

**ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ, ЧТО МЫ
ЗНАЕМ И ПЫТАЕМСЯ УЗНАТЬ.**

Zhevlakov Alexey (TSU).

$$E = mc^2$$

$$1 \text{ eV (electronvolt)} = 1,6 \cdot 10^{-19} \text{ J} \sim 1,78 \cdot 10^{-36} \text{ kg}$$

$$1 \text{ keV} = 1000 \text{ eV}$$

$$1 \text{ MeV} = 1000 \text{ 000 eV}$$

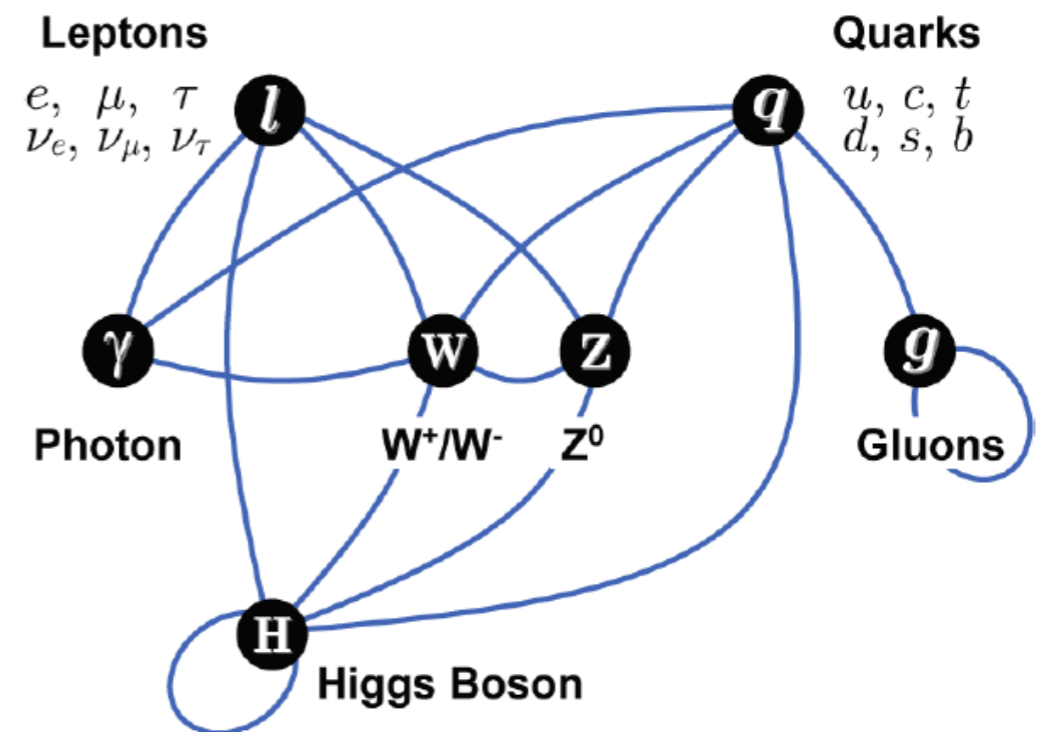
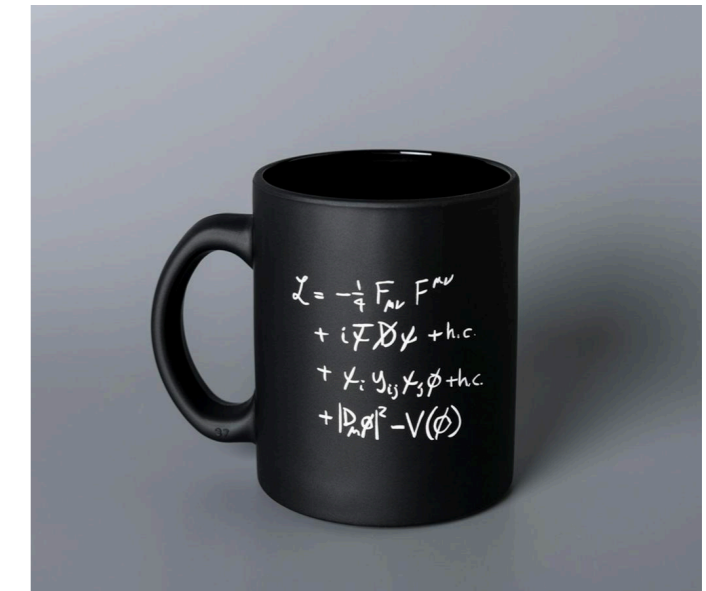
$$1 \text{ GeV} = 1000 \text{ 000 000 eV}$$

$$1 \text{ TeV} = 1000 \text{ 000 000 000 eV}$$

Энергии в мире элементарных частиц тоже слишком малы, чтоб измерять их в Джоулях. Вместо этого используют единицу энергии **электронвольт (эВ)**. 1 эВ, по определению, это энергия, которую приобретет электрон в электрическом поле при прохождении разности потенциалов в 1 Вольт. 1 эВ примерно равен $1,6 \cdot 10^{-19}$ Дж.

КАРТИНА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ:

	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	



Source: AAAS

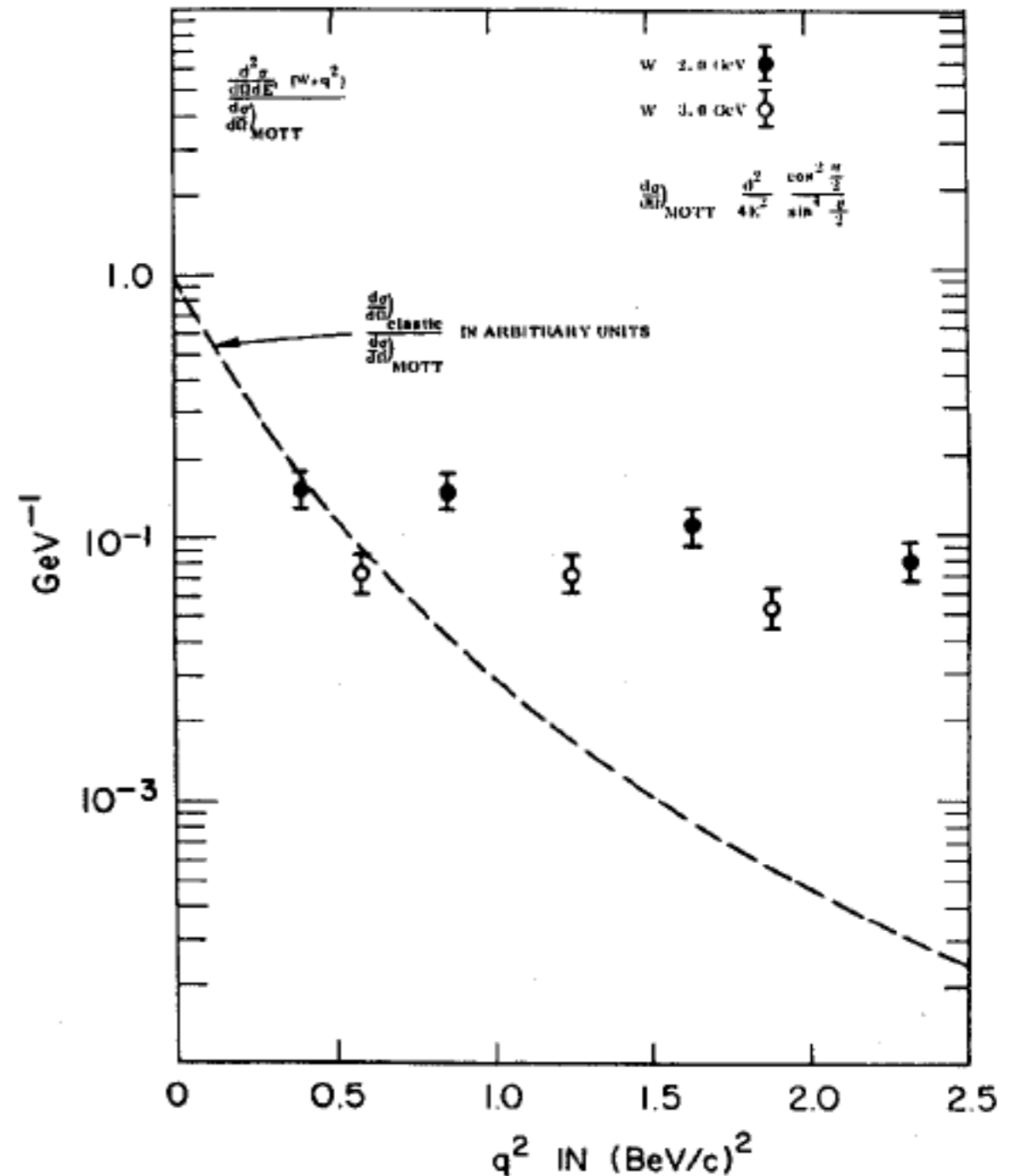
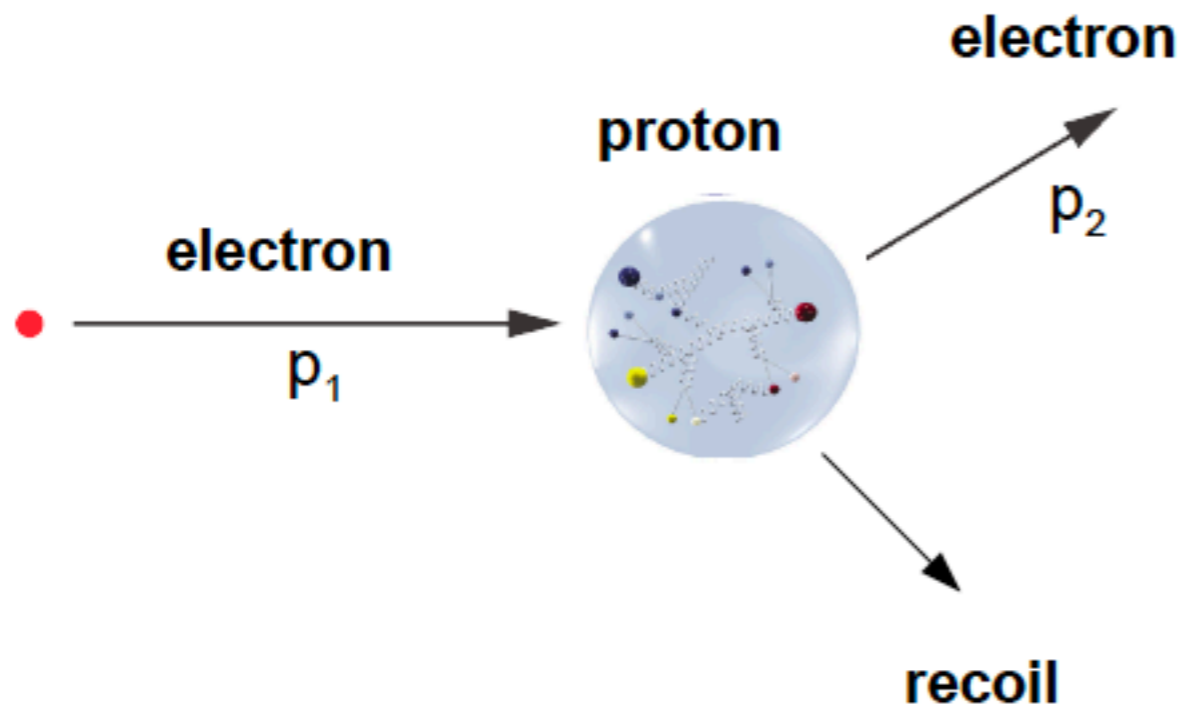
Exercise 1.1.1.1.1a: Given locality, causality, Lorentz invariance, and known physical data since 1860, show that the Lagrangian describing all observed physical processes (sans gravity) can be written:

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{adc} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
 & \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
 & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \right. \\
 & \left. \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+)] - ig s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
 & \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
 & gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \\
 & \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \\
 & \frac{ig}{4c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \\
 & \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_c^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{g}{2} \frac{m_s^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
 & m_u^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
 & \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_t^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_b^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
 & \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
 & \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \\
 & \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
 & igM s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

Discovery of partons

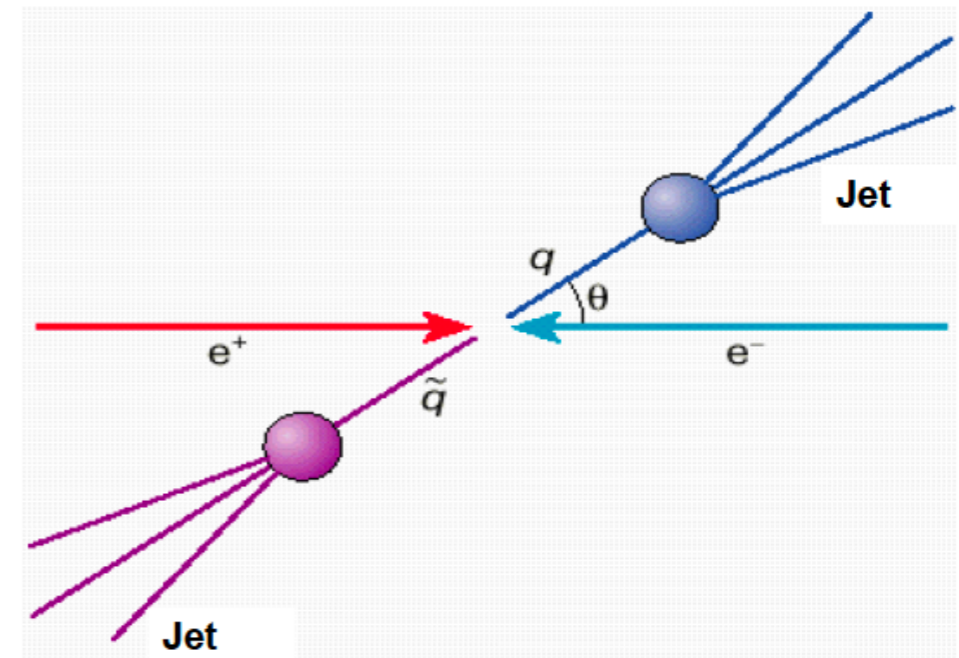
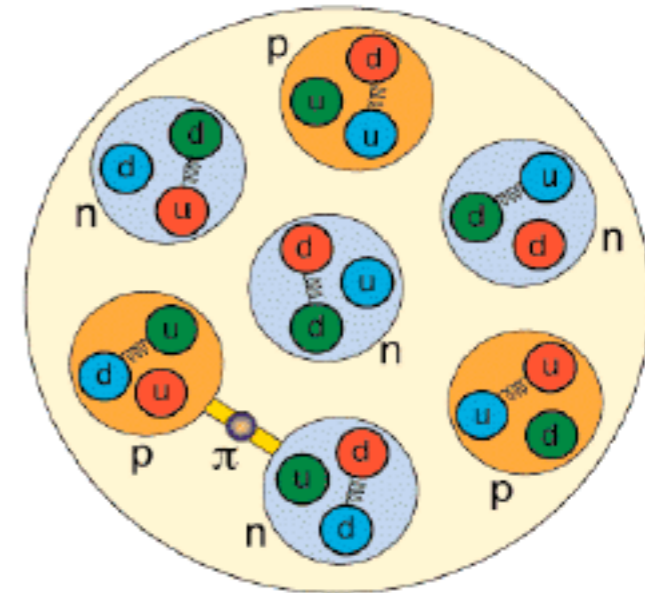
Friedman, Kendall, Taylor, SLAC, 1968

