粒子物理与近代科学

-- 粒子物理标准模型的唯像理解

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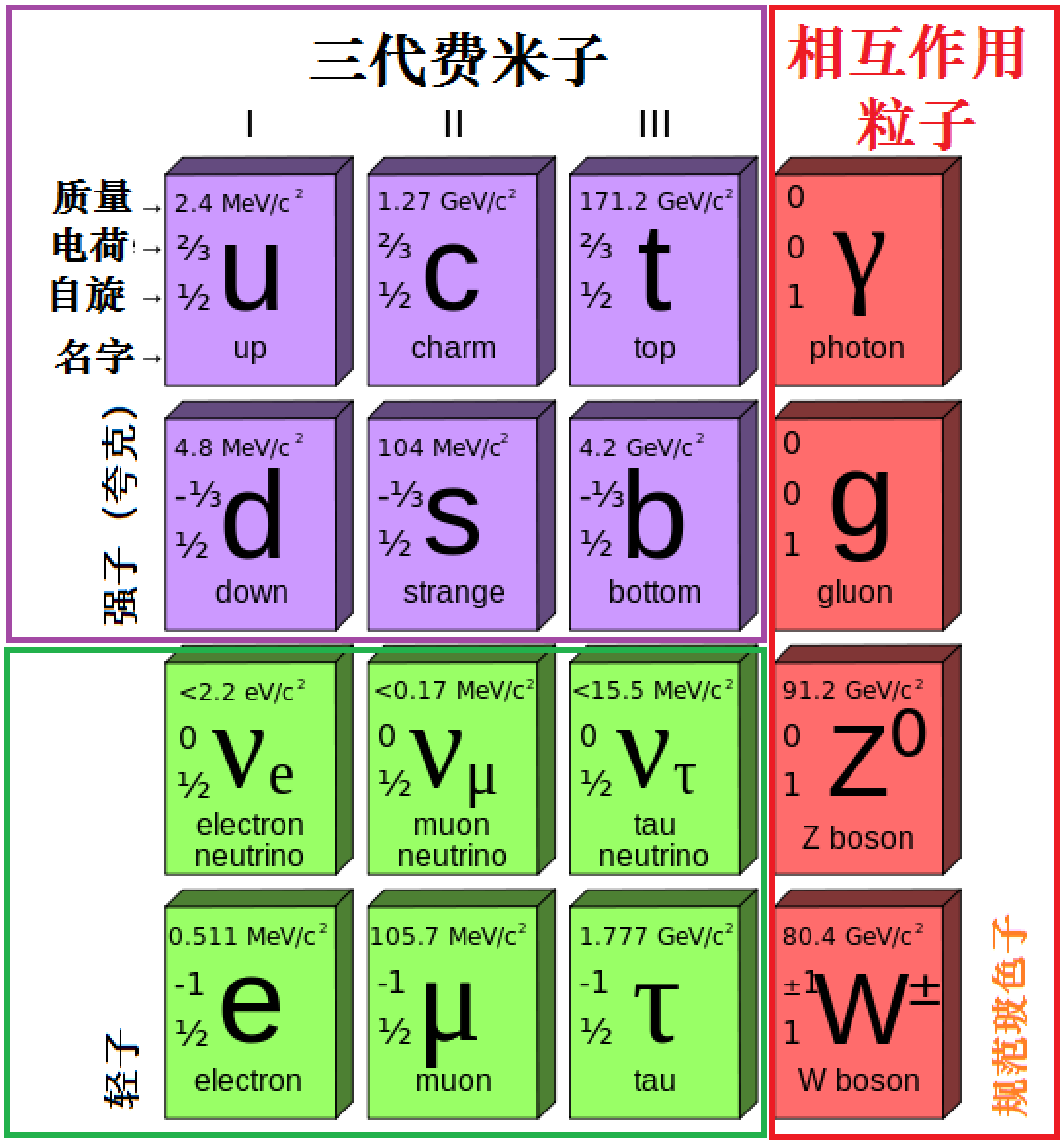
Standard Model(SM): Interactions



➢ 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**:

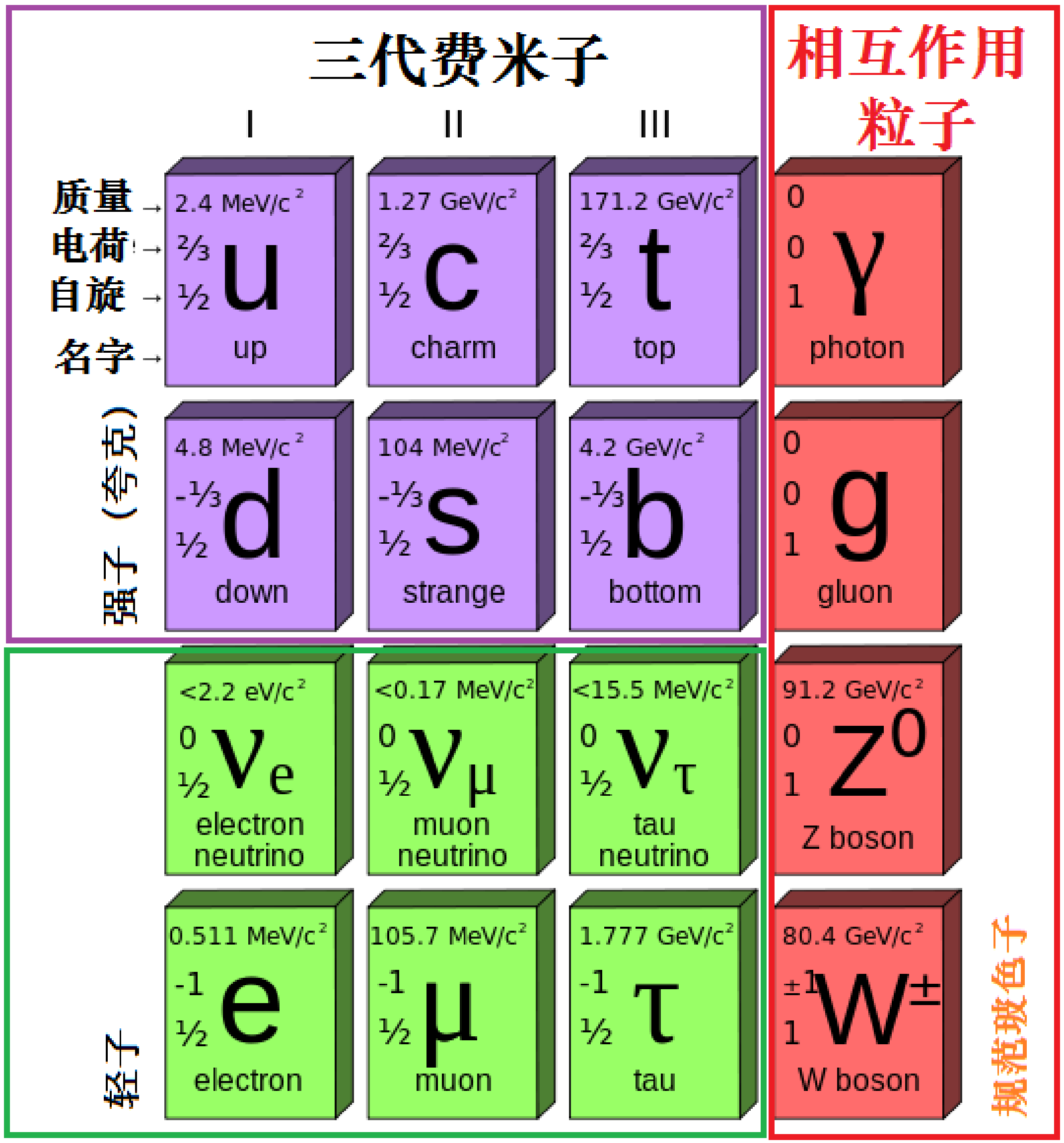
  中微子振荡 + CP破坏?

  NOνA vs. 大亚湾

II. 电弱对称性及其破缺

The Electroweak Symmetry Breaking

Standard Model(SM): Interactions



➢ 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

- **$W^{\pm}/Z^0$:** $m(Z) \sim$ **90**GeV

  $m(W) \sim$ **80**GeV

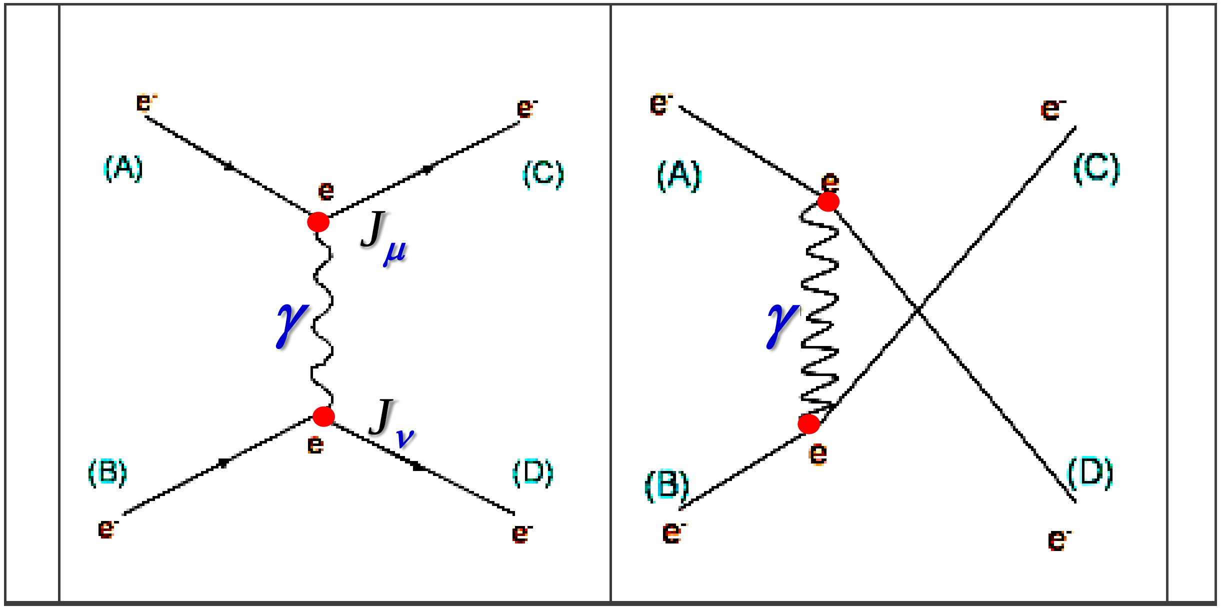
  弱相互作用

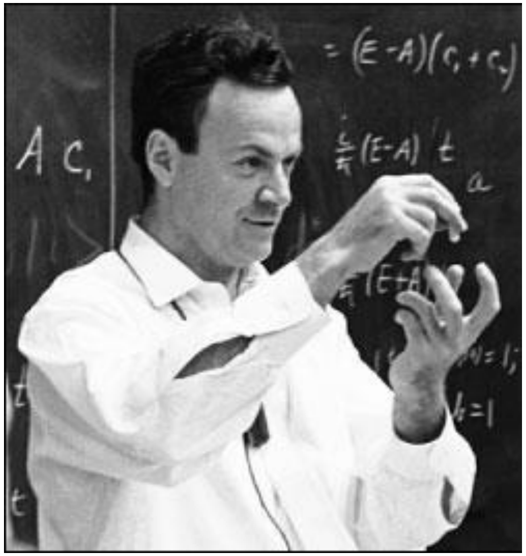
Theory: QFT & QED

规范理论：*U(1)*不变

$$\psi \rightarrow \psi e^{-ie\cdot\theta(x)}$$

- Quantum ***electro*** dynamics **QED** $\alpha = e^2/4\pi$





Richard Feynman
(1918-1988)

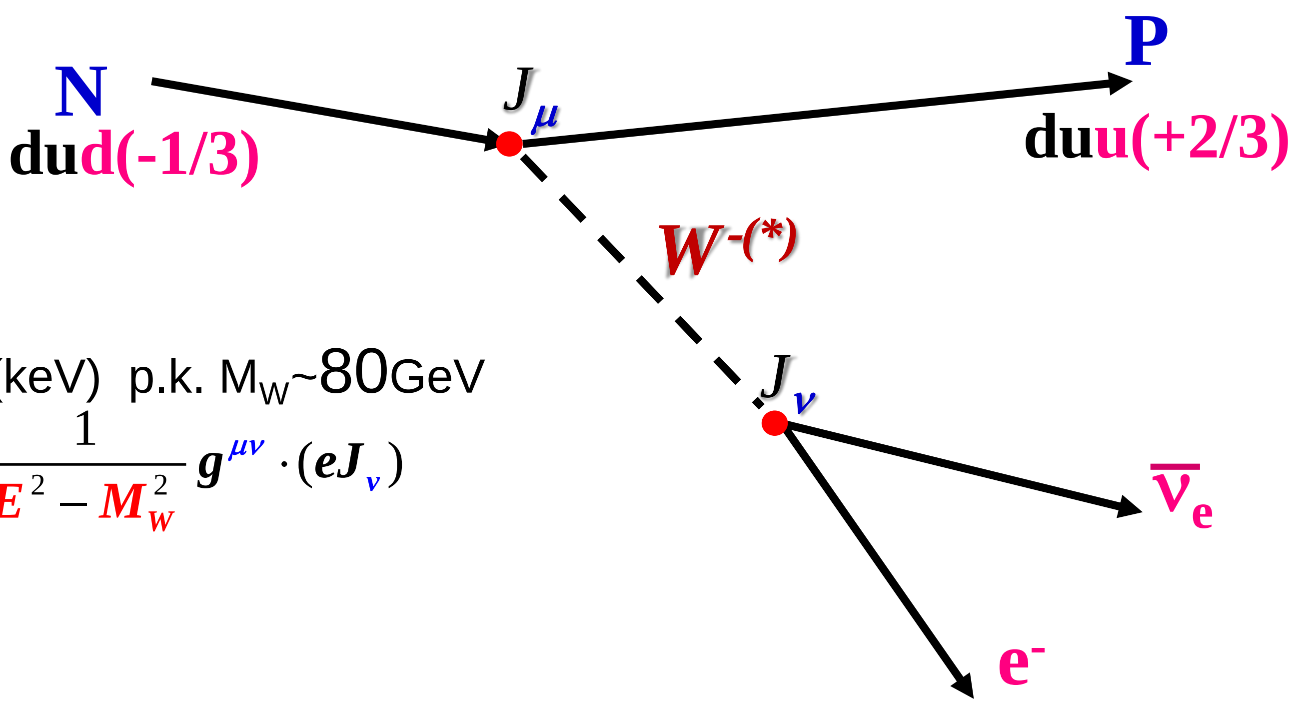
$$\Phi \sim (eJ_\mu[A \rightarrow C]) \cdot \frac{1}{E^2 - m^2} g^{\mu\nu} \cdot (eJ_\nu[B \rightarrow D])$$

Charge current Weak interaction

规范理论：*SU(2)*不变

$$\psi \rightarrow \psi e^{-i\vec{\tau}\cdot\vec{\theta}(x)}$$

- **Charged current *Weak* interaction: *nuclei β-decay***



-- Solar fusion E~O(keV) p.k. M_W~80GeV

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

e.g. 太阳燃烧

$$p + p + p + p \rightarrow {}^4He + e^+ + e^+ + \nu_e + \nu_e + \gamma$$

电弱相互作用(I): SU(2)×U(1)规范群

$$SU(2)_L \otimes U(1)_Y$$

$$\left.\begin{array}{lcl} SU(2)_L & \longrightarrow & W_\mu^1\,,\ W_\mu^2\,,\ W_\mu^3\,, \\ U(1)_Y & \longrightarrow & B_\mu\,. \end{array}\right\}$$

