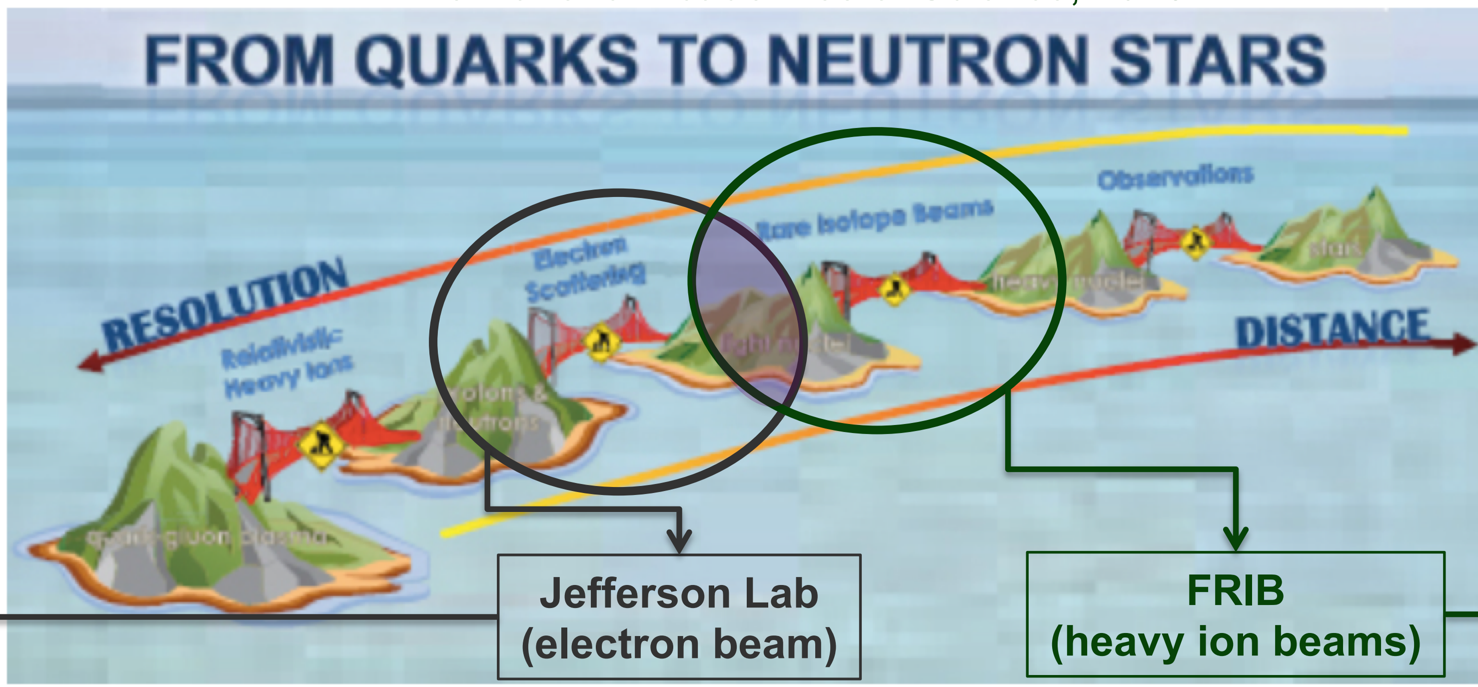
Polarized electron/positron beams for rare isotope studies at FRIB

Paul Guèye, Ambar Rodriguez Alicea, Peter Ostroumov, Jeremy Rebenstock, Maya Wallach

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Two Probes + One Target = Scaling

The National Academies of Science, 2013



Jefferson Lab (electron beam)

FRIB (heavy ion beams)

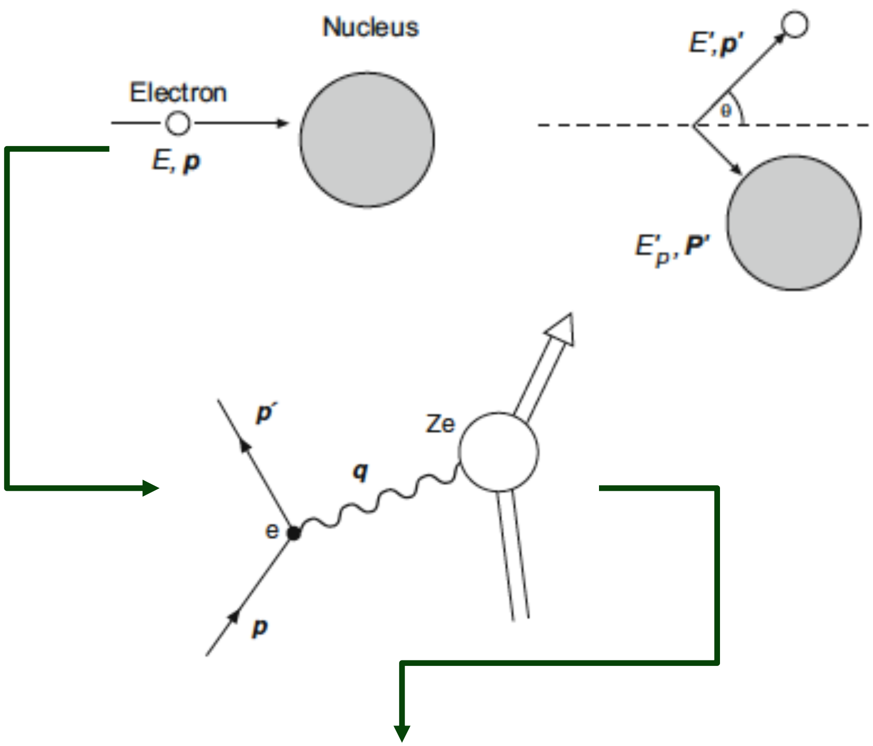
<u>Nucleons Structure</u>
4 GeV→ 6 GeV → 12 GeV → 22 GeV

<u>Nuclei Structure</u>
100 MeV/u → 200 MeV/u → 400 MeV/u

… interface …

Peaking Inside Closed Rooms

Bogdan Povh, Klaus Rith, Christoph Scholz, Frank Zetsche • Werner Rodejohann
Particles and Nuclei: An Introduction to the Physical Concepts

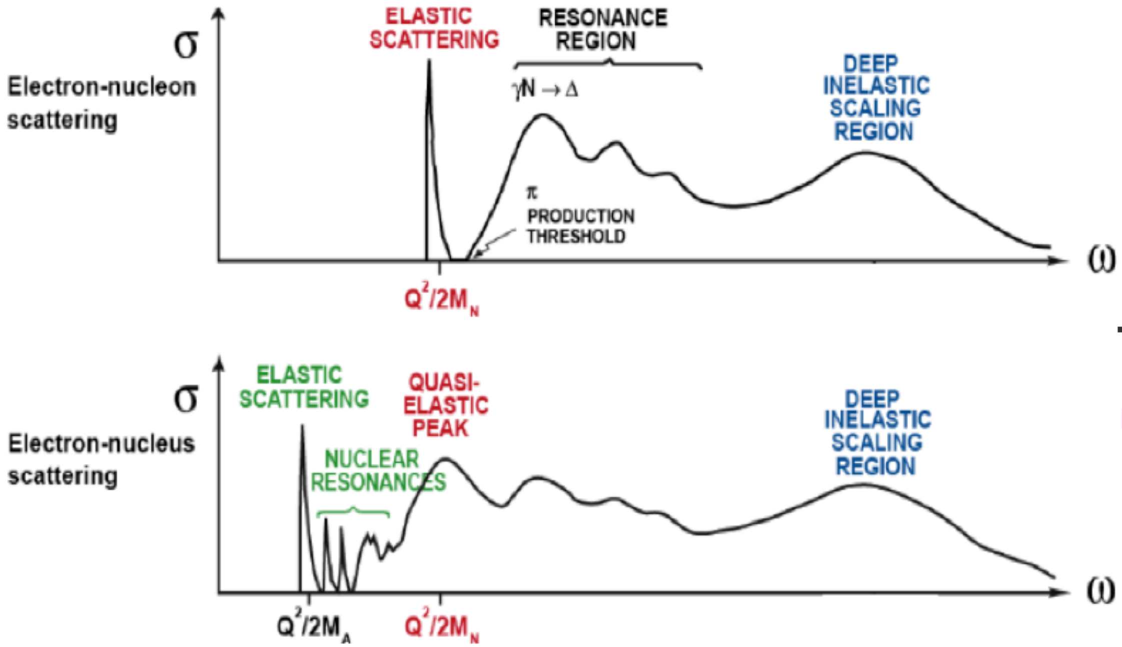


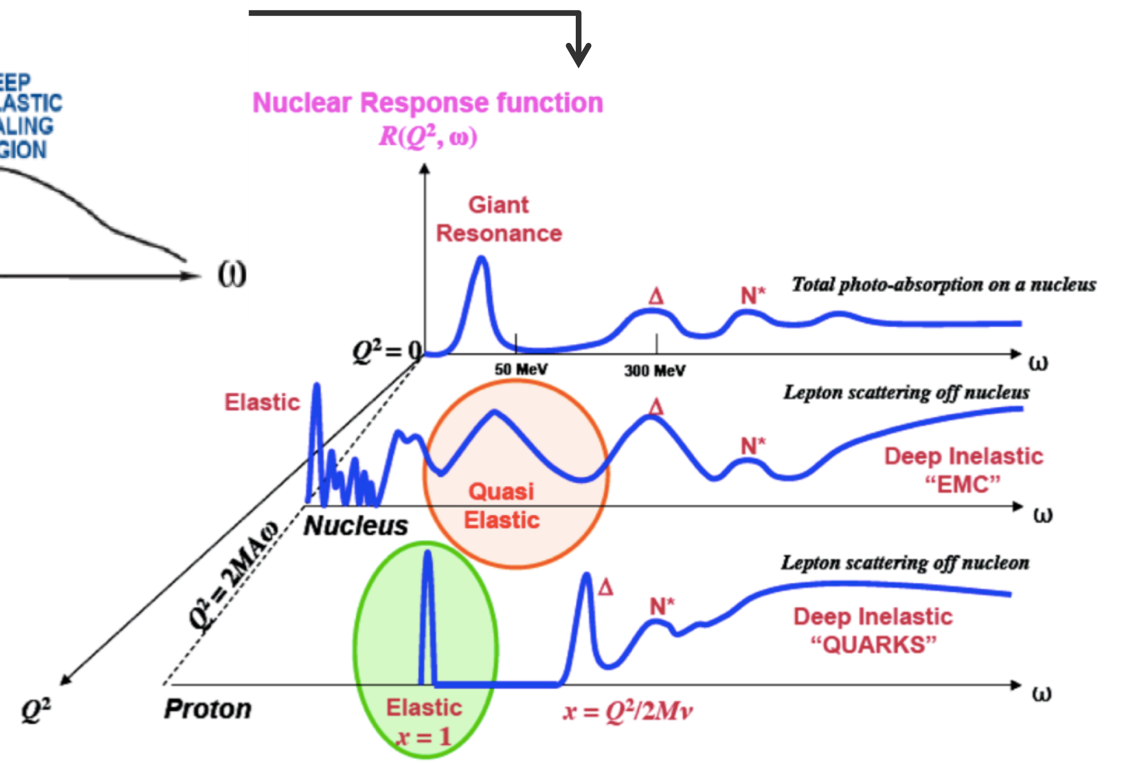
“seeing” inside a closed room

https://www.123rf.com/photo_38569847_stock-vector-house-cartoon-interior-cartoon-living-rooms-with-furniture-.html

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp.}} = \left(\frac{d\sigma}{d\Omega}\right)^{*}_{\text{Mott}} \cdot \left|F(q^2)\right|^2$$

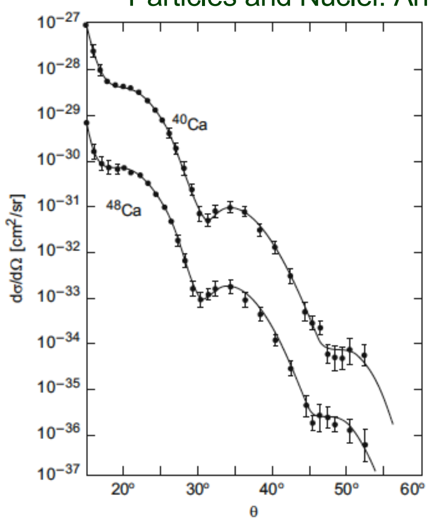
Electron Scattering Experiments

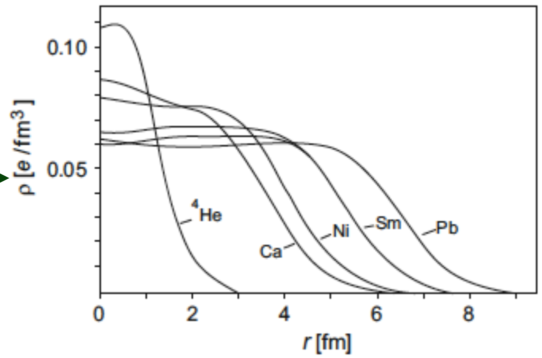




Nuclear Radii

Bogdan Povh, Klaus Rith, Christoph Scholz, Frank Zetsche • Werner Rodejohann
Particles and Nuclei: An Introduction to the Physical Concepts





