Introduction to particle physics: experimental part

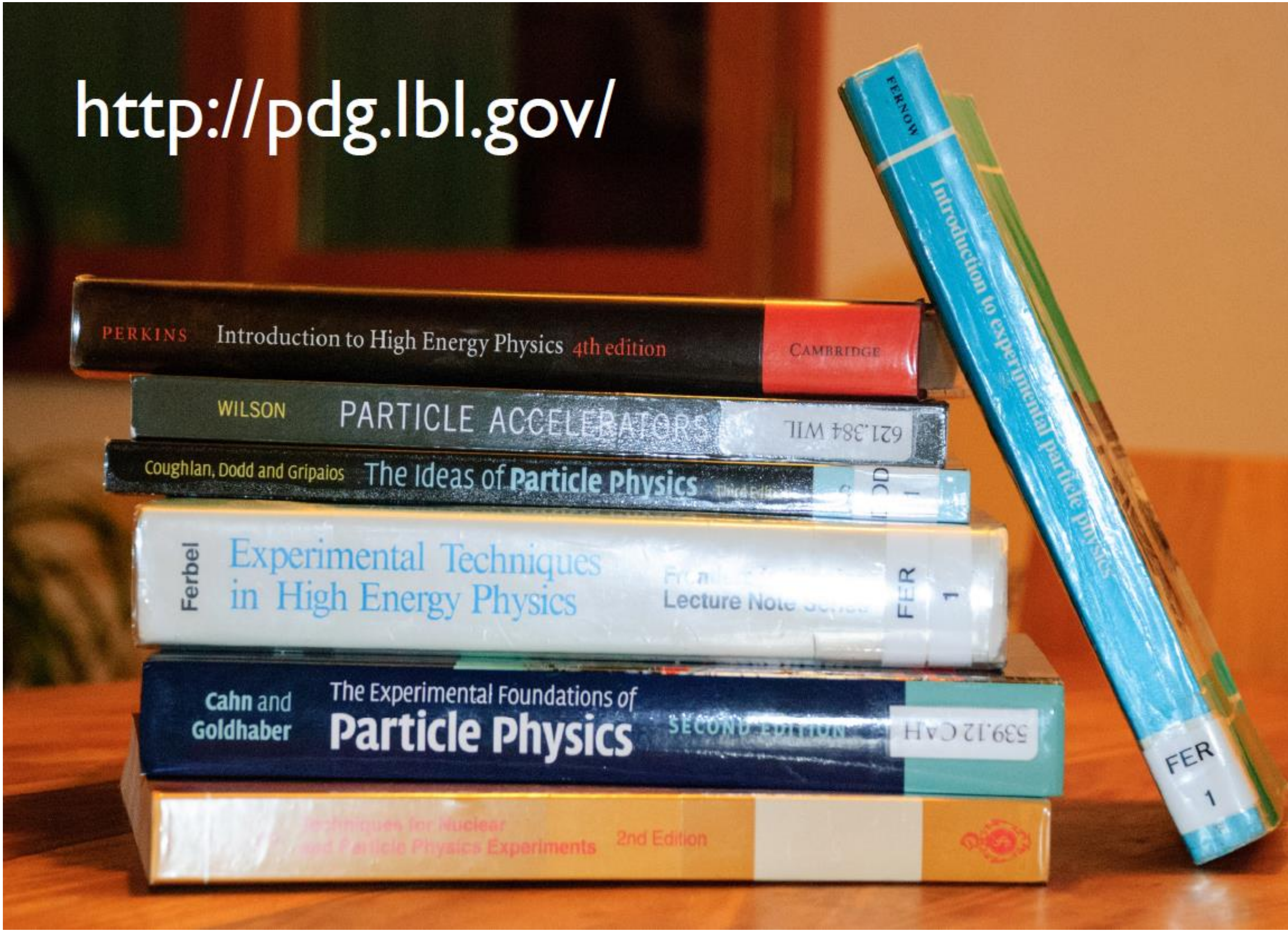
Introduction

Units, kinematics

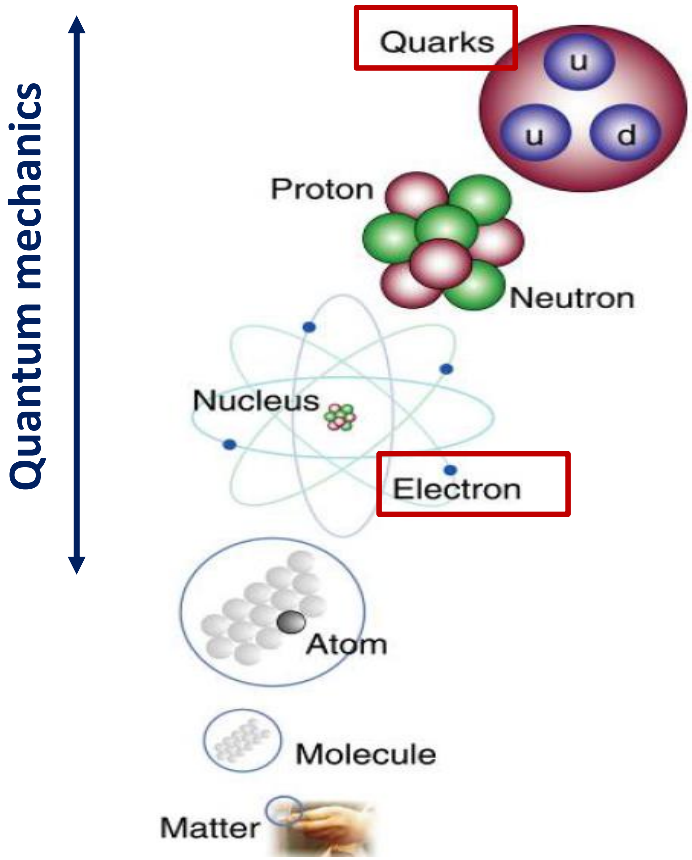
Large fraction of those slides from M. Delmastro lectures at ESIPAP school