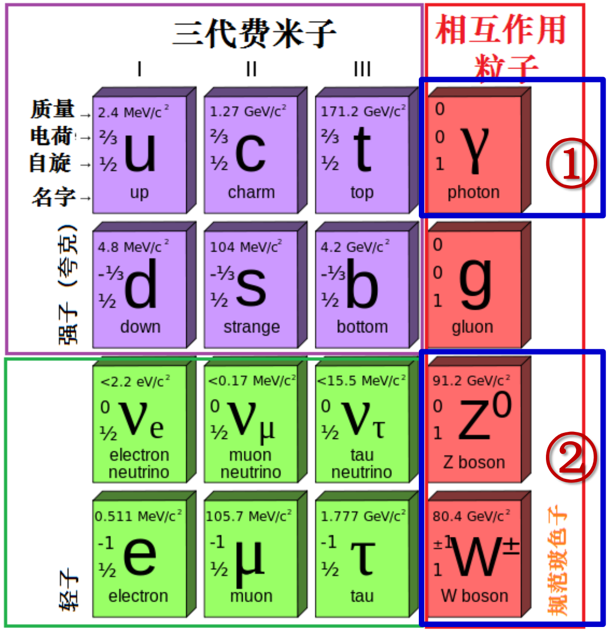
***Massless*!**

in theory

$$SU(2)_L \otimes U(1)_Y \to U(1)_{\rm em}$$

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

$$\sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}} \qquad e = g\sin\theta_W = g'\cos\theta_W;$$



$SU(2)_W \times U(1)_{EM}$

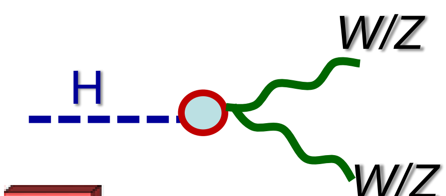
$m(\gamma) = \mathbf{0}$

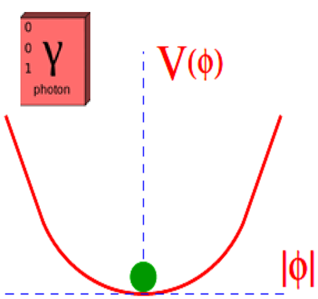
$m(Z) =$ **91.187**GeV

$m(W)=$ **80.403**GeV

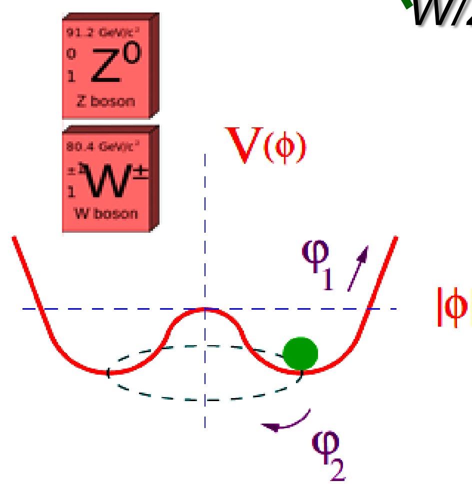
$m(g) = \mathbf{0}$

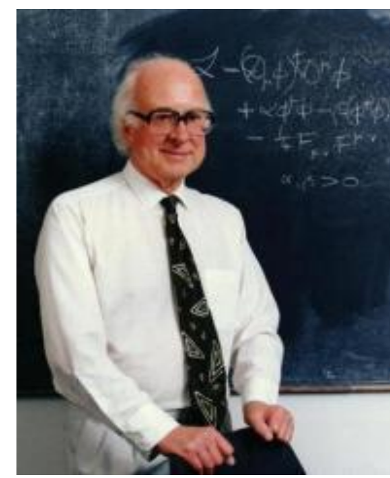
- Last missing piece: **m**=f/a?
- Higgs机制：



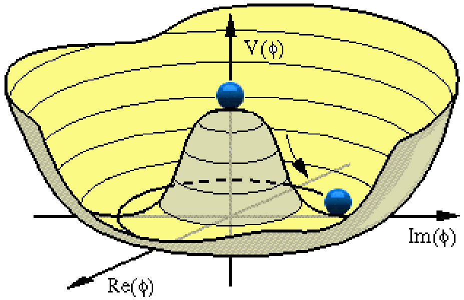


真空对称性
自发破缺？





Higgs mechanics

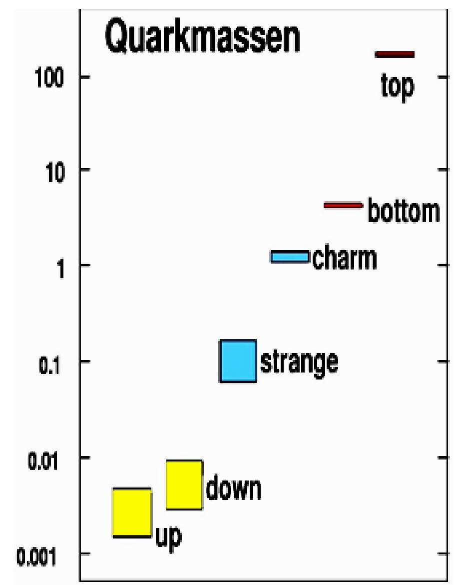


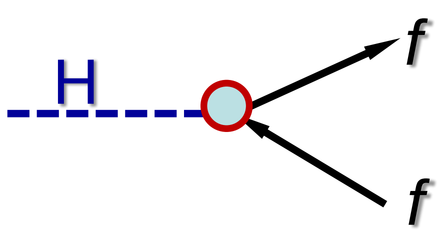
➢ 0^+自旋标量场

$$\mathcal{L}_{\mathrm{H}} = \left| \left(\partial_\mu + \frac{i}{2} \left(g' Y_{\mathrm{W}} B_\mu + g \vec{\tau} \vec{W}_\mu \right) \right) \varphi \right|^2 - \frac{\lambda^2}{4} \left(\varphi^\dagger \varphi - v^2 \right)^2 .$$

- Spontaneous electro-weak symmetry breaking (EWSB) : ν / λ

+ gauge invariance preserved
+ introduce massive vector bosons $M_W^2 = \frac{1}{2} g^2 v^2, \quad M_Z^2 = \frac{M_W^2}{\cos^2 \theta}$
+ introduce Higgs particle $m_H = 2v\sqrt{\lambda}$
+ Yukawa couplings for fermions' mass $\sim g \frac{m_f}{M_W} \bar{\psi} \phi \psi$

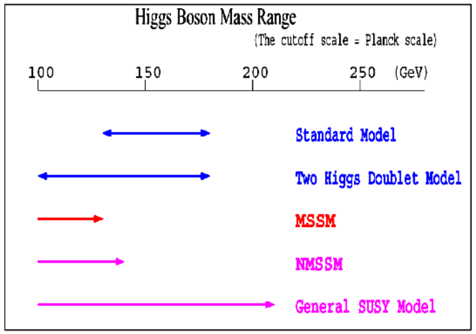




➢ 仅与有质量的物质场直接耦合

A glance at the feature of the Higgs

- A **Higgs scalar** directly coupled to "***everything***" with **mass**
- A **light Higgs**, if the theory weakly coupled up to the Plank scale



$m_H < 200$ GeV

- Mass spectrum

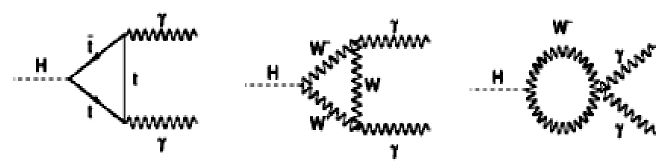
m(e) = 0.511MeV
m(m) = 130MeV
m(t) = 1.7GeV
m(n) = 0
m(u) ~ m(d) ~ 0
m(s) ~ 150MeV
m(c) ~ 1.7GeV
m(b) ~ 5GeV
m(t) ~ 175GeV

- A light Higgs dominantly decays to

① $bb/\tau\tau$: $Hf\bar{f} \propto \frac{m_f}{M_W}$

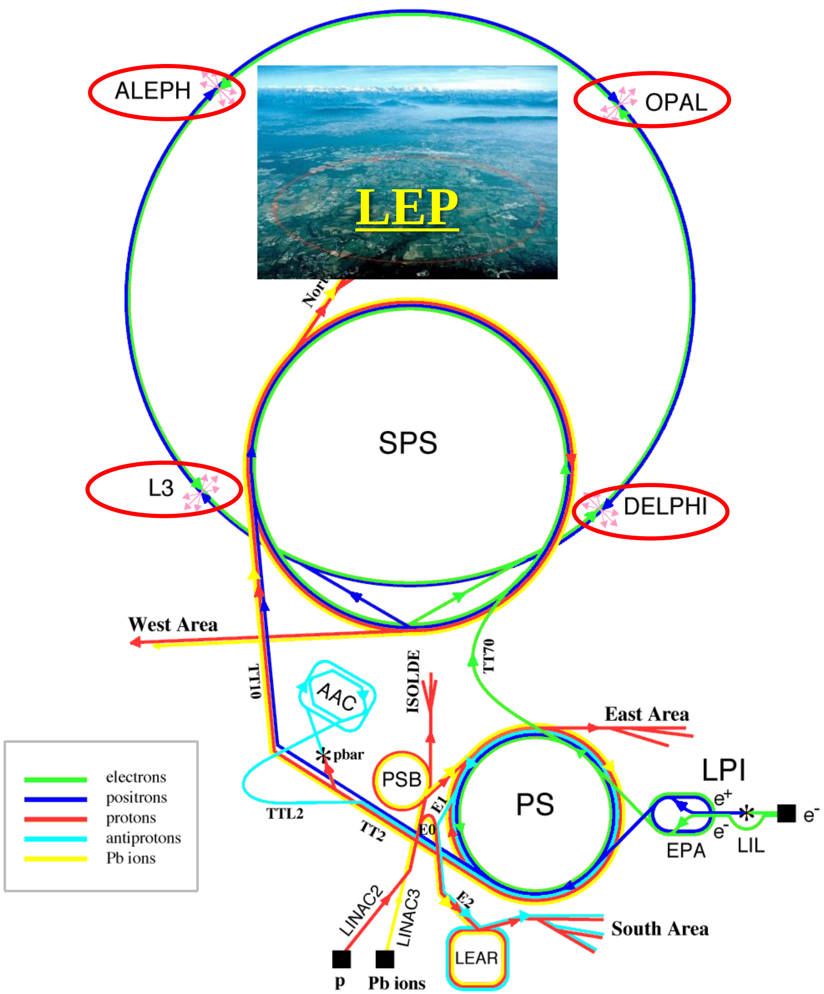
② WW^*/ZZ^*: $HVV \propto M_W$

③ $\gamma\gamma$: via loop contributions

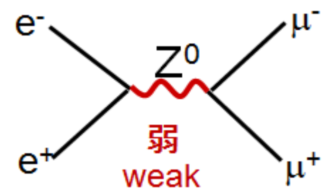


pre-LHC: LEP (Large Electron Positron collider)

Run e^+e^- from **1988**-2000 @

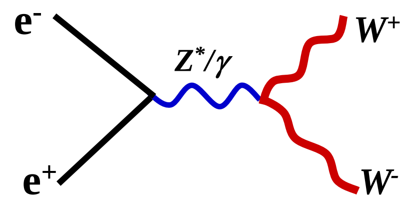


- **90** GeV → **Z line shape**



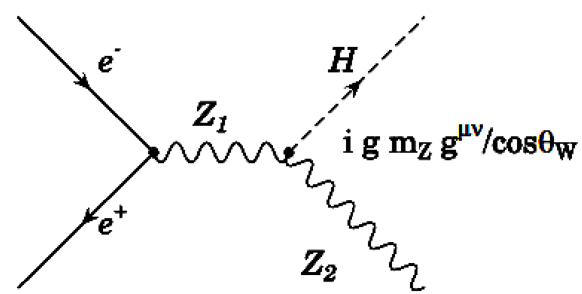
⇨ M_Z, $\sin^2\theta_W$

- **160** GeV → ***WW*** pair production



⇨ M_W

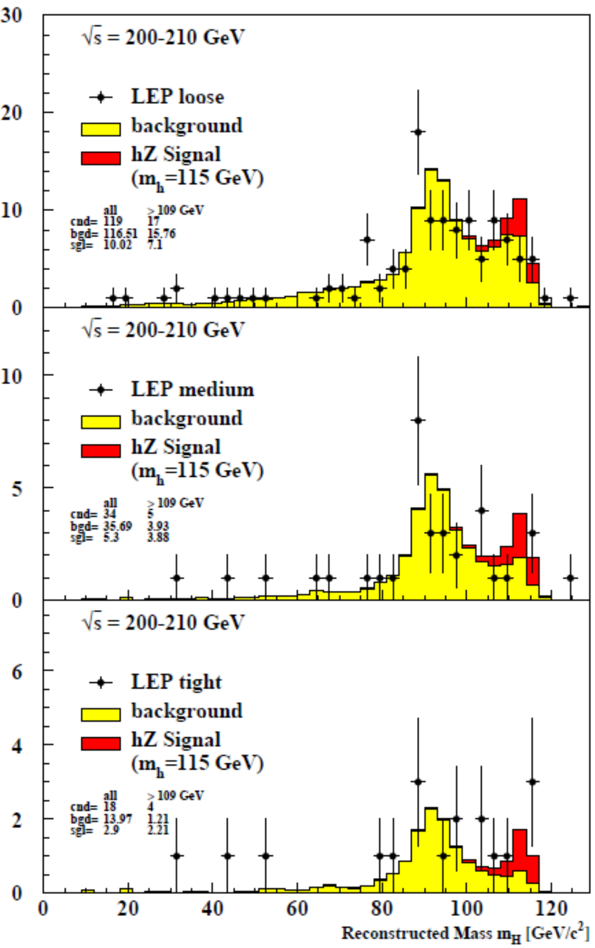
- **207** GeV → ***ZH*** associative production

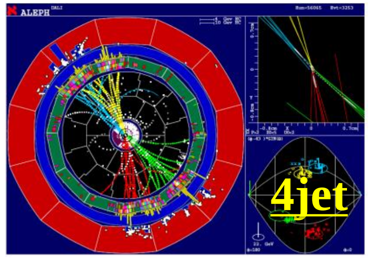


⇨ Higgs?

