粒子物理

28. EW Theory at the Colliders

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北京大学物理学院

Who am I?

Why am I here?

Where am I going?

Lamb’s Nobel Lecture

WILLIS E. LAMB, JR.

Fine structure of the hydrogen atom

Nobel Lecture, December 12, 1955

When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called « elementary particles »: the electron and the proton. A deluge of other « elementary » particles appeared after 1930; neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons. I have heard it said that « the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine ».

Tears of Joy

- History of particle hunting
  - W and Z boson discovery (1983)
    Theory 1973 — 10 years
  - Top-quark discovery (1995)
    Existence: $b\bar{b}$ FB asymmetry (1977) — 18 years
  - Higgs-like scalar discovery (2012)
    Theory 1964 — 48 years

History is not just a thing of the past!

July 4th , 2012

July 4th 2012 The discovery of a new particle

From J. Ellis's talk at 7th workshop of TeV scale physics at Tsinghua University, 11-11-2012

Tears of Joy

- History of particle hunting
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    10 years
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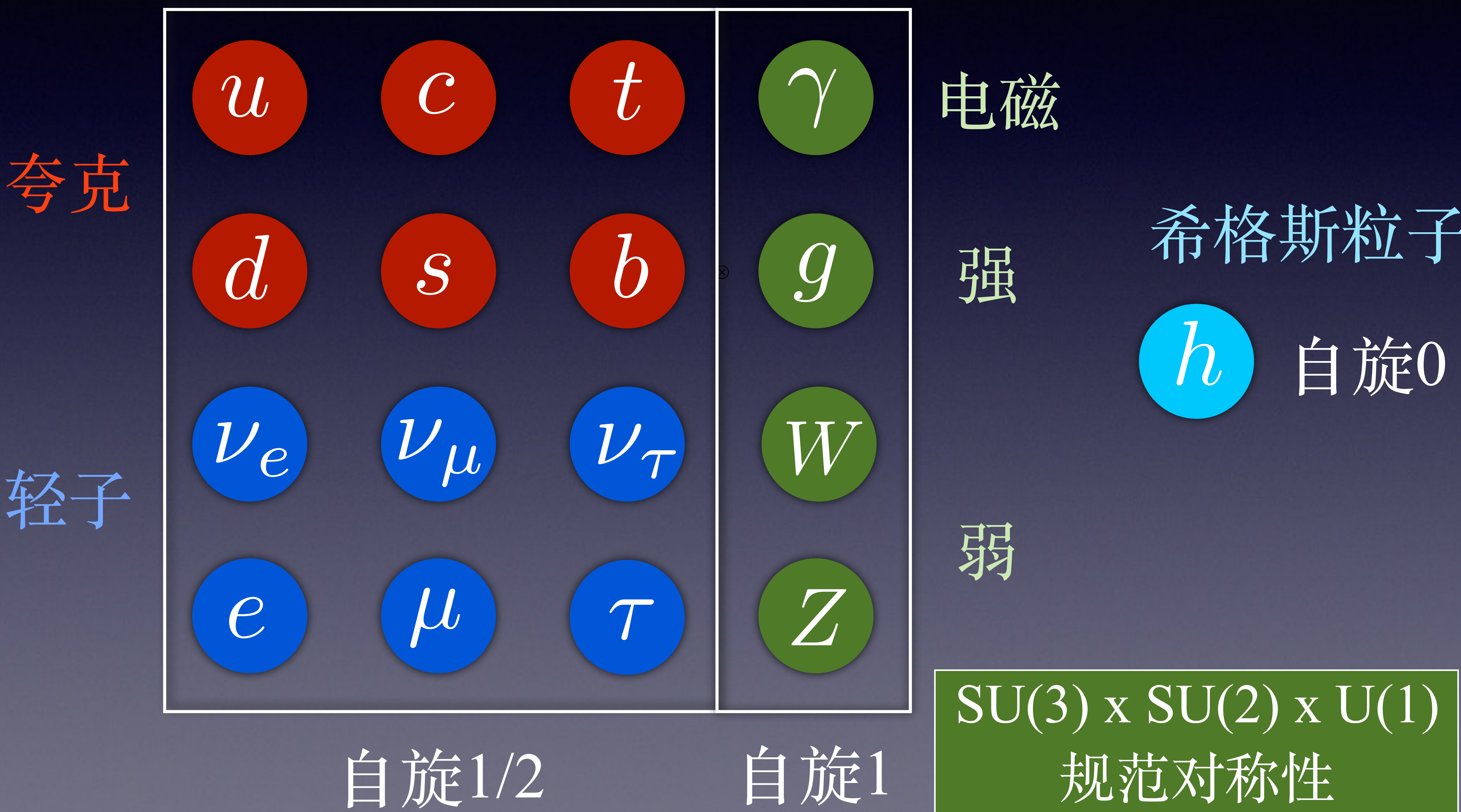
    18 years
  - Higgs-like scalar discovery (2012)
    Theory 1967
    48 years
  - New Physics beyond the SM
    Extra dim (KK, 1921)
    SUSY (1966)
    ?years

粒子物理的标准模型

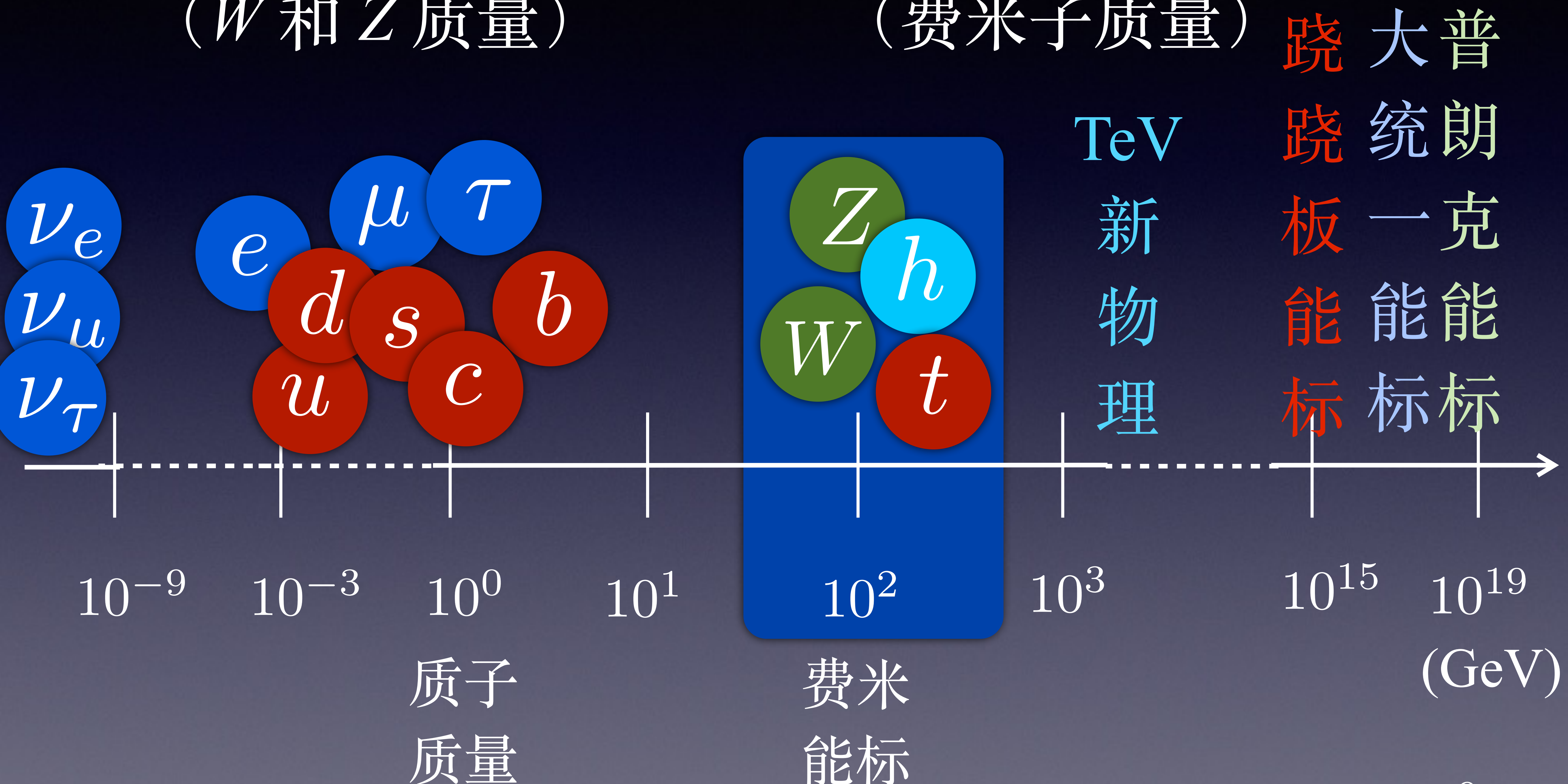
已知基本粒子谱



标准模型的两大疑难

电弱对称性破缺起源 和 味对称性破缺起源

（W 和 Z 质量） （费米子质量）

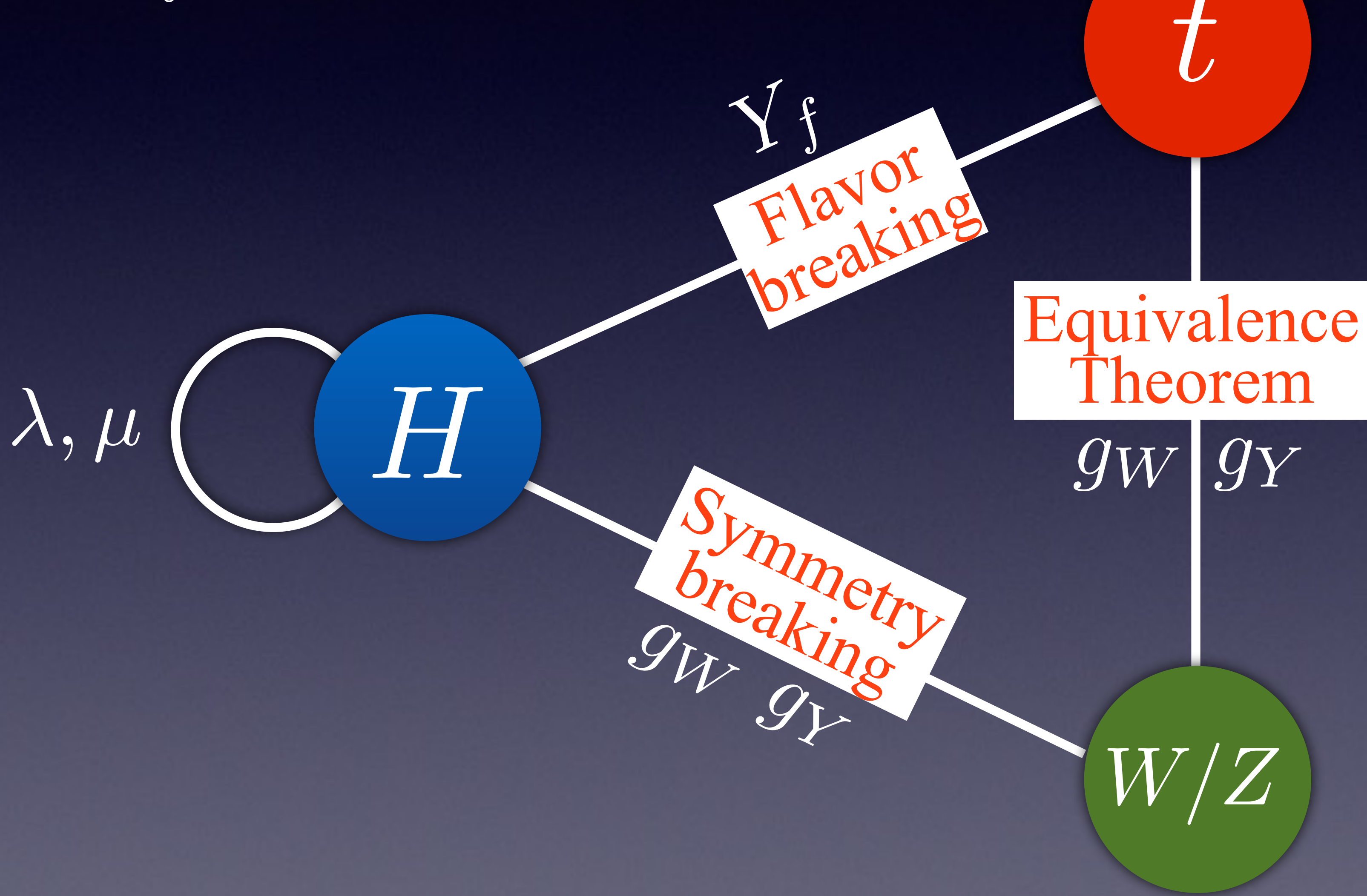


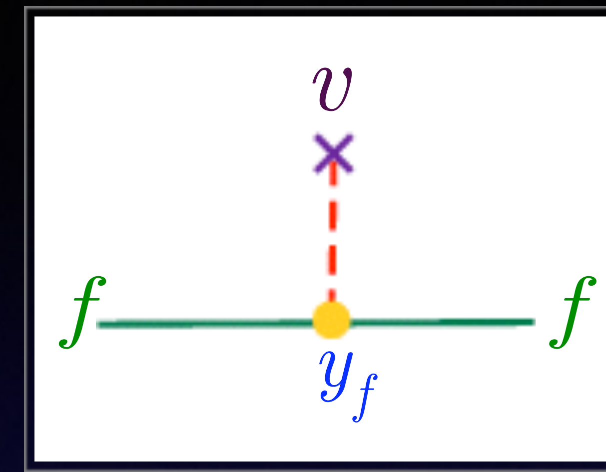
$\text{GeV} = 10^9\text{eV}$

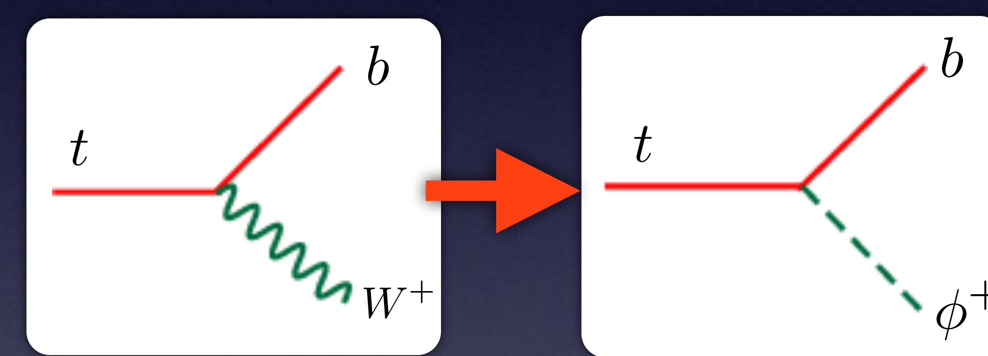
Electroweak triangle

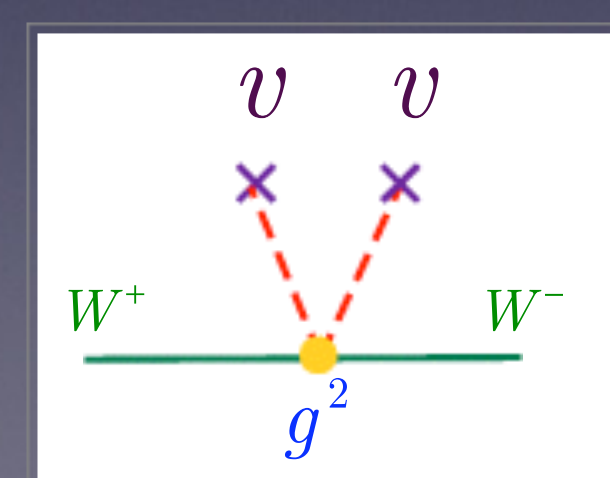
$$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$

$$+ y_f \bar{F}_L \Phi f_r + \cdots$$





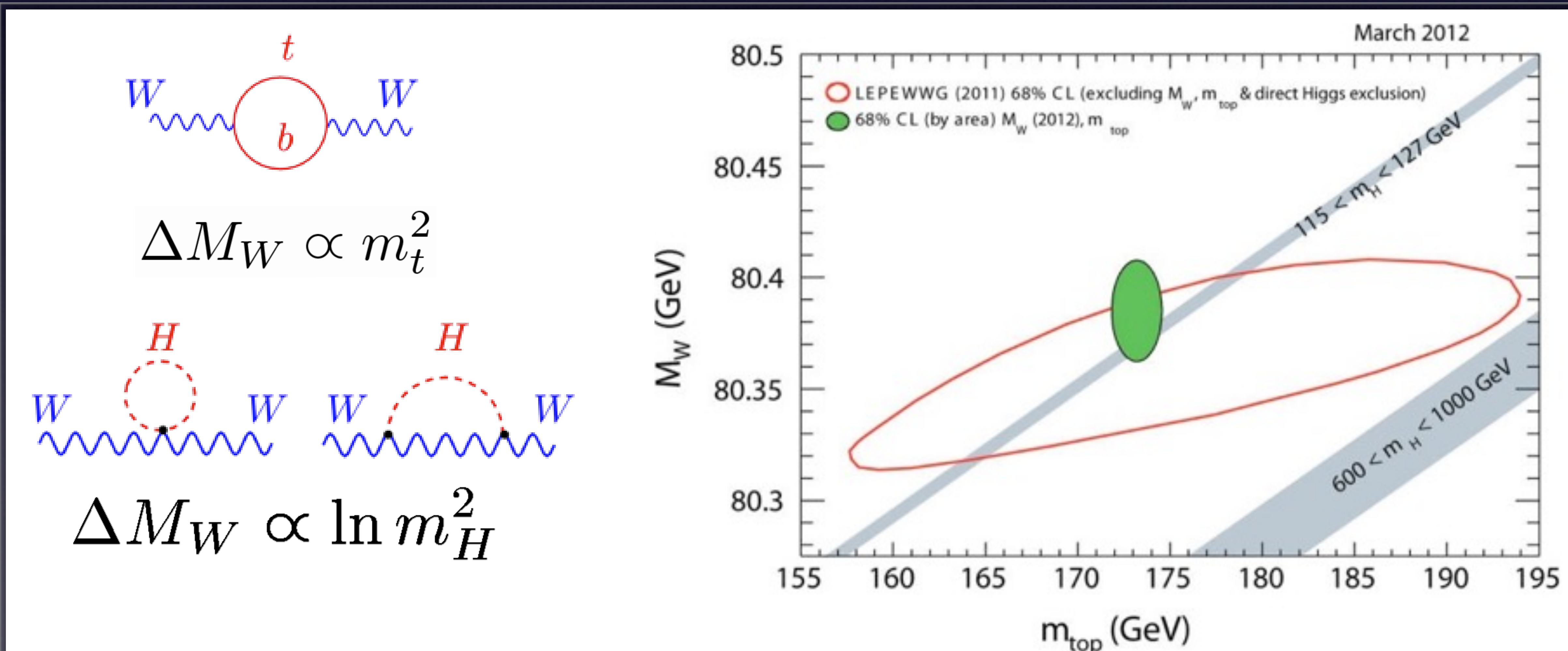




W-boson, Top-quark and Higgs boson

- Highly correlated at the quantum level

$$M_W = 80.3827 - 0.0579 \ln\left(\frac{M_H}{100\text{ GeV}}\right) - 0.008 \ln^2\left(\frac{M_H}{100\text{ GeV}}\right)$$
$$+0.543\left(\left(\frac{m_t}{175\text{ GeV}}\right)^2 - 1\right) - 0.517\left(\frac{\Delta\alpha^{(5)}_{had}(M_Z)}{0.0280} - 1\right) - 0.085\left(\frac{\alpha_s(M_Z)}{0.118} - 1\right)$$



Outline

- LEP

  Precision machine

- Tevatron

  Precision machine + discovery machine

- LHC

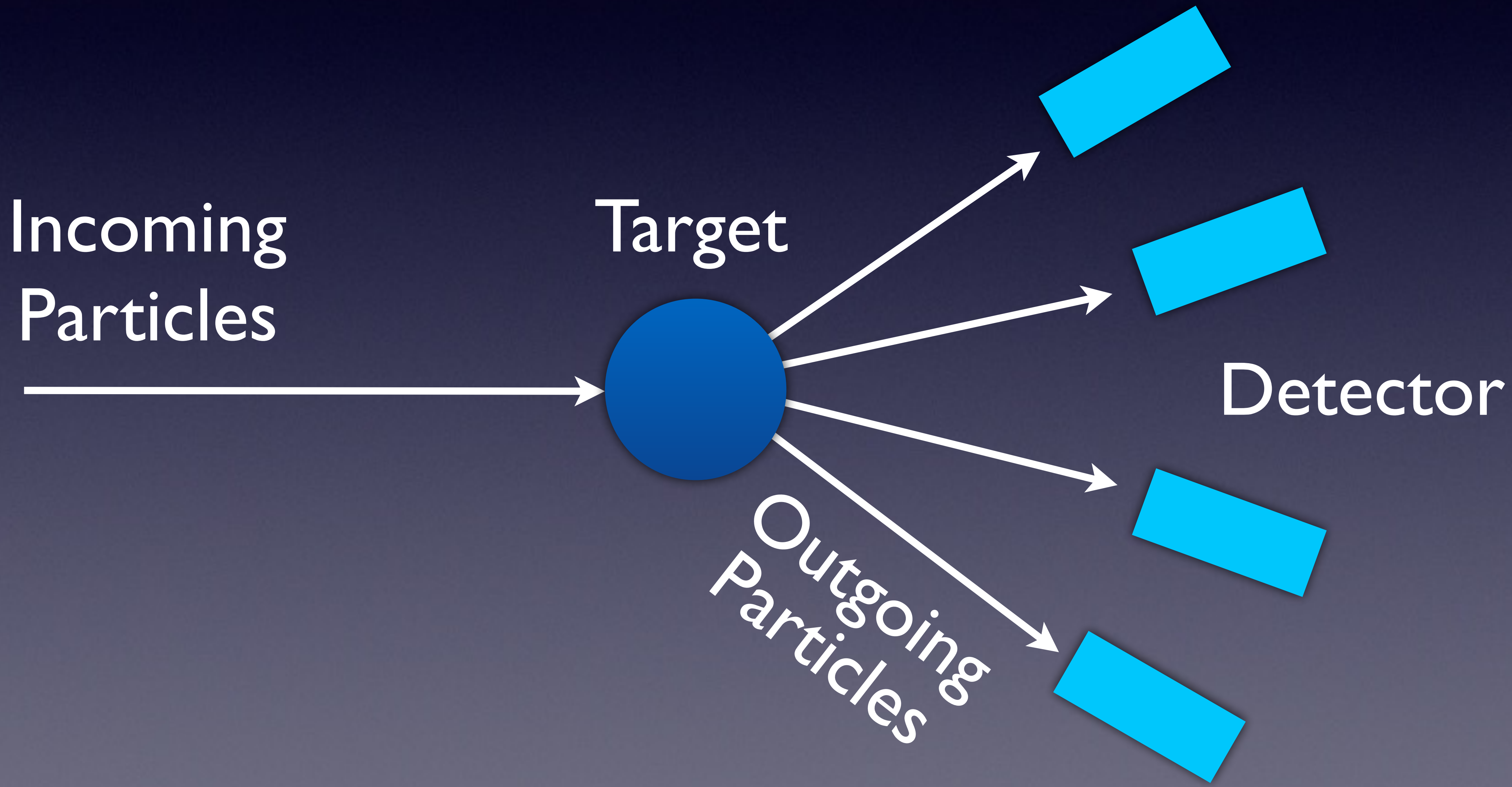
  Discovery machine + Precision machine

  Higgs boson and others

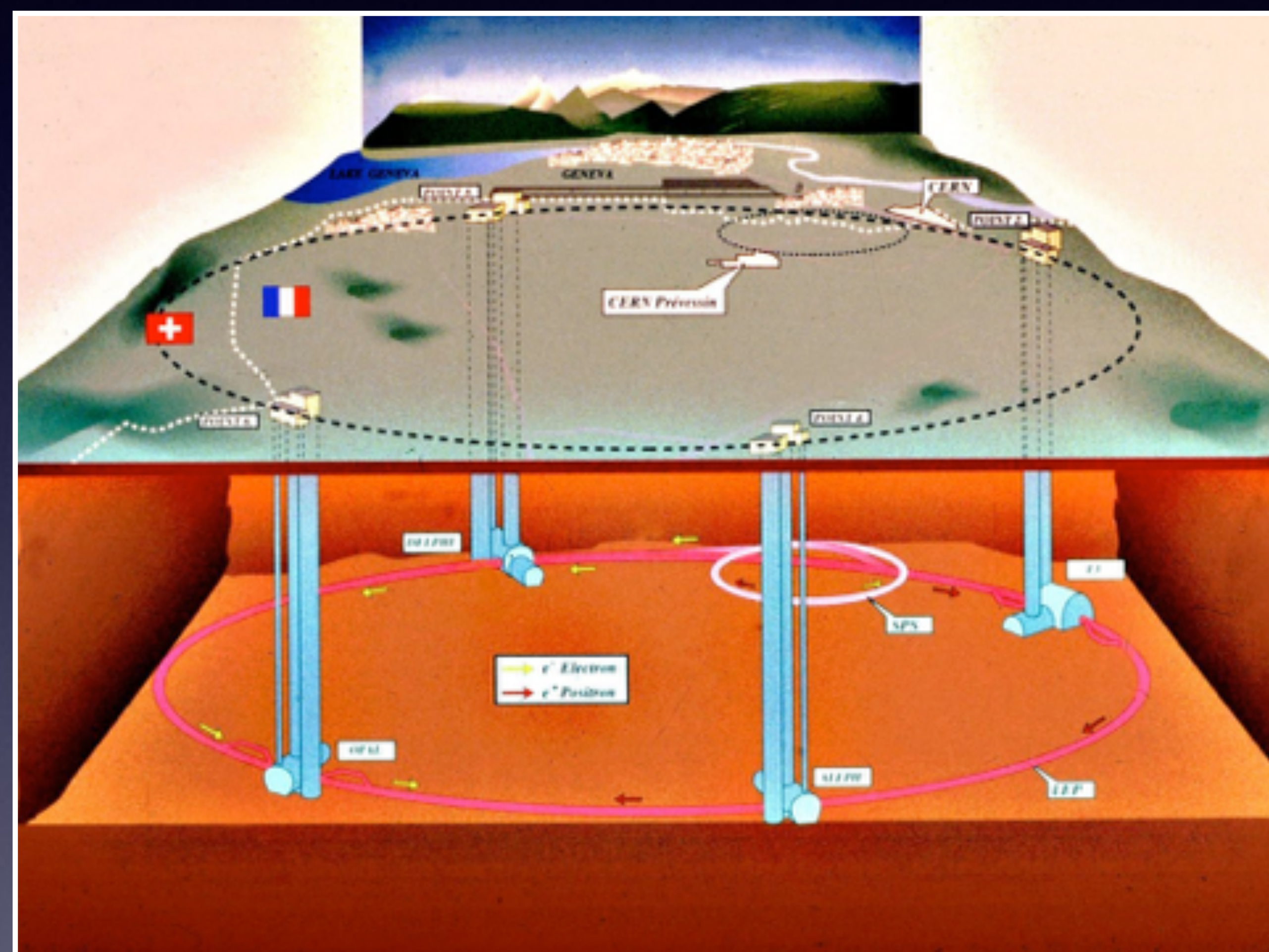
- SLHC, VLHC, Higgs Factory, ILC, ...

Rutherford scattering

1909-1911 : The begin of the collider experiments

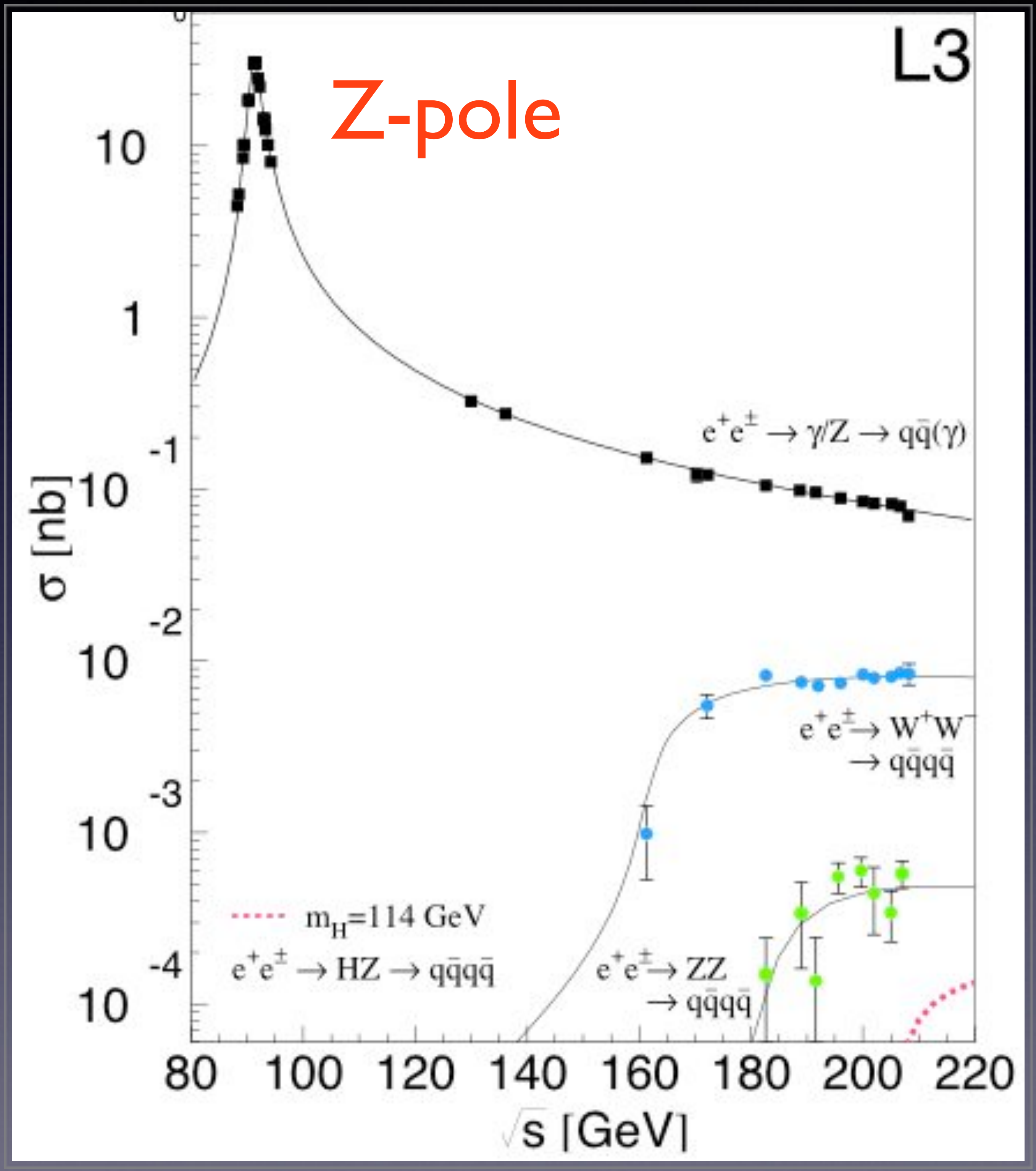


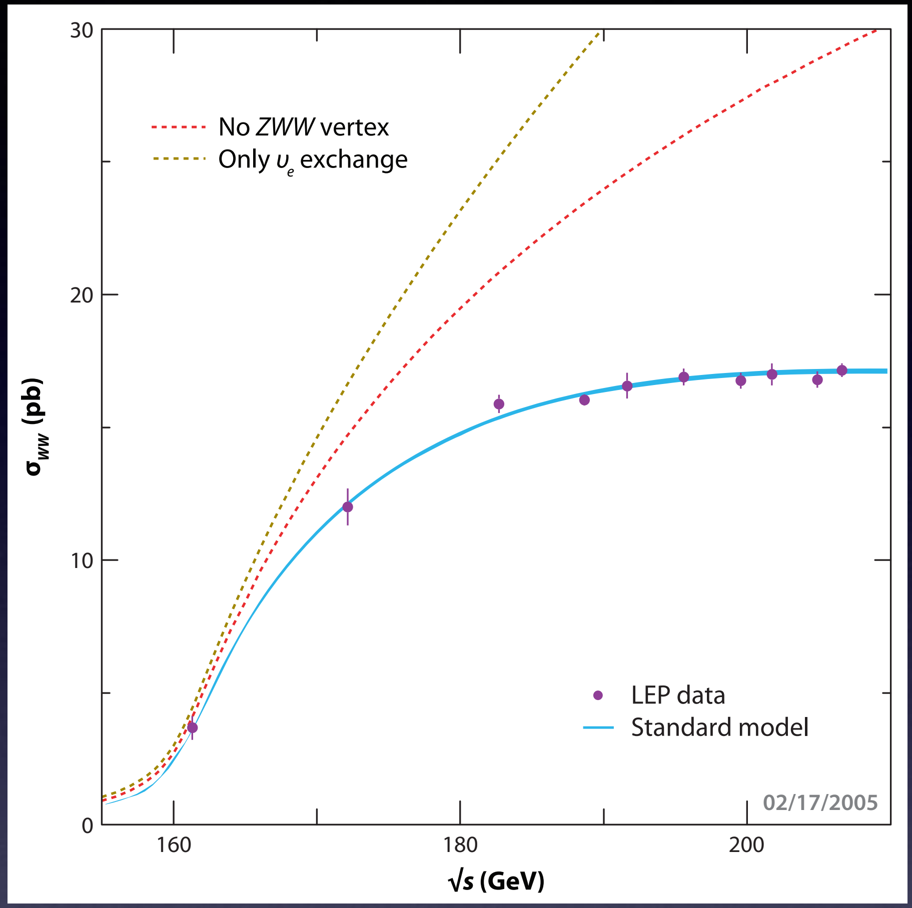
Large Electron-Positron Collider (1989-2001)

