Of Contact Interactions and Colliders

A Bessaa, **Sacha Davidson**, S. Descotes-Genon, P. Verdier
IPN de Lyon/CNRS, France
1409.2772, 1410.4798

Suppose the LHC does not find new particles.

...build a bigger one?

...develop new acceleration technology?

Can look for deviations in tails of distributions.

Is it useful/justified to use Contact Interactions at the LHC?

A Bessaa, **Sacha Davidson**, S. Descotes-Genon, P. Verdier
IPN de Lyon/CNRS, France
1409.2772, 1410.4798

Suppose the LHC does not find new particles.

...build a bigger one? ...develop new acceleration technology?

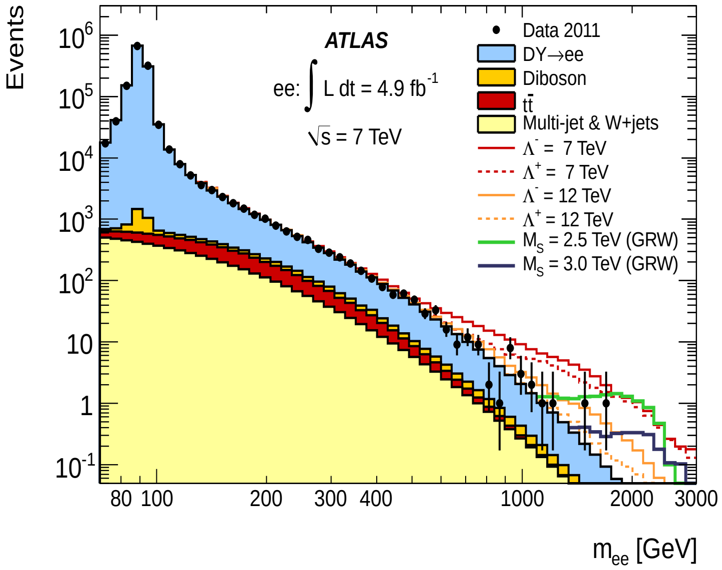
Can look for deviations in tails of distributions.

Are Contact Interactions useful/justified at the LHC?

A Bessaa, **Sacha Davidson**, S. Descotes-Genon, P. Verdier
IPN de Lyon/CNRS, France
1409.2772, 1410.4798

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

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



...rather than simulating and constraining models...*fit* the data (1307.5068 etal + Santiago)

...rather than contact interactions ...use *non-local* "form factors"

Outline: looking for New Physics in the tail of $pp \to e^+e^-$

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: CI assumes $\hat{s} \ll \Lambda^2$ ... its not.

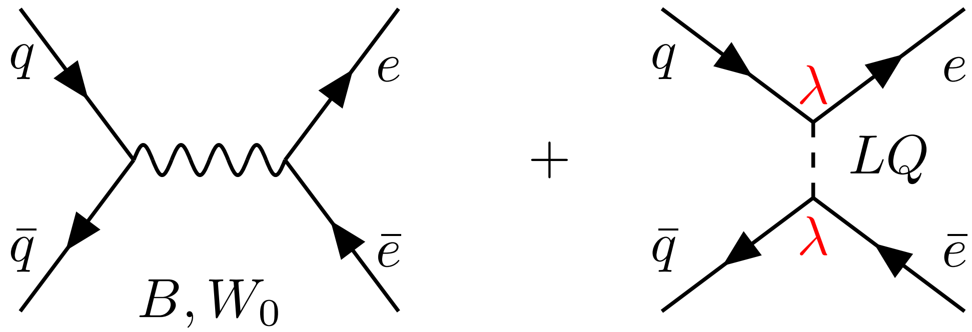
$\hat{s}$ = cm energy
CI coeff $= \frac{4\pi}{\Lambda^2}$

2. instead: *fit* the data ($= pp \to e^+e^-$) ...to what?
   - $\frac{d\sigma}{d\hat{s}}(pp \to e^+e^-) \propto$ partonic cross-section
   - choose fit parameters from partonic cross-section (whose parameters are "almost observables")

3. our estimated bounds from $pp \to e^+e^-$
   - one plot: constrain any t-channel leptoquarks any combo of contact interactions

Use bounds on contact interactions to constrain leptoquarks?

