Polarimetry at the EIC

Ross Corliss

Stony Brook University

CFNS Summer School 2026

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Center for Frontiers in Nuclear Science

Outline

- Polarized Measurements at EIC (Why and How)
- Creating Polarized Beams
- Maintaining Polarized Beams
- Measuring Polarization

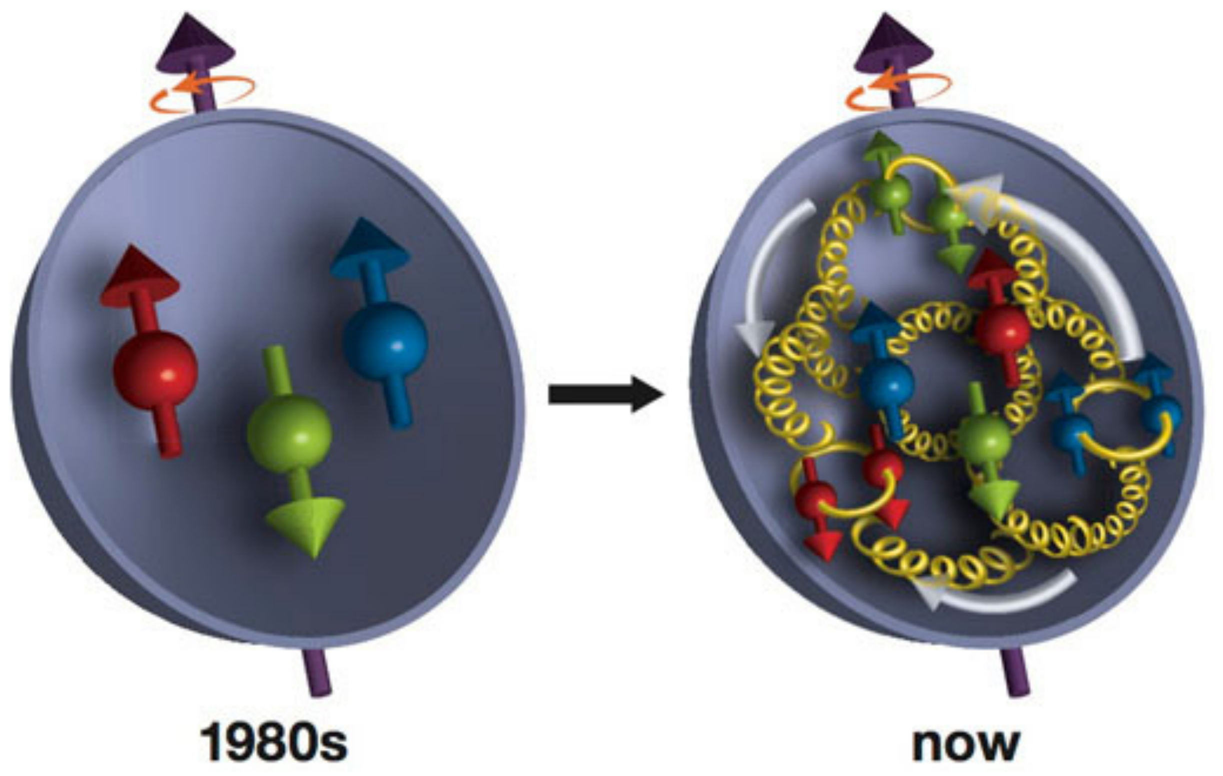
Understanding Proton Spin

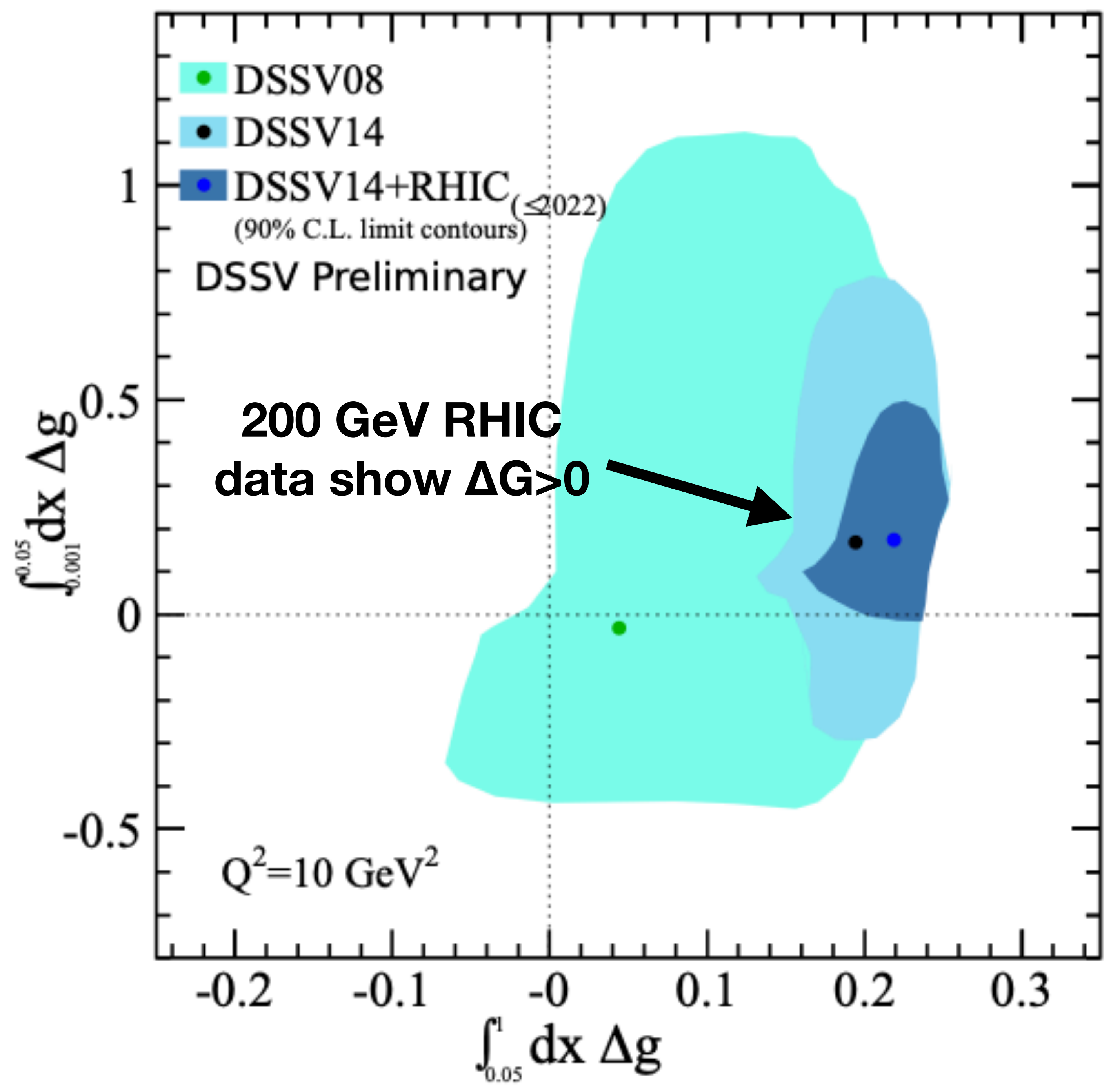
- Valence quarks do not carry all the spin. More complex dynamics are at hand:

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta Q + \Delta G + L_q + L_g$$

quarks | gluons | orbital motion

- **Longitudinal** -- how do partons polarize wrt the proton?
- **Transverse** -- how are proton spin and parton transverse momentum / spin correlated?





arxiv:2302.00605

Motivation: 3D Tomography

- Polarized DIS: Structure functions dSig, dG
  - onward to low x <~0.01 (global fits die out at that point). EIC can continue down to x<1e-4, better accessing gluons
  - prove whether gluons are a major source of gluon spin
- SIDIS: flavor-separated du, dubar, etc
  - Transverse Momentum Dependent pdfs
- Exclusive: Generalized Parton Distributions (coord. space), aiming for Lg, Lq.

- For the neutron as well as the proton
- And explore parity-violating BSM

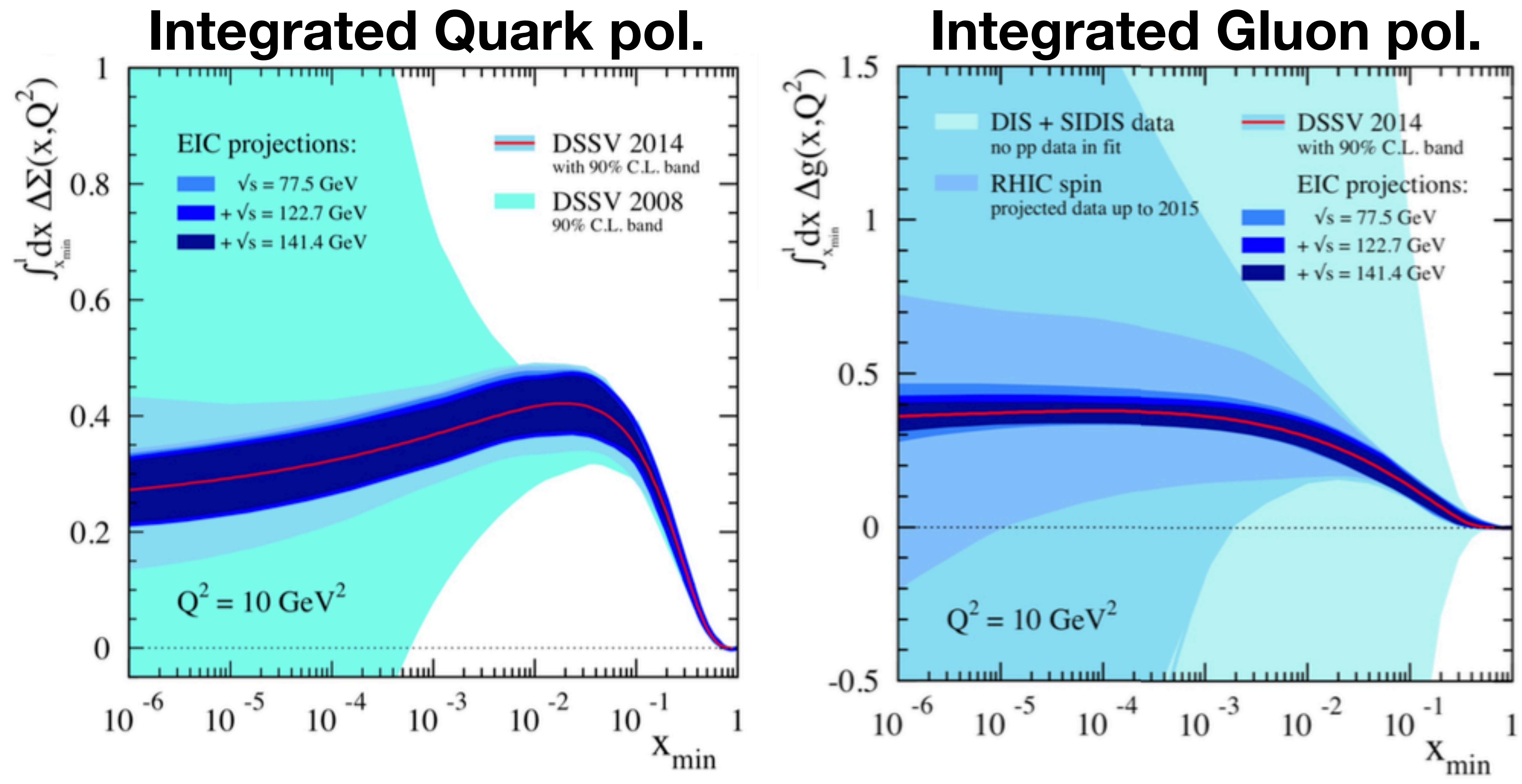


Figure 6: Comparison of polarized PDFs at $Q = 10$ GeV obtained from the `pDIS+SIDIS base` fit and from fits including projected EIC SIDIS pseudodata for the two beam-energy configurations $E_e \times E_p = 5 \times 41$ GeV^2 and 18×275 GeV^2, using the default hadron-energy cut $z > z_{\rm min} = 0.2$.

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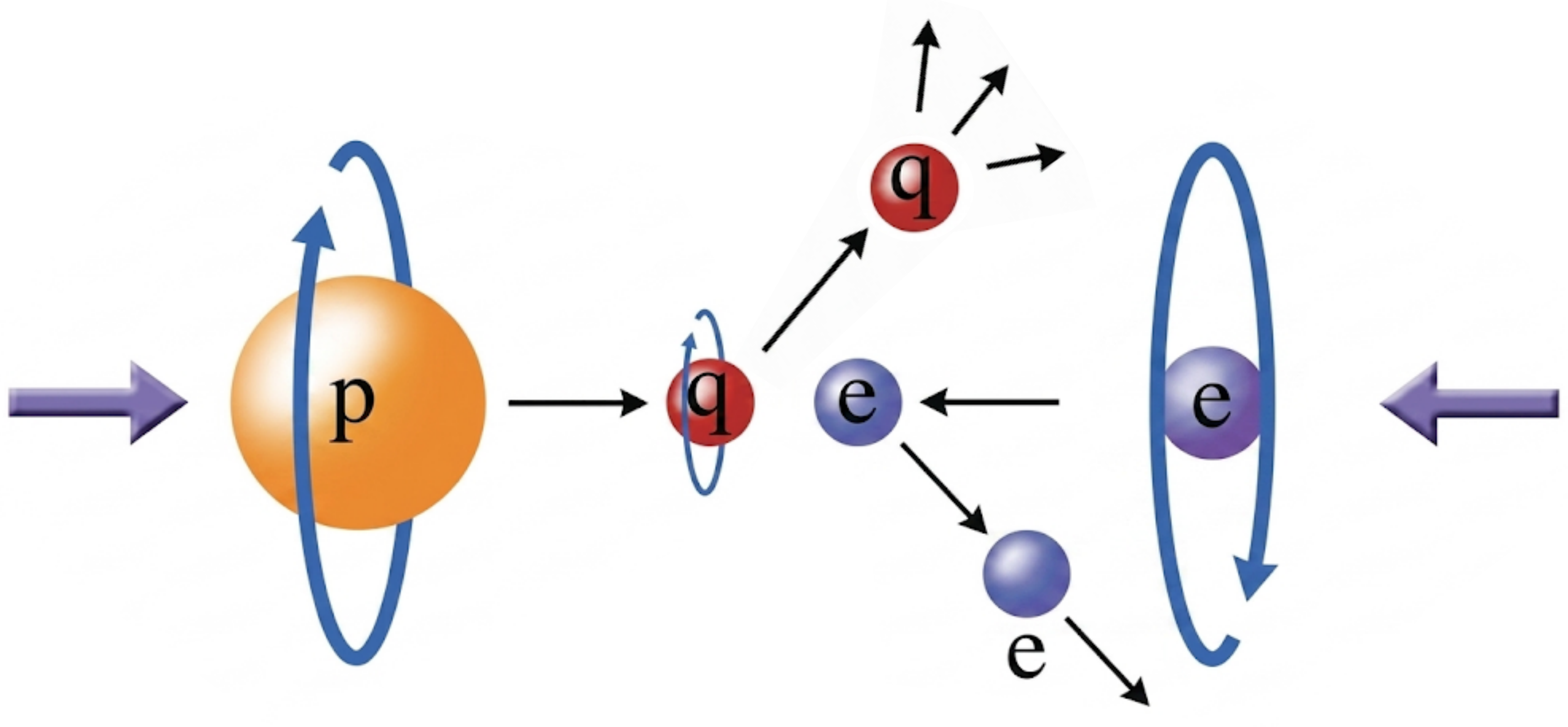
Longitudinal Asymmetries

$$A_{LL} = \frac{\sigma^{-\Uparrow} - \sigma^{+\Uparrow}}{\sigma^{-\Uparrow} + \sigma^{+\Uparrow}} = \frac{\Delta\sigma}{\sigma_0}$$

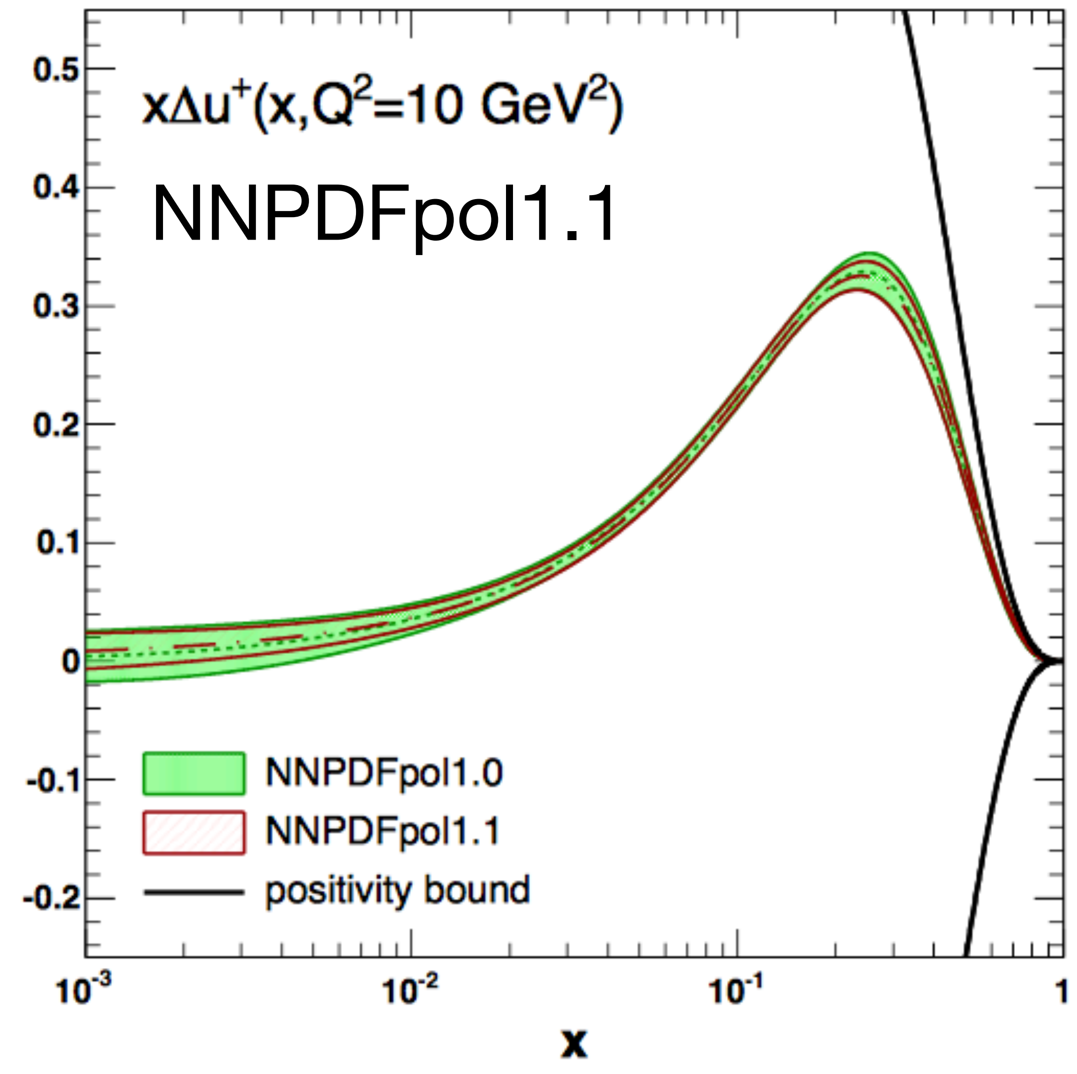
$$\Delta\sigma = \sum_a \Delta f_{a/p} \otimes \Delta\sigma_{ea}$$

$$\Delta\sigma = \left[e_u^2 \Delta u(x) + e_d^2 \Delta d(x) + e_s^2 \Delta s(x) + \ldots\right] \otimes \Delta\sigma_{\mathrm{ea}}$$



$\Delta q(x) =$ 

- Partonic asymmetries can be large
- In inclusive DIS, all the quarks contribute to the scattered e- data
- Combine different targets (p,d,n) and scan Q² to tease apart underlying pPDFs via global fit



arxiv:1406.5539 : Nucl.Phys.B 887, 276 (2014)

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Beam Polarization

- For spin-1/2, we define the polarization of a beam in terms of the populations in each spin state: -1<P<1: $P = \frac{N_+ - N_-}{N_+ + N_-}$
- For spin-1, there are three states. We could write $P_z = \frac{N_+ - N_-}{N_+ + N_0 + N_-}$,
- But traditionally we normalize so that: $N_+ + N_0 + N_- = 1$.
  - Vector polarization: $P_z = N_+ - N_-$
  - Tensor polarization: $P_{zz} = 1 - 3N_0$ (+1: all spins along pol. axis. -2: all spins transverse to pol axis)
  - Unpolarized: $N_+ = N_0 = N_- = \frac{1}{3}$

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Polarized Scattering: Asymmetry

- The polarized physics is related to the asymmetry of the pure-spin cross sections:
- But our beams will not be perfectly polarized:
- So the *observed* cross section will mix contributions from every spin combination in our beams:
- We can write this in terms of the pure spin σ's: *(using (+,↑)=(-,↓) and (-,↑)=(+,↓) by parity)*
- By measuring once with $+P_e$, once with $-P_e$, we can make linear combinations of σ_{mix} terms:
- And our A_{exp} can be written in terms of polarization factors and pure cross sections
- So we can get the pure asymmetry by dividing the measured, mixed asym by the polarization:
- In fact, these σ_{mix} will have many terms in common

$$A = \frac{\sigma^{+,\uparrow} - \sigma^{-,\uparrow}}{\sigma^{+,\uparrow} + \sigma^{-,\uparrow}}$$

$$P_e = \frac{N^+ - N^-}{N^+ + N^-} \quad \rightarrow \quad N^{\pm} = \frac{1}{2}(N^+ + N^-)(1 \pm P_e) \quad \text{(and sim. for } \uparrow / \downarrow\text{)}$$

$$\sigma_{mix} = \frac{N^+N^\uparrow\sigma^{+,\uparrow} + N^+N^\downarrow\sigma^{+,\downarrow} + N^-N^\uparrow\sigma^{-,\uparrow} + N^-N^\downarrow\sigma^{-,\downarrow}}{(N^+ + N^-)(N^\uparrow + N^\downarrow)}$$

$$\sigma_{mix}(P_e, P_T) = \left(\frac{\sigma^{+,\uparrow} + \sigma^{-,\uparrow}}{2}\right) + P_e P_T \left(\frac{\sigma^{+,\uparrow} - \sigma^{-,\uparrow}}{2}\right)$$

$$A_{exp} = \frac{\sigma_{mix}(+P_e, P_T) - \sigma_{mix}(-P_e, P_T)}{\sigma_{mix}(+P_e, P_T) + \sigma_{mix}(-P_e, P_T)}$$

$$A_{exp} = \frac{P_e P_T(\sigma^{+,\uparrow} - \sigma^{-,\uparrow})}{\sigma^{+,\uparrow} + \sigma^{-,\uparrow}}$$

$$A = \frac{1}{P_e \cdot P_T}\left(\frac{\sigma_{mix}(+P_e, P_T) - \sigma_{mix}(-P_e, P_T)}{\sigma_{mix}(+P_e, P_T) + \sigma_{mix}(-P_e, P_T)}\right)$$

$$A = \frac{1}{P_e \cdot P_T}\left(\frac{n_+ - Rn_-}{n_+ + Rn_-}\right) \qquad R = \frac{L_+}{L_-}$$

Polarized Scattering: Figure of Merit

- We are essentially counting the number of scattering events (with some selection criteria) in each spin configuration:

$$A = \frac{1}{P_e P_T}\left(\frac{n_+ - n_-}{n_+ + n_-}\right)$$

- We can do standard error prop.:

$$(\Delta A)^2 = \left(\frac{\partial A}{\partial n_+}\right)^2 (\Delta n_+)^2 + \left(\frac{\partial A}{\partial n_-}\right)^2 (\Delta n_-)^2$$

$$\frac{\partial A}{\partial n_+} = \frac{1}{P_e P_T}\left[\frac{2n_-}{(n_+ + n_-)^2}\right] = \frac{1}{P_e P_T}\left(\frac{2n_-}{n_{tot}^2}\right) \qquad \frac{\partial A}{\partial n_-} = \frac{1}{P_e P_T}\left[\frac{2n_+}{(n_+ + n_-)^2}\right] = \frac{1}{P_e P_T}\left(\frac{-2n_+}{n_{tot}^2}\right)$$

$$(\Delta A)^2 = \frac{1}{P_e^2 P_T^2 N_{tot}^4}\left[4n_-^2 n_+ + 4n_+^2 n_-\right]$$

- The variance on the counts is just $\sqrt{n}$.
- If our yields are approximately the same *

$$n_+ \approx n_- \approx \frac{1}{2} N_{tot}$$

- Then the uncertainty on our physics observable is

$$(\Delta A)^2 = \frac{1}{P_e^2 P_T^2 N_{tot}}$$

- To minimize this, we maximize our Figure of Merit:

$$\mathrm{FOM} = N_{tot} P_e^2 P_T^2$$

- So: Need high statistics and high-polarization beams.

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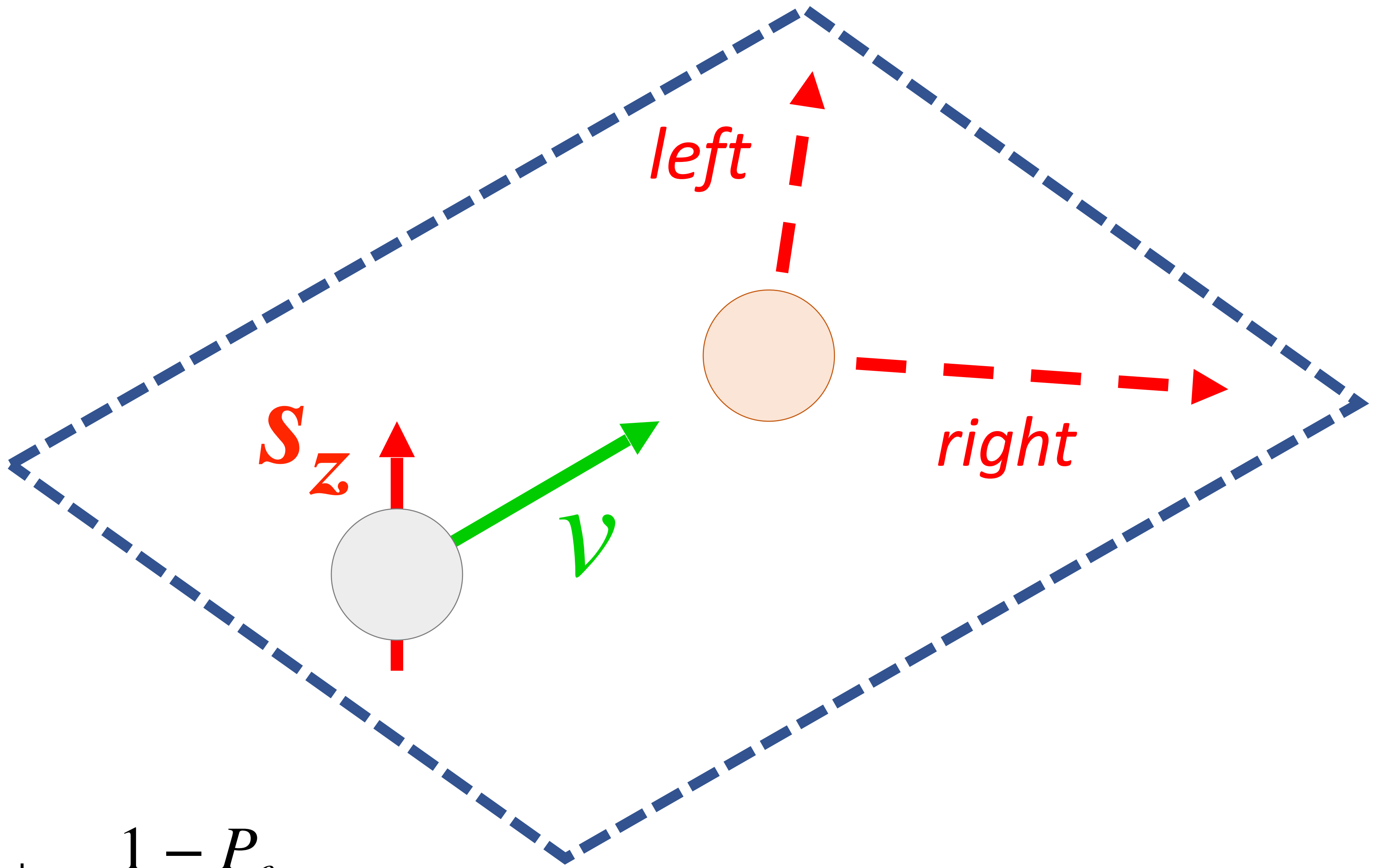
Transverse Asymmetries

$$A_y = \frac{\sigma_L(\uparrow) - \sigma_R(\uparrow)}{\sigma_L(\uparrow) + \sigma_R(\uparrow)}$$



- Not handedness! Literally Leftward and Rightward!
- We only need one transversely polarized object. $\vec{s} \times \vec{v}$ fully defines Left and Right.
- We can follow the same prescription as in Long.: $f^{\uparrow} = \frac{1+P_e}{2} \quad f^{\downarrow} = \frac{1-P_e}{2}$
- Mixed beams have fractional up and down contributions:
- So the *observed* cross section will mix contributions from every spin combination in our beams:

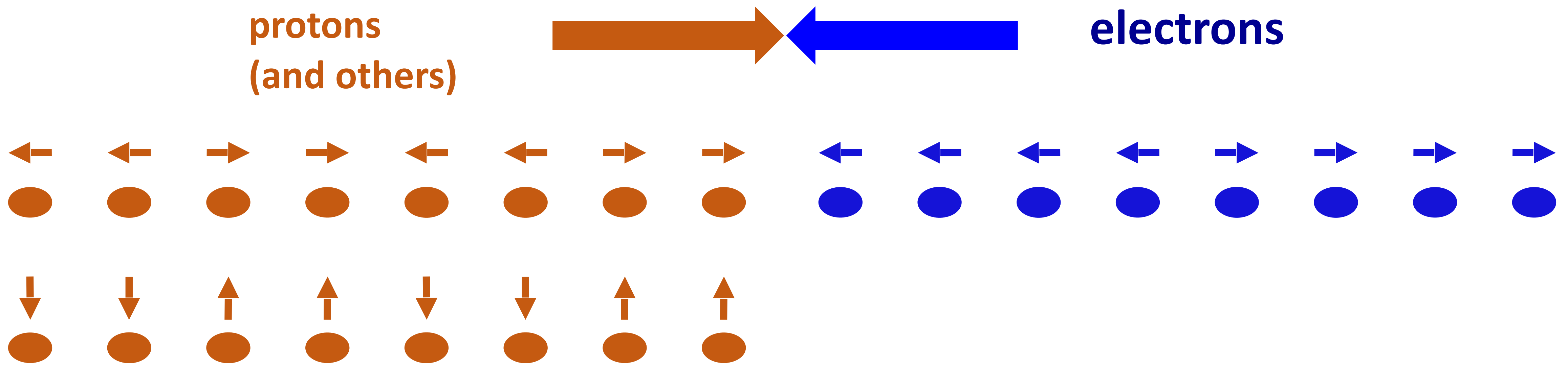
$$\sigma_{\mathrm{mix},L}(+P_e) = \left(\frac{1+P_e}{2}\right)\sigma_L(+) + \left(\frac{1-P_e}{2}\right)\sigma_L(-)$$

- and our measured asymmetry will relate to the pure state asymmetry:

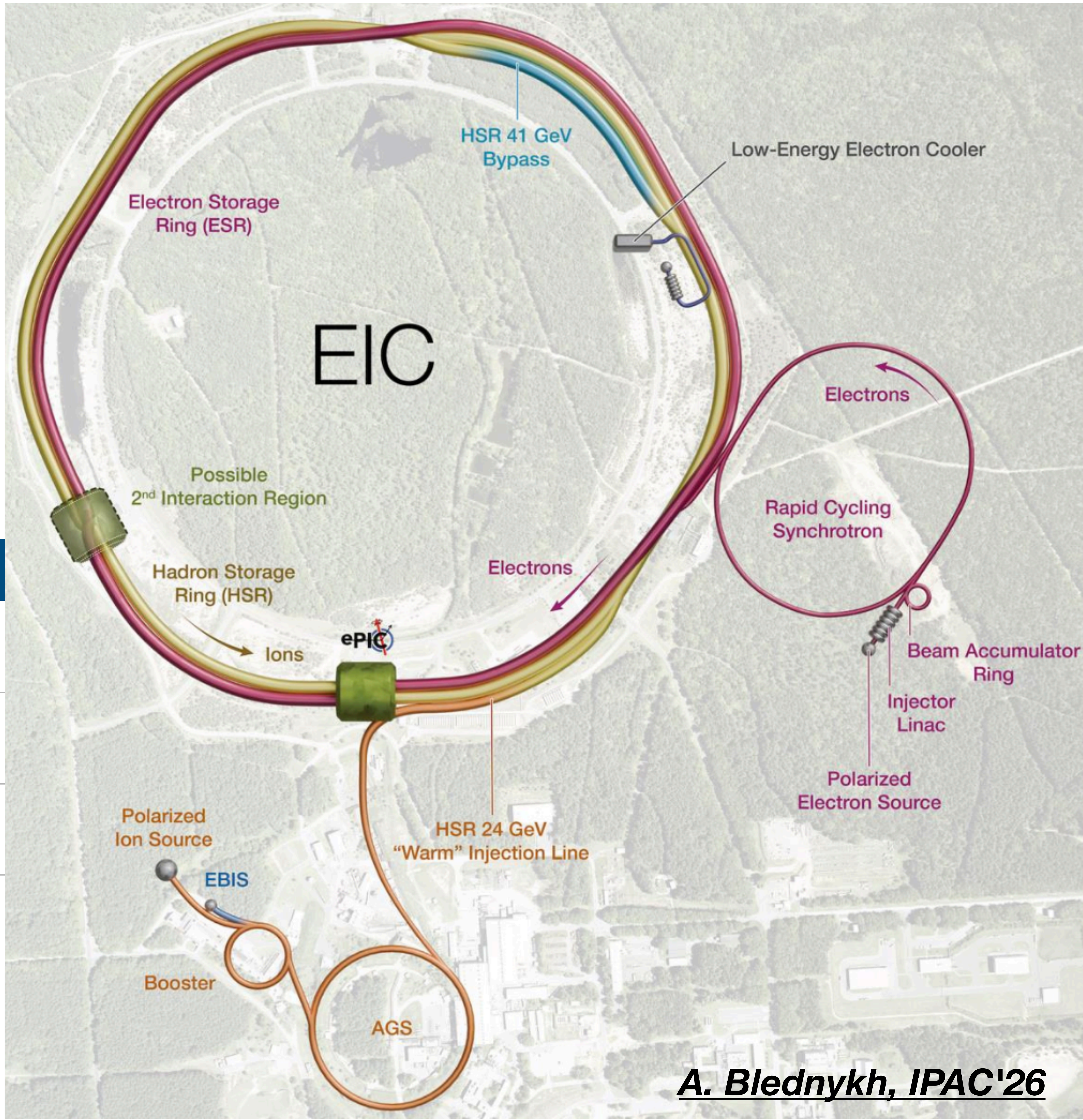
$$A_{\exp} = \frac{P_e\left(\sigma_L(\uparrow) - \sigma_R(\uparrow)\right)}{\sigma_L(\uparrow) + \sigma_R(\uparrow)} = P_e A_y$$

Polarized Beams at EIC

- Electrons: 5-18 GeV
- Protons: 41-275 GeV



Beam	Bunch intensity	injection Pol %	Study	Source	Physics Principle
H^+	2E+11	~80%	low-x proton structure	OPPIS	laser polarize e-, HF transfer to nucleus
$^3He^{++}$	2E+11	>80%	neutron structure	MEOP+EBIS	laser polarize e-, HF transfer to nucleus
d^+	2E+11	~90%	tensor nuclear (s=1) structure	Atomic Beam Source +EBIS	Stern-Gerlach *(not in these slides)*
e^-	*1.7E+11* 6.3E+10	~85%	***everything!***	Polarized Electron Source	Polarized photo-electric effect



