Four-Quark Effective Operators at Hadron Colliders

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July 25, 2015

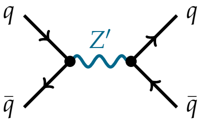
CONSTRAINING BSM RESONANCES

How do we constrain heavy BSM resonances with the LHC?

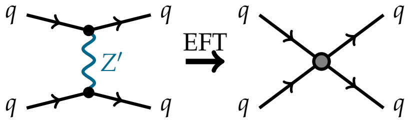
EXAMPLE:

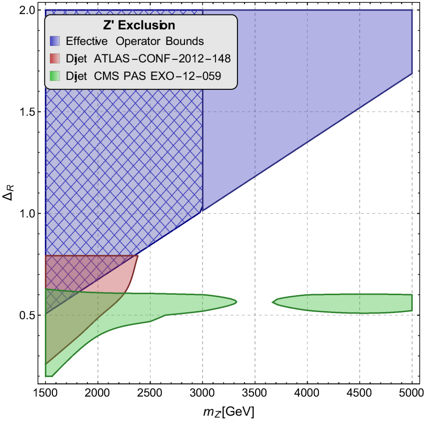
Hadronic Z': massive spin-1 resonance coupling to quarks

ON-SHELL (DIJET RESONANCE)



OFF-SHELL (4-QUARK EFT)





CONSTRAINING BSM RESONANCES

How do we constrain heavy BSM resonances with the LHC?

EXAMPLE:

Hadronic Z': massive spin-1 resonance coupling to quarks

ON-SHELL (DIJET RESONANCE)

Only narrow widths ($\Gamma/m < 15\%$)

Constrains only low couplings

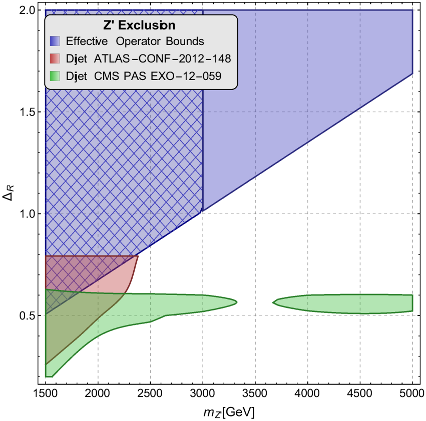
Only for moderate masses

OFF-SHELL (4-QUARK EFT)

Constrains high couplings

Validity for $m \sim \sqrt{q} \sim 1$ TeV?

Topic of this talk!

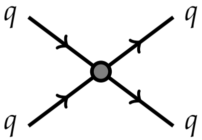


EFFECTIVE OPERATORS AT HADRON COLLIDERS

- Focus on four-quark effective operators
- LHC constrains Λ in the operator:

$$\mathcal{L} = \pm \frac{2\pi}{\Lambda^2} \left(\bar{q}\gamma^\mu q\right)\left(\bar{q}\gamma^\mu q\right)$$

[CMS arXiv:1202.5535]
[ATLAS arXiv:1210.1718]



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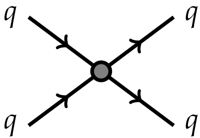

What about the validity of these limits on Λ from the LHC?

- EFT expansion depends on q^2/m^2, where q^2 is the transfer energy and m the mass of the particle being integrated out
- Validity of the EFT expansion is in trouble if $q^2 \simeq m^2$ (true for LHC processes), so need to control errors on the Λ limits

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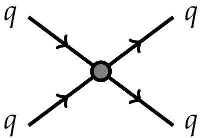

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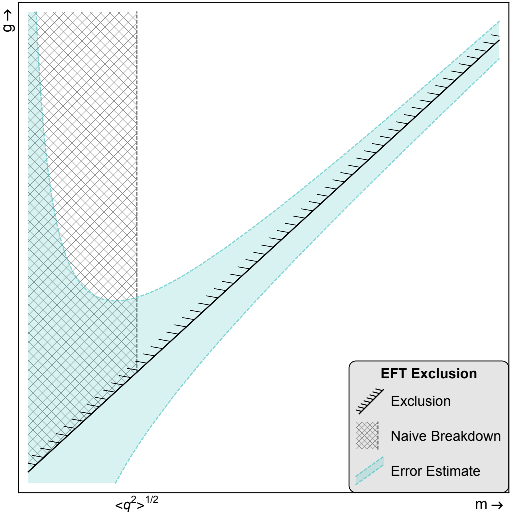
Goal: Estimate the errors and the validity of EFT limits at hadron colliders when translated to BSM theories

