2025 TIDC Summer School Of Experimental High Energy Physics

2025 實驗高能物理暑期學校 6月30日–7月5日

Introduction of High-Energy Physics (HEP)
- An experimentalist’s view

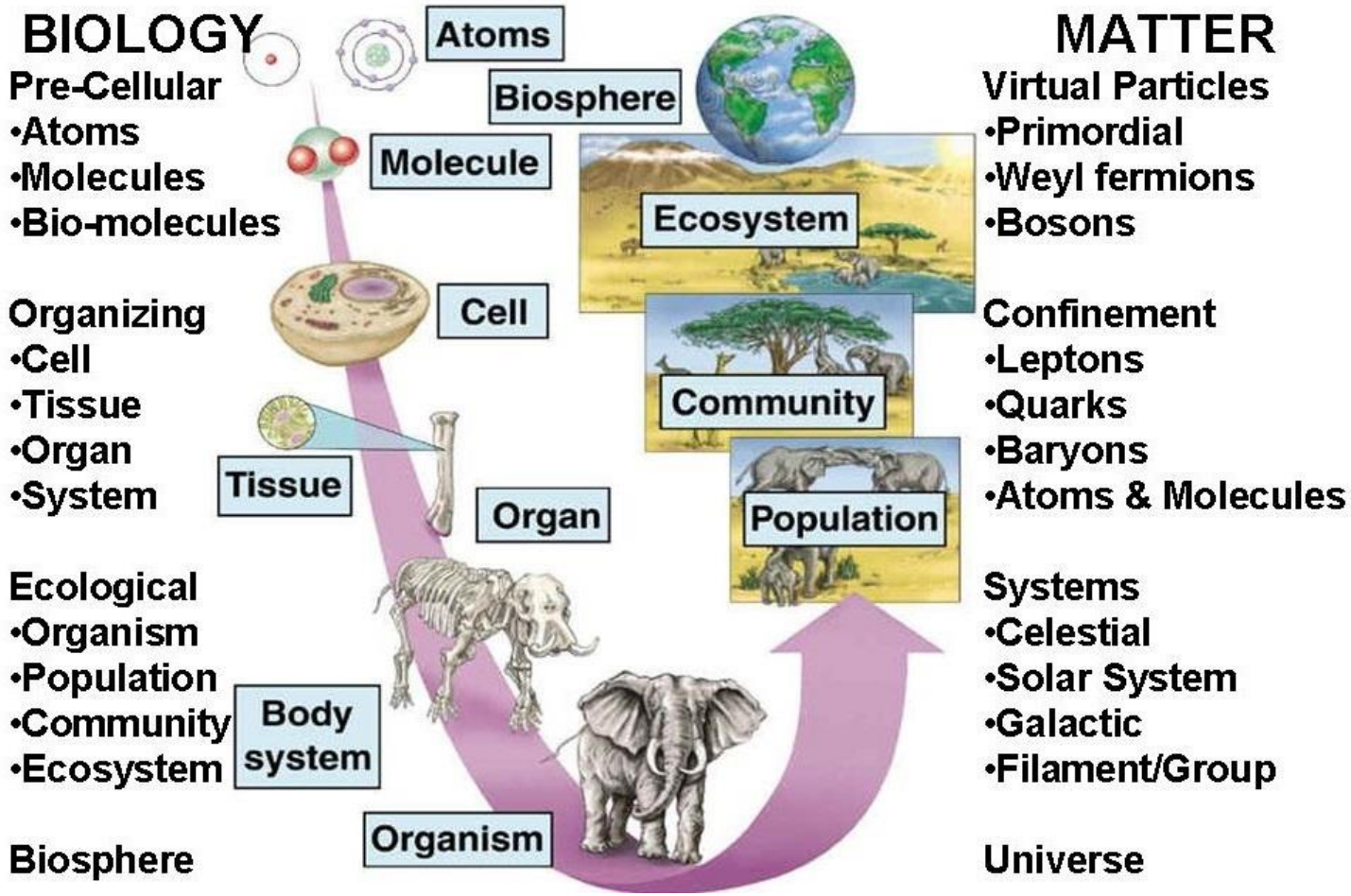
章文箴

中央研究院 物理研究所

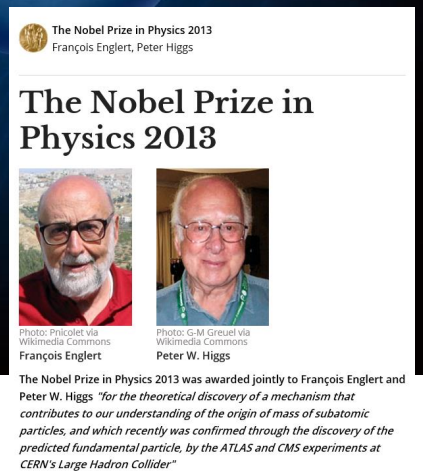
Outline

- Standard model of HEP
- Basics of experimental HEP
- Milestone experiments of HEP

Degree of Freedoms



Standard Model of High-Energy Physics



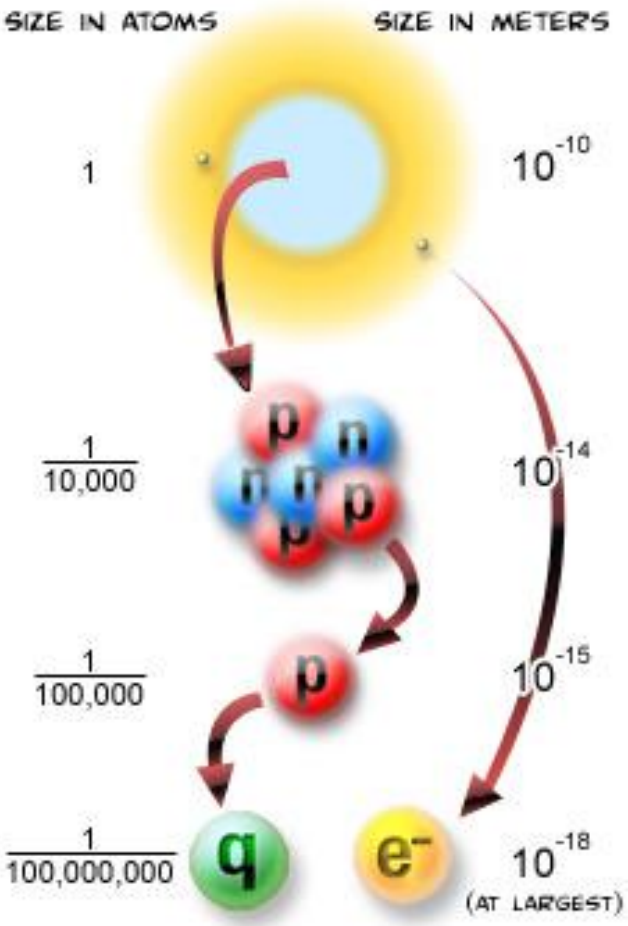
The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

Photo: Pnicolet via Wikimedia Commons
François Englert

Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*



Leptons and Quarks

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, …

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Hadrons: Mesons & Baryons

Meson

Name	Quark content	Lifetime [s]	Mass $\times c^2$ [MeV]	Main decay modes
π^+	$\{u, \bar{d}\}$	$2.6\ 10^{-8}$	139.6	$\mu^+\ \nu_\mu$
π^-	$\{d, \bar{u}\}$	$2.6\ 10^{-8}$	139.6	$\mu^-\ \bar{\nu}_\mu$
π^0	$\{u, \bar{u}\}, \{d, \bar{d}\}$	$1.2\ 10^{-17}$	135.0	$2\ \gamma$
K^+	$\{u, \bar{s}\}$	$1.2\ 10^{-8}$	473.7	$(\mu^+\ \nu_\mu), (2\pi), (3\pi)$
K^-	$\{s, \bar{u}\}$	$1.2\ 10^{-8}$	473.7	$(\mu^-\ , \bar{\nu}_\mu), (2\pi), (3\pi)$
K_l^o	$\{s\ \bar{d}\}, \{d\ \bar{s}\}$	$5.2\ 10^{-8}$	497.7	$3\ \pi$
K_s^0	$\{s, \bar{d}\}, \{d, \bar{s}\}$	$8.9\ 10^{-11}$	497.7	$2\ \pi$
proton	$\{u, u, d\}$	$>10^{32}$ year	938.3	
neutron	$\{d, d, u\}$	898	939.6	$p\ e\ \bar{\nu}_e$
Λ^0	$\{d, s, u\}$	$2.63\ 10^{-10}$	1115.7	$(n\ \pi^0), (p\ \pi^-)$
$\bar{p}$	$\{\bar{u}, \bar{u}, \bar{d}\}$	$>10^{32}$ year	938.3	
$\bar{n}$	$\{\bar{d}, \bar{d}, \bar{u}\}$	898	939.6	$\bar{p}\ e^+ \nu_e$
$\bar{\Lambda}^0$	$\{\bar{d}, \bar{s}, \bar{u}\}$	$2.63\ 10^{-10}$	1115.7	$(\bar{n}\ \pi^0), (\bar{p}\ \pi^+)$

Baryon

Fundamental Interactions & Gauge Bosons

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60
	Long range	Short range	Long range	Short range

BOSONS

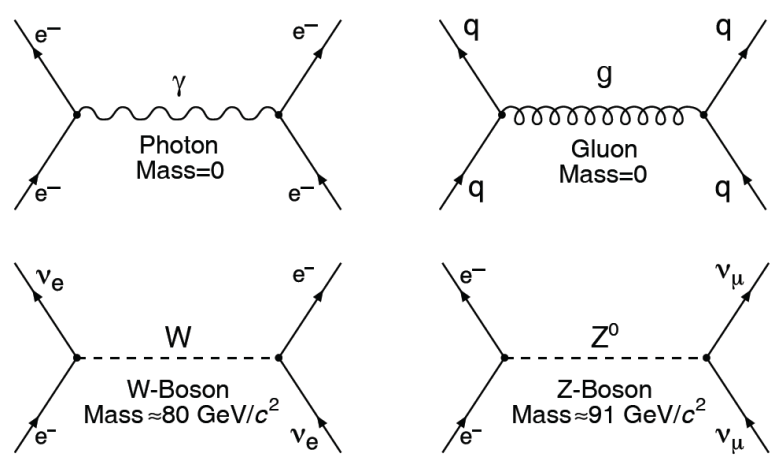
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0



Standard Model and its parameters

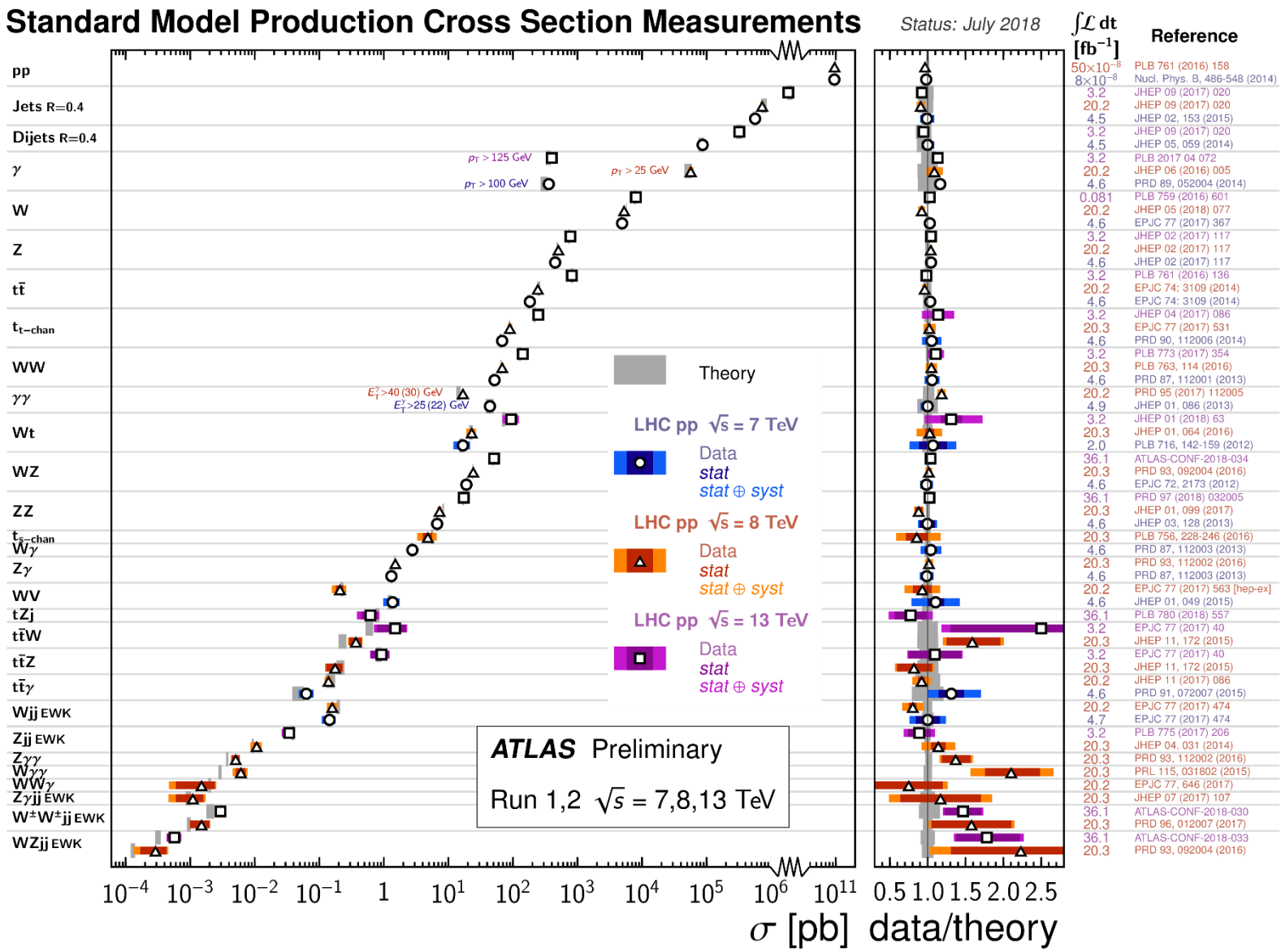
$$
\begin{aligned}
\mathcal{L}_{SM} = & -\frac{1}{2}\partial^\nu g^{a\mu}\partial_\nu g_{a\mu} - g_s f^{abc}\partial^\mu g^{a\nu} g^b_\mu g^c_\nu - \frac{1}{4} g_s^2 f^{abc} f^{ade} g^{b\mu} g^{c\nu} g^d_\mu g^e_\nu \\
& -\partial^\nu W^{+\mu}\partial_\nu W^-_\mu + m_W^2 W^{+\mu} W^-_\mu - \frac{1}{2}\partial^\nu Z^{0\mu}\partial_\nu Z^0_\mu + \frac{m_W^2}{2c_w^2} Z^{0\mu} Z^0_\mu - \frac{1}{2}\partial^\nu A^\mu \partial_\nu A_\mu + \frac{1}{2}\partial^\mu H \partial_\mu H - \frac{1}{2} m_H^2 H^2 \\
& +\partial^\nu \phi^+ \partial_\nu \phi^- - m_W^2 \phi^+\phi^- + \frac{1}{2}\partial^\nu \phi^0 \partial_\nu \phi^0 - \frac{m_W^2}{2c_w^2}(\phi^0)^2 - \beta_H\left[\frac{2m_W^2}{g^2} + \frac{2m_W}{g}H + \frac{1}{2}\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right)\right] + \frac{2m_W^4}{g^2}\alpha_H \\
& -ig c_w\left[\partial^\nu Z^{0\mu}\left(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu\right) - Z^{0\nu}\left(W^{+\mu}\partial_\nu W^-_\mu - W^{-\mu}\partial_\nu W^+_\mu\right) + Z^{0\mu}\left(W^{+\nu}\partial_\nu W^-_\mu - W^{-\nu}\partial_\nu W^+_\mu\right)\right] \\
& -ig s_w\left[\partial^\nu A^\mu\left(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu\right) - A^\nu\left(W^{+\mu}\partial_\nu W^-_\mu - W^{-\mu}\partial_\nu W^+_\mu\right) + A^\mu\left(W^{+\nu}\partial_\nu W^-_\mu - W^{-\nu}\partial_\nu W^+_\mu\right)\right] \\
& -\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\left(Z^{0\mu} W^+_\mu Z^{0\nu} W^-_\nu - Z^{0\mu} Z^0_\mu W^{+\nu} W^-_\nu\right) \\
& +g^2 s_w^2\left(A^\mu W^+_\mu A^\nu W^-_\nu - A^\mu A_\mu W^{+\nu} W^-_\nu\right) + g^2 s_w c_w\left[A^\mu Z^{0\nu}\left(W^+_\mu W^-_\nu + W^+_\nu W^-_\mu\right) - 2A^\mu Z^0_\mu W^{+\nu} W^-_\nu\right] \\
& -g\alpha_H m_W\left[H^3 + H(\phi^0)^2 + 2H\phi^+\phi^-\right] - \frac{1}{8}g^2\alpha_H\left[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 2H^2(\phi^0)^2 + 4H^2\phi^+\phi^-\right] \\
& +g m_W W^{+\mu} W^-_\mu H + \frac{1}{2}g\frac{m_W}{c_w^2} Z^{0\mu} Z^0_\mu H + \frac{1}{2}ig\left[W^{+\mu}\left(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0\right) - W^{-\mu}\left(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0\right)\right] \\
& -\frac{1}{2}g\left[W^{+\mu}\left(H\partial_\mu\phi^- - \phi^-\partial_\mu H\right) + W^{-\mu}\left(H\partial_\mu\phi^+ - \phi^+\partial_\mu H\right)\right] - \frac{1}{2}\frac{g}{c_w} Z^{0\mu}\left(H\partial_\mu\phi^0 - \phi^0\partial_\mu H\right) \\
& +ig\frac{s_w^2}{c_w} m_W Z^{0\mu}\left(W^+_\mu\phi^- - W^-_\mu\phi^+\right) - ig s_w m_W A^\mu\left(W^+_\mu\phi^- - W^-_\mu\phi^+\right) \\
& +ig\frac{s_w^2 - c_w^2}{2c_w} Z^{0\mu}\left(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+\right) - ig s_w A^\mu\left(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+\right) \\
& +\frac{1}{4}g^2 W^{+\mu} W^-_\mu\left[H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right] + \frac{1}{8}\frac{g^2}{c_w^2} Z^{0\mu} Z^0_\mu\left[H^2 + (\phi^0)^2 + 2\left(s_w^2 - c_w^2\right)\phi^+\phi^-\right] \\
& +\frac{1}{2}g^2\frac{s_w^2}{c_w} Z^{0\mu}\phi^0\left[W^+_\mu\phi^- + W^-_\mu\phi^+\right] + \frac{1}{2}ig^2\frac{s_w^2}{c_w} Z^{0\mu} H\left[W^+_\mu\phi^- - W^-_\mu\phi^+\right] - \frac{1}{2}g^2 s_w A^\mu\phi^0\left[W^+_\mu\phi^- + W^-_\mu\phi^+\right] \\
& -\frac{1}{2}ig^2 s_w A^\mu H\left[W^+_\mu\phi^- - W^-_\mu\phi^+\right] + g^2\frac{s_w}{c_w}\left(c_w^2 - s_w^2\right) A^\mu Z^0_\mu\phi^+\phi^- + g^2 s_w^2 A^\mu A_\mu\phi^+\phi^- \\
& +\bar{\nu}^\sigma\left(i\gamma^\mu\partial_\mu - m_e^\sigma\right)e^\sigma + \bar{\nu}^\sigma i\gamma^\mu\partial_\mu\nu^\sigma + \bar{d}^\sigma_j\left(i\gamma^\mu\partial_\mu - m_d^\sigma\right)d^\sigma_j + \bar{u}^\sigma_j\left(i\gamma^\mu\partial_\mu - m_u^\sigma\right)u^\sigma_j \\
& +g s_w A^\mu\left[-\left(\bar{\nu}^\sigma\gamma_\mu e^\sigma\right) - \frac{1}{3}\left(\bar{d}^\sigma_j\gamma_\mu d^\sigma_j\right) + \frac{2}{3}\left(\bar{u}^\sigma_j\gamma_\mu u^\sigma_j\right)\right] + \frac{g}{4c_w} Z^{0\mu}\left[\left(\bar{\nu}^\sigma\gamma_\mu\left(1-\gamma^5\right)\nu^\sigma\right) + \left(\bar{e}^\sigma\gamma_\mu\left(4s_w^2 - \left(1-\gamma^5\right)\right)e^\sigma\right)\right. \\
& \left.+\left(\bar{d}^\sigma_j\gamma_\mu\left(\frac{4}{3}s_w^2 - \left(1-\gamma^5\right)\right)d^\sigma_j\right) + \left(\bar{u}^\sigma_j\gamma_\mu\left(-\frac{8}{3}s_w^2 + \left(1-\gamma^5\right)\right)u^\sigma_j\right)\right] \\
& +\frac{g}{2\sqrt{2}} W^{+\mu}\left[\left(\bar{\nu}^\sigma\gamma_\mu\left(1-\gamma^5\right)P^{\sigma\tau}e^\tau\right) + \left(\bar{u}^\sigma_j\gamma_\mu\left(1-\gamma^5\right)C^{\sigma\tau}d^\tau_j\right)\right] \\
& +\frac{g}{2\sqrt{2}} W^{-\mu}\left[\left(\bar{e}^\sigma\gamma_\mu\left(1-\gamma^5\right)P^{\dagger\sigma\tau}\nu^\tau\right) + \left(\bar{d}^\sigma_j\gamma_\mu\left(1-\gamma^5\right)C^{\dagger\sigma\tau}u^\tau_j\right)\right] \\
& +i\frac{g}{2\sqrt{2}}\frac{m_e^\sigma}{m_W}\left[-\phi^+\left(\bar{\nu}^\sigma\left(1+\gamma^5\right)e^\sigma\right) + \phi^-\left(\bar{e}^\sigma\left(1-\gamma^5\right)\nu^\sigma\right)\right] - \frac{g}{2}\frac{m_e^\sigma}{m_W}\left[H\bar{e}^\sigma e^\sigma - i\phi^0\bar{e}^\sigma\gamma^5 e^\sigma\right] \\
& +i\frac{g}{2\sqrt{2}\,m_W}\phi^+\left[-m_d^\tau\left(\bar{u}^\sigma_j C^{\sigma\tau}\left(1+\gamma^5\right)d^\tau_j\right) + m_u^\tau\left(\bar{u}^\sigma_j C^{\sigma\tau}\left(1-\gamma^5\right)d^\tau_j\right)\right] \\
& +i\frac{g}{2\sqrt{2}\,m_W}\phi^-\left[m_d^\tau\left(\bar{d}^\sigma_j C^{\dagger\sigma\tau}\left(1-\gamma^5\right)u^\tau_j\right) - m_u^\tau\left(\bar{d}^\sigma_j C^{\dagger\sigma\tau}\left(1+\gamma^5\right)u^\tau_j\right)\right] \\
& -\frac{g}{2}\frac{m_u^\sigma}{m_W} H\bar{u}^\sigma_j u^\sigma_j - \frac{g}{2}\frac{m_d^\sigma}{m_W} H\bar{d}^\sigma_j d^\sigma_j - i\frac{g}{2}\frac{m_u^\sigma}{m_W}\phi^0\bar{u}^\sigma_j\gamma^5 u^\sigma_j + i\frac{g}{2}\frac{m_d^\sigma}{m_W}\phi^0\bar{d}^\sigma_j\gamma^5 d^\sigma_j \\
& -\frac{1}{2}i g_s\bar{d}^\sigma_i\gamma^\mu\lambda^a_{ij} d^\sigma_j g^a_\mu - \frac{1}{2}i g_s\bar{u}^\sigma_i\gamma^\mu\lambda^a_{ij} u^\sigma_j g^a_\mu \\
& -\bar{X}^+\left(\partial^\mu\partial_\mu + m_W^2\right)X^+ - \bar{X}^-\left(\partial^\mu\partial_\mu + m_W^2\right)X^- - \bar{X}^0\left(\partial^\mu\partial_\mu + \frac{m_W^2}{c_w^2}\right)X^- - \bar{Y}\partial^\mu\partial_\mu Y \\
& -ig c_w W^{+\mu}\left(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0\right) - ig s_w W^{+\mu}\left(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y\right) \\
& -ig c_w W^{-\mu}\left(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+\right) - ig s_w W^{-\mu}\left(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+\right) \\
& -ig c_w Z^{0\mu}\left(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-\right) - ig s_w A^\mu\left(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-\right) \\
& -\frac{1}{2}g m_W\left[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H\right] \\
& +\frac{s_w^2 - c_w^2}{2c_w} i g m_W\left[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right] + \frac{1}{2c_w} i g m_W\left[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right] \\
& +i g m_W s_w\left[\bar{X}^- Y\phi^- - \bar{X}^+ Y\phi^+\right] + i\frac{1}{2}g m_W\left[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right] \\
& -\bar{G}^a\partial^\mu\partial_\mu G^a - g_s f^{abc}\partial^\mu\bar{G}^a G^b g^c_\mu
\end{aligned}
$$

m_u $2.14^{+0.49}_{-0.26}$ MeV/c^2	m_c 1.27 ± 0.02 GeV/c^2	m_t 172.9 ± 0.4 GeV/c^2	
m_d $4.67^{+0.48}_{-0.17}$ MeV/c^2	m_s 93^{+11}_{-5} MeV/c^2	m_b $4.18^{+0.03}_{-0.02}$ GeV/c^2	
m_e 0.5109989461(31) MeV/c^2	m_μ 105.6583745(24) MeV/c^2	m_τ 1776.86(0.12) MeV/c^2	
M_Z 91.1876 ± 0.0021 GeV/c^2	M_H 125.10 ± 0.14 GeV/c^2		
α $7.2973525664(17) \times 10^{-3}$	G_F $1.1663787(6) \times 10^{-5}$ GeV^{-2}	$\alpha_s(M_Z)$ 0.1179(10)	
λ 0.22453 ± 0.00044	A 0.836 ± 0.015	ρ 0.122 ± 0.0175	η 0.355 ± 0.0115
Derived quantities	$\sin^2\theta_W$ 0.23129 ± 0.00005	$M_W = M_z \cos\theta_w$ 80.385 ± 0.015 GeV/c^2	$\sin^2 2\theta_w = \frac{\alpha\pi}{8G_F M_Z^2}$

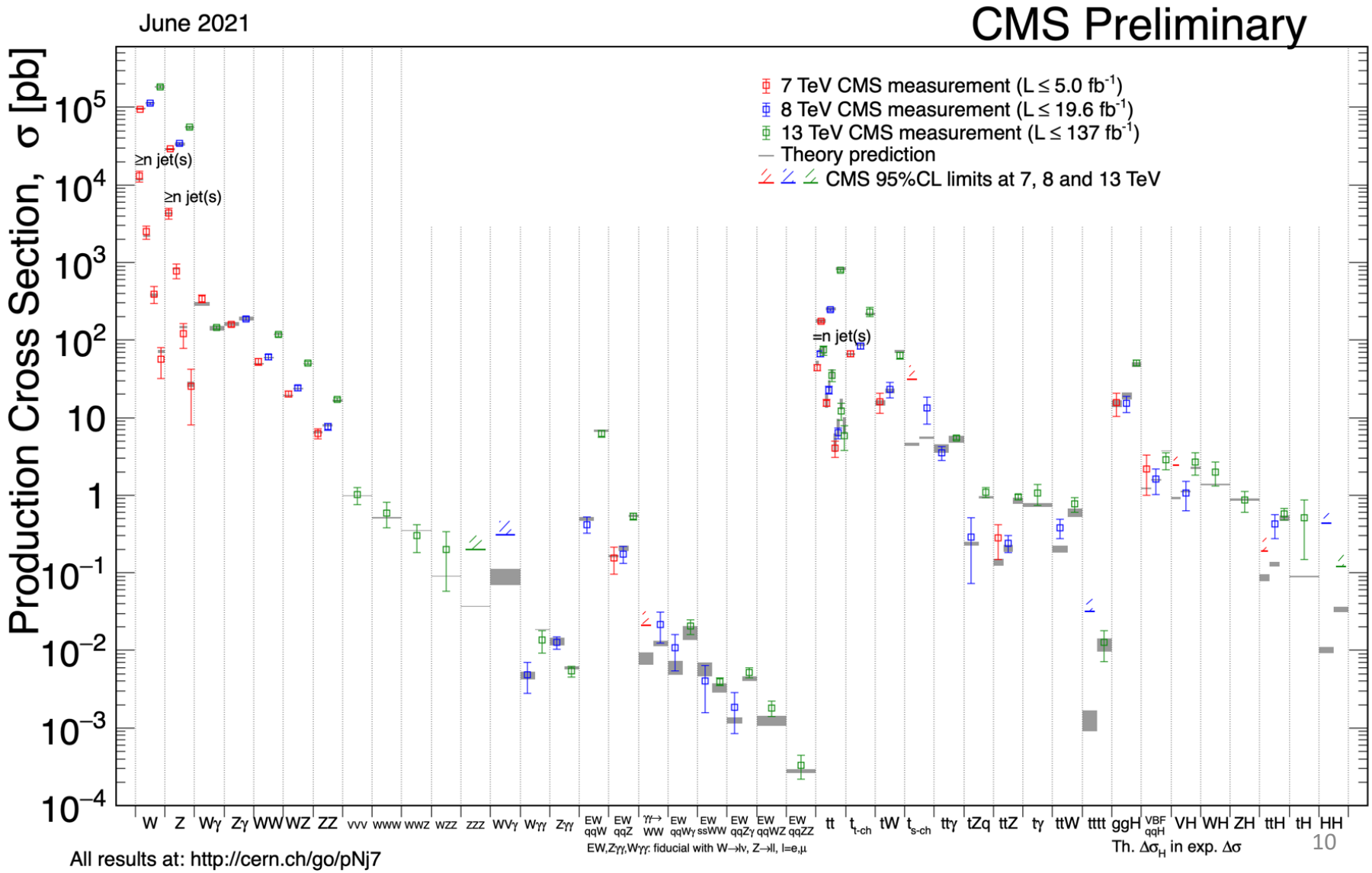
1. The quark masses (m_u, m_d), (m_c, m_s), (m_t, m_b);
2. the charged lepton masses m_e, m_μ, m_τ;
3. the Z^0 mass M_Z;
4. the Higgs Mass M_H;
5. the electromagnetic coupling constant α;
6. the strong coupling constant $\alpha_s(M_Z)$;
7. the weak coupling constant G_F; and
8. the Cabibbo-Kobayashi-Maskawa (CKM) parameters in the Wolfenstein parametrization λ, A, ρ and η.

