

The Standard Model

표준모형

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$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \chi_i Y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

우리의 목표

- 표준모형의 이론적 기반이 무엇인지 안다.
- **표준모형 라그랑지안을 쓰고 구조를 관찰한다.**
- 표준모형이 실험적으로 어떻게 검증되었는지를 배운다.

알고 있어야 하는 건...

- Special relativity
- Quantum mechanics

다루지 않는 건...

- Quantization of fields
- Group theory
- Renormalization
- ...

Outline

1. 표준모형의 이론적 기초 I : QED
2. 표준모형의 이론적 기초 II :
Higgs 메커니즘 / Yang-Mills 이론
3. 표준모형 라그랑지안 :
gauge 구조 / flavour 구조
4. 표준모형의 실험적 검증

Part I The QED

표준모형의 이론적 기초

특수 상대성 이론

양자론

게이지 이론

힉스 메카니즘

특수 상대성 이론

4-vector 표현

$$x^\mu = (x^0, x^1, x^2, x^3) = (t, x, y, z)$$

$$x_\mu = (x^0, -x^1, -x^2, -x^3) = (t, -x, -y, -z)$$

$$\partial_\mu = \left(\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$$

$$\partial^\mu = \left(\frac{\partial}{\partial t}, -\frac{\partial}{\partial x}, -\frac{\partial}{\partial y}, -\frac{\partial}{\partial z} \right)$$

$$p^\mu = (E, \vec{p}) = (p^0, p^1, p^2, p^3)$$

$$p_\mu = (E, -\vec{p}) = (p^0, -p^1, -p^2, -p^3)$$

메트릭 텐서 metric tensor

$$g^{\mu\nu} = g_{\mu\nu} \equiv \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}_{\mu\nu}$$

$$A^\mu = g^{\mu\nu} A_\nu, \quad A_\mu = g_{\mu\nu} A^\nu, \quad A \cdot B = g_{\mu\nu} A^\mu B^\nu = g^{\mu\nu} A_\mu B_\nu$$

로렌츠 변환

$$\Lambda^\mu{}_\nu = \frac{\partial x'^\mu}{\partial x^\nu}$$

예를 들어 x축 방향으로 움직이는 관성계는

$$\Lambda^\mu{}_\nu = \begin{pmatrix} \gamma & \gamma\beta & 0 & 0 \\ \gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

맥스웰 방정식

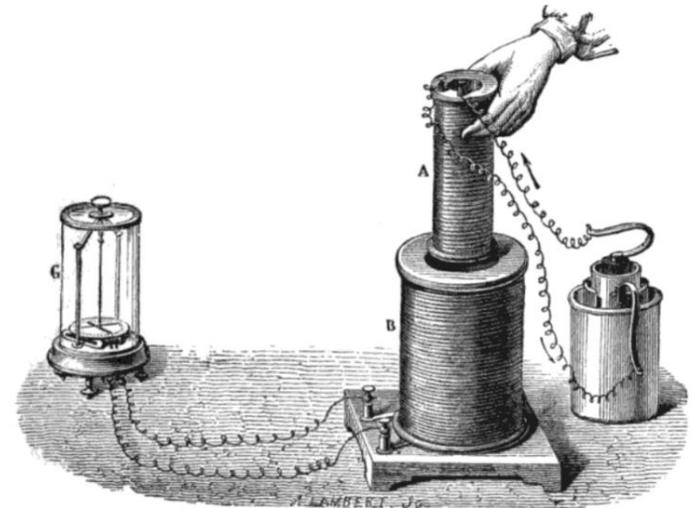
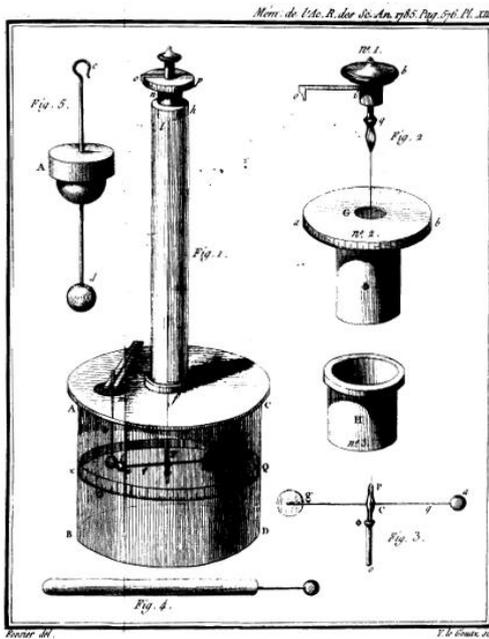
쿨롱, 앙페르, 패러데이의 경험적 법칙

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$



전기장, 자기장, 스칼라 퍼텐셜, 벡터 퍼텐셜

$$\vec{\nabla} \cdot \vec{E} = \rho \quad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \vec{\nabla} \cdot \vec{B} = 0 \quad \vec{\nabla} \times \vec{B} = \vec{J} + \frac{\partial \vec{E}}{\partial t}$$

8 eqs., 6 vars. ?

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \vec{\nabla} \phi \quad \vec{B} = \vec{\nabla} \times \vec{A}$$

4 vars.! 4-vector structure!

$$A^\mu = (\phi, \vec{A})$$

또 다른 4-vector structure: 연속 방정식

$$\partial_\nu J^\nu = \frac{\partial \rho}{\partial t} + \frac{\partial J_x}{\partial x} + \frac{\partial J_y}{\partial y} + \frac{\partial J_z}{\partial z} = \frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \vec{J} = 0$$

게이지 대칭성 : 맥스웰 방정식에서

맥스웰 방정식의 게이지 대칭성

$$\vec{A} \rightarrow \vec{A}' = \vec{A} - \vec{\nabla}\chi \quad \phi \rightarrow \phi' = \phi + \frac{\partial\chi}{\partial t}$$

$$A^\mu \rightarrow A'^\mu = A^\mu + \partial^\mu\chi \quad \text{4-vector structure again!}$$

게이지 불변량 : Field strength tensor

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu = \begin{pmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & -B_z & B_y \\ E_y & B_z & 0 & -B_x \\ E_z & -B_y & B_x & 0 \end{pmatrix}$$

 $F'^{\mu\nu} = \partial^\mu(A^\nu + \partial^\nu\chi) - \partial^\nu(A^\mu + \partial^\mu\chi) = F^{\mu\nu}$

$$F_{\mu\nu} = g_{\mu\alpha}F^{\alpha\beta}g_{\beta\nu} = \begin{pmatrix} 0 & E_x & E_y & E_z \\ -E_x & 0 & -B_z & B_y \\ -E_y & B_z & 0 & -B_x \\ -E_z & -B_y & B_x & 0 \end{pmatrix}$$

게이지 불변이고 로렌츠 공변인 방정식을 써보면

$$\partial_{\mu} F^{\mu\nu} = J^{\nu}$$

$$\partial_{\mu} F_{\nu\lambda} + \partial_{\nu} F_{\lambda\mu} + \partial_{\lambda} F_{\mu\nu} = 0,$$

이것은 맥스웰 방정식!!!!

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

CHECK!

이 방정식을 체계적으로 얻기 위한 라그랑지안 (밀도)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J_{\mu}A^{\mu}$$

Euler-Lagrange 방정식 이용

CHECK!

$$\partial_{\mu} \left(\frac{\partial \mathcal{L}}{\partial (\partial_{\mu} A_{\nu})} \right) - \frac{\partial \mathcal{L}}{\partial A_{\nu}} = 0$$

맥스웰 방정식은

특수 상대성 이론

양자론

게이지 이론

힉스 메카니즘

양자역학

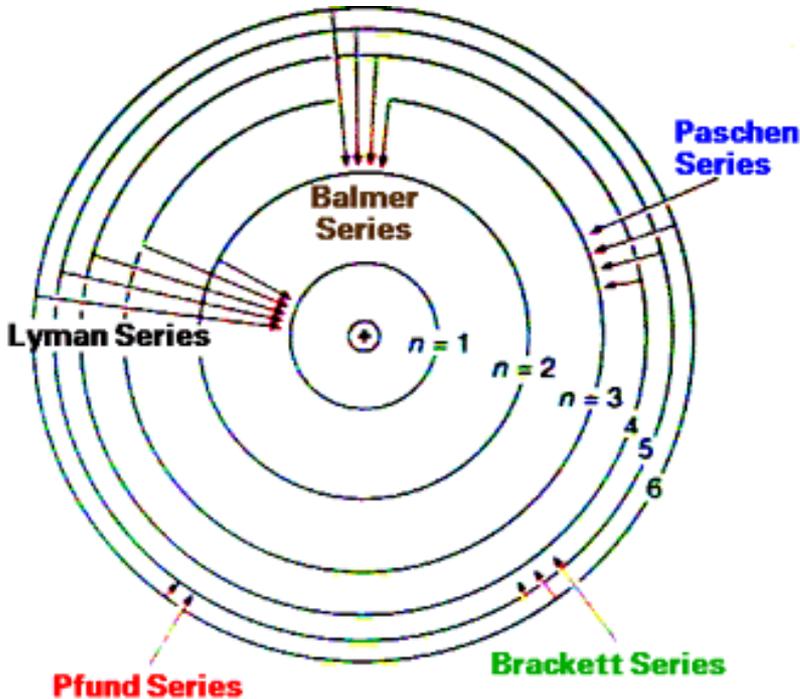
양자역학

- 양자상태 = 파동함수 = 상태벡터 = 고유벡터 = ...
- 관측량 = (에르미트) 연산자 = 행렬 = ...
- 동역학적 조건 $[x,p]=i\hbar$
- 측정은 고유치 방정식으로 표현 $H|\psi(t)\rangle = E|\psi(t)\rangle$
- 시간에 따른 변화는 슈뢰딩거 방정식을 따름

$$\frac{i\hbar}{2\pi} \frac{d}{dt} |\psi(t)\rangle = H|\psi(t)\rangle$$

양자역학의 철학

보어의 원자모형에 대한 러더퍼드의 질문
“전자가 도착하는 곳을 어떻게 아는가?”



보어의 대답

"....."

고전역학의 철학 :

원인(=힘)이 있어야 결과가 있다.

=무슨 일인가 일어났다면 원인이 있다.

양자역학의 철학 :

일어날 수 있는 일은 모두 일어난다.

=금지되지 않은 일(=대칭성에 어긋나지 않는 일)은 모두 일어난다. 우리는 각각의 일이 일어나는 확률만 알 뿐이다.

상대론적 양자역학

슈뢰딩거 방정식

$$i \frac{d}{dt} |\psi(t)\rangle = H |\psi(t)\rangle$$
$$H |\psi(x)\rangle = E |\psi(x)\rangle$$

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

$$\vec{p} \rightarrow -i\vec{\nabla}, \quad E \rightarrow i \frac{\partial}{\partial t}$$

비상대론적 방정식

상대론적 방정식?

$$E^2 = |\vec{p}|^2 + m^2 \quad \rightarrow \quad \frac{\partial^2 \psi}{\partial t^2} = \vec{\nabla}^2 \psi - m^2 \psi$$

Klein-Gordon 방정식

Dirac의 착안

$$i \frac{d}{dt} |\psi(t)\rangle = H |\psi(t)\rangle = \sqrt{E^2} |\psi(t)\rangle$$

 $\sqrt{E^2} = \sqrt{p^2 + m^2} \equiv \alpha \cdot p + \beta m$

$\alpha, \beta \equiv$ q-number, operator, matrix-valued!

$$\left(-i\alpha_x \frac{\partial}{\partial x} - i\alpha_y \frac{\partial}{\partial y} - i\alpha_z \frac{\partial}{\partial z} + \beta m \right) \left(-i\alpha_x \frac{\partial}{\partial x} - i\alpha_y \frac{\partial}{\partial y} - i\alpha_z \frac{\partial}{\partial z} + \beta m \right) \psi = -\frac{\partial^2 \psi}{\partial t^2}$$

 $-\frac{\partial^2 \psi}{\partial t^2} = -\frac{\partial^2 \psi}{\partial x^2} - \frac{\partial^2 \psi}{\partial y^2} - \frac{\partial^2 \psi}{\partial z^2} + m^2 \psi$

$$\begin{aligned}
-\frac{\partial^2 \psi}{\partial t^2} &= -\alpha_x^2 \frac{\partial^2 \psi}{\partial x^2} - \alpha_y^2 \frac{\partial^2 \psi}{\partial y^2} - \alpha_z^2 \frac{\partial^2 \psi}{\partial z^2} + \beta^2 m^2 \psi \\
&\quad -(\alpha_x \alpha_y + \alpha_y \alpha_x) \frac{\partial^2 \psi}{\partial x \partial y} - (\alpha_y \alpha_z + \alpha_z \alpha_y) \frac{\partial^2 \psi}{\partial y \partial z} - (\alpha_z \alpha_x + \alpha_x \alpha_z) \frac{\partial^2 \psi}{\partial z \partial x} \\
&\quad -(\alpha_x \beta + \beta \alpha_x) m \frac{\partial \psi}{\partial x} - (\alpha_y \beta + \beta \alpha_y) m \frac{\partial \psi}{\partial y} - (\alpha_z \beta + \beta \alpha_z) m \frac{\partial \psi}{\partial z}
\end{aligned}$$

$$\alpha_x^2 = \alpha_y^2 = \alpha_z^2 = \beta^2 = 1$$

$$\alpha_j \beta + \beta \alpha_j = 0$$

$$\alpha_j \alpha_k + \alpha_k \alpha_j = 0 \quad (j \neq k)$$

A solution (Dirac representation)

$$\beta = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}, \quad \alpha_j = \begin{pmatrix} 0 & \sigma_j \\ \sigma_j & 0 \end{pmatrix}$$

CHECK!

$$\gamma^0 \equiv \beta; \quad \gamma^1 \equiv \beta \alpha_x; \quad \gamma^2 \equiv \beta \alpha_y; \quad \gamma^3 \equiv \beta \alpha_z \quad : \gamma \text{ 행렬}$$

$$i\gamma^1 \frac{\partial \psi}{\partial x} + i\gamma^2 \frac{\partial \psi}{\partial y} + i\gamma^3 \frac{\partial \psi}{\partial z} - m\psi = -i\gamma^0 \frac{\partial \psi}{\partial t}$$

$$\boxed{(i\gamma^\mu \partial_\mu - m)\psi = 0} \quad : \text{Dirac 방정식}$$

$$\psi_i = u_i(E, \vec{p}) e^{i(\vec{p} \cdot \vec{x} - Et)}$$

$$u_1 = N_1 \begin{pmatrix} 1 \\ 0 \\ \frac{p_z}{E+m} \\ \frac{p_x + ip_y}{E+m} \end{pmatrix}; \quad u_2 = N_2 \begin{pmatrix} 0 \\ 1 \\ \frac{p_x - ip_y}{E+m} \\ \frac{-p_z}{E+m} \end{pmatrix}; \quad u_3 = N_3 \begin{pmatrix} \frac{p_z}{E-m} \\ \frac{p_x + ip_y}{E-m} \\ 1 \\ 0 \end{pmatrix}; \quad u_4 = N_4 \begin{pmatrix} \frac{p_x - ip_y}{E-m} \\ \frac{-p_z}{E-m} \\ 0 \\ 1 \end{pmatrix}$$

이 방정식의 라그랑지안

$$\mathcal{L} = \bar{\psi}(i\gamma_\mu \partial^\mu - m)\psi$$

(자유 전자의) 디랙 방정식은

특수 상대성 이론

양자론

게이지 이론

힉스 메카니즘

한가지 더!

전자와 빛의 상호작용을 그리려면?

: 양자 장 이론

- 디랙 : 전자기장도 입자로 생각
- 페르미 : 전자는 입자로 전자기장은 장으로 생각
- 하이젠베르크와 파울리 : 전자도 장으로 생각

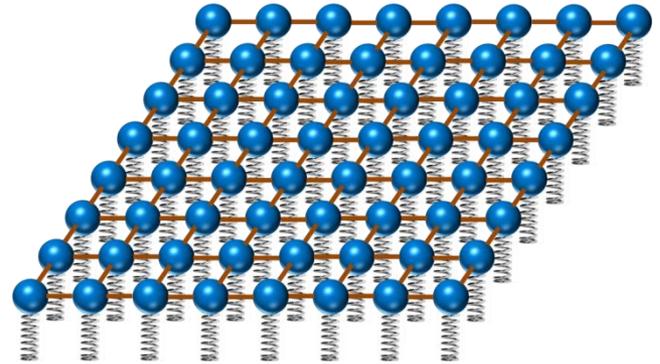
- F. Dyson, Physics Today, **58**, 48 (2005)

양자역학 vs. 양자 장 이론

- 양자역학의 파동함수

: 함수로 표현, 힐베르트 공간의 벡터

→ 양자 상태



- 양자 장 이론의 양자 장

: 시공간 모든 점에 존재하는 Oscillator

→ a, a^+ 연산자로 표현

양자상태를 생성하고 없애는 연산자

(2차 양자화)

- the real scalar field

$$\phi(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_{\vec{p}}}} \left(a_{\vec{p}} e^{-ip \cdot x} + a_{\vec{p}}^\dagger e^{ip \cdot x} \right)$$

a_p :annihilation
 a_p^\dagger :creation

a_p :particle
 b_p^S :anti-particle

- the Dirac field

$$\psi(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_{\vec{p}}}} \sum_s \left(a_{\vec{p}}^s u^s(p) e^{-ip \cdot x} + b_{\vec{p}}^{s\dagger} v^s(p) e^{ip \cdot x} \right)$$

$$\bar{\psi}(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_{\vec{p}}}} \sum_s \left(b_{\vec{p}}^s \bar{v}^s(p) e^{-ip \cdot x} + a_{\vec{p}}^{s\dagger} \bar{u}^s(p) e^{ip \cdot x} \right)$$

- the massless spin-1 field

$$A_\mu(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_{\vec{p}}}} \sum_{i=1,2} \left(a_{\vec{p}} \epsilon_\mu^i(p) e^{-ip \cdot x} + a_{\vec{p}}^\dagger \epsilon_\mu^{i*}(p) e^{ip \cdot x} \right)$$

- 입자의 수가 변할 수 있다.
→ 특수 상대성 이론에 의한 쌍생성, 쌍소멸 가능
e.g. Klein의 역설
- Hilbert 공간의 확장 = 1-ptl.⊗2-ptl.⊗3-ptl.⊗...
: Fock 공간
- 진공 : 가장 낮은 에너지 상태
~ 입자가 없는 상태

양자장 이론으로서의 디랙 방정식

특수 상대성 이론

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게이지 대칭성 : 슈뢰딩거 방정식에서

슈뢰딩거 방정식의 Local Gauge Transform (필기)

Local Gauge Transform에 대해서 방정식이 변함

양자역학 + 전자기 상호작용

- 로렌츠 힘

$$\mathbf{F} = q (\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

- 일반화된 해밀토니언

$$H = \frac{1}{2m} (\mathbf{p} - q\mathbf{A})^2 + q\varphi,$$

CHECK!

- 전자기 상호작용을 포함하는 슈뢰딩거 방정식 $\mathbf{p} \rightarrow -i\hbar\nabla$,

$$i\hbar \frac{\partial \Psi}{\partial t} = \left[\frac{1}{2m} (-i\hbar\nabla - q\mathbf{A})^2 + q\varphi \right] \Psi.$$

바일의 게이지 이론 I

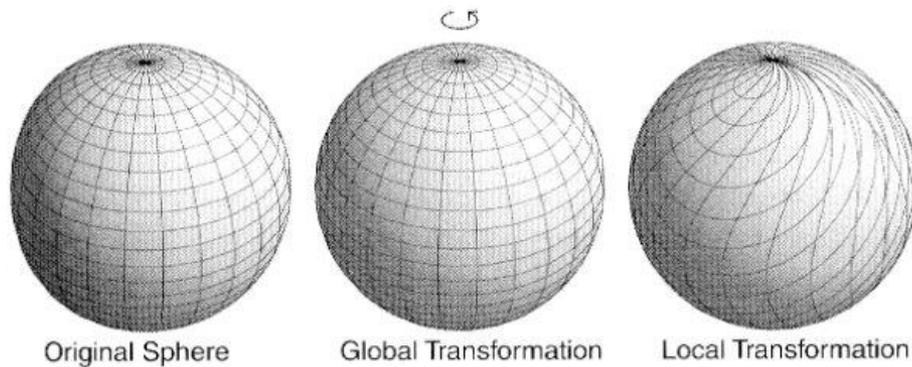


- 헤르만 바일 <중력과 전기> (1918)
- 리만기하학을 곡률의 변화뿐 아니라 길이(scale)의 변화까지 포함하도록 일반화해서 일반상대성 이론에 적용
- 스케일의 변환식이 전자기 퍼텐셜의 게이지 변환과 같은 형태임에 착안해서 중력과 전자기력을 통일 (하나의 이론으로 만듦)
- 아인슈타인의 격찬 "천재의 작품이다!", 그리고 비판 "하지만 물리학 이론은 아니다."

바일의 게이지 이론 II

- 슈뢰딩거 (1922), 런던 (1927), 포크 (1927)
- 바일의 scale factor \rightarrow 파동함수의 위상 $e^\lambda \rightarrow e^{i\lambda(x)}$
- 바일 <전자와 중력> (1929)
- 파동함수의 위상이 위치의 함수라면 슈뢰딩거 방정식(디랙 방정식)만으로는 위상의 변화에 따라 방정식이 일정하게 유지되지 못하며 (=게이지 불변이 아니며) 전자기장을 포함시켜서 위상함수에 의해 게이지 변환을 해야 전체적으로 불변이 된다.

CHECK!

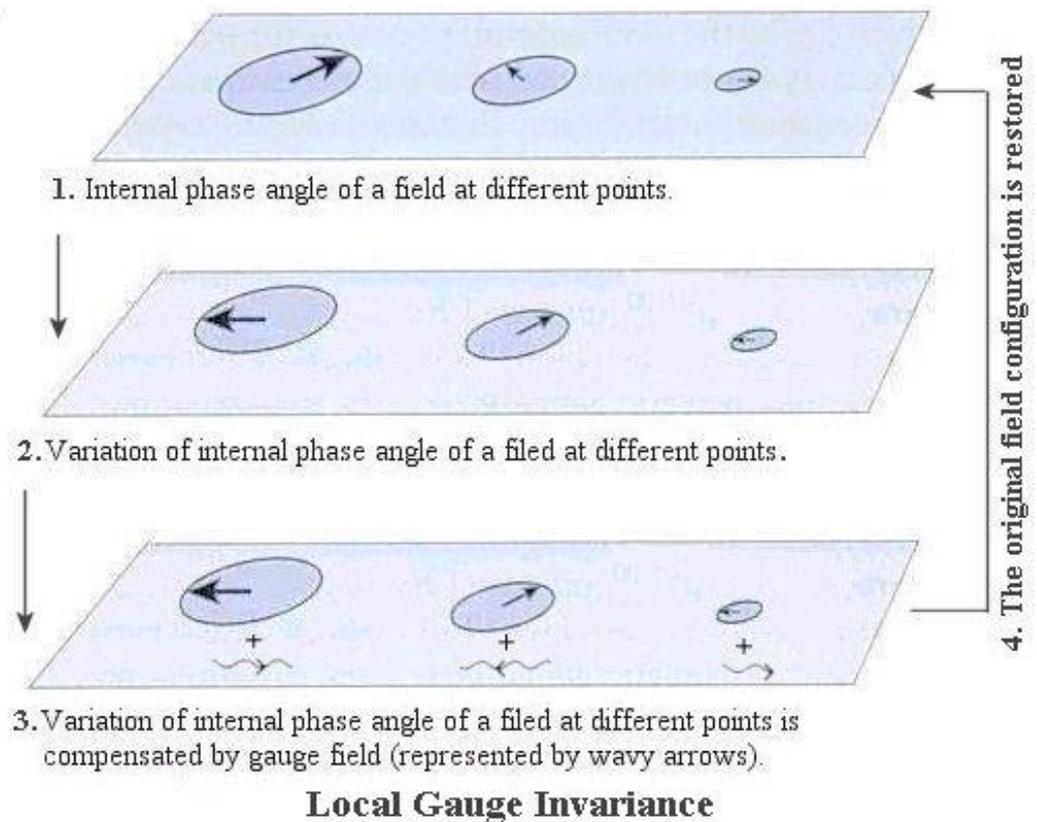


모든 위치에서 자유로운 내부 공간을 가질 수 있다.

→ 내부 공간의 변화를 게이지 장이 보충해 준다.

→ 게이지 장이 상호작용 (= 힘)을 전달한다.

게이지 이론은 양자역학에 필수적인가?



전자기장을 넣은 슈뢰딩거 방정식은

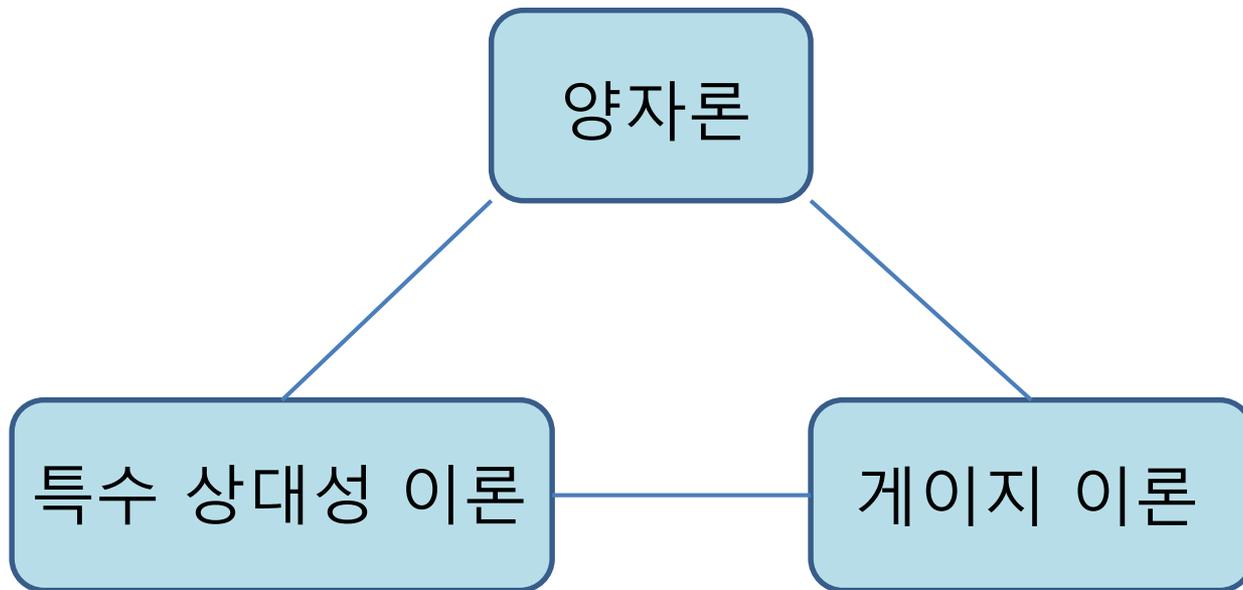
특수 상대성 이론

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물리학 이론의 필수적인 구조?



이 모든 것을 만족시키는 이론

Quantum Electrodynamics (QED)

특수 상대성 이론

양자론

게이지 이론

힉스 메카니즘

QED 라그랑지안 쓰기

게이지 변환에 대한 covariant derivative

$$D_\mu \psi(x) = \left(\partial_\mu + ieQA_\mu(x) \right) \psi(x)$$

$$A_\mu(x) \rightarrow A'_\mu(x) = A_\mu(x) + \partial_\mu \alpha(x)$$

$$\begin{aligned} D_\mu \psi(x) \rightarrow [D_\mu \psi(x)]' &= \left(\partial_\mu + ieQ \{ A_\mu(x) + (\partial_\mu \alpha(x)) \} \right) e^{-ieQ\alpha(x)} \psi(x) \\ &= e^{-ieQ\alpha(x)} \left(\partial_\mu + ieQA_\mu(x) + ieQ(\partial_\mu \alpha(x)) - ieQ(\partial_\mu \alpha(x)) \right) \psi(x) \\ &= e^{-ieQ\alpha(x)} D_\mu \psi(x) \end{aligned}$$

게이지 변환에 대해서 운동항을 불변으로 쓸 수 있게 해준다.

$$\begin{aligned} \bar{\psi}(x) i\gamma^\mu D_\mu \psi(x) \rightarrow [\bar{\psi}(x) i\gamma^\mu D_\mu \psi(x)]' &= \bar{\psi}(x) e^{+ieQ\alpha(x)} i\gamma^\mu e^{-ieQ\alpha(x)} D_\mu \psi(x) \\ &= \bar{\psi}(x) i\gamma^\mu D_\mu \psi(x) \end{aligned}$$

Field strength tensor의 일반적인 정의

$$\begin{aligned} [D_\mu, D_\nu] \psi(x) &= (D_\mu D_\nu - D_\nu D_\mu) \psi(x) \\ &= [(\partial_\mu + ieQA_\mu(x))(\partial_\nu + ieQA_\nu(x)) - (\partial_\nu + ieQA_\nu(x))(\partial_\mu + ieQA_\mu(x))] \psi(x) \\ &= [\partial_\mu ieQA_\nu(x) + ieQA_\mu(x)\partial_\nu - \partial_\nu ieQA_\mu(x) - ieQA_\nu(x)\partial_\mu] \psi(x) \\ &= ieQ \left[(\partial_\mu A_\nu(x)) - (\partial_\nu A_\mu(x)) \right] \psi(x) \\ &= ieQ F_{\mu\nu} \psi(x) \end{aligned}$$

맥스웰 이론과 디랙 이론의 라그랑지안으로부터

$$\mathcal{L} = \bar{\psi} i \gamma^\mu D_\mu \psi - m \bar{\psi} \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

양자전기역학 = 양자론 + 상대성 이론 + 게이지 대칭성
= 게이지 양자장 이론

One more issue : Renormalizability

"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"



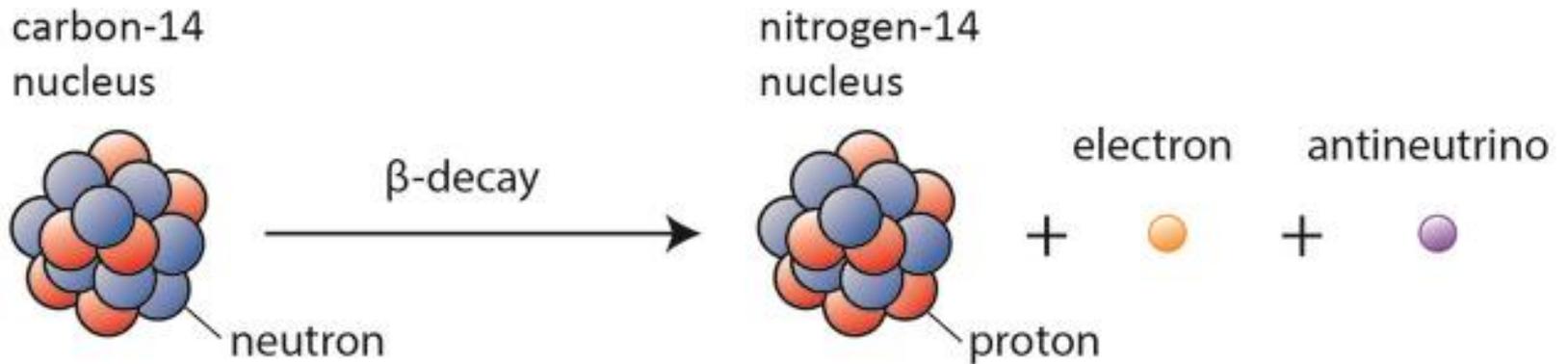
Part II Yang-Mills Theory / Higgs Mechanism

스핀과 아이소스핀 (필기)

Yang-Mills Theory (1954)



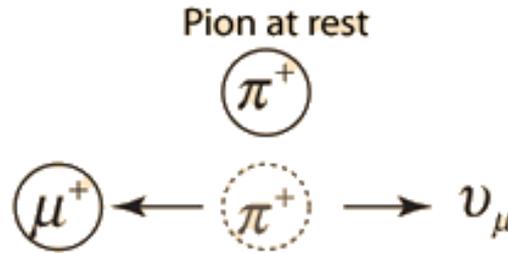
Weak Interaction



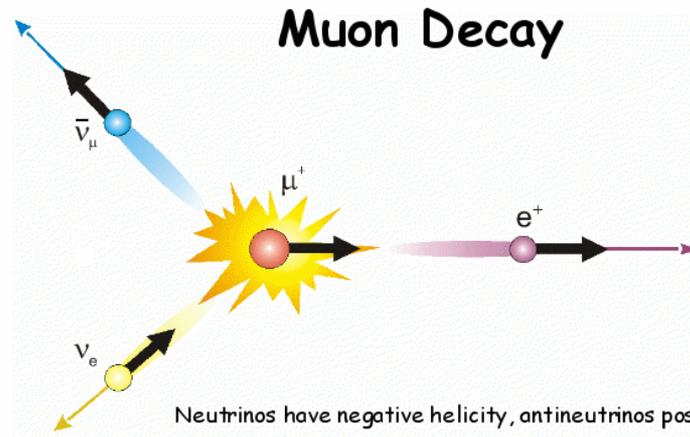
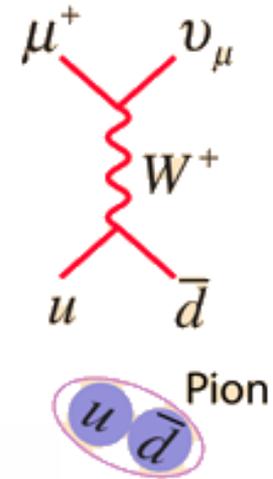
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

139.57 MeV 105.66 MeV

Q = 33.91 MeV



Two-particle decays give definite values of energy and momentum to the products.



Neutrinos have negative helicity, antineutrinos positive.
 An ultrarelativistic positron behaves like an antineutrino.
 Thus the positron tends to be emitted along the muon spin
 when ν_e and $\bar{\nu}_\mu$ go off together (highest energy e^+).

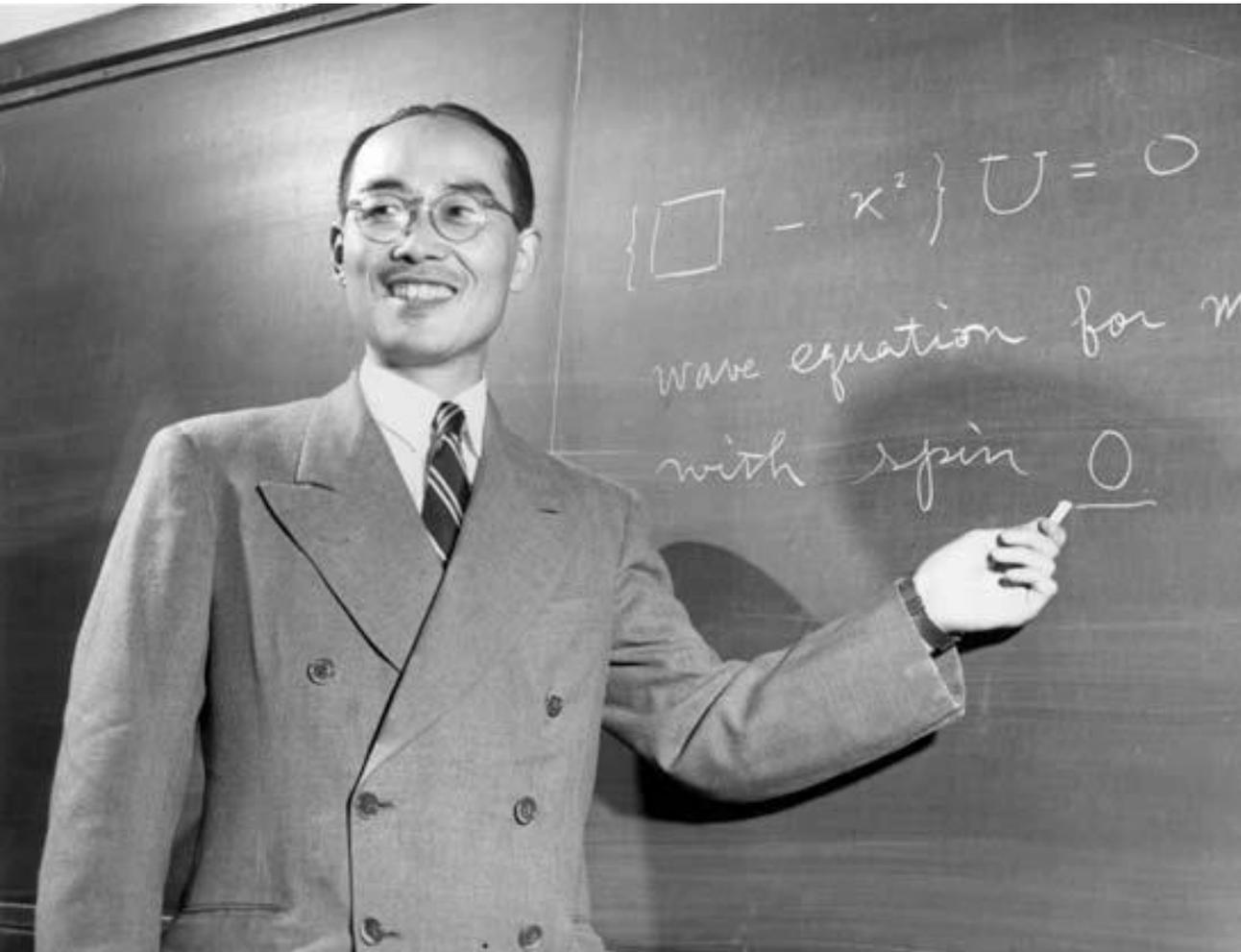
Universal Fermi interaction (UFI)

SU(2) for weak interaction



슈빙거-글래쇼 – 중성류의 가능성 최초 언급

Strong Interaction



핵력이 새로운 힘이라는 걸 명백히 하고 그 새로운 힘의 성질에 대해 논의.

새로운 힘은 빛 대신 무거운 입자의 교환을 통해 전해지므로 매우 짧은 거리에만 작용한다고 제안

퍼텐셜의 형태를 추측

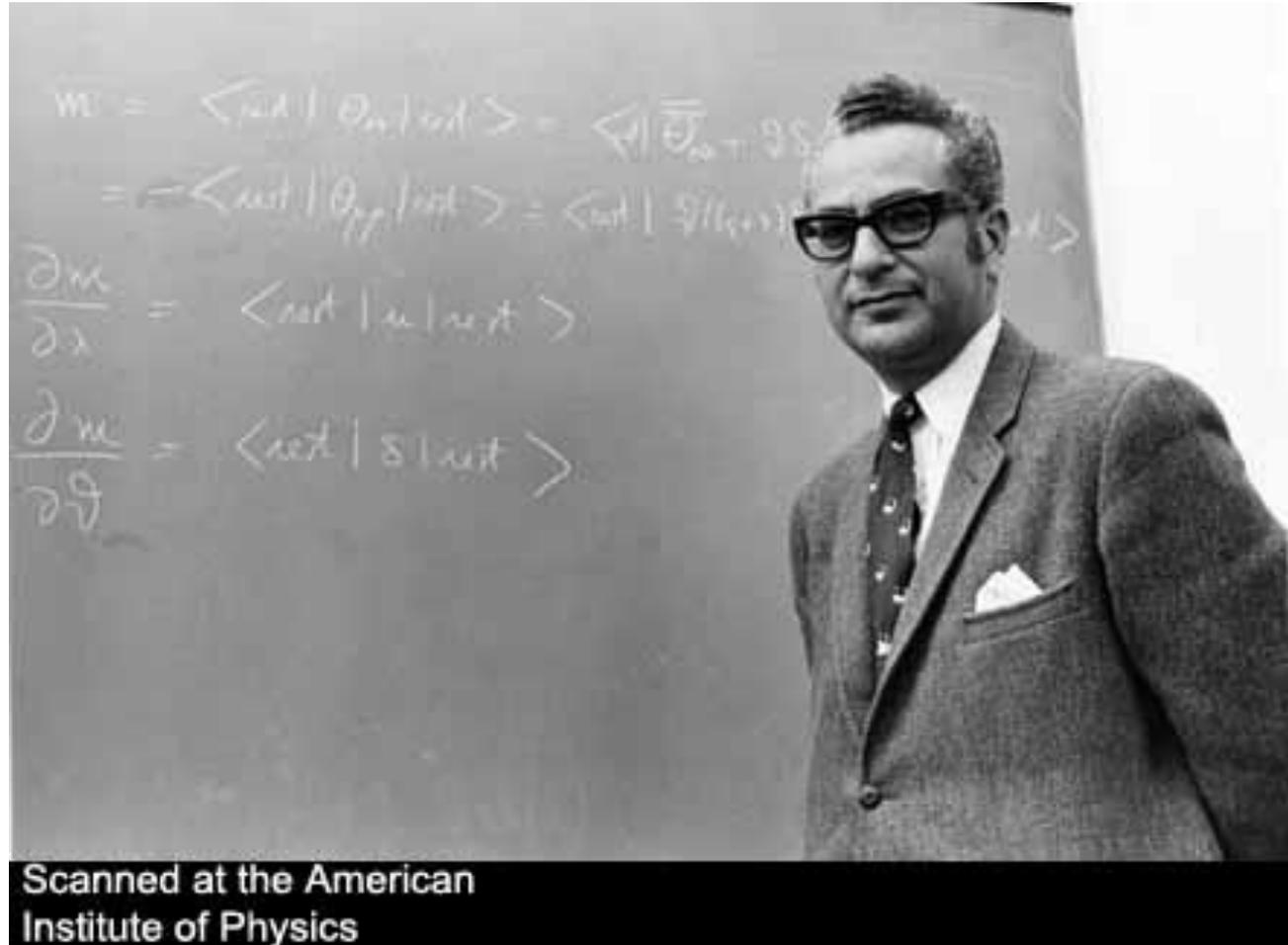
유카와 히데키

SU(3) for strong interaction

하드론들 사이에 SU(3)
대칭성으로 표현되는
구조가 있음을 발견

(당시까지 발견된) 하드
론들은 SU(3)의 기본 요
소인 3개의 기본 입자로
이루어져 있음을 가정
하면 설명될 수 있다고
제안

→ 쿼크



머레이 겔만

돌고래

구름

달

아이폰

해바라기

반가사유상

롤스로이스

연필

타란툴라

빗방울

냉면

...

세상 만물

수소

헬륨

산소

탄소

철

나트륨

칼슘

...

원자

(1-118)

원자핵 - 양성자
중성자

전자

양전자
뮤온

파이온
케이온

반양성자

...

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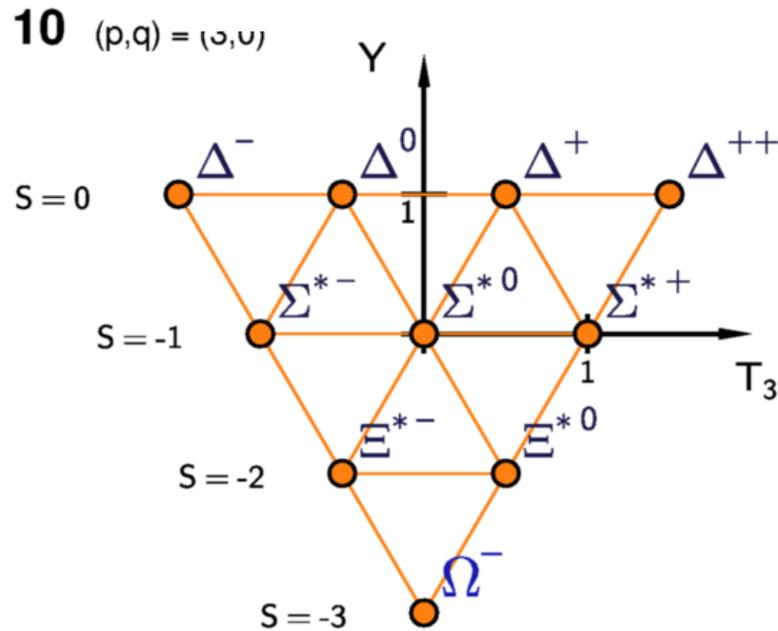
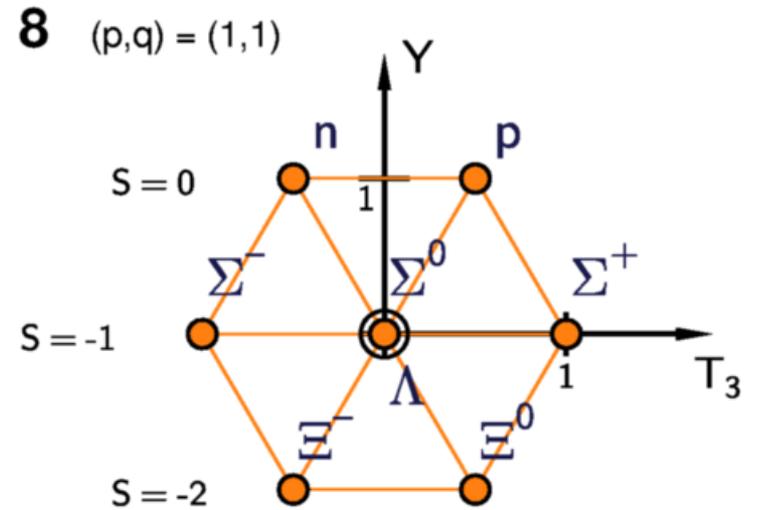
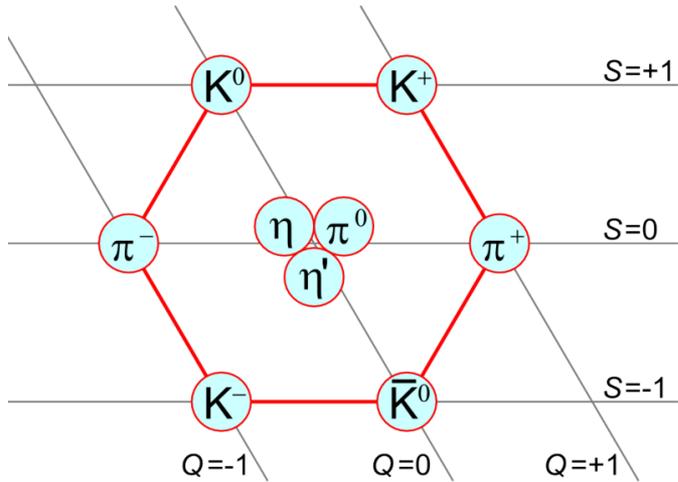
K^*

K(870)

...

???