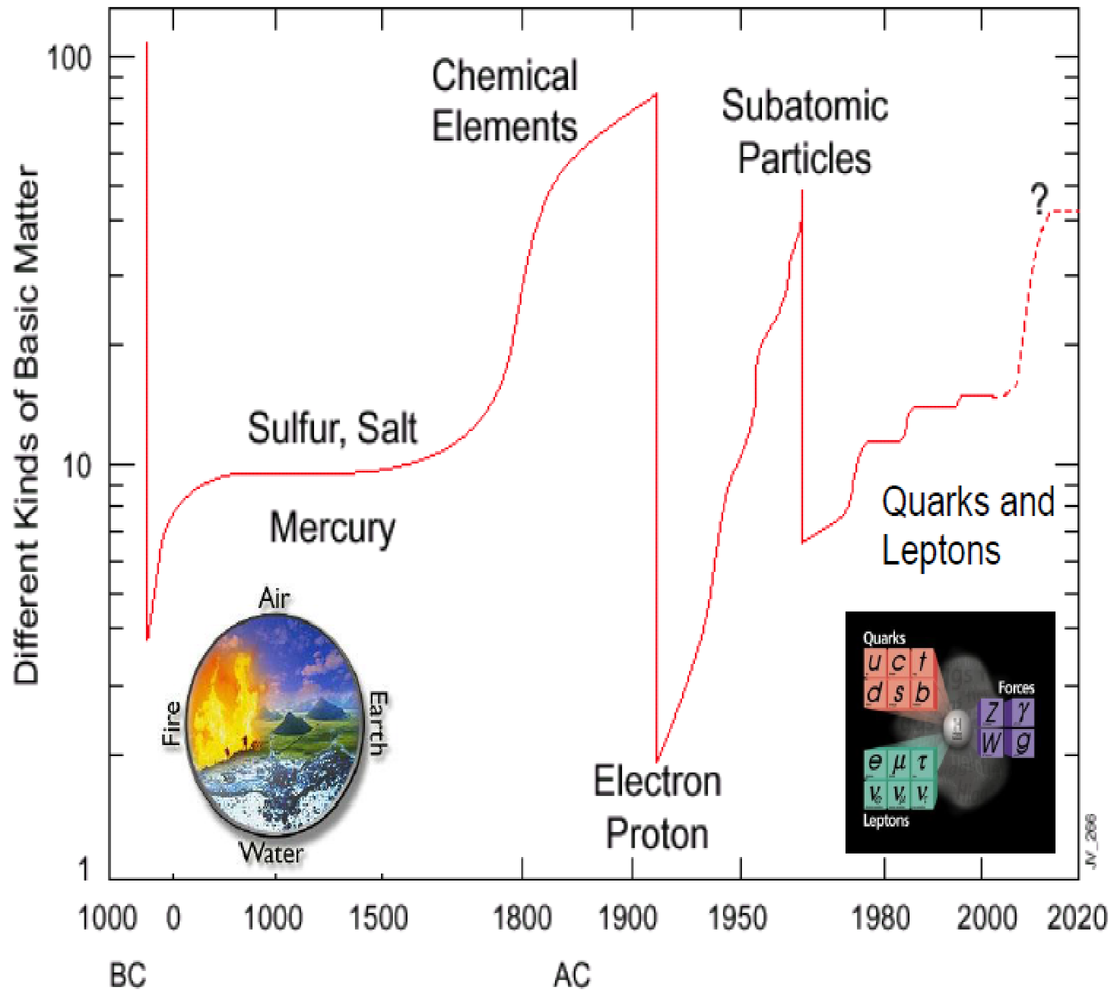
Prof. dr hab. Elżbieta Richter-Wąs

http://pdg.lbl.gov/

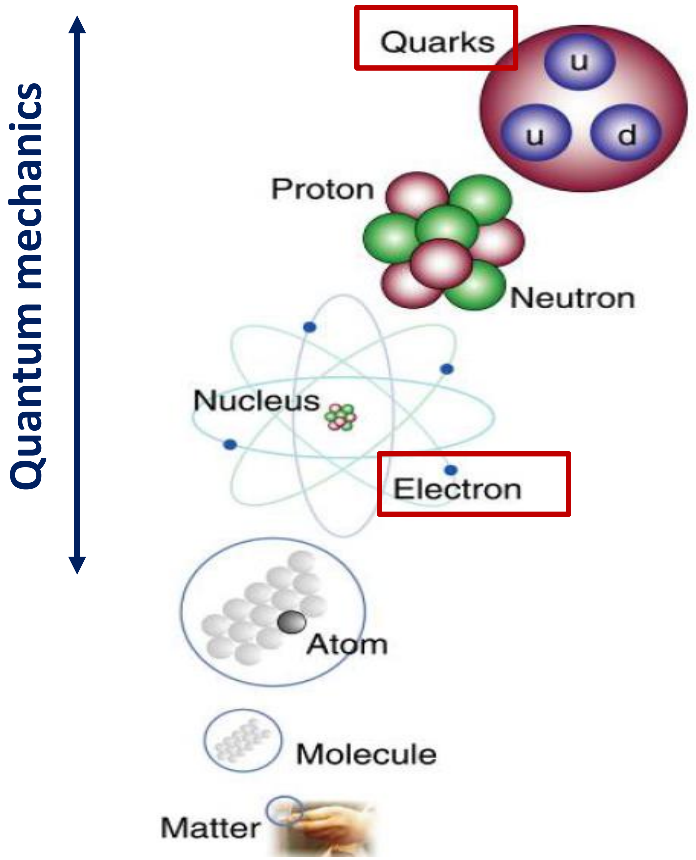


Constituents of matter along History



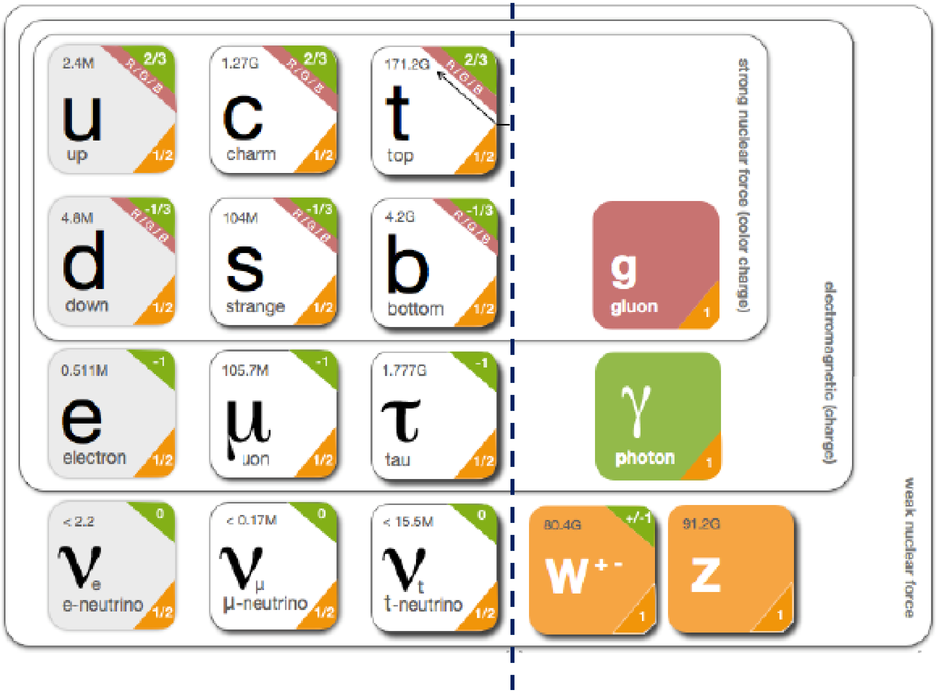


Particles of the Standard Model



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

Interaction particles



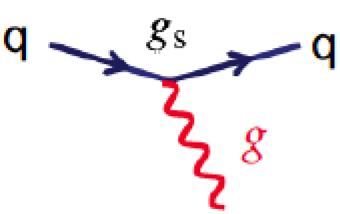
Higgs particle
Is not a matter particle and not a interaction particle

