Dark Forces at the Tevatron

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TevPa2011

Fermilab

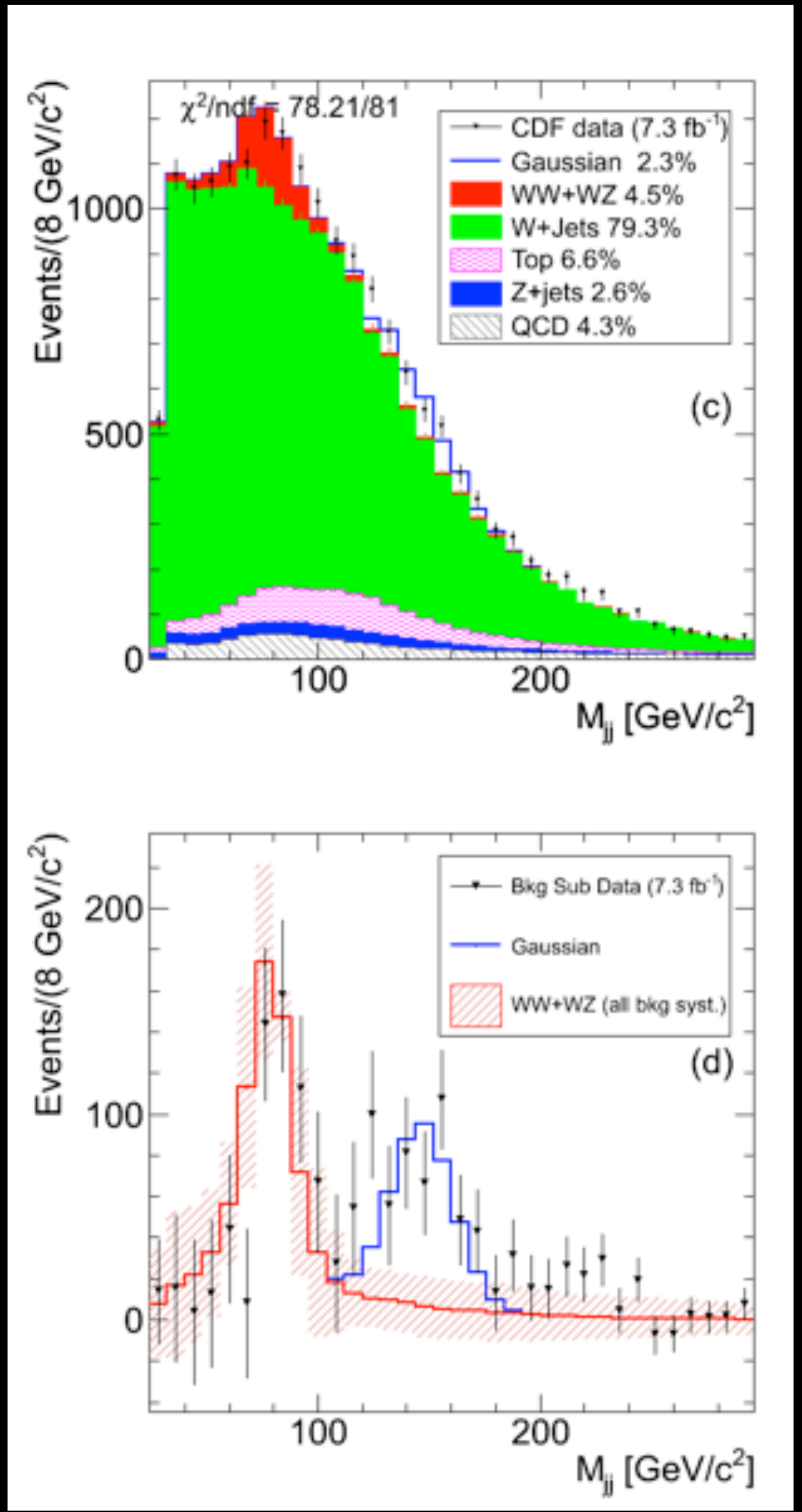
$W^{\pm} + jj$ Anomaly

- Found in CDF's $\ell\nu + jj$ channel
- In $4.3\ \mathrm{fb}^{-1}$, significance is 3.2σ
- Updated to 4.1σ in $7.3\ \mathrm{fb}^{-1}$

