Bottom-quark Forward-Backward Asymmetry, Dark Matter and the LHC

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### Electro-weak precision measurement

| Measurement                  | Measurement Value | Fit Value   |
|------------------------------|-------------------|-------------|
| $\Delta \alpha_{\text{had}}^{(5)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02768     |
| $m_Z$ (GeV)                  | 91.1875 ± 0.0021  | 91.1874     |
| $\Gamma_Z$ (GeV)             | 2.4952 ± 0.0023   | 2.4959      |
| $\sigma^{0}_{\text{had}}$ (nb) | 41.540 ± 0.037    | 41.479      |
| $R_1$                        | 20.767 ± 0.025    | 20.742      |
| $A_{\text{fb}}^{0,1}$        | 0.01714 ± 0.00095 | 0.01645     |
| $A_{\text{fb}}(P_\tau)$     | 0.1465 ± 0.0032   | 0.1481      |
| $R_b$                        | 0.21629 ± 0.00066 | 0.21579     |
| $R_c$                        | 0.1721 ± 0.0030   | 0.1723      |
| $A_{\text{fb}}^{0,1}$        | 0.0992 ± 0.0016   | 0.1038      |
| $A_{\text{fb}}^{0,1}$        | 0.0707 ± 0.0035   | 0.0742      |
| $A_{b}$                      | 0.923 ± 0.020     | 0.935       |
| $A_{c}$                      | 0.670 ± 0.027     | 0.668       |
| $A_{l}(\text{SLD})$          | 0.1513 ± 0.0021   | 0.1481      |
| $\sin^2\theta_{\text{eff}}(Q_{\text{fb}})$ | 0.2324 ± 0.0012  | 0.2314      |
| $m_W$ (GeV)                  | 80.399 ± 0.023    | 80.379      |
| $\Gamma_W$ (GeV)             | 2.085 ± 0.042     | 2.092       |
| $m_t$ (GeV)                  | 173.3 ± 1.1       | 173.4       |

July 2010
## Electro-weak precision measurement

| Measurement          | Fit       | $|\Delta \alpha^{(5)}_{\text{had}}(m_Z)|$ | $m_Z$ (GeV) | $\Gamma_Z$ (GeV) | $\sigma^0_{\text{had}}$ (nb) | $R_l$    | $A^{0,1}_{tb}$ | $A^{0,1}_{tb}$ |
|----------------------|-----------|-------------------------------------|-------------|------------------|-------------------------------|----------|----------------|----------------|
| $\Delta \alpha^{(5)}_{\text{had}}(m_Z)$ | 0.02758 ± 0.00035 | 0.0276 | 91.1875 ± 0.0021 | 91.1874 | 2.4952 ± 0.0023 | 2.4959 | 41.540 ± 0.037 | 41.479 |
| $m_Z$ (GeV)           | 91.1875 ± 0.0021 |         |                |               |                               |          |                |                |
| $\Gamma_Z$ (GeV)      | 2.4952 ± 0.0023 |         |                |               |                               |          |                |                |
| $\sigma^0_{\text{had}}$ (nb) | 41.540 ± 0.037 |         |                |               |                               |          |                |                |
| $R_l$                 | 20.767 ± 0.025 |         |                |               |                               |          |                |                |
| $A^{0,1}_{tb}$        | 0.01714 ± 0.00095 |        |                |               |                               |          |                |                |

### $A_{fb}^{0,b}$

$$A_{fb}^{0,b} = 0.0992 ± 0.0016 \quad 0.1038$$

### Parameters

- $A_b$
- $A_c$
- $A_l$(SLD)
- $\sin^2 \theta^\text{lep}_{\text{eff}}(Q_{fb})$
- $m_W$ (GeV)
- $\Gamma_W$ (GeV)
- $m_t$ (GeV)
- July 2010
B-quark Forward-Backward Asymmetry

\[ A_{FB}^b = \frac{\sigma(y > 0) - \sigma(y < 0)}{\sigma(y > 0) + \sigma(y < 0)} \]

\[ A_{FB}^b = \frac{3}{4} \mathcal{A}_e \mathcal{A}_b = \frac{3}{4} \times \frac{(g_L^e)^2 - (g_R^e)^2}{(g_L^e)^2 + (g_R^e)^2} \times \frac{(g_L^b)^2 - (g_R^b)^2}{(g_L^b)^2 + (g_R^b)^2} \]
Di-jet search @ LHC

CMS Preliminary

$\sigma_{95\% \, CL}$ (pb)

