Beyond the Standard Model

Lecture 3

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Outline:

- *Electroweak symmetry breaking (Lecture 1)*
- *Quark and lepton masses; vectorlike quarks (Lecture 2)*
- **New gauge bosons (Lecture 3)**
- *WIMPs and cascade decays (Lecture 4)*
- *How to search for new phenomena (Lecture 5)*

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Standard Model

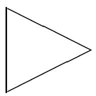
Fermion and scalar gauge charges:

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
quark doublet: $q_L^i = (u_L^i, d_L^i)$	3	2	$1/3$
right-handed up-type quark: u_R^i	3	1	$4/3$
right-handed down-type quark: d_R^i	3	1	$-2/3$
lepton doublet: $l_L^i = (\nu_L^i, e_L^i)$	1	2	-1
right-handed charged lepton": e_R^i	1	1	-2
Higgs doublet: H	1	2	$+1$

$i = 1, 2, 3$ *labels the fermion generations.*

Anomaly cancellation

Gauge symmetries may be broken by quantum effects.
Cure: sums over fermion triangle diagrams must vanish.



Standard Model: anomalies cancel within each generation

$[SU(3)]^2 U(1)$: $\quad 2(1/3) + (-4/3) + (2/3) = 0$

$[SU(2)]^2 U(1)$: $\quad 3(1/3) + (-1) = 0$

$[U(1)]^3$: $\quad 3\left[2(1/3)^3 + (-4/3)^3 + (2/3)^3\right] + 2(-1)^3 + (-2)^3 = 0$

$U(1)$-gravitational: $\quad 2(1/3) + (-4/3) + (2/3) = 0$

Z' bosons

Z' = any new electrically-neutral gauge boson (spin 1).

Consider an $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_z$ gauge symmetry spontaneously broken down to $SU(3)_C \times U(1)_{\rm em}$ by the VEVs of a doublet H and an $SU(2)_W$-singlet scalar, φ.

The mass terms for the three electrically-neutral gauge bosons, $W^{3\mu}$, B_Y^μ and B_z^μ, arise from the kinetic terms for the scalars:

$$\frac{v_H^2}{8}\left(gW^{3\mu} - g_Y B_Y^\mu - z_H g_z B_z^\mu\right)\left(gW_\mu^3 - g_Y B_{Y\mu} - z_H g_z B_{z\mu}\right)$$

$$+\frac{v_\varphi^2}{8} g_z^2 B_z^\mu B_{z\mu}$$

Mass-square matrix for B_Y^μ, $W^{3\mu}$ and B_z^μ:

$$\mathcal{M}^2 = \frac{g^2 v_H^2}{4\cos^2\theta_w} U^\dagger \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -z_H t_z \cos\theta_w \\ 0 & -z_H t_z \cos\theta_w & (r + z_H^2)\, t_z^2 \cos^2\theta_w \end{pmatrix} U$$

where $t_z \equiv g_z/g$, $\tan\theta_w = g_Y/g$, $r = v_\varphi^2/v_H^2$

$$U = \begin{pmatrix} \cos\theta_w & \sin\theta_w & 0 \\ -\sin\theta_w & \cos\theta_w & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

relates the neutral gauge bosons to the physical states in the case $z_H = 0$.

The relation between the neutral gauge bosons and the corresponding mass eigenstates can be found by diagonalizing $\mathcal{M}^2$:

$$\begin{pmatrix} B_Y^\mu \\ W^{3\mu} \\ B_z^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_w & -\sin\theta_w\cos\theta' & \sin\theta_w \sin\theta' \\ \sin\theta_w & \cos\theta_w\cos\theta' & -\cos\theta_w\sin\theta' \\ 0 & \sin\theta' & \cos\theta' \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \\ Z'^\mu \end{pmatrix}$$

A^μ is the photon field

Z^μ is the field associated with the observed Z boson

Z'^μ is a neutral gauge boson, not discovered yet.