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

Interactions

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

STRONG



Only quarks

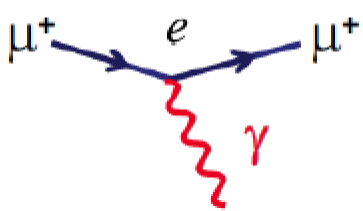
Never changes flavour

$\alpha_S \sim 1$

Gluons

massless

EM



All charged fermions

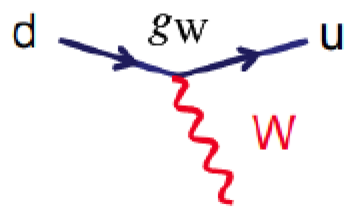
Never changes flavour

$\alpha \simeq 1/137$

Photon

massless

WEAK CC



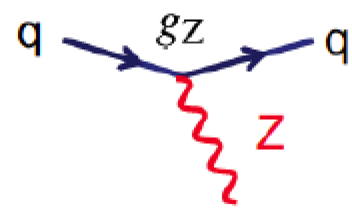
All fermions

Always changes flavour

W+, W-

very massive

WEAK NC



All fermions

Never changes flavour

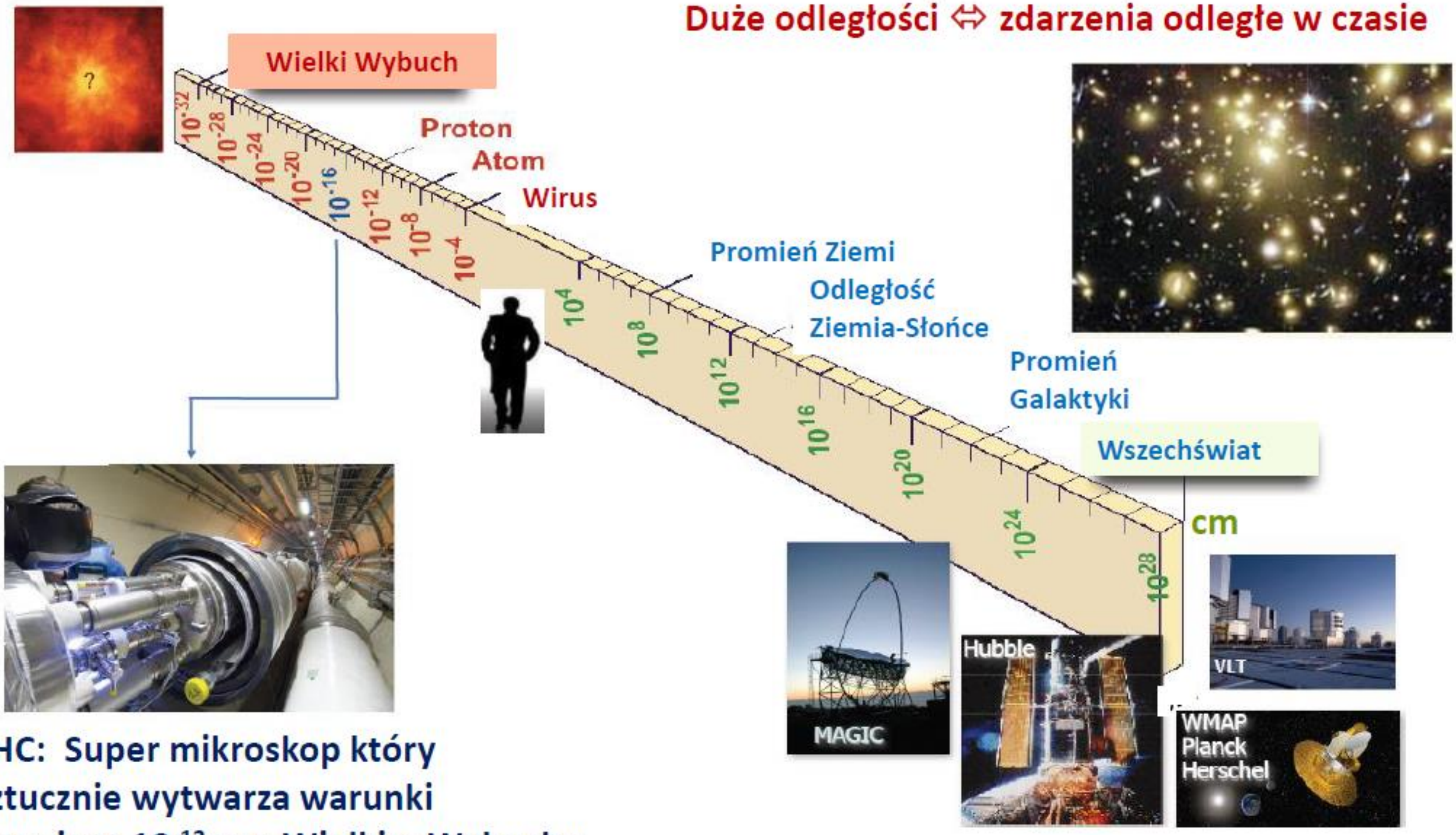
$\alpha_{W/Z} \sim 1/40$

Z^0

very massive

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

GREEN - theoretical
BLUE - experimental

1964: „Higgs mechanism" was born


Leon M. Lederman


Melvin Schwartz


Jack Steinberger


Carlo Rubbia


Simon van der Meer


Georges Charpak


Gerardus 't Hooft

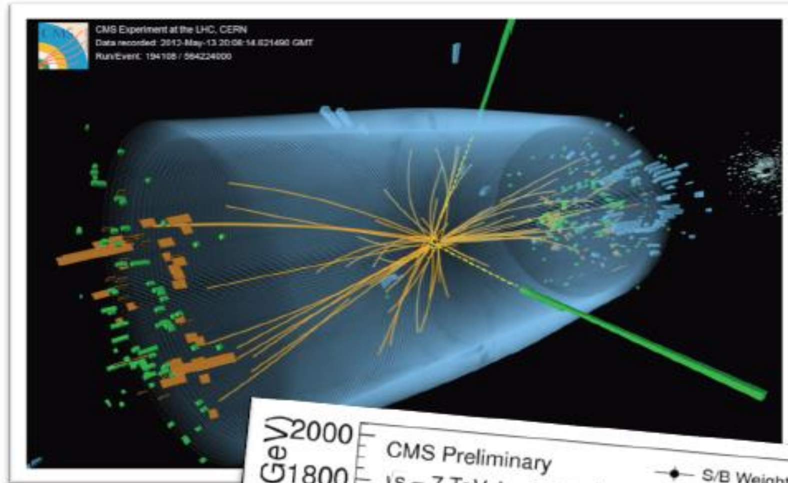

Martinus J.G. Veltman

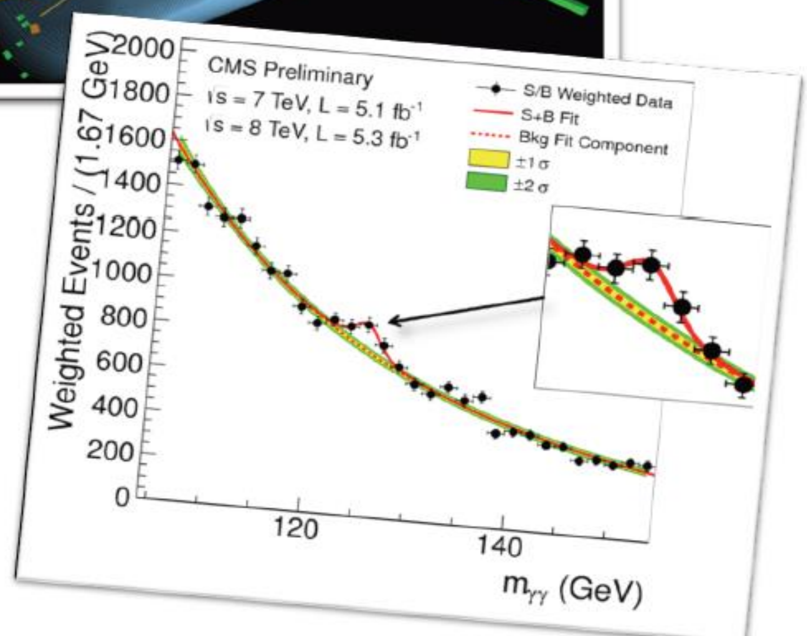

M. Gell-Mann

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

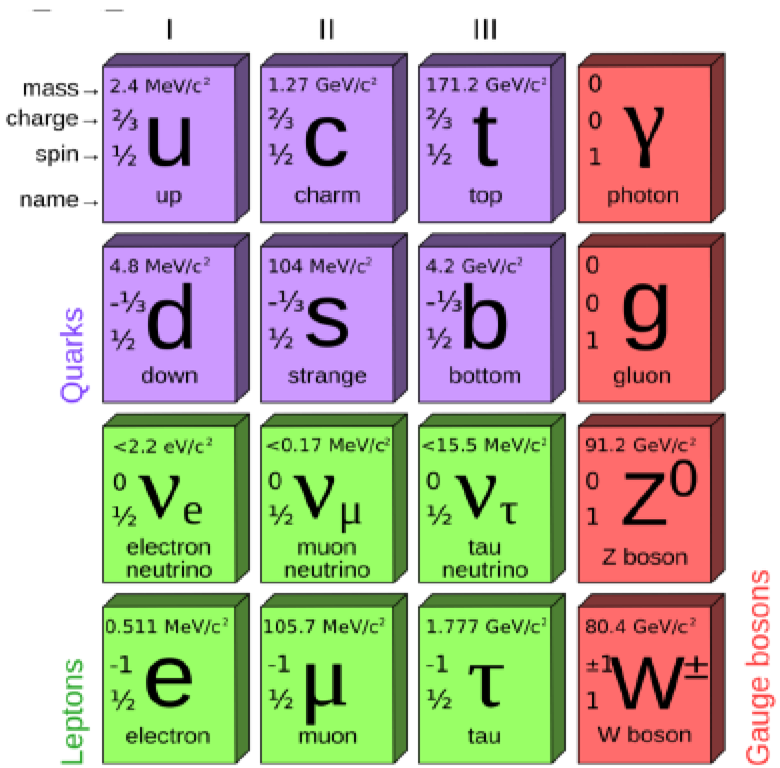
2012: „Higgs particle" was discovered

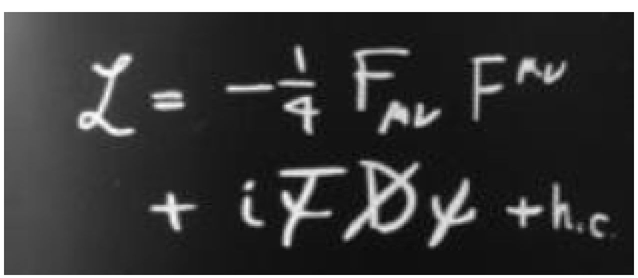
Experiment = probing theories with data



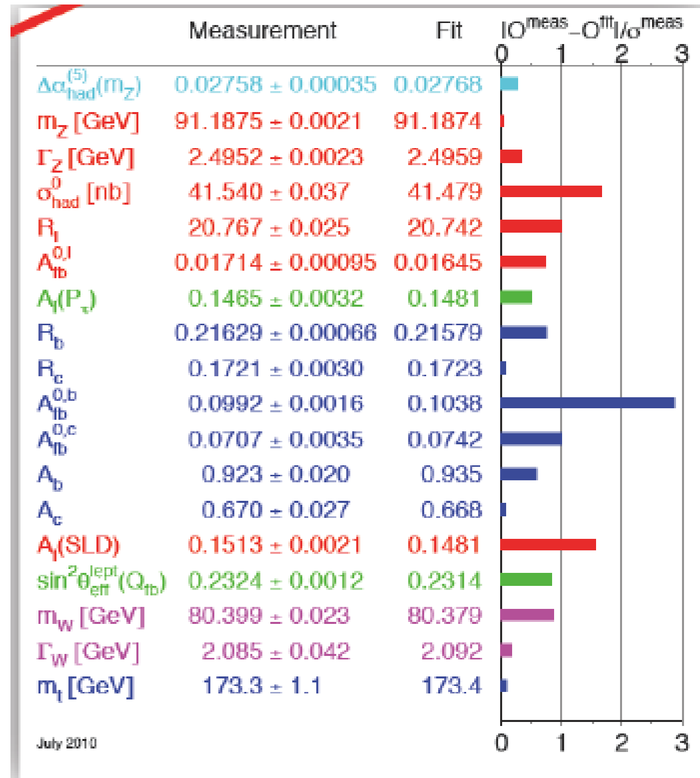


Standard Model confirmed by the data





STANDARD MODEL OF ELEMENTARY PARTICLES



	Measurement	Fit	$\lvert O^{meas} - O^{fit}\rvert / \sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	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_{had}^0 [nb]	41.540 ± 0.037	41.479	