$\lambda = h/p$
 10 GeV/c \sim 0,1 fm
 Nucleon radius \sim 1 fm



КОНФАЙНМЕНТ КВАРКОВ

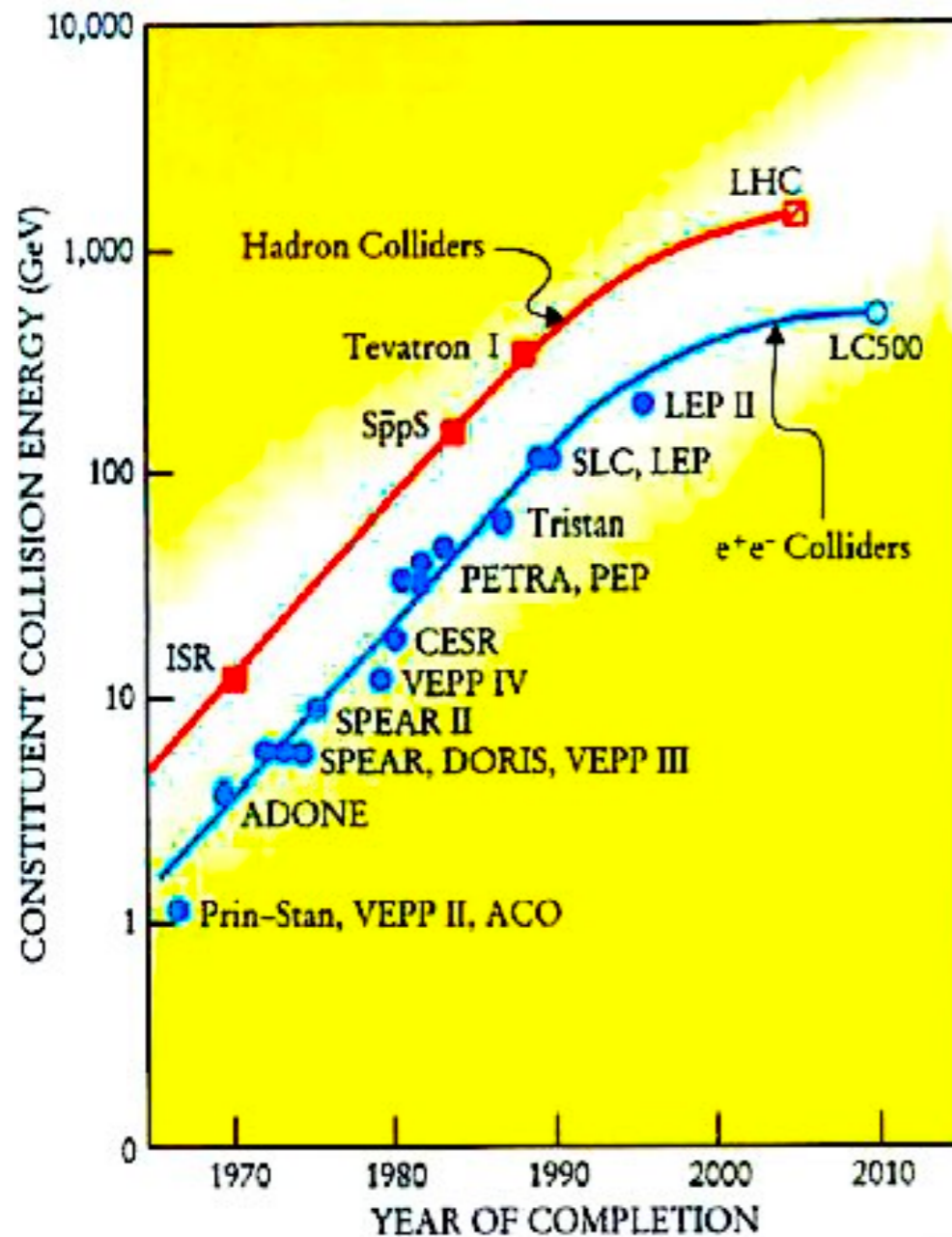
- Невозможно наблюдать свободные состояния кварков
- Все наблюдающиеся состояния адронов являются бесцветными - мезоны ($\bar{q}q$) и барионы (qqq)



Jet formation in the reaction



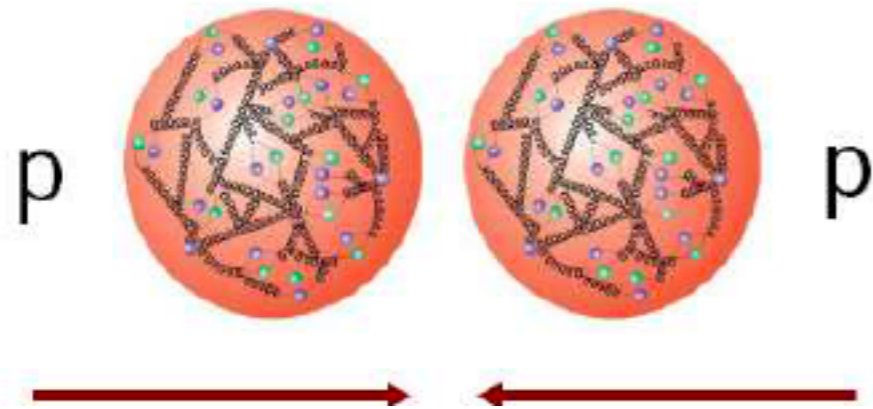
ИСТОРИЯ РАЗВИТИЯ КОЛЛАЙДЕРОВ



История развития электронных и адронных машин имеет долгую и плодотворная линию.

- J/ψ at SPEAR (e^+e^-) and AGS (proton fixed target)
- Υ discovery at E288 (p fixed target), precision B studies at the e^+e^- B factories
- ...
- top quark at LEP and Tevatron
- LHC, EIC, NICA, etc

СРАВНЕНИЕ АДРОННОГО И ЭЛЕКТРОННОГО КОЛЛАЙДЕРА



Протон (антипротон) коллайдер

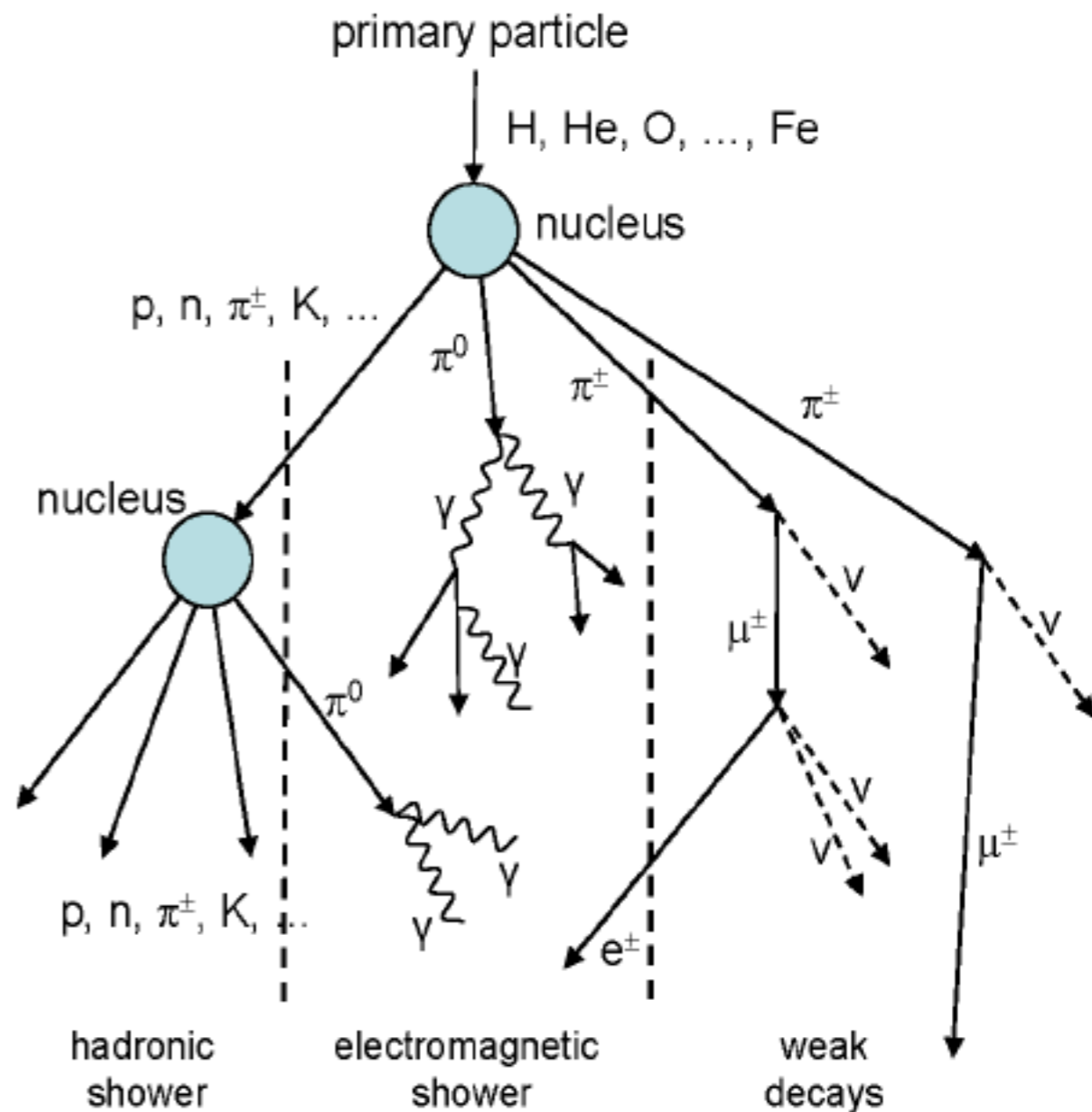
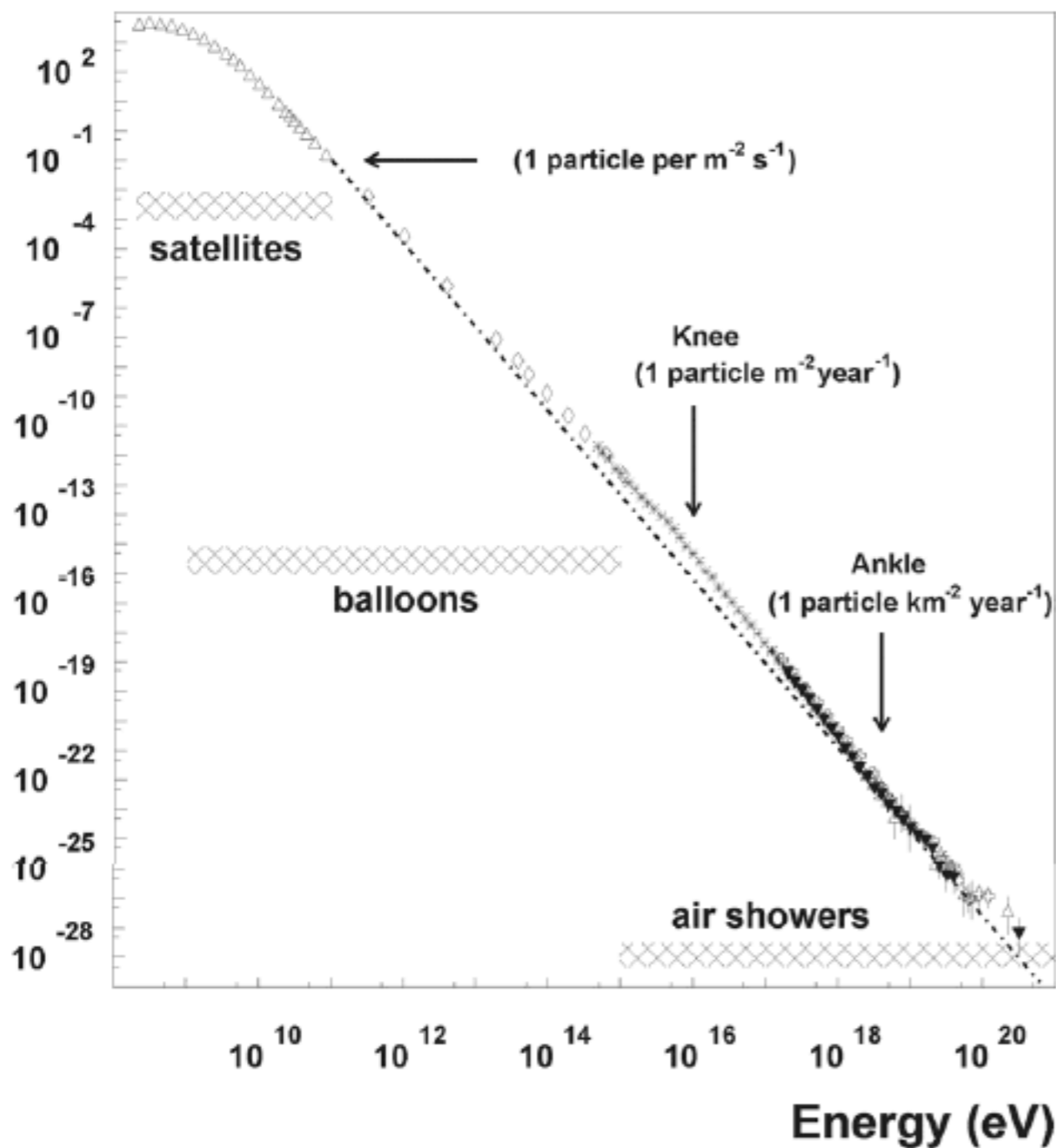
- *Более высокие энергии, ограничение силой магнитов.*
- *Композитные частицы: неизвестные и разные столкновения составляющие, энергии в каждом столкновении*
- *Открыли (W, Z, t)*
- *В некоторых случаях: возможны точные измерения (масса W бозона на тэватроне)*