A. Blednykh, IPAC'26

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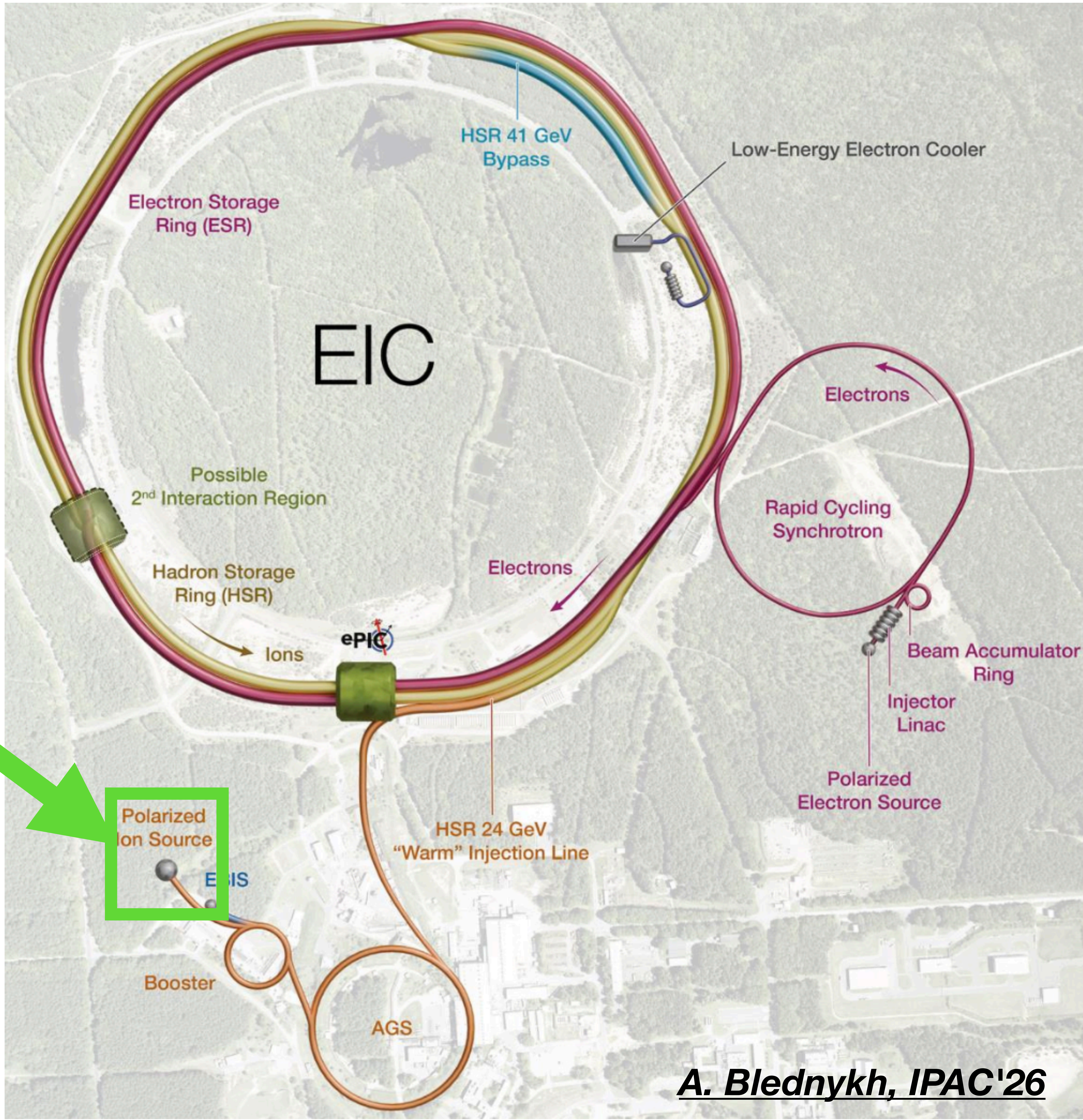
Producing Polarized Protons: OPPIS



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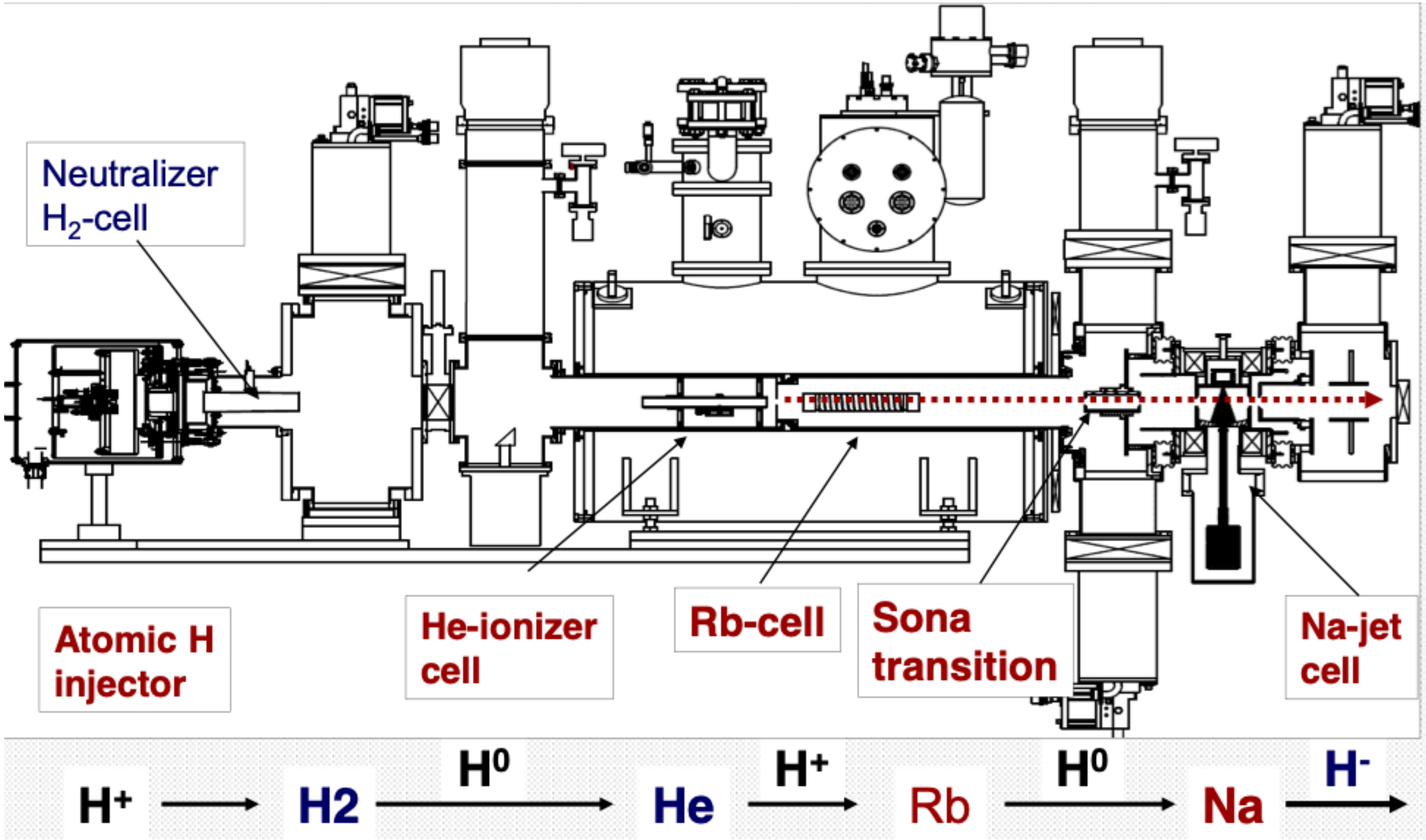
Plan: Transfer the electron spin from Rb atoms to H, and to the nucleus

OPPIS

	STEP	State	Energy (keV)
1	Fast Atomic Beam Source injects beam	H^+	6.5
2	Pass through H_2 to pick up e^-	H^0	6.5
3	Neutral beam enters B without deflection	H^0	6.5
4	Pass through He to strip e^-	H^+	6.5
5	Electrostatic braking	H^+	2.5
6	Pass through Rb to pick up e^-↑	H^0, e↑	2.5
7	Neutral beam exits B without deflection	H^0, e↑	2.5
8	Pass through Sona region to swap ↑ to	H^0↑	2.5
9	Pass through Na cell to pick up e^-	H^-↑	2.5
10	Electrostatic acceleration to ground	H^-↑	35.0



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https://indico.jlab.org/event/663/contributions/13118/

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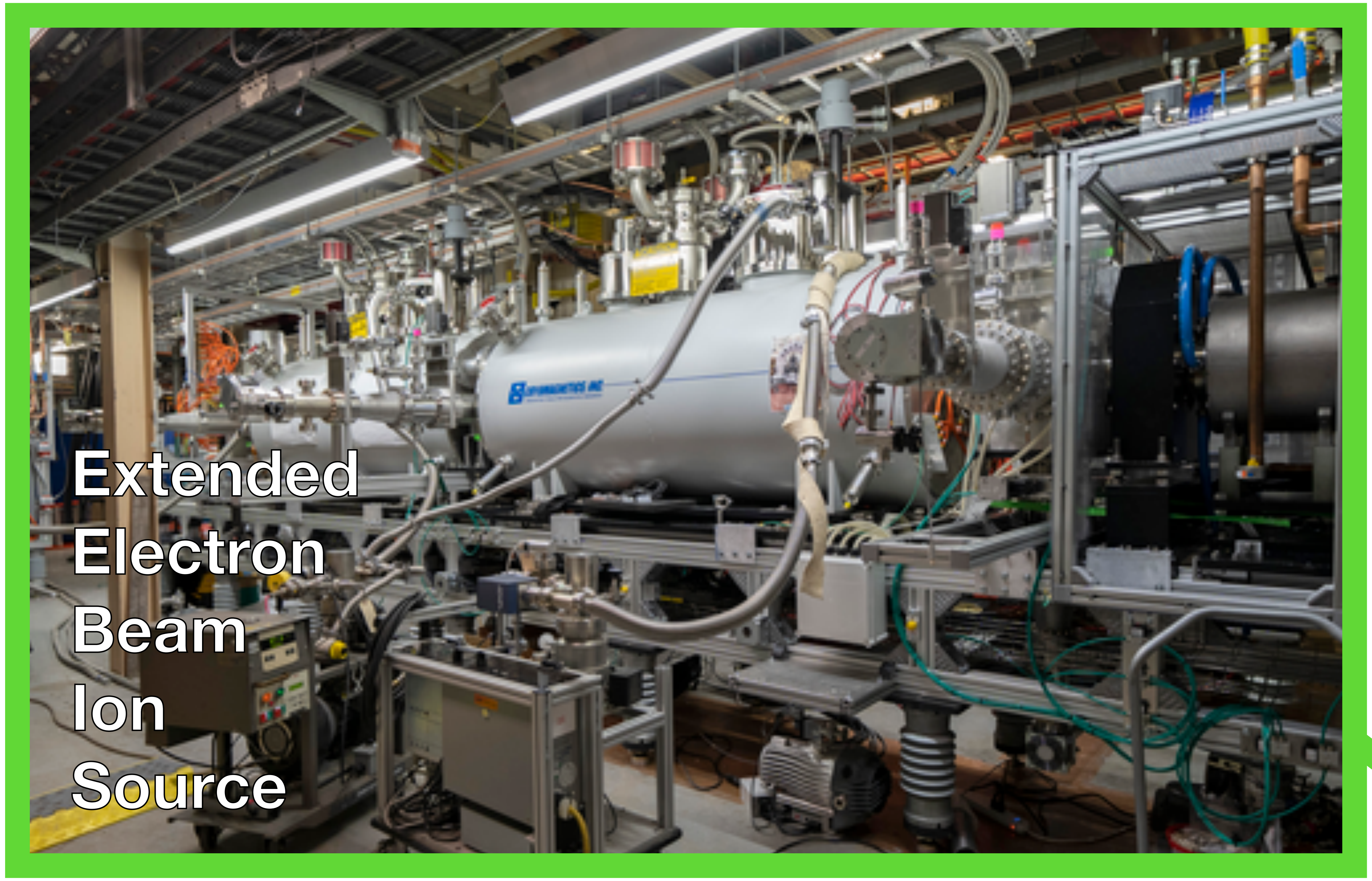
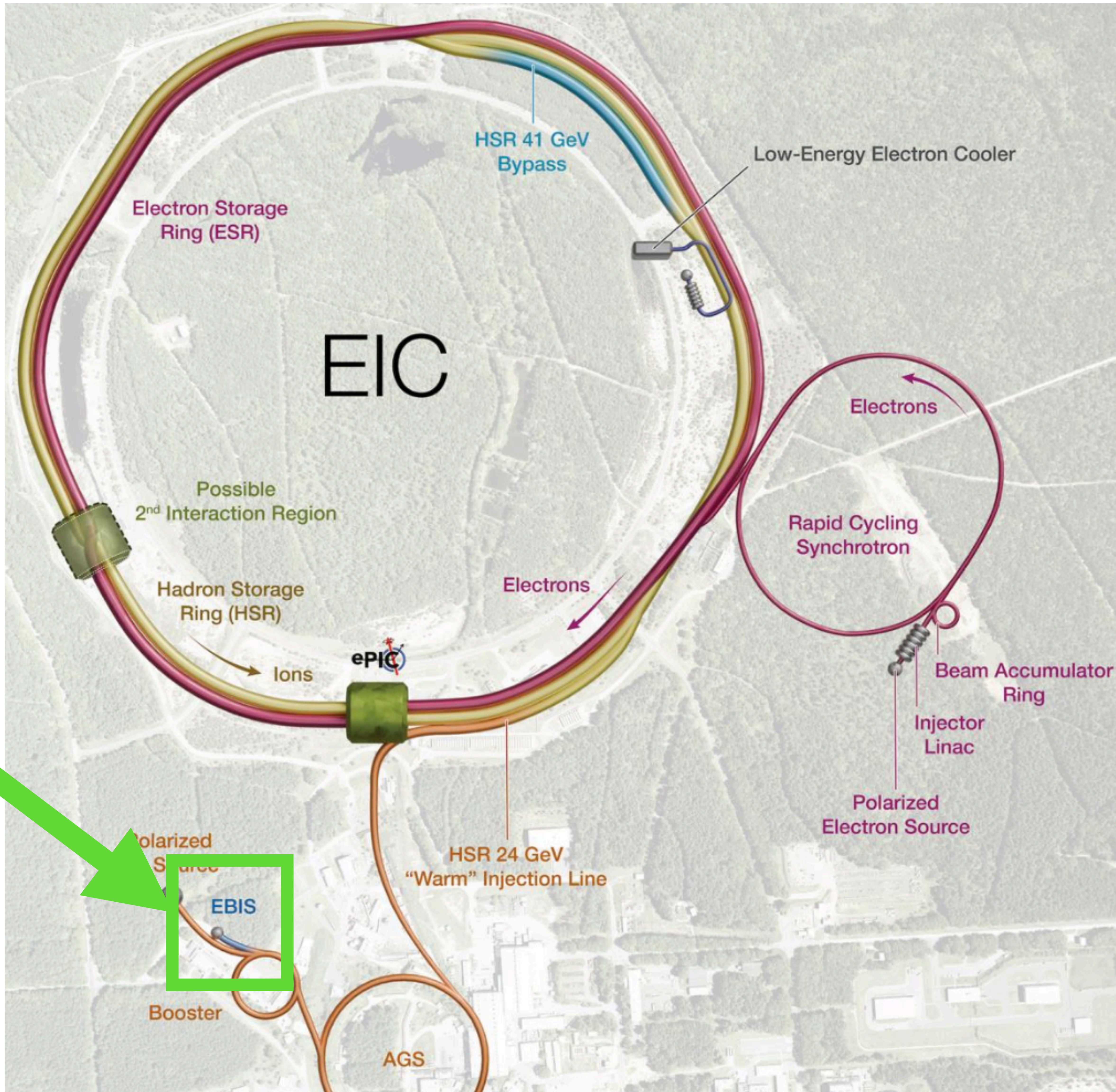
Producing Polarized ^{3}He: EBIS





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Plan: Pump 3He e- to a spin state and let HF transfer it to the nucleus

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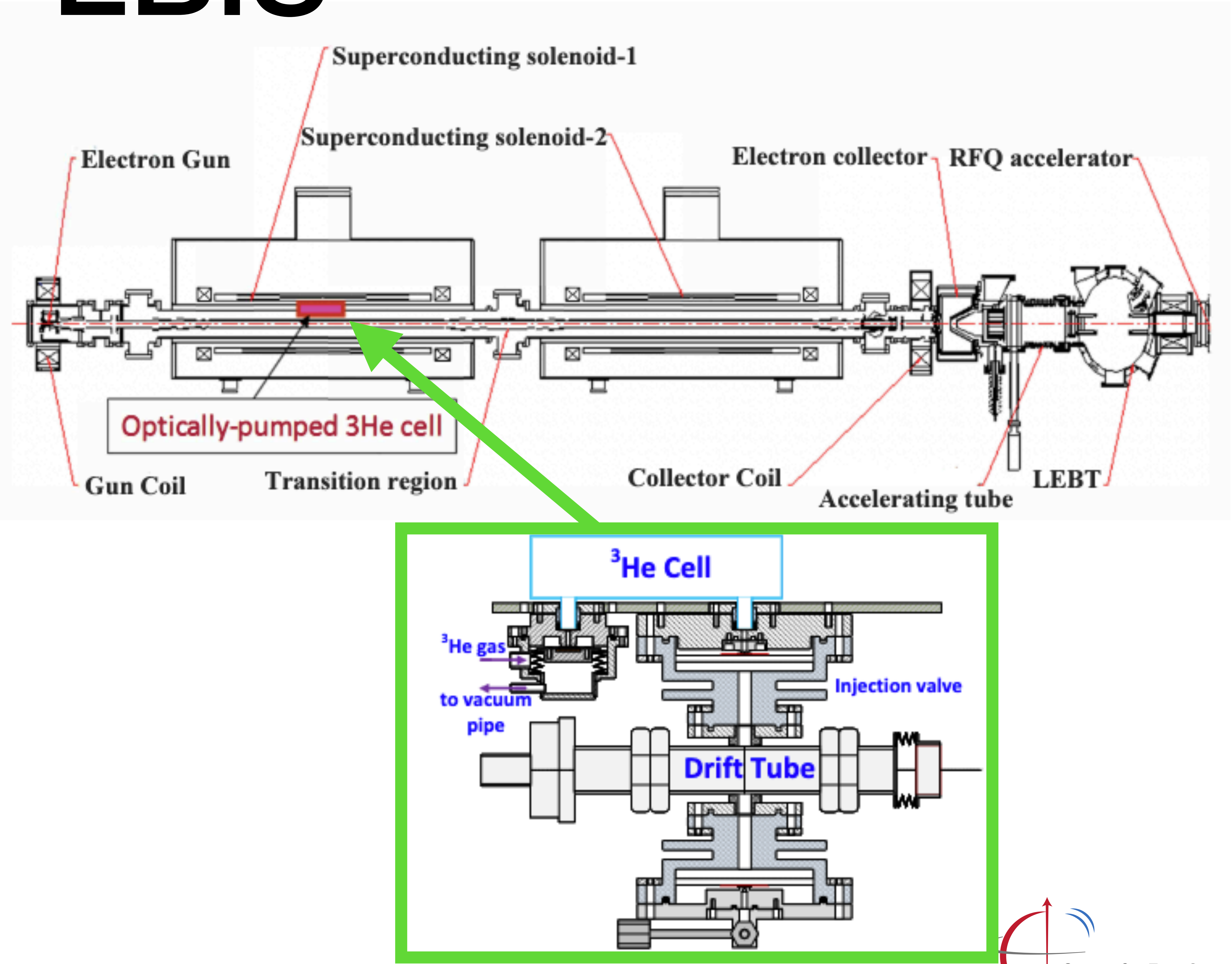
EBIS

	STEP	State	Energy (keV)
1	Bottle provides 10 Torr gas	$^3He^0$	~0
2	MEOP Pumping	$^3He^0\uparrow$	~0
3	Pulsed injection into EBIS (100um aperture)	$^3He^0\uparrow$	~0
4	Contact with 10A e- beam strips e-	$^3He^{++}\uparrow$	~0
5	Collect in longitudinal electrostatic trap	$^3He^{++}\uparrow$	~0
6	Pulsed extraction to injectors	$^3He^{++}\uparrow$	45/ion



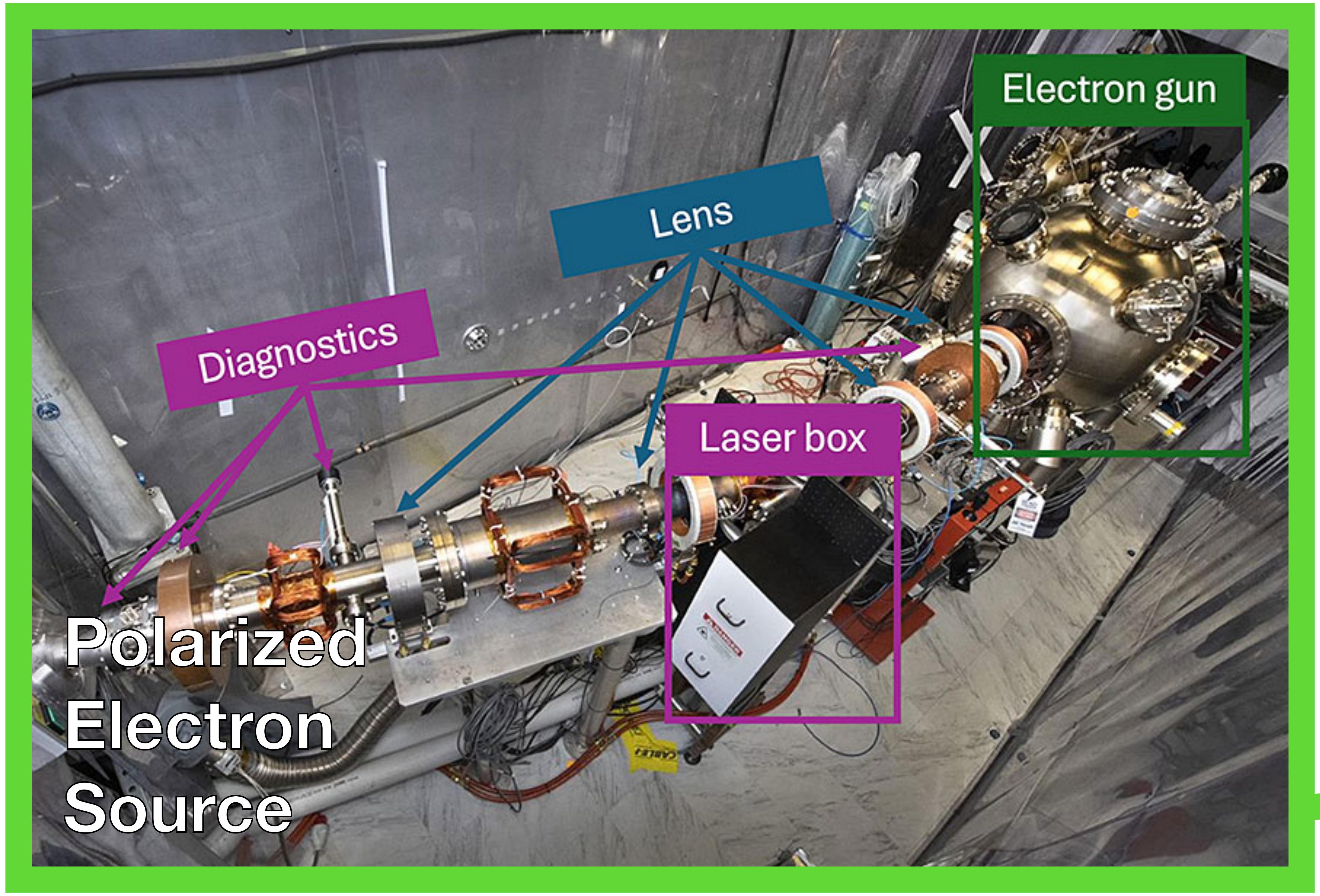
MEOP in EBIS

Metastability-Exchange Optical Pumping:

- Strong field (5T) separates m_F+3/2 levels. Laser can address individual pairssplitting out of laser bandwidth
- Metastable+ground collisions exchange entire electronic shell

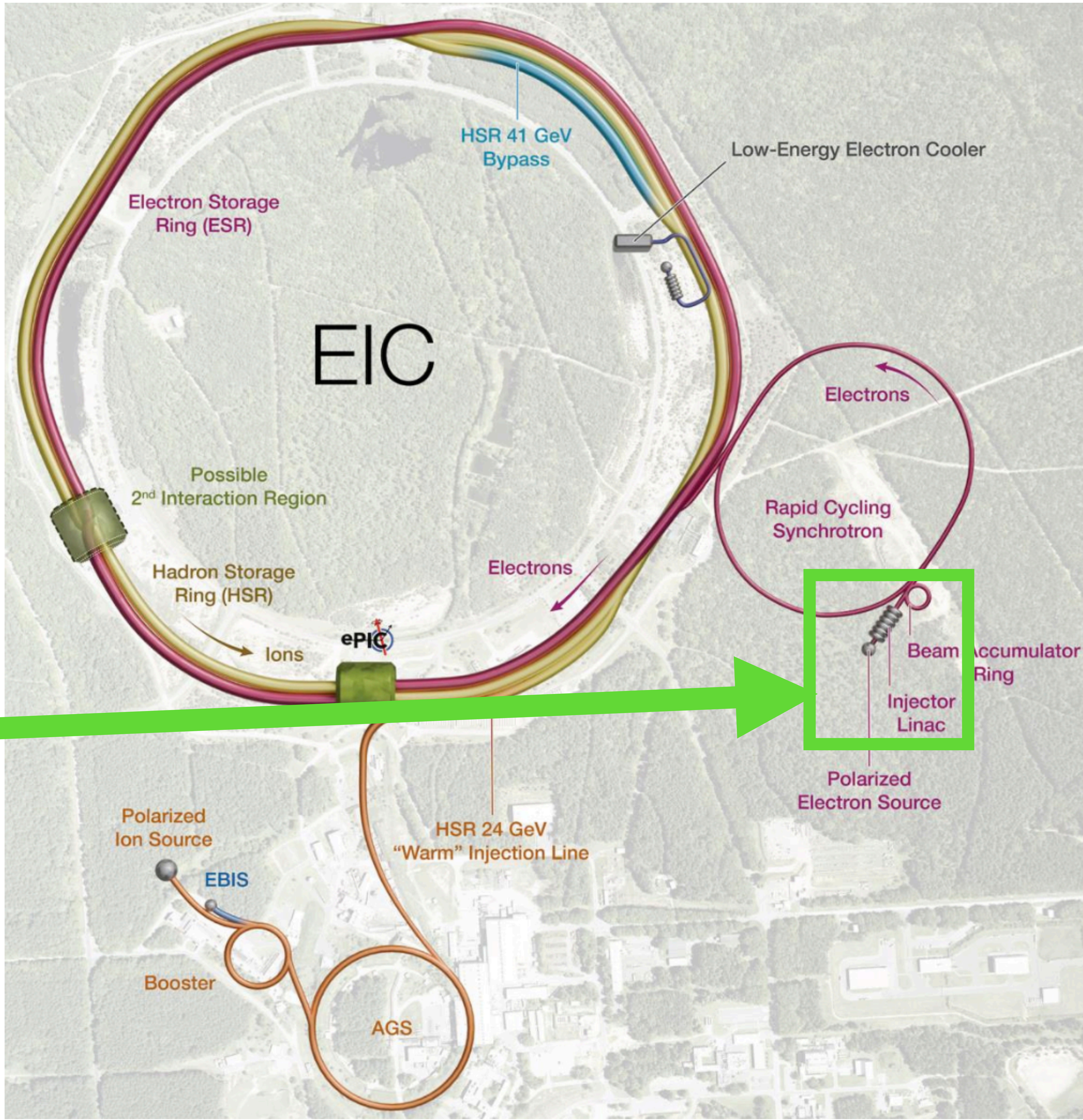
	Interaction	State		State
1	RF Plasma Ionization (e-)	$\vert\tfrac{1}{2},M_n\rangle\vert 00\rangle\vert 00\rangle$	$\Rightarrow$	$\vert\tfrac{1}{2},M_n\rangle\vert 00\rangle\vert 1M_s\rangle$
2	HF Mixing (m_F=+½)	$\vert\tfrac{1}{2},-\tfrac{1}{2}\rangle\vert 00\rangle\vert 11\rangle$	$\Leftrightarrow$	$\vert\tfrac{1}{2},+\tfrac{1}{2}\rangle\vert 00\rangle\vert 10\rangle$
3	HF Mixing (m_F=-½)	$\vert\tfrac{1}{2},+\tfrac{1}{2}\rangle\vert 00\rangle\vert 1\text{-}1\rangle$	$\Leftrightarrow$	$\vert\tfrac{1}{2},-\tfrac{1}{2}\rangle\vert 00\rangle\vert 10\rangle$
4	IR pumping (m_F=+5/2)	$\vert\tfrac{1}{2},+\tfrac{1}{2}\rangle\vert 00\rangle\vert 10\rangle$	$\Rightarrow$	$\vert\tfrac{1}{2},+\tfrac{1}{2}\rangle\vert 11\rangle\vert 11\rangle$
5	IR pumping (m_F=+3/2)	$\vert\tfrac{1}{2},-\tfrac{1}{2}\rangle\vert 00\rangle\vert 10\rangle$	$\nRightarrow$	$\vert\tfrac{1}{2},-\tfrac{1}{2}\rangle\vert 11\rangle\vert 11\rangle$
	Spont. Fluorescent Decay	$\vert\tfrac{1}{2},M_n\rangle\vert 11\rangle\vert 1M_s\rangle$	$\Rightarrow$	$\vert\tfrac{1}{2},M_n\rangle\vert 00\rangle\vert 1M_s\rangle$
6	*(in particular)*	$\vert\tfrac{1}{2},+\tfrac{1}{2}\rangle\vert 11\rangle\vert 11\rangle$	$\Rightarrow$	$\vert\tfrac{1}{2},+\tfrac{1}{2}\rangle\vert 00\rangle\vert 11\rangle$
7	*(and the -½)*	$\vert\tfrac{1}{2},-\tfrac{1}{2}\rangle\vert 11\rangle\vert 11\rangle$	$\Rightarrow$	$\vert\tfrac{1}{2},-\tfrac{1}{2}\rangle\vert 00\rangle\vert 11\rangle$
	Metastability Exchange	$\vert\tfrac{1}{2},M_n\rangle\vert 00\rangle\vert 1M_s\rangle$	$\Rightarrow$	$\vert\tfrac{1}{2},M_n\rangle\vert 00\rangle\vert 00\rangle$
8	*(in particular)*	$\vert\tfrac{1}{2},+\tfrac{1}{2}\rangle\vert 00\rangle\vert 11\rangle$	$\Rightarrow$	$\vert\tfrac{1}{2},+\tfrac{1}{2}\rangle\vert 00\rangle\vert 00\rangle$
9	*(and the -½)*	$\vert\tfrac{1}{2},-\tfrac{1}{2}\rangle\vert 00\rangle\vert 11\rangle$	$\Rightarrow$	$\vert\tfrac{1}{2},-\tfrac{1}{2}\rangle\vert 00\rangle\vert 00\rangle$

Producing Polarized Electrons: PES



*Actually, this was taking in the basement of this building

Plan: Use a strong laser and an complex cathode to directly produce $e^{-}\uparrow$



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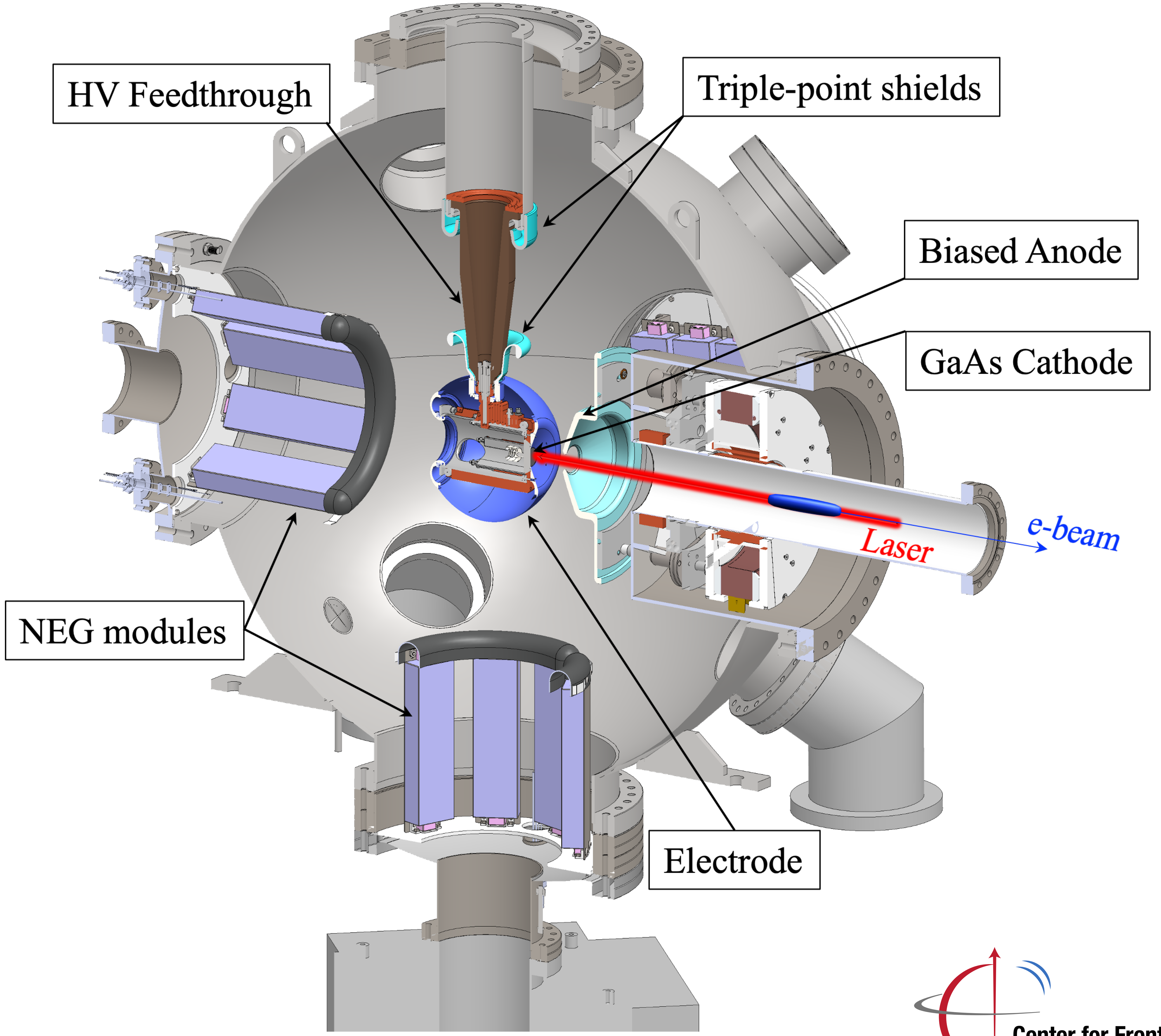
Polarized Electron Source

	STEP	State	Energy (keV)
1	Strained GaAs photocathode provides e^- in split valence band	e (bound)	~0
2	Circularly polarized IR laser excites only one spin state to conduction band	e^-↑ (conduction)	~0
3	Mobile electrons diffuse to surface	e^-↑ (surface)	~0
4	...and emit into the vacuum	e^-↑	~0
5	Electrostatic acceleration toward Anode	e^-↑	320.0
6	Wien Filters adjust spin orientation	e^-↑	320.0
7	Bunching and extraction to the Pre-Injector Linac	e^-↑	320.0



The Strained GaAs Photocathode

- Structured crystal to help the electrons escape
- but also to improve photon quantum efficiency!

