Fundamental Symmetries
and
Weak Interaction through Parity Violation

(Particularly with Polarized Electron Scattering)

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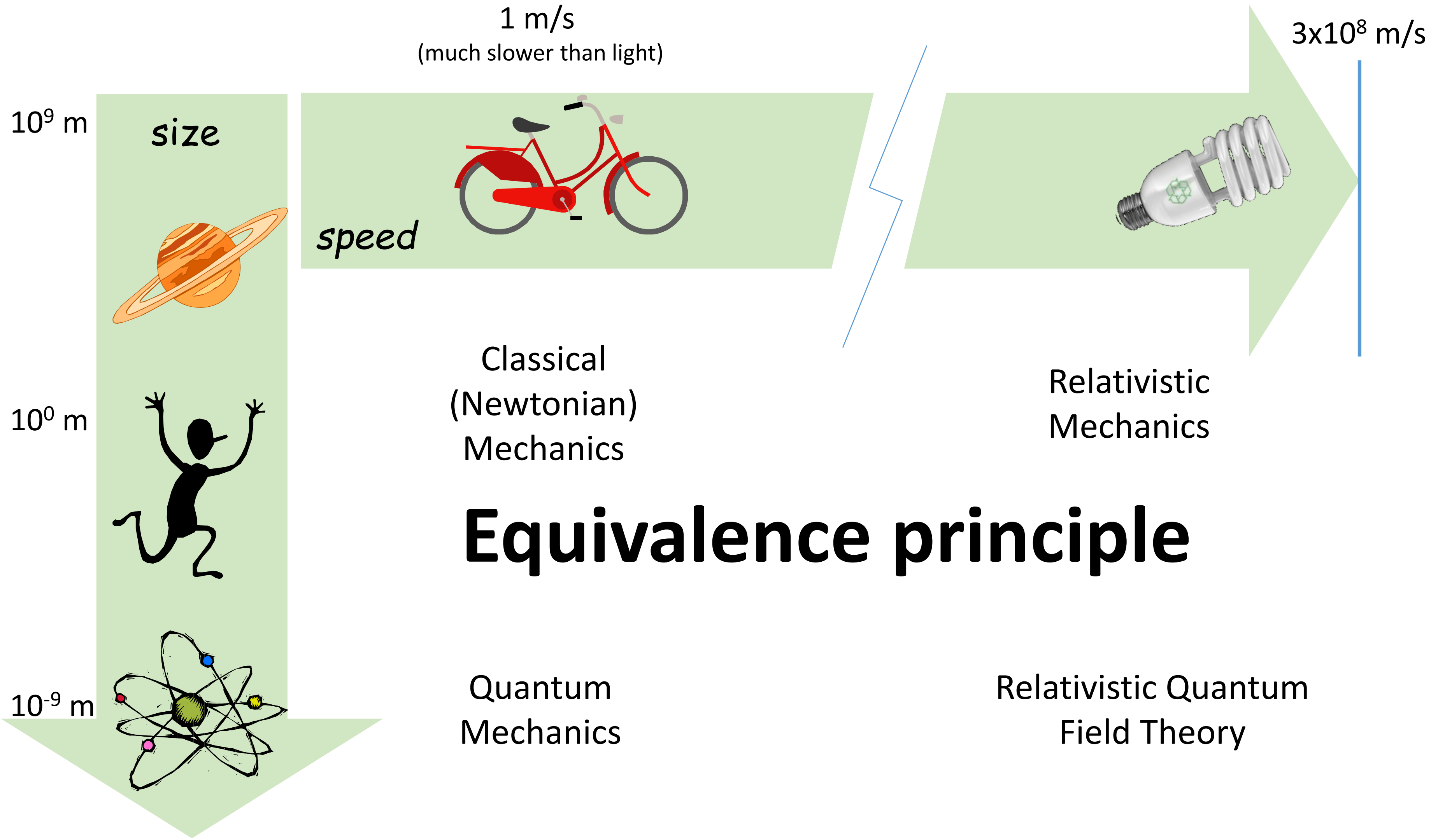
Modern Physics



Quantum Mechanics from Classical Mechanics

Matrix formulation of Hamiltonian in classical mechanics
Canonical invariants – Poisson brackets are invariant under canonical transformations

$$[u, v]_{q,p} = \frac{\partial u}{\partial q_i}\frac{\partial v}{\partial p_i} - \frac{\partial u}{\partial p_i}\frac{\partial v}{\partial q_i}.$$

Poisson bracket is replaced by an appropriate commutator for quantum mechanics

Much of the formal structure of quantum mechanics is a close copy of the Poisson bracket formulation of classical mechanics

Position and momentum are conjugate variables (Heisenberg uncertainty principle)

$$p \rightarrow \hat{p} = -i\hbar\frac{\partial}{\partial x}$$

If I have seen further it is by standing on the sholders [*sic*] of Giants
Isaac Newton, 1676

Two components of L cannot simultaneously be canonical momenta

→ L_i and L_j can't have simultaneous eigenvalues but L_2 can be quantized with any one of the L_i

EM as a (Classical) Gauge Theory

$$\nabla \cdot \mathbf{E} = 4\pi\rho \qquad \nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{B} = \frac{1}{c}\left(4\pi\mathbf{J} + \frac{\partial \mathbf{E}}{\partial t}\right)$$

$$\mathbf{E} = -\nabla\phi$$

$$\mathbf{E} = -\nabla\phi - \frac{\partial \mathbf{A}}{\partial t}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\Box = \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \nabla^2$$

$$\Box\phi = \frac{\rho}{\epsilon_0}$$

$$\Box\mathbf{A} = \mu_0\mathbf{j}$$

$$A^\alpha = (\phi/c, \mathbf{A})$$

$$J^\alpha = \left(c\rho, j^1, j^2, j^3\right) = (c\rho, \mathbf{j})$$

$$\Box A^\alpha = \mu_0 J^\alpha$$

(Lorenz gauge $\partial_\alpha A^\alpha = 0$)

Scalar function $\psi(\vec{r}, t)$

$$\mathbf{A} \to \mathbf{A} + \nabla\psi$$

$$\varphi \to \varphi - \frac{\partial \psi}{\partial t}$$

Existence of arbitrary numbers of $\psi(\vec{r}, t)$ is the U(1) "gauge freedom"

(Coulomb gauge $\nabla \cdot \mathbf{A}(\mathbf{r}, t) = 0$)

$$\varphi(\mathbf{r}, t) = \frac{1}{4\pi\varepsilon_0}\int \frac{\rho(\mathbf{r}', t)}{R}\, \mathrm{d}^3\mathbf{r}'$$

$$\mathbf{A}(\mathbf{r}, t) = \nabla \times \int \frac{\mathbf{B}(\mathbf{r}', t)}{4\pi R}\, \mathrm{d}^3\mathbf{r}'$$

Local vs. Global

$$E_i = cF_{0i},$$

where c is the speed of light, and

$$B_i = -\frac{1}{2}\epsilon_{ijk}F^{jk},$$

where ϵ_{ijk} is the Levi-Civita tensor.

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu = \begin{bmatrix} 0 & -E_x/c & -E_y/c & -E_z/c \\ E_x/c & 0 & -B_z & B_y \\ E_y/c & B_z & 0 & -B_x \\ E_z/c & -B_y & B_x & 0 \end{bmatrix}$$

$$\mathcal{L} = -\frac{1}{4\mu_0}F_{\mu\nu}F^{\mu\nu} - J^\mu A_\mu$$

$$\psi(x) \rightarrow \psi(x)e^{i\alpha(x)},$$

$$A_\mu(x) \rightarrow A_\mu(x) - \frac{1}{q}\partial_\mu\alpha(x).$$

Introduce covariant derivative:

$$D_\mu = \partial_\mu + iqA_\mu(x)$$

Restore local symmetry; $F^{\mu\nu}$ and Lagrangian are unchanged

Gauge fields – introduced to restore local symmetry – dictate the form of the couplings

Quantized EM → QED

$$\mathcal{L} = \bar{\psi}\left(i\hbar c\,\gamma^{\alpha} D_{\alpha} - mc^2\right)\psi - \frac{1}{4\mu_0} F_{\alpha\beta} F^{\alpha\beta};$$

Creation and annihilation of particles

The fields

The four-vectors are Lorentz covariant solutions to the Dirac equation (relativistic generalization of the Schrodinger equation)

The conserved vector current is:

$$j^{\mu} = -e\bar{\psi}\gamma^{\mu}\psi$$

$$\gamma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \quad \gamma^1 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}$$

$$\gamma^2 = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix}, \quad \gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

$$\gamma^5 := i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

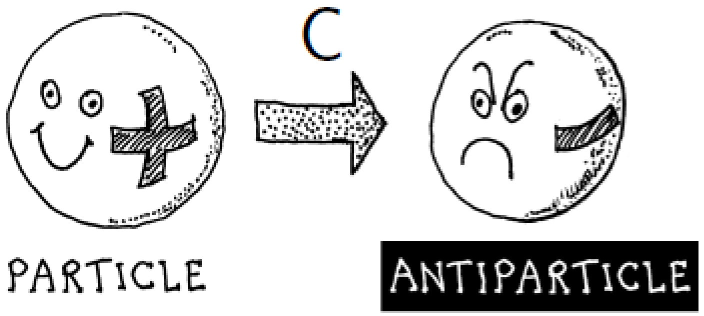
Discrete symmetries

Charge

$$C|p\rangle = |\bar{p}\rangle$$

$\hat{Q}$ is an operator that can measure the "charge", like the position and momentum operators $\hat{x}$ and $\hat{p}$

$$C^{-1}\hat{Q}C = -\hat{Q}$$



Credit: Quantum Field Theory for the Gifted Amateur

Not just EM charge, but also lepton number, hypercharge, etc.

Parity

$$P^{-1}\hat{x}P = -\hat{x}.$$

$$\hat{x}P = -P\hat{x},$$

$$P^{-1}\hat{p}P = -\hat{p}.$$

The symmetries discussed so far were continuous:

SU(3), SU(2) or U(1)

Time Reversal

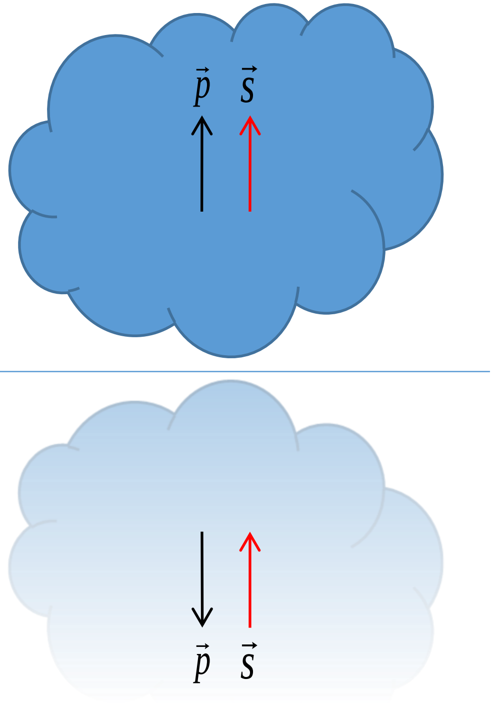
$$T^{-1}\hat{x}T = \hat{x}$$

perators $\hat{x}$ and $\hat{p}$

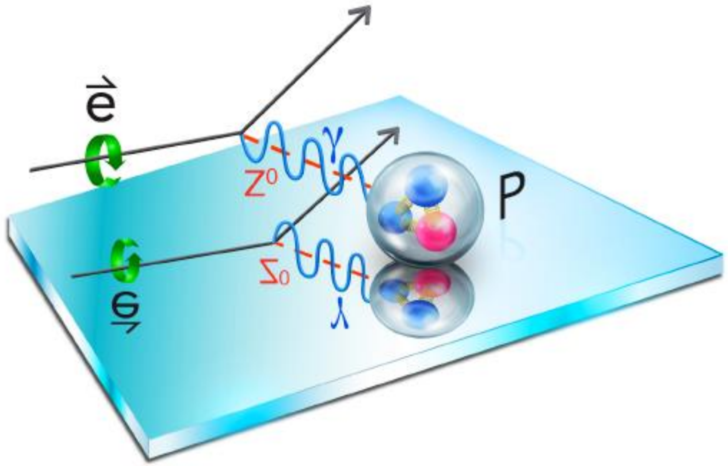
Discrete symmetries are represented by finite groups

