Diquark scalar production of a vectorlike quark pair at the LHC

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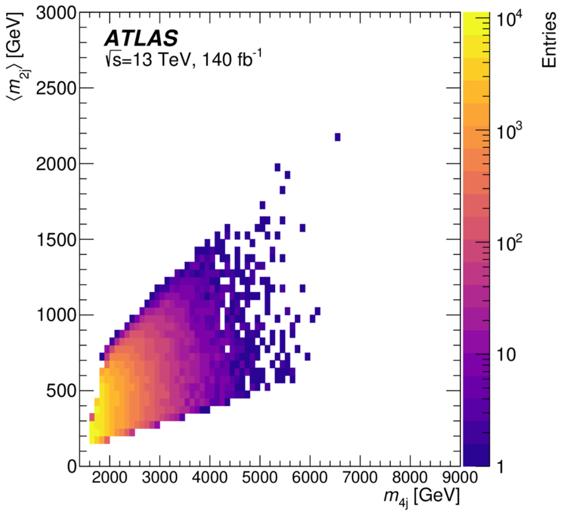
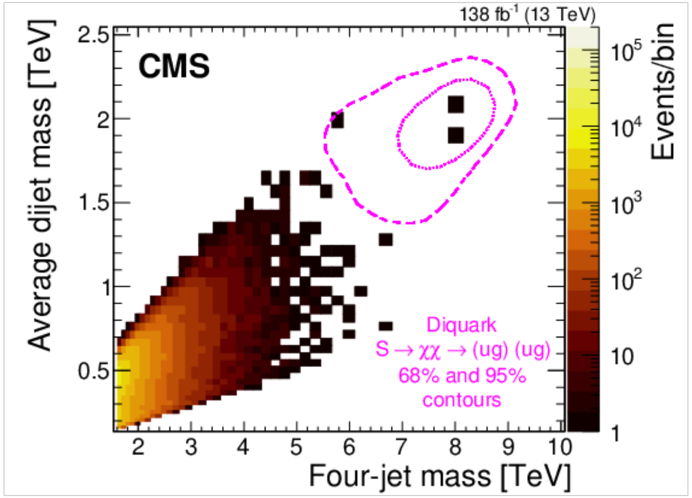
Motivation for high-mass resonances studies

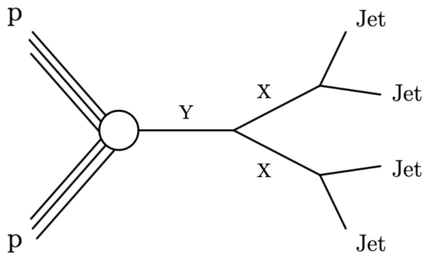
- Physics near the 10 TeV scale: composite Higgs (low mass vectorlike quarks), quarks and lepton compositeness, extended gauge symmetries, extra dimensions etc.
- Run 3 and HL-LHC increase the discovery potential for BSM physics, especially for ultraheavy particles testing the collider kinematic limitations.
- CMS: excess of events (3.9σ) with 4-jet masses around 8 TeV.

arXiv:2307.14944



arXiv:2206.09997





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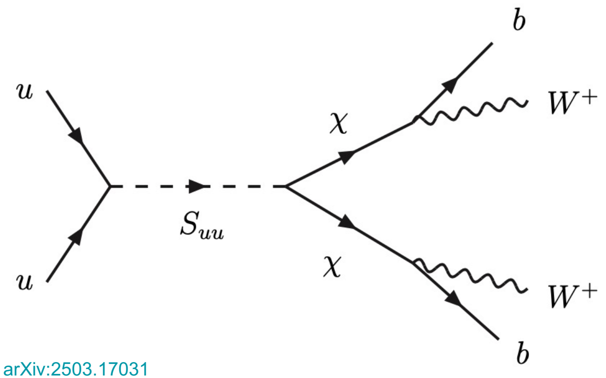
Theoretical framework

- The theoretical model (*arXiv:1810:09429*) includes two BSM particles: a diquark scalar S_{uu} with (6,1,+4/3) and vectorlike quarks χ with (3,1,+2/3).