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



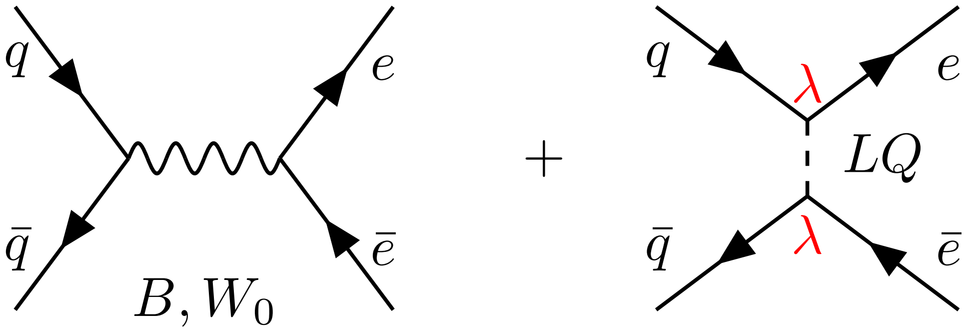
Want to set bound on a t-channel (scalar) leptoquark (7 possibilities)

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: $\frac{|\lambda_R|^2}{2m_{LQ}^2} = \frac{4\pi}{\Lambda^2}$

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)

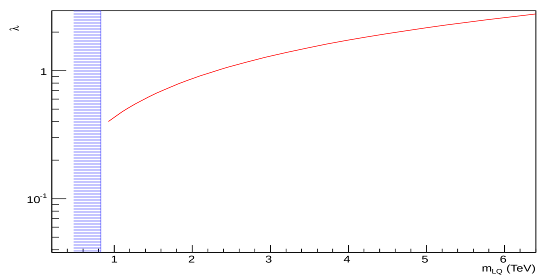
(why?): pair production bound:

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

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

New Physics (leptoquark, contact interaction,...) can interfere with the SM

magnitude + sign of interference $\begin{cases} \text{model} - \text{dependent} \\ \text{control shape of deviation from SM} \end{cases}$

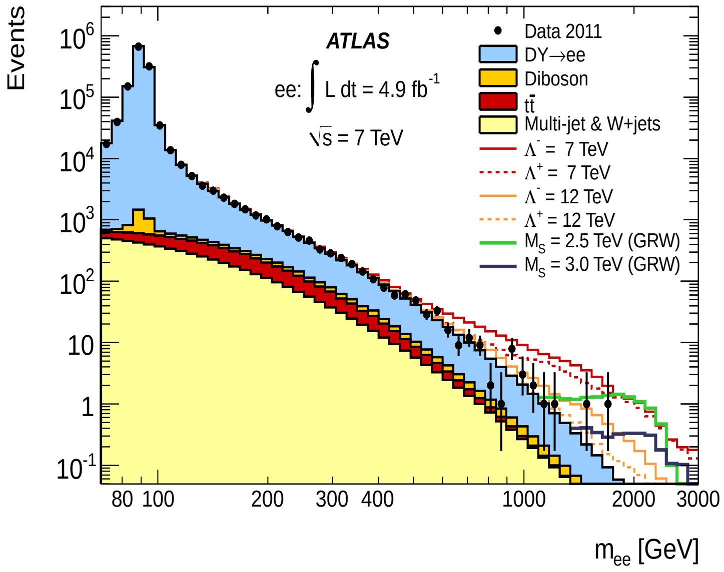
Why bounds on contact interactions are not useful 1: interference

New Physics (leptoquark, contact interaction,...) can interfere with the SM

magnitude + sign of interference $\begin{cases} \text{model} - \text{dependent} \\ \text{control shape of deviation from SM} \end{cases}$

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...

