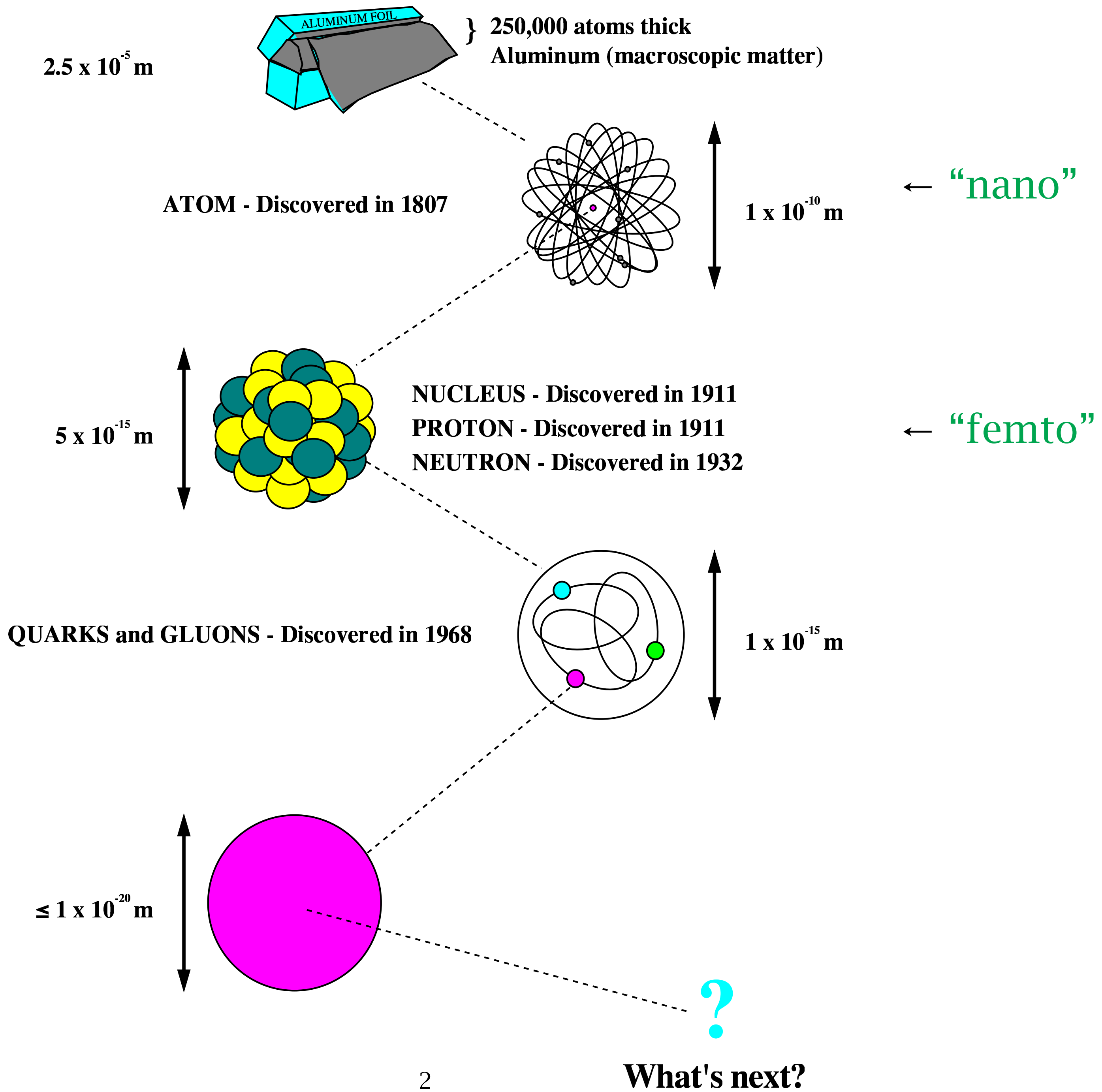
Exploring the structure of nucleons by electron scattering

S. Širca, FMF and IJS UNG, March 21, 2011

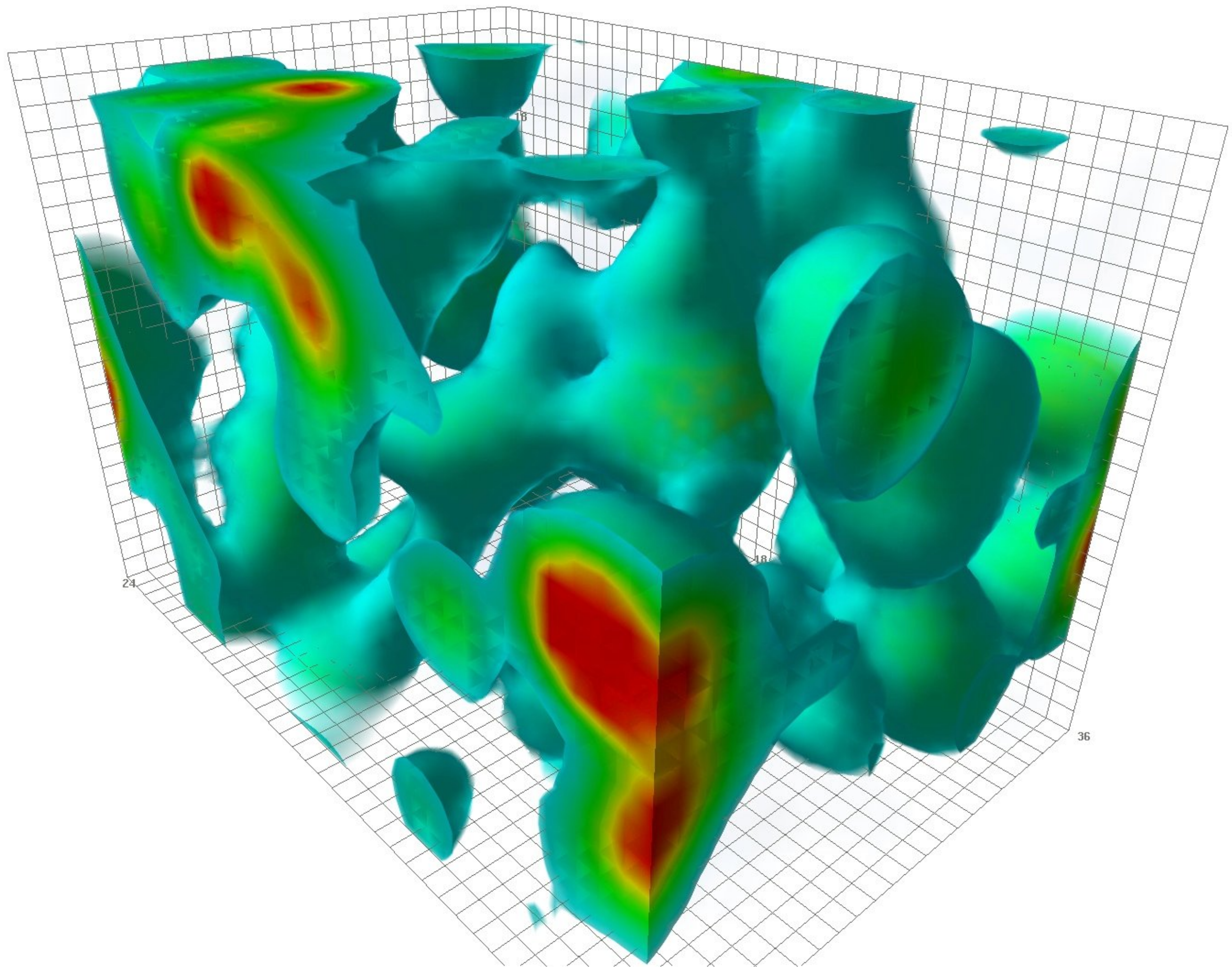
How Scientists' Ideas About Matter Have Changed



Motivation

Structure of nucleons (quarks + gluons)

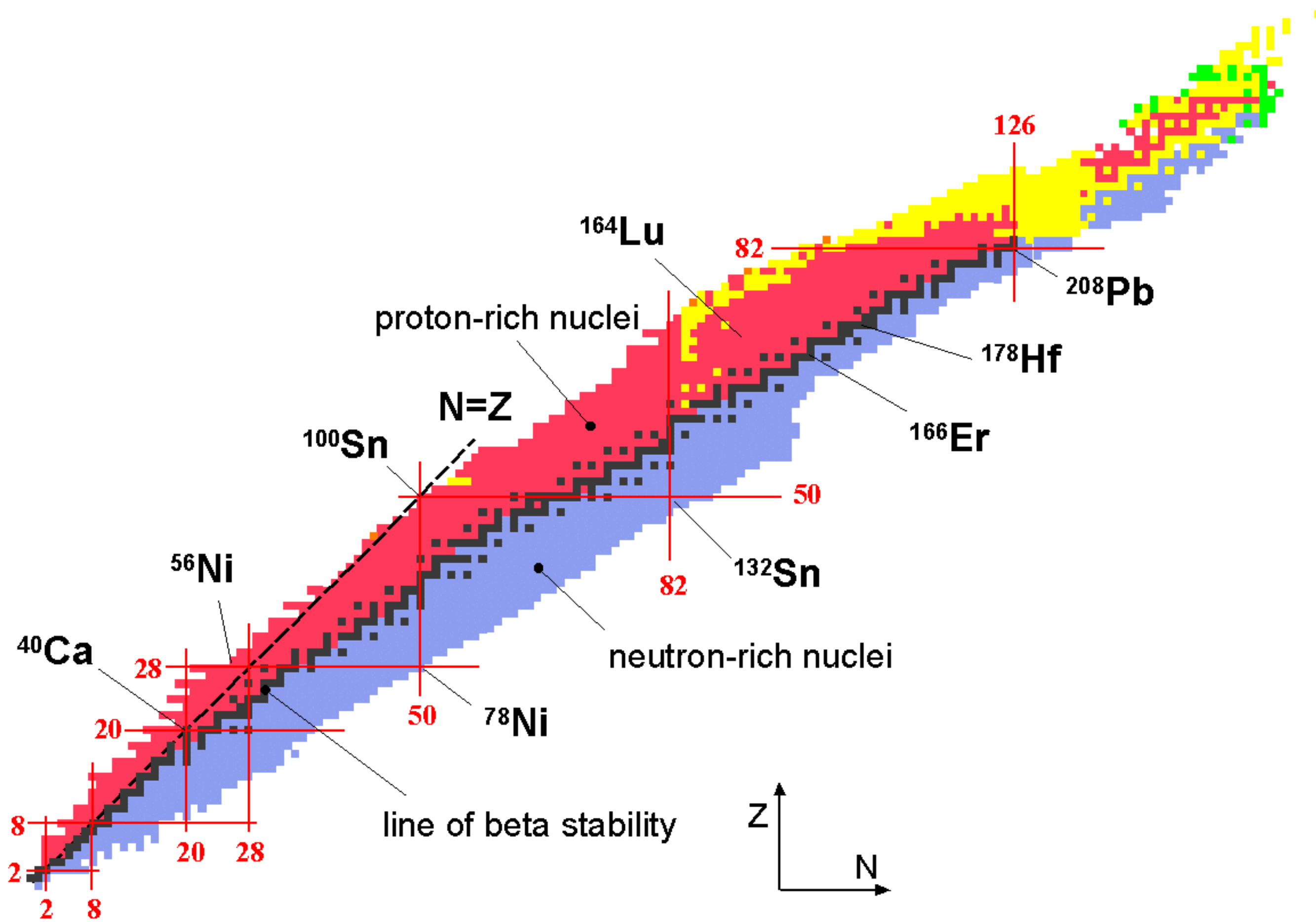
Constituents of nuclei, neutron stars; fundamental theory of QCD; structure of vacuum



Motivation

Structure of nuclear matter

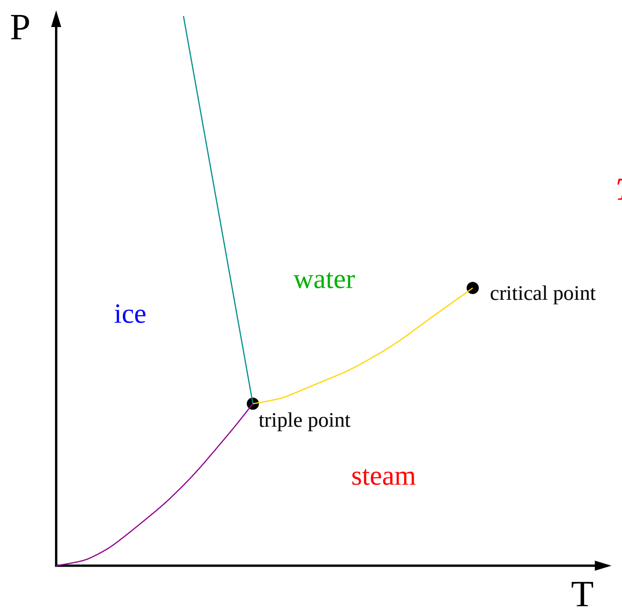
Unstable nuclei; connection of QCD and multi-body description of nuclei