R_l	20.767 ± 0.025	20.742	
$A_{fb}^{0,l}$	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	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038	
$A_{fb}^{0,c}$	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	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	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
$\hbar = h/2$	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

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

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

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

Relativistic kinematics

$$\ell = \frac{\ell_0}{\gamma}$$
$$t = t_0\gamma$$

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

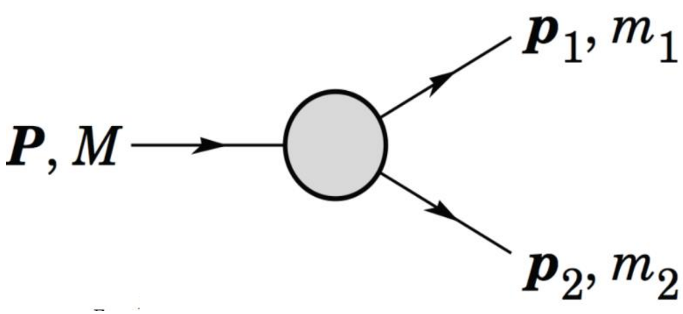
Center of mass energy

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

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

Kinematics

2-bodies decays



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

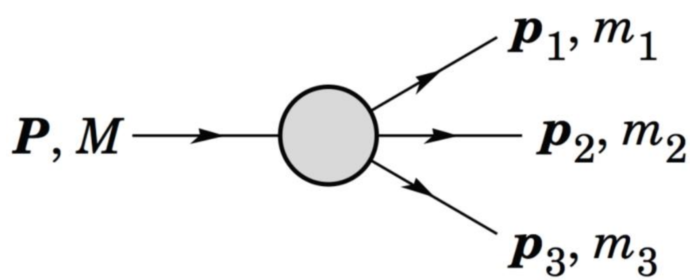
$$|\boldsymbol{p}_1| = |\boldsymbol{p}_2|$$

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

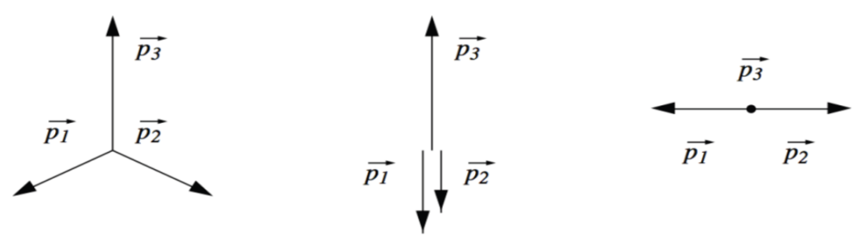
Invariant mass

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

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)

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

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

A real example: pion decays

pion decays at rest

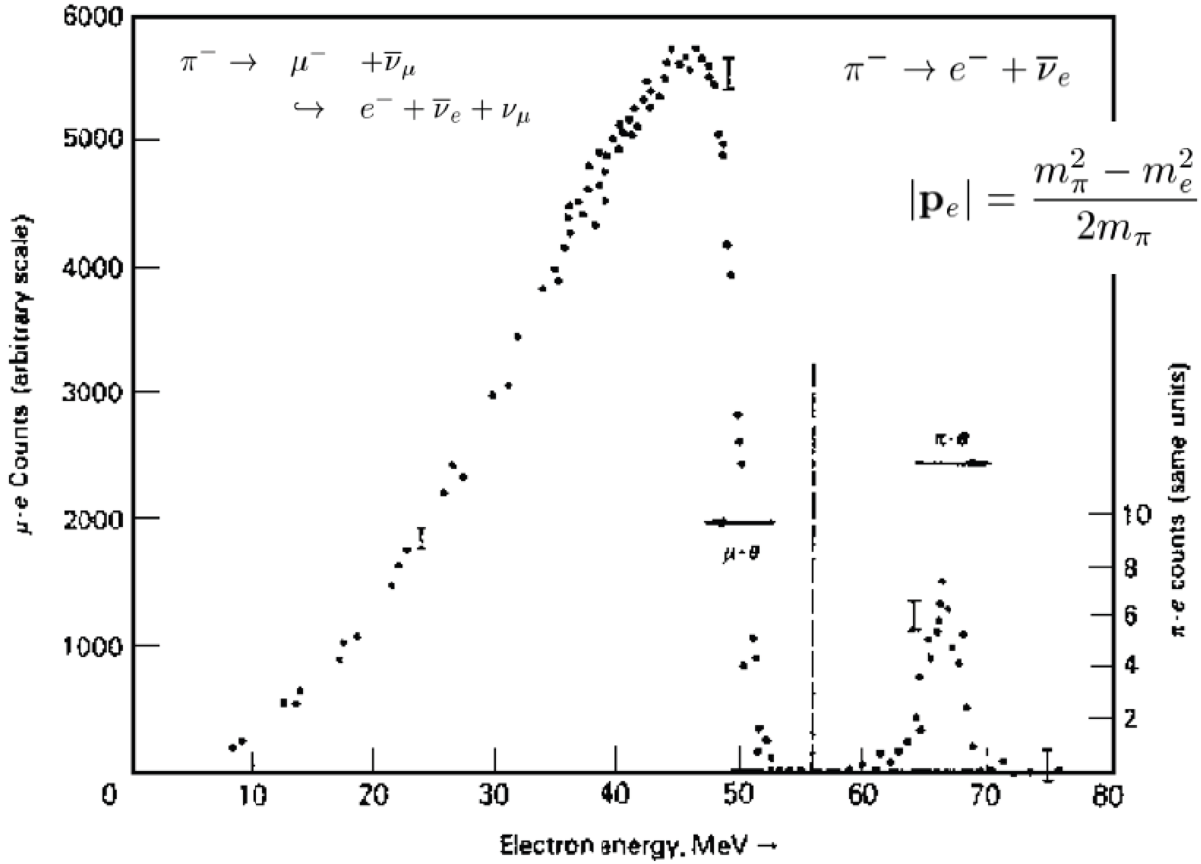
$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}c \simeq 30\,\mathrm{MeV/c}$$