- Diquarks are heavy particles, with masses in the TeV range, that couple to two quarks. We study the S_{uu} s-channel resonant production, with S_{uu} coupling to up quarks and VLQs.

- Parameter choices, such that the theory renormalizability is preserved:
  - $y_{uu} < 1$ and $y_{\chi\chi} < 1$
  - $m_\chi = 2$ TeV
  - $M_S \in [7, 8.5]$ TeV
  - $y_{\chi\chi}/y_{uu} = 1.5$
  - $y_{uu}BR(\chi \to W^+b) = 0.1, 0.2$ with $BR(\chi \to W^+b) = 50\%$
  - $BR(S_{uu} \to \chi\chi) \sim 63\%$



arXiv:2503.17031

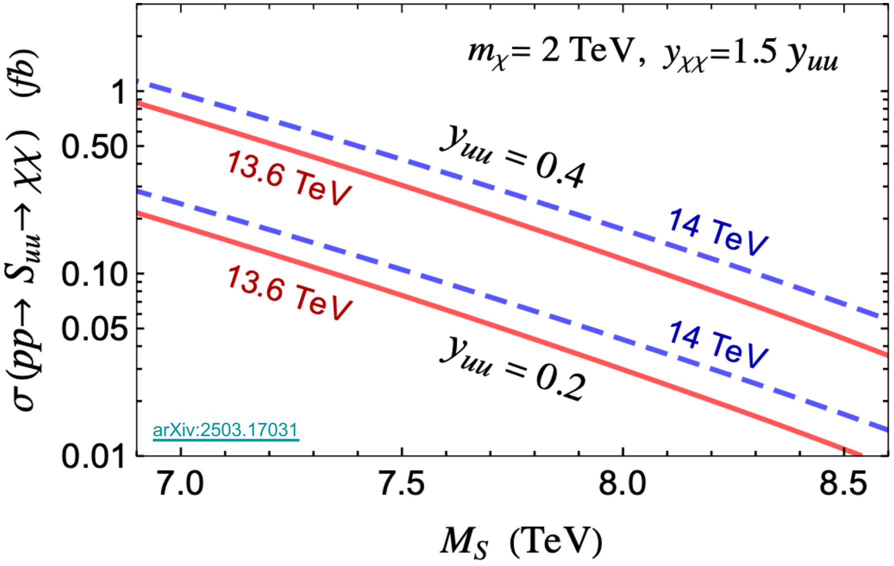
$$\frac{y_{uu}}{2} S_{uu} \overline{u}_R u_R^c + \frac{y_{\chi\chi}}{2} S_{uu} \overline{\chi}_R \chi_R^c + \text{H.c.}$$

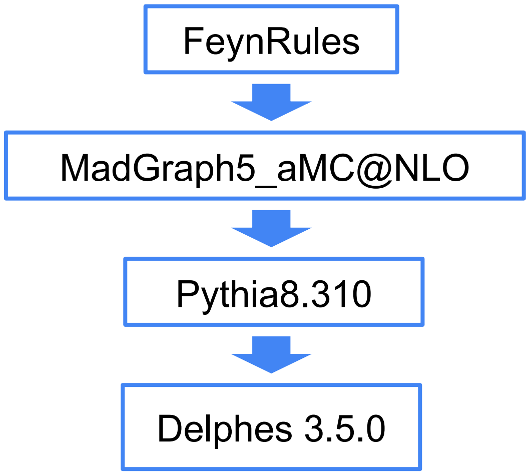
arXiv:1810:09429

Signal and background data samples

- We explore the W hadronic channel using the ATLAS detector parametrization at $\sqrt{s}$ = 13.6 and 14 TeV (6-jet final state).