https://link.springer.com/chapter/10.1007/978-3-030-38207-0_10

Test of Standard Model



Test of Standard Model



2025 TIDC Summer School

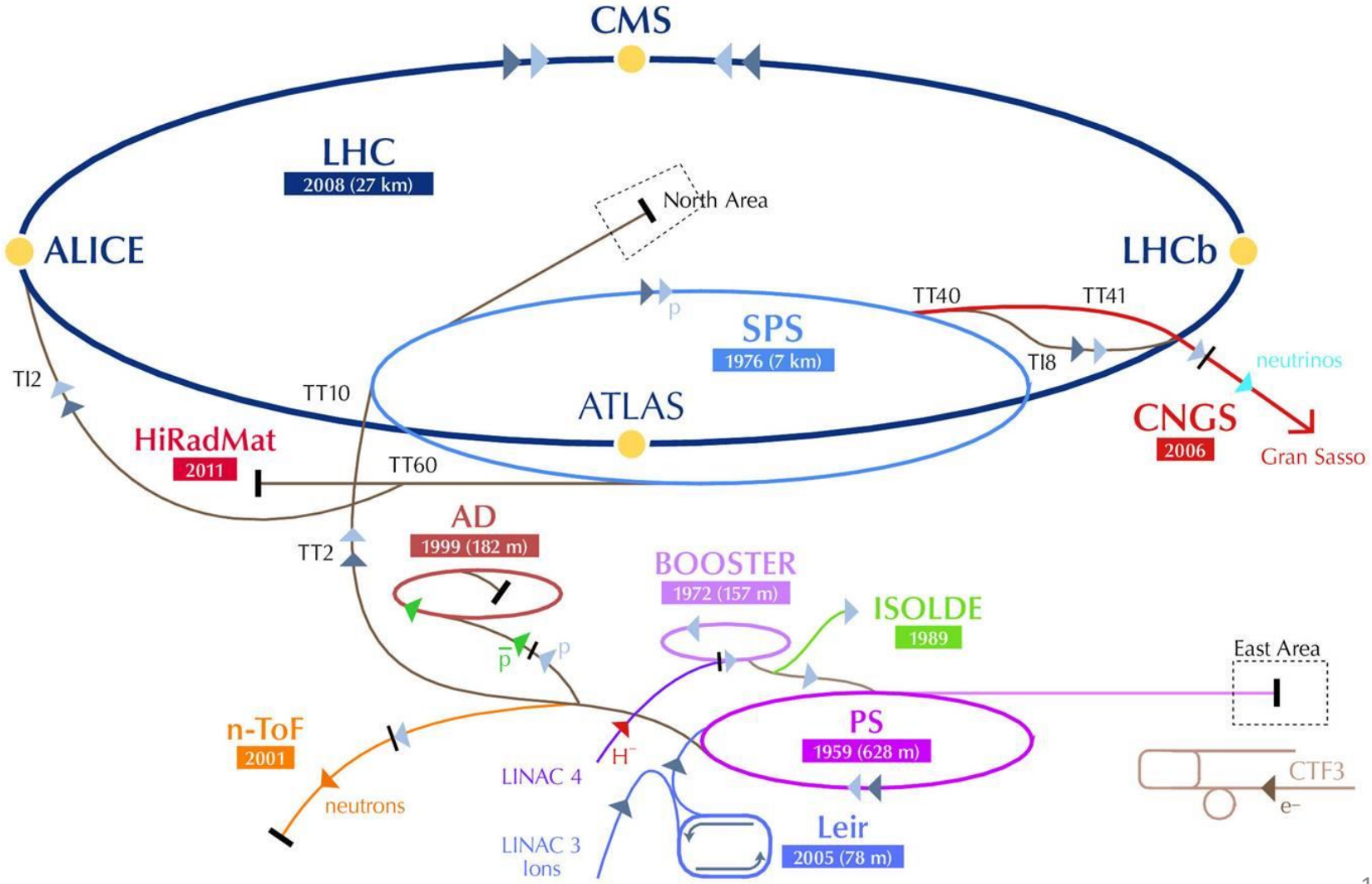
	Mon / Jun 30, 2025	Tue / Jul 1, 2025	Wed / Jul 2, 2025	Thu / Jul 3, 2025	Fri / Jul 4, 2025	Sat / Jul 5, 2025
8:40 ~ 9:00	Registration					
9:00 ~ 10:00	Opening ——— Rong-Shyang Lu (NTU)	Particle Detectors I ——— Prof. Minzu Wang (NTU)	Particle Detectors II ——— rof. Minzu Wang (NTU)	Statistics in HEP ——— Prof. Pin-Jung Chiu (NTU)	LHC Physics ——— Prof. Chia-Ming Kuo (NCU)	
10:00 ~ 10:20	COFFEE BREAK					
10:20 ~ 11:20	Introduction to High-Energy Physics I ——— Prof. Wen-Chen Chang (AS)	Particle Physics I ——— Prof. Jiunn-Wei Chen (NTU)	Particle Detectors III ——— rof. Minzu Wang (NTU)	Statistics in HEP ——— Prof. Pin-Jung Chiu (NTU)	LHC Physics ——— Prof. Chia-Ming Kuo (NCU)	
11:20 ~ 12:20	Introduction to High-Energy Physics II ——— Prof. Wen-Chen Chang (AS)	Particle Physics II ——— Prof. Jiunn-Wei Chen (NTU)	Axion DM and Haloscope exp. ——— Prof. Yung-Fu Chen (NCU)	Cosmic ray and AMS exp. ——— Dr. Hsin-Yi Chou (AS)	EIC Physics ——— Prof. Chia-Ming Kuo (NCU)	
12:20 ~ 13:30	LUNCH BREAK					13:30 Sign In
13:30 ~ 17:30	EXERCISES					
	Linux / ROOT	GEANT4 Simulation	Silicon Detector/ Alibava	Scintillator + SiPM	Machine Learning	Student Report
	Prof. Kai-Feng Chen (NTU)	Prof. Rong-Shyang Lu (NTU)		Prof. Chia-Ming Kuo (NCU)	Prof. Kai-Feng Chen (NTU)	
18:00 ~	RECEPTION				BANQUET	

Experimental HEP

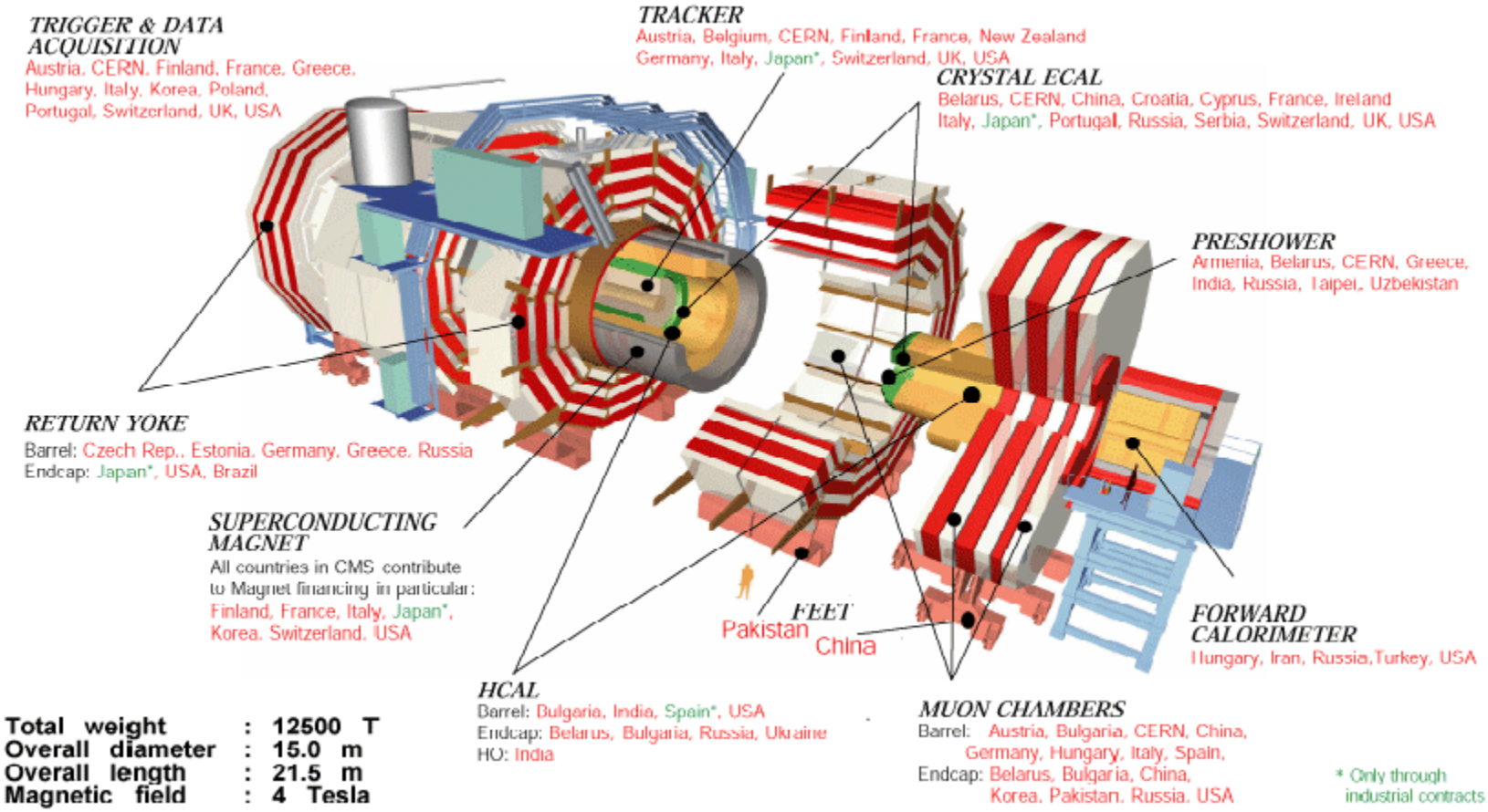
- **Accelerator**: high-energy and high-flux collisions
- **Particle Detectors** (Scintillator, Silicon, …)
- **Front End Electronics** (SiPM)
- **Trigger & Data acquisition system** (DAQ)
- **Data Analysis** (Machine learning)
  - Calibration & Data Reduction
  - ROOT Analysis (Linux/ROOT)
  - Monte-Carlo Simulation (GEANT4)
  - Error estimation

CERN Accelerator Complex

Watch the video on http://home.web.cern.ch/about/accelerators

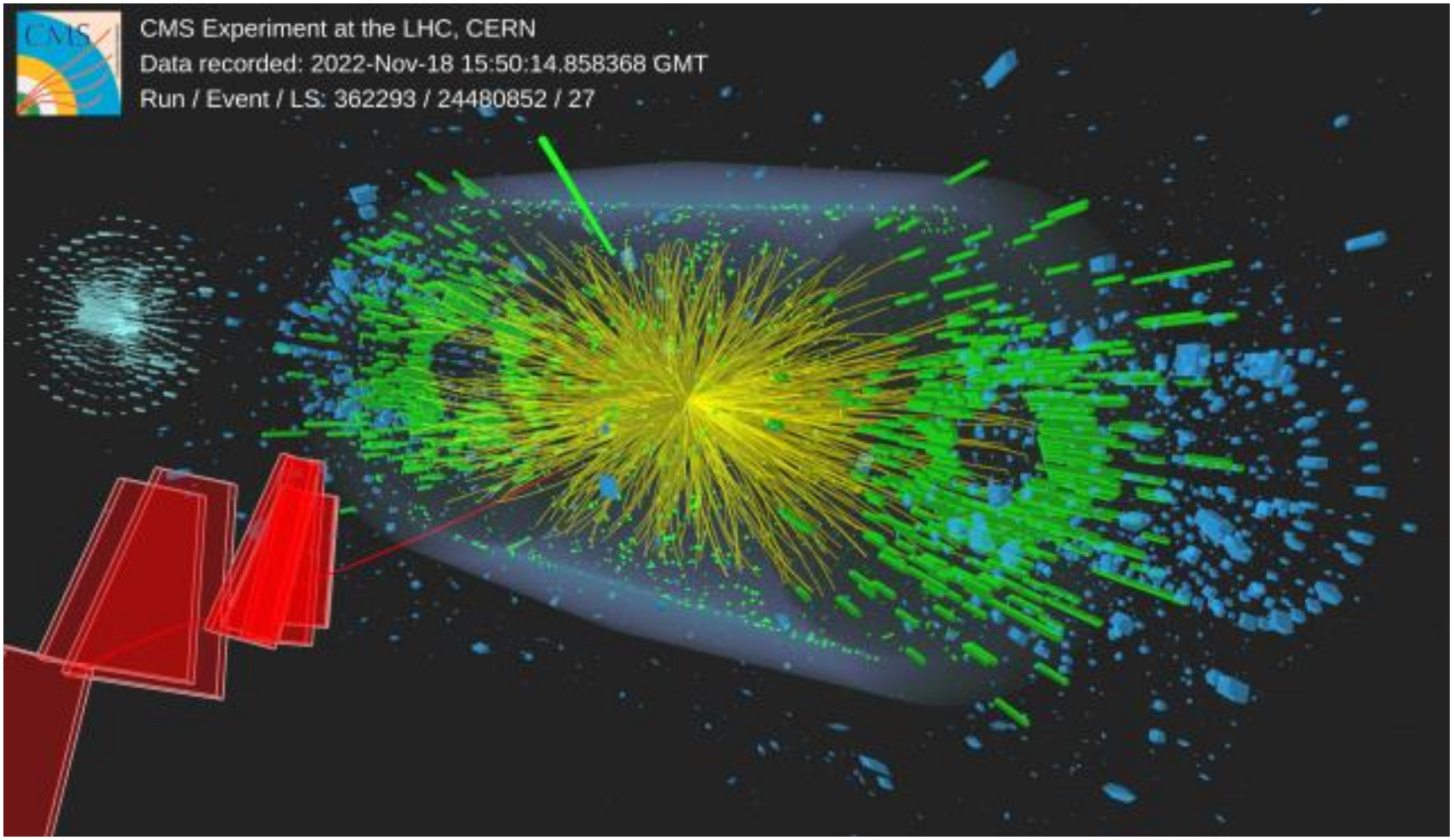


CMS Detectors

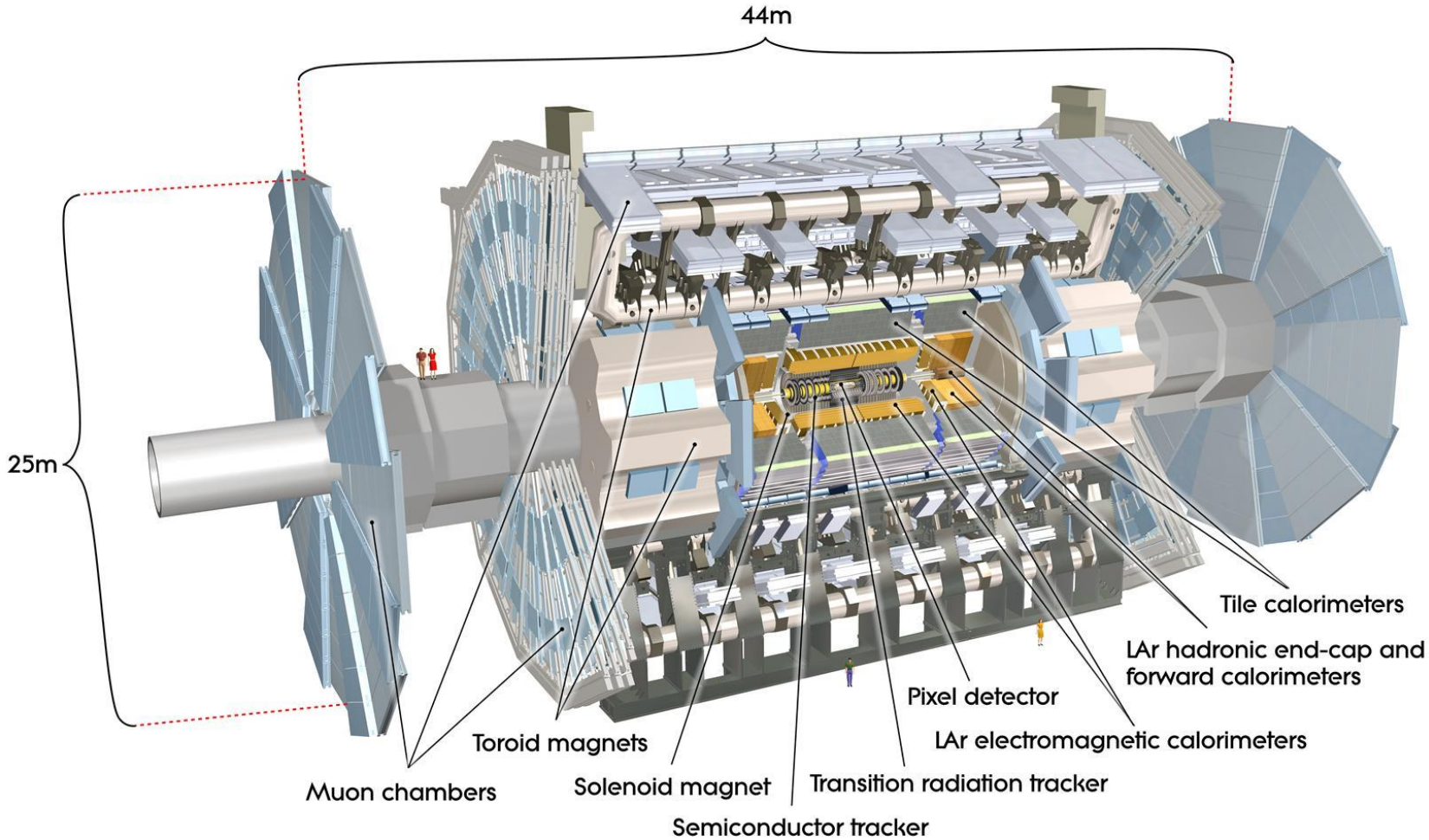


https://twiki.cern.ch/twiki/bin/view/CMSPublic/WorkBookCMSExperiment

Collision and Reconstruction



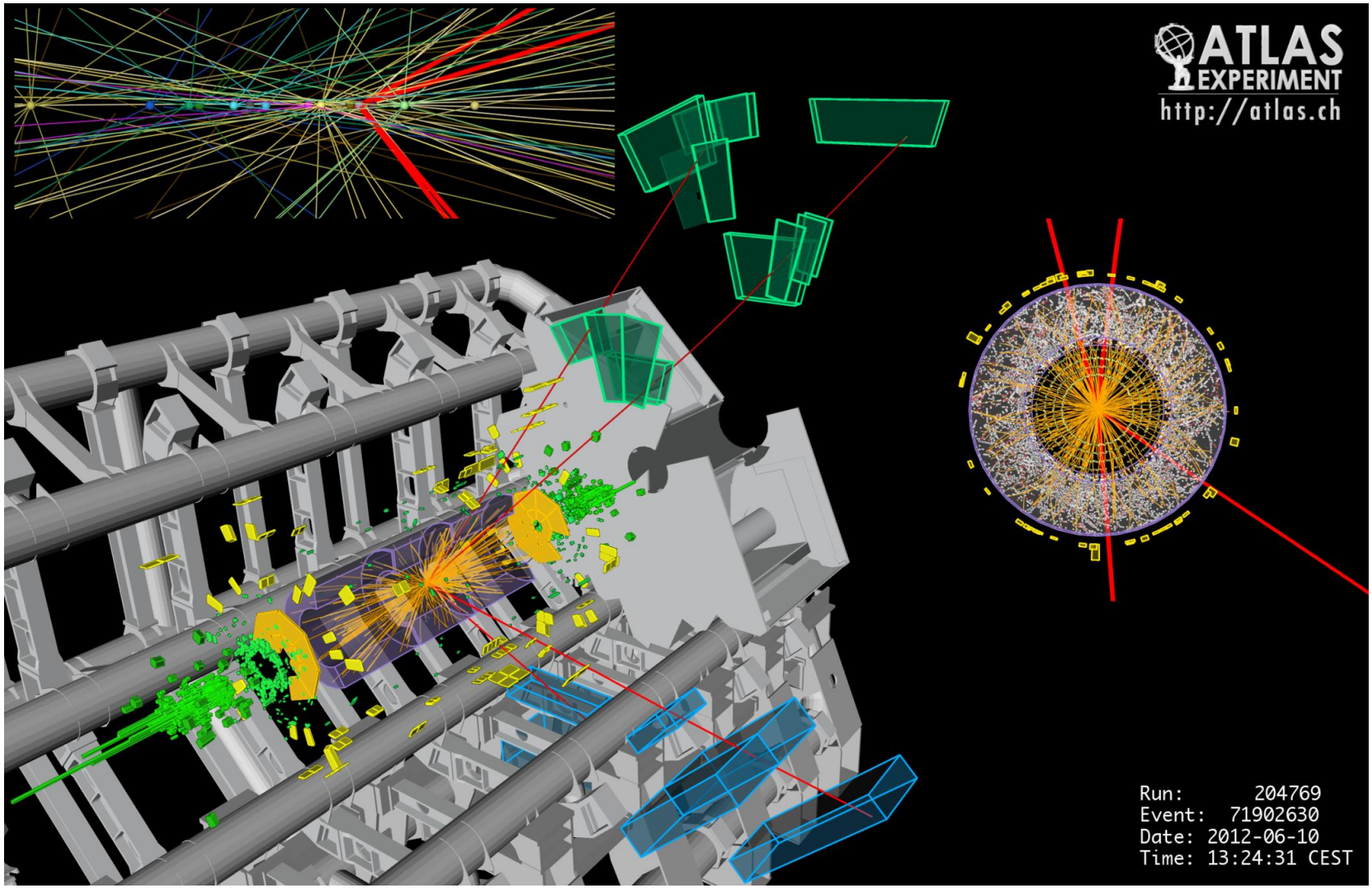
ATLAS Detectors



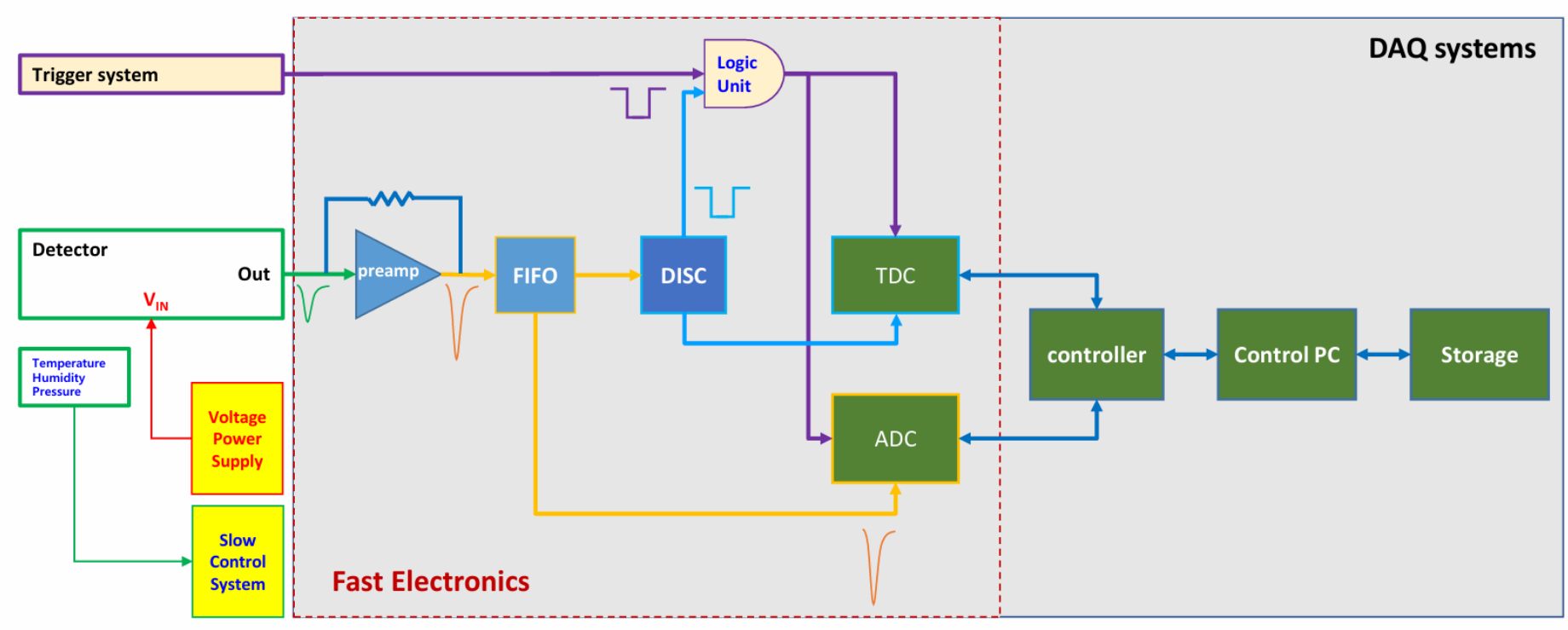
https://atlasopendata.docs.cern.ch/docs/documentation/introduction/introduction_ATLAS/#the-atlas-detector

Take a virtual walk!

Collision and Reconstruction



Detectors, FEMs, Trigger and DAQ (Online)



https://indico.knu.ac.kr/event/698/contributions/1027/attachments/925/1518/20240117%20-%20DAQ%20with%20Fast%20Electronics%20-%20mryu.pdf

Digital Camera

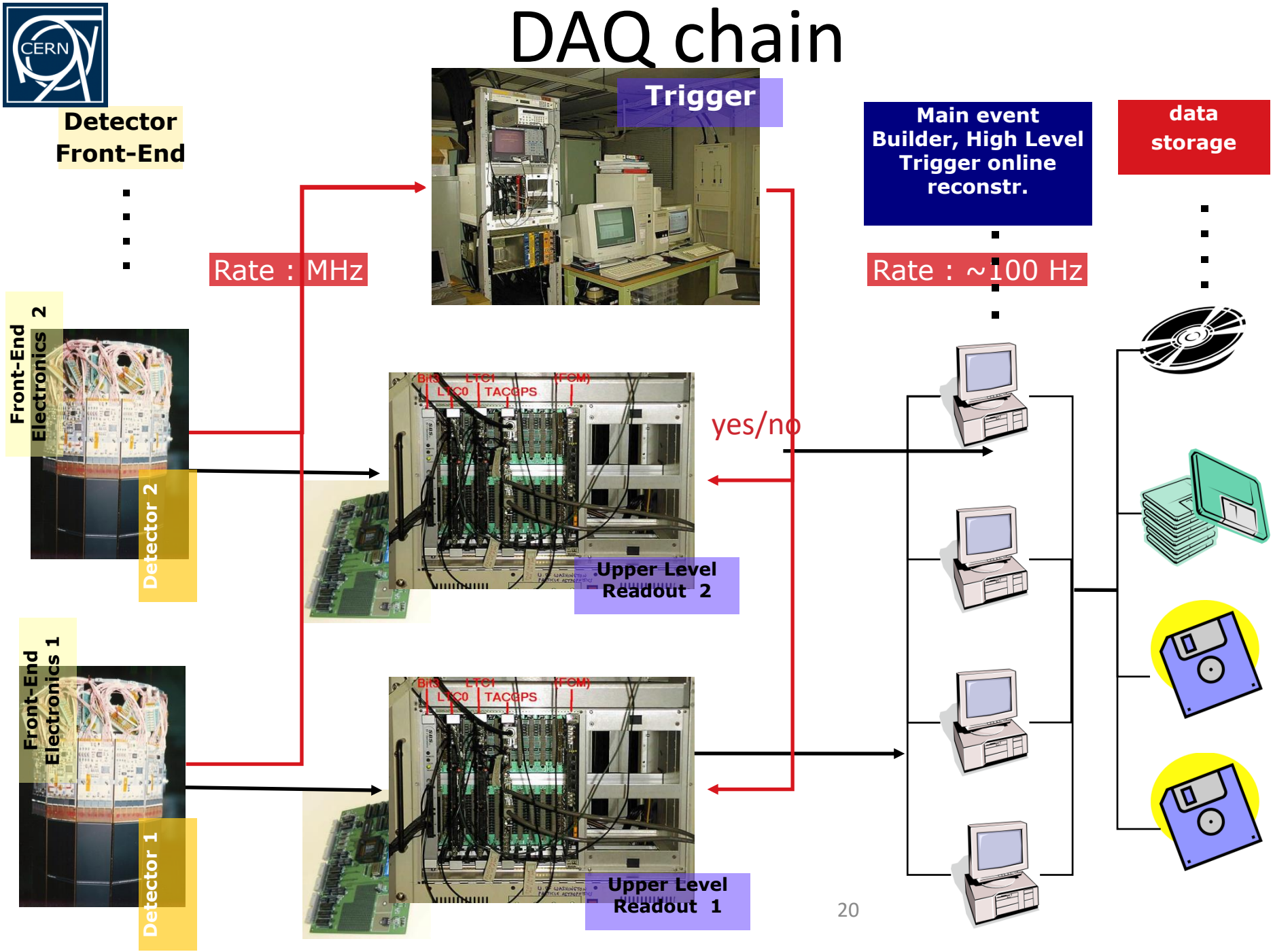
Display (LCD): online and offline monitoring system

Push-button: trigger

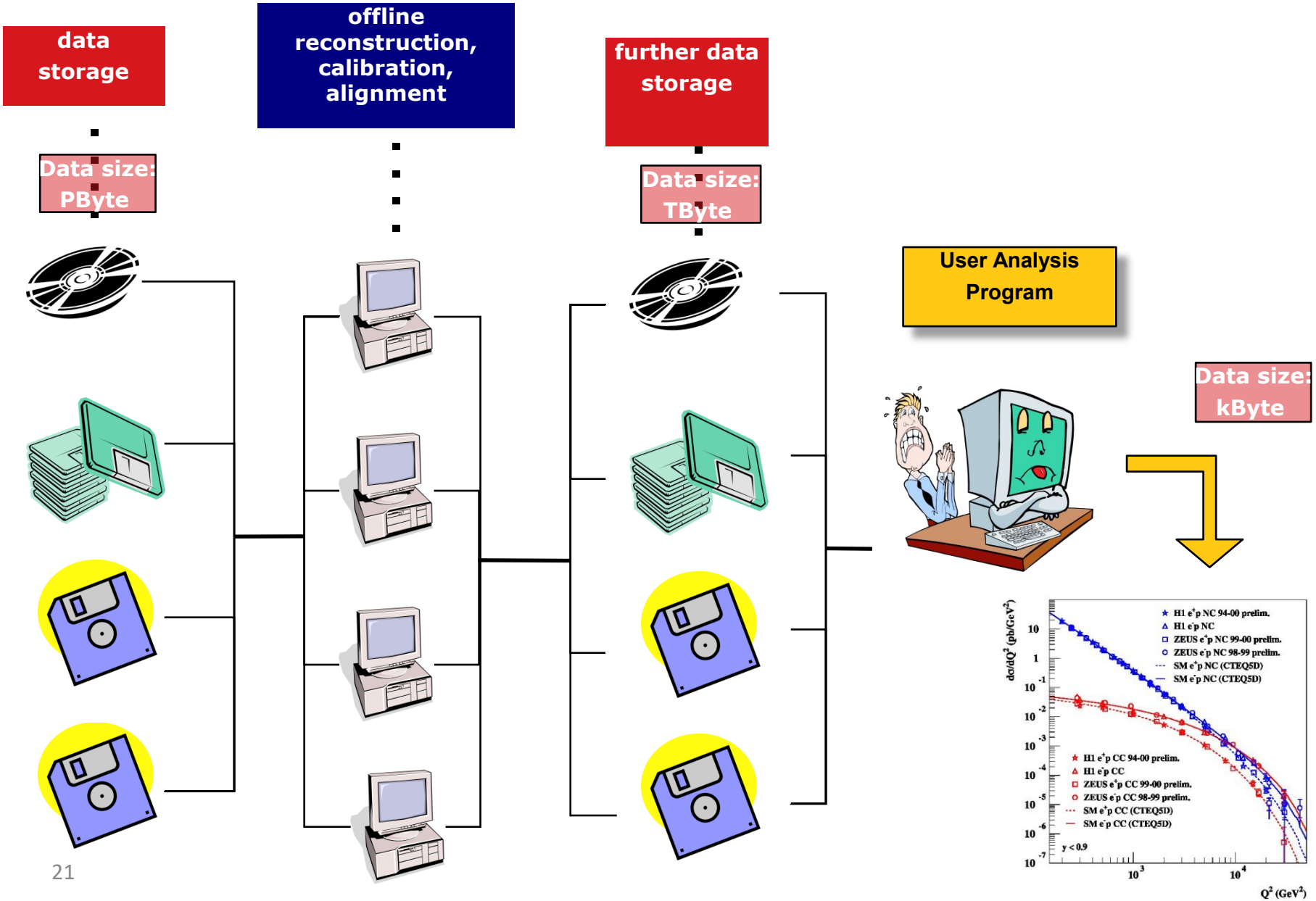
Memory card: storage

Sensor (CCD): detector & front-end electronics

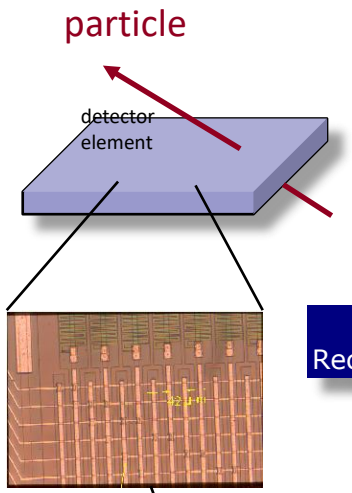
DAQ chain


Detector
Front-End
Trigger
Main event
Builder, High Level
Trigger online
reconstr.
data
storage
Rate : MHz
Rate : ~100 Hz
Front-End
Electronics 2
Detector 2
Front-End
Electronics 1
Detector 1
yes/no
Upper Level
Readout 2
Upper Level
Readout 1

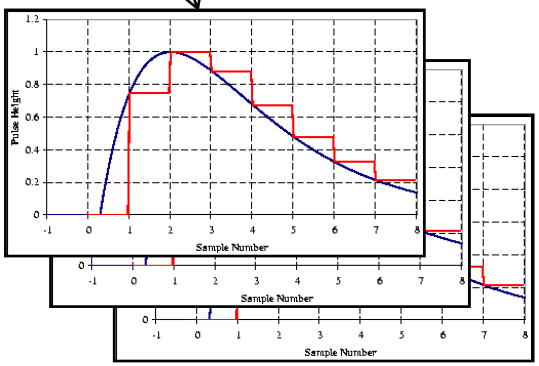
Offline Analysis Chain



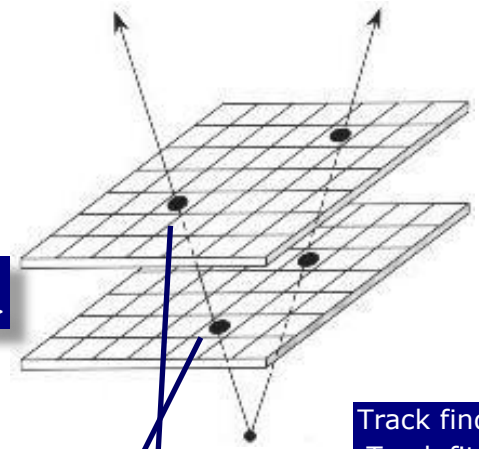
Data reduction/abstraction



Digitization/ Reconstruction --->

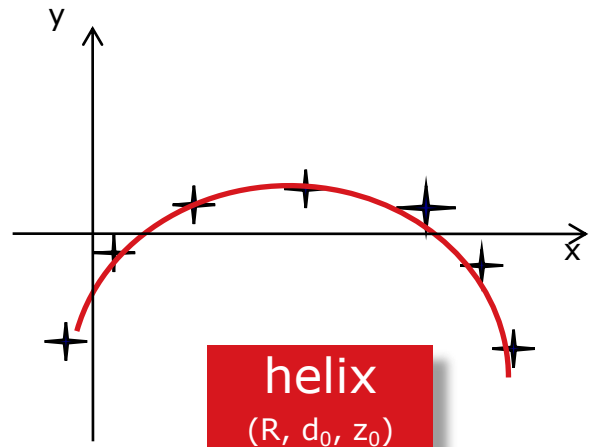


Analog signals



Track finding + Track fit --->

hits
(x_1, y_1, z_1, t_1)
(x_2, y_2, z_2, t_2)
...

