W质量、缪子反常磁矩和新物理

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Outline

0 Introduction

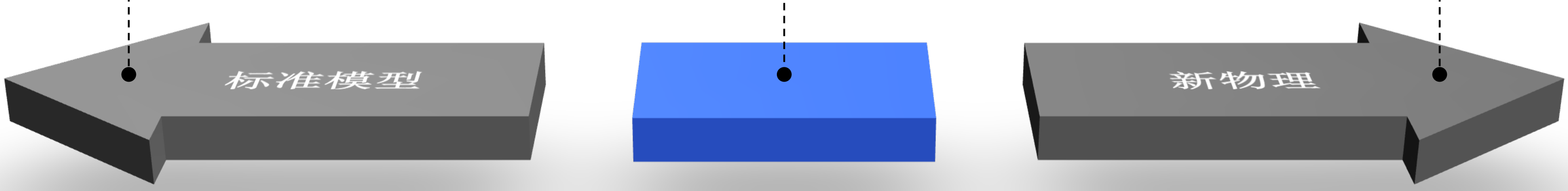
希 格 斯 粒 子 发 现 之 后

高能物理的主要目标

（后 希 格 斯 时 代）

精确检验希格
斯粒子的性质

探索超出标准
模型的新物理



Physics thrives on crisis. We all recall the great progress made while finding a way out of the various crises of the past.

Steven Weinberg

Rev. Mod. Phys. 61,1(1989)

目前有没有实验上的crisis？

muon g-2

flavor

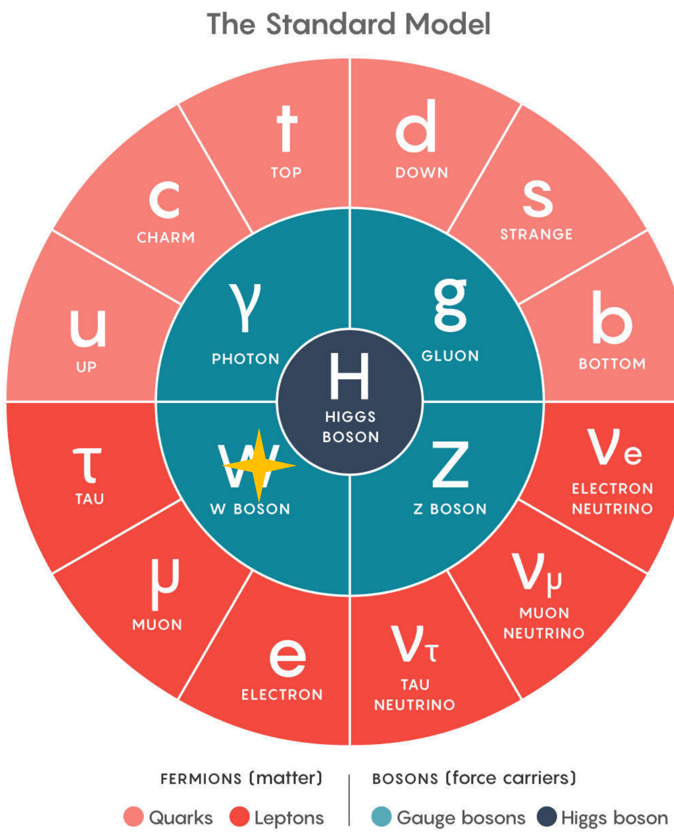
（最近LHCb文章2212.09152否定了其之前发现的R_K 和R_{K^*} 的反常）

