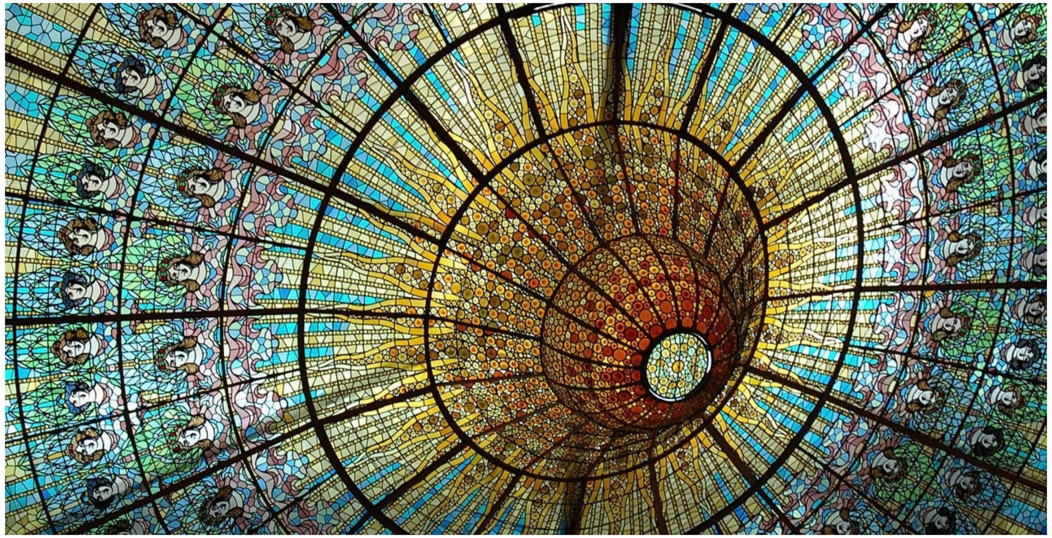
Fundamental Symmetries

Lecture 1: Introduction to fundamental symmetries

Lecture 2: Nuclei, atoms, and molecules

Lecture 3: Time-reversal violation (CP). Dark matter searches
Nuclear matter



Catalan Music in Barcelona Credit: S. ADAMS/GETTY
Lluís Domènech i Montaner (1908)

R.F. Garcia Ruiz
MIT

Open Questions

How did visible matter come into being and how does it evolve?

What is the origin of the elements in the universe?

How does subatomic matter organize itself and what phenomena emerge?

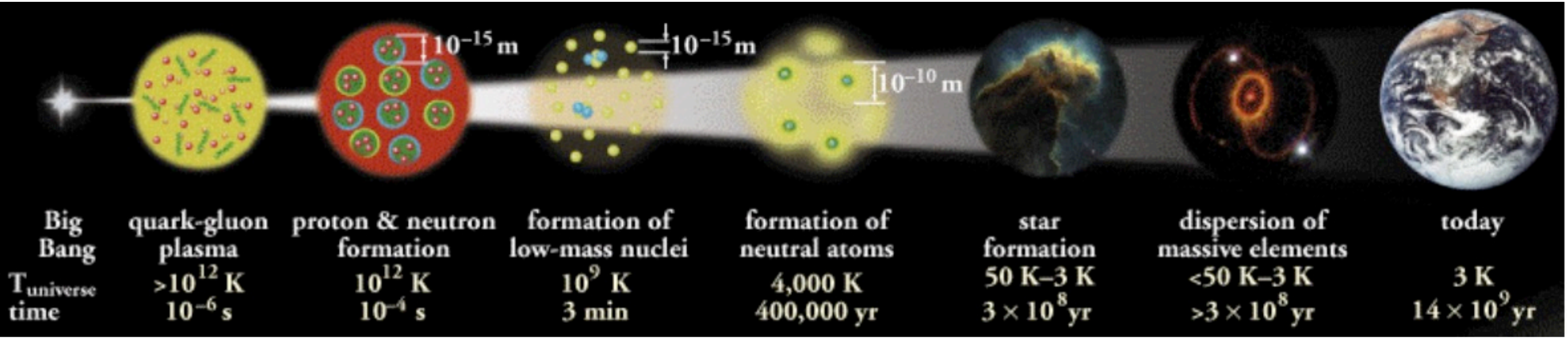
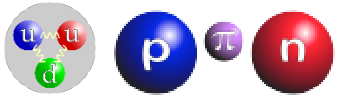
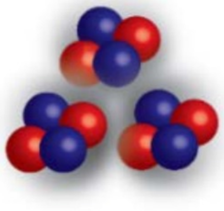


Figure: www.lbl.gov/abc/wallchart/

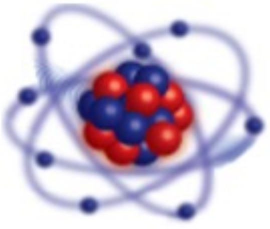
What are the fundamental particles and interactions?



10^{-15} m



10^{-14} m



10^{-10} m

10^{4} m

What are the properties of nuclear matter?

Fundamental Particles and Interactions

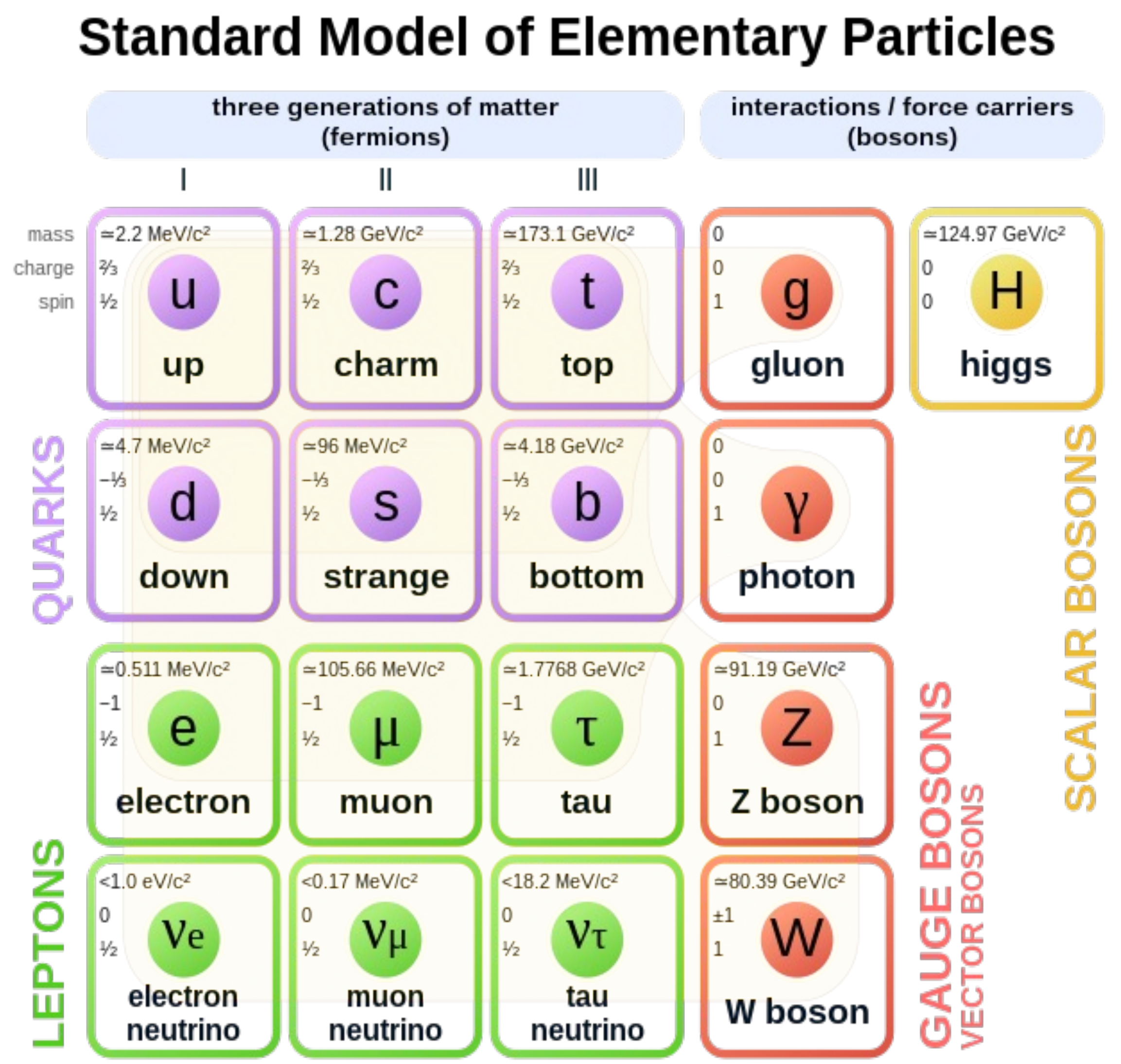
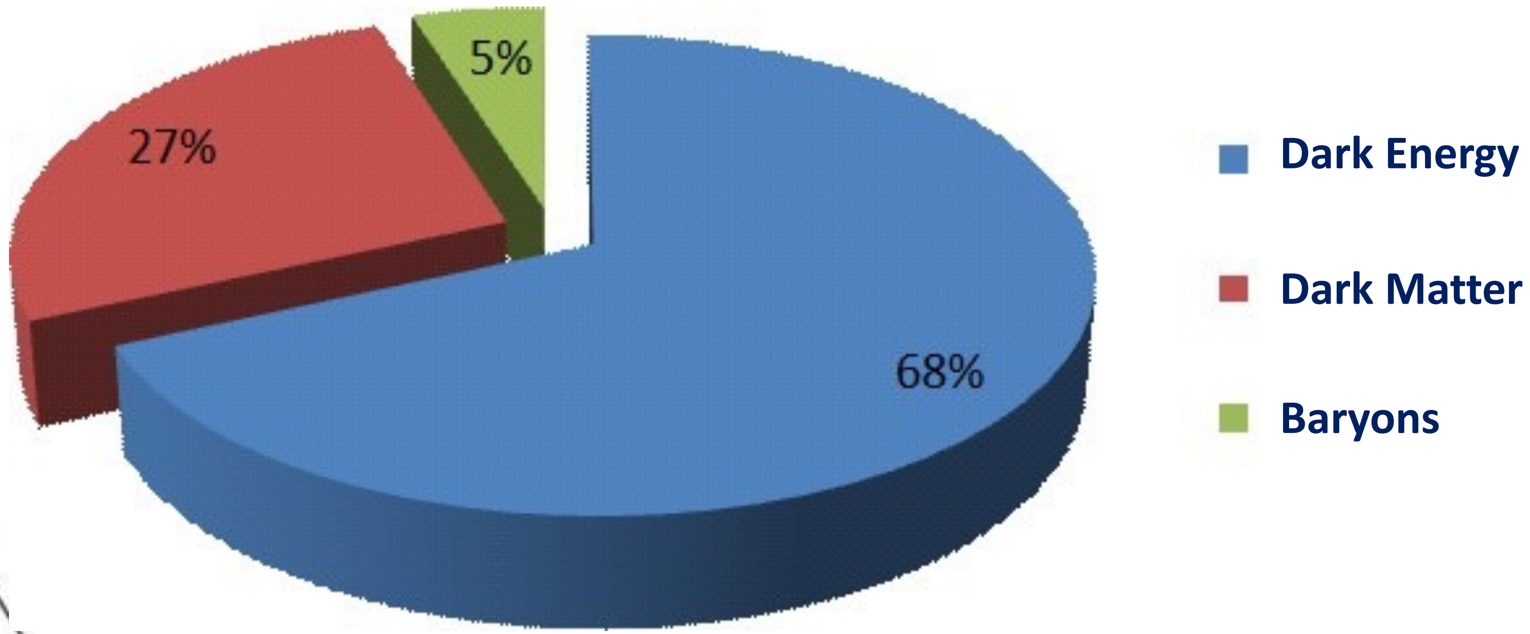
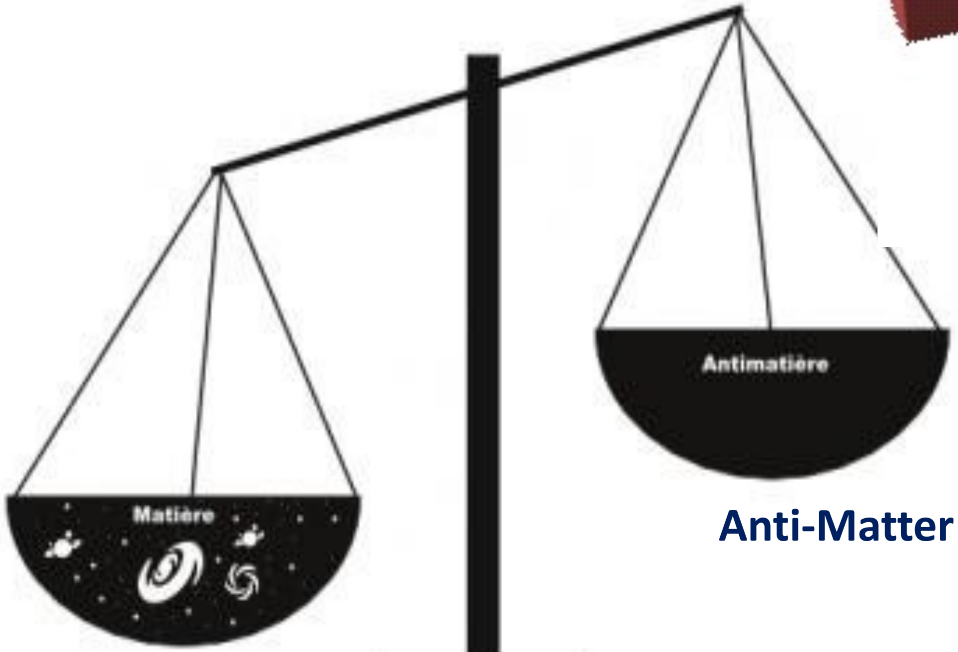