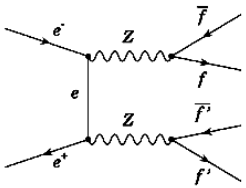
*suppressed by 10^{-10} @ LEP via eeH Yukawa

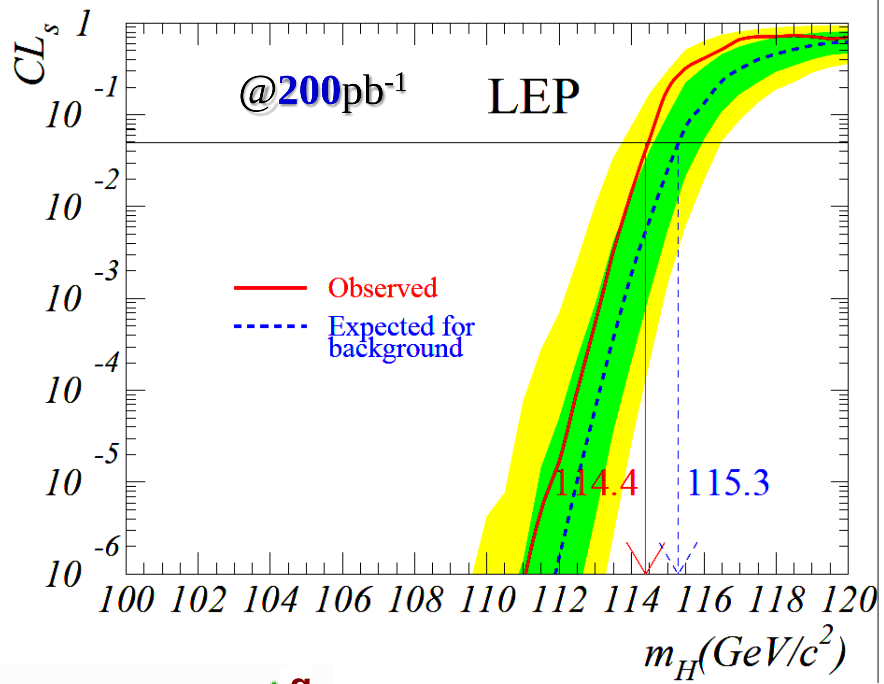
Results of direct search @ LEP



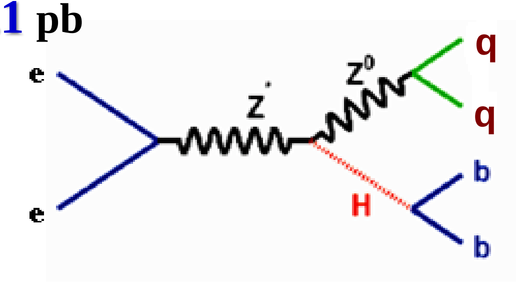


① Background:~ **100** pb





② Signal:~ **0.1** pb



➢ **@ 95% CL, m_H > 114.4 GeV**

http://lephiggs.web.cern.ch/LEPHIGGS/www/Welcome.html

Fundamental constants of the SM

- Gauge theory : $SU(2)_L \times U(1)_Y$ + $Higgs$ → $SU(2)_W \times U(1)_{em}$

- Parameters : weak g, hypercharge g' and vacuum expectation v/λ ⇨

$$e = g \sin\theta_W = g' \cos\theta_W ; \qquad G_F = \frac{\pi\alpha}{\sqrt{2} M_W^2 \sin^2\theta_W};$$

$$sin\theta_W^2 = \frac{g'^2}{g'^2 + g^2} = 1 - \frac{M_W^2}{M_Z^2}$$

$$M_Z = \frac{M_W}{\cos\theta_W}; \qquad M_W = \frac{gv}{2}; \qquad \boxed{m_H = 2v\sqrt{\lambda}}$$

State of the art

$$\alpha = 1/137.035999679(94)$$ ($e^{\pm}$ g_2)

$$G_F = 1.166367(5) \times 10^{-5}\ \mathrm{GeV}^{-2}$$ ($\mu^{\pm}$ lifetime)

$$M_Z = 91.1876 \pm 0.0021\ \mathrm{GeV}$$ (Z line-shape)

$$M_W\ [\mathrm{GeV}] = \begin{array}{l} 80.428 \pm 0.039 \\ 80.376 \pm 0.033 \end{array}$$ (LEP)

(Tevatron)

$$\sin^2\theta_W = 0.23152 \pm 0.00014$$ (Z line-shape)

$$\mathbf{m_H} = ?$$

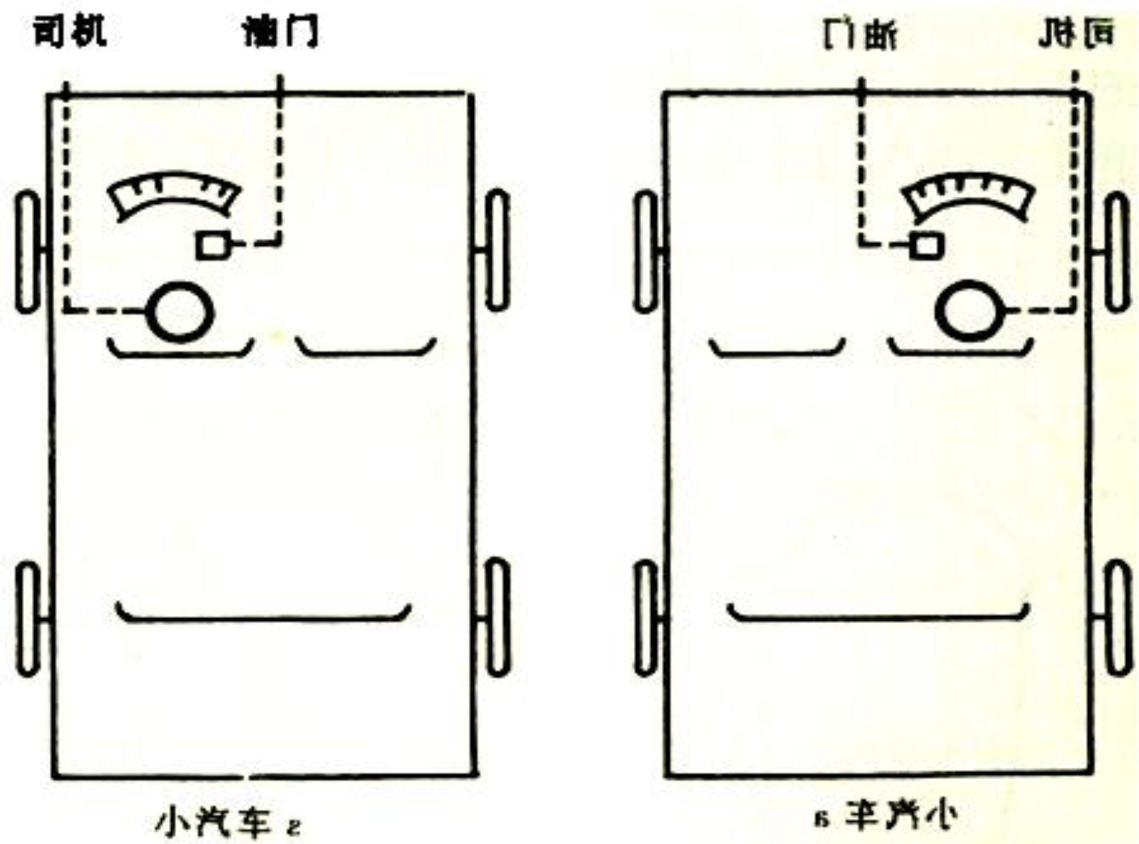
宇称(P)变换

- 定义为空间坐标反号，但时间不变的变换，

$x \to -x$，$t \to t$

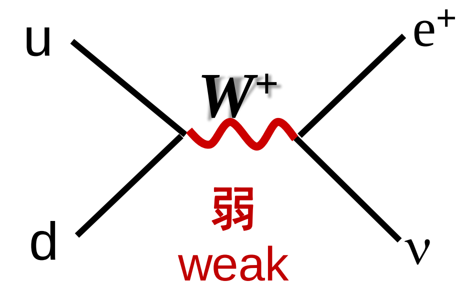
P变换是一种典型的分立变换

在微观物理范围内，P变换不变性直接和宇称守恒相联系

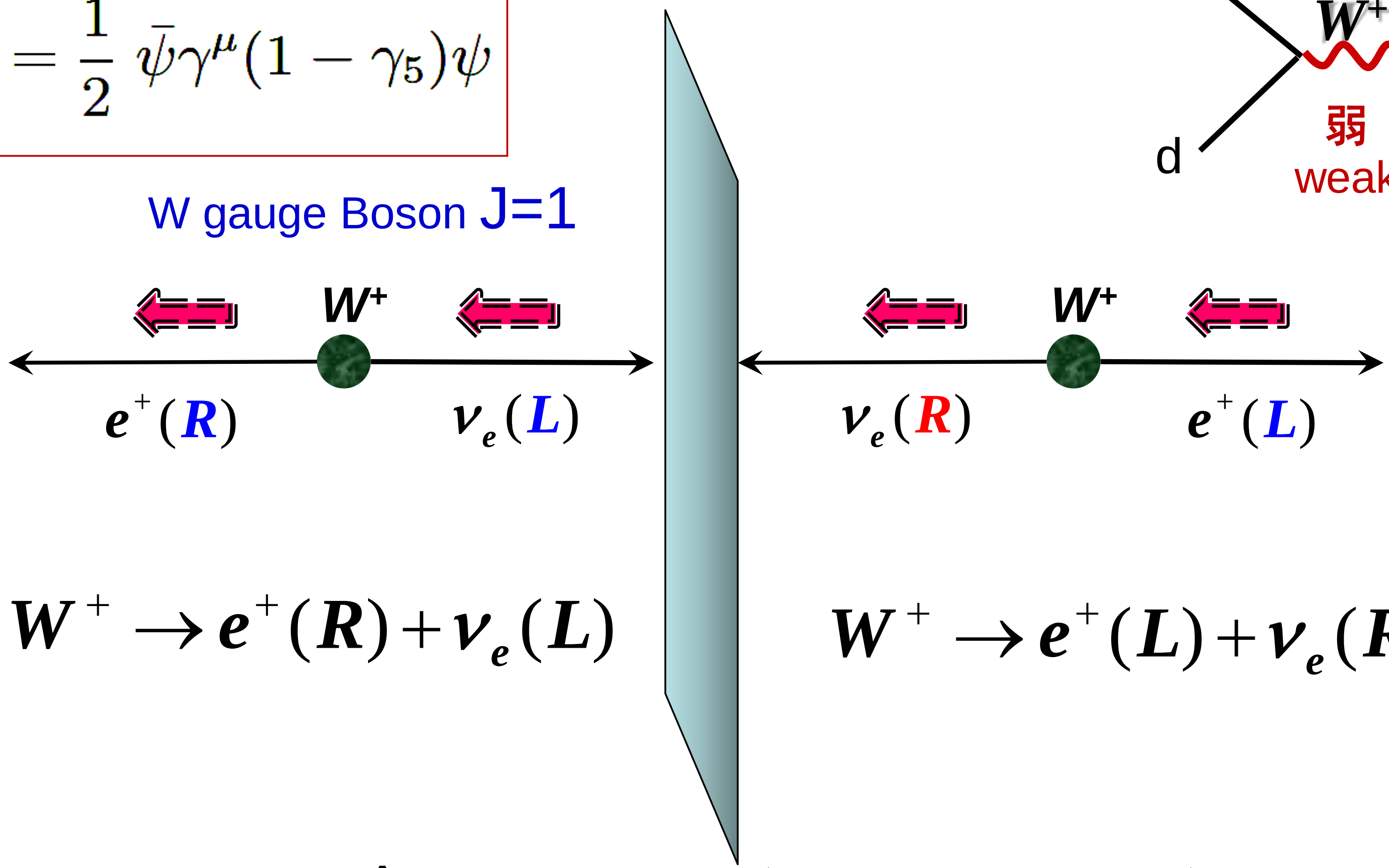


Weak charged current V-A couplings

$$\bar{\psi}\gamma^{\mu} L \psi = \frac{1}{2}\,\bar{\psi}\gamma^{\mu}(1-\gamma_5)\psi$$



W gauge Boson J=1



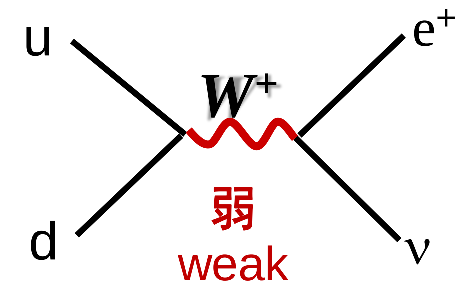
$$W^{+} \rightarrow e^{+}(R) + \nu_e(L)$$

$$W^{+} \rightarrow e^{+}(L) + \nu_e(R)$$

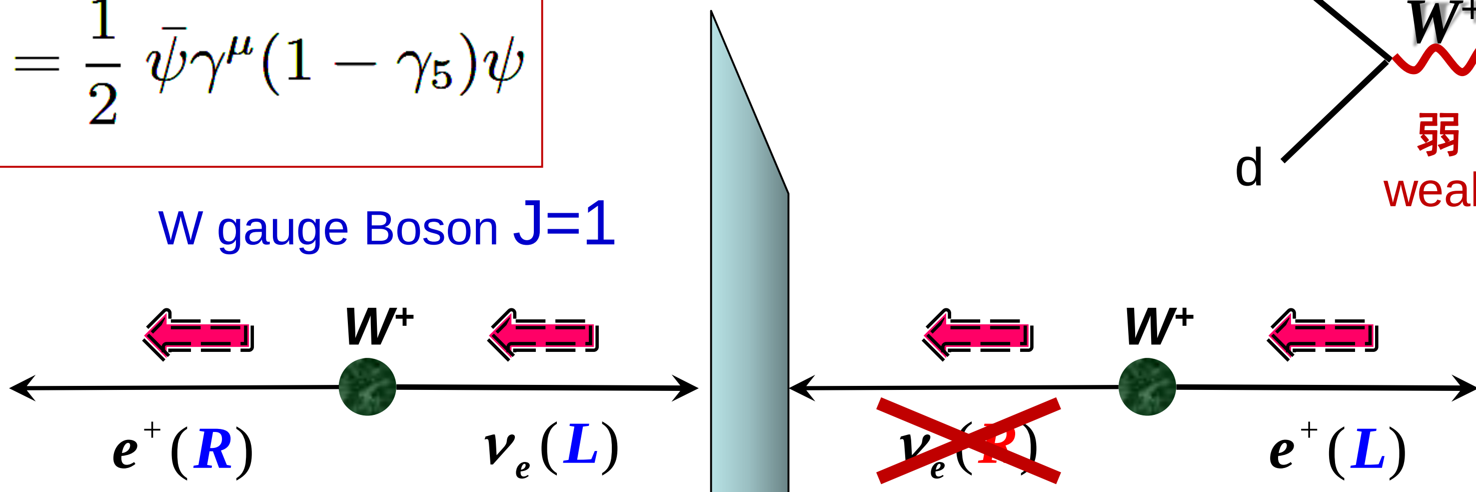
Parity $\hat{P}\ :\ \vec{x} \Rightarrow -\vec{x};\ \vec{J} = \vec{r} \times \vec{p} \Rightarrow \vec{J}$

Weak charged current V-A couplings

$$\bar{\psi}\gamma^{\mu}L\psi = \frac{1}{2}\,\bar{\psi}\gamma^{\mu}(1-\gamma_5)\psi$$



W gauge Boson J=1



$$W^{+} \rightarrow e^{+}(R) + \nu_e(L)$$

~~$W^{+} \rightarrow e^{+}(L) + \nu_e(R)$~~

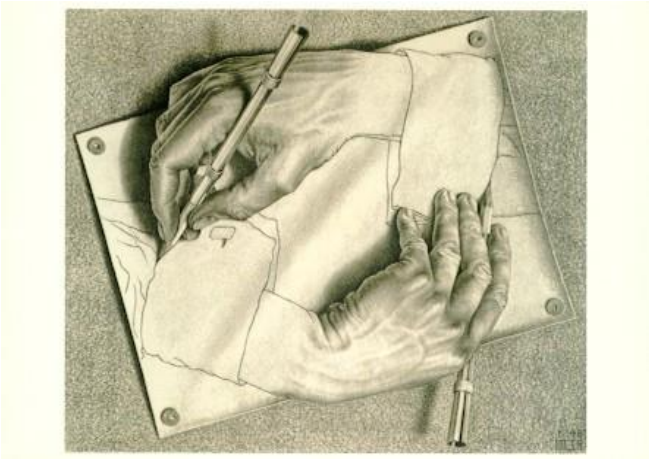
Parity $\hat{P}\ :\ \vec{x} \Rightarrow -\vec{x};\ \vec{J} = \vec{r} \times \vec{p} \Rightarrow \vec{J}$

Parity violation in Weak interaction

$$P:\begin{pmatrix}x\\y\\z\end{pmatrix}\mapsto\begin{pmatrix}-x\\-y\\-z\end{pmatrix}.$$

