Karlsruhe Institute of Technology

Introduction to Particle Physics

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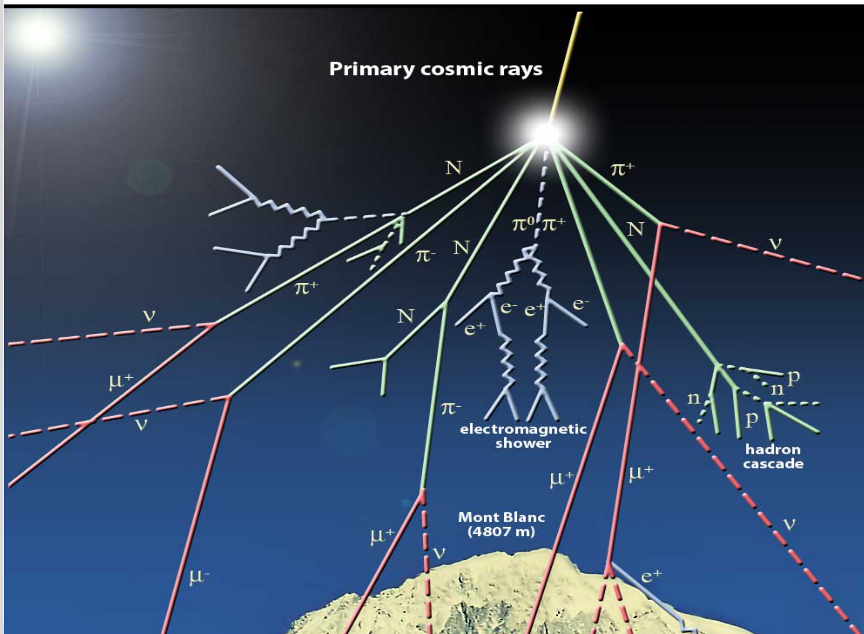
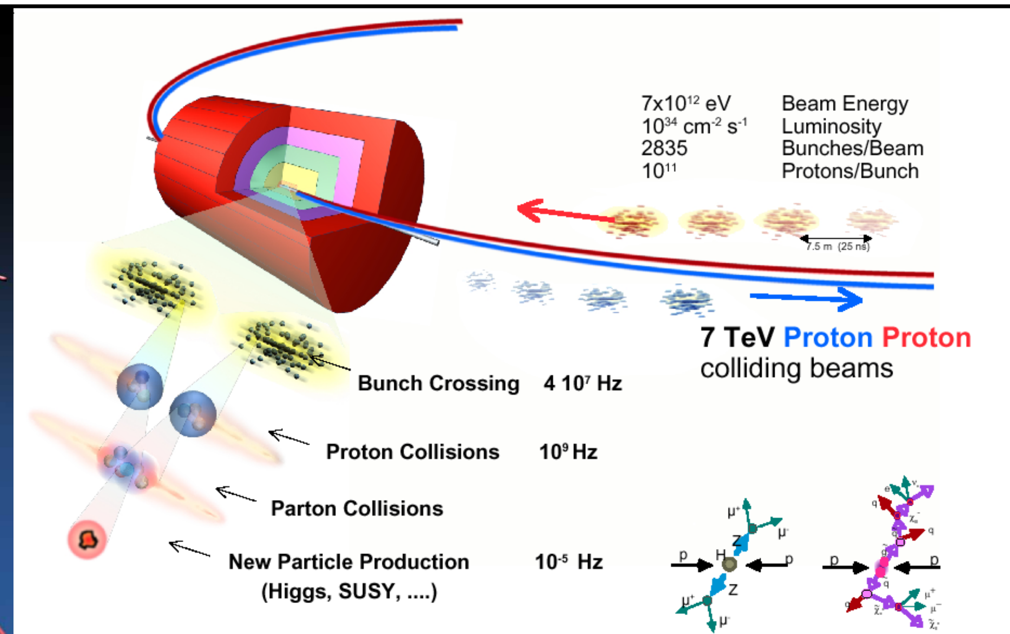
INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY

Astroparticle vs. particle physics

- Highest beam energies (up to 10^{21} $\mathrm{eV}\rightarrow$ fixed target).
- Complicated detection medium ($\rightarrow$ atmosphere).
- Large area detectors required.

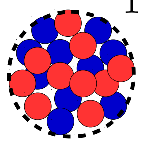
- Perfect control over initial state under ideal laboratory conditions.
- Compact and tailored detector designs.





Collision kinematics

$$\begin{pmatrix} E \\ 0 \\ 0 \\ E \end{pmatrix} \quad \Rightarrow p \quad 10^{19}\ \text{eV}$$



$^{16}_{8}O$

$$\begin{pmatrix} M \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Center of mass energy of a relativistic two body collision:

$$\begin{aligned} s^2 &= (p_1^\mu + p_2^\mu)^2 \\ &= p_1^2 + p_2^2 + 2p_1^\mu p_{\mu,2} \\ &\approx 2p_1^\mu p_{\mu,2} \end{aligned}$$

Boost along z-direction:

$$E' = \gamma\,(E - \beta p_z)$$

$$p_z' = \gamma\,(p_z - \beta E)$$

$$\begin{pmatrix} E \\ 0 \\ 0 \\ E \end{pmatrix} \quad \Rightarrow p \quad 7\ \text{TeV} \qquad p \Leftarrow \quad 7\ \text{TeV} \quad \begin{pmatrix} E \\ 0 \\ 0 \\ -E \end{pmatrix}$$

$$s^2 = 2 \begin{pmatrix} E \\ 0 \\ 0 \\ E \end{pmatrix} \begin{pmatrix} E \\ 0 \\ 0 \\ -E \end{pmatrix} = 4E^2$$

$$E_{cms} = \sqrt{s^2} = \sqrt{4E^2} = 2E = 14\,\text{TeV}$$

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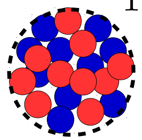

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$$E_{cms} = \sqrt{s^2} = \sqrt{2EM} \approx 567\,\mathrm{TeV}$$

$$\sqrt{\frac{EM}{2}} = \gamma M \rightarrow \gamma = \sqrt{\frac{E}{2M}} \approx 17'678$$

$$\gamma = \sqrt{\frac{1}{1-\beta^2}} \rightarrow \beta = \sqrt{\frac{\gamma^2 - 1}{\gamma^2}} \approx 0.99999999$$

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7 TeV 7 TeV

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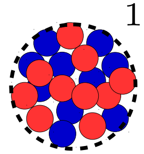

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expect 1 collision per year detector w/ 1 km^2 surface.

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7 TeV   7 TeV

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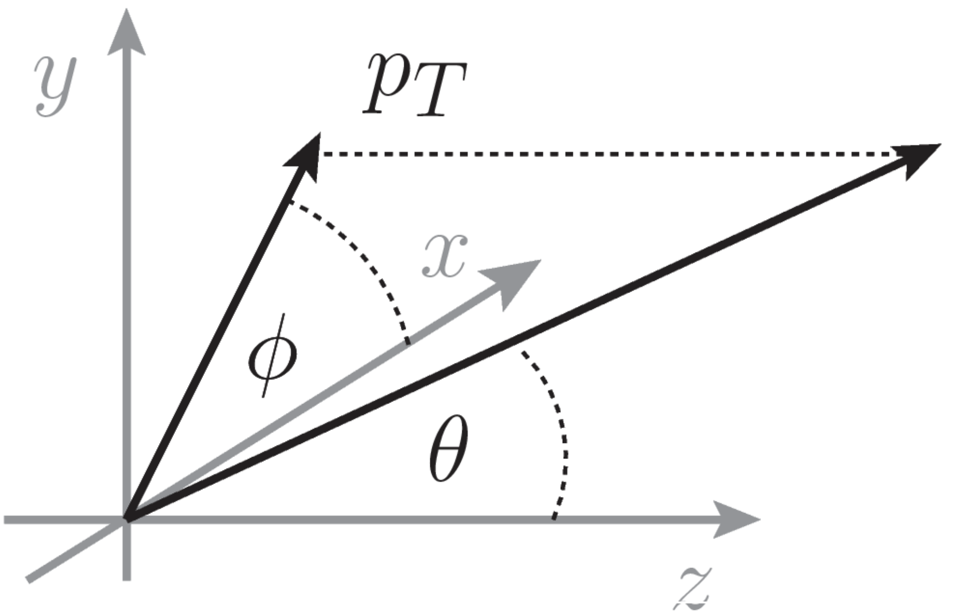
expect 40M collisions per second.

Particle kinematics

- For known mass the kinematics of a single particle are completely described by three variables: $(\;p_x \quad p_y \quad p_z\;)$ or better $(\;p_T \quad \phi \quad \theta\;)$



p_T and ϕ in the plane perpendicular to z are invariant under *boosts* along z, θ not.
Therefore we usually replace θ by:

Rapidity:

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

which is form invariant under *boosts* along z.