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

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

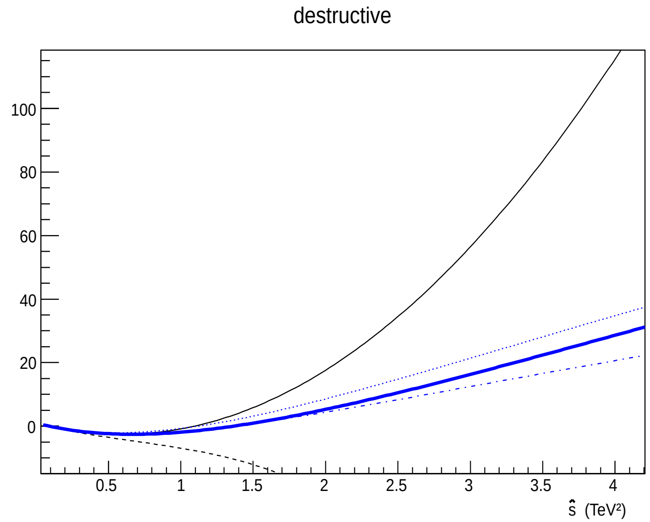
Why bounds on contact interactions are not useful 2: $\hat{s} \sim \Lambda_{NP}^2$

Can see a contact interaction above SM background when : $\frac{4\pi}{\Lambda^2} > \frac{e^2}{\hat{s}} \quad \Rightarrow \Lambda^2 < \frac{\hat{s}}{\alpha_{em}}$

But need : $\Lambda^2 \gg \hat{s}$ in contact approximation ...how much bigger?

Consider partonic cross-section for singlet leptoquark $\hat{\sigma}(q\bar{q} \to e^+e^-)$:

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



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

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

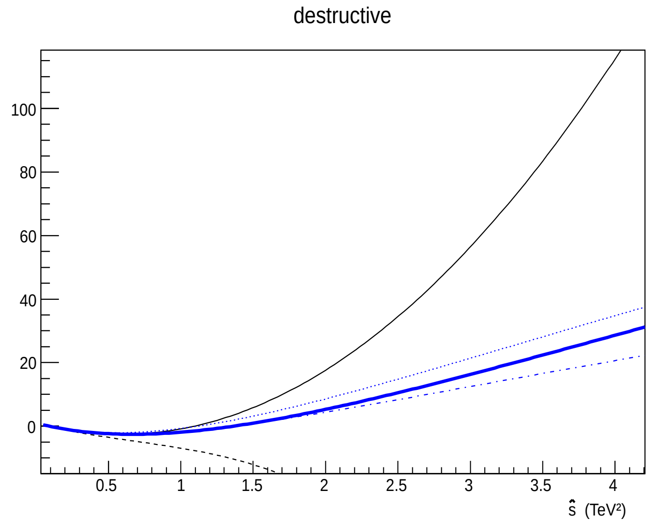
Can see a contact interaction above SM background when : $\frac{4\pi}{\Lambda^2} > \frac{e^2}{\hat{s}} \quad \Rightarrow \Lambda^2 < \frac{\hat{s}}{\alpha_{em}}$

But need : $\Lambda^2 \gg \hat{s}$ in contact approximation ...how much bigger?

Consider partonic cross-section for singlet leptoquark $\hat{\sigma}(q\bar{q} \to e^+e^-)$:

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

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



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

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

Can see a contact interaction above SM background when : $\frac{4\pi}{\Lambda^2} > \frac{e^2}{\hat{s}} \quad \Rightarrow \Lambda^2 < \frac{\hat{s}}{\alpha_{em}}$

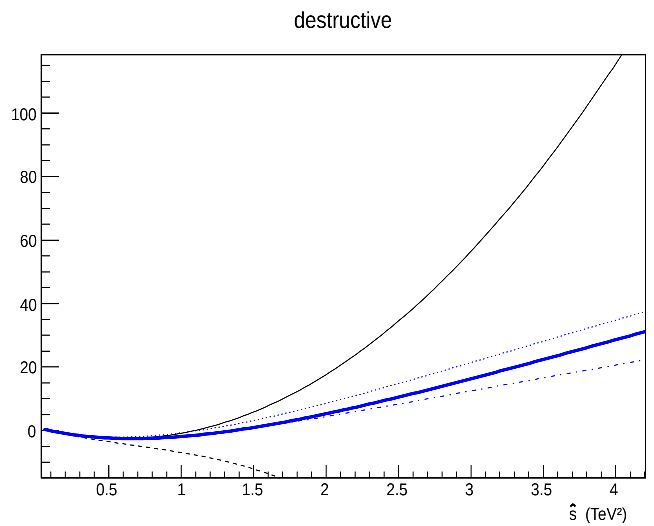
But need : $\Lambda^2 \gg \hat{s}$ in contact approximation ...how much bigger?