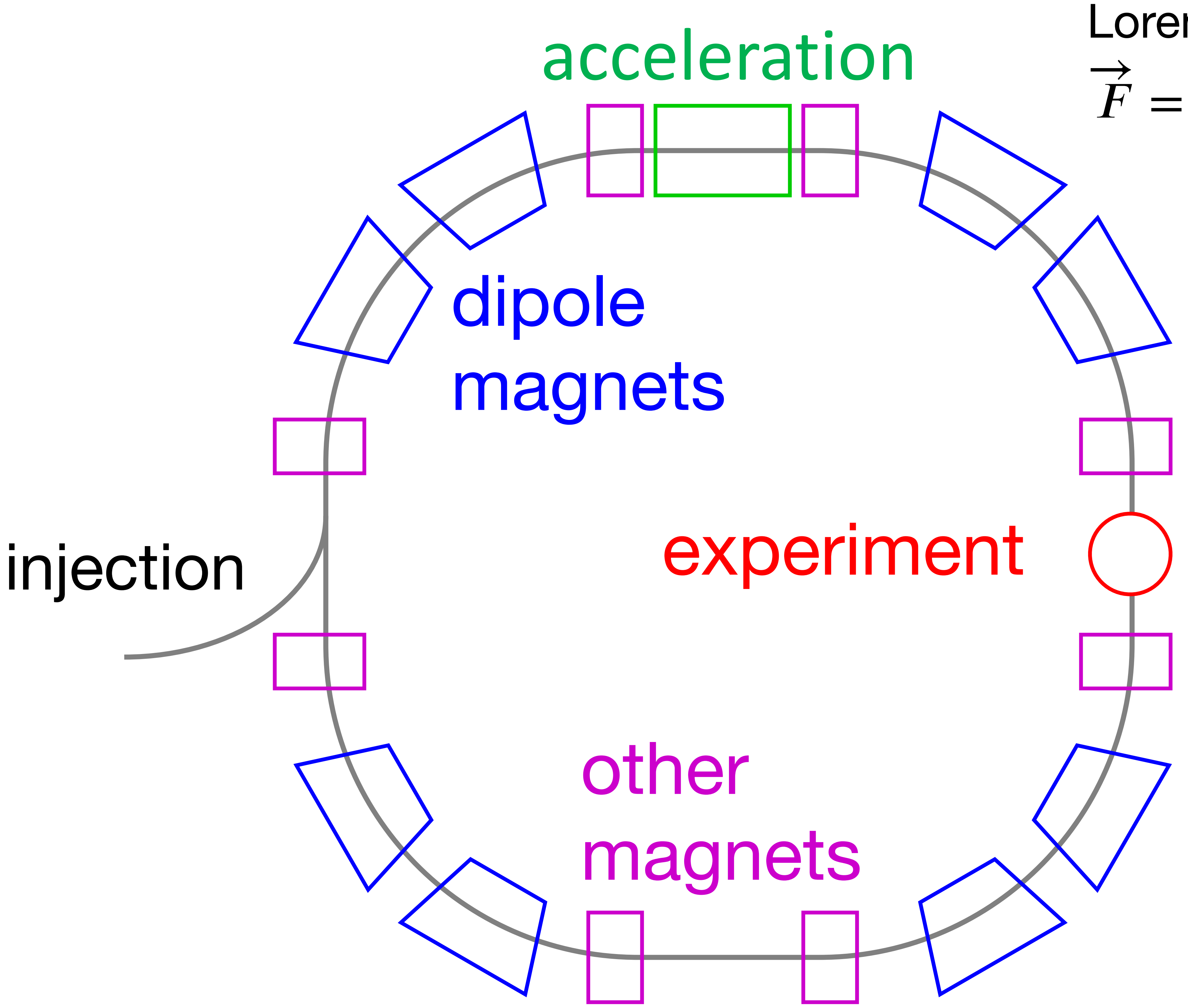
IR Photons

Purpose	Layer	Thickness	p-Doping
Negative Electron Affinity	Cs or other		
Highly doped layer slopes energy bands down in this direction	GaAs	5nm	5×10^{19} /cm^3
Superlattice layers mechanically strain each other. **e- excited in uniform spin state**	GaAs/GaAsP	(3.8/2.8 nm) ×14	5×10^{17} /cm^3
Tuned spacing to set up Fabry-Perot resonance	$GaAs_{0.65}P_{0.35}$	750nm	5×10^{18} /cm^3
"**Distributed Bragg Reflector**": tuned to reflect the IR laser	GaAsP/AlInP	(54/64 nm) ×12	5×10^{17} /cm^3
Stable block with desired spacing	$GaAs_{0.65}P_{0.35}$	2.5um	5×10^{18} /cm^3
Step slowly toward the spacing of our desired material w/ more P (x=0→x=0.35)	Graded $GaAsP_x$	6um	5×10^{18} /cm^3
Flatten the substrate	GaAs	500nm	2×10^{18} /cm^3

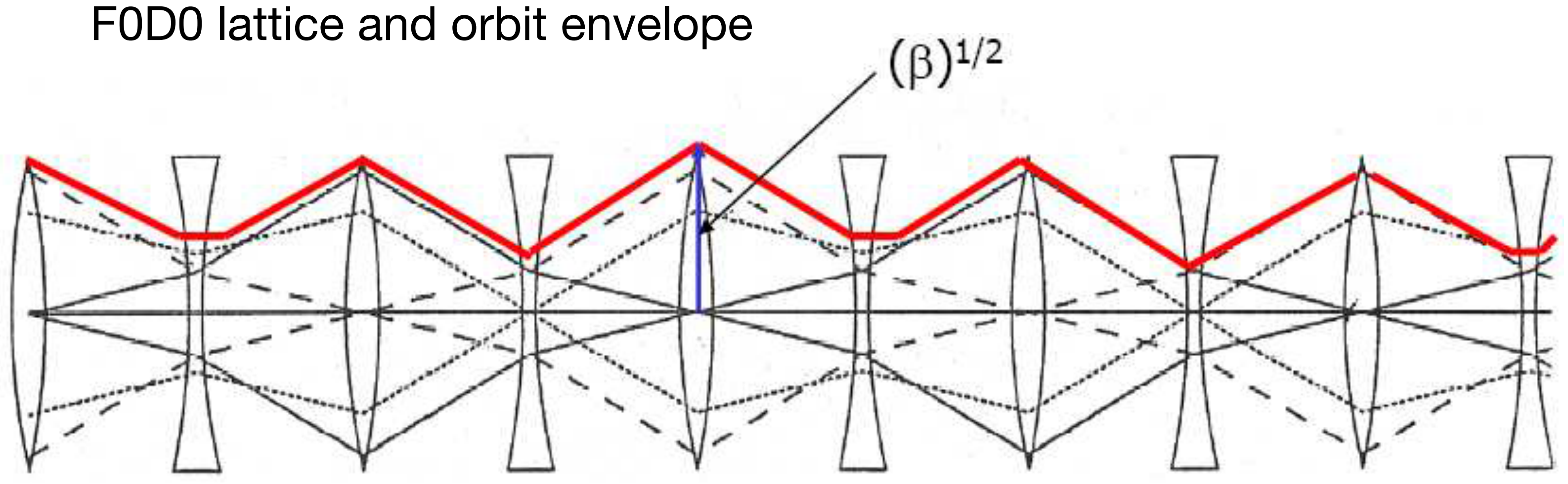
Keeping Beams

- We need to keep the particles in a closed orbit.
- Beam has a size and momentum spread.
- Particles oscillate around the closed orbit (betatron oscillation).
- FODO: Focus-drift-Defocus-drift to keep the beam in an envelope (Can't magnetically focus in both axes at once)

Lorentz Force:
$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B})$



F0D0 lattice and orbit envelope

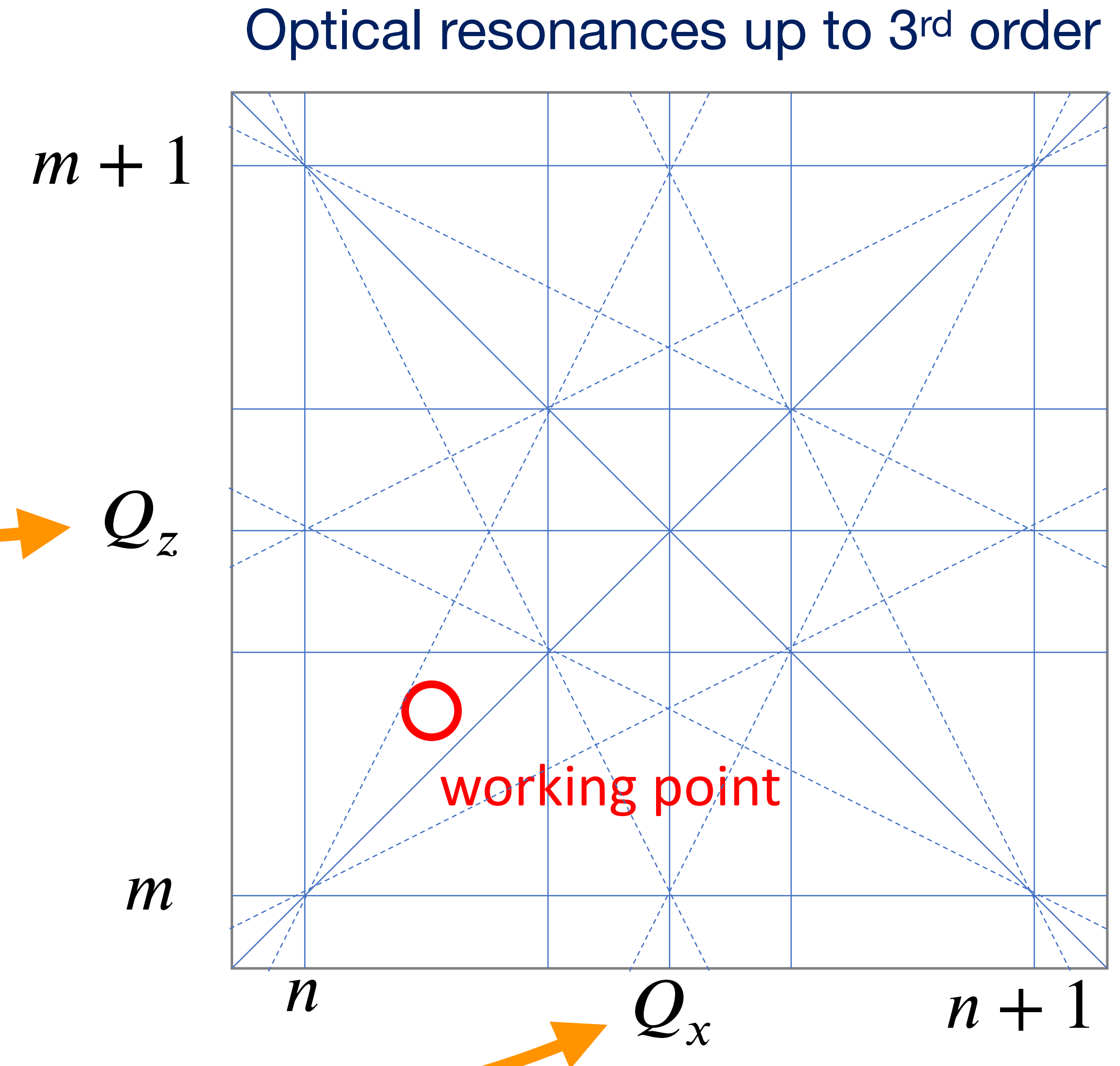


Keeping Beams

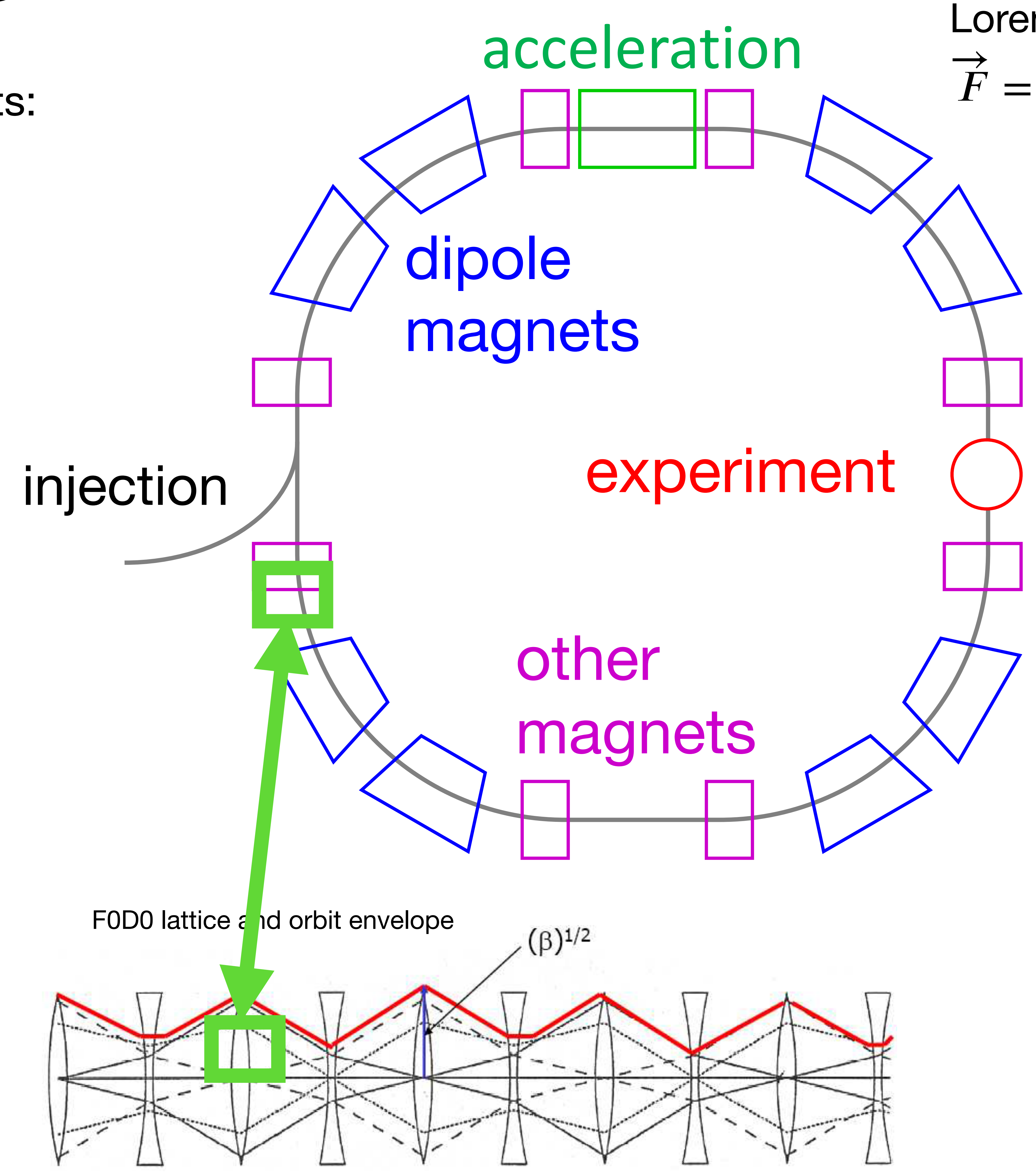
- We want to avoid getting into a beat pattern with magnetic defects:
  - Beam particles should not be in the same transverse position each time they pass the defect
  - Nor every nth time. Nor should their x and z positions be correlated.
  - Avoid integers m,n,p: $$mQ_x + nQ_z = p$$

Vertical Tune: How many vertical oscillations in one lap

Horizontal Tune



Lorentz Force:
$$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B})$$



Adapted from Frank Rathman's CFNS 2024 Summer School slides

Keeping Polarized Beams

- Magnetic moment *S* precesses per orbit (and so does the beam velocity vector):

$$\frac{d\vec{S}}{dt} = -\left(\frac{e}{\gamma m}\right)\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel}\right] \times \vec{S}$$

$$\frac{d\vec{v}}{dt} = -\left(\frac{e}{\gamma m}\right)\vec{B} \times \vec{v}$$

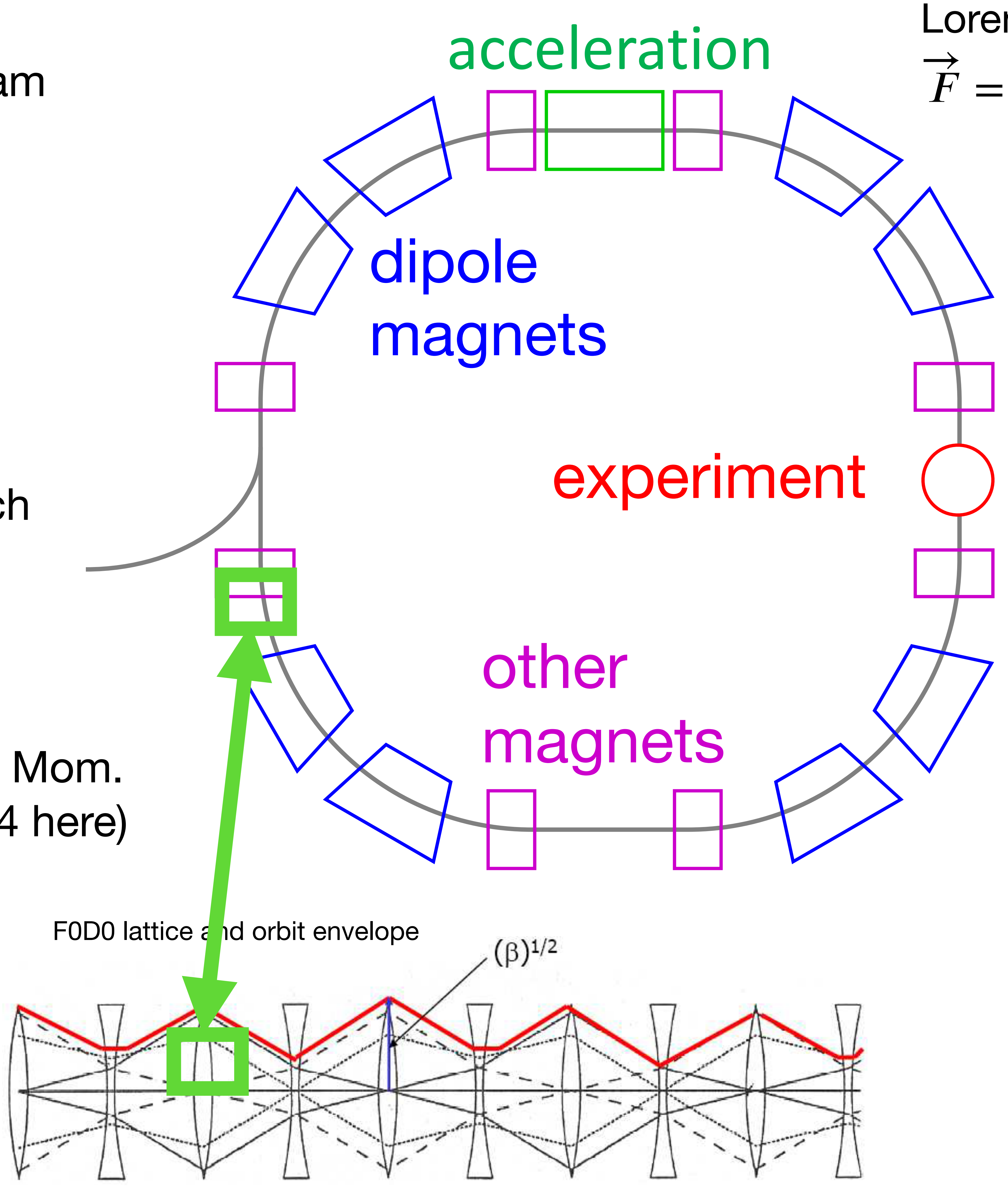
- Beam particles should not be in the same *spin orientation* each time they pass the defect
- 'Flat' spin tune is not tunable: $Q_s = \gamma G$

Imperfection: $\gamma G = k$

Intrinsic: $\gamma G = kP \pm Q_z$

G: Anomalous Mag. Mom.
P: Ring Periodicity (4 here)
γ: (relativistic γ)
k: an integer

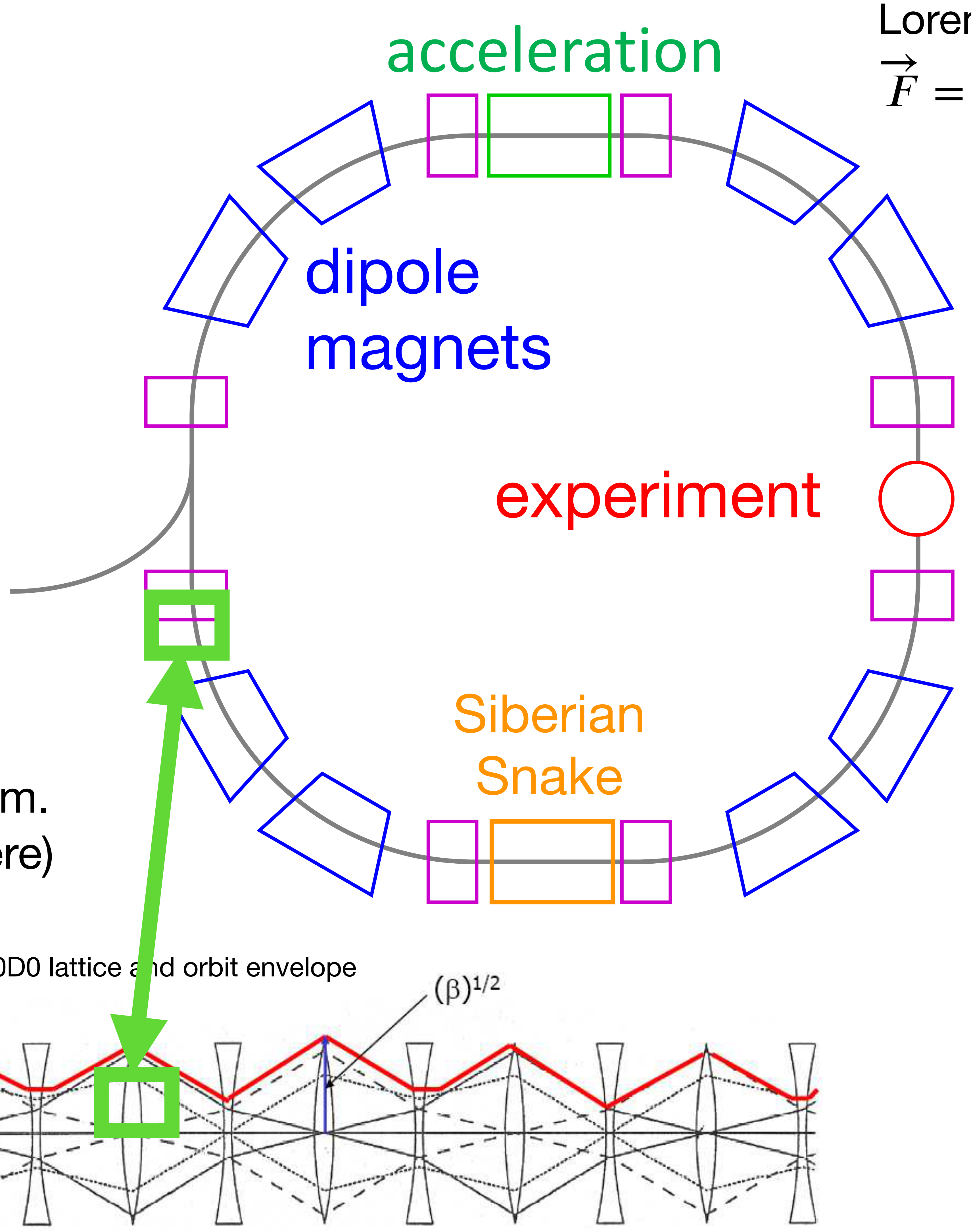
Lorentz Force:
$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B})$



Keeping Polarized Beams

- 'Flat' spin tune is not tunable: $Q_s = \gamma G$
- Intrinsic: adjust Qz when we get near a resonance
- Imperfection? Manually precess the spin with a Siberian Snake

Lorentz Force:
$\vec{F} = e(\vec{E} + \vec{v} \times \vec{B})$



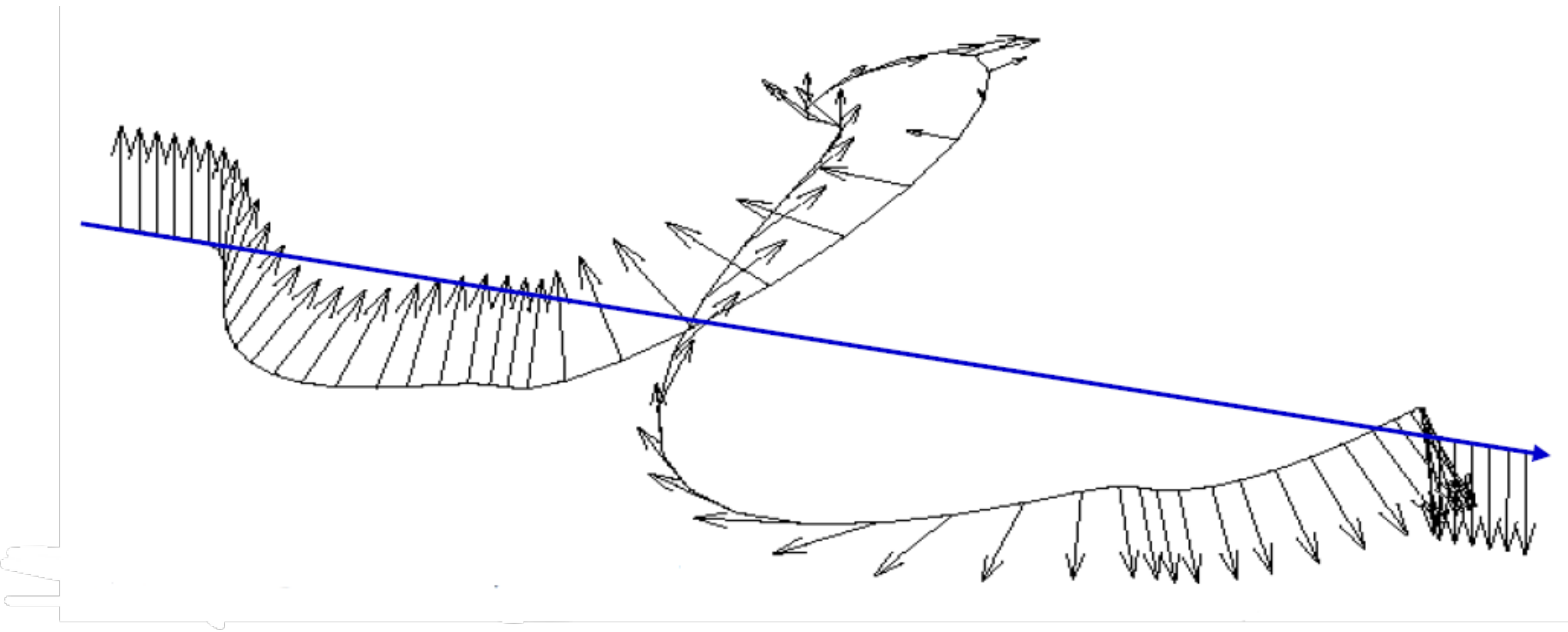
Imperfection: $\gamma G = k$

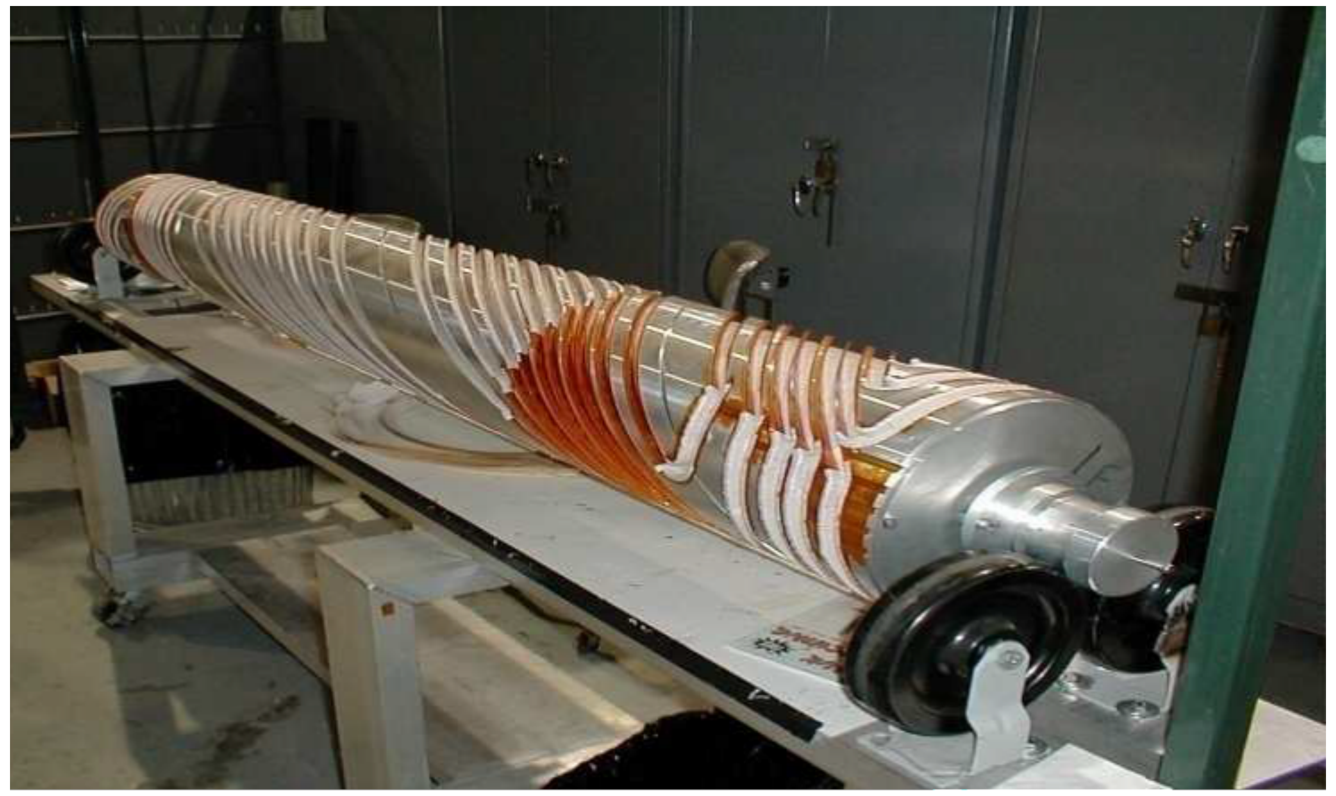
Intrinsic: $\gamma G = kP \pm Q_z$

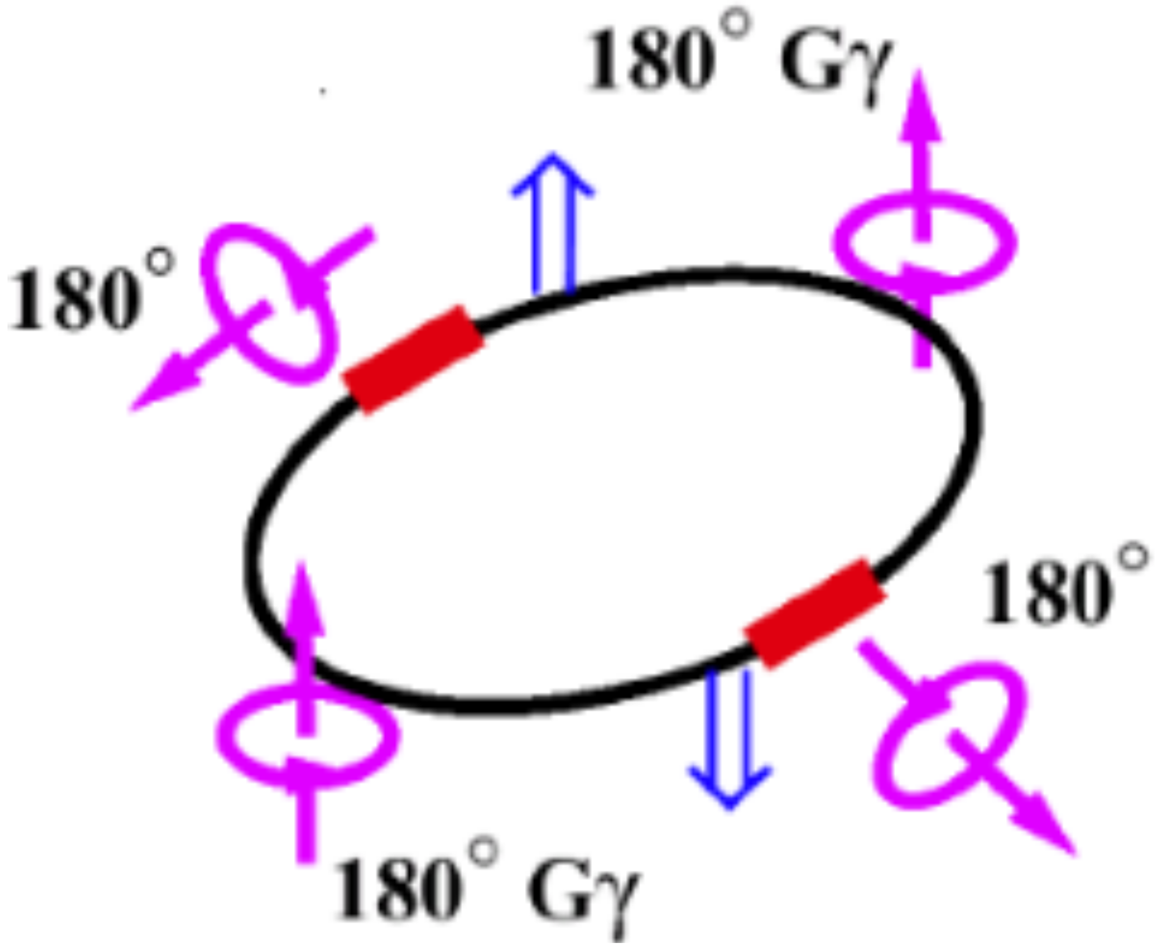
G: Anomalous Mag. Mom.
P: Ring Periodicity (4 here)
γ: (relativistic γ)
k: an integer

Siberian Snake

- Set of dipoles with alternating field directions rotates the spin vector 180°
- Oversimplified: Precession flips sign each time it goes through, so all resonances cancel out
- Paired: We need a pair, one in s, one in x (with dipole in y)
- Better: At high E, resonances accumulate within a ring period. Use multiple pairs, so that we pass through them faster than the betatron tunes.





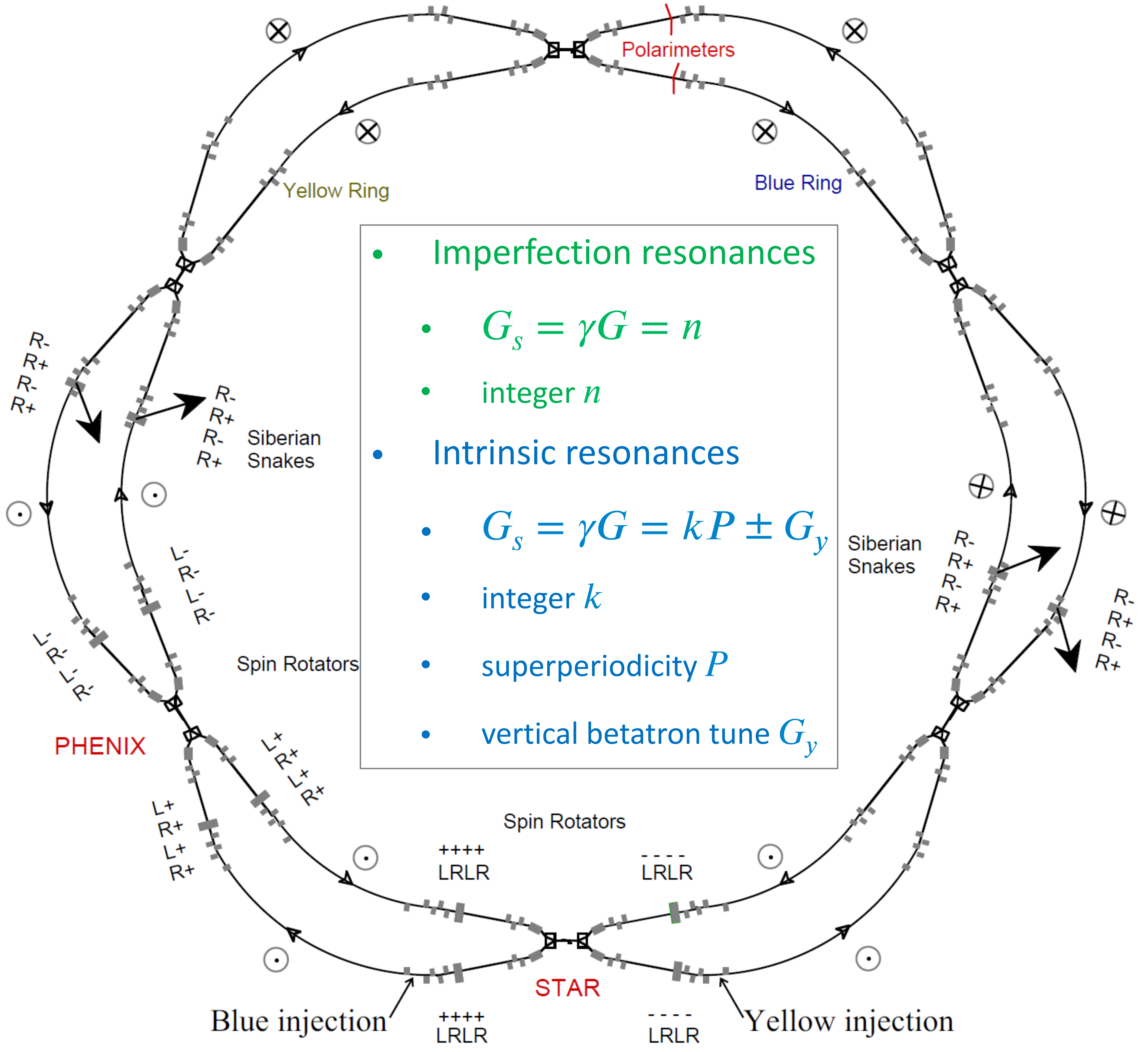


$$Q_s = \frac{1}{\pi} |\phi_1 - \phi_2| = \frac{1}{2}$$

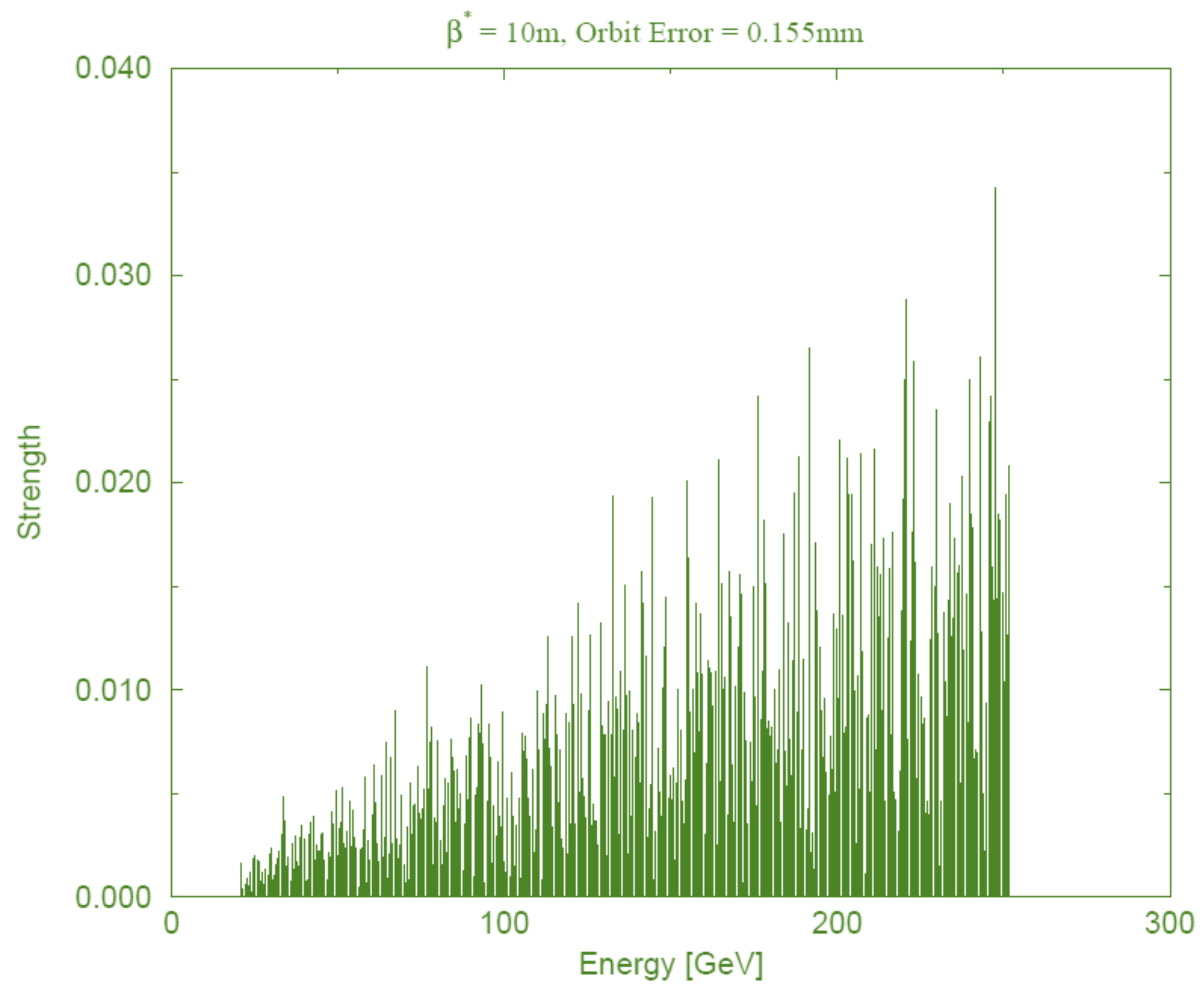
$$\phi_1 = 0 \quad \phi_2 = 90^\circ$$

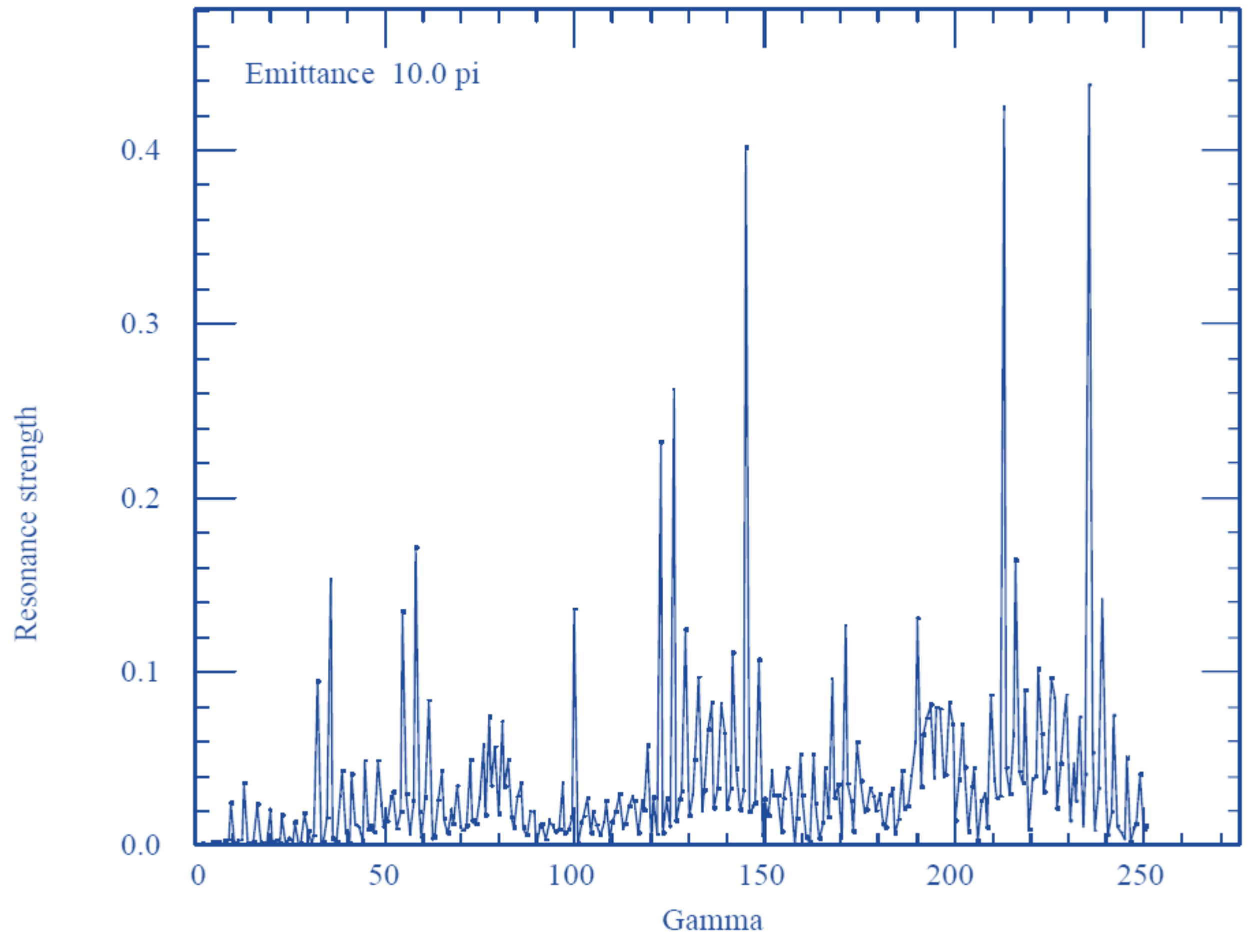
Siberian Snakes: Ya. S. Derbenev, A.M. Kondratenko "Polarization kinematics of particles in storage rings." Sov. Phys. JETP 37 (1973)