Электрон-позитронный коллайдер

- *Энергия ограничена синхротронным излучением.*
- *Точечные частицы: точно знаем начальные состояния частиц и их квантовые числа*
- *Точная машина*
- *Большой потенциал открытия, но ограничено энергетически*

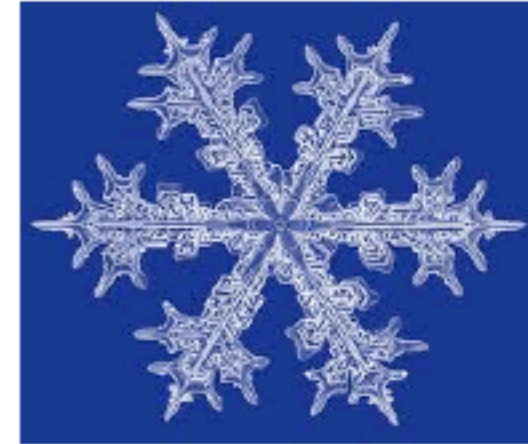
Extensive Air Showers

Flux ($\text{m}^2 \text{sr s GeV}^{-1}$)



Симметрии как возможность поиска частиц

Symmetries



Emmy
Noether



Symmetries imply
conservation laws!

Conserved quantities



Electric Charge

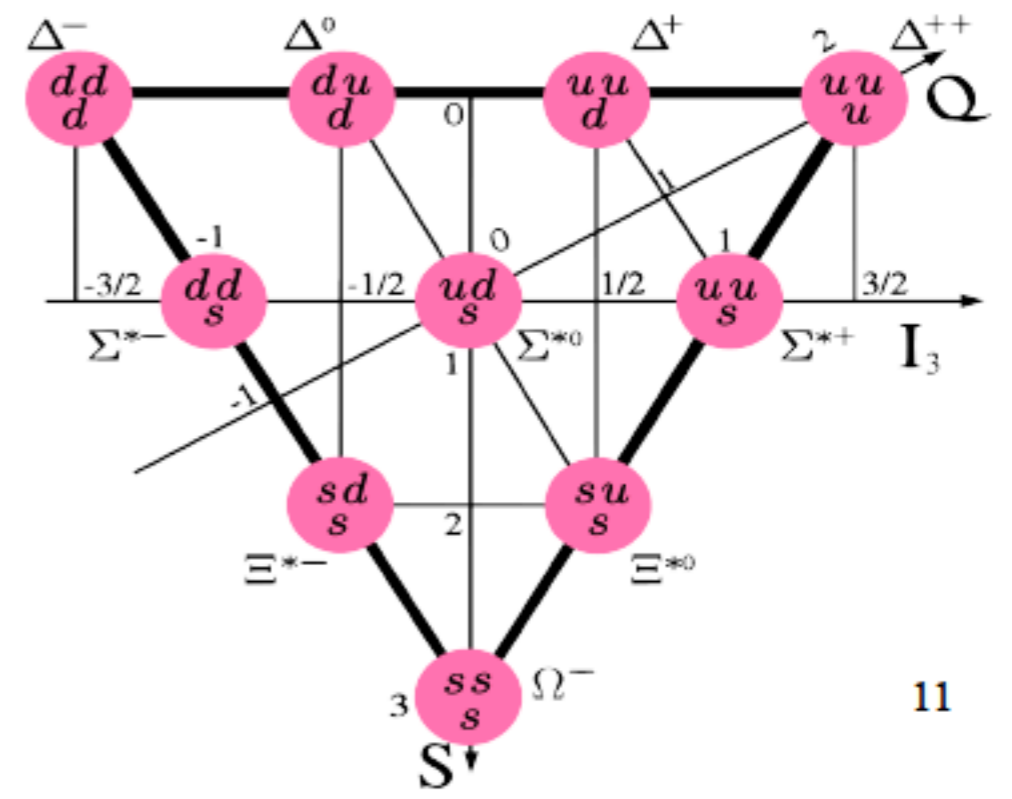
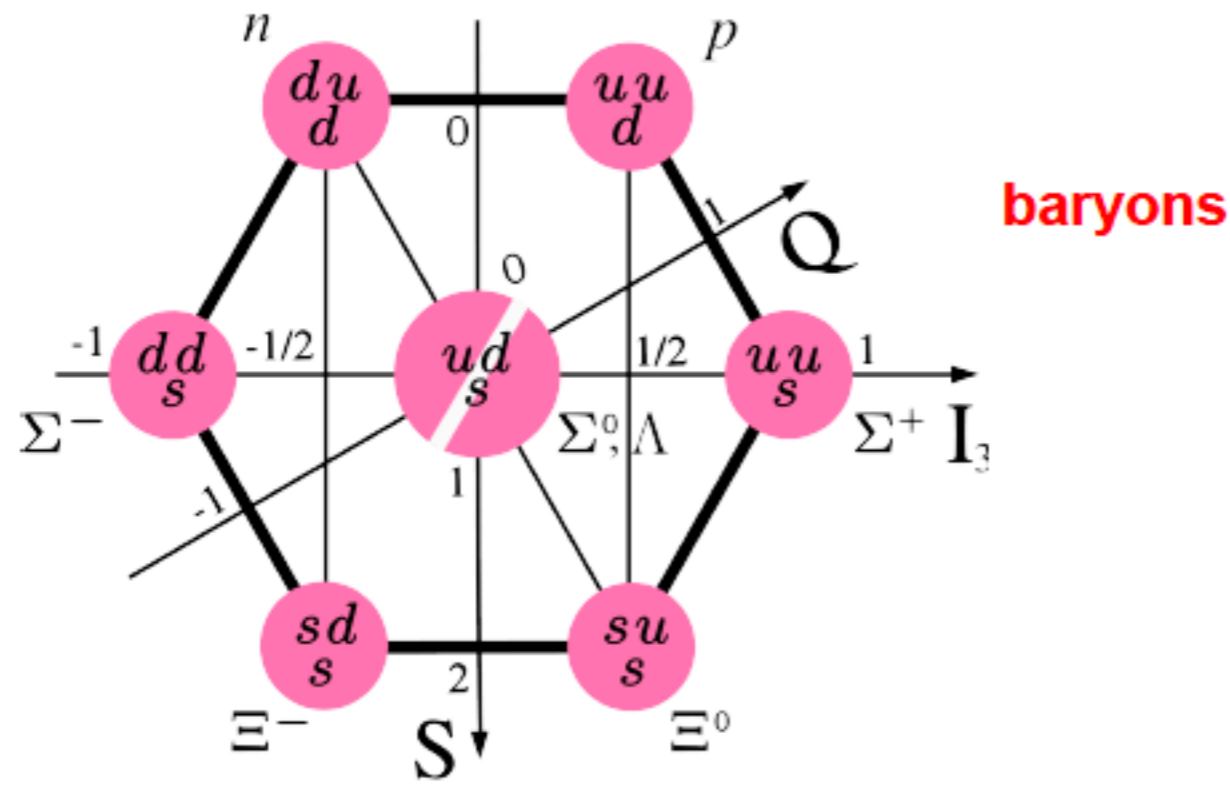
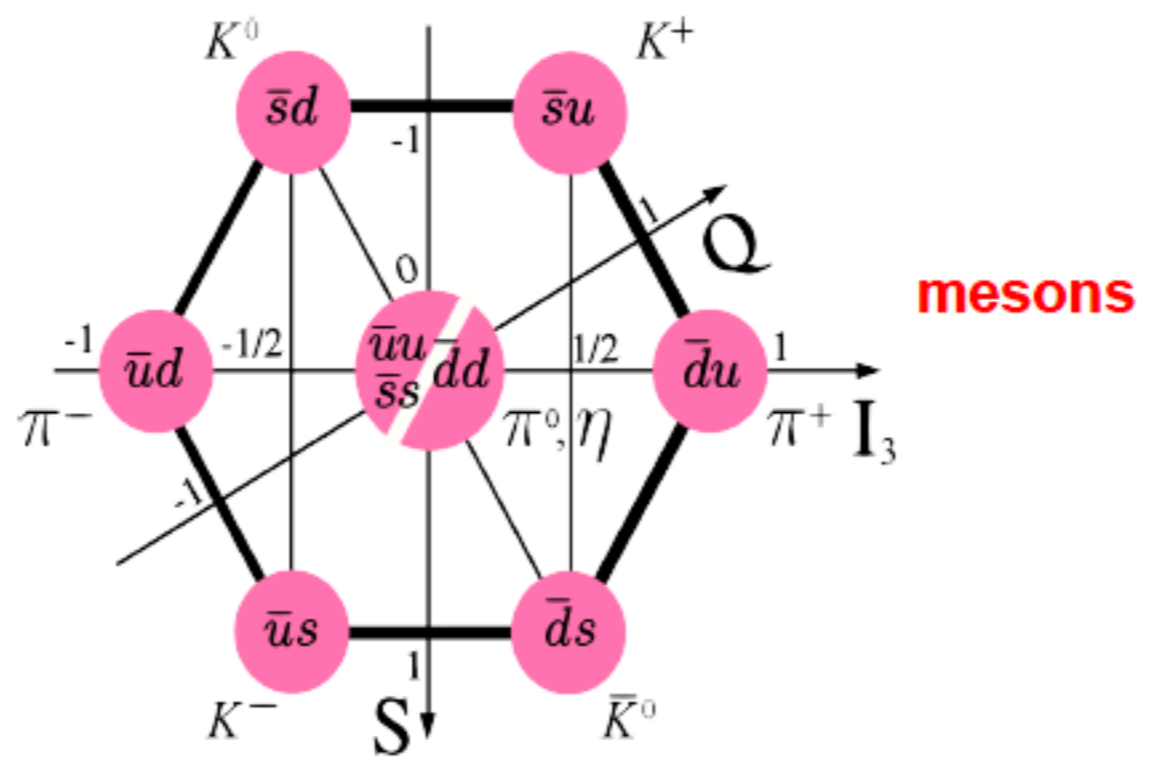