- Background (32 SM processes)
    - 2→2 QCD, W+jets, Higgs processes, dibosons, ttbar etc.
    - Phase space is restricted at generation level in Pythia8 (*mHatMin* ∈ [5.5, 8] TeV).





Data analysis

- Signal and background events are classified using a machine learning Random Forest (RF) algorithm.

- A multidimensional discriminator (D) is built by RF using 75 input variables: jet kinematics ($p_T^{(i)}$, $\eta^{(i)}$, $\phi^{(i)}$), dijet angular distance, jet multiplicity, 2-jet and 3-jet invariant masses etc.

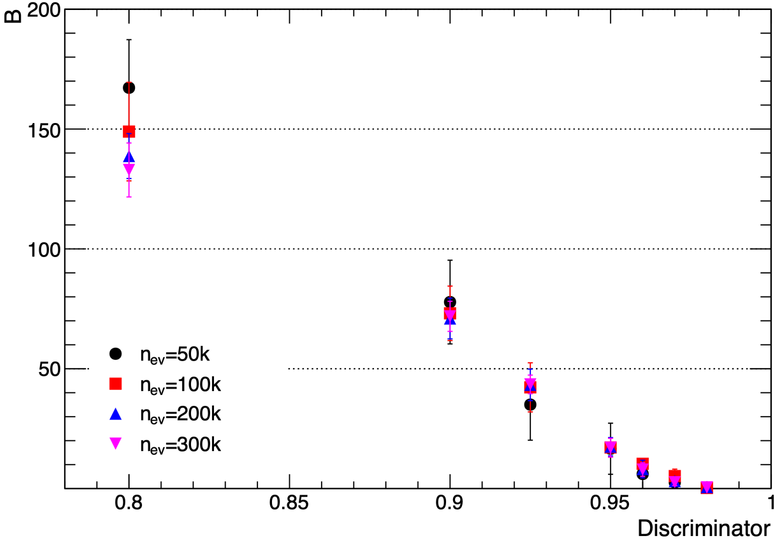
- Each event is assigned a probability score ($P = [0,1]$). If $P>D$, then the event is classified as signal. However, if $P \leq D$ events are classified as background.

- A wide range of discriminator values is considered, with $D \in [0.2, 0.99]$.

- K-fold cross validation method is used to assess model performance.

Signal selection study (I)

- Number of signal events (S_{ev}) and background events (B_{ev}) are obtained at $\sqrt{s} = 13.6$, 14 TeV for $\mathcal{L} = 3000$ fb^{-1}, M_S= 7.5 TeV and $\hat{m}_{min}$= 6 TeV.
- RF method uncertainties for S_{ev} are below 0.1%.
- We explore the algorithm performance dependency on sample size.