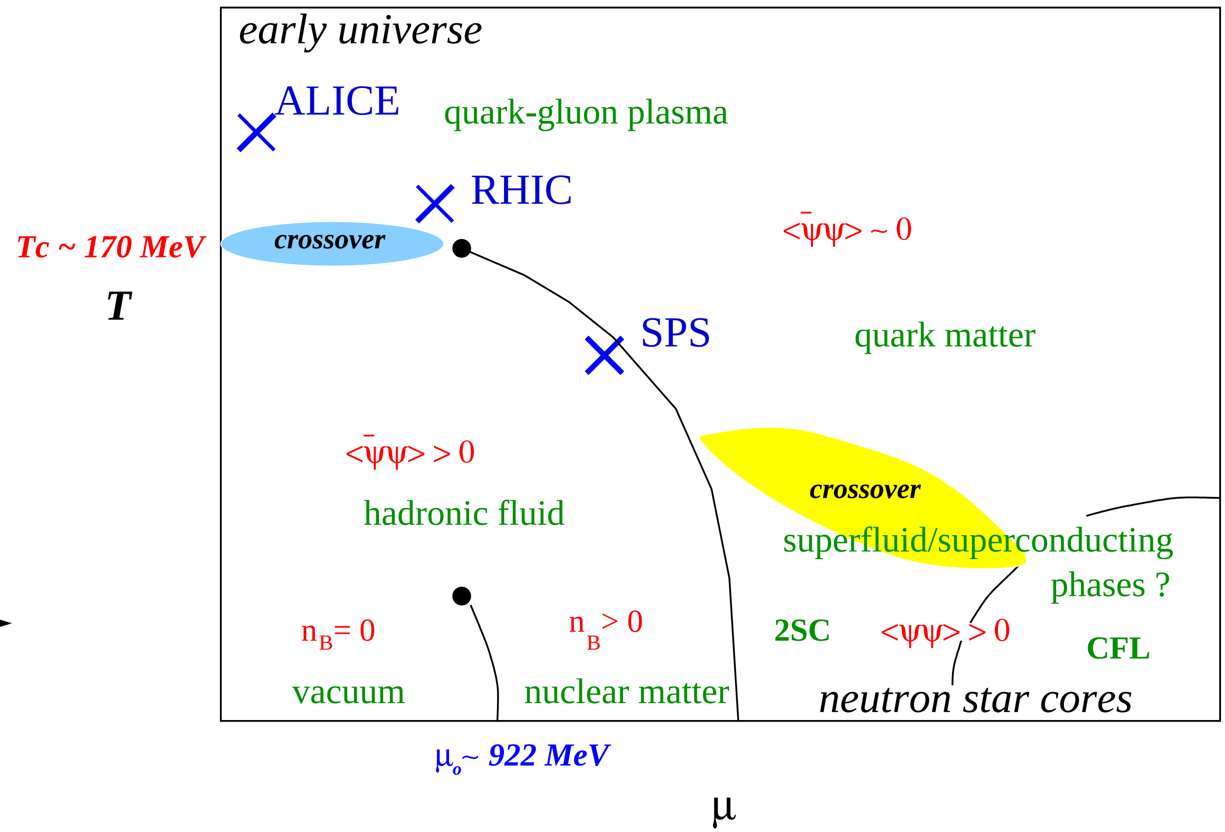


Motivation

Properties of hot and/or dense nuclear matter

Quark-gluon plasma

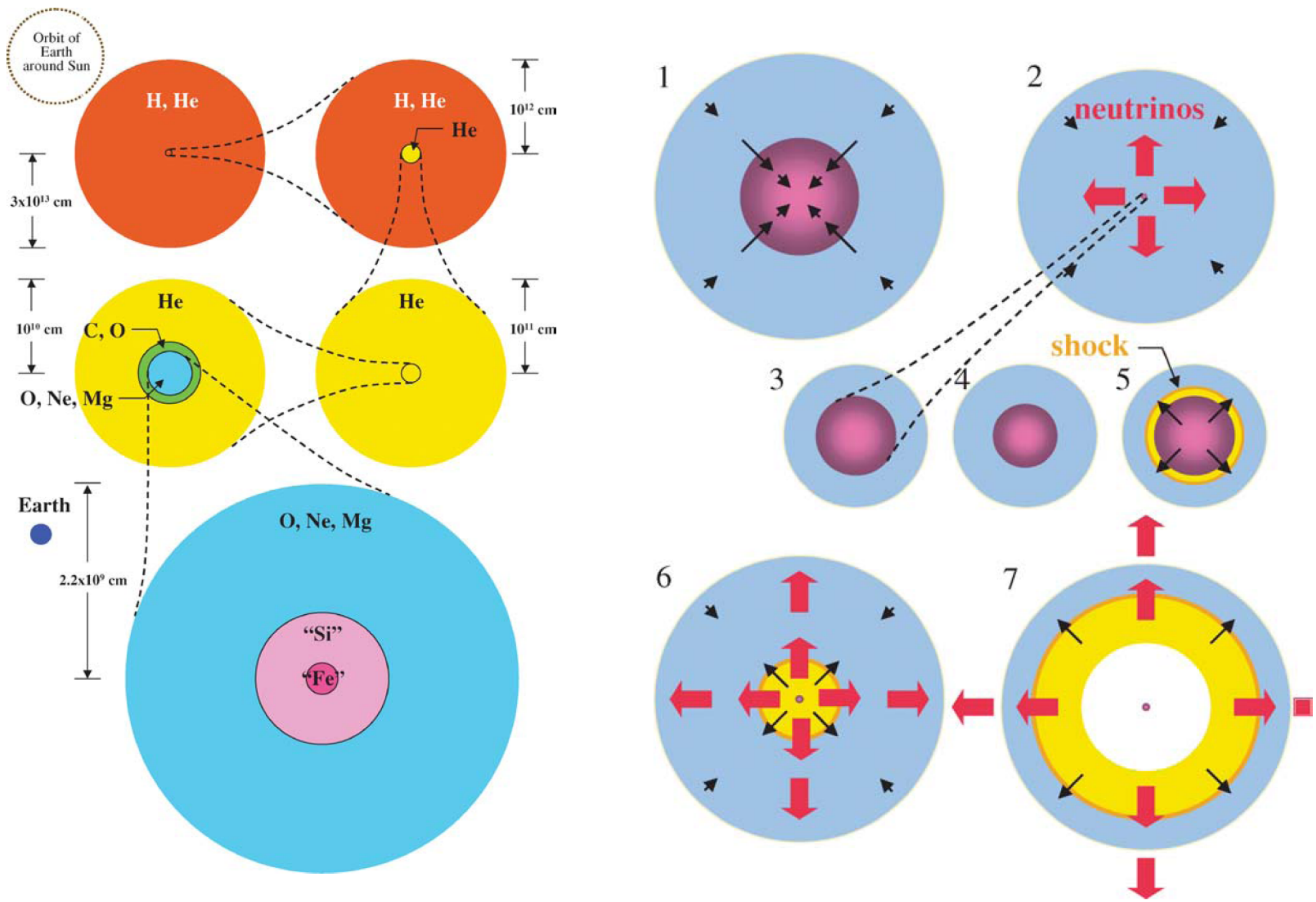




Motivation

Nuclear micro-physics of the Universe

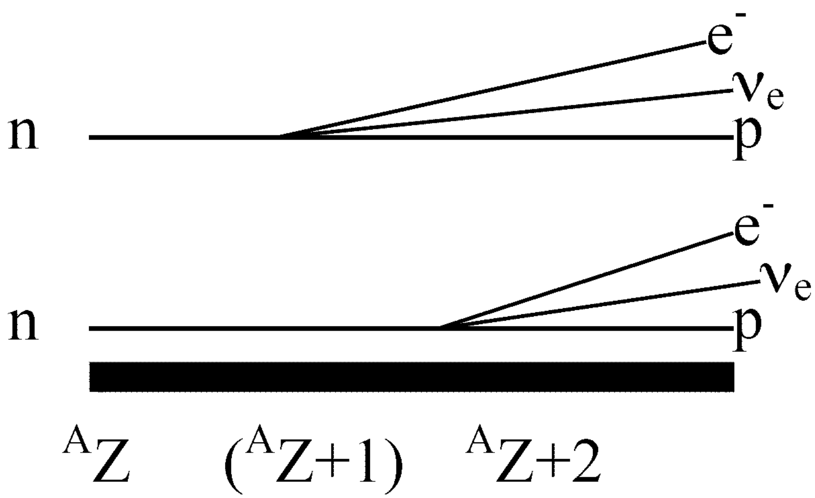
Origin of elements; neutron stars; supernova explosions; cosmic rays; gamma-ray sources

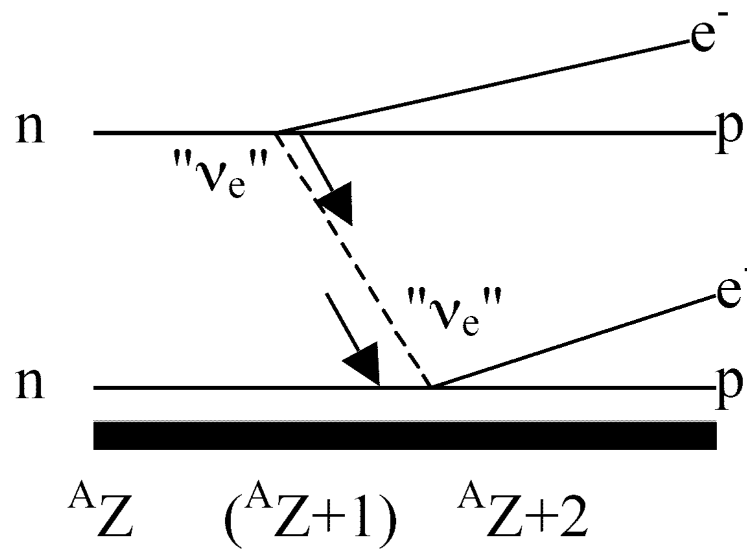


Motivation

New standard model

Solving the solar and atmospheric neutrino puzzles; neutrino-less double beta decay





“Microscopy of nucleons”

I Electro-magnetic form-factors

Spatial distribution of charge and magnetization

II Polarizability

Response to external field

III Resonances

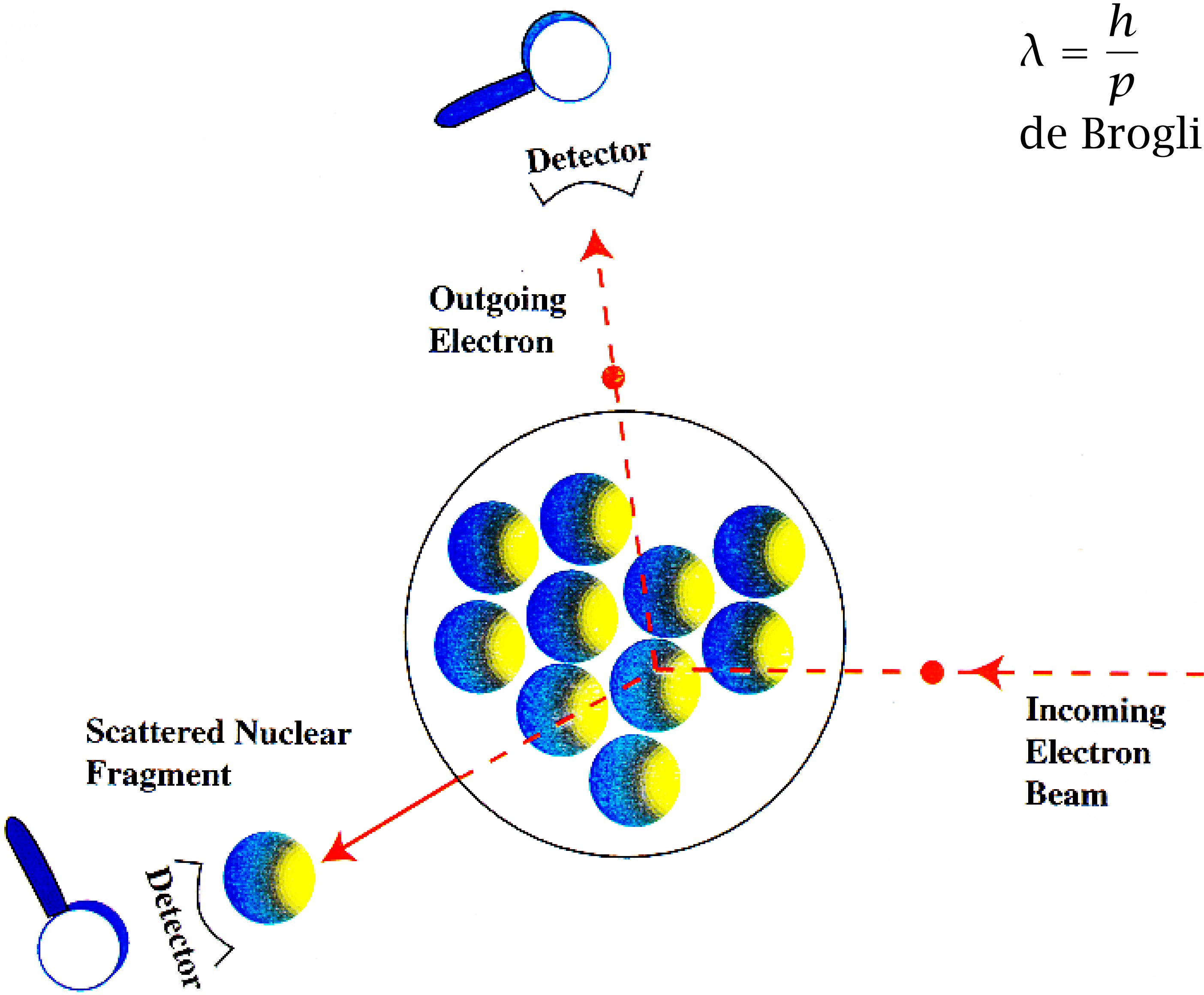
Dynamics

IV Parity violation

Proton in the mirror

V Axial structure and spin

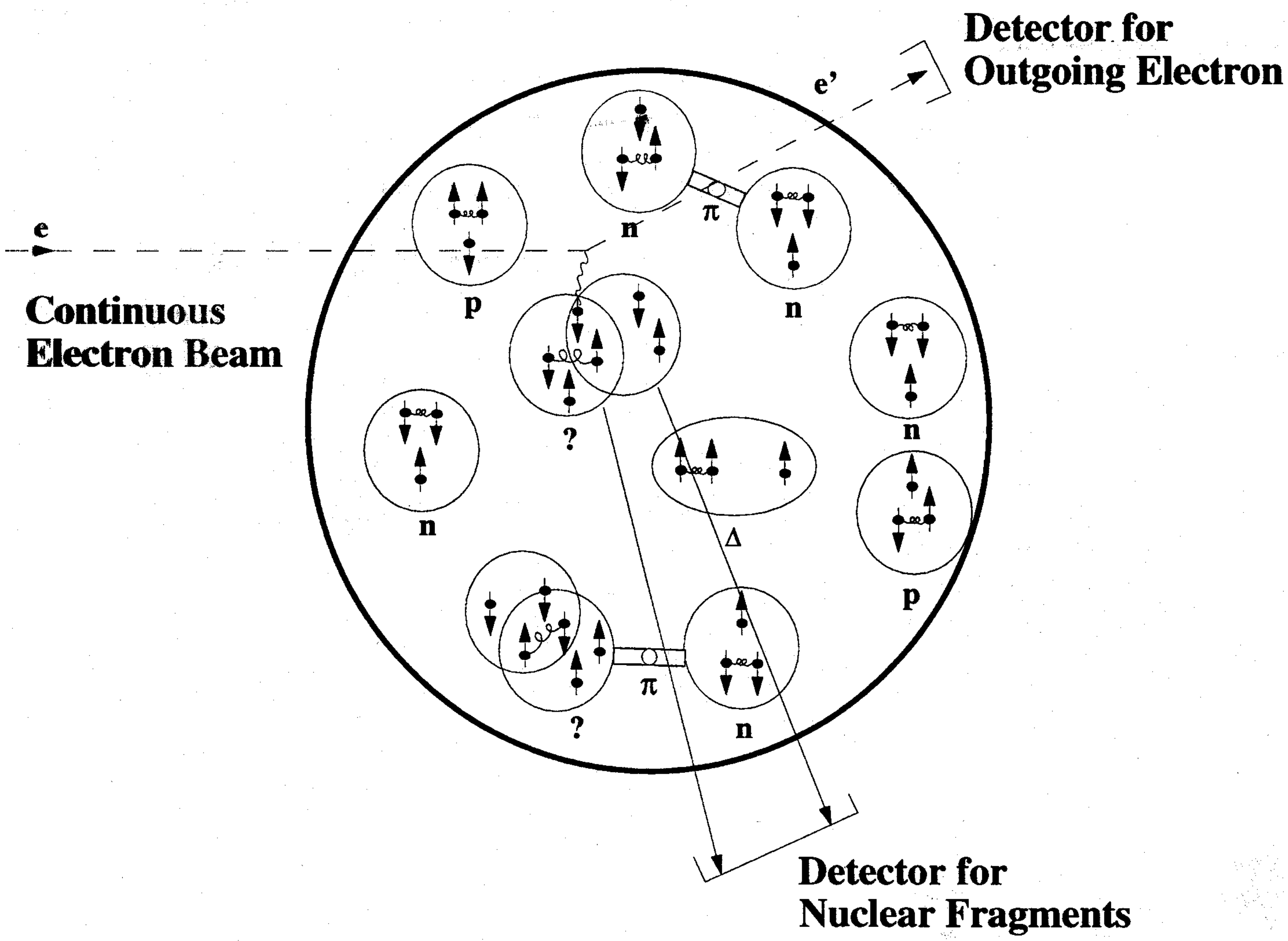
What carries the nucleon spin?