- Consistent with the decay of a narrow resonance at 147 GeV into a pair of jets
- Required cross section of

$$3.0 \pm 0.7\ \mathrm{pb}$$

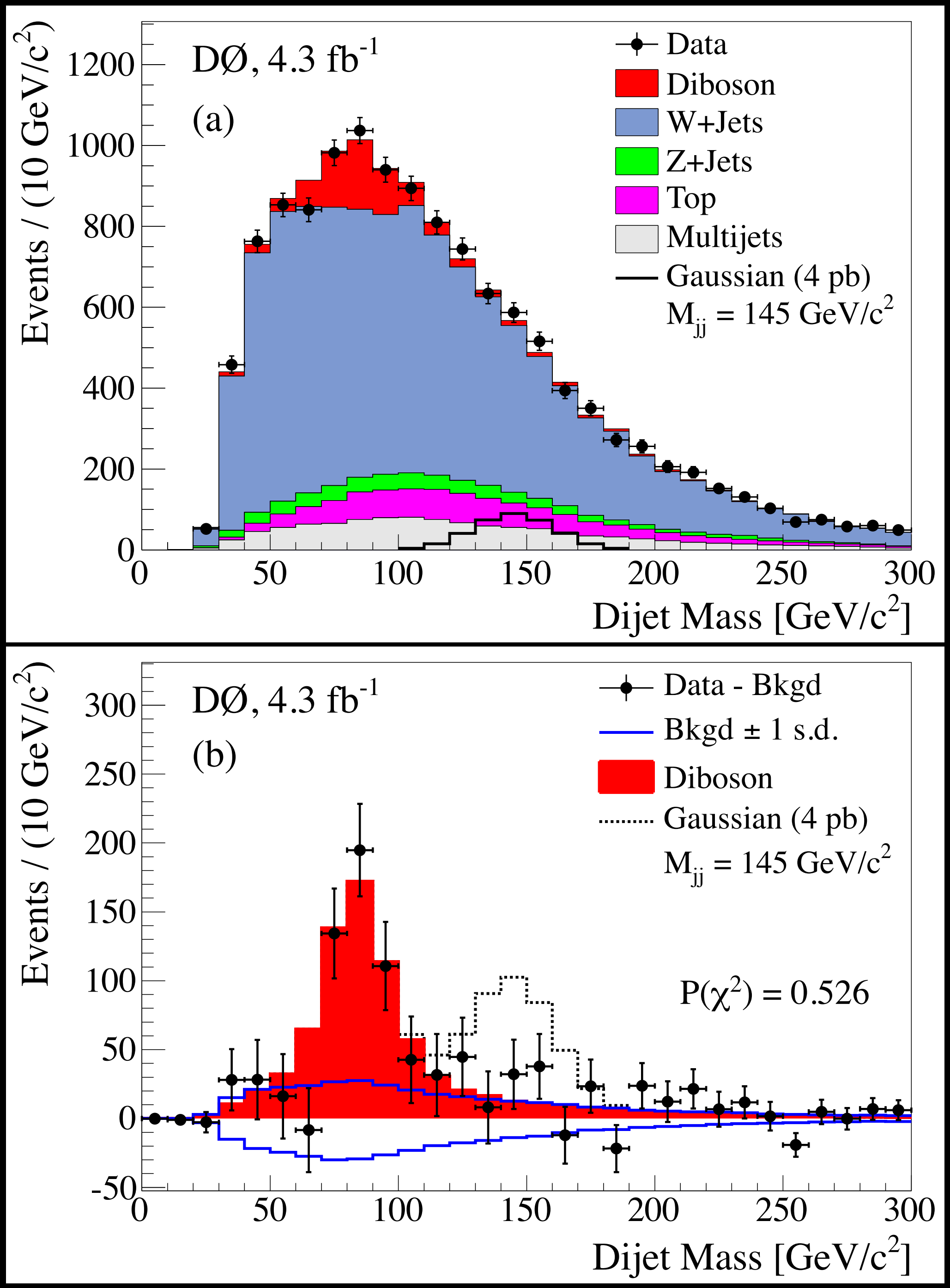
(before BR & kinematic cuts)



