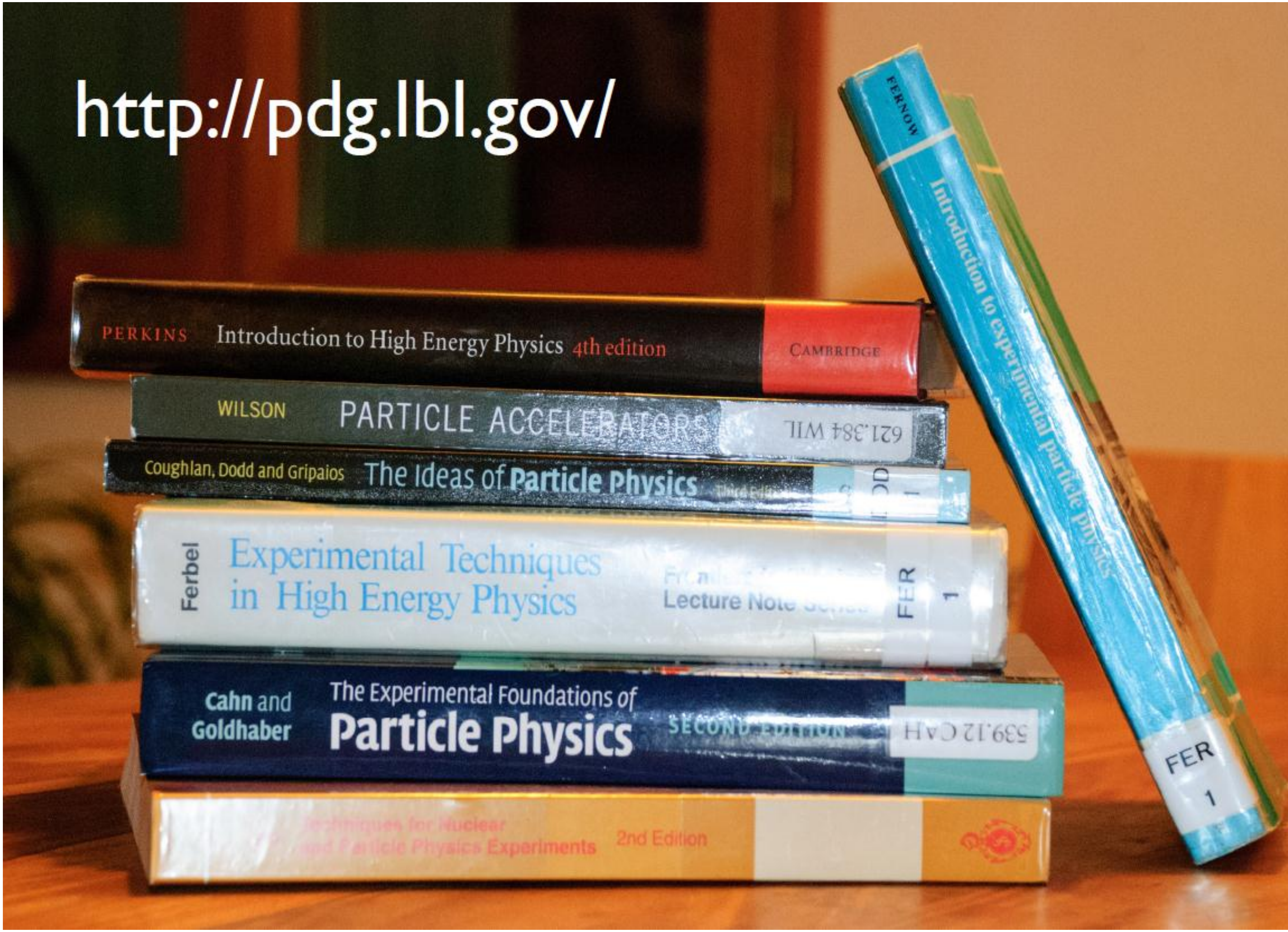
Introduction to particle physics: experimental part

Introduction

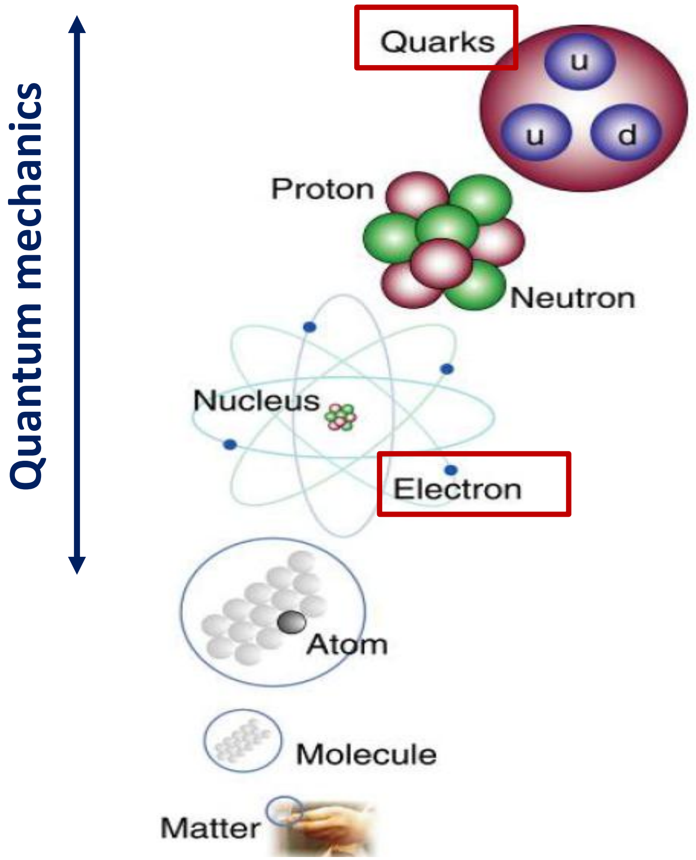
Units, kinematics

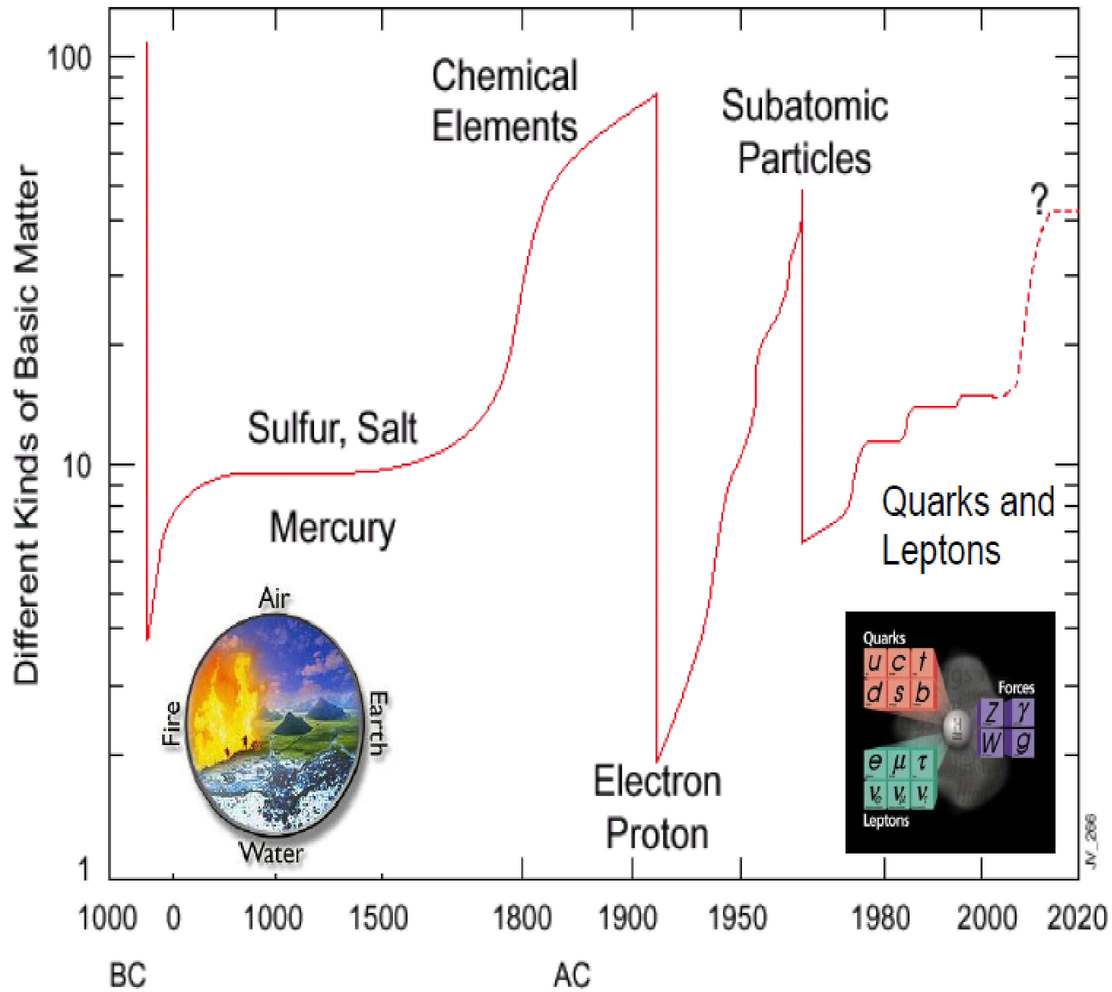
Large fraction of those slides from M. Delmastro lectures at ESIPAP school

Prof. dr hab. Elżbieta Richter-Wąs

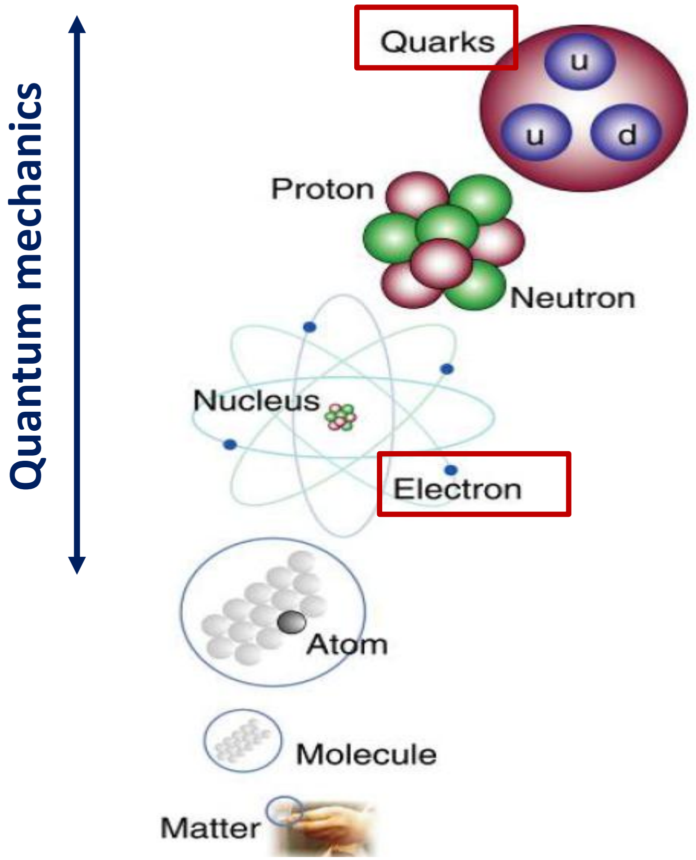

http://pdg.lbl.gov/
PERKINS
Introduction to High Energy Physics 4th edition
CAMBRIDGE
WILSON
PARTICLE ACCELERATORS
621.384 WIL
Coughlan, Dodd and Gripaios
The Ideas of Particle Physics
Ferbel
Experimental Techniques in High Energy Physics
FER 1
Cahn and Goldhaber
The Experimental Foundations of Particle Physics
SECOND EDITION
539.12 CAH
2nd Edition
FERNOW
Introduction to experimental particle physics
FER 1