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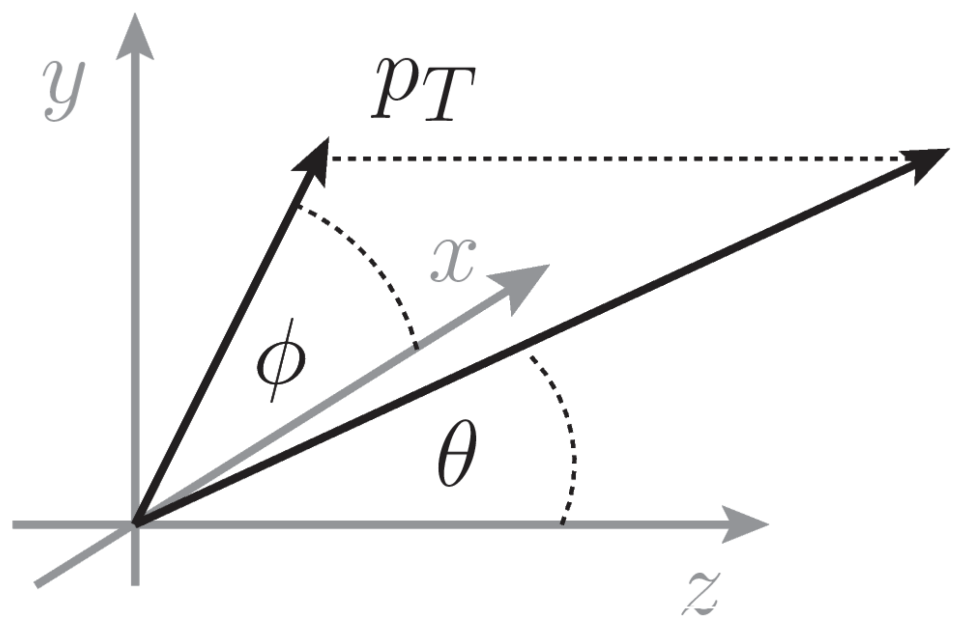

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which is form invariant under

$$y = \frac{1}{2} \ln \left(\frac{E' + p'_z}{E' - p'_z} \right) = \frac{1}{2} \ln \left(\frac{(E - \beta p_z) + (p_z - \beta E)}{(E - \beta p_z) - (p_z - \beta E)} \right) = \frac{1}{2} \ln \left(\frac{(1-\beta)(E + p_z)}{(1+\beta)(E - p_z)} \right)$$

$$= \frac{1}{2} \left(\ln \left(\frac{1-\beta}{1+\beta} \right) + \ln \left(\frac{E + p_z}{E - p_z} \right) \right) = y + \frac{1}{2} \ln \left(\frac{1-\beta}{1+\beta} \right)$$

Pseudorapidity

- For $E \gg m$ the rapidity turns into the pseudorapidity η, which itself only depends on the polar angle θ.

Pseudorapidity:

$$\eta = -\ln\left(\tan(\theta/2)\right)$$

$$y = \frac{1}{2}\ln\left(\frac{E(1+\cos\theta)}{E(1-\cos\theta)}\right)$$

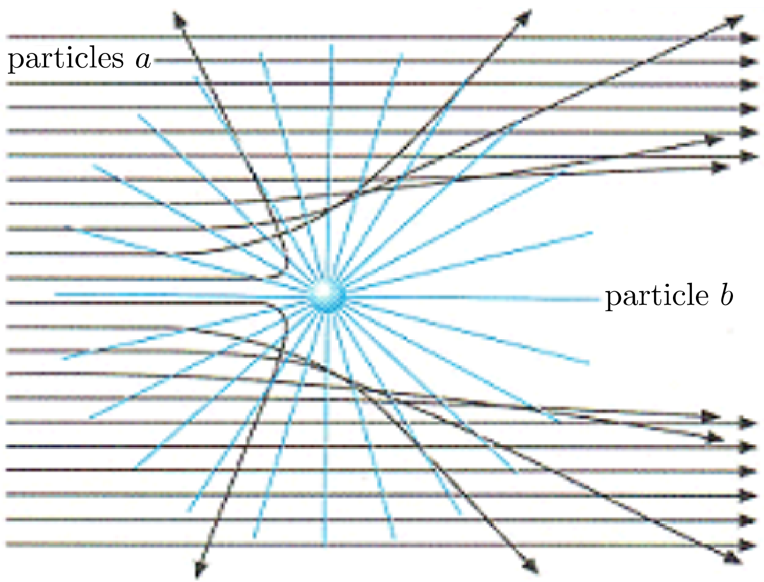
$$= \frac{1}{2}\ln\left(\frac{(\sin^2 \theta/2 + \cos^2 \theta/2) + (\cos^2 \theta/2 - \sin^2 \theta/2)}{(\sin^2 \theta/2 + \cos^2 \theta/2) - (\cos^2 \theta/2 - \sin^2 \theta/2)}\right)$$

$$= \frac{1}{2}\ln\left(\frac{\cos^2 \theta/2}{\sin^2 \theta/2}\right) = -\ln\left(\tan \theta/2\right) = \eta$$

Imagine in the air shower of slide 4 a particle were scattered at 90° to the axis of its incident direction in the center of mass frame. What is the scattering angle in the **laboratory frame**?

Cross section (classic)

- Imagine a continuous flux of (small) incident particles a impinging on a target particle b at rest and the elastic reaction $a + b \rightarrow a + b$:



$$n_a \ : \ \text{incident particle density} \ \left[\frac{\text{particles}}{m^3}\right].$$

$$v \ : \ \text{incident particles velocity} \ \left[\frac{m}{s}\right].$$

$$\phi = n_a \cdot v \ : \ \text{incident part flux} \ \left[\frac{\text{particles}}{m^2\, s}\right].$$

$$W = \phi \cdot \sigma \ : \ \text{scattering rate} \ \left[\frac{1}{s}\right].$$

$$\sigma = \frac{W}{\phi} \ : \ \text{reaction rate/incident part flux.}$$

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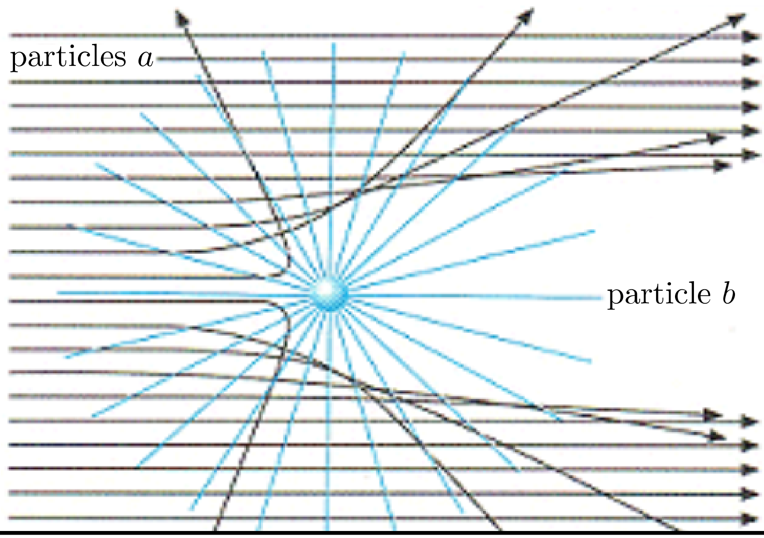


n_a : incident particle density $\left[\frac{\text{particles}}{m^3}\right]$.

v : incident particles velocity $\left[\frac{m}{s}\right]$.

$\phi = n_a \cdot v$: incident part flux $\left[\frac{\text{particles}}{m^2\, s}\right]$.

$W = \phi \cdot \sigma$: scattering rate $\left[\frac{1}{s}\right]$.

$\sigma = \frac{W}{\phi}$: reaction rate/incident part flux.

Cross section:

$$\sigma = \frac{N_{obs} - N_{BG}}{\phi \cdot \epsilon \cdot A} \frac{1}{T}$$

N_{obs} : N observed reactions.

N_{BG} : N expected BG reactions.

ϵ : detection efficiency.

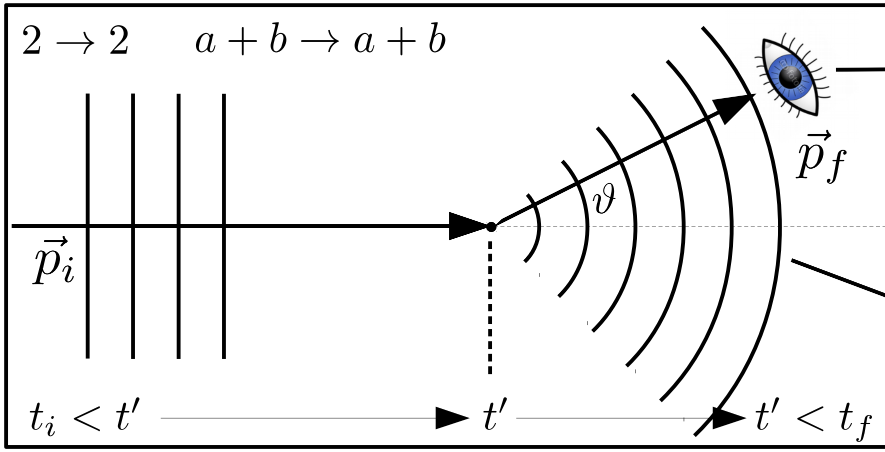
A : detector acceptance.

T : observation time.

In classic elastic scattering the cross section is πr^2.

Cross section (QM)

- Imagine a continuous flux of (small) incident particles a impinging on a target particle b at rest and the elastic reaction $a+b\rightarrow a+b$:



Observation (in $\Delta\Omega$): projection of plain wave ϕ_f out of spherical scattering wave ψ_{scat}.

Spherical scattering wave ψ_{scat}.

Initial particle: described by plain wave ϕ_i.

Localized potential.

Observation probability:

$$\mathcal{S}_{fi} = \phi_f^\dagger \cdot \psi_{\text{scat}} = \phi_f^\dagger \cdot \mathcal{S} \cdot \phi_i$$

Scattering matrix $\mathcal{S}$ transforms initial state wave function ϕ_i into scattering wave ψ_{scat} ($\psi_{\text{scat}} = \mathcal{S}\cdot\phi_i$).