Parity

quantum mechanical operator that reverses the spatial sign (P: x -> -x)



$$h = \frac{\vec{s}\cdot\vec{p}}{|\vec{s}\cdot\vec{p}|}$$



We describe physical processes as interacting currents by constructing the most general form which is consistent with Lorentz invariance

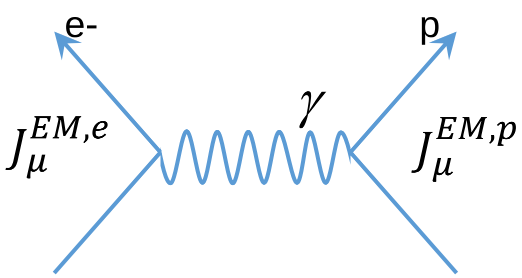
Terms of the form $\overline{\psi}\,(4\times 4)\,\psi$ where $\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3$

Scalar	$\overline{\psi}\psi$
Pseudoscalar	$\overline{\psi}\gamma^5\psi$
Vector	$\overline{\psi}\gamma^\mu\psi$
Axial Vector	$\overline{\psi}\gamma^\mu\gamma^5\psi$
Tensor	$\overline{\psi}\sigma^{\mu\nu}\psi$

Note: P (V*V) = +1 P (A*A) = + 1 P (A*V) = -1

EM and Weak Interactions : Historical View

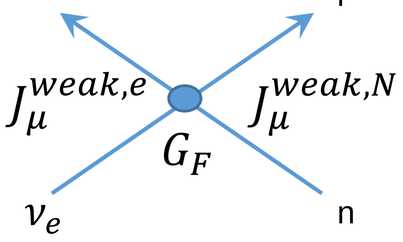
EM: e + p → e + p elastic scattering



$$M = J_\mu^{EM,p}\left(-\frac{e^2}{Q^2}\right)J^{\mu,EM,e} = \left(\overline{\psi}_p\gamma_\mu\psi_p\right)\left(-\frac{e^2}{Q^2}\right)\left(\overline{\psi}_e\gamma^\mu\psi_e\right)$$

V x V

Weak: n → e⁻ + p + $\bar{\nu}_e$ neutron beta decay



Fermi (1932) : contact interaction, form inspired by EM

$$M = J_\mu^{weak,N}\,G_F\,J^{\mu,weak,e} = \left(\overline{\psi}_p\gamma_\mu\psi_n\right)G_F\left(\overline{\psi}_e\gamma^\mu\psi_{\nu_e}\right)$$

V x V

Parity Violation (1956, Lee, Yang; 1957, Wu)
required modification to form of current - need axial vector as well as vector to get a parity-violating interaction

$$M = J_\mu^{weak,N}\,G_F\,J^{\mu,weak,e} = \left(\overline{\psi}_p\gamma_\mu \quad \psi_n\right)G_F\left(\overline{\psi}_e\gamma^\mu \quad \psi_{\nu_e}\right)$$

(V - A) x (V - A)

Note: weak interaction process here is charged current (CC)

Experiment

Can only measure something if it is "observable"

→ Transition rates or scattering cross sections

"Fermi's Golden Rule"

$$Fd\sigma = |M^2| dQ$$

The incident flux times the differential cross section is proportional to the product of the square of the matrix element and the Lorentz invariant phase space

$$\sigma \propto |M^2|$$

All the physics is in the matrix element

The Dirac Equation

Dirac equation for free electron: $$(i\gamma^{\mu}\partial_{\mu} - m)\,\psi = 0$$

where:

$$\gamma^{\mu} = \left(\gamma^{0}, \vec{\gamma}\right) \qquad \gamma^{0} = \begin{pmatrix} \vec{1} & 0 \\ 0 & -\vec{1} \end{pmatrix} \qquad \vec{\gamma} = \begin{pmatrix} 0 & \vec{\sigma} \\ -\vec{\sigma} & 0 \end{pmatrix}$$

with: $\mu = 0$ time, $\mu = 1,2,3$ space

leads to electron four-vector current density:

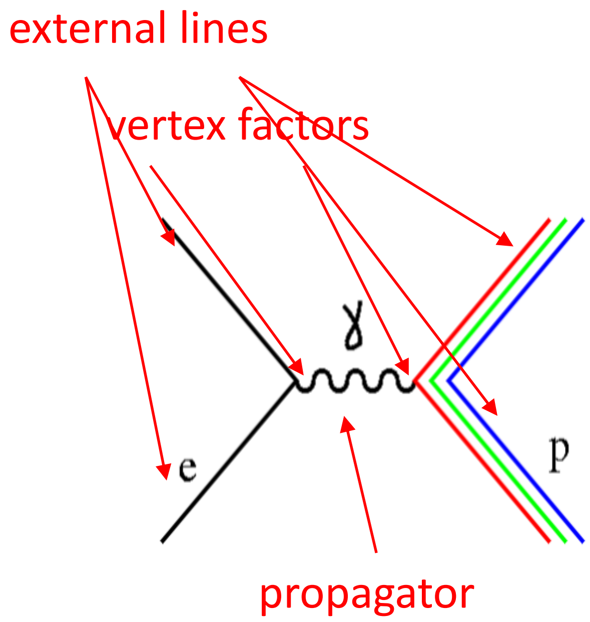
$$j^{\mu} = -e\,\overline{\psi}\gamma^{\mu}\psi$$ where the adjoint is: $$\overline{\psi} \equiv \psi^{+}\gamma^{0}$$

satisfies the continuity equation: $$\partial_{\mu} j^{\mu} = 0$$

the matrix element

Further reading: Looking for consistency in the construction and use of Feynman diagrams

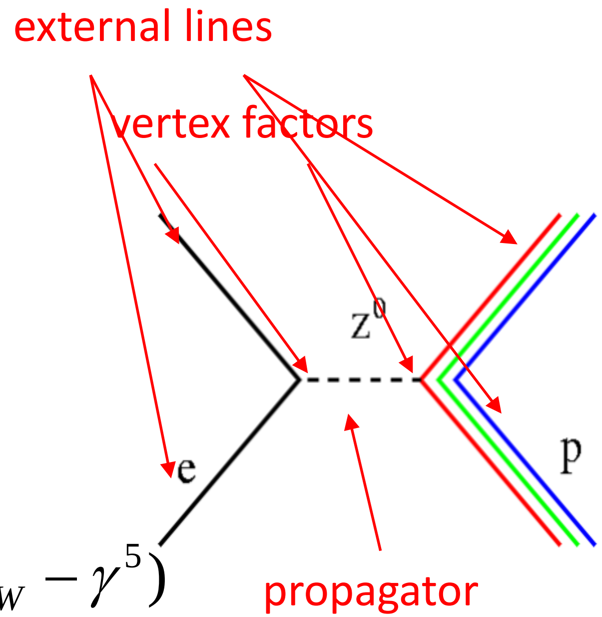
Peter Dunne , *Phys. Educ.* **36** No 5 (September 2001) 366-374



$$u(k)\, ie\gamma^{\mu}\, \bar{u}(k')e^{i(k'-k)\cdot x} \quad \frac{-ig_{\mu\nu}}{q^2} \quad u(p)e^{i(p'-p)\cdot x}\,[\qquad]\,\bar{u}(p')$$

$$M_{EM} \sim \frac{1}{Q^2} J_{\mu}^{EM,e} J_{\mu}^{EM,p}$$

the matrix element



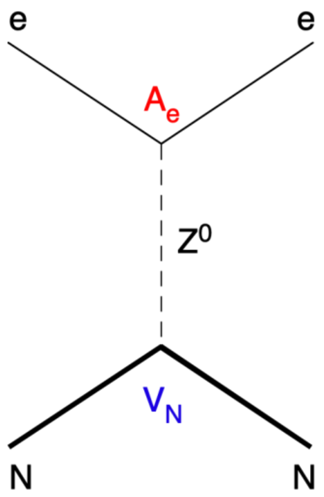
$$i\frac{g}{4\cos\theta_W}\gamma^\mu(1-4\sin^2\theta_W-\gamma^5)$$

$$J_\mu^{NC,e} = \bar{u}(k')e^{i(k'-k)\cdot x}\left[g_V^e V_\mu^{NC,e} + g_A^e A_\mu^{NC,e}\right]u(k) \qquad \frac{-i(g_{\mu\nu}-k_\mu k_\nu/M^2)}{q^2-M_Z{}^2} \qquad J_\mu^{NC,N} = \bar{u}(p')e^{i(p'-p)\cdot x}\left[V_\mu^{NC,N}+A_\mu^{NC,N}\right]u(p')$$

$$M_{NC} \sim \frac{G}{2\sqrt{2}} J_\mu^{NC,e} J_\mu^{NC,p}$$

Atomic Parity Violation

Z-boson exchange between atomic electrons and the quarks in the nucleus



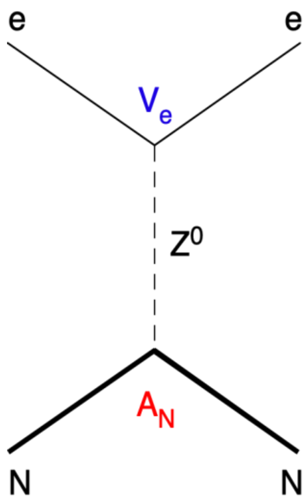
H_{PNC} mixes electronic *s* & *p* states

$< n's' | H_{PNC} | np > \ \propto Z^3$

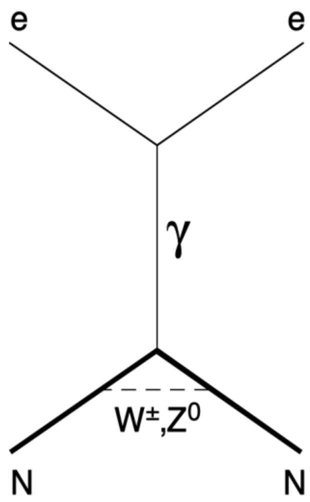
Drive s → s E1 transition!

$$Q_W = 2(\kappa_{1p} Z + \kappa_{1n} N)$$

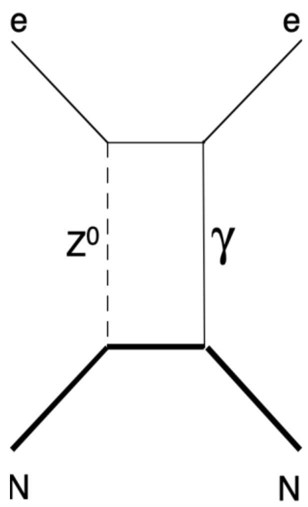
$$\kappa_{1p} = \frac{1}{2}(1 - 4\sin^2\theta_W), \kappa_{1n} = -\frac{1}{2}$$



NSD Z-exchange



PV hadronic interactions
⇒ PV anapole moment of the nucleus



hyperfine correction to the weak neutral current

nucl. spin *independent* interaction coherent over all nucleons

$$H_{\rm PNC}^{nsi} = \frac{G}{\sqrt{2}} \frac{Q_W}{2} \gamma_5\, \delta(\mathbf{r}).$$

Cs: 6s → 7s osc. strength f ≈ 10^{-22}

use interference:

$f \propto | A_{PC} + A_{PNC} |^2$
$\approx A_{PC}^2 + A_{PC} A_{PNC} \cos \varphi$

nucl. spin *dependent*, interaction only with valence nucleons

Credit: Gerald Gwinner

Why Cs ? Not particularly heavy...

