Ultraheavy resonances and vectorlike fermions

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- **Exotic decays of vectorlike quarks** *(with Felix Yu, 1612.01909)*
- **Ultraheavy resonances** *(with Robert Harris, Joshua Isaacson, 1810.09429)*
- **Cascade decays of a leptophobic Z'** *(1506.04435)*

November 13, 2018 – talk at the LPC workshop on "Boosted objects for new physics searches"

Exotic decays of vectorlike quarks

with Felix Yu, 1612.01909

A vectorlike quark χ that transforms as (3,1,+2/3) under $SU(3)_c \times SU(2)_W \times U(1)_Y$ would mix with the SM top quark.

Mass eigenstates: t and t'. Mixing $\sin\theta_L \equiv s_L$.

'Standard' widths of t':

$$\Gamma(t' \to W^+ b) = \frac{s_L^2\, m_{t'}^3}{32\pi v_H^2}\left[1 + O\left(\frac{M_W^4}{m_{t'}^4}\right)\right]$$

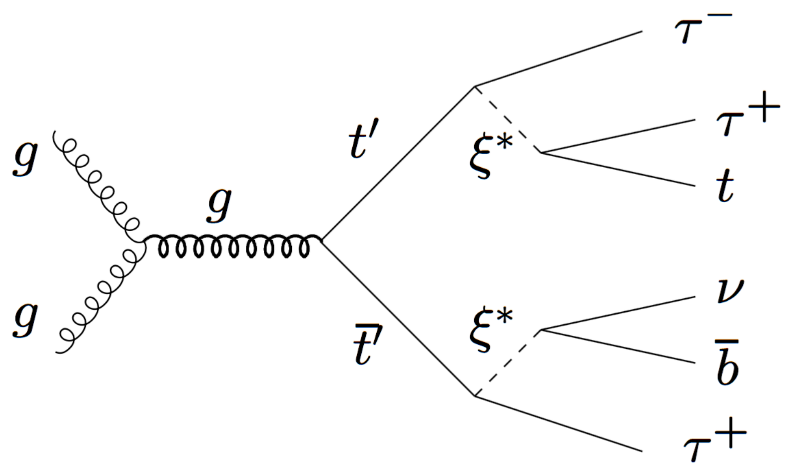
$$\Gamma(t' \to Zt) \approx \Gamma(t' \to ht) = \frac{s_L^2 c_L^2\, m_{t'}^3}{64\pi v_H^2}\left[1 + O\left(\frac{m_t^2}{m_{t'}^2}\right)\right]$$

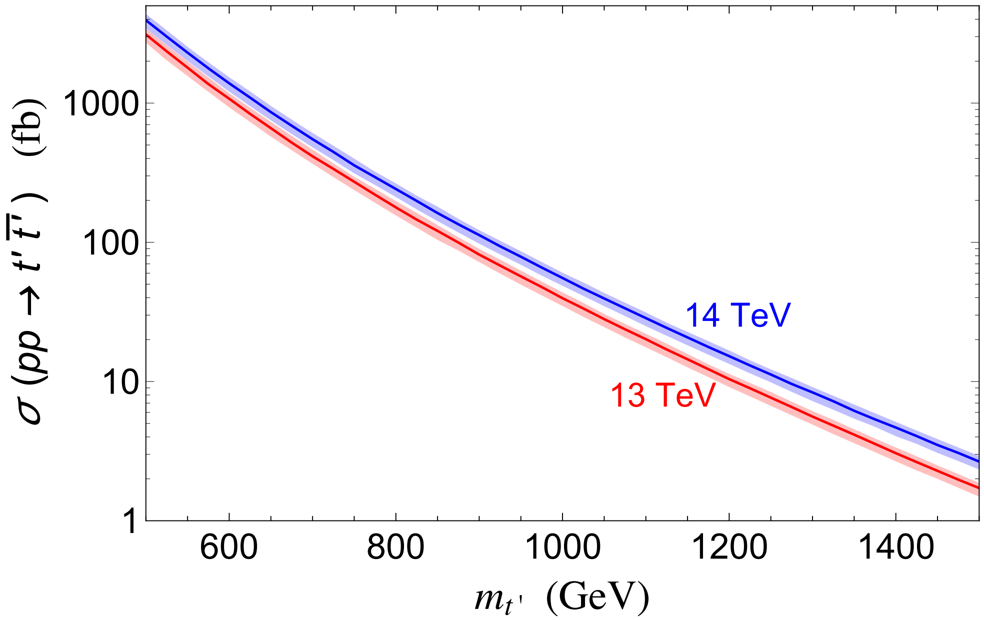
For $s_L \ll 1$, exotic decays of vectorlike quarks could dominate!

E.g., **4-fermion operator** $(\overline{\chi}_R l_L^3) i\sigma_2 (\overline{\tau}_R q_L^3) \;\Rightarrow\; t' \to \tau^+\tau^- t \;,\; \tau^+\nu b$

Example of UV completion: scalar leptoquark ξ heavier than t'.

$m_{t'} \gg m_t$: t-tagged jet $+ \; 3\tau \; + \; b\nu$





More LHC signatures: $t\bar{t} + 4\tau$, $t\bar{t}\tau^+\tau^-\nu\nu$, $tb\tau + 3\nu$ or $t\bar{t} + 4\nu$.

Other 4-fermion operators, *e.g.,* $\dfrac{\kappa_\chi \kappa_t}{M_\zeta^2}(\overline{\chi}^c_R b_R)(\bar{b}_R t^c_R)$

lead to a final state with: two t-tagged jets $+4b$.

Scalar diquark particle

with Robert Harris, Joshua Isaacson, 1810.09429

Spin-0 particle S_{uu} that couples to two up quarks:

$$\frac{y_{uu}}{2}\, S_{uu}\, u_R\, u_R$$

Large production rate because the u PDF is the largest one.