- Observed
- Expected
- $\pm$ 1 std. deviation
- $\pm$ 2 std. deviation
- Theory, $g_q = 0.17$
- Theory, $g_q = 0.08$

$35.9 \, fb^{-1}$ (13 TeV)

Z' mass (GeV)

CMS-PAS-EXO-17-001
Dark Matter
2HDM+S Model

The SM Higgs-like doublet which gives the other SM fermions and the gauge bosons masses will be denoted as \( \Phi \). Another SM gauge singlet scalar \( \chi \) charged under \( U(1)_D \) is needed to give mass to the \( K \) gauge boson. It is clear that within this setup, we can not write down the normal Yukawa interaction for the bottom and charm quark directly. To solve the problem, we add two vector-like quarks \( b, c \), which have the same SM charges as \( b_R \) and \( c_R \), but without \( U(1)_D \) charge. The masses of the bottom and charm quarks are obtained by their mixing with the heavy vector-like quarks, which is in the same spirit of partial compositeness [11].

The particle contents of our model and their gauge group charges are listed in Table I.

| filed | \( SU(3)_C \) | \( SU(2)_L \) | \( U(1)_Y \) | \( U(1)_D \) |
|-------|----------------|----------------|-------------|-------------|
| \( \Phi_1 \) | 1 | 2 | \( \frac{1}{2} \) | X |
| \( \Phi_2 \) | 1 | 2 | \( \frac{1}{2} \) | 0 |
| \( \Phi_3 \) | 1 | 1 | 0 | -X |
| \( b_R \) | 3 | 1 | \( -\frac{1}{3} \) | X |
| \( c_R \) | 3 | 1 | \( \frac{2}{3} \) | -X |
| \( \chi_{1,R} \) | 1 | 1 | -1 | X |
| \( \chi_{2,R} \) | 1 | 1 | 0 | -X |
| \( \chi_{1,L} \) | 1 | 1 | -1 | 0 |
| \( \chi_{2,L} \) | 1 | 1 | 0 | 0 |
| \( \psi_b \) | 3 | 1 | \( -\frac{1}{3} \) | 0 |
| \( \psi_c \) | 3 | 1 | \( \frac{2}{3} \) | 0 |
Gauge Sector

* Mixing between mass eigenstates

\[
\begin{pmatrix}
  m_Z^2 & -\frac{2g_Dc_\beta^2}{\sqrt{g^2+g'^2}}m_Z^2 \\
  \frac{-2g_Dc_\beta^2}{\sqrt{g^2+g'^2}}m_Z^2 & m_K^2 + \frac{4g_D^2c_\beta^2}{g^2+g'^2}m_Z^2
\end{pmatrix}
\]

\[
\begin{pmatrix}
  Z_\mu \\
  K_\mu
\end{pmatrix}
= \begin{pmatrix}
  \cos \alpha & \sin \alpha \\
  -\sin \alpha & \cos \alpha
\end{pmatrix}
\begin{pmatrix}
  \tilde{Z}_\mu \\
  \tilde{K}_\mu
\end{pmatrix}
\]

\[
m_{\tilde{Z}}^2 \approx m_Z^2 - \sin^2 \alpha (m_K^2 - m_Z^2) \sim 10^{-3} m_Z^2
\]

\[
m_{\tilde{K}}^2 \approx m_K^2 + \frac{4g_D^2c_\beta^2}{g^2+g'^2}m_Z^2 + \sin^2 \alpha (m_K^2 - m_Z^2) \sim 0
\]
Fermion Sector

* Source of b mass

\[
\mathcal{L}_q = \sum_q i\bar{q}\lambda q - m_{b,\psi}\bar{\psi}_b\psi_b - m_{c,\psi}\bar{\psi}_c\psi_c - \left(\bar{Q}_L y_{2u}^i \Phi_2 u_R^i + \bar{Q}_L y_{2d}^i \Phi_2 d_R^i + h.c.\right)
- y_{2b,\psi}^i \bar{Q}_L^i \Phi_2^b \psi_{b,R} - y_{2c,\psi}^i \bar{Q}_L^i \Phi_2^c \psi_{c,R} - y_{3b,\psi}^i \bar{\psi}_{b,L}^i \Phi_3^b b_R - y_{3c,\psi}^i \bar{\psi}_{c,L}^i \Phi_3^c c_R + h.c.
\]

\[
M_b = \begin{pmatrix} m_{b,\psi} & \frac{y_{3b,\psi} v_D}{\sqrt{2}} \\ \frac{y_{2b,\psi} v_2}{\sqrt{2}} & 0 \end{pmatrix} \equiv \begin{pmatrix} m_{b,\psi} & m_{12}^b \\ m_{21}^b & 0 \end{pmatrix}
\]