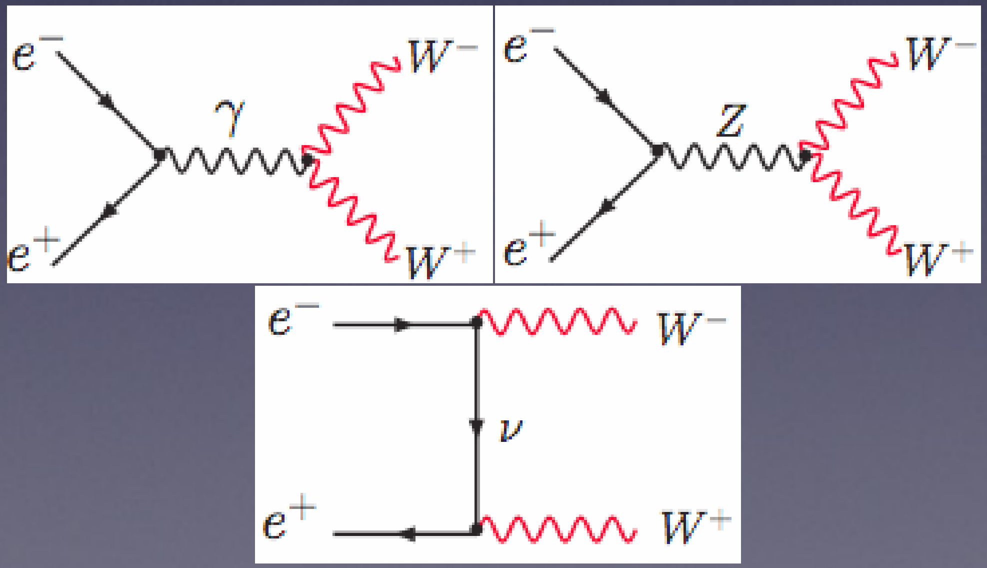


A Precision machine of EW interaction

Electroweak theory tested at tree level



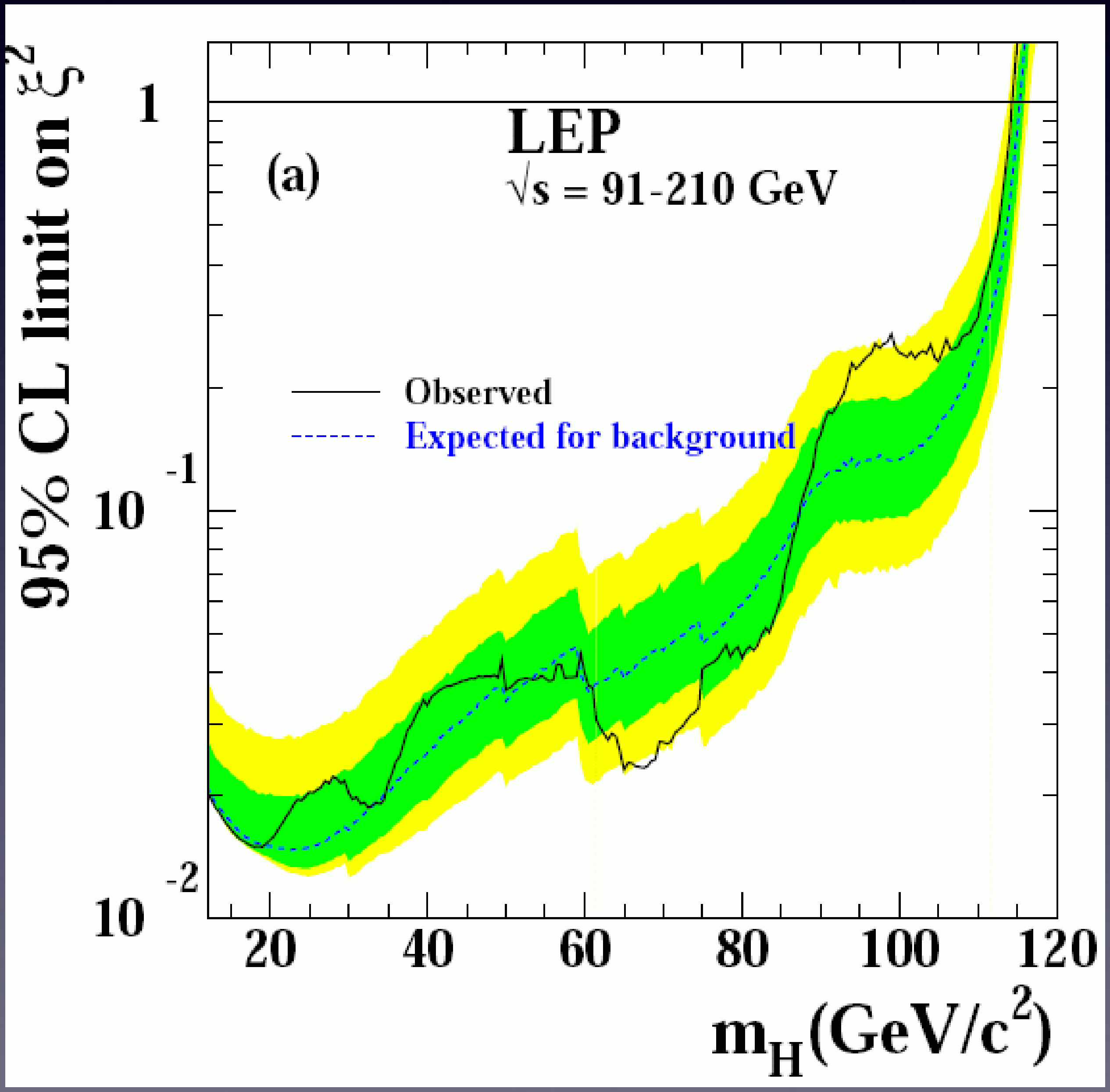


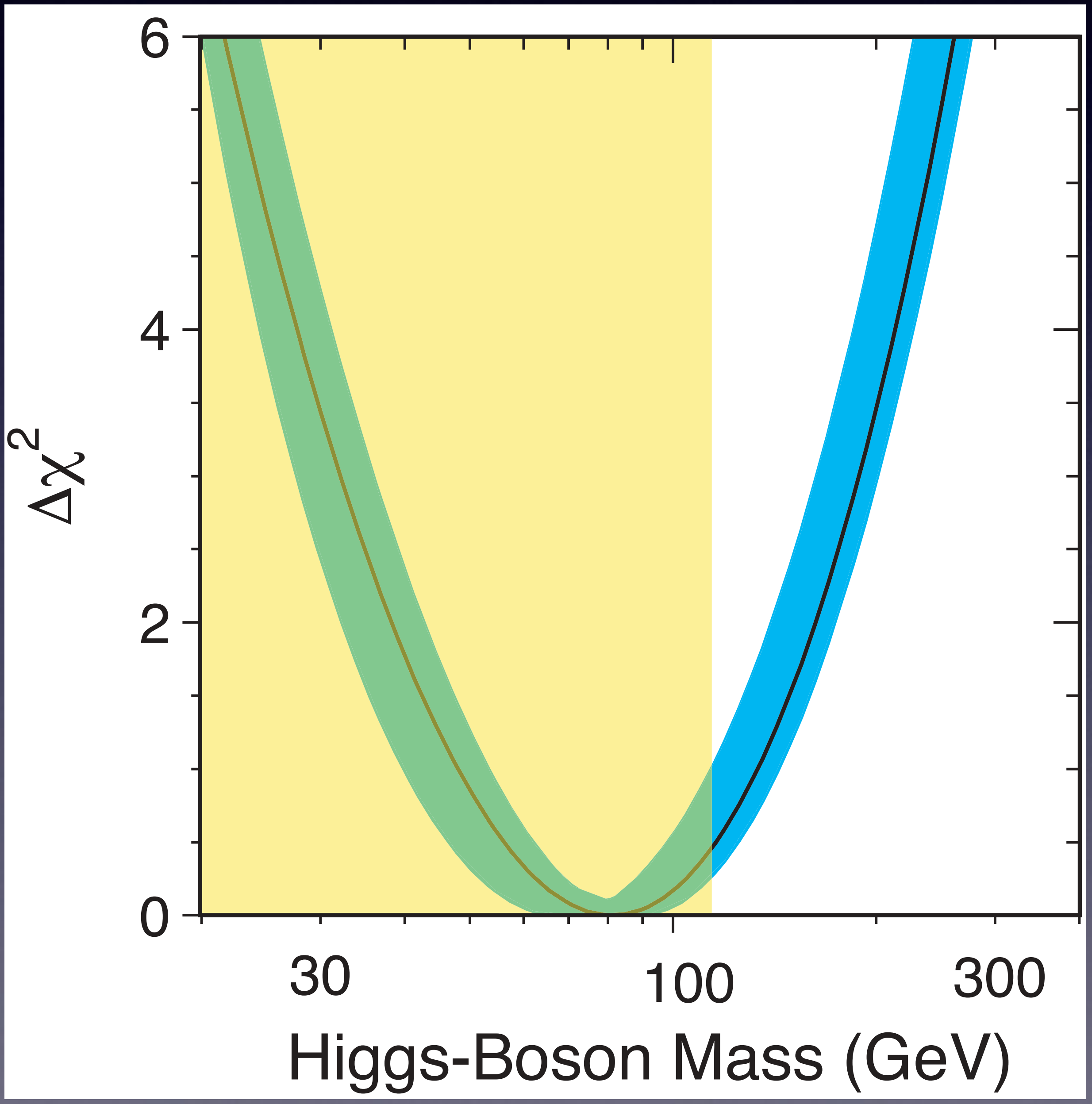


Higgs searches at the LEP-II

No evidence for Higgs

$m_h > 114$ GeV



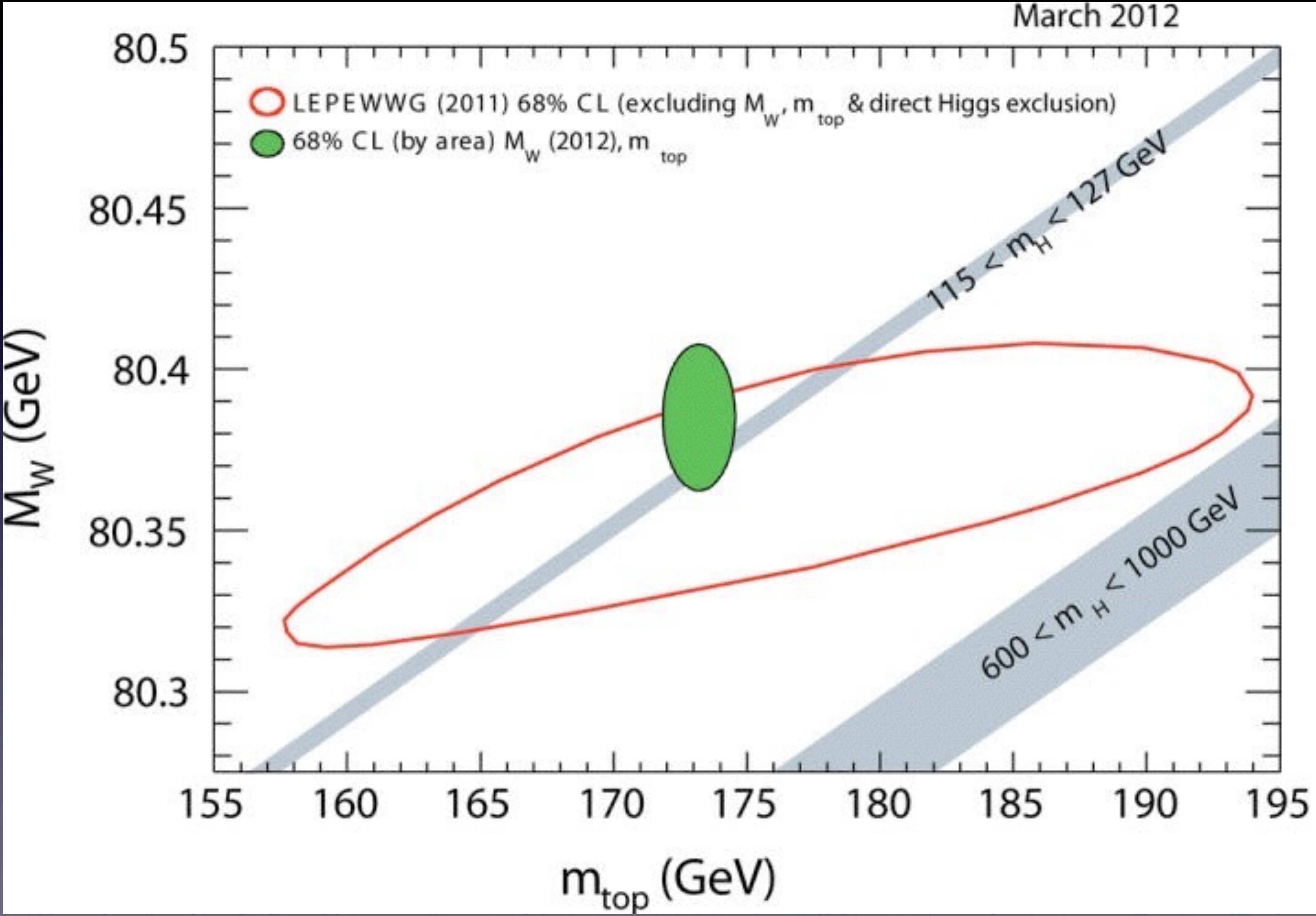


Tevatron

(1983-2011)

A precision machine built to test QCD
A precision machine of Electroweak
A discovery machine of Top-quark

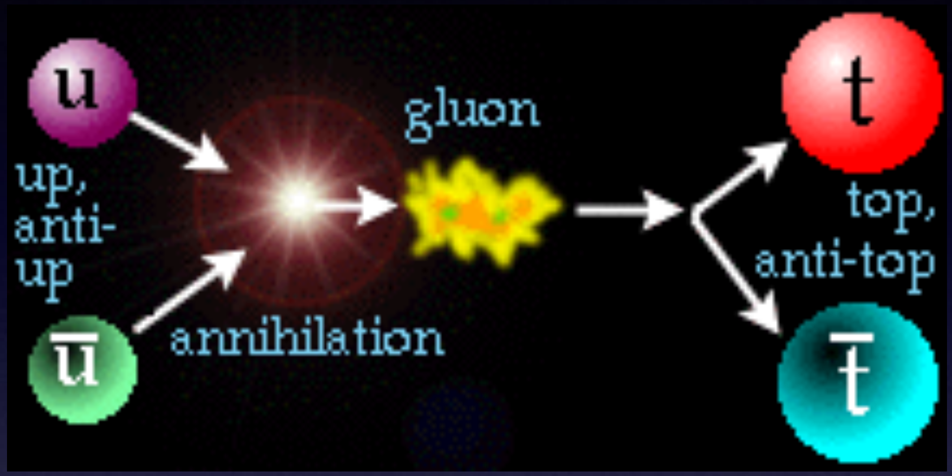
Triumph of *W*-boson Precision

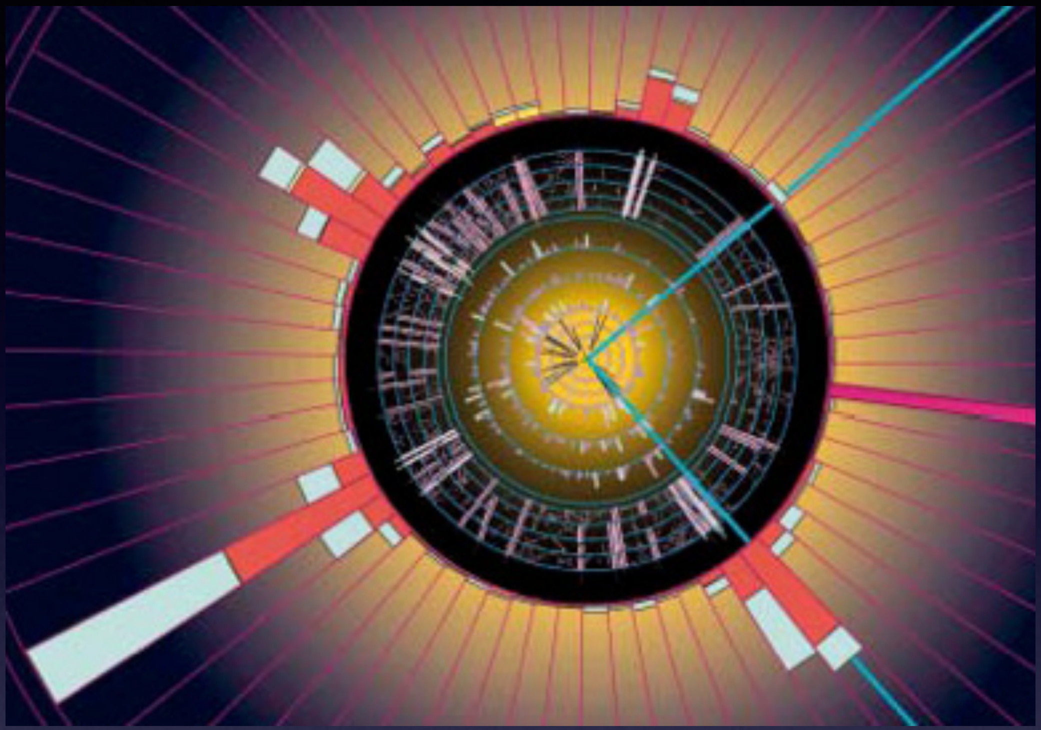


Top Quark Discovery

Such a Long Journey

March 2, 1995





High energy physicists had
Champaign
to celebrate the discovery of
the Top Quark at FNAL Tevatron by D0 &
CDF groups.

Recently,

$$m_t = (173.1 \pm 1.0)\mathrm{GeV}$$

Top Exists
(induced from data)

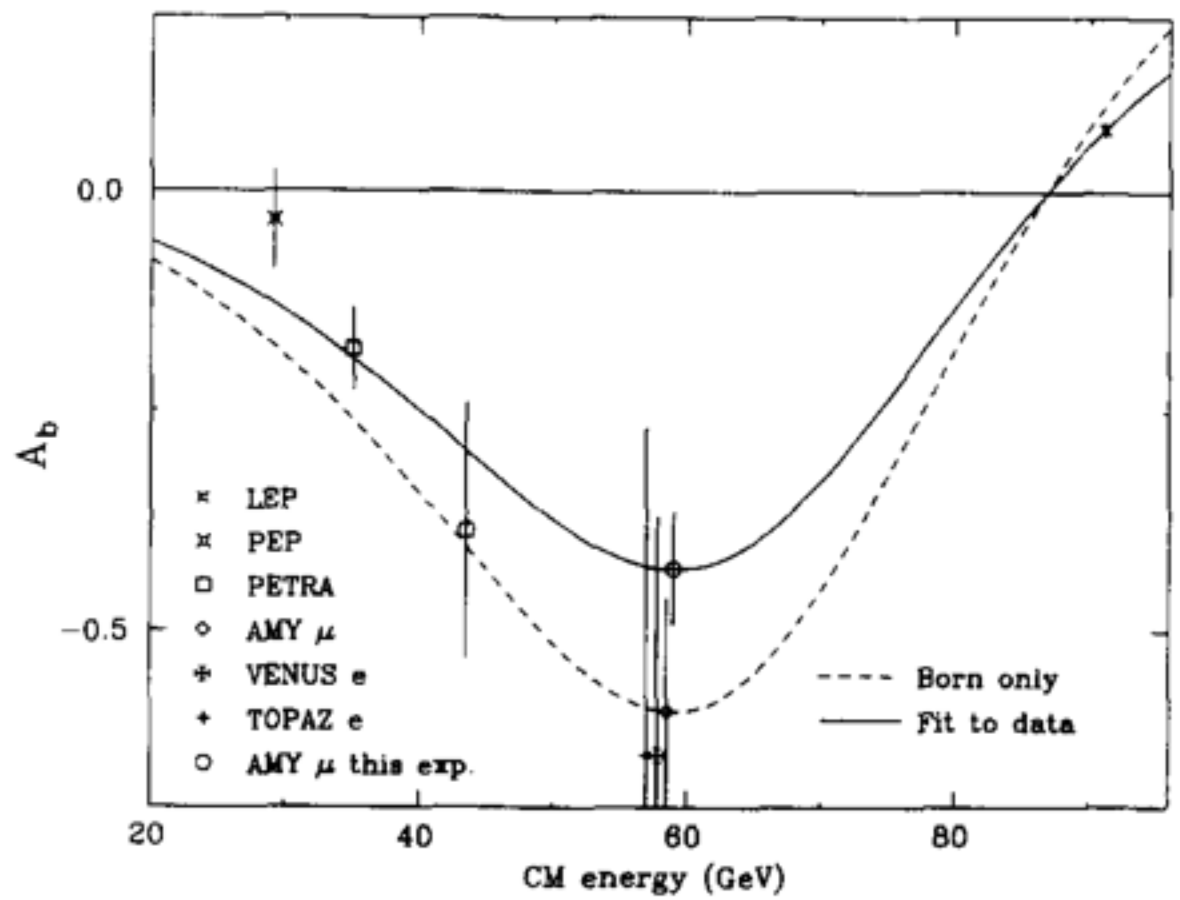


Fig. 5. The present measurement of the asymmetry A_b together with other experiments. The statistical and systematic errors are added in quadrature. The two curves are the Born term prediction without mixing (broken line) and the fit to the data (solid line) with mixing parameter χ. See the text.

Forward-Backward Asymmetry of bottom quark (A_b) in

$$e^+e^- \rightarrow b\bar{b}$$

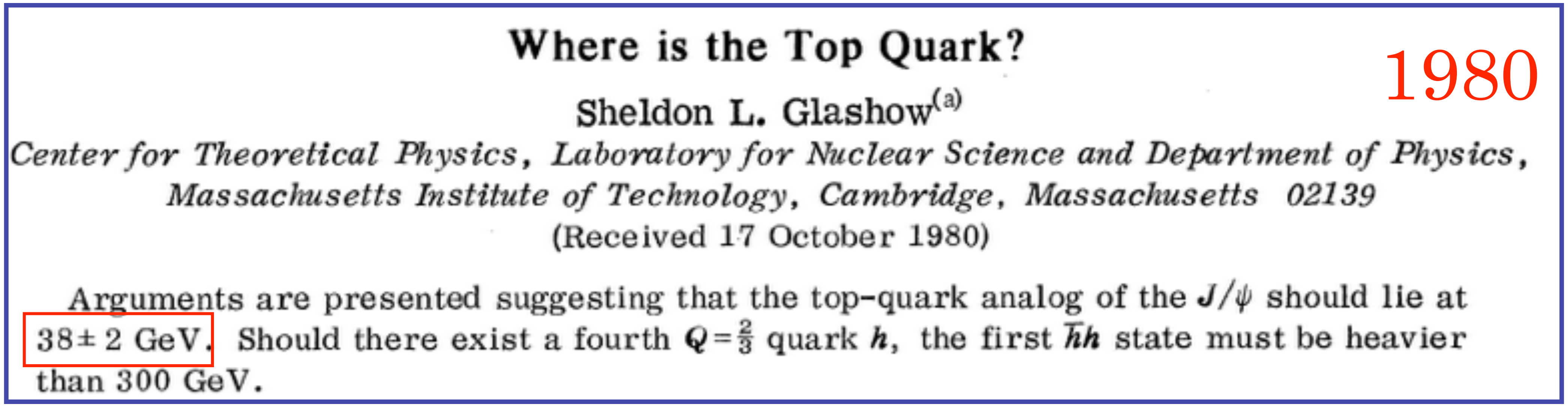
confirmed weak isospin of b

$$T_3 = -\frac{1}{2}$$

⇒ $T_3 = \frac{1}{2}$ state must exist, which is called TOP.

But it was such a long journey to find the TOP quark.

Chronology of Top Hunting



1980

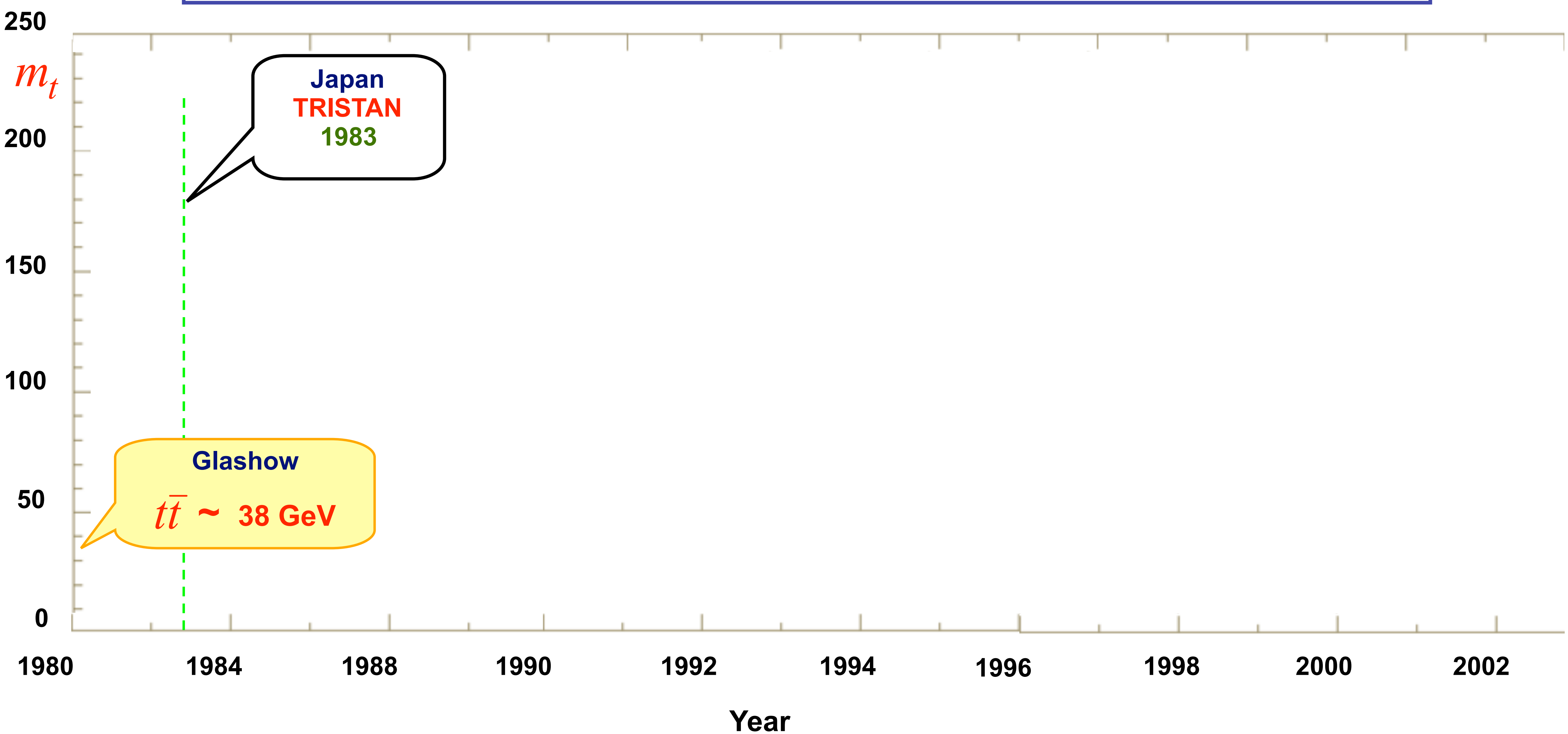
Where is the Top Quark?

Sheldon L. Glashow[(a)]

Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 17 October 1980)

Arguments are presented suggesting that the top-quark analog of the J/ψ should lie at 38± 2 GeV. Should there exist a fourth $Q=\frac{2}{3}$ quark h, the first $\bar{h}h$ state must be heavier than 300 GeV.



Chronology of Top Hunting

TOWARDS A REALISTIC SUGRA-GUT

1983

L.E. IBÁÑEZ

Departamento de Fisica Téorica C-XI, Universidad Autonoma de Madrid, Cantablanco, Madrid-34, Spain

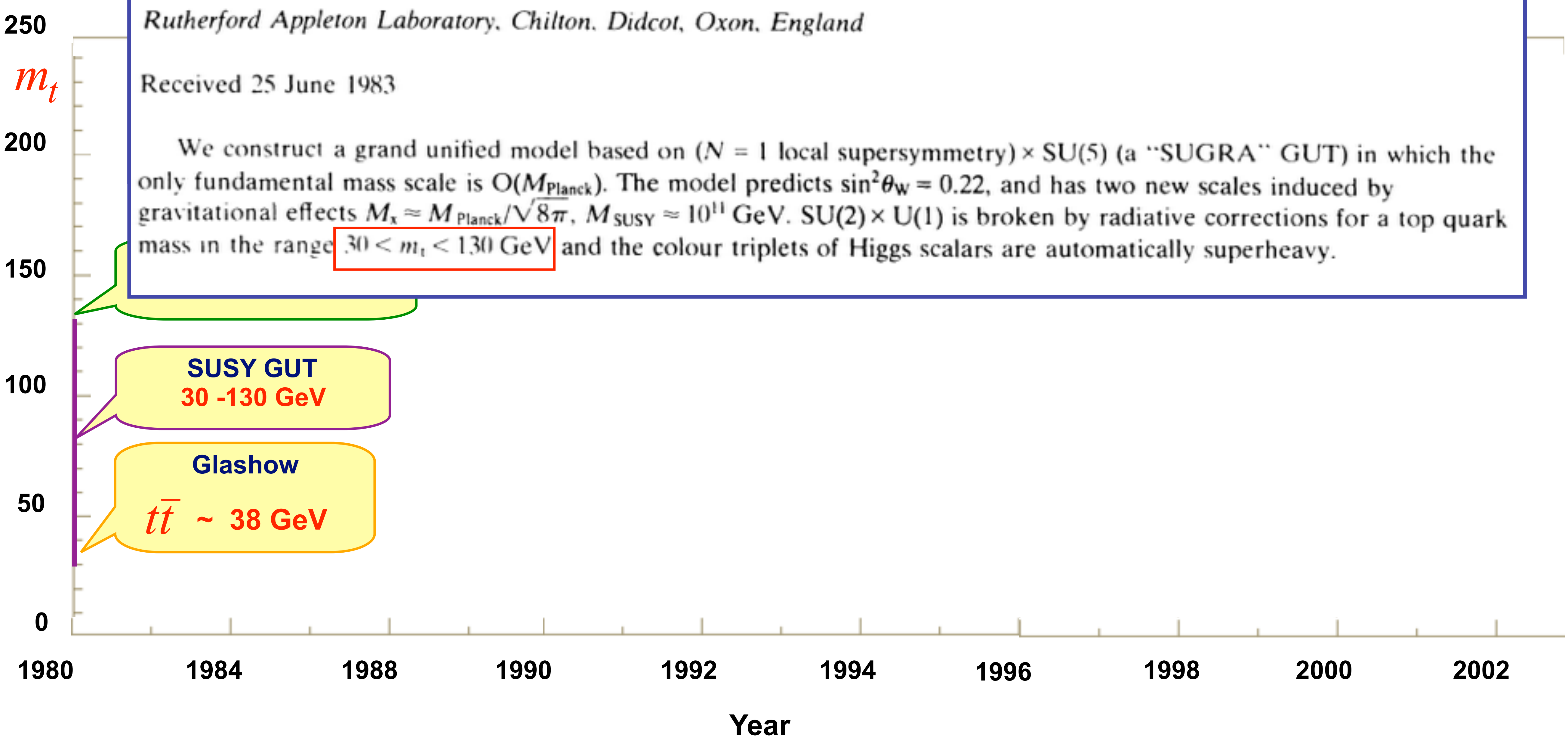
and

G.G. ROSS[1]

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England

Received 25 June 1983

We construct a grand unified model based on (N = 1 local supersymmetry) × SU(5) (a "SUGRA" GUT) in which the only fundamental mass scale is $O(M_{\rm Planck})$. The model predicts $\sin^2\theta_W = 0.22$, and has two new scales induced by gravitational effects $M_x \approx M_{\rm Planck}/\sqrt{8\pi}$, $M_{\rm SUSY} \approx 10^{11}$ GeV. SU(2) × U(1) is broken by radiative corrections for a top quark mass in the range $30 < m_t < 130$ GeV and the colour triplets of Higgs scalars are automatically superheavy.



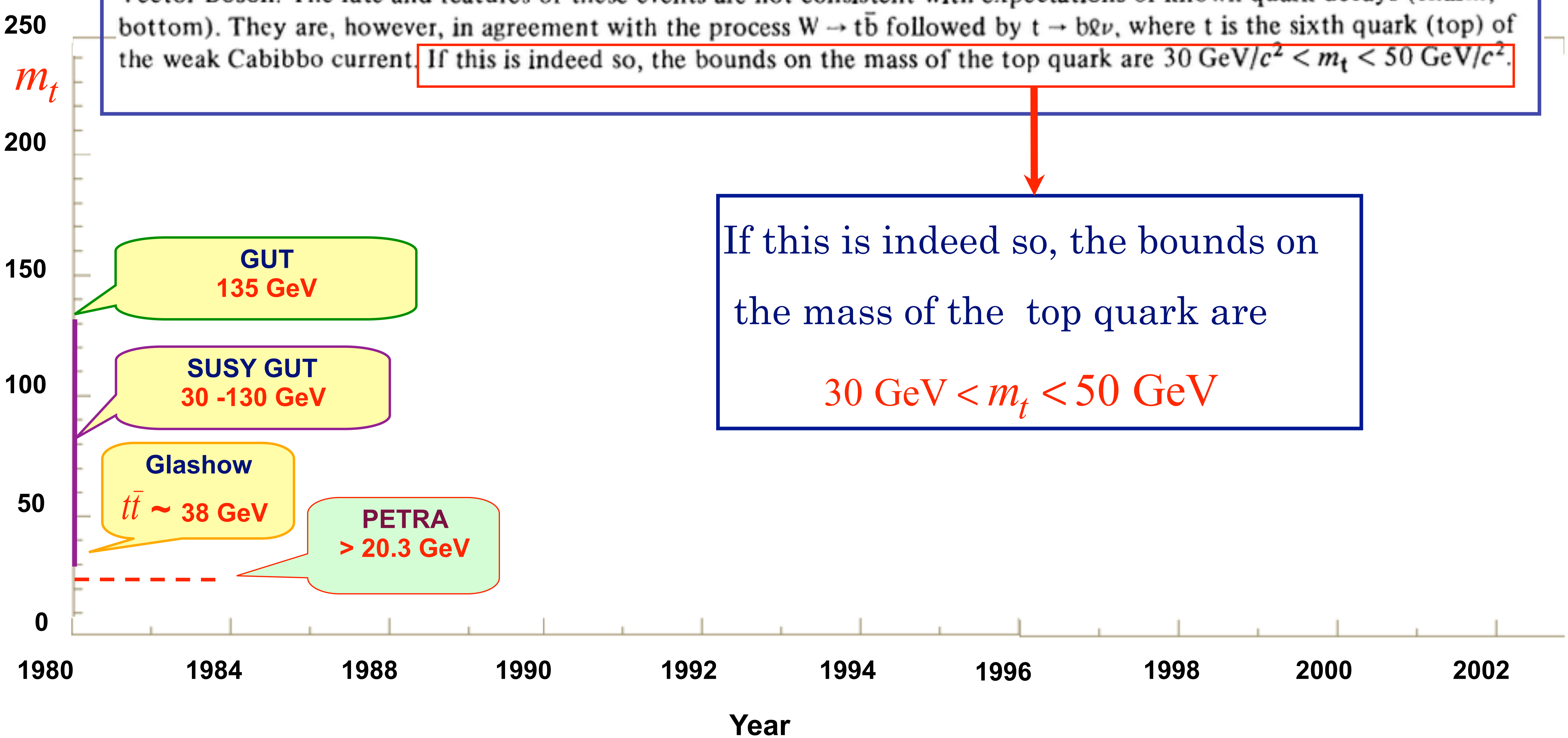
Chronology of Top Hunting

1984

ASSOCIATED PRODUCTION OF AN ISOLATED, LARGE-TRANSVERSE-MOMENTUM LEPTON (ELECTRON OR MUON), AND TWO JETS AT THE CERN $p\bar{p}$ COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

A clear signal is observed for the production of an isolated large-transverse-momentum lepton in association with two or three centrally produced jets. The two-jet events cluster around the $W^{\pm}$ mass, indicating a novel decay of the Intermediate Vector Boson. The rate and features of these events are not consistent with expectations of known quark decays (charm, bottom). They are, however, in agreement with the process $W \to t\bar{b}$ followed by $t \to b\ell\nu$, where t is the sixth quark (top) of the weak Cabibbo current. If this is indeed so, the bounds on the mass of the top quark are $30\ \mathrm{GeV}/c^2 < m_t < 50\ \mathrm{GeV}/c^2$.

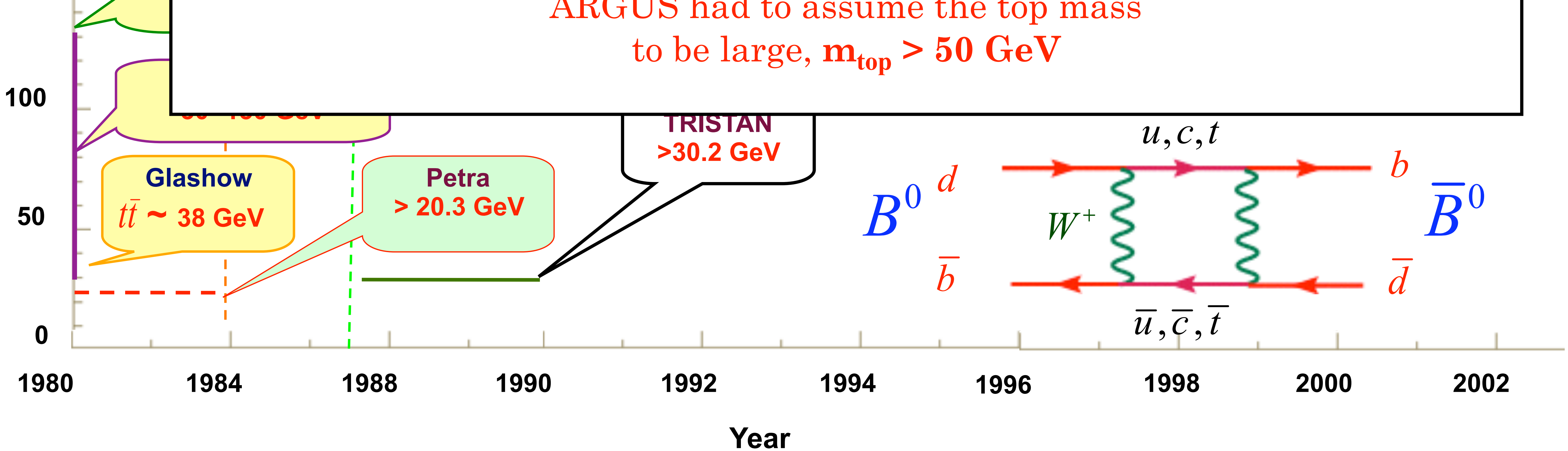


Chronology of Top Hunting

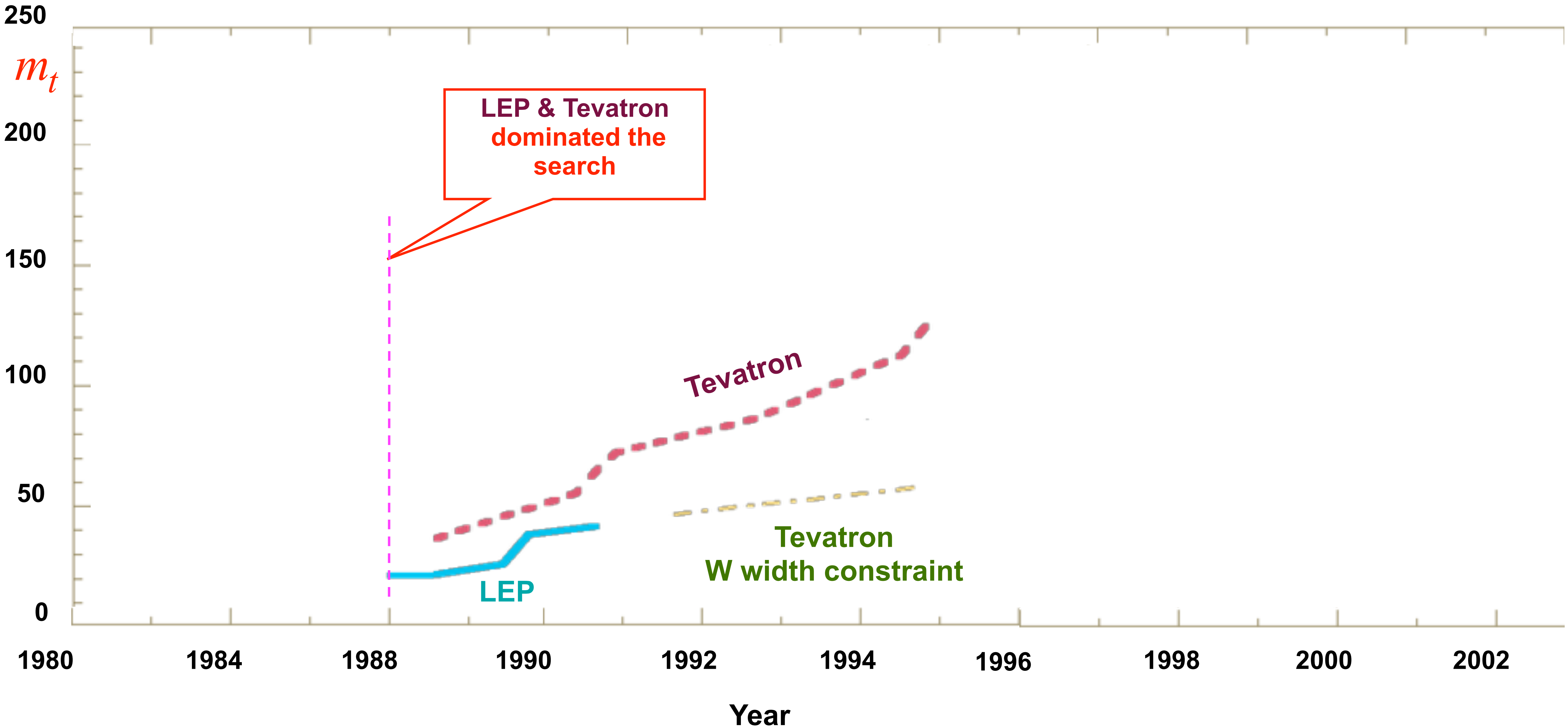
Observation of $B^0 - \bar{B}^0$ mixing
ARGUS Collaboration
Received 9 April 1987

Using the ARGUS detector at the DORIS II storage ring we have searched in three different ways for $B^0 - \bar{B}^0$ mixing in $\Upsilon(4S)$ decays. One explicitly mixed event, a decay $\Upsilon \to B^0 \bar{B}^0$, has been completely reconstructed. Furthermore, we observe a 4.0 standard deviation signal of 24.8 events with like-sign lepton pairs and a 3.0 standard deviation signal of 4.1 events containing one reconstructed $B^0(\bar{B}^0)$ and an additional fast $l^+(l^-)$. This leads to the conclusion that $B^0 - \bar{B}^0$ mixing is substantial. For the mixing parameter we obtain r=0.21±0.08.