Figure: Wikipedia

Open Questions





Anti-Matter

Matter

- What is the origin of the matter-antimatter asymmetry of the Universe?
  CP->T Violation
- EW symmetry breaking
- Are there new particle and forces?
- Is there physics beyond the Standard Model (BSM)?
- Neutrino properties
- What are the properties of nuclear matter?
- ….

Warning!

<u>This lecture:</u> **Focused on atomic and molecular experiments!**

There are many other ongoing efforts:

- ***Neutrino physics***
- ***Beta decay***
- ***Colliders***
- ***EDMs***
- ***Electron scattering***
- ***neutrons***
- ***Muons***
- ***Pions and Photons***

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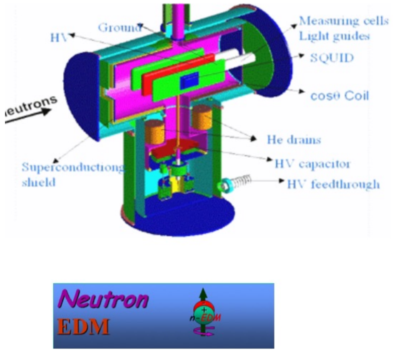
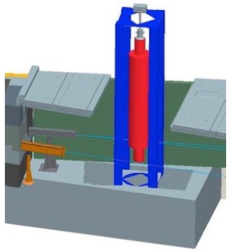
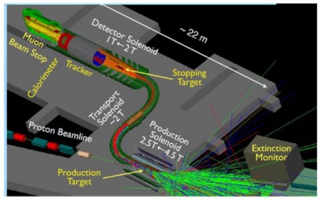


nEDM

Nab

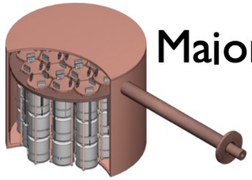




Mu2e

muon g-2

PEN



Majorana

Qweak

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Slide: V. Cirigliano

Suggested Material

Previous NNPSS lectures:

- 2019: Fundamental Symmetries and Weak Interaction through Parity Violation
  Juliette Mammei
- 2018: Neutrons and Fundamental Symmetries
  Susan Gardner, Chen-Yu Liu
- 2017: Fundamental Symmetries
  David Hertzog
- 2016: Fundamental Symmetries
  Vincenzo Cirigliano
- 2015: Fundamental Symmetries and Neutrinos
  A. Baha Balantekin

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Outline

- **Symmetries in Nature**

  -> Conservation laws and symmetries

  -> “Fundamental” symmetries

- **Precision tests**

  -> Atoms and molecules for nuclear science

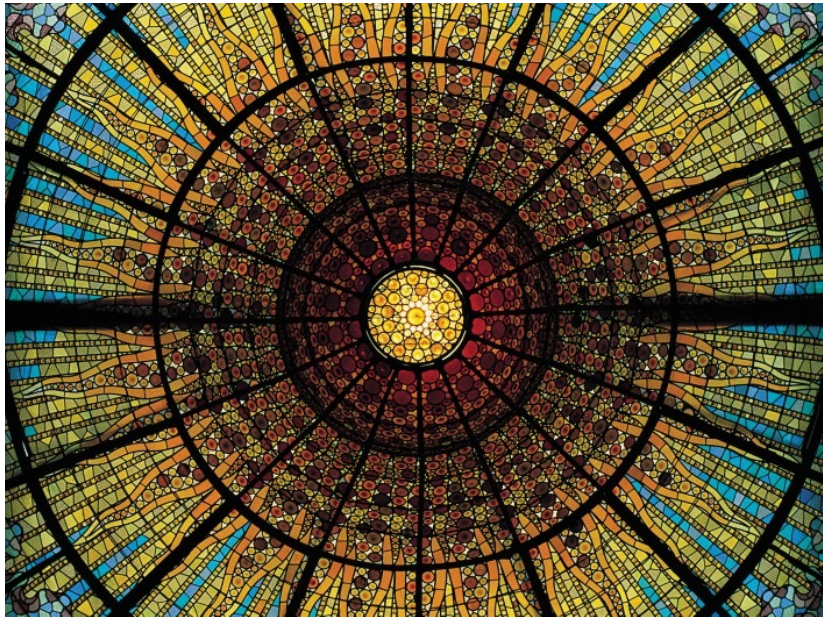
- **Searches for symmetry violations**

  -> Experimental tests

  -> BSM searches

Symmetries in Nature

Credit: urmamasmama



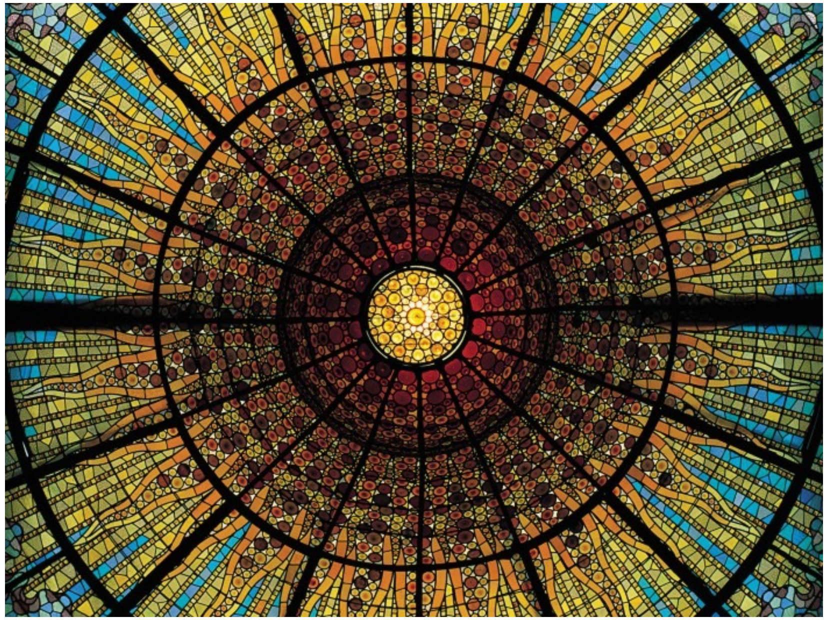
Catalan Music in Barcelona Credit: S. ADAMS/GETTY

Credit: Museo Civico di Storia Naturale Giacomo Doria - Genoa

R. P. Feynman‘s interpretation of Weyl’s definition of symmetry:
“a thing is symmetrical if one can subject it to a certain operation and it appears exactly the same after the operation.”