NAIVE EFT EXCLUSIONS



- EFT is an expansion:

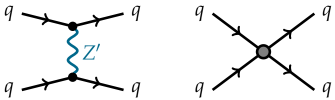
$$\frac{g^2}{q^2 - m^2} \stackrel{q^2 \to 0}{=} -\frac{g^2}{m^2}\left[1 + \mathcal{O}\left(\frac{q^2}{m^2}\right)\right]$$

- Limits on $\Lambda \simeq \frac{m}{g}$
- Naive validity: $m^2 > \langle q^2 \rangle$
- In reality the errors scale as $\frac{q^2}{m^2}$, since only looking at the first term in the expansion

STRATEGY: TOY MODELS

- Investigate two toy models: hadronic Z' and G' (only couples to quarks)
- Full theory: coupling g and mass m
- Effective theory: $\frac{2\pi}{\Lambda^2} = -\frac{g^2}{2m^2}$

Full & EFT Description:



[See back up slides for toy model details]

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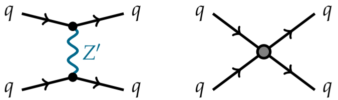


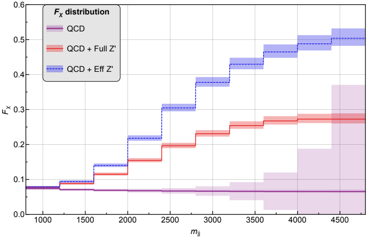
[See back up slides for toy model details]

> Compare full and effective description in actual experimental dijet analysis

[CMS arXiv:1202.5535; ATLAS arXiv:1210.1718]

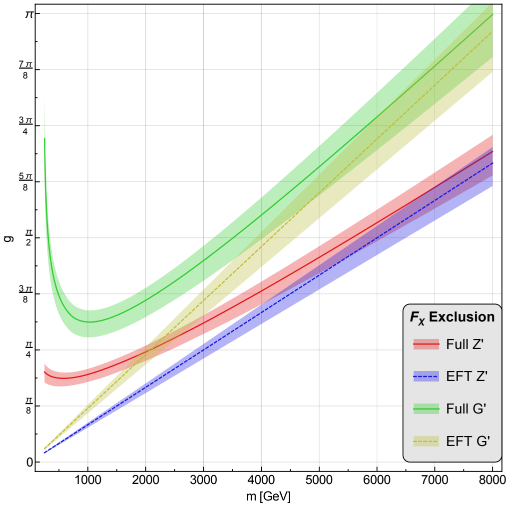
- ATLAS and CMS look into angular deviations from dijet QCD
- ATLAS: $F_\chi = \frac{N_{\text{central}}}{N_{\text{total}}}$ binned in m_{dijet}

[See back up slides for the analysis]



> Scan over full theory m and g and effective theory Λ and compare their exclusion regions in the coupling versus mass plane

EFT versus Full Theory Exclusion

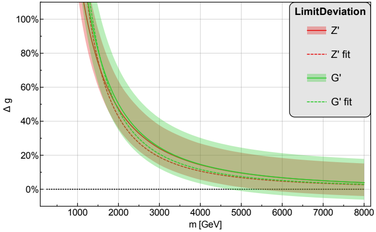


[See back up slides for 14 TeV results]

- Region above lines is excluded: EFT (solid) full theory (dashed)
- Bands: theory error
- $\Lambda_{Z'} = 13.5^{+1.1}_{-0.7}$ TeV
  $\Lambda_{G'} = 9.4^{+1.0}_{-0.6}$ TeV
- EFT overestimates real exclusion
- Deviation decreases with increasing mass
- Continuous effect, dangerous to speak about EFT cut-off
- $\langle q^2 \rangle \approx 0.5 - 1.5$ TeV

EXISTING LIMIT RECAST

- Extract deviation between full and effective description by comparing limit on g for variable mass
- Quantify using $\Delta g \equiv \frac{g_{\text{full}} - g_{\text{eff}}}{g_{\text{eff}}}$
- Can be fitted as $\Delta g \simeq \frac{C^2}{m^2}$
- Result: $C_{Z'} = 1.31^{+0.20}_{-0.20}$ TeV