The mixing angle $-\pi/4 \le \theta' \le \pi/4$ satisfies

$$\tan 2\theta' = \frac{2 z_H t_z \cos\theta_w}{(r + z_H^2) t_z^2 \cos^2\theta_w - 1}$$

The Z and Z' masses are given by

$$M_{Z,Z'} = \frac{g v_H}{2\cos\theta_w}\left[\frac{1}{2}\left((r+z_H^2)t_z^2\cos^2\theta_w + 1\right) \mp \frac{z_H t_z \cos\theta_w}{\sin 2\theta'}\right]^{1/2}$$

Z' is heavier than Z when $(r + z_H^2)t_z^2 \cos^2\theta_w > 1$.

The mass and couplings of the Z' boson are described by the following parameters:

- gauge coupling g_z
- VEV v_φ
- $U(1)_z$ charge of the Higgs doublet, z_H
- fermion charges under $U(1)_z$ – constrained by anomaly cancellation conditions and requirement of fermion mass generation

Nonexotic Z'

Nonanomalous $U(1)_z$ gauge symmetry *without* new fermions charged under $SU(3)_C \times SU(2)_W \times U(1)_Y$

Allow an arbitrary number of ν_R's

Assume:
- generation-independent charges,
- quark and lepton masses from standard model Yukawa couplings

Gravitational-$U(1)_z$ and $[U(1)_z]^3$ anomaly cancellation conditions:

$$\frac{1}{3}\sum_{k=1}^{n} z_k = -4z_q + z_u$$

$$\left(\sum_{k=1}^{n} z_k\right)^3 = 9\sum_{k=1}^{n} z_k^3$$

- For $n \leq 2$:

$z_1 = -z_2 \Rightarrow z_u = 4z_q \Rightarrow$ trivial or Y-sequential $U(1)_z$-charges

- For $n \geq 3$:

$U(1)_{B-L}$ charges: $z_1 = z_2 = z_3 = -4z_q + z_u$

or $z_1 = z_2 = -(4/5)z_3 = -16z_q + 4z_u = -4$

ν masses: three LH Majorana,
two dimension-7 and one dimension-12 Dirac operators,
RH Majorana ops. of dimension ranging from 4 to 13

or ...

Fermion and scalar gauge charges:

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_z$
q_L^i	3	2	$1/3$	z_q
u_R^i	3	1	$4/3$	z_u
d_R^i	3	1	$-2/3$	$2z_q - z_u$
l_L^i	1	2	-1	$-3z_q$
e_R^i	1	1	-2	$-2z_q - z_u$
ν_R^k , $k = 1, ..., n$	1	1	0	z_k
H	1	2	$+1$	$-z_q + z_u$
φ	1	1	0	1

$[SU(3)_C]^2 U(1)_z$, $[SU(2)_W]^2 U(1)_z$, $U(1)_Y [U(1)_z]^2$ and $[U(1)_Y]^2 U(1)_z$ anomalies cancel

LEP I requires $\theta' \lesssim 10^{-3} \Rightarrow M_{Z'} \gtrsim 2$ TeV

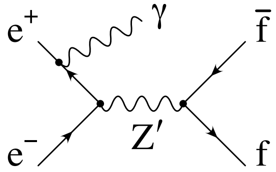
Special case: $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_{B-L}$

$$z_q = z_u = z_d = -\frac{z_l}{3} = -\frac{z_e}{3} = -\frac{z_\nu}{3} \quad \Longrightarrow \quad z_H = 0$$

No Z_{B-L}-Z mixing at tree level ($\theta' = 0$)!

Best bounds on $z_l g_z$ come from limits on direct production at the LHC, Tevatron and LEP II.