To explain the large mixing parameter,
ARGUS had to assume the top mass
to be large, $\mathbf{m_{top}}$ **> 50 GeV**



Chronology of Top Hunting



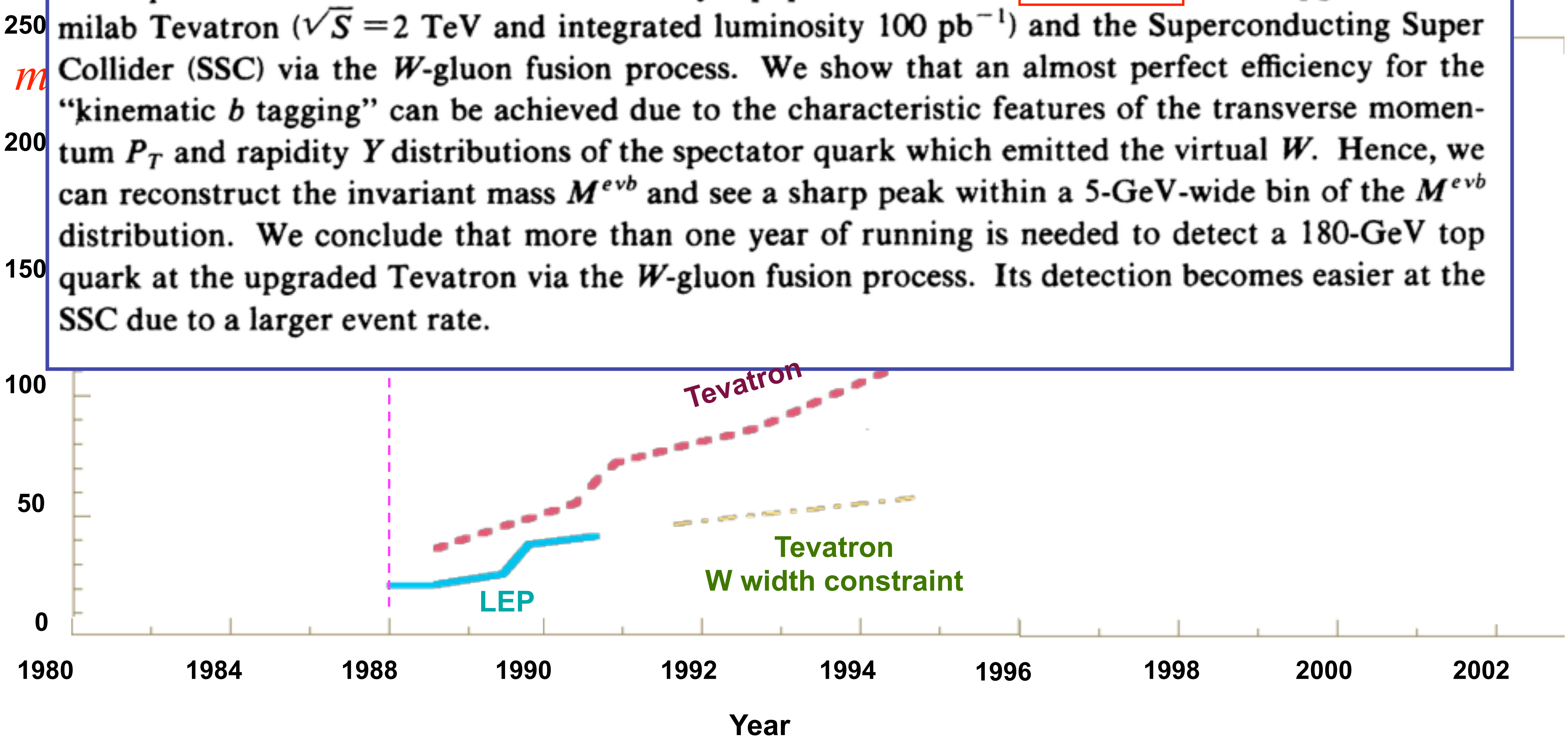
Chronology of Top Hunting

New method to detect a heavy top quark at the Fermilab Tevatron

C.-P. Yuan
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

(Received 15 May 1989)

We present a new method to detect a heavy top quark with mass ~180 GeV at the upgraded Fermilab Tevatron ($\sqrt{S} = 2$ TeV and integrated luminosity 100 pb^{-1}) and the Superconducting Super Collider (SSC) via the W-gluon fusion process. We show that an almost perfect efficiency for the "kinematic b tagging" can be achieved due to the characteristic features of the transverse momentum P_T and rapidity Y distributions of the spectator quark which emitted the virtual W. Hence, we can reconstruct the invariant mass M^{evb} and see a sharp peak within a 5-GeV-wide bin of the M^{evb} distribution. We conclude that more than one year of running is needed to detect a 180-GeV top quark at the upgraded Tevatron via the W-gluon fusion process. Its detection becomes easier at the SSC due to a larger event rate.



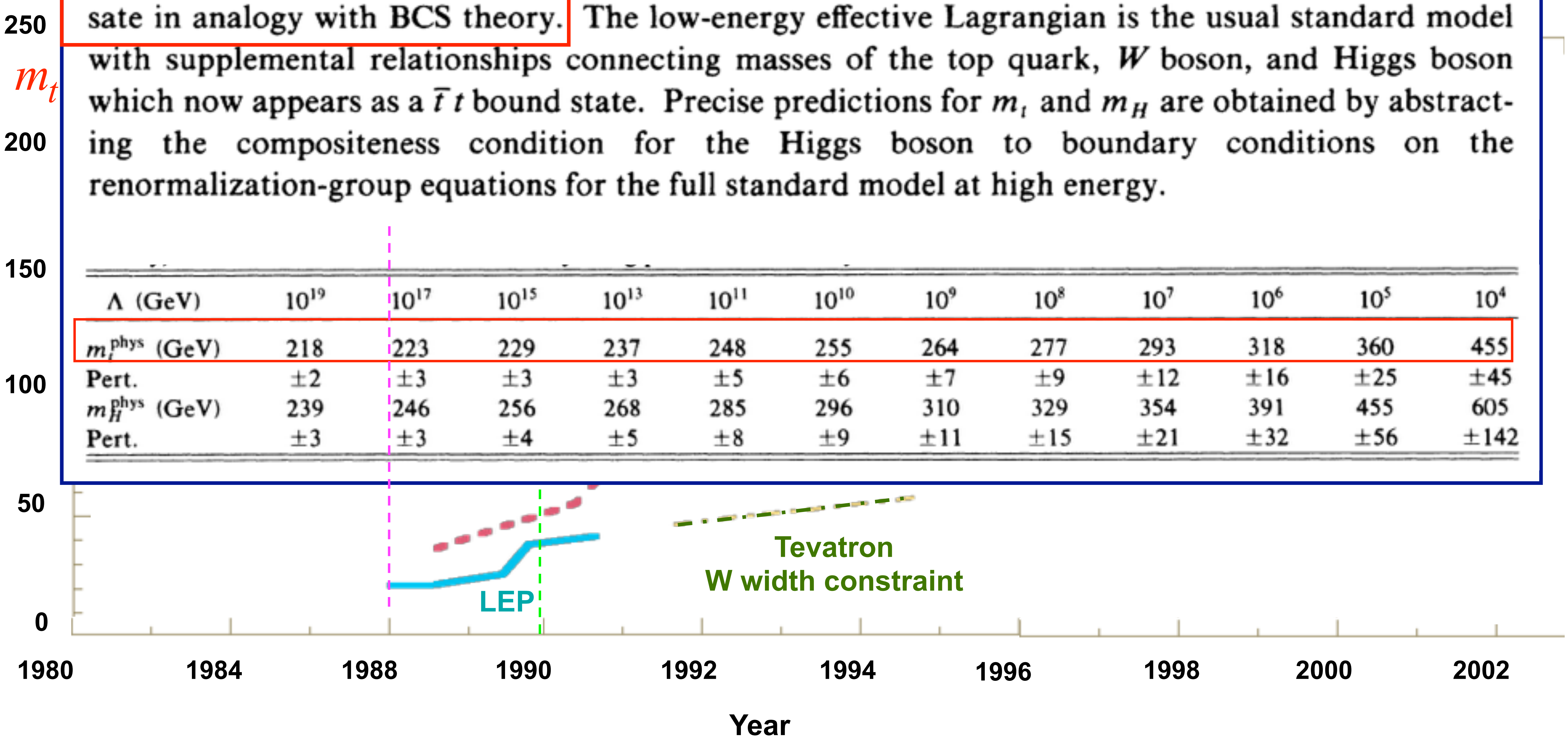
Chronology of Top Hunting

Minimal dynamical symmetry breaking of the standard model

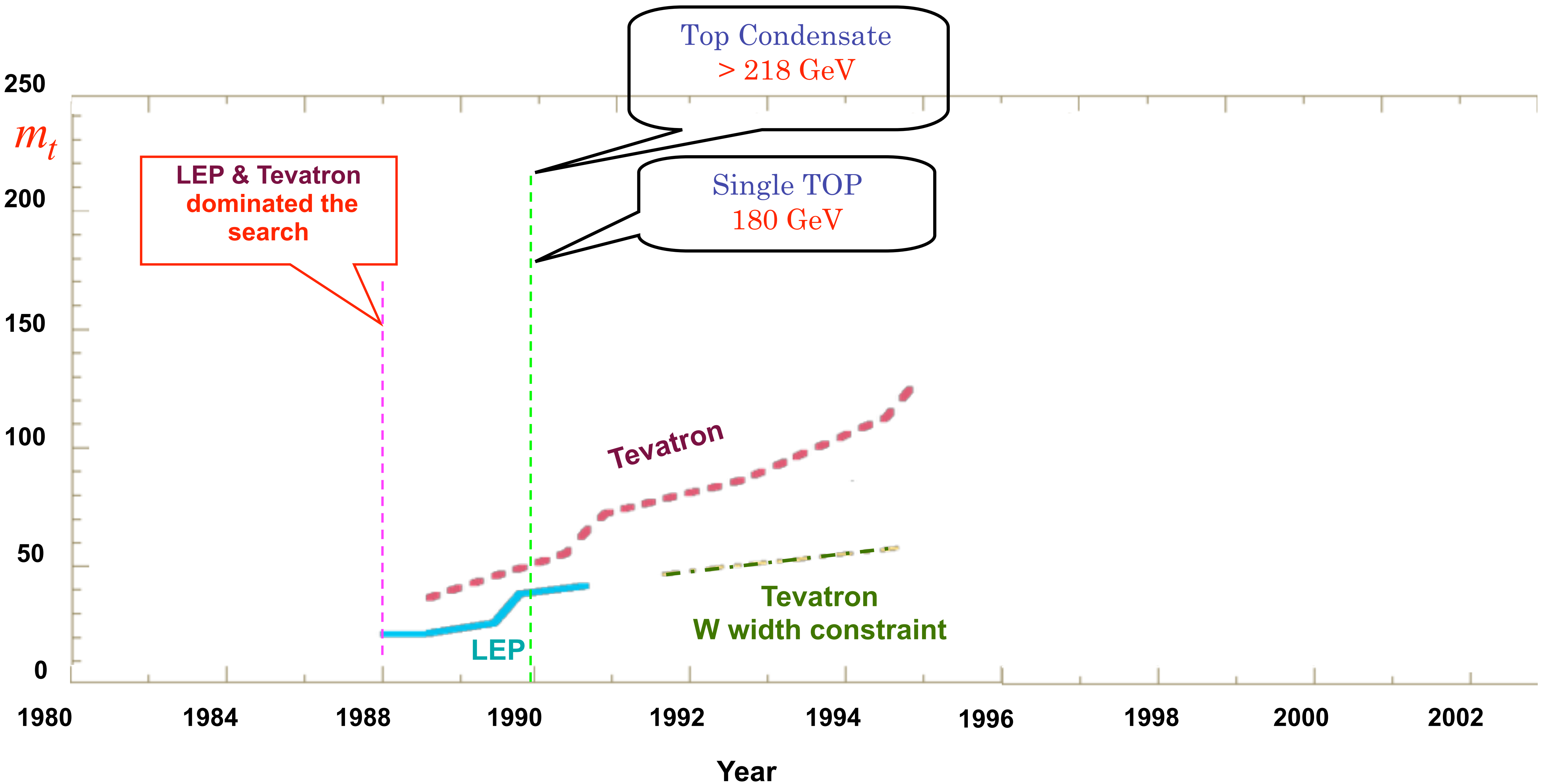
William A. Bardeen, Christopher T. Hill, and Manfred Lindner
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
(Received 21 July 1989; revised manuscript received 2 November 1989)

We formulate the dynamical symmetry breaking of the standard model by a top-quark condensate in analogy with BCS theory. The low-energy effective Lagrangian is the usual standard model with supplemental relationships connecting masses of the top quark, W boson, and Higgs boson which now appears as a $\bar{t}t$ bound state. Precise predictions for m_t and m_H are obtained by abstracting the compositeness condition for the Higgs boson to boundary conditions on the renormalization-group equations for the full standard model at high energy.

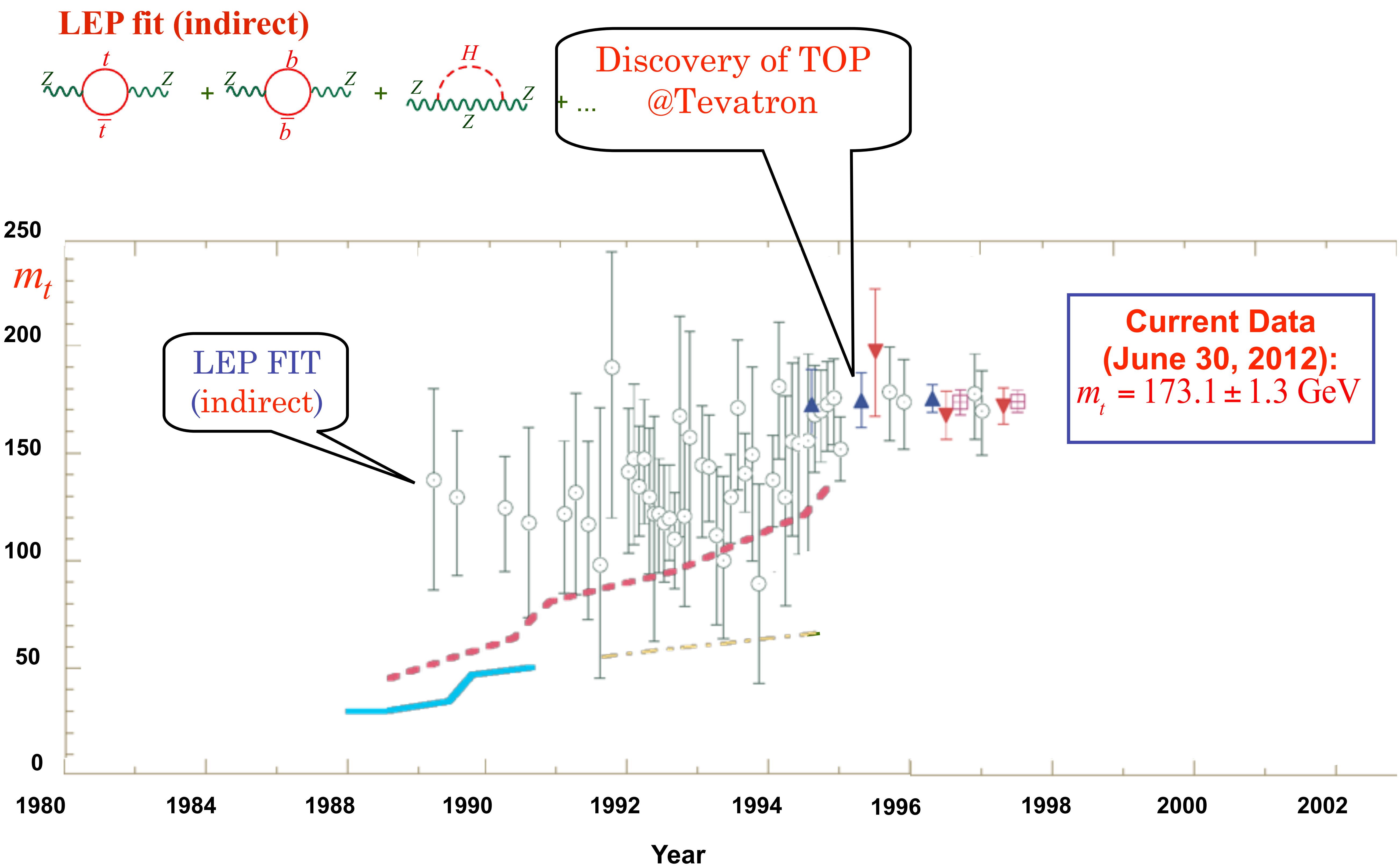
Λ (GeV)	10^{19}	10^{17}	10^{15}	10^{13}	10^{11}	10^{10}	10^{9}	10^{8}	10^{7}	10^{6}	10^{5}	10^{4}
m_t^{phys} (GeV)	218	223	229	237	248	255	264	277	293	318	360	455
Pert.	±2	±3	±3	±3	±5	±6	±7	±9	±12	±16	±25	±45
m_H^{phys} (GeV)	239	246	256	268	285	296	310	329	354	391	455	605
Pert.	±3	±3	±4	±5	±8	±9	±11	±15	±21	±32	±56	±142



Chronology of Top Hunting



Chronology of Top Hunting



Top discovery: EW theory tests at Loop level

Bardeen, Hill, Lindner
Top-condensation (1989)
$m_t > 218$GeV

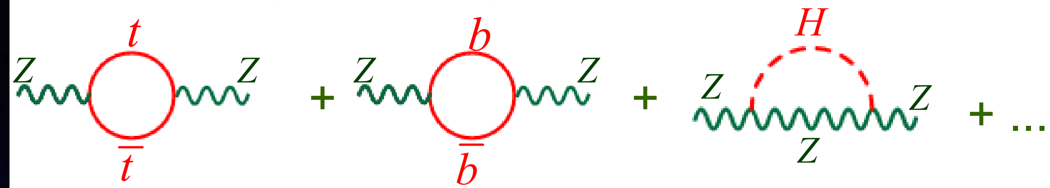
Ibanez, Ross
SUGRA-GUT (1983)
$30 < m_t < 150$GeV

Pendleton, Ross
GUT (1980)
$m_t = 130$GeV

Glashow (1980)
$m_{tt} > 38$GeV

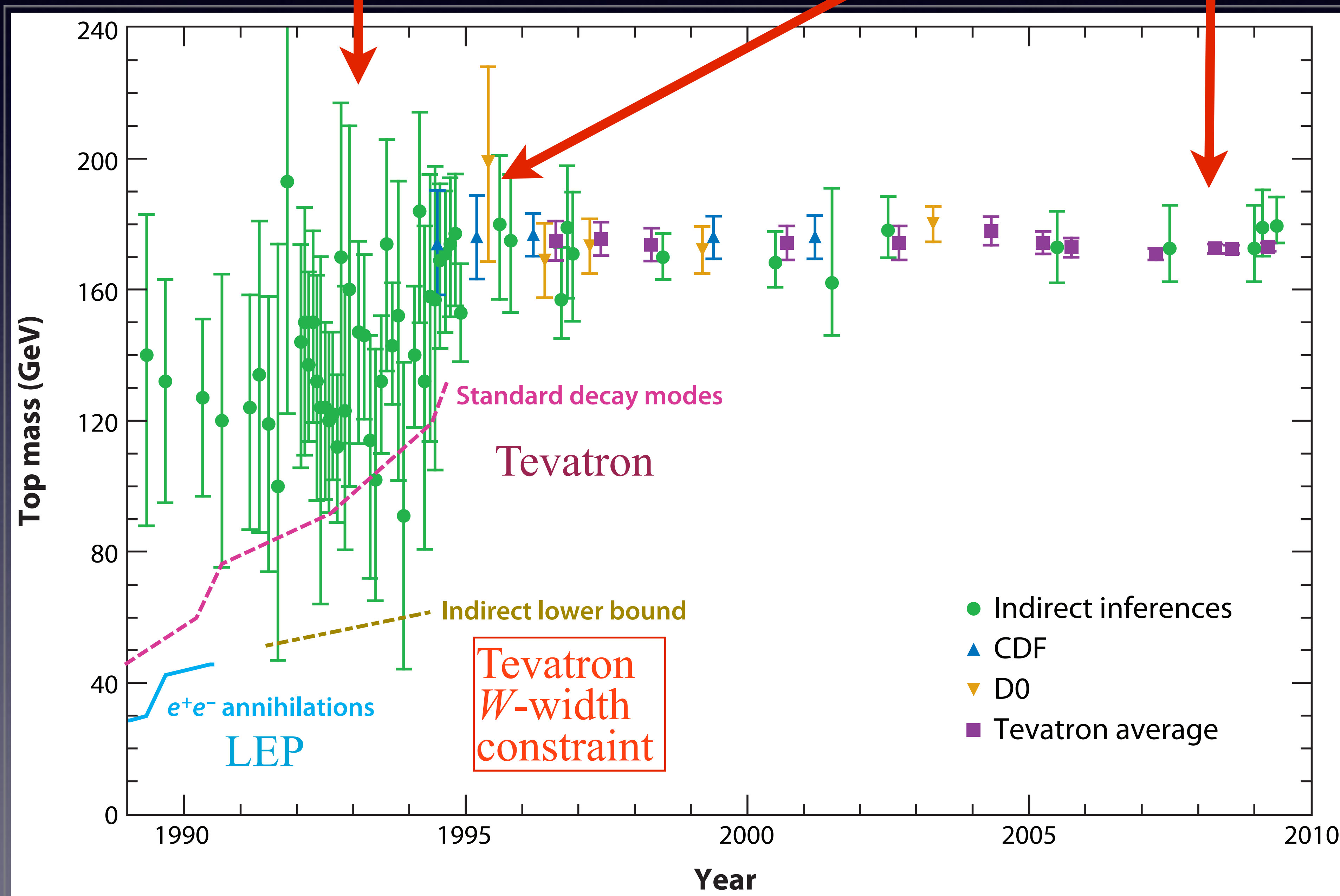
Tristan
1983

LEP fit (indirect)

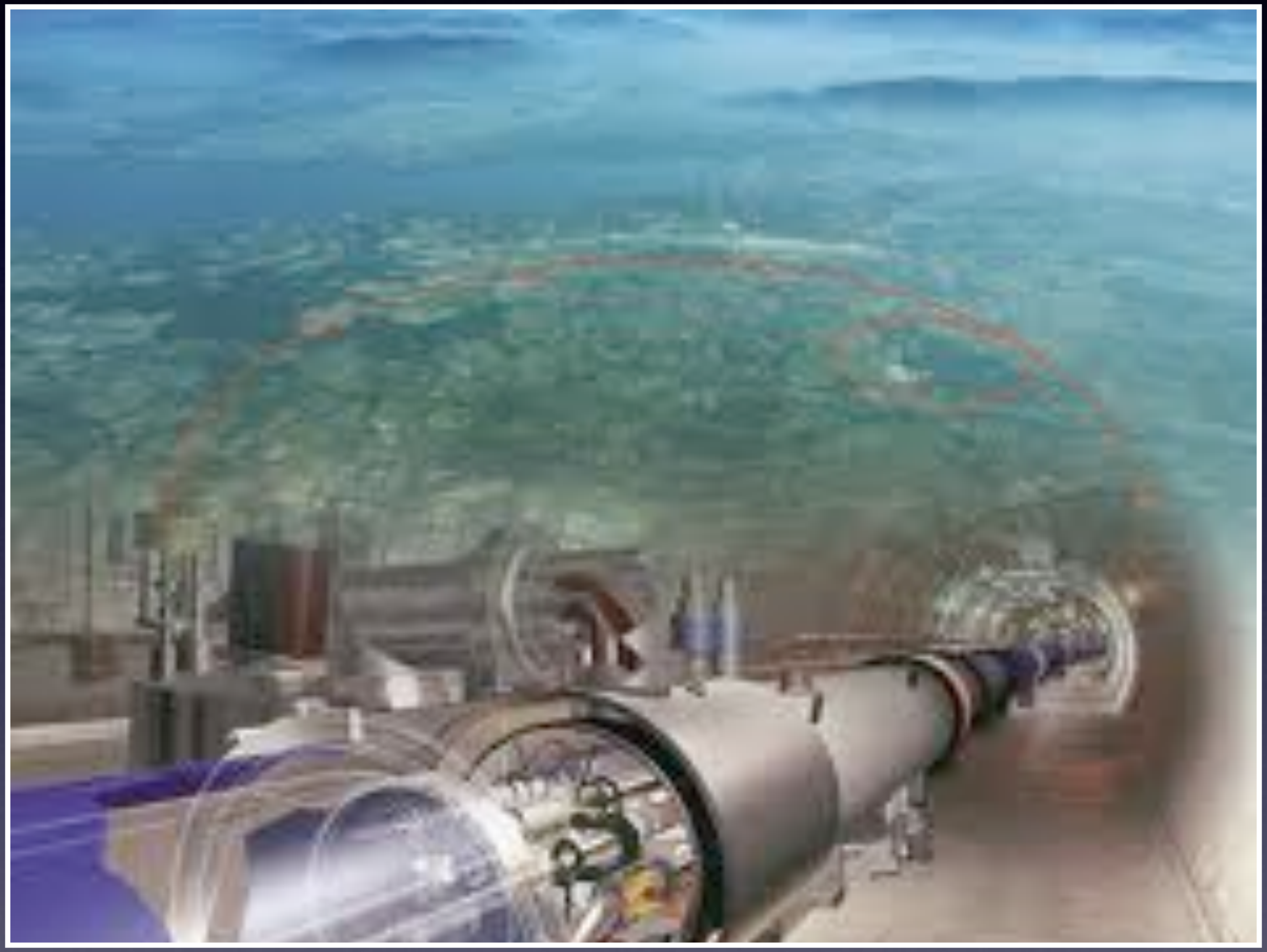


Tevatron
(1995)
Discovery

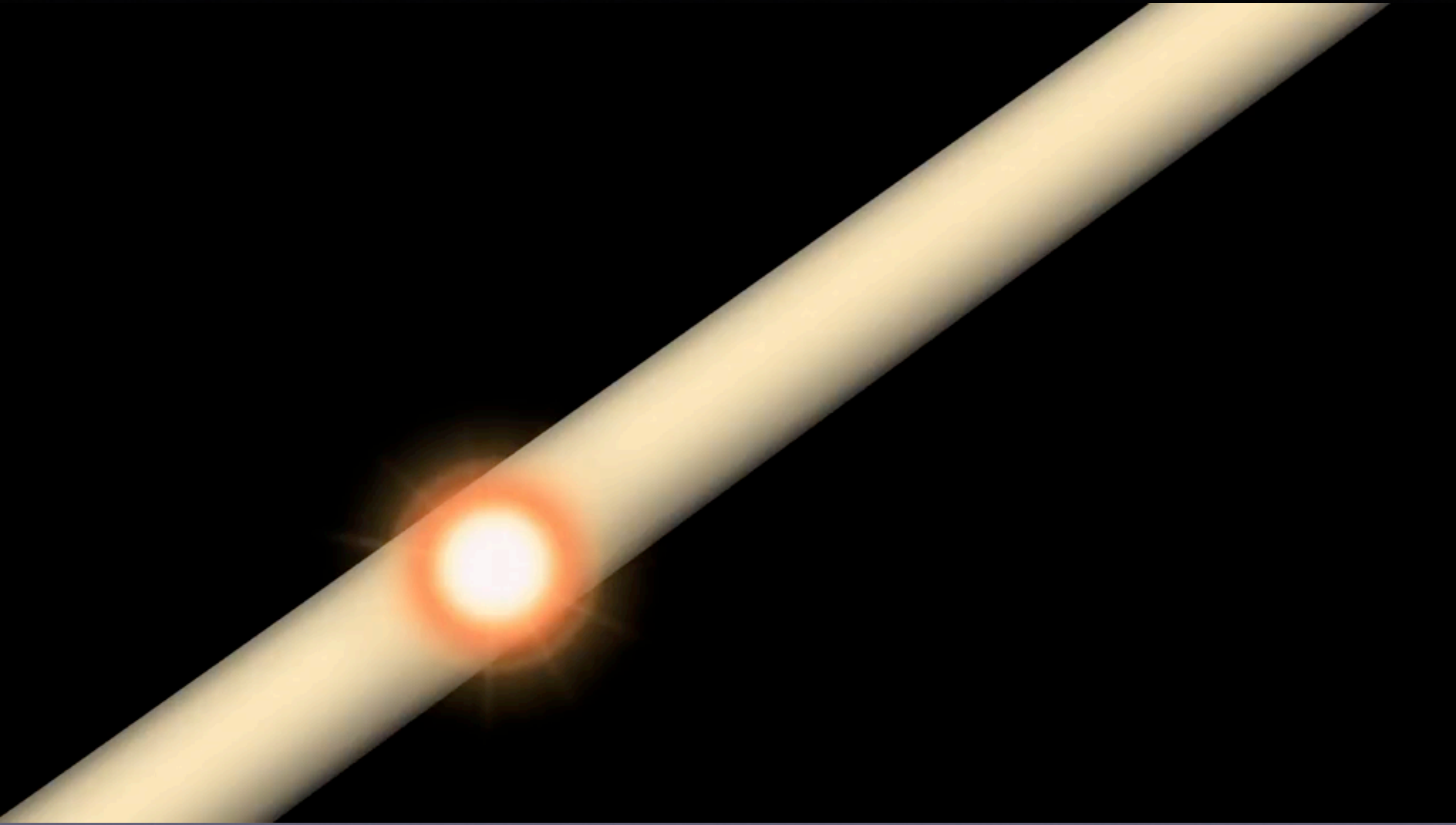
Tevatron
Precision



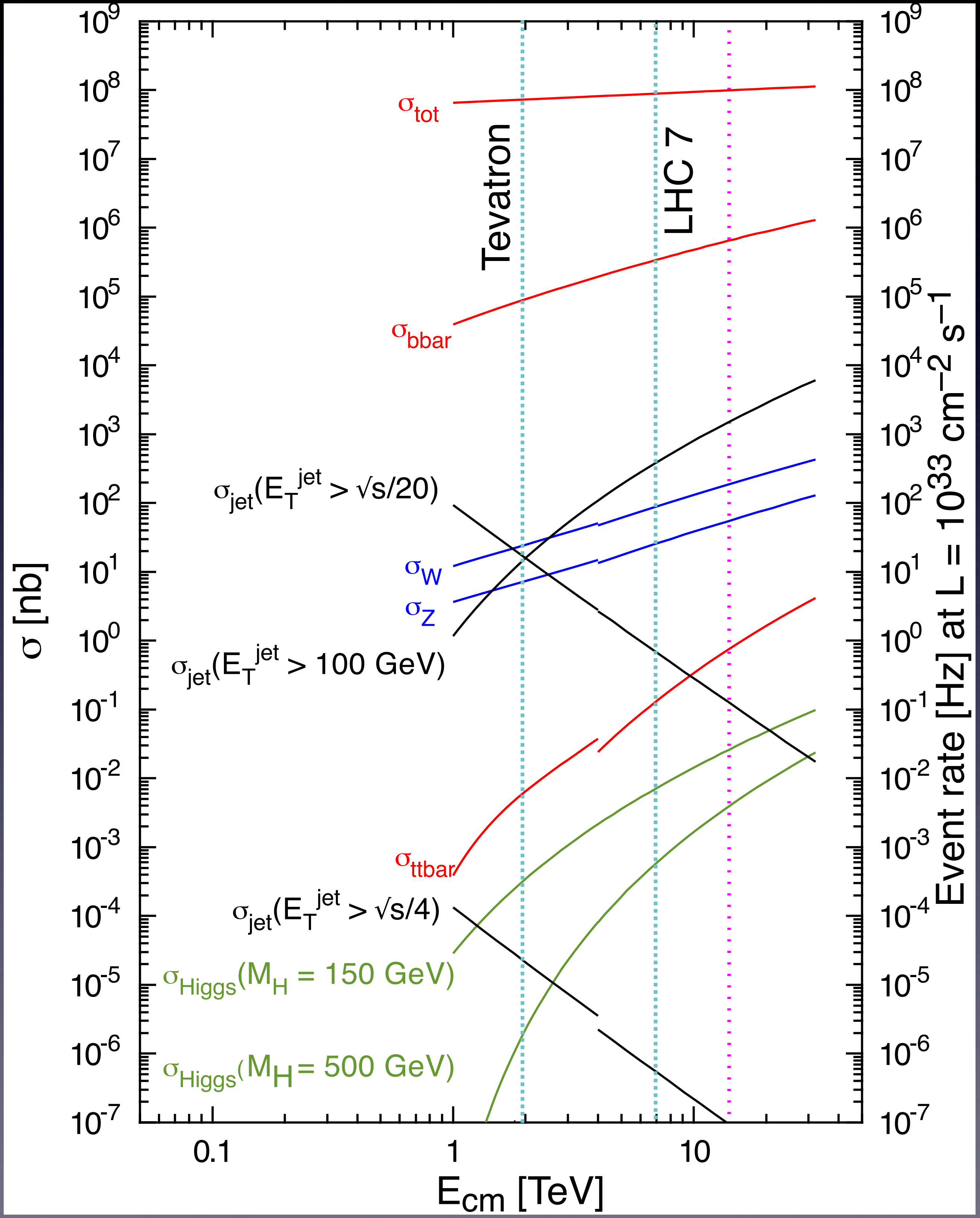
Large Hadron Collider
(2007-?)