It's the heaviest, stable 'simple atom'

10^{10} excitations /sec

atomic structure factor

nuclear structure factors

$$\langle i | H_{\mathrm{PNC},1} | j \rangle = \frac{G_F}{2\sqrt{2}} C_{ij}(Z) \mathcal{N} \times \left[-N q_n + Z(1 - 4\sin^2\theta_W) q_p \right]$$

$$q_n = \int \rho_n(r) f(r) d^3r, \quad q_p = \int \rho_p(r) f(r) d^3r.$$

from Pollock et al. 1992

Precise experiments in Tl (and Bi, Pb) have been limited by their more complicated atomic structure!

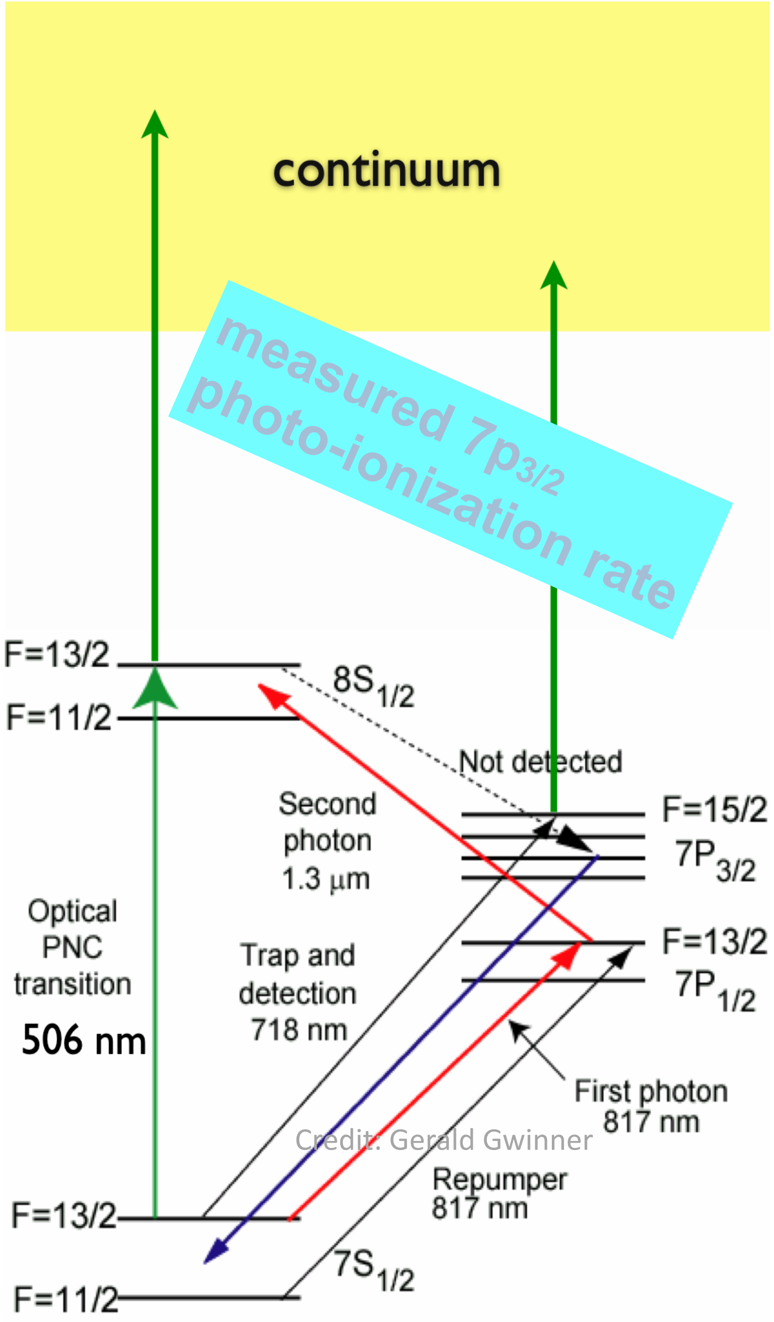
Use francium (Z=87) excitation rate per atom: 30 s^{-1}

atomic structure (theory) understood at the same level as in Cs

APNC effect 18 x larger! APNC possible with 10^6 - 10^7 atoms!

Problems: (i) no stable isotope
(ii) need to know neutron radius better than for Cs expt.

Answers: (i) go to TRIUMF's actinide target to get loads of Fr
(ii) the upcoming PREX experiment at Jefferson Lab will measure the neutron radius of ^{208}Pb

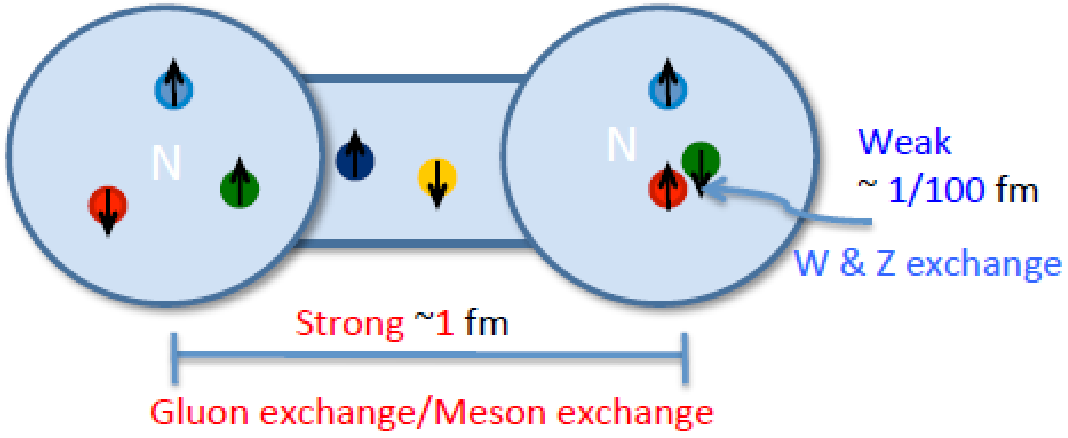


Hadronic Weak Interaction at Low Energies

$$\mathcal{H}_W^{\Delta S=0} = \frac{G_F}{2\sqrt{2}}[\cos^2\theta_W J_\mu^{W,0\dagger} J^{W,0\mu} + \sin^2\theta_W J_\mu^{W,1\dagger} J^{W,1\mu} + J_\mu^{Z\dagger} J^{Z\mu}]$$

Initial motivation: Neutral weak currents can be accessed via $\Delta S = 0$, $\Delta I = 1$

Systems that can access HWI:



- few body nucleon-nucleon (NN) interactions
  - large level spacings, small PV admixtures
  - need lots of statistics
  - n-p, p-p, n-d, n-^{3}He, n-^{4}He, p-^{4}He, γ-d, etc.
- nuclear systems
  - small level spacings, large PV admixtures, not as theoretically clean
  - not a lot of statistics needed
  - ^{18}F, ^{19}F, many more heavier compound neuclei

Strategy: NPDGamma and other few nucleon systems work really hard to measure 10^{-8} asymmetries. **Theory is reliable and interpretable.**

Credit: Jason Fry

Hadronic Weak Interaction: Theories

An Overview:

- DDH meson exchange model: PV potential π, ρ, and ω with strong and weak vertex. 7 Weak couplings h_π^1, $h_\rho^{0,1,2}$, $h_\rho^{1\prime}$, and $h_\omega^{0,1}$
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  - L. Girlanda, Phys. Rev. C77 (2008) 067001
  - D. R. Phillips, M. R. Schindler, and R. P. Springer, Nucl. Phys. A822 (2009) 1
- $1/N_c$ expansions: $N_c \to$ large gives hierarchy of couplings
  - D. Phillips, D. Samart, and C. Schat, PRL 114 (2015) 062301
  - M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502
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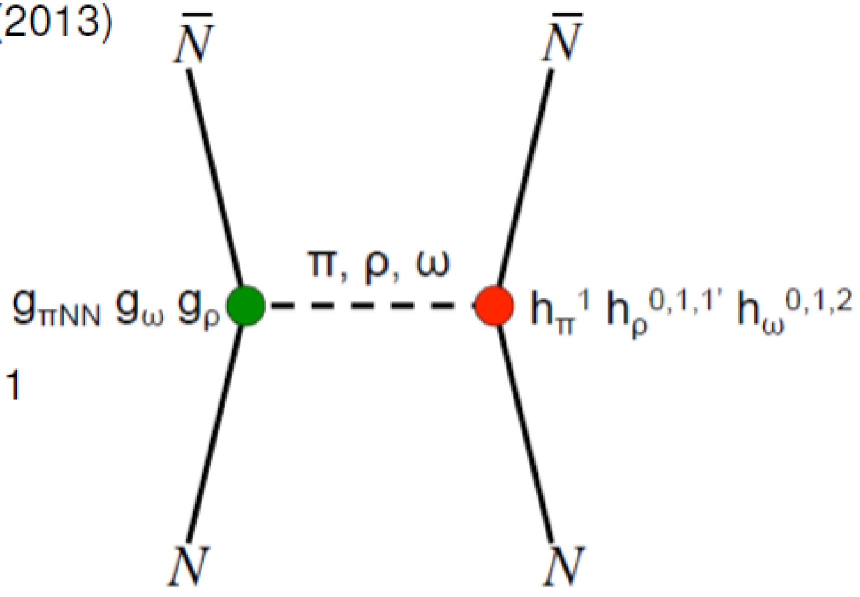
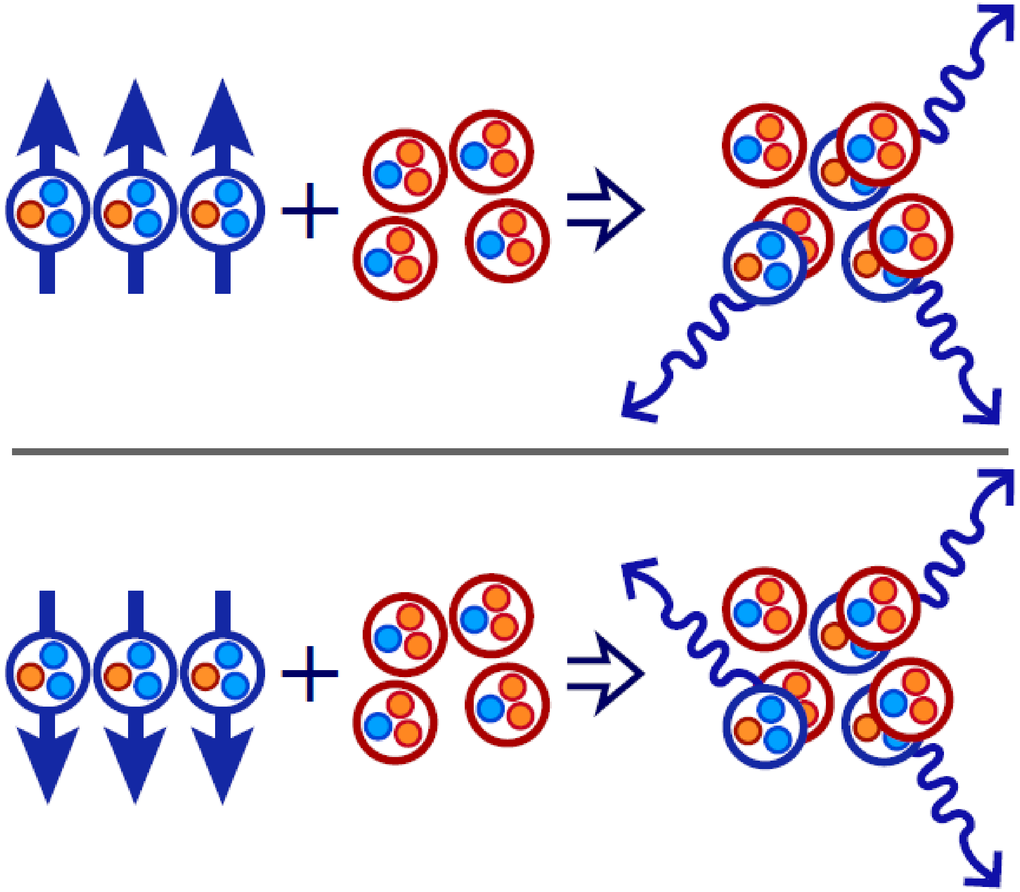