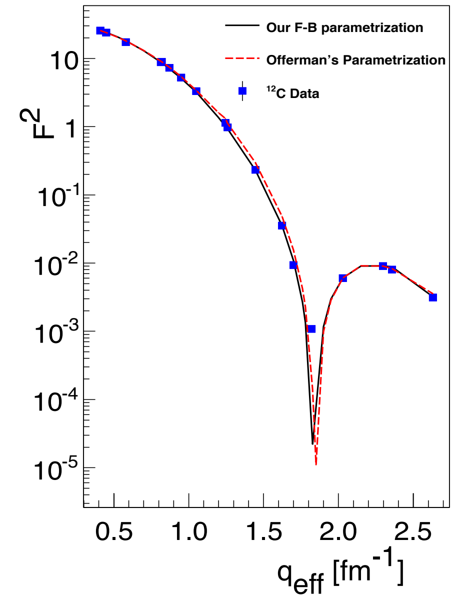
ρ(r)	|F(q²)|	Example
pointlike	constant	Electron
exponential	dipole	Proton
gauss	gauss	^{6}Li
homogeneous sphere	oscillating	–
sphere with a diffuse surface	oscillating	^{40}Ca
r ⟶	|q| ⟶	

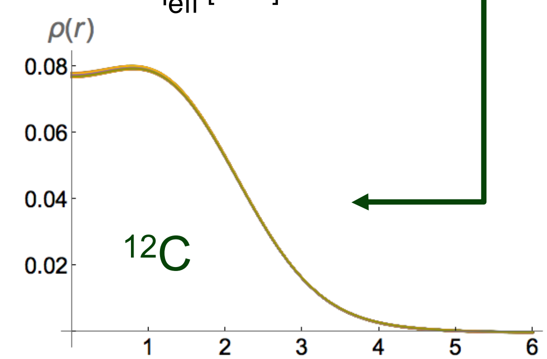
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \mid F(Q^2) \mid^2$$

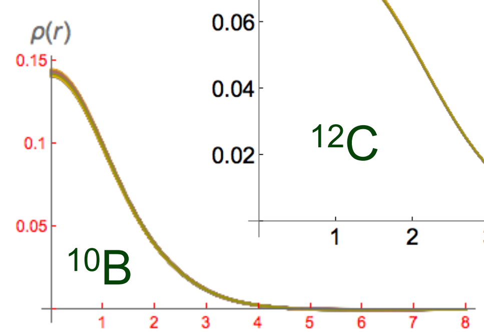
$$F_p(q^2) = \frac{1}{4\pi}\int d^3r j_0(qr)\rho_p(r)$$

$$ZF_p = 4\pi \int_0^\infty \rho_p r^2 dr = \sum_{\nu=1}^{\infty} (-1)^{\nu+1} \frac{4\pi R_p}{q_\nu^2} a_\nu$$

A. Kabir, PhD Thesis (2019)
Low Energy Deuteron Experiment, JLab

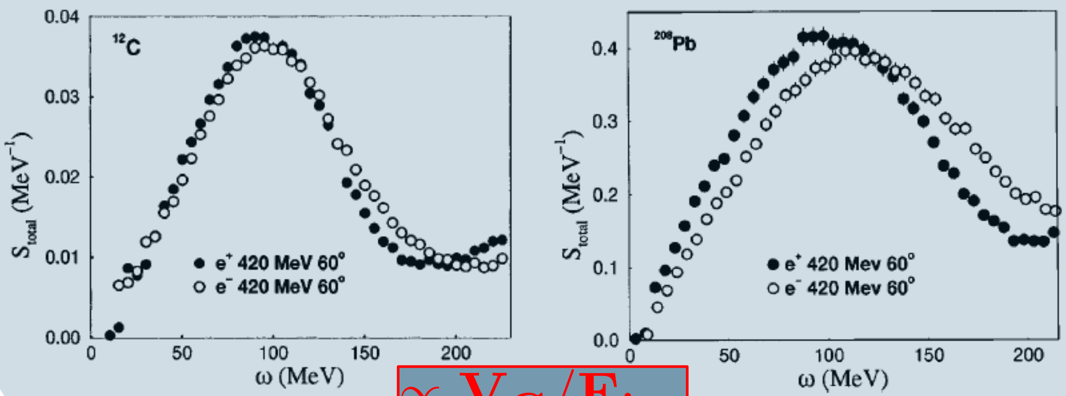






What About Higher Orders Corrections?

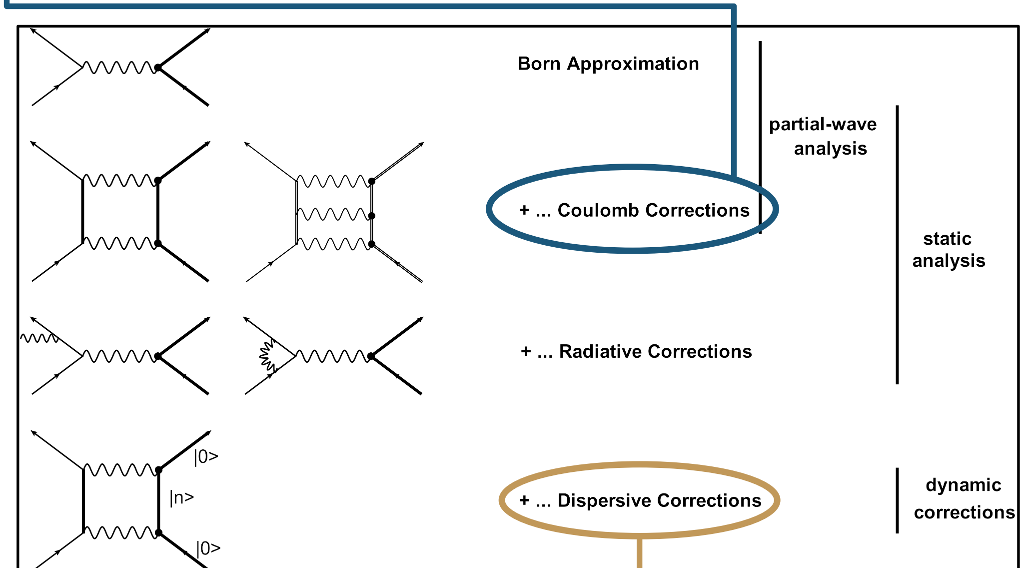
P. Guèye *et al.*, Phys. Rev., **C60** , 044308 (1999)



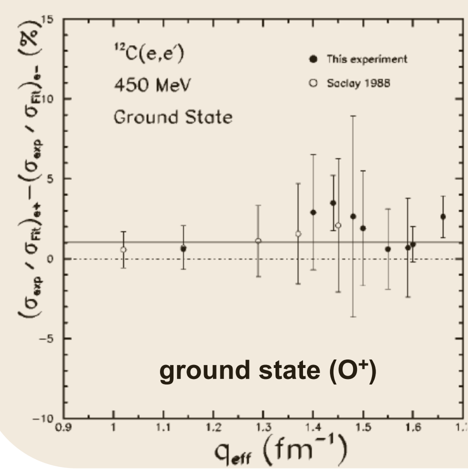
$\propto V_C/E_{inc}$

Effective Momentum Approximation (EMA)

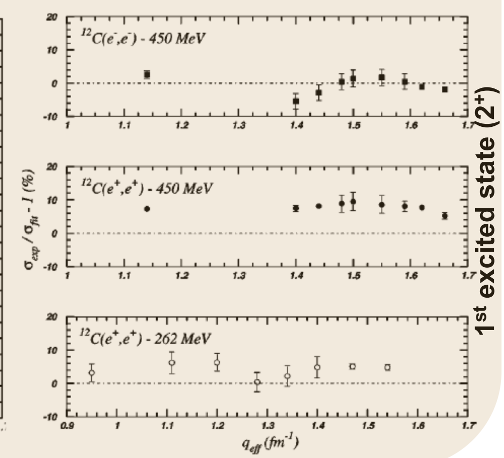
Nucleus	$\langle r^2\rangle^{1/2}_{exp}$ (fm)	$\lvert V_C(0)\rvert$ (MeV)	$\lvert V_C\rvert$ (MeV)	$\lvert V_C\rvert_{fit}$ (MeV)
^{12}C	2.464	4.6	3.3	3.1±0.25
^{40}Ca	3.450	10.5	7.9	7.4±0.6
^{48}Ca	3.451	10.4	7.9	7.4±0.6
^{56}Fe	3.714	12.5	9.5	8.9±0.7
^{90}Zr	4.258	16.7	12.8	11.9±0.9
^{154}Gd	5.124	21.8	16.9	15.9±1.2
^{208}Pb	5.503	25.9	20.1	18.9±1.5



P. Guèye *et al.*, Phys. Rev., **C57** , 2107 (1998)



P. Guèye *et al.*, Phys. Rev., **C63**, 051303(R) (2001)

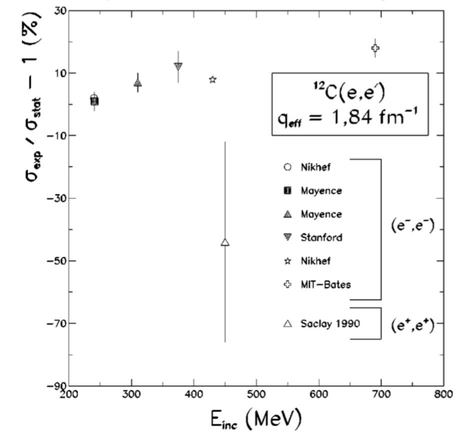


negligible

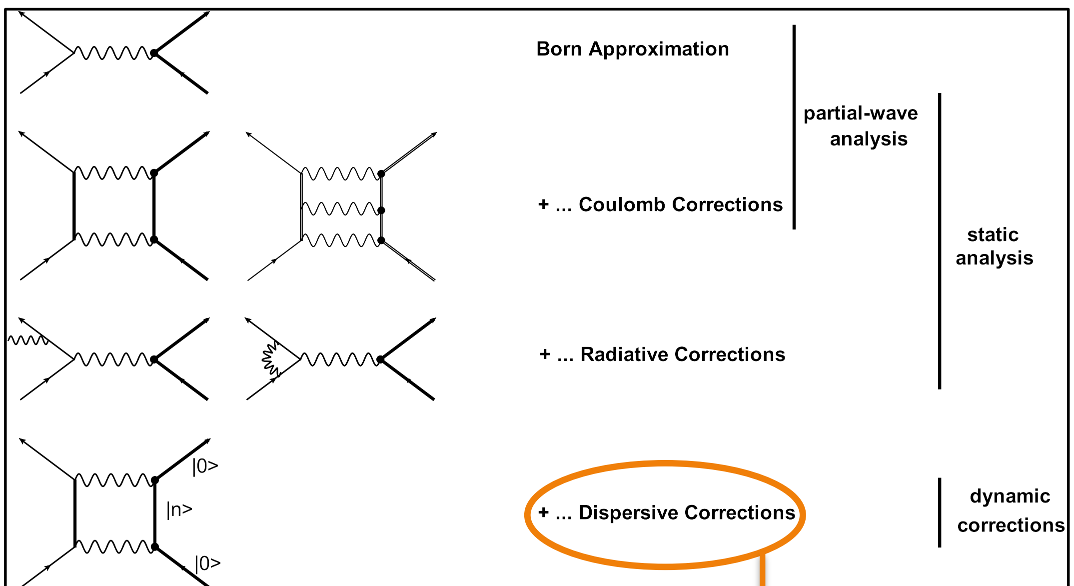
Are Dispersive Effects really negligible?

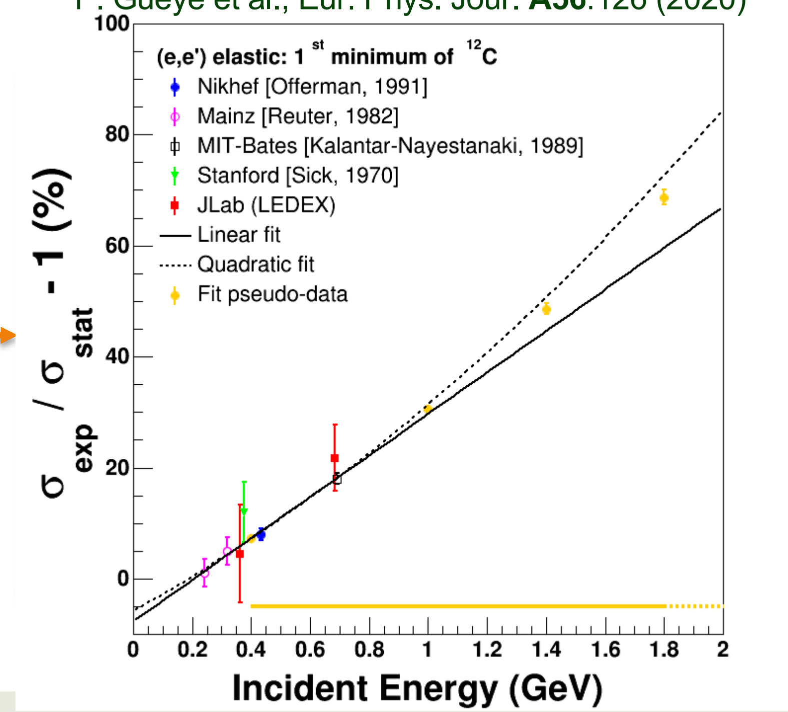
- **Coulomb Corrections**
  - ✓ PWBA → DWBA
  - ✓ Effective Momentum Approximation
- **Dispersive Effects**
  - ✓ Energy Dependence?