Rules for interactions

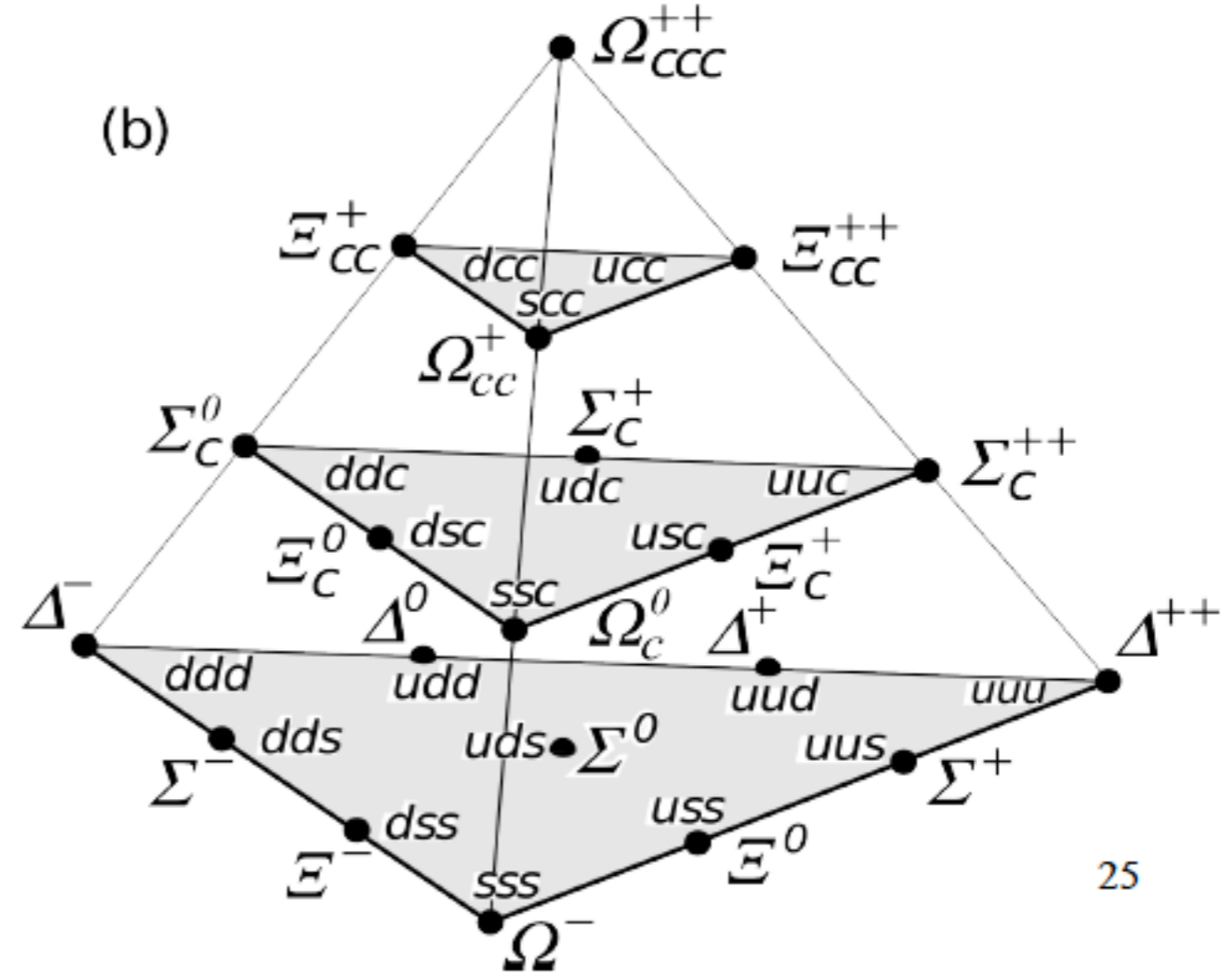
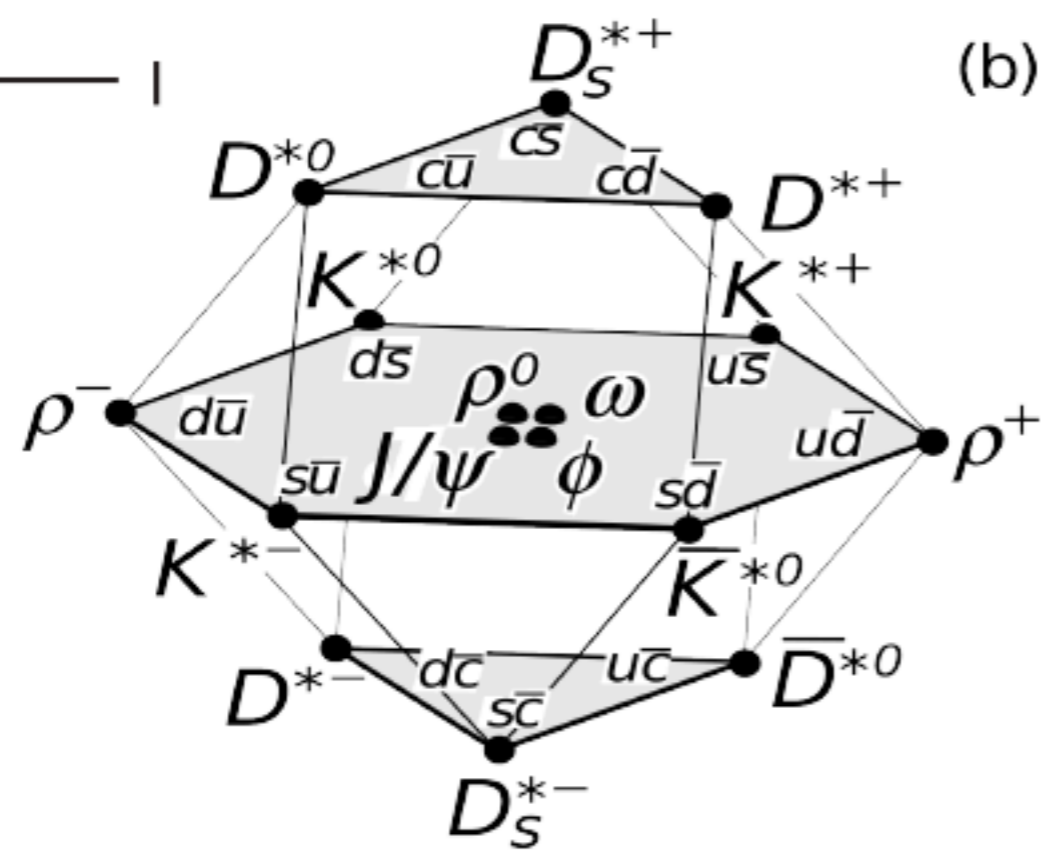
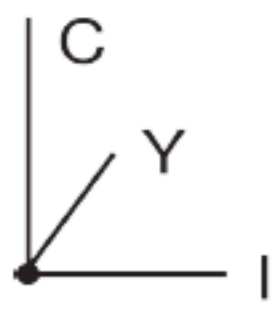
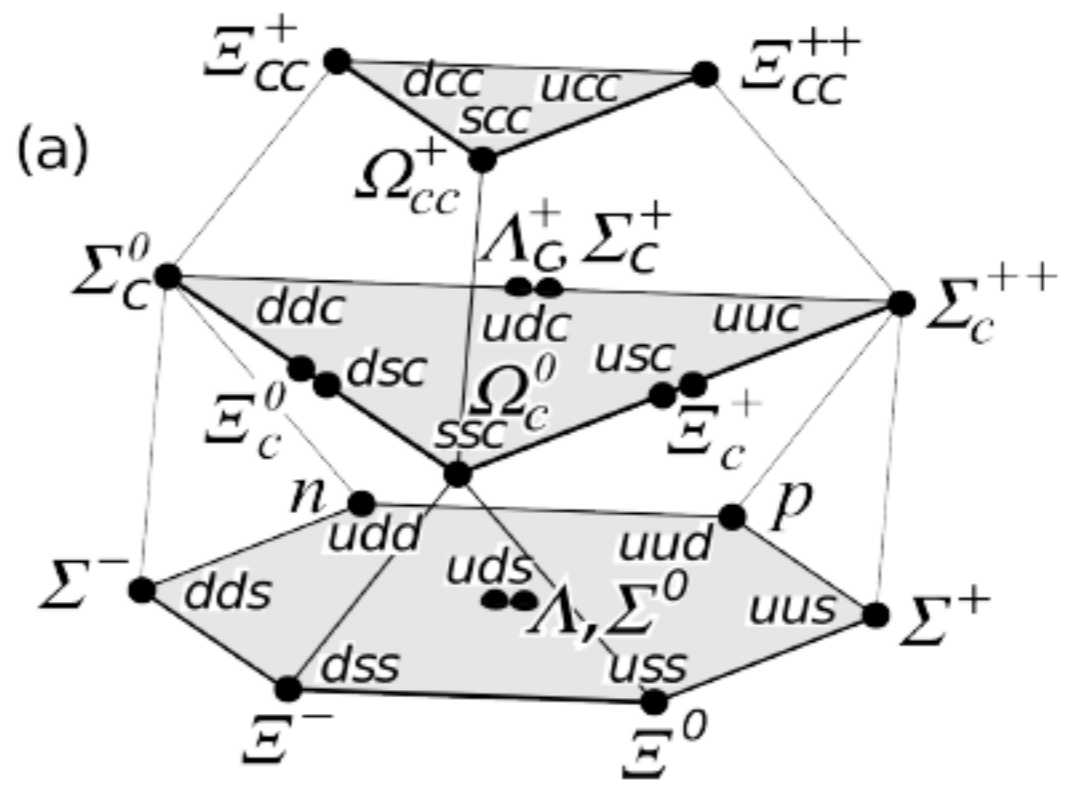
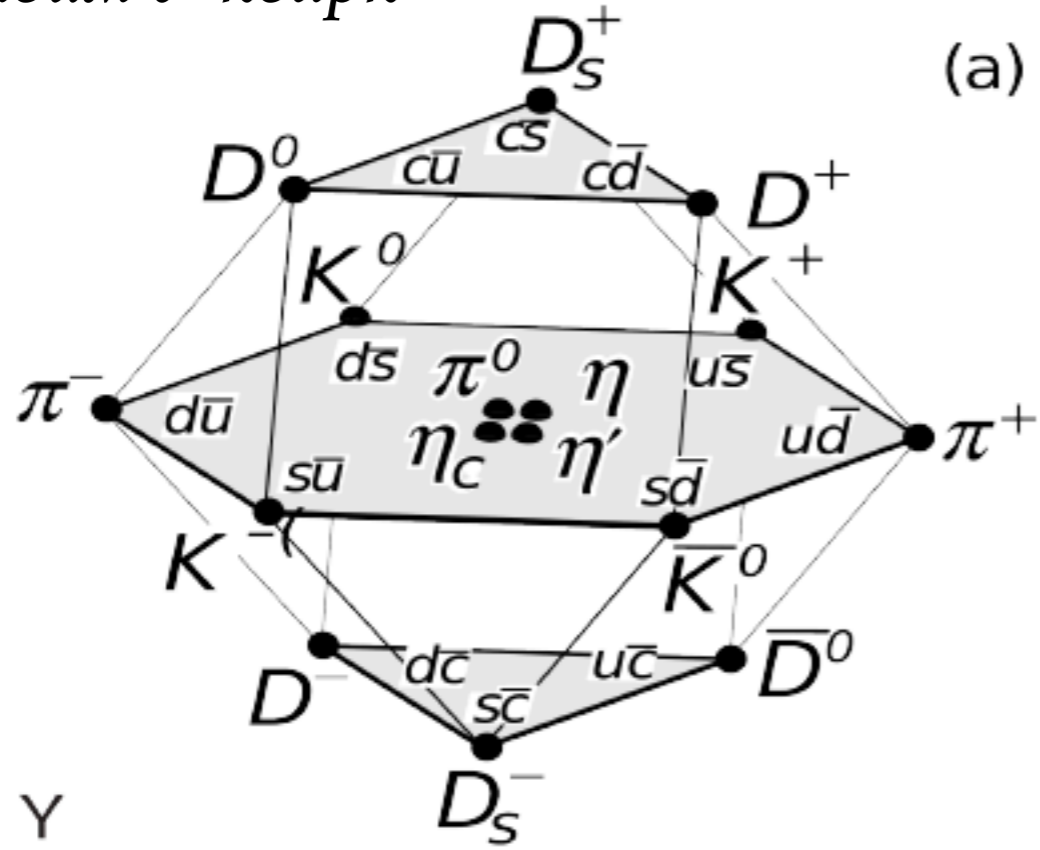


Gauge symmetry

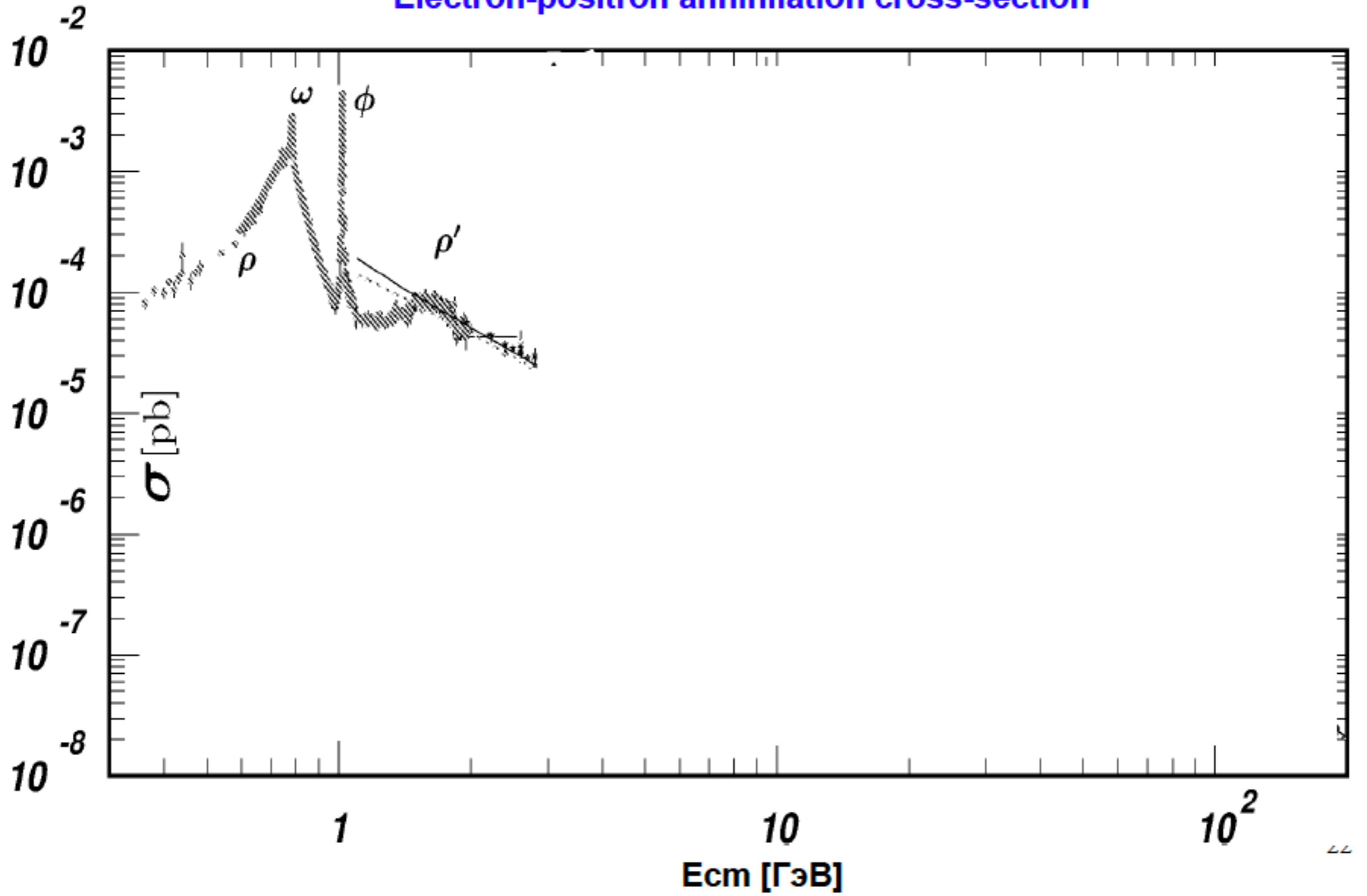
Симметрии в мезонах и барионах (u,d,s)