Initial state radiation at LEP for a narrow Z_{B-L} resonance at $M_{Z'} < \sqrt{s}$:



$$\sigma\left(e^+e^- \to \gamma Z_{B-L}\right) \mathrm{Br}\left(Z_{B-L} \to \mu^+\mu^-\right) \approx \frac{3\alpha}{74}(z_l g_z)^2 \frac{s^2 + M_{Z'}^4}{s^2\left(s - M_{Z'}^2\right)} \ln\left(\frac{s}{m_e^2}\right)$$

LEPII has run at $\sqrt{s} \approx 130, 136, 161, 172, 183, 189, 192 - 209$ GeV

For a Z_{B-L} with $M_{Z'} \sim 140$ GeV:

Number of $\mu^+\mu^-$ events at $\sqrt{s} \approx 161$ GeV due to Z_{B-L}:

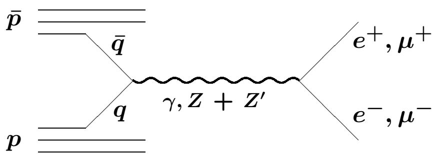
$$N(Z_{B-L}) \approx 3 \times 10^4 \, (z_l g_z)^2$$

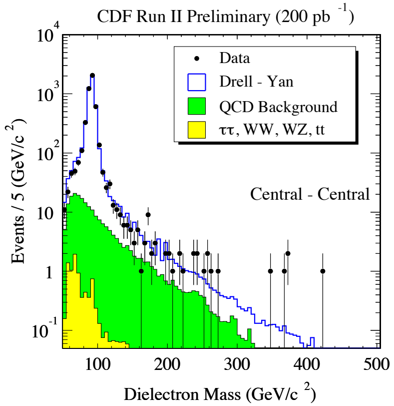
Main background: $e^+e^- \to \gamma^*\gamma, Z^*\gamma \to \mu^+\mu^-\gamma$
(~ 6.4 events in an energy bin of 5 GeV)

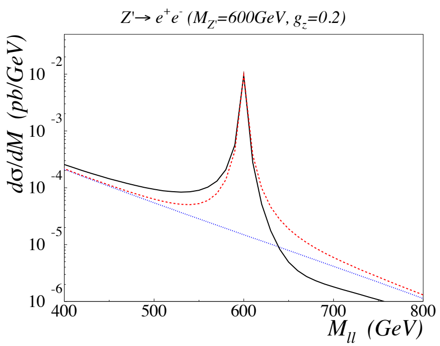
At the 95% confidence-level: $z_l g_z \lesssim 10^{-2}$

If $\sqrt{s} = M_{Z'}$: no need for initial state radiation.
Strongest bound for $M_{Z'} \sim 189$ GeV: $z_l g_z < 10^{-3}$

Z' searches at the Tevatron



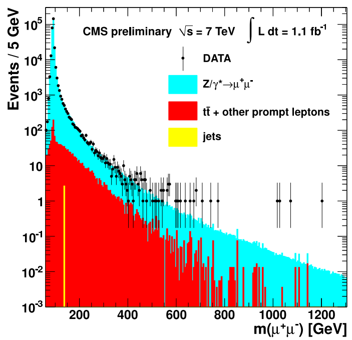


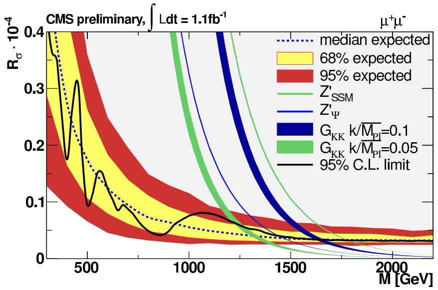


More general charges are allowed in the presence of new fermions:

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-xL}$	$U(1)_{q+xu}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$
q_L	3	2	$1/3$	$1/3$	$1/3$	$1/3$	0
u_R	3	1	$4/3$	$1/3$	$x/3$	$-1/3$	$-x/3$
d_R	3	1	$-2/3$	$1/3$	$(2-x)/3$	$-x/3$	$1/3$
l_L	1	2	-1	$-x$	-1	$x/3$	$(-1+x)/3$
e_R	1	1	-2	$-x$	$-(2+x)/3$	$-1/3$	$x/3$
ν_R	1	1	0	-1	$(-4+x)/3$	$(-2+x)/3$	$-x/3$
ν'_R				$\cdot$	$\cdot$	$-1-x/3$	$\cdot$
ψ^l_L	1	2	-1	-1	$\cdot$	$-(1+x)/3$	$-2x/5$
ψ^l_R				$-x$	$\cdot$	$2/3$	$(-1+x/5)/3$
ψ^e_L	1	1	-2	-1	$\cdot$	$\cdot$	$\cdot$
ψ^e_R				$-x$	$\cdot$	$\cdot$	$\cdot$
ψ^d_L	3	1	$-2/3$	$\cdot$	$\cdot$	$-2/3$	$(1-4x/5)/3$
ψ^d_R				$\cdot$	$\cdot$	$(1+x)/3$	$x/15$