$m_\nu = 0.$

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

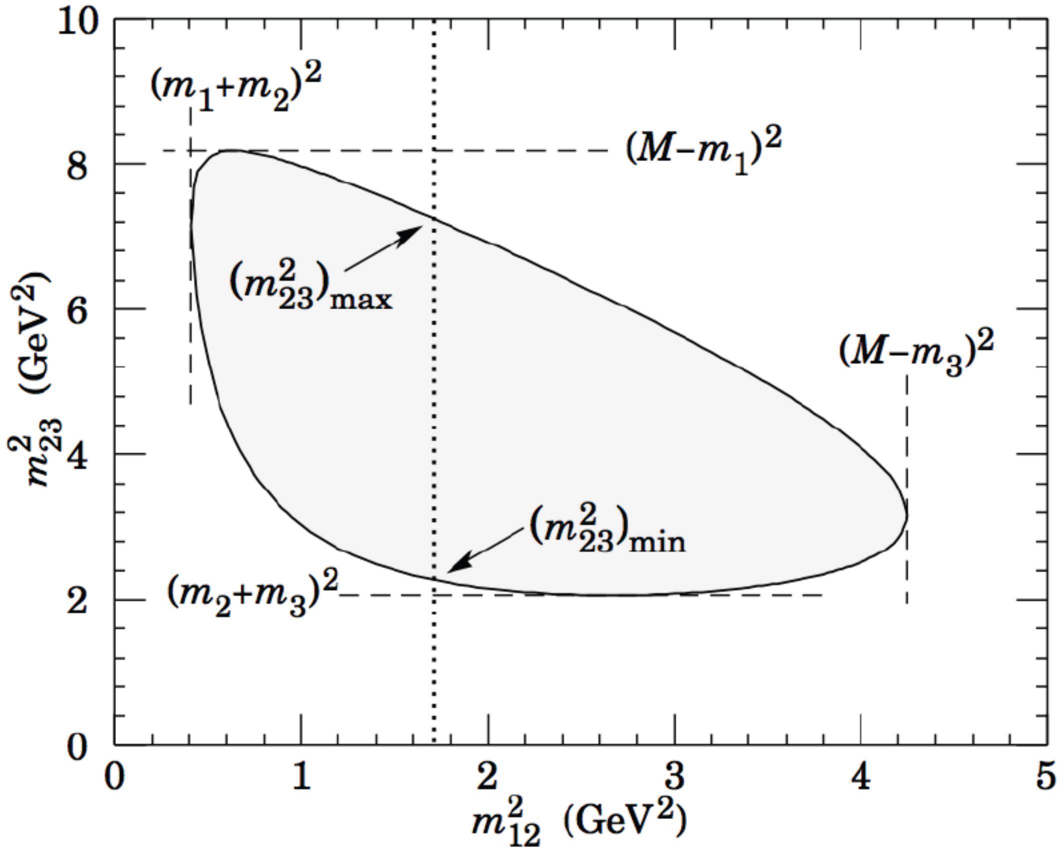
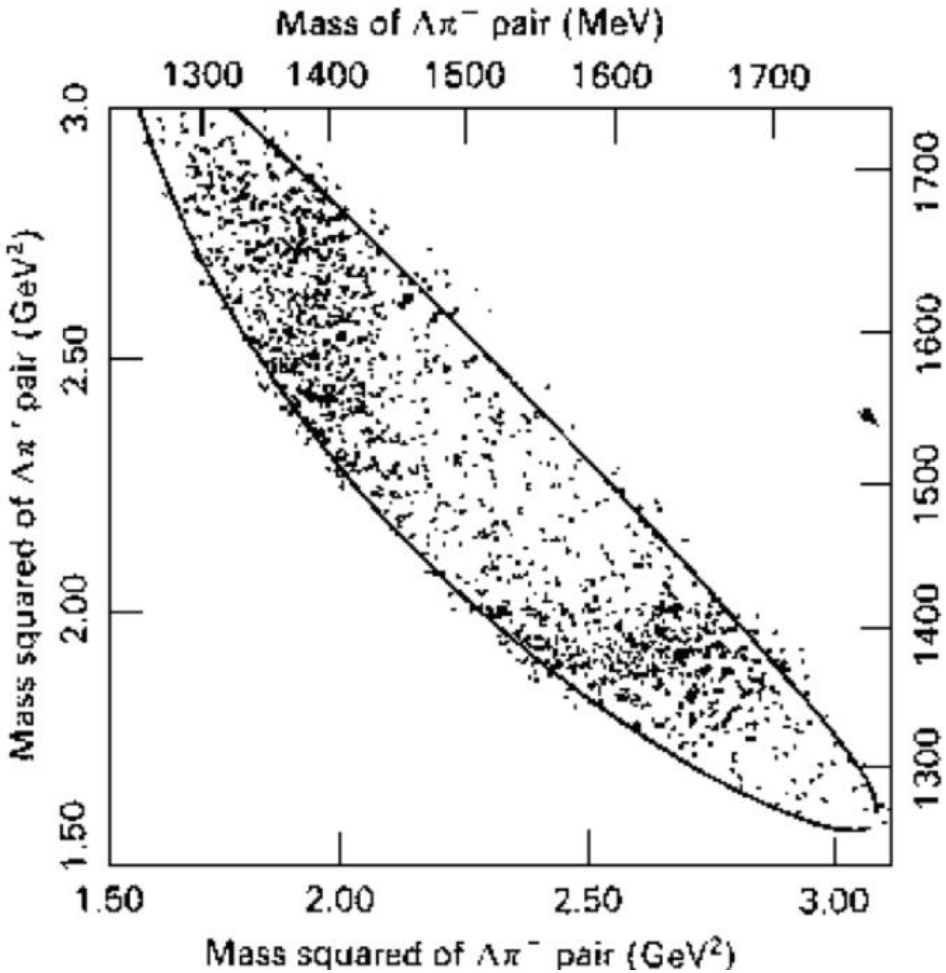


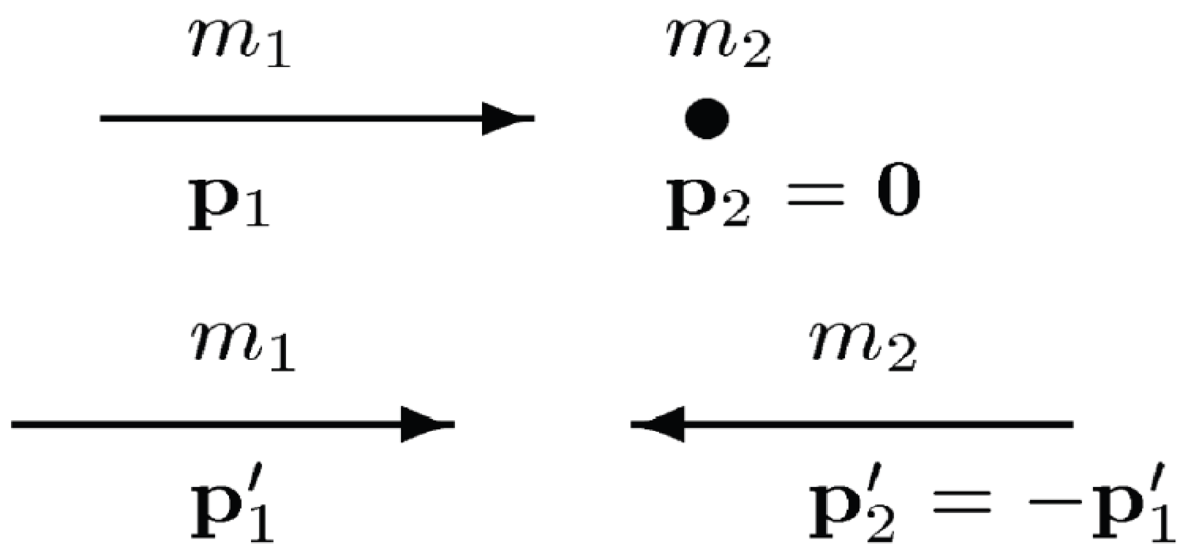
Figure 45.3: Dalitz plot for a three-body final state. In this example, the state is $\pi^+\overline{K}^0p$ at 3 GeV. Four-momentum conservation restricts events to the shaded region.

