Of Contact Interactions and Colliders

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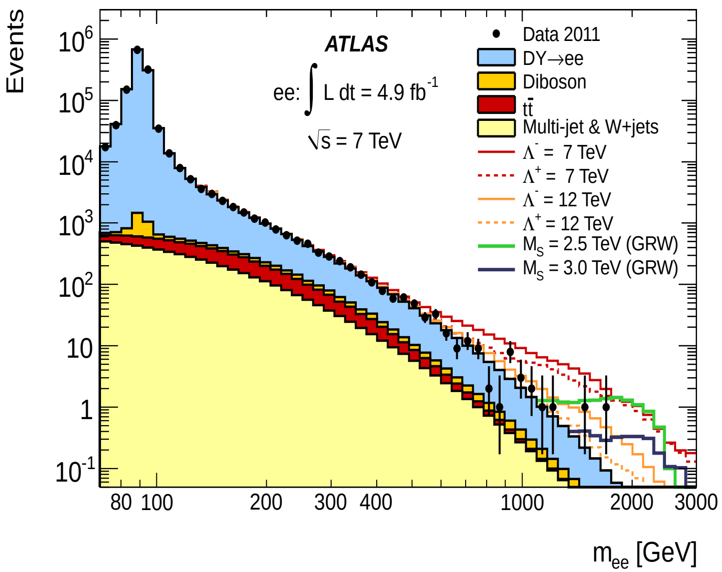
1409.2772, 1410.4798

Suppose the LHC does not find new particles.

Can look for deviations in tails of distributions.

....what to learn from:

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



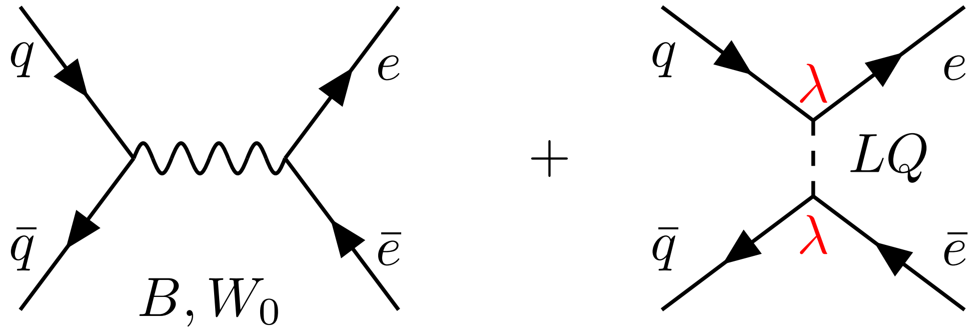
Of Mice and Men

Robbie Burns, J Steinbeck

1. why *not* to set bounds on contact interactions? A leptoquark example
   - interference
   - insufficient hierarchy of scales ($\hat{s} \sim \Lambda^2$)
2. looking for New Physics in the tail of $pp \to e^+e^-$
   - $\frac{d\sigma}{d\hat{s}} \approx C(\hat{s})\hat{\sigma}$ ...
     ... could *fit* the data?
   - fit it to what?
     form factors vs contact interactions
3. our estimated bounds from $pp \to e^+e^-$
   - one plot: constrain any t-channel leptoquarks $\to$ 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?

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



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

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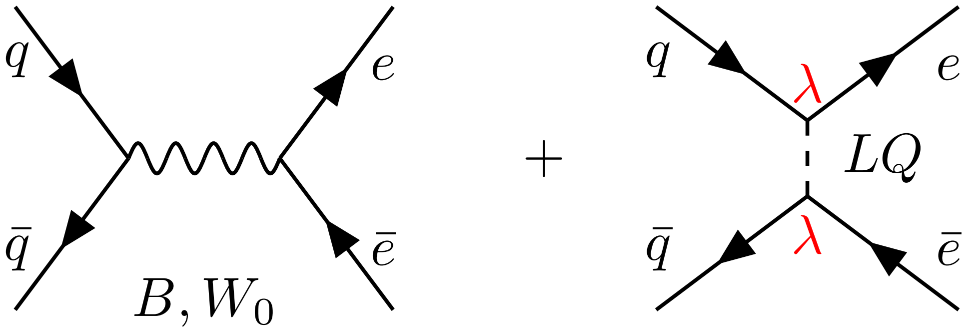

Want to set bound on a t-channel (scalar) leptoquark (7 possibilities)

(why?): pair production bound:

$$m_{LQ} \lesssim 1 \text{ TeV} \quad , \quad 10^{-8} \lesssim \lambda \lesssim 2\sqrt{\pi}$$

whereas $q\bar{q}e^+e^-$ contact interaction bound :

$$\Lambda \gtrsim 10 - 20 \text{ TeV}, \ \lambda^2 = 8\pi$$

$\Rightarrow$ **is there sensitivity to $m_{LQ} \gtrsim$ TeV , $\lambda \gtrsim 1$?**