V. Cavaliere Thesis
arXiv:1104.0699
http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html

DØ Weighs In

- Analysis of $4.3\ \mathrm{fb}^{-1}$
- Disagrees with CDF at $p = 8 \times 10^{-6}$
- Cross section < 1.9 pb at 95% confidence
- Some differences in the two analyses: jet ΔR, and out-of-cone corrections



arXiv:1106.1921

Where do we go next?

- No clear error in either CDF or $\mathrm{D}\emptyset$
- $\sim 4\sigma$ discrepancy between two mature experiments not an acceptable resolution
- New physics not likely to exist only in one channel; can look elsewhere

	$\ell\nu + jj$	$\ell\ell + jj$	$\nu\nu + jj$	$\gamma + jj$
	2400 fb	840 fb	840 fb	420 fb
Z' left-handed	41 fb	6.1 fb	23 fb	2.1 fb
	$S/\sqrt{N} = 6.6$	$S/\sqrt{N} = 2.5$	$S/\sqrt{N} = 1.7$	$S/\sqrt{N} = 0.7$
	2400 fb	970 fb	970 fb	840 fb
Z' universal	40 fb	6.9 fb	25 fb	4.0 fb
	$S/\sqrt{N} = 6.6$	$S/\sqrt{N} = 2.8$	$S/\sqrt{N} = 1.9$	$S/\sqrt{N} = 1.4$
	2310 fb	530 fb	530 fb	541 fb
Technicolor	60 fb	6.8 fb	18 fb	2.8 fb
	$S/\sqrt{N} = 9.7$	$S/\sqrt{N} = 2.8$	$S/\sqrt{N} = 1.4$	$S/\sqrt{N} = 1.1$

assuming $10\ \mathrm{fb}^{-1}$

arXiv:1107.5799

LHC to the Rescue

- LHC does not yet have sufficient luminosity to test most new physics scenarios
- This will not be true for much longer!

	$\ell\nu + jj$	$\ell\ell + jj$	$\nu\nu + jj$	$\gamma + jj$
	11400 fb	3400 fb	3400 fb	3450 fb
Z' left-handed	145 fb	13.7 fb	99 fb	5.3 fb
	6.4 fb^{-1}	75 fb^{-1}	6.5 fb^{-1*}	170 fb^{-1}
	11400 fb	3800 fb	3800 fb	6900 fb
Z' universal	143 fb	14.4 fb	106 fb	11.9 fb
	6.6 fb^{-1}	67 fb^{-1}	5.7 fb^{-1*}	34.4 fb^{-1}
	7970 fb	2200 fb	2200 fb	1870 fb
Technicolor	188 fb	18.8 fb	75 fb	6.9 fb
	3.8 fb^{-1}	40 fb^{-1}	11.3 fb^{-1*}	103 fb^{-1}

arXiv:1107.5799

New Physics

- If the CDF signal is really new physics, we'll know within the year (maybe sooner)
  - If not, then something subtle has gone wrong with CDF background modeling, figuring this out is important.

