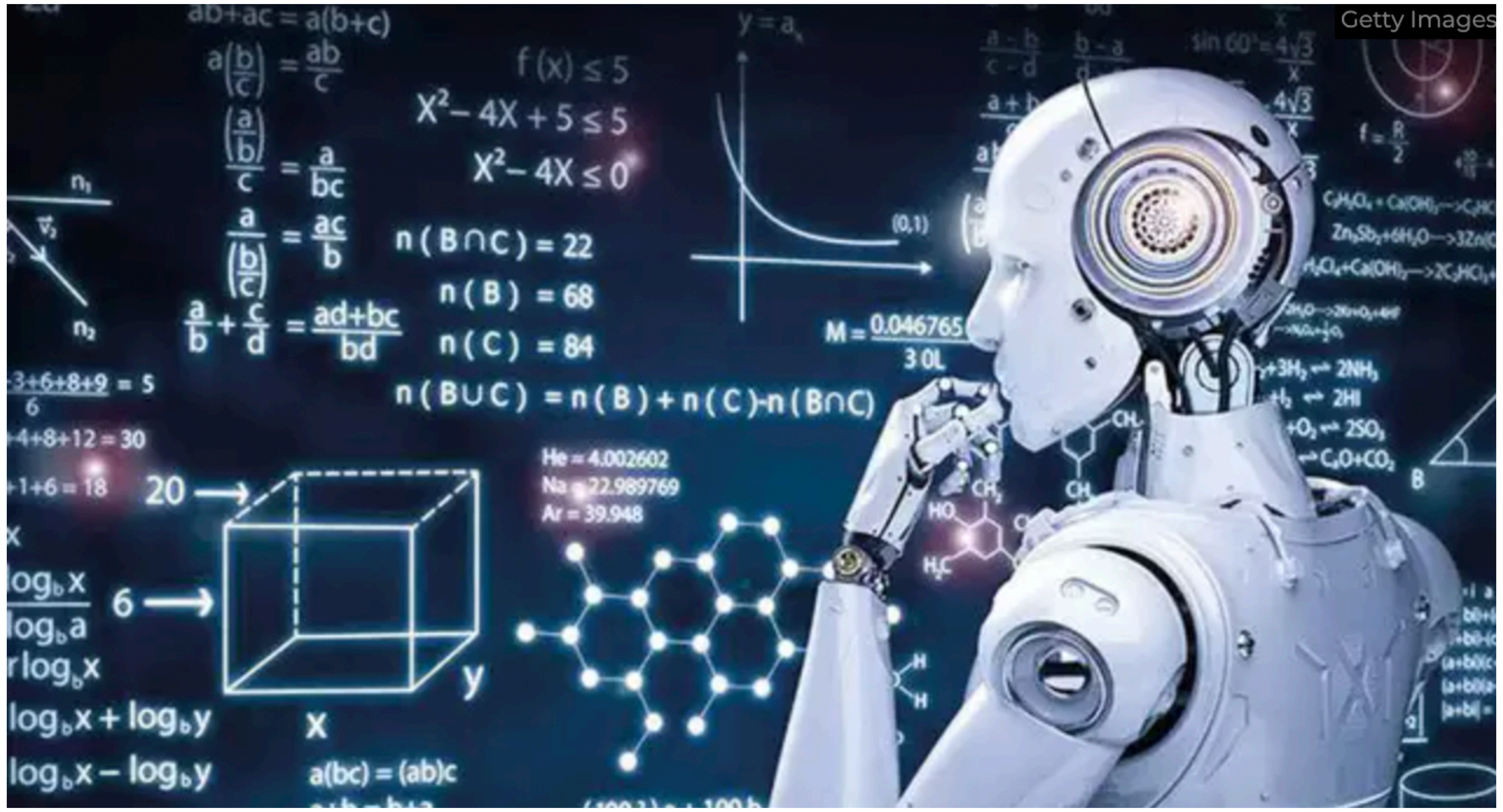
2045

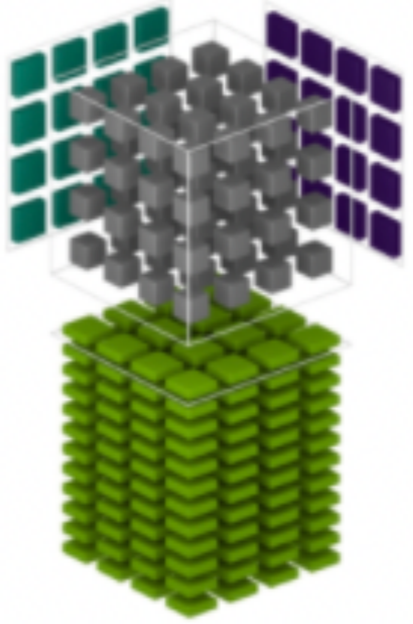
- Starting about 50 years after the perceptron
- Computational power doubling 100 days
- Speed has increased 300K from ‘12
- A pfs-day: #NN operations/s for 1 day

Some Important ANNs

With applications to our field

- Feedforward Neural Networks
- Radial basis function Neural Networks
- Self Organizing Neural Networks
- Recurrent Neural Networks
- Convolution Neural Networks
- Modular Neural Networks
- Graph Neural Networks





NVIDIA Tensor Cores

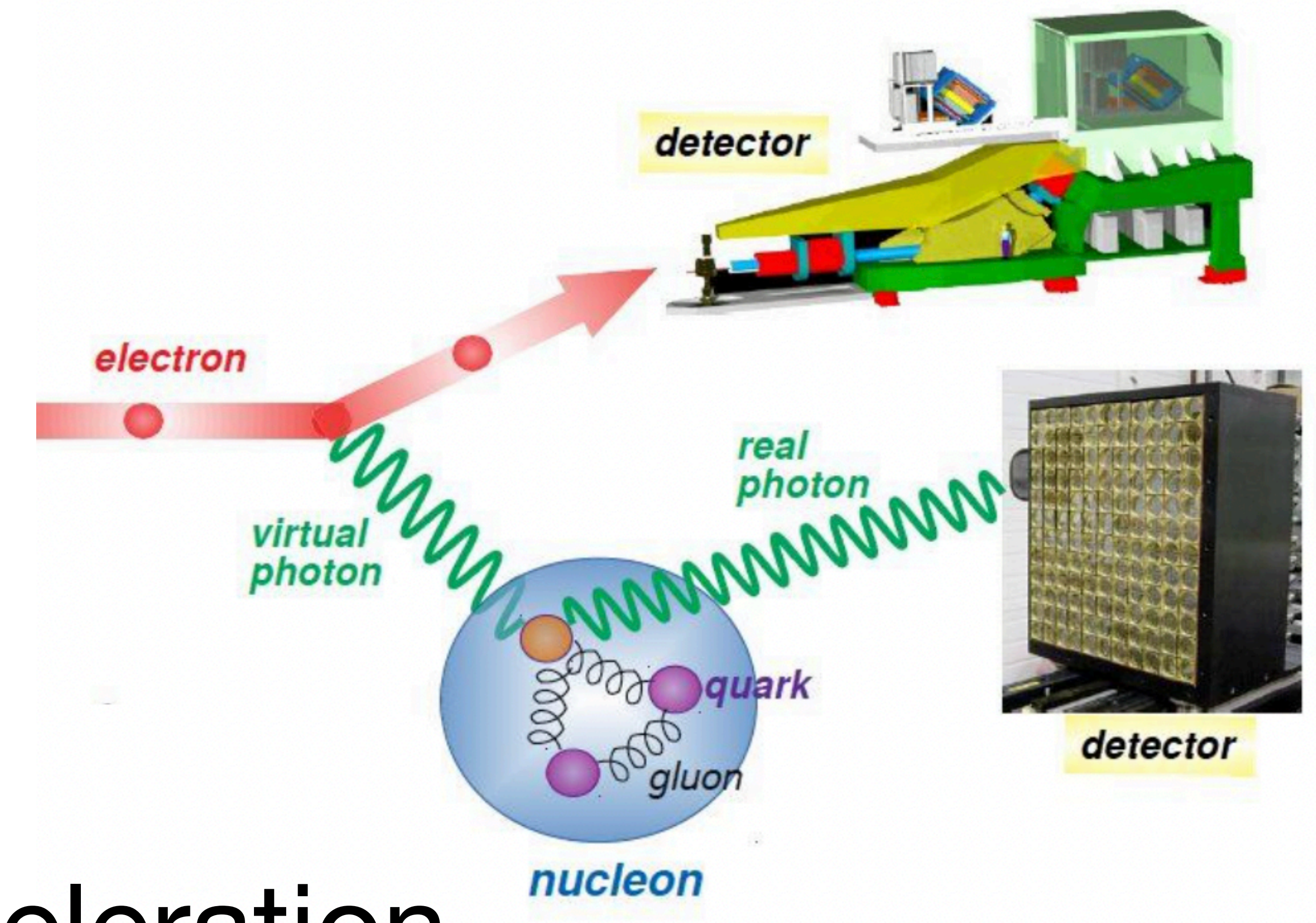
Train Model SavedModel → Optimize with TF-TRT → Run Inference

GPGPU Computing

Bogdan Oancea, Tudorel Andrei, Raluca Mariana Dragoescu
arXiv:1408.6923v1

Caffe, Caffe2, Chainer, MATLAB, Microsoft Cognitive Toolkit, mxnet, PaddlePaddle, PyTorch, TensorFlow, torch, Wolfram Language

Machine Learning
In Nuclear and Particle Physics

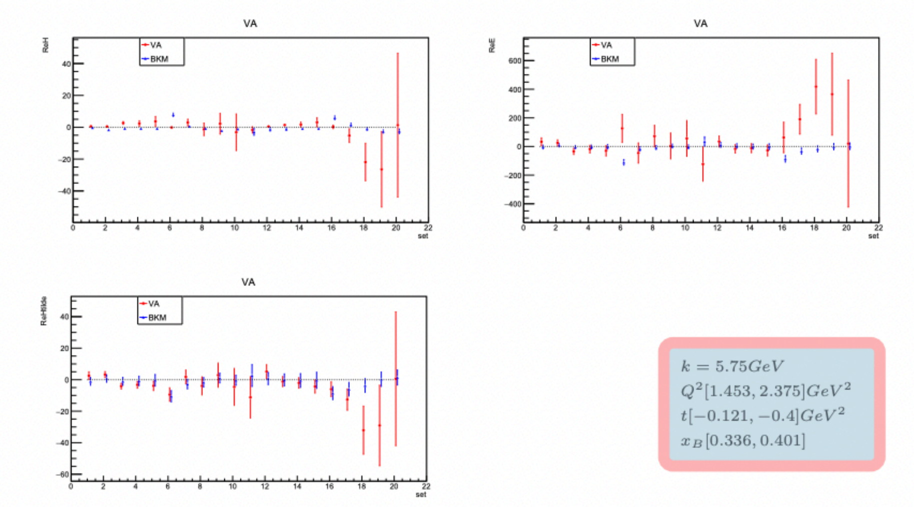


- Event-level Classification
- Trigger and Pattern Recognition
- Tracking/Event Reconstruction
- Cluster Reconstruction in Calorimeters
- Jet Representations and Preprocessing
- Jet Tagging
- Regression of detector drifts

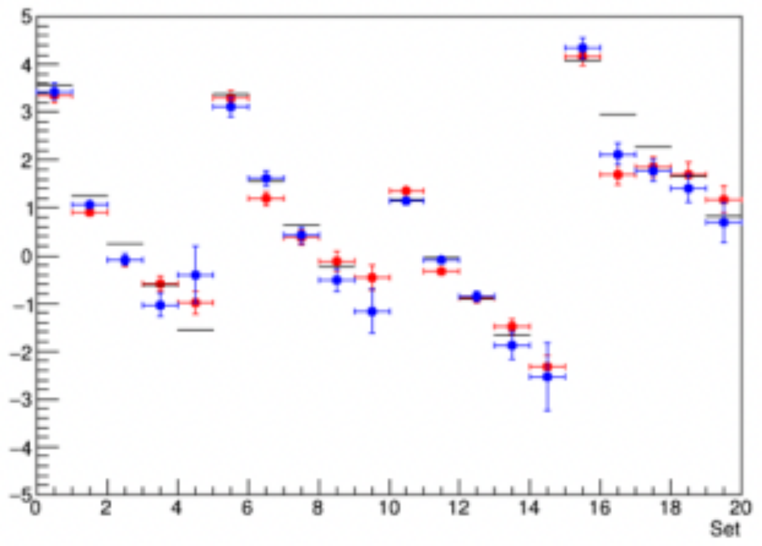
- Simulation acceleration
- Systems Automation
- Detector Design
- Accelerator Design
- Optimization of workflow
- Detector Readout Optimization
- Cut Optimization

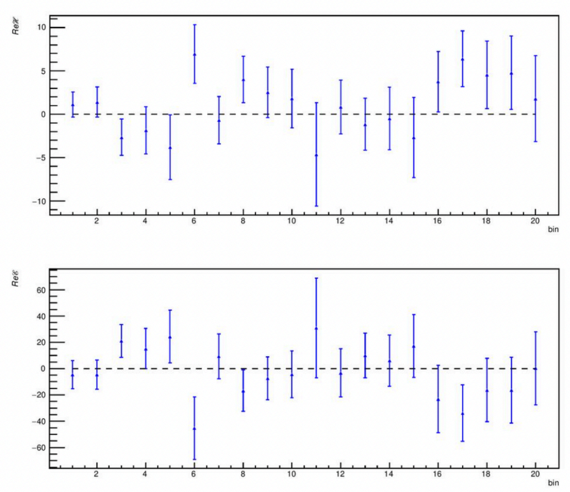
Machine Learning

In Spin Physics



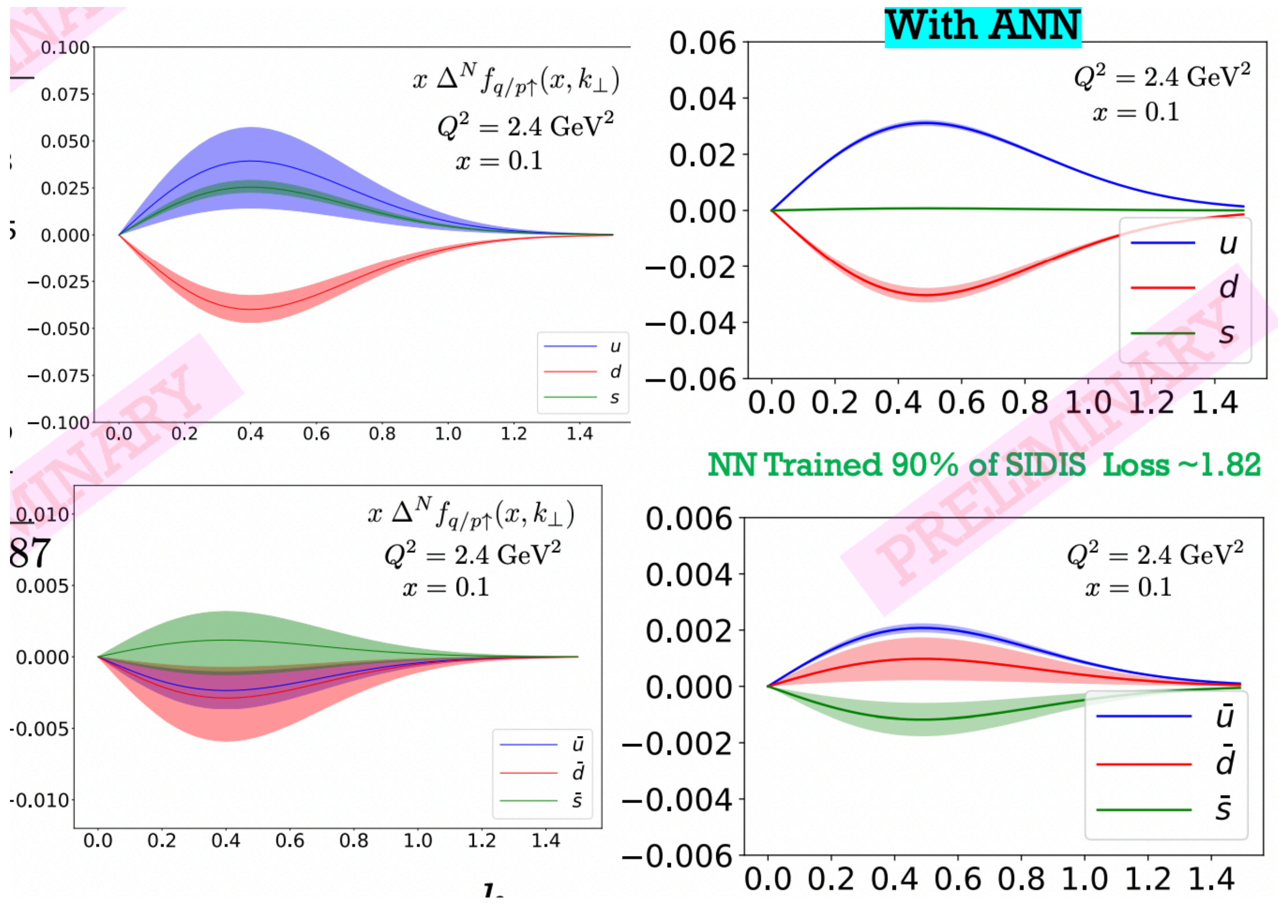
Improve results by imposing fit constraints.



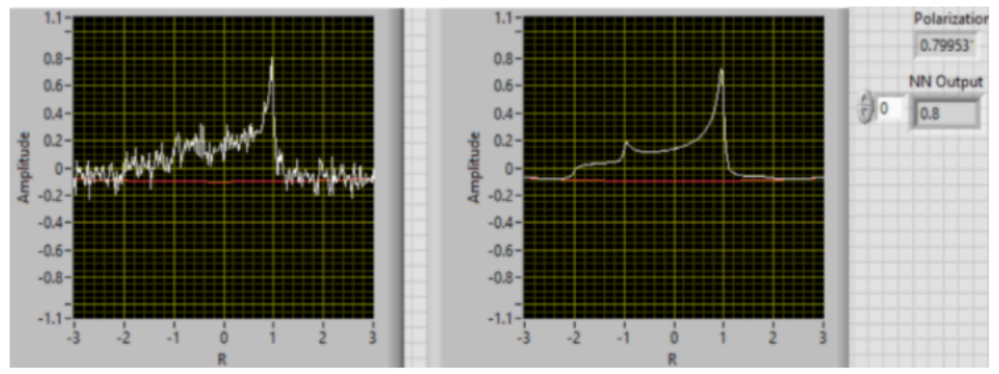


Liliet Diaz: 141. Novel CFFs Extraction in Unpolarized DVCS
JST 21 Oct 2021, 09:10 = EDT 20 Oct 2021, 20:10

Ishara Fernando: 126. SU(3)-flavor TMD PDFs extraction with global fits & ANN
JST 22 Oct 2021, 09:16 = EDT 21 Oct 2021, 20:16



- Spin Phenomenology (information extraction)
- Model Polarized Mechanisms in PT → Anchit Arora
- Polarization Enhancement in PT ✱
- Material Analysis in PT → Librado Anglero



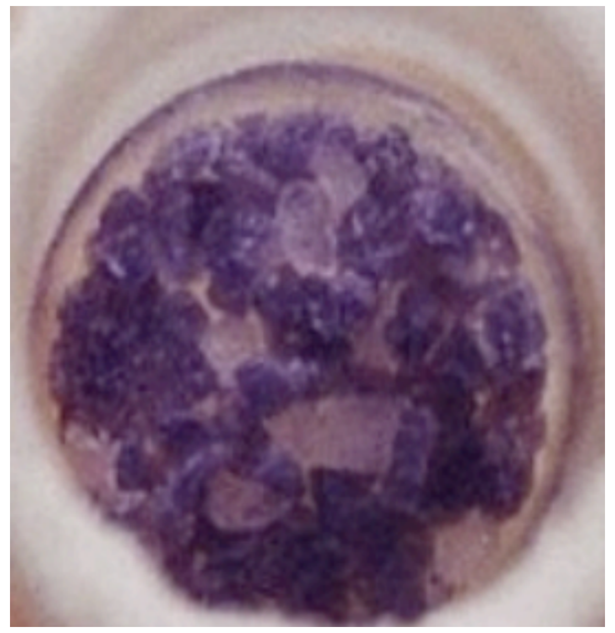
- NMR Measurements → ***Devin Seay***: 120. NMR With Machine Learning
  JST 22 Oct 2021, 09:40 = EDT 21 Oct 2021, 20:40
- Tracking and Online Monitoring → ***Arthur Conover:*** 136. Machine Learning Online Monitoring for the SpinQuest
  JST 22 Oct 2021, 07:25 = EDT 21 Oct 2021, 18:25
- Construction and Visualization of Models ✱
- Data Analysis on event level and asymmetry extraction → Multiple folks

Some Examples

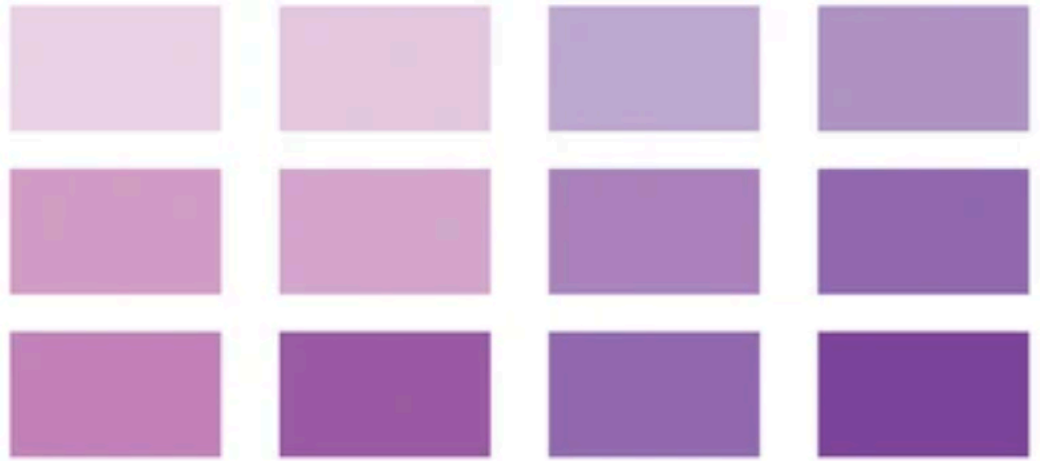
In Polarized Targets

- Traveling-wave electron linac
- Irradiated to $10^{17}\ e^{-}/\text{cm}^2$
- 14 GeV 10 μA under Liquid Argon (~87 K)
- Proton knocked out to from free radicals
- Also form color centers
- Material color is correlated to the dose
- Optimized for field and temperature

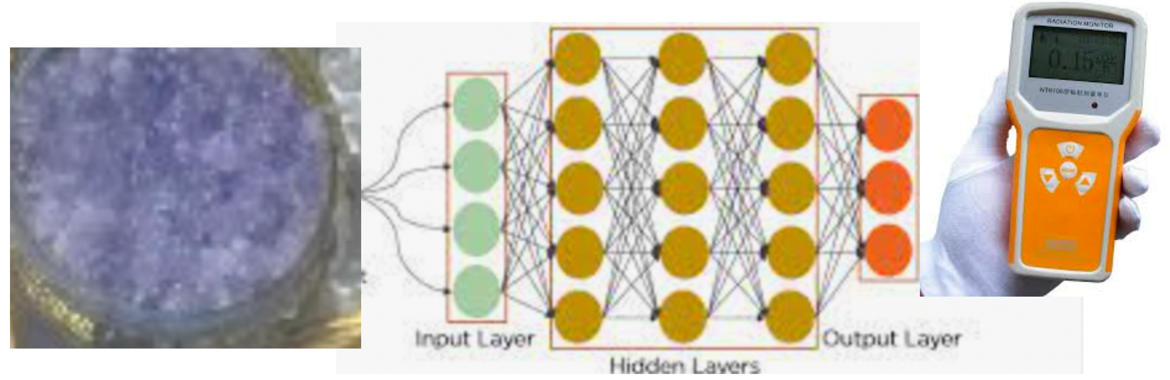
Irradiation Performed at NIST (MIRF Accelerator)



