HIERARCHICAL FERMIONS AND DETECTABLE Z' FROM AN EFFECTIVE TWO-HIGGS-TRIPLET 3-3-1 MODEL

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Outline

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- Neutrino masses and oscillations

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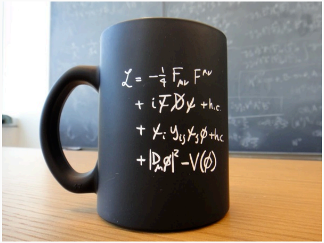
OPEN QUESTIONS AND THE STANDARD MODEL

Some issues with the SM

- Based on the gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$, the SM is very successful but far from being complete.
- Open questions:
  - # fermion families;
  - fermion mass hierarchy;
  - neutrino masses and oscillations;
  - Strong CP problem;
  - dark matter;
  - etc;

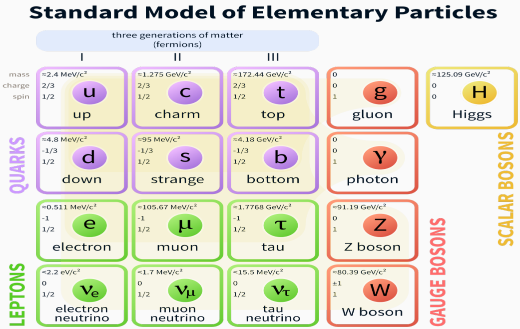


Fermion mass hierarchy

- 3 fermion generations are described in the SM.
- But why 3 exactly and not more? The SM does not provide an answer.
- In the SM, fermions couple to the Higgs doublet according to:

$$\lambda^f_{\alpha\beta}\,(\bar{F}_{\alpha L}\phi)\,f_{\beta R} \rightarrow m^f_{\alpha\beta}\,\bar{f}_{\alpha L}\,f_{\beta R}, \quad \mathbf{m}^{\mathbf{f}} = \lambda^{\mathbf{f}}\mathbf{v}\,. \tag{1}$$

- For up-type quarks, *e.g.*, we have $\lambda_t \sim \mathcal{O}(1)$ and $\lambda_u/\lambda_t \sim \mathcal{O}(10^{-5})$.
- Strong fermion mass hierarchy.



- How to explain these hierarchies more naturally?
- The Froggatt-Nielsen mechanism makes use of a $U(1)$ flavour symmetry.[1]
- In this case, fermion masses are given by

$$\lambda^f \left(\frac{S}{\Lambda}\right)^x (\bar{F}_L \phi)\, f_R \to m^f\, \bar{f}_L\, f_R, \quad m^f = \lambda^f_{eff} v\ , \tag{2}$$

so that $\lambda^f_{eff} = \lambda^f \left(\frac{\langle S \rangle}{\Lambda}\right)^x$ and $\lambda^f \sim \mathcal{O}(1)$.

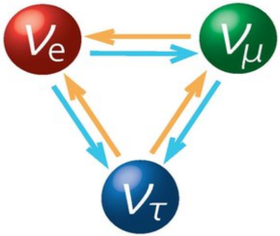
- The suitable exponent x is fixed by the flavour symmetry according to which the "Flavon", S, and fermions get their charges.
- This symmetry can be identified with the Peccei-Quinn symmetry[2] that solves the strong CP problem and may explain DM abundance.

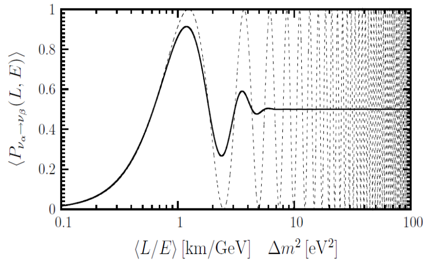
[1] C. D. Froggatt and H. B. Nielsen, (1979).
[2] R.D. Peccei and H R. Quinn, (1977)

Neutrino masses

- Only LH neutrinos are present in the SM $\Rightarrow$ Massless neutrinos.
- However, flavour oscillations have been observed, requiring neutrinos to be very light, but massive.

$$\mathcal{P}_{\nu_\alpha \to \nu_\beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right) . \tag{3}$$