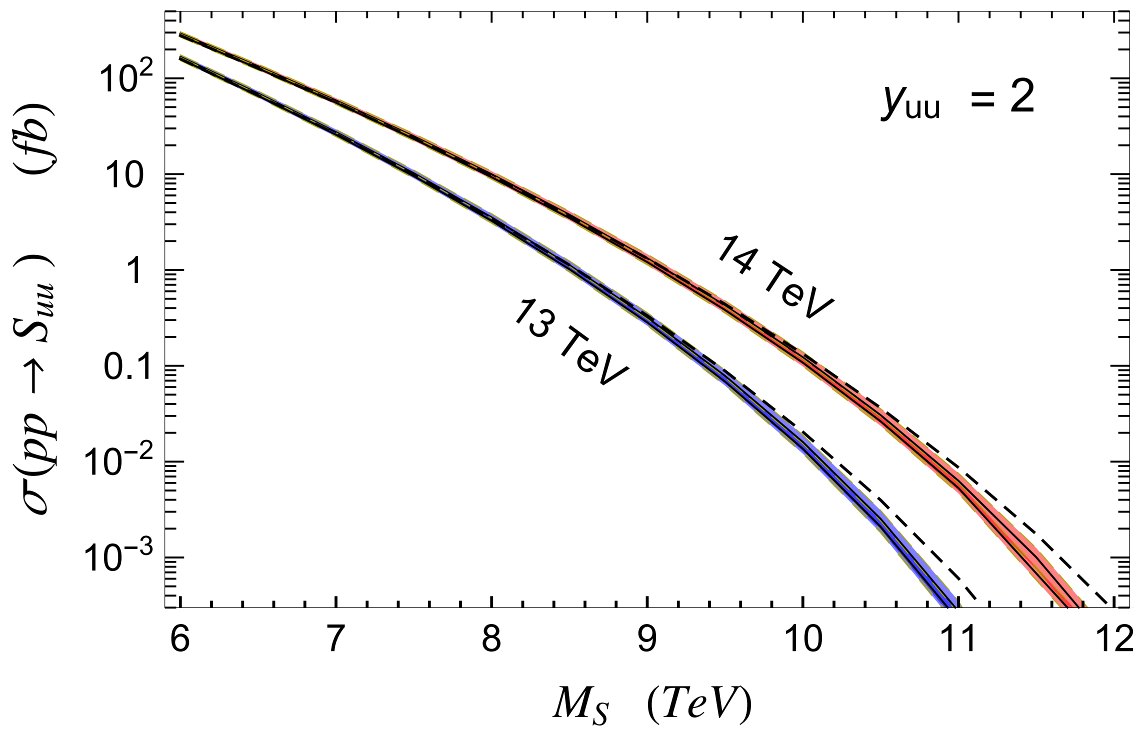
The scalar decays into two jets:

$$\Gamma_S(S_{uu} \to u\, u) = \frac{y_{uu}^2}{32\pi}\, M_S$$

Narrow resonance: $\Gamma/M_S < 4\%$ for $y_{uu} \leq 2$.

$$\sigma(pp \to S_{uu}) = \frac{\pi}{6\,s}\, y_{uu}^2 \int_{M_S^2/s}^{1} \frac{dx}{x}\, u\Big(x, M_S^2\Big)\; u\Big(M_S^2/(sx), M_S^2\Big)$$

NLO: T. Han, I. Lewis, T. McElmurry, 0909.2666



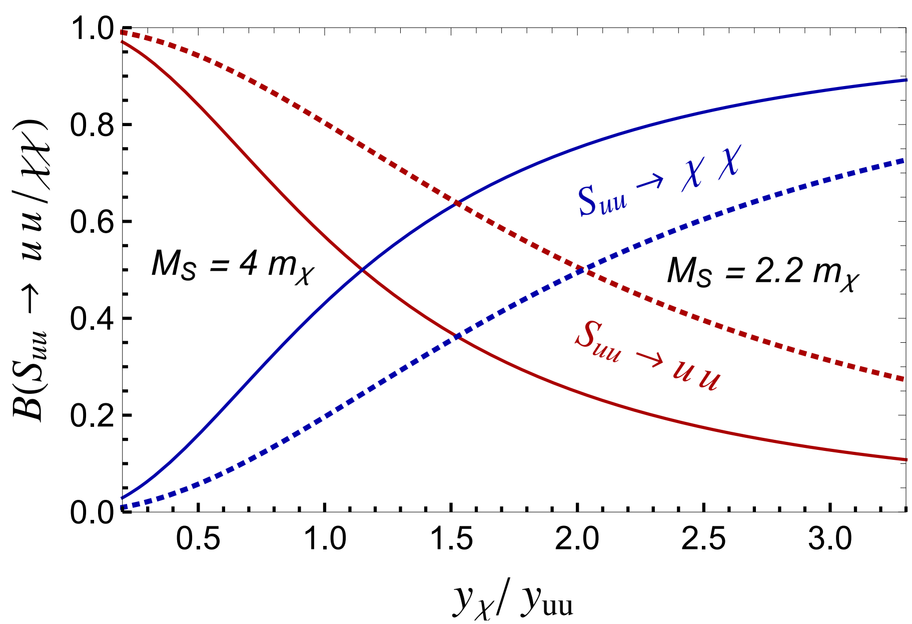
The QCD jj background is smaller by an order of magnitude.

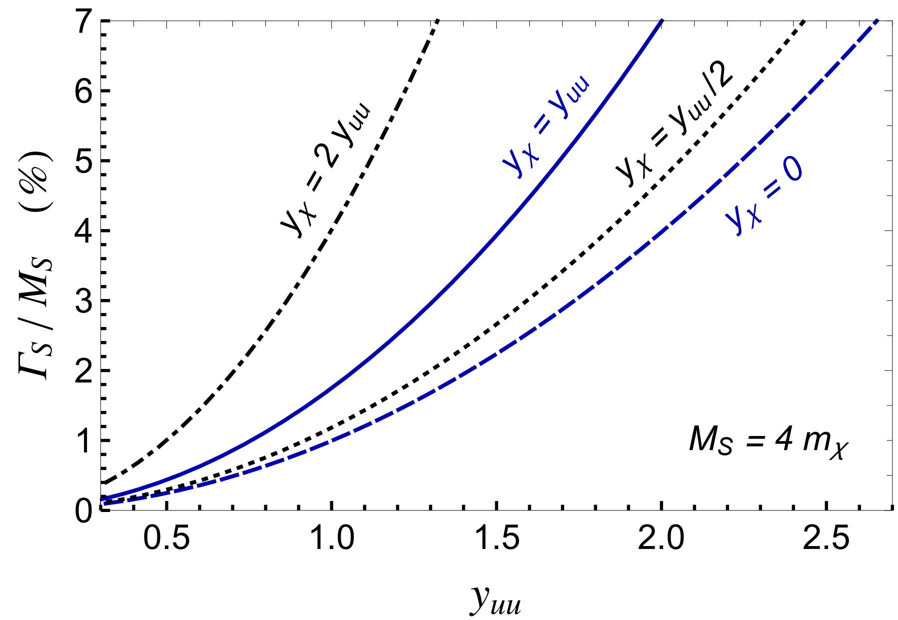
With 3000 fb^{-1}, an S_{uu} as heavy as 11.5 TeV may be discovered!

