Exotic quarks from composite models

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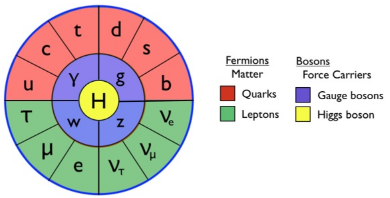
September 14, 2017

Outline

- Introduction
- Composite models
- Production of excited composite quarks at LHC
- Signal and background study
- Bounds from recasting an experimental analysis

The Standard Model, its shortcomings and extensions

The Standard Model



Particles of the Standard Model

- The fermions are the foundamental blocks of the matter
- The bosons mediate the interactions
- The standard model had great success in describing the experimental observations
- However it has some shortcomings

Shortcomings of SM

It can not accomodate

- neutrino masses
- gravitational interaction
- dark matter
- matter-antimatter asymmetry

Extensions of SM

- GUT
- String theory
- Supersymmetry
- Extra-dimensions
- Composite models

Composite model for quarks and leptons

- Compositness of leptons and quarks is one possible scenario beyond the Standard Model
- In a composite scenario fermions are assumed to have an internal substructure.
- In a composite scenario we expect to observe excited leptons and quarks
- In general the following parameters are introduced:
  - m_*: mass of the excited states
  - Λ: Energy scale at which the internal substructure becomes manifest

In our study we will use the parameterization $m_* = \Lambda$

Extended weak isospin model

- It describes the excited states trough the weak isospin symmetry
- It doesn't refer to the internal dynamics
- Analogy with strong isospin $\rightarrow$ prediction of hadronic states before the discovery of quarks and gluons
- SM $q, \ell \in I_W = 0, 1/2$ e $W^{\pm}, Z, \gamma \in I_W = 0, 1$
  $\Rightarrow$ excited fermions $\in I_W \leq 3/2$

I_W	Multiplet	Q	Y
0	L^-	-1	-2
$\frac{1}{2}$	$\mathbf{L} = \begin{pmatrix} L^0 \\ L^- \end{pmatrix}$	$\begin{matrix} 0 \\ -1 \end{matrix}$	-1
1	$\mathbf{L} = \begin{pmatrix} L^0 \\ L^- \\ L^{--} \end{pmatrix}$	$\begin{matrix} 0 \\ -1 \\ -2 \end{matrix}$	-2
$\frac{3}{2}$	$\mathbf{L} = \begin{pmatrix} L^+ \\ L^0 \\ L^- \\ L^{--} \end{pmatrix}$	$\begin{matrix} 1 \\ 0 \\ -1 \\ -2 \end{matrix}$	-1

I_W	Multiplet	Q	Y
0	U	$2/3$	$4/3$
0	D	$-1/3$	$-2/3$
$\frac{1}{2}$	$\Psi = \begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{matrix} 2/3 \\ -1/3 \end{matrix}$	$1/3$
1	$U = \begin{pmatrix} U^+ \\ U \\ D \end{pmatrix}$	$\begin{matrix} 5/3 \\ 2/3 \\ -1/3 \end{matrix}$	$4/3$
1	$D = \begin{pmatrix} U \\ D \\ D^- \end{pmatrix}$	$\begin{matrix} 2/3 \\ 1/3 \\ -4/3 \end{matrix}$	$-2/3$
$\frac{3}{2}$	$\Psi = \begin{pmatrix} U^+ \\ U \\ D \\ D^- \end{pmatrix}$	$\begin{matrix} 5/3 \\ 2/3 \\ -1/3 \\ -4/3 \end{matrix}$	$1/3$

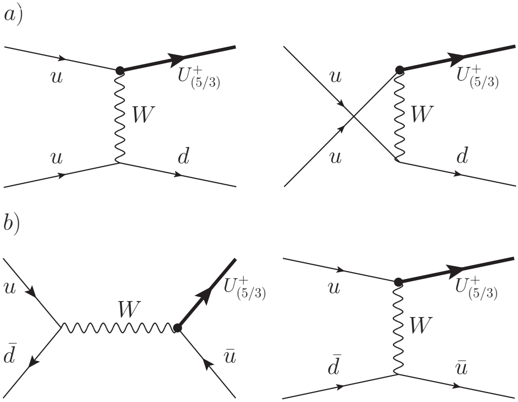
The higher isospin multiplets in the quark sector

