

# 粒子物理与近代科学

-- 粒子物理标准模型的唯一理解

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# Great Puzzle:



who am I?  
what Universe made of?

where am I from?  
how Universe begin?

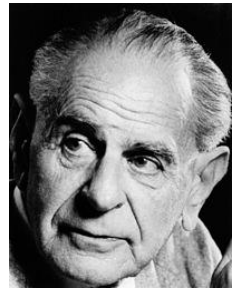
God and his DESIGN!  
**the 1<sup>st</sup> DRIVE**

宇宙内在、统一的  
第一驱动原理

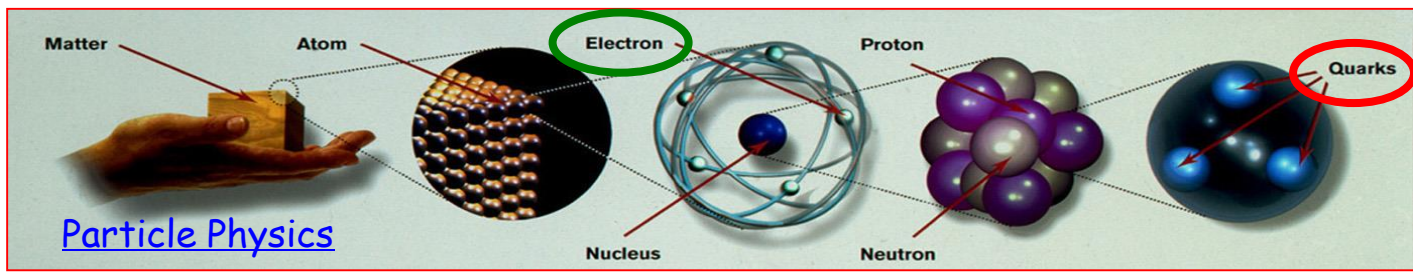
## Science religion:

Principle 1 **Beauty & Simple** e.g. 围棋( $10^{23} \times 10^{23}$ )/象棋 → “**纸片上的宇宙**”

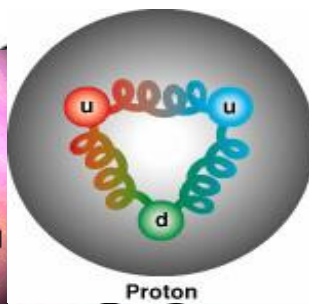
Principle 2 **Falsification** --Sir Karl Raimund Popper → “**测量**” vs. “**描述**”



**粒子物理:** “**最基本结构及其相互作用**” → Reductionism 还原论



# 标准模型： 物质基本构成 及其4种相互作用

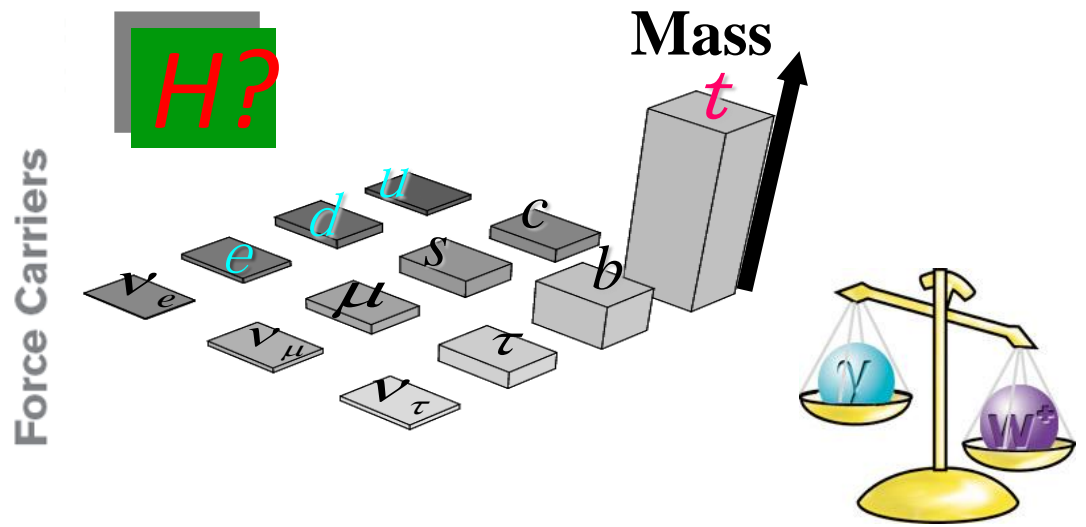


	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	Photon	Gluon

## Standard model particles are Quarks and Leptons

	I	II	III	
Quarks	$u$	$c$	$t$	$\gamma$
	$d$	$s$	$b$	$g$
Leptons	$\nu_e$	$\nu_\mu$	$\nu_\tau$	$Z$
	$e$	$\mu$	$\tau$	$W$

Three Generations of Matter



# 大统一 GUT (Grand Unification Theory)?

天上的  
地下的

**Gravity**  
 $\sim G_N M^2 / r^2$   
(Newton 1687)

新时空观

**General Relativity**  
(Einstein 1916)  
 $\sim \sqrt{g} \cdot G^{-1} R?$

磁: 磁石  
电: 1785 Coulomb  
静电扭秤  
 $\sim e^2 / r^2$   
1789 Galvani → Volta  
1800 青蛙腿 化学电池

1819  
Oested  
电流磁场

**电磁学**  
**Electro-Magnetic**

伟大的时代

- ✓ 1867  
**Maxwell Equations**  
EM wave = 光
- ✓ 1905 Einstein:  
新时空观 → **Special Relativity**
- ✓ 1925  
**Quantum Mechanics**  
(新物质观: 波粒二象性)

量子电动力学  
**QED U1**  
(1948)

Great Achievement

$SU_W(2) \times U_Y(1)$

弱作用  
**Weak SU2**  
(1958)  
eg 太阳反应  $4P \rightarrow \alpha + 2e^+ + 2\nu$

强作用  
**Strong SU3**  
(1930)  
eg 核子聚合作用

$SU_C(3)$

**基本粒子**  
(“极小空间”)  
**相互作用力学**  
**及其统一**

?

# Modern Physics

Two scientific revolutions that are the foundation of modern physics occurred in the first half of the 20<sup>th</sup> Century.

These breakthroughs occurred when physicists tried to extend the laws of physics beyond everyday experience.

- **Relativity** 相对论
- **Quantum mechanics** 量子力学

# Relativity

To describe things moving *very fast* requires the theory of relativity.

## Special Relativity

- We cannot catch up with light.
- time-space

时空一致  $(t, \vec{x})$

- Mass is a form of energy.

质能关系  $E = m c^2$

“重”新粒子

→ 能量阈值 **threshold** 效应



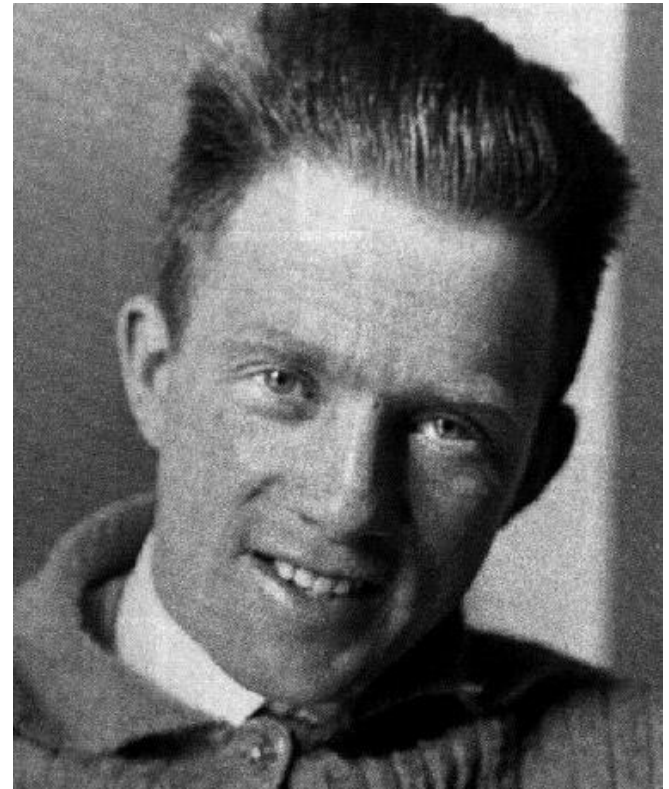
# Quantum Mechanics

To describe things that at *very small* requires quantum mechanics.

## The Heisenberg uncertainty principle:

- The more precisely we know the position of an object, the worse we know its momentum.

$$\Delta p \cdot \Delta x \sim \Delta E \cdot \Delta t \sim h$$



量子力学:测不准原理, 波粒二相性, 波函数几率解释...

$\Delta p \Delta x \sim h$ : 探测极小的空间  $\Delta x \rightarrow 0$ , 需要极大的能量  $\Delta p \rightarrow \infty$

# 自然单位制 Natural Units

- 1. 经典SI单位制: 千克·米·秒
- 2. 基本粒子物理:

量子力学 Quantum Mechanics + 相对论 Relativity → 量子场论 Quantum Field Theory

↓

$h \sim 197 \text{ MeV}\cdot\text{fm}$   
( $6.63 \times 10^{-34} \text{ J}\cdot\text{s}$ )

↓

$c \sim 3 \times 10^8 \text{ m}\cdot\text{s}^{-1}$

3. Natural Units:

$[h] = [c] = 1$

$V=L/T \rightarrow [L] = [T]$  时空一致

$E=h\omega \rightarrow [E] = [T]^{-1}$

$E=mc^2 \rightarrow [E] = [M] = [P]$

$[E] = [M] = [P] = [L]^{-1} = [T]^{-1}$

-  $1\text{eV}=1.6 \times 10^{-19}\text{J}$ ,  $1\text{MeV}=10^6\text{eV}$ ,  $1\text{GeV}=10^3\text{MeV}$ ,  $1\text{TeV}=10^3\text{GeV}$

-  $M_e=0.511\text{MeV}$ ,  $M_p=1.0073\text{u}=938.3\text{MeV}$ ,  $M_N=1.0087\text{u}=939.6\text{MeV}$

- e.g.  $[F] = [ma] = [-\nabla U] = [E]^2 = [e^2 Q^2 / r^2]$ ,  $[V_N] = [G_N \cdot \frac{M^2}{r}] = [E] \rightarrow [G_N] = [M]^{-2}$

$h \cdot c$

$\sim 200 \text{ MeV}\cdot\text{fm}$



# 物理能标 Energy Scale(1)

太阳表面~6000K  
(K~10<sup>-4</sup>eV)

~ 0.5 eV

太阳核心~10<sup>7</sup>K

~ keV

热核聚变(氢弹)

~ 10 keV

电子质量m<sub>e</sub>

= 0.511 MeV

质子质量M<sub>p</sub>

~ 1 GeV

电弱统一 SU(2)×U(1)

真空破缺 Higgs

~ 100 GeV

New Physics

~ 1-10 TeV ?

大统一能标GUT?

~ 10<sup>19</sup> TeV!

探测“**最小**”时空结构

Heisenberg:

$$\Delta x \sim h/\Delta p$$



TeV Accelerator  
高能加速器物理



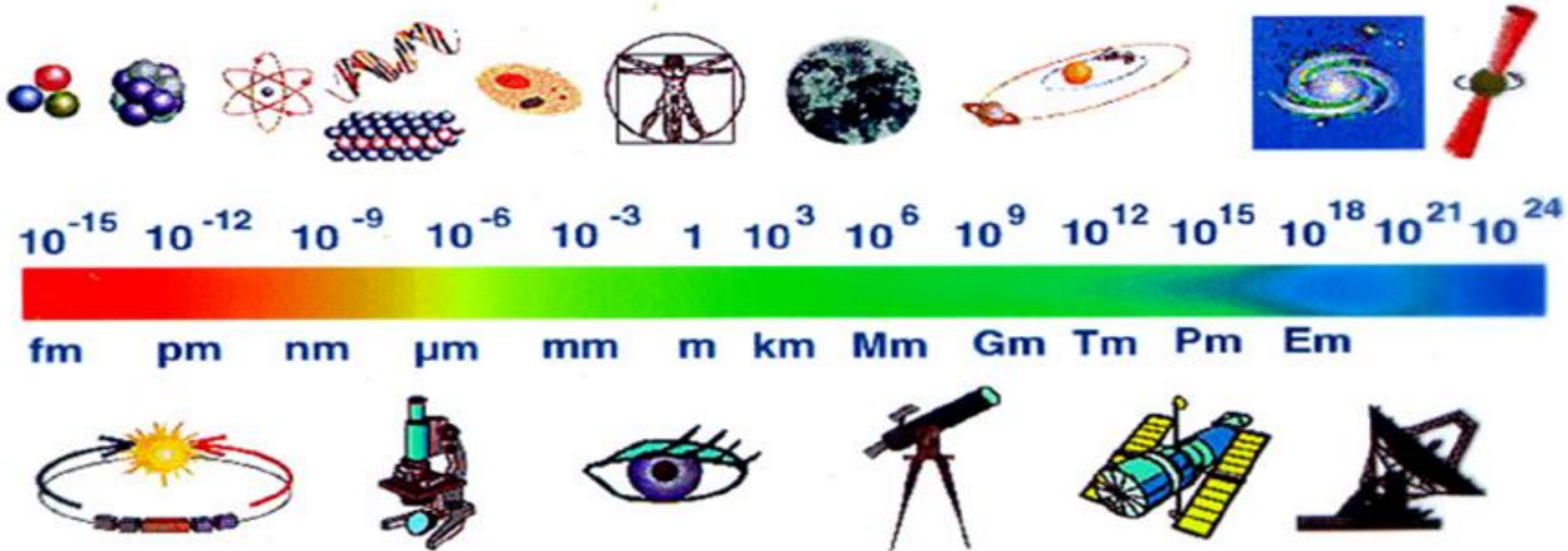
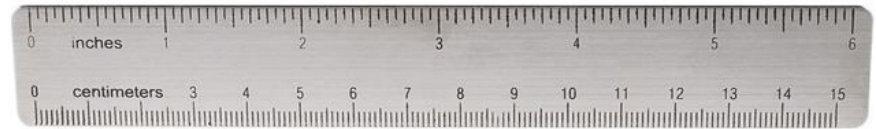
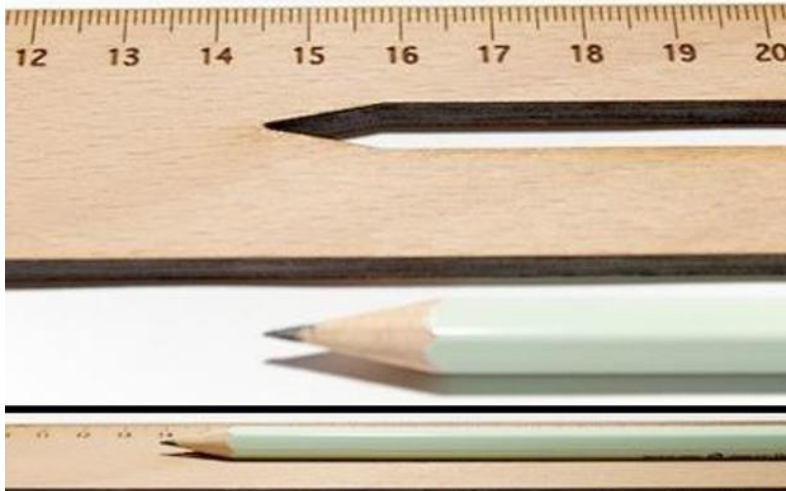
Einstein:

$$m = E/c^2$$

产生“重”新粒子

- Ref: 1eV=1.6×10<sup>-19</sup>J, 1MeV=10<sup>6</sup>eV, 1GeV=10<sup>3</sup>MeV, 1TeV=10<sup>3</sup>GeV=10<sup>12</sup>eV

# 测量：尺子与物体必须相匹配

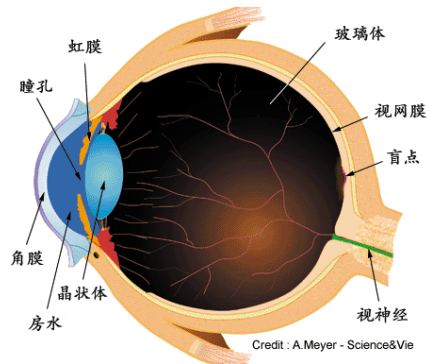
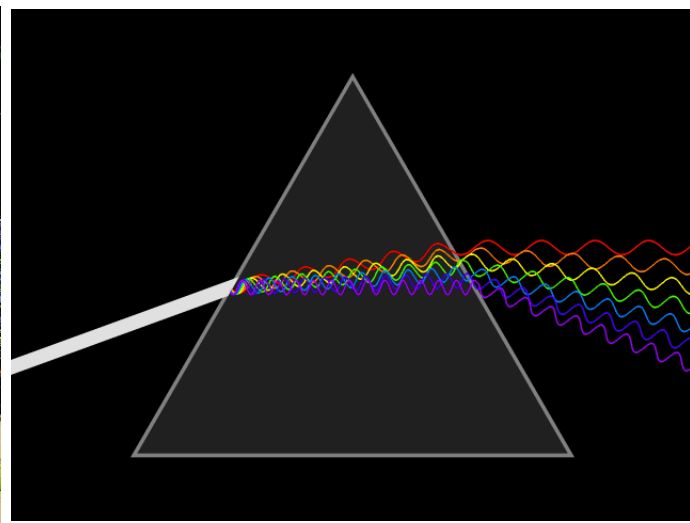


# 肉眼可看见的尺度

# 0.1mm

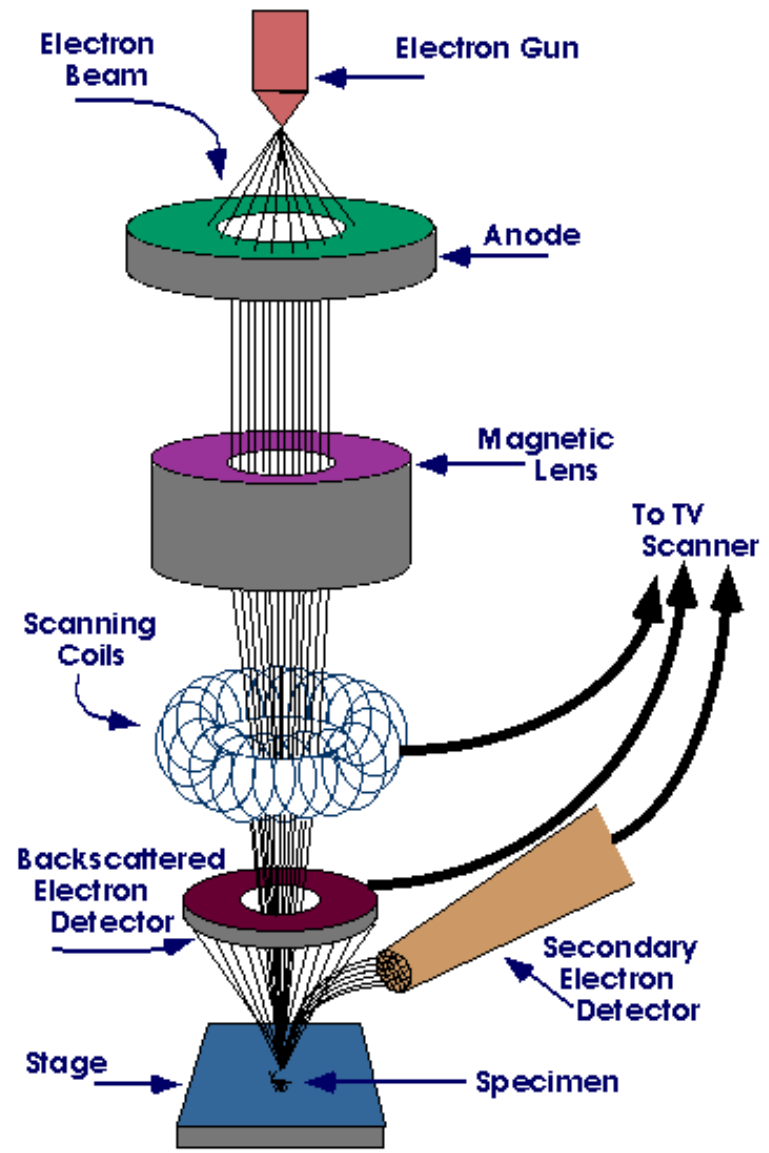
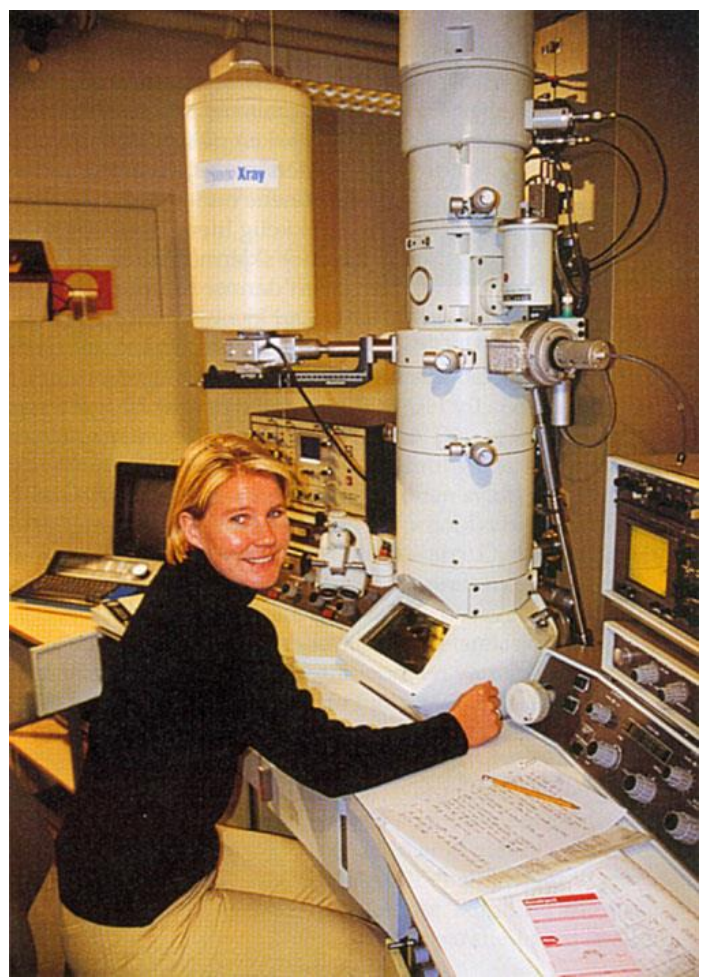
标准对数视力表

距离 (米)	视力
50	4.0
39.72	4.1
31.55	4.2
25.06	4.3
19.91	4.4
15.81	4.5
12.56	4.6
9.98	4.7
7.93	4.8
6.30	4.9
5.0	5.0
3.97	5.1
3.15	5.2
2.51	5.3



原子能看得见吗？可以，借用**电子显微镜**！

加速电压为 50~100千伏时，  
 **$\lambda$ 约0.0053~0.0037纳米**



# CERN: Large Hadron Collider (LHC)

Tunnel circumference: 27 km  
Diameter: 3.8 m  
Depth: 140 m



**CMS**

**LHCb**

**ALICE**

**ATLAS**

**ATLAS**

3000 Physicists  
176 Institutions  
38 countries  
550 MCHF

**CMS**

2900 Physicists  
184 Institutions  
38 countries  
550 MCHF

**ALICE**

1000 Physicists  
105 Institutions  
30 countries  
150 MCHF

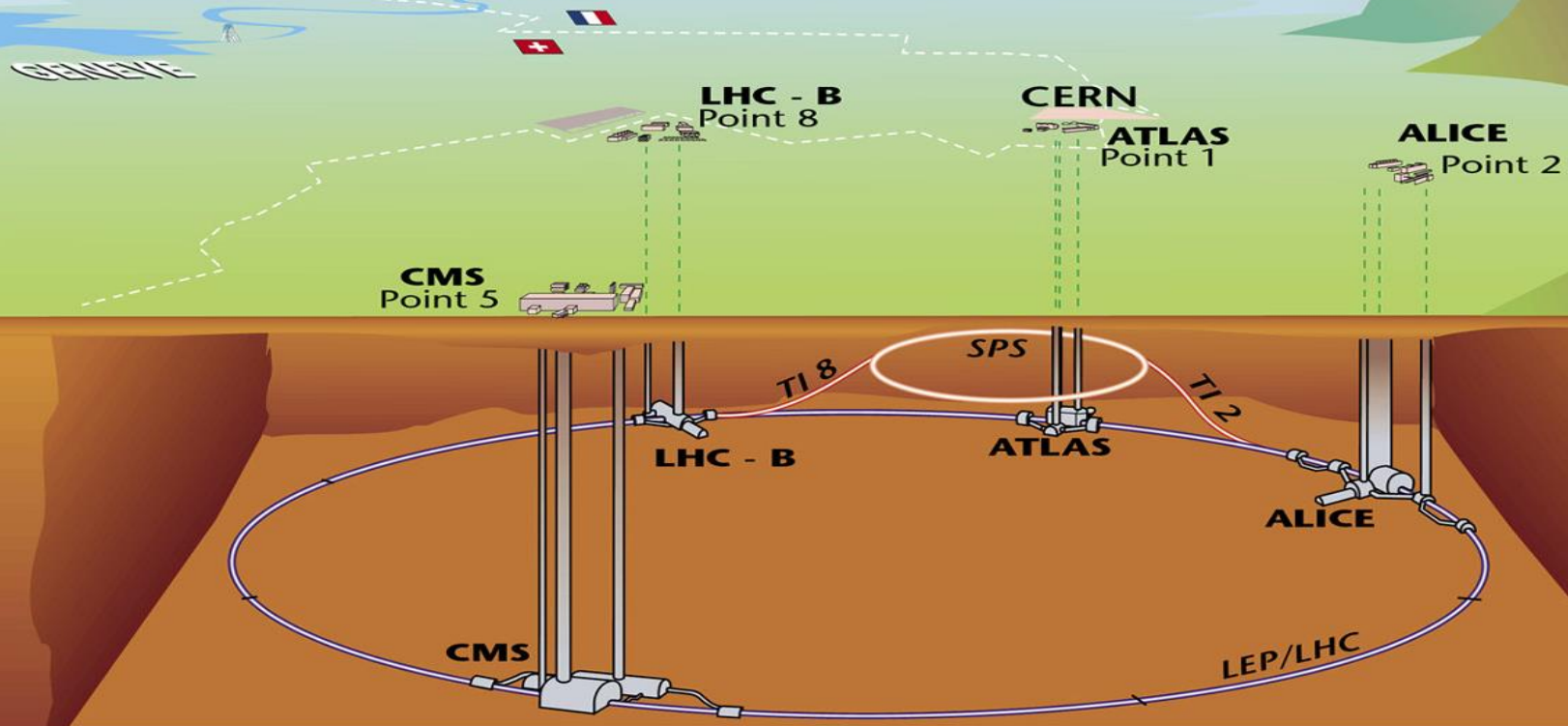
**LHC b**

730 Physicists  
54 Institutions  
15 countries  
75 MCHF

# Large Hadron Collider (LHC)

## Overall view of the LHC experiments.

- ✓ 高能前沿: **7+7** TeV质子-质子 @ **2E34** cm<sup>-2</sup>s<sup>-1</sup>
- ✓ 基本问题: 宇宙“最初” **10<sup>-13</sup> - 10<sup>-14</sup>**秒
- pre-LHC era: **LEP e<sup>+</sup>e<sup>-</sup> 100+100GeV @ ALEPH + DELPHI + L3 + OPAL**