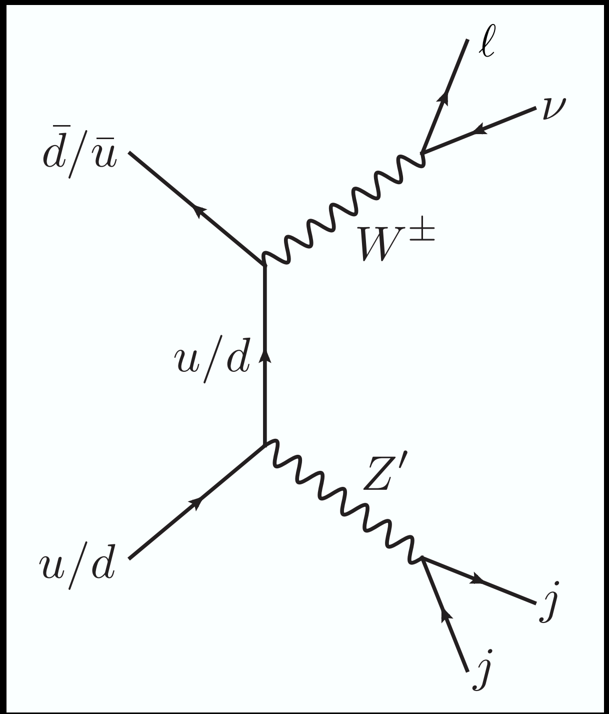
- Let's consider the implications of the new physics explanation
- Lots of options, I'll concentrate on one...

New Gauge Boson

- Introduce new broken $U(1)$ which couples to quarks with ~SM gauge strength
  - Resulting in Z' that can be produced in association with $W^{\pm}$