W-mass

dark matter

1 W-mass anomaly

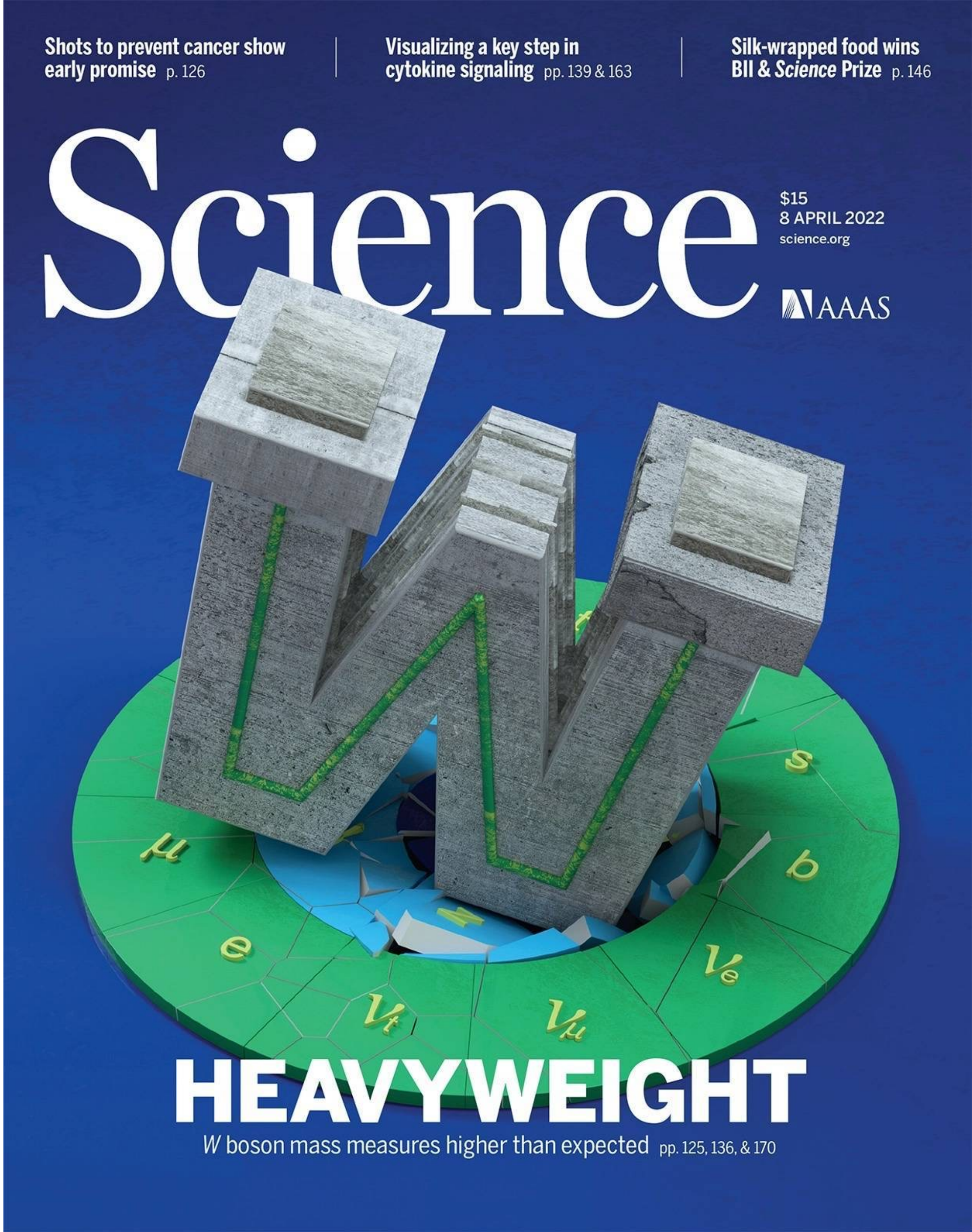
1.1 W-mass measurement



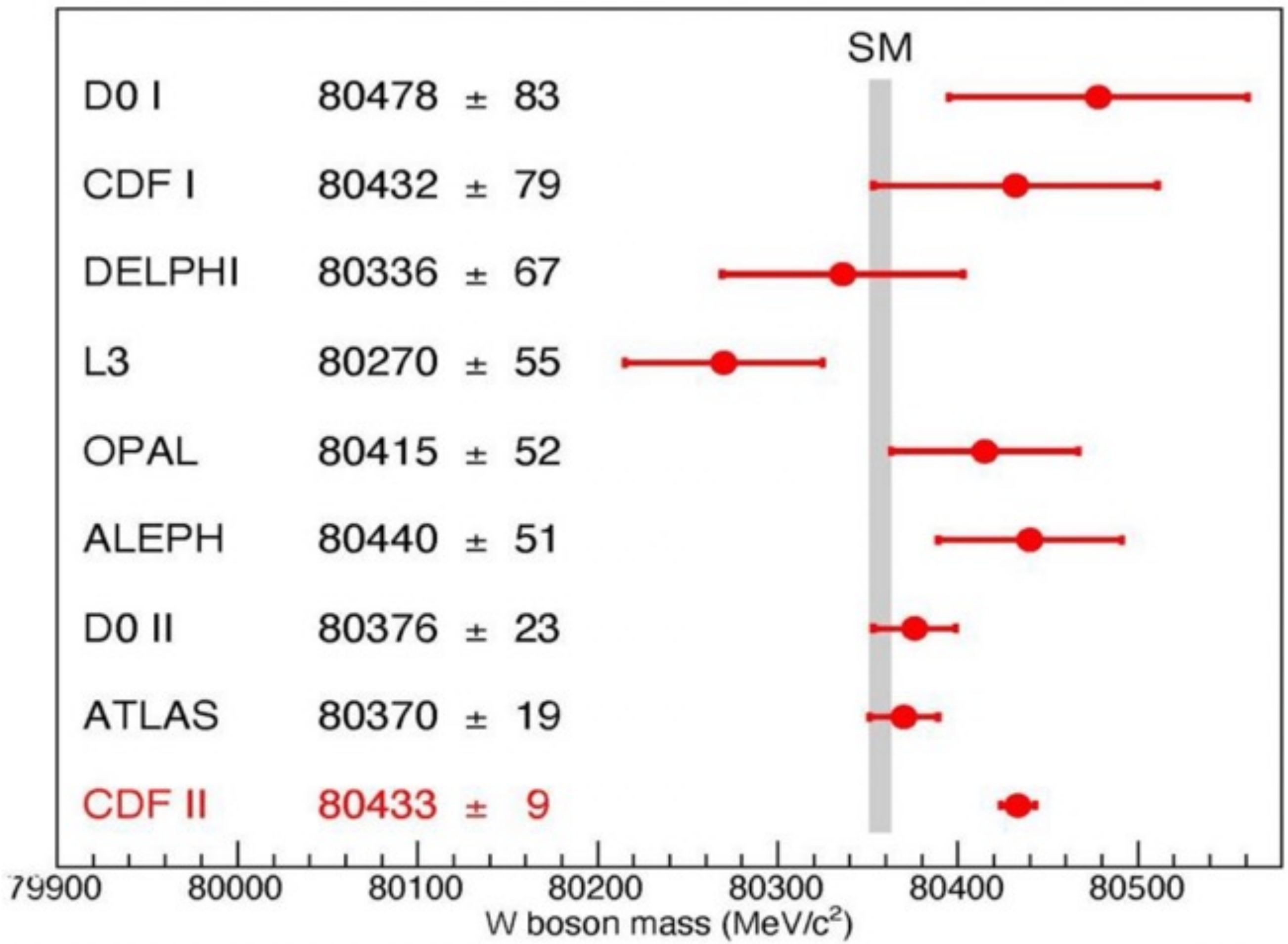
2022年4月8日

《科学》封面

作者有近400位 CDF II合作组



测量W玻色子质量



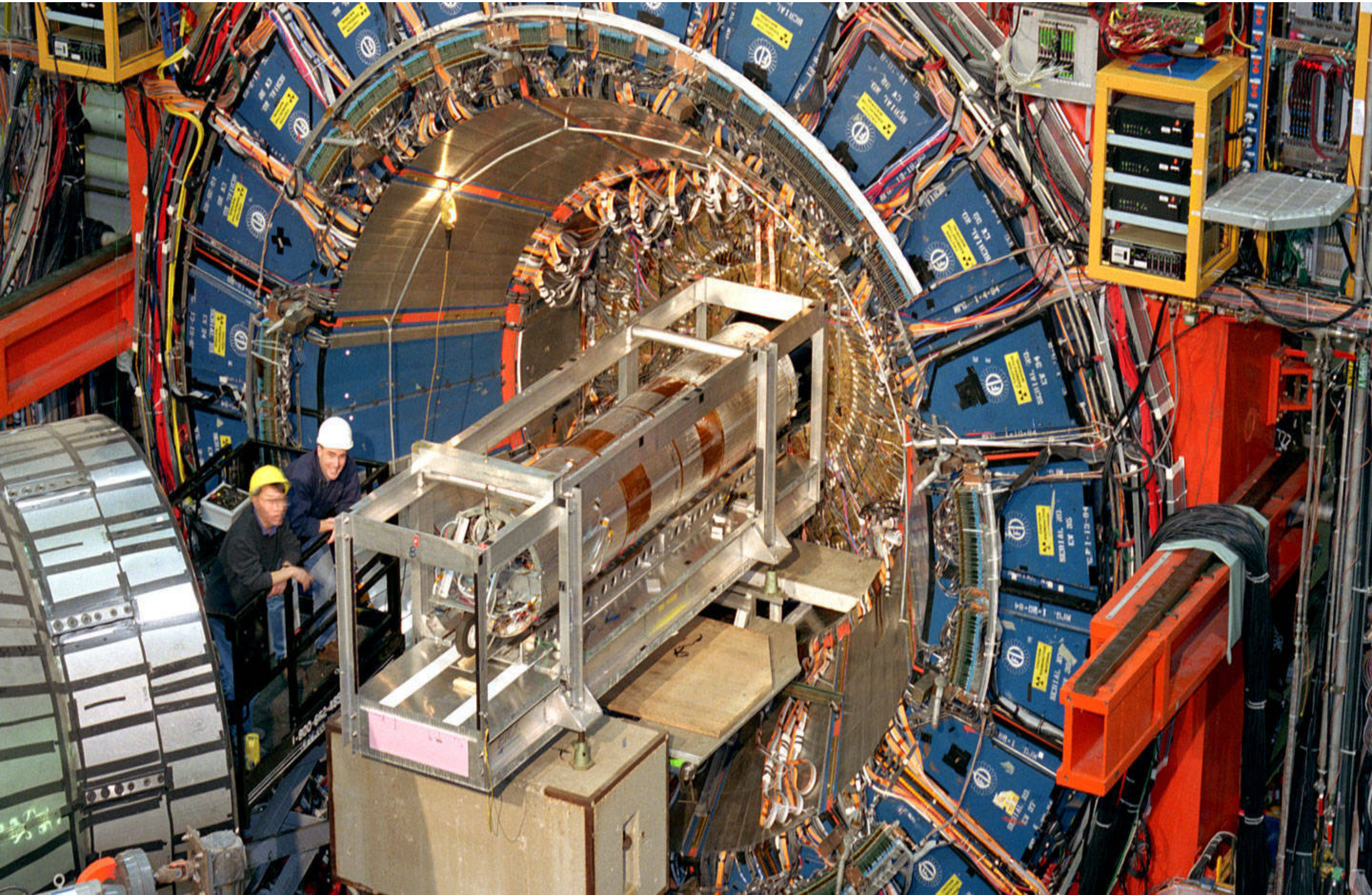
- 欧洲核子中心CERN的大型正负电子对撞机LEP上的实验组（ALEPH、DELPHI、L3、OPAL）和大型强子对撞机LHC上的实验组（ATLAS、LHCb）
- 美国费米实验室的质子-反质子对撞机Tevatron上的实验组（CDF、D0）

标准模型预期的W玻色子质量应为 80357+/-6MeV

此次测量结果显示其质量测量值为 80434+/-9MeV

CDF II合作组的W玻色子质量的测量达到了前所未有的精度—0.01%

费米实验室Tevatron对撞机上的探测器(CDF) （Collider Detector at Fermilab）



美国费米实验室的Tevatron对撞机是LHC之前的最高能量对撞机（1985-2011）

Tevatron把质子和反质子加速到它们的静止质量的1000倍，然后对撞，大量产生的各种粒子包括W玻色子

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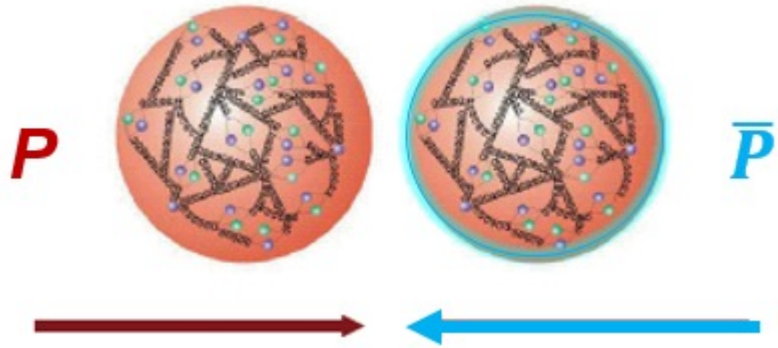
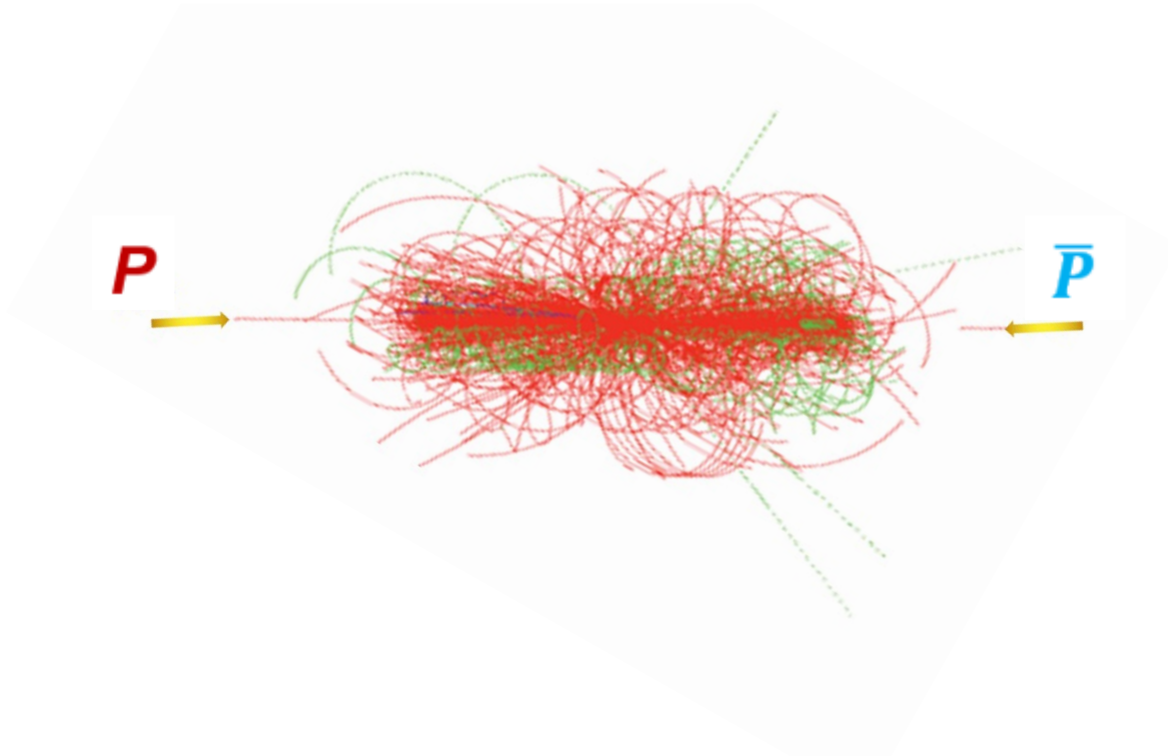




费米实验室的Tevatron对撞机（1985-2011）

在2011年停止运行之后，CDF合作组中Ashutosh Kotwal领导的小组（400名科学家）继续对数据进行细致深入分析，十年磨一剑，最终将论文发表出来

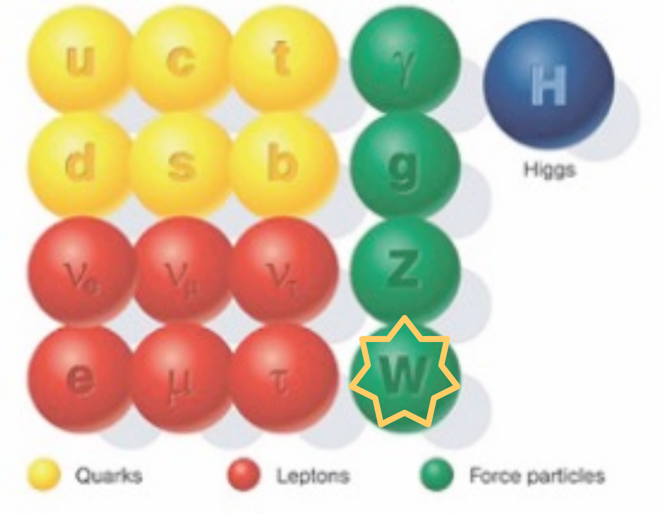
- CDF这项结果目前只是一个实验的结果，尚需别的实验验证
- 它与目前世界上第二精确的测量即ATLAS实验的测量结果也不一致

易凯教授（南京师大）

1.2 W-mass in the SM

- 标准模型

$$SU(3) \times SU(2) \times U(1)$$



$$\underbrace{SU(3)_{\text{Color}}}_{\text{QCD}} \otimes \underbrace{SU(2)_{\text{Left}} \otimes U(1)_{\text{Hyper charge}}}_{\text{WEAK} \oplus \text{QED}}$$

(Unification of Weak and Electromagnetic)

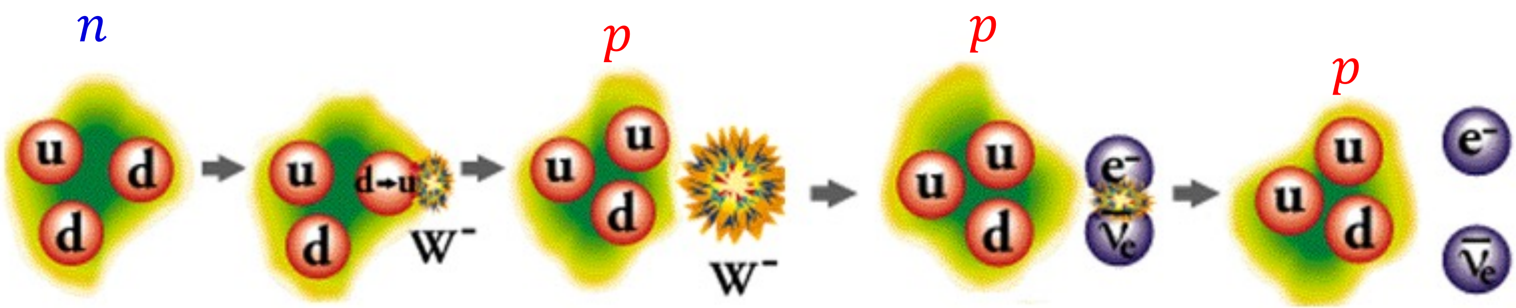
Spontaneously Broken
(Higgs Mechanism)