Spin Resonances in RHIC



- Imperfection resonances
  - $G_s = \gamma G = n$
  - integer n
- Intrinsic resonances
  - $G_s = \gamma G = kP \pm G_y$
  - integer k
  - superperiodicity P
  - vertical betatron tune G_y

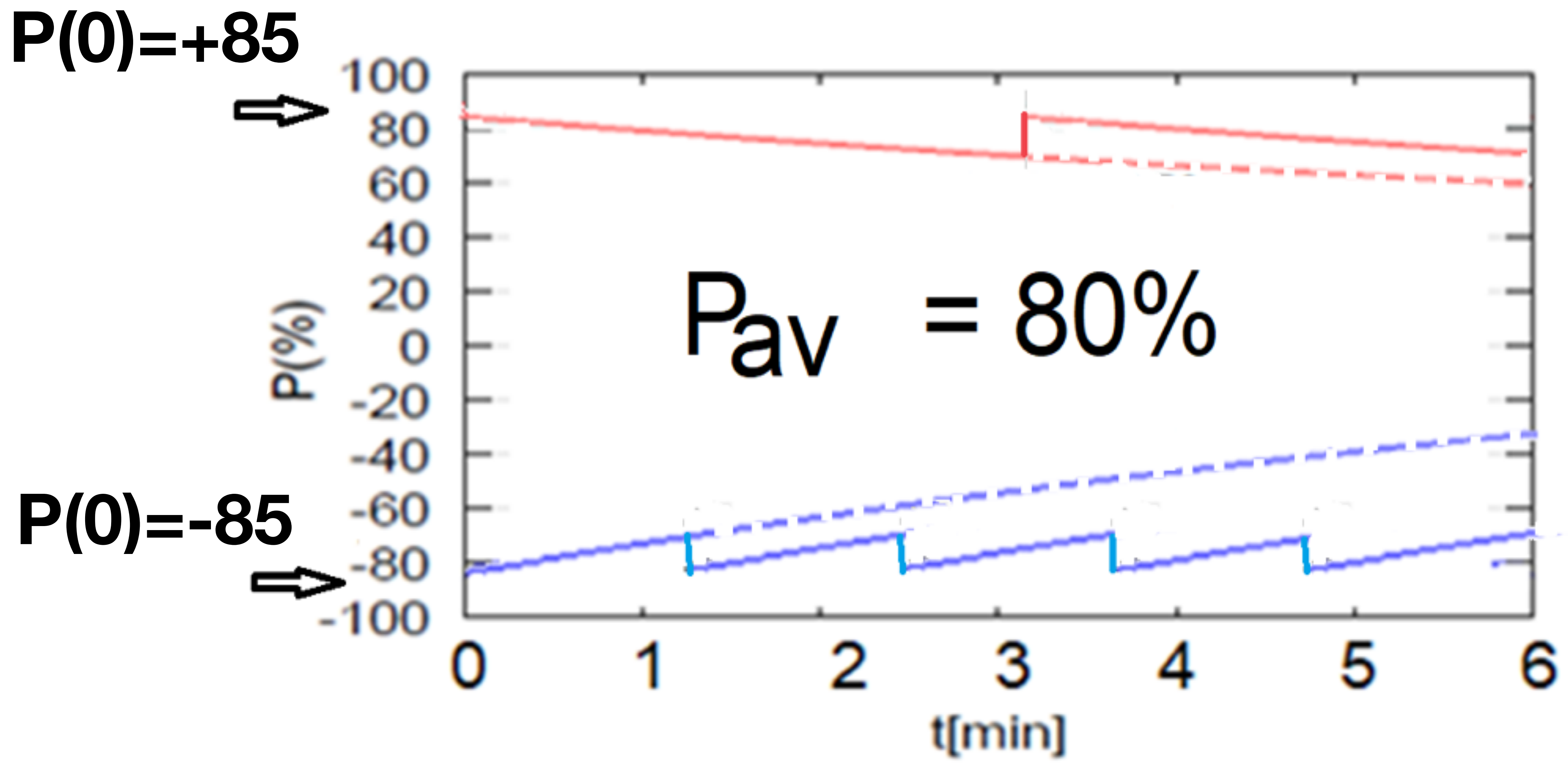




Adapted from Frank Rathman's CFNS 2024 Summer School slides

Keeping Polarized Electrons

- **Static Tune**: Fixed E, so design spin and vertical tune to avoid all resonances
- **Stochastic Depolarization**: Electrons emit random synchrotron light $P \propto E^4/\rho$
- (Siberian Snakes won't work. The deflections are nondeterministic, so we can't invert them.)
- Re-inject individual bunches at ≲1Hz (but two spin states do not decay equally)



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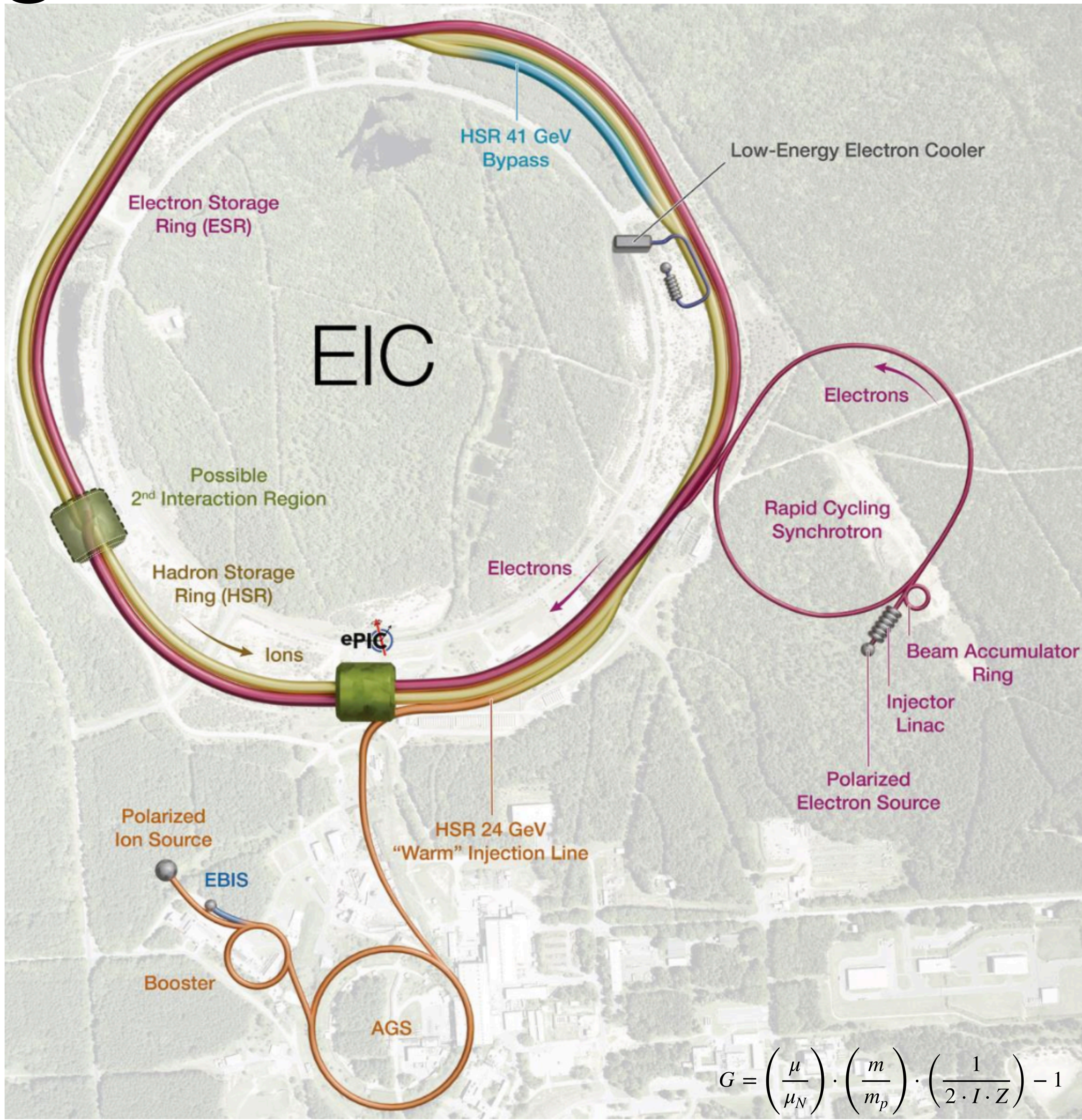
Polarization Management at EIC

Species	G	max |Gγ|	No. of Resonances
p	1.7928	525	1575
D	-0.1430	21	63
$^3He^{2+}$	-4.1842	819	2457
$^6Li^{3+}$	-0.1818	27	81
$^7Li^{3+}$	1.5196	191	573
e	0.0011		0

- Six Siberian Snakes (one in each side of the hexagon) to maintain $Q_s = 1/2$ at all E.
- Polarimeters operate during ramp and across full energy ranges ($50GeV<E_p<275GeV$), ($5GeV<E_e<18GeV$)
- Polarimeters in booster stages to track evolution
- Polarimeters at experimental hall



$$G = \left(\frac{\mu}{\mu_N}\right)\cdot\left(\frac{m}{m_p}\right)\cdot\left(\frac{1}{2\cdot I\cdot Z}\right) - 1$$

EIC Polarimetry Requirements

Conditions:

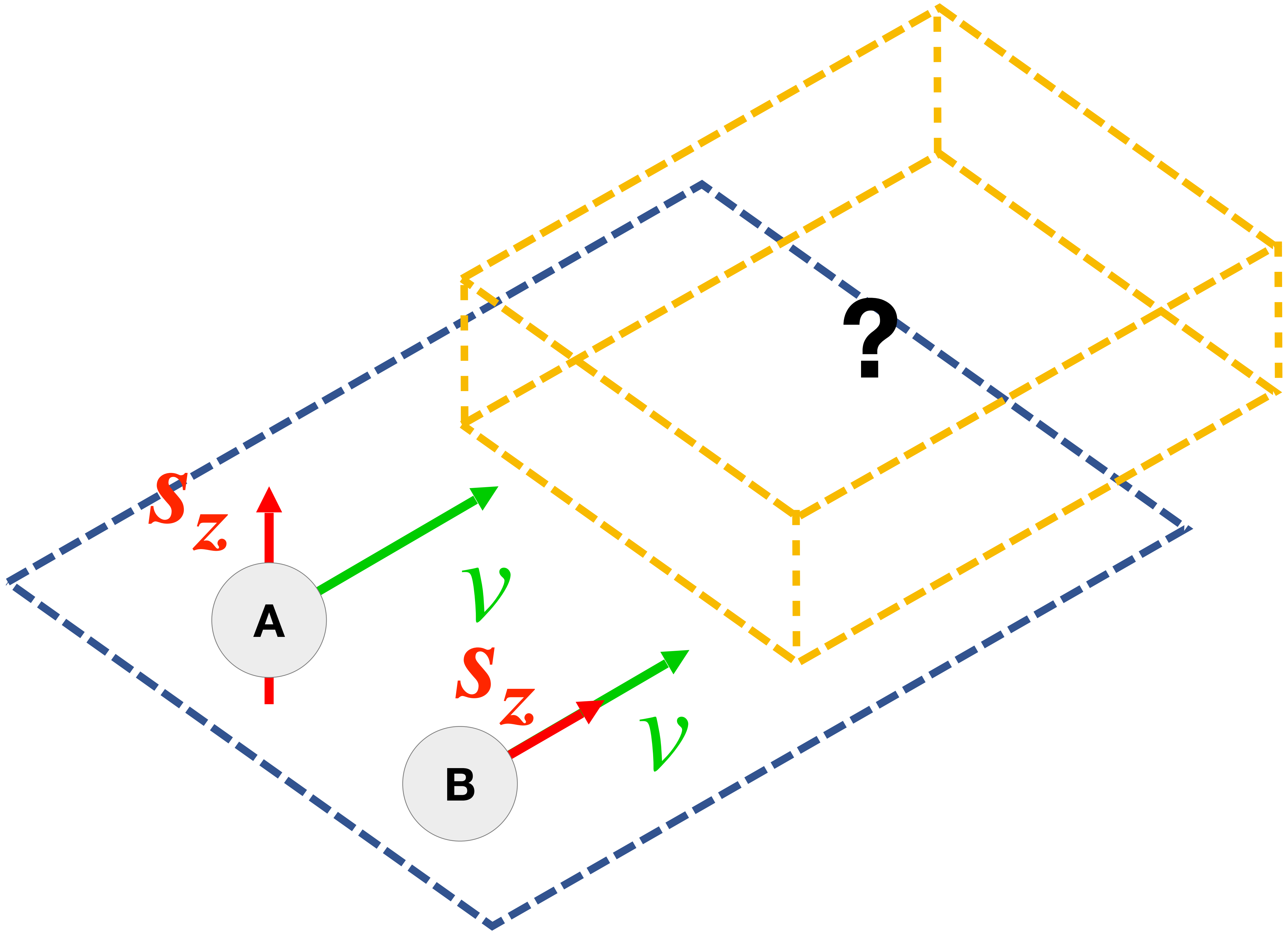
- Measure electron beam polarization 5GeV<E_e<18GeV.
- Measure proton beam polarization 50GeV<E_p<275GeV.
- Each store may be 8 hours long.
- Polarimetry should be non-destructive.
- The beams are bunched and will have alternating polarization states to reduce time-dependent systematic uncertainties.
- Bunch spacing is around 10ns (about 1300 bunches in each ring).

Measure:

- Absolute beam polarization w/ $\Delta P/P \approx 1\,\%$
- Time-dependence (polarization decay)
- Bunch-by-bunch polarization
- Polarization profile of bunches
- Polarization during ramp (acceleration)
- Polarization vector at experiment

Measuring Polarization

- So. We need a detector that can take a group of particles in and tell us how many are spinning one way vs another.
  - A? B?
- What interactions could we use?
- What detectors would we need?
- (We need a non-destructive measurement, but that can mean just 'don't interact with too many')



Measuring Transverse Polarization

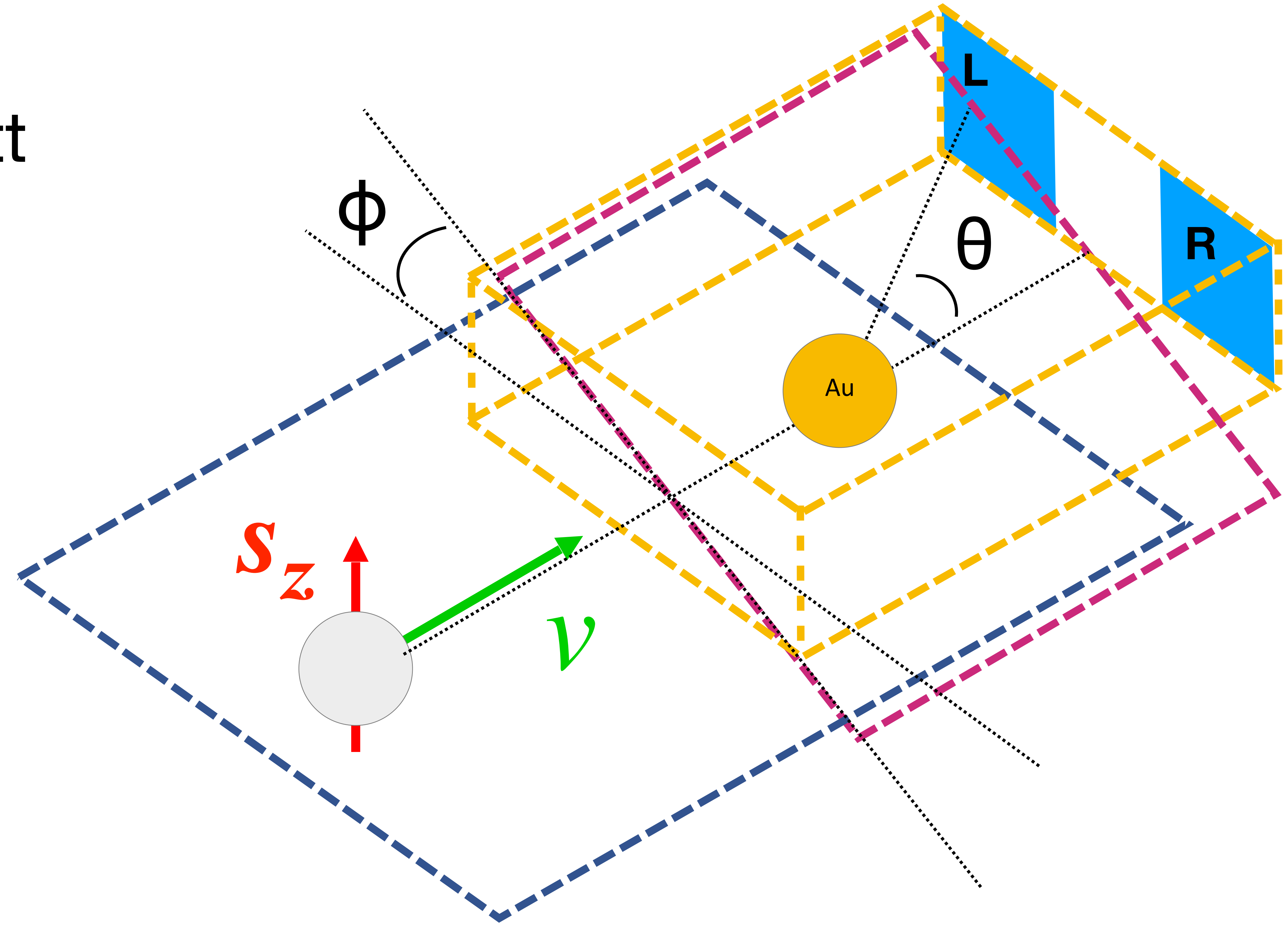
- We need a spin-dependent interaction. Mott Scattering has a spin term:

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \sigma_{\text{Mott},0}(\theta)\left(1 + S(\theta)\,\overrightarrow{P}_e \cdot \hat{n}\right)$$

- $\hat{n}$ is normal to the scattering plane (≠ the plane our e- is traveling in),

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \sigma_0(\theta)\left[1 + P_y S(\theta)\cos\phi\right]$$

- Left: ϕ=0° Right: ϕ=180°
- Our detectors each integrate over a $d\Omega$ patch



Measuring Transverse Polarization

- If our detectors are symmetric, we would expect events rates:

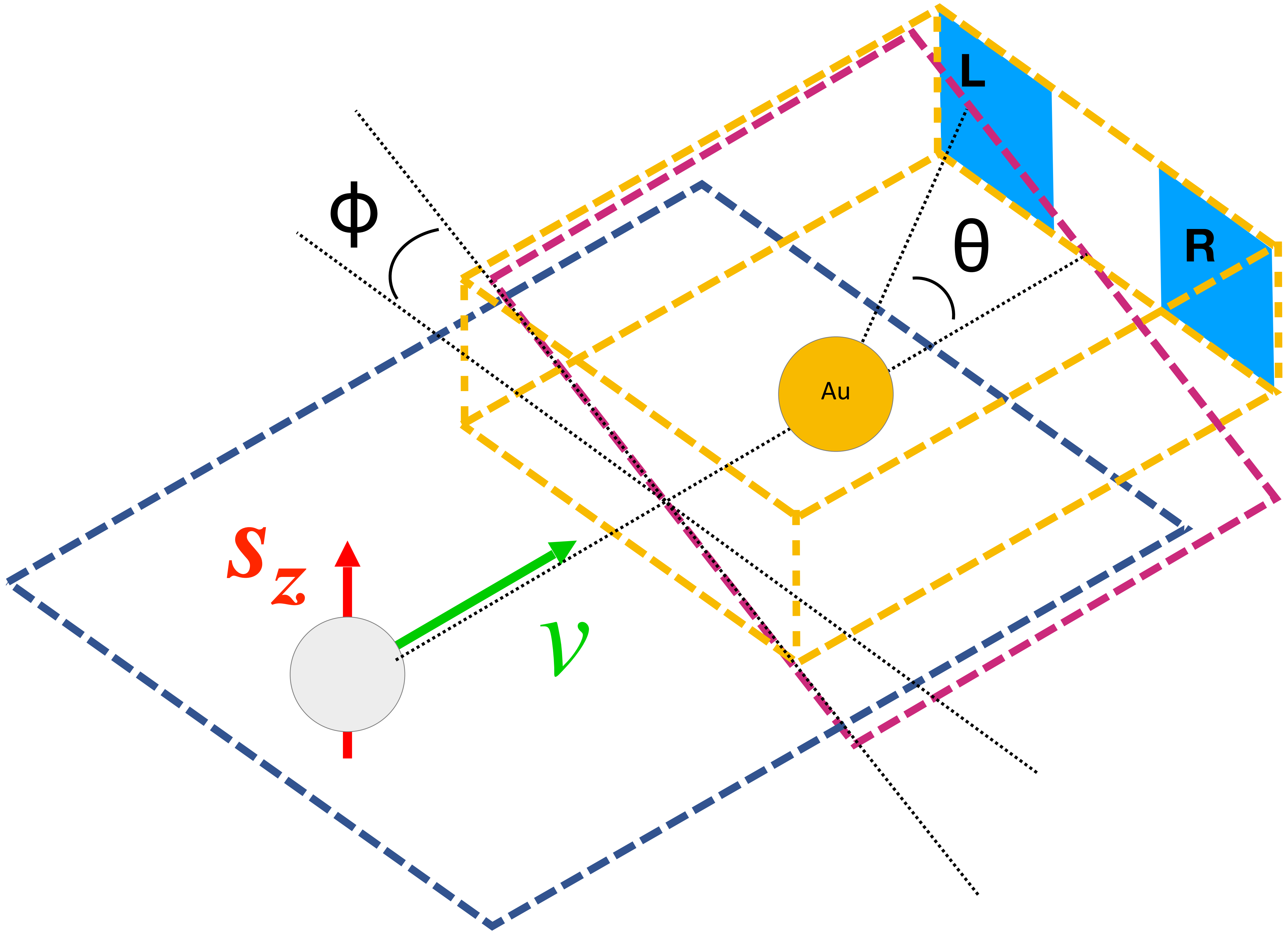
$$N_L = K \cdot \sigma_{\text{Mott},0}(\theta)\left(1 + S(\theta)P_y\right),$$

$$N_R = K \cdot \sigma_{\text{Mott},0}(\theta)\left(1 - S(\theta)P_y\right)$$

- So our left-right asymmetry is:

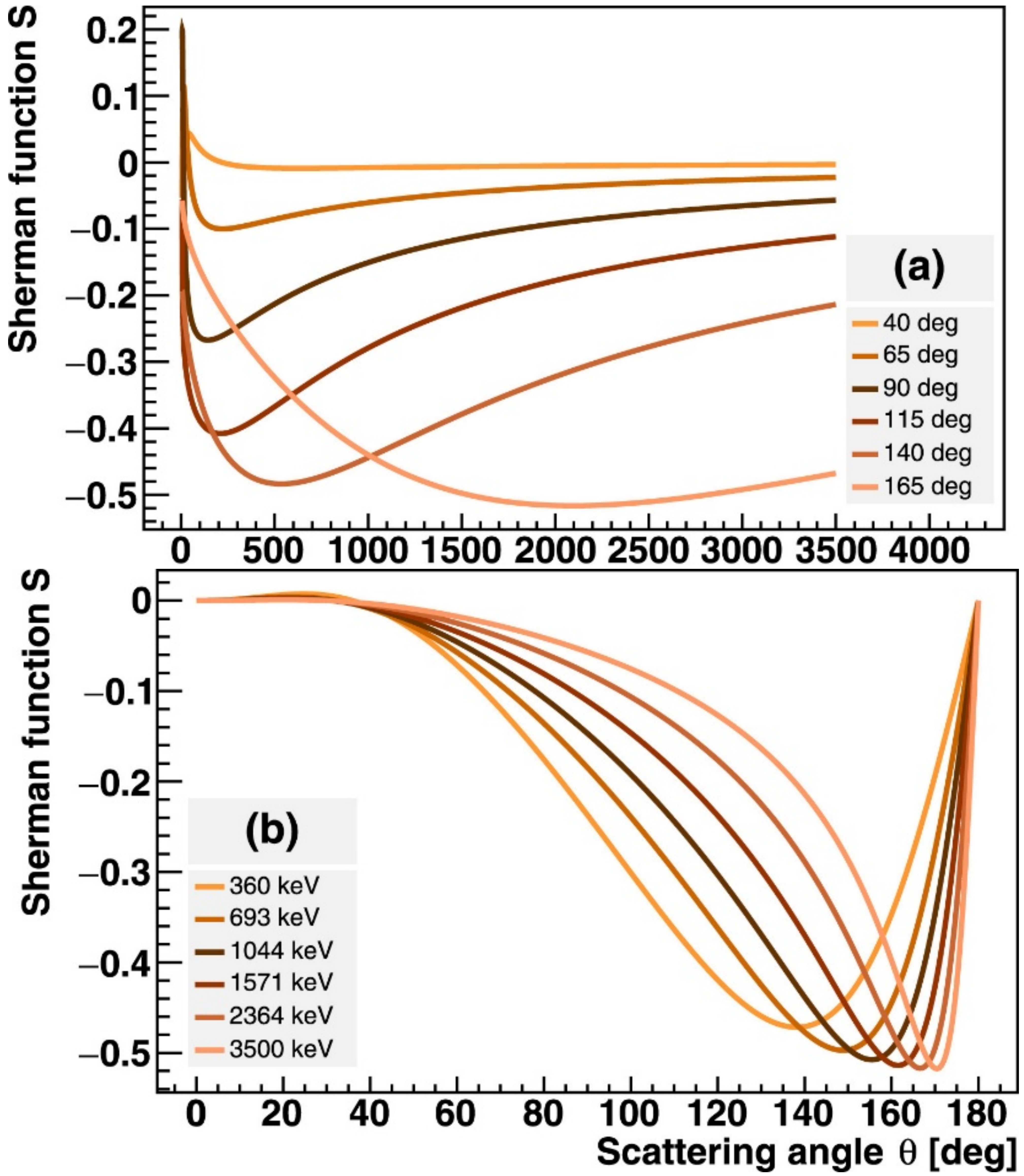
$$A = \frac{N_L - N_R}{N_L + N_R} = \frac{K\sigma_{\text{Mott},0}[(1 + S(\theta)P_y) - (1 - S(\theta)P_y)]}{K\sigma_{\text{Mott},0}[(1 + S(\theta)P_y) + (1 - S(\theta)P_y)]}$$

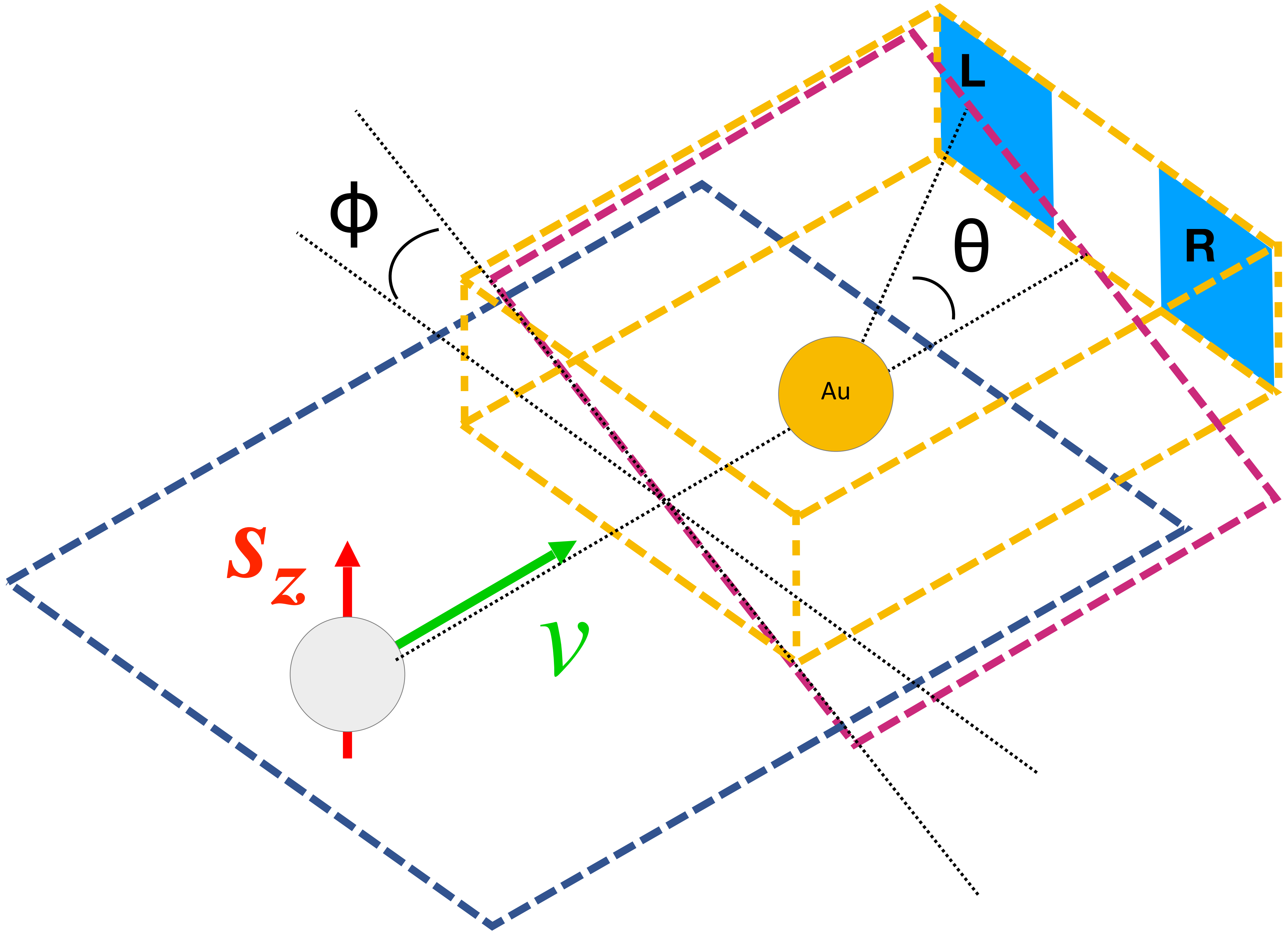
$$A = \frac{(1 + S(\theta)P_y) - (1 - S(\theta)P_y)}{(1 + S(\theta)P_y) + (1 - S(\theta)P_y)} = S(\theta)P_y$$



- $S(\theta)$ is the Sherman function, which we can (mostly) calculate:

Measuring Transverse Polarization

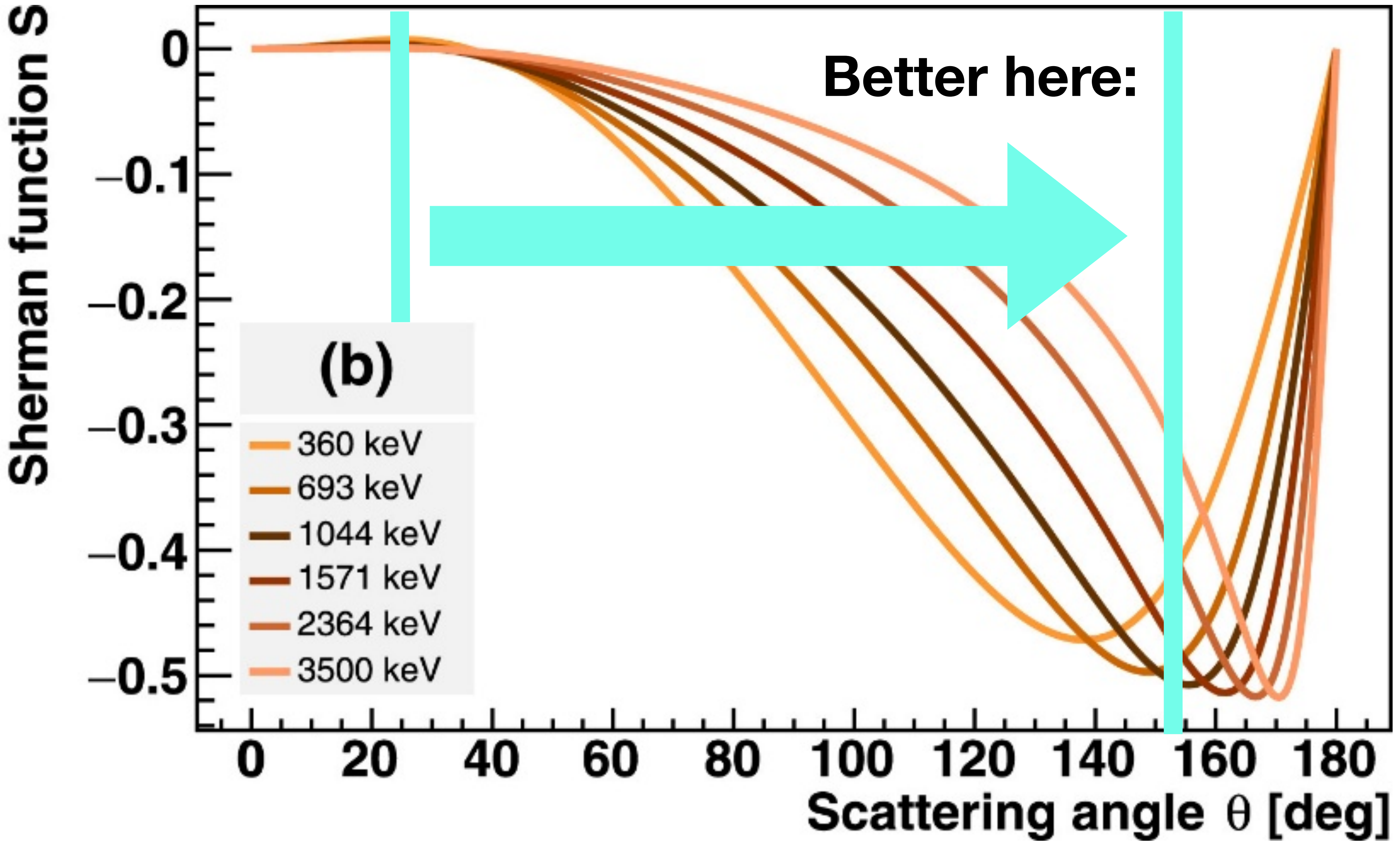


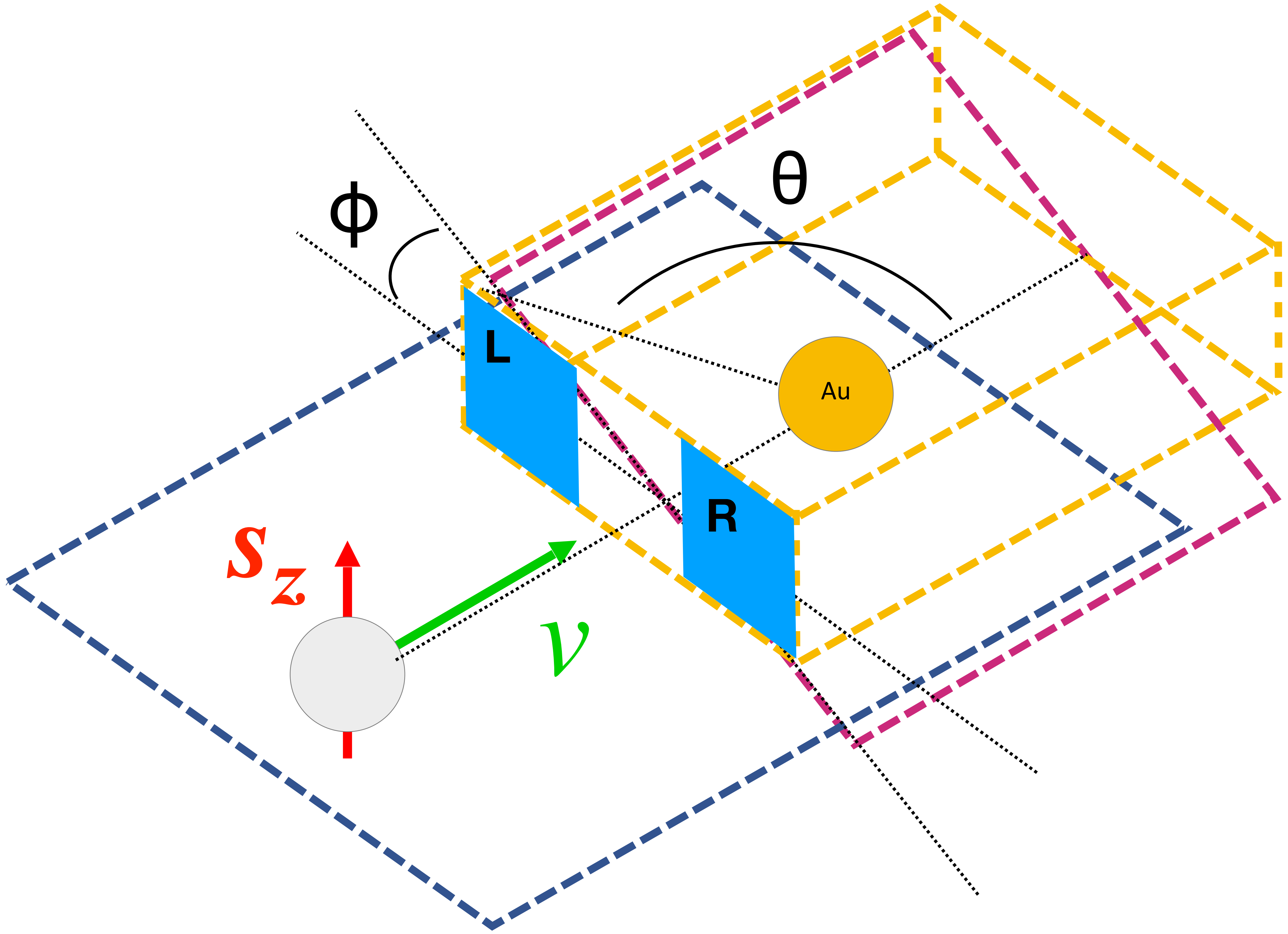


- What should we fix?