- Problems with precision EW
  - Assume no $Z - Z'$ mixing

- Anomaly cancellation?
  - We'll come back to that

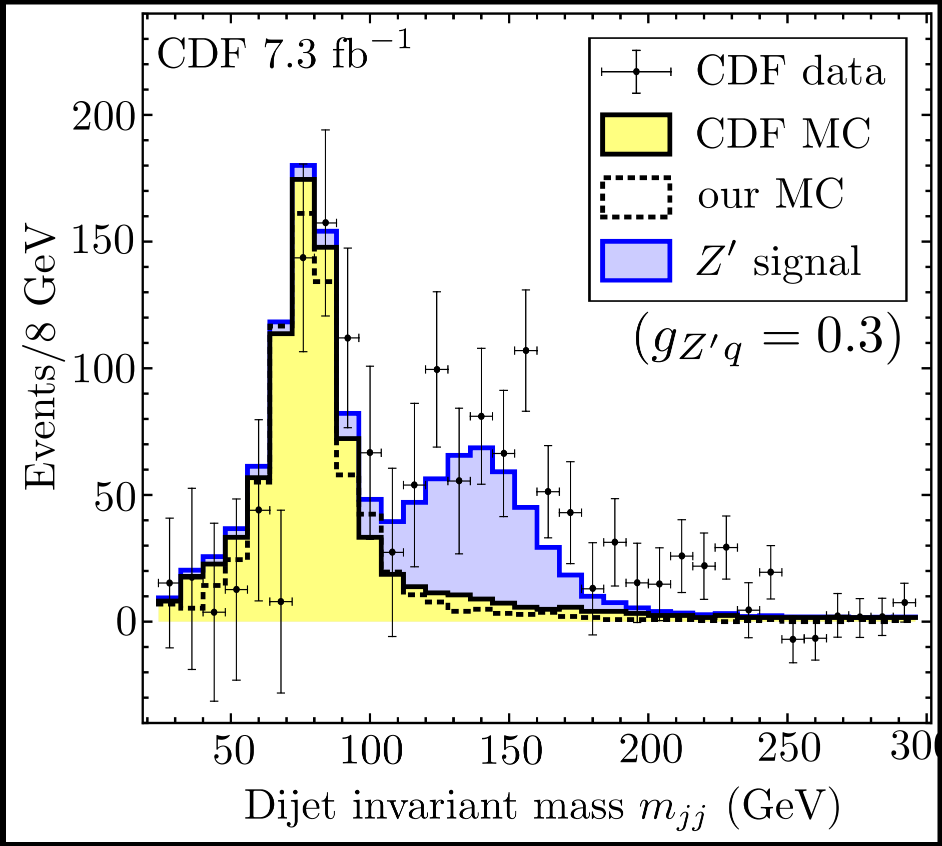


Fitting the Excess

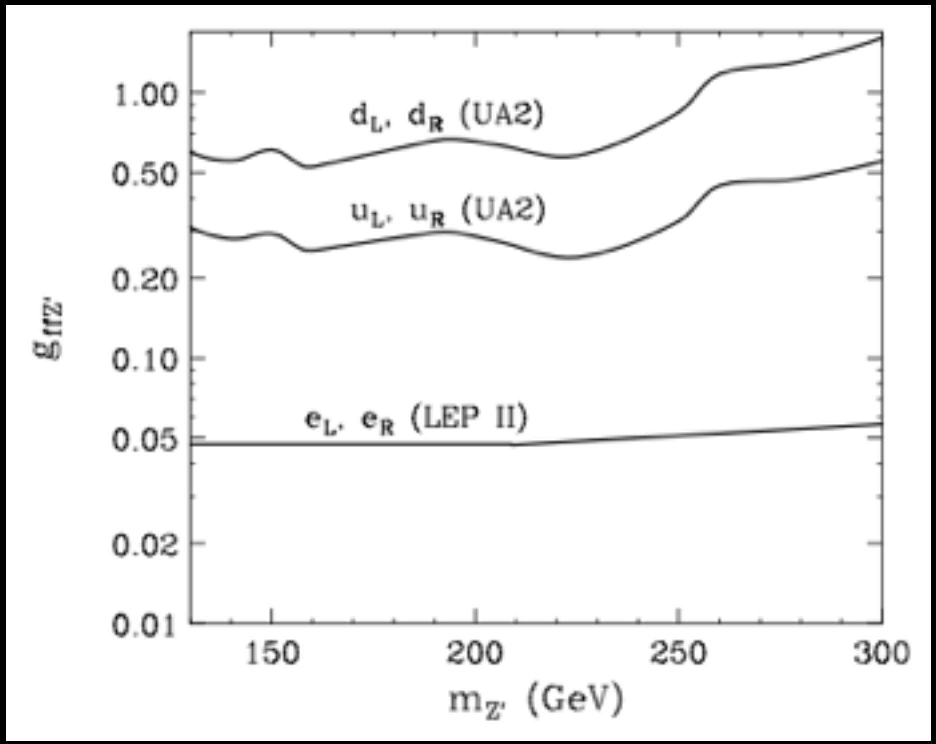
- Mass fixed, couplings to left-handed quarks derived directly from CDF data