Homework 3.1:
Identify the couplings of the Z' arising from the $SO(10) \to SU(5)$ GUT breaking.



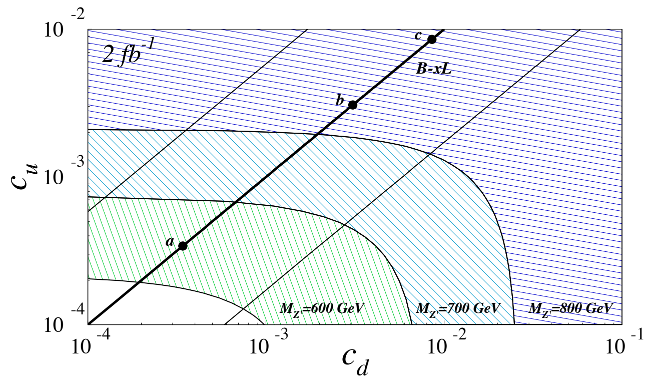


A user-friendly parametrization (hep-ph/0408098):

$$\sigma\left(p\bar{p}\to Z'X\to l^+l^-X\right)=\frac{\pi}{48\,s}\left[c_u\,w_u\left(\frac{M_{Z'}^2}{s},M_{Z'}\right)+c_d\,w_d\left(\frac{M_{Z'}^2}{s},M_{Z'}\right)\right]$$

All the information about charges is contained in:

$$c_{u,d}=g_z^2\,(z_q^2+z_{u,d}^2)\,\mathrm{Br}(Z'\to l^+l^-)$$



$$\sigma\left(pp\to Z'X\to l^+l^-X\right)=\frac{\pi}{48\,s}\left[c_u\,w_u'\left(\frac{M_{Z'}^2}{s},M_{Z'}\right)+c_d\,w_d'\left(\frac{M_{Z'}^2}{s},M_{Z'}\right)\right]$$

w_u' and w_d' contain all the information about QCD: values at the LHC are different than at the Tevatron

$\Rightarrow$ c_u and c_d can be determined independently if a Z' is observed at both the Tevatron and the LHC.

More information about Z' couplings ($U(1)_z$ charges) can be extracted from angular distributions, etc.

Homework # 3.2:
What are the analytical formulas for $w'_{u,d}$ at LO in α_s?

"Gluon-prime": a heavy spin-1 color-octet particle

Gauge extension of QCD ("Topcolor", C. Hill 1991):
$SU(3)_1\times SU(3)_2\to SU(3)_c$ spontaneously broken by the VEV of a scalar Σ transforming as $(3,\bar{3})$

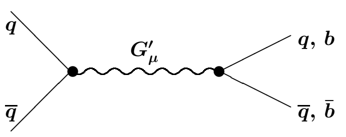
G_μ^a - massless gluon of QCD, with $g_s=\frac{h_1h_2}{\sqrt{h_1^2+h_2^2}}$ ($h_{1,2}$ are the $SU(3)_{1,2}$ gauge couplings)

$G_\mu'^a$ - massive "gluon-prime"
("topgluon" or "coloron" depending on its couplings to t, b)

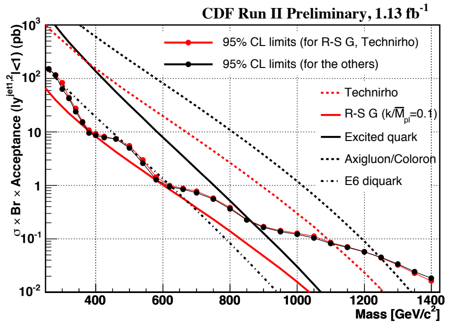
Interactions: $g_s r\; G_\mu'^a\,\bar{q}\gamma^\mu T^a q$ where $r=h_1/h_2$.