$$\lambda = \frac{h}{p}$$

de Broglie

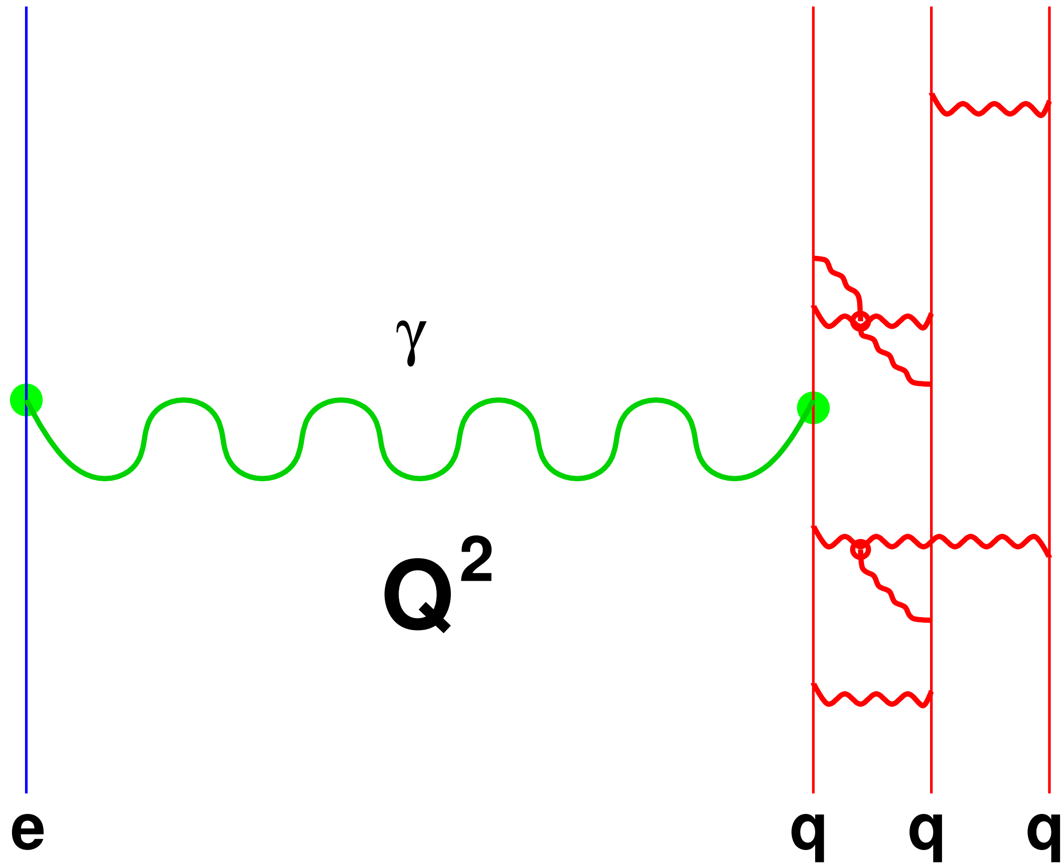
What do we observe under the "microscope"?



Why electro-magnetic interaction?

$\alpha = 1/137$

$\sigma \sim 1\,\mu\text{b}$

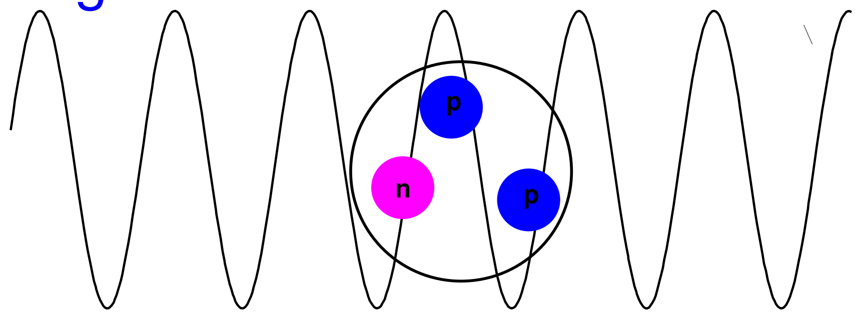


$$\frac{d\sigma}{d\Omega} \propto \quad v_L R_L + v_T R_T + v_{LT} R_{LT} + v_{TT} R_{TT} + \cdots$$

$$\lambda_{\mathrm{deBroglie}} \sim \frac{h}{Q}$$

Nuclear (coherent) scattering

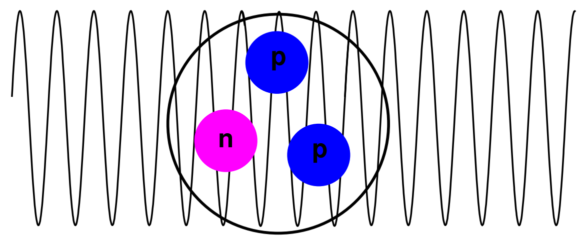
$Q^2 < 0.1\ \mathrm{GeV}^2$



$\gtrsim 1\ \mathrm{fm}$

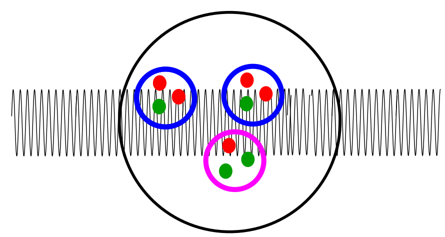
Transition Region

$0.1\ \mathrm{GeV}^2 < Q^2 < 1\ \mathrm{GeV}^2$

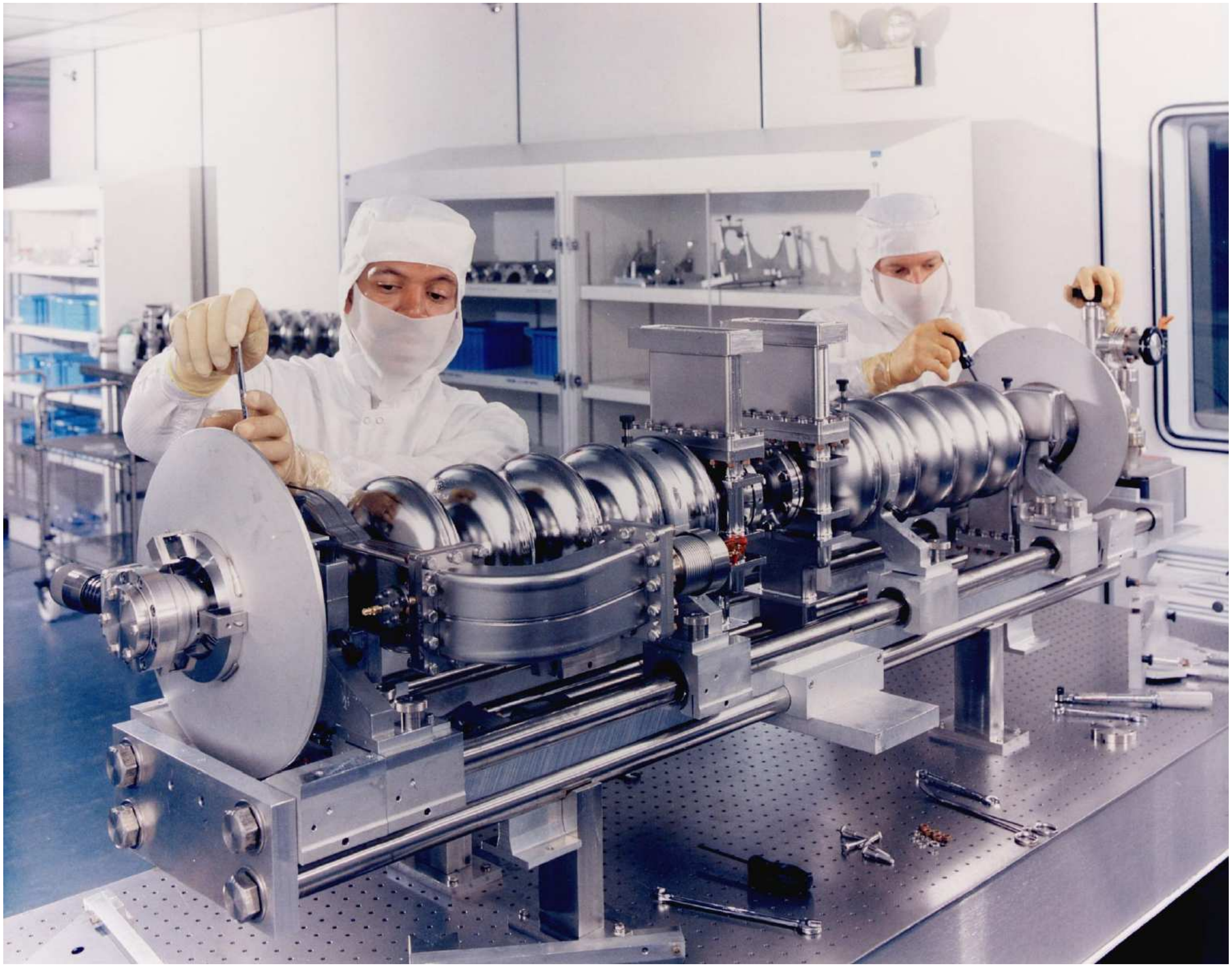


Parton (incoherent) scattering

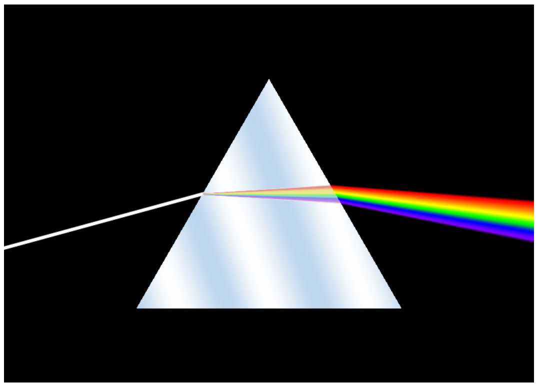
$Q^2 > 1\ \mathrm{GeV}^2$

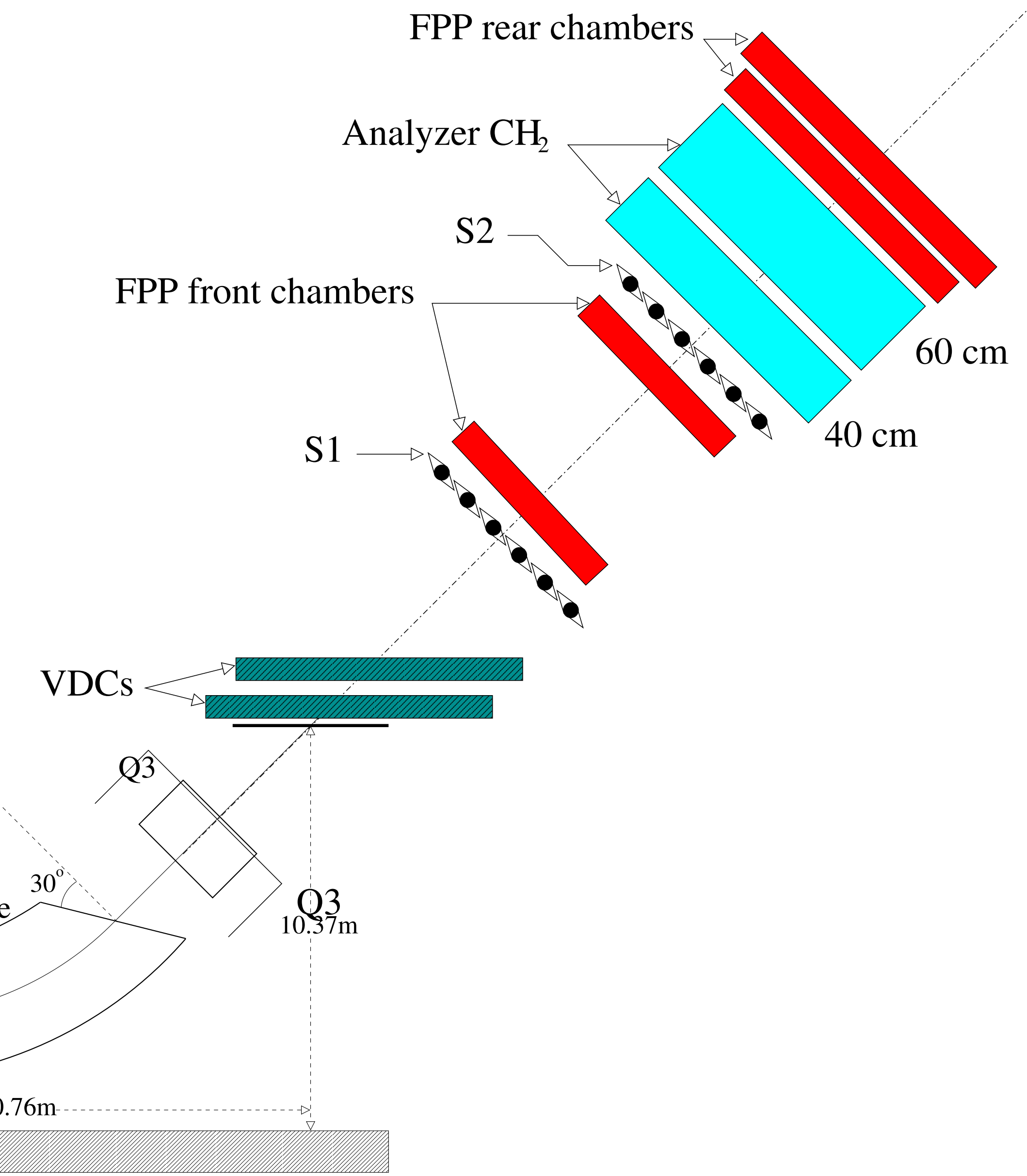


$\lesssim 0.1\ \mathrm{fm}$



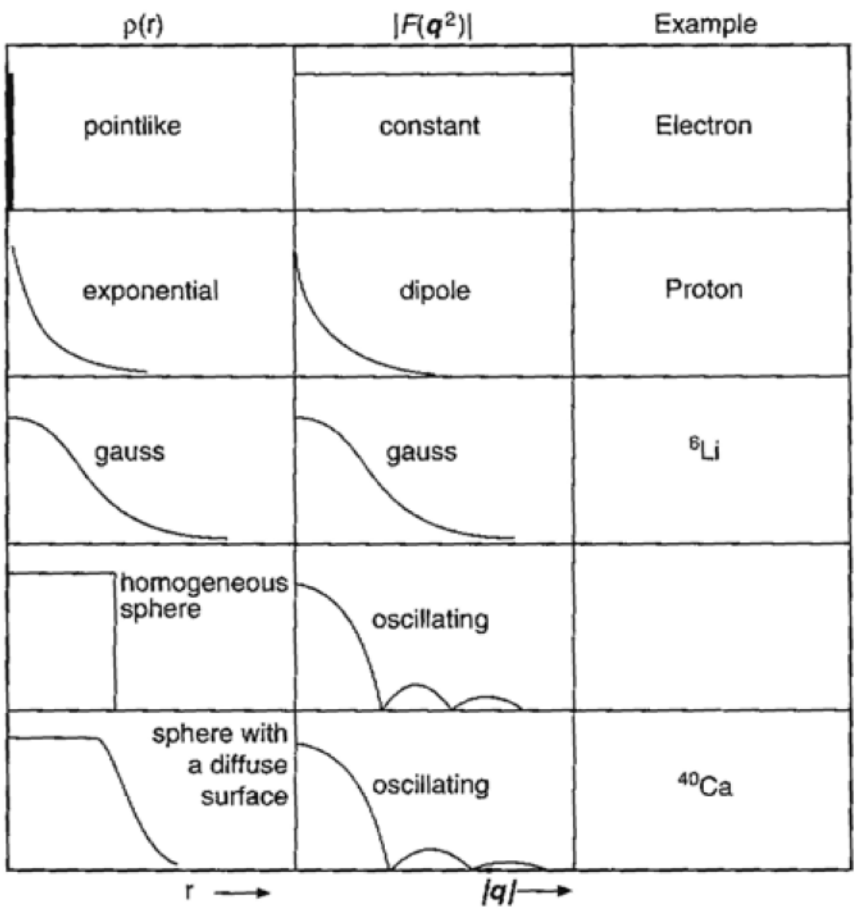
“Optical system”