If Define:

\[
\begin{pmatrix} \psi_{b,L} \\ b_L \end{pmatrix} = \begin{pmatrix} c_{b,L} & s_{b,L} \\ -s_{b,L} & c_{b,L} \end{pmatrix} \begin{pmatrix} \bar{\psi}_{b,L} \\ \bar{b}_L \end{pmatrix}, \quad \begin{pmatrix} \psi_{b,R} \\ b_R \end{pmatrix} = \begin{pmatrix} c_{b,R} & s_{b,R} \\ -s_{b,R} & c_{b,R} \end{pmatrix} \begin{pmatrix} \bar{\psi}_{b,R} \\ \bar{b}_R \end{pmatrix}
\]

\[
m_{\tilde{b}} \simeq -s_{b,L} s_{b,R} m_{b,\psi}
\]

* The same for c mass

\[
m_{\tilde{c}} \simeq -s_{c,L} s_{c,R} m_{c,\psi}
\]
are of opposite sign, while for the left-handed couplings, they arise from the normalization modifications to the
where the mixing angles are defined in the previous two sections. We can clearly see that
and for the neutral
gauge bosons read:
First, we notice that in the gauge basis, the interaction Lagrangian in the quark sector reads:

\[
\mathcal{L}_{int}^Z = \tilde{b}_L \gamma^\mu \tilde{b}_L \frac{g \cos \alpha}{c_w} \left( \frac{s_w^2}{3} - \frac{1}{2} c_{b,L}^2 \right) + \tilde{b}_R \gamma^\mu \tilde{b}_R \left( \frac{g s_w^2}{3 c_w} \cos \alpha - g_D \sin \alpha c_{b,R}^2 \right) \\
+ \tilde{c}_L \gamma^\mu \tilde{c}_L \frac{g \cos \alpha}{c_w} \left( -\frac{2 s_w^2}{3} + \frac{1}{2} c_{c,L}^2 \right) + \tilde{c}_R \gamma^\mu \tilde{c}_R \left( -\frac{2 g s_w^2}{3 c_w} \cos \alpha + g_D \sin \alpha c_{c,R}^2 \right) \\
+ \frac{g \cos \alpha s_w^2}{3 c_w} \tilde{Z}_\mu \left\{ \left[ c_{b,L}^2 \tilde{\psi}_{b,L} \gamma^\mu \tilde{\psi}_{b,L} + (L \leftrightarrow R) \right] - 2 \left[ c_{c,L}^2 \tilde{\psi}_{c,L} \gamma^\mu \tilde{\psi}_{c,L} + (L \leftrightarrow R) \right] \right\} \\
+ \frac{g \cos \alpha}{2 c_w} \left[ (c_{b,L} s_{b,L} \tilde{\psi}_{b,L} \gamma^\mu \tilde{b}_L + g_D \sin \alpha c_{b,R} s_{b,R} \tilde{\psi}_{b,R} \gamma^\mu \tilde{b}_R + h.c.) - (b \leftrightarrow c) \right]
\]

Z Interactions to SM particle

Heavy NP particles’ decay
Electroweak Precision Measurement

* T parameter

\[ \hat{\alpha}(m_Z) T = -\frac{\Delta m_Z^2}{m_Z^2} \sim \sin^2 \alpha \frac{m_K^2 - m_Z^2}{m_Z^2} \in [-0.00121, 0.00246] \]

* Z pole measurement

\[ R_{b,c} \equiv \frac{\Gamma(\tilde{Z} \rightarrow \tilde{b}\tilde{b}(\tilde{c}\tilde{c}))}{\Gamma(\tilde{Z} \rightarrow \text{hadrons})} \approx \frac{\left( g_L^{(\bar{b},\bar{c})} \right)^2 + \left( g_R^{(\bar{b},\bar{c})} \right)^2}{\sum_q \left( g_L^q \right)^2 + \left( g_R^q \right)^2} \]

\[ A_{FB}^{b,c} = \frac{3}{4} A_e A_{b,c} \approx \frac{3}{4} A_e \left( g_L^{(\bar{b},\bar{c})} \right)^2 - \left( g_R^{(\bar{b},\bar{c})} \right)^2 \]

With

\[ A_f \equiv \frac{\left( g_L^f \right)^2 - \left( g_R^f \right)^2}{\left( g_L^f \right)^2 + \left( g_R^f \right)^2} \]
III. ELECTROWEAK PRECISION MEASUREMENTS