Добавим c -кварк



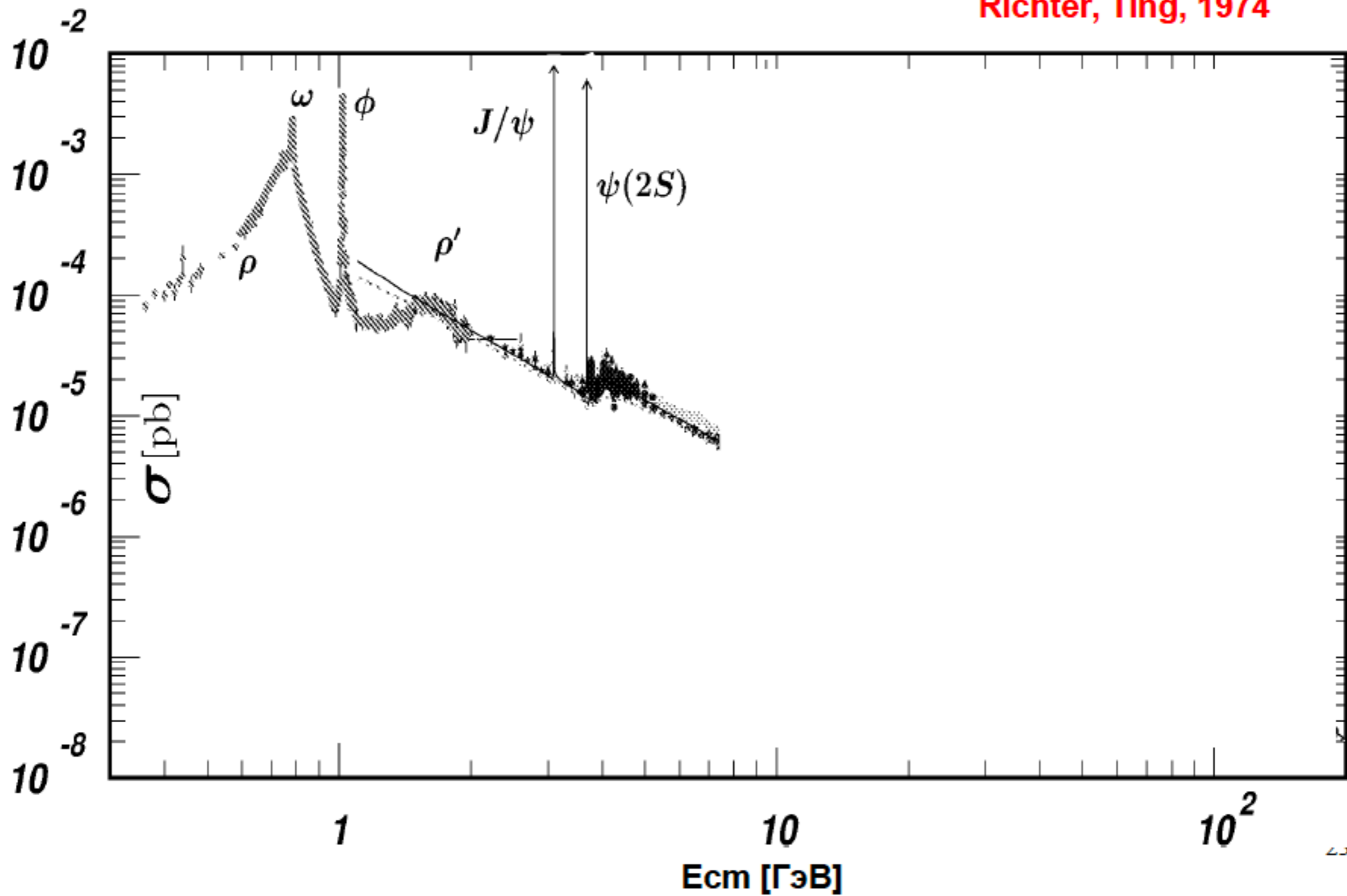
Electron-positron annihilation cross-section



1974

Electron-positron annihilation cross-section

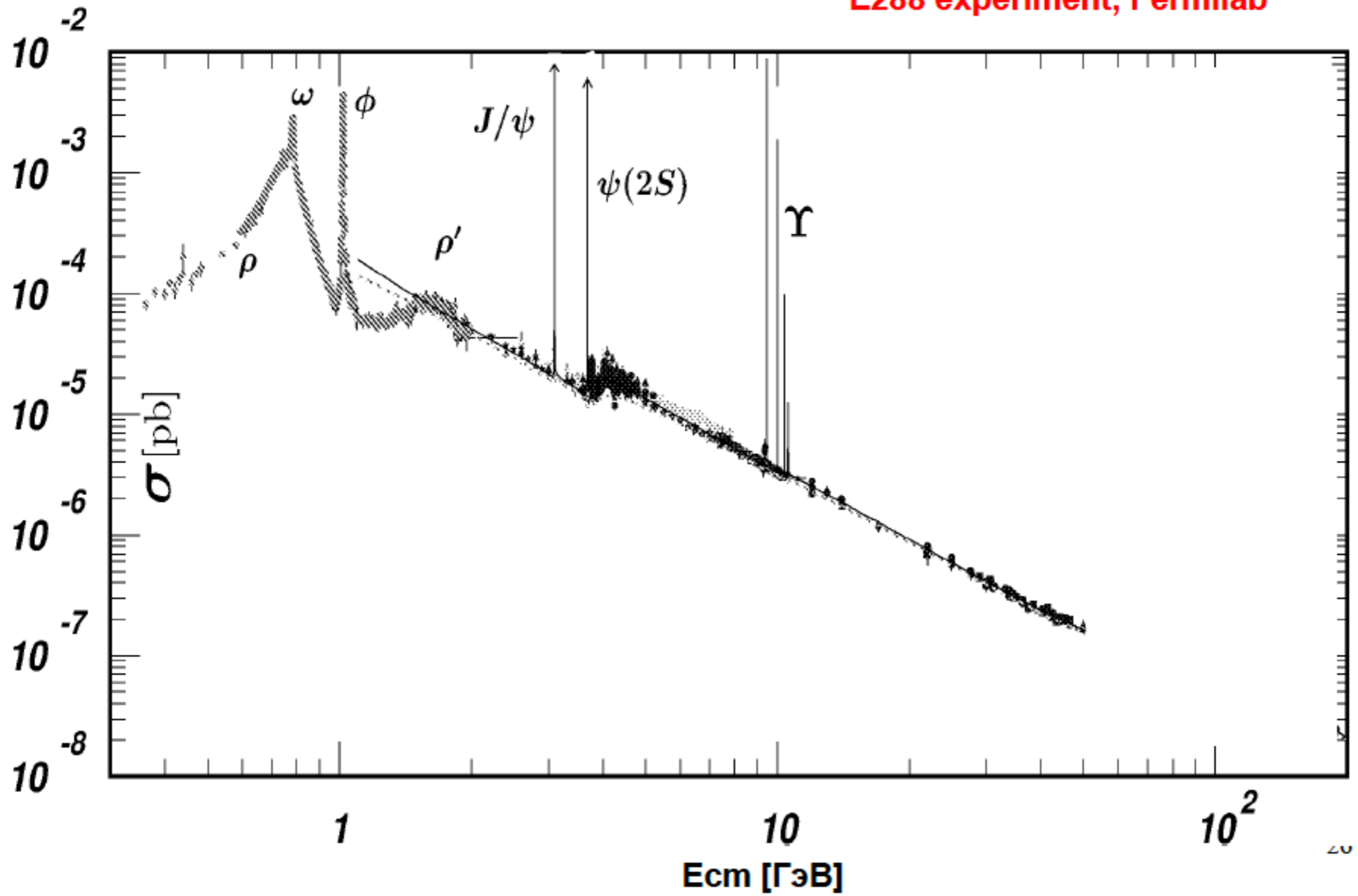
Richter, Ting, 1974



1974

Electron-positron annihilation cross-section

E288 experiment, Fermilab



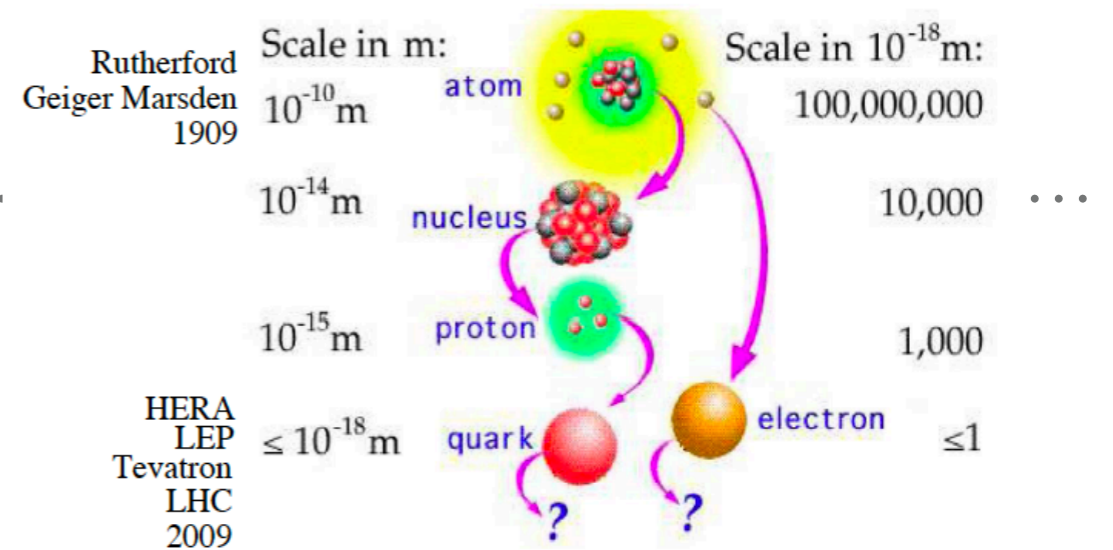
1977

ЧТО МЫ ИЗУЧАЕМ?

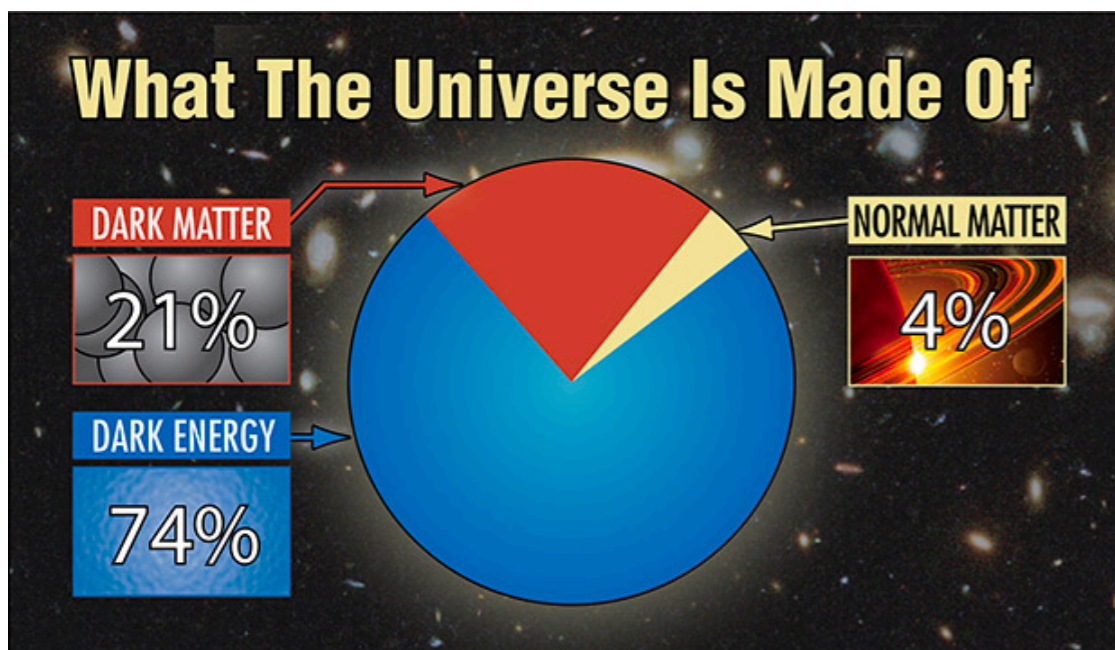
Модели:

Standard Model,

EFT (ChPT, NRQCD) and etc.



