Particle Wars

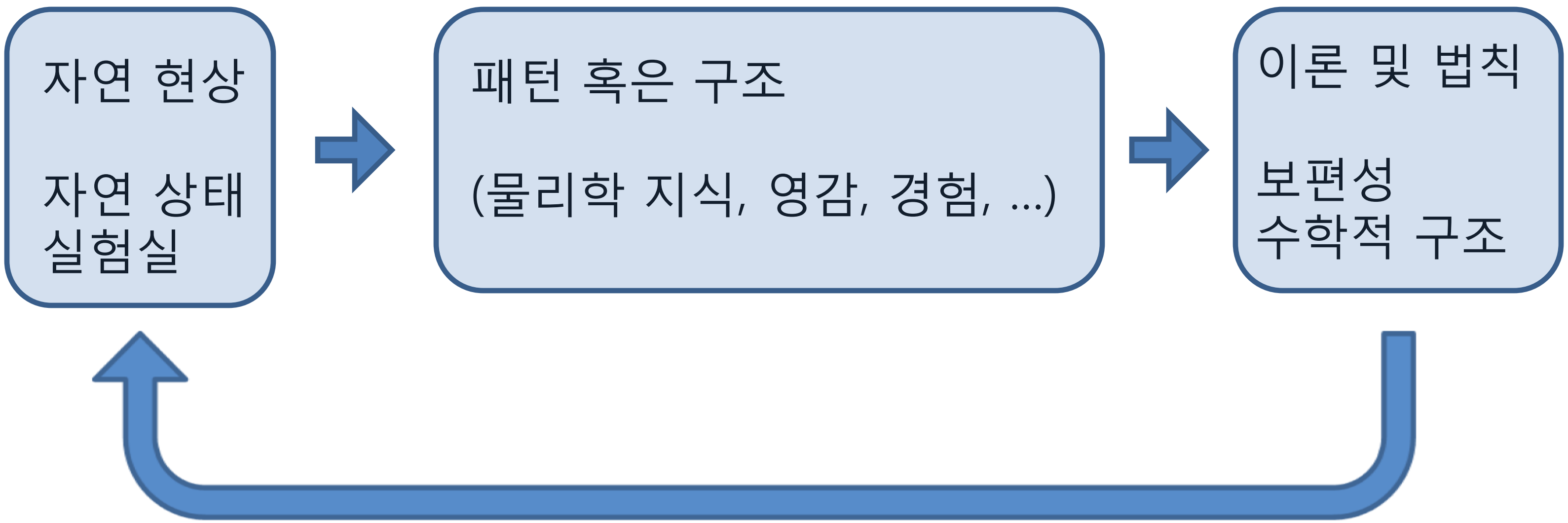
유럽과 미국의 가속기 경쟁사

그리고

LHC

@한국물리학회 2011.04.

왜 가속기인가?

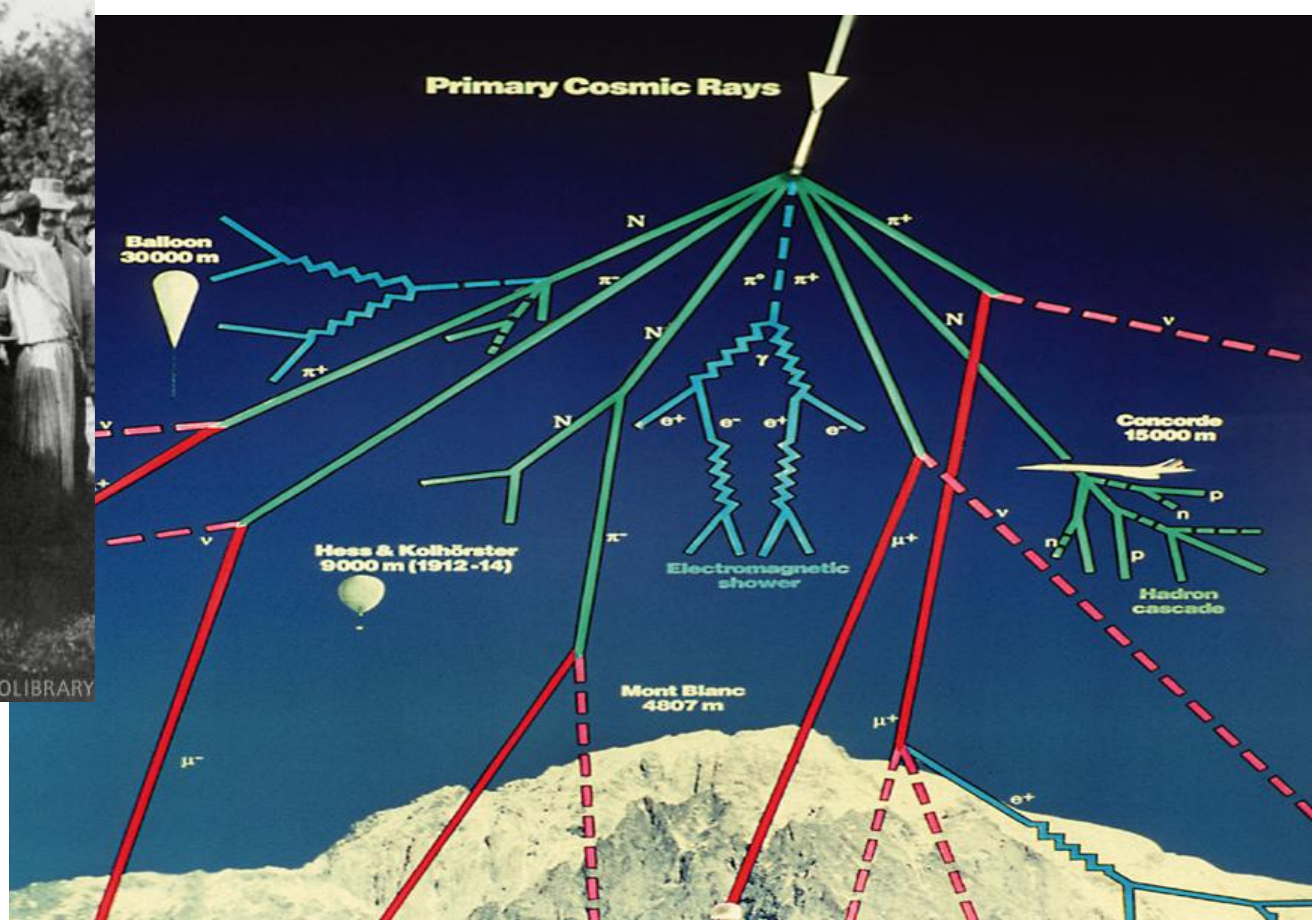


입자물리학이 연구하는 자연 현상 : 높은 에너지 상태

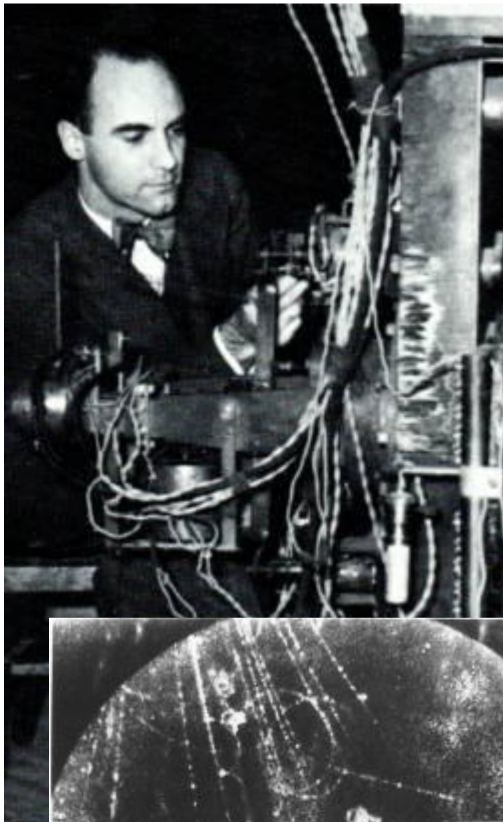
: 초기 우주, 우주선, 가속기

가속기 이전 - 우주선 Cosmic Ray

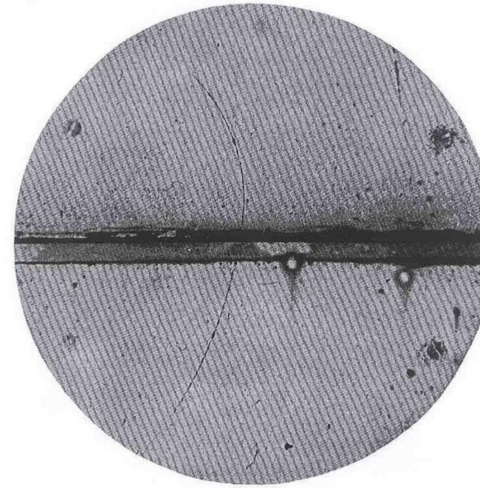
우주선의 발견 (1912)
오스트리아의 헤스 (Victor F. Hess), 5000m 상공에 띄운 기구



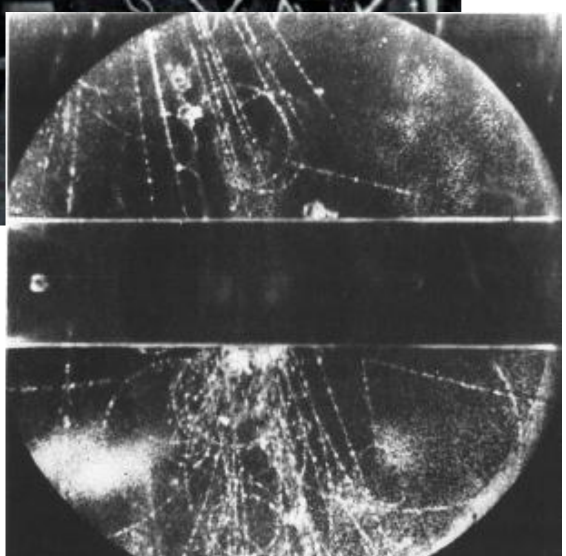
우주선에서 발견된 입자



앤더슨 (C. Anderson)
양전자 (1932)와 뮤온 (1936) 발견
캘리포니아 공과대학

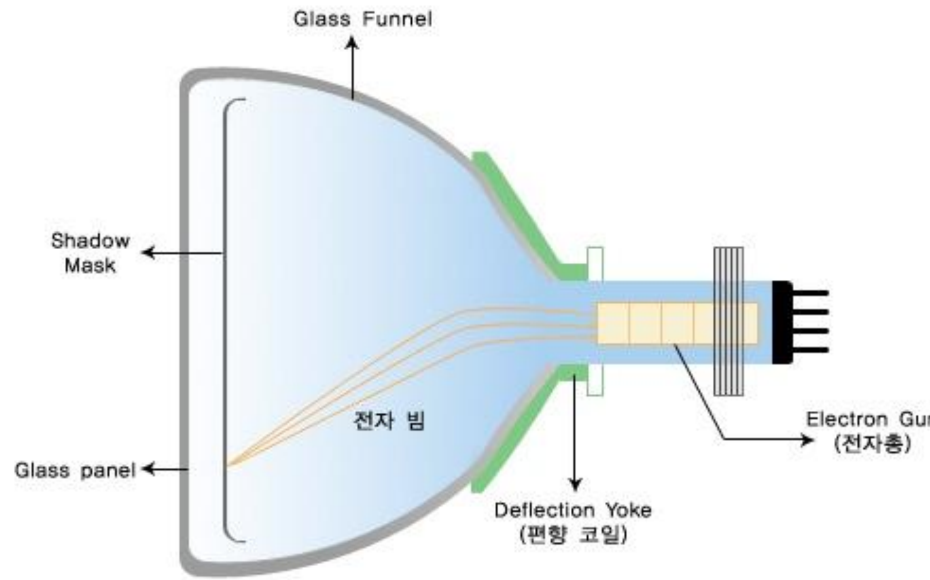


파웰 (C. T. Powell),
오키알리니 (G. Occhialini)
전기를 띤 파이온 발견
1947, 브리스톨



로체스터 (G. D. Rochester),
버틀러 (Cl. C. Butler)
V자 궤적으로부터 케이온 발견
1947, 맨체스터

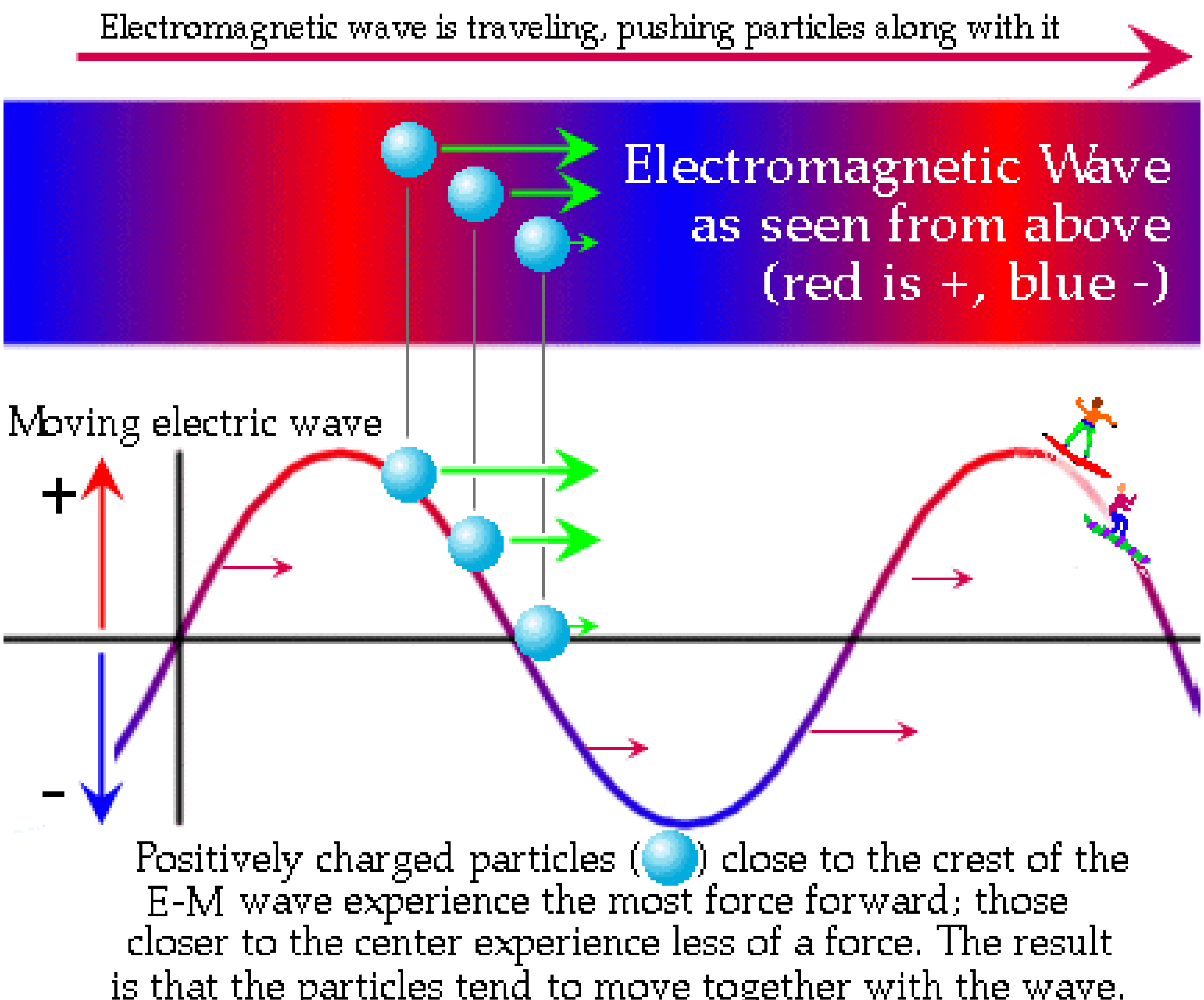
가속기 accelerator



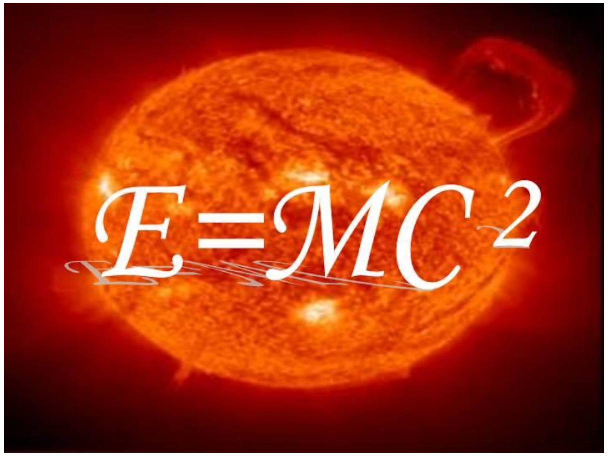
브라운관의 구조

콕크로프트 (J. D. Cockcroft)와 월튼 (E. T. S. Walton)
1932

가속기의 원리

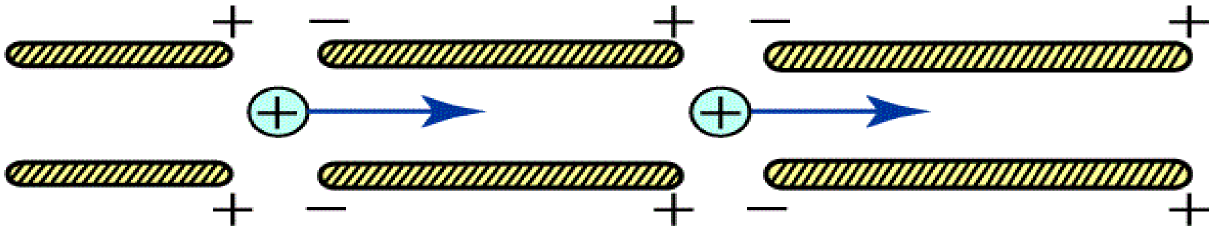

Electromagnetic wave is traveling, pushing particles along with it
Electromagnetic Wave
as seen from above
(red is +, blue -)
Moving electric wave
+
-
Positively charged particles ( ) close to the crest of the
E-M wave experience the most force forward; those
closer to the center experience less of a force. The result
is that the particles tend to move together with the wave.

질량 ↔ 에너지



$$E^2 = m^2c^4 + p^2c^2$$

가속기의 출력을 높이면 새로운 입자를 볼 것이다!



가속기의 출력을 높이려면? 반복해서 가속시킨다!

사이클로트론 Cyclotron
– 현대 가속기의 시작

최초의 사이클로트론

반지름 약 4.5cm

제작비 $25

출력 양성자를 80,000eV로 가속
(빛의 속도의 약 1%)

어니스트 로런스 Ernest Orlando Lawrence
– 사이클로트론의 발명가

1931 사이클로트론 발명

1934 사이클로트론 특허

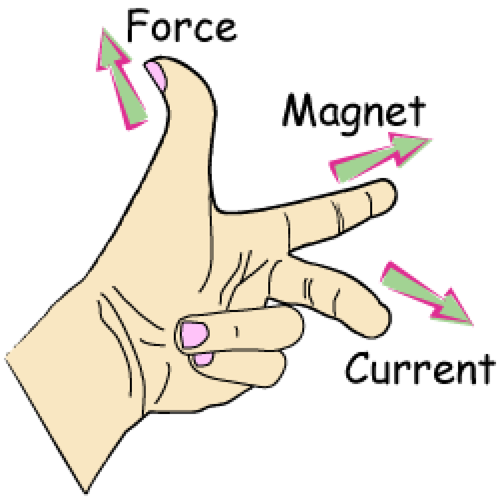
1936 방사선 연구소 (Radiation Laboratory) 설립

1939 노벨 물리학상

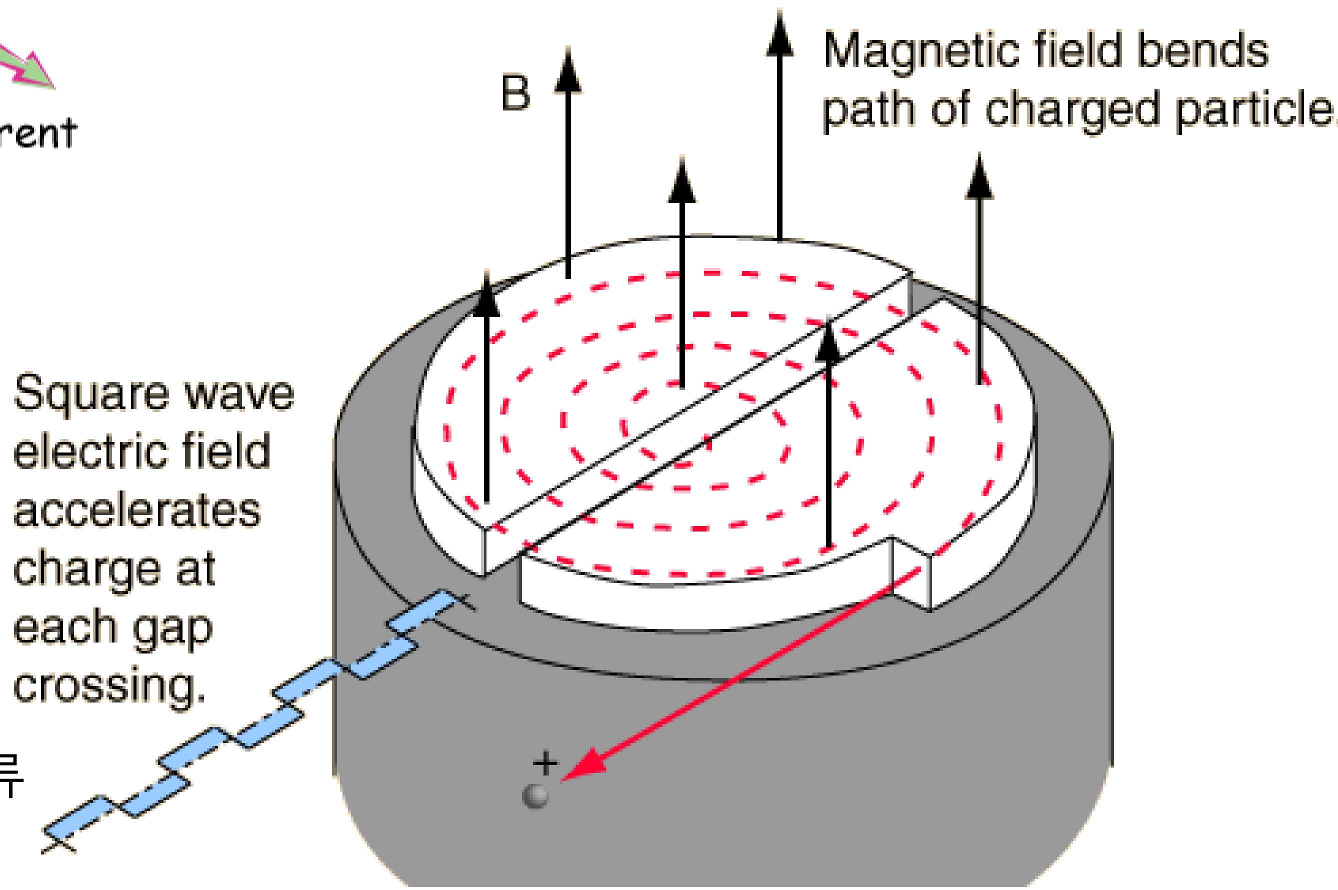
사후 방사선 연구소는 로런스 버클리 연구소로 개명.