P. Gueye et al., PRC**57**, 5 (1998)

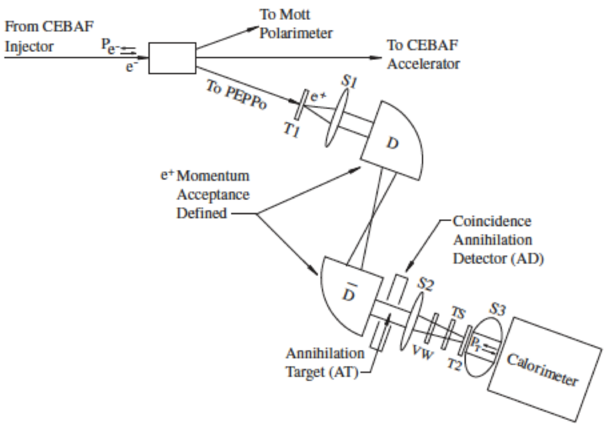


P. Gueye et al., Eur. Phys. Jour. **A56**:126 (2020)



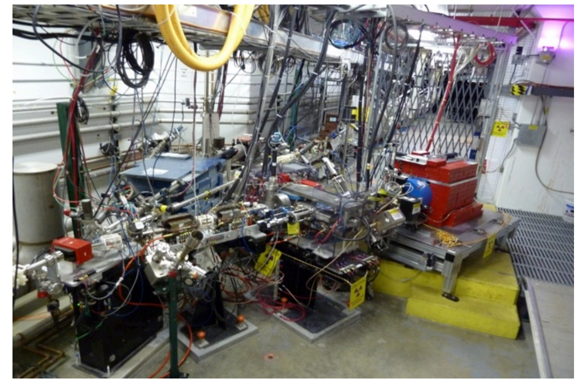


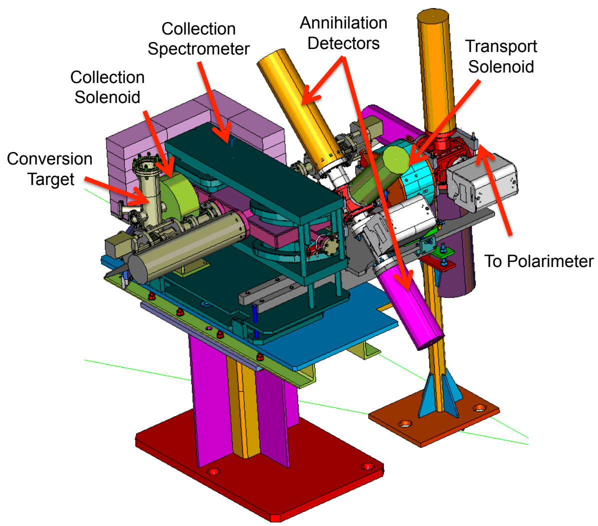
Polarized Positron Beams – 20 years later! (... possible scheme for the EIC)

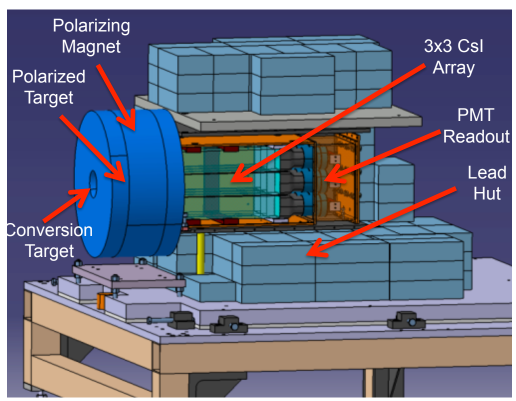


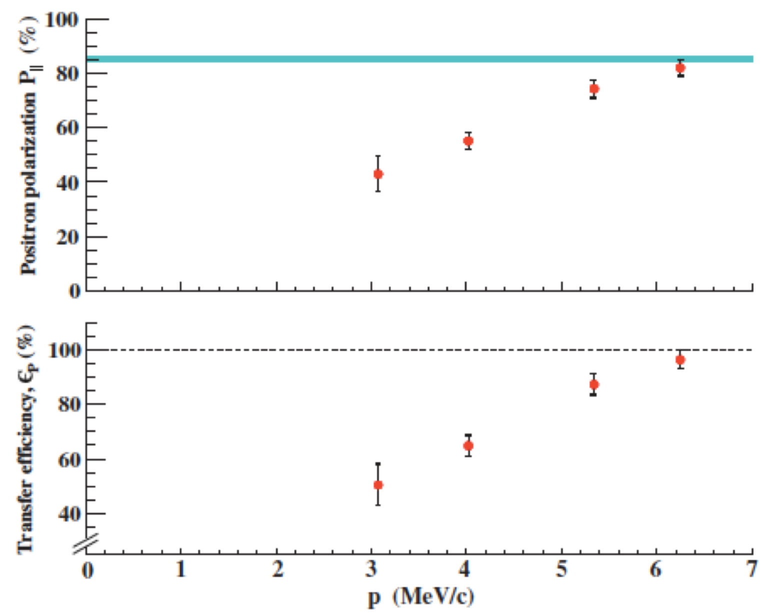
Polarized Electrons for Polarized Positrons
D. Abbott *et al.*, PRL **116**, 214801 (2016)

- Experiment in the CEBAF injector
- Highly polarized positrons
- 80% @ 6.5 MeV
- R&D for EIC
- **Last PhD @ HU (A. Adeyemi, 2016)**





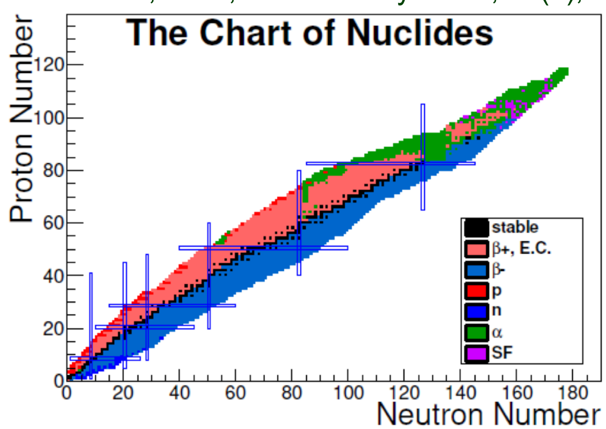


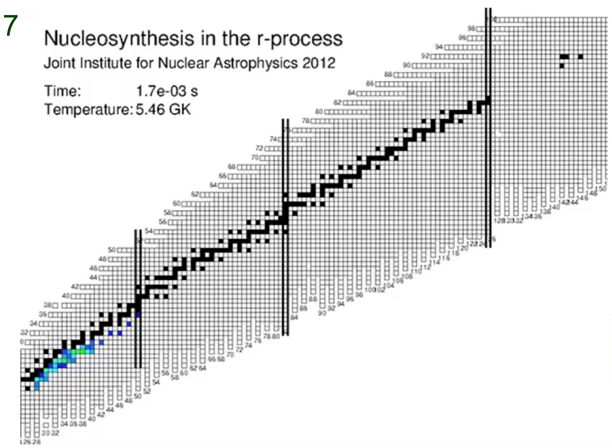


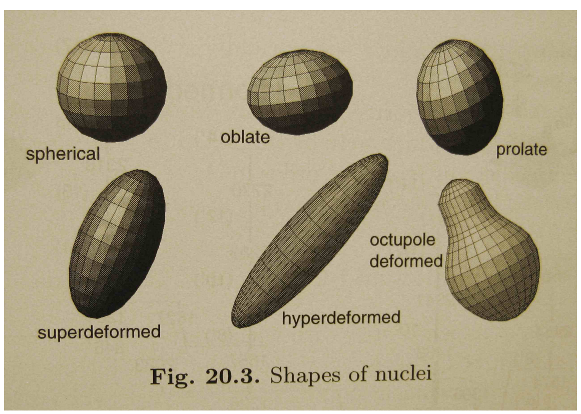
Nuclear Chart & Nuclear Science

- 288 stables ($T_{1/2}$>life of the solar system)
- 3,308 different isotopes have been discovered (status in 2019)

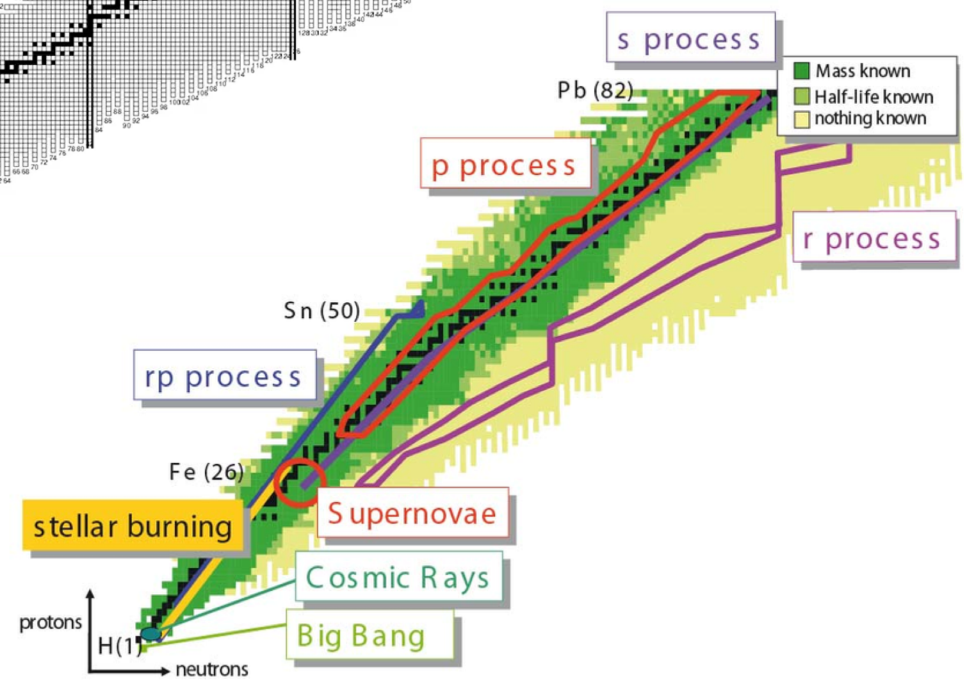
Data from G. Audi, *et al.*, Chinese Physics C, 41(3),030001, 2017





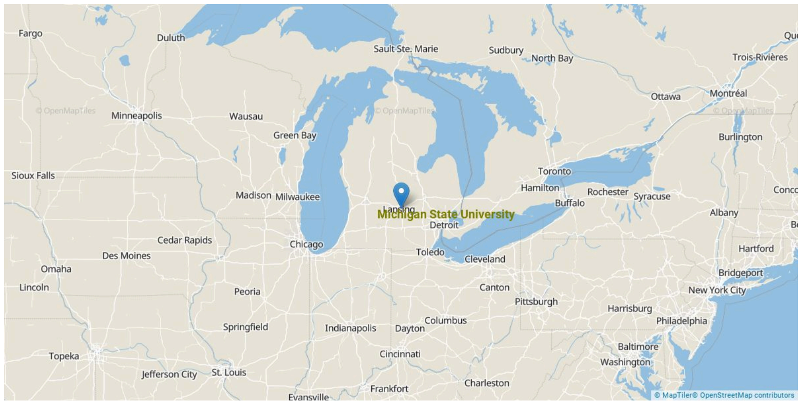


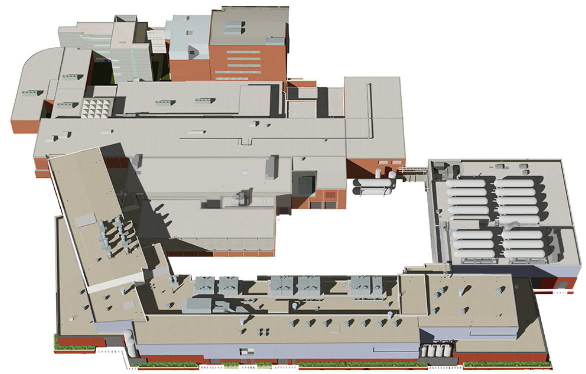
https://web2.ph.utexas.edu/~coker2/index.files/rotation2.htm

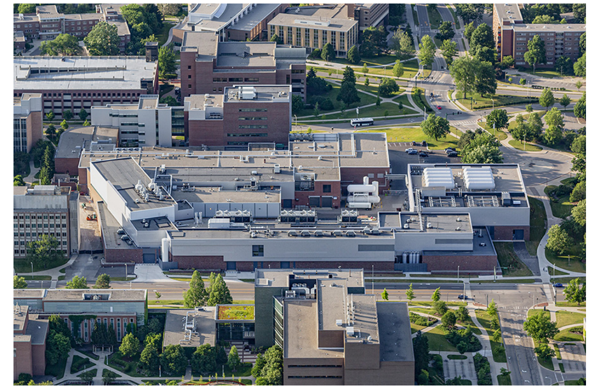


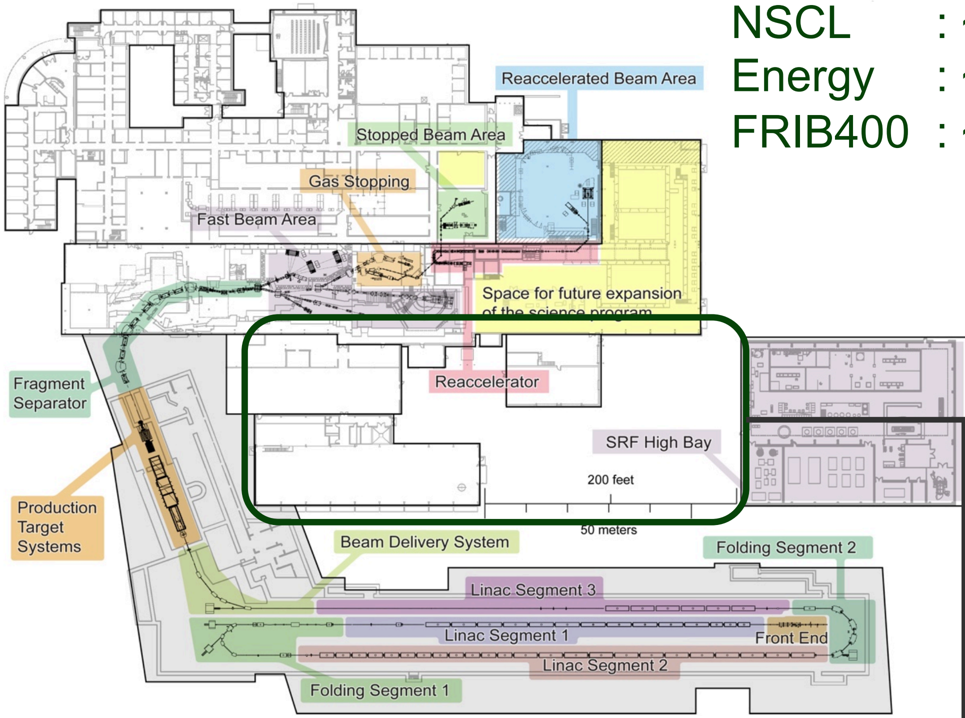
K.Blaum et al., Contemporary Physics, **51**, 149-175 2010