■ LHC:  $7\text{TeV} + 7\text{TeV} = 14\text{TeV}$

$$1 [\text{TeV}] = 1 \times 10^{12} [\text{eV}]$$

● 单核子能量  $E_p$

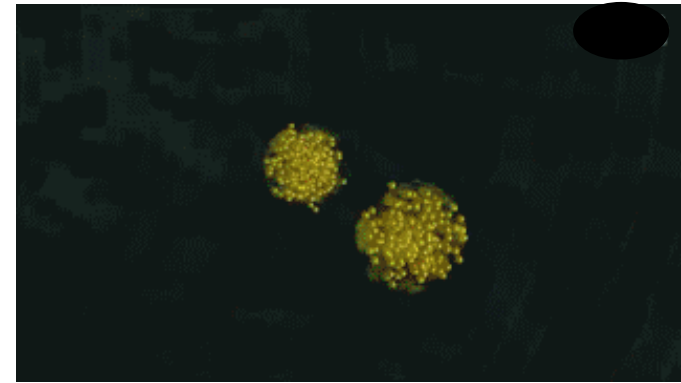
$$1 \times 10^{12} [\text{eV}] \left( \frac{1.6 \times 10^{-19} [\text{J}]}{1 [\text{eV}]} \right) = 1.6 \times 10^{-7} [\text{J}]$$

$$E = mc^2$$

● 束流瞬时亮度  $L_{ins}$ :  $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

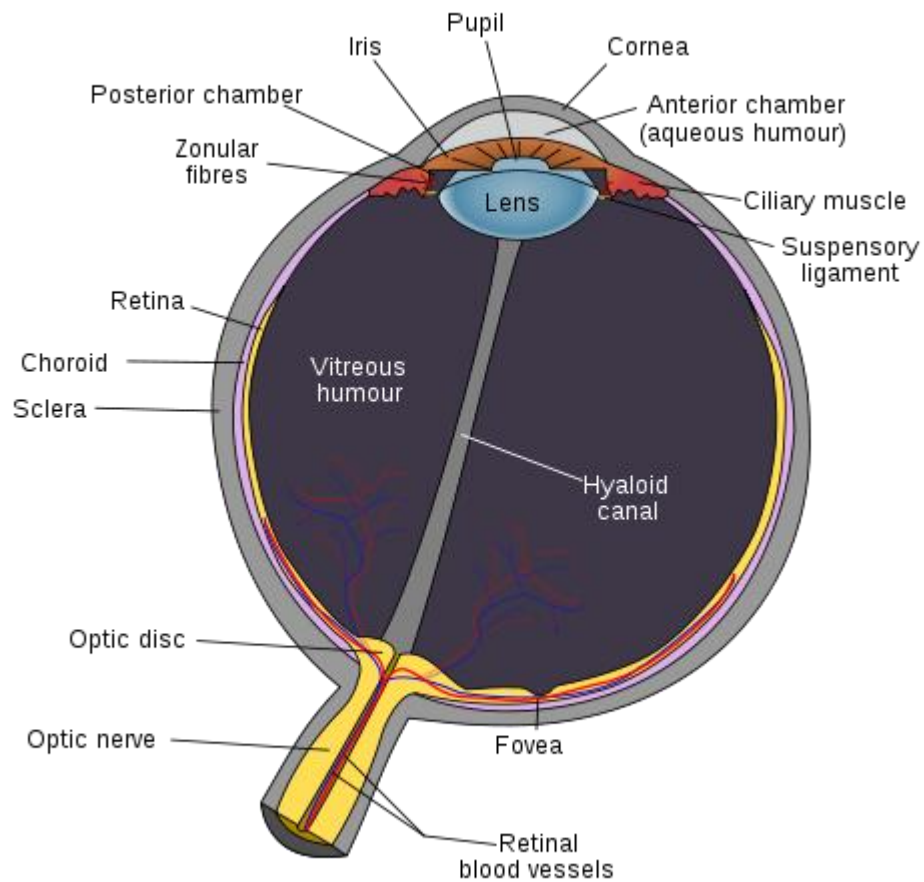
● 束团功率子  $E_p \times L_{ins}$ :  $3 \times 10^{27} \text{ J}/(\text{cm}^2\text{s})$

$$\lambda = hc/E = 200 \text{ MeV} \cdot \text{fm} / 14 \text{ TeV}$$
$$\sim 1 \times 10^{-19} [\text{m}]$$

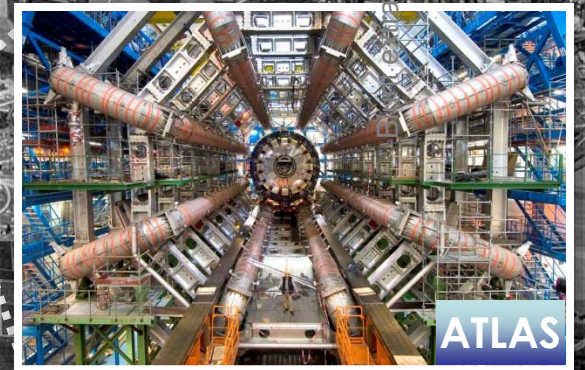
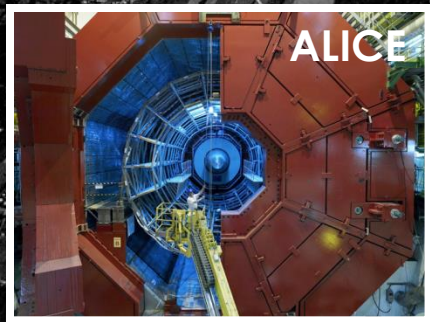
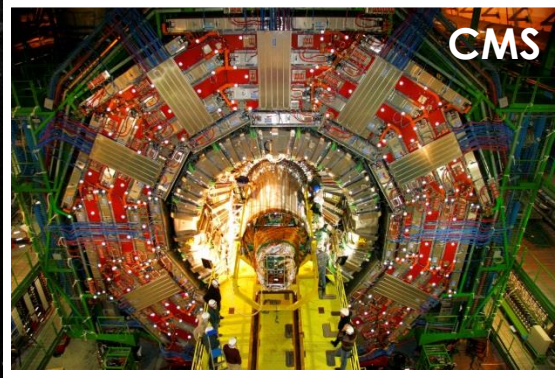


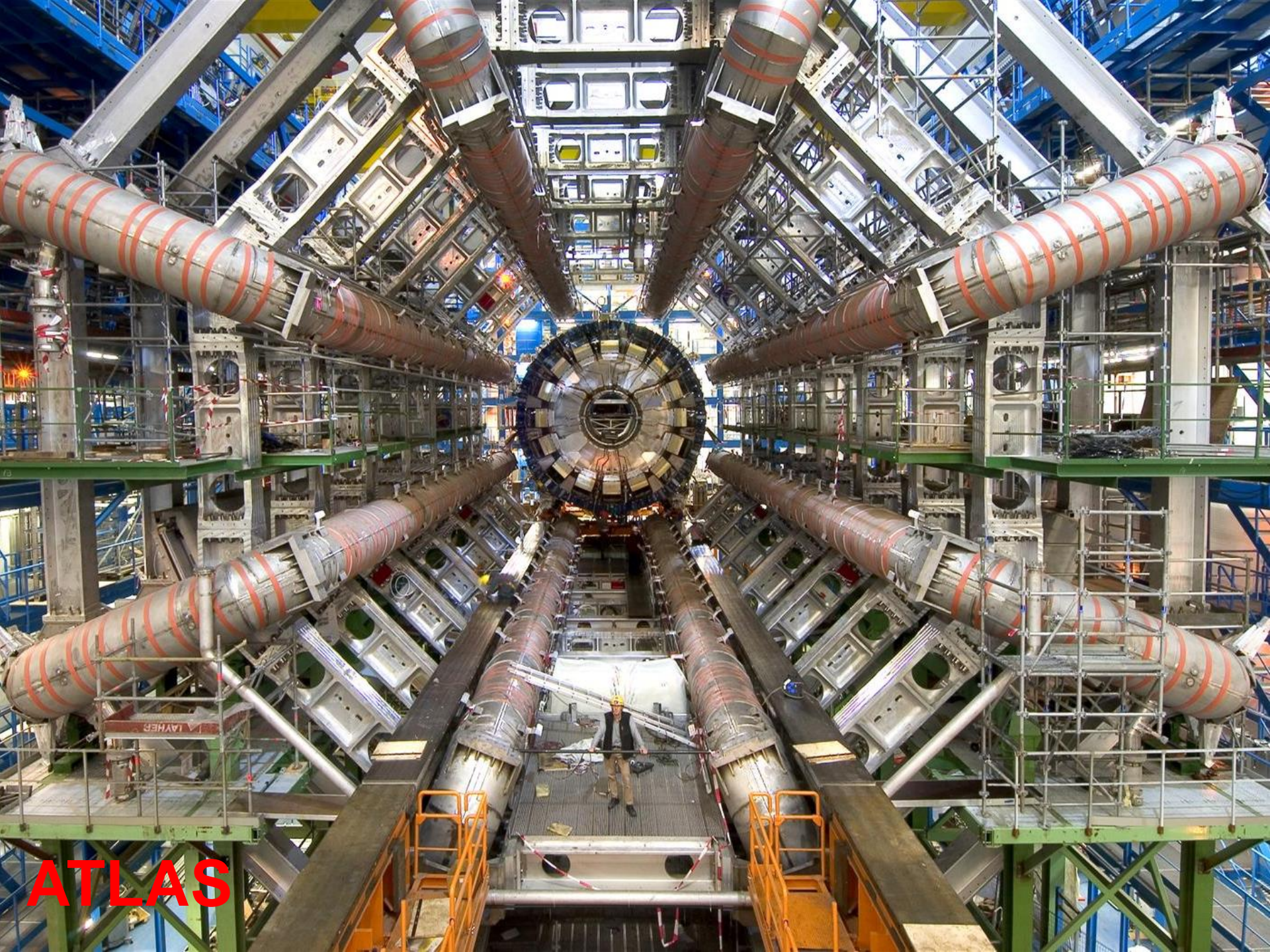
# 探测器：“眼睛”