Constituents of matter along History



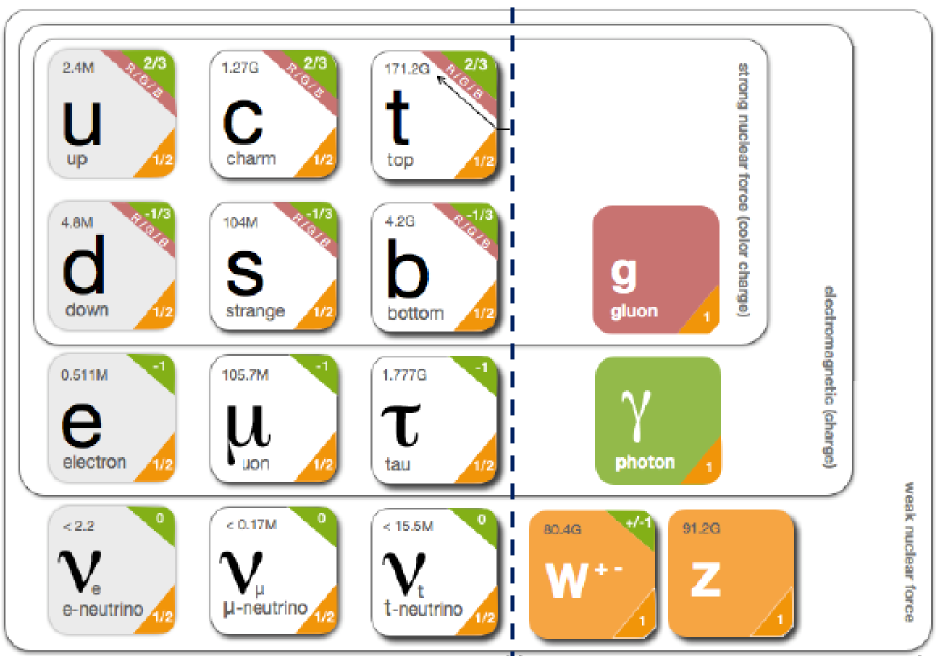


Particles of the Standard Model



Matter particles
(< 10 $^{-16}$ cm)

Interaction particles



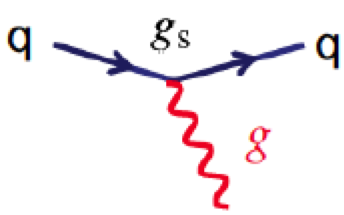
Higgs particle
Is not a matter particle
nor an interaction particle

$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 + \frac{g^2}{4}(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu)(\lambda^2 + 2\lambda H + H^2) + \sum_{l,q,q'}(\frac{m_l}{\lambda}\bar{l}l + \frac{m_q}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q}'q')H$$

Interactions

The interaction of gauge bosons with fermions is described by the Standard Model

STRONG



Only quarks

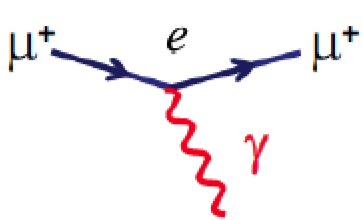
Never changes flavour

$\alpha_S \sim 1/5$

Gluons

massless

EM



All charged fermions

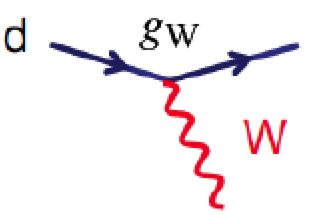
Never changes flavour

$\alpha \simeq 1/137$

Photon

massless

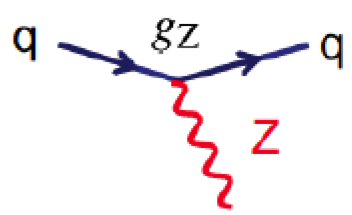
WEAK CC



All fermions

Always changes flavour

WEAK NC



All fermions

Never changes flavour

$\alpha_{W/Z} \sim 1/40$

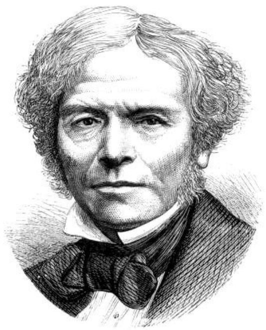
W+, W-

very massive

Z^0

very massive

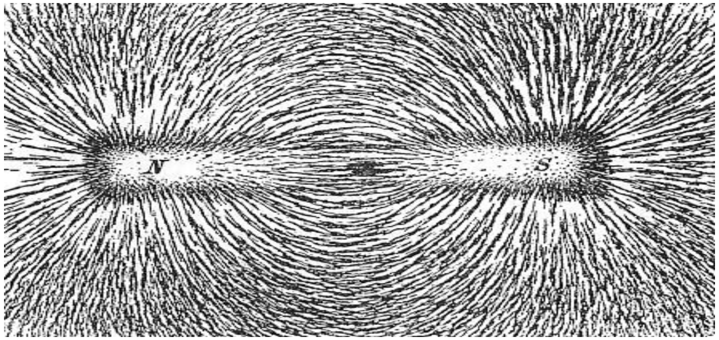
Vacuum → Concept of the field → Higgs mechanism



Michael Faraday (1845)

Introduced concept of field into description of magnetic interactions. Magnetic field has a source.

Force lines of the magnetic field



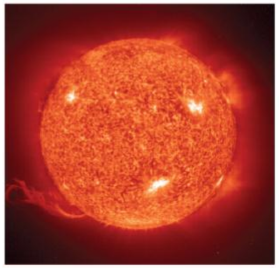
In classical understanding vacuum = „empty space”, or state of „energy = 0”.
In quantum mechanics vacuum is „full of life”. Just bubbling with creation and annihilation of matter particles. Symmetries dictate laws of interactions.
Stable state of vacuum does not necessarily has an energy = zero.

Higgs mechanism (1964):

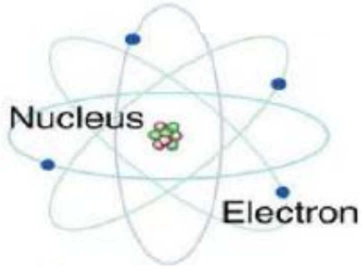
Quantum vacuum is not empty, is full of the „Higgs field”. This field has no structure nor sources. After „symmetry is spontaneously broken”, field is not „neutral” anymore and interaction of elementary particles with this field gives masses to the elementary particles . This mechanism predicted also the existence of a massive scalar particle, so called, „Higgs particle” which is the quantum fluctuation of the Higgs field.

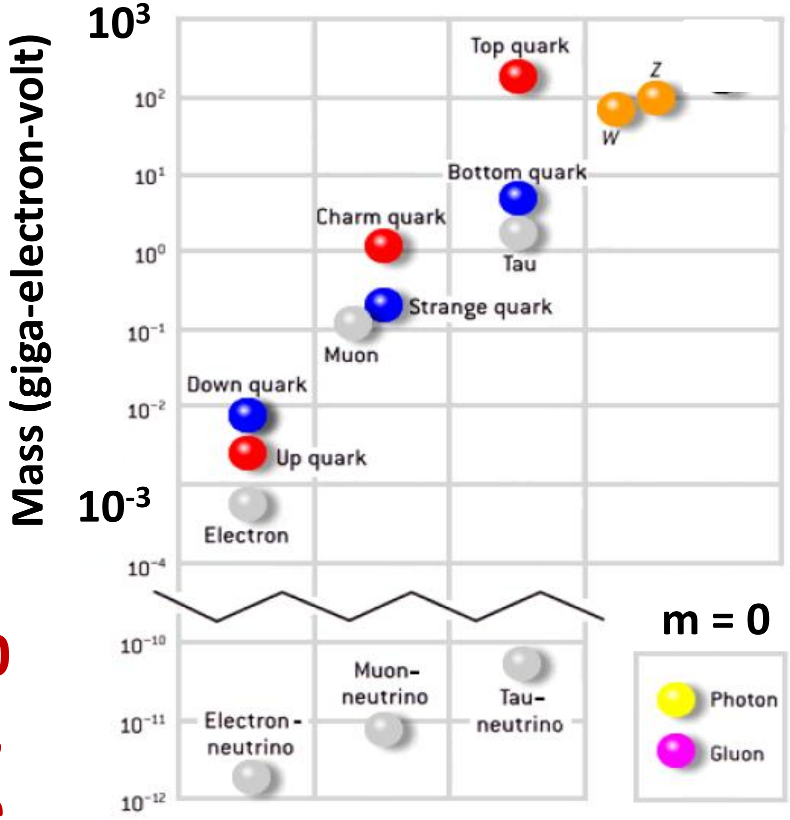
Mass Spectrum of Elementary Particles

If the mass of the W boson was smaller, time of combustion of the sun (nuclear fussion) would be shorter and at lower temperature.



Sun shield





Mass of the electrons is 25000 times smaller than mass of W, but if it was exactly zero there would be no atomic binding.

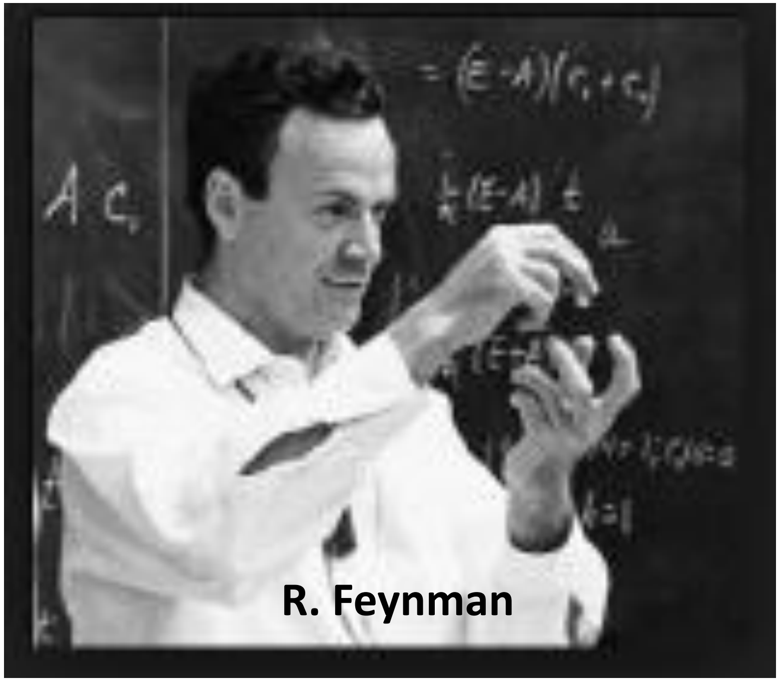
If the masses of elementary particles were different the Universe, as we know it, would not exist.