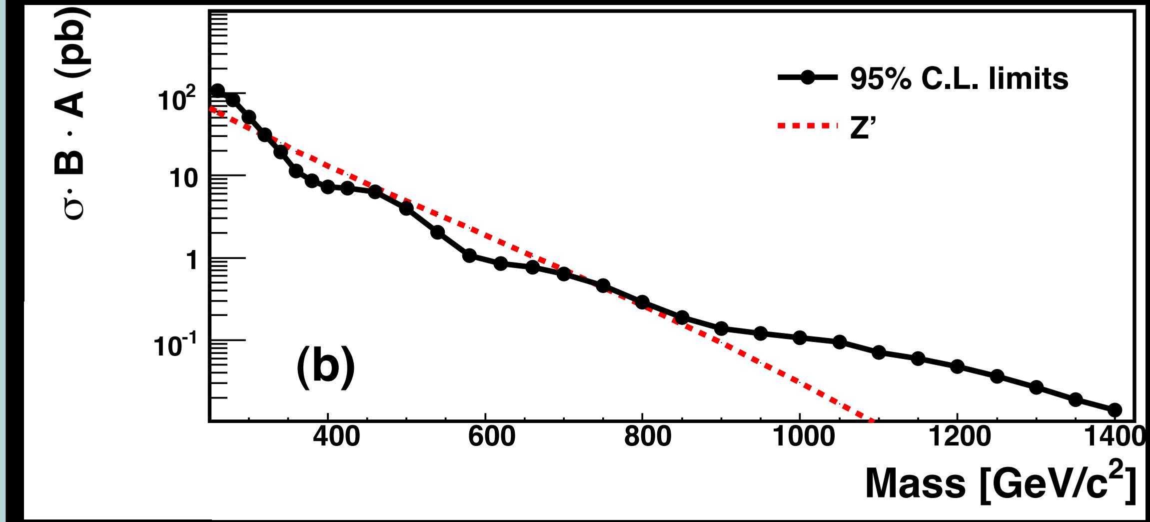
$$q_{Z' q_L} \sim 0.2 - 0.3$$

- This coupling not in violation of the UA2 bounds
  - (Tevatron dijet bounds weaker)



1103.6035 and 1107.5799





CDF 0812.4036

What's Dark Matter got to do with it?

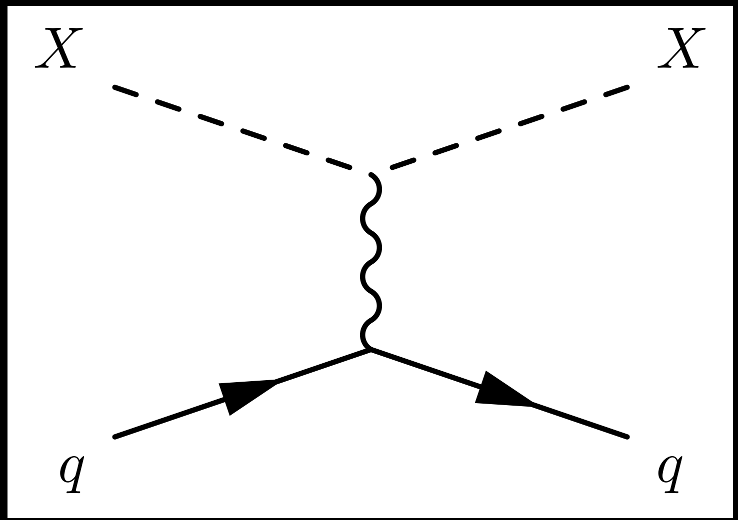
Or, why am I talking about this at TevPA?

Anomaly Cancellation

- B-L the only anomaly-free new $U(1)$ in the SM
- Leptophobic Z' must have new fermions charged under $SU(3)_C$
  - Must be chiral, so can't be arbitrarily heavy
- Among the new fermions, there is often a $SU(3)_C \times U(1)_{EM}$ singlet (X)
- Examples of known gauge groups we don't see large scales between particle's charge assignment
  - *i.e.* $g_{Z'X} \sim g_{Z'q_L}$

Dark Forces

- SM singlet: ideal dark matter candidate
  - Has coupling to nucleons through Z'