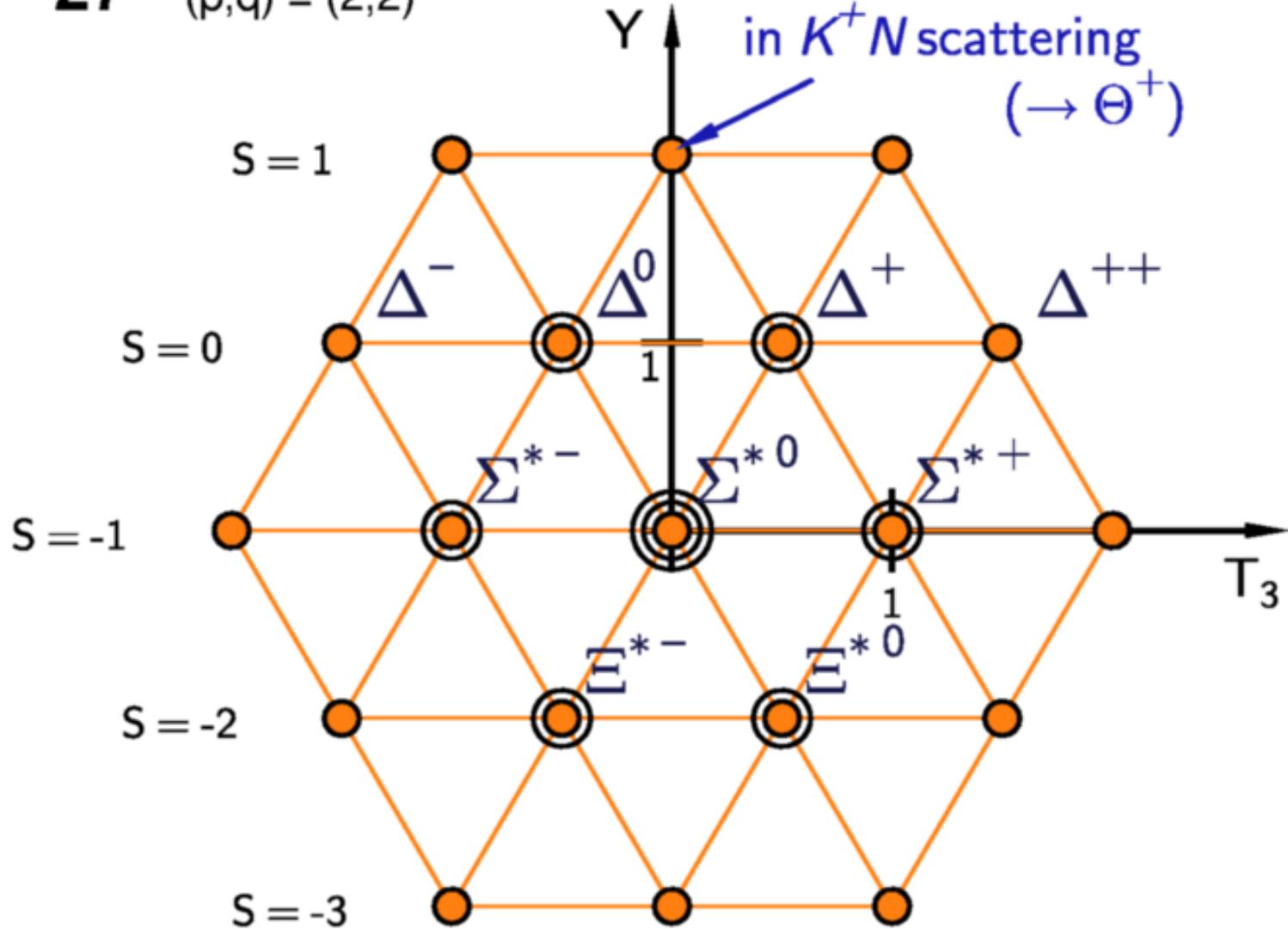
Classification of Hadrons



$SU(3)$ 대칭성

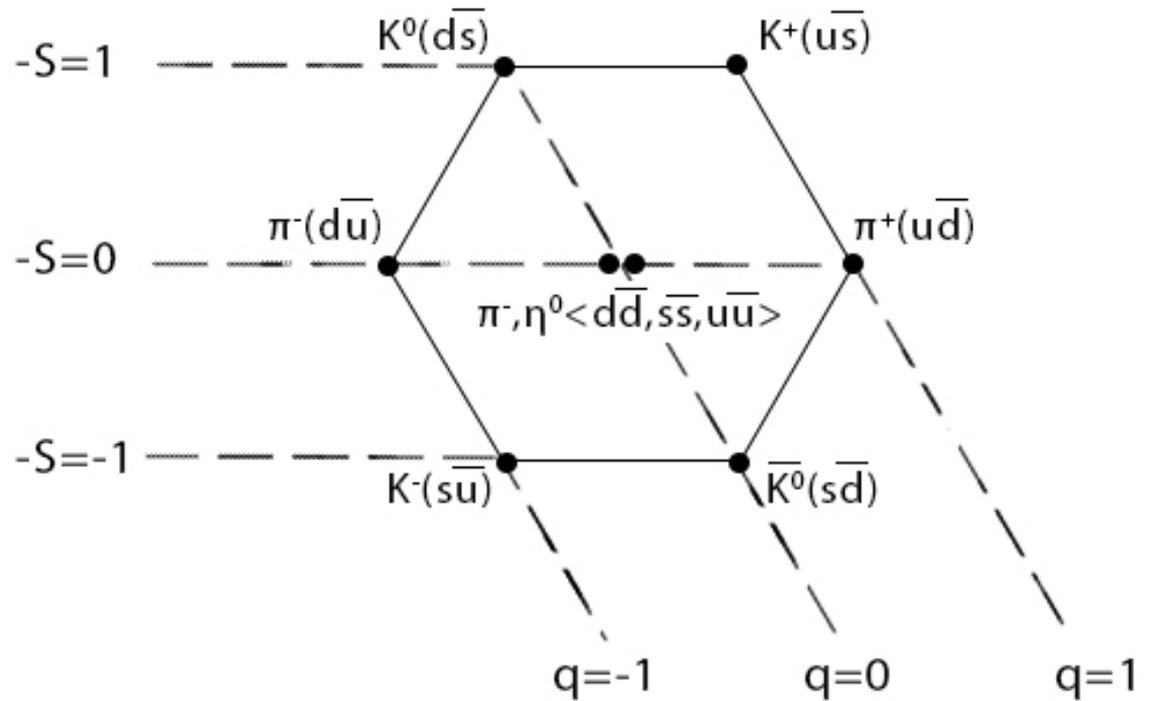
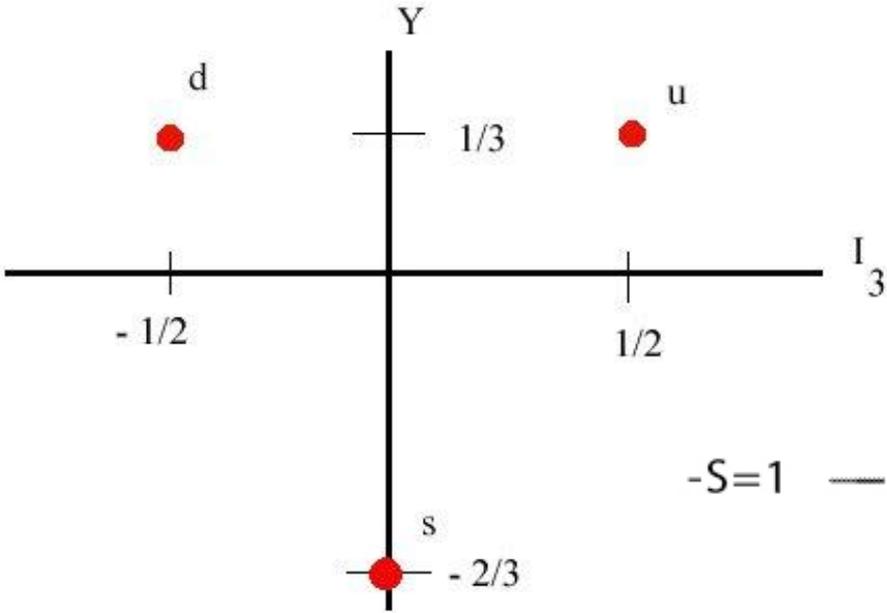
27 $(p,q) = (2,2)$

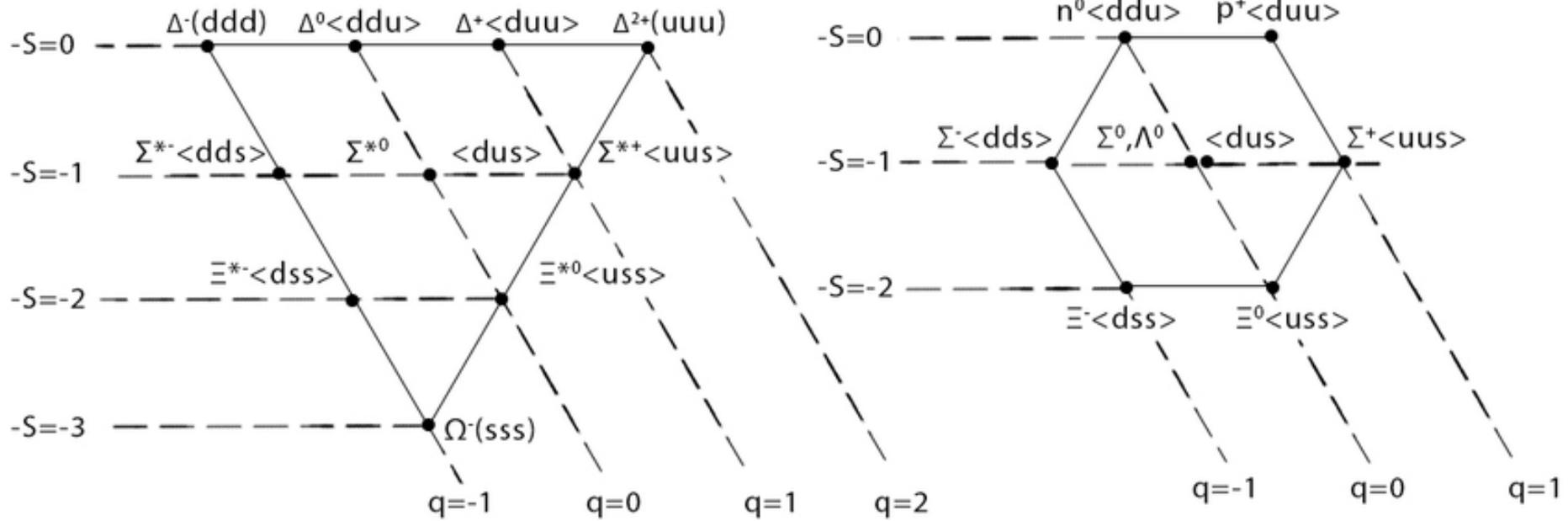
The "Goldhaber Gap"
in K^+N scattering
($\rightarrow \Theta^+$)



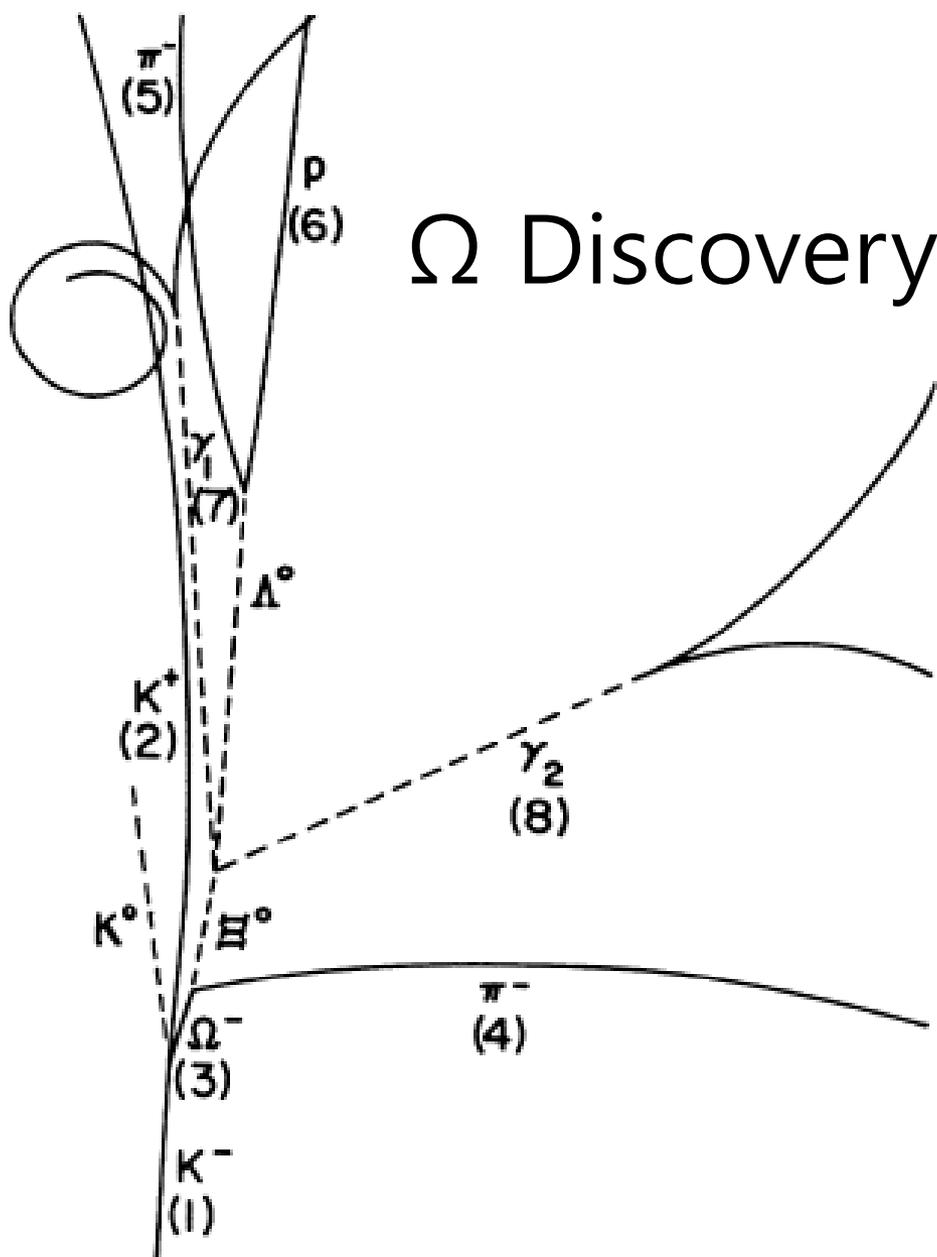
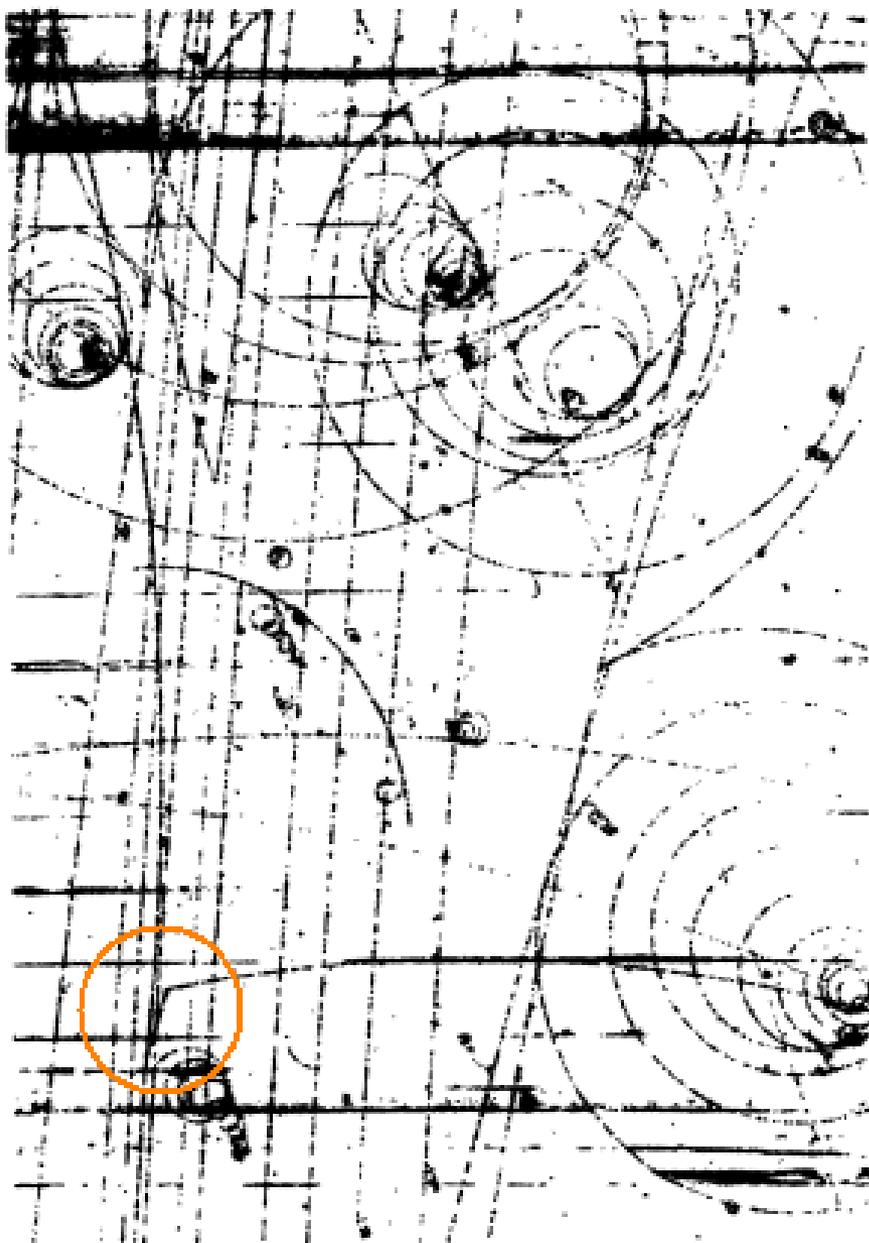
쿼크의 탄생

$$Q = I_3 + \frac{1}{2}Y$$





Ω is missing.



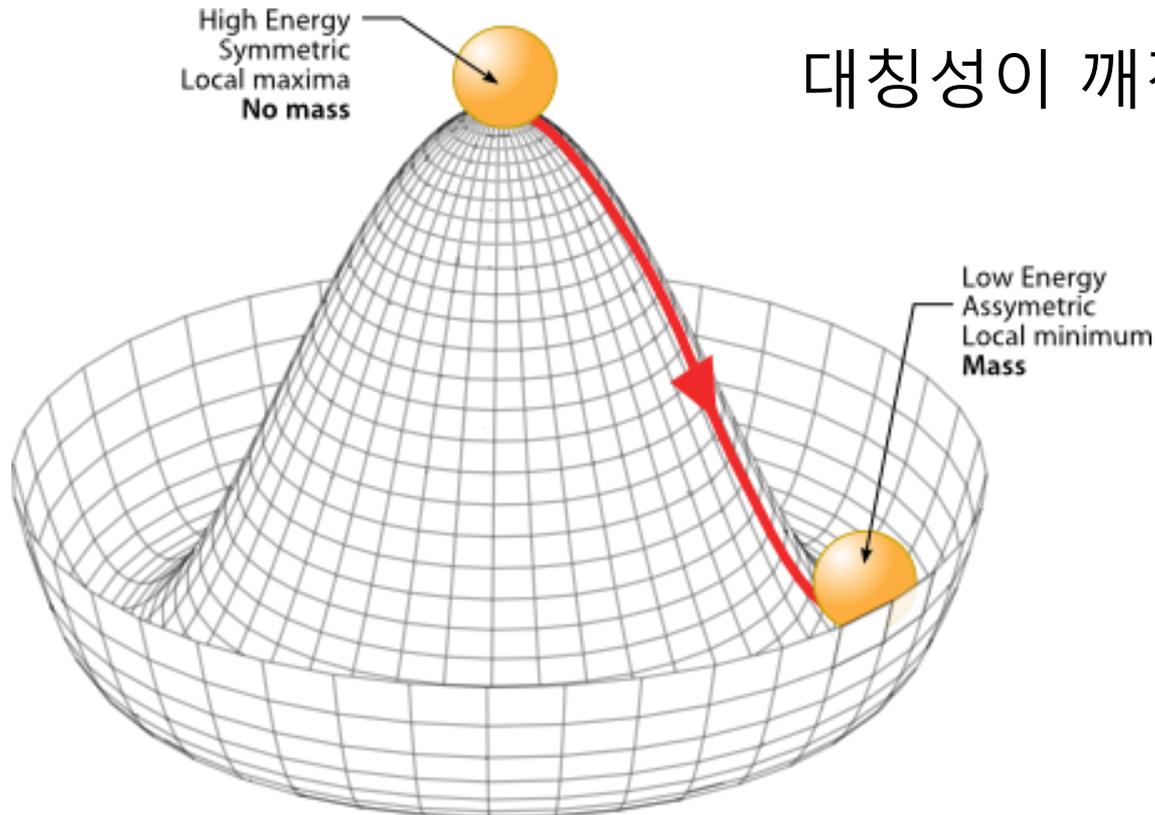
Ω Discovery

힉스 메커니즘 (필기)

Higgs mechanism

대칭성을 가지는 방정식

대칭성이 깨진 해



자발적 대칭성 깨짐

피에르 퀴리

베르너 하이젠베르크 - 상자성 이론

란다우-긴즈버그 - 초유동

BCS 이론 - 초전도

난부 요이치로

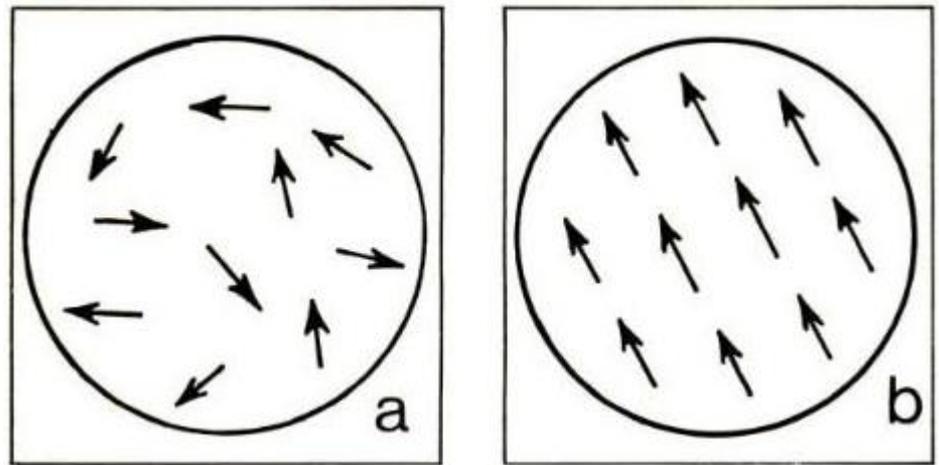
제프리 골드스톤

필립 앤더슨

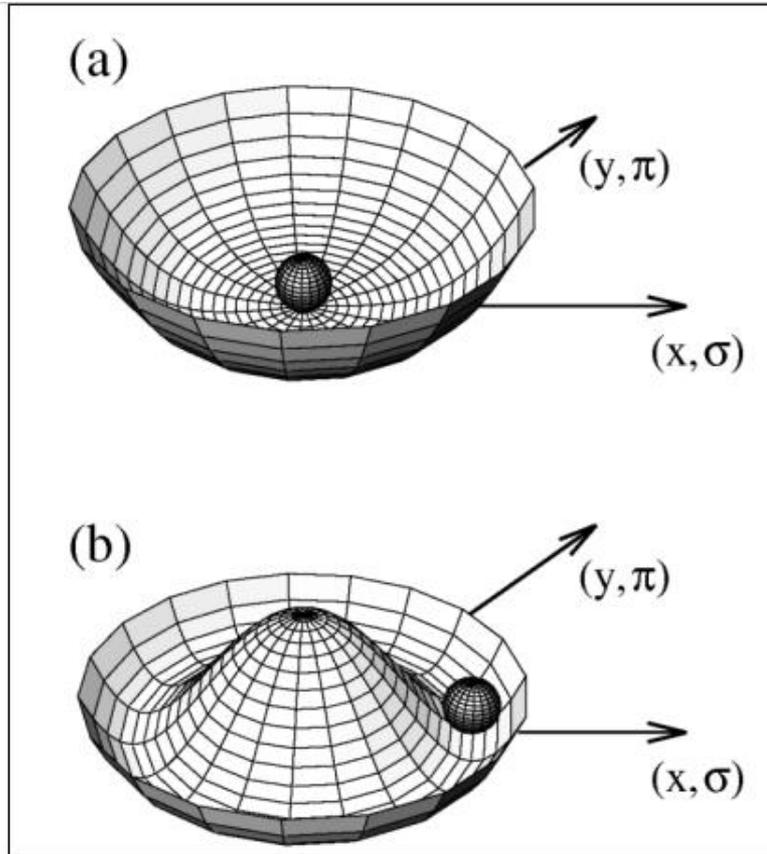
앵글레르-브라우

힉스

구랄니크-하겐-키블



하이젠베르크의 상자성 이론



양자장 이론에서
대칭성이 자발적으로 깨진다는 것

전체적인 대칭성은 남아있지만
물리적인 상태는 대칭성이 깨진 상태



난부 요이치로 Nambu Yoichiro
2008년 노벨 물리학상 수상

Very simple (too simple) classification

- Special relativity + Gauge symmetry = Classical EM (Maxwell Eqs.)
- Special relativity + Quantum mechanics at low energy = Relativistic quantum mechanics (Klein-Gordon/Dirac Eq.)
- Special relativity + Quantum mechanics at high energy = Quantum field theory (Heisenberg & Pauli)
- Special relativity + Quantum mechanics + (abelian) Gauge symmetry = QED
- Special relativity + Quantum mechanics + (non-abelian) Gauge symmetry = Yang-Mills theory (QCD)
- Special relativity + Quantum mechanics + (non-abelian) Gauge symmetry + Higgs mechanism = Electroweak theory (SM)

Part III The Standard Model

마침내 표준모형

이론적 도구는

특수 상대성 이론

양자론

게이지 이론

힉스 메카니즘

4(=3+1) 차원에서의 이론이다 (특수 상대론)

스핀이 0, $\frac{1}{2}$, 1인 입자들이 존재해서, 이들의 운동항과 “가능한” 상호작용항을 모두 쓴다. (양자론)

주어진 게이지 대칭성을 준수한다=라그랑지안은 주어진

게이지 변환에 대해서 불변이다. (게이지 이론)

약한 상호작용의 게이지 대칭성은 자발적으로 깨어져 있다.

(힉스 메커니즘)

Anomaly가 없도록 한다.

Renormalizability를 갖도록 한다. (not must)

Gauge Structure

Flavour Structure

(경험적 지식)

Gauge Structure (경험적 지식) :

- 전자기력 $U(1)$, 약한 상호작용 $SU(2)$, 강한 상호작용 $SU(3)$
- (전자, 중성미자), (u, d) 등 : $SU(2)$ 쌍 (이중항)
- 약한 상호작용 부분은 자발적으로 깨어짐 (힉스 메커니즘)
- $SU(2)$ 는 chiral하게 작용함
- 쿼크 : 컬러 3중항

Weinberg's paper (1967)

¹¹ In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

¹² M. Ademollo and R. Gatto, *Nuovo Cimento* **44A**, 282 (1966); see also J. Pasupathy and R. E. Marshak, *Phys. Rev. Letters* **17**, 888 (1966).

¹³ The predicted ratio [eq. (12)] from the current algebra

is slightly larger than that (0.23%) obtained from the ρ -dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta \rightarrow \pi^+ \pi^- \gamma) / \Gamma(\gamma \gamma)$ calculated in Refs. 12 and 14.

¹⁴ L. M. Brown and P. Singer, *Phys. Rev. Letters* **8**, 460 (1962).

A MODEL OF LEPTONS*

Steven Weinberg†

Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite¹ these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.² This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.³ The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L = \begin{bmatrix} \frac{1}{2}(1 + \gamma_5) \begin{pmatrix} \nu_e \\ e \end{pmatrix} \end{bmatrix} \quad (1)$$

$$\mathcal{L} = -\frac{1}{4}(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g \vec{A}_\mu \times \vec{A}_\nu)^2 - \frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R} \gamma^\mu (\partial_\mu - ig' B_\mu) R - L \gamma^\mu (\partial_\mu + ig \vec{T} \cdot \vec{A}_\mu - i\frac{1}{2} g' B_\mu) L$$

$$- \frac{1}{2} i \partial_\mu \varphi - ig \vec{A}_\mu \cdot \vec{T} \varphi + i\frac{1}{2} g' B_\mu \varphi^2 - C_e (\bar{L} \varphi R + \bar{R} \varphi^\dagger L) - M_1^2 \varphi^\dagger \varphi + h(\varphi^\dagger)^2. \quad (4)$$

We have chosen the phase of the R field to make G_e real, and can also adjust the phase of the L and Q fields to make the vacuum expectation value $\lambda = \langle \varphi^0 \rangle$ real. The "physical" φ fields are then φ^-

and on a right-handed singlet

$$R = \begin{bmatrix} \frac{1}{2}(1 - \gamma_5) e \end{bmatrix}. \quad (2)$$

The largest group that leaves invariant the kinetic terms $-\bar{L} \gamma^\mu \partial_\mu L - \bar{R} \gamma^\mu \partial_\mu R$ of the Lagrangian consists of the electronic isospin \vec{T} acting on L , plus the numbers N_L , N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q = T_3 - N_R - \frac{1}{2} N_L$, and the electron number $N = N_R + N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,⁴ and there is no massless particle coupled to N ,⁵ so we must form our gauge group out of the electronic isospin \vec{T} and the electronic hypercharge $Y = N_R + \frac{1}{2} N_L$.

Therefore, we shall construct our Lagrangian out of L and R , plus gauge fields \vec{A}_μ and B_μ coupled to \vec{T} and Y , plus a spin-zero doublet

$$\varphi = \begin{pmatrix} \varphi^0 \\ \varphi^- \end{pmatrix} \quad (3)$$

whose vacuum expectation value will break \vec{T} and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under \vec{T} and Y gauge transformations is



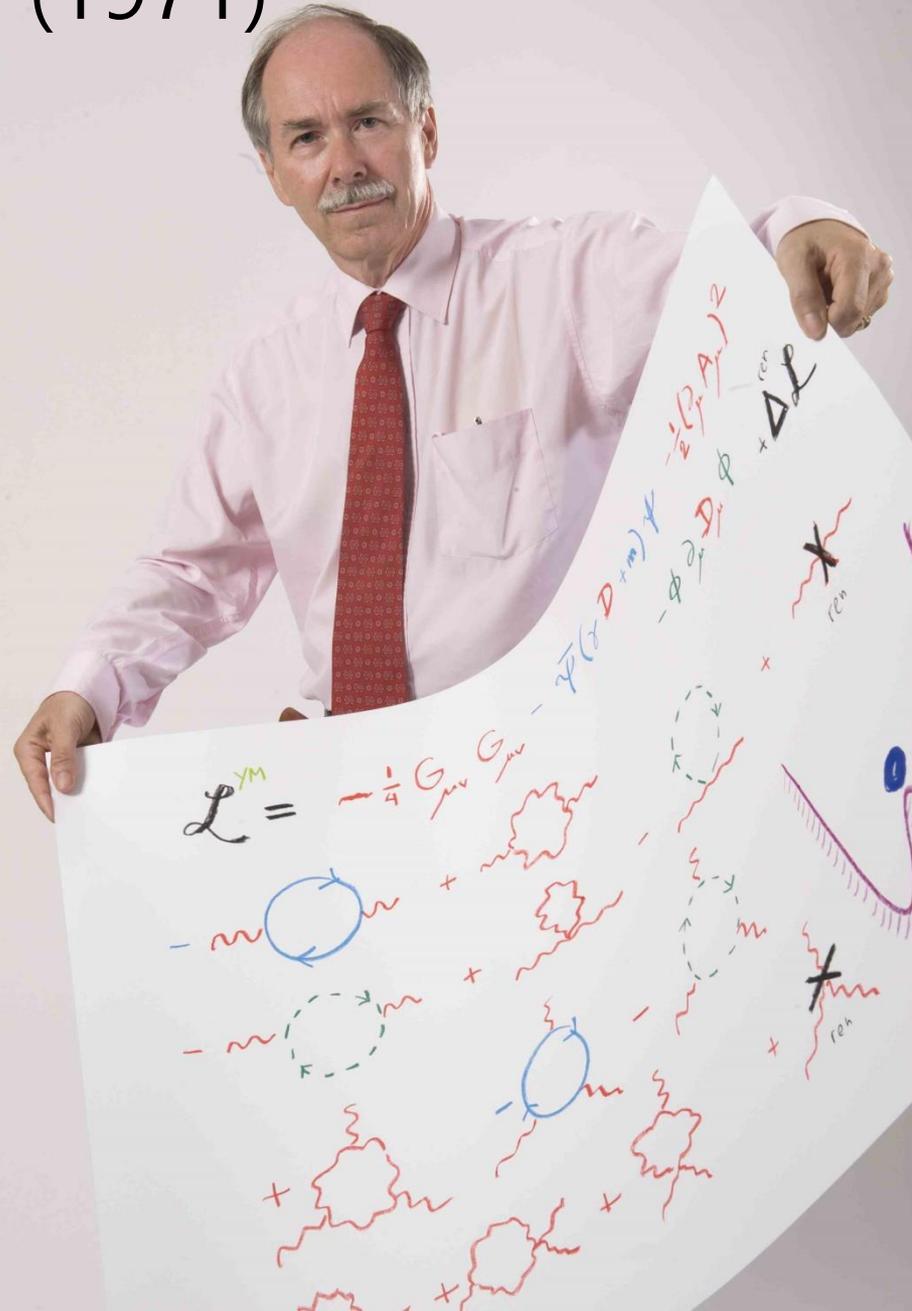
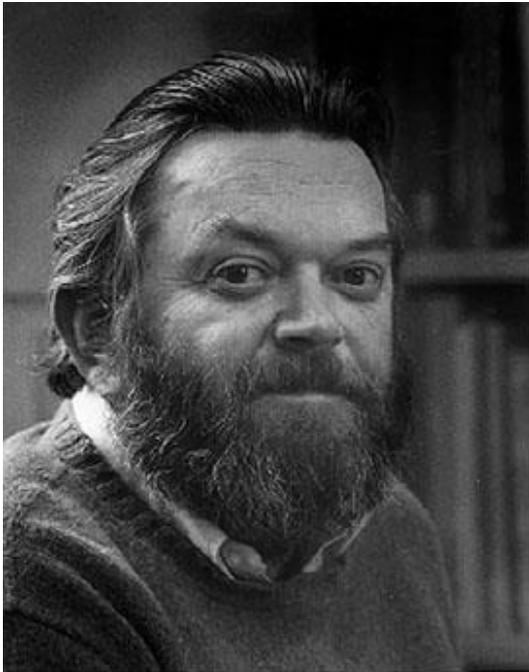
Scanned at the American Institute of Physics

와인버그가 "렙톤 모형"에서 한 일

- 힉스 메커니즘을 electroweak interaction 쪽에 적용한다.
- SU(2)와 U(1) 게이지 대칭성이 섞이고 남은 대칭성이 전자기 역을 나타내는 $U(1)_{EM}$ 이 된다.
- 유가와 상호작용 항을 통해 페르미온과 힉스 보손의 상호작용을 얻는다.
- 힉스 메커니즘의 결과로 유가와 항으로부터 페르미온의 질량을 얻는다.

t 'Hooft-Veltman의 증명 (1971)

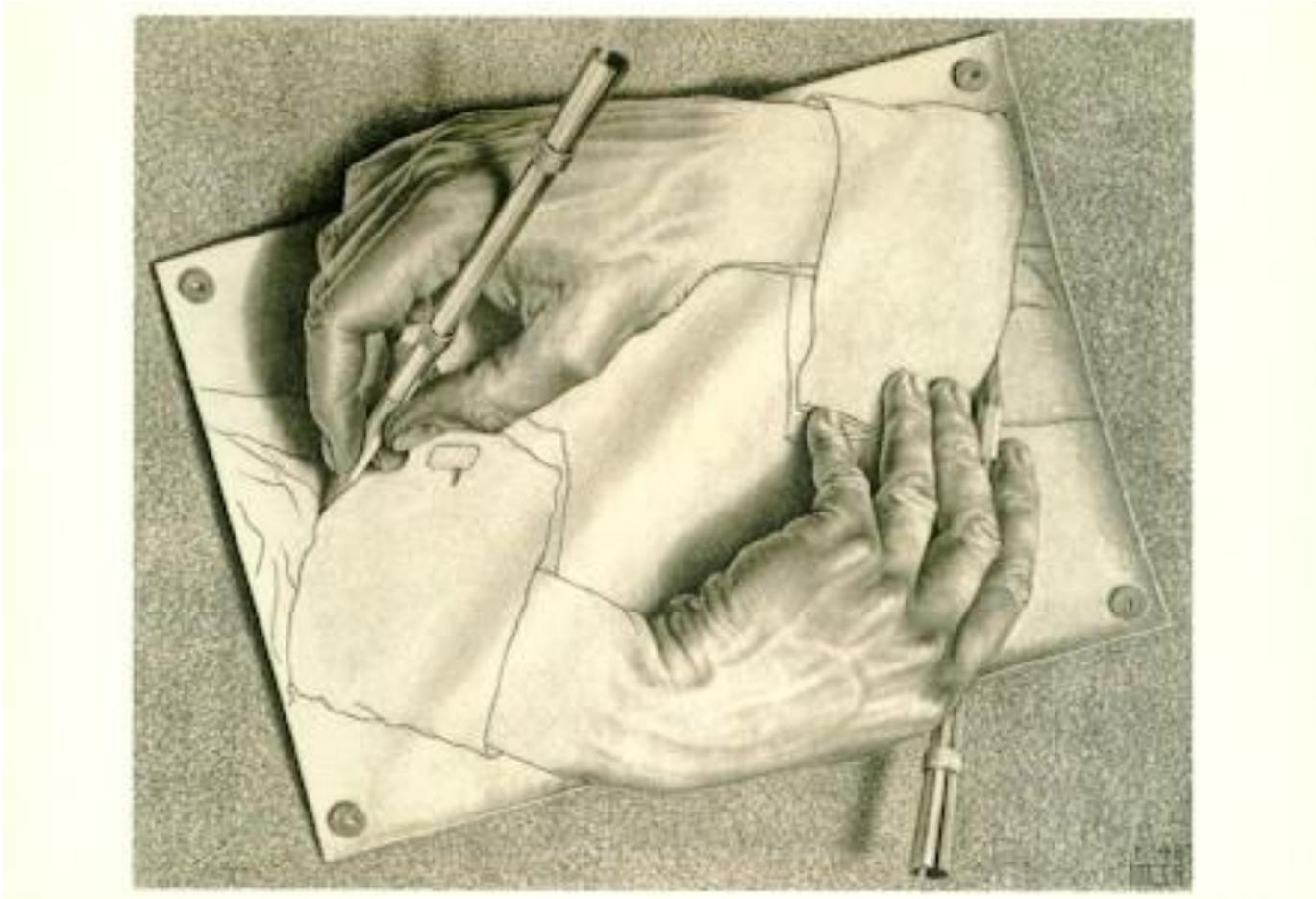
Yang-Mills 이론도
양자역학적으로 다룰 수 있다
(renormalizability).

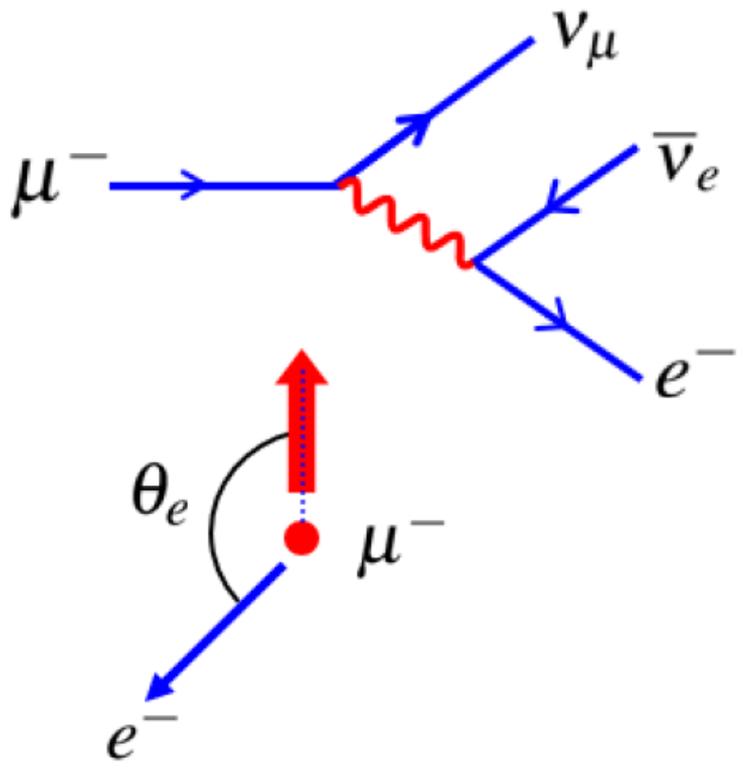
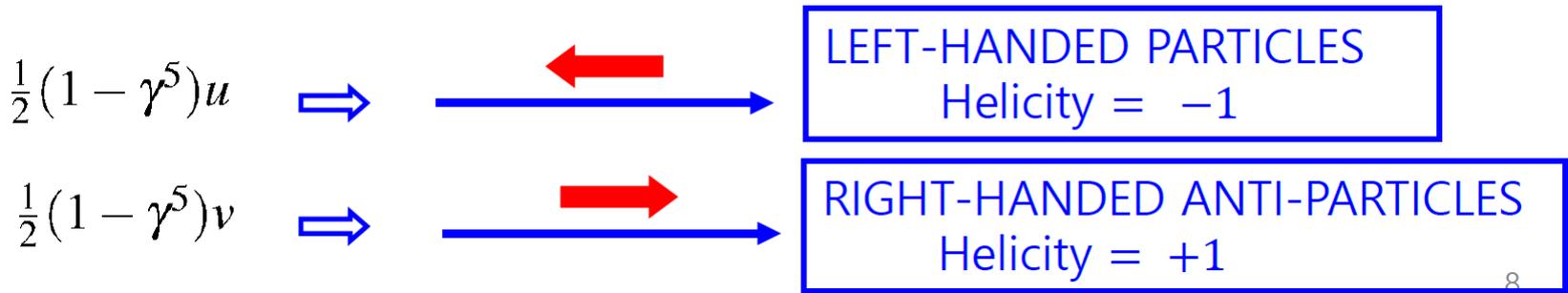


$SU(2)_L \times U(1)_Y$ + 힉스 메커니즘

- 카이랄 이론이다 = 페르미온의 왼쪽 성분과 오른쪽 성분에 다르게 작용한다.
- 힉스 메커니즘에 의해서 게이지 대칭성이 일부 깨져있다 = 게이지 보손의 일부가 질량을 가진다.
- 질량을 가지는 $W^{+/-}$, Z^0 보손과 질량이 없는 전자기장이 게이지 보손으로 존재하고 각각이 약한 상호작용과 전자기력을 전달한다.

카이랄리티 Chirality



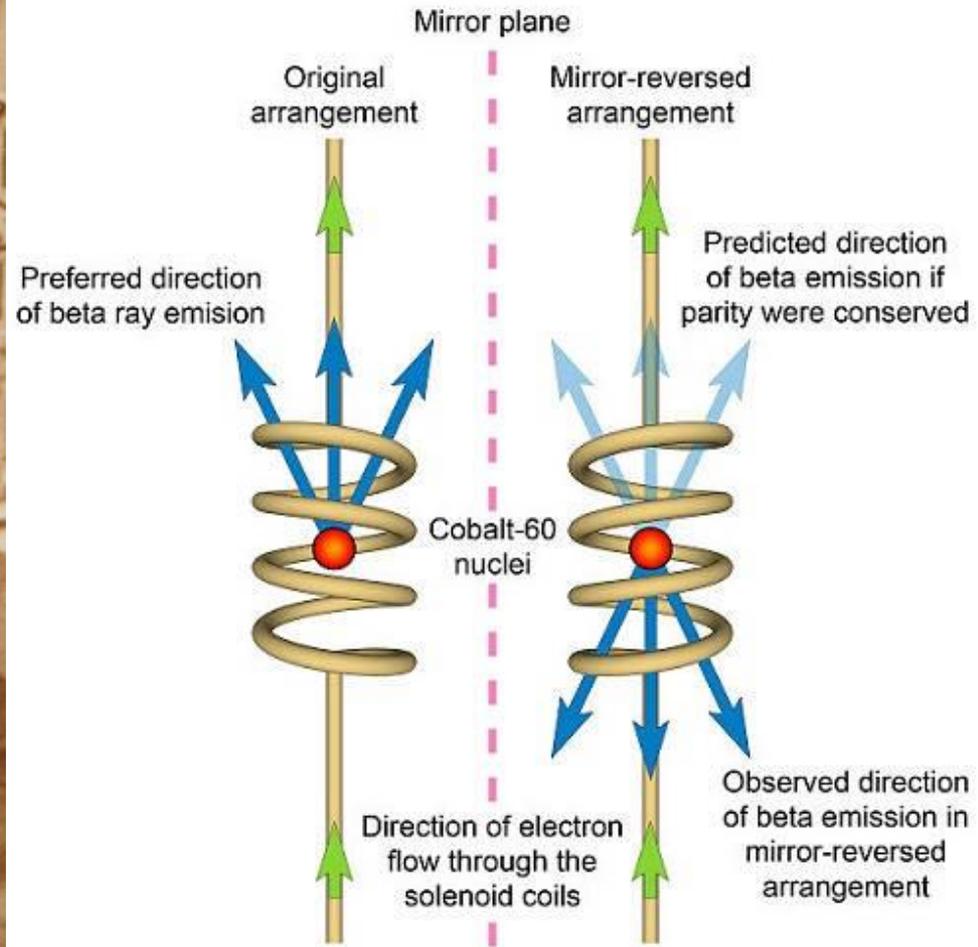
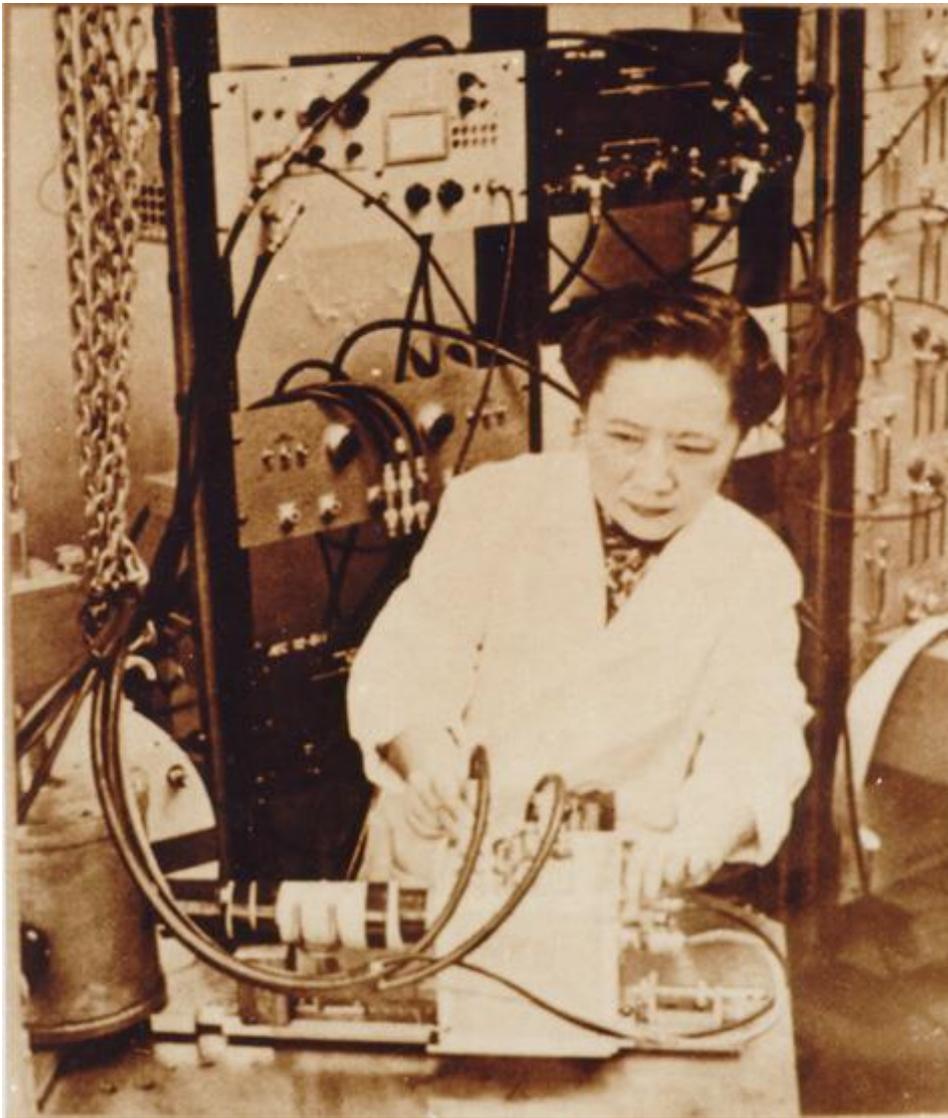


붕괴 후 입자의 방향이 특정한 방향성을 가지게 된다. 뮤온 붕괴의 경우 뮤온의 스핀 방향과 전자의 방향 사이의 관계를 생각할 수 있다.

Parity 붕괴 발견 (1956)



Lee와 Yang이 τ - θ 퍼즐로 알려진 문제를 연구하던 중에 약한 상호작용에서의 패리티 문제를 제시.



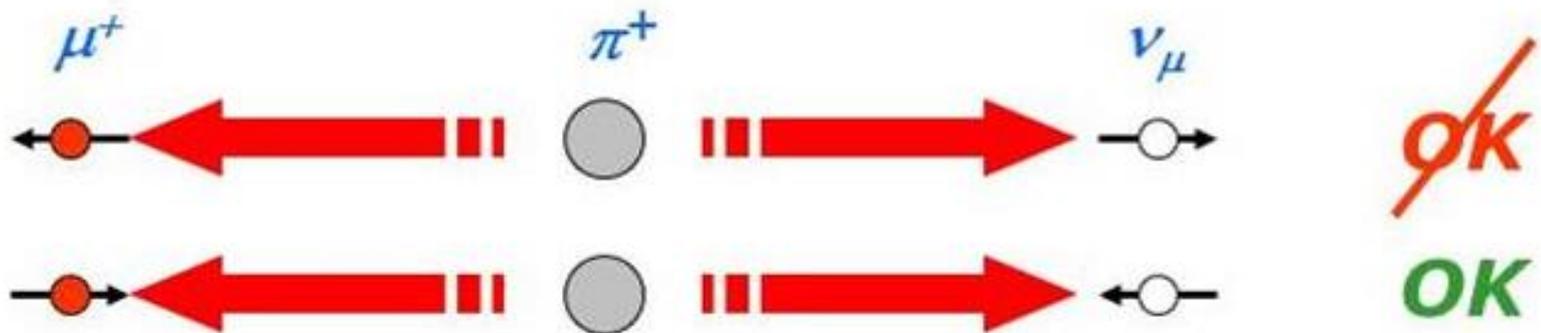
C. S. Wu가 스핀을 정렬시킨 코발트의 베타붕괴에서 방향성을 확인

레더만-가윈

텔레그디-프리드먼

파이온-뮤온 붕괴에서 방향성을 확인

“모든 중성미자는 왼쪽 방향 페르미온이다”

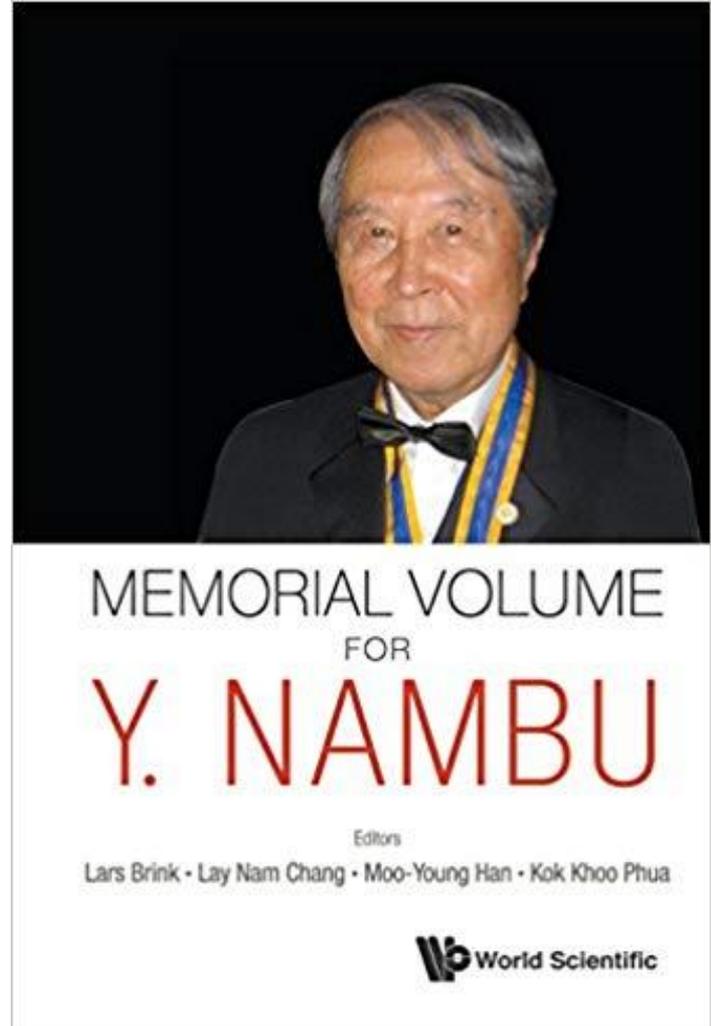


$SU(3)_C$

Quantum Chromodynamics (QCD)

- 쿼크에만 작용한다.
- 게이지 대칭성이 깨지지 않고 그대로 남아있다.
- 상호작용이 매우 크다 = 게이지 결합 상수가 매우 크다.
- $SU(3)_C$ 대칭성의 charge를 color라고 부른다. 왜냐 하면...
- 왜 $SU(3)$ 이냐 하면...