Facility for Rare Isotope Beams (www.frib.msu.edu; start: May 10, 2022)

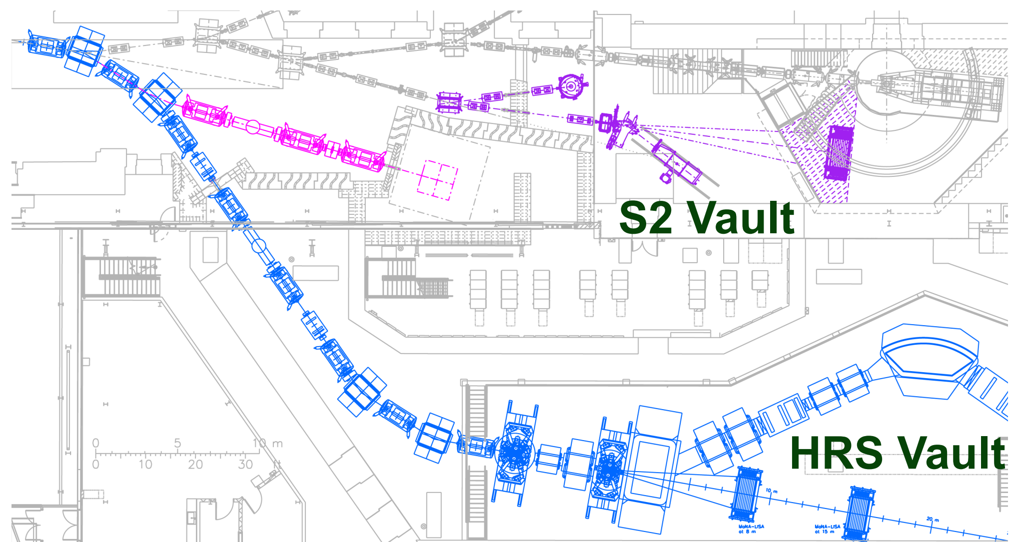








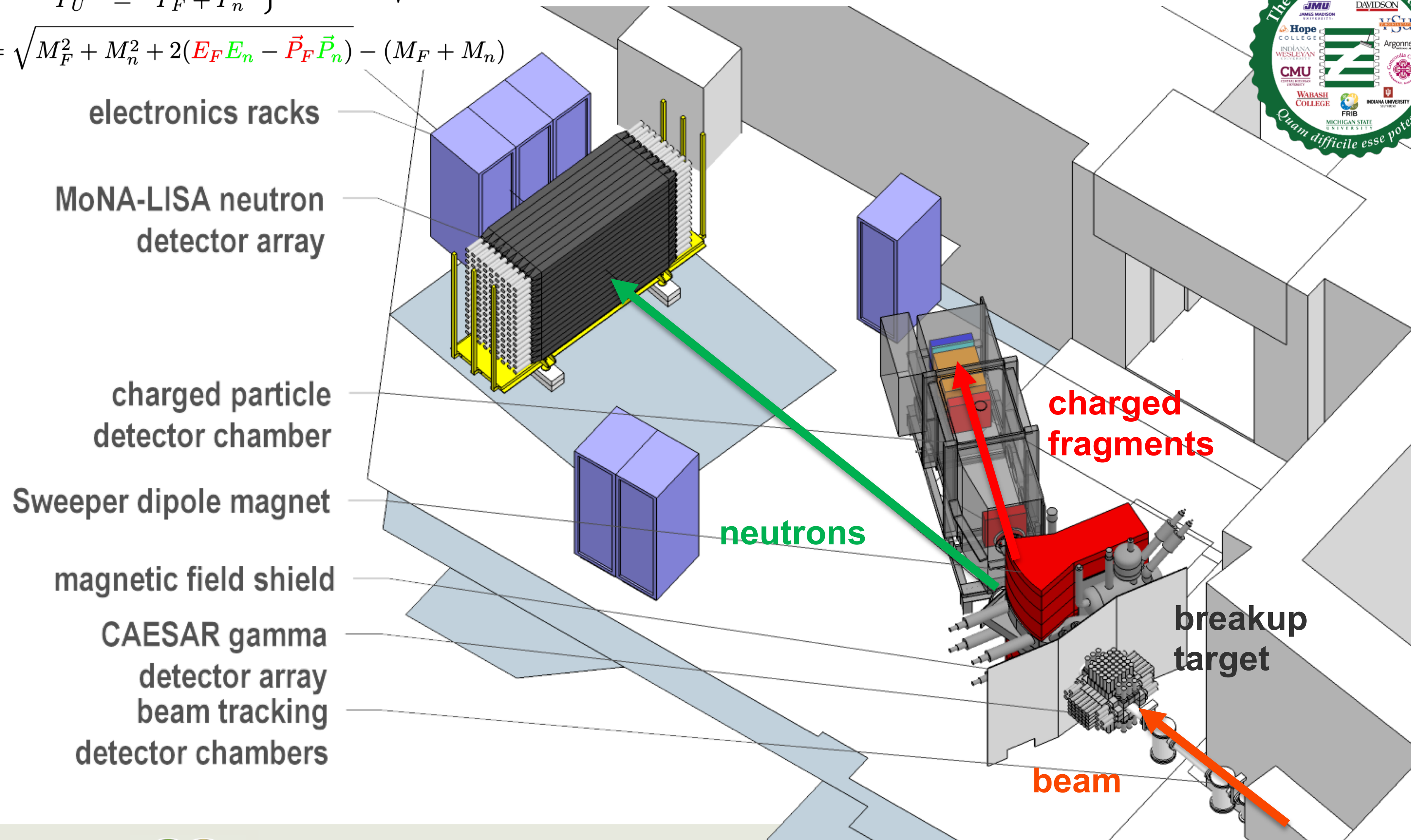
NSCL : ~100 MeV/u
Energy : ~200 MeV/u
FRIB400 : ~400 MeV/u



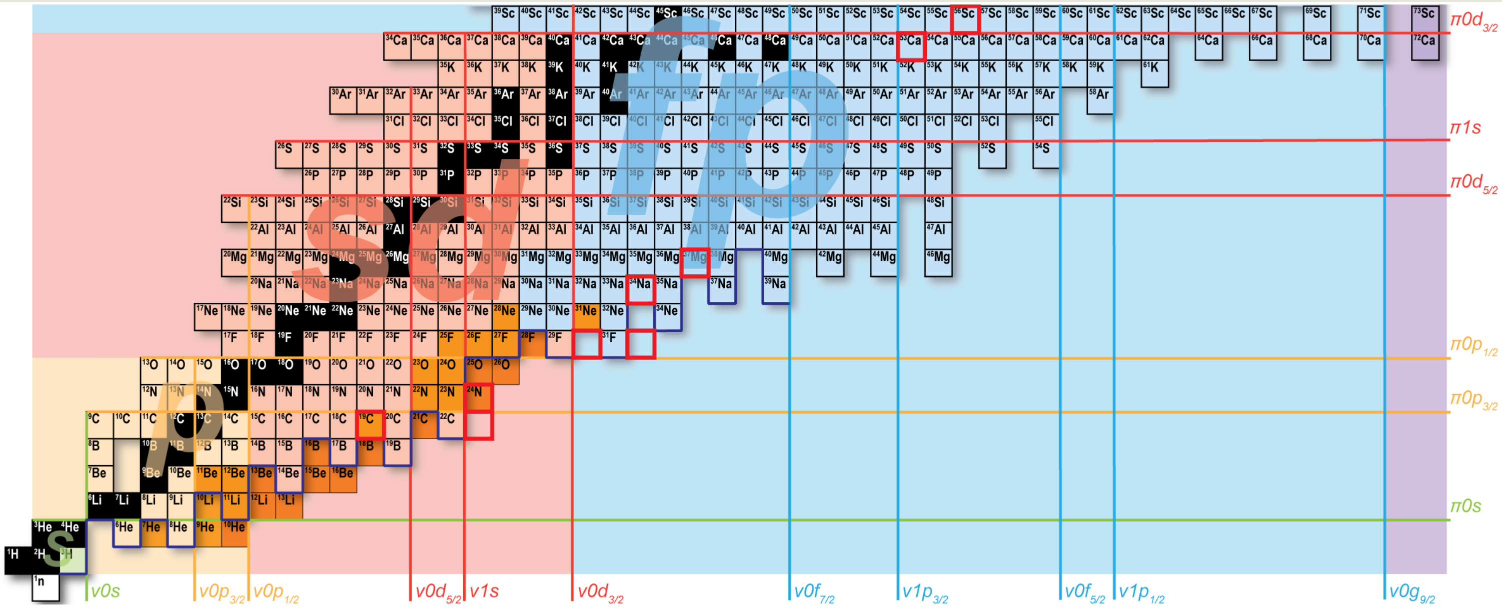
Invariant Mass Technique (MoNA Collaboration – S2 Vault)

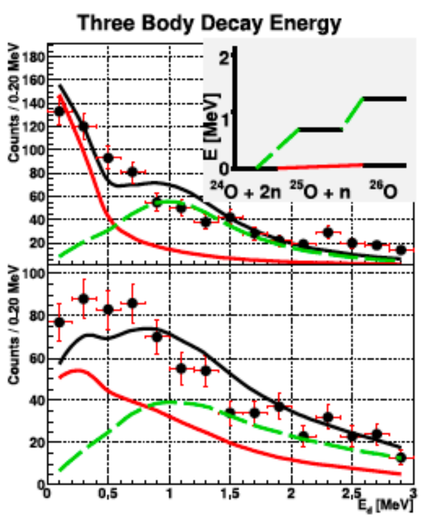
$$\left.\begin{array}{rcl} E_U & = & E_F + E_n \\ \vec{P}_U & = & \vec{P}_F + \vec{P}_n \end{array}\right\} \rightarrow M_U = \sqrt{E_U^2 - \vec{P}_U^2}$$

$$E_{\rm decay} = \sqrt{M_F^2 + M_n^2 + 2(E_F E_n - \vec{P}_F \vec{P}_n)} - (M_F + M_n)$$

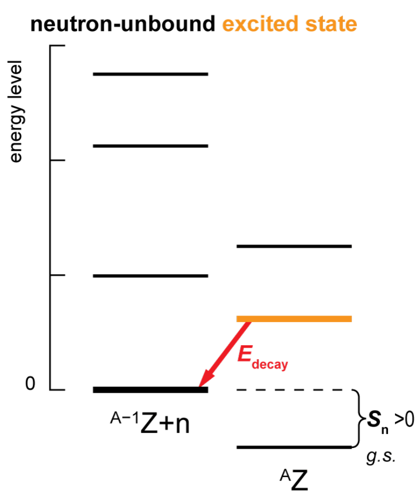


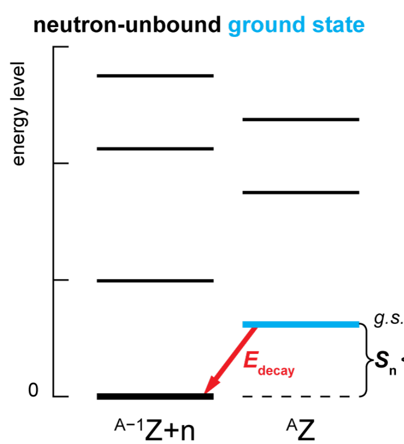
Neutron Unbound States

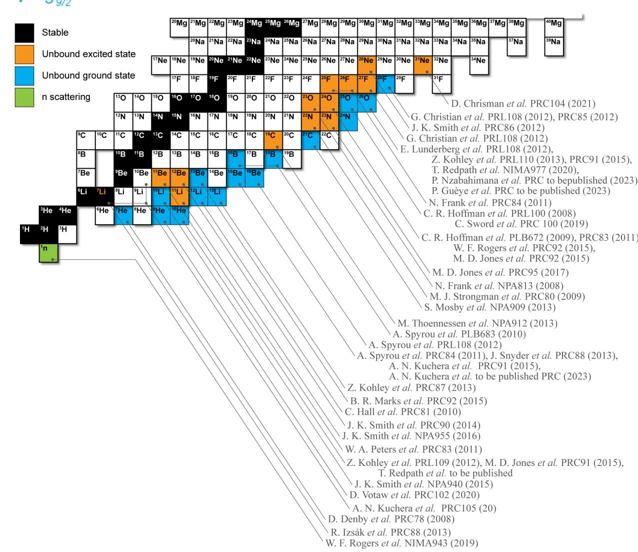




T. Redpath et al, NIMA, **97**, 164284 (2020)







Nuclear Tomography?
What About Polarization?