Theory has to be confirmed by experiment

„It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiments, it's wrong."

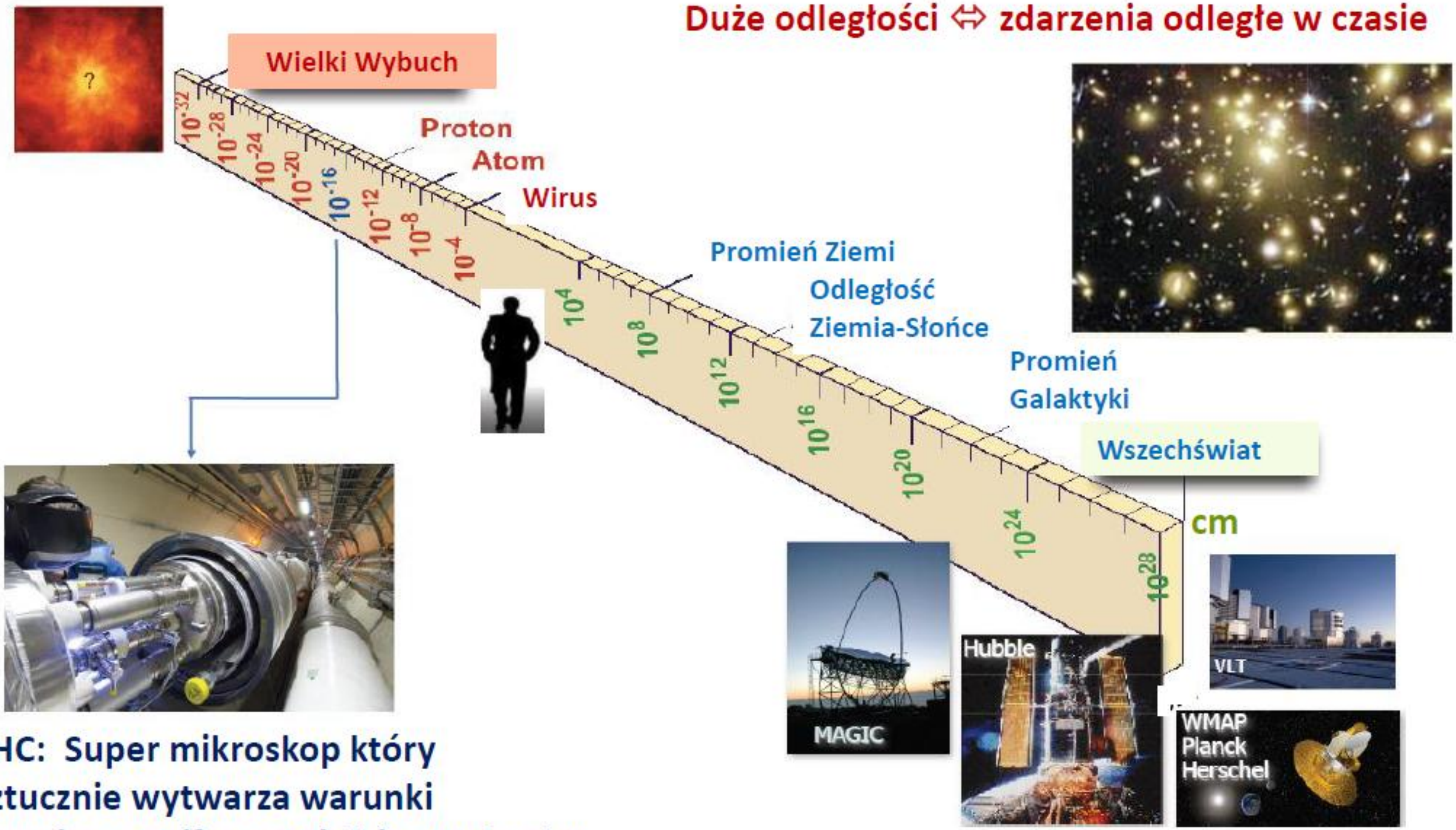
R. Feynman

(To nie ma znaczenia jak piękna jest twoja teoria, nie ma znaczenia jaki jesteś inteligentny. Jeżeli nie zgadza się z eksperymentem to ta teoria jest nieprawdziwa.)



How we are probing structure of matter and how structure of the Universe

Duże odległości ⇔ zdarzenia odległe w czasie



LHC: Super mikroskop który sztucznie wytwarza warunki panujące 10^{-12}s po Wielkim Wybuchu

Małe odległości ⇔ bardzo duże energie

Nobel Prizes in Elementary Particle Physics


Sin-Itiro Tomonaga


Julian Schwinger


Richard P. Feynman


Sheldon Lee Glashow


Abdus Salam


Steven Weinberg


Leon M. Lederman


Melvin Schwartz


Jack Steinberger


Carlo Rubbia


Simon van der Meer


Georges Charpak


Gerardus 't Hooft


Martinus J.G. Veltman


M. Gell-Mann

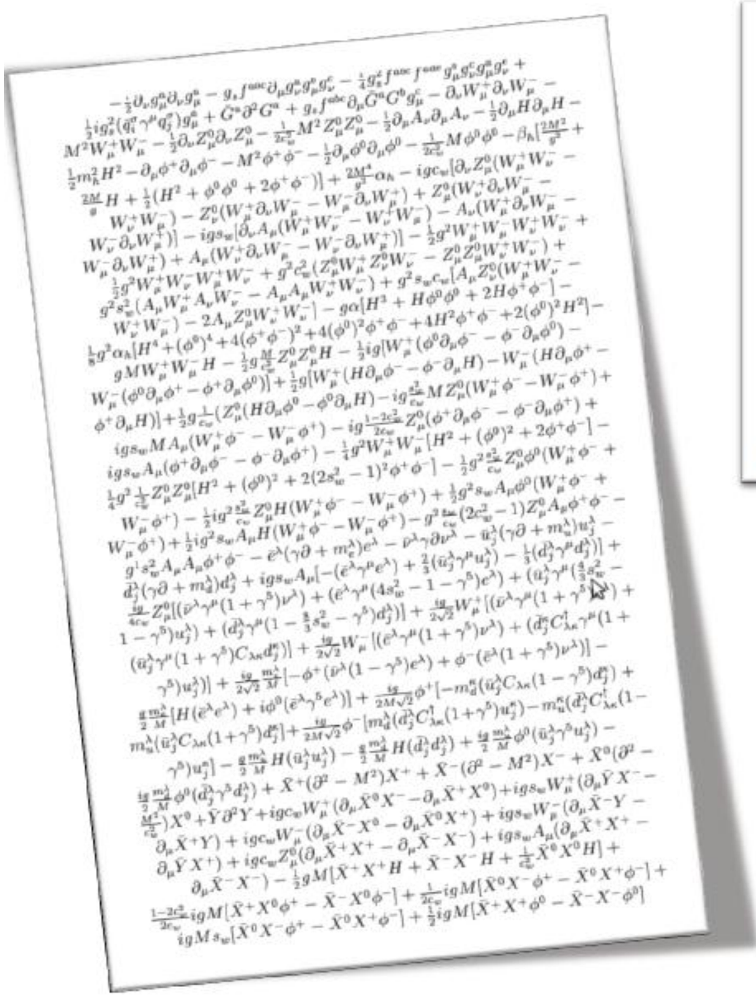
GREEN - theoretical
BLUE - experimental

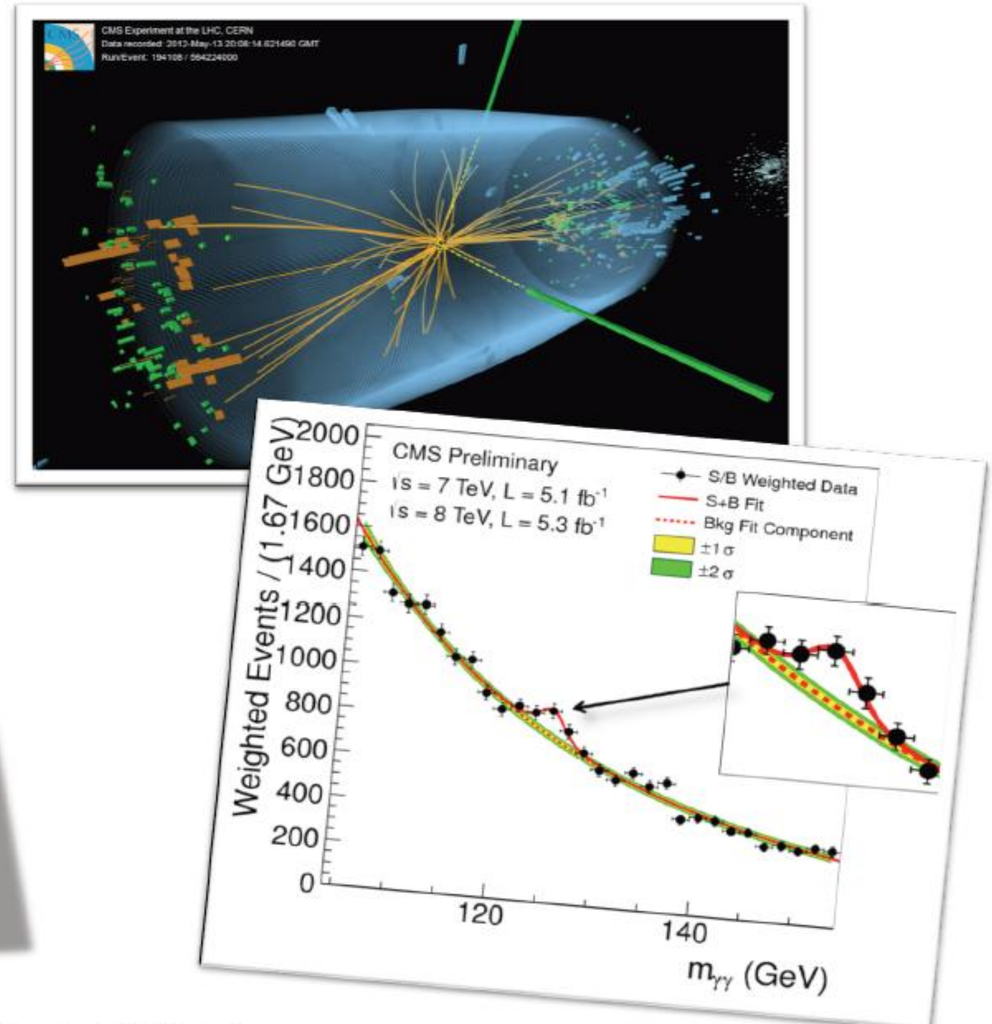
1964: „Higgs mechanism" was born

1957 – C. N. Yang, T. Lee
1965 – S. I. Tomonaga, J. Schwinger, R.P Feynman
1969 – M. Gell-Mann
1976 – B. Richter and S. Ting
1979 – S.L. Glashow, A. Salam, S. Weinberg
1980 – J. Cronin, V. Fitch
1984 – C. Rubbia, S. van der Meer
1988 – L. M. Lederman, M. Schwartz, J. Steinberger
1990 – J. Friedman, J. Kendall, R. Taylor
1992 - G. Charpak
1995 – M. Perl, F. Reines
1999 - G. tHooft, M. J. Veltman
2004 - D. J. Gross, H. D. Politzer, F. Wilczek
2008 – Y. Nambu, M. Kobayashi, T. Masakawa
2013 – F. Englert and P. Higgs
2015 – T. Kajita and A. B. McDonald