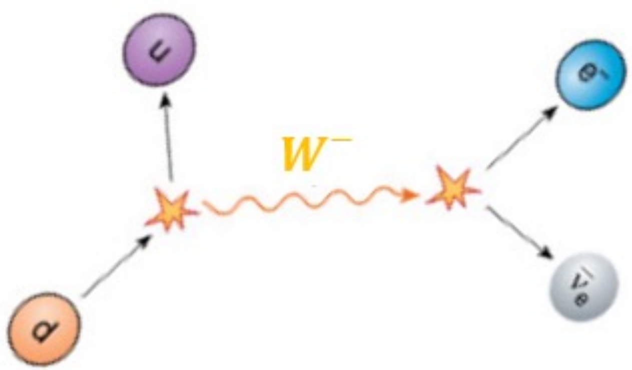
↓

$$U(1)_{\text{E.M.}}$$

QED
(Electromagnetic Interaction)

W粒子传递弱作用





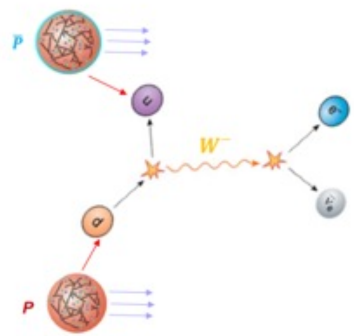
W粒子的发现

The **UA1 experiment** (an abbreviation of **Underground Area 1**) was a high-energy physics experiment that ran at CERN's Proton-Antiproton Collider (**SppS**), a modification of the one-beam Super Proton Synchrotron (**SPS**). The data was recorded between 1981 and 1990. The joint discovery of the W and Z bosons by this experiment and the UA2 experiment in 1983 led to the Nobel Prize for physics being awarded to Carlo Rubbia and Simon van der Meer in 1984.

Volume 122B, number 1 PHYSICS LETTERS 24 February 1983

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland



- 卡洛·鲁比亚和西蒙·范德梅尔在1983年一月进行的一连串实验给出了明显的W粒子证据,这些实验称作UA 1和 UA 2
- UA 1和UA 2在几个月后的1983年五月找到Z粒子
- 很快地鲁比亚和范德梅尔因此迅速得到了1984年的诺贝尔物理学奖

Exp:

The result of a fit on electron angle and energy and neutrino transverse energy with allowance for systematic errors, is

$$m_W = (81^{+5}_{-5})\ \mathrm{GeV}/c^2 ,$$

in excellent agreement with the expectation of the Weinberg–Salam model [2].

Th:

Properties of IVBs become better specified within the theoretical frame of the unified weak and electromagnetic theory and of the Weinberg–Salam model [2]. The mass of the IVB is precisely predicted [3]:

$$M_{W\pm} = (82 \pm 2.4)\ \mathrm{GeV}/c^2$$

W粒子的来源和其质量来源

The gauge group is $SU(2) \times U(1)$

with gauge bosons $\vec{A}_\mu$ and B_μ

$$L_1 = -\frac{1}{4} F^i_{\mu\nu} F^{i\mu\nu} - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$

$$F^i_{\mu\nu} = \partial_\mu A^i_\nu - \partial_\nu A^i_\mu + g\varepsilon^{ijk} A^j_\mu A^k_\nu$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\nu$$

gauge coupling for the $SU(2)$ group

W粒子的来源和其质量来源

scalar fields is $SU(2)$ doublet $\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$, $Y = 1/2$

$Q = T_3 + Y$

Lagrangian containing ϕ is

$$L_2 = \left(D_\mu \phi\right)^\dagger \left(D^\mu \phi\right) - V(\phi)$$

$$V(\phi) = -\mu^2 \left(\phi^\dagger \phi\right) + \lambda \left(\phi^\dagger \phi\right)^2$$

$$D_\mu \equiv \partial_\mu - igt^a A_\mu^a - ig' Y B_\mu$$

W粒子的来源和其质量来源

$$V(\phi) = -\mu^2\left(\phi^\dagger\phi\right) + \lambda\left(\phi^\dagger\phi\right)^2$$

$$\langle\phi\rangle_0 \equiv \langle 0\,|\phi|\,0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad v = \sqrt{\frac{\mu^2}{\lambda}}$$

Write the scalar fields

Goldstone bosons

$$\phi = \begin{pmatrix} iG^+ \\ \frac{v+h-iG^0}{\sqrt{2}} \end{pmatrix} = e^{i\frac{\vec{\sigma}\cdot\vec{\chi}}{v}}\begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

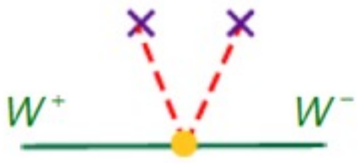
use the gauge transformation to remove $e^{i\frac{\vec{\sigma}\cdot\vec{\chi}}{v}}$

$$\phi \longrightarrow \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

called Higgs field

W粒子的来源和其质量来源

$$D_\mu = \partial_\mu - igW_\mu^a \frac{\sigma^a}{2} - ig' Y B_\mu$$



$$\Rightarrow \quad M_W = \frac{1}{2} g v$$

$$D_\mu \phi = D_\mu \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

$$= \begin{pmatrix} 0 \\ \frac{\partial_\mu h}{\sqrt{2}} \end{pmatrix} - \frac{i}{\sqrt{2}} \left[\frac{g}{2} \begin{pmatrix} W_\mu^3 & W_\mu^1 - iW_\mu^2 \\ W_\mu^1 + iW_\mu^2 & -W_\mu^3 \end{pmatrix} + \frac{g'}{2} B_\mu \right] \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$= \begin{pmatrix} 0 \\ \frac{\partial_\mu h}{\sqrt{2}} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} g W_\mu^+ \\ \frac{-1}{\sqrt{2}} \sqrt{g^2 + g'^2} Z_\mu \end{pmatrix} (v+h)$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp i W_\mu^2) \qquad \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} c_W & -s_W \\ s_W & c_W \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix}$$

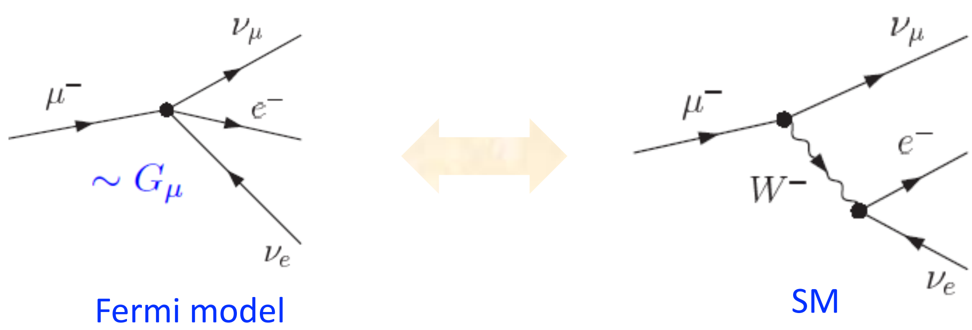
$$(D_\mu \phi)^\dagger (D_\mu \phi) = \frac{1}{2} (\partial_\mu h)(\partial^\mu h)$$

$$+ \left[\left(\frac{gv}{2} \right)^2 W_\mu^+ W^{-\mu} + \frac{1}{2} \frac{(g^2 + g'^2) v^2}{4} Z_\mu Z^\mu \right] (1 + \frac{h}{v})^2$$

$$= \frac{1}{2} (\partial_\mu h)(\partial^\mu h) + \left[M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu \right] (1 + \frac{h}{v})^2$$

Georg Weiglein, Seminar, Nanjing Normal University 04 / 2022

W粒子的来源和其质量来源



$$M_{\mathrm{W}}^2\left(1-\frac{M_{\mathrm{W}}^2}{M_{\mathrm{Z}}^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

⇕

loop corrections

$$\Delta r=\Delta\alpha-\frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho+\cdots$$

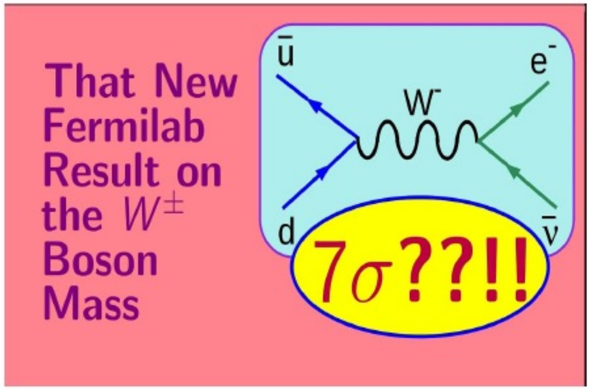
$$\delta M_W\simeq\frac{M_W}{2}\frac{\cos^2\theta_W}{\cos^2\theta_W-\sin^2\theta_W}\Delta\rho \qquad \Delta\rho=\frac{\Sigma^Z(0)}{M_Z^2}-\frac{\Sigma^W(0)}{M_W^2}$$

W粒子质量预言值与实验值的偏差

$$m_W^{\mathrm{SM}} = 80.357 \pm 0.006\ \mathrm{GeV}$$

$$m_W^{\mathrm{CDF}} = 80.4335 \pm 0.0094\ \mathrm{GeV}$$

Science, 2022, CDF Collaboration



1.3 Implication for new physics

究竟是不是新物理?

The W boson Mass and Muon $g-2$: Hadronic Uncertainties or New Physics?