Another SU(3)



Han, Nambu, PRD 139, B1006 (1965)

Δ^{++} (Ω_s) statistic problem:

Spin $J(\Delta^{++})=3/2$ ($L=0$), quark content $|uuu\rangle$

$\rightarrow |\Delta^{++}\rangle = |u\uparrow u\uparrow u\uparrow\rangle$ forbidden by Fermi statistics

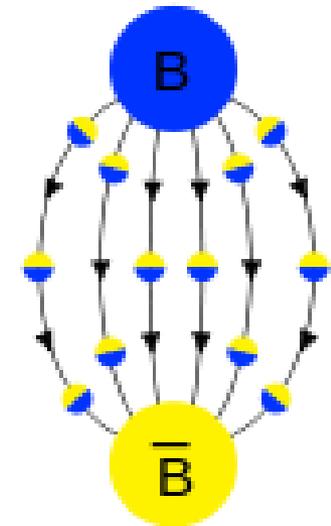
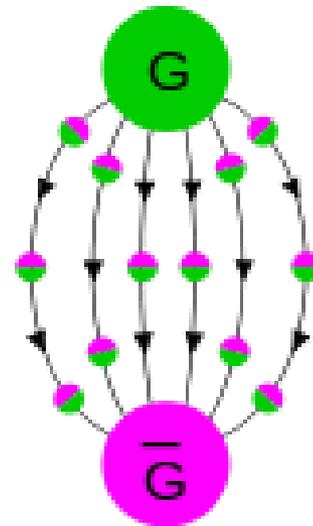
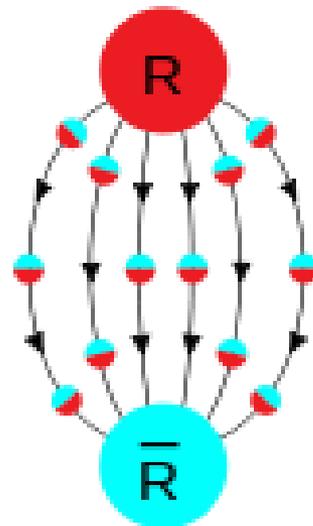
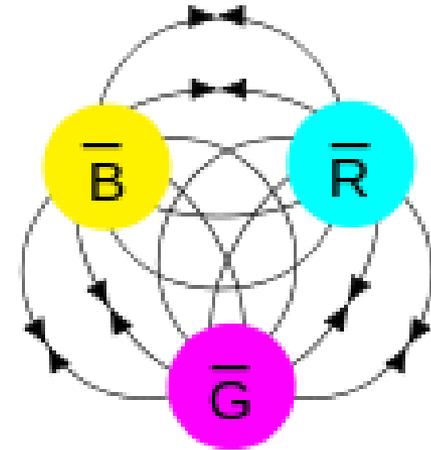
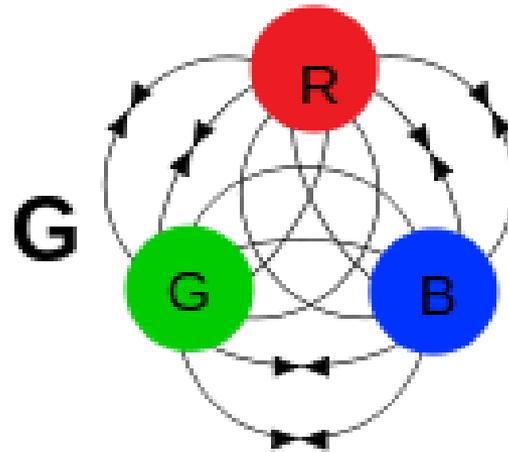
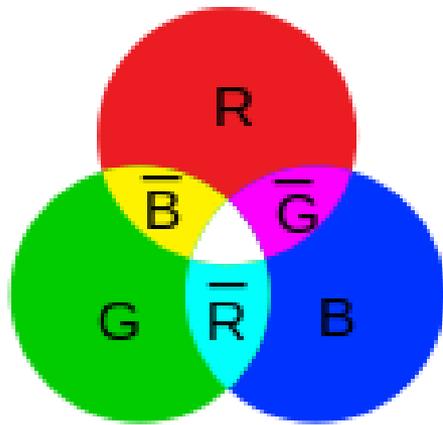
Solution is additional quantum number for quarks (color)

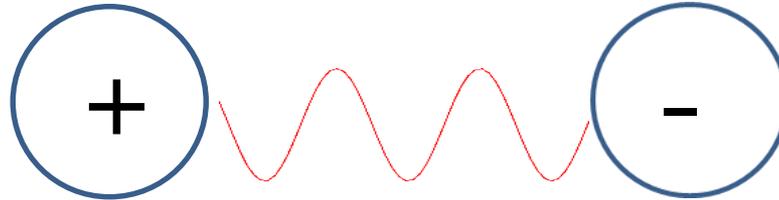
$$|\Delta^{++}\rangle = \frac{1}{\sqrt{6}} \varepsilon_{ijk} |u_i\uparrow u_j\uparrow u_k\uparrow\rangle \quad i, j, k = \text{color index}$$

원자 속 전자의 상태 : 같은 상태에 2개의 전자 \rightarrow 스핀 SU(2)

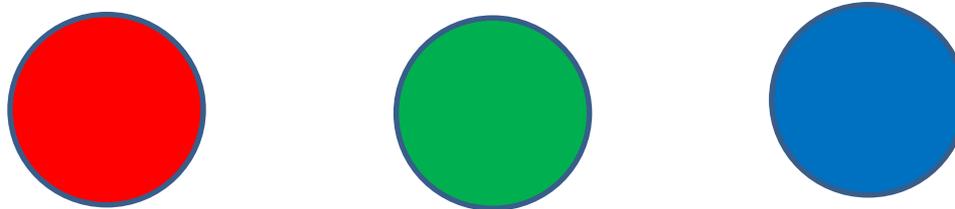
Δ 속 쿼크의 상태 : 같은 상태에 3개의 쿼크 \rightarrow 컬러 SU(3)

Color=SU(3) charge의 구조





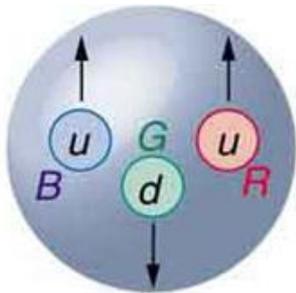
QED vs. QCD



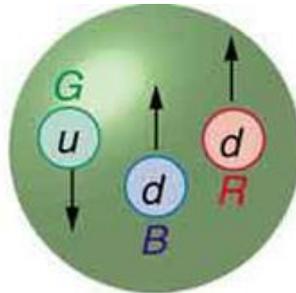
세 종류의 성질이 존재한다면?

하드론 (hadron):

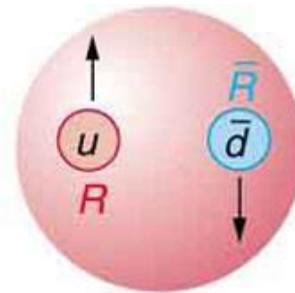
- 쿼크가 강한 상호작용에 의해 결합해서 만들어진 color-singlet / -octet 입자
- 페르미온인 하드론 : 바리온 baryon, 상대적으로 무거움
- 보손인 하드론 : 메손 meson, 상대적으로 가벼움.



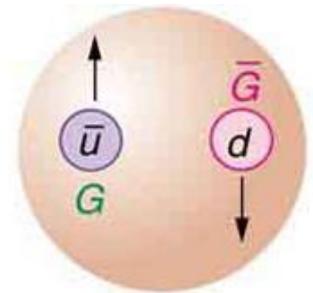
Proton



Neutron

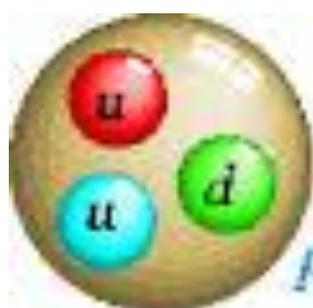


π^+

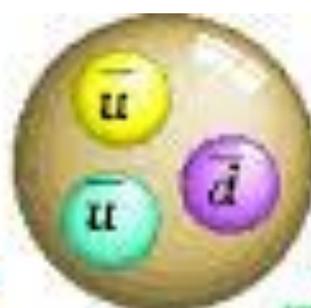


π^-

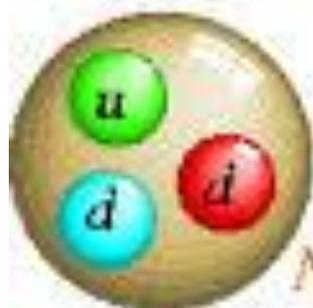
Spin	$\frac{1}{2} + \frac{1}{2} - \frac{1}{2} = \frac{1}{2}$	$-\frac{1}{2} + \frac{1}{2} + \frac{1}{2} = \frac{1}{2}$	$+\frac{1}{2} - \frac{1}{2} = 0$	$+\frac{1}{2} - \frac{1}{2} = 0$
Charge	$+\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1$	$+\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$	$+\frac{2}{3} + \frac{1}{3} = +1$	$-\frac{2}{3} - \frac{1}{3} = -1$



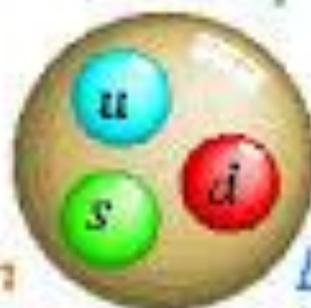
Proton



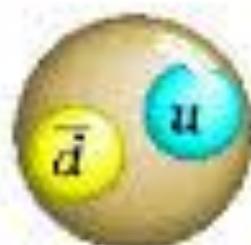
Anti-proton



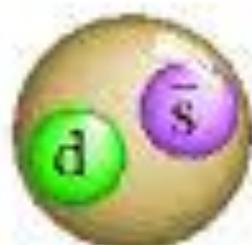
Neutron



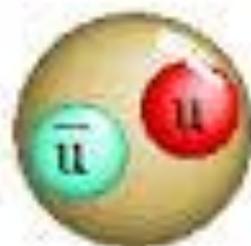
Lambda



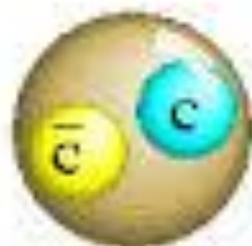
π^+



K^0

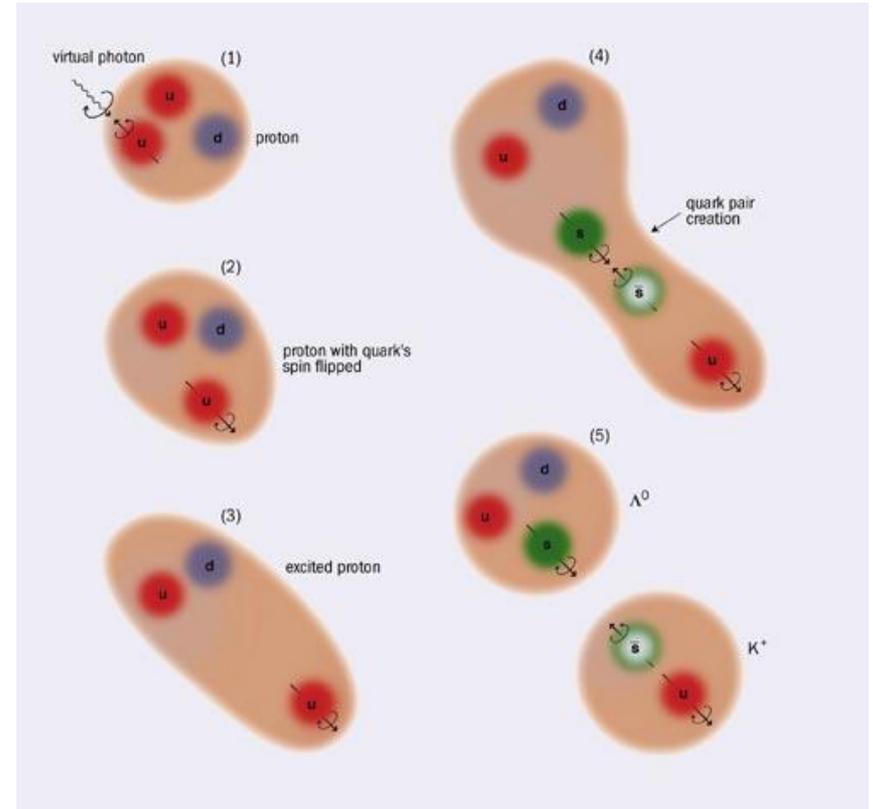
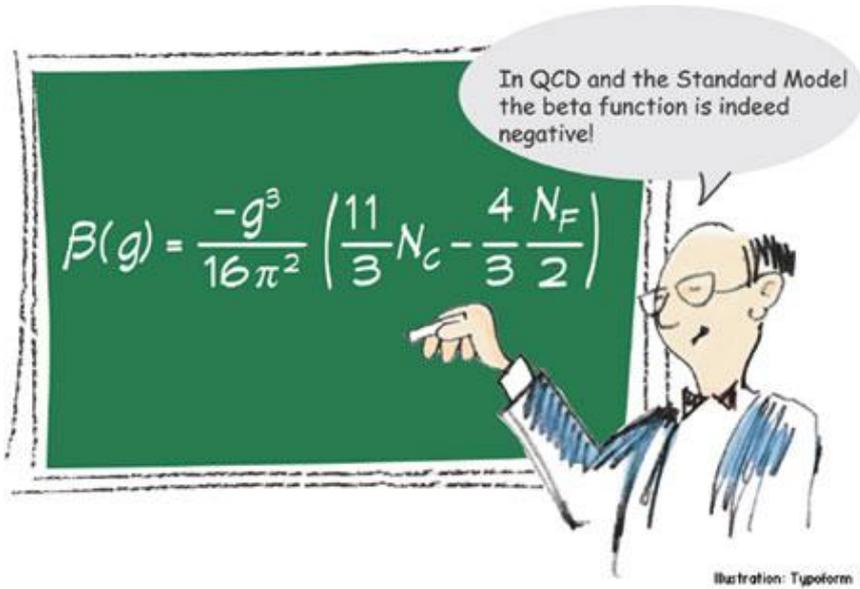


π^0



J/ψ

쿼크는 왜 보이지 않는가?



쿼크는 멀어질수록 더 강하게 끌어당기기 때문에 혼자 있지 못하고 하드론 상태로만 존재한다.

표준모형 (gauge structure) :

- 쿼크와 렙톤의 상호작용을 기술하는 이론
- $SU(3)_C \times SU(2)_L \times U(1)_Y$ 게이지 양자 장 이론으로, 강한 상호작용, 약한 상호작용, 전자기 상호작용을 설명함.
- 힉스 메커니즘에 의해 $SU(2)_L \times U(1)_Y$ 게이지 대칭성이 깨져서 $U(1)_{EM}$ 만 남고, W, Z 게이지 보손이 질량을 가짐.
- 유가와 상호작용으로 페르미온과 힉스 보손의 상호작용을 기술하며, 힉스 메커니즘에 의해 페르미온이 질량을 가짐.

입자가 존재하는 방식

렙톤 : (ν, e)

쿼크 : (u, d) (u, d) (u, d)

힉스 보손 : (H^+, H^0)

- SU(2) 이중항
- SU(3) 단일항 / 삼중항
- U(1) hypercharge – 단순 숫자, 제한?

표준모형 라그랑지안 쓰기

$$\begin{aligned}
\mathcal{L} = & -\frac{1}{4}G_{\mu\nu}^a G^{a\mu\nu} - \frac{1}{4}W_{\mu\nu}^i W^{i\mu\nu} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu} & i, j = 1, 2, 3 \\
& + i\bar{q}_L^i \gamma^\mu D_\mu q_L^i + i\bar{u}_R^i \gamma^\mu D_\mu u_R^i + i\bar{d}_R^i \gamma^\mu D_\mu d_R^i + i\bar{l}_L^i \gamma^\mu D_\mu l_L^i + i\bar{e}_R^i \gamma^\mu D_\mu e_R^i \\
& + (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2 \\
& + Y_{ij}^d \bar{q}_L^i \phi d_R^j + Y_{ij}^u \bar{q}_L^i \tilde{\phi} u_R^j + Y_{ij}^e \bar{l}_L^i \phi e_R^j + h. c.
\end{aligned}$$

(Before Electroweak Symmetry Breaking)

주어진 (게이지) 대칭성을 만족하는

스핀이 0, 1/2, 1인 입자들의 가능한 모든 상호작용 항

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \chi_i Y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

Physical State로 표준모형 라그랑지안 쓰기

CHECK! But...

Flavour Structure (경험적 지식) :

- 쿼크 vs. 렙톤 : 강한 상호작용을 하는/안 하는 페르미온
- flavor : 입자의 종류 (e.g. 전자, c 쿼크, ...)
- SU(2) 이중항으로 존재 : "Flavourdynamics"
- generation 이라는 개념, 한 세트의 쿼크와 렙톤
- 3 generation이 존재 ← 원리?
- generation 사이의 섞임이 존재 → 새로운 개념 등장

Flavour 사이의 섞임에 관하여

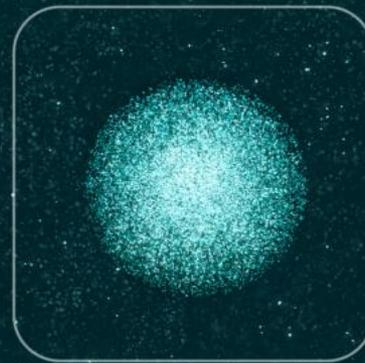
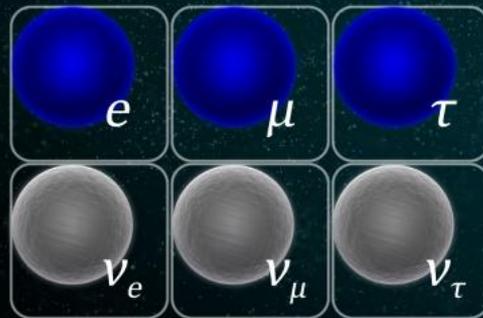
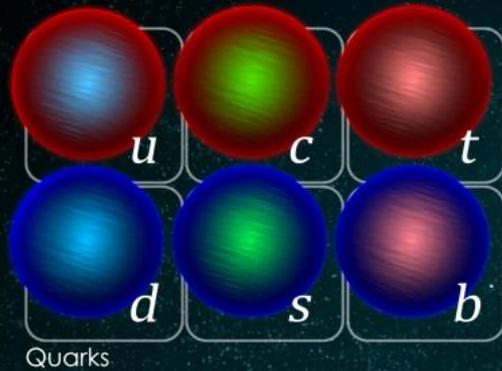
- 유가와 항의 문제
- 쿼크 vs. 렙톤 : 섞임이 없음 (charge? New symmetry?)
- 렙톤 generation : 섞임이 없음 (\because 중성미자 질량이 없음)
- 쿼크 generation : 일반적으로 섞임 CKM 섞임 행렬
- 2 generation 섞임 \rightarrow 실수 행렬 (1개의 각도)
- 3 generation 섞임 \rightarrow 복소수 행렬 (3 각도, 1 위상) \rightarrow **CP 깨짐**

- Physical state란 무엇인가?
- 양자역학에서 basis를 바꾼다는 것.
- Gauge eigenstate vs. Flavour eigen state.
- 게이지 보손 섞임, 쿼크 섞임, 중성미자 진동.

중성미자 문제

- 원래의 (Weinberg의) 표준모형에서는 Left-handed fermion만 존재 (관측 결과), R-handed part decoupled.
- 질량이 0 (질량항이 존재하지 않음).
- 렙톤에는 섞임이 존재하지 않음.
- 중성미자 진동을 실험적으로 확인 (1998~)
 - 중성미자 질량 존재
 - 렙톤 (중성미자) 섞임, PMNS 행렬
- 중성미자 질량을 어떻게 (이론적으로) 구현할 것인가?
- 중성미자 질량을 어떻게 (실험적으로) 측정할 것인가?

최종적으로



전자란...

- 질량 = $0.5109989461 \pm 0.00000000031 \text{ MeV}/c^2$
- 전하 = -1
- T3 = -1/2
- 칼라 = 0
- 스핀 = 1/2

이 숫자들은...

중력 : 우주를 움직이는 힘

$$\vec{F} = -G \frac{m_1 m_2}{r^2} \hat{r}$$

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

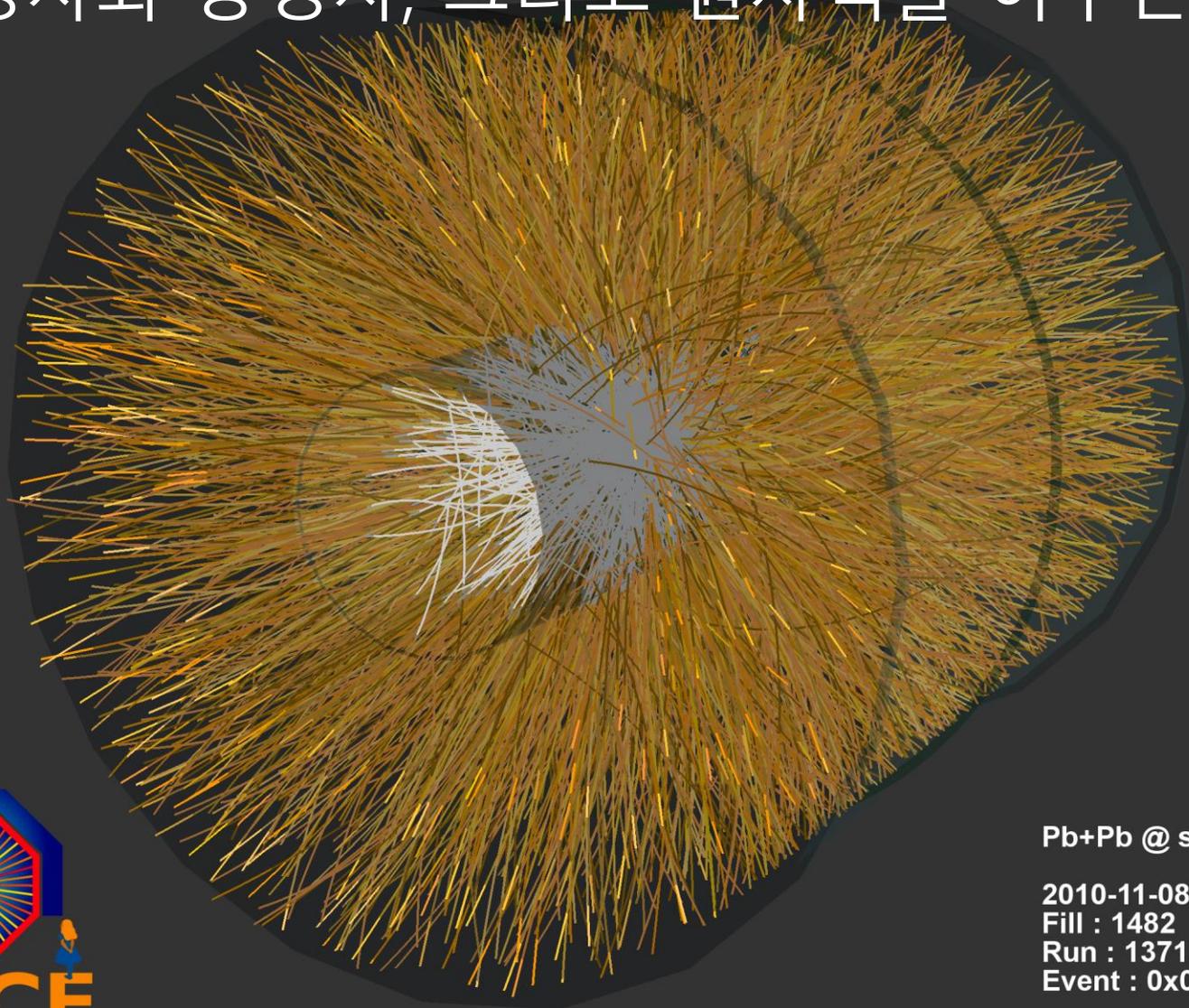
전자기력

: 원자를 이루고 우리의 일상을 지배하는 힘



강한 상호작용

: 양성자와 중성자, 그리고 원자핵을 이루는 힘



Pb+Pb @ $\sqrt{s} = 2.76$ ATeV

2010-11-08 11:30:46

Fill : 1482

Run : 137124

Event : 0x00000000D3BBE693

- 질량 = $0.5109989461 \pm 0.00000000031 \text{ MeV}/c^2$

- 전하 = -1

- T3 = $-\frac{1}{2}$

- 칼라 = 0

전자가 네 가지 힘을 느끼는 정도

- 스핀 = $\frac{1}{2}$

3+1 시공간에서의 존재 방식

상호작용이 존재를 결정한다!

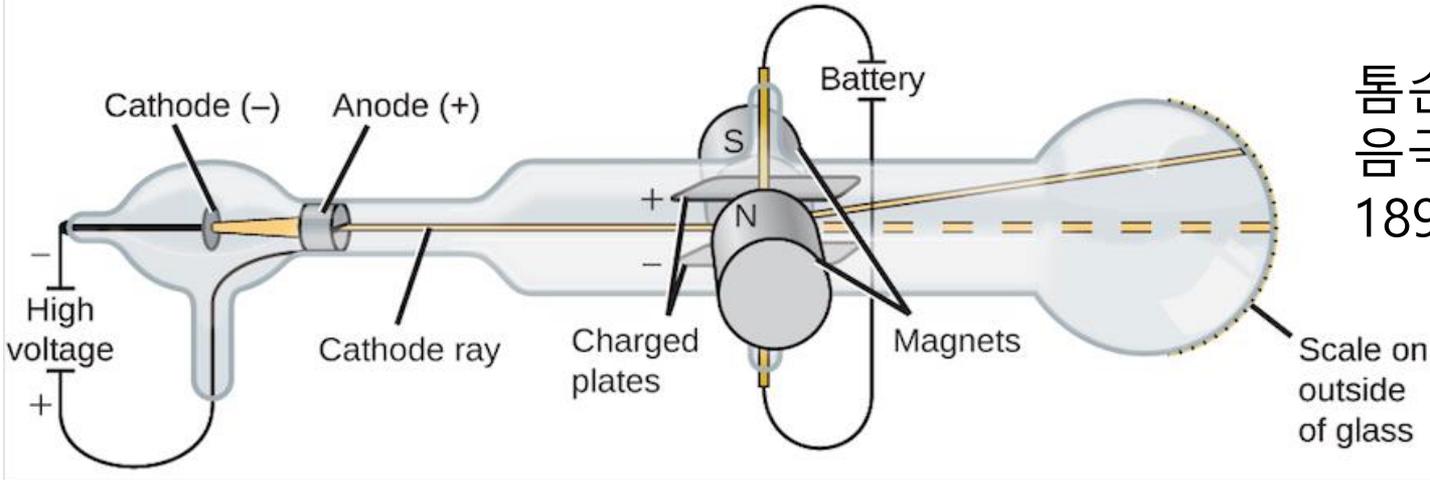
Part IV Experimental Verification

Particle Discovery

Particle Discovery Timeline, Before the SM

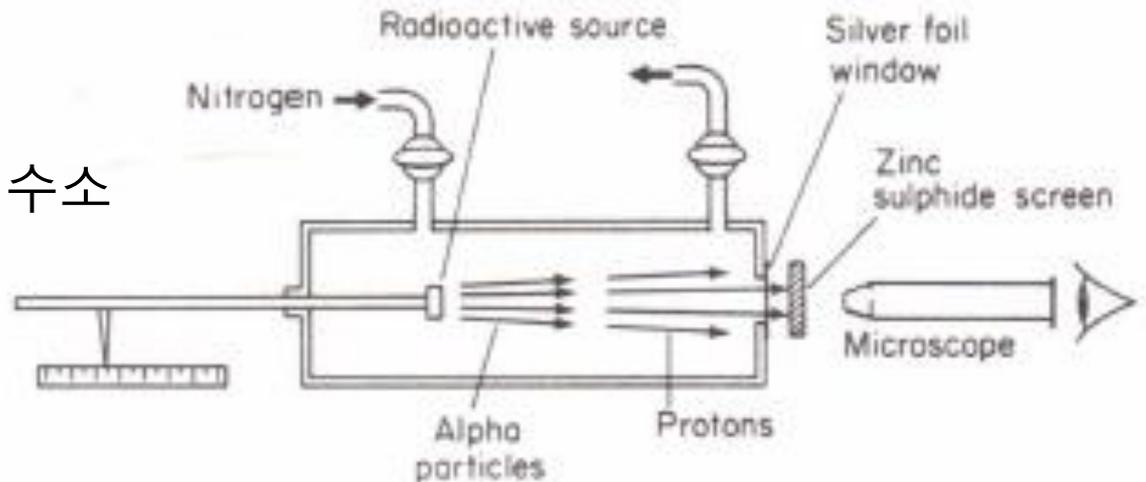
- 1897 전자 by J. J. Thompson
- 1919 양성자 by E. Rutherford
- 1928(?) 광자 by M. Planck, A. Einstein, A. Compton
- 1932 중성자 by J. Chadwick
- 1932 양전자 by C. Anderson
- 1936 뮤온 by C. Anderson, S. Neddmeyer
- 1947 파이온 by C. F. Powell
- 1947 케이온 by G. D. Rochester, C. C. Butler
- Many many hadrons in 50s and 60s ...
- 1956 (전자)중성미자 by C. Cowan, F. Reines
- 1962 뮤온중성미자 by Lederman, Schwartz, Steinberger
- 1968 (업,다운)쿼크 by Taylor, Friedman, Kendall

전자와 양성자

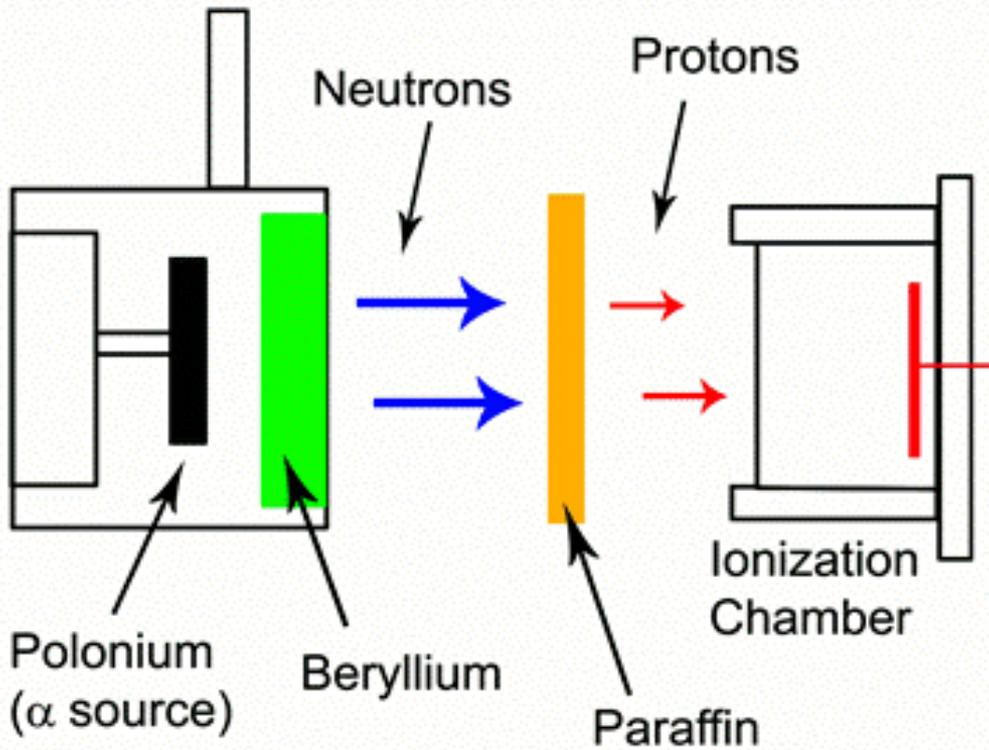


톰슨 (J. J. Thomson)
음극선의 e/m 측정
1897, 케임브리지

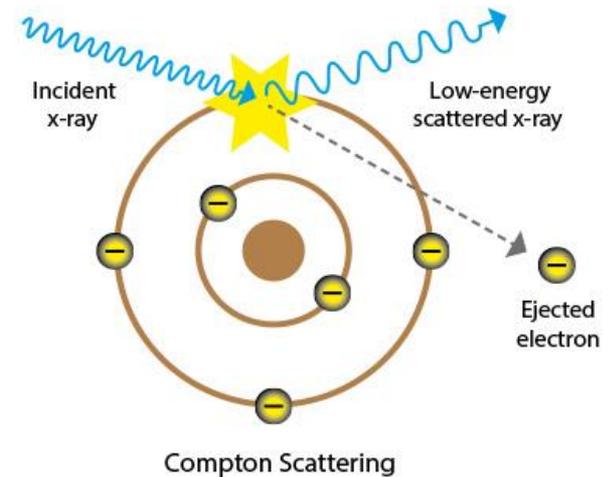
러더퍼드 (E. Rutherford)
알파선 + 질소 \rightarrow 산소 + 수소
1919, 맨체스터



중성자



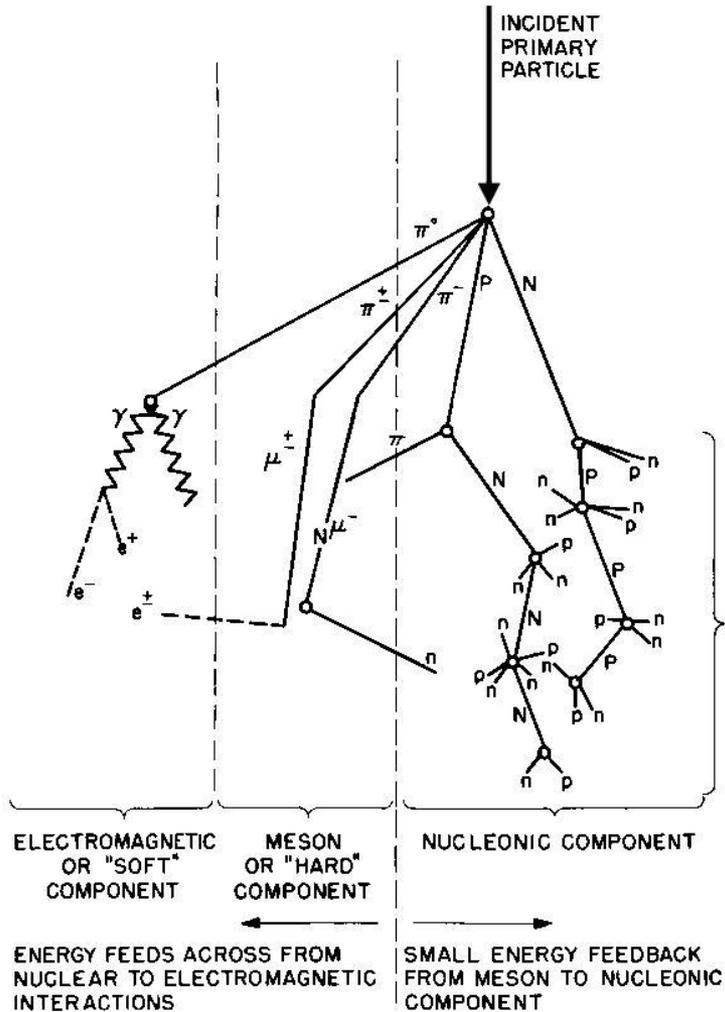
보테 (W. Bothe) 1930
졸리오퀴리 부부
(F. & I. Joliot-Curie) 1932
채드윅 (J. Chadwick) 1932



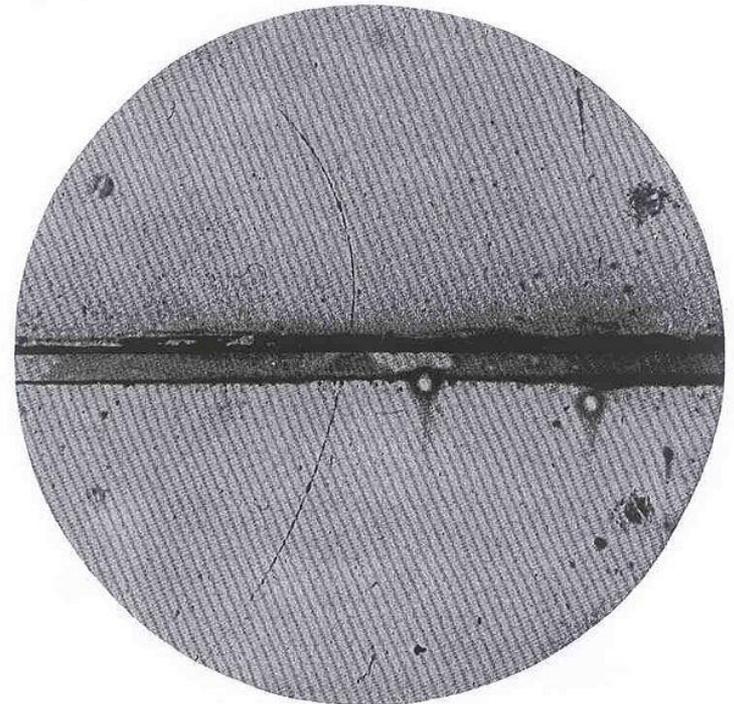
Cf. 콤프턴 산란과의 비교

양전자와 뮤온

앤더슨 (C. Anderson)
우주선 cosmic ray을 통해 새로운 입자를 발견.
1932 (양전자), 1936 (뮤온)

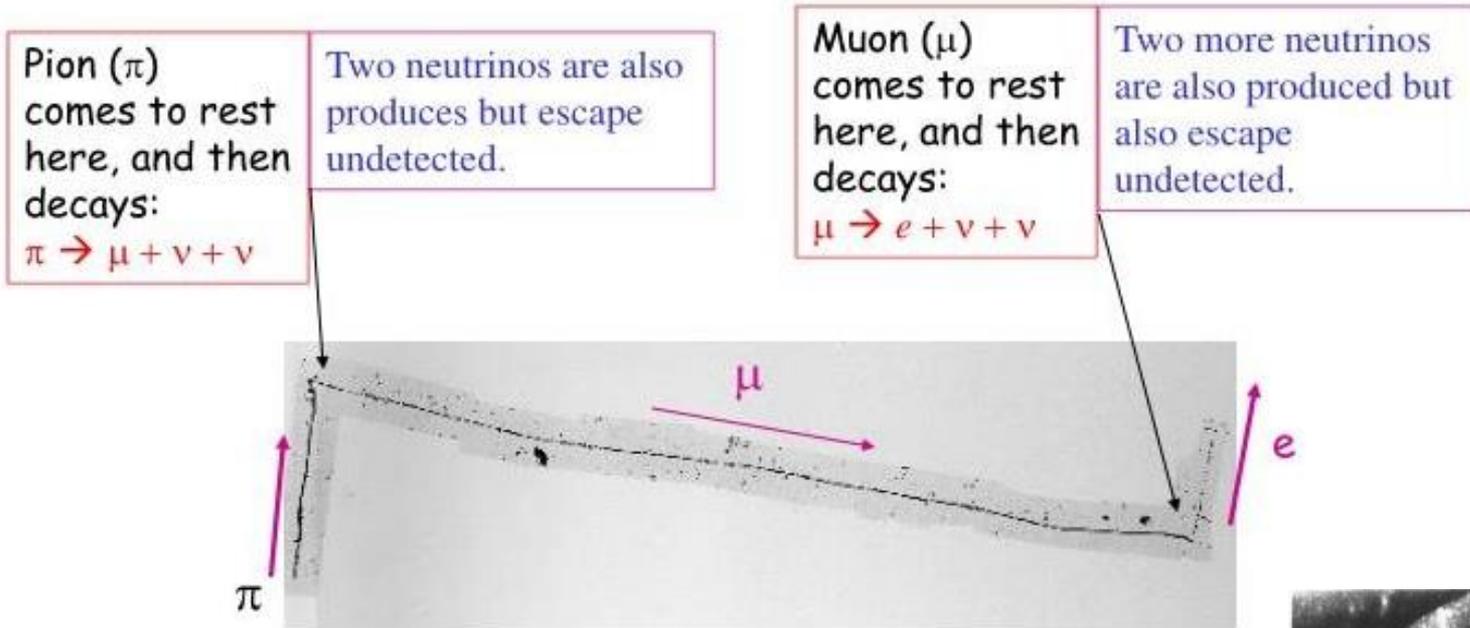


LOW ENERGY NUCLEONIC COMPONENT
(DISINTEGRATION PRODUCT NEUTRONS DEGENERATE TO "SLOW" NEUTRONS)



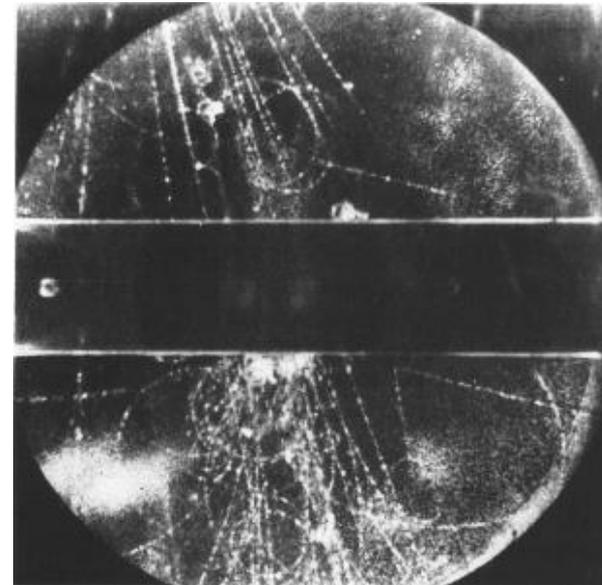
Schematic Diagram of Cosmic Ray Shower

파이온과 케이온

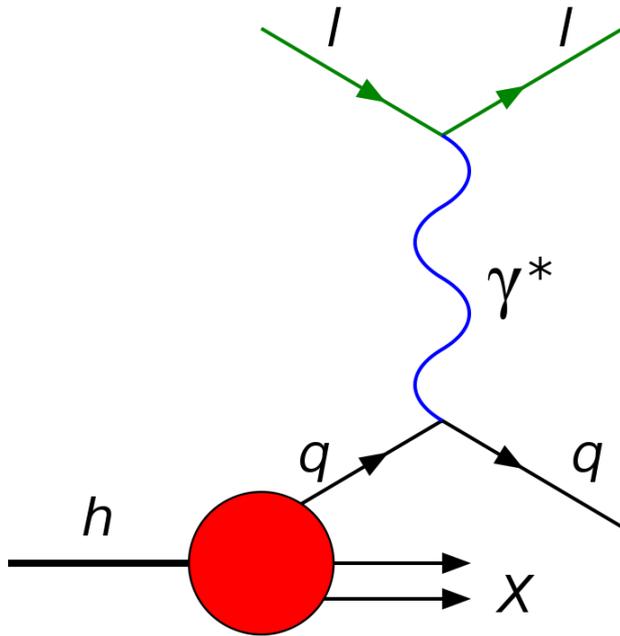


파웰 (C. T. Powell), 오키알리니 (G. Occhialini)
전기를 띤 파이온 발견
1947, 브리스톨

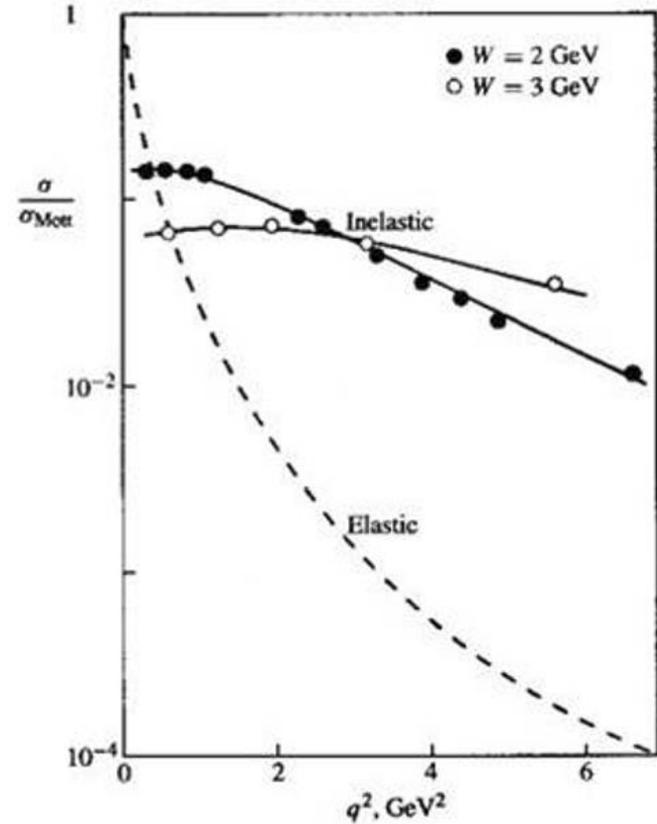
로체스터 (G. D. Rochester), 버틀러 (Cl. C. Butler)
V자 궤적으로부터 케이온 발견
1947, 맨체스터



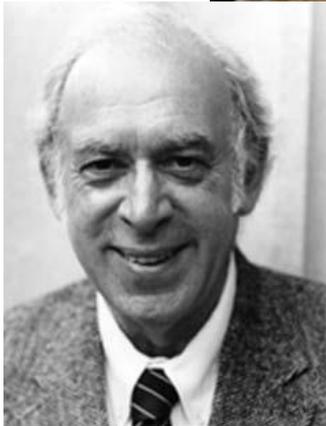
쿼크 (양성자 속의 점입자)



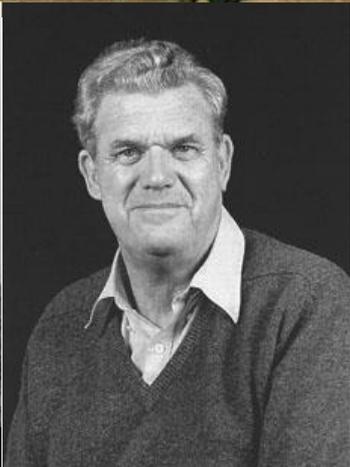
Deep inelastic scattering
SLAC, 1968



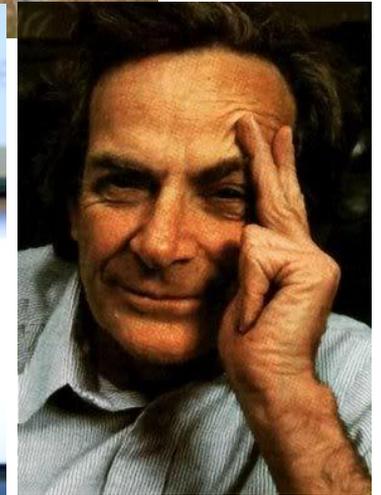
Early SLAC measurements of the inelastic electron-proton scattering cross-section divided by the Mott (pointlike) cross-section, for two values of the invariant mass W of the hadronic final state. The ratio is seen to be only weakly q^2 -dependent, in contrast with the strong q^2 dependence of the elastic scattering process.



Scanned at the American Institute of Physics



Scanned at the American Institute of Physics

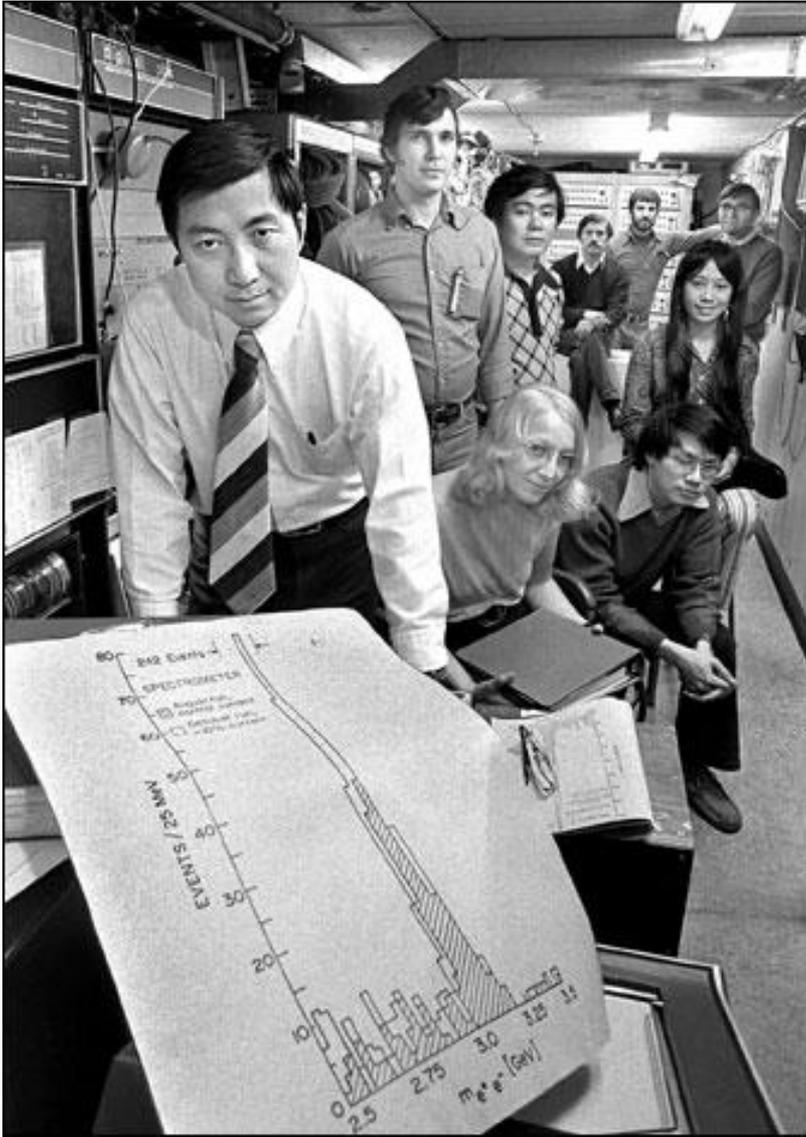


Particle Discovery Timeline, After the SM

- 1974 참 쿼크 by B. Richter, S. Ting
- 1975 타우 렙톤 by M. L. Perl
- 1977 보텀 쿼크 by L. M. Lederman
- 1979 글루온 by TASSO collaboration
- 1983 W와 Z 보손 by C. Rubbia
- 1995 톱 쿼크 by CDF and D0 collaboration
- 2000 타우 중성미자 by DONUT collaboration
- 2012 힉스 보손 by CMS and ATLAS collaboration

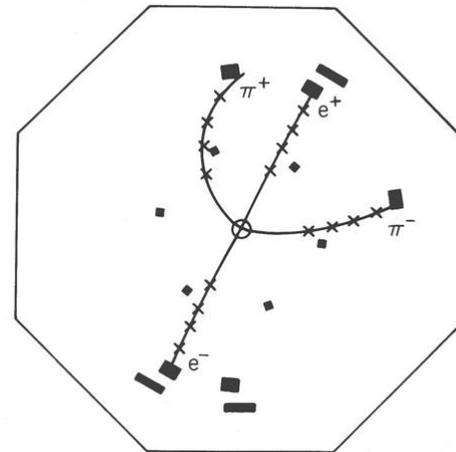
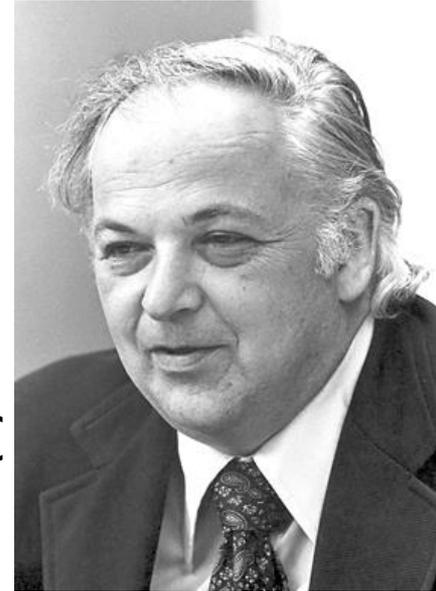
SM finalized!

참 쿼크의 발견 (1974) : November Revolution



Ting at BNL

Richter at SLAC



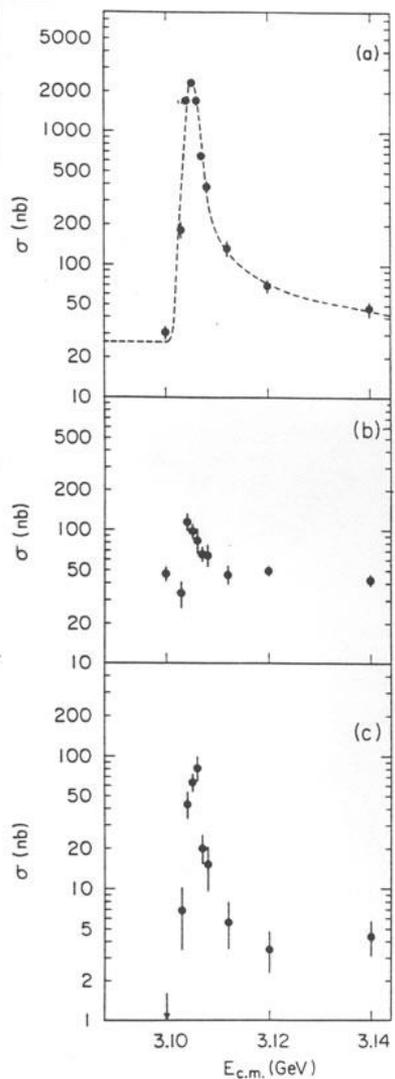


FIG. 1. Cross section versus energy for (a) multi-pion final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, π^+ , and K^+K^- final states. The curve in (a) is the expected shape of a δ -function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b)

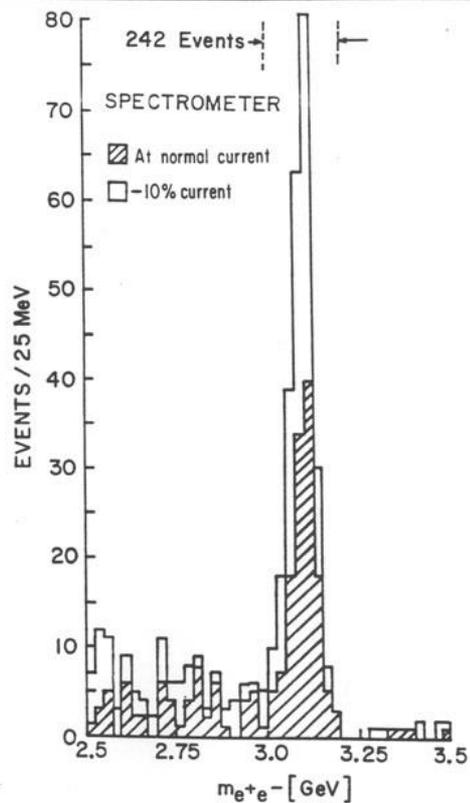
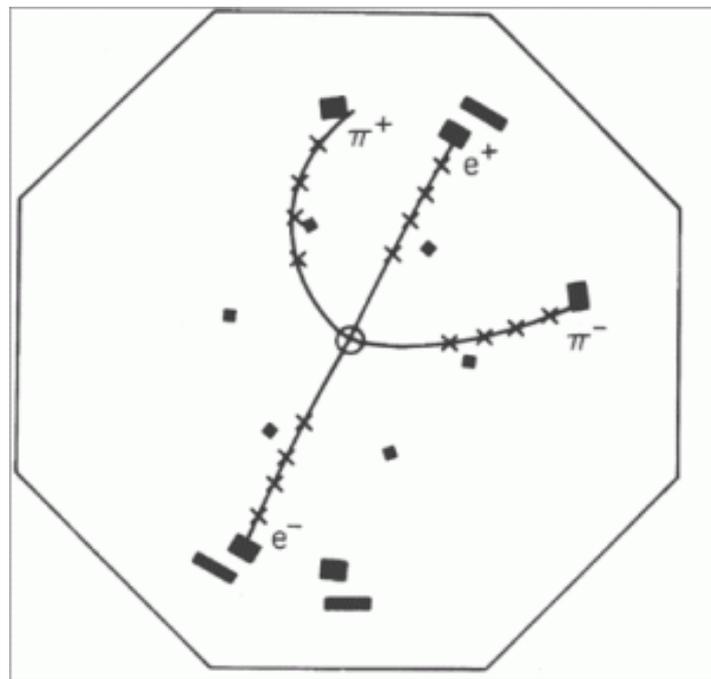


FIG. 2. Mass spectrum showing the existence of J . Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.