G'_μ production (in the narrow width approximation):

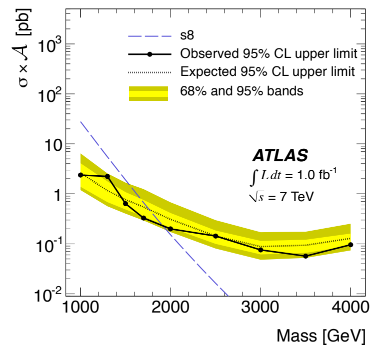
$$\sigma\left(p\bar{p} \to G'_\mu X\right) \approx \frac{16\pi^2 \alpha_s r^2}{9s} \sum_q \int_{M^2/s}^{1} \frac{dx}{x} \left[q(x)\, q\left(\frac{M^2}{xs}\right) + \bar{q}(x)\, \bar{q}\left(\frac{M^2}{xs}\right) \right]$$

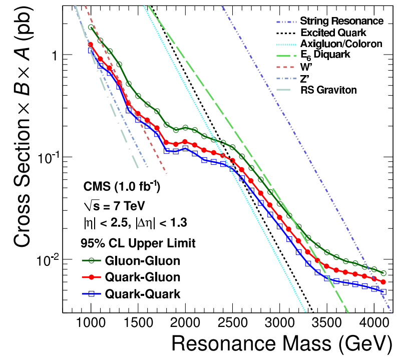


Limit on dijet resonance of ~300 GeV: $r^2 \mathcal{B}(G'_\mu \to jj) < 0.04$



Dijet resonance searches at the LHC 7:





My wishes: extend the search to lower masses;
show theory predictions for several choices of the coupling (r);

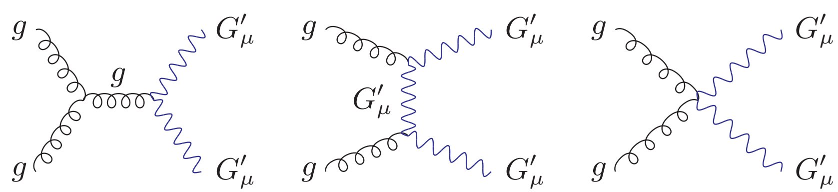
Model "independent" search for Gluon-prime

work with KC Kong and Rakhi Mahbubani hep-ph/0709.2378

G'_μ couplings to quarks are model dependent: if they are small enough, the mass limits from dijet resonance searches are evaded.

G'_μ couplings to gluons are fixed by gauge invariance. G'_μ couples only in pairs to the gluon.

Pair production of heavy gluons from gluon-gluon initial state:



A pair of gluon-primes decays to 2 pairs of dijets (or $jjb\bar{b}$, $b\bar{b}b\bar{b}$).

Dominant background: QCD 4-jet production.
Background simulated at tree level using MadGraph (checked with NJETS), taking the b-tagging efficiency to be 50%.

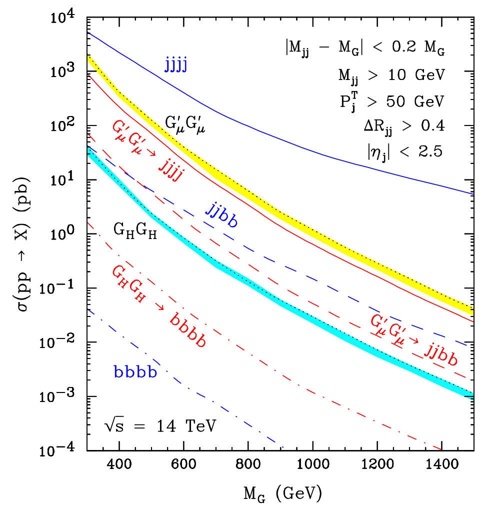
Production and decay of gluon-primes (G'_μ) at the LHC:

The jets reconstruct (in pairs) resonances of equal mass.