Peter Athron (Nanjing Normal U.), Andrew Fowlie (Nanjing Normal U.), Chih-Ting Lu (Nanjing Normal U.), Lei Wu (Nanjing Normal U.), Yongcheng Wu (Nanjing Normal U.) et al. (Apr 8, 2022)

e-Print: 2204.03996 [hep-ph]

To appear in «Nature Communication»

超对称（SUSY）：

Science Bulletin 67 (2022) 1430–1436

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

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Science Bulletin

www.scibull.com

Article

Low energy SUSY confronted with new measurements of *W*-boson mass and muon $g-2$

Jin-Min Yang [b,c], Yang Zhang [a,b,*]

两个希格斯（2HDM）：

Chinese Physics C Vol. 46, No. 10 (2022) 103105

Joint explanation of *W*-mass and muon *g*–2 in the 2HDM*

Xiao-Fang Han(韩小芳)[1] Fei Wang(王飞)[2] Lei Wang(王磊)[1†] Jin-Min Yang(杨金民)[3,4] Yang Zhang(张阳)[2]

JHEP

Published for SISSA by Springer

Received: *April 25, 2022*
Revised: *September 16, 2022*
Accepted: *September 28, 2022*
Published: *October 7, 2022*

Electroweak phase transition in 2HDM under Higgs, Z-pole, and W precision measurements

Huayang Song,[c,1] Wei Su[a,b,2] and Mengchao Zhang[d,1]

暗物质模型：

Open Access

Inert Higgs Dark Matter for CDF II W-Boson Mass and Detection Prospects

Yi-Zhong Fan, Tian-Peng Tang, Yue-Lin Sming Tsai, and Lei Wu

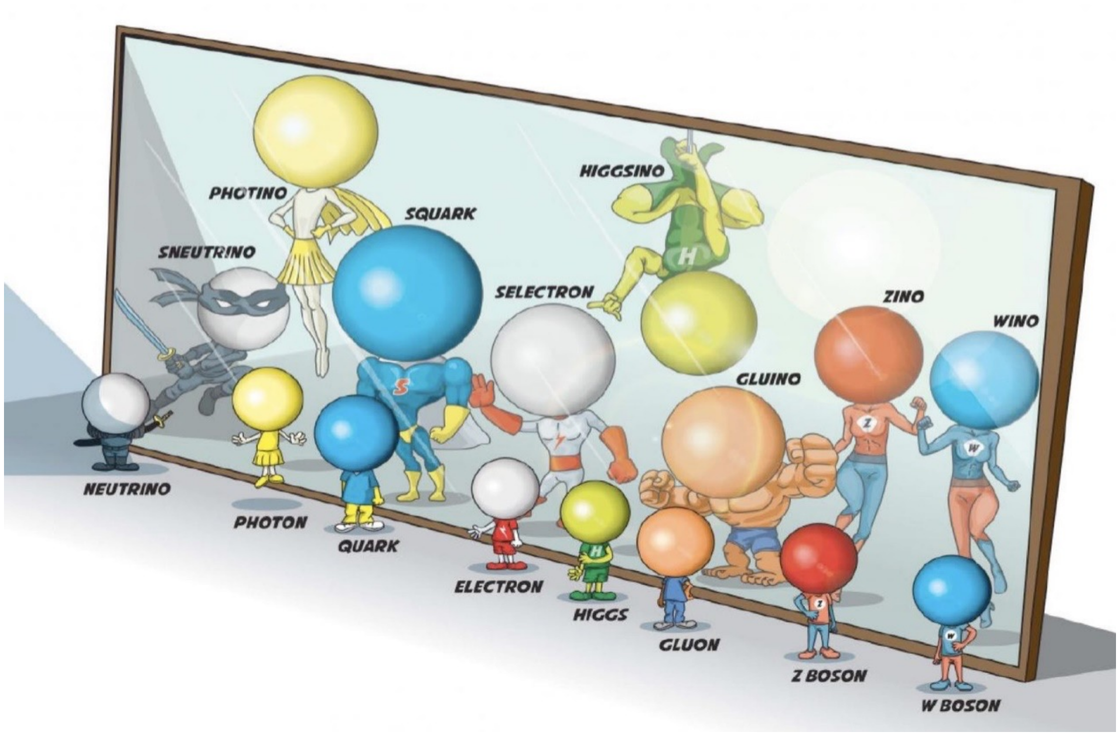
Phys. Rev. Lett. **129**, 091802 – Published 24 August 2022

例子：超对称理论

Low energy SUSY confronted with new measurements of W-boson mass and muon g-2

Jin Min Yang (Beijing, Inst. Theor. Phys. and Beijing, GUCAS), Yang Zhang (Zhengzhou U.) (Apr 8, 2022)

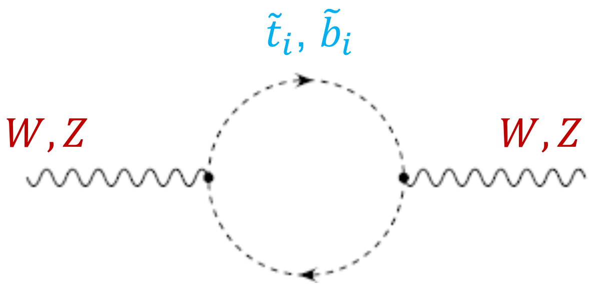
Published in: *Sci.Bull.* 67 (2022) 14, 1430-1436 • e-Print: 2204.04202 [hep-ph]

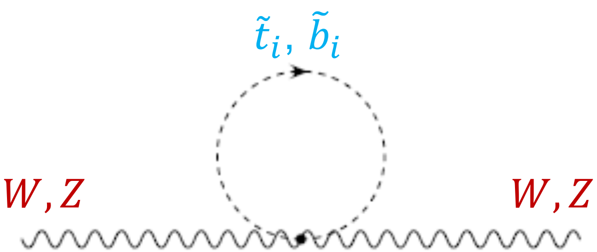


S. Heinemeyer, W. Hollik, G. Weiglein, hep-ph/0412214

W-mass in SUSY:

$$\delta M_W \simeq \frac{M_W}{2} \frac{\cos^2\theta_W}{\cos^2\theta_W - \sin^2\theta_W} \Delta\rho \qquad \Delta\rho = \frac{\Sigma^Z(0)}{M_Z^2} - \frac{\Sigma^W(0)}{M_W^2}$$





$$\Delta\rho_0^{\rm SUSY} = \frac{3G_F}{8\sqrt{2}\pi^2}\Big[-\sin^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{t}} F_0(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2) - \sin^2\theta_{\tilde{b}}\cos^2\theta_{\tilde{b}} F_0(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2)$$
$$+ \cos^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{b}} F_0(m_{\tilde{t}_1}^2, m_{\tilde{b}_1}^2) + \cos^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{b}} F_0(m_{\tilde{t}_1}^2, m_{\tilde{b}_2}^2)$$
$$+ \sin^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{b}} F_0(m_{\tilde{t}_2}^2, m_{\tilde{b}_1}^2) + \sin^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{b}} F_0(m_{\tilde{t}_2}^2, m_{\tilde{b}_2}^2)\Big]$$

Low energy SUSY confronted with new measurements of W-boson mass and muon g-2

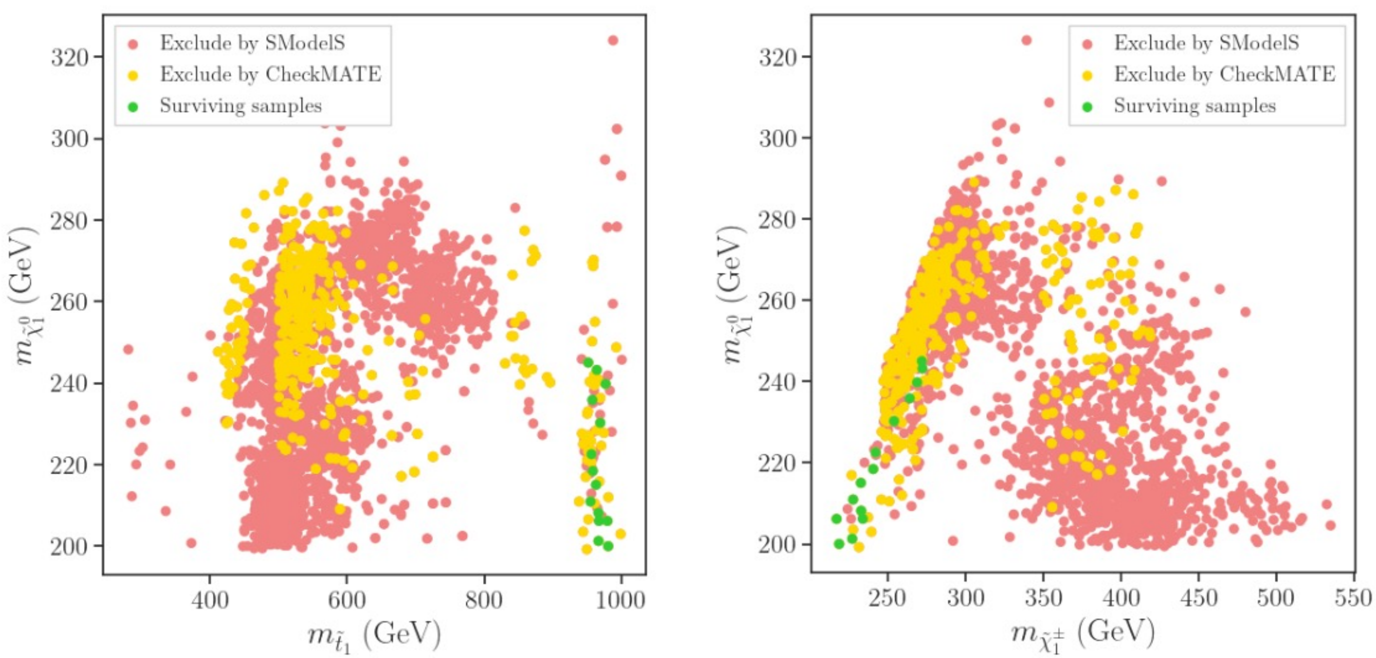
Jin Min Yang (Beijing, Inst. Theor. Phys. and Beijing, GUCAS), Yang Zhang (Zhengzhou U.) (Apr 8, 2022)

Published in: Sci.Bull. 67 (2022) 14, 1430-1436 • e-Print: 2204.04202 [hep-ph]

W质量来自超对称的贡献

(W-mass⊕muon g-2 ⊕ DM)

- In the parameter space allowed by current experimental constraints from colliders and dark matter detections, MSSM can simultaneously explain both measurements at 2σ level.
- The favored parameter space, characterized by a compressed spectrum between (bino, wino, stau), with top-squark around 1 TeV.