relative scale $\sim m_\pi / m_W \sim 10^{-7}$

Credit: Jason Fry

Hadronic Weak interaction: NPDGamma

NPDGamma $(\vec{\sigma} \cdot \vec{k})$ at the SNS at ORNL, goal: $h_\pi^1 \sim 1 \times 10^{-7}$

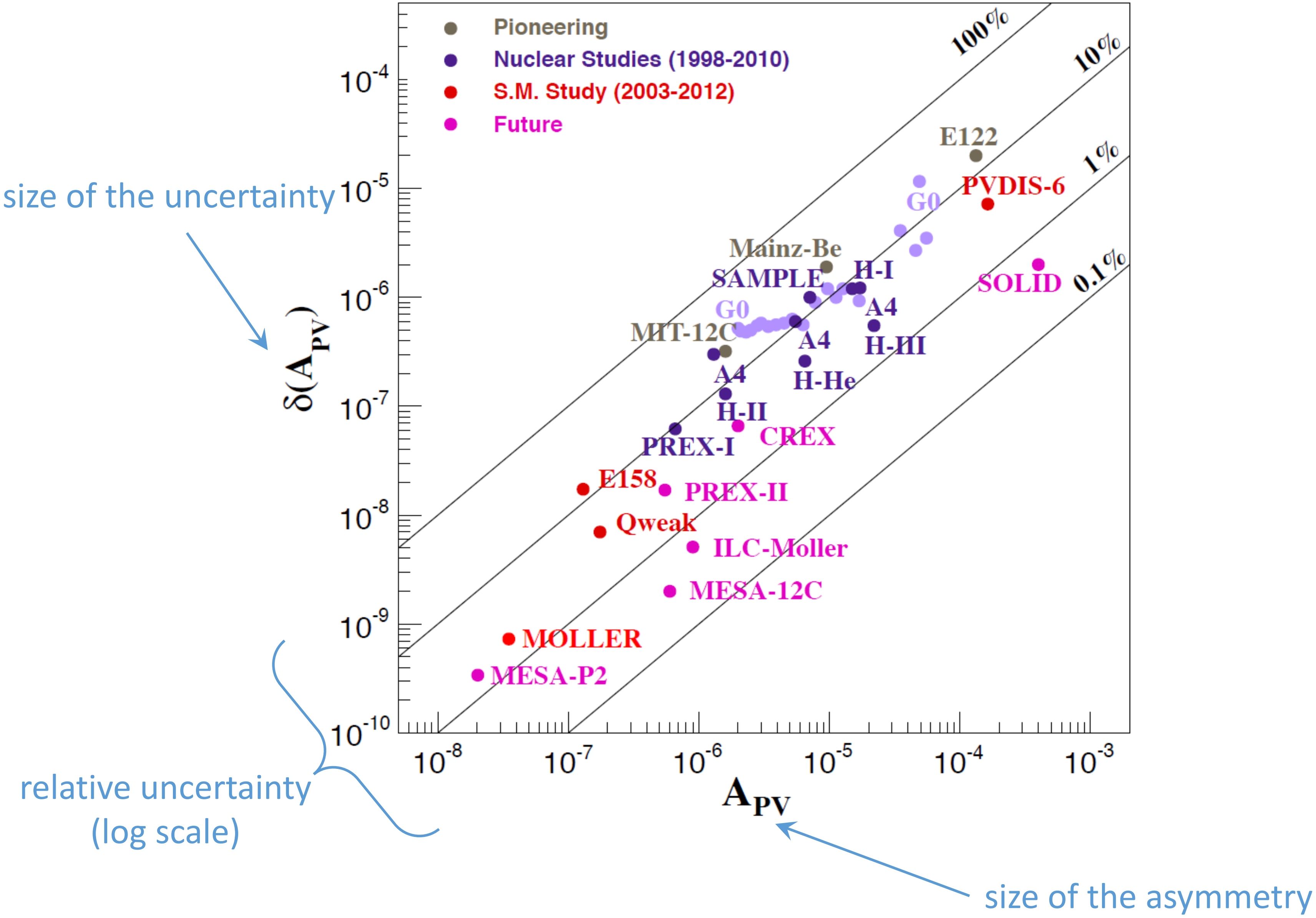


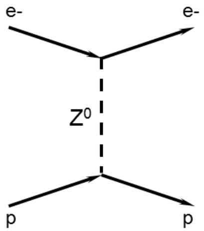
- Flipping the neutron polarization is equivalent to a parity transformation
- NPDG measures the asymmetry between the neutron polarization and the emitted photon's momentum
- Large statistics! Must collect 10^{16} photons to see 10^{-8} asymmetry!

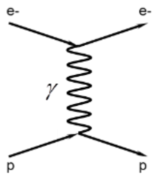
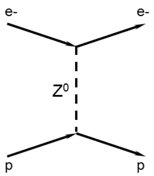
Credit: Jason Fry

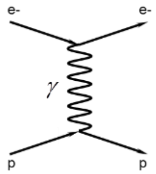
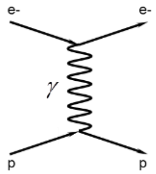
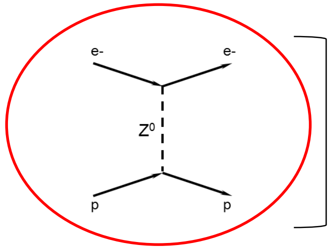
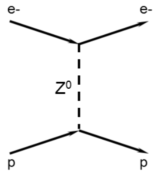
$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 - 2\sqrt{2}\frac{\langle \mathbf{E1} \rangle}{\langle \mathbf{M1} \rangle}\cos\theta\right), \quad A_\gamma \equiv -2\sqrt{2}\frac{\langle \mathbf{E1} \rangle}{\langle \mathbf{M1} \rangle}, \quad A_\gamma = \frac{\frac{d\sigma}{d\Omega}_+ - \frac{d\sigma}{d\Omega}_-}{\frac{d\sigma}{d\Omega}_+ + \frac{d\sigma}{d\Omega}_-}$$

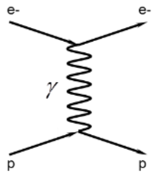
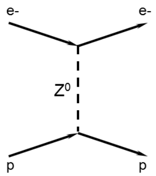
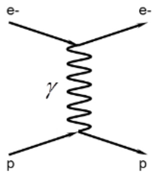
PVES Experiment Summary



How does PVES measure  ?

$\sigma \propto$ [ + ]^2

= []^2 $+ h_e$ [ ] + []^2

$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx$ ( ) / []^2 $= \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\left[Q_W^p + B_4 Q^2 + \cdots\right]$

$\approx 10^{-6} - 10^{-5} \approx 1 - 10\, ppm$

Hand-waving derivation of the parity-violating asymmetry in electron-proton scattering

$$J_\mu^{EM,e} = Q_e \overline{\psi}_e \gamma_\mu \psi_e = Q_e V_\mu^{EM,e}$$

$$M_{EM} \sim \frac{1}{Q^2} J_\mu^{EM,e} J_\mu^{EM,p} \quad \sim \frac{1}{Q^2} Q_e V_\mu^{EM,e} V_\mu^{EM,N}$$

$$J_\mu^{EM,N} = V_\mu^{EM,N}$$

$$J_\mu^{NC,e} = \left(-1 + 4\sin^2\theta_W\right)\overline{\psi}_e \gamma_\mu \psi_e + \overline{\psi}_e \gamma_5 \gamma_\mu \psi_e$$

$$J_\mu^{NC,N} = V_\mu^{NC,N} + A_\mu^{NC,N}$$

$$M_{NC} \sim \frac{G}{2\sqrt{2}} J_\mu^{NC,e} J_\mu^{NC,p} \quad \sim \frac{G}{2\sqrt{2}}\left[g_V^e V_\mu^{NC,e} V_\mu^{NC,N} + g_A^e A_\mu^{NC,e} V_\mu^{NC,N} + g_V^e V_\mu^{NC,e} A_\mu^{NC,N} + g_A^e A_\mu^{NC,e} A_\mu^{NC,N}\right]$$

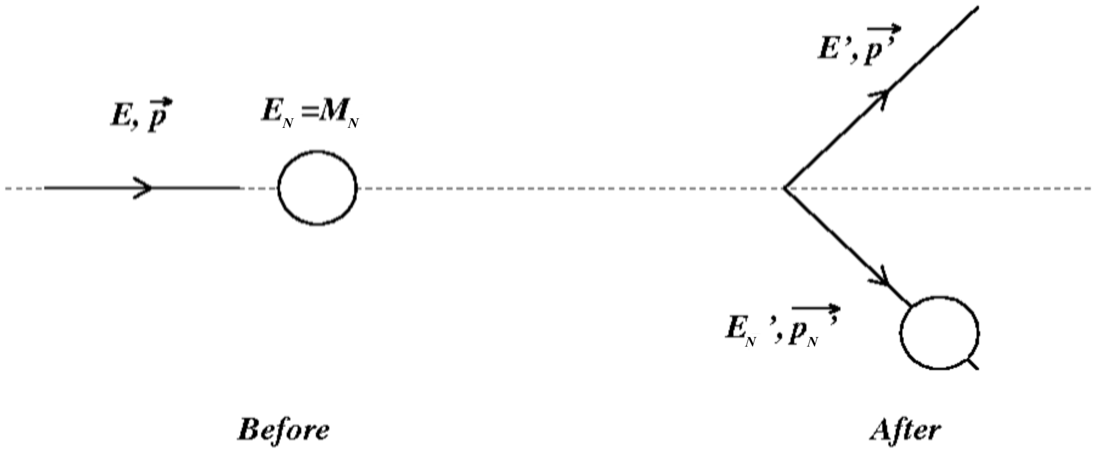
Asymmetry

$$\sigma_{\pm} \propto [M_{EM} \pm M_{NC}]^2 = |M_{EM}|^2 \pm 2Re(M_{EM}^* M_{NC}) + |M_{NC}|^2$$

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$$\Rightarrow \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{\left(Q_e V_\mu^{EM,e} V_\mu^{EM,N} g_A^e A_\mu^{NC,e} V_\mu^{NC,N} + Q_e V_\mu^{EM,e} V_\mu^{EM,N} g_V^e V_\mu^{NC,e} A_\mu^{NC,N}\right)}{\left(Q_e V_\mu^{EM,e} V_\mu^{EM,N}\right)^2}$$

