Of Contact Interactions and Colliders are Contact Interactions useful/justified at the LHC?

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Suppose the LHC does not find new particles/physics.....what to learn from:



(ATLAS $pp \rightarrow e^+e^-$)

Of Mice and Men

Robbie Burns, J Steinbeck

1. why not to set bounds on Contact Interactions (CI)? A leptoquark example

- problem 1: bound from shape: not translatable from one CI to next
- problem 2: Cl assumes $\hat{s} \ll \Lambda^2$... its not.

 $\hat{s} = {
m cm} \ {
m energy}$ CI coeff $= {4\pi\over\Lambda^2}$

- 2. instead: *fit* the data (= $pp \rightarrow e^+e^-$) ...to what?
 - $\frac{d\sigma}{d\hat{s}}(pp \rightarrow e^+e^-) \propto \text{ partonic cross-section}$
 - choose fit parameters from partonic cross-section (whose parameters are "almost observables")
- 3. our estimated bounds from $pp \rightarrow e^+e^-$
 - one plot: constrain any *t*-channel leptoquark, or any combination of contact interactions
- 4. summary
 - *fit* the data, then compare models to parameters of the fit (not simulate models: there are to many)
 - use form factors (forget local contact interactions("EFT"); its a poor approx when $\hat{s} \sim \Lambda^2$)

Use bounds on contact interactions to constrain leptoquarks?



Want to set bound on a *t*-channel (scalar) leptoquark (7 possibilities)

Consider $pp \rightarrow e^+e^-$

 $\hat{s} = (p_e + p_{\bar{e}})^2$

single LQ exchange in pair-production Dorsner,Fajfer,Greljo

induces contact interaction
$$-\frac{|\lambda_R|^2}{2m_{LQ}^2}(\overline{u}\gamma^{\mu}P_R u)(\overline{e}\gamma_{\mu}P_R e)$$
 (in $\hat{s} \ll m_{LQ}^2$ limit)
Conventional normalisation: $\frac{|\lambda_R|^2}{2m_{LQ}^2} = \frac{4\pi}{\Lambda^2}$

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Want to set bound on a *t*-channel (scalar) leptoquark (7 possibilities)

(why?): pair production bound: $m_{LQ} \lesssim 1 \text{ TeV}$, $10^{-8} \lesssim \lambda \lesssim 2\sqrt{\pi}$ whereas $q\bar{q}e^+e^-$ contact interaction bound : $\Lambda \gtrsim 10 - 20 \text{ TeV}$, $\lambda^2 = 8\pi$ \Rightarrow is there sensitivity to $m_{LQ} \gtrsim \text{ TeV}$, $\lambda \gtrsim 1$?



Why bounds on contact interactions are not useful 1: interference

New Physics (leptoquark, contact interaction,...) can interfere with the SM magnitude + sign of interference $\begin{cases} model - dependent \\ control shape of deviation from SM \end{cases}$

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• Consider SM singlet leptoquark S_0 , interaction $\lambda S_0 \overline{e} P_R u^c$ (one of 7 scalar LQs)

induces contact interaction $-\frac{|\lambda_R|^2}{2m_{LQ}^2}(\overline{u}\gamma^{\mu}P_Ru)(\overline{e}\gamma_{\mu}P_Re)$ in $\hat{s} \ll m_{LQ}^2$ limit, and partonic cross section (in CI limit) $\hat{\sigma} = \left(\frac{11g^4}{96\hat{s}} - \frac{8g^2}{27}\frac{\lambda^2}{2m_{LQ}^2} + \frac{2}{3}\frac{\lambda^4\hat{s}}{4m_{LQ}^4}\right)$ •Whereas exptal contact interaction :- $\sum_{q=u,d} \frac{\lambda^2}{2m_{LQ}^2}(\overline{q}\gamma^{\mu}P_Lq)(\overline{e}\gamma_{\mu}P_Le)$ which gives a partonic cross section : $\hat{\sigma} = \left(\frac{11g^4}{96\hat{s}} - \frac{g^2}{6}\frac{\lambda^2}{2m_{LQ}^2} + \frac{\lambda^4\hat{s}}{4m_{LQ}^4}\right)$

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exptal limit arises from deviation $|SM|^2$ - $|SM + NP|^2$ over several bins.... but different NP have different shapes...