A discovery machine of Higgs boson
Energy Frontier
A top-quark factory



LHC: perfect for SM and NP



Rate at 8TeV LHC
with $\mathcal{L} = 10^{33}\mathrm{cm}^{-2}s^{-1}$

★ Inelastic p-p reactions: $10^8/s$

★ bottom quark pairs: $5 \times 10^5/s$

★ top quark pairs: $1/s$

★ $W \to \ell\nu$: $15/s$

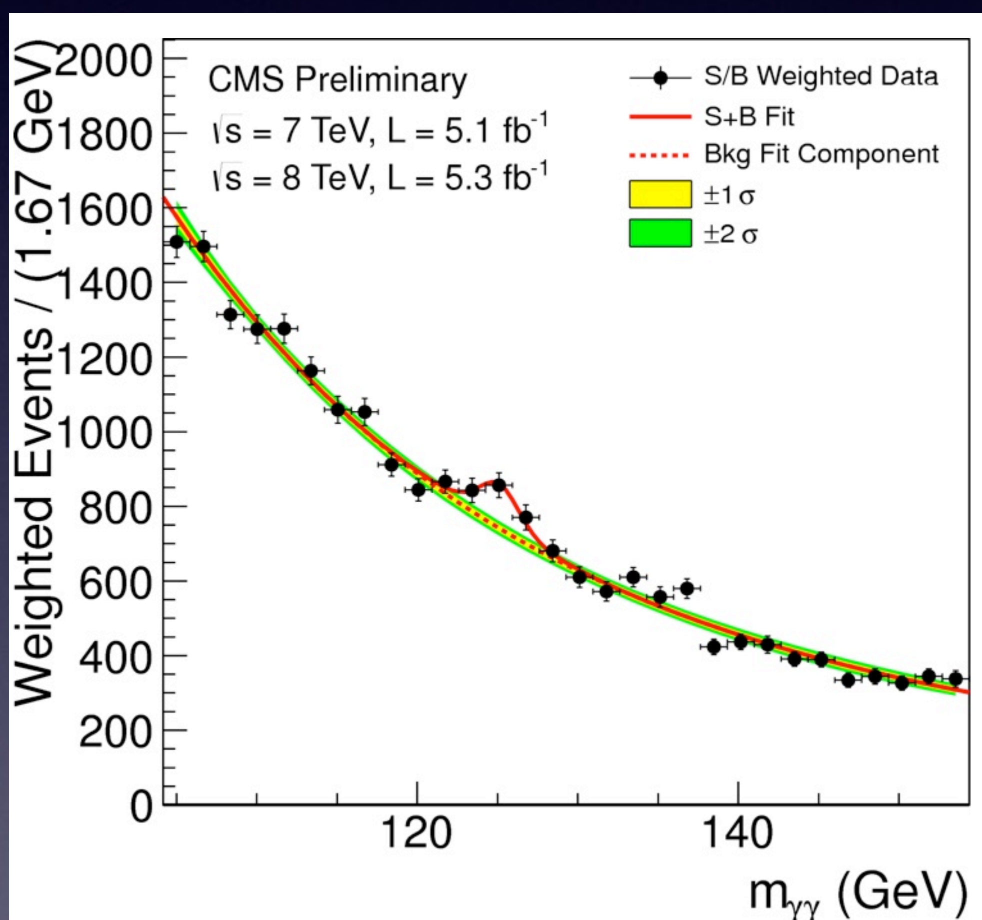
★ $Z \to \ell\ell$: $1.5/s$

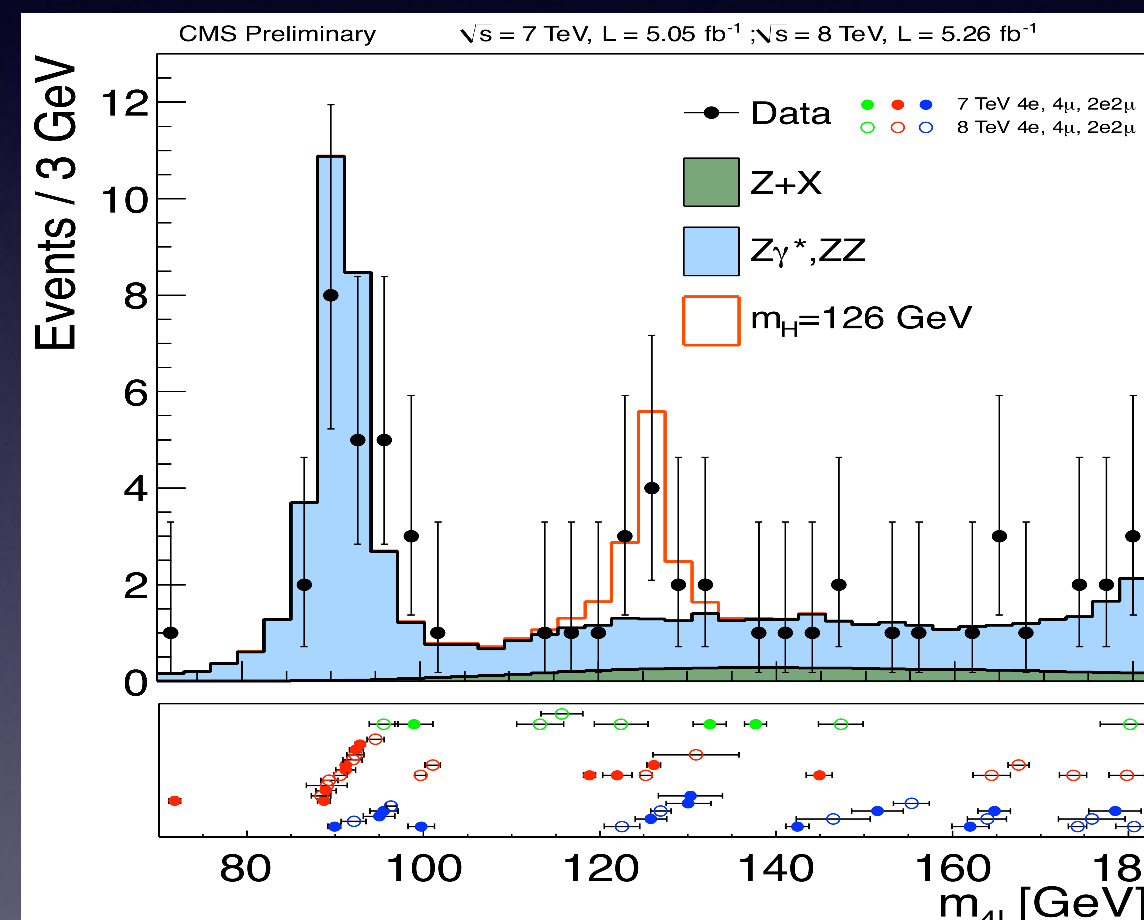
★ Higgs boson $0.02/s$

★ Gluino, Squarks : (1TeV) $0.003/s$

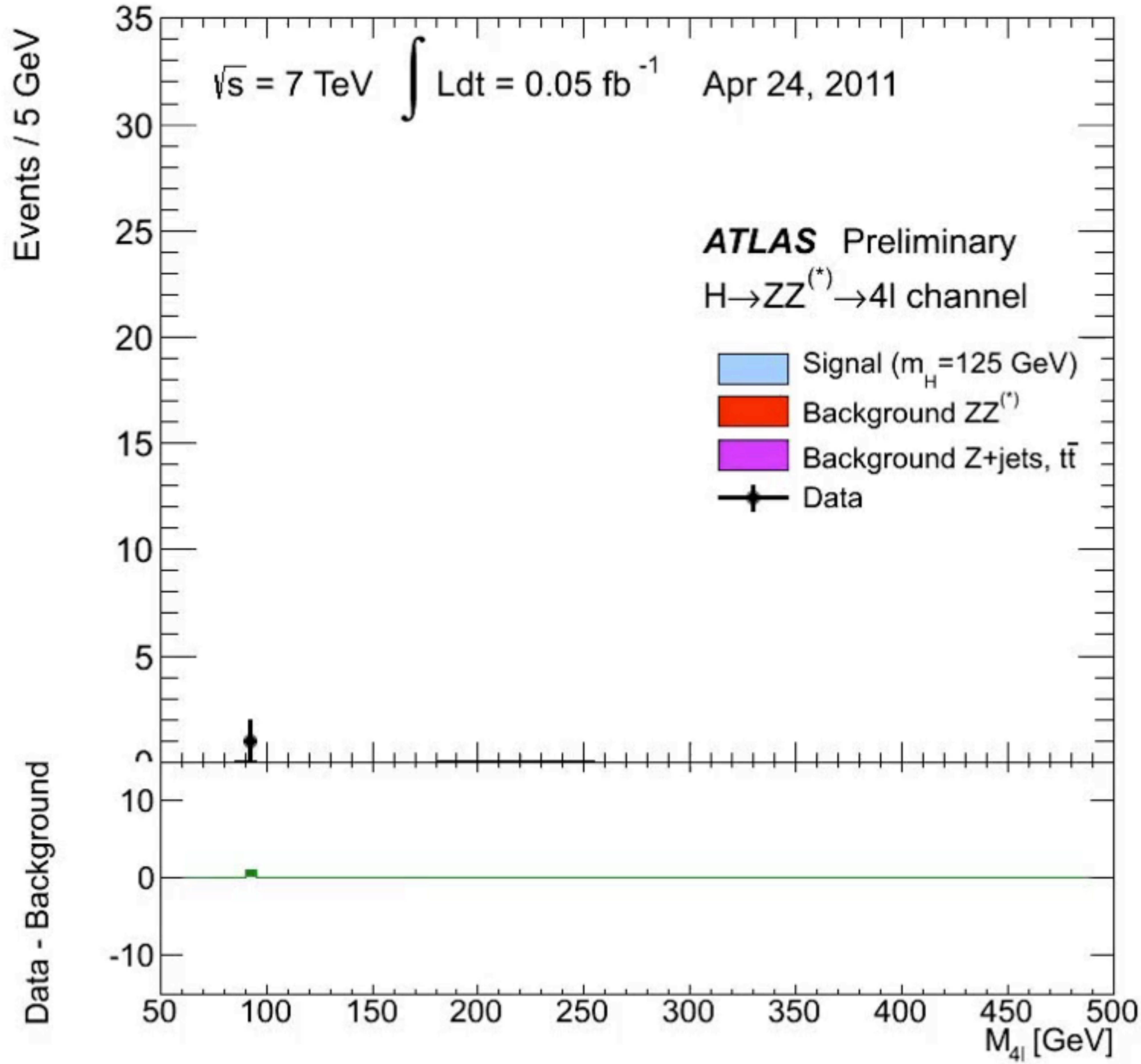
A new boson found ~125GeV

- The evidence is strong that the new particle decays to $\gamma\gamma$ and ZZ with rates roughly consistent with those predicted for the SM Higgs boson.





The observed decay modes indicate that the new particle is a boson.



√s = 7 TeV ∫ Ldt = 0.05 fb^-1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M_4l [GeV]

Higgs mechanism in the SM

- Higgs mechanism: the most economical and simple choice to achieve the spontaneous symmetry breaking

$$\mathscr{L}_{\rm higgs}(\phi, A_a, \psi_i) = D\phi^+ D\phi - V(\phi)$$

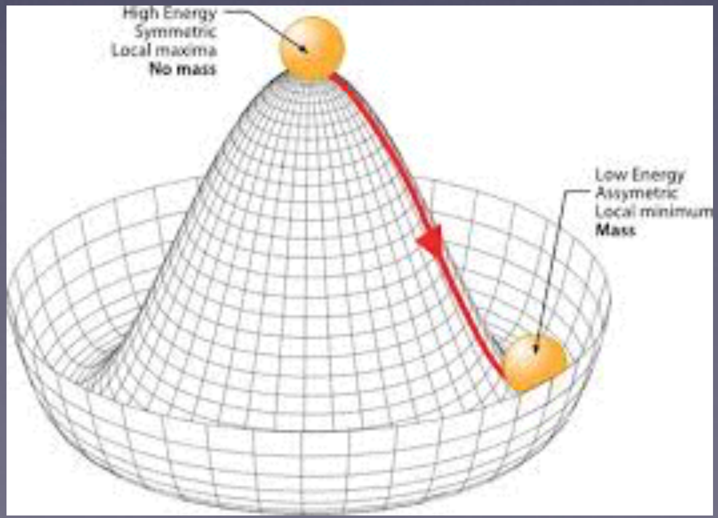
$$V(\phi) = -\mu^2 \phi^+\phi + \lambda(\phi^+\phi)^2 + Y^{ij}\, \psi_L{}^i\, \psi_R{}^j\, \phi$$

The ground state determined was tested with good accuracy (thanks to Tevatron)

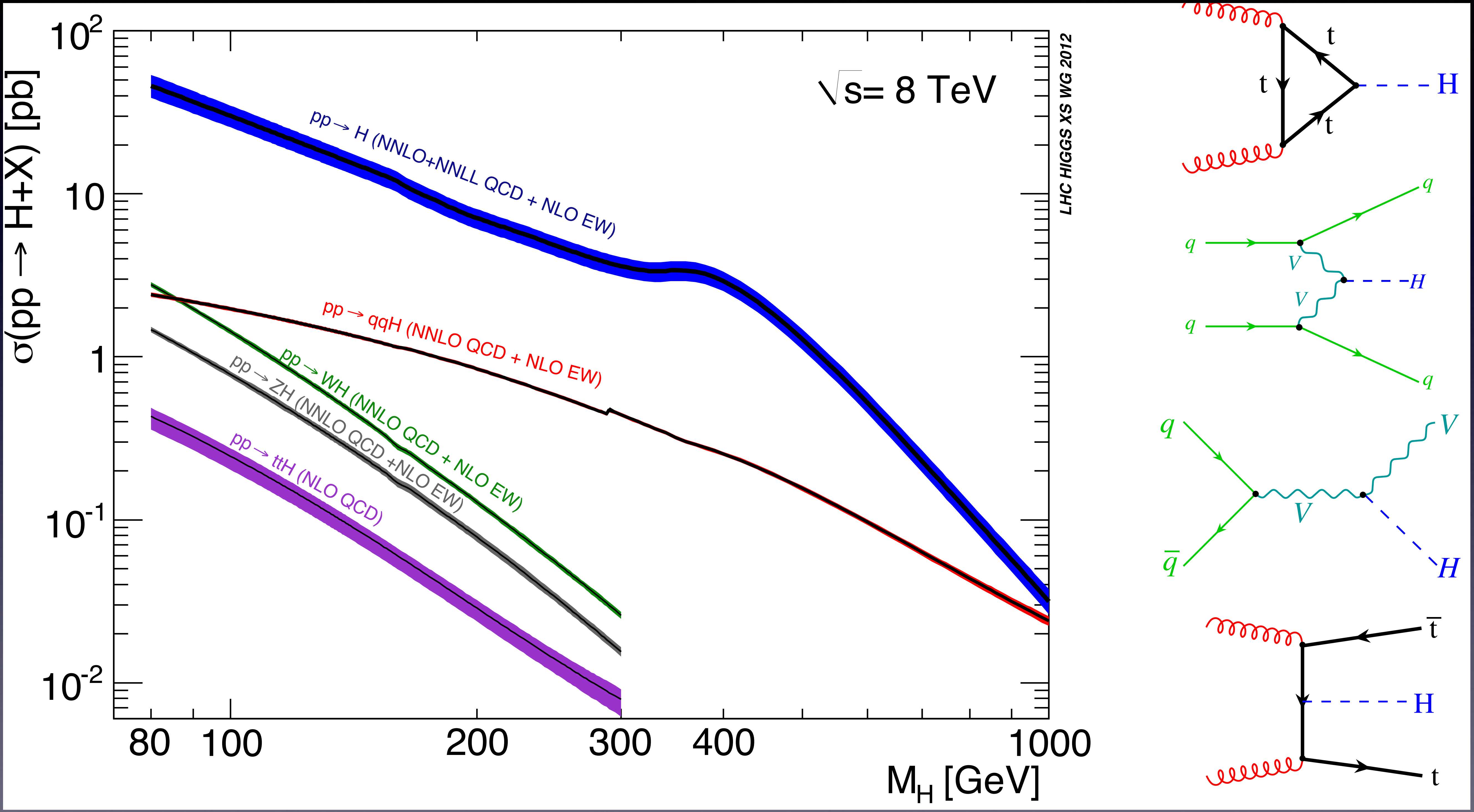
$$v = \langle \phi^+\phi \rangle^{1/2} \sim 246 \text{ GeV} \quad [\, m_W = \tfrac{1}{2}\, g\, v \,]$$

On July 4th, the 4th d.o.f. of the Higgs field is observed.

$$\lambda_{\rm (tree)} = \tfrac{1}{2}\, m_h{}^2 / v^2 \sim 0.13$$

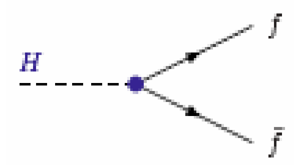


Higgs boson production

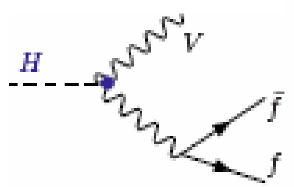


Higgs boson decay

bb dominant
m_H< 120 GeV

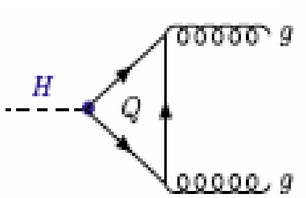


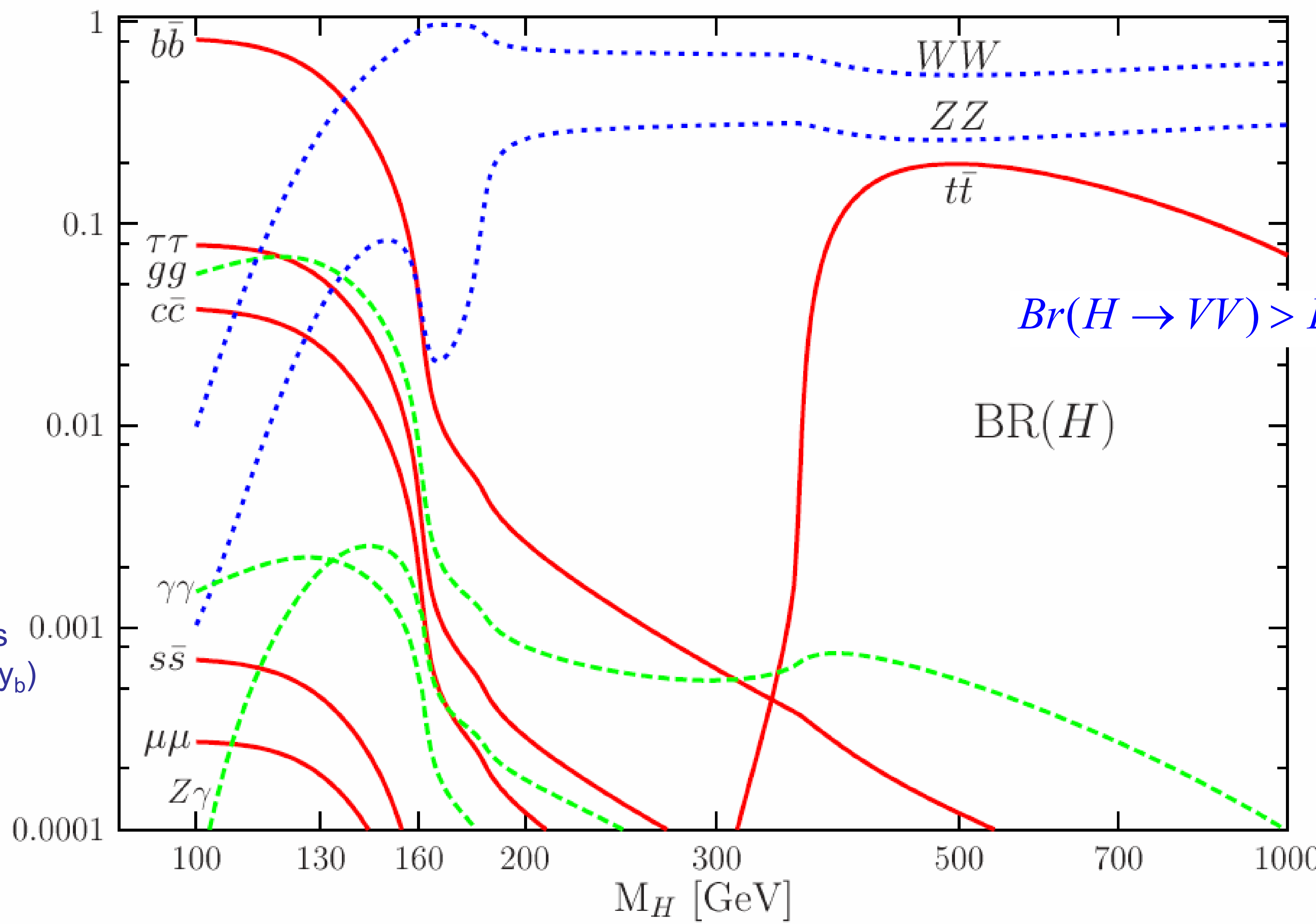
WW dominant
m_H> 130 GeV



(gauge coupling is much larger than y_b)

gg large
m_H<130 GeV

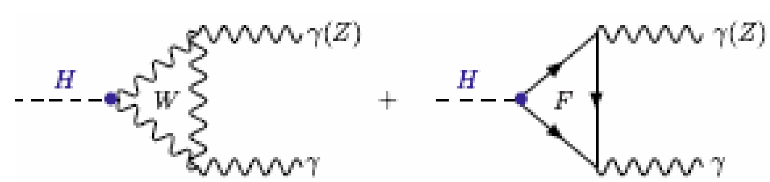




$$\frac{\Gamma(h \to WW)}{\Gamma(h \to ZZ)} \sim 2$$

$$Br(H \to VV) > Br(H \to tt)$$

γγ reaches maximal
m_H~130 GeV
(Important at LHC)



Questions of the top priority

scalar #:
one or two
or more?

Spin:
0 or 2?

CP:
even or odd?

Mass (accuracy)
Width (?)

1. What can we learn from 125GeV?

Theoretical problems

$$V(\phi) = - \mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^i \psi_R^j \phi$$

vacuum instability

possible internal inconsistency of the model ($\lambda < 0$) at large energies

[*key dependence on* m_h]

Quadratic sensitivity to the cut-off

$$\Delta\mu^2 \sim \Delta m_h^2 \sim \Lambda^2$$

(indication of *new physics* close to the electroweak scale ?)

SM flavour problem

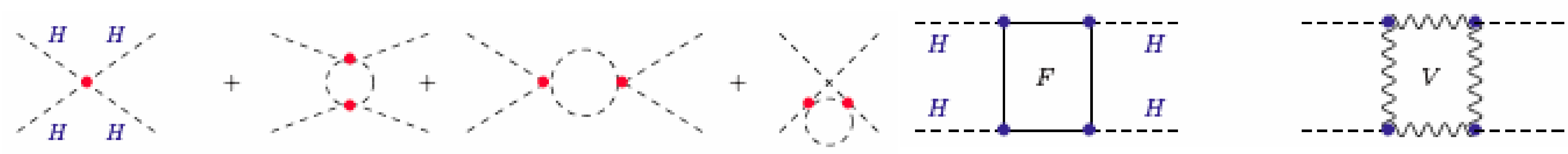
(unexplained span over 5 orders of magnitude and strongly hierarchical structure of the Yukawa coupl.)

Vacuum stability

- At large field values the shape of the Higgs potential is determined by the RGE evolution of the Higgs self coupling

$$V_{\text{eff}}(|\phi| \gg v) \approx \lambda(|\phi|)\,|\phi|^4 + \mathcal{O}(v^2\,|\phi|^2)$$

- Due to quantum correction, the Higgs self coupling as well as the masses depend on considered energy



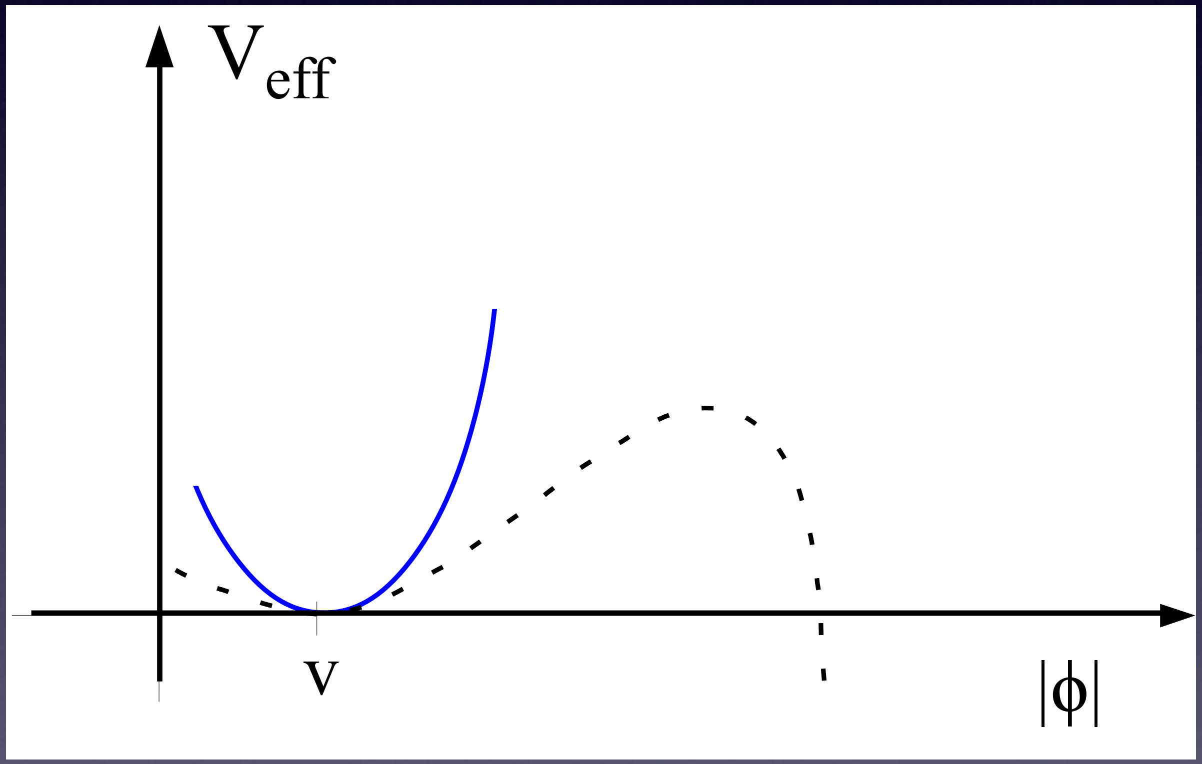
$$\frac{d\lambda}{d\ln Q^2} \simeq \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda(3g_2^2 + g_1^2) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

$$\lambda(|\phi|) < 0 \longrightarrow V(|\phi|) < V(v)$$

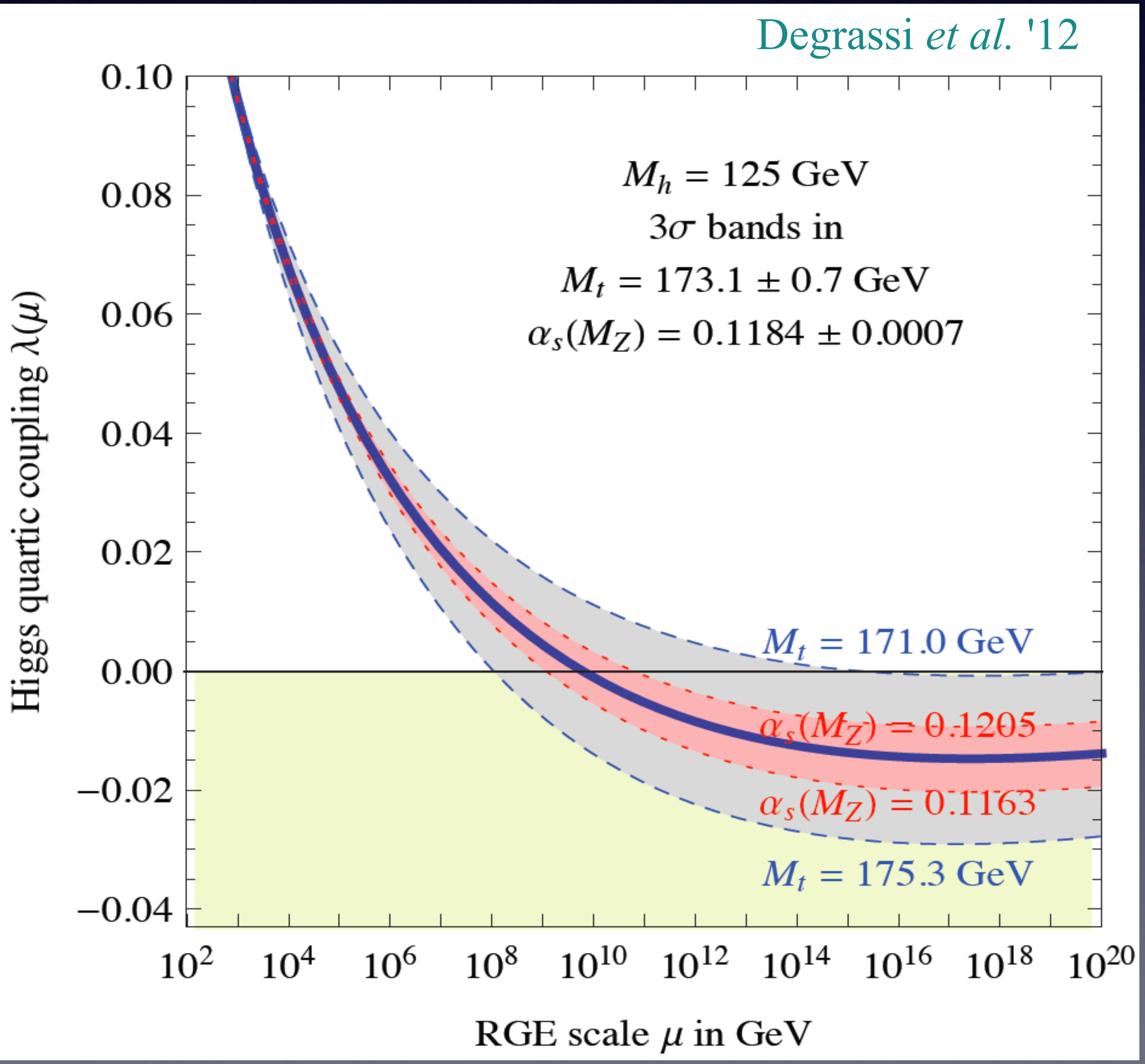
Vacuum unstable

Vacuum stability bound at NNLO

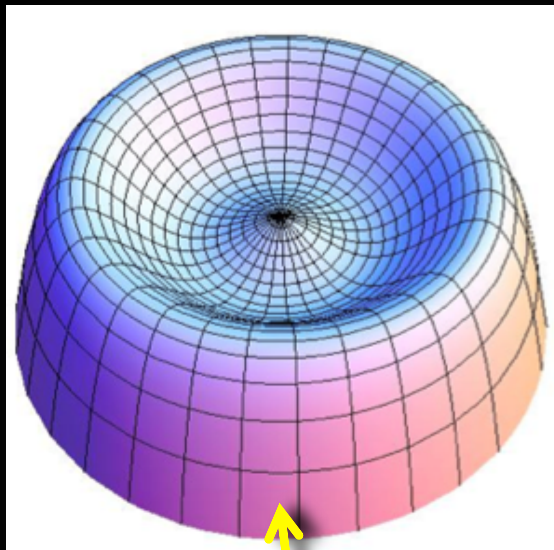
$$M_h\ [\text{GeV}] > 129.4 + 2.0\left(\frac{M_t\ [\text{GeV}] - 173.1}{1.0}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}$$



Might we live in a metastable vacuum?

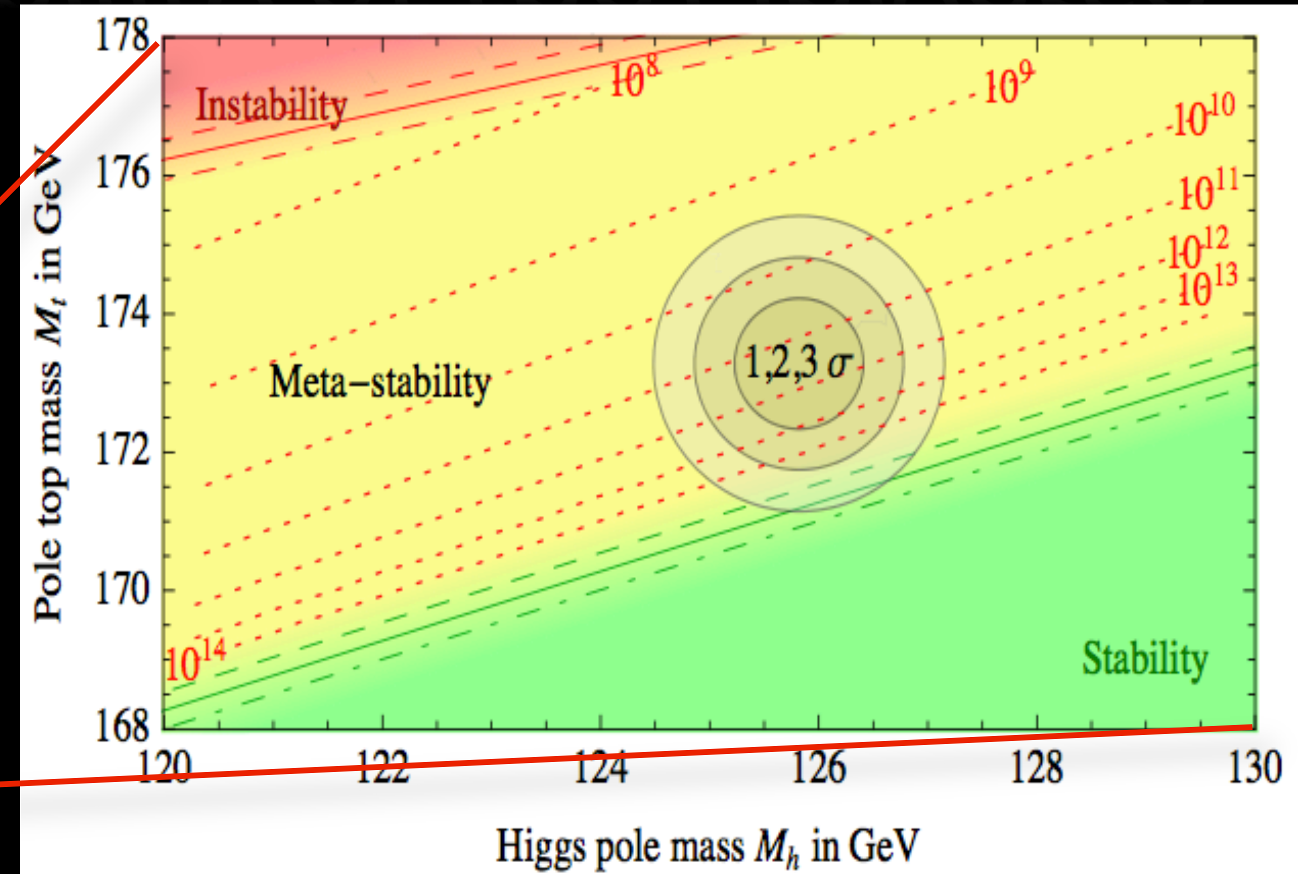


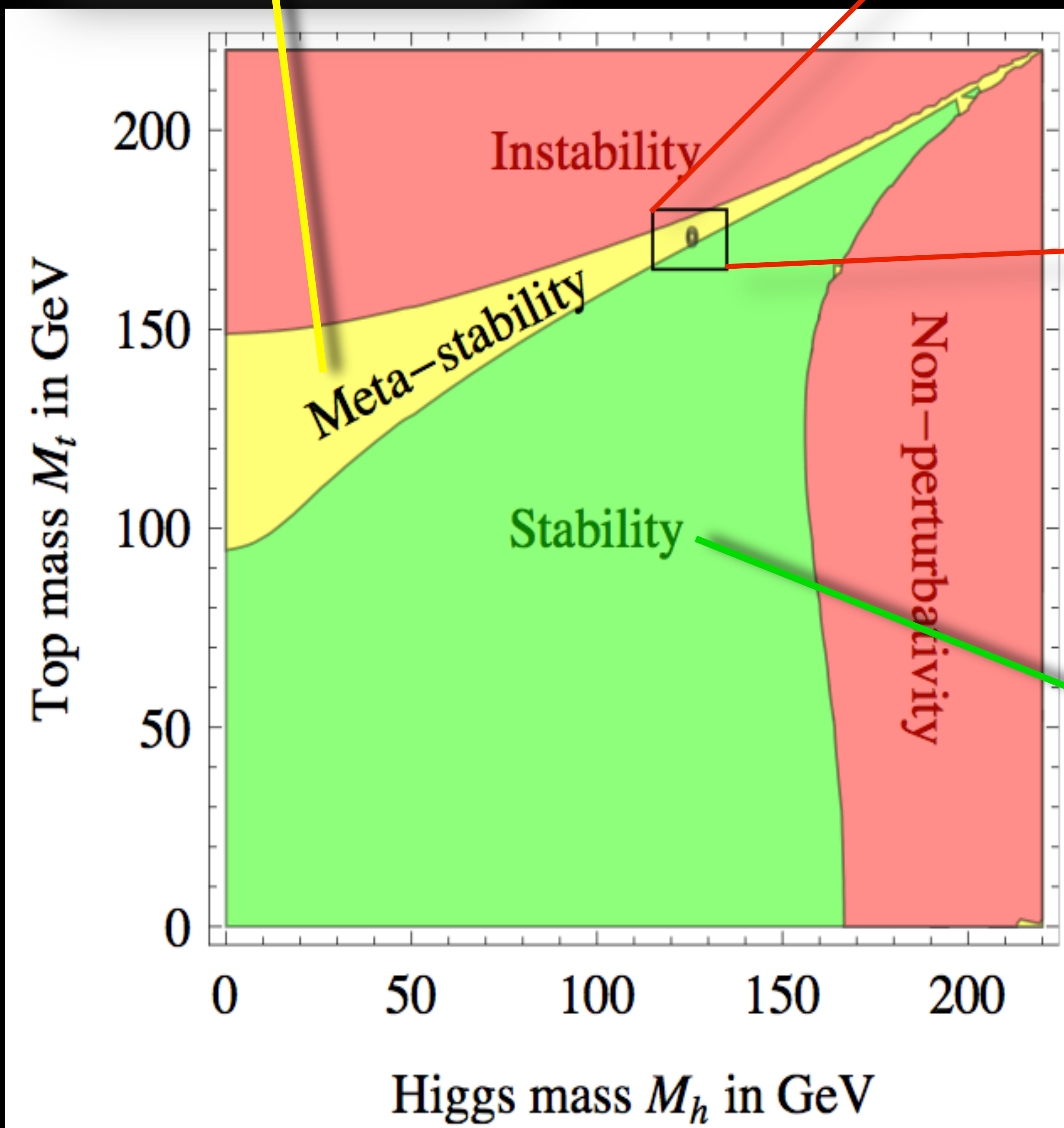
Stability of the Universe

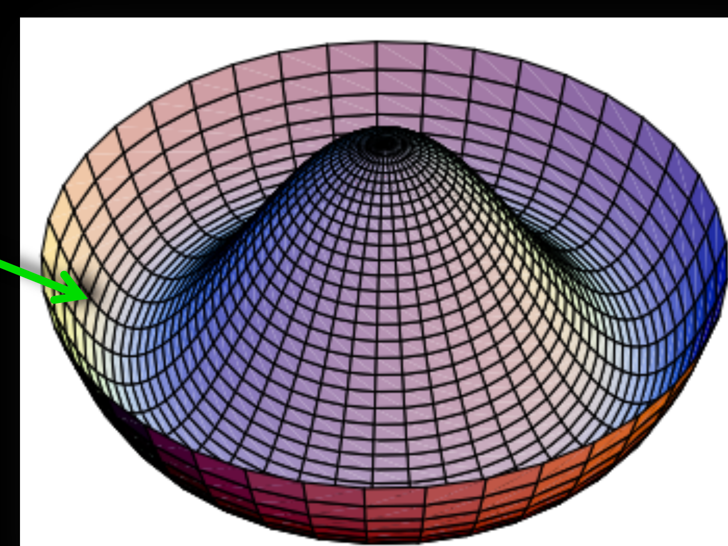


m_{top} ~ 173 GeV

m_H ~ 126 GeV







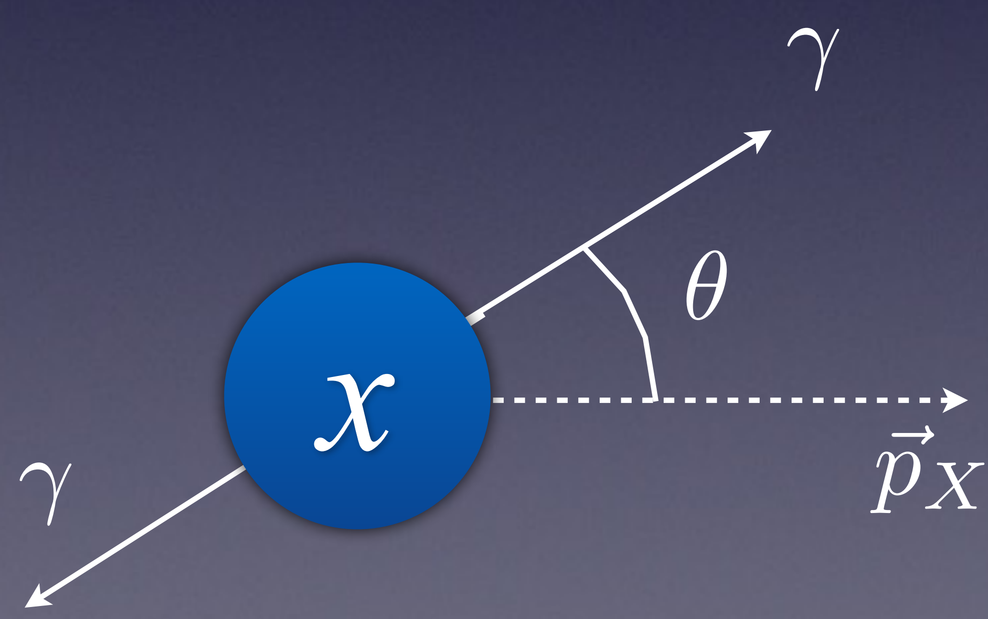
2. What about spin?