Elastic Scattering



from ^{208}Pb or ^{48}Ca

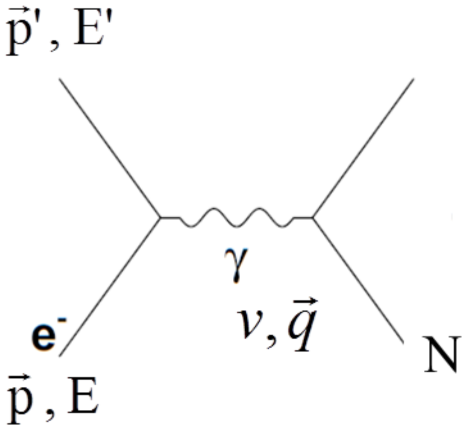
or

from p or d or He

or

from e

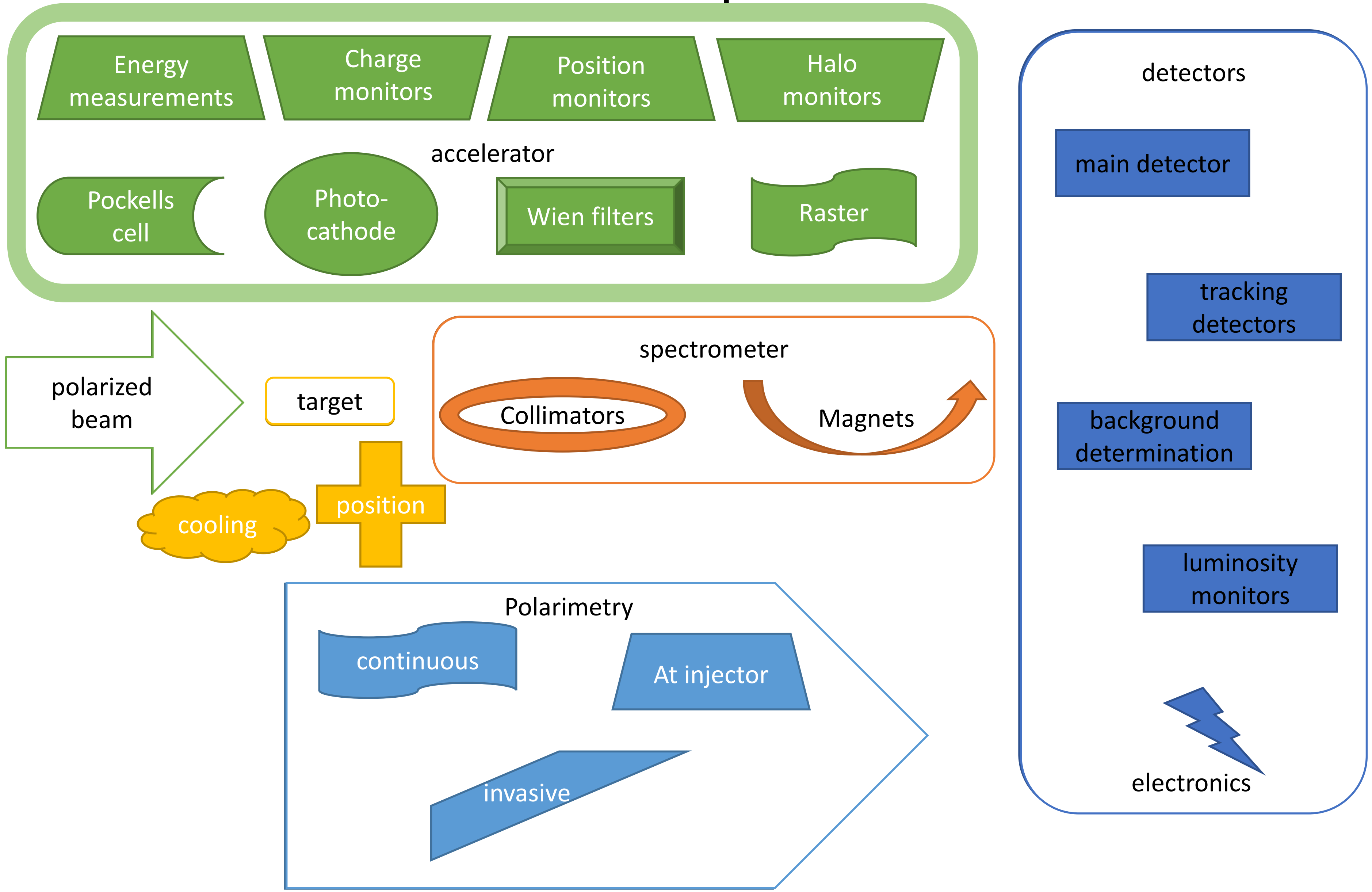
$$e + N \rightarrow e + N$$



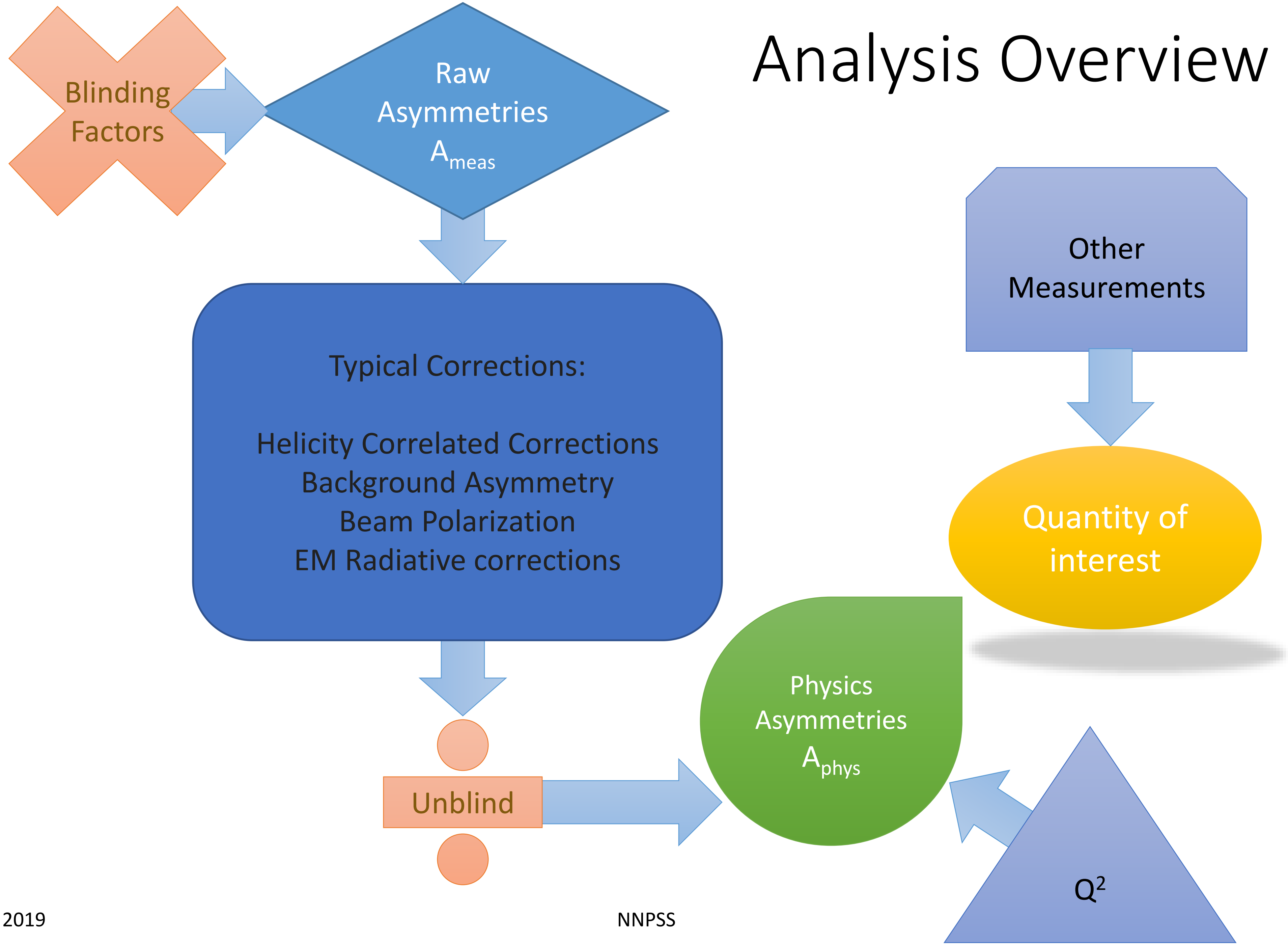
$$-q^2 = Q^2 = 4\,E\,E'\sin^2\left(\frac{\theta_e}{2}\right) = \frac{4E^2\sin^2\frac{\theta_e}{2}}{1+\frac{2E}{M_N}\sin^2\frac{\theta_e}{2}}$$

Q^2 is related to the wavelength of the virtual photon probe - $\lambda = h/q$

Cartoon Experiment



Analysis Overview



Blinding

Why would anyone want to "hide" the result from oneself?

The need for blind analysis (in fact, *double-blind* analysis in which the subject (the patient) and the researcher are both unaware of who is getting the medicine and who is getting the placebo) is well established in medicine – no clinical trial is taken seriously unless it is *double-blind.*

Double-blind technique first used in 1942

*But, you say, we are **physicists** – rigorous, objective, unbiased...*

Why should we want to blind?

Suggestions for further reading*:

Credit: D. Armstrong

- *Joshua R. Klein, Aaron Roodman,* Annu. Rev. Nucl. Part. Sci. 2005. **55**:141
- *P. F. Harrison, J. Phys. G: **28** 2679* (2002)
- *F.G. Dunnington*, Phys. Rev. 43, 404, (1933).
- *R. Feynman, "Surely You're Joking, Mr. Feynman!"* New York: W.W. Norton (1985)

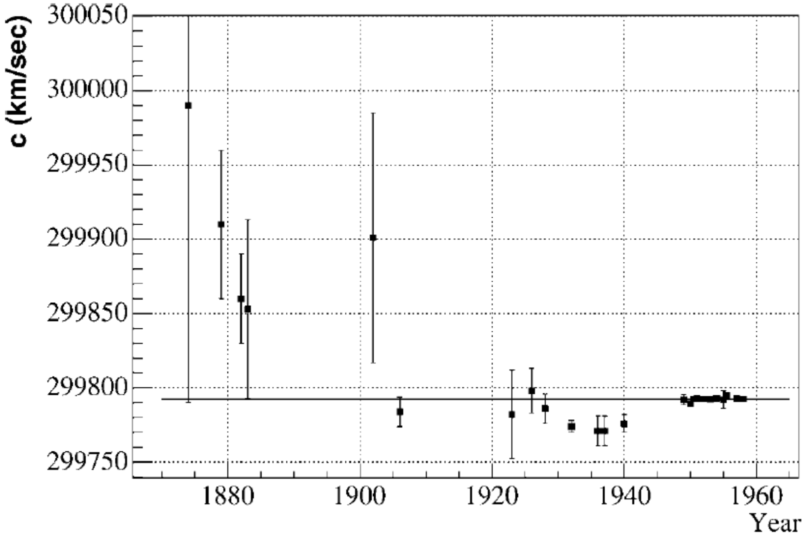
**much of this talk shamelessly borrowed from these sources*