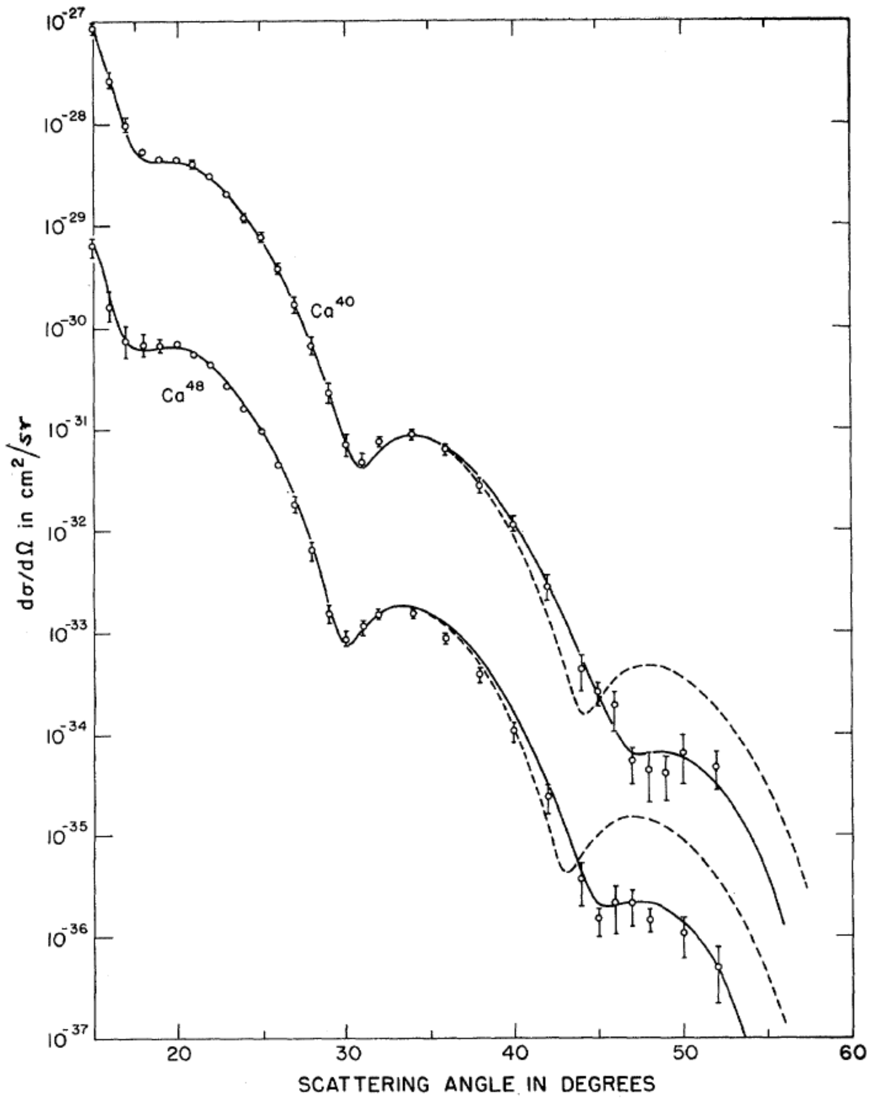




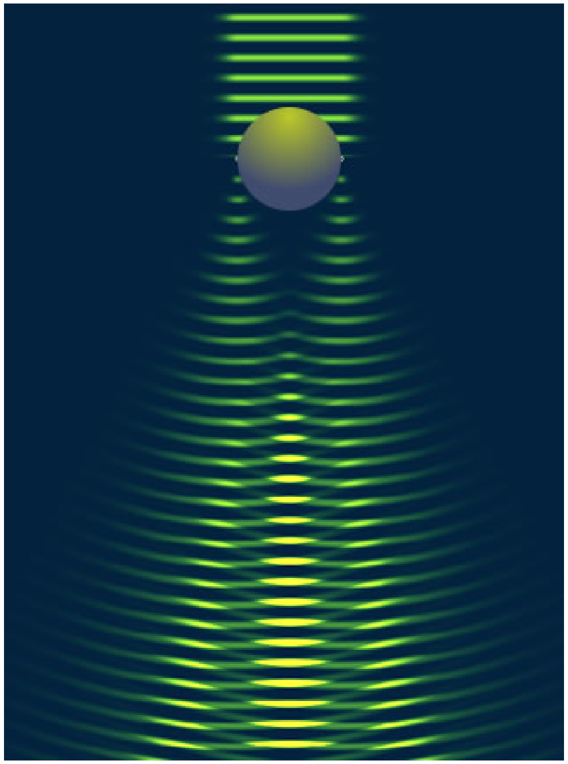
$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} \cdot \left| F_{\text{charge}}(Q) \right|^2$$

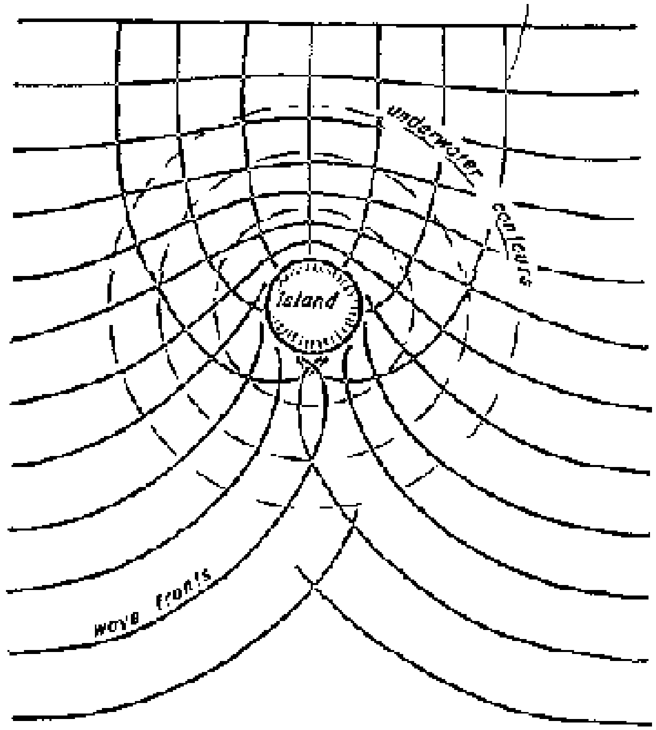
$$F_{\text{charge}}(Q) = \frac{1}{Z} \int d^3\vec{r}\, \rho(\vec{r})\, e^{i\vec{q}\cdot\vec{r}}$$

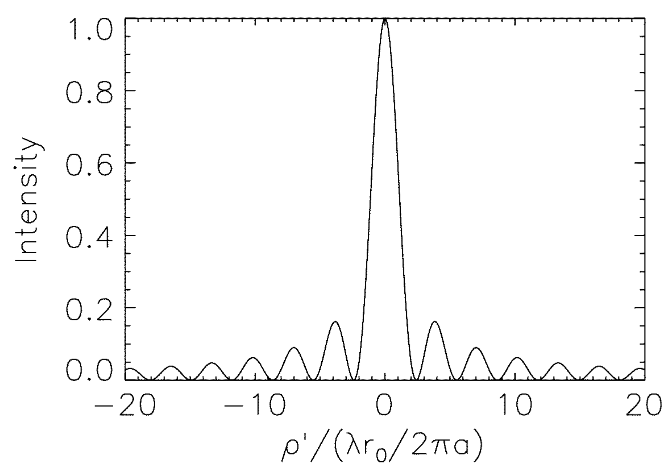




I — Analogies: wave diffraction on circular obstacle

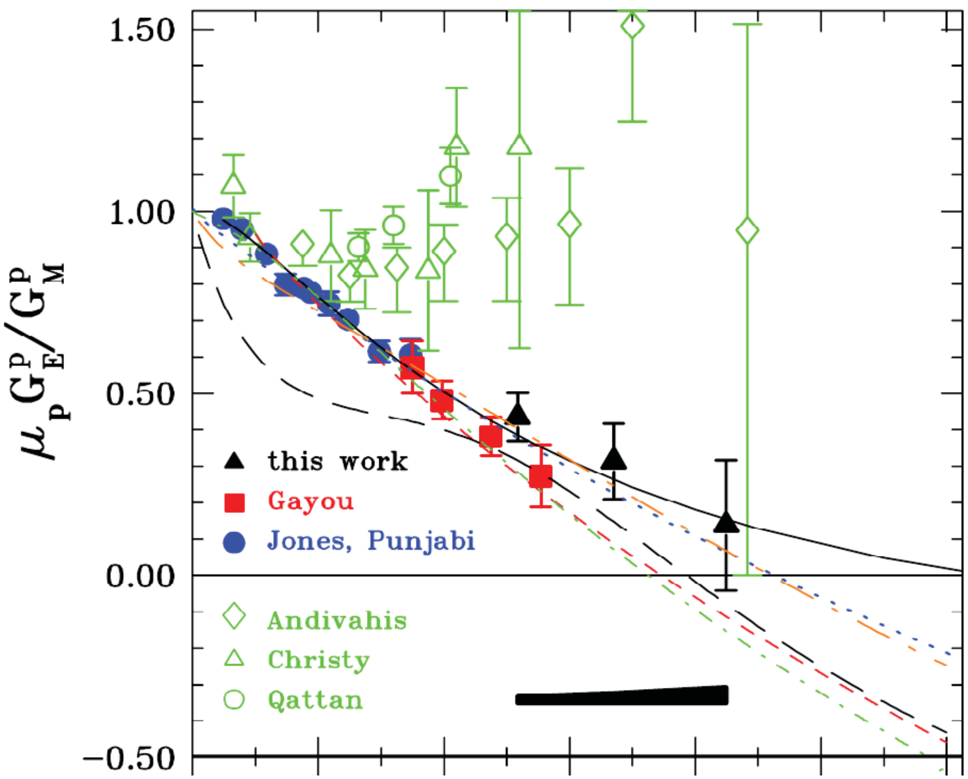


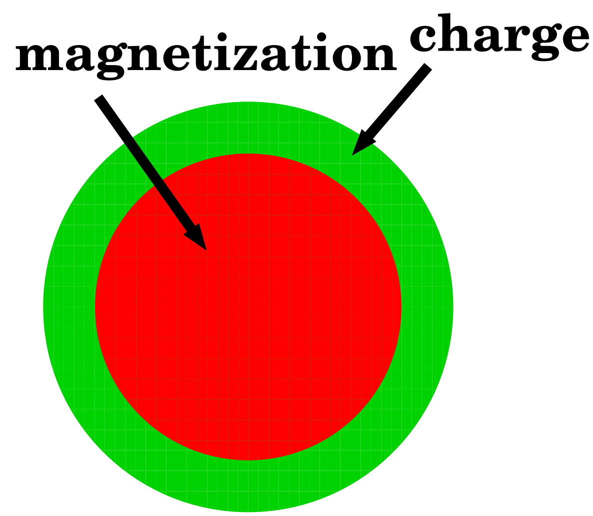




I — Electric and magnetic form-factor of proton (SPIN 1/2)

$$\frac{G_E^p(Q^2)}{G_M^p(Q^2)} = -\frac{P_t}{P_l}\frac{E_e + E'_e}{2M}\tan\frac{\theta_e}{2} \qquad \text{in process } \vec{e} + p \to e + \vec{p}$$





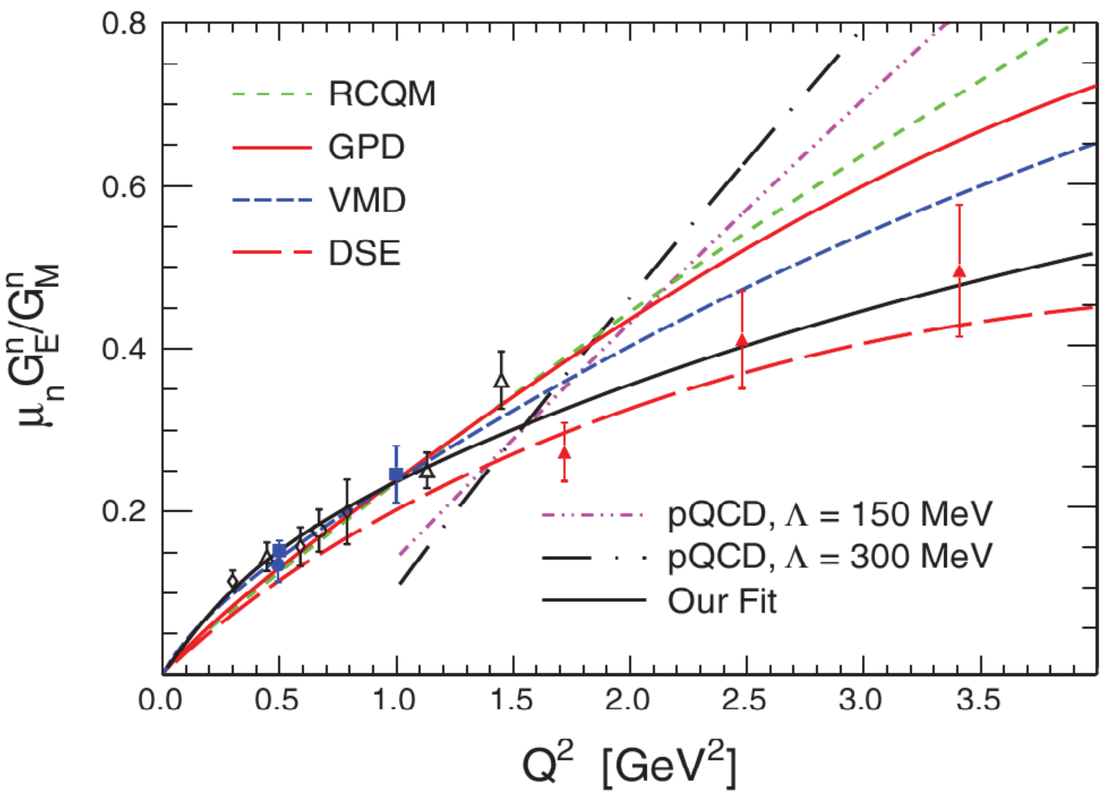
$R_{\text{charge}} > R_{\text{magnetization}}$

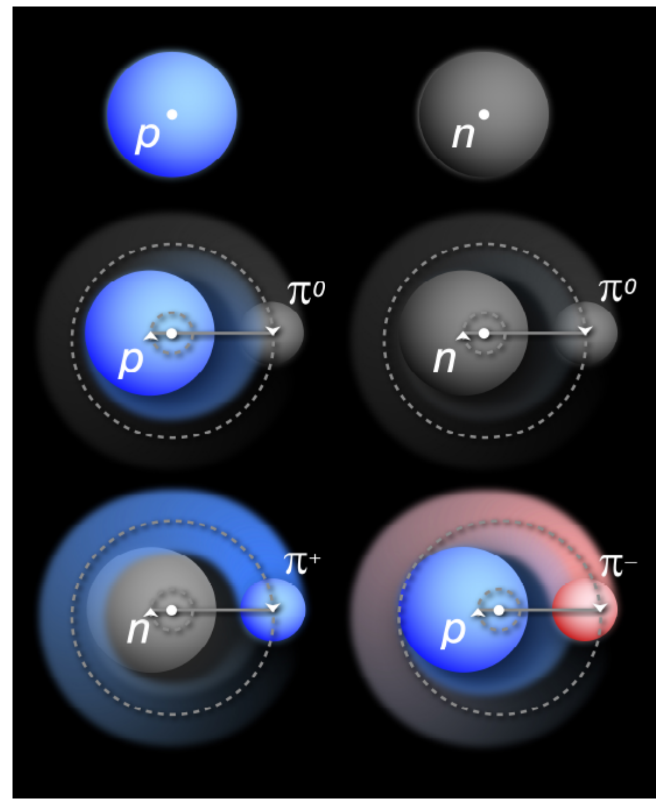
3 (?) quarks (?)