E. O. Lawrence
(1901 –1958)

사이클로트론의 원리



로렌츠의 힘



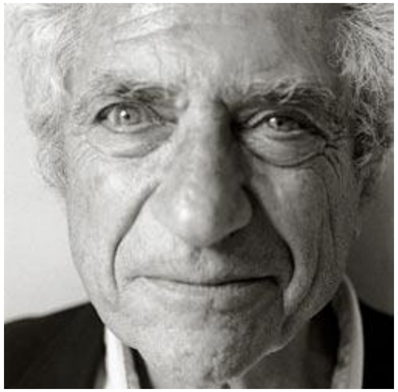
일정한 자기장

일정한 주파수의 교류전류

37.5인치 사이클로트론

60인치 사이클로트론

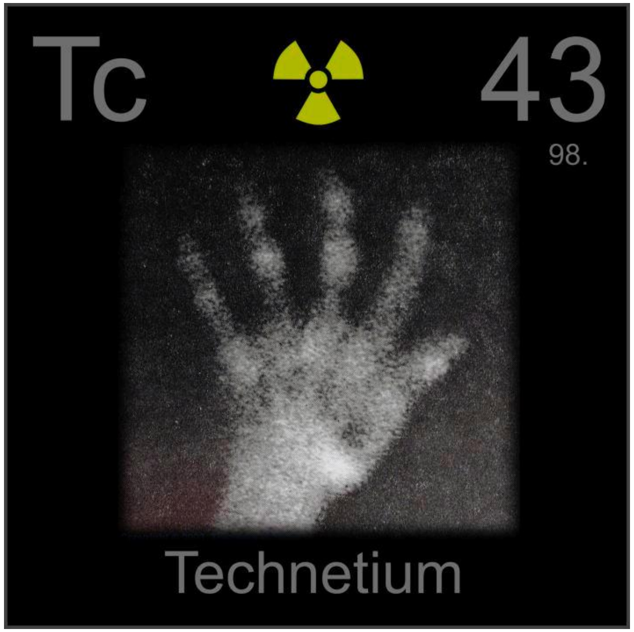
사이클로트론의 활약



Jack Steinberger
(1921 -)

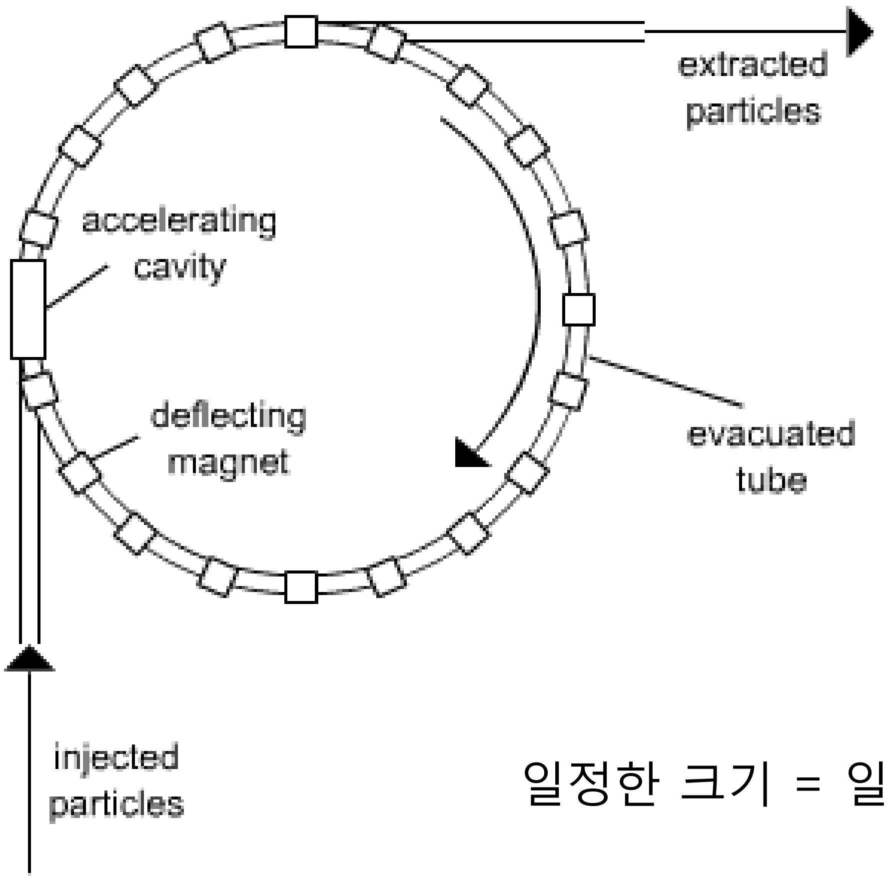
슈타인버거 (J. Steinberger), 파노프스키 (W.K.H. Panofsky), 스텔라 (J. Stellar) 중성 파이온 발견.
1950, 버클리
우주선이 아니라 가속기에서 최초로 발견된 첫 입자.

테크네튬 동위원소의 발견



오늘날 의료 분야에서 사이클로트론은 널리 쓰이고 있다.

싱크로트론의 원리



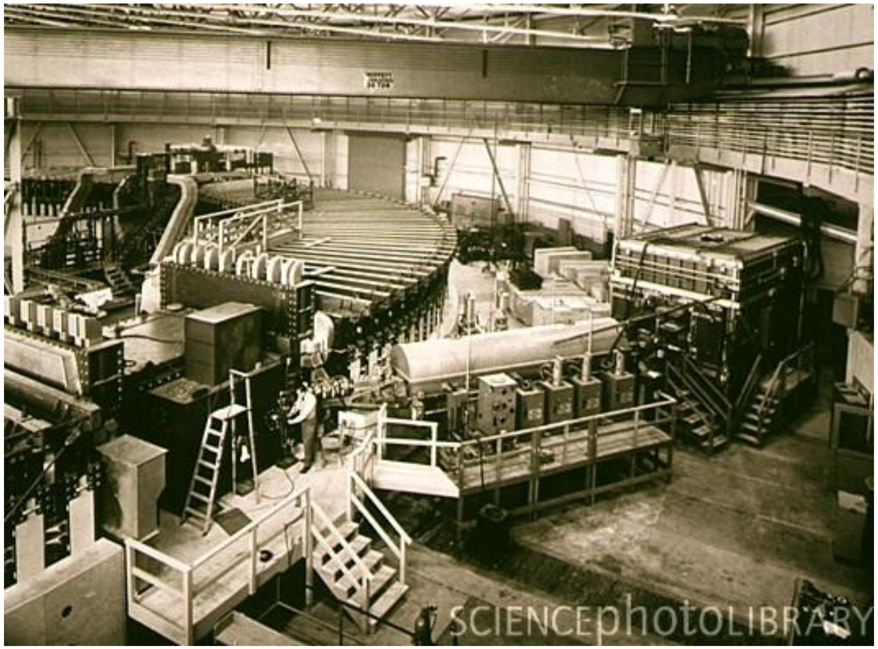
사이클로트론의 한계

- 크기의 한계
- 상대론적 효과

일정한 크기 = 일정한 궤도

자기장과 가속 전자기장은 속도에 따라 변화

초기의 중요한 싱크로트론

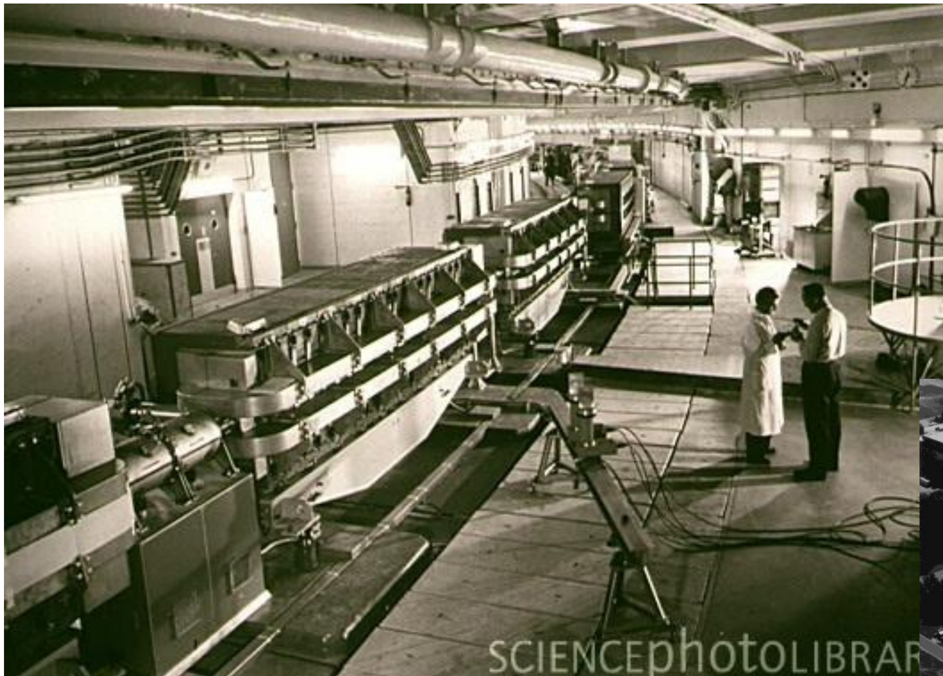


베바트론 (Bevatron)
@로런스 버클리 연구소
1954 – 1993
6.3 GeV (proton)
반양성자 발견

코스모트론 (Cosmotron)
@브룩헤이븐 국립 연구소
1953 – 1966
3.3 GeV (proton)

CERN (1954 -)

PS vs. AGS



Proton Synchrotron (PS)
@CERN
1959. 11. –
28 GeV (proton)
중성류 발견 (가가멜)

Alternate Gradient Synchrotron (AGS)
@ 브룩헤이븐 국립 연구소
1960. 7. –
32 GeV (proton)
뮤온 중성미자, CP 대칭성 깨짐, J/ψ 발견

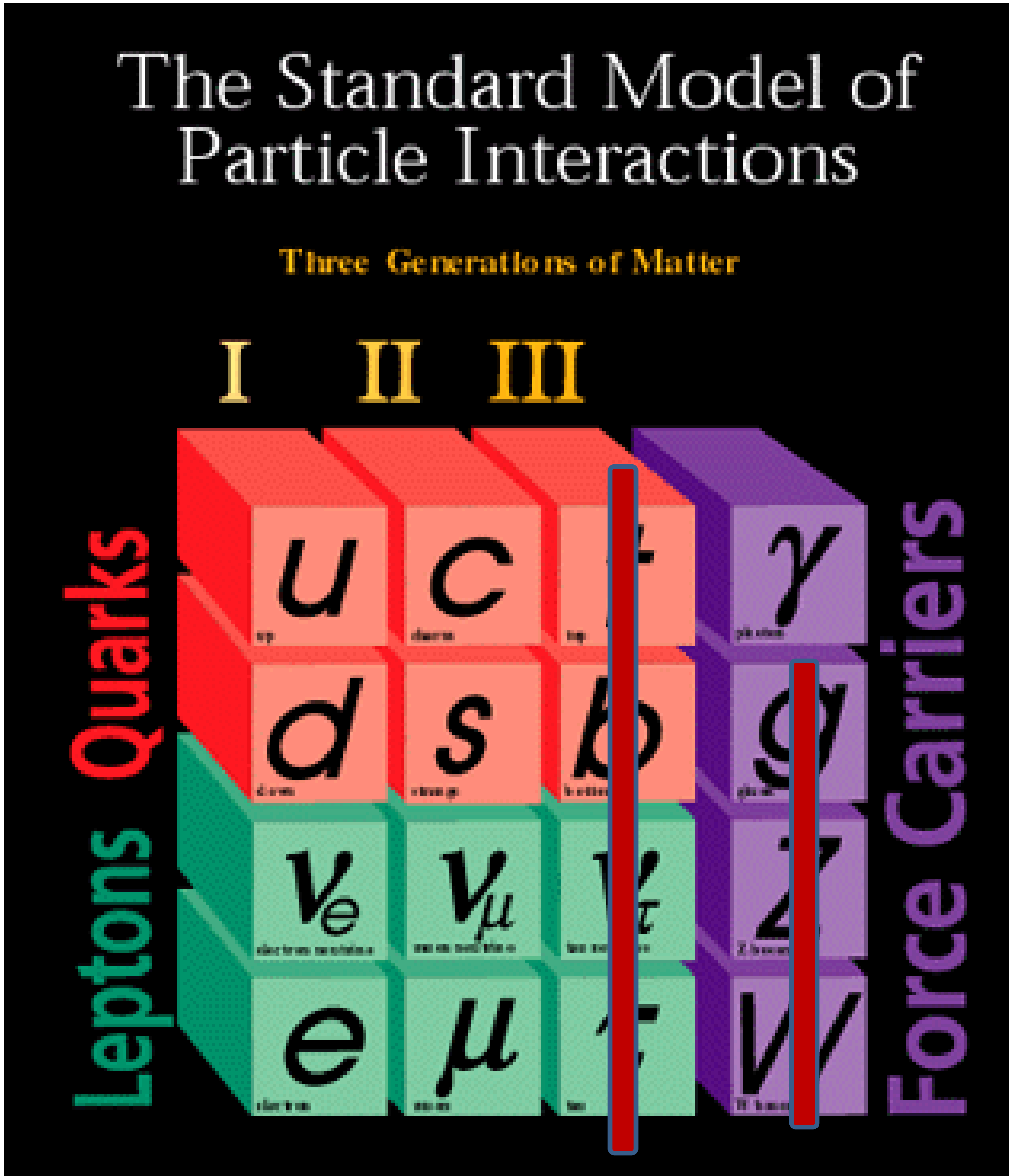
AGS vs. SPEAR
: 11월 혁명

버튼 릭터 (Burton Richter)
SPEAR 가속기 @SLAC
ψ 발견 (1974. 11. 10.)

J/ψ

새뮤얼 팅(Samuel C. C. Ting)
AGS 가속기 @브룩헤이븐
J 발견 (1974. 11.)

$(c\bar{c})$ 상태 : 4번째 쿼크의 발견
→ 입자물리학의 표준모형이 성립됨.


The Standard Model of
Particle Interactions
Three Generations of Matter
I
II
III
Quarks
Leptons
Force Carriers
u
c
d
s
b
ν_e
ν_μ
e
μ
γ
g
Z
W

W와 Z 게이지 보손

- 약한 상호작용을 매개하는 게이지 입자
  ~ 전자기 상호작용에서의 “빛”

- 약한 상호작용의 구조를 확인

- 게이지 대칭성이 깨져있음을 확인

SPS vs. Fermilab 주 가속기

Main ring (현재의 테바트론)
@페르미 국립 가속기 연구소
1975 –
512 GeV (proton)
(당시) 1억 2천만 달러
보텀쿼크 발견

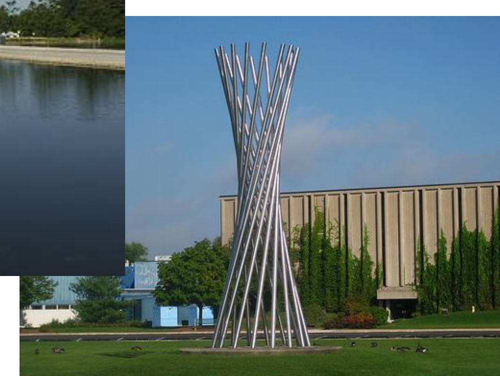
Super Proton Synchrotron (SPS)
@CERN
1976 –
400 GeV (proton)

로버트 윌슨 Robert Rathbun Wilson

Robert Rathbun Wilson
(1914 –2000)

물리학자, 조각가
맨해튼 프로젝트 팀장
코넬 대학교 교수
페르미 연구소 설계
페르미 연구소 소장
(1967–1978)

윌슨 홀



Pastore: Is there anything connected with the hopes of this accelerator that in any way involves the security of this country?

Wilson: No sir, I don't believe so.

Pastore: Nothing at all?

Wilson: Nothing at all.

Pastore: It has no value in that respect?

John Orlando Pastore
(1907 –2000)

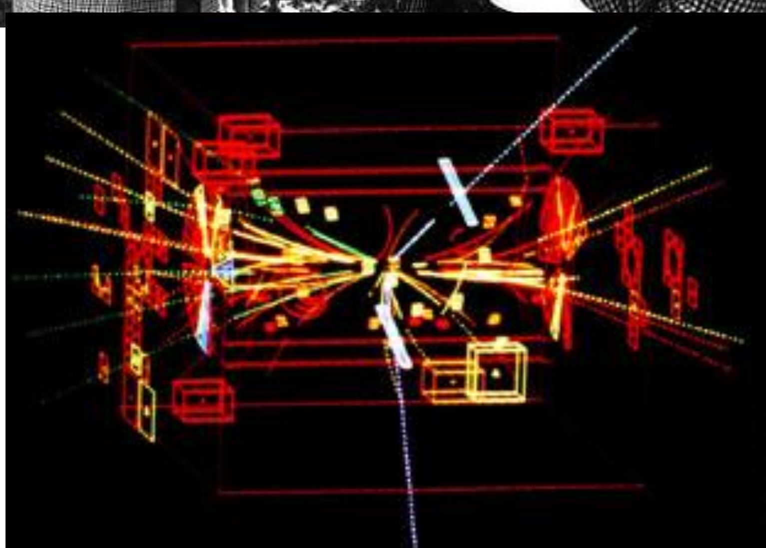
Wilson: It has only to do with the respect with which we regard one another, the dignity of men, our love of culture. It has to do with whether we are good painters, good sculptors, great poets. I mean all the things we really venerate in our country and are patriotic about.
It has nothing to do directly with defending the country except to make it worth defending.

1969. 4. 17. 미국 의회 에너지 위원회에서

"가속기가 관계 있는 것은 인간의 존엄, 문화에 대한 사랑, 그러니까 훌륭한 화가나 조각가, 위대한 시인 같은 것입니다. 가속기는 나라를 지키는데 관계 있는 것이 아니라 나라가 지킬만한 가치가 있도록 하는 데 관계가 있습니다."

$\mathrm{Sp\bar{p}S}$ vs. ISABELLE

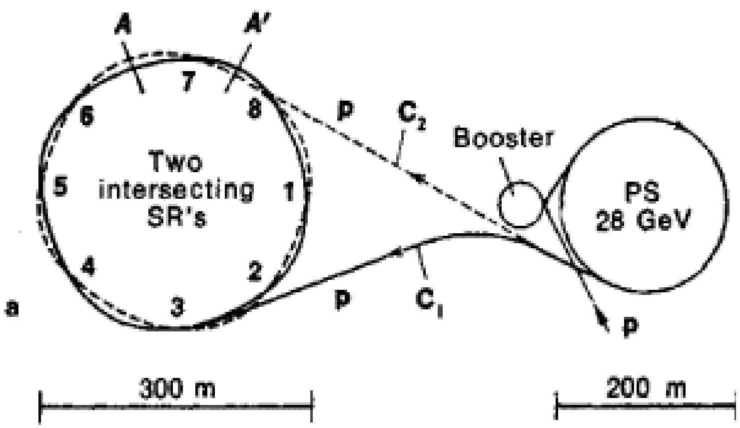
브룩헤이븐 연구소
윗쪽의 큰 링이 ISABELLE 자리다.

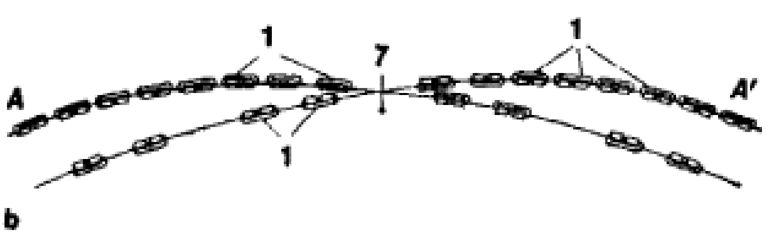


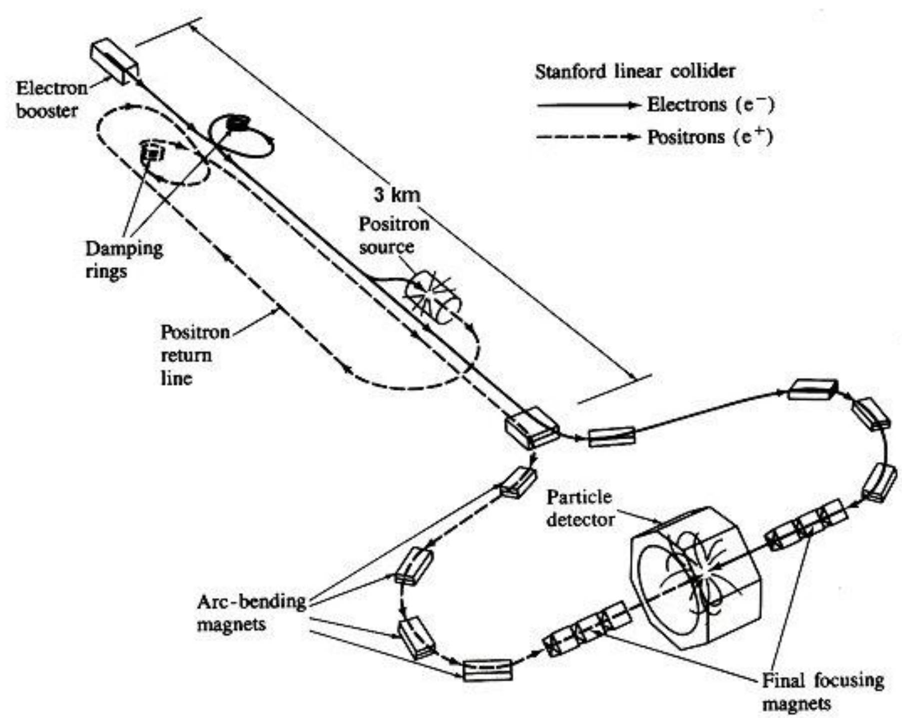
반 데르메르 (Simon Van der Meer)와
카를로 루비아 (Carlo Rubbia)
1983년 루비아가 이끄는 UA1 팀이 발견한
Z 보손의 신호
표준모형의 완성 (?)