Fermi's golden rule:

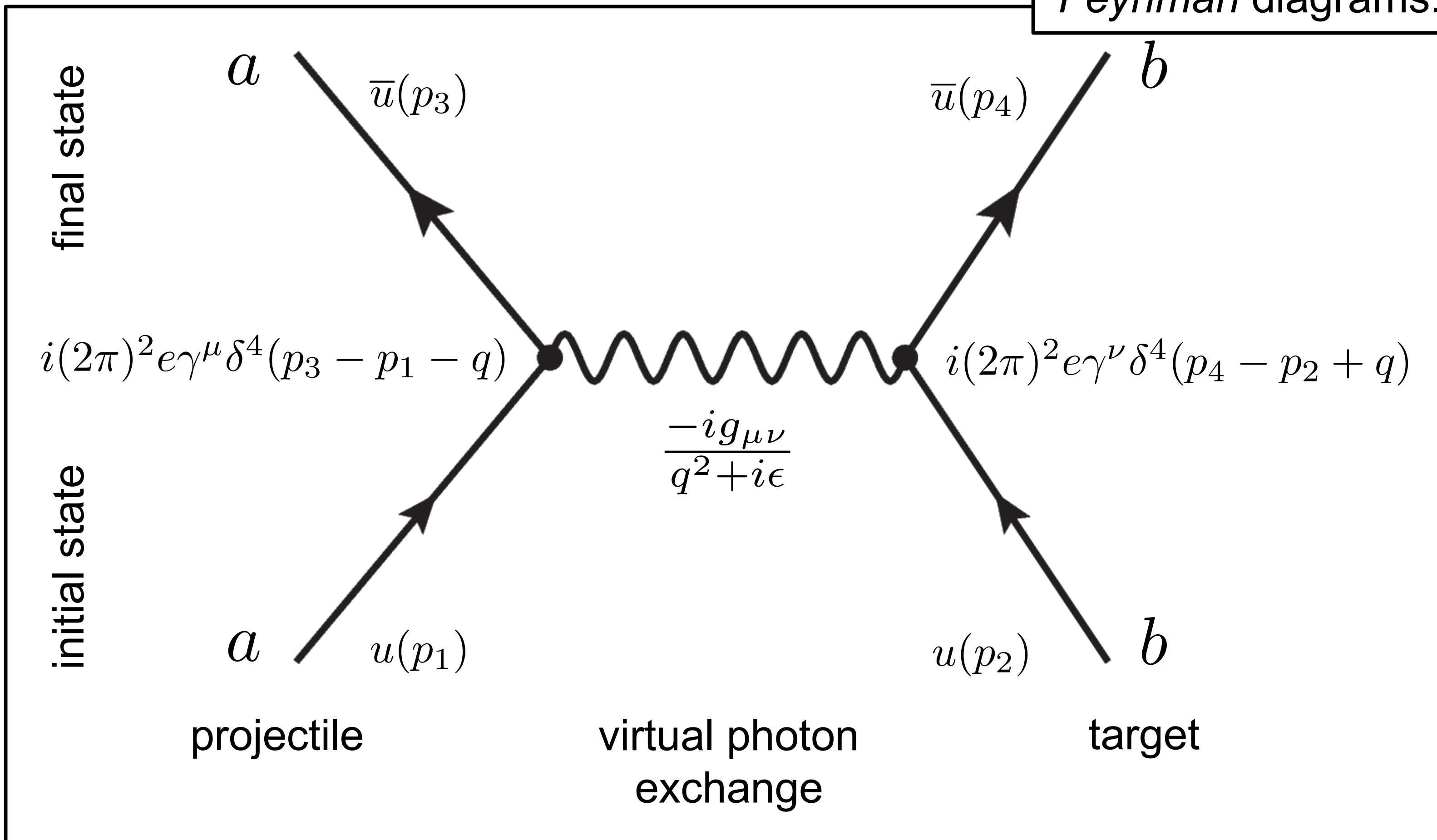
$$W = 2\pi\left|\mathcal{S}_{fi}\right|^2\rho_f$$

$$\rho_f = \int\prod_{i=a,b}(2\pi)^{-3}p_i^2\mathrm{d}p_i\mathrm{d}\Omega_i$$

phasespace factor for final state products.

The matrix element $\mathcal{S}_{fi}$

Matrix element calculations can be represented pictorially with the help of *Feynman* diagrams.

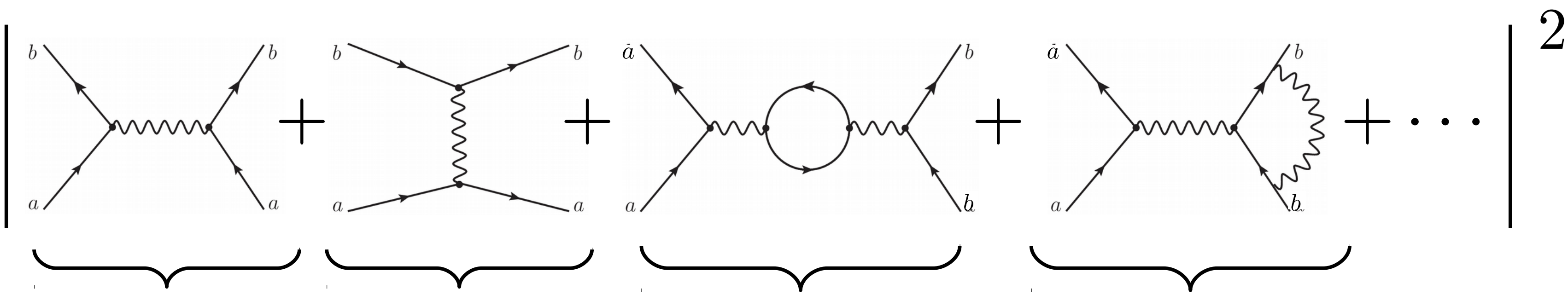


$$\mathcal{S}_{fi}^{(1)} = i\left((2\pi)^2 e\right)^2 \cdot \int \mathrm{d}^4 q \; \delta^4(p_3 - p_1 - q)\overline{u}(p_3)\gamma^\mu u(p_1)\frac{-g_{\mu\nu}}{q^2 + i\epsilon}\delta^4(p_4 - p_2 + q)\overline{u}(p_4)\gamma^\nu u(p_2)$$

The matrix element $\mathcal{S}_{fi}$

- The full calculation (ideally) includes all possible diagrams to all orders in QM perturbation theory:

$$|\mathcal{S}_{fi}|^2 =$$



s-channel, if allowed. | t-channel. | Higher order correction to propagator. | Higher order correction to vertex.

- Coherent sum: includes absolute value squares of individual diagrams and interference terms across different diagrams.

History of particle physics

- Relativistic QM (→ Dirac-Equation 1928)
- Theory of weak IA (→ E. Fermi 1933 – 34)
- Discovery $\mu^{+/-}$ (→ C. D. Anderson 1937) 
- Discovery $\pi^{+/-}$ (→ C. Powel/G. Occhialini 1947) 
- Discovery π^0 (→ R. Bjorklund et al 1950) 
- Discovery $K^{+/-}$ (→ “V”-particles 1947 – 49) 
- Discovery K^0, Λ^0 (→ “V”-particles 1947) 
- Discovery Σ’s, Ξ’s (→ 1950’s) 
- Discovery Δ^{++}, Δ^{+}, Δ^{0}, Δ^{-} (→ 1952) 
- Invention of bubble chamber (→ D. Glaser 1952)
- Observation of ν_e (→ C. Cowan, F. Reines 1956)
- Observation P violation of weak IA (→ C. Wu, R. Garwin 1556)
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- Discovery J/ψ’s (→ B. Richter, S.Thing, 1974) 
- Discovery Υ’s (→ L. Lederman, E288 collaboration, 1977) 
- Discovery of W, Z (→ UA1 & UA2 collaboration, 1983) 
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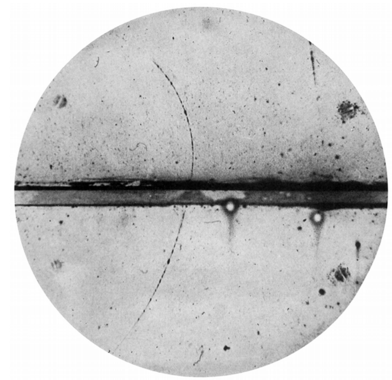
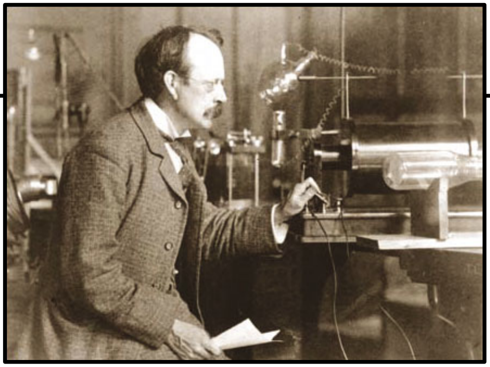
- Observation of ν_τ (→ DONUT collaboration 2000)
- Discovery of H (→ ATLAS & CMS collaboration 2012)

Discovery of the positron (1932)



C. D. Anderson (1905 – 1991)

Discovery of the electron (1897)



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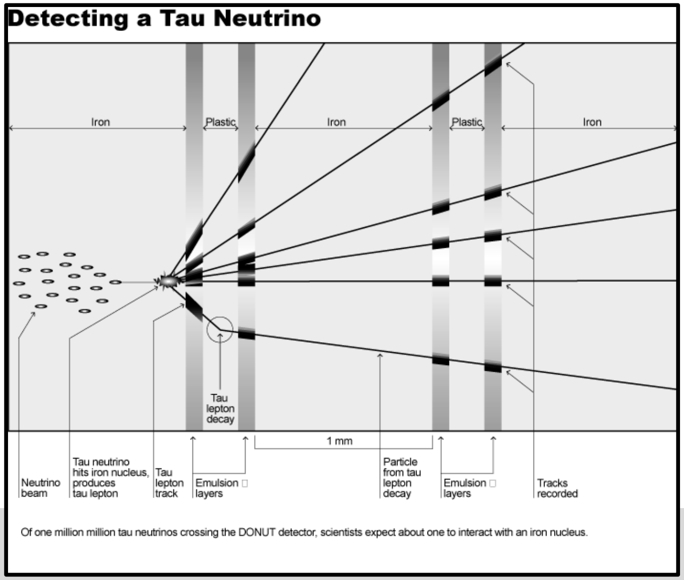