Work by Jack Beaty, UVA



Material Photo



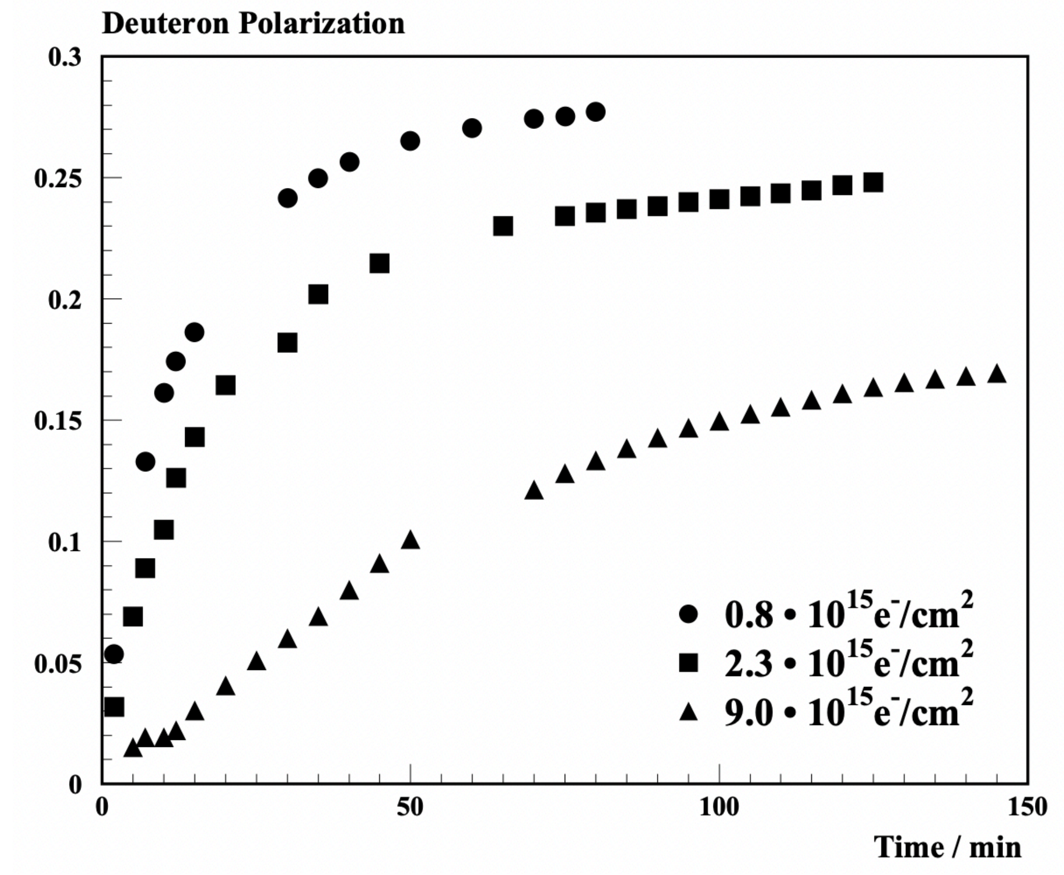
Accumulated dose

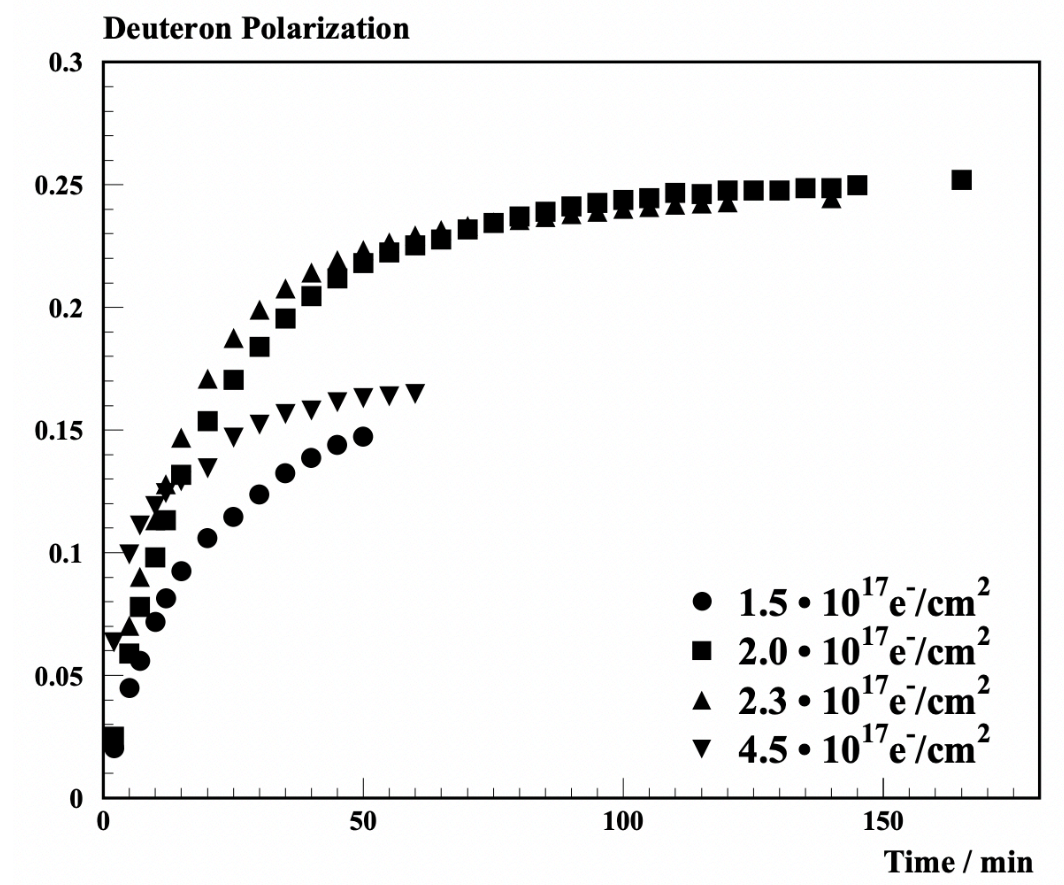
Some Examples

In Polarized Targets

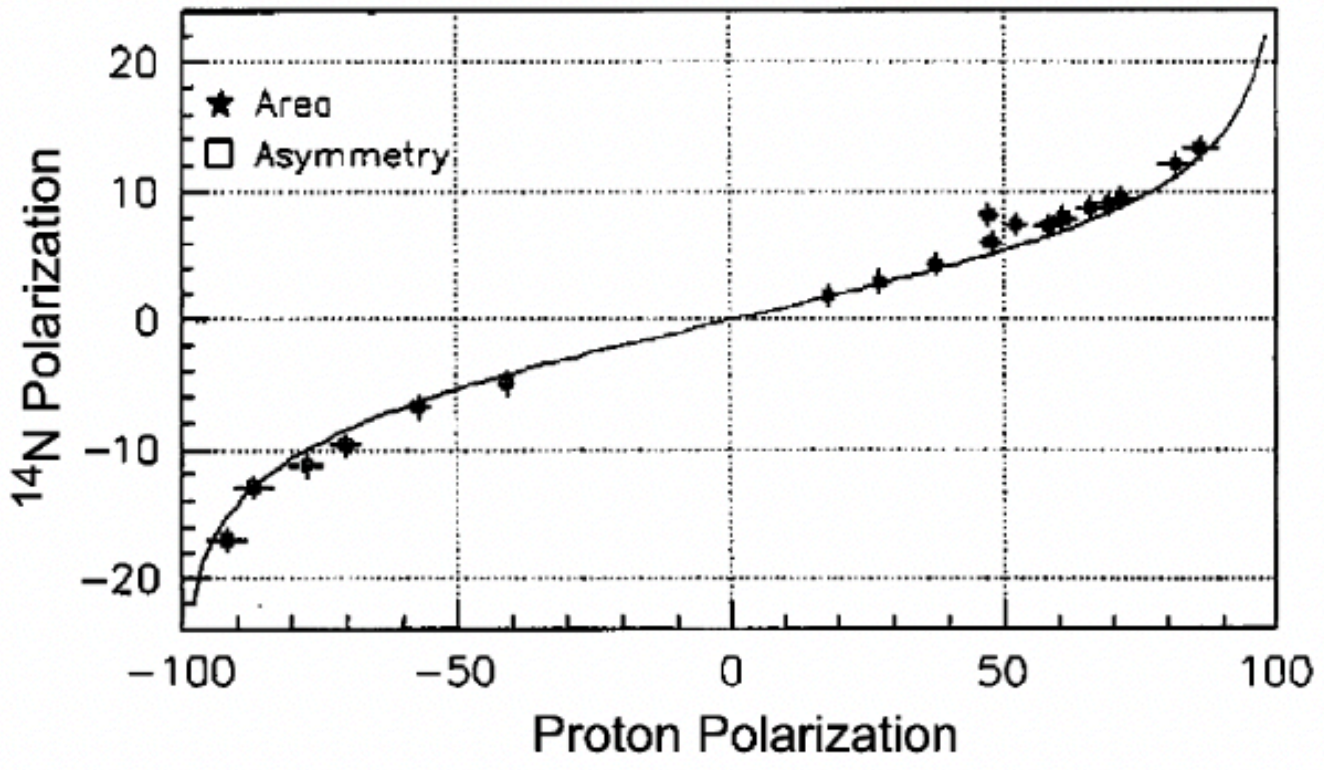
Preliminary Predication using ANN Model (3% rel. error)

Target	Field (T)	Temp (K)	Dose	P(max)
ND3(D)	6.5	0.7	2.7	68%
LiD(Li7)	7.0	1	3.8	82%
CD2(D)	7.0	1	2.5	73%
LiH(Li7)	7.0	0.5	2.3	93%
LiF(F)	6.0	1	3.3	78%

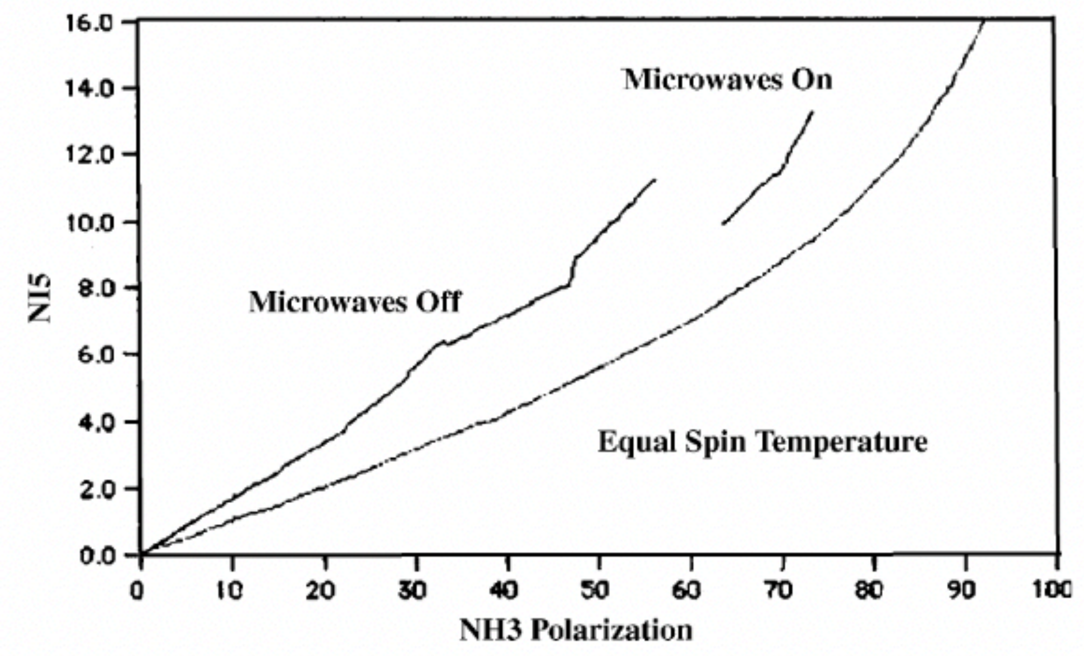




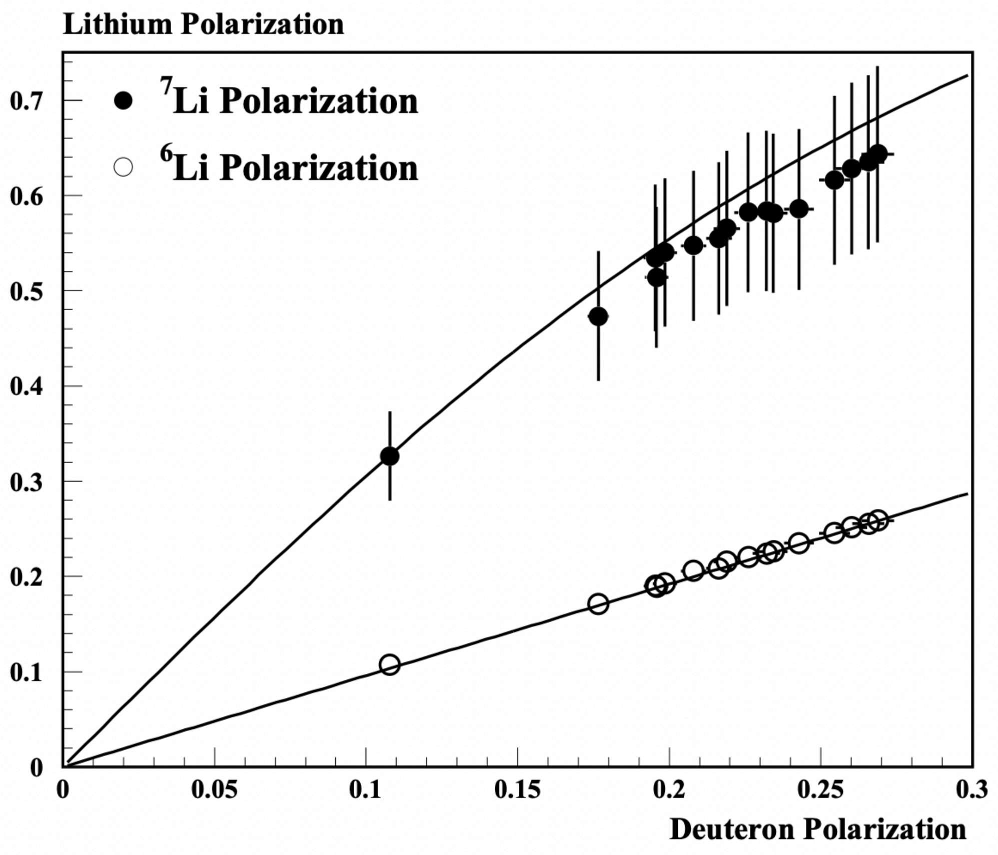
S. Bultmass et al, NIM 425 (1999) 23-36



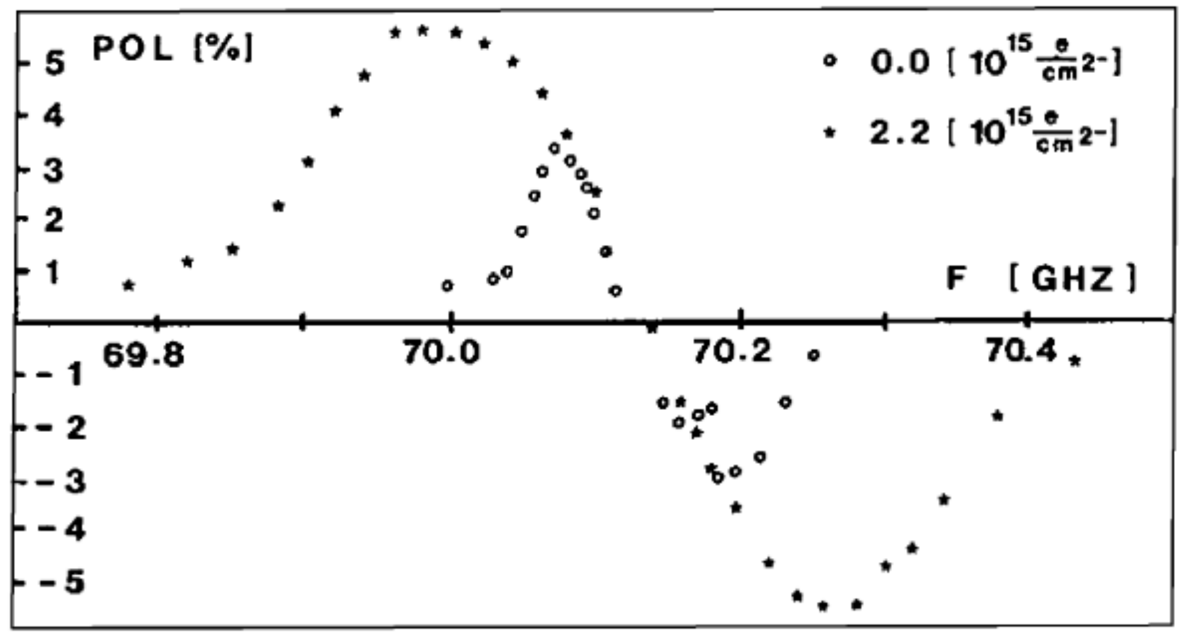
D. Crabb, W. Meyer, Annu. Rev. NPC (1997) 47



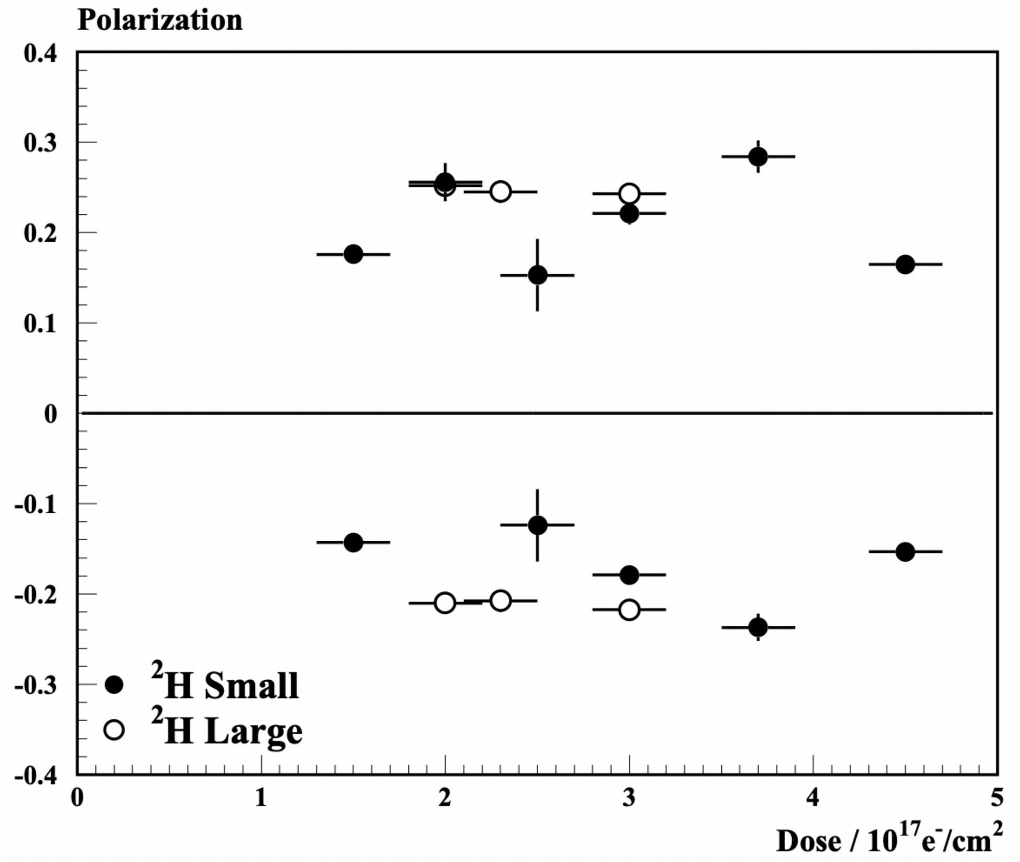
W. Meyer, NIM A526 (2004) 12-21



S. Bultmass et al, NIM 425 (1999) 23-36

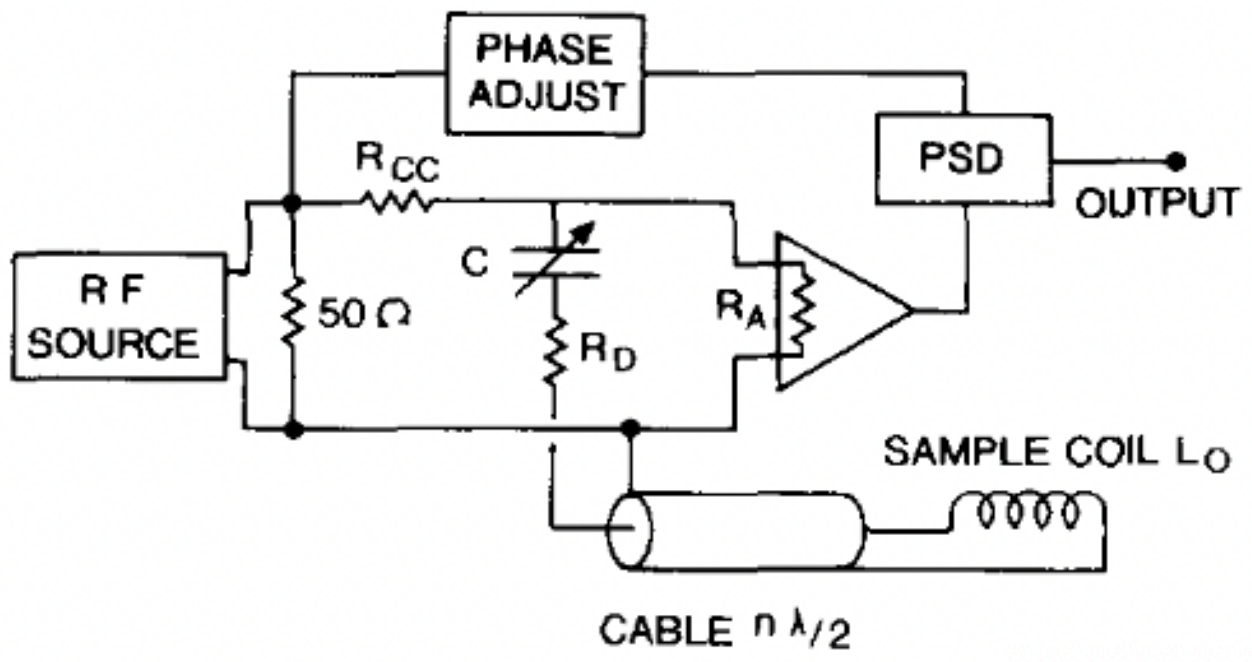


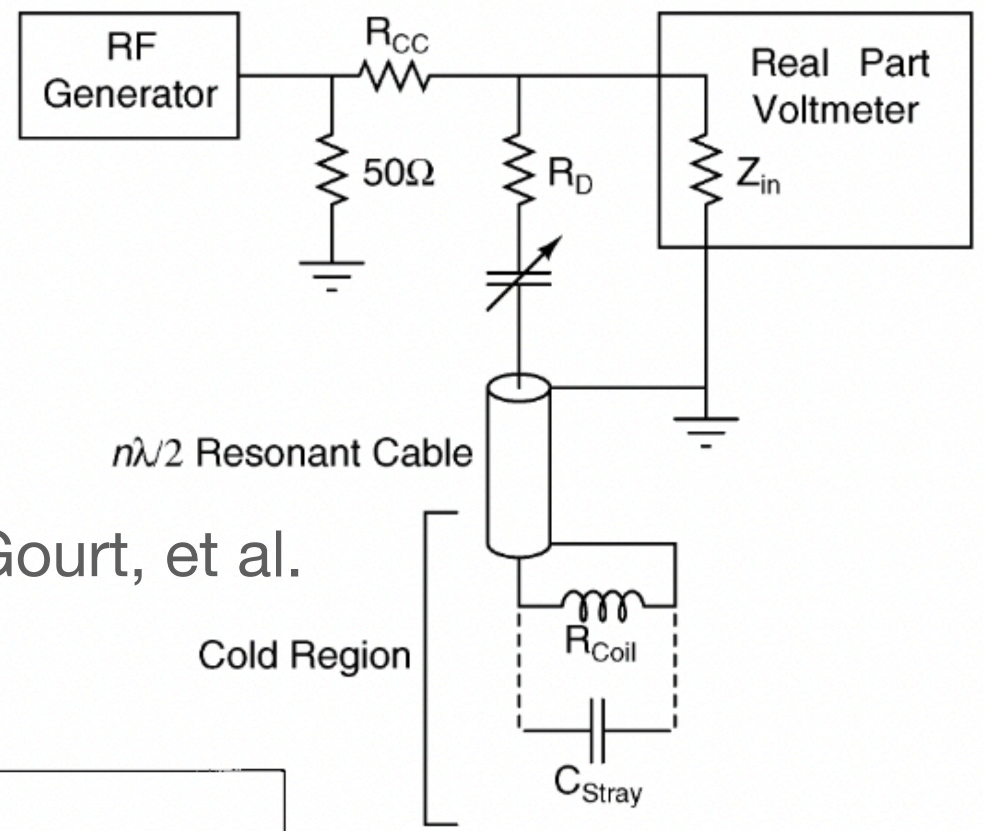
W. Meyer, NIM A526 (2004) 12-21



Some Examples

In Polarized Targets





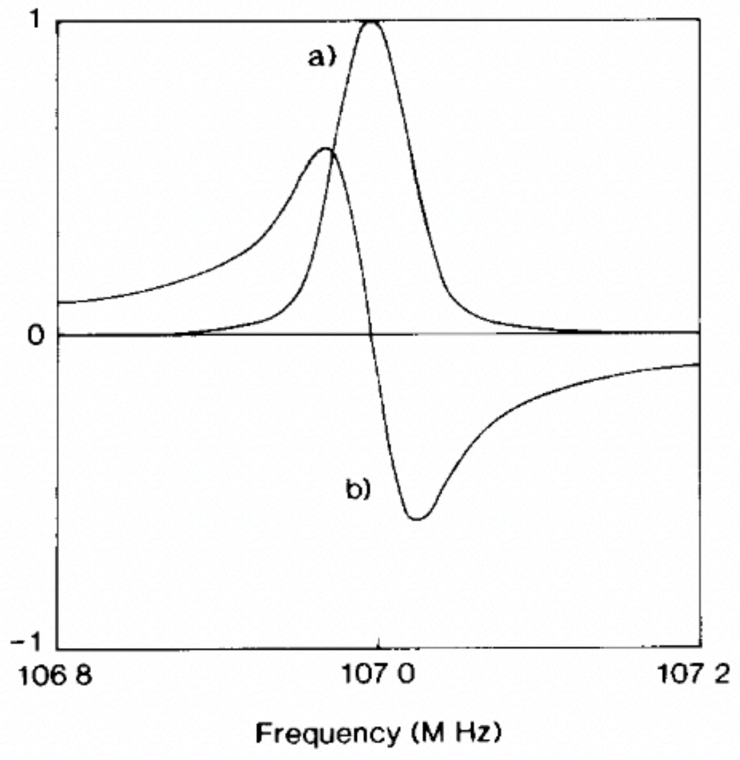
G.R. Gourt, et al.