Cutting around the resulting peak decreases the background dramatically.

A spin-0 color octet (G_H) has similar properties, except it decays into the heaviest quarks.
Signal: $p\bar{p} \to G_H G_H \to (b\bar{b})(b\bar{b})$

LHC mass reach for a G'_μ is
$M_G \lesssim$ 1 TeV with 1 fb^{-1}



Could there exist massless gauge bosons other than the photon?

$U(1)_{B-L}$ is the only global symmetry of the standard model that can be gauged and unbroken.

Z_{B-L} coupling to ordinary matter: $N_n\, g_z$
($N_n =$ number of neutrons)

To avoid deviations from Newton's law:

$$g_z \ll \frac{m_n}{M_{\rm Pl}} \sim 10^{-19}$$

Tests of the equivalence principle: $g_z < 10^{-24}$

But even when $z_q = z_u = z_d = z_l = z_e = 0$

there can still be interactions of the standard model fields with the new massless gauge boson:

higher-dimensional operators!

γ' couplings to leptons:

$$\frac{1}{M^2} P_{\mu\nu} \;\left(\bar{l}_L \sigma^{\mu\nu} F_e H e_R + {\rm h.c.}\right)$$

F_e: 3×3 matrix in flavor space,
dimensionless parameters

γ' couplings to quarks: similar dimension-6 operators

In the mass eigenstate basis $F_e \to F'_e = U_L^e F_e U_R^{e\dagger}$

U_L^e and U_R^e are the unitary matrices that diagonalize the masses of the electrically-charged leptons.

• Interactions of the mass-eigenstate leptons with P^μ

(chirality-flip operators $\sim v_h \approx 174$ GeV) :

$$\frac{v_h}{M^2} P_{\mu\nu}\, \overline{e'} \sigma^{\mu\nu} \left(\mathrm{Re} F'_e + i\, \mathrm{Im} F'_e \gamma_5\right) e'$$

$\to$ magnetic-like and electric-like dipole moments

$\mathrm{Re}(F'_e)^{ij}$, $\mathrm{Im}(F'_e)^{ij}$ could have any value $\lesssim 4\pi$, but:

chirality-flip operators $\to$ probably $\left|F_e^{ij}\right| \lesssim \left|\lambda_e^{ij}\right|$

$$\Longrightarrow \quad \left|F_e'^{ij}\right| \lesssim \frac{m_\tau}{v_h} \approx 10^{-2}$$

$\left|F_e'^{11}\right|$ may naturally be below $m_e/v_h \approx 3 \times 10^{-6}$

Kinetic mixing of $U(1)_Y \times U(1)_z$ gauge bosons:

$c_0 B^{\mu\nu} P_{\mu\nu}$ **dimension-four operator!**

Holdom 1985:

Kinetic terms can be diagonalized and canonically normalized by a $SL(2,R)$ transformation.

Global $SO(2)$ symmetry: linear combination of $U(1)$ fields that couples to hypercharge is the real B^μ.

Orthogonal combination (“paraphoton” $= \gamma'$) does not have any renormalizable couplings to standard model fields.

Conclusion:
kinetic mixing has no effect on the standard model fields other than a renormalization of the hypercharge gauge coupling.

Bosonic interactions of the paraphoton:

$$\frac{1}{M^2} H^\dagger H \left(c_1 B_{\mu\nu} + \tilde{c}_1 \widetilde{B}_{\mu\nu} + c_2 P_{\mu\nu} + \tilde{c}_2 \widetilde{P}_{\mu\nu}\right) P^{\mu\nu}$$

• renormalize the $U(1)$ gauge couplings

• include vertices with two $U(1)$ gauge bosons and Higgs bosons.

These are all operators of $d \leq 6$ involving both γ' and SM fields

The strength of the γ' interaction with the electrons depends on

$$c_e \equiv \frac{v_h}{m_e} \left| (C'_e)_{11} \right| \lesssim O(1)$$

Similar parameters defined for interactions such as $\mu^+\mu^-\gamma'$, $\mu^\pm e^\mp \gamma'$, ...

