

# 超出标准模型之外的新物理

*A faked experimentalist's perspective*

曹庆宏

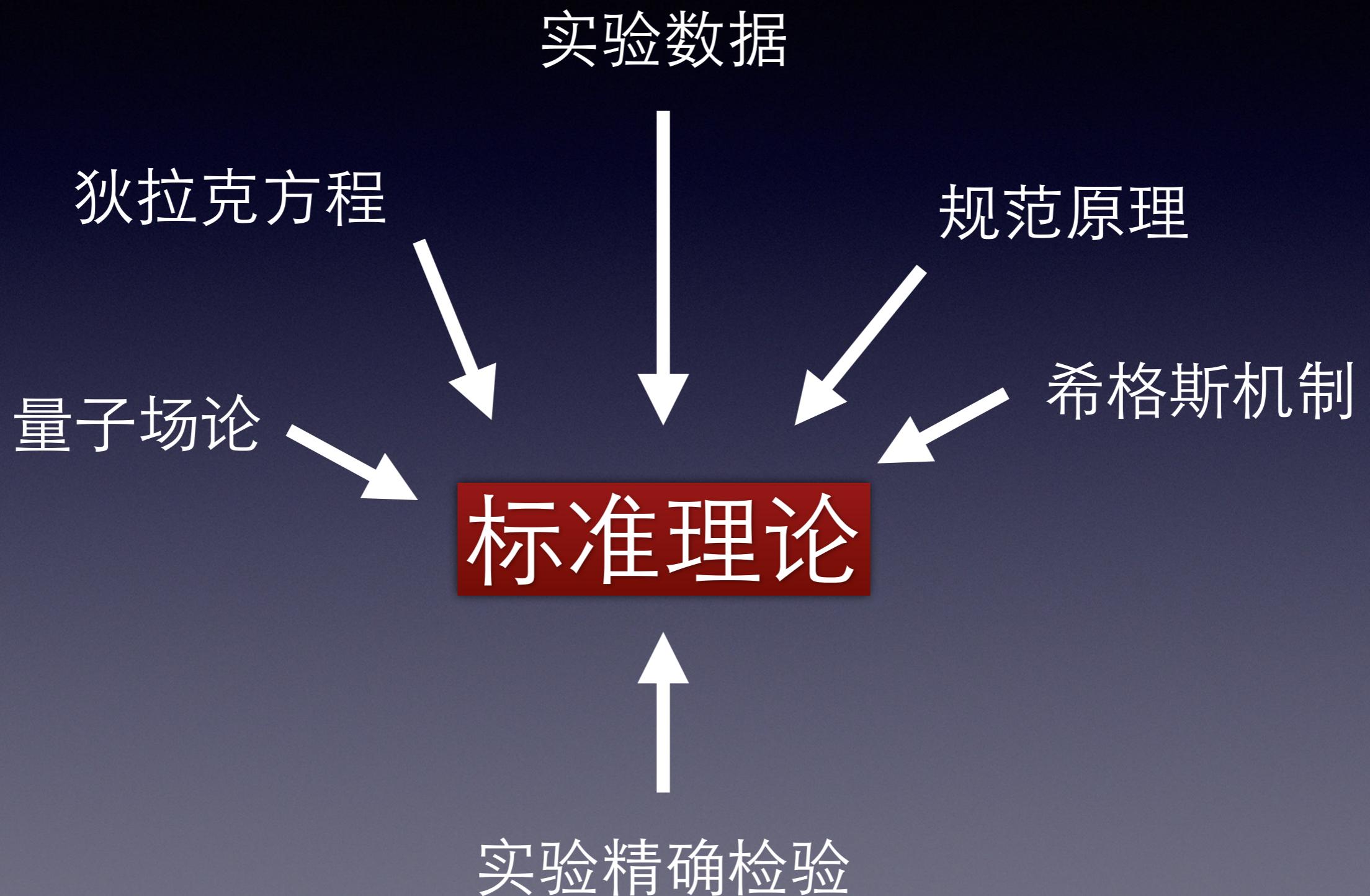
北京大学物理学院

2015年8月16日于山东大学

# 报告提纲

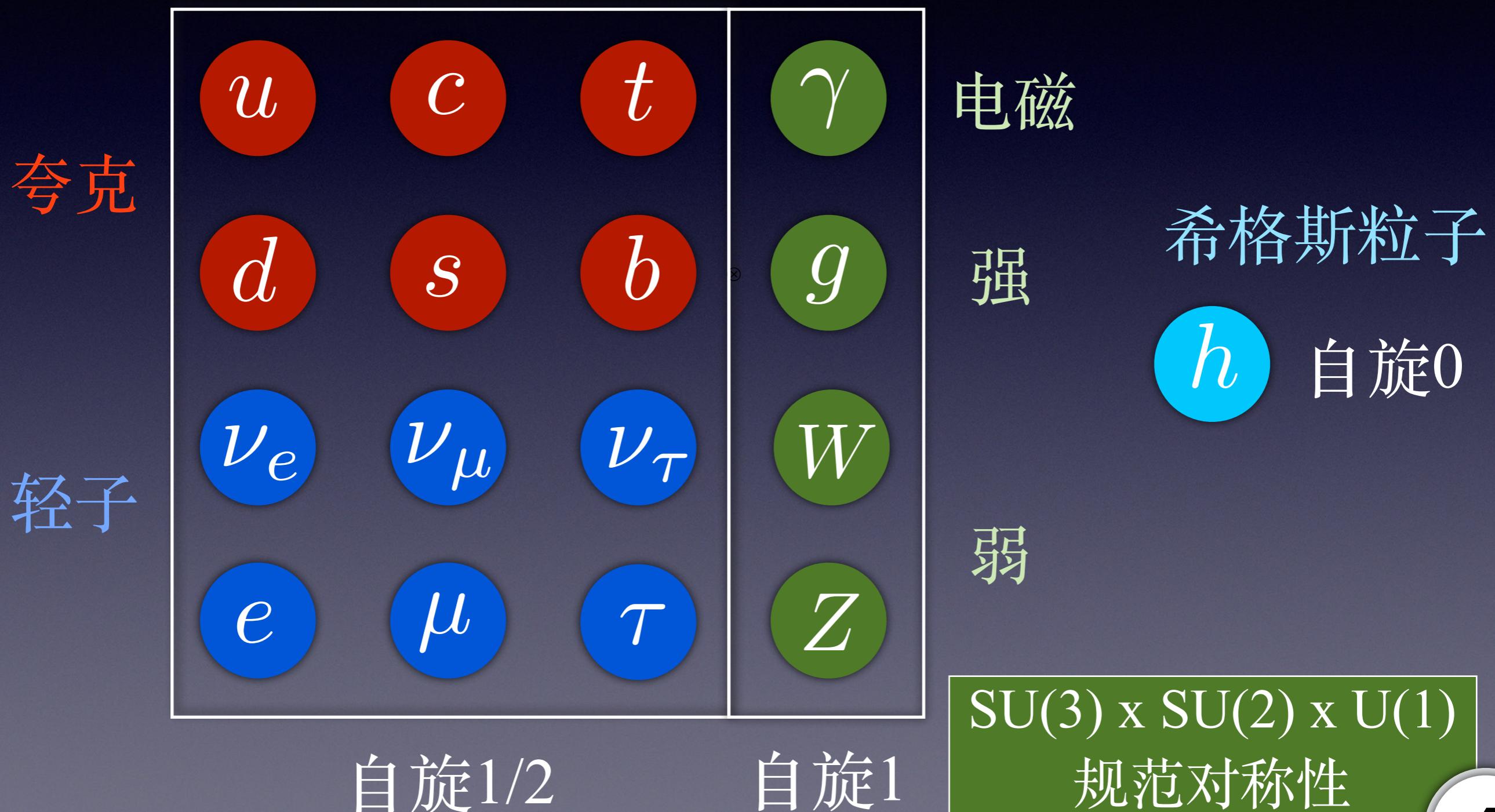
- 1) 标准模型回顾
- 2) 为什么寻找标准模型之外的新物理?
- 3) 如何探测新物理粒子? 探测器简介
- 4) 中微子质量
- 5) 暗物质粒子起源
- 6) 新物理粒子、模型及其对撞机信号

# 粒子物理的标准模型



# 粒子物理的标准模型

已知的基本粒子谱



# 标准模型中相互作用

量子力学中的自旋轨道角动量耦合

$$\begin{pmatrix} \uparrow \\ \downarrow \end{pmatrix}_1 \otimes \begin{pmatrix} \uparrow \\ \downarrow \end{pmatrix}_2 = \begin{pmatrix} \uparrow_1 \uparrow_2 \\ \frac{1}{\sqrt{2}} (\uparrow_1 \downarrow_2 + \downarrow_1 \uparrow_2) \\ \downarrow_1 \downarrow_2 \end{pmatrix}$$

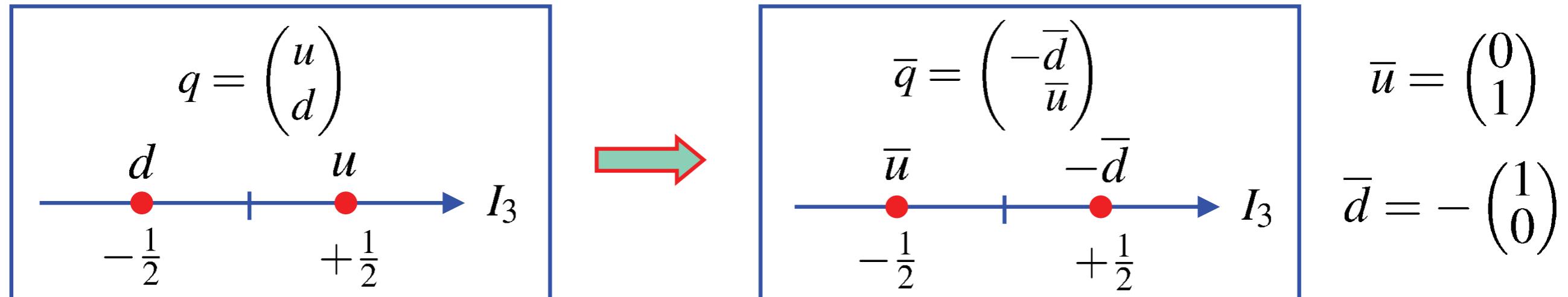
$$\oplus \frac{1}{\sqrt{2}} (\uparrow_1 \downarrow_2 - \downarrow_1 \uparrow_2)$$

$$2 \otimes 2 = 3 \oplus 1$$

$$2 \otimes \bar{2} = 3 \oplus 1$$

# Anti-quarks and Mesons (u and d)

★ The u, d quarks and  $\bar{u}$ ,  $\bar{d}$  anti-quarks are represented as isospin doublets



- Subtle point: The ordering and the minus sign in the anti-quark doublet ensures that anti-quarks and quarks transform in the same way (see Appendix I). This is necessary if we want physical predictions to be invariant under  $u \leftrightarrow d$ ;  $\bar{u} \leftrightarrow \bar{d}$
- Consider the effect of ladder operators on the anti-quark isospin states

e.g.  $T_+ \bar{u} = T_+ \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} = -\bar{d}$

- The effect of the ladder operators on anti-particle isospin states are:

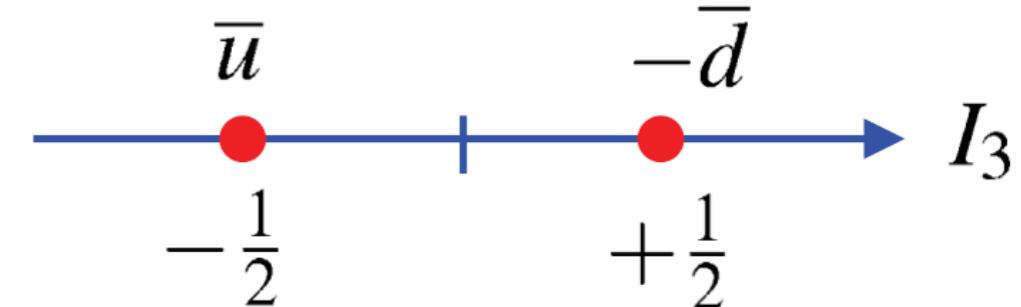
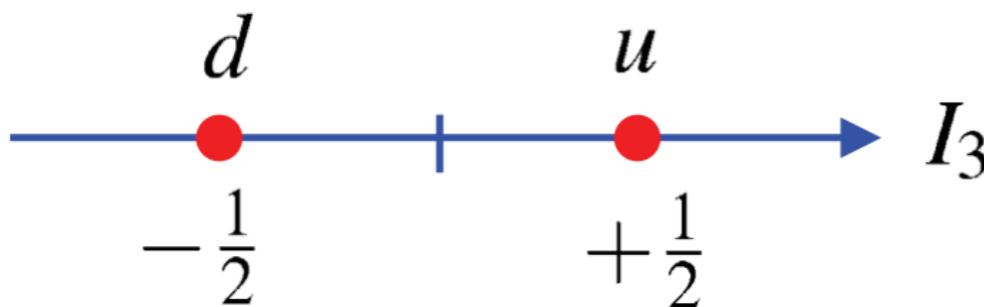
$$T_+ \bar{u} = -\bar{d} \quad T_+ \bar{d} = 0 \quad T_- \bar{u} = 0 \quad T_- \bar{d} = -\bar{u}$$

Compare with

$$T_+ u = 0 \quad T_+ d = u \quad T_- u = d \quad T_- d = 0$$

# Light ud Mesons

Can now construct meson states from combinations of up/down quarks



Consider the  $q\bar{q}$  combinations in terms of isospin

$$|1,+1\rangle = |\frac{1}{2}, +\frac{1}{2}\rangle \overline{|\frac{1}{2}, +\frac{1}{2}\rangle} = -u\bar{d}$$

$$|1,-1\rangle = |\frac{1}{2}, -\frac{1}{2}\rangle \overline{|\frac{1}{2}, -\frac{1}{2}\rangle} = d\bar{u}$$

The bar indicates this is the isospin representation of an anti-quark

To obtain the  $I_3 = 0$  states use ladder operators and orthogonality

$$T_- |1,+1\rangle = T_- [-u\bar{d}]$$

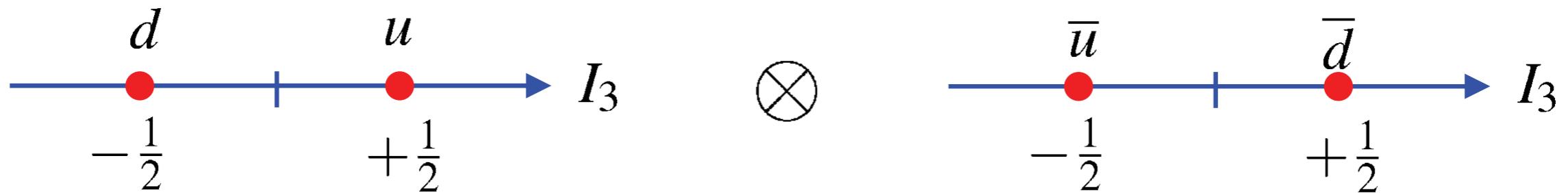
$$\begin{aligned} \sqrt{2} |1,0\rangle &= -T_- [u] \bar{d} - u T_- [\bar{d}] \\ &= -d\bar{d} + u\bar{u} \end{aligned}$$



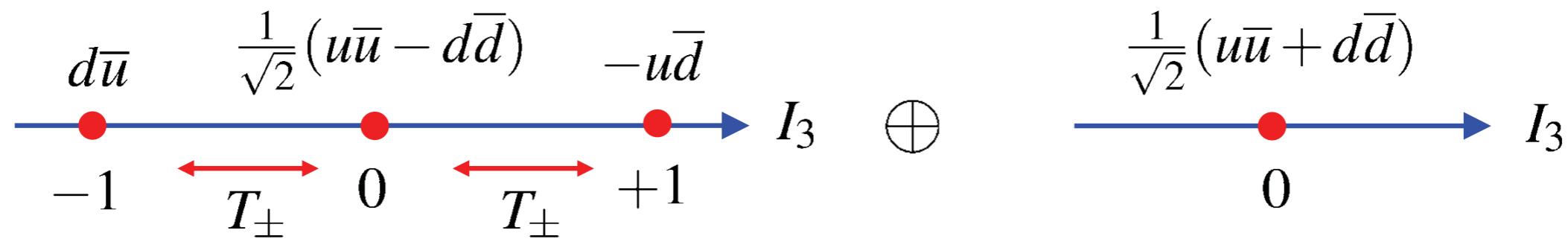
$$|1,0\rangle = \frac{1}{\sqrt{2}} (u\bar{u} - d\bar{d})$$

Orthogonality gives:  $|0,0\rangle = \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d})$

★ To summarise:



**Triplet of  $I = 1$  states and a singlet  $I = 0$  state**



- You will see this written as

**Quark doublet**

$$2 \otimes \bar{2} = 3 \oplus 1$$

**Anti-quark doublet**

- To show the state obtained from orthogonality with  $|1,0\rangle$  is a singlet use ladder operators

$$T_+ |0,0\rangle = T_+ \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) = \frac{1}{\sqrt{2}}(-u\bar{d} + u\bar{d}) = 0$$

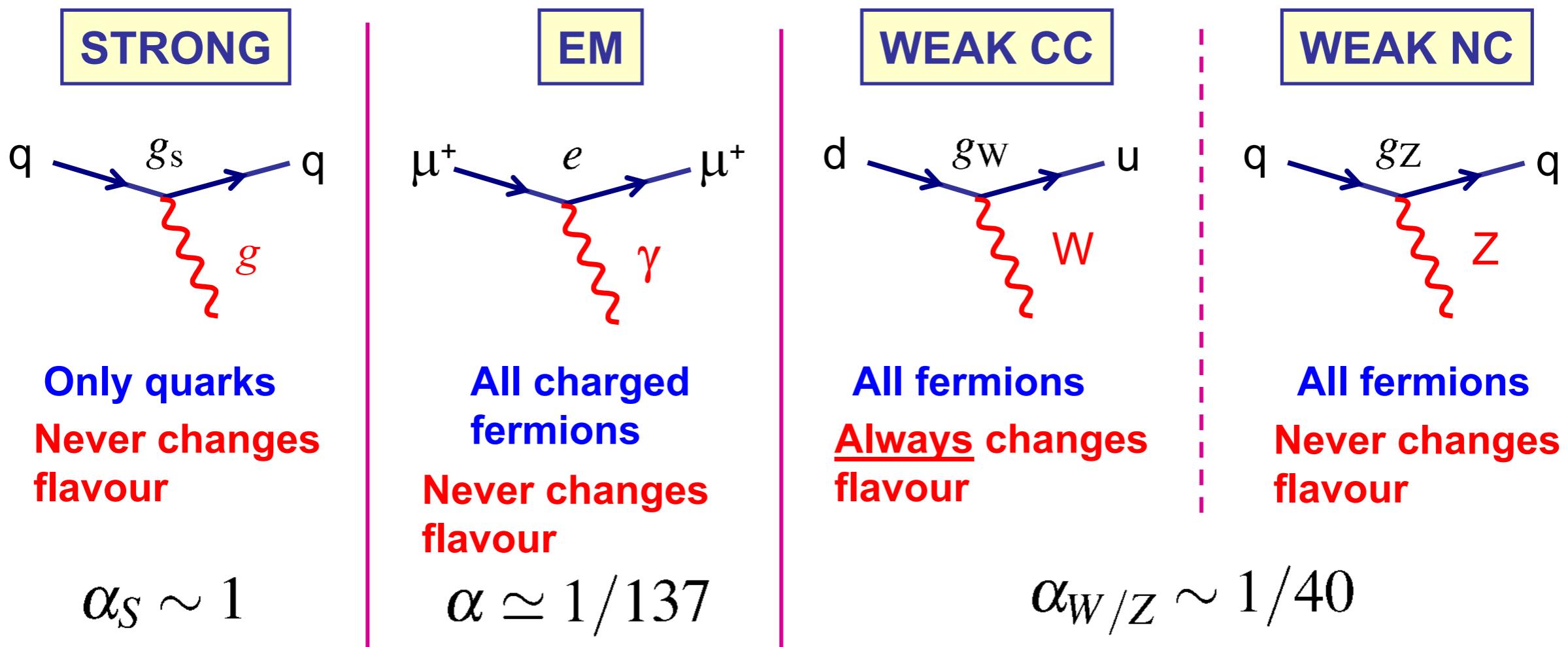
similarly  $T_- |0,0\rangle = 0$

★ A singlet state is a “dead-end” from the point of view of ladder operators

# 标准模型中相互作用：费曼图

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad u_R \quad d_R \quad e_R$$

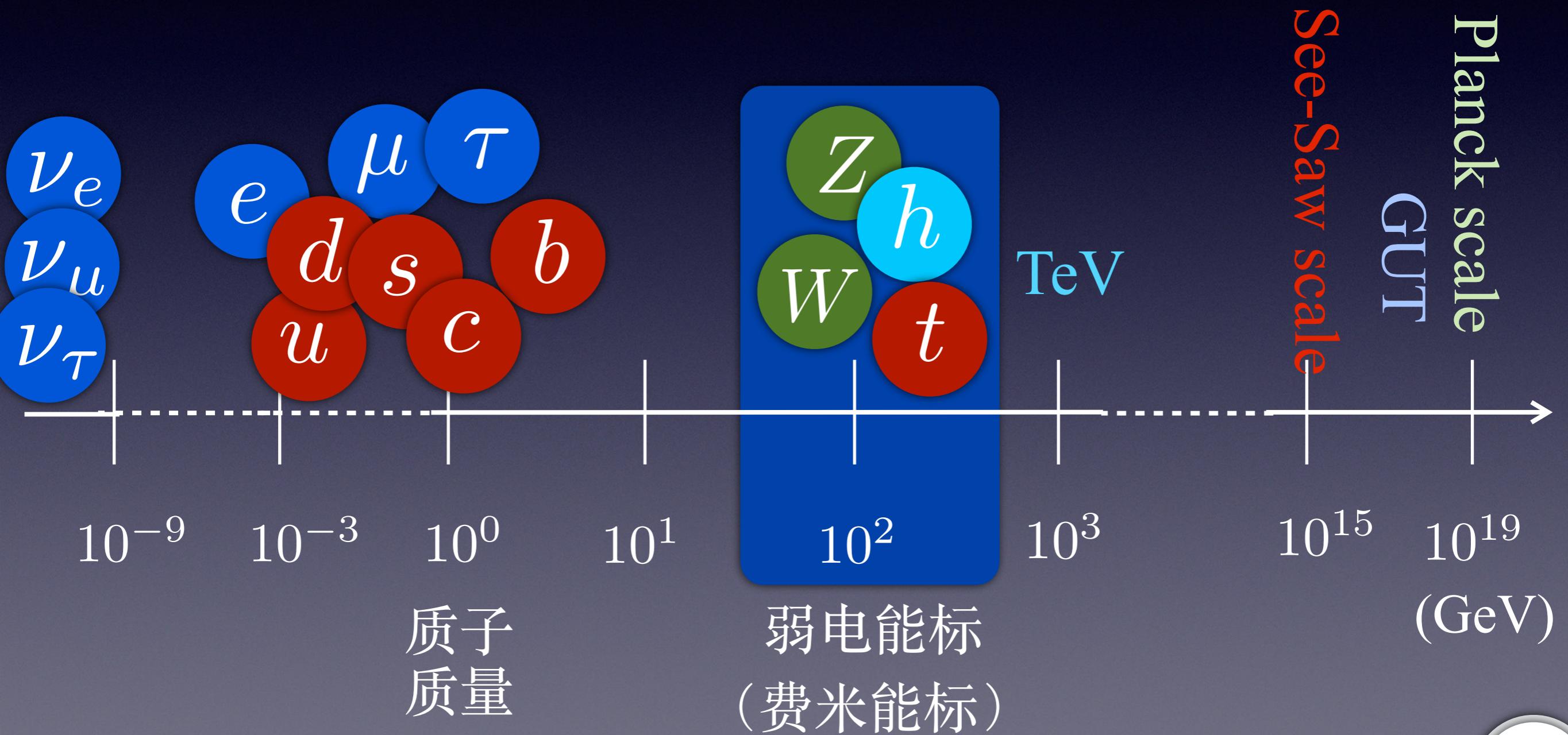
- ★ Interaction of gauge bosons with fermions described by SM vertices
- ★ Properties of the gauge bosons and nature of the interaction between the bosons and fermions determine the properties of the interaction



为什么寻找新物理?  
(标准模型有什么不妥之处吗?)

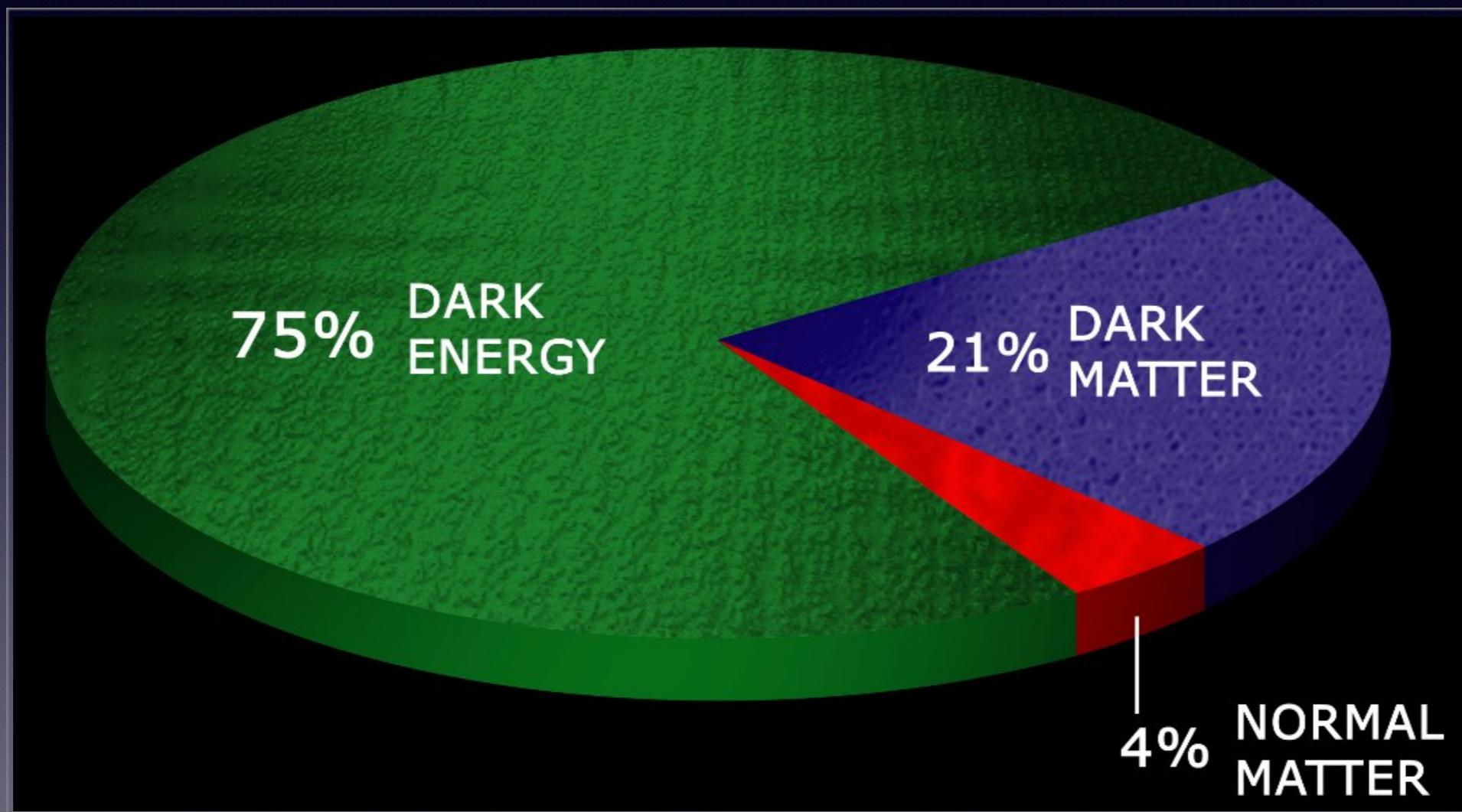
# 标准模型的不足之处

- 1) 标准模型的粒子谱具有非常大的质量差异和中微子质量起源



# 标准模型的不足之处

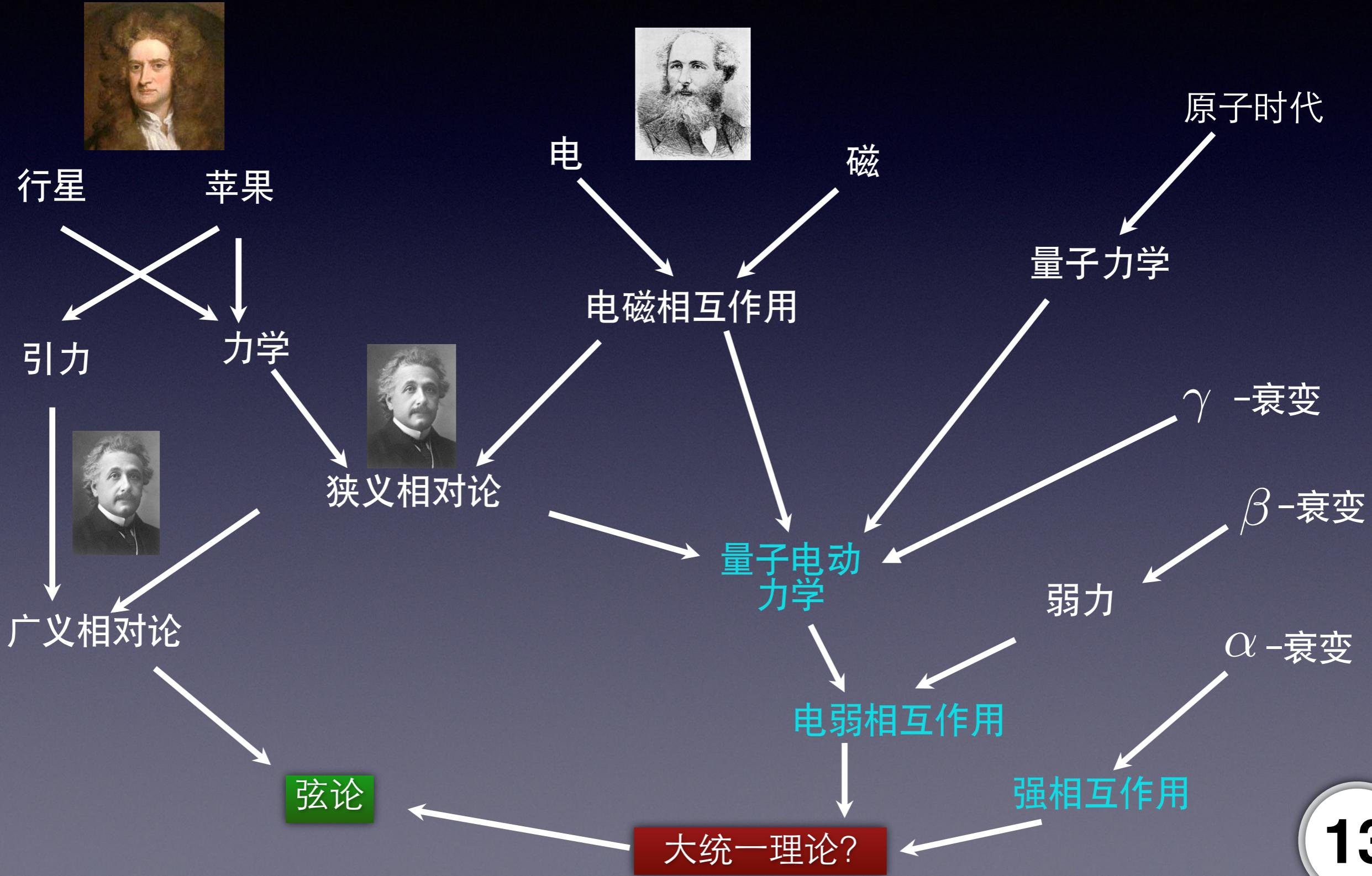
## 2) 暗物质的粒子物理起源



标准模型中没有暗物质候选者

# 标准模型的不足之处

## 3) 大统一理论

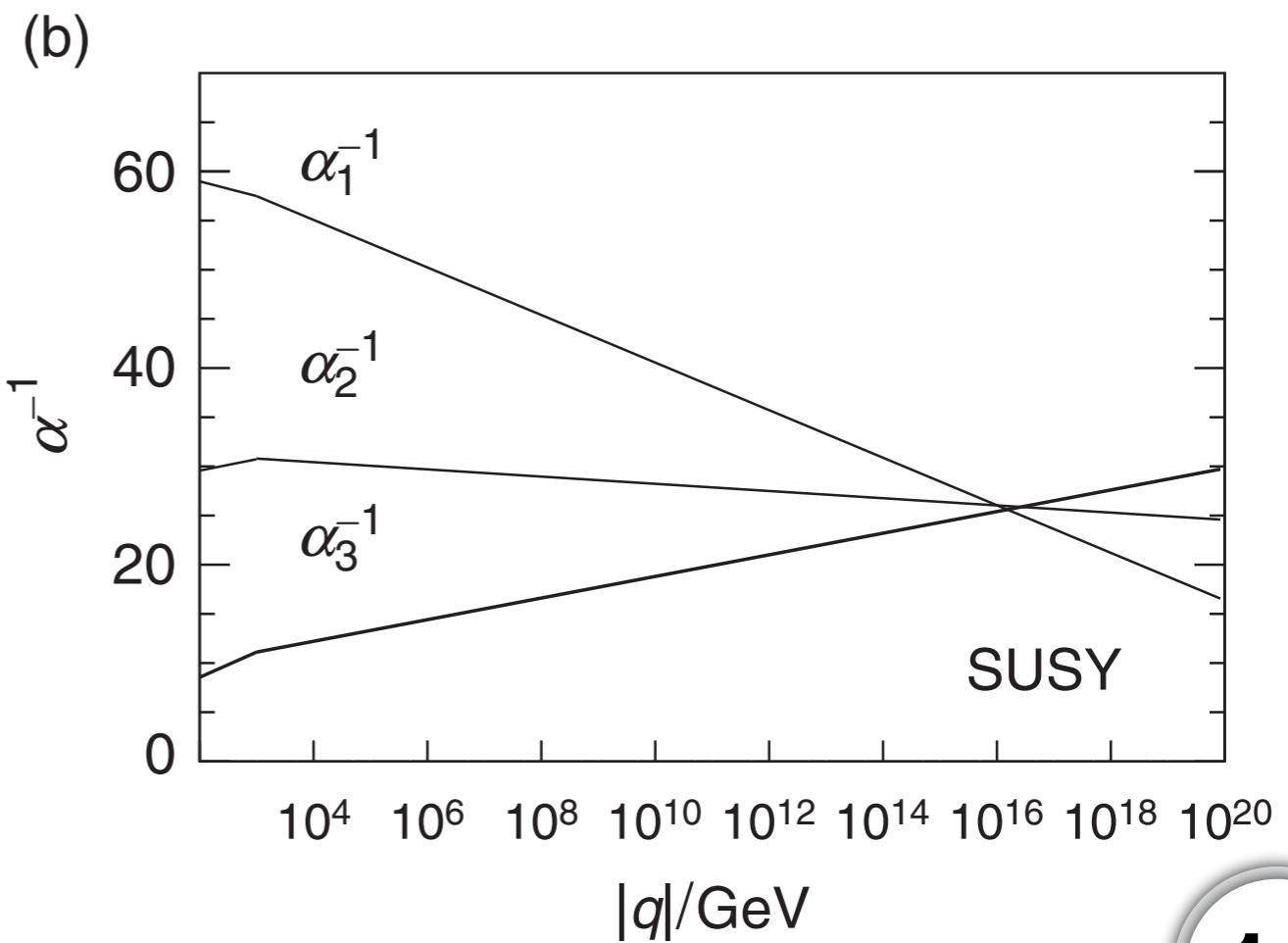
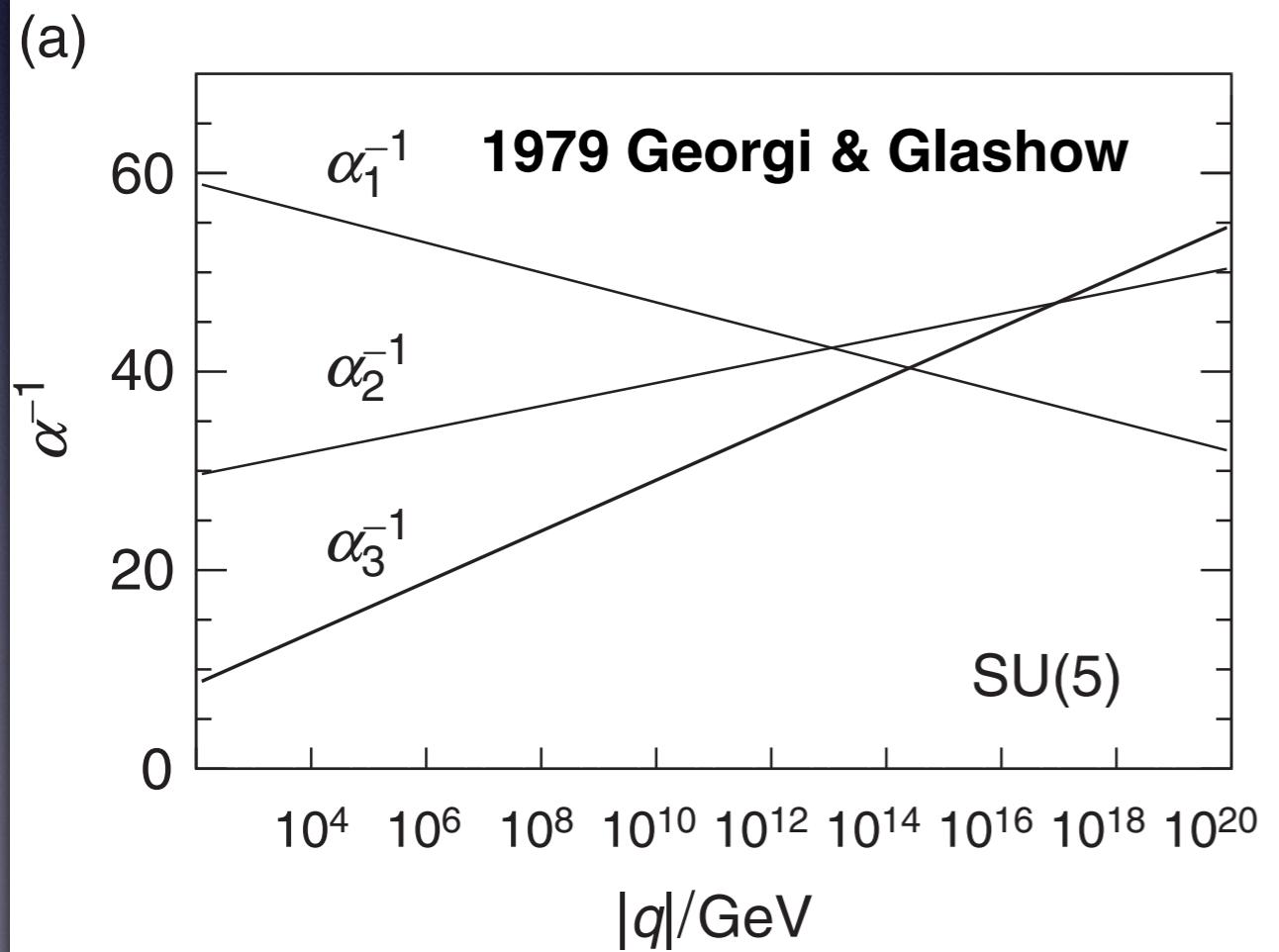