Why bounds on contact interactions are not useful 1: interference

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

induces contact interaction $-\frac{|\lambda_R|^2}{2m_{LQ}^2}(\overline{u}\gamma^\mu P_R u)(\overline{e}\gamma_\mu P_R e)$ in $\hat{s} \ll m_{LQ}^2$ limit,

and partonic cross section (in CI limit) $\quad \hat{\sigma} = \left(\frac{11g^4}{96\hat{s}} - \frac{8g^2}{27}\frac{\lambda^2}{2m_{LQ}^2} + \frac{2}{3}\frac{\lambda^4 \hat{s}}{4m_{LQ}^4} \right)$

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Whereas exptal contact interaction :$-\sum_{q=u,d} \frac{\lambda^2}{2m_{LQ}^2}(\overline{q}\gamma^\mu P_L q)(\overline{e}\gamma_\mu P_L e)$

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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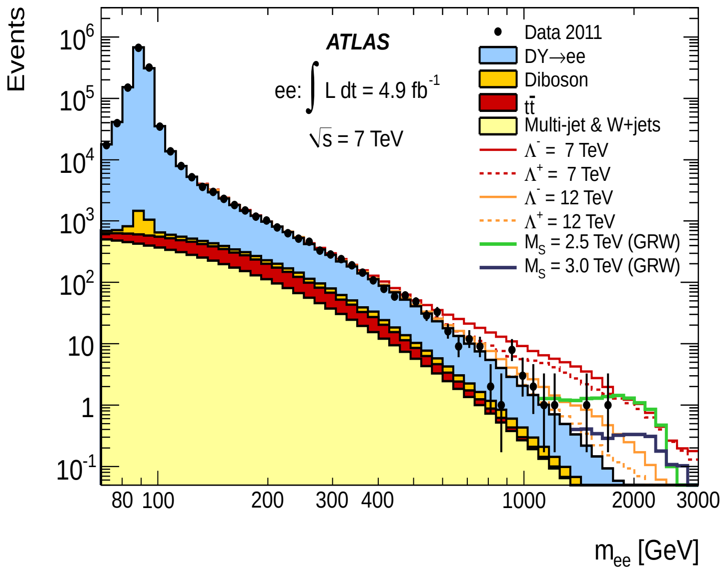
How to set a bound on the leptoquark?

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



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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...

Why bounds on contact interactions are not useful 2: $\hat{s} \sim \Lambda_{NP}^2$

Consider same SM singlet leptoquark S_0, interaction $\lambda S_0 \overline{e} P_R u^c$
partonic cross-section (not in CI limit) $\hat{\sigma}(q\bar{q} \to e^+e^-)$:

$$\hat{\sigma}_{DY} + \frac{1}{48\pi\hat{s}}\left[-\frac{2{g'}^2\lambda^2}{3}\left(\frac{1}{2} - \frac{m_{LQ}^2}{\hat{s}} + \frac{m_{LQ}^4}{\hat{s}^2}\ln(\frac{m_{LQ}^2+\hat{s}}{m_{LQ}^2})\right) + \frac{\lambda^4}{4}\left(1 - 2\frac{m_{LQ}^2}{\hat{s}}\ln(\frac{m_{LQ}^2+\hat{s}}{m_{LQ}^2}) + \frac{m_{LQ}^2}{(m_{LQ}^2+\hat{s})}\right)\right]$$

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

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

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   "form factors": non-local, not obtain from $\mathcal{L}$

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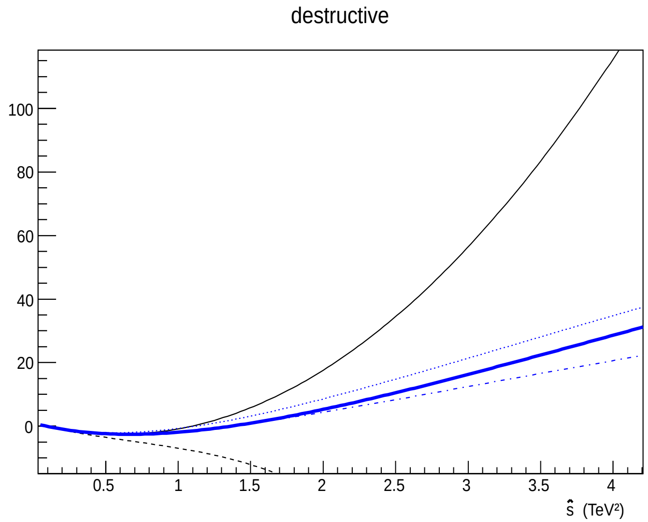