Meson electro-production

$$\frac{d\sigma_v}{d\Omega_\eta} = \frac{|\mathbf{k}|}{k_\gamma^{cm}} P_\alpha P_\beta \{ R_T^{\beta\alpha} + \varepsilon_L R_L^{\beta\alpha}$$
$$+ [2\varepsilon_L (1+\varepsilon)]^{1/2} ({}^c R_{TL}^{\beta\alpha} \cos\phi_\eta + {}^s R_{TL}^{\beta\alpha} \sin\phi_\eta)$$
$$+ \varepsilon ({}^c R_{TT}^{\beta\alpha} \cos 2\phi_\eta + {}^s R_{TT}^{\beta\alpha} \sin 2\phi_\eta)$$
$$+ h\,[2\varepsilon_L(1-\varepsilon)]^{1/2} ({}^c R_{TL'}^{\beta\alpha} \cos\phi_\eta + {}^s R_{TL'}^{\beta\alpha} \sin\phi_\eta)$$
$$+ h(1-\varepsilon^2)^{1/2} R_{TT'}^{\beta\alpha} \}, \qquad (12)$$

G. Knöchlein, D. Drechsel, L. Tiator
Z. Phys. **A352**, 327-343 (1995)

3D nucleon tomography!!
(DVCs, parton distributions …)

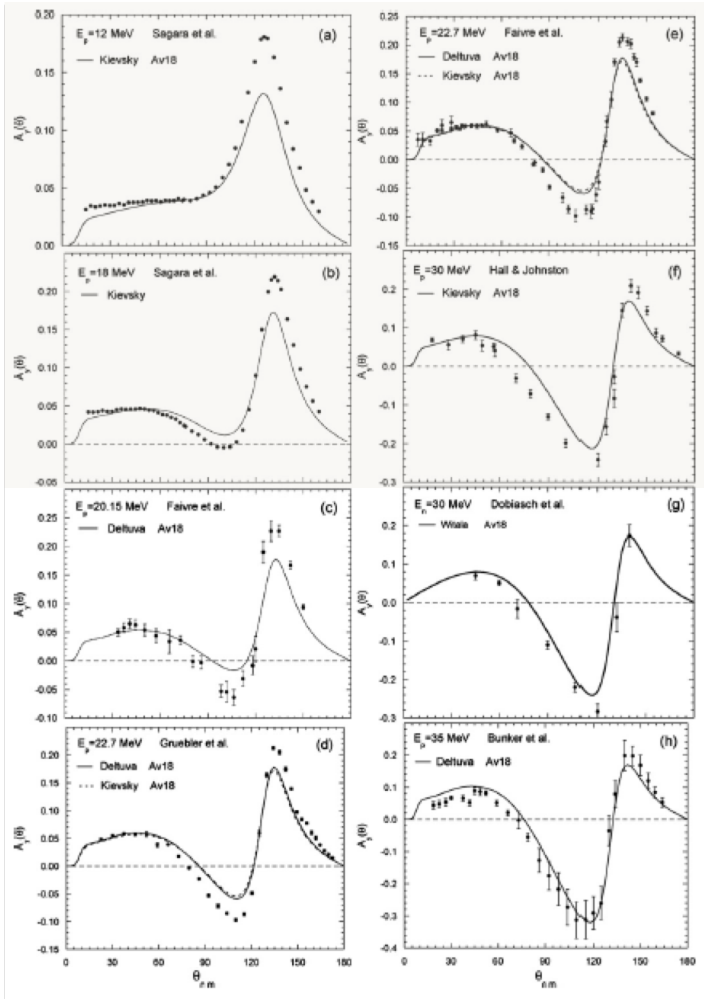
Table 1. Polarization observables in pseudoscalar meson electroproduction. A star denotes a response function which does not vanish but is identical to another response function via a relation in App. A

unpolarized | polarized

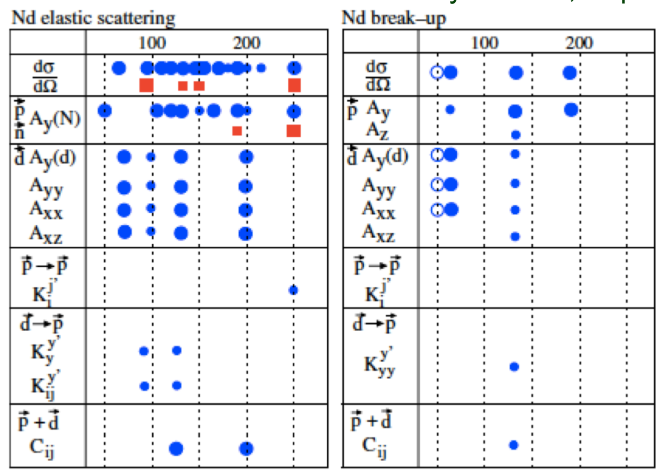
		Target			Recoil			Target + Recoil								
β	–	–	–	–	x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
α	–	x	y	z	–	–	–	x	y	z	x	y	z	x	y	z
T	R_T^{00}	0	R_T^{0y}	0	0	$R_T^{y'0}$	0	$R_T^{x'x}$	0	$R_T^{x'z}$	0	*	0	$R_T^{z'x}$	0	$R_T^{z'z}$
L	R_L	0	R_L^{0y}	0	0	*	0	$R_L^{x'x}$	0	$R_L^{x'z}$	0	*	0	*	0	*
${}^cTL$	${}^cR_{TL}^{00}$	0	${}^cR_{TL}^{0y}$	0	0	*	0	${}^cR_{TL}^{x'x}$	0	*	0	*	0	${}^cR_{TL}^{z'x}$	0	*
${}^sTL$	0	${}^sR_{TL}^{0x}$	0	${}^sR_{TL}^{0z}$	${}^sR_{TL}^{x'0}$	0	${}^sR_{TL}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^cTT$	${}^cR_{TT}^{00}$	0	*	0	0	*	0	*	0	*	0	*	0	*	0	*
${}^sTT$	0	${}^sR_{TT}^{0x}$	0	${}^sR_{TT}^{0z}$	${}^sR_{TT}^{x'0}$	0	${}^sR_{TT}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^cTL'$	0	${}^cR_{TL'}^{0x}$	0	${}^cR_{TL'}^{0z}$	${}^cR_{TL'}^{x'0}$	0	${}^cR_{TL'}^{z'0}$	0	*	0	*	0	*	0	*	0
${}^sTL'$	${}^sR_{TL'}^{00}$	0	${}^sR_{TL'}^{0y}$	0	0	*	0	${}^sR_{TL'}^{x'x}$	0	*	0	*	0	${}^sR_{TL'}^{z'x}$	0	*
TT'	0	$R_{TT'}^{0x}$	0	$R_{TT'}^{0z}$	$R_{TT'}^{x'0}$	0	$R_{TT'}^{z'0}$	0	*	0	*	0	*	0	*	0

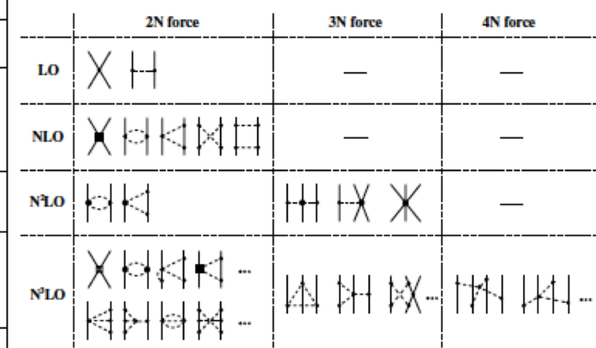
Polarization in Heavy Ion Physics

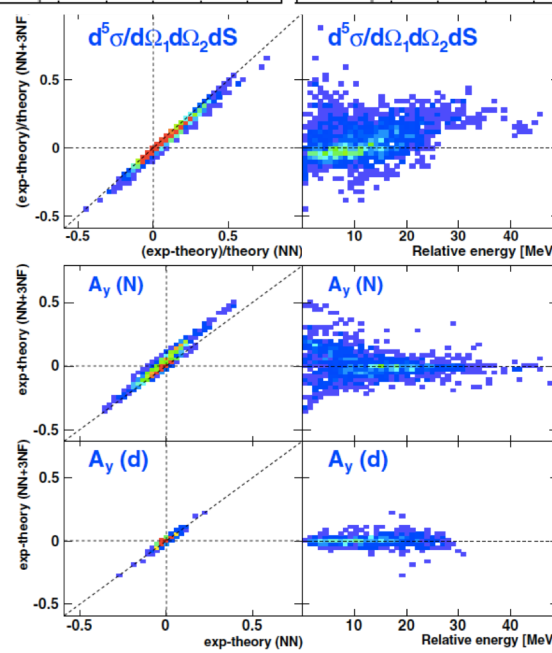
Torrow et al., Nucl. Part. Phys. **35** (2008) 125104

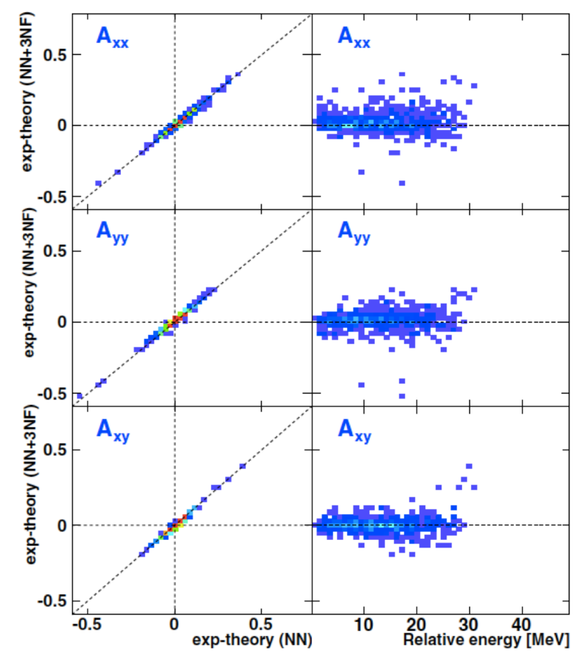


Kalantar-Nayestanaki, Rep. Prog. Phys. **75** (2012) 016301







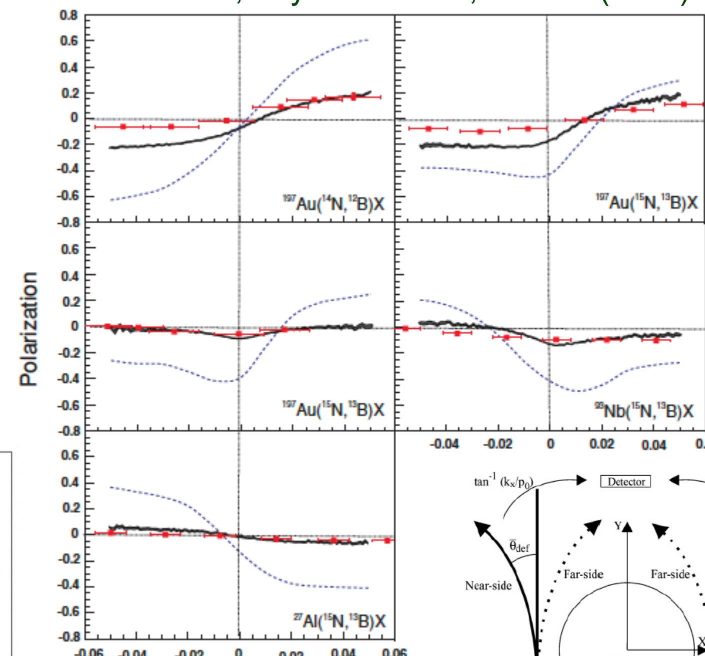


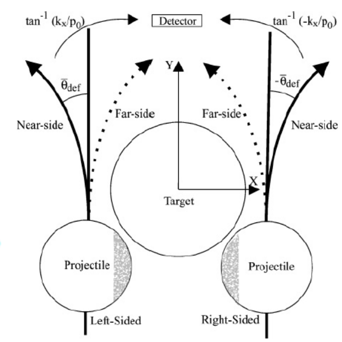
Measuring Polarized Observables with Rare Isotopes

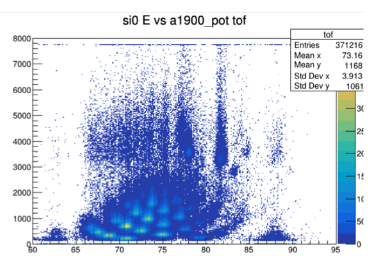
Georgia Votta, GS

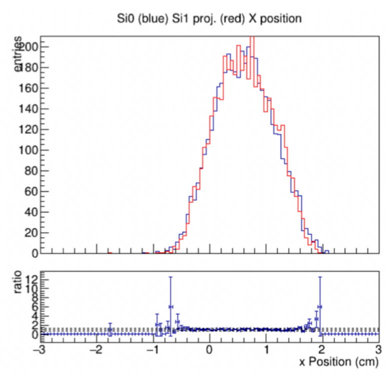
- Another "nitch" @ FRIB
- Beam polarization
  - ✓Spin polarization in nuclear structure: allows spin-parity assignment
  - ✓Fragments are (always) longitudinally polarized: spin flip (polarized $^{31}Na^{+}$ @ TRIUMF)
  - ✓Some good references
    - ➢P. Mantica *et al.*, Phys. Rev. **C55**, 2501 (1997)
    - ➢D. Hoff *et al.*, PRL **119**, 232501 (2017);
    - ➢D. Hoff *et al.*, Phys. Rev. **C97**, 054605 (2018)
- Target polarization
  - ✓The A_y puzzle (n-d scattering)
  - ✓Asymmetry in <30 MeV
  - ✓3N & 4N forces

Groh et al., Phys. Rev. **C76**, 054608 (2007)