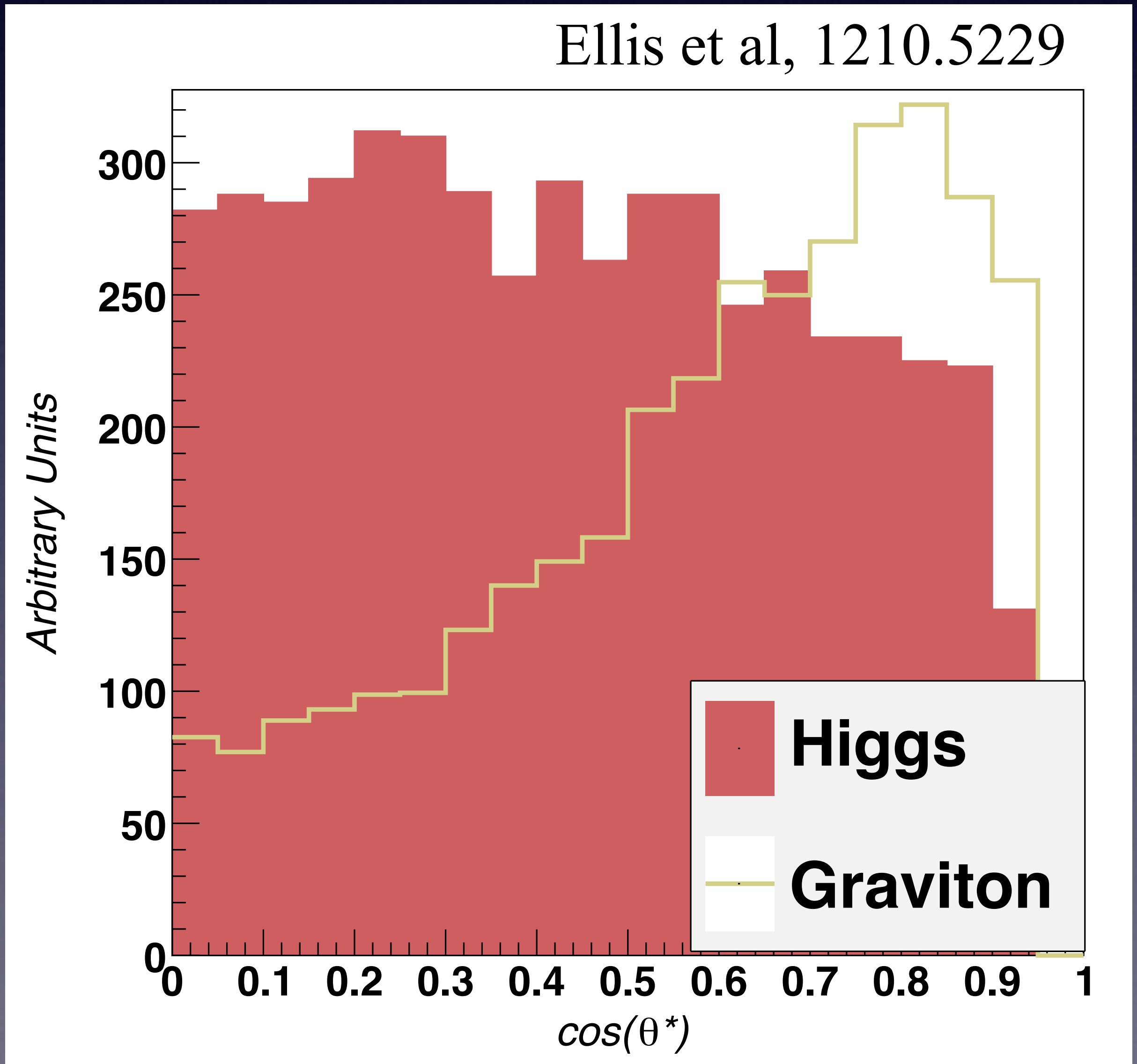
Spin-0 or Spin-2

- It is very likely to be spin-0, but we have to check it.

Spin-2: $$\frac{d\sigma}{d\cos\theta} \sim \frac{1}{4} + \frac{3}{2}\cos^2\theta + \frac{1}{4}\cos^4\theta$$

Spin-0: $$\frac{d\sigma}{d\cos\theta} \sim 1$$





3. CP Property

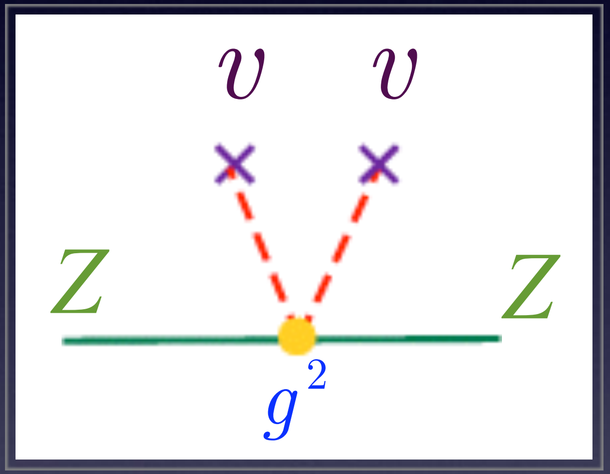
CP-even or CP-odd

- It is very likely to be CP-even, but we also need check it.

- In the SM the couplings of the Higgs boson to pair of Ws and Zs are fixed by gauge structure

$$(D\phi)^2 \rightarrow (1+\frac{h}{v})^2 m_V^2 V_\mu V^\mu$$

$$g_{hVV} = -2i\frac{m_V^2}{v}g_{\mu\nu}$$

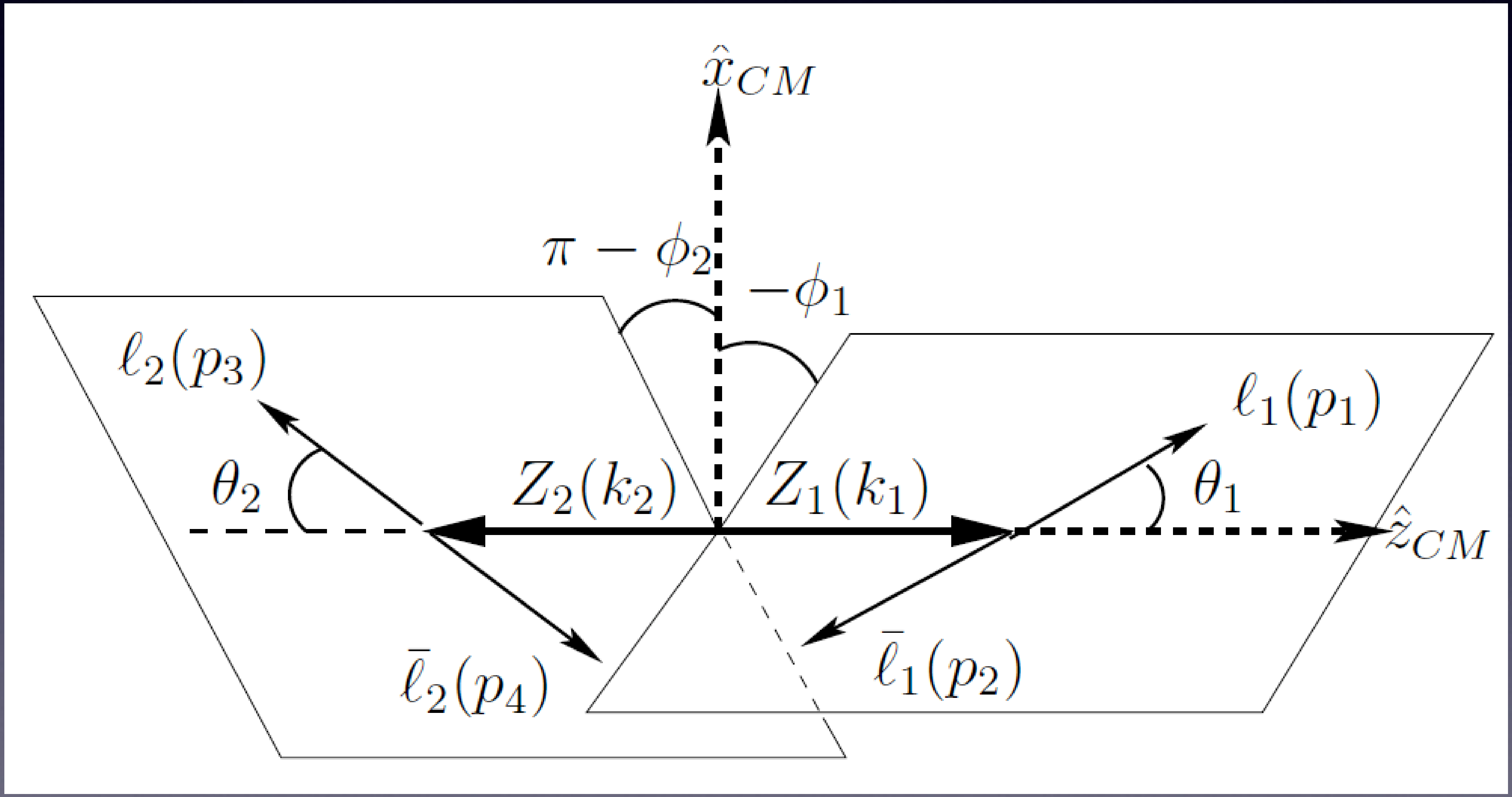


- A field without vacuum expectation value can couple to Ws and Zs through dimension-5 operators. In a weak-coupling theory the operators come from loops.

$$\frac{A}{M}hF_{\mu\nu}F^{\mu\nu} + \frac{B}{M}h\epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

Decay plane correlation

- One particular angle is very useful: the azimuthal angle between the decay plane



Decay plane correlation

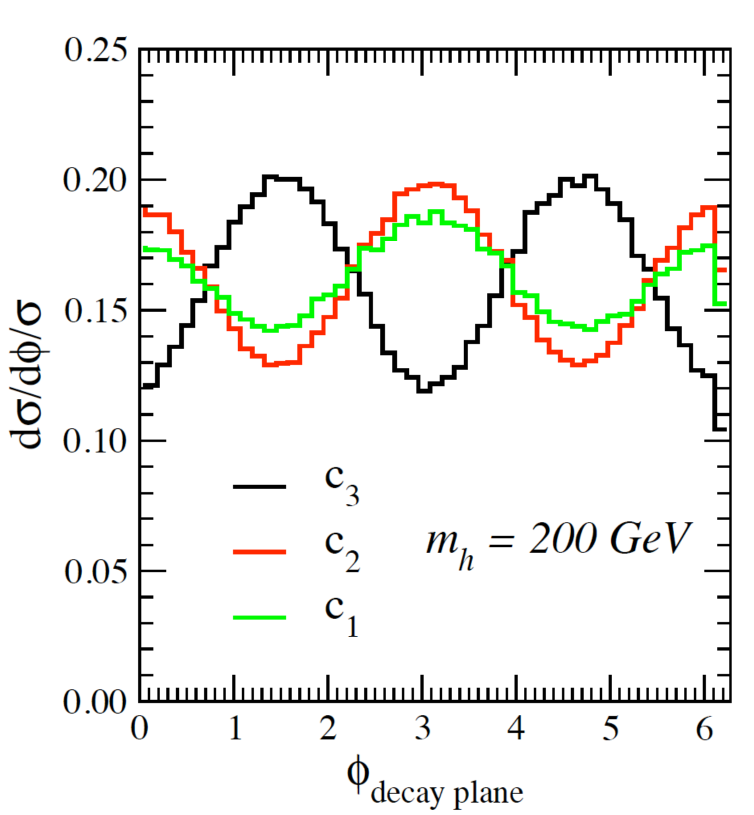
$$\mathcal{L}_{eff} = \frac{1}{2} m_S\, S \left(c_1 Z^\nu Z_\nu + \frac{1}{2}\frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4}\frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

$$\frac{d\Gamma}{\Gamma d\phi} = \frac{1}{N} \left\{ \frac{8}{9}\cos(2\phi + 2\delta) + \frac{\pi^2}{2}\frac{M_L}{M_T}\left(\frac{g_R^2 - g_L^2}{g_R^2 + g_L^2}\right)^2 \cos(\phi + \delta) + \frac{16}{9}\left(\frac{M_L^2}{M_T^2} + 2\right) \right\}$$

Negligible (~0.06) in the SM!

$\delta = 0$ for vanishing c_3
(CP-even scalar!)

$\delta = \pi/2$ for vanishing c_1 and c_2
(CP-odd scalar!)



4. Is it just the SM Higgs?

Higgs boson couplings

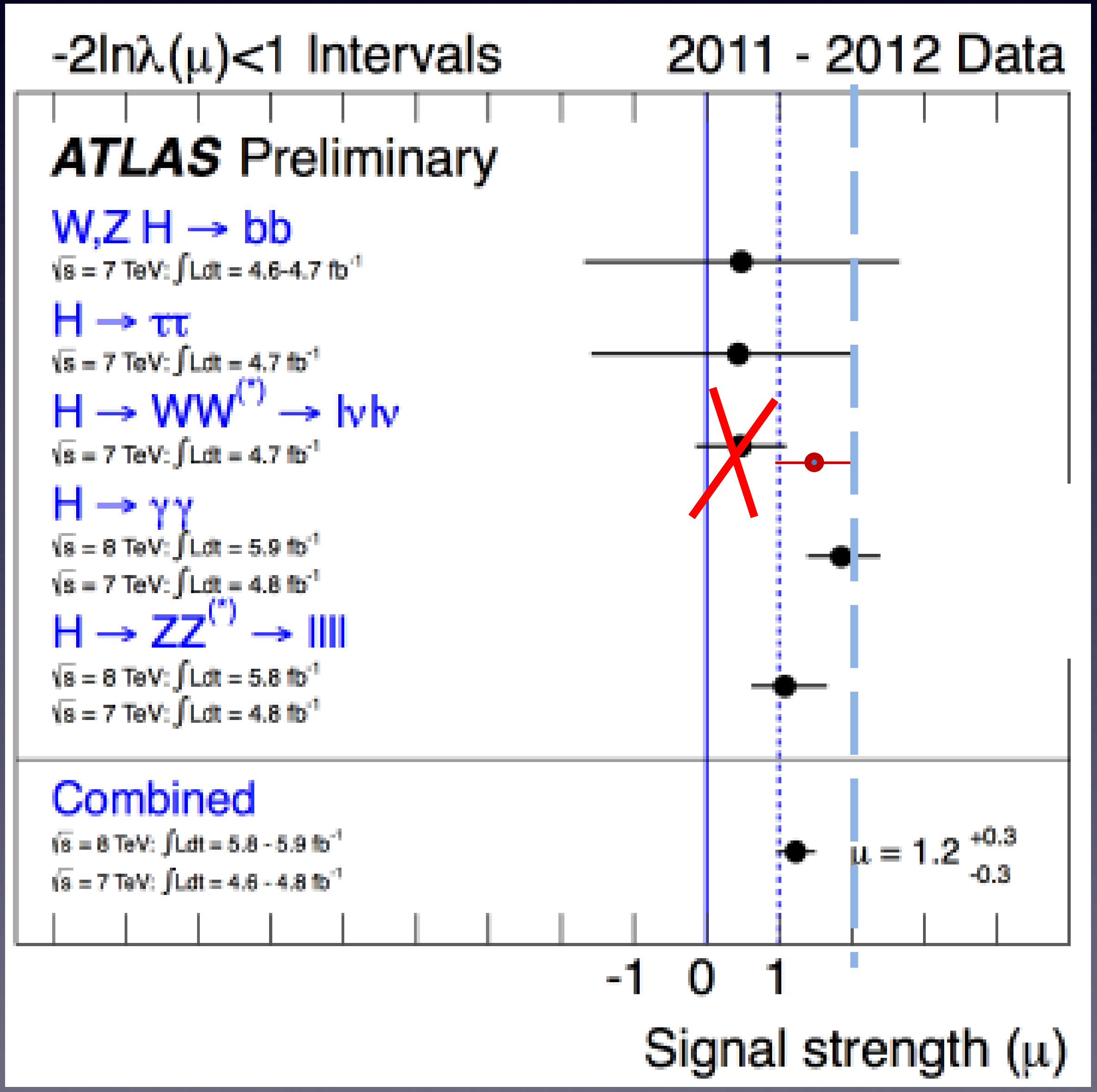
- New set of reference SM parameters

$$m_H \sim 126 \text{ GeV} \quad \Gamma_H = 4.2 \text{ MeV} \quad \lambda = (m_H/v)^2/2 = 0.131$$

$Br(H \to WW^*) = 23\%$ ★
$Br(H \to ZZ^*) = 2.9\%$ ★

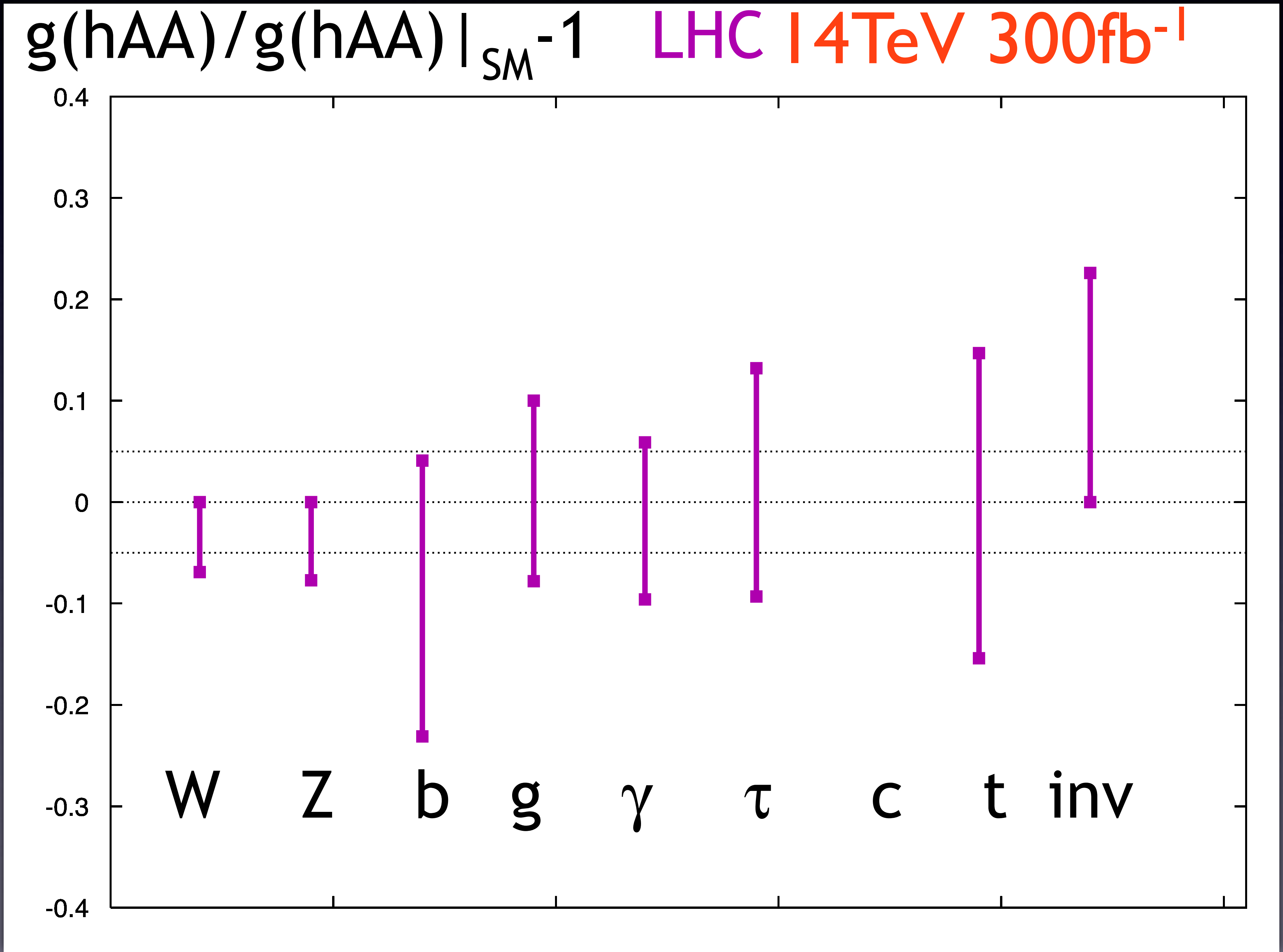
$Br(H \to bb) = 56\%$ ★
$Br(H \to cc) = 2.8\%$
$Br(H \to \tau\tau) = 6.2\%$ ★
$Br(H \to \mu\mu) = 0.021\%$

$Br(H \to gg) = 8.5\%$ ★
$Br(H \to \gamma\gamma) = 0.23\%$ ★
$Br(H \to \gamma Z) = 0.16\%$ ★



Higgs boson couplings

Peskin, 1208.5152



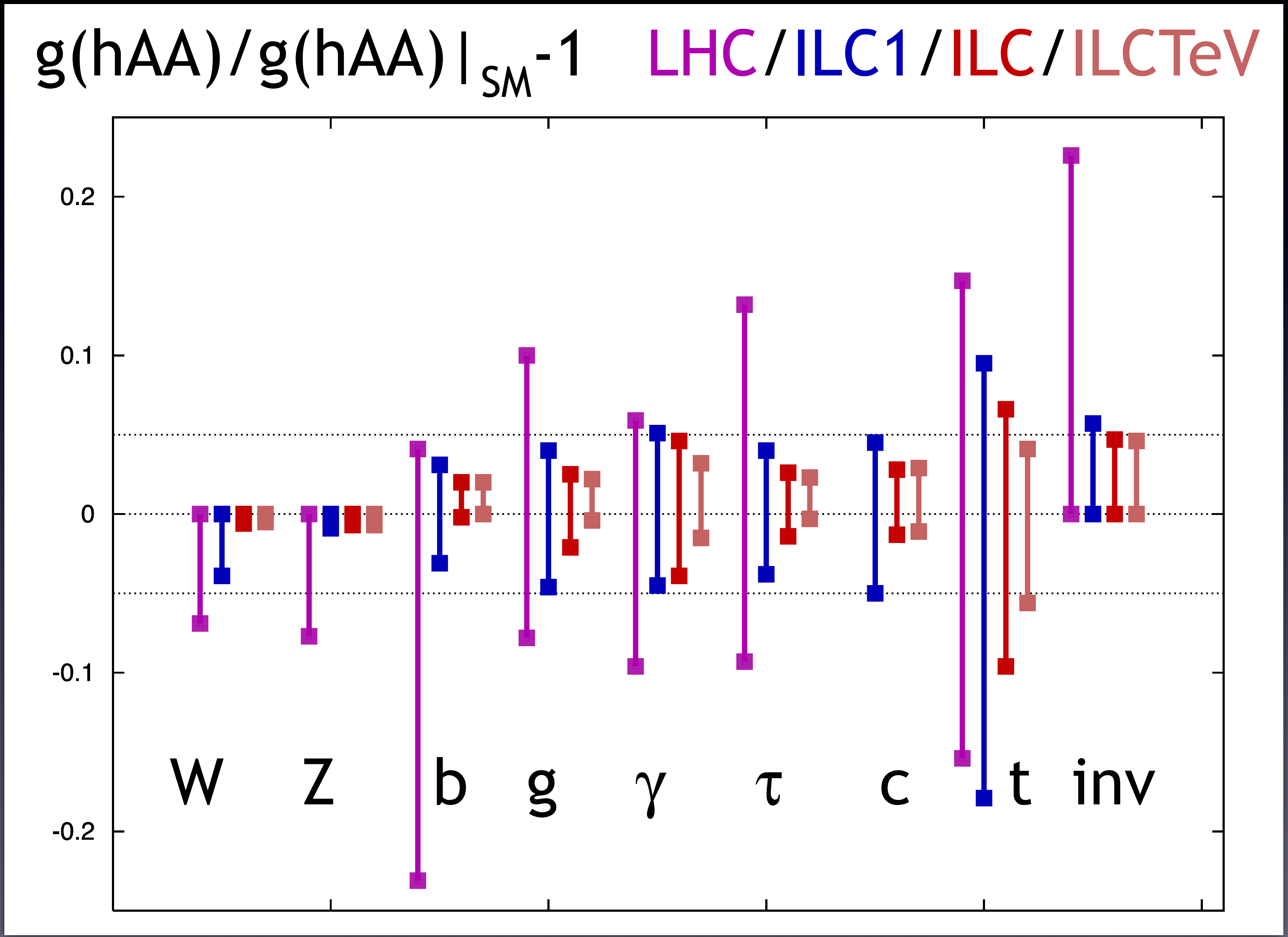
Higgs boson couplings at LC

LHC:
14TeV
300fb^{-1}

ILC1:
250GeV
250fb^{-1}

ILC:
500GeV
500fb^{-1}

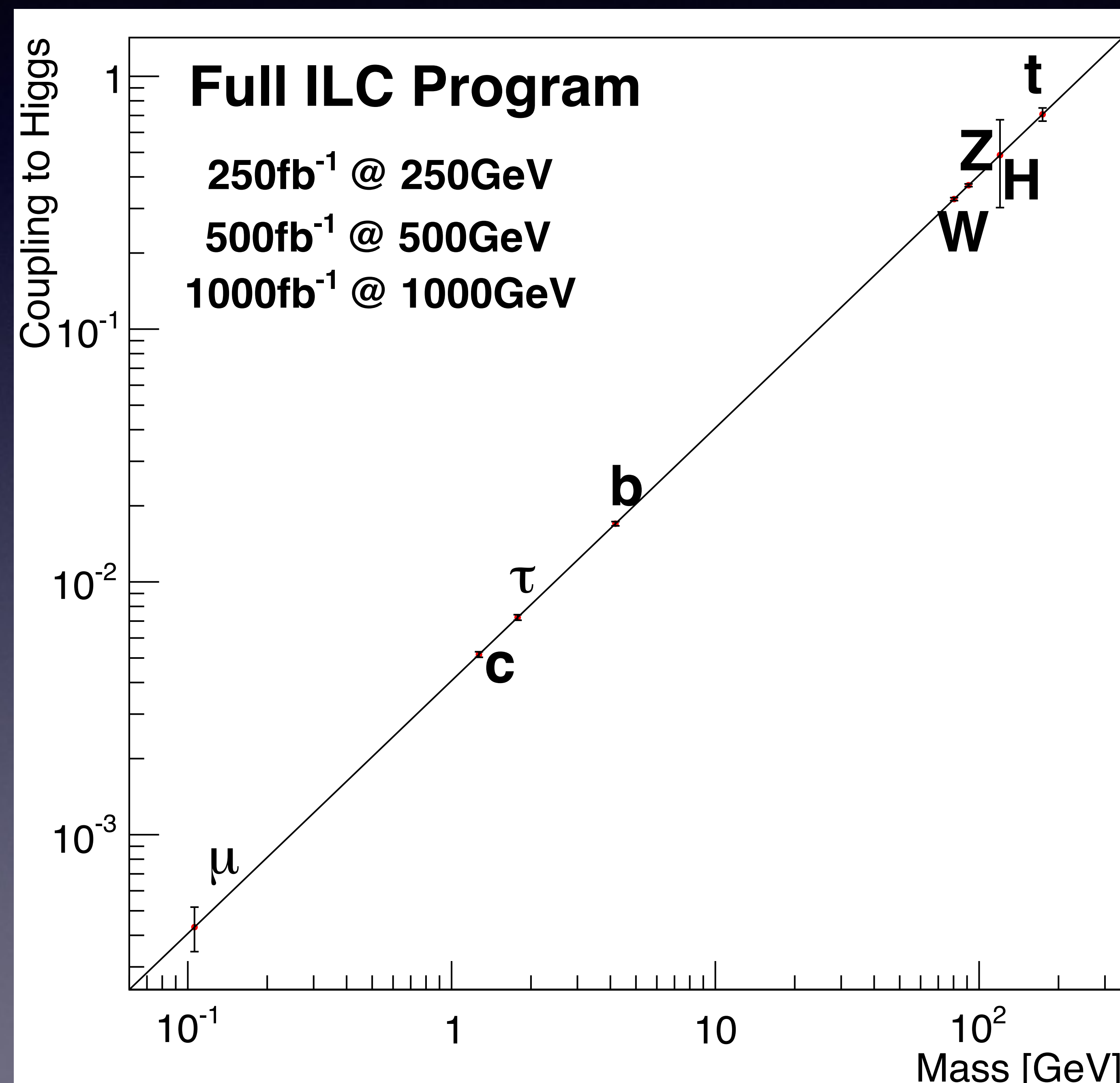
ILC TeV:
1000GeV
1000fb^{-1}



Higgs boson couplings at LC

- If the simple scalar Higgs model is correct, the Higgs couplings to each particle is proportional to its mass.

We can test this hypothesis to high accuracy.

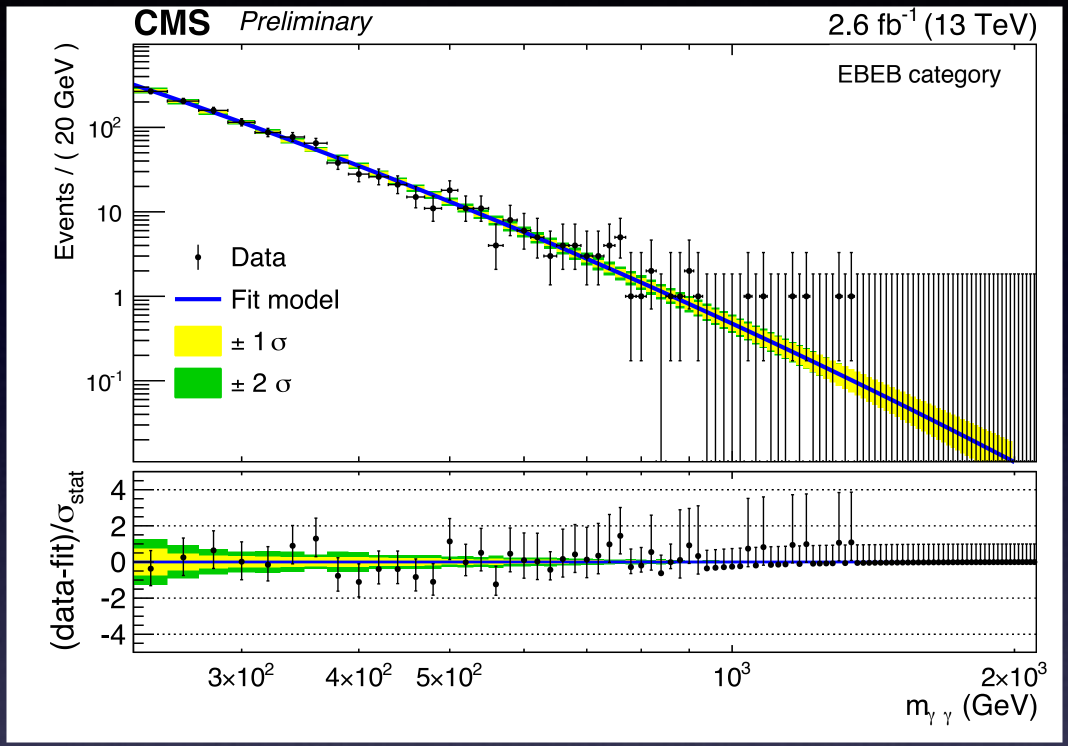


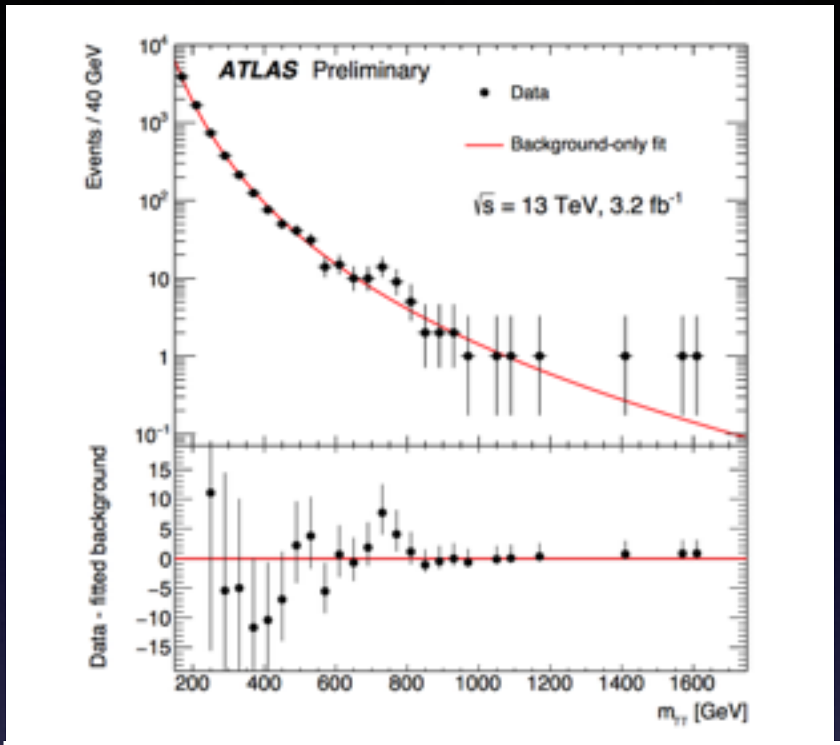
2002
ACFA
LC study

5. Only one scalar?

Excess around 750 GeV ?