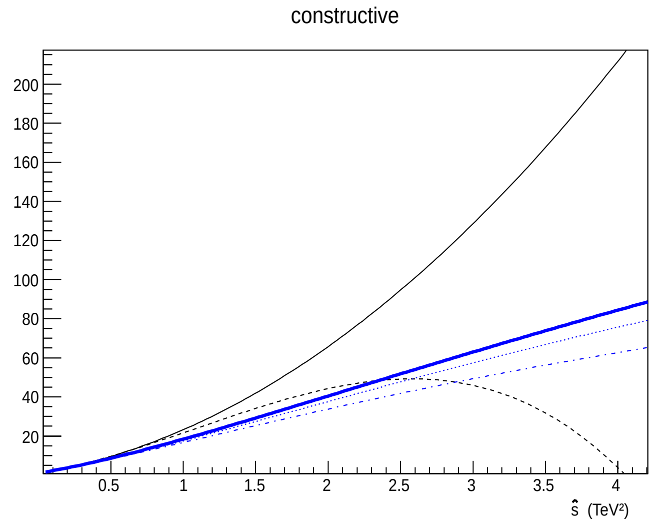

$m_{LQ} = 2\text{TeV}$

Using $pp \to \ell^+\ell^-$ Contact Interaction searches to constrain "strongly interacting" leptoquarks, exchanged in t channel, is not simple:
1) the shape of the deviation from the SM depends on LQ
2) contact interaction poor approx $\hat{\sigma}$ at $\hat{s} \simeq m_{LQ}^2$

What to do instead?

fit the data?

to what?

Fitting the data

claim: can write

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

Why is this interesting?: Can normalise to SM:

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

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]
\end{aligned}
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\end{aligned}$$

Guess a **form-factor** parametrisation from NP partonic x-section:

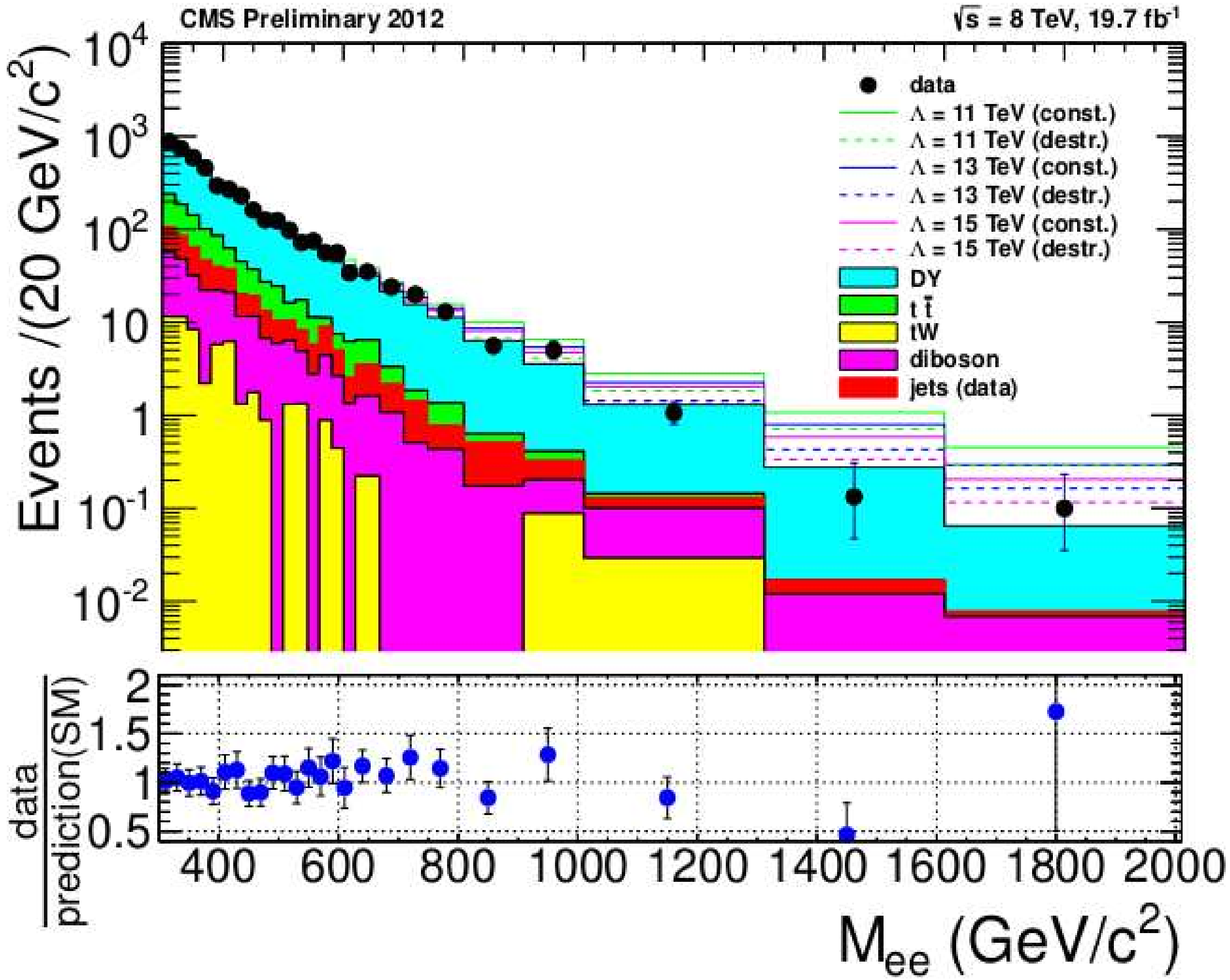
$$\frac{d\sigma}{d\hat{s}}(pp\to e^+e^-) = \frac{d\sigma_{SM}}{d\hat{s}}\left(1 + a\frac{\hat{s}}{1+c\hat{s}} + b\frac{\hat{s}^2}{(1+c\hat{s})^2}\right)$$