Symmetries in Nature

Credit: urmamasmama



Catalan Music in Barcelona Credit: S. ADAMS/GETTY

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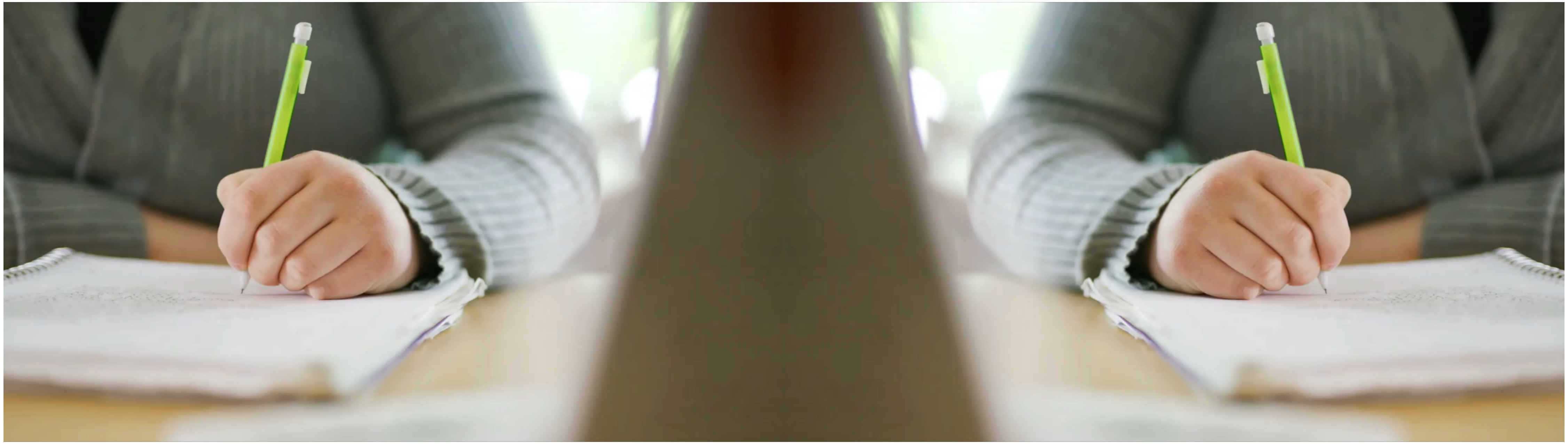
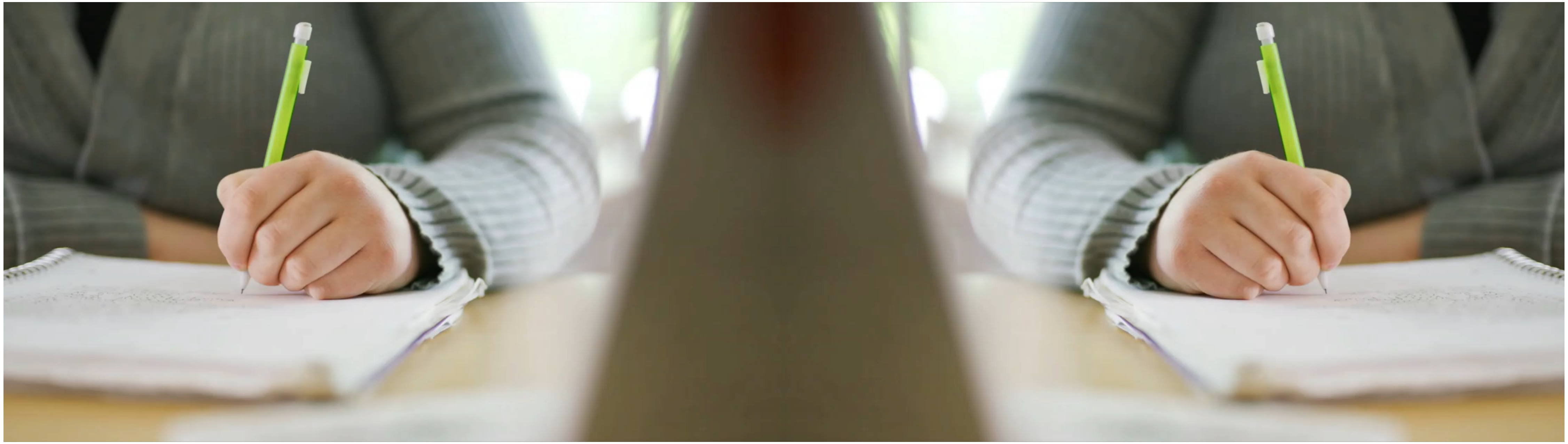
Why do we care?

What is the mirror of image?



What is the mirror of image?



(Fundamental) Symmetries in Nuclear Physics

(Fundamental) Symmetries in Nuclear Physics

- Time invariance, rotational invariance, translational invariance…

(Fundamental) Symmetries in Nuclear Physics

- **Time invariance, rotational invariance, translational invariance…**

- **Isospin…**

(Fundamental) Symmetries in Nuclear Physics

- **Time invariance, rotational invariance, translational invariance…**

- **Isospin…**

- **Parity (P)**

  -> If a process is permitted by the laws of physics, its mirror image is also permitted

- **Charge conjugation (C)**

  -> The laws of physics do not change if particles are replaced by antiparticles.

- **Time reversal (T)**

  -> The laws of physics are the same whether time is running forward or backward

Why are these symmetries useful?

Symmetries and Conservation Laws

Emmy Noether (1882-1935)

Conservation laws imply symmetries:

- **Energy -> Time invariance**
- **Linear momentum -> Translation invariance**
- **Angular momentum -> Rotational invariance**

Baryon Asymmetry

Sakharov (1967): Conditions to achieve matter-antimatter asymmetry via baryogenesis:

- C and CP-violation
- B violation
- Deviation from thermal equilibrium

Matter-antimater asymmetry

$$\xi = \frac{n_B - n_{\overline{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \approx \mathbf{10^{-11}}$$

Symmetry Operations

$$\mathbf{r} \xrightarrow{P}$$

$$\mathbf{p} = -i\hbar\nabla \xrightarrow{P}$$

$$\mathbf{A} \xrightarrow{P}$$

$$\mathbf{E} = -\nabla\varphi - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t} \xrightarrow{P}$$

$$\mathbf{L} = \mathbf{r} \times \mathbf{p} \xrightarrow{P}$$

$$\mathbf{S} \xrightarrow{P}$$

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

?

Symmetry Operations

$$\mathbf{r} \xrightarrow{P} -\mathbf{r}$$

$$\mathbf{p} = -i\hbar\nabla \xrightarrow{P} -\mathbf{p}$$

$$\mathbf{A} \xrightarrow{P} -\mathbf{A}$$

$$\mathbf{E} = -\nabla\varphi - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t} \xrightarrow{P} -\mathbf{E}$$

$$\mathbf{L} = \mathbf{r} \times \mathbf{p} \xrightarrow{P} \mathbf{L}$$

$$\mathbf{S} \xrightarrow{P} \mathbf{S}$$

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

Symmetry Operations

$$? \xleftarrow{T} \mathbf{r} \xrightarrow{P} -\mathbf{r}$$

$$\xleftarrow{T} \mathbf{p} = -i\hbar\nabla \xrightarrow{P} -\mathbf{p}$$

$$\xleftarrow{T} \mathbf{A} \xrightarrow{P} -\mathbf{A}$$

$$\xleftarrow{T} \mathbf{E} = -\nabla\varphi - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t} \xrightarrow{P} -\mathbf{E}$$

$$\xleftarrow{T} \mathbf{L} = \mathbf{r} \times \mathbf{p} \xrightarrow{P} \mathbf{L}$$

$$\xleftarrow{T} \mathbf{S} \xrightarrow{P} \mathbf{S}$$

$$\xleftarrow{T} \mathbf{B} = \nabla \times \mathbf{A} \xrightarrow{P} \mathbf{B}$$

Symmetry Operations

$$\mathbf{r} \xleftarrow{T} \mathbf{r} \xrightarrow{P} -\mathbf{r}$$

$$-\mathbf{p} \xleftarrow{T} \mathbf{p} = -i\hbar\nabla \xrightarrow{P} -\mathbf{p}$$

$$-\mathbf{A} \xleftarrow{T} \mathbf{A} \xrightarrow{P} -\mathbf{A}$$

$$\mathbf{E} \xleftarrow{T} \mathbf{E} = -\nabla\varphi - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t} \xrightarrow{P} -\mathbf{E}$$

$$-\mathbf{L} \xleftarrow{T} \mathbf{L} = \mathbf{r} \times \mathbf{p} \xrightarrow{P} \mathbf{L}$$

$$-\mathbf{S} \xleftarrow{T} \mathbf{S} \xrightarrow{P} \mathbf{S}$$

$$-\mathbf{B} \xleftarrow{T} \mathbf{B} = \nabla \times \mathbf{A} \xrightarrow{P} \mathbf{B}$$

Dipole Moments

Rev. Mod. Phys. 90, 025008 (2018)

Magnetic dipole moment:

$$\boldsymbol{\mu} = \mu \mathbf{S}$$

$$H_{md} = -\boldsymbol{\mu} \bullet \mathbf{B} \xrightarrow{P}$$

$$\xrightarrow{T}$$

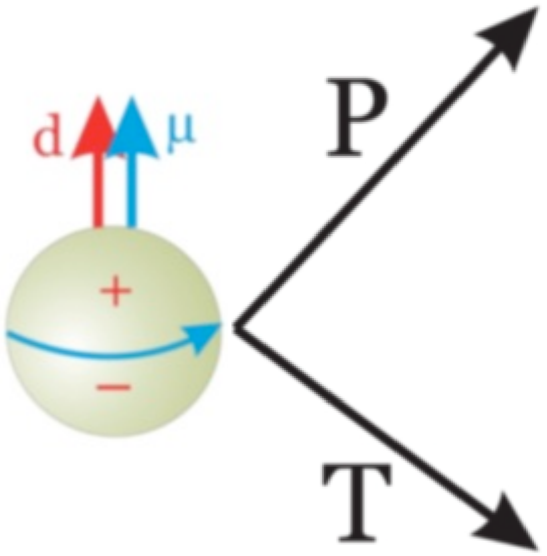
Electric dipole moment (EDM):

$$\mathbf{d} = d\mathbf{S}$$

$$H_{ed} = -\mathbf{d} \bullet \mathbf{E} \xrightarrow{P}$$

$$\xrightarrow{T}$$

?