1.4 Summary

- CDF II的最新的W-质量测量结果目前只是一个实验的结果，尚需别的实验验证；
  它与目前世界上第二精确的测量LHC的ATLAS实验的测量结果也不一致

- 超对称等新物理可以解释CDF II的W-质量测量结果

  - light stop

    should be accessible at LHC

2 Muon g-2 anomaly

2.1 What is muon g-2

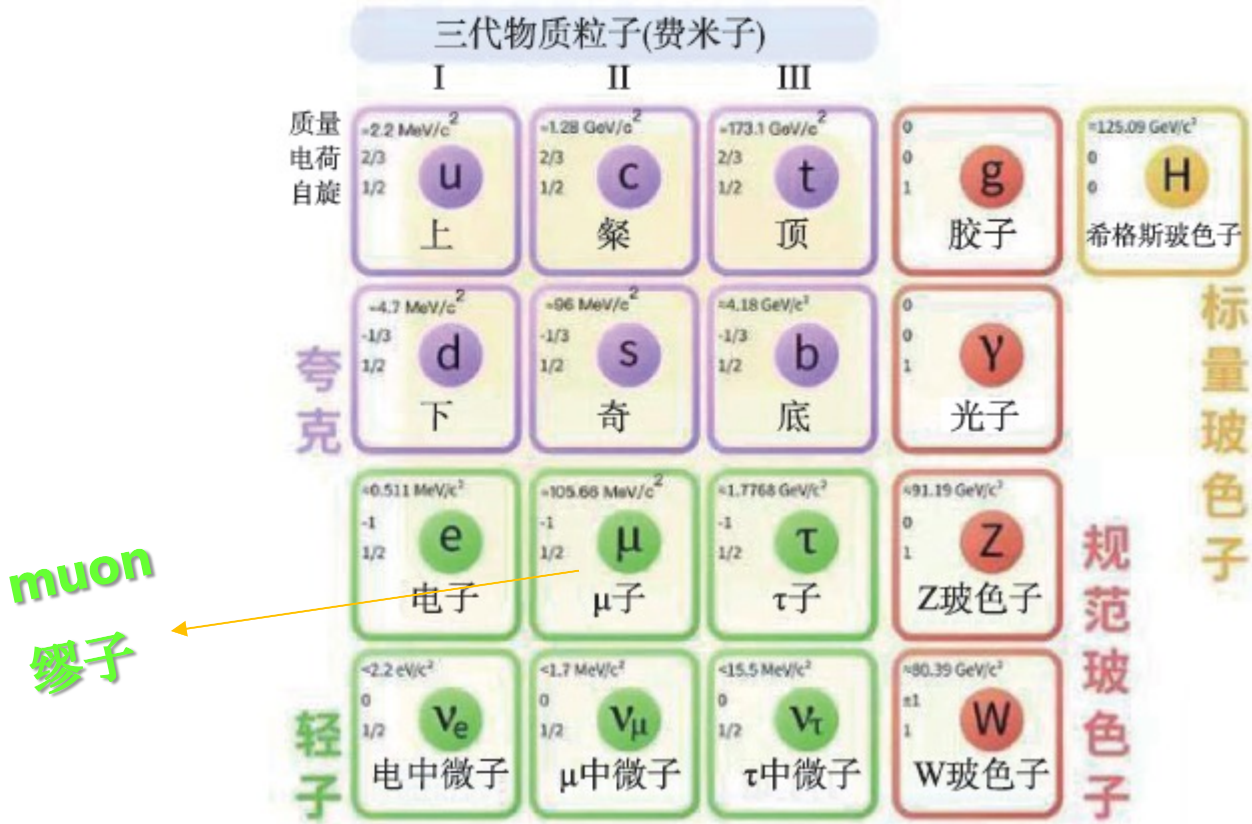
现代物理知识

缪子反常磁矩浅析

李 松 肖 洋 杨金民

（中国科学院理论物理研究所 100190; 中国科学院大学物理科学学院 100049）

粒子物理标准模型



三代物质粒子(费米子)
I
II
III
质量
电荷
自旋
≈2.2 MeV/c²
2/3
1/2
u
上
≈1.28 GeV/c²
2/3
1/2
c
粲
≈173.1 GeV/c²
2/3
1/2
t
顶
0
0
1
g
胶子
≈125.09 GeV/c²
0
0
H
希格斯玻色子
≈4.7 MeV/c²
-1/3
1/2
d
下
≈96 MeV/c²
-1/3
1/2
s
奇
≈4.18 GeV/c²
-1/3
1/2
b
底
0
0
1
γ
光子
≈0.511 MeV/c²
-1
1/2
e
电子
≈105.66 MeV/c²
-1
1/2
μ
μ子
≈1.7768 GeV/c²
-1
1/2
τ
τ子
≈91.19 GeV/c²
0
1
Z
Z玻色子
<2.2 eV/c²
0
1/2
νe
电中微子
<1.7 MeV/c²
0
1/2
νμ
μ中微子
<15.5 MeV/c²
0
1/2
ντ
τ中微子
≈80.39 GeV/c²
±1
1
W
W玻色子
夸克
轻子
规范玻色子
标量玻色子
muon
缪子

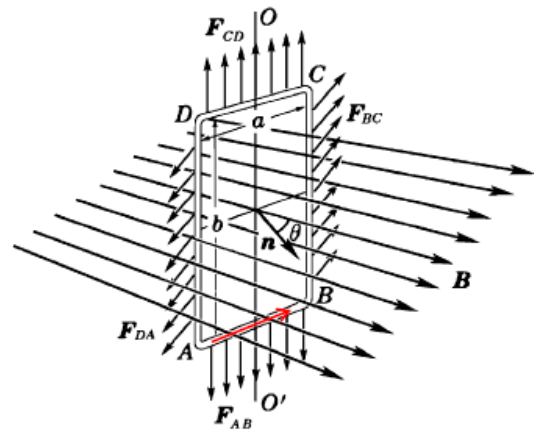
• 矩形载流线圈的磁矩

合力 = 0，合力矩 ≠ 0

力矩 = 径向矢量×作用力

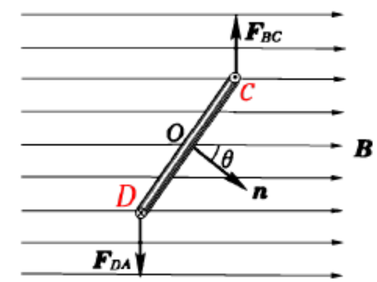
$$L = F_{BC}\frac{a}{2}\sin\theta + F_{DA}\frac{a}{2}\sin\theta$$

$$= IabB\sin\theta = ISB\sin\theta$$



$$\vec{L} = IS\vec{n} \times \vec{B} = \begin{cases} \text{大小} & ISB\sin\theta \\ \text{方向} & \vec{n}\times\vec{B} \text{ 的方向} \end{cases}$$

从上往下看



注意：$\vec{n}$的方向与线圈电流成右手关系

$\vec{m} = IS\vec{n}$ 线圈的磁矩

- **任意载流线圈的磁矩**

线圈受合力是0 但受力矩不是0 有转动趋势

力矩 = 径向矢量×作用力

将线圈分割成若干个小窄条

小窄条所受力矩 dL

$$dF_1 = Idl_1 B\sin\theta_1 = IBh$$

$$dF_2 = Idl_2 B\sin\theta_2 = IBh$$

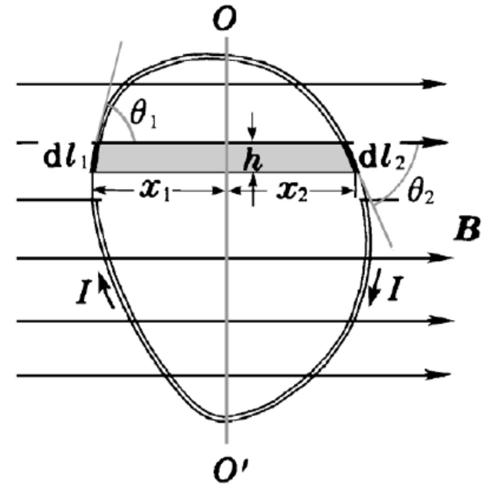
$$dL = IBh(x_1 + x_2) = IBdS$$

$$L = \sum dL = \sum IBdS = IBS$$

方向：向下

若线圈平面与磁场成任意角度

$$\vec{L} = IS(\vec{n} \times \vec{B}) = \vec{m} \times \vec{B}$$

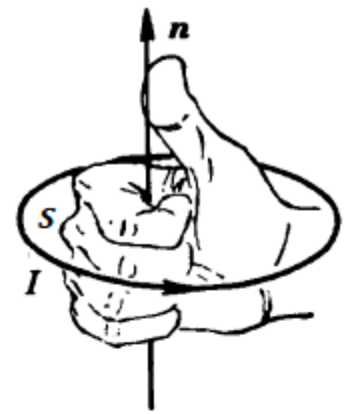


$$\vec{m} = IS\,\vec{n}$$

线圈的磁矩

注意：$\vec{n}$的方向与线圈电流成右手关系

- **任意载流线圈的磁矩**



线圈的磁矩 $\vec{m} = IS\vec{n}$

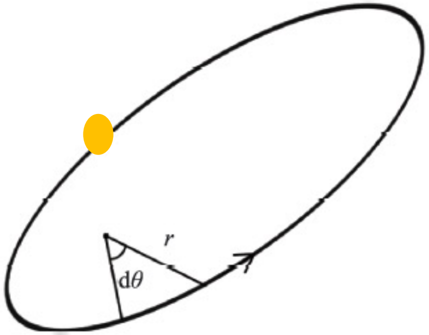
所受的力矩 $\vec{L} = \vec{m} \times \vec{B}$

线圈受合力是0
但受力矩不是0
有转动趋势

所受合力 = 0

- **缪子的轨道运动磁矩（经典）**

$$M = IA = \frac{e}{\tau}\ \frac{L\tau}{2m} = \frac{e}{2m}\ L$$



$I = e/\tau$ τ 周期（运动一周需要的时间）

面积 $A = \int_0^{2\pi} \frac{1}{2} r \cdot r\mathrm{d}\theta = \int_0^{\tau} \frac{1}{2} r^2 \omega \mathrm{d}t = \frac{1}{2m} \int_0^{\tau} m r^2 \omega \mathrm{d}t$