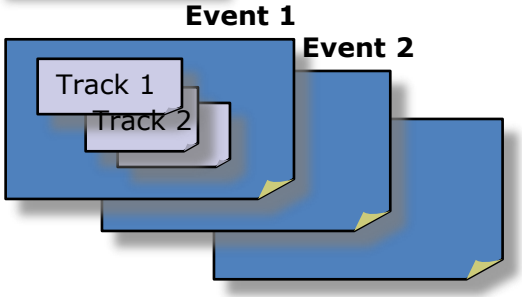


helix
(R, d_0, z_0)

Magnetic field B: reconstruct

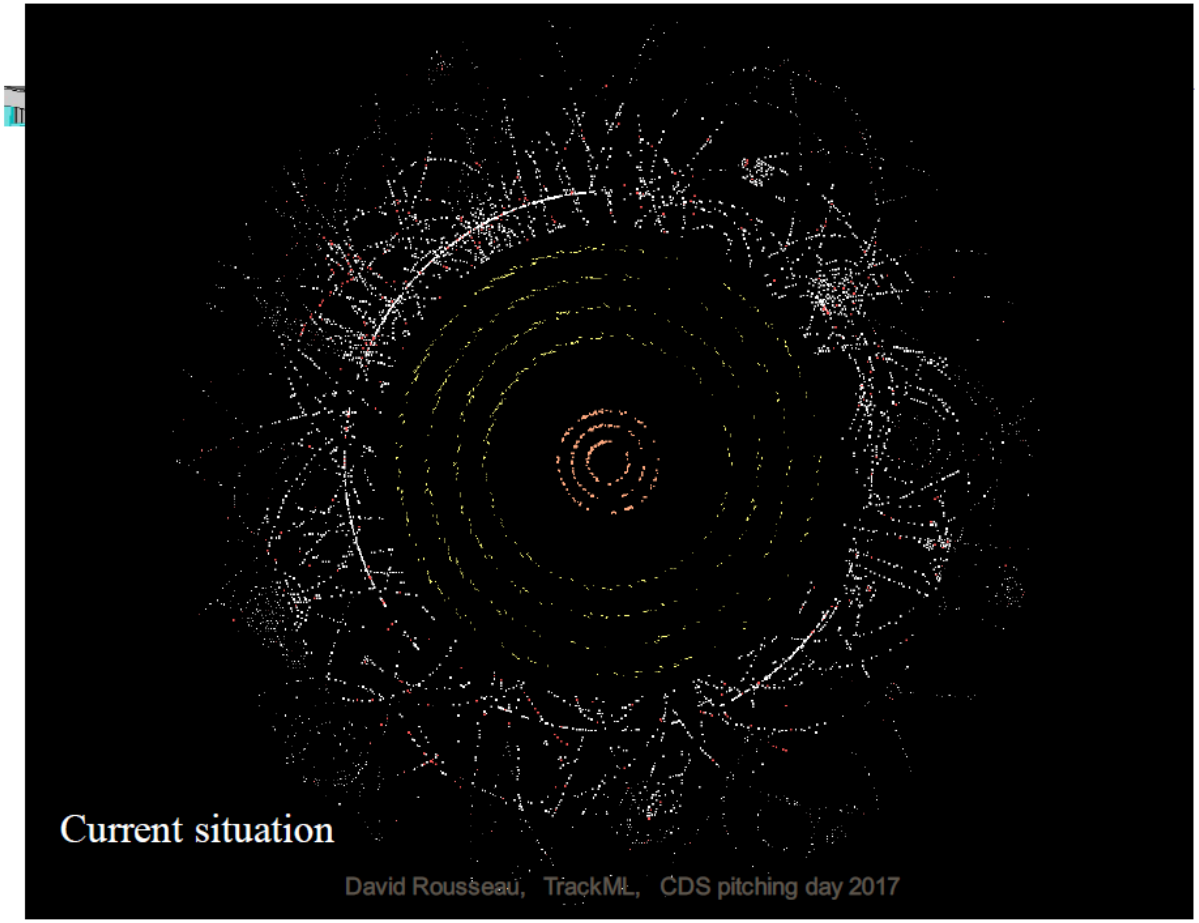
$$p = \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}$$

Track momentum

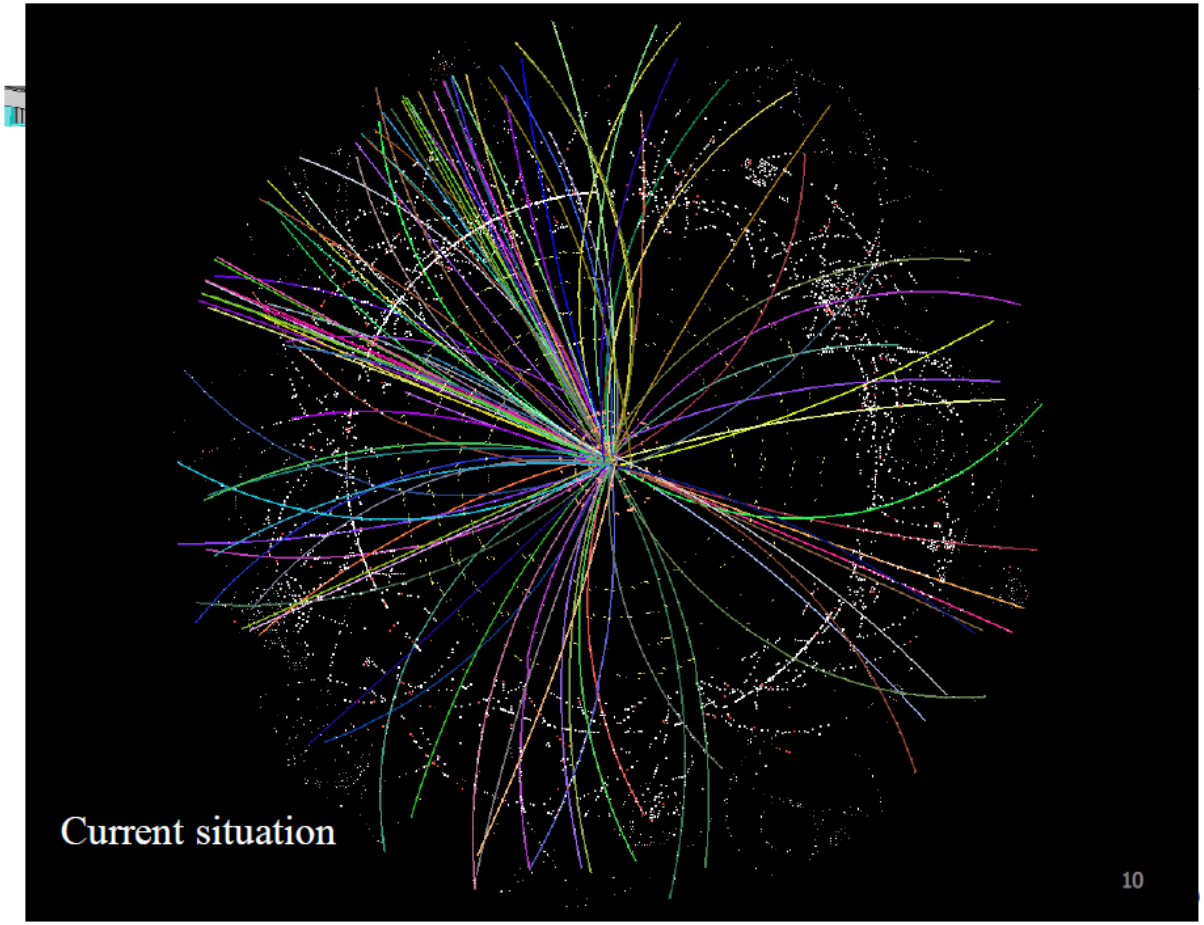


Store the info for every event and every track <-------

Hits


Current situation
David Rousseau, TrackML, CDS pitching day 2017

Tracks



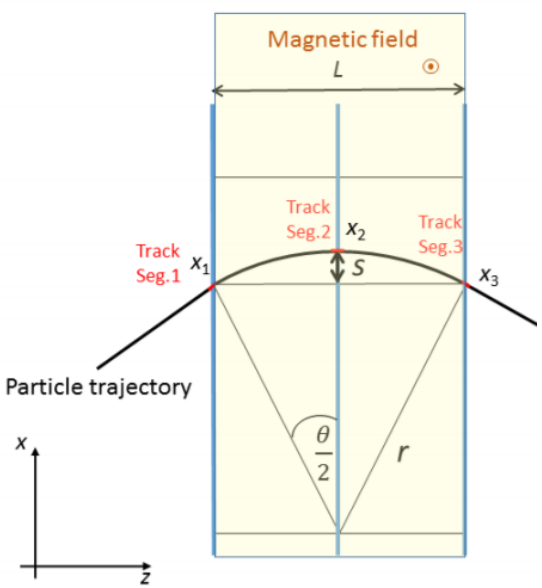
Momentum/Charge of Tracks

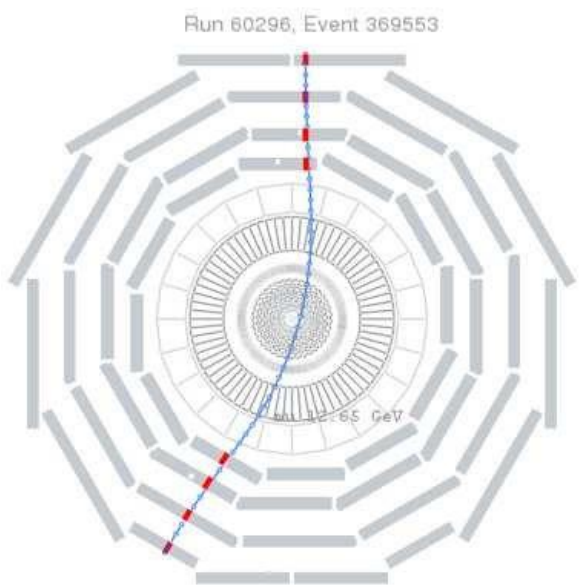
- Momentum (p), charge (Z) and curvature (r):

$$P = M v \gamma = Ze\,B\,r$$

In convenient units this relation is written as

$$\{Pc\}\ [\mathrm{GeV}] = 0.29979 \cdot \mathrm{Z} \cdot \mathrm{B[tesla]} \cdot \mathrm{r[m]} \tag{3.1}$$

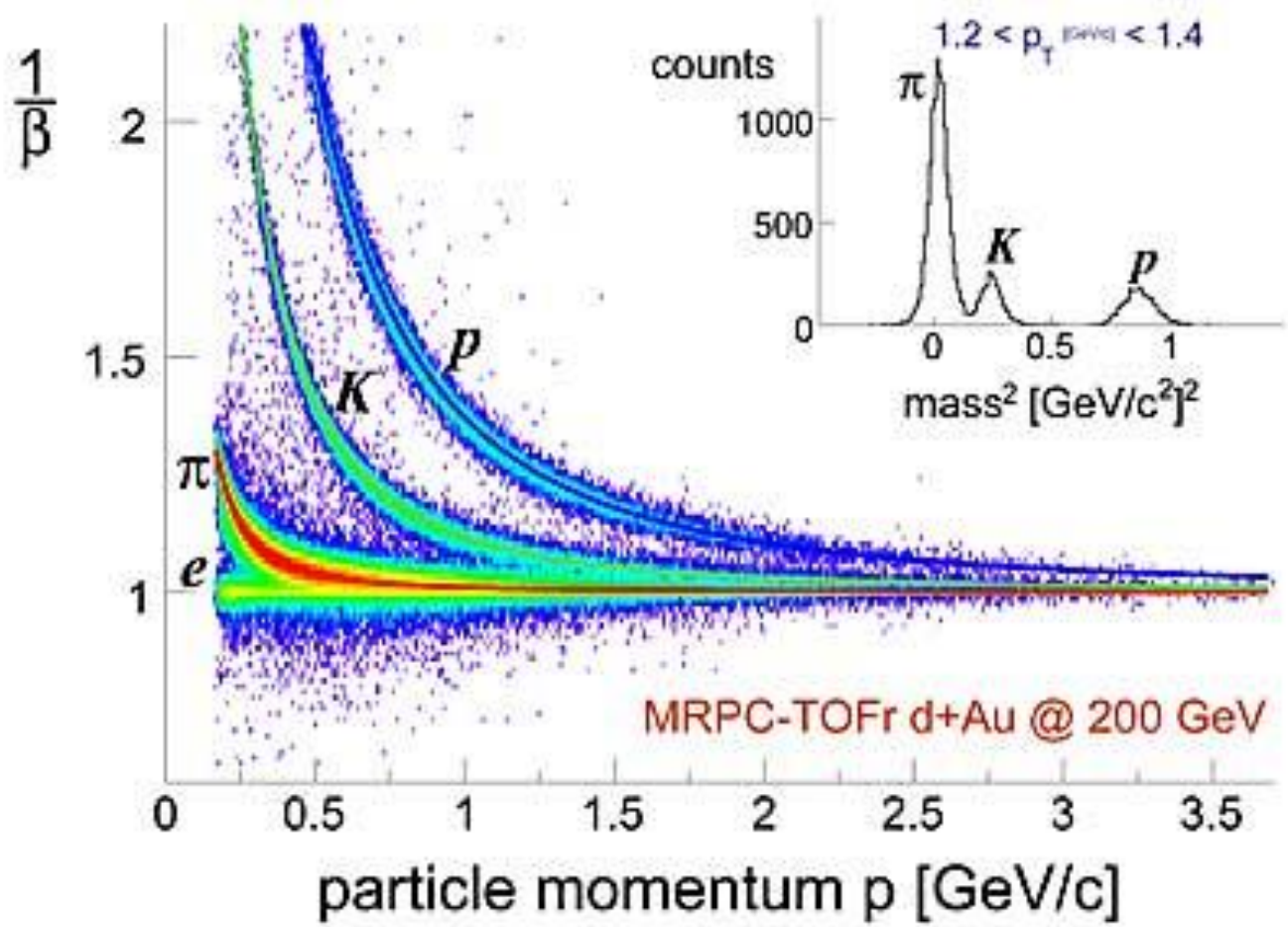




Particle Identification by Mass

$$d = \gamma\beta c\Delta t = \frac{\beta c\Delta t}{\sqrt{1-\beta^2}}$$

$$m = p/\gamma v = p/\gamma\beta c$$

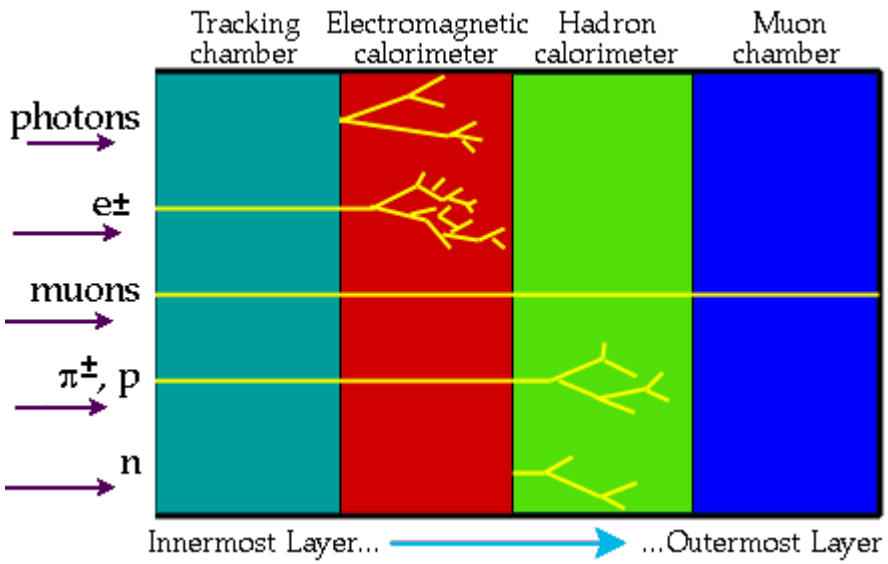


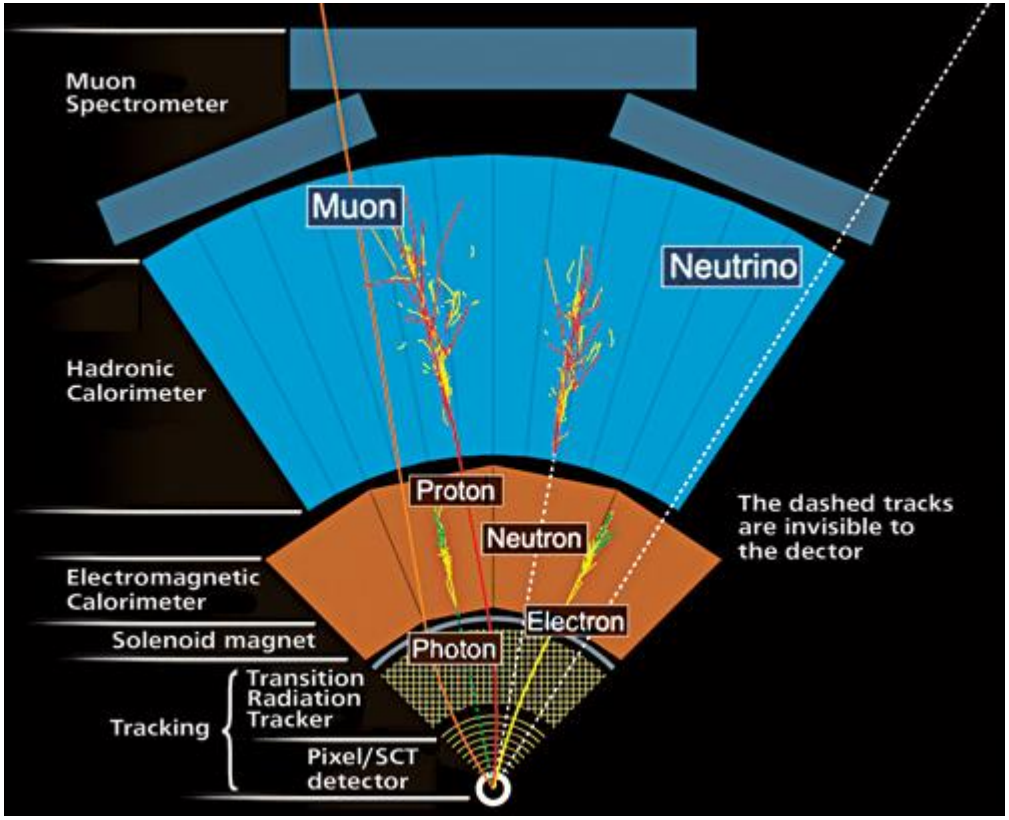
Hadrons

- Instead of making do with jet reconstruction, often the physics under study requires the identification of *individual* hadrons
- Most are unstable, and decay into a few long-lived particles:

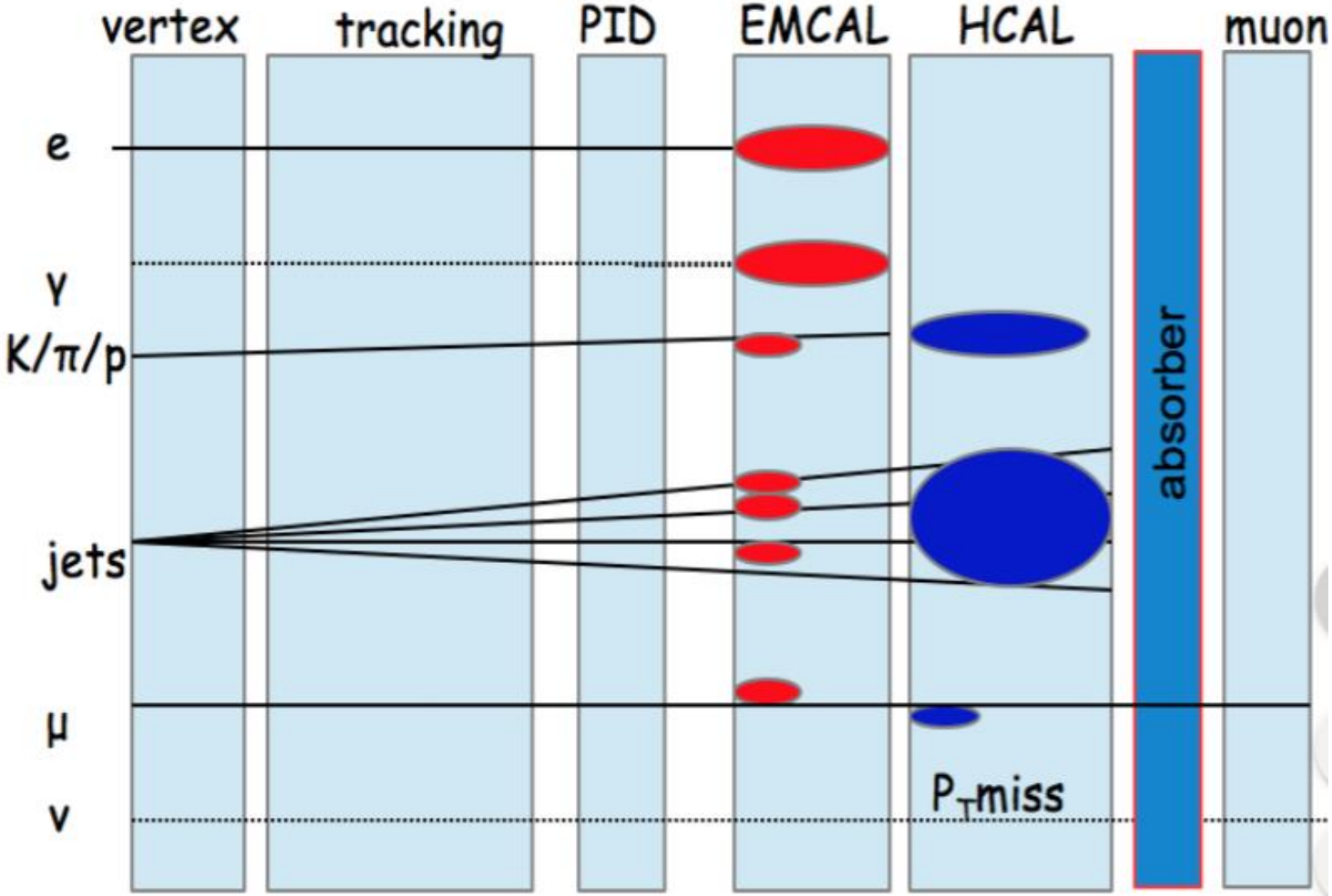
Particle	m [MeV]	Quarks	Main decay	Lifetime	$c\tau$ [cm]
$\pi^{\pm}$	140	$u\bar{d}$	$\mu\nu_{\mu}$	2.6×10^{-8} s	780
$K^{\pm}$	494	$u\bar{s}$	$\mu\nu_{\mu}$, $\pi\pi^{0}$	1.2×10^{-8} s	370
K_S^0	498	$d\bar{s}$	$\pi\pi$	0.9×10^{-10} s	2.7
K_L^0	498	$d\bar{s}$	$\pi\pi\pi$, $\pi l\nu$	5×10^{-8} s	1550
p	938	uud	stable	$> 10^{25}$ years	∞
n	940	udd	$pe\nu_e$	890 s	2.7×10^{13}
Λ	1116	uds	$p\pi$	2.6×10^{-10} s	7.9

Interaction of particles within detectors





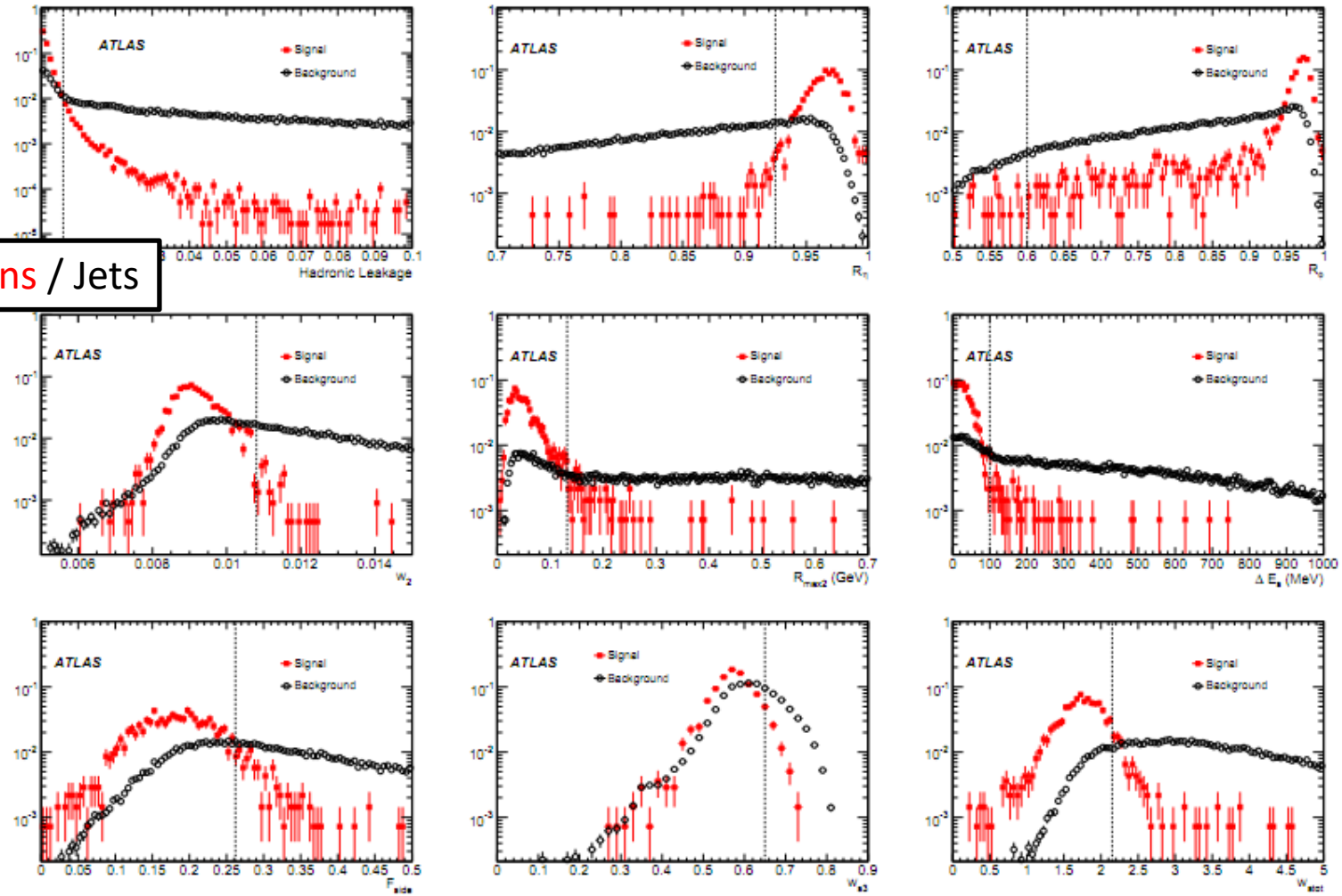
Machine Learning for particle identification: Multivariate Classification



https://www.jlab.org/indico/event/307/session/1/contribution/4/material/slides/0.pdf

Electron/Photon Backgrounds: Multivariate Classification

Electrons / Jets



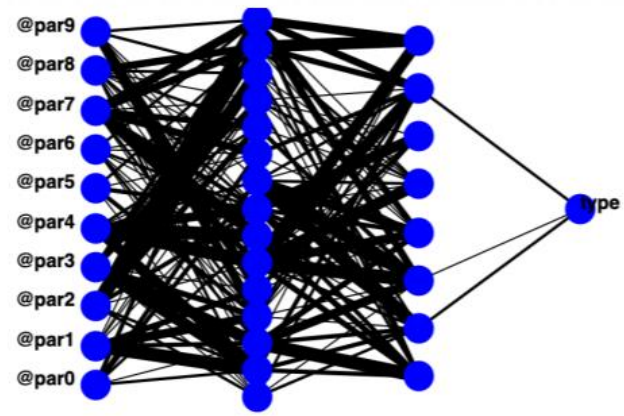
Example of different calorimeter shower shape variables used to distinguish electron showers from jets in ATLAS

Machine Learning for particle identification: Multivariate Classification

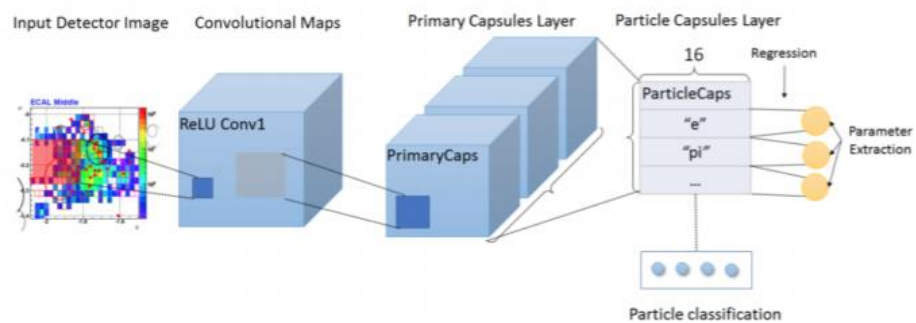
Machine Learning tools

Multivariate classification:

- **JETNET** (Fortran based Artificial Neural Network)
- **ROOT-based Toolkit** for Multivariate Data Analysis (TMVA) https://root.cern.ch/tmva:
  - -> Deep networks (DN)
  - -> Multilayer perception (MP)
  - -> Boosted decision trees



Capsule Networks (pixelated)

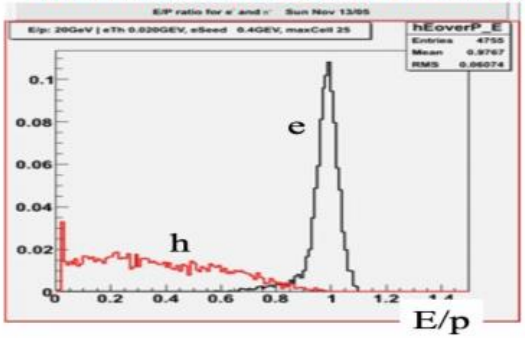


https://www.jlab.org/indico/event/307/session/1/contribution/4/material/slides/0.pdf

Machine Learning for particle identification: Multivariate Classification

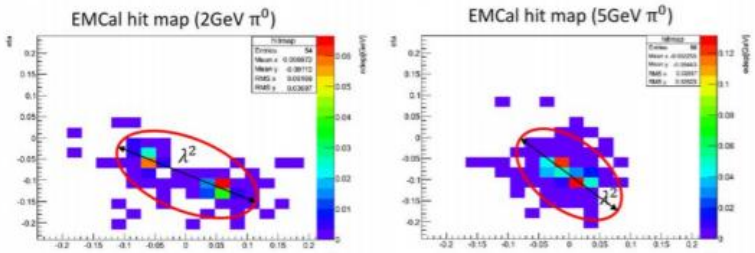
- EMCAL Calorimeter:
  - electron/hadron identification (shower profile, E/p)

  Multivariate classification



  - gamma vs $\pi^0 \rightarrow \gamma\gamma$ (cluster profile)