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- Neutrino masses: SM ν_L + N_R (singlets). In the flavour basis $((\nu_L)^c, N_R)$

$$\mathcal{M}^\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \Rightarrow m_\nu \simeq \frac{(m_D)^2}{M_R} \text{ and } m_N \simeq M_R. \text{ (For } M_R \gg m_D\text{)} \tag{4}$$

- The heavier N_R, the lighter $\nu_L \Rightarrow$ Seesaw Mechanism ($M_R \sim 10^{14}$ GeV).
- Neutrino masses: SM ν_L + N_R (singlets) + S_R (singlets). $((\nu_L)^c, N_R, S_R)$

$$\mathcal{M}^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & m_R \\ 0 & (m_R)^T & \mu \end{pmatrix} \Rightarrow m_\nu \simeq \mu \frac{(m_D)^2}{m_R^2}. \tag{5}$$

- $m_\nu \to 0$ when $\mu \to 0 \Rightarrow$ Low-scale (inverse) seesaw mechanism[3] ($m_D \sim 10^2, m_R \sim 10^4, \mu \sim 10^{-5}$ in GeV).

[3] R.N. Mohapatra and J.W.F. Valle (1986)

EXTENDING THE SM

- In view of the many open questions, several extensions of the SM have been proposed.
- Enlarging its gauge structure, so that the SM is seen as an effective model at low energies, is a common approach.
- In particular, we have extensions of the SM electroweak sector

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \rightarrow SU(3)_c \otimes SU(M)_L \otimes SU(N)_R \otimes U(1)_X \,. \qquad (6)$$

- When $M = N \geq 2$, a left-right (LR) symmetry can be imposed.
- LR models can provide a dynamical origin for parity violation.
- For $M = N = 2$, we have the minimal LR SM extension[4] $\Rightarrow$ for each LH fermion doublet in the SM, a RH copy is added, *e.g.*

$$L_L = (\nu_L \;\; l_L)^T \quad \rightarrow \quad L_R = (\nu_R \;\; l_R)^T \,. \qquad (7)$$

- Therefore, RH neutrinos are essential in the minimal LR model, and the seesaw mechanism can be implemented.

[4] G. Senjanovic, R. N. Mohapatra (1975)

- The 3-3-1 model ($M = 3$, $N = 1$), invariant under $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$, with the electric charge operator given by[5]

$$Q = T_3 + \beta T_8 + XI \; . \tag{8}$$

- Anomaly cancellation + asymptotic freedom $\Rightarrow$ 3 fermion families.
- For this to happen, $\#\mathbf{3} = \#\mathbf{3}^*$ of $SU(3)_L$,

$$\begin{aligned}
\psi_{iL} &= \left(\nu_i \; e_i^- \; k_i^q\right)_L^T \sim \left(\mathbf{1}, \mathbf{3}, \frac{q-1}{3}\right), \\
Q_{aL} &= \left(d_a \; -u_a \; J_a^{-q-1/3}\right)_L^T \sim \left(\mathbf{3}, \mathbf{3}^*, -\frac{q}{3}\right), \\
Q_{3L} &= \left(u_3 \; d_3 \; J_3^{q+2/3}\right)_L^T \sim \left(\mathbf{3}, \mathbf{3}, \frac{q+1}{3}\right),
\end{aligned} \tag{9}$$

where $i = 1, 2, 3$, $a = 1, 2$ and $q = -1/2(1 + \sqrt{3}\beta)$.

- Such a feature can generate different mass patterns among the quarks and lead to FCNC.

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[5] M. Singer, J. W. F. Valle, J. Schechter (1980)

- Arbitrary β versions are generally associated with exotic fermions and non-perturbativity at low scales.
- When $\beta = \pm 1/\sqrt{3}$ though, such issues are avoided.
- Symmetry breaking happens in two stages:

$$SU(3)_c \otimes SU(3)_L \otimes U(1)_X \to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \to SU(3)_c \otimes U(1)_Q. \quad (10)$$

- This can be obtained with two scalar triplets χ and ρ, with

$$\langle \chi_3^0 \rangle = w \text{ and } \langle \rho_1^0 \rangle = v \sim 246 \text{ GeV} \ll w. \quad (11)$$

- The non-SM fields (new scalars, gauge bosons and fermions) are expected to get masses around the TeV scale (w).

