Quark Compositeness

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Theory

- At various times we have thought that we had identified non-composite particles (atoms, protons), so what if quarks are composite too?

- Composite quarks could help us to better understand issues with the standard model

Theory - Contact Interactions

- If quarks have substructure, we expect new interactions
- These interactions stem from quarks exchanging their constituent particles, or exchanging the quanta of the force which binds the constituent particles
- The dominant effect comes from the contact terms, which look like:

$$\mathfrak{L}_{\psi\psi} = (g^2/2\Lambda^2)[\eta_{LL}\bar{\psi}_L\gamma_\mu\psi_L\bar{\psi}_L\gamma^\mu\psi_L + \eta_{RR}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_R\gamma^\mu\psi_R + 2\eta_{RL}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_L\gamma^\mu\psi_L]$$

Theory - Contact Interactions

$$\mathcal{L}_{\psi\psi} = (g^2/2\Lambda^2)[\eta_{LL}\bar{\psi}_L\gamma_\mu\psi_L\bar{\psi}_L\gamma^\mu\psi_L + \eta_{RR}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_R\gamma^\mu\psi_R + 2\eta_{RL}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_L\gamma^\mu\psi_L]$$

- This Lagrangian is the most general flavor-diagonal color singlet chirally invariant contact interaction

- The parameter Λ is the compositeness energy scale; it suppresses contact interactions for energies much smaller than it

- Chiral invariance explains why quark masses are much smaller than Λ

Searching for Contact Interactions

- These interactions can interfere constructively or destructively with Standard Model predictions
- QCD tells us that quark contact interactions would lead to an angular distribution that is more isotropic than Standard Model predictions
  - This difference manifests as an excess at low values of the parameter χ

What is χ?

- χ= exp(|y_1 - y_2|), where y_1 and y_2 are the rapidities of our two jets
  - We choose the jets with highest transverse momentum
- χ is approximately (1+cos(θ))/(1 - cos(θ))
- Why χ?
  - Rutherford scattering, which is proportional to:
    - 1/(1-cos(θ))^2, is independent of χ

Experimental Details

- Will focus on ATLAS experiment
- Analyzed events with 2 jets if the leading jet had transverse momentum of 440 GeV
    - Leads to 99.5% efficiency for analyzed events
- Ignore events if any of the jets with transverse momentum greater than 60 GeV could be explained with calorimeter noise or non-collision background

Experimental Details

- Monte Carlo multijet events from Standard Model physics are generated with Pythia

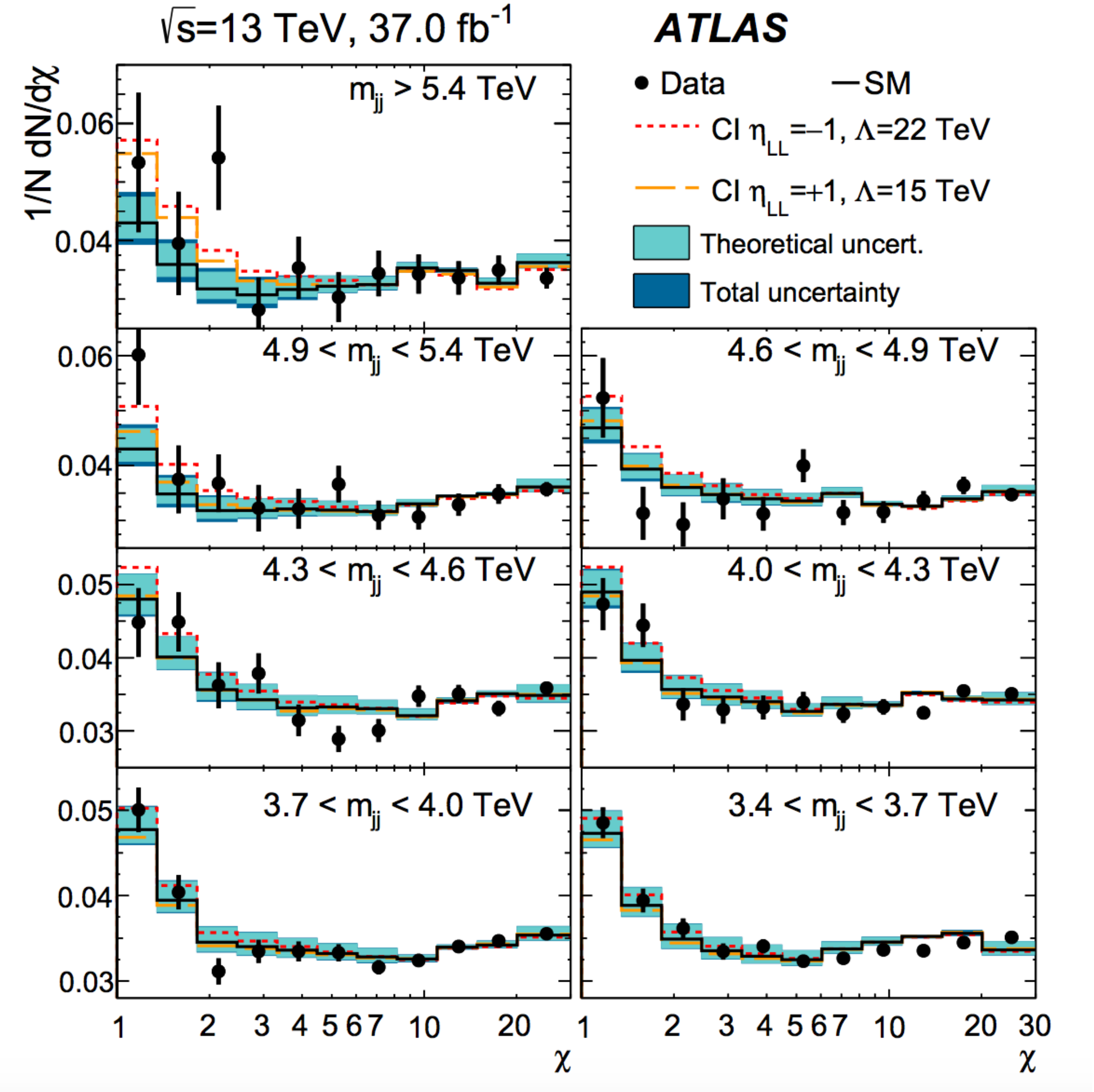
- Contact Interaction signals are also generated with Pythia, and they are found to have a more isotropic χ distribution