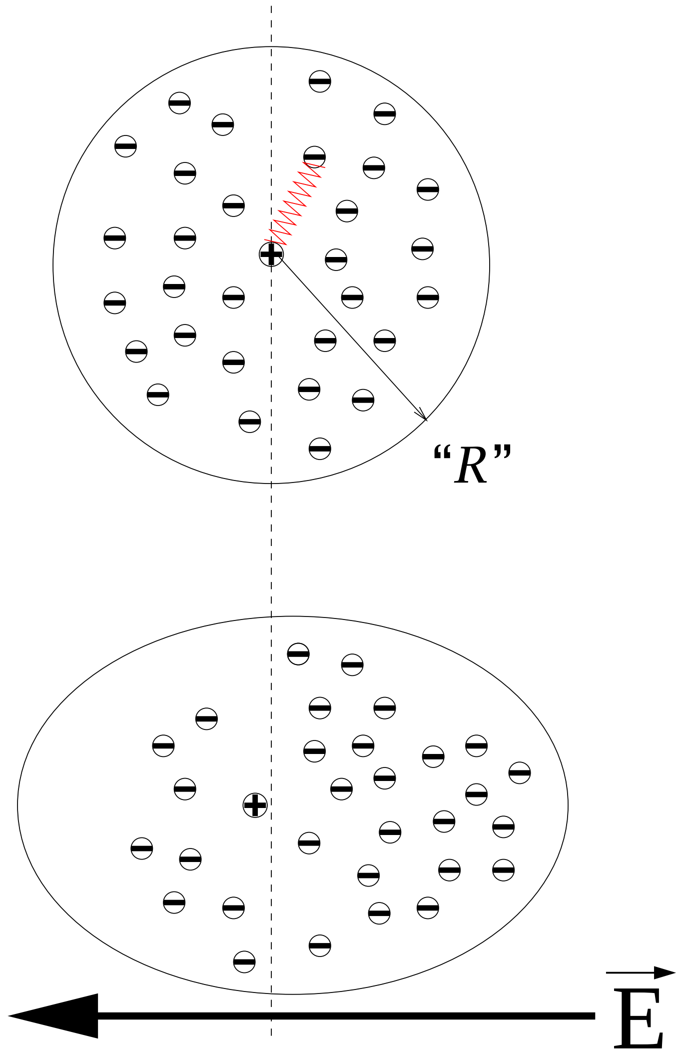
(in fact, NO)

I — Electric and magnetic form-factor of neutron (SPIN 1/2)

- electrically neutral (net charge zero); pion-cloud effects
- need polarized ^{3}He targets







Neutral atom in external field $\vec{E}$

$$\vec{F} = m\omega^2 \vec{x} = e_0 \vec{E}$$

$$\vec{p} = e_0 \vec{x} = \frac{e_0^2}{m\omega^2} \vec{E} \equiv \alpha_{\text{atom}}\, \varepsilon_0\, \vec{E}$$

$\alpha_{\text{atom}} \approx 10^{-28}\,\text{m}^3 \sim \mathcal{O}(R^3)$

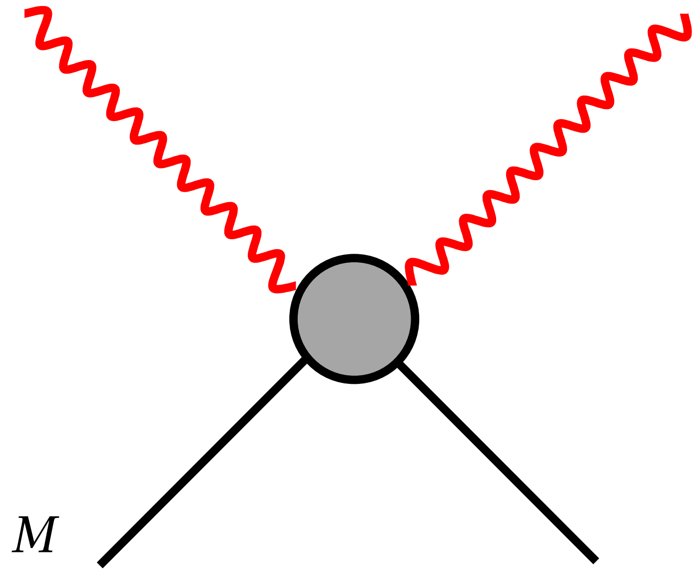
$x \approx 10^{-6}\,\text{nm}$ for $E = 10\,\text{kV/cm}$

$\Longrightarrow \alpha_{\text{proton}} < 10^{-15}\,\alpha_{\text{atom}}$

$\Longrightarrow x$ unmeasurably small for macroscopic E

II — Polarizability

$$\boldsymbol{A} = \frac{\boldsymbol{\epsilon}}{\sqrt{2\omega}}\,\mathrm{e}^{\mathrm{i}\boldsymbol{k}\boldsymbol{x}}$$



$$\boldsymbol{A}' = \frac{\boldsymbol{\epsilon}'}{\sqrt{2\omega'}}\,\mathrm{e}^{\mathrm{i}\boldsymbol{k}'\boldsymbol{x}}$$

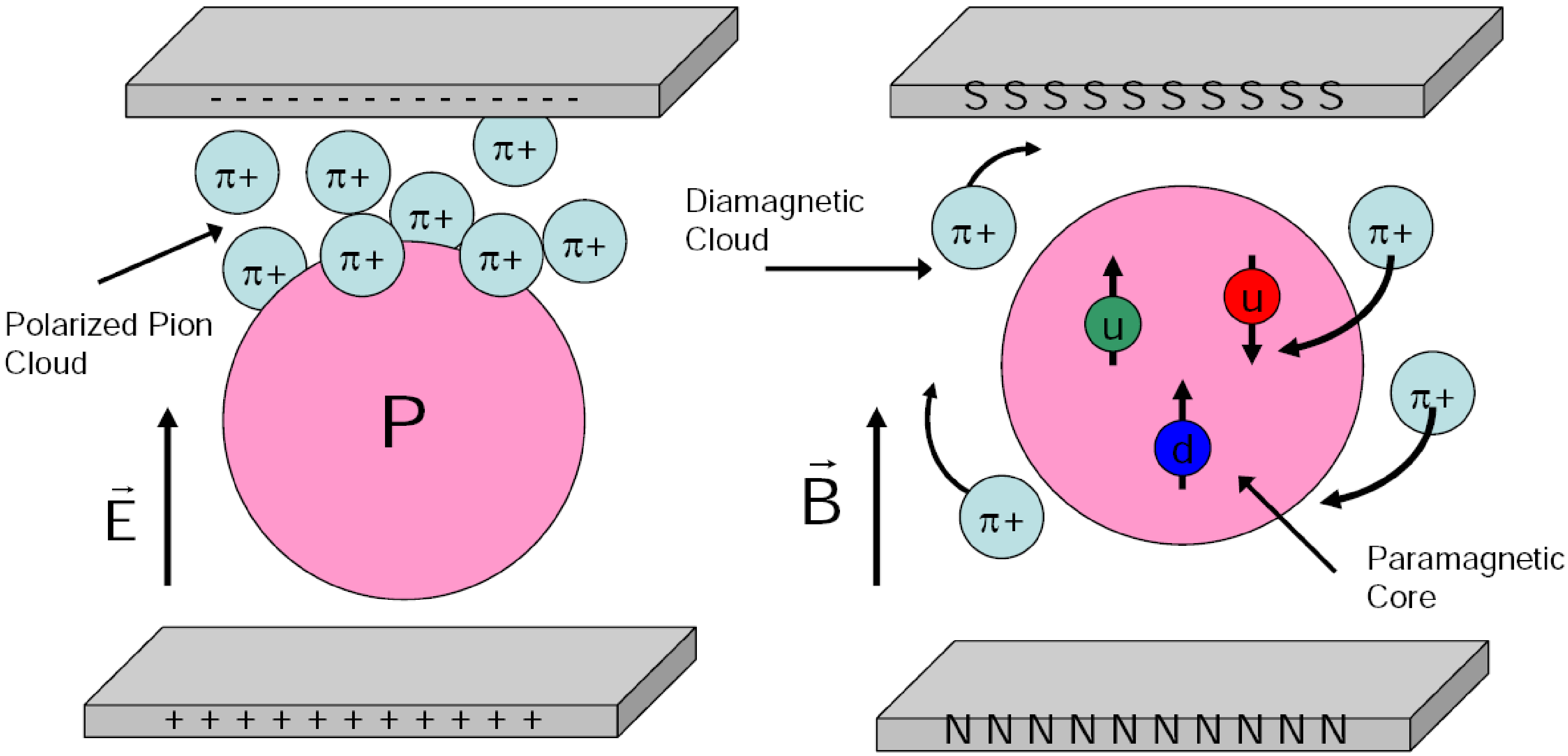
$$T = -\frac{e_0^2}{M}\,\boldsymbol{\epsilon}\boldsymbol{\epsilon}' + \overline{\alpha}\,\omega^2\,\boldsymbol{\epsilon}\boldsymbol{\epsilon}' + \overline{\beta}\,\omega^2\,(\boldsymbol{\epsilon}' \times \hat{\mathbf{k}}')(\boldsymbol{\epsilon} \times \hat{\mathbf{k}})$$

Thomson

$$\overline{\alpha} = \alpha + \frac{e_0^2}{3M}\langle r^2 \rangle$$

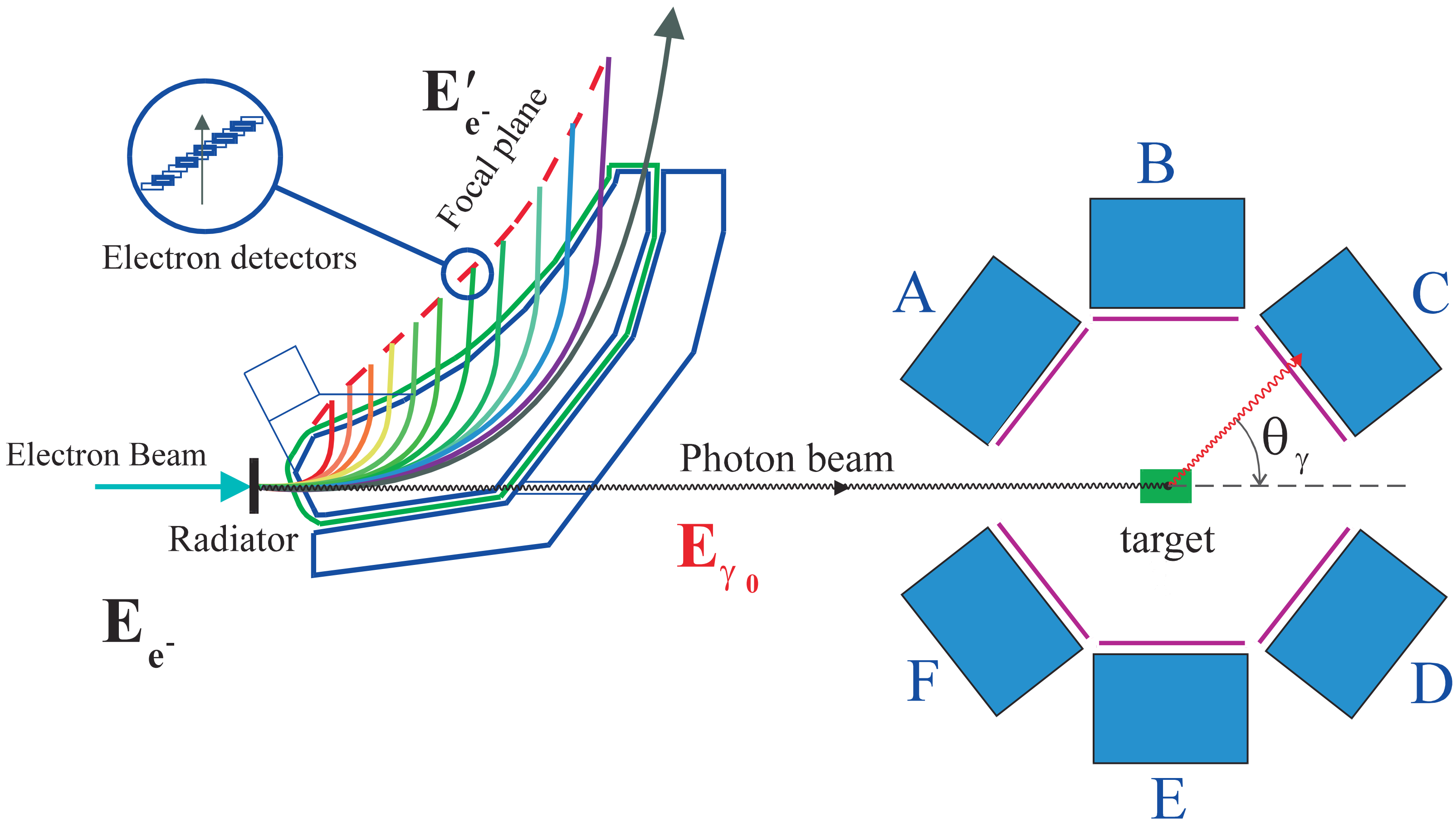
$$\overline{\beta} = \beta_{\text{para}} + \beta_{\text{dia}}$$

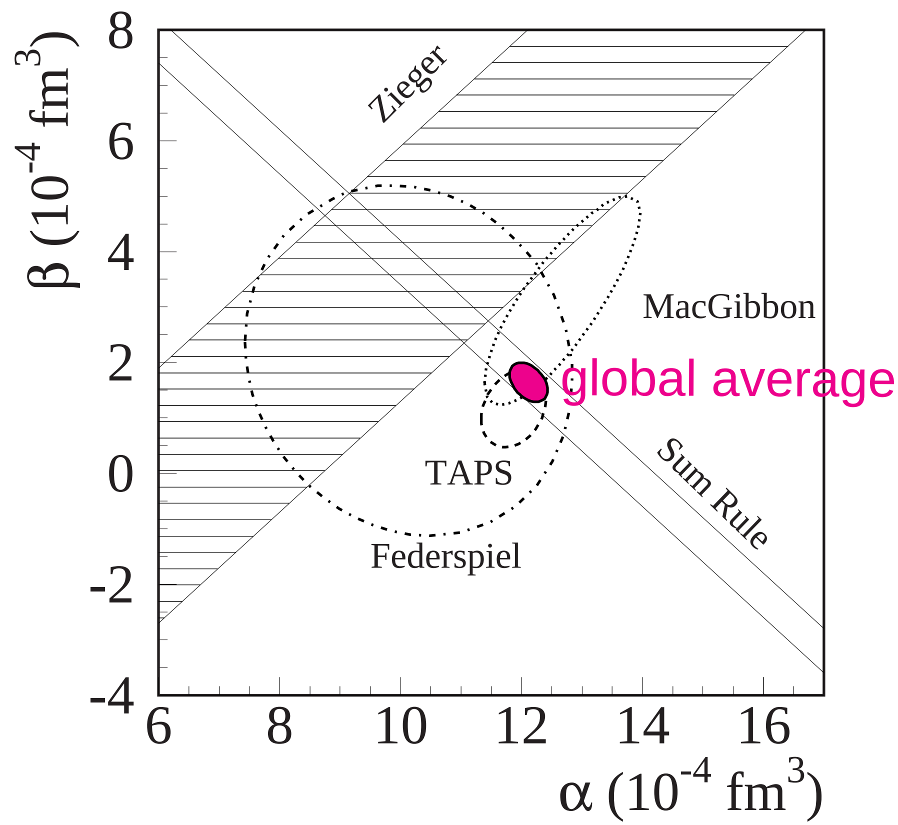
Nucleon Polarizabilities



Electric Polarizability:
Proton between Charged
Parallel Plates

Magnetic Polarizability:
Proton between Poles of
A Magnetic


E'_{e^-}
Focal plane
Electron detectors
Electron Beam
Radiator
E_{e^-}
Photon beam
$E_{\gamma\,0}$
B
A
C
θ_γ
target
F
D
E