Collider = accelerator + accelerator

ISR@CERN
최초의 양성자-양성자 충돌장치

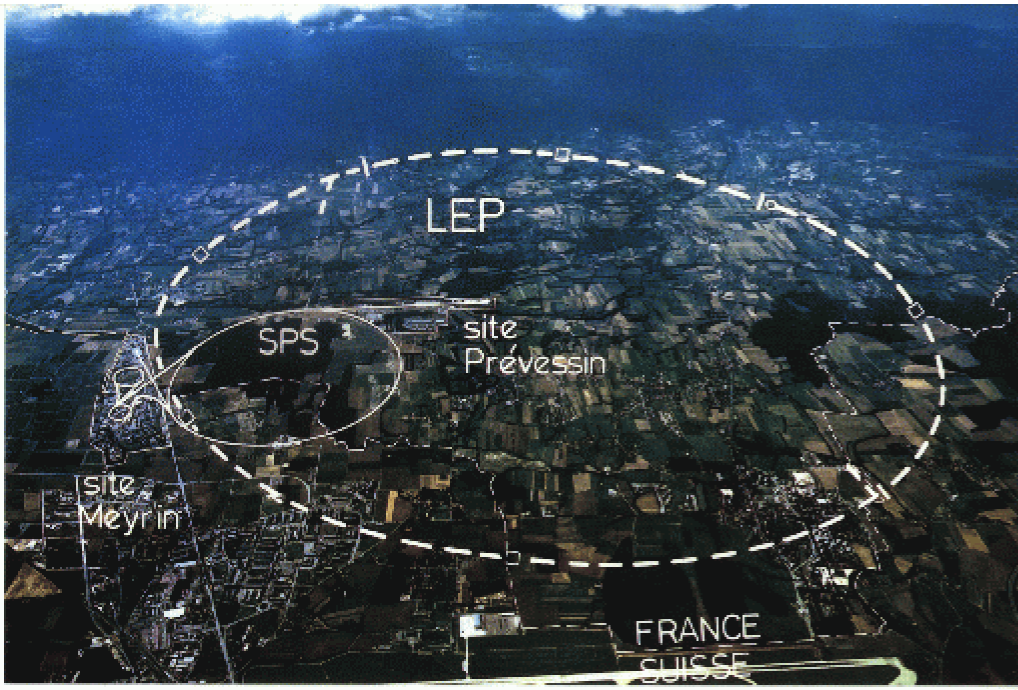




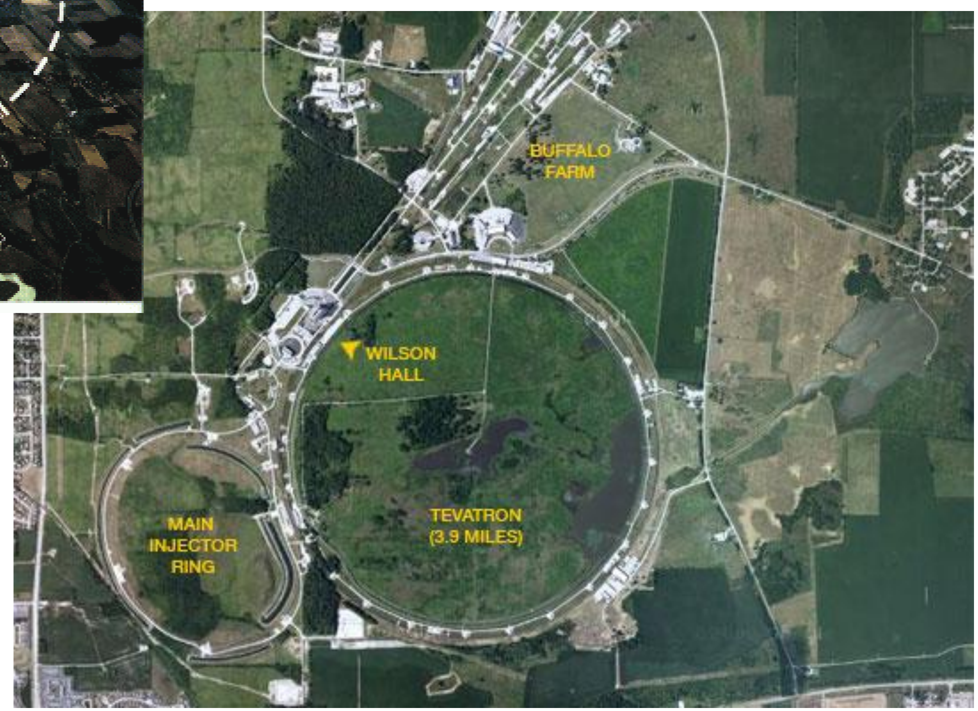


SLAC의 전자-양전자 충돌장치

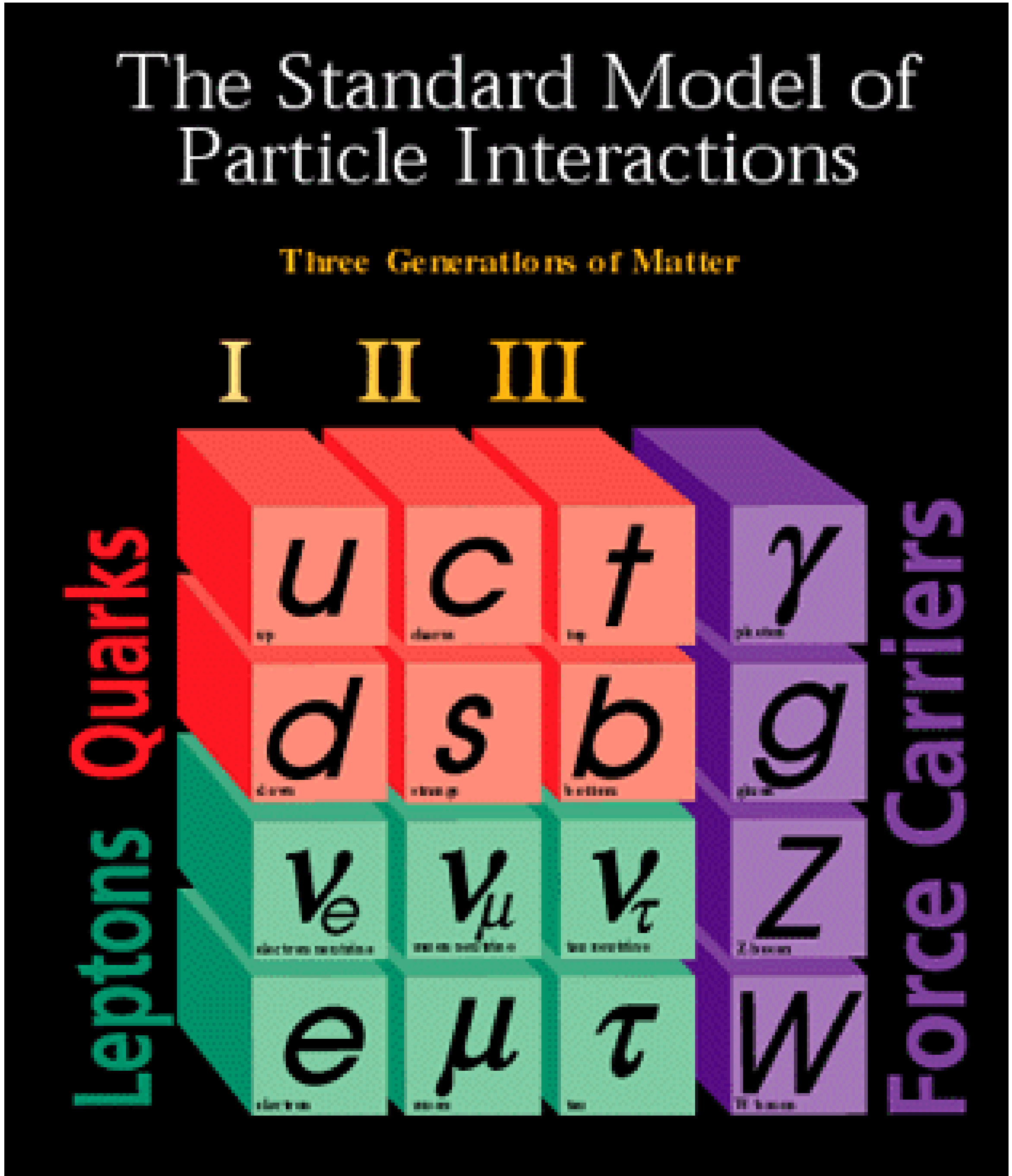
LEP vs. Tevatron



LEP
@CERN
1989 – 2000
91 – 208 GeV (e^-e^+)
표준모형의 정밀 확인, 중성미자 종류



테바트론
@페르미 국립 가속기 연구소
1999-
1.96 TeV (proton-antiproton)
톱쿼크 발견


The Standard Model of Particle Interactions
Three Generations of Matter
I
II
III
Quarks
Leptons
Force Carriers
u
c
t
d
s
b
ν_e
ν_μ
ν_τ
e
μ
τ
γ
g
Z
W

SSC vs. LHC and…

Superconducting SuperCollider

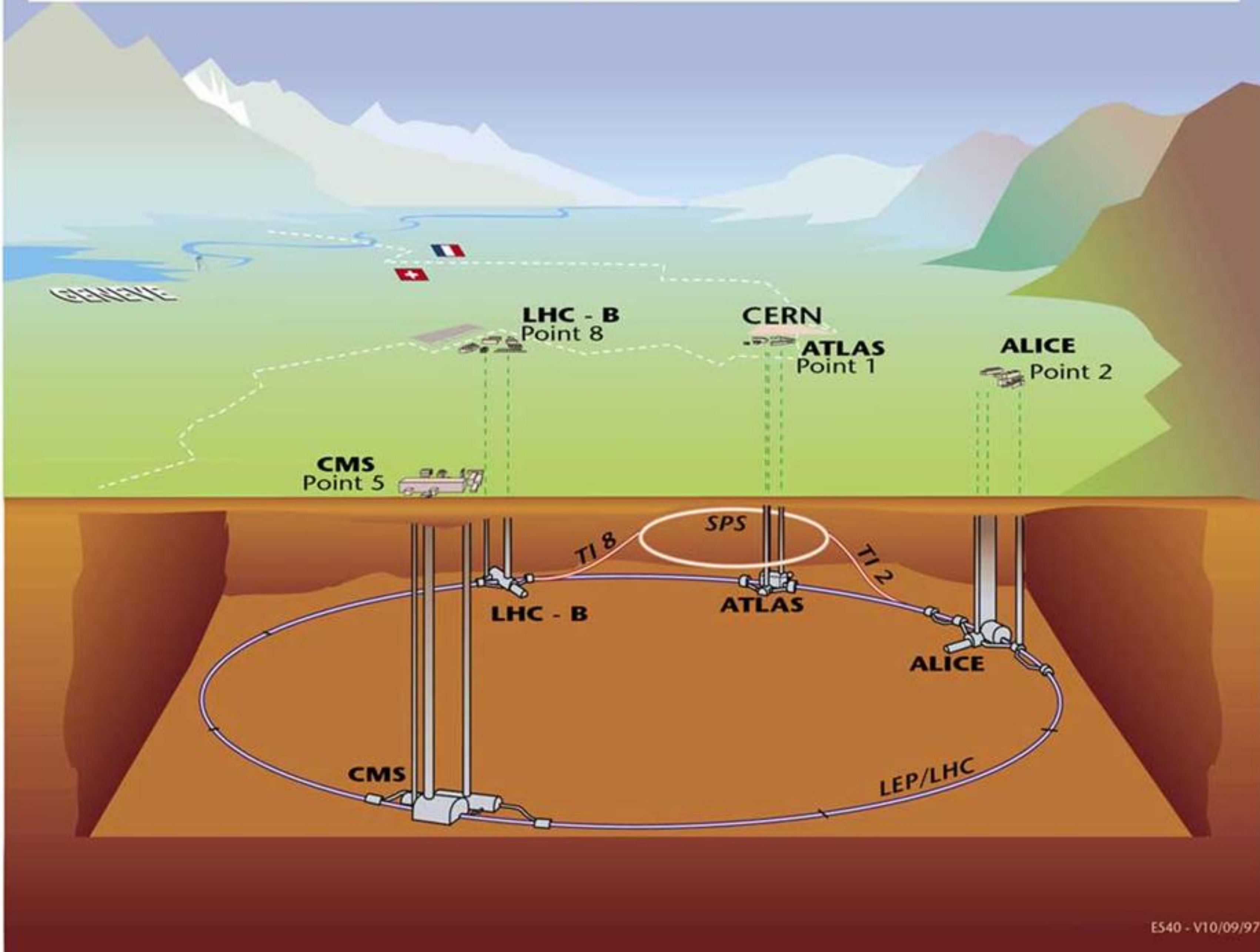
40 TeV (=20 TeV + 20 TeV)

둘레 약 80 km

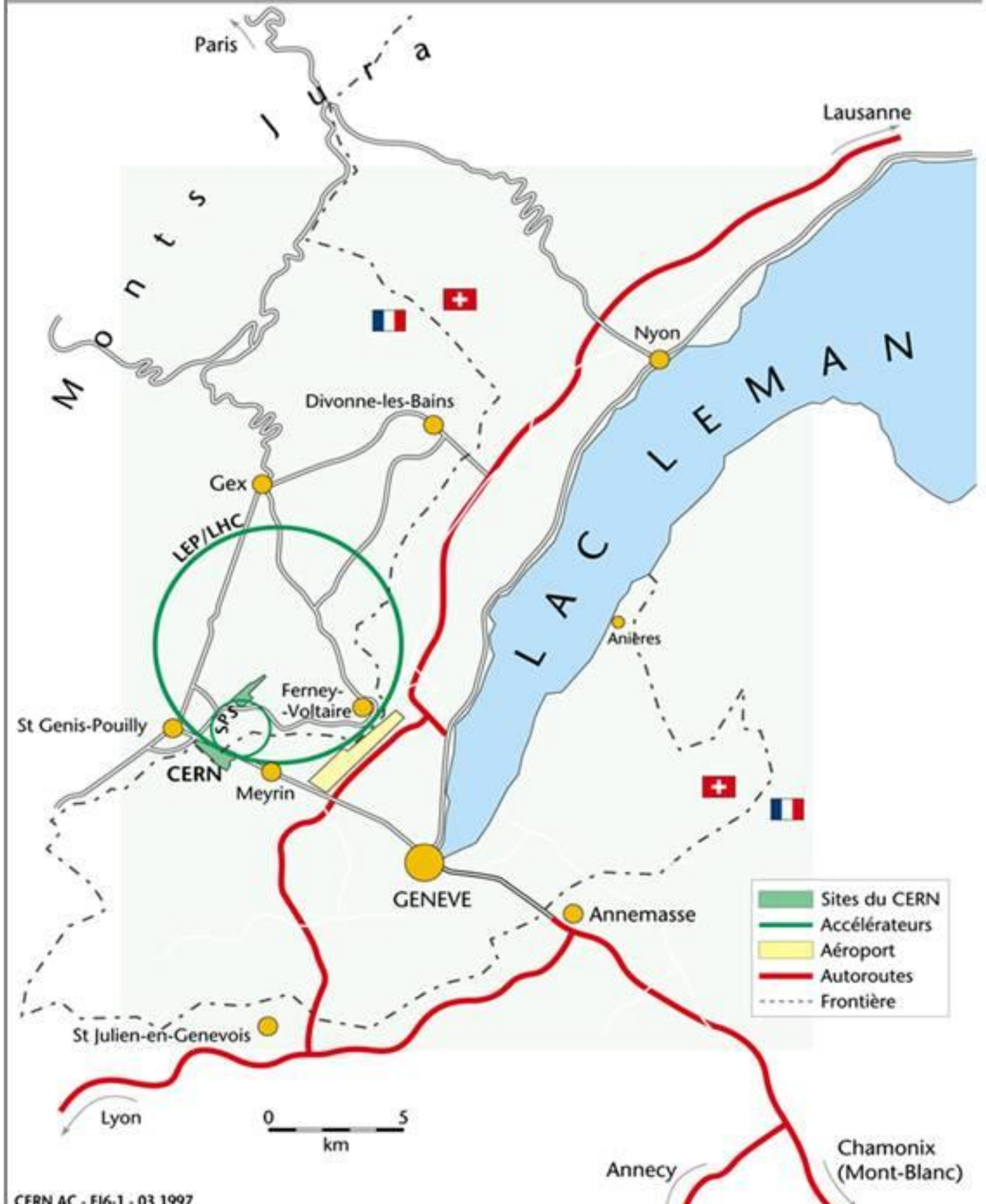
1993
SSC 계획 전격 취소
터널 폐쇄


LHC

Overall view of the LHC experiments.



Carte de situation



CERN AC - EI6-1 - 03 1997

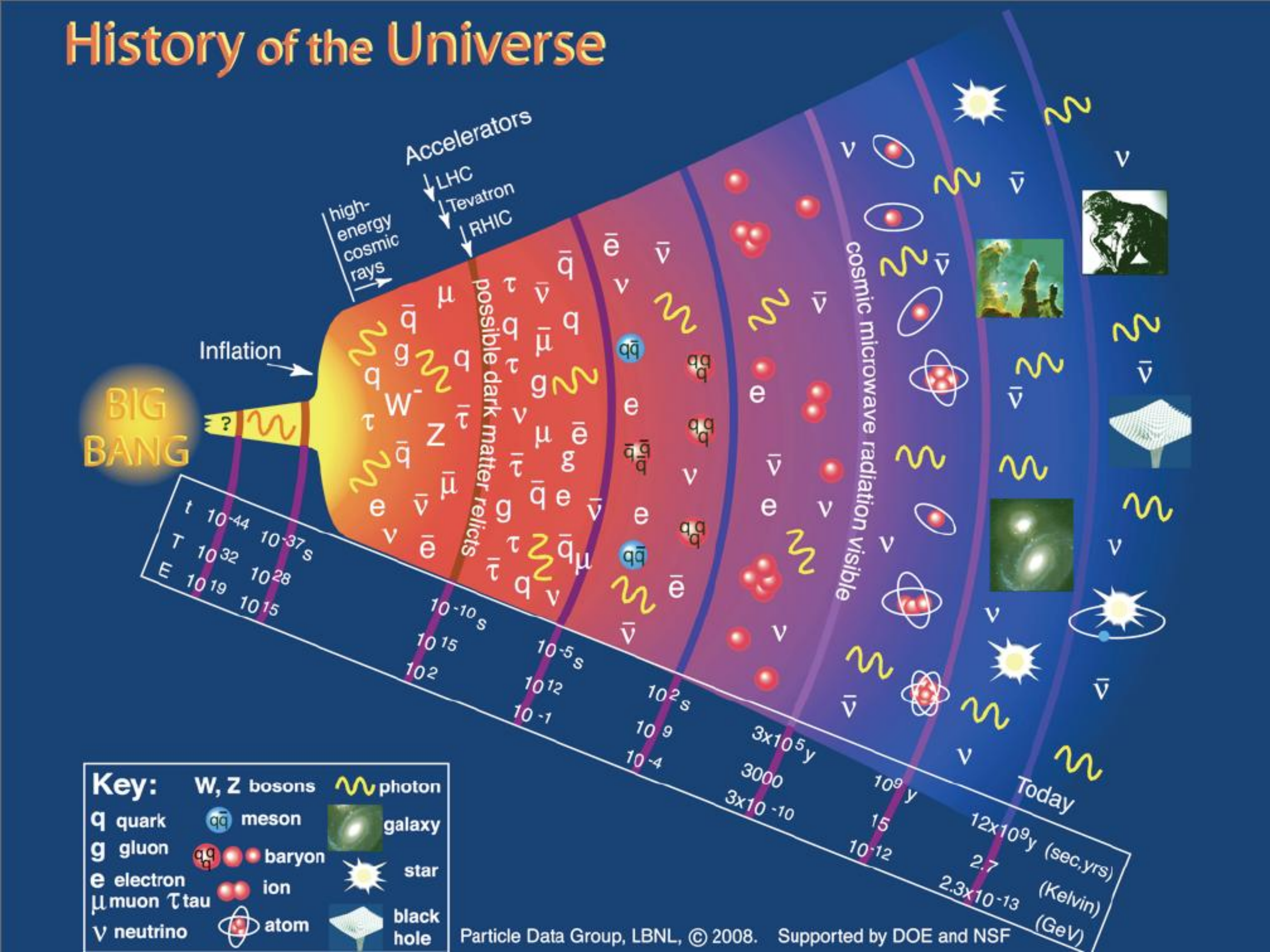
Large

- 둘레 26658.883미터

- 충돌에너지 14 TeV
  양성자 빔의 에너지 7 TeV
  빛의 속도의 99.99991%

- 광도 10^{34} $cm^{-2}s^{-1}$

- 현재 에너지 7 TeV (3.5 TeV + 3.5 TeV)
- 현재 광도 10^{32} $cm^{-2}s^{-1}$


History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10-12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

H adron

- 하드론 hadron (강입자) = 메손 + 바리온
  쿼크로 이루어져 있어 강한 상호작용을 하는 입자
- 렙톤 lepton (경입자)
  강한 상호작용을 하지 않는 페르미온, $e^{\pm}, \mu^{\pm}, \tau^{\pm}, \nu_{e,\mu,\tau}$
- 쿼크 quark
  하드론을 이루는 페르미온,
  강한 상호작용을 하는 페르미온, u, d, c, s, t, b
- 메손 meson (중간자)
  스핀이 정수인 하드론, $\pi, K, \rho, \phi, J/\psi, \eta, ...$
- 바리온 baryon (중입자)
  스핀이 반정수인 하드론 $p, n, \Lambda, \Xi, \Omega, ...$