Various measurements set limits on these parameters.

Spin-dependent long-range forces:

$$V(r) = -\frac{c_e^2 m_e^2}{\pi M^4} \frac{1}{r^3} \left[3(\sigma_1 \cdot r)(\sigma_2 \cdot r) - \sigma_1 \cdot \sigma_2 \right]$$

Measurements of $e - e$ long range forces impose that

$$\frac{M}{\sqrt{c_e}} \gtrsim 3 \text{ GeV}$$

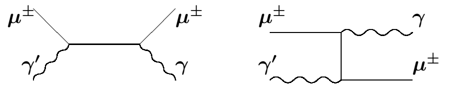
Primordial Nucleosynthesis

Constraints on new particles with mass below several MeV.

Maximum number of new relativistic degrees of freedom:

$\Delta g_*^{\max} = \frac{7}{8} \Delta N^{\max}$;   at the 2σ level: $\Delta N_\nu^{\max} \approx 0.6$

γ' must go out of equilibrium at $T_P > T_{\rm BBN} \approx 1$ MeV



Measurements of light element abundances set a limit on the effective mass scale:

$$M \gtrsim 1.5 \text{ TeV} \times \sqrt{c_\mu}$$

Star cooling

Effective coupling of γ' to electrons: $g_{\gamma' e} = \frac{c_e}{M^2} m_e^2$

Red giant stars: γ' emission via Bremsstrahlung & Compton-like processes

$$g_{\gamma' e}^2 / 4\pi < 2.5 \times 10^{-27} \quad \Rightarrow \quad \frac{M}{\sqrt{c_e}} \gtrsim 3.2 \text{ TeV}$$

For supernovae: ν emission rate $\gg$ γ' emission rate
$\Rightarrow$ no useful bound on electron-γ' coupling
(strong bound on quark-γ' couplings)

Flavor-changing neutral currents

Chirality-flip transition: $\Gamma\left(\mu \to e\gamma'\right) = c_{e\mu}^2 \dfrac{m_\mu^5}{8\pi M^4}$

Standard model: $\Gamma\left(\mu \to e\nu\bar{\nu}\right) = \dfrac{m_\mu^5 G_F^2}{192\pi^3} \approx 3.2 \times 10^{-10}\mathrm{eV}$

$$\mathrm{Br}\left(\mu \to e\gamma'\right) < 3 \times 10^{-5} \qquad \Rightarrow \qquad \frac{M}{\sqrt{c_{e\mu}}} \gtrsim 15\ \mathrm{TeV}$$

Conclusions so far

The LHC explores the TeV scale (= "terra incognita").
Many possibilities for what can be discovered:

- extended Higgs sectors (Lecture 1)
- Vectorlike fermions (Lecture 2)
- New gauge bosons (Z', G', ...) (this lecture)

New very light (even massless) particles may also exist.

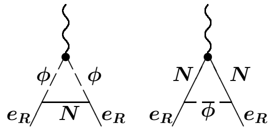
E.g., a γ' may couple to quarks and leptons via dimension-6 operators suppressed by the TeV scale!

An UV origin of the dimension-6 operators:

	l_L	e_R	N_L	N_R	H	ϕ
$SU(2)_W$	2	1	1	1	2	1
$U(1)_Y$	-1	-2	0	0	$+1$	-2
$U(1)_D$	0	0	$+1$	$+1$	0	-1

Yukawa interaction: $\lambda_\phi^j\, \bar{e}_R^j N_L\, \phi + \mathrm{h.c.}$

Contribution to the $iP_{\mu\nu}\bar{e}_R\gamma^\mu\partial^\nu e_R$ operator ($\sim P_{\mu\nu}\bar{l}_L\sigma^{\mu\nu}e_R H$):



$$\Rightarrow \quad (C_e)_{ij} = \frac{g_P}{192\pi^2}\sum_k \left(\lambda_\phi^i \lambda_\phi^{*k} \lambda_e^{kj} + \lambda_e^{ik}\lambda_\phi^k\lambda_\phi^{*j}\right)$$