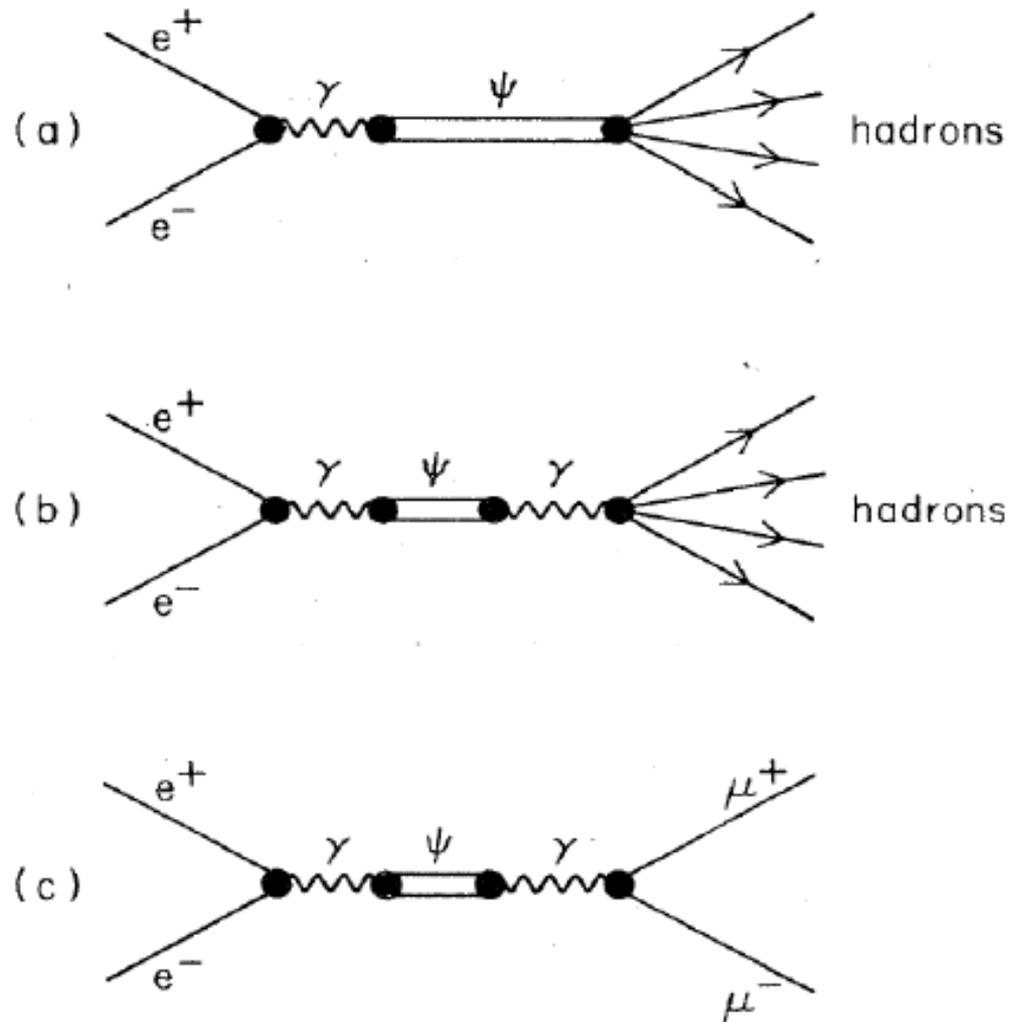
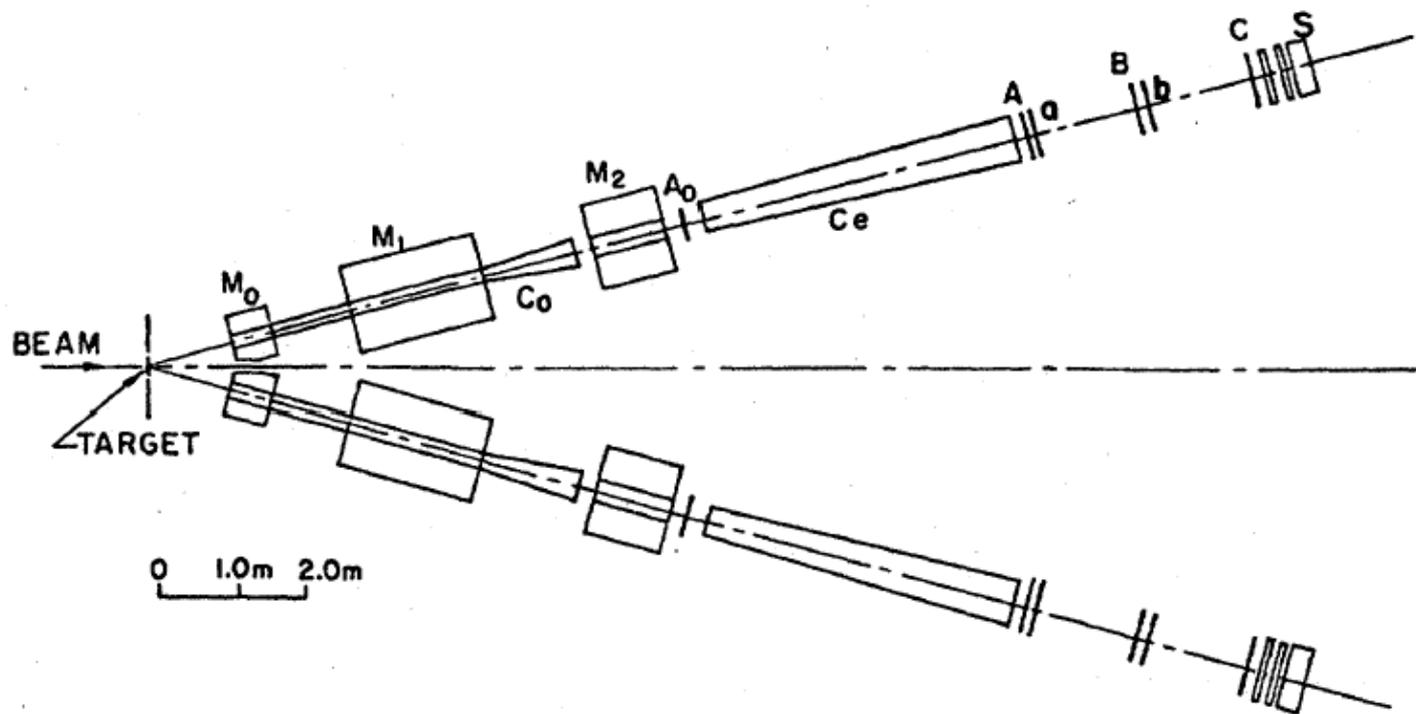


Figure: Feynman diagrams for ψ production and decay.



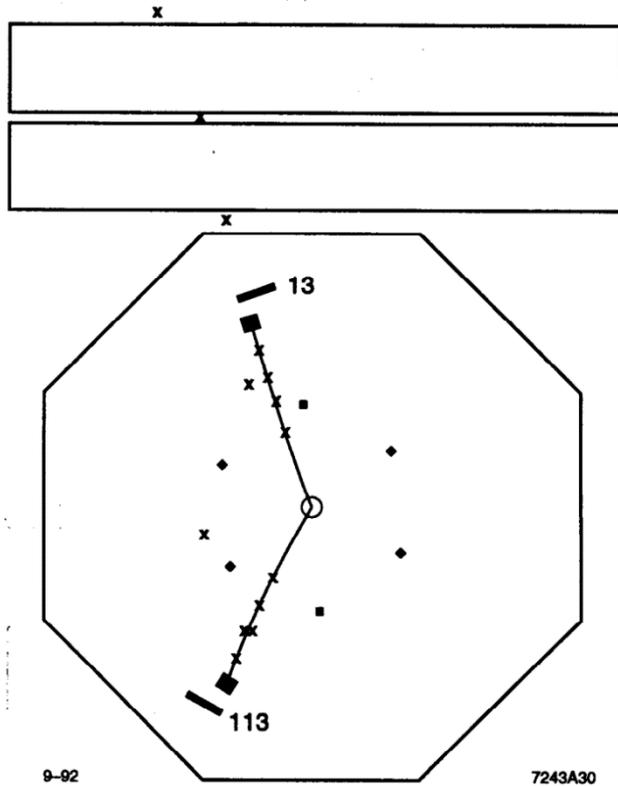
(a) Plan view

Figure: "Schematic diagram of the experimental setup for the double-arm spectrometer." [5]



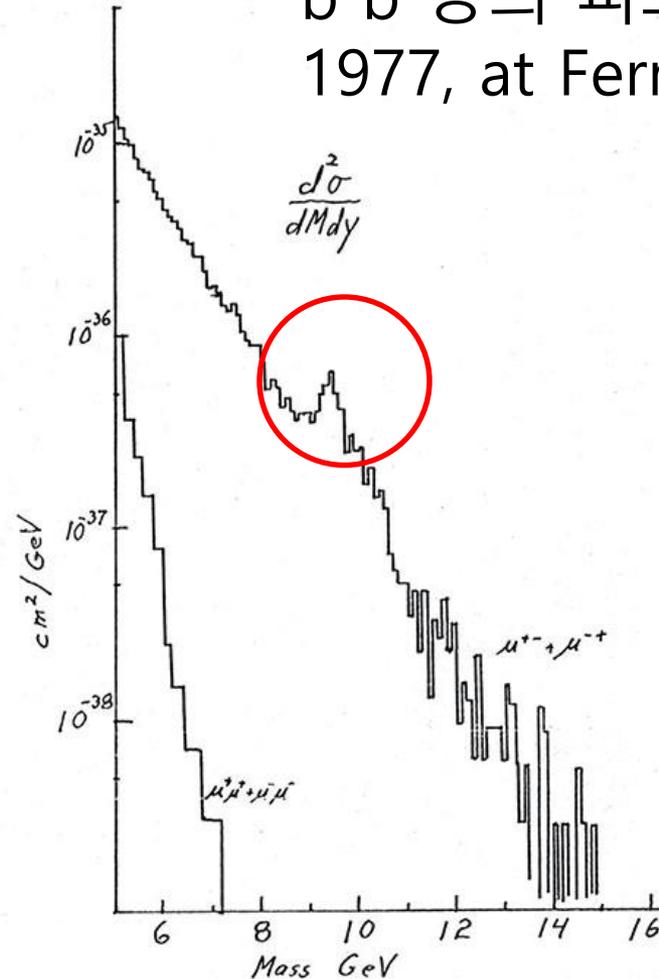
B. Richter and S. C. C. Ting

세 번째 세대의 등장



펄(M. Perl)
전자-뮤온 쌍 관측
1975, at SPEAR, SLAC

레더먼(L. Lederman)
b b 쌍의 피크 관측
1977, at Fermilab



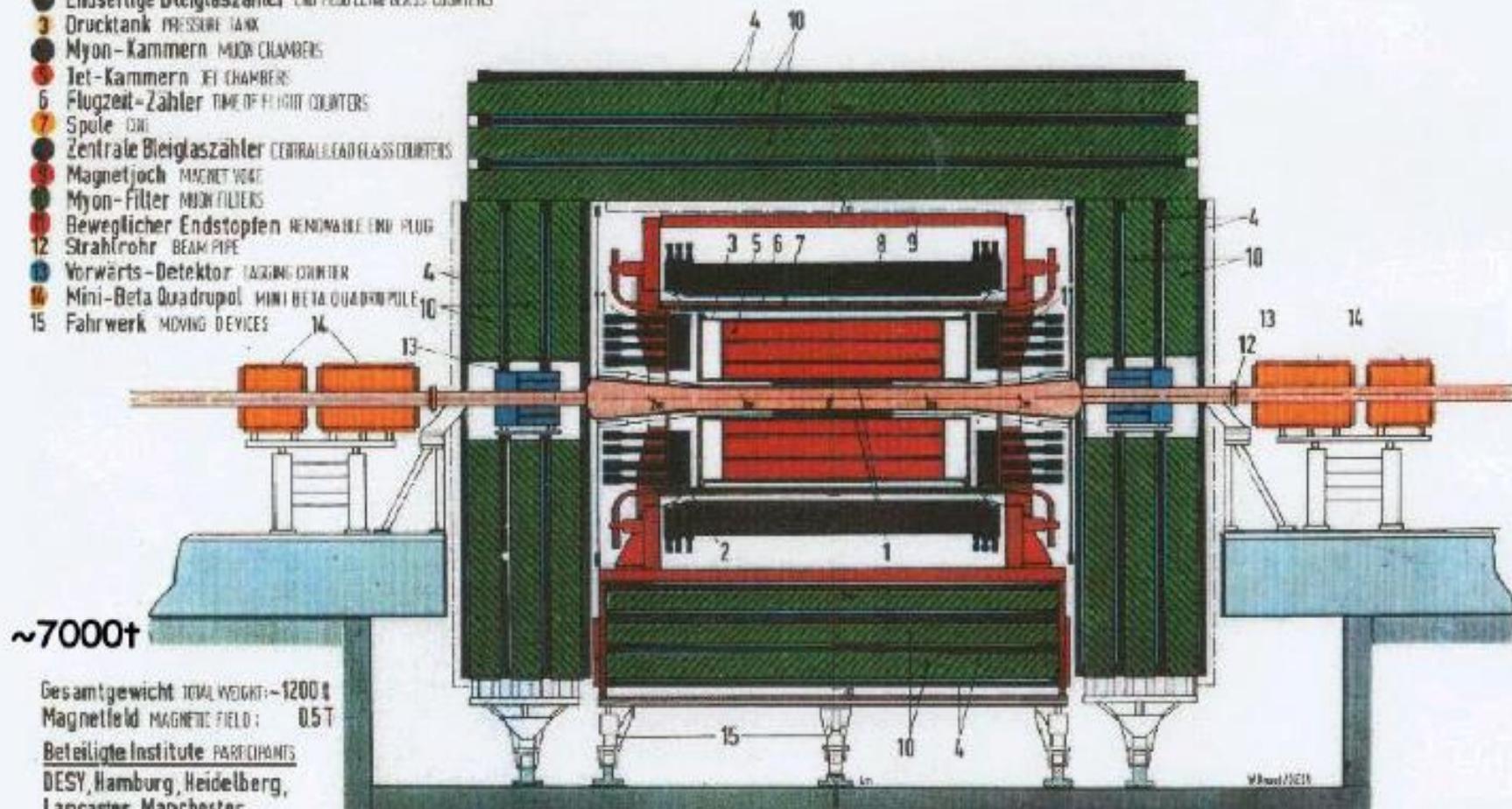
독일 DESY 가속기 연구소



Example: JADE detector

MAGNETDETEKTOR **JADE** MAGNET DETECTOR

- 1 Strahlrohrzähler BEAM PIPE COUNTERS
- 2 Endseitige Bleiglaszähler END PLUG LEAD GLASS COUNTERS
- 3 Drucktank PRESSURE TANK
- 4 Myon-Kammern MUON CHAMBERS
- 5 Tet-Kammern TET CHAMBERS
- 6 Flugzeit-Zähler TIME OF FLIGHT COUNTERS
- 7 Spule COIL
- 8 Zentrale Bleiglaszähler CENTRAL LEAD GLASS COUNTERS
- 9 Magnetjoch MAGNET YOKE
- 10 Myon-Filter MUON FILTERS
- 11 Beweglicher Endstopfen REMOVABLE END PLUG
- 12 Strahlrohr BEAM PIPE
- 13 Vorwärts-Detektor TAGGING COUNTER
- 14 Mini-Beta Quadrupol MINI BETA QUADRUPOLE
- 15 Fahrwerk MOVING DEVICES



~7000t

Gesamtgewicht TOTAL WEIGHT: ~1200 t

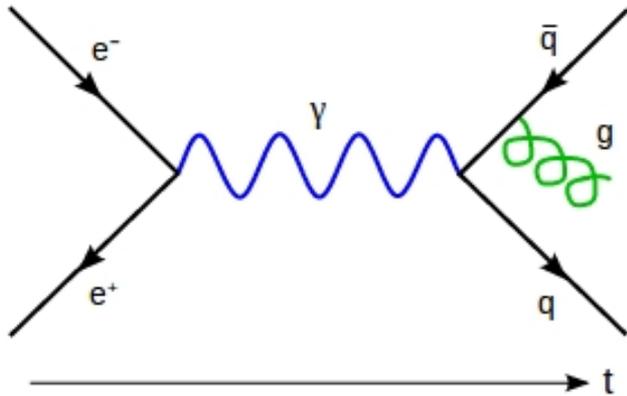
Magnetfeld MAGNETIC FIELD: 0.5 T

Beteiligte Institute PARTICIPANTS

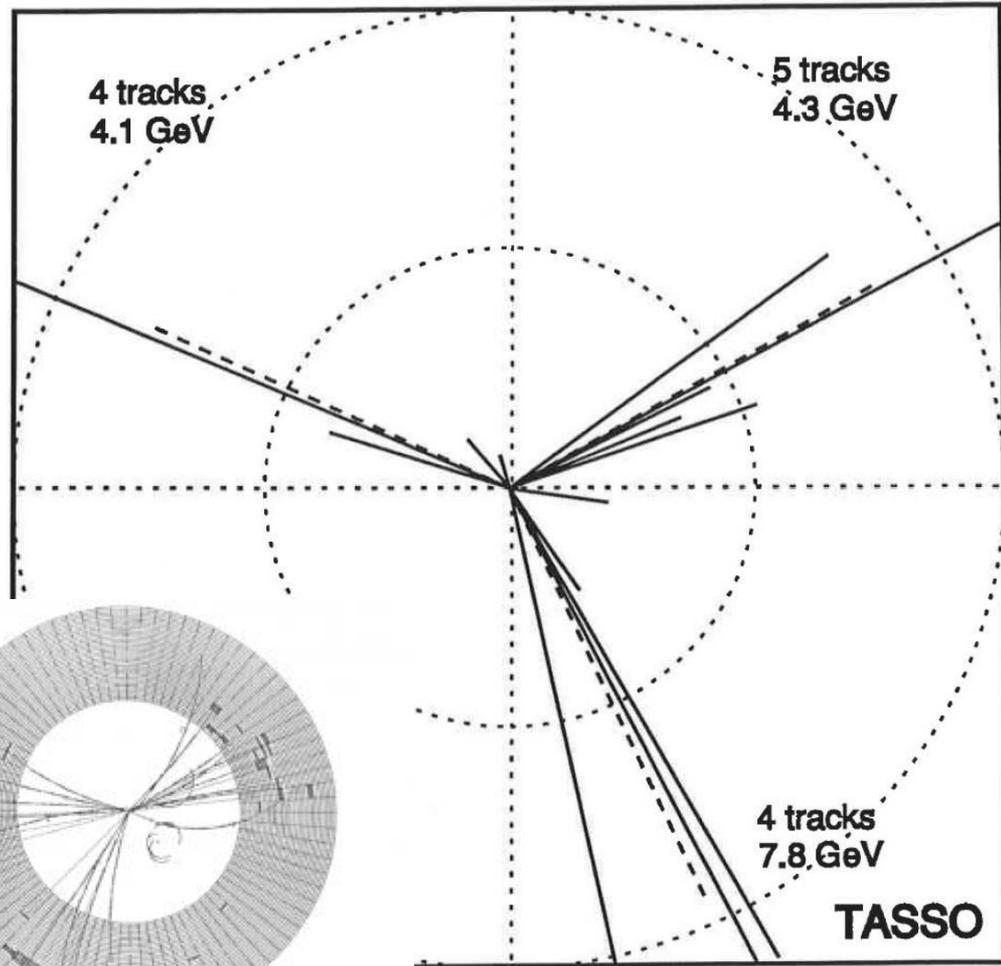
DESY, Hamburg, Heidelberg,
Lancaster, Manchester,
Rutherford Lab., Tokio

W. Faust / DESY

글루온의 증거



TASSO collaboration 등
3 jet event 관측
1979, at PETRA, DESY

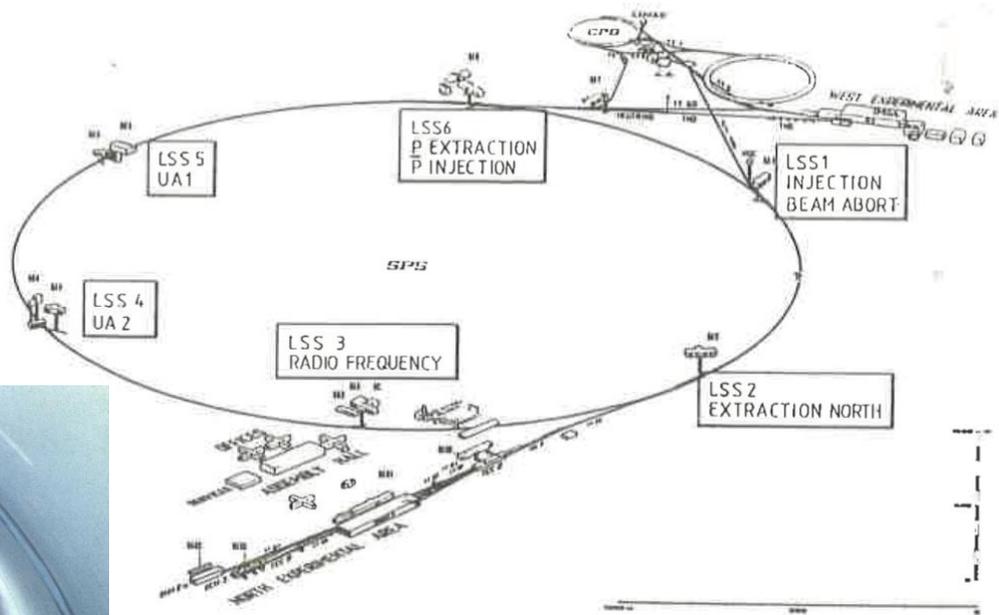


CERN (1954 -)



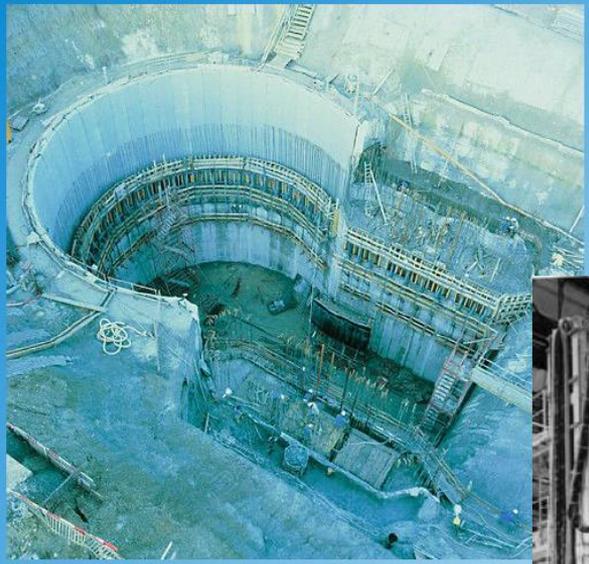
W 와 Z 보손의 발견 (1983)

SPS at CERN (1976)

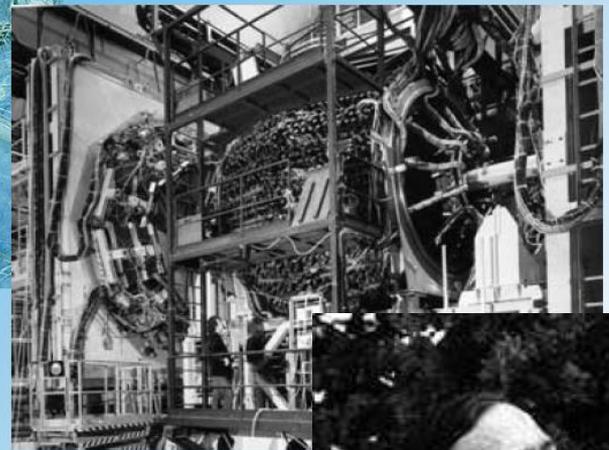


Sp \bar{p} S : SPS를 개조한
양성자-반양성자 충돌기

UA1 Experiment



“modern” high energy
collider experiment able
to run at high collision rates
(fast electronics)



루비아 (C. Rubbia)
UA1 collaboration
반데르메르
(S. van der Meer)
반양성자 대량 공급



W,Z Production in Hadron Collisions

Reaction:

$$q \bar{q} \rightarrow W (Z) X$$

Collider energy:

$$s^{1/2} \sim 500 \text{ GeV}$$

Boson masses

$$M_{W,Z} \sim 100 \text{ GeV}$$

$$M_{W,Z} \sim \hat{s} = x_1 x_2 s$$

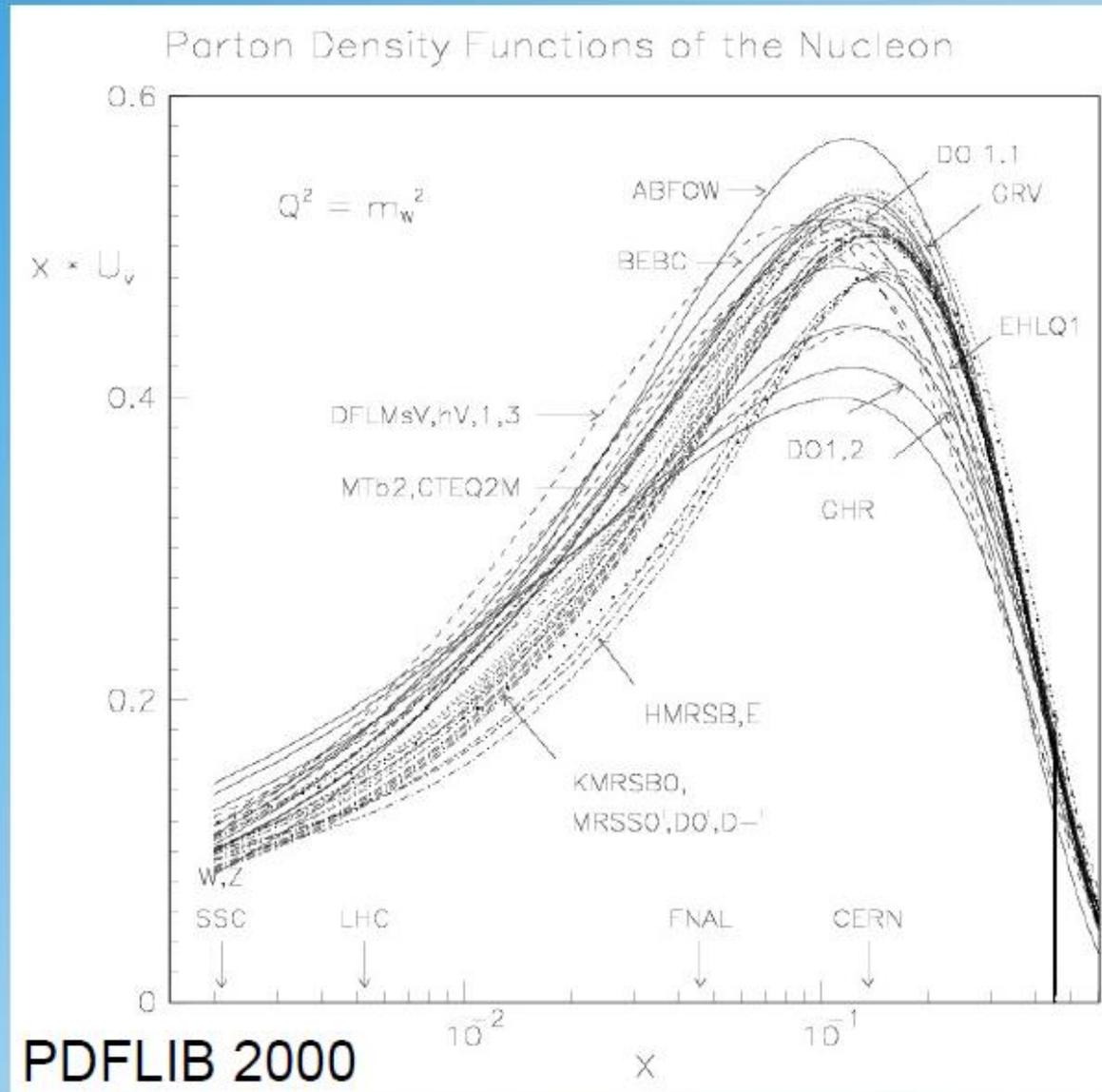
parton momentum fractions:

$$x_1, x_2 \sim 0.2$$

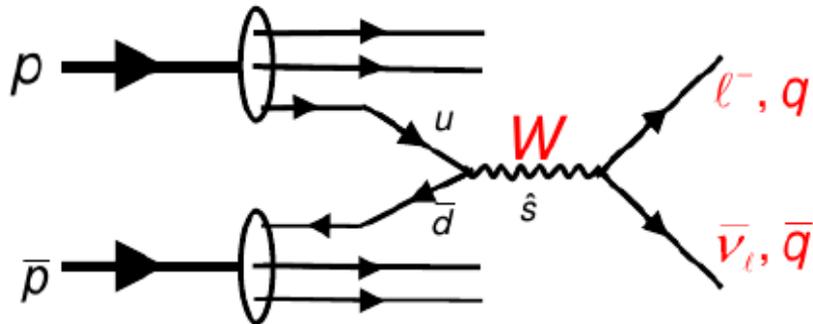
→ valence-quark region

$$p \bar{p} \rightarrow W (Z) X$$

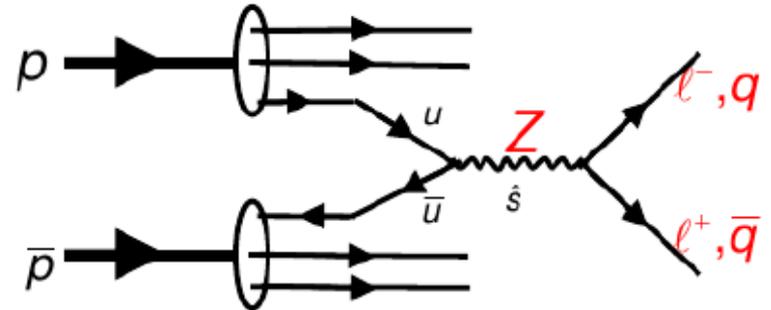
anti-protons needed!



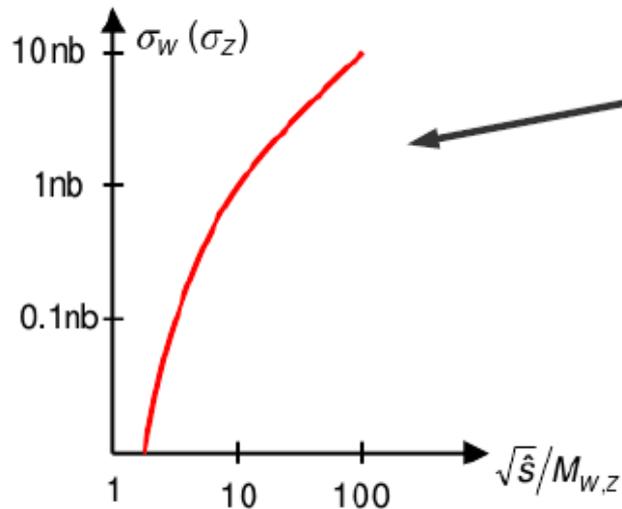
W,Z Cross Section



$$p\bar{p} \rightarrow W \rightarrow l\bar{\nu}_l + X$$



$$p\bar{p} \rightarrow Z \rightarrow f\bar{f} + X$$



Reasonable cross section of 0.1 nb at

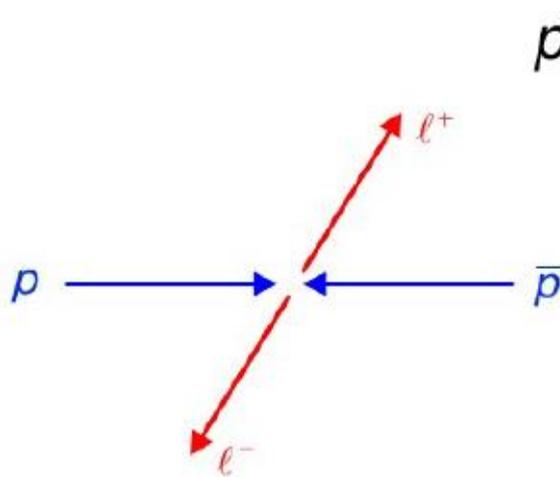
$$\sqrt{s}^{1/2}/M_W \sim 2$$

Typically:

$$x_1, x_2 \sim 0.4$$

need high luminosity!

Z-candidate Event Signature



$$p\bar{p} \rightarrow Z \rightarrow f\bar{f} + X$$

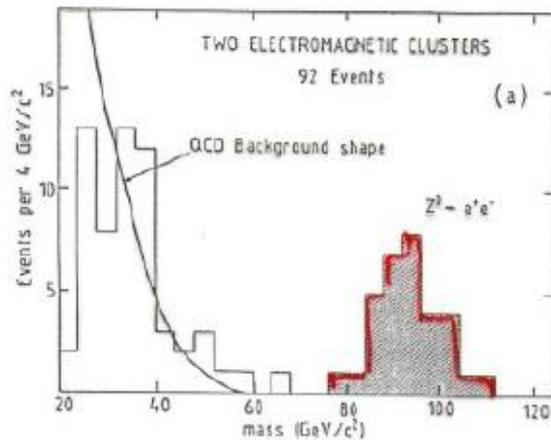
$$p + \bar{p} \rightarrow Z^0 + X$$

$$\quad \quad \quad \downarrow$$

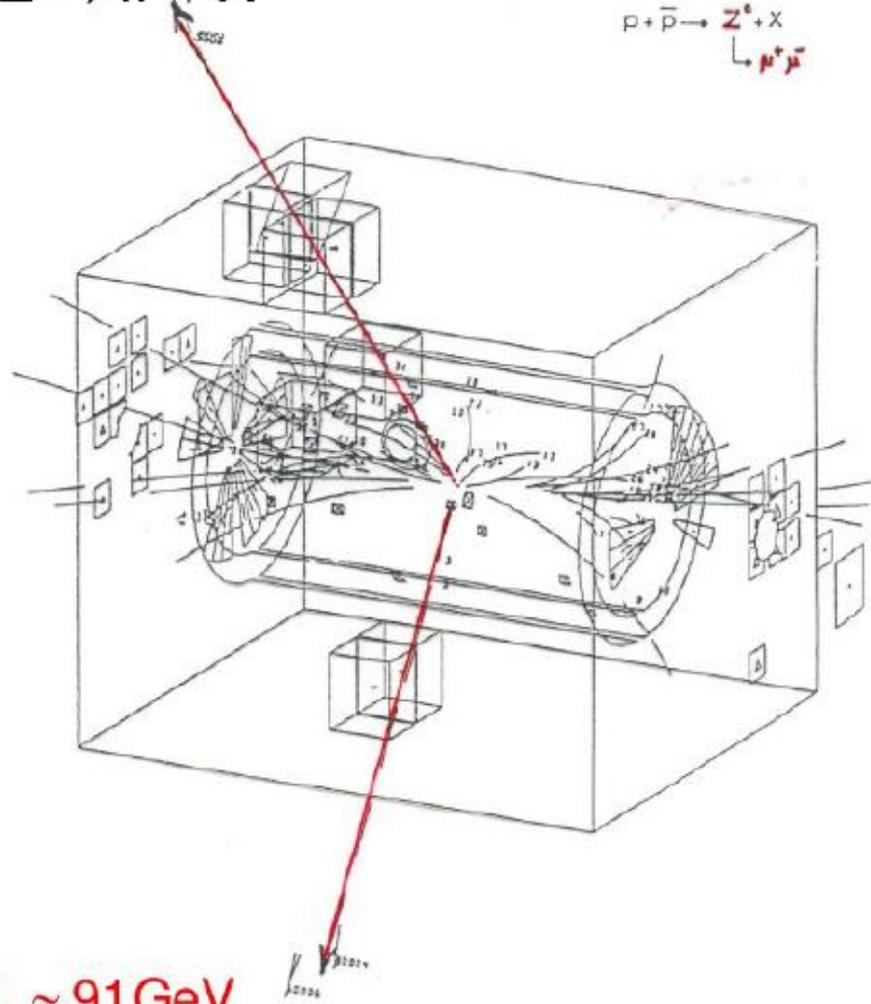
$$\quad \quad \quad \mu^+ \mu^-$$

High-energy lepton pair:

$$m_{\ell\ell}^2 = (p_{e^+} + p_{e^-})^2 = M_Z^2$$

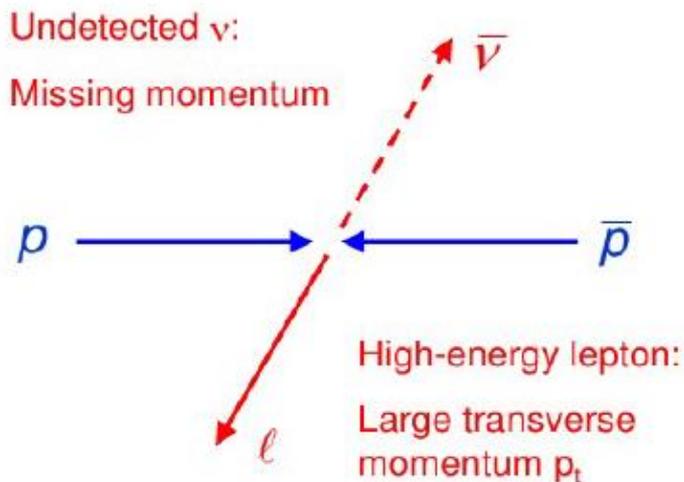


$$M_Z \approx 91 \text{ GeV}$$



W-candidates

$$p\bar{p} \rightarrow W \rightarrow \ell \bar{\nu}_\ell + X \quad W^- \rightarrow e \bar{\nu}$$



How can the W mass be reconstructed ?

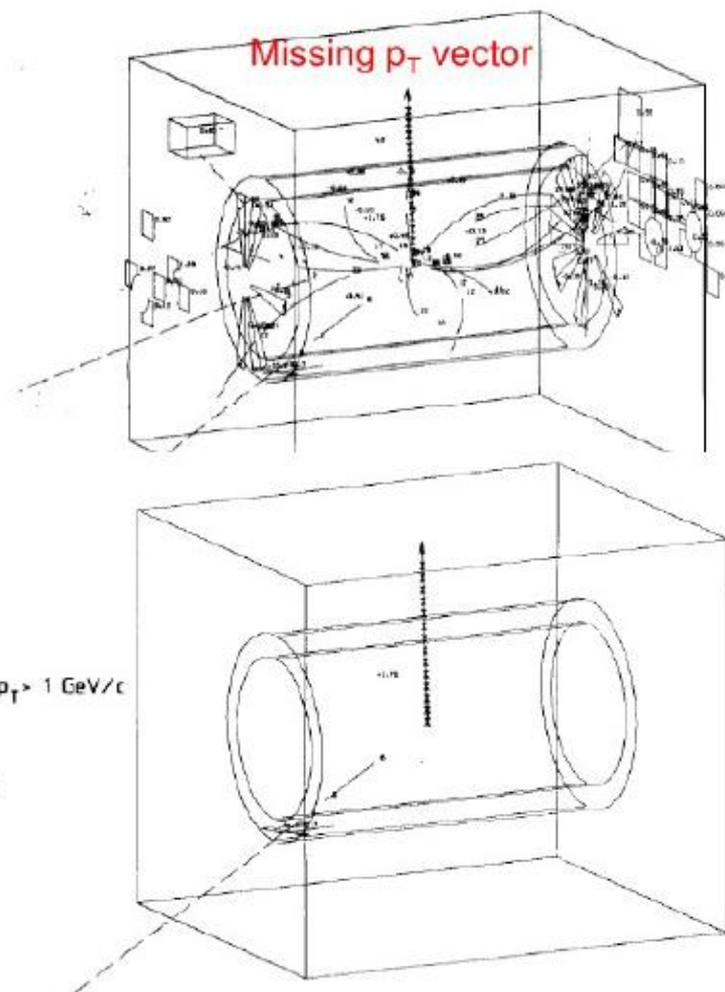
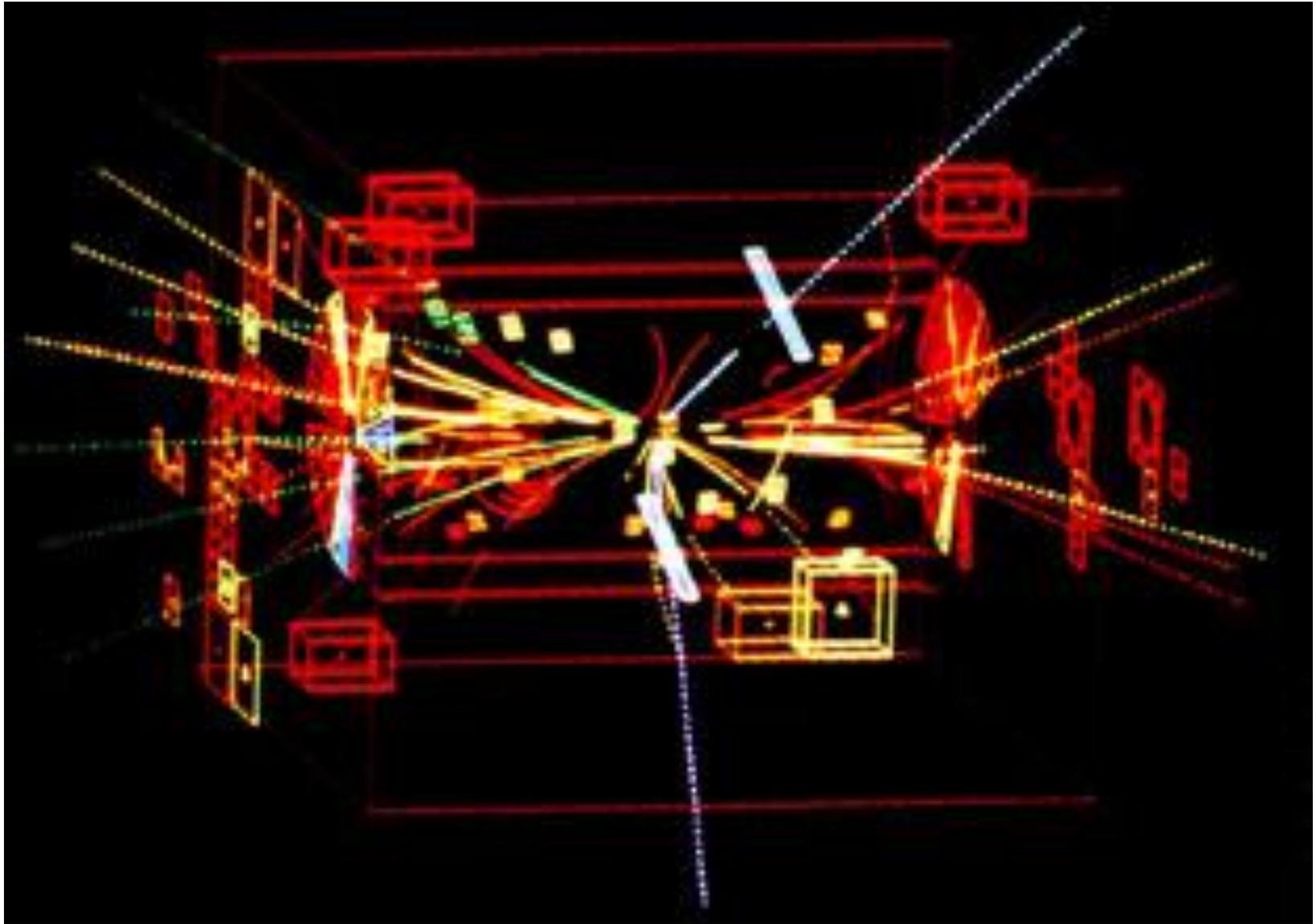
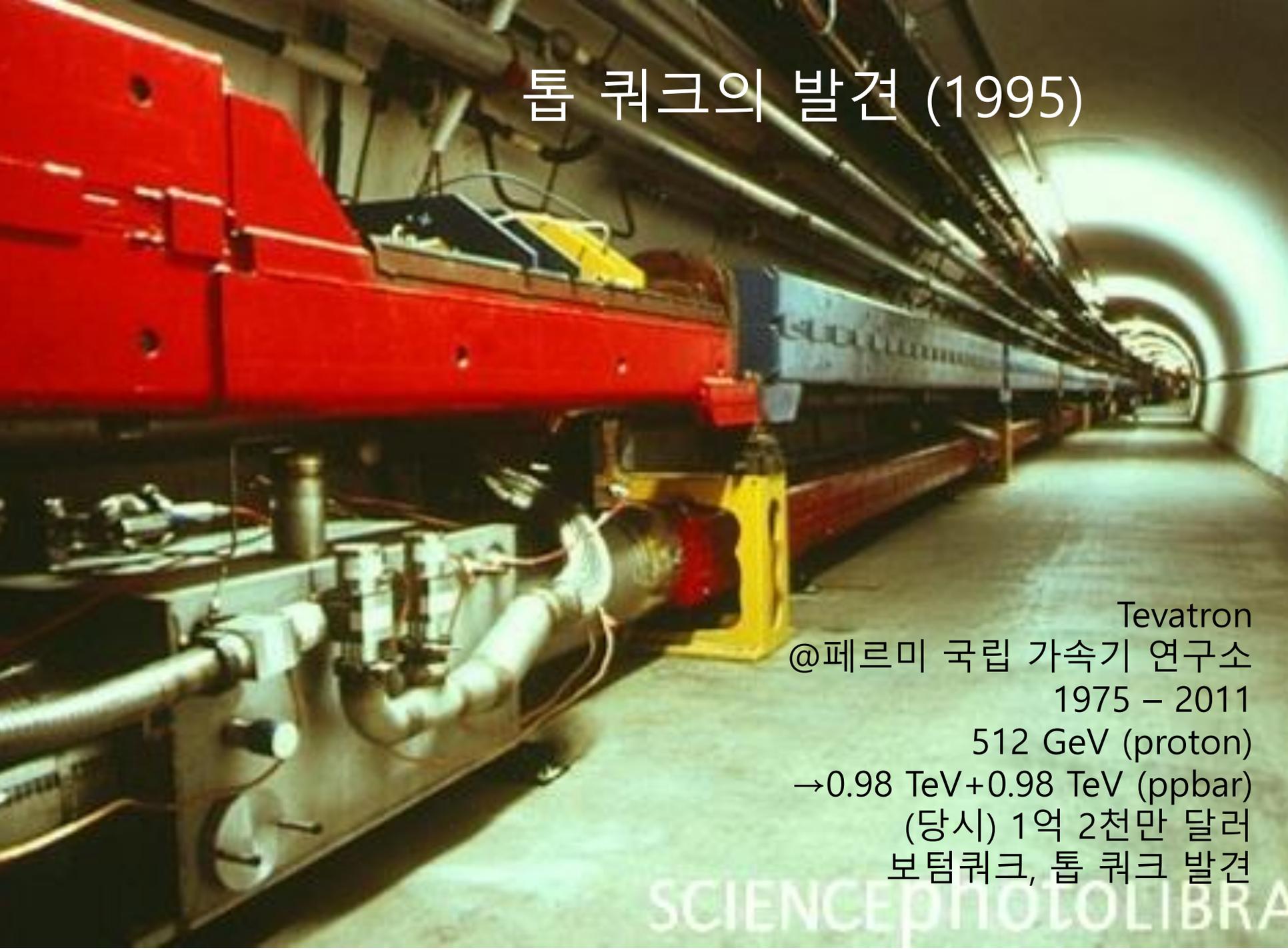


Fig. 165. The same as picture (a), except that now only particles with $p_T > 1 \text{ GeV}/c$ and calorimeters with $E_T > 1 \text{ GeV}$ are shown.