DONUT collaboration

 discovered in airshower experiments
 discovered in collider experiments

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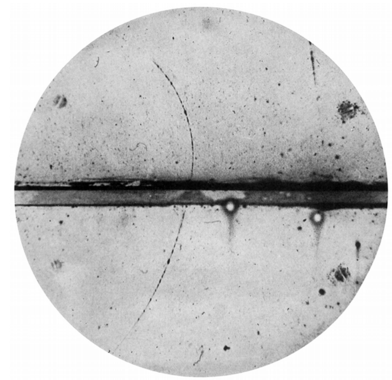

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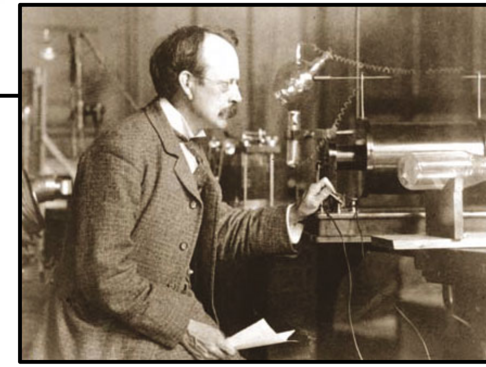

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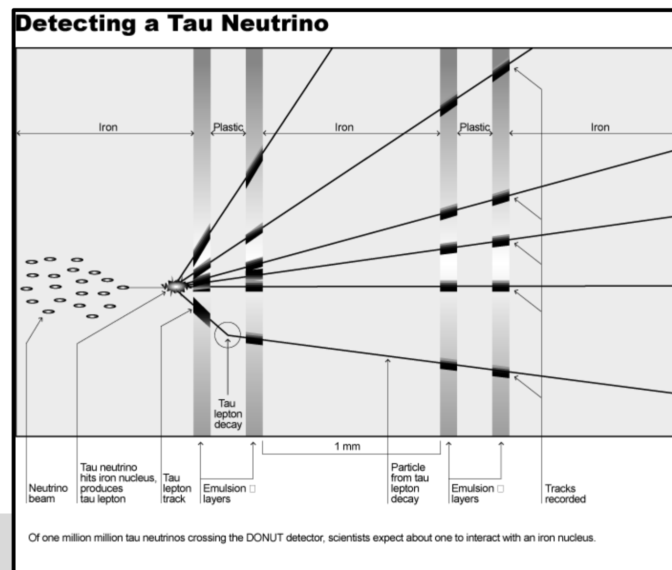
Overall $\mathcal{O}(30)$ Nobel prizes in physics went to directly particle physics related topics.



DONUT collaboration

discovered in airshower experiments
discovered in collider experiments

Hadrons:

Baryons:

Leptons:

e^-

μ^-

τ^-

ν_τ

ν_e

ν_μ

Mesons:

The PARTICLE ZOO

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Hadrons:

Leptons:

e^- μ^- τ^- ν_e ν_μ ν_τ

Mesons:

π^- D^0 B^- η η' η_c B^+ π^+ π^0 η_b D_s^- K^+ D_s^+ K^- K_L^0 K_S^0 D^- D^+ B_c^+ B_s^0 B^0 B_c^-

$J^P = 0^-$

Baryons:

Hadrons:

Leptons:

e^- μ^- τ^- ν_τ ν_e ν_μ

Mesons:

π^- D^0 B^- η J/ψ η' ϕ K^{*-} ρ^0 η_c B^+ ω π^+ ρ^- π^0 ρ^+ η_b D_s^- D_s^+ K^{*+} K^+ Υ K^- K^{*0} D_s^{*-} K_S^0 K_L^0 D^{*+} D^- B_c^{*-} B_c^{*+} D^{*-} D^+ B_c^+ B_s^0 B^{*+} D^{*0} B^{*0} D_s^{*+} B^0 B_c^- B_s^{*0}

Baryons:

$J^P = 0^-$ $J^P = 1^-$

The PARTICLE ZOO

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Hadrons:

Leptons:

e^- μ^- τ^- ν_τ ν_e ν_μ

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Baryons:

Ξ_c^+ Σ^0 Ω_{bb}^- p n Σ^+ Ξ^- Λ_b^+ Δ^{++} Ξ^0 $\Xi_{cb}'^0$ $\Xi_{cb}'^+$ Σ^- Λ^0 Λ_c^+ $\Xi_{bb}'^-$ Σ_c^+ Δ^+ Δ^- Σ_c^{++} Ξ_{cb}^+ Σ_b^- Δ^0 Ξ_c^0 Σ_b^+ Σ_b^0 Ξ_{cc}^{++} $\Xi_c'^+$ Ξ_{cb}^0 $\Xi_c'^0$ Ξ_b^- Ξ_b^0 Ξ_{cc}^+ $\Xi_{bb}'^0$ Σ_c^0 $\Xi_b'^-$ Ω_b^- Ω_c^0 Ω_{cbb}^0 Ω_{cb}^0 Ω_{ccb}^+ Ω_{cc}^+ $\Xi_b'^0$ $\Omega_{cb}'^0$

$J^P = 0^-$ $J^P = 1^-$ $J^P = {}^1\!/_2^{\,+}$

Hadrons:

Leptons:

e^- μ^- τ^- ν_τ ν_e ν_μ

Mesons:

π^- D^0 B^- η J/ψ η' ϕ K^{*-} ρ^0 η_c B^+ ω π^+ ρ^- π^0 ρ^+ η_b D_s^- D_s^+ K^{*+} K^+ Υ K^- K^{*0} D_s^{*-} K_S^0 K_L^0 D^{*+} D^- B_c^{*-} B_c^{*+} D^{*-} D^+ B_c^+ B_s^0 B^{*+} D^{*0} B^{*0} D_s^{*+} B^0 B_c^- B_s^{*0}

+150 further known Meson resonances.

Baryons:

Ω_{bbb}^{++} Ξ_c^+ Σ^0 Ω_{bb}^- p n Ω_{ccc}^{++} Ω_{cbb}^{*0} Ω_{ccb}^{*+} Σ^+ Ξ^- Ω_{bb}^{*-} Λ_b^+ Δ^{++} Ξ^0 $\Xi_{cb}^{\prime 0}$ Δ^{++} $\Xi_{cb}^{\prime +}$ Ω_b^{*-} Σ^- Ω_c^{*0} Λ^0 Λ_c^+ $\Xi_{bb}^{\prime -}$ Ξ^{*-} Ω_{cb}^{*0} Ω^- Σ_c^+ Δ^- Δ^+ Δ^- Ω_{cc}^{*+} Σ_b^{*+} Ξ_{bb}^{*0} Σ_c^{++} Ξ_{cb}^+ Ξ_b^{*0} Σ_b^- Δ^0 Ξ_{cb}^{*0} Ξ^{*0} Ξ_c^0 Σ_b^+ Δ^0 Ξ_{cb}^0 $\Xi_c^{\prime 0}$ Ξ_b^{*-} Σ_b^0 Ξ_{cc}^{++} $\Xi_c^{\prime +}$ Ξ_{cc}^+ Ξ_b^- Ξ_b^0 $\Xi_{bb}^{\prime 0}$ Σ_b^{*-} Σ_c^0 Ξ_{bb}^{*-} $\Xi_b^{\prime -}$ Ξ_{cc}^{*++} Ξ_{cb}^{*+} Ω_b^- Ω_c^0 Ω_{cbb}^0 Σ_b^{*0} Ξ_c^{*+} Σ^{*-} Ω_{ccb}^+ Σ_c^{*+} Ω_{cb}^0 $\Xi_b^{\prime 0}$ Δ^+ Ω_{cc}^+ Ξ_c^{*0} Σ^{*0} Σ_c^{*++} $\Omega_{cb}^{\prime 0}$ Σ^{*+} Σ_c^{*0} Ξ_{cc}^{*+}

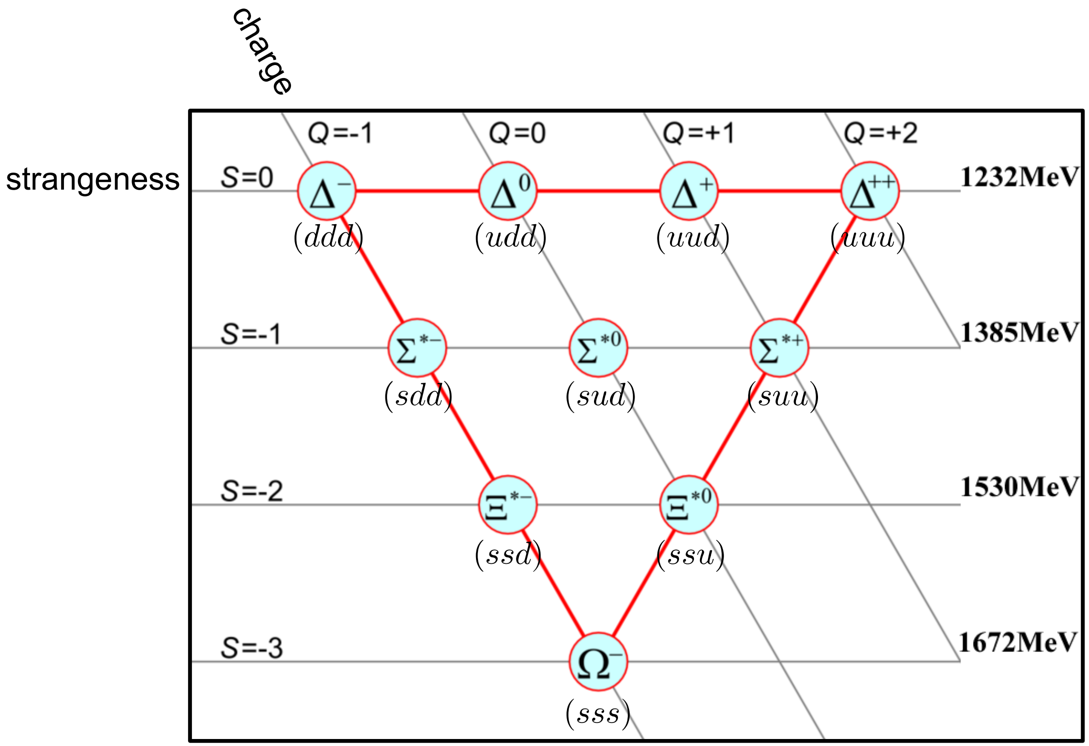
+152 further known Baryon resonances.