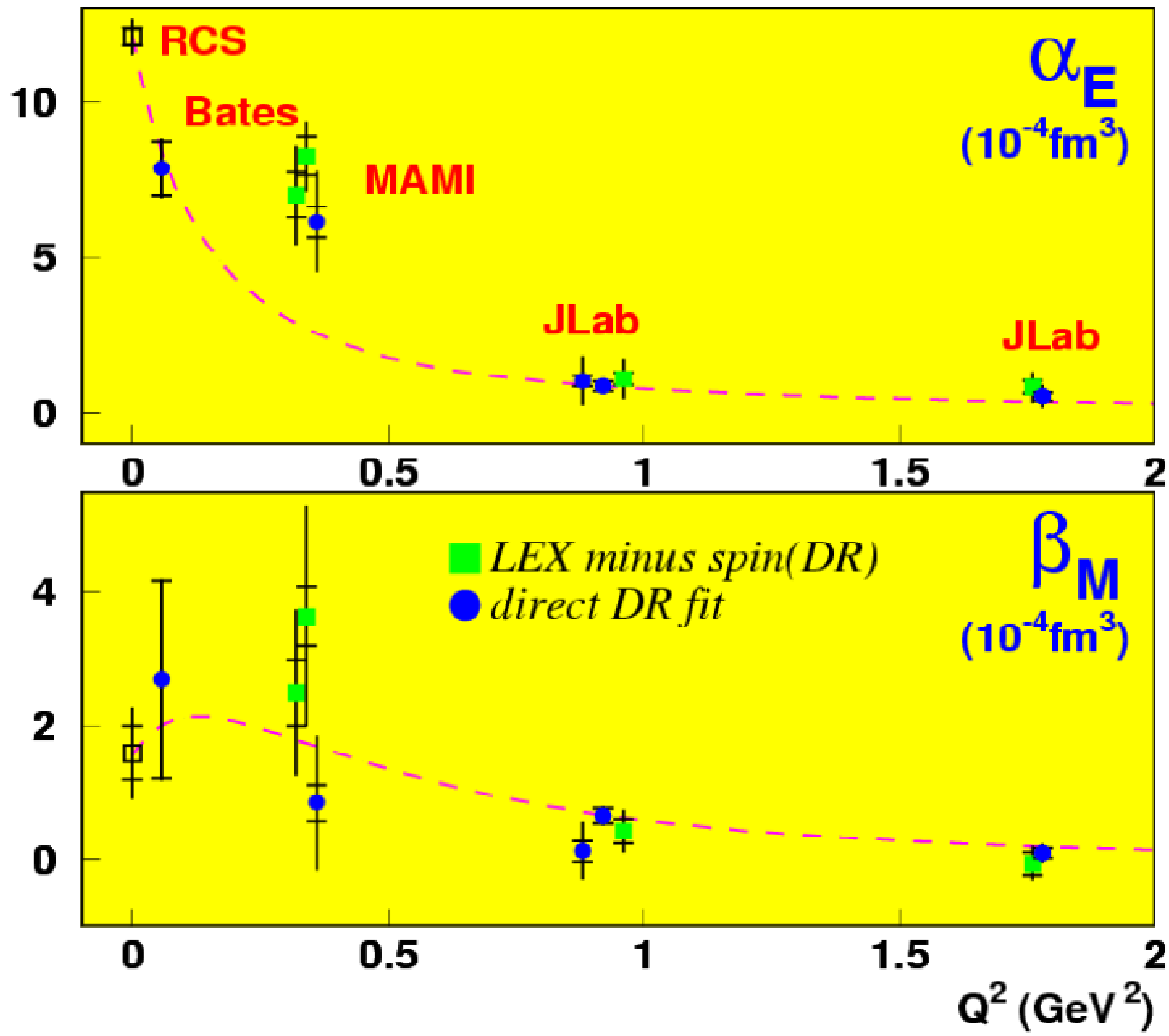


$$\alpha_{\mathrm{p}} = (12.0 \pm 0.6) \cdot 10^{-4}\mathrm{fm}^3$$

$$\beta_{\mathrm{p}} = (1.9 \mp 0.6)$$

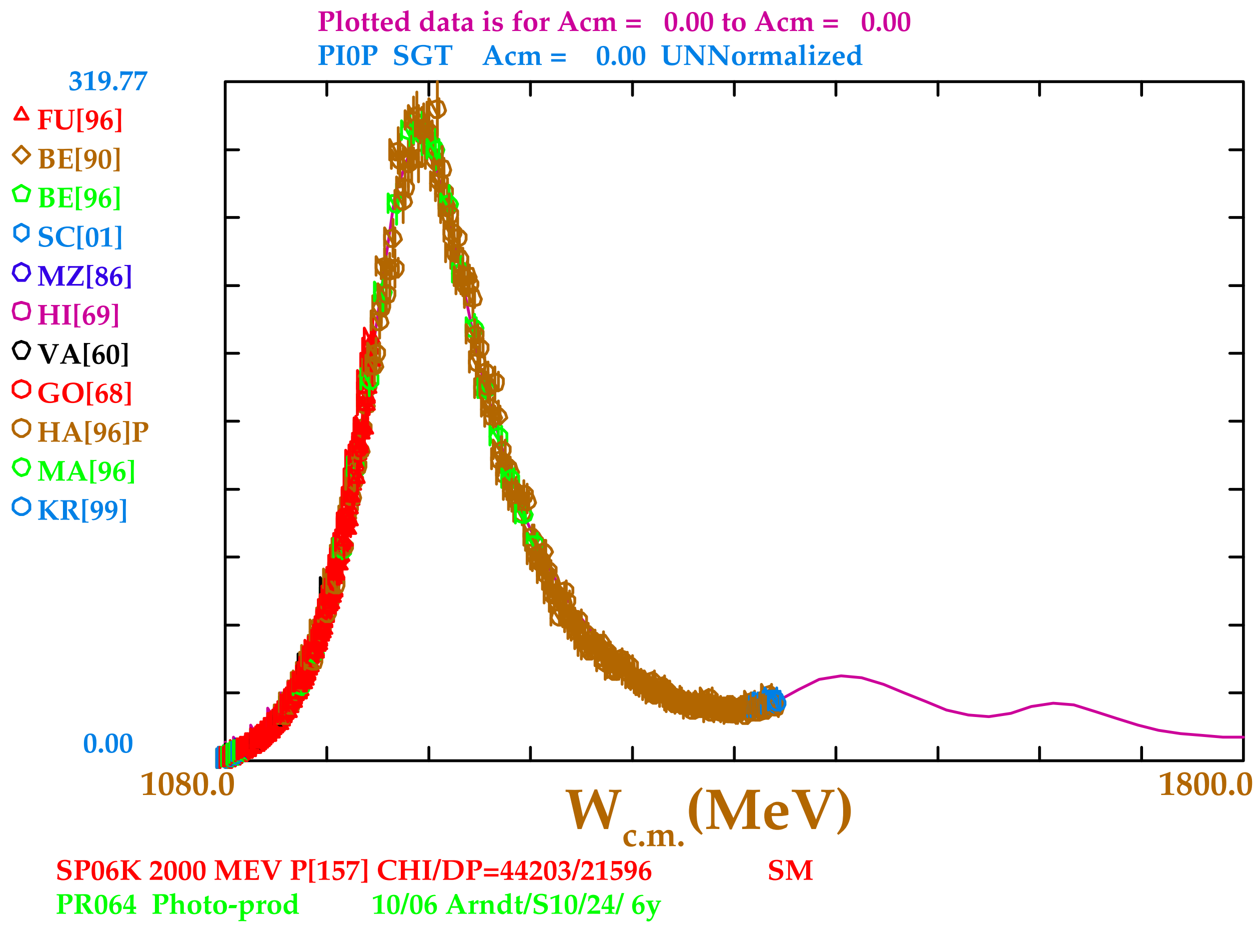
$$\alpha_{\mathrm{p}} + \beta_{\mathrm{p}} = (13.6 \pm 1.0)$$ Baldin's sum rule

Electric and magnetic polarizability

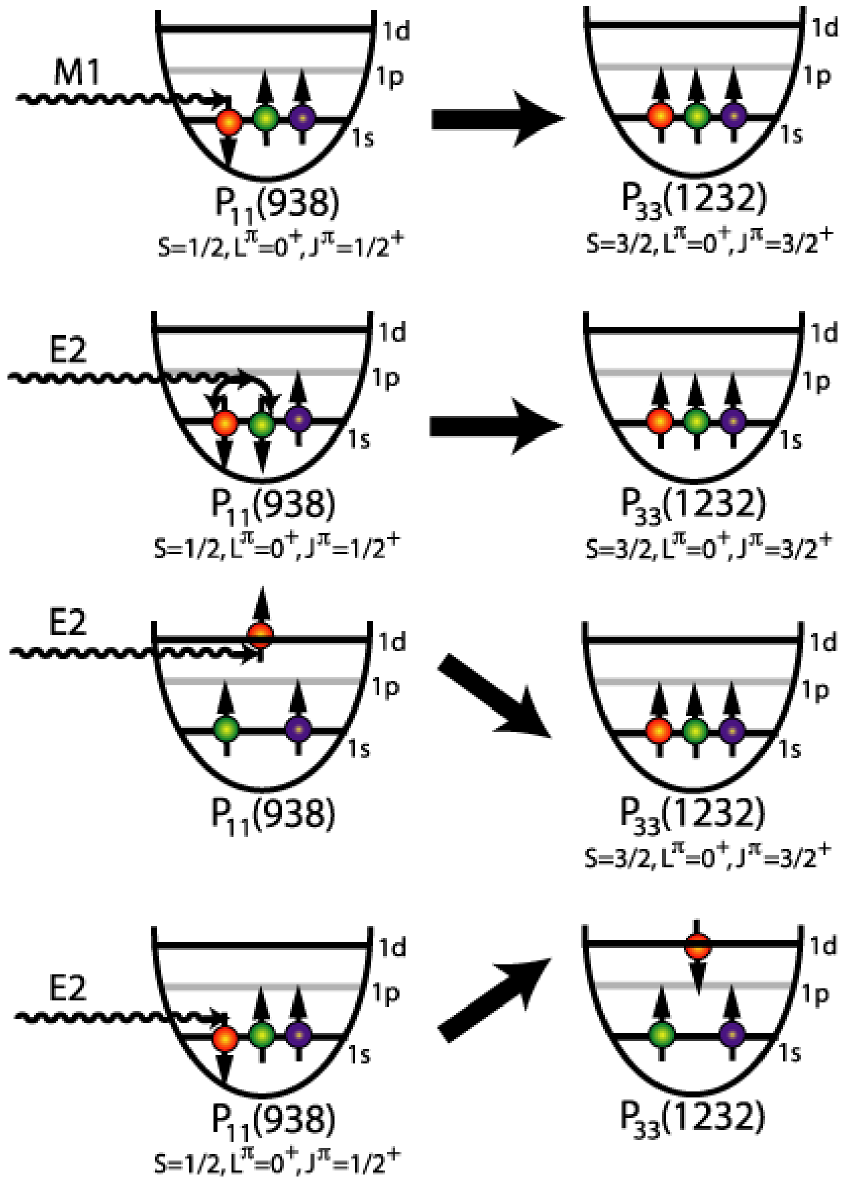


$$\gamma + \mathrm{p} \to W_{\mathrm{c.m.}} \to \mathrm{p} + \pi^0$$

$$\left.\begin{aligned} q &= (\omega, \vec{q}) \\ p &= (M, \vec{0}) \end{aligned}\right\} \qquad W_{\mathrm{c.m.}}^2 = (q+p)^2 = M^2 + 2M\omega + q^2$$