None of the LQ induce the exptal CI



Bounds on complete set of operators does NOT help:

- 1) all ops contribute to same observable (despite that few interefere).
- 2) Constrain a deviation from SM (\pm) ...so sum of operators whose intereference terms cancel can be less constrained...

Can see a contact interaction above SM background when : $\frac{4\pi}{\Lambda^2} > \frac{e^2}{\hat{s}} \Rightarrow \Lambda^2 < \frac{\hat{s}}{\alpha_{em}}$ But need : $\Lambda^2 \gg \hat{s}$ in contact approximation ...how much bigger?

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Consider partonic cross-section for S_0 leptoquark (not in Cl limit) $\hat{\sigma}(q\bar{q} \rightarrow e^+e^-)$: $\hat{\sigma}_{DY} + \frac{1}{48\pi\hat{s}} \left[-\frac{2g'^2\lambda^2}{3} \left(\frac{1}{2} - \frac{m_{LQ}^2}{\hat{s}} + \frac{m_{LQ}^4}{\hat{s}^2} \ln(\frac{m_{LQ}^2 + \hat{s}}{m_{LQ}^2}) \right) + \frac{\lambda^4}{4} \left(1 - 2\frac{m_{LQ}^2 + \hat{s}}{\hat{s}^2} \ln(\frac{m_{LQ}^2 + \hat{s}}{m_{LQ}^2}) + \frac{m_{LQ}^2}{(m_{LQ}^2 + \hat{s})} \right) \right]$



$$m_{LQ} = 2 \text{TeV}, \quad \hat{s} = (p_e + p_{\bar{e}})^2$$

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1. expand
$$\ln(1 + \frac{\hat{s}}{m_{LQ}^2}) \simeq \frac{\hat{s}}{m_{LQ}^2} - \frac{\hat{s}^2}{m_{LQ}^4} + \dots$$

"EFT" : tower of *local* operators (*e.g.* $\propto \hat{s}/m_{LQ}^4$ at dim 8), diverge $\hat{s} > m_{LQ}^2$



Can see a contact interaction above SM background when : $\frac{4\pi}{\Lambda^2} > \frac{e^2}{\hat{s}} \Rightarrow \Lambda^2 < \frac{\hat{s}}{\alpha_{em}}$ But need : $\Lambda^2 \gg \hat{s}$ in contact approximation ...how much bigger?

Consider partonic cross-section for singlet leptoquark $\hat{\sigma}(q\bar{q} \rightarrow e^+e^-)$: $\hat{\sigma}_{DY} + \frac{1}{48\pi\hat{s}} \left[-\frac{2g^{\prime 2}\lambda^2}{3} \left(\frac{1}{2} - \frac{m_{LQ}^2}{\hat{s}} + \frac{m_{LQ}^4}{\hat{s}^2} \ln(\frac{m_{LQ}^2 + \hat{s}}{m_{LQ}^2}) \right) + \frac{\lambda^4}{4} \left(1 - 2\frac{m_{LQ}^2}{\hat{s}} \ln(\frac{m_{LQ}^2 + \hat{s}}{m_{LQ}^2}) + \frac{m_{LQ}^2}{(m_{LQ}^2 + \hat{s})} \right) \right]$

1. expand in $\frac{\hat{s}}{m_{LQ}^2}$: "EFT" : tower of local operators, diverge $\hat{s} > m_{LQ}^2$

2. expand in $\frac{\hat{s}}{m_{LQ}^2 + \hat{s}}$: "form factors", non-local, not obtain from \mathcal{L} , better fit.