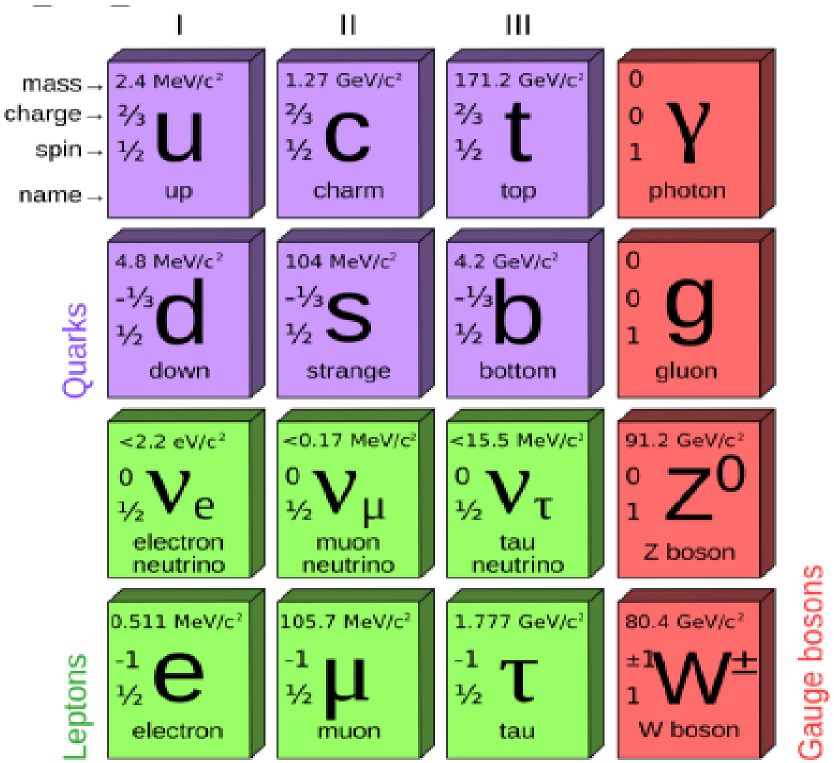
2012: „Higgs particle" was discovered

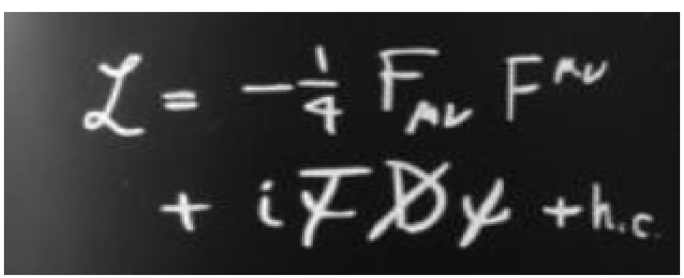
Experiment = probing theories with data



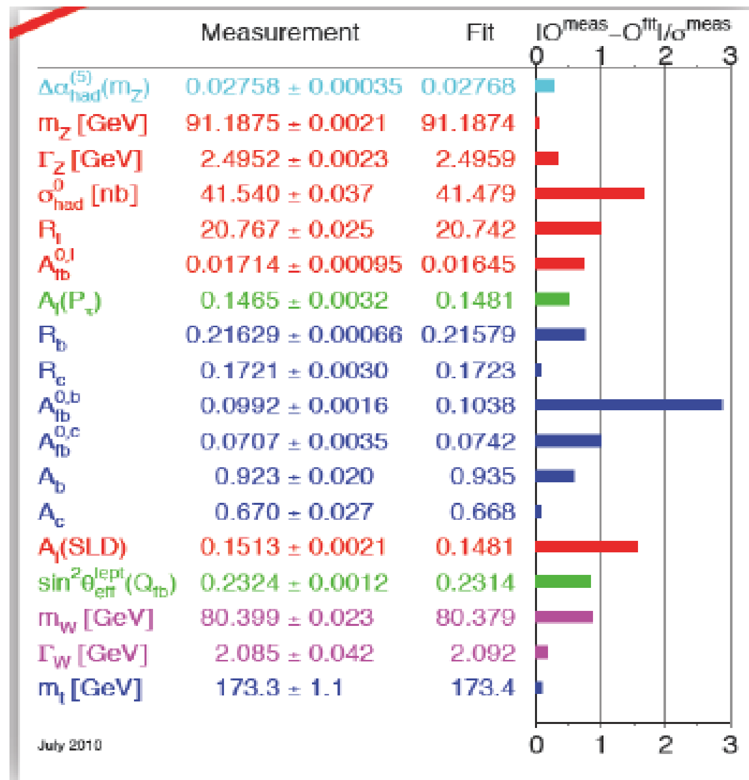


Standard Model confirmed by the data





STANDARD MODEL OF ELEMENTARY PARTICLES



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4

Confirmed at sub 1% level!

HEP, SI and „natural" units

Quantity	HEP units	SI units
length	1 fm	10^{-15} m
charge	e	$1.602 \cdot 10^{-19}$ C
energy	1 GeV	1.602×10^{-10} J
mass	1 GeV/c^2	1.78×10^{-27} kg
$\hbar = \mathbf{h/2\pi}$	6.588×10^{-25} GeV s	1.055×10^{-34} Js
c	2.988×10^{23} fm/s	2.988×10^{8} m/s
$\hbar c$	197 MeV fm	…

	"natural" units ($\hbar = c = 1$)
mass	1 GeV
length	1 GeV^{-1} = 0.1973 fm
time	1 GeV^{-1} = 6.59×10^{-25} s

Measuring particles

- Particles are characterized by
  - ✓ Mass [Unit: eV/c^2 or eV]
  - ✓ Charge [Unit: e]
  - ✓ Energy [Unit: eV]
  - ✓ Momentum [Unit: eV/c or eV]
  - ✓ (+ spin, lifetime, …)

Particle identification via measurement of:

e.g. (E, p, Q) or (p, β , Q)
(p, m, Q) ...

- … and move at relativistic speed

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\ell = \frac{\ell_0}{\gamma}$$ length contraption

$$t = t_0 \gamma$$ time dilatation

$$E^2 = \vec{p}^2 c^2 + m^2 c^4$$

$$E = m\gamma c^2 = mc^2 + E_{\text{kin}}$$

$$\vec{\beta} = \frac{\vec{p}c}{E} \qquad \vec{p} = m\gamma\vec{\beta}c$$

Relativistic kinematics

$$\ell = \frac{\ell_0}{\gamma}$$

$$t = t_0 \gamma$$

$$E^2 = \vec{p}^2 + m^2$$

$$E = m\gamma$$

$$\vec{p} = m\gamma\vec{\beta}$$

$$\vec{\beta} = \frac{\vec{p}}{E}$$

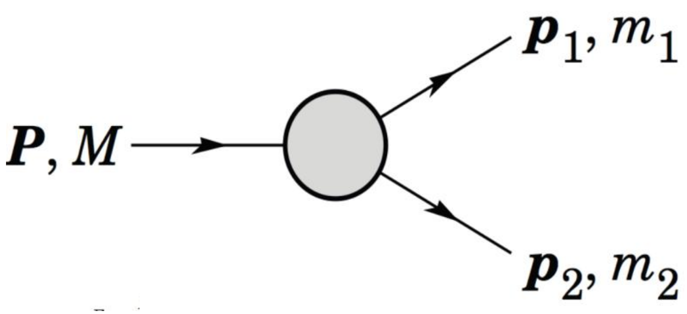
Center of mass energy

- In the center of mass frame the total momentum is 0
- In laboratory frame center of mass energy can be computed as:

$$E_{\mathrm{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

Kinematics

2-bodies decays



$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M}$$

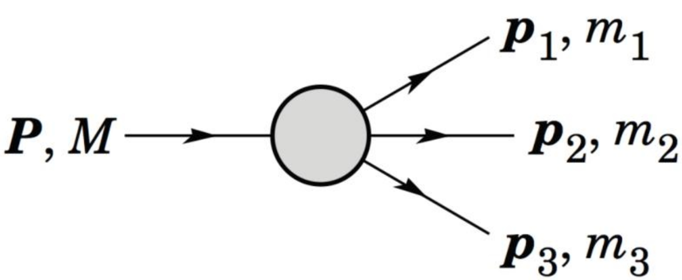
$$|\boldsymbol{p}_1| = |\boldsymbol{p}_2|$$

$$= \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M}$$

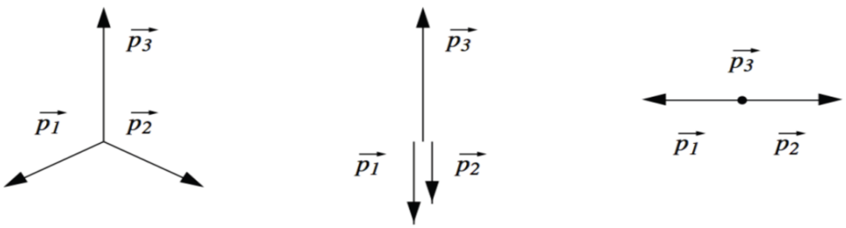
Invariant mass

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

3-bodies decays



$$|\boldsymbol{p}_3| = \frac{\left[\left(M^2 - (m_{12} + m_3)^2\right)\left(M^2 - (m_{12} - m_3)^2\right)\right]^{1/2}}{2M}$$



(a) (b) (c)