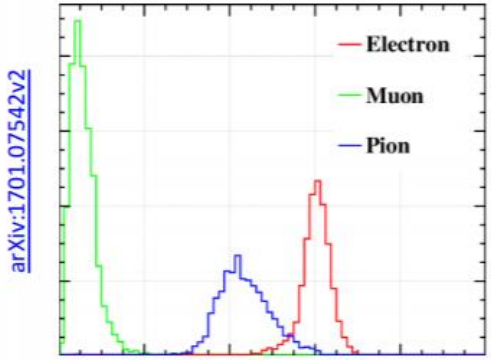
  Capsule (pixelated) ML algorithms



- Hadronic Calorimeter :
  - electron/hadron identification (shower profile, EMCAL/HCAL)
  - Muons (EMCAL/HCAL)

  Multivariate classification

Fractal dimension using both ECAL and HCAL for e − , μ − and π + at 40 GeV



arXiv:1701.07542v2

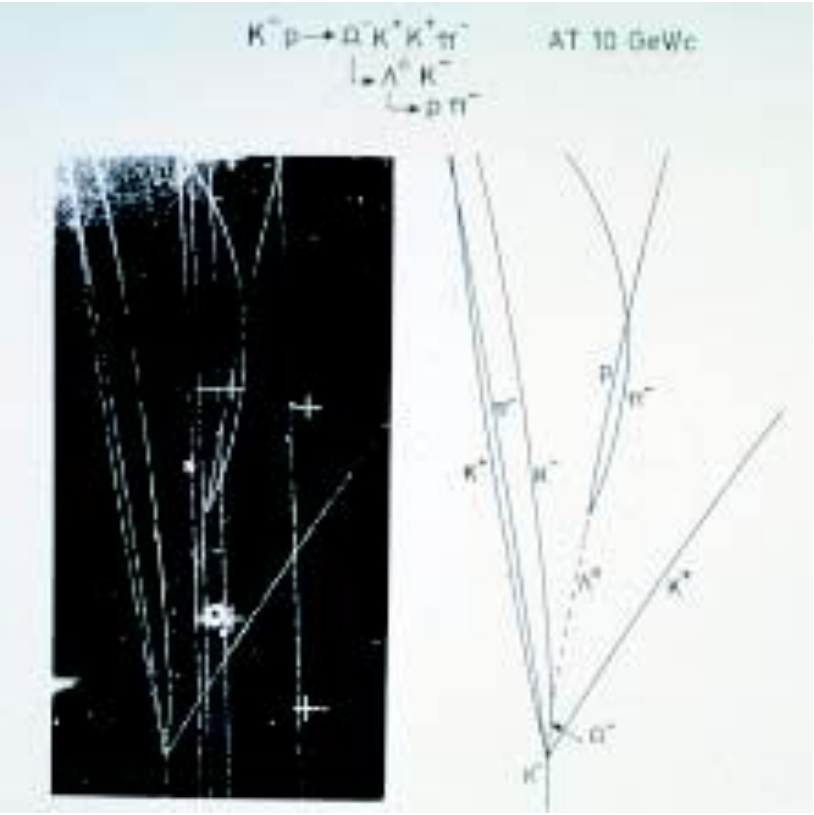
- Jets

  Capsule (pixelated) ML algorithms

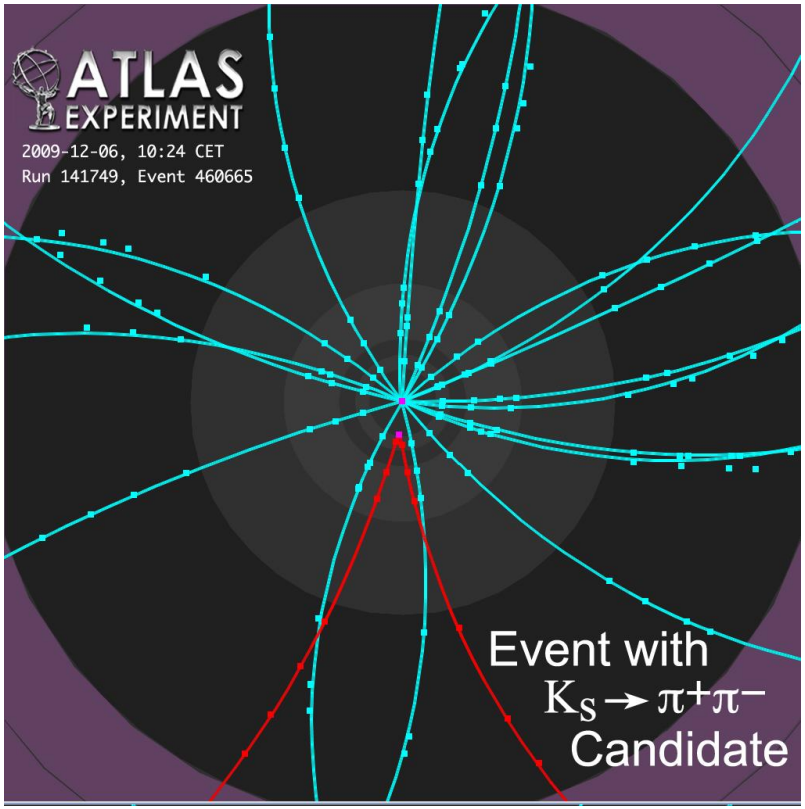
https://www.jlab.org/indico/event/307/session/1/contribution/4/material/slides/0.pdf

Decay and V^0s

- K_S^0 and Λ are collectively known as V^0s, due to their characteristic two-prong decay vertex

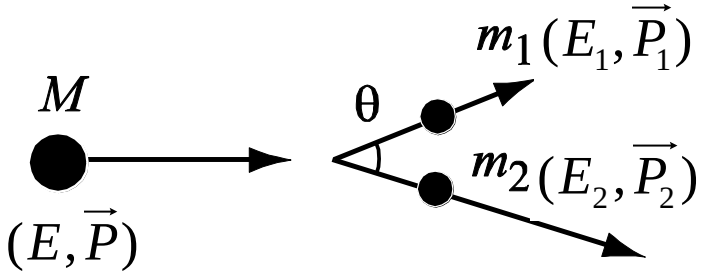


$$\Lambda \rightarrow p\pi^-$$



$$K_s \rightarrow \pi^+\pi^-$$

Invariant Mass



4-vectors	Invariant quantities
$x^\mu = (t, x, y, z)$	$x^\mu x_\mu = t^2 - x^2 - y^2 - z^2$
$p^\mu = (E, p_x, p_y, p_z)$	$p^\mu p_\mu = E^2 - p_x^2 - p_y^2 - p_z^2 = m^2$

$$M^2 = E^2 - \vec{P}^2$$

$$= (E_1 + E_2)^2 - (\vec{P}_1 + \vec{P}_2)^2$$

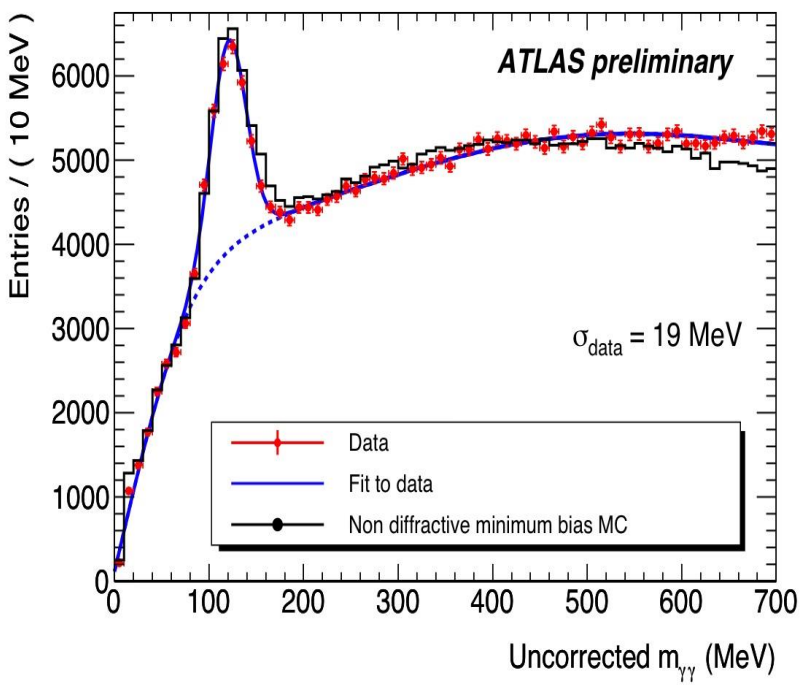
Energy and momentum conservation

$$= m_1^2 + m_2^2 - 2E_1E_2 - 2\vec{P}_1 \bullet \vec{P}_2$$

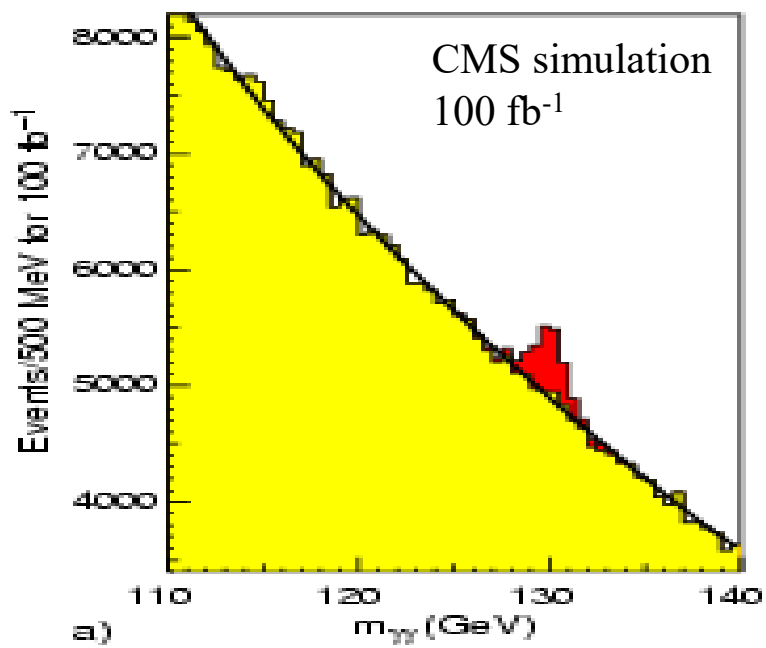
Mass reconstruction

- Typical example of reconstruction of a particle decay: $\pi^0 \rightarrow \gamma\gamma$
  one of the first composite particles reconstructed in the LHC experiments
- This technique an also be used to search for more exciting signals:

$m(\pi^0) = 135$ MeV

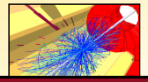


$H \rightarrow \gamma\gamma$



Making the connection

Reality



Raw Data

The imperfect measurement of a (set of) interactions in the detector

Reconstructed Events

A unique happening:
eg. Run 23458, event 1345
which contains a Z → $\mu^+\mu^-$ decay

Analysis : We "confront theory with experiment" by comparing the measured quantity (observable) with the prediction.

Observables

cross sections (probabilities for interactions), branching ratios (BR), ratios of BRs, specific lifetimes, ...

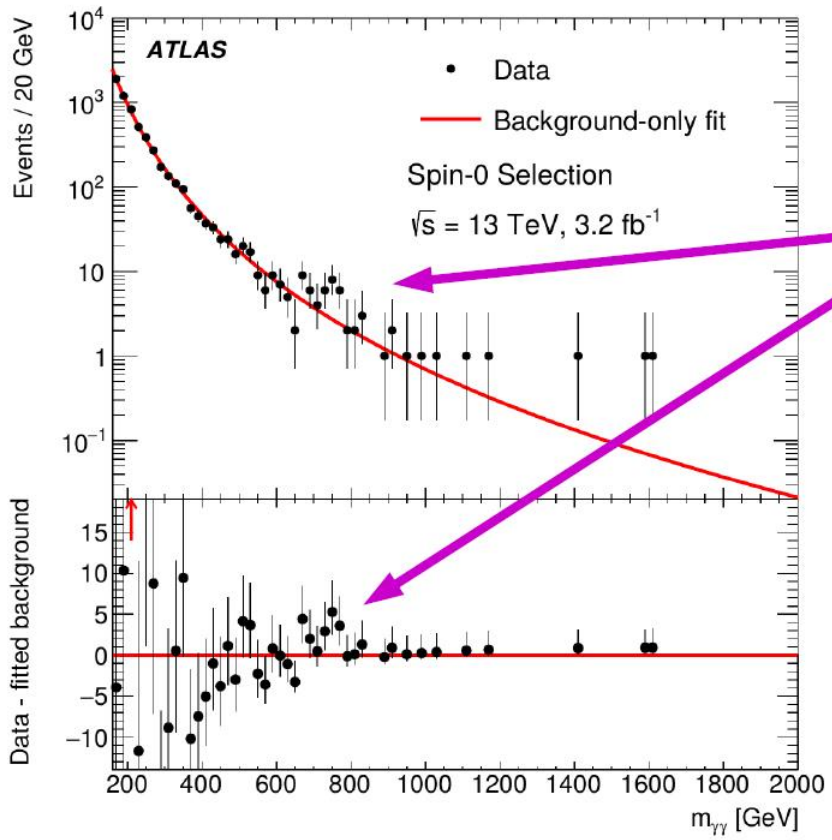
Theory

$$S = \mathrm{i} \int \mathrm{d}^4x \, \mathcal{L}(x)$$

A small number of general equations, with some parameters (poorly or not known at all)

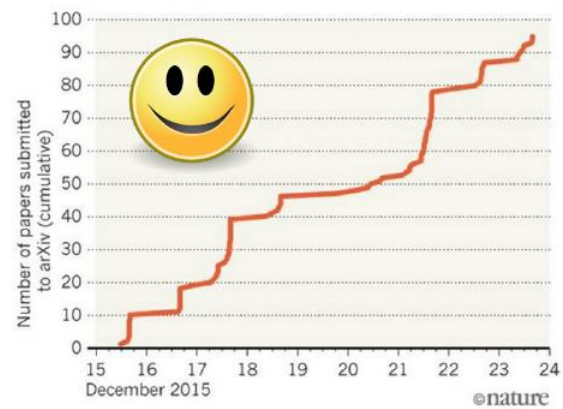
Signals and Error Estimation

Sometimes difficult to distinguish a bona fide discovery from a **background fluctuation**…



New Physics ?

3.9σ ? 2.1σ ?



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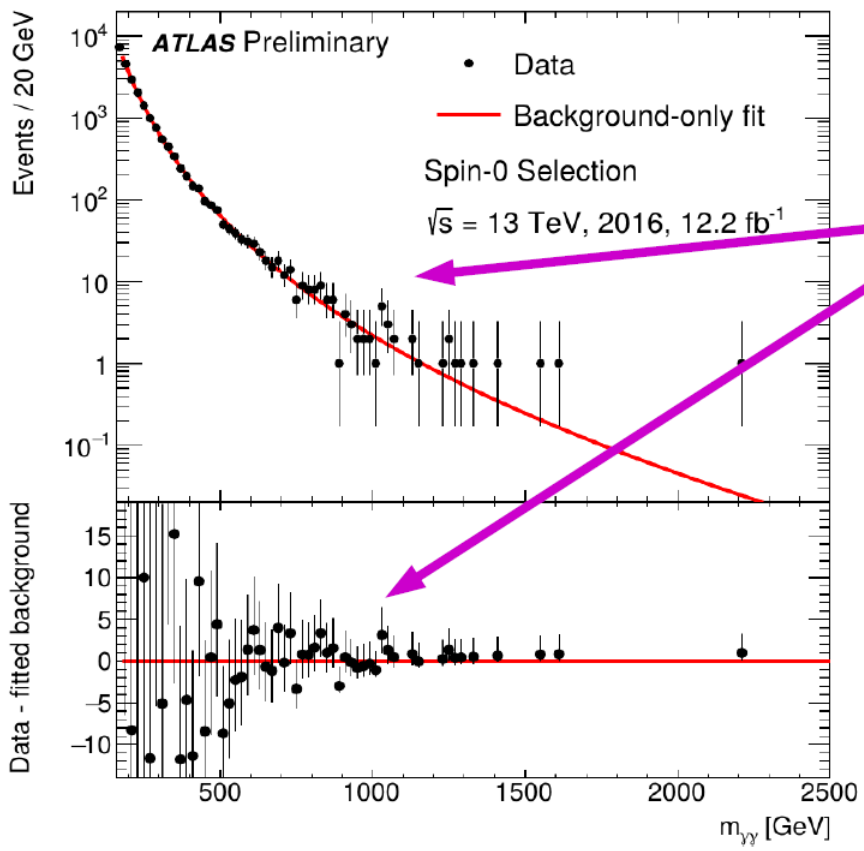
Signals and Error Estimation

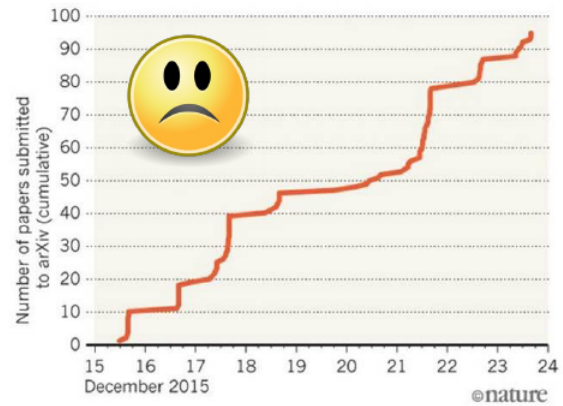
Sometimes difficult to distinguish a bona fide discovery from a **background fluctuation**…



A few months later…

~~New Physics ?~~

~~3.9σ ? 2.1σ ?~~



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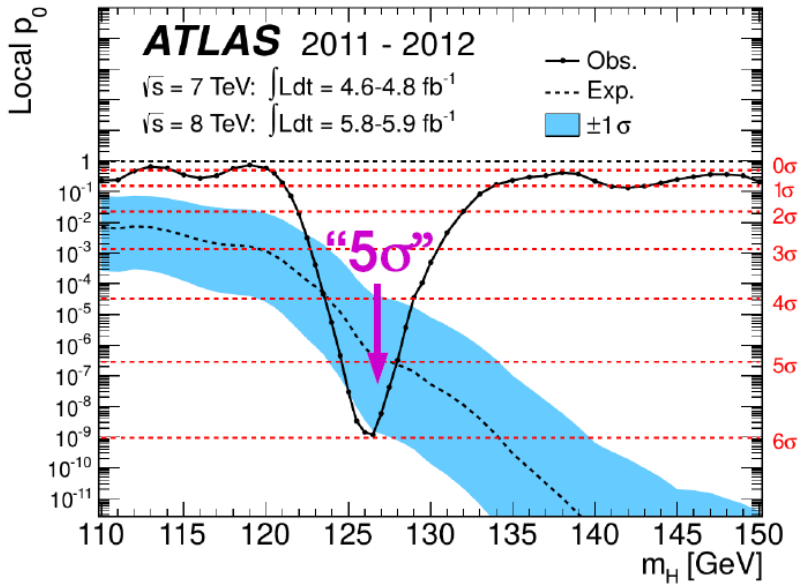
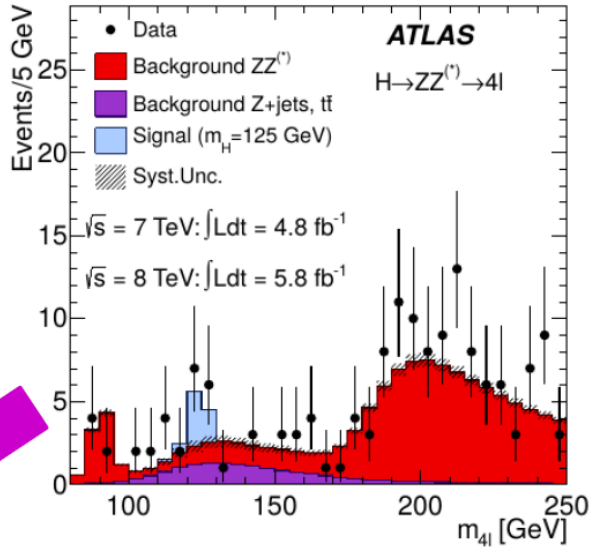
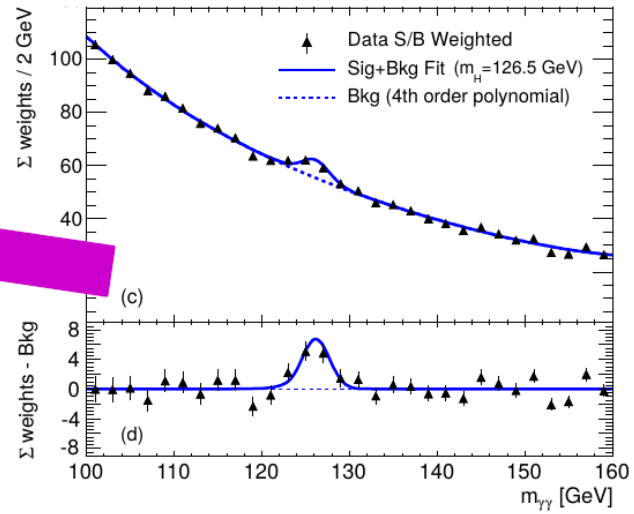
Signals and Error Estimation

Higgs discovery : **"We have 5σ" !**



Phys. Lett. B 716 (2012) 1-29





Elastic Scattering and Inelastic Scattering

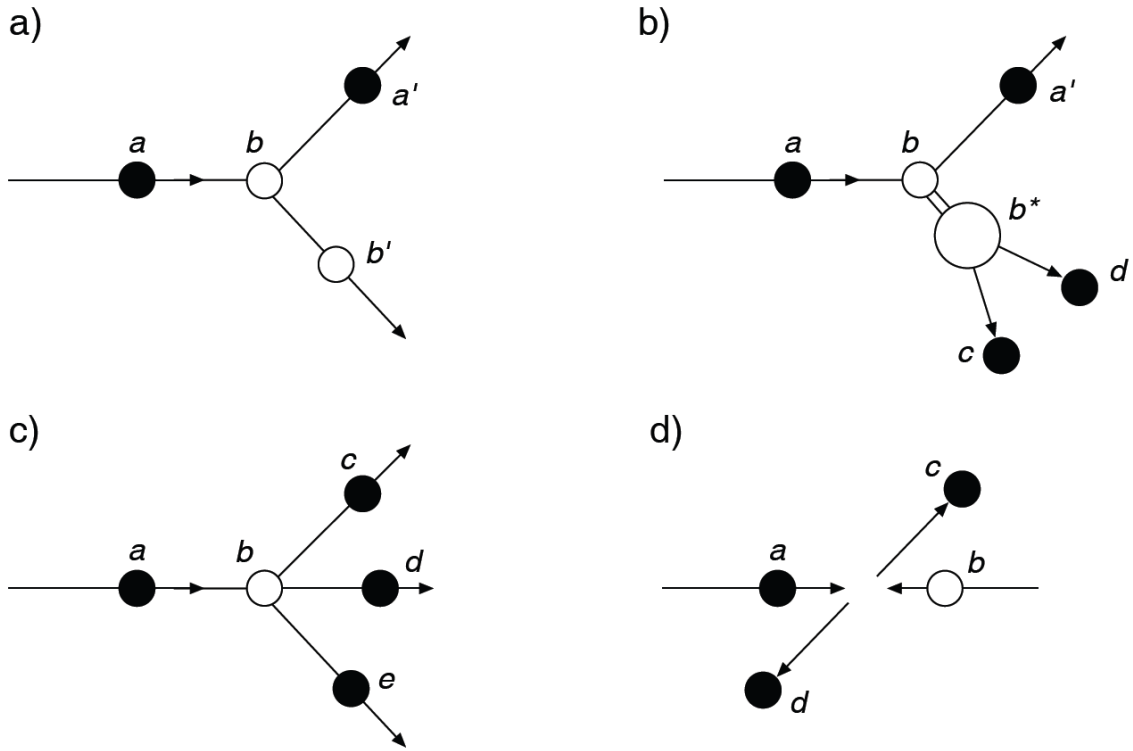


Fig. 4.1. Scattering processes: (**a**) elastic scattering; (**b**) inelastic scattering – production of an excited state which then decays into two particles; (**c**) inelastic production of new particles; (**d**) reaction of colliding beams.

Interaction Cross Sections

where $\mathrm{v} = \mathrm{v}_a + \mathrm{v}_b$. Hence the interaction rate for each particle of type a is

$$r_a = \frac{\mathrm{d}P}{\mathrm{d}t} = n_b \mathrm{v} \sigma.$$

For a beam of particles of type a, with number density n_a confined to a volume V, the total interaction rate is

$$\text{rate} = r_a \, n_a V = (n_b \mathrm{v} \sigma) \, n_a V. \tag{3.24}$$

The expression of (3.24) can be rearranged into

$$\text{rate} = (n_a \mathrm{v})(n_b V)\sigma = \phi \, N_b \, \sigma.$$

Thus the total rate is equal to

$$\boxed{\text{rate} \;=\; \text{flux} \;\times\; \text{number of target particles} \;\times\; \text{cross section},}$$

which is consistent with the definition of (3.23). More formally, the cross section for a process is defined as

$$\sigma = \frac{\text{number of interactions per unit time per target particle}}{\text{incident flux}}.$$

Large cross section = High probability for observing an event

Luminosity

We call the constant of proportionality which encompasses all those machine effects the **luminosity**

$$\boxed{\mathcal{L} = \frac{W}{\sigma}.}$$

W: event rate (T^{-1})

It has dimensions of $[L]^{-2}[T]^{-1}$ and is useful to factor out if you don't care about the details of the machine and just want to know the rates of various processes. The time-integrated luminosity times the cross section gives the expected count of the events of any type

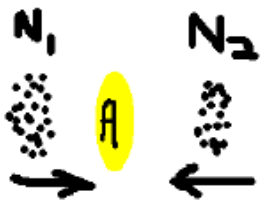
$$N_{\text{events, i}} = \sigma_i \int \mathcal{L}\, dt \ .$$

For a machine colliding opposing bunches containing N_1 and N_2 particles at rate f, you should be able to show that the luminosity is

f: frequency (Hz)

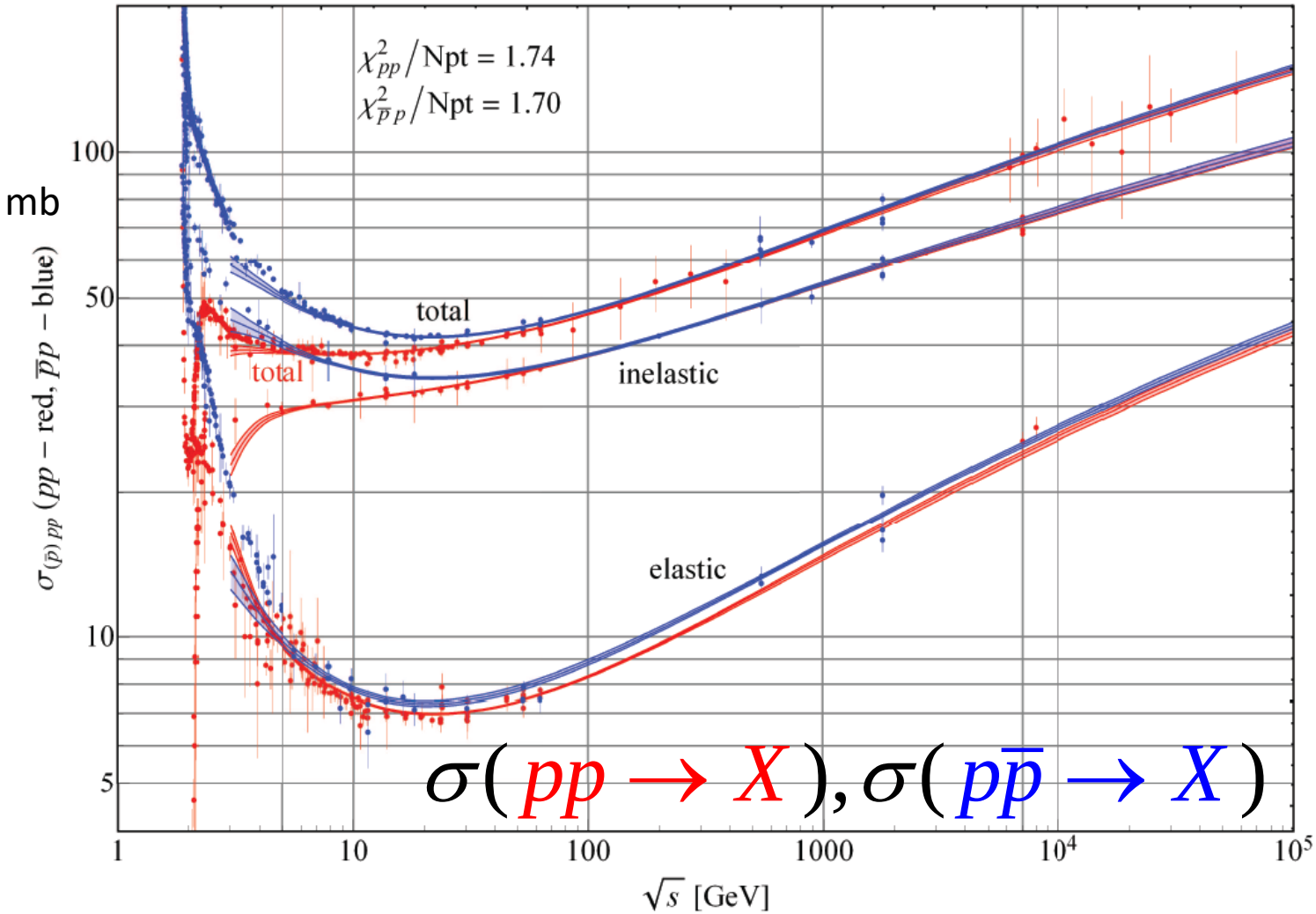
$$\boxed{\mathcal{L} = \frac{N_1 N_2 f}{A},}$$

where A is the cross-sectional area of each bunch (perpendicular to the beam direction).