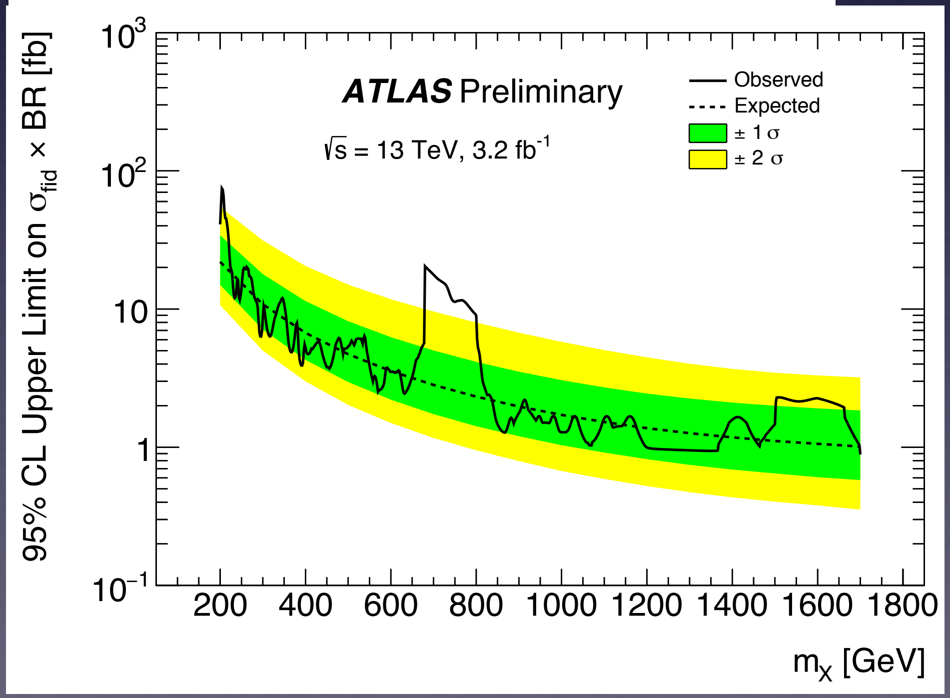
Dec 18, 2015

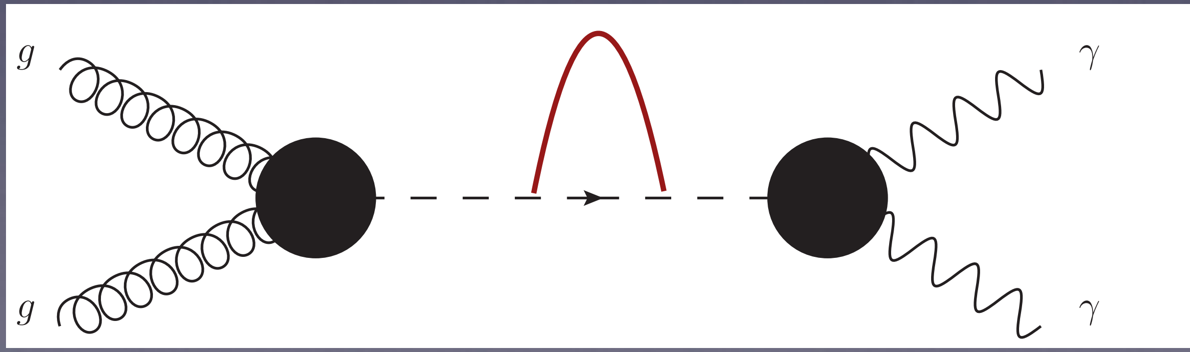




2.6σ (local)

1.2σ (global)





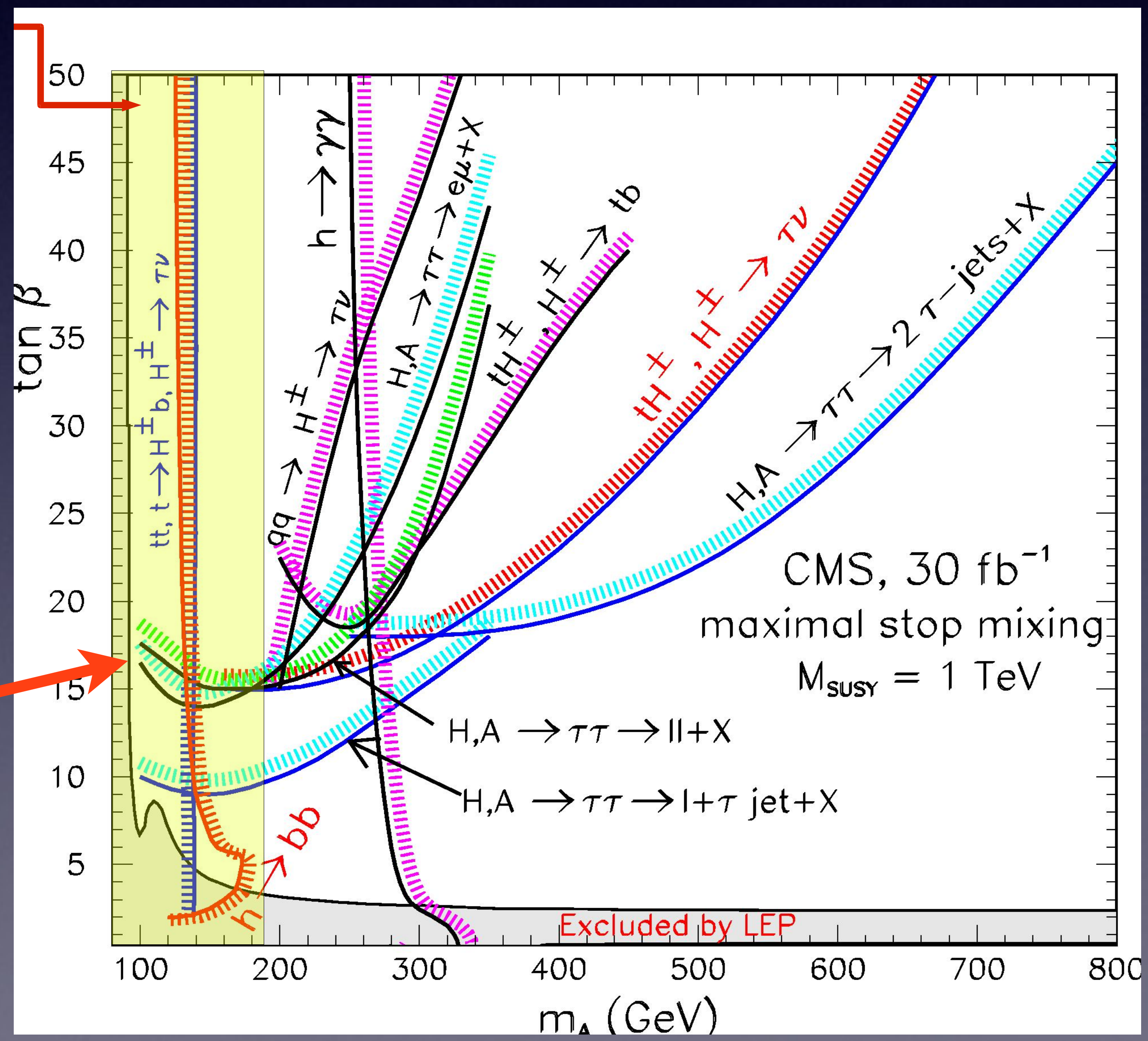
3.9σ (local)

2.3σ (global)

Charged Higgs boson

- In the MSSM: 5 physical Higgs fields

2 CP-even Higgs boson h and H
1 CP-odd Higgs boson A
2 Charged Higgs boson $H^{\pm}$



Entire Yellow shaded region can be covered by $AH^{\pm}$ production

Direct searches of New Physics

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

Techicolor

Composite Higgs

Supersymmetry

理论家的贡献

Little Higgs Model

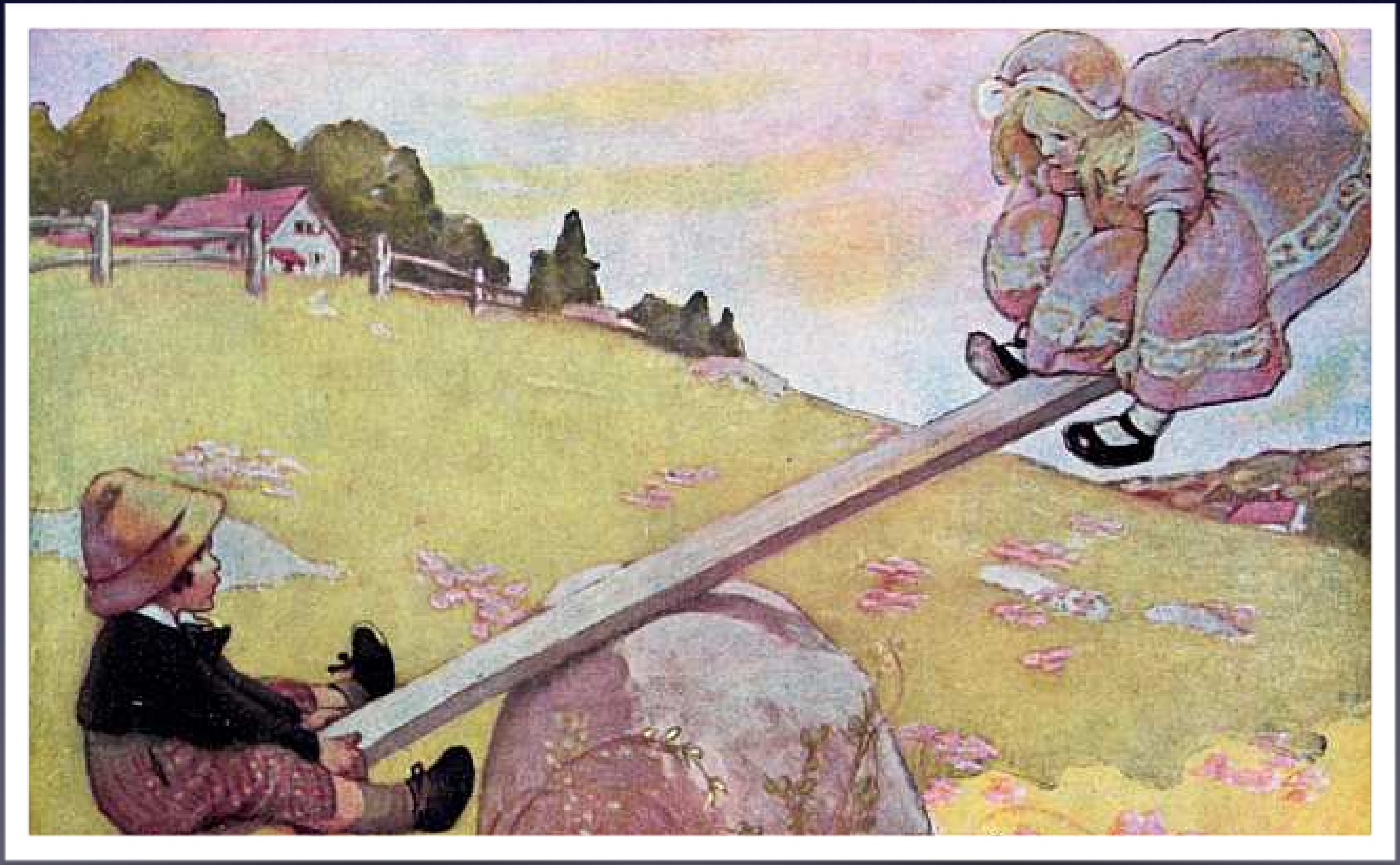
Twin Higgs

nd Unification

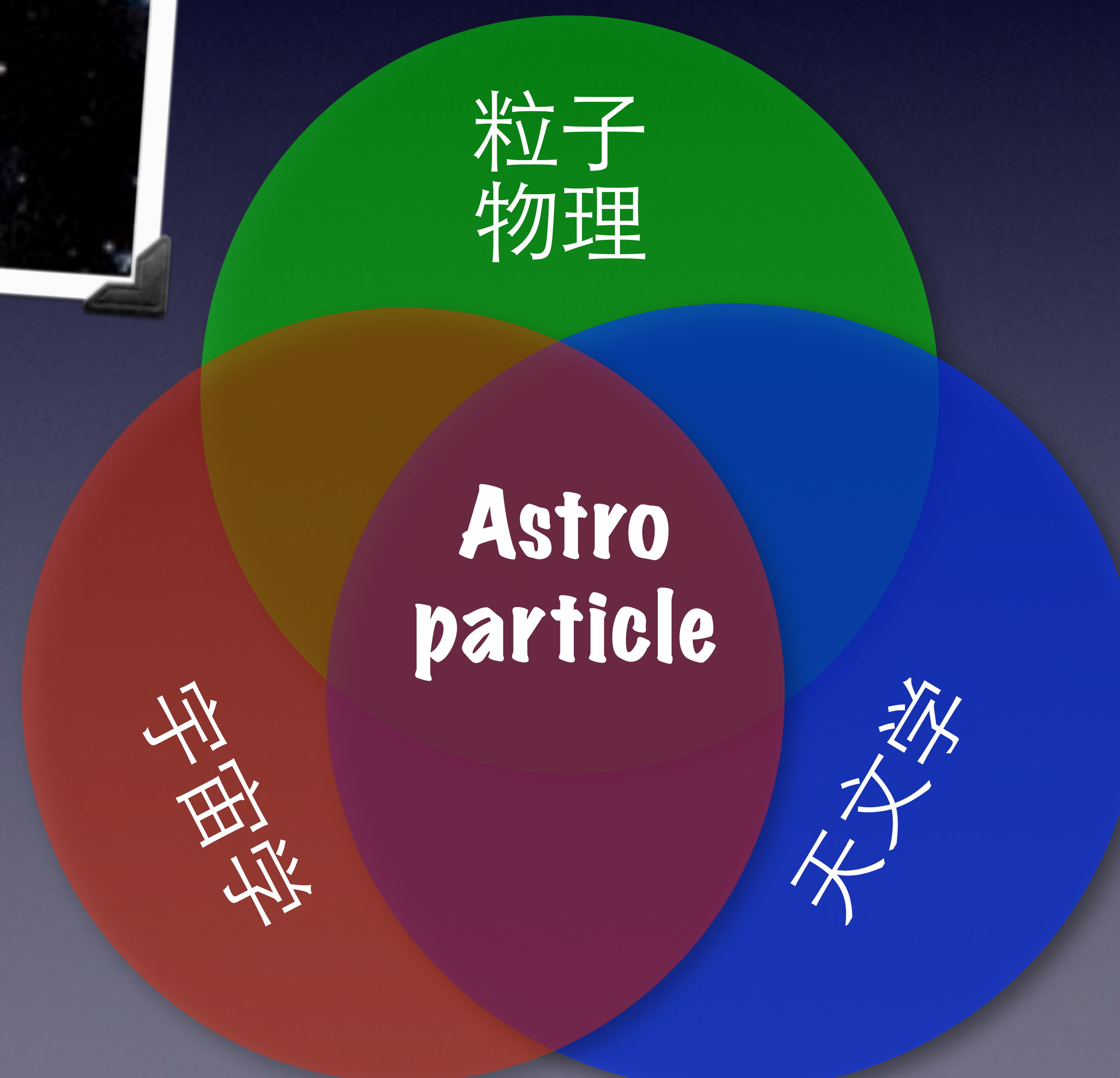
1） 中微子质量起源

—— 跷跷板机制

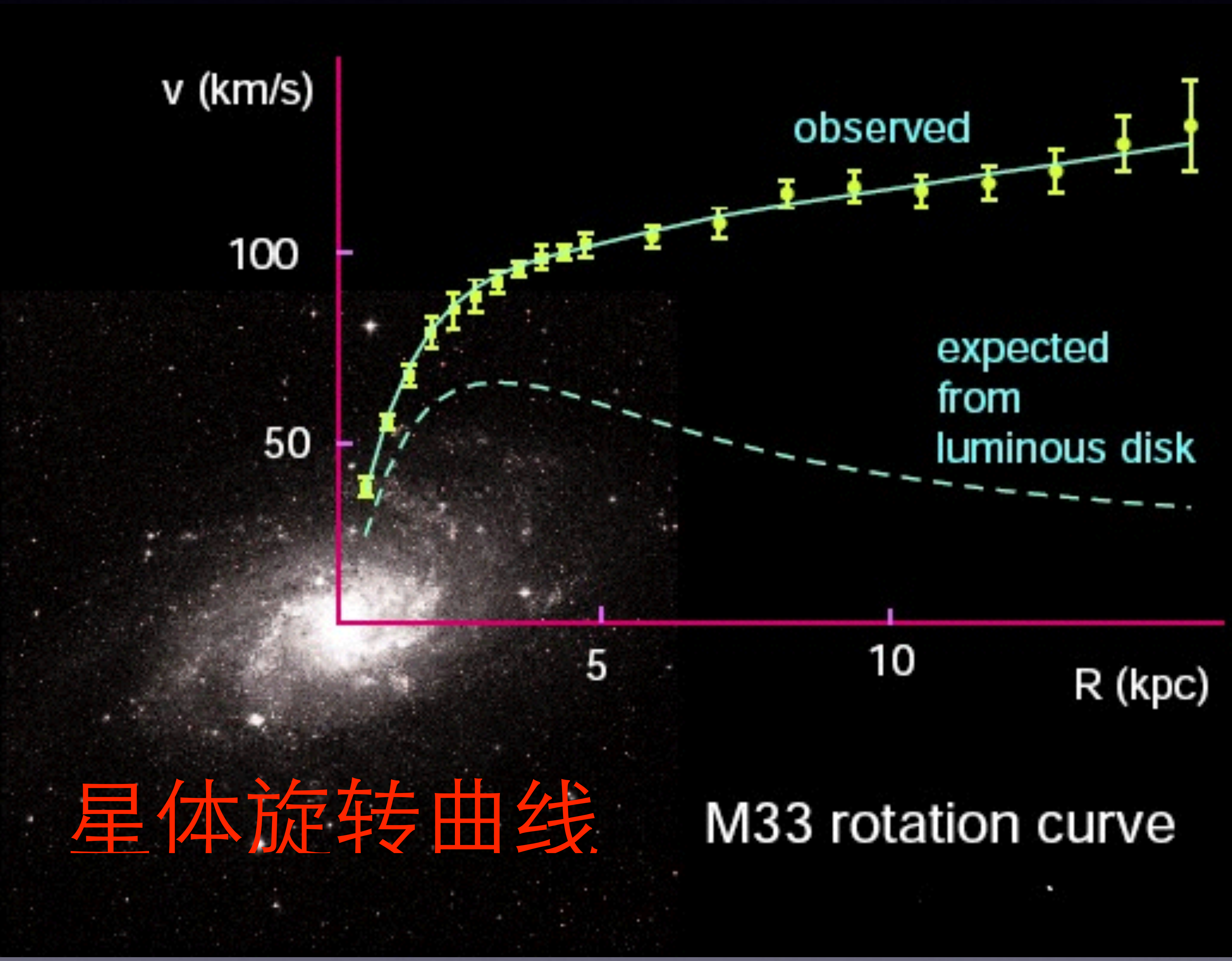
See-Saw Mechanics

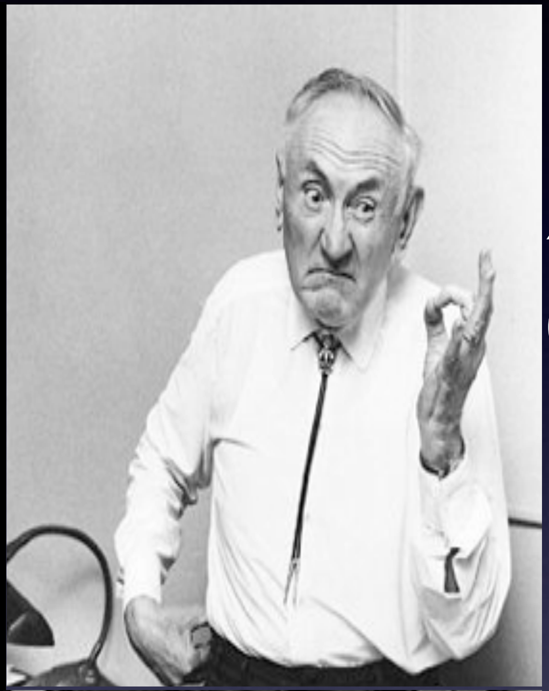


2. 暗物质 (粒子宇宙学)



暗物质 (Dark Matter)





Fritz Zwicky (1933)

Vera Rubin (1970's)

暗物质

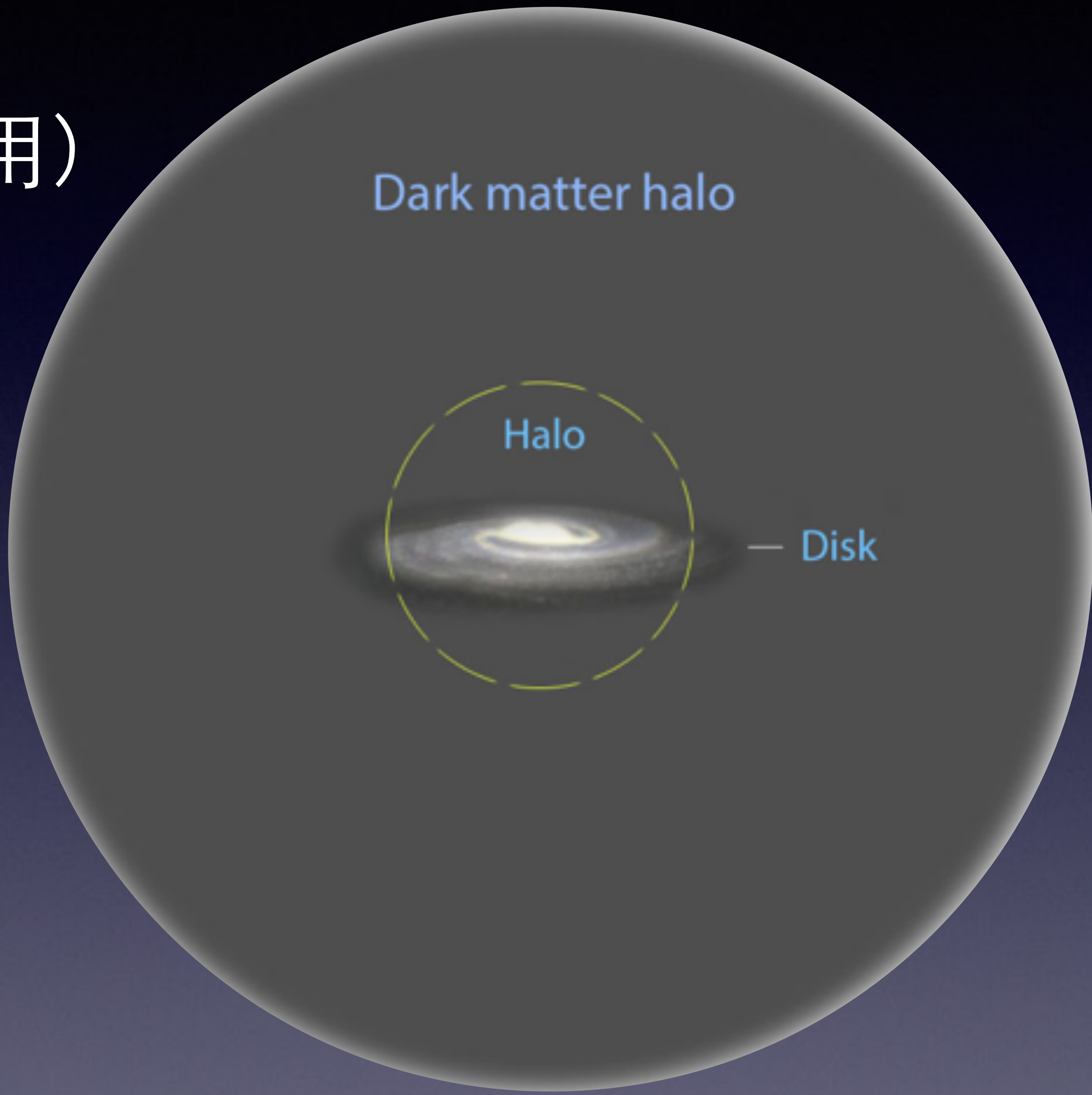
已知信息：

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

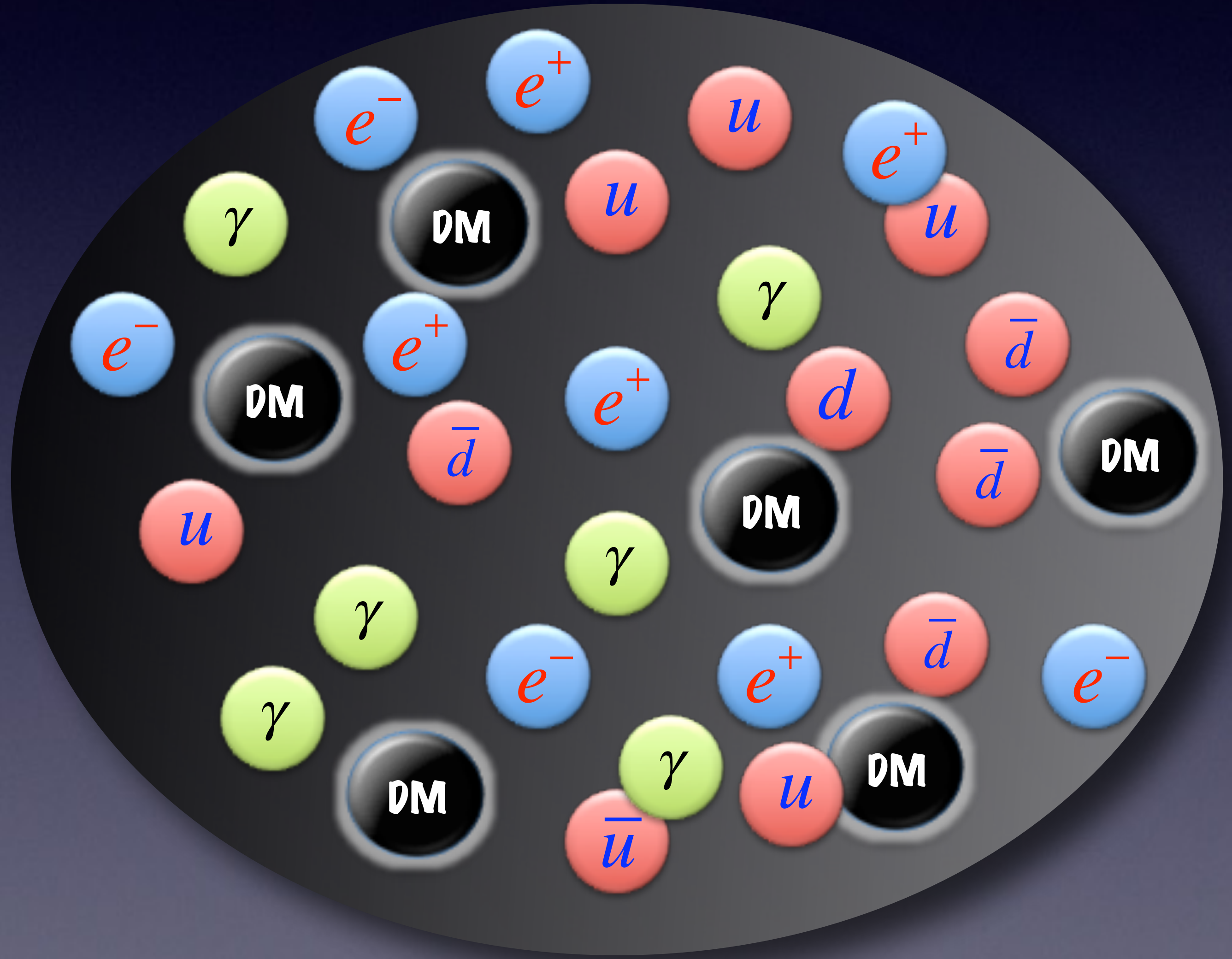
更糟的是，我们甚至不知道
“什么是我们不知道的”