Design Needed

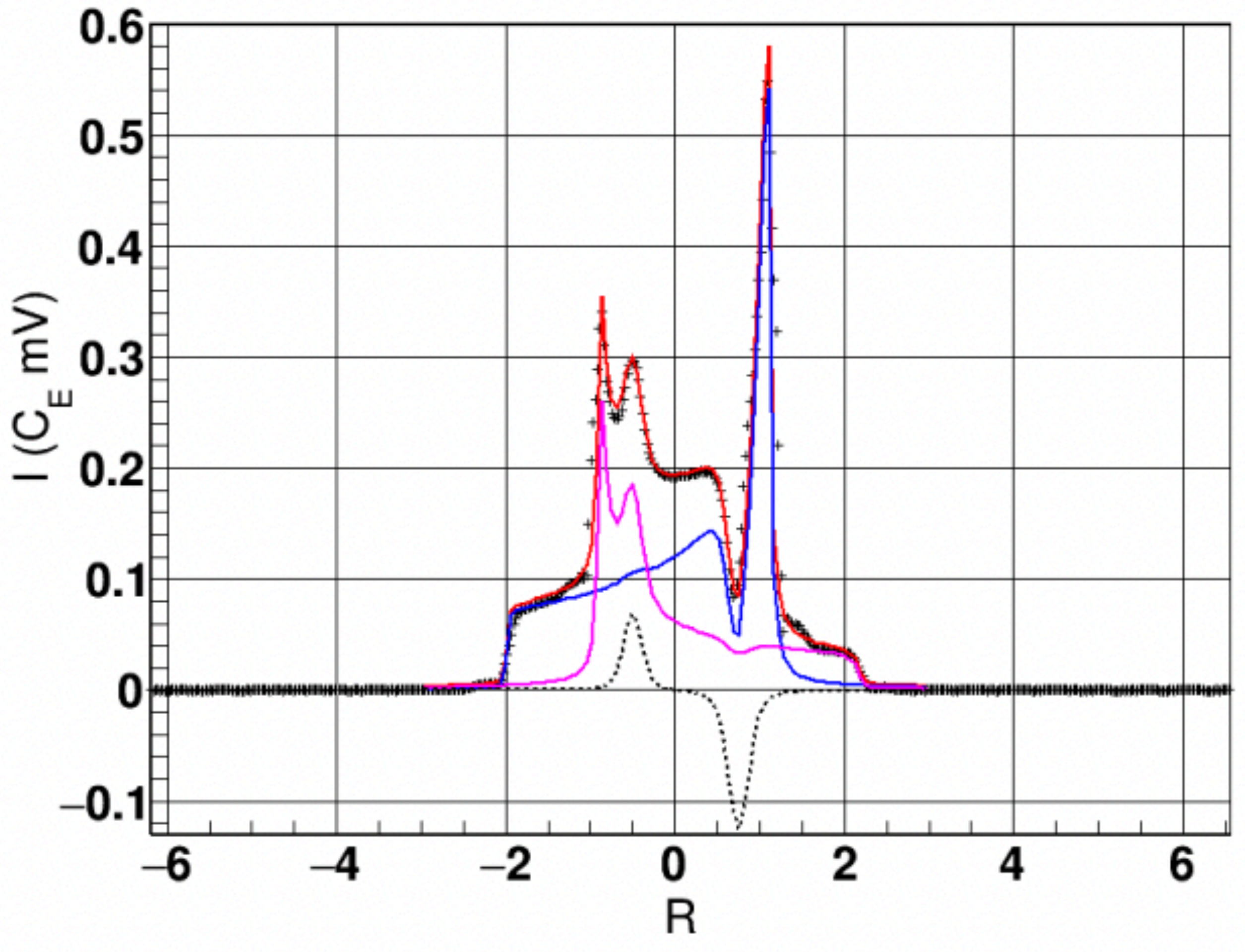
- Absorption/Dispersion
- Fast Phase Sampling
- Adjustable destructive RF
- Separation of RF range

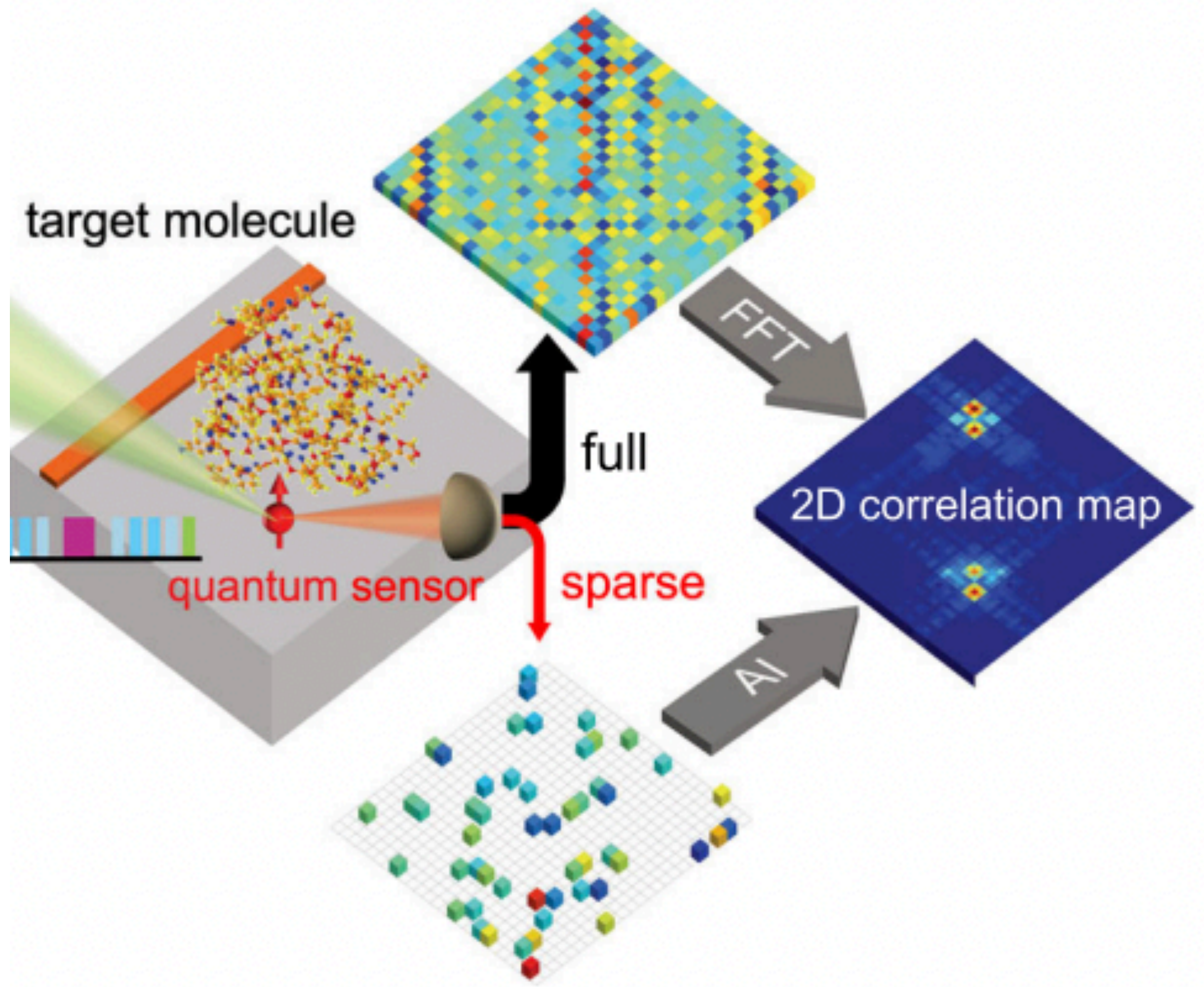
Original Liverpool design

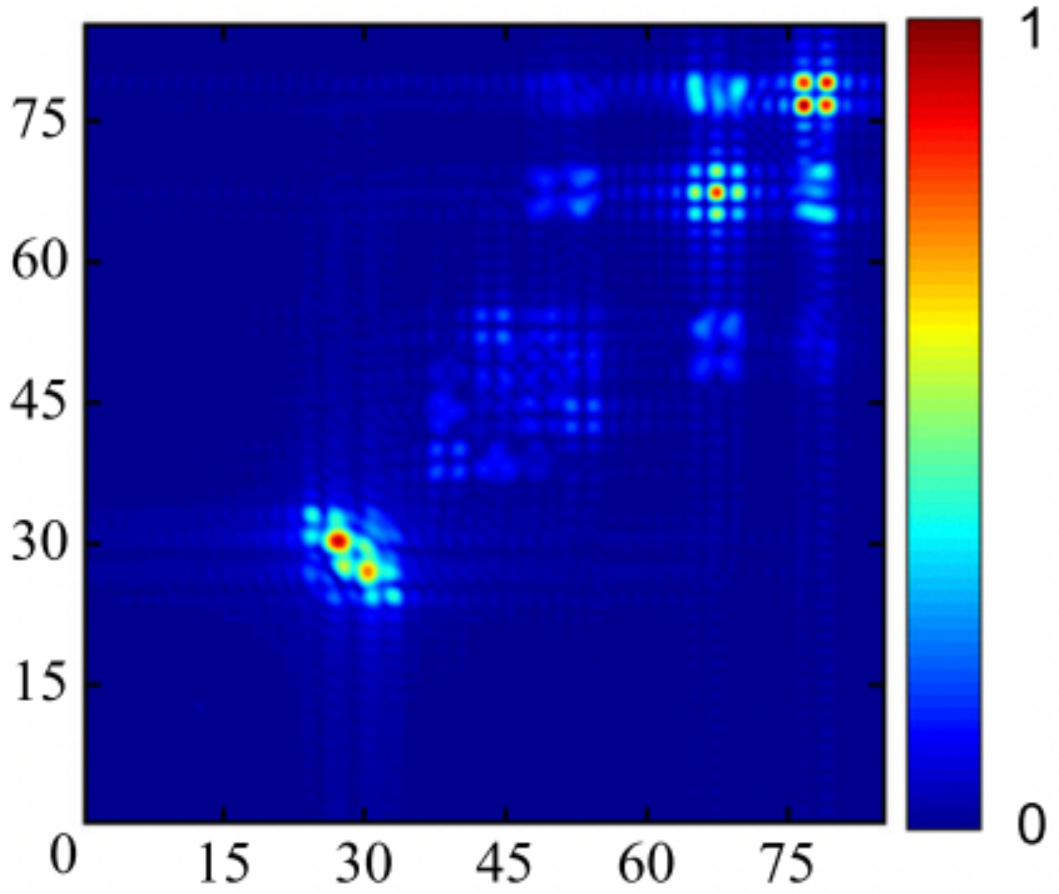
- Phase Sensitive detector
- Constant Current
- Non-destructive (low amplitude)
- Full spectral range