(Recall, for t-channel LQ exchange, had

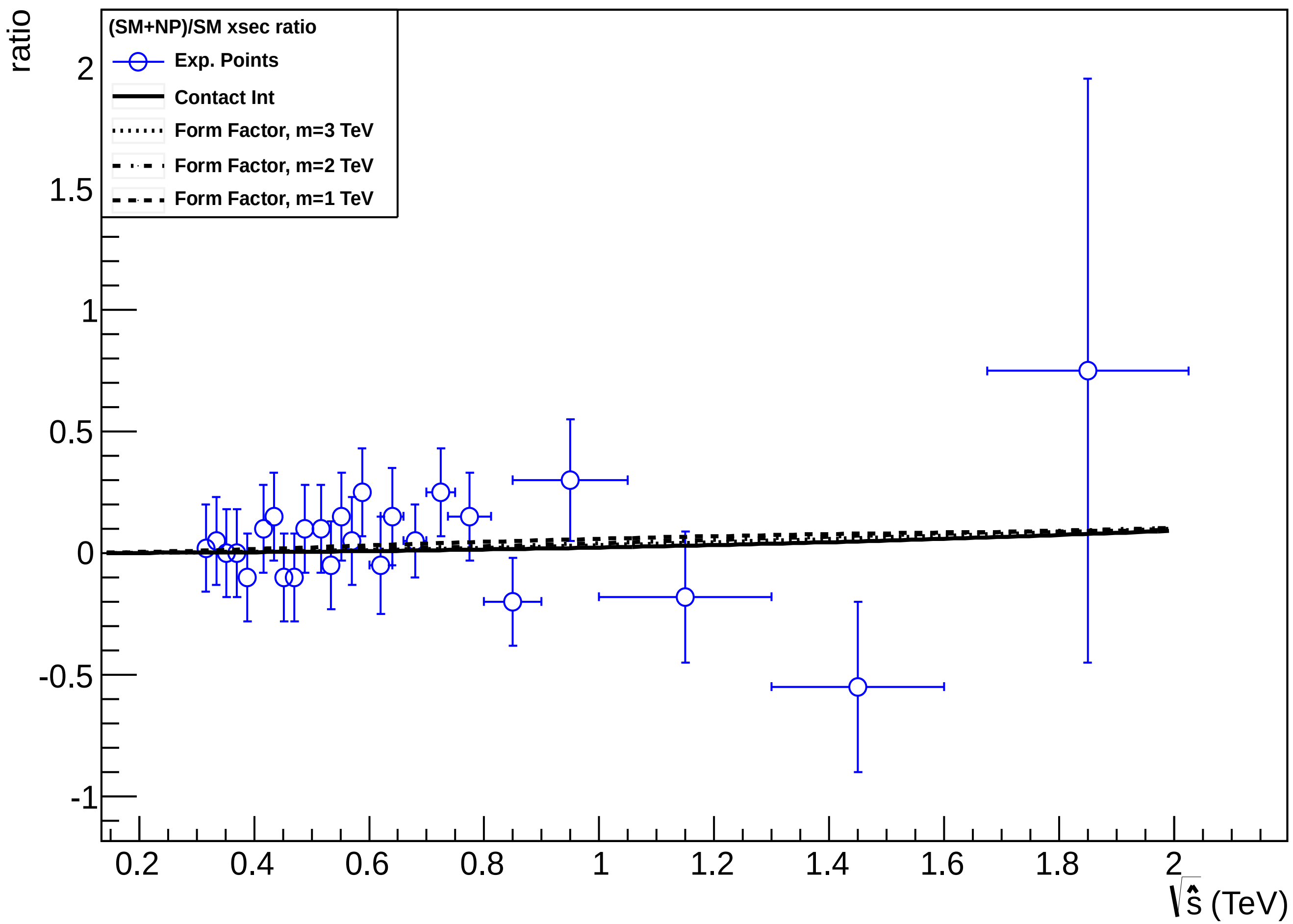
$$\hat{\sigma} \simeq \frac{1}{\hat{s}}\left(\frac{g_2^4}{8} + \epsilon_{int} g_2^2 \frac{4\pi}{\Lambda^2}\frac{\hat{s}}{(1+\hat{s}/m^2)} + \epsilon_{NP}\frac{16\pi^2}{\Lambda^4}\frac{\hat{s}^2}{(1+\hat{s}/m^2)^2}\right) \qquad 4\pi/\Lambda^2 \leftrightarrow \lambda^2/2m^2$$