$\max(|\vec{p}_3|)$ $\quad (m_{12})_{min} = m_1 + m_2$

$\min(|\vec{p}_3|)$ $\quad (m_{12})_{max} = M - m_3$

A real example: pion decays

pion decays at rest

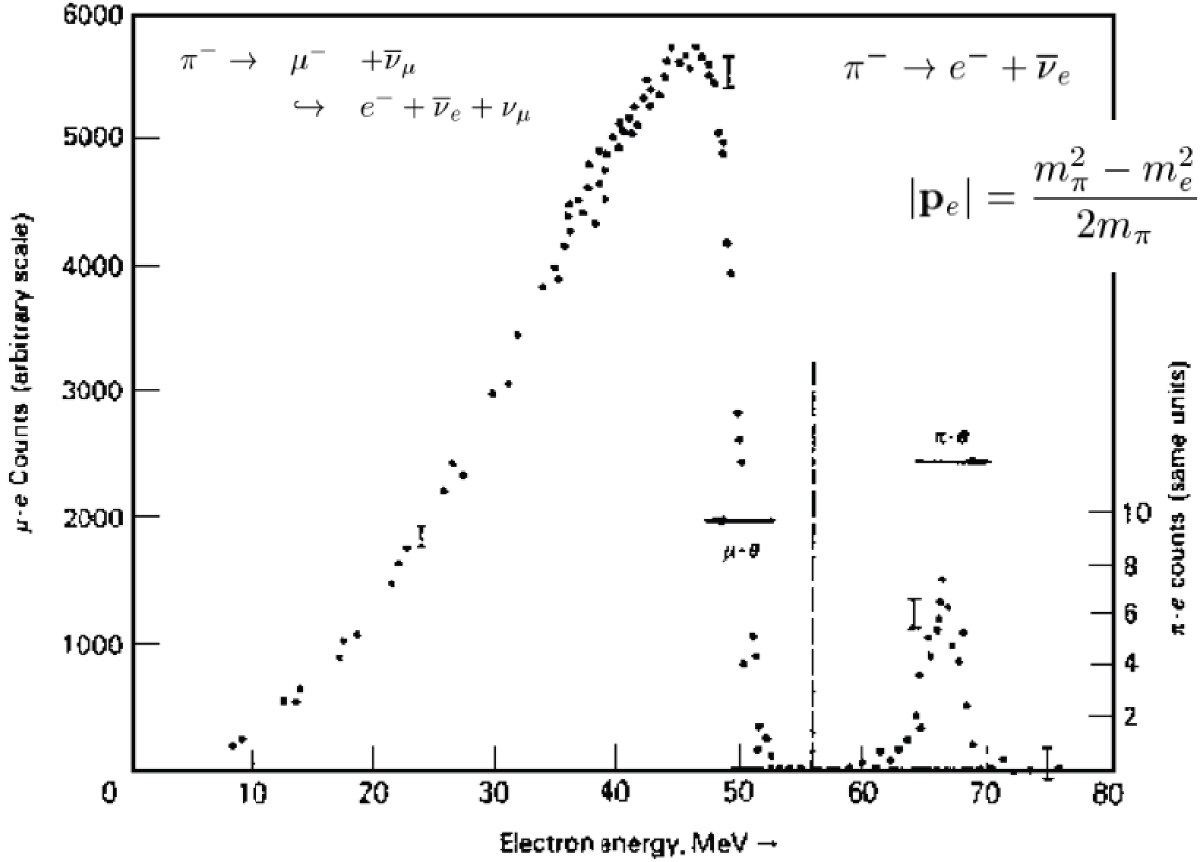
$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} c \simeq 30\,\mathrm{MeV/c}$$

$$m_\nu = 0.$$

in most cases muon decays at rest

$$|\mathbf{p}_e|_{max} = \frac{m_\mu^2 - m_e^2}{2m_\mu} c \simeq 52\,\mathrm{MeV/c}$$

$$|\mathbf{p}_e|_{min} = 0$$



$$|\mathbf{p}_e| = \frac{m_\pi^2 - m_e^2}{2m_\pi} c \simeq 70\,\mathrm{MeV/c}$$

3-bodies decay: Dalitz plot

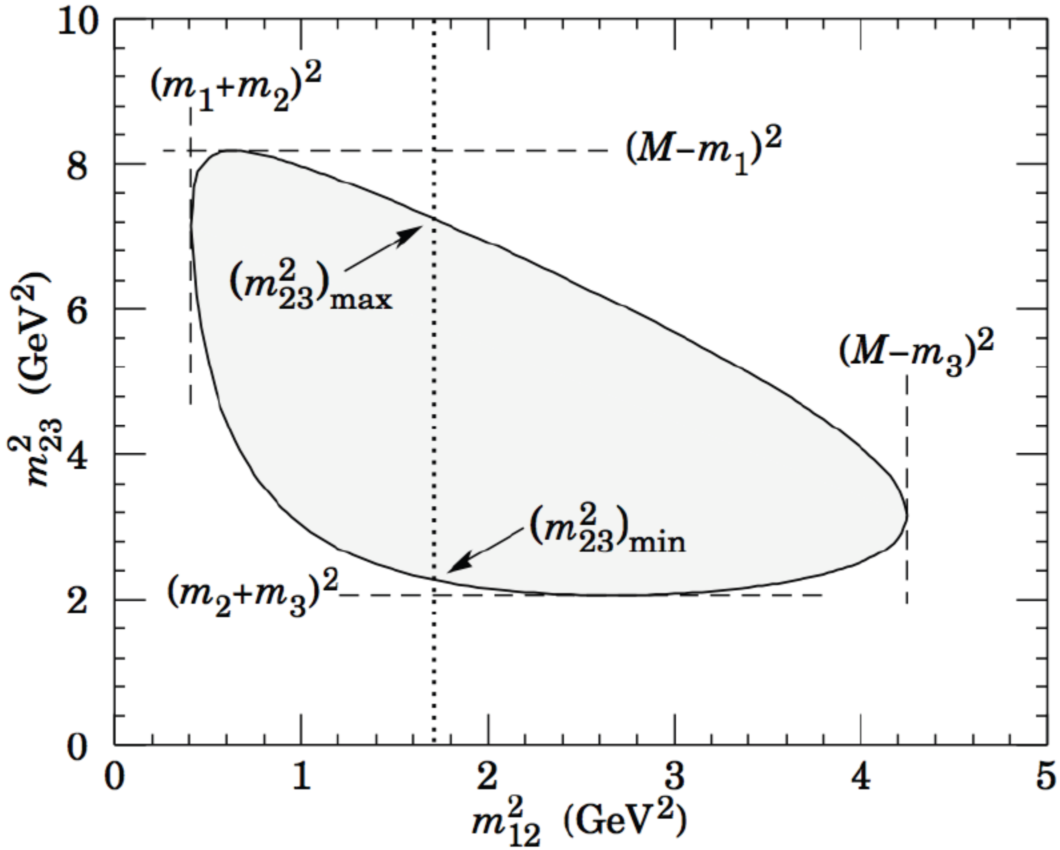
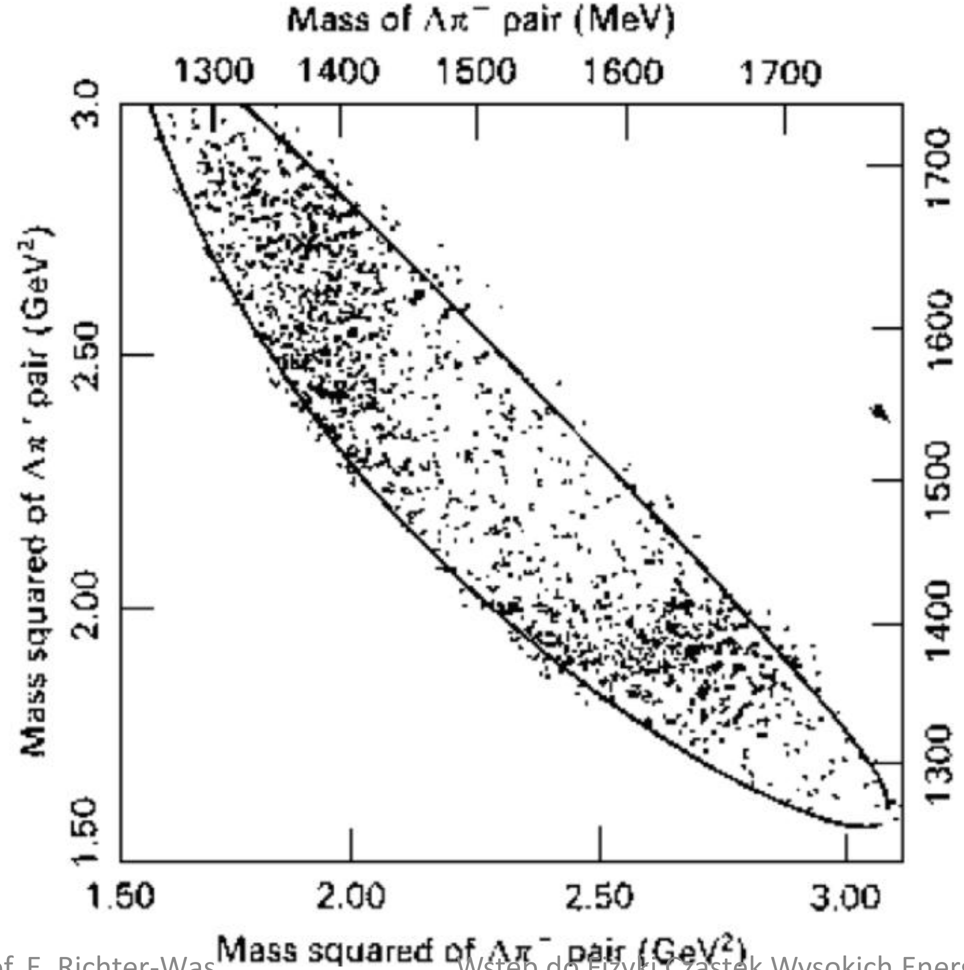


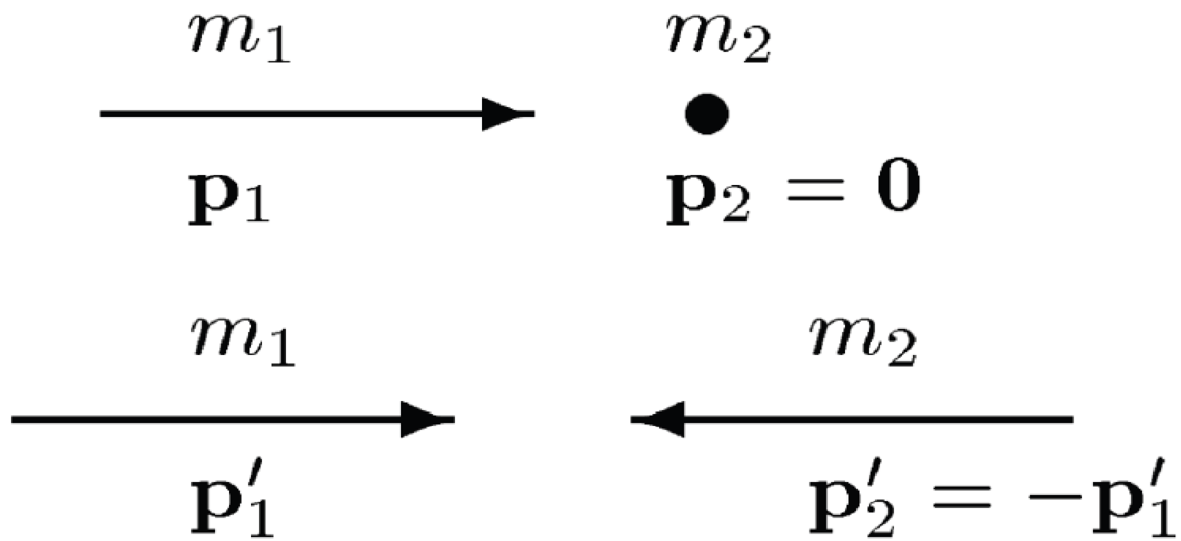
Figure 45.3: Dalitz plot for a three-body final state. In this example, the state is $\pi^+\overline{K}^0 p$ at 3 GeV. Four-momentum conservation restricts events to the shaded region.