Scalar diquark plus vectorlike quark

S_{uu} **coupling to a vectorlike quark** χ**:**

$$\frac{1}{2}\, K^n_{ij}\, S^n_{uu}\, \left(y_{\chi_R}\, \overline{\chi}_{R\,i}\, \chi^c_{R\,j} + y_{\chi_L} e^{i\beta_\chi}\, \overline{\chi}_{L\,i}\, \chi^c_{L\,j} \right)$$





$\Rightarrow$ S_{uu} **may be a narrow ultraheavy resonance.**

If χ has "standard" decays:

$pp \to S_{uu} \to \chi\chi \to (Wb)(h^0 t) \to$ **3-prong jet + 5-prong jet**

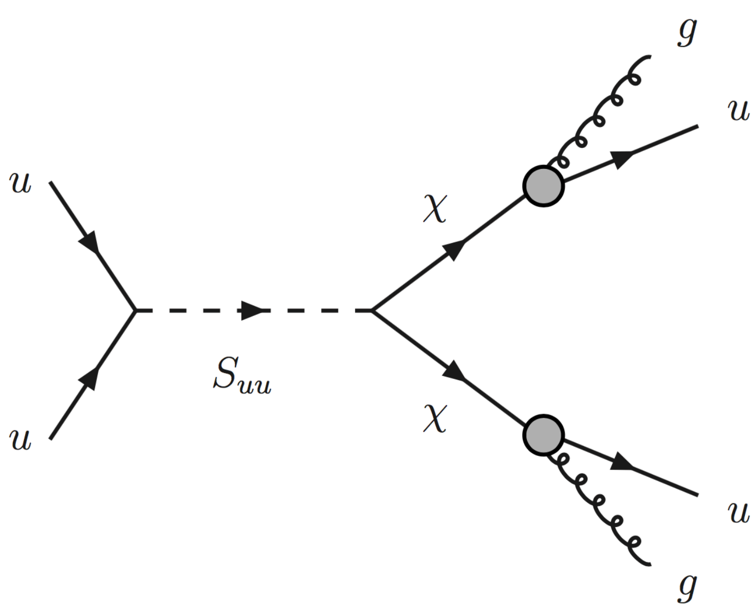
$(Wb)(Wb) \to$ **two 3-prong jets**

...

If χ has exotic decays $\to$ various final states

E.g., χ **decay into a quark and a gluon via a dimension-5 operator:**

$$\frac{C_g}{M_\star} \left(\overline{u}_R \gamma^\mu \gamma^\nu T^a \chi_L\right) G^a_{\mu\nu}$$

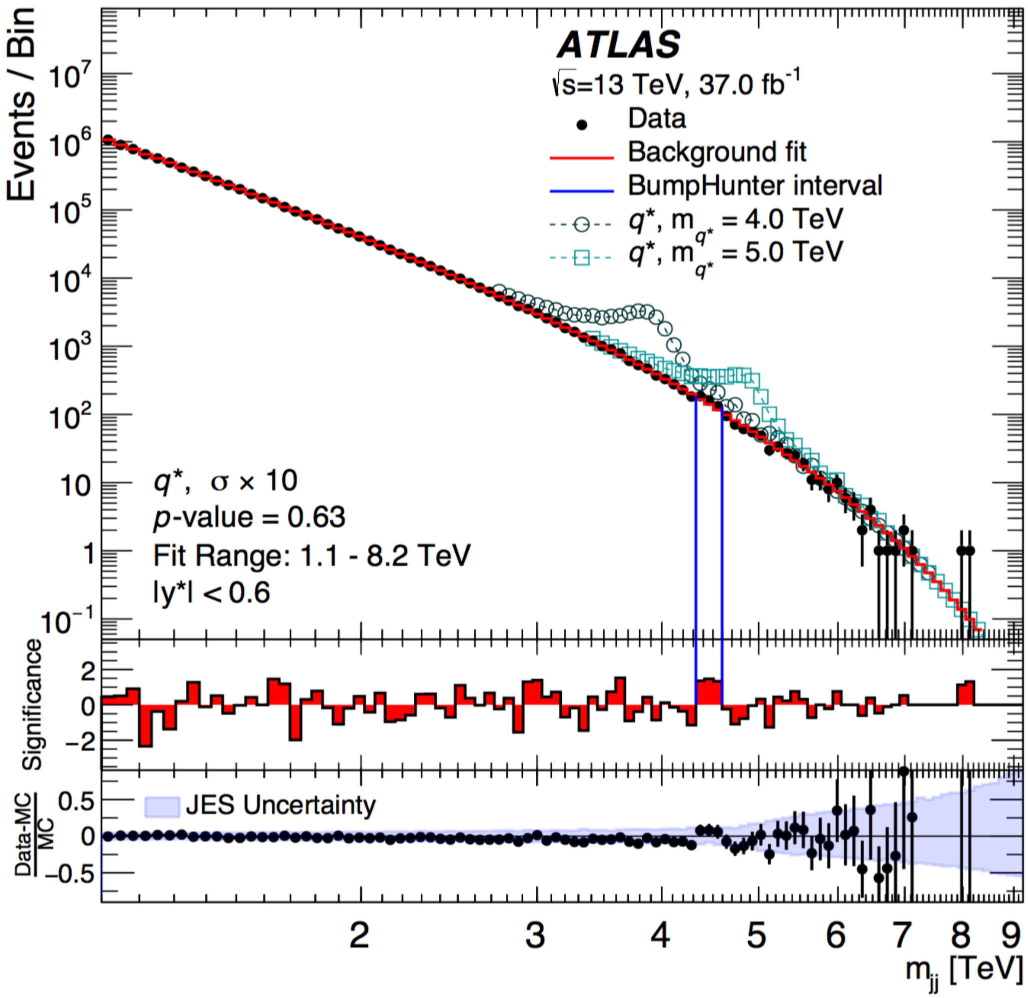


For $m_\chi \ll M_S$:

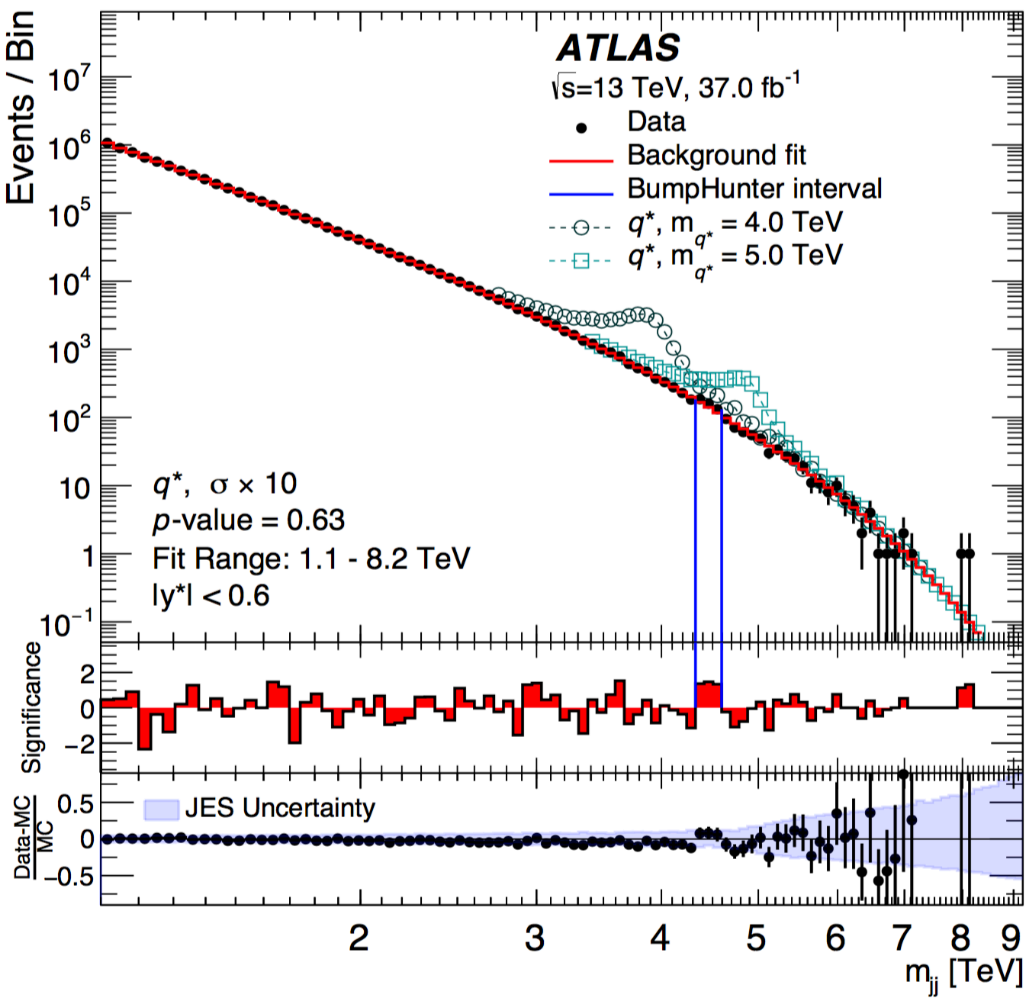
two wide jets, each with

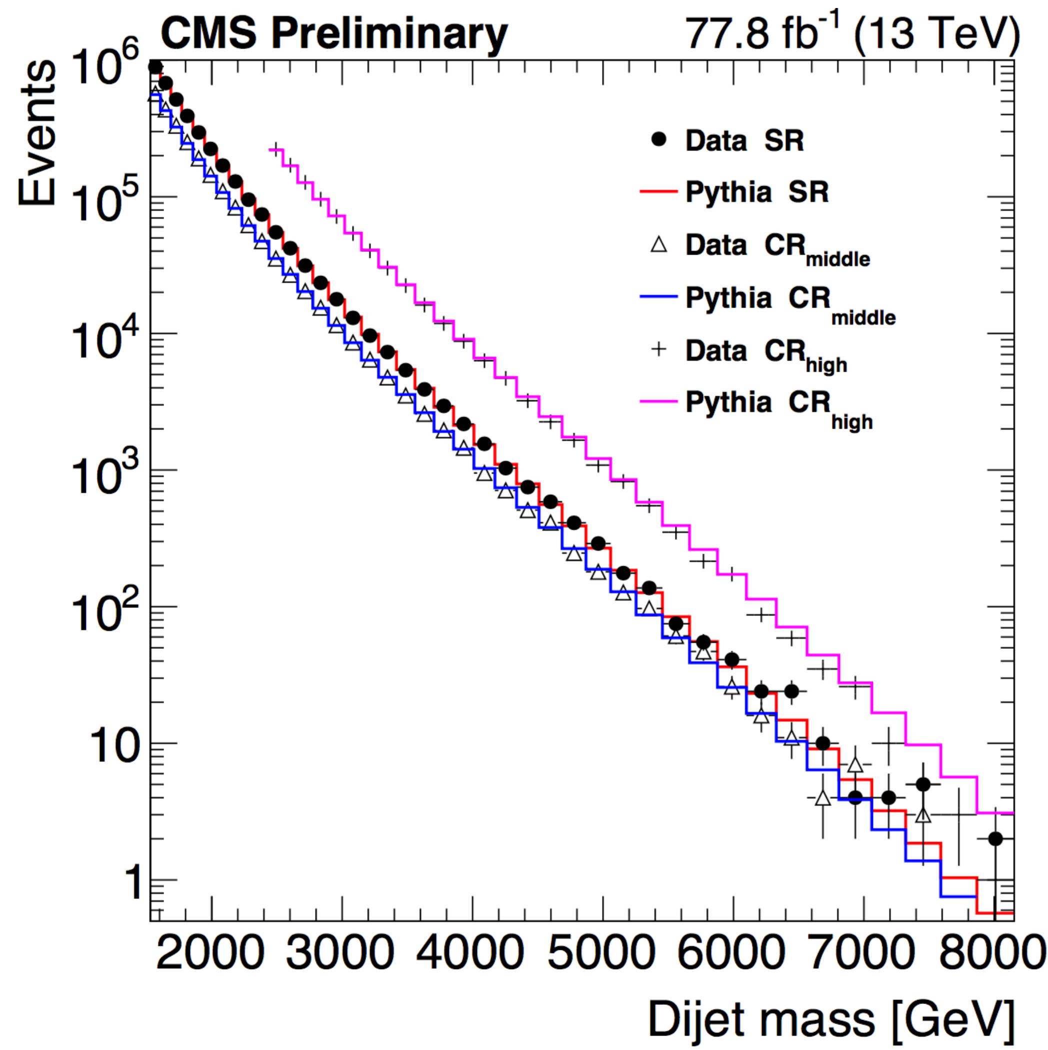
2-prong substructure.