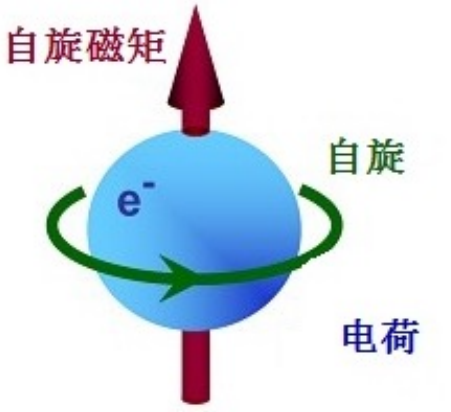
$= \frac{L\tau}{2m}$

L 轨道运动角动量

- **缪子的自旋磁矩（经典）**

$$M = \frac{e}{2m} S$$

（S 缪子的自旋）

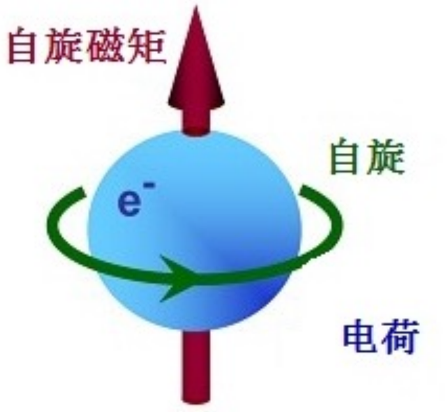


- **缪子的自旋磁矩（量子）**

从狄拉克方程（量子力学）可以推出来（曾谨言书上有推导）

$$M = \frac{e}{m} S$$

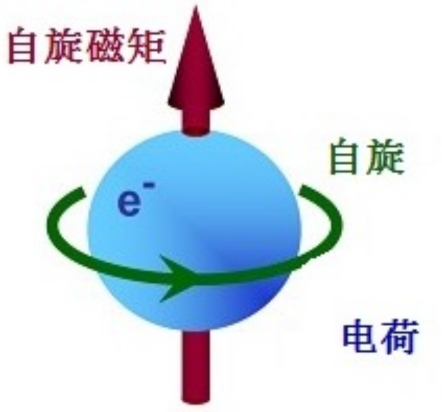
（S 缪子的自旋）



- **缪子的自旋磁矩（量子）**

从狄拉克方程（量子力学）可以推出来（曾谨言书上有推导）

$$M = \frac{e}{m} S = \frac{ge}{2m} S \qquad (g = 2)$$



$$\boldsymbol{a} \equiv \frac{g-2}{2}$$

反常磁矩（简称 muon g-2）

- **缪子的自旋磁矩（量子）**

$$a \equiv \frac{g-2}{2}$$

$= 0$

- 狄拉克方程（量子力学）（曾谨言书上有推导）
- 量子场论（量子电动力学QED）的树图

$\neq 0$

- 量子场论（量子电动力学QED）的圈图

反常磁矩（简称 muon g-2）

- **缪子的自旋磁矩（量子）**

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- 量子场论（量子电动力学QED）的树图

$\neq 0$

- 量子场论（量子电动力学QED）的圈图

反常磁矩（简称 muon g-2）

- **缪子的自旋磁矩（量子）**

$$a \equiv \frac{g-2}{2} = 0$$

$$(g = 2)$$

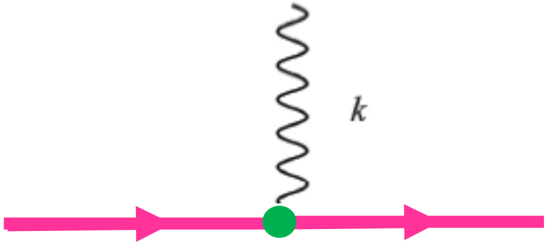
带电粒子在磁场 $\vec{B}(x)$ 中的势能

$$V(x) = -\vec{M}\cdot\vec{B}(x)$$

计算出相应粒子在磁场中的势能，

就可以把磁矩找出来

- **量子场论（量子电动力学QED）的树图**



$$\mathcal{H}_I = eA_\mu(x)\overline{\psi}(x)\gamma^\mu\psi(x)$$

一阵猛算（此处省去20步推导）

$$\approx -\frac{e}{m}\vec{B}\cdot\left[(\zeta' e^{-ip'x})^\dagger\frac{\vec{\sigma}}{2}(\zeta e^{-ipx})\right]$$

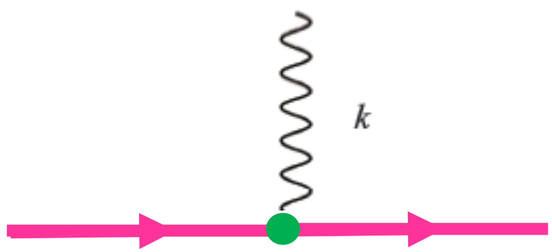
$\vec{S}$

- **缪子的自旋磁矩（量子）**

$$a \equiv \frac{g-2}{2} = 0$$

$$(g=2)$$

- **量子场论（量子电动力学QED）的树图**



带电粒子在磁场 $\vec{B}(x)$ 中的势能

$$V(x) = -\vec{M}\cdot\vec{B}(x)$$

$$\mathcal{H}_I = eA_\mu(x)\overline{\psi}(x)\gamma^\mu\psi(x)$$

一阵猛算（此处省去20步推导）

$$\approx -\frac{e}{m}\vec{B}\cdot\left[(\zeta' e^{-ip'x})^\dagger \frac{\vec{\sigma}}{2}(\zeta e^{-ipx})\right]$$

$$\vec{S}$$

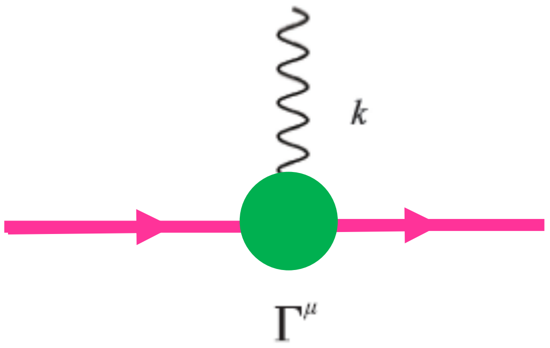
$$M_{tree} = \frac{e}{m} S = \frac{ge}{2m} S \quad (g=2)$$

- **缪子的反常磁矩** $a \equiv \frac{g-2}{2}$

量子场论（量子电动力学QED）的圈图

有效相互作用

$$-ie\epsilon_{\mu}(k)\bar{u}(p')\Gamma^{\mu}u(p)$$



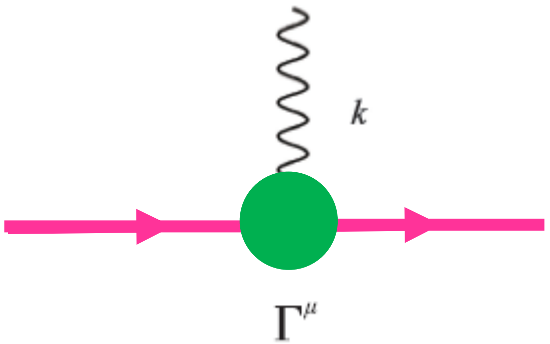
$$\Gamma^{\mu}=\gamma^{\mu}F_{E}(k^{2})+\left(\gamma^{\mu}-\frac{2mk^{\mu}}{k^{2}}\right)\gamma_{5}F_{A}+i\sigma^{\mu\nu}\frac{k_{\nu}}{2m}F_{M}(k^{2})+\sigma^{\mu\nu}\frac{k_{\nu}}{2m}\gamma_{5}F_{D}(k^{2})$$

- **缪子的反常磁矩** $a \equiv \frac{g-2}{2}$

量子场论（量子电动力学QED）的圈图

有效相互作用

$$-ie\epsilon_{\mu}(k)\bar{u}(p')\Gamma^{\mu}u(p)$$



$$\Gamma^{\mu}=\gamma^{\mu}F_E(k^2)+\left(\gamma^{\mu}-\frac{2mk^{\mu}}{k^2}\right)\gamma_5 F_A+i\sigma^{\mu\nu}\frac{k_{\nu}}{2m}F_M(k^2)+\sigma^{\mu\nu}\frac{k_{\nu}}{2m}\gamma_5 F_D(k^2)$$

一阵猛算（此处省去10步推导）

$$-\frac{eF_M(0)}{m}\vec{B}\cdot\left[\left(\zeta' e^{-ip'x}\right)^{\dagger}\frac{\vec{\sigma}}{2}\left(\zeta e^{-ipx}\right)\right]$$

$\vec{S}$

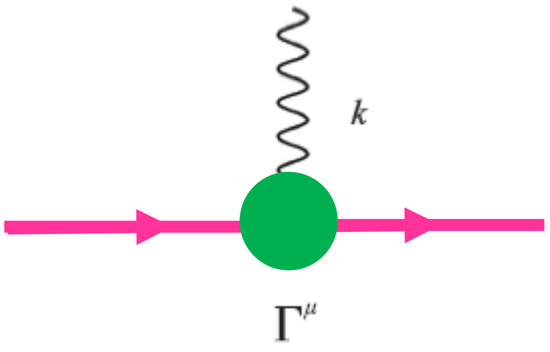
带电粒子在磁场 $\vec{B}(x)$ 中的势能

$V(x)=-\vec{M}\cdot\vec{B}(x)$

$$M_{loop}=\frac{eF_M(0)}{m}S$$

- **缪子的反常磁矩** $a \equiv \frac{g-2}{2}$

量子场论（量子电动力学QED）的圈图



有效相互作用

$$-ie\epsilon_{\mu}(k)\bar{u}(p')\Gamma^{\mu}u(p)$$

$$\Gamma^{\mu}=\gamma^{\mu}F_E(k^2)+\left(\gamma^{\mu}-\frac{2mk^{\mu}}{k^2}\right)\gamma_5 F_A+i\sigma^{\mu\nu}\frac{k_\nu}{2m}F_M(k^2)+\sigma^{\mu\nu}\frac{k_\nu}{2m}\gamma_5 F_D(k^2)$$

一阵猛算（此处省去10步推导）

$$-\frac{eF_M(0)}{m}\vec{B}\cdot\left[\left(\zeta' e^{-ip'x}\right)^{\dagger}\frac{\vec{\sigma}}{2}\left(\zeta e^{-ipx}\right)\right]$$

$\vec{S}$

带电粒子在磁场 $\vec{B}(x)$ 中的势能

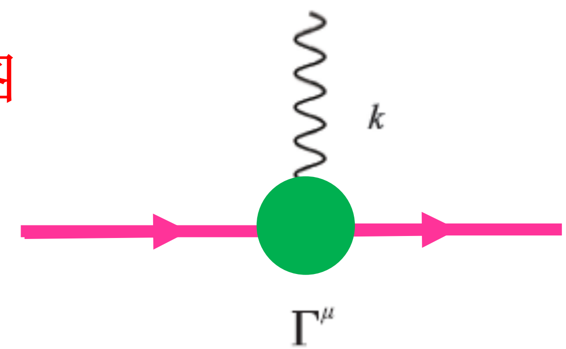
$V(x)=-\vec{M}\cdot\vec{B}(x)$

$$M_{loop}=\frac{eF_M(0)}{m}\,S$$

$$M_{tree}=\frac{e}{m}\,S$$

- **缪子的反常磁矩** $a \equiv \frac{g-2}{2}$

量子场论（量子电动力学QED）的圈图



有效相互作用

$$-ie\epsilon_{\mu}(k)\bar{u}(p')\Gamma^{\mu}u(p)$$

$$\Gamma^{\mu} = \gamma^{\mu}F_E(k^2) + \left(\gamma^{\mu} - \frac{2mk^{\mu}}{k^2}\right)\gamma_5 F_A + i\sigma^{\mu\nu}\frac{k_{\nu}}{2m}F_M(k^2) + \sigma^{\mu\nu}\frac{k_{\nu}}{2m}\gamma_5 F_D(k^2)$$

$$a = F_M(0)$$

$$-\frac{eF_M(0)}{m}\vec{B}\cdot\left[\left(\zeta' e^{-ip'x}\right)^{\dagger}\frac{\vec{\sigma}}{2}\left(\zeta e^{-ipx}\right)\right]$$

$\vec{S}$

带电粒子在磁场 $\vec{B}(x)$ 中的势能

$$V(x) = -\vec{M}\cdot\vec{B}(x)$$

$$M_{loop} = \frac{eF_M(0)}{m}\,S$$

$$M_{tree} = \frac{e}{m}\,S$$

For a charged lepton ℓ the magnetic moment:

spin

$$\vec{\mu}_\ell = g_\ell \frac{e\hbar}{2m_\ell c} \vec{s}$$

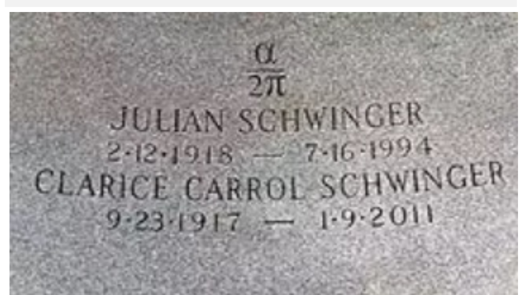
$g_\ell = 2$ at tree level (classical level)
from Dirac Equation (Dirac 1928)