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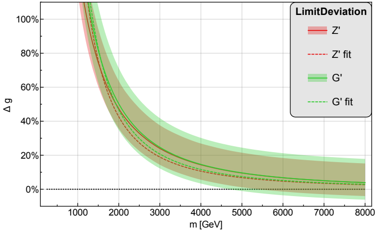
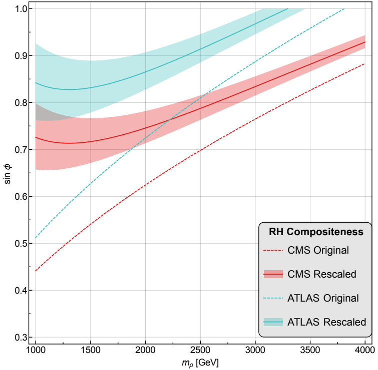
- Result: $C_{Z'} = 1.31^{+0.20}_{-0.20}$ TeV
- The fitted deviation can be used to rescale existing bounds from effective operators to more reliable limits

[Redi et al. arXiv:1305.3818]

- Composite Higgs example: Colour octet ρ with couplings to SM quarks
- Large deviations are observed and generally expected for strongly coupled physics

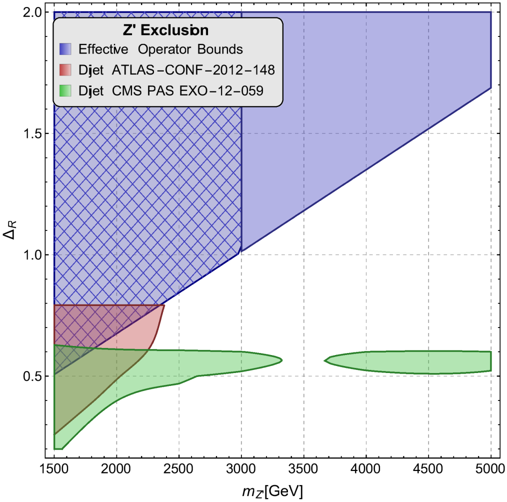




Z' Recast

Rescale the EFT limits on the Z' to obtain reliable limits

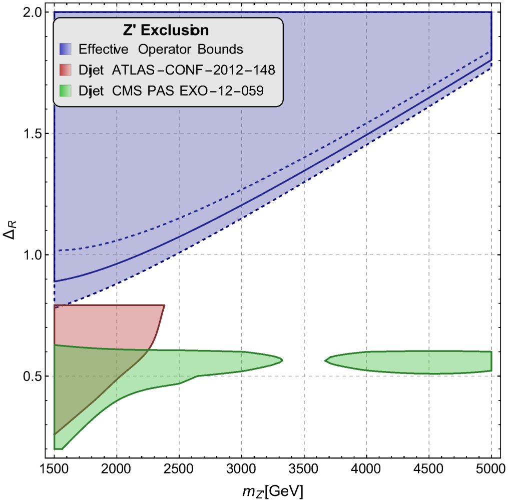
- Original limits constrain Z' up to 2 TeV for reasonably large couplings
- Compare rescaled limit with the original in blue



Z' Recast

Rescale the EFT limits on the Z' to obtain reliable limits

- Original limits constrain Z' up to 2 TeV for reasonably large couplings
- Compare rescaled limit with the original in blue
- Highly reduced limits
- Constraint on Z' is gone due to open window around $\Delta_R = 0.85$
- Need for dedicated and improved searches



RECOMMENDATION: TRANSFER ENERGIES

Important: Average transfer energies of the events used in the limit setting determine the validity of the EFT constraints

[Englert, Spannowsky arXiv:1408.5147]

THEORETICALLY

We can calculate $\langle\hat{s}\rangle$, $\langle\hat{t}\rangle$, $\langle\hat{u}\rangle$ for specific binning in $\hat{s}$ and χ:

[See back up slides for actual values]

$$\langle\hat{t}\rangle = \frac{1}{\sigma_{\text{tot}}} \int_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} d\hat{s} \int_{\chi_{\text{min}}}^{\chi_{\text{max}}} d\chi \, \frac{-\hat{s}}{1+\chi} \frac{d^2\sigma}{d\hat{s}d\chi}$$

EXPERIMENTALLY

- Known: $\hat{s}$ and χ on an event by event basis (dijet system)
- Average over all events using $\hat{s} + \hat{t} + \hat{u} = 0$

Easy to obtain and allows for more reliable interpretation of the EFT limits

REQUEST: RECAST Z'/G'