$\Rightarrow$ fix $c = 1/m_{LQ}^2$ do linear fit data to a,b

CMS PAS EXO-12-020

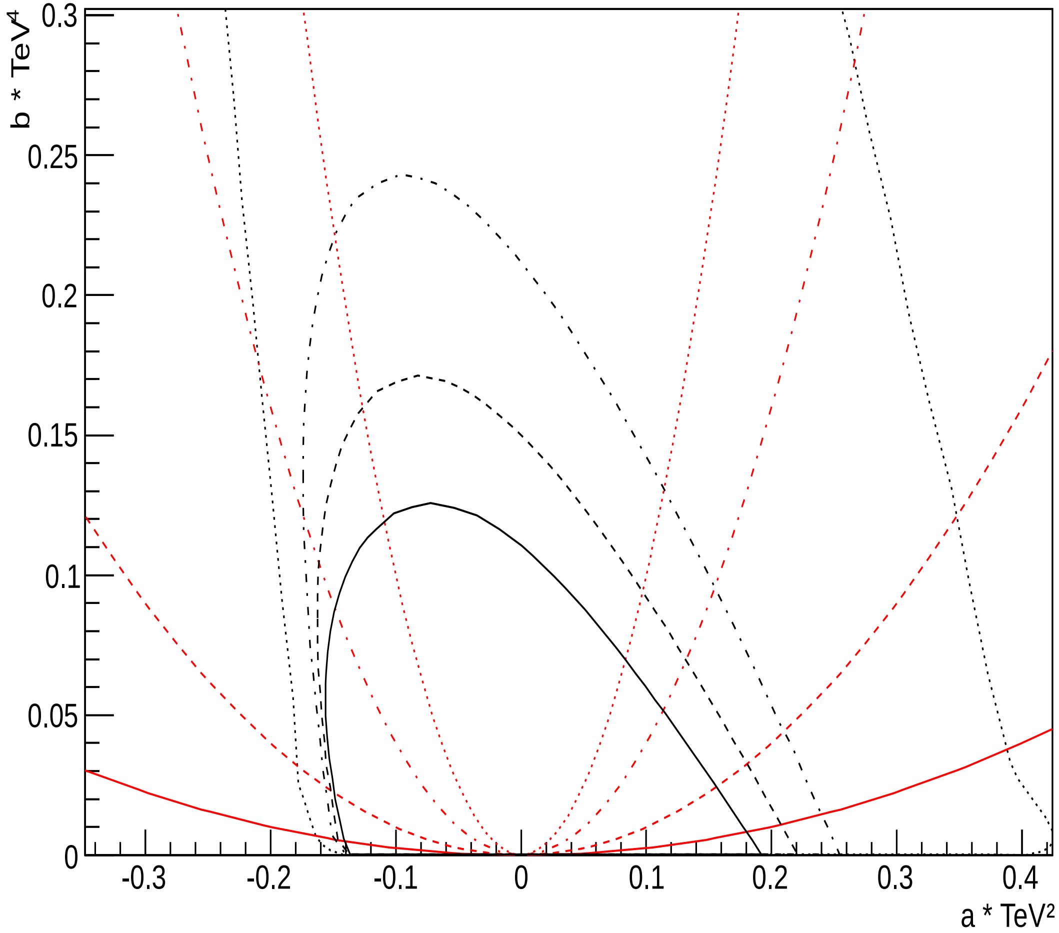


ee Cross Section Ratio



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

fit to e+e- data



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

To constrain a model

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

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

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

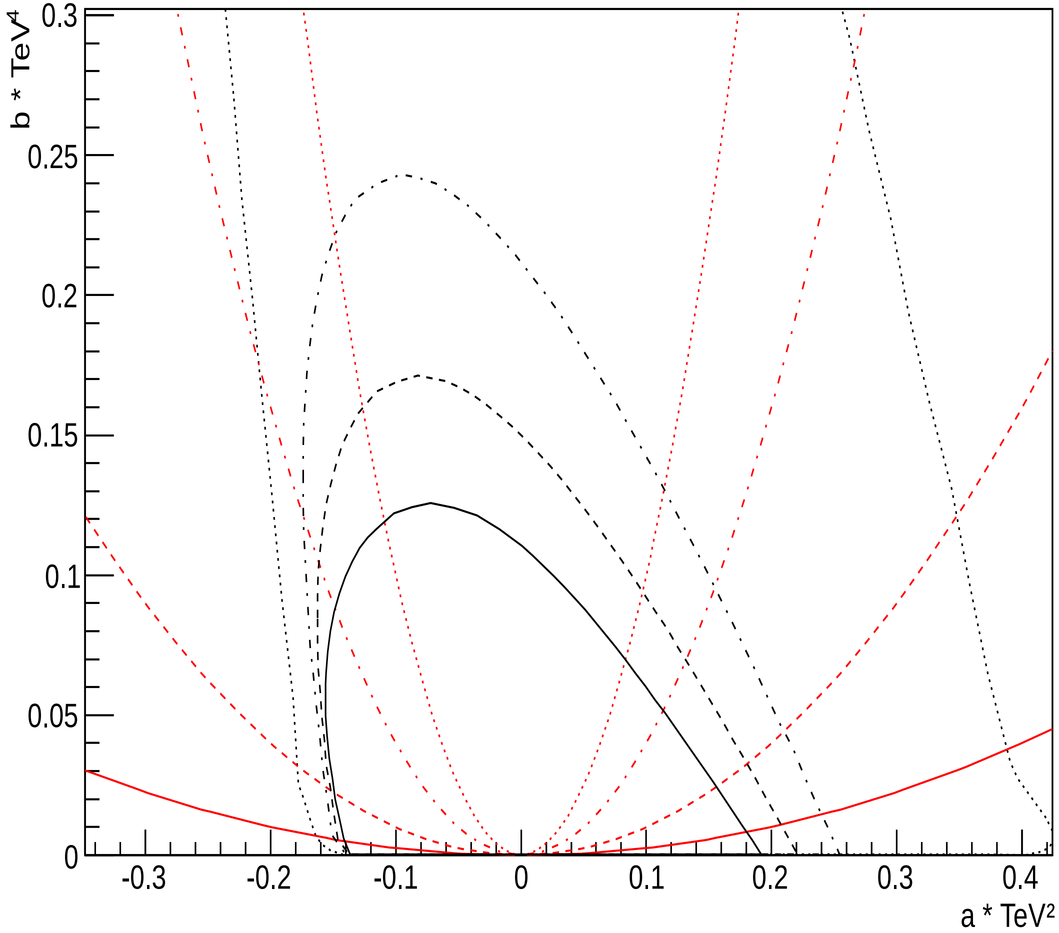
a, b, c *calculable* from partonic x-section of New Physics model

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

$$a = \frac{72\pi\epsilon_{int}}{\Lambda^2} \quad , \quad b \simeq \frac{\epsilon_{NP}}{[\Lambda/9.0]^4} \quad , \quad c = \frac{1}{m^2}$$

λ, 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



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So what? (summary)

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

Rather than simulate a model, or a collection of contact interactions, we fit the $pp \to \ell^+\ell^-$ data to form factors.

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

$$\Lambda_{des}^{DDGV} \geq 16.3 \text{ TeV} , \Lambda_{con}^{DDGV} \geq 19.0 \text{ TeV} , \Lambda_{des}^{CMS} \geq 13.5 \text{ TeV} , \Lambda_{con}^{CMS} \geq 18.3 \text{ TeV}$$

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.

Questions

1. does it really work with real data?
   (...unfolding, binning, etc...)

2. does it work for $pp \to 2j$ contact interaction searches?

   QCD contribution to $qq \to qq$ has t-channel divergence, so SM contribution diverges along beam-pipe

3. relation to "κ parameters" of Higgs data? Are contact interactions an acceptable NP parametrisation for Higgs physics?

...or we can always talk about axions...

What about s-channel New Physics?