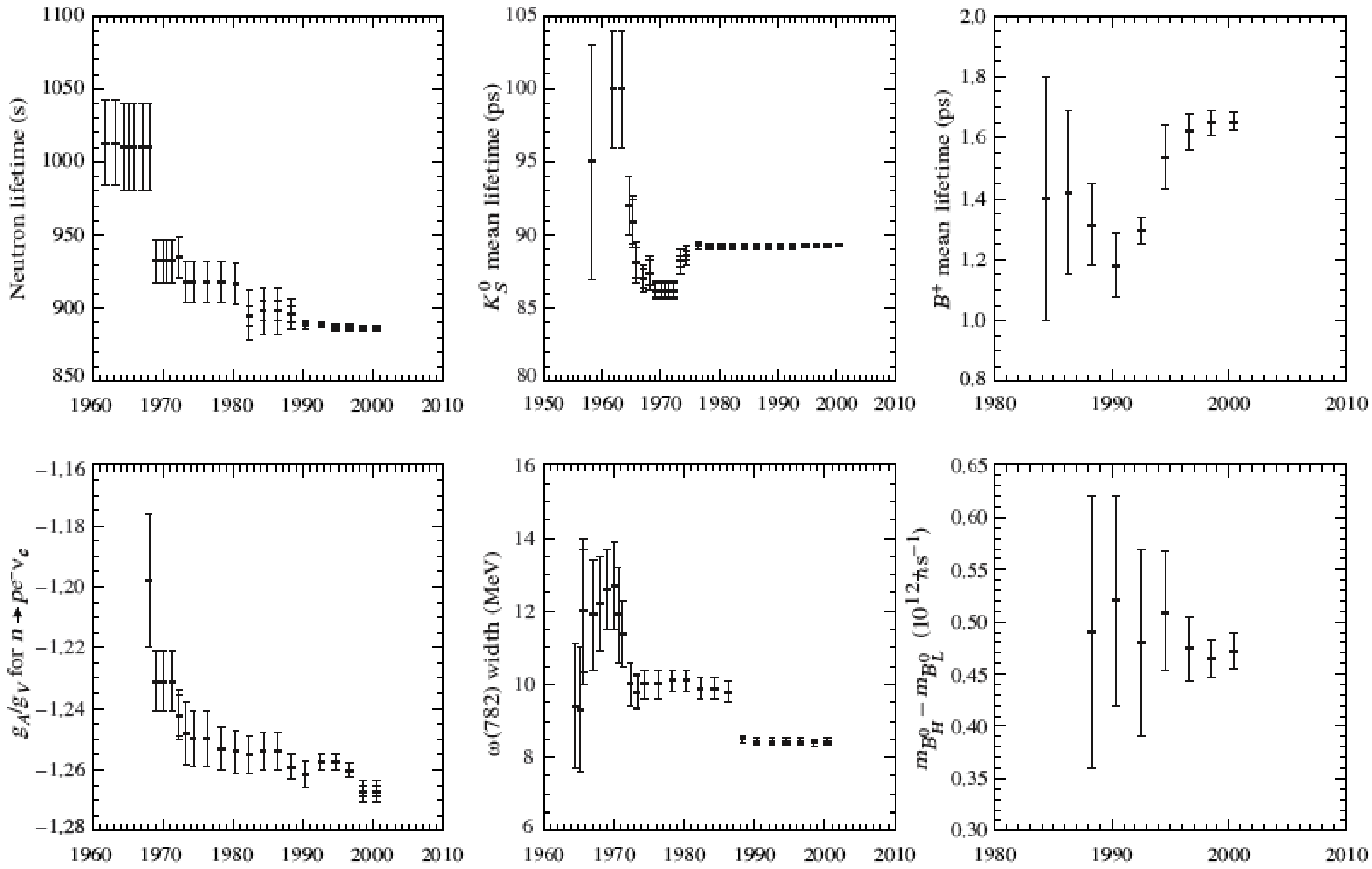
Examples

The speed of light vs. year

Just a coincidence that there are several measurements in a row that have close to the same central values?

Even with such large uncertainties?





Credit: D. Armstrong

When to Blind

Armstrong's criterion:

Blinding is a good idea* for any analysis in which:

a) there is judgment involved - eg. setting cuts, choosing data sets, deciding on background subtraction techniques, which polarimeter to trust, linear regression vs. beam modulation, Q^2 ambiguities, GEANT 3 vs GEANT 4 radiative corrections, *etc.*

and

b) there is an "expected" answer, eg. from precise previous experiments or theoretical prediction – eg. Standard Model tests!

*translation: *absolutely flipping essential*

Credit: D. Armstrong

Unconscious (?) bias

An experimenter's natural tendency is to looks for bugs or additional systematic errors when a result does not agree with expectation, and to not look so hard if it does…as well, to only look for those systematic errors that will work in the "right direction" to "explain" the deviation….

Blinding prevents this from happening – all systematics are treated in an unbiased, objective manner

But, you say, what if I remove the blinding, and my result is "crazy" (say, 6 σ from Standard Model) – aren't there lots of checks I should do before I publish?

Answer: make a list of all those checks and studies and do them all *before* you unblind – if you haven't done them all, you don't deserve to publish a test of the Standard Model !!

Credit: D. Armstrong

Aside: blinding, of course, is no protection against deliberate fraud by experimenter…

Measuring A_{PV} with ES

- unpolarized target
- high current
- highly polarized beam

$$A_{PV} = \frac{A_{sig}}{P_{beam}}$$

$$A_{sig} = \frac{A_{corr} - A_{back}\, f_{back}}{f_{sig}}$$

$$A_{corr} = A_{meas} - \sum_{i=1}^{N} \frac{1}{2Y} \left(\frac{\partial Y}{\partial P_i} \right) \Delta P_i$$

where $\Delta P_i = P_+ - P_-$

$$A_{meas} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

- polarimetry
- elastic electrons from target (resolution of the spectrometers)
- beam property monitoring
- active feedback to minimize helicity correlations
- rapid helicity reversal
- slow helicity reversal as a cross check

Statistical Uncertainty on A_{PV}

The statistical uncertainty in a counting experiment is given by

$$\sigma_N = \sqrt{N} \qquad \frac{\delta N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

$$A_{meas} = \frac{N_1 - N_2}{N_1 + N_2}$$

The expected width, σ_A, is calculated from $\sigma_A^2 = \sum \sigma_{N_i}^2 \left(\frac{\partial A}{\partial N_i}\right)^2$ $\qquad \sigma_{N_i} = \sqrt{N_i}$

$$\frac{\partial A}{\partial N_1} = \frac{2N_2}{(N_1 + N_2)^2} \qquad \frac{\partial A}{\partial N_2} = \frac{-2N_1}{(N_1 + N_2)^2}$$

Hint:

$$N_1 \sim N_2 = \frac{N}{2}$$

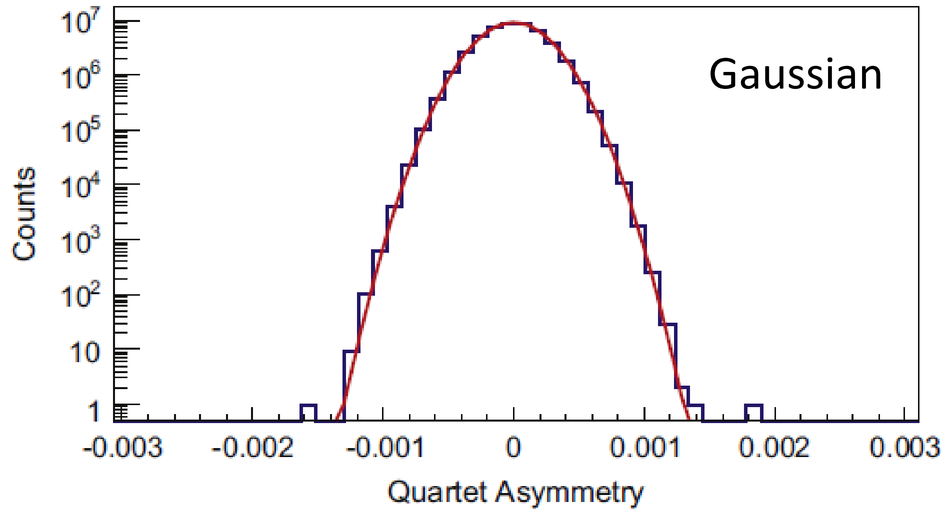
$$\sigma_A^2 = N_1 \left(\frac{2N_2}{(N_1 + N_2)^2}\right)^2 .$$

Statistical Uncertainty

$$\sigma_A^2 = \frac{4N_1N_2(N_1+N_2)}{(N_1+N_2)^4}$$

$$N = N_1 + N_2 \qquad N_1 \sim N_2 = \frac{N}{2}$$

$$\sigma_A^2 = \frac{4\frac{N^2}{4}N}{N^4} = \frac{1}{N} \qquad \sigma_A = \frac{1}{\sqrt{N}}$$

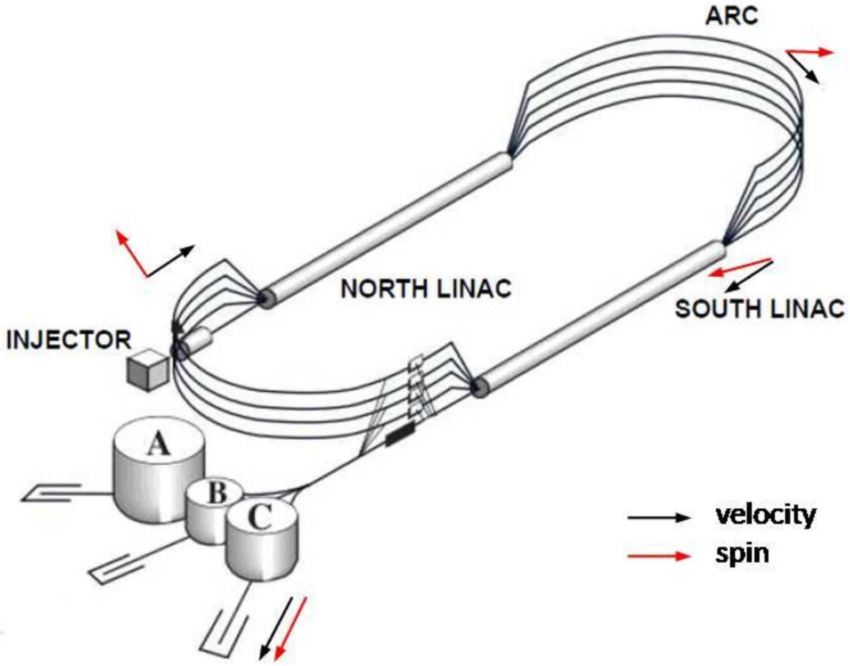


The expected width, σ_A, is:

$$\sigma_A = \frac{1}{\sqrt{\frac{1}{flip\ rate} \times beam\ current(\mu A) \times Rate\ (Hz/\mu A) \times \#flips\ \times \#\ dets}}$$

$$= \frac{1}{\sqrt{\left(\frac{1}{120Hz}\right)(50\mu A)\left(\frac{34MHz}{\mu A} \times \frac{1e^6Hz}{1MHz}\right)(4)(1)}} = 132ppm$$

Jefferson Lab



Parity quality beam >85% using strained GaAs photocathodes

~100 μA max (multi-hall running)