Rare Isotope Nuclear Radii

Ambar Rodriguez Alicea, GS

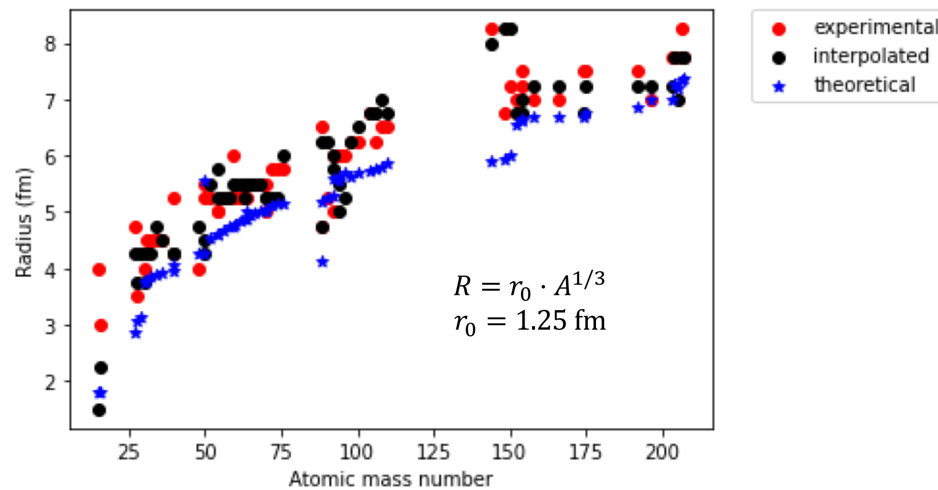
$$\rho(r) = \frac{1}{2\pi^2}\int F(q)\,\frac{\sin(qr')}{qr}\,q^2 dq$$

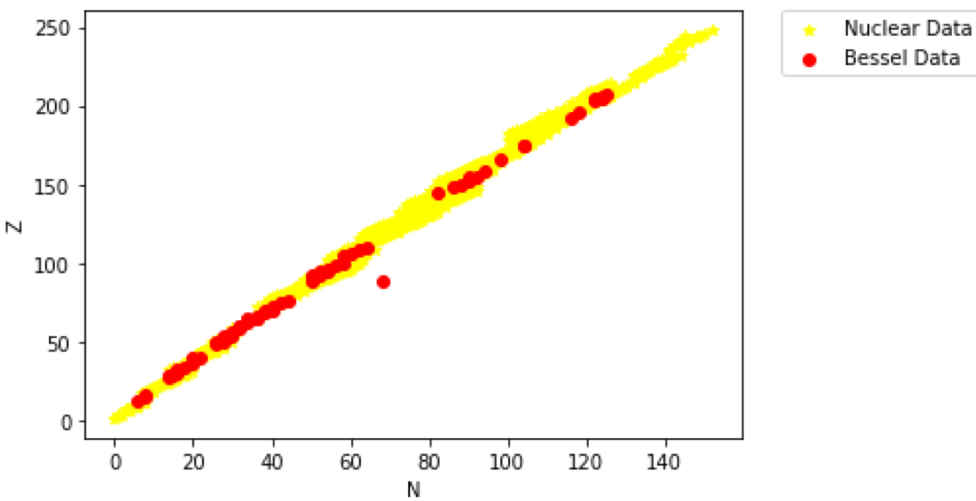
$$= \sum a_\nu j_0(qr)$$

$$F(q) = 4\pi\int \frac{\sin(qr'/\hbar)}{qr'/\hbar}\,r'^2\rho(r')dr'$$

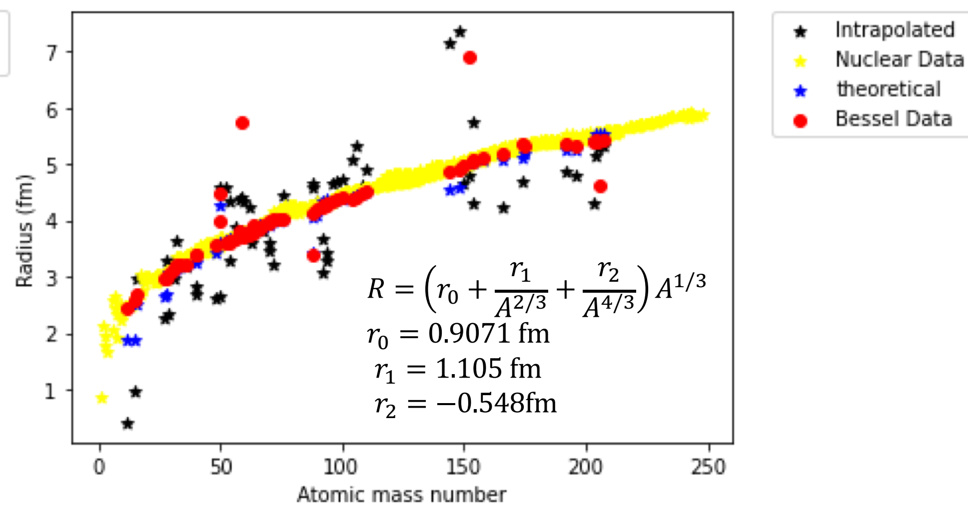
$$j_0(qr) = \sum_{n=0}^{\infty}\frac{(-1)^n (qr)^{2n}}{2^{2n}(n!)^2} = \frac{\sin(qr)}{qr}$$

H. DeVries etal., At. Data Nuc. Data Tables, **36**, 495-536 (1987)



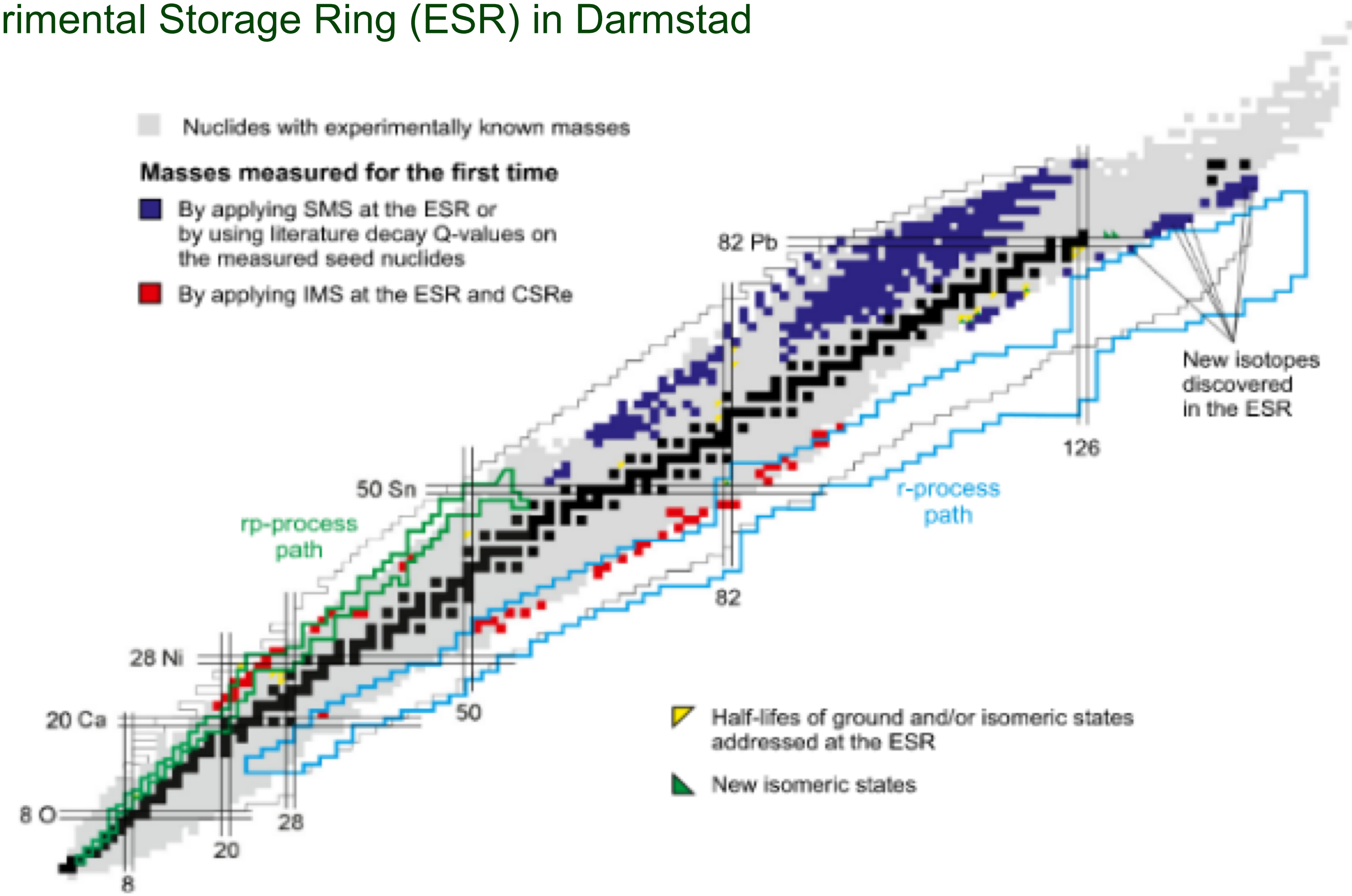


I. Angeli and K. P. Marinova, At. Data Nuc. Data Tables, **99**, 69-95 (2013)



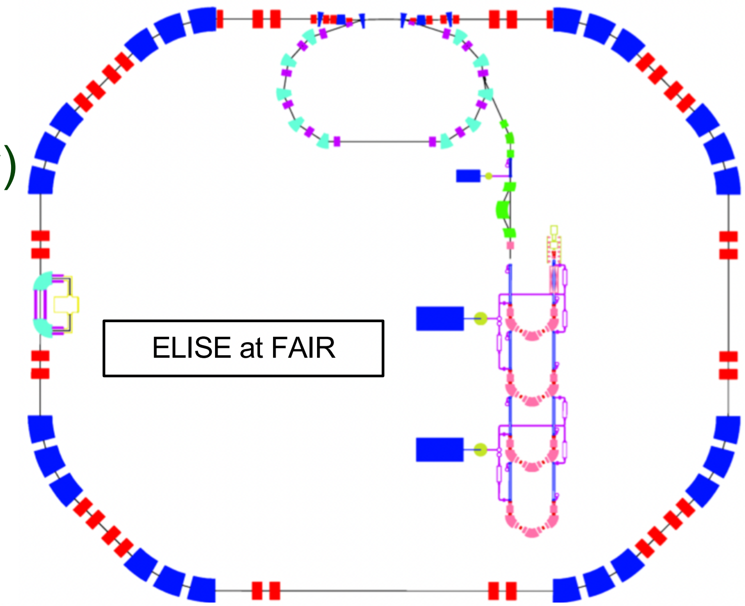
Storage Rings & Mass Measurements

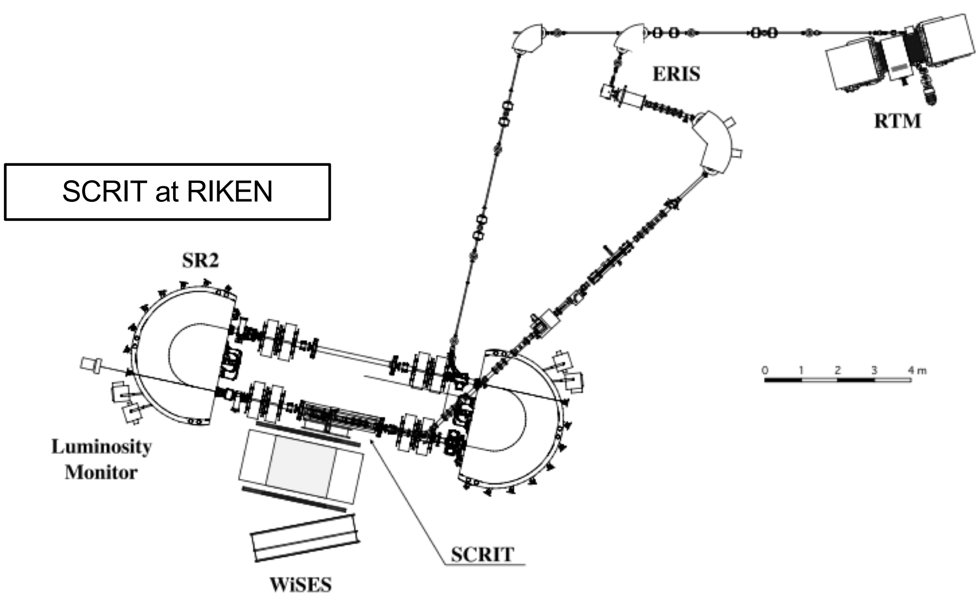
Experimental Storage Ring (ESR) in Darmstad

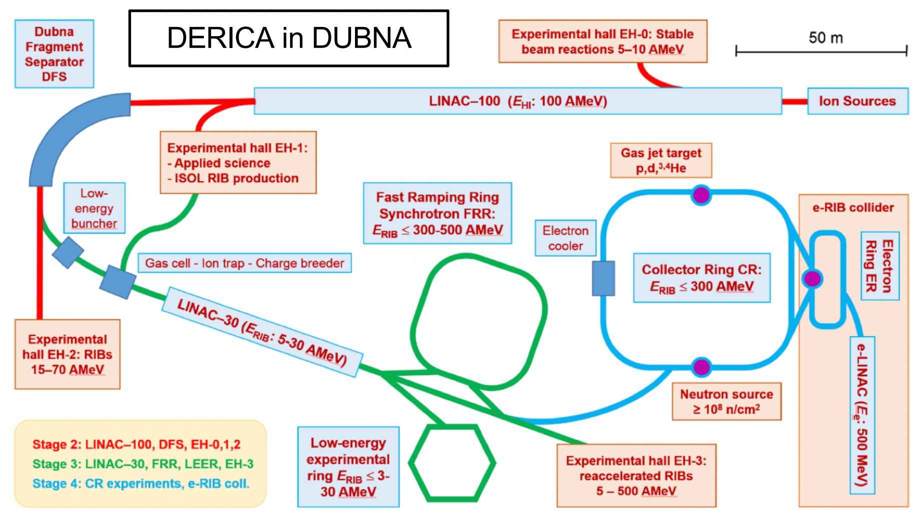


Electron/Rare Isotopes Systems

- RI-RIKEN
  - SCRIT: Self-Confining Radioactive isotope Ion Target
- Facility for Anti-proton and Ion Research (FAIR, Germany)
  - ELISE: Electron-Ion Scattering in a Storage Ring
- DUBNA (Russia)
  - DERICA: Dubna Electron-Radioactive Ion Collider fAcility