Measuring Transverse Polarization

- Want backwards!
- $A_{meas} = S(\theta)P_y$
- $S(\theta)$ is our **analyzing power** $A_{meas} = A_y P_y$
- A_y tells us how big an asymmetry it is possible to measure. $A_y = 0$ means we have no sensitivity





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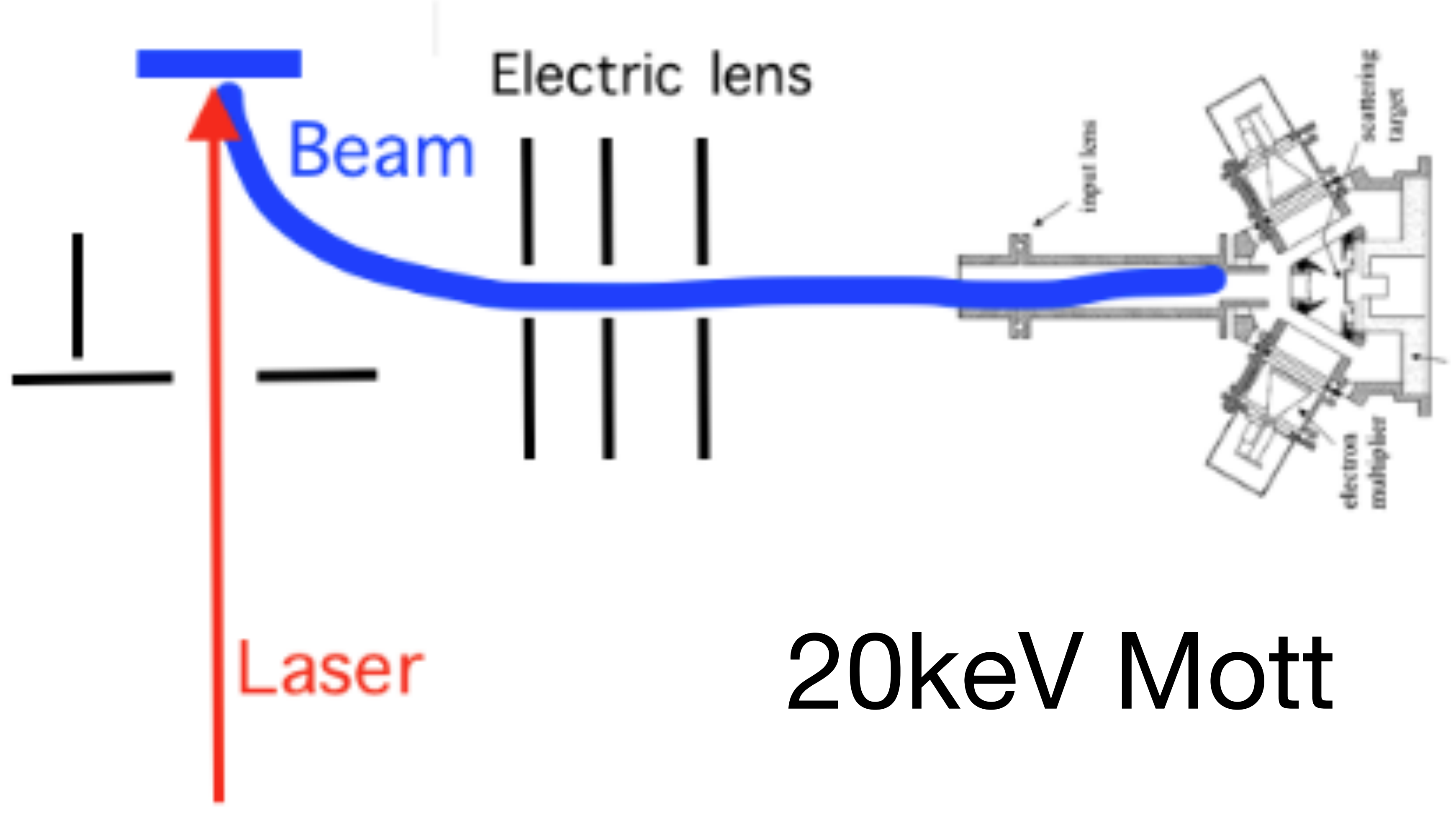
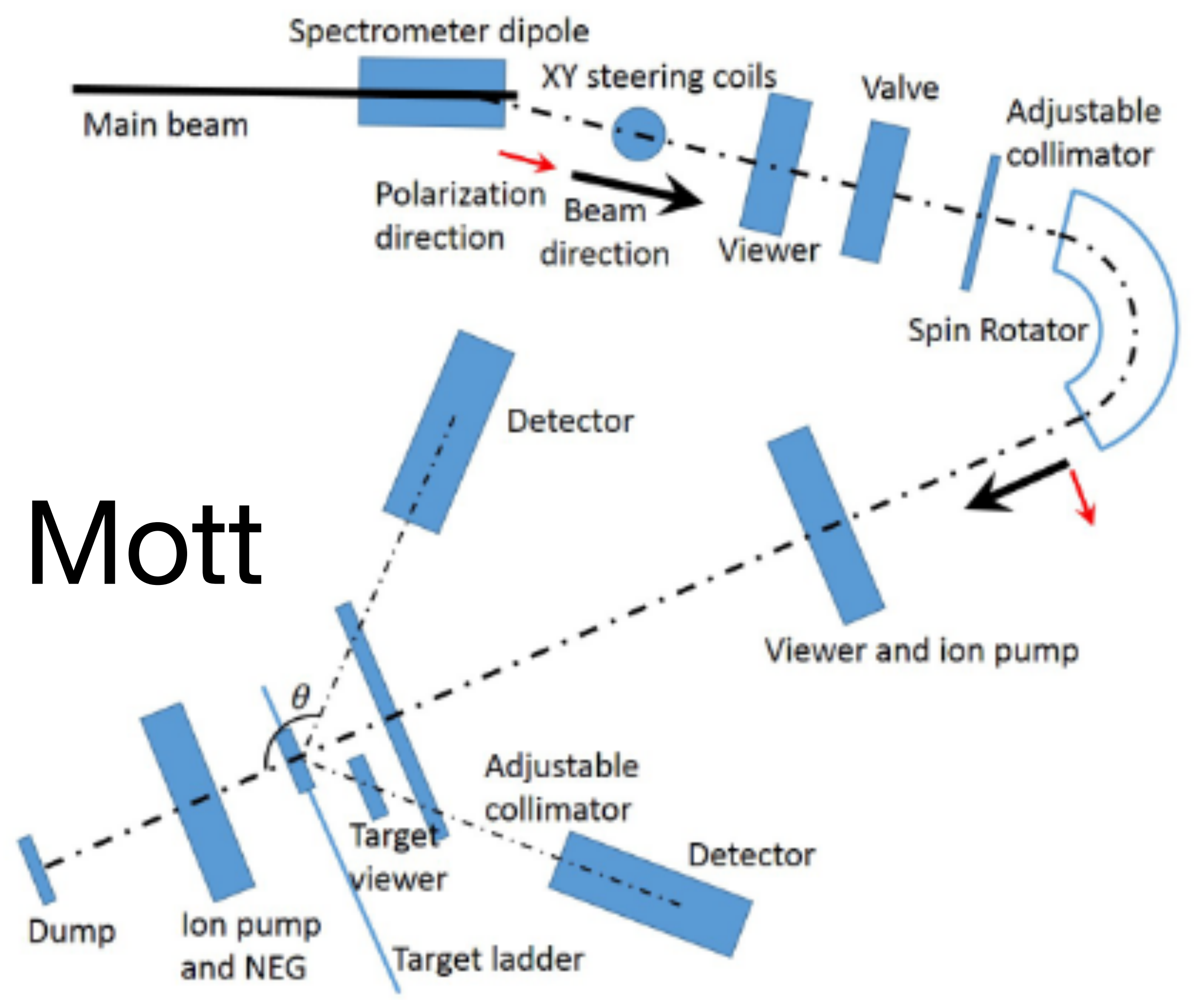
Electron Mott Polarimeters

- Gold foil (probably), so it eats the whole electron beam.
- Useful to calibrate our gun, but can't use it all the time.
- Two at the injector:
    - 20keV immediately after gun
    - 300keV before electrons get bunched



20keV Mott



300keV Mott

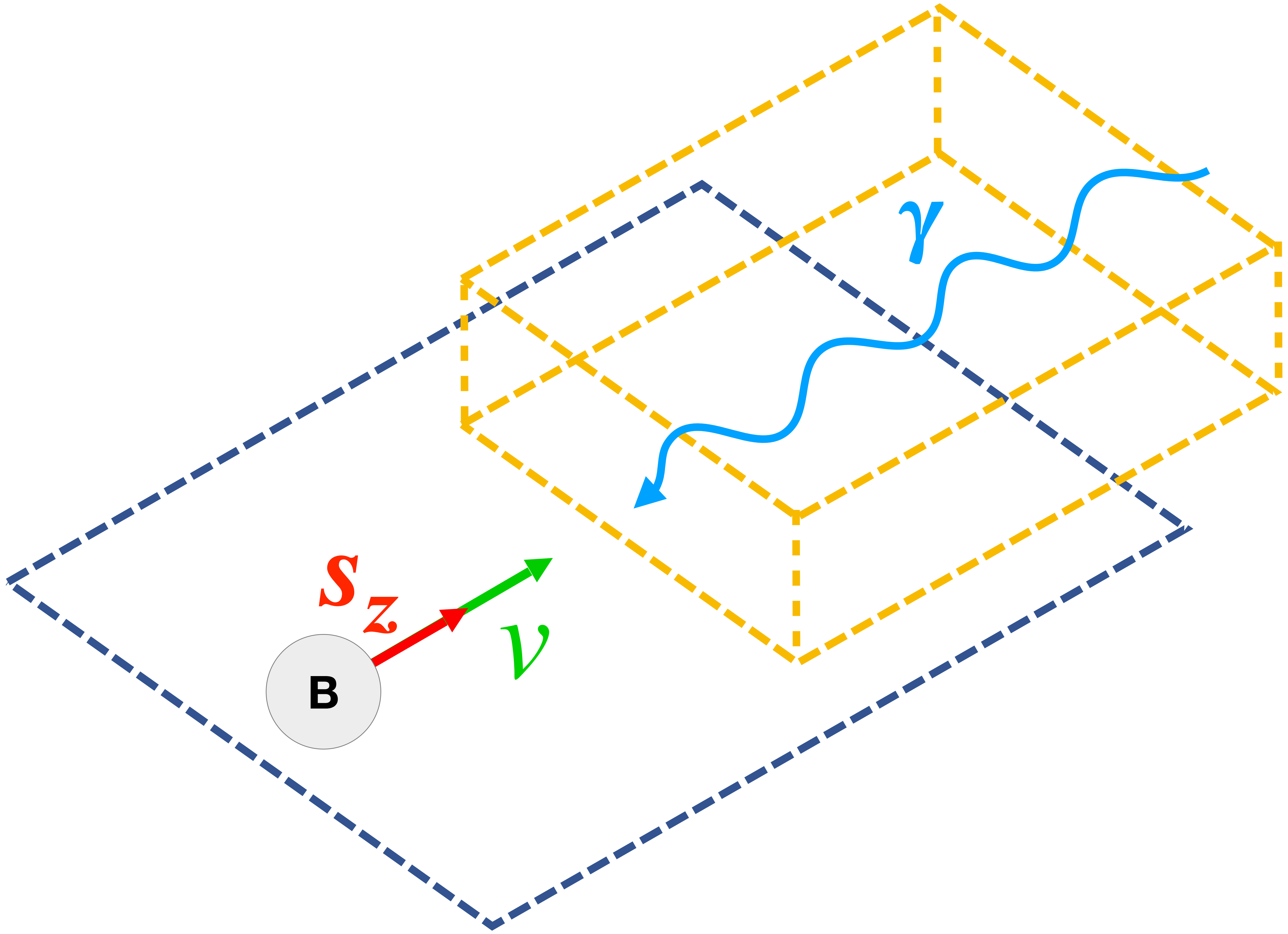
Measuring Longitudinal Polarization

- We could also have chosen B:
- Polarized Compton Scattering modifies the Klein-Nishina formula:

$$\frac{d\sigma}{dk'} = \left(\frac{d\sigma}{dk'}\right)_0 \left(1 + P_e P_\gamma A_c(k')\right)$$

where P_γ is the circular polarization of the photon.

- But here we don't have right-left.What interactions could we use?
- What detectors would we need?



Measuring Longitudinal Polarization

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- Polarized Compton Scattering modifies the Klein-Nishina formula:

$$\frac{d\sigma}{dk'} = \left(\frac{d\sigma}{dk'}\right)_0 \left(1 + P_e P_\gamma A_c(k')\right)$$

where P_γ is the circular polarization of the photon.

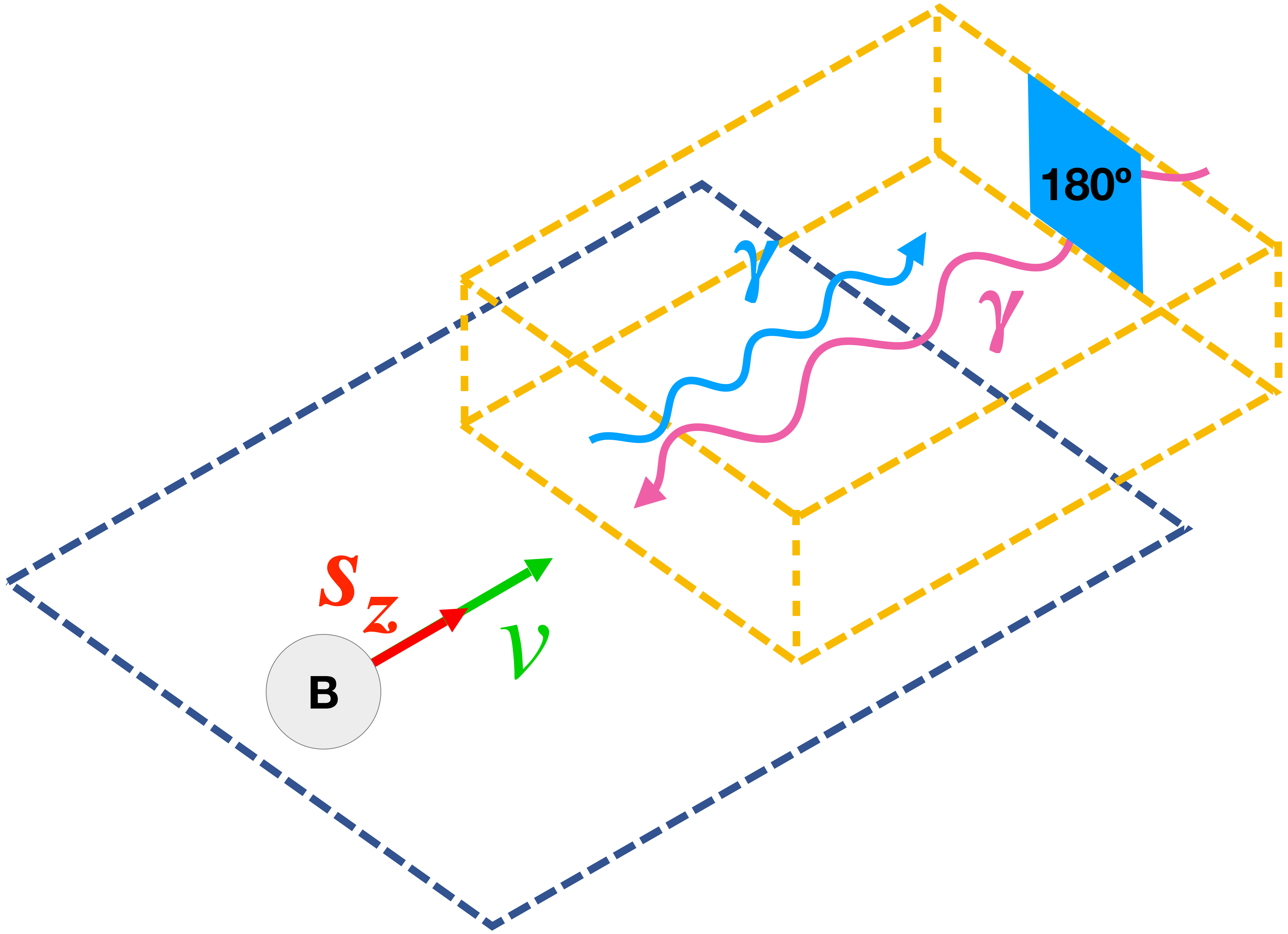
- Flip laser helicity and count at a single detector as a function of helicity:

$$N_+ = K \cdot \left(\frac{d\sigma}{dk'}\right)_0 \left(1 + P_e P_\gamma A_c(k')\right)$$

$$N_- = K \cdot \left(\frac{d\sigma}{dk'}\right)_0 \left(1 - P_e P_\gamma A_c(k')\right)$$

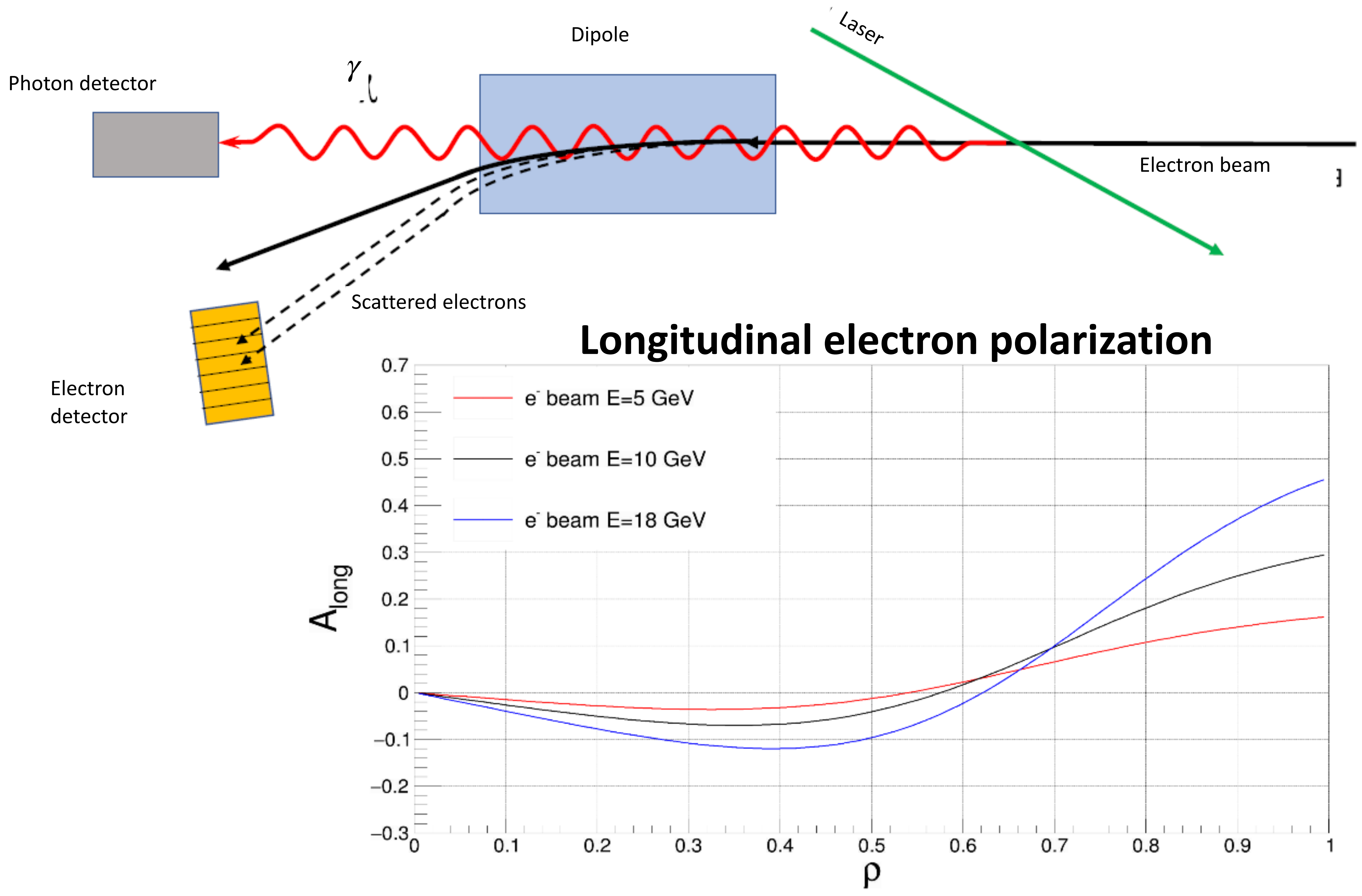
- We form the asymmetry like before, and get lots of cancellation like before:

$$A_{\mathrm{exp}} = P_e P_\gamma A_c(k')$$



Electron Compton Polarimeters

- This is completely analytic:
- Backscattering gives us the the largest photon energy: $\rho = k'/k'_{\max}$ and largest **analyzing power.**
- Magnet bends the electrons out of the recoiling photons' way: the beam can continue into the ring
- Count the photons (or just the total light) as a function of laser polarization
- Some of the electrons lose enough energy that they leave the beam



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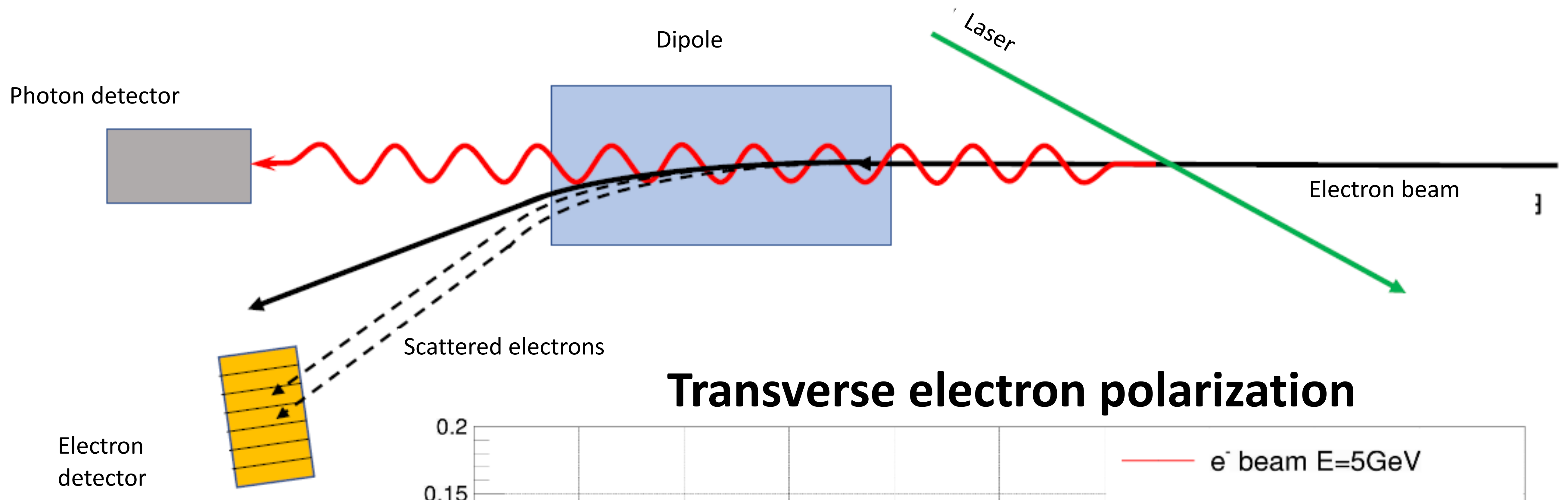
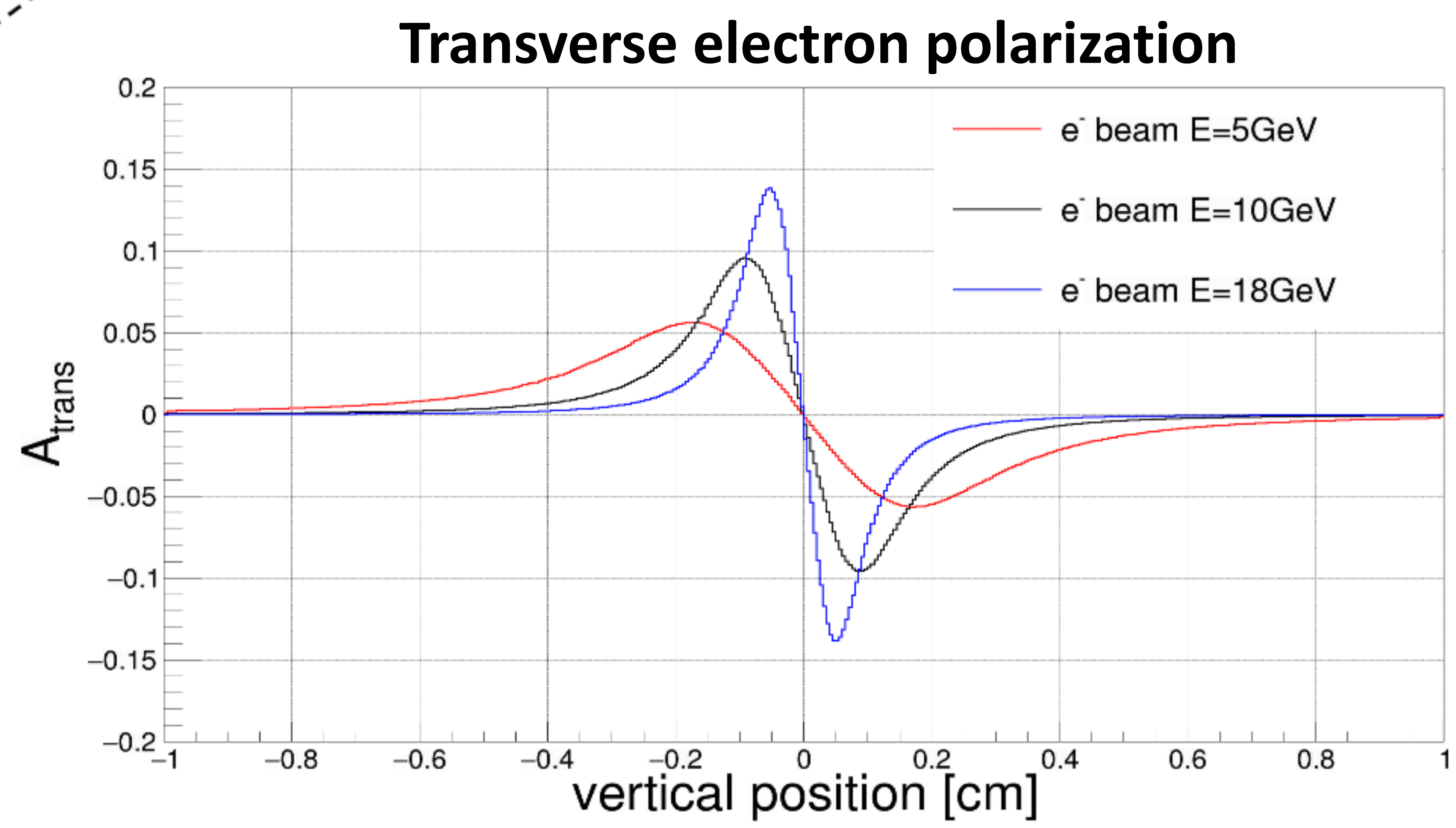
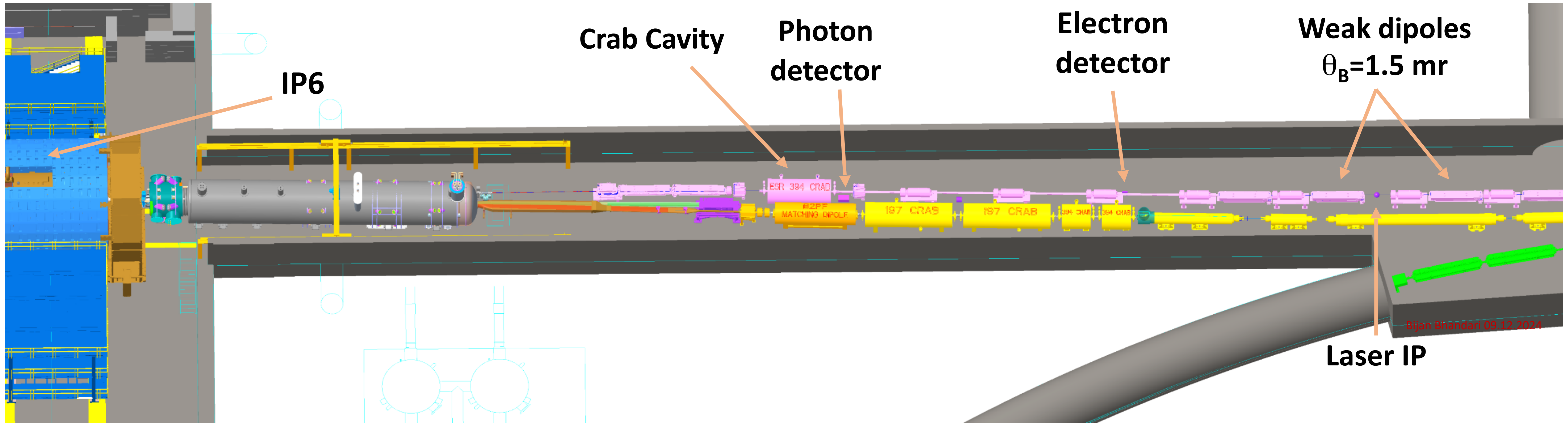
Electron Compton Polarimeters

- Wait! There's a transverse analyzing power too! What can we do here?

$$\frac{d\sigma}{dk'd\phi} = \left(\frac{d\sigma}{dk'd\phi}\right)_0 \left[1 + P_L P_\gamma A_L(k') + P_T P_\gamma A_T(k',\phi)\cos\phi\right]$$







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Compton Polarimeter

- Design based on JLab Hall C (scaled power requirements)
- Analyzing power depends on the photon energy: Gain-switched seed laser (1064 nm) with frequency doubling system (532 nm)
- 10-20W laser power to match beam intensity and meet the statistical demand.
- Must pulse at RF frequency of electron beam (25 and 100 MHz) and resolve individual bunches
-

- Photon detectors designed for tough environment:
  - Separate the signal from nearby beam
  - Avoid synchrotron background
  - Use a combination of tracking with calorimetryhe synchrotron radiation background
- Tungsten converter in front of diamond strips

Hadron Polarization

- Hadrons are tougher: We can't do the QCD calculations the way we can QED.
- Elastic scattering in Coulomb-Nuclear Interference (CNI):
  $\sigma \propto |M_{\text{Coulomb}} + M_{\text{Nuclear}}|^2$
  $\sigma \propto |M_{\text{Coulomb}}|^2 + |M_{\text{Nuclear}}|^2 + 2 \cdot \text{Re}(M^*_{\text{Coulomb}} \cdot M_{\text{Nuclear}})$
  - Near t~0.003 GeV^2), ~few % analyzing power:
    $A_{\text{beam}} = A_N \cdot P_{\text{beam}}$ or $A_{\text{tar.}} = A'_N \cdot P_{\text{tar.}}$
  - Hydrogen Jet
  - proton-carbon scattering