Темная материя

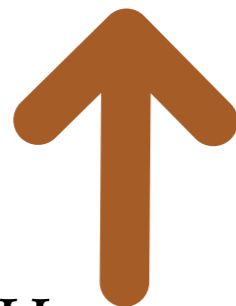


НАРУШЕНИЯ СИММЕТРИЙ:

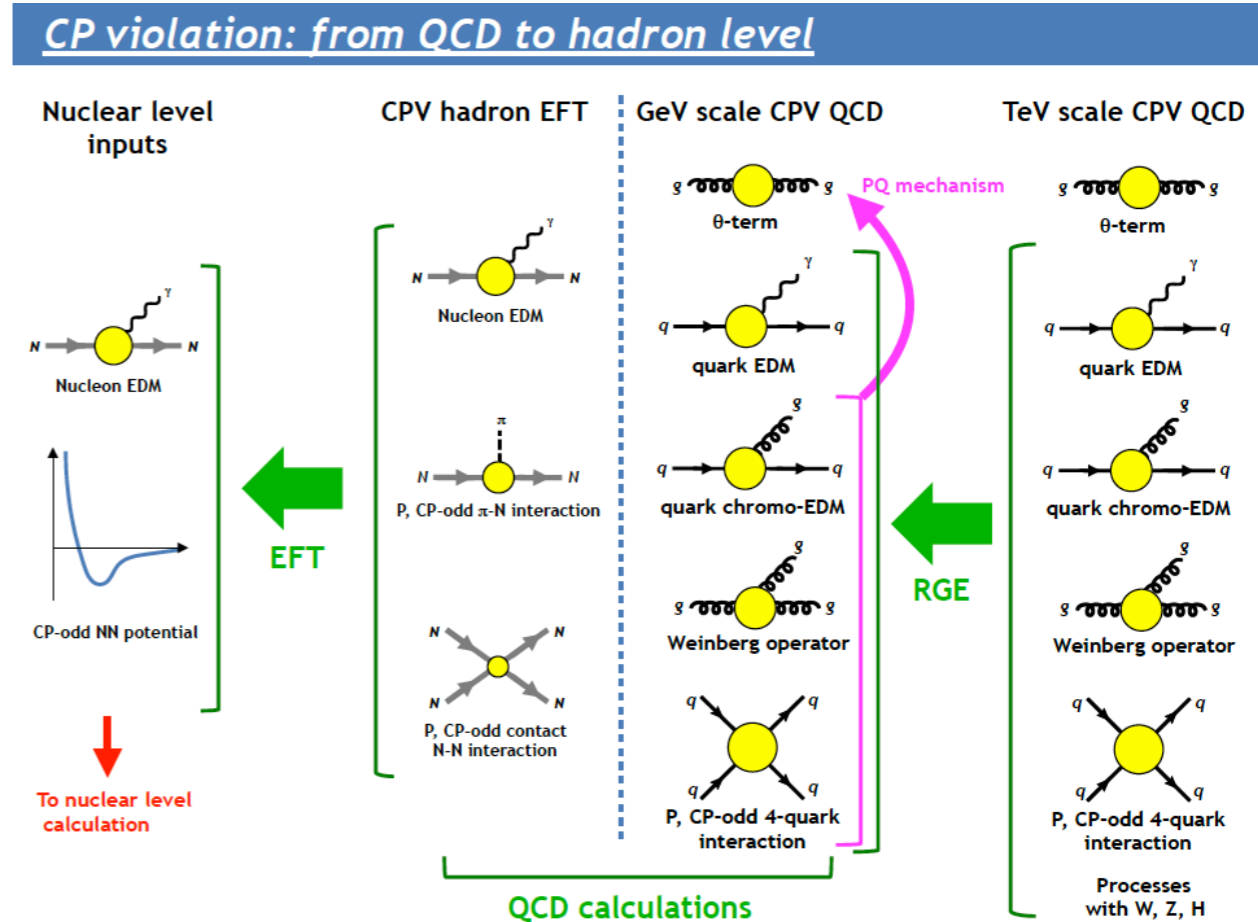
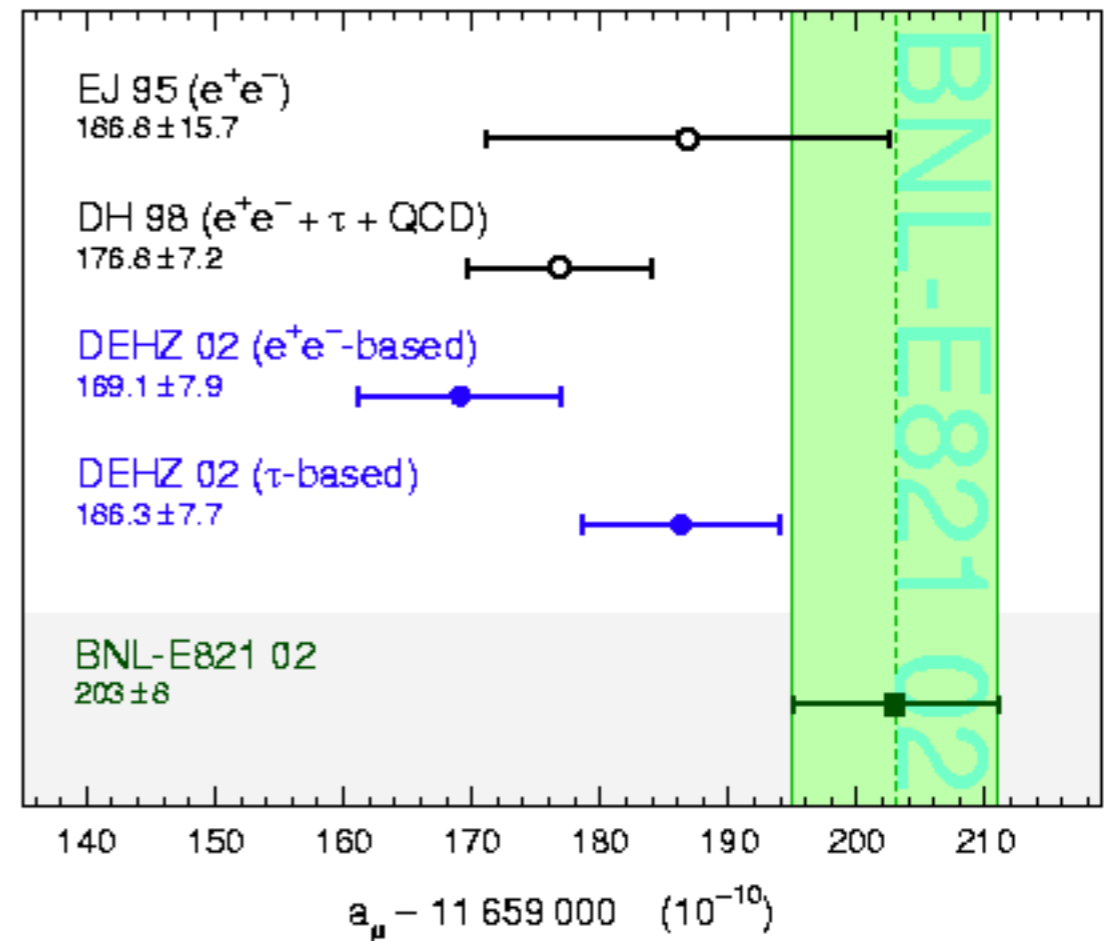
Поиск нарушения симметрий: C , P , T , CP , CPT , $Lorenz$, нарушение лептонного заряда, барионного числа



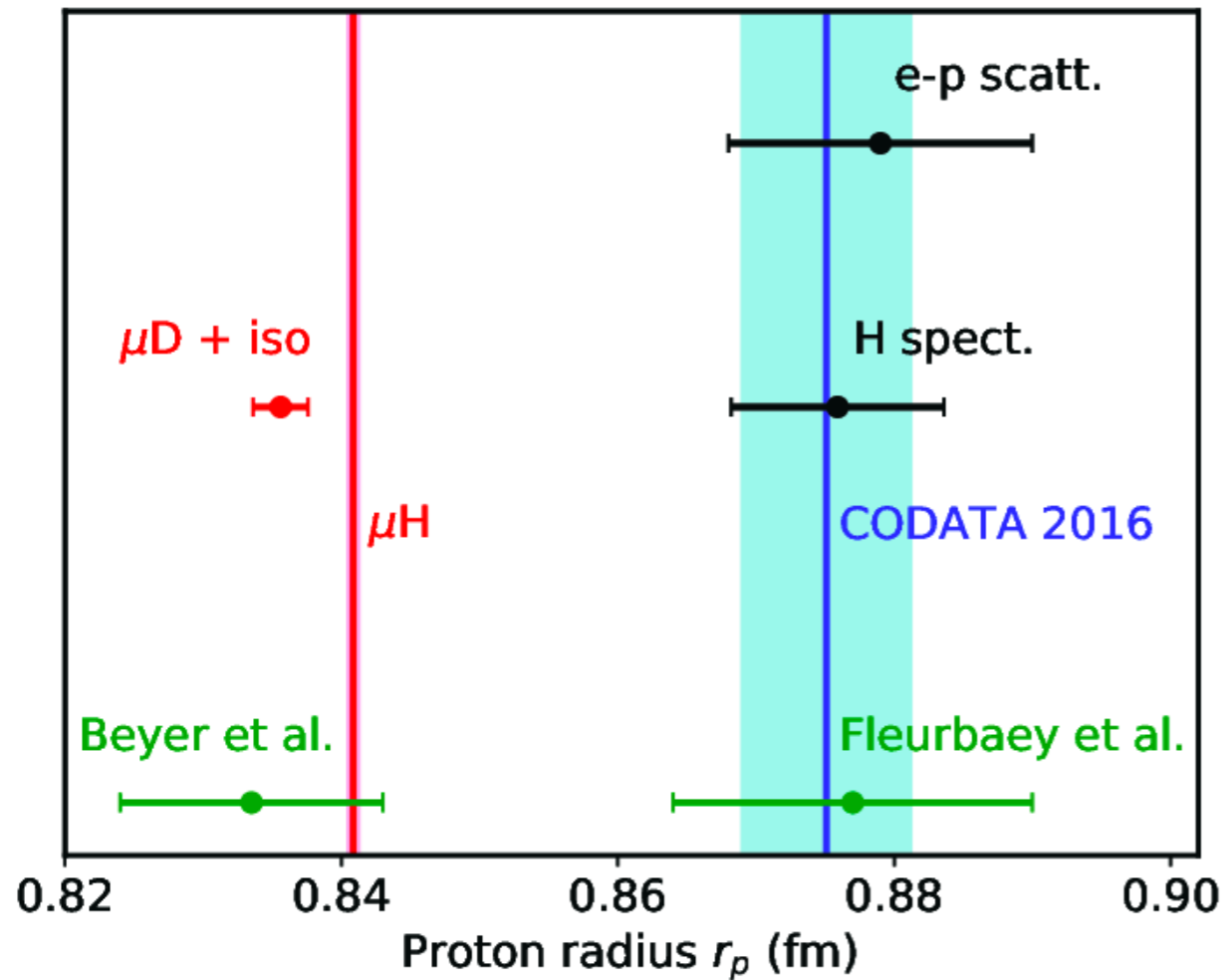
Поиск новой физики, путем отклонения от Стандартной модели



Построение Новых теорий для частиц темной материи с учетом взаимодействия

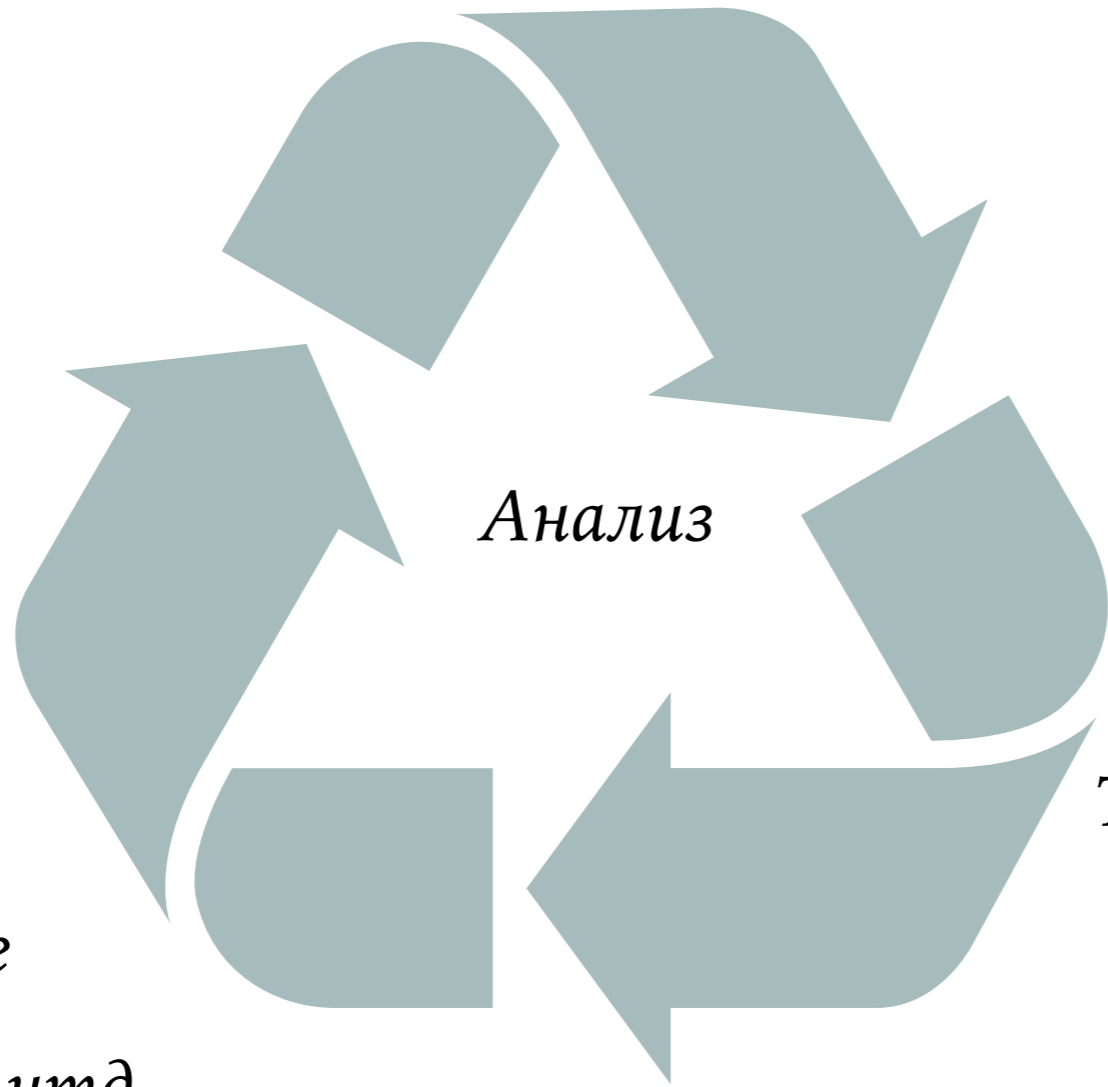


ПРОТОН РАДИУС PUZZLE



Все такие отличия дают сигнал для поиска и обоснования наличия новой физики участвующей и дающей вклад в наблюдаемую величину.