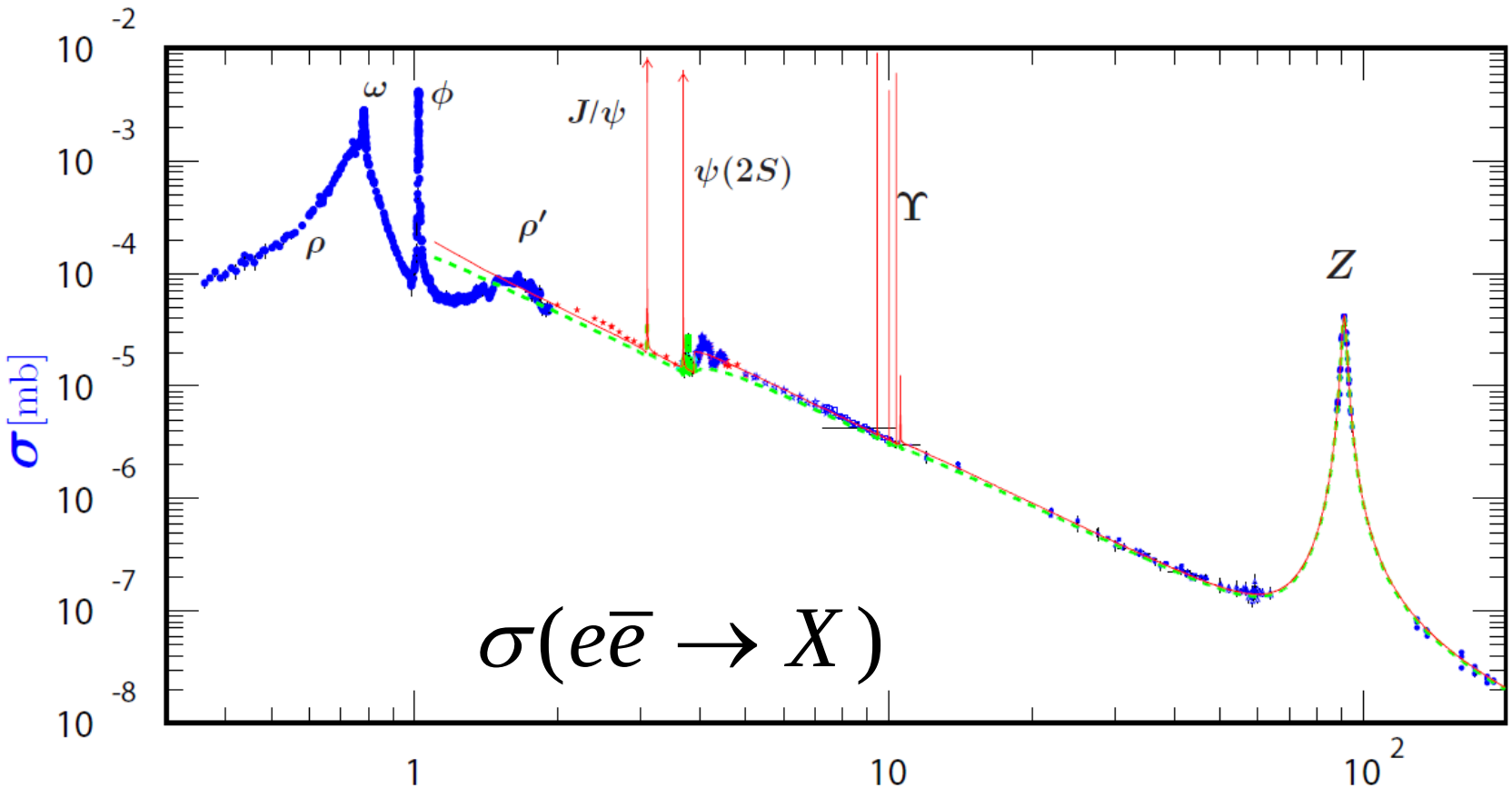
Cross Sections

http://www-pdg.lbl.gov/2016/reviews/rpp2016-rev-cross-section-plots.pdf



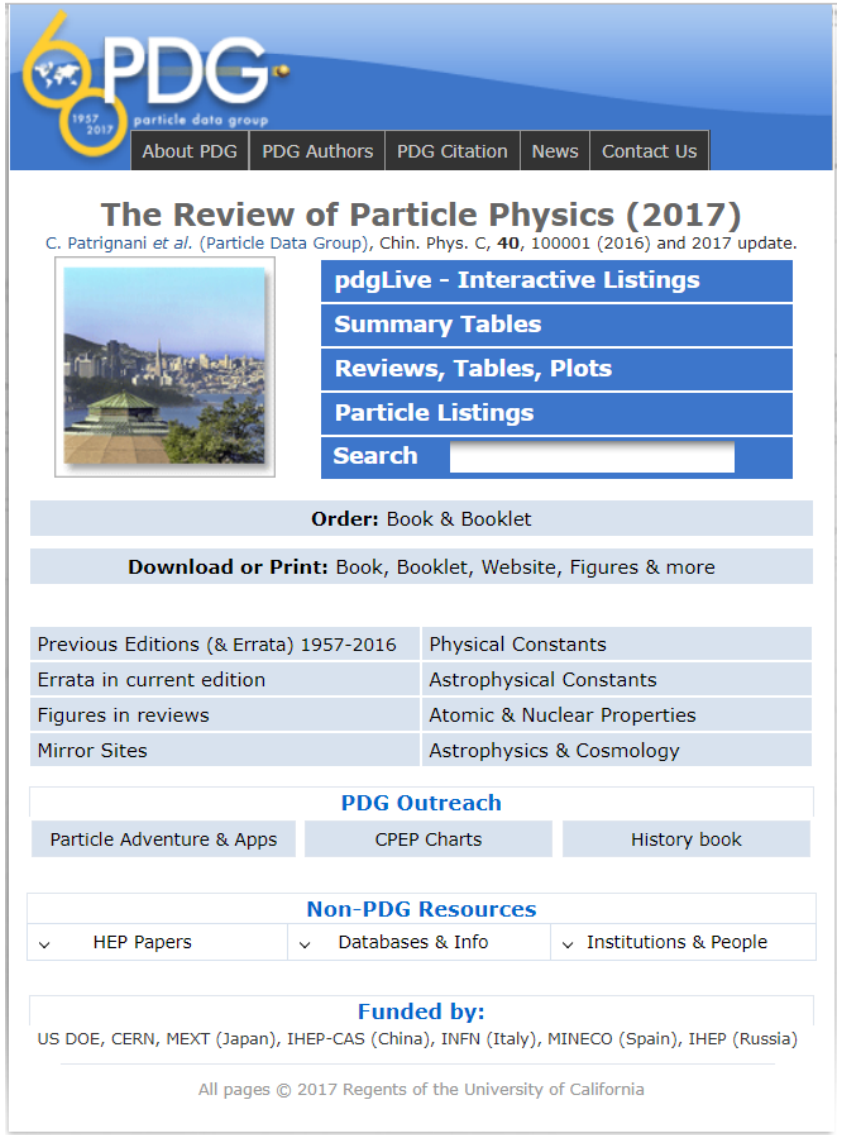
Cross Sections

http://www-pdg.lbl.gov/2016/reviews/rpp2016-rev-cross-section-plots.pdf



Particle Data Group (PDG)

https://pdg.lbl.gov/



Units and Physical Constants

http://www-pdg.lbl.gov/2016/reviews/rpp2016-rev-phys-constants.pdf

Quantity	Symbol, equation	Value	Uncertainty (ppb)
speed of light in vacuum	c	299 792 458 m s^{-1}	exact*
Planck constant	h	6.626 070 040(81)$\times 10^{-34}$ J s	12
Planck constant, reduced	$\hbar \equiv h/2\pi$	1.054 571 800(13)$\times 10^{-34}$ J s	12
		= 6.582 119 514(40)$\times 10^{-22}$ MeV s	6.1
electron charge magnitude	e	1.602 176 6208(98)$\times 10^{-19}$ C = 4.803 204 673(30)$\times 10^{-10}$ esu	6.1, 6.1
conversion constant	$\hbar c$	197.326 9788(12) MeV fm	6.1
conversion constant	$(\hbar c)^2$	0.389 379 3656(48) GeV^2 mbarn	12
electron mass	m_e	0.510 998 9461(31) MeV/c^2 = 9.109 383 56(11)$\times 10^{-31}$ kg	6.2, 12
proton mass	m_p	938.272 0813(58) MeV/c^2 = 1.672 621 898(21)$\times 10^{-27}$ kg	6.2, 12
		= 1.007 276 466 879(91) u = 1836.152 673 89(17) m_e	0.090, 0.095
deuteron mass	m_d	1875.612 928(12) MeV/c^2	6.2
unified atomic mass unit (u)	(mass ^{12}C atom)/12 = (1 g)/(N_A mol)	931.494 0954(57) MeV/c^2 = 1.660 539 040(20)$\times 10^{-27}$ kg	6.2, 12
permittivity of free space	$\epsilon_0 = 1/\mu_0 c^2$	8.854 187 817 ... $\times 10^{-12}$ F m^{-1}	exact
permeability of free space	μ_0	$4\pi \times 10^{-7}$ N A^{-2} = 12.566 370 614 ... $\times 10^{-7}$ N A^{-2}	exact
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	7.297 352 5664(17)$\times 10^{-3}$ = 1/137.035 999 139(31)†	0.23, 0.23
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 3227(19)$\times 10^{-15}$ m	0.68
(e^- Compton wavelength)/2π	$\lambdabar_e = \hbar/m_e c = r_e \alpha^{-1}$	3.861 592 6764(18)$\times 10^{-13}$ m	0.45
Bohr radius ($m_{\text{nucleus}} = \infty$)	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$	0.529 177 210 67(12)$\times 10^{-10}$ m	0.23
wavelength of 1 eV/c particle	$hc/(1\text{ eV})$	1.239 841 9739(76)$\times 10^{-6}$ m	6.1
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$	13.605 693 009(84) eV	6.1
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	0.665 245 871 58(91) barn	1.4

Wavelength of Particles

$$\hbar c = 197 MeV \cdot fm$$

$$1\, fm = 10^{-15} m$$

$$hc = 197 * 2\pi MeV \cdot fm = 1237 * 10^{-15} MeV \cdot m$$

$$\lambda = \frac{h}{P} = \frac{hc}{Pc} = \frac{1237[\mathrm{MeV}]10^{-15}[\mathrm{m}]}{Pc} \tag{1.8}$$

If the momentum Pc of a particle is 1237 MeV, the corresponding wavelength is 10^{-15} m. To probe the structure of objects much smaller than 10^{-15} m, we need

$$1 \text{ keV} = 10^3 \text{ eV}$$
$$1 \text{ MeV} = 10^6 \text{ eV}$$
$$1 \text{ GeV} = 10^9 \text{ eV}$$
$$1 \text{ TeV} = 10^{12} \text{ eV}$$

Units and Physical Constants

http://www-pdg.lbl.gov/2016/reviews/rpp2016-rev-phys-constants.pdf

Bohr magneton	$\mu_B = e\hbar/2m_e$	$5.788\ 381\ 8012(26)\times10^{-11}$ MeV T^{-1}	0.45
nuclear magneton	$\mu_N = e\hbar/2m_p$	$3.152\ 451\ 2550(15)\times10^{-14}$ MeV T^{-1}	0.46
electron cyclotron freq./field	$\omega^e_{\rm cycl}/B = e/m_e$	$1.758\ 820\ 024(11)\times10^{11}$ rad s^{-1} T^{-1}	6.2
proton cyclotron freq./field	$\omega^p_{\rm cycl}/B = e/m_p$	$9.578\ 833\ 226(59)\times10^{7}$ rad s^{-1} T^{-1}	6.2
gravitational constant‡	G_N	$6.674\ 08(31)\times10^{-11}$ m^3 kg^{-1} s^{-2}	4.7×10^4
		$= 6.708\ 61(31)\times10^{-39}\ \hbar c\ (\mathrm{GeV}/c^2)^{-2}$	4.7×10^4
standard gravitational accel.	g_N	$9.806\ 65$ m s^{-2}	exact
Avogadro constant	N_A	$6.022\ 140\ 857(74)\times10^{23}$ mol^{-1}	12
Boltzmann constant	k	$1.380\ 648\ 52(79)\times10^{-23}$ J K^{-1}	570
		$= 8.617\ 3303(50)\times10^{-5}$ eV K^{-1}	570
molar volume, ideal gas at STP	$N_A k(273.15\ \mathrm{K})/(101\ 325\ \mathrm{Pa})$	$22.413\ 962(13)\times10^{-3}$ m^3 mol^{-1}	570
Wien displacement law constant	$b = \lambda_{\max}T$	$2.897\ 7729(17)\times10^{-3}$ m K	570
Stefan-Boltzmann constant	$\sigma = \pi^2k^4/60\hbar^3c^2$	$5.670\ 367(13)\times10^{-8}$ W m^{-2} K^{-4}	2300
Fermi coupling constant**	$G_F/(\hbar c)^3$	$1.166\ 378\ 7(6)\times10^{-5}$ GeV^{-2}	500
weak-mixing angle	$\sin^2\widehat{\theta}(M_Z)\ (\overline{\mathrm{MS}})$	$0.231\ 29(5)$††	2.2×10^5
$W^\pm$ boson mass	m_W	$80.385(15)$ GeV/c^2	1.9×10^5
Z^0 boson mass	m_Z	$91.1876(21)$ GeV/c^2	2.3×10^4
strong coupling constant	$\alpha_s(m_Z)$	$0.1181(11)$	1.0×10^7

$\pi = 3.141\ 592\ 653\ 589\ 793\ 238$ $\quad$ $\mathrm{e} = 2.718\ 281\ 828\ 459\ 045\ 235$ $\quad$ $\gamma = 0.577\ 215\ 664\ 901\ 532\ 861$

1 in $\equiv 0.0254$ m $\quad$ 1 G $\equiv 10^{-4}$ T $\quad$ 1 eV $= 1.602\ 176\ 6208(98)\times10^{-19}$ J $\quad$ kT at 300 K $= [38.681\ 740(22)]^{-1}$ eV

1 Å $\equiv 0.1$ nm $\quad$ 1 dyne $\equiv 10^{-5}$ N $\quad$ 1 eV/$c^2 = 1.782\ 661\ 907(11)\times10^{-36}$ kg $\quad$ 0 °C $\equiv 273.15$ K

1 barn $\equiv 10^{-28}$ m^2 $\quad$ 1 erg $\equiv 10^{-7}$ J $\quad$ $2.997\ 924\ 58\times10^9$ esu $=$ 1 C $\quad$ $1\ mb = 10^{-3}b$ $\quad$ 1 atmosphere $\equiv 760$ Torr $\equiv 101\ 325$ Pa

$1\ \mu b = 10^{-6}b$

$1\ \mathrm{n}b = 10^{-9}b$

$1\ \mathrm{p}b = 10^{-12}b$

$1\ \mathrm{f}b = 10^{-15}b$

Radius of a nucleus of A atomic mass: $R = R_0A^{1/3}$

$R_0 \sim 1.2\ fm = 1.2*10^{-15}m$

1 barn is the rough cross section of a nucleus.

The experimental foundations of particle physics

–Robert N. Cahn and Gerson Goldhaber

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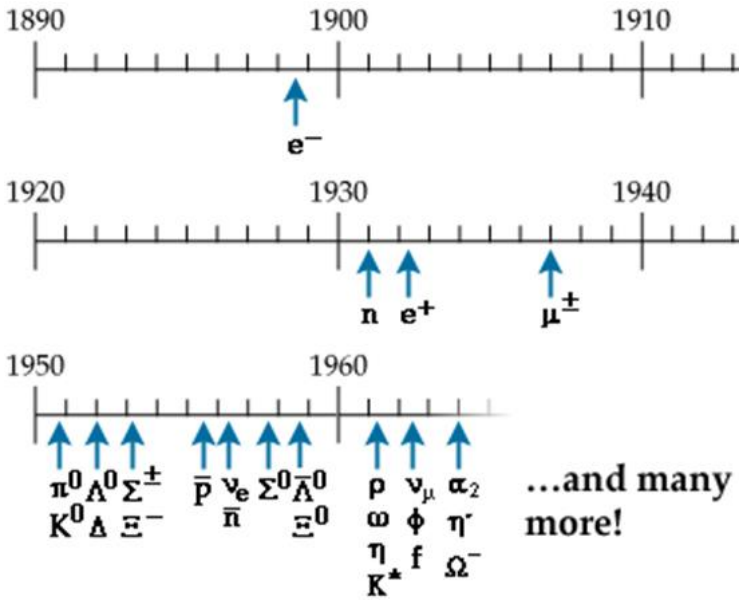
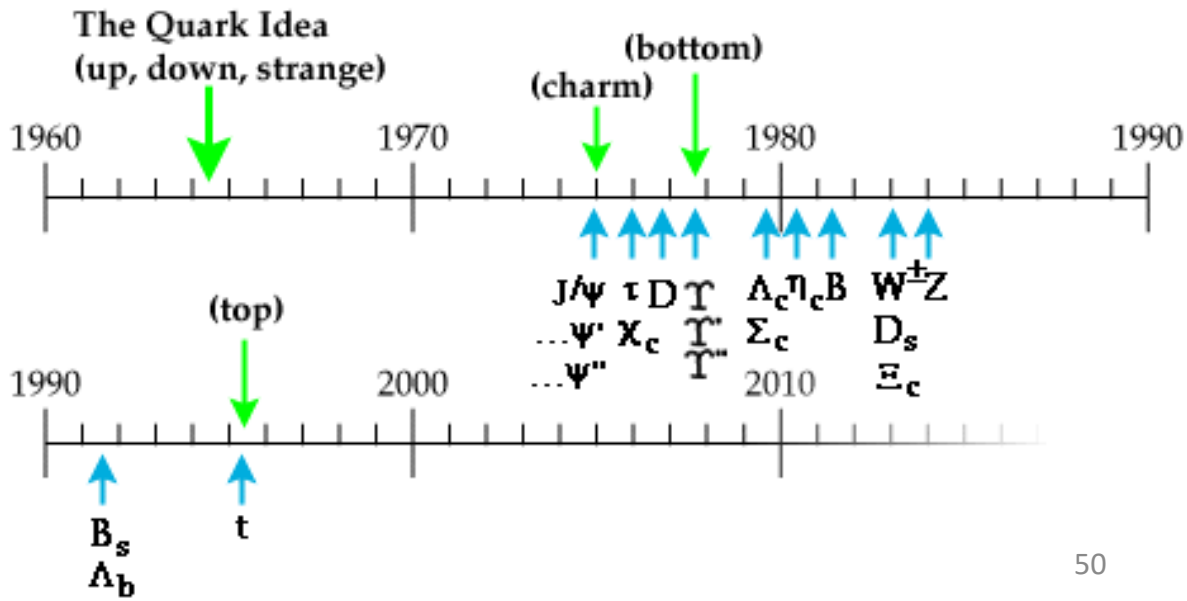
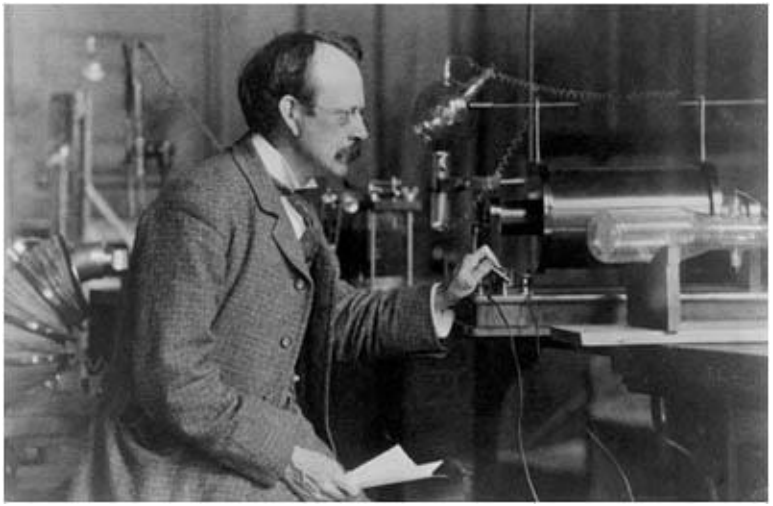
(I) Particles discovered 1898 - 1964

(II) Modern View (Standard Model) timeline: 1964 - present





1897 Discovery of electron



- **1897** English experimental physicist John Joseph Thomson discovered the electron, the first elementary particle, at Cambridge University's Cavendish Laboratory in 1897. He used a cathode ray tube to measure the charge/mass ratio of the cathode ray particles that we now know are electrons.

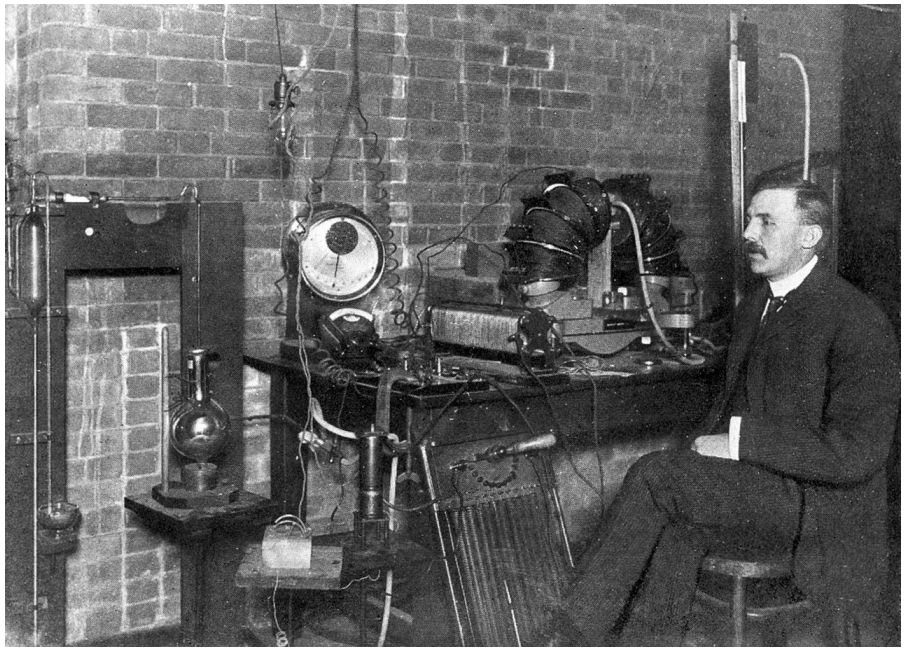
The Nobel Prize in Physics 1906: J.J. Thomson

1911 Rutherford Scattering

- **1911** John Ratcliffe and Ernest Rutherford (smoking) at the Cavendish Laboratory. In 1911, Rutherford discovered the atomic nucleus, using a "scattering" experiment, that would become a classic technique of particle physics.

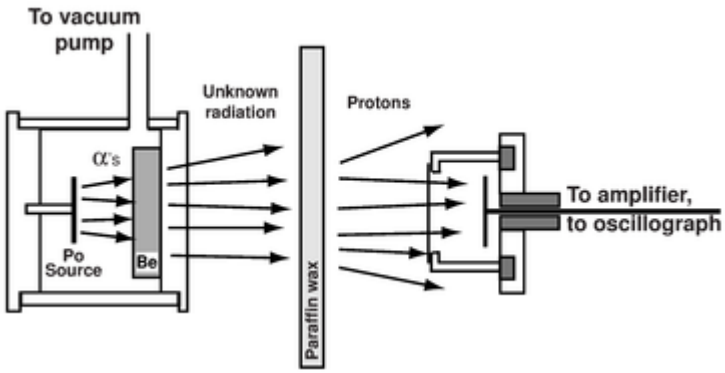
The Nobel Prize in Chemistry 1908: Ernest Rutherford

1919 Discovery of Proton



- 1917-1919 Ernest Rutherford comes back to H-particles: he uses α-particles to bombard B, F, Na, Al, P, and N and sees H-particles kicked off from all of them. The H-particles, protons, must be constituents of all elements.
- This conclusion (and experiments it is based on) may be considered the discovery of a new elementary particle, proton, in addition to an electron .

1932 Discovery of Neutron



- When Herbert Becker and Walter Bothe directed alpha particles (helium nuclei) at beryllium in 1930, a strong, penetrating radiation was emitted. One hypothesis was that this could be high-energy electromagnetic radiation.
- In 1932, however, James Chadwick proved that it consisted of a neutral particle with about the same mass as a proton. Ernest Rutherford had earlier proposed that such a particle might exist in atomic nuclei. Its existence now proven, it was called a "neutron".

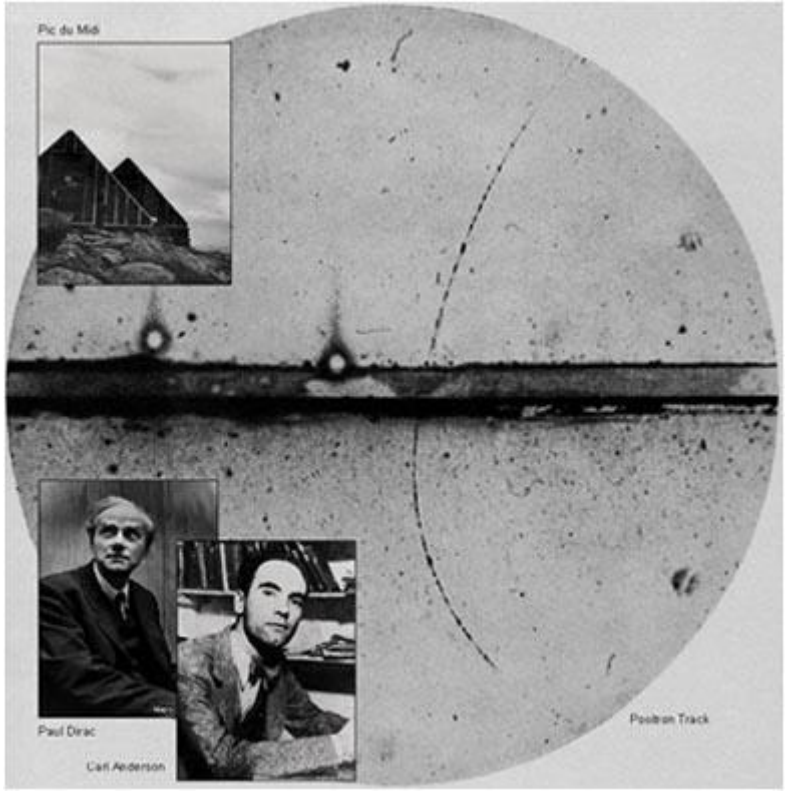
The Nobel Prize in Physics 1935: James Chadwick

1912 Discover of “Cosmic Rays”

The Nobel Prize in Physics 1936
Victor F. Hess

- **1912** In a balloon, at an altitude of 5,000 meters, in 1912 Victor Hess, the father of cosmic ray research, discovered "penetrating radiation" coming from space.
- In the days before particle accelerators existed, physicists climbed mountains and went up in balloons to observe cosmic rays, naturally-occurring high-energy particles in the atmosphere.
- Today, particle physicists still study cosmic rays to explore unanswered questions about the structure of matter and the universe.

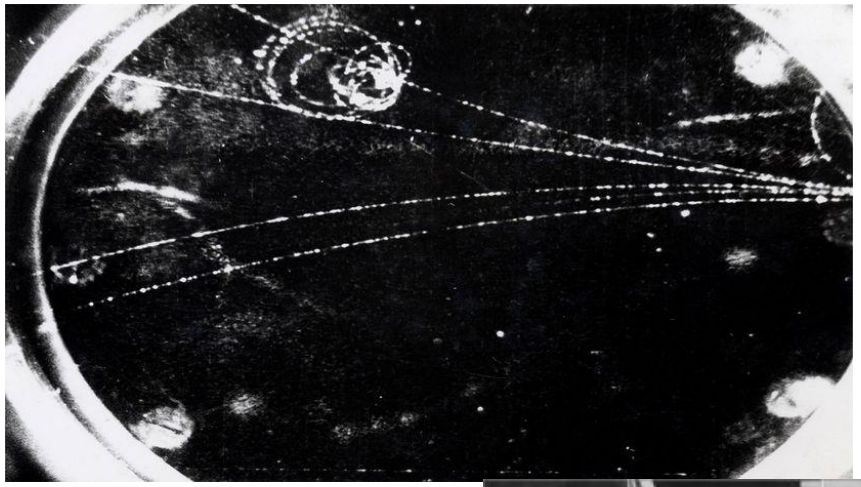
1932 Discovery of “Positron”

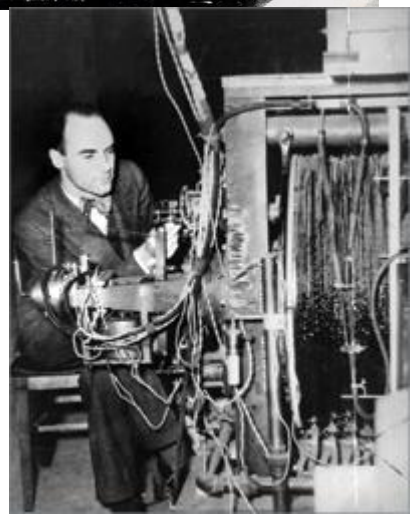


- **1932** The first sight of antimatter came in a particle track observed in a cloud chamber at Caltech by physicist Carl Anderson in 1932.
- The track curved in the opposite way from the track of an electron, showing that the particle had a positive charge. But the track was too faint to come from a positively-charged proton. Anderson had discovered the positively charged electron, or positron, predicted by Paul Dirac in 1929.

The Nobel Prize in Physics 1936
Carl D. Anderson

1936 Discovery of “Muon”

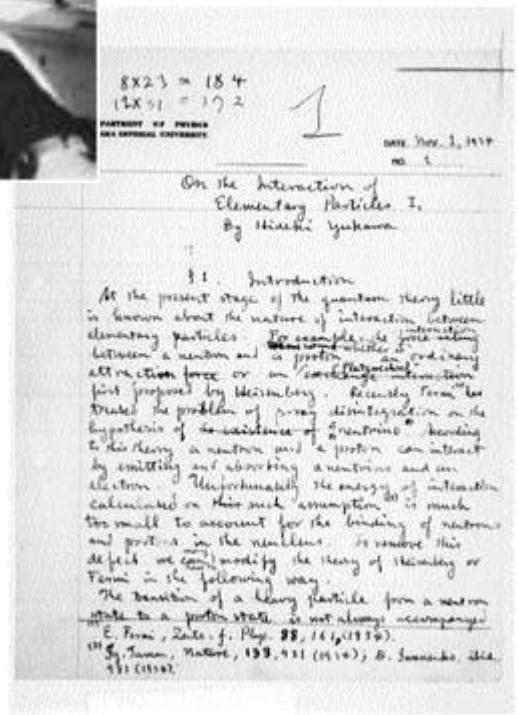




A cosmic ray shower, taken by Carl Anderson (1905-1991), who discovered the muon and the positron.

- Muons were discovered by Carl D. Anderson and Seth Neddermeyer at Caltech in 1936 while studying cosmic rays. The muon was discovered when Anderson found particle tracks just like an electron but with Z/m 207 times smaller.
- The existence of the muon was confirmed in 1937 by J. C. Street and E. C. Stevenson's cloud chamber experiment.

1934 Prediction of π Meson



8×23 = 184
12×51 = 172

1

On the Interaction of Elementary Particles. I.
By Hideki Yukawa

§1. Introduction

At the present stage of the quantum theory little is known about the nature of interaction between elementary particles. For example, the force acting between a neutron and a proton is ordinary attraction force or an exchange interaction first proposed by Heisenberg. Recently Fermi[1] has studied the problem of β-ray disintegration on the hypothesis of the existence of neutrino. According to this theory a neutron and a proton can interact by emitting and absorbing a neutrino and an electron. Unfortunately the energy of interaction calculated on this such assumption is much too small to account for the binding of neutrons and protons in the nucleus. To remove this defect we modify the theory of Heisenberg or Fermi in the following way.

The transition of a heavy particle from a neutron state to a proton state is not always accompanied

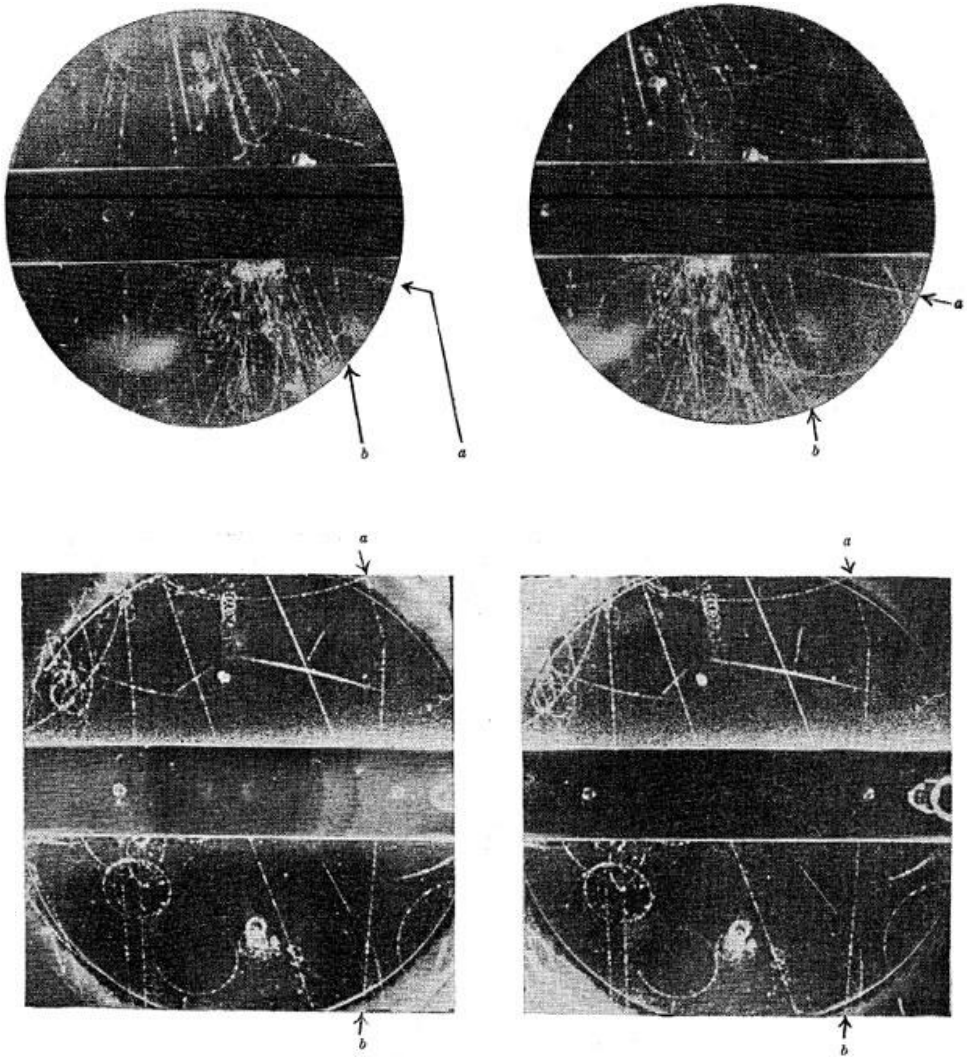
[1] E. Fermi, Zeits. f. Phys. 88, 161 (1934).

[1] G. Fermi, Nature, 133, 911 (1934); D. Ivanenko, ibid. 911 (1934).

The Nobel Prize in Physics 1949
Hideki Yukawa

- In this 1934 draft manuscript, Japanese physicist Hideki Yukawa predicted the existence of a particle—a meson—with a mass about 200 times that of the electron.
- At first the muon, discovered in 1937, looked like a good candidate for the meson, but soon it became clear that the muon's properties did not match those predicted by Yukawa.
- Then, in 1947, Cecil Powell discovered the π meson, or pion, which did have the predicted meson properties. We know now that the muon is an elementary particle, cousin to the electron, and that mesons, including the pion, are combinations of a quark and an antiquark.