The main motivation behind this model is the observed 3 deviation of the bottom-quark forward-backward asymmetry \( A_{FB} \) measured at the LEP experiment at CERN. It is well known that this asymmetry may be modified by varying the right-handed bottom coupling \([5, 9, 13-17]\). In general, the modification of the couplings produces other effects that have relevant implications on the precision electroweak observables, which should be considered simultaneously. In fact, the strongest constraints on this model come precisely from the Electroweak precision measurements \([3, 18-21]\) including the T parameter and the Z-pole observables. In our setup, the mixing between \( \tilde{K} \) and \( \tilde{Z} \) will induce the custodial symmetry breaking, which modifies the \( \tilde{Z} \) mass without changing the mass of the \( W \) boson. The corresponding contribution to the T-parameter is given by:

\[
\hat{\alpha} \left( m_Z \right) T = \frac{m_Z^2}{m_K^2} \left( \frac{m_Z^2}{m_Z^2} \right),
\]

where \( \hat{\alpha} \left( m_Z \right) \) is evaluated at the Z-pole, whose value is \([22, 23]\):

\[
\hat{\alpha} \left( m_Z \right) = \frac{1}{127.95}. \tag{54}
\]
$\mathcal{L}_{int}^K = \frac{g \sin \alpha}{c_w} \tilde{K}_\mu J_{Z,q}^\mu + \tilde{K}_\mu \left[ \tilde{b}_L \gamma_\mu b_L \frac{g \sin \alpha}{c_w} \left( \frac{s_w^2}{3} - \frac{1}{2} c_{b,L}^2 \right) + \tilde{b}_R \gamma_\mu \tilde{b}_R \left( \frac{g s_w^2}{3 c_w} \sin \alpha + g_D \cos \alpha c_{b,R}^2 \right) \right]$

$+ \tilde{K}_\mu \left[ \tilde{c}_L \gamma_\mu c_L \frac{g \sin \alpha}{c_w} \left( -\frac{2 s_w^2}{3} + \frac{1}{2} c_{c,L}^2 \right) + \tilde{c}_R \gamma_\mu \tilde{c}_R \left( -\frac{2 g s_w^2}{3 c_w} \sin \alpha - g_D \cos \alpha c_{c,R}^2 \right) \right]$

$+ \tilde{K}_\mu \left( \tilde{\psi}_{b,L} \gamma_\mu \tilde{b}_L \frac{g}{2 c_w} \sin \alpha c_{b,L} s_{b,L} - \tilde{\psi}_{b,R} \gamma_\mu \tilde{b}_R g_D \cos \alpha c_{b,R} s_{b,R} \right)$

$- \tilde{K}_\mu \left( \tilde{\psi}_{c,L} \gamma_\mu \tilde{c}_L \frac{g}{2 c_w} \sin \alpha c_{c,L} s_{c,L} - \tilde{\psi}_{c,R} \gamma_\mu \tilde{c}_R g_D \cos \alpha c_{c,R} s_{c,R} \right)$
Search @ colliders

* $\tilde{K}$ Constraint

**FIG. 3:** The constraints from collider searches on $\tilde{K}$ for $g_D \sin \alpha = -0.011$. The mixing angle between heavy vector-like quarks and SM $b, c$ quarks are chosen following Fig. 1, where the EWPT constraint is the T parameter constraint under such choice. The red (blue) shaded regions correspond to exotic $Z'$ search in dijet (b-jet pair) channel from CMS at 13 TeV [25] (27), labeled as "13 TeV CMS $Z' \rightarrow jj" ("13 TeV CMS $Z' \rightarrow \bar{b}b"). The $Z'$ dilepton searches at LHC are shown as magenta and green shaded area, from 7TeV [28] and 13TeV [29] ATLAS, labeled as "7TeV ATLAS $Z' \rightarrow \mu^+\mu^-" and "13TeV ATLAS $Z' \rightarrow \mu^+\mu^-". The gray region is excluded because $\cos \beta > 1$, while above the line has $\cos \beta < 1$.

Note that the mass of the new gauge boson $\tilde{K}$ is very close to SM Higgs mass. For this benchmark point, the Drell-Yan cross section for $\tilde{K}$ production at the 13 TeV LHC will be sizable, around $3.1 \times 10^3 \text{ pb}$. The associated production cross section at LHC with another one or two jets are also listed in Table II.