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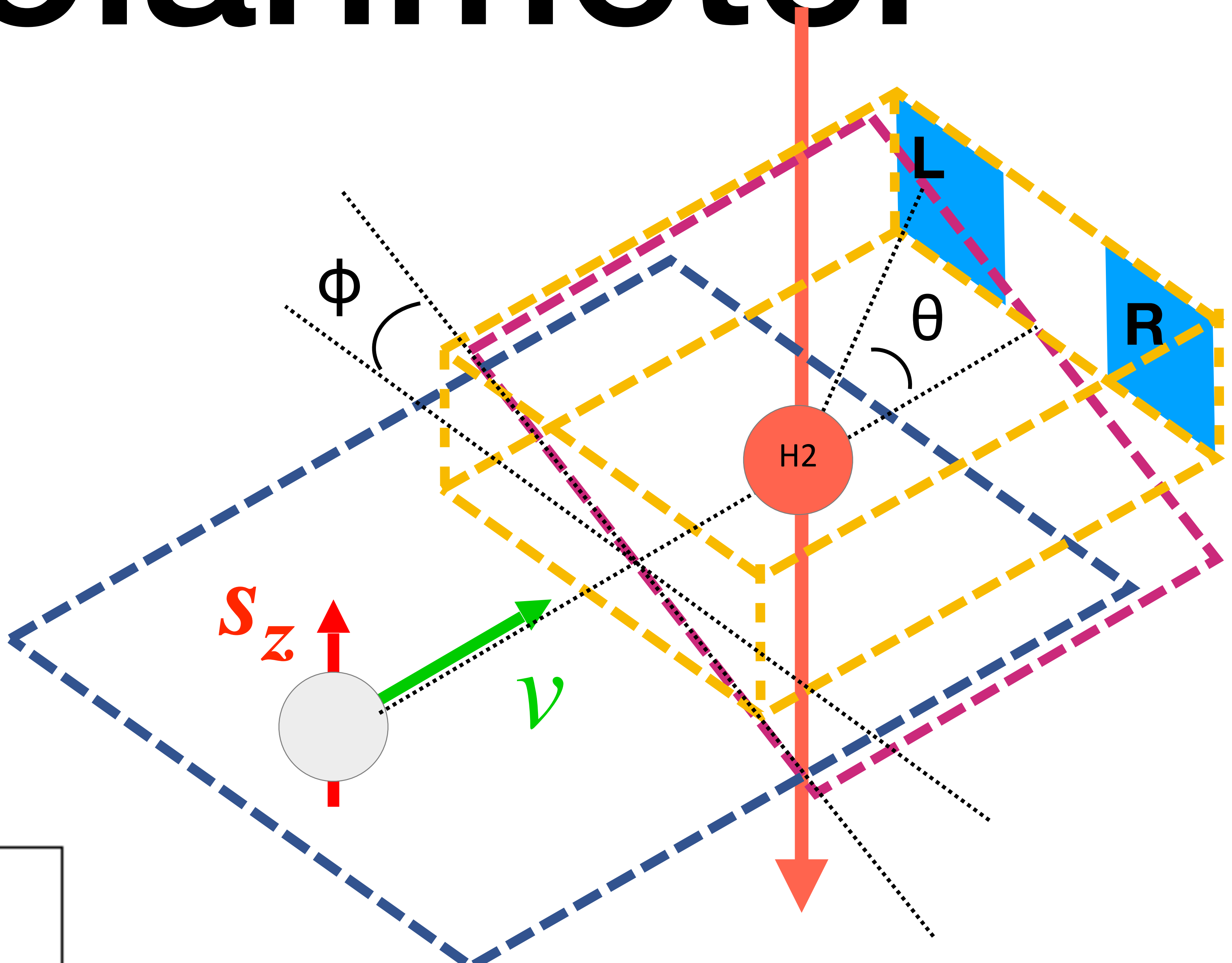
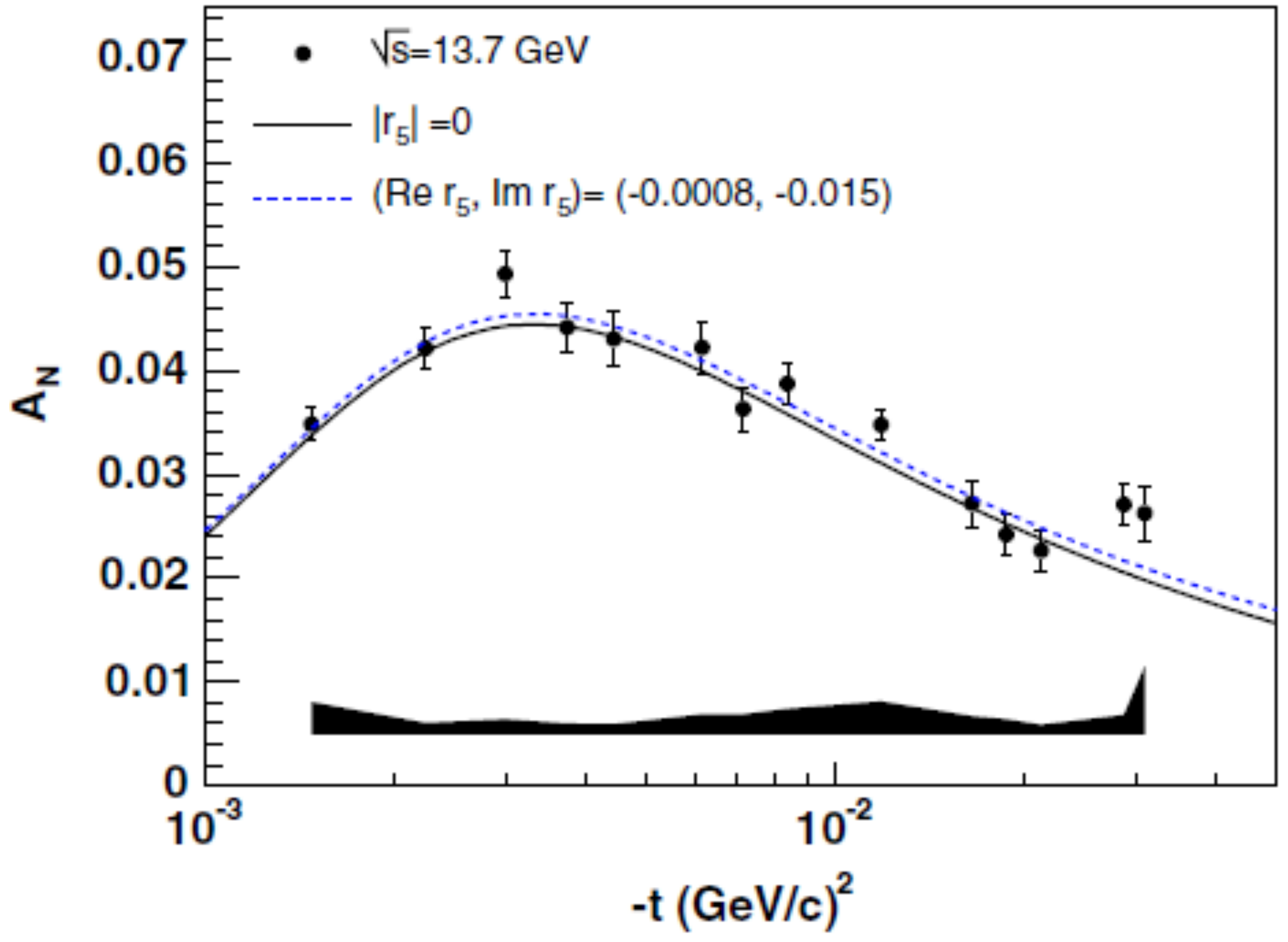
Hydrogen Jet Polarimeter

- $A_{\text{beam}} = A_N \cdot P_{\text{beam}}$ or $A_{\text{jet}} = A_N \cdot P_{\text{jet}}$
- Because we have identical particles (pp), the **analyzing power** of each really is the same term. Detector positions etc exactly cancel out!



$$\frac{A_{\text{beam}}}{A_{\text{jet}}} = \frac{A_N \cdot P_{\text{beam}}}{A_N \cdot P_{\text{jet}}}$$

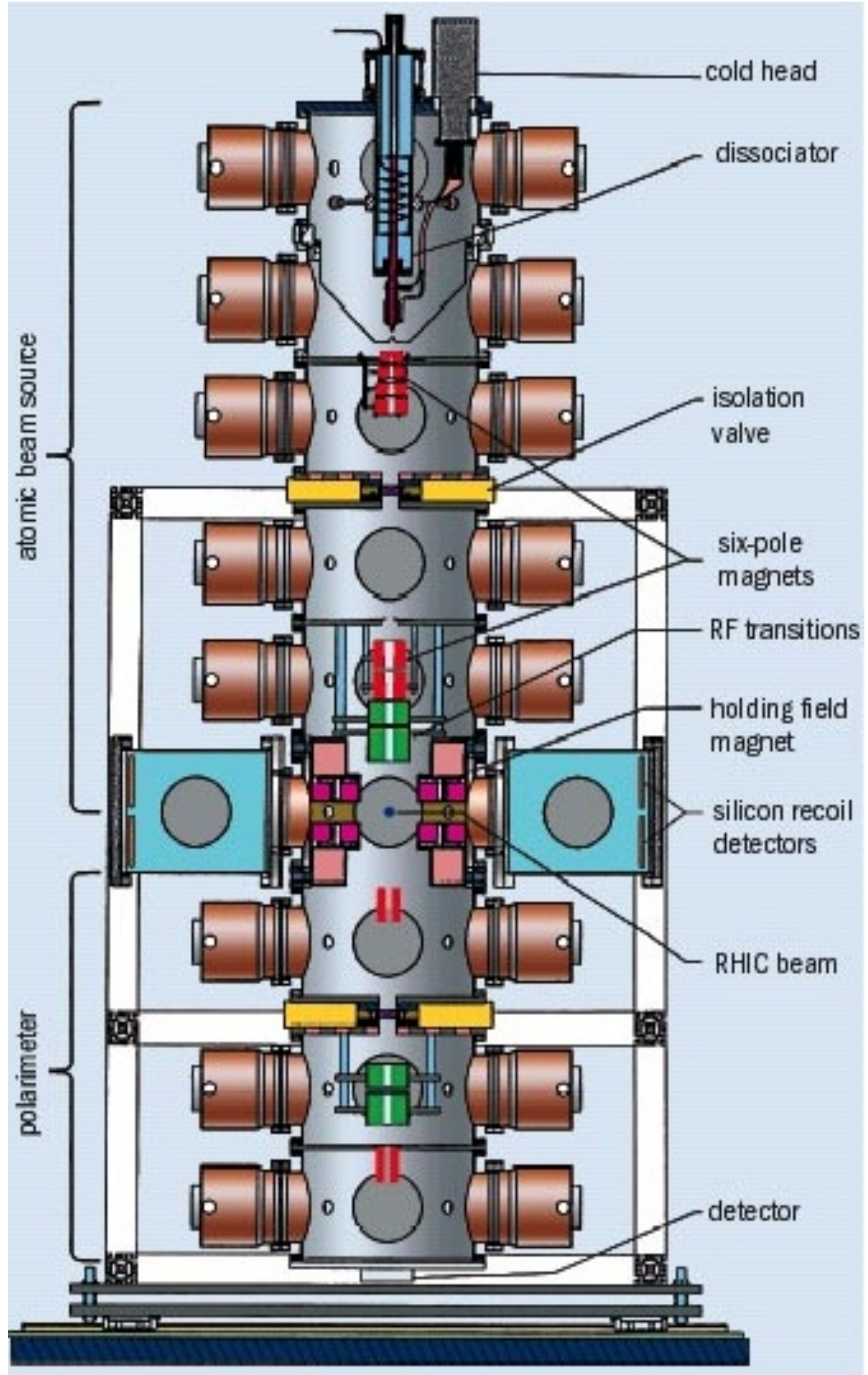
$$P_{\text{beam}} = \left(\frac{A_{\text{beam}}}{A_{\text{jet}}}\right) P_{\text{jet}}$$

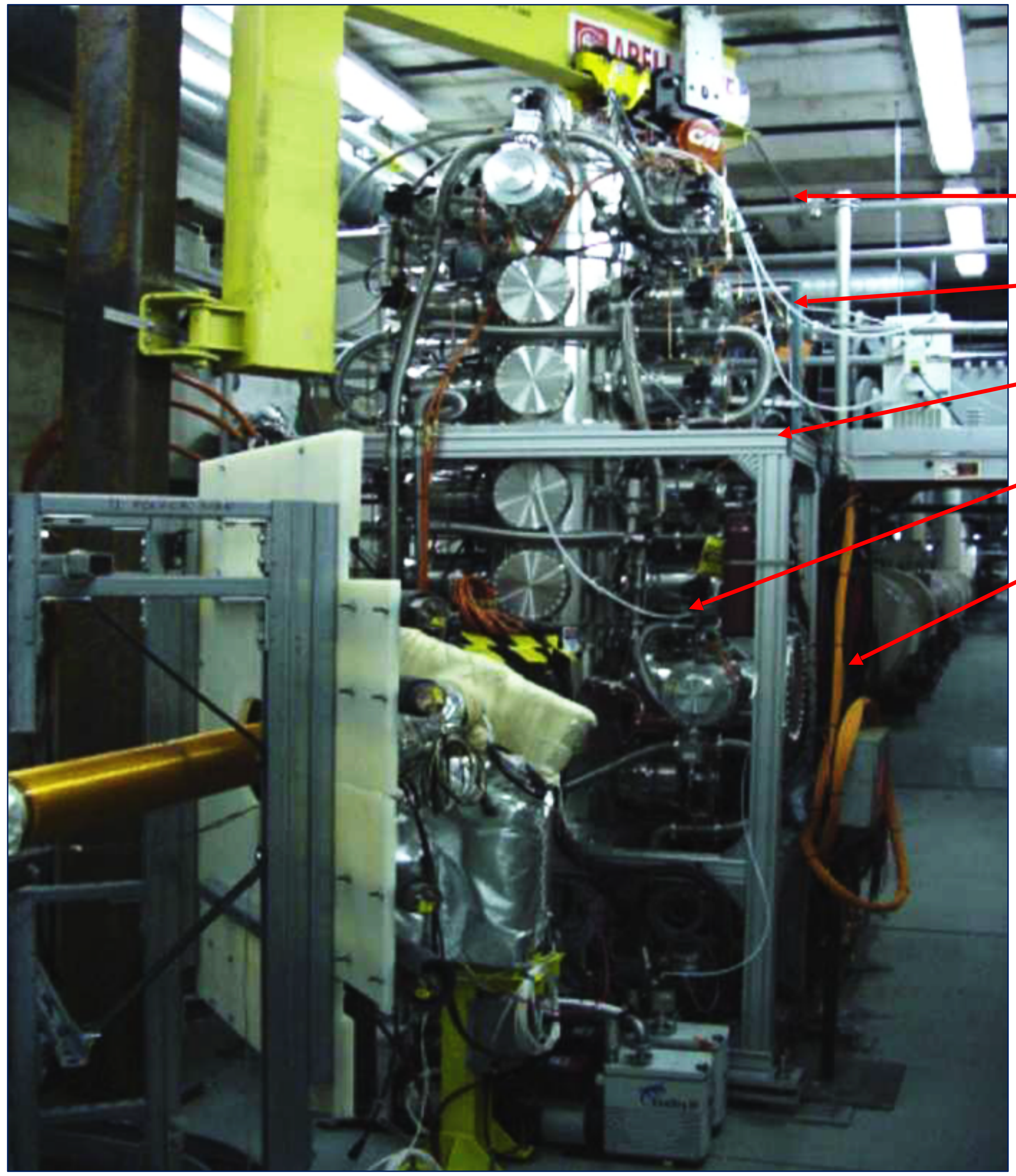


Mandelstam t: $t = -2p^2(1 - \cos\theta)$

Hydrogen Jet Polarimeter

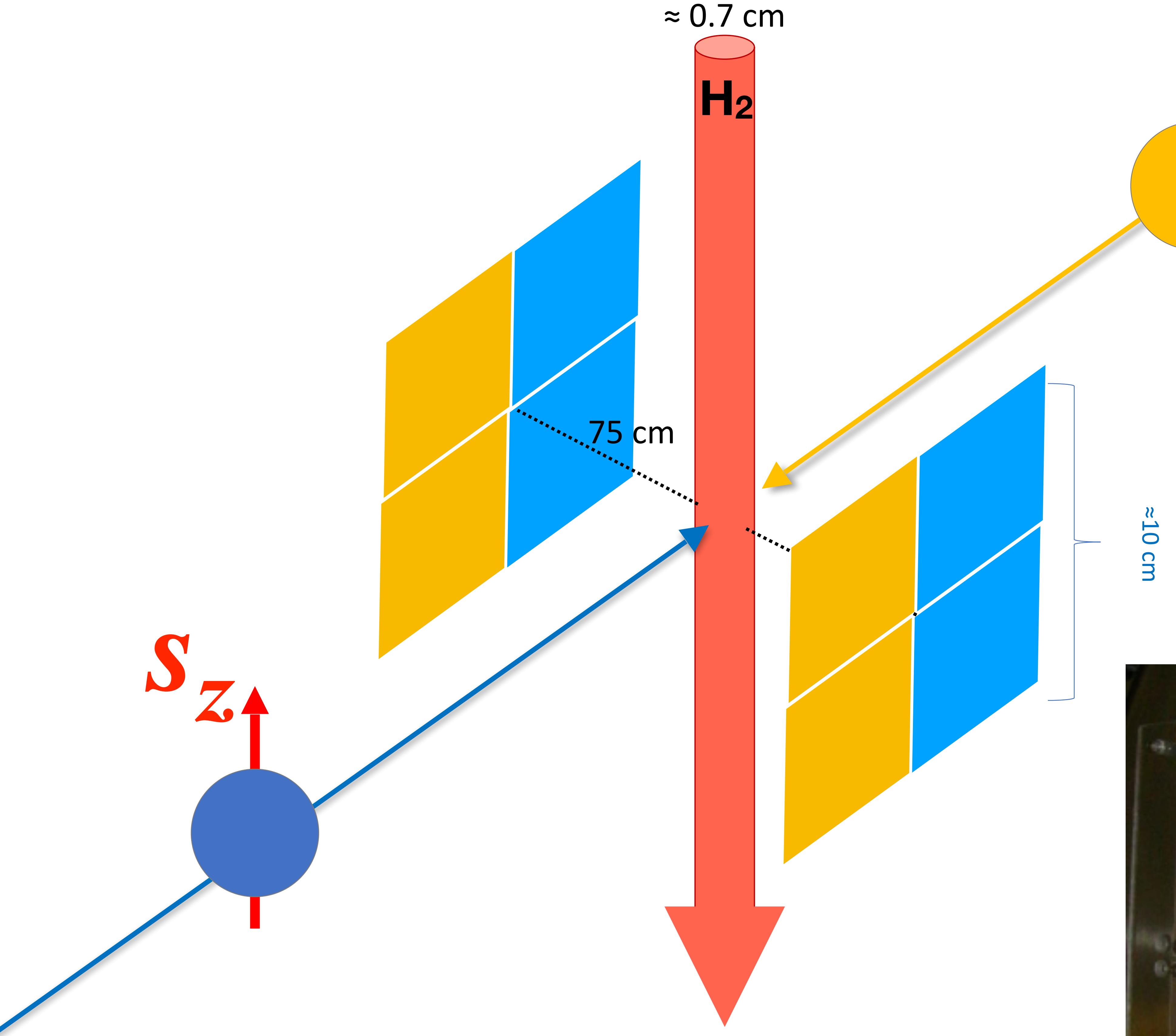
- So measure the jet polarization separately (we do) and measure the asymmetry wrt beam and jet, and we have an absolute polarimeter:
- Polarized target
- Continuous operation
- $\Delta P/P \approx 0.5 + 2\,\%$ per 8 hours of operation

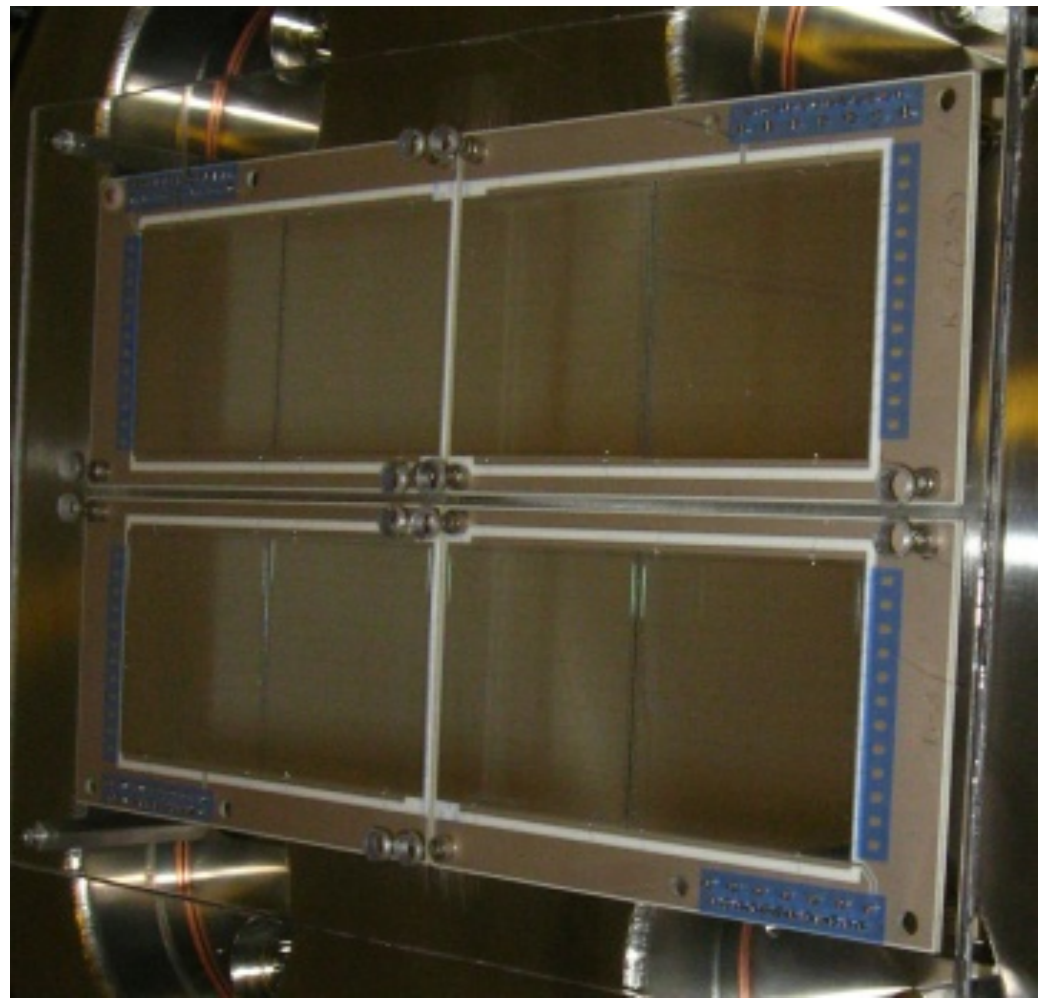




arxiv:2212.08628

Hydrogen Jet Polarimeter





- Polarized atomic hydrogen jet target (HJET)
- Set of eight Hamamatsu Si strip detectors
- 12 vertical strips
  - 3.75mm pitch
  - 500 um thick
- Uniform dead layer ~1.5um
- Both RHIC beams present

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Adapted from Oleg Eyser's CFNS 2025 Summer School slides

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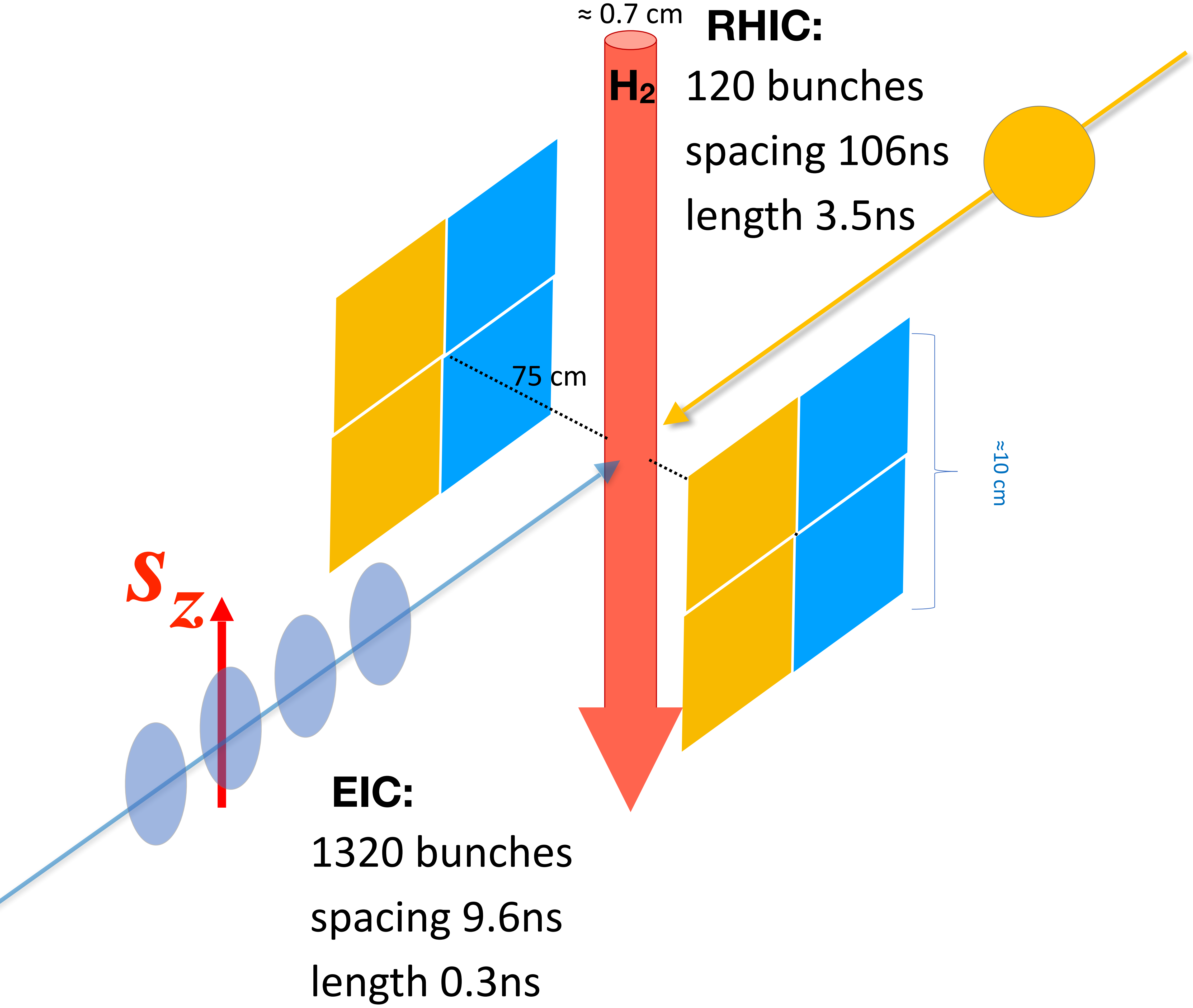
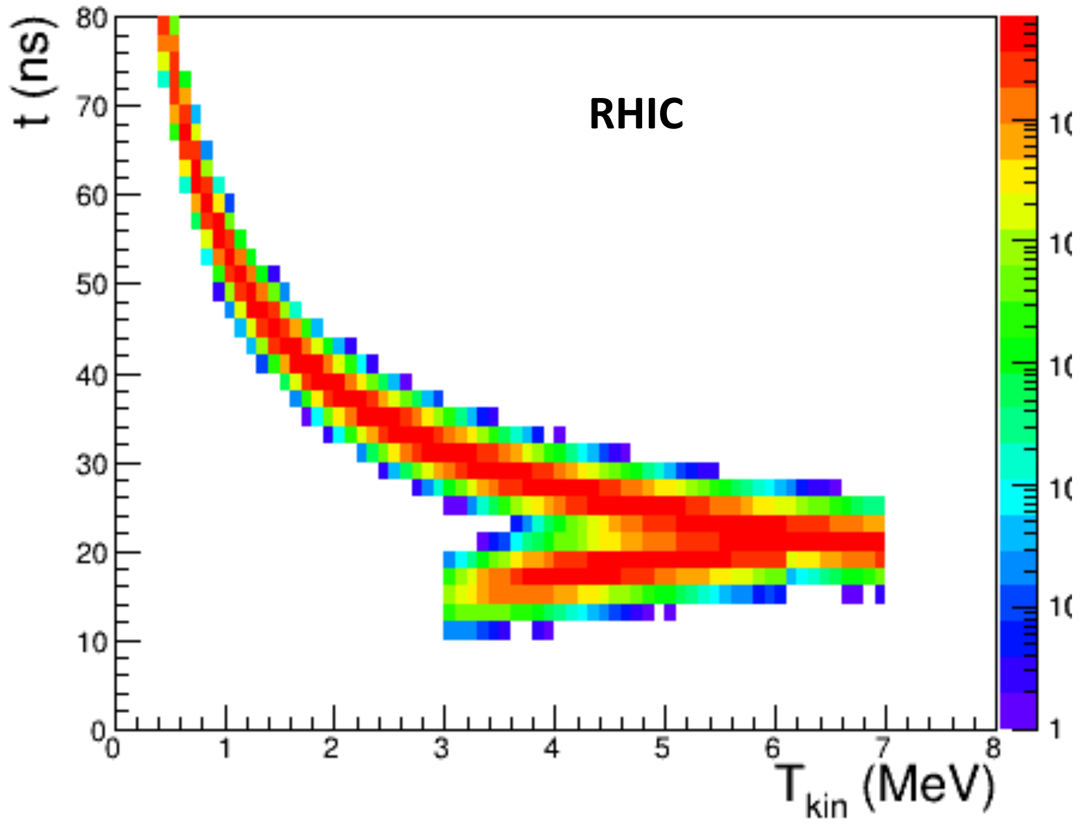
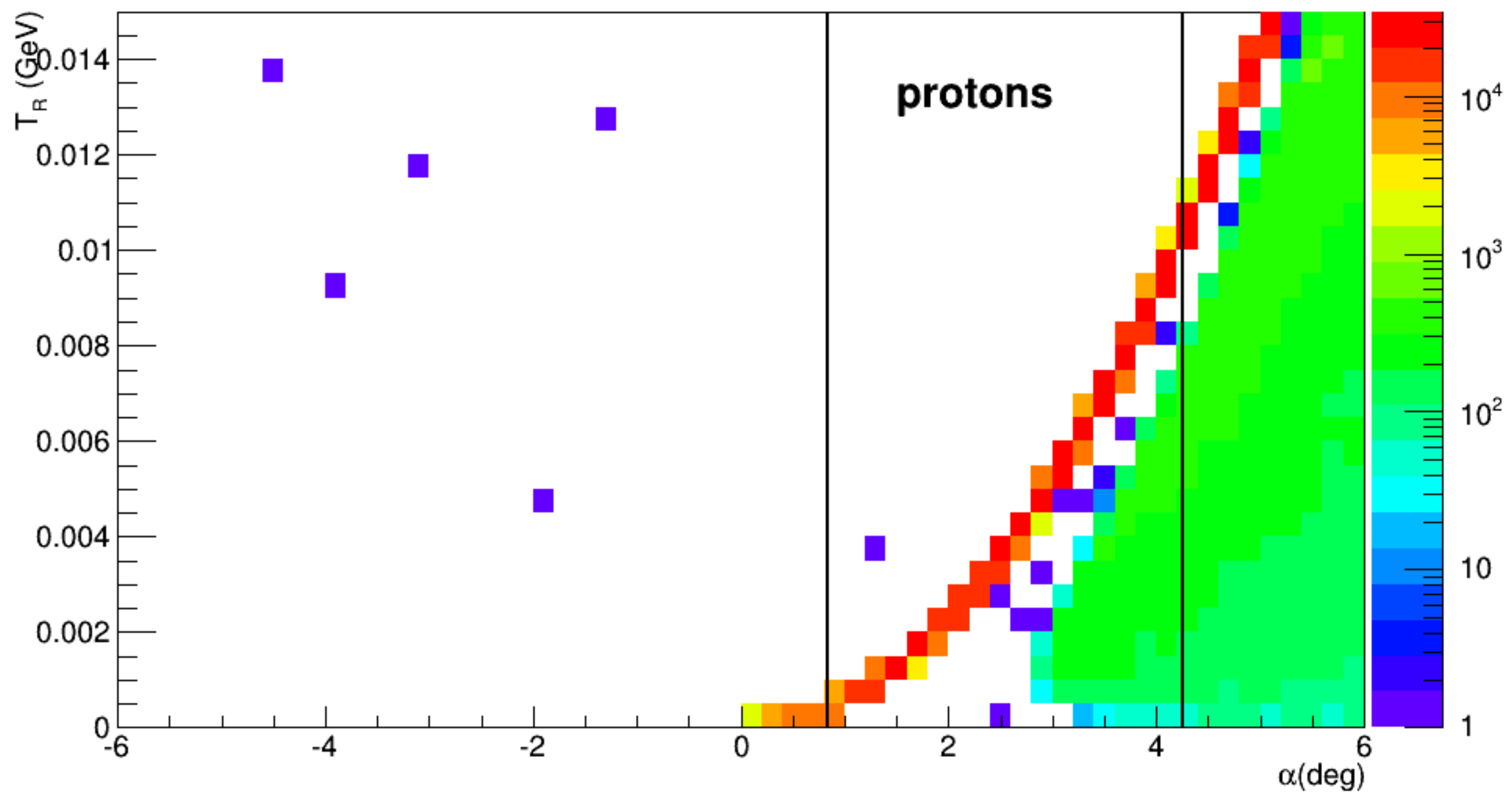
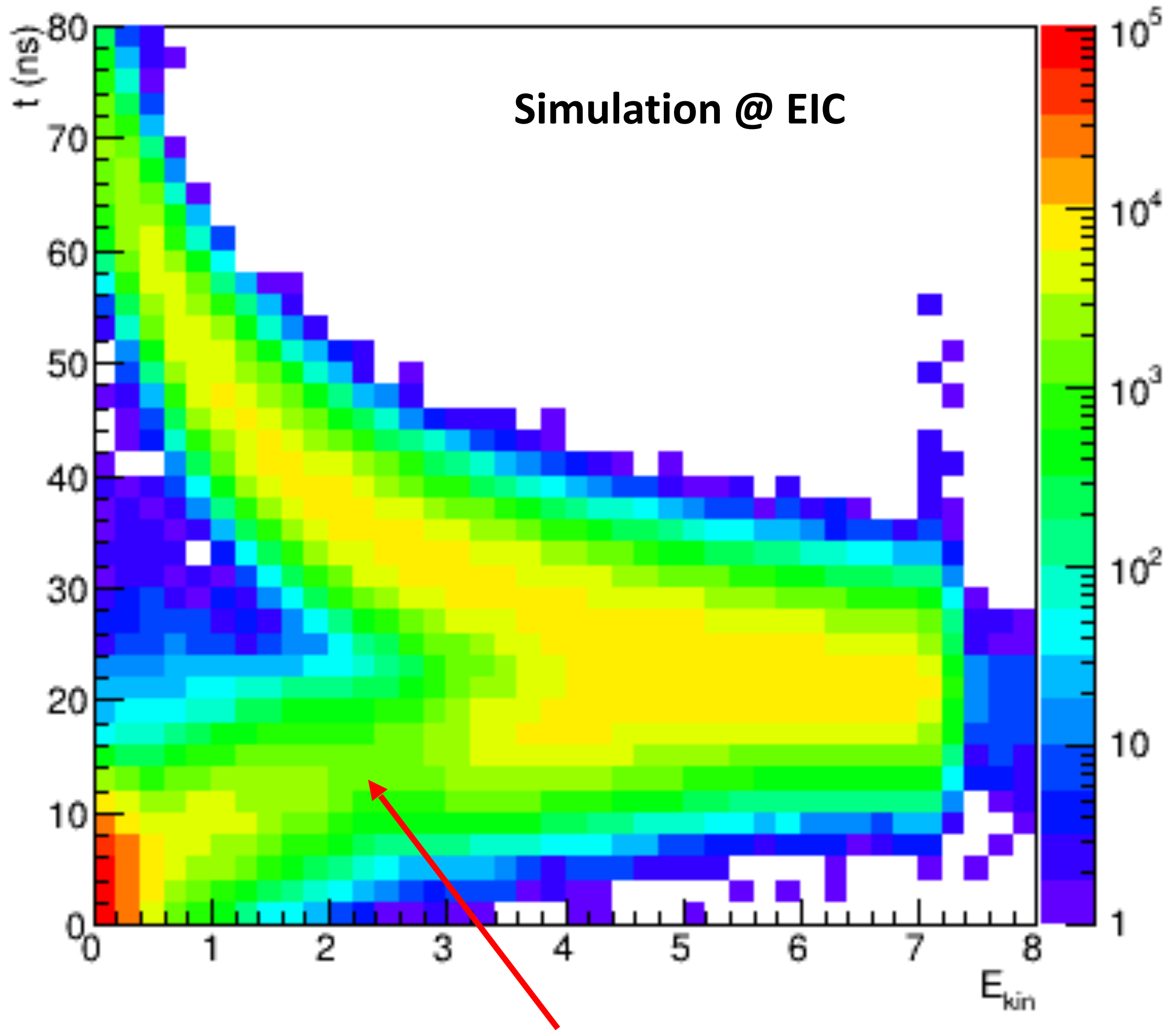
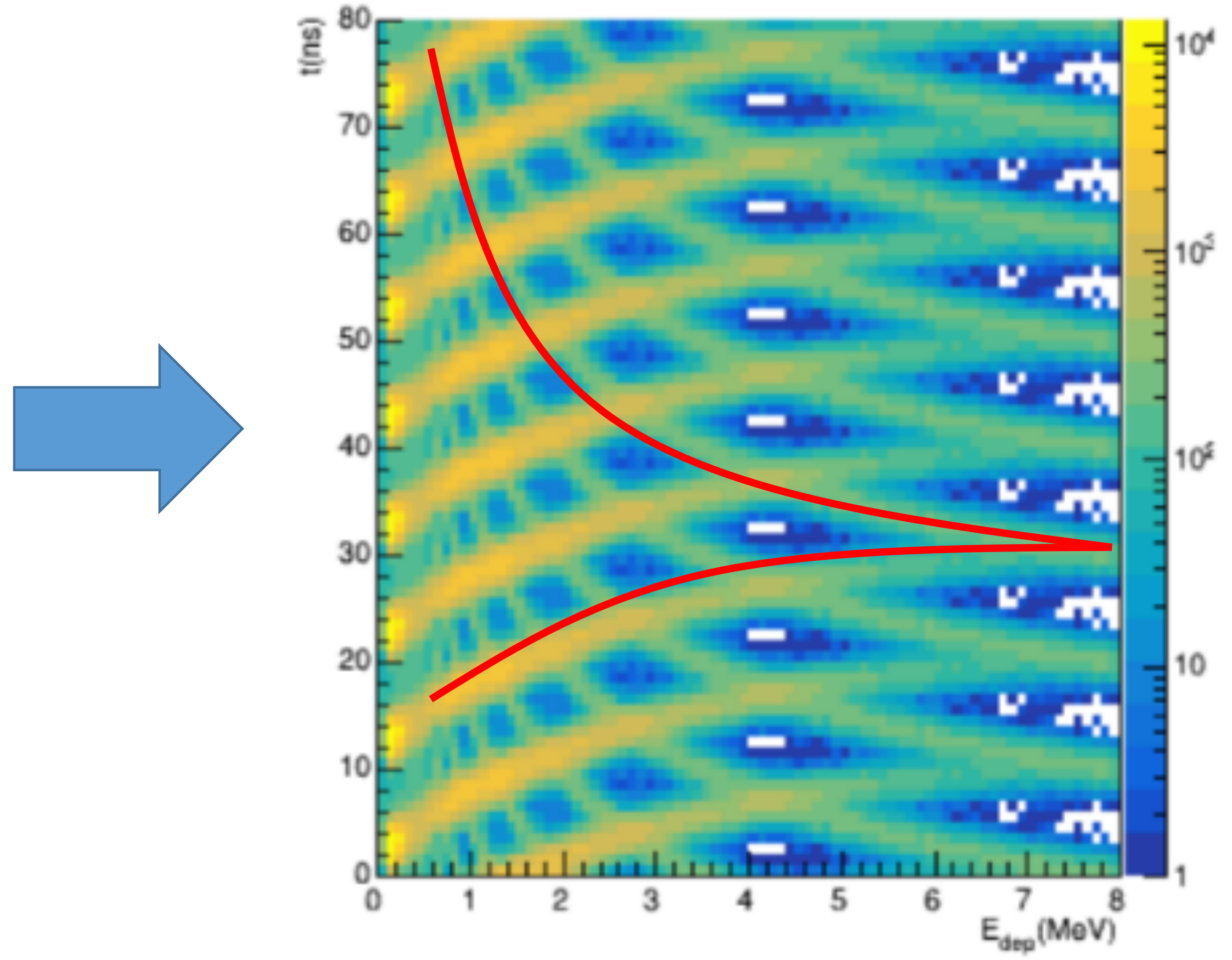
Hydrogen Jet Polarimeter