# ATLAS & CMS



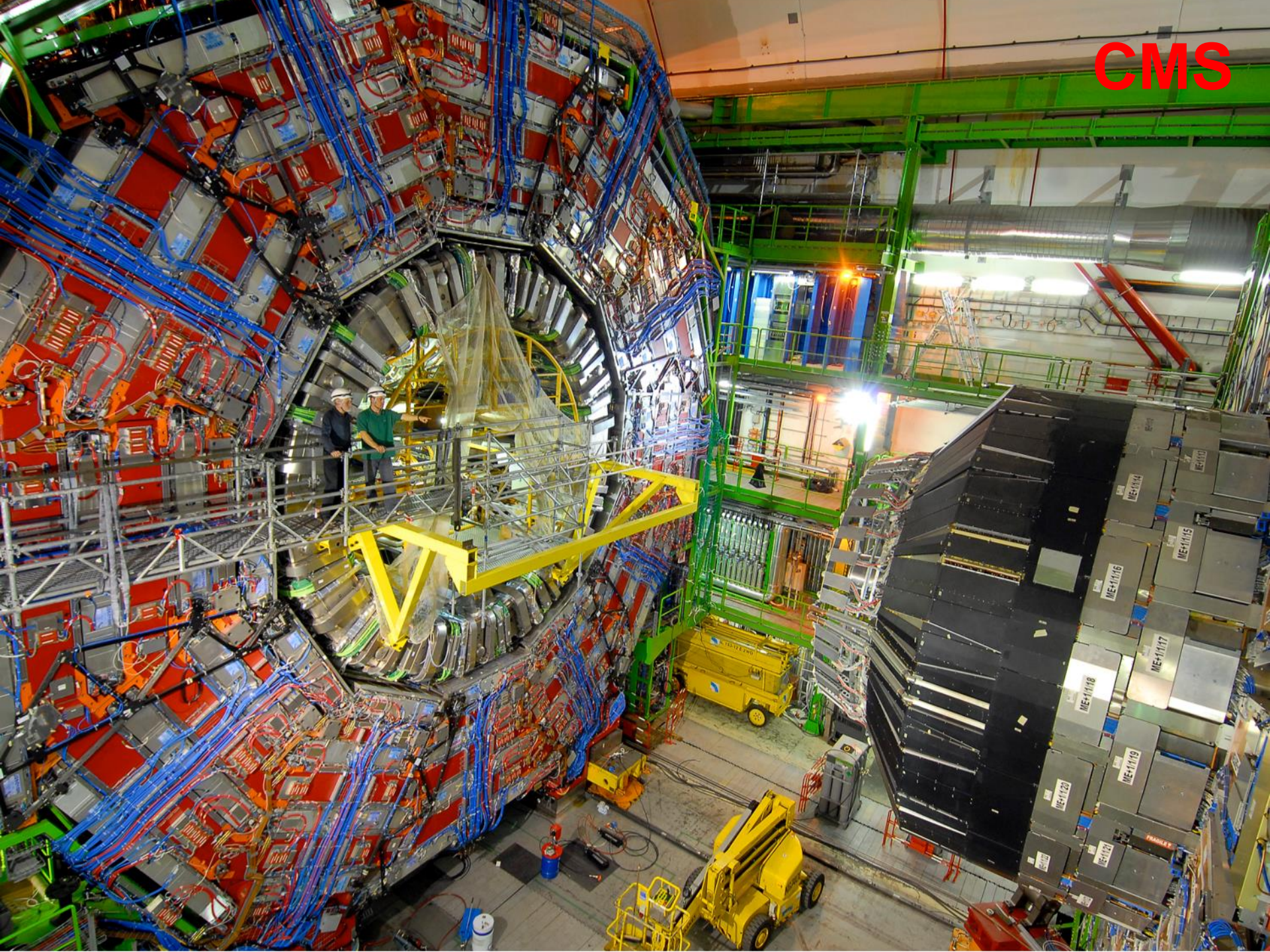




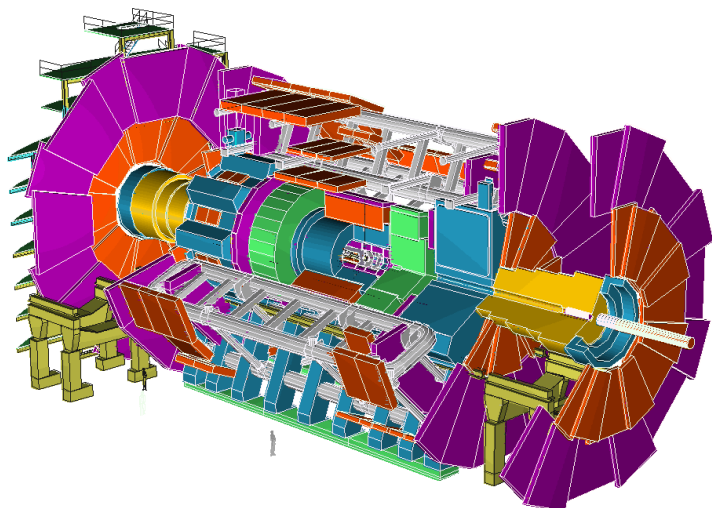


**ATLAS**

CMS



# ATLAS探测器



## 径迹室 Tracker

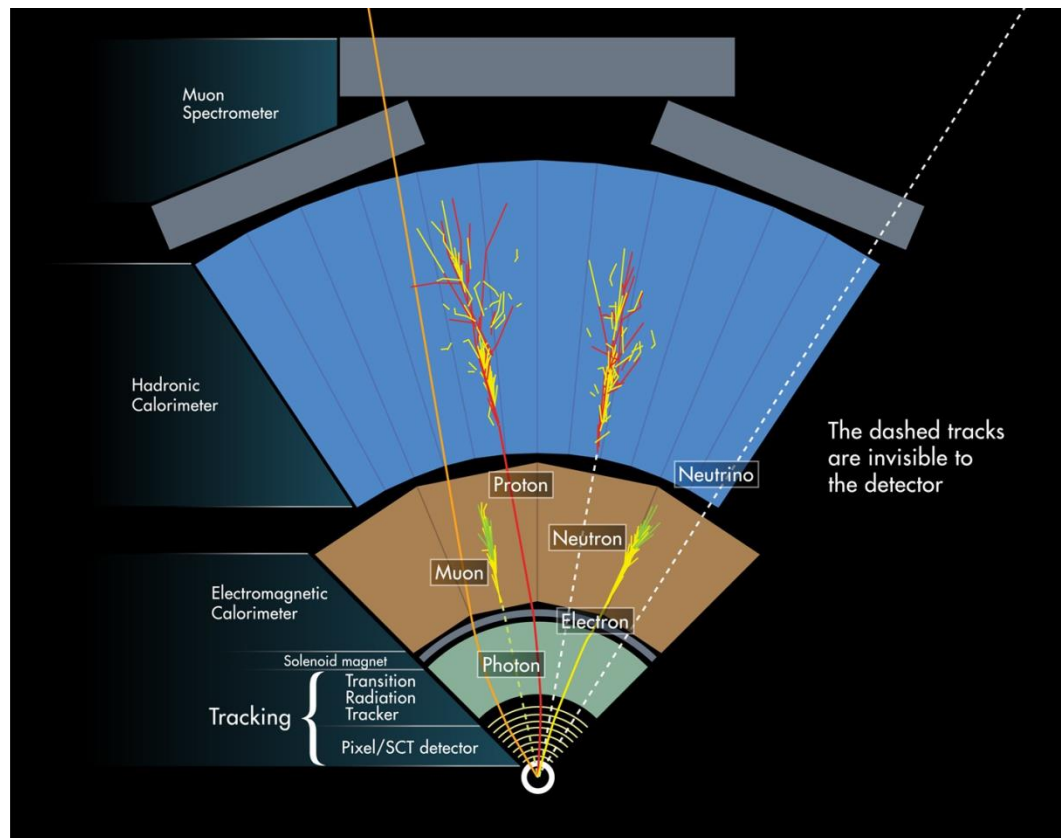
- 原理: 带电粒子电离 + 磁场B中偏转 → 径迹
- 材料: Silicon Pixel + Strip
- 测量: 原初反应点IP + 横动量 $p_T$

## 量能器 Calorimeter

- 原理: 电磁(e) + 强作用(h)簇射能损
- 材料: 高z值金属 + LAr
- 测量: e/ $\gamma$ /强子的全部能量 + MET

## Muon谱仪

- 原理:  $\mu$ 穿过量能器, 在谱仪B中偏转
- 材料: 气体径迹室
- 测量:  $\mu$ 粒子横动量 $p_T$



# I. 粒子物理标准模型

## The Standard Model of Particle Physics

# Review of Glory:

- 1895	伦琴	} 电磁相互作用 $eV \rightarrow keV$	X-射线
- 1896	贝克勒尔&居里		核放射性 $\gamma, \beta(e), \alpha(^4He_2)$
- 1898	J.J.汤姆逊, 阴极射线 $\rightarrow$		电子
- 1911	卢瑟夫 $\alpha$ 粒子金箔散射		原子模型( $1A \rightarrow 1fm$ )
- 1919	卢瑟夫以 $\alpha$ 粒子轰击氮气		质子
- 1929	查德威克以 $\alpha$ 粒子轰击Be原子		中子(核模型确立)
- 1928-32	狄拉克预言正电子, 安得森宇宙线发现, 新味道轻子(36)	反粒子	
- 1922-33	核 $\beta$ 衰变之谜 $N \rightarrow P + e^-$ : 自旋破坏, $\beta$ 连续谱(22) 泡利提出中微子假说 $N \rightarrow P + e^- + \nu^b$ (31) 费米提出 $\beta$ 衰变4费米子 $G_F$ 理论 (33) Davis证明太阳 $\nu$ 与反应堆 $\nu^b$ 不同(55) 科恩探测反应堆中微子 $\nu^b + P \rightarrow N + e^+$ (59) 太阳标准模 $p + p + p + p \rightarrow ^4He + e^+ + e^+ + \nu_e + \nu_e + \gamma$	<u><math>\mu</math>轻子</u>	
- 1935-47	原子核与核反应 汤川秀树提出交换介子而产生的强作用 宇宙线中发现 $\mu$ "介子" (轻子), $\pi$ 介子	中微子 弱相互作用	
- 1956-64	高能电子轰击质子 $\rightarrow$ 核子有结构 ~30种稳定的、~400种不稳定强子	轻子数	
- 1956	李,杨,吴 $\rightarrow$ 镜子里的世界不完美	a) <u>强作用及其传递者</u> b) <u>新一代轻子</u>	
- 1980-90s	CERN发现 $W^\pm(80GeV), Z^0(90GeV)$ 粒子 Fermi-Lab发现top夸克, tau中微子	<u>夸克模型</u>  <u>弱作用P宇称不守恒</u>  <u>弱作用机制+电弱统一</u> <u>标准模型SM确立</u>	

# Standard Model(SM): Elementary Particles

三代费米子			相互作用 粒子	
	I	II		III
质量	2.4 MeV/c <sup>2</sup>	1.27 GeV/c <sup>2</sup>	171.2 GeV/c <sup>2</sup>	0
电荷	2/3	2/3	2/3	0
自旋	1/2	1/2	1/2	1
名字	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon
强子 (夸克)	4.8 MeV/c <sup>2</sup>	104 MeV/c <sup>2</sup>	4.2 GeV/c <sup>2</sup>	0
	-1/3	-1/3	-1/3	0
	1/2	1/2	1/2	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
轻子	<2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>
	0	0	0	0
	1/2	1/2	1/2	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> Z boson
	0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>
	-1	-1	-1	±1
1/2	1/2	1/2	1	
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> W boson

➤ 自旋J=1/2费米子

- Quark:

分数电荷 + 色禁闭

北京正负电子对撞机BES

- Lepton:

中微子振荡 + CP破坏?

NOvA vs. 大亚湾

规范玻色子

# Standard Model(SM): Interactions

三代费米子			相互作用 粒子	
	I	II		III
质量 电荷 自旋 名字	2.4 MeV/c <sup>2</sup> 2/3 1/2 <b>u</b> up	1.27 GeV/c <sup>2</sup> 2/3 1/2 <b>c</b> charm	171.2 GeV/c <sup>2</sup> 2/3 1/2 <b>t</b> top	0 0 1 <b>γ</b> photon
强子 (夸克)	4.8 MeV/c <sup>2</sup> -1/3 1/2 <b>d</b> down	104 MeV/c <sup>2</sup> -1/3 1/2 <b>s</b> strange	4.2 GeV/c <sup>2</sup> -1/3 1/2 <b>b</b> bottom	0 0 1 <b>g</b> gluon
轻子	<2.2 eV/c <sup>2</sup> 0 1/2 <b>ν<sub>e</sub></b> electron neutrino	<0.17 MeV/c <sup>2</sup> 0 1/2 <b>ν<sub>μ</sub></b> muon neutrino	<15.5 MeV/c <sup>2</sup> 0 1/2 <b>ν<sub>τ</sub></b> tau neutrino	91.2 GeV/c <sup>2</sup> 0 1 <b>Z<sup>0</sup></b> Z boson
	0.511 MeV/c <sup>2</sup> -1 1/2 <b>e</b> electron	105.7 MeV/c <sup>2</sup> -1 1/2 <b>μ</b> muon	1.777 GeV/c <sup>2</sup> -1 1/2 <b>τ</b> tau	80.4 GeV/c <sup>2</sup> ±1 1 <b>W<sup>±</sup></b> W boson
				规范玻色子

## ➤ 自旋J=1规范场

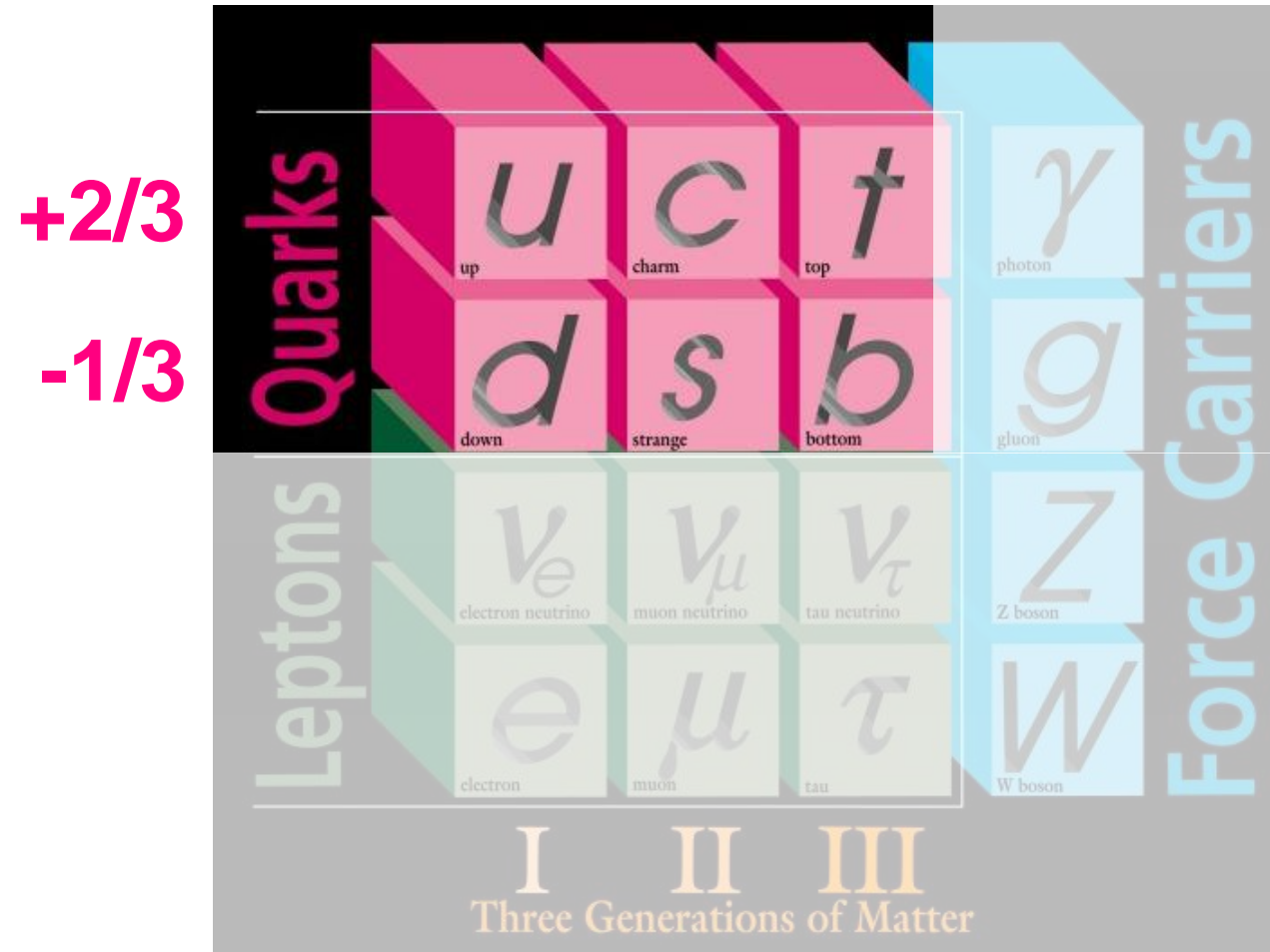
- **Photon**:  $m(\gamma) = 0$   
电磁相互作用