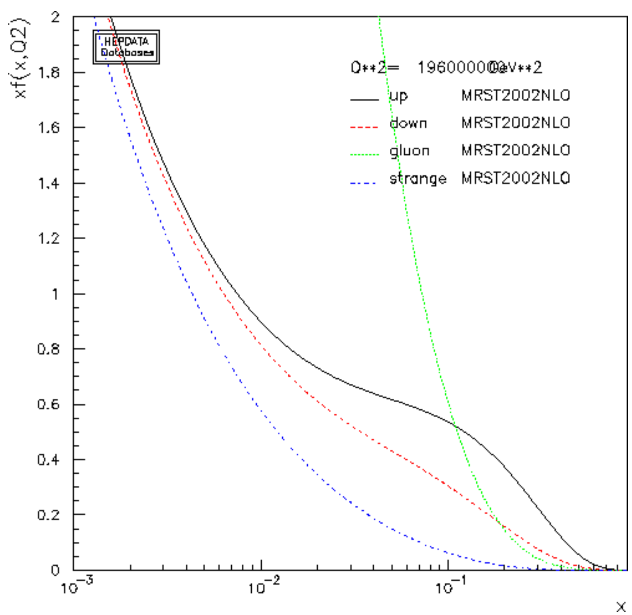
양성자의 구조

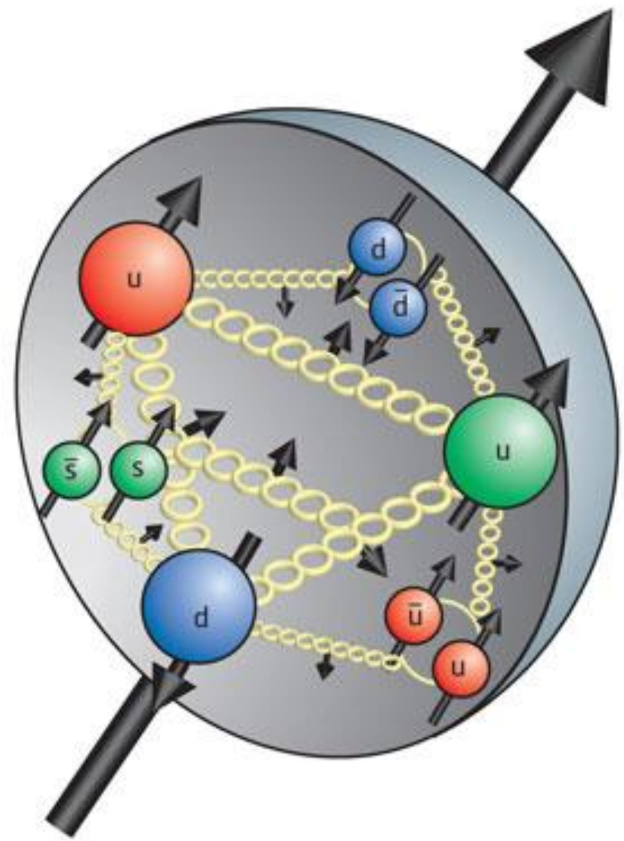
드러난 쿼크 (valence quark) : u u d

숨은 쿼크 (sea quark)

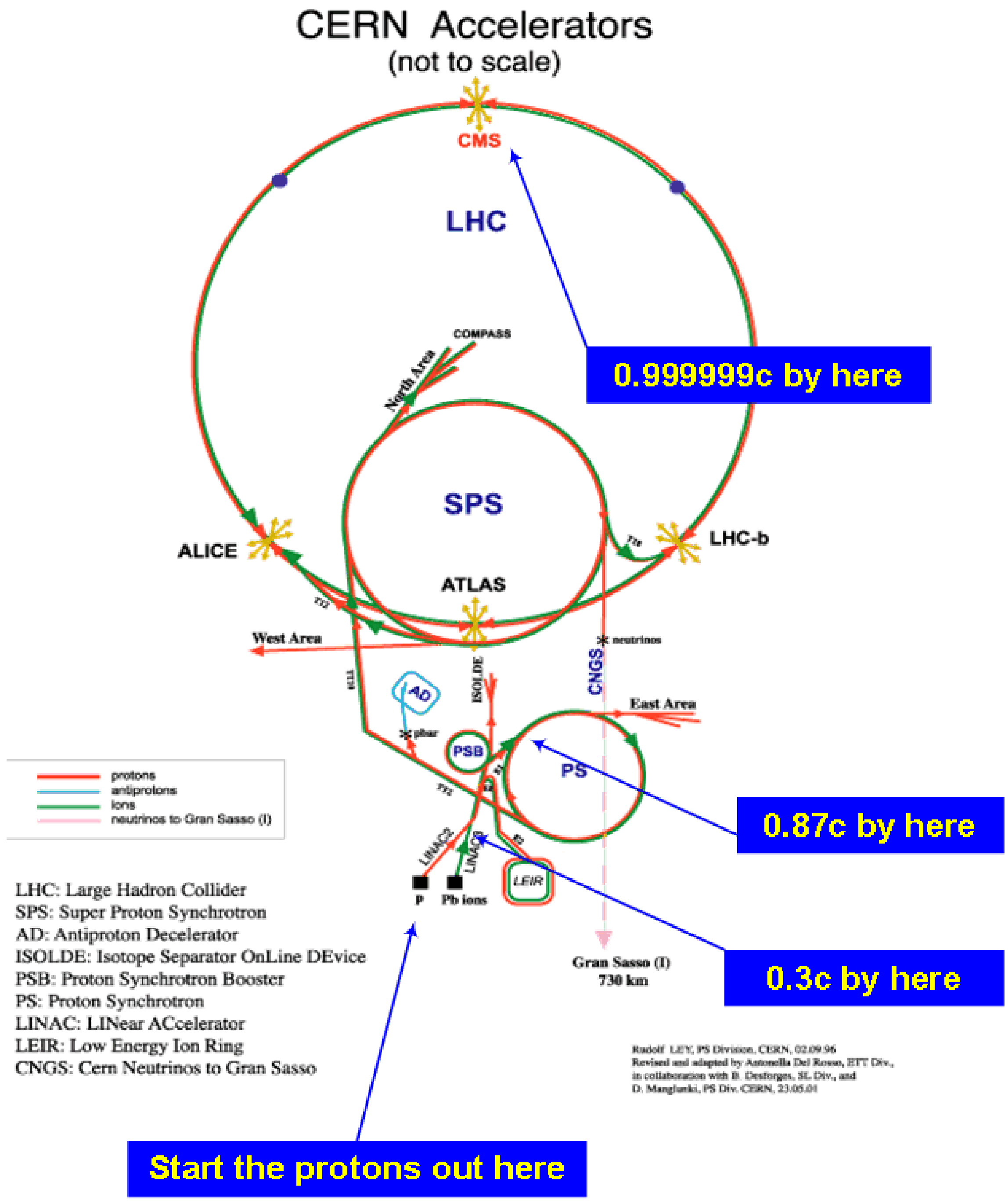
글루온 (gluon)

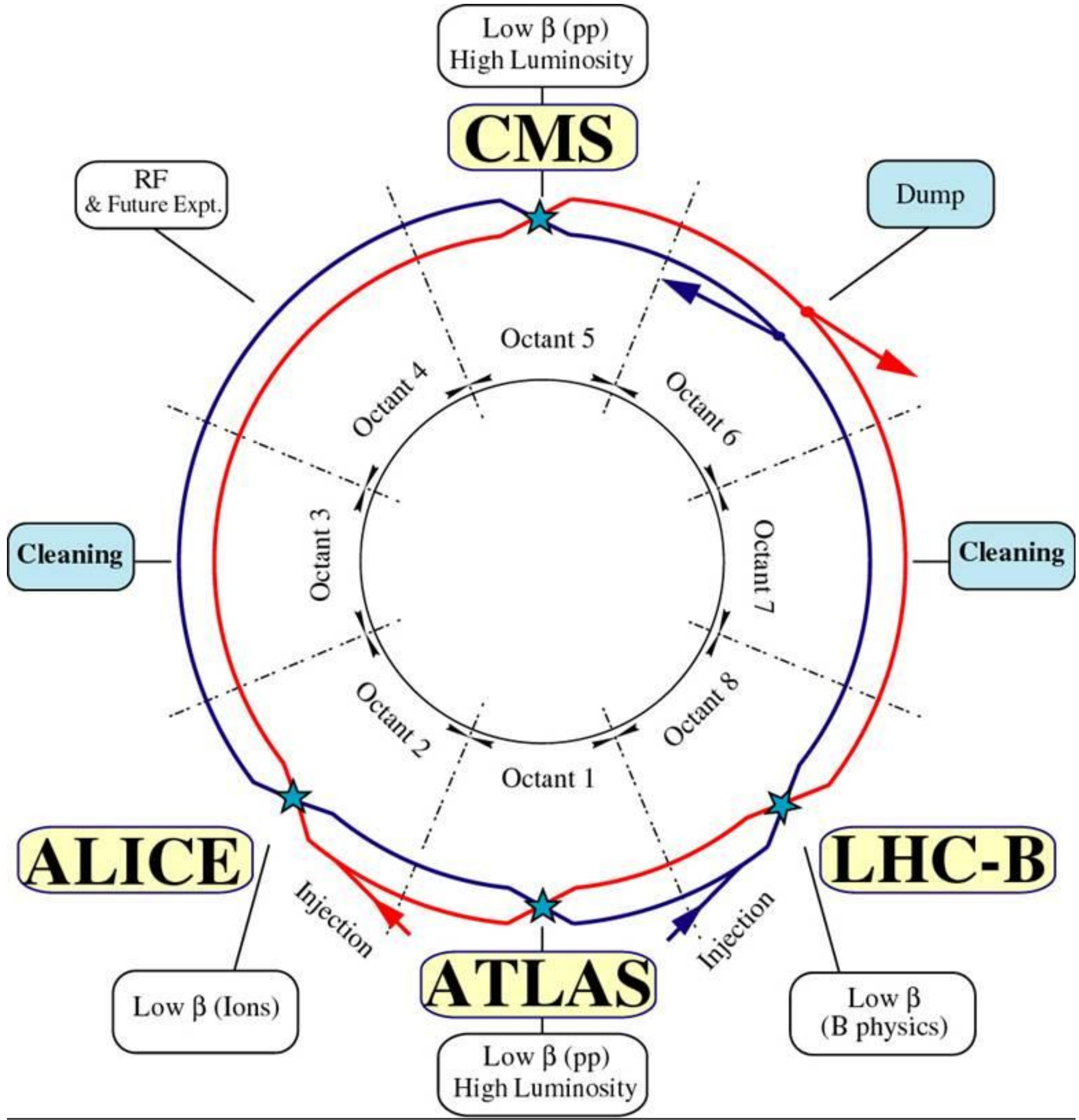
파톤 분포 함수





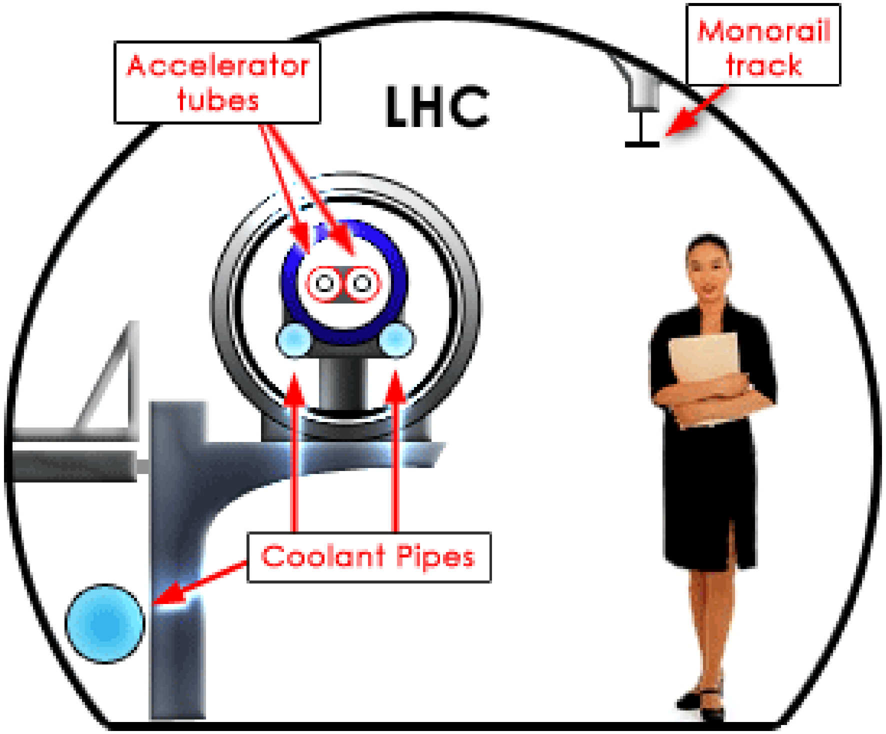
C ollider

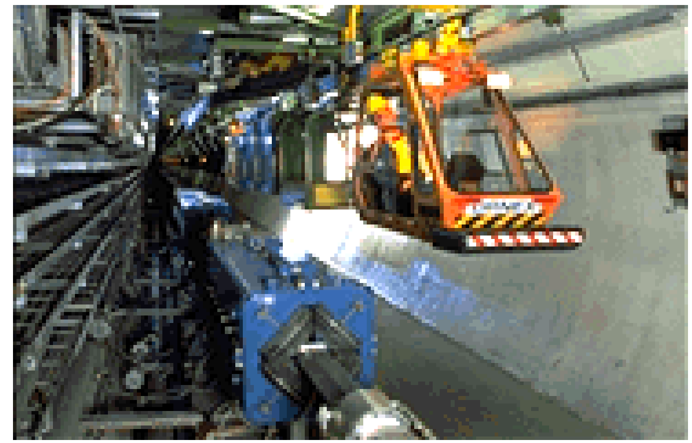

CERN Accelerators
(not to scale)
CMS
LHC
COMPASS
North Area
SPS
ALICE
ATLAS
LHC-b
West Area
neutrinos
CNGS
ISOLDE
AD
pbar
East Area
PSB
PS
LINAC2
LINAC3
LEIR
p
Pb ions
Gran Sasso (I)
730 km
protons
antiprotons
ions
neutrinos to Gran Sasso (I)
LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso
Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, ETT Div.,
in collaboration with B. Desforges, SL Div., and
D. Manglunki, PS Div. CERN, 23.05.01
0.999999c by here
0.87c by here
0.3c by here
Start the protons out here

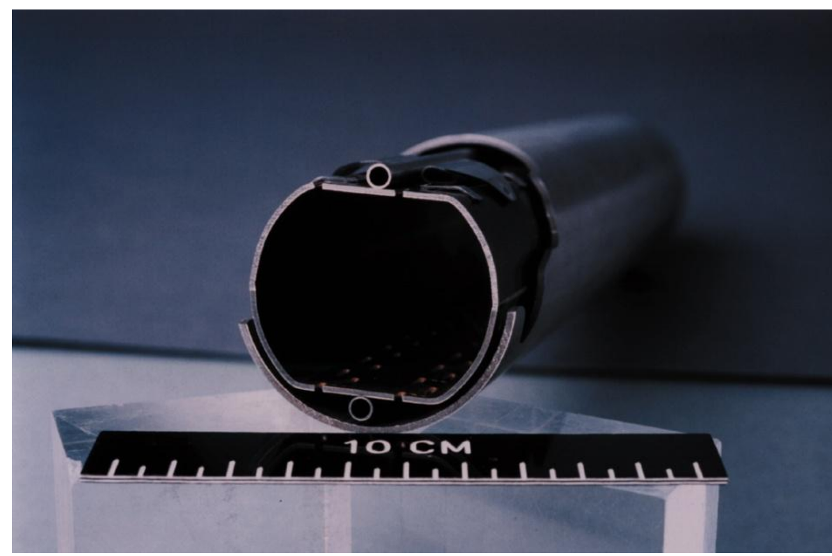


Low β (pp)
High Luminosity
CMS
RF
& Future Expt.
Dump
Octant 5
Octant 4
Octant 6
Octant 3
Octant 7
Cleaning
Cleaning
Octant 2
Octant 8
Octant 1
ALICE
LHC-B
Injection
Injection
ATLAS
Low β (Ions)
Low β
(B physics)
Low β (pp)
High Luminosity

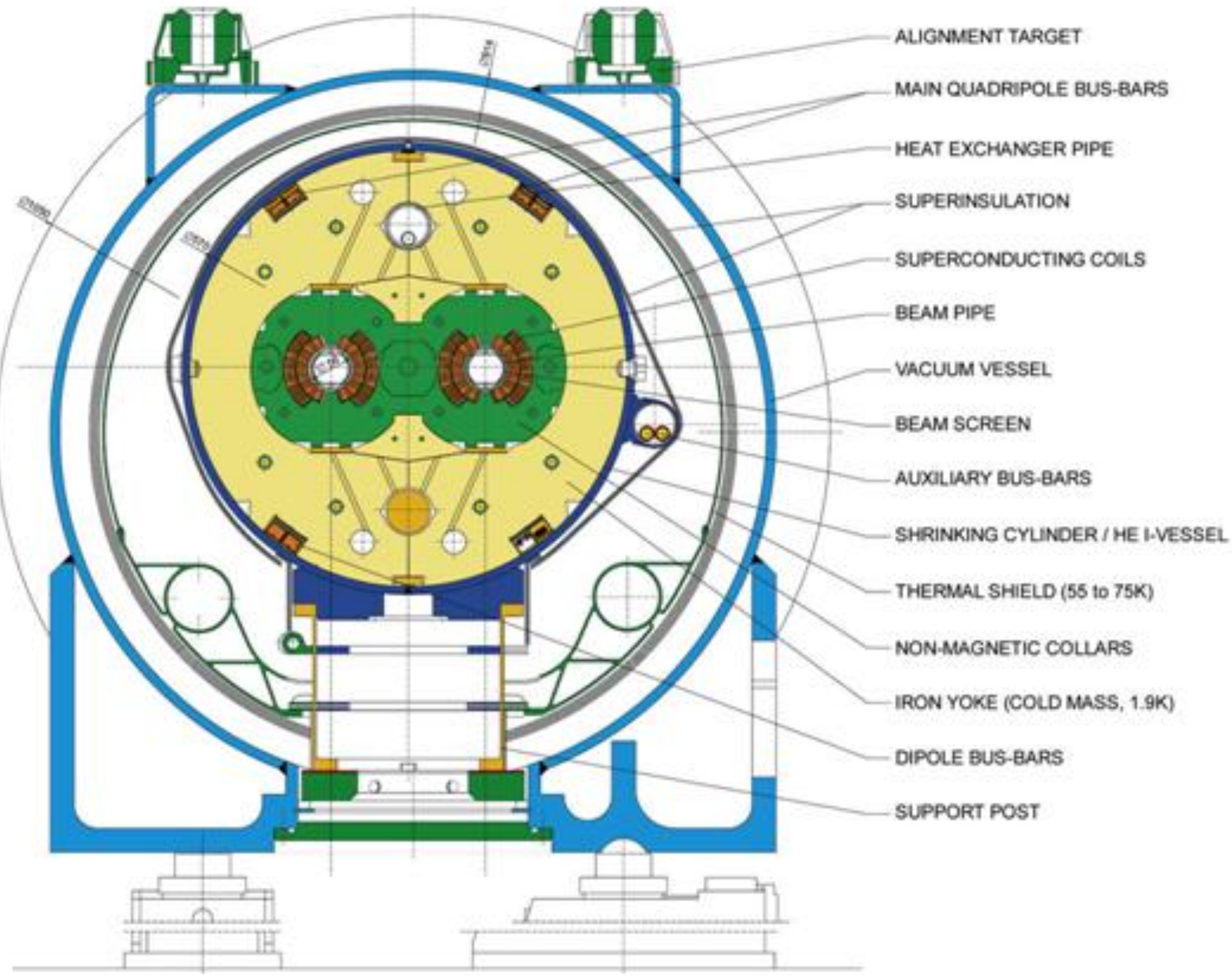
LHC 내부







LHC DIPOLE : STANDARD CROSS-SECTION

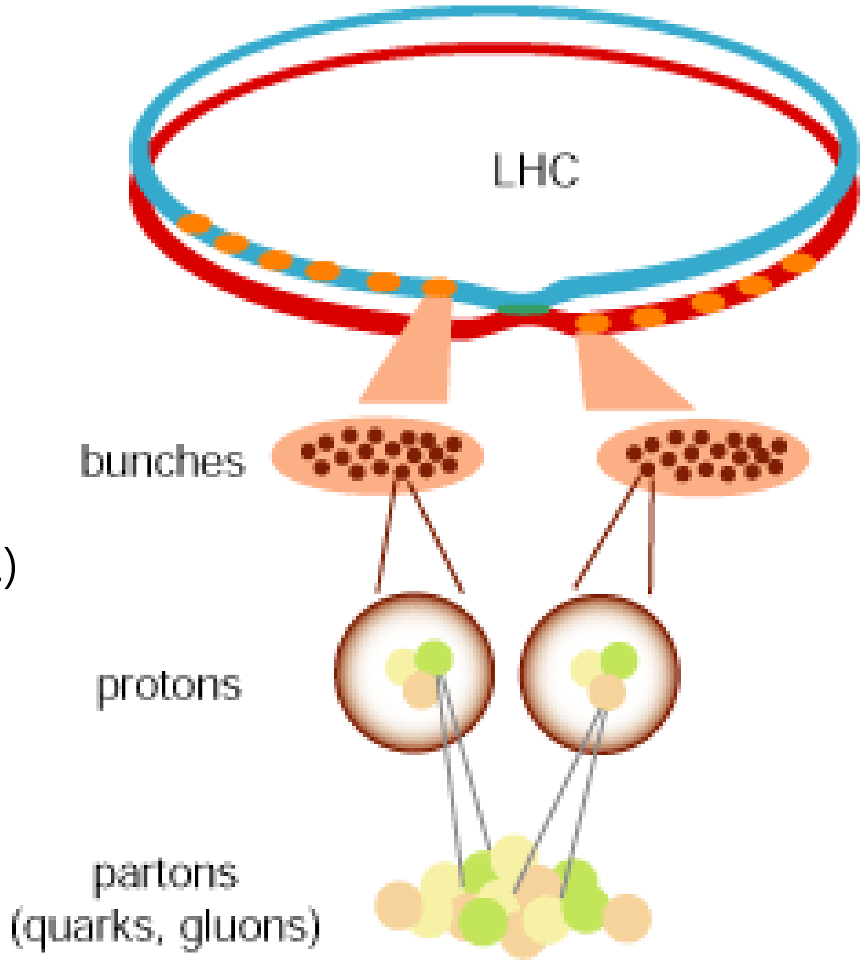


LHC 빔

1 빔 = 2,808 양성자 뭉치
1 뭉치 = 1.15X10^{11} 양성자

뭉치 길이 수 cm
뭉치 폭 1 mm → 16 μm
뭉치 간격 25 ns (약 7.5 m)

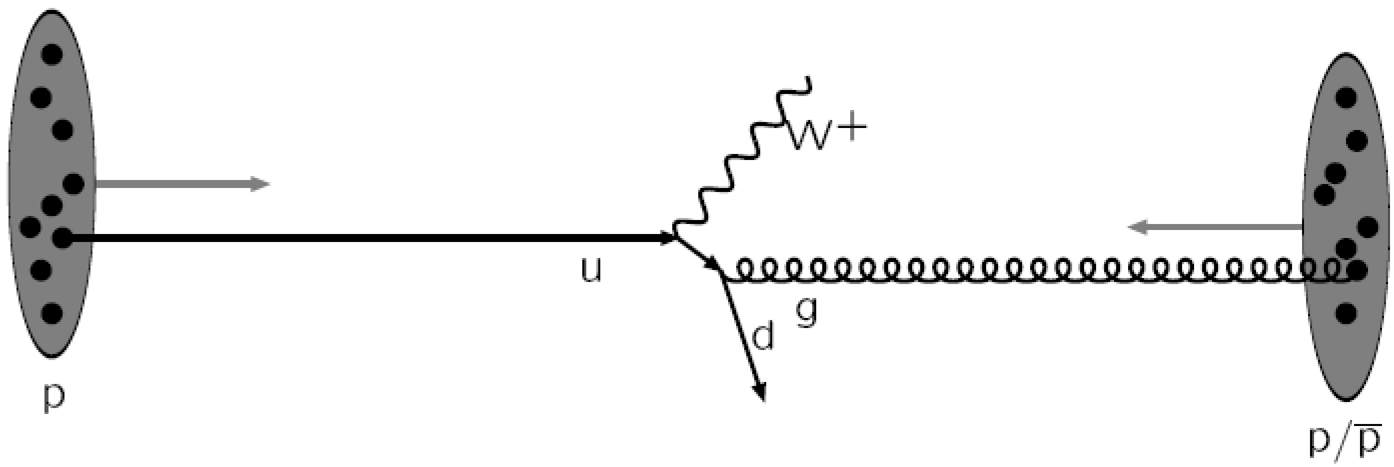
빔 수명 약 10 시간
(공기 분자와의 충돌,
빔 교차 시 흐트러짐.)