Multi-bodies decay

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



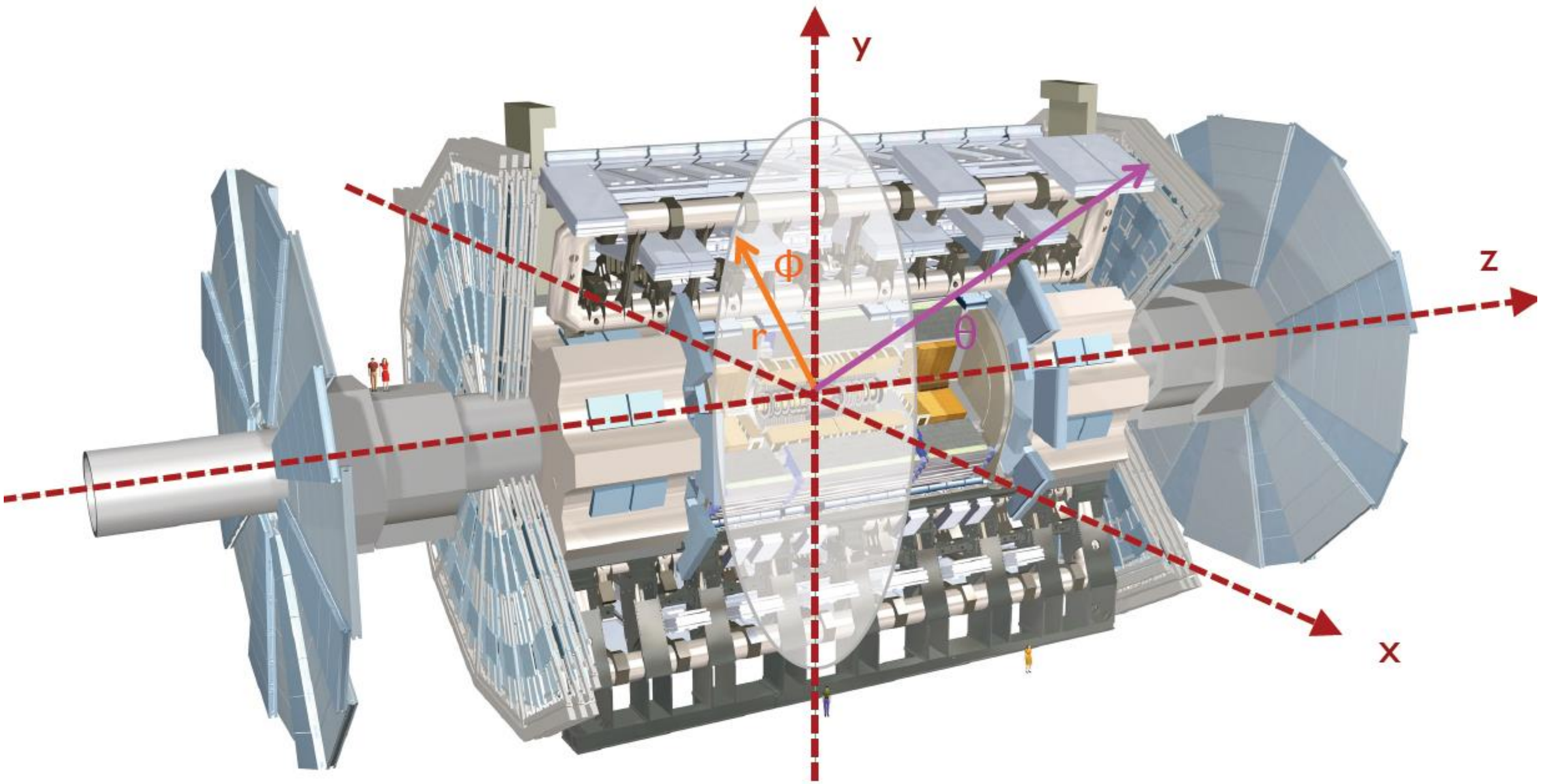
Fixed target vs collider



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

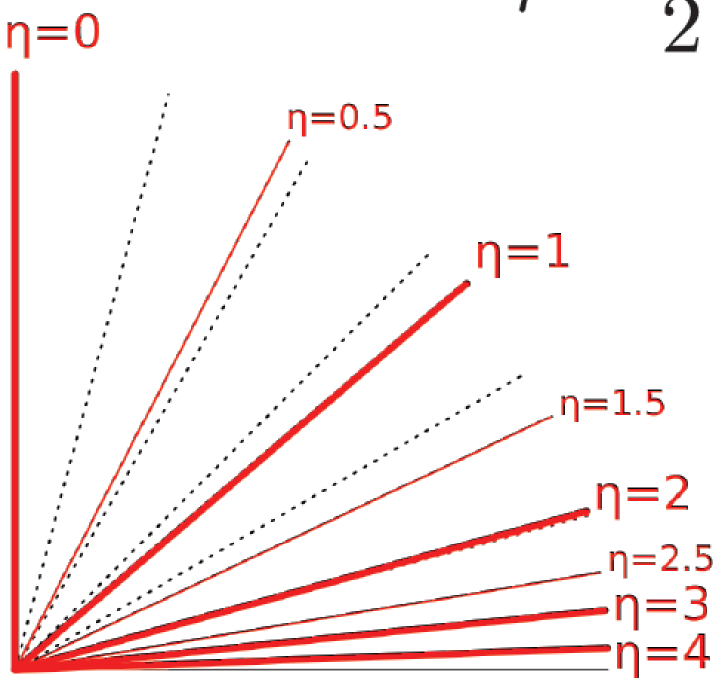
$$\eta = \frac{1}{2}\ln\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}$$

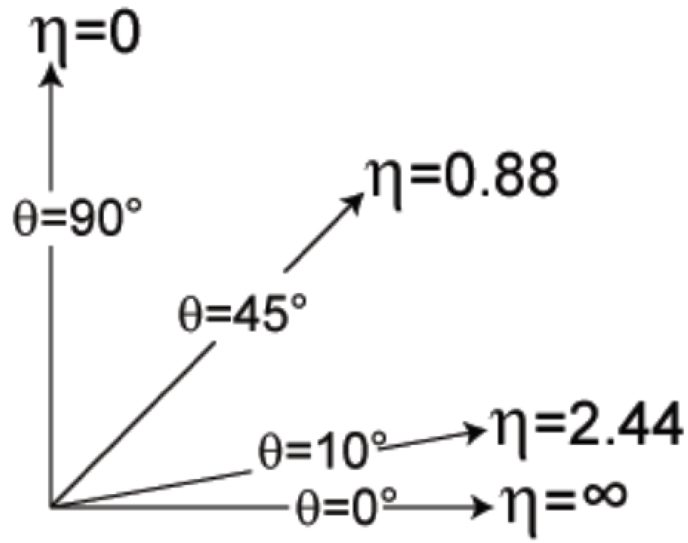
$$\eta = \frac{1}{2}\ln\left(\tan\frac{\theta}{2}\right)$$

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

$$\eta \simeq y$$

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

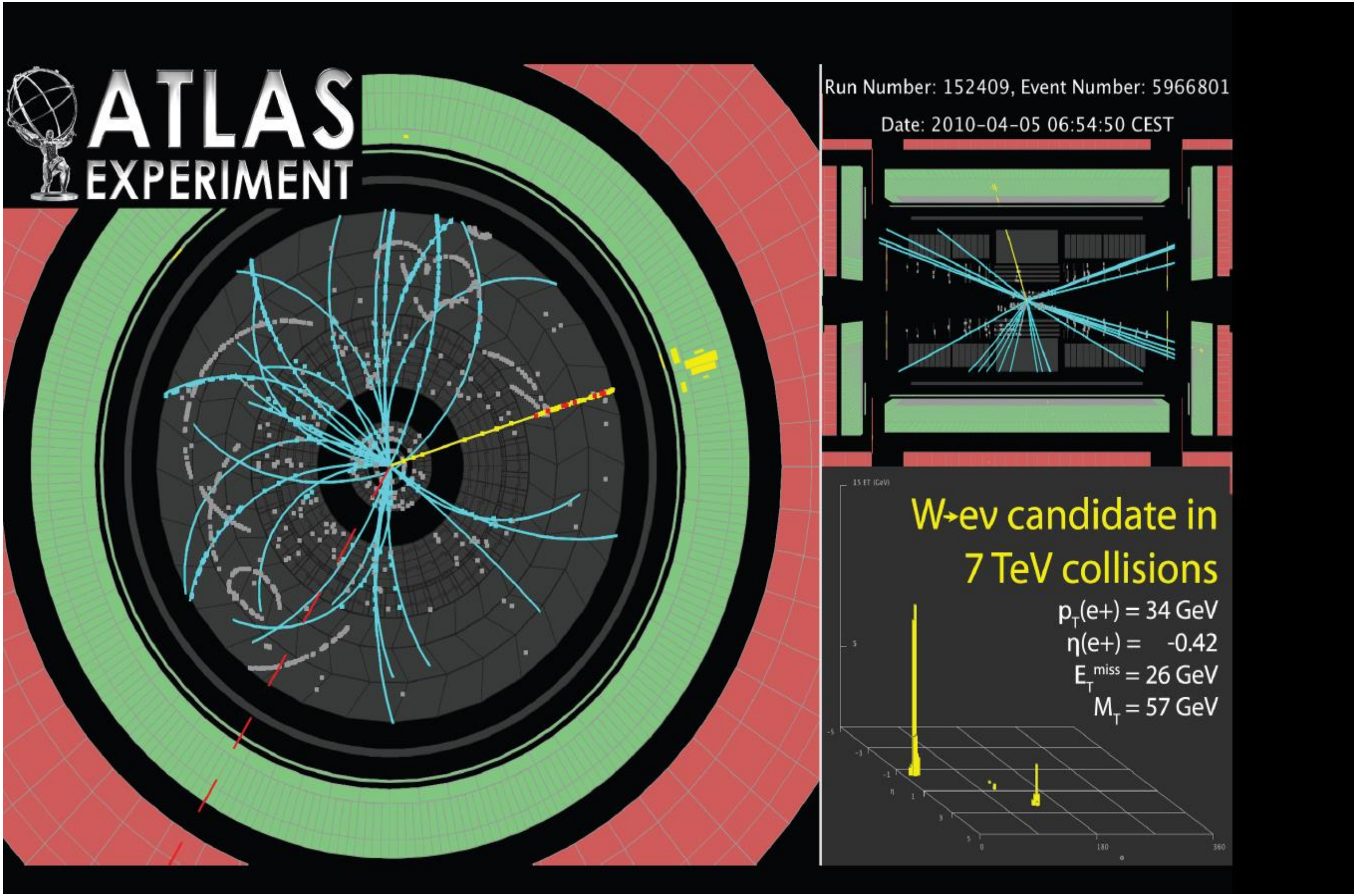
- If invisible particle are created, only their transverse momentum can be constrained: missing transverse energy