Uncertainty

- Theoretical uncertainty in the simulations comes from choice of PDF (< 1%) and renormalization (12%) and factorization scales (8%), where the renormalization and factorization uncertainties shown are the largest values they take on at high mass and small χ
- The signal uncertainty includes jet energy scale (1.5%-3%), choice of PDF (1%) , and luminosity (3.2%)
- The dominant experimental uncertainty for the χ distribution is the jet energy scale, which is at 15% for high masses

Experimental Results - Angular Distribution

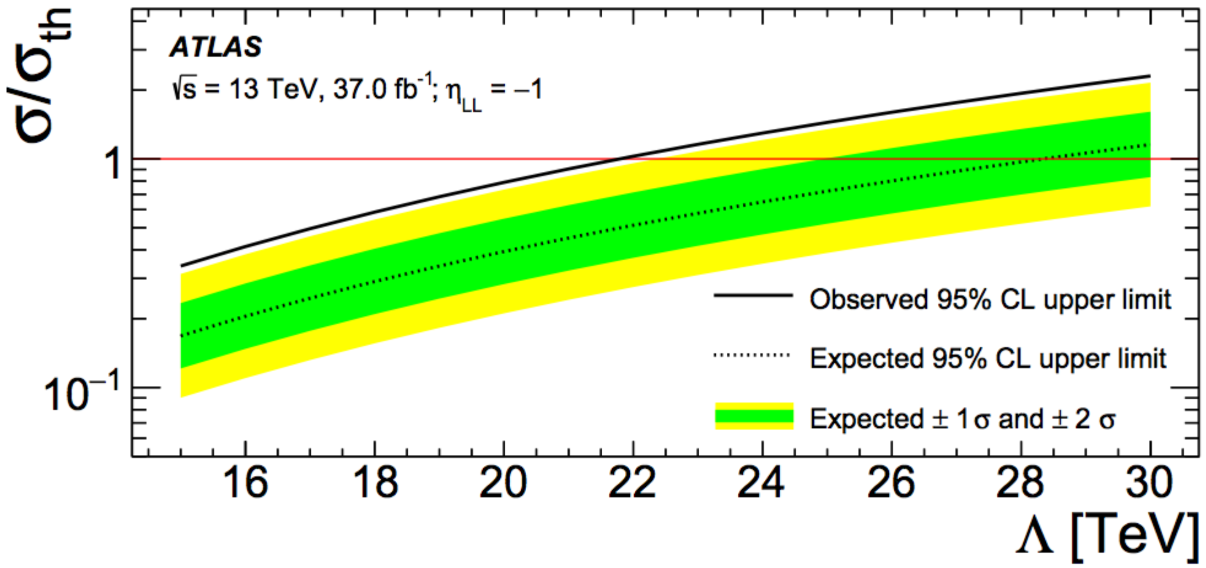
- Data well described by Standard Model predictions
- We can use this result to set limits on the contact interaction scale Λ