T.D.Lee

C.N.Yang

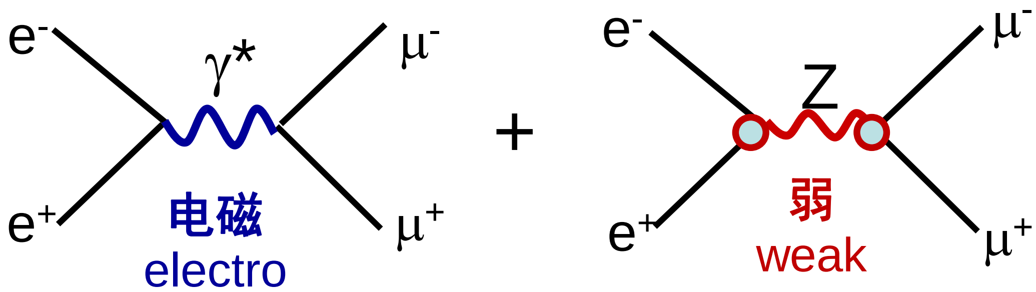


Electromagnetic/
Strong/Gravity

Weak

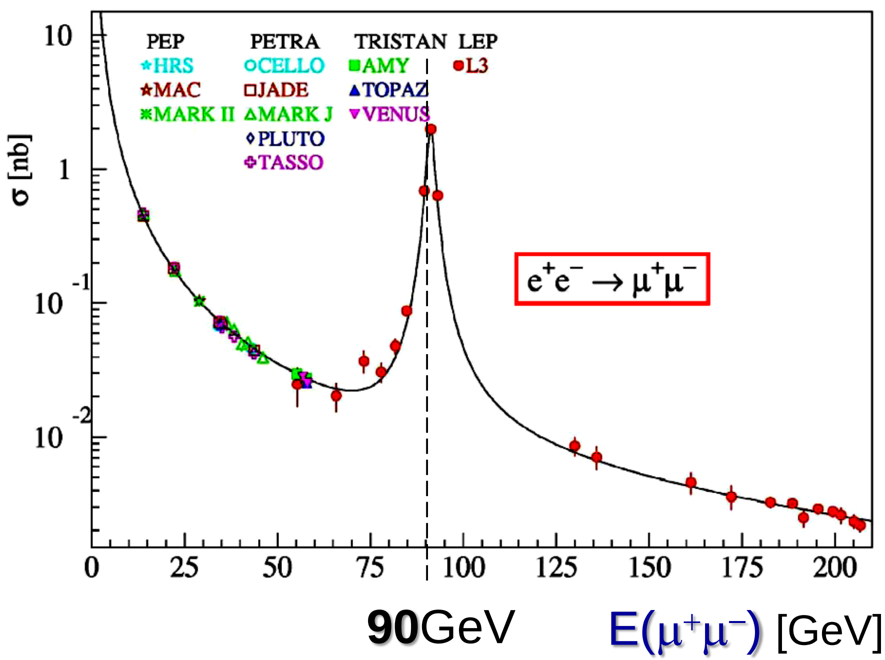
电弱相互作用(II): Electro-Weak中性流

- $e^+e^- \rightarrow \mu^+\mu^-$ predicted by the SM and test



⇨ Z^0玻色子质量：M_Z

For example, what observed at LEP/SLC



✓ cross section

$$\sigma \propto \frac{1}{E^2 - M^2 + i\Gamma \cdot M}$$

➔ Britten-Wigner @ **90**GeV

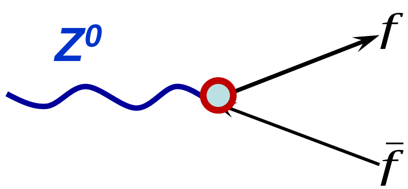
➔ Electro vs. weak @ 1GeV

$1 : 10^{-4}$

标准模型SM物理参数:

精细结构常数： $\alpha = \frac{e^2}{4\pi}$;　费米常数： G_F;　Z^0玻色子质量： M_Z;　$W^\pm$玻色子质量： M_W;　弱混合角： $\sin\theta_W^2 = \frac{g'^2}{g'^2 + g^2}$

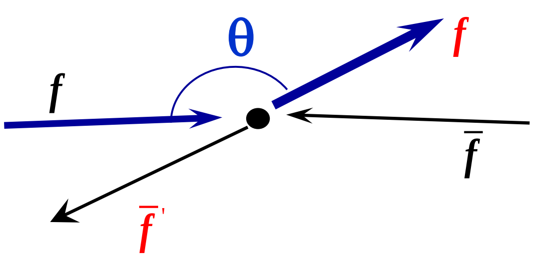
➢弱相互作用中性流



$$-\frac{g}{2\cos\theta_W}\sum_i \overline{\psi_i}\,\gamma^\mu(g_V^i - g_A^i\gamma^5)\,\psi_i\,Z_\mu$$

$$\frac{g_{Vf}}{g_{Af}} = 1 - 4|Q_f|\sin^2\theta_{eff}^f$$

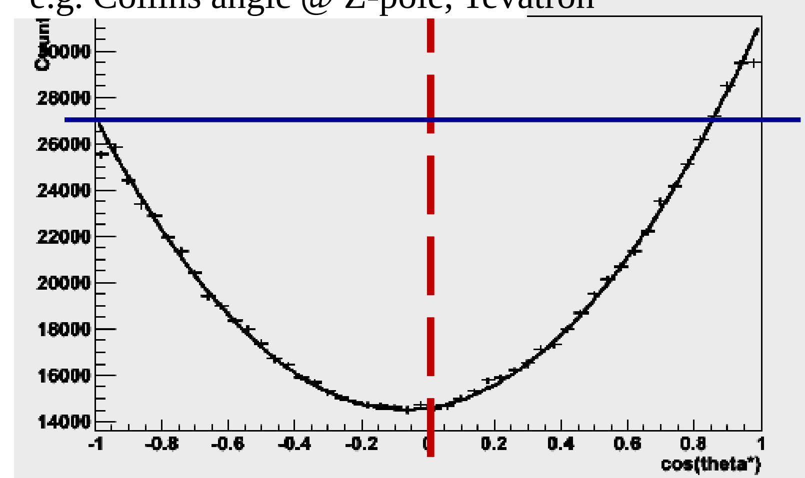
➢空间反演宇称破缺 → Forward/Backward Asymmetry A_{FB}



$$\sigma_{F/B} = \int_{0/-1}^{+1/0} \frac{d\sigma}{d\cos\theta}\, d\cos\theta$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

e.g. Collins angle @ Z-pole, Tevatron

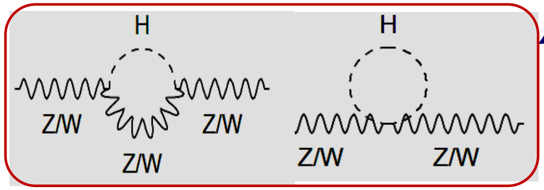


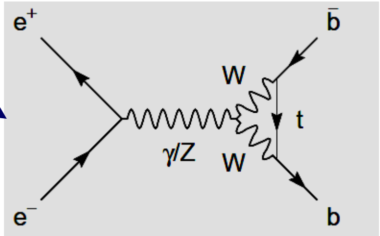
Effective mixing angle

- Defined at Z-pole as, flavor specified

$$
\begin{aligned}
\sin^2\theta_{\rm eff}^{\rm f} &\equiv \kappa_{\rm f}\sin^2\theta_{\rm W} \\
g_{\rm Vf} &\equiv \sqrt{\rho_{\rm f}}\,(T_3^{\rm f} - 2Q_{\rm f}\sin^2\theta_{\rm eff}^{\rm f}) \\
g_{\rm Af} &\equiv \sqrt{\rho_{\rm f}}\,T_3^{\rm f}\,,
\end{aligned}
$$

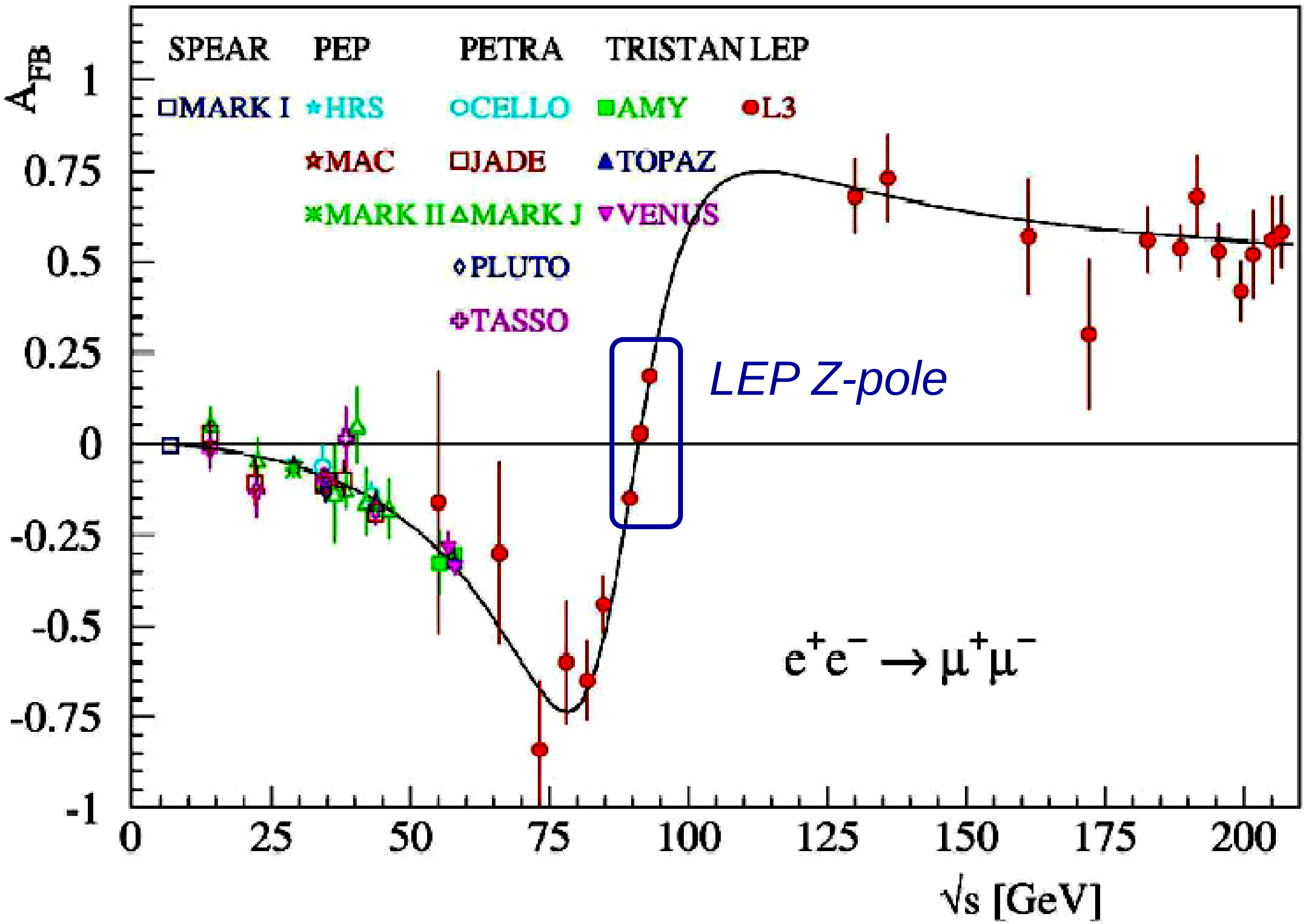
$$\kappa_{\rm f} \equiv \Re(\mathcal{K}_{\rm f}) = 1 + \boxed{\Delta\kappa_{\rm se}} + \boxed{\Delta\kappa_{\rm f}}$$





$$\frac{3G_{\rm F}m_{\rm W}^2}{8\sqrt{2}\pi^2}\left[\frac{m_{\rm t}^2}{m_{\rm W}^2}\frac{\cos^2\theta_{\rm W}}{\sin^2\theta_{\rm W}} - \frac{10}{9}\left(\ln\frac{m_{\rm H}^2}{m_{\rm W}^2} - \frac{5}{6}\right) + \cdots\right]$$

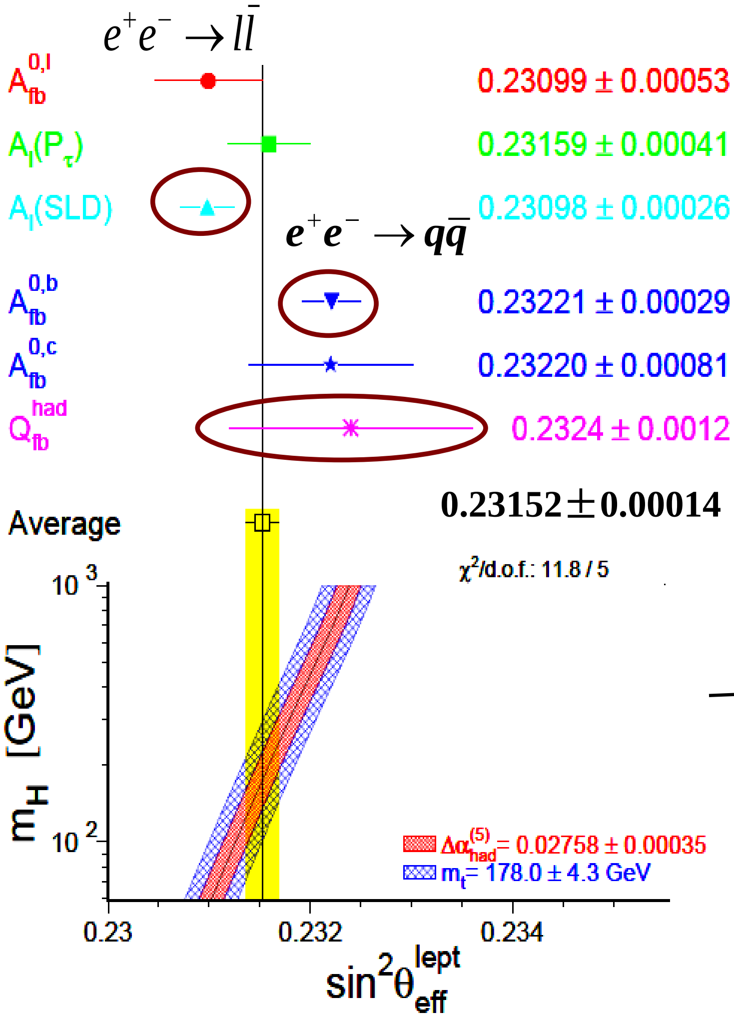
➢ ***A_{FB}*** Observable: $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$



Indirect measurement @ LEP/SLD

PDG: 世界最精确弱混合角 $sin^2\theta_W$测量结果

➢ **正负电子e^+e^-对撞机LEP/SLD精确测量:**

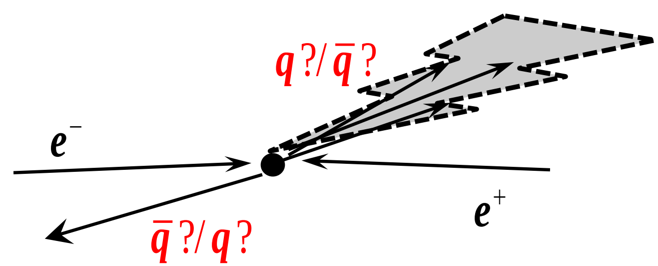


- **纯轻子测量与第三代夸克过程存在显著偏离**

  $A_L(SLD)$ vs. $A_{fb}^{0,b}$ → 3.5σ

- **检验Zuu/Zdd轻夸克过程**

  -- LEP强子单举测量 Q_{fb}^{had} :