$\mathcal{O}(400)$ known elementary particles.

$J^P = 0^-$ $\quad J^P = 1^-$ $\quad J^P = 1/2^+$ $\quad J^P = 3/2^+$

More order into the chaos...

… could be achieved once it was realized that *hadrons* are composed of more fundamental constituents → quarks (first only sorting principle):



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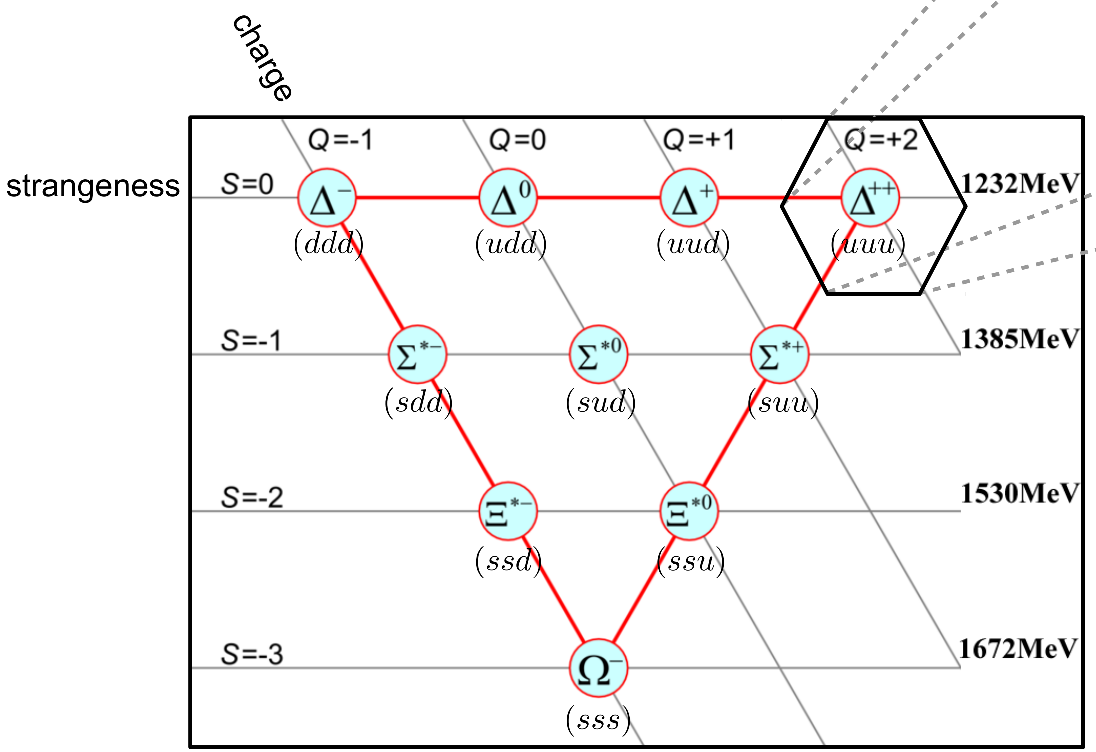


$J^P = {}^3/_2{}^+$ *baryon* $SU(3)$ decuplet.

Δ^{++} requires:

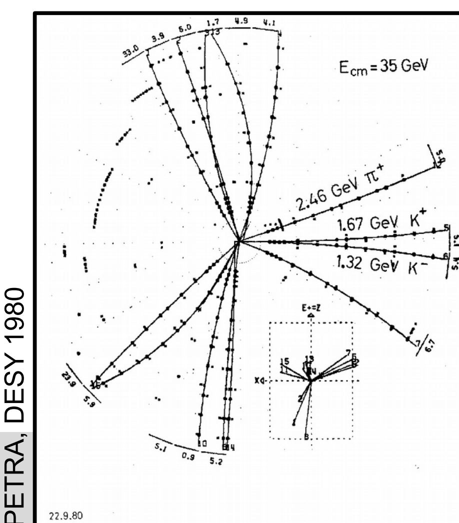
- all spins up $(\uparrow\uparrow\uparrow)$.
- all same flavors (uuu).
- No orbital momentum $(L=0)$.

As spin ½ fermion Δ^{++} needs anti-symmetric wave function:

$$\psi = \phi \cdot \chi(uuu) \cdot \eta(\uparrow\uparrow\uparrow)$$

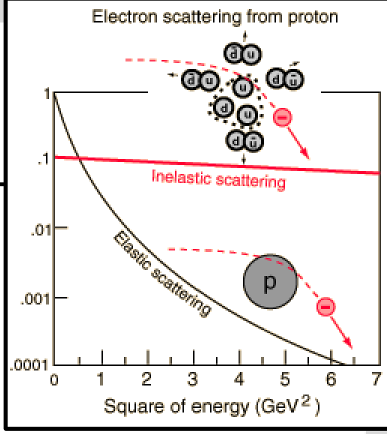
- ϕ: symmetric → Space wave function
- $\chi(uuu)$: symmetric → Flavor wave function
- $\eta(\uparrow\uparrow\uparrow)$: symmetric → Spin wave function

New quantum number required to obtain anti-symmetric wave function (→ first indication for **color**).



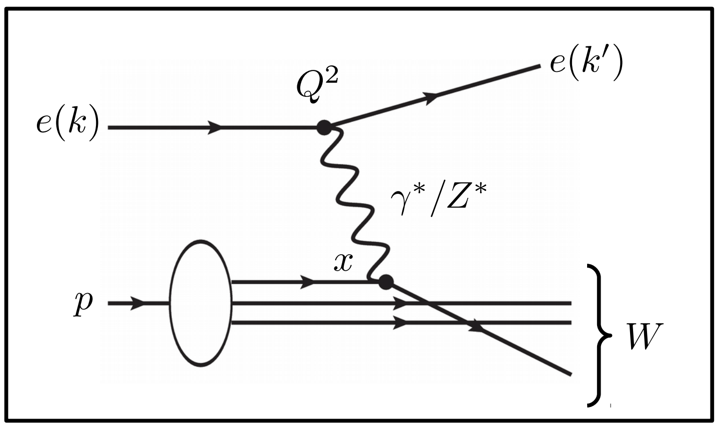
PETRA, DESY 1980

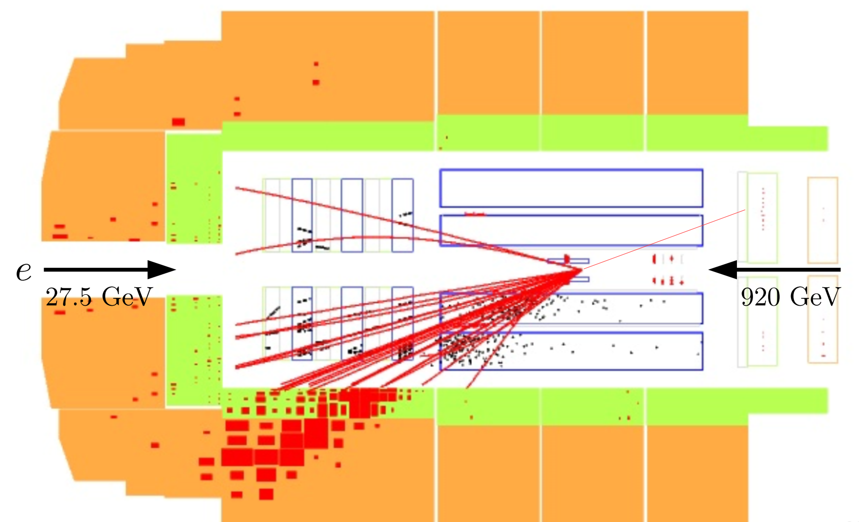
The evidence of quarks...