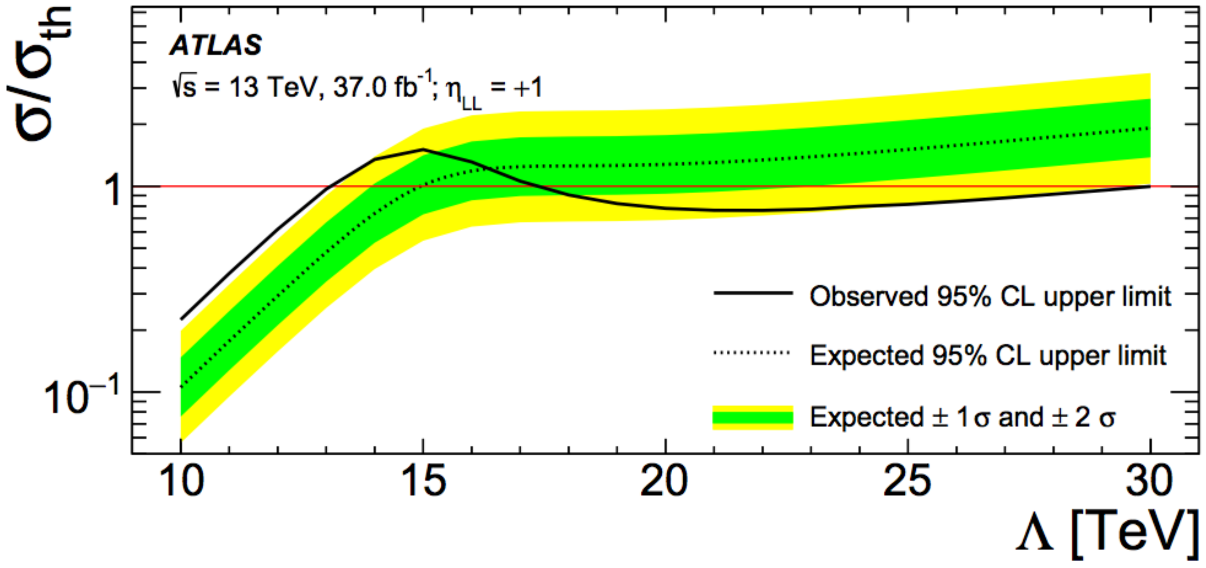


Experimental Results - Limits

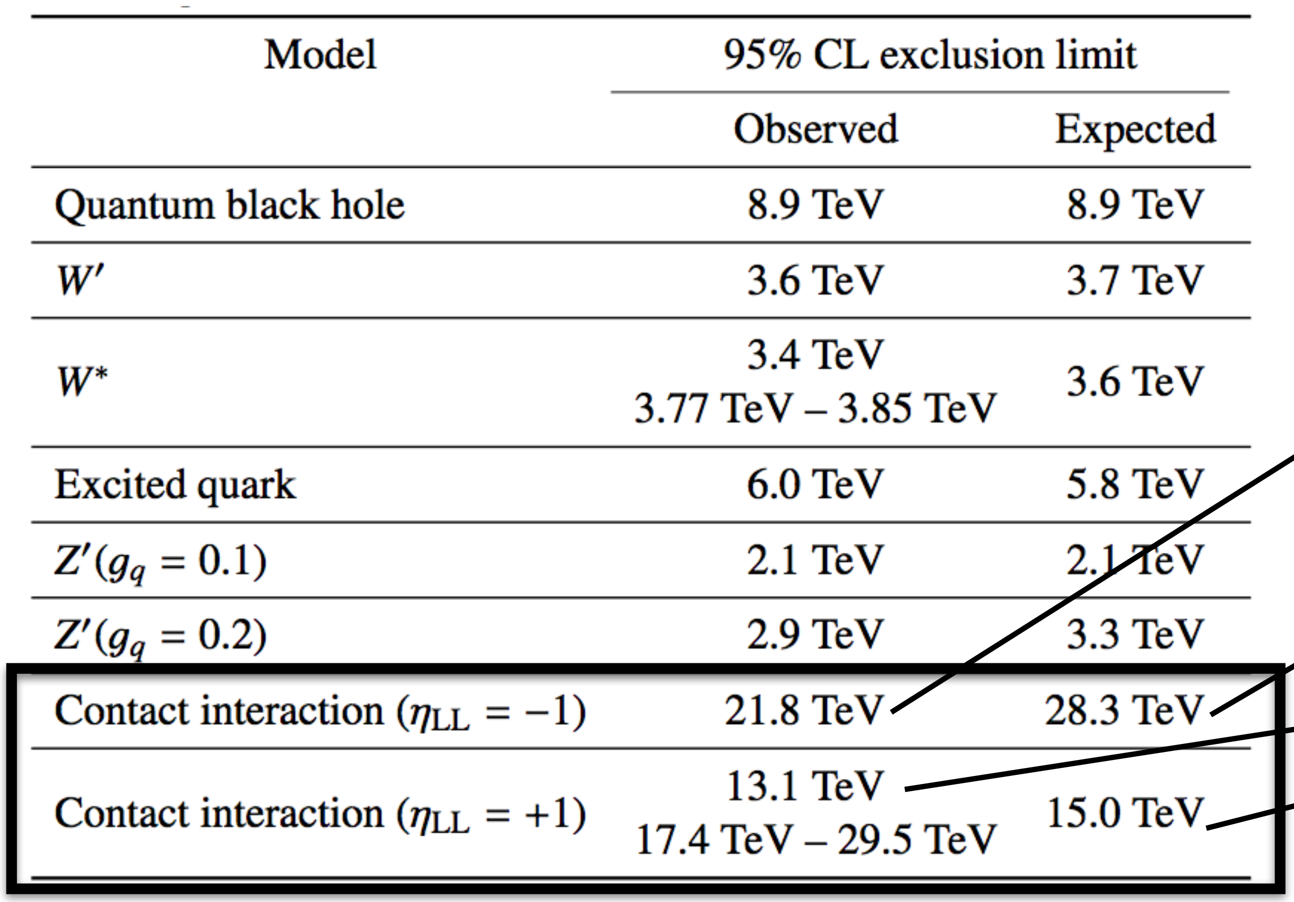
- By doing fits for different values of Λ, we can see how well they correspond to the previous histogram

- These show the limits on the CI cross section divided by the theoretical cross section for constructive interference (top) and destructive interference (bottom)
  - Values of Λ where lines are below 1 are excluded