暗物质候选者之一

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

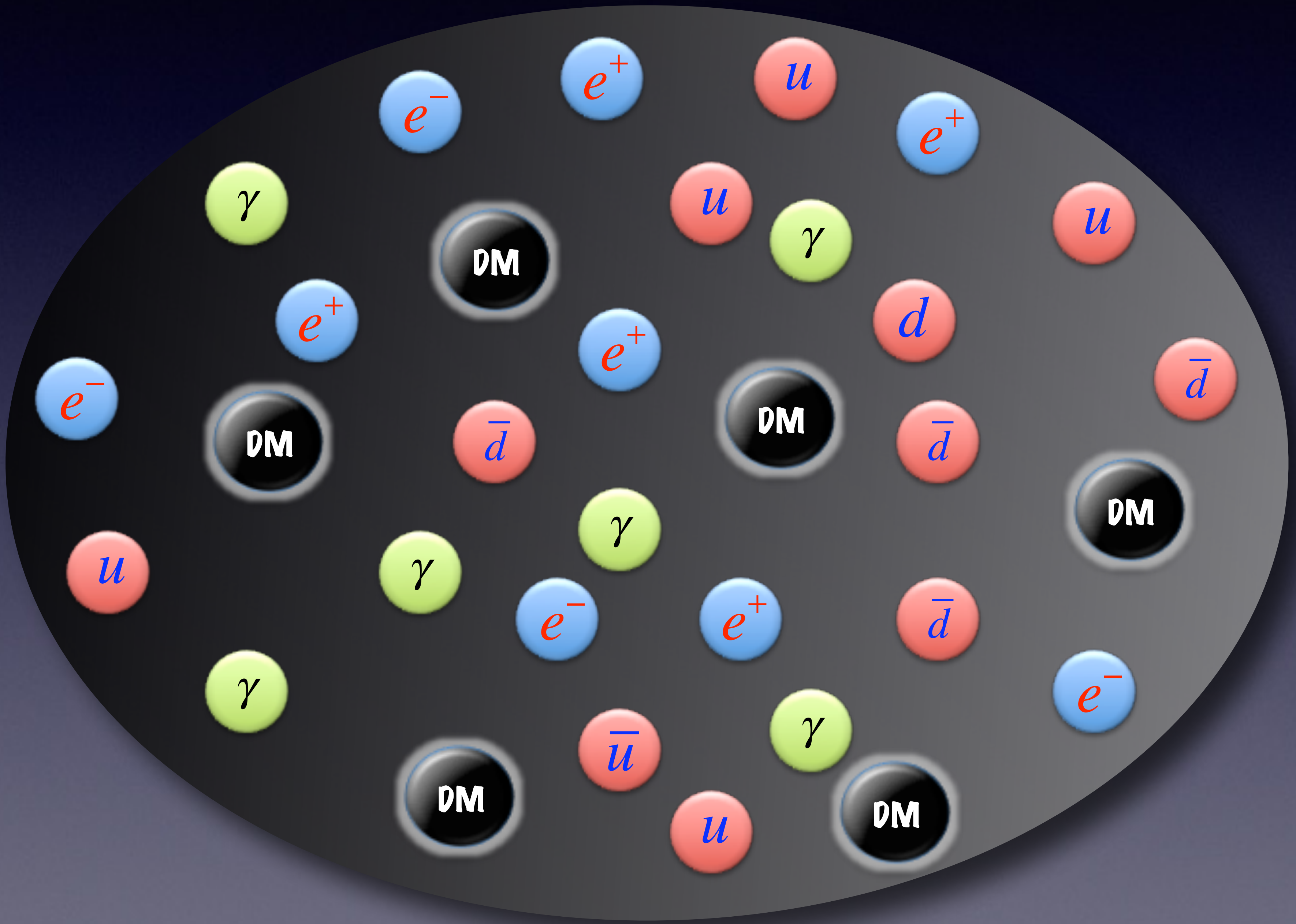
暗物质残留丰度

1）宇宙早期暗物质和可见物质处于热力学平衡态



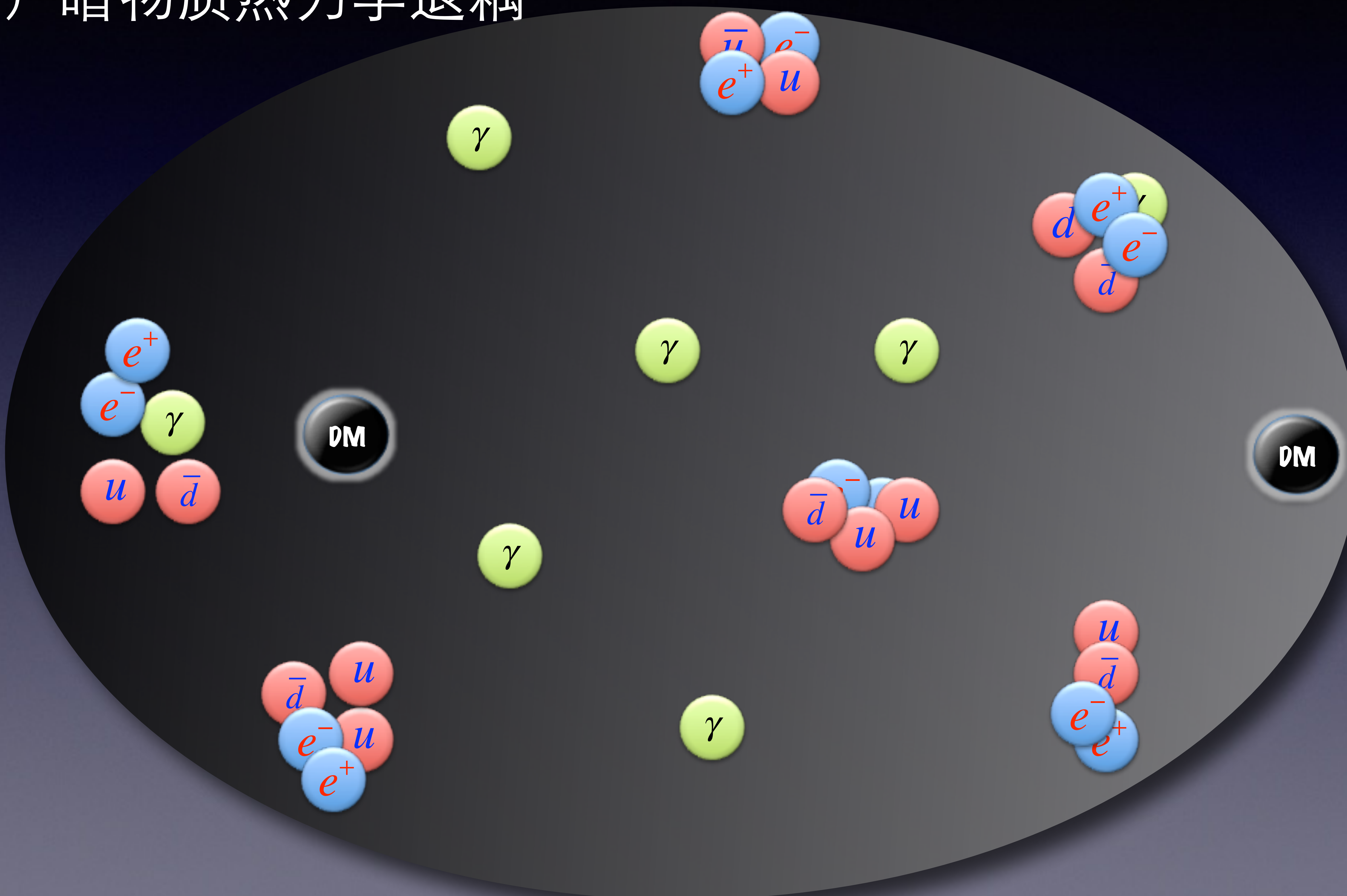
暗物质残留丰度

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

1. 暗物质和可见物质处于热力学平衡态

$$\chi\chi \leftrightarrow f f$$

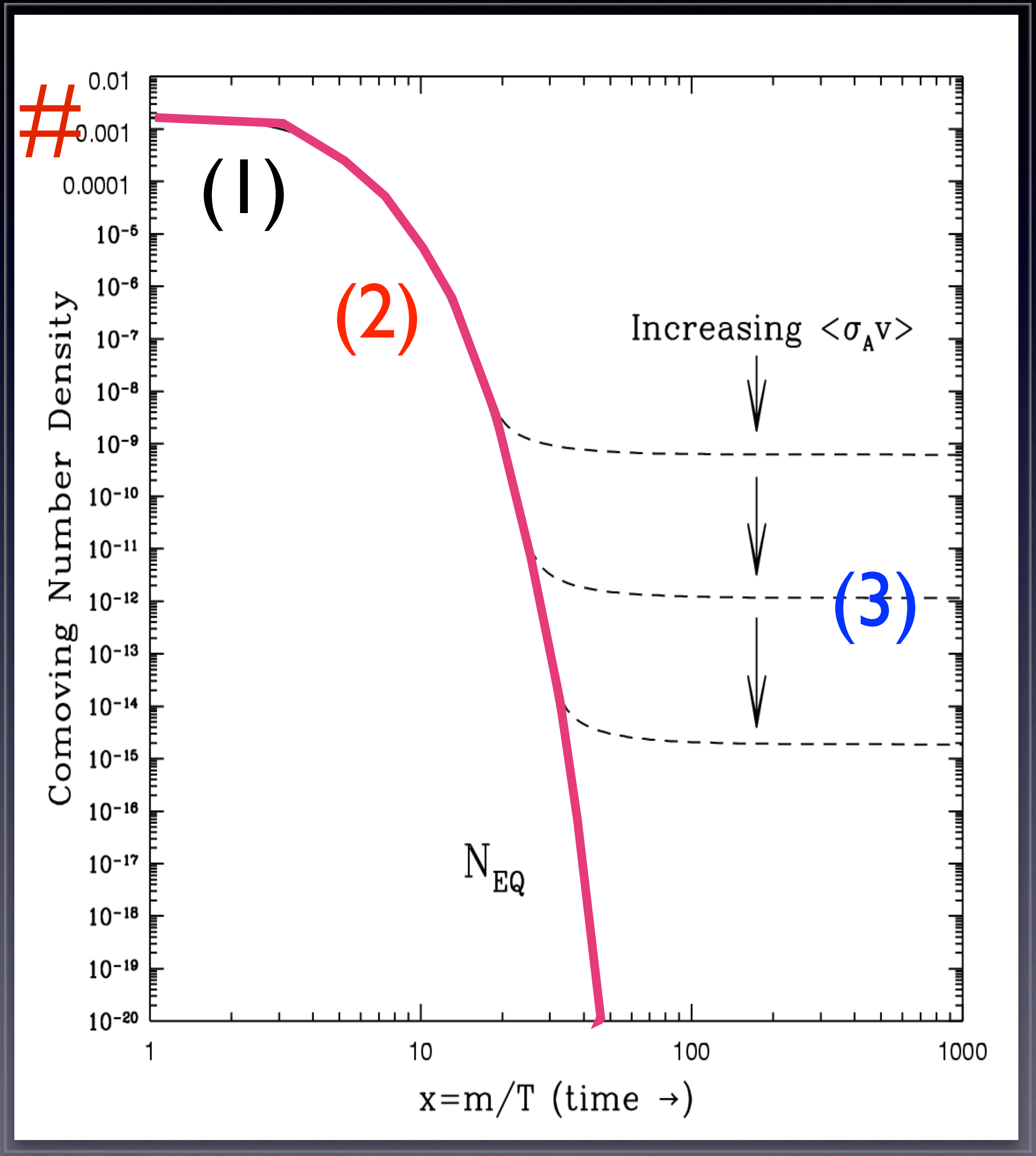
2. 宇宙膨胀冷却

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

3. 暗物质从热库中退耦

$$N \sim \mathrm{Constant}$$

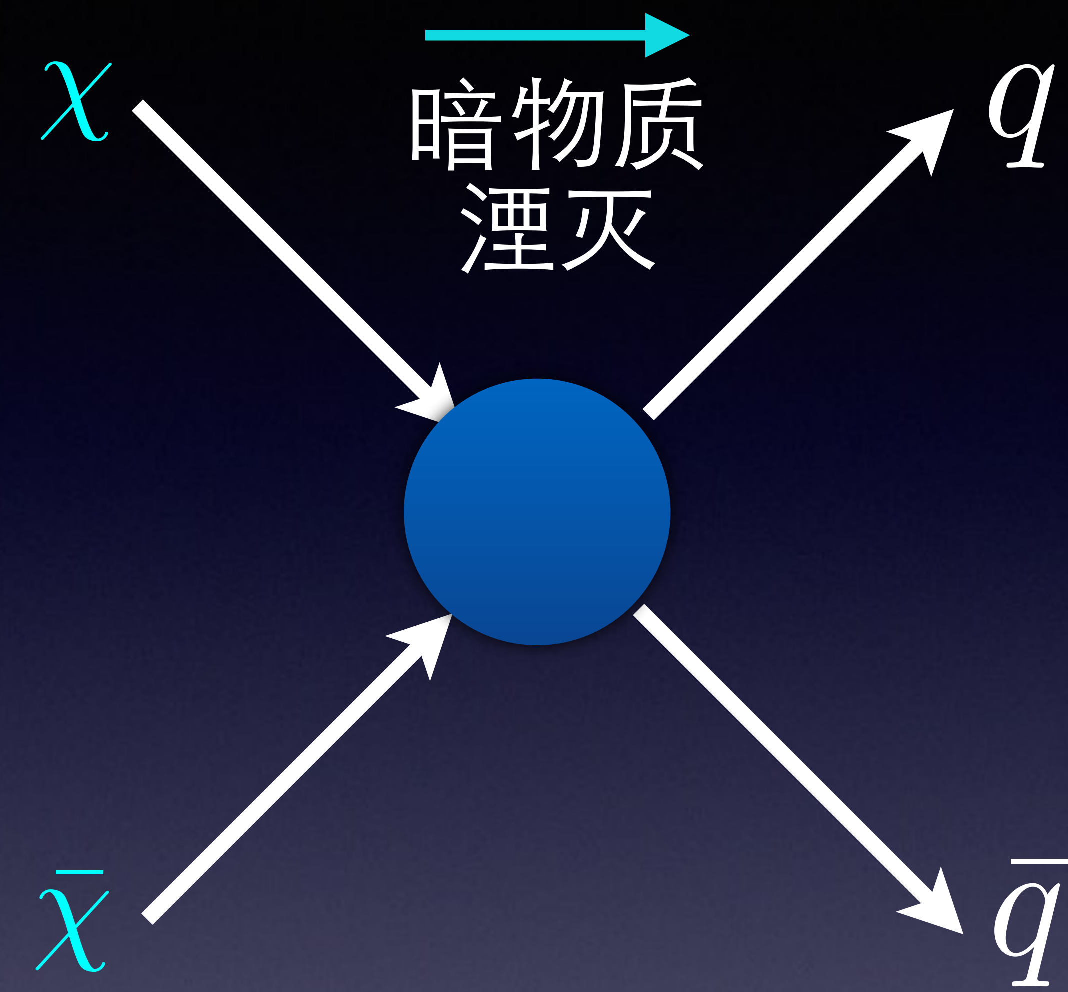
脱耦温度 $T_F \simeq \frac{m_\chi}{20}$



WIMP奇迹

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

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



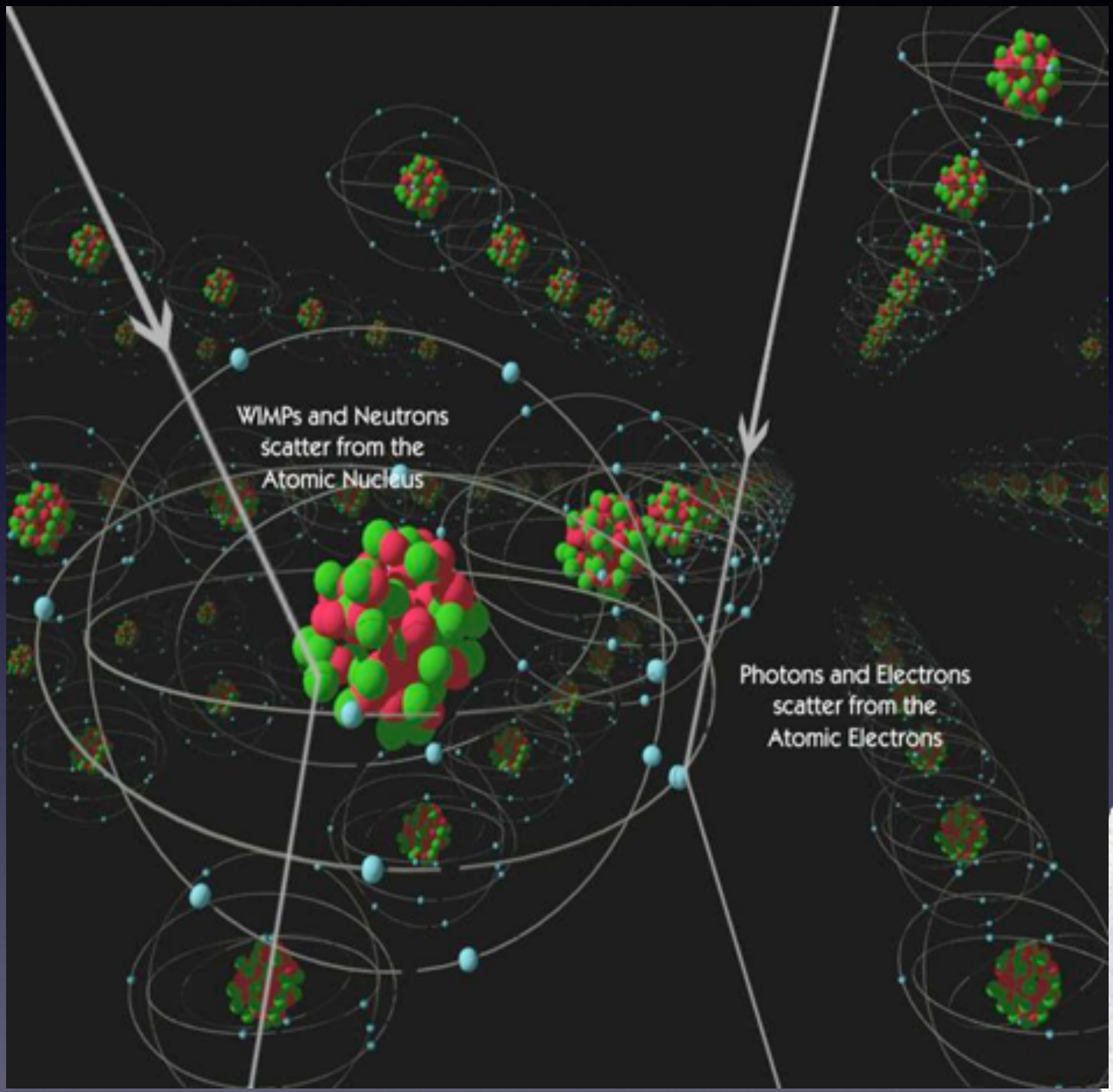
$$\langle \sigma(\chi\chi \to qq) v \rangle \propto \frac{g^4}{m_\chi^2} \sim \text{pb}$$

$$\Rightarrow g \sim g_{\text{weak}} \qquad m_\chi \sim m_W$$

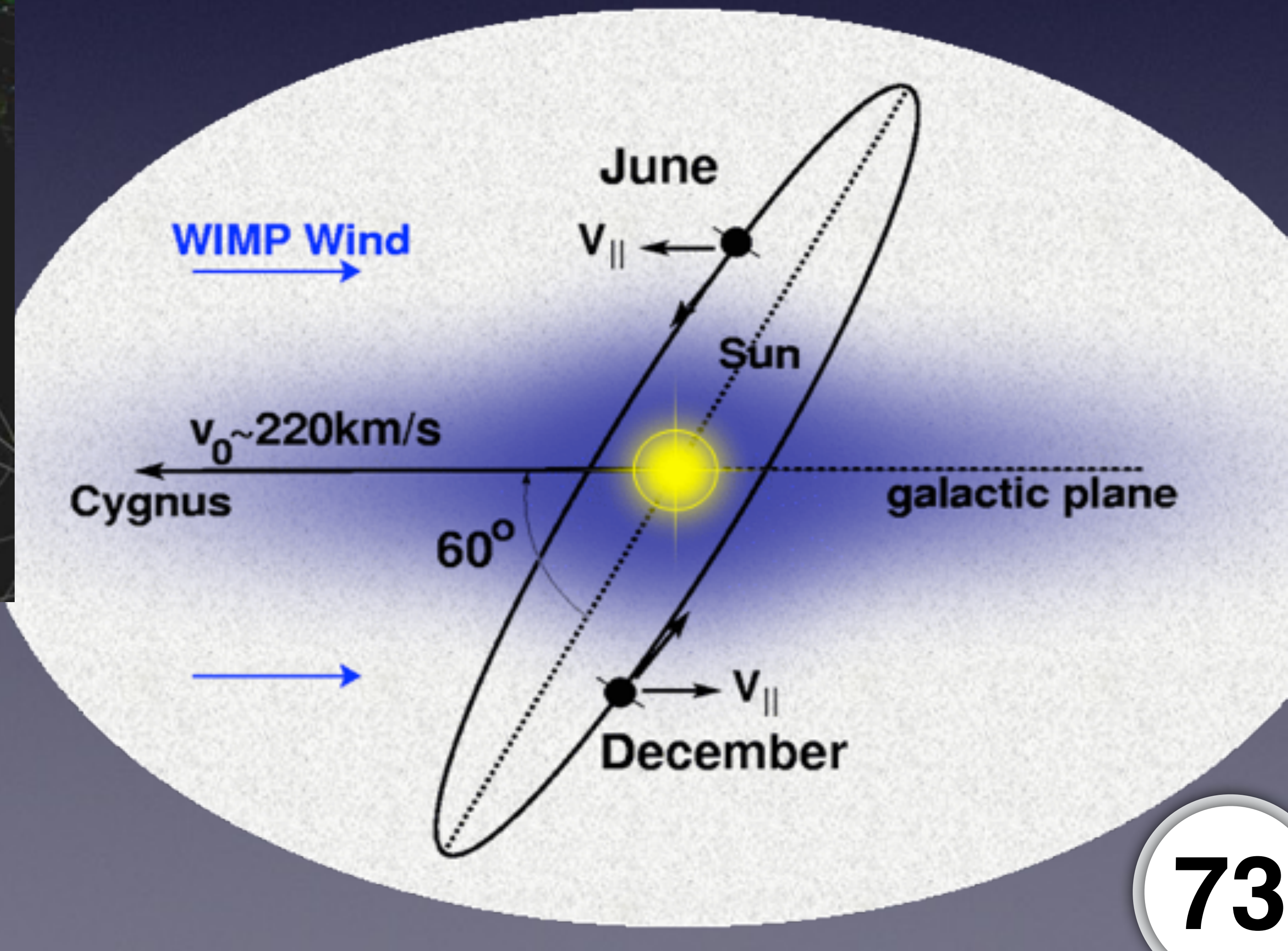
Weakly interacting massive particles at the weak scale!

神奇的巧合！理论家的最爱！

暗物质直接探测

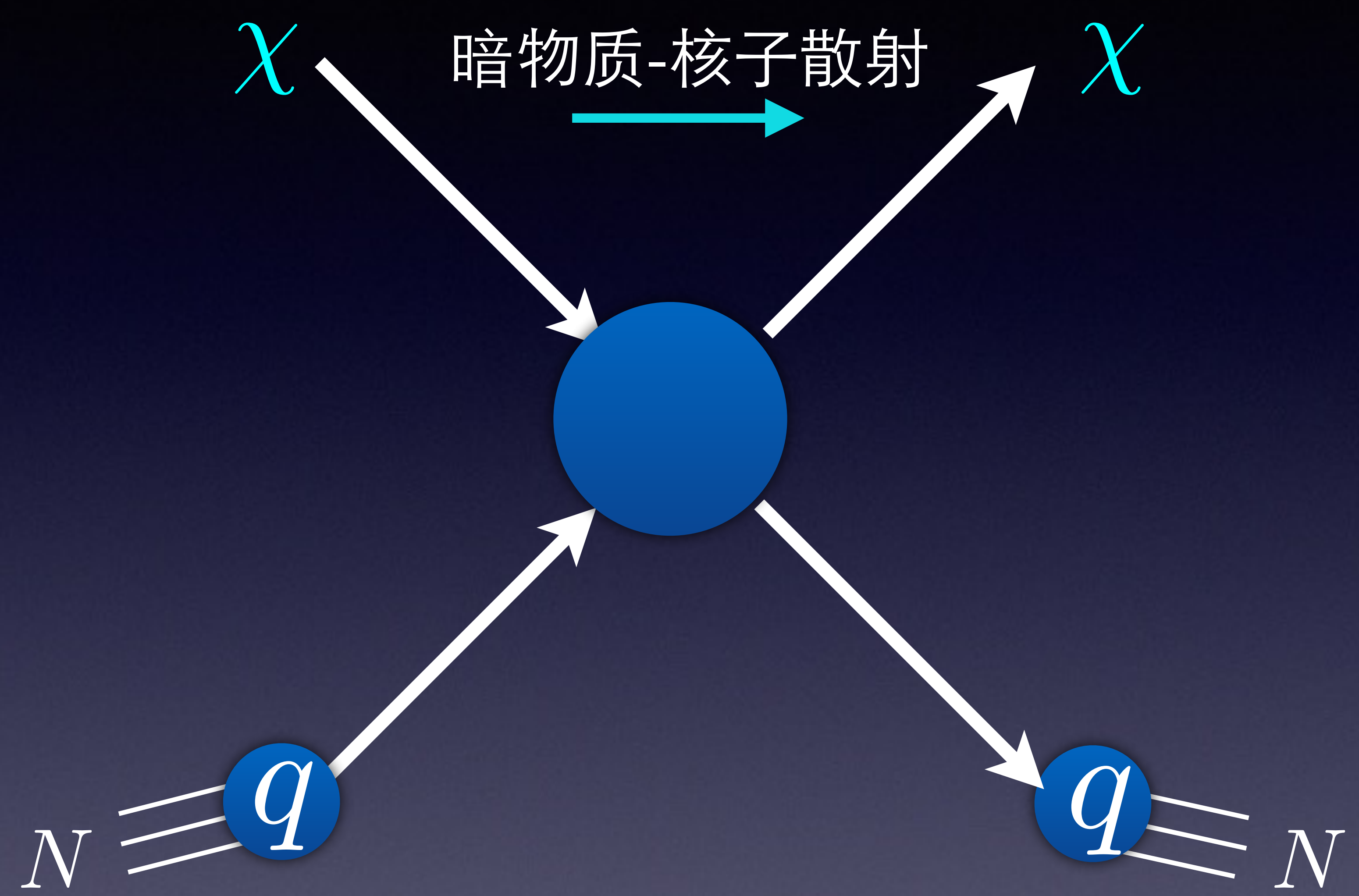


- 直接探测暗物质和原子的弹性散射。
- 信号：热，光，电



年调制效应

暗物质直接探测

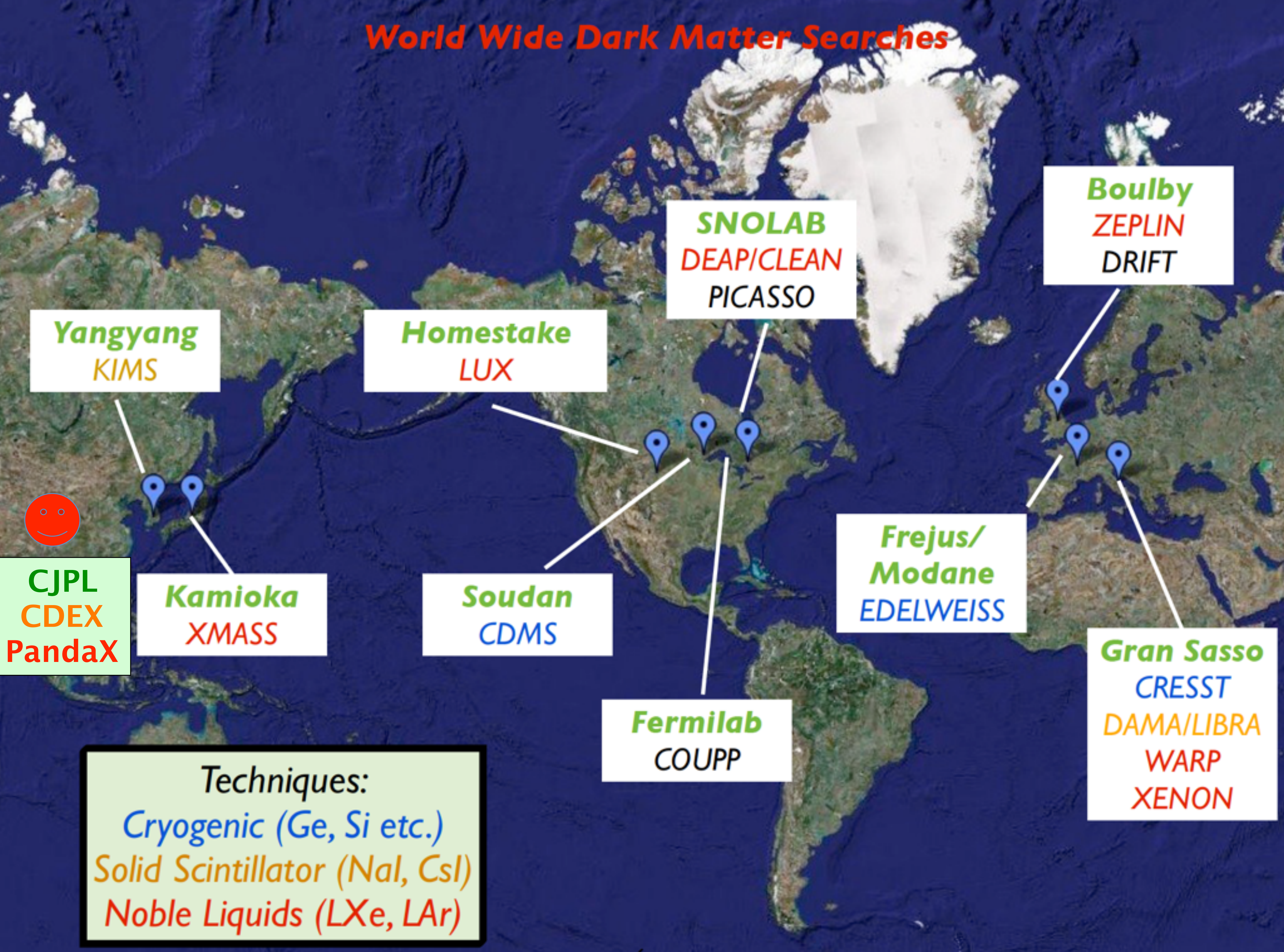


自旋无关的散射

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

自旋相关的散射

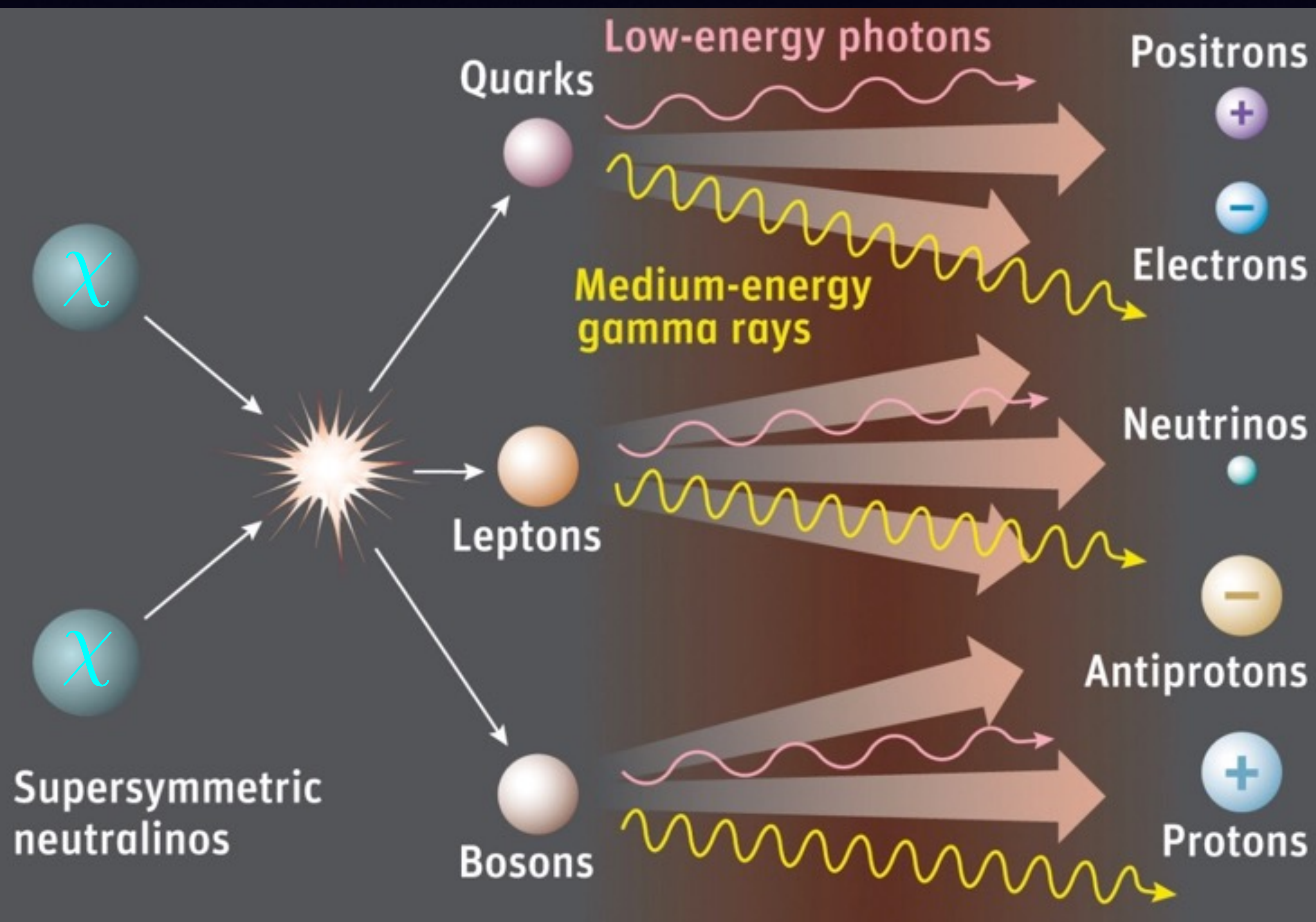
$$\bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q$$



World Wide Dark Matter Searches
Yangyang
KIMS
Homestake
LUX
SNOLAB
DEAP/CLEAN
PICASSO
Boulby
ZEPLIN
DRIFT
CJPL
CDEX
PandaX
Kamioka
XMASS
Soudan
CDMS
Frejus/
Modane
EDELWEISS
Fermilab
COUPP
Gran Sasso
CRESST
DAMA/LIBRA
WARP
XENON
Techniques:
Cryogenic (Ge, Si etc.)
Solid Scintillator (NaI, CsI)
Noble Liquids (LXe, LAr)

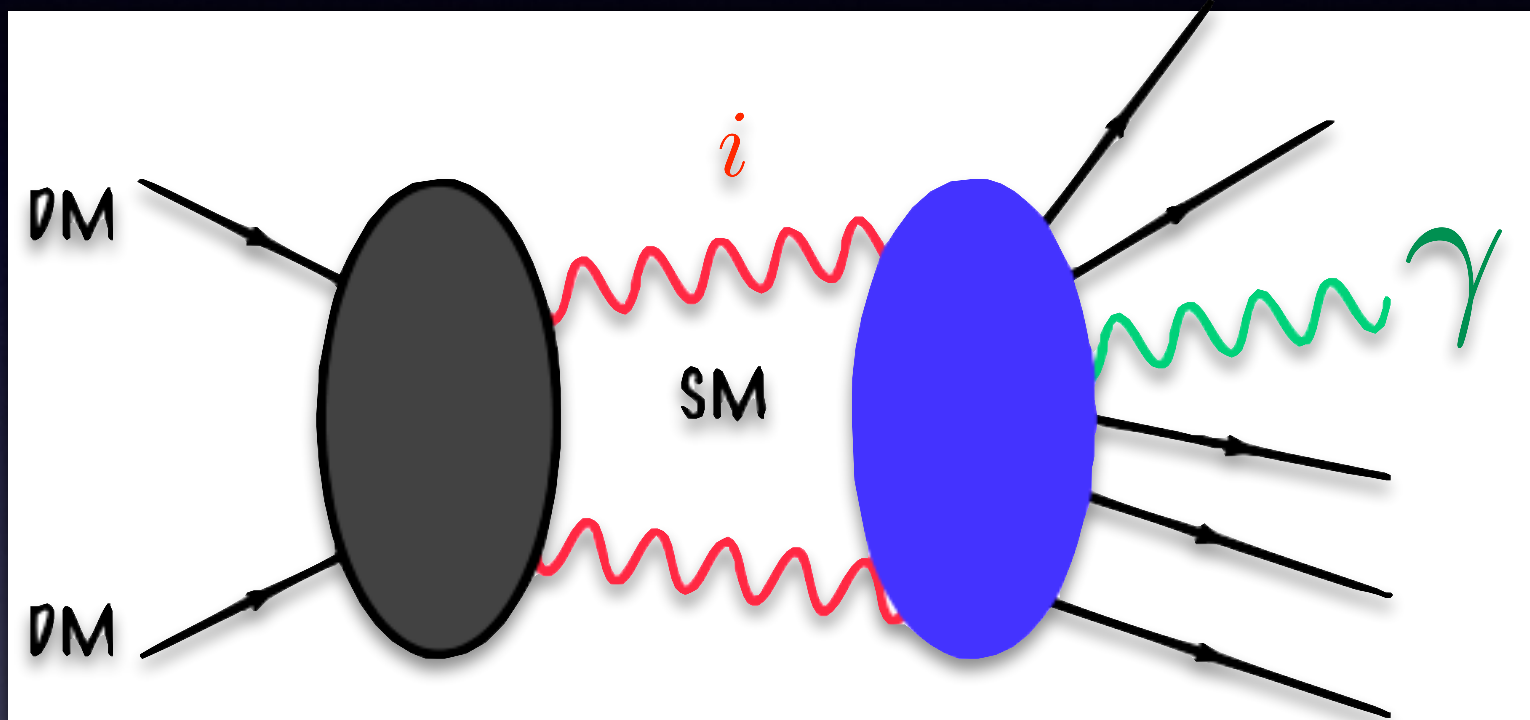
暗物质间接测量

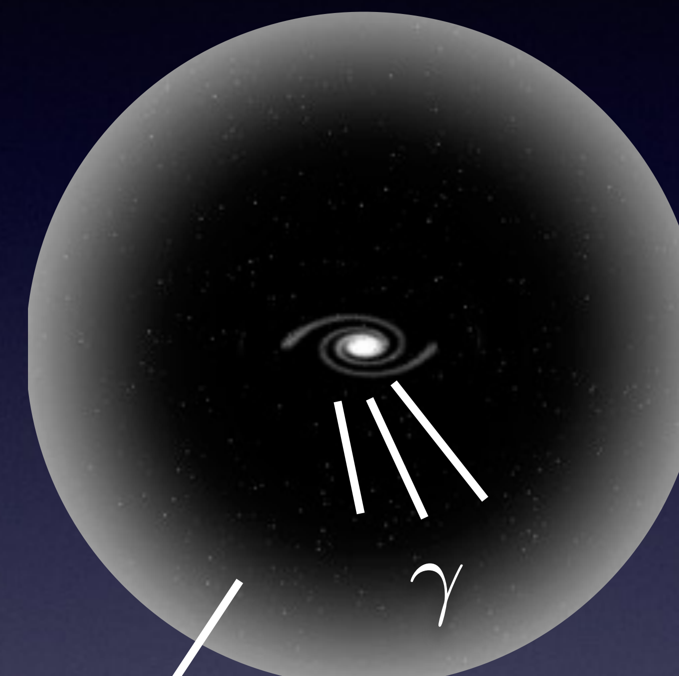
暗物质在宇宙中湮灭产生正反电子，正反质子，光子，中微子



Cosmic Gamma-Ray

$\eta\eta \to WW, ZZ, \cdots$ in the Galactic halo



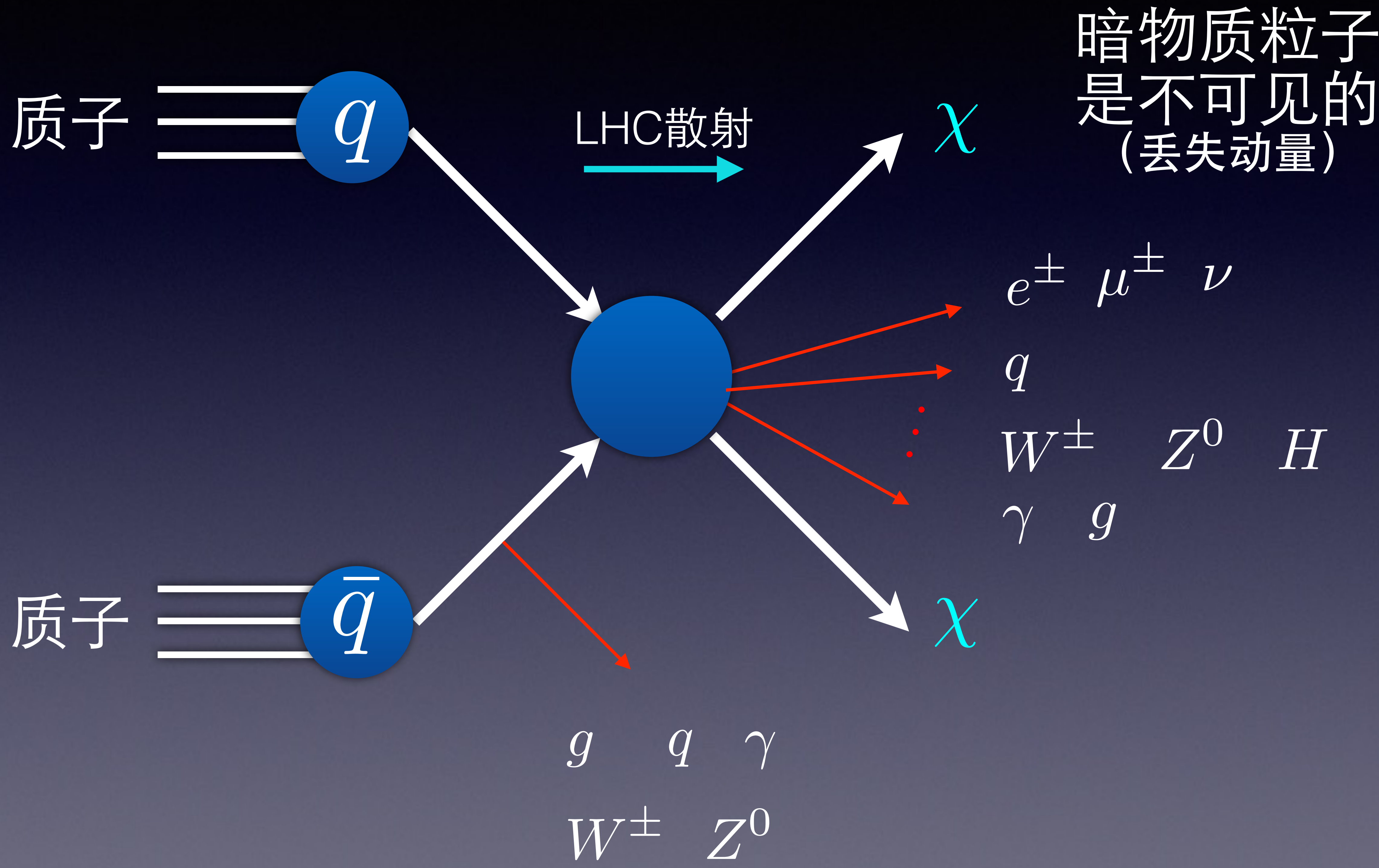


$$\frac{d\Phi}{d\Omega dE} = \sum_i \langle \sigma v \rangle_i \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}^2} \int_{\mathrm{l.o.l}} \rho^2 dl$$

Particle Physics

Astrophysics

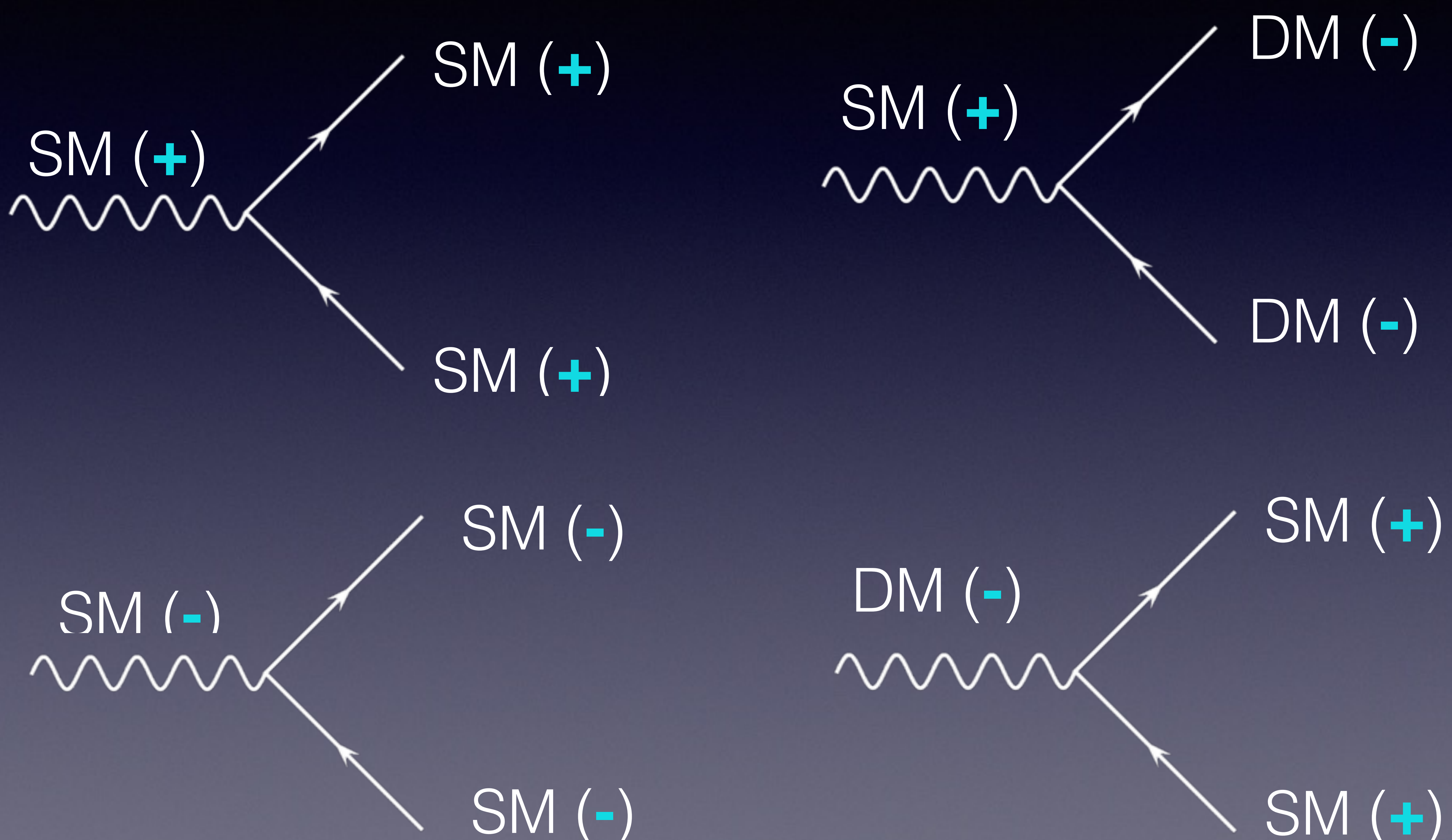
暗物质对撞机信号


暗物质粒子
是不可见的
（丢失动量）
质子
q
LHC散射
χ
$e^{\pm}$ $\mu^{\pm}$ ν
q
$W^{\pm}$ Z^0 H
γ g
质子
$\bar{q}$
χ
g q γ
$W^{\pm}$ Z^0