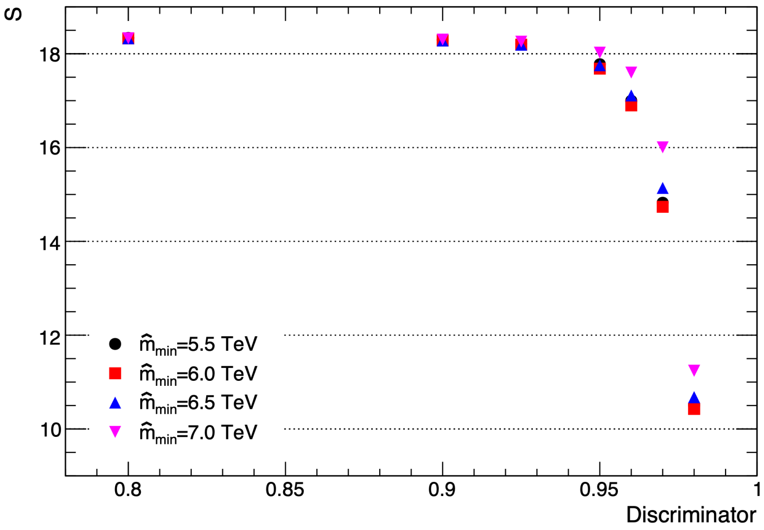


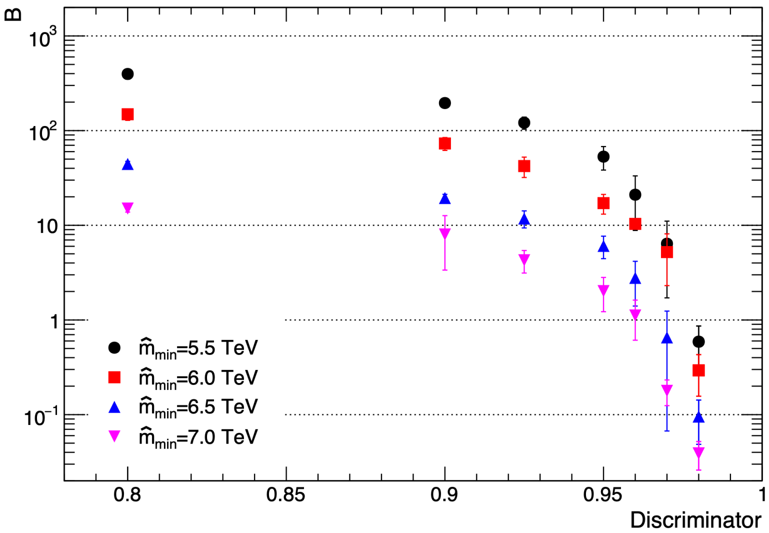
	$D = 0.80$	$D = 0.90$	$D = 0.95$	$D = 0.96$	$D = 0.97$
			$\sqrt{s} = 13.6$ TeV		
S_{ev}	18.3	18.3	17.7	16.9	14.7
B_{ev}	149±21	73.1±11.4	17.2±4.0	10.4±0.6	5.2±2.9
			$\sqrt{s} = 14$ TeV		
S_{ev}	25.3	25.3	24.4	23.3	20.3
B_{ev}	209±9	113±5	21.8±7.2	14.7±6.8	3.1±2.4

Signal selection study (II)

- S_{ev} and B_{ev} dependency on $\widehat{m}_{min}$ for $\sqrt{s} = 13.6$ TeV and M_S= 7.5 TeV.

- The best results are obtained for the highest phase space cut (smaller cross-sections).





Ultraheavy diquark scalar discovery potential

- The number of signal events (S_{ev}) for $y_{uu}BR(\chi \to W^+ b)$ = 0.1, 0.2 and the number of background events (B_{ev}) obtained for 4 diquark masses.

- Poisson statistics is used to compute the probability of the SM to have such a large fluctuation.

$$P(n|B_{ev}) = \frac{e^{-B_{ev}} {B_{ev}}^n}{n!}$$

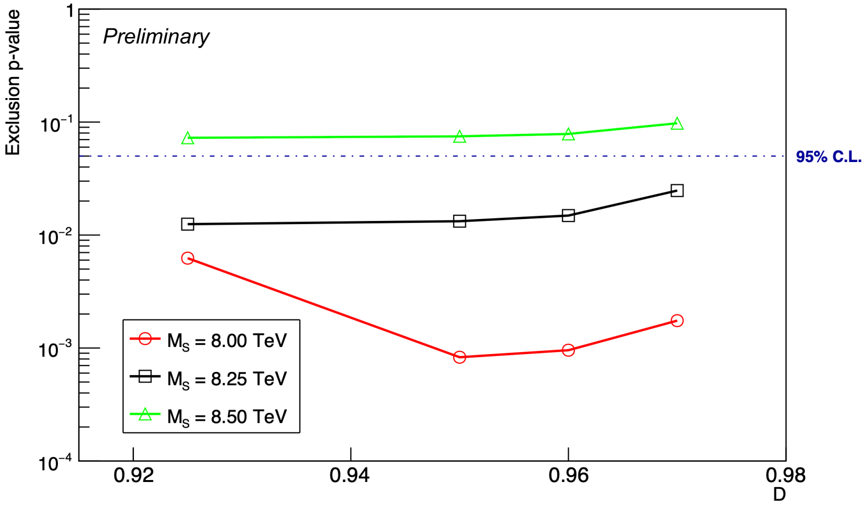
- For M_S = 8 TeV and D = 0.96, with $n = S_{ev} + B_{ev}$, n ≈ 7 expected events, we get $1.1 \cdot 10^{-7}$ p-value, corresponding to a significance of ~5σ and can be considered a discovery.