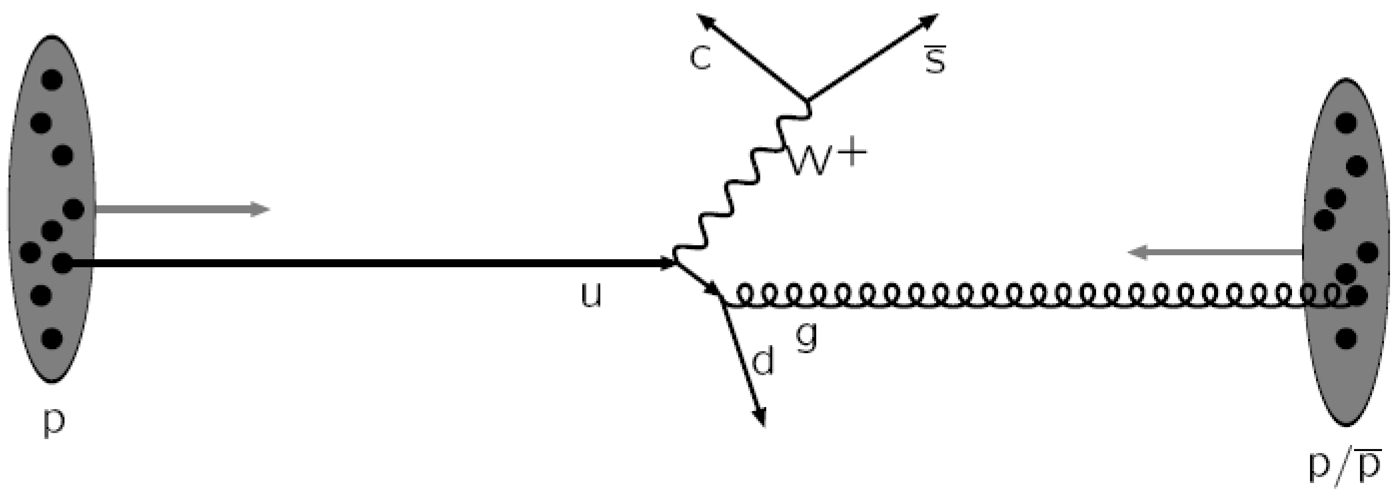
The structure of an event

Warning: schematic only, everything simplified, nothing to scale, . . .

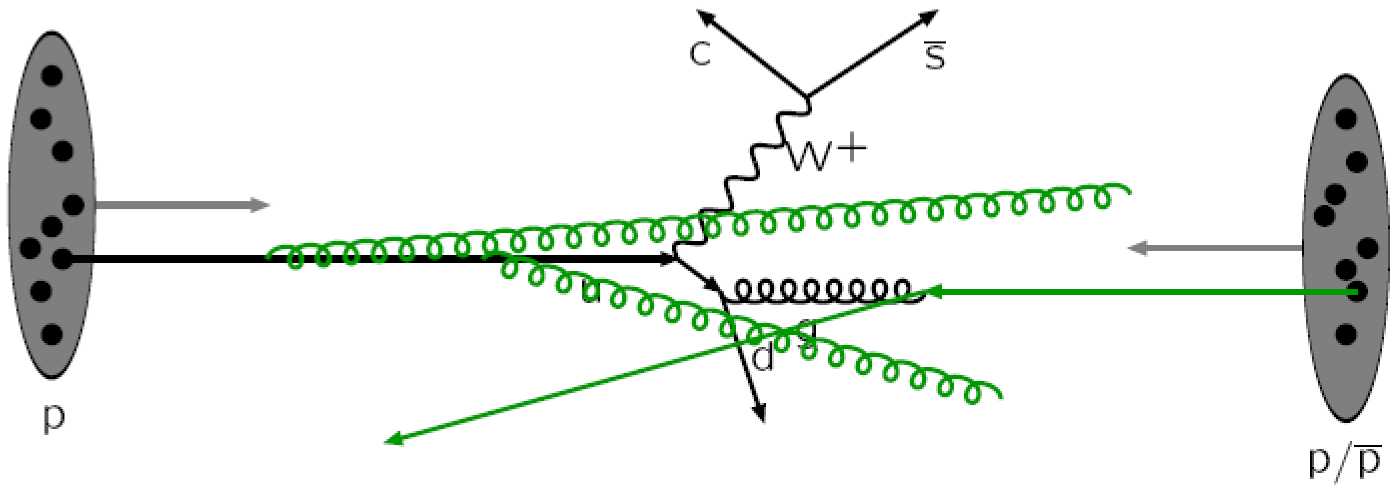
Incoming beams: parton densities



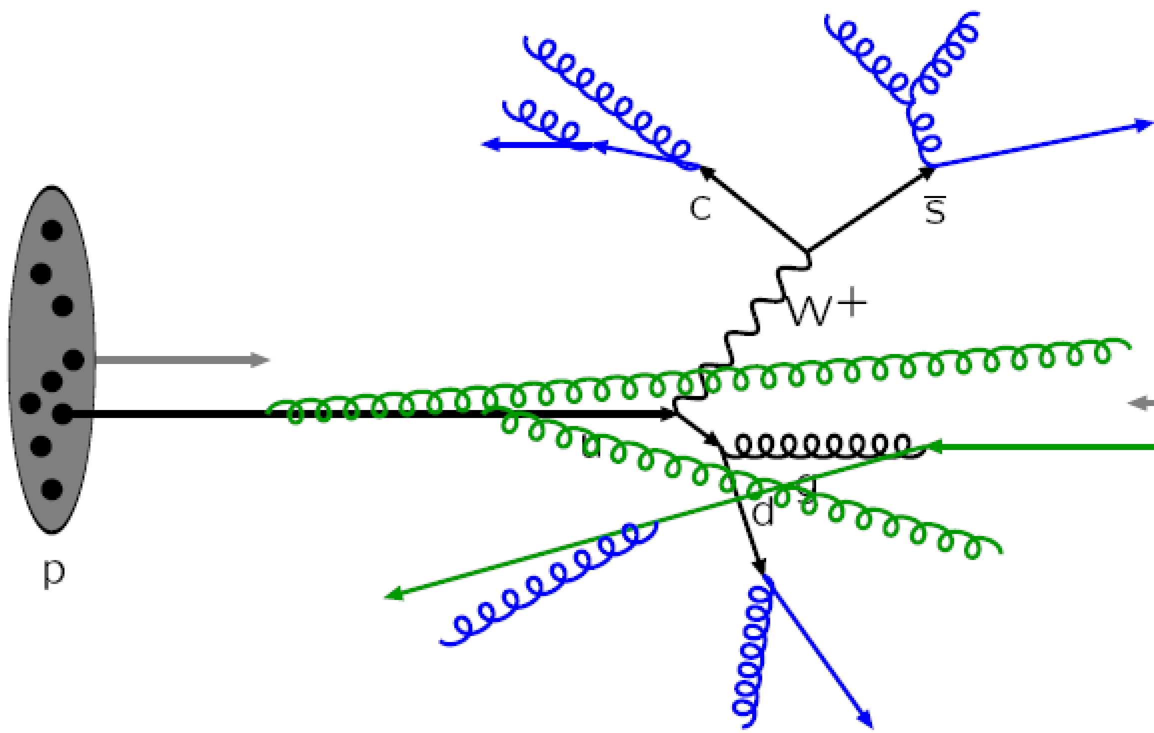
Hard subprocess: described by matrix elements



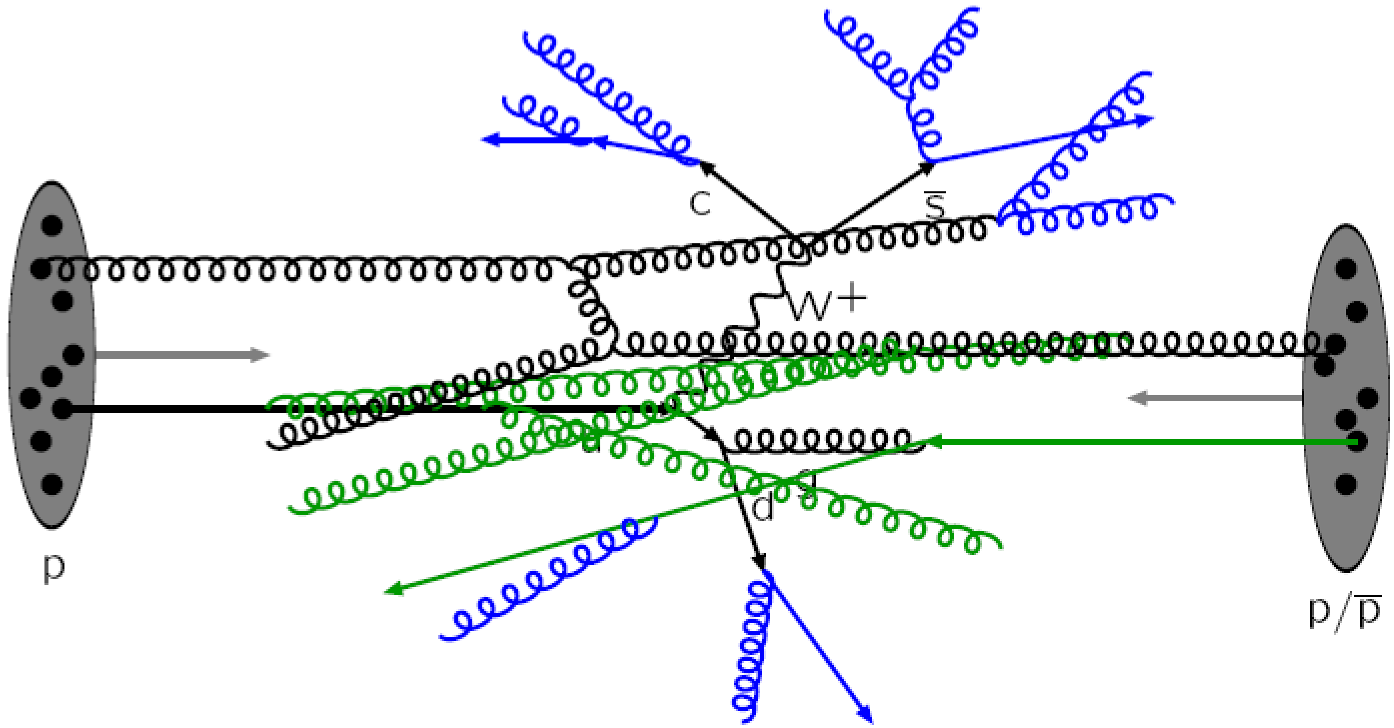
Resonance decays: correlated with hard subprocess



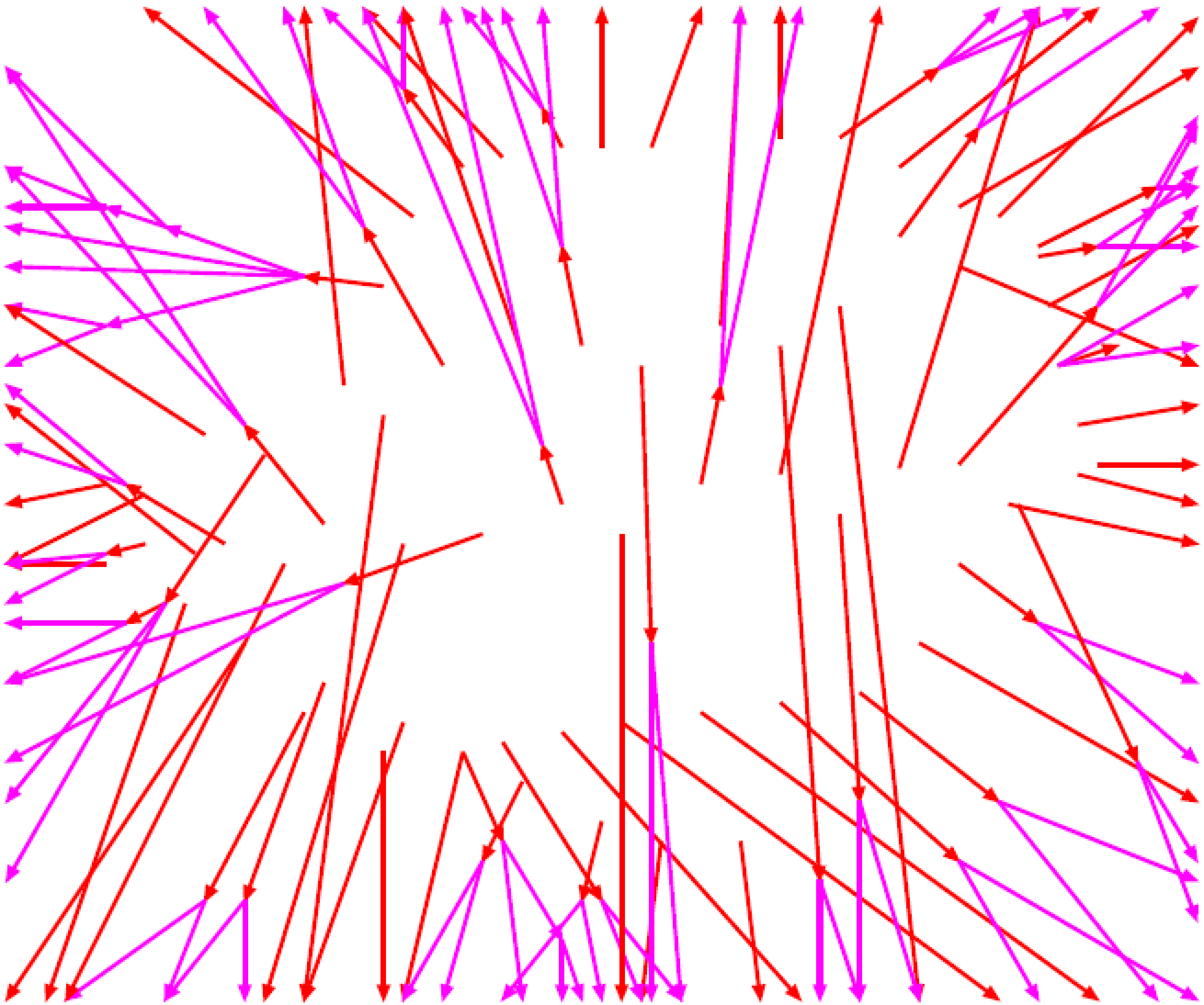
Initial-state radiation: spacelike parton showers



Final-state radiation: timelike parton showers

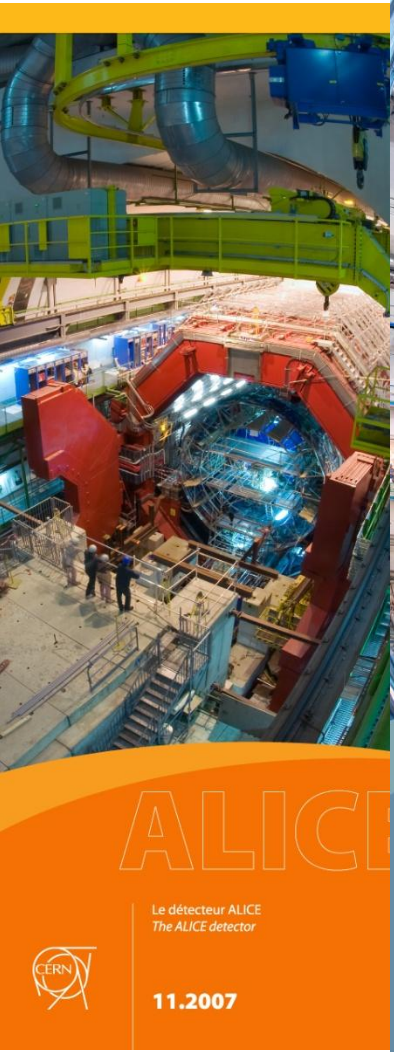


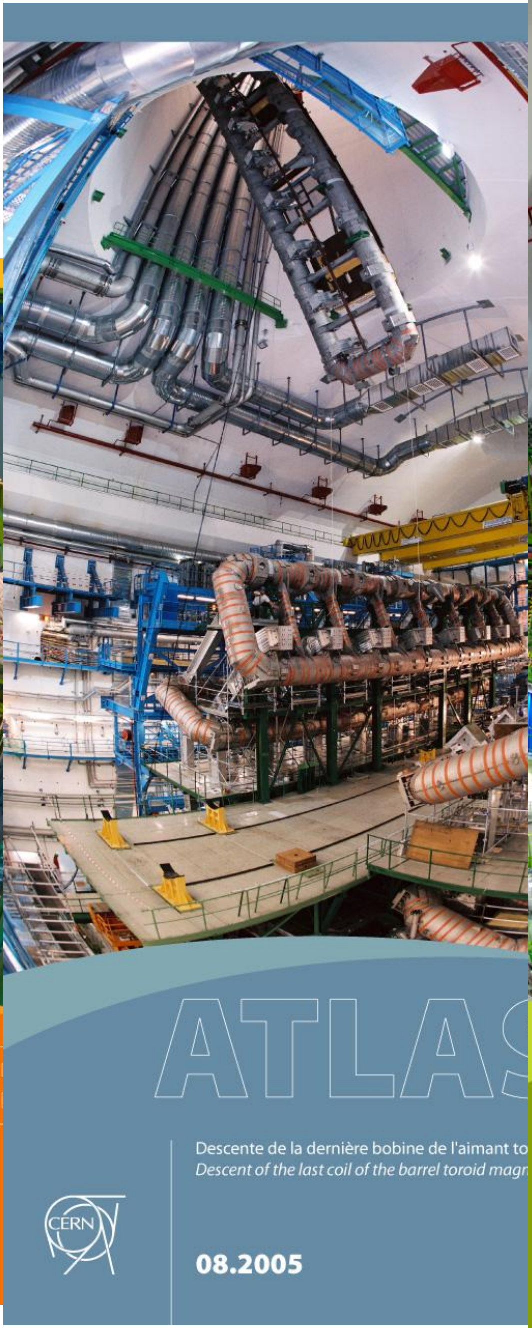
. . . with its initial- and final-state radiation