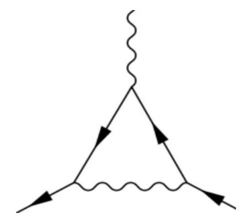
The anomalous magnetic moment is defined as

fine structure constant

$$a_\ell = \frac{g_\ell - 2}{2} = \frac{\alpha}{2\pi} + \cdots$$

one-loop result
Schwinger 1948
engraved on his tombstone





The anomalous magnetic moment of a charged lepton ℓ is a probe to new physics

$$\delta a_\ell \propto \frac{\alpha}{\pi} \frac{m_\ell^2}{M^2} \quad (M \gg m_\ell)$$

$$(m_\mu / m_e)^2 \simeq 4 \times 10^4$$

muon g-2 is a best probe to NP
(tau lepton is too short-lived)

$$\tau_e = \infty$$

$$\tau_\mu = 2.197 \times 10^{-6} \text{ s}$$

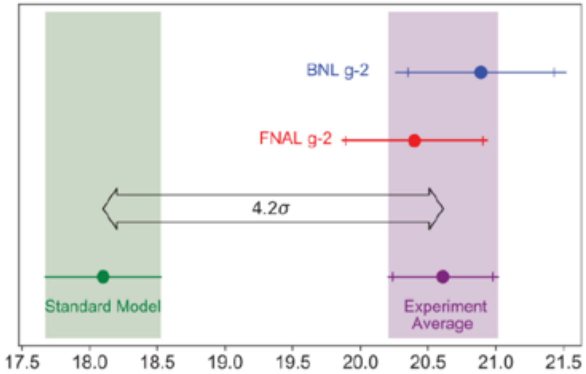
$$\tau_\tau = 2.906 \times 10^{-13} \text{ s}$$

2.2 Muon g-2 measurement

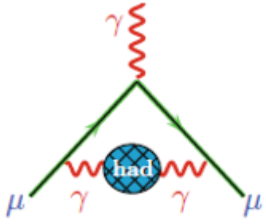
$$a_\mu^{\mathrm{QED}} = 116\,584\,718.9(1) \times 10^{-11}$$
$$a_\mu^{\mathrm{EW}} = 153.6(1.0) \times 10^{-11}$$
$$a_\mu^{\mathrm{HVP,\,LO}} = 6931(40) \times 10^{-11}$$
$$a_\mu^{\mathrm{HVP,\,NLO}} = -98.3(7) \times 10^{-11}$$
$$a_\mu^{\mathrm{HVP,\,NNLO}} = 12.4(1) \times 10^{-11}$$
$$a_\mu^{\mathrm{HLBL}} + a_\mu^{\mathrm{HLBL,\,NLO}} = 92(18) \times 10^{-11}$$

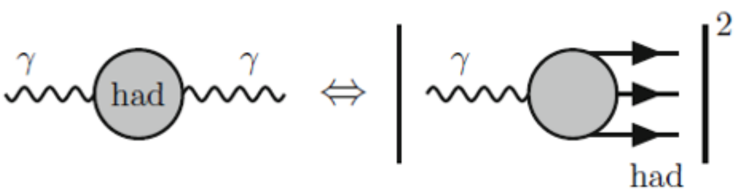
$$a_\mu^{\mathrm{SM}} = 116\,591\,810(43) \times 10^{-11}$$

$$a_\mu^{\mathrm{Exp}} = 116\,592\,061(41) \times 10^{-11}$$
$$a_\mu^{\mathrm{Exp}} - a_\mu^{\mathrm{SM}} = 251(59) \times 10^{-11}$$



Theory uncertainty mainly from HVP





Naturalness and the muon magnetic moment

2021年6月11日 上午9:50
40m
Zoom

报告人

Nima Arkani-Hamed (IAS)

My Take.

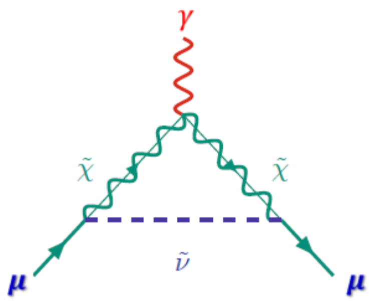
* ~10% chance it's new phys.

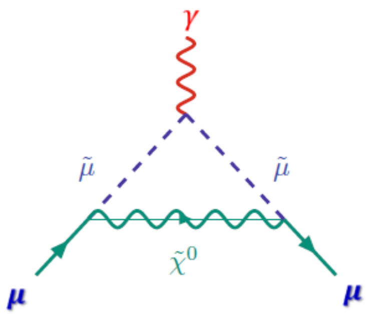
(Much more plausible than other anom.!)

* Lattice QCD groups should converge on ~1–2 year timescale
* ... But not easy to mess with disp. relation results!
* FNAL should reduce error bars by ~×4
* JPARC indep exp. by ~2025

2.3 Implication for new physics

SUSY can explain muon g-2, **but** not so easy





$$\delta a_\mu^{\mathrm{SUSY}} = 14 \tan\beta \left(\frac{100\ \mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2 10^{-10}$$

Moroi
hep-ph/9512396

Require light slepton, light electroweakino

(uncolored sparticles are light)

MSSM
g-2 is OK

2104.03262
Wang, Wu, Xiao, Yang, Zhang

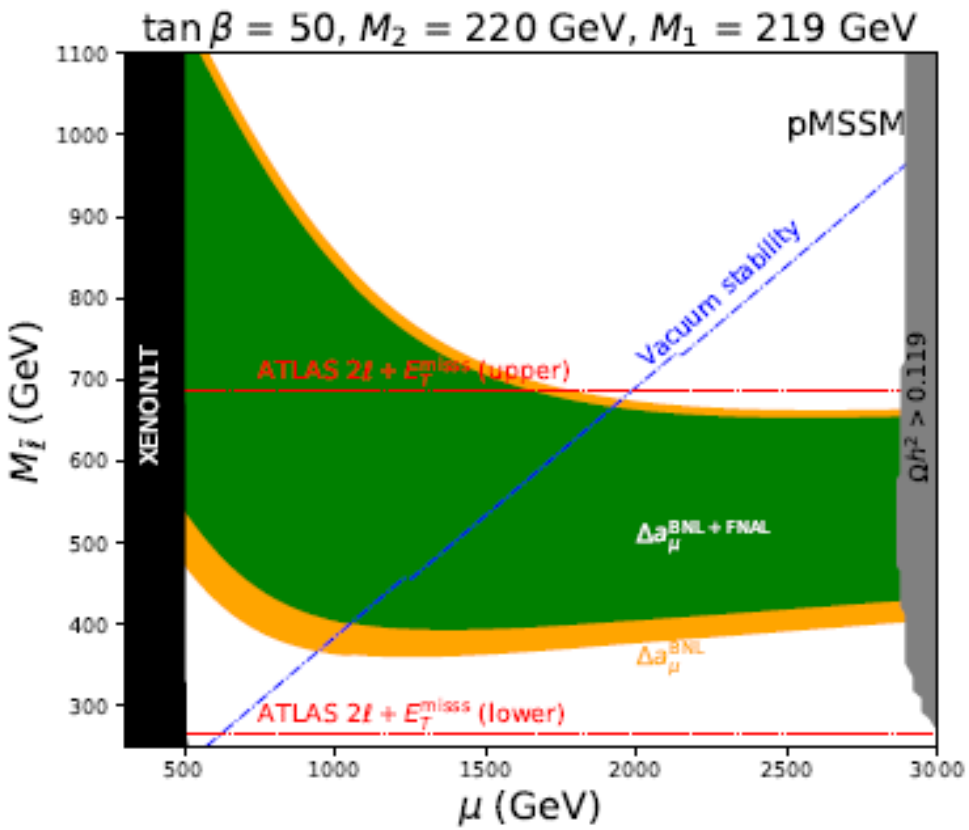


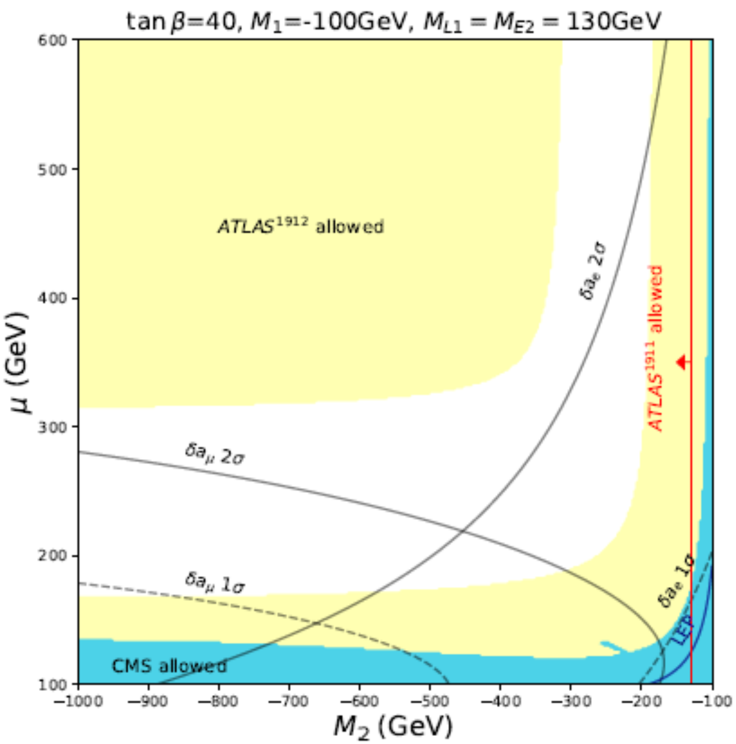
Figure 2. FNAL+BNL and BNL Δa_μ constraints for the BW scenario in the pMSSM. The orange and dark green regions can explain the BNL and the FNAL+BNL Δa_μ measurements at 2σ CL. The black region is excluded by Xenon-1T at 90% CL, while in the brown region the LSP is not bino-like neutralino. The areas between the two ATLAS $2\ell + E_T^{\rm miss}$ limits (red dash lines) are excluded by 13 TeV LHC searches for slepton-pair production at 95% CL. The regions on the right of blue dash lines spoil stability of the electroweak vacuum.

MSSM： muon g-2 and electron g-2 simultaneously OK !