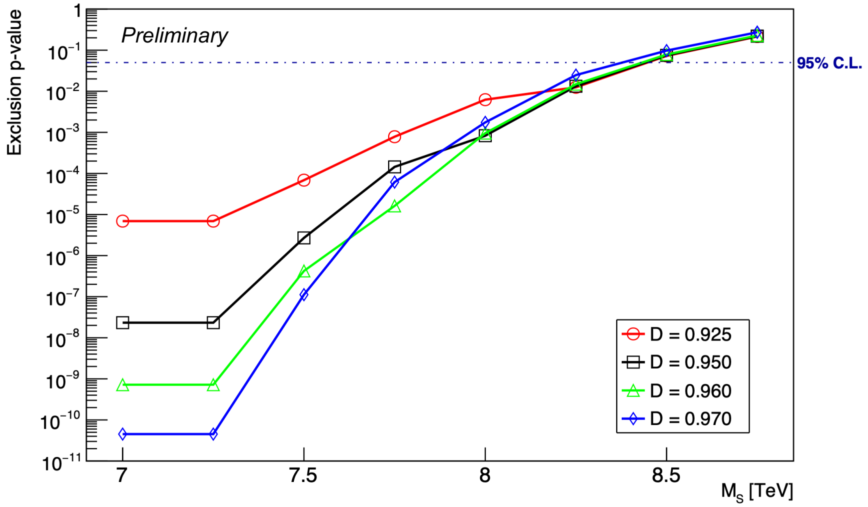
	$D = 0.80$	$D = 0.90$	$D = 0.95$	$D = 0.96$	$D = 0.97$
	$M_S = 7.0$ TeV				
$S_{ev}(0.1)$	43.9	43.8	43.0	41.9	37.9
$S_{ev}(0.2)$	197	196	193	188	170
B_{ev}	42.4	17.9	5.05	3.96	0.79
	$M_S = 7.5$ TeV				
$S_{ev}(0.1)$	18.3	18.3	18.0	17.6	16.0
$S_{ev}(0.2)$	81.9	81.8	80.5	78.6	71.5
B_{ev}	15.0	8.00	2.03	1.12	0.18
	$M_S = 8.0$ TeV				
$S_{ev}(0.1)$	7.20	7.20	7.10	6.95	6.35
$S_{ev}(0.2)$	32.4	32.4	31.9	31.3	28.5
B_{ev}	5.34	5.34	0.67	0.36	0.09
	$M_S = 8.5$ TeV				
$S_{ev}(0.1)$	2.63	2.63	2.59	2.54	2.33
$S_{ev}(0.2)$	11.8	11.8	11.6	11.4	10.5
B_{ev}	1.72	1.72	0.17	0.09	0.02

Ultraheavy diquark scalar exclusion limit

- The exclusion p-values dependency on discriminator and diquark scalar mass.

- The 95% CL is reached for $M_S \leq 8.25$ TeV and $D \in [0.925, 0.97]$.
- For $M_S > 8.25$ TeV, cross-sections are significantly smaller. This theoretical model does not exclude $M_S < 8.25$ TeV diquark scalars.