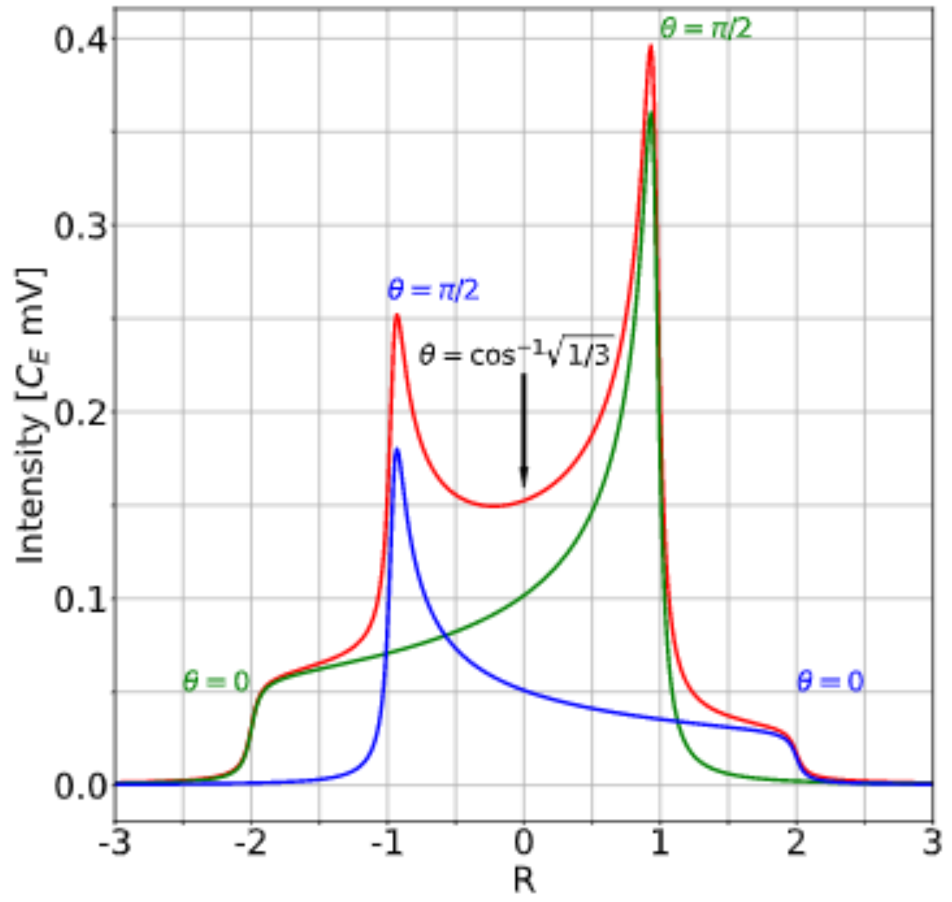


Standard Error in
Experiments: 4%
Theoretical Limit: 0.8%



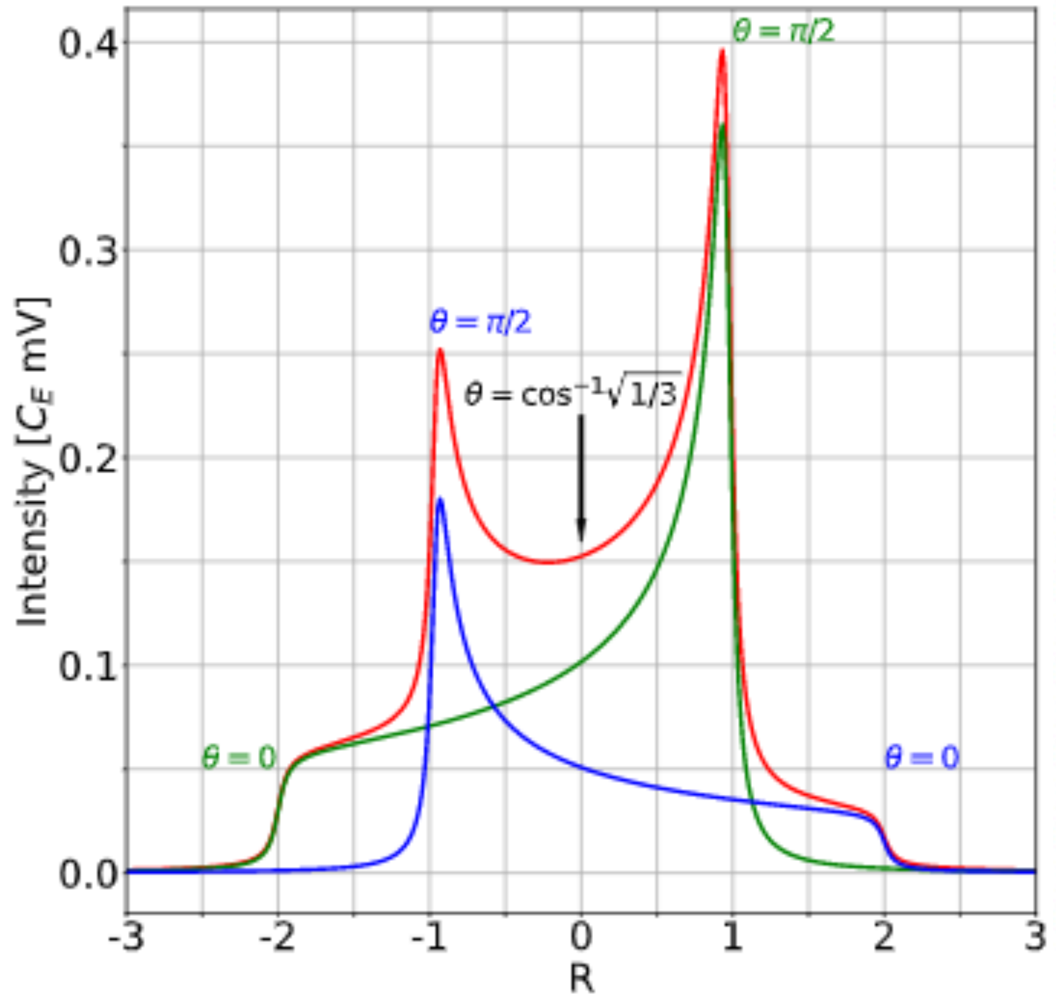




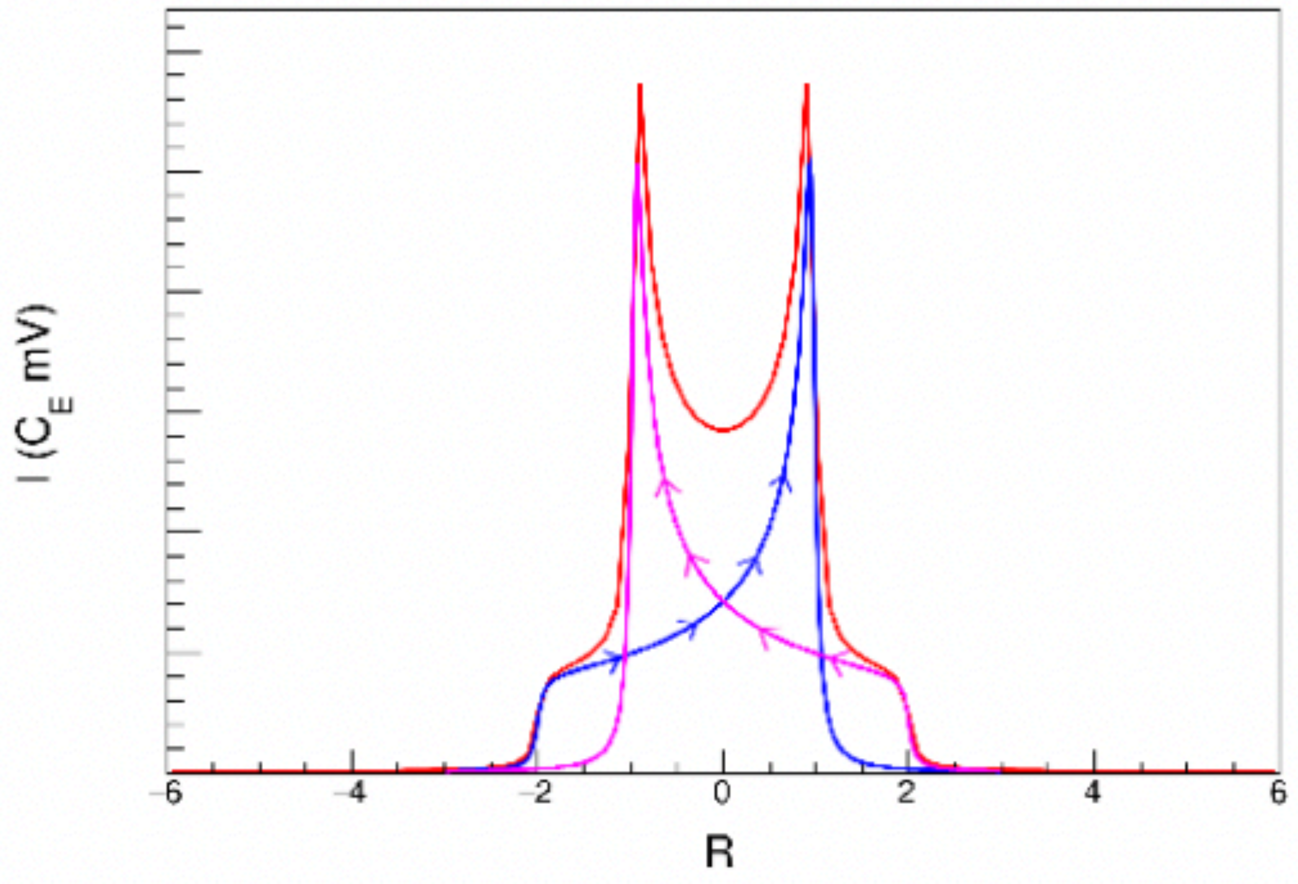


Some Examples
In Polarized Targets

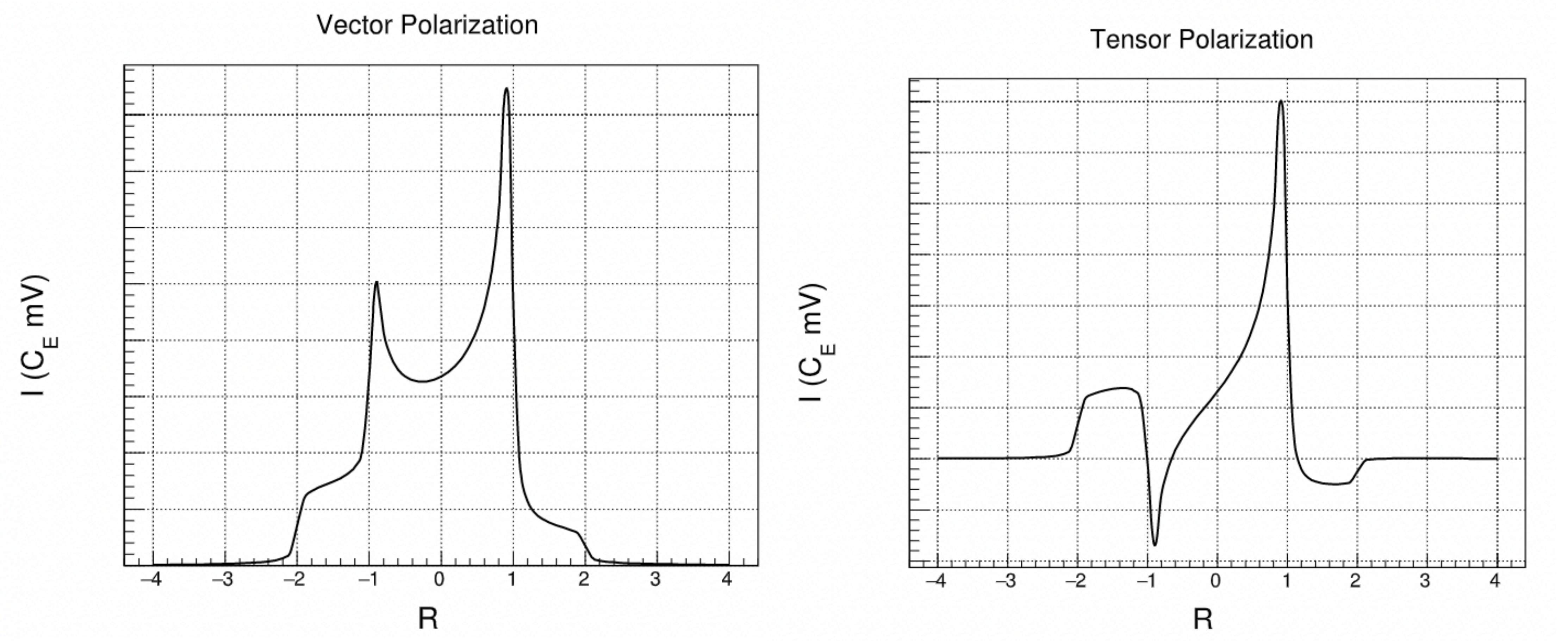
EPJA 53 (2017) 7-13



$P = I^+ + I^-$

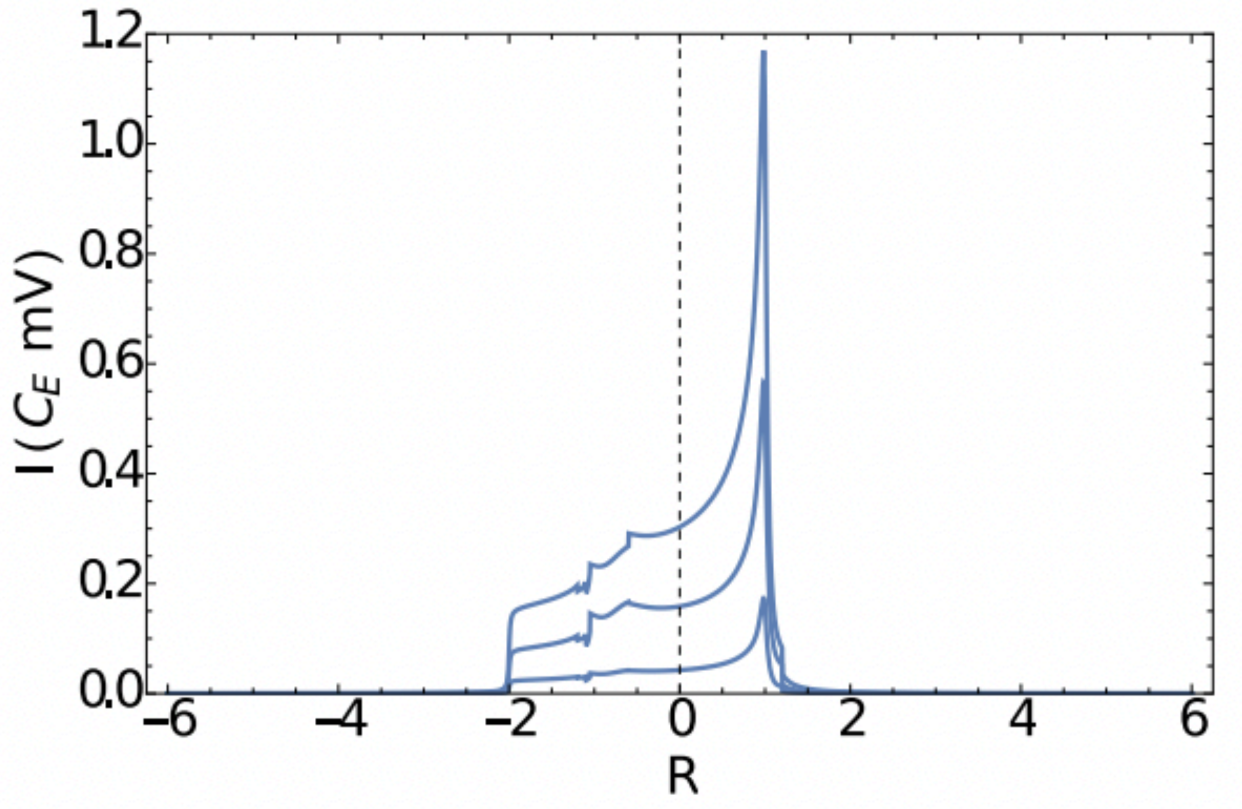


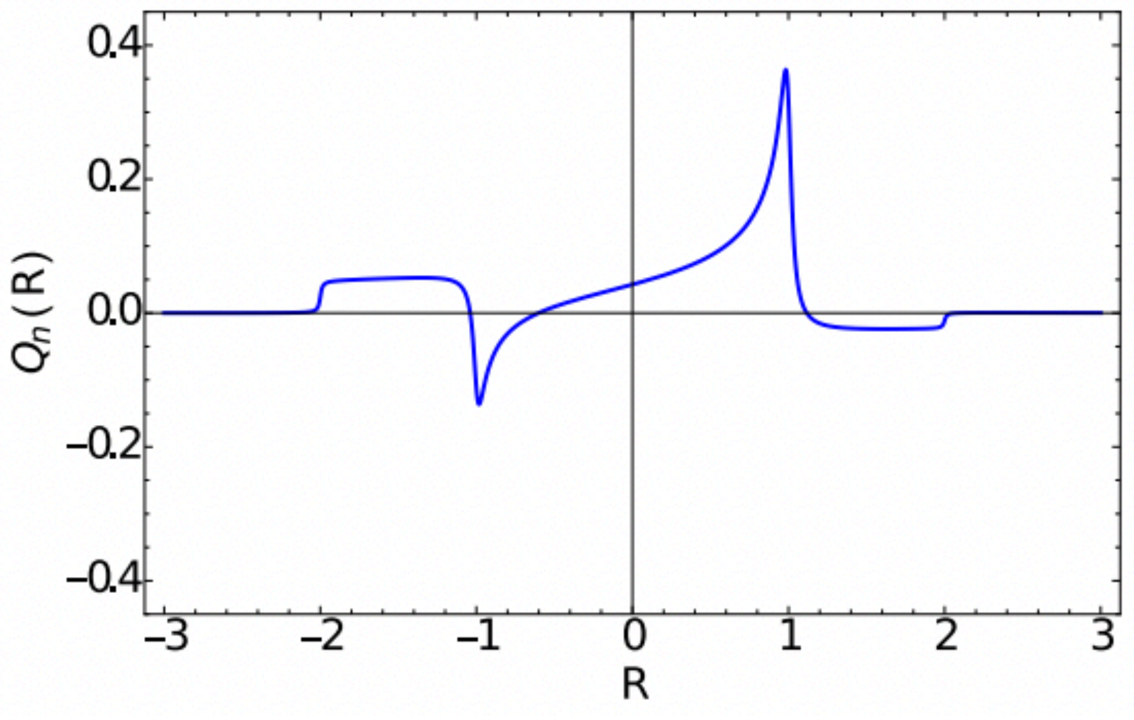
$Q = I^+ - I^-$

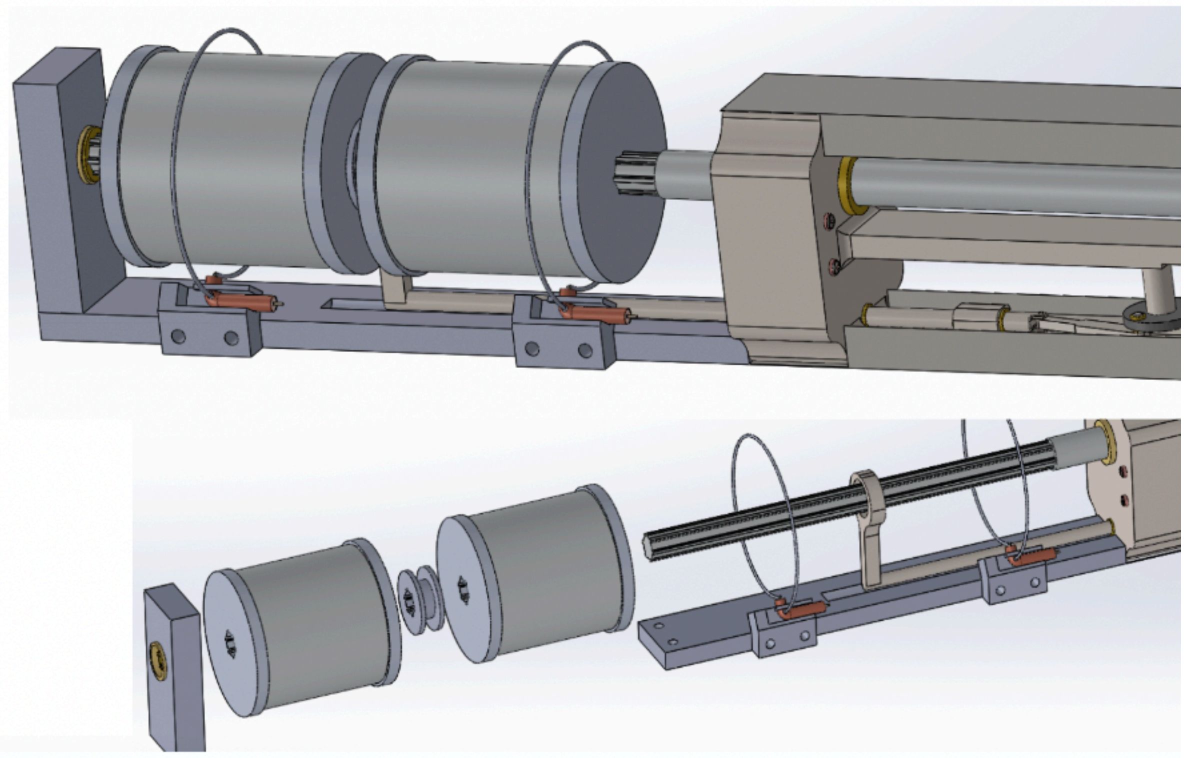


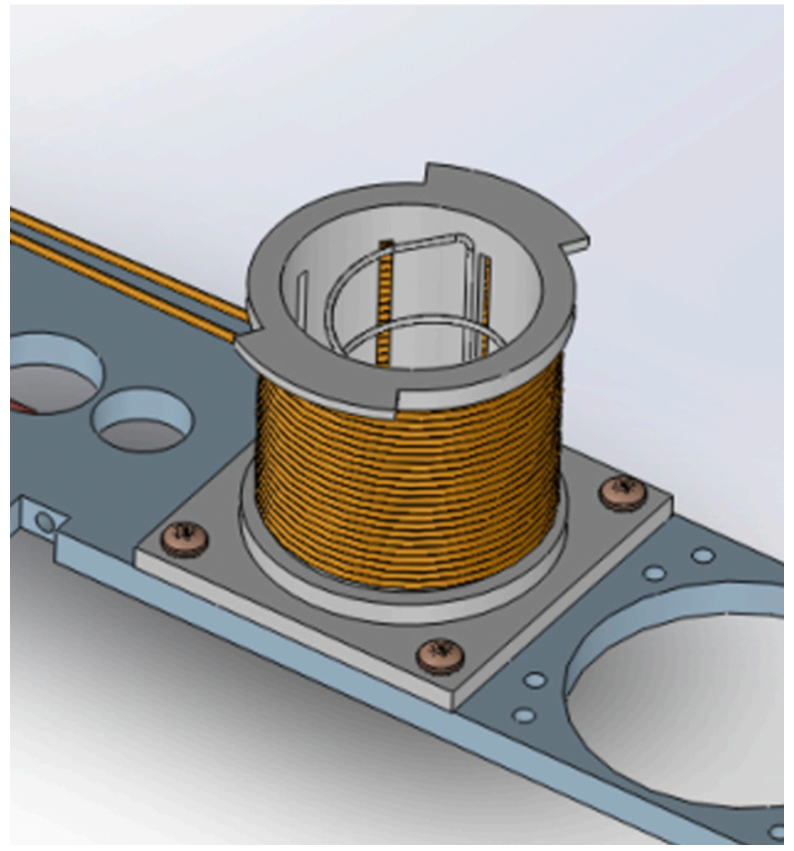
NIMA 981 (2020) 164504

- High Power RF to induce transition
- Selective Semi-saturation
- Must Optimize and Measure in real-time
- Signal Changes as a Function of Beam Dose
- NMR-AI measures and enhances Q bin by bin