1947 Discovery of “Kaon”



- In 1947, G. D. Rochester and Clifford Charles Butler of the University of Manchester published two cloud chamber photographs of cosmic ray-induced events, one showing what appeared to be a neutral particle decaying into two charged pions, and one which appeared to be a charged particle decaying into a charged pion and something neutral. The estimated mass of the new particles was very rough, about half a proton's mass. More examples of these "V-particles" were slow in coming.
- "Evidence for the existence of new unstable elementary particles" *G. D. Rochester & C. C. Butler*, Nature **160** (1947) 855-857

1930 “Neutrino”

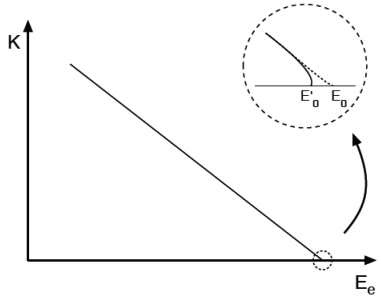


Fig. 17.20. Kurie plot of the β-spectrum. If the neutrino mass is not zero the straight line must bend near the maximum energy and cross the axis vertically at $E_0' = E_0 - m_\nu c^2$.

The Nobel Prize in Physics 1995
Martin L. Perl, Frederick Reines

- In 1930, German physicist Wolfgang Pauli postulated a new particle to explain the apparent nonconservation of energy in radioactive decays. But the theoretical particle he described had properties that made it so elusive that even Pauli wondered whether anyone would ever see it.
- In 1933, Italian physicist Enrico Fermi gave the particle a name, "neutrino,“.
- In 1956 two American physicists, Frederick Reines and Clyde Cowan, discovered it utilizing a nuclear reactor as the neutrino source.

1950 Bevatron & Discovery of anti-proton

- **1950's** In the 1950s, the Bevatron (a weak-focusing proton synchrotron) accelerator at the Department of Energy's Lawrence Berkeley National Laboratory accelerated protons to 6 GeV.
- The Bevatron is best known for the antiproton, discovered there in 1955 by Emilio Segré and Owen Chamberlain.

The Nobel Prize in Physics 1959
Emilio Segrè, Owen Chamberlain

1947 SLAC
(Stanford Linear Accelerator Center)

- **1947** William Hansen (right) and colleagues with a section of an early linear accelerator that operated at Stanford University in 1947. It was 3.6 meters long and could accelerate electrons to 6 MeV.

Damping
Rings
Main Linac
LCLS
Injector
PEP-II
End
Station B
SABER
NLCTA
End
Station A
SPEAR3
Guest
House
LCLS
LCLS
Near Hall
LCLS
Far Hall
CEH
BABAR

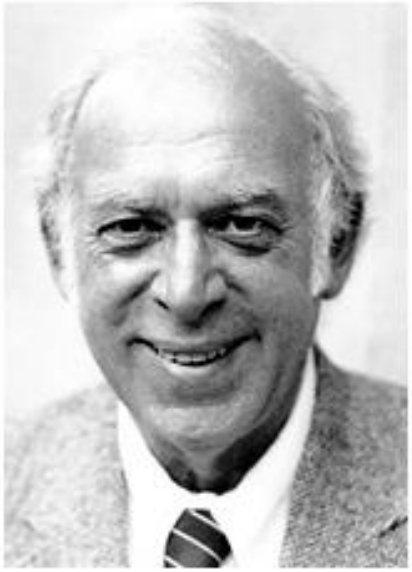
1966 Discovery of “Quark”

- From 1966–1978, Richard Taylor (SLAC), Henry Kendall (MIT) and Jerome Friedman (MIT) conducted experiments to study how high-energy electrons bounce off protons and neutrons in a target. Their results indicated that there were more electrons bouncing back with high energy at large angles than could be explained if protons and neutrons were uniform spheres of matter.
- The experiments they conducted came to reveal the extremely small, dense objects moving around within the protons and neutrons known as quarks. For their pioneering work in the development of the quark model of particle physics, these scientists shared the Nobel Prize in Physics in 1990.

The Nobel Prize in Physics 1990

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

- **The Nobel Prize in Physics 1990**
- Nobel Prize Award Ceremony
- Jerome I. Friedman
- Henry W. Kendall
- Richard E. Taylor



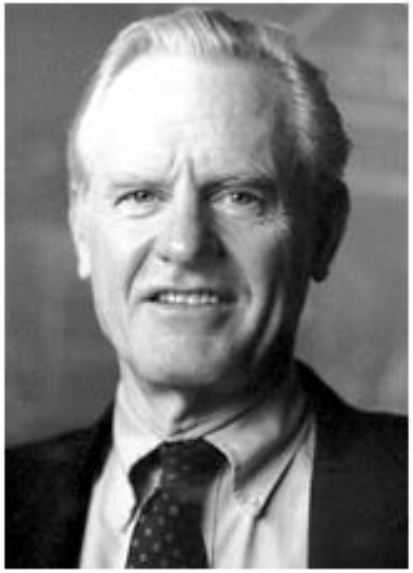
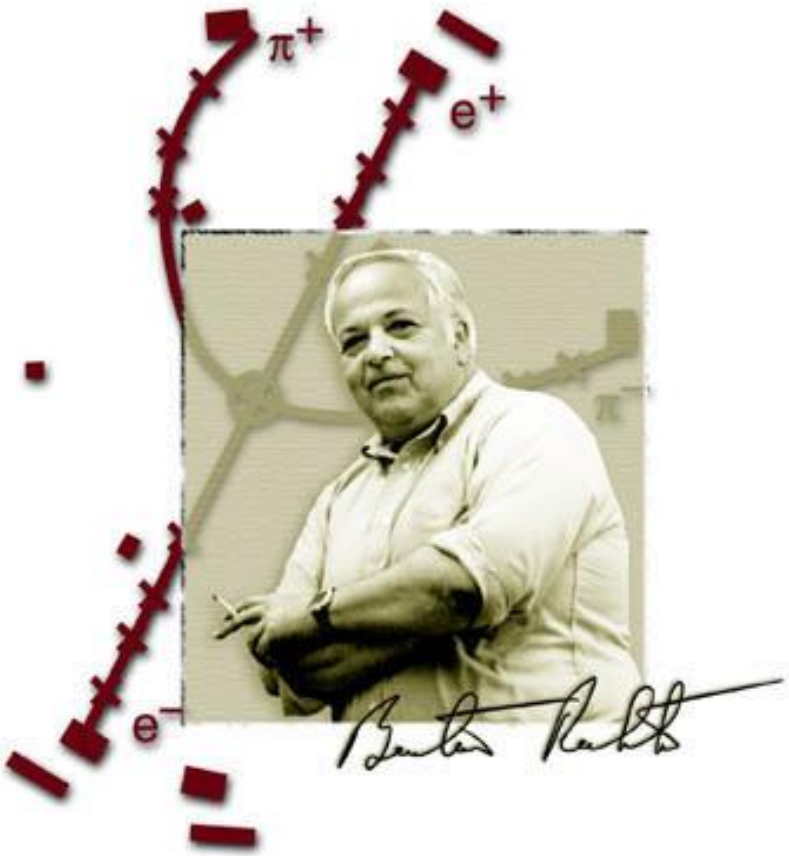


Photo: T. Nakashima

Jerome I. Friedman | Henry W. Kendall | Richard E. Taylor

The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor *"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle*

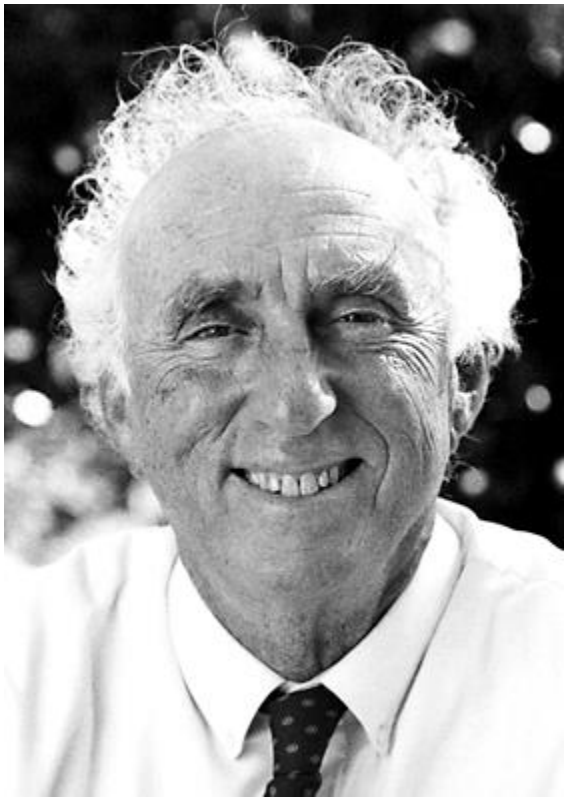
1974 Discovery of J/psi (charm quark)



The Nobel Prize in Physics 1976
Burton Richter, Samuel C.C. Ting

- 1973-1974 Leading the group that designed and built the Stanford Positron Electron Asymmetric Ring, Burton Richter (SLAC) conducted a series of experiments from 1973–1974 to study the rate of occurrence of events in which a colliding electron and a positron annihilate, disappearing and producing other particles in the process. At certain energies the rate of annihilation seemed inexplicably large. On November 10, 1974, re-measurements in the problematic energy range confirmed a dramatic rate increase whose cause was due to the production of particles containing a new kind of quark, the charm quark. For their work towards the discovery of a new heavy elementary particle, Burton Richter and Samuel Ting (Brookhaven) received the Nobel Prize in Physics in 1976.

1975 Discovery of "τ"



The Nobel Prize in Physics 1995
Martin L. Perl, Frederick Reines

- In 1975, using experimental data from 1973–1974, Martin Perl discovered that sometimes when an electron and positron annihilate one another, the detector records only one electron-type track and one muon-type track. These events were noted at rates that could only be explained by postulating a new particle type, one just like the electron only 3,000 times more massive. The resulting discovery of the Tau lepton earned Martin Perl the Nobel Prize in Physics in 1995 for his instrumental contribution to lepton physics.

1960 The Alternating Gradient Synchrotron at Brookhaven

Proton beam 33 GeV

Courant, Livingston, Schneider

Mel Schwartz and spark chamber

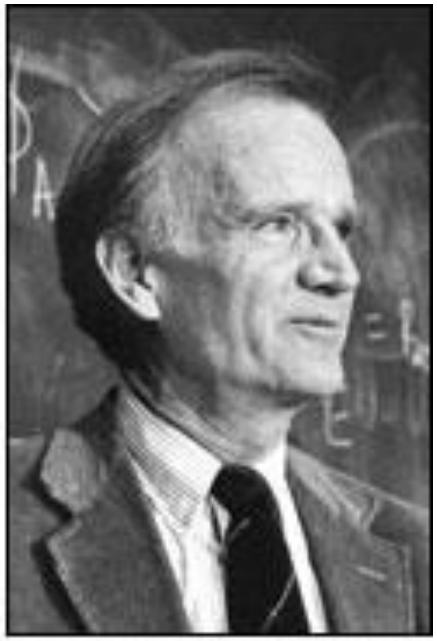
1974 Discovery of J/psi (charm quark)

- The 1976 Nobel Prize in physics was shared by a Massachusetts Institute of Technology researcher who used Brookhaven's Alternating Gradient Synchrotron to discover a new particle and confirm the existence of the charmed quark.
- Samuel C.C. Ting was credited for finding what he called the "J" particle, the same particle as the "psi" found at nearly the same time at the Stanford Linear Accelerator Center by a group led by Burton Richter. The particle is now known as the J/psi. Winning the Nobel Prize, they also helped confirm the existence of the charmed quark -- the J/psi is composed of a charmed quark bound to its antiquark.

The Nobel Prize in Physics 1976
Burton Richter, Samuel C.C. Ting

1963 Discovery of "CP violation in neutral Kaon Decay"

James Cronin



Val Fitch

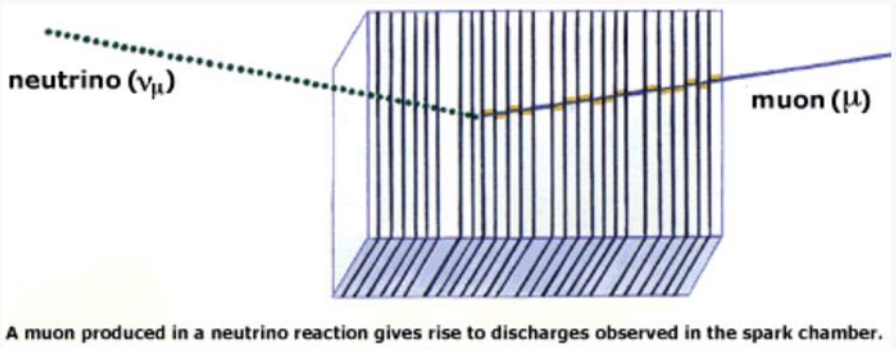
The Nobel Prize in Physics 1980
James Cronin, Val Fitch

$$K_L^0(CP-) \rightarrow \pi\pi(CP+)$$

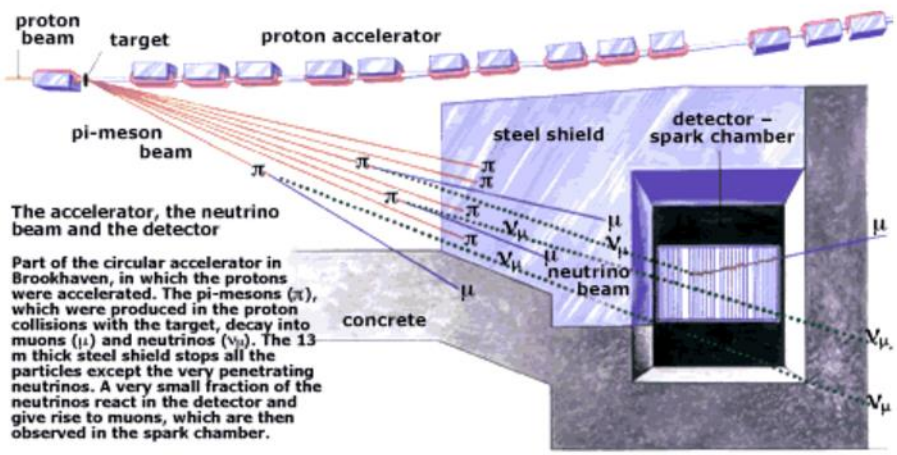
https://cds.cern.ch/record/314578/files/9611284.pdf

- James W. Cronin and Val L. Fitch, both then of Princeton University, proposed using Brookhaven's AGS to verify a fundamental tenet of physics, known as CP symmetry, by showing that two different particles did not decay into the same products. They picked as their example neutral K mesons, which are routinely produced in collisions between a proton beam and a stationary metal target.
- Their experiment, in 1963, set out to show that in millions of collisions, the short-lived variety of K meson always decayed into two pi mesons, while the long-lived variety never did. But to their surprise, a "suspicious-looking hump" in the data showed an unexpected result that years of subsequent experimentation and theory have been unable to explain: occasionally, the long-lived neutral K meson does decay into two pi mesons. Cronin and Fitch had found an example of CP violation.

1962 Discovery of “muon-neutrinos”



A muon produced in a neutrino reaction gives rise to discharges observed in the spark chamber.



The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American, March 1963.

- The experiment used a beam of the AGS's energetic protons to produce a shower of pi mesons, which traveled 70 feet toward a 5,000-ton steel wall made of old battleship plates. On the way, they decayed into muons and neutrinos, but only the latter particles could pass through the wall into a neon-filled detector called a spark chamber. There, the impact of neutrinos on aluminum plates produced muon spark trails that could be detected and photographed -- proving the existence of muon-neutrinos.

The Nobel Prize in Physics 1988

Leon M. Lederman, Melvin Schwartz, Jack Steinberger

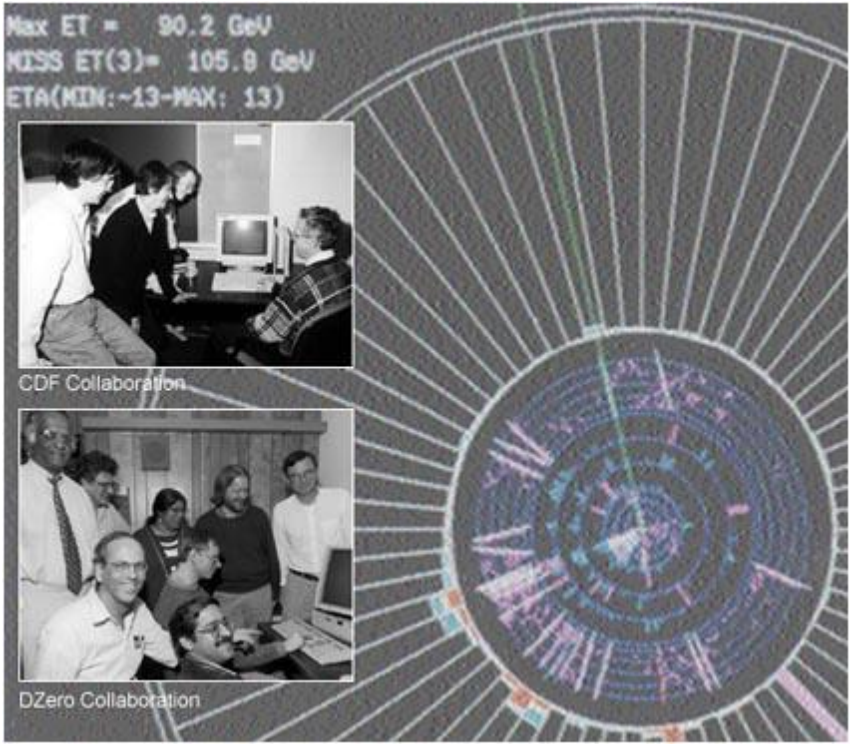
1983 Tevatron at Fermilab

Proton and anti-proton beams: 1 TeV

1977 Discovery of “bottom” quark

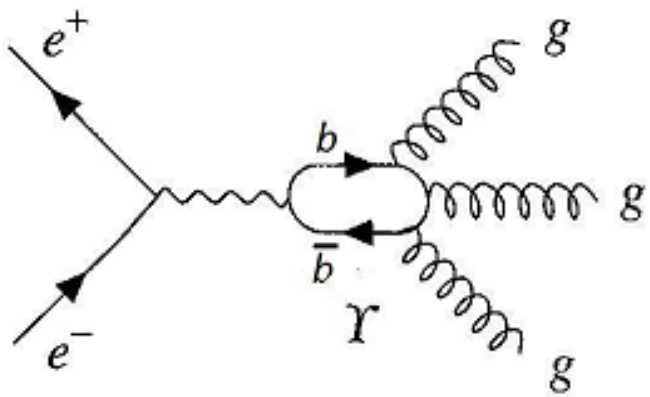
- The **Upsilon meson** (ϒ) is a flavorless meson formed from a bottom quark and its antiparticle. It was discovered by the E288 collaboration, headed by Leon Lederman, at Fermilab in 1977, and was the first particle containing a bottom quark to be discovered because it is the lightest that can be produced without additional massive particles.

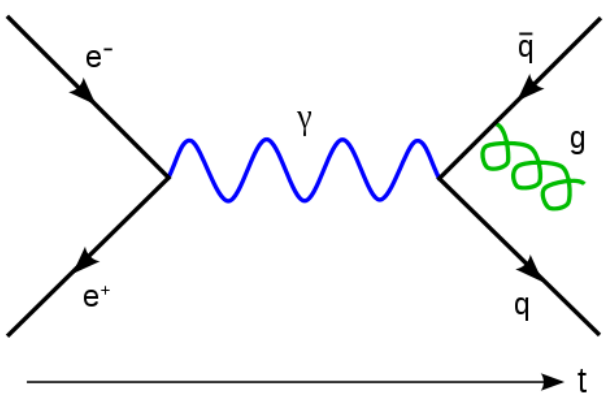
1995 Discovery of “top” quark



- **1995** On Friday, February 24, 1995, at precisely 11 a.m. Central Standard Time, collaborators from DOE Fermilab’s CDF and DZero experiments simultaneously pushed the buttons on their computers submitting to Physical Review Letters their papers announcing the discovery of the top quark, the last remaining quark of the Standard Model.

1979 – Gluon observed indirectly in three jet events at DESY

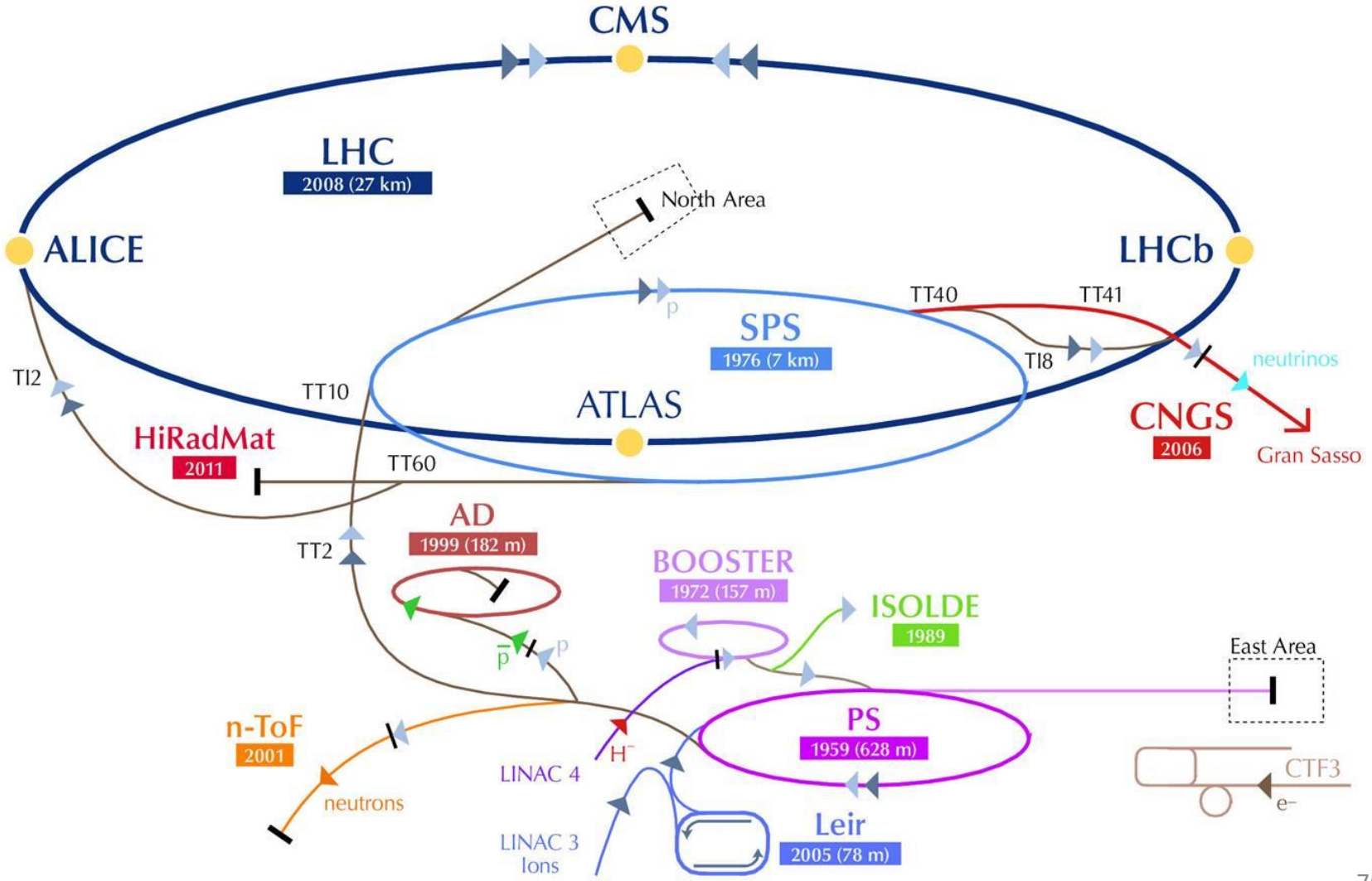




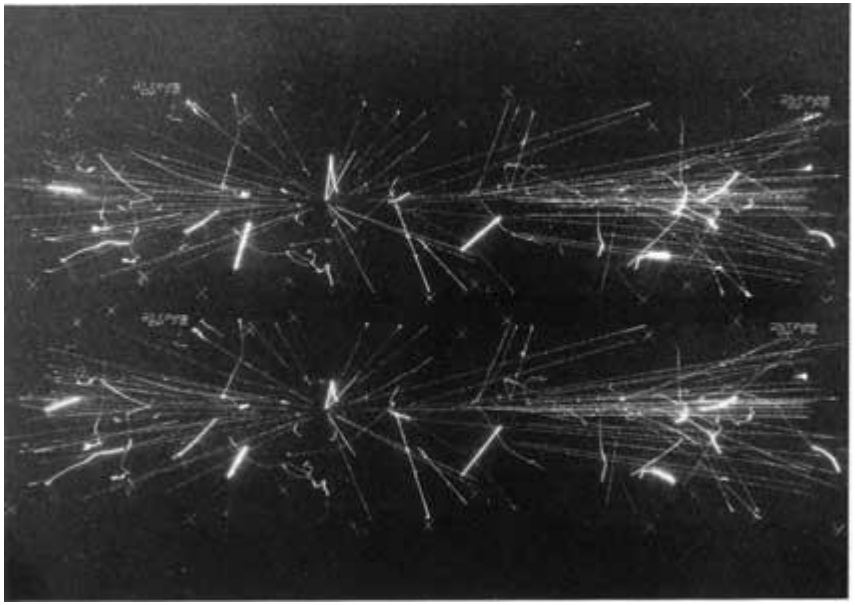
- The year 1979 marks the actual discovery of gluons at the PETRA Electron-Positron Storage Ring at DESY. This important measurement did much to establish the new theory of forces between quarks. (High Energy Physics Prize of the European Physical Society for Günter Wolf, Paul Söding, Sau Lan Wu and Björn Wiik).

CERN Accelerator Complex

Watch the video on http://home.web.cern.ch/about/accelerators



1976 the Super Proton Synchrotron at CERN

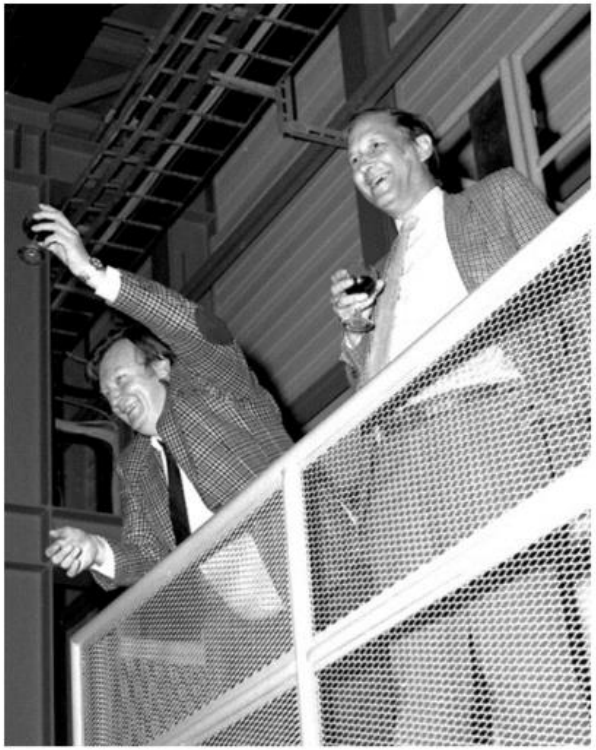


One of the first pictures of a 450 GeV proton-antiproton collision, as recorded in the big streamer chambers of the UA5 experiment at the CERN SPS.

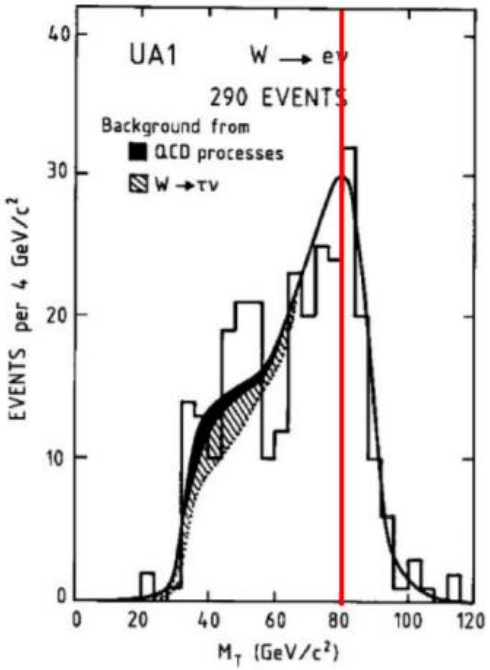
Proton beams: 450 GeV

- Measuring 7 km in circumference, the Super Proton Synchrotron (SPS) was the first of CERN's giant rings. Built in a tunnel, it was also the first accelerator to cross the Franco–Swiss border.
- Initially conceived as a proton accelerator with a beam energy of 300 GeV, the SPS operates today at up to 450 GeV, and has handled many different kinds of particles.
- When it switched on, the SPS became the workhorse of CERN's particle physics program, providing beams to two large experimental areas.