# 标准模型的不足之处

3) 大统一理论：标准模型三种作用力无法统一

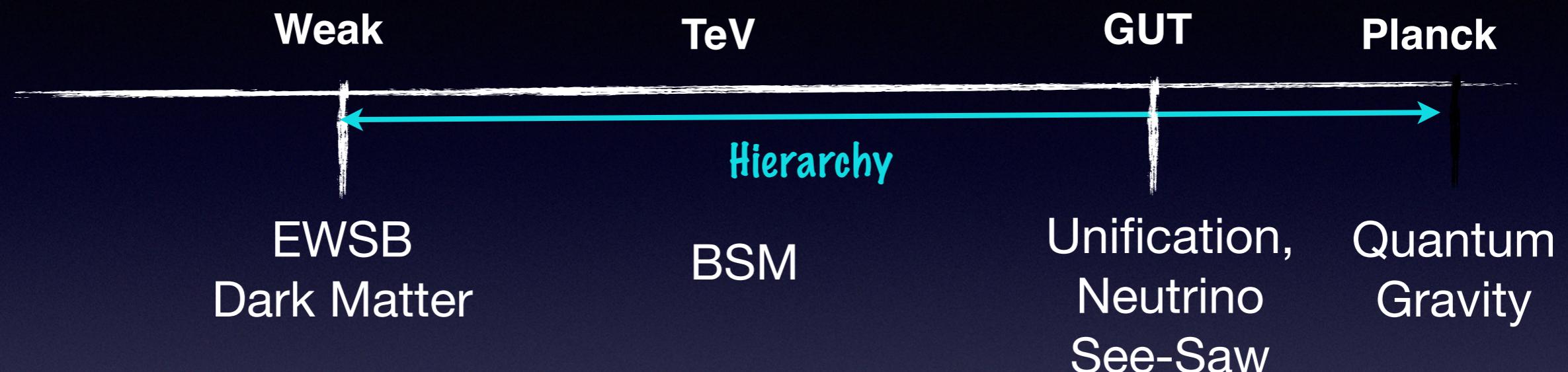
$$\alpha^{-1} : \alpha_W^{-1} : \alpha_S^{-1} \approx 128 : 30 : 9$$

$$[\alpha_i(q^2)]^{-1} = [\alpha_i(\mu^2)]^{-1} + \beta \ln\left(\frac{q^2}{\mu^2}\right)$$



# 标准模型的不足之处

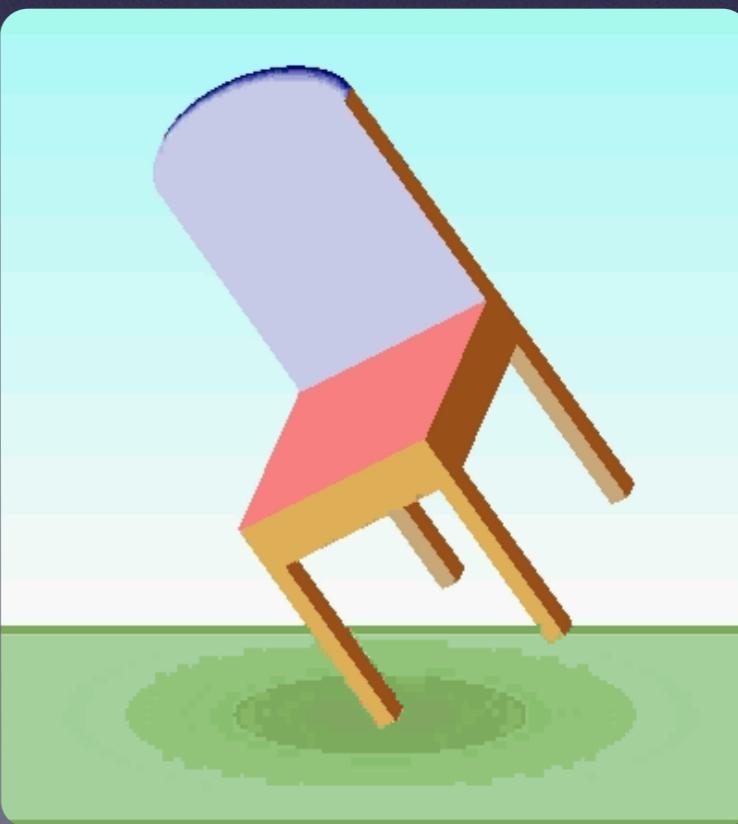
#### 4) 等级性问题（精细调节问题）



If SM valid up to GUT scale,  
the theory has  
extreme fine-tuning !

$$m_h^2 = m_0^2 - \delta m_h^2$$

125 bare  $\Lambda^2 / 52$



下面，我们将重点讨论各种新物理模型以及它们在对撞机上的实验信号

# 大型强子对撞机

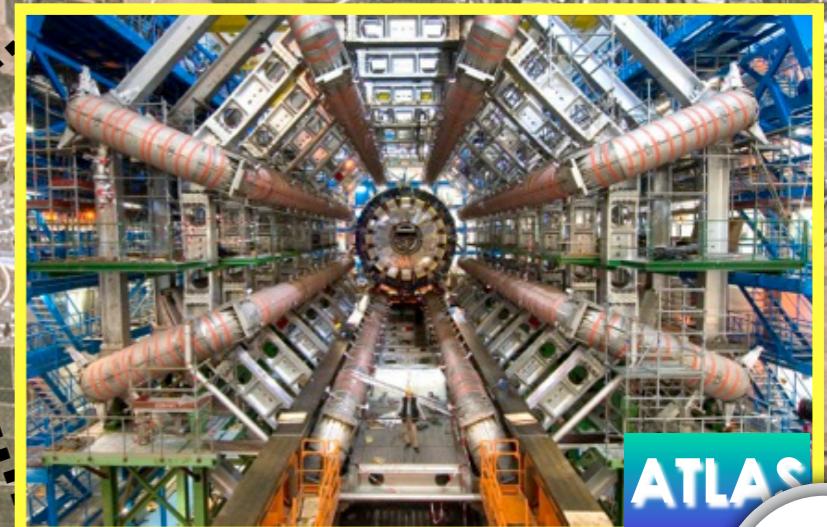
质心系能量14TeV

An aerial photograph showing the Large Hadron Collider (LHC) ring, which is a circular structure about 27 km in circumference, located in the French-Swiss border region. The ring is represented by a white circle overlaid on the image. The surrounding area consists of green fields and some urban developments.

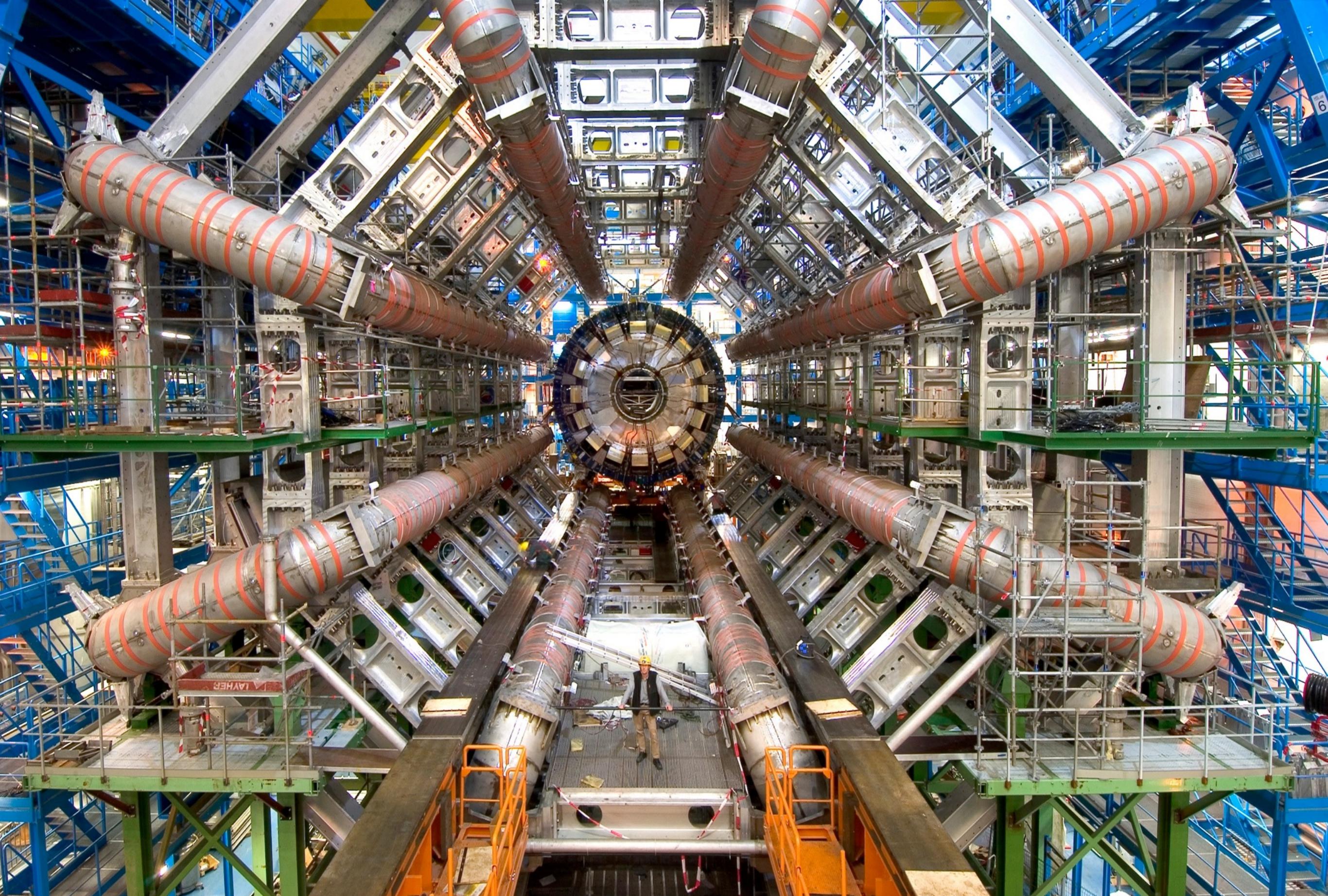
LHC ring:  
27 km circumference

# 大型强子对撞机

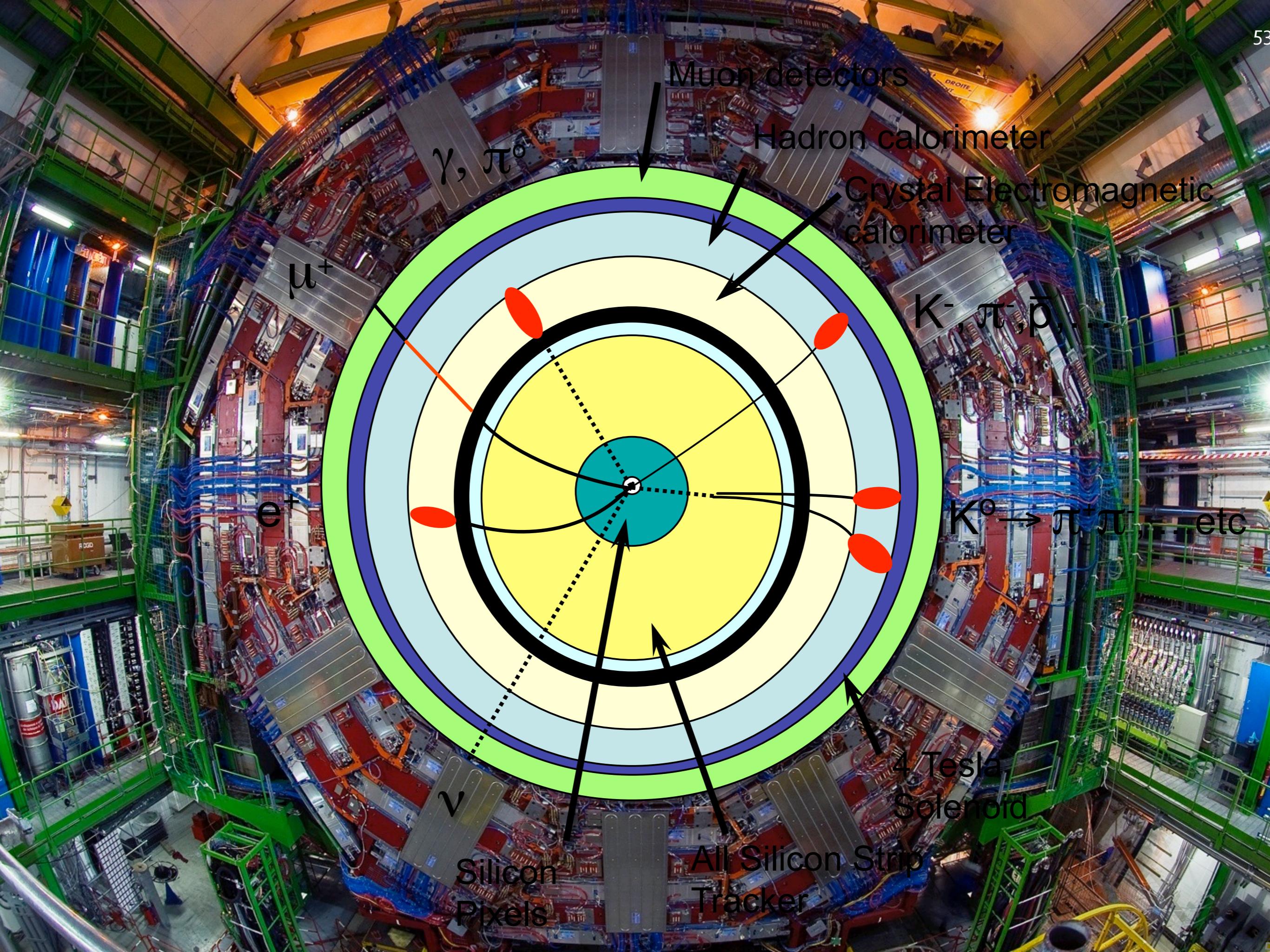
质心系能量14TeV

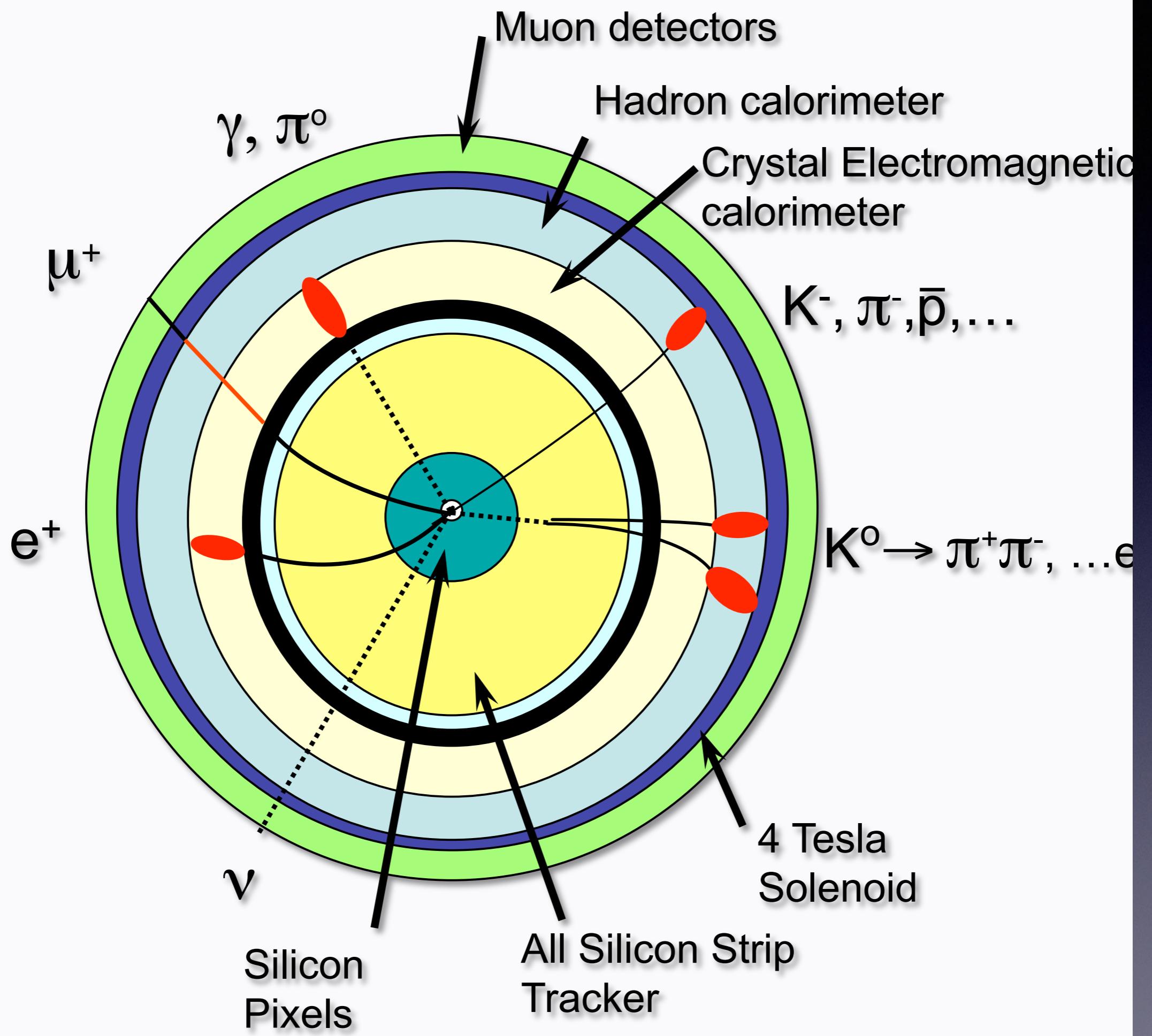


LHC ring:  
27 km circumference



**ATLAS:** 长46米，高25米，宽25米，7千吨

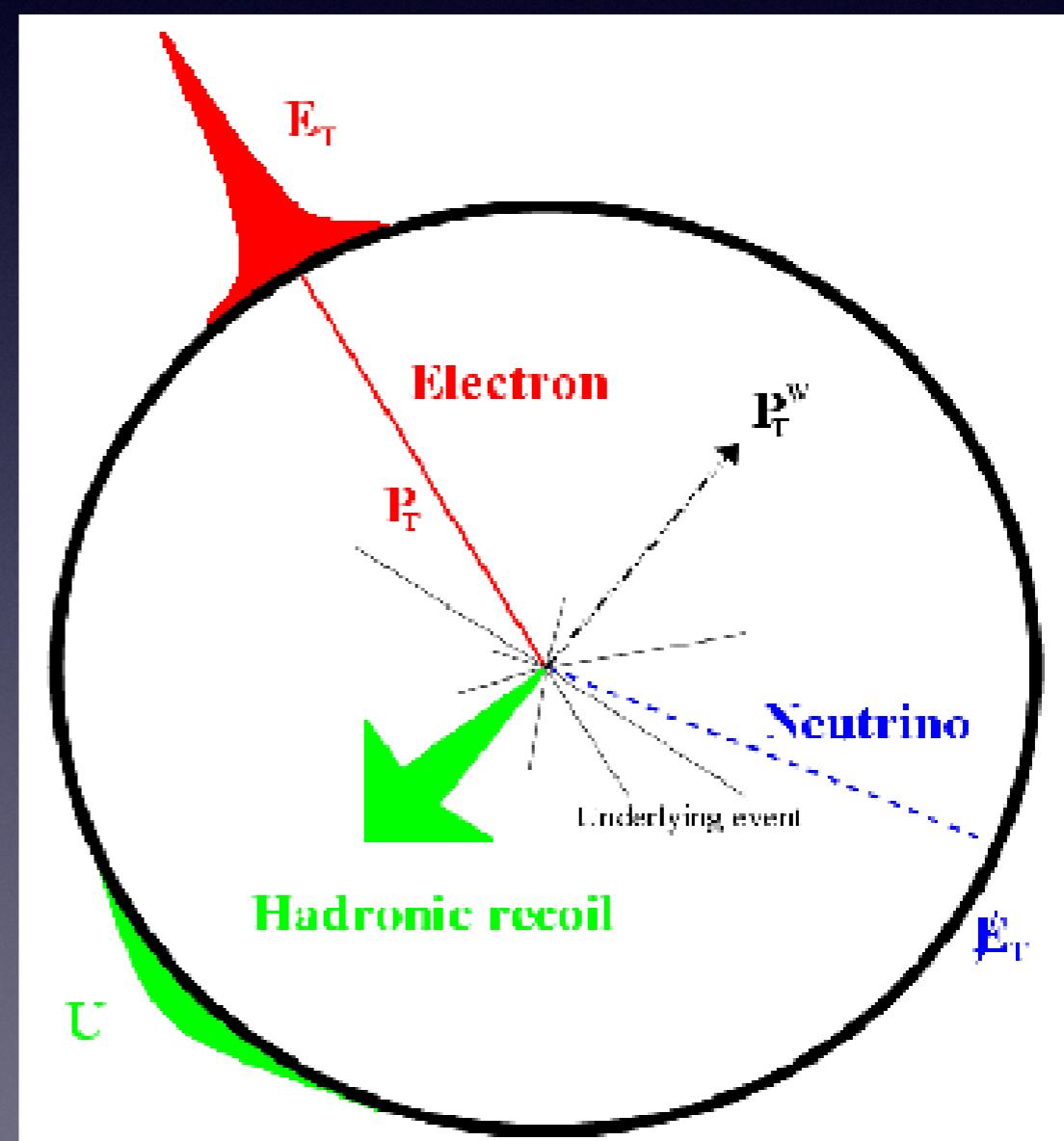
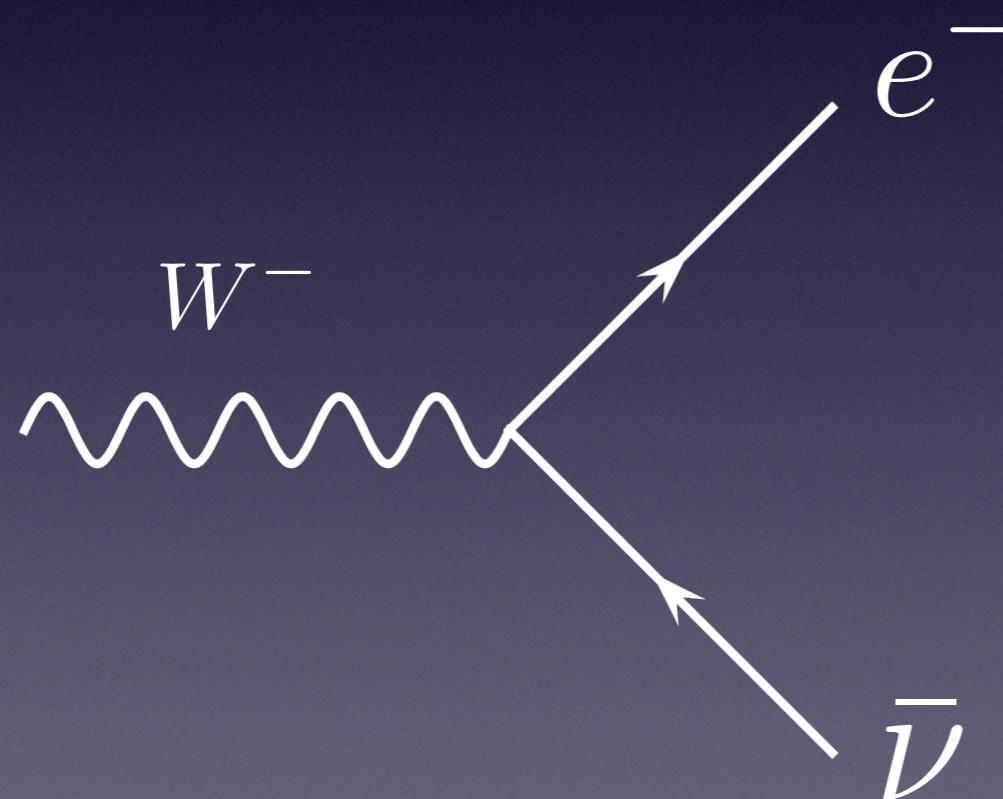




# 不可见粒子：丢失动量

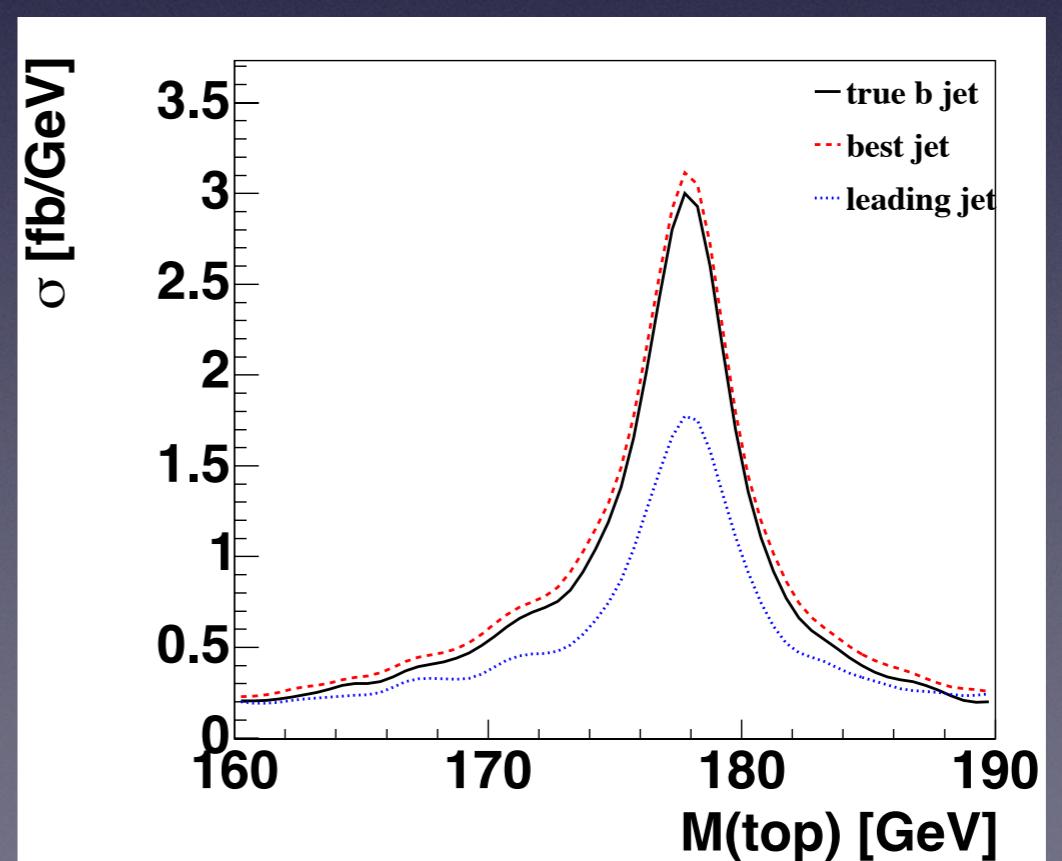
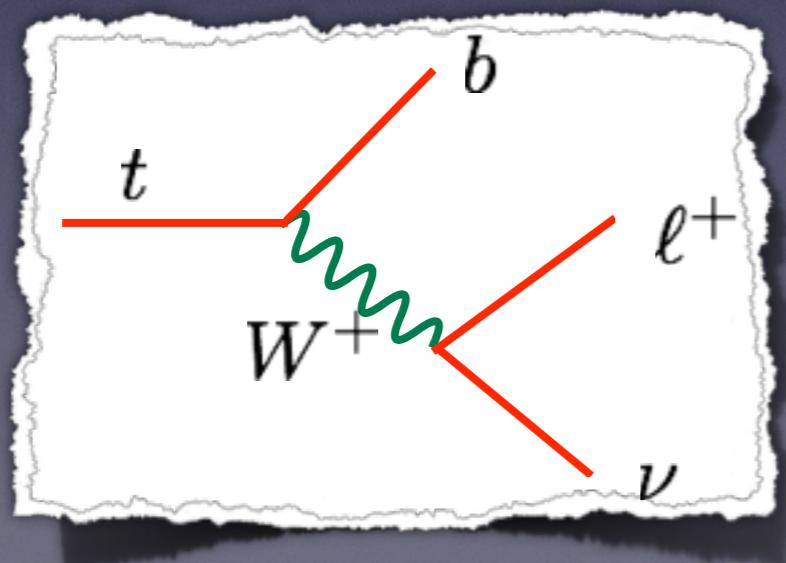
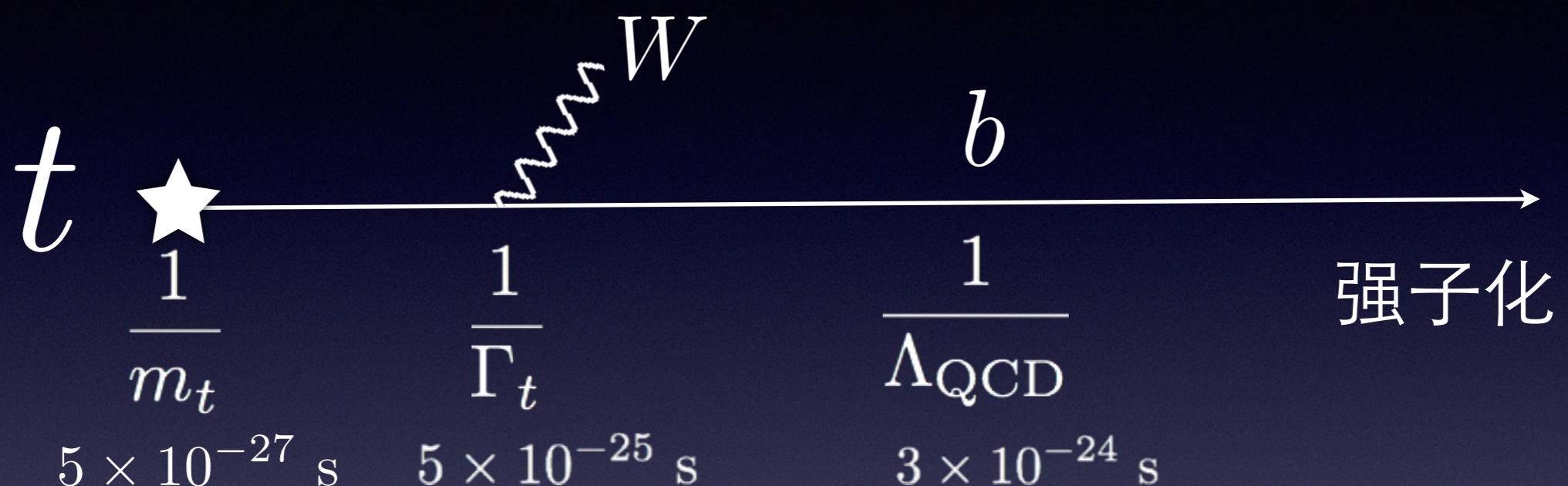
中微子和暗物质候选者粒子都不参与电磁相互作用和强相互作用，因此不会在探测器内留下痕迹。

例如：W玻色子的轻子衰变



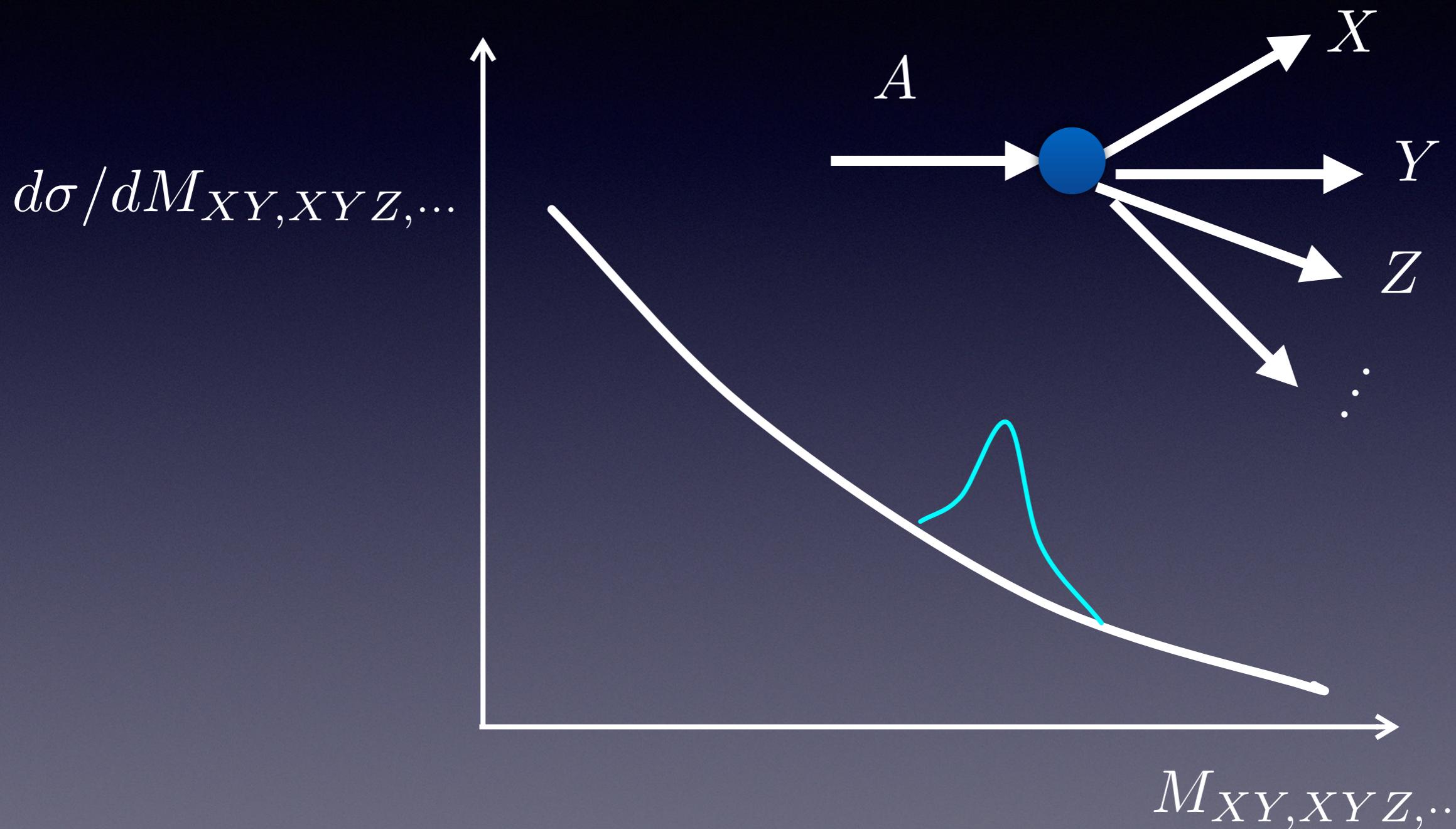
# 不稳定粒子：共振态

极短的寿命，例如顶夸克



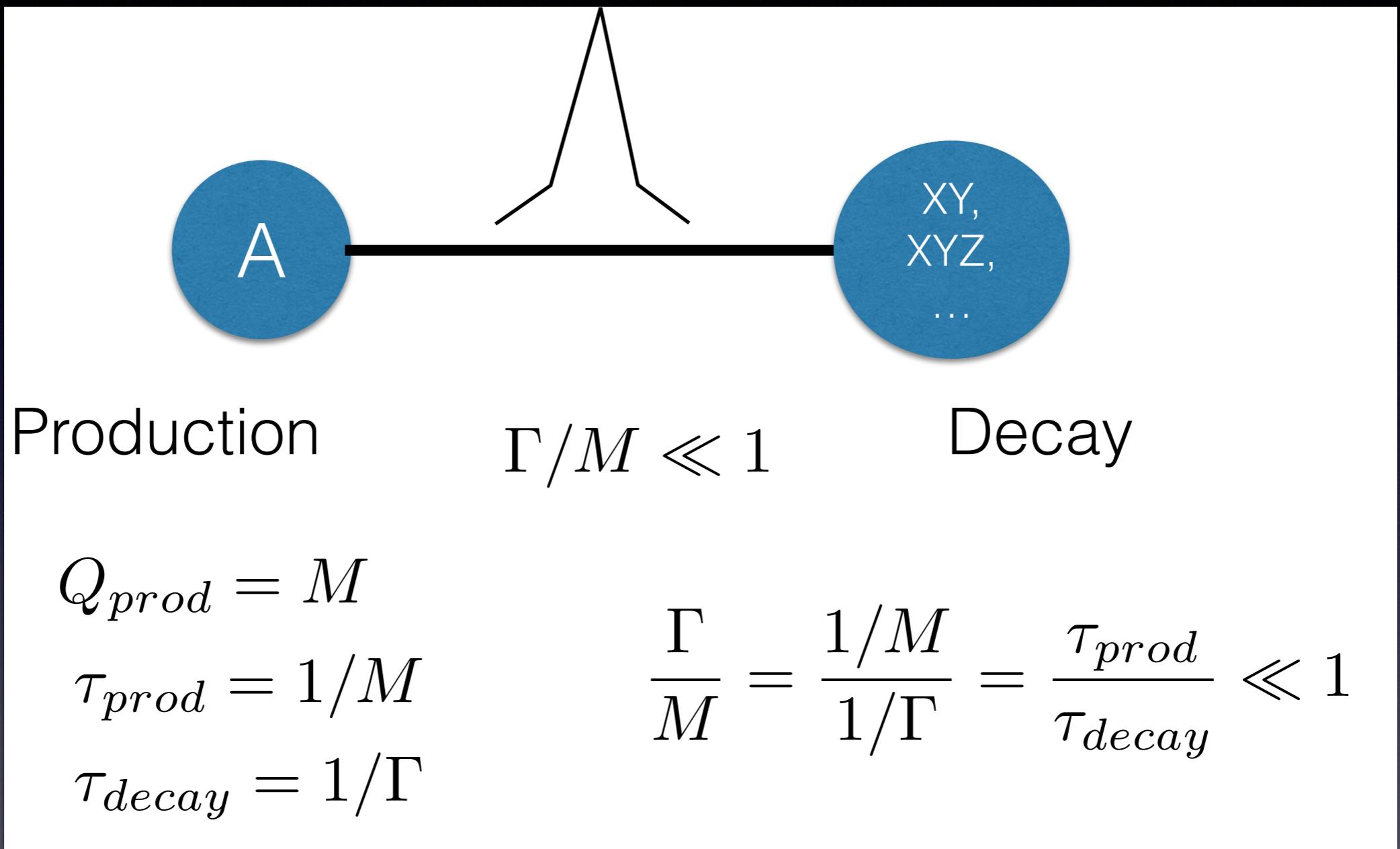
# 实验家 / 唯象学家 / 理论家

生活在不同的不同时空维度中



不变质量谱保证我们可以相互交流

# 窄宽度近似



$$\sigma(pp \rightarrow A \rightarrow XY) \approx \sigma(pp \rightarrow A) \times \text{BR}(A \rightarrow XY)$$