Limits in the mass versus coupling plane for Z' and G' toy models help to estimate the EFT validity and can be recasted to specific BSM resonances (for reliable limits)

- Provide limits on the toy models:

$$\mathcal{L}_{Z'} \supset -\frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + g_{Z'}\, \bar{q}_i \gamma^{\mu} \delta_{ij} q_j\, Z'_{\mu}$$

$$\mathcal{L}_{G'} \supset -\frac{m_{G'}^2}{2} G'^{a\mu} G'^{a}_{\mu} + g_{G'}\, \bar{q}_i \gamma^{\mu} T^a_{ij} q_j\, G'^{a}_{\mu}$$

- Same angular analysis for the Z' and G' in the t-channel
- Scan over m and g and exclude these two toy models
- Present the limits in the coupling versus mass plane

[Dobrescu, Yu arXiv:1306.2629]

$\Longrightarrow$ Happy theorists!

CONCLUSIONS

- Effective Field Theory limits for BSM particles with masses ranging from 1 to 10 TeV should be interpreted with care

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- Collaborations are requested to quote average transfer energies and apply their analysis to the two toy models

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Thank you for your attention!

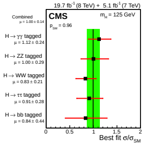
EFT EXAMPLES AT LHC

EFTs are popular in LHC searches, since they provide an easy description of new physics with minimal new parameters

HIGGS PHYSICS

[Corbett et al. arXiv:1207.1344;...]

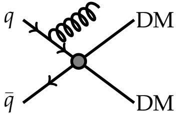
For example anomalous Higgs couplings:
e.g. $|H|^2 W_{\mu\nu} W^{\mu\nu}$ modifies hWW coupling
EFT Validity discussed in [arXiv:1406.7320;1408.5147;...]



DM SEARCHES

[CMS arXiv:1408.3583; ATLAS-CONF-2012-147]

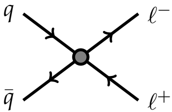
Mediator for dark matter annihilation is integrated out, EFT leads to Monojet + MET
EFT Validity discussed in [arXiv:1307.2253;1308.6799;1502.04701;...]



BSM RESONANCES

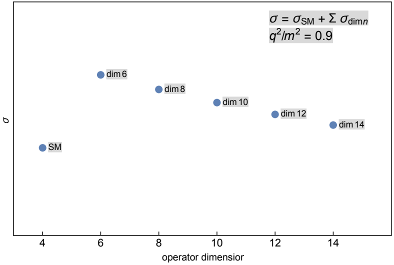
[CMS arXiv:1412.6302; ATLAS arXiv:1407.2410]

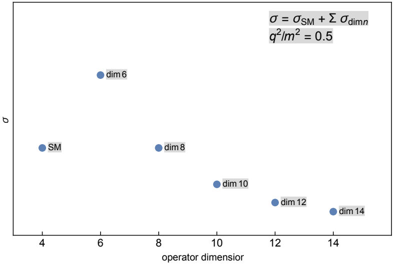
Lots of different possibilities: for example a Z' coupling to quarks and leptons

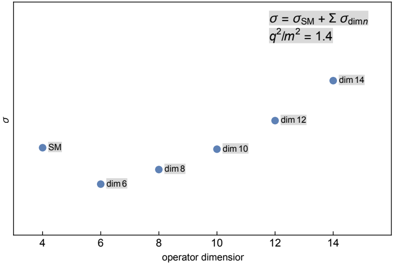


EFT Expansion versus Dimension Six

- EFT is an infinite expansion in q^2/m^2
- The expansion is strictly valid for $q^2 < m^2$
- Experiments only constrain dim-6 operator
- Error: $\Delta\sigma = \sigma_{\text{full}} - \sigma_{\text{dim6}}$







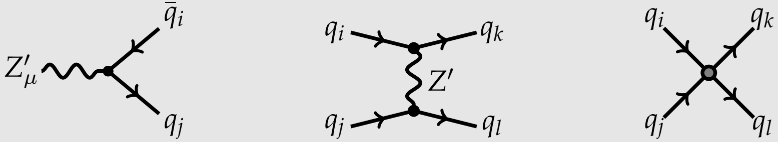
STRATEGY: CAPTURE MODELS

Different BSM models can be constrained by four-quark effective operator searches at the LHC

- Vector resonances in composite Higgs models [Redi et al. arXiv:1305.3818]
- Connecting DM mediator EFT with monojet EFT [Dreiner et al. arXiv:1303.3348]
- DM: axial vector mediator [Chala et al. arXiv:1503.05916]
- DM: coloured scalar mediator [Godbole et al. arXiv:1506.01408]
- Simplified models for DM [DM@LHC 2014 arXiv:1506.03116]
- Z' models in flavour physics [Buras et al. arXiv:1404.3824]
- And many more examples ...