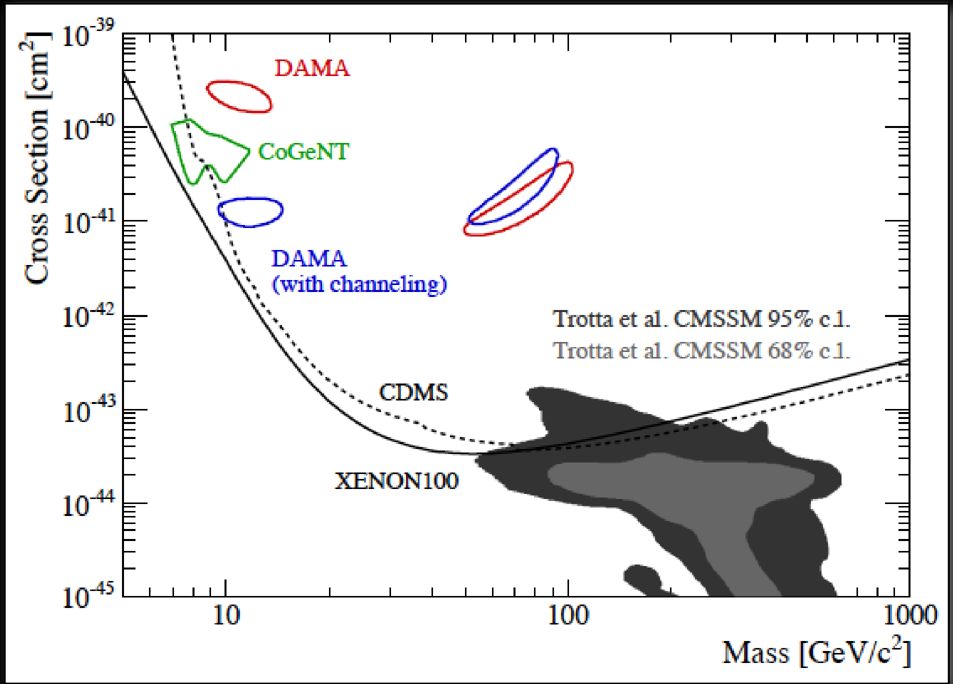
- Leads to direct detection cross section

$$\sigma_{Xp}^{\mathrm{SI}} = \frac{36 m_X^2 m_p^2 g_{Z'X}^2 g_{Z'q}^2}{\pi (m_X + m_p)^2 m_{Z'}^4}$$

- For $g_{Z'q} = 0.25$

$$\sigma_{Xp}^{\mathrm{SI}} = 2 \times 10^{-40}\ \mathrm{cm}^2 \left(\frac{m_X}{m_X + m_p}\right)^2 \left(\frac{g_{Z'X}}{g_{Z'q}}\right)^2$$

- *i.e.* DAMA & CoGeNT region



Explicit Example 1

1104.3145

- Can't use B-L for CDF excess
  - Gauge B and L separately
- Cancel anomalies through a single generation with B and L charges 3x of SM
- 4th generation decays requires a $SU(3)_C \times U(1)_{\rm EM}$ singlet, stable scalar with $B = 2/3$
- Early Universe relic density cannot just go though Z'_B
  - Loop-induced annihilations involving scalars carrying lepton number

$$XX \to e^- e^+, \mu^- \mu^+, \tau^- \tau^+$$

Explicit Example 2 1106.3583

- Grand Unified E_6 model
  - Two new $U(1)$ gauge groups
  - Can be broken down to single low-energy $U(1)_\eta$, not leptophobic
  - RGE running of $U(1)_\eta \times U(1)_Y$ mixing can generically lead to (mostly) leptophobic $U(1)'$