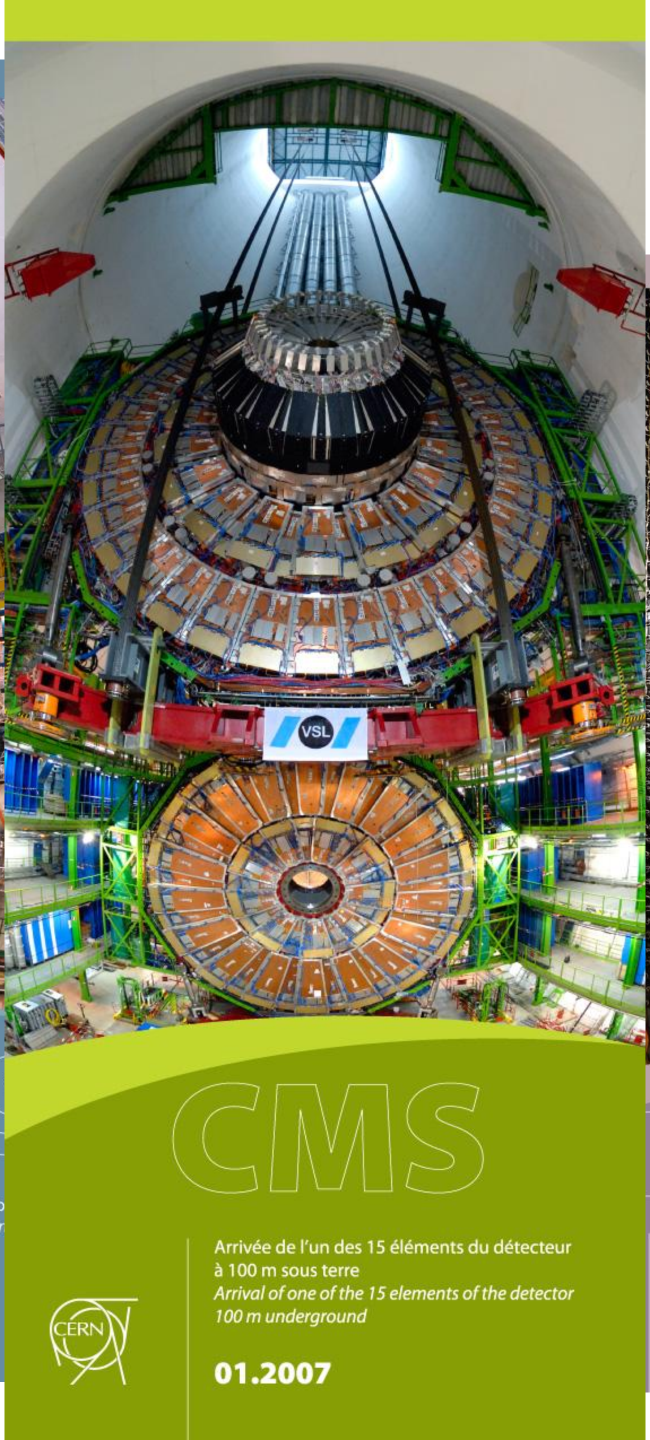


Many hadrons are unstable and decay further

LHC의 실험들

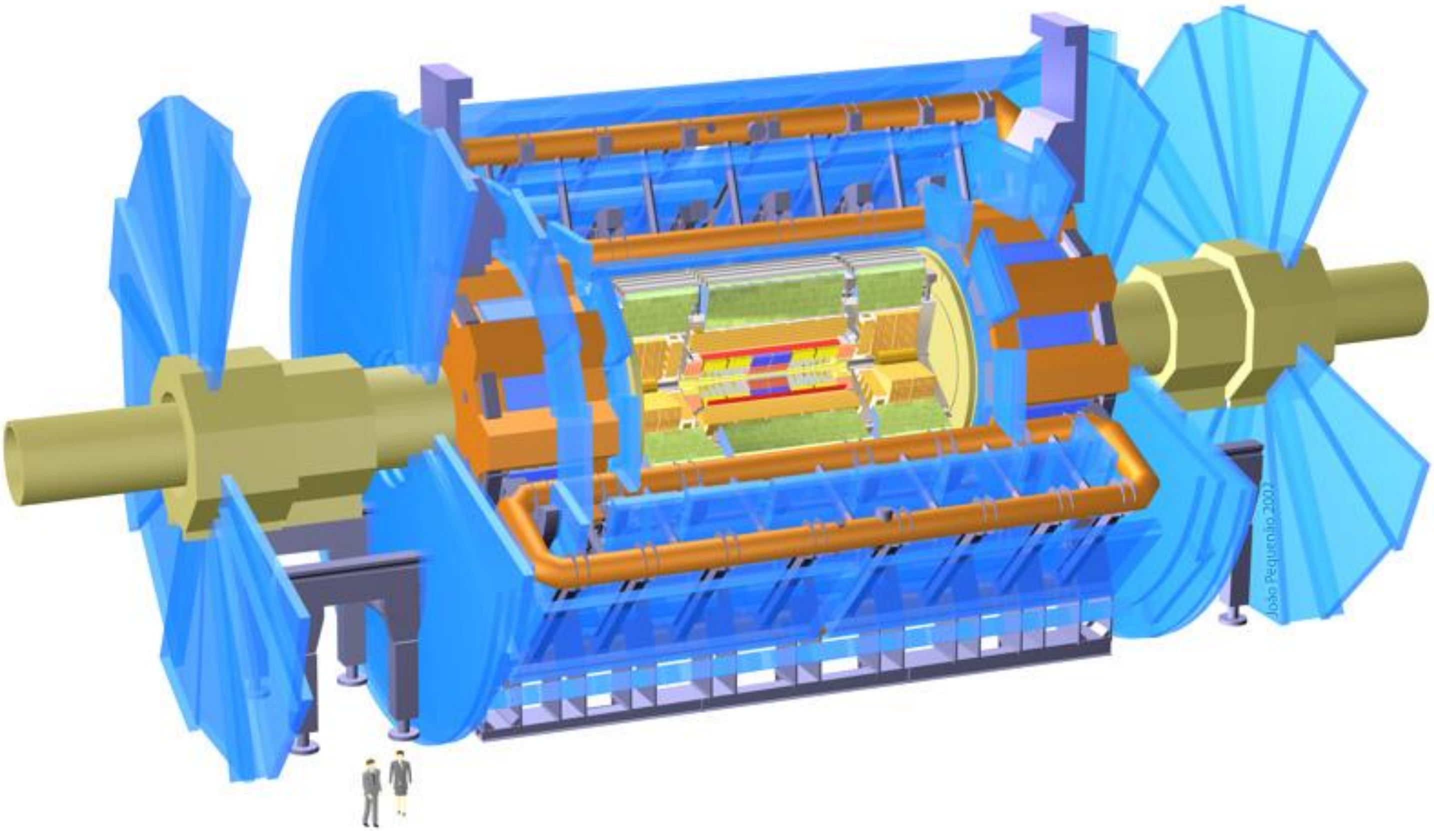

ALICE
Le détecteur ALICE
The ALICE detector
CERN
11.2007


ATLAS
Descente de la dernière bobine de l'aimant to
Descent of the last coil of the barrel toroid magn
CERN
08.2005

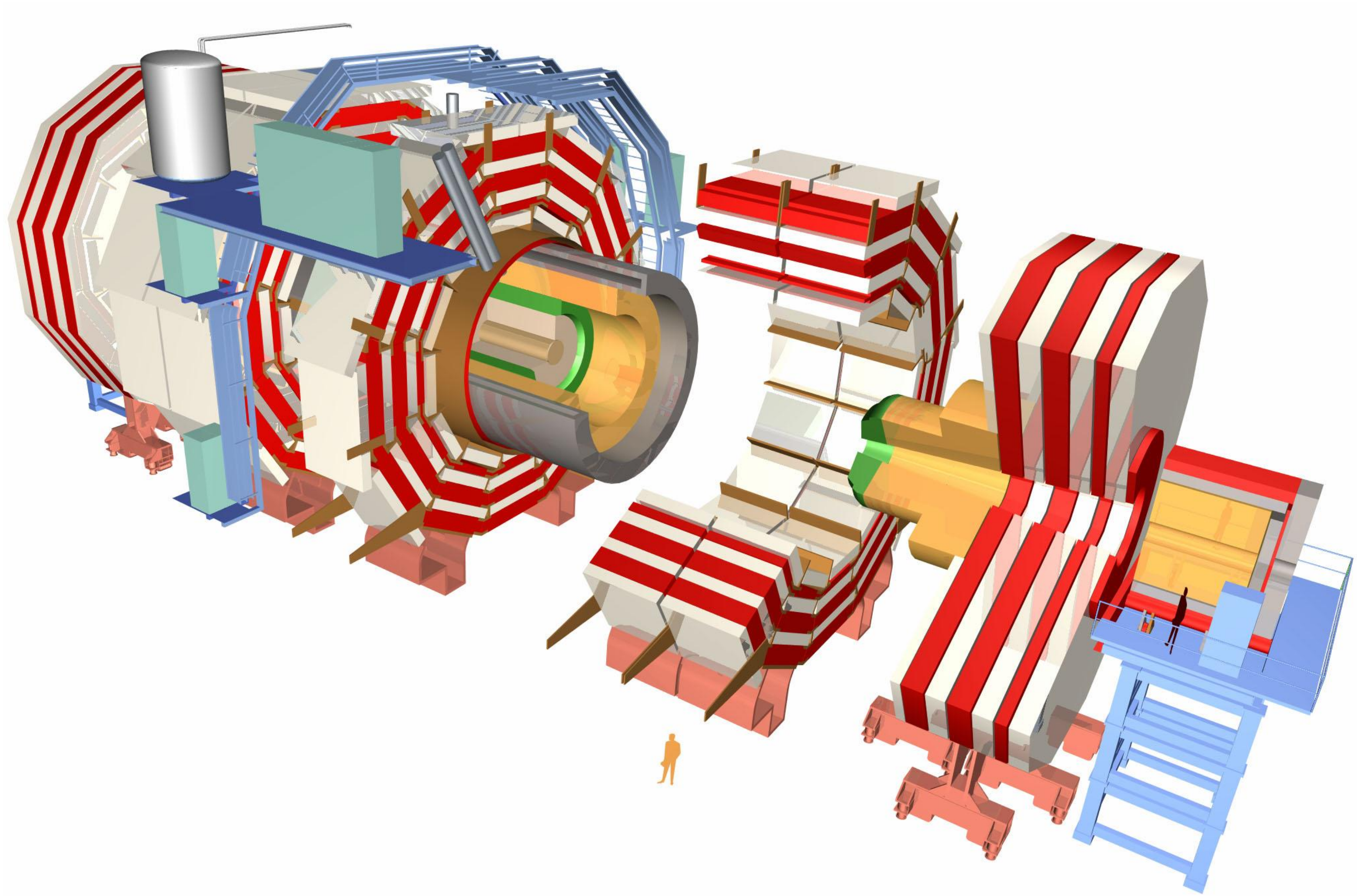

VSL
CMS
Arrivée de l'un des 15 éléments du détecteur
à 100 m sous terre
Arrival of one of the 15 elements of the detector
100 m underground
CERN
01.2007

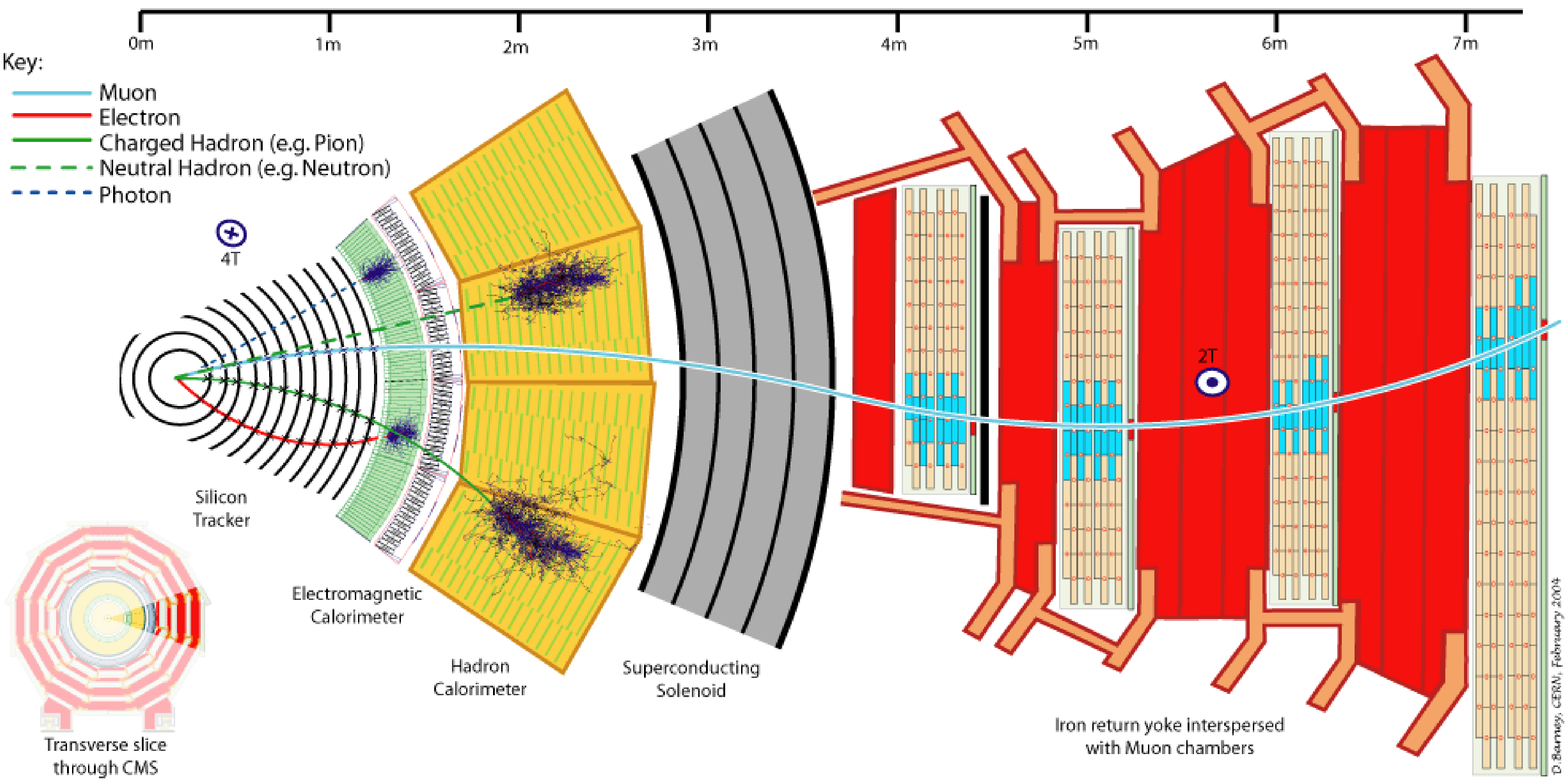

LHCb
Les photomultiplicateurs du calorimètre
électromagnétique
Photomultipliers of the ECAL calorimeter
07.2006