估计新物理信号大小的关键公式

新物理的可能扩充方式

问题：新物理应该包含哪些新元素？

物质和辐射

问题：新物理应该包含哪些新元素？

物质和辐射

新费米子（新夸克、新轻子）

新规范玻色子（带电的和中性的）

新标量粒子（带电的和中性的）

高自旋粒子（引力子？）

高激发态（复合粒子）

。 。 。

# 新物理模型

MSSM      NMSSM  
Supersymmetry

Excited quark

Fourth Generation

Extra dimension

Seesaw mechanism

Dark Matter

Grand Unification

Twin Higgs

Chiral symmetry

Techicolor

Composite Higgs

Little Higgs Model

String

Two Higgs Doublet Model

Private Higgs

Deconstruction

理论家的贡献



# 新物理模型

MSSM      NMSSM  
Supersymmetry  
Excited quark

Fourth Generation

Extra dimension

Seesaw mechanism

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Techicolor

Composite Higgs

Little Higgs Model

理论家的贡献



# 新物理模型

MSSM

NMSSM

Supersymmetry

Techicolor

理论家的贡献

Composite Higgs

Little Higgs Model

Twin Higgs

and Unification

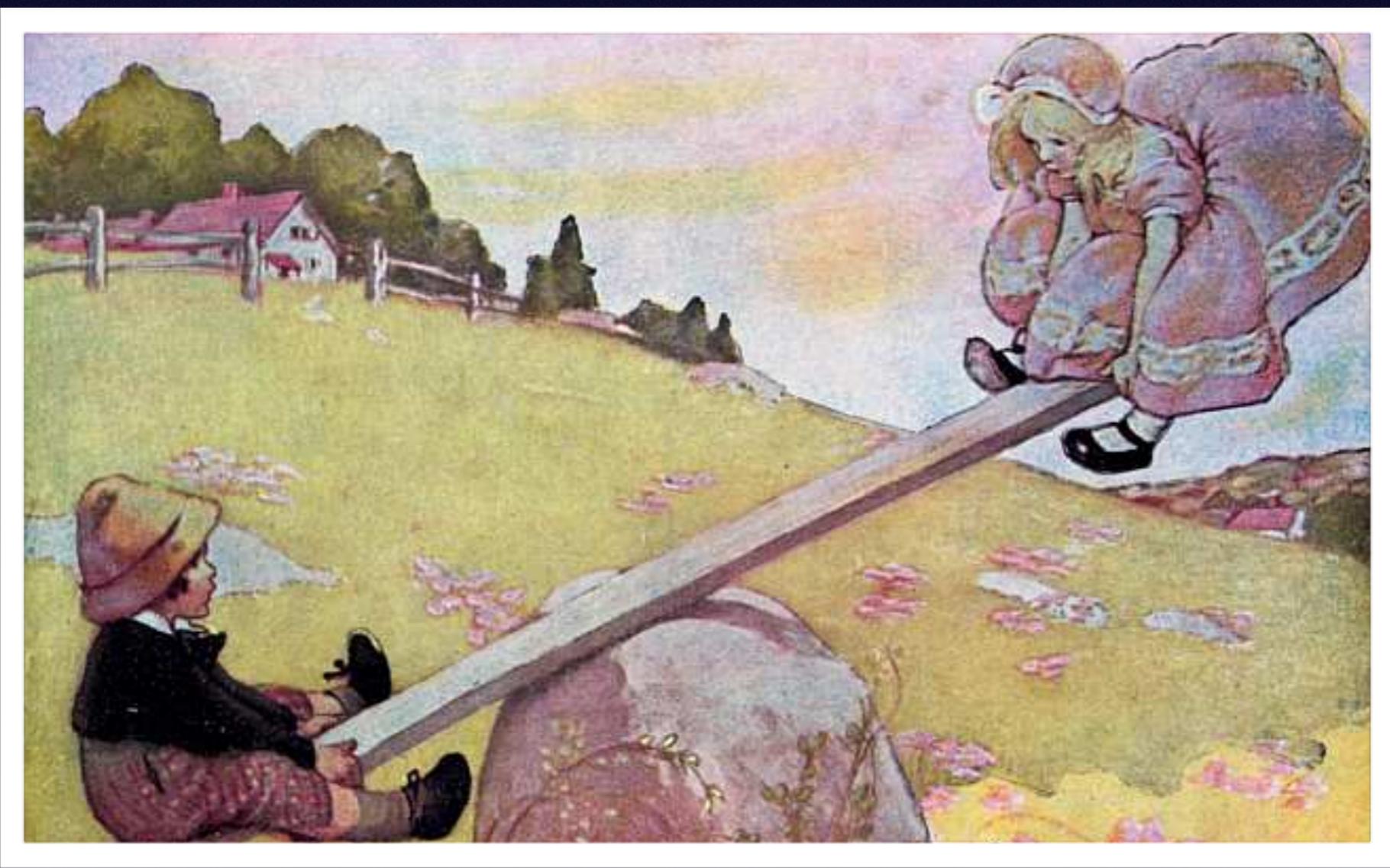


# 新物理模型的组分

- 1) 中微子质量: 味物理
- 2) 暗物质: 粒子宇宙学、超对称模型
- 3) 新费米子: 第四代, 新夸克, 新轻子
- 4) 新规范玻色子: 新的对称性 (新的力)
- 5) 新标量粒子: 电弱对称性破缺机制
- 6) 额外时空维度 (如果时间允许)

# 1) 中微子质量起源 — 跷跷板机制

See-Saw Mechanics

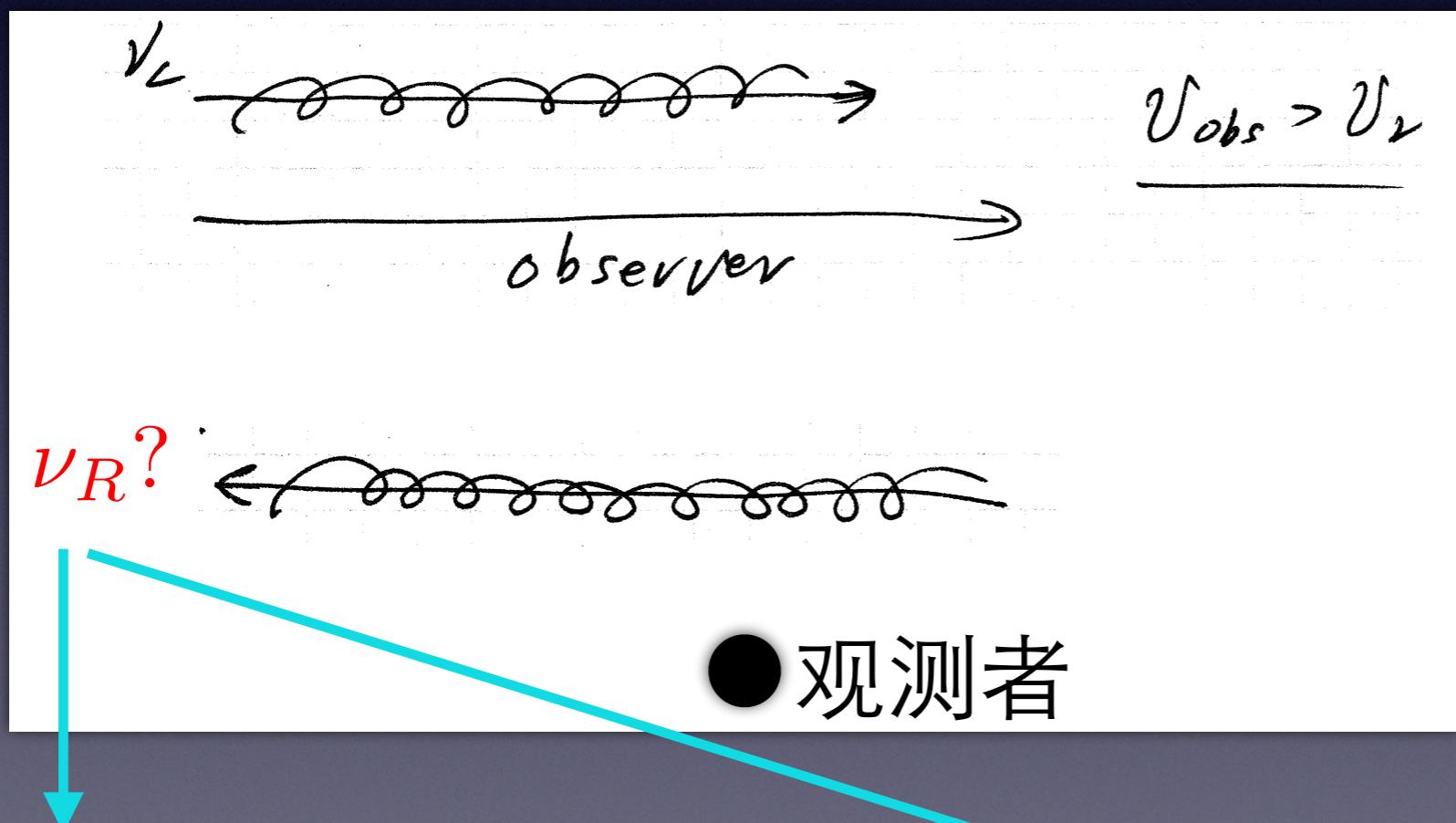


# 有质量的中微子

中微子不能以光速运动  $\rightarrow$  螺旋度不再是好量子数

洛伦兹不变性要求：右手中微子  $\nu_R$

$$m\bar{\psi}_L \psi_R$$



最小标准模型中  
没有右手中微子

New particle  $\nu_R$   
(Dirac)

$\nu_L^T$  old anti-neutrino  
(Majorana)

# 右手中微子

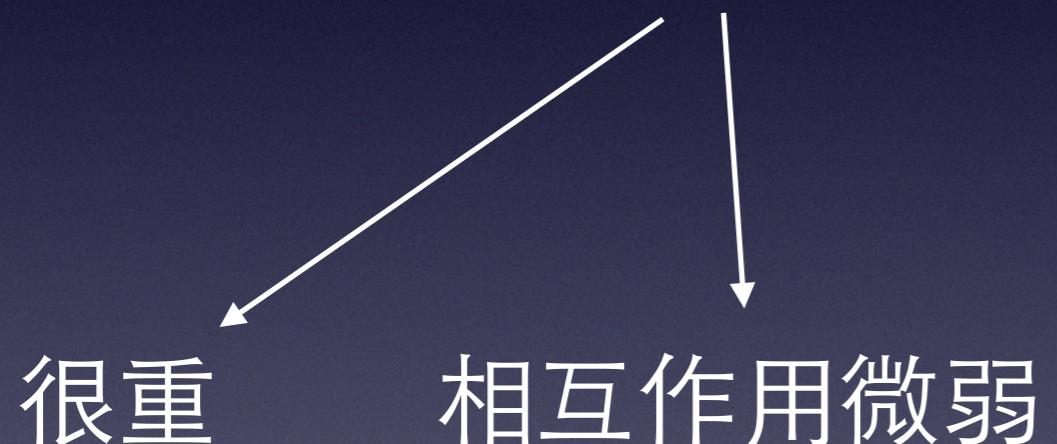
\* Dirac型中微子

$$m\bar{\psi}_L \psi_R$$

\* Majorana型中微子

$$m\bar{\psi}_L^c \psi_L$$

尚未观测到  $\nu_R$



不需要引入新的物质场

No fundamental distinction  
between neutrinos and  
anti-neutrinos

# 为何中微子质量如此之小？

跷跷板机制 —— 简单优雅的解决方案

1) 加入一个新的  $\nu_R$ , (SM +  $\nu_R$ )

SM neutral not gauged under  $SU(2) \times U(1)$

2) 对角化中微子质量矩阵

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

→  $m_\nu = \frac{m_D^2}{M} \sim \frac{\text{TeV}^2}{M} \sim \text{eV}$

→  $M \sim \frac{\text{TeV}^2}{\text{eV}} = \frac{(10^3 \text{GeV})^2}{10^{-9} \text{GeV}} = 10^{15} \text{GeV}$

# 跷跷板机制的种类

探测新物理的强力工具 — 有效场论

BSM ( $\Lambda$ )

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{\mathcal{O}^{(5)}}{\Lambda} + \frac{\mathcal{O}^{(6)}}{\Lambda^2} + \dots$$

SM ( $m_W$ )

High dimensional operator

$\mathcal{O}^{(5,6,\dots)}$

are made of SM fields  
with respect to the SM symmetry  
 $SU(2) \times U(1)_Y$

# 温伯格中微子质量算符

1979年温伯格指出标准模型中存在唯一一个量纲为5的算符  
可以给中微子质量

$$\frac{(L\Phi)^2}{\Lambda} \quad L = \begin{pmatrix} \nu \\ e \end{pmatrix} \quad [L] = \frac{3}{2}$$
$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad [\Phi] = 1$$

$$\mathcal{L}_{m_\nu} = -\frac{f_{ij}}{2\Lambda} (\nu_i \phi^0 - \ell_i \phi^+) (\nu_j \phi^0 - \ell_j \phi^+) + h.c.$$

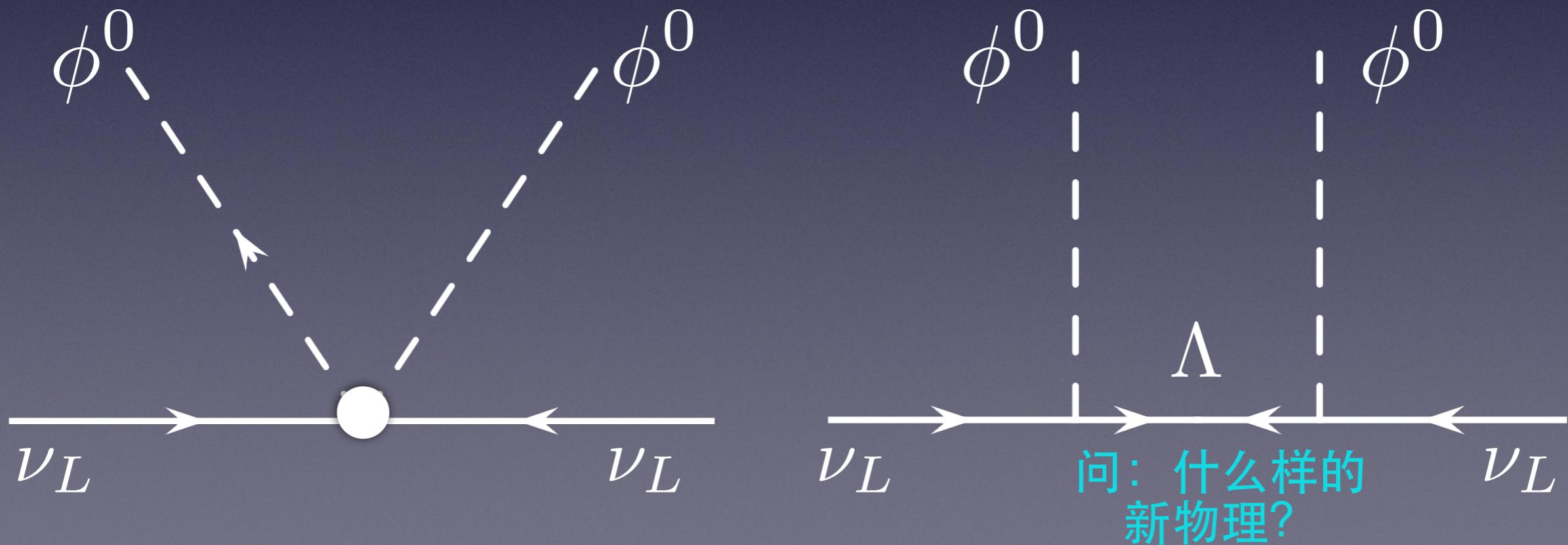
$$\rightarrow (m_\nu)_{ij} = \frac{f_{ij} \langle \phi^0 \rangle^2}{\Lambda} = \frac{f_{ij} v^2}{\Lambda}$$

# 温伯格中微子质量算符

1979年温伯格指出标准模型中存在唯一一个量纲为5的算符可以给中微子质量

$$\mathcal{L}_{m_\nu} = -\frac{f_{ij}}{2\Lambda} (\nu_i \phi^0 - \ell_i \phi^+) (\nu_j \phi^0 - \ell_j \phi^+) + h.c.$$

$$\rightarrow (m_\nu)_{ij} = \frac{f_{ij} \langle \phi^0 \rangle^2}{\Lambda} = \frac{f_{ij} v^2}{\Lambda} \quad [\phi] = 1 \\ [\nu] = 3/2$$



# 温伯格算符

$$\frac{(L\Phi)^2}{\Lambda}$$

角动量耦合

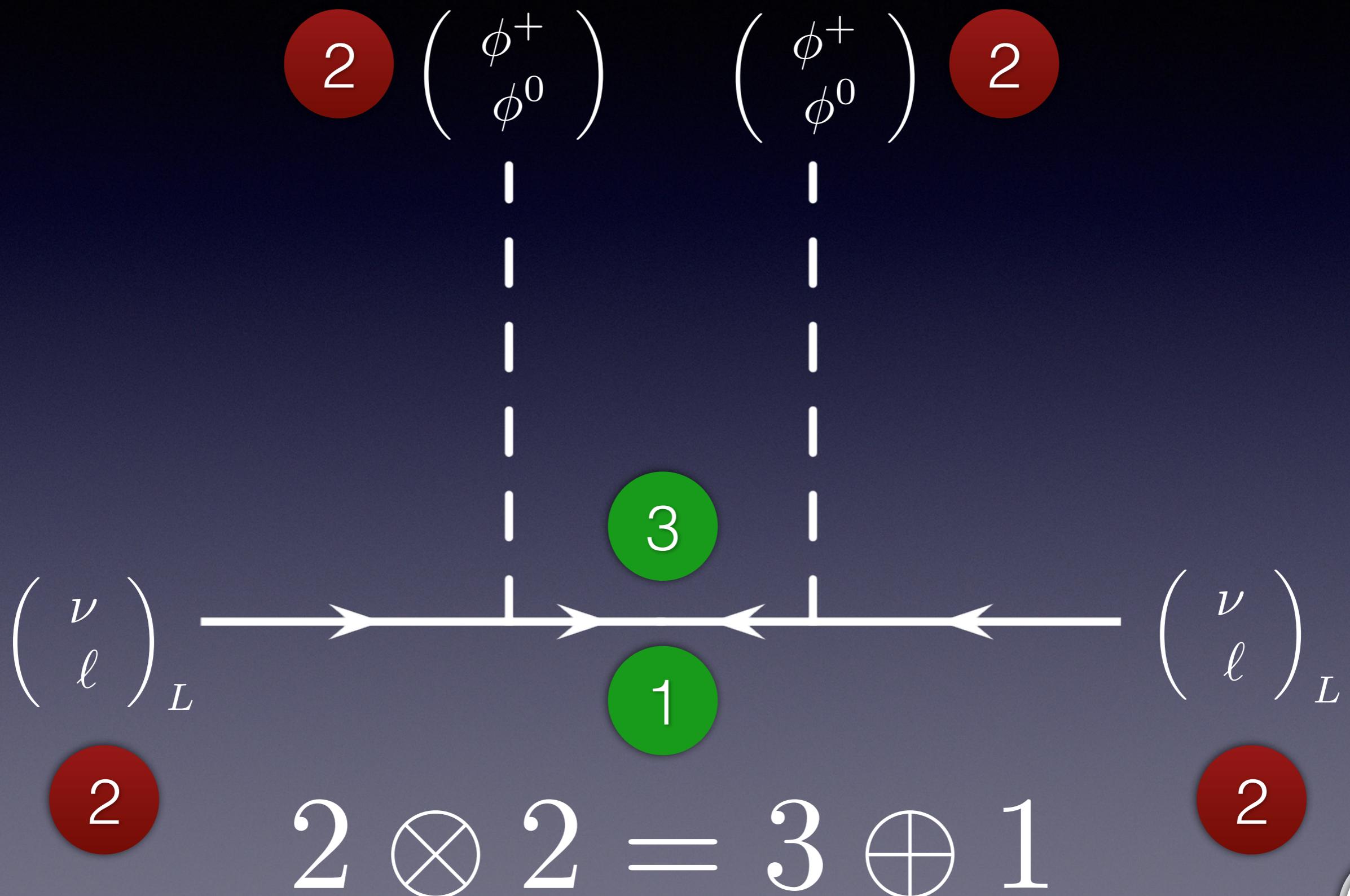
$$\left( \begin{array}{c} \uparrow \\ \downarrow \end{array} \right)_1 \otimes \left( \begin{array}{c} \uparrow \\ \downarrow \end{array} \right)_2 = \left( \begin{array}{c} \frac{1}{\sqrt{2}} (\uparrow_1 \downarrow_2 + \downarrow_1 \uparrow_2) \\ \downarrow_1 \downarrow_2 \end{array} \right) \oplus \frac{1}{\sqrt{2}} (\uparrow_1 \downarrow_2 - \downarrow_1 \uparrow_2)$$

标准模型  $SU(2) \times U(1)$

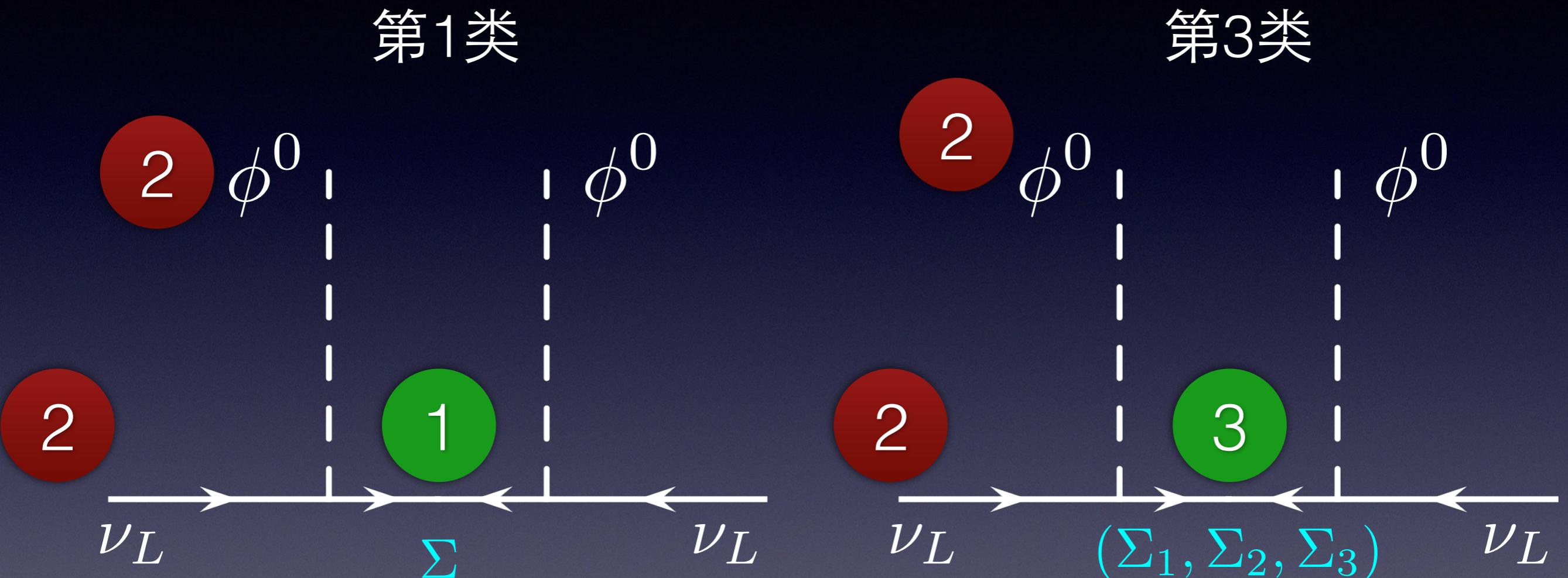
$$(L\Phi) = \left( \begin{array}{c} \nu \\ \ell \end{array} \right) \otimes \left( \begin{array}{c} \phi^+ \\ \phi^0 \end{array} \right) = \left( \begin{array}{c} \sqrt{2}\nu\phi^+ \\ \underline{\nu\phi^0 + \ell\phi^+} \\ \sqrt{2}\ell\phi^0 \end{array} \right) \oplus \left( \underline{\nu\phi^0 - \ell\phi^+} \right)$$



# 树图跷跷板机制



# 树图跷跷板机制：第1和第3类



角动量耦合

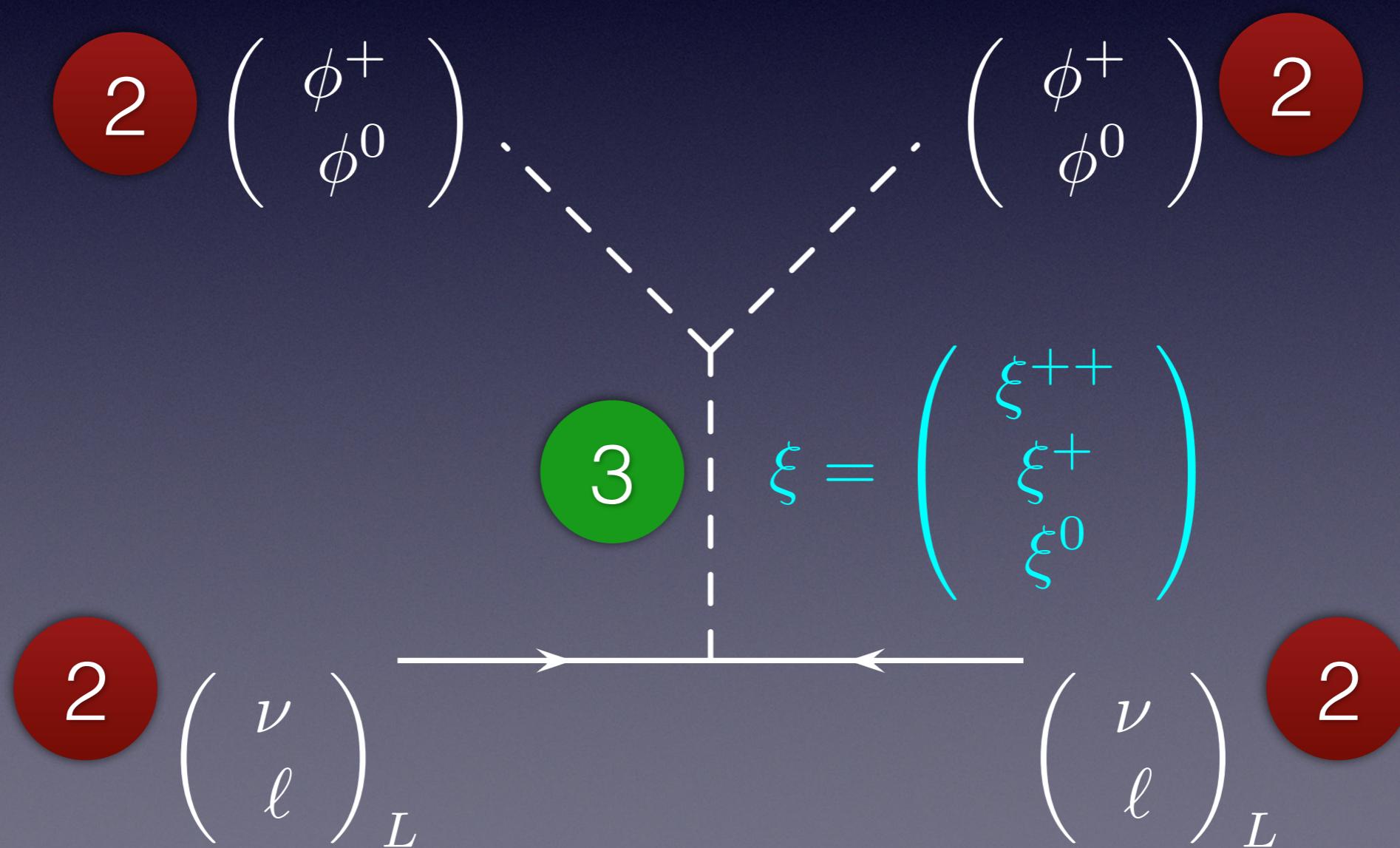
$$\vec{J} = \vec{L}_1 + \vec{L}_2$$

$$|J| = |L_1 - L_2|, \dots, L_1 + L_2$$

# 树图跷跷板机制：第2类

$$(LL) = \begin{pmatrix} \nu \\ \ell \end{pmatrix}_i \otimes \begin{pmatrix} \nu \\ \ell \end{pmatrix}_j = \begin{pmatrix} \overline{\nu_i \nu_j} \\ \nu_i \ell_j + \ell_j \nu_i \\ \ell_i \ell_j \end{pmatrix} \oplus (\nu_i \ell^j - \ell_i \nu_j)$$

相互作用  
非质量项



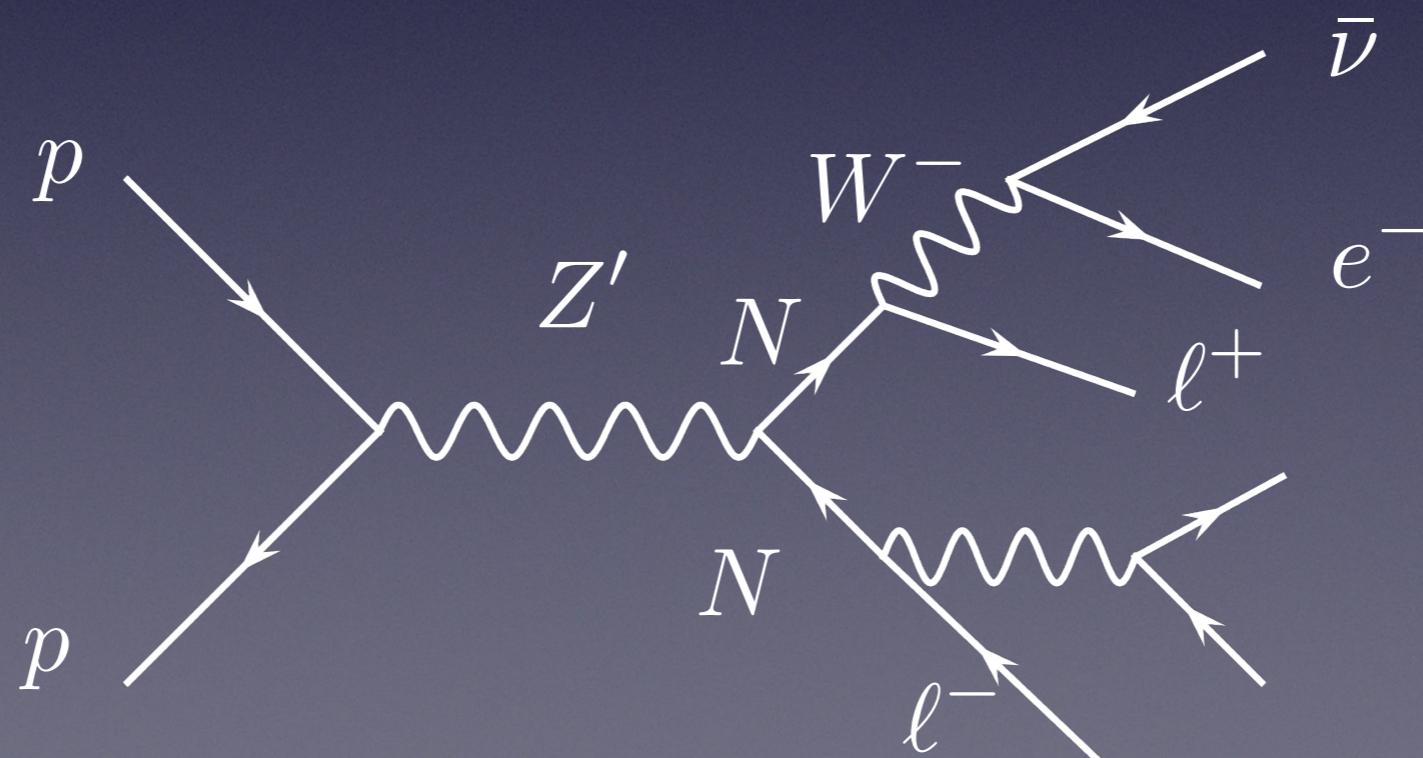
# 中微子跷跷板模型的对撞机信号

第1类和第3类树图跷跷板模型：

困难：跷跷板能标非常高， $\sim 10^{15} \text{GeV}$

右手中微子非常重，耦合微弱，难以探测

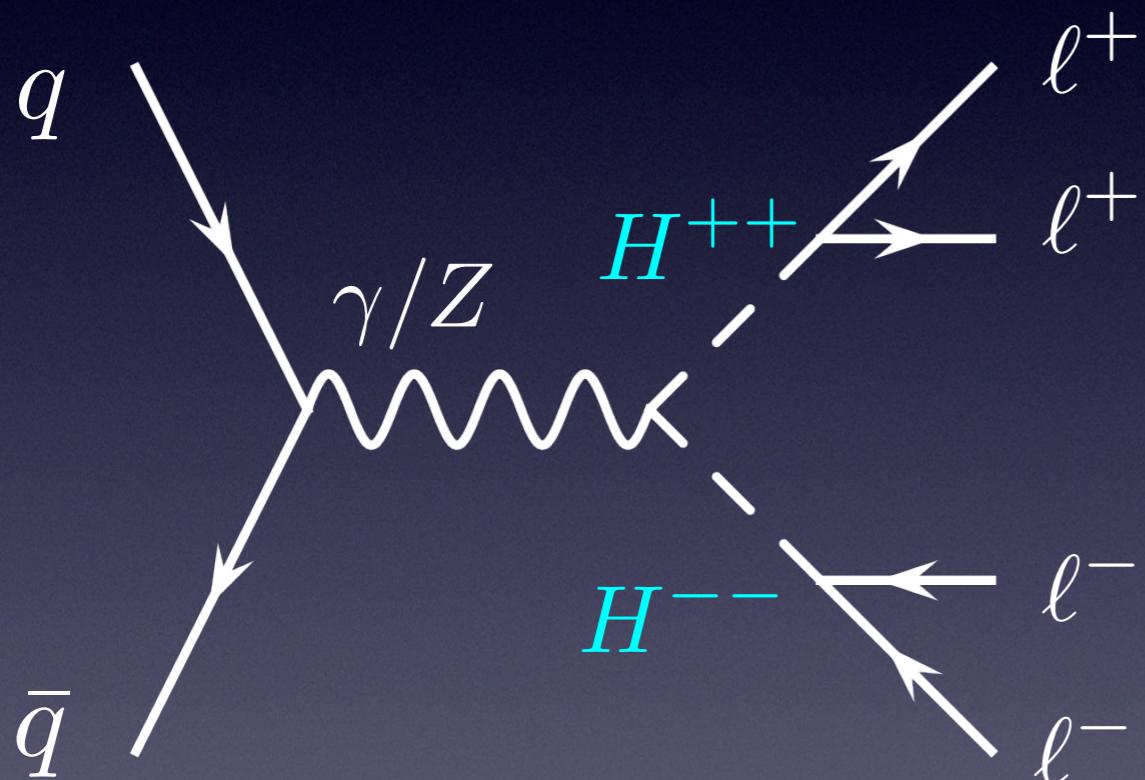
方法之一：引入 $U(1)_{B-L}$ 的超对称扩充模型，  
将跷跷板能标压低到TeV