… emerged from deep inelastic scattering (DIS) experiments (first @SLAC 1969, here shown @HERA ~2000):

$$Q^2 = -q^2 = (k' - k)^2$$
$$s = (p - k)^2 = 4E_pE_e$$
$$x = \frac{Q^2}{2pq}$$
$$y = \frac{pq}{pk}$$
$$Q^2 = xys$$



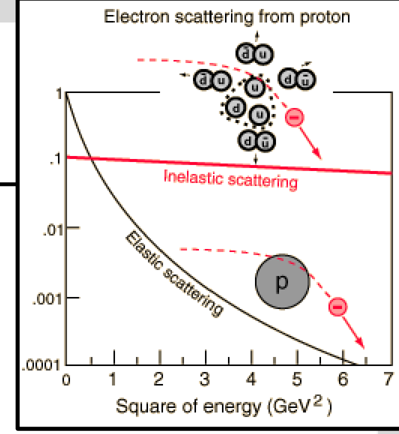


H1 Experiment @ HERA

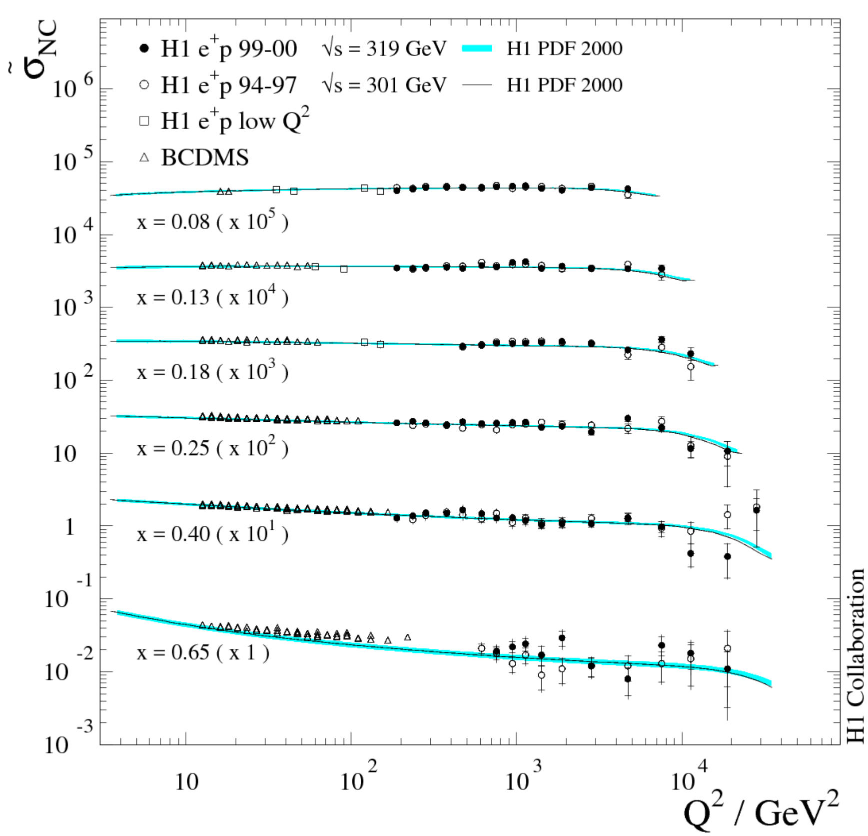
For the DIS process:

$$(xp + q)^2 = m_q^2 + 2xpq - Q^2 = m_q^2$$
$$x = \frac{Q^2}{2pq}$$

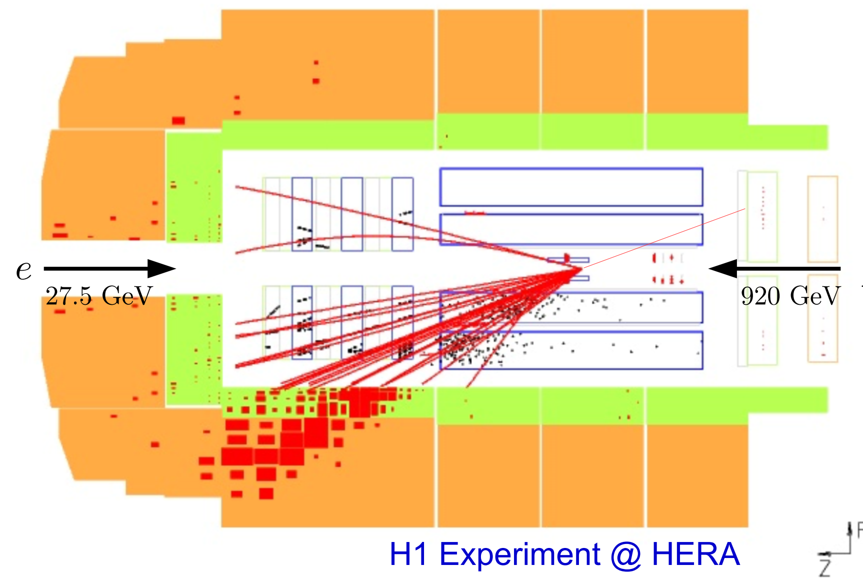
The evidence of quarks...



… emerged from deep inelastic scattering (DIS) experiments (first @SLAC 1969, here shown @HERA ~2000):



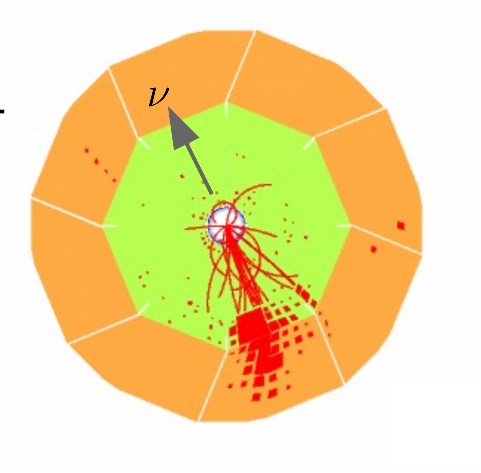
$\tilde{\sigma}_{NC}$: cross section divided by expectation for point-like particle.

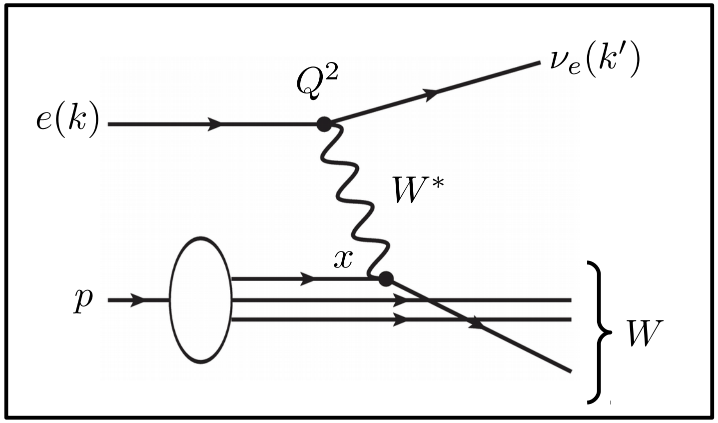


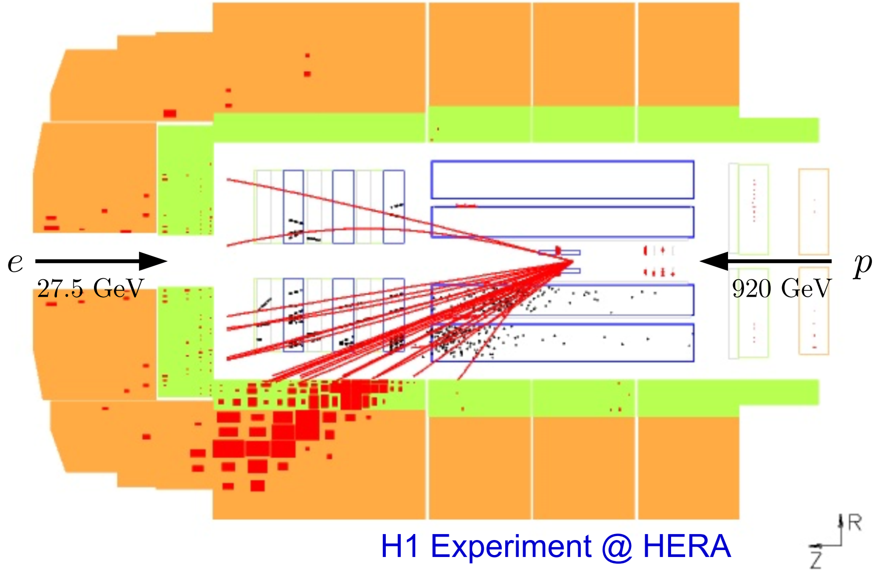
H1 Experiment @ HERA

Change of flavor & charge

- In the scattering vertex the electron can change flavor and charge and leave detector unobserved.
- Opposed to the neutral current (NC) process this is called charged current (CC) process.