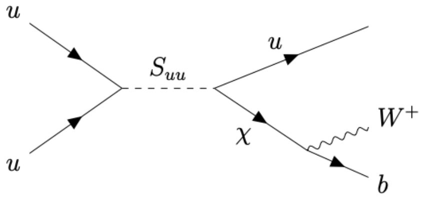


Preliminary results in the (uχ) channel

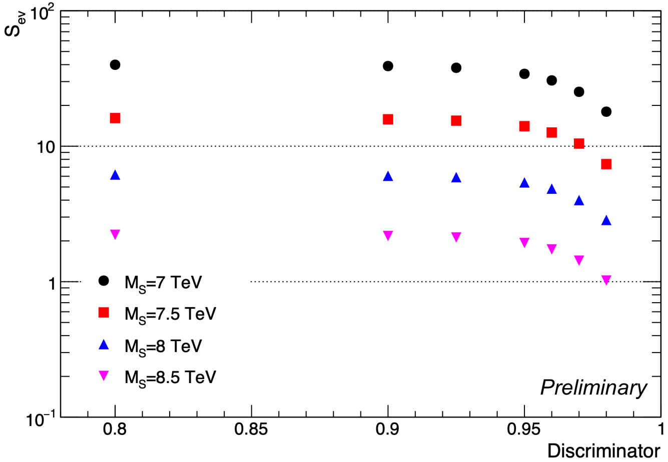
- This theoretical framework also allows for a $S_{uu} \rightarrow u\chi$ decay (~14% BR), which may increase the sensitivity of S_{uu} searches.

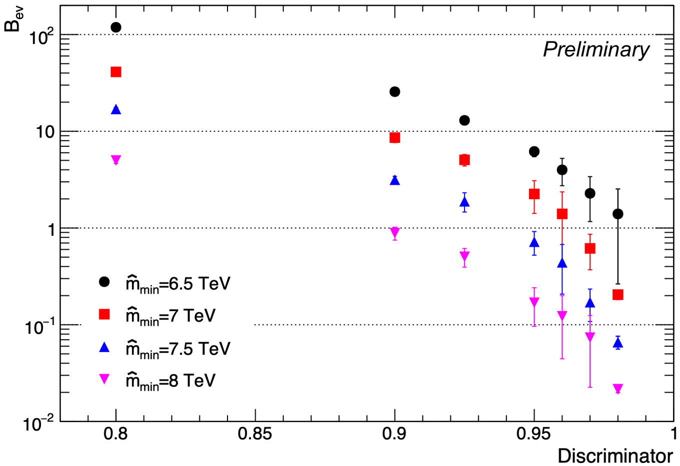
$$\Gamma(S_{uu} \rightarrow u\chi) = \frac{M_S}{16\pi} |y_{u\chi}|^2 \left(1 - \frac{{m_\chi}^2}{{M_S}^2}\right)^2$$

https://arxiv.org/pdf/1912.13155



- For M_S = 8 TeV and D = 0.96, with ~5.4 expected events, we get $8.9 \cdot 10^{-5}$ p-value with a corresponding significance of ~4σ – *promising preliminary result*.





Conclusions

- We explored the observation potential of an ultraheavy diquark scalar S_{uu} (with 7 to 8.5 TeV mass) at the LHC experiments. We analysed a more standard decay of $\chi \rightarrow (W^{+}b)$ which leads to a 6-jet final state.

- A Random Forest algorithm is employed in the signal selection study of the process $pp \rightarrow S_{uu} \rightarrow \chi\chi \rightarrow (W^{+}b)(W^{+}b) \rightarrow (jjb)(jjb)$.

- Our study indicates that for this 6-jet channel, with a 3000 fb^{-1} LHC integrated luminosity, ATLAS and/or CMS searches may discover or rule out a diquark scalar of mass near 8 TeV.

- The sensitivity of this study may be improved by looking into other diquark scalar decays ($S_{uu} \rightarrow u\chi$) or even other vectorlike quarks decay modes (Zt, $h^{0}t$).