Dijet resonance searches:



Dijet resonance searches:

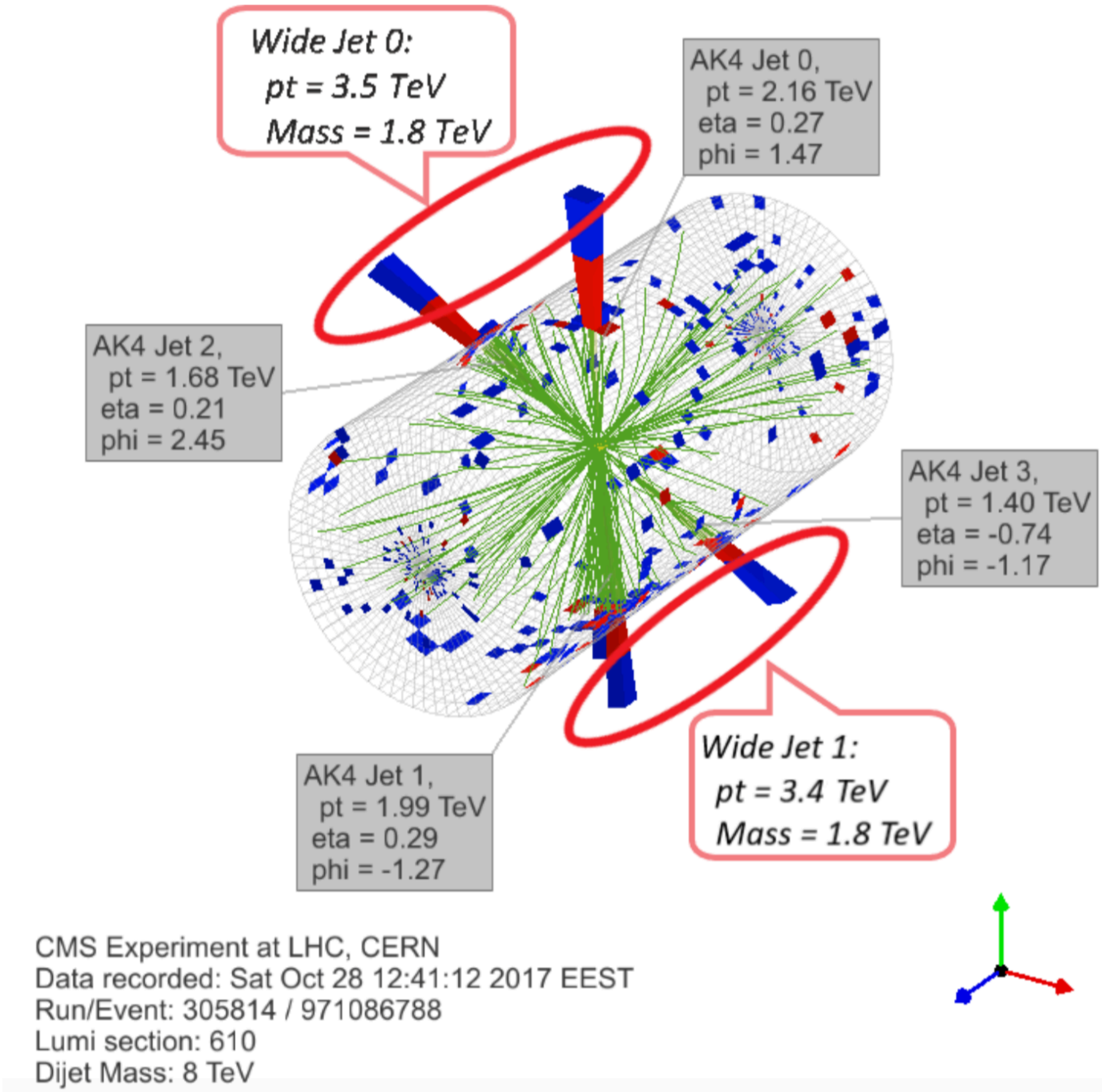




4 dijet events in the mass range 7.9–8.1 TeV.

Background ≈ 1.6 events in the 7.7–8.3 TeV range

One of the “dijet” events,
with $m = 8$ TeV, is peculiar:



CMS-PAS-EXO-17-026

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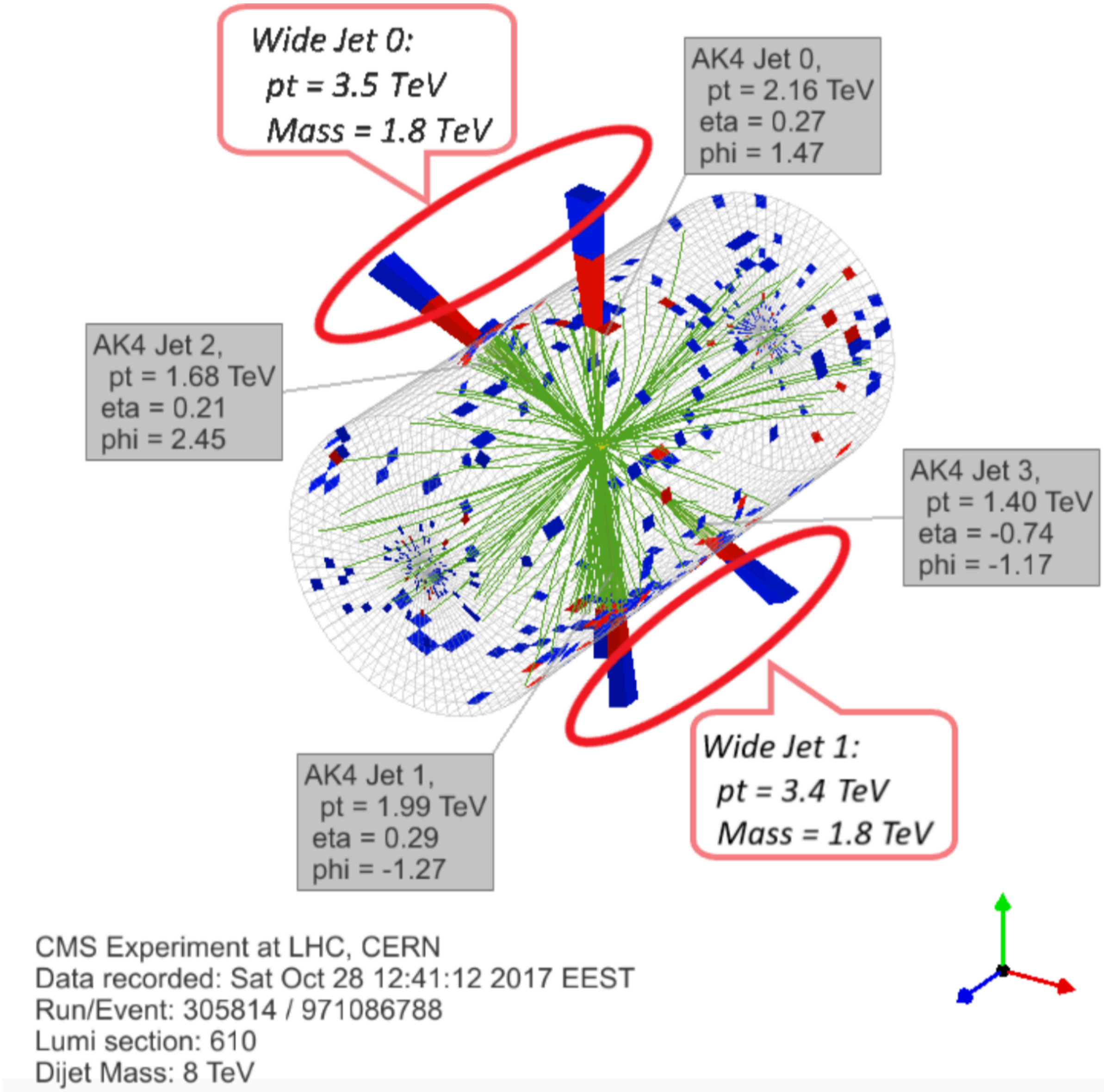
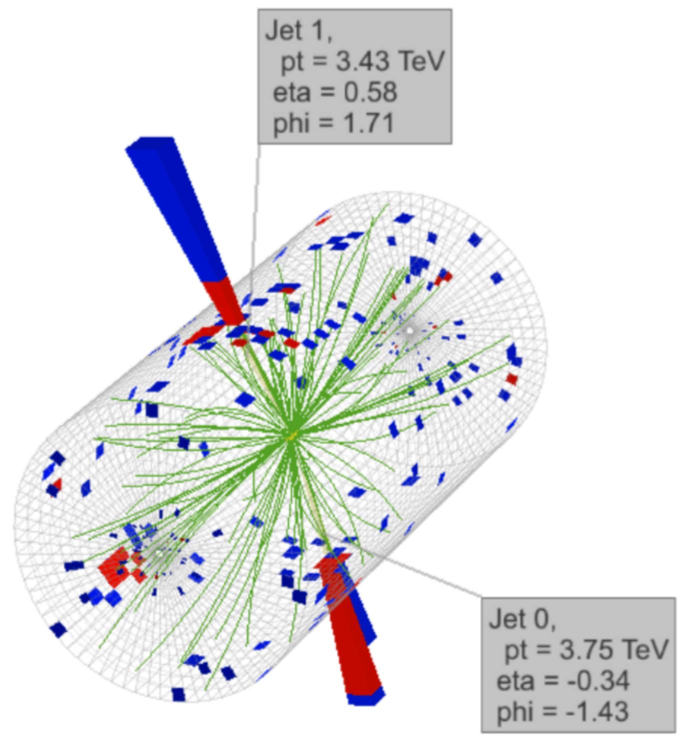
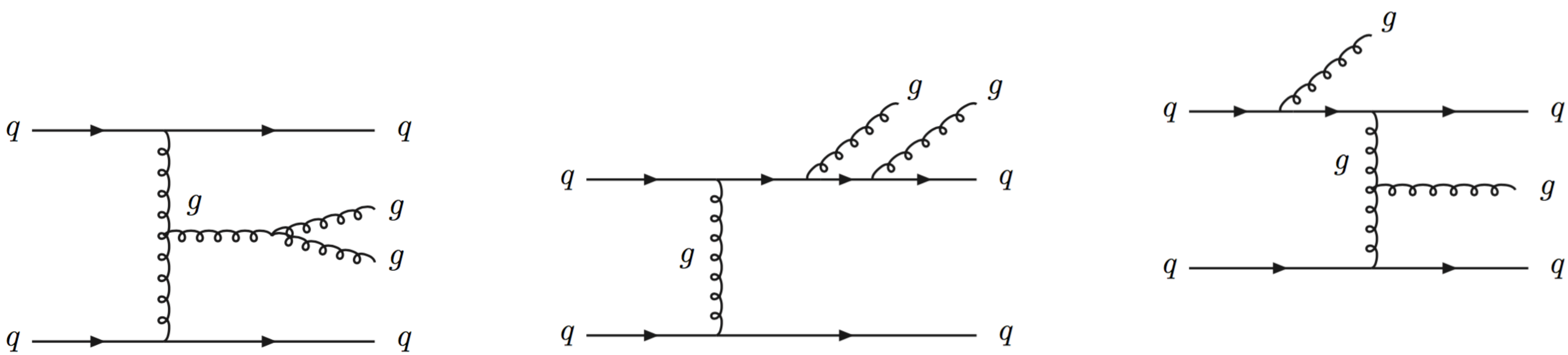


CMS-PAS-EXO-17-026

The other CMS event, with $m = 7.9$ TeV, is a clean dijet event:



QCD can produce high mass 4-jet events:



Cuts: $m_{4j} \geq 8$ TeV, $m_{J1} \geq 1.8$ TeV, $m_{J2} \geq 1.8$ TeV.

QCD prediction (computed with MadGraph at LO):

4.5×10^{-5} events expected in 77.8 fb^{-1}.

Probability that the 8 TeV 4-jet event is due to QCD:

$$\mathbf{4.5 \times 10^{-5}}$$

(B. Dobrescu, R. Harris, J. Isaacson, 1810.09429)

Look-elsewhere effect is large and hard to estimate.
For future 8 TeV events, though, there is no more LEE.