Capture this plethora with two toy models: Z' and G'

TOY MODELS



Toy models based on Z' (and G') bosons:

$$\mathcal{L}_{\text{full}} \subset -\frac{m_{Z'}^2}{2} Z'^\mu Z'_\mu + g_{Z'}\, \bar{q}_i \gamma^\mu \delta_{ij} q_j\, Z'_\mu$$

Widths are: $\Gamma_{Z' \to q\bar{q}} = \alpha_{Z'} \frac{m_{Z'}^2 + 2m_q^2}{m_{Z'}^2} \sqrt{m_{Z'}^2 - 4m_q^2} \simeq \alpha_{Z'}\, |m_{Z'}|$

Effective description:

$$\mathcal{L}_{\text{eff}} \subset -\frac{g_{Z'}^2}{2m_{Z'}^2} \left[\bar{q}_i \gamma^\mu \delta_{ij} q_j\right]^2$$

Perform comparison of experimental limits between full and effective description of both toy models

ANGULAR DISTRIBUTIONS

- Starting point is: $\frac{d\sigma}{d\hat{t}}\left(\hat{s}, \hat{t}, \hat{u}, \alpha\right)$
- Use $x_{1/2} = \sqrt{\frac{\hat{s}}{s}}\, e^{\pm Y}$ and PDFs to get:

$$\frac{d^3\sigma}{dY d\hat{s} d\hat{t}} = x_1 f_1(x_1)\, x_2 f_2(x_2) \frac{d\sigma}{d\hat{t}} \frac{1}{\hat{s}}$$

- This can be re-expressed using χ:

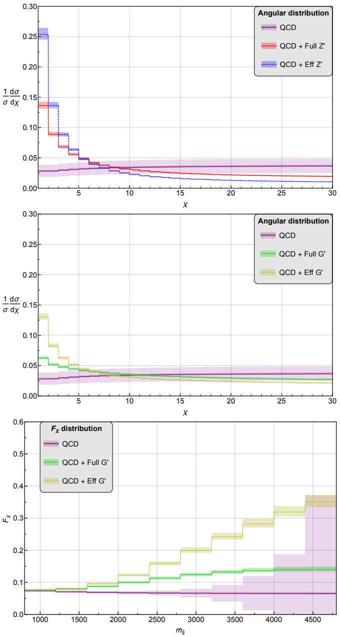
$$\frac{d\sigma}{d\chi} = \int_{\hat{s}_{\mathrm{min}}}^{\hat{s}_{\mathrm{max}}} d\hat{s} \int_{Y_{\mathrm{min}}}^{Y_{\mathrm{max}}} dY x_1 f_1(x_1)\, x_2 f_2(x_2) \frac{d\sigma}{d\hat{t}} \frac{\hat{t}^2}{\hat{s}^2}$$

- This distribution is used in CMS analysis
- For ATLAS analysis we have the variable:

$$F_\chi = \frac{N(1<\chi<\chi_{\mathrm{central}})}{N(1<\chi<\chi_{\mathrm{total}})}$$

which is then binned in $m_{jj} = \hat{s}$

- Plots shown for $g = \frac{\pi}{2}$ and $m = 2$ TeV



EXPANSION

[Gounaris, Sakurai; Kühn, Santamaria]

Narrow-width approximation not valid in t-channel propagators, use alternative description

- Propagator gets modified and reads ($q^2 = \hat{s}, \hat{t}$ or $\hat{u}$)

$$P = \frac{1}{q^2 - m^2 + i\sqrt{q^2}\,\Gamma(q^2)}$$

- Where the q^2 dependent width equals ($m_q = 0$)