- **Gluon**:  $m(g) = 0$   
强相互作用

- **W<sup>±</sup>/Z<sup>0</sup>**:  $m(Z) \sim 90 \text{ GeV}$   
 $m(W) \sim 80 \text{ GeV}$   
弱相互作用

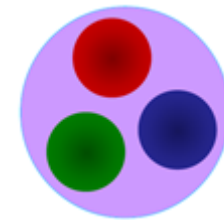


# The Standard Model (I): Quarks



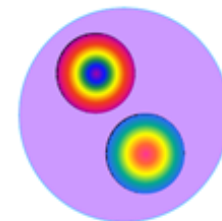
- $s=1/2$
- fractional charged
- colored

➤ 重子:

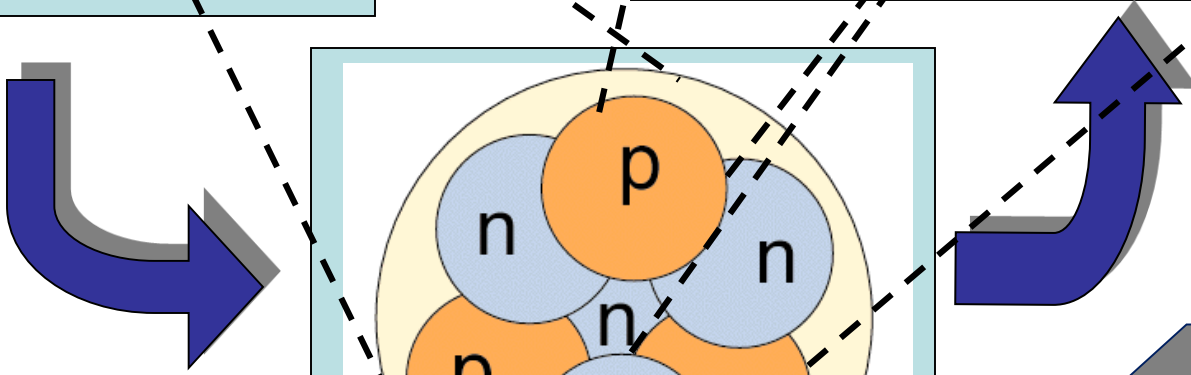
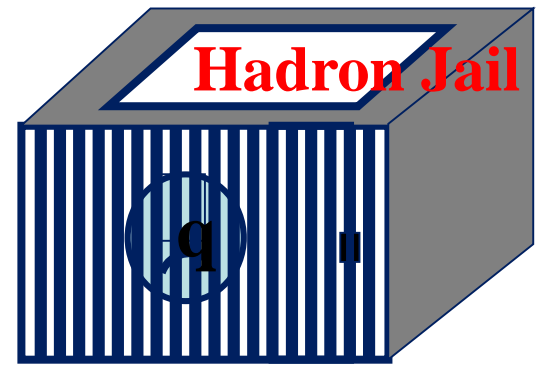
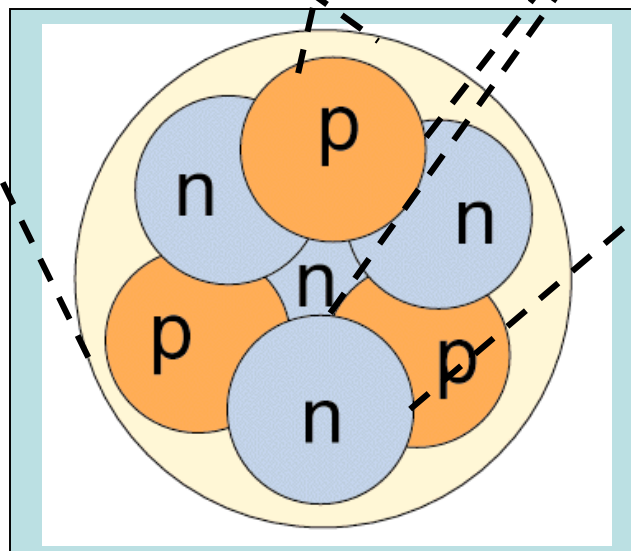
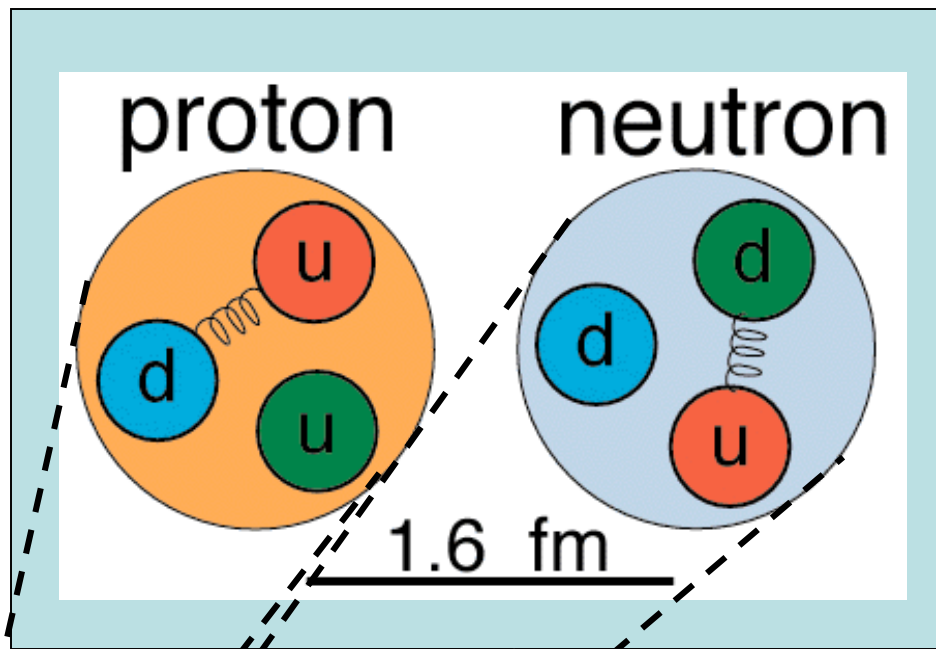
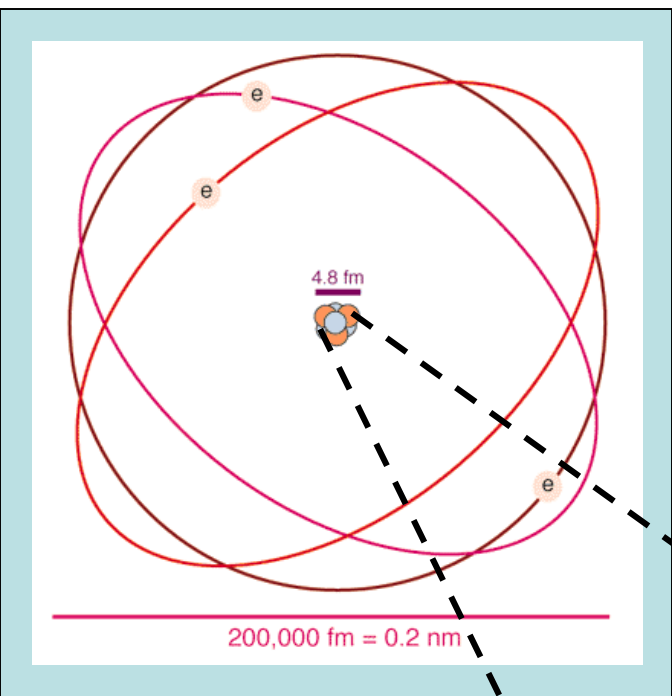


质子(**uud**)  
中子(**udd**)

➤ 介子:



$\pi^+ (u\bar{d})$   
 $J/\psi (c\bar{c})$



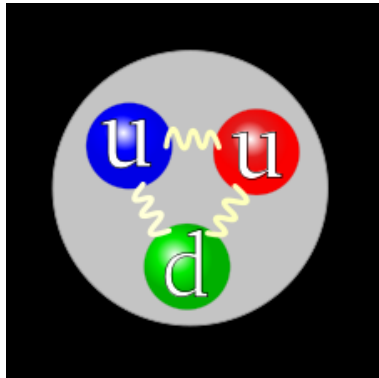
# 强相互作用: Quantum Chromodynamics (QCD)

➤ 基本假设: quark模型, 自旋1/2, 分数电荷, 带“色”荷 → “色紧闭”不存在自由夸克

✓ 低能(~keV)情况:

质子

$s=1/2$ ,  $m_p \sim 1\text{GeV}$



- $s_u = s_d = 1/2$
- $Q_u = +2/3$
- $Q_d = -1/3$
- $m_u \sim m_d \sim 0$

双电荷重子:

$$\Delta^{++} = \frac{1}{\sqrt{6}} \epsilon^{\alpha\beta\gamma} |u_\alpha u_\beta u_\gamma\rangle$$

✓ 高能(~10GeV)情况:

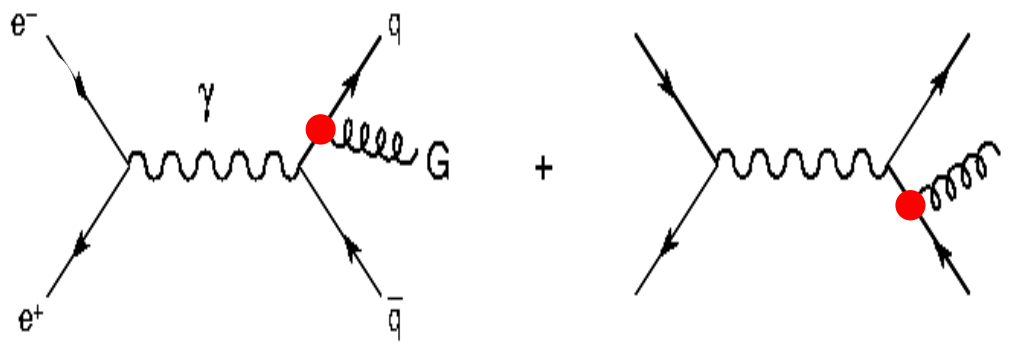
+ 不再能够鉴别强子类型,

e.g. 极端相对论情况下固有质量可忽略

+ 强子簇射能量损失 → “喷注” jet,

i.e. 探测器中行为可区别与电子/光子

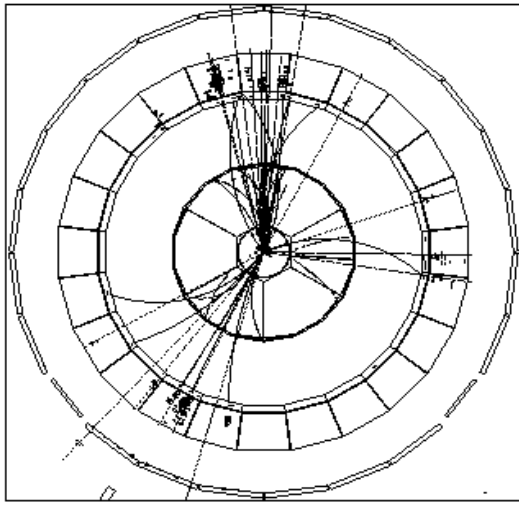
➤ quark模型实验检验(I): 3喷注测量



- 3-jets, not 3 EM object, i.e. not  $e^+ + e^- \rightarrow e^+ + e^- + \gamma$
- fractional charge :  $Q_e$  vs  $Q_q$
- strong coupling ( $qqG$ ) vs. electroweak ( $qq\gamma$ )

$\alpha \sim 1/137$  vs.  $\alpha_s \sim 0.2$

- Colors of quark and gluon



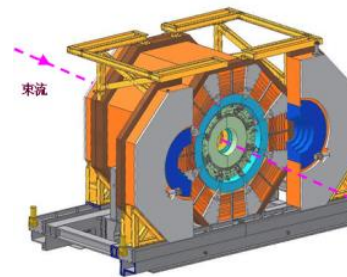
Three-jet event from the hadronic decay of a Z boson

# BES正负电子对撞强子物理研究

世界上唯一运行在 $\tau$ - $c$ 能区的 $e^+e^-$ 对撞机!