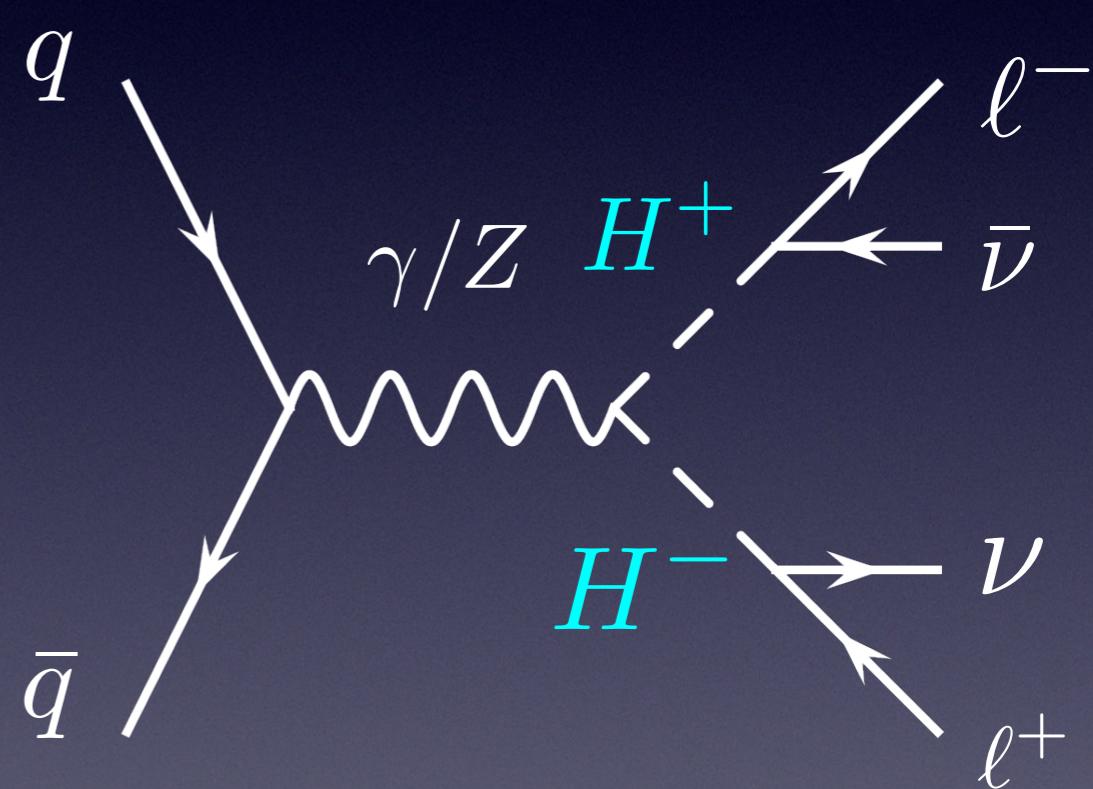
# 中微子跷跷板模型的对撞机信号

第2类树图跷跷板模型：

- \* 轻的标量三重态粒子



同号轻子  
构成的共振态  
非常干净的信号

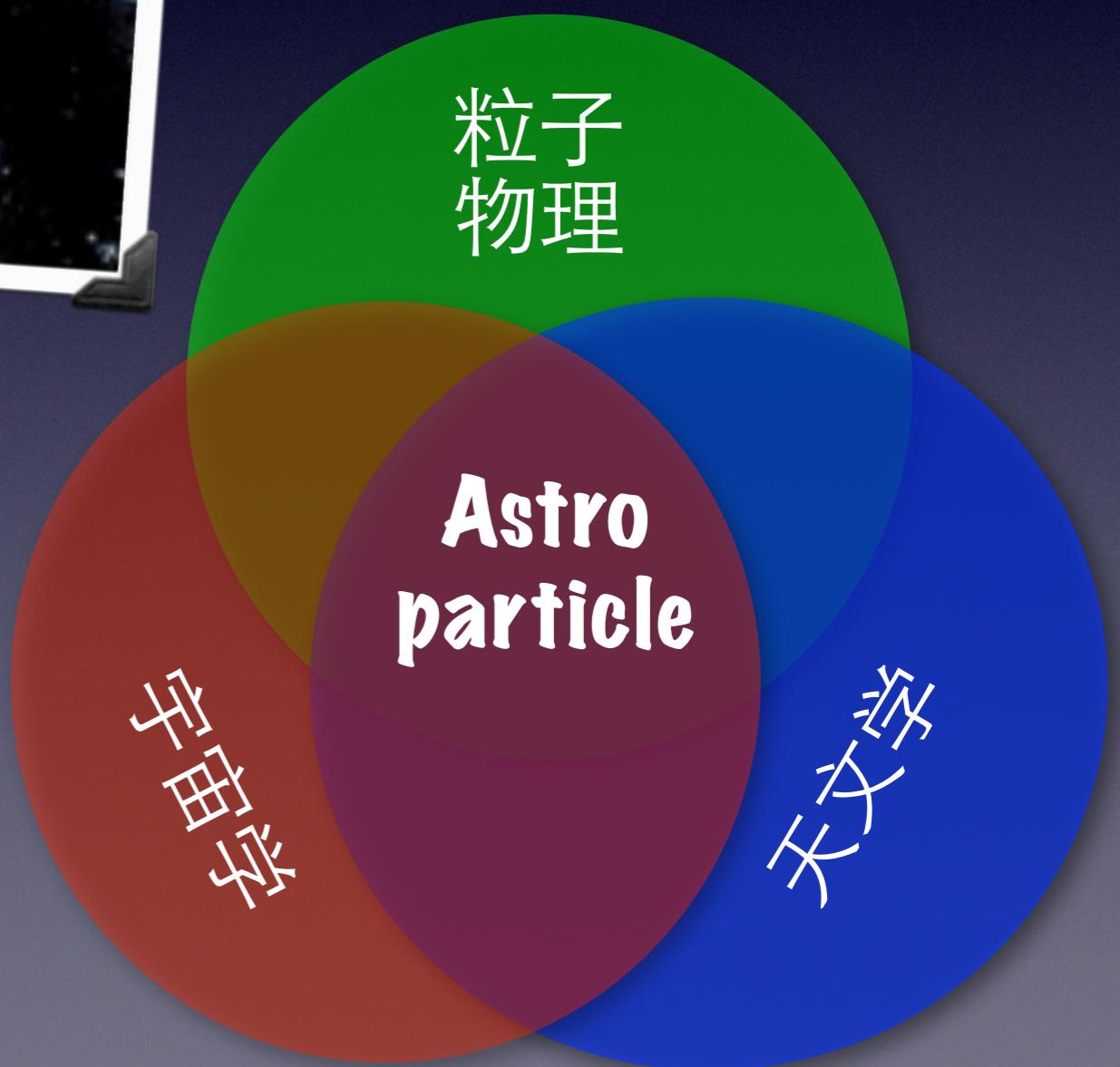


丢失动量

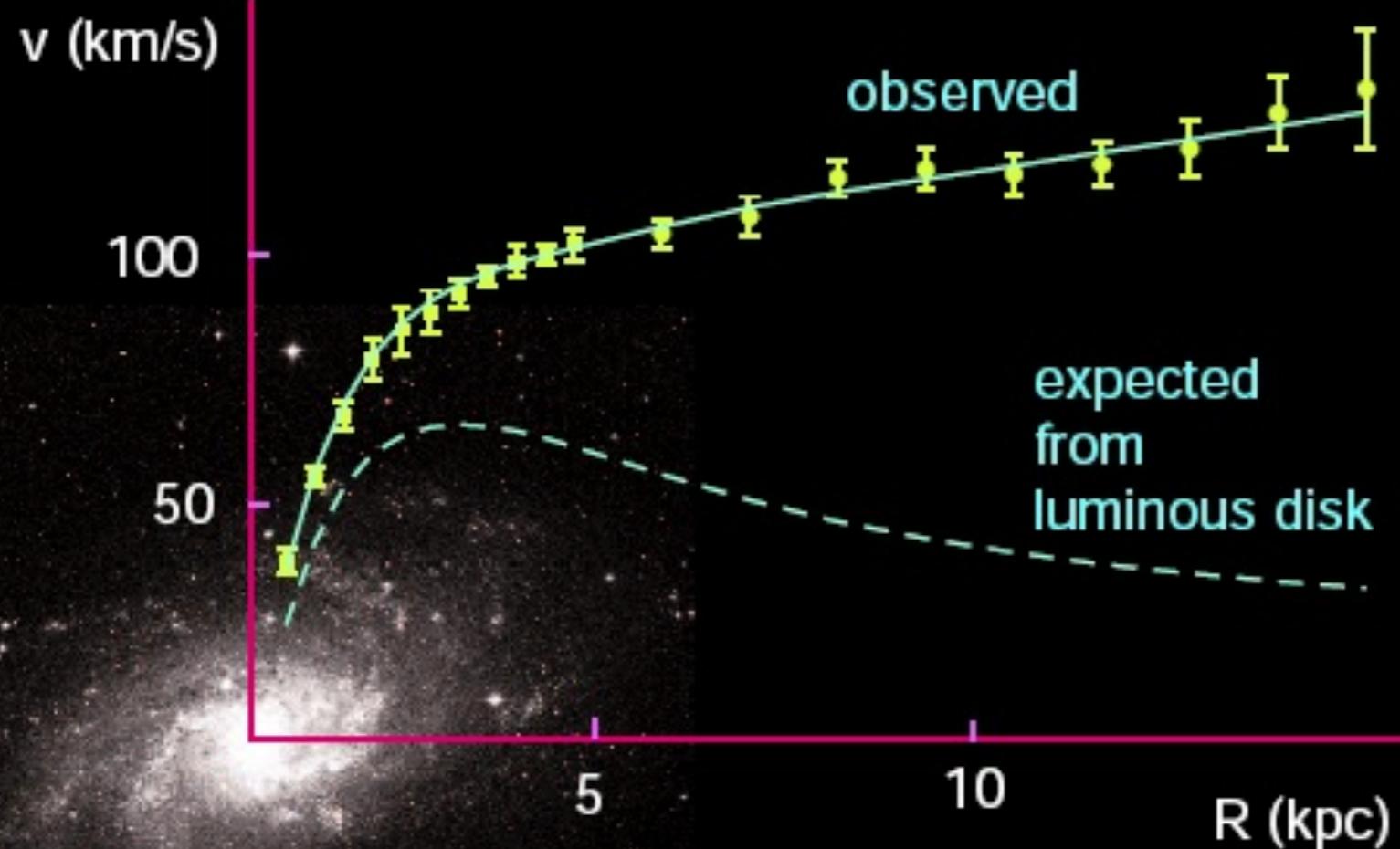
- \* 重标量三重态粒子唯象学依赖于衰变分支比



## 2. 暗物质 (粒子宇宙学)



# 暗物质 (Dark Matter)



星体旋转曲线

M33 rotation curve



Fritz  
Zwicky  
(1933)

Vera  
Rubin  
(1970's)

# 暗物质

## 已知信息：

不发光物质（无电磁相互作用）

寿命非常长或绝对稳定

非重子

大质量

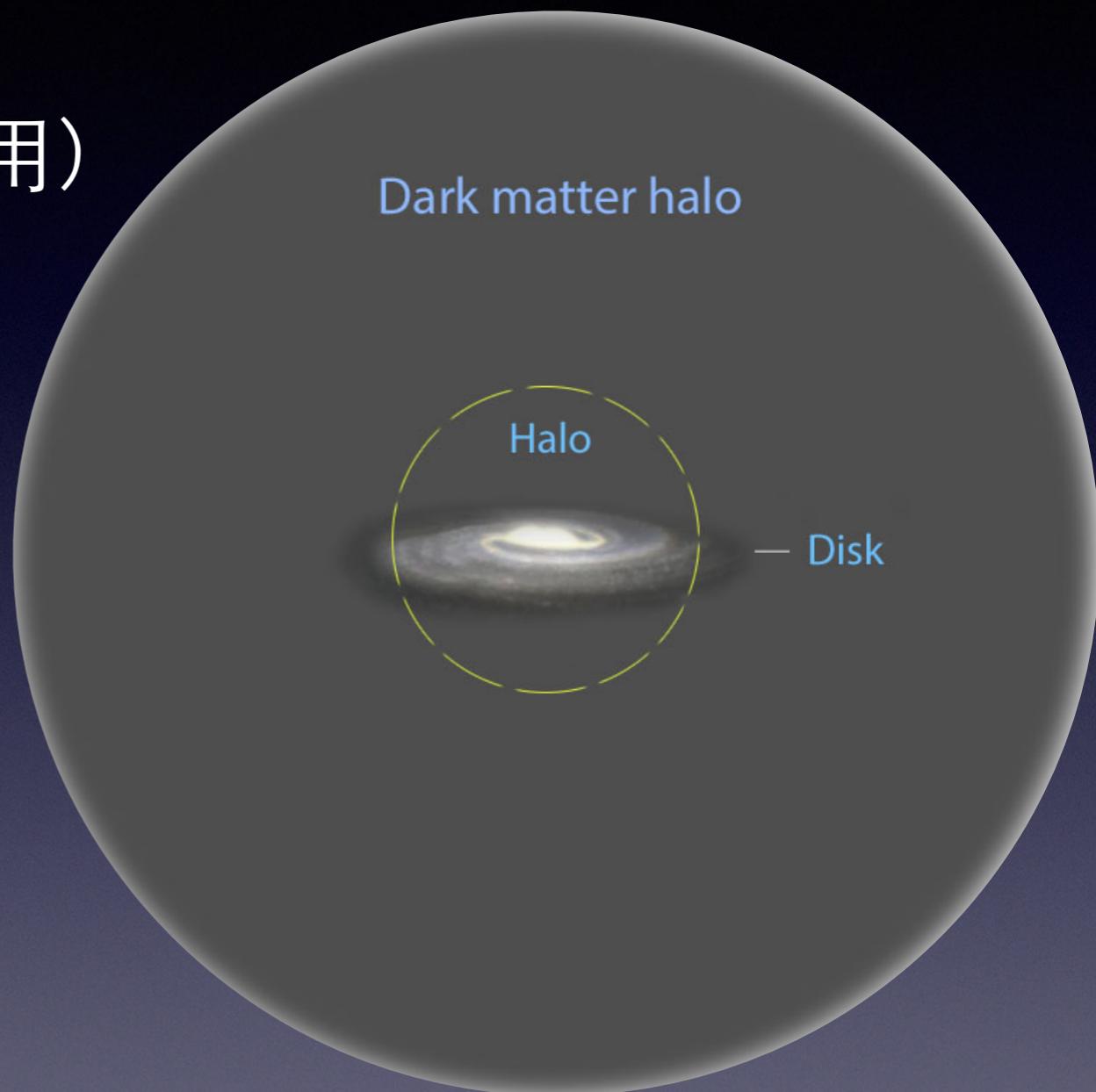
## 未知信息：

质量和自旋

相互作用形式

种类和数目

更糟的是，我们甚至不知道  
“什么是我们不知道的”



# 暗物质

## 已知信息：

不发光物质（无电磁相互作用）

寿命非常长或绝对稳定

非重子

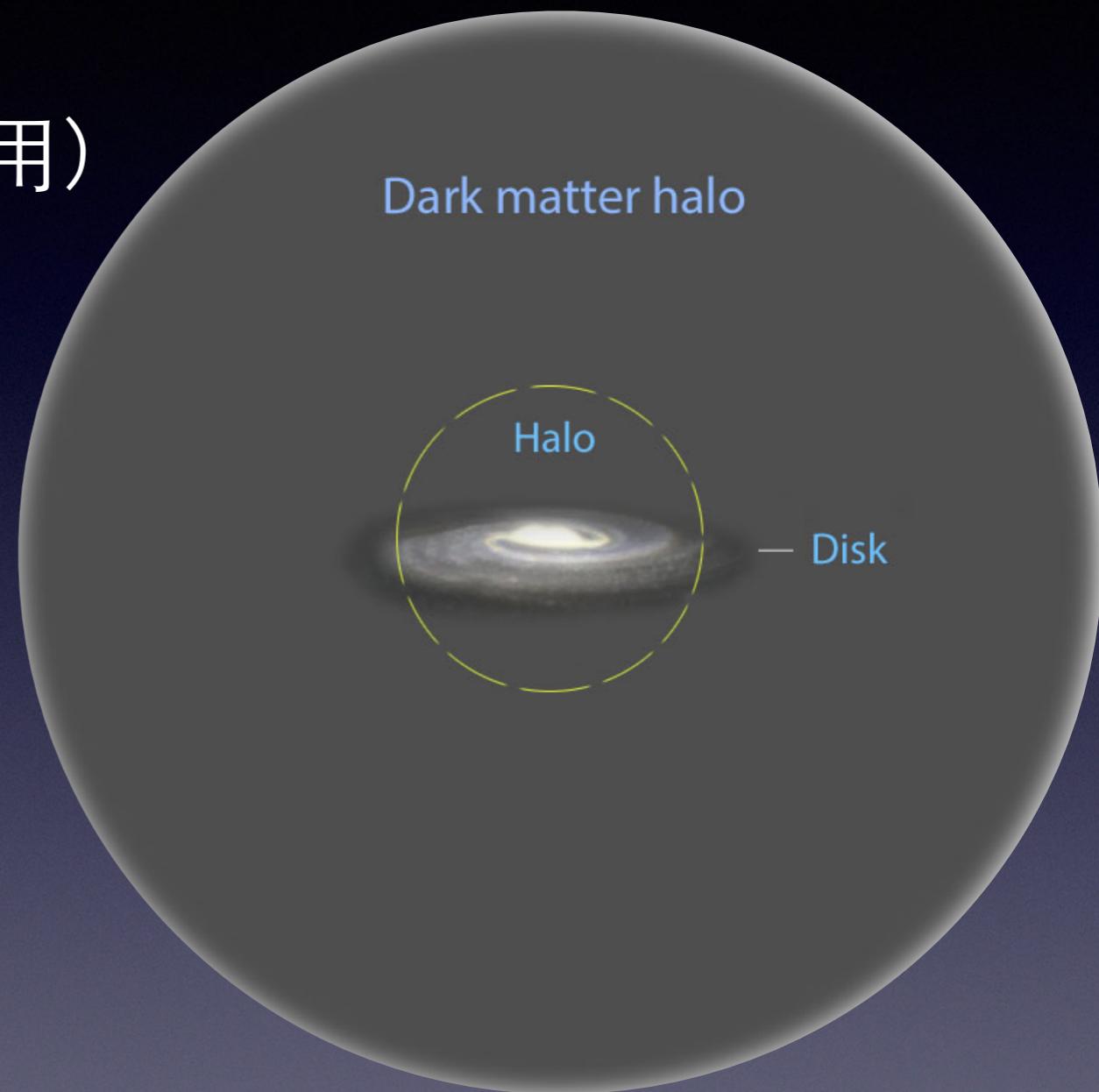
大质量

## 未知信息：

质量和自旋

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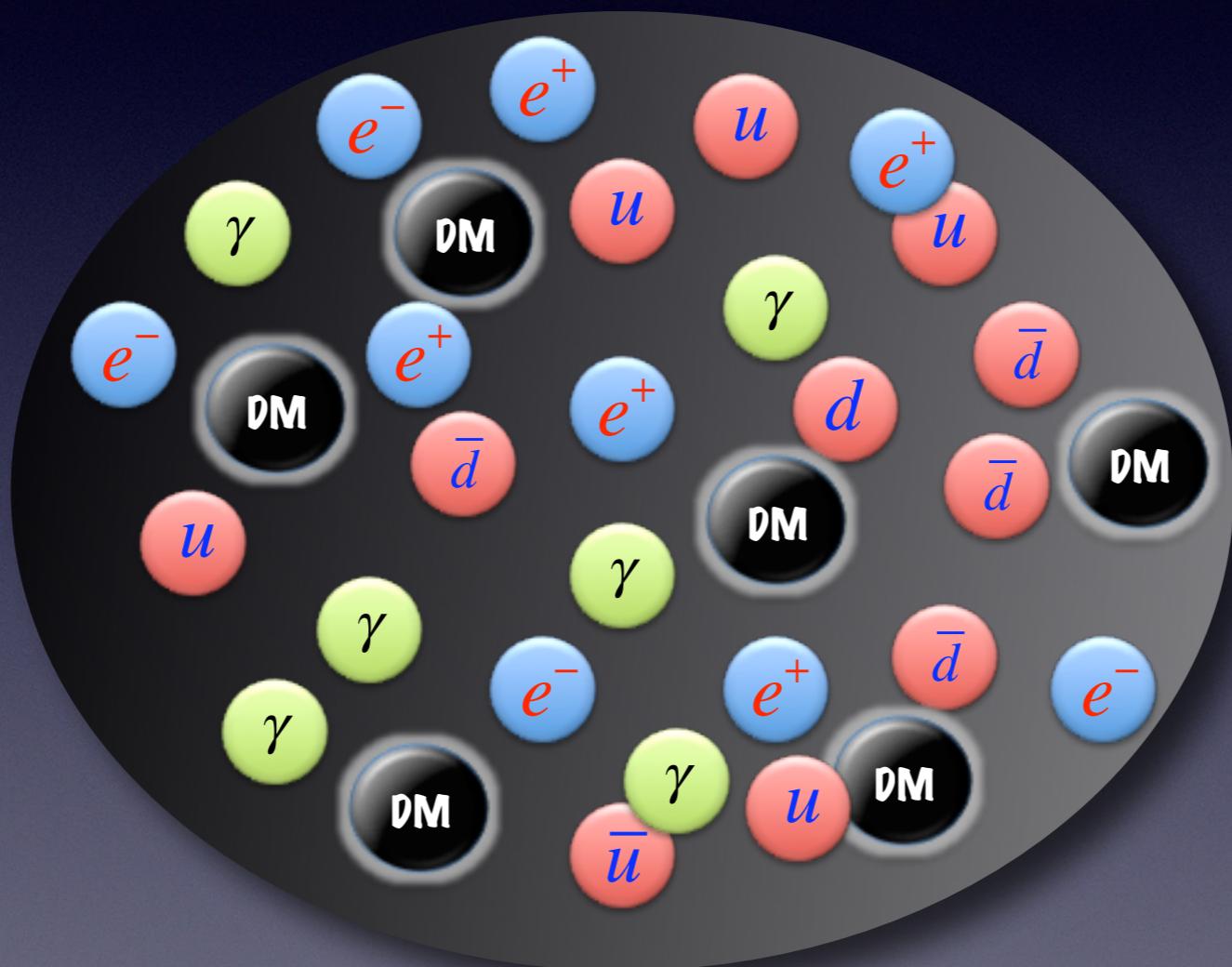
更糟的是，我们甚至不知道  
“什么是我们不知道的”

# 暗物质候选者之一

作用力微弱的大质量粒子  
(Weakly interacting massive Particle)

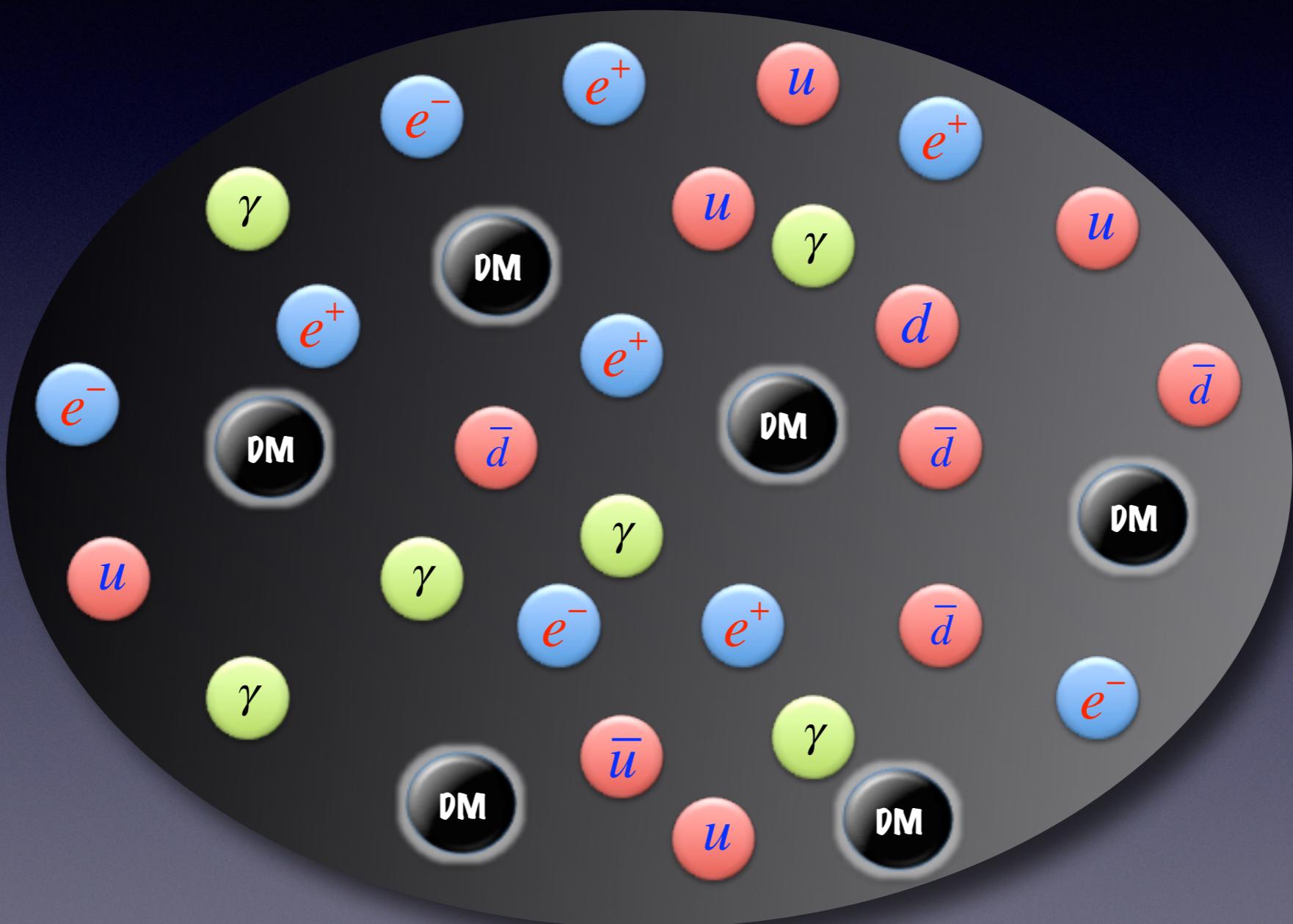
# 暗物质残留丰度

1) 宇宙早期暗物质和可见物质处于热力学平衡态



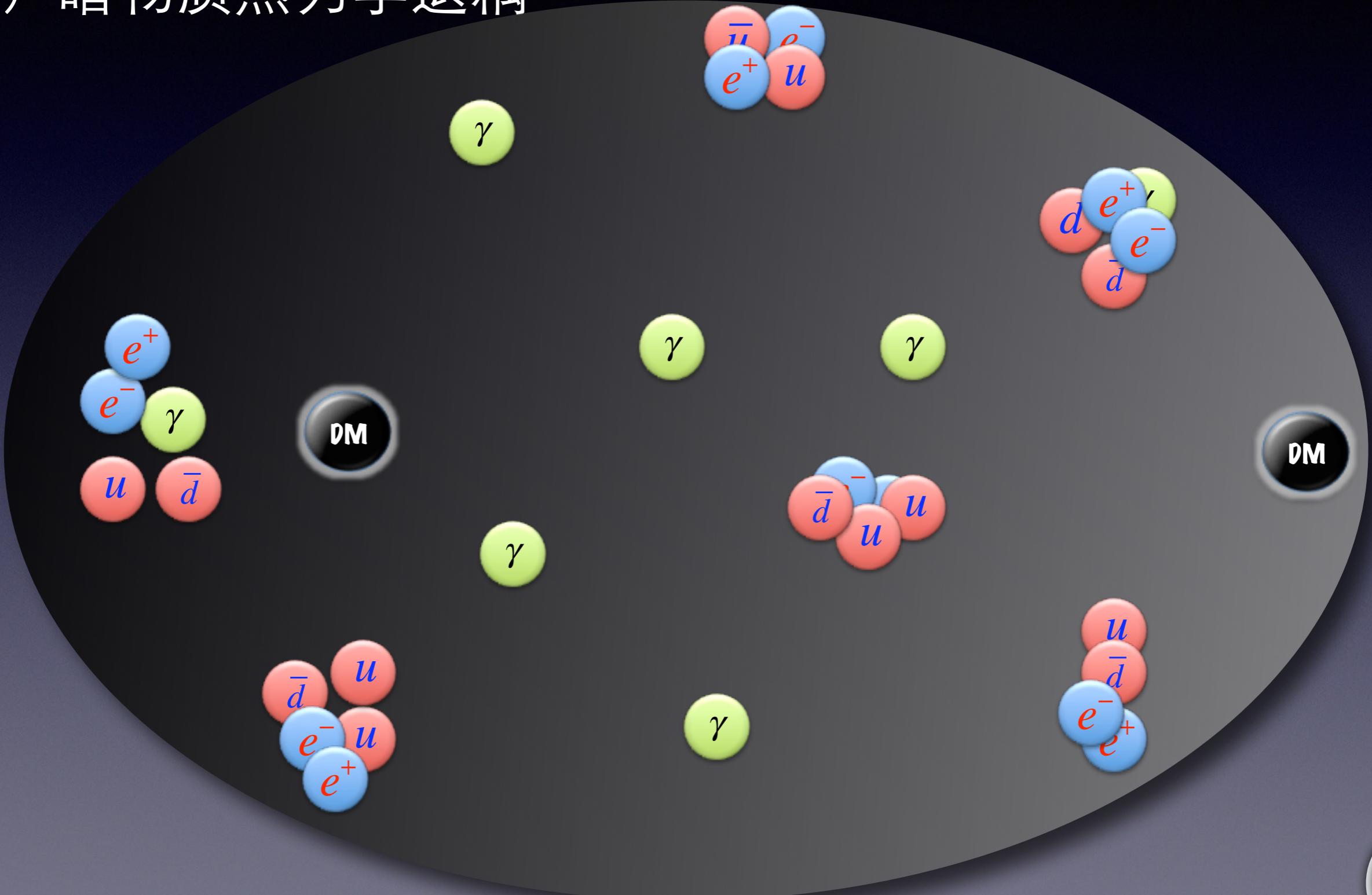
# 暗物质残留丰度

2) 宇宙膨胀 (温度降低, 暗物质变为非相对论性)



# 暗物质残留丰度

## 3) 暗物质热力学退耦



# 暗物质残留丰度

I. 暗物质和可见物质处于热力学平衡态



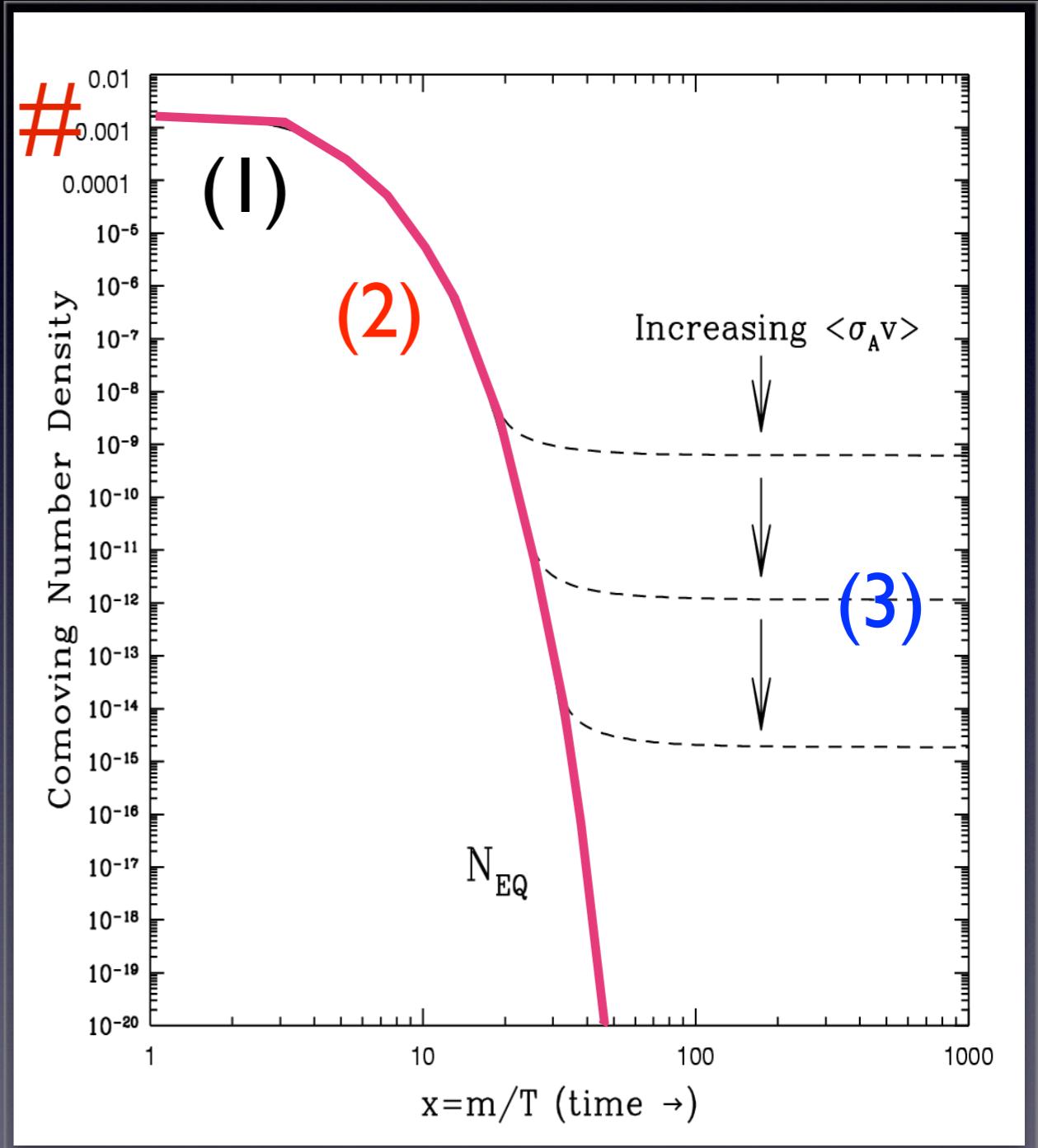
2. 宇宙膨胀冷却

$$N = N_{EQ} \sim e^{-\frac{m}{T}}$$

3. 暗物质从热库中退耦

$$N \sim \text{Constant}$$

$$\text{脱耦温度 } T_F \simeq \frac{m_\chi}{20}$$



# WIMP奇迹

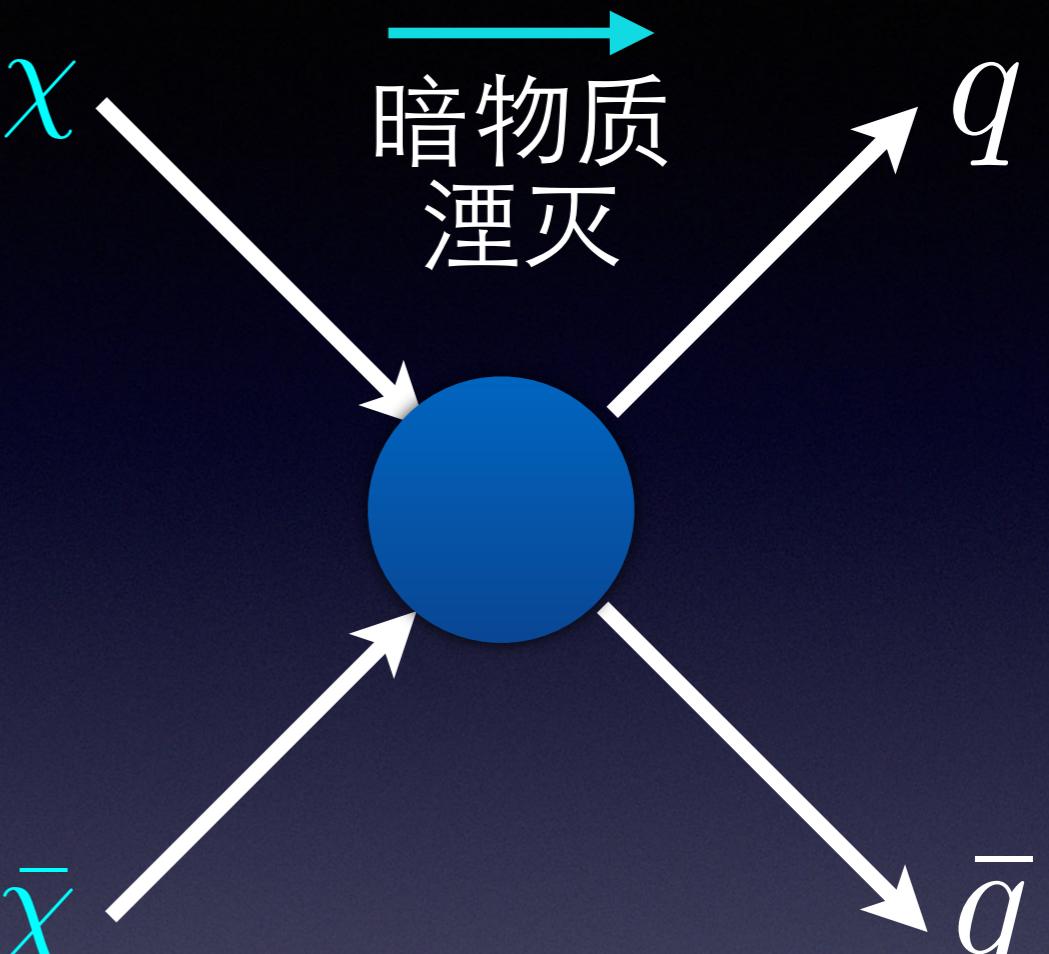
$$T_F \simeq \frac{m_\chi}{20}$$

$$\Omega h^2 \simeq \frac{0.1 \text{ pb}}{\langle \sigma(\chi\chi \rightarrow qq)v \rangle} = 0.1$$

$$\langle \sigma(\chi\chi \rightarrow qq)v \rangle \propto \frac{g^4}{m_\chi^2} \sim \text{pb}$$