Multi-bodies decay

$$K^- + p \rightarrow \pi^+ + \pi^- + \Lambda$$



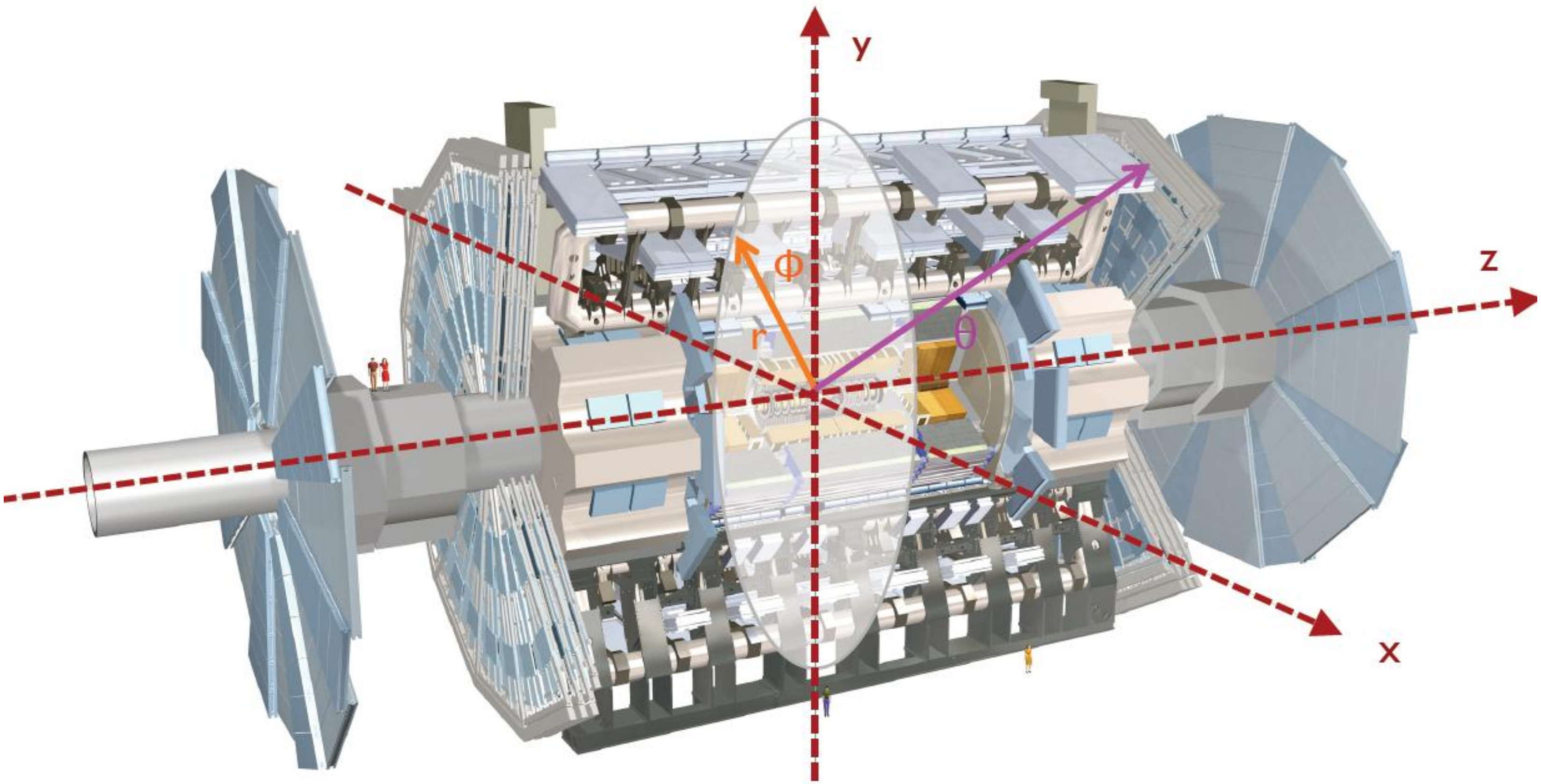
Fixed target vs collider



How much energy should a fixed target experiment have to equal the center of mass energy of two colliding beam?

$$E_{\text{fix}} = 2\frac{E_{\text{col}}^2}{m} - m$$

Collider experiment coordinates



Rapidity

Lorentz factor $\gamma = \frac{1}{\sqrt{1-\beta^2}} = \cosh\varphi$ Hyperbolic cosine of "rapidity"

$$E = m\cosh\varphi$$
$$|\vec{p}| = m\sinh\varphi$$

$$\varphi = \tanh^{-1}\frac{E}{|\vec{p}|} = \frac{1}{2}\ln\frac{E+|\vec{p}|}{E-|\vec{p}|}$$

- Particle physicists prefer to use modified rapidity along beam axis

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

Pseudorapidity

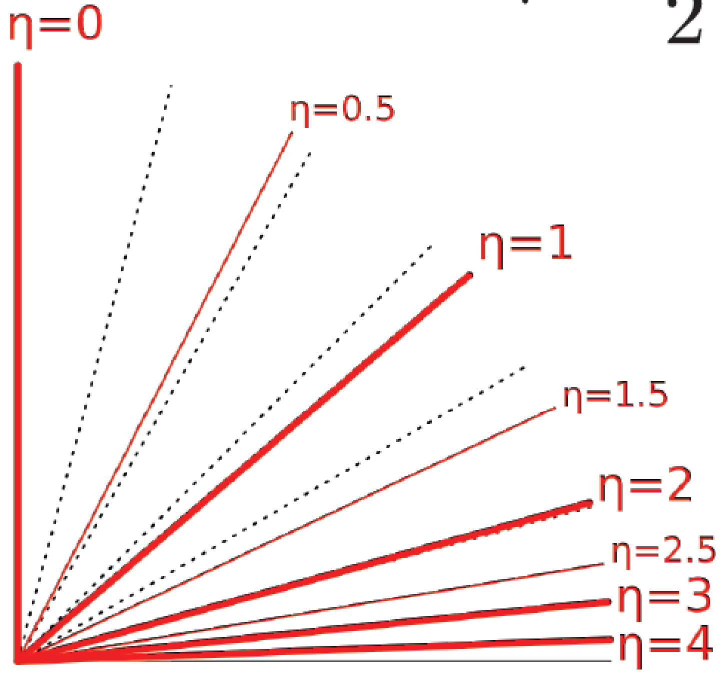
$$\eta = \frac{1}{2}\ln\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}$$

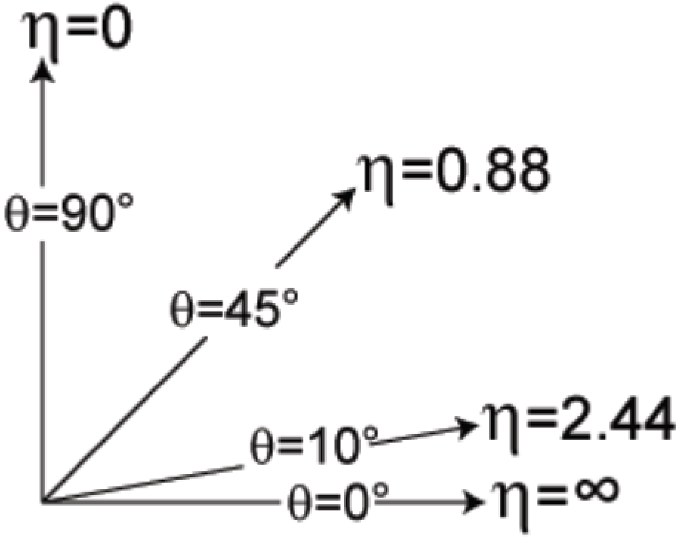
$$\eta = \frac{1}{2}\ln\left(\tan\frac{\theta}{2}\right)$$

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$$

$$\eta \simeq y$$

if E >> m





Transverse variables

- At hadron colliders, a significant and unknown fraction of the beam energy in each event escapes down the beam pipe.
- Net momentum can only be constrained in the plane transverse to the beam z-axis!

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$p_x = p_T \cos\phi$$
$$p_y = p_T \sin\phi$$
$$p_z = p_T \sinh\eta$$