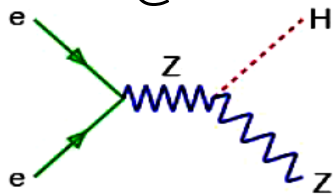


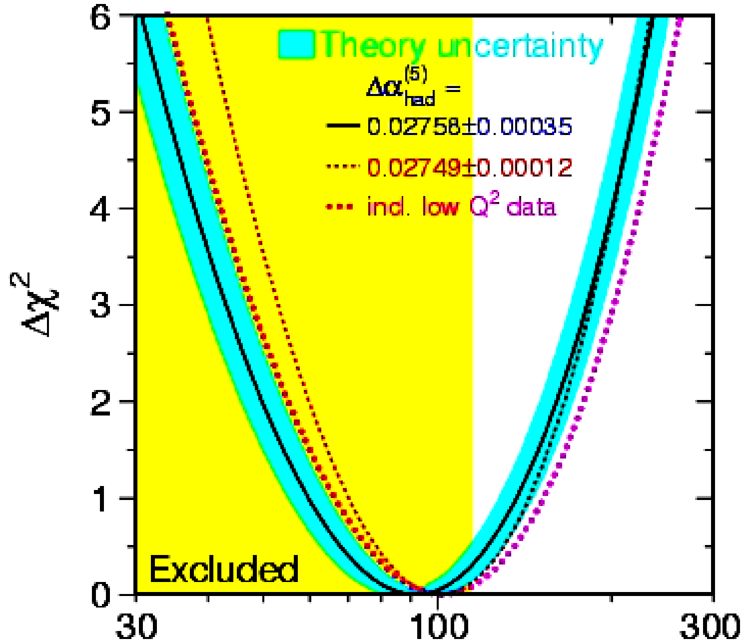
LEP实验存在末态quark强子化电荷不确定性, 从而引入很大的系统误差

0.2324 ±0.0012

Bounds on Higgs Mass

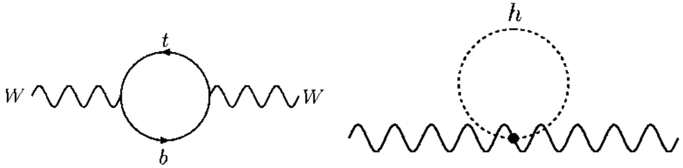
- Direct searches @ LEP

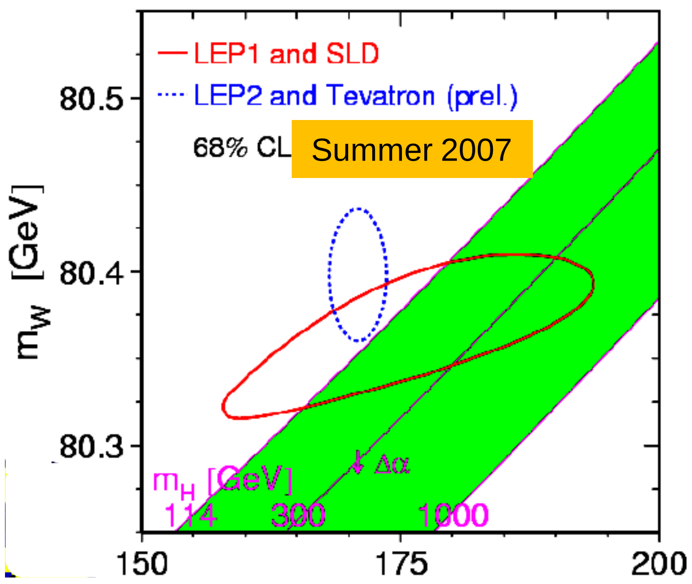




m_H>114 GeV @95%CL

- Indirect constraints: e.g. precision of M_W

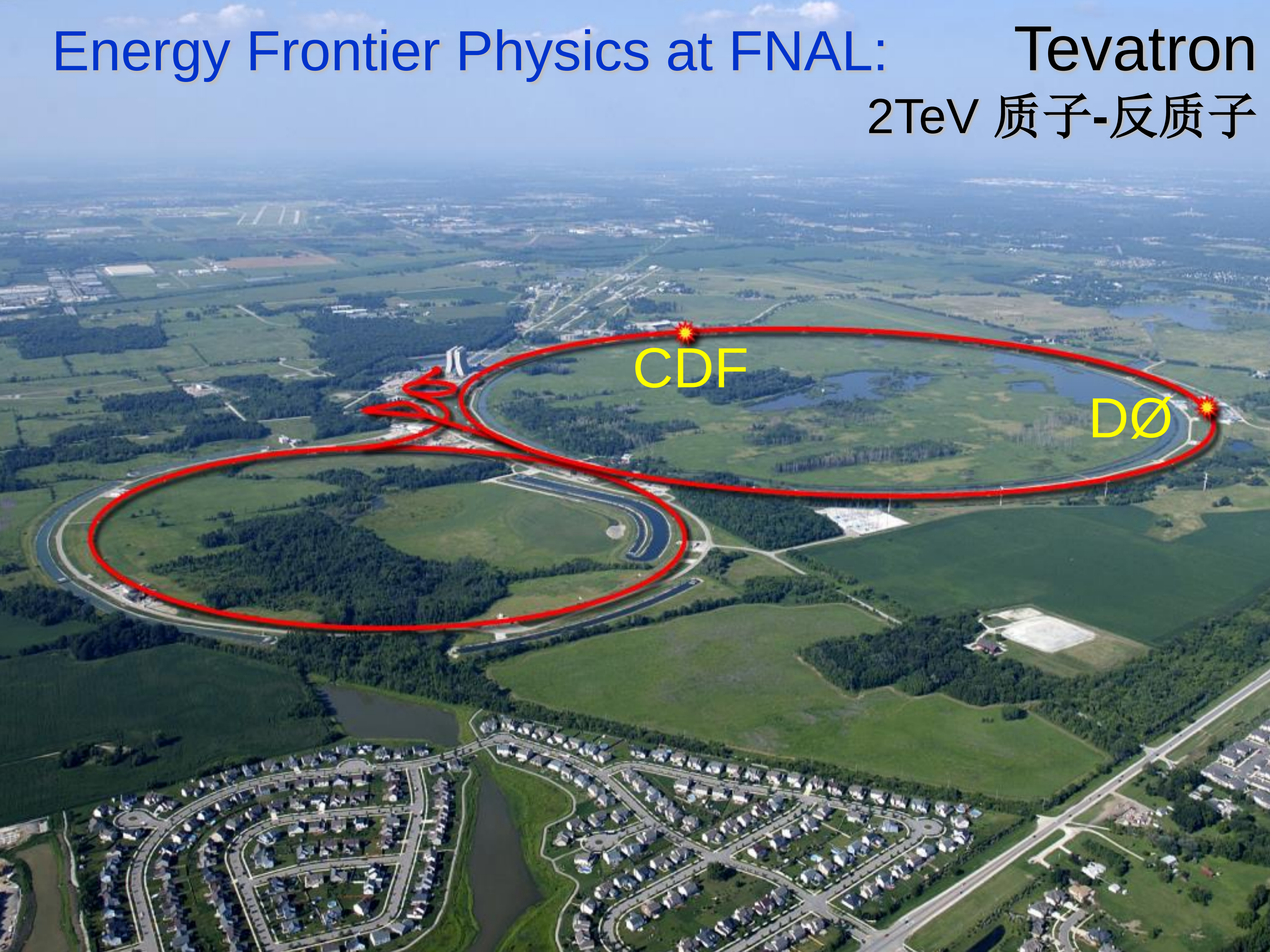




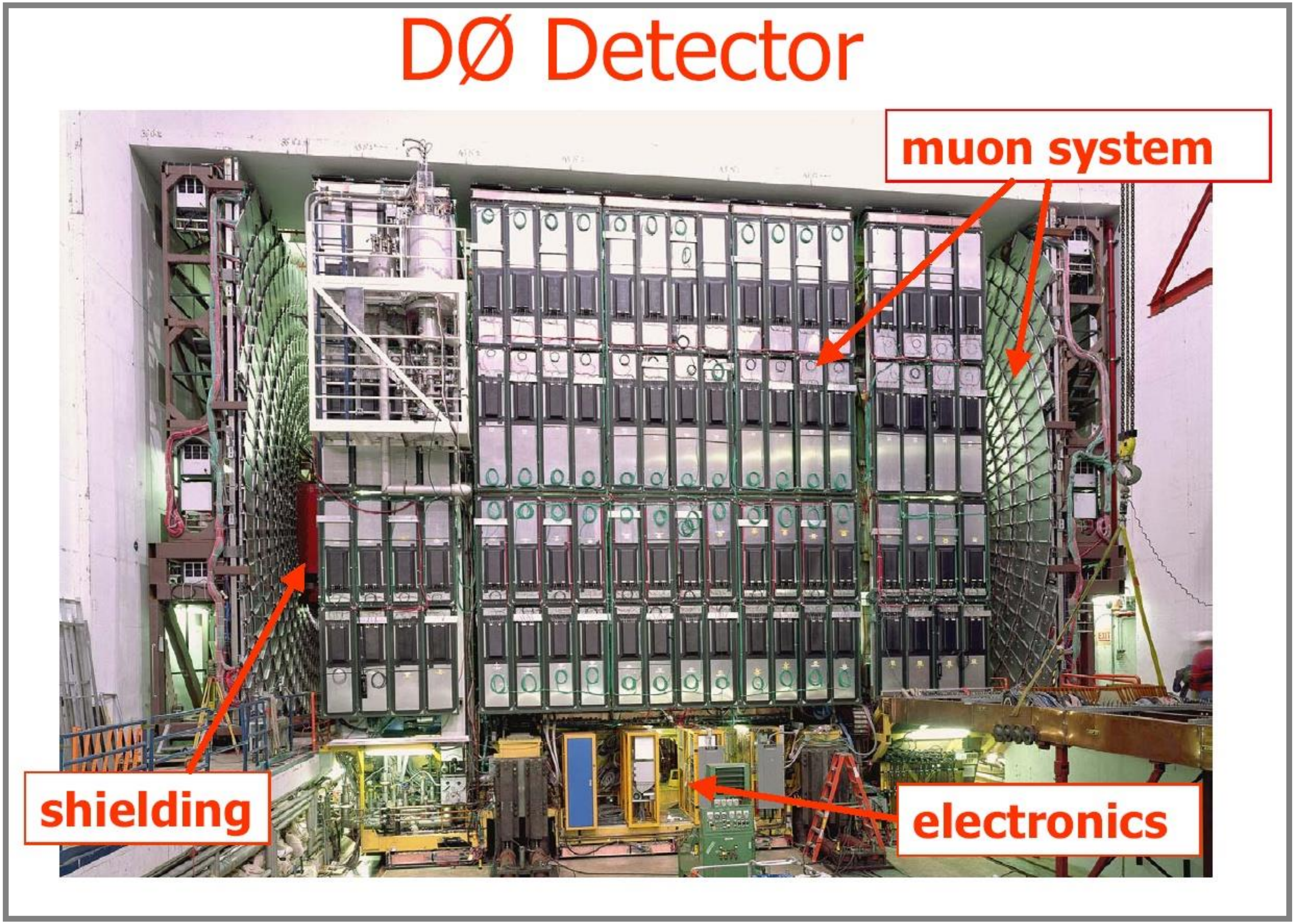
m_H<186 GeV @95%CL

Energy Frontier Physics at FNAL: Tevatron

2TeV 质子-反质子

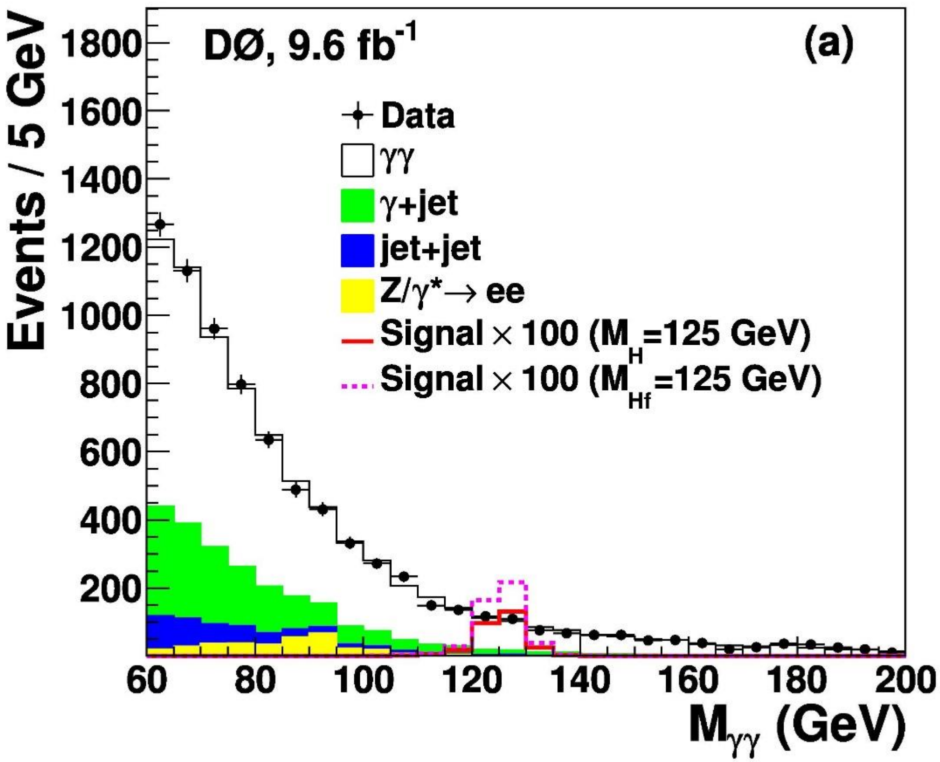


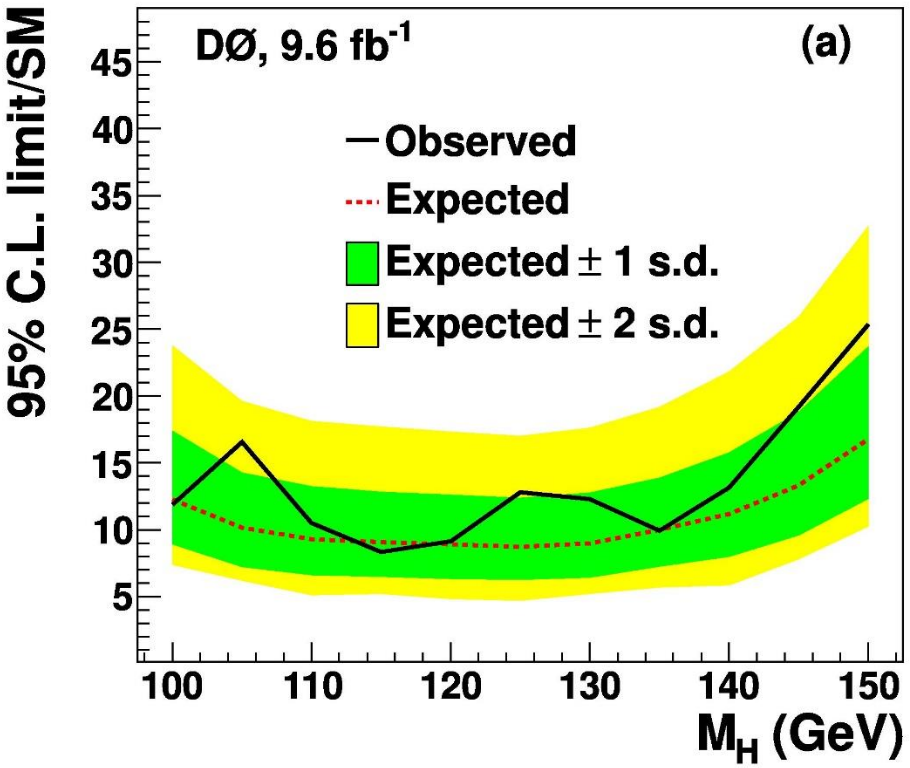
Detector, which we use to "see" particles:



Constraint of direct searching Higgs

$H \rightarrow \gamma\gamma$ @ D0

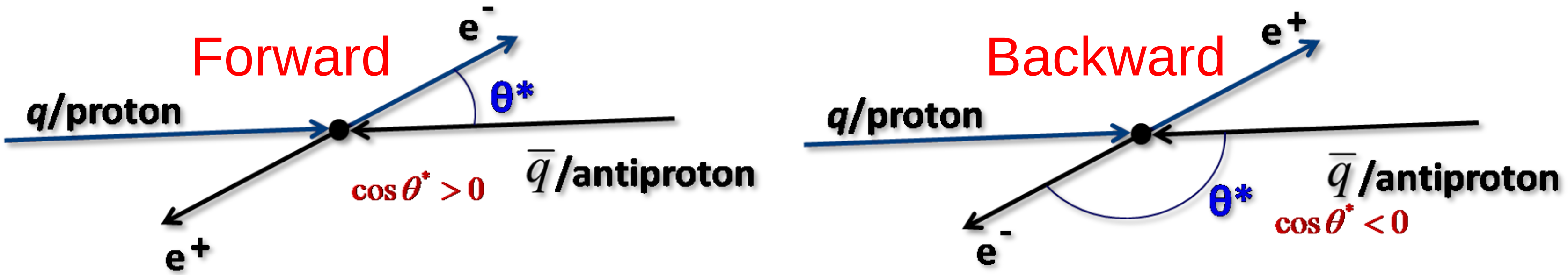




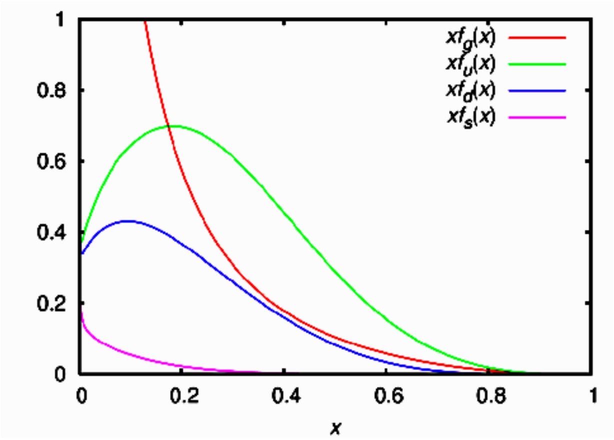
105 < m_H < 145 GeV @ Tevatron

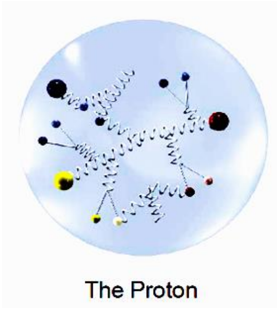
AFB @ Tevatron

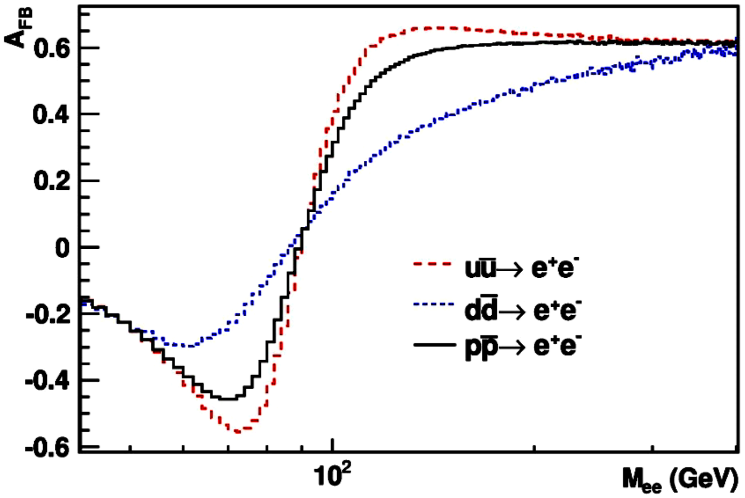
- Drell-Yan process : $P\overline{P} \rightarrow q\overline{q} \rightarrow Z/\gamma^{*} \rightarrow e^{+}e^{-}$



✓ Reversed process of LEP hadron inclusive, i.e.
quark component final *Fragmentation* → *initial Parton Distribution Function* (PDF)

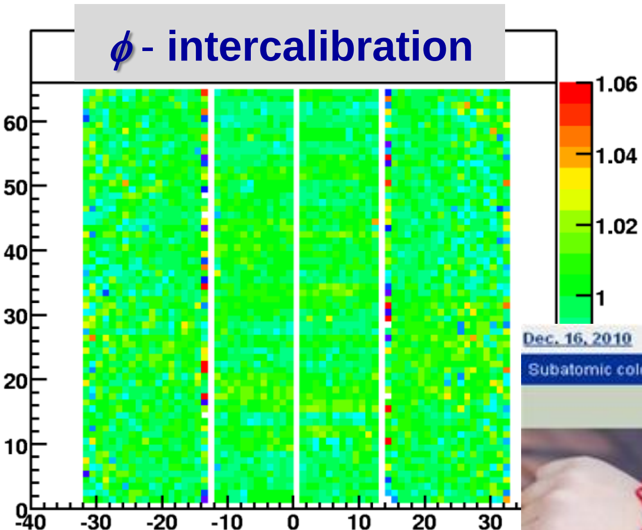




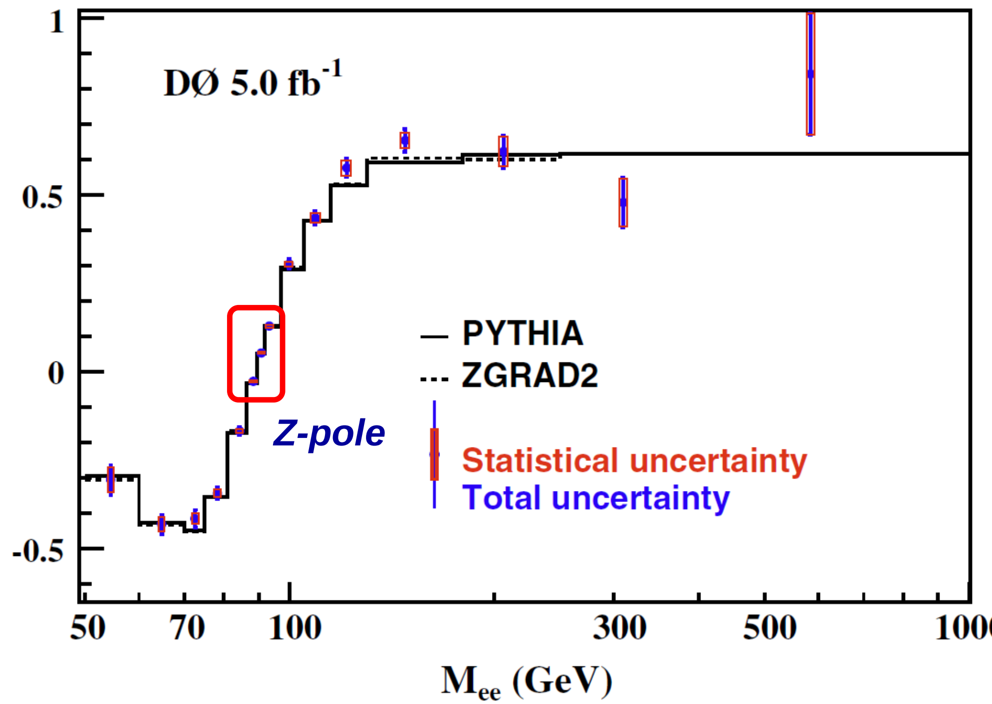


What can be achieved @ Tevatron

- **Calorimeter and electron energy/resolution calibration**



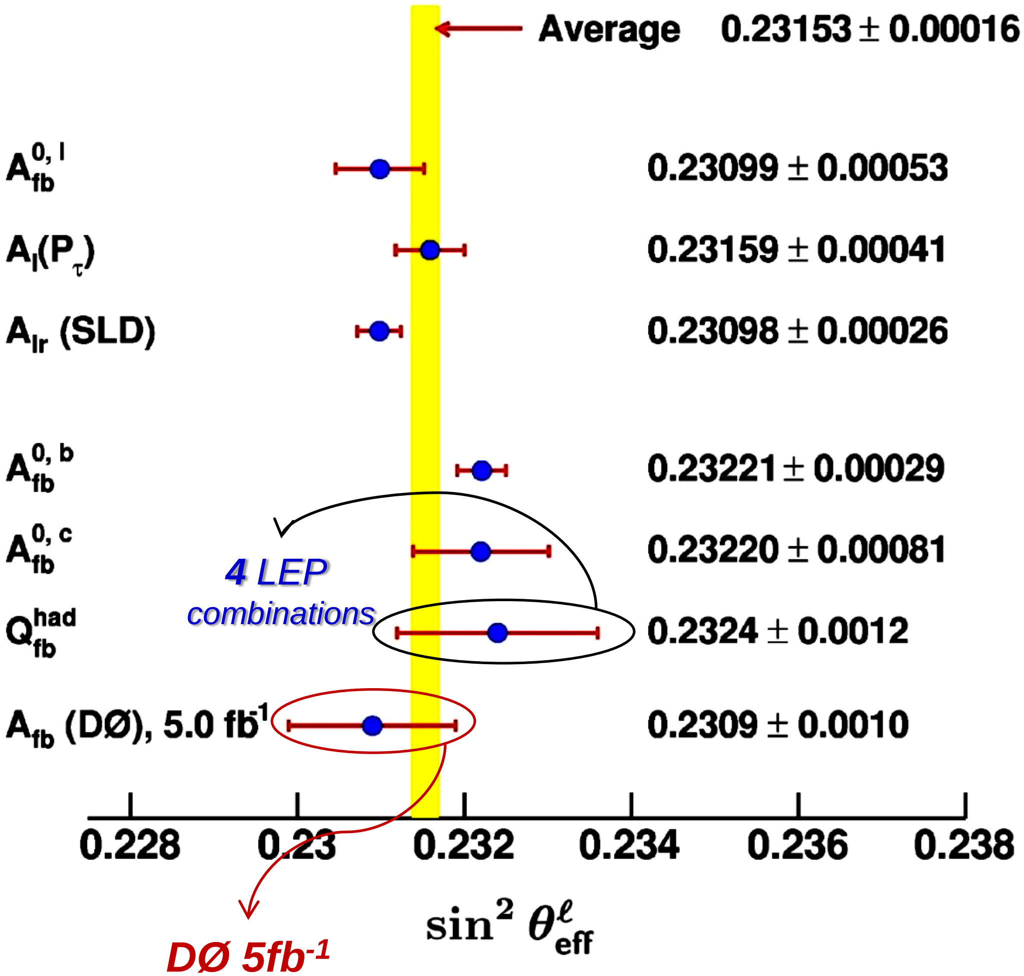
σ_e<< 1GeV @ Z-pole



The latest DØ result

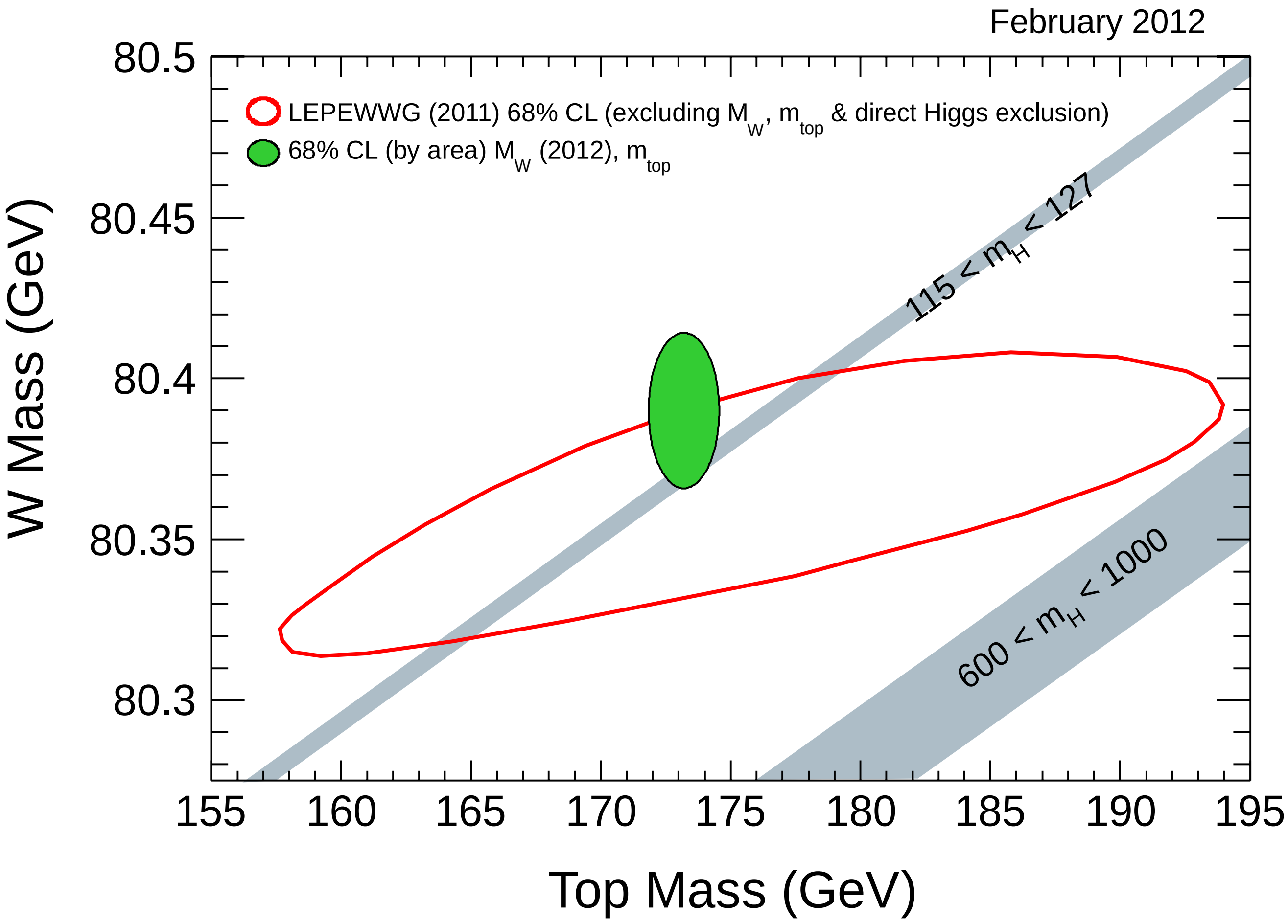
$0.2309 \pm 0.0008 \pm 0.0006$

(stat. dominated) (systematic)



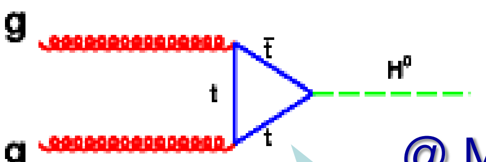
- 世界最精确的轻强子观测
- 统计误差仍大于系统误差

Indirect constraints on Higgs



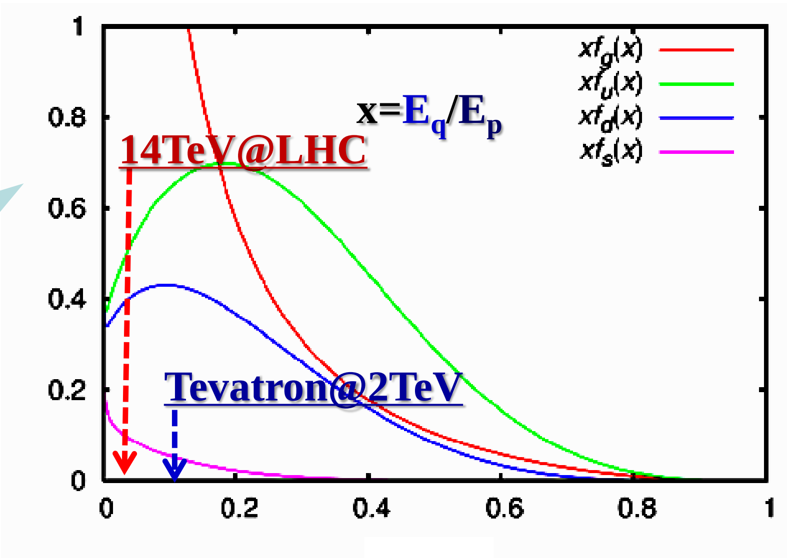
$115 < m_H < 127$ GeV @95%CL

Search the Higgs@LHC



@ M_H=125GeV

$$\sigma(pp \to H) \propto \int_0^1 \hat{\sigma}[g_1 g_2 \to H @ x_1 x_2 s, \alpha_s] \cdot f(x_1) f(x_2) \cdot dx_1 dx_2$$



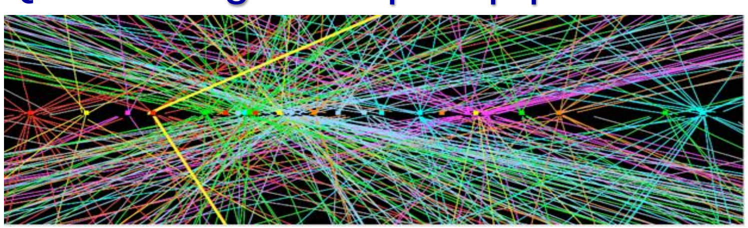
- 优势: high signal event yield @ LHC

	LHC	Tevatron
反应截面(pb)	～ 20	～ 1
峰值亮度($cm^{-2}s^{-1}$)	～7E33	～4E32

⇨ 稀有过程测量, e.g.