루비아가 이끄는 UA1 팀이 발견한 $Z \rightarrow ee$

톱 쿼크의 발견 (1995)



Tevatron
@페르미 국립 가속기 연구소
1975 - 2011
512 GeV (proton)
→0.98 TeV+0.98 TeV (ppbar)
(당시) 1억 2천만 달러
보텀쿼크, 톱 쿼크 발견

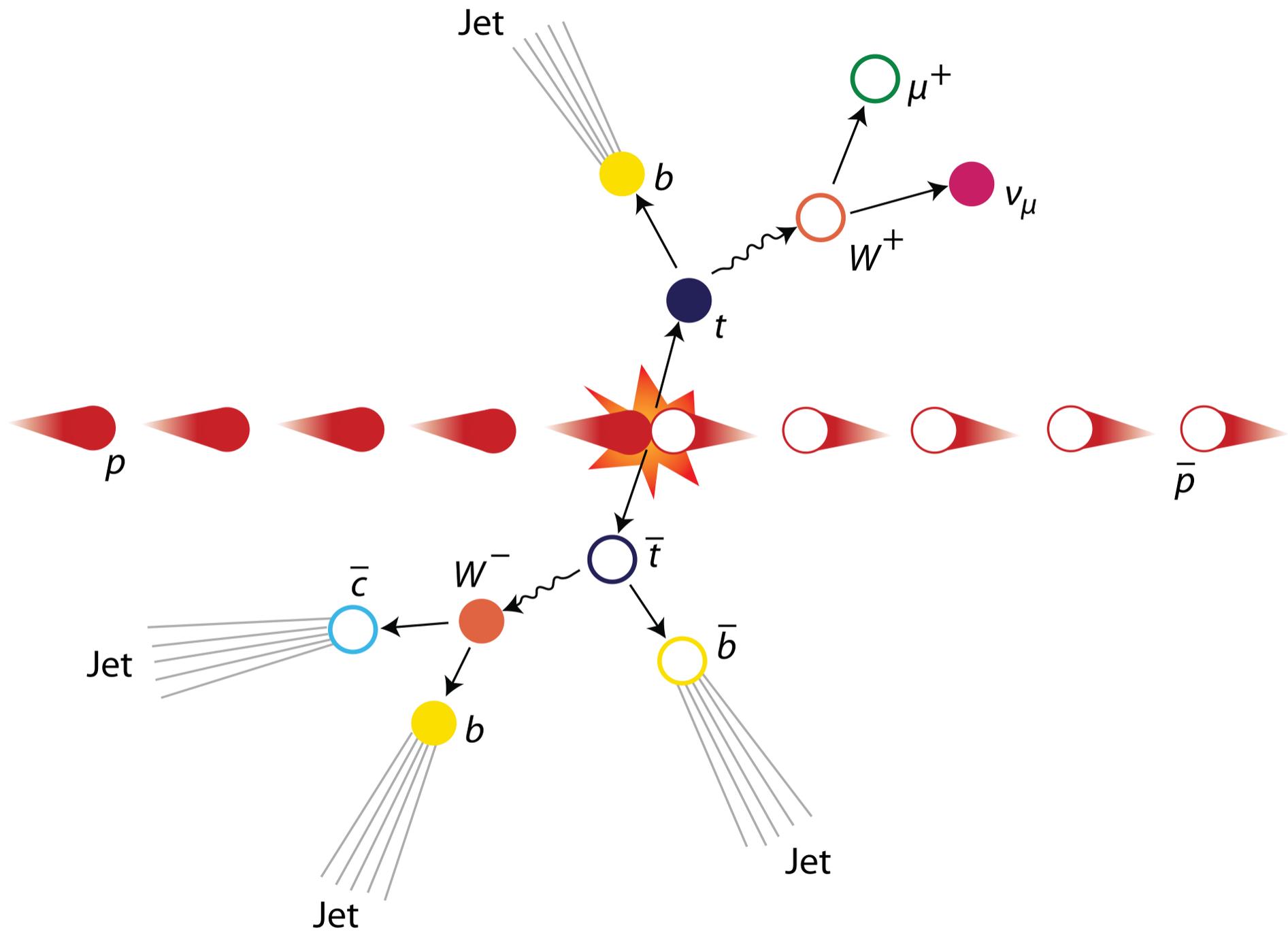


BUFFALO
FARM

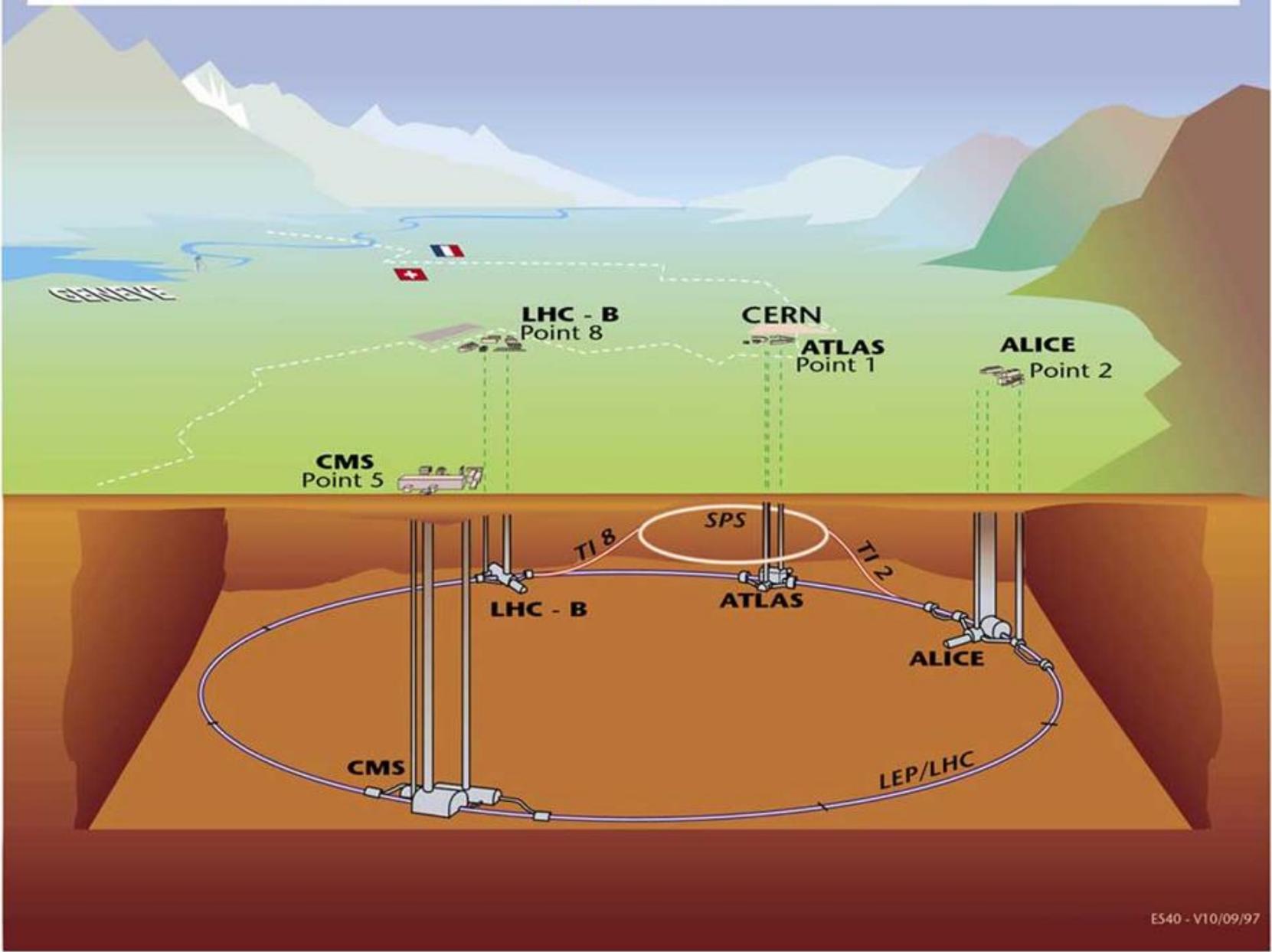
▼ WILSON
HALL

TEVATRON
(3.9 MILES)

MAIN
INJECTOR
RING



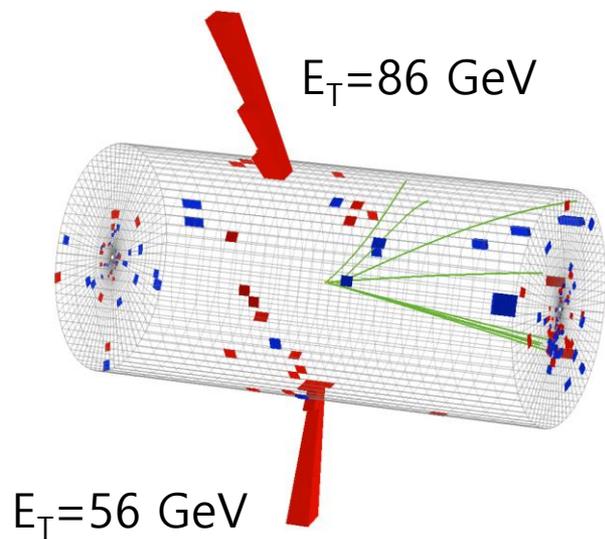
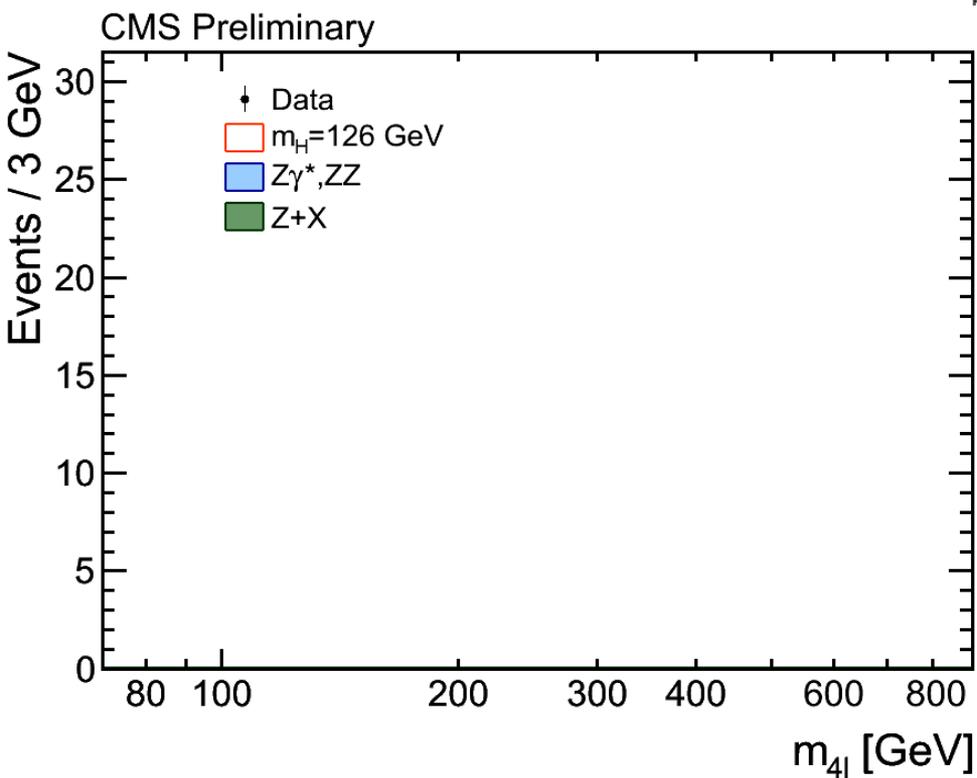
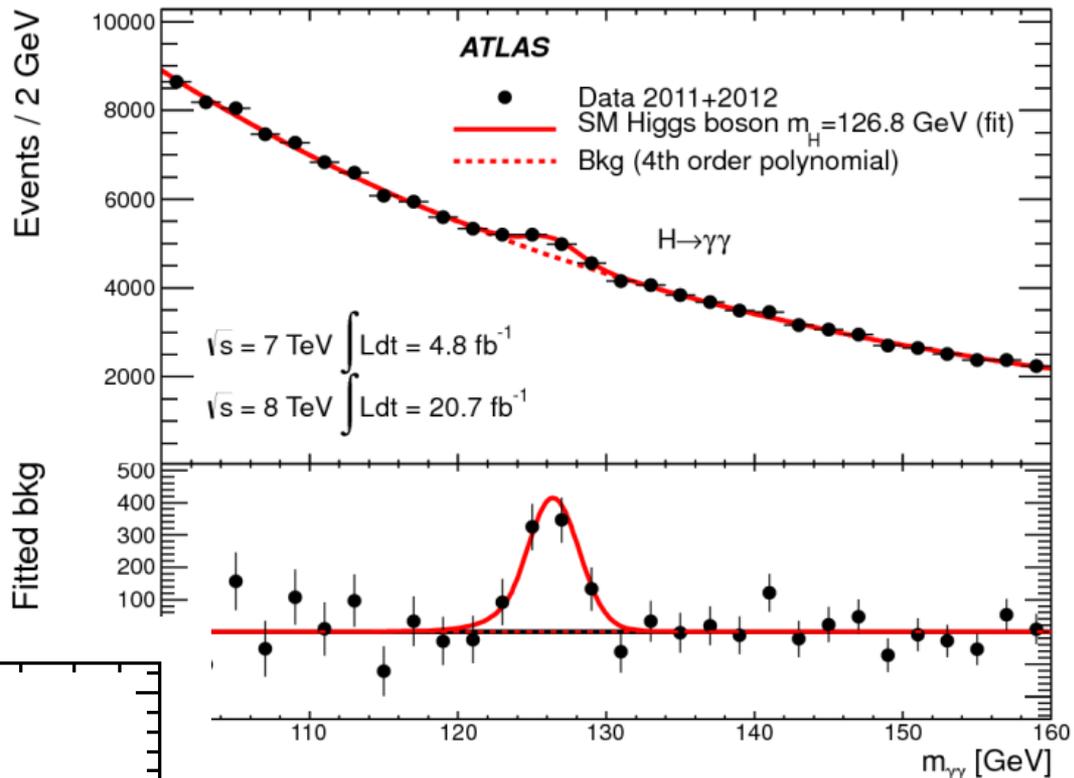
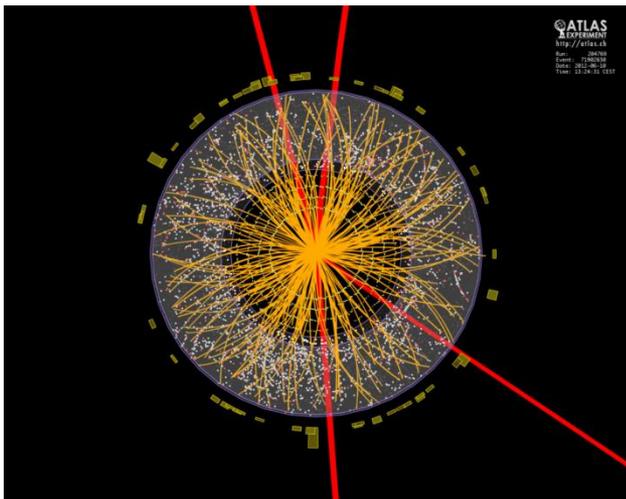
Overall view of the LHC experiments.



힉스 보손 발견

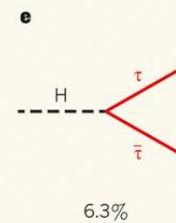
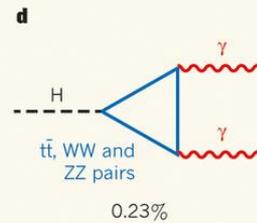
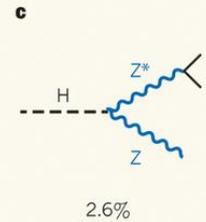
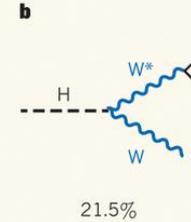
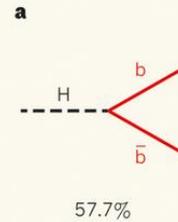
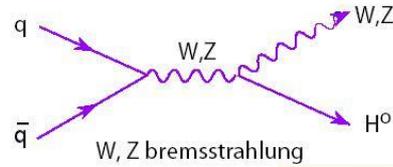
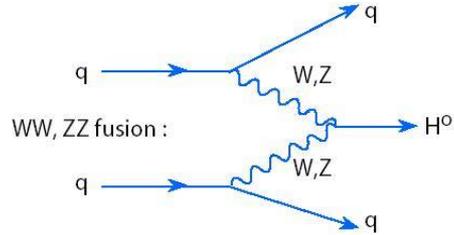
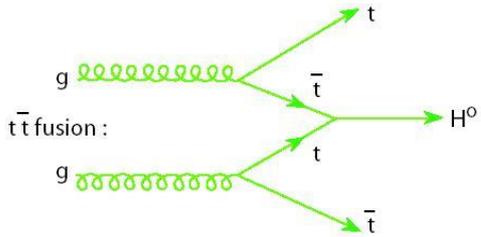
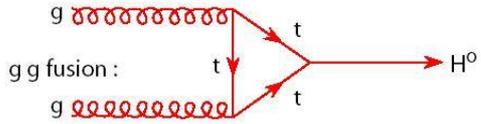


2012. 7. 4.





힉스 보손의 생성과 검출





The Nobel Prize in Physics 2013

François Englert, Peter Higgs

The Nobel Prize in Physics 2013

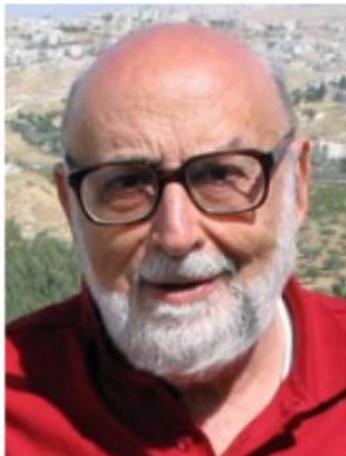


Photo: Pnicolet via
Wikimedia Commons

François Englert

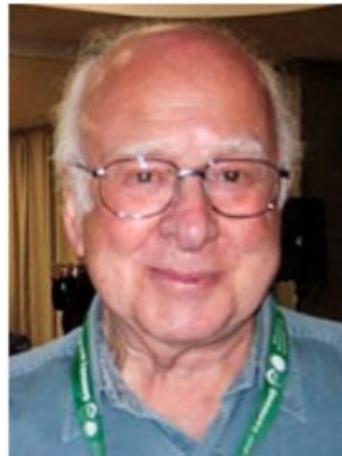
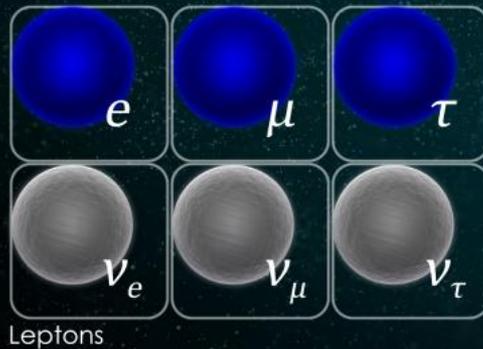
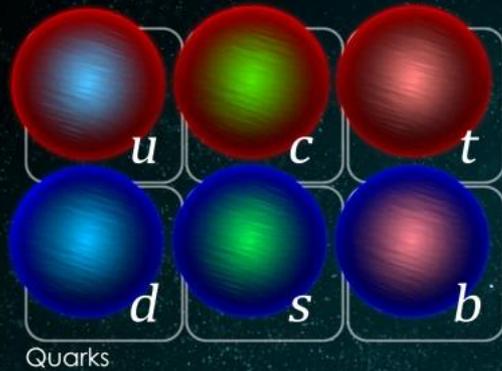


Photo: G-M Greuel via
Wikimedia Commons

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"*

최종적으로

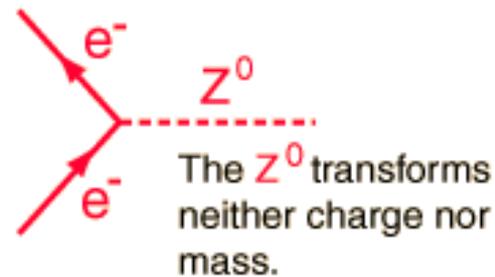
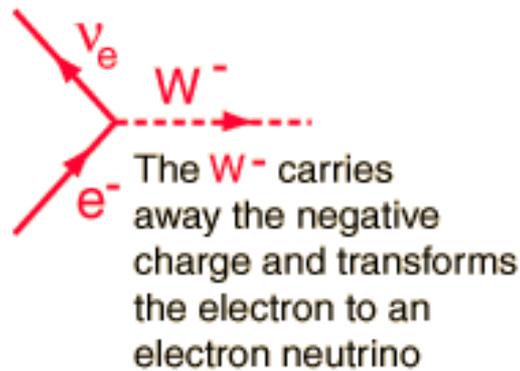


Interactions

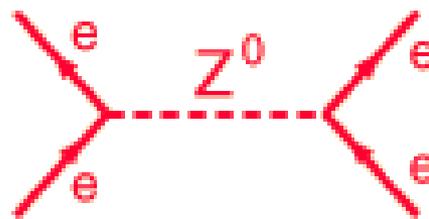
Really $SU(2)$?

- 중성류 (Z 보손) 상호작용의 존재
- W와 Z 보손 사이의 질량 관계
: ρ 파라미터
- 와인버그 각의 측정
- Z 보손 상호작용의 성질
: 전자-양전자 충돌에서 전-후방 비대칭성
: 원자에서 패리티 붕괴
- W, Z, A 게이지 보손끼리의 상호작용
: 3중 게이지 결합
: 4중 게이지 결합
-

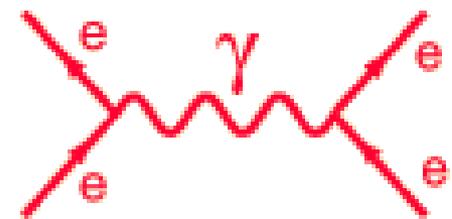
1) 중성류 찾기



전자기력과 구별하기 어렵다.



Neutral weak interaction



Electromagnetic interaction

Gargamelle

- a bubble chamber designed to detect neutrinos

대형 거품상자

지름 1.8m

길이 4.8m

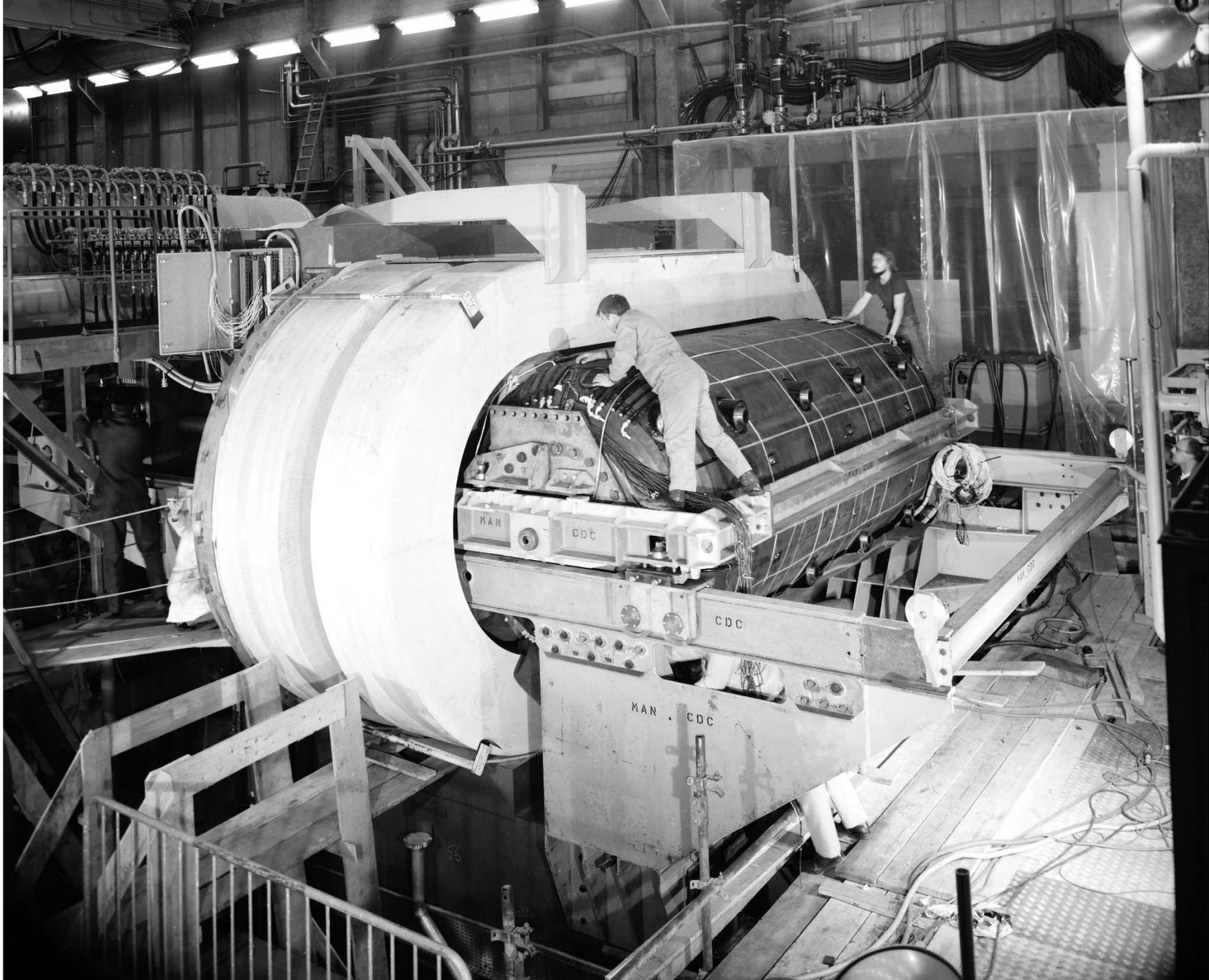
내용물 CF_3Br 18t

PS 가속기에서 만든
중성미자 검출.

1973년 7월

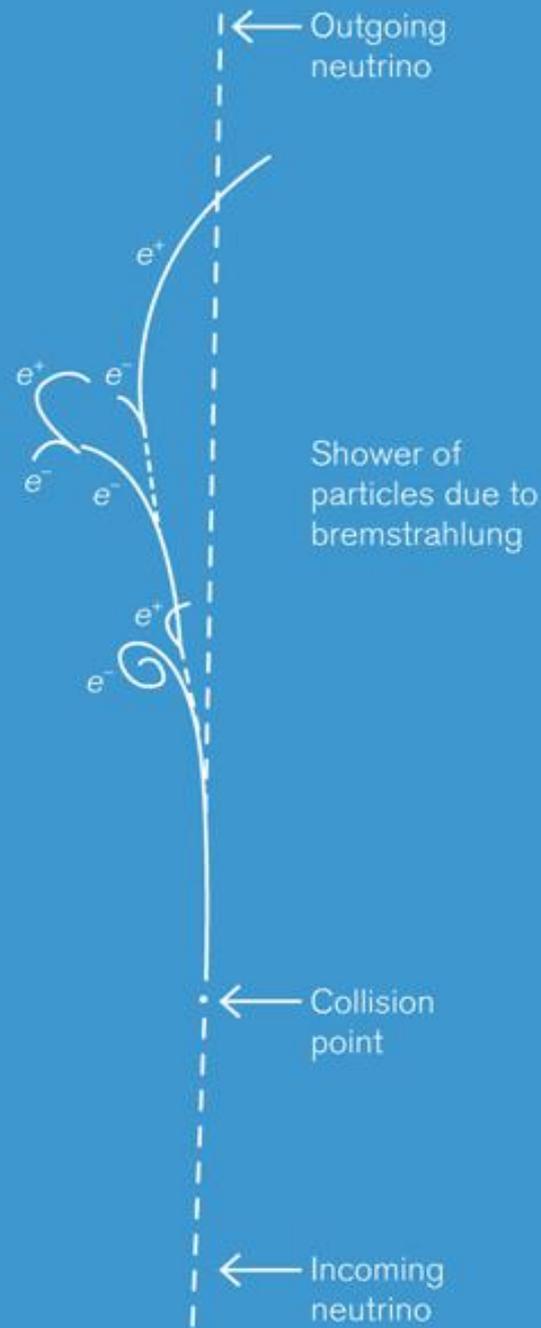
중성류 관측 첫 발표





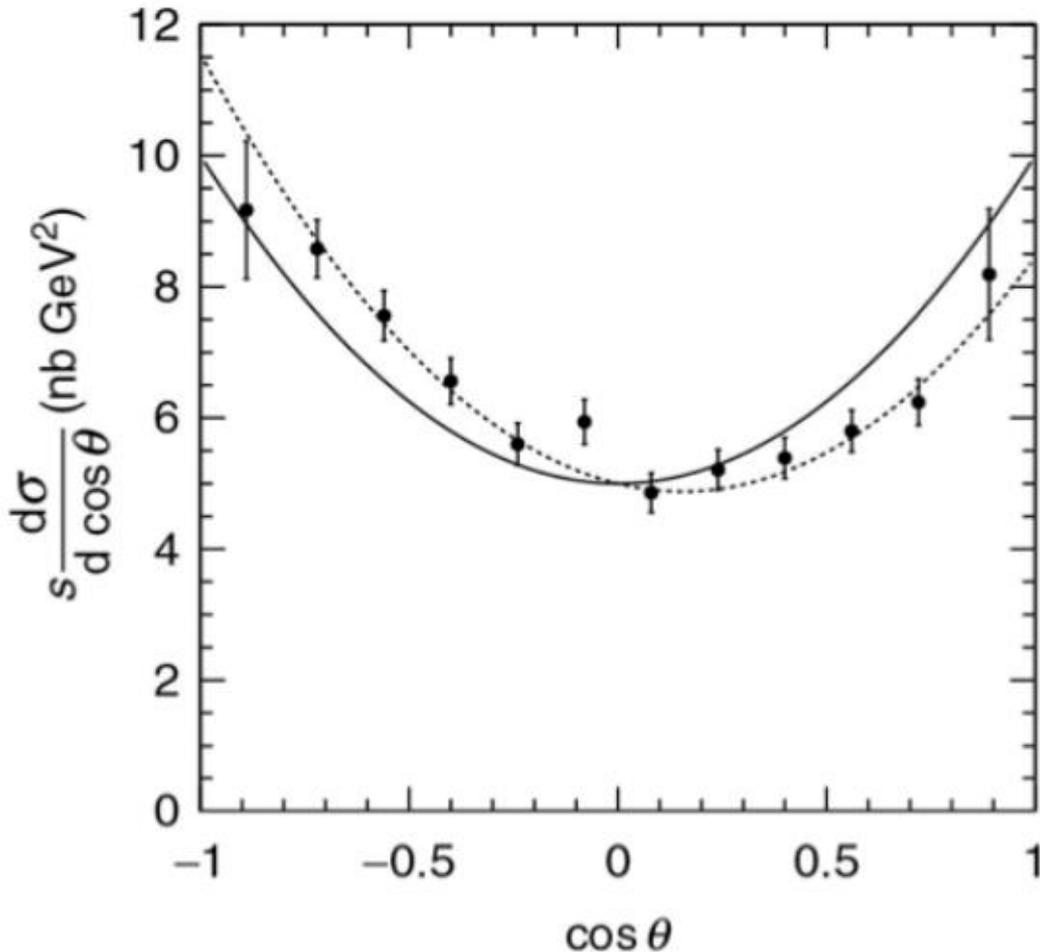
Gargamelle's priorities

1. W search
2. deep inelastic scattering, scaling
3. current algebra sum rules, CVC, PCAC
4. Diagonal Model
5. $\Delta S = 1$ processes, inverse hyperon decay, $\bar{\nu}_\mu + p \rightarrow \Lambda + \mu^+$
6. inverse muon decay, $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$
7. electron-muon universality
8. neutral-current search
9. form factors in exclusive reactions
10. search for heavy leptons





2) Forward-backward asymmetry



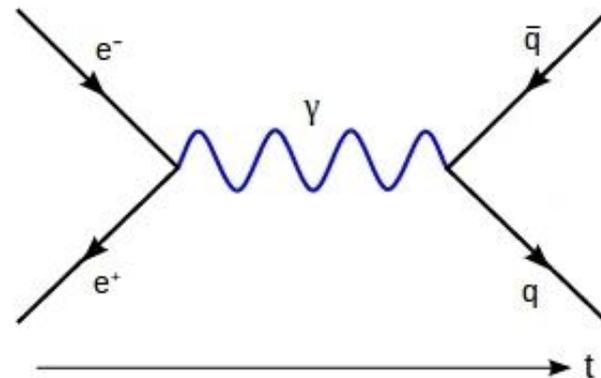
Z 보손의 결합은 전자기 상호작용과는 달리 왼쪽 페르미온과의 결합 크기와 오른쪽 페르미온과의 결합 크기가 다르기 때문에 F-B asymmetry가 생긴다.

$$A_{FB} = \frac{F - B}{F + B}$$

PETRA의 JADE 실험 결과

Really $SU(3)$?

전자-양전자 충돌실험에서 2-jet 발생 사건 분석.



$$\frac{d\sigma}{d\Omega} \sim (1 + \cos^2\theta)$$

$$R_{had} = \frac{\sigma(ee \rightarrow hadrons)}{\sigma(ee \rightarrow \mu\mu)}$$

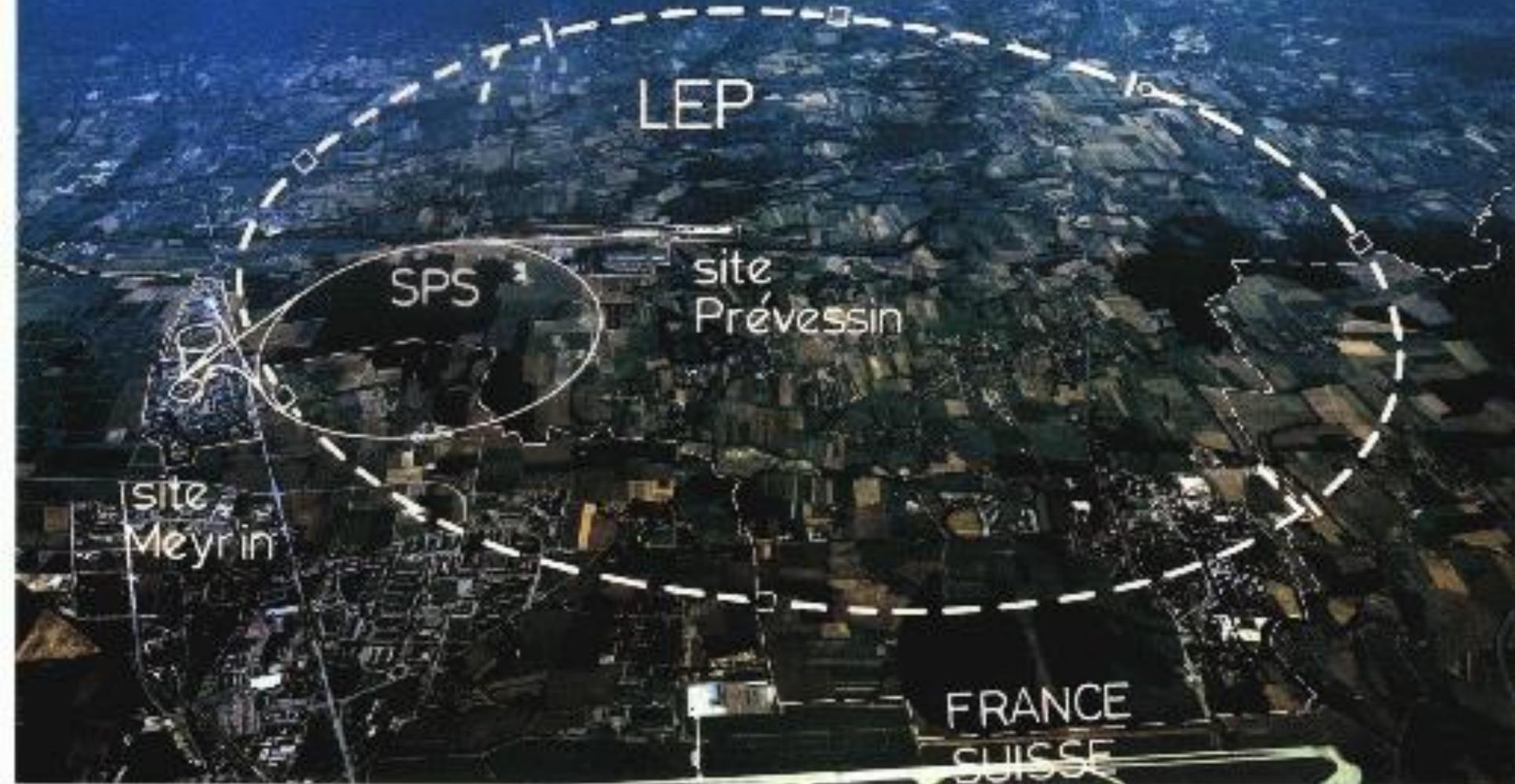
indicates fractional charges and $N_c=3$

And more...

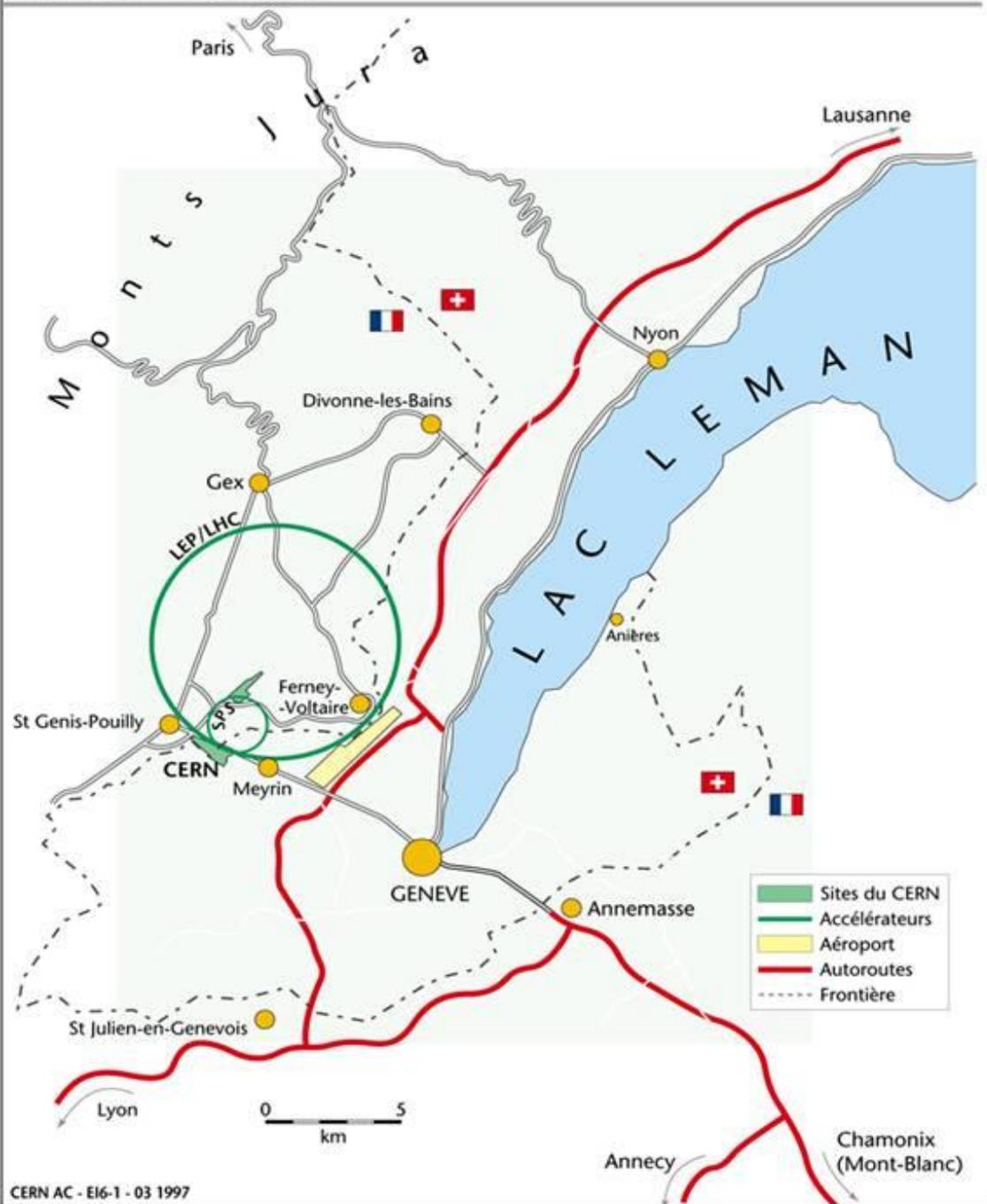
LEP@CERN, 1989 – 2000

91 – 208 GeV (e^-e^+)

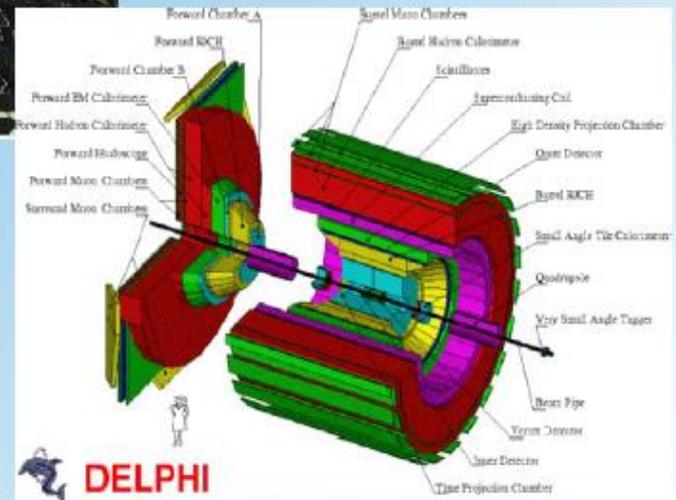
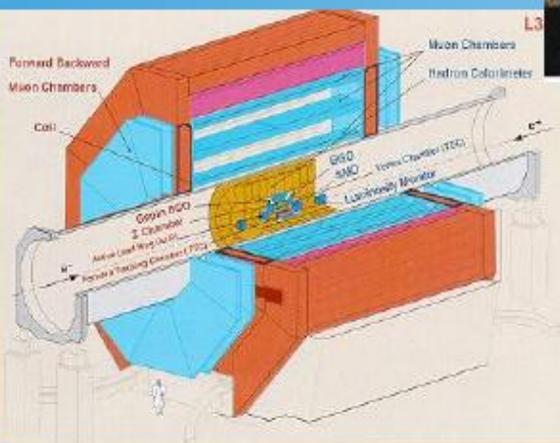
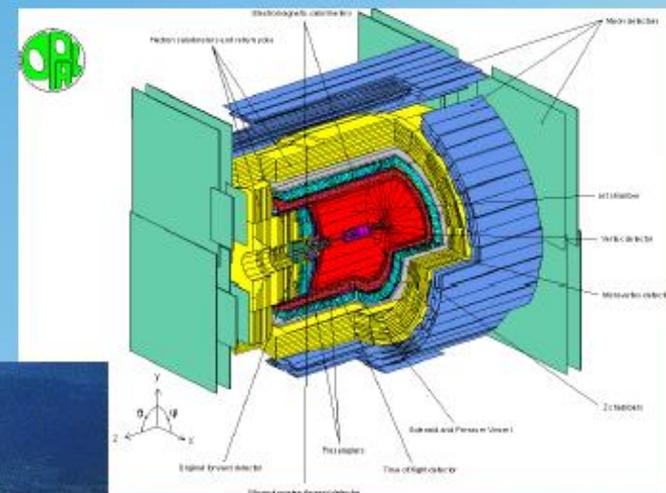
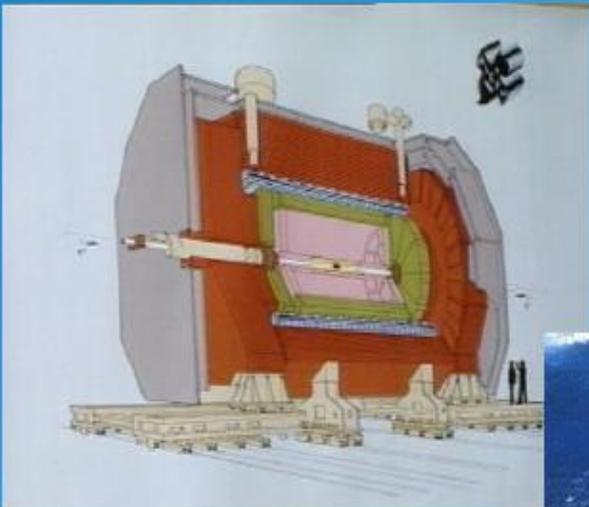
표준모형의 정밀 확인, 가벼운 중성미자 종류 수 결정



Carte de situation



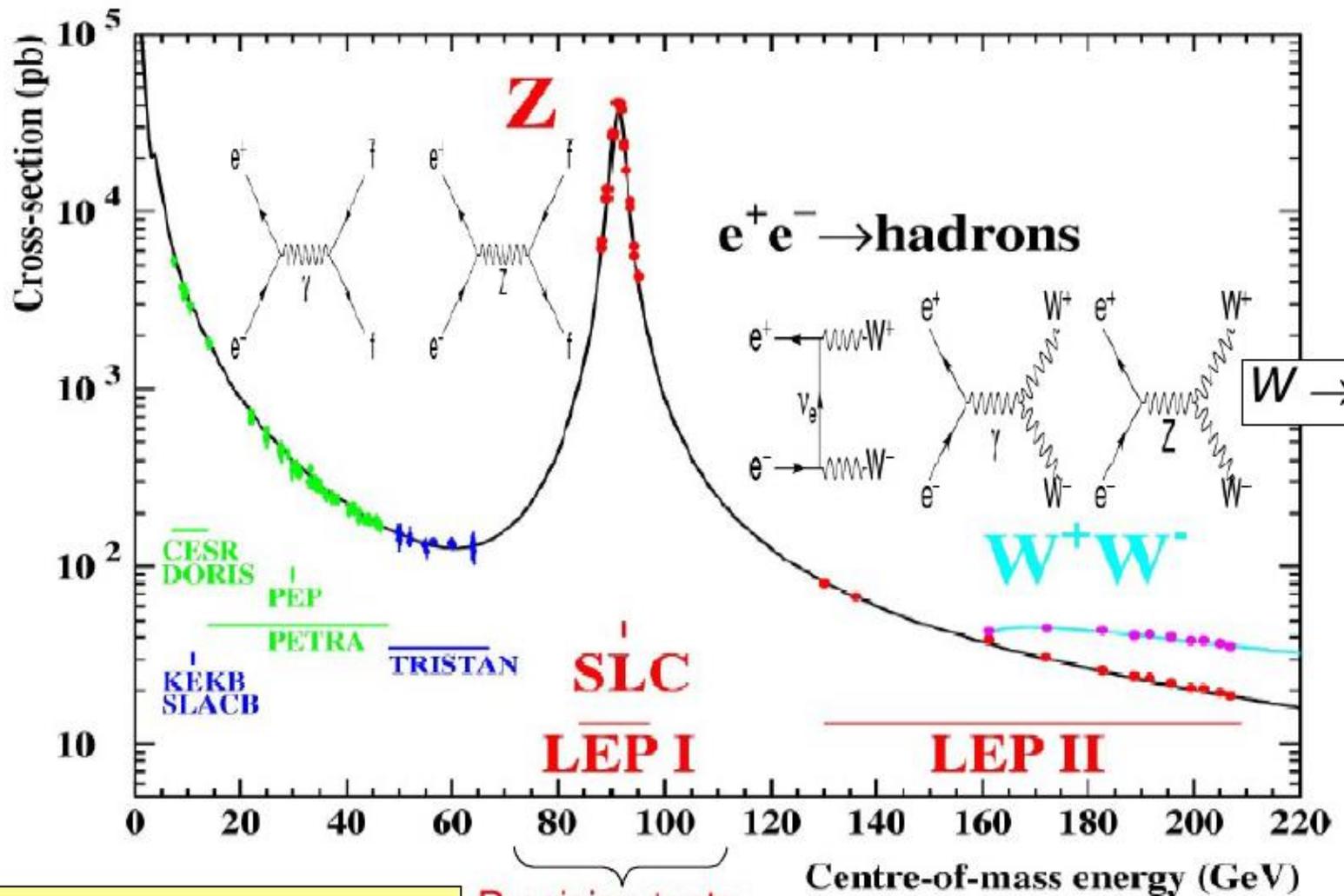
Large Electron Positron Collider



e^+e^- collider
 $s^{1/2} = 90-200 \text{ GeV}$

DELPHI

Hadron Production in e^+e^-



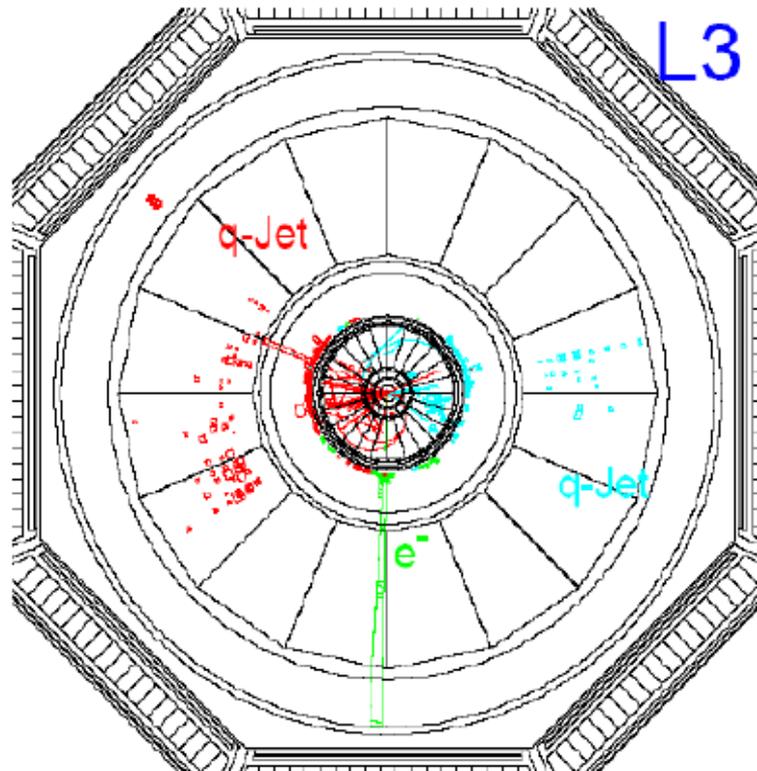
$$M_Z = 91.1876 \pm 0.0021 \text{ GeV}$$

Precision tests
of the Z sector

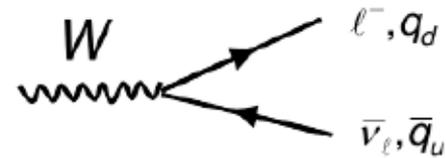
Tests of the W sector

WW Pair Production at LEP

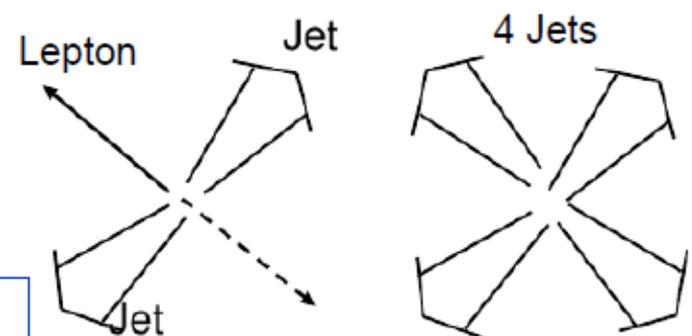
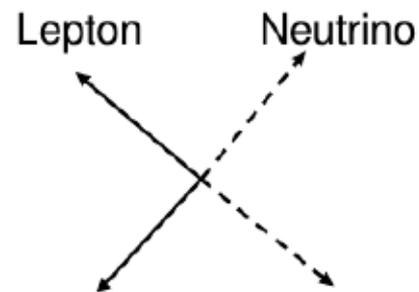
W decays