Consider partonic cross-section for singlet leptoquark $\hat{\sigma}(q\bar{q} \to e^+e^-)$:

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

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

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



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

fit the data?

to what?

Fitting the data

claim: can write

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

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)

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

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

Why is this interesting?: Can normalise to SM:

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

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

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

Why is this interesting?: Can normalise to SM:

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

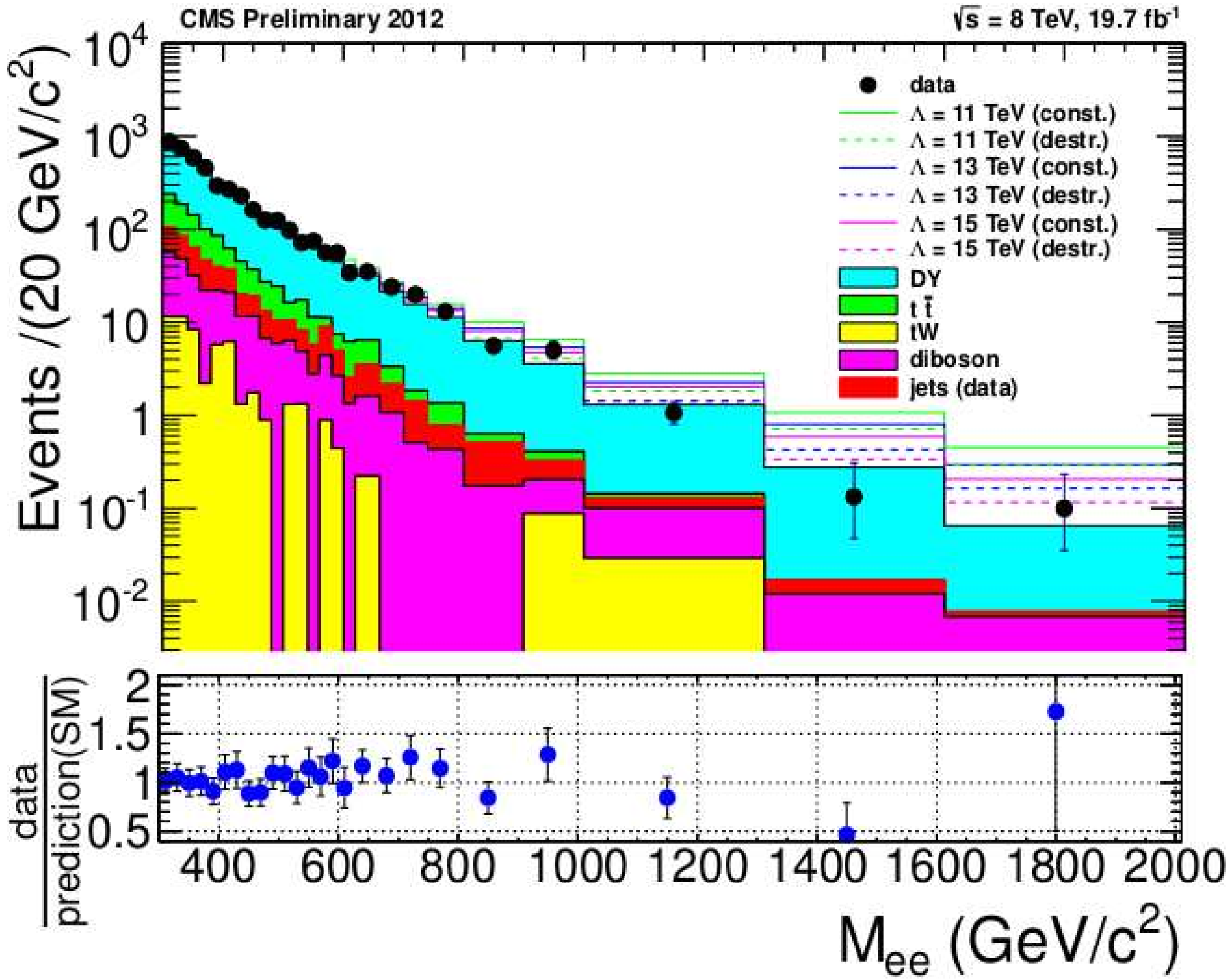
$$\frac{d\sigma}{d\hat{s}}(pp \to e^+e^-) \quad = \quad \frac{d\sigma_{SM}}{d\hat{s}}\left(1 + a\frac{\hat{s}}{1+c\hat{s}} + b\frac{\hat{s}^2}{(1+c\hat{s})^2}\right)$$