*Экспериментальное
Измерение*

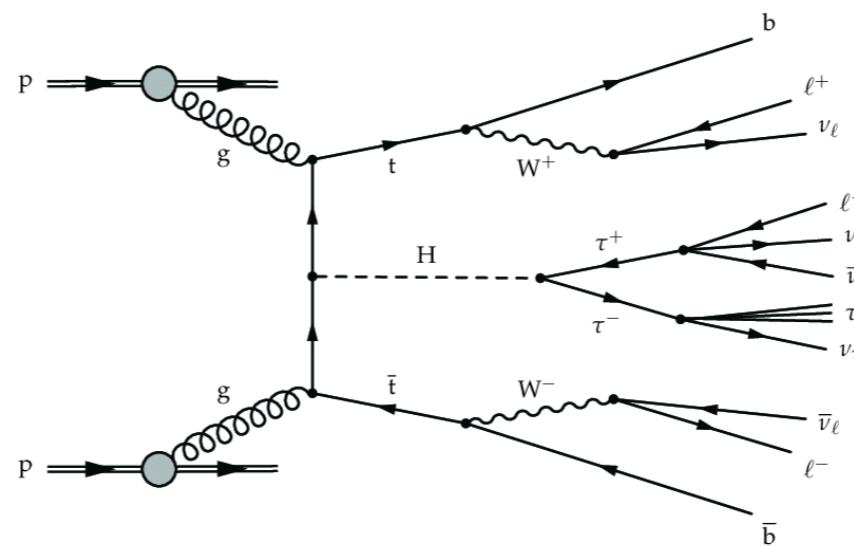
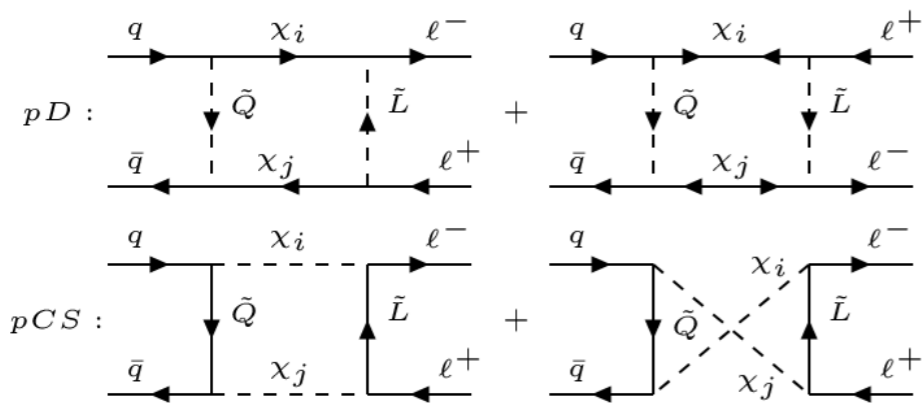
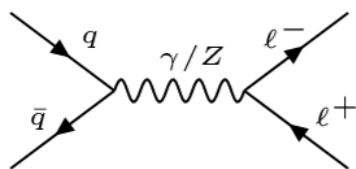
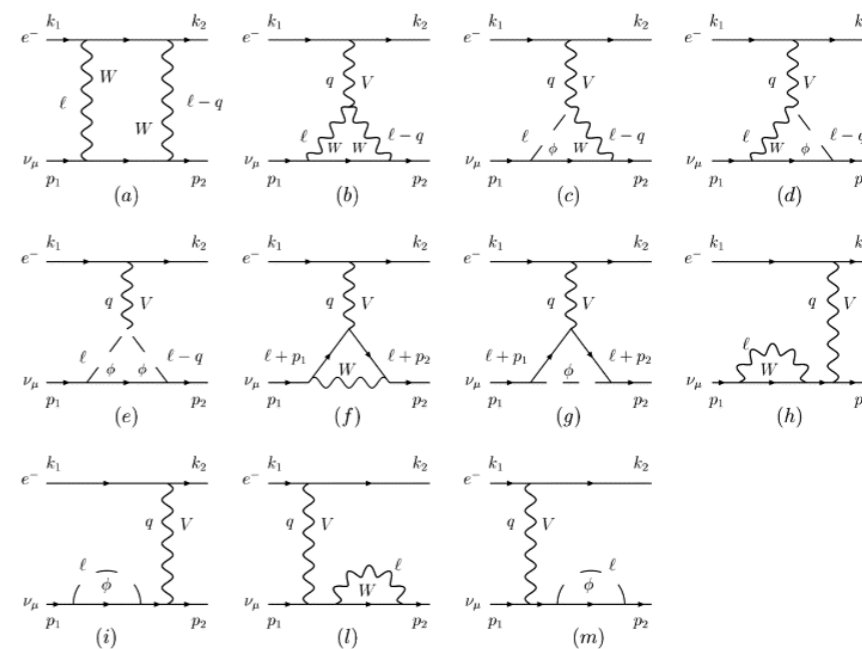
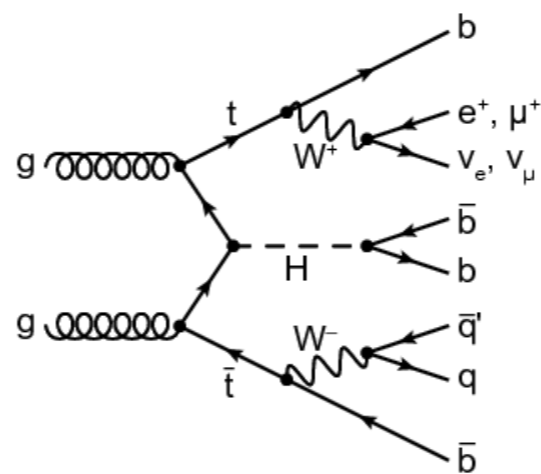
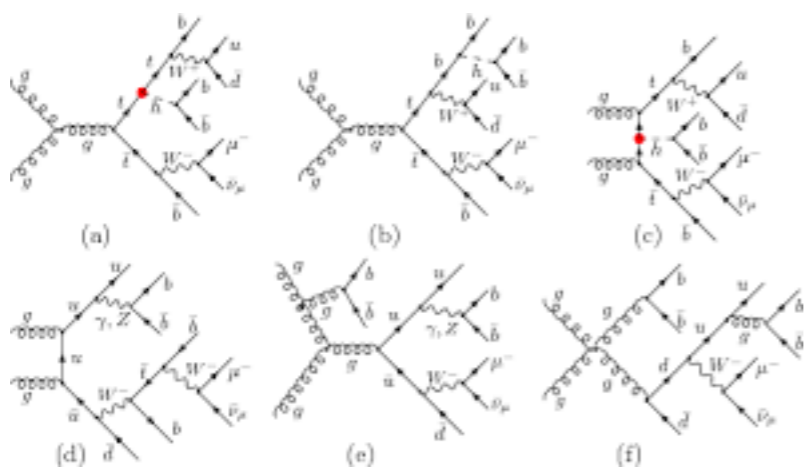


Анализ

Теория

*Моделирование
(Gaent4, Root) итд.*

Как считают это в теории?



Free real scalar field

Lagrangian

$$L = \frac{1}{2} (\partial_\mu \varphi) (\partial^\mu \varphi) - \frac{m^2}{2} \varphi^2$$

Free real scalar field

Lagrangian

$$L = \frac{1}{2} (\partial_\mu \varphi) (\partial^\mu \varphi) - \frac{m^2}{2} \varphi^2$$

Functional integral $m^2 \rightarrow m^2 - i0$

$$\langle T \{ \varphi(x_1) \varphi(x_2) \} \rangle = \frac{\int e^{iS(\varphi)} \varphi(x_1) \varphi(x_2) D\varphi}{\int e^{iS(\varphi)} D\varphi}$$

$$S(\varphi) = \int L d^4x \quad D\varphi = \prod_x d\varphi(x)$$

Free real scalar field

Lagrangian

$$L = \frac{1}{2} (\partial_\mu \varphi) (\partial^\mu \varphi) - \frac{m^2}{2} \varphi^2$$

Functional integral $m^2 \rightarrow m^2 - i0$

$$\langle T\{\varphi(x_1)\varphi(x_2)\} \rangle = \frac{\int e^{iS(\varphi)} \varphi(x_1)\varphi(x_2) D\varphi}{\int e^{iS(\varphi)} D\varphi}$$

$$S(\varphi) = \int L d^4x \quad D\varphi = \prod_x d\varphi(x)$$

Generating functional

$$\langle T\{\varphi(x_1)\varphi(x_2)\} \rangle = \left[\frac{1}{Z(J)} \frac{1}{i} \frac{\delta}{\delta J(x_1)} \frac{1}{i} \frac{\delta}{\delta J(x_2)} Z(J) \right]_{J=0}$$

$$Z(J) = \int e^{iS(\varphi, J)} D\varphi(x) \quad S(\varphi, J) = \int (L + J\varphi) d^4x$$

Quadratic form

$$L = \frac{1}{2} \varphi \hat{M} \varphi \quad \hat{M}(\partial) = -\partial^2 - m^2$$

Minimum of $S(\varphi, J)$

$$\hat{M} \varphi_0 + J = 0 \quad \varphi_0 = -\hat{G} J \quad \hat{G} = \hat{M}^{-1}$$

$$\varphi_0(x) = - \int G(x-y) J(y) d^4 y \quad \hat{M} G(x-y) = \delta(x-y)$$

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Momentum space

$$G(p) = M^{-1}(-ip) = \frac{1}{p^2 - m^2 + i0}$$

$$G(x) = \int G(p) e^{-ipx} \frac{d^4 p}{(2\pi)^4}$$

Free propagator

$$\langle T\{\varphi(x_1)\varphi(x_2)\}\rangle = \begin{array}{c} \bullet \text{---} \bullet \\ x_1 \quad x_2 \end{array} = iG(x_1 - x_2)$$

Wick theorem

$$\begin{aligned} \langle T\{\varphi(x_1)\varphi(x_2)\varphi(x_3)\varphi(x_4)\}\rangle &= \langle T\{\varphi(x_1)\varphi(x_2)\}\rangle \langle T\{\varphi(x_3)\varphi(x_4)\}\rangle \\ &+ \langle T\{\varphi(x_1)\varphi(x_3)\}\rangle \langle T\{\varphi(x_2)\varphi(x_4)\}\rangle \\ &+ \langle T\{\varphi(x_1)\varphi(x_4)\}\rangle \langle T\{\varphi(x_2)\varphi(x_3)\}\rangle \end{aligned}$$

$$= \begin{array}{c} x_1 \quad x_2 \\ \bullet \text{---} \bullet \\ x_3 \quad x_4 \end{array} + \begin{array}{c} x_1 \\ \bullet \\ | \\ \bullet \\ x_3 \end{array} \begin{array}{c} x_2 \\ \bullet \\ | \\ \bullet \\ x_4 \end{array} + \begin{array}{c} x_1 \quad x_2 \\ \bullet \quad \bullet \\ \diagdown \quad \diagup \\ \bullet \quad \bullet \\ x_3 \quad x_4 \end{array}$$

Interaction

$$L = L_0 + L_1 \quad L_0 = \frac{1}{2} (\partial_\mu \varphi) (\partial^\mu \varphi) - \frac{m^2}{2} \varphi^2 \quad L_1 = -\frac{\lambda}{4!} \varphi^4$$

Symmetry $\varphi \rightarrow -\varphi$

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Perturbation theory

$$Z(J) = \int e^{iS_0(\varphi, J)} (1 + iS_1(\varphi) + \dots) D\varphi$$

Vacuum \rightarrow vacuum

$$\begin{aligned} \langle 0|0\rangle &= \langle 1\rangle_0 - \frac{i}{4!}\lambda \int \langle \varphi^4(x)\rangle_0 d^4x + \dots \\ &= 1 - \frac{i}{4!}\lambda \text{ (diagram with two bubbles)} + \dots \end{aligned}$$

Vacuum energy density \rightarrow phase

Propagator

$$\int e^{iS_0(\varphi)} (1 + iS_1(\varphi) + \dots) \varphi(x_1)\varphi(x_2) D\varphi =$$