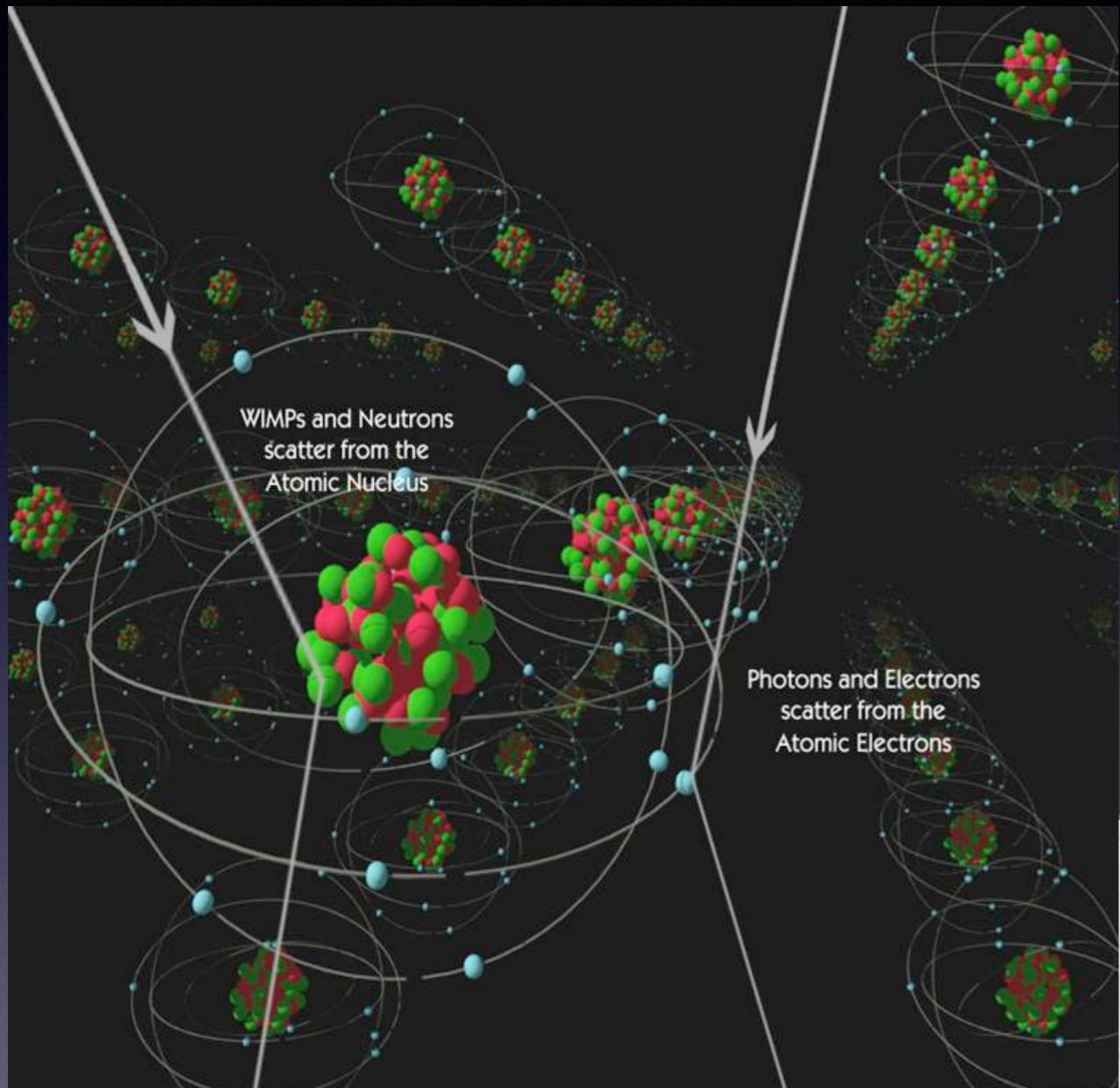
$$g \sim g_{\text{weak}}$$



$$m_\chi \sim m_W$$

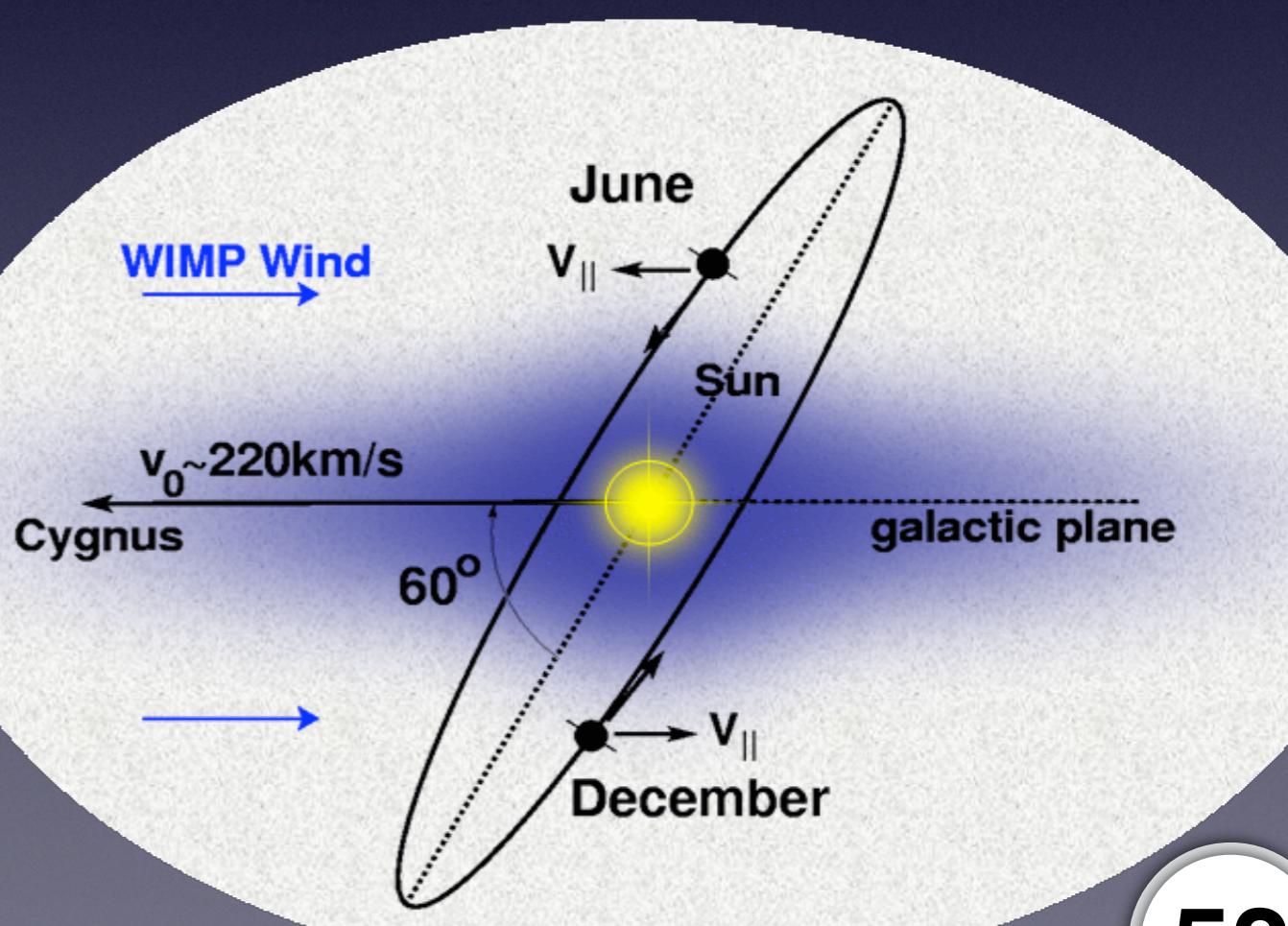
Weakly interacting massive particles at the weak scale!  
神奇的巧合！理论家的最爱！

# 暗物质直接探测

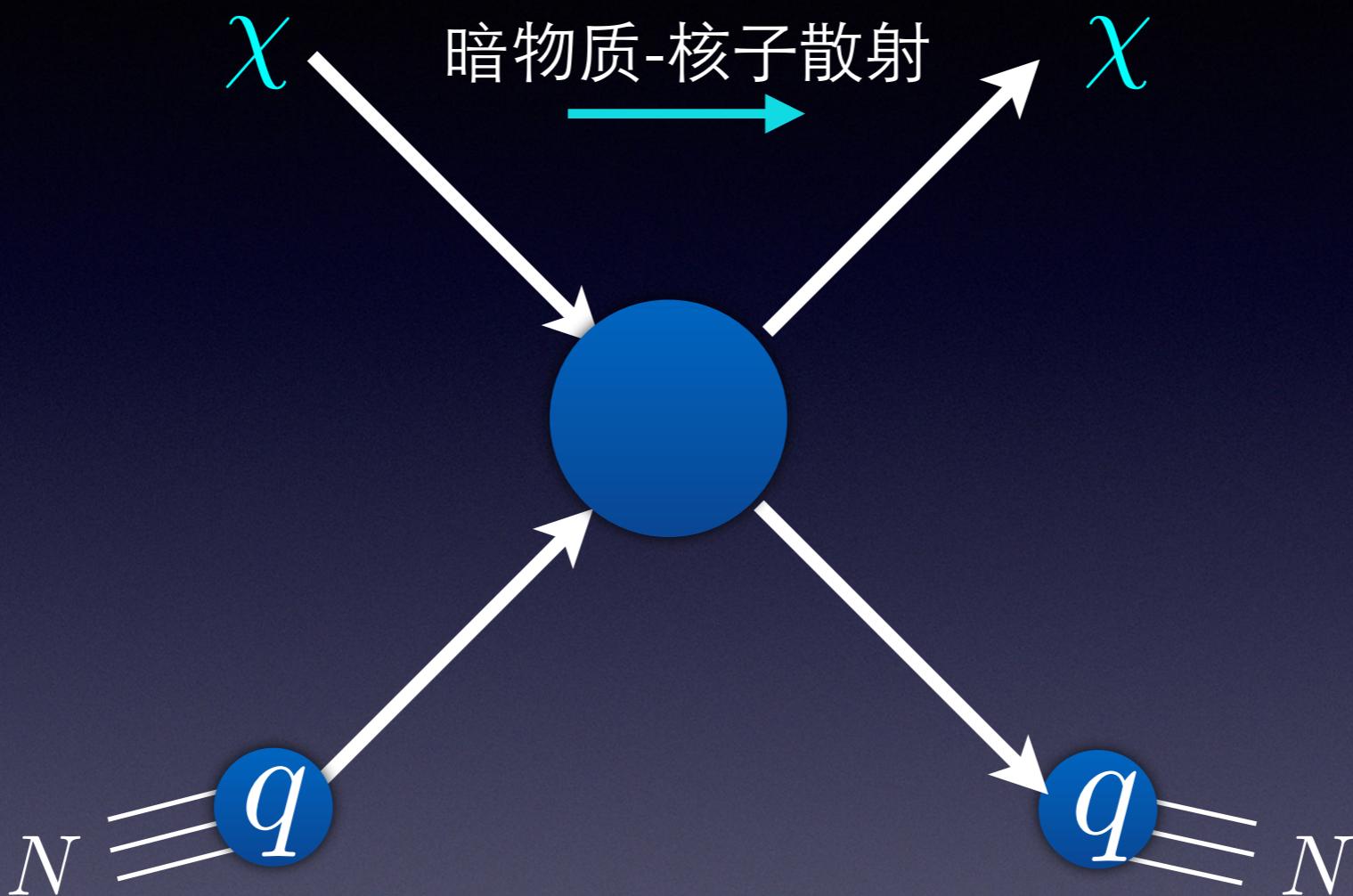


年调制效应

- 直接探测暗物质和原子的弹性散射。
- 信号：热，光，电



# 暗物质直接探测



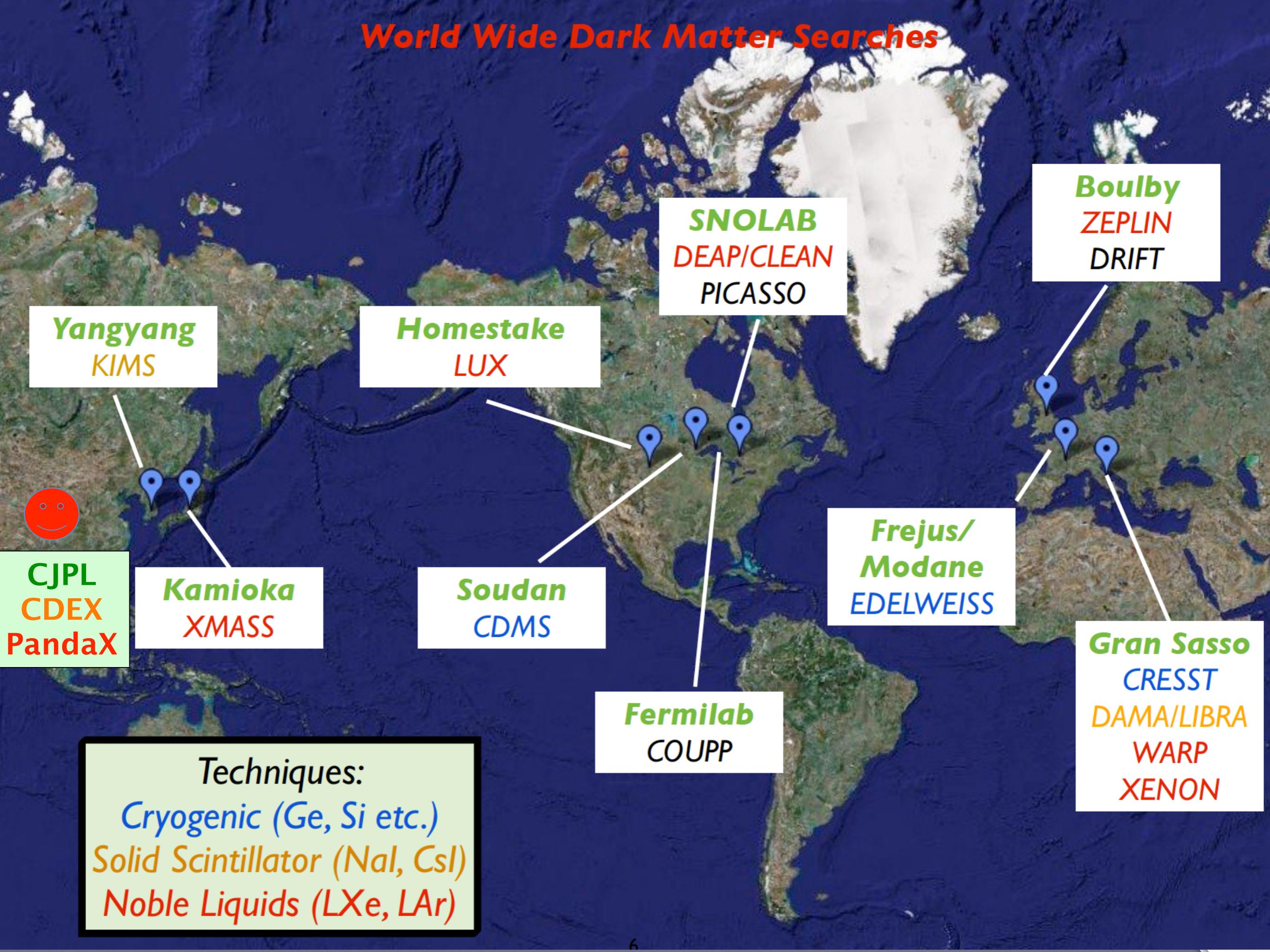
自旋无关的散射

$$\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

自旋相关的散射

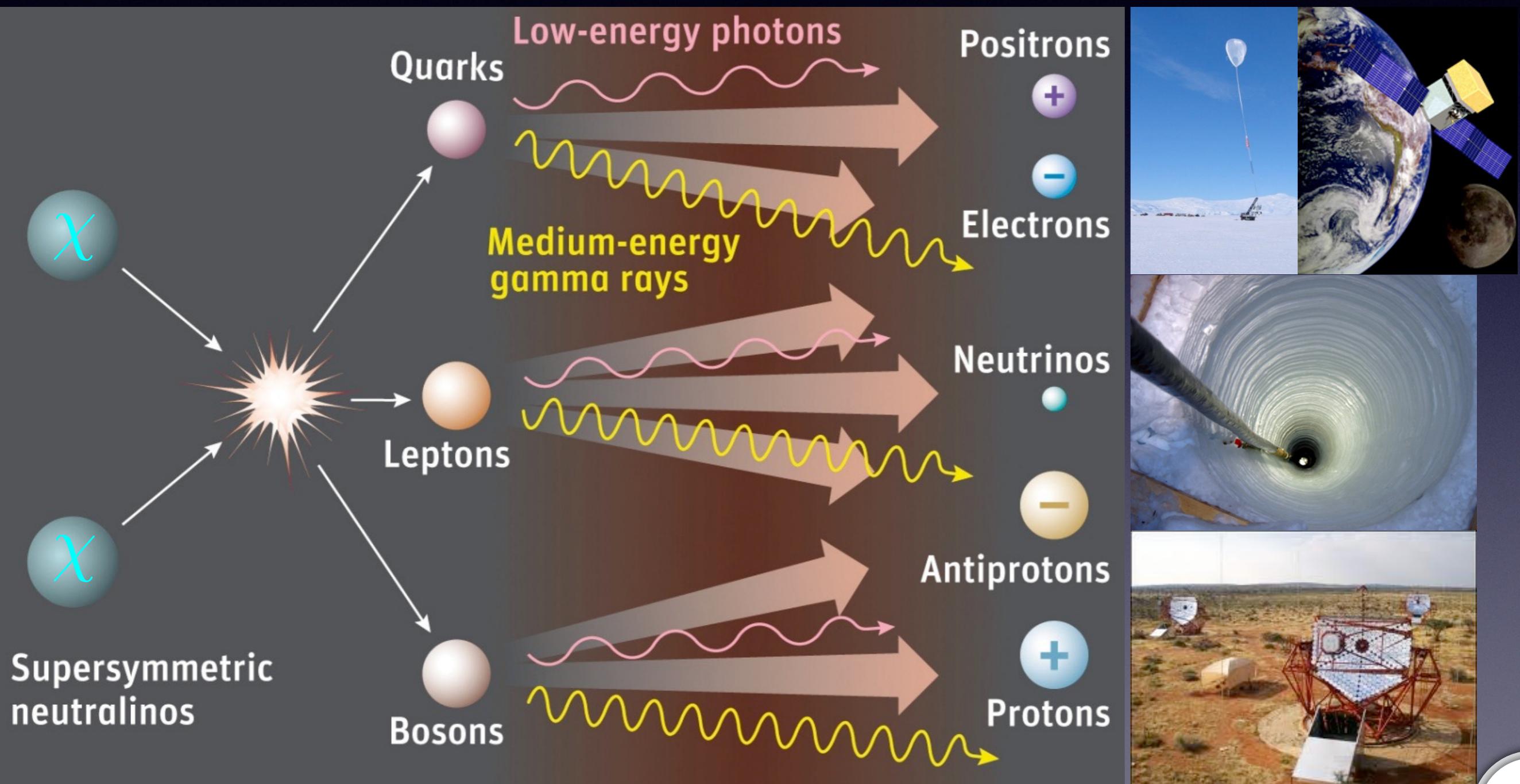
$$\bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q$$

# World Wide Dark Matter Searches



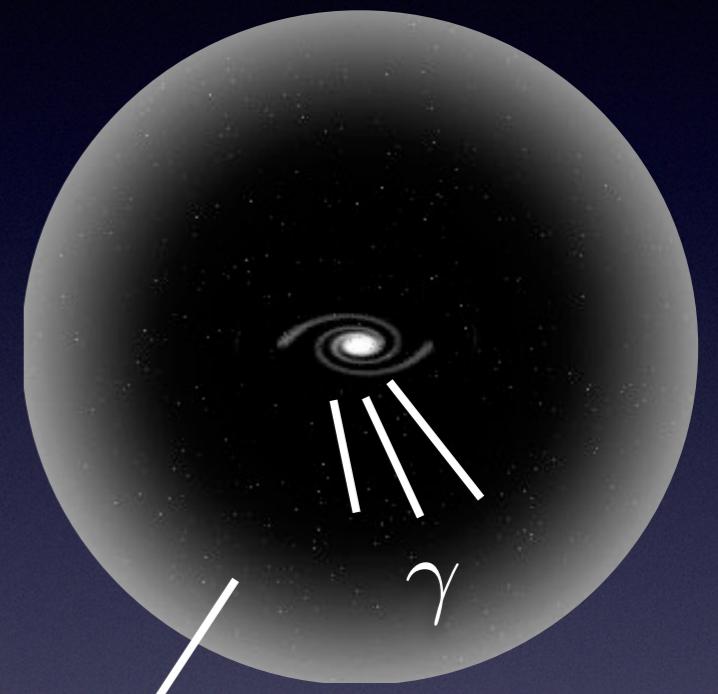
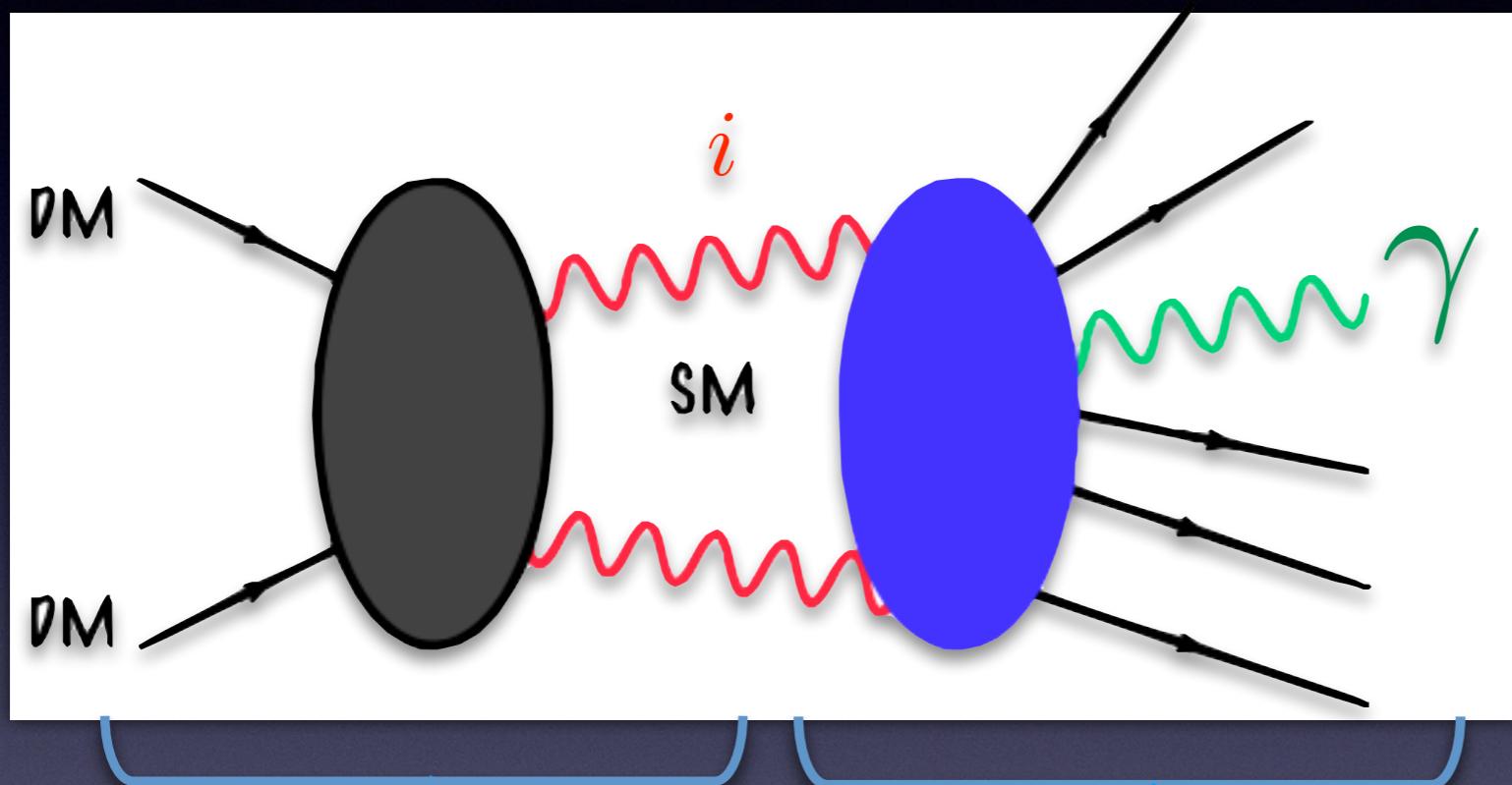
# 暗物质间接测量

暗物质在宇宙中湮灭产生正反电子，正反质子，光子，中微子



# Cosmic Gamma-Ray

$\eta\eta \rightarrow WW, ZZ, \dots$  in the Galactic halo

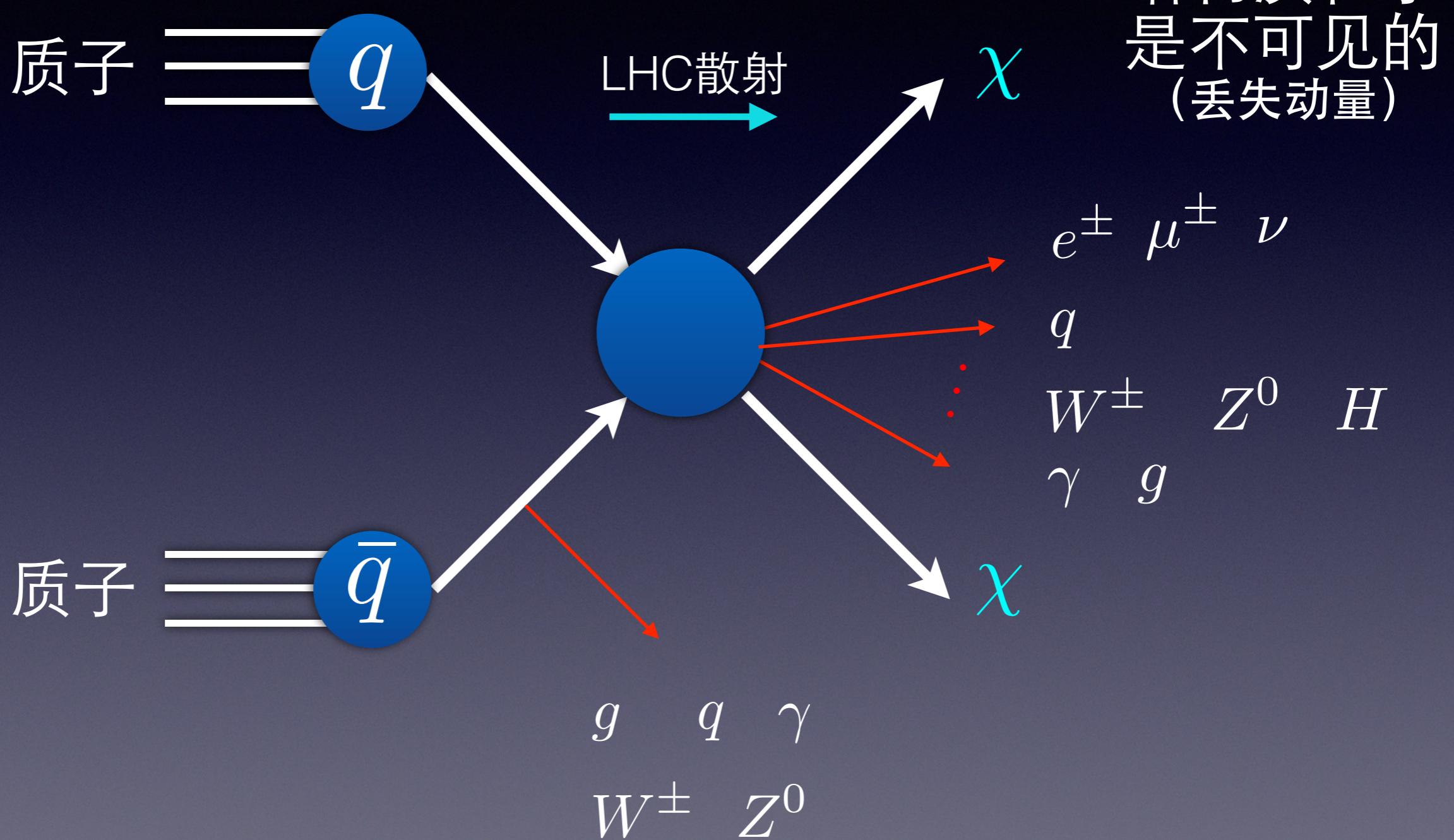


$$\frac{d\Phi}{d\Omega dE} = \sum_i \langle \sigma v \rangle_i \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}^2} \int_{\text{l.o.l}} \rho^2 dl$$

Particle  
Physics

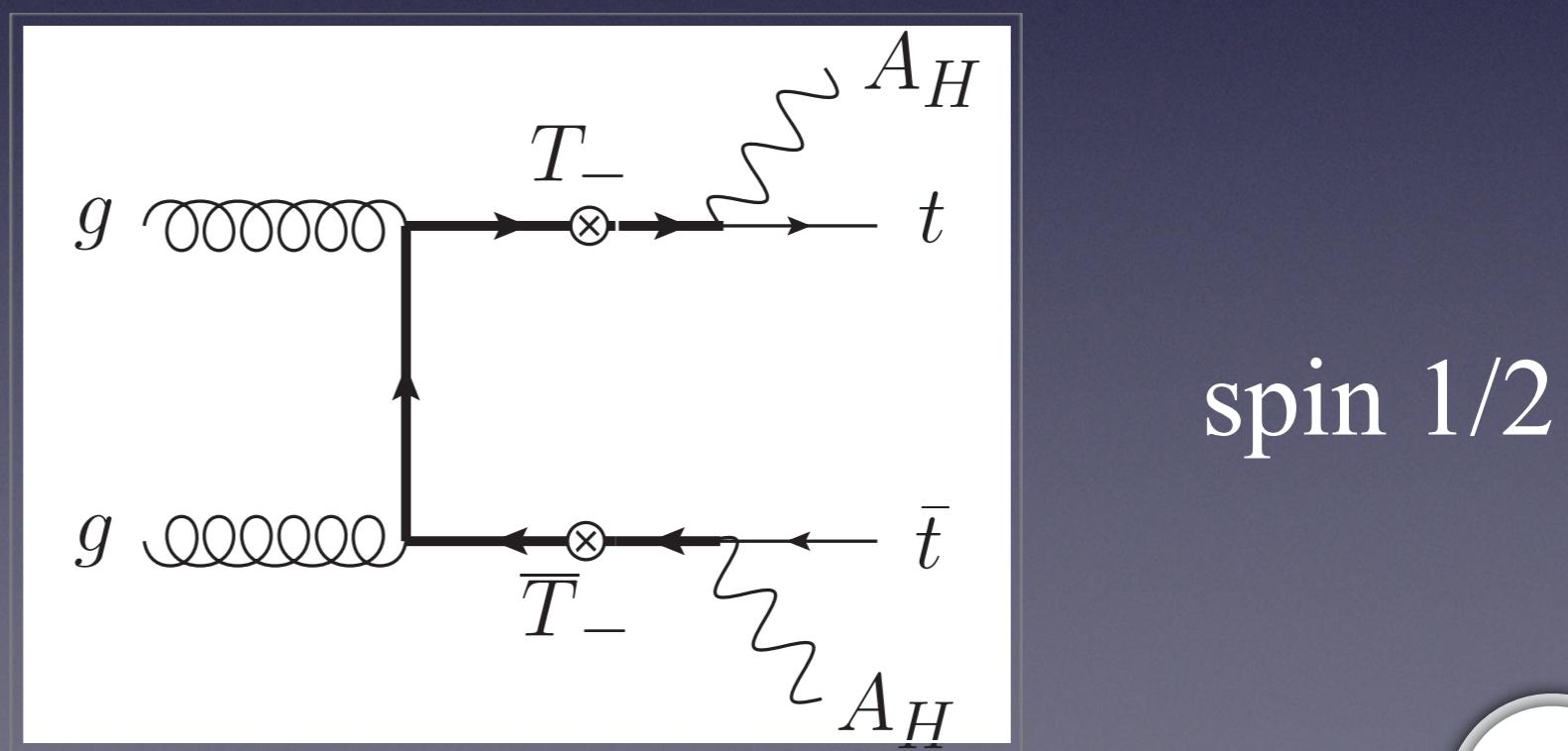
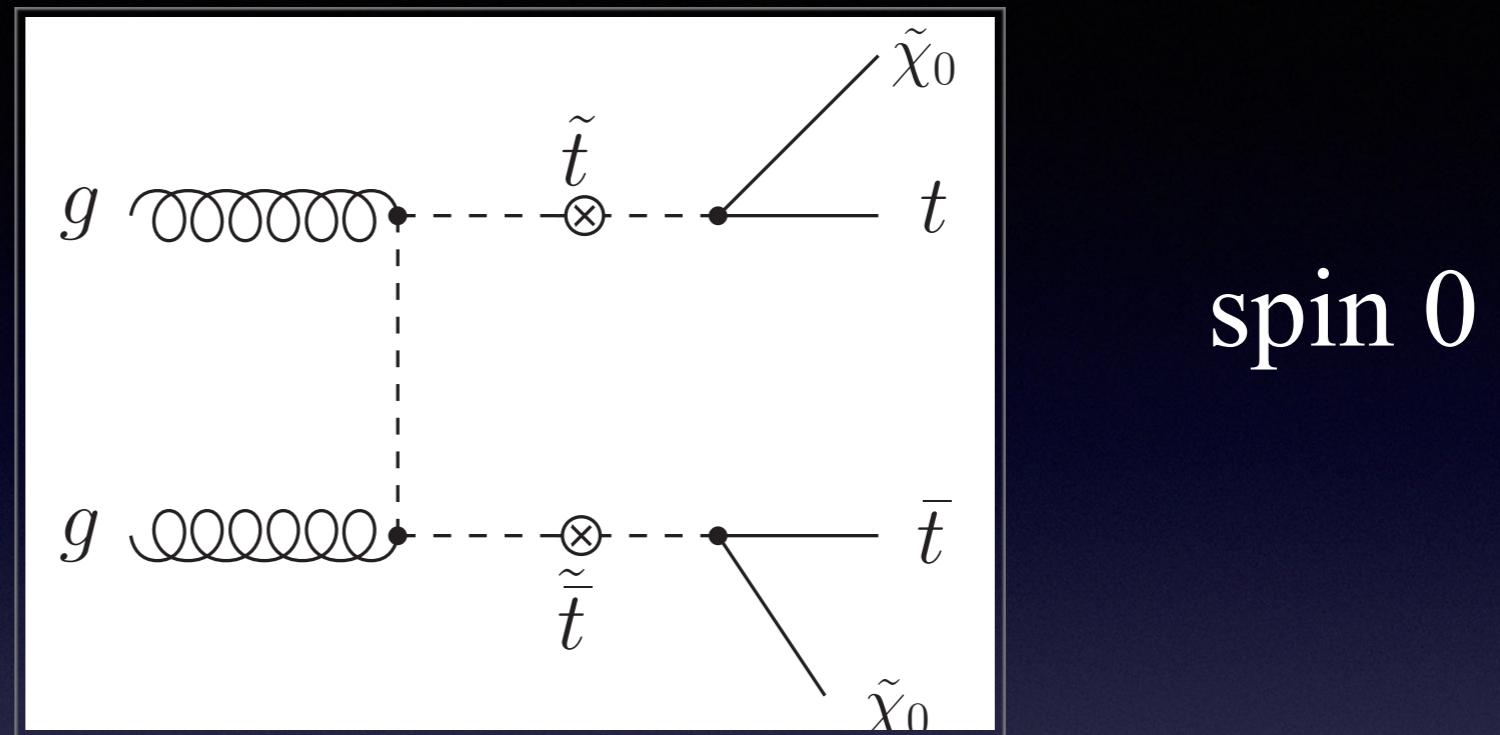
Astrophysics

# 暗物质对撞机信号



# 暗物质对撞机信号示例

- Minimal Supersymmetric extension of the Standard Model (MSSM)
- Little Higgs Model with T-parity (LHT)
- Universal Extra Dimension Model (UED)

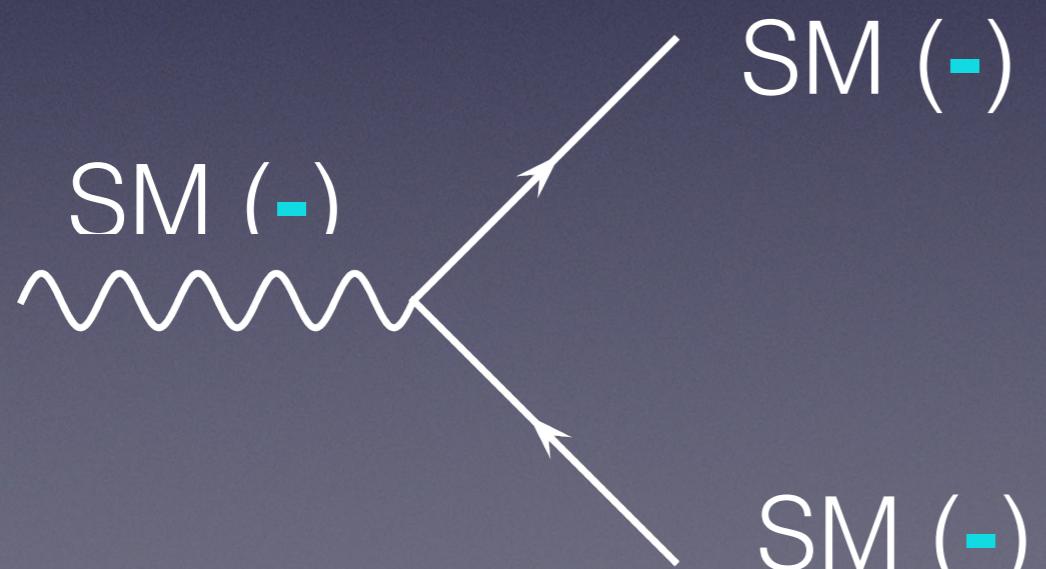
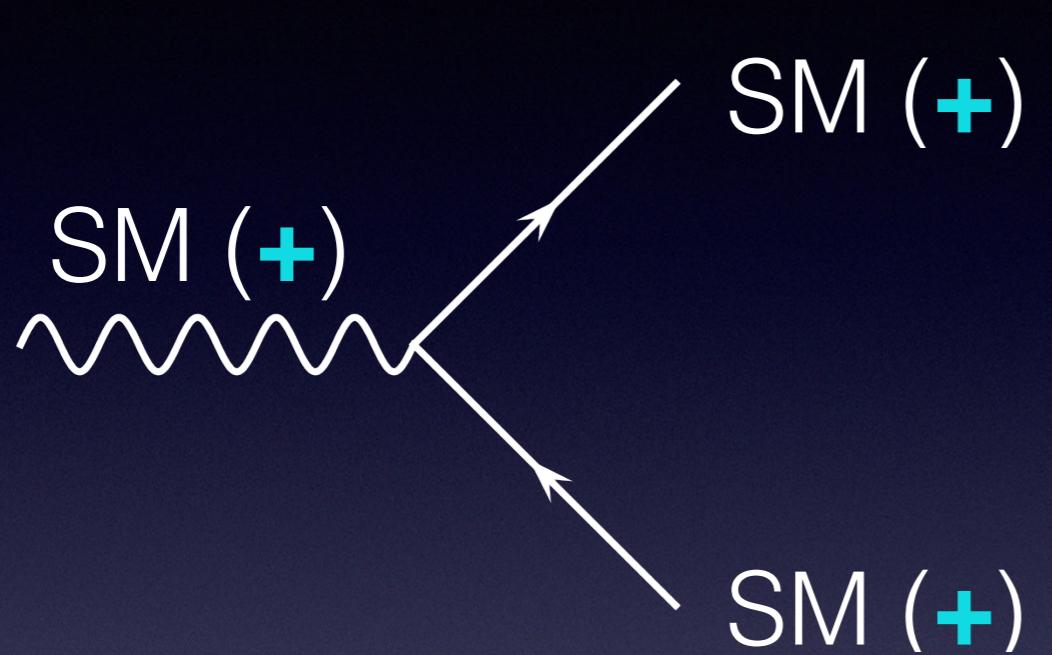