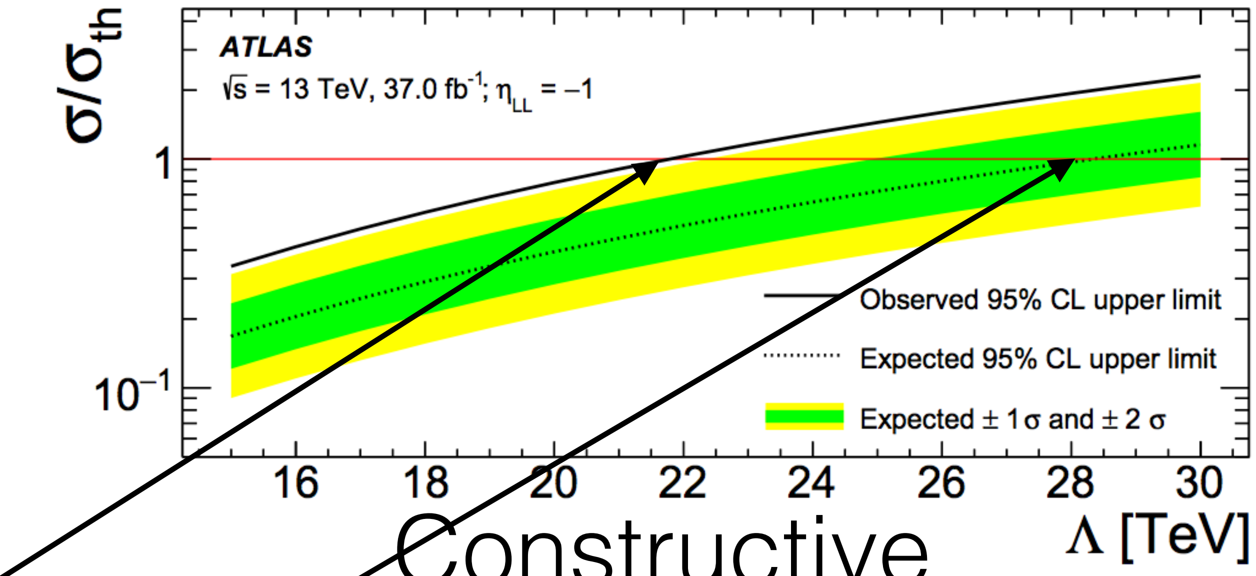




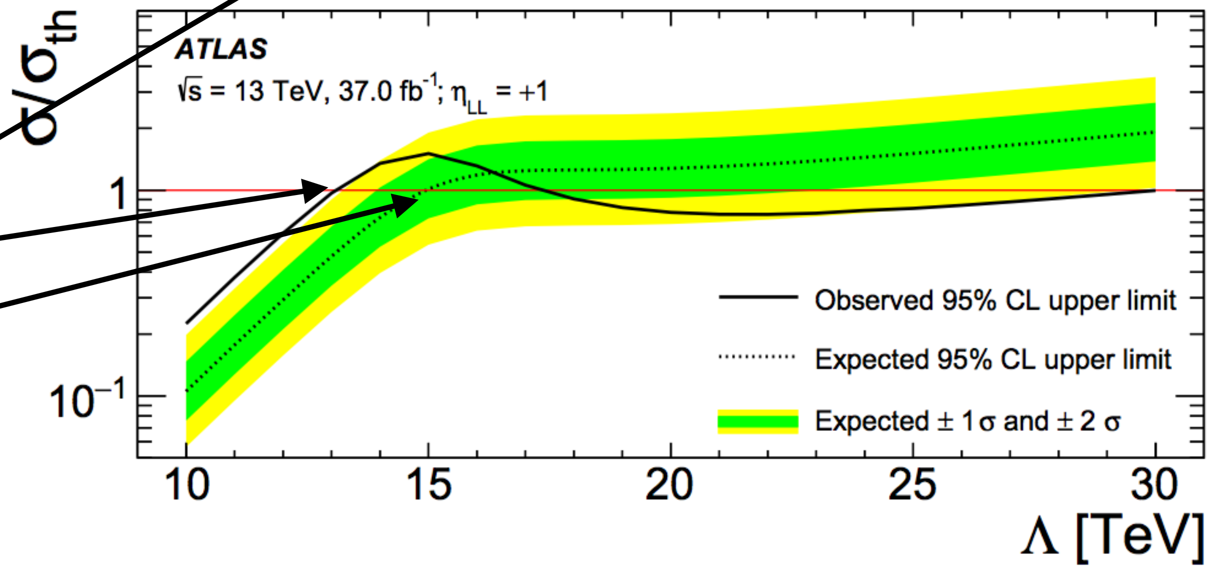
Exclusion Limits



Model	95% CL exclusion limit	
	Observed	Expected
Quantum black hole	8.9 TeV	8.9 TeV
W'	3.6 TeV	3.7 TeV
W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	6.0 TeV	5.8 TeV
$Z'(g_q = 0.1)$	2.1 TeV	2.1 TeV
$Z'(g_q = 0.2)$	2.9 TeV	3.3 TeV
Contact interaction ($\eta_{LL} = -1$)	21.8 TeV	28.3 TeV
Contact interaction ($\eta_{LL} = +1$)	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV



Constructive



Destructive

ATLAS/CMS Results

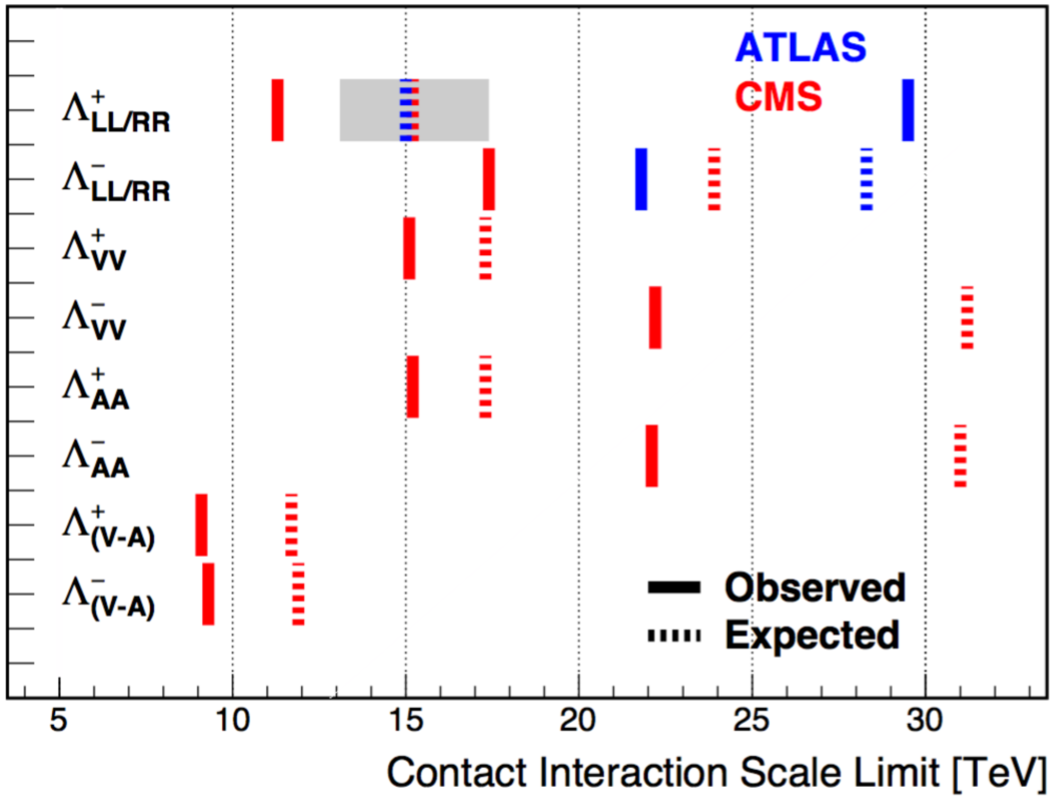
$$\Lambda = \Lambda^{\pm}_{LL} \quad \text{for} \quad (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm 1, 0, 0) \,,$$

$$\Lambda = \Lambda^{\pm}_{RR} \quad \text{for} \quad (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (0, \pm 1, 0) \,,$$

$$\Lambda = \Lambda^{\pm}_{VV} \quad \text{for} \quad (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm 1, \pm 1, \pm 1) \,,$$

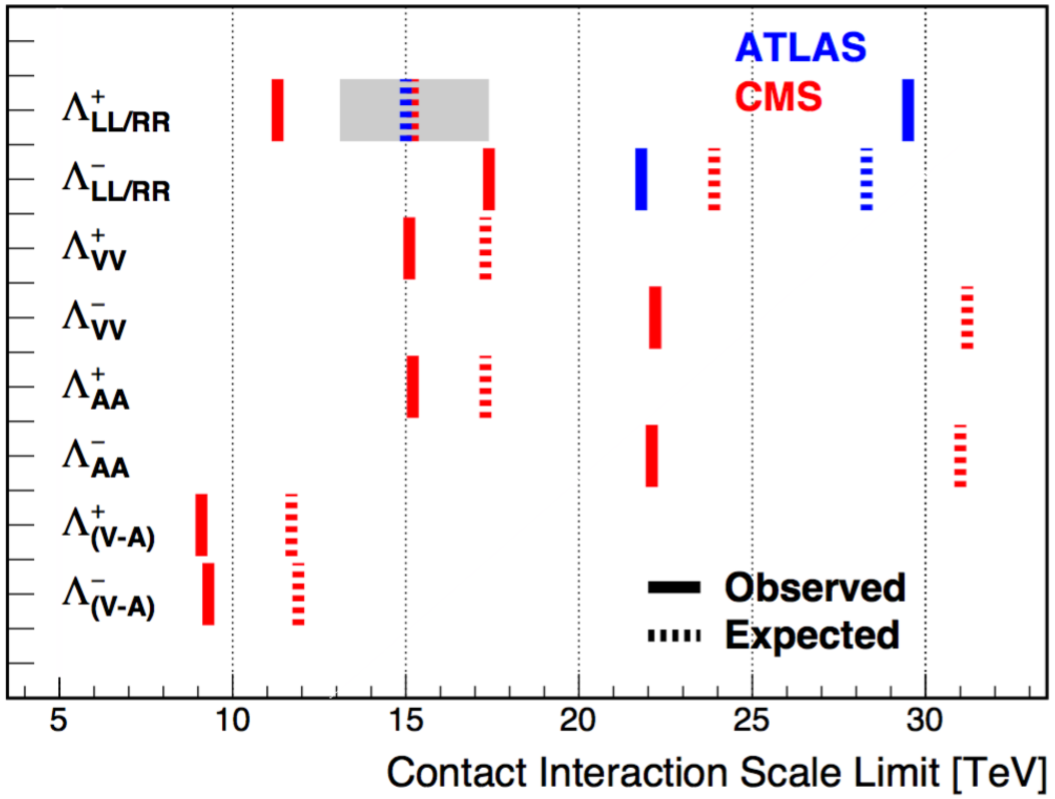
$$\Lambda = \Lambda^{\pm}_{AA} \quad \text{for} \quad (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (\pm 1, \pm 1, \mp 1) \,,$$

$$\Lambda = \Lambda^{\pm}_{V-A} \quad \text{for} \quad (\eta_{LL}, \eta_{RR}, \eta_{LR}) = (0, 0, \pm 1) \,.$$