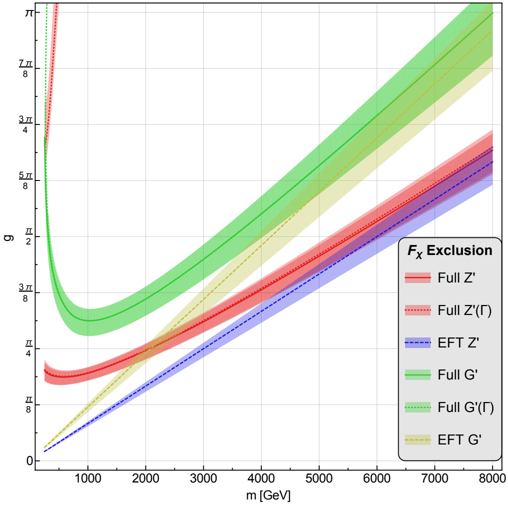
$$\Gamma\left(q^2\right) = \frac{\sqrt{q^2}}{m}\Gamma = 6\alpha\sqrt{q^2}$$

- Then expanding the propagator results in

$$P = -\frac{1}{m^2}\left[1 + \frac{q^2}{m^2}\left(1 + i\frac{\Gamma}{m}\right) + \cdots\right]$$

- Dimension six operator is independent of the width, however, full theory description is not

Width Effects



- Width effect in full theory shown by the dotted lines
- Narrow width approximation not valid [Gounaris, Sakurai]
- Width does not affect dim-6 operator in EFT
- Main influence on the validity for low masses and high couplings

Effective DM Recast

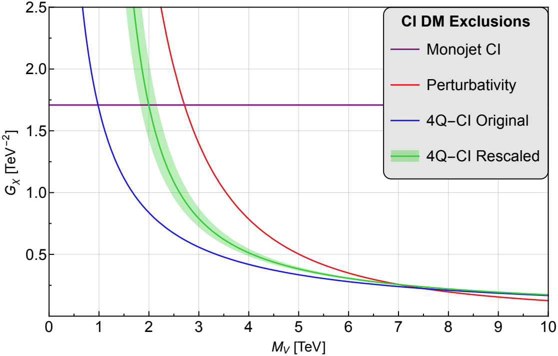
[Dreiner et al. arXiv:1303.3348]

Use 4 quark CI to constrain monojet CI for a vector mediator

$$\mathcal{L}_{\text{EFT}} \supset -\frac{g_q^2}{2M_V^2}(\bar{q}q)(\bar{q}q) - \frac{g_q g_\chi}{M_V^2}(\bar{q}q)(\bar{\chi}\chi) + \mathcal{O}\left(\frac{\hat{s}}{M_V^2}\right)$$

Define $G_q \equiv \frac{g_q^2}{M_V^2}, G_\chi \equiv \frac{g_q g_\chi}{M_V^2} \Rightarrow G_\chi = \frac{g_\chi}{M_V}\sqrt{G_q} + \mathcal{O}\left(\frac{\hat{s}_{\text{mono}}}{M_V^2}, \frac{\hat{s}_{4\text{q}}}{M_V^2}\right)$

- Perturbativity:
  $g_{q,\chi}^2 \leq 4\pi$
- Monojet constraint:
  $G_\chi \leq (765\ \text{GeV})^2$
- Four-quark constraint:
  $G_q \leq 4\pi(7.5\ \text{TeV})^2$
  Translates into:
  $G_\chi \leq \frac{1}{M_V}\frac{4\pi}{7.5\ \text{TeV}}$



$\mathcal{O}\left(\frac{\hat{s}_{4\text{q}}}{M_V^2}\right)$ effects not taken into account $\Longrightarrow$ Rescaled limits

Average Transfer Energies

Average transfer energies are determined by the process, in case of dijet three possibilities:

$$\langle \hat{s} \rangle = \frac{1}{\sigma_{\text{tot}}} \int_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} d\hat{s} \int_{\chi_{\text{min}}}^{\chi_{\text{max}}} d\chi \, \hat{s} \frac{d^2\sigma}{d\hat{s} d\chi}$$

$$\langle \hat{t} \rangle = \frac{1}{\sigma_{\text{tot}}} \int_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} d\hat{s} \int_{\chi_{\text{min}}}^{\chi_{\text{max}}} d\chi \, \frac{-\hat{s}}{1+\chi} \frac{d^2\sigma}{d\hat{s} d\chi}$$

$$\langle \hat{u} \rangle = \frac{1}{\sigma_{\text{tot}}} \int_{\hat{s}_{\text{min}}}^{\hat{s}_{\text{max}}} d\hat{s} \int_{\chi_{\text{min}}}^{\chi_{\text{max}}} d\chi \, \frac{-\hat{s}\,\chi}{1+\chi} \frac{d^2\sigma}{d\hat{s} d\chi}$$