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

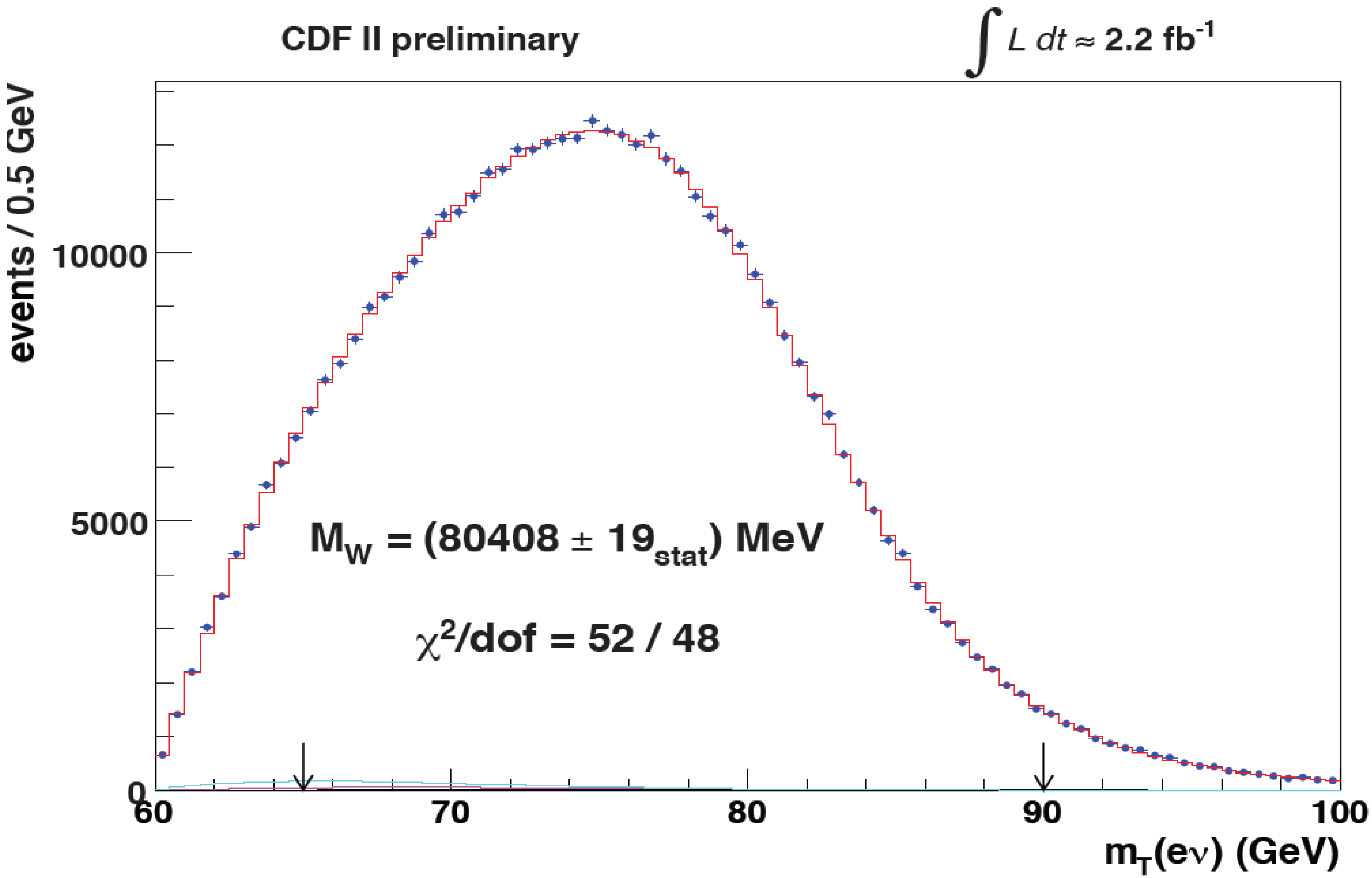
- If a heavy particle is produced and decays in two particles one of which is invisible, the mass of the parent particle can constrained with the transverse mass quantity

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

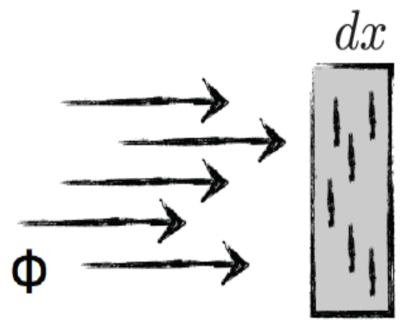
if $m_1 = m_2 = 0$ $\qquad M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1 - \cos\phi_{12})$


ATLAS
EXPERIMENT
Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST
W→eν candidate in
7 TeV collisions
pT(e+) = 34 GeV
η(e+) = -0.42
ET miss = 26 GeV
MT = 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)

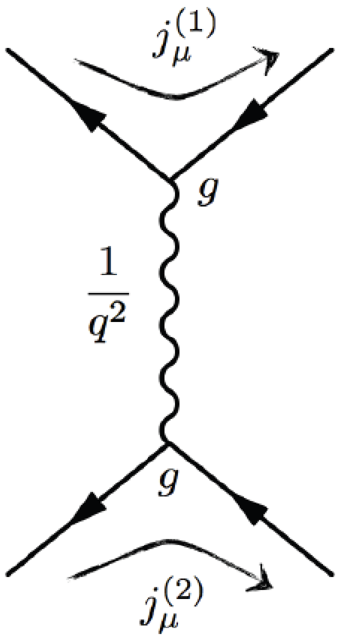
Fermi Golden rule

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]