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

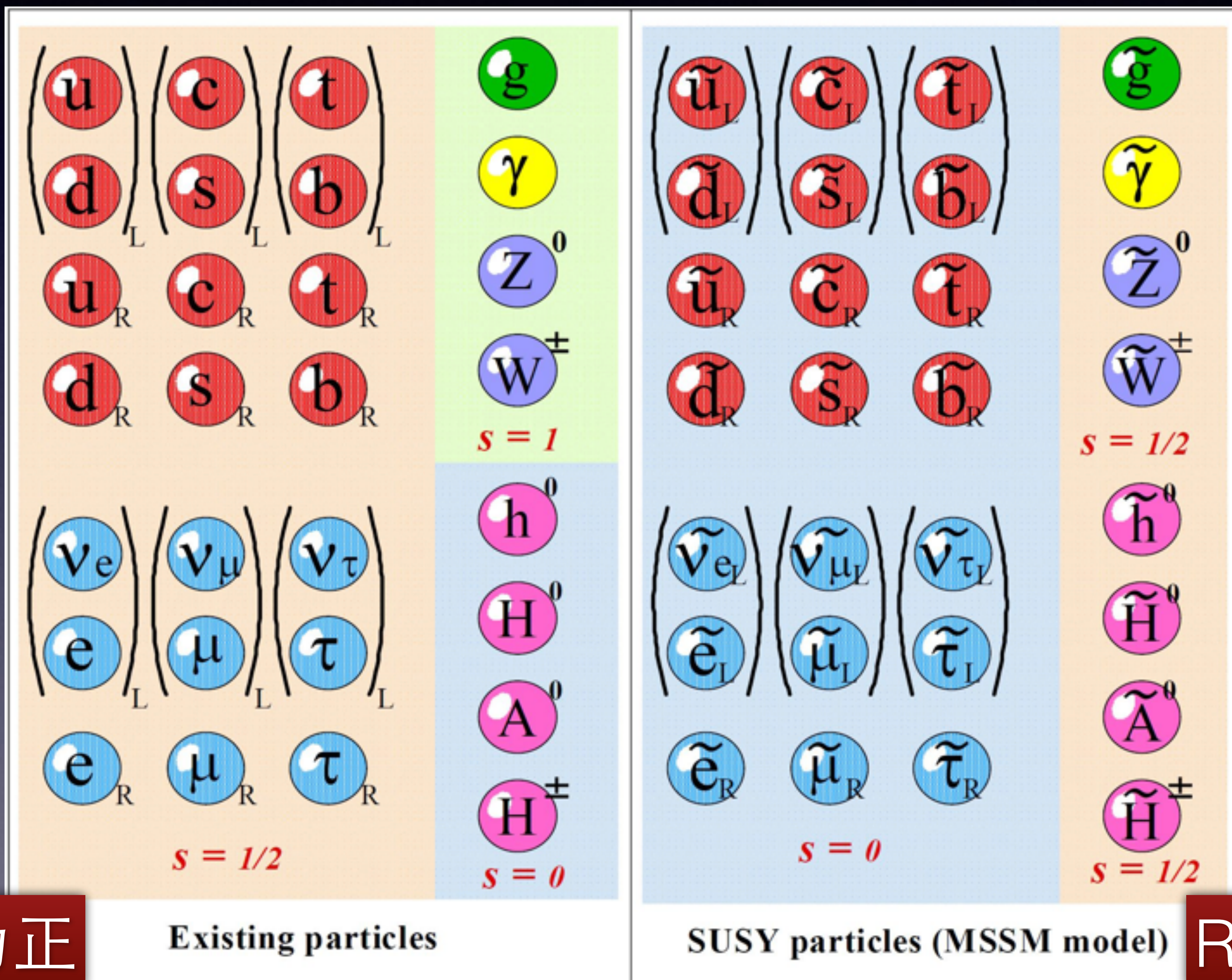


SM不能是Z_2-odd

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

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



R宇称为正

R宇称为负

最小超对称模型：5个标量粒子

$$\Phi_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

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

Count degree of freedom:

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

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

Before SSB

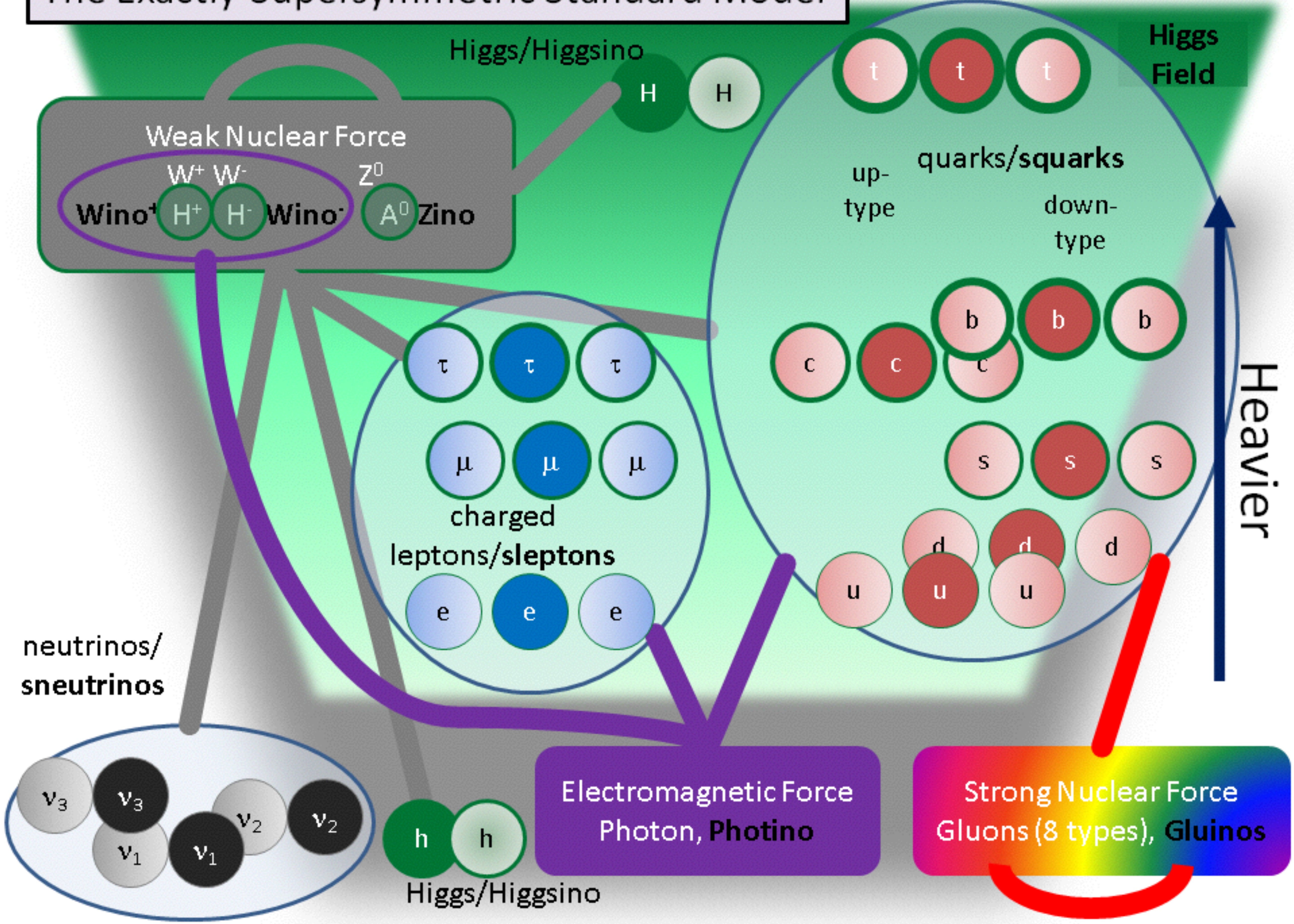
Massless	$W_\mu^{i=1,2,3}, B_\mu$	8
Complex	Φ_u, Φ_d	8
Total		16

After SSB

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

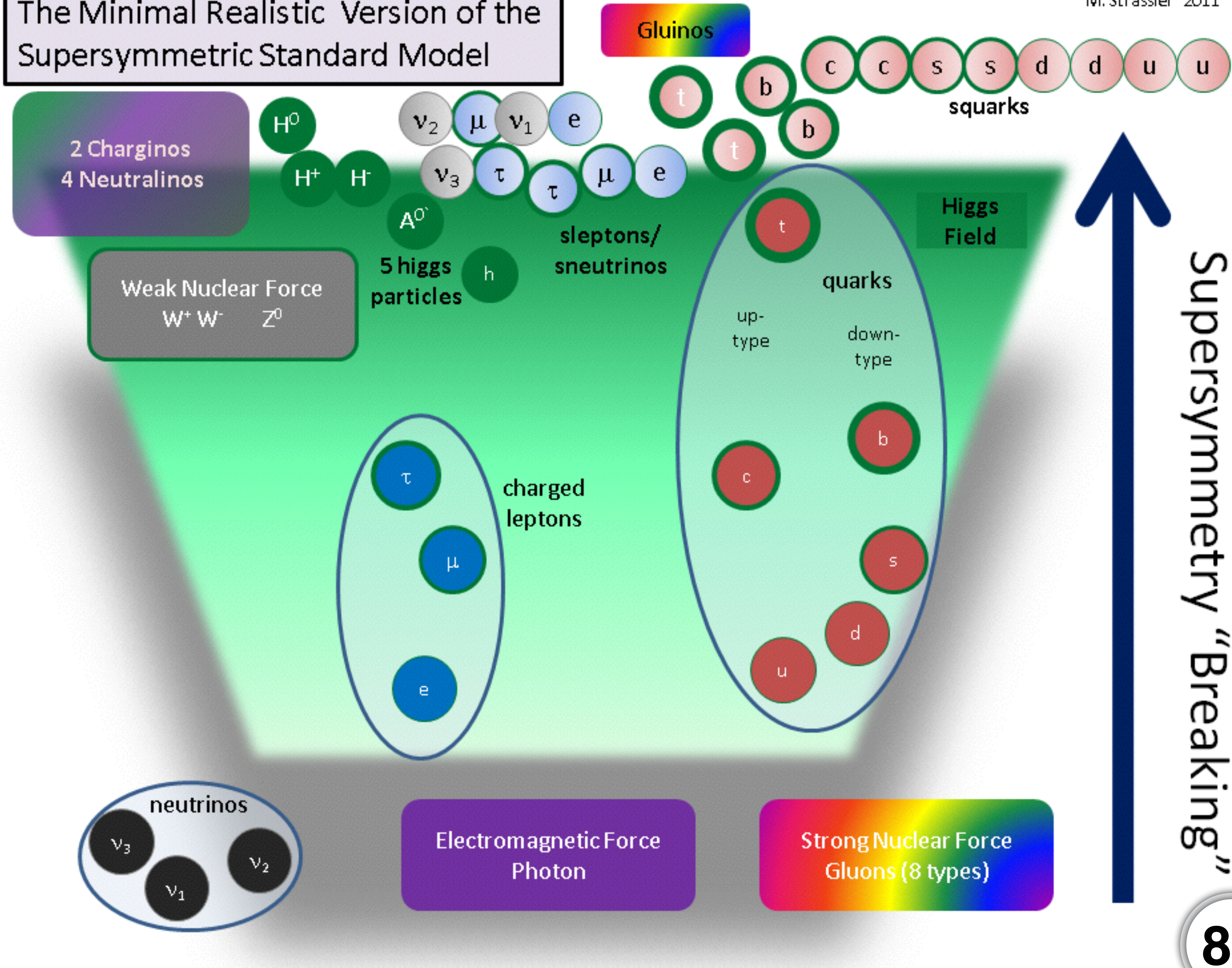
The Exactly-Supersymmetric Standard Model

M. Strassler 2011



The Minimal Realistic Version of the Supersymmetric Standard Model

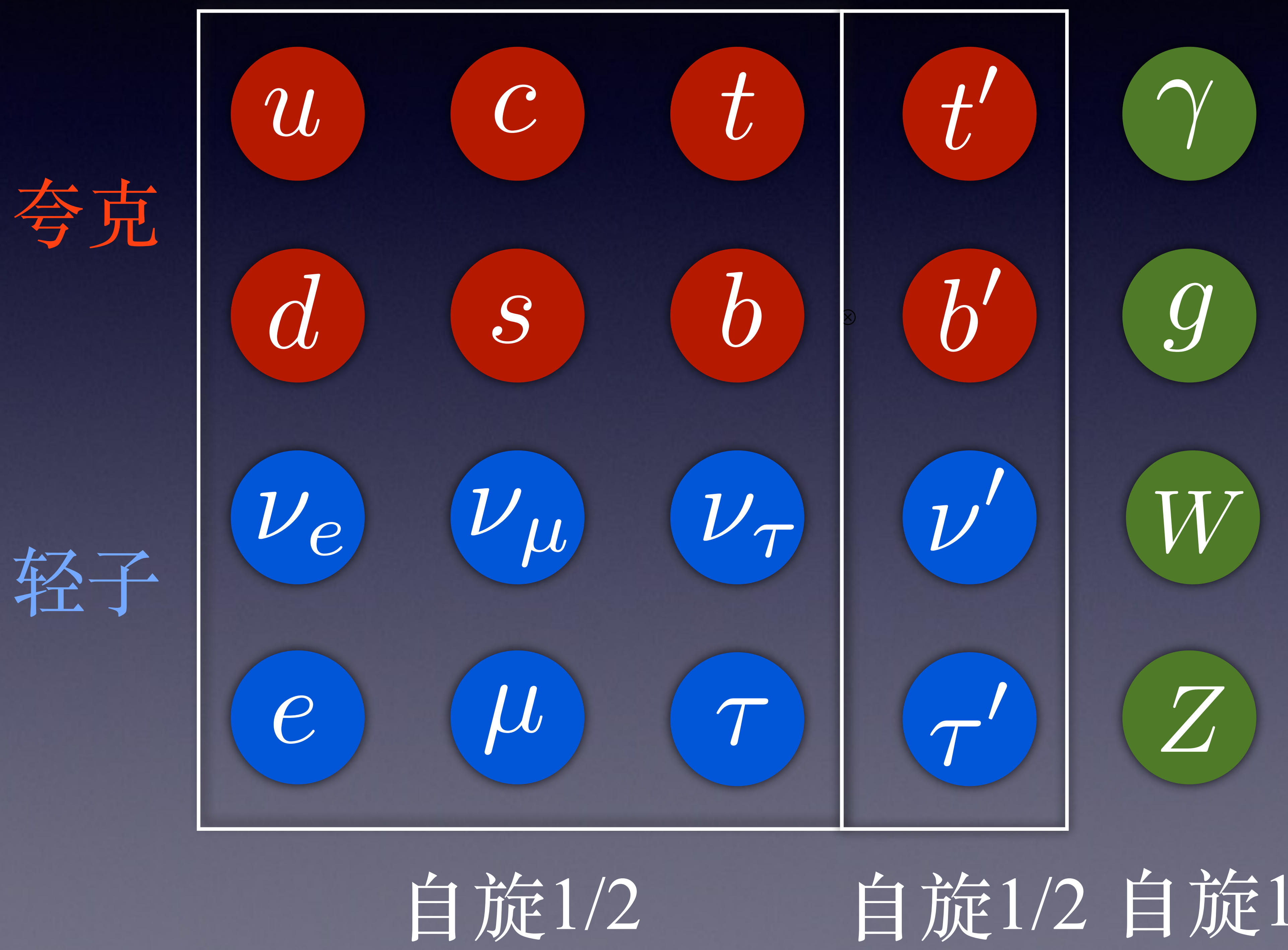
M. Strassler 2011



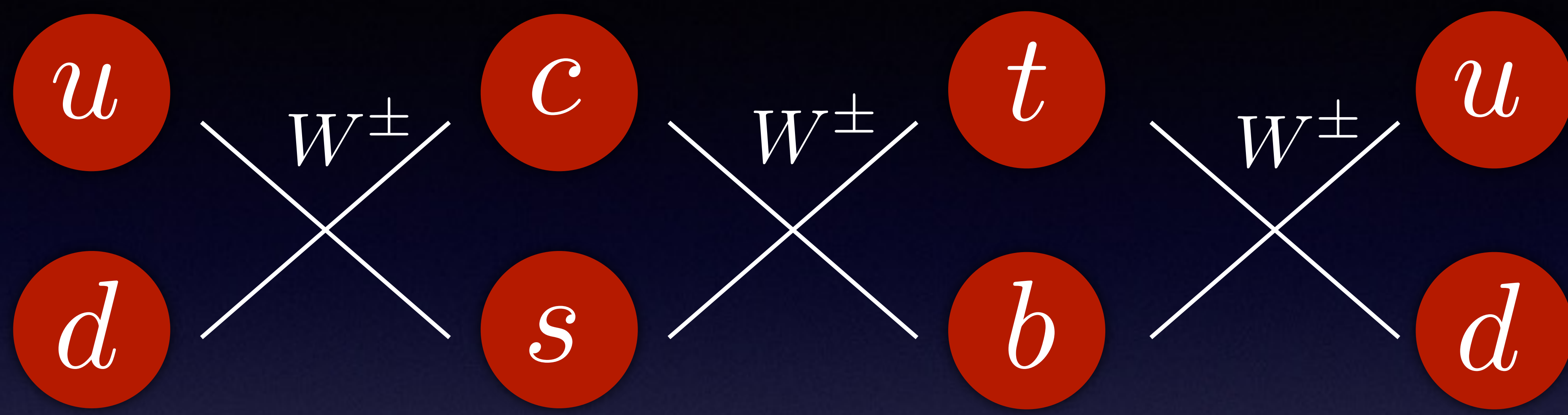
3. 新费米子

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。



CKM混合矩阵

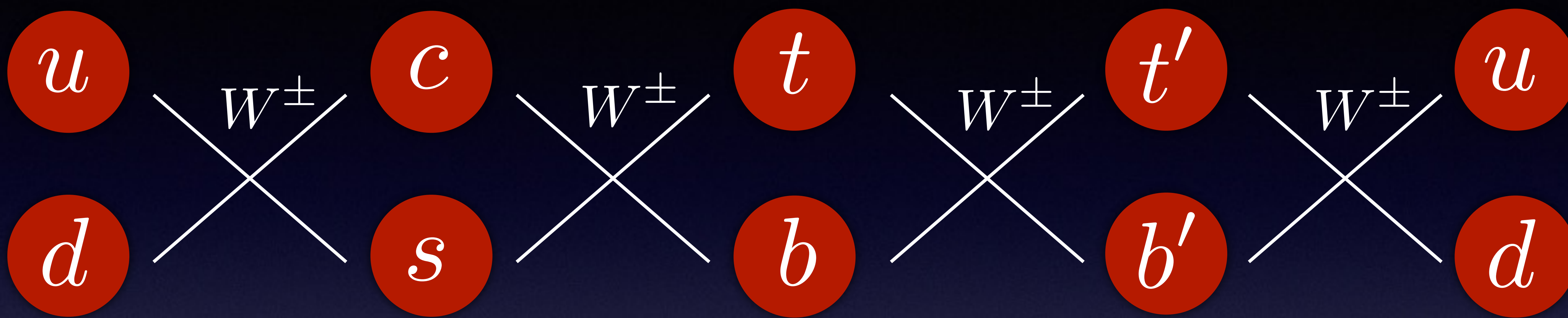


$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{weak}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}}$$

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

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

CKM混合矩阵

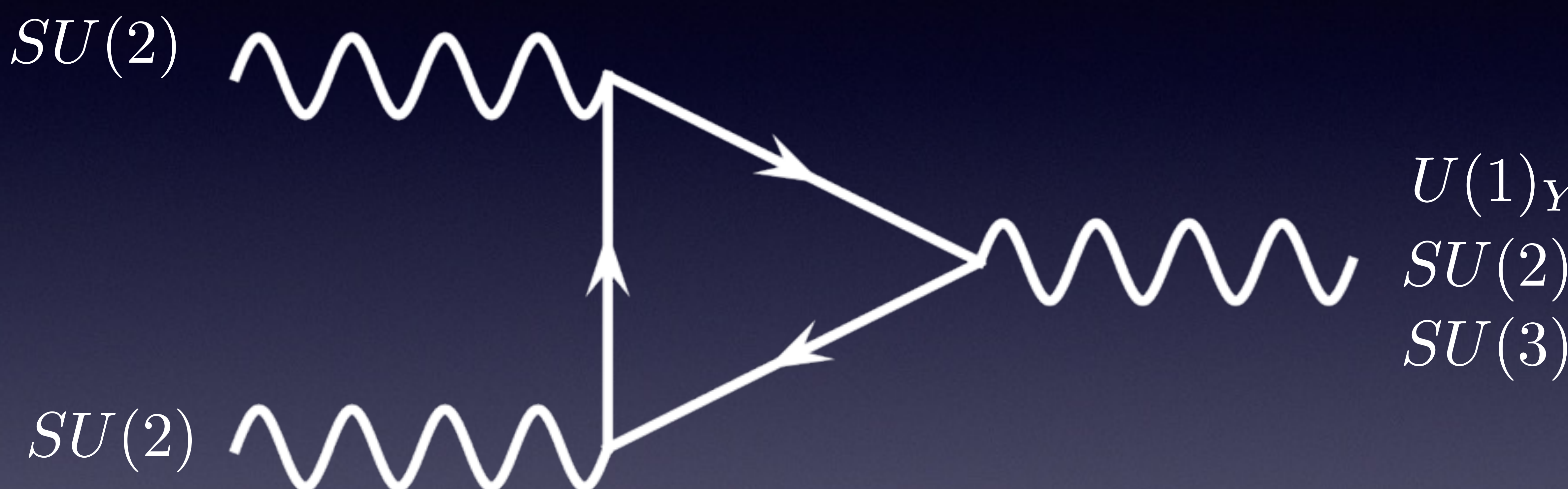


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix}$$

幺正性被放宽 $\longrightarrow V_{tb} < 1$

为何引入一整代费米子?

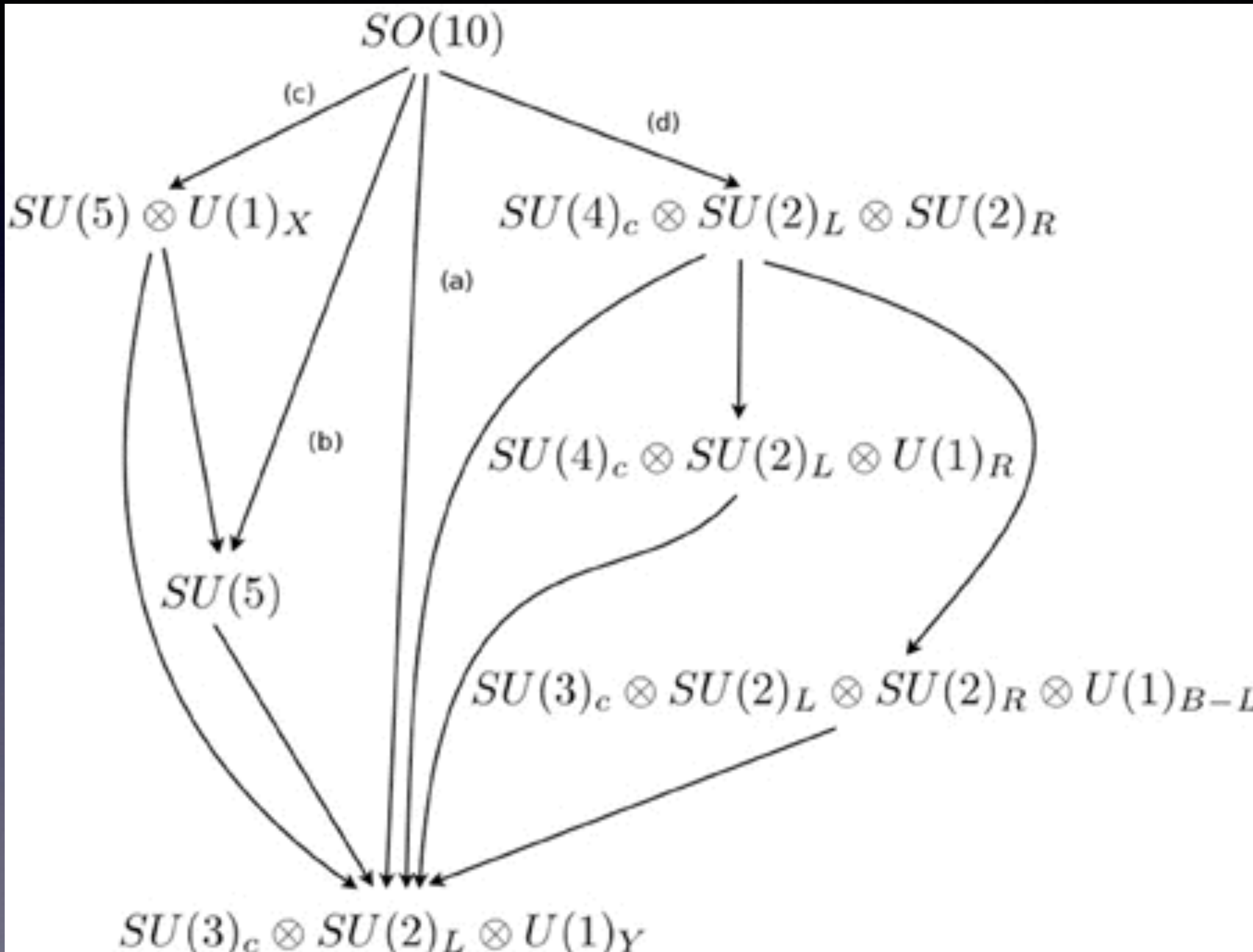
手征性费米子 —— 规范反常问题



标准模型中每一代费米子都消除规范反常

4. 新规范玻色子

大统一理论的破缺



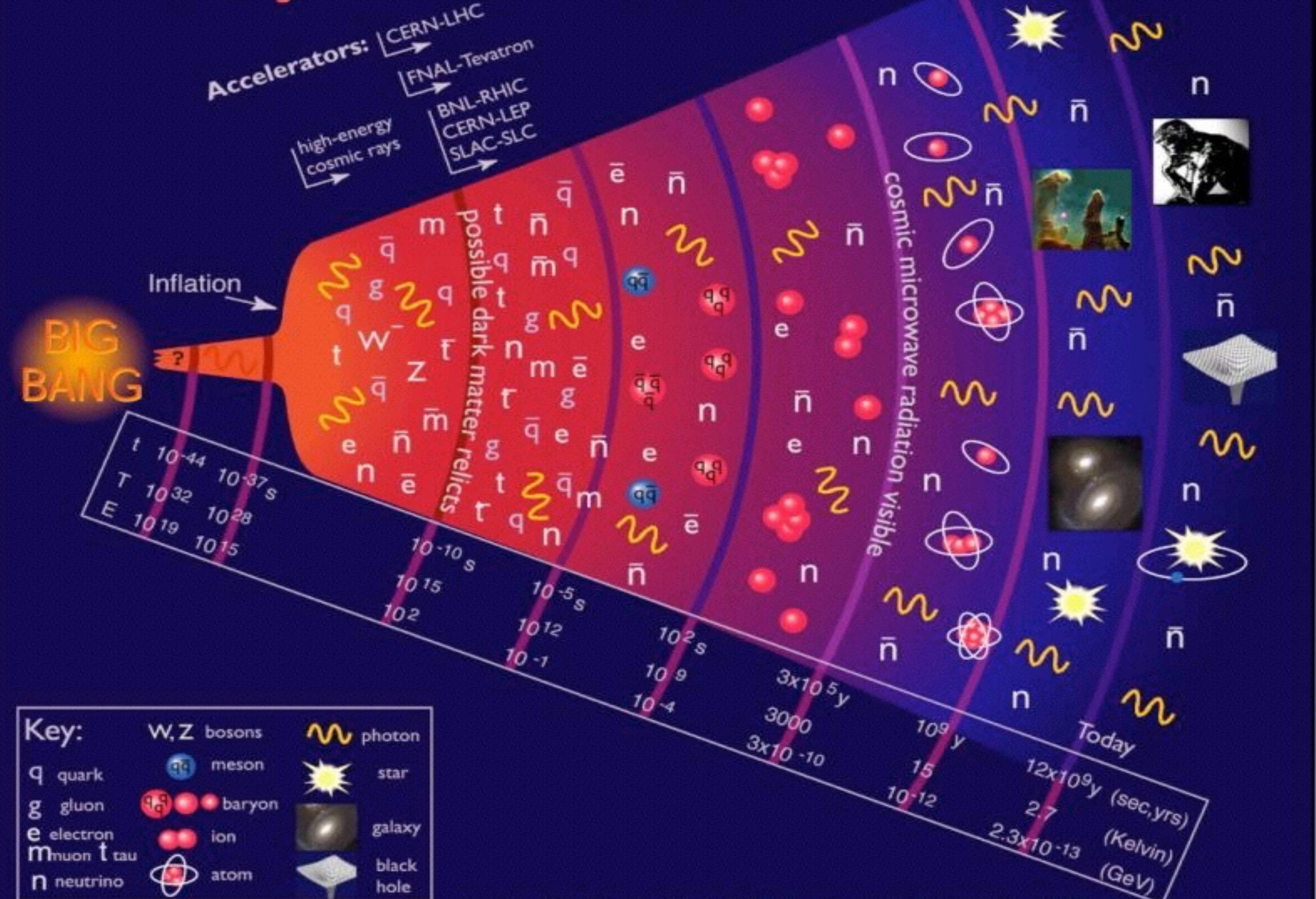
$SO(10)$
(c)
(d)
$SU(5) \otimes U(1)_X$
$SU(4)_c \otimes SU(2)_L \otimes SU(2)_R$
(a)
(b)
$SU(4)_c \otimes SU(2)_L \otimes U(1)_R$
$SU(5)$
$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

生逢其时，何其幸也！

为什么希格斯粒子质量为125GeV?
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?

……

History of the Universe



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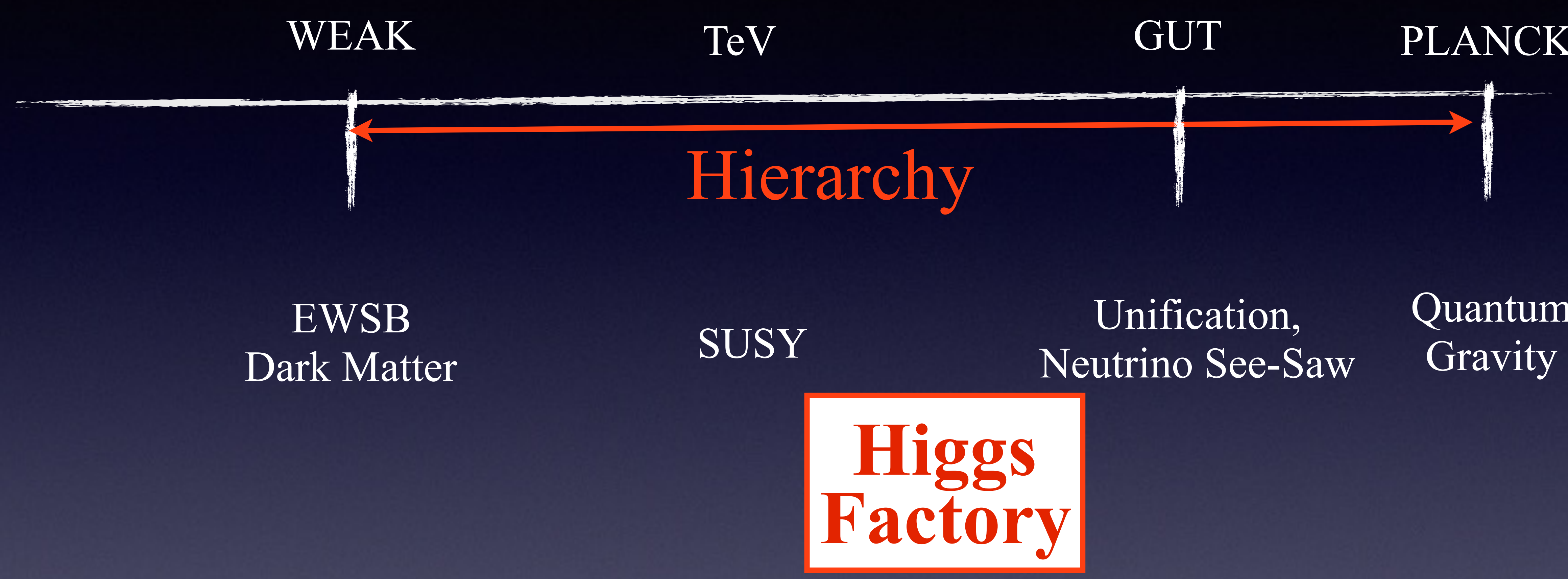
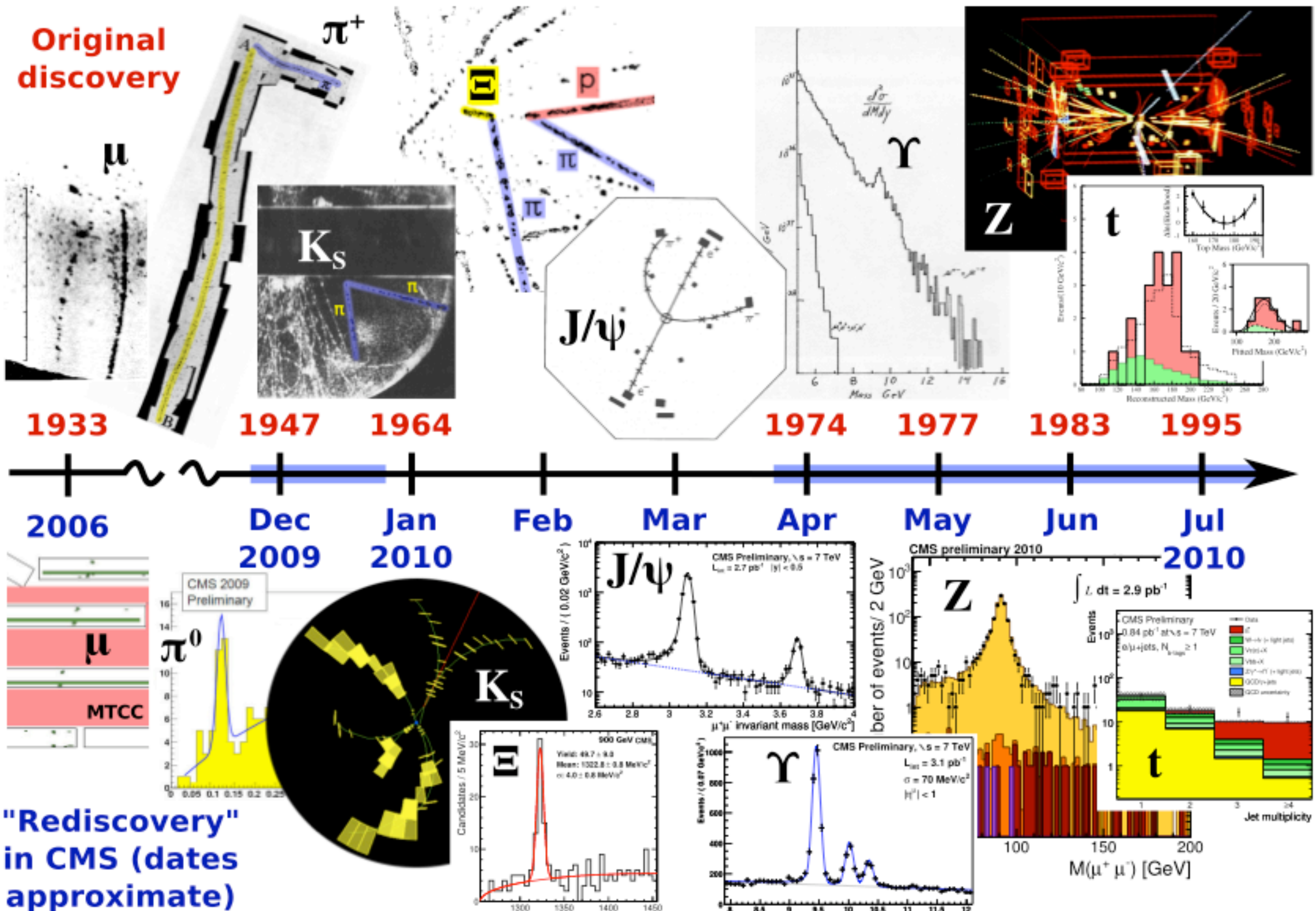
Experiments versus Theories

- Physics is associated with many scales



discovery of the Standard Model



考试时间：1月6日上午8:30
地点：物理学院南楼408

新年快乐！