ATLAS/CMS Results

- The gray shaded region is a region that ATLAS didn't exclude due to statistical fluctuations



Excited Quarks

- If quarks are composite particles, then we could expect to see excited quarks, where their constituent particles are bound in a higher energy state
- We can get excited quarks from pair production, or from their coupling to ordinary quarks via contact interactions
- Excited quarks could also couple with gluons

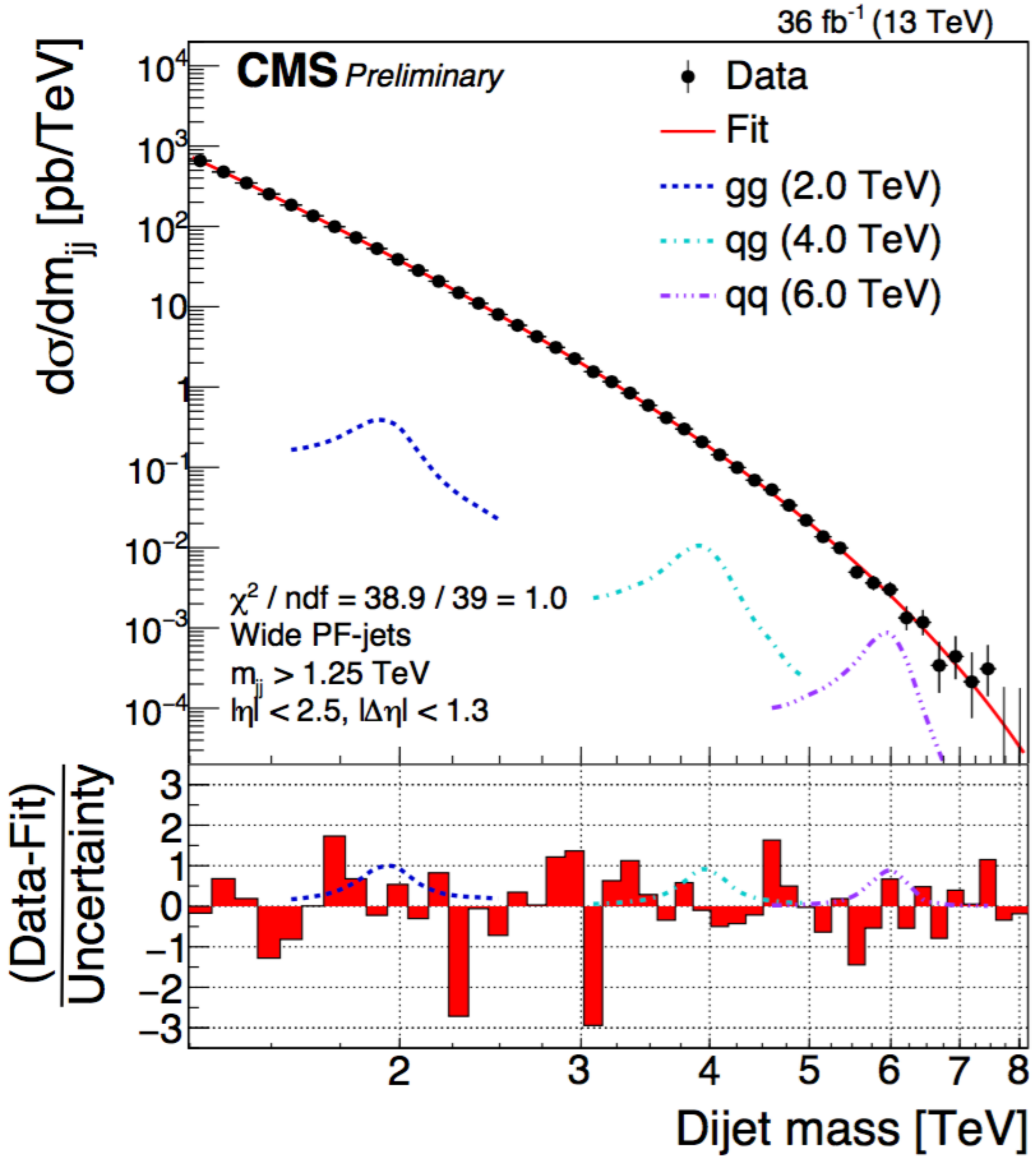
Looking for Excited Quarks

- Excited quarks can be seen at hadron colliders from a narrow resonant peak in the invariant mass distribution of their decay products