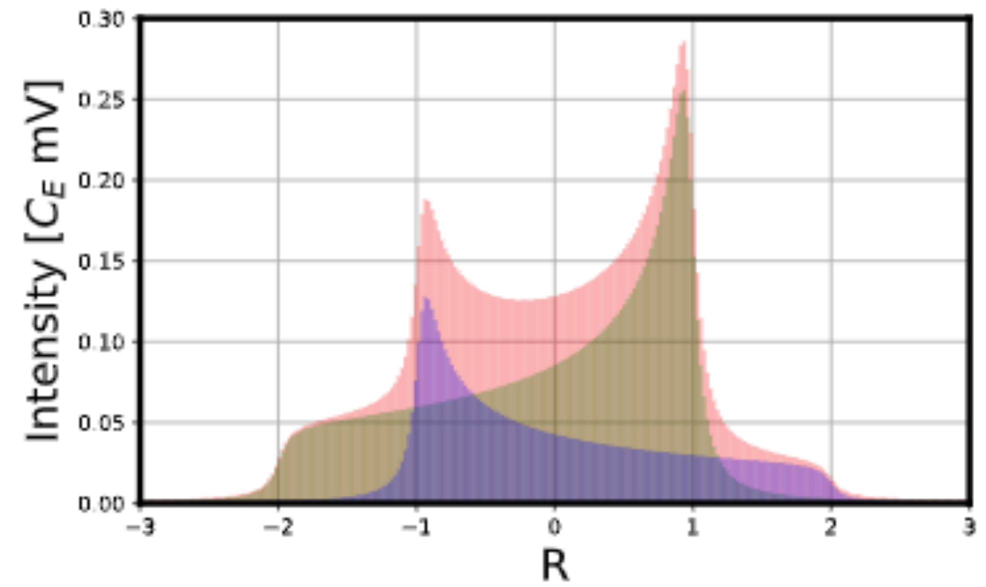


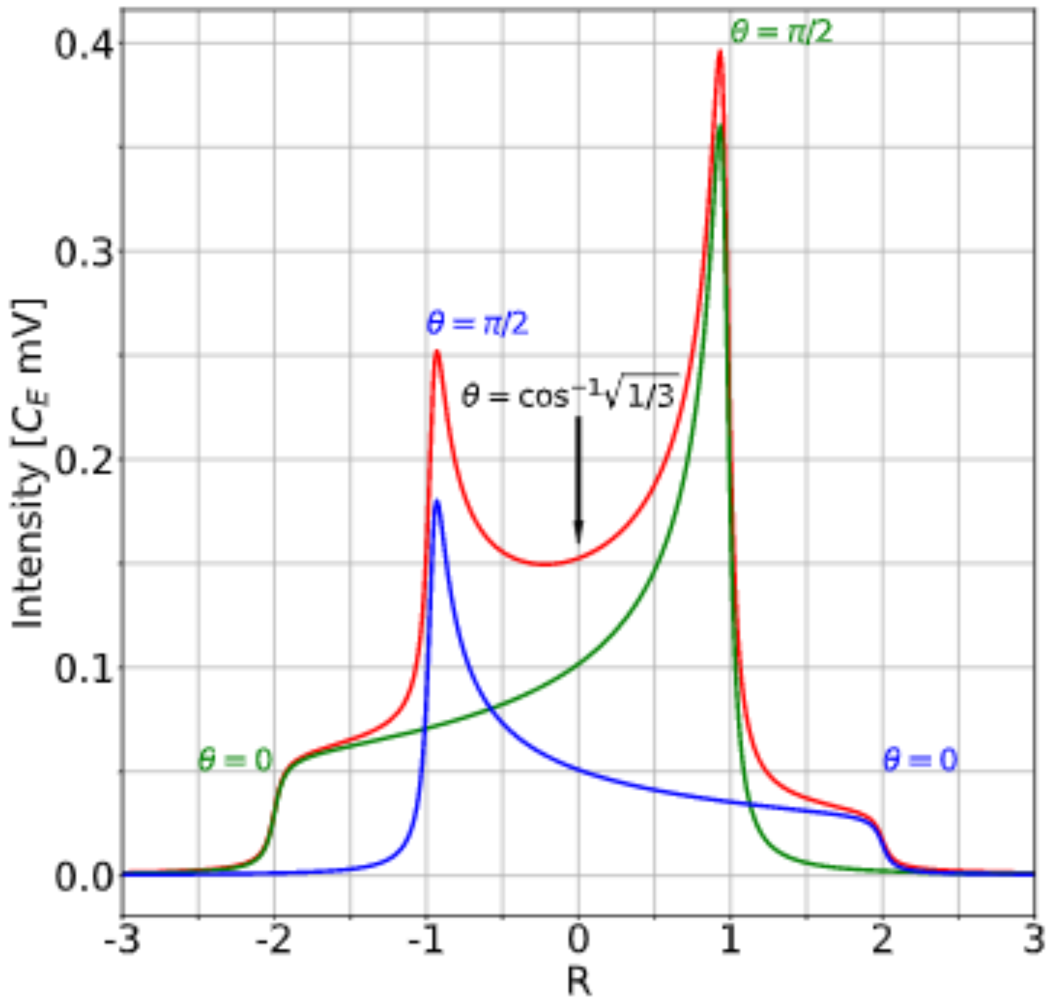


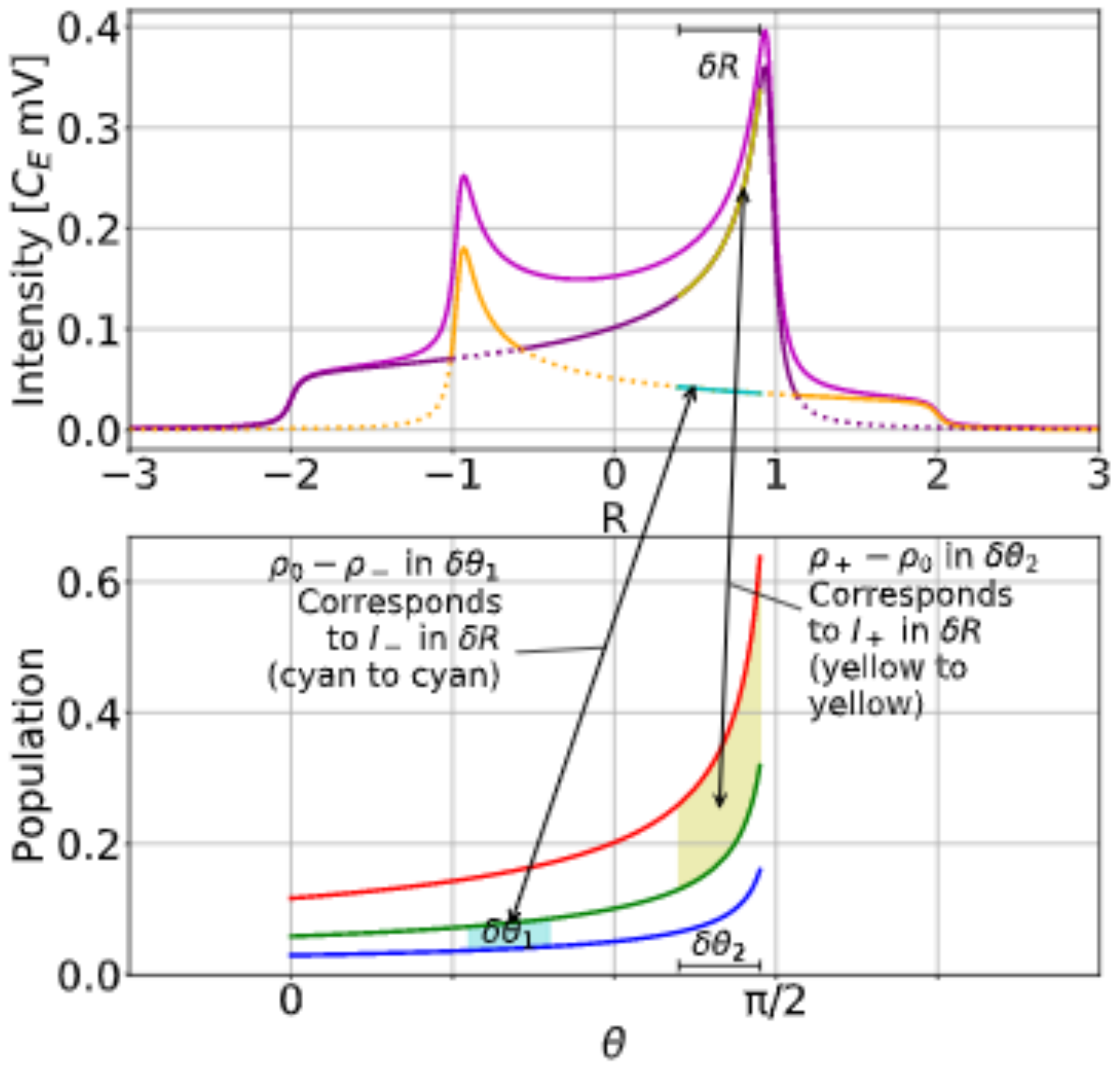


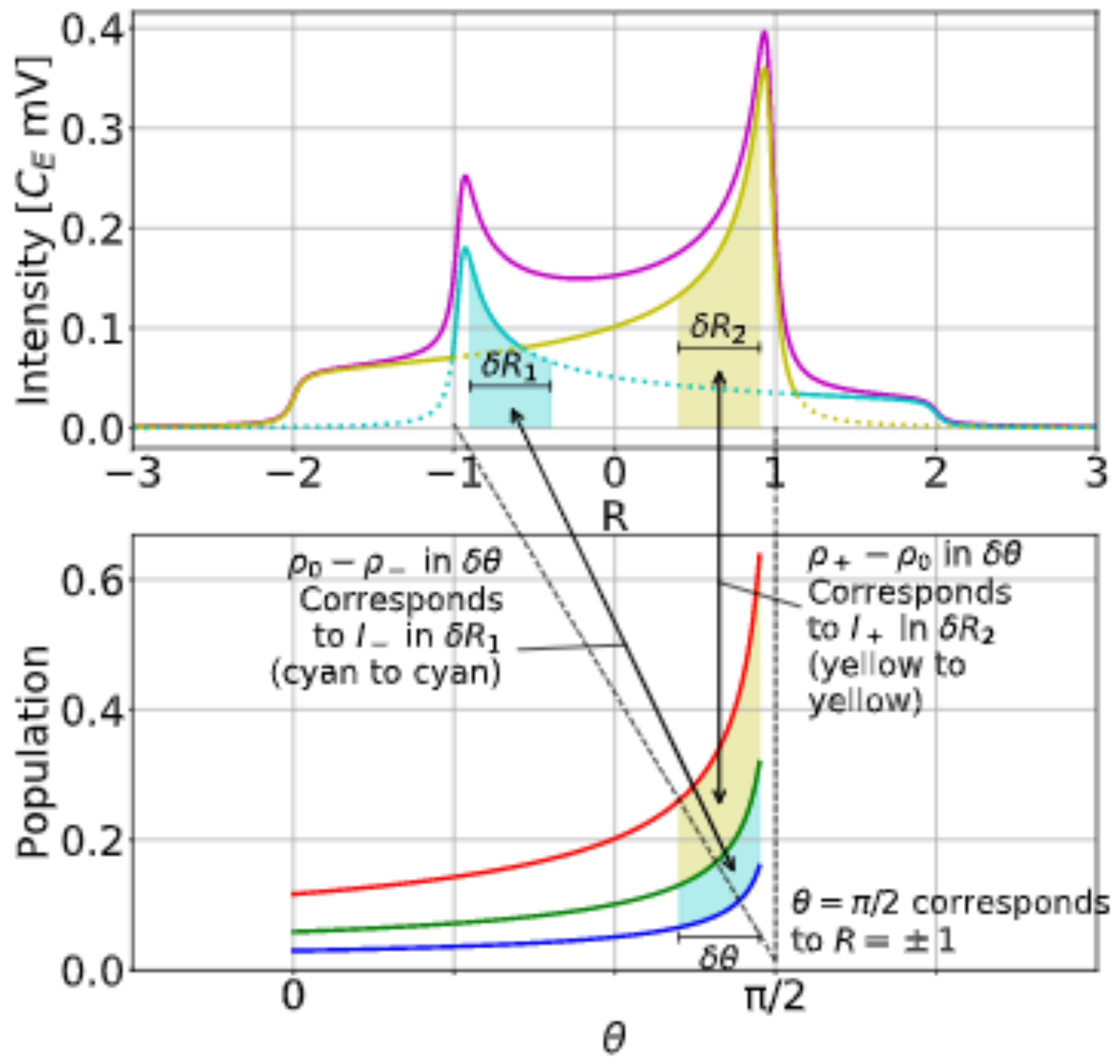
Some Examples

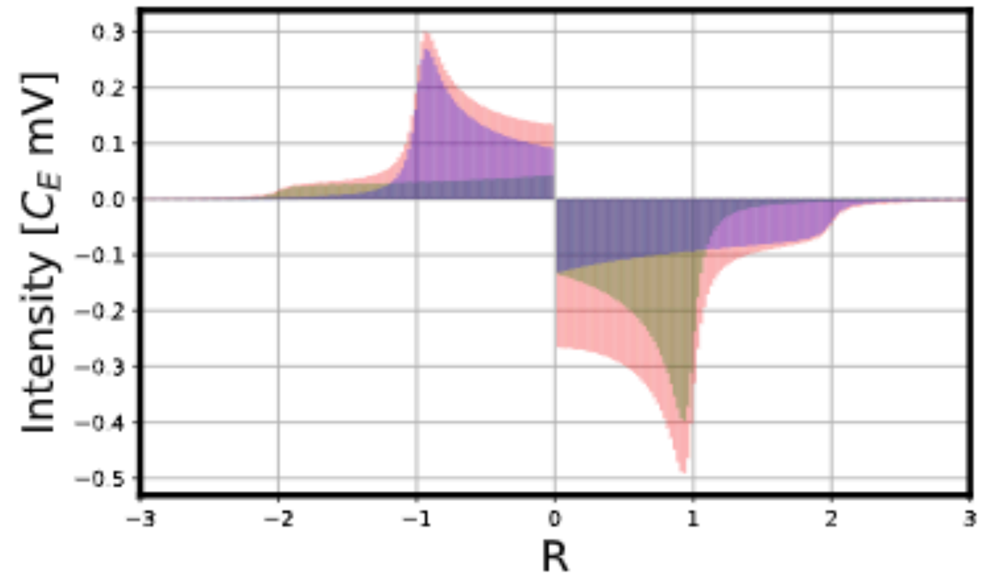
In Polarized Targets

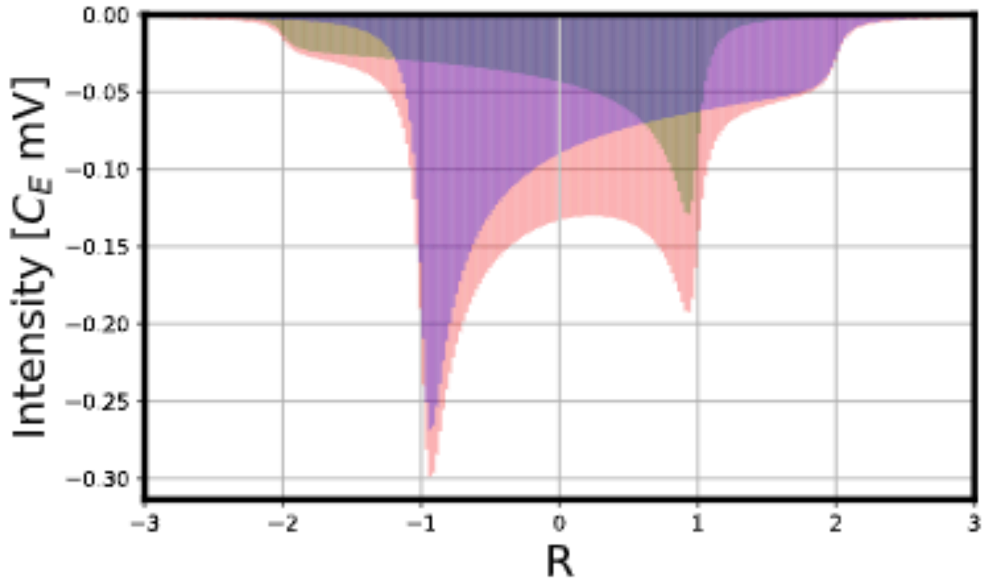


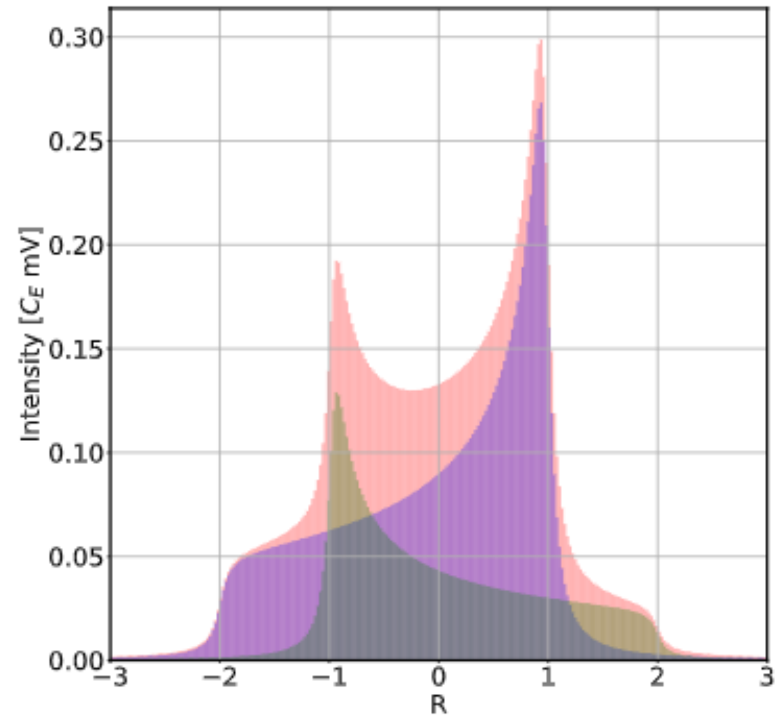


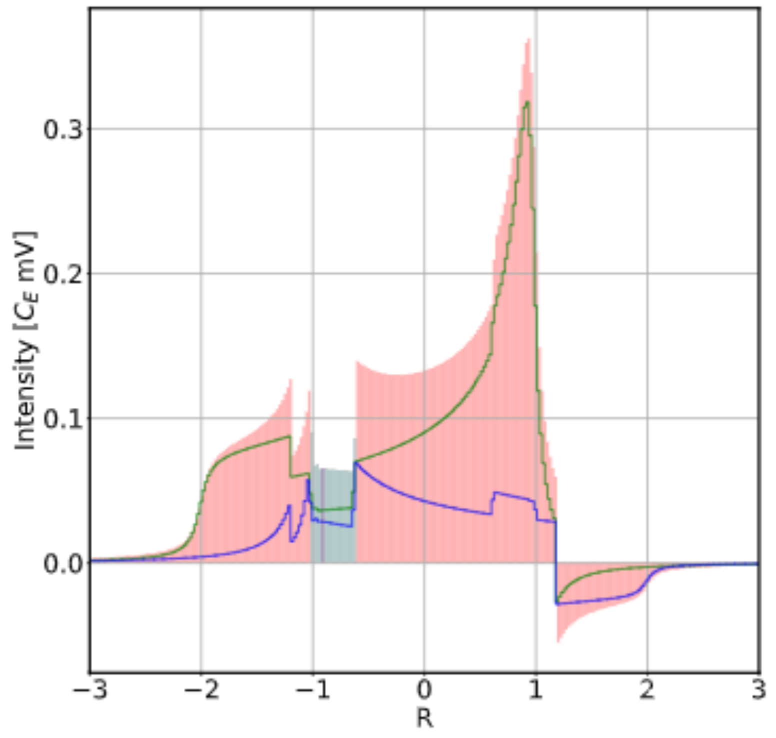


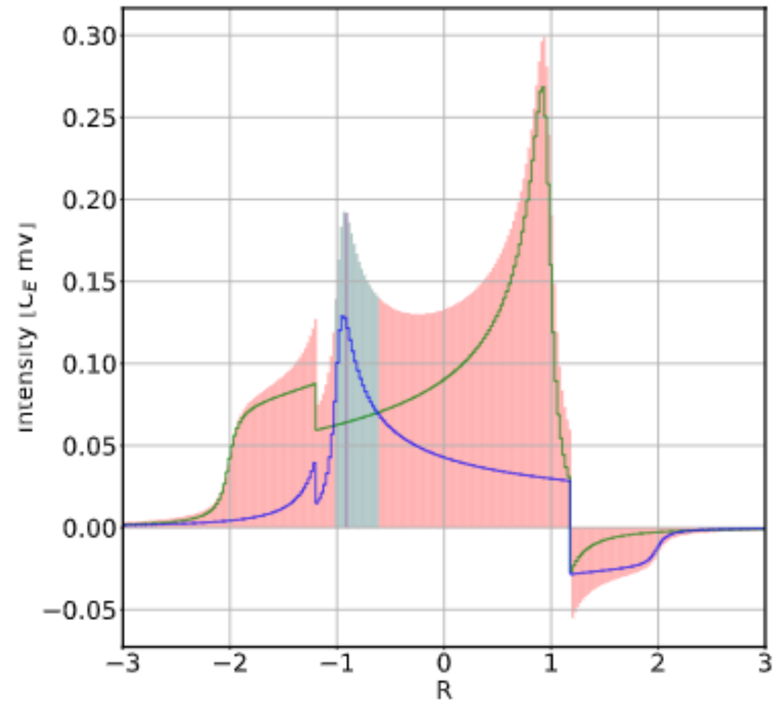


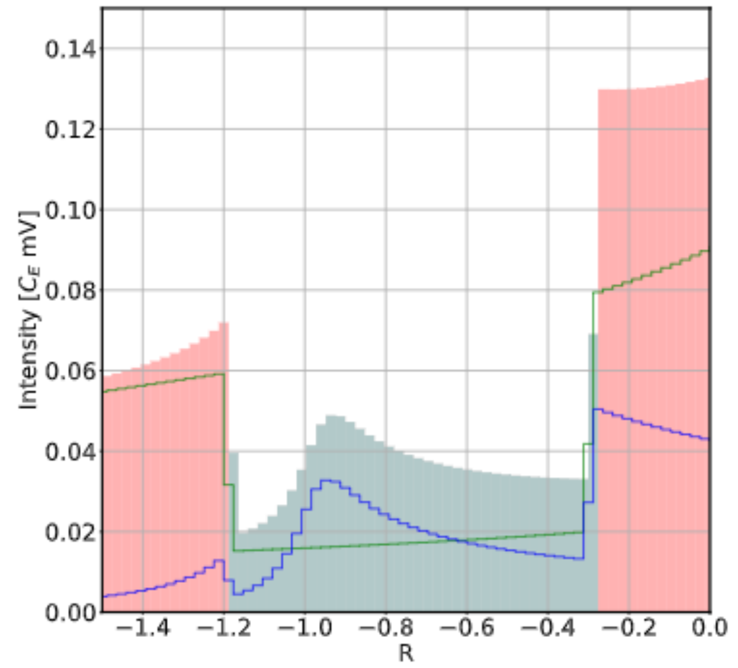


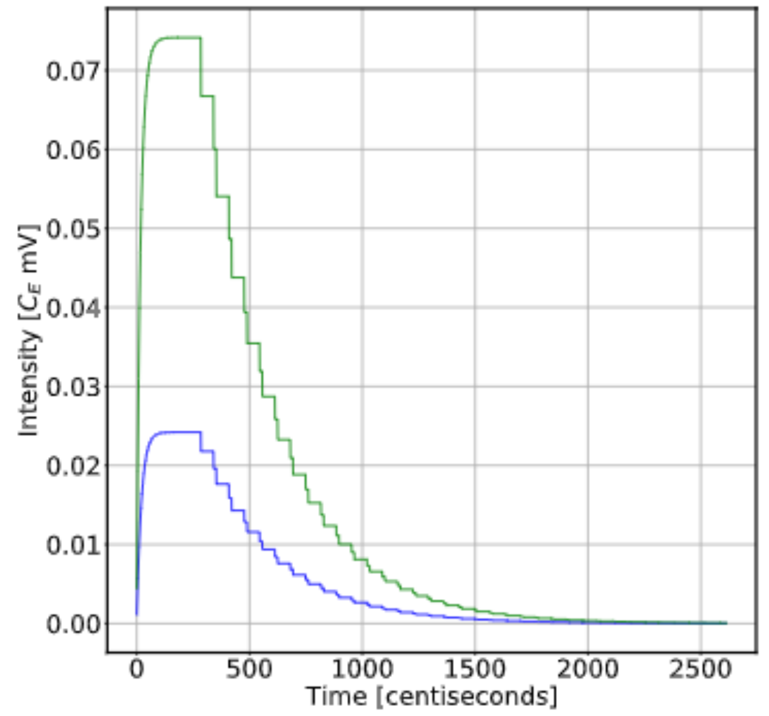












Some Examples

In Phenomenology (Understanding Femtoscale Dynamics)

- Inverse Problem: Determine definitive measures of proton structures using experimental information, Lattice Calculations, and Phenomenology
  - Extraction of GPDs while eliminating the reliance of model fits
  - Extraction of TMDs without assuming a Gaussian factorized form
- Curse of Dimensionality: Understanding the Mother Function (Wigner?) in terms of processes and physical observables (interpretation yields inherent sparsity)
  - How can we impose constraints at the higher-level to interpret dynamics and geometry
  - How do we best obtain information from experiments that gets us the farthest

Candidate Mother Distribution

$W(x, b_T, k_r)$
Wigner Distribution

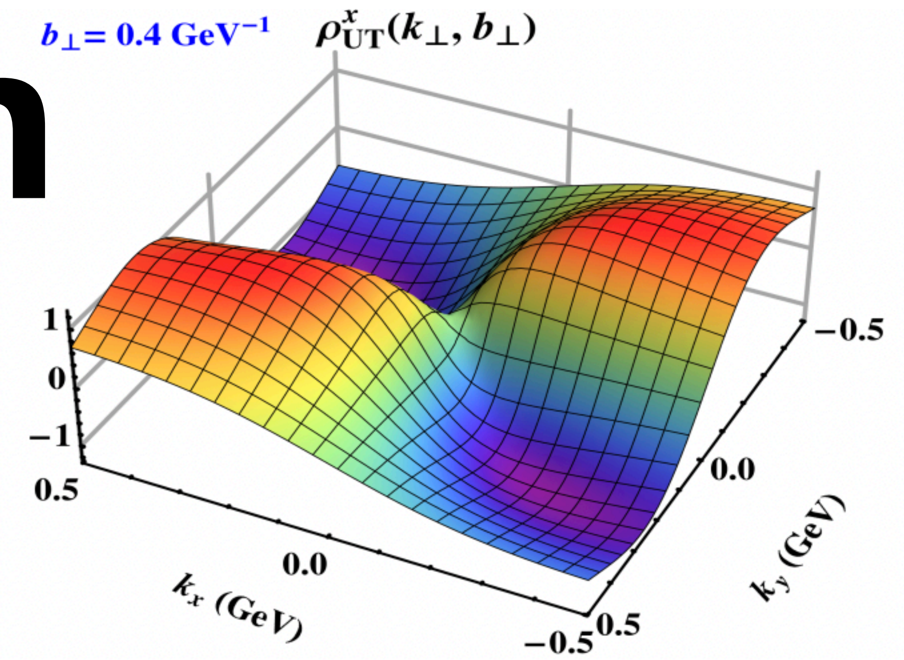
$\int d^2 b_T$ $\int d^2 k_T$

TMDs $f(x, k_T)$ $f(x, b_T)$ Impact Parameter

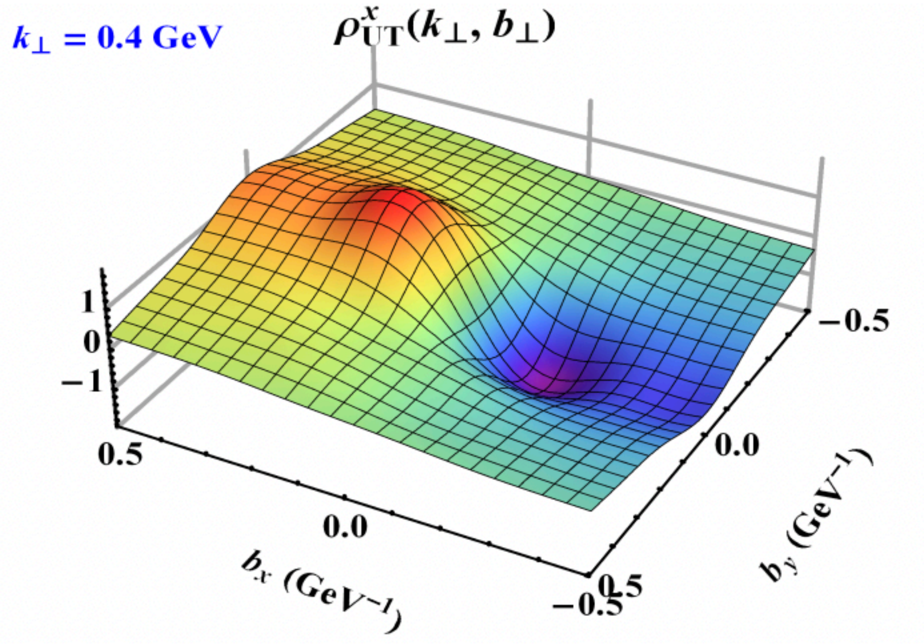
$\int d^2 k_T$ $\int d^2 b_T$

$f(x)$
PDFs

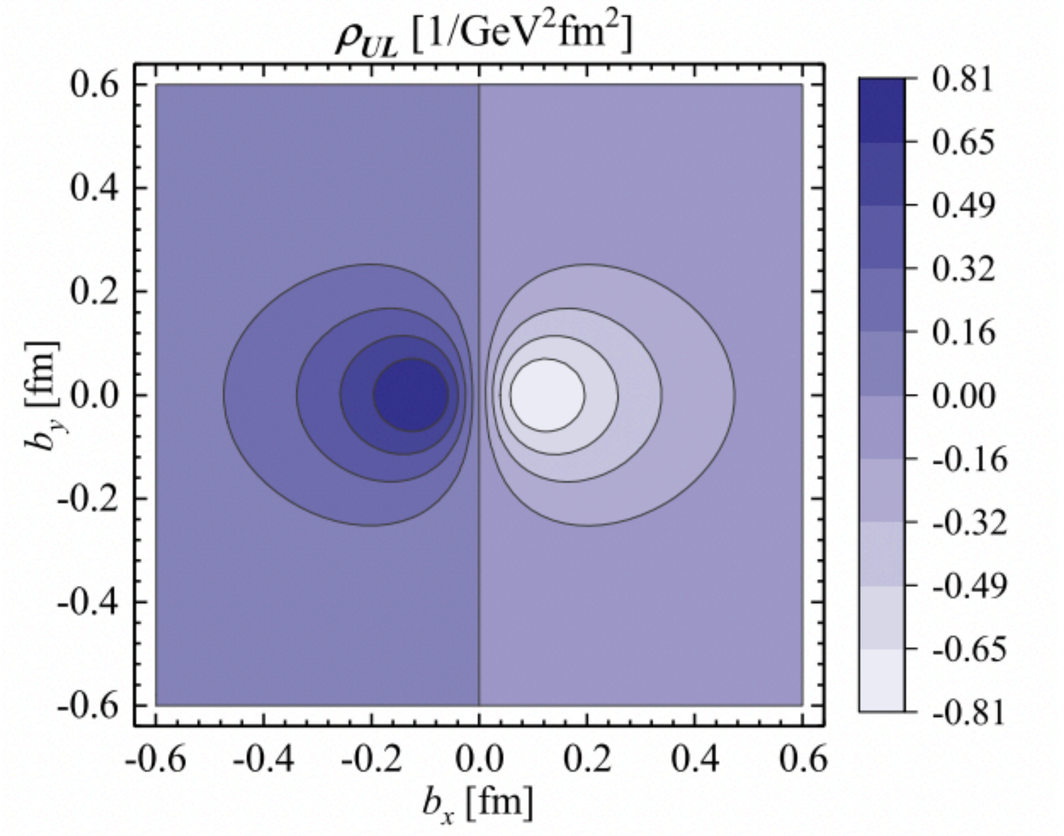
TMDs and Impact Parameters give complementary information about partons and are fundamentally connected to the Wigner Distribution



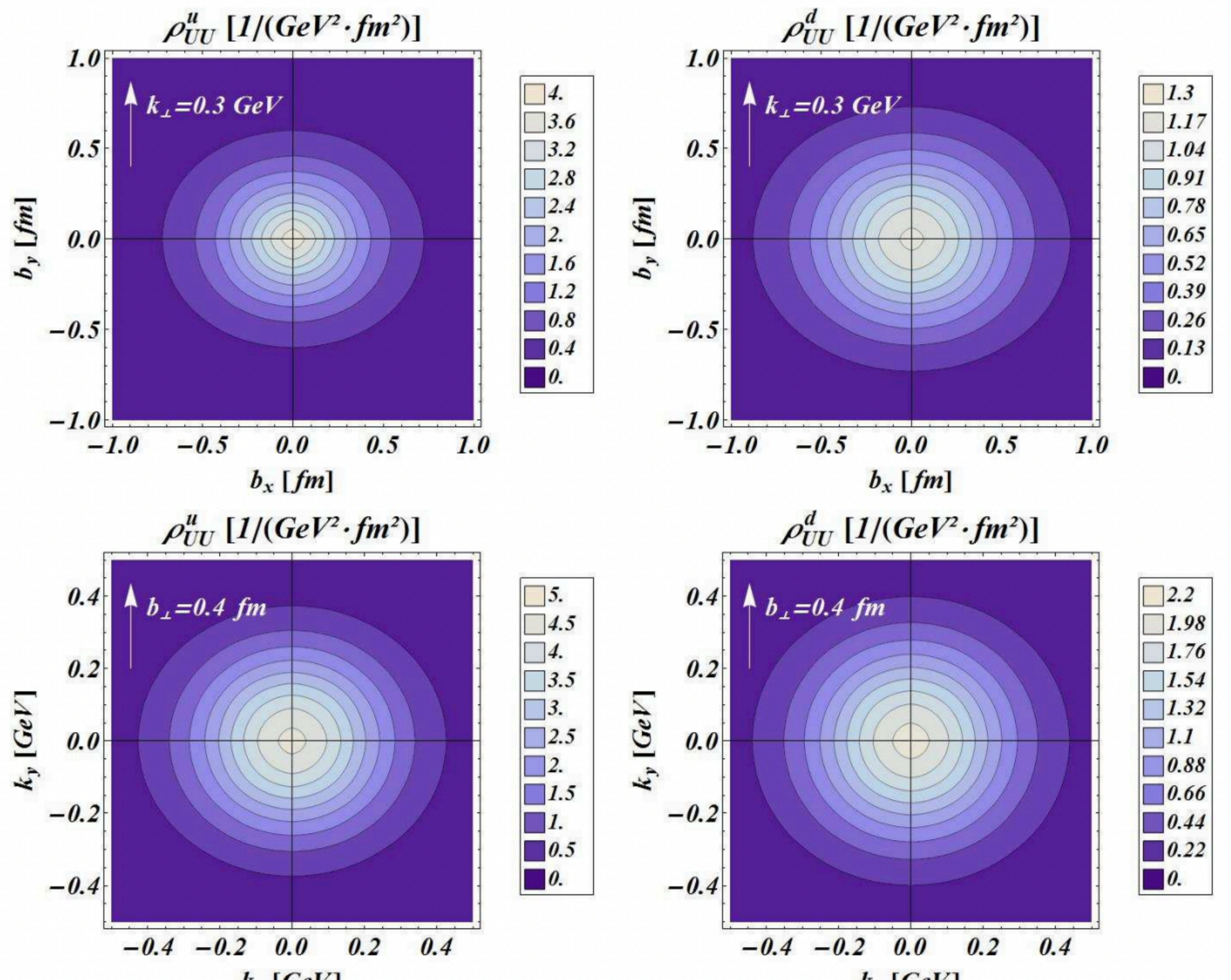
More, AM, Nair, PRD 95, 074039 (2017)



(Liu and Ma, PRD 91, 034019 (2015))



Lorce and Pasquini, PRD 84, 014015 (2011); Liu and Ma, PRD 91, 034019 (2015)