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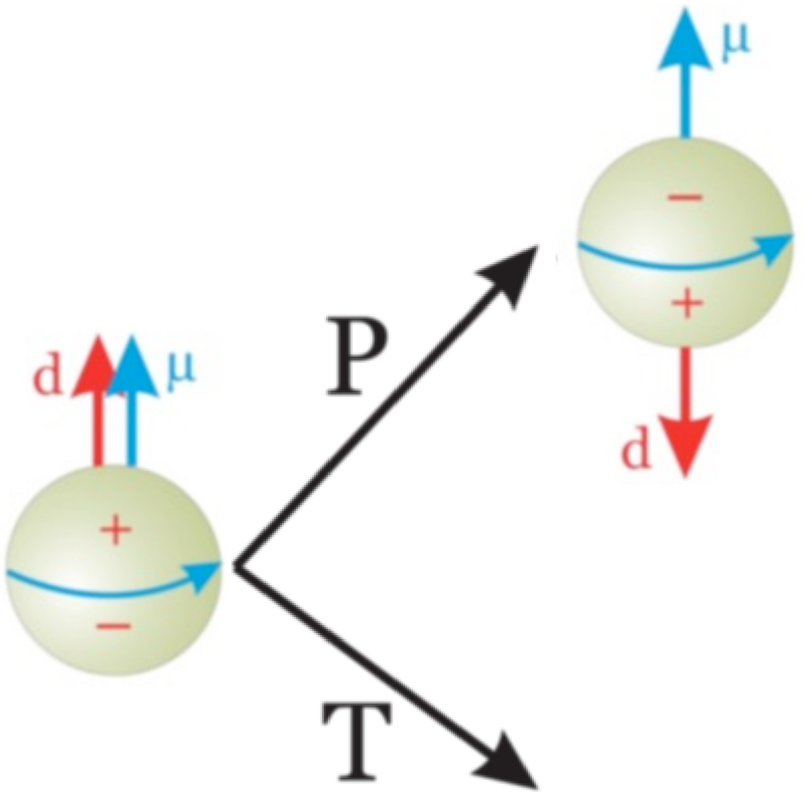

Dipole Moments

Magnetic dipole moment:

$$\mu = \mu \mathbf{S}$$

$$H_{md} = -\mu \bullet \mathbf{B} \xrightarrow{P} -\mu \bullet \mathbf{B}$$

$$\xrightarrow{T}$$

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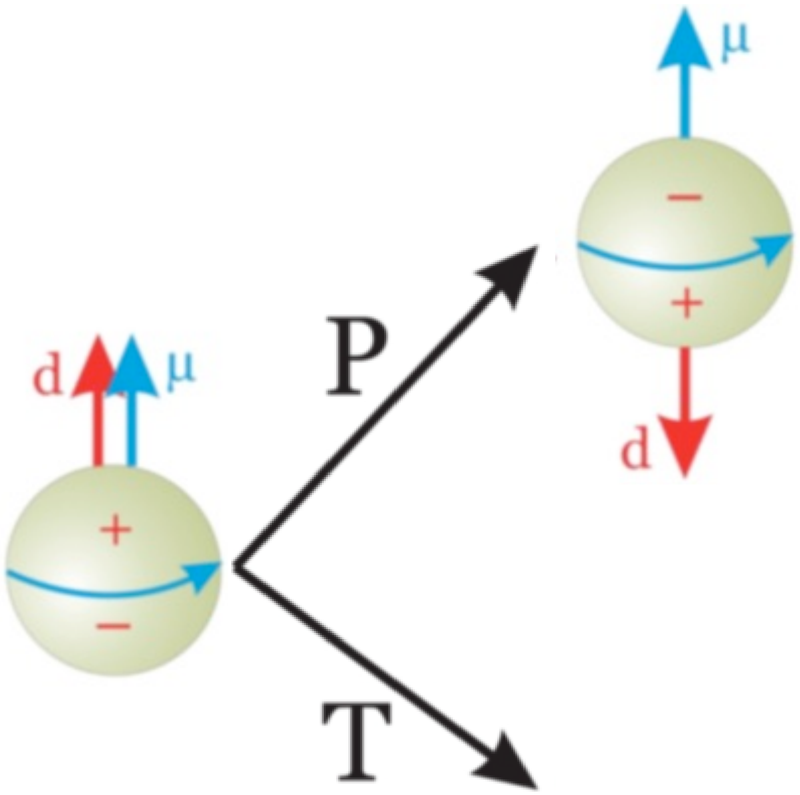
$$\xrightarrow{T}$$



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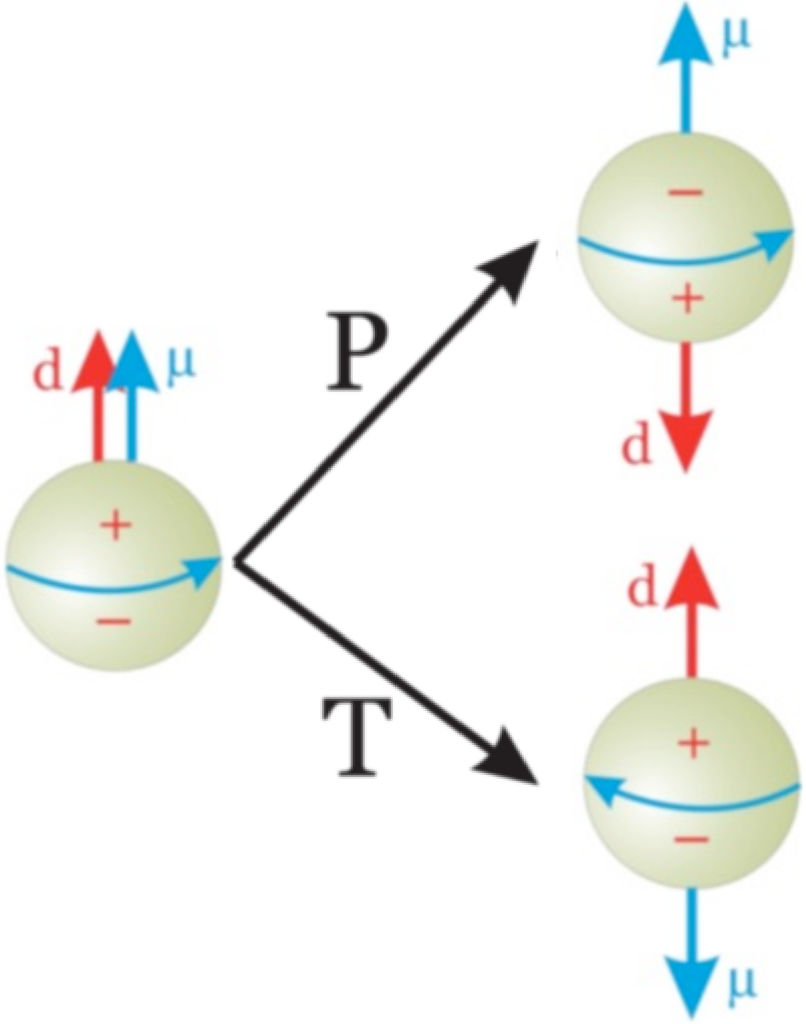

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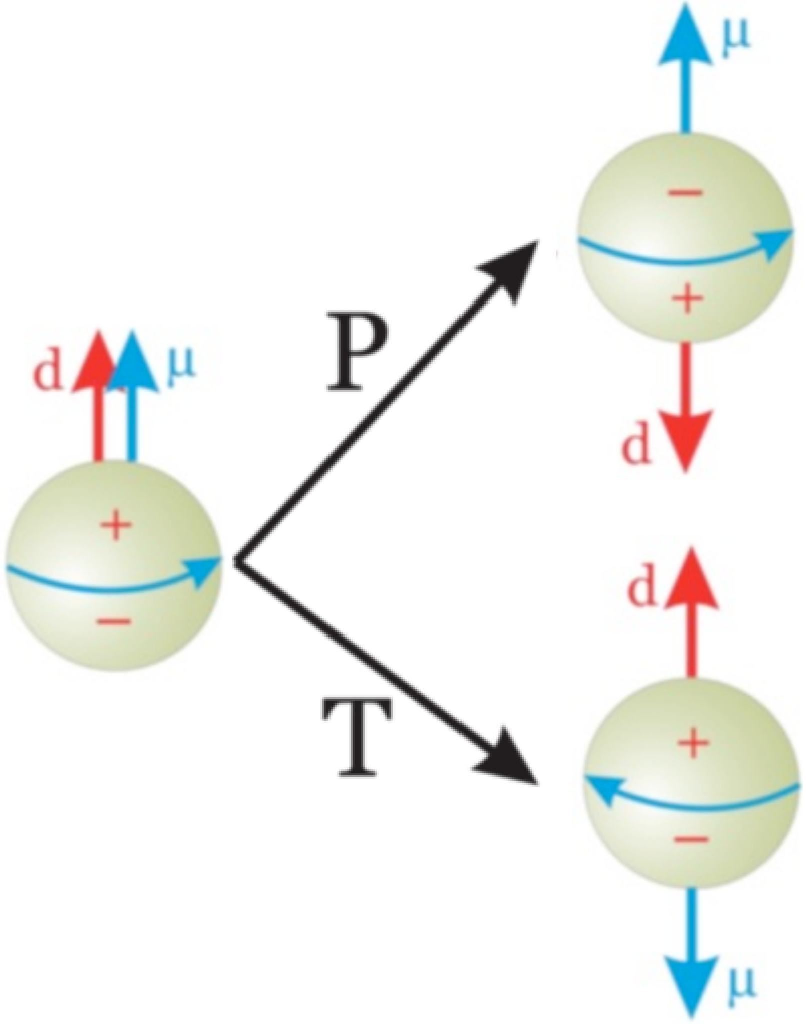

Dipole Moments

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Electric dipole moment (EDM):

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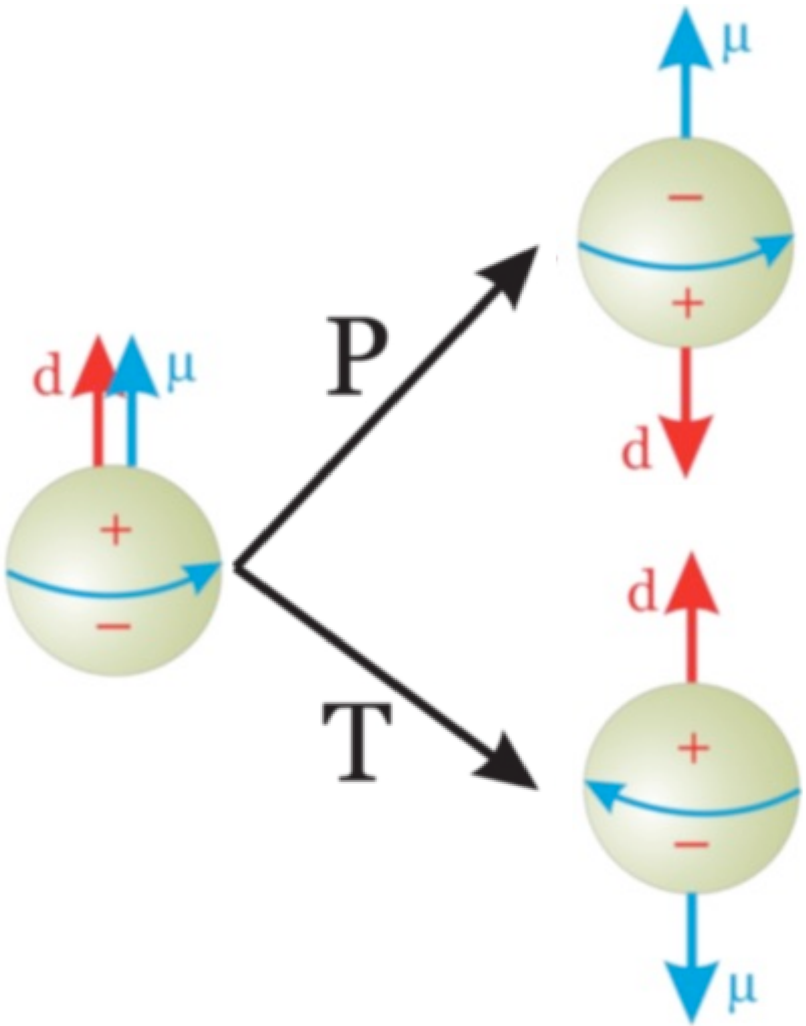
$$\xrightarrow{T} \mathbf{d} \bullet \mathbf{E}$$



Observation of a non-zero value of an EDM requires PT violation (CP) violation!