# 暗物质的稳定性

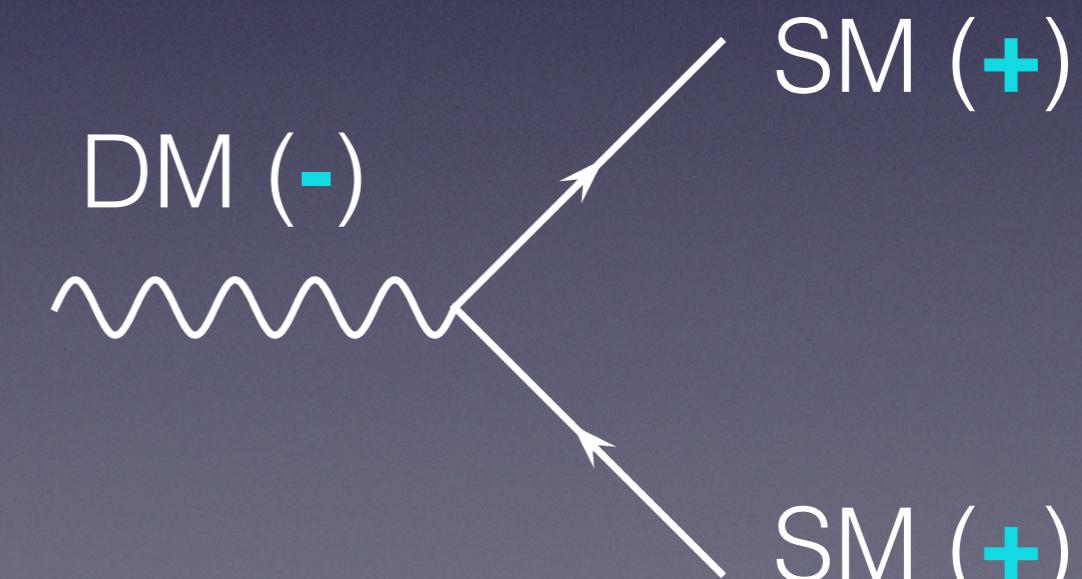
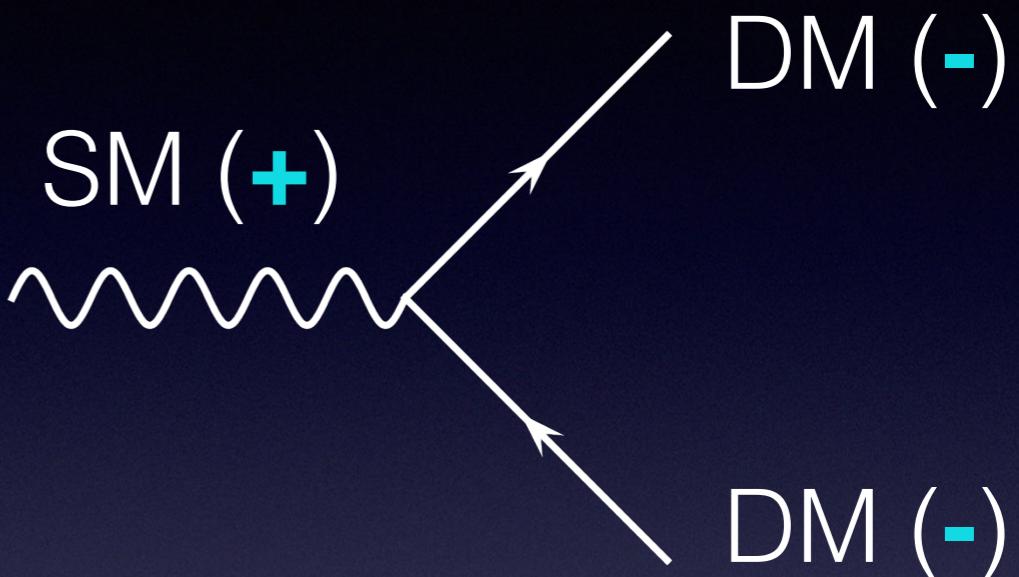
(示例：超对称模型)

# 暗物质的稳定性

通常通过引入离散对称性(例如  $Z_2$ )来保证暗物质的绝对稳定



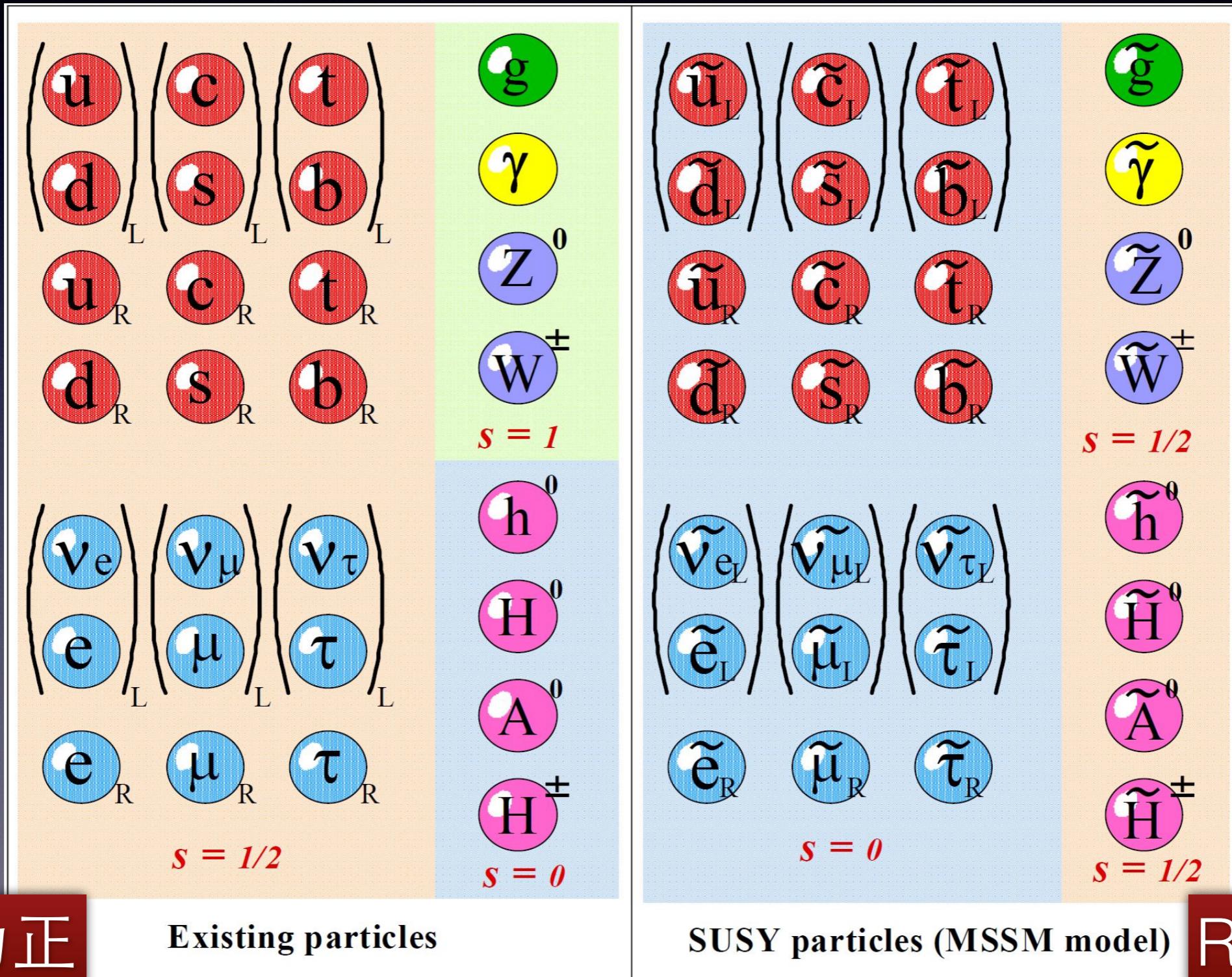
SM不能是 $Z_2$ -odd



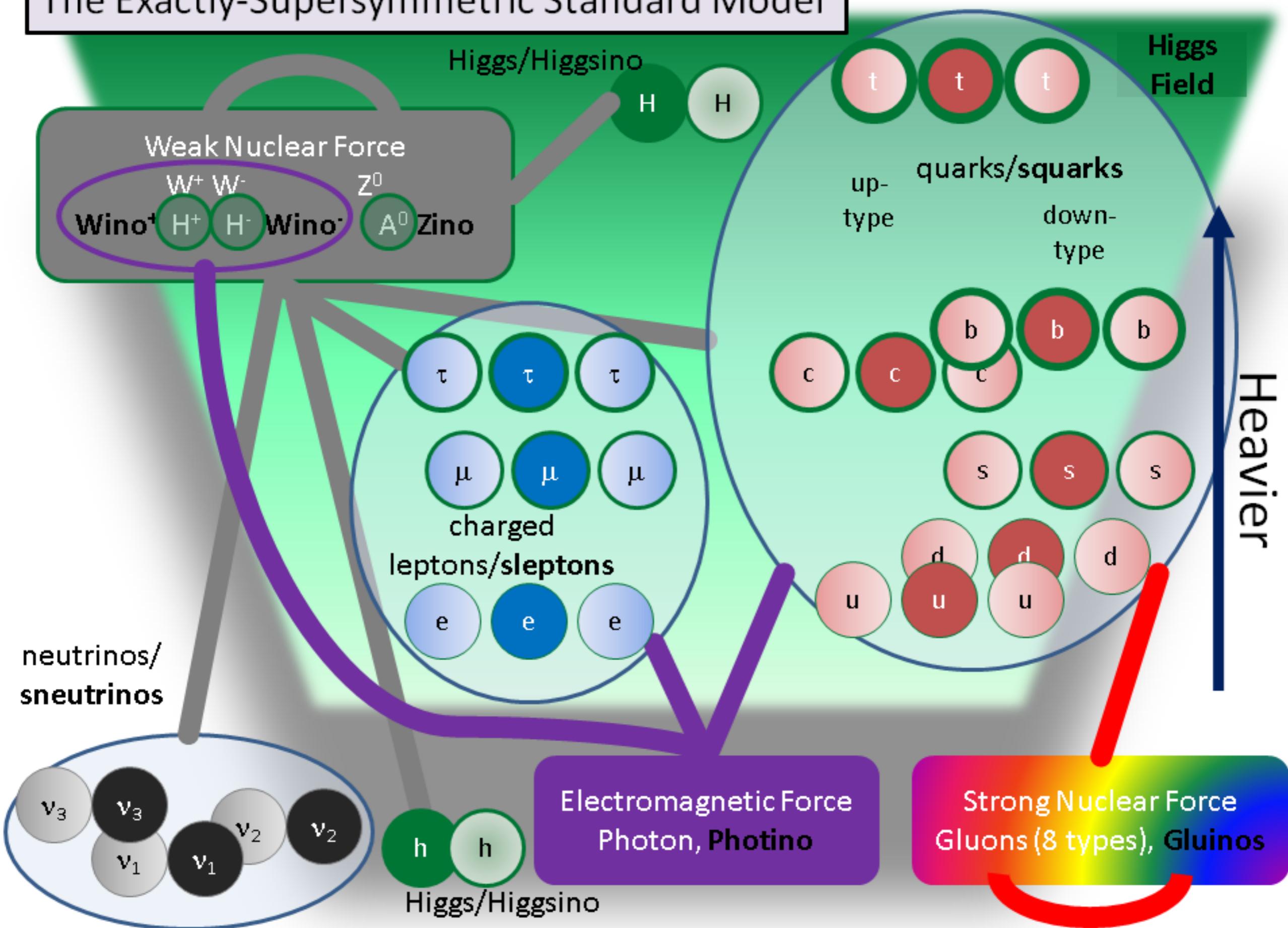
暗物质不能衰变到标准模型粒子

# R-宇称守恒的超对称理论

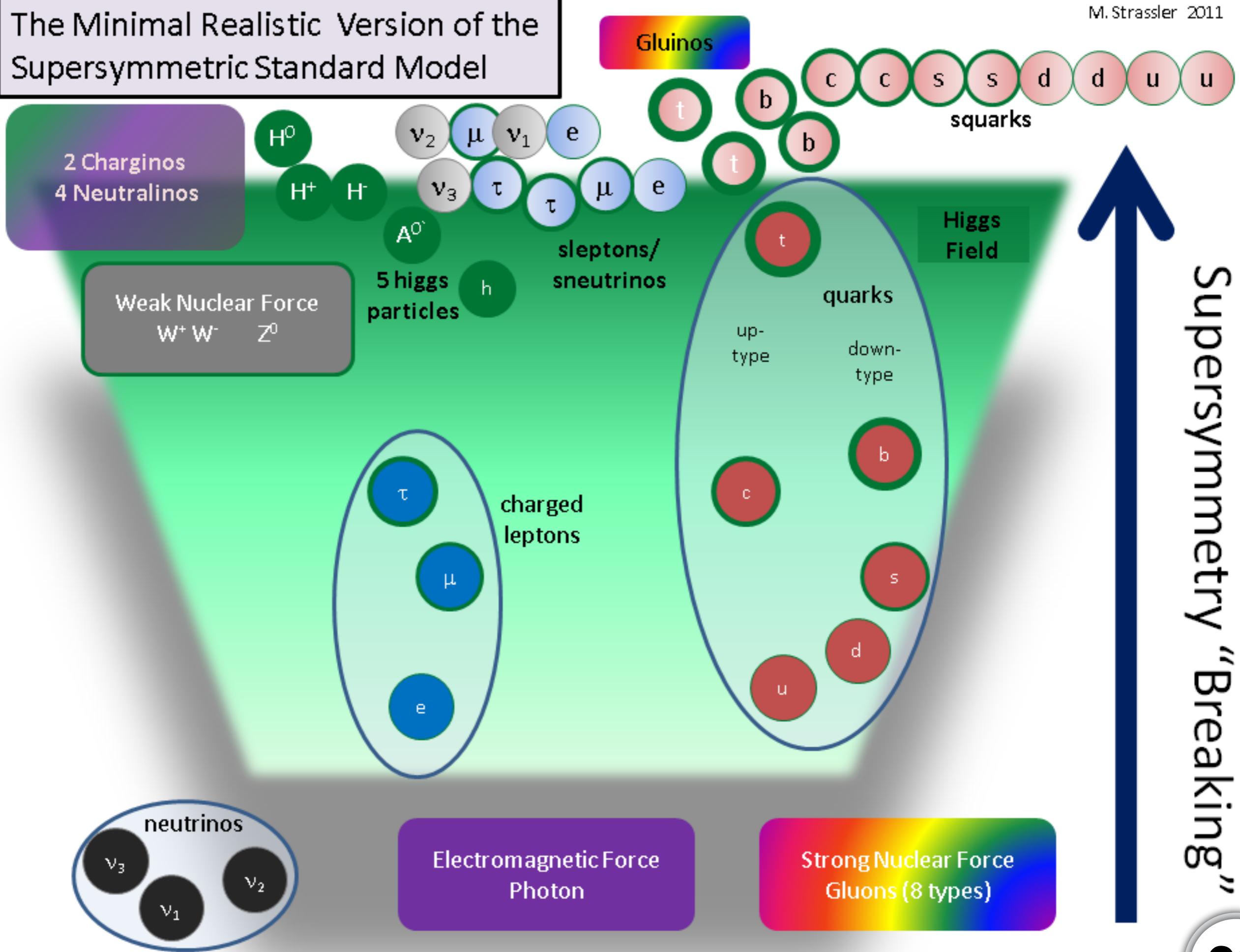
$$R = (-1)^{3(B-L)+2S}$$



# The Exactly-Supersymmetric Standard Model



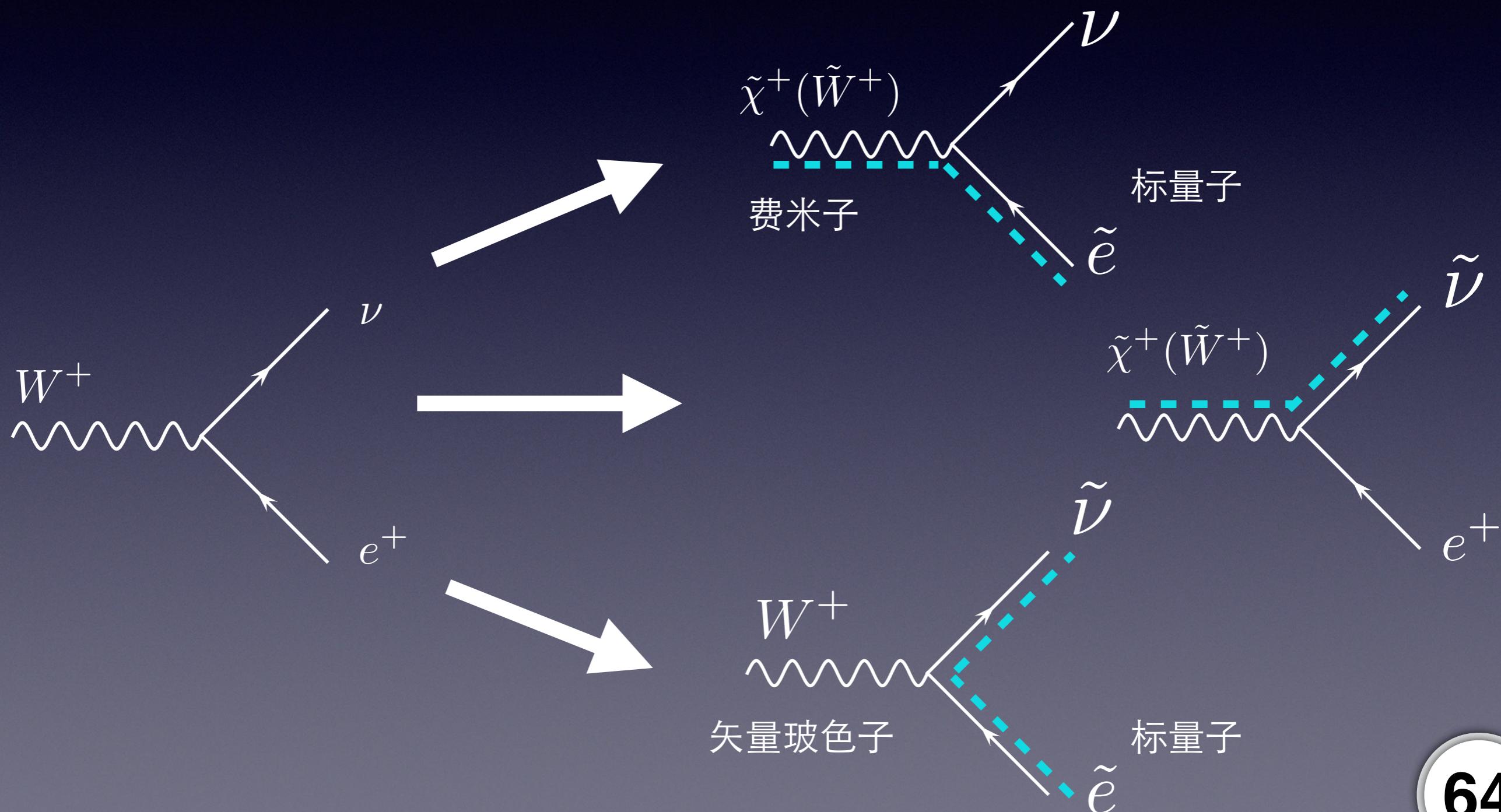
# The Minimal Realistic Version of the Supersymmetric Standard Model



# 如何理解R宇称守恒的MSSM费曼图

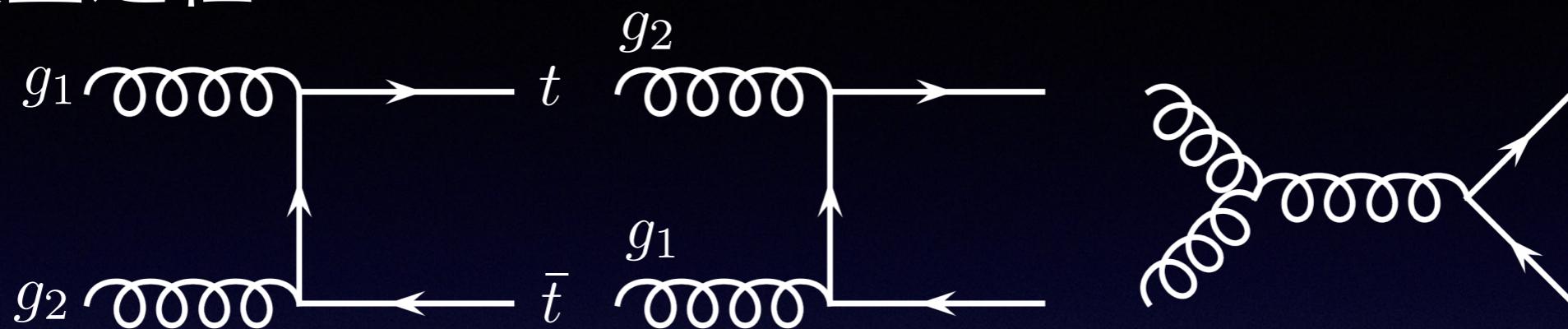
(R宇称的SUSY线)

大部分的费曼图可以通过标准模型的图形得到

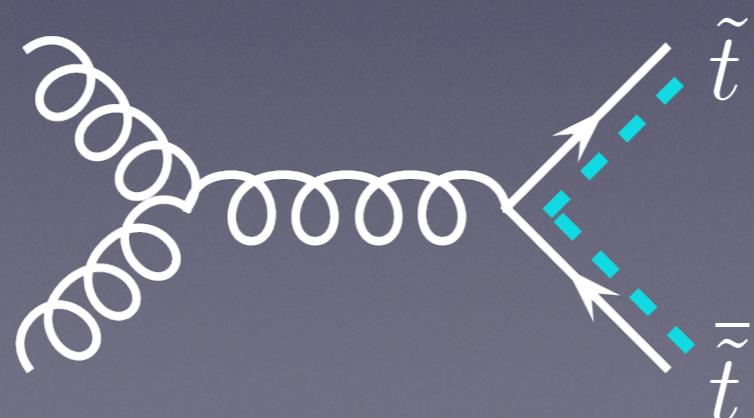
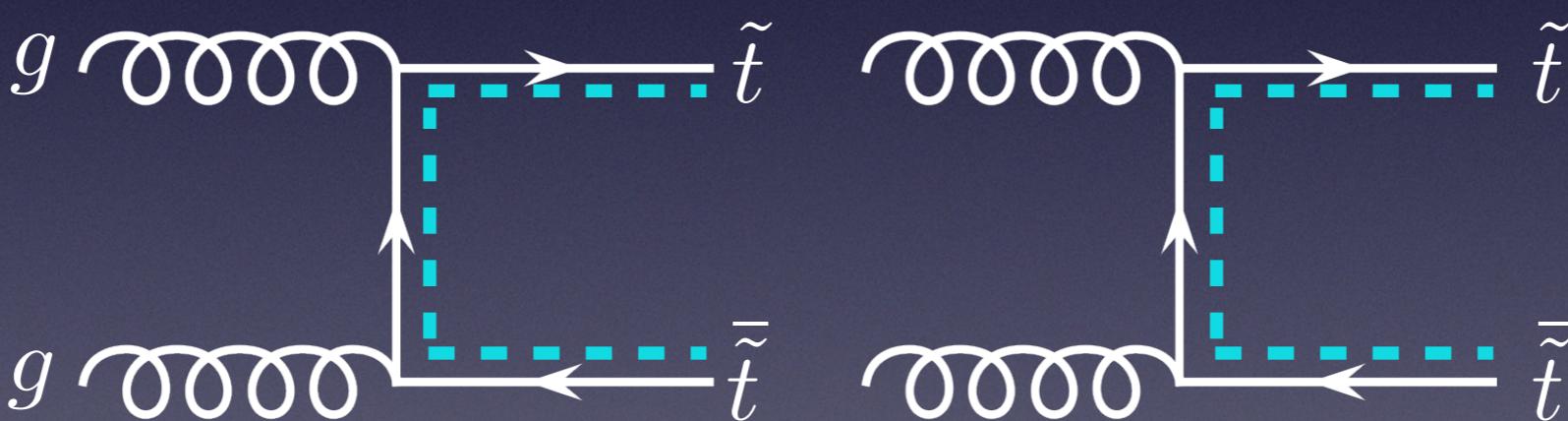


# 顶夸克对产生和其超对称伴子过程

标准模型过程  $gg \rightarrow t\bar{t}$

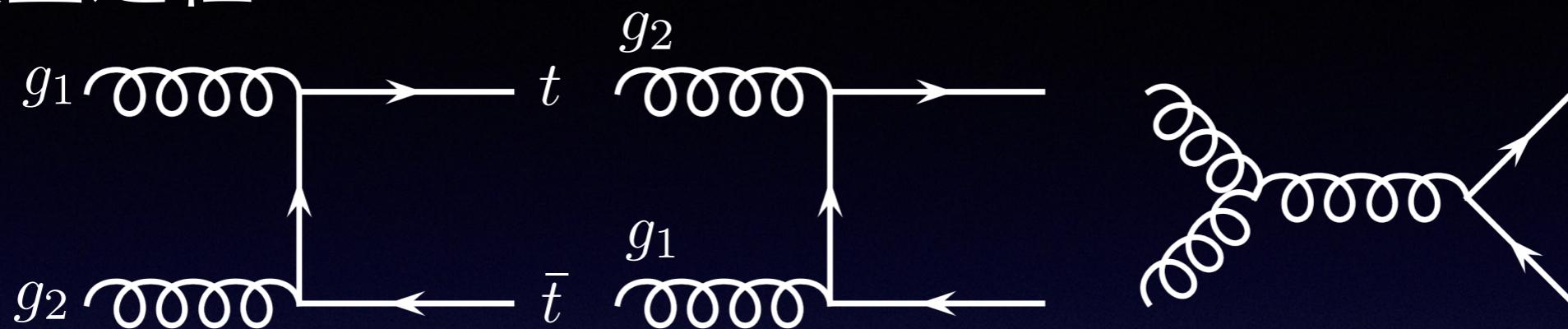


最小超对称模型过程  $gg \rightarrow \tilde{t}\tilde{\bar{t}}$

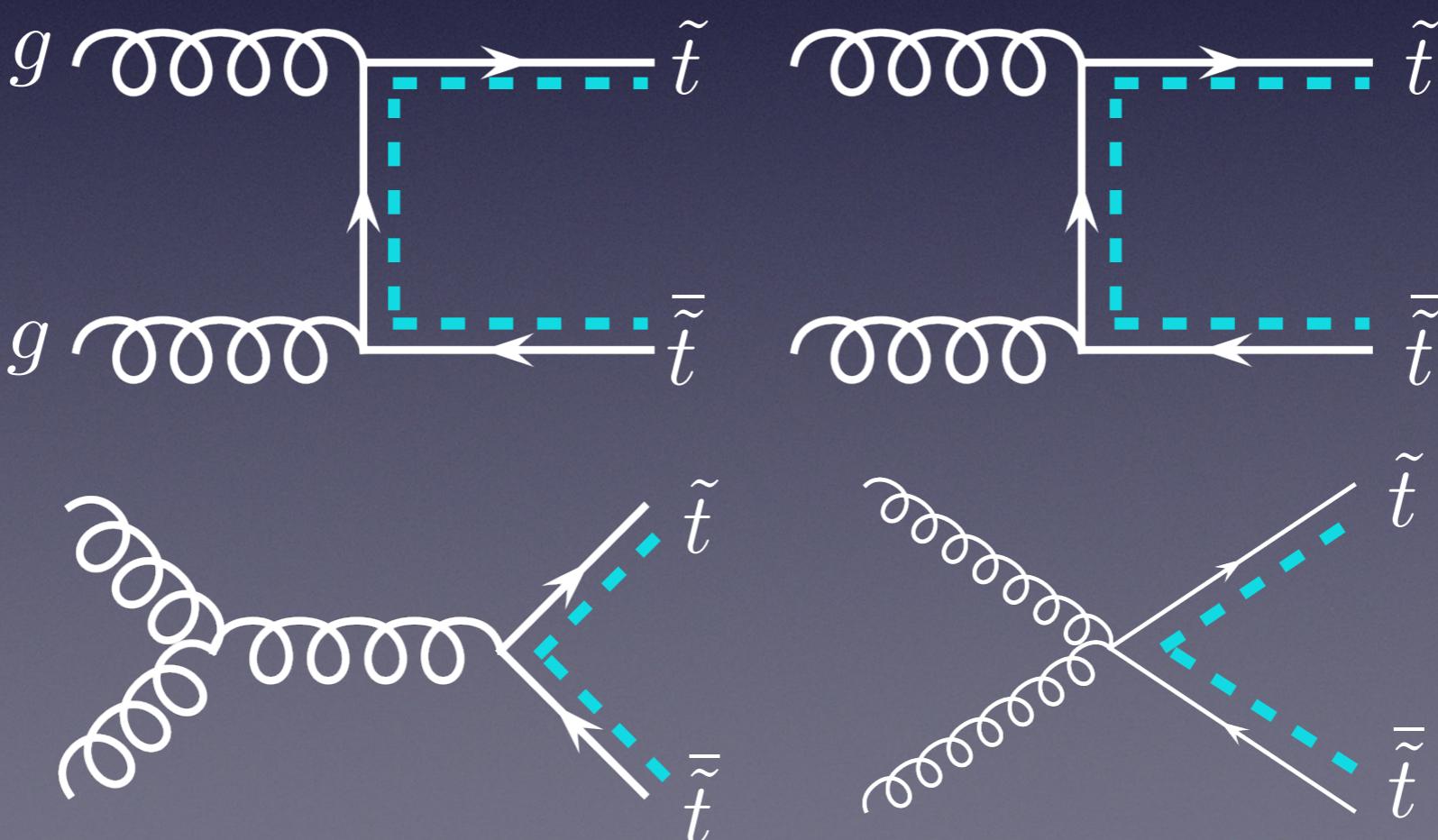


# 顶夸克对产生和其超对称伴子过程

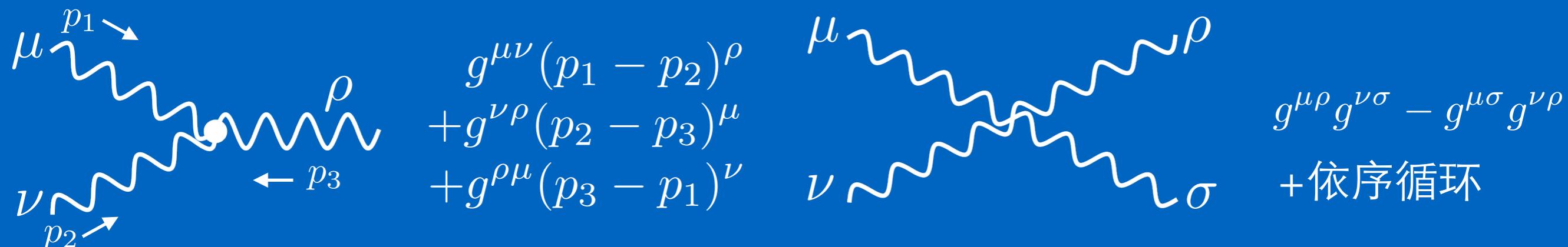
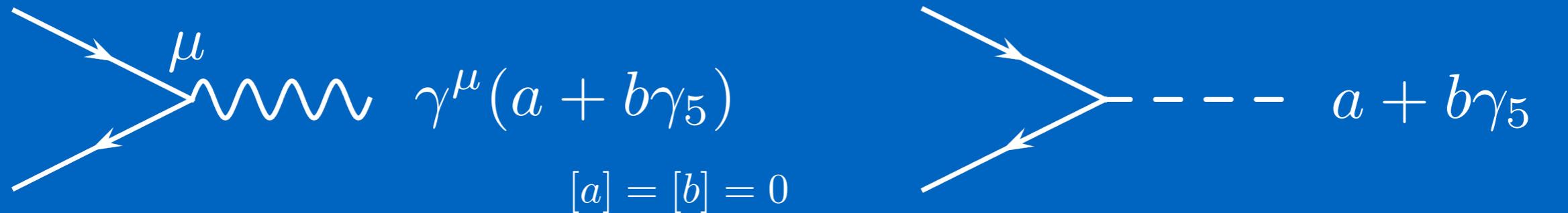
标准模型过程  $gg \rightarrow t\bar{t}$



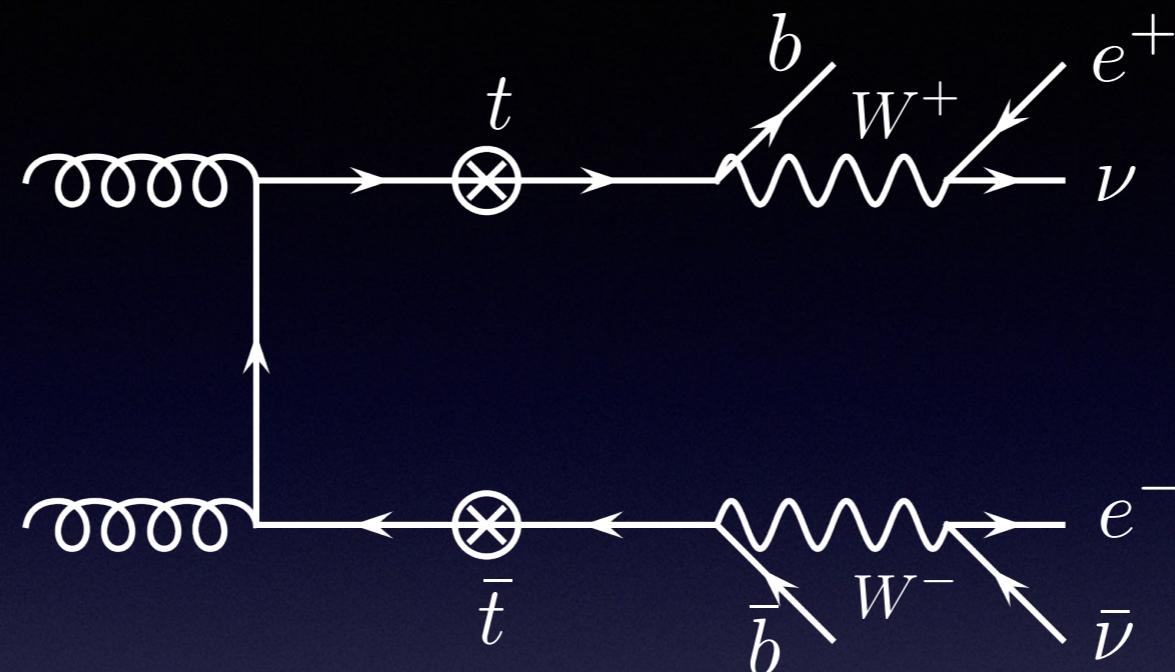
最小超对称模型过程  $gg \rightarrow \tilde{t}\tilde{\bar{t}}$