ATLAS

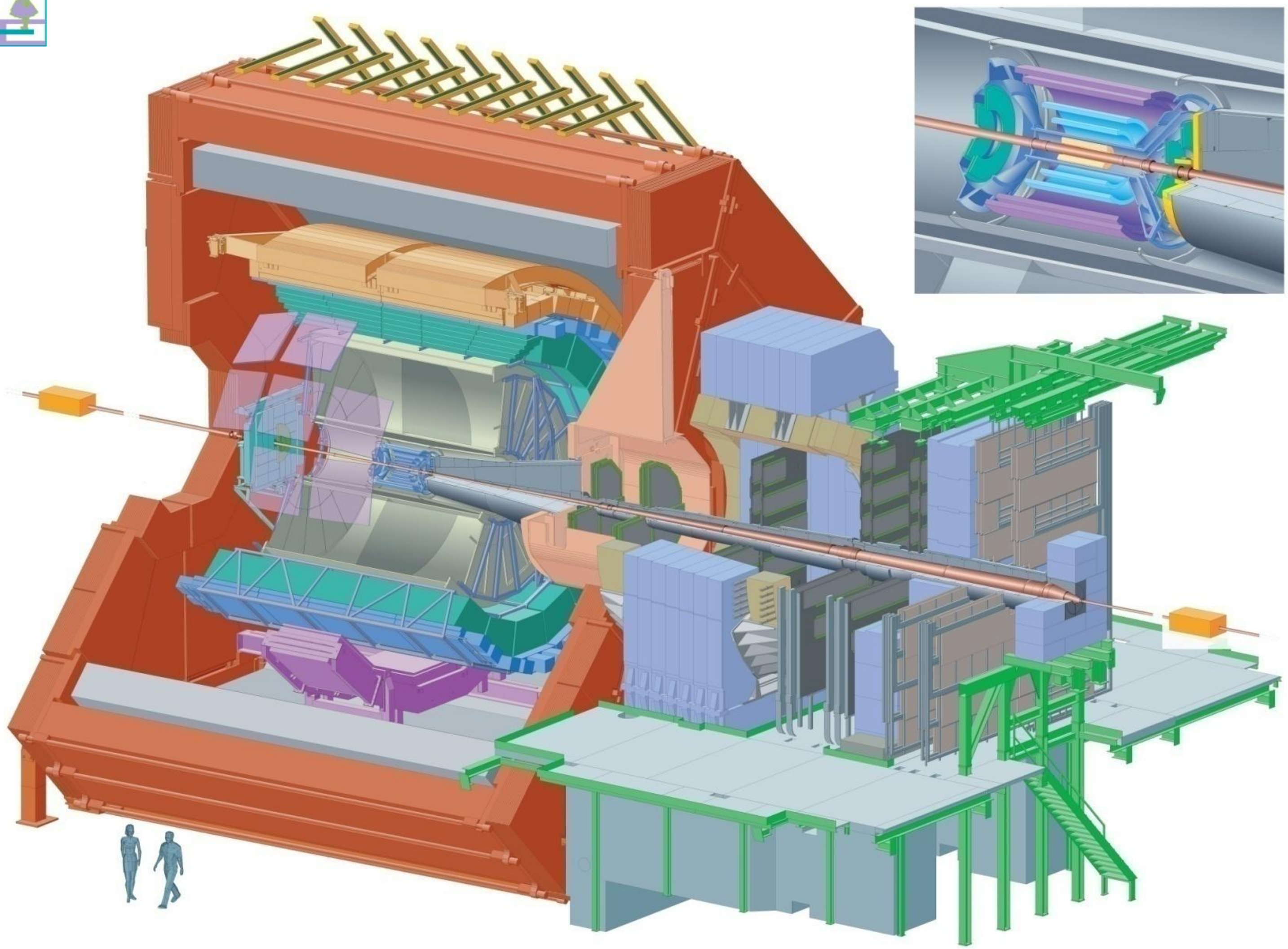


CMS

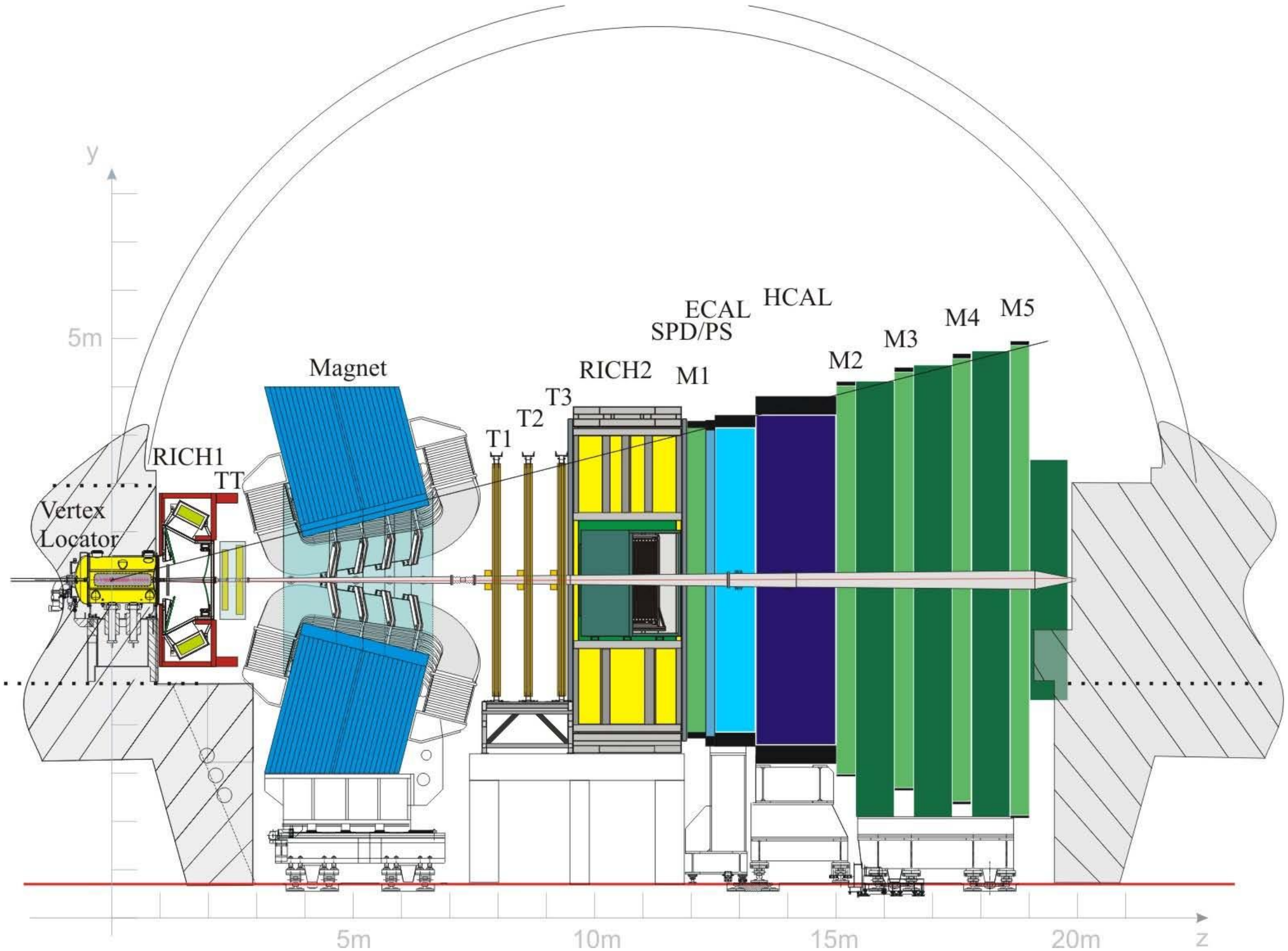



0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

ALICE

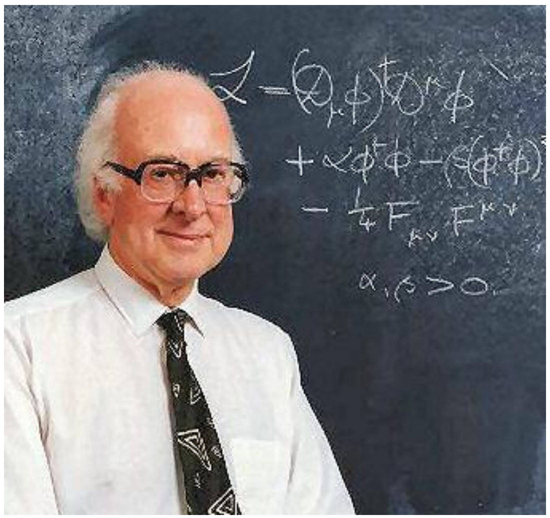


LHCb


y
5m
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

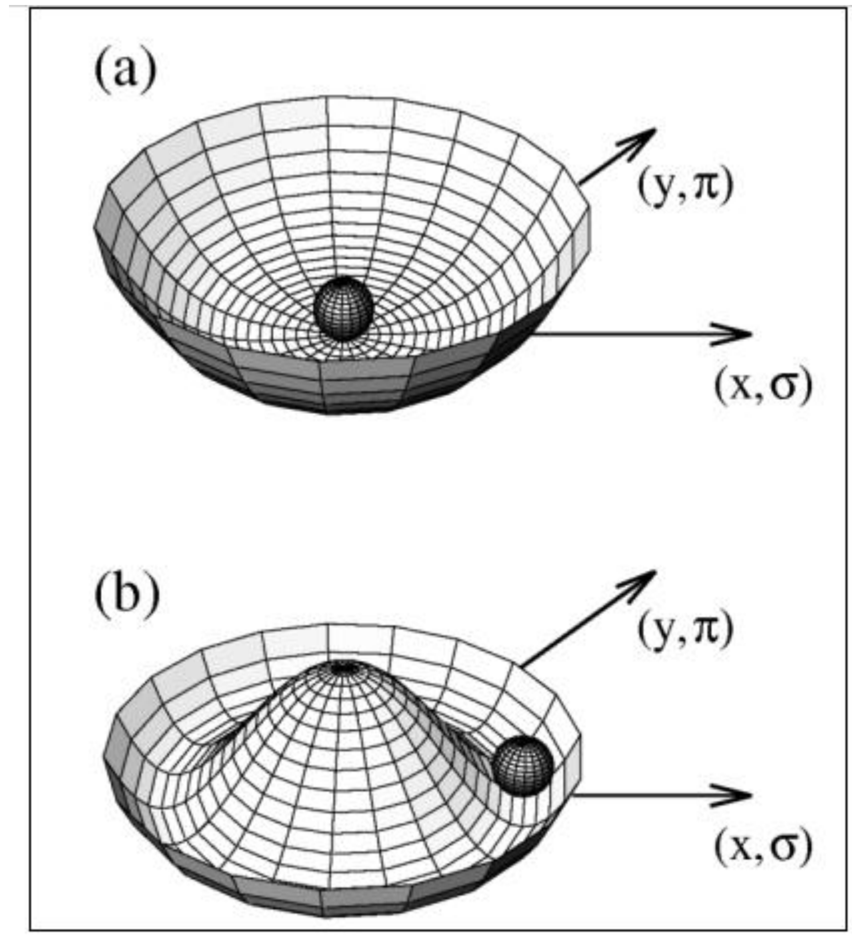
LHC의 물리학

힉스 보손 Higgs boson



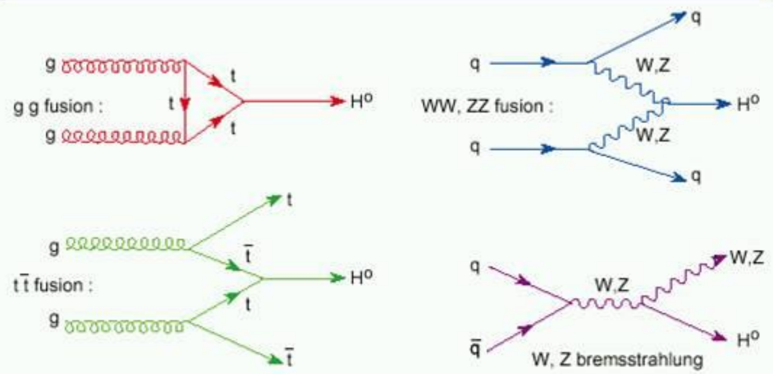
Peter Higgs
(1929 -)

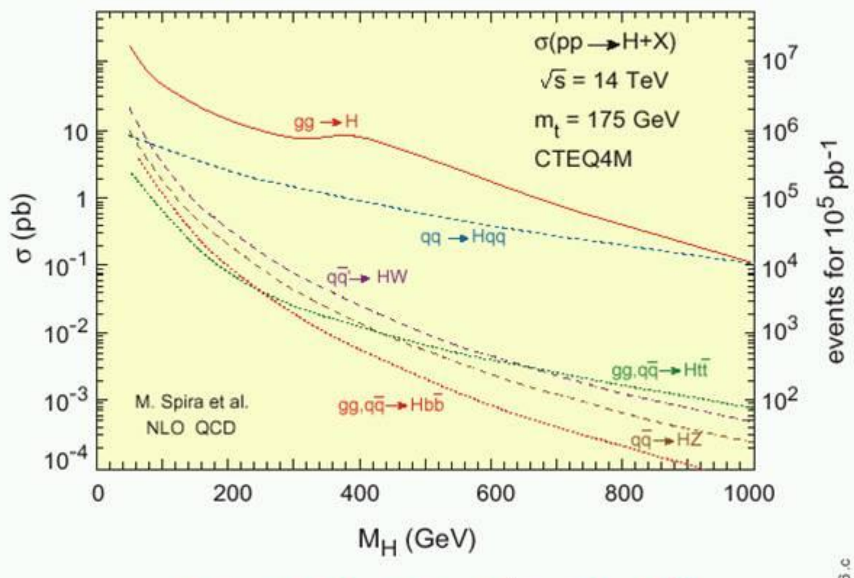
약한 상호작용을 게이지 이론으로 기술할 때 반드시 나타나게 되는 스핀이 0인 입자.



Phenomenology : Standard Model Higgs at LHC (I)

H^o production at hadron colliders:

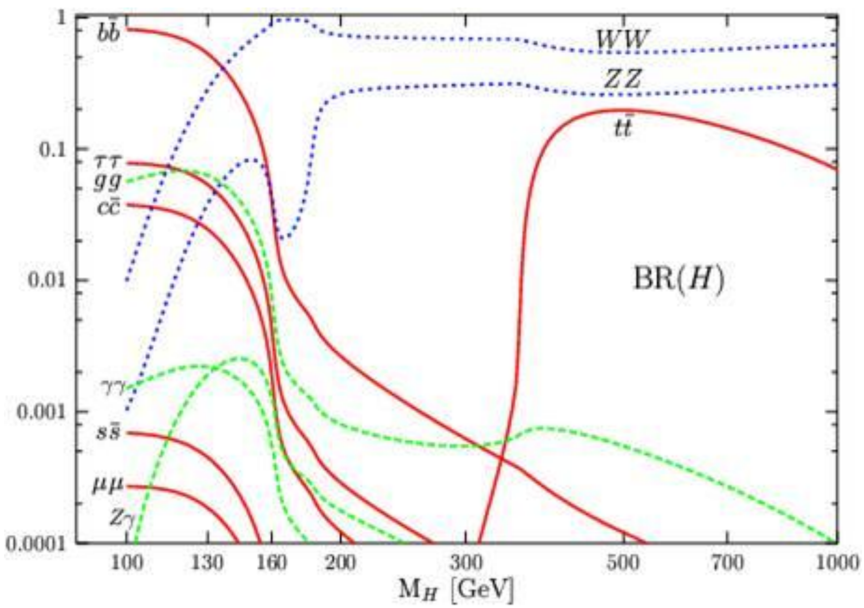


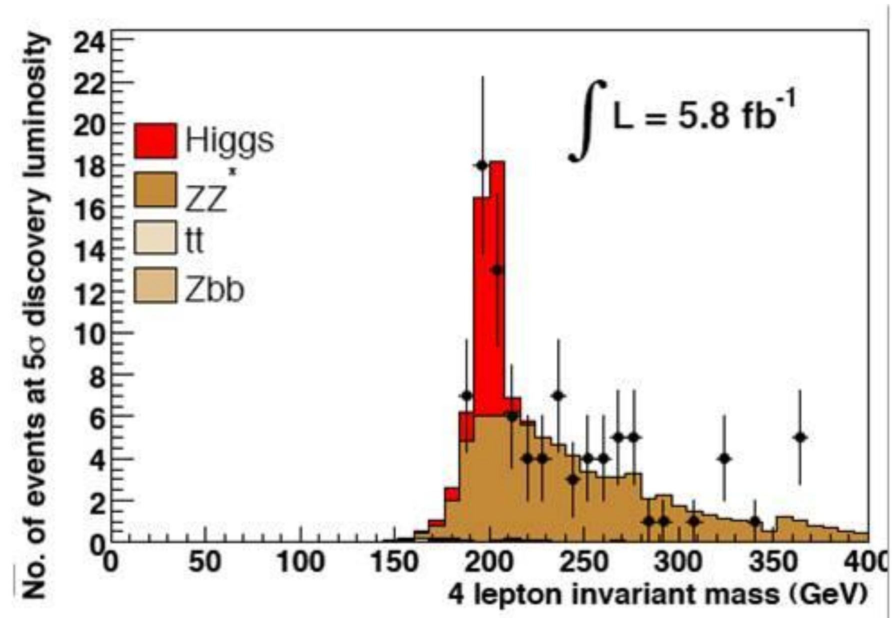


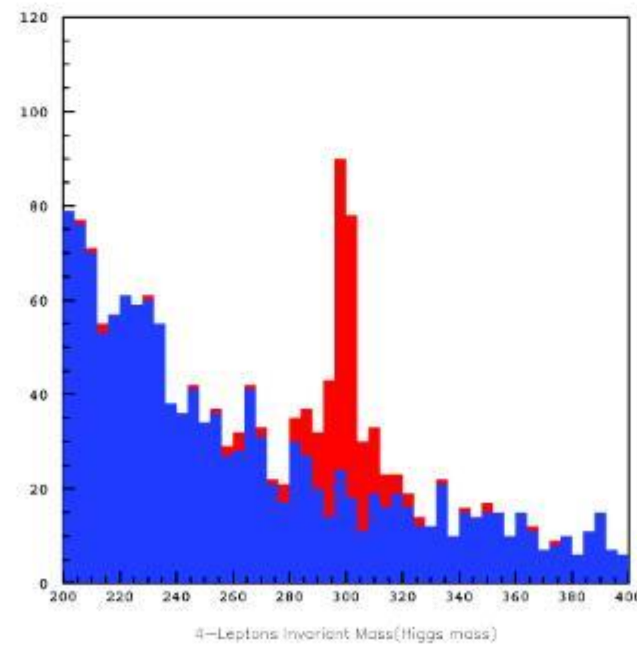
But : $BR(H \to Z^\circ Z^\circ \to 4l^\pm) = 1.4 \cdot 10^{-3}$