E_6 Particle Content

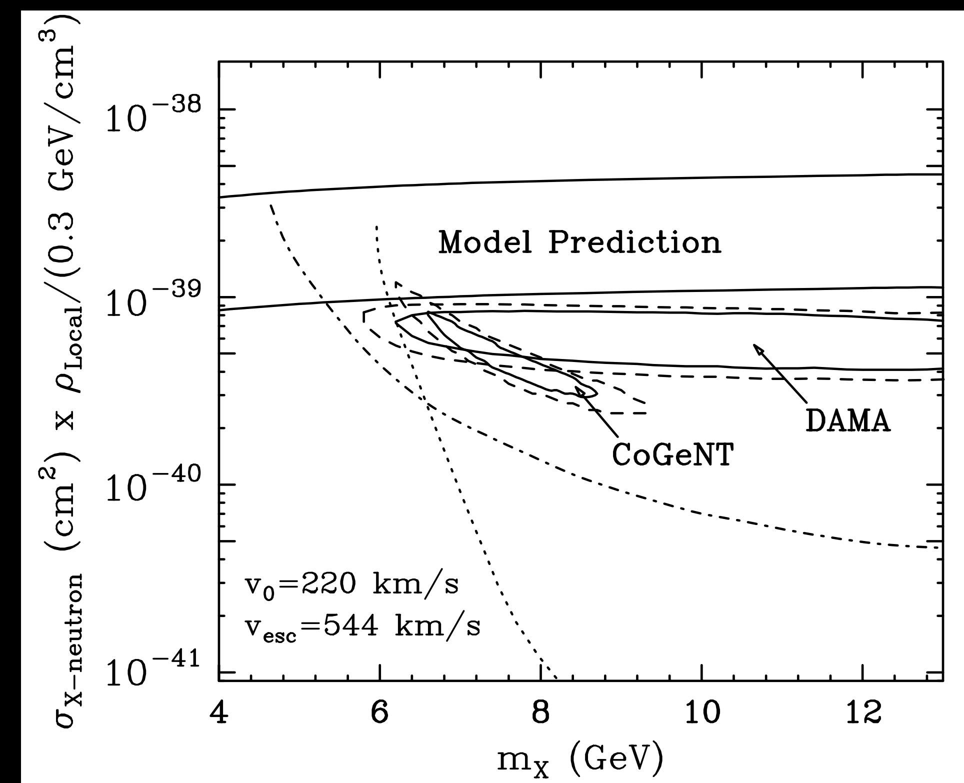
- Each generation fits into a **27** of E_6
  - 12 new fields, including two SM singlets

$$S_L, \bar{\nu}_R$$

  - Both have $U(1)'$ charges, $\bar{\nu}_R$ is our DM

	$SU(3)_C$	$SU(2)_L$	$\sqrt{5/3}Y$	$2\sqrt{3/5}Q'(\delta = 1/3)$
Q_L	$\mathbf{3}$	$\mathbf{2}$	1/6	-1/3
$\bar{u}_R$	$\bar{\mathbf{3}}$	$\mathbf{1}$	-2/3	-2/3
$\bar{d}_R$	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	1/3
L_L	$\mathbf{1}$	$\mathbf{2}$	-1/2	0
$\bar{e}_R$	$\mathbf{1}$	$\mathbf{1}$	+1	0
$\bar{H}$	$\mathbf{1}$	$\mathbf{2}$	+1/2	1
H	$\mathbf{1}$	$\mathbf{2}$	-1/2	0
h_L	$\mathbf{3}$	$\mathbf{1}$	-1/3	2/3
$\bar{h}_R$	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	1/3
$\bar{\nu}_R$	$\mathbf{1}$	$\mathbf{1}$	0	-1
S_L	$\mathbf{1}$	$\mathbf{1}$	0	-1

E_6 Dark Matter



- Pure leptophobic E_6 has zero coupling to protons
- Direct Detection signal close to CoGeNT/DAMA
- As in $U(1)_B$, need additional interactions to get relic density
  - General superpotential contains $\lambda_{11} \bar{H} L \bar{\nu}_R$

$$\begin{aligned} \langle \sigma v \rangle &\approx 2.3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \\ &\times \left(\frac{\lambda_{11}}{1}\right)^4 \left(\frac{110\,\mathrm{GeV}}{m_H}\right)^4 \left(\frac{m_X}{7\,\mathrm{GeV}}\right)^2 \left(\frac{20}{x_{\mathrm{FO}}}\right) \end{aligned}$$

Conclusions

- CDF W+jj excess still unexplained and interesting
- A simple explanation is a leptophobic Z'
  - UV-completions often require a SM singlet: a Dark Matter candidate
  - Parameters that fit CDF excess also give a CoGeNT-sized direct detection signal.
  - Also contain strongly interacting, TeV-scale fermions
- Could CDF be seeing the mediating force for the dark sector?