Poisson statistics

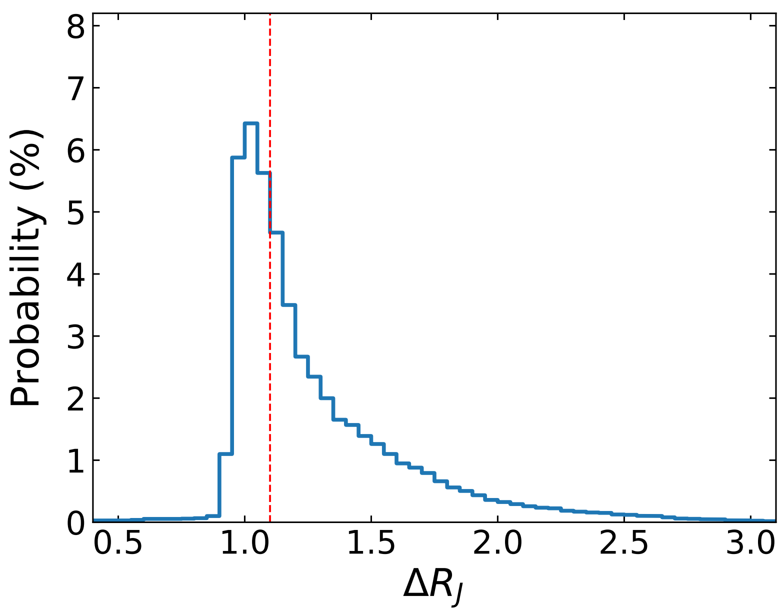
SM probability of $\left\{ \begin{array}{l} \textbf{2 events} \\ \textbf{3 events} \\ \quad \ldots \end{array} \right.$ **in 300 fb**$^{-1}$**:** $\left\{ \begin{array}{l} \mathbf{1.5 \times 10^{-8}} \\ \mathbf{8.7 \times 10^{-13}} \\ \quad \ldots \end{array} \right.$

This is a case where sensitivity grows much faster than $\sqrt{\mathcal{L}}$.

In principle, a discovery could be made with slightly more data.

$pp \to S_{uu} \to \chi\chi \to (ug)(ug)$ signal, with $M_S = 8$ TeV and $m_\chi = 1.8$ TeV.

ΔR_J distribution *(separation of the AK4 jets within the wide jets):*



Acceptance can be improved by an order of magnitude: remove the $\Delta R_J < 1.1$ and $\Delta\eta_{JJ} < 1.1$ cuts.

Constraint from the CMS search for a pair of dijets with 35.9 fb^{-1} (no events of dijet mass > 1.6 TeV)

Example of coupling values in the uu diquark + vectorlike quark model:

$$y_{uu} = 0.3 \;,\; y_{\chi_R} = 0.5 \;,\; y_{\chi_L} = 0 \;\longrightarrow\; \sigma(pp \to S_{uu}) \approx 8.0 \times 10^{-2} \text{ fb}$$

$$B(S_{uu} \to \chi\chi) \approx 69\%$$

Expected number of signal 4-jet events:

$N_{4j}^{\rm exp} \approx 0.34$ **in the CMS dijet search** *(observed: 1)*

$N_{2\times 2j}^{\rm exp} \approx 0.79$ **in the CMS pair of dijets search** *(observed: 0)*

Expected number of signal jj events in the CMS+ATLAS searches:

$N_{jj}^{\rm exp} \approx 1.4$ *(observed: 3 ; background ∼1.6)*

New gauge bosons

Spin-1 fields are well behaved in the UV provided that they are bound states (not discussed here) or gauge bosons.

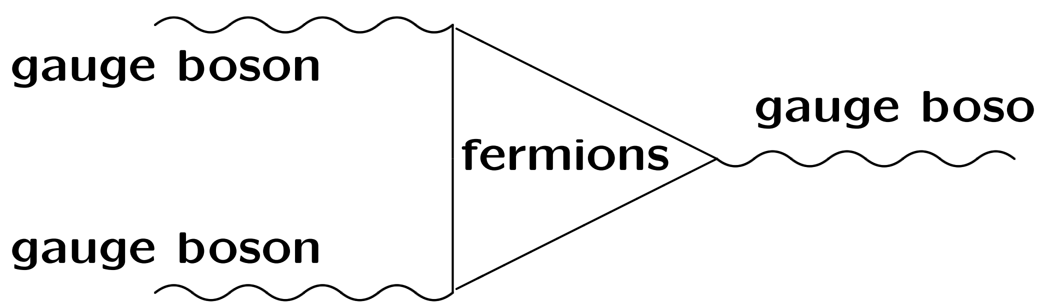
New gauge bosons (Z', W', G', ...) require more particles:

- **The new gauge symmetry must be spontaneously broken.**

  Simple choice: a new scalar field ϕ acquires a VEV.

- **All gauge anomalies must cancel**

$\Rightarrow$ *there must be new fermions ("anomalons"), which are vectorlike with respect to $SU(3)_c \times SU(2)_W \times U(1)_Y$, and chiral with respect to the new gauge group, with charges such that the sums over fermion triangle diagrams vanish.*



Flavor-universal leptophobic Z'

New fields carrying $U(1)_B$ charge in a minimal model:

B.A. Dobrescu, C. Frugiuele, 1404.3947

field	spin	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_B$
L_L L_R	1/2	1	2	$-1/2$	-1 $+2$
E_L E_R	1/2	1	1	-1	$+2$ -1
N_L N_R	1/2	1	1	0	$+2$ -1
ϕ	0	1	1	0	$+3$

There are two charged "anomalons", E and L^e, which can mix, and two neutral anomalons, N and L^ν, which can also mix.

$$\mathcal{L}_{N\text{mass}} = -\left(\overline{N}_R\,,\,\overline{L}_R^{\nu}\right)\begin{pmatrix} y_N\,\langle\phi\rangle & y_{NL}\,v_H \\ y_{LN}e^{i\theta_N}\,v_H & y_L\,\langle\phi\rangle \end{pmatrix}\begin{pmatrix} N_L \\ L_L^{\nu} \end{pmatrix} + \text{H.c.}$$

Left-handed neutral anomalons in the mass eigenstate basis:

$$\begin{pmatrix} N_{S_L} \\ N_{D_L} \end{pmatrix} = \begin{pmatrix} c_N & -s_N \\ s_N & c_N \end{pmatrix}\begin{pmatrix} N_L \\ L_L^{\nu} \end{pmatrix}$$

Small mass splitting between the charged and neutral physical states that are mostly part of the weak-doublet anomalon:

The decays of the anomalons depend on their mass ordering. (1506.04435)

$U(1)_B$ symmetry is spontaneously broken down to Z_3.

The anomalons have Z_3 charge $+1$

$\Rightarrow$ lightest anomalon is stable (in the minimal model), can be a DM component if it is N_S.