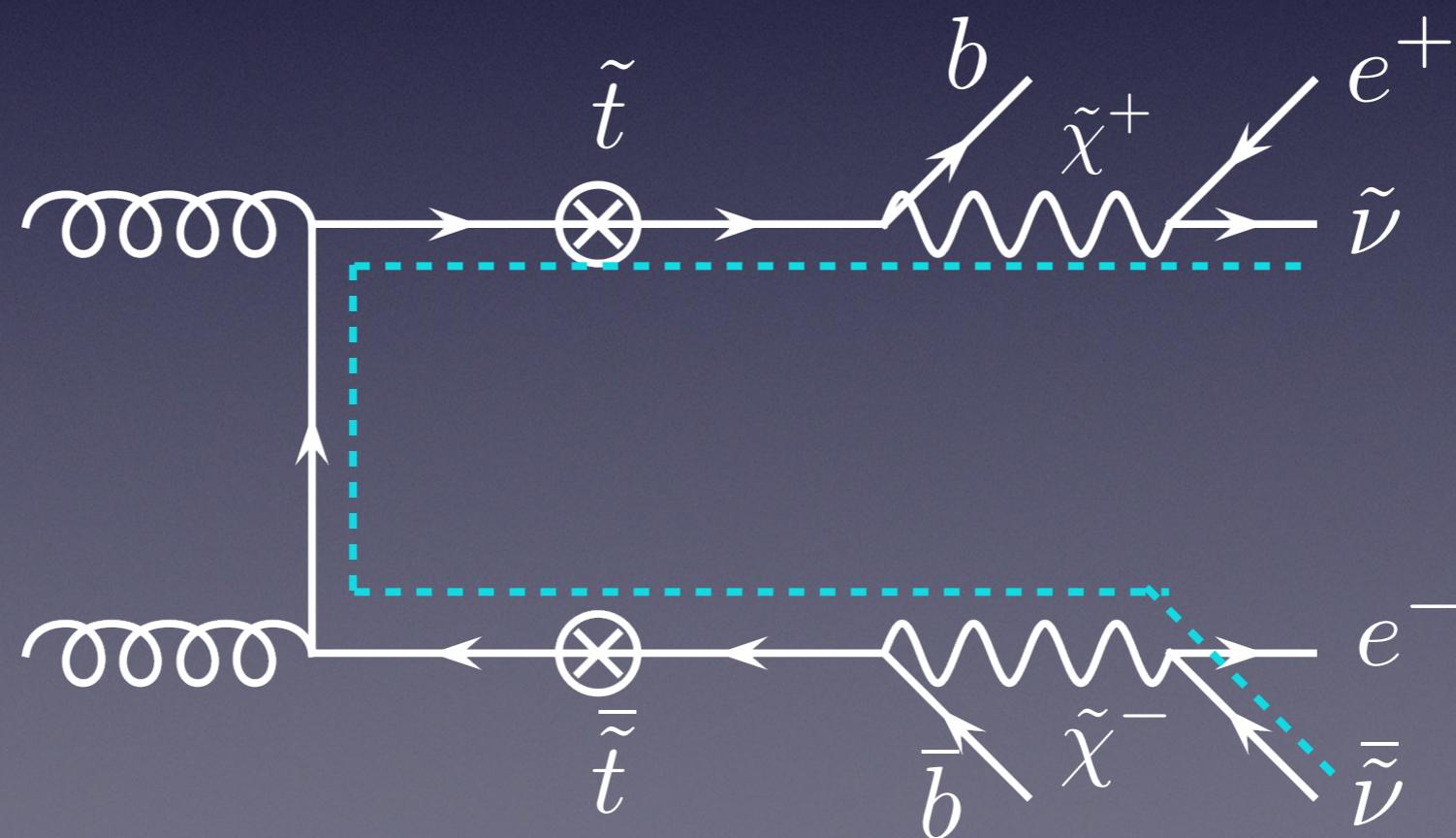
# 一般性的费曼顶点



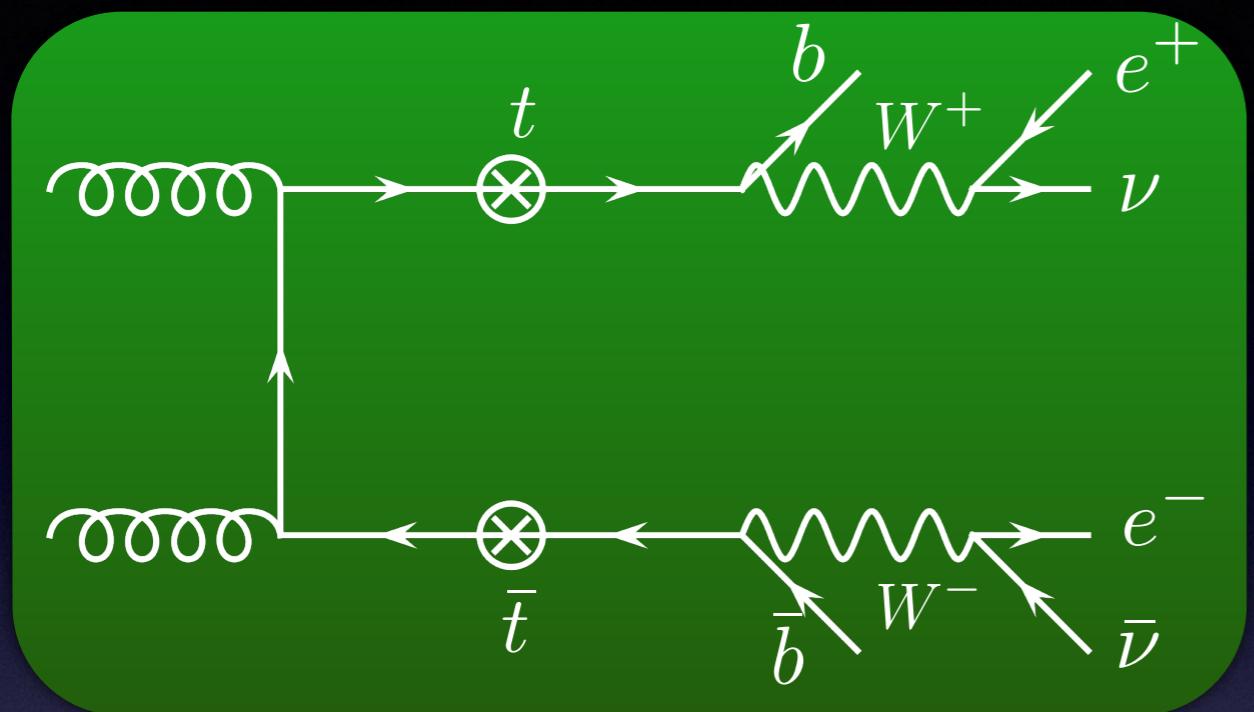
# Stop-夸克对的产生和衰变



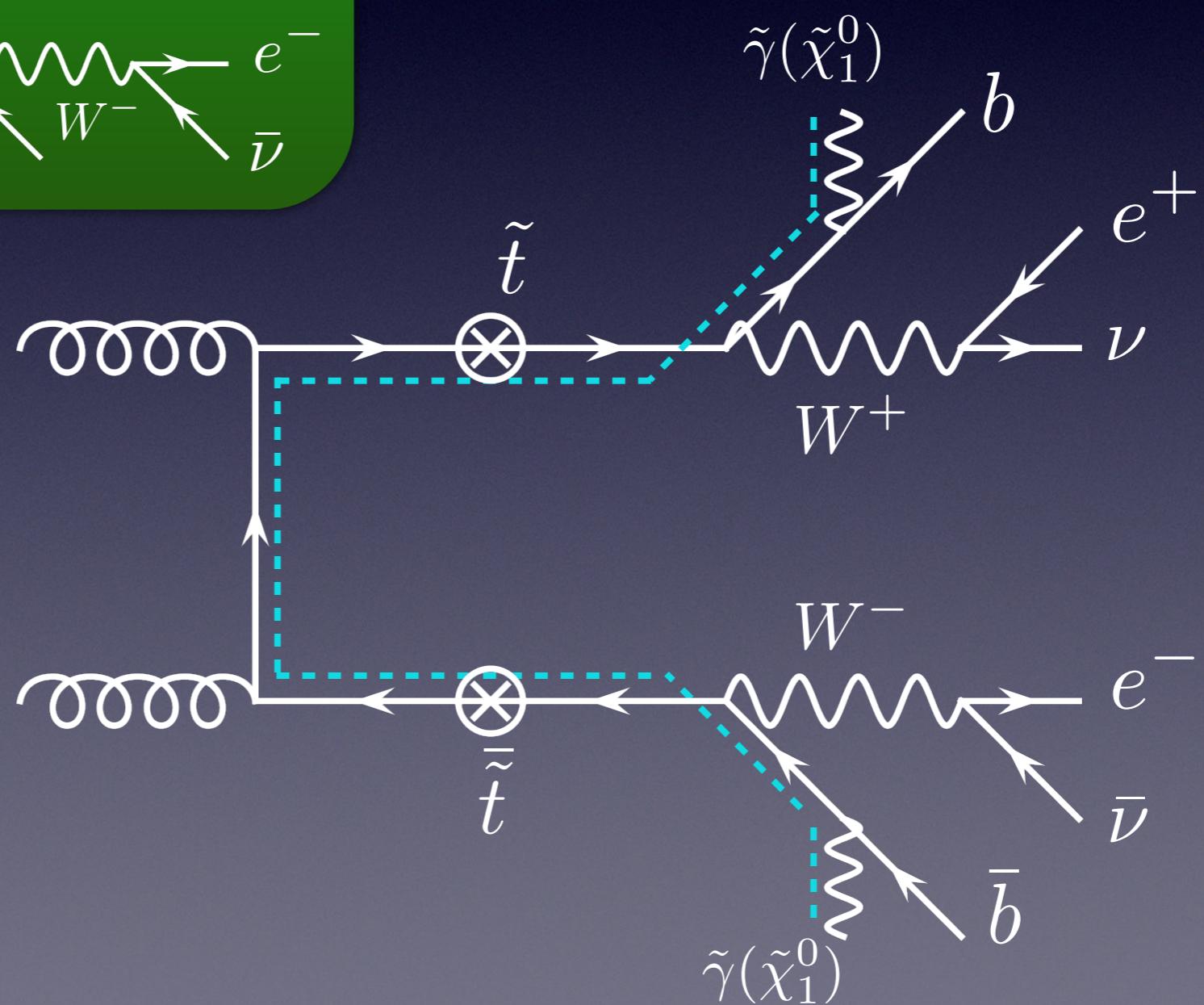
先不考虑  
具体的理论要求和  
实验数据限制。



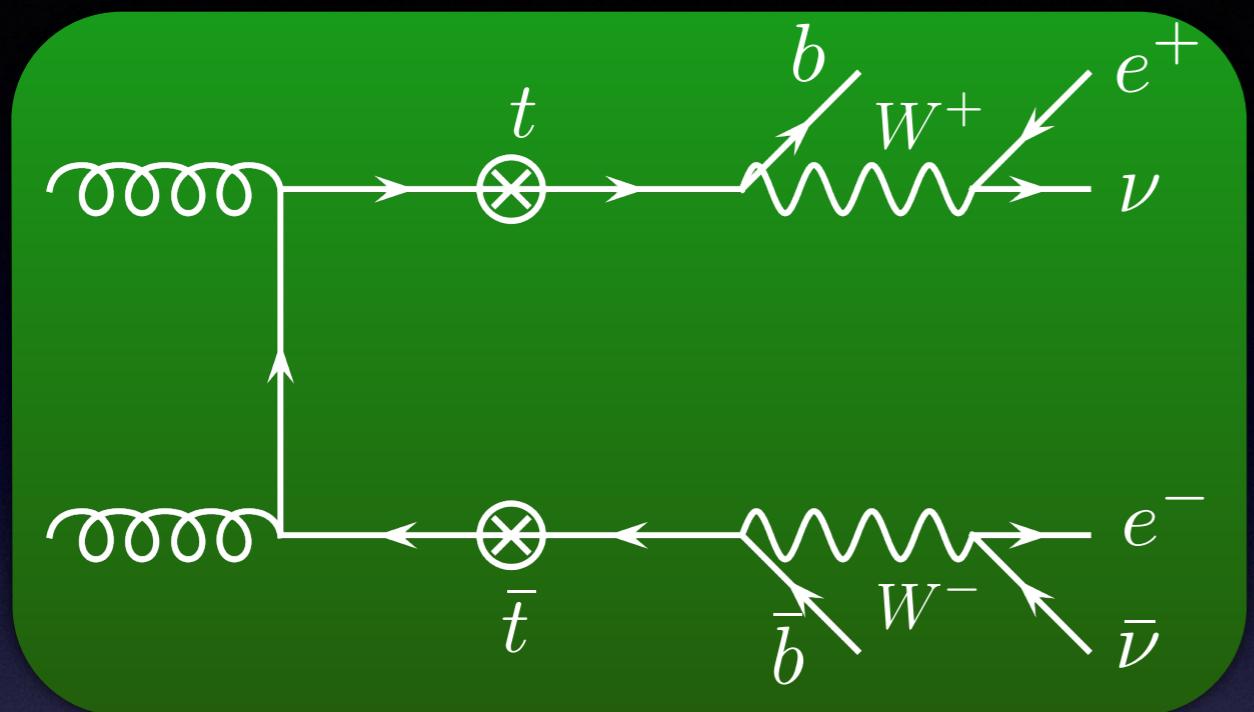
# Stop-夸克对的产生和衰变



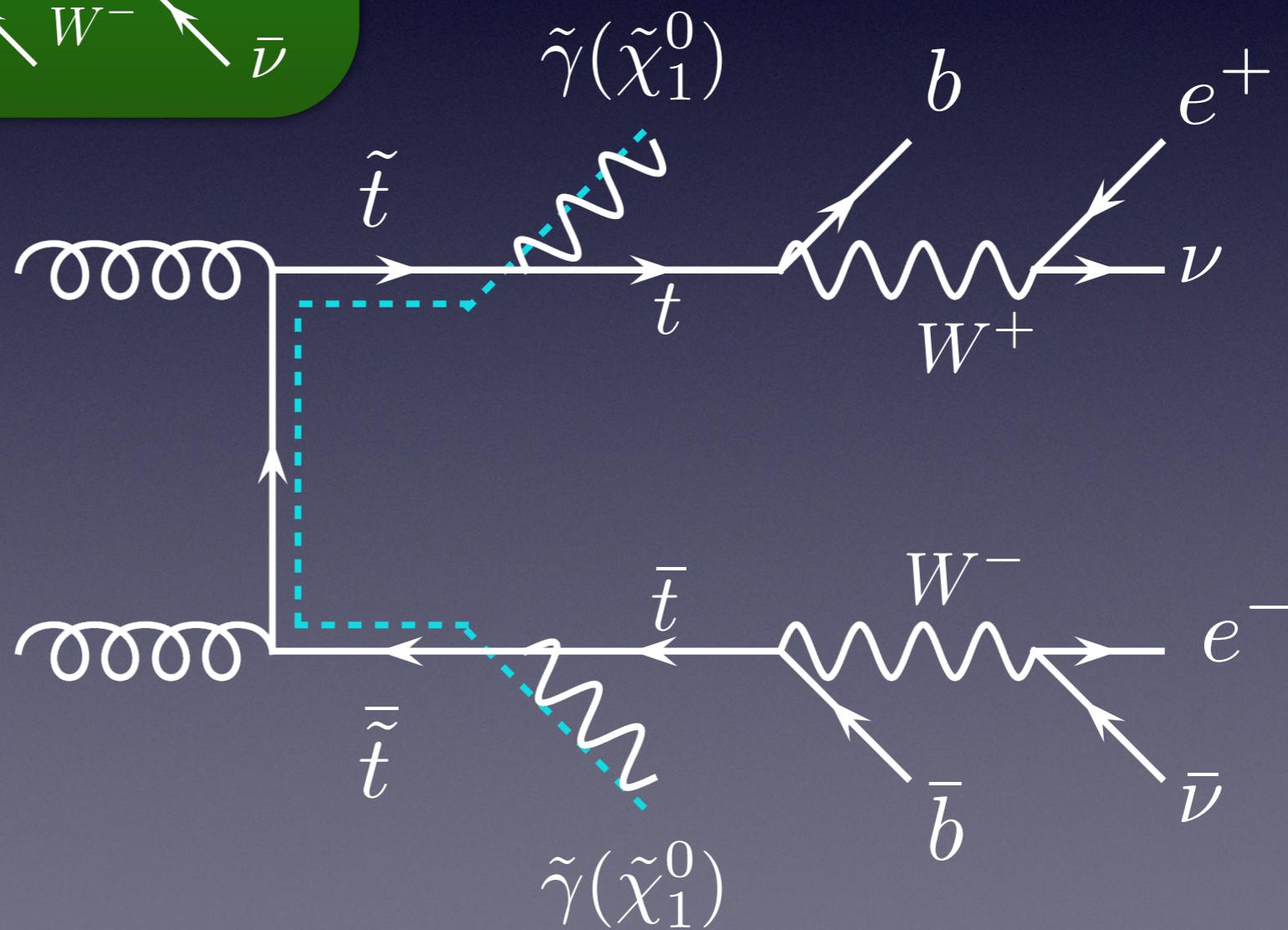
先不考虑  
具体的理论要求和  
实验数据限制。



# Stop-夸克对的产生和衰变



先不考虑  
具体的理论要求和  
实验数据限制。



# 最小超对称模型：5个标量粒子

$$\Phi_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

$$\langle \Phi_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \quad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \longrightarrow h, H, A, H^+, H^-$$

Count degree of freedom:

Massless gauge bosons have 2 transverse d.o.f.

Massive gauge bosons also have longitudinal d.o.f.

Before SSB

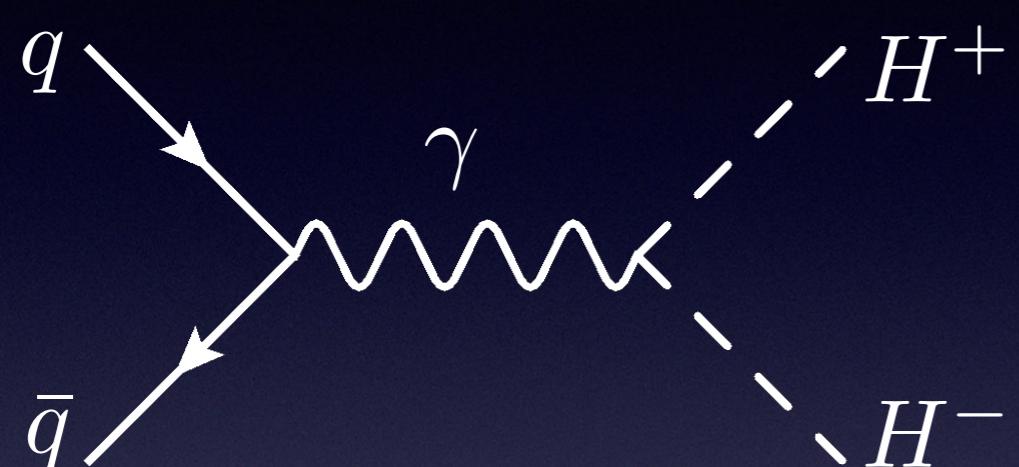
Massless $W_\mu^{i=1,2,3}, B_\mu$	8
Complex $\Phi_u, \Phi_d$	8
Total	16

After SSB

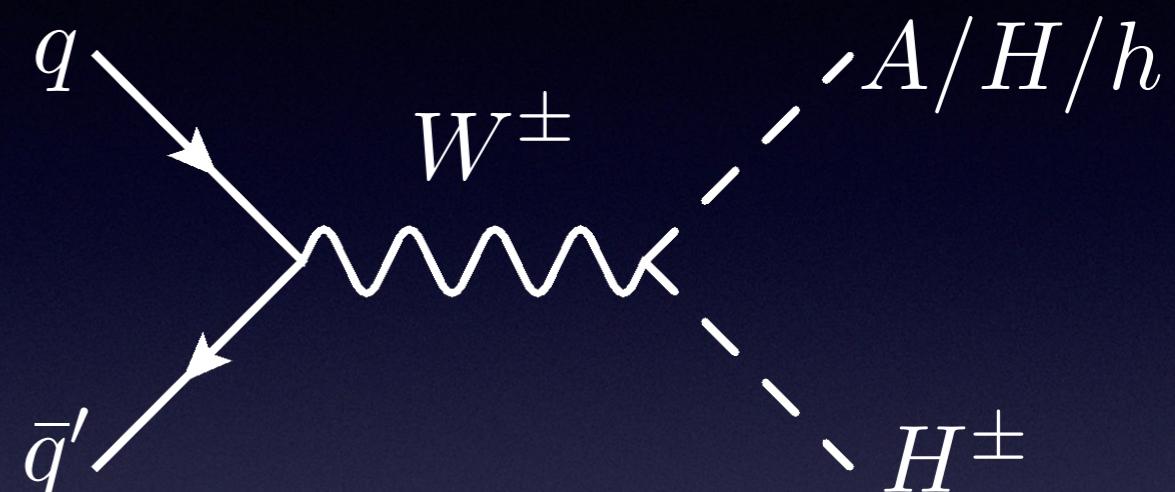
Massive $W^\pm, Z$	9
Massless $\gamma$	2
Complex $h, H, A, H^\pm$	5
Total	16

# 荷电希格斯粒子：确凿无疑的新物理信号

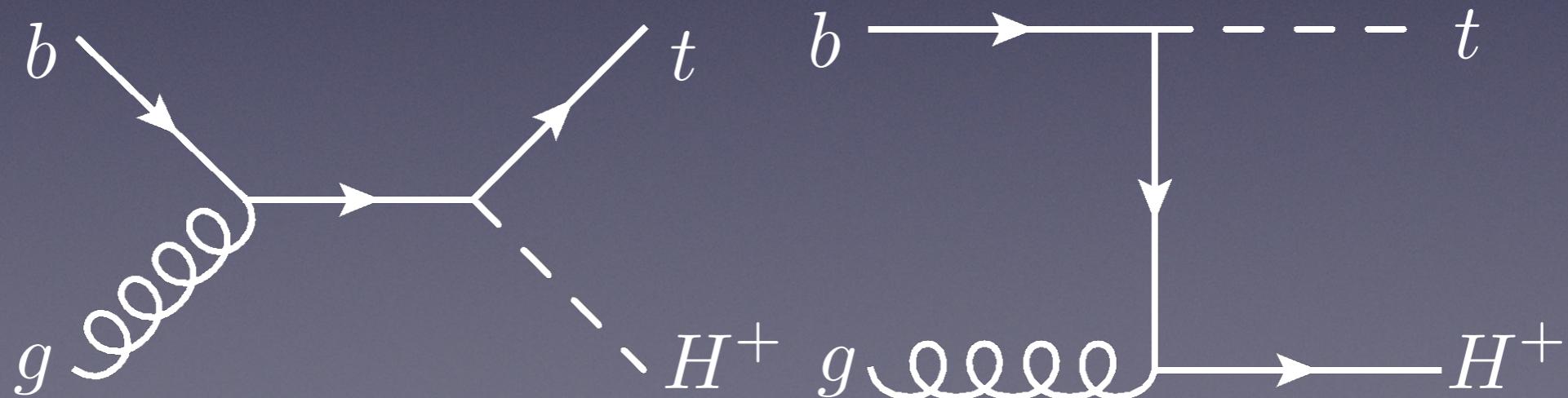
$H^\pm H^\mp$  production



$H^\pm A/H/h$  production

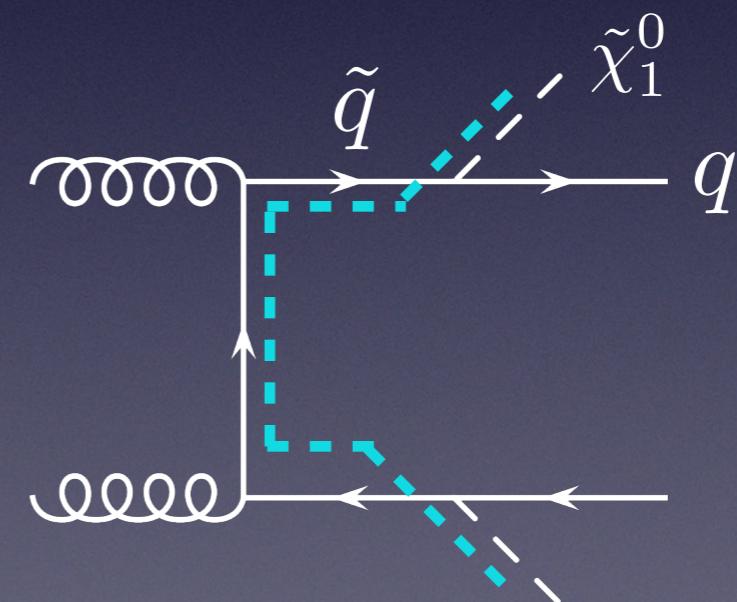
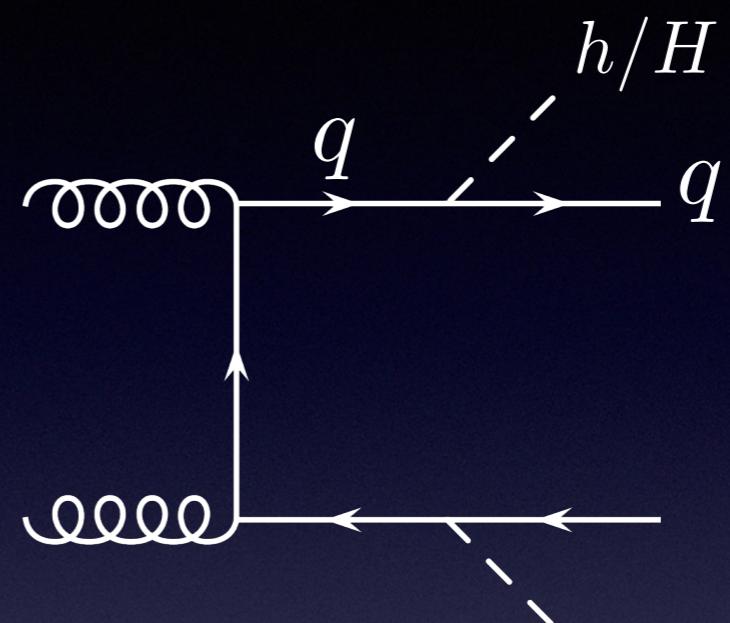
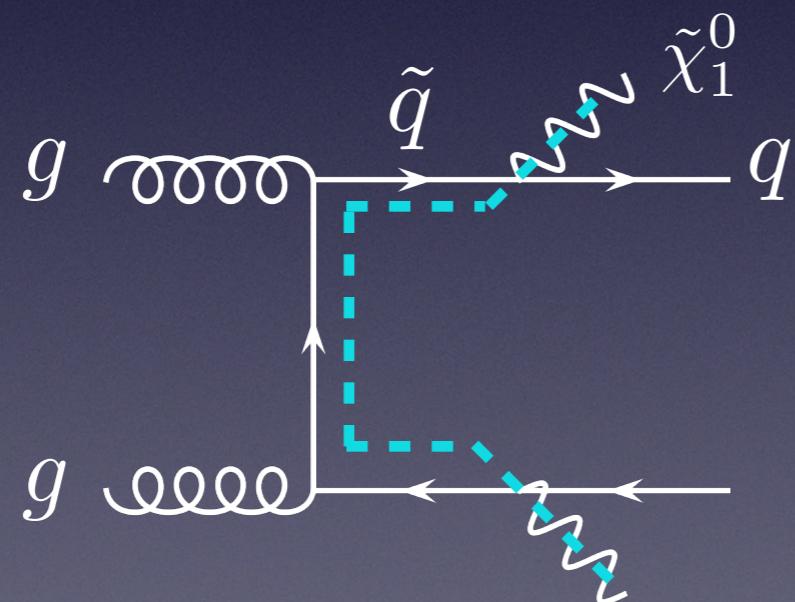
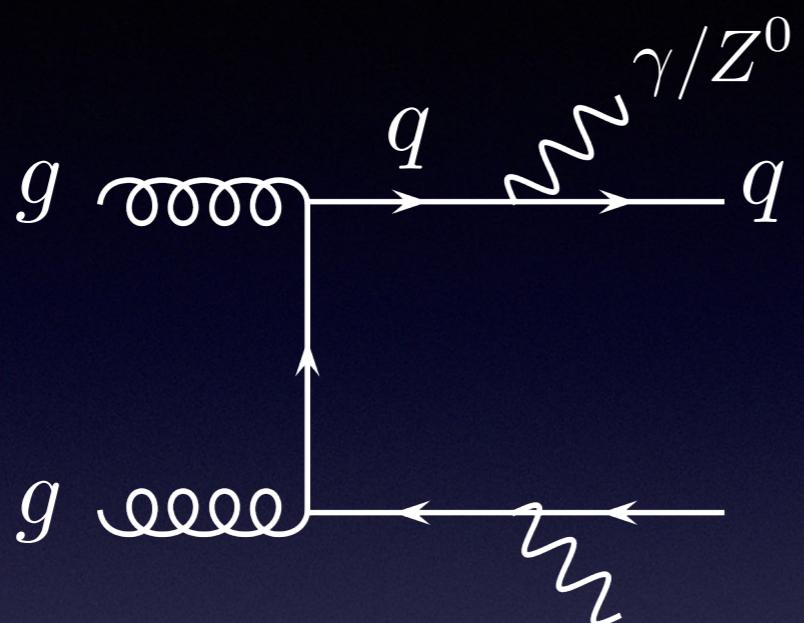


$H^-t$  production



# Neutralino: Lightest SUSY Particle (LSP)

暗物质候选者



$$\left( \tilde{B}_1, \tilde{W}_3, \tilde{H}_u, \tilde{H}_d \right) \xrightarrow[\text{对角化}]{\text{质量矩阵}} \left( \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0 \right)$$

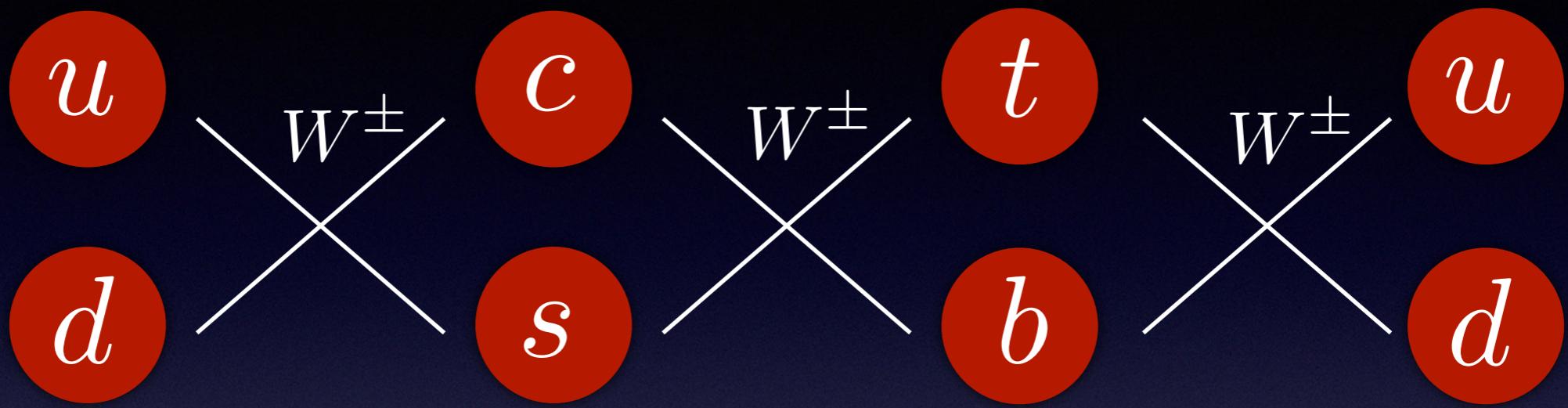
# 3. 新费米子

# 第4代费米子

如果自然界只有3代费米子，那我们需要知道为什么。

夸克	$u$	$c$	$t$	$t'$	$\gamma$
	$d$	$s$	$b$	$b'$	$g$
轻子	$\nu_e$	$\nu_\mu$	$\nu_\tau$	$\nu'$	$W$
	$e$	$\mu$	$\tau$	$\tau'$	$Z$
自旋1/2		自旋1/2		自旋1	

# CKM混合矩阵

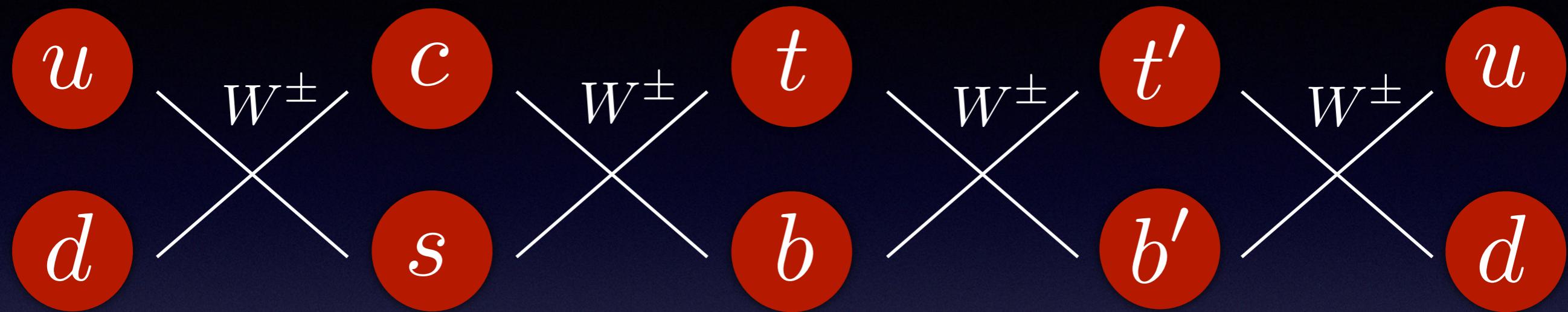


$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{weak}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}}$$

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix}_{\text{weak}} \equiv \begin{pmatrix} u \\ c \\ t \end{pmatrix}_{\text{mass}}$$

$$V_{tb} = 0.99914 \pm 0.00005$$

# CKM混合矩阵

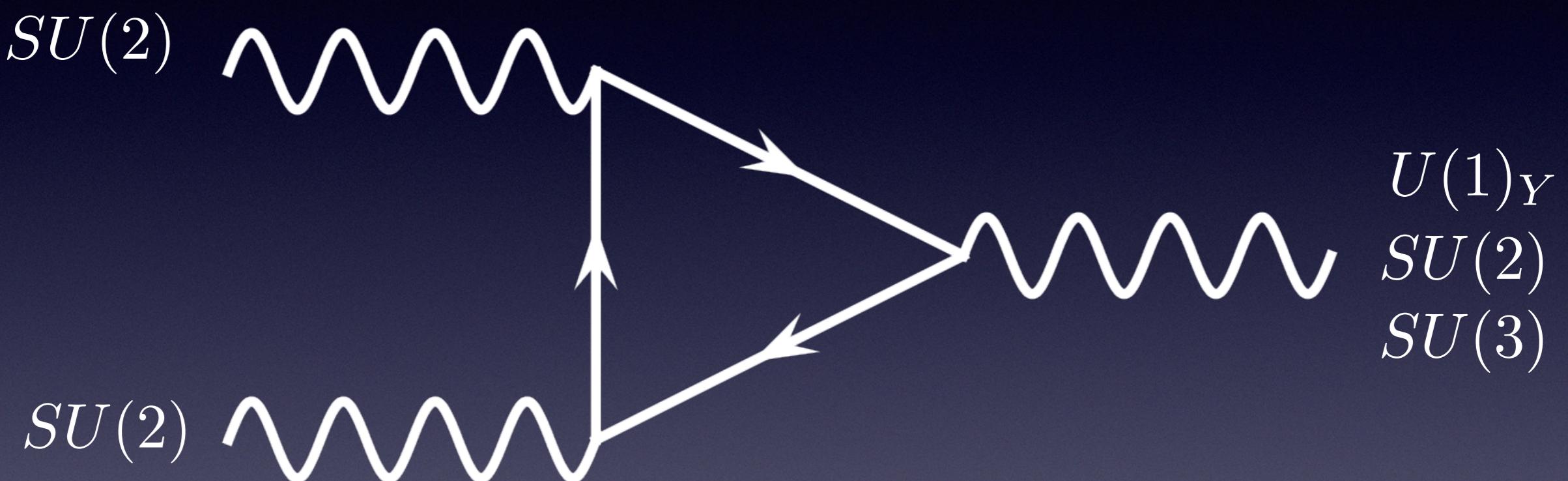


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

幺正性被放宽  $\longrightarrow V_{tb} < 1$

# 为何引入一整代费米子？

手征性费米子 —— 规范反常问题



标准模型中每一代费米子都消除规范反常

# 矢量型夸克

## □ Chiral doublet

$$-\mathcal{L}_Q = Y_U^{ij} \bar{Q}_L \tilde{\Phi} U_R + Y_D^{ij} \bar{Q}_L \Phi D_R + h.c.$$

## □ SU(2) doublet

$$-\mathcal{L}_Q = Y_t \overline{q_{0L}} \tilde{\Phi} t_{0R} + Y_T \overline{Q_{0L}} \tilde{\Phi} t_{0R} + Y_B \overline{Q_{0L}} \Phi b_{0R} + M \overline{Q_{0L}} Q_{0R} + \text{H.c.}$$

$$-\mathcal{L}_{Q'} = Y_t \overline{q_{0L}} \tilde{\Phi} t_{0R} + Y_T \overline{Q'_{0L}} \Phi t_{0R} + M \overline{Q'_{0L}} Q'_{0R} + \text{H.c.}$$

$$Q_{0L} = \begin{pmatrix} T_{0L} \\ B_{0L} \end{pmatrix}, Q_{0R} = \begin{pmatrix} T_{0R} \\ B_{0R} \end{pmatrix} \quad Q'_{0L} = \begin{pmatrix} X_{0L} \\ T_{0L} \end{pmatrix}, Q'_{0R} = \begin{pmatrix} X_{0R} \\ T_{0R} \end{pmatrix}$$

## □ SU(2) triplet

**Exotic Q=5/3 fermion**

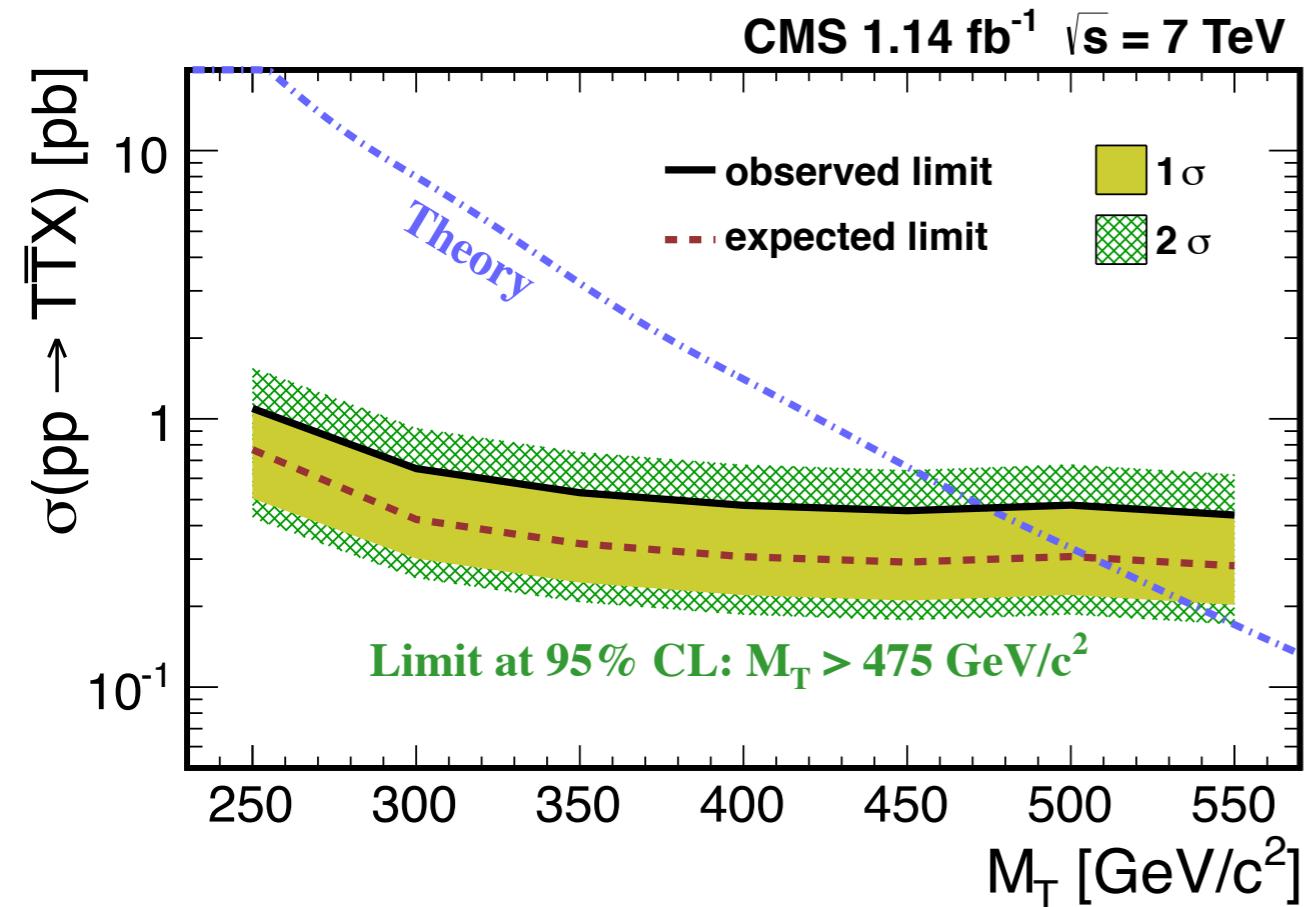
$$-\mathcal{L}_\Sigma = Y_t \overline{q_{0L}} \tilde{\Phi} t_{0R} + Y_T \overline{q_{0L}} \tau^a \tilde{\Phi} \Sigma_{0R} + M \overline{\Sigma_{0L}} \Sigma_{0R} + \text{H.c.}$$

$$-\mathcal{L}_{\Sigma'} = Y_t \overline{q_{0L}} \tilde{\Phi} t_{0R} + Y_T \overline{q_{0L}} \tau^a \Phi \Sigma'_{0R} + M \overline{\Sigma'_{0L}} \Sigma'_{0R} + \text{H.c.}$$