7 TeV

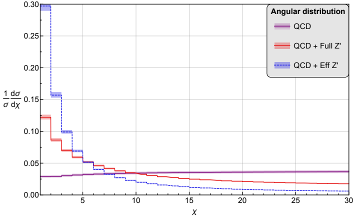
$\sqrt{\lvert\langle q^2 \rangle\rvert}$	QCD	Full Z'	Eff Z'
$\sqrt{\lvert\langle \hat{s} \rangle\rvert}$	$1.43^{+0.16}_{-0.13}$	$1.45^{+0.16}_{-0.13}$	$1.47^{+0.16}_{-0.13}$
$\sqrt{\lvert\langle \hat{t} \rangle\rvert}$	$0.43^{+0.05}_{-0.04}$	$0.46^{+0.05}_{-0.04}$	$0.49^{+0.05}_{-0.04}$
$\sqrt{\lvert\langle \hat{u} \rangle\rvert}$	$1.36^{+0.15}_{-0.13}$	$1.37^{+0.15}_{-0.12}$	$1.38^{+0.15}_{-0.12}$

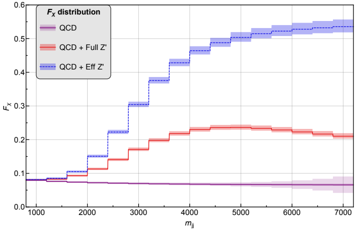
14 TeV

$\sqrt{\lvert\langle q^2 \rangle\rvert}$	QCD	Full Z'	Eff Z'
$\sqrt{\lvert\langle \hat{s} \rangle\rvert}$	$2.42^{+0.24}_{-0.21}$	$2.52^{+0.23}_{-0.20}$	$2.78^{+0.23}_{-0.20}$
$\sqrt{\lvert\langle \hat{t} \rangle\rvert}$	$0.73^{+0.07}_{-0.06}$	$0.87^{+0.08}_{-0.06}$	$1.15^{+0.09}_{-0.08}$
$\sqrt{\lvert\langle \hat{u} \rangle\rvert}$	$2.31^{+0.23}_{-0.20}$	$2.36^{+0.22}_{-0.18}$	$2.53^{+0.21}_{-0.18}$

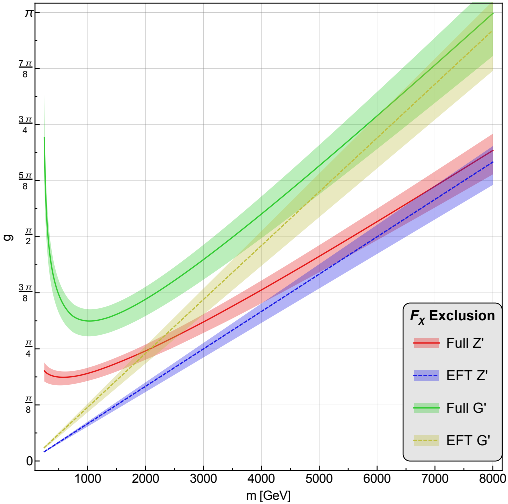
LHC14: Distributions

- Validity even more concerning at high energy due to high transfer energies
- Average transfer energies roughly factor of 2 higher compared to 7 TeV run, see previous slide
- These results are for 100 fb^{-1} of integrated luminosity and 14 TeV collider energy
- Exclusion limits based on binned F_χ data up to $\sqrt{\hat{s}} = 7.2$ TeV





LHC14: Results



- Higher limits on Λ due to increase in cross section and luminosity
- $\Lambda_{Z'} = 28.3^{+2.4}_{-1.4}$ TeV
  $\Lambda_{G'} = 19.9^{+2.1}_{-1.2}$ TeV
- Same effects as for 7 TeV: EFT overestimates and continuous effect
- $\langle q^2 \rangle \approx 1.0 - 2.5$ TeV

LHC14: DEVIATION

- EFT Limits improve compared to 7 TeV
- But deviation is greater as well
- Compare 7 TeV (upper plot) with 14 TeV (lower plot)
- Increase in deviation due to higher transfer energies
- $\langle q^2 \rangle_7 \approx 0.5 - 1.5$ TeV
- $\langle q^2 \rangle_{14} \approx 1.0 - 2.5$ TeV