BES探测器



BESIII探测器



Leptons Quarks	$u$ up	$c$ charm	$t$ top
	$d$ down	$s$ strange	$b$ bottom
	$\nu_e$ e- neutrino	$\nu_\mu$ $\mu^-$ neutrino	$\nu_\tau$ $\tau^-$ neutrino
	$e$ electron	$\mu$ muon	$\tau$ tauon
	I	II	III
	Three Generations of Matter		

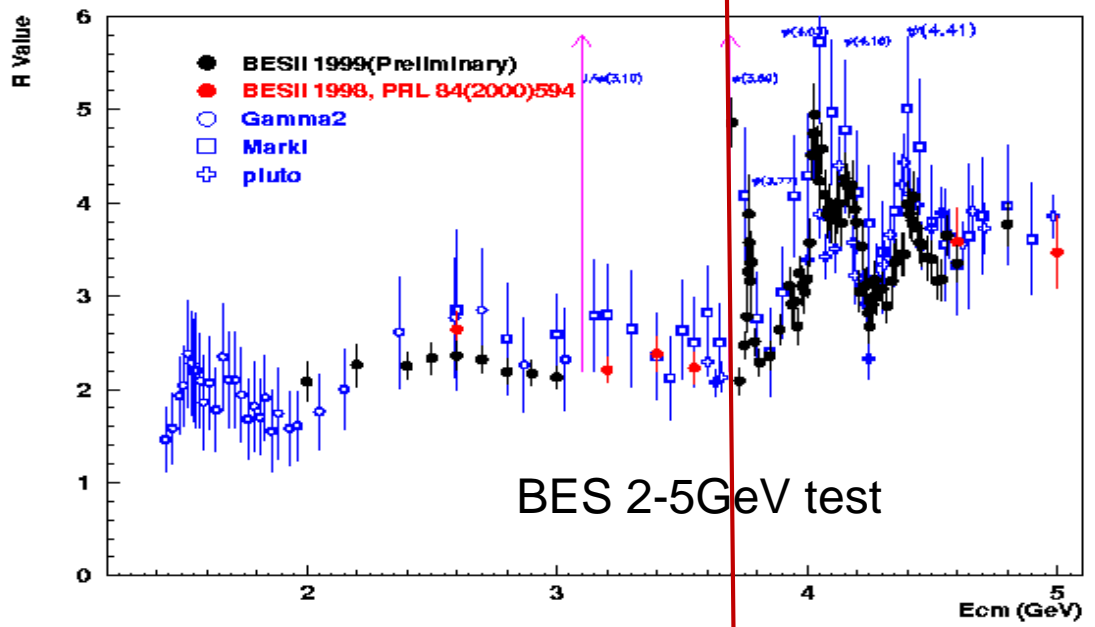
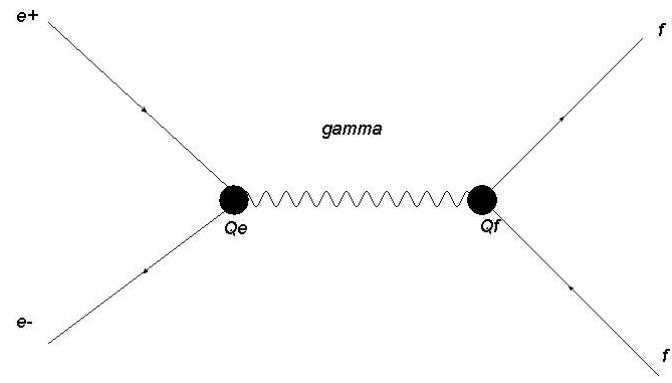
$E_{\text{beam}}$ : 1.0-2.1 (2.3) GeV

$\sigma_E$ :  $5.16 \times 10^{-4}$

L:  $0.65 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  @3770

➤ quark模型实验检验(II): BSE实验强子R值测量  $R \equiv \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$

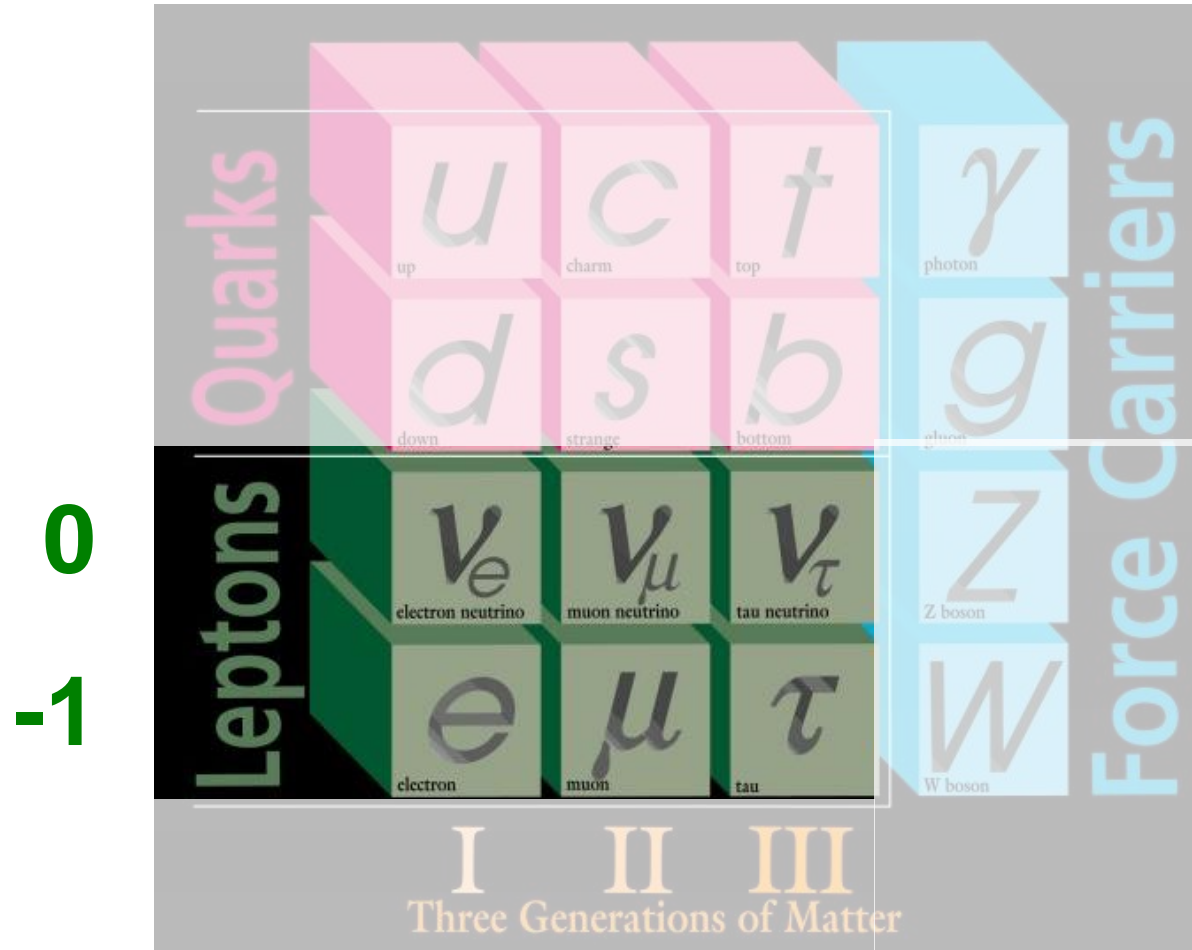
- $m(u) \sim m(d) \sim m(s) \sim 0$
- $m(c) \sim 1.7\text{GeV}$
- $Q(u) = Q(c) = 2/3, Q(d) = Q(s) = 1/3$
- **Colors** and **fractional** charge of quarks



$R \sim [(2/3)^2 + 2 \times (1/3)^2] \times 3 = 2$

$[2 \times (2/3)^2 + 2 \times (1/3)^2] \times 3 = 3$

# The Standard Model (II): Leptons



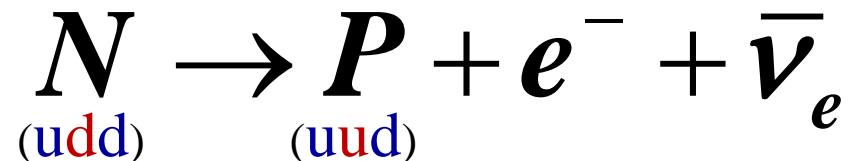
- $s=1/2$
- integral charged
- stringent L-number

$$L_e[e^-] = +1, \quad L_e[e^+] = -1$$

$$L_e[\nu_e] = +1, \quad L_e[\bar{\nu}_e] = -1$$

$$L_\mu[e^\pm, \nu_e, \bar{\nu}_e] = L_\tau[e^\pm, \nu_e, \bar{\nu}_e] = 0$$

**3 families**



# 理论引领发现：反物质粒子的存在



狄拉克方程：自旋1/2自由粒子量子力学波动方程

$$\left( \beta mc^2 + \sum_{k=1}^3 \alpha_k p_k c \right) \psi(\mathbf{x}, t) = i\hbar \frac{\partial \psi(\mathbf{x}, t)}{\partial t}$$

能量解：

$$E = c\sqrt{p^2 + m^2c^2},$$

$E > 0$ , 自由粒子动能

$E < 0$ , ?  $\longrightarrow$  **Dirac反粒子假说**



# 第一个在实验上发现反物质粒子的 科学家是中国科学家



1930年赵忠尧观测正负电子  
湮灭 $e^+e^- \rightarrow \gamma\gamma$ 致光信号

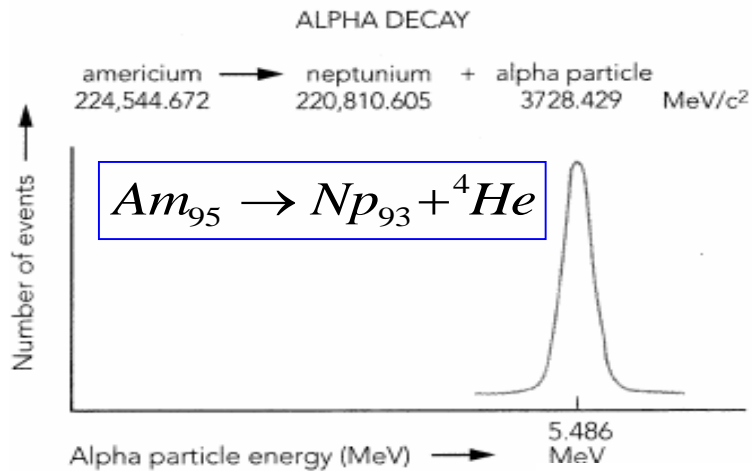


1932年安德逊在宇宙线中  
观测正电子 $e^+$ 径迹

# 实验对理论的推动：中微子

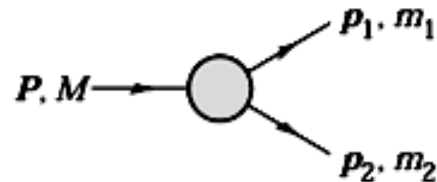
- Human body = 20 mg of Potassium  $^{40}\text{K}$  emitting 340 million neutrinos per day!
- 100,000 billion pass through your body each second from the sun
  - Your body will stop **1** neutrino which passes through it in a lifetime!





- 2 body  $\alpha$  decay, energy E of decay products always the same

## Two Body Decay Kinematics:



**Figure 38.1:** Definitions of variables for two-body decays.

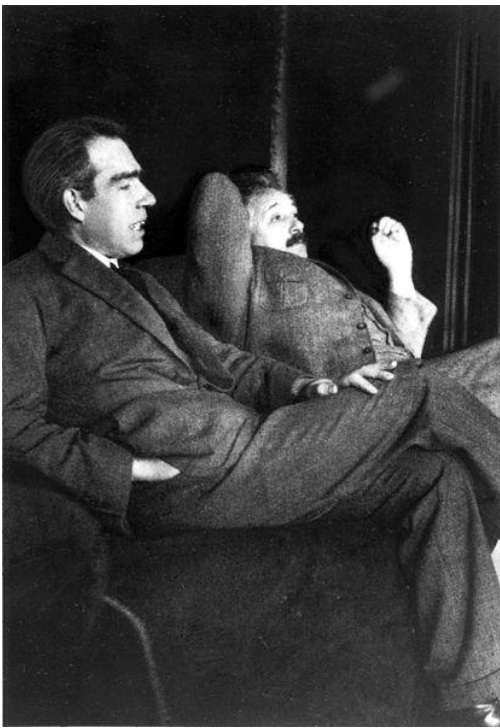
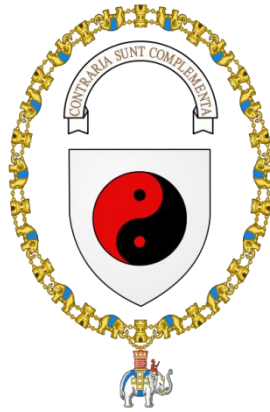
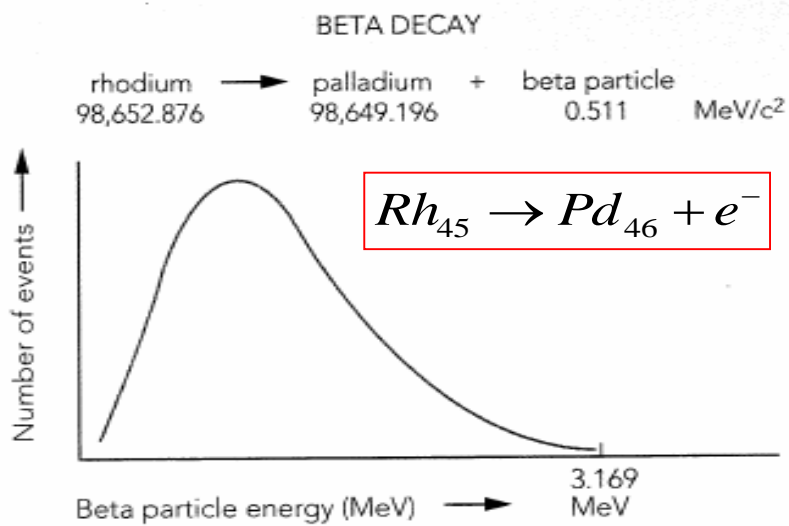
### 38.4.2. *Two-body decays:*

In the rest frame of a particle of mass  $M$ , decaying into 2 particles labeled 1 and 2,

$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M}, \quad (38.15)$$

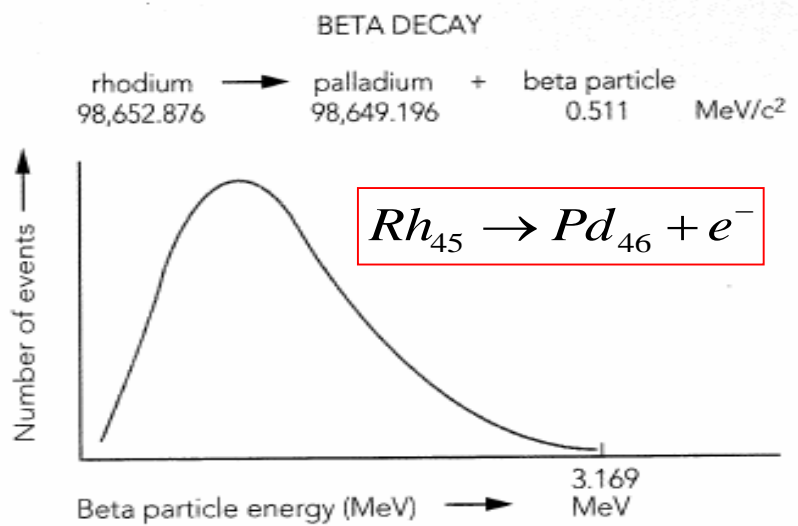
$$|\mathbf{p}_1| = |\mathbf{p}_2|$$

● 1913 - 1930 :  $\beta$  decay  $\rightarrow$  continuous spectrum of E ?!