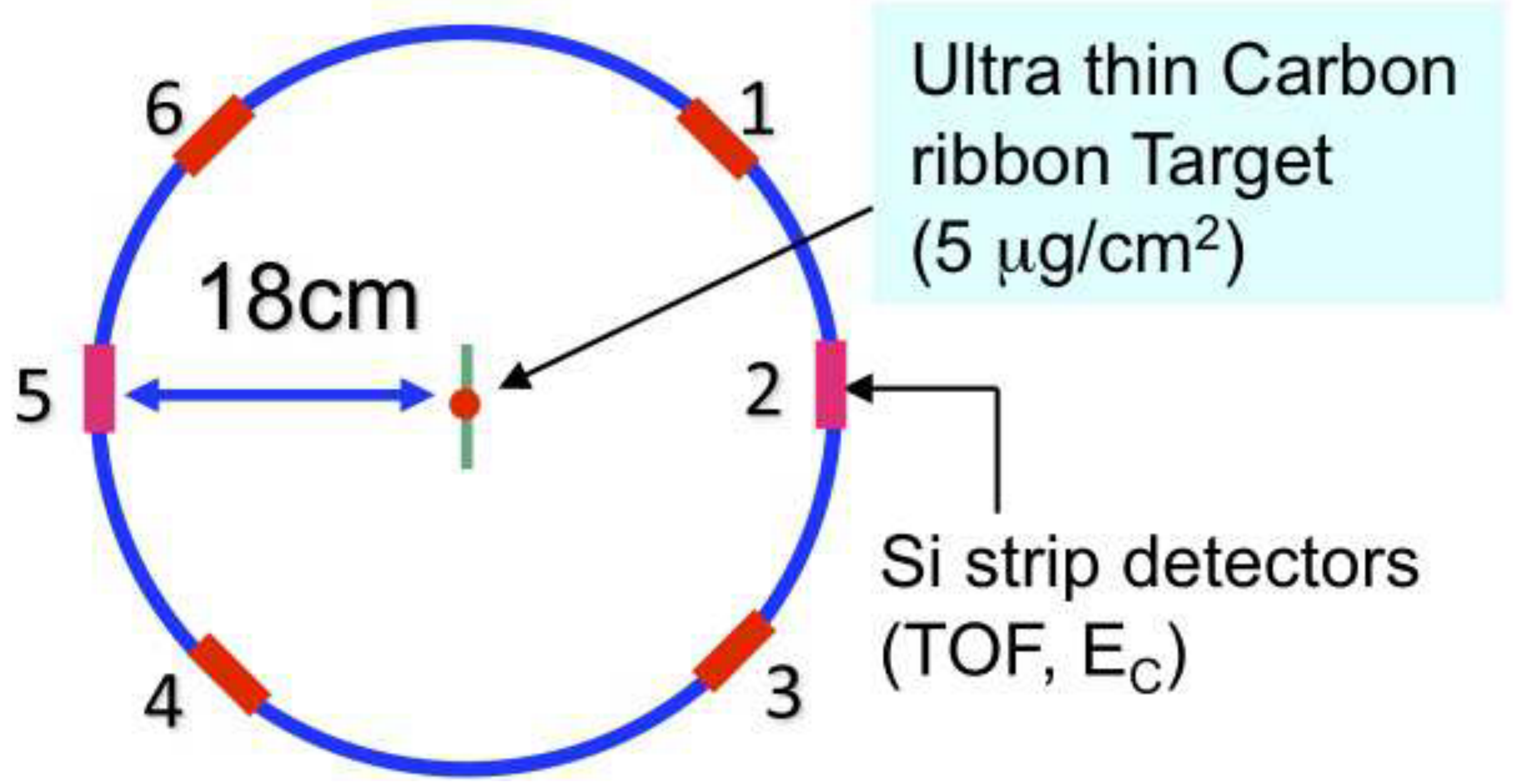


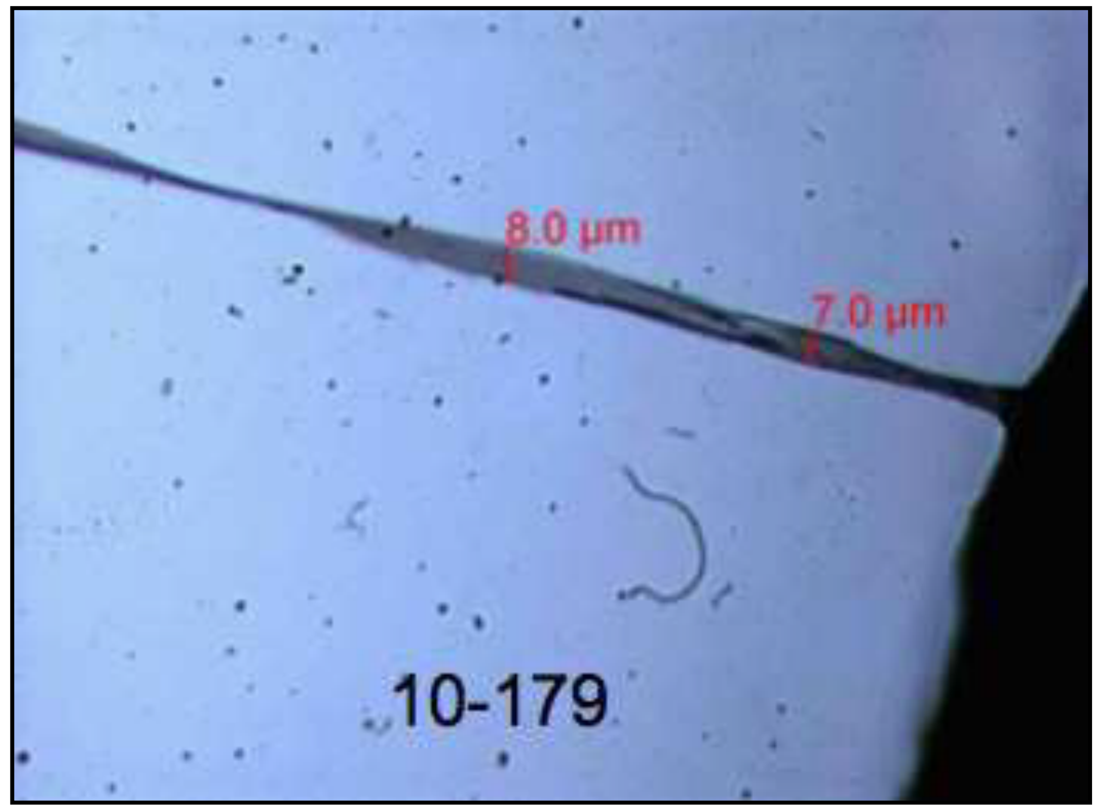


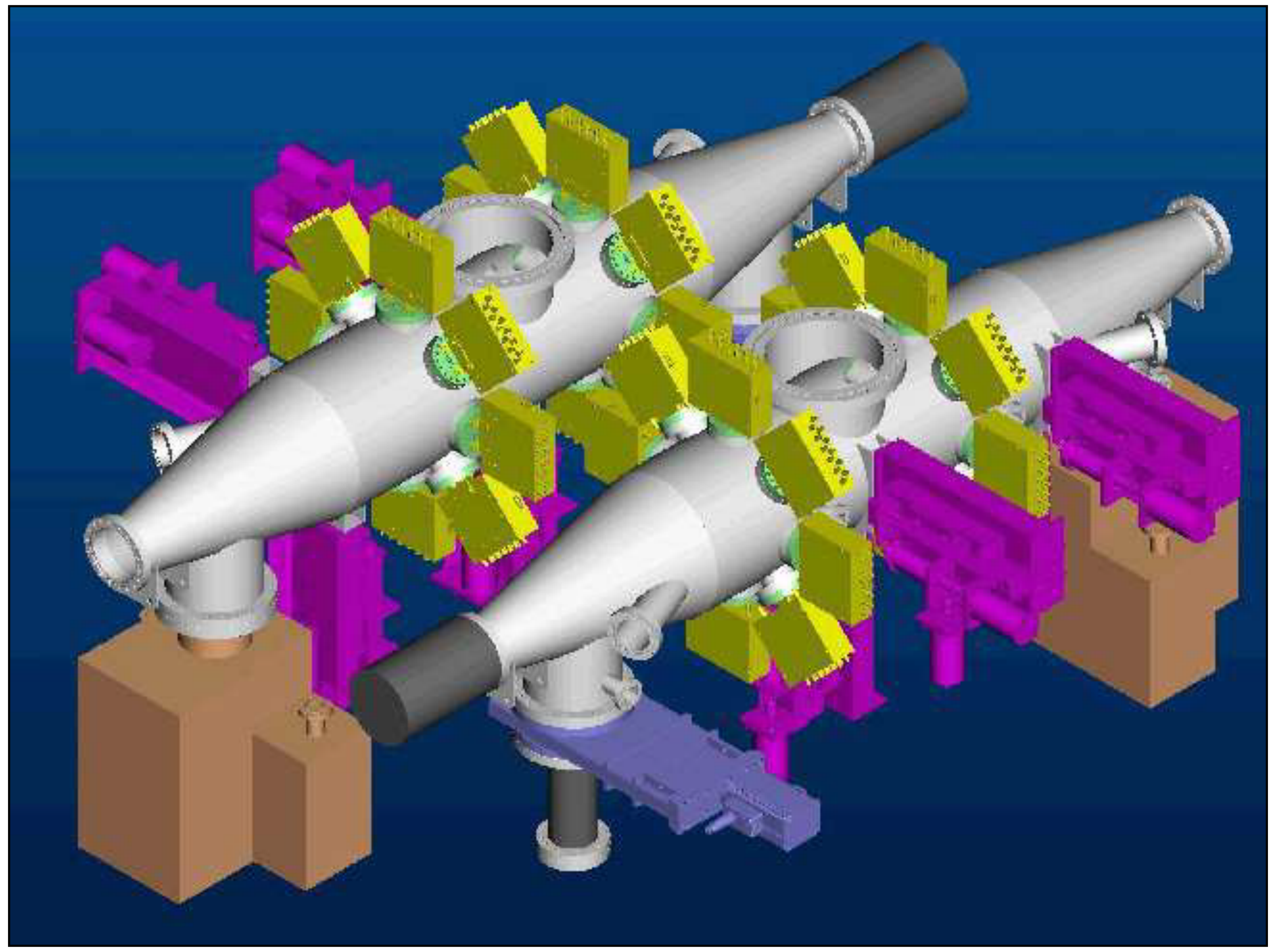


Carbon Fiber Polarimeter

- CNI polarimeter. Tiny Q^2: C recoil at 90º.
- Ultra-thin ribbon moves rapidly across the beam
    - ~10um x 100nm
    - manageable heat
    - negligible beam loss
    - negligible Pol loss
    - $\Delta P/P \approx 4\,\%$ per sweep
- Target holder inside the beam pipe
- pC≠pp, so needs external calibration
- Normalize to Hjet data







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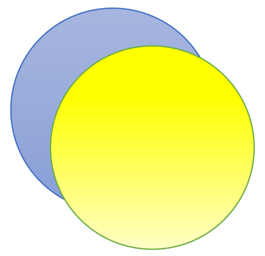
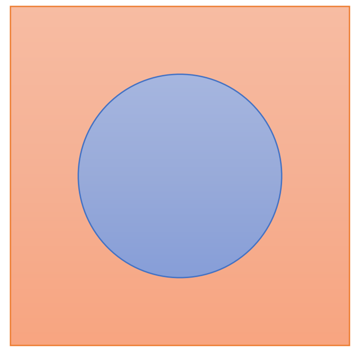
Carbon Fiber Polarimeter

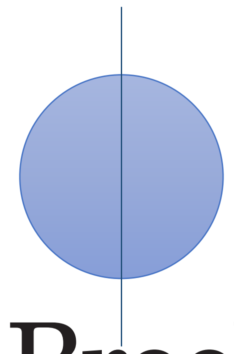
- Fiber correlates (x,P,I): We can get a polarization profile and intensity profile in one go!
- Monitor P losses as a function of position ==> improved luminosity-weighter polarization



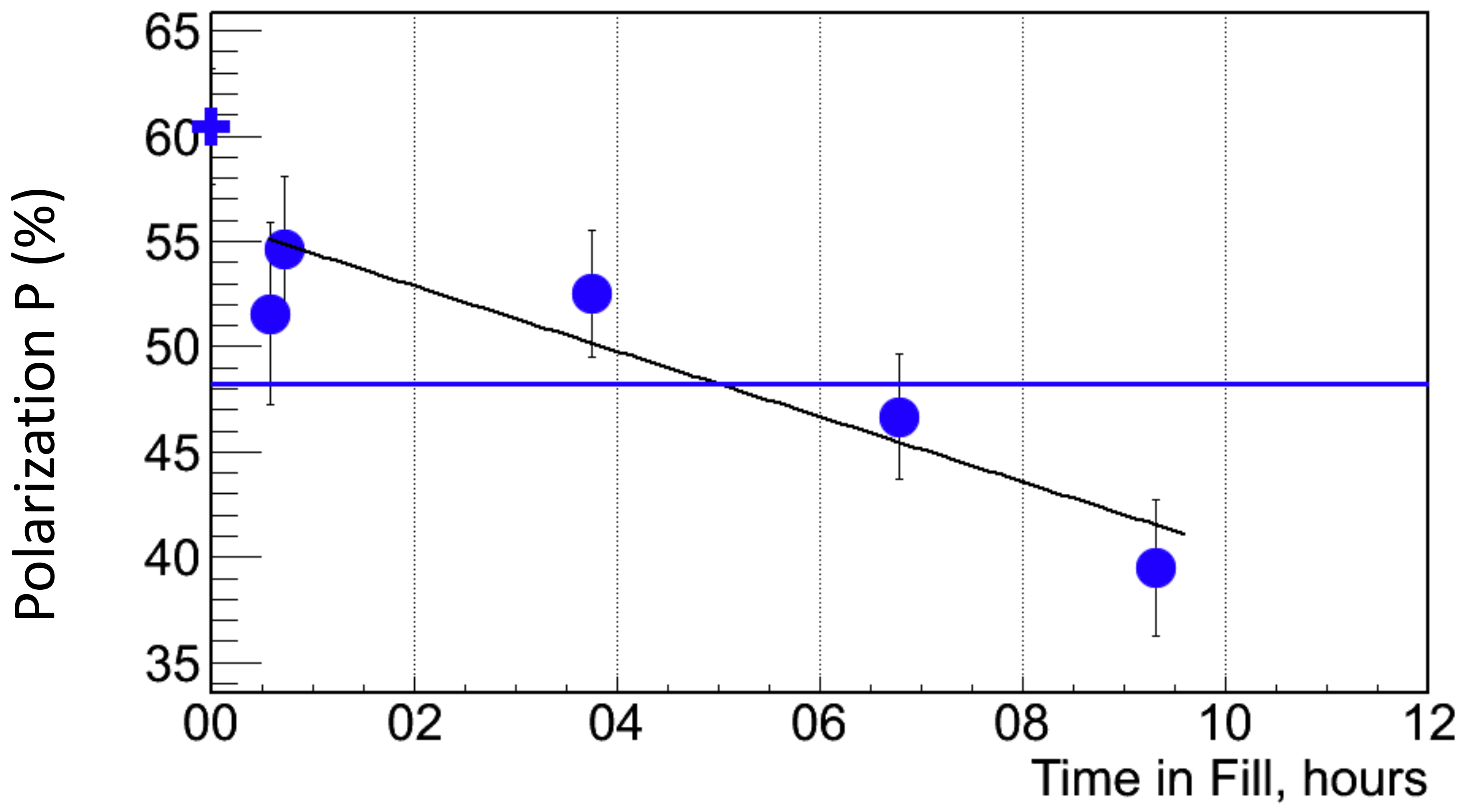
$$P_{coll} = \frac{\int dxdy P(x,y) I_B(x,y) I_Y(x,y)}{\int dxdy I_B(x,y) I_Y(x,y)}$$

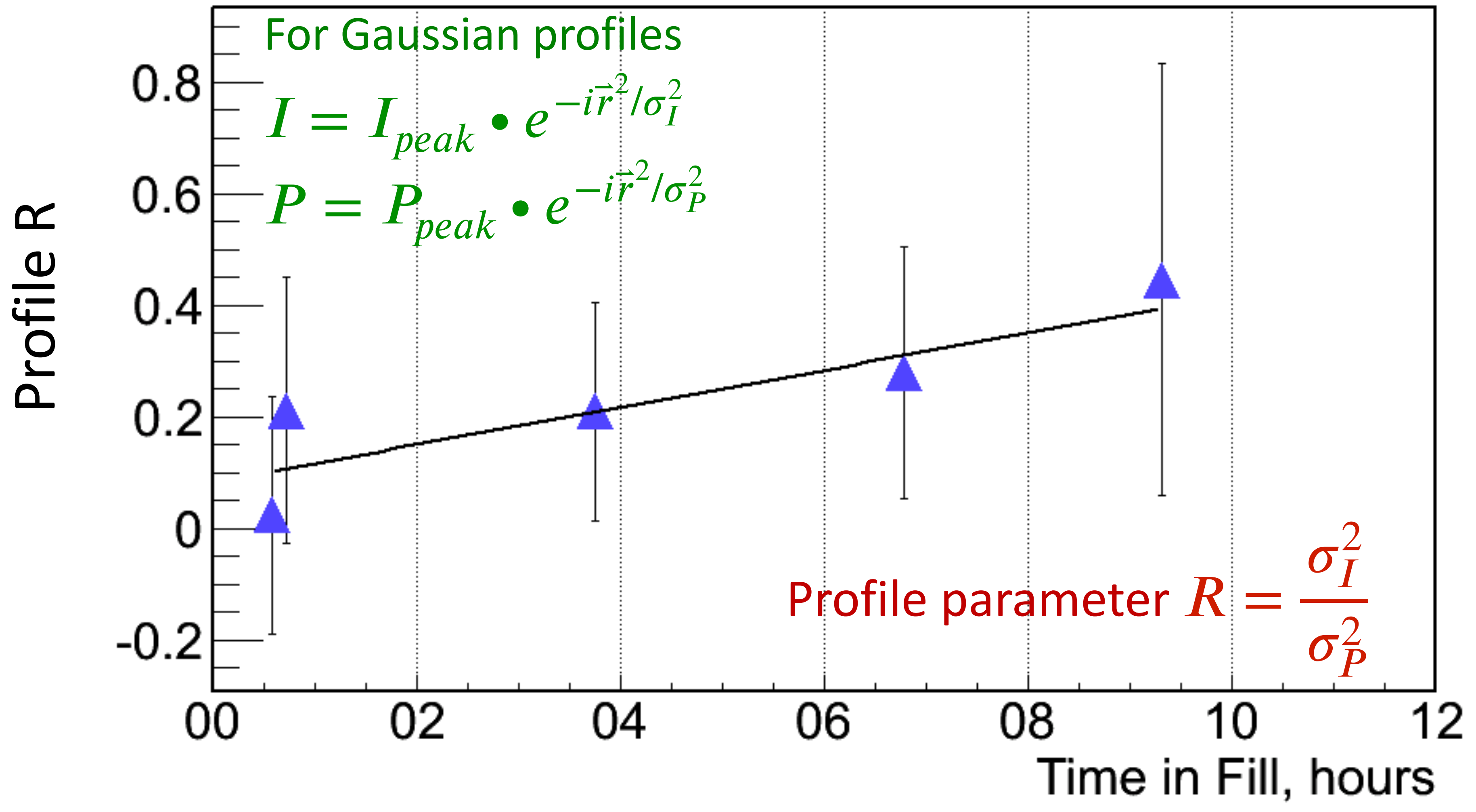


$$P_{jet} = \frac{\int dxdy P(x,y) I_B(x,y)}{\int dxdy I_B(x,y)}$$



$$P_{sweep} = \frac{\int dy P(y) I_B(y)}{\int dy I_B(y)}$$





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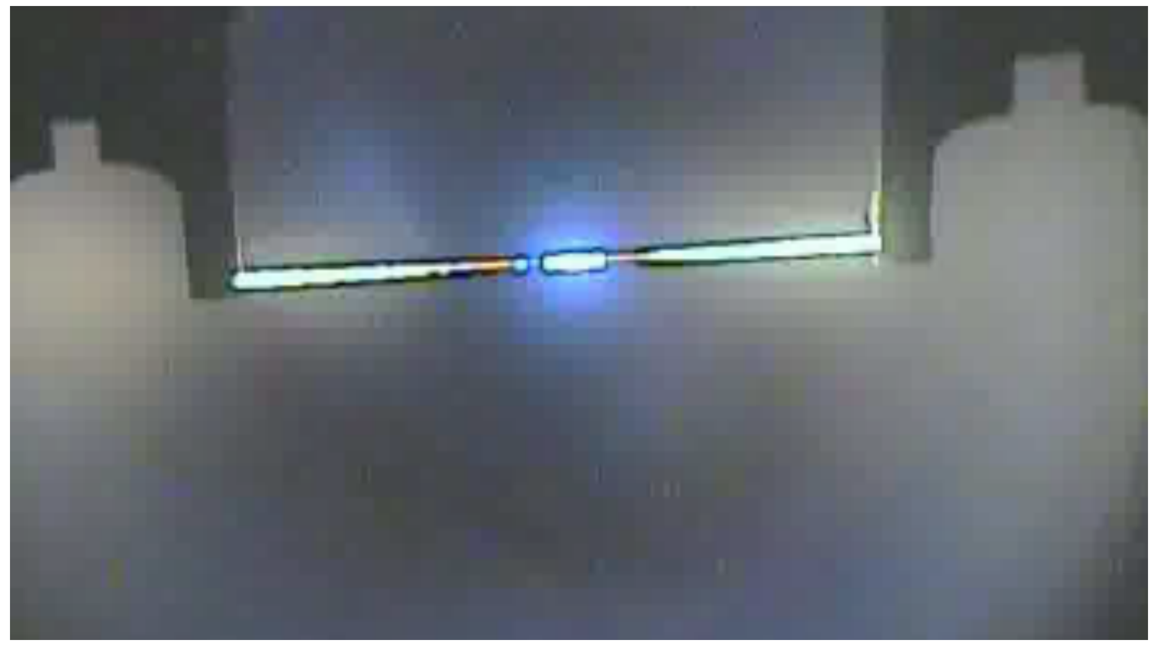
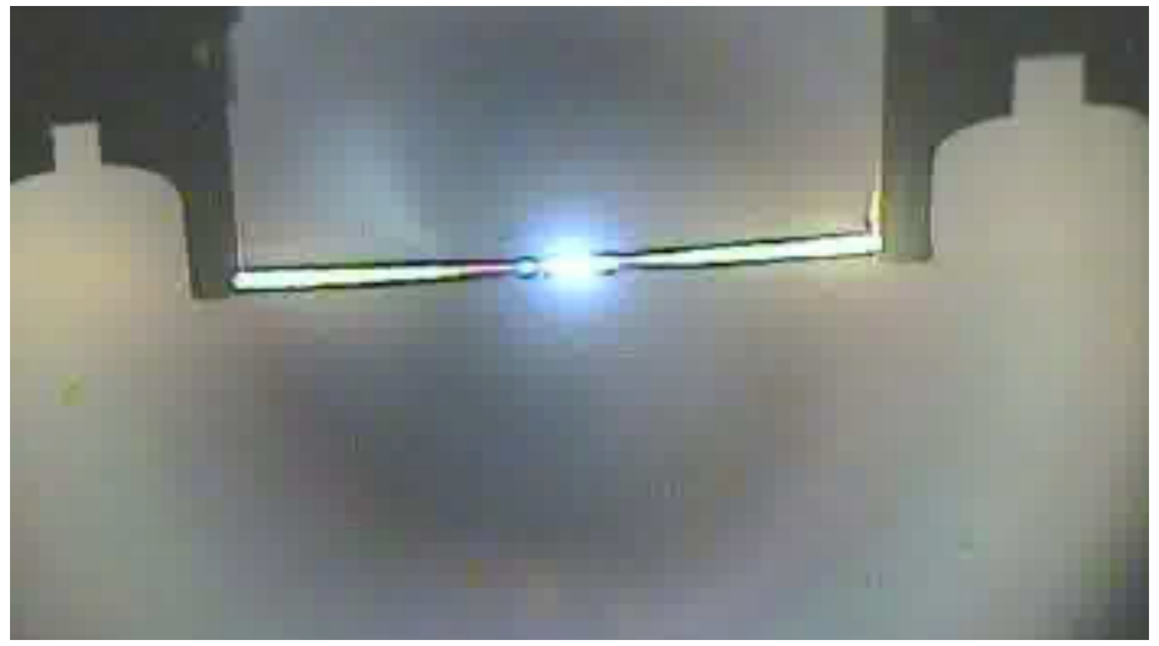
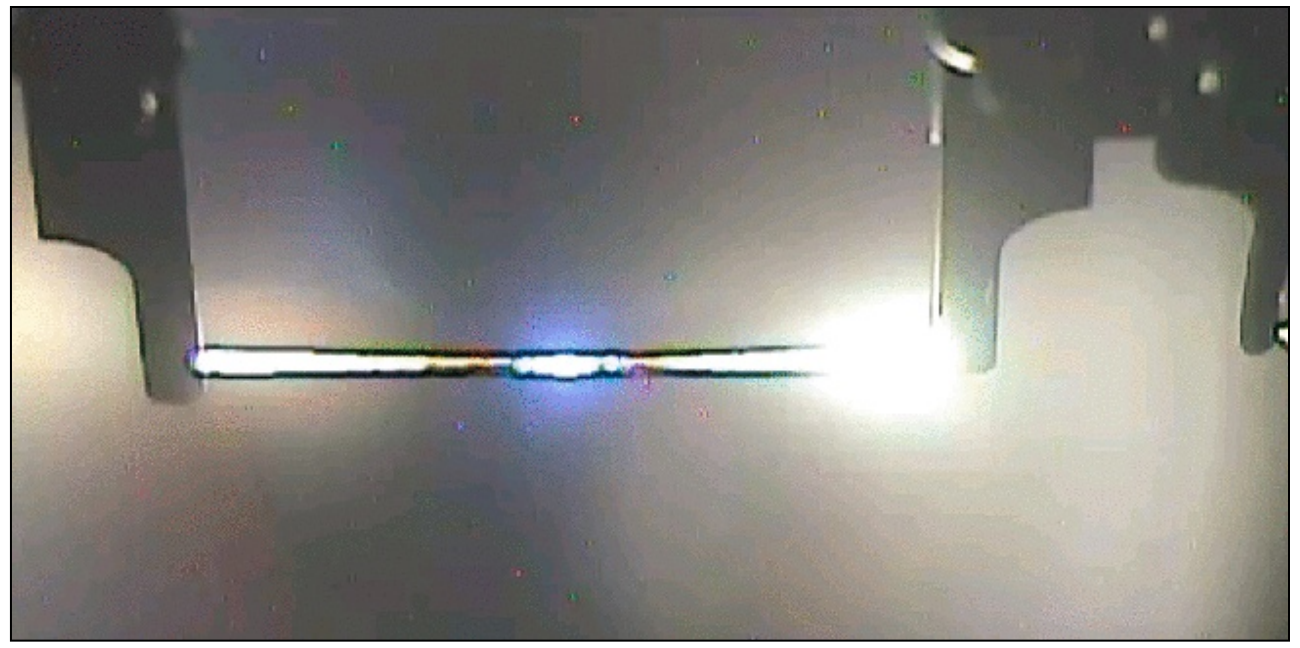
Carbon Fiber Polarimeter





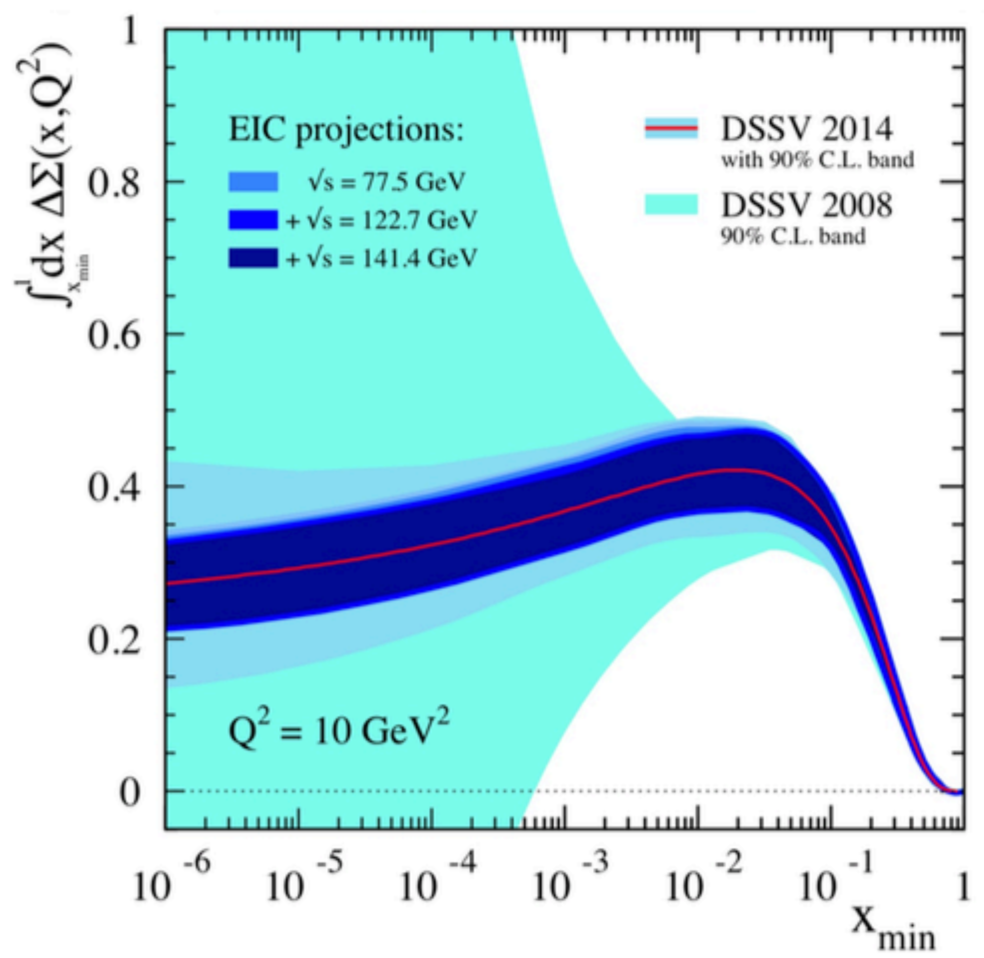


- EIC's high-intensity, high-E environment will put stress on the fiber target:
  - More beam energy deposited in the fiber
  - More electrostatic attraction = more mechanical stress
  - More wakefield induction on target ends
  - Targets will have a limited lifetime

Summary

- To investigate the spin structure of p (d, n, ...) we need polarized beams.
- EIC wants precision: higher intensity, higher polarization, and more precise measurement of polarization
- Polarized sources: OPPIS, EBIS, PES*: Prototypes or more exist for each
- Techniques to accelerate and preserve beams: reuse and expand on RHIC
- ep Polarimetry (analyzing power): reuse and improve.

$$\frac{1}{2} = \underbrace{\frac{1}{2}\sum_q \Delta Q}_{\text{quarks}} + \underbrace{\Delta G}_{\text{gluons}} + \underbrace{L_q + L_g}_{\text{orbital motion}}$$



Beam	Bunch intensity	injection Pol %	Study	Polarimeter	Source Principle
H^+	2E+11	~80%	low-x proton structure	CNI: HJET, pC	laser polarize e-, HF transfer to nucleus
$^3He^{++}$	2E+11	>80%	neutron structure	HJET?	laser polarize e-, HF transfer to nucleus
d^+	2E+11	~90%	tensor nuclear (s=1) structure	?	Stern-Gerlach *(not in these slides)*
e^-	*1.7E+11* 6.3E+10	~85%	***everything!***	Mott, Compton	Polarized photo-electric effect

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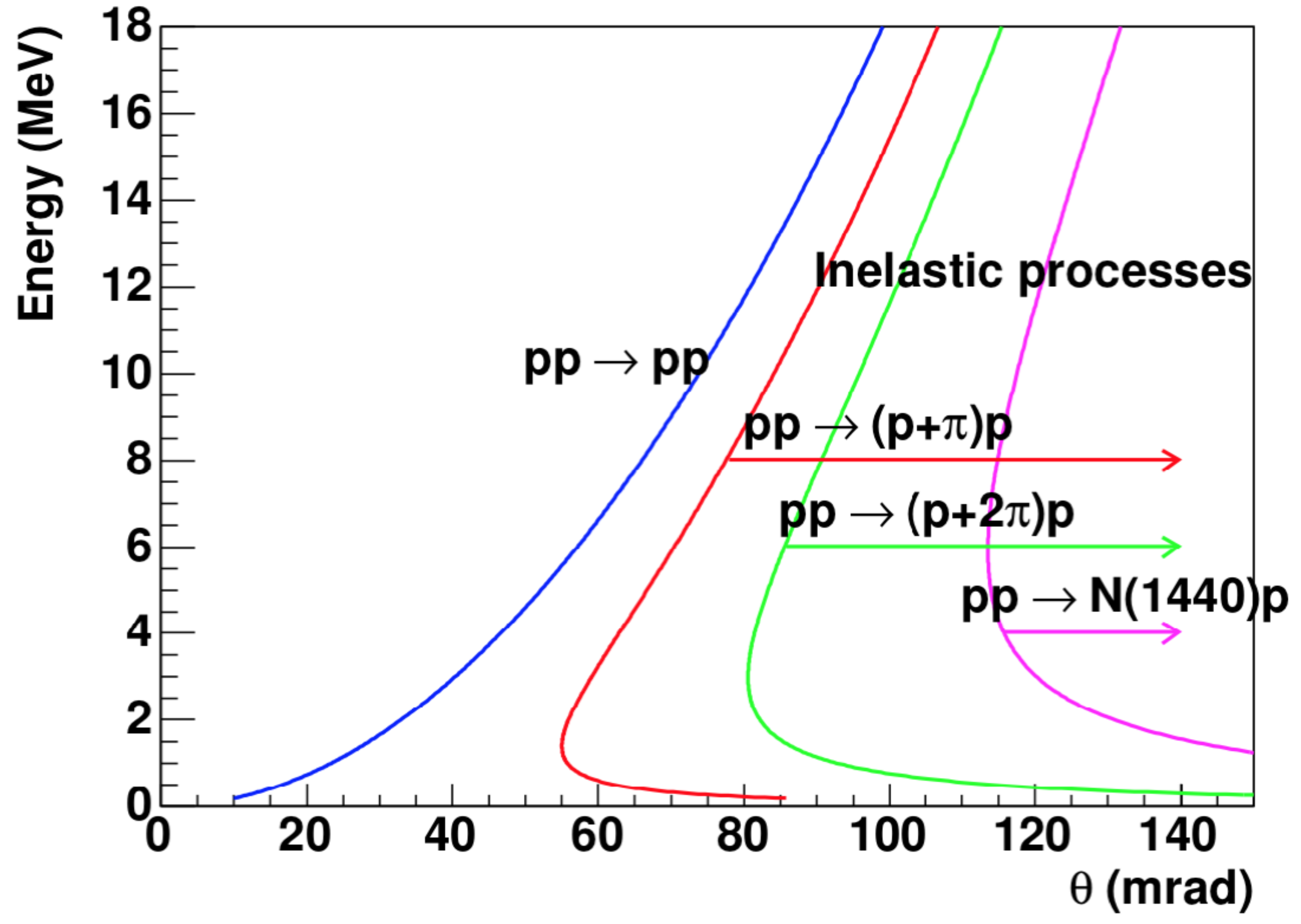
What's Next?