- The isospin multiplets with $I_W = 1$ and $I_W = 3/2$ contain ordinary charged excited quarks (U, D) and exoticly charged excited quarks (U^+, D^-)
- The higher isospin multiplets contribute solely to the iso-vector current and do not contribute to the hypercharge current
- The exoticly charged excited quarks interact with the standard model fermions only via W^+ and W^- gauge bosons
- Because all gauge fields carry no hypercharge Y, a given multiplet couples truogh the gauge field to light multiplet with the same Y
- In order to conserve the $SU(2)$ currents, the couplings between excited and ordinary fermions are magnetic moment type transition couplings.
- The lagrangians are:
  $\mathcal{L}^{(I_W=3/2)} = \frac{gf_{3/2}}{\Lambda} \sum_{M,m,m'} C(\frac{3}{2}, M|1, m; \frac{1}{2}, m') \times (\bar{\Psi}_M \sigma_{\mu\nu} q_{Lm'}) \partial^\nu (W^m)^\mu + h.c.$
  $\mathcal{L}^{(I_W=1)} = \frac{gf_1}{\Lambda} \sum_{m=-1,0,1} \left[(\bar{U}_m \sigma_{\mu\nu} u_R) + (\bar{D}_m \sigma_{\mu\nu} d_R) \right] \partial^\nu (W^m)^\mu + h.c.$

  (g is the $SU(2)$ coupling, $f_1, f_{3/2} = 1$, C are the Clebsch-Gordan coefficients, we assume $\Lambda = m_*$).

Production process for U^+

- For the $uu \to U^+ d$ sub-process we have t and $u-$channel
- For the $u\bar{d} \to U^+ \bar{u}$ sub-process we have s and $t-$channel



For the production of D^- we have a similar situation

Partonic sub-processes cross sections ($I_W = 1$)

The case $I_W = 1$ is characterized by the absence of the interference between the kinematic channels

$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)^{I_W=1}_{uu\to U^+d} = \frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_1^2}{16\pi}\frac{\hat{t}}{(\hat{t}-M_W^2)^2}\left[m_*^2(\hat{t}-m_*^2)+2\hat{s}\hat{u}+m_*^2(\hat{s}-\hat{u})\right] + \frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_1^2}{16\pi}\frac{u}{(\hat{u}-M_W^2)^2}\left[m_*^2(\hat{s}-m_*^2)+2\hat{t}\hat{u}+m_*^2(\hat{t}-\hat{u})\right]$$

$$\left(\frac{d\hat{\sigma}}{d\hat{t}}\right)^{I_W=1}_{u\bar{d}\to U^+\bar{u}} = \frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_1^2}{16\pi}\frac{\hat{s}}{(\hat{s}-M_W^2)^2}\left[m_*^2(\hat{s}-m_*^2)+2\hat{t}\hat{u}+m_*^2(\hat{t}-\hat{u})\right] + \frac{1}{4\hat{s}^2 m_*^2}\frac{g^4 f_1^2}{16\pi}\frac{\hat{t}}{(\hat{t}-M_W^2)^2}\left[m_*^2(\hat{t}-m_*^2)+2\hat{s}\hat{u}+m_*^2(\hat{s}-\hat{u})\right]$$

Partonic sub-processes cross sections ($I_W = 3/2$)

The case $I_W = 3/2$ is characterized by nonzero interference between the kinematic channels

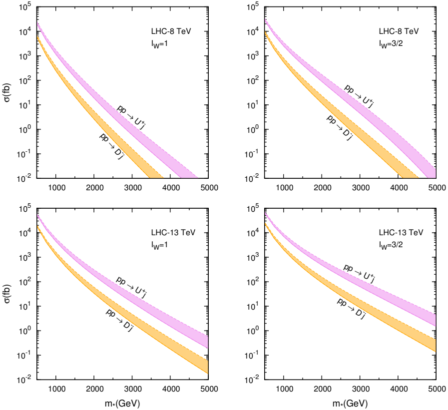
$$\left(\frac{d\hat\sigma}{d\hat t}\right)^{I_W=3/2}_{uu\to U^+ d} = \frac{1}{4\hat s^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{\hat t}{(\hat t - M_W^2)^2}\left[m_*^2(\hat t - m_*^2) + 2\hat s\hat u - m_*^2(\hat s - \hat u)\right]$$
$$+\frac{1}{4\hat s^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{\hat u}{(\hat u - M_W^2)^2}\left[m_*^2(\hat u - m_*^2) + 2\hat s\hat t - m_*^2(\hat s - \hat t)\right]$$
$$+\frac{1}{4\hat s^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{1}{(\hat u - M_W^2)}\frac{1}{(\hat t - M_W^2)}\left(\hat s\hat t\hat u + \frac{3}{8}\hat u\hat t m_*^2\right)$$