$$|p| = p_T \cosh\eta$$

$$E_T = \frac{E}{\cosh\eta}$$

$$\sum p_X(i) = 0 \qquad \sum p_Y(i) = 0$$

Missing transverse energy and transverse mass

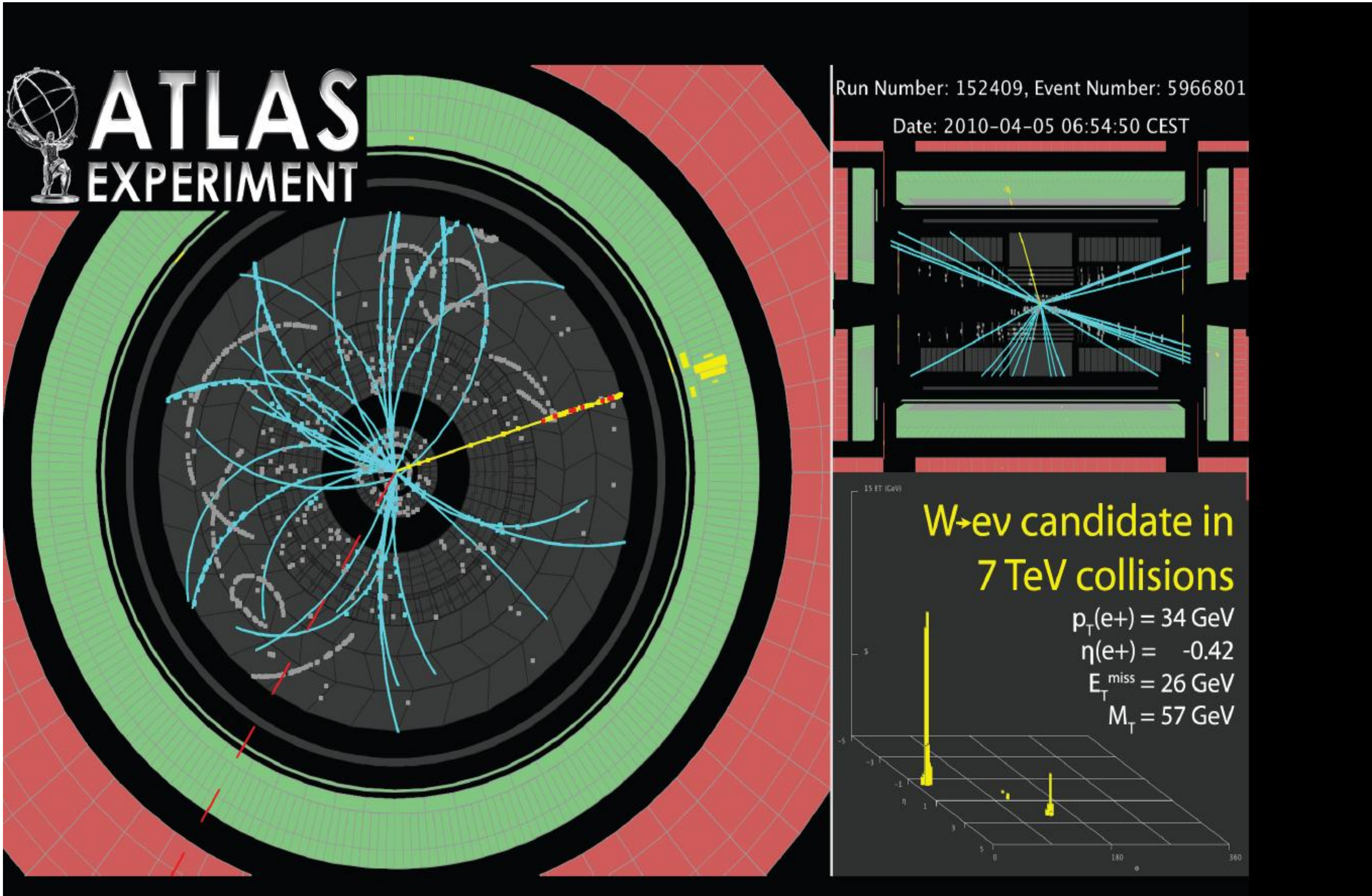
- If invisible particle are created, only their transverse momentum can be constrained: missing transverse energy

$$E_T^{\text{miss}} = \sum p_T(i)$$

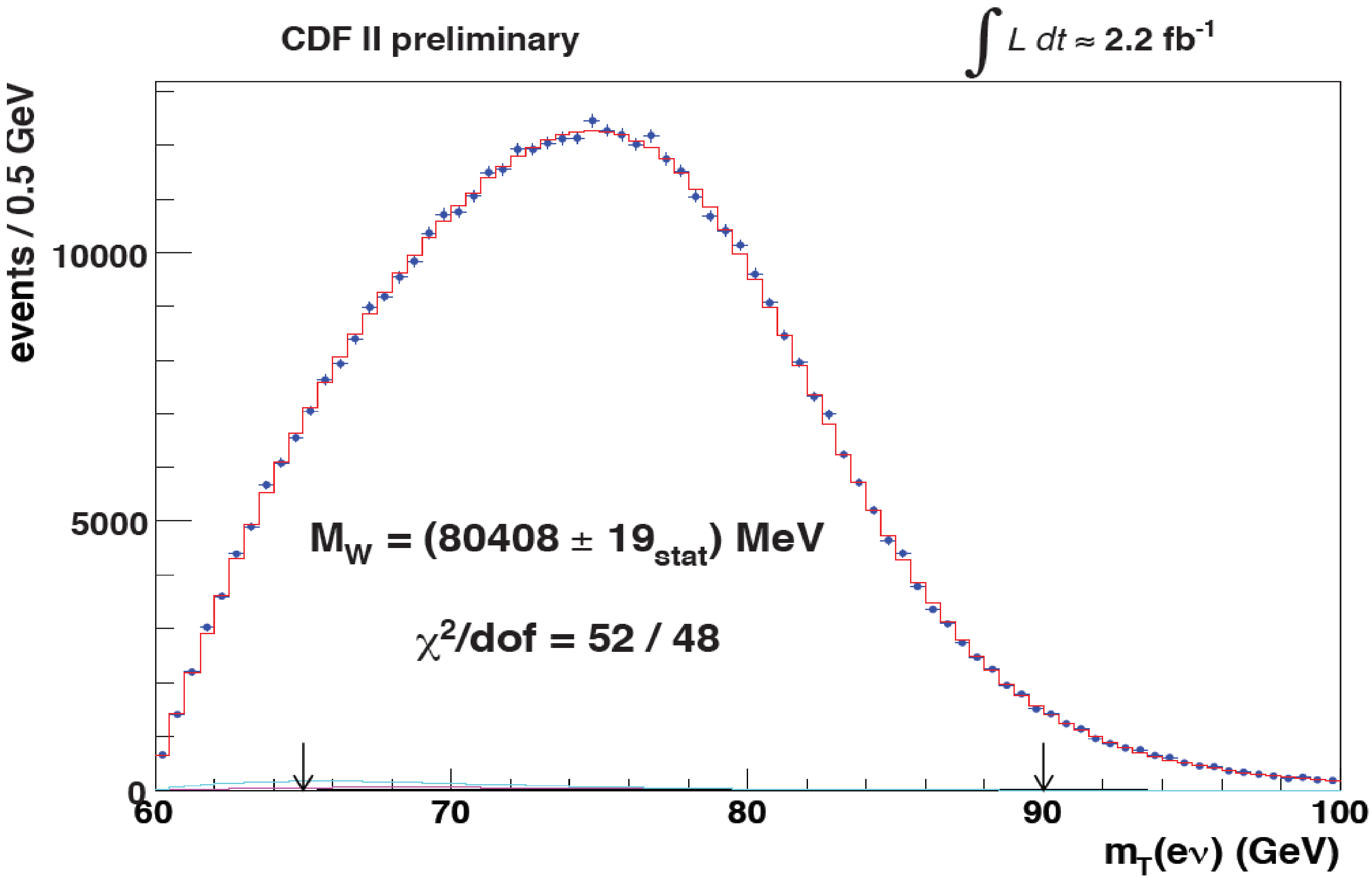
- If a heavy particle is produced and decays in two particles one of which is invisible, the mass of the parent particle can constrained with the transverse mass quantity

$$\begin{aligned} M_T^2 &\equiv [E_T(1) + E_T(2)]^2 - [\boldsymbol{p}_T(1) + \boldsymbol{p}_T(2)]^2 \\ &= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \boldsymbol{p}_T(1)\cdot\boldsymbol{p}_T(2)] \end{aligned}$$

if $m_1 = m_2 = 0$ $\quad M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1-\cos\phi_{12})$

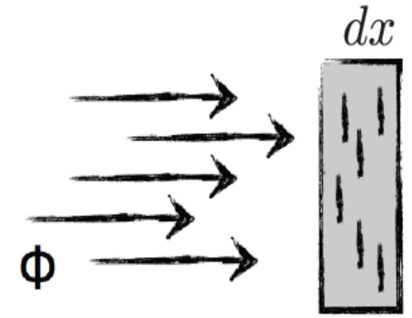

ATLAS
EXPERIMENT
Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST
W→eν candidate in
7 TeV collisions
$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV

Mass of the W boson



Interaction cross-section

Flux $\Phi = \frac{1}{S}\frac{dN_i}{dt}$ [$L^{-2}t^{-1}$]



area obscured by target particle

Reactions per unit of time $\frac{dN_{\mathrm{reac}}}{dt} = \Phi \sigma N_{\mathrm{target}} dx$ [t^{-1}]

[$L^{-2}t^{-1}$] [?] [L^{-1}] [L]

Reaction rate per target particle $W_{if} = \Phi\sigma$ [t^{-1}]

Cross section per target particle $\sigma = \frac{W_{if}}{\Phi}$ [L^2] = reaction rate per unit of flux

1b = 10^{-28} m^2 (roughly the area of a nucleus with A = 100)

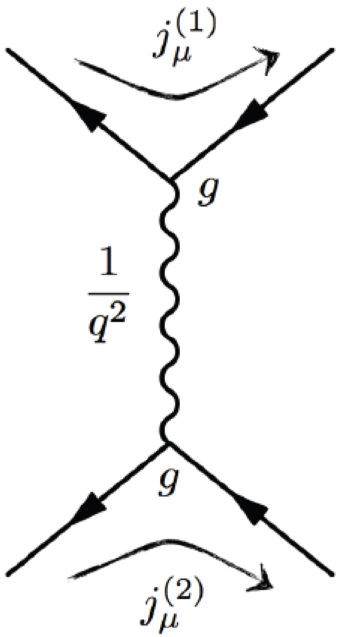
Fermi Golden rule

From non-relativistic perturbation theory…

transition probability — *matrix element* — *energy density of final states*

$$W_{if} = \frac{2\pi}{\hbar}|M_{if}|^2 \frac{dN}{dE_f}$$

[t⁻¹] [E] [E⁻¹]



$$M_{if} = -i\int j_\mu^{(1)}\left(\frac{1}{q^2}\right) j_\mu^{(2)} d^4x$$

$$\sigma \sim |M_{if}|^2 \sim g^4\left(\frac{1}{q^4}\right)$$

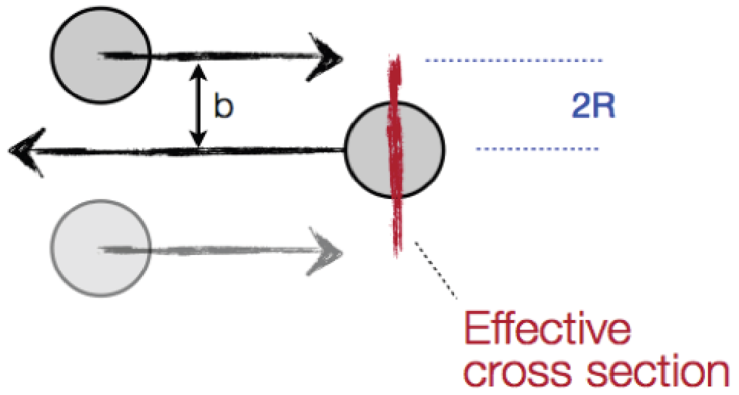
Cross-section: magnitude and units

Standard
cross section unit: $[\sigma] = \text{mb}$ with $1\ \text{mb} = 10^{-27}\ \text{cm}^2$

or in
natural units: $[\sigma] = \text{GeV}^{-2}$ with $1\ \text{GeV}^{-2} = 0.389\ \text{mb}$
$1\ \text{mb} = 2.57\ \text{GeV}^{-2}$

using: $\hbar c = 0.1973\ \text{GeV fm}$
$(\hbar c)^2 = 0.389\ \text{GeV}^2\ \text{mb}$