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

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

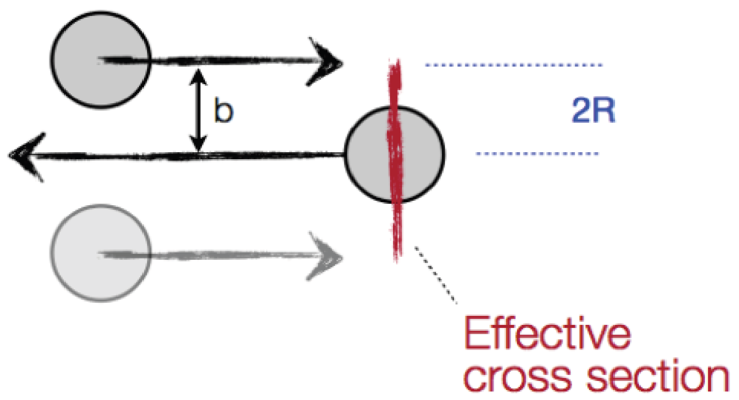
Cross-section: magnitude and units

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

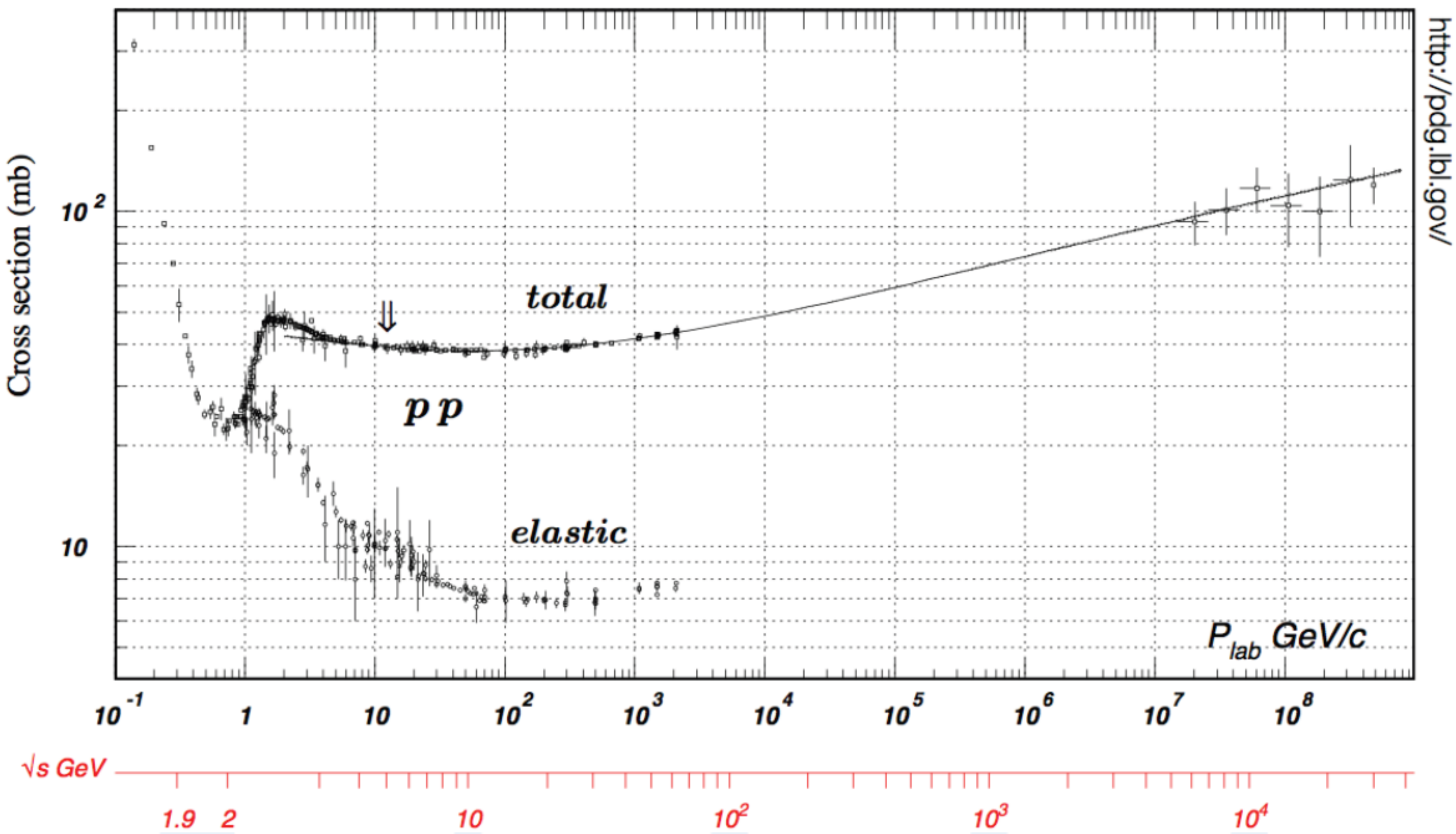
Estimating the
proton-proton cross section:



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

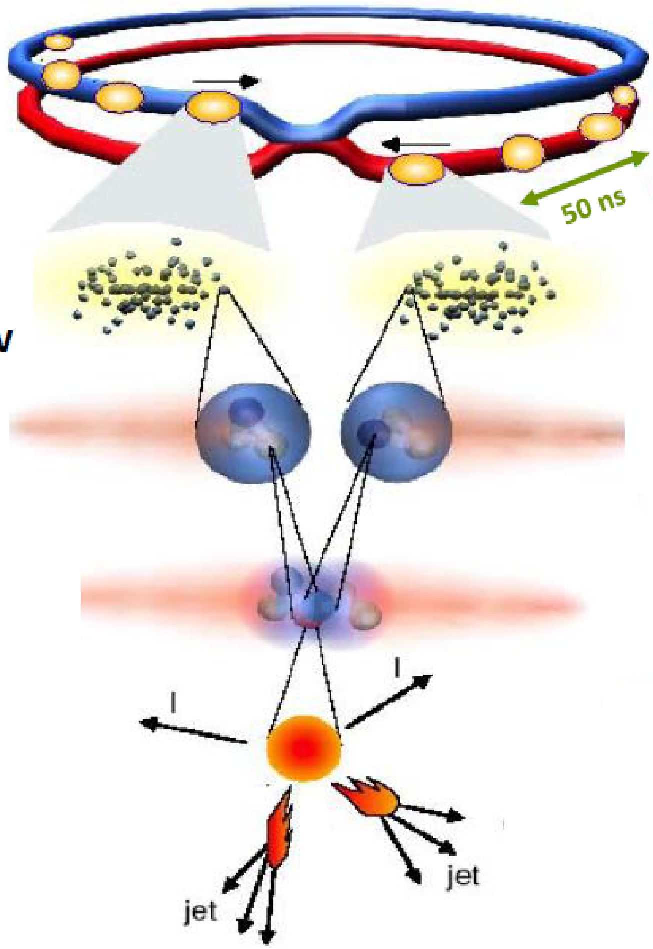
Proton-Proton 1380 paczek/wiązkę
Protonów/paczka 1.7 10^{11}
Energia wiązki 4 TeV

Paczka protonów

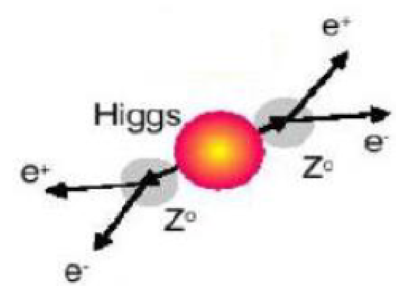
Proton

Składniki protonu

Produkty zderzeń

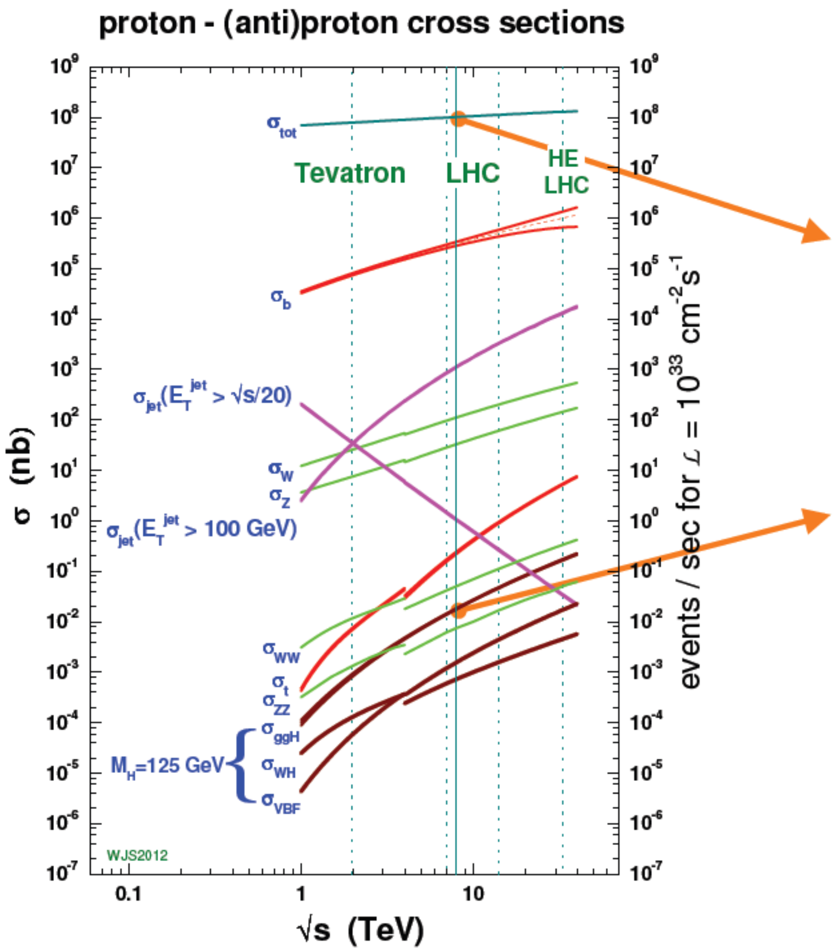


Każdy proton porusza się z prędkością bliską prędkości światła i niesie kinetyczną energię muchy w locie, okrąża pierścień akceleratora 1100 razy na sekundę.
Rozmiar poprzeczny wiązki: 16μm (4 razy mniejszy niż grubość ludzkiego włosa).
Każda z wiązek niesie energię pociągu TGV o dł. 200 m i jadącego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



Takie zdarzenie pojawia się raz na 10 bilionów 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