Leptoquarks could affect the tail of $pp \rightarrow e^+e^-$. But 1) the bound arises from the shape of the deviation from the SM, which is model-dep 2) Contact Interaction approx doubtful for TeV $< m_{LQ} < \text{few} \times \sqrt{\hat{s}} \gtrsim 2$ TeV

fit the data? to what?

Desiderata: a functional form allowing for arbitrary New Physics fit parameters easy to relate to model parameters

Fitting the data

claim: can write

$$\frac{d\sigma}{d\hat{s}}(pp \to e^+e^-) \simeq \frac{2F(\hat{s})}{s} \left(2\hat{\sigma}(\bar{u}u \to e^+e^-) + \hat{\sigma}(\bar{d}d \to e^+e^-)\right)$$

1: $f_u(x) = 2f_d(x)$, $f_{\overline{u}}(x) = f_{\overline{d}}(x)$

2: integrate all angles (expts cut out the beam pipe)

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Why is this interesting?: Can normalise to SM:

$$\frac{d\sigma}{d\hat{s}} = \frac{d\sigma_{SM}}{d\hat{s}} \left(1 + \text{"form factors" chosen from NP partonic xsection}\right)$$

 \checkmark functional form from partonic cross-section

 \checkmark fit parameters \simeq partonic cross-section parameters

What approximations to get that form?

$$\frac{d\sigma}{d\hat{s}} = \frac{2}{s} \int d\eta^+ d\hat{t} \left[f_u(x_1) f_{\bar{u}}(x_2) \frac{d\hat{\sigma}}{d\hat{t}} (\bar{u}u \to e^+ e^-) + f_d(x_1) f_{\bar{d}}(x_2) \frac{d\hat{\sigma}}{d\hat{t}} (\bar{d}d \to e^+ e^-) \right]$$

 $(x_i \propto \hat{s}e^{\pm\eta+})$

1 assume
$$f_{\bar{u}}(x) = f_{\bar{d}}(x)$$
, $f_u(x) = 2f_d(x)$

2 simple integration limits : $-\hat{t}: [0, \hat{s}]$

(no forward divergences)

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$$= \frac{2}{s} \int d\eta^+ f_d(x_1) f_{\bar{d}}(x_2) \int d\hat{t} \left[2 \frac{d\hat{\sigma}}{d\hat{t}} (\bar{u}u \to e^+e^-) + \frac{d\hat{\sigma}}{d\hat{t}} (\bar{d}d \to e^+e^-) \right]$$

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$$\simeq \frac{2}{s} \int d\eta^+ f_d(x_1) f_{\bar{d}}(x_2) \int d\hat{t} \left[2 \frac{d\hat{\sigma}}{d\hat{t}} (\bar{u}u \to e^+e^-) + \frac{d\hat{\sigma}}{d\hat{t}} (\bar{d}d \to e^+e^-) \right]$$

$$\simeq \frac{2F(\hat{s})}{s} \left[2\hat{\sigma}(\bar{u}u \to e^+e^-) + \hat{\sigma}(\bar{d}d \to e^+e^-) \right]$$

A "form factor" fit

claim: can write

$$\frac{d\sigma}{d\hat{s}}(pp \to e^+e^-) \simeq \frac{2F(\hat{s})}{s} \left(2\hat{\sigma}(\bar{u}u \to e^+e^-) + \hat{\sigma}(\bar{d}d \to e^+e^-)\right)$$

1: $f_u(x) = 2f_d(x)$, $f_{\bar{u}}(x) = f_{\bar{d}}(x)$

2: integrate all angles (expts cut out the beam pipe)

Why is this interesting?: Can normalise to SM:

in CI limit : 1307.5068 etal + Santiago

$$\frac{d\sigma}{d\hat{s}}(pp \to e^+e^-) = \frac{d\sigma_{SM}}{d\hat{s}} \left(1 + a\frac{\hat{s}}{1+c\hat{s}} + b\frac{\hat{s}^2}{(1+c\hat{s})^2}\right)$$