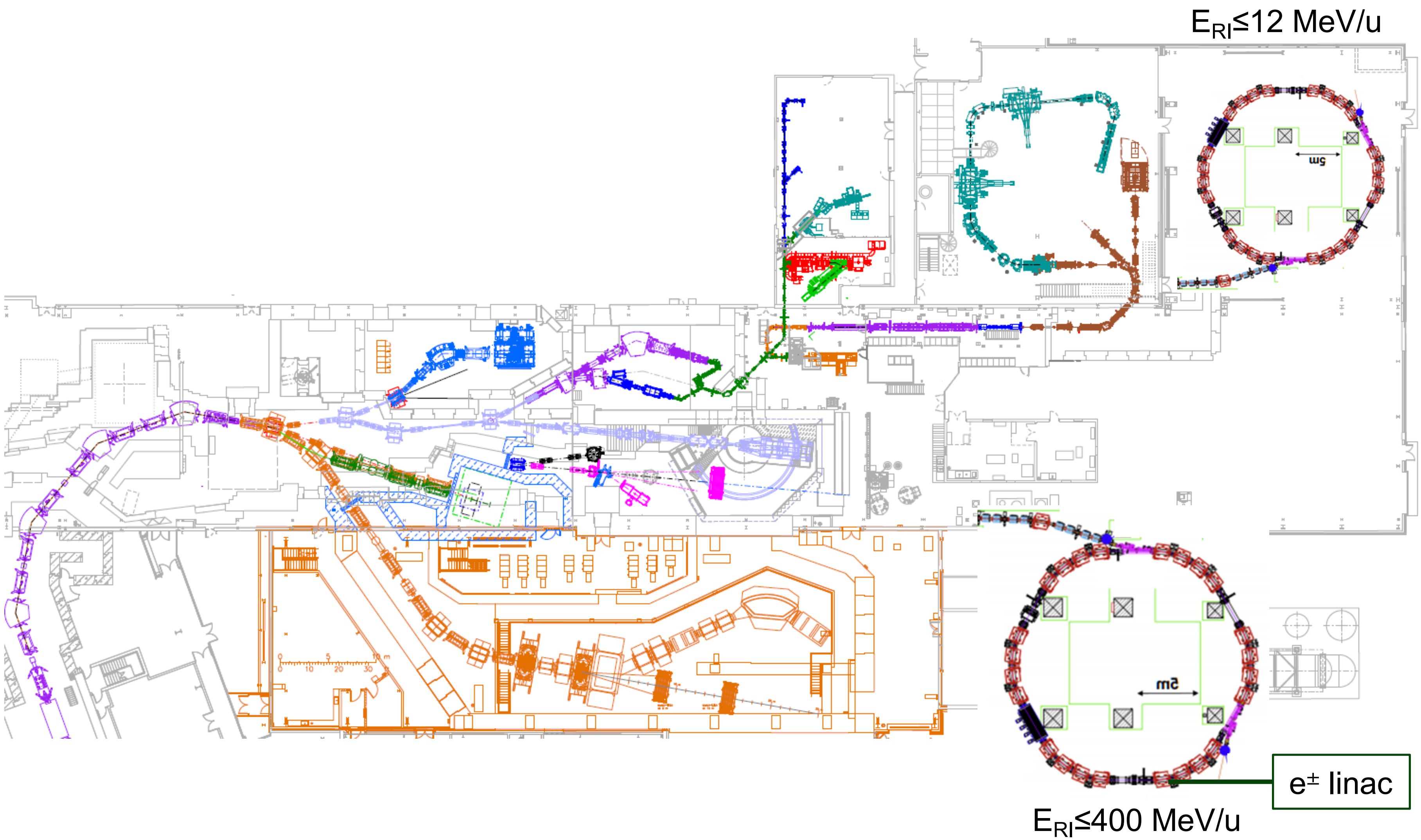




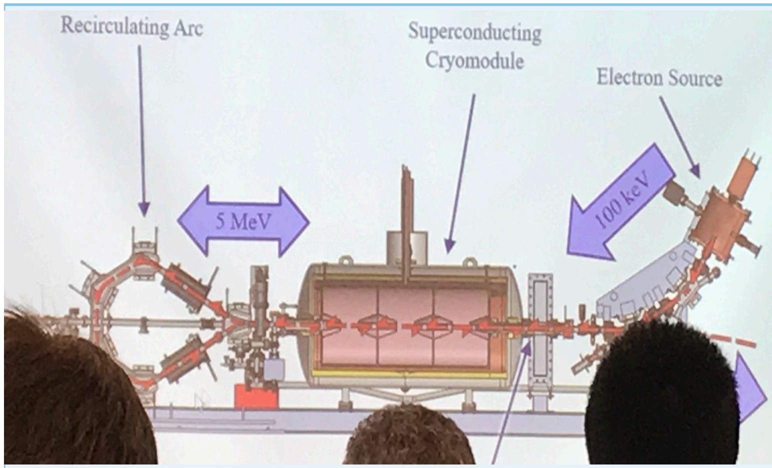
Workshop, Symposia & Brainstorming Sessions

- North America Storage Rings & Neutron Captures Workshop
  - June 28-30, 2021
  - https://meetings.triumf.ca/event/235/overview
- APS/DNP symposia
  - October 11-14, 2021
  - JF: Advances and Opportunities in Polarized Targets and Beams I
  - KF: Advances and Opportunities in Polarized Targets and Beams II
- Brainstorming sessions
  - March 25, 2022 and April 01, 2022
  - Participants: Eric Voutier, Toshimi Suda, Maya Wallach, Claude Marchand, Dominic Marchand, Joe Grames, Kei Minamisono, Peter Ostroumov, Kent Paschke, Ryan Richards, Or Hen, Alain Lapierre, Michael Kohl

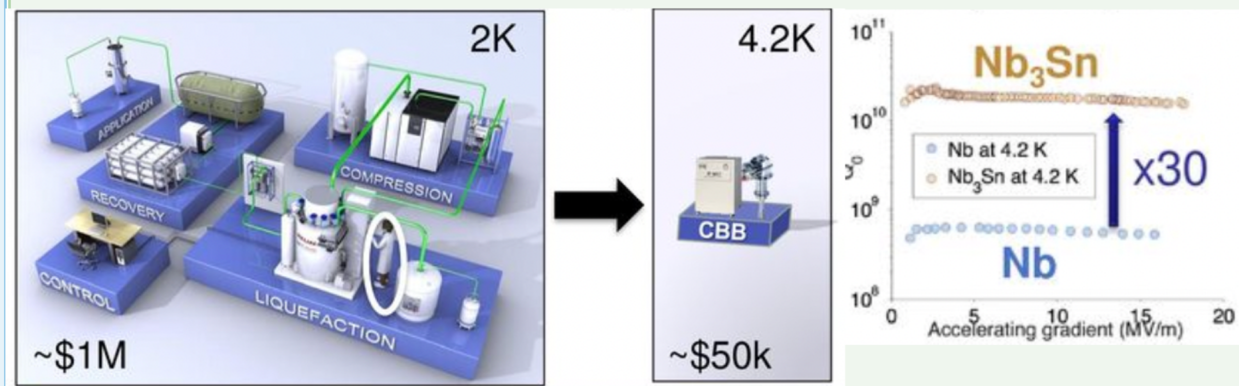
e±-FRIB Concept



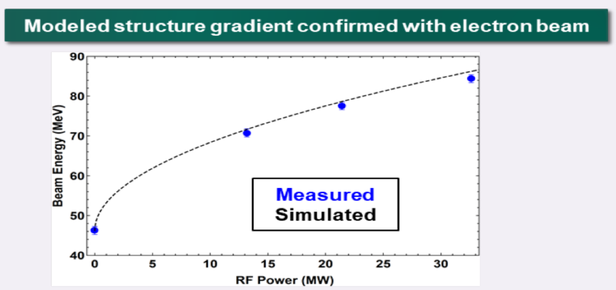
Electron/Positron Beam

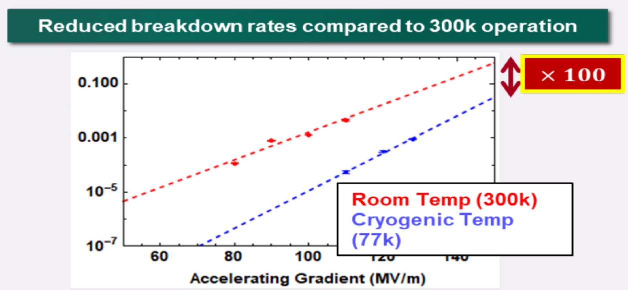


Niowave, https://www.niowaveinc.com

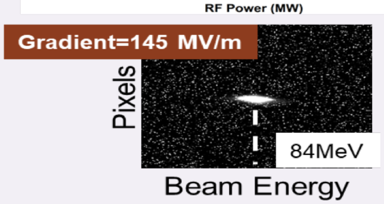


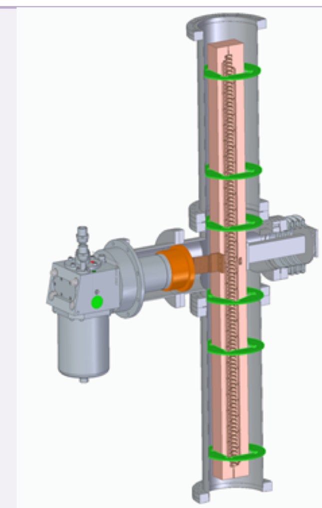
Center for Bright Beams @ Cornell, https://cbb.cornell.edu





Stepped pulse with flat gradient of 200ns





Very High Energy Electron (VHEE) @ SLAC

- Compact, ultrahigh efficiency/gradient linac
- Operating at 80K, require 20 MW to reach 100 MV/m
- Typical linacs would have required about 200 MW of power

RI Storage Rings – 1

Experimental Storage Ring, ESR at GSI

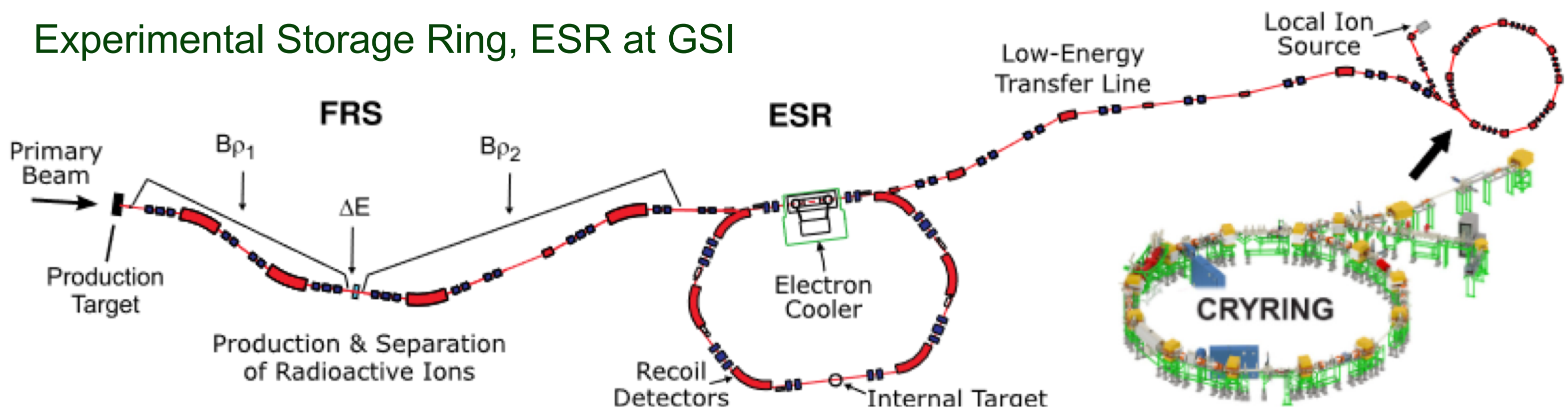
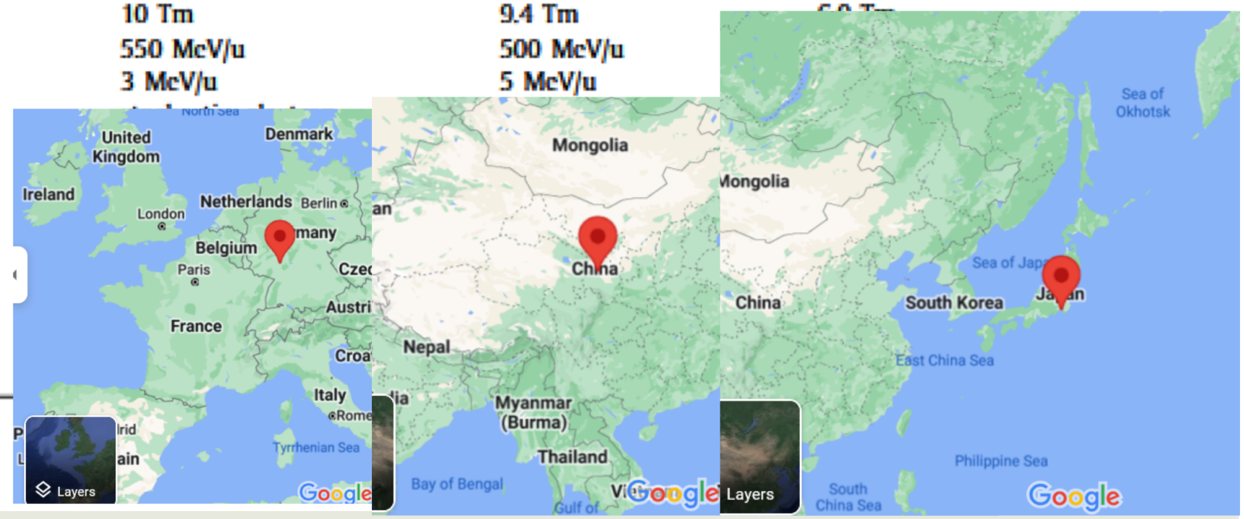
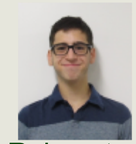


Table 1
Active heavy ion storage rings.