3-3-1 MODEL WITH TWO-HIGGS-TRIPLETS

- We assume $\beta = \frac{1}{\sqrt{3}}$ and choose a minimal scalar sector with:[6]

$$\rho \equiv (\rho_1^0 \;\; \rho_2^- \;\; \rho_3^-)^T \,, \quad \chi \equiv (\chi_1^+ \;\; \chi_2^0 \;\; \chi_3^0)^T \,. \tag{12}$$

- The third components of the fermion triplets are E_{iL}^-, U_{aL} and D_L.
- We add a RH fermion singlet for each LH fermion in the triplets.
- The scalar potential and Yukawa Lagrangian follow

$$\begin{aligned} V &= \mu_1^2(\rho^\dagger\rho) + \mu_2^2(\chi^\dagger\chi) + \lambda_1(\rho^\dagger\rho)^2 + \lambda_2(\chi^\dagger\chi)^2 \\ &\quad + \lambda_3(\rho^\dagger\rho)(\chi^\dagger\chi) + \lambda_4(\chi^\dagger\rho)(\rho^\dagger\chi) \,, \end{aligned} \tag{13}$$

$$\begin{aligned} -\mathcal{L}_Y &= h_{is}^E \overline{\psi_{iL}}\, \chi\, e'_{sR} + h_{ij}^\nu \overline{\psi_{iL}}\, \rho\, \nu_{jR} + \frac{1}{2} m_{ij}^R \overline{(\nu_{iR})^c} \nu_{jR} + h_{am}^U \overline{Q_{aL}}\, \chi^* u'_{mR} \\ &\quad + h_{an}^d \overline{Q_{aL}}\, \rho^* d'_{nR} + h_m^u \overline{Q_{3L}}\, \rho\, u'_{mR} + h_n^D \overline{Q_{3L}}\, \chi\, d'_{nR} + h.c. \end{aligned} \tag{14}$$

- With only two triplets some fermions remain massless as a result of a residual (Peccei-Quinn-like) symmetry in the model.

[6] E. R. Barreto, A. G. Dias, **J. Leite**, C. C. Nishi, R. L. N. Oliveira and W. C. Vieira, (2018).

- 12 d.o.f. (2 triplets) - 8 (GB) = 4 physical scalars: h, H and $\varphi_\pm$.
- The spectrum is thus compact and does not contain CP-odd neutral scalars.
- h, the SM Higgs, and H, the heavy Higgs, mix according to

$$\begin{aligned} m_h^2 &\simeq \left[\lambda_1 - \lambda_3^2/(4\lambda_2)\right] v^2 = (125\ \text{GeV})^2\ , \quad m_H^2 \simeq \lambda_2 w^2\ , \\ \tan(2\theta) &= \frac{\lambda_3 v w}{\lambda_2 w^2 - \lambda_1 v^2}\ . \end{aligned} \tag{15}$$

- $\varphi_\pm$ is also heavy

$$m_{\varphi_\pm}^2 = \frac{\lambda_4}{2}(v^2 + w^2)\ . \tag{16}$$

- The symmetry gauge bosons are

$$P_\mu = \frac{g}{2}\begin{pmatrix} W_{3\mu} + \frac{W_{8\mu}}{\sqrt{3}} + 2tB_\mu X & \sqrt{2}W^+_\mu & \sqrt{2}V^+_\mu \\ \sqrt{2}W^-_\mu & -W_{3\mu} + \frac{W_{8\mu}}{\sqrt{3}} + 2tB_\mu X & \sqrt{2}V^0_\mu \\ \sqrt{2}V^-_\mu & \sqrt{2}V^{0\dagger}_\mu & -\frac{2W_{8\mu}}{\sqrt{3}} + 2tB_\mu X \end{pmatrix}, \tag{17}$$