After upgrade to 12 GeV beam energy, addition of a new Hall D

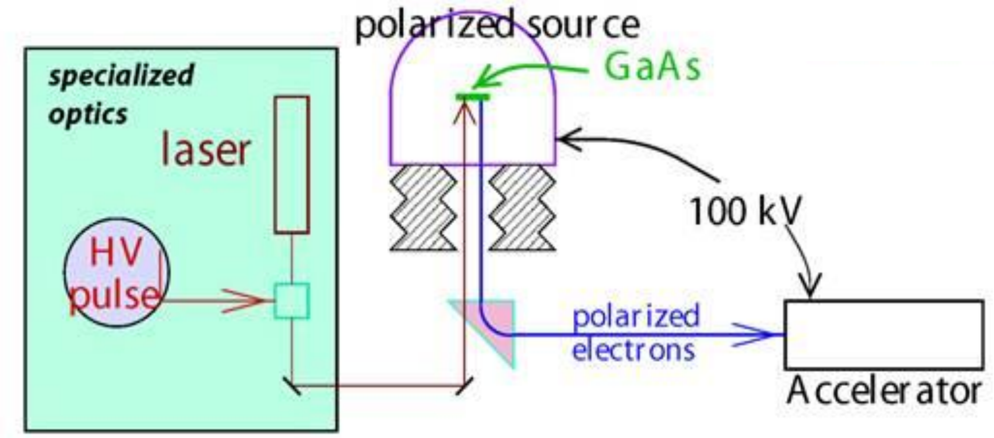
Polarized Electron Source

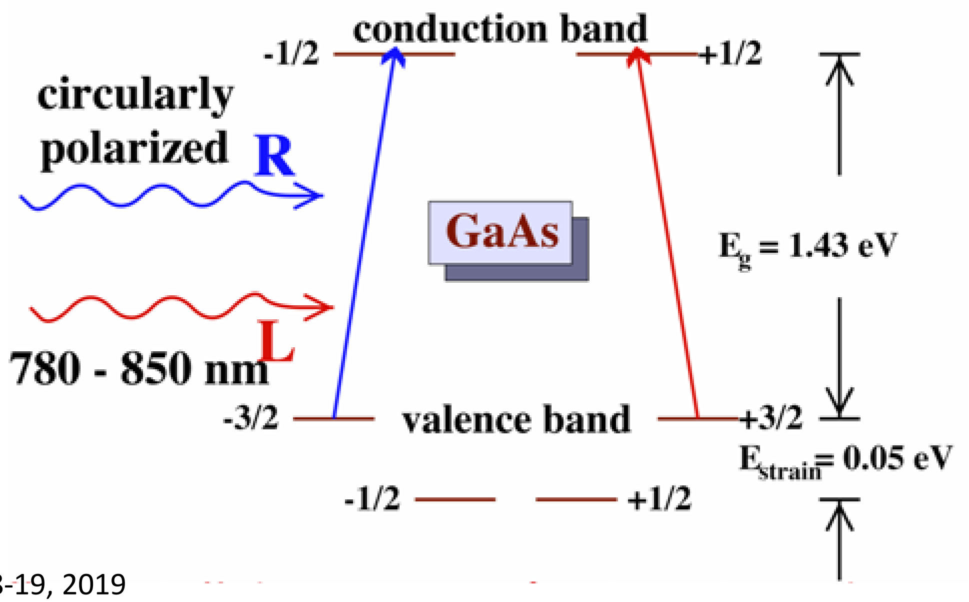
photoemission of electrons from GaAs

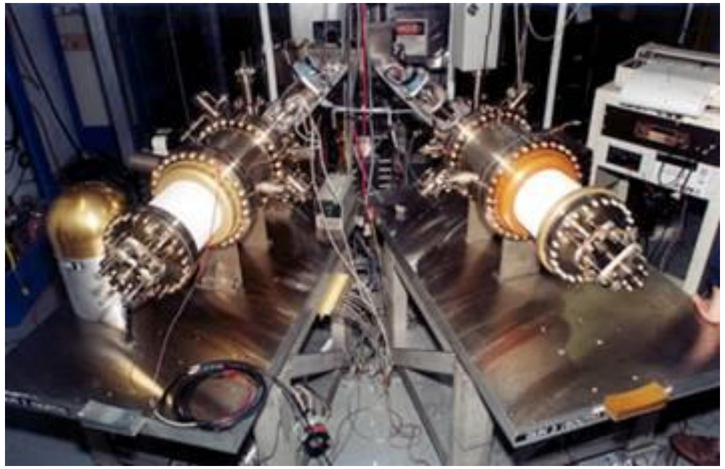
→"Bulk" GaAs typical P_e ~ 37%
theoretical maximum - 50%

→ "Strained" GaAs = typical P_e ~ 80%
theoretical maximum - 100%

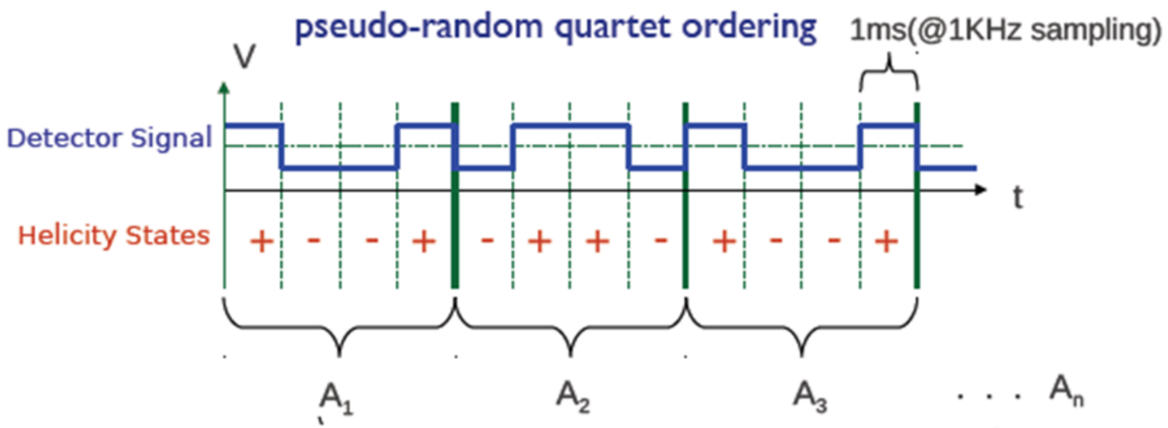
"Figure of Merit" $\propto I P_e^2$

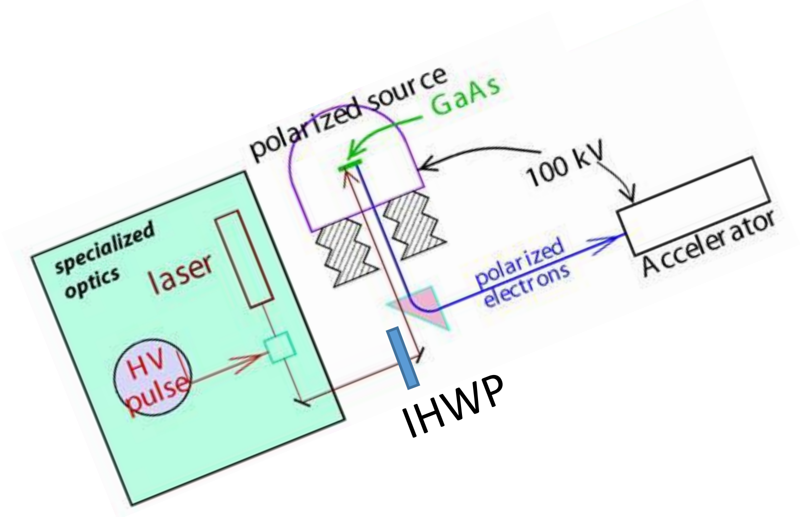


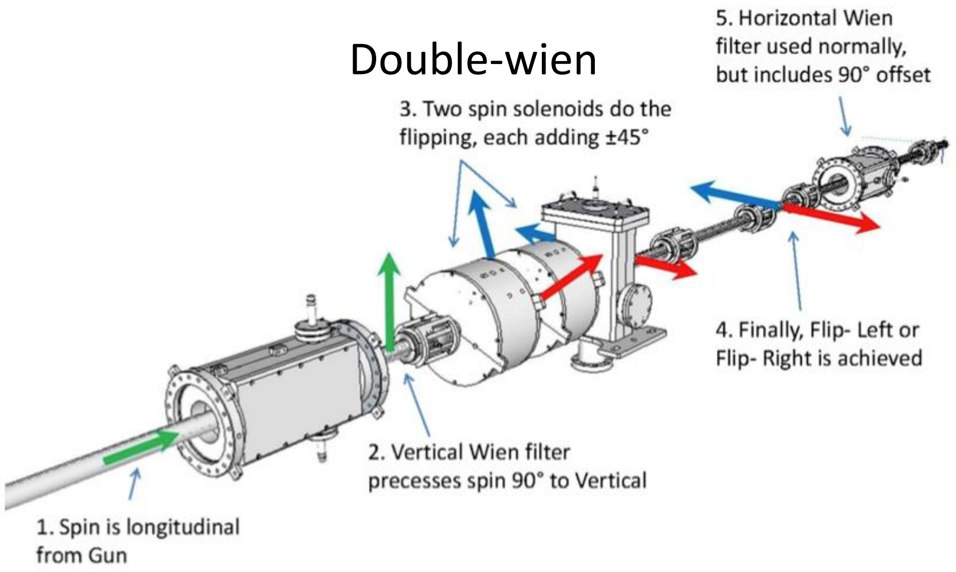




Helicity reversals





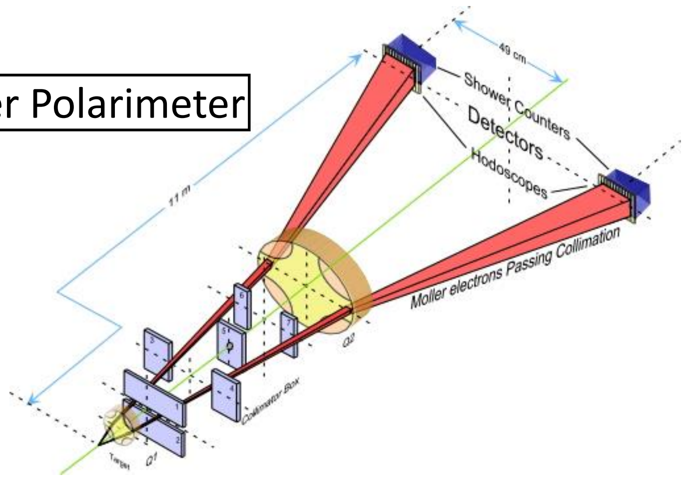


- Rapid, random helicity reversal
- Electrical isolation from the rest of the lab
- Feedback on Intensity Asymmetry