Recall, for SM + t-channel LQ exchange, had

$$\hat{\sigma} \simeq \frac{1}{\hat{s}} \left(\frac{g_2^4}{8} + \epsilon_{int} g_2^2 \frac{4\pi}{\Lambda^2} \frac{\hat{s}}{(1+\hat{s}/m^2)} + \epsilon_{NP} \frac{16\pi^2}{\Lambda^4} \frac{\hat{s}^2}{(1+\hat{s}/m^2)^2} \right) \qquad 4\pi/\Lambda^2 \leftrightarrow \lambda^2/2m^2$$

What about s-channel NP?

Contact interaction approx ok for rise to resonance ...

CMS PAS EXO-12-020



ee Cross Section Ratio



MINUIT fit to
$$\left(1 + a\frac{\hat{s}}{1 + c\hat{s}} + b\frac{\hat{s}^2}{(1 + c\hat{s})^2}\right) - 1$$
, for $c = \frac{\text{TeV}^2}{m^2} = 0, \frac{1}{9}, \frac{1}{4}, 1$

fit to e+e- data



$$\frac{d\sigma_{SM}}{d\hat{s}} \left(1 + a\frac{\hat{s}}{1 + c\hat{s}} + b\frac{\hat{s}^2}{(1 + c\hat{s})^2} \right) \quad \text{for } c = \frac{\text{TeV}^2}{m^2} = 0, \frac{1}{9}, \frac{1}{4}, 1$$

To constrain a model

Guessed a form-factor parametrisation from NP partonic x-section:

$$\frac{d\sigma}{d\hat{s}}(pp \to e^+e^-) = \frac{d\sigma_{SM}}{d\hat{s}} \left(1 + a\frac{\hat{s}}{1+c\hat{s}} + b\frac{\hat{s}^2}{(1+c\hat{s})^2}\right)$$

 \Rightarrow allowed ellipses in a, b for given c.

 $a, b, c \ calculable$ from partonic x-section of New Physics model

$$\begin{split} \hat{\sigma} \simeq \frac{1}{\hat{s}} \left(\frac{g_2^4}{8} + \epsilon_{int} g_2^2 \frac{4\pi}{\Lambda^2} \frac{\hat{s}}{(1+\hat{s}/m^2)} + \epsilon_{NP} \frac{16\pi^2}{\Lambda^4} \frac{\hat{s}^2}{(1+\hat{s}/m^2)^2} \right) & 4\pi/\Lambda^2 \leftrightarrow \lambda^2/2m^2 \\ a = \frac{72\pi\epsilon_{int}}{\Lambda^2} \ , \quad b \simeq \frac{\epsilon_{NP}}{[\Lambda/9.0]^4} \ , \quad c = \frac{1}{m^2} \end{split}$$

 $\lambda, m \ parameters$ to constrain:

 $\epsilon_{int}, \epsilon_{NP} \ constants \ of \ NP \ model, \ calculable \ from \ partonic \ xsection: \ a^2 \propto \frac{\epsilon_{int}}{\epsilon_{NP}^2} b$

fit to e+e- data



models have oneunknown $= \lambda$, are red lines. Parabola $a^2 \propto b$ determined by amount of interference

$$a^2 \propto \frac{\epsilon_{int}}{\epsilon_{NP}^2} b$$
, $b \simeq \frac{\epsilon_{NP}}{[\Lambda/9.0]^4}$, $c = \frac{\text{TeV}^2}{m^2} = \mathbf{0}, \frac{1}{9}, \frac{1}{4}, 1$

Limits

Our "contact interaction ellipse" reproduces the CMS bound on the contact interaction they simulate:

 $\Lambda^{DDGV}_{des} \geq 16.3~{\rm TeV}\;,\; \Lambda^{DDGV}_{con} \geq 19.0~{\rm TeV}\;,\; \Lambda^{CMS}_{des} \geq 13.5~{\rm TeV}\;,\; \Lambda^{CMS}_{con} \geq 18.3~{\rm TeV}$

$$\mathcal{L}_{LQ} = S_0(\lambda_{LS_0}\overline{\ell}i\tau_2q^c + \lambda_{RS_0}\overline{e}u^c) + \tilde{S}_0\tilde{\lambda}_{R\tilde{S}_0}\overline{e}d^c + S_2(\lambda_{LS_2}\overline{\ell}u + \lambda_{RS_2}\overline{e}q[i\tau_2]) + \tilde{S}_2\tilde{\lambda}_{L\tilde{S}_2}\overline{\ell}d + \vec{S}_1\lambda_{LS_1}\overline{\ell}i\tau_2\vec{\tau}q^c \cdot h.c.$$

leptoquark	$m_{LQ} = 3 \text{ TeV}, \lambda^2 <$	$m_{LQ} = 2 \text{ TeV}, \lambda^2 <$	$m_{LQ} = 1 \text{ TeV}, \lambda^2 <$
S_o, λ_{LS_o}	0.54	0.24	0.07
S_o, λ_{RS_o}	0.54	0.24	0.07
$\tilde{S}_o, \lambda_{R\tilde{S}_o}$	1.4	0.74	0.32
S_2, λ_L	0.90	0.48	0.20
S_2, λ_R	0.84	0.45	0.20
$ ilde{S}_2, \lambda_{L ilde{S}_2}$	1.9	0.98	0.47
S_1, λ_{LS_1}	0.94	0.49	0.23

Summary

We are looking for traces of New Particles in the highest energy $pp \rightarrow \ell^+ \ell^-$ events

Rather than simulate a model, or a collection of contact interactions, we fit the $pp \rightarrow \ell^+ \ell^-$ data to "form factors." The form factors are motivated by the partonic cross-section, so translating bounds on fit parameters to models is simple.

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 $\Lambda_{des}^{DDGV} \geq 16.3 \text{ TeV}, \ \Lambda_{con}^{DDGV} \geq 19.0 \text{ TeV}, \ \Lambda_{des}^{CMS} \geq 13.5 \text{ TeV}, \ \Lambda_{con}^{CMS} \geq 18.3 \text{ TeV}$ Our ellipse also give bounds on any other contact interaction (eg s-channel New Physics).

Our "form factor ellipses" allow to constrain new particles exchange in the *t*-channel (all possible leptoquarks), for arbitrary couplings and masses.



What about *s*-channel New Physics?

The rise towards the peak, for $\hat{s} \ll M^2$ can be parametrised as a contact interaction ($c \rightarrow 0$).

However, the expansion in $\hat{s}/(\hat{s} + M^2)$, (useful for *t*-channel exchange), has no advantages in this case.



For $M^2 < \hat{s}$, possible (??) that an *s*-channel resonance could contribute a shoulder (like *t*-channel exchange) in the binned $pp \rightarrow \ell^+ \ell^-$ data.

(...depends on pdfs, binning, resonance properties...)

The $pp \rightarrow \mu^+ \mu^-$ data $\mu\mu$ Cross Section Ratio



$$\frac{\frac{d\sigma}{d\hat{s}}|_{data}}{\frac{d\sigma_{SM}}{d\hat{s}}} = \left(1 + a\frac{\hat{s}}{1 + c\hat{s}} + b\frac{\hat{s}^2}{(1 + c\hat{s})^2}\right) \quad , \quad \text{for } c = \frac{\text{TeV}^2}{m^2} = \mathbf{0}, \frac{1}{9}, \frac{1}{4}, 1$$



$$\frac{d\sigma_{SM}}{d\hat{s}} \left(1 + a \frac{\hat{s}}{1 + c\hat{s}} + b \frac{\hat{s}^2}{(1 + c\hat{s})^2} \right) \quad , \quad \text{for } c = \frac{\text{TeV}^2}{m^2} = 0(1\sigma), \mathbf{0}(2\sigma), \frac{1}{9}, \frac{1}{4}, 1$$