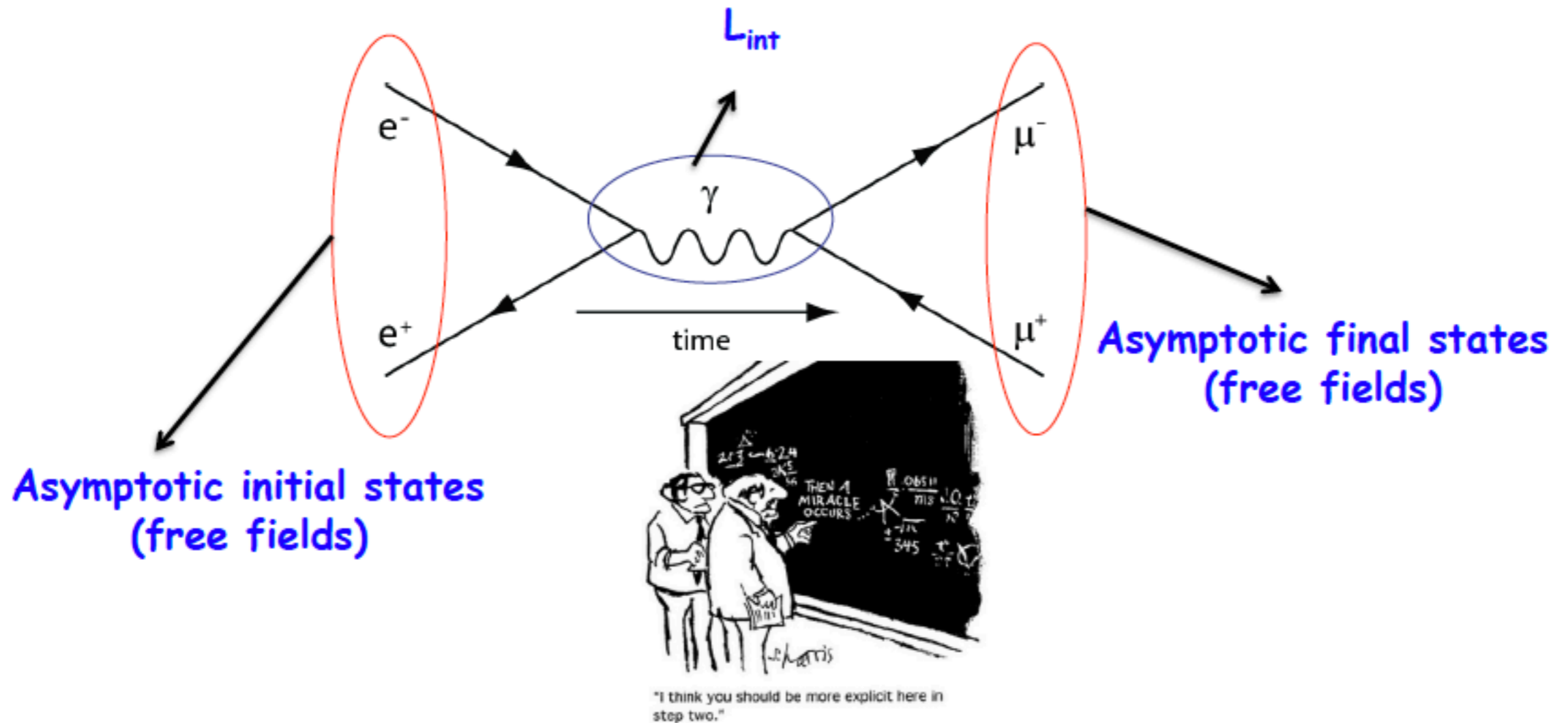
$$\text{(diagram with two external points)} - \frac{i}{4!}\lambda \text{(diagram with bubble)} - \frac{i}{4!}\lambda \text{(diagram with two bubbles)} + \dots$$

Diagrams with vacuum bubbles cancel

Feynman rules

$$\begin{array}{l} \text{---} \xrightarrow{p} \text{---} = iG_0(p) \\ \times = -i\lambda \end{array} \quad G_0(p) = \frac{1}{p^2 - m^2 + i0}$$

Beware of symmetry factors!



Электрон и позитрон сталкиваются, обмениваются виртуальным фотоном и создают пару мюон и анти-мюон.

Стрелка времени говорит нам, что диаграмма должна читаться слева направо. Однако есть диаграммы, где стрелка времени идет снизу вверх.

Начальное и конечное состояния являются свободными состояниями, подчиняющимися уравнению Дирака.

The matrix elements for a scattering or decay process are written in terms of an invariant amplitude $-i\mathcal{M}$. As an example, the S -matrix for $2 \rightarrow 2$ scattering is related to \mathcal{M} by

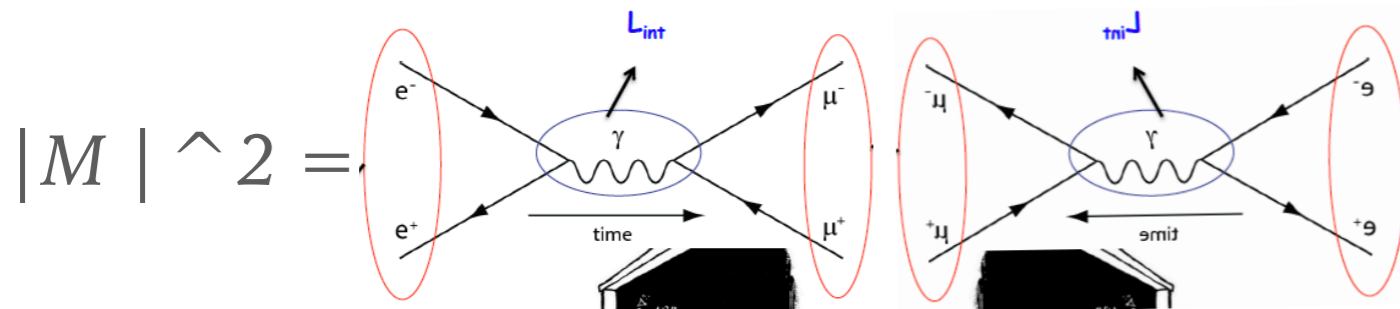
$$\langle p'_1 p'_2 | S | p_1 p_2 \rangle = I - i(2\pi)^4 \delta^4(p_1 + p_2 - p'_1 - p'_2) \times \frac{\mathcal{M}(p_1, p_2; p'_1, p'_2)}{(2E_1)^{1/2} (2E_2)^{1/2} (2E'_1)^{1/2} (2E'_2)^{1/2}} . \quad (47.8)$$

The state normalization is such that

$$\langle p' | p \rangle = (2\pi)^3 \delta^3(p - p') . \quad (47.9)$$

For a $2 \rightarrow 2$ scattering process producing unstable particles $1'$ and $2'$ decaying via $1' \rightarrow 3'4'$ and $2' \rightarrow 5'6'$ the matrix element for the complete process can be written in the narrow width approximation as:

$$\mathcal{M}(12 \rightarrow 3'4'5'6') = \sum_{h_{1'}, h_{2'}} \frac{\mathcal{M}(12 \rightarrow 1'2') \mathcal{M}(1' \rightarrow 3'4') \mathcal{M}(2' \rightarrow 5'6')}{(m_{3'4'}^2 - m_{1'}^2 + im_{1'}\Gamma_{1'}) (m_{5'6'}^2 - m_{2'}^2 + im_{2'}\Gamma_{2'})} . \quad (47.10)$$



$$d\sigma = \frac{(2\pi)^4 |\mathcal{M}|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}} \times d\Phi_n(p_1 + p_2; p_3, \dots, p_{n+2}) .$$

The partial decay rate of a particle of mass M into n bodies in its rest frame is given in terms of the Lorentz-invariant matrix element \mathcal{M} by

$$d\Gamma = \frac{(2\pi)^4}{2M} |\mathcal{M}|^2 d\Phi_n (P; p_1, \dots, p_n), \quad (47.11)$$

where $d\Phi_n$ is an element of n -body phase space given by

$$d\Phi_n(P; p_1, \dots, p_n) = \delta^4 \left(P - \sum_{i=1}^n p_i \right) \prod_{i=1}^n \frac{d^3 p_i}{(2\pi)^3 2E_i}. \quad (47.12)$$

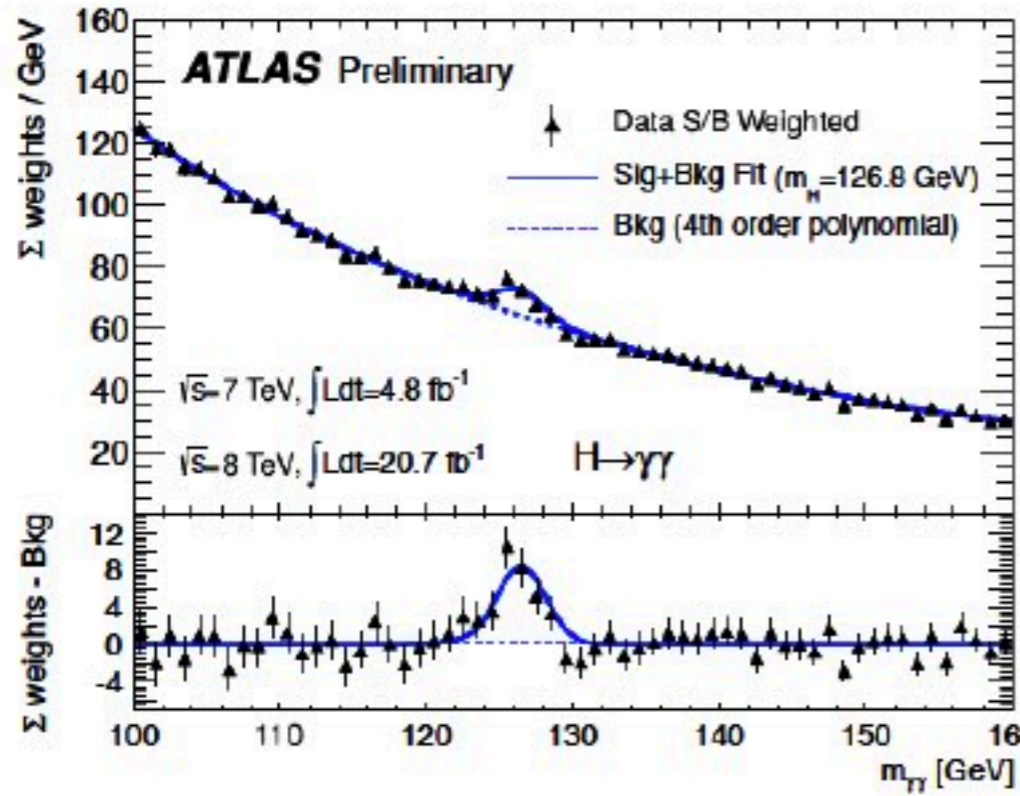
This phase space can be generated recursively, viz.

$$\begin{aligned} d\Phi_n(P; p_1, \dots, p_n) &= d\Phi_j(q; p_1, \dots, p_j) \\ &\times d\Phi_{n-j+1}(P; q, p_{j+1}, \dots, p_n) (2\pi)^3 dq^2, \end{aligned} \quad (47.13)$$

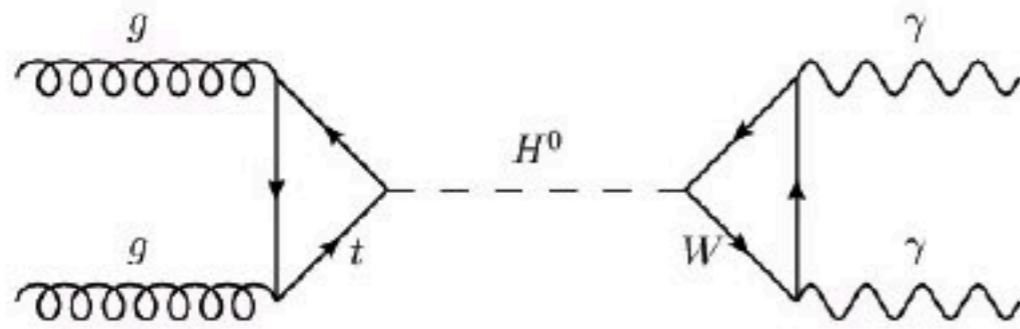
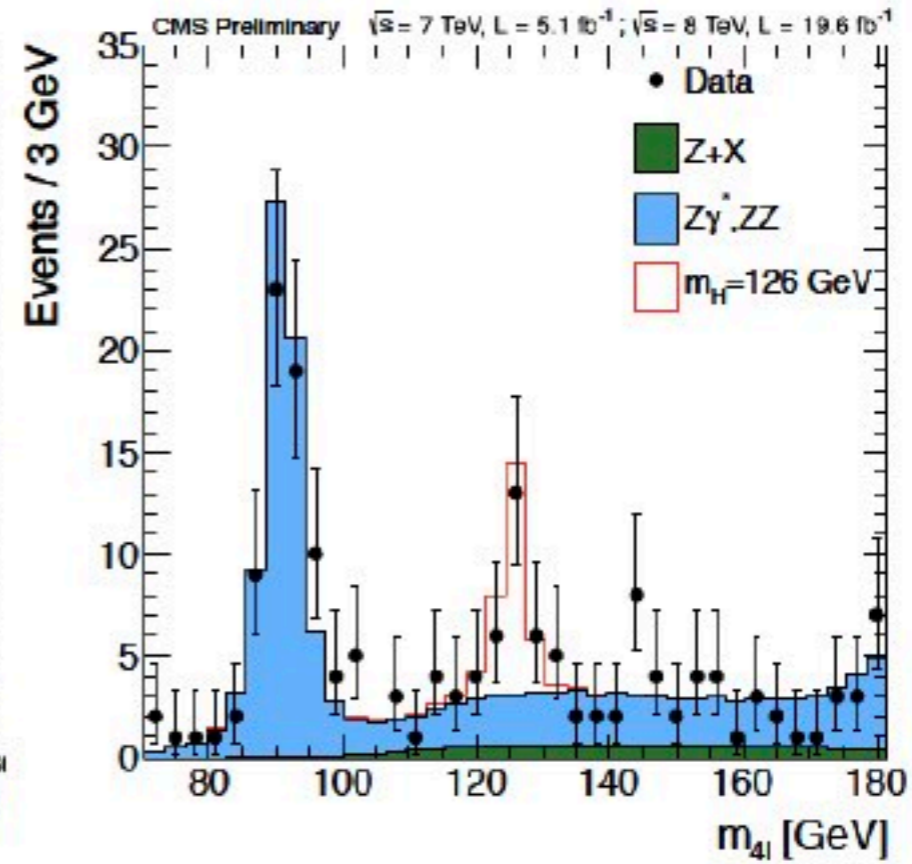
where $q^2 = (\sum_{i=1}^j E_i)^2 - \left| \sum_{i=1}^j \mathbf{p}_i \right|^2$. This form is particularly useful in the case where a particle decays into another particle that subsequently decays.

LHC Discovery of a New Scalar Particle

ATLAS-CONF-2013-12



CMS-PAS-HIG-13-002



Signal and background

a few

a lot