EDM experiments

	Result	95% u.l.	
Paramagnetic systems			
Xe^m	$d_A = (0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22}	e cm
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23}	e cm
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25}	e cm
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}	
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.6×10^{-7}	$\mu_N R_{Cs}$
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24}	e cm
	$d_e = (6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27}	e cm
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27}	e cm
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29}	e cm
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}	
HfF^+	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28}	e cm
Diamagnetic systems			
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30}	e cm
^{129}Xe	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27}	e cm
^{225}Ra	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23}	e cm
TlF	$d = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23}	e cm
n	$d_n = (-0.21 \pm 1.82) \times 10^{-26}$	3.6×10^{-26}	e cm
Particle systems			
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19}	e cm
τ	$Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17}	e cm
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16}	e cm

Rev. Mod. Phys. 91, 015001 (2019)

Parity Violation

A bit of history

- 1928 R. T. Cox, G. C. McIlwraith, and B. Kurrelmeyer, reported parity violation in weak decays, but were ignored.
- In 1929 Hermann Weyl explored the existence of a two-component massless particle of spin one-half. The idea was rejected by Pauli, because it implied parity violation

[Wu Nishina Memorial Lecture (1983)]

- 1956: Theory Tsung-Dao Lee and Chen Ning Yang
  Theoretical suggestion of parity-violation for the weak interaction
- 1956: Feynman and Gell-Mann V-A theory
- **1956: Chien Shiung Wu: Experimental evidence of parity violation**

Beauty of broken symmetries!

- ***1956: End of the romanticism in physics!***

The Hunchback of Notre-Dame

Victor Hugo (1831)

- ***1850: End of the romanticism in literature!***

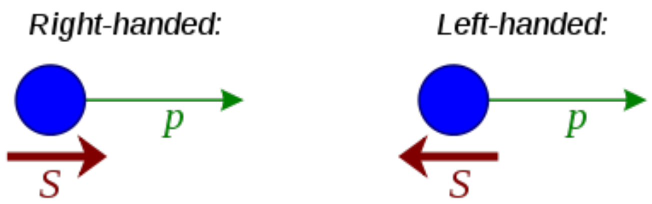
Beauty of broken symmetries!

- ***1956: End of the romanticism in physics!***

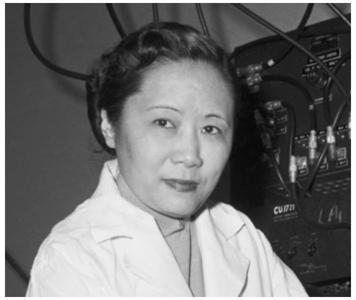
Parity Violation in the Weak Interaction

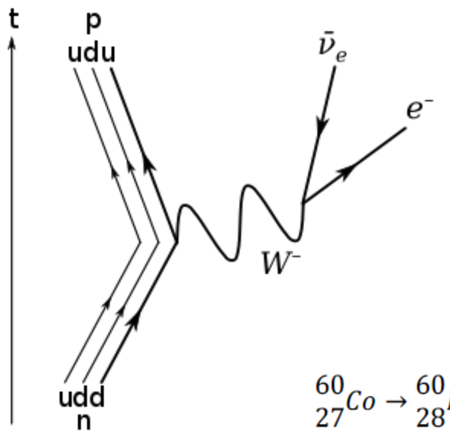
- 1956: Theory Tsung-Dao Lee and Chen Ning Yang

helicity

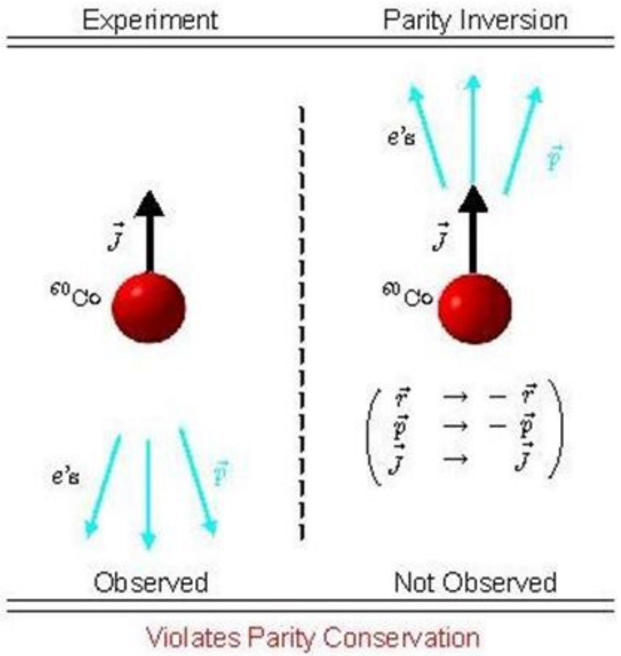


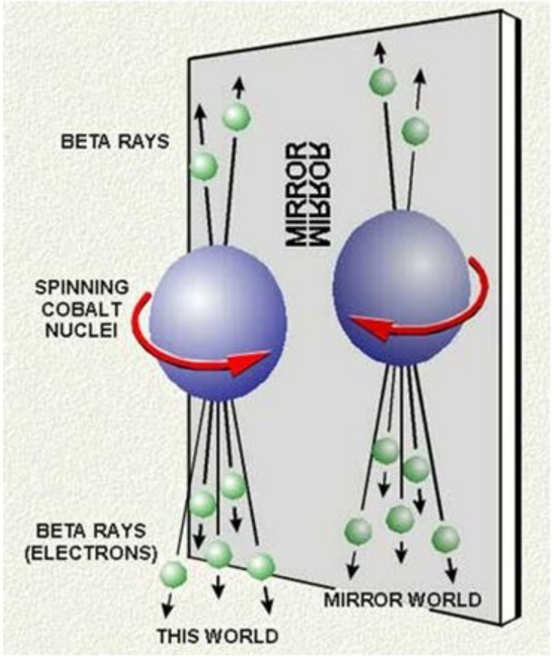
- **1956: Chien Shiung Wu**





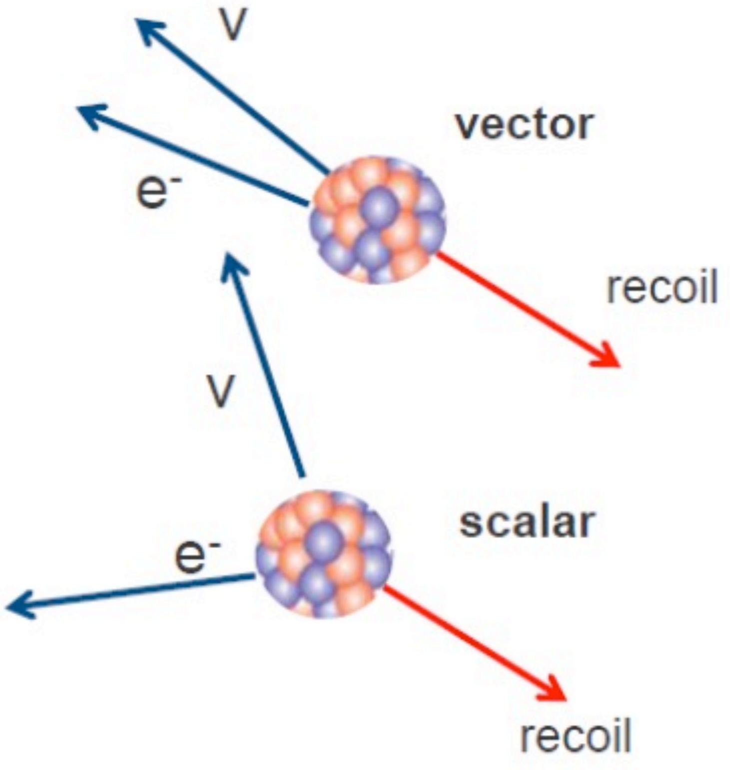
$$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + e^- + \bar{\nu}$$





Beta Decay -> V-A theory

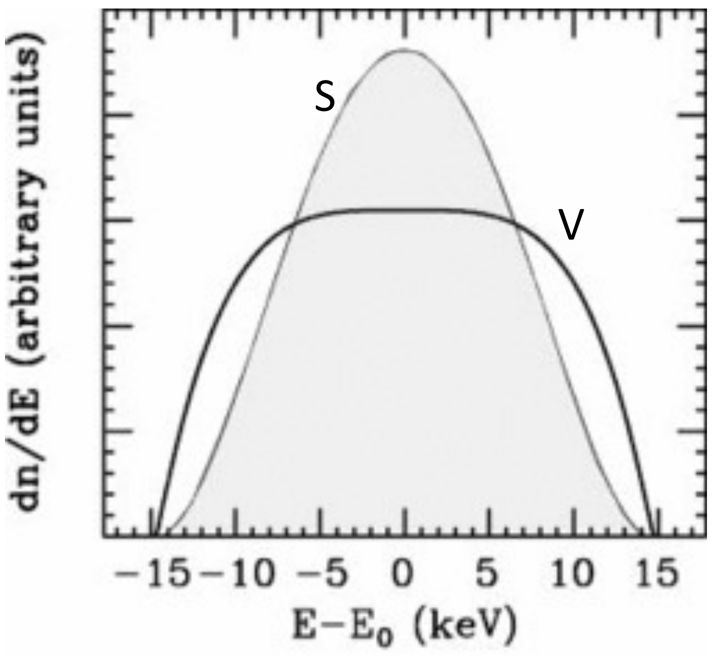
$$H_\beta = \overbrace{H_{Vector} + H_{Axial}}^{\text{Standard Model}} + \overbrace{H_{Scalar} + H_{Tensor}}^{\text{Non-SM}}$$