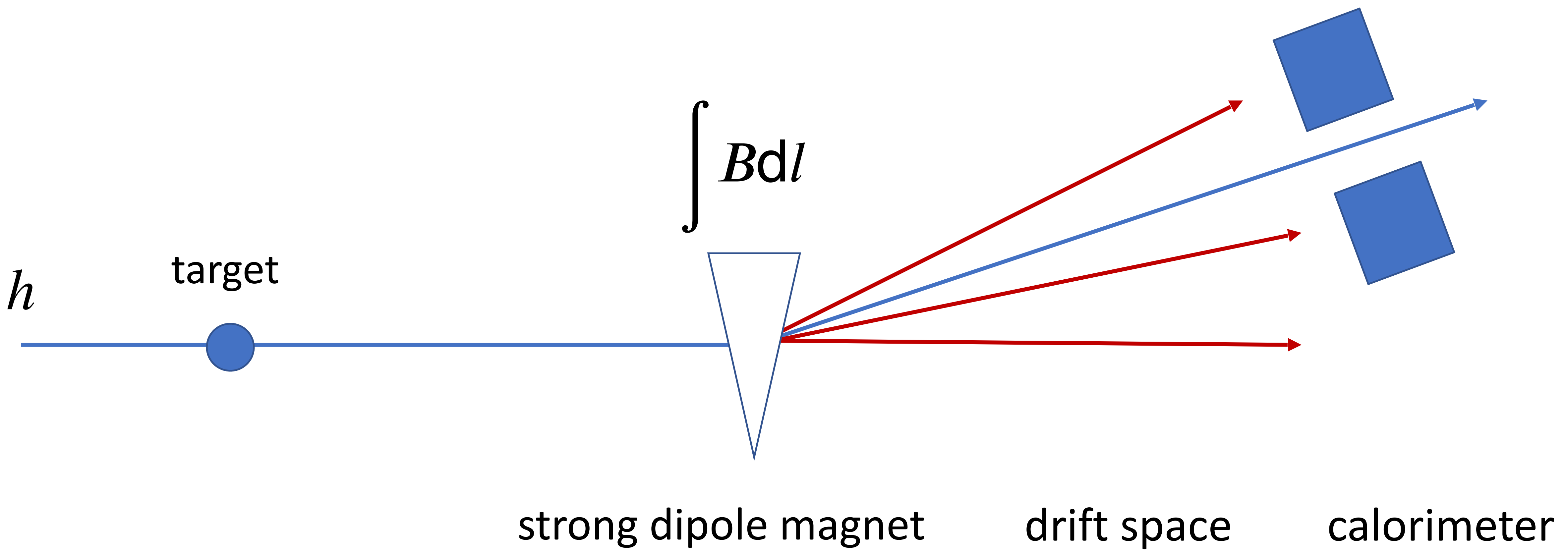
- Compton Polarimeter for the Rapid Cycling Synchrotron
- Investigate depolarization in Hjet due to beam wakefield
- More resilient carbon fibers
- Polarimetry for the other ions?

Light Ion Polarimetry at EIC

- Polarized d and h beams are not part of the EIC baseline design.
- Absolute polarization will (likely) require a polarized target.
  - Elastic scattering needed for sign-flip of A_N
  - Breakup energy is only 5.5 MeV: problematic if beam breaks up $3\text{He (h)} \rightarrow pd$
  - Or intentionally break it up in HJET and detect products ($pp \rightarrow pp\pi$)
  - Tag/veto breakup products downstream of the polarimeter
  - Identical particle target?

threshold for $pp \rightarrow pp\pi$





$p: e/m = 1$

$h: e/m = 2/3$

$d: e/m = 1/2$

$n: e/m = 0$

Polarized Scattering Minutiae

- Four a particular spin configuration, the matrix element is:

$$|\mathcal{M}|^2 \propto [\bar{u}(p', s')\gamma^\mu u(p, s)]\,[\bar{u}(p, s)\gamma^\nu u(p', s')]$$

- Where u(p,s) is a four-component vector:

$$u(p, s) = \sqrt{E+m}\begin{pmatrix}\chi_s \\ \frac{\sigma\cdot p}{E+m}\chi_s\end{pmatrix} \qquad \sigma = (\sigma_x, \sigma_y, \sigma_z)$$

$$\sigma\cdot p = \sigma_x p_x + \sigma_y p_y + \sigma_z p_z = \begin{pmatrix} p_z & p_x - ip_y \\ p_x + ip_y & -p_z \end{pmatrix}$$

- so at rest we have solutions like this:

$$u(0, \uparrow) = \sqrt{2m}\begin{pmatrix}1\\0\\0\\0\end{pmatrix} \qquad u^{(3)}(0) = \sqrt{2m}\begin{pmatrix}0\\0\\1\\0\end{pmatrix}$$

- and the bar is the adjoint.

$$\bar{u} = u^\dagger\gamma^0$$

- (and there are also two more solutions where the nonzero element is in the bottom two. These correspond to the negative-energy solutions -- in which holes are antiparticles.)

Polarized Scattering: Gritty Details

I'm not a theorist but I play one on TV

- If the initial and final states are completely known, ep→e'X :

$$d\sigma \propto \delta^4(p + P - p' - p_X)|\mathcal{M}|^2$$

- matrix element is*:

$$\mathcal{M} = [(\bar{u}(p', s')(-ie\gamma^\mu)u(p, s)] \frac{-ig_{\mu\nu}}{q^2} \langle X| J^\nu_{\text{had}} |P, S\rangle$$

- So dσ is zero or propto:

$$|\mathcal{M}|^2 = \frac{e^4}{q^4}[\bar{u}(p', s')\gamma^\mu u(p, s)\bar{u}(p, s)\gamma^\alpha u(p', s')] \cdot [\langle P, S| J_{\mu,\text{had}} |X\rangle \langle X| |J_{\alpha,} |P, S\rangle^*]$$

- Decompose into Leptonic and Wadronic tensors:

$$L_{\mu\alpha}(s, s') = [\bar{u}(p', s')\gamma^\mu u(p, s)\bar{u}(p, s)\gamma^\alpha u(p', s')]$$

$$W^{\mu\alpha}(S, X) = [\langle P, S| J_{\mu,\text{had}} |X\rangle \langle X| J_{\alpha,} |P, S\rangle^*]$$

- if we knew initial and final states entirely, we could measure M2, factor out $L_{\mu\alpha}(s, s')$, hand sets of $W^{\mu\alpha}(S, X)$ functions over to theorists and let them compare to QCD calculations, but...

$$|\mathcal{M}|^2 = \frac{e^4}{q^4} L_{\mu\alpha}(s, s') W^{\mu\alpha}(S, X)$$

Polarized Scattering: Grittier Details

The final state is not completely known.

- Sum over the unknowns: In inclusive DIS, we take all possible final states.

$$d\sigma \propto \sum_X \delta^4(p + P - p' - p_X)|\mathcal{M}|^2$$

- And generally can't tell the e- spin state

$$d\sigma \propto \sum_{s'} \sum_X \delta^4(p + P - p' - p_X)|\mathcal{M}|^2$$

- In practice we absorb these sums into the tensors

$$L_{\mu\alpha}(s) = \sum_{s'} [\bar{u}(p', s')\gamma_\mu u(p, s)] [\bar{u}(p, s)\gamma_\alpha u(p', s')]$$

$$W^{\mu\alpha}(S) = \sum_X \delta^4(p + P - p' - p_X) [\langle P, S| J_\mu |X\rangle \langle X| J_\alpha |P, S\rangle]$$

$$d\sigma \propto |\mathcal{M}|^2$$

- And keep the matrix element tidy

$$|\mathcal{M}|^2 = \frac{e^4}{q^4} L_{\mu\alpha}(s) W^{\mu\alpha}(S)$$

Polarized Scattering: Grittier Details

The initial state is also not known

- We handle this with a spin density matrix ρ_e
- And replace our pure matrix with the new one:
- Use the QFT identity (and let's pick longitudinally polarized): $\rho_e = \frac{1}{2}(\not{p} + m_e)(1 + P\gamma^5)$
- Just some math now:
  - Rearrange (remember u, ubar are row and column matrices!) and spot the complete set of states $\sum_{s'} u_j(p', s')\bar{u}_k(p', s') = (\not{p}' + m_e)_{jk}$
  - Apply trace rules and distribute (m_e~0)
- We have a symmetric (spin-independent) and antisymmetric (spin-dependent) part:

$$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i| = \frac{1}{2}(\not{p} + m)(1 + \gamma^5 \not{s})$$

$$p_i \neq \delta_{ix}$$

$$L^{\text{mix}}_{\mu\alpha} = \sum_{s'} \left[\bar{u}(p', s')\gamma_\mu \left(\sum_s p_s\, u(p, s)\bar{u}(p, s) \right) \gamma_\alpha u(p', s') \right]$$

$$L^{\text{mix}}_{\mu\alpha} = \sum_{s'} u_j(p', s')\bar{u}_k(p', s')(\gamma_\mu)_{kl} \left[\frac{1}{2}(\not{p} + m_e)(1 + P\gamma^5) \right]_{li} (\gamma_\alpha)_{ij}$$

$$L^{\text{mix}}_{\mu\alpha} = (\not{p}' + m_e)_{jk}(\gamma_\mu)_{kl} \left[\frac{1}{2}(\not{p} + m_e)(1 + P\gamma^5) \right]_{li} (\gamma_\alpha)_{ij}$$

$$L^{\text{mix}}_{\mu\alpha} = \text{Tr} \left[(\not{p}' + m_e)\gamma_\mu \cdot \left[\frac{1}{2}(\not{p} + m_e)(1 + P\gamma^5) \right] \cdot \gamma_\alpha \right]$$

$$L^{\text{mix}}_{\mu\alpha} = \frac{1}{2}\text{Tr}\left[\not{p}'\gamma_\mu \not{p}\gamma_\alpha\right] + \frac{1}{2}P\text{Tr}\left[\not{p}'\gamma_\mu \not{p}\gamma^5\gamma_\alpha\right]$$

$$L^{\text{mix}}_{\mu\alpha} = L^{\text{S}}_{\mu\alpha} + L^{\text{A}}_{\mu\alpha}$$

Polarized Scattering: Putting it Together

- We can do the same sort of thing with the hadronic tensor, but the Dirac identities aren't valid here
- So we insert the density matrix,
- ... and then get stuck.
- Since we can't go from first principles, let's work backward from the most general W we can have:
- We can't just separate terms, but we can access these terms by measuring, then measuring again with a flipped spin, and comparing.

$$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i| = \frac{1}{2}(\not{p}+m)(1+\gamma^5\not{s})$$

$$W^{\mu\alpha}(S) = \sum_X \delta^4(p+P-p'-p_X)\left[\langle P,S|\,J_\mu\,|X\rangle\,\langle X|\,J_\alpha\,|P,S\rangle\right]$$

$$W^{\mu\alpha}_{\text{mix}} = \sum_X \left[\delta^4(p+P-p'-p_X)\left(\sum_i p_i\,|P,S_i\rangle\,\langle P,S_i|\right)J_\mu\,|X\rangle\,\langle X|\,J_\alpha\right]$$

$$W^{\mu\alpha}(S) = W^{\mu\alpha}_{\text{S}} + W^{\mu\alpha}_{\text{A}}$$

$$W^{\mu\alpha}_{\text{A}} = \frac{i}{P\cdot q}\epsilon^{\mu\alpha\rho\sigma}q_\rho\left[S_\sigma \mathbf{g_1}(\mathbf{x},\mathbf{Q^2}) + \left(S_\sigma - \frac{S\cdot q}{P\cdot q}P_\sigma\right)\mathbf{g_2}(\mathbf{x},\mathbf{Q^2})\right]$$

$$d\sigma(P_e,P_h) \propto L_{\mu\alpha} = L^{\text{S}}_{\mu\alpha}W^{\mu\alpha}_{\text{S}} + L^{\text{A}}_{\mu\alpha}(P_e)W^{\mu\alpha}_{\text{A}}(P_h)$$

Polarized Scattering: Asymmetry

- In our +helicity mixed state beam there are some e- in the wrong direction.
- Define Average Beam Polarization Pe:
- We can tease out the N+ and N-
- The observed xs depends on the population
- But we can write it in terms of its pure-helicity xs
- Consider two mixed states. One with pol Pe, one with -Pe.
- We can connect these back to the pure states, and back to the structure functions
- Must measure polarization!
- Overall uncertainty scales with Pe, PT unc.

$$d\sigma(P_e, P_h) \propto L_{\mu\alpha} = L^{\mathrm{S}}_{\mu\alpha} W^{\mu\alpha}_{\mathrm{S}} + L^{\mathrm{A}}_{\mu\alpha}(P_e) W^{\mu\alpha}_{\mathrm{A}}(P_h)$$

$$P_e = \frac{N^+ - N^-}{N^+ + N^-} \qquad N_{\mathrm{tot}} = N^+ + N^-$$

$$N^+ = \frac{1}{2} N_{\mathrm{tot}}(1 + P_e) \quad \text{and} \quad N^- = \frac{1}{2} N_{\mathrm{tot}}(1 - P_e)$$

$$\sigma_{\mathrm{mix}} = \frac{N^+ \sigma^+ + N^- \sigma^-}{N^+ + N^-}$$

$$\sigma_{\mathrm{mix}} = \frac{1}{2}(1 + P_e)\sigma^+ + \frac{1}{2}(1 - P_e)\sigma^- = \left(\frac{\sigma^+ + \sigma^-}{2}\right) + P_e \left(\frac{\sigma^+ - \sigma^-}{2}\right)$$

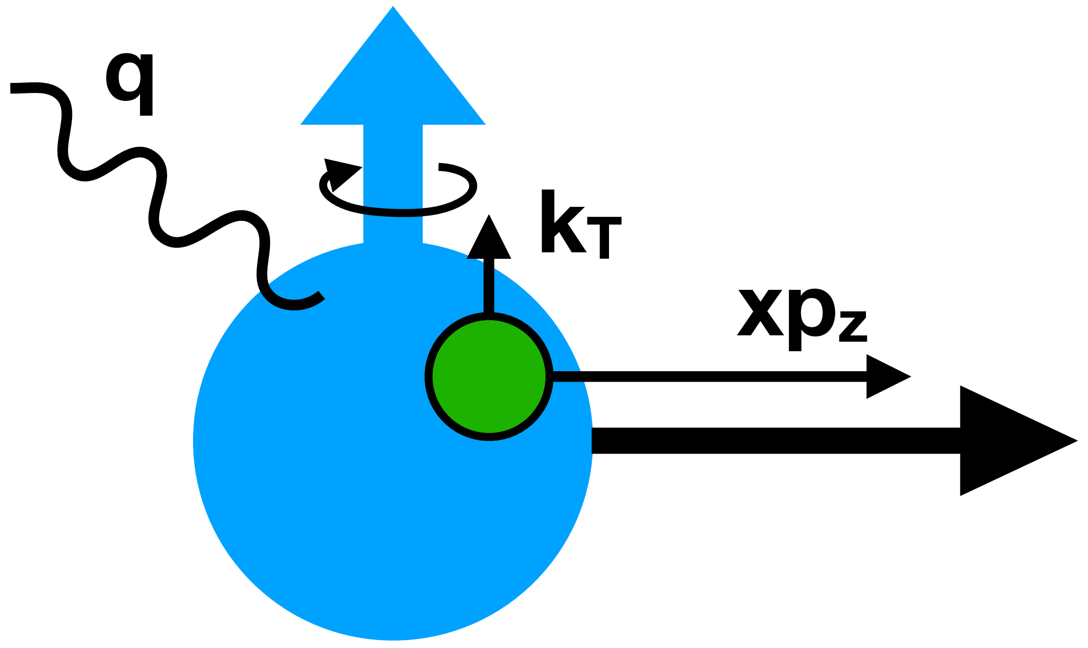
$$\sigma_{\mathrm{mix}}(+P_e) - \sigma_{\mathrm{mix}}(-P_e) = P_e(\sigma^+ - \sigma^-)$$

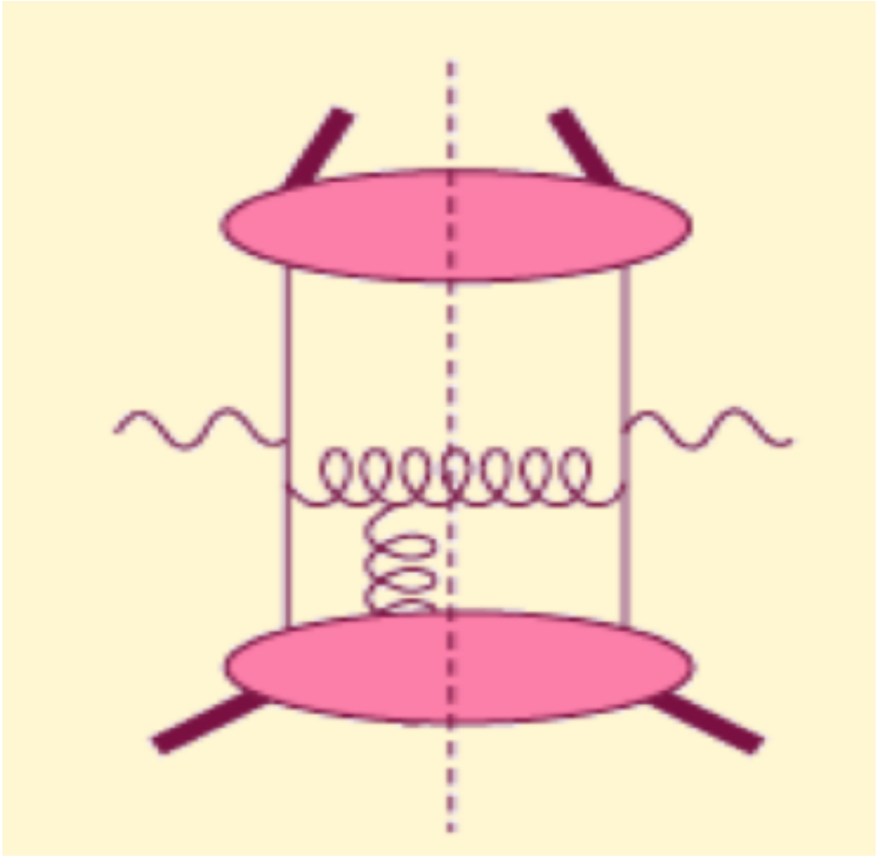
$$\sigma_{\mathrm{mix}}(+P_e) + \sigma_{\mathrm{mix}}(-P_e) = (\sigma^+ + \sigma^-)$$

$$A_{\mathrm{raw}} = \frac{\sigma_{\mathrm{mix}}(+P_e) - \sigma_{\mathrm{mix}}(-P_e)}{\sigma_{\mathrm{mix}}(+P_e) + \sigma_{\mathrm{mix}}(-P_e)} = P_e \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = P_e P_T \cdot f D(y) \frac{g_1(x, Q^2)}{F_1(x, Q^2)}$$

Describing Large TSSAs

- Two frameworks to describe large TSSAs:
  1. nonperturbative Transverse Momentum Dependent Functions:
     - explicit dependence on k_T
     - need access to both Q *and* k_T in observables
  2. Higher-twist effects:
     - Collinear: Single hard scale, pT
     - Twist-3: ~'NLO'. Matrix Element contains interference between two- parton and three-parton interactions.
       (eg Efremov, Teryaev, Qiu, Sterman)





- Some success relating these two approaches:

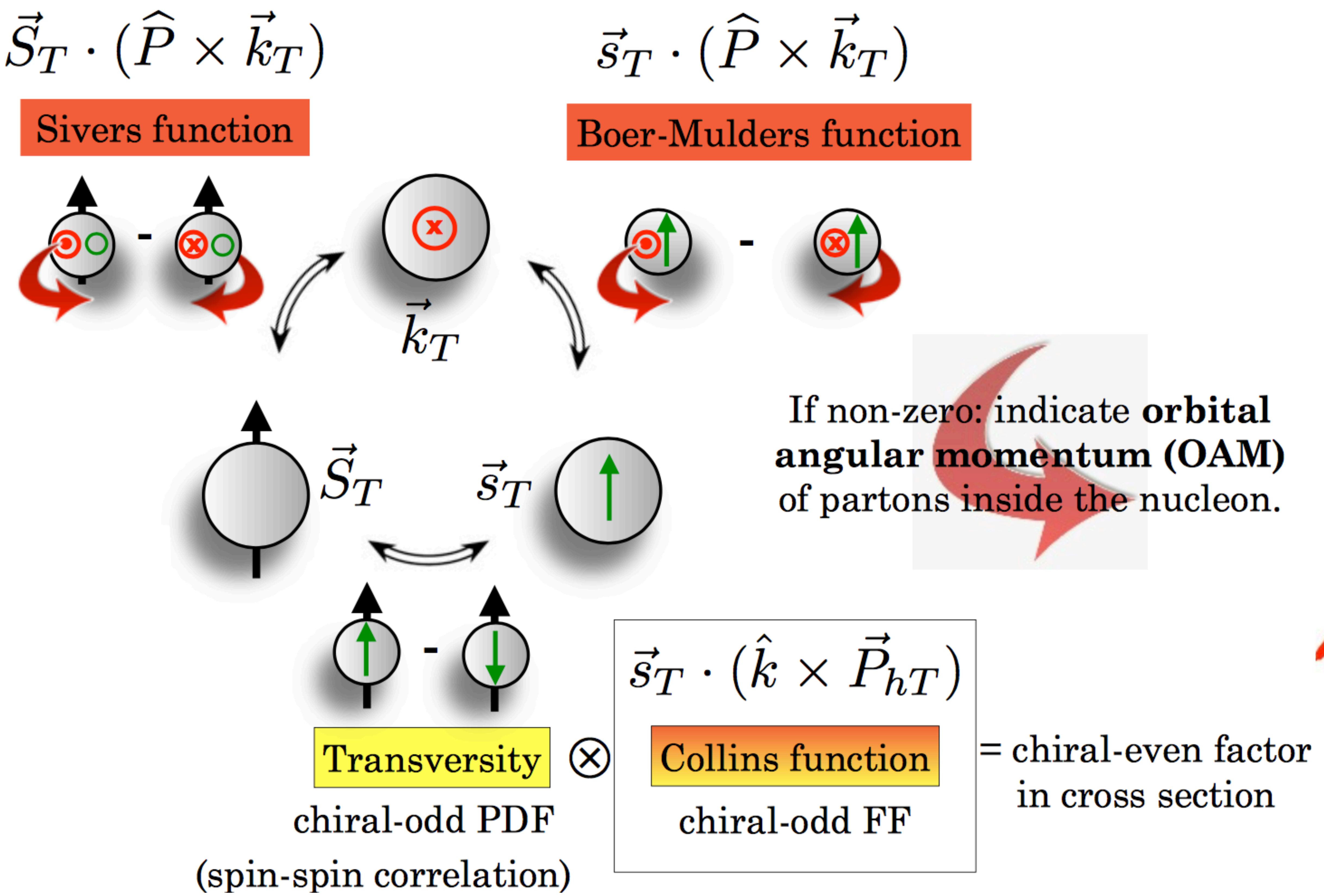
$$-\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x, k_\perp^2)|_{SIDIS} = T_{q,F}(x, x)$$

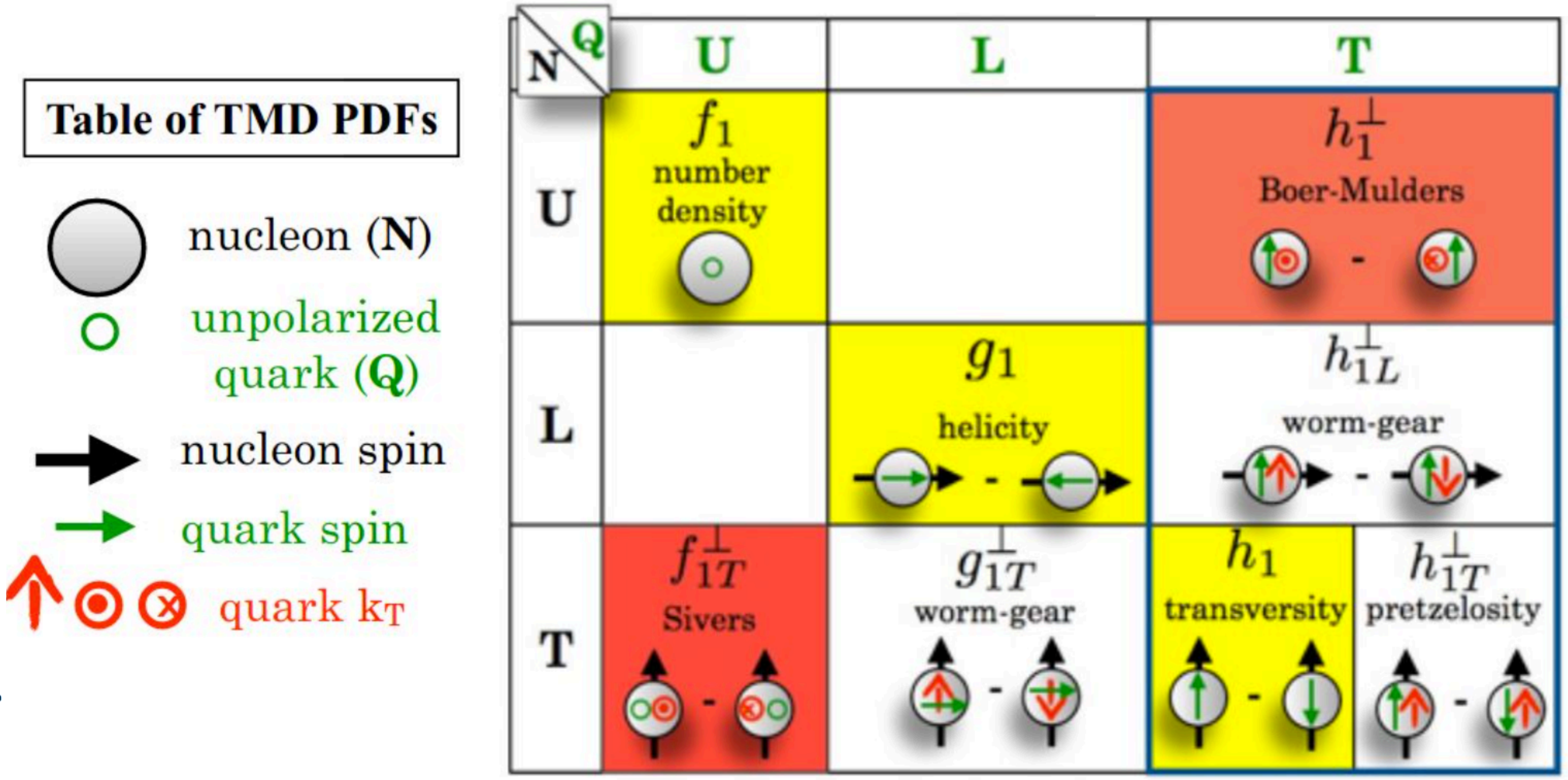
Sivers TMD <==> ETQS

Stony Brook University

Center for Frontiers in Nuclear Science

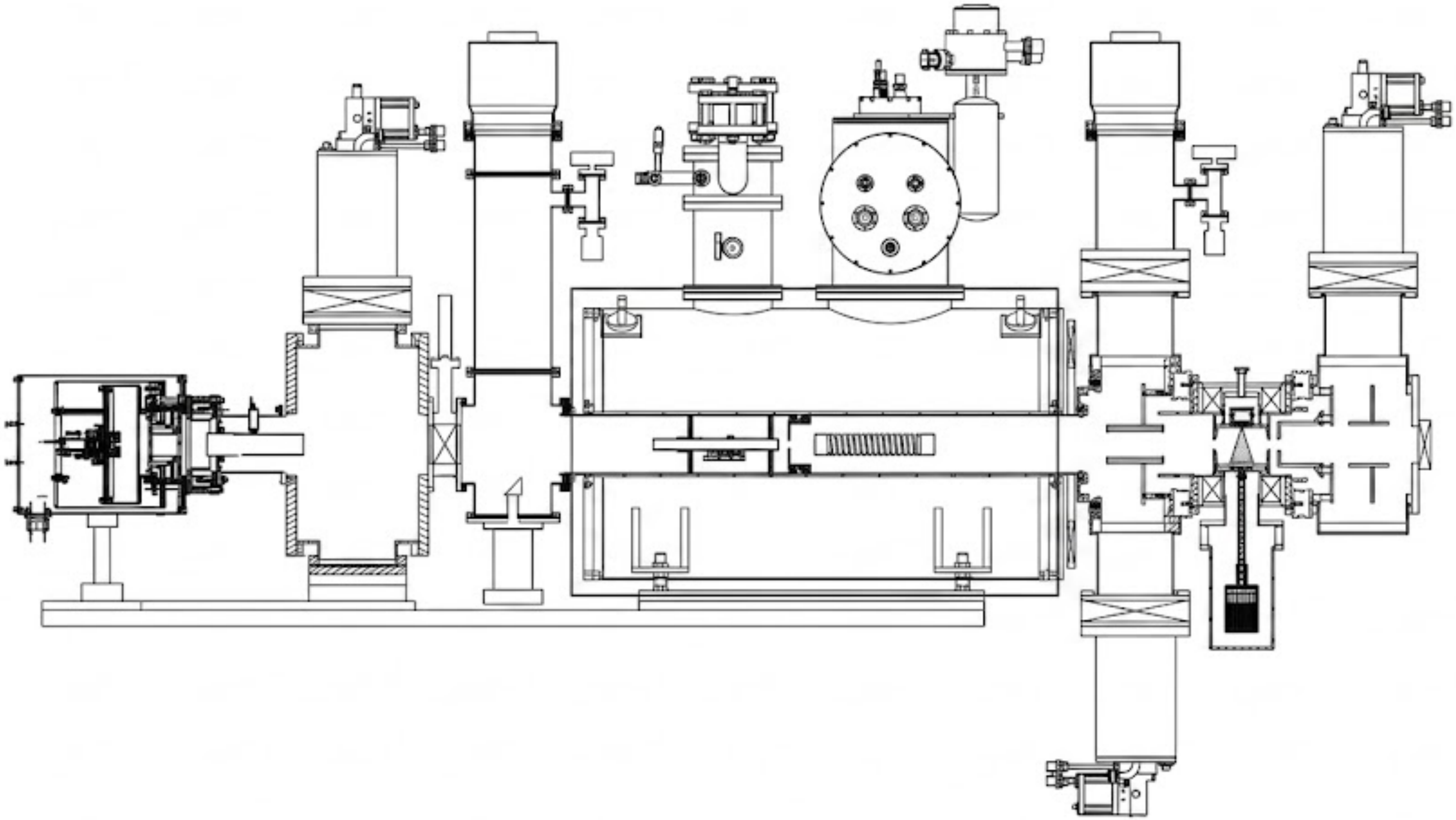
TMDs



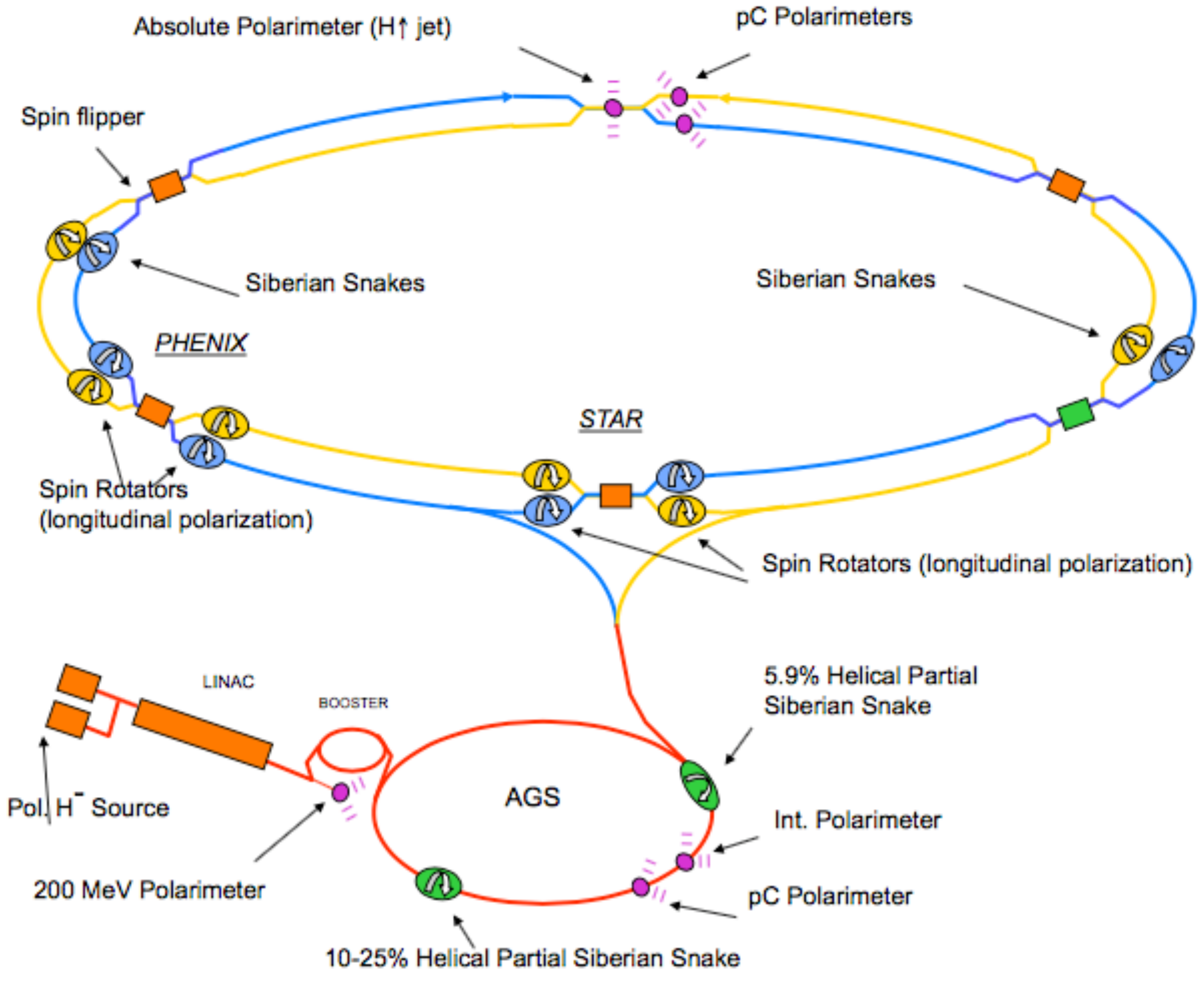


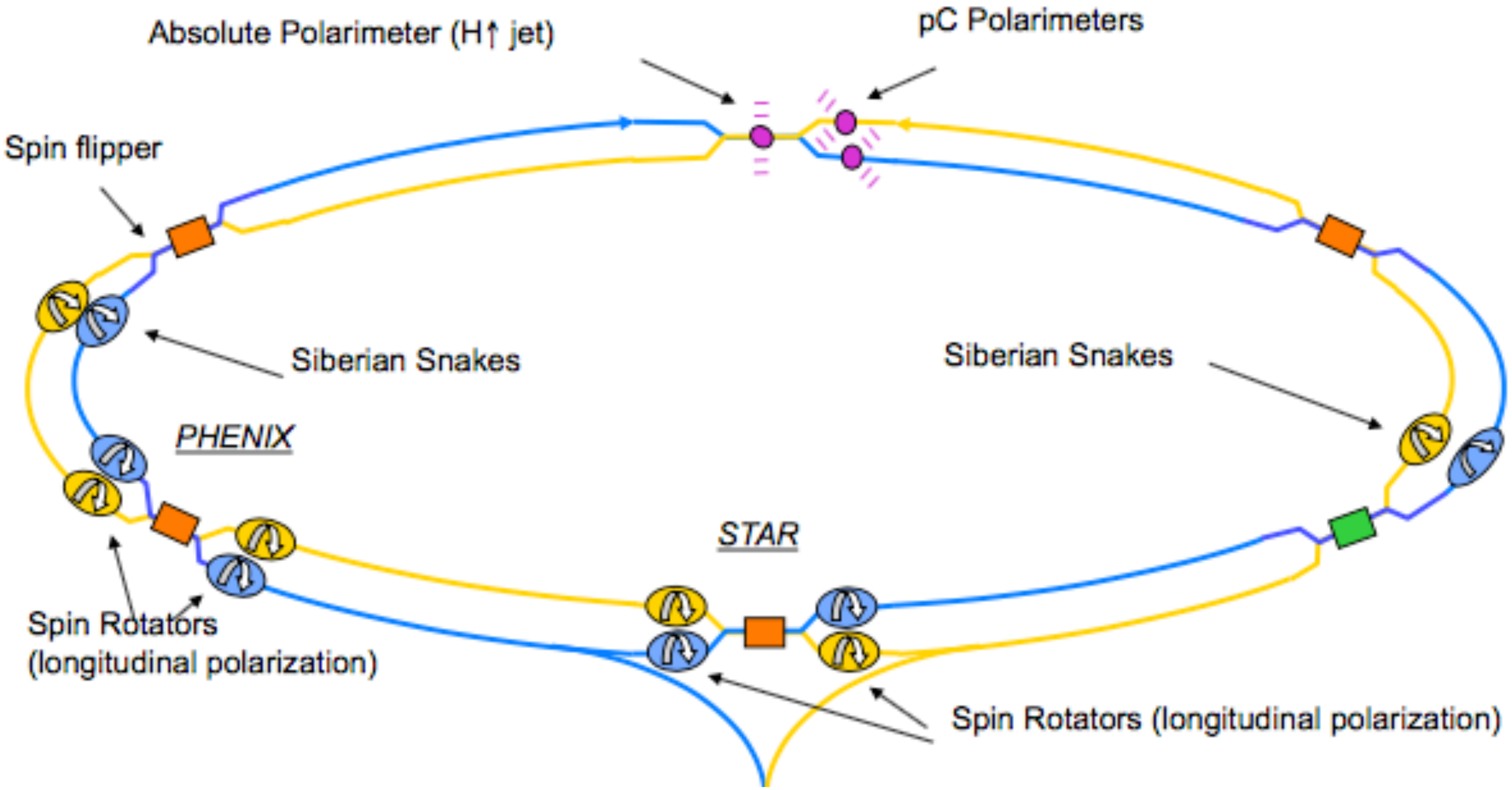
Graphics from Caroline Riedl's APS 2016 Talk

OPPIS (Blank Version...)



RHIC Ring


Absolute Polarimeter (H↑ jet)
pC Polarimeters
Spin flipper
Siberian Snakes
Siberian Snakes
PHENIX
STAR
Spin Rotators
(longitudinal polarization)
Spin Rotators (longitudinal polarization)
LINAC
BOOSTER
5.9% Helical Partial
Siberian Snake
Pol. H⁻ Source
AGS
Int. Polarimeter
200 MeV Polarimeter
pC Polarimeter
10-25% Helical Partial Siberian Snake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