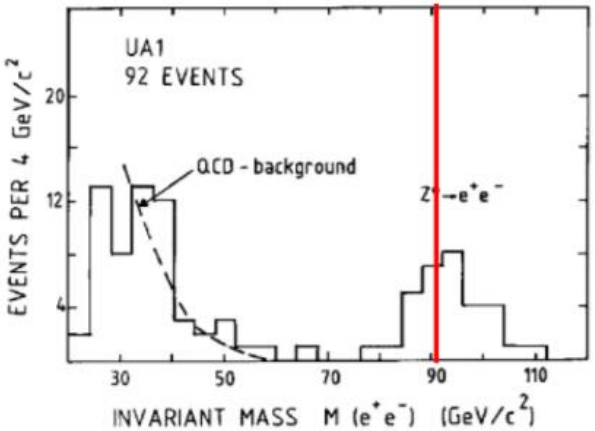
1983 Discovery of the W and Z particles



C. Rubbia & S. van der Meer
Nobel Prize 1984



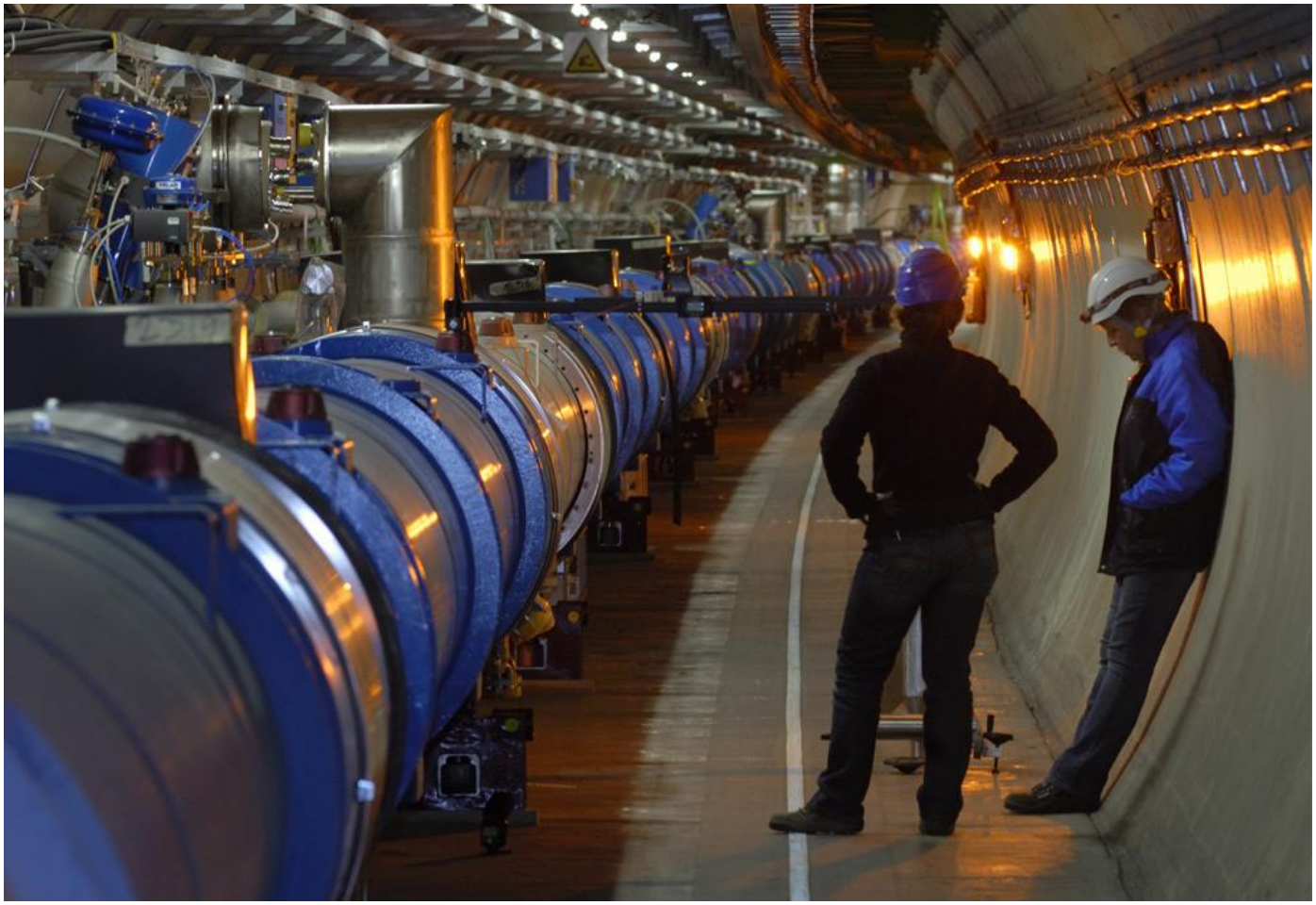
m_W = 80.3 GeV



m_Z = 91.2 GeV

The Nobel Prize in Physics 1984
Carlo Rubbia, Simon van der Meer

LHC



Inside The World's Largest Particle Accelerator

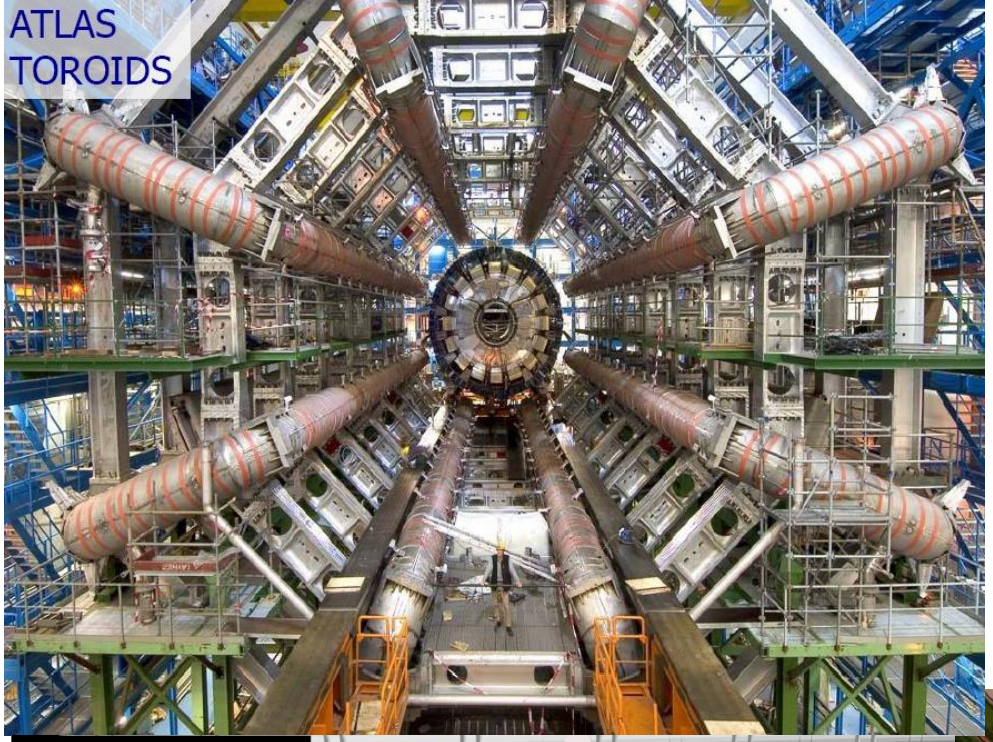
Proton beams: 7 TeV

https://www.youtube.com/watch?v=328pw5Taeg0

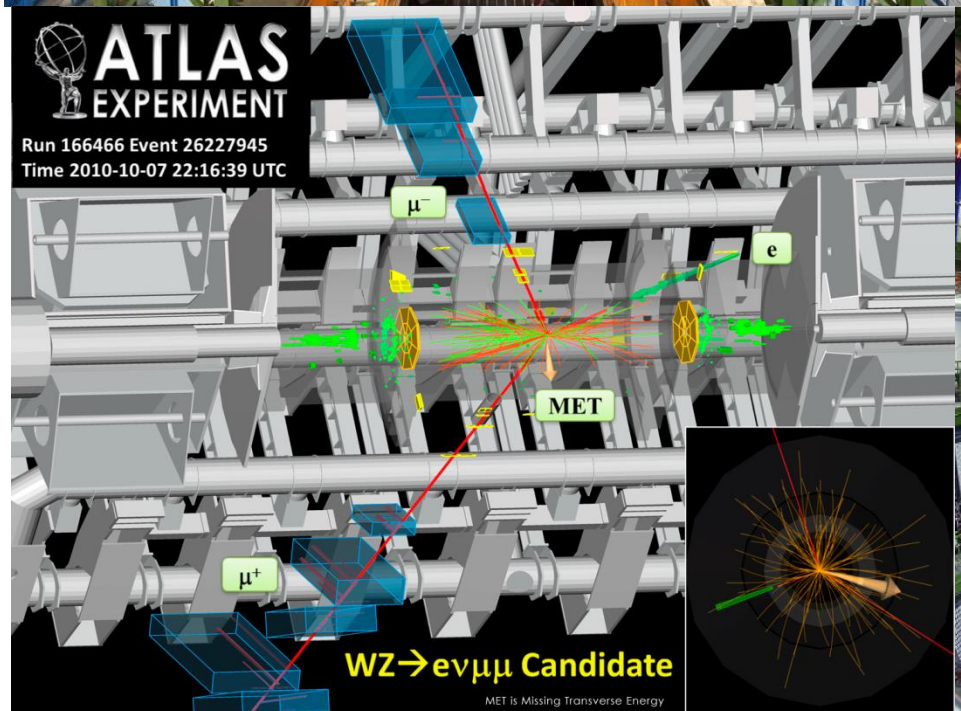
CERN Animation of CERN accelerator network

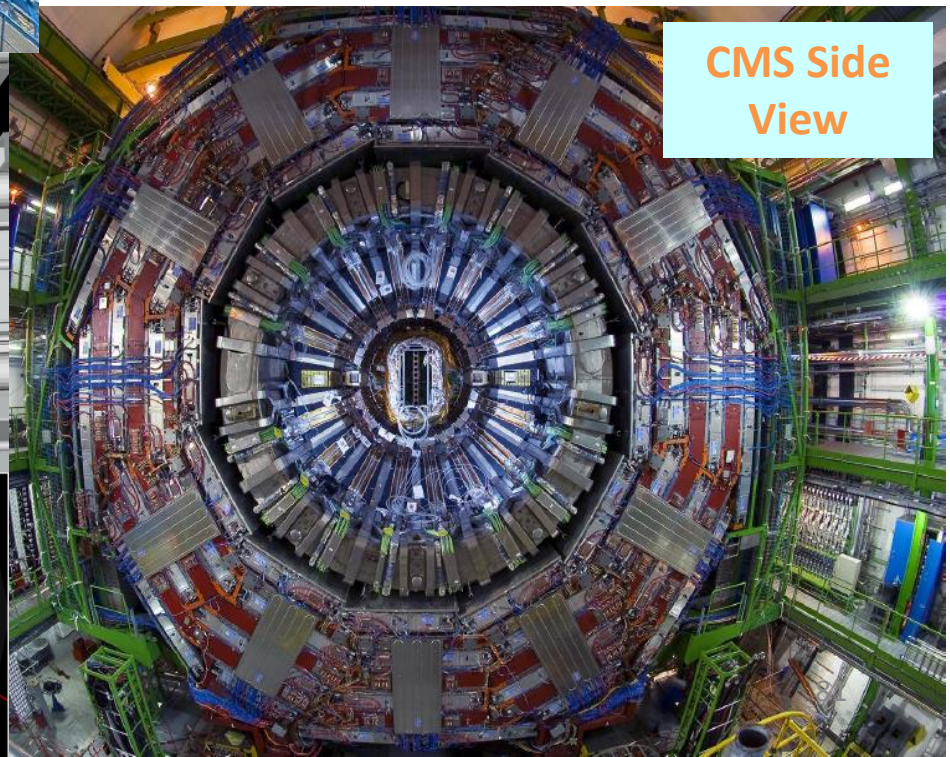
https://www.youtube.com/watch?v=RDdPuL-uOQc

The Large Hadron Collider at CERN


ATLAS
TOROIDS

DCS
Control Room


ATLAS
EXPERIMENT
Run 166466 Event 26227945
Time 2010-10-07 22:16:39 UTC
μ⁻
e
MET
μ⁺
WZ→eνμμ Candidate
MET is Missing Transverse Energy


CMS Side
View

LHC physics reach

$$N = L \cdot \sigma$$

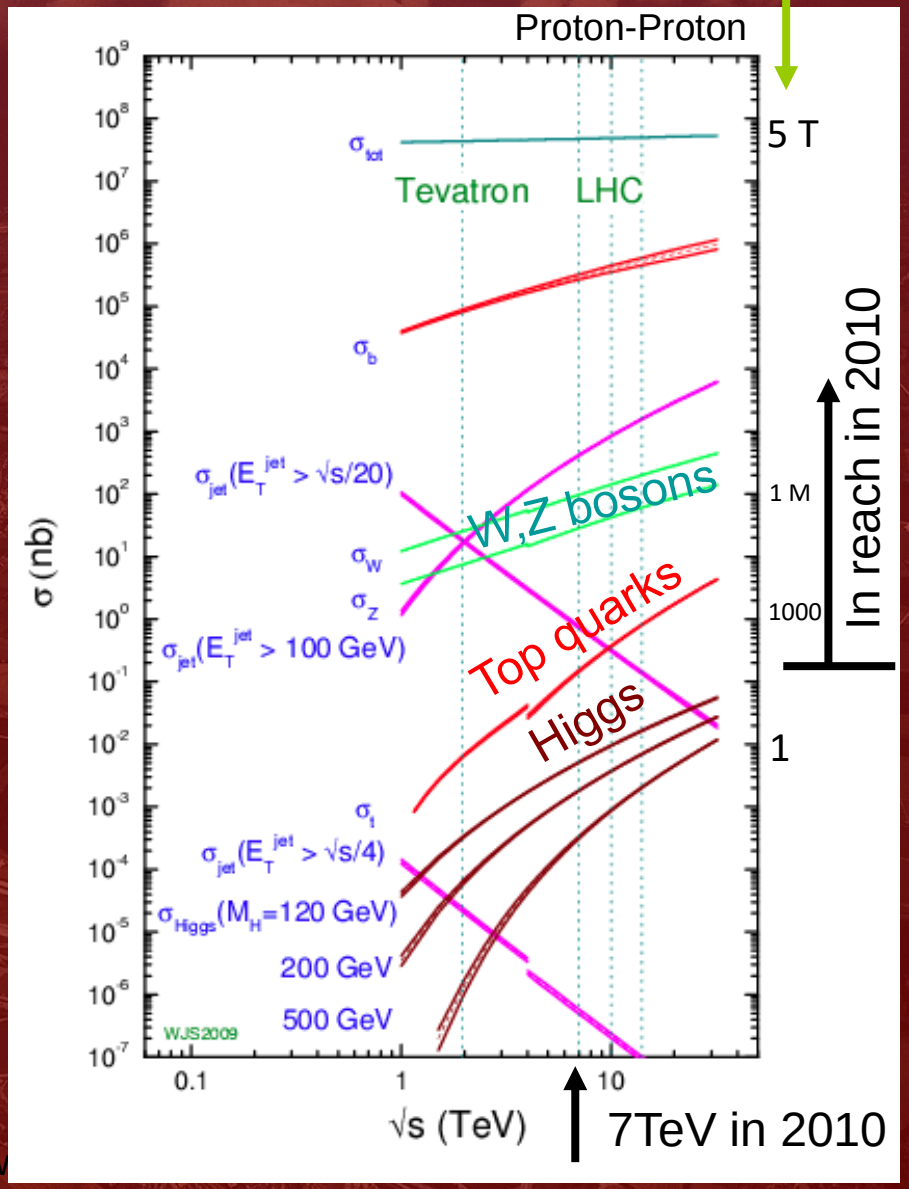
N = # collisions
L = Luminosity
σ = cross-section

- Production Cross-section of top quarks and W, Z bosons are measurable with 2010 data!
- Top, W,Z signals are important:
  1. Standard candles for calibration
  2. Background to new physics & Higgs searches

Promising final states:
H → W^+W^- → 2 leptons + EtMiss
H → ZZ → 4 leptons
Also H → 2 photons

jargon: lepton=electron or muon

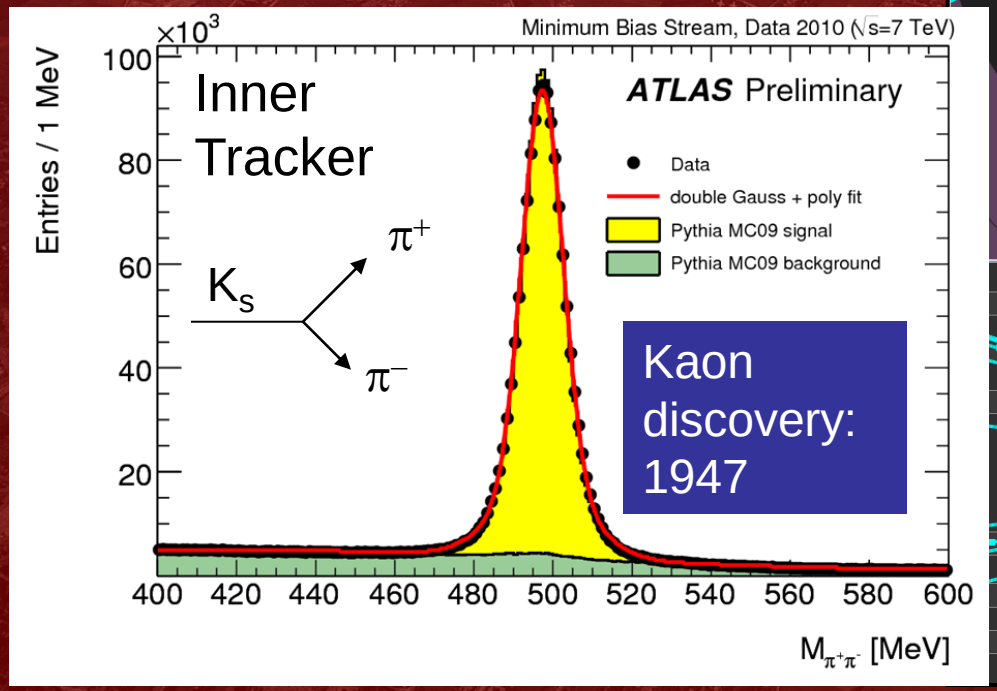
events in 2010

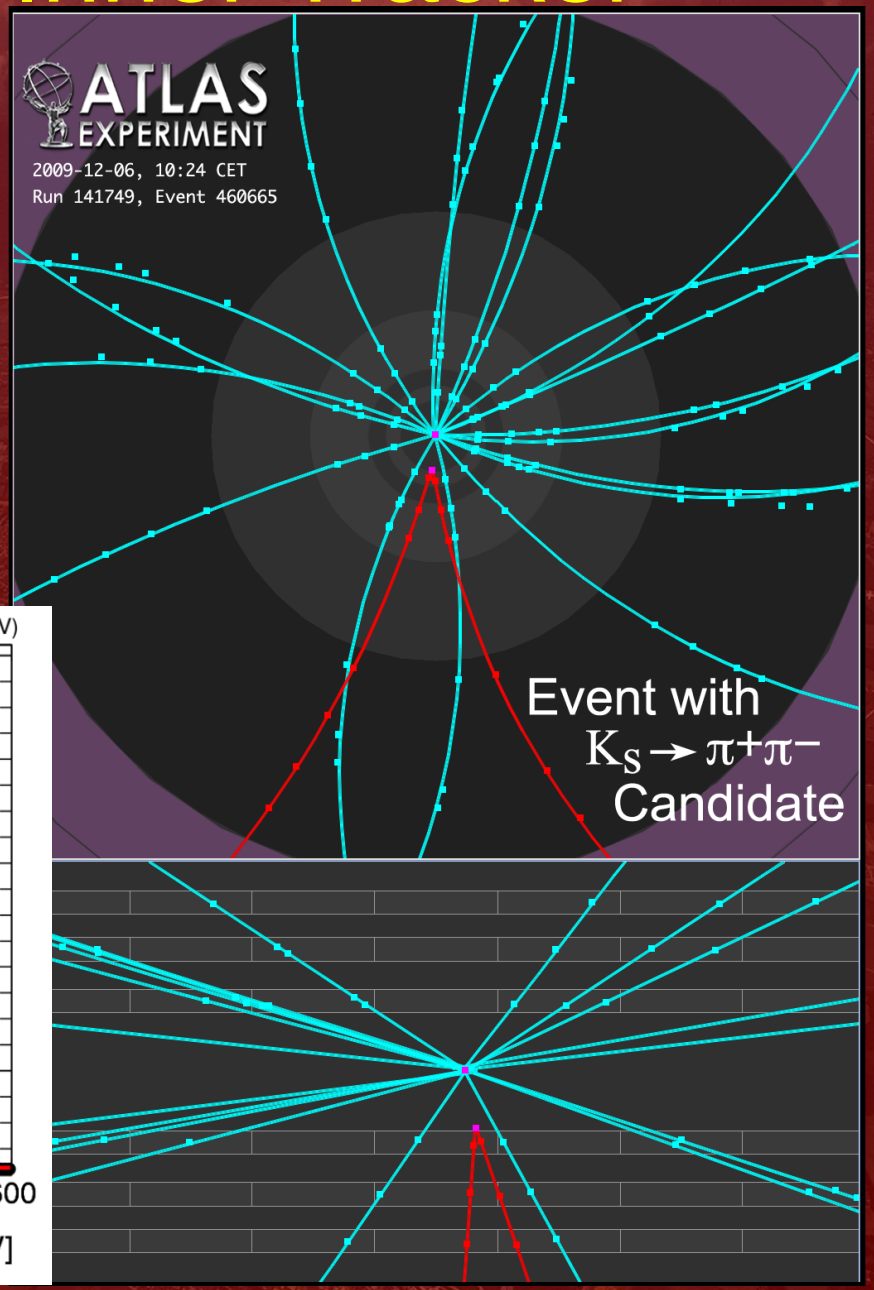


Performance Inner Tracker

Pixel detector (80M channels)
Silicon strips (6M channels)
TRT (350k channels)
Operational for 97.5%

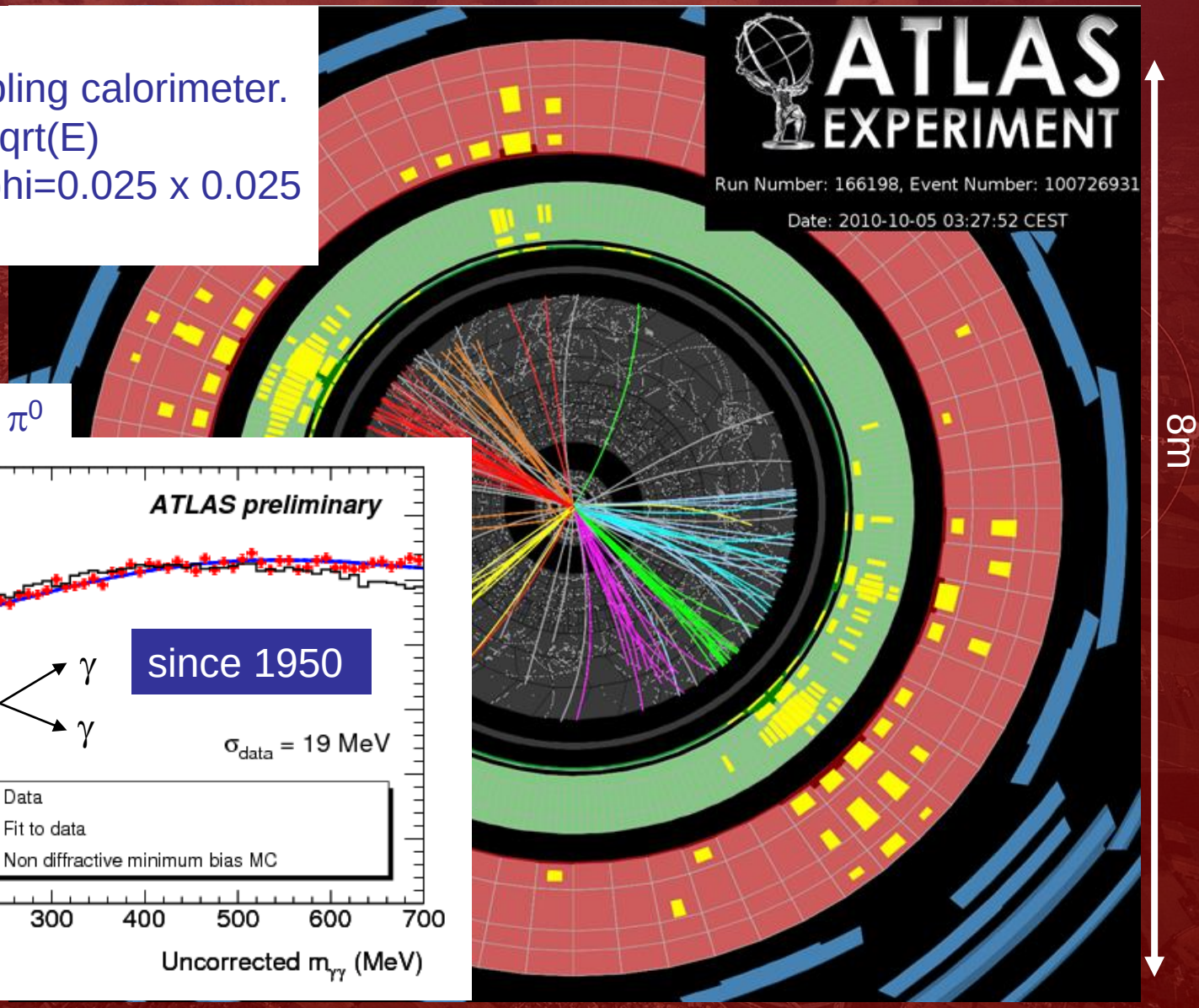
Momentum measurement in magnetic field of 2T
Resolution $\sigma(pT)/pT = 0.05\% pT \oplus 1\%$



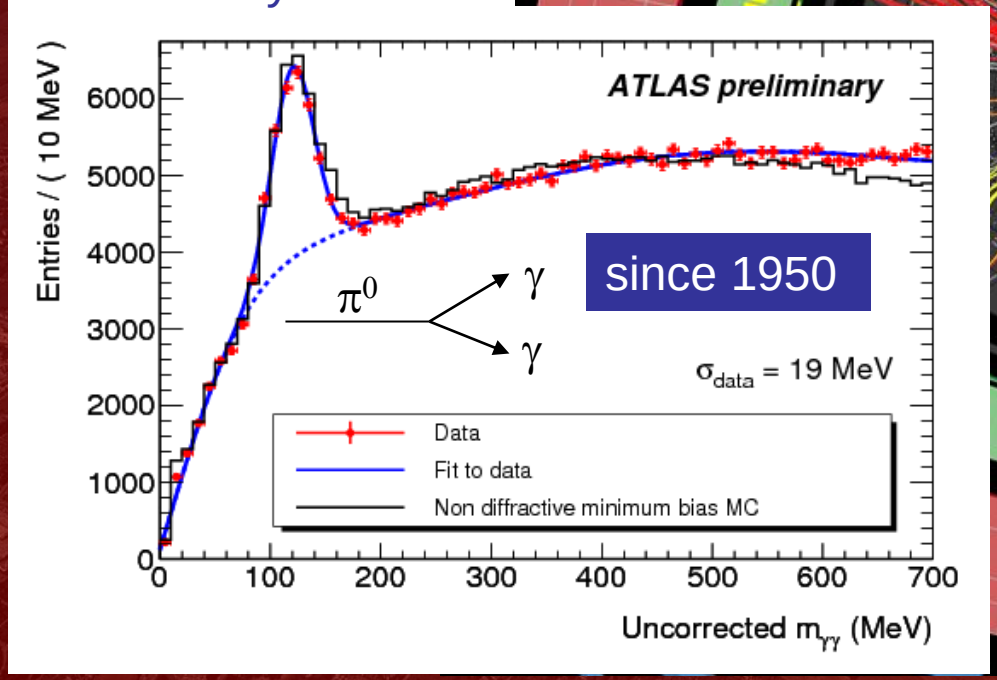


Performance Calorimeter

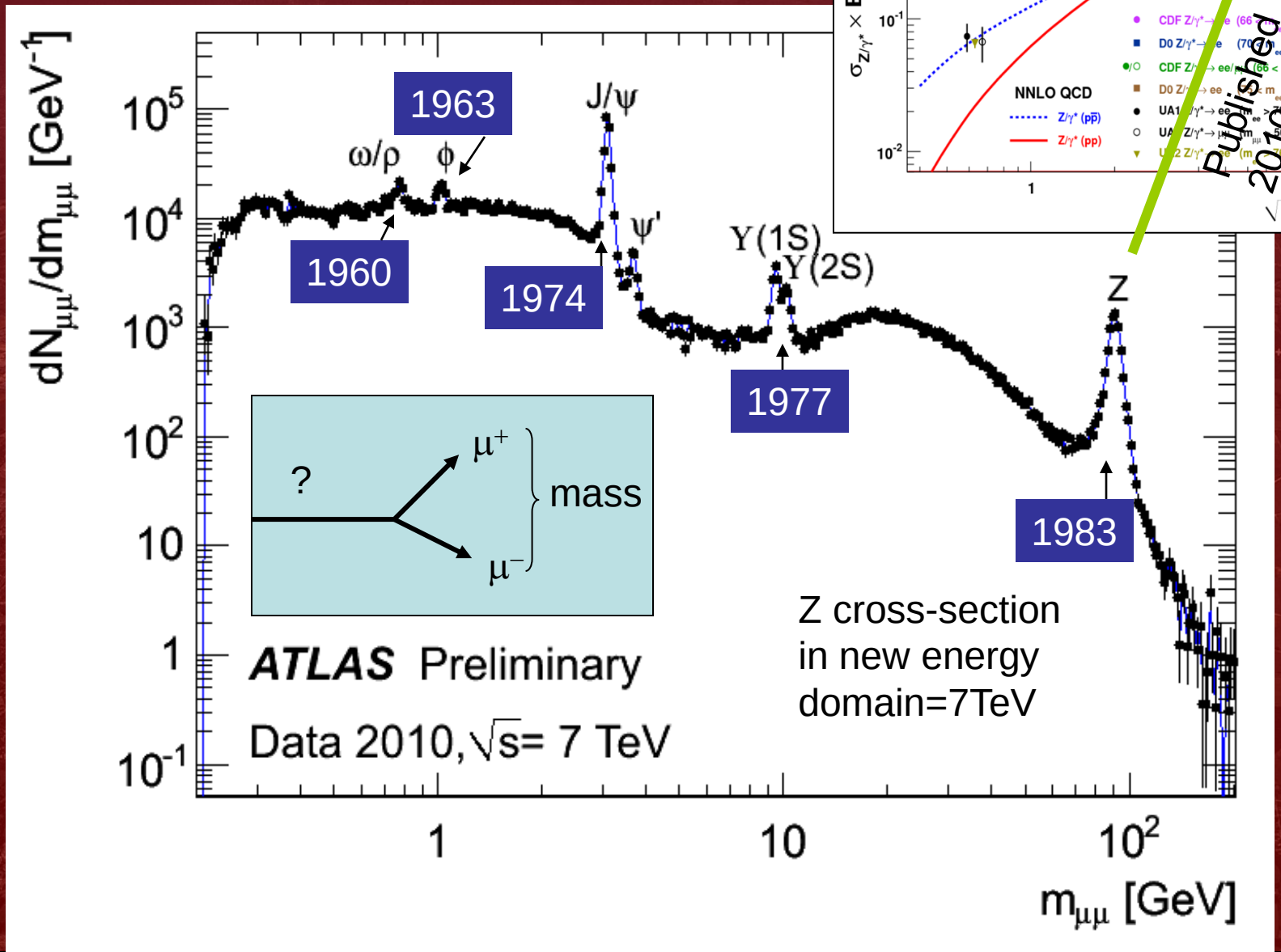
electromagnetic:
Liquid Argon sampling calorimeter.
Resolution ~10%/sqrt(E)
Granularity: eta x phi=0.025 x 0.025

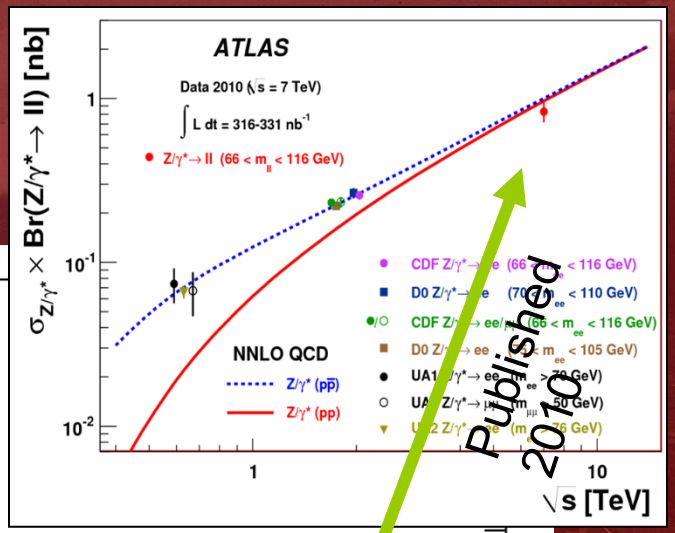


Rediscovery of the π^0

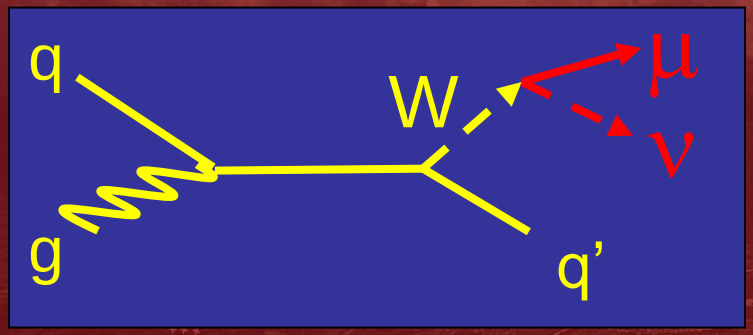


Muon resonances ATLAS 2010





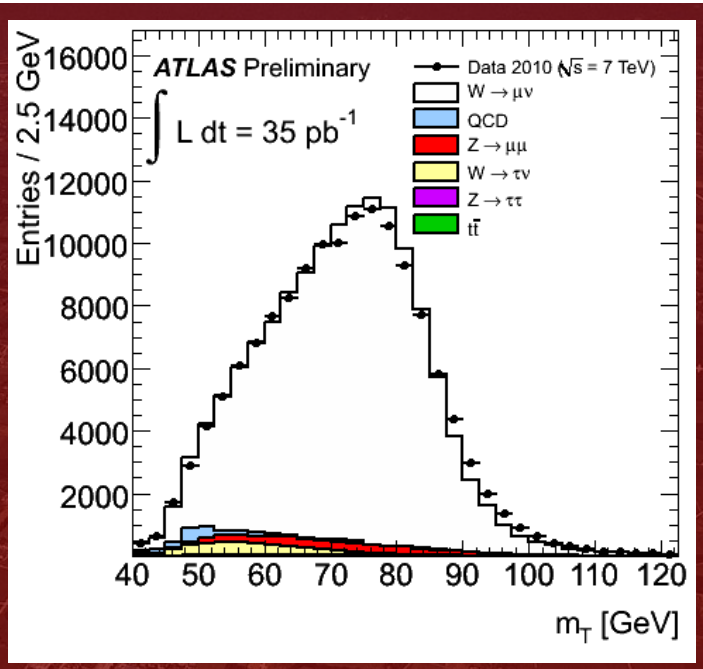
W boson production

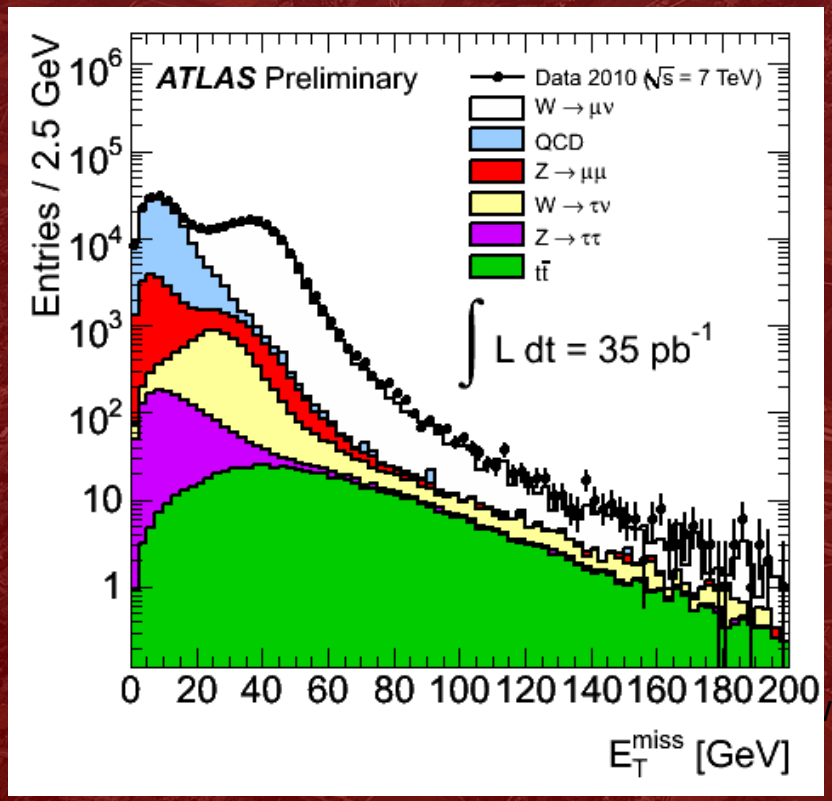


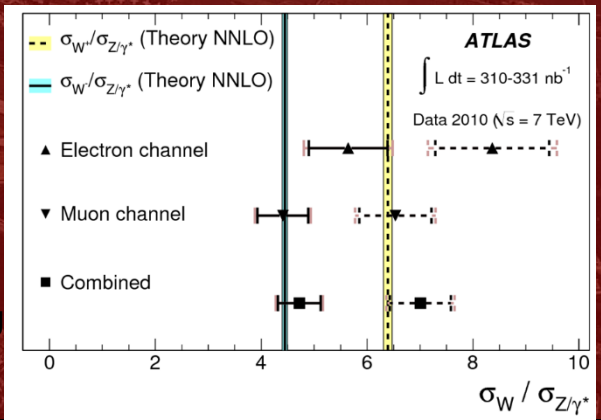
W decays to muon + (unseen) neutrino.
→ Missing transverse energy.