Standard Model

Non-SM

Shapes of the β delayed proton group



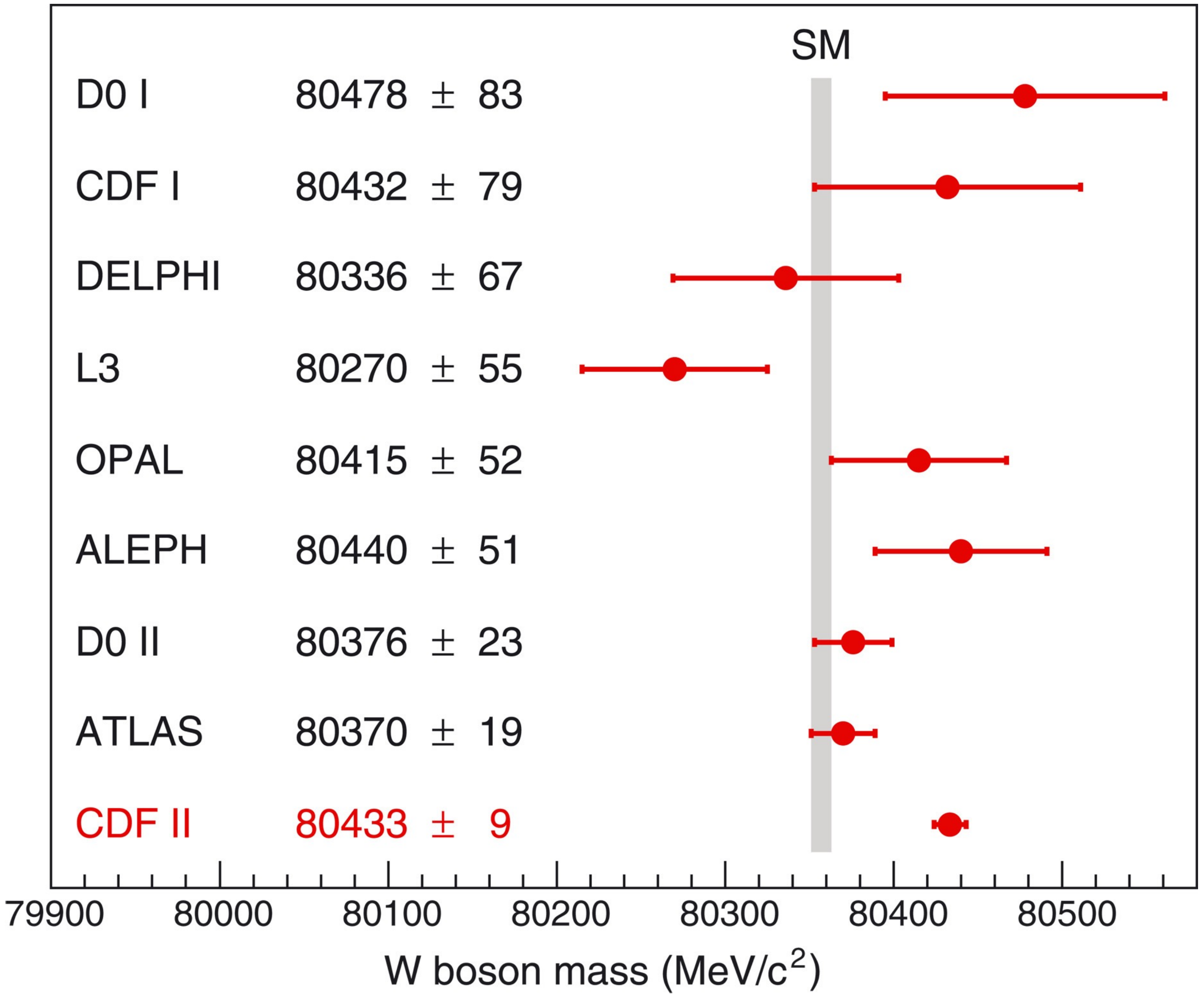
Rev. Mod. Phys. 78, 991 (2006)

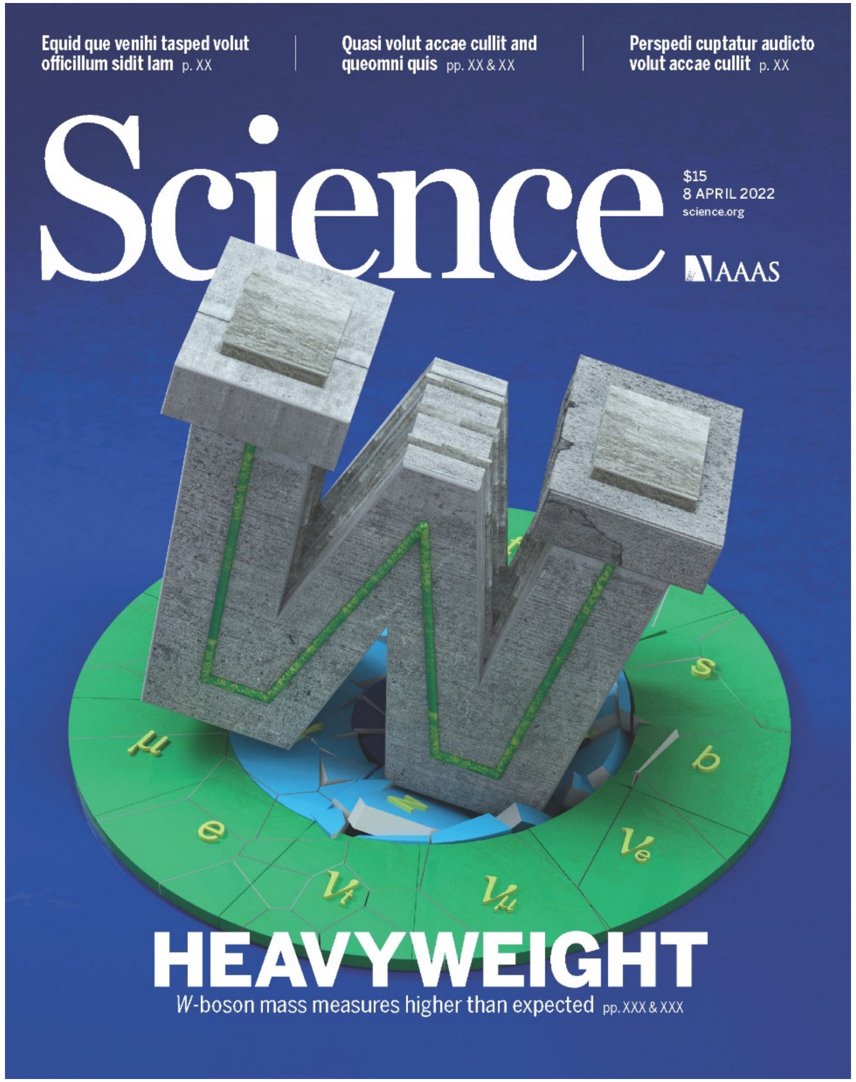
“One should be prepared for further surprises with beta decay”

Niels Bohr, 1933

“One should be prepared for further surprises with the weak interaction”

Science 376, 170 (2022)





Electroweak Symmetry Breaking

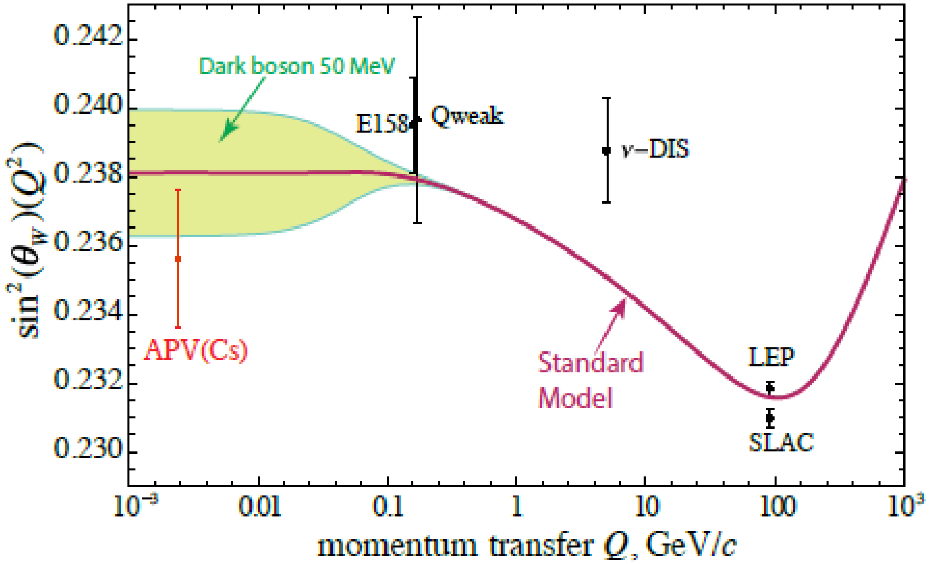
- S Glashow, A Salam, S Weinberg
  1979 Nobel Prize "Unification of the weak and electromagnetic interaction"

Weinberg angle -> parameterizes the mixing between the two neutral currents

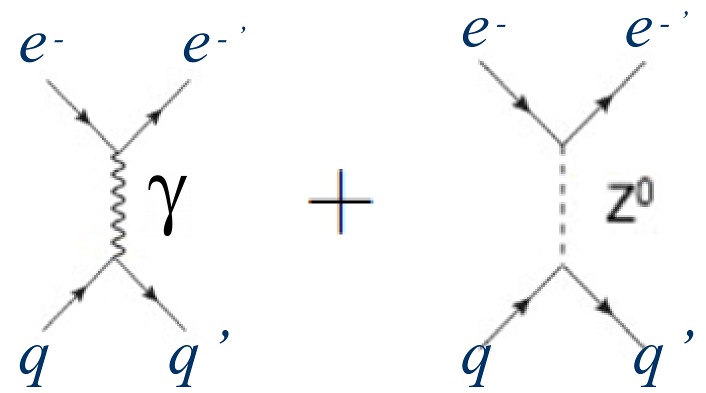
Angle by which spontaneous symmetry breaking rotates the original W_0 and B_0 vector boson plane, producing as a result the Z_0 boson, and the photon.