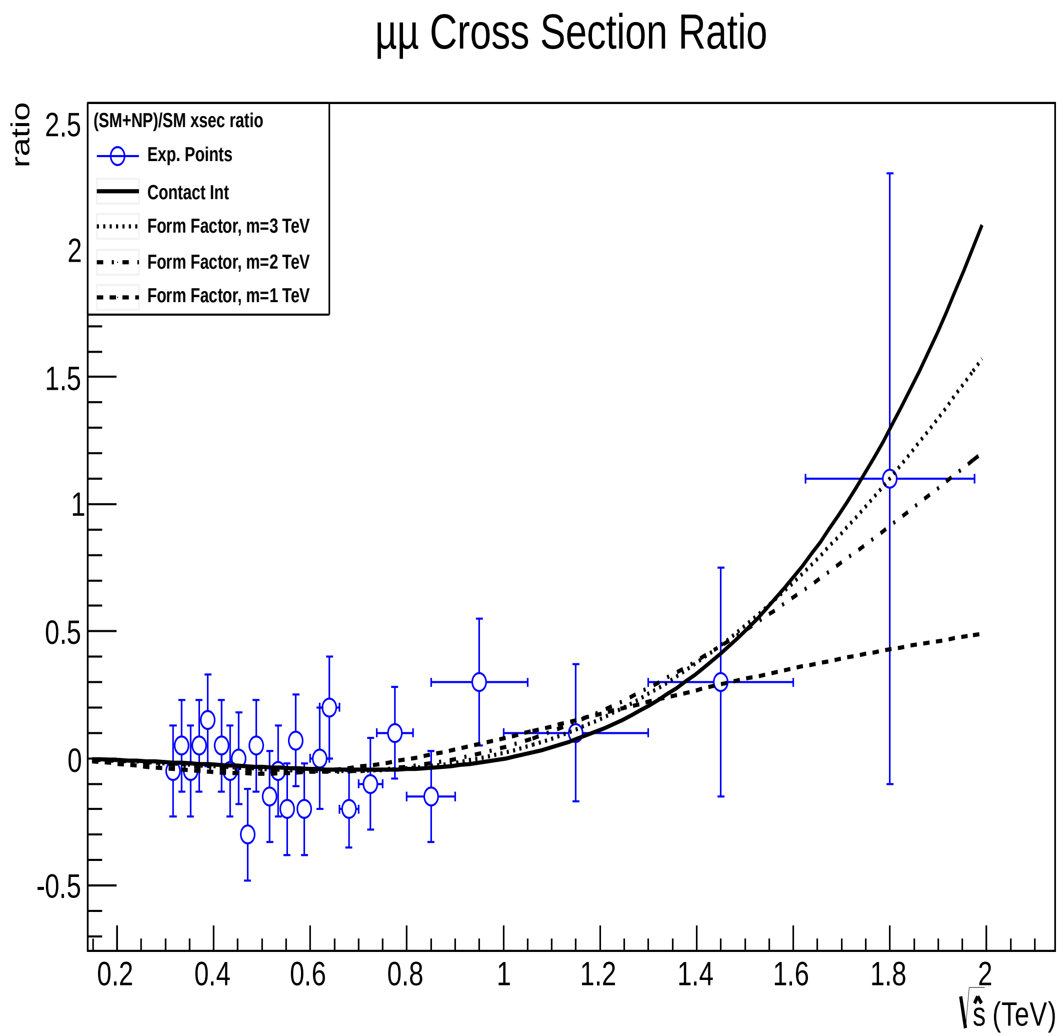
The rise towards the peak, for $\hat{s} \ll M^2$ can be parametrised as a contact interaction ($c \to 0$).

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

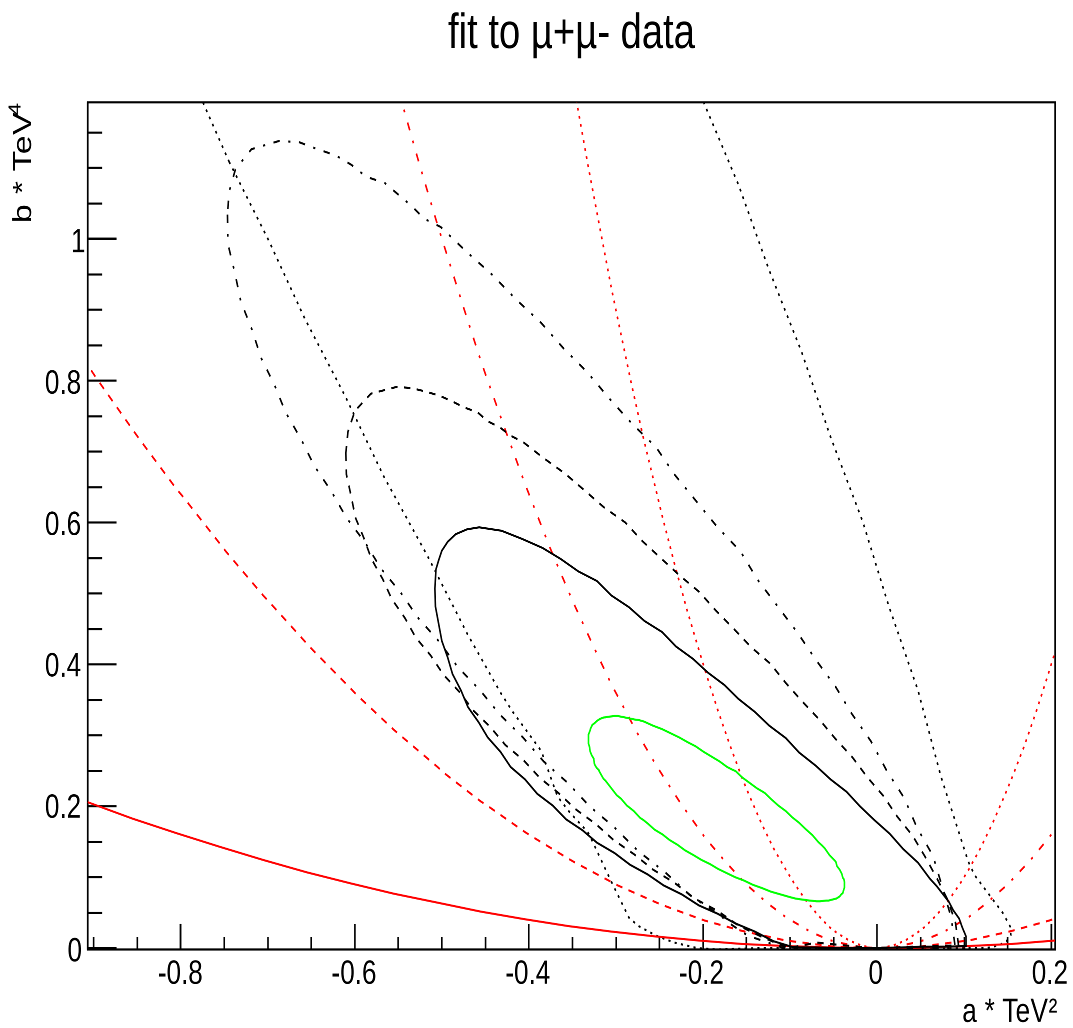
For $M^2 < \hat{s}$, possible (??) that an s-channel resonance could contribute a shoulder (like t-channel exchange) in the binned $pp \to \ell^+\ell^-$ data.