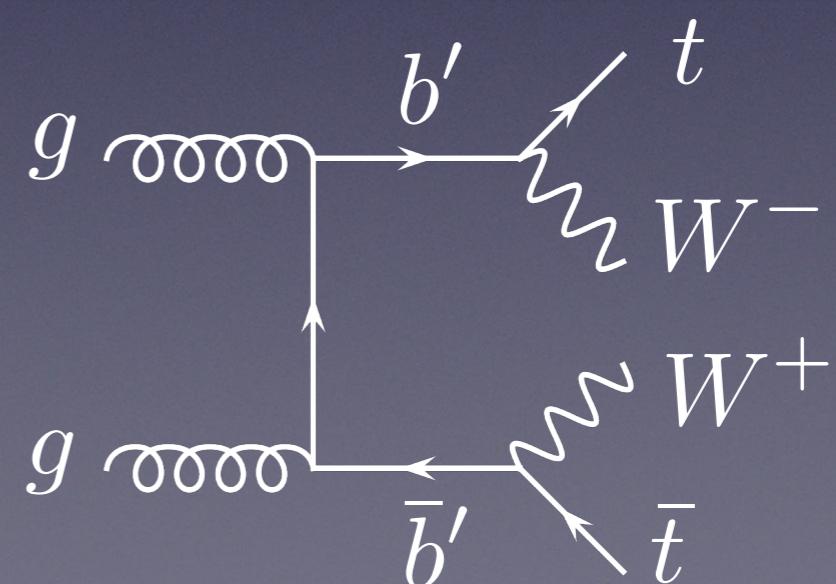
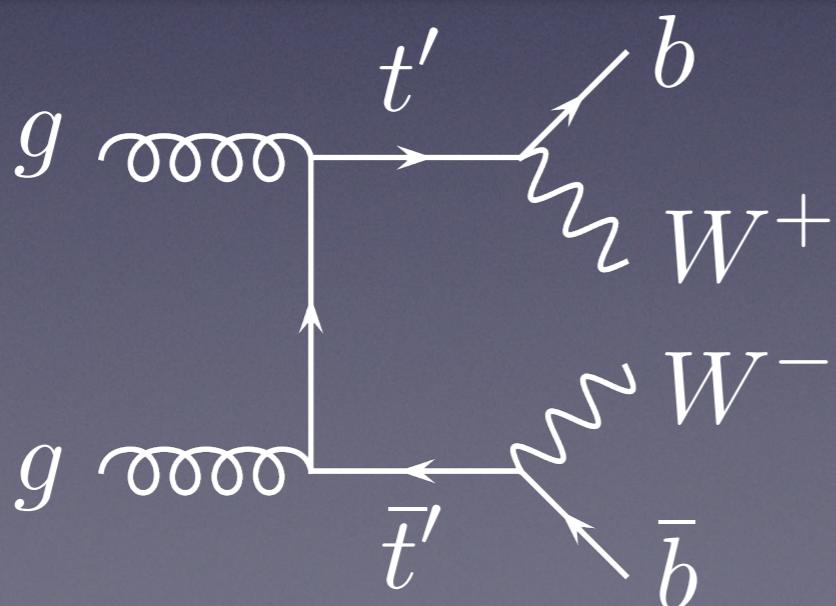
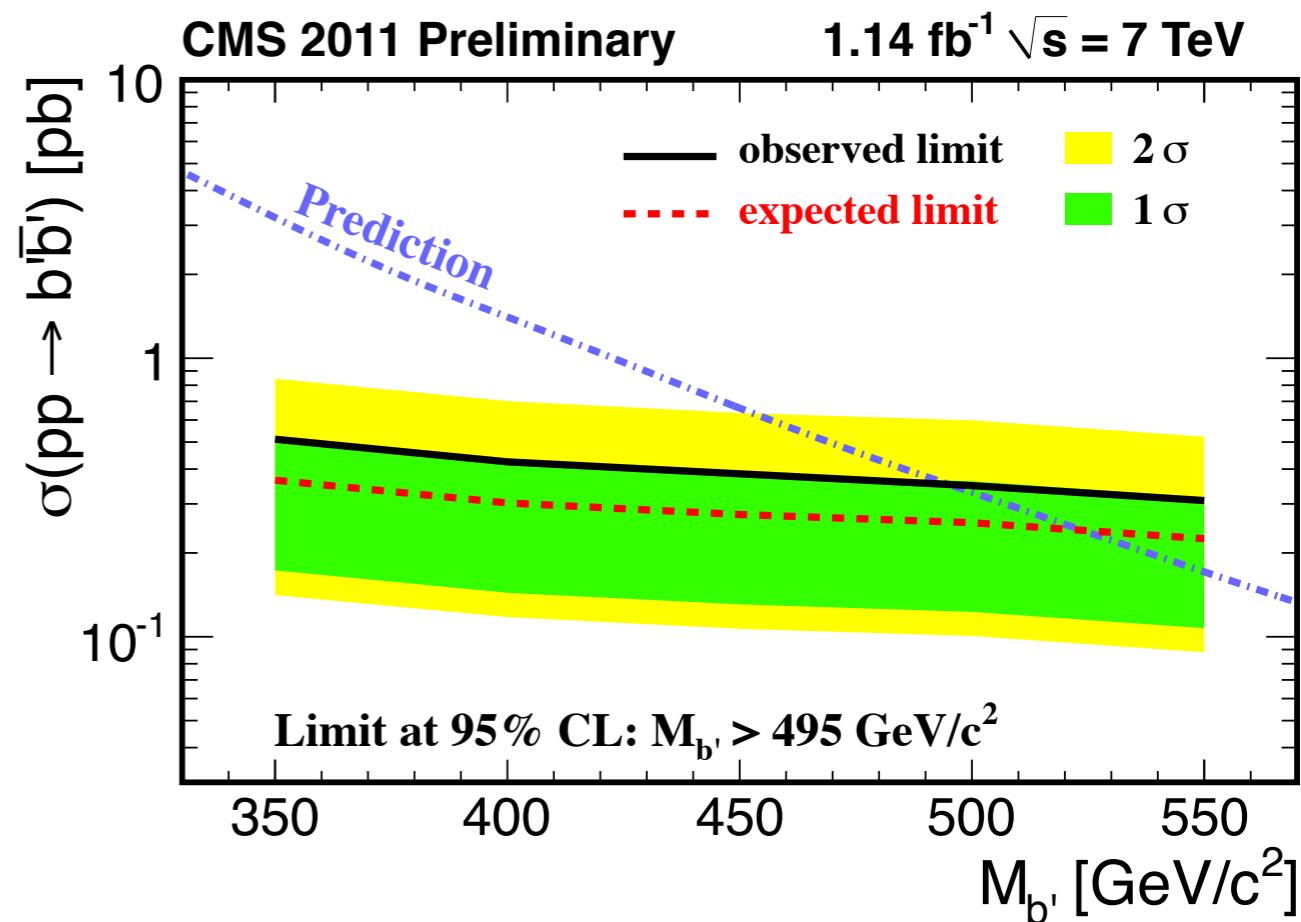
$$\Sigma_{0L} = \begin{pmatrix} X_{0L} \\ T_{0L} \\ B_{0L} \end{pmatrix}, \Sigma_{0R} = \begin{pmatrix} X_{0R} \\ T_{0R} \\ B_{0R} \end{pmatrix} \quad \Sigma'_{0L} = \begin{pmatrix} T_{0L} \\ B_{0L} \\ X_{0L} \end{pmatrix}, \Sigma'_{0R} = \begin{pmatrix} T_{0R} \\ B_{0R} \\ X_{0R} \end{pmatrix}$$

# 实验结果

$$t'\bar{t}' \rightarrow WbW\bar{b} \rightarrow \ell\nu b\bar{q}\bar{q}\bar{b}$$

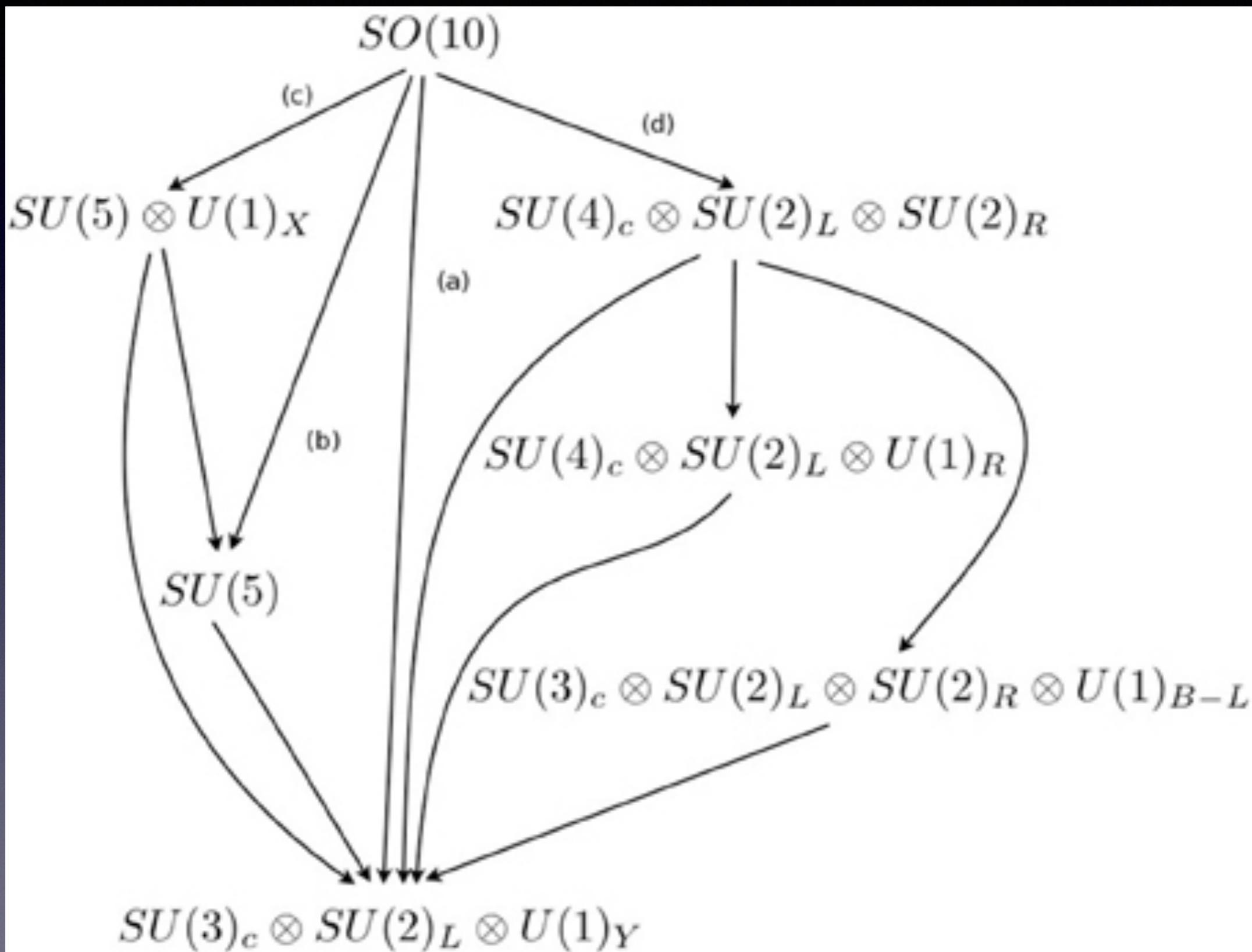


$$b'\bar{b}' \rightarrow tW^- \bar{t}W^+$$



# 4. 新规范玻色子

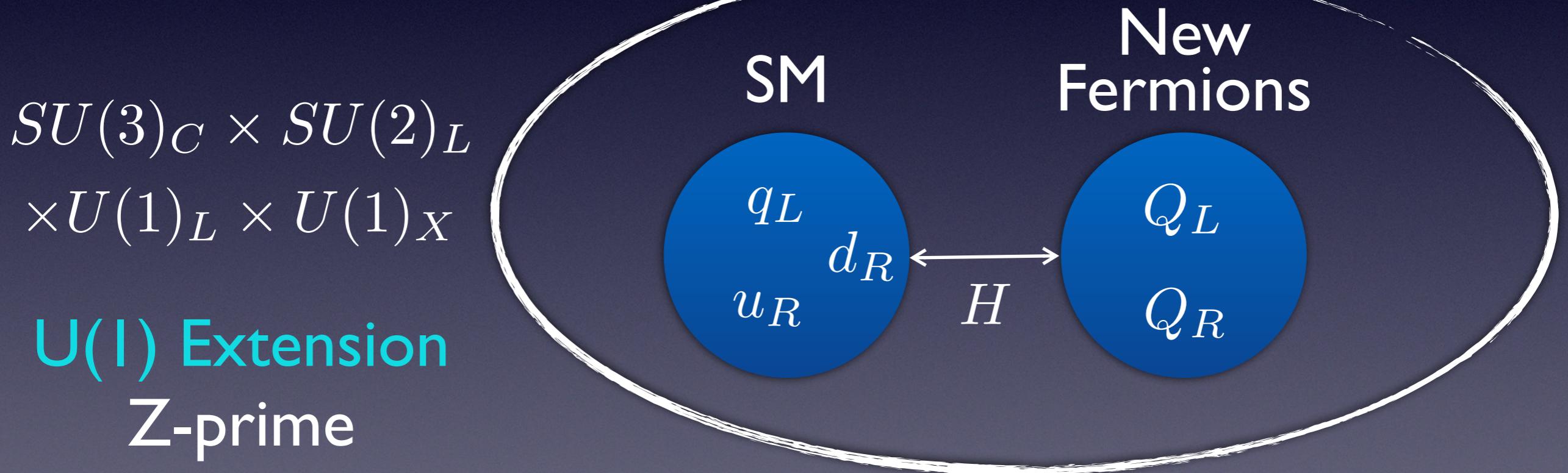
# 大统一理论的破缺



# 额外的“力”

G(221) Model

$$SU(3)_C \times SU(2)_1 \times SU(2)_2 \times U(1)_X$$



G(331) Model

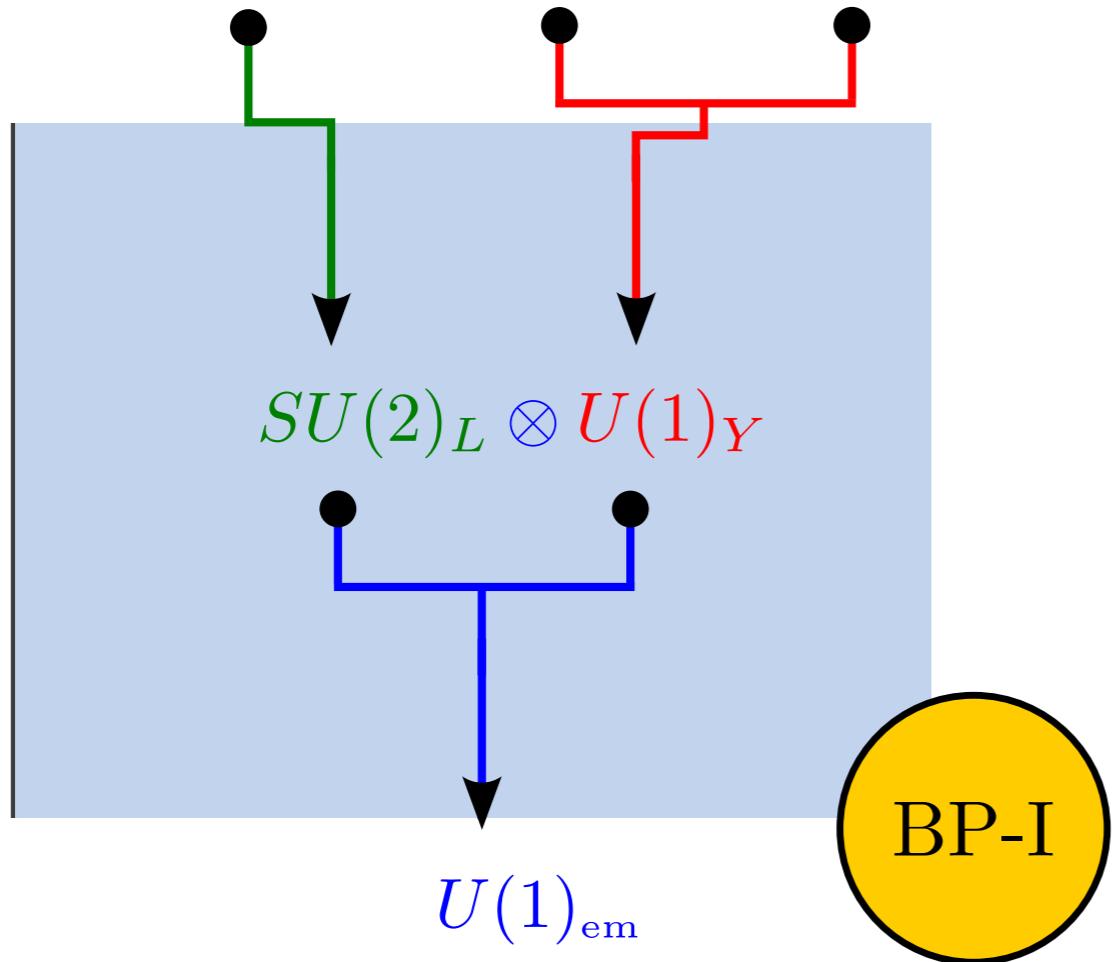
$$SU(3)_C \times SU(3)_W \times U(1)_X$$

$$SU(3)_C \otimes SU(2)_1 \otimes SU(2)_2 \otimes U(1)_X$$

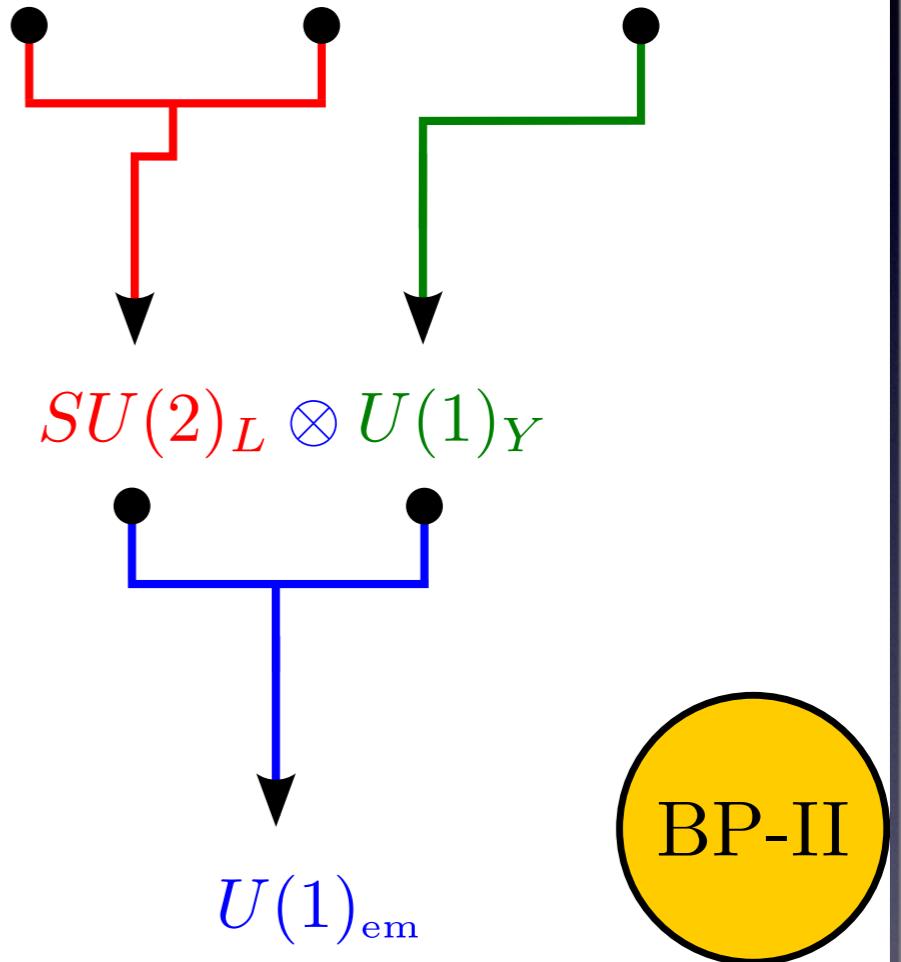
Model	$SU(2)_1$	$SU(2)_2$	$U(1)_X$
Left-right (LR)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}, \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $-\frac{1}{2}$ for leptons.
Lepto-phobic (LP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $Y_{\text{SM}}$ for leptons.
Hadro-phobic (HP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$Y_{\text{SM}}$ for quarks, $-\frac{1}{2}$ for leptons.
Fermio-phobic (FP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$		$Y_{\text{SM}}$ for all fermions.
Un-unified (UU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$Y_{\text{SM}}$ for all fermions.
Non-universal (NU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{1^{\text{st}}, 2^{\text{nd}}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{1^{\text{st}}, 2^{\text{nd}}}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{3^{\text{rd}}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{3^{\text{rd}}}$	$Y_{\text{SM}}$ for all fermions.

$$SU(3)_C \otimes SU(2)_1 \otimes SU(2)_2 \otimes U(1)_X$$

$$SU(2)_1 \otimes SU(2)_2 \otimes U(1)_X$$



$$SU(2)_1 \otimes SU(2)_2 \otimes U(1)_X$$



$$SU(3)_C \otimes SU(3)_W \otimes U(1)_X$$

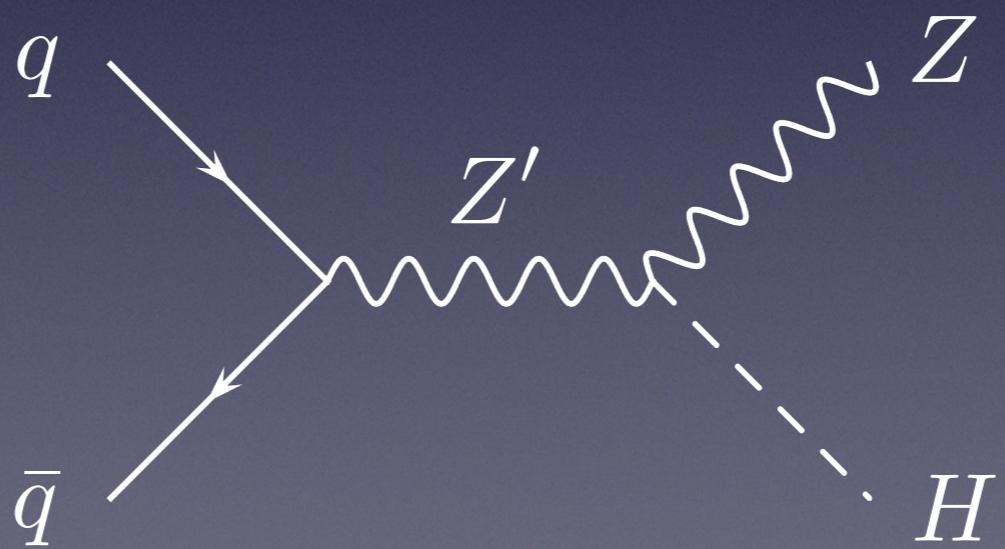
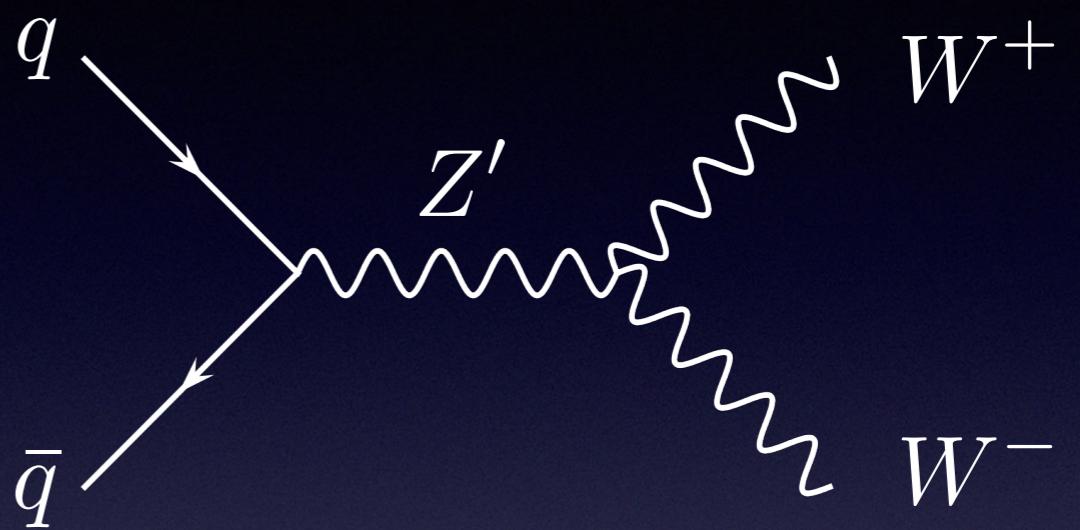
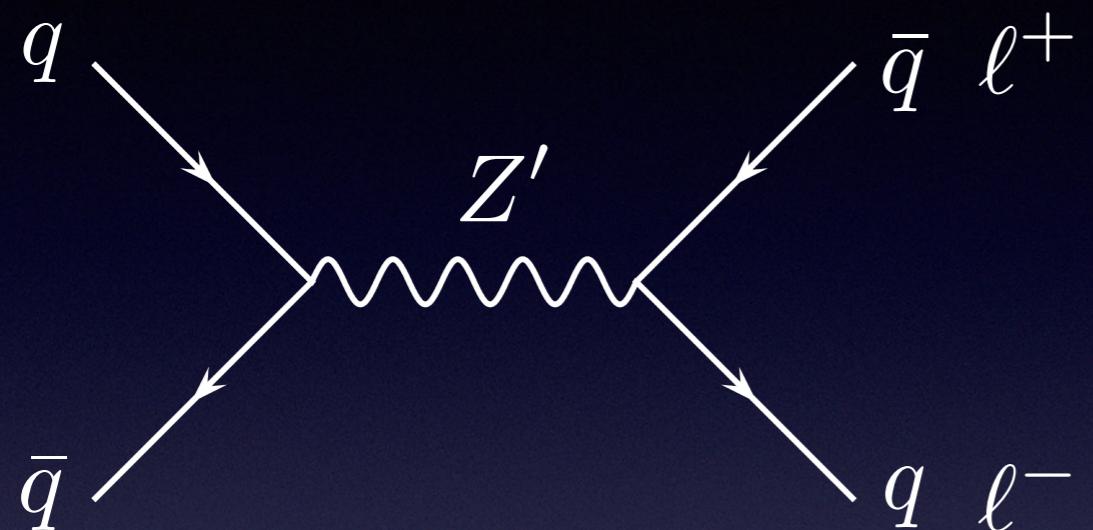
$$SU(3) \times U(1)_X \xrightarrow{H_1} SU(2)_L \times U(1)_Y \xrightarrow{H_2} U(1)_{\text{em}}$$

$$\begin{array}{ccc} \begin{pmatrix} u \\ d \\ D \end{pmatrix} & \begin{pmatrix} c \\ s \\ S \end{pmatrix} & \begin{pmatrix} b \\ -t \\ T \end{pmatrix} \\ 3 & 3 & \overline{3} \end{array}$$

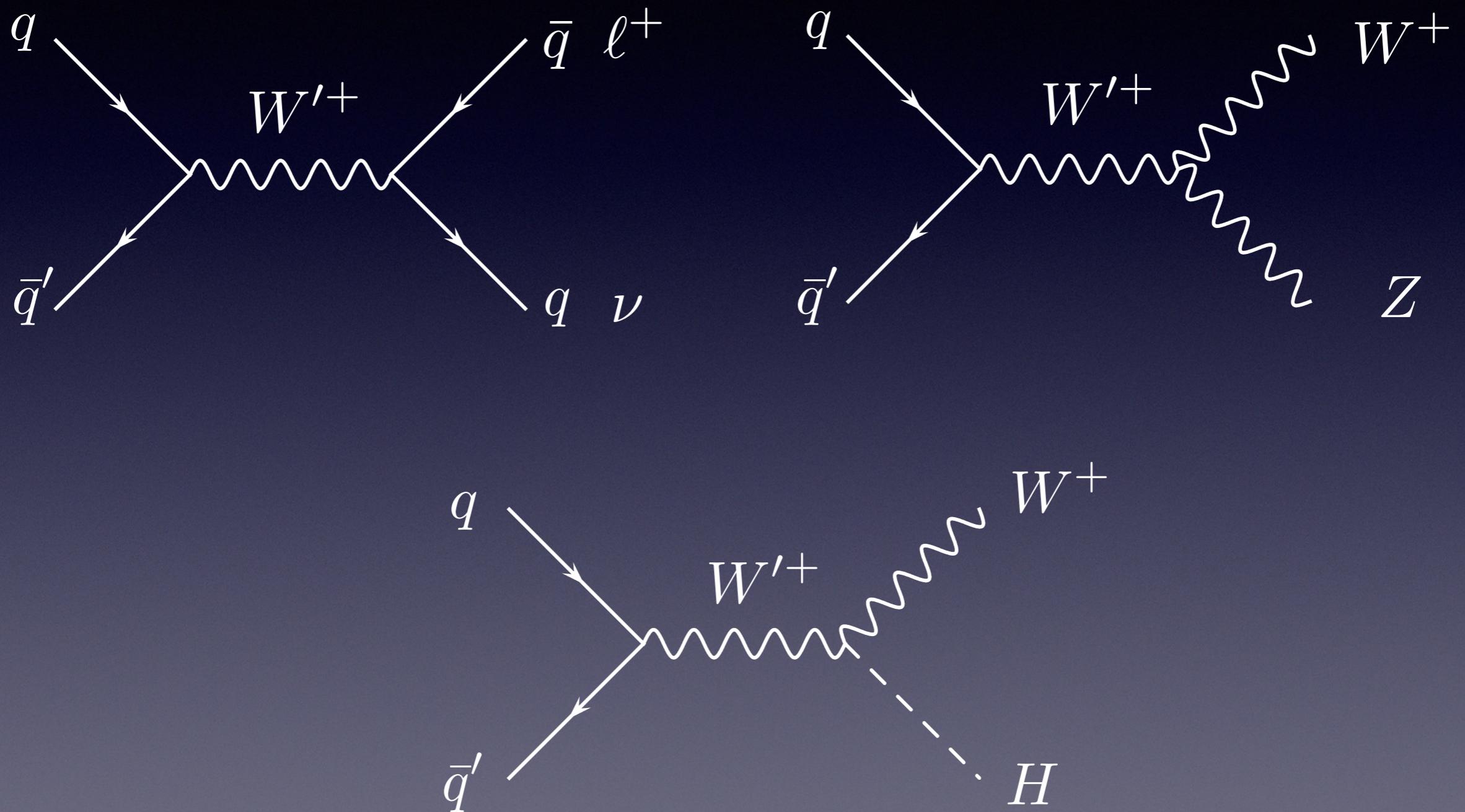
$$\langle \rho \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_\rho \\ 0 \end{pmatrix} \quad \langle \eta \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_\eta \\ 0 \\ 0 \end{pmatrix} \quad \langle \chi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ v_\chi \end{pmatrix}$$

规范反常相消要求有三代费米子，  
第1代+第2代的反常之和抵消第3代反常

# Z-prime产生和衰变



# W-prime产生和衰变



# 新胶子

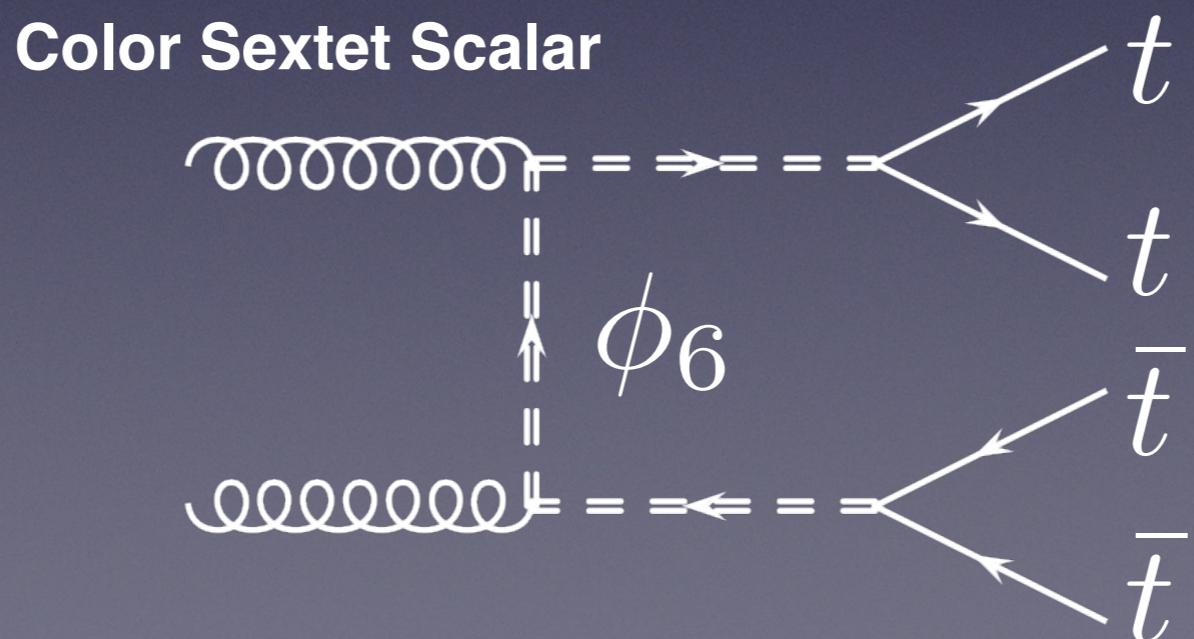
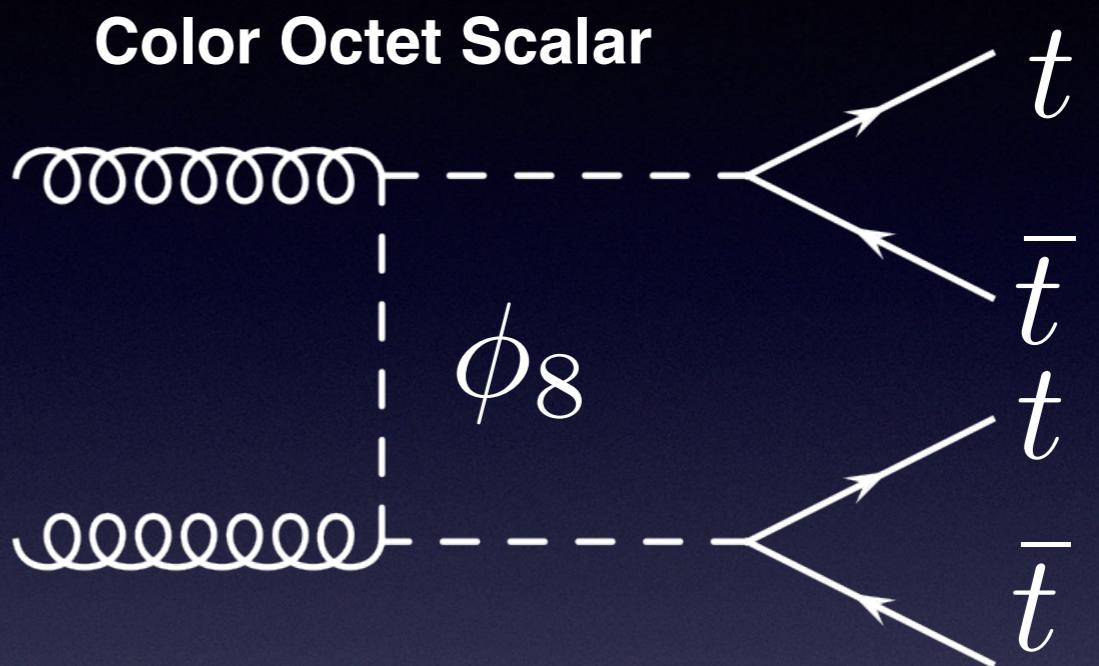
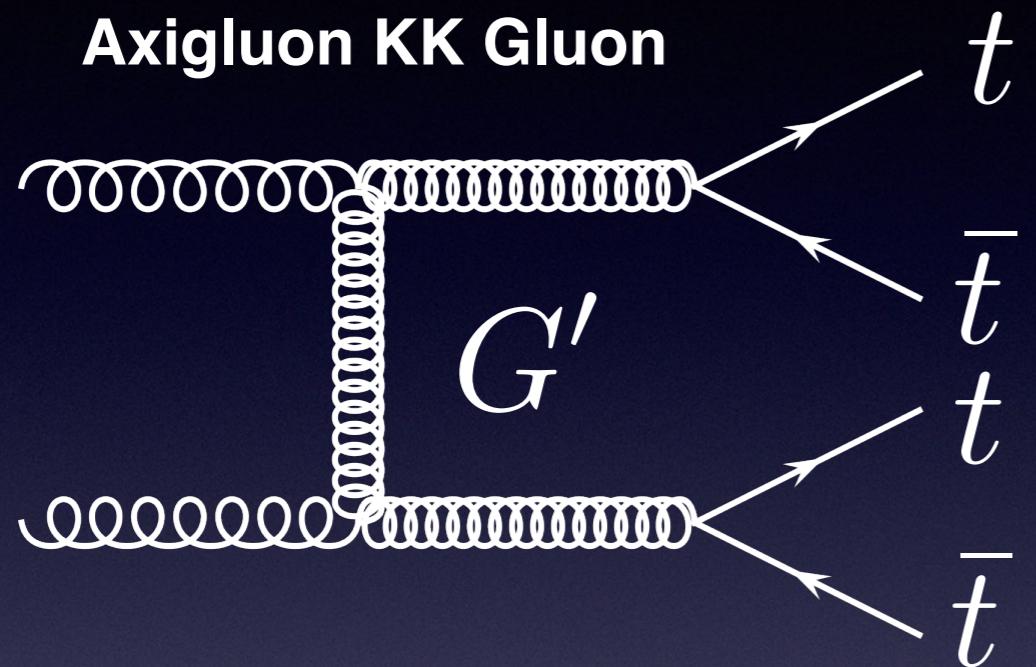
$$SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_C$$

$q=u,d,c,s$

Model	$SU(3)_1$	$SU(3)_2$	
Classic Axigluon	$t_R \ b_R \ q_R$	$q_L \ (t, b)_L$	dijet, AFB(t)
Frampton, Glashow (1987)			
New Axigluon	$q_L \ t_R \ b_R$	$(t, b)_L \ q_R$	dijet, AFB(t)
Frampton, Shu, Wang (2010)			
Topgluon	$q_L \ q_R$	$(t, b)_L \ t_R \ b_R$	dijet, FCNC
Hill (1991)			

对称性破缺要求：额外的带色标量粒子

# 色标量粒子产生和衰变



总结



为什么希格斯粒子质量为 $125\text{GeV}$ ?  
费米子和玻色子质量起源是否相同?  
大CP破坏产生机制?  
为何仅有3代夸克和轻子?  
是否有4代物质场粒子?  
能否把自然界中所有力统一?  
是否存在新相互作用?  
夸克和轻子是否有内部结构?  
暗物质的内禀属性及其相互作用?  
什么是暗能量?  
是否有额外的空间维度?  
.....



生逢其时，何其幸也！