- The non-diagonal fields get the following masses ($M^2_{V\pm} - M^2_{V^0} = M^2_{W\pm}$)

$$M^2_{W\pm} = \frac{g^2 v^2}{4}\,,\ \ M^2_{V\pm} = \frac{g^2}{4}(v^2 + w^2)\,,\ \ M^2_{V^0} = M^2_{V^{0\dagger}} = \frac{g^2}{4}w^2\,. \tag{18}$$

- The diagonal fields mix and give rise to A, Z_1 and Z_2 with masses

$$M^2_A = 0\,,\ \ M^2_{Z_1} \simeq \frac{g^2 v^2}{4\cos^2\theta_W}\,,\ \ M^2_{Z_2} \simeq \frac{g^2\cos^2\theta_W w^2}{3 - 4\sin^2\theta_W}\,. \tag{19}$$

- And there is also the prediction, at tree level, that $M^2_{Z_2}/M^2_{V^0} \approx 1.48$.

$$\Delta\rho_0 \equiv \frac{M^2_W}{\cos^2\theta_W M^2_{Z_1}} - 1 \approx \frac{(v/w)^2}{4\cos^4\theta_W} \ \ \Rightarrow\ \ w \geqslant 6.5\text{ TeV} \tag{20}$$

- Neutrino masses follow from the terms below

$$-\mathcal{L}_\nu = h^\nu_{ij}\overline{\psi_{iL}}\,\rho\,\nu_{jR} + \frac{1}{2}m^R_{ij}\overline{(\nu_{iR})^c}\nu_{jR} + h.c. \quad (21)$$

- With $m_R \gg m_D = \frac{h^\nu v}{\sqrt{2}}$, a type-I seesaw mechanism takes place, with sub-eV LH neutrinos ($m_\nu \simeq m_D^2/m_R$) and very heavy RH ones ($m_R \sim 10^{14}$ GeV).
- Other options, such as including a scalar sextet, could be explored but the scalar spectrum would possibly become less attractive.

- To break the residual PQL symmetry and generate mass to all charged fermions, we introduce

$$-\mathcal{L}_5 = \frac{y^e_{is}}{\Lambda}\overline{\psi_{iL}}\,\chi^*\rho^* e'_{sR} + \frac{y^u_{am}}{\Lambda}\overline{Q_{aL}}\,\chi\,\rho\,u'_{mR} + \frac{y^d_{n}}{\Lambda}\overline{Q_{3L}}\,\chi^*\rho^* d'_{nR} + h.c.\,, \qquad (22)$$

- The second component of the effective scalar triplet develops a vev

$$\frac{\langle\chi^*\rho^*\rangle}{\Lambda} = \frac{vw}{2\Lambda} = \frac{\epsilon}{\sqrt{2}}\,, \qquad (23)$$

with $\Lambda \gg w, v$ so that $\epsilon \ll v, w$.

- These operators can emerge from a UV complete model, containing a heavy scalar triplet (Λ) which is integrated out.
- When it comes to charged fermions, three energy scales are relevant

$$v, \quad w \quad \text{and} \quad \epsilon \text{ (or } \Lambda).$$

- Non-standard fermions obtain masses proportional to w (TeV scale).

- The 6×6 charged lepton mass matrix, in the basis $(e_i, E_i)_{L,R}$, has the form

$$\mathcal{M}^l = \frac{1}{\sqrt{2}} \begin{pmatrix} \epsilon\, \mathbf{y}^e \\ w\, \mathbf{h}^E \end{pmatrix} = \begin{pmatrix} M_e & M_{eE} \\ 0_{3\times 3} & M_E \end{pmatrix}, \tag{24}$$

- The SM charged leptons obtain masses proportional to ϵ so that we take $\epsilon \sim m_\tau \sim 1$ GeV ($\Lambda \sim 10^3$ TeV).
- To obtain m_e, we need $\lambda \sim 10^{-3}$; in the SM 10^{-5} is required.
- For the up-type quarks, in the basis $(u_i, U_a)^T_{L,R}$,

$$\mathcal{M}^u = \frac{1}{\sqrt{2}} \begin{pmatrix} -\epsilon \mathbf{y}^u \\ v \mathbf{f}^u \\ w \mathbf{h}^U \end{pmatrix} = \begin{pmatrix} M_u & M_{uU} \\ 0_{2\times 3} & M_U \end{pmatrix}, \quad M_u = \frac{1}{\sqrt{2}} \begin{pmatrix} \epsilon y^u_i \\ v f^u_i \end{pmatrix} = \begin{pmatrix} \tilde{M}_u & \tilde{M}_{ut} \\ 0_{1\times 2} & m_t \end{pmatrix}, \tag{25}$$