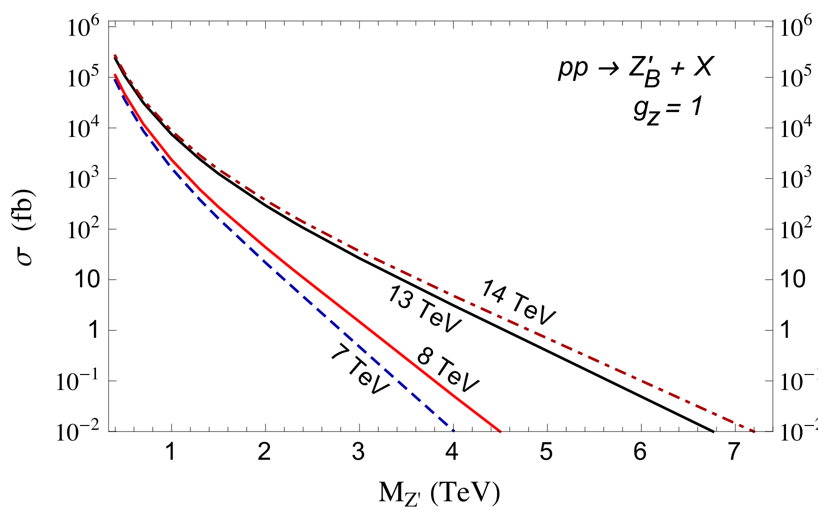
If $m_{E_S} > m_{E_D} \approx m_{N_D} > m_{N_S}$:

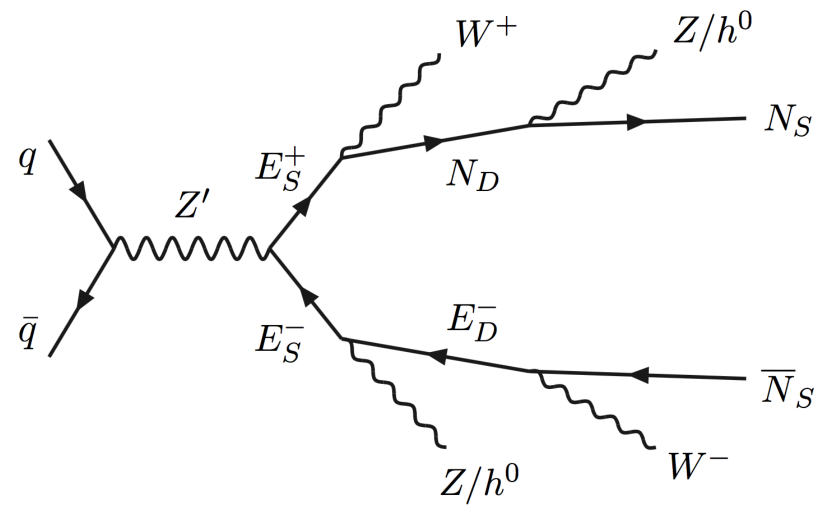
E_S decays into $N_D W$, $E_D\, Z$ or $E_D\, h^0$ ($N_S W$ has small BR)

E_D decays mostly into $N_S W$

N_D decays into $N_S\, h^0$ or $N_S\, Z$ (equal BR's for $m_{N_D} - m_{N_S} \gg M_h$)

Cascade decays via anomalons:
(1506.04435)

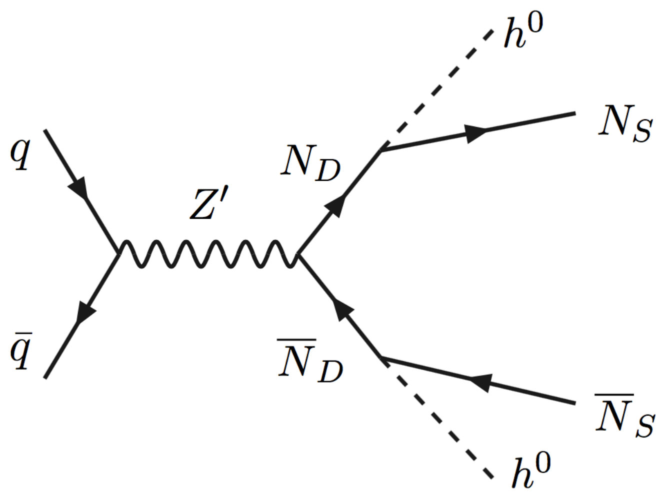




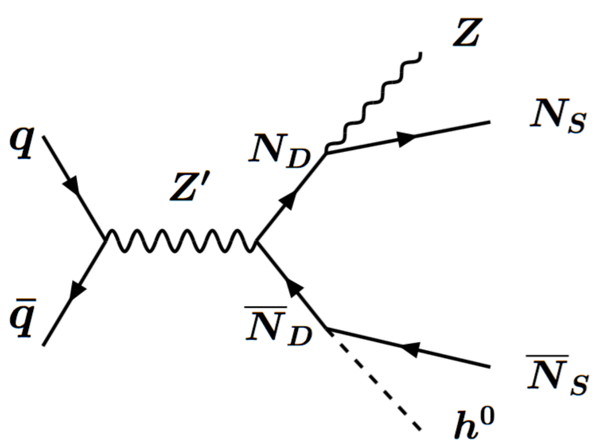
For $M_{Z'} \gg M_{E_S}$: two (WZ) or (Wh^0)-tagged jets + $\not{E}_T$

For $M_{Z'} > 2M_{E_S} \gg 2M_{E_D}$: four V or h^0-tagged jets + $\not{E}_T$

For $M_{Z'} \gg M_{N_D}$ or $M_{N_D} \gg M_{N_S}$:



two h^0-tagged jets + $\not{E}_T$



h^0-tagged jet + Z-tagged jet + $\not{E}_T$

Also: two Z-tagged jets + $\not{E}_T$, and two W-tagged jets + $\not{E}_T$.

Conclusions

LHC is exploring "Terra Incognita" $\rightarrow$ huge potential for surprises

Many additional searches (and novel techniques – jet substructure, quark vs. gluon jets, etc.) necessary for probing new physics

• Vectorlike quarks may have exotic signatures: $t'\bar{t}' \rightarrow t\bar{b} + 3\tau + \not{E}_T$
...

• S_{uu} scalar may decay into two vectorlike quarks (χ) leading to various final states.

$pp \rightarrow S_{uu} \rightarrow \chi\chi \rightarrow (ug)(ug)$ signal with $M_S = 8$ TeV and $m_\chi = 1.8$ TeV may be the origin of the CMS 4-jet event.

• Z' bosons may undergo cascade decays through anomalons, leading to final states with W, Z, Higgs bosons and $\not{E}_T$.