Precision Polarimetry

Require measurement of the beam polarization to sub- $dP/P = 1\%$

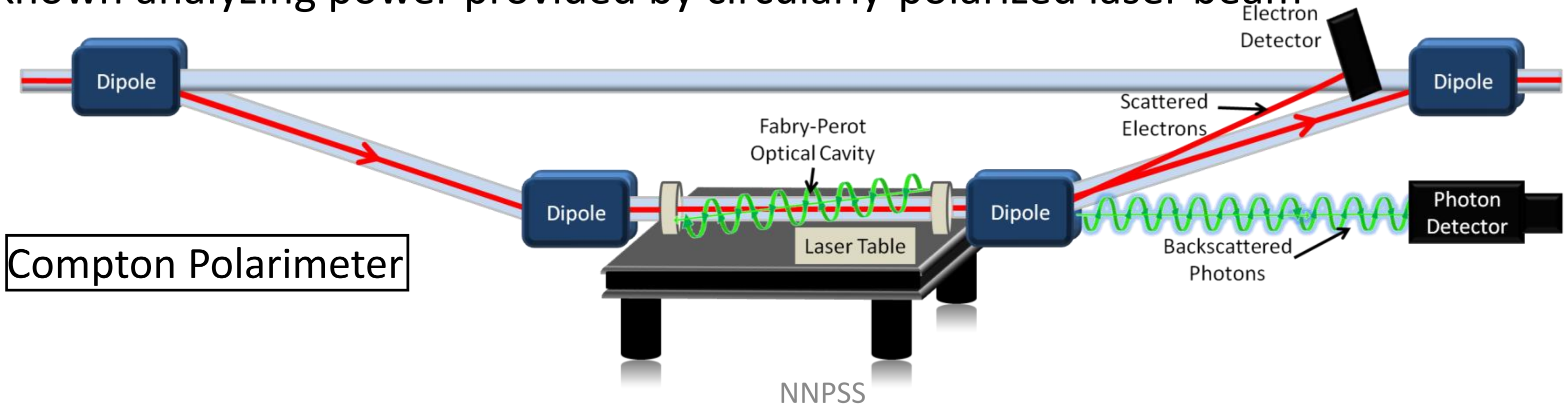
Møller Polarimeter



Strategy: use 2 independent polarimeters

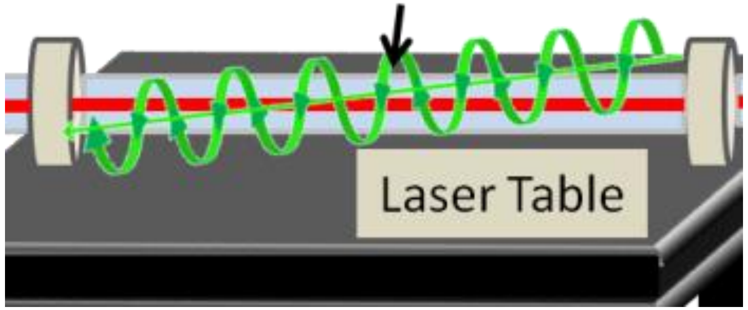
- Use existing Hall C Møller polarimeter to measure absolute beam polarization to <1% at low beam currents
- Known analyzing power provided by polarized Iron foil in high magnetic field

- Use Compton polarimeter to provide continuous, non-destructive measurement of beam polarization
- Known analyzing power provided by circularly-polarized laser beam

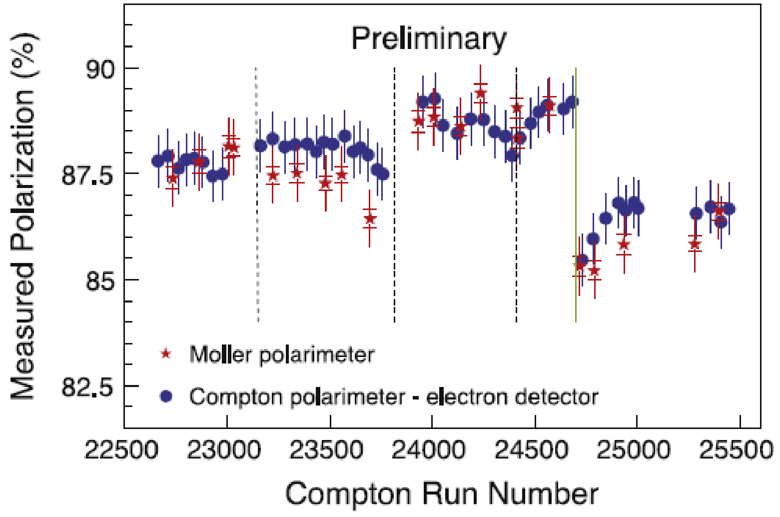


Compton Polarimeter

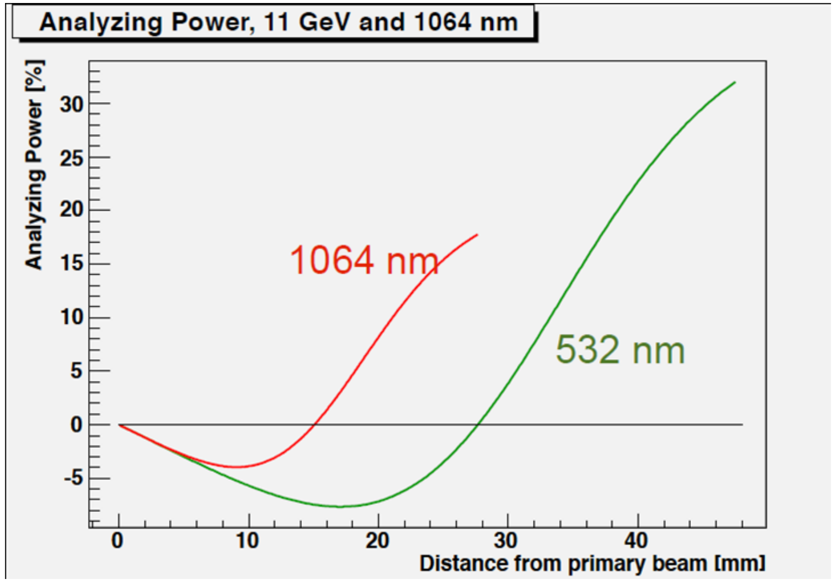
Compton Polarimeter



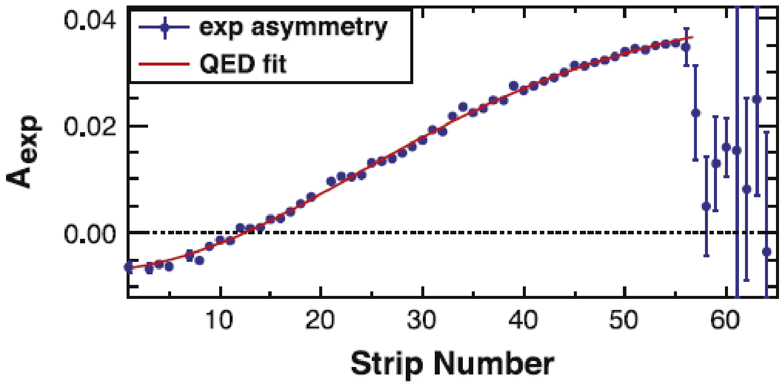
$$\alpha_c = 1.346°$$
$$P_L = 10kW$$
$$\lambda = 532nm$$



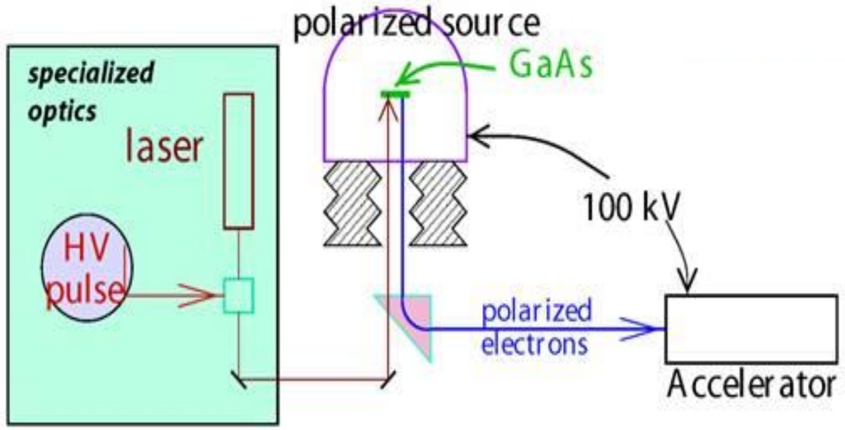
$$\mathcal{L} \simeq \frac{(1. + cos(\alpha_c))}{\sqrt{2\pi}} \frac{I_e}{e} \frac{P_L\ \lambda}{h\ c^2} \frac{1}{\sqrt{\sigma_e^2 + \sigma_\gamma^2}} \frac{1}{sin(\alpha_c)}$$

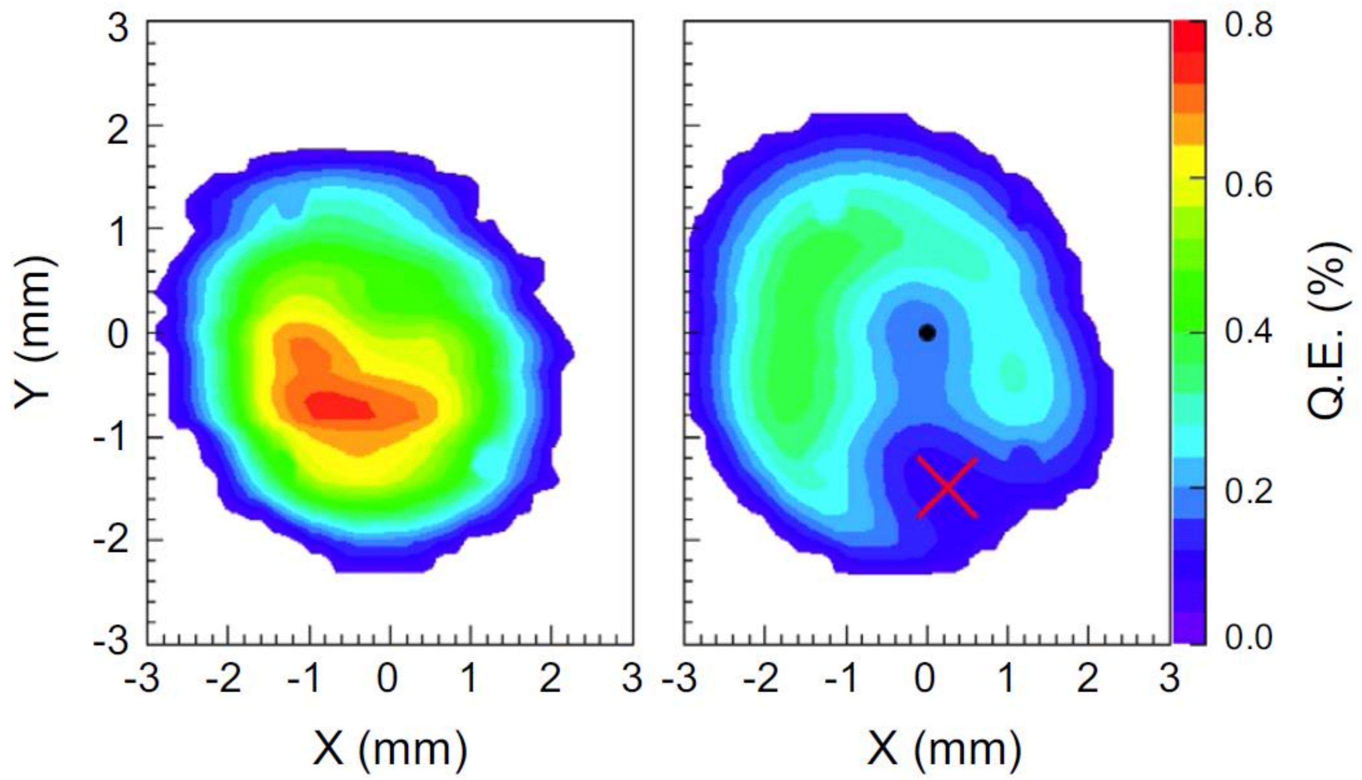


$$\sigma_\gamma^2 = 80\mu m$$
$$\sigma_e^2 = 80\mu m$$
$$\sigma_{tot} = 49\ fm^{-2}$$



False asymmetries from helicity correlated beam properties





Average position differences at the target controlled to order ~10 nm

The width of human hair is 50,000 nanometers!!!