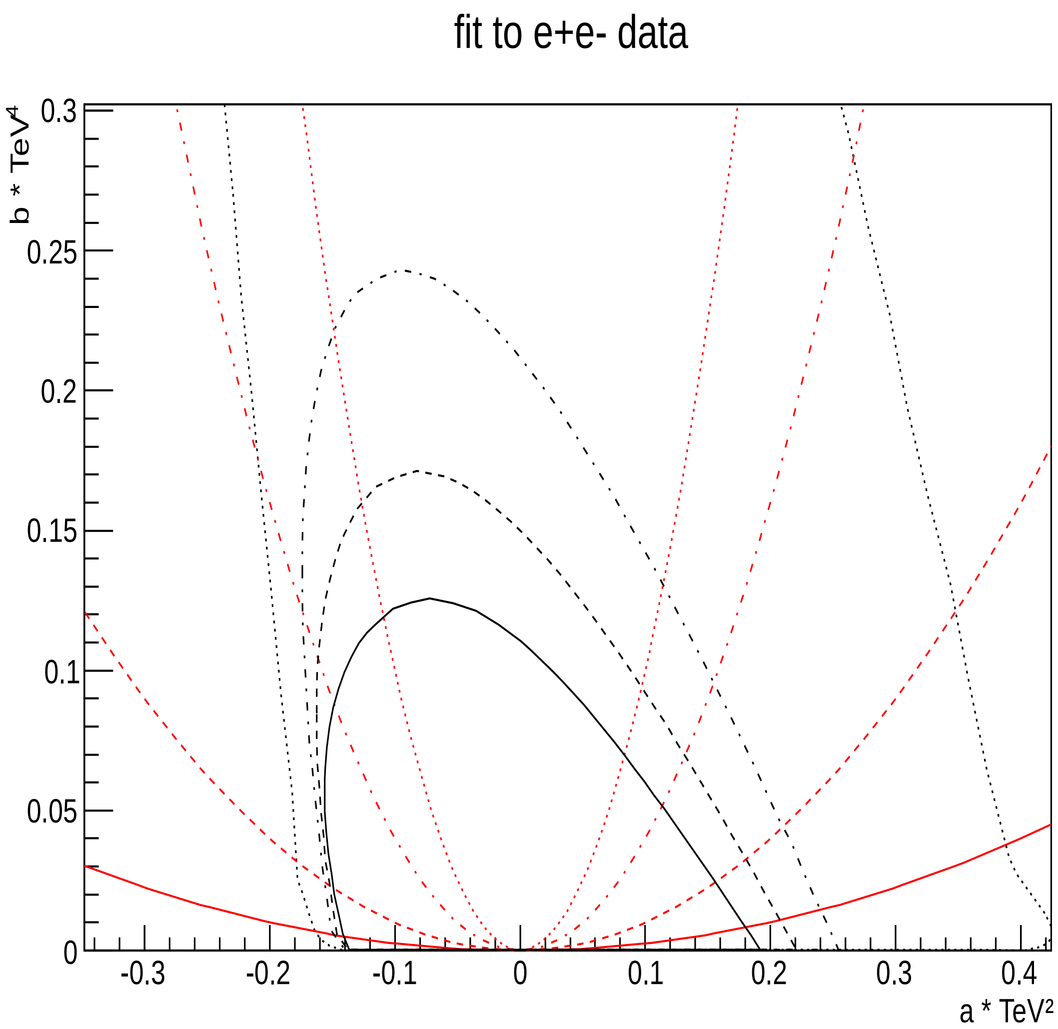
(Recall, for t-channel LQ exchange, had

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

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

CMS PAS EXO-12-020





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

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

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." The form factors are motivated by the partonic cross-section, so translating bounds on fit parameters to models is simple.