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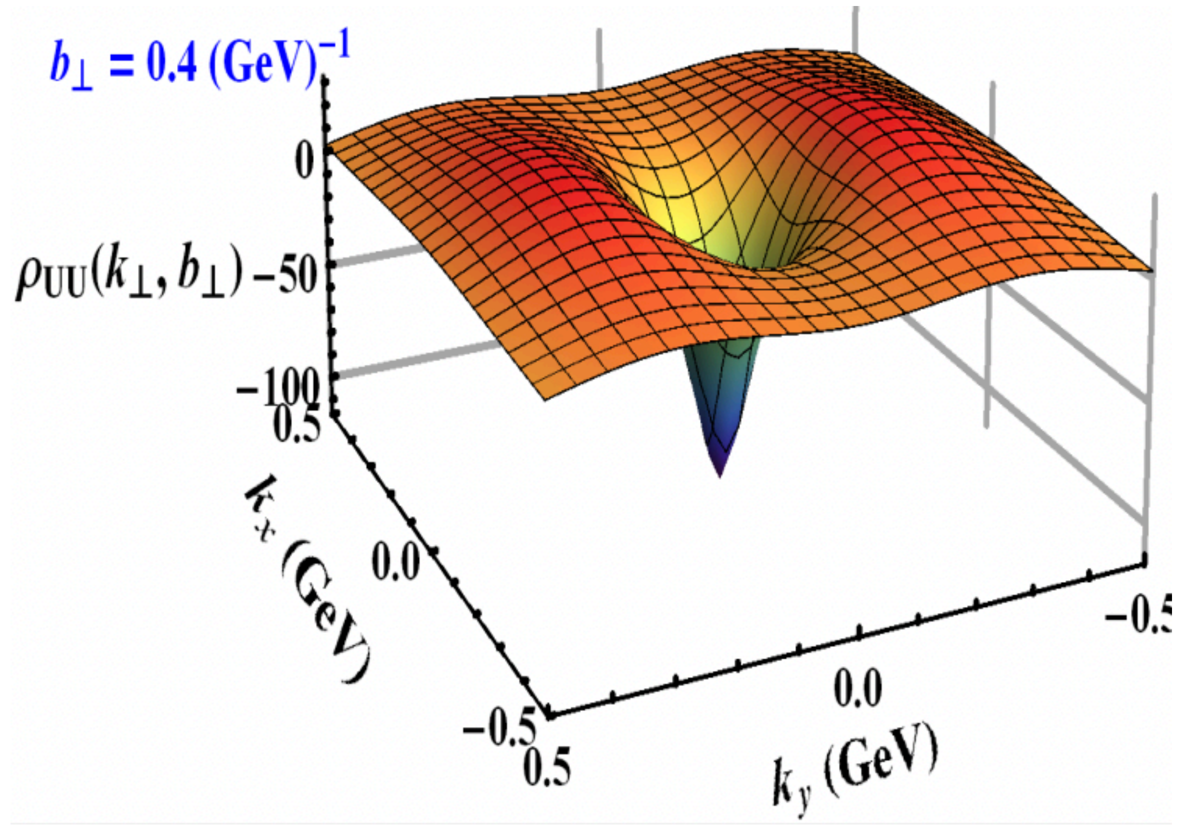
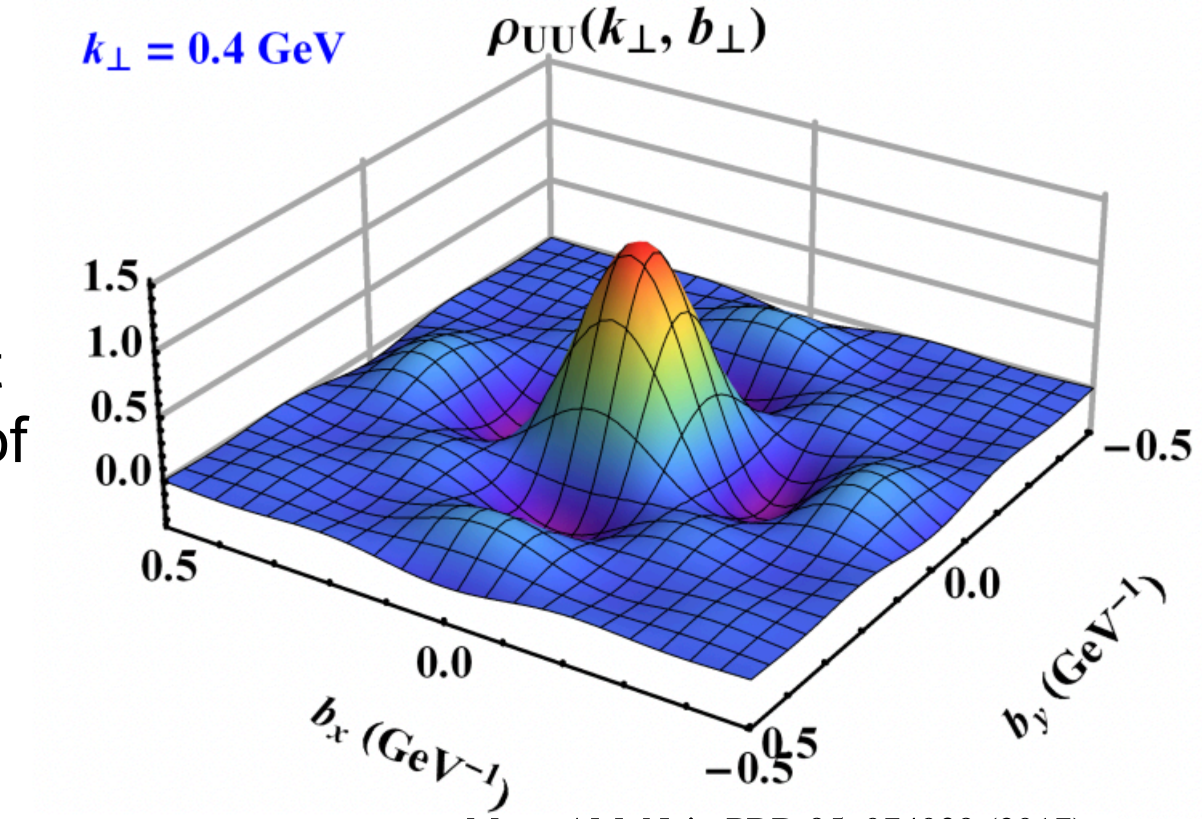


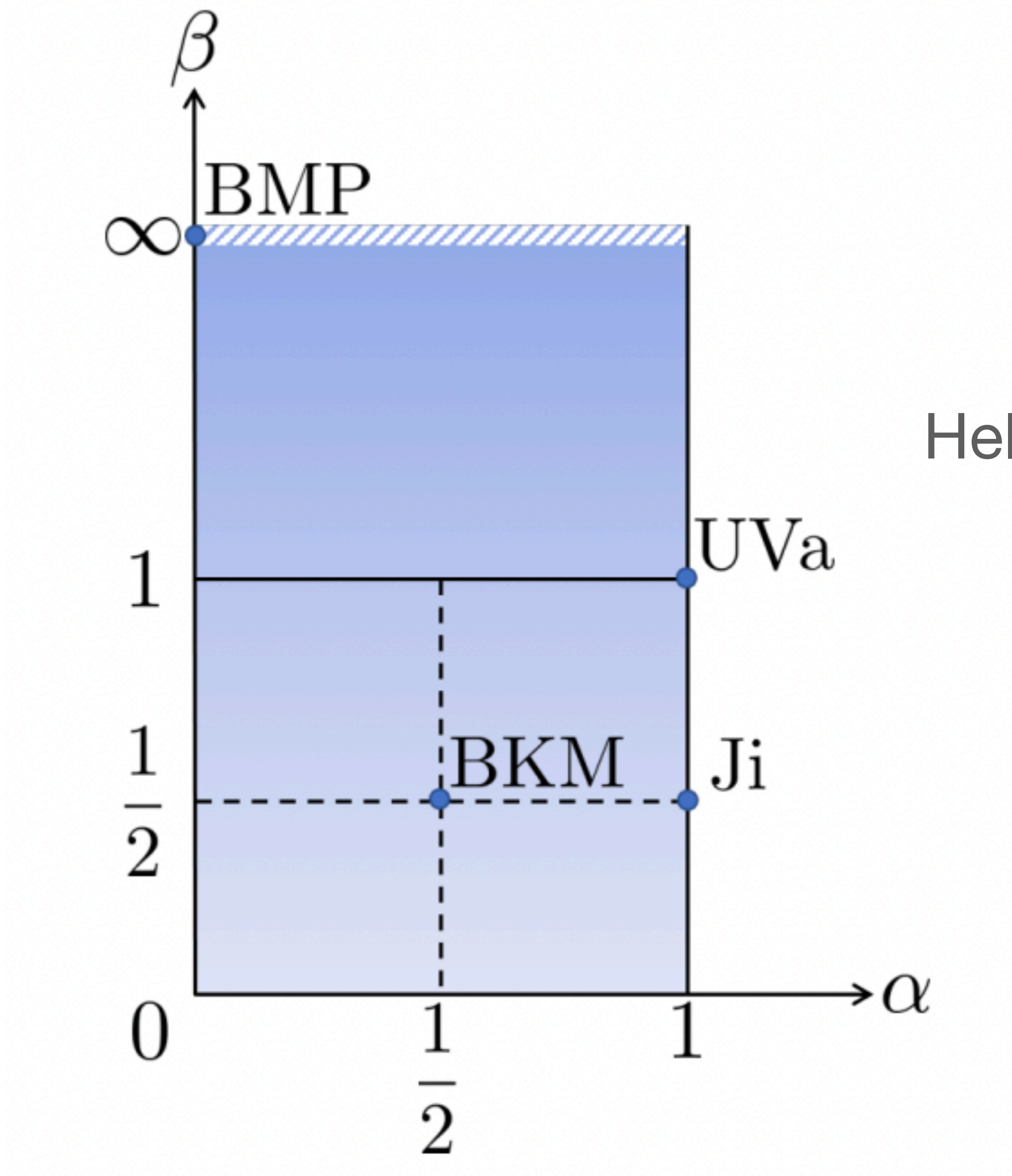
Husimi distributions have a Gaussian regularization factor in the integrand that keeps them positive in the entire range of transverse space coordinate

Zhi-Lei Ma and Zhun Lu
Phys. Rev. D **98**, 054024



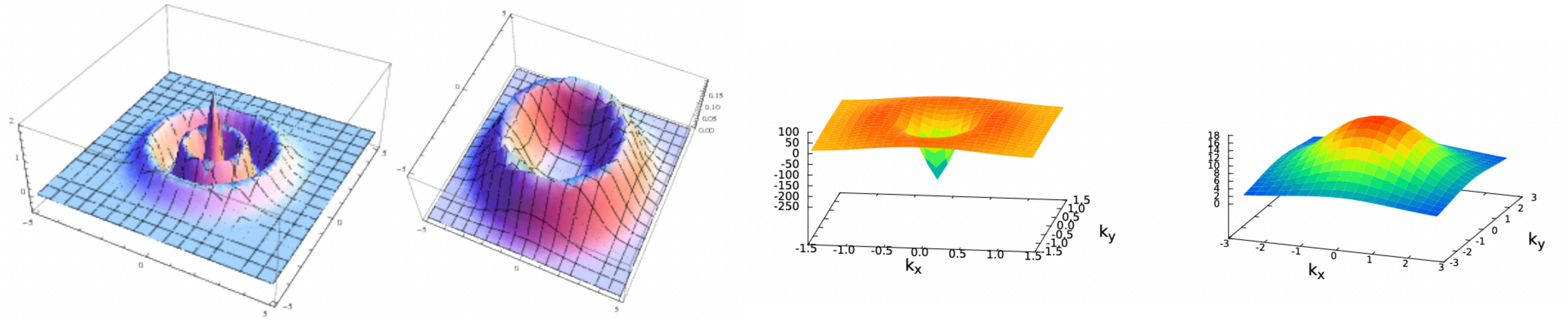
More, AM, Nair, PRD 95, 074039 (2017)

Challenges in the Interpretation



Y. Guo, at el., arxiv2109.10373

Helicity Amplitudes



Hagiwara and Hattaj.nuclphysa.2015.04.005, arxiv:1412.4591

$$H(x,x,t) = \frac{n\,r}{1+x}\left(\frac{2x}{1+x}\right)^{-\alpha(t)}\left(\frac{1-x}{1+x}\right)^{b}\frac{1}{\left(1-\frac{1-x}{1+x}\frac{t}{M^2}\right)^{p}}$$

GPDs

$$f_{q/p}(x,k_\perp) = f_q(x)\frac{1}{\pi\langle k_\perp^2\rangle}e^{-k_\perp^2/\langle k_\perp^2\rangle}$$

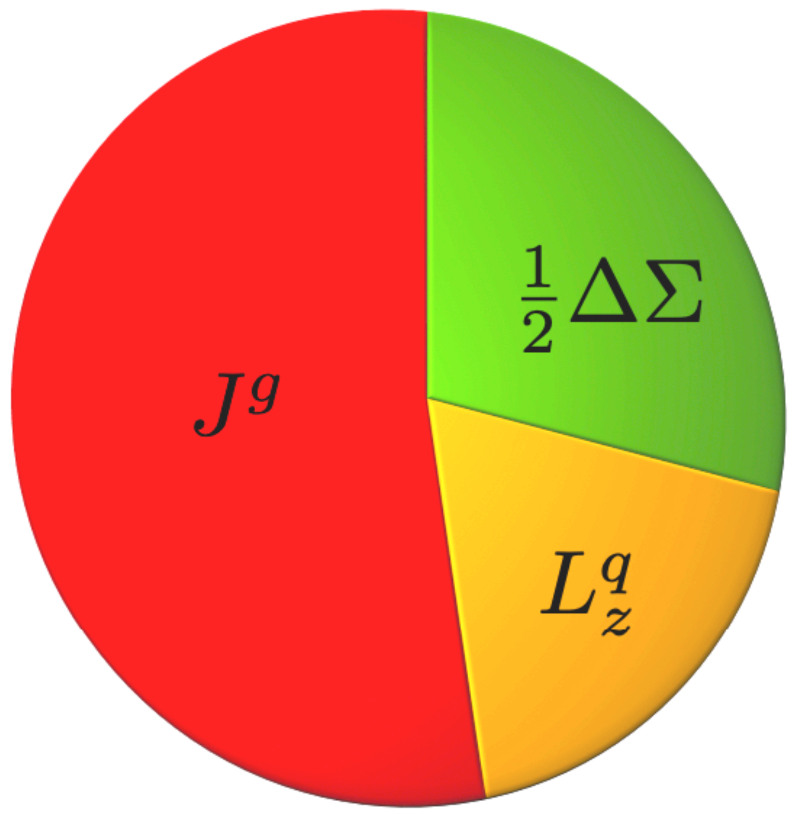
$$\Delta^N f_{q/p^\uparrow}(x,k_\perp) = 2\mathcal{N}_q(x)h(k_\perp)f_{q/p}(x,k_\perp)$$

$$h(k_\perp) = \sqrt{2e}\frac{k_\perp}{M_1}e^{-k_\perp^2/M_1^2}$$

TMDs

$$\mathcal{N}_q(x) = N_q x^{\alpha_q}(1-x)^{\beta_q}\frac{(\alpha_q+\beta_q)^{(\alpha_q+\beta_q)}}{\alpha_q^{\alpha_q}\beta_q^{\beta_q}} \qquad \mathcal{N}_{\bar q}(x) = N_{\bar q}$$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_z^q(\mu) + J^g(\mu) \qquad \frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \ell_z^q(\mu) + \ell_z^g(\mu) + \Delta G(\mu)$$



M. Engelhardt *et al.*, PRD102, 074505 (2020)

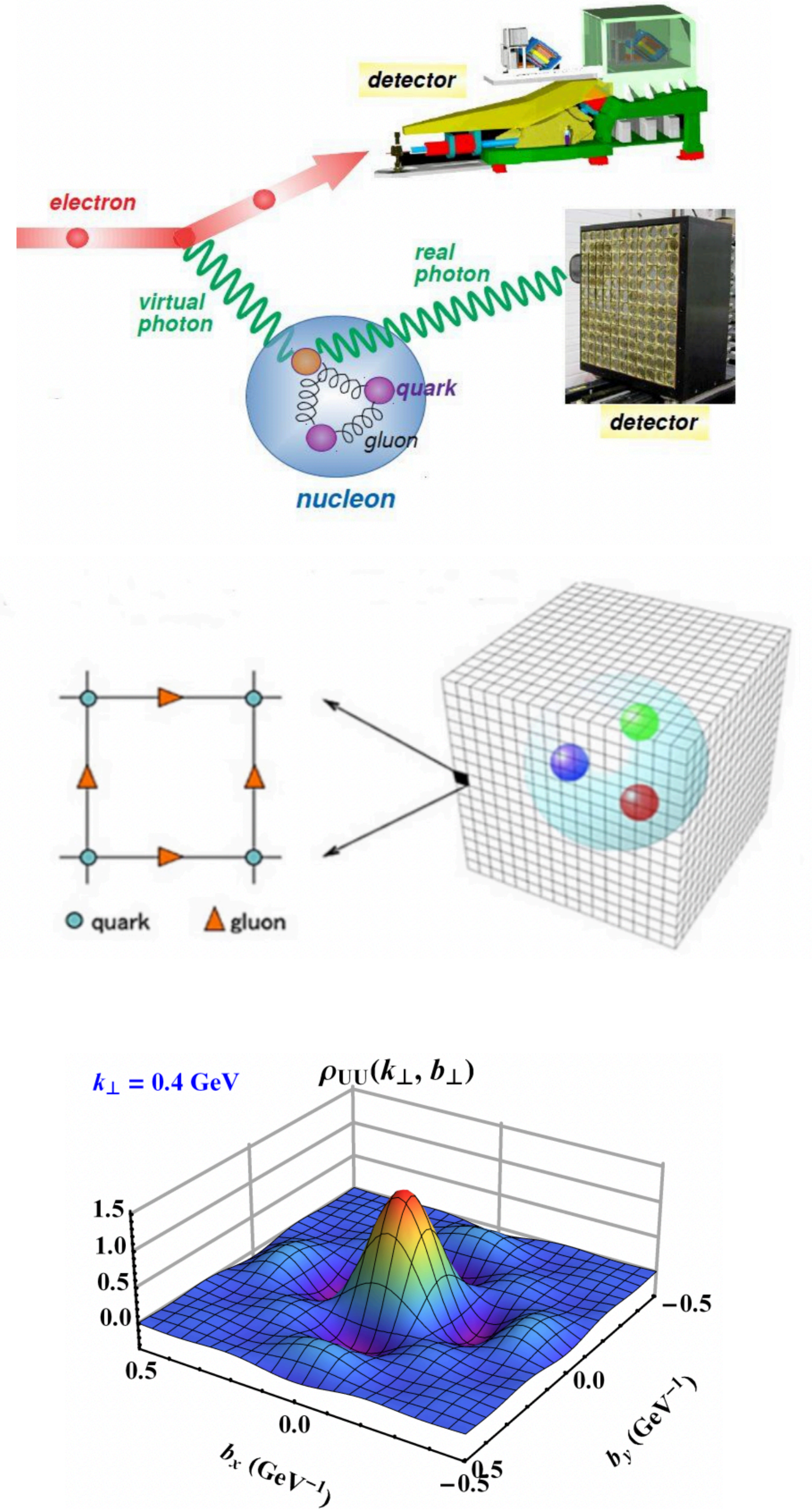
A. Adare *et al.*, PRD93, 011501 (2016)

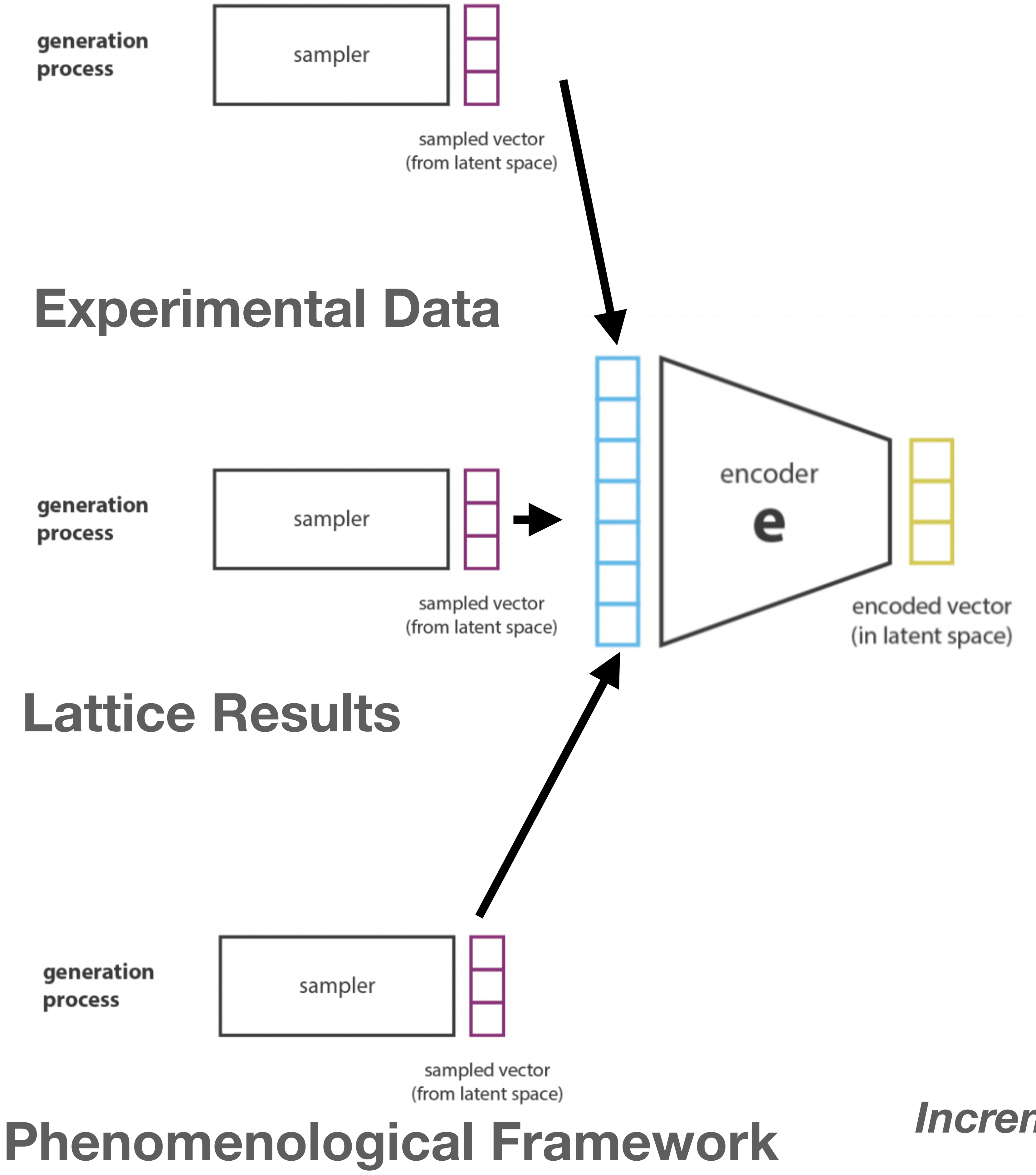
C. Alexandrou *et al.*, PRL119,142002 (2017)

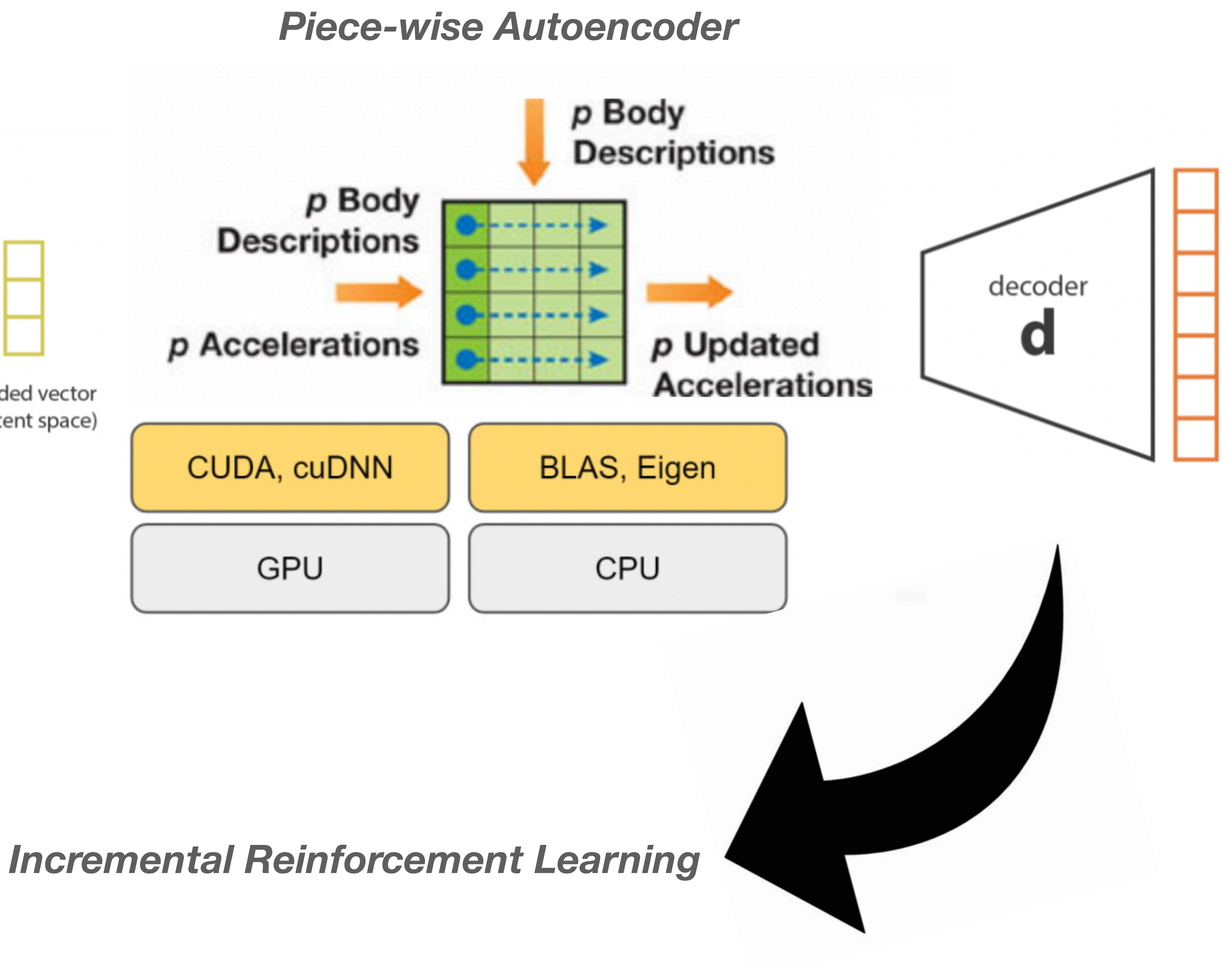
Explore the Feature Space

A Second Look at Multilayered Integration

- ANN Global Analysis
- Feed in Data, Constraints, Framework
- Run encoder to map to GPU n-body sims
- Output through decoder to map to observables and data visualization
- User results as training input to exploit latent space
- Front End Visualization Studio