? “E or P not conserved in Sub-Atom World ”  
(Niels Bohr)

● 1913 - 1930 :  $\beta$  decay  $\rightarrow$  continuous spectrum of E ?!



Hypothesis of Neutrino:

- Massless,  $mv = 0$
- No or very weak interaction  $\rightarrow$  **undetectable**

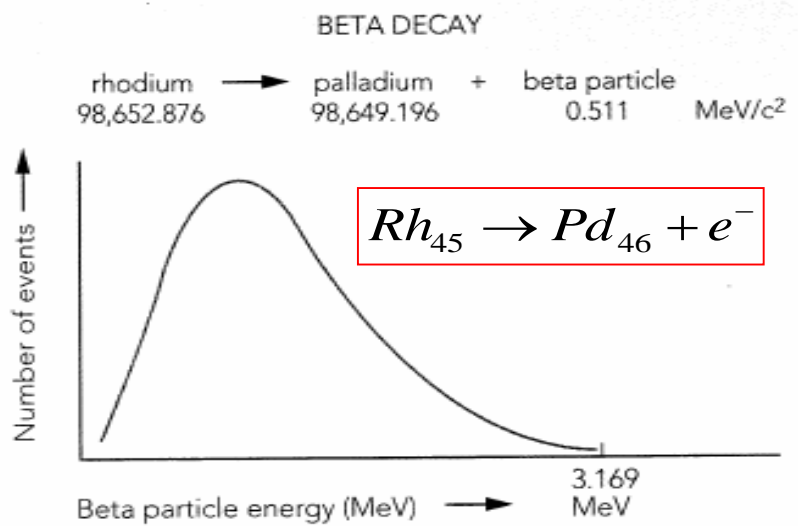


Wolfgang E Pauli (1930)

$$N \rightarrow P + e^{-} + \bar{\nu}_e$$



● 1913 - 1930 :  $\beta$  decay  $\rightarrow$  continuous spectrum of E ?!



? “I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do.”

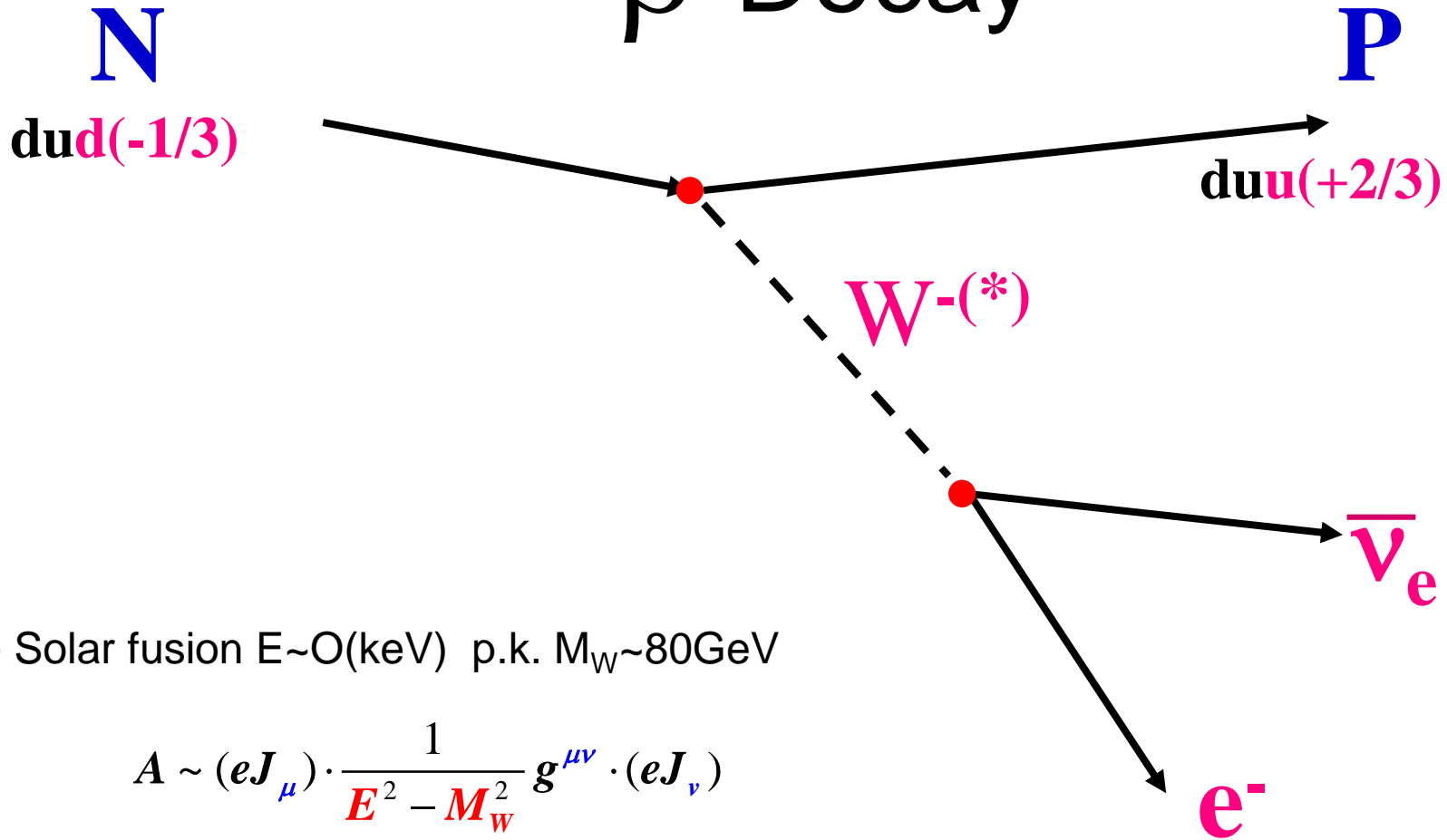


Wolfgang E Pauli (1930)

$$N \rightarrow P + e^{-} + \bar{\nu}_e$$



# $\beta$ Decay

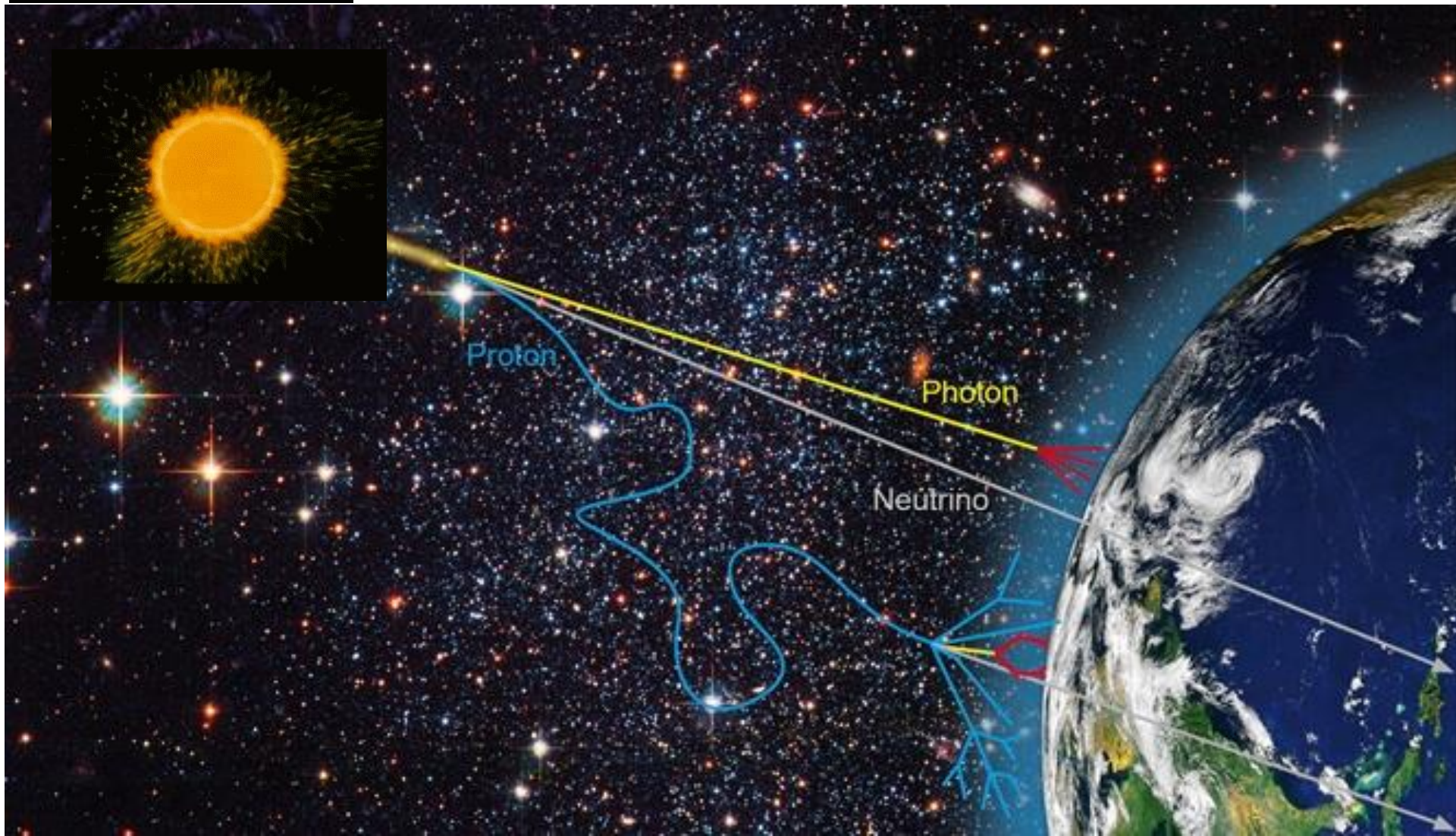
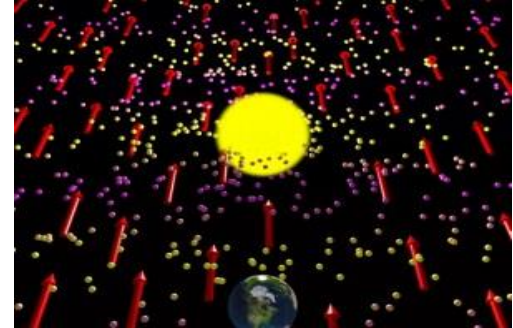


-- Solar fusion  $E \sim O(\text{keV})$  p.k.  $M_W \sim 80 \text{ GeV}$

$$A \sim (eJ_\mu) \cdot \frac{1}{E^2 - M_W^2} g^{\mu\nu} \cdot (eJ_\nu)$$

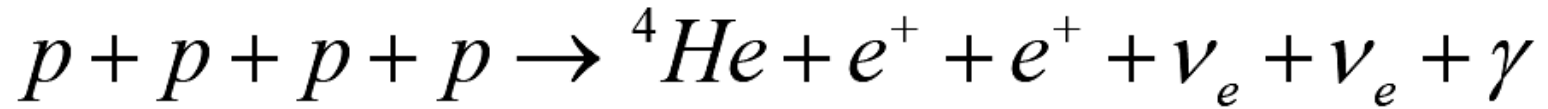
-- Fusion interaction rate highly suppressed of  $M_W$