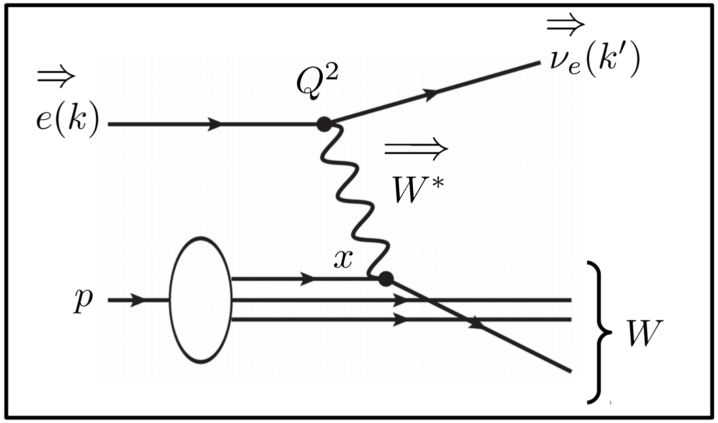


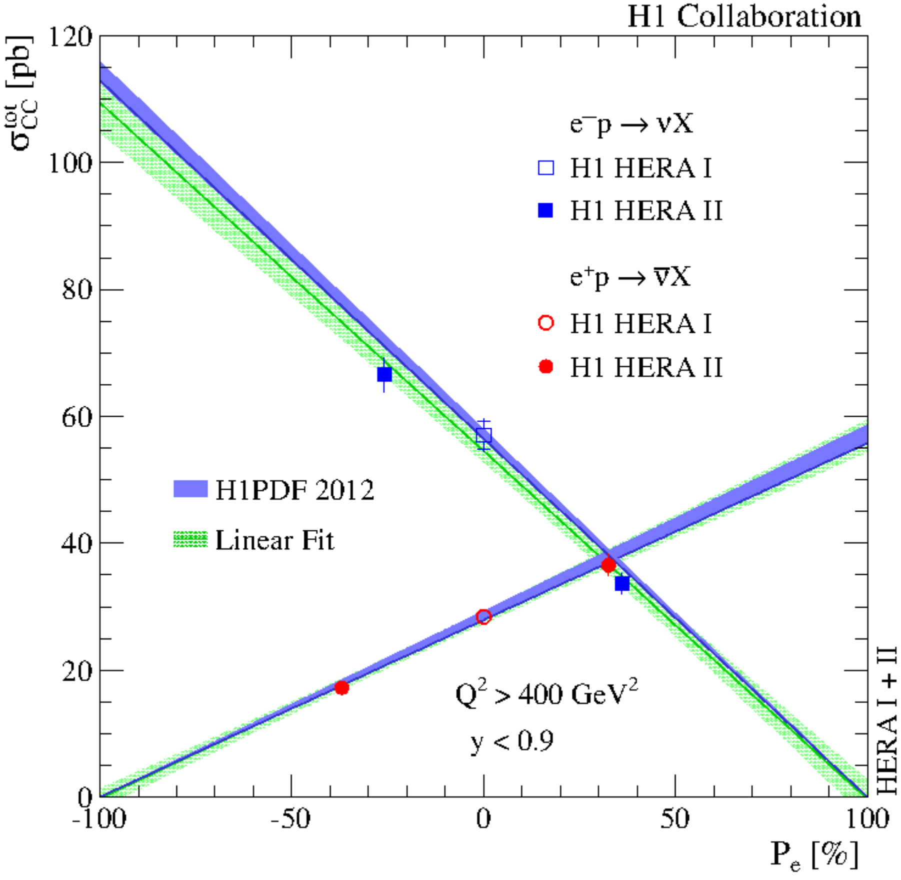




Parity violation

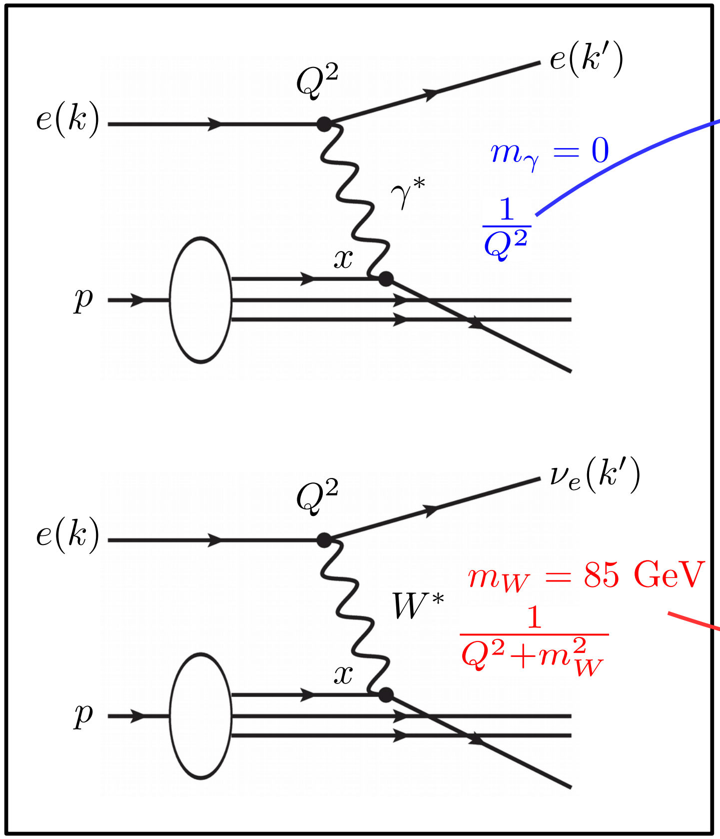
- HERA ran with e-beams of different polarization:
- CC reaction is maximally parity violating!
- W bosons couple only to left-handed particles (right-handed anti-particles).

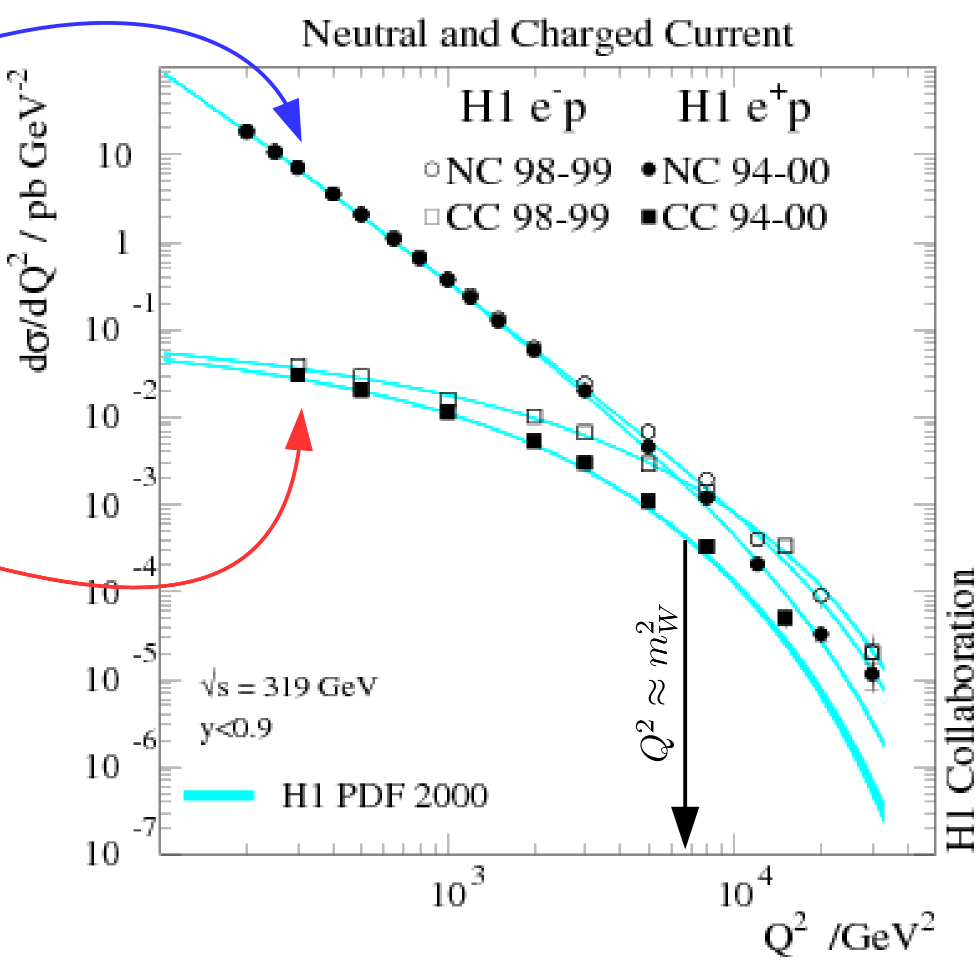




- NB: weak interaction intrinsically also violating CP.

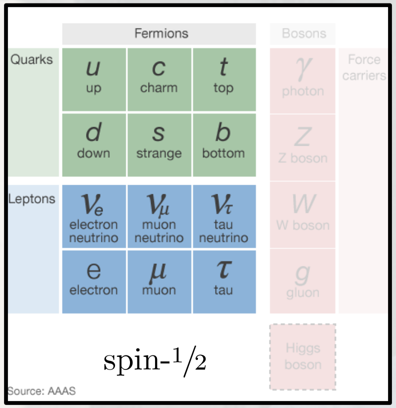
Massive force mediators





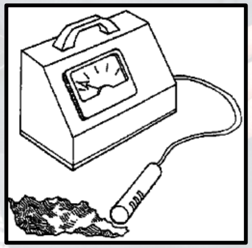
The case of matter

- All matter we know is made up of six quark flavors and six lepton flavors:

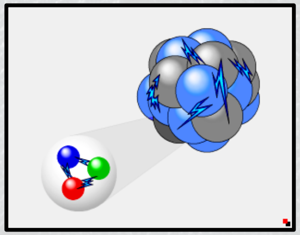


Four fundamental forces act between them (three of importance for particle physics).