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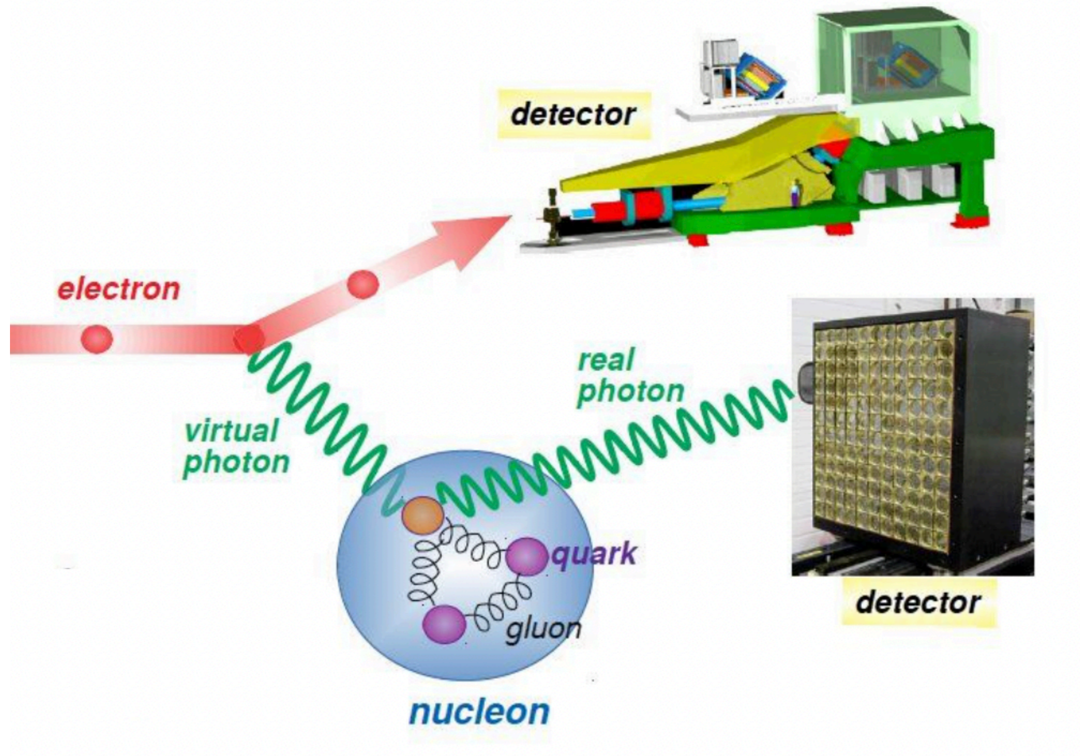
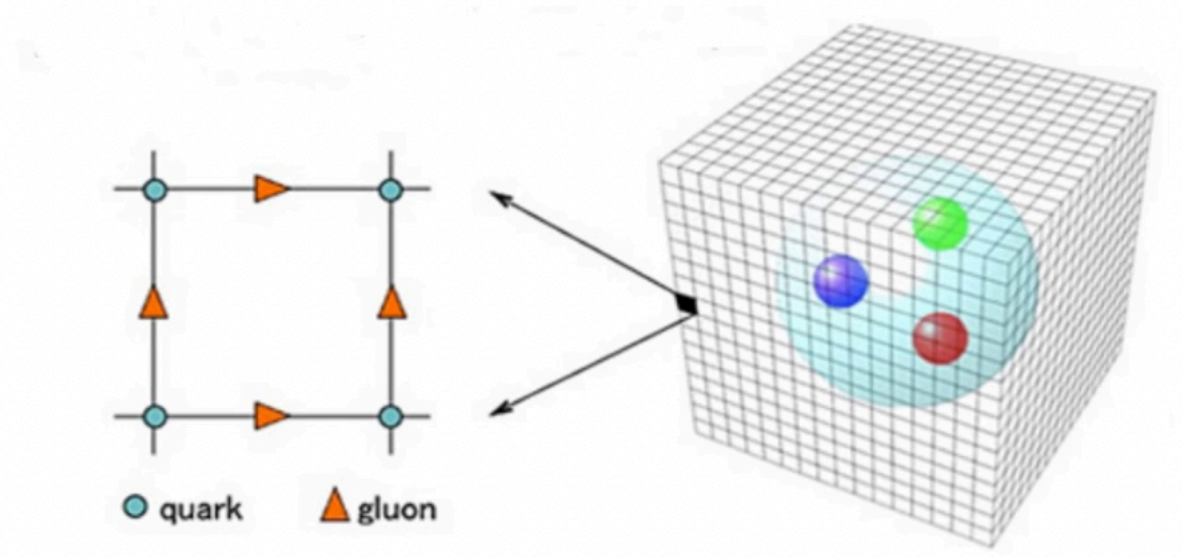
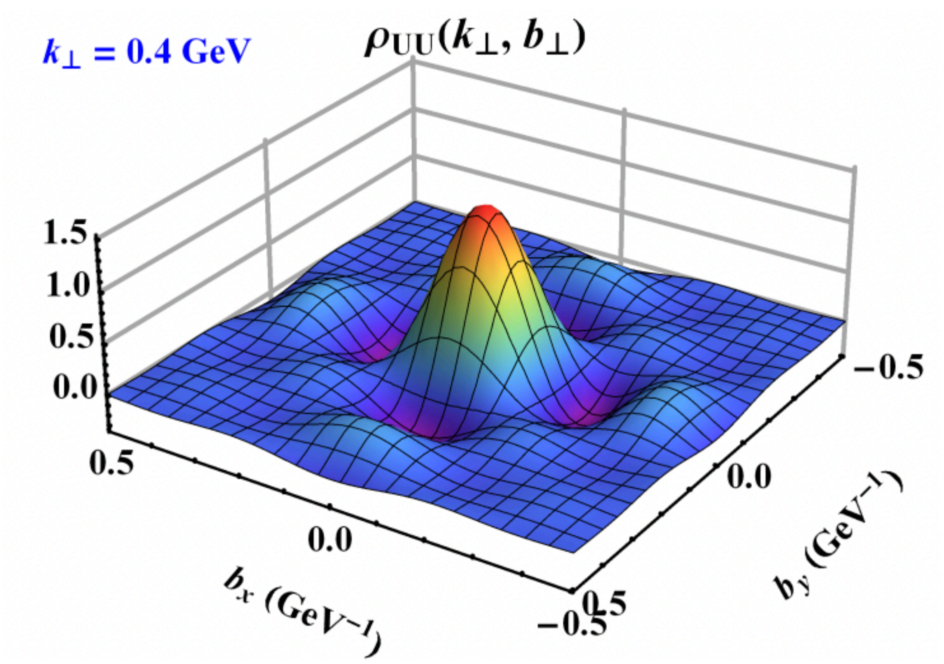
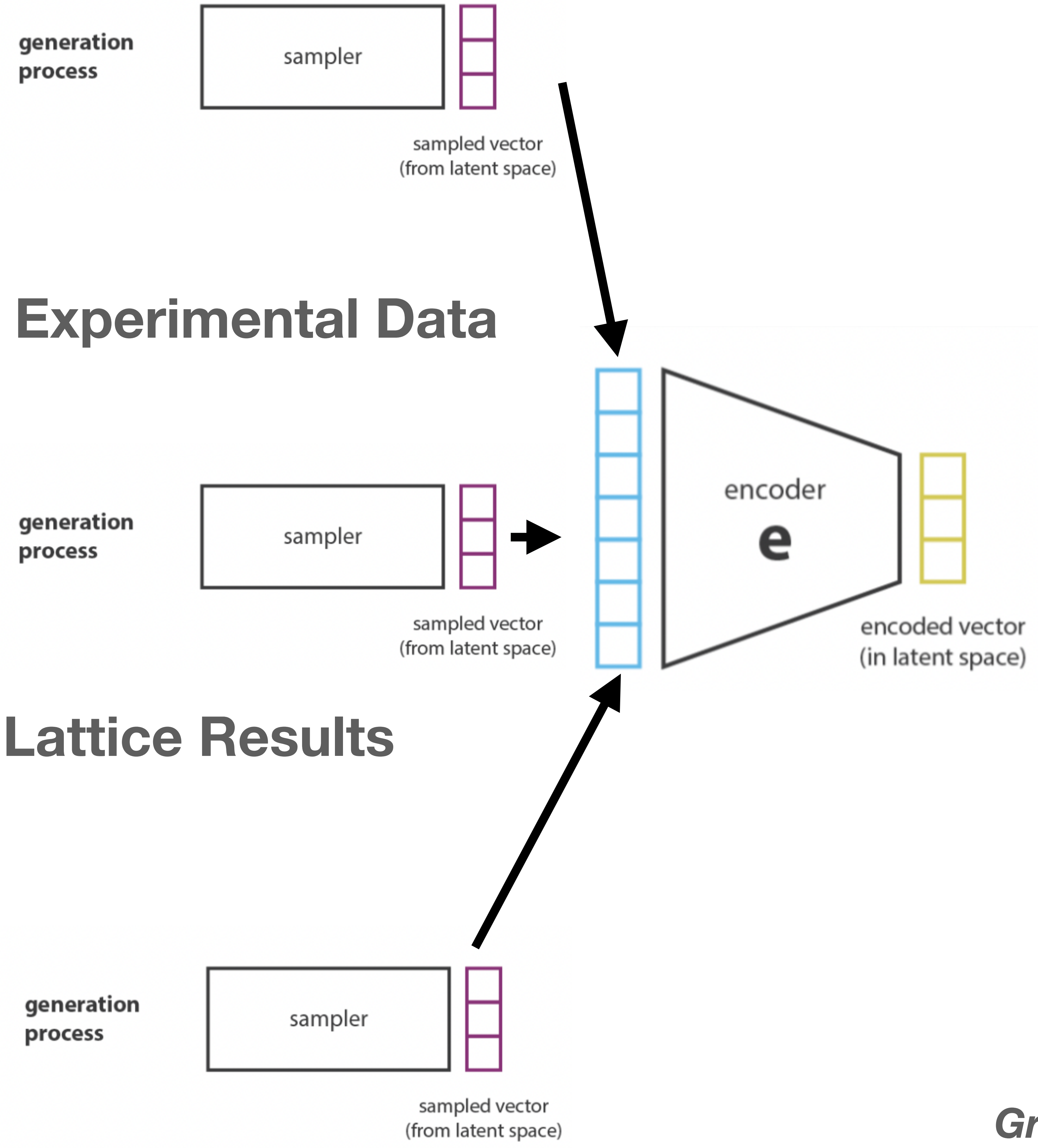


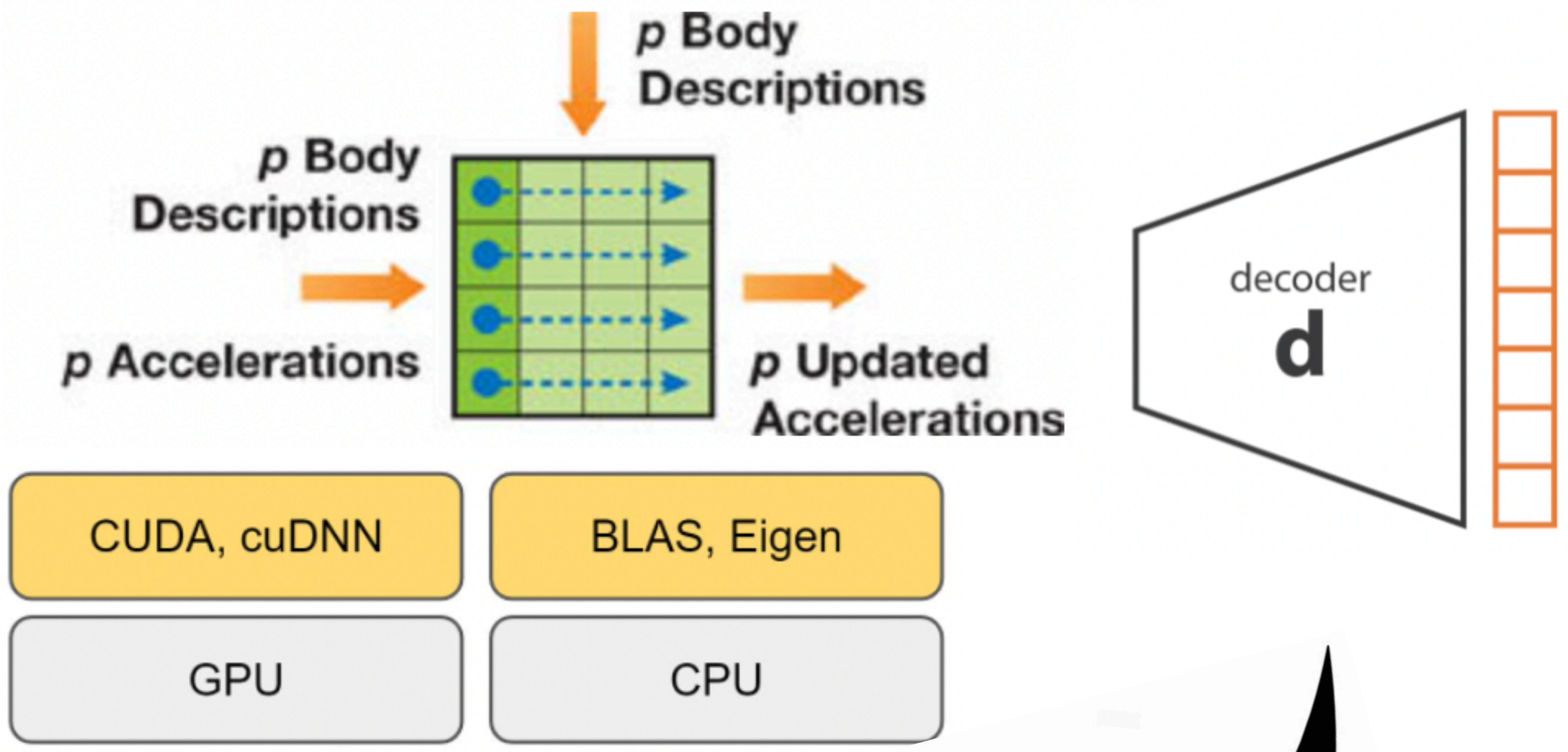




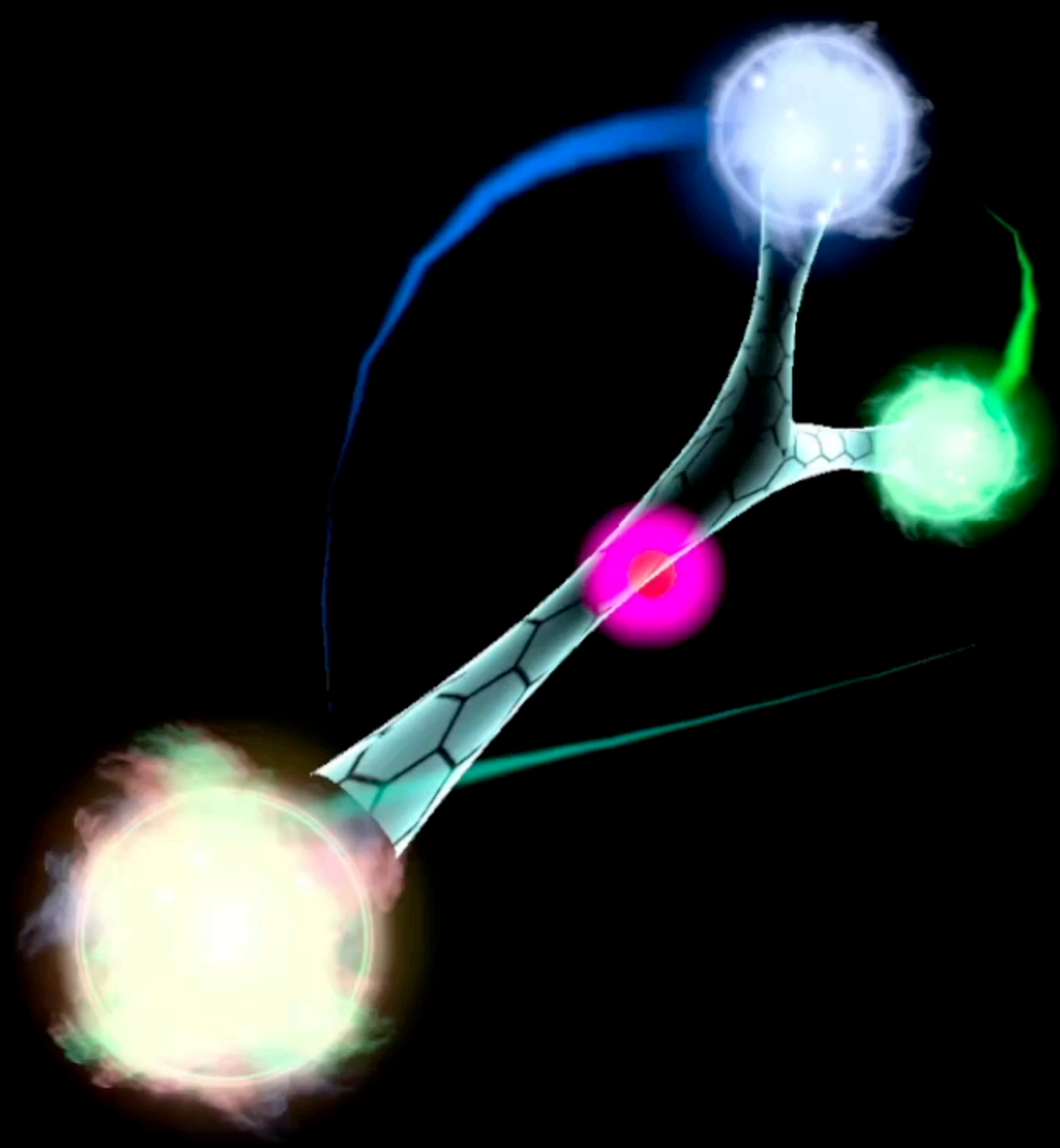


Phenomenological Framework

Piece-wise Autoencoder



Graduate Student Samuel Liu
Front End Visualization in Next Slide



AI in Future Experiments

And the Future of Fermilab Spin

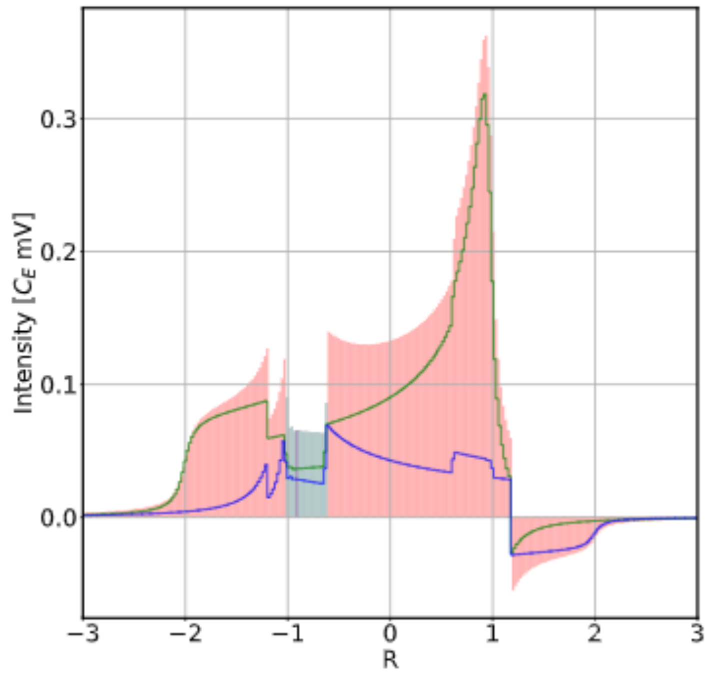
Yoshiyuki Miyachi: Room 601. Polarized Dell-Yan experiment at Fermilab…
JST 22 Oct 2021, 09:34

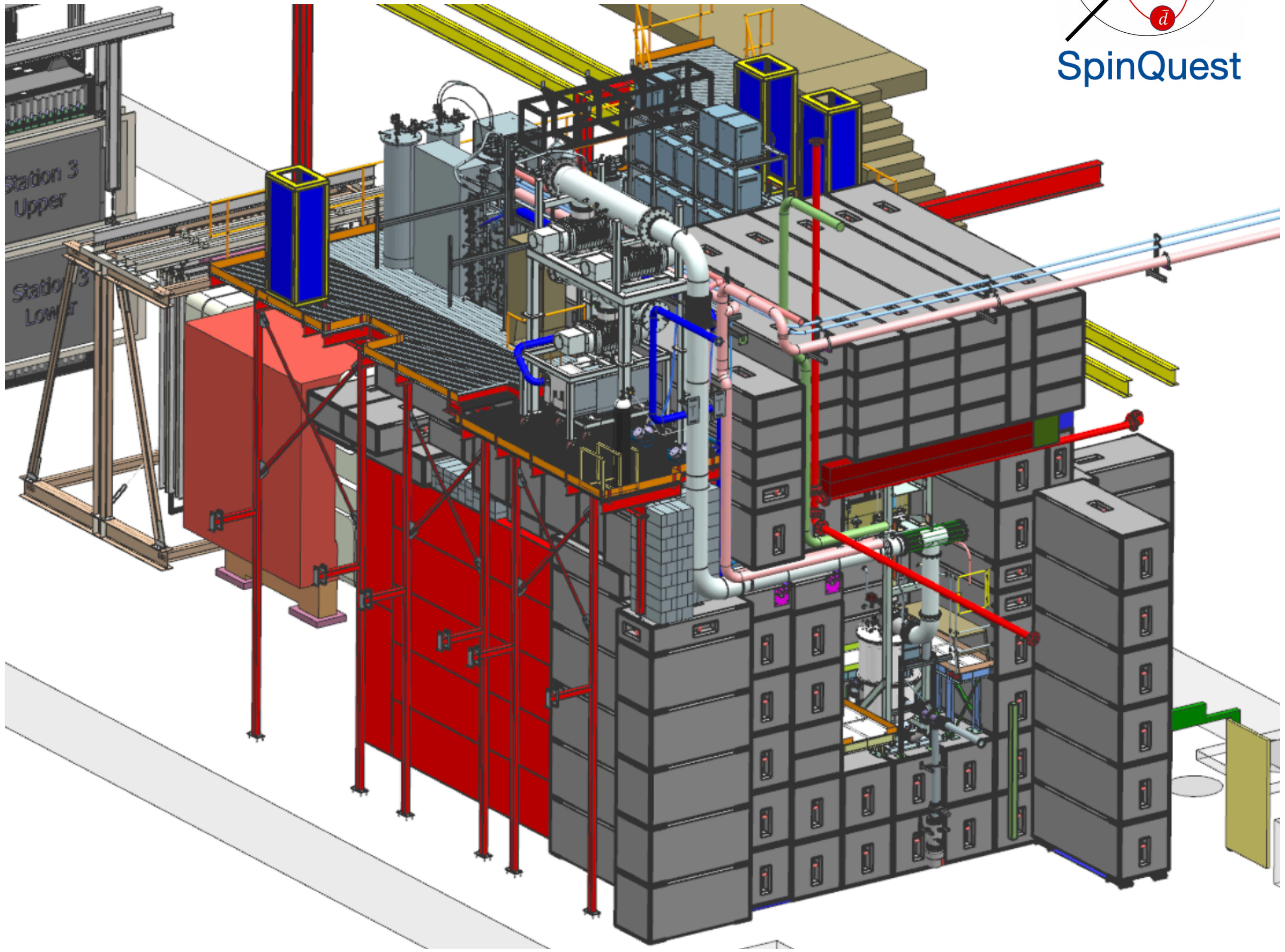
Zulkaida Akbar: Room 137. Dynamical Behavior of the SpinQuest Polarized Target…
JST 22 Oct 2021, 09:00

SpinQuest

- 120 GeV proton beam
- $\sqrt{s} = 15.5$ GeV
- 1×10^{12} pro/sec for 4.4 sec/min