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

$$m_Z = \frac{m_W}{\cos\theta_W}$$



Parity-Violating Electron (PVE) Scattering



$$\mathcal{L}_{PV}^{NC} = -\frac{G_F}{\sqrt{2}} \left[g_A^e \left(\bar{e}\gamma_\mu\gamma_5 e\right) \cdot \sum_q g_V^q \left(\bar{q}\gamma^\mu q\right) + g_V^e \left(\bar{e}\gamma_\mu e\right) \cdot \sum_q g_A^q \left(\bar{q}\gamma^\mu\gamma_5 q\right) \right]$$

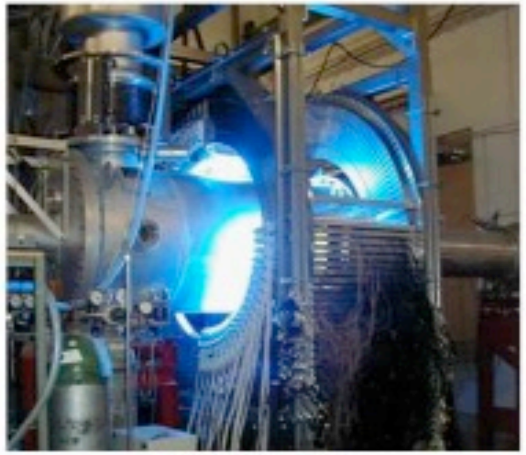
$$= -\frac{G_F}{2\sqrt{2}} \left[\sum_q C_{1q} \left(\bar{e}\gamma_\mu\gamma_5 e\right) \cdot \left(\bar{q}\gamma^\mu q\right) + \sum_q C_{2q} \left(\bar{e}\gamma_\mu e\right) \cdot \left(\bar{q}\gamma^\mu\gamma_5 q\right) \right]$$

Particle	Electric charge	Weak vector charge	Weak axial charge
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \approx +\frac{1}{3}$	$-2C_{2u} = -1 + 4\sin^2\theta_W \approx 0$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -\frac{2}{3}$	$-2C_{2d} = +1 - 4\sin^2\theta_W \approx 0$
p(uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0$	
n(udd)	0	$Q_W^n = -1$	
e	-1	$Q_W^e = -2g_A^e g_V^e = -1 + 4\sin^2\theta_W \approx 0$	

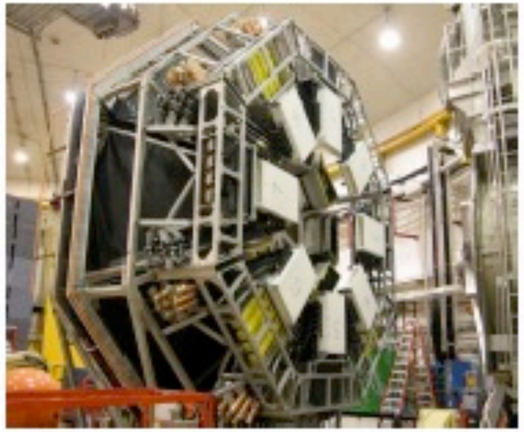
$$\sin^2\theta_W \approx \frac{1}{4}$$

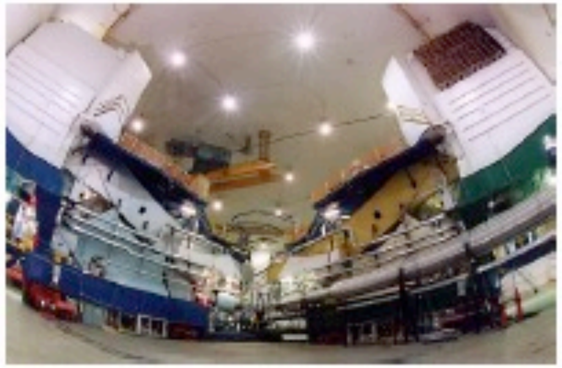
Parity-Violating Electron (PVE) Scattering

a (E158, SLAC)

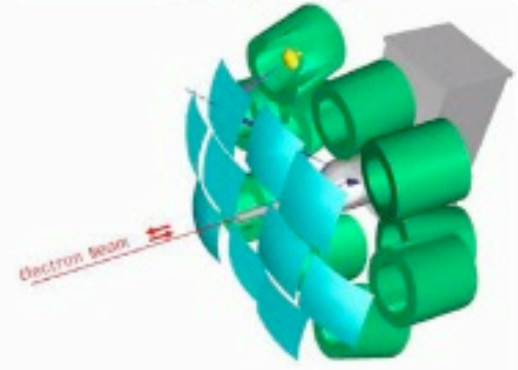


b (PVA4, Mainz)

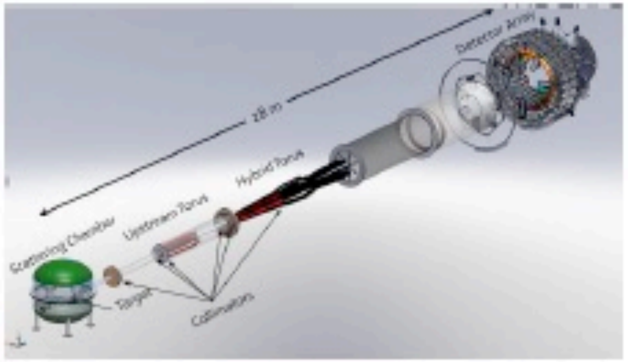




c (HAPPEx, JLab)



d (SAMPLE, MIT-Bates)



SOLID, P2...

Slide taken from: Juliette Mammei

Fundamental Particles and Interactions

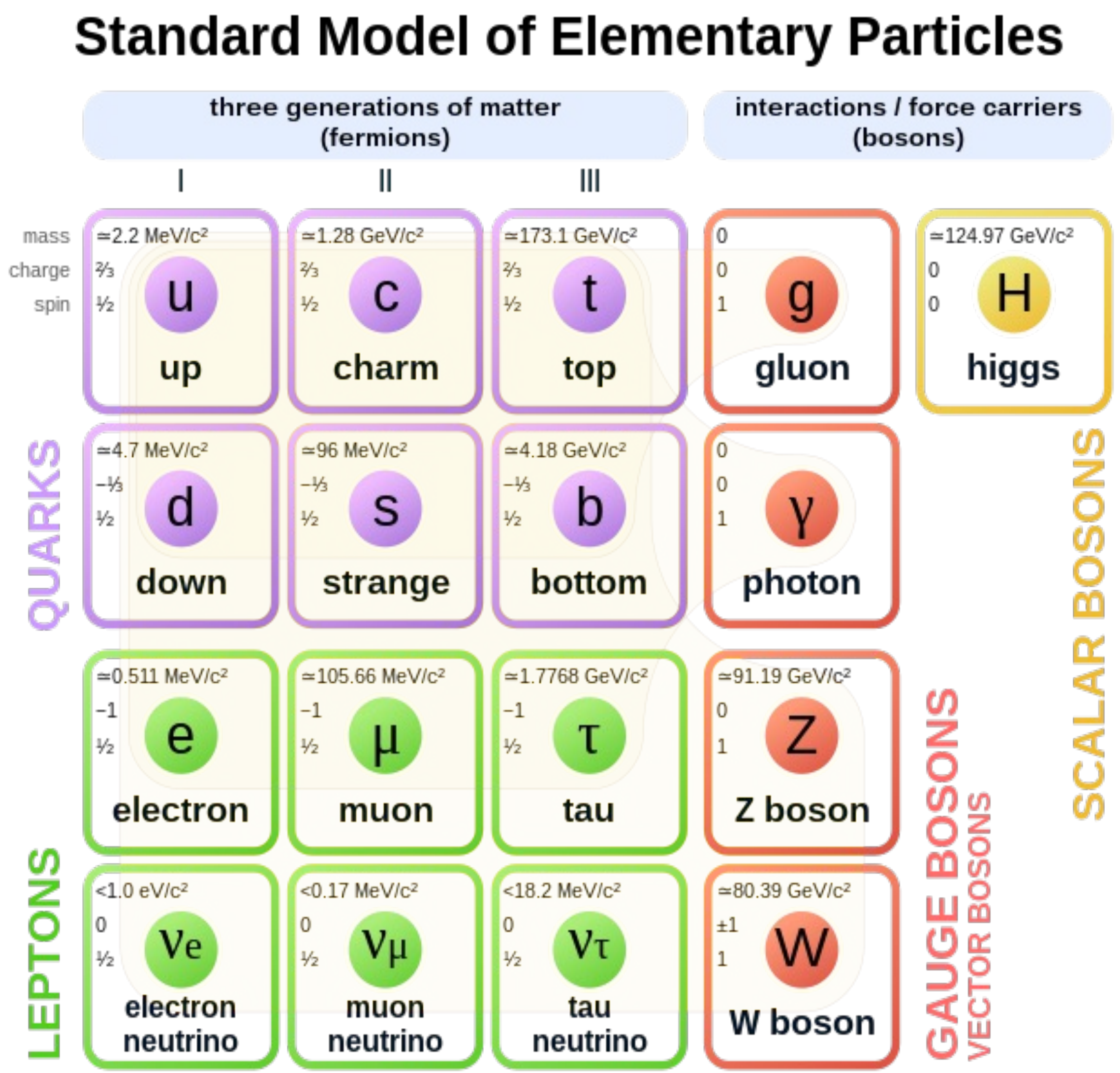


Figure: Wikipedia

Interactions

Interaction	Field quantum	Range (m)	Relative strength	Typical cross section (m^2)	Typical time scale (s)
Strong	Gluon	10^{-15}	1	10^{-30}	10^{-23}
Weak	$W^{\pm}, Z^0$	10^{-18}	10^{-5}	10^{-44}	10^{-8}
Electromagnetic	Photon	∞	$\alpha = \frac{1}{137}$	10^{-33}	10^{-20}
Gravity	Graviton	∞	10^{-38}	–	–