$$\left(\frac{d\hat\sigma}{d\hat t}\right)^{I_W=3/2}_{u\bar d\to U^+ \bar u} = \frac{1}{4\hat s^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{\hat s}{(\hat s - M_W^2)^2}\left[m_*^2(\hat s - m_*^2) + 2\hat t\hat u - m_*^2(\hat t - \hat u)\right]$$
$$+\frac{1}{4\hat s^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{\hat t}{(\hat t - M_W^2)^2}\left[m_*^2(\hat t - m_*^2) + 2\hat s\hat u - m_*^2(\hat s - \hat u)\right]$$
$$+\frac{1}{4\hat s^2 m_*^2}\frac{g^4 f_{3/2}^2}{16\pi}\frac{1}{(\hat s - M_W^2)}\frac{1}{(\hat t - M_W^2)}\left(\hat s\hat t\hat u + \frac{3}{8}\hat s\hat t m_*^2\right)$$

Production cross section

$\sigma = \sum_{a,b} \int_{\frac{m^{*2}}{s}}^{1} d\tau \int_{\tau}^{1} \frac{dx}{x} f_a(x, \hat{Q}) f_b(\frac{\tau}{x}, \hat{Q}) \hat{\sigma}(\tau s, m_*)$

($\hat{\sigma}$: partonic cross section calculated in the center of mass frame, f_a: partonic distribution function, x: longitudinal partonic momentum fraction, $\hat{Q}$: factorization scale.)



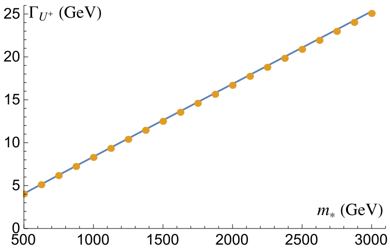
The bands correspond to the varition of the factorization scale from $\hat{Q} = M_W$ to $\hat{Q} = m_*$

The production of U^+ has a larger cross section because this process involves sub-processes with u quarks in the initial state, that is the most available quark in the proton.

Excited quarks decay and final signature

$$U^+ \to W^+ u$$

$$\Gamma = \alpha \frac{f^2}{\sin^2\theta_w} \frac{m_*}{8} \left(2 + \frac{M_W^2}{m_*^2}\right) \left(1 - \frac{M_W^2}{m_*^2}\right)^2$$



We consider the decay chain $Q \to W^+ q \to \ell^+ \nu q$

$\Rightarrow$ The final signature is $\ell^+ \not{p}_T jj$

This signature can be given by the processes:

$pp \to U^+ j \to W^+ jj \to \ell^+ \not{p}_T jj$

$pp \to \bar{D}^- j \to W^+ jj \to \ell^+ \not{p}_T jj$

$pp \to U j \to W^+ jj \to \ell^+ \not{p}_T jj$

$pp \to \bar{D} j \to W^+ jj \to \ell^+ \not{p}_T jj$

All these contributions are included in the simulations

Contributions to the final signature

The U^+ and $\bar{D}^-$ interact with the SM Gauge boson W, the U and $\bar{D}$ interact with the SM gauge bosons W, Z, γ:

- The U^+ and $\bar{D}^-$ contribute to Wqq channel with branching ratio $\mathcal{B}(Q \to W^+q) = 1$, while the U and $\bar{D}$ with $\mathcal{B}(Q \to W^+q) \approx 0.22$
- The U and $\bar{D}$ production happen with diagrams involving all the SM gauge bosons, this enhances these contributions

$I_W = 1$

m_* (GeV)	U^+ (fb)	U (fb)	$\bar{D}$ (fb)	$\bar{D}^-$ (fb)	$\sigma_{\rm tot}(e^+\not{p}_T jj)$ (fb)
500	7782.0	6303.0	2594.0	2679.0	19358.0
1000	1277	978	329.4	357.3	2941.7
1500	344.6	250.30	73.390	90.400	758.69
2000	107.7	74.580	23.370	28.330	233.98
2500	39.05	24.740	8.689	9.1740	81.653
3000	13.5	9.5770	4.043	2.459	29.579
3500	4.281	3.612	1.119	0.7004	9.7124
4000	1.424	1.3470	0.2401	0.2161	3.2272
4500	0.4957	0.4958	0.06098	0.06365	1.11613
5000	0.1799	0.18530	0.01819	0.0211	0.4045