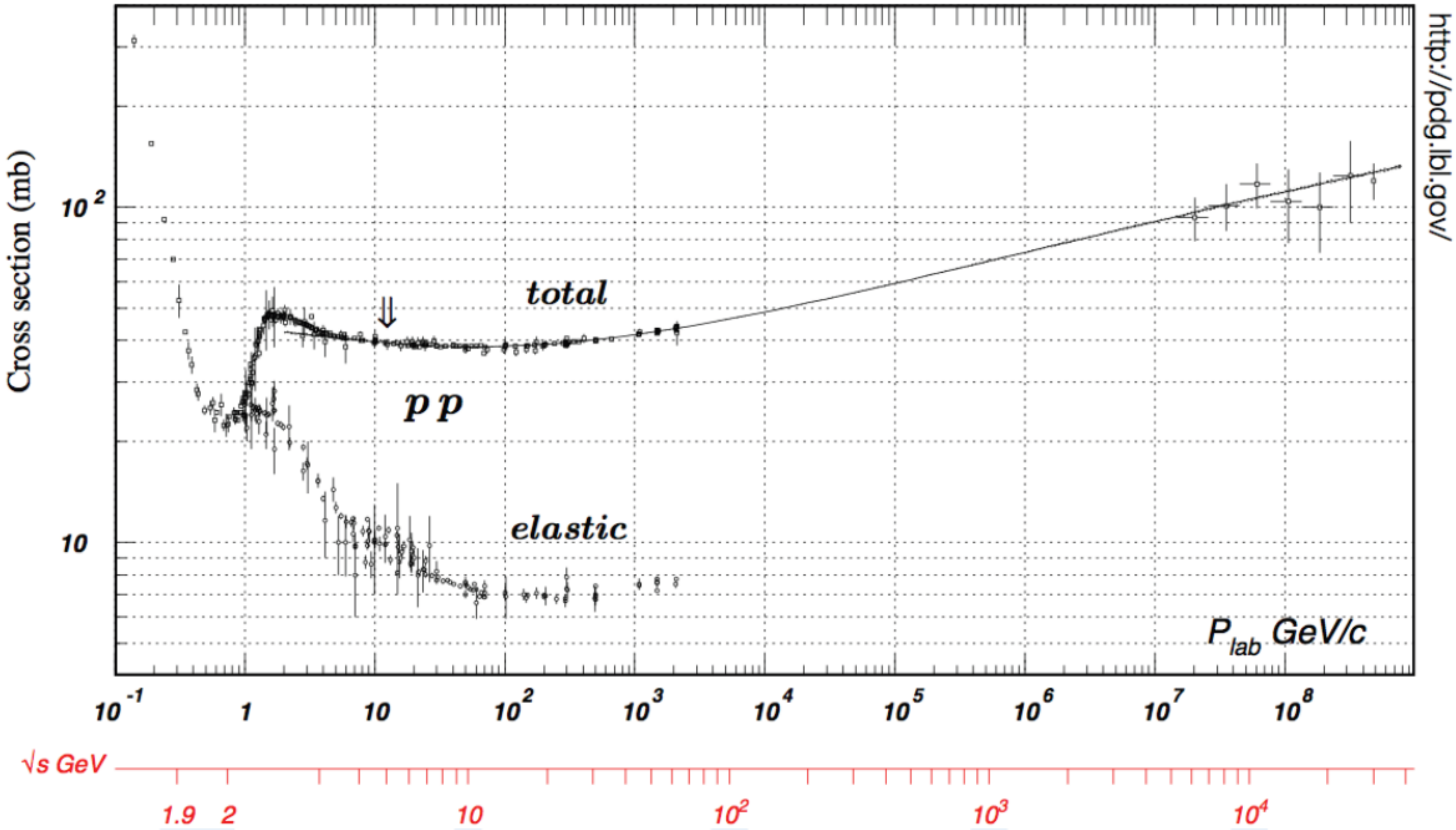
Estimating the
proton-proton cross section:



Proton radius: R = 0.8 fm
Strong interactions happens up to b = 2R

$$\sigma = \pi(2R)^2 = \pi \cdot 1.6^2\ \text{fm}^2$$
$$= \pi \cdot 1.6^2\ 10^{-26}\ \text{cm}^2$$
$$= \pi \cdot 1.6^2\ 10\ \text{mb}$$
$$= 80\ \text{mb}$$

Proton-proton scattering cross-section



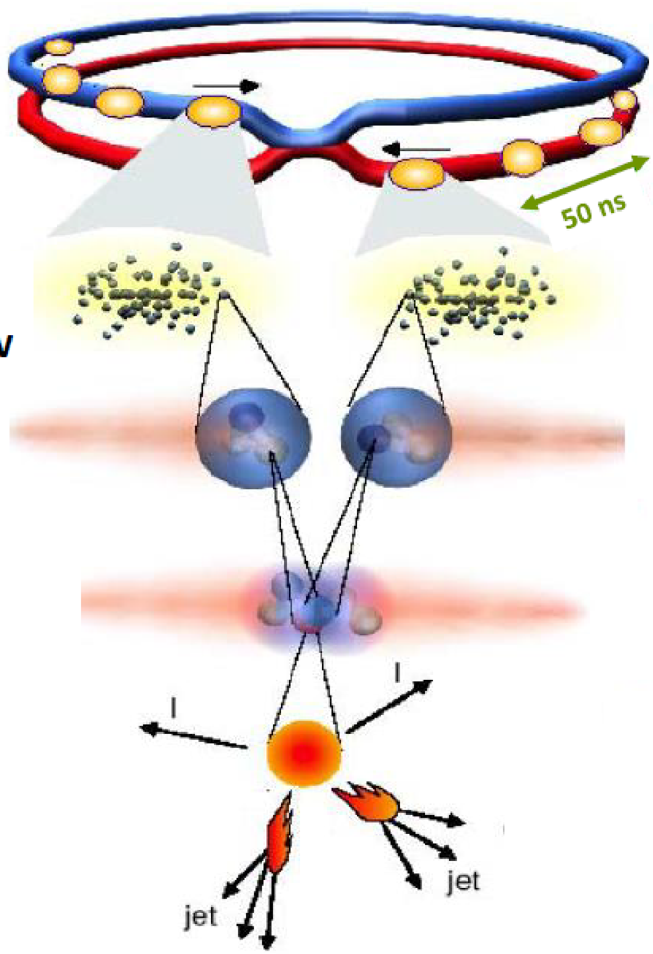
Proton-proton collisions at LHC

Paczka protonów

Proton

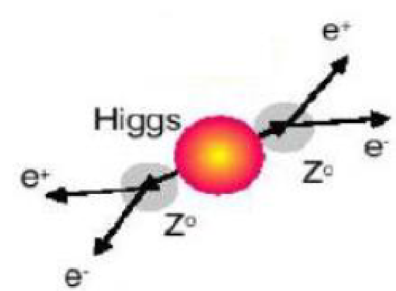
Składniki protonu

Produkty zderzeń



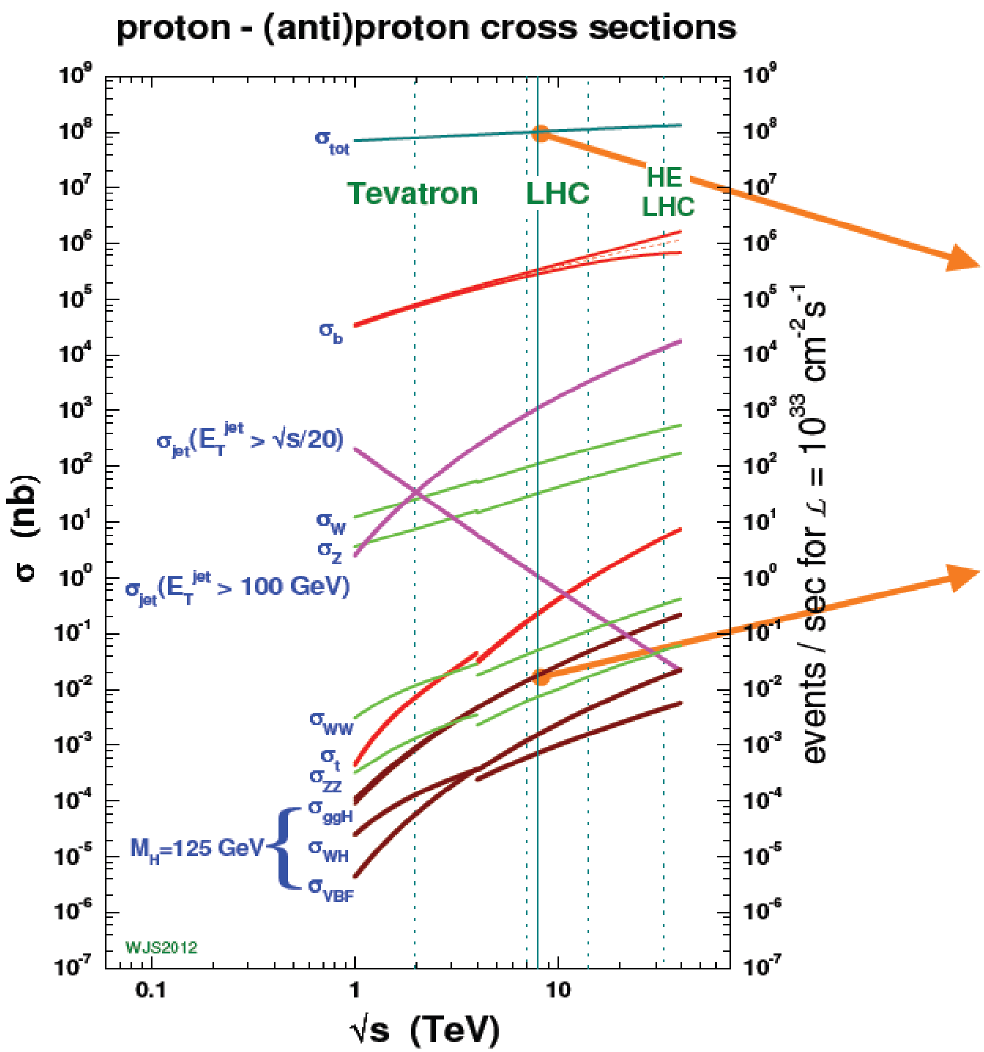
Proton-Proton	1380 paczek/wiązkę
Protonów/paczka	1.7 10^{11}
Energia wiązki	3.5, 4.0, 6.5 TeV

Każdy proton porusza się z prędkością bliską prędkości światła i niesie kinetyczną energię muchy w locie, okrąża pierścień akceleratora 1100 razy na sekundę.
Rozmiar poprzeczny wiązki: 16µm (4 razy mniejszy niż grubość ludzkiego włosa).
Każda z wiązek niesie energię pociągu TGV o dł. 200 m i jadącego z prędkością 155km/godz (360M Jula).



Takie zdarzenie pojawia się raz na 10 bilio-nów zderzeń

Cross-sections at LHC



10^8 events/s

$\sim 10^{10}$

10^{-2} events/s ~

10 events/min

[m_H ~ 125 GeV]

0.2% H → γγ

1.5% H → ZZ