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

The $pp \to \mu^+\mu^-$ data



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



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Leptoquark limits

leptoquark	$m_{LQ} = 3$ TeV, $\lambda^2 <$	$m_{LQ} = 2$ TeV, $\lambda^2 <$	$m_{LQ} = 1$ 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
$\tilde{S}_2, \lambda_{L\tilde{S}_2}$	1.9	0.98	0.47
S_1, λ_{LS_1}	0.94	0.49	0.23

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

interaction	Fierz − transformed $\mathcal{M}$
$(\lambda_{LS_o}\overline{q^c}i\sigma_2\ell+\lambda_{RS_o}\overline{u^c}e)S_o^\dagger$	$(\overline{u}\gamma^\mu P_R u)(\overline{e}\gamma_\mu P_R e)\left(\frac{\|\lambda_R\|^2}{2(m_o^2-\hat{\tau})}-\frac{2}{3}\frac{g'^2}{\hat{s}}\right)$ $(\overline{u}\gamma^\mu P_L u)(\overline{e}\gamma_\mu P_L e)\left(\frac{\|\lambda_L\|^2}{2(m_o^2-\hat{\tau})}-\frac{1}{4}\frac{g^2}{\hat{s}}\right)$
$\lambda_{R\tilde{S}_o}\overline{d^c}e\tilde{S}_o^\dagger$	$(\overline{d}\gamma^\mu P_R d)(\overline{e}\gamma_\mu P_R e)\left(\frac{\|\lambda_R\|^2}{2(\tilde{m}_o^2-\hat{\tau})}+\frac{1}{3}\frac{g'^2}{\hat{s}}\right)$
$(\lambda_L\overline{u}\ell+\lambda_R\overline{q}i\sigma_2 e)S_2^\dagger$	$(\overline{u}\gamma^\mu P_R u)(\overline{e}\gamma_\mu P_L e)\left(-\frac{\|\lambda_L\|^2}{2(m_2^2-\hat{\tau})}-\frac{1}{3}\frac{g'^2}{\hat{s}}\right)$ $(\overline{u}\gamma^\mu P_L u)(\overline{e}\gamma_\mu P_R e)\left(-\frac{\|\lambda_R\|^2}{2(m_2^2-\hat{\tau})}-\frac{1}{6}\frac{g'^2}{\hat{s}}\right)$ $+(\overline{d}\gamma^\mu P_L d)(\overline{e}\gamma_\mu P_R e)\left(-\frac{\|\lambda_R\|^2}{2(m_2^2-\hat{\tau})}-\frac{1}{6}\frac{g'^2}{\hat{s}}\right)$
$\lambda_{L\tilde{S}_2}\overline{d}\ell\tilde{S}_2^\dagger$	$(\overline{d}\gamma^\mu P_R d)(\overline{e}\gamma_\mu P_L e)\left(-\frac{\|\lambda_L\|^2}{2(\tilde{m_2}^2-\hat{\tau})}+\frac{1}{6}\frac{g'^2}{\hat{s}}\right)$
$\lambda_{LS_1}\overline{q^c}i\sigma_2\vec{\sigma}\ell\cdot\vec{S_1}^\dagger$	$(\overline{u}\gamma^\mu P_L u)(\overline{e}\gamma_\mu P_L e)\left(\frac{\|\lambda_L\|^2}{2(m_1^2-\hat{\tau})}-\frac{1}{4}\frac{g^2}{\hat{s}}\right)$ $+(\overline{d}\gamma^\mu P_L d)(\overline{e}\gamma_\mu P_L e)\left(\frac{\|\lambda_L\|^2}{(m_1^2-\hat{\tau})}+\frac{1}{4}\frac{g^2}{\hat{s}}\right)$