	ESR	CSRe	R3
Circumference	108.4 m	128.8 m	60.4 m
Maximum magnetic rigidity	10 Tm	9.4 Tm	
Maximum beam energy U^{92+}	550 MeV/u	500 MeV/u	
Minimum beam energy U^{92+}	3 MeV/u	5 MeV/u	
Beam cooling			
Internal target			
Standard mode			
Tunes Q_x/Q_y			
Acceptance (A_x/A_y) [μm]/(δp/p) [%]			
Isochronous mode			
Tunes Q_x/Q_y			
Acceptance (A_x/A_y) [μm]/(δp/p) [%]			
Transition energy γ_t			

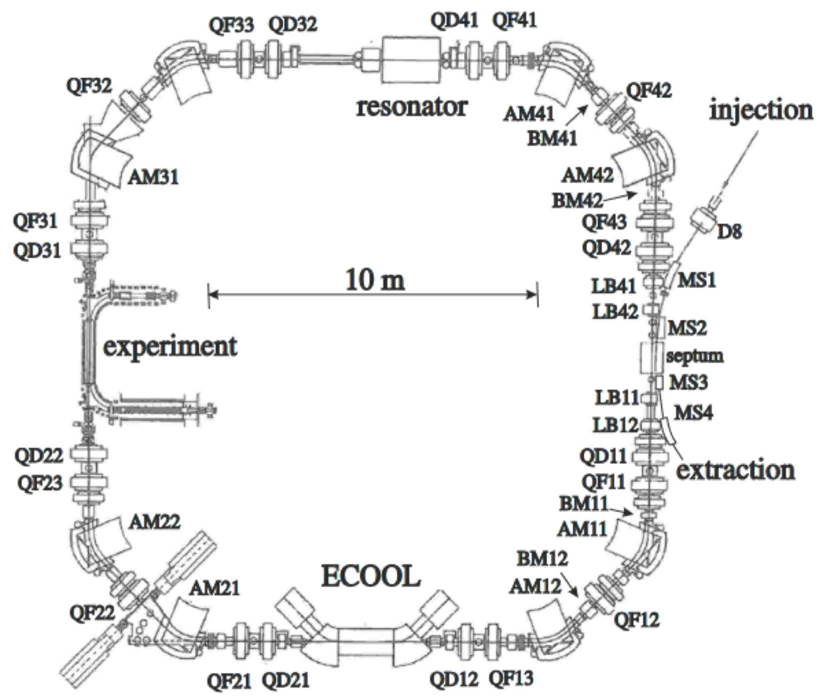


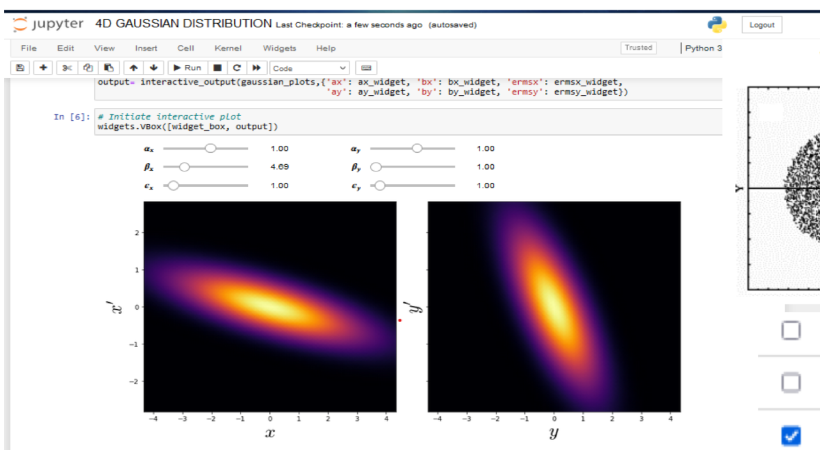
RI Storage Ring – 2

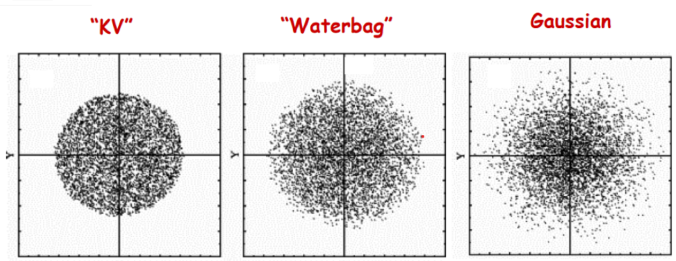


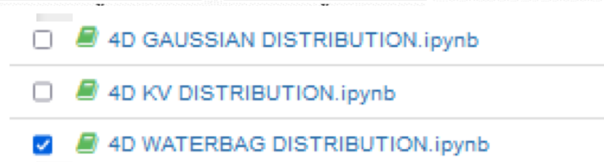
Jeremy Rebenstock, UG

- Components
  - Injection
  - Beam cooling system (phase space)
  - Internal target
  - Magnet system
  - Detector (diagnostics) system
  - Extraction
- Test Storage Ring facility (model)
  - Heidelberg, 1988-2012









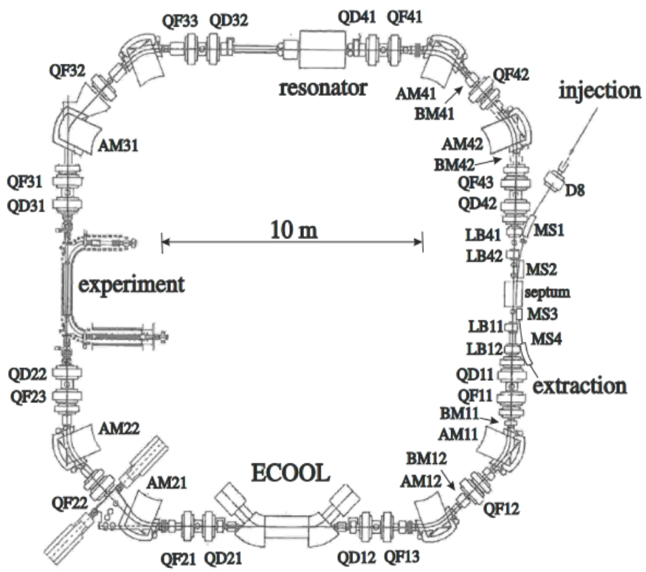
The equation for the beam ellipse, with our Twiss parameterization can be written as:

$$\varepsilon = \gamma x^2 + 2\alpha x x' + \beta x'^2$$

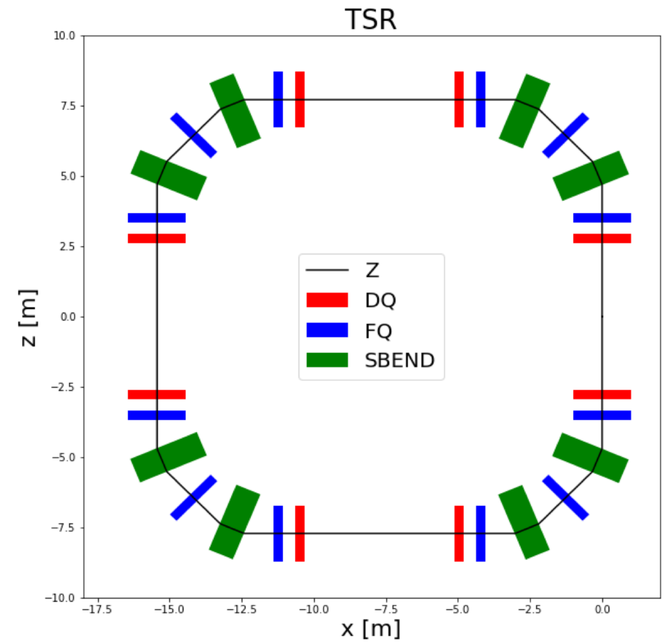
$$\gamma = \frac{1+\alpha^2}{\beta}$$

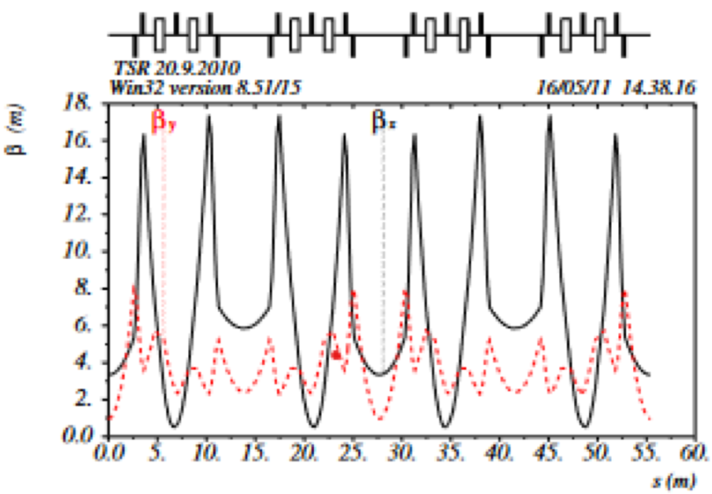
RI Storage Ring – 3

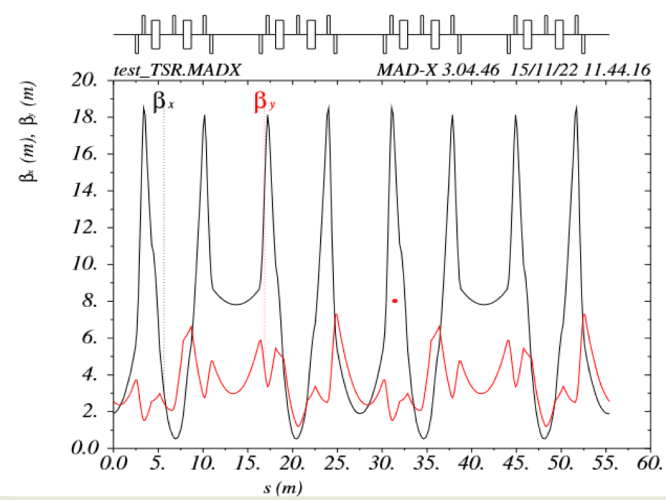
Jeremy Rebenstock, UG



Cristhian Gonzalez Ortiz
PhD advisor: P. Ostroumov
TSR Conceptual report







Some numbers …

T. Suda and H. Simon, Prog. Part. Nucl. Phys., **96**, 1-31 (2017)

Table 2
Estimate for the required luminosities for different studies in colliding beam kinematics. It is assumed that the maximum running time shall not exceed four weeks.

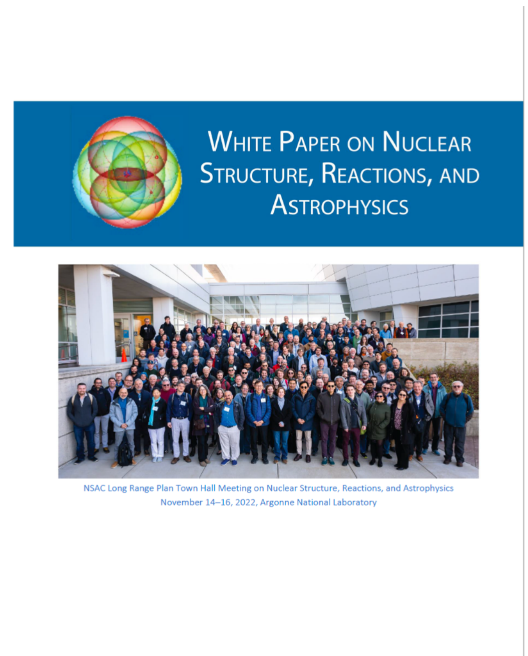
Reaction	Deduced quantity	Target nuclei	Luminosity $\mathcal{L}$ cm^{-2} s^{-1}
Elastic scattering at small q	r.m.s. charge radii	Light Medium	10^{24}
First minimum in elastic form-factor	Density distribution with 2 parameters	Light Medium Heavy	10^{28} 10^{26} 10^{24}
Second minimum in elastic form-factor	Density distribution with 3 parameters	Medium Heavy	10^{29} 10^{26}
Giant resonances	Position, width, strength, decays	Medium Heavy	10^{28} 10^{28}
Quasi-elastic scattering	Spectroscopic factors, spectral function, momentum distributions	Light	10^{29}

	Ee (GeV)	Beam Current	Ne/s	Target (/cm^2)	L (/cm^2/s)
Hofstadter (1950)	0.15	1 nA	6.25 x 10^{09}	6.0 x 10^{19}	3.8 x 10^{29}
JLab	12	100 µA	6.25 x 10^{14}	6.0 x 10^{22}	3.8 x 10^{37}
SCRIT (20 W)	0.15-0.30	300 mA	1.88 x 10^{18}	1.0 x 10^{09}	1.9 x 10^{27}
FRIB (400 kW)	0.2	300 mA	1.88 x 10^{18}	1.9 x 10^{13}	3.6 x 10^{31}
positrons (1/100)	0.2	3 mA	1.88 x 10^{16}	1.9 x 10^{13}	3.6 x 10^{29}

Next Steps

- Science case
  - Rare isotope rings: nuclear astrophysics community
  - $e^{\pm}$ scattering: electron scattering community
  - Goals
    - » Series of (hybrid) workshops: summer 2023, fall 2023, spring 2024
    - » Science report: spring/summer 2024

- Accelerator systems
  - RI ring systems: White Paper NSAC LRP
    - » Nuc. Astro. team is working on it
  - $e^{\pm}$ system
    - » Interest: Cornell, BNL … Jlab



Thank You!

Paul Guèye

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