Electromagnetism



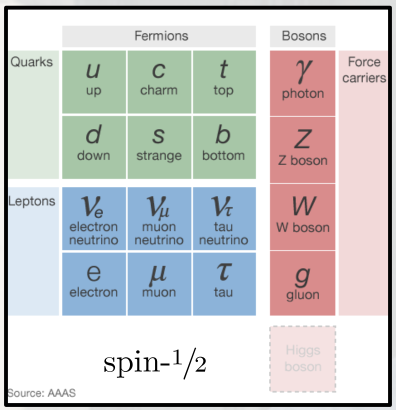
Weak force

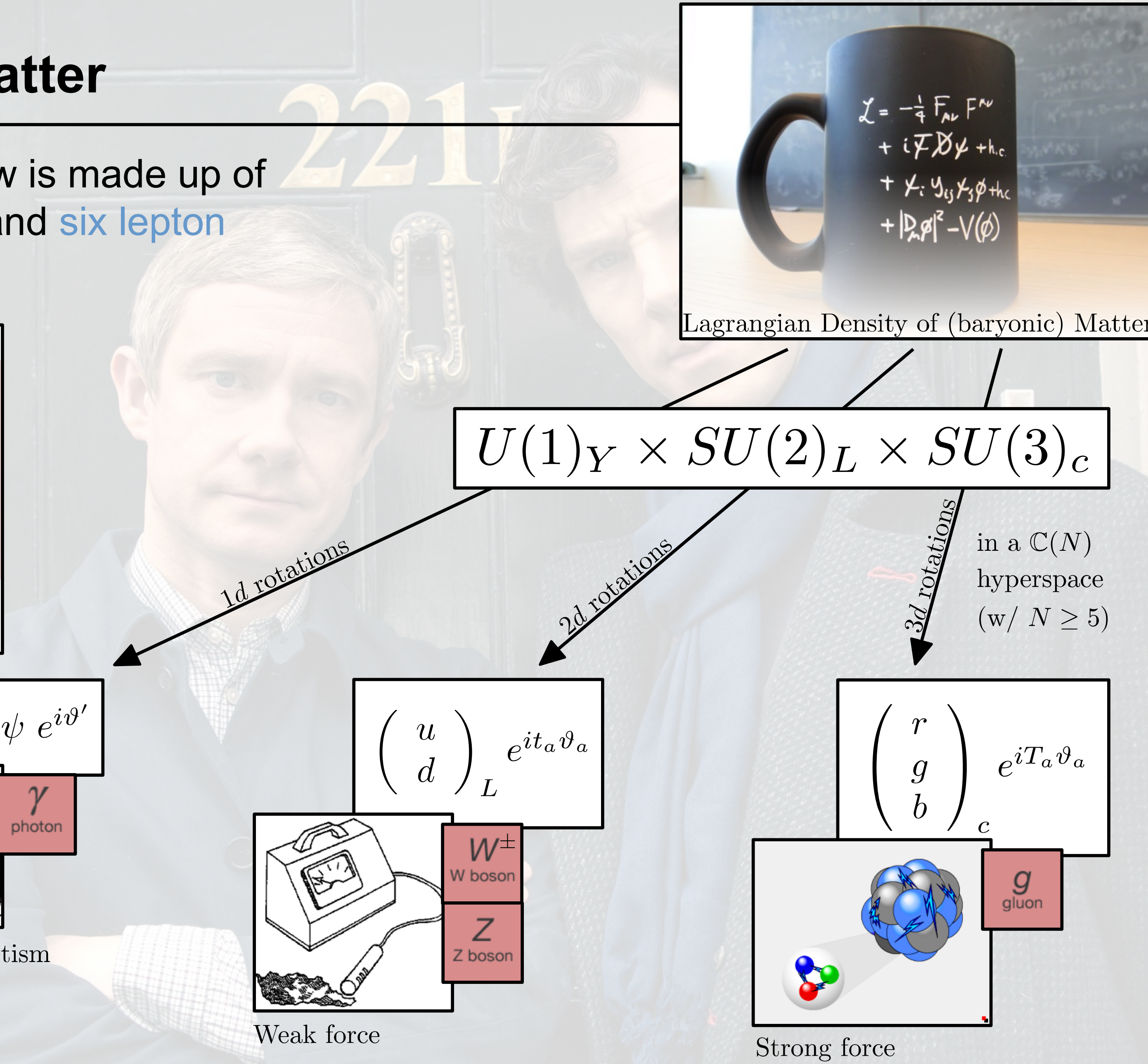


Strong force

The case of matter

- All matter we know is made up of six quark flavors and six lepton flavors:





A wealth of structures

$$\mathcal{L}^{\text{SM}} = \mathcal{L}^{\text{Lepton}}_{\text{kin}} + \mathcal{L}^{CC}_{\text{IA}} + \mathcal{L}^{NC}_{\text{IA}} + \mathcal{L}^{\text{Gauge}}_{\text{kin}} + \mathcal{L}^{\text{Higgs}}_{kin} + \mathcal{L}^{\text{Higgs}}_{V(\phi)} + \mathcal{L}^{\text{Higgs}}_{\text{Yukawa}}$$

$$\mathcal{L}^{\text{Lepton}}_{\text{kin}} = i\bar{e}\gamma^{\mu}\partial_{\mu}e + i\bar{\nu}\gamma^{\mu}\partial_{\mu}\nu$$

$$\mathcal{L}^{CC}_{\text{IA}} = -\frac{e}{\sqrt{2}\sin\theta_W}\left[W^{+}_{\mu}\bar{\nu}\gamma_{\mu}e_L + W^{-}_{\mu}\bar{e}_L\gamma_{\mu}\nu\right]$$

$$\mathcal{L}^{NC}_{\text{IA}} = -\frac{e}{2\sin\theta_W\cos\theta_W}Z_{\mu}\left[(\bar{\nu}\gamma_{\mu}\nu) + (\bar{e}_L\gamma_{\mu}e_L)\right] - e\left[A_{\mu} + \tan\theta_W Z_{\mu}\right](\bar{e}\gamma_{\mu}e)$$

$$\mathcal{L}^{\text{Gauge}}_{\text{kin}} = -\frac{1}{2}Tr\left(W^{a}_{\mu\nu}W^{a\mu\nu}\right) - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}\Bigg|_{\substack{B_{\mu}\to A_{\mu}\\ W^{3}_{\mu}\to Z_{\mu}}}$$

$$\mathcal{L}^{\text{Higgs}}_{\text{kin}} = \frac{1}{2}\partial_{\mu}H\partial^{\mu}H + \left(1 + \frac{1}{v}\frac{H}{\sqrt{2}}\right)^2 m_W^2 W^{+}_{\mu}W^{\mu-} + \left(1 + \frac{1}{v}\frac{H}{\sqrt{2}}\right)^2 m_Z^2 Z_{\mu}Z^{\mu}$$

$$\mathcal{L}^{\text{Higgs}}_{V(\phi)} = -\frac{m_H^2 v^2}{4} + \frac{m_H^2}{2}\left(\frac{H}{\sqrt{2}}\right)^2 + \frac{m_H^2}{v}\left(\frac{H}{\sqrt{2}}\right)^3 + \frac{m_H^2}{4v^2}\left(\frac{H}{\sqrt{2}}\right)^4$$

$$\mathcal{L}^{\text{Higgs}}_{\text{Yukawa}} = -\left(1 + \frac{1}{v}\frac{H}{\sqrt{2}}\right)m_e\bar{e}e$$

Full SM Lagrangian density (first lepton generation)

The power of symmetry

- The SM draws its explaining and predictive power from the level of symmetry of $\mathcal{L}$.
- Each symmetry of $\mathcal{L}$ is related to a conserved quantity. This relation is revealed by the *Noether* theorem:

For illustration assume:

$$\mathcal{L} = \left(\partial_\mu \phi^\dagger \partial^\mu \phi\right) - m^2 \phi^\dagger \phi$$

And the symmetry operation:

$$\begin{aligned} \phi_j &\longrightarrow \phi'_j &&= \phi_j + \delta\phi_j \\ \partial_\mu \phi_j &\longrightarrow (\partial_\mu \phi_j)' &&= \partial_\mu \phi_j + \delta\partial_\mu \phi_j \end{aligned}$$

Taylor expansion, symmetry requirement:

$$\mathcal{L}(\{\phi_j + \delta\phi_j\}, \{\partial_\mu \phi_j + \delta\partial_\mu \phi_j\}) = \mathcal{L}(\{\phi_j\}, \{\partial_\mu \phi_j\}) + \underbrace{\frac{\delta\mathcal{L}}{\delta(\partial_\mu \phi_j)} \delta\partial_\mu \phi_j + \frac{\delta\mathcal{L}}{\delta\phi_j} \delta\phi_j}_{=0} = \mathcal{L}(\{\phi_j\}, \{\partial_\mu \phi_j\})$$

$$\frac{\delta\mathcal{L}}{\delta(\partial_\mu \phi_j)} \delta\partial_\mu \phi_j + \frac{\delta\mathcal{L}}{\delta\phi_j} \delta\phi_j = \underbrace{\frac{\delta\mathcal{L}}{\delta(\partial_\mu \phi_j)} \delta\partial_\mu \phi_j + \partial_\mu \frac{\delta\mathcal{L}}{\delta(\partial_\mu \phi_j)} \delta\phi_j}_{} = 0$$

$$\partial_\mu \frac{\delta\mathcal{L}}{\delta(\partial_\mu \phi_j)} - \frac{\delta\mathcal{L}}{\delta\phi_j} = 0$$

(on shell requirement)

$$\partial_\mu \left(\frac{\delta\mathcal{L}}{\delta(\partial_\mu \phi_j)} \delta\phi_j \right) = 0$$

$$J^\mu = \frac{\delta\mathcal{L}}{\delta(\partial_\mu \phi_j)} \delta\phi_j \quad \text{(conserved current)}$$

$$\int \mathrm{d}^3x \partial_\mu J^\mu = \int \mathrm{d}^3x \left(\partial_0 J^0 - \partial_i J^i\right) = 0$$

$$\int \mathrm{d}^3x \; \partial_t J^0 = \int \mathrm{d}^3x \; \vec{\nabla}\vec{J} = \int \mathrm{d}\vec{\Omega}\vec{J} \; = 0$$

J^0 (conserved charge)

The conserved charge is the generator of the symmetry operation that creates it.

Examples of symmetries

- A few examples of symmetry operations and/or conserved quantities on $\mathcal{L}$ are given below (→ try to complete the missing parts on your own):

	internal	external	symmetry	conserved quantity
discrete symmetry		☑	C, P, T, CP, CPT	...
		☑	rotation in $\mathbb{R}^3$	$\vec{L}$
continuous symmetry		☑	tranlsation in $\mathbb{R}^3$	$\vec{p}$
		☑	tranlsation in t	E
symmetry only on fields	☑		$U(1)_Y$, $SU(2)_L$, $SU(3)_c$	...
symmetry only on fields & arguments	☑	☑	Lortentz transformation	...
symmetry only on fields & arguments	☑	☑	Lortentz transformation	...
...	...	...	...	baryon number
...	...	...	...	lepton number

- One last non-trivial symmetry on $\mathcal{L}$ is the symmetry against an operation that transforms bosons into fermions and vice versa.

Remaining lecture program

	Monday (19.09):	Tuesday (20.09.):	Wednesday (21.09.):
13:30 15:00	Introdu ✔ particle physics	Proton structure, QCD and physics with jets (MM).	Flavor physics - including top-quarks (MM).
15:15 16:45	Particle acceleration & detection; data analysis (RW).	Physics with gauge bosons (MM).	Higgs physics (RW).

- In case of questions – contact us matthias.mozer@cern.ch (Bld. 30.23 Room 9-8)
  roger.wolf@cern.ch (Bld. 30.23 Room 9-20).

Backup