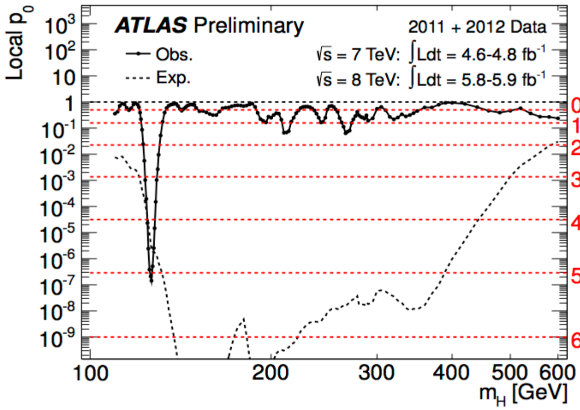
BR(H→γγ) ~ 0.1%

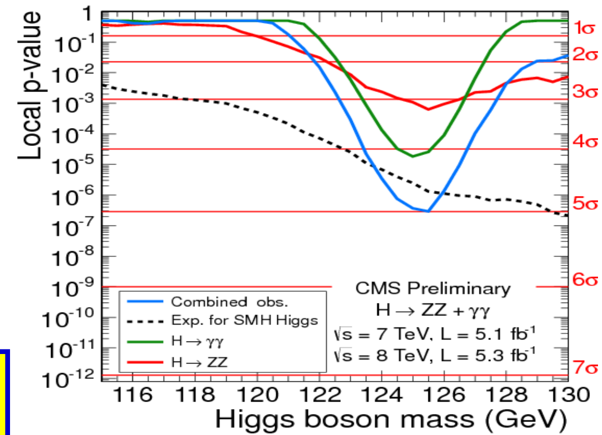
- 问题: high QCD background pileup production



⇨ **Impracticable for H→bb**

The Discovery of Higgs





5σ

The last missing piece was found
The great success of SM self-consistency

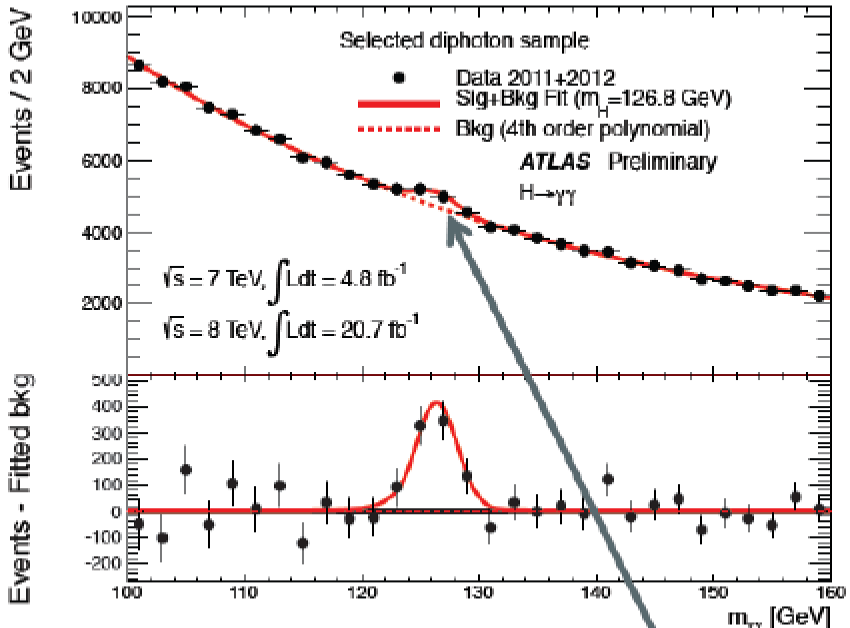
NEW:

Higgs particle at LHC (ATLAS, CMS)

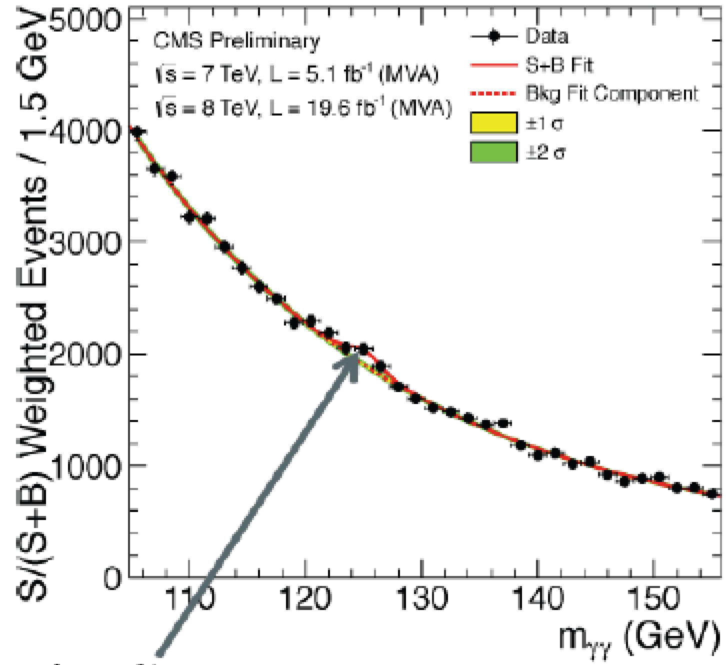
$H \to \gamma\gamma$

All 2011+2012 Data

ATLAS



CMS



7.4σ !

This is a Higgs signal!

3.2σ !

Both experiments expect around 4σ significance

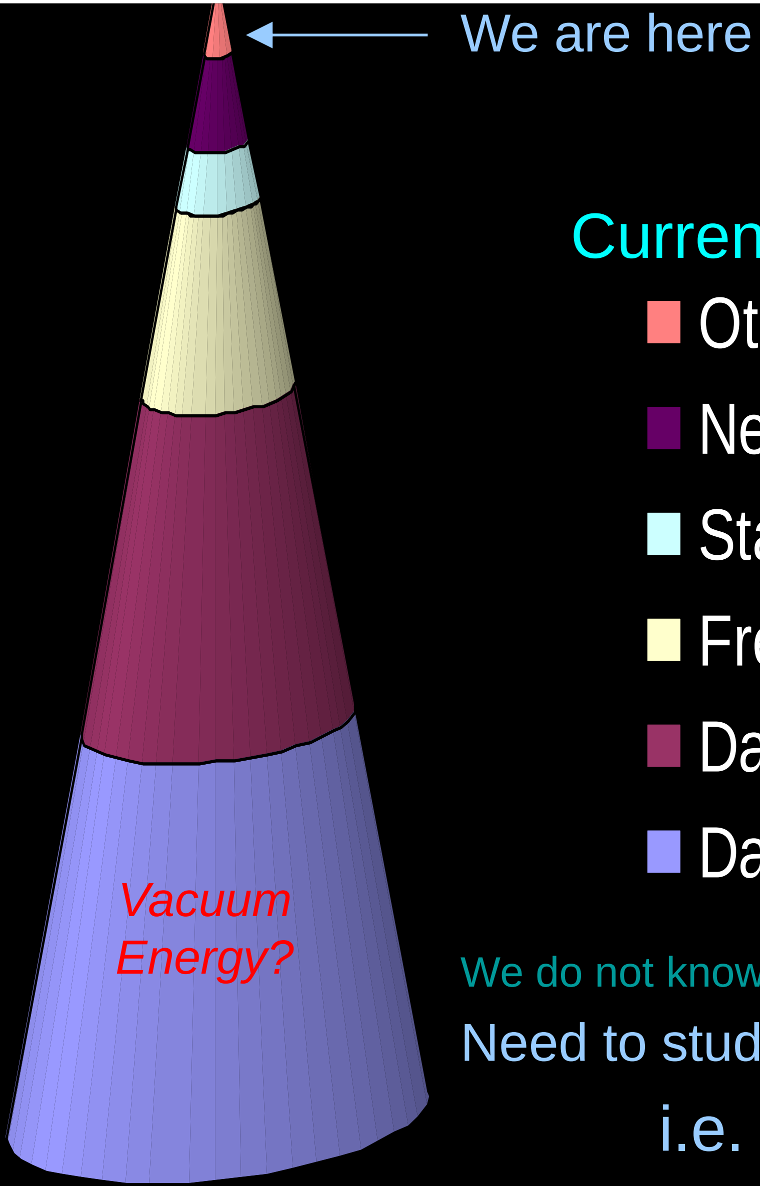
CMS (2013-01-01): m_h=126.2 ± 0.6 (stat.) ± 0.2 (syst.) GeV

ATLAS (2013-01-13): m_h=126.0 ± 0.4 (stat) ± 0.4 (sys)GeV

III. 新物理
New Physics

新世纪的关键科学问题

1. 什么是**暗物质**？
2. 什么是**暗能量**？
3. **宇宙**是如何开始的？
4. 如何结合爱因斯坦的**引力**理论和**量子效应**？
5. **中微子**问题？
6. **超高能粒子（宇宙线）**来自哪里？
7. **质子**不稳定吗？
8. 在极高密度和温度下，**新形态的物质**是什么样的？
9. 从**铁到铀**的各种重元素是如何形成的？
10. 是否存在**额外的时空维度**？
11. 四种相互作用力的**大统一**？



Current Universe Composition:

Other elements	0.03%
Neutrinos	0.3%
Stars	0.5%
Free H and He	4%
Dark matter	23%
Dark energy	72%

We do not know what makes up 95% of the universe.

Need to study it in controlled experiments,

i.e. @ Collider Physics

天上 vs. 地下: Dark Matter

Astronomical observations :

-- Gravity lensing : $G\frac{mM}{R^2} = m\frac{V^2}{R}$

-- Galaxy rotation $V^2 \neq G\frac{M}{R}$

But its properties do not fit any of the standard particles.

Dark Matter is a new form of matter

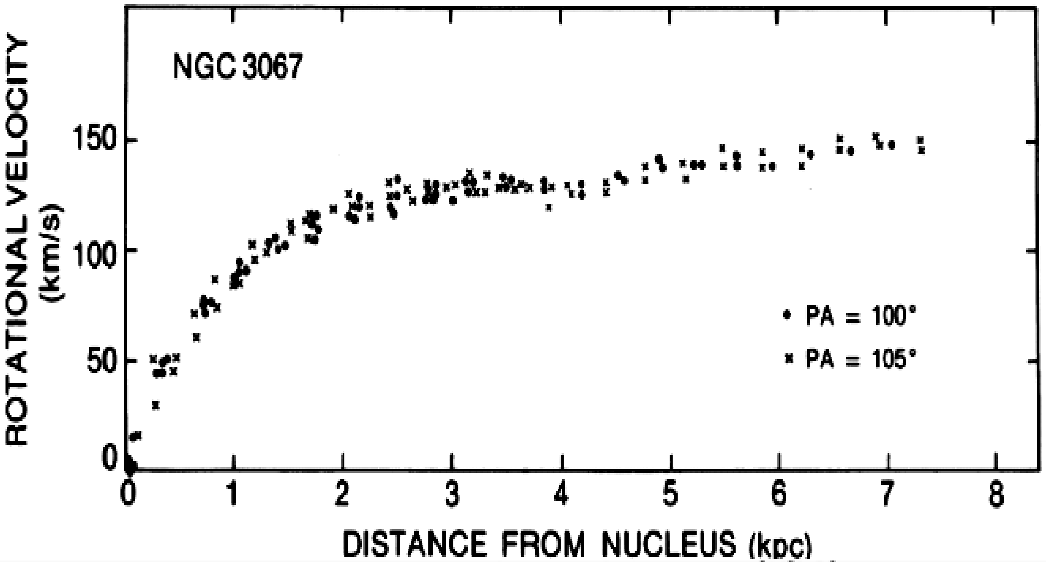
暗物质的基本粒子物理解释？*超对称新粒子* $\tilde{\chi}^0$?

• Exercise :

$F = ma = m(GM/R^2)$
$= m\, v^2/R$

$v^2 = GM/R$

• What really happens:



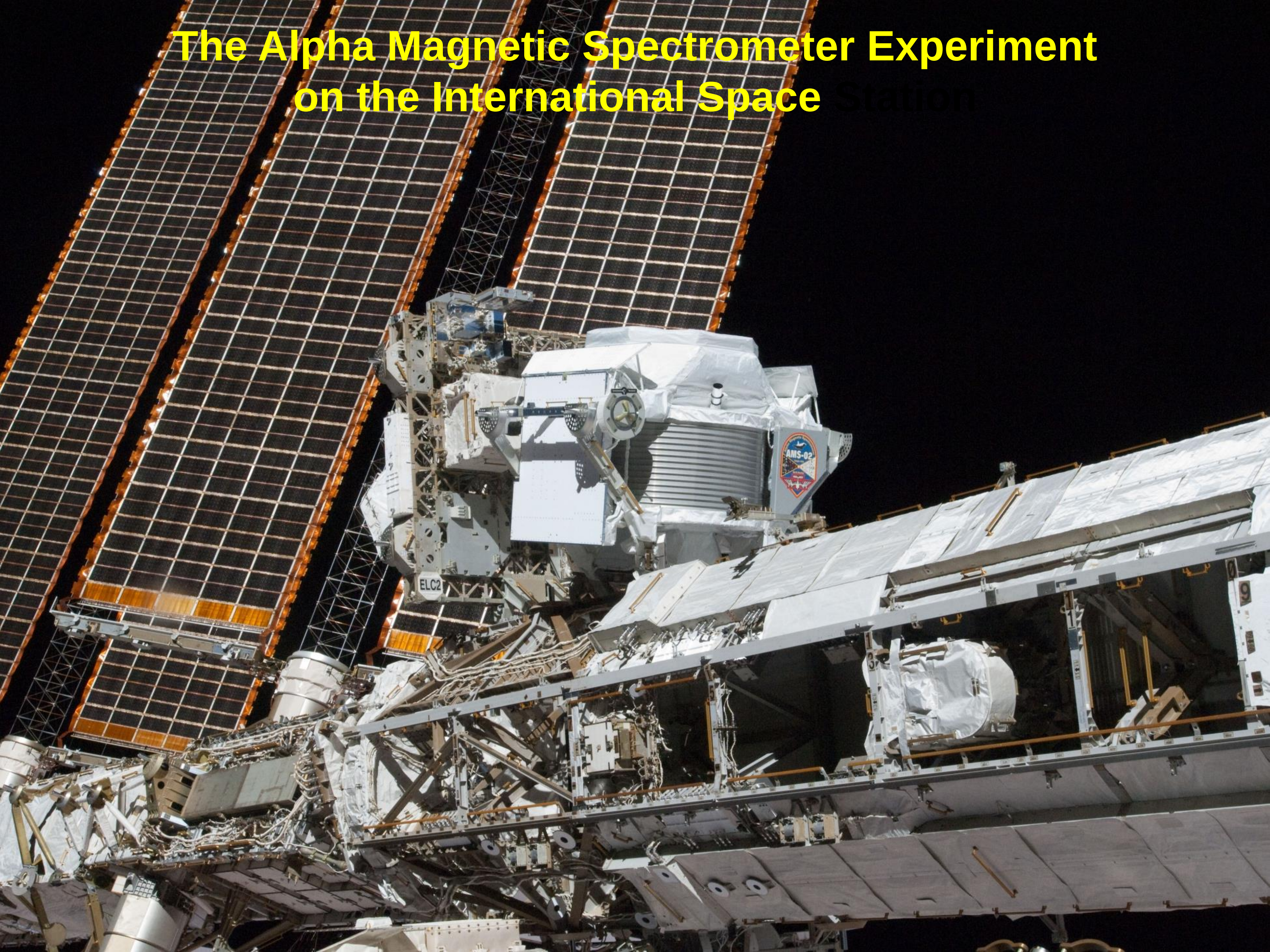
Vera Rubin

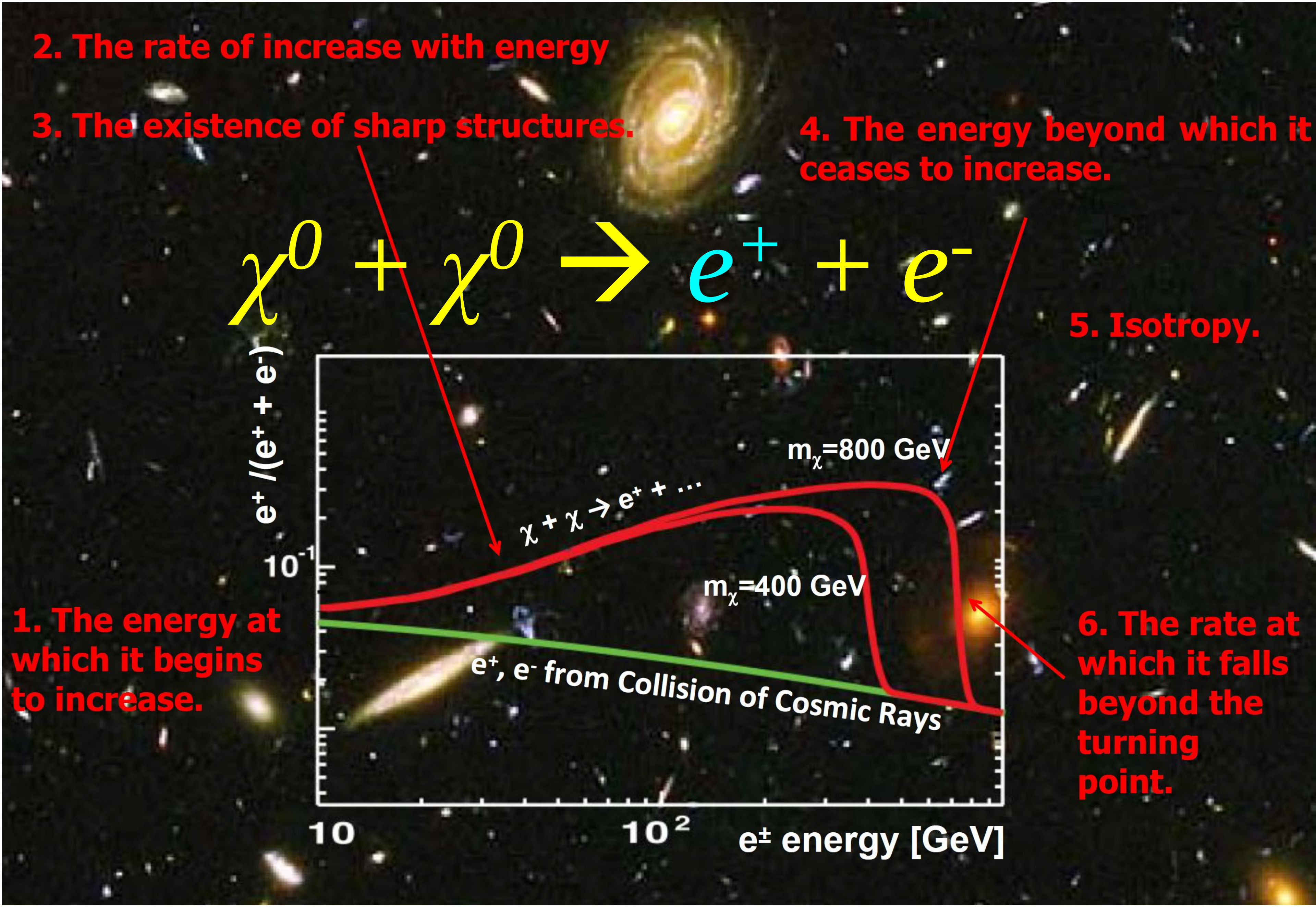
Rubin, Thonnard, Ford

"Such a velocity implies that 94% of the mass is located beyond the optical image; this mass has a ratio M/L greater than 100."

The Alpha Magnetic Spectrometer (AMS) Experiment

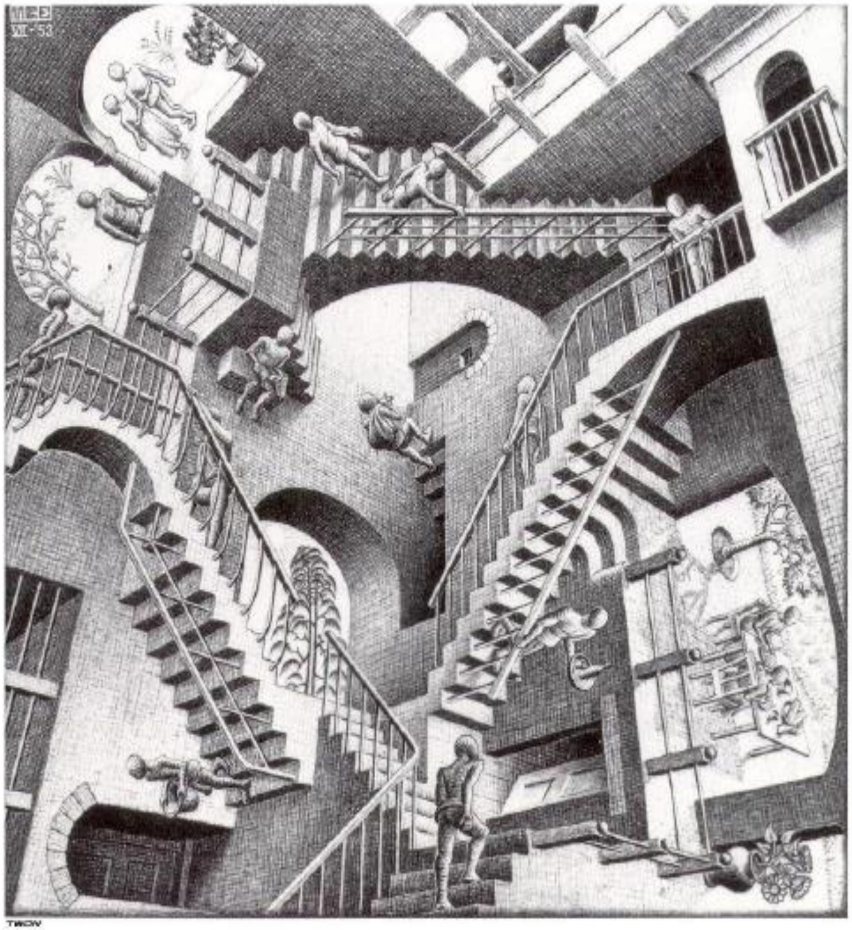
The Alpha Magnetic Spectrometer Experiment on the International Space Station





2. The rate of increase with energy
3. The existence of sharp structures.
4. The energy beyond which it ceases to increase.
$\chi^0 + \chi^0 \rightarrow e^+ + e^-$
5. Isotropy.
$e^+/(e^+ + e^-)$
10^{-1}
m_χ=800 GeV
$\chi + \chi \rightarrow e^+ + \dots$
m_χ=400 GeV
1. The energy at which it begins to increase.
e^+, e^- from Collision of Cosmic Rays
6. The rate at which it falls beyond the turning point.
10
10^2
$e^\pm$ energy [GeV]

最小空间结构：3维 or 3+n维？



M.C.Escher, Relativity (1953)

M.C.Escher, Mobius Strip II (1963)

最小空间结构：3维 or 3+n维？

3d space → a compactified n-torus with

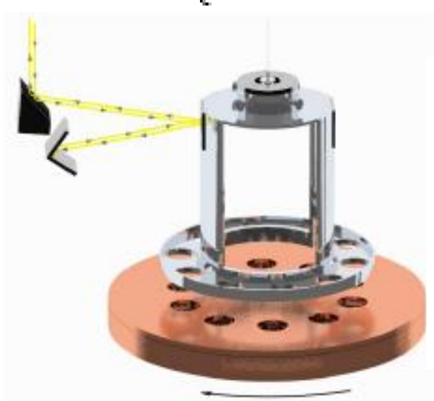
(x,y,z) → R radius

$V_n=(2\pi R)^n$ volume

eg "1+1":

Gravitational potential

$$
\begin{cases}
V(r) = \dfrac{1}{M_D^{n+2}} \dfrac{m_1 m_2}{r^{n+1}}, & \text{for } r \ll R \\
V(r) = \dfrac{1}{M_D^{n+2}} \dfrac{m_1 m_2}{R^n r} \propto \dfrac{1}{M_{Pl}^2} \dfrac{m_1 m_2}{r}, & \text{for } r \gg R
\end{cases}
$$



The Eöt-Wash results rule out n=2 extra dimensions for R > 0.19 mm (or M_S < 1.9 TeV)

→ 额外空间维度？

n≥3, R≤10nm

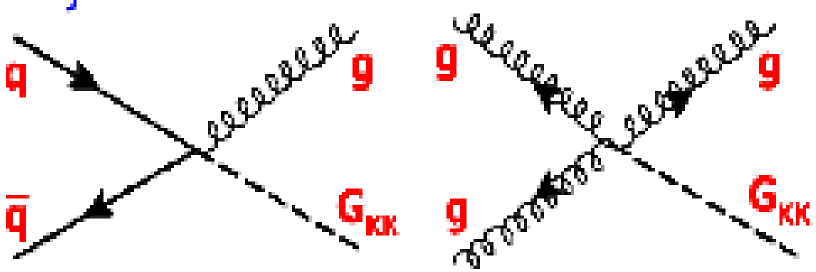
Graviton

in extra (3+n)D: massless → a large number of excitations → in ordinary 3D: massive Kaluza-Klein modes G_{kk}, couple to energy-momentum tensor

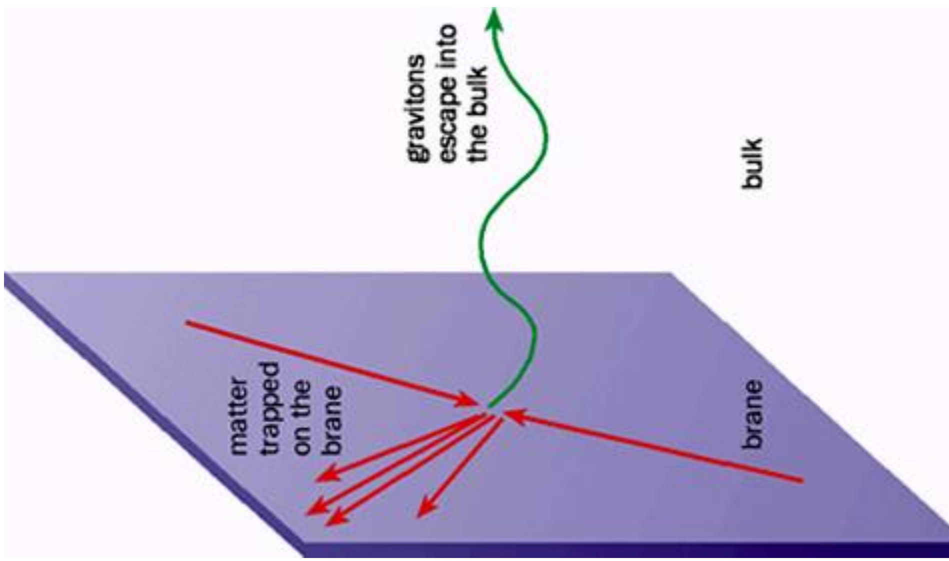
How to test?

Real Graviton Emission

Monojets at hadron colliders



Signal: monojet+missing ET



Universal written in a piece of paper

$$S = \int dx \cdot \sqrt{g} \left[\frac{1}{G} R + \frac{1}{g^2} F^2 + \bar{\psi} \not{D} \psi + (D\phi)^2 + V(\phi) + \bar{\psi} \phi \psi \right]$$

引力的本质?

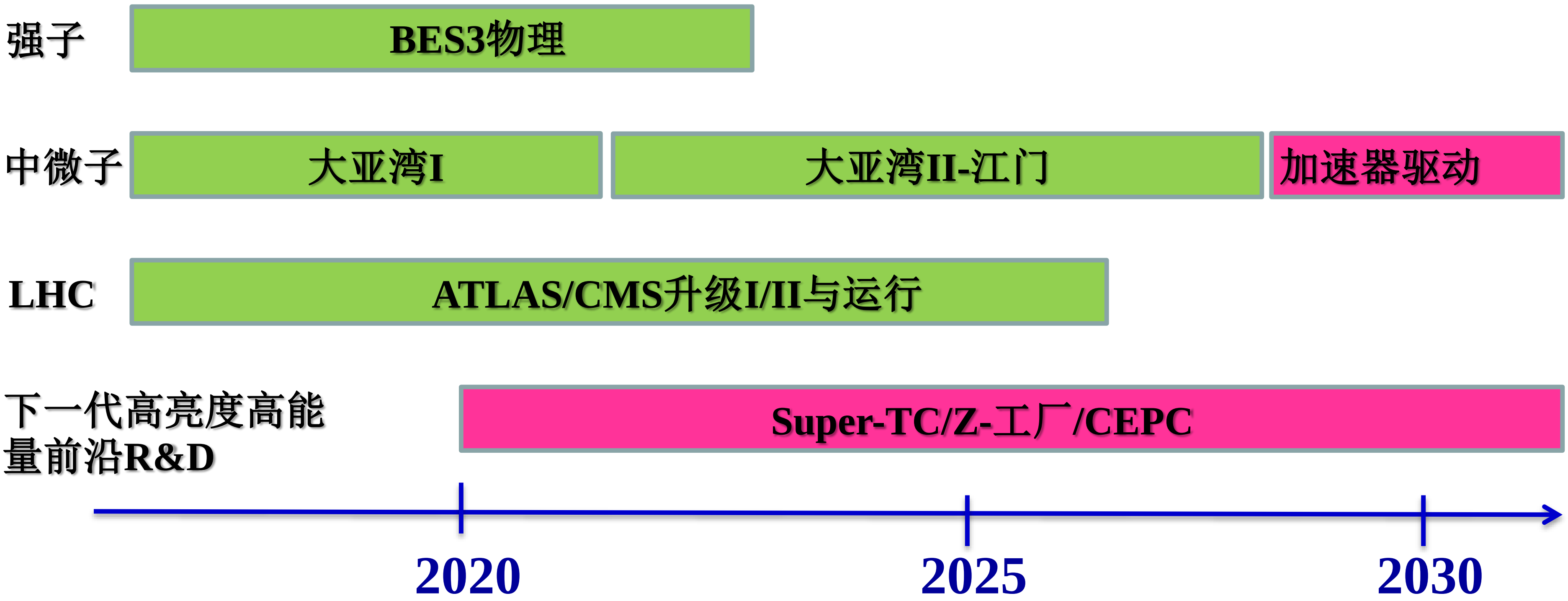
创世纪
上帝说: **“要有光!”**

宇宙的基石:
基本粒子
及其相互作用

“最小”时空结构?
真空是什么?

基本粒子的
质量来源?

中国粒子物理发展路线图



通过未来20-30年的努力：

- 建成具有国际领先水平的实验装置，获得具有突破性的科学研究成果
- 成为世界最高水平的高能物理中心之一