$I_W = 3/2$

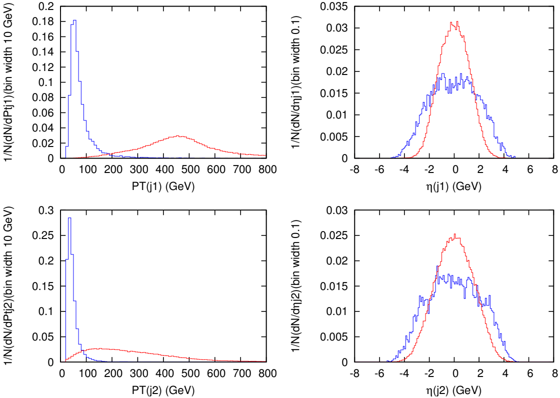
m_* (GeV)	U^+ (fb)	U (fb)	$\bar{D}$ (fb)	$\bar{D}^-$ (fb)	$\sigma_{\rm tot}(e^+\not{p}_T jj)$ (fb)
500	11080	3446.0	1506.0	477.60	16509.6
1000	2240	623.70	151.30	47.46	3062.46
1500	806.3	203.20	28.750	8.8000	1047.05
2000	343.2	82.890	6.3130	1.954	434.357
2500	159.9	40.760	1.7260	0.5253	202.911
3000	60.25	24.130	0.44890	0.15880	84.9877
3500	23.55	8.5430	0.12390	0.053250	32.2702
4000	9.347	2.0480	0.03894	0.018810	11.4527
4500	3.191	0.6354	0.01335	0.006457	3.84621
5000	1.043	0.2034	0.004864	0.002433	1.2537

Analysis structure

- Partonic processes simulation (CalcHEP)
  - $m^* \in [500, 5000]\ GeV$ with steps of 250 GeV
  - 100000 events per sample
- Study of the kinematic variables $\rightarrow$ kinematic cuts
- Simulation of detector effects (DELPHES): efficiency, resolution, geometrical acceptance etc.
- Study of the statistical significance

Kinematical cuts

- The main background is the process $pp \to Wjj \to \ell^+ \not{p}_T jj$
- We want to find kinematical cuts that can separate the signal and the backround



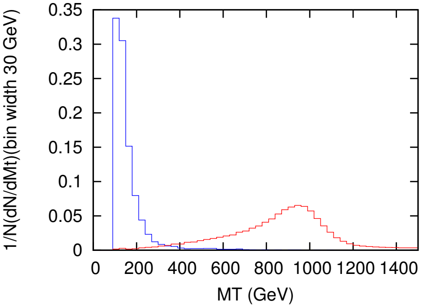
- We can separate signal and background with the cuts
  $p_T(j1) \geq 180\ GeV \qquad p_T(j2) \geq 100\ GeV$

Transverse mass

- One of the decay product of the excited quark is a neutrino
- For neutrinos it is not possible to reconstruct the longitudinal momentum
- therefore it is not possible to exactly reconstruct the excited quark mass
- we can reconstruct the transverse mass

The transverse mass is defined in terms of the reconstructed trensverse momentum of the W gauge boson ($p_{TW} = p_{T\ell} + p_{T\nu}$) and the transverse momentum of the leading jet:

$$M_T^2 = \left(\sqrt{p_{TW}^2 + M_W^2} + p_{Tj1}\right)^2 - (p_{TW} + p_{Tj1})^2$$

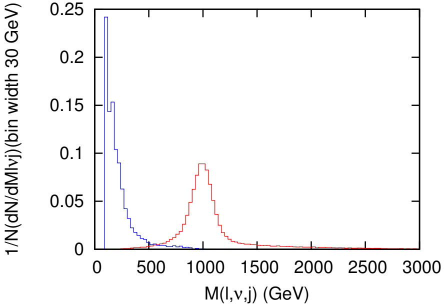


The transverse mass distribution shows a peak with a relatively sharp end-point at $M_T \approx m_*$

Excited quark reconstructed mass (with approximation)

We can still reconstruct the invariant mass of the exotic quark to some degree of accuracy

- We start from the conservation of four-momento: $M_W^2 = (p_\ell + p_\nu)^2$
- From it we obtain a second-order equation for p_L^ν
- Among the two solutions we select the one that gives the more central (smaller pseudorapidity) W
- Now we can reconstruct the invariant mass $M_{\ell\nu_\ell j_1}$



The $M_{\ell\nu_\ell j_1}$ distribution has a clear peak in correspondence of the excited quark mass

Reconstruction and selection efficiencies

Selection:

2 jets and 1 lepton with

$p_T(j1) \geq 180\ GeV$,

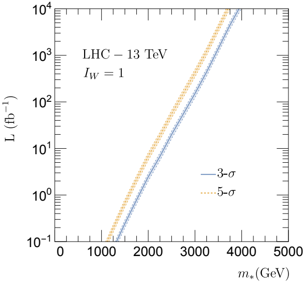
$p_T(j2) \geq 100\ GeV$

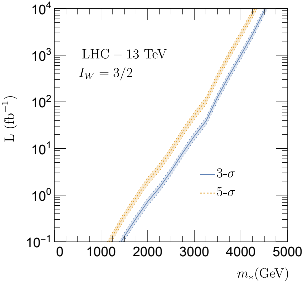
Background			
	σ_b before cut (fb)	σ_b after cut (fb)	(ϵ_b)
	8200000	14678	0.00179
Signal ($I_W = 1$)			
m_* (GeV)	σ_* before cut (fb)	σ_* after cut (fb)	(ϵ_*)
500	19358	12213.1	0.630906
1000	2941.7	2367.87	0.804931
1500	758.69	643.786	0.848549
2000	233.98	203.191	0.868412
2500	81.653	71.5896	0.876754
3000	29.579	26.1131	0.882824
3500	9.7124	8.6383	0.88941
4000	3.2272	2.87522	0.890934
4500	1.11613	0.994357	0.890897
5000	0.4045	0.362569	0.896339
Signal ($I_W = 3/2$)			
m_* (GeV)	σ_* before cut (fb)	σ_* after cut (fb)	(ϵ_*)
500	16509.6	8888.19	0.538365
1000	3062.46	2257.67	0.737208
1500	1047.05	841.233	0.803432
2000	434.357	358.925	0.826336
2500	202.911	169.963	0.837622
3000	84.9877	73.1053	0.860187
3500	32.2702	27.4566	0.850835
4000	11.4527	9.31689	0.813507
4500	3.84621	3.13297	0.814562
5000	1.2537	1.01801	0.812003

Statistical significance study

Statistical Significance: $S = \frac{N_s}{\sqrt{N_s + N_b}}$, with $N_s = L\sigma_s\epsilon_s$, $N_b = L\sigma_b\epsilon_b$

Luminosity needed to have a given S: $L = \frac{S^2}{\sigma_s\epsilon_s}\left[1 + \frac{\sigma_b\epsilon_b}{\sigma_s\epsilon_s}\right]$





	3-σ	5-σ
L (fb^{-1})	m_* (GeV)	m_* (GeV)
30	$2570 + 50 - 30$	$2330 + 40 - 30$
300	$3130 + 50 - 40$	$2890 + 60 - 40$
3000	$3630 + 50 - 40$	$3420 + 60 - 50$

	3-σ	5-σ
L (fb^{-1})	m_* (GeV)	m_* (GeV)
30	$3140 + 70 - 50$	$2820 + 50 - 40$
300	$3730 + 40 - 50$	$3450 + 50 - 50$
3000	$4260 + 30 - 50$	$4035 + 30 - 30$

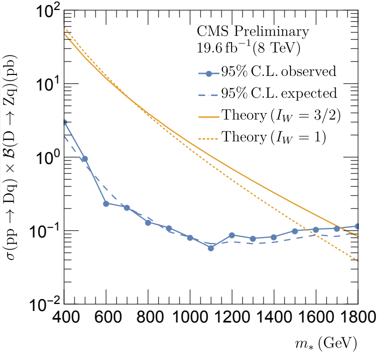
Recast of an experimental analysis

We give bounds on the excited quarks in $I_W = 1, 3/2$ multiplets by recasting results from CMS-PAS-B2G-12-016

CMS-PAS-B2G-12-016

- Search for exotic light flavour quark partners
- $\sqrt{s} = 8$ TeV
- 19.6 fb^{-1}

- We compare the observed limit on $\sigma(pp \to Dq) \times \mathcal{B}(D \to Zq)$ of the experimental analysis with the prediction of our model
- In our model this signature is produced by the states D, $\bar{D}$, U, $\bar{U}$



$I_W = 1 \to m_* > 1150$ GeV
$I_W = 3/2 \to m_* > 1710$ GeV

Conclusions

This is the first study of the production at the LHC of the excited quarks which appear in composite models with weak isospin multiplets $I_W = 1$ and $I_W = 3/2$

- Cross section for excited quarks
- Implementation of the magnetic type Gauge interactions in the CalcHEP generator
- Fast simulation of the detector reconstruction for signal and relevant background based on DELPHES
- Luminosity curves as function of m_* for S=3 and S=5
- Bound on the excited quark mass by recasting an experimental analysis

Future improvement of the study:

- The two dimensional parameter space (Λ, m_*) could be fully explored
- The effect of expected contact interaction should be taken into account