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.

 *fit data to "form factors"* 

Other things

! Thank you !
to organisers and speakers
for an interesting conference

In July 2017, there will be summer school at Les Houches about EFT (organised by Matthias Neubert, Mikko Laine, Paolo Gambino and me).
Suggestions (topics, lecturers, organisation) are welcome, and please send your students :)

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...)

To constrain a model

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

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

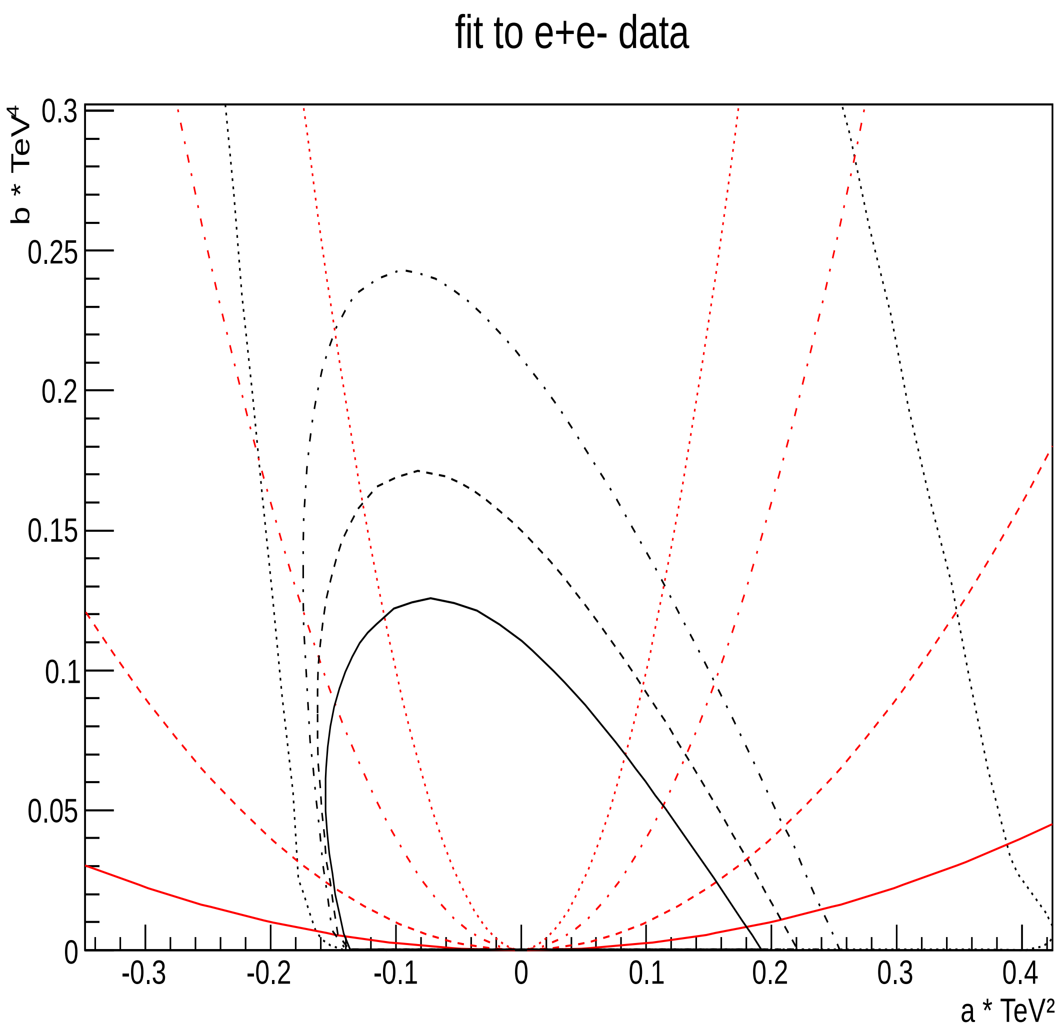
$\Rightarrow$ allowed ellipses in a, b for given c.