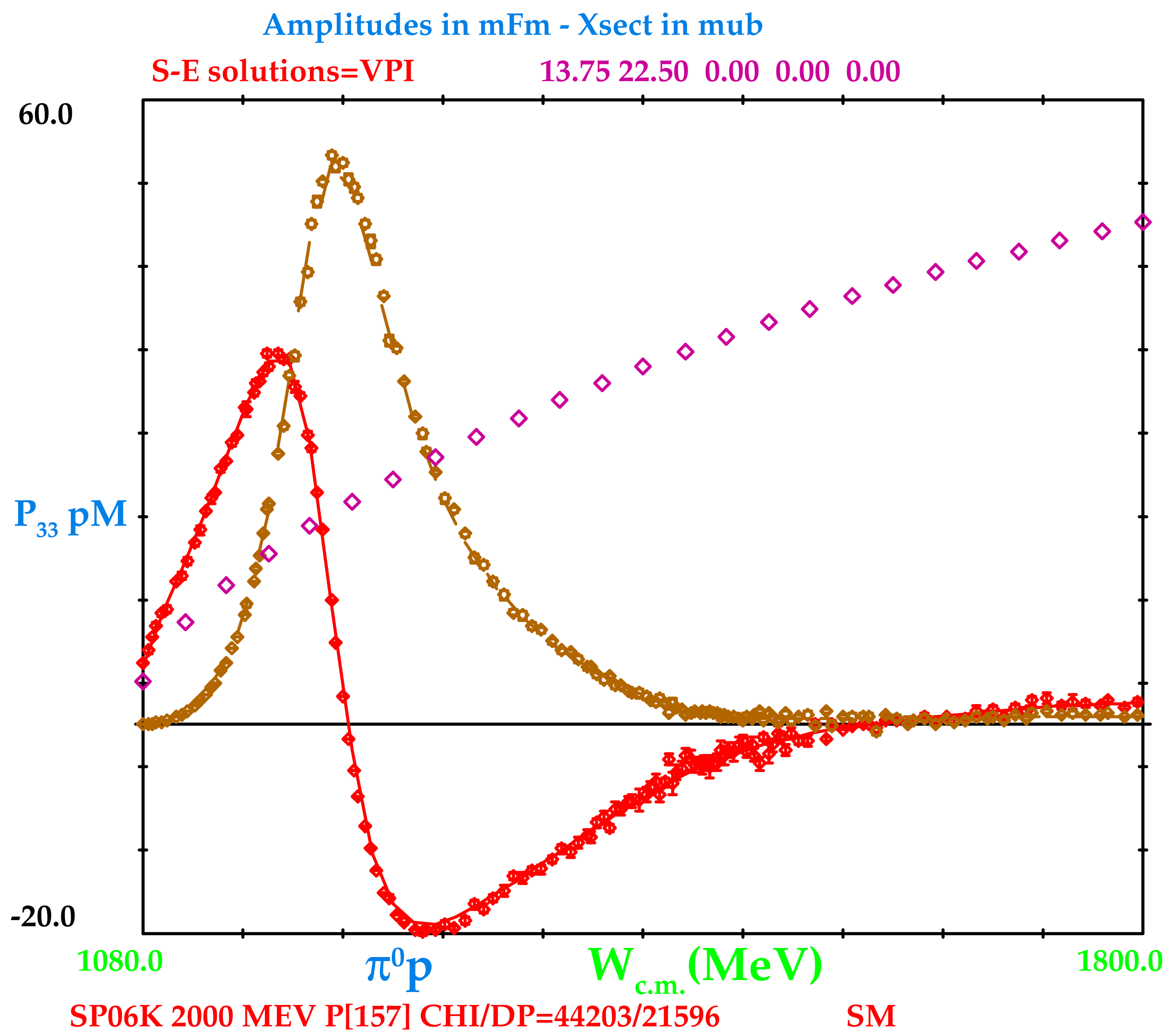


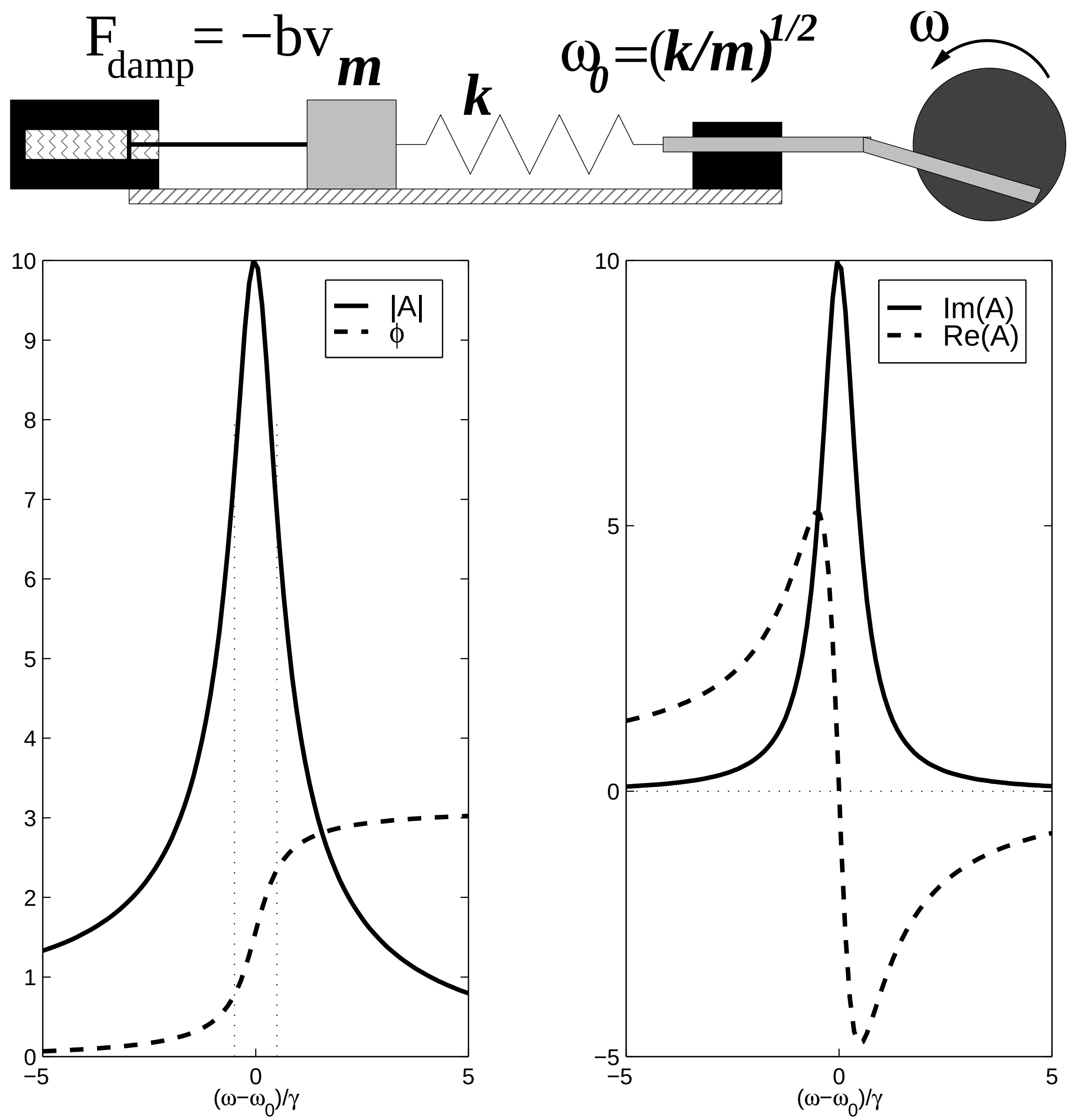
$\gamma + N(938) \to \Delta(1232)$



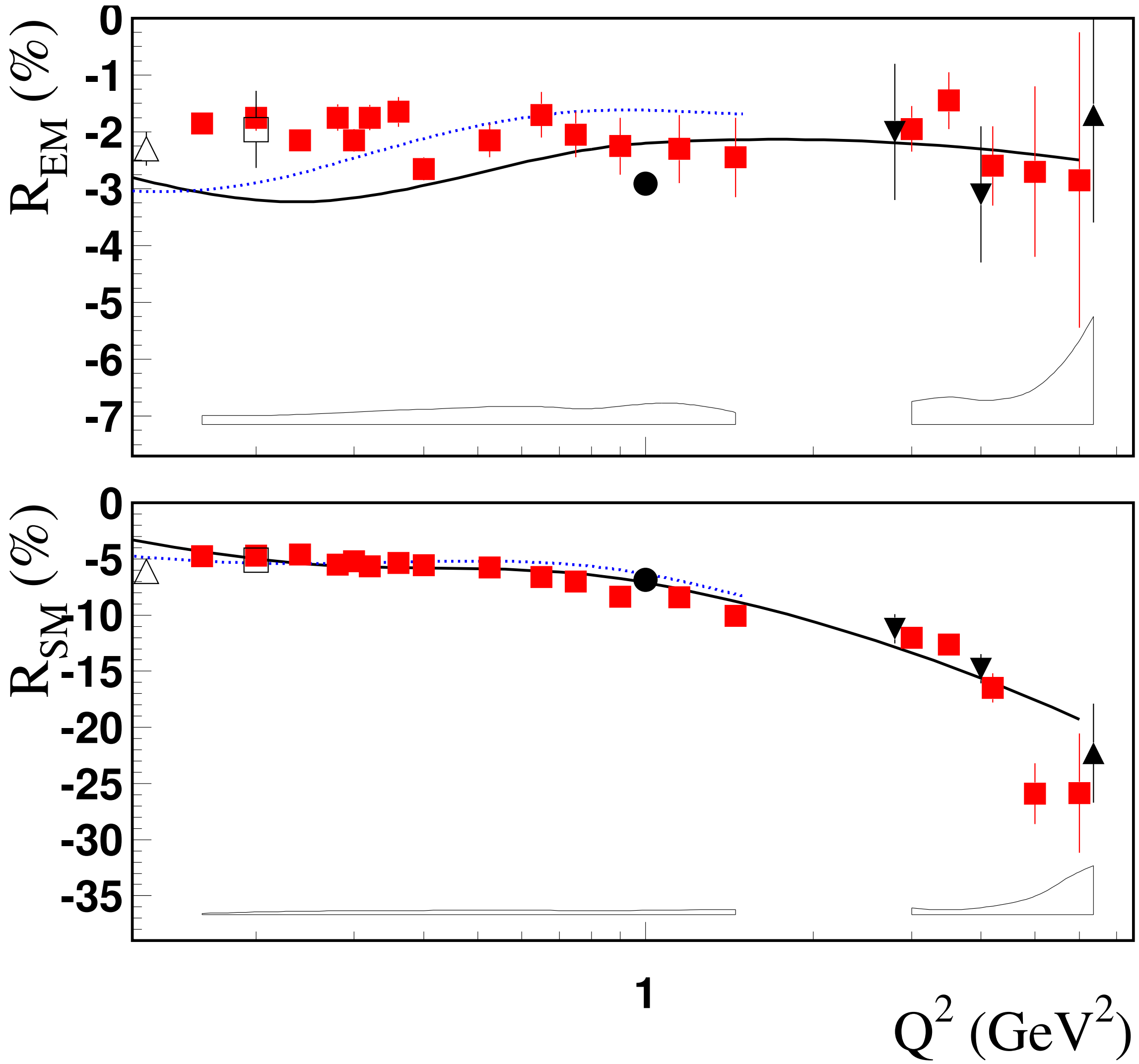
III — Resonances

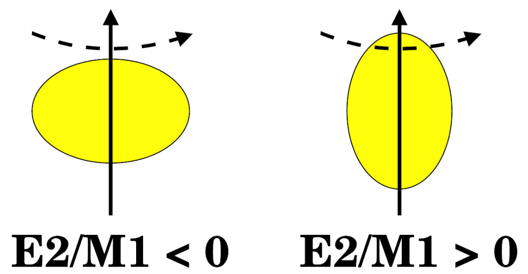
$\gamma + N \rightarrow \Delta \rightarrow p + \pi^0$



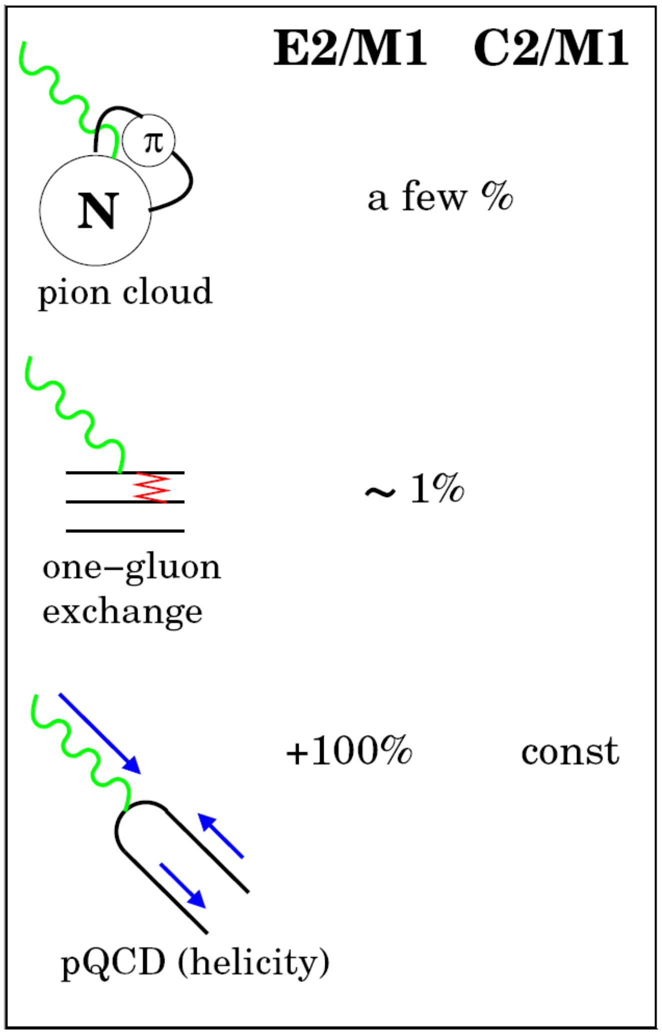

F_damp = −bv
m
k
ω0 =(k/m)^1/2
ω
|A|
ϕ
(ω−ω0)/γ
Im(A)
Re(A)
(ω−ω0)/γ

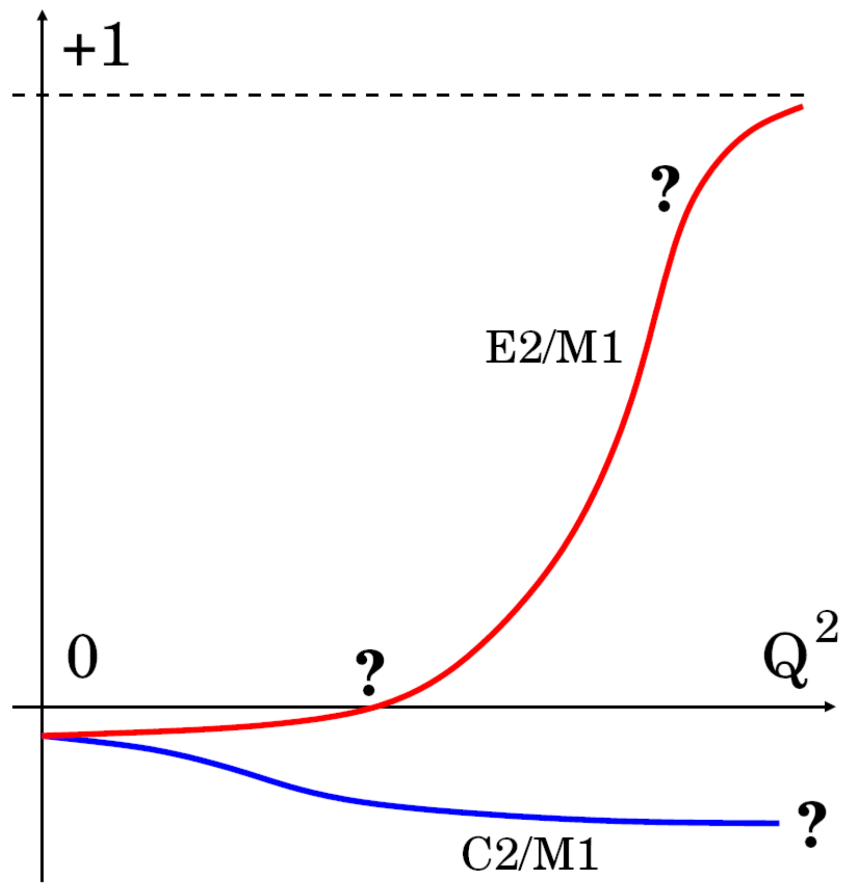
 $\gamma + N(938) \rightarrow \Delta(1232)$



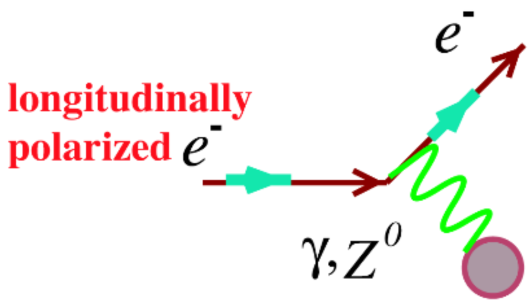


III — Electro-excitation of $\Delta(1232)$ resonance at high Q^2





Interference of electro-magnetic (V_{em}) and weak ($[V - A]_{weak}$) interaction