Run # 945004 Event # 4035 DAQ Time : 02.11.2000 4.25.34 h



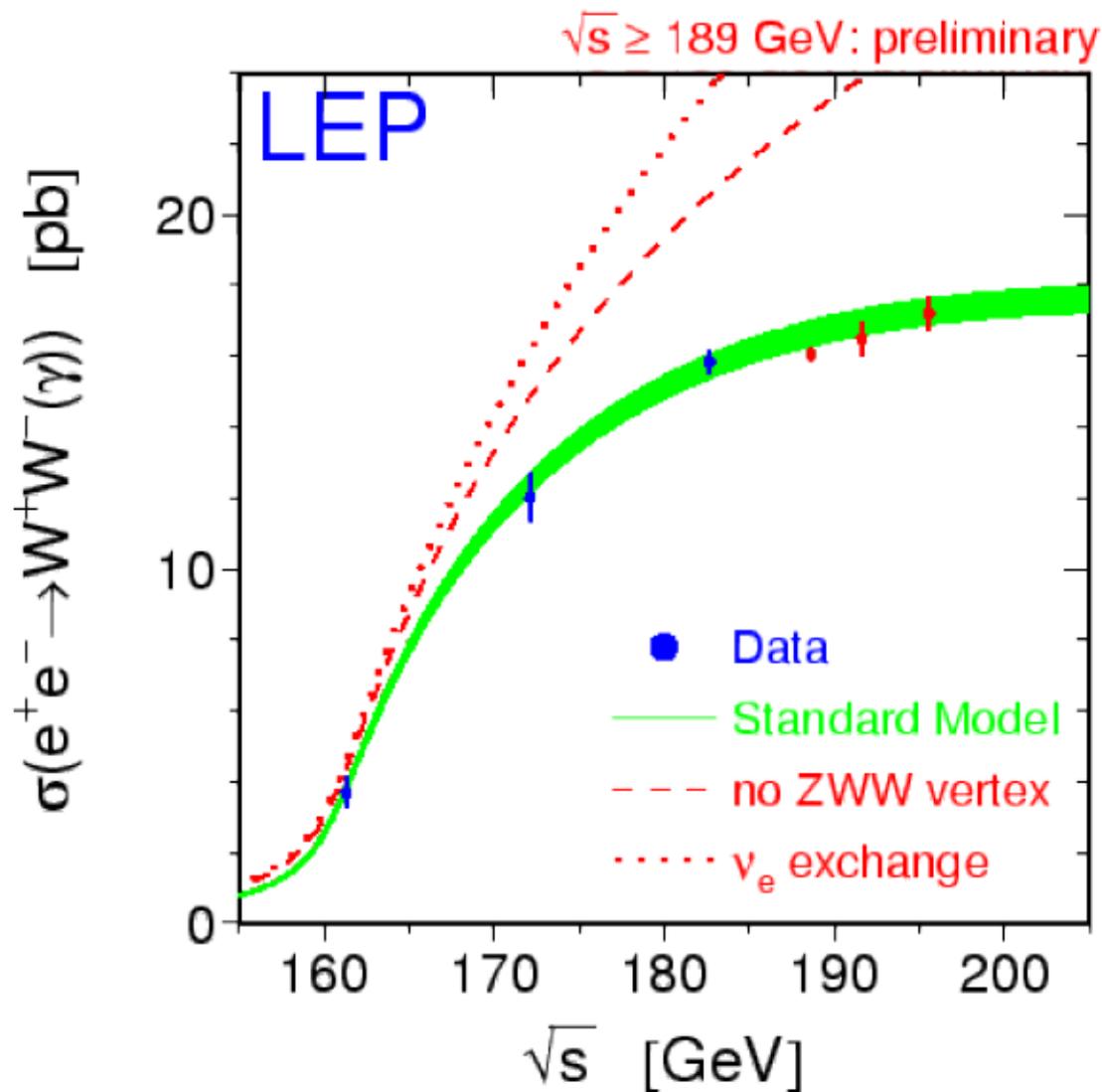
WW → $\left\{ \begin{array}{l} qq\ell\nu \text{ 44\%} \\ qq\bar{q}q \text{ 45\%} \\ \ell\nu\ell\nu \text{ 11\%} \end{array} \right.$



Easiest signature for a mass measurement:

$W_1 \rightarrow \ell\nu$ $W_2 \rightarrow \text{JetJet}$: use JetJet invariant mass

W-Pair Production at LEP2

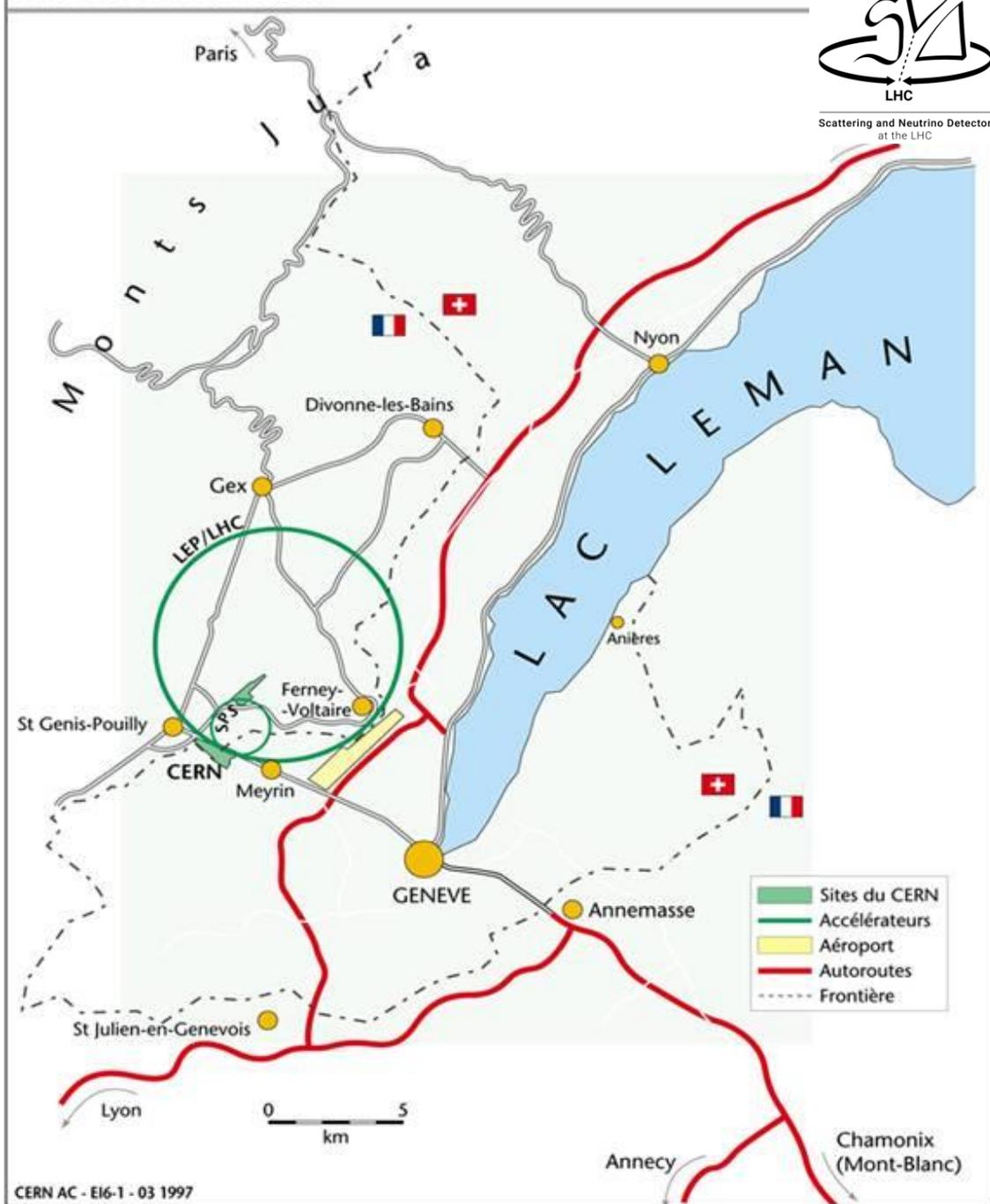


LEP의 성취

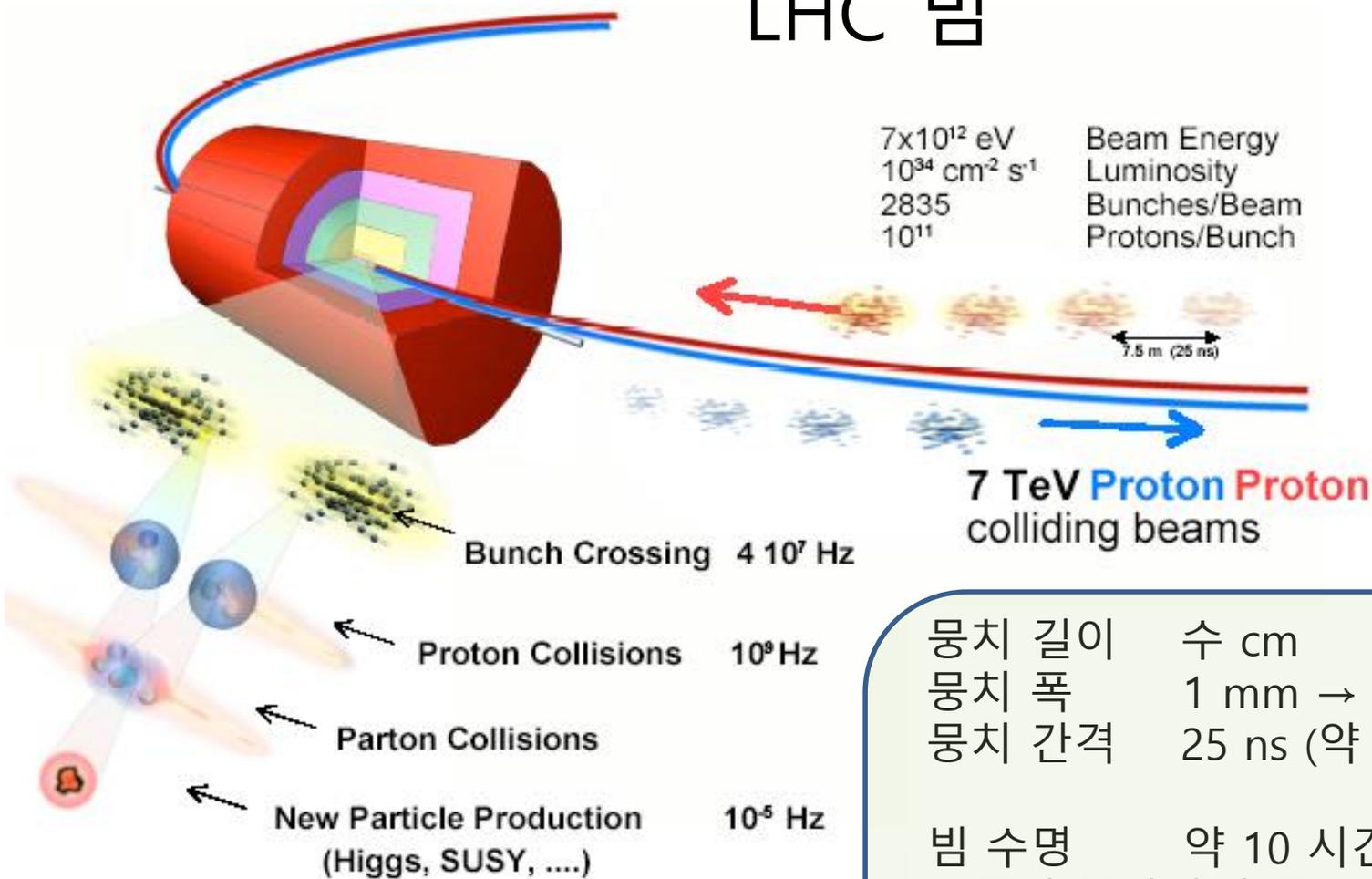
- Z 보손의 질량 및 기타 성질을 정밀하게 측정.
- WWZ 등 게이지 보손 상호작용을 최초로 측정.
- Z 보손이 가벼운 입자(=중성미자)로 붕괴할 확률을 정확하게 측정해서 가벼운 중성미자의 개수를 결정.
- W 보손의 질량 및 성질을 정밀하게 측정
- 표준모형의 양자효과를 검증
- 기타 표준모형의 여러 가지 성질을 정밀하게 측정

LHC

- 둘레 26658.883미터
- p-p / Pb-Pb 충돌장치
- 충돌에너지 14 TeV
(pp, 각 7 TeV)
빛의 속도의 99.99991%
- 광도 $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- 현재 에너지 13.6 TeV
(6.8 TeV + 6.8 TeV)



LHC 빔

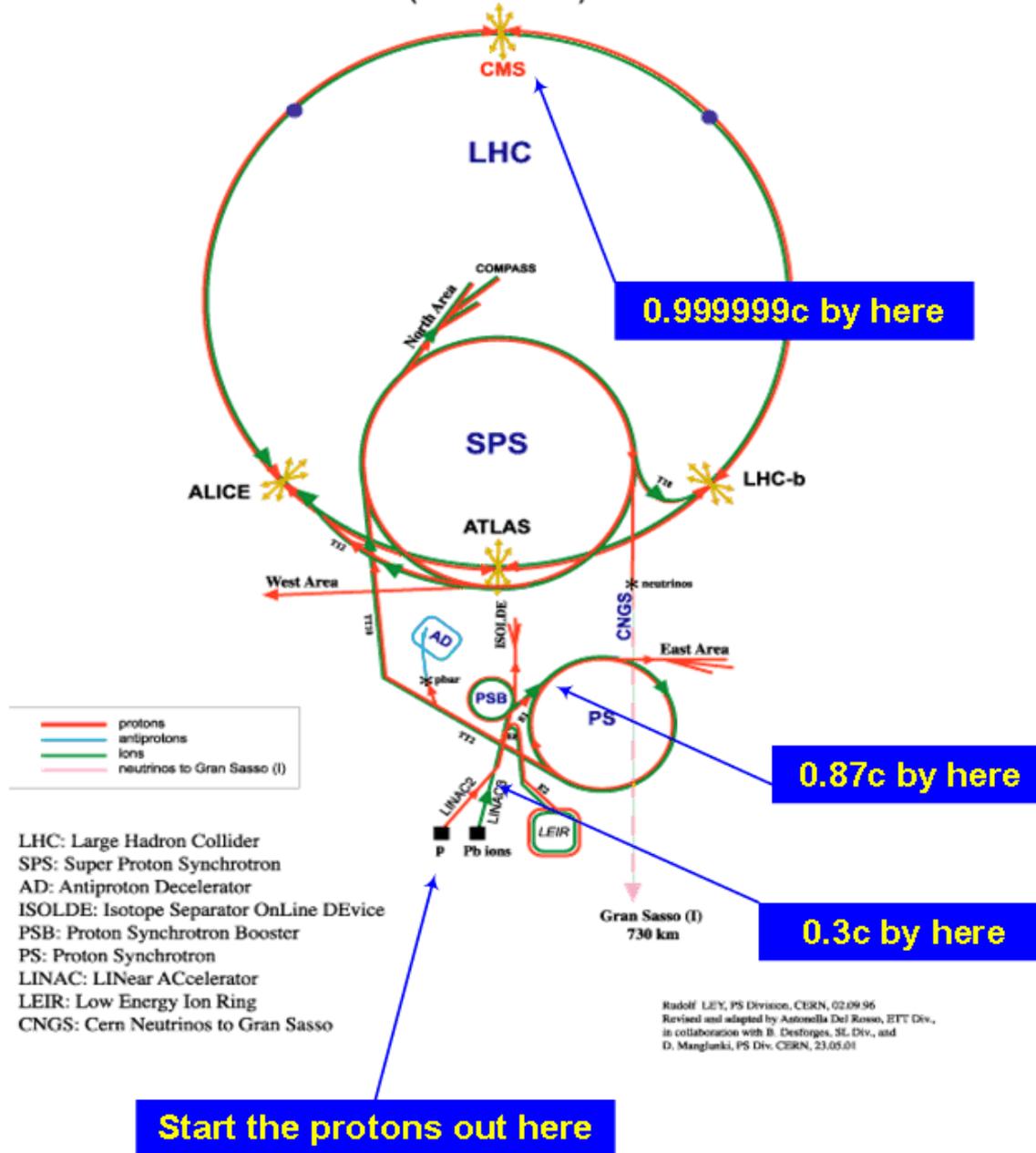


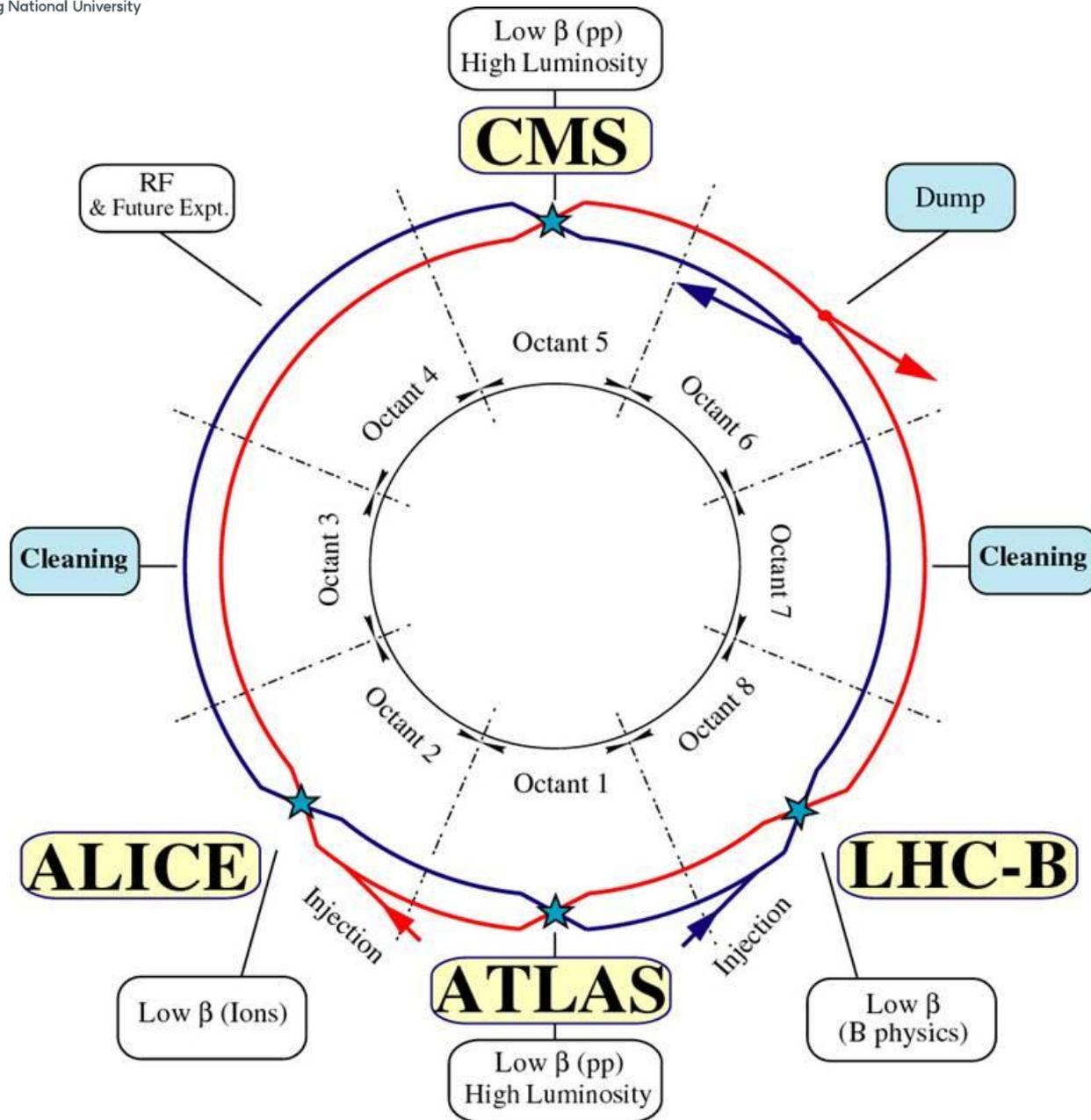
뭉치 길이 수 cm
 뭉치 폭 1 mm → 16 μm
 뭉치 간격 25 ns (약 7.5 m)

빔 수명 약 10 시간
 (공기 분자와 충돌 & 뭉치 교차 시
 교란에 의해 흐트러짐)

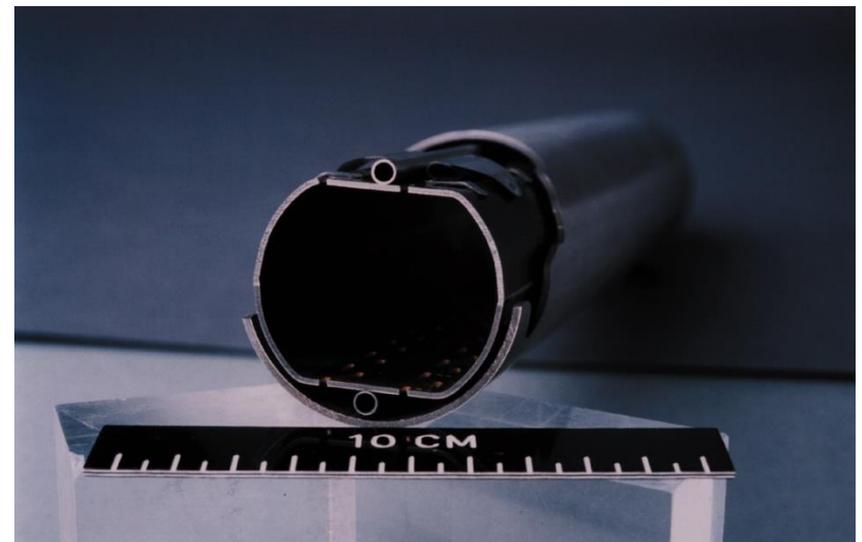
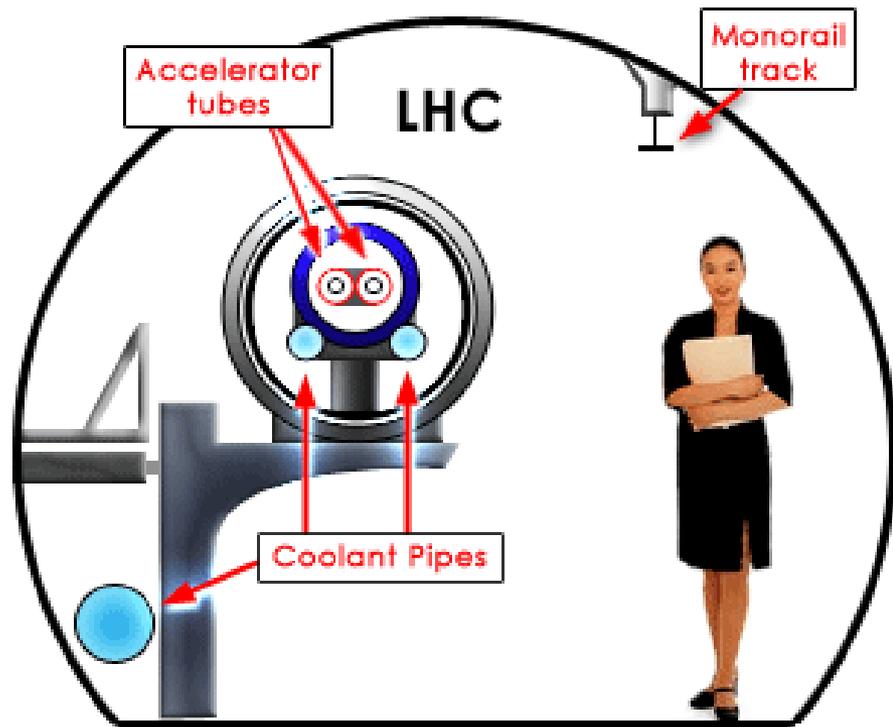
충돌 = 빔의 교차
 = 빔 뭉치의 교차
 ~ 매회 양성자 약 20회 충돌

CERN Accelerators (not to scale)





LHC 내부





ALICE

Le détecteur ALICE
The ALICE detector



11.2007

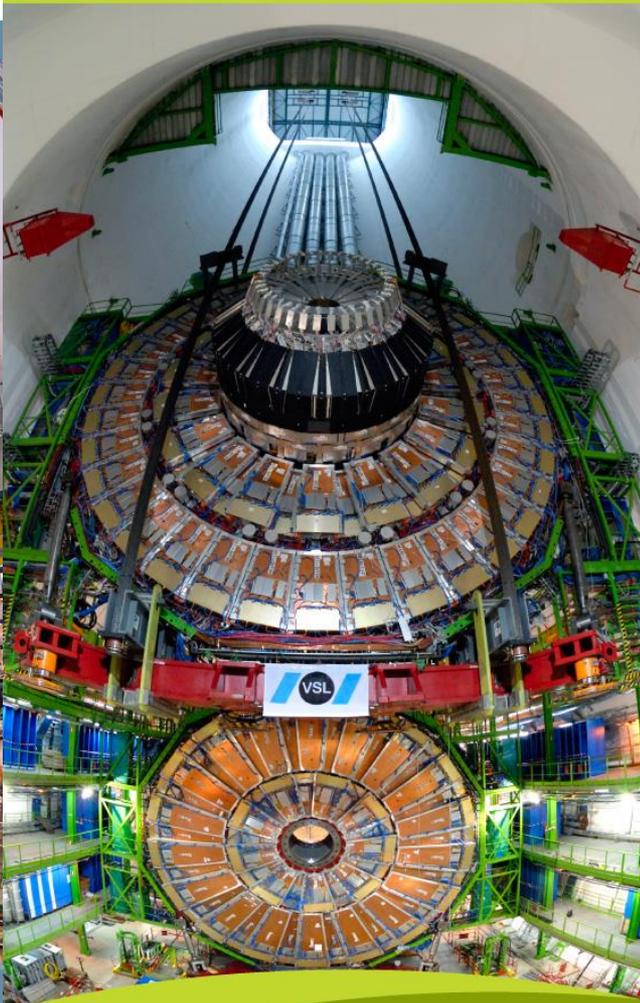


ATLAS

Descente de la dernière bobine de l'aimant toroïdal
Descent of the last coil of the barrel toroid magnet



08.2005



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



01.2007



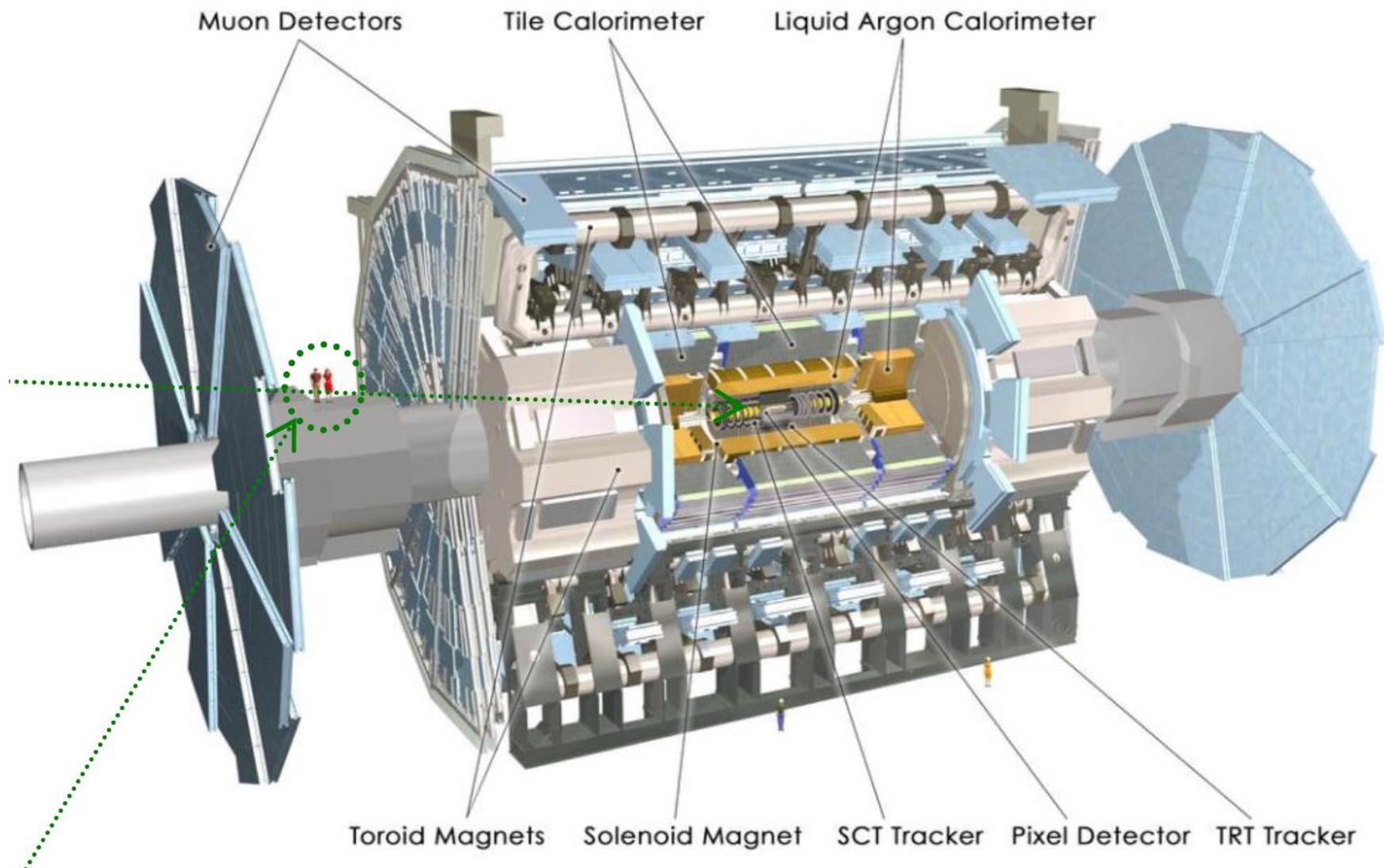
LHCb

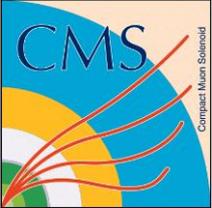
Les photomultiplicateurs du calorimètre
électromagnétique
Photomultipliers of the ECAL calorimeter

07.2006



ATLAS



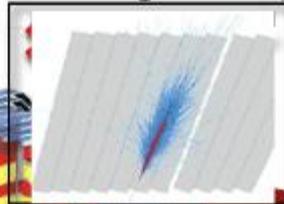


CMS

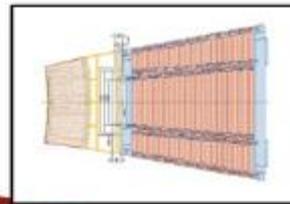
SUPERCONDUCTING COIL

Total weight : 12,500 t
 Overall diameter : 15 m
 Overall length : 21.6 m
 Magnetic field : 4 Tesla

CALORIMETERS
ECAL Scintillating PbWO₄ Crystals

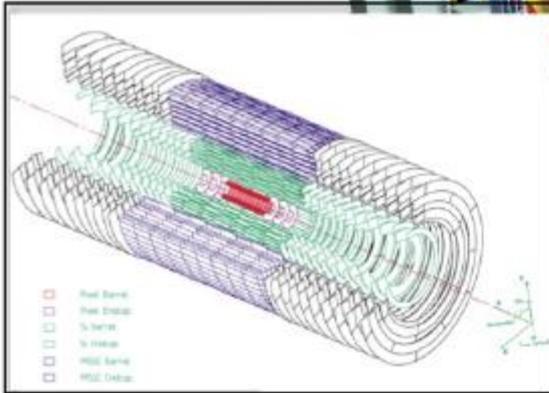


HCAL Plastic scintillator
 brass sandwich



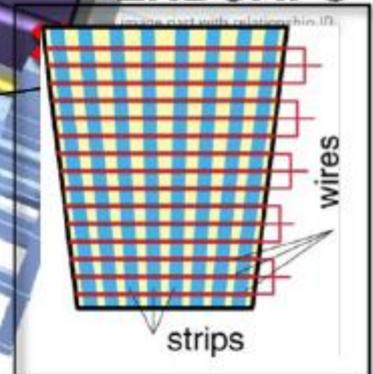
IRON YOKE

TRACKERS

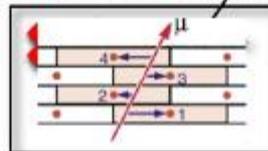


Silicon Microstrips
 Pixels

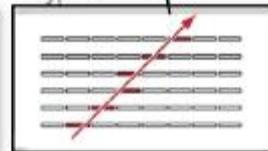
MUON ENDCAPS



MUON BARREL

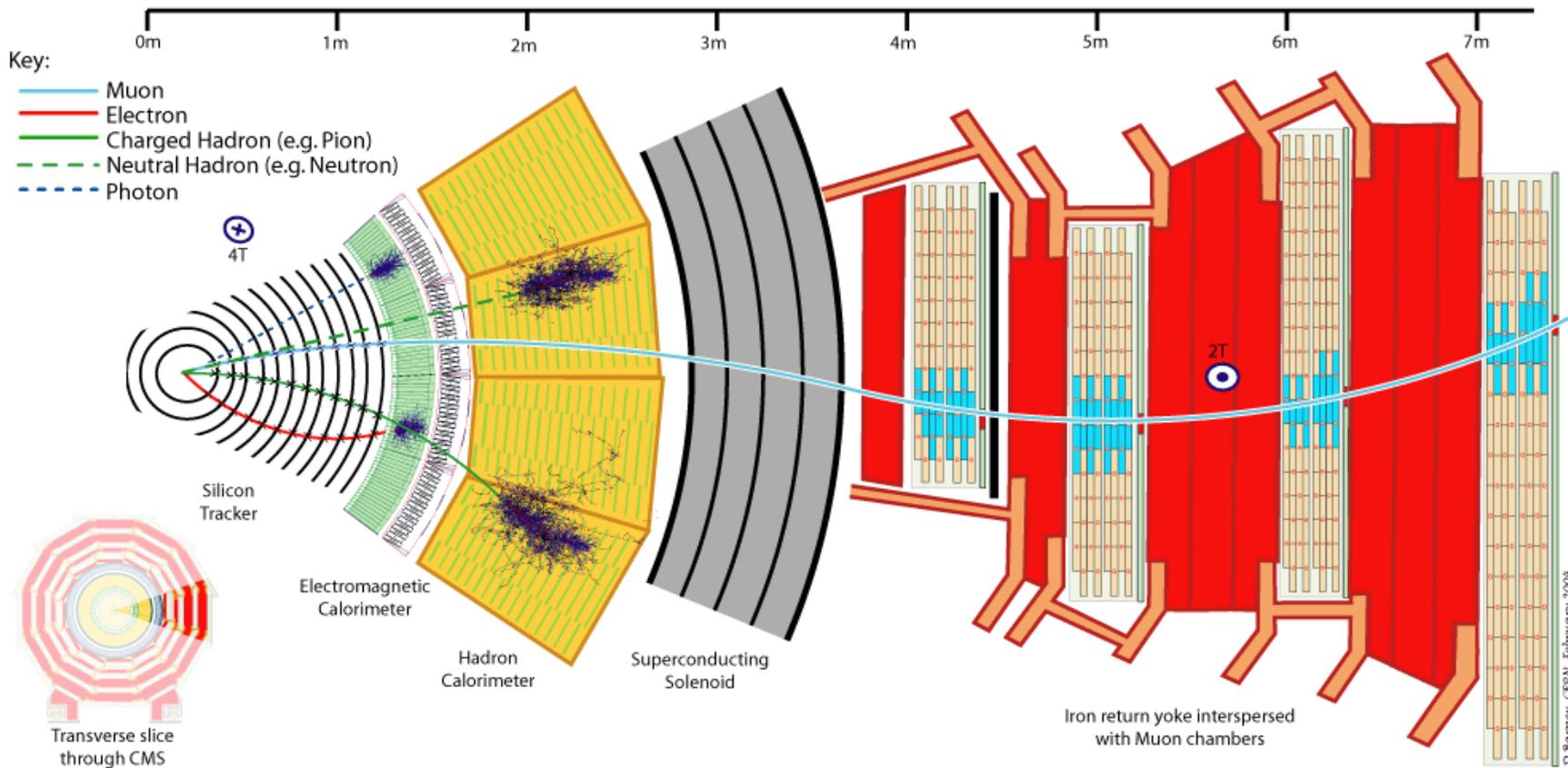


Drift Tube
 Chambers (DT)

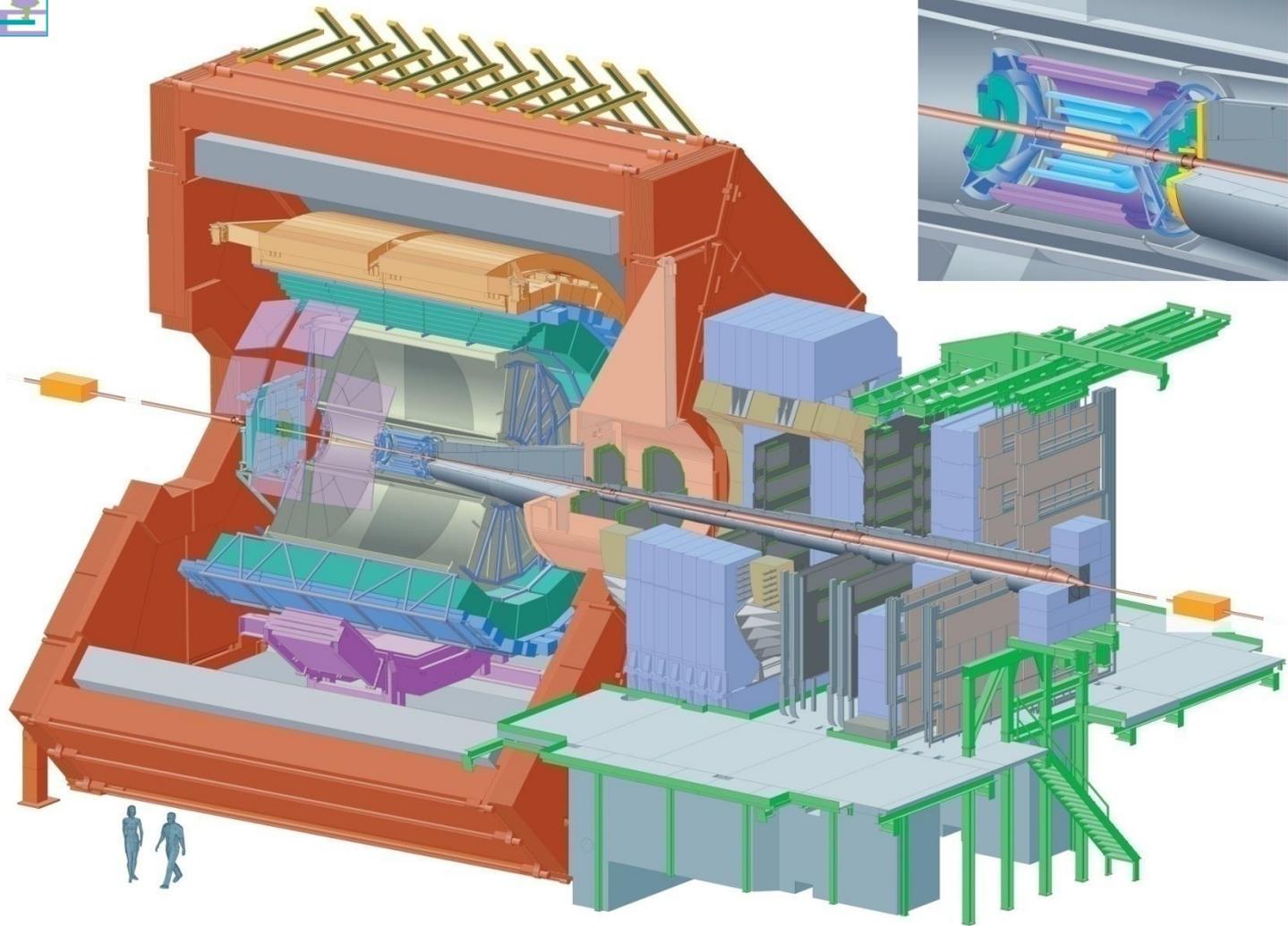


Resistive Plate
 Chambers (RPC)

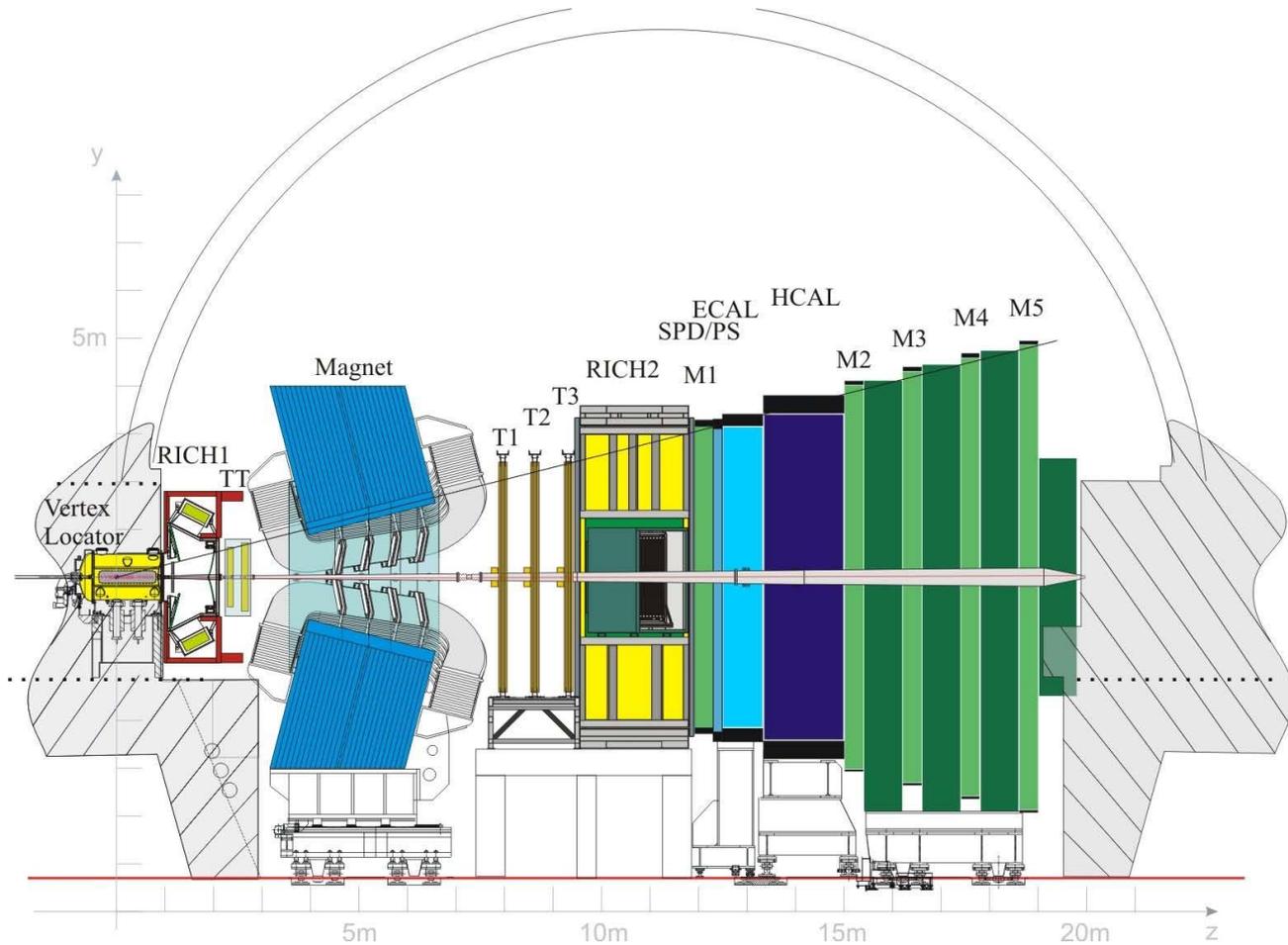
Cathode Strip Chambers (CSC)
 Resistive Plate Chambers (RPC)



ALICE



LHCb



Unsolved Problems

- 중성미자의 질량은?
- 중력은? → quantum gravity? naturalness?
- 게이지 그룹은? → 대통일 이론?
- 왜 3세대? 입자들의 질량은?
- QCD vacuum? Axion?

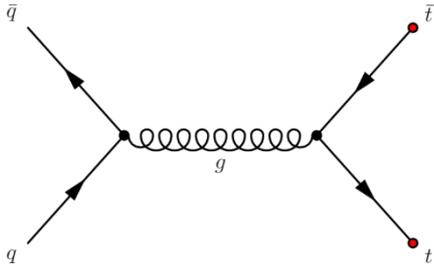
- 암흑물질은?
- CP 붕괴/바리온 생성?

- 초대칭? Compositeness? Extra dimension? 그 밖에 표준모형이 설명하지 못하는 문제들...

여러분의 문제!!!

감사합니다.

추가

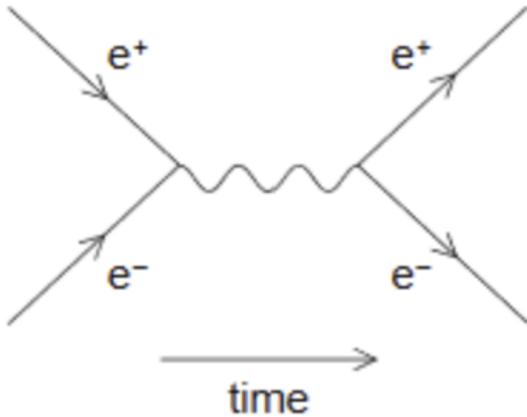


Strong interaction

$$\alpha_s \sim 1$$

EM interaction

$$\alpha \sim \frac{1}{137}$$



Weak interaction

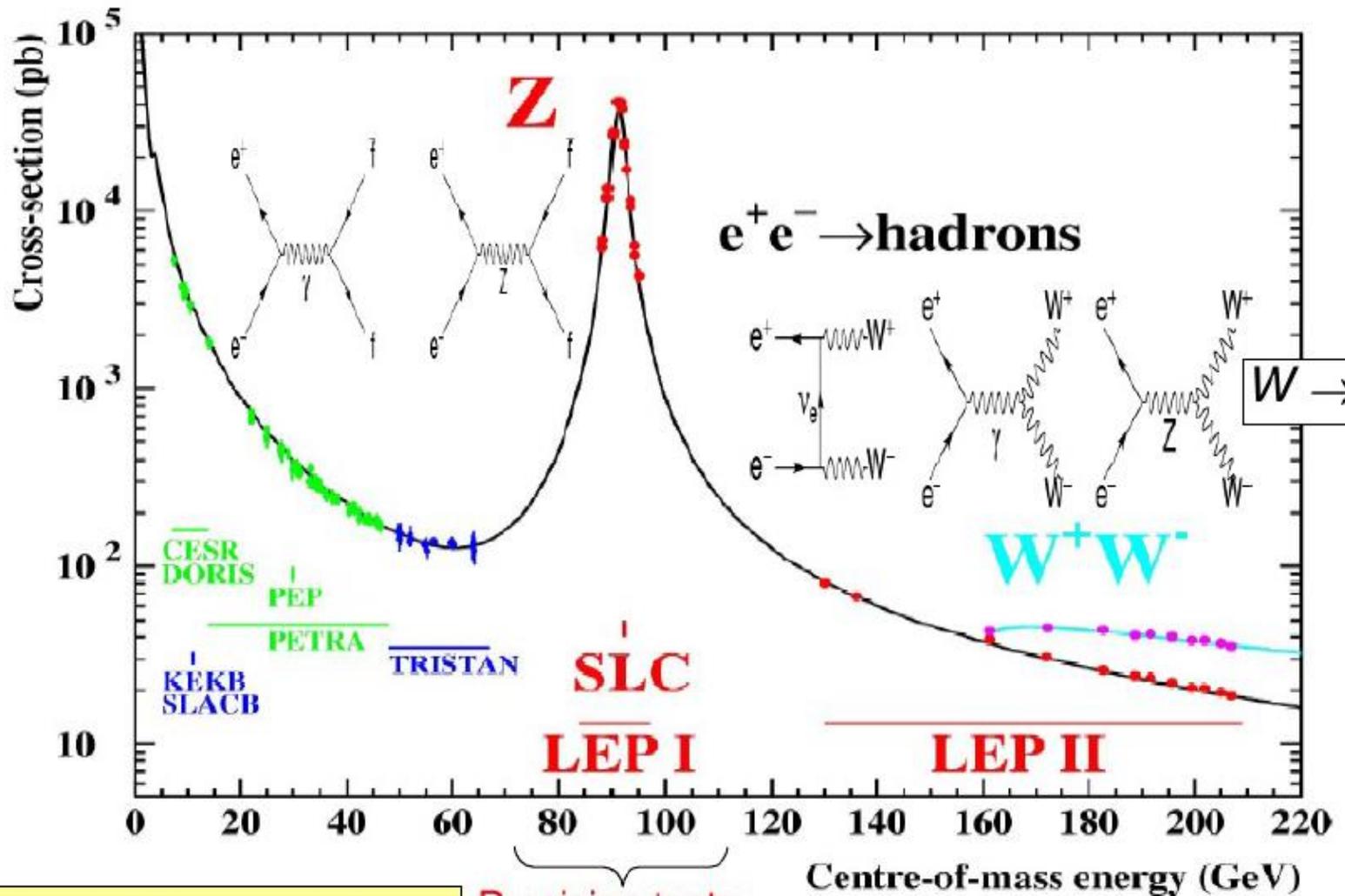
$$G_F \sim 1.166 \times 10^{-5} \text{ (GeV}^{-2}\text{)}$$

$$= -\frac{g^{\mu\nu} - \frac{k^\mu k^\nu}{k^2}}{k^2 - M^2 + i\epsilon}$$

Cf. Gravity

$$G_N \sim 6.7 \times 10^{-39} \text{ (GeV}^{-2}\text{)}$$

Hadron Production in e^+e^-



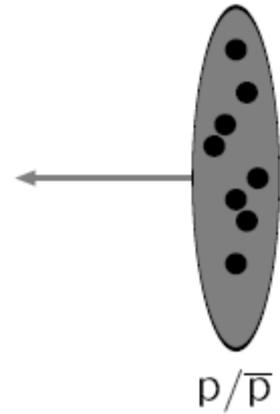
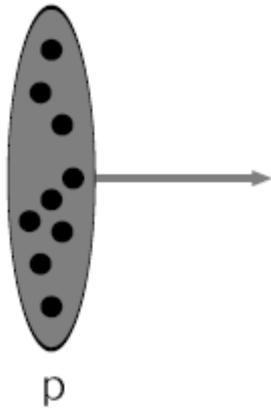
$M_Z = 91.1876 \pm 0.0021 \text{ GeV}$

Precision tests
of the Z sector

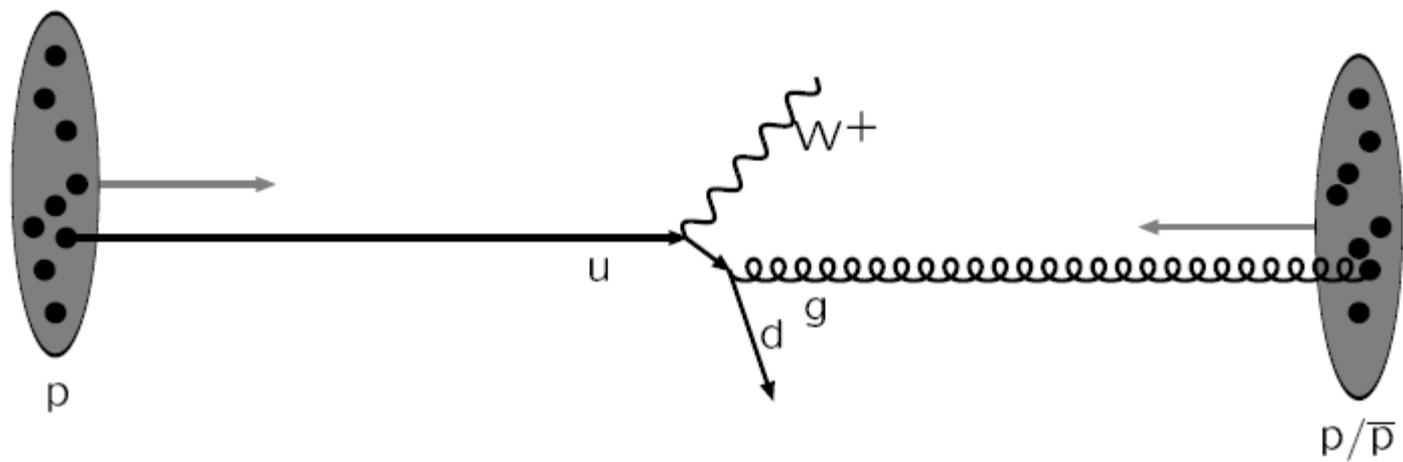
Tests of the W sector

The structure of an event

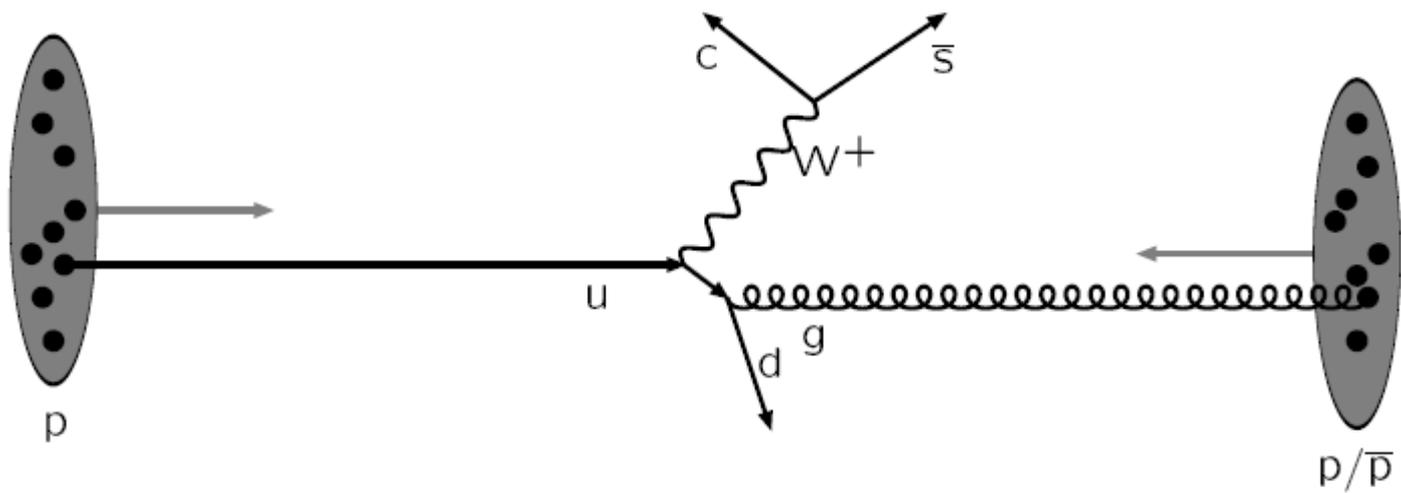
Warning: schematic only, everything simplified, nothing to scale, ...