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

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

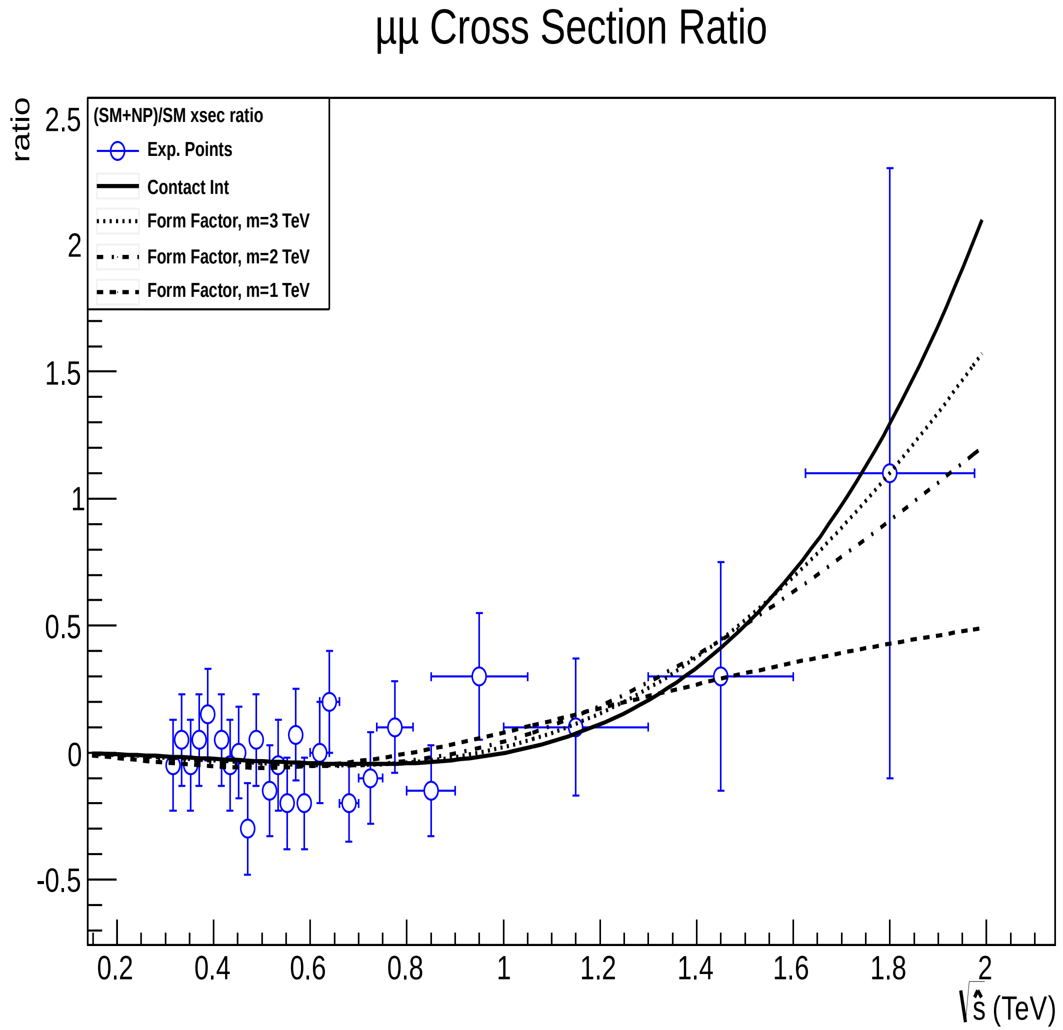
$$a = \frac{72\pi\epsilon_{int}}{\Lambda^2} \quad , \quad b \simeq \frac{\epsilon_{NP}}{[\Lambda/9.0]^4} \quad , \quad c = \frac{1}{m^2}$$