Transverse W mass:

$$m_T = \sqrt{2p_T^l p_T^\nu (1 - cos[\phi^l - \phi^\nu])}$$



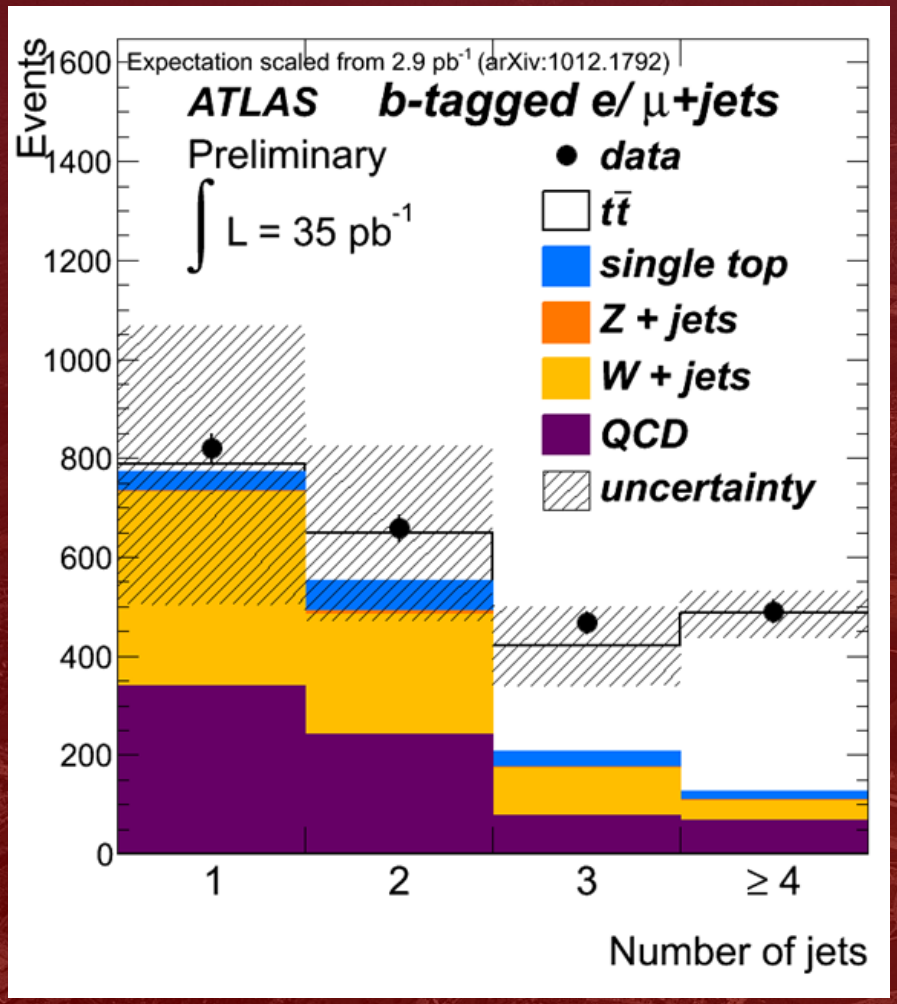


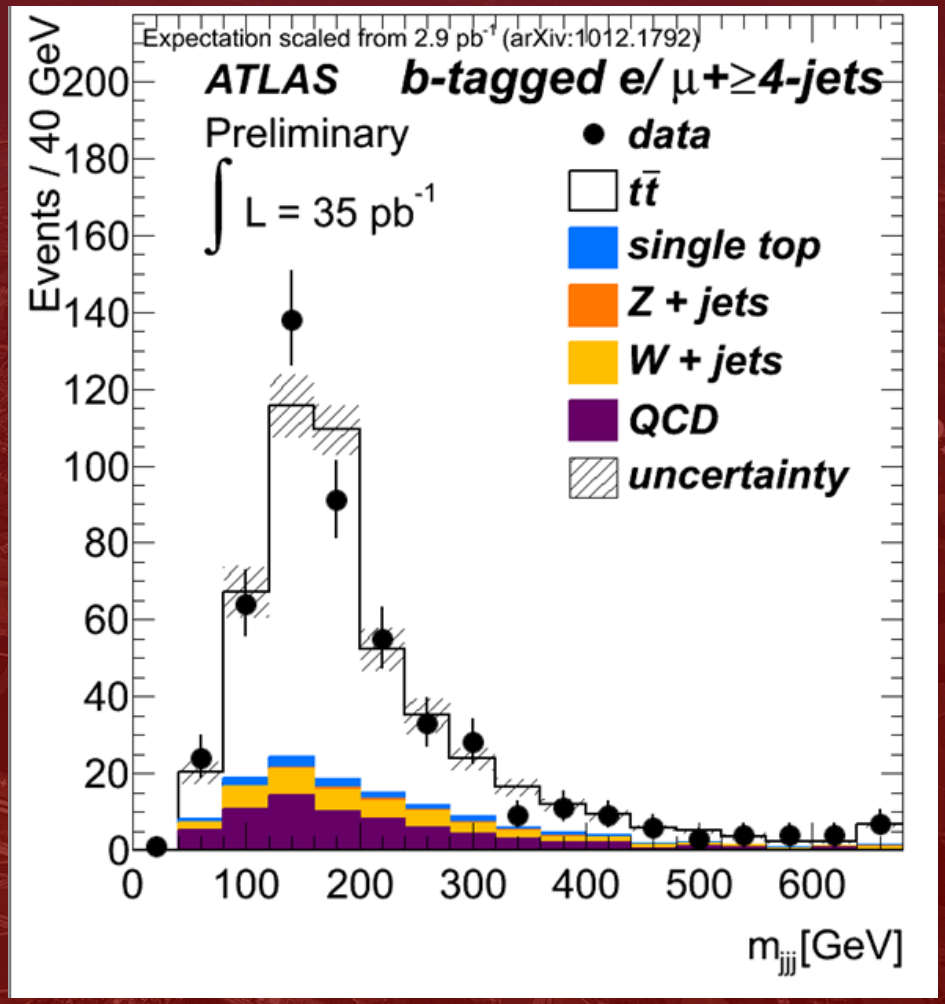


Van Tera naar 100evts selectie
Speld hooi

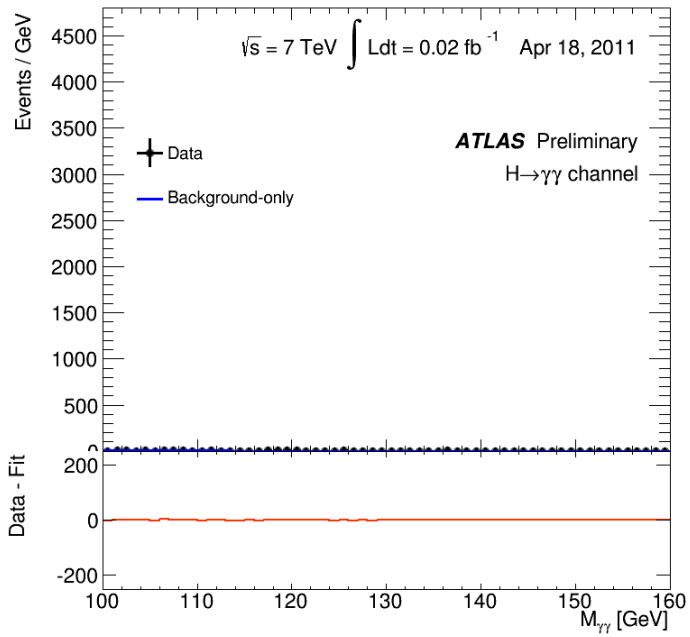
ttbar

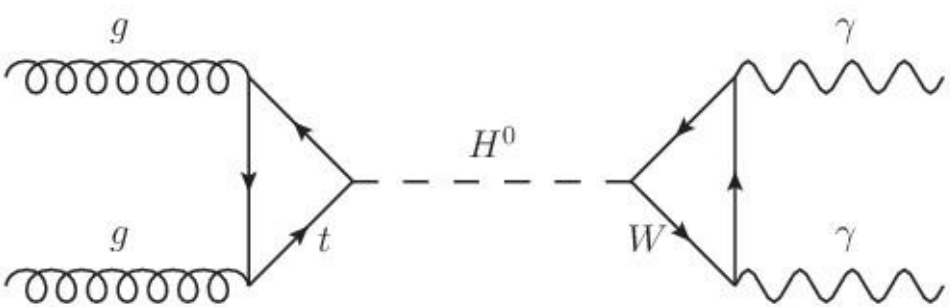
More info on poster by Ido & Hegoi N. from Nikhef

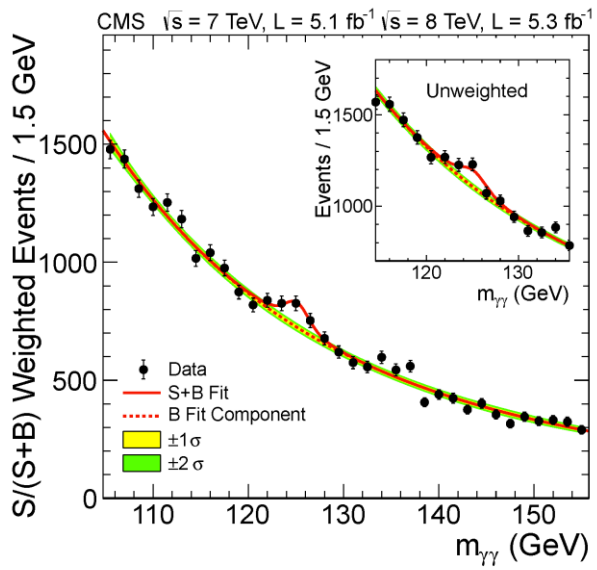




Higgs Discovery:
Announcement at CERN, July 4, 2012.







The Nobel Prize in Physics 2013

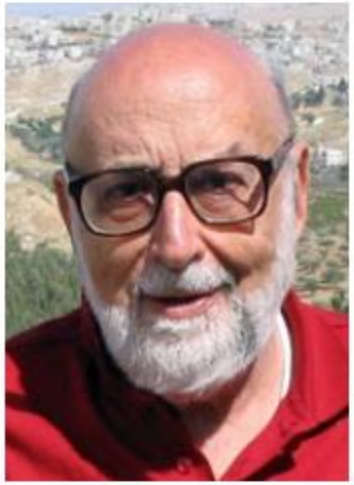


Photo: Pnicolet via Wikimedia Commons

François Englert

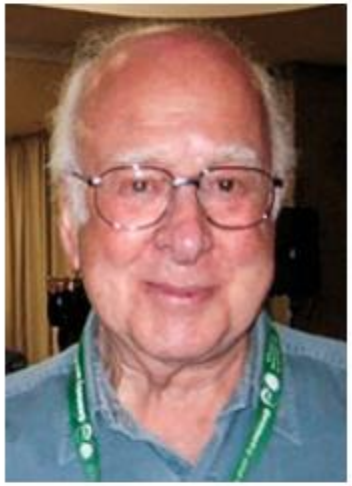


Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

KEKB Accelerator

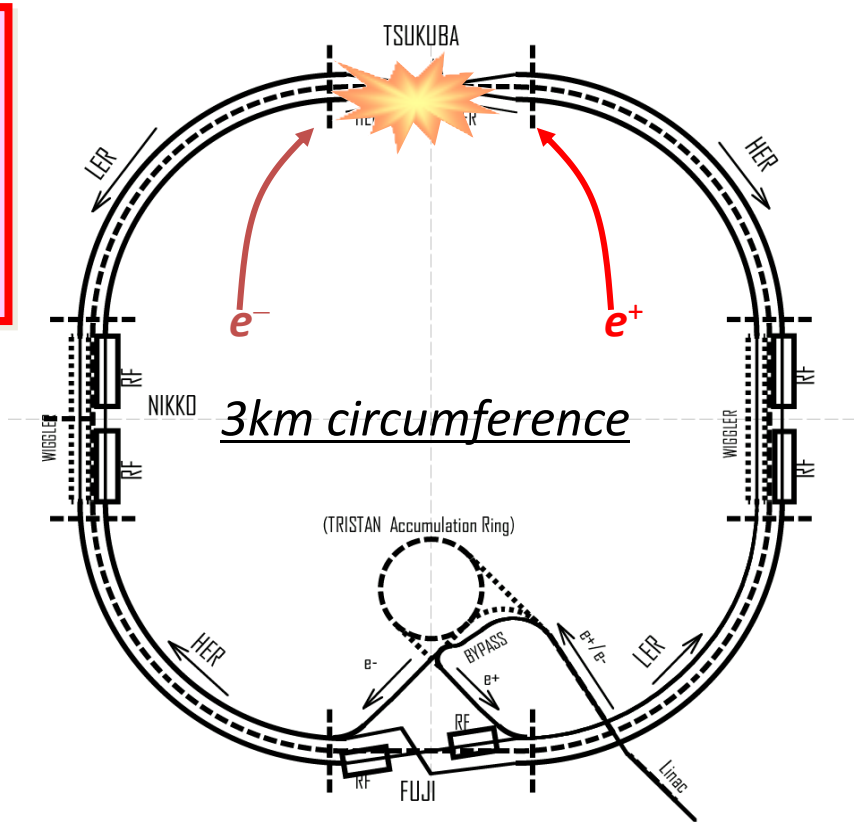
- 3.5 GeV e^+ × 8.0 GeV e^- (11 mrad)

World Records

$L = (1.06 \times 10^{34})/\mathrm{cm}^2/\mathrm{sec}$

$\int L\,dt = 158\ \mathrm{fb}^{-1}$

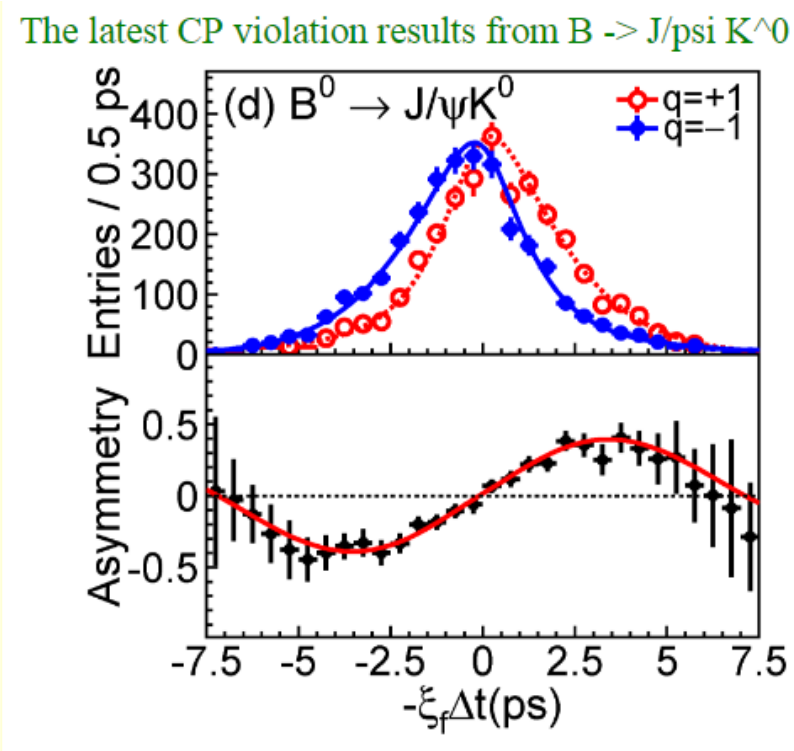
On-resonance 140 fb^{-1}



2001 Discovery of CP Violation in B Mesons

$$q = +1 \text{ (CP+)} \ : B \to J/\psi K_L$$

$$q = -1 \text{ (CP-)} \ : B \to J/\psi K_S$$

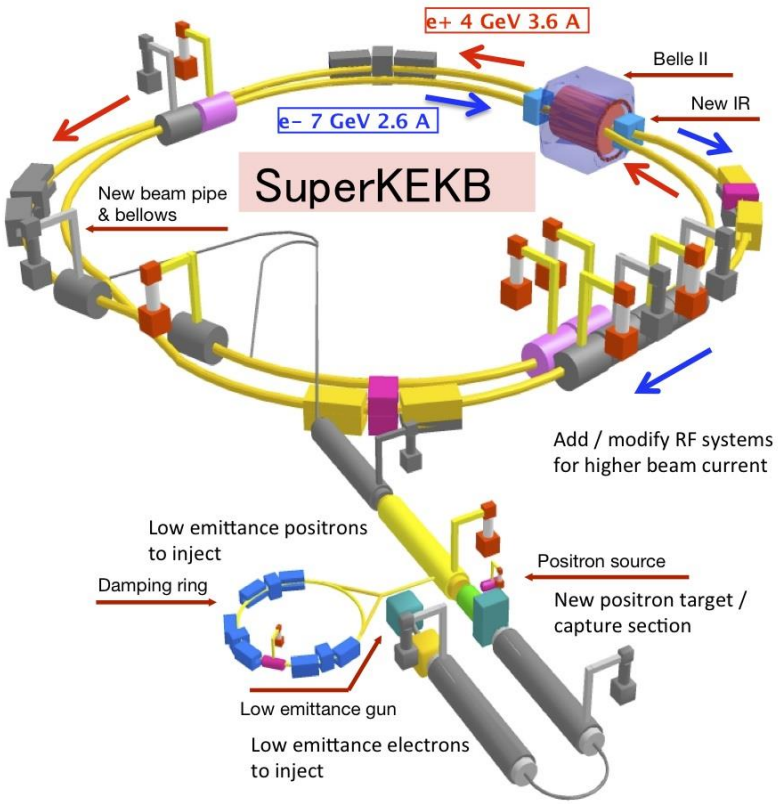


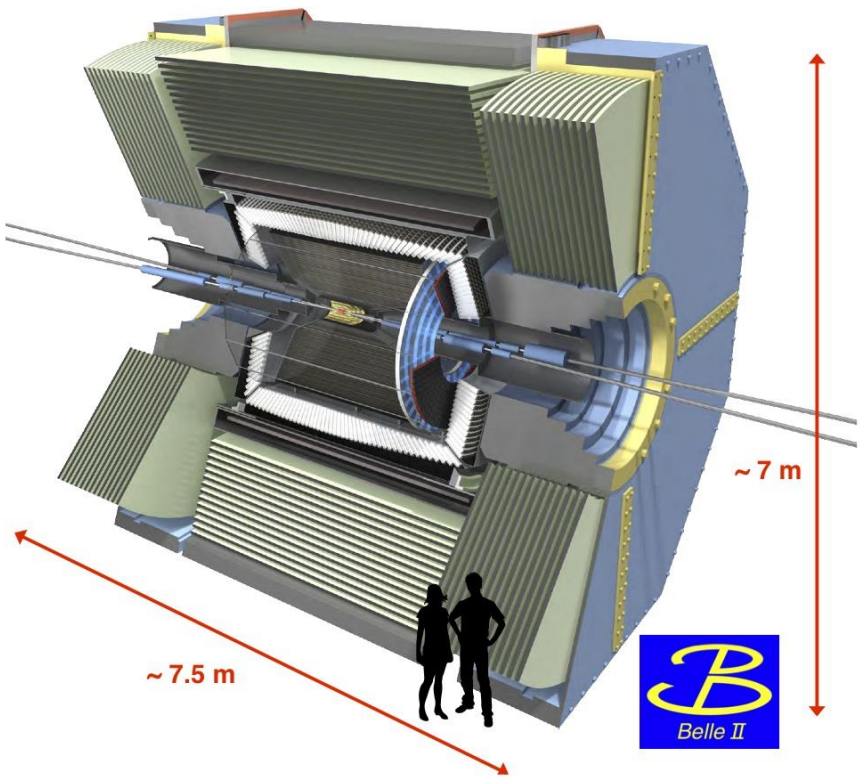
- Kobayashi and Maskawa's explanation of the origin of CP symmetry violation predicted that large CP asymmetries could be observed in the decays of particles containing b-quarks. Verification of their hypothesis was one of the primary goals of the B-factory experiments, Belle at KEKB and BaBar at PEP-II.
- As indicated in the press release from the Nobel foundation the experimental results confirmed that Kobayashi and Maskawa's brillant and bold hypothesis that all CP violation is due to a single complex number was indeed correct.

The Nobel Prize in Physics 2008

Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa

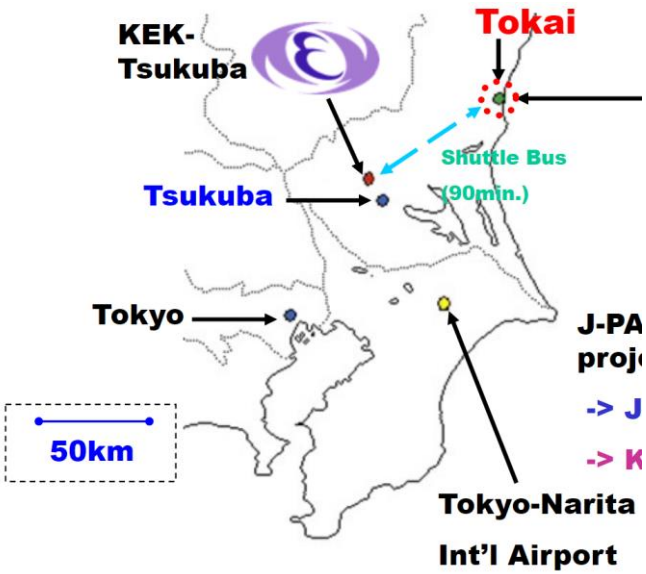
Super KEKB and Belle II

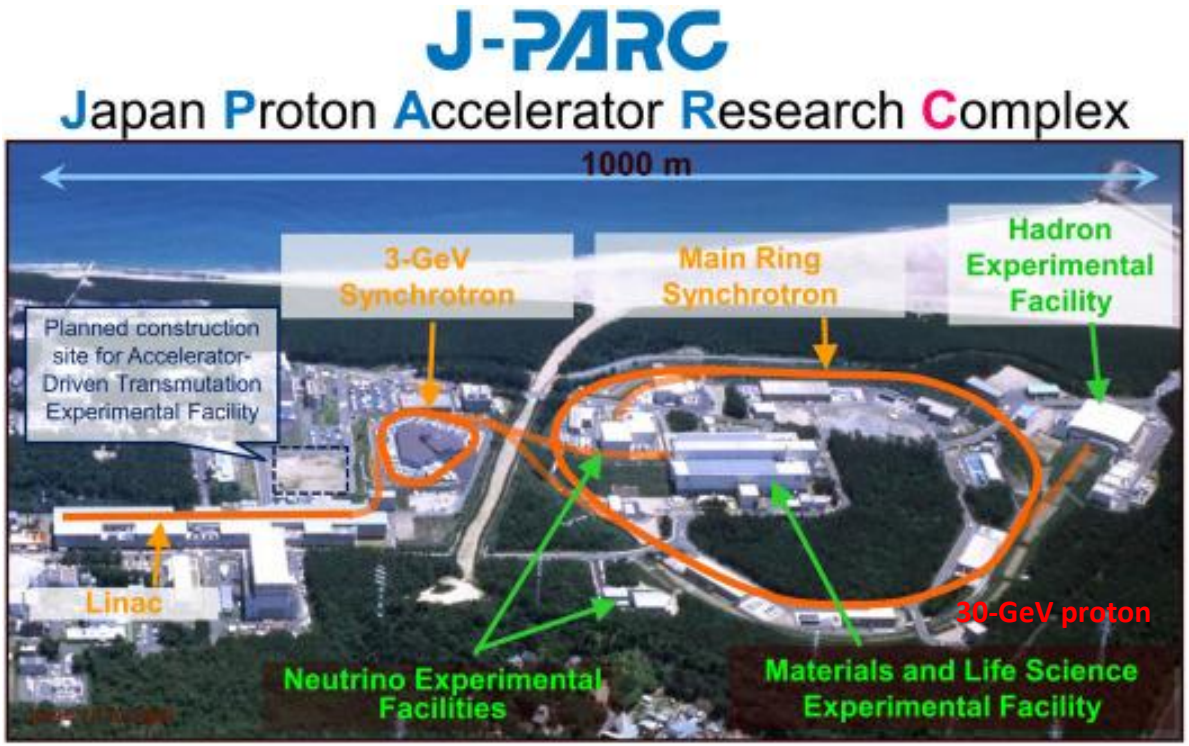




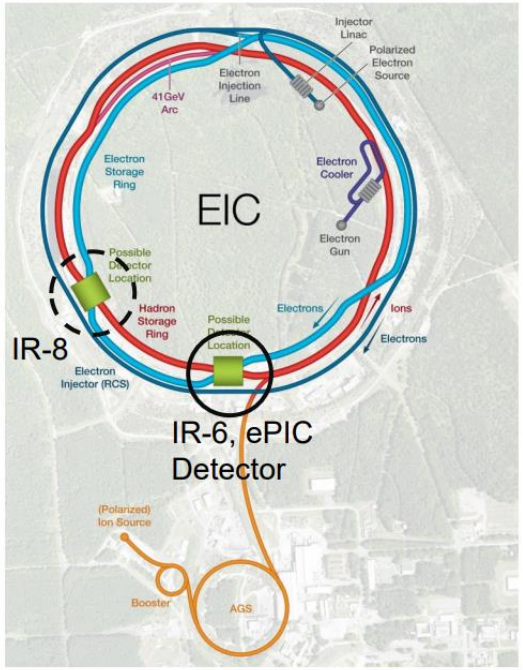
J-PARC

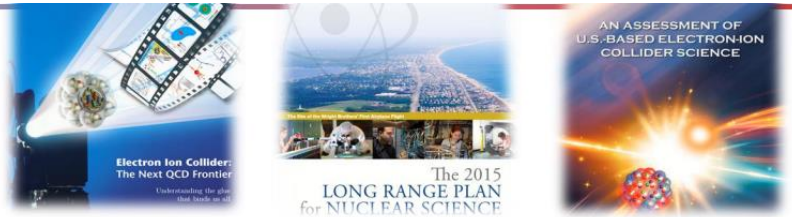
Japan Proton Accelerator Research Complex





U.S. Electron-Ion Collider (EIC)





Project Design Goals

- High Luminosity: L= 10^{33} – 10^{34}cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

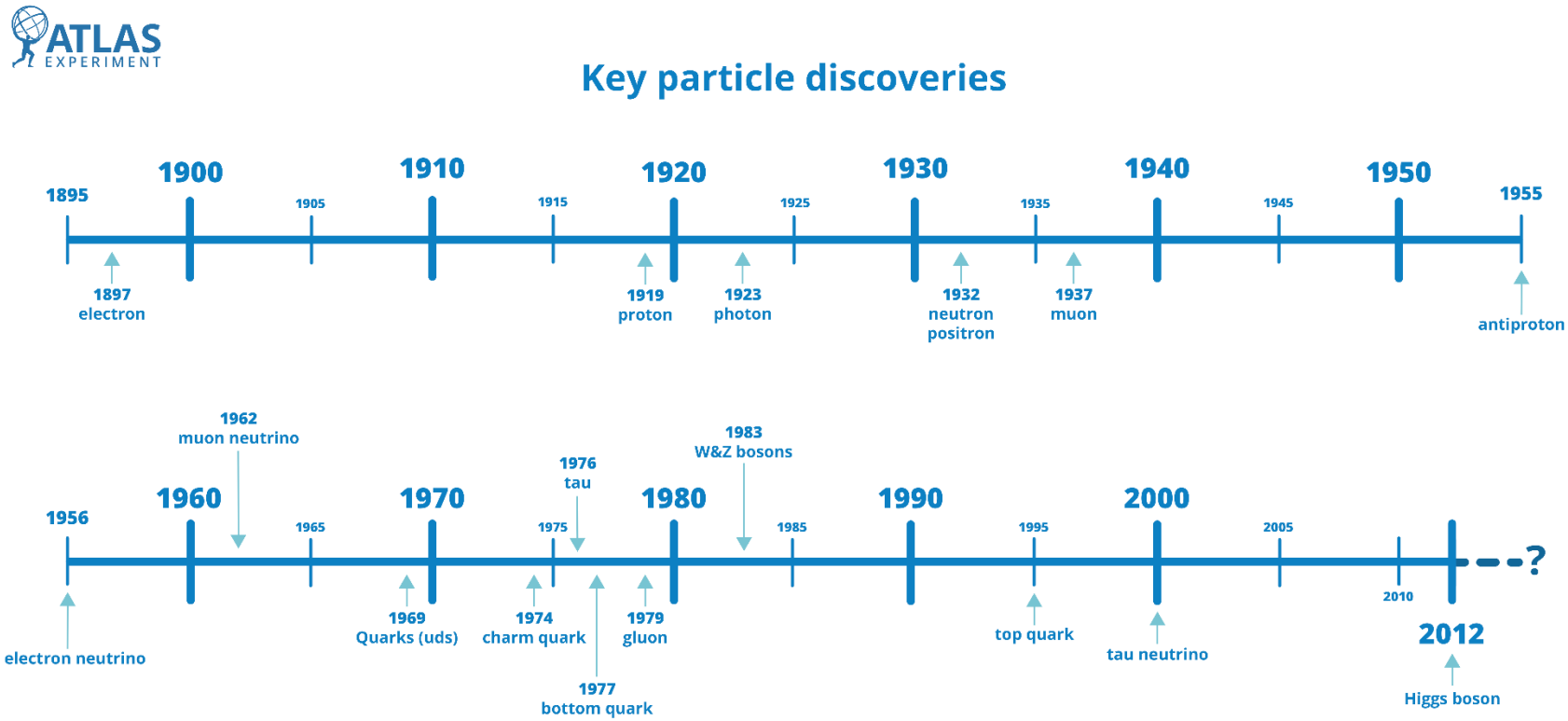
IR-8

p: 41 GeV, 100 to 275 GeV → p/A beam

← e beam e: 5 GeV to 18 GeV

https://indico.phys.sinica.edu.tw/event/88/contributions/416/attachments/501/1250/EIC_Status_NCKU_012924.pdf

Timeline of Key Particle Discovery



台灣高能實驗物理研究團隊

- 台大：CMS, Belle II, KOTO, JUNO, LEGEND, EIC
- 中研院：ALTAS, STAR, AMS, TEXONO, COMPASS, J-PARC, EIC
- 中央：CMS, sPHENIX, COMPASS, Jlab, EIC
- 清華：ATLAS
- 交大：JUNO
- 彰師大：KOTO
- 高師大：KOTO, JUNO