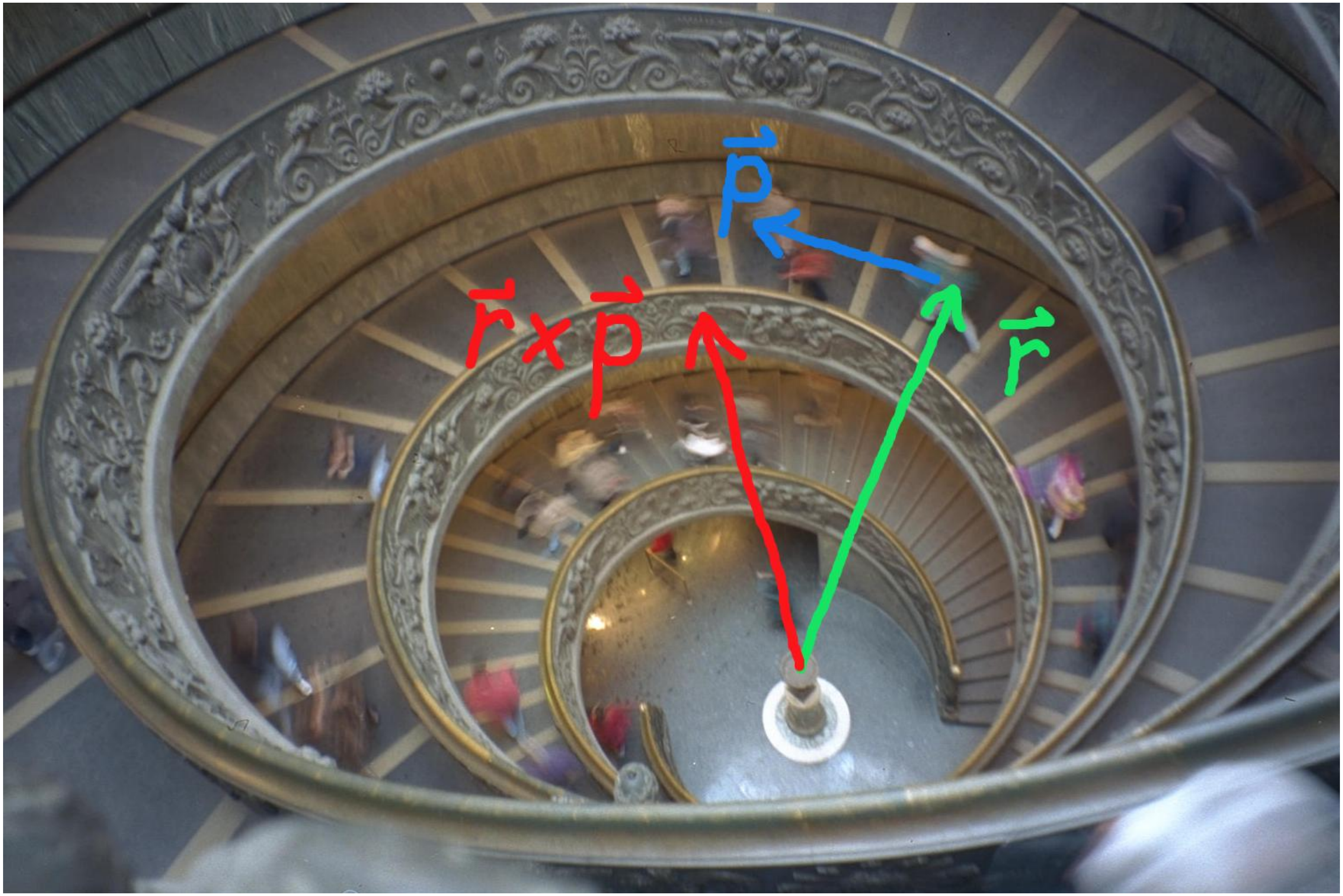


$$\sigma \;\; \alpha \; | A_\gamma + A_{weak} |^2$$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F\, Q^2}{4\,\pi\,\alpha}$$

$$Q^2 \sim 0.01 - 1\ \mathrm{GeV}^2 \longrightarrow A_{PV} \lesssim 10^{-7} - 10^{-4}$$

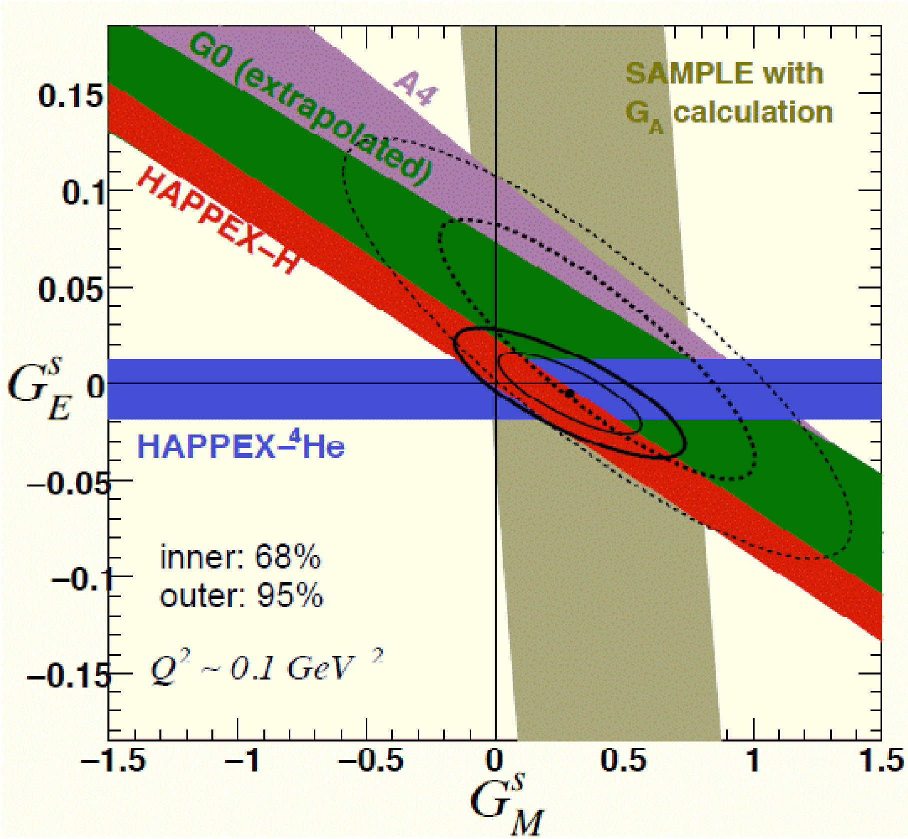
Intermezzo: axial vector



IV — Parity violation

H $\left(\frac{1}{2}^+\right)$ $$A_{\rm PV} \propto \frac{G_{\rm F}}{\alpha}\left\{1 - 4\sin^2\theta_{\rm W} - \frac{\varepsilon G_{\rm E}^{\rm p}(G_{\rm E}^{\rm n} + G_{\rm E}^{\rm s}) + \tau G_{\rm M}^{\rm p}(G_{\rm M}^{\rm n} + G_{\rm M}^{\rm s})}{\varepsilon (G_{\rm E}^{\rm p})^2 + \tau (G_{\rm M}^{\rm p})^2} + \cdots\right\}$$

He (0^+) $$A_{\rm PV} \propto 2\sin^2\theta_{\rm W} - \frac{G_{\rm E}^{\rm s}}{G_{\rm E}^{\rm p} + G_{\rm E}^{\rm n}}$$



$G_{\rm E}^{\rm s}(0.1) \approx -0.006 \pm 0.016$

$G_{\rm M}^{\rm s}(0.1) \approx 0.28 \pm 0.20$

$\approx (0.2 \pm 0.5)\%$ of $G_{\rm E}^{\rm p}$

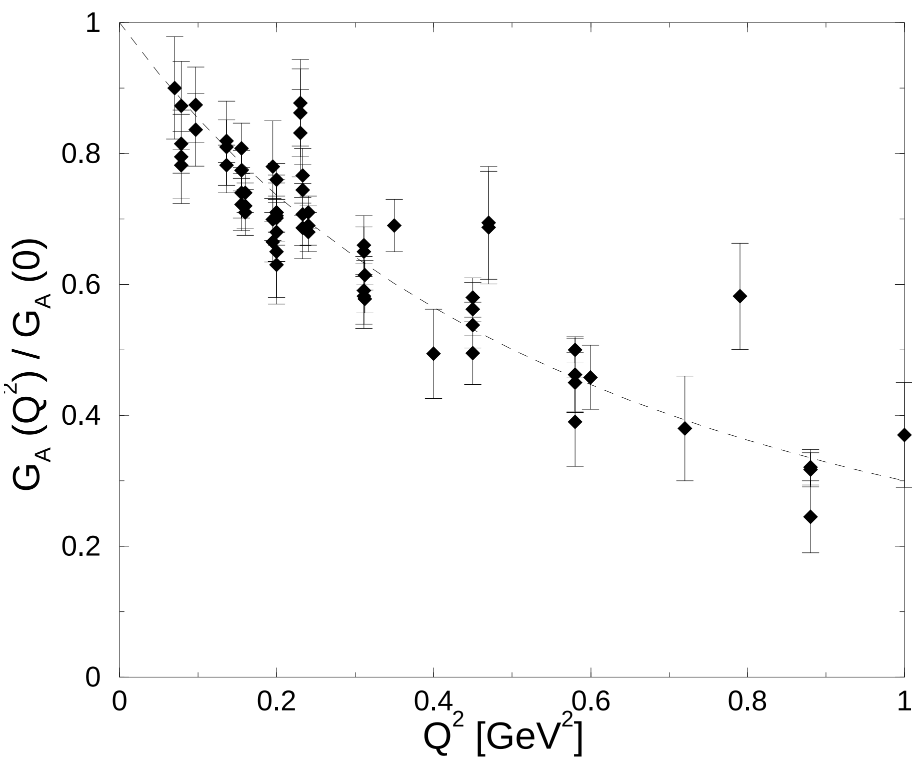
$\approx (3.0 \pm 2.3)\%$ of $G_{\rm M}^{\rm p}$

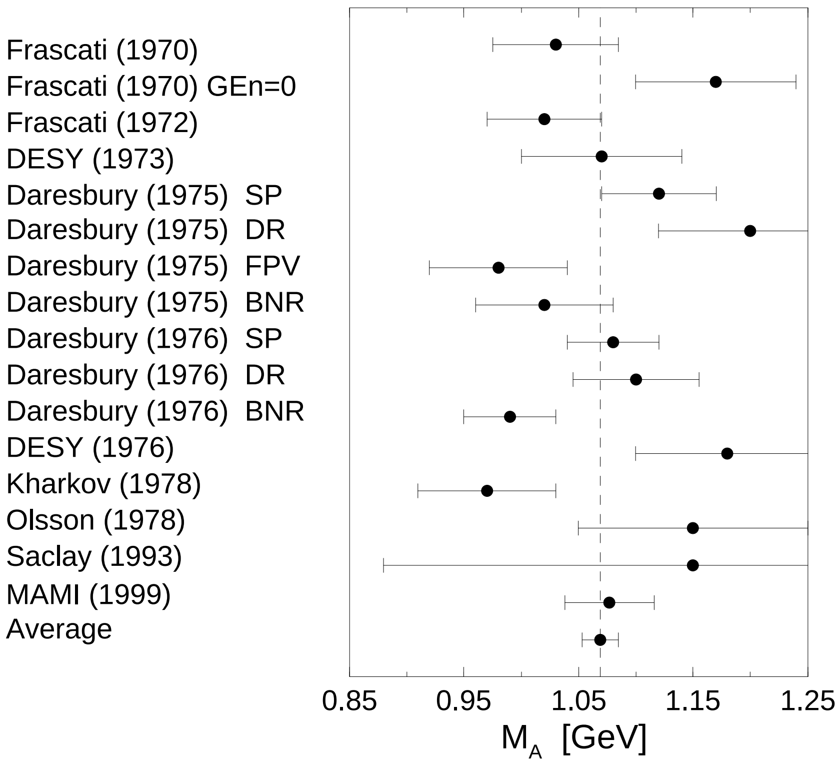
V — Axial structure and spin

$e + p \to e' + n + \pi^+$

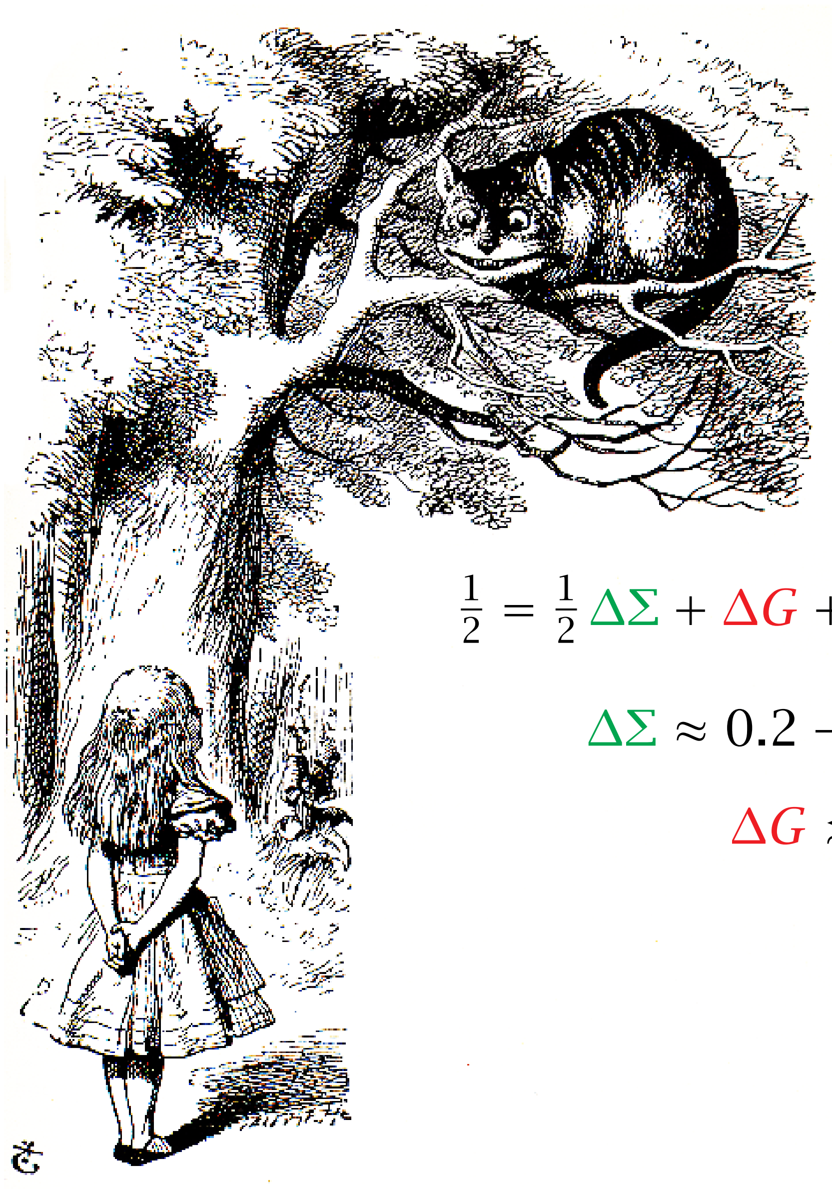
$$\left\langle n\left(+\tfrac{\vec{q}}{2}\right) \left| \vec{A}_a(0) \right| p\left(-\tfrac{\vec{q}}{2}\right)\right\rangle = \chi'^{\dagger}\left[\, G_A(Q^2)\,\vec{\sigma} + \cdots \right]\chi$$

$$G_A(Q^2) = \frac{G_A(0)}{\left[1 + \frac{Q^2}{M_A^2}\right]^2}$$





V — What carries the nucleon spin?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{\mathrm{q+g}}$$

$$\Delta\Sigma \approx 0.2 - 0.3 \qquad (\text{“spin crisis”})$$

$$\Delta G \lesssim 0.2\ ?$$

$$L_{\mathrm{q+g}} = ?$$

“*Well! I’ve often seen a cat without a grin*,” thought Alice,
“*but a grin without a cat! It’s the most curious thing*
I ever saw in my life!”

Never mentioned

- deuteron
- ^{3}H and ^{3}He
- ^{4}He