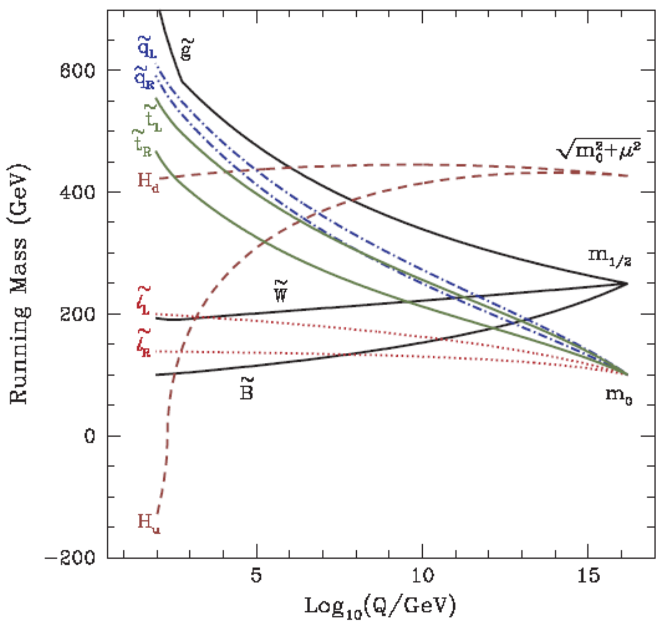
$$\Delta a_e^{\mathrm{Exp-SM}} = a_e^{\mathrm{Exp}} - a_e^{\mathrm{SM}}(\mathrm{Cs}) = (-8.8 \pm 3.6) \times 10^{-13}$$

2107.04962
Li, Xiao, Yang

from measurement of fine-structure constant using ^{133}Cs atoms at Berkeley is 2.4σ below SM prediction



CMSSM/mSUGRA, GMSB, AMSB： g-2 not OK



125 GeV Higgs → heavy top squarks

→ m_0 is large

→ heavy sleptons

→ cannot explain g-2

GMSB/AMSB：g-2 not OK

Baer, Barger, Mustafayev, 1202.4038

To give a 125 GeV Higgs, SUSY particles are above 10 TeV

→ g-2 cannot be explained

GMSB/AMSB： g-2 not OK

Extend GMSB:

1203.2336

Kang, Li, Liu, Tong, Yang

For example,

A Heavy SM-like Higgs and a Light Stop from Yukawa-Deflected Gauge Mediation

$$W_1 = \lambda_u S \bar{\Phi}_L H_u + \lambda_d \bar{S} \Phi_L H_d,$$

can have large A_t， giving 125 GeV Higgs without very heavy stops

→ *g-2* can be explained

GMSB/AMSB： g-2 not OK

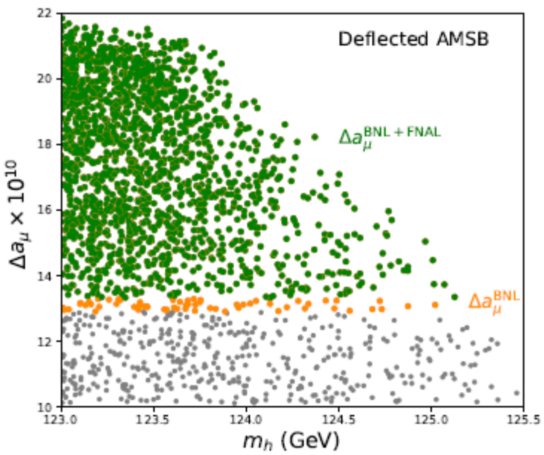
Extend AMSB:

For example,

1505.02785

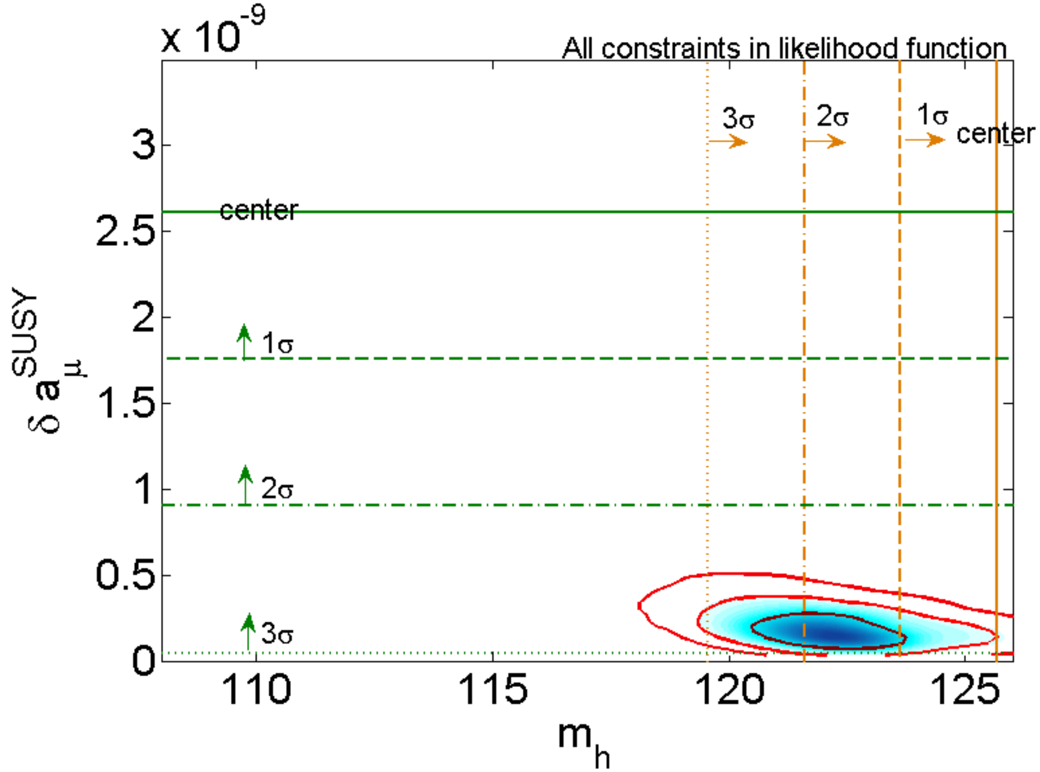
Wang, Wang, Yang, Zhang

Heavy colored SUSY partners from deflected anomaly mediation



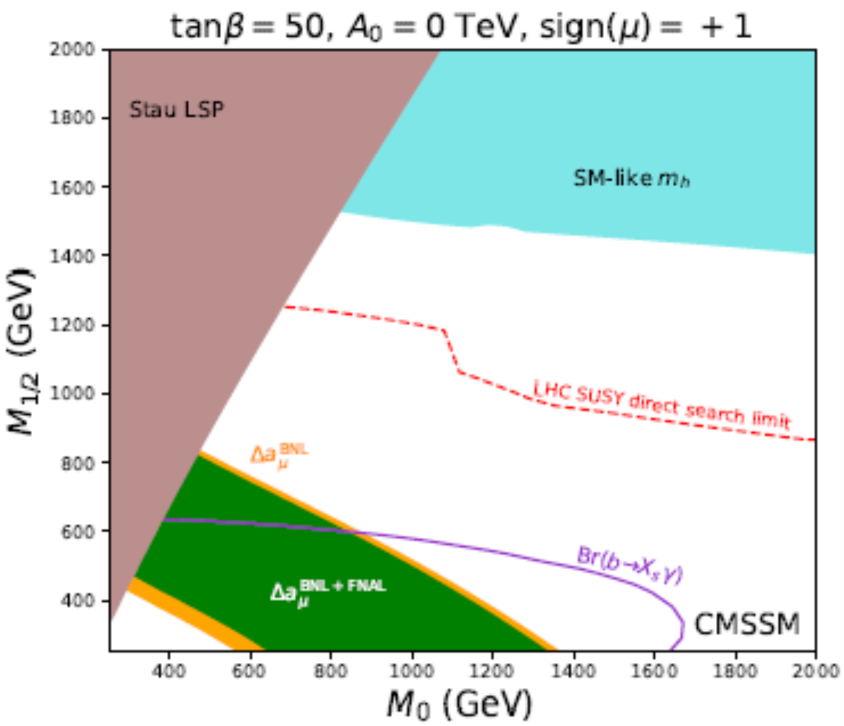
→ *g*-2 can be explained

CMSSM/mSUGRA： g-2 not OK



1612.02296
Han, Hikasa, Wu, Yang, Zhang

CMSSM/mSUGRA： g-2 not OK



2104.03262

Wang, Wu, Xiao, Yang, Zhang

CMSSM/mSUGRA：g-2 not OK

Extend CMSSM/mSUGRA:

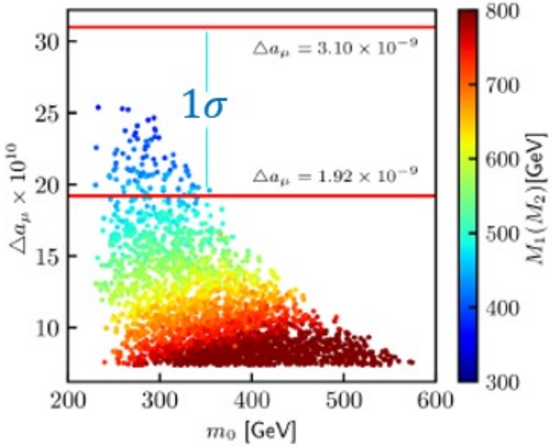
For example,

Reconcile muon g-2 anomaly with LHC data in SUGRA with generalized gravity mediation

Wang, Wang, Yang, 1504.00505

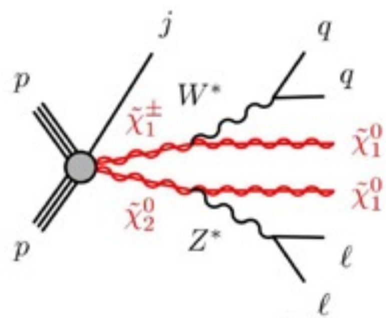
Wang, Wang, Yang, Zhu, 1808.10851

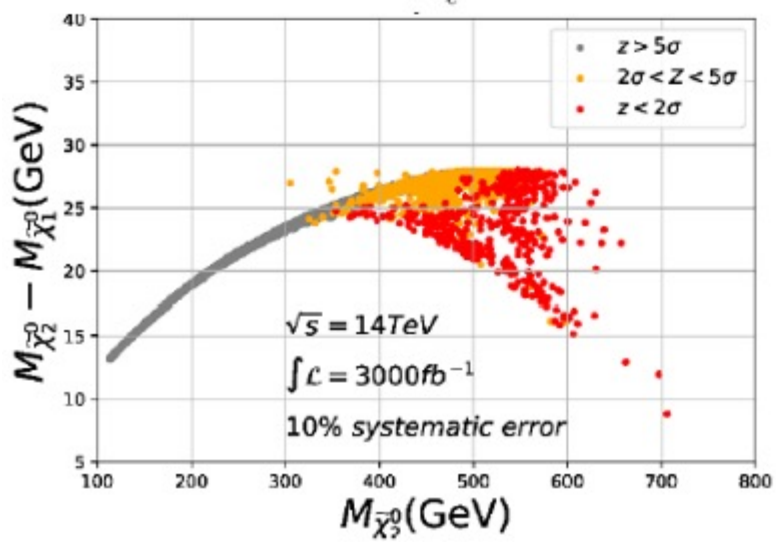
Gluino-SUGRA scenarios in light of FNAL muon g-2



Li, Liu, Wang, Yang, Zhang, 2106.04466

Implication for MSSM search at LHC





1909.07792

Abdughani, Hikasa, Wu, Yang, Zhao

2.4 Summary

- **Muon g-2 implication for SUSY:**

  CMSSM/mSUGRA, GMSB, AMSB: need to be extended

  MSSM: ok

  - light electroweakinos
  - light sleptons

  } Most hopefully accessible at LHC

- **New results from muon g-2 experiment at Fermilab will be unveiled in a scientific seminar on August 10, 2023 at 10:00am US central time:**

  https://muon-g-2.fnal.gov/?fbclid=IwAR3DzsYngx-DiIZ8BfEEk7t5g-2dmYP2o2yTSR0kyspqLf1augkdea8o4wA

Thanks for your attention ！

科学家并不是因为大自然有用才去研究它，他研究大自然是因为他感到乐趣，而他对大自然感到乐趣是因为它的美丽，如果大自然不美，那就不值得认识，如果大自然不值得认识，就不值得活下去。

彭加勒（H. Poincare）