Applications in AI-NMR

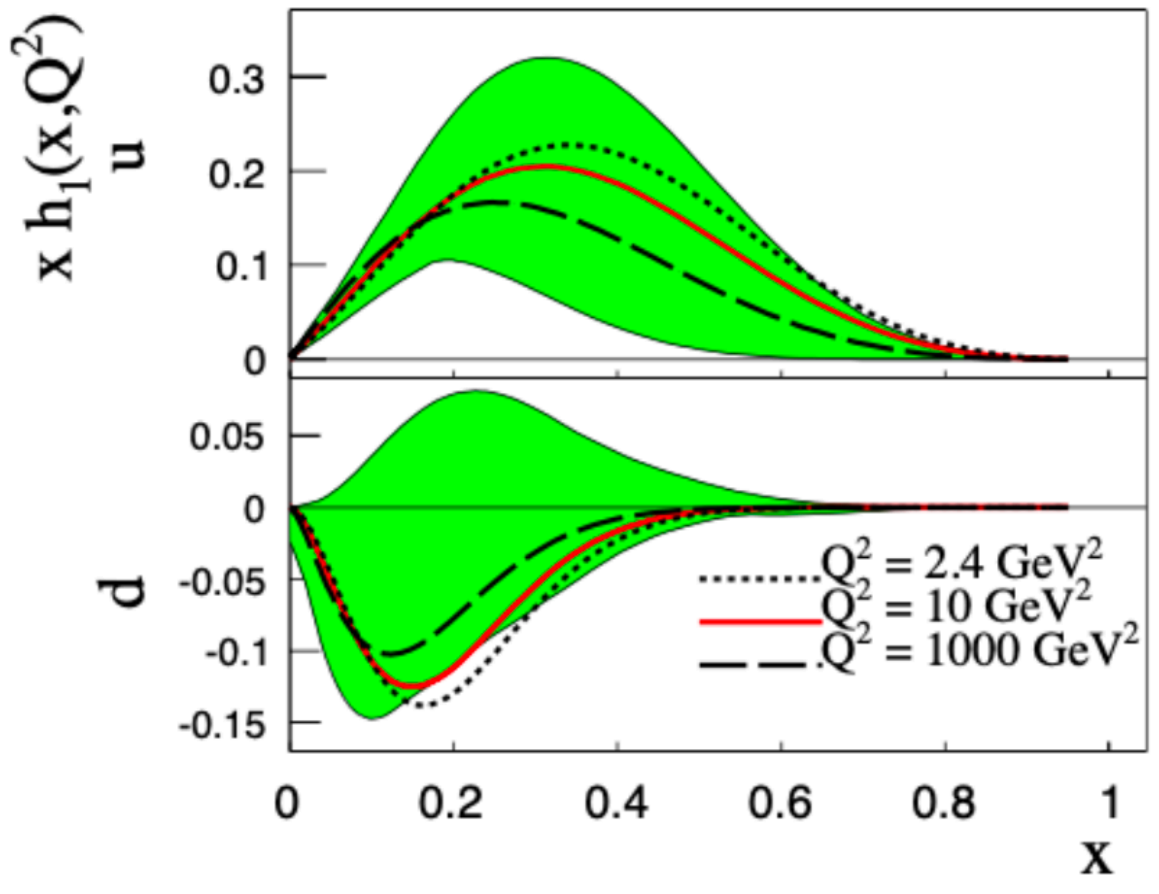




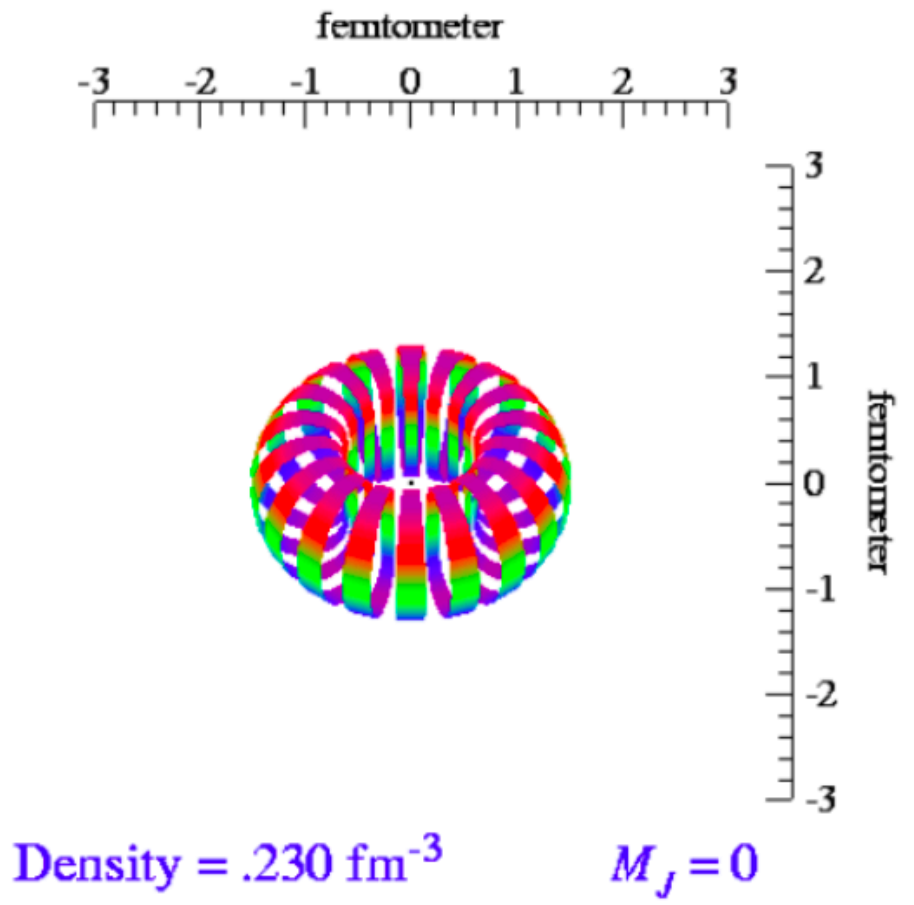
AI in Future Experiments

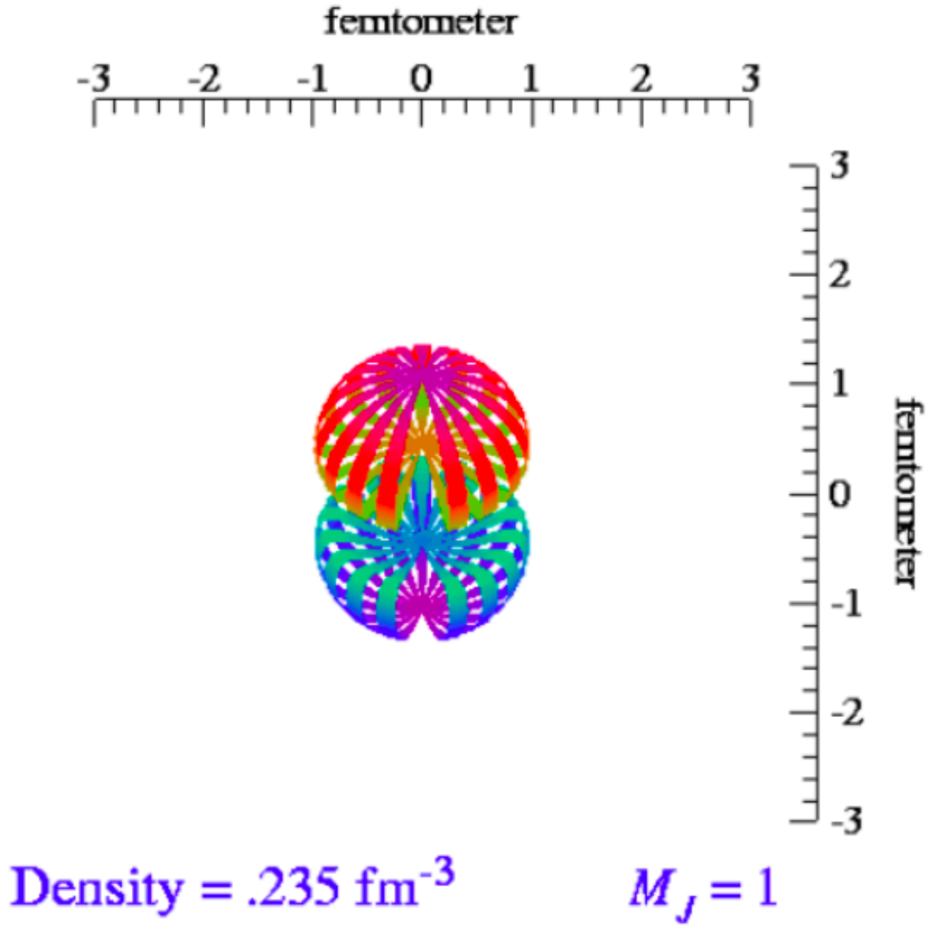
And the Future of Fermilab Spin

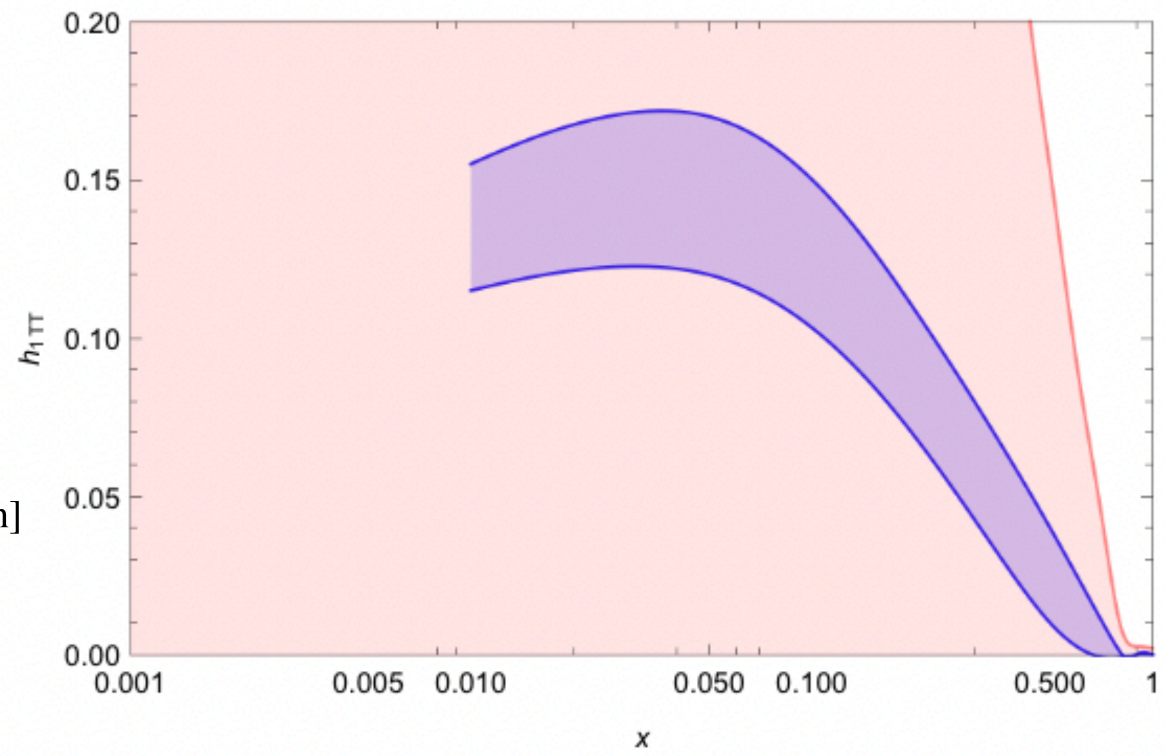
leading twist	quark operator		
target polarization	unpolarized [U]	longitudinal [L]	transverse [T]
U	$f_1 =$ unpolarized		$h_1^\perp =$ Boer-Mulders
L		$g_1 =$ helicity	$h_{1L}^\perp =$ worm gear 1
T	$f_{1T}^\perp =$ Sivers	$g_{1T} =$ worm gear 2	$h_1 =$ transversity; $h_{1T}^\perp =$ pretzelosity
TENSOR	$f_{1LL}(x, k_T^2)$, $f_{1LT}(x, k_T^2)$, $f_{1TT}(x, k_T^2)$	$g_{1TT}(x, k_T^2)$, $g_{1LT}(x, k_T^2)$	$h_{1LL}^\perp(x, k_T^2)$, h_{1TT}, $h_{1TT}^\perp$, h_{1LT}, $h_{1LT}^\perp$

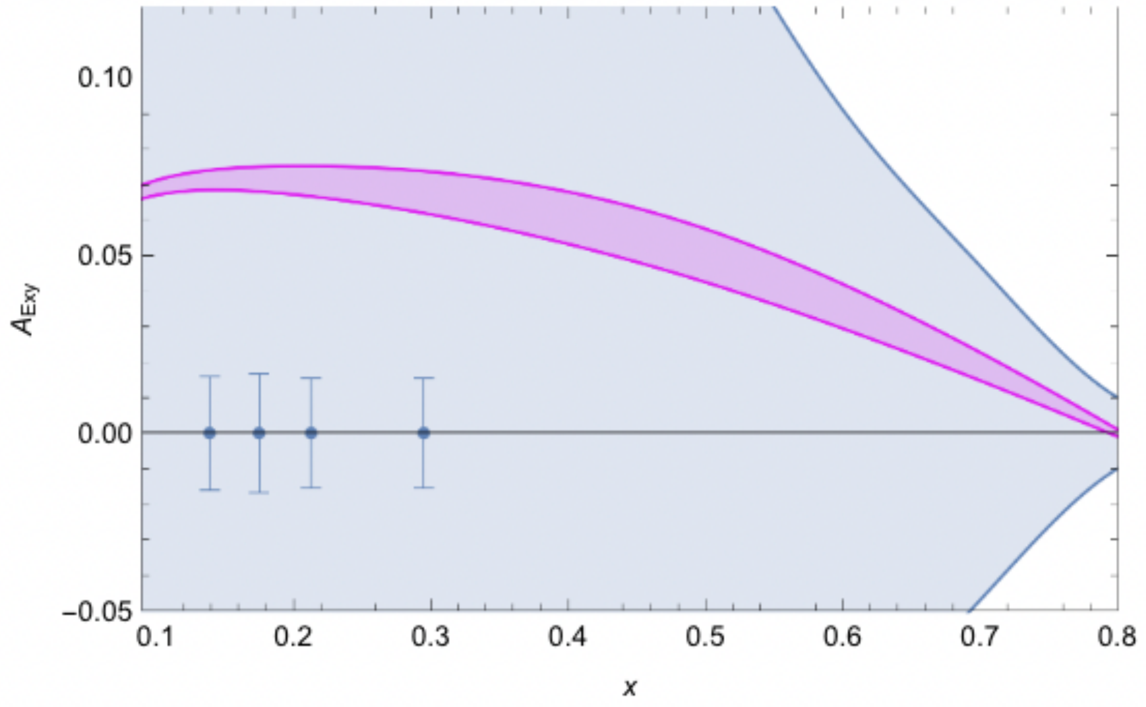


Zhong-Bo Kang, et al. JLAB-THY-15-2044, arXiv:1505.05589v1 [hep-ph]



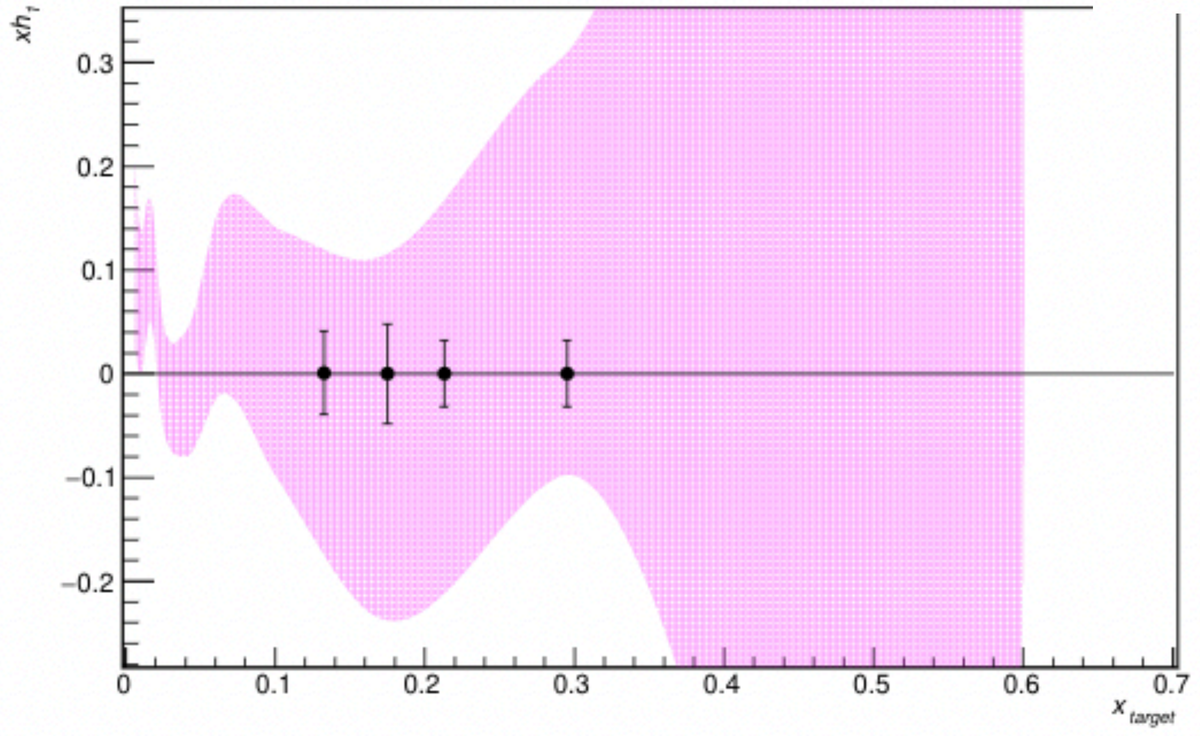


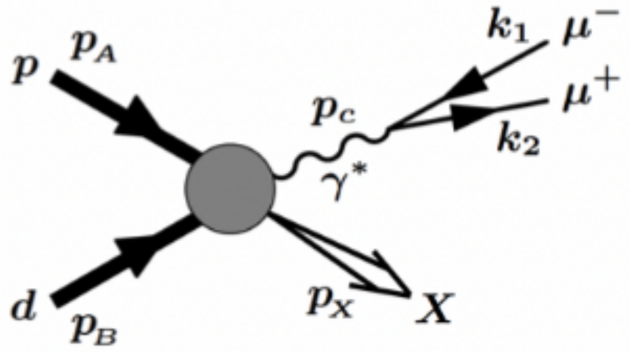


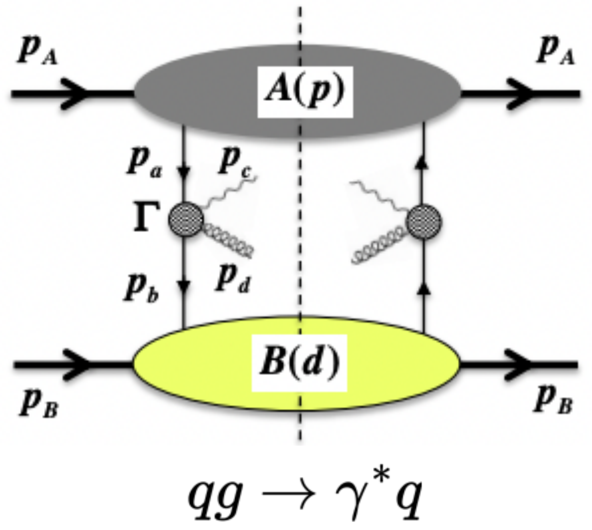


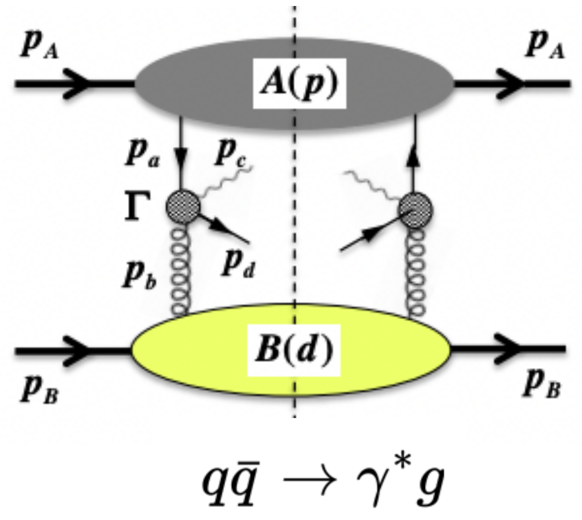
Gluon Operator

Target Polarization	Leading Twist	Unpolarized	Circular	Linear
Vector Polarized	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$
Tensor Polarized	LL	f_{1LL}		$h_{1LL}^\perp$
	LT	f_{1LT}	g_{1LT}	h_{1LT}, $h_{1LT}^\perp$
	TT	f_{1TT}	g_{1TT}	h_{1TT}, $h_{1TT}^\perp$, $h_{1TT}^{\perp\perp}$









S. Kumano and Qin-Tao Song DIS2021

S. Kumano and Qin-Tao Song, Phys. Rev. D 101 (2020) 054011 & 094013.

https://confluence.its.virginia.edu/display/twist/FNAL+Proposal+2020?preview=/18177846/18177847/FNAL_proposal_2020.pdf

AI in (Possible) Future Experiments

And the Future of Fermilab Spin

Transversely Polarized Target

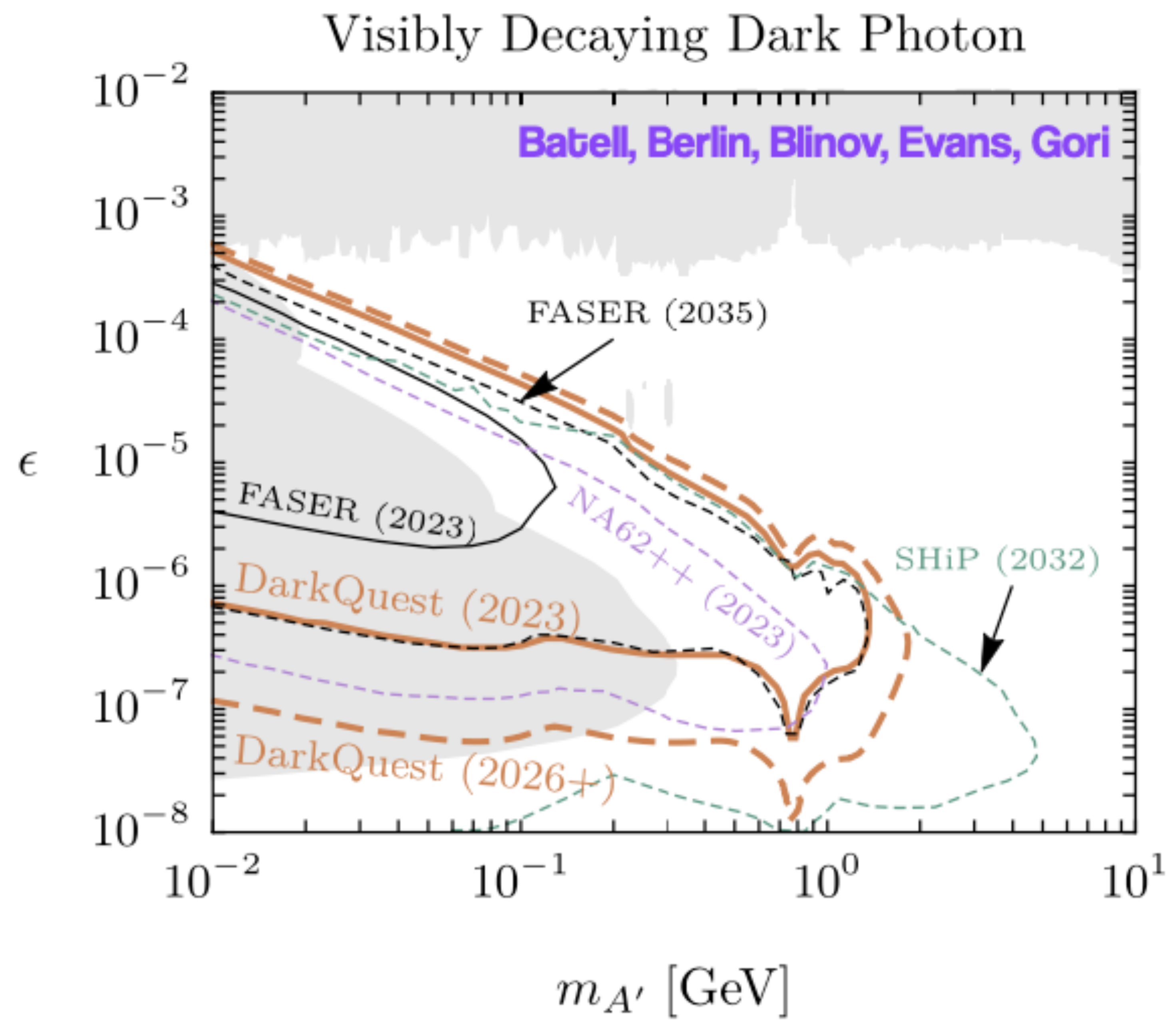
- Tensor/Vector Polarized (ND3 Target) — ***Quark/Gluon Transversity***
- Proton vs Deuteron (Mixed ND3-NH3) — ***Spin Dependent Flavor Asymmetry***
- Li-7, F — ***Polarized EMC Study***
- N14(spin-1), N15(spin-1/2) — ***Nuclei TMDs and gluon structure***

Longitudinally Polarized Target

- Polarized (NH3 Target) — ***Helicity***
- Proton vs Deuteron (Mixed ND3-NH3) — ***Spin Dependent Flavor Asymmetry***
- ND3 — ***Tensor Pol SF***

Dark Sector Physics at SpinQuest

A Unified Effort



- SpinQuest has unique potential for dark sector searches
  - Large dark sector production cross section, 120 GeV p beam
  - Geometry sensitive to unique lifetime baseline, covers open phase space
    - KMAG provides good momentum measurement for forward decays
  - EMCal upgrade opens up new final states distinct from muon backgrounds
- Wide array of signatures in electron, muon, photon, and pion final states
  - Testing many dark sector signatures: dark photon, SIMPs, inelastic DM, heavy neutrino, ALPs, g-2, etc.
  - New personpower joining SpinQuest collaboration to build this program!

Thinking of Joining SpinQuest or Future Projects: (dustin@virginia.edu)

https://spinquest.fnal.gov/

http://twist.phys.virginia.edu/E1039/