For our benchmark point $m_{\tilde{K}} = 115 \text{ GeV}$, since it can decay into $\tilde{b}\bar{b}$ at around 50%, it can easily fake a $b\bar{b}$ decaying SM Higgs boson $m_h = 125 \text{ GeV}$ at the LHC, because the large uncertainty for reconstructing hadronically decaying particles. In this case, it is important to check the constraints coming from SM Higgs searches with the Higgs decaying into bottom.
Dark Matter Search

• Lagrangian for Dirac case

\[ \mathcal{L}_{\chi_2} \simeq -g_D \cos \alpha \tilde{K}_\mu \bar{\chi}_{2,R} \gamma^\mu \chi_{2,R} + g_D \sin \alpha \tilde{Z}_\mu \bar{\chi}_{2,R} \gamma^\mu \chi_{2,R} + \frac{m_{\chi_2}}{v_D} \bar{\chi}_2 \chi_2 \left( \frac{v}{v_D} \cos \beta H_1^0 + U_{23} H_2^0 - U_{33} H_3^0 \right) + \frac{i m_{\chi_2} v}{v_D^2} \cos \beta A^0 \bar{\chi}_2 \gamma_5 \chi_2 \left( + \frac{1}{2} M_m \bar{\chi}_{2,L} \chi_{2,L}^c \right) \]

• Simplify for Majorana case

\[ \mathcal{L}_{\chi'_2} \simeq \begin{cases} \frac{-g_D}{2} \bar{\chi}'_2 \gamma^\mu \gamma_5 \chi'_2 \left( \cos \alpha \tilde{K}_\mu + \sin \alpha \tilde{Z}_\mu \right) - \frac{m_{\chi_2}}{v_D} \bar{\chi}'_2 \chi'_2 U_{33} H_3^0 & (M_m \ll m_{\chi_2}) \\ -g_D \bar{\chi}'_2 \gamma^\mu \gamma_5 \chi'_2 \left( \cos \alpha \tilde{K}_\mu + \sin \alpha \tilde{Z}_\mu \right) & (M_m \gg m_{\chi_2}) \end{cases} \]
**Annihilation Cross section**

\[
(\sigma v)^{q=b,c}_{\chi_2 \tilde{\chi}_2' \rightarrow q\bar{q}} = \frac{g_D^4 c_{\chi_2}^2}{4\pi} \frac{\sqrt{1 - \frac{4m_q^2}{s}}}{(s - m_K^2)^2 + m_K^2 \Gamma_K^2} \left\{ (s - 4m_{\chi_2}^2) + m_q^2 \left[ 2m_{\chi_2'}^2 \left( \frac{5m_K^4 - 6m_K^2 s + 3s^2}{sm_K^4} \right) - 1 \right] \right\}
\]

**Direct Detection**

\[
\sigma_{SI}^N = \frac{16\mu_N^2}{729\pi\nu_D^4} \left( f_{TG}^{(N)} \frac{m_{\chi_2'} m_N}{m_{H_3^0}^2} \right)^2
\]
FIG. 6: The constraints for Majorana dark matter from LHC searches, direct detection and relic abundance. The labels are similar as in Fig. 4.

For \( m_m \approx m_{\chi^2} \), the branching ratio \( \text{BR}(\tilde{K}/\chi^1) \) is similar to \( \text{BR}(\tilde{K}/\chi^2) \) for \( m_m \approx m_{\chi^2} \), where each channel contributes approximately \( 1/4 \). But for sizable mass splitting between \( \chi^1 \) and \( \chi^2 \), the limits will be weaker because some channels \( \chi^1 \chi^2 \) or \( \chi^1 \chi^1 \) may not be kinematically accessible.

If \( m_{\chi^2} > m_{\tilde{K}/2} \), for the search of jet+MET at ATLAS, we compare our cross-section ✰ 0.01 pb after cut \( p_{T,j} > 250 \text{ GeV} \) to the constraint at 13 TeV LHC which is 0.57 pb \(^{61}\). It shows that o-shell \( \tilde{K}/\chi^2 \) is very safe from limits from mono-jet searches. We also check the process \( jj/\bar{\chi}^2 \) with our benchmark setup and found it is even safer from the constraints obtained in Ref. \(^{45}\).
**Summary**

- **$A_{FB}^b$ Anomaly**
  - Can be explained via a new U(1) gauge boson.

- **Dark Matter Candidate:**
  - Vector like singlet which can cancel the anomaly can be dark matter candidate.

- **CMS di-jet resonance excess:**
  - Can be explained by the U(1) gauge boson with mass 115 GeV.
Any Questions?

Thank You :)