λ, m *parameters* to constrain:
$\epsilon_{int}, \epsilon_{NP}$ *constants* of NP model, calculable from partonic xsection: $a^2 \propto \frac{\epsilon_{int}}{\epsilon_{NP}^2} b$



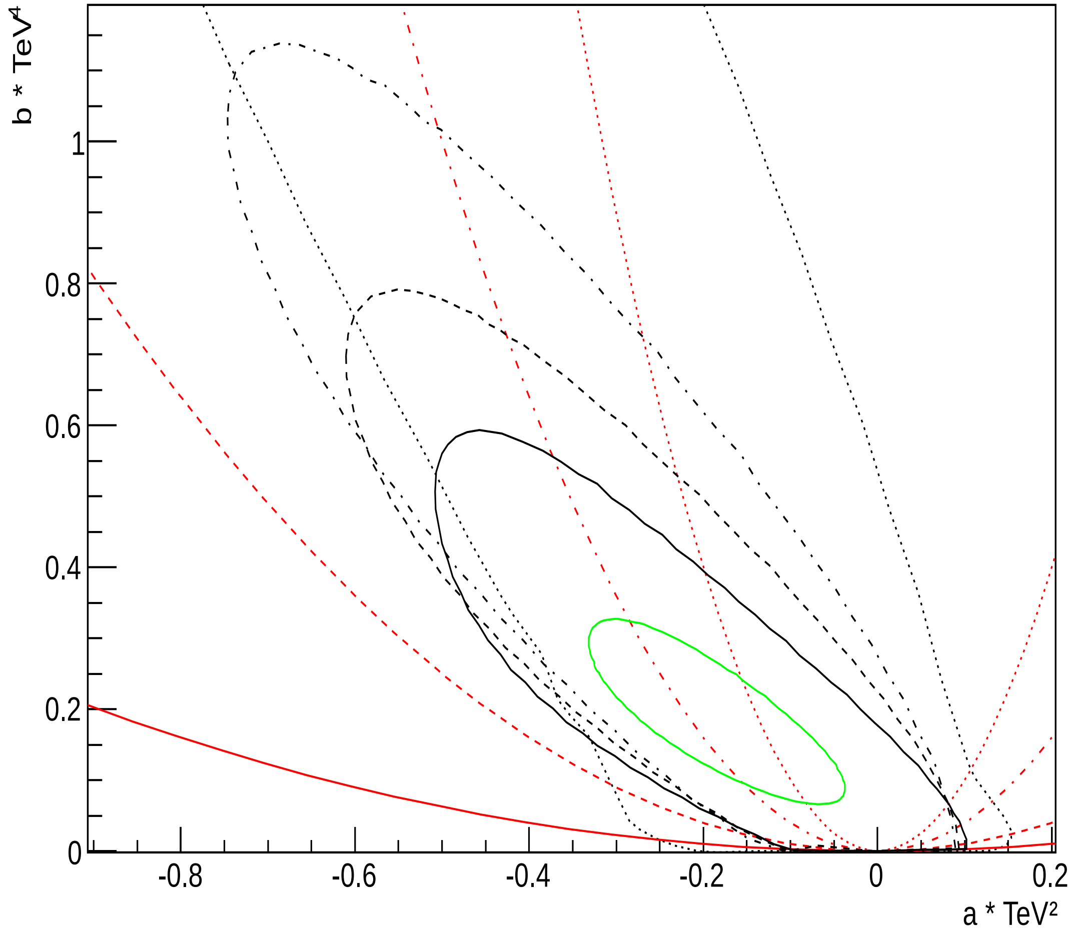
$$a^2 \propto \frac{\epsilon_{int}}{\epsilon_{NP}^2} b \quad , \quad b \simeq \frac{\epsilon_{NP}}{[\Lambda/9.0]^4} \quad , \quad c = \frac{\mathrm{TeV}^2}{m^2} = \mathbf{0}, \frac{1}{9}, \frac{1}{4}, 1$$

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



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

fit to μ+μ- data



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

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

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

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