$BR(H \to Z^\circ Z^\circ \to 4\mu^\pm) = 3 \cdot 10^{-4}$

힉스 보손이 다른 입자로 붕괴하는 방법

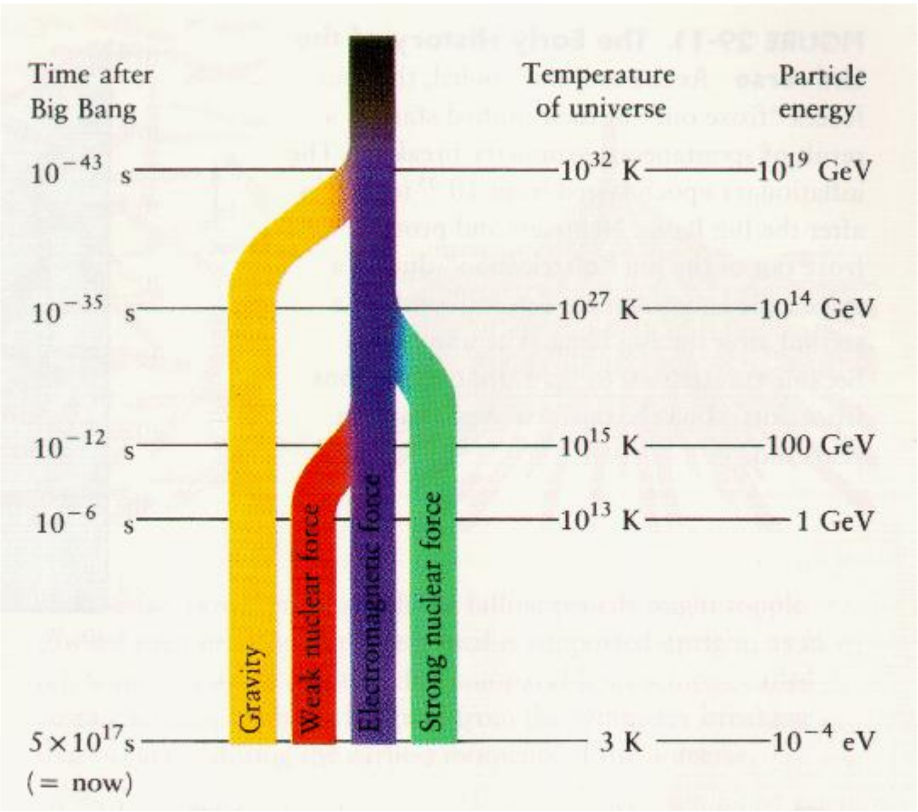


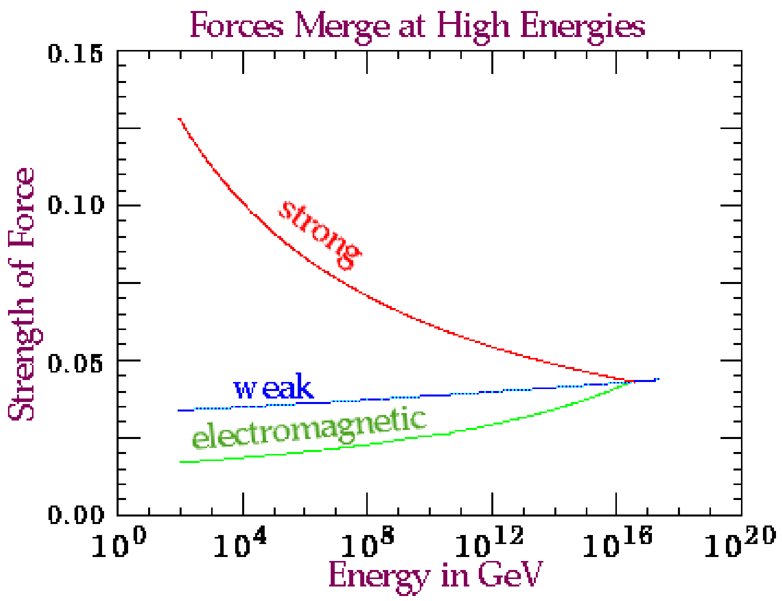




대통일 이론

하나의 게이지 이론 → 세 게이지 이론





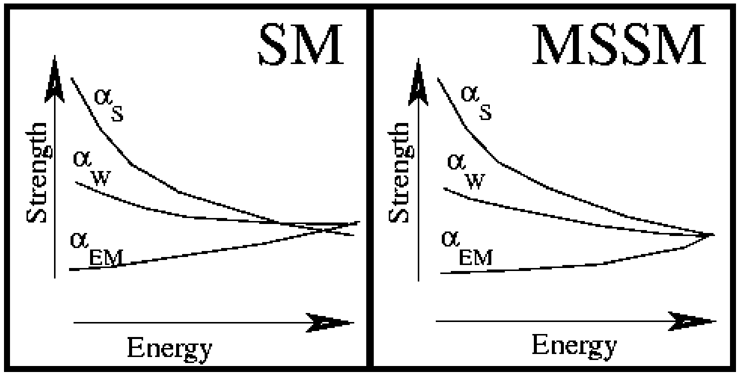
양성자 붕괴

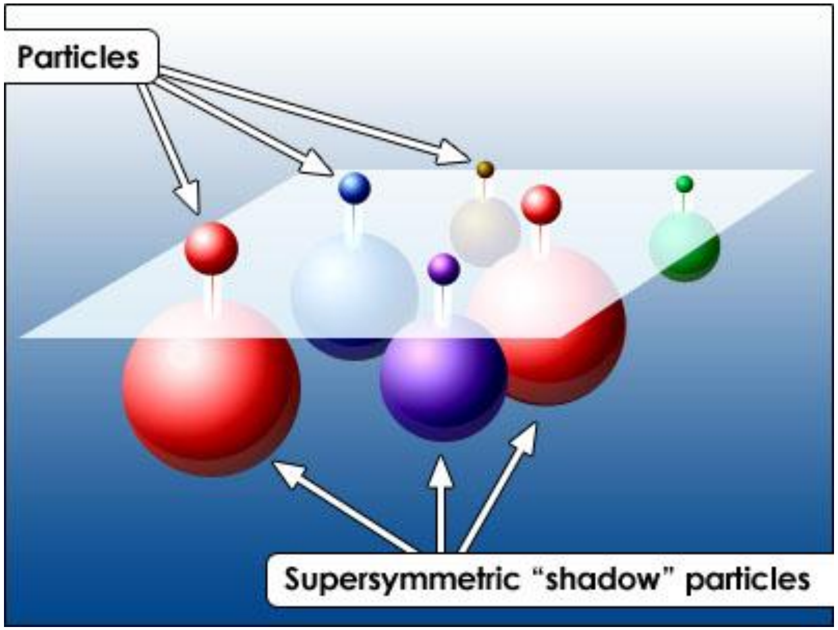
무거운 게이지 입자

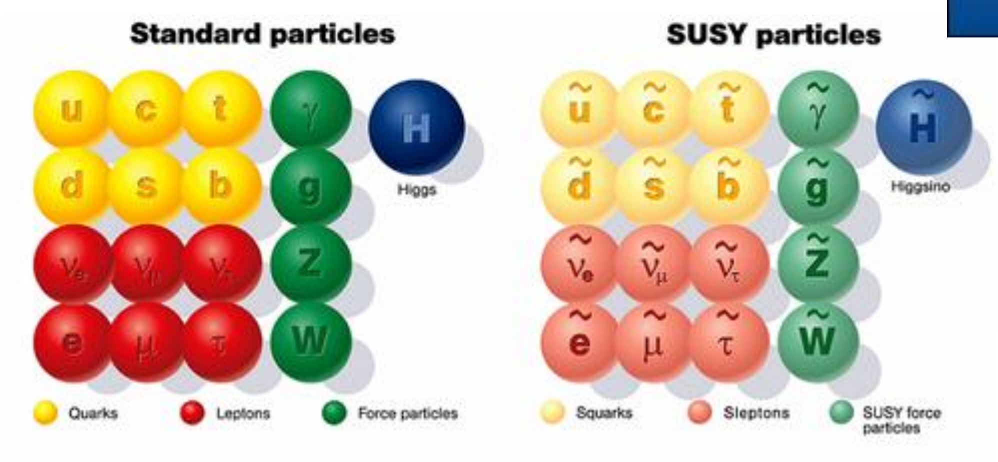
쿼크-렙톤 상호작용

…

초대칭 Supersymmetry

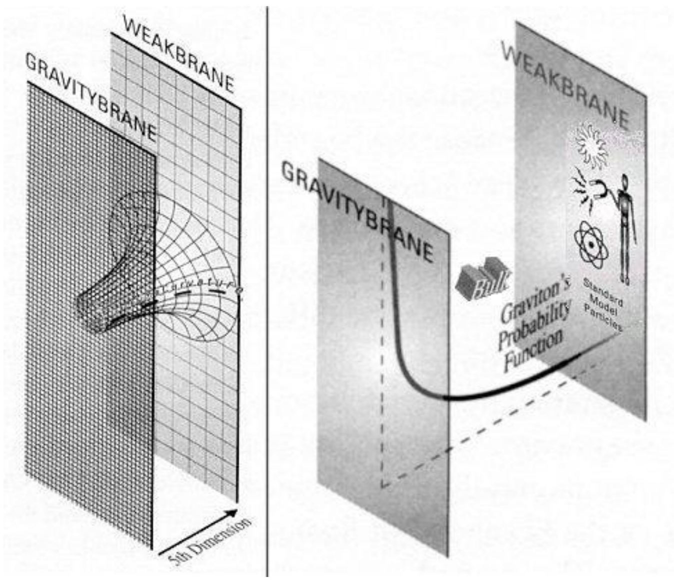


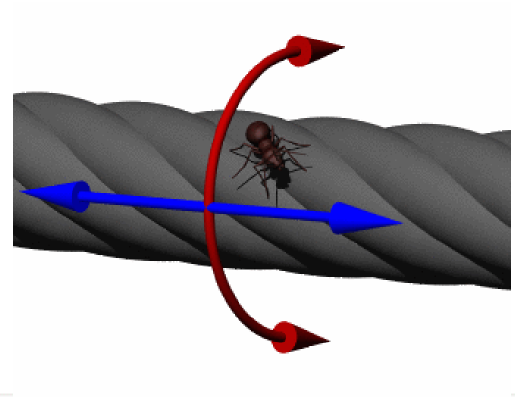




보손 - 페르미온

덧차원 Extra Dimensions

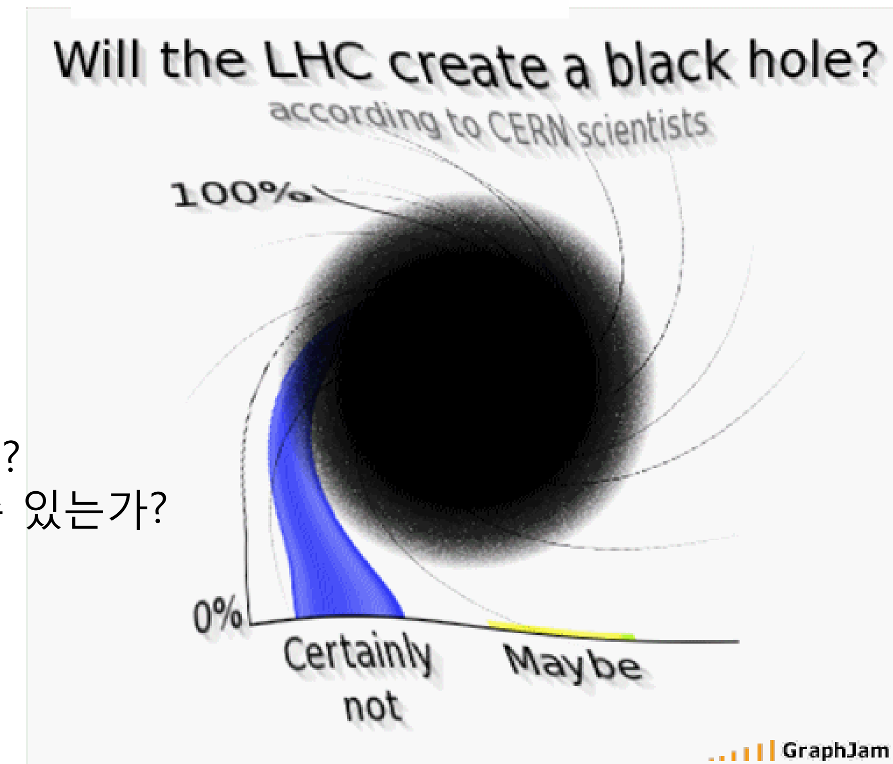




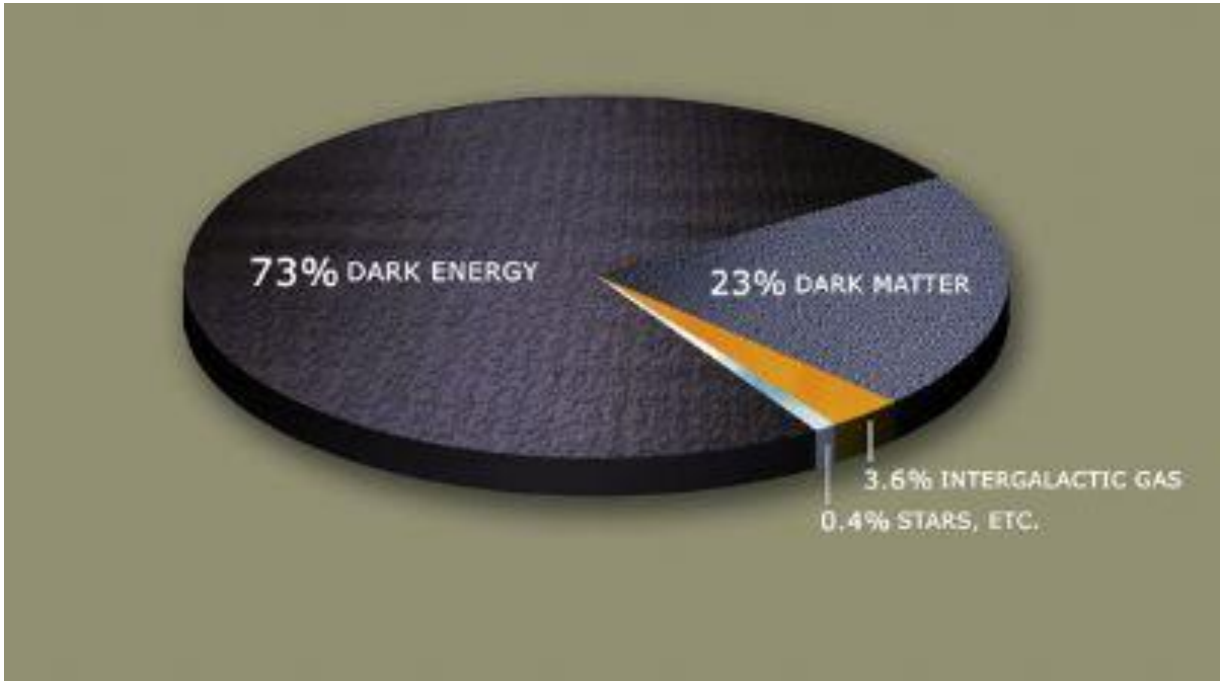
시공간은 4차원인가?

중력이 왜 다른 힘보다 그렇게 작은가?

중력과 다른 힘을 같은 원리로 생각할 수 있는가?
→ 중력이 중요해지는 에너지가 1 TeV 근처일 수 있는가?
→ 1 TeV 근처에서 블랙홀을 볼 수 있는가?



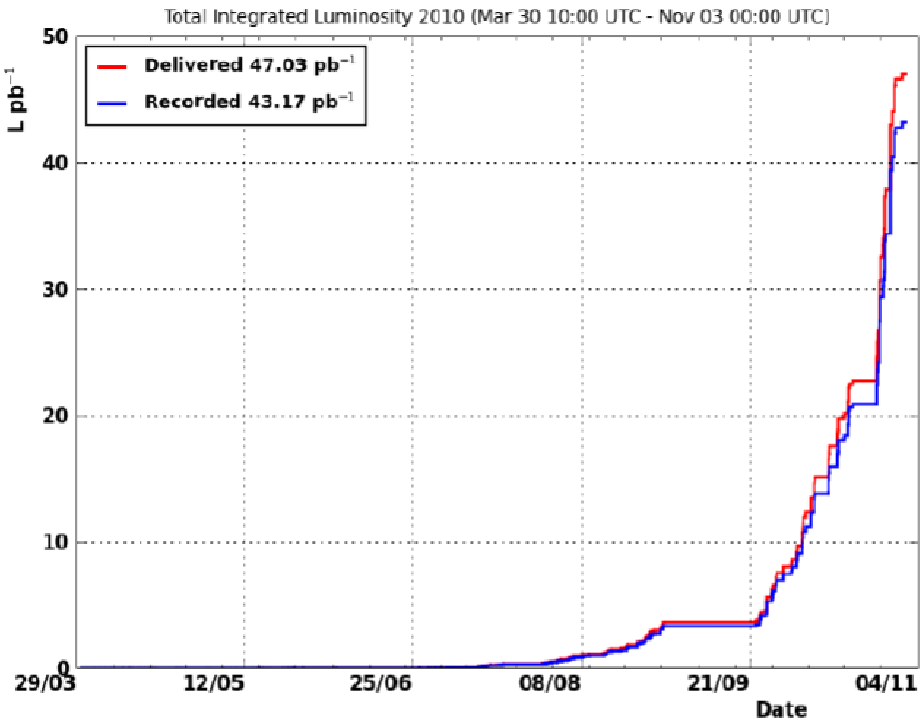
암흑 물질



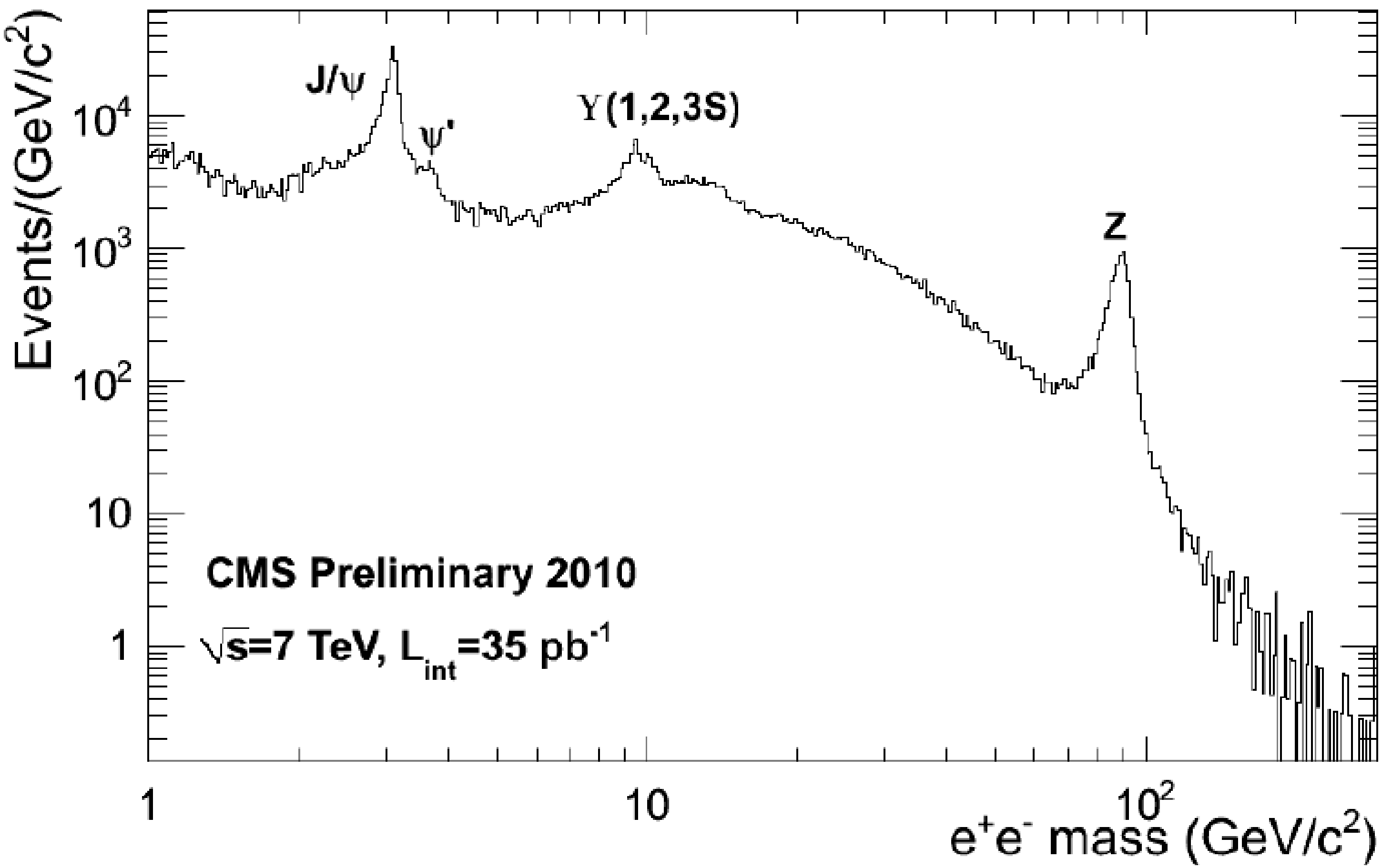
우리가 아는 것은 이 우주의 4% 뿐...........

LHC 2010

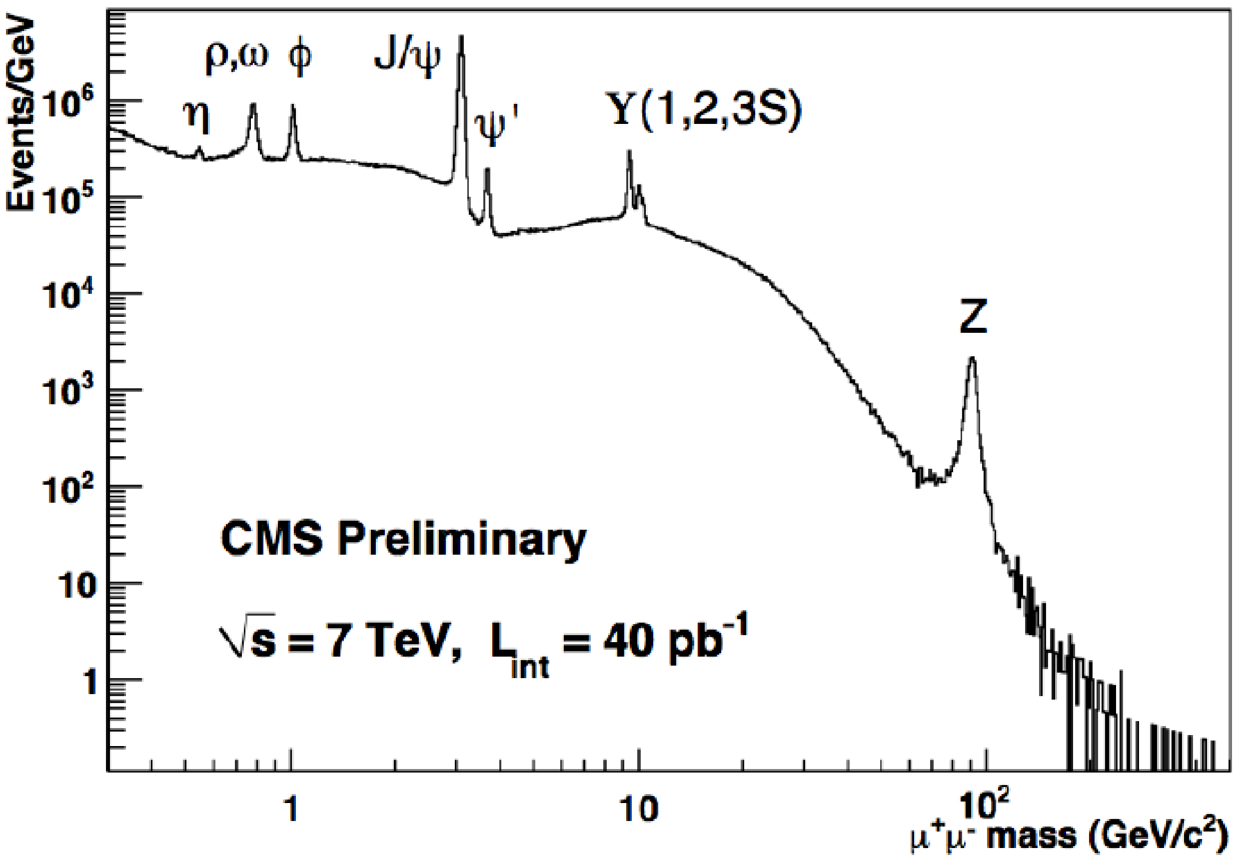
LUMINOSITIES AT CMS



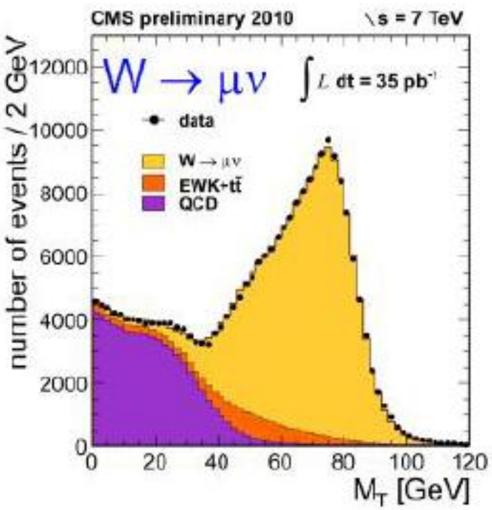
Resonances in Dielectron Mass Spectra

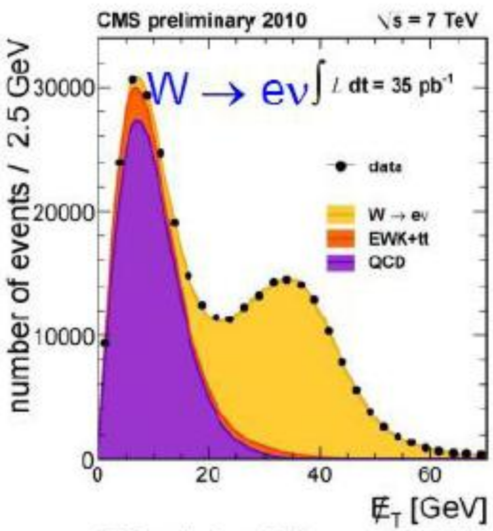


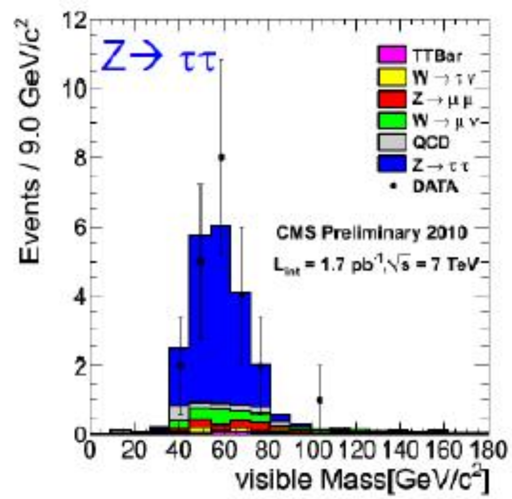
RESONANCES IN DIMUON MASS SPECTRA

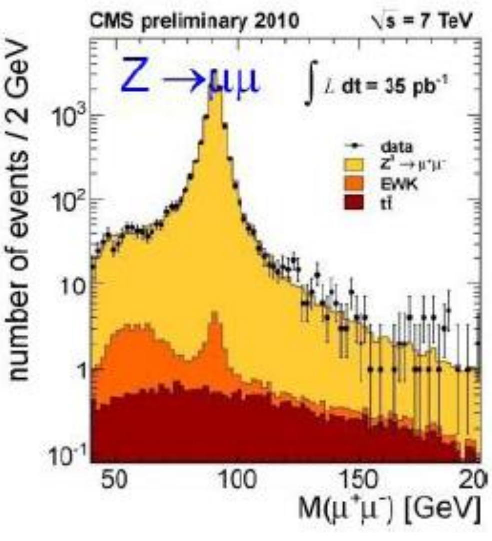


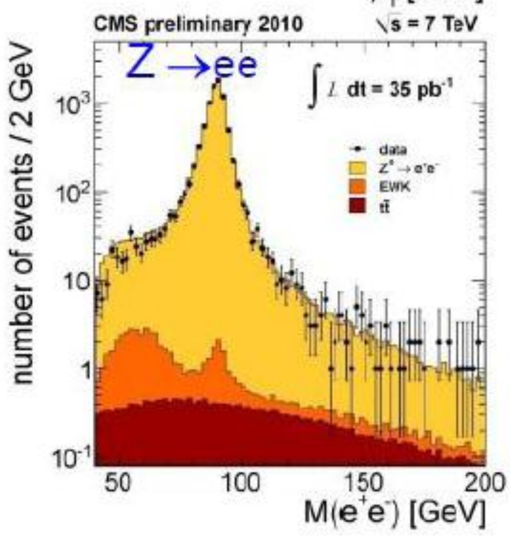
W AND Z BOSONS AT CMS



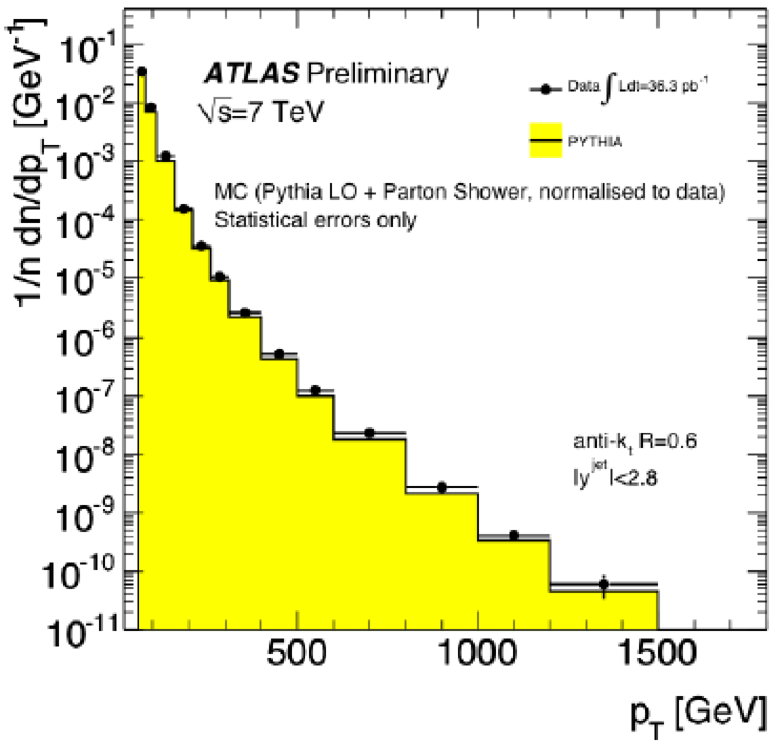




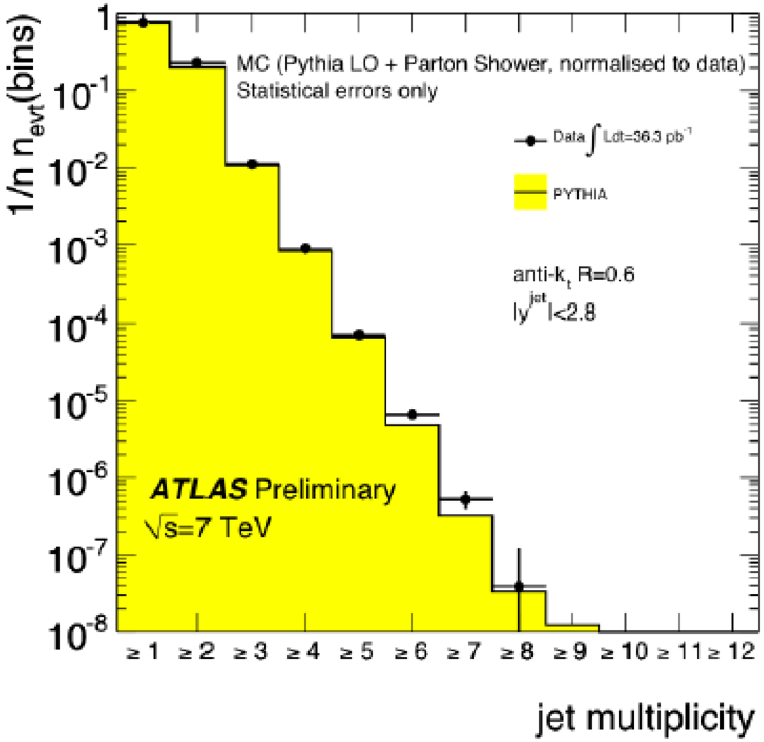




JETS



ATLAS Preliminary
$\sqrt{s}$=7 TeV
Data $\int$ Ldt=36.3 pb^{-1}
PYTHIA
MC (Pythia LO + Parton Shower, normalised to data)
Statistical errors only
anti-k_t R=0.6
$|y^{jet}|$<2.8
1/n dn/dp$_T$ [GeV^{-1}]
p$_T$ [GeV]



MC (Pythia LO + Parton Shower, normalised to data)
Statistical errors only
Data $\int$ Ldt=36.3 pb^{-1}
PYTHIA
anti-k_t R=0.6
$|y^{jet}|$<2.8
ATLAS Preliminary
$\sqrt{s}$=7 TeV
1/n n$_{evt}$(bins)
jet multiplicity

2011 LHC

- 2011. 2. 19.　스위치가 켜짐
- 2011. 3. 13.　7 TeV에서 충돌 시작
- 2011. 3. 24.　작년 데이터의 절반을 넘어섬.

감사합니다.