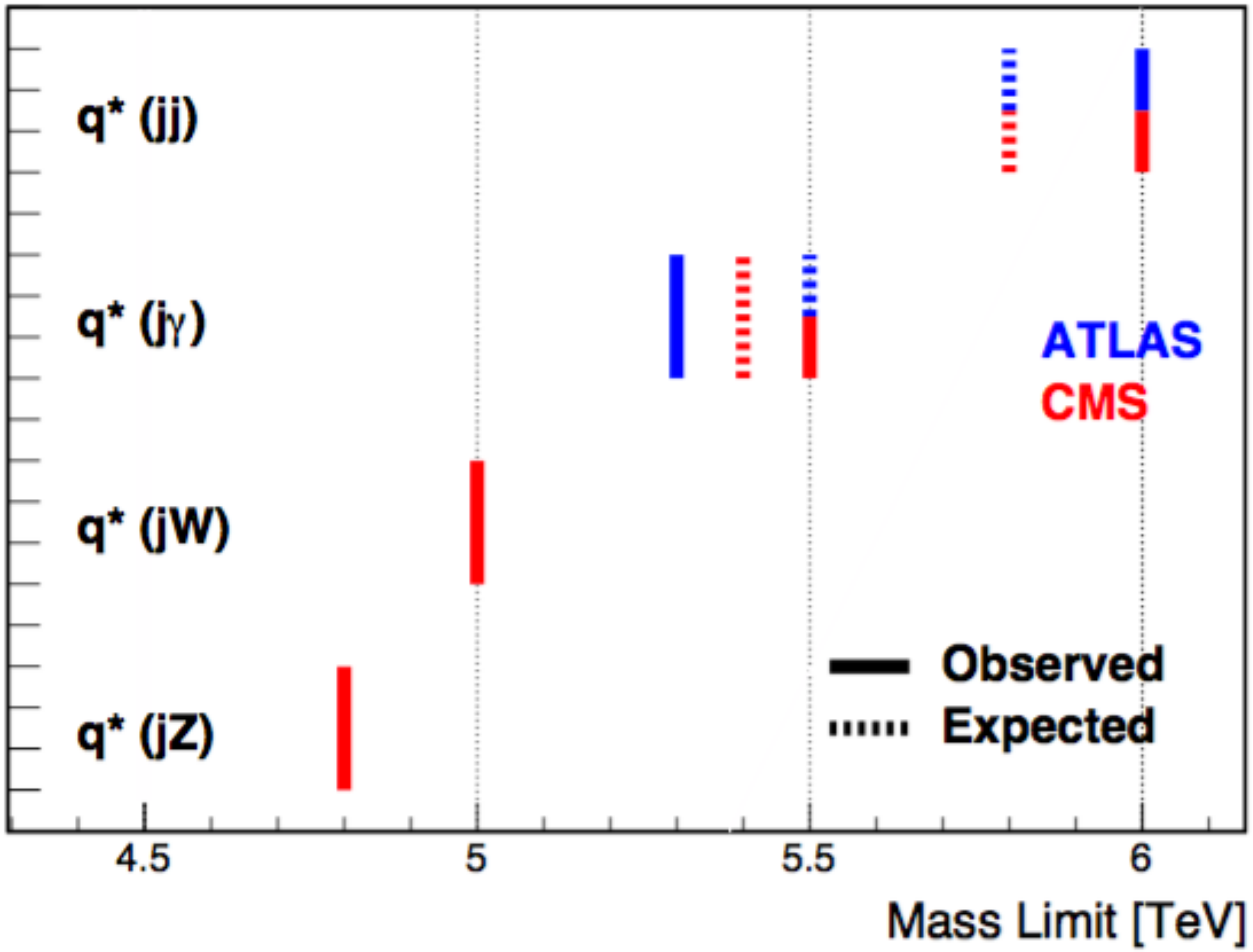
- Both ATLAS and CMS have searched for decay of excited quarks via coupling to gluons by looking at dijet final states

Excited Quark Limits

- ATLAS and CMS excluded excited quarks in dijet resonances up to 6.0 TeV



Excited Quark Limits for Other Final States



References

- PDG, 112. Searches for Quark and Lepton Compositeness
- ATLAS Collaboration, Search for new phenomena in dijet events using 37 fb^(-1) of pp collision data…