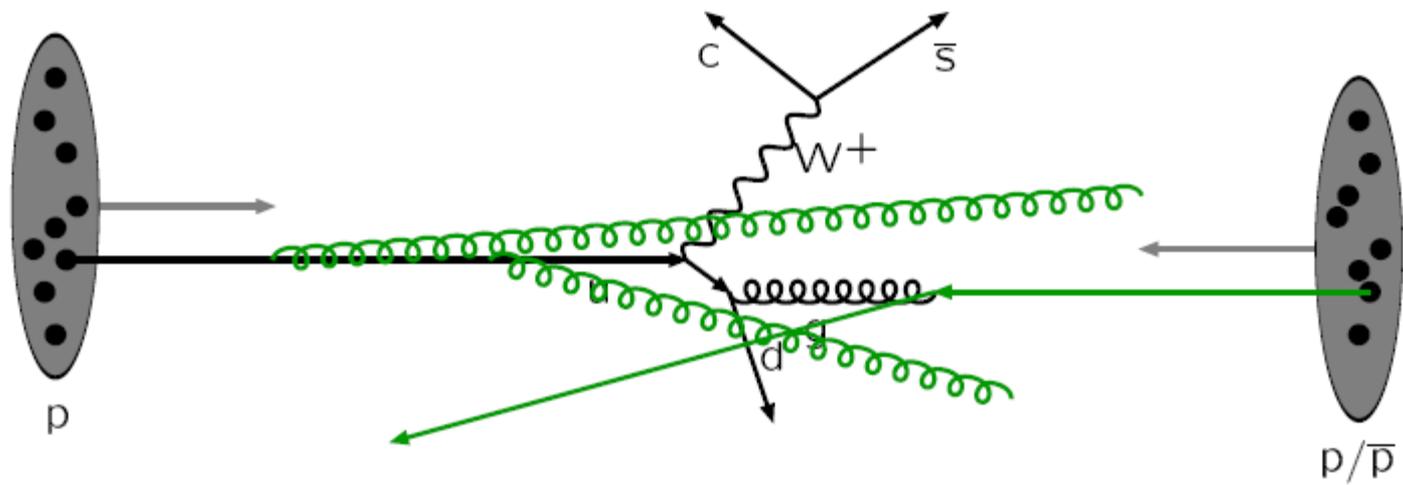
Incoming beams: parton densities



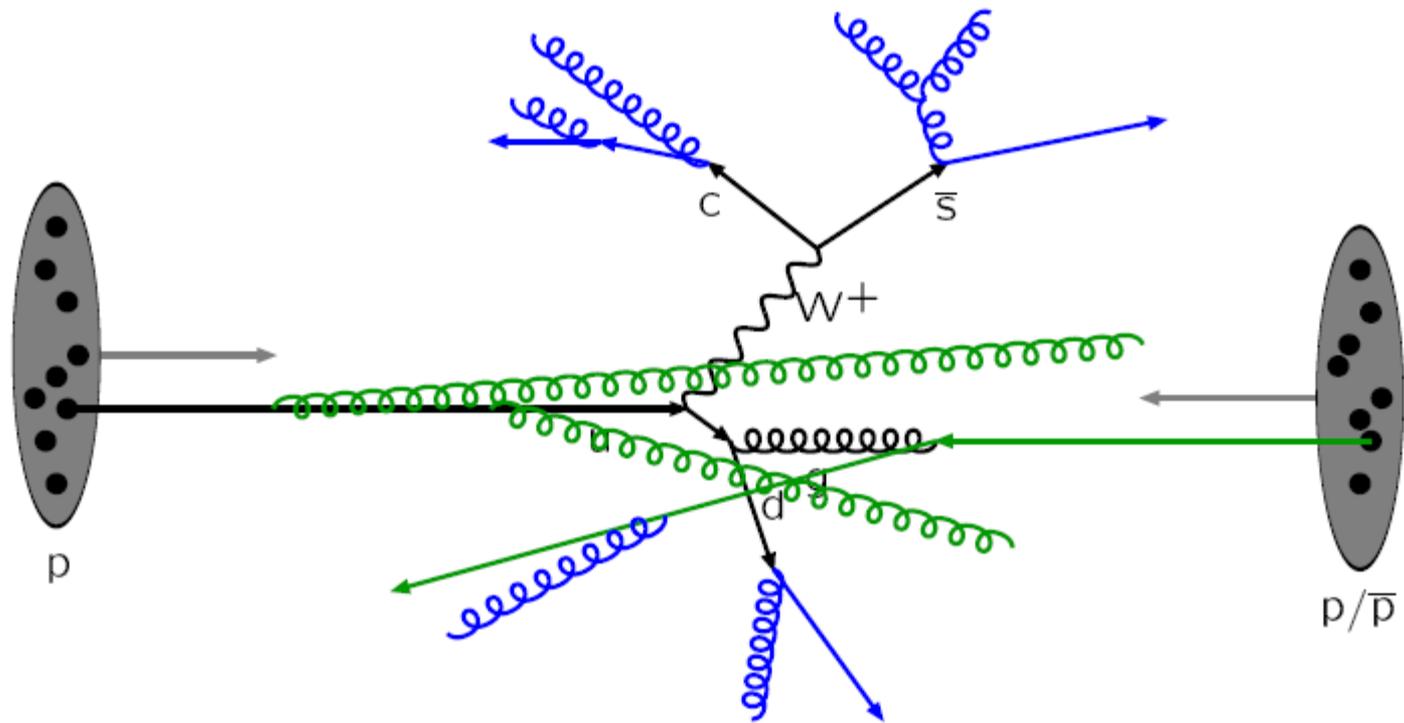
Hard subprocess: described by matrix elements



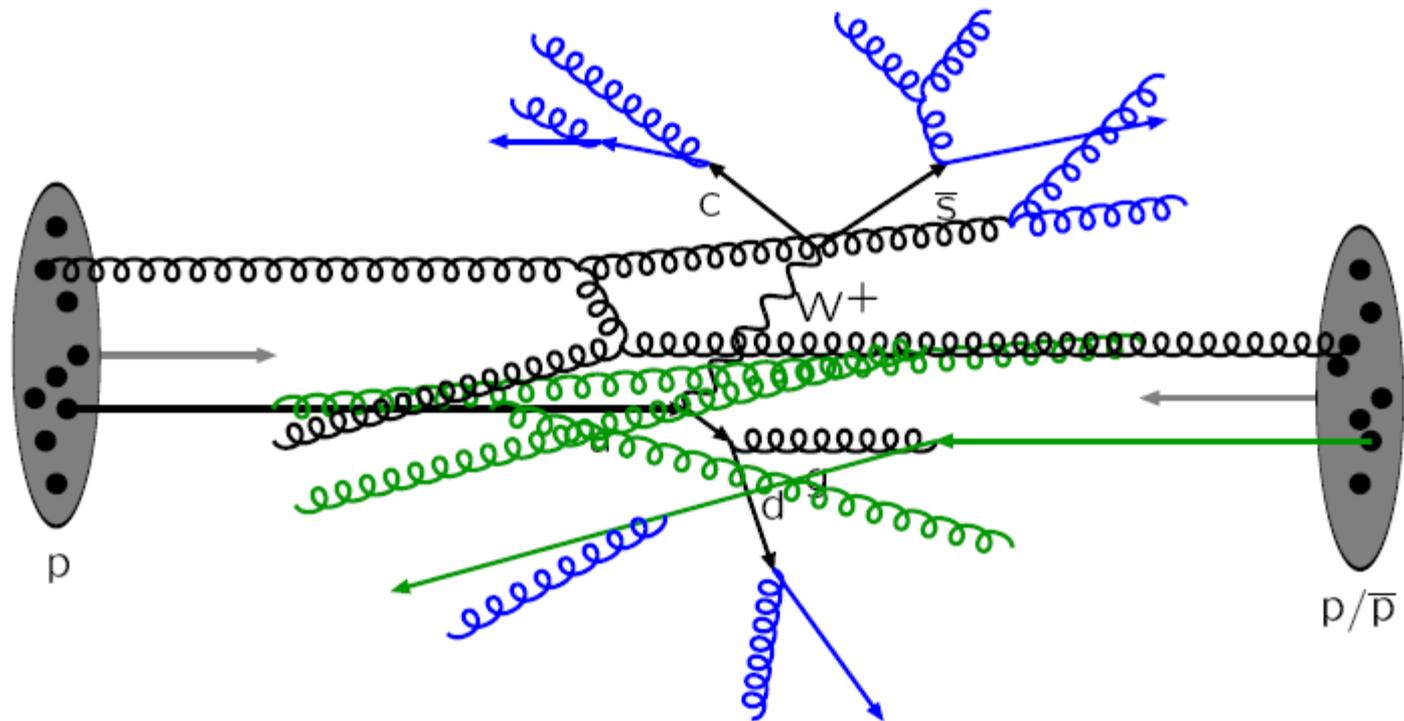
Resonance decays: correlated with hard subprocess



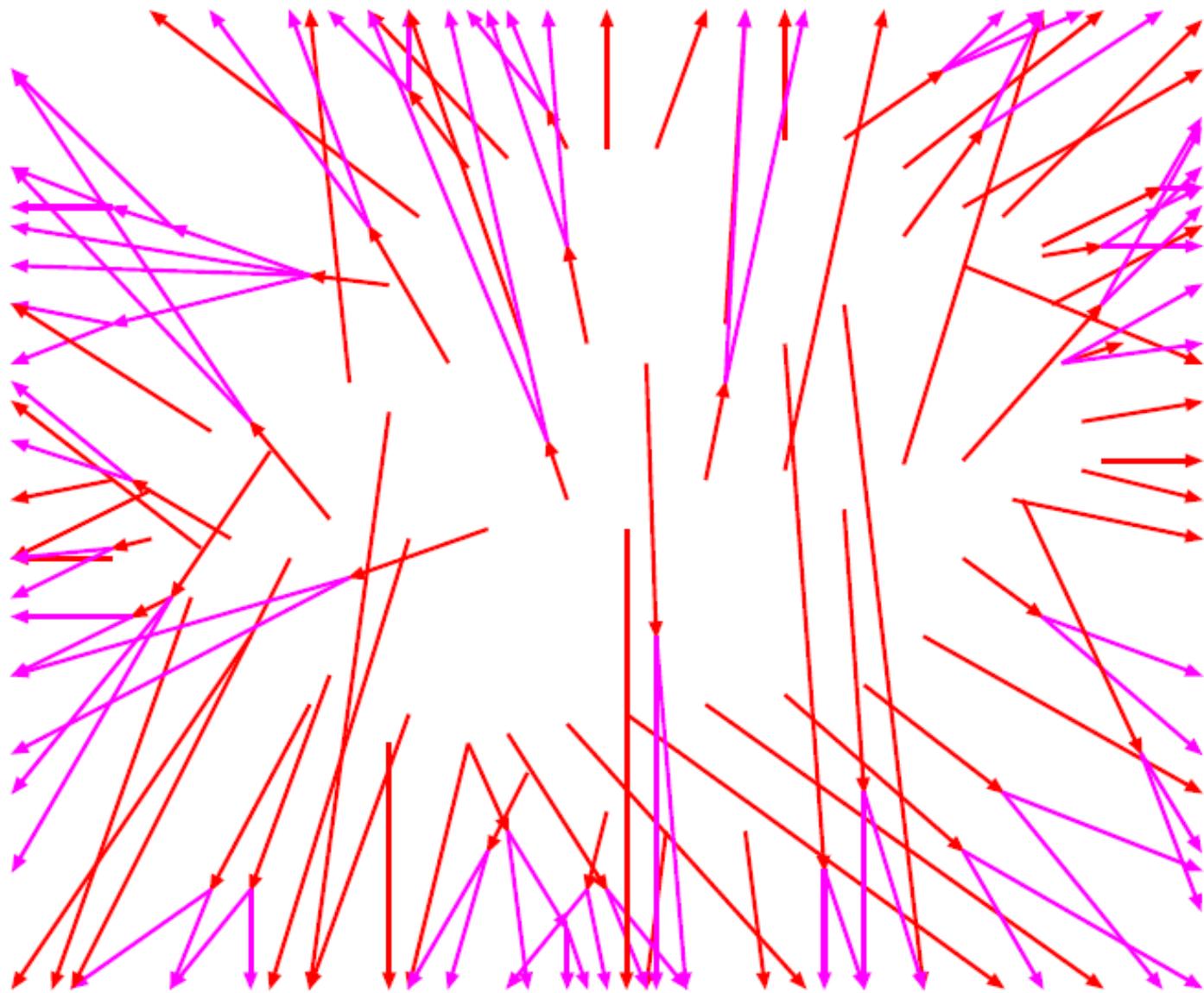
Initial-state radiation: spacelike parton showers



Final-state radiation: timelike parton showers



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



Many hadrons are unstable and decay further

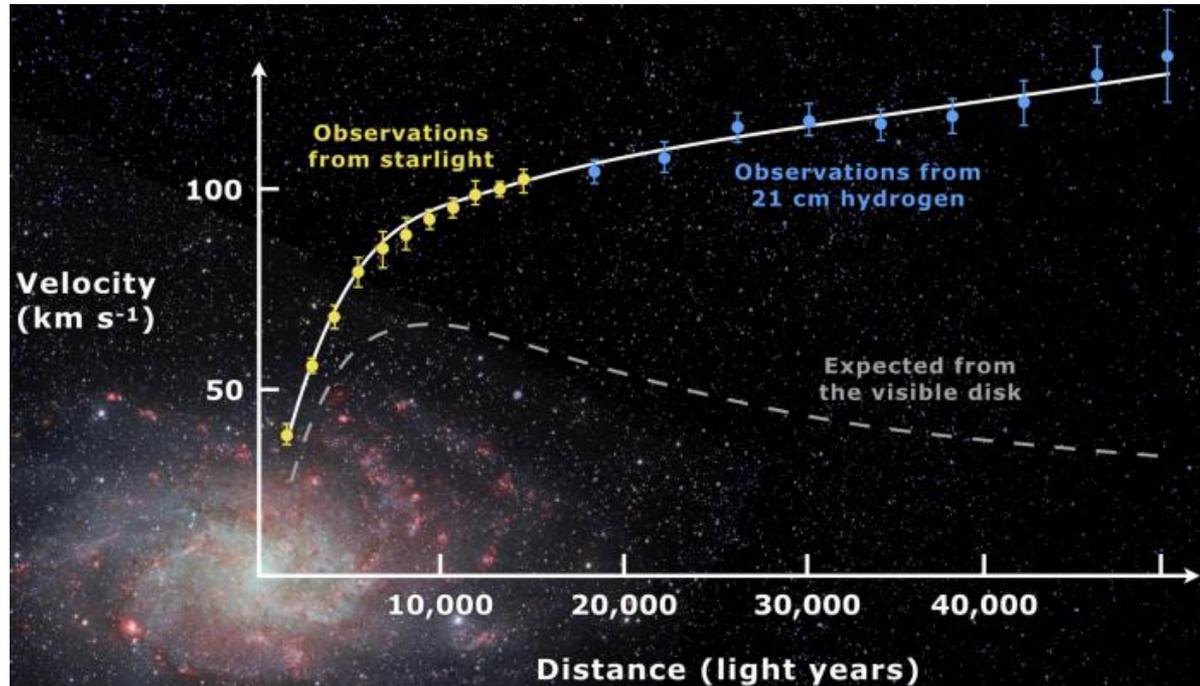
암흑물질

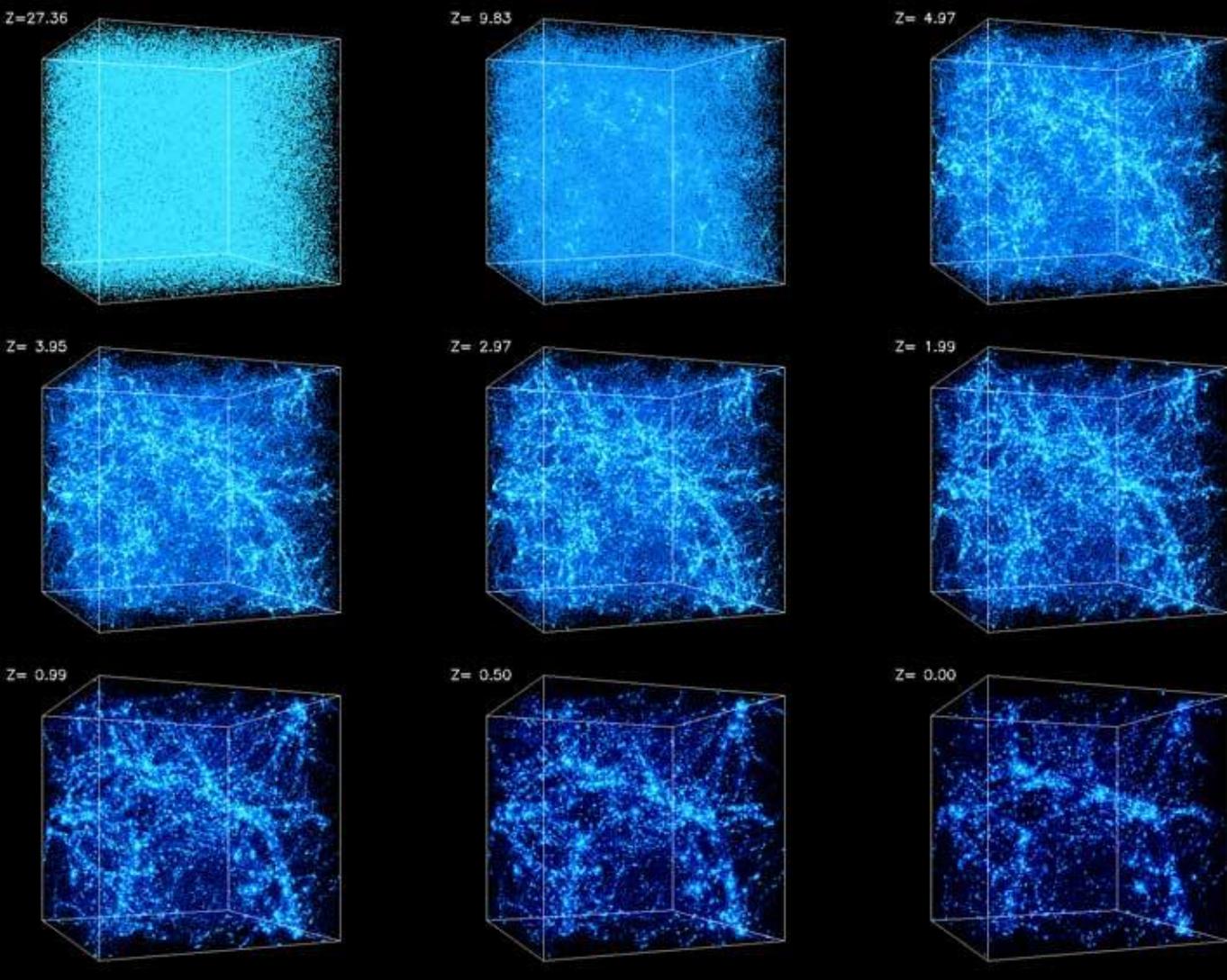
은하의 회전 곡선

$$\frac{GM(r)}{r^2} = \frac{V^2}{r} \rightarrow V(r) = \sqrt{\frac{GM(r)}{r}} \text{ rotation curve}$$

다른 해법도 있긴 하다

- 1) M을 바꾼다 - 암흑물질
- 2) 좌변을 바꾼다 - Modified Gravity
- 3) 우변을 바꾼다 - Modified Newtonian Dynamics (MoND)



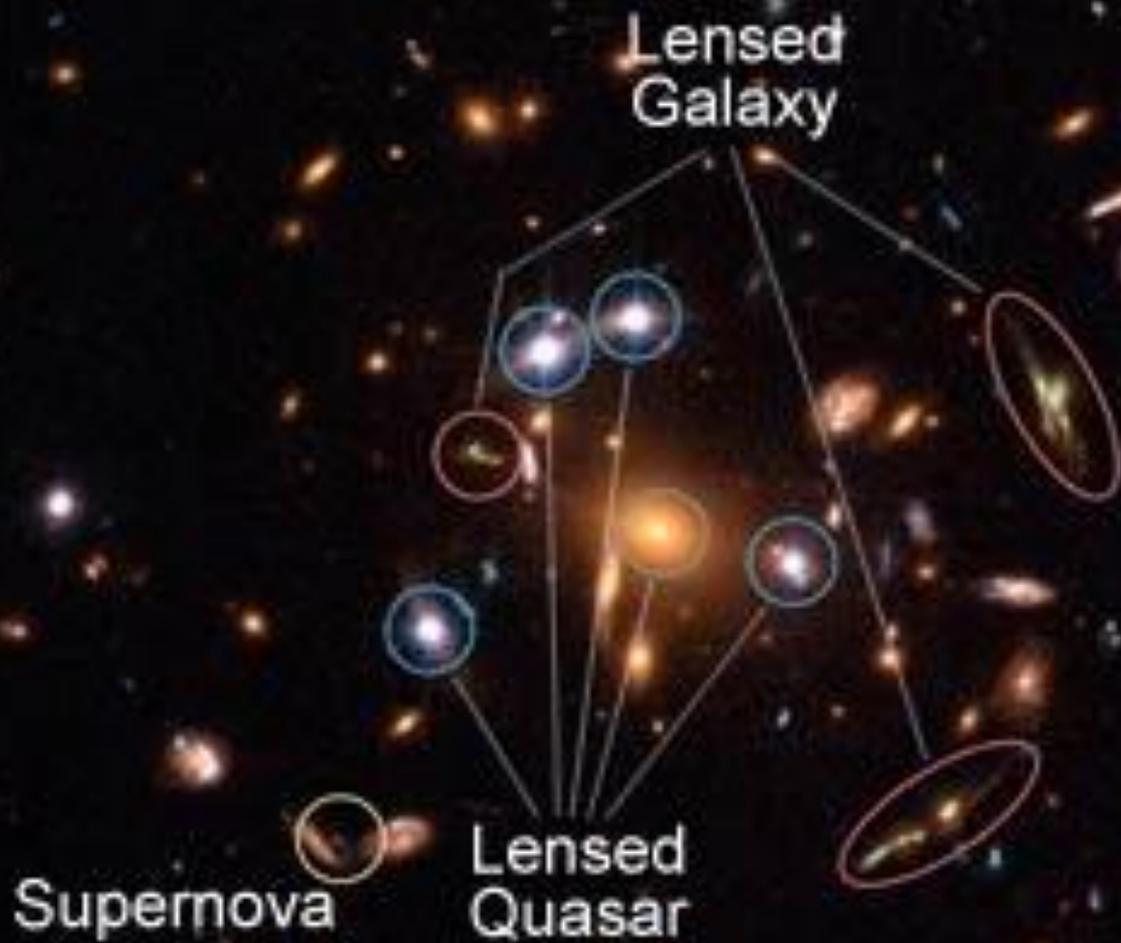


무언가 물질이 더 있어야 중력의 효과로 별과 은하가 우리가 보는 것처럼 생성될 수 있다.

우주의 광역 구조 형성

Galaxy Cluster SDSS J1004+4112

HST ACS/WFC



10''

암흑물질에 의한 중력 렌즈 효과

Bullet cluster(NASA)

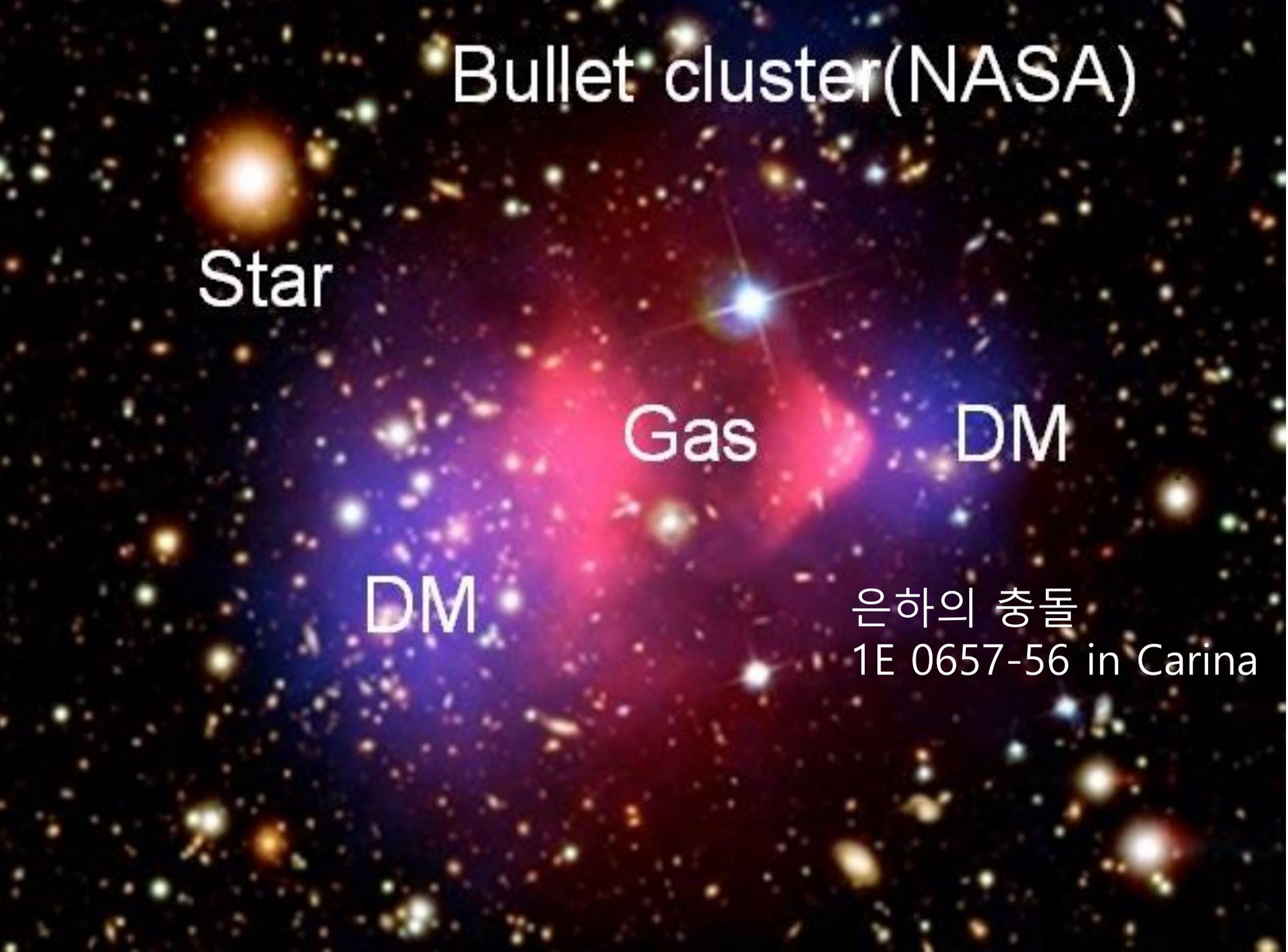
Star

Gas

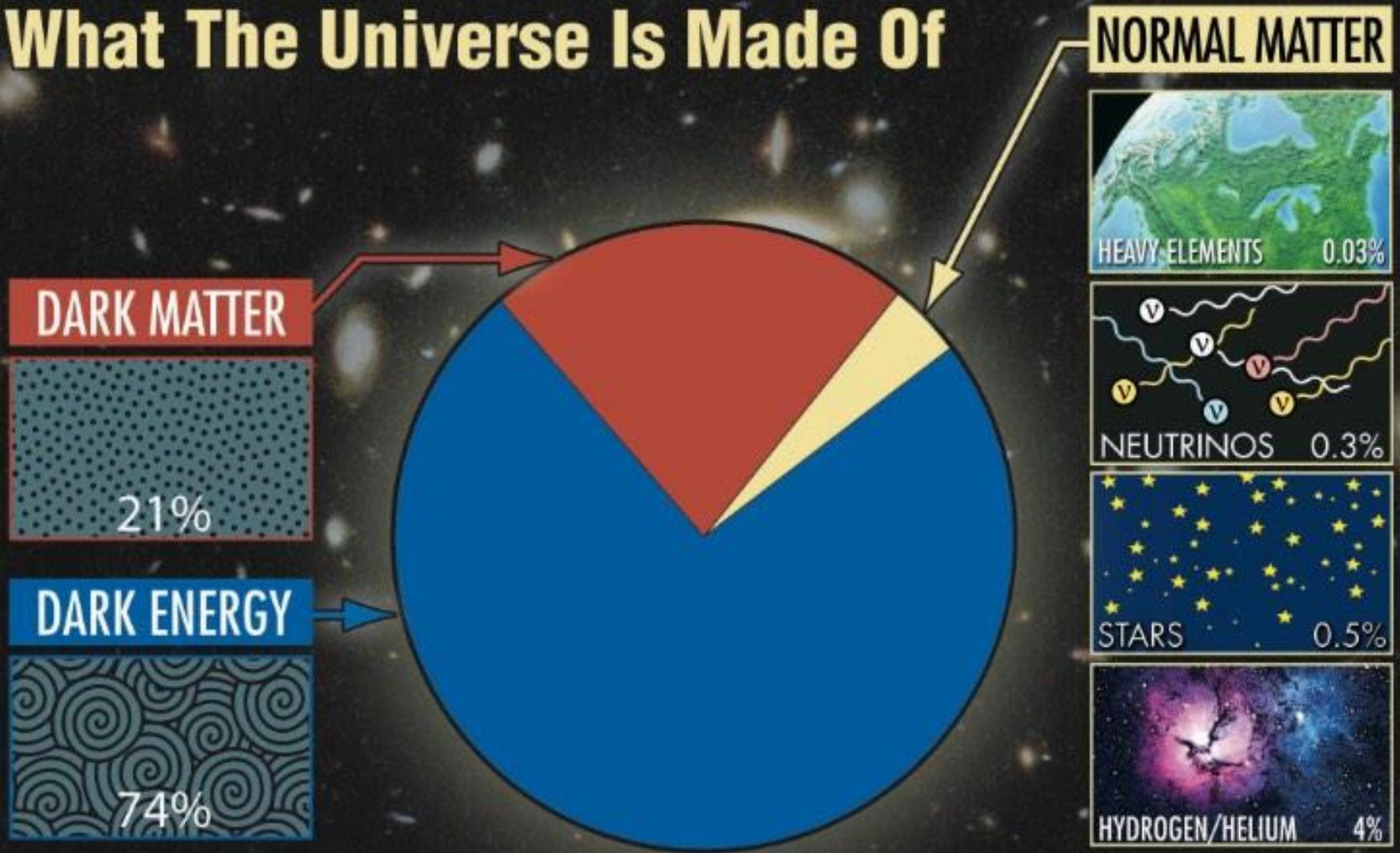
DM

DM

은하의 충돌
1E 0657-56 in Carina

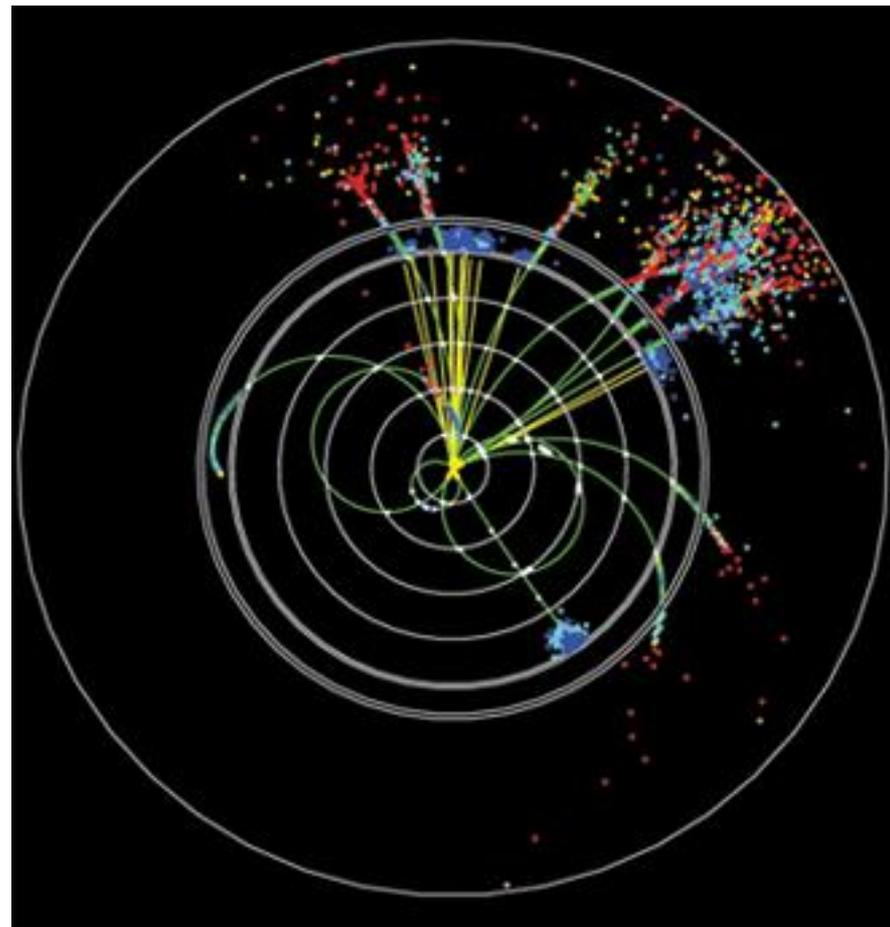
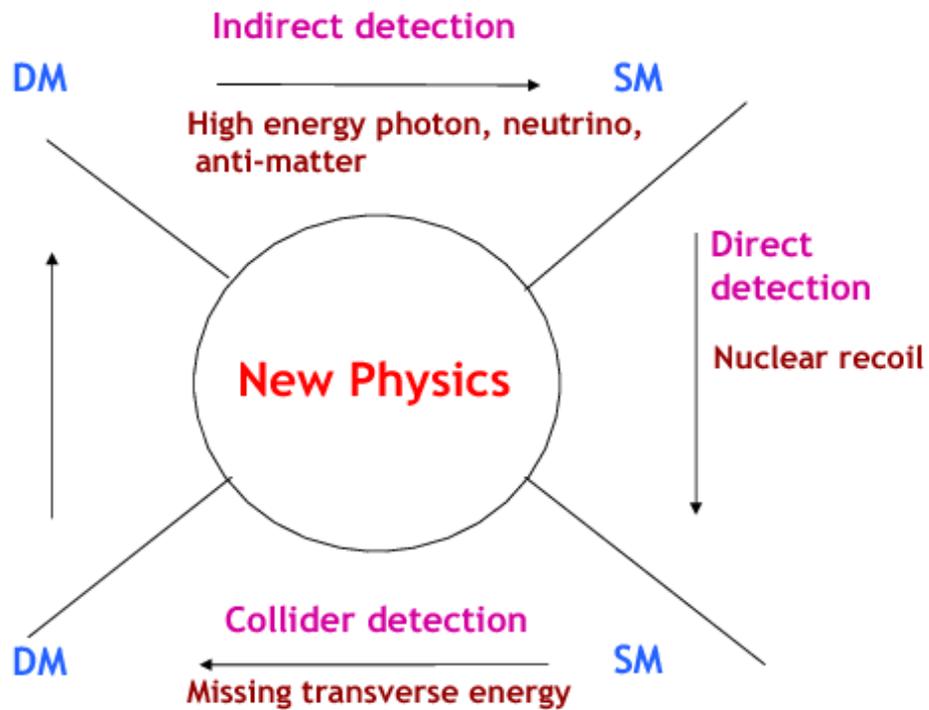


What The Universe Is Made Of



암흑물질과 암흑에너지가 필요하다!

암흑 물질을 보는 방법



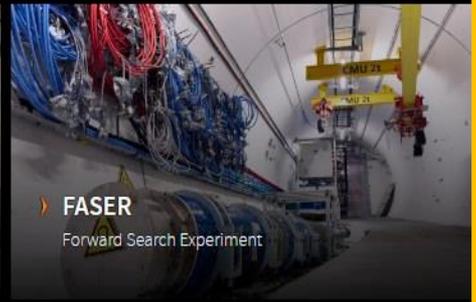
가속기, 지하 실험, 천체 관측, ...

SND@LHC

Official LHC Experiments



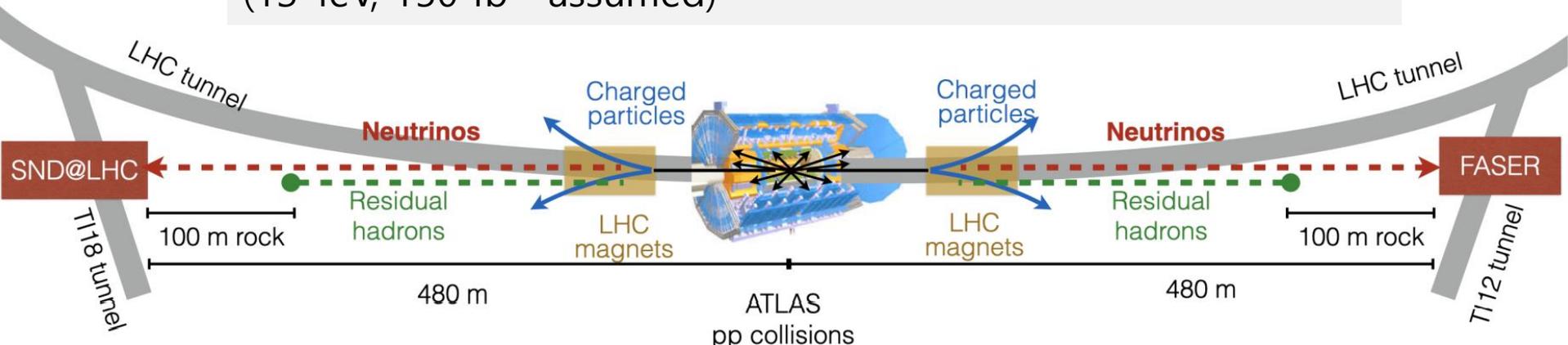
ABOUT NEWS SCIENCE RESOURCES Q SEARCH | EN ▾



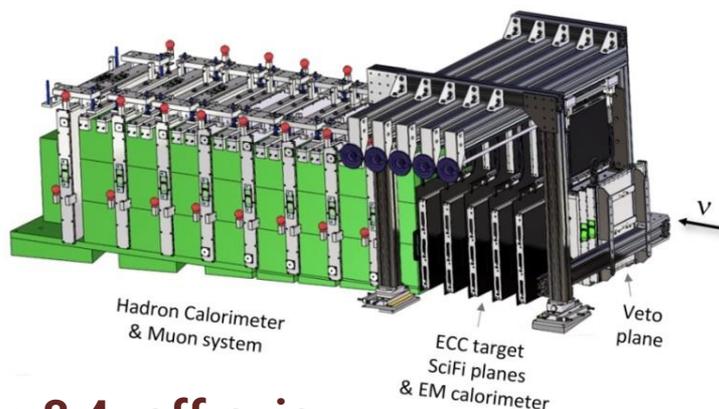
Forward Experiments at the LHC

Physics in the Forward Region

10^{16} inelastic pp scattering events for LHC Run 3
 $10^{17} \pi^0$, $10^{16} \eta$, $10^{15} D$, $10^{13} B$, ... expected for each hemisphere
 (13 TeV, 150 fb^{-1} assumed)

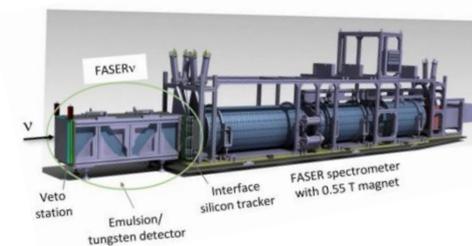


SND@LHC



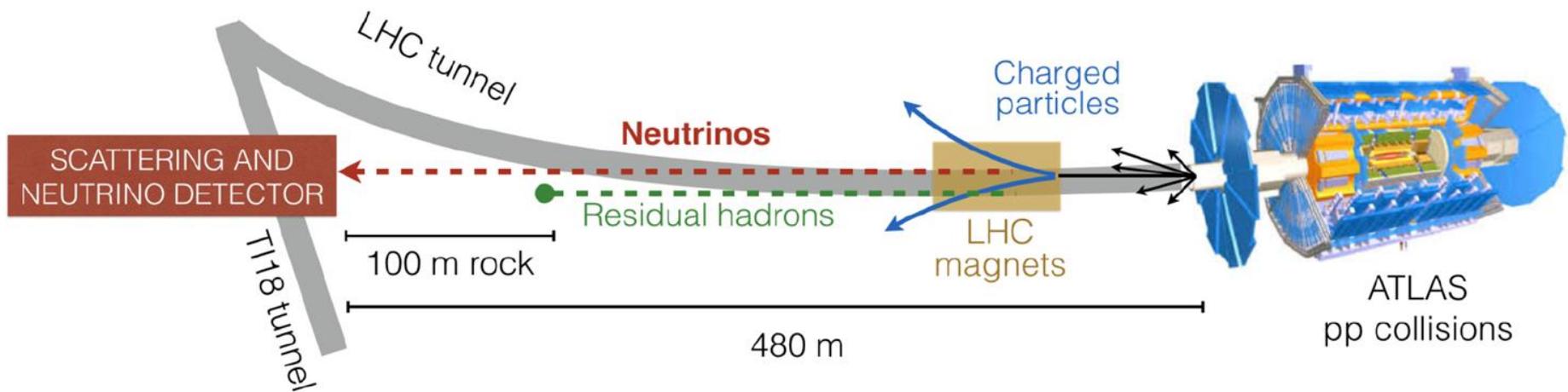
$7.2 < \eta < 8.4$, off-axis

FASER & FASERv



$\eta > 8.8$
 on-axis

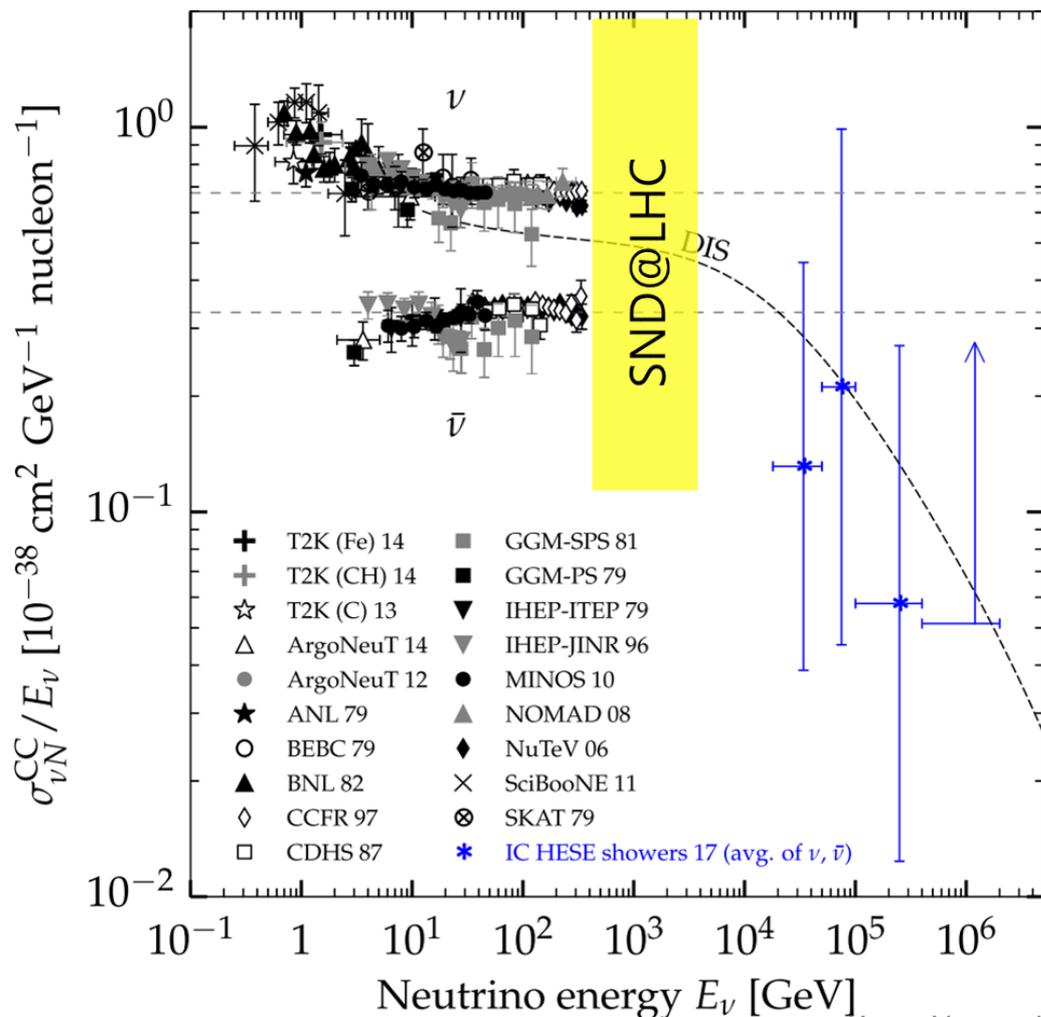
The SND@LHC



- 480 m away from the ATLAS interaction point (IP1)
- Located in the T118 tunnel, former positron transfer line to LEP
- Shielded by 100 m rock
- LHC magnet deflects charged particles
- Neutrinos and (if exist) feebly interacting particles (FIPs) arrive at the detector

Neutrinos at the LHC

PRL 122 (2019) 041101

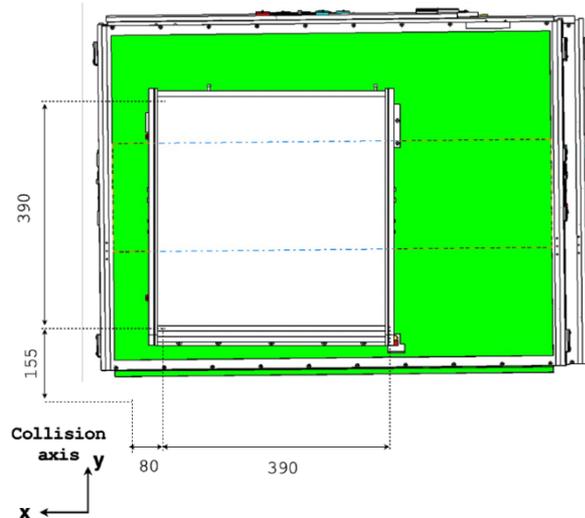


LHC 중성미자는 매우 흥미로운 주제입니다. 왜냐하면...

- 충돌기에서 만들어진 중성미자를 직접 검출하는 일은 최초.
- 이렇게 높은 에너지의 중성미자를 연구하는 일은 최초.
- 300 GeV ~ a few TeV
- 세 종류의 중성미자를 동시에 연구하는 일은 최초.
- LHC 전방으로 충분히 많은 수의 중성미자가 생성됨.