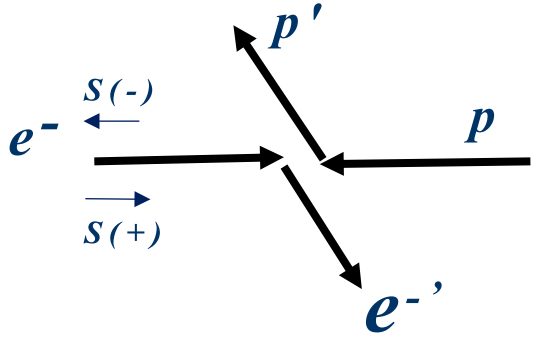
Wong's book

1 fm = 10^{-15} m

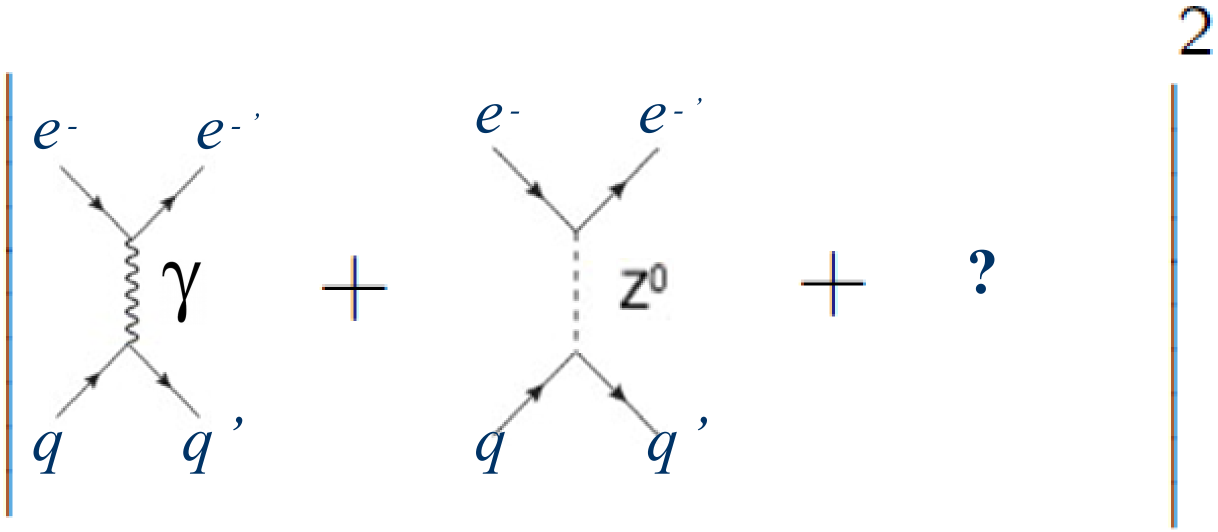
Parity-Violating Electron (PVE) Scattering

Helicity

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



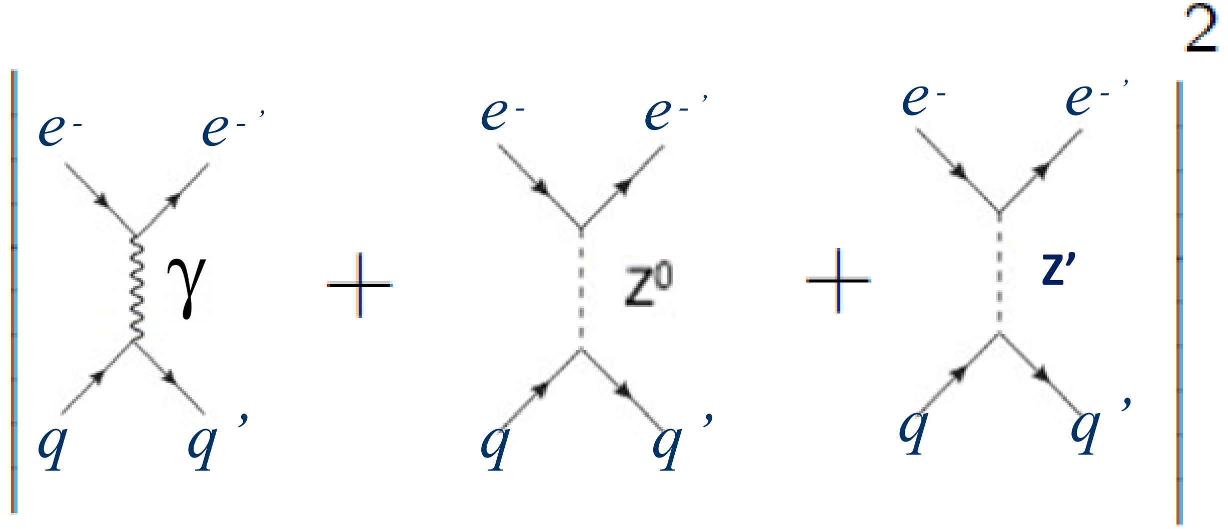
$\sigma =$



Parity-Violating Electron (PVE) Scattering

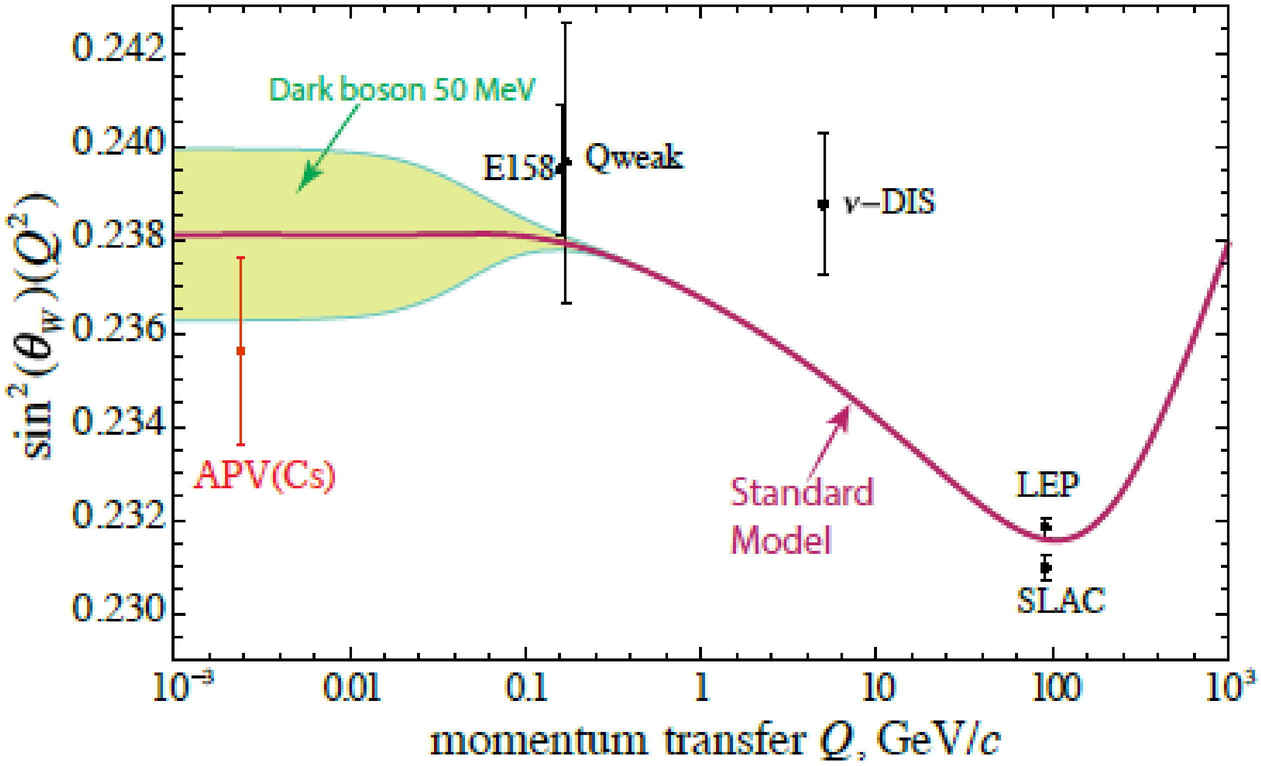
$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

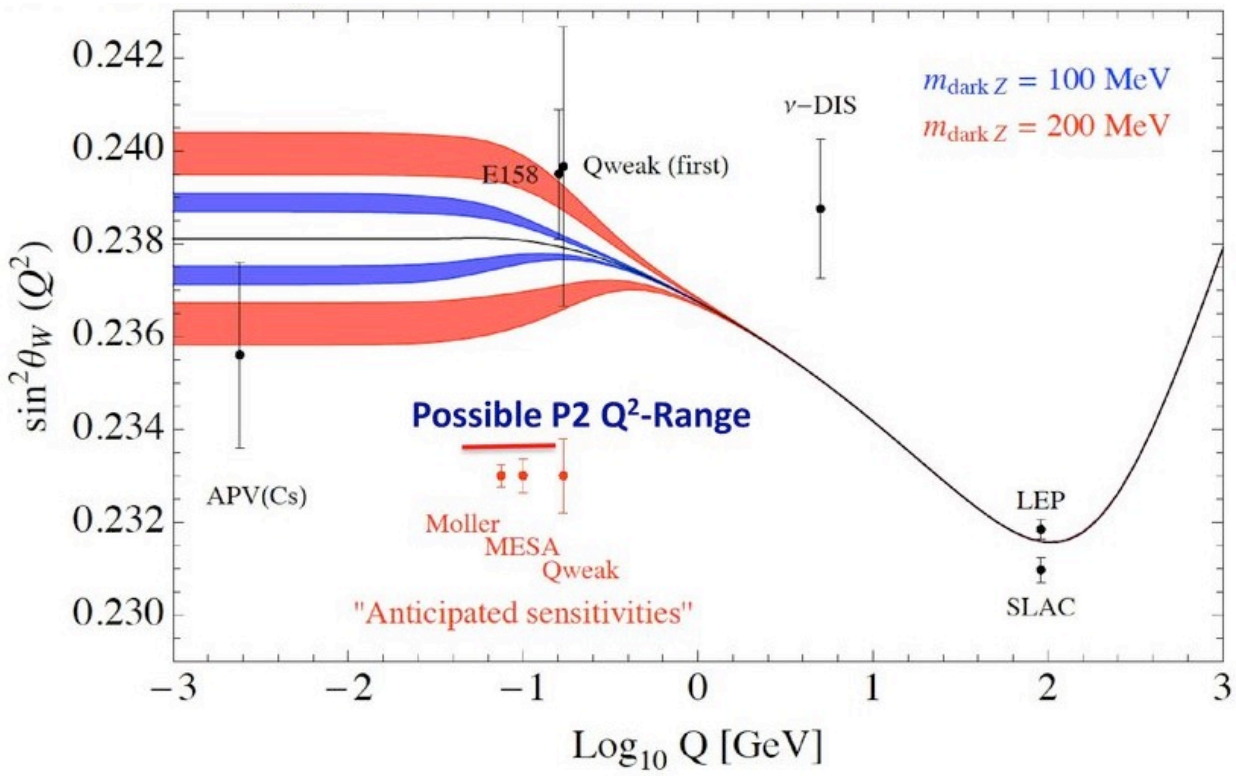
$\sigma =$



Parity-Violating Electron (PVE) Scattering

Running of Sin² (Θ$_w$)





Rev. Mod. Phys. 90, 025008 (2018)

Bill Marciano

Summary

- Symmetries have played a central role in the development of physics

- Particular interest on the study of
  - Parity
  - Charge conjugation
  - Time reversal

- Broken symmetries provide compelling guidance to find new physics beyond the Standard Model.