interaction	$ m Fierz-transformed \ {\cal M}$
$(\lambda_{LS_o} \overline{q^c} i \sigma_2 \ell + \lambda_{RS_o} \overline{u^c} e) S_o^{\dagger}$	$\left(\overline{u}\gamma^{\mu}P_{R}u\right)\left(\overline{e}\gamma_{\mu}P_{R}e\right)\left(\frac{ \lambda_{R} ^{2}}{2(m_{o}^{2}-\hat{\tau})}-\frac{2}{3}\frac{g^{\prime2}}{\hat{s}}\right)$
	$(\overline{u}\gamma^{\mu}P_{L}u)(\overline{e}\gamma_{\mu}P_{L}e)\left(\frac{ \lambda_{L} ^{2}}{2(m_{o}^{2}-\hat{\tau})}-\frac{1}{4}\frac{g^{2}}{\hat{s}}\right)'$
$\lambda_{R\tilde{S}_o}\overline{d^c}e\tilde{S}_o^\dagger$	$\left(\overline{d}\gamma^{\mu}P_{R}d\right)\left(\overline{e}\gamma_{\mu}P_{R}e\right)\left(\frac{ \lambda_{R} ^{2}}{2(\tilde{m}_{o}^{2}-\hat{\tau})}+\frac{1}{3}\frac{g^{\prime2}}{\hat{s}}\right)$
$(\lambda_L \overline{u}\ell + \lambda_R \overline{q} i\sigma_2 e) S_2^{\dagger}$	$\left(\overline{u}\gamma^{\mu}P_{R}u\right)\left(\overline{e}\gamma_{\mu}P_{L}e\right)\left(-\frac{ \lambda_{L} ^{2}}{2(m_{2}^{2}-\hat{\tau})}-\frac{1}{3}\frac{g^{\prime2}}{\hat{s}}\right)$
	$\left(\overline{u}\gamma^{\mu}P_{L}u\right)\left(\overline{e}\gamma_{\mu}P_{R}e\right)\left(-\frac{ \lambda_{R} ^{2}}{2(m_{2}^{2}-\hat{\tau})}-\frac{1}{6}\frac{g^{\prime2}}{\hat{s}}\right)$
	$+ \left(\overline{d}\gamma^{\mu}P_{L}d\right)\left(\overline{e}\gamma_{\mu}P_{R}e\right)\left(-\frac{ \lambda_{R} ^{2}}{2(m_{2}^{2}-\hat{\tau})}-\frac{1}{6}\frac{g^{\prime2}}{\hat{s}}\right)$
$\lambda_{L\tilde{S}_{2}}\overline{d}\ell\tilde{S}_{2}^{\dagger}$	$\left(\overline{d}\gamma^{\mu}P_{R}d\right)\left(\overline{e}\gamma_{\mu}P_{L}e\right)\left(-\frac{ \lambda_{L} ^{2}}{2(\tilde{m}_{2}^{2}-\hat{\tau})}+\frac{1}{6}\frac{g^{\prime2}}{\hat{s}}\right)$
$\lambda_{LS_1} \overline{q^c} i \sigma_2 \vec{\sigma} \ell \cdot \vec{S_1}^{\dagger} \qquad (\overline{u} \gamma^{\mu} P_L u) (\overline{e} \gamma_{\mu} P_L e) \left(\frac{ \lambda_L ^2}{2(m_1^2 - \hat{\tau})} - \frac{1}{4} \frac{g^2}{\hat{s}} \right)$	
	$+ \left(\overline{d}\gamma^{\mu}P_{L}d\right)\left(\overline{e}\gamma_{\mu}P_{L}e\right)\left(\frac{ \lambda_{L} ^{2}}{(m_{1}^{2}-\hat{\tau})} + \frac{1}{4}\frac{g^{2}}{\hat{s}}\right)$