- The mixing angles with the new quarks are at most of order 10^{-2} and 10^{-4} for t_L and (u_L, c_L), respectively.
- The mixing between t_L and (u_L, c_L) has a natural hierarchy of $\epsilon/v \sim 10^{-2}$.

- For the down-type quarks, in the basis $(d_i, D)^T_{L,R}$, we have

$$\mathcal{M}^d = \frac{1}{\sqrt{2}} \begin{pmatrix} v\mathbf{h}^d \\ \epsilon\mathbf{y}^d \\ w\mathbf{f}^D \end{pmatrix} = \begin{pmatrix} M_d & M_{dD} \\ 0_{1\times3} & M_D \end{pmatrix}, \tag{26}$$

  Not a natural hierarchy between the first two and the third families.
- However, if h^d_{an} is an effective coupling, we have

$$vh^d_{an} = \epsilon' \bar{h}^d_{an} \sim 6 \times 10^{-4}\, v\bar{h}^d_{an}\,, \tag{27}$$

  with $\bar{h}^d_{an} \sim 1$ and $\epsilon' \sim m_s \sim 0.1$ GeV, then $m_b \sim \epsilon \sim 1$ GeV and $m_s \sim \epsilon'$.
- This can be arranged by introducing a scalar singlet φ and a Z_2 symmetry under which only $\varphi, Q_{aL}, u_{aR}, U_{aR}$ are odd.
- Instead of $h^d_{an}\overline{Q_{aL}}\,\rho^* d'_{nR}$, we would have $\bar{h}^d_{an}(\varphi/\Lambda')\overline{Q_{aL}}\,\rho^* d'_{nR}$.
- Could φ be introduced with a $U(1)$ chiral symmetry and give rise to a "flaxion"?

- A UV completion is achieved with a heavy scalar triplet $\eta \sim (\mathbf{1}, \mathbf{3}, 1/3)$.
- η couples to fermions according to

$$-\mathcal{L}_5 = y^e_{is} \overline{\psi_{iL}}\, \eta\, e'_{sR} + y^u_{am} \overline{Q_{aL}}\, \eta^*\, u'_{mR} + y^d_n \overline{Q_{3L}}\, \eta d'_{nR} + h.c.\ , \qquad (28)$$

- and the potential contains new terms, in special,

$$V_\eta \quad = \quad M^2 \eta^\dagger \eta - (f\, \eta \rho \chi + h.c.) + \cdots\ , \qquad (29)$$

where $M^2 > 0$ and $[f] = [M]$.

- When $M \gg w, v$, the new scalar can be integrated out, so that at low energies it is effectively given by

$$\eta \approx \frac{\rho^* \chi^*}{\Lambda} + \cdots\ , \quad \text{with} \quad \Lambda = \frac{M^2}{f}. \qquad (30)$$

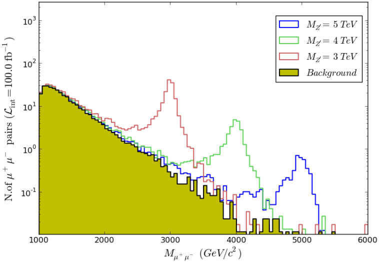
Upon replacing (30) into (28), we obtain the effective operators needed.