# 太阳中微子探测

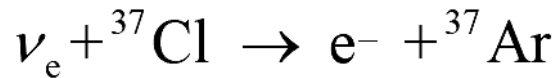




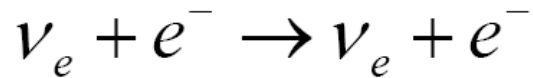
# Solar Neutrino puzzle



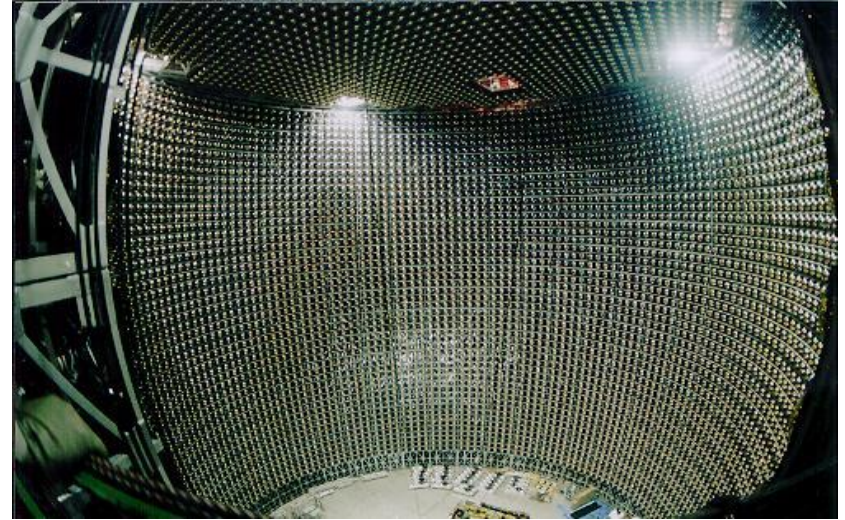
--1964, South Dakota "Homestake"



-- 1985-2000, [Kamiokanda](#), Japan



**1000米地下, 50000吨高纯水, 13000个PMT**



Experiment	$\langle E_\nu \rangle$	$P(\nu_e \rightarrow \nu_e)$
SNO	$\sim 8\text{MeV}$	$0.348 \pm 0.029$
SAGE	$\sim 0.8\text{MeV}$	$0.54 \pm 0.06$
Gallex+GNO	$\sim 0.8\text{MeV}$	$0.56 \pm 0.07$
Homestake	$\sim 8\text{MeV}$	$0.34 \pm 0.03$

# Neutrino Oscillation

## -- Neutrino Mixing Hypothesis

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

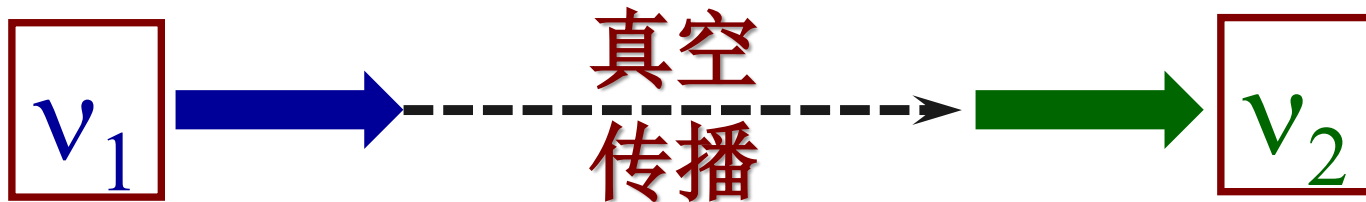
-- 流本征态  $\alpha, \beta = e, \mu, \tau$   
-- 质量本征态  $i, j = 1, 2, 3..$

- free particle travelling in vacuum

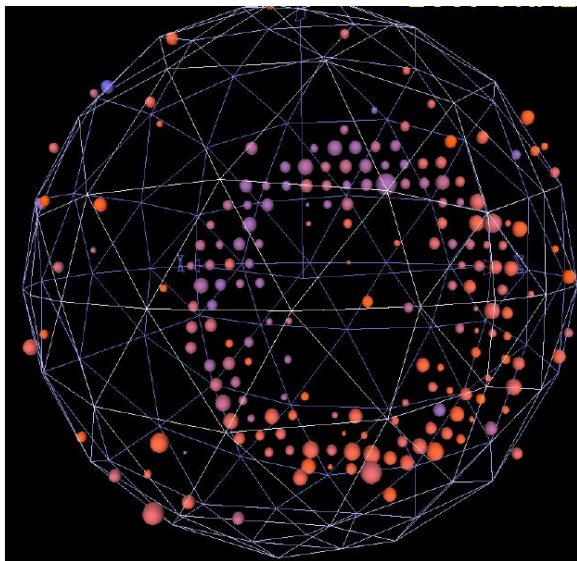
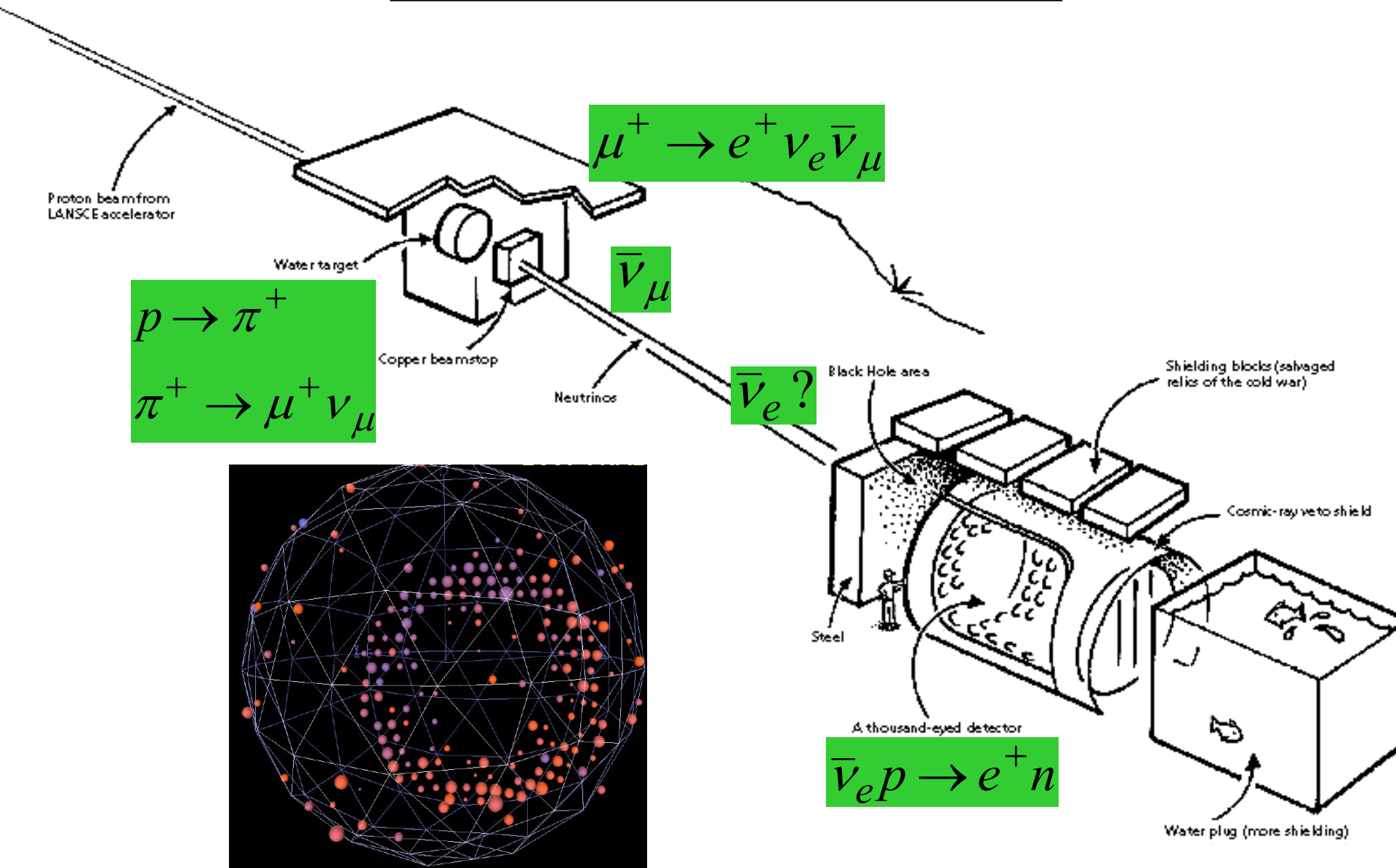
- oscillation between different eigenstate  $\rightarrow \psi(t) = \psi(0) \cdot e^{-i\hat{H}t}$

$$\hat{H} = \hat{E} = \Delta m \cdot c^2$$

$$P(\alpha \rightarrow \alpha) = 1 - \sin^2 2\theta \sin^2 \left[ 1.27 \Delta m_{ij}^2 \left( \frac{L}{E} \right) \right]$$



# Neutrino Oscillation



# The NOvA Experiment

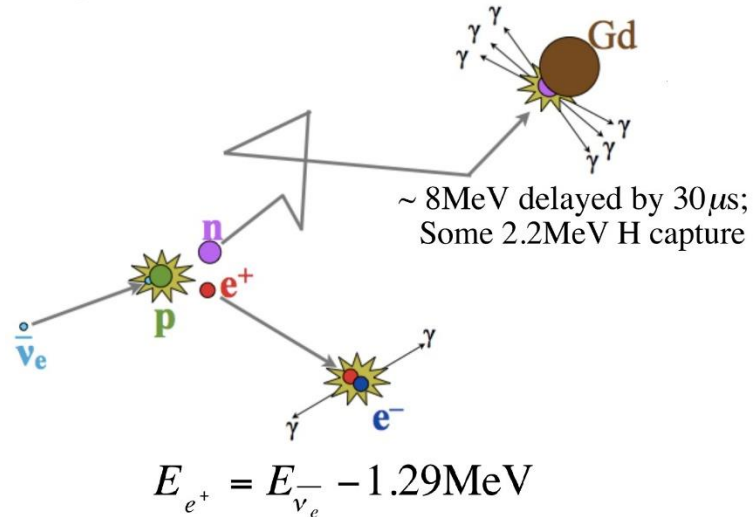
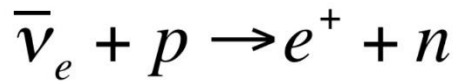
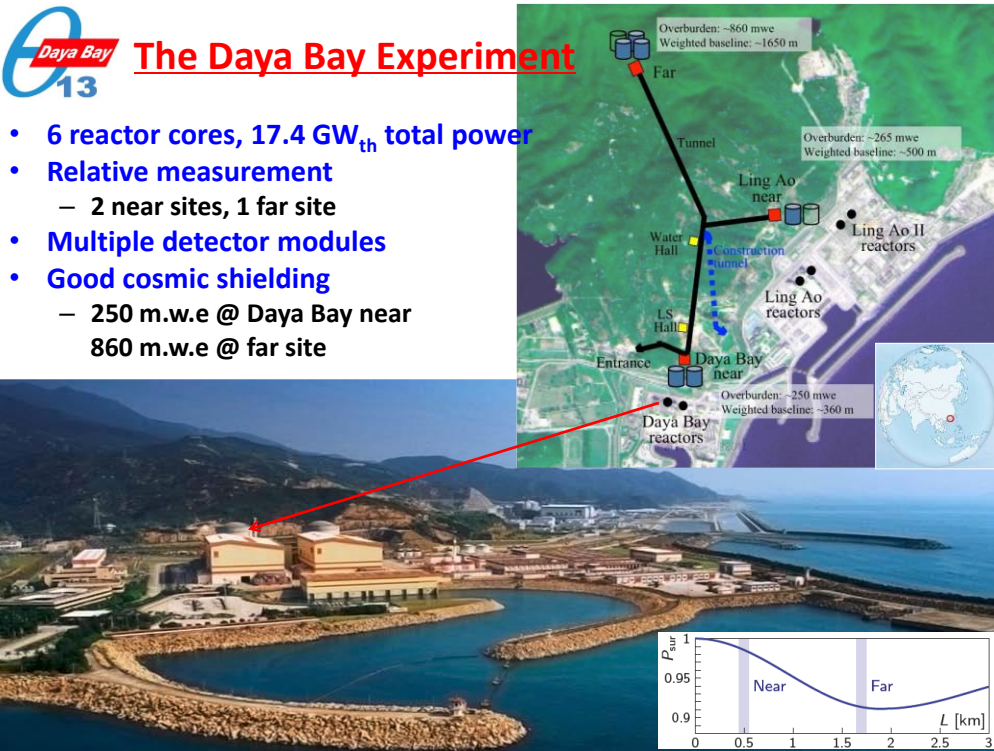


## NuMI Off-axis $\nu_e$ Appearance

- Two detector, long-baseline neutrino oscillation experiment;
- Off-axis neutrinos from NuMI beam;
- $L/E \sim 400 \text{ km/GeV}$ ; atmospheric  $\Delta m^2$
- Physics goals:
  - Precision measurements of  $\Delta m^2$ ,  $\theta_{23}$  from  $\nu_\mu$  disappearance;
  - Search for  $\nu_\mu$  to  $\nu_e$  transitions with both neutrinos and antineutrinos;
    - Measure/limit  $\theta_{13}$ ;
    - Determine mass hierarchy;
    - Constrain CP violation phase;

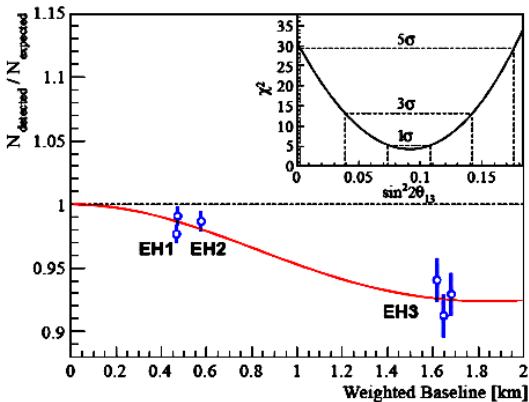


# 大亚湾反应堆中微子实验



➤ I期关键科学问题：中微子振荡 $\theta_{13}$

➤ II期升级： $m(\nu_i)$ 质量顺序 + CP破坏?



$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$

$$\nu_i \rightarrow \nu_j @ \theta_{ij}$$