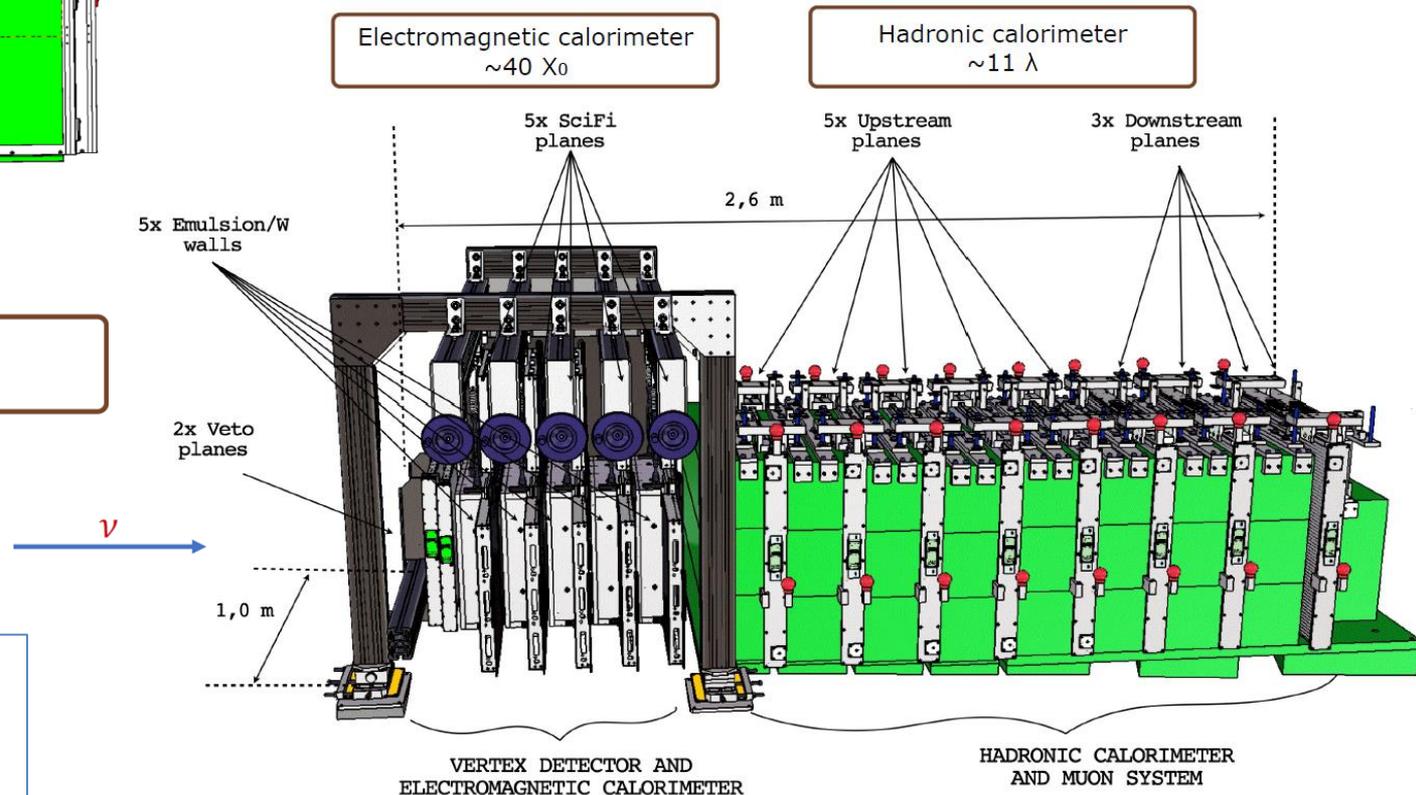
The SND@LHC Detector

**FRONT
VIEW**



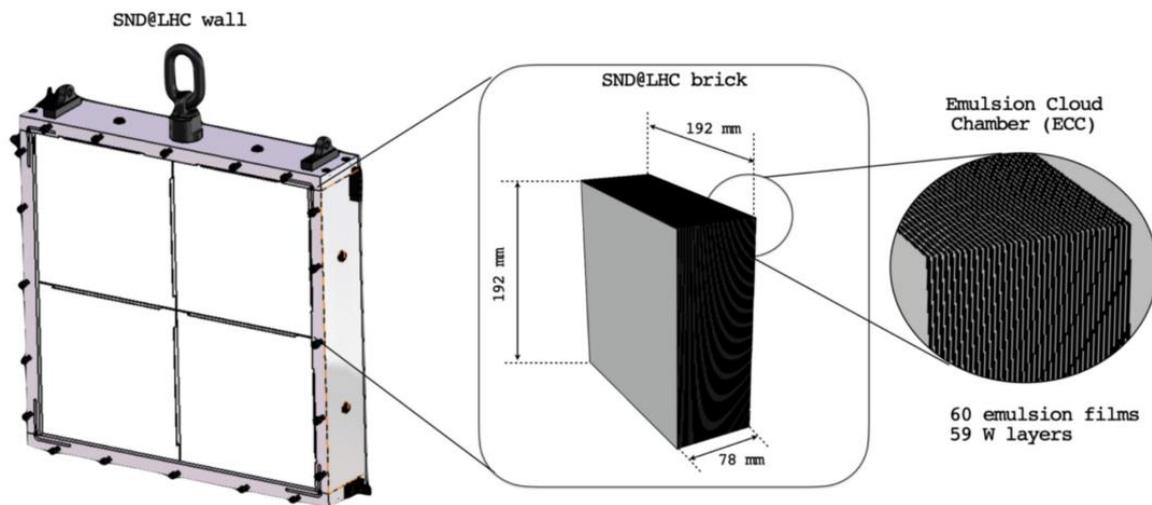
Off axis location

Hybrid detector optimised for the identification of all three neutrino flavours and the FIPs



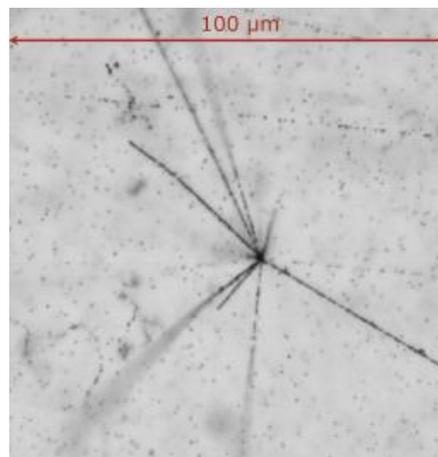
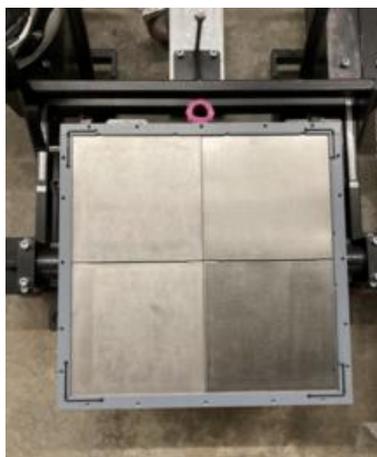
Detector paper :
arXiv 2210.02784
to appear on JINST

Emulsion Cloud Chamber

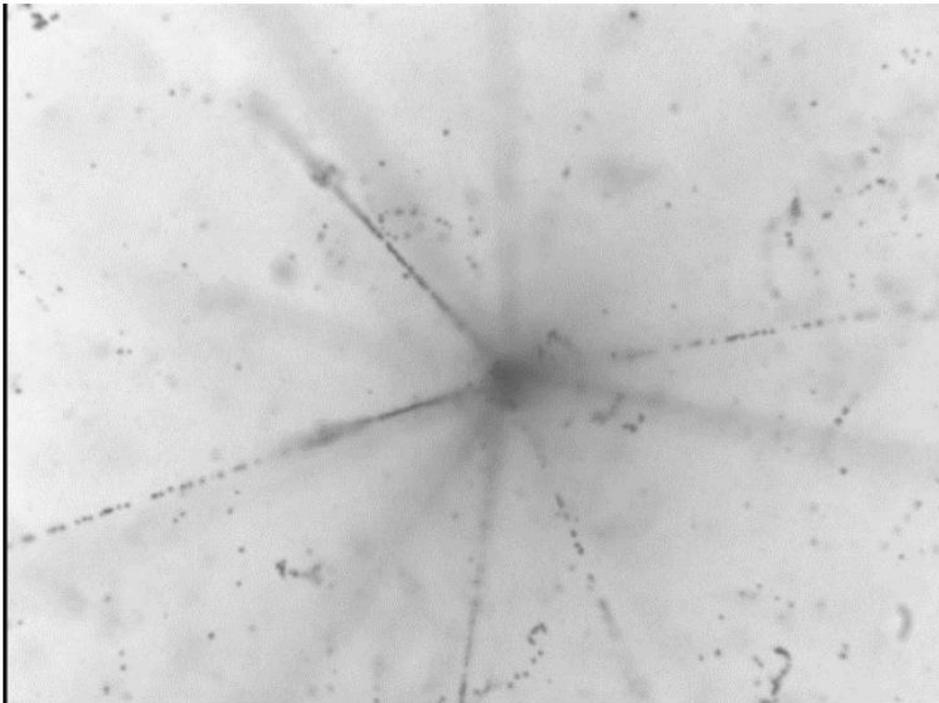


Emulsion target

- Emulsion cloud chamber (ECC) brick consists of 60 emulsion films interleaved with 59 tungsten plates
- Total tungsten mass 830 kg
- 5 walls x 4 bricks x 60 emulsion films
- Replaced every 20 fb⁻¹



Nuclear emulsion



200 GeV/nucleon Sulfur ($^{32}_{16}\text{S}$) interaction

원자핵건판

- 브롬화은 AgBr의 반응으로 입자가 지나간 흔적을 기록
- 뛰어난 공간 해상도 (마이크로미터 이하)
- PID, 운동량, 에너지 측정 가능
- 파이온, 케이온을 발견하는 등 입자물리의 역사에 중요한 기여
- 현재도 타우 중성미자 발견, 희귀 핵 검출 등 특수한 목적에 사용

경상대학교 원자핵건판 그룹의 참여 실험들



- 1978 - 1983 **FNAL E531** ~ 100 kg
 charm, $\nu_\mu \rightarrow \nu_\tau$
- 1990 - 2000 **CHORUS (CERN WA95)** ~ 1 ton
 $\nu_\mu \rightarrow \nu_\tau$ short baseline
 No ν_τ event, ~140,000 ν_μ events, ~2000 charm

- 1994 - 2001 **DONuT (FNAL E872)** ~ 1 ton
 ν_τ direct observation **(9 events)**



- 2000 - **OPERA (CERN CNGS)** ~ 1250 ton
 $\nu_\mu \rightarrow \nu_\tau$ long baseline
 Appearance mode **(10 events)**



- 2021 - **SND@LHC, SHiP**

The results of CHORUS, DONuT and OPERA are consistent with each other.

Emulsion Activities



2022
16 ECC Brick walls assembled
3522 emulsion films developed (140 m²)

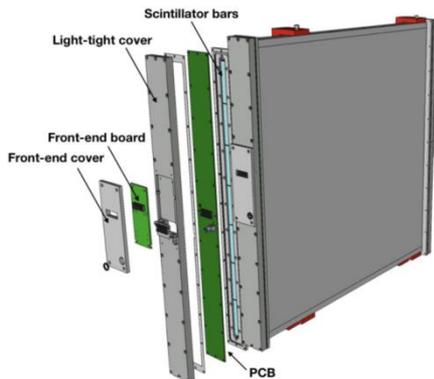
2023
10 ECC Brick walls assembled
2300 emulsion films developed (92 m²)
2000L disposed chemical solutions



Kang Young Lee



Other Detector Components



Veto system

- Tags incoming charged particles and consists of 2 planes with 7 Sci bars

SciFi detector

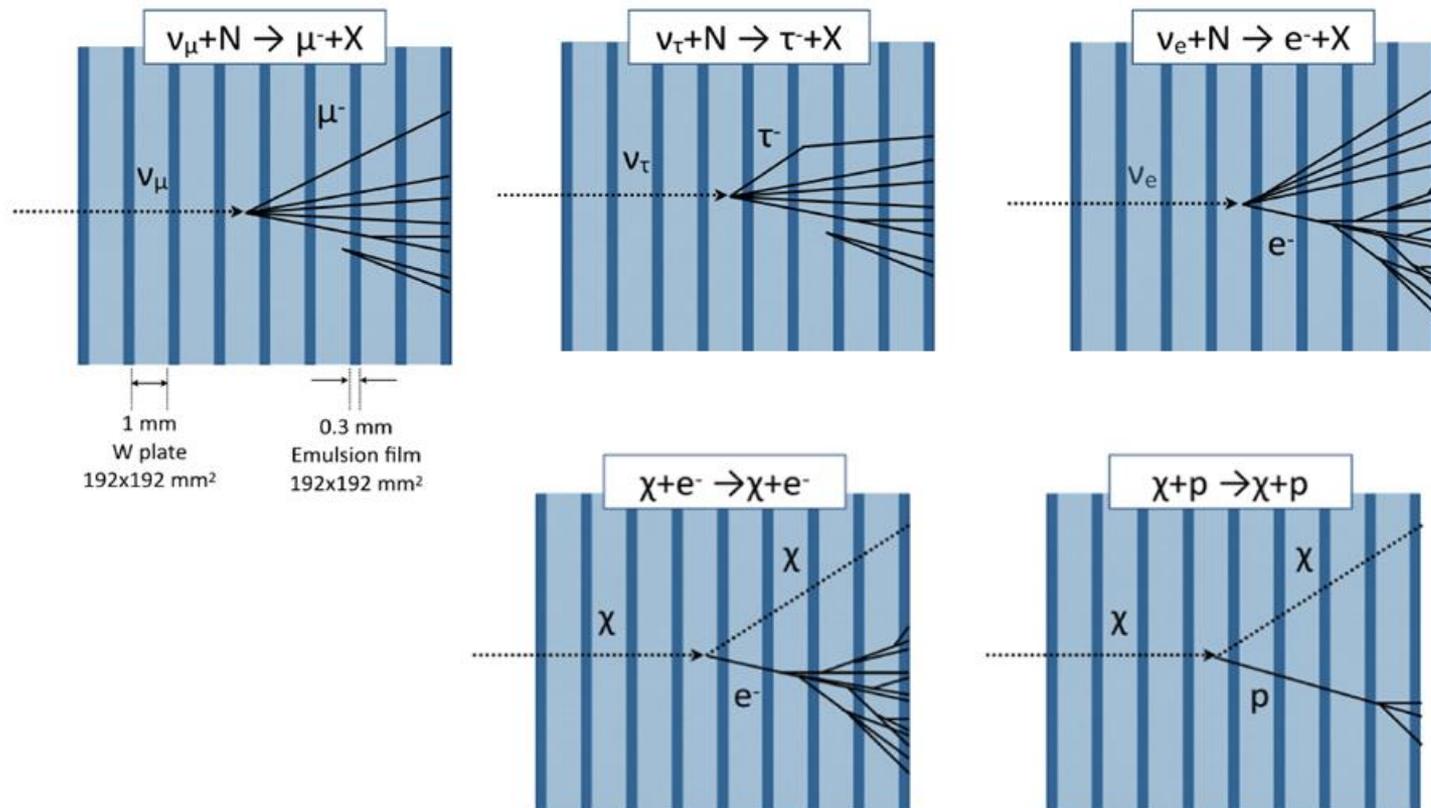
- Scintillating Fiber detectors interface emulsion with electronic detectors for position prediction and timing of outgoing particles.
- Electromagnetic calorimetry



Hadronic calorimeter and muon system

- Upstream : 5 stations of Fe blocks with 10 Sci bars for hadronic calorimetry
- Downstream : 3 stations with 60 horizontal and 60 vertical Sci bars for muon tagging

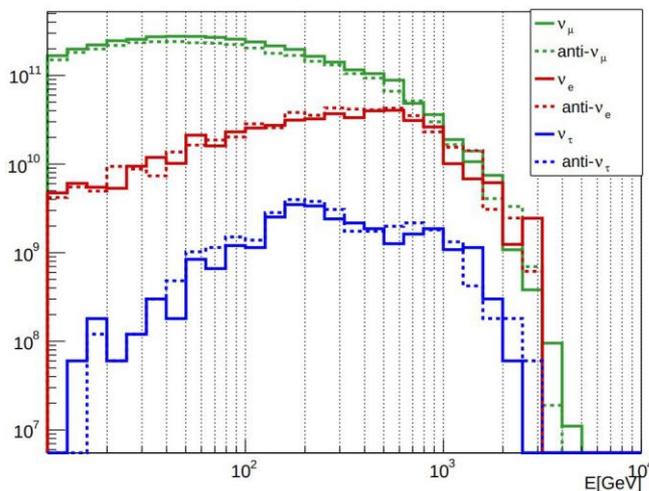
Physics Cases – Event Topology



Identification of all three neutrino flavours and FIPs by event topologies in the ECC brick

Physics Cases – Neutrino Production

Incoming Neutrinos to SND

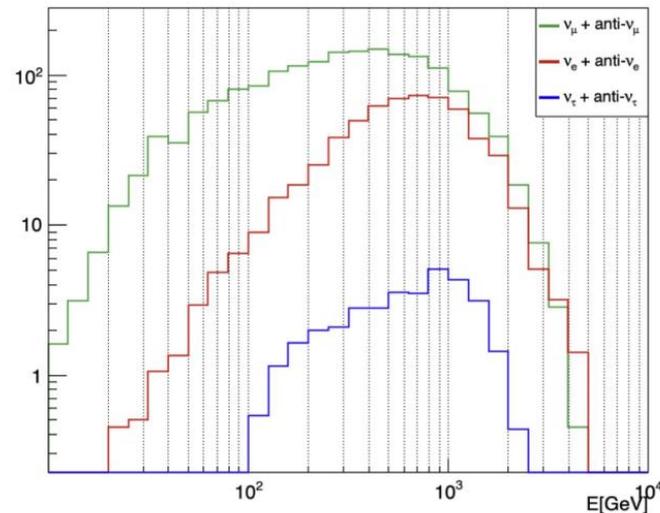


Measurement of $\sigma(pp \rightarrow \nu X)$

- $\nu_\mu + \bar{\nu}_\mu$ charged-current: 1447
- $\nu_e + \bar{\nu}_e$ charged-current: 450
- $\nu_\tau + \bar{\nu}_\tau$ charged-current: 34

Estimated from
 290 fb⁻¹ in LHC Run 3
 Angular acceptance $7.2 < \eta < 8.4$

Neutrino interactions in SND



Flavour	Neutrinos in acceptance		CC neutrino interactions		NC neutrino interactions	
	$\langle E \rangle$ [GeV]	Yield	$\langle E \rangle$ [GeV]	Yield	$\langle E \rangle$ [GeV]	Yield
ν_μ	120	3.4×10^{12}	450	1028	480	310
$\bar{\nu}_\mu$	125	3.0×10^{12}	480	419	480	157
ν_e	300	4.0×10^{11}	760	292	720	88
$\bar{\nu}_e$	230	4.4×10^{11}	680	158	720	58
ν_τ	400	2.8×10^{10}	740	23	740	8
$\bar{\nu}_\tau$	380	3.1×10^{10}	740	11	740	5
TOT		7.3×10^{12}		1930		625

First Observation of Collider Neutrinos

PHYSICAL REVIEW LETTERS **131**, 031802 (2023)

Editors' Suggestion

Observation of Collider Muon Neutrinos with the SND@LHC Experiment

R. Albanese^{1,2}, A. Alexandrov¹, F. Alicante^{1,2}, A. Anokhina³, T. Asada^{1,2}, C. Battilana^{4,5}, A. Bay⁶,
 C. Betancourt⁷, R. Biswas⁸, A. Blanco Castro⁹, M. Bogomilov¹⁰, D. Bonacorsi^{4,5}, W. M. Bonivento¹¹,
 P. Bordalo⁹, A. Boyarsky^{12,13}, S. Buontempo¹, M. Campanelli¹⁴, T. Camporesi⁸, V. Canale^{1,2}, A. Castro^{4,5},
 D. Centanni^{1,15}, F. Cerutti⁸, M. Chernyavskiy³, K.-Y. Choi¹⁶, S. Cholak⁶, F. Cindolo⁴, M. Climescu¹⁷,
 A. P. Conaboy¹⁸, G. M. Dallavalle⁴, D. Davino^{1,19}, P. T. de Bryas⁶, G. De Lellis^{1,2}, M. De Magistris^{1,15},
 A. De Roeck⁸, A. De Rújula⁸, M. De Serio^{20,21}, D. De Simone⁷, A. Di Crescenzo^{1,2}, R. Donà^{4,5}, O. Durhan²²,
 F. Fabbri⁴, F. Fedotovs¹⁴, M. Ferrillo⁷, M. Ferro-Luzzi⁸, R. A. Fini²⁰, A. Fiorillo^{1,2}, R. Fresa^{1,23}, W. Funk⁸,
 F. M. Garay Walls²⁴, A. Golovatiuk^{1,2}, A. Golutvin²⁵, E. Graverini⁶, A. M. Guler²², V. Guliaeva³,
 G. J. Haefeli⁶, J. C. Helo Herrera^{26,27}, E. van Herwijnen²⁵, P. Iengo¹, S. Ilieva^{1,2,10}, A. Infantino⁸, A. Iuliano^{1,2},
 R. Jacobsson⁸, C. Kamiscioglu^{22,28}, A. M. Kauniskangas⁶, E. Khalikov³, S. H. Kim²⁹, Y. G. Kim³⁰,
 G. Klioutchnikov⁸, M. Komatsu³¹, N. Konovalova³, S. Kovalenko^{26,32}, S. Kuleshov^{26,32}, H. M. Lacker¹⁸,
 O. Lantwin³, F. Lasagni Manghi⁴, A. Lauria^{1,2}, K. Y. Lee²⁹, K. S. Lee³³, S. Lo Meo⁴, V. P. Loschiavo^{1,19},
 S. Marcellini⁴, A. Margiotto^{4,5}, A. Mascellani⁶, A. Miano^{1,2}, A. Mikulenko¹², M. C. Montesi^{1,2},
 F. L. Navarria^{4,5}, S. Ogawa³⁴, N. Okateva³, M. Ovchinnikov¹², G. Paggi^{4,5}, B. D. Park²⁹, A. Pastore²⁰,
 A. Perrotta⁴, D. Podgrudkov³, N. Polukhina³, A. Prota^{1,2}, A. Quercia^{1,2}, S. Ramos⁹, A. Reghunath¹⁸,
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 V. Scalera^{1,15}, O. Schneider⁶, G. Sekhniaidze¹, N. Serra⁷, M. Shaposhnikov⁶, V. Shevchenko³, T. Shchedrina³,
 L. Shchutska⁶, H. Shibuya^{34,36,†}, S. Simone^{20,21}, G. P. Siroti^{4,5}, G. Sirri⁴, G. Soares⁹, O. J. Soto Sandoval^{26,27},
 M. Spurio^{4,5}, N. Starkov³, I. Timiryasov³⁵, V. Tioukov¹, F. Tramontano¹, C. Trippi⁶, E. Urssov³,
 A. Ustyuzhanin^{1,36}, G. Vankova-Kirilova¹⁰, V. Verguilo¹⁰, N. Viegas Guerreiro Leonardo⁹, C. Vilela^{9,*},
 C. Visone^{1,2}, R. Wanke¹⁷, E. Yaman²², C. Yazici²², C. S. Yoon²⁹, E. Zaffaroni⁶ and J. Zamora Saa^{26,32}

(SND@LHC Collaboration)

SHiP

SHiP 은

LHC와 상호보완적으로

GeV 정도의 질량을 갖고,

아주 약하게 상호작용하면서

수명이 긴 입자를 발견하기 위한

고정 표적 충돌 실험이다.

SHiP@ECN3

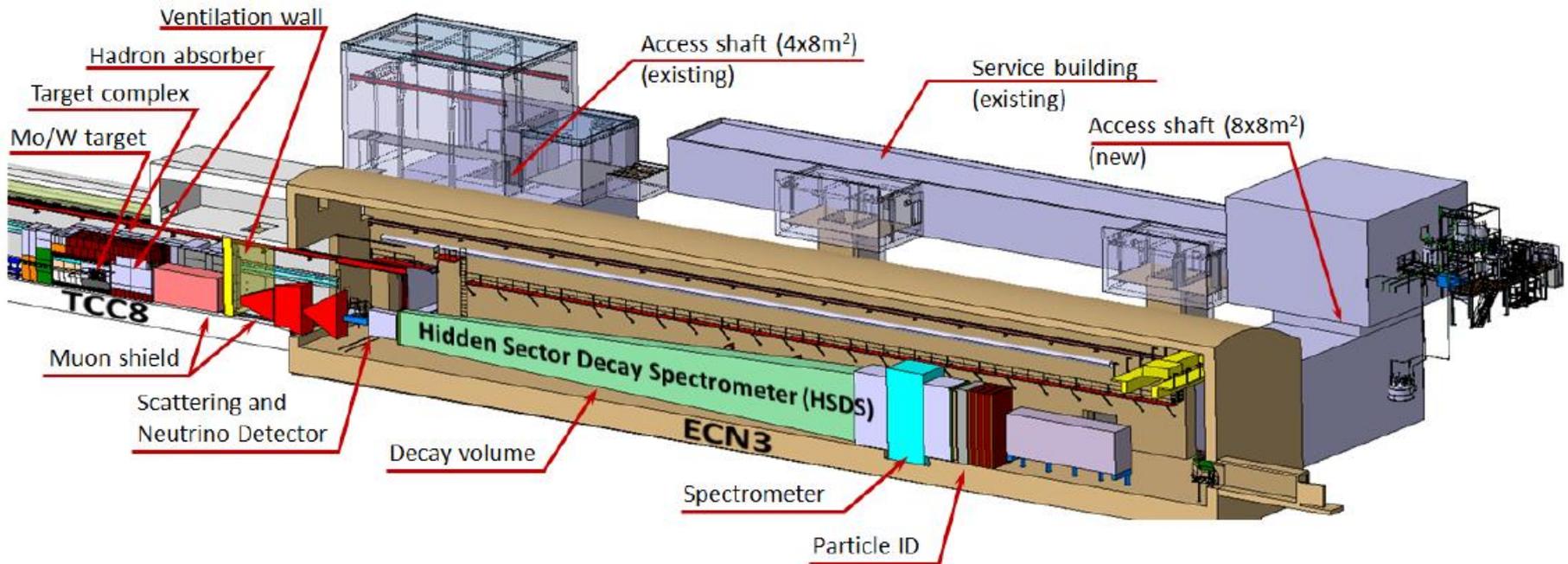
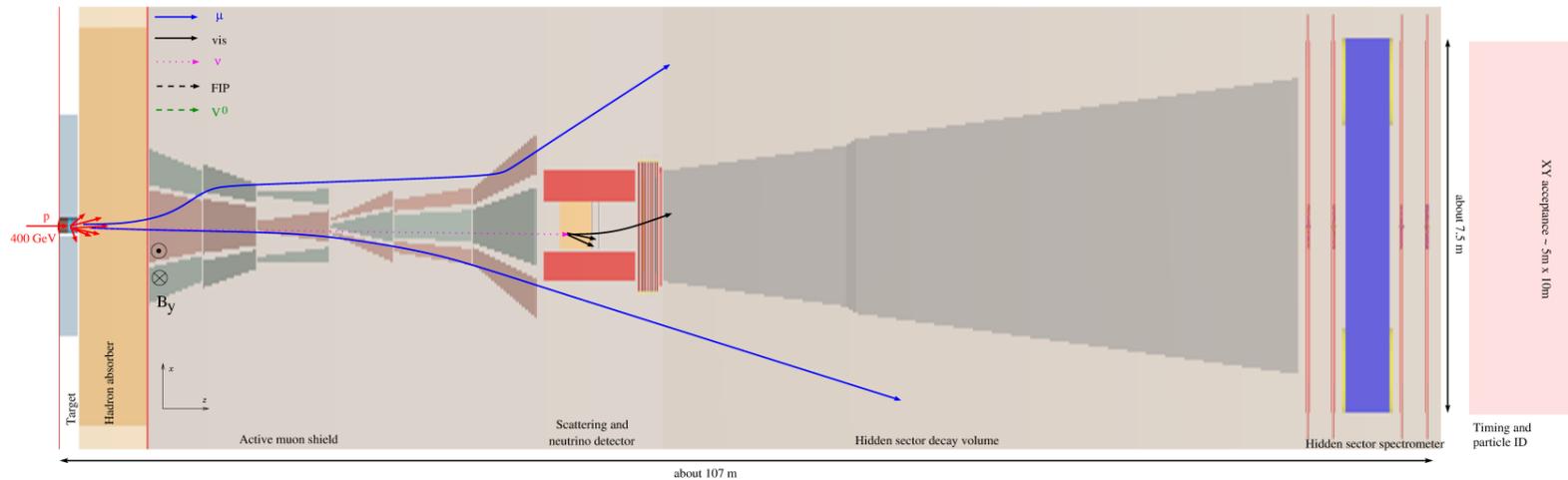
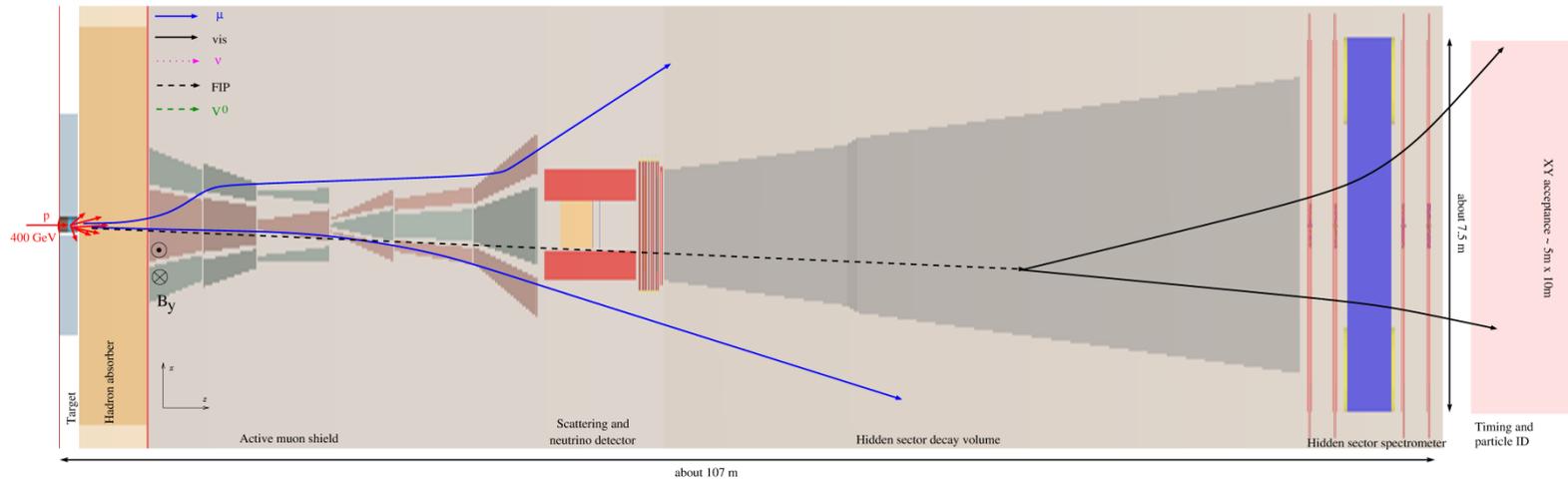
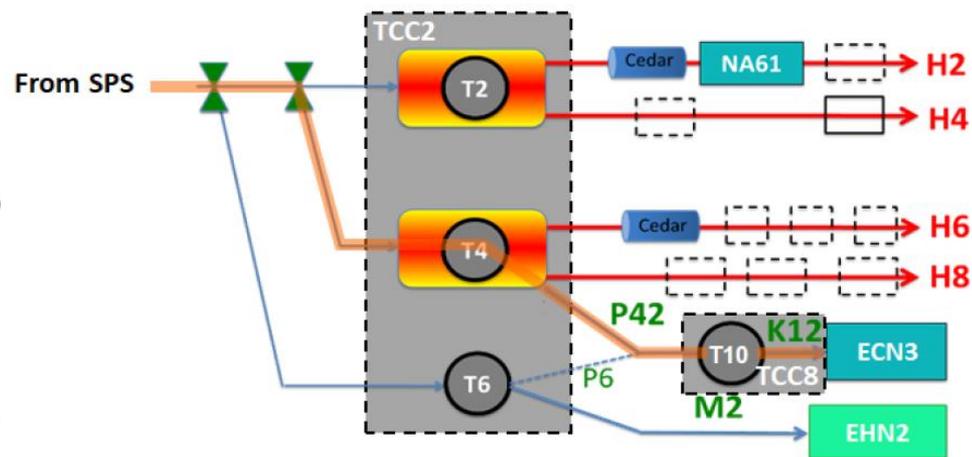
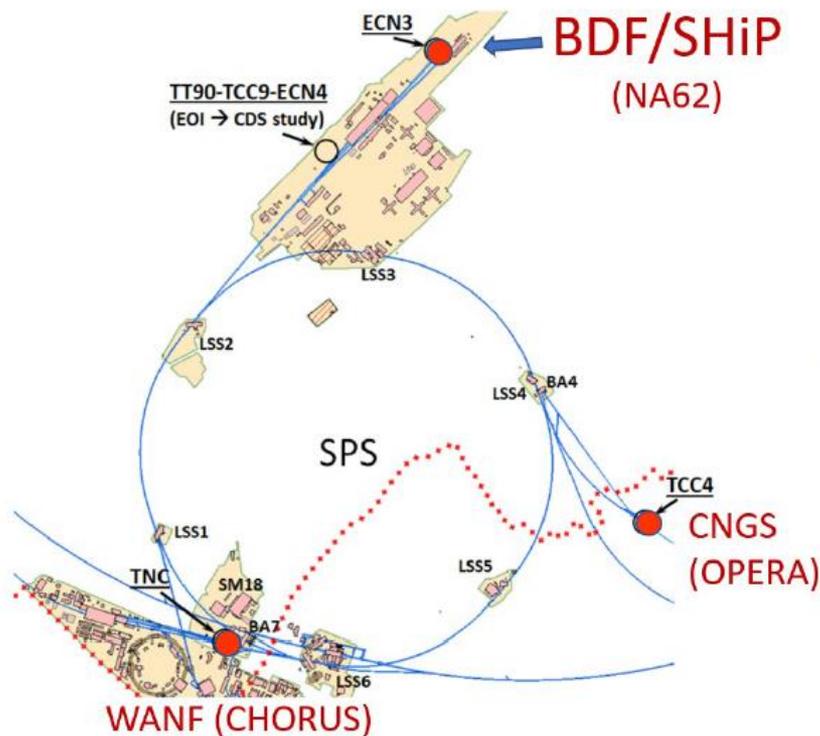


Figure 5: Overview of the BDF/SHiP experimental setup in the SPS TCC8/ECN3 experimental facility.

Physics Processes at SHiP



Site and Information

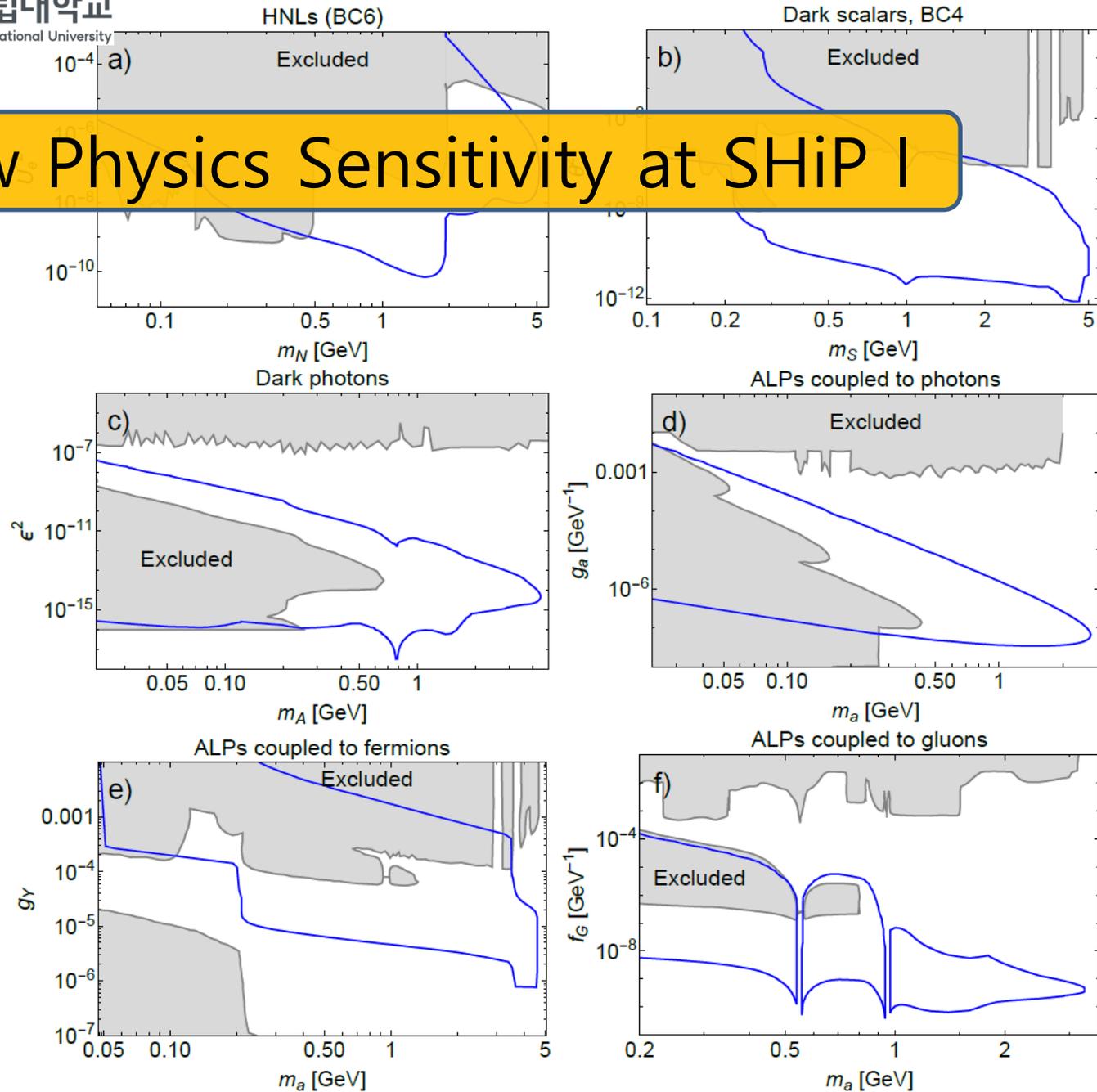


SPS proton beam $E = 400 \text{ GeV}$

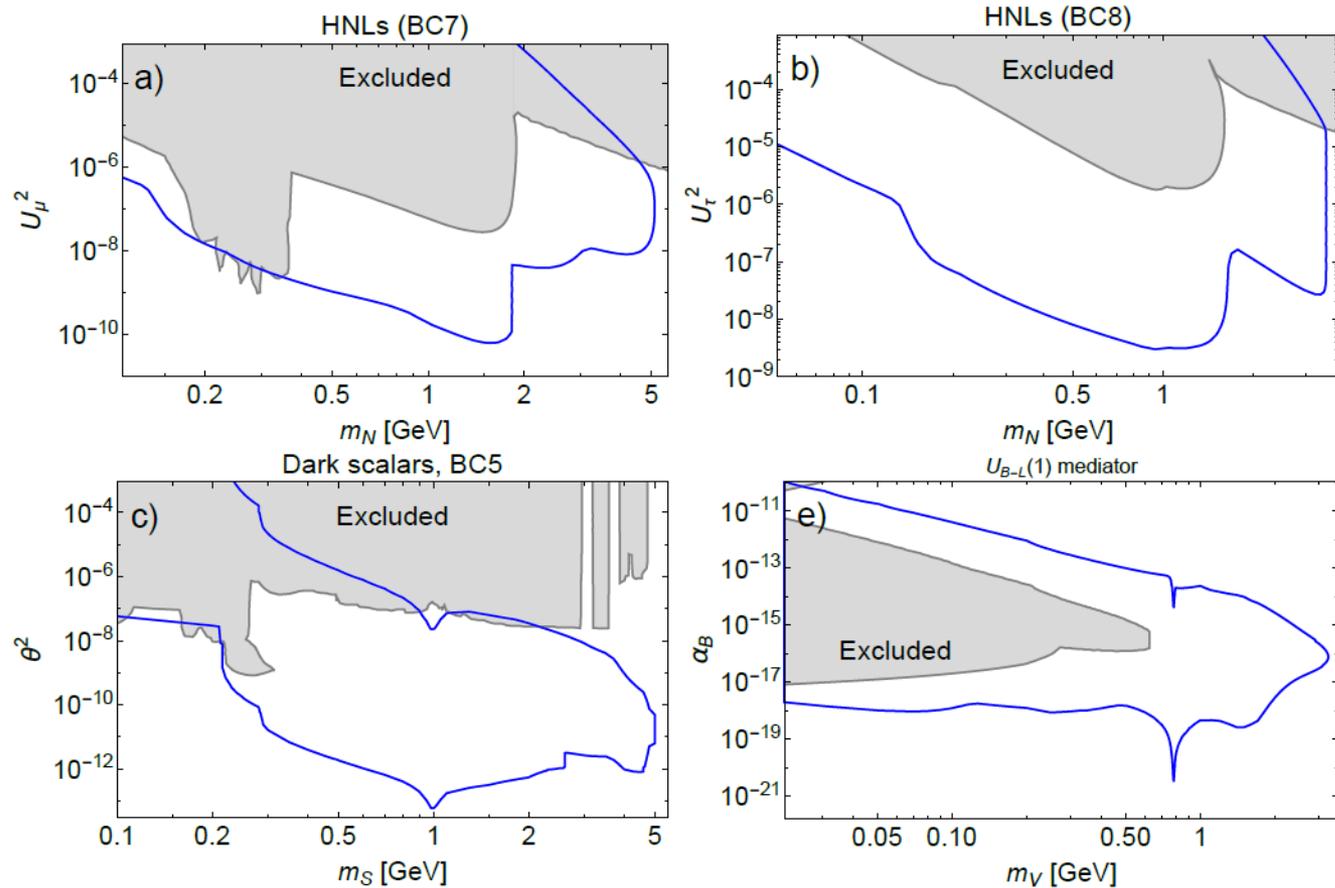
$N_{\text{PoT}} = 6 \times 10^{20}$ for 15 yr run

$37 \text{ m} < \text{decay length} < 87 \text{ m}$

New Physics Sensitivity at SHiP I



New Physics Sensitivity at SHiP II



Prospects of SHiP

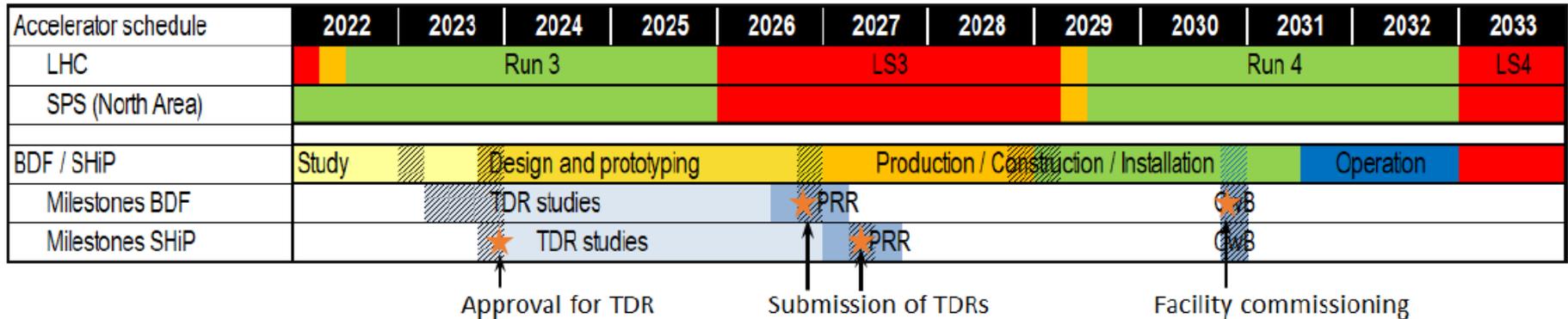


Figure 60: Implementation timeline for BDF/SHiP in ECN3.

From CERN RB,

This additional information will be brought to the next Research Board in March 2024 where a final decision will be made between the two options, in time for resource allocation in the Medium-Term Plan of 2024.

SND@LHC Collaboration

Collaboration: 160 members

24 Institutes in 14 Countries and CERN



Korean Group

Korean group member (SND@LHC & SHIP)

Gyeongsang National University (GNU)

S. H. Kim, K. Y. Lee, B. D. Park, J. Y. Sohn, C. S. Yoon

Korea University (KU)

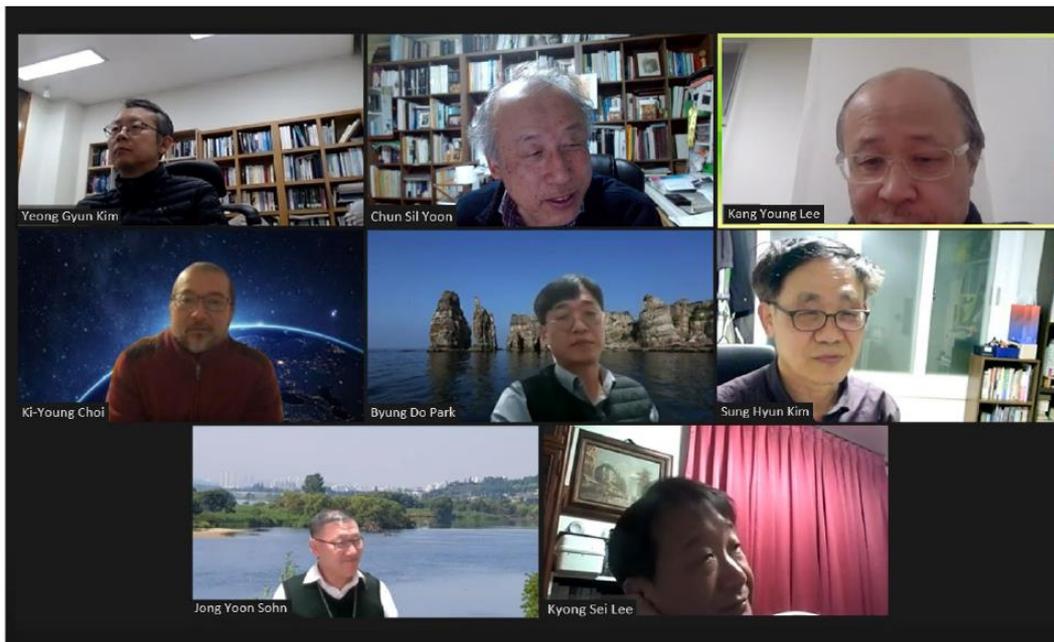
K. S. Lee

Gwangju National University of Education (GNUE)

Y. G. Kim

Sungkyunkwan University (SKKU)

K.-Y. Choi





Professor Joachim Mnich
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 CH – 1211 Geneva 23

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 Tel. secretariat: +41 22 767 1240
 Email: joachim.mnich@cern.ch

Our reference: DG-DI-RCS-2021-056

Dear Professor Kang Young Lee,

On behalf of CERN, I have signed the enclosed Memorandum of Understanding for Construction of the Scattering and Neutrino Detector at LHC (SND@LHC Experiment).

May I ask you to sign the two copies of the signature page (page 7), keep the fully signed version for your records and return one signature page to my office:

Office of the Director for Research and Computing
 CERN
 DG-DI-RCS (C00420)
 CH-1211 Geneva 23

Thanking you in advance, I remain

Prof. Kang Young Lee
 Gyeongsang National University
 Department of Physics Education
 501 Jinju-daero
 52828 Jinju
 Republic of Korea

Geneva, 23 August 2021

Yours sincerely,

Joachim Mnich



Professor Joachim Mnich
 Director for Research and Computing
 CERN
 CH – 1211 Geneva 23

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Our reference: DG-DI-RCS-2022-124

Dear Professor Kang Young Lee,

On behalf of CERN, I have signed the enclosed Memorandum of Understanding for the Maintenance and Operation of the Scattering and Neutrino Detector at LHC (SND@LHC Experiment).

May I ask you to sign the two copies of the signature page (page 7), keep the fully signed version for your records and return one signature page to my office:

Office of the Director for Research and Computing
 CERN
 DG-DI-RCS (C00420)
 CH-1211 Geneva 23

Thanking you in advance, I remain

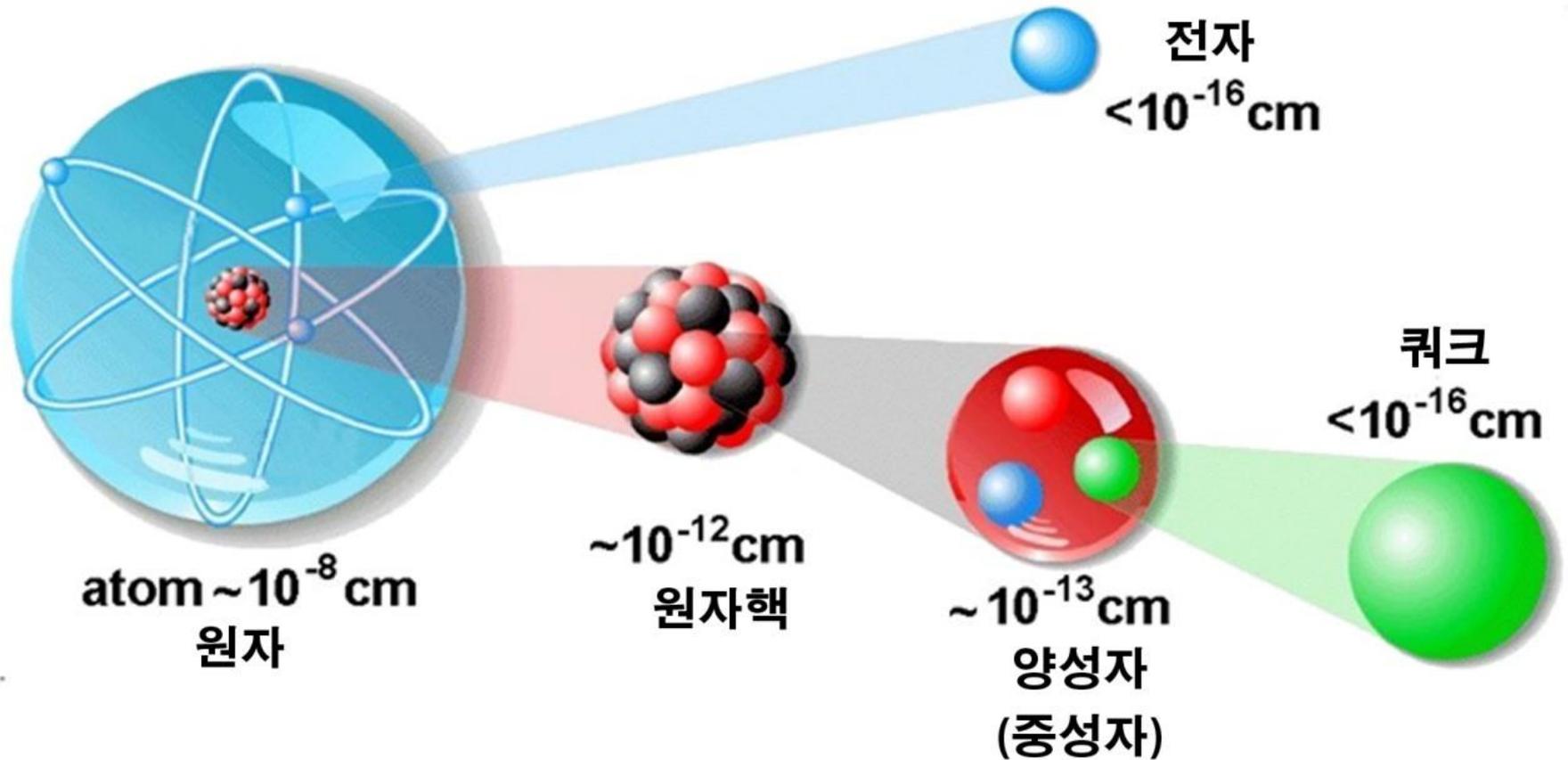
Prof. Kang Young Lee
 Gyeongsang National University
 Department of Physics Education
 501 Jinju-daero
 52828 Jinju
 Republic of Korea

Geneva, 7 September 2022

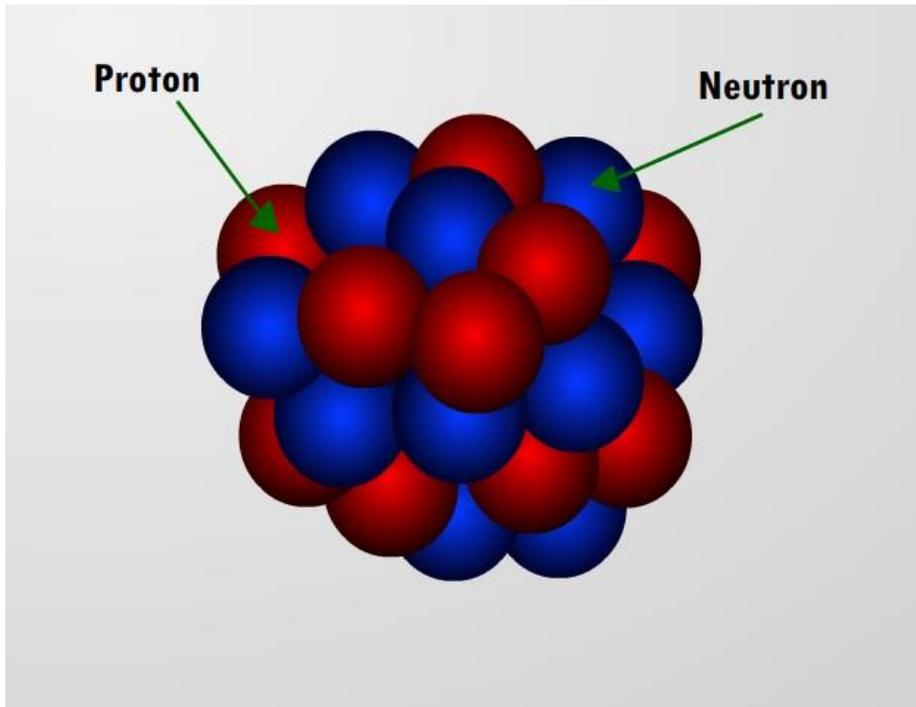
Yours sincerely,

Joachim Mnich

원자 이하의 계층 구조



원자핵은...



원자핵은 양성자와 중성자가 뭉쳐 있는 상태.

원자핵의 밀도는 모든 원자에서 대략 비슷하다. 즉 옆의 그림처럼 양성자와 중성자가 그냥 뭉쳐있다고 생각할 수 있다.

새로운 스케일이 나타나지 않는다.

적어도 하나의 관계는 알고 있습니다.

강한 핵력 >> 전자기력

핵 크기 << 원자의 크기

새로운 힘 = 새로운 스케일

그러면,

기본입자의 스케일은 무엇인가?

어디에서 오는가?

현대 (입자) 물리학의 가장 심오한 문제!