- Two main types of interactions involving FCNC:
  - i) due to the mixing between the third family of quarks and the other two;
  - ii) due to the mixing between the heavy and the SM fermions;
- For Z', for example, the flavour changing piece is

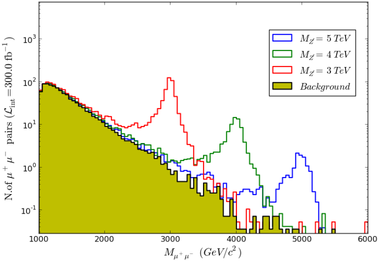
$$\begin{aligned} g_{Z'}^{-1} J^{\mu}_{Z'}\big|_{\mathrm{FCNC}} \quad = \quad & (-c_W^2)\overline{u}_{3L}\gamma^{\mu} u_{3L} + (-c_W^2)\overline{d}_{3L}\gamma^{\mu} d_{3L} + (-\frac{3}{2} + 2s_W^2)\overline{U}_{aL}\gamma^{\mu} U_{aL} \\ & +(\frac{1}{2} - s_W^2)\overline{D}_L\gamma^{\mu} D_L + (c_{2W} + \frac{1}{2})\overline{E}_{iL}\gamma^{\mu} E_{iL}\,, \end{aligned} \tag{31}$$

- For type (i), the mixing is naturally suppressed by $\epsilon/v \sim m_s/m_b \sim 10^{-2}$ which is typically below the current limits coming from meson mixing.
- For type (ii), FCNC are constrained by the search for singlet VLQs at the LHC and by indirect constraints coming from precision electroweak observables and from LEP.
- According to these, our heavy quarks of masses with mixing angle of less than 10^{-2} are not currently observable.
- FCNC mediated by the remaining gauge bosons and scalars are similarly suppressed.

- The Z' branching ratios, for exotic masses just above 1 TeV, are $\mathrm{Br}[Z' \to \nu\bar{\nu}] \simeq 45\%$, $\mathrm{Br}[Z' \to \ell\bar{\ell}] \simeq 13\%$ and $\mathrm{Br}[Z' \to q\bar{q}] \simeq 42\%$.
- Since the SM $\mathrm{Br}[Z \to \ell\bar{\ell}] \simeq 3\%$, we consider the Z' search via a clean dilepton signal at the LHC.
- We focus on the invariant mass distribution of the emerging leptons at the LHC: $p + p \longrightarrow \mu^+ + \mu^- + X$ at 14 TeV, with $\mathcal{L} = 100, 300\ \mathrm{fb}^{-1}$.
- In order to suppress the SM background, we look at $M_{\mu\mu} > 1$ TeV.
- We assume three values for $M_{Z'}$, *i.e.* $3, 4, 5$ TeV.
- A simple analysis is also performed considering the transverse momentum of the final muons.
- A considerable number of events is then predicted.



$M_{Z'} = 5$ TeV
$M_{Z'} = 4$ TeV
$M_{Z'} = 3$ TeV
Background
N.of $\mu^+\mu^-$ pairs ($\mathcal{L}_{int} = 100.0\ fb^{-1}$)
$M_{\mu^+\mu^-}$ (GeV/c^2)



$M_{Z'} = 5$ TeV
$M_{Z'} = 4$ TeV
$M_{Z'} = 3$ TeV
Background
N.of $\mu^+\mu^-$ pairs ($\mathcal{L}_{int} = 300.0\ fb^{-1}$)
$M_{\mu^+\mu^-}$ (GeV/c^2)

CONCLUSIONS

- We study a 3-3-1 model with $\beta = 1/\sqrt{3}$. (3-3-1 $\rightarrow$ SM at the TeV scale).
- 2 scalar triplets at low energies $\Rightarrow h, H, \varphi^{\pm}$ (no CP-odd neutral scalar).
- A residual symmetry is explicitly broken with effective operators so that all fermions become massive.
- UV completion is obtained with a heavy scalar triplet ($M \gg \mathcal{O}(\text{TeV})$).
- Neutrino masses via the type-I seesaw mechanism.
  - $m_{E_i^-}, m_{D_a}, m_U \sim w \sim 10$ TeV;
  - $m_e, m_\mu, m_\tau, \sim \epsilon \sim 1$ GeV;
  - $m_u, m_c \sim \epsilon$ and $m_t \sim v \sim 10^2$ GeV;
  - $m_d, m_s \sim v$ and $m_b \sim \epsilon$;
- Natural mass hierarchies lead to small mixing and suppressed FCNC.
- By studying the decay of Z' into muons at the LHC, through the invariant mass and p_T, the existence of Z' can be confirmed.

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