Improving the Top EFT Fit with Boosted Reconstruction Techniques

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LHC Top Working Group
EFT Session

- Absence of evidence for BSM states in $t\bar{t}$ resonance searches $\implies$ $\Lambda_{\text{NP}} \gg v$: low-energy signature of New Physics in the top sector should be well-described by the SMEFT
- Leading non-resonant effects in top physics arise from dimension-six operators with unknown couplings $\implies$ use measurements to constrain Wilson Coefficients $C_i/\Lambda^2_{\text{NP}}$
- EFT operators' influence most pronounced at large momentum transfers $d\sigma_{\text{D6}} \propto \frac{p_T^2}{\Lambda^2_{\text{NP}}}$ $\implies$ high top p_T $\iff$ NP enhanced
- Extracting information from sensitive region of phase space requires $t\bar{t}$ reconstruction at 13 TeV (and beyond)

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Objective:

Quantify scope for strengthening current constraints by applying jet substructure algorithms to efficiently reconstruct boosted tops.

EFT 101

$$\mathcal{L}_{\mathrm{BSM}}(\{\Phi_{\mathrm{SM}}\},\{\mathcal{X}_{\mathrm{NP}}\}) \rightarrow \mathcal{L}_{SM}(\{\Phi_{\mathrm{SM}}\}) + \frac{C_i}{\Lambda^2}\mathcal{O}_i(\{\Phi_{\mathrm{SM}}\}) + \ldots$$

UV Completion $\rightarrow$ Standard Model $+$ Dimension Six Operators

- In the regime $q^2 < m_{\mathcal{X}}^2$, heavy states interacting with SM degrees of freedom decouple, generating a set of local operators $\mathcal{O}_i$.
- The short-distance structure of the theory determines the values of the effective coupling constants $\frac{C_i}{\Lambda^2} = \frac{f(g_{\mathcal{X}})}{m_{\mathcal{X}}^2}$
- Gauge invariance + B-conservation identifies 59 independent operators $\mathcal{O}_i$ at dimension-six **(Grzadkowski et al. 1008.4884)**
- The leading modifications to observables arise from the interference of SM matrix elements with those mediated by $\mathcal{O}_i$;
$d\sigma_{\mathrm{D6}} \propto \frac{C_i}{\Lambda^2}\int d\Pi\ \Re(\mathcal{M}_{\mathrm{SM}}^*\mathcal{M}_{\mathrm{D6}}) + \mathcal{O}(\Lambda^{-4}) = \frac{q^2}{\Lambda^2}\times(\ldots)$

$t\bar{t}$ Production in the SMEFT

Coefficient C_i	Operator $\mathcal{O}_i$
C_G	$f_{ABC}G_{\mu}^{A\nu}G_{\nu}^{B\lambda}G_{\lambda}^{C\mu}$
C_{uG}^{33}	$(\bar{q}\sigma^{\mu\nu}T^A u)\tilde{\varphi}G_{\mu\nu}^A$
$C_{qq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$
$C_{qq}^{(3)}$	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$
C_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$
$C_{qu}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$
$C_{qd}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$
$C_{ud}^{(8)}$	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$

Table : D6 operators in $t\bar{t}$ production. ψ^4 operators interfere in four linear combinations $C_{u,d}^{1,2}$.

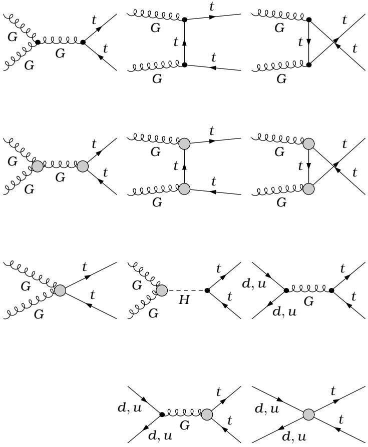

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Table : Leading D6 operators in $t\bar{t}$ production and some possible UV origins.

Broad coverage of candidate UV-complete models:

- Heavy coloured fermions, technihadrons, gluon substructure . . . **(Cho et al. 9307345)**
- Composite top scenarios **(Englert et al. 1401.1502)**
- W' & Z's **(Buckley et al. 1512.03360)**
- Heavy axigluons **(Cvetic et al. 1209.2741)**

An (Abridged) Brief History of t-EFT

- SMEFT $t\bar{t}$ phenomenology initially explored in e.g. **(Zhang et al. 1008.3869, Degrande et al. 1010.6304)** and more . . .
- Steadily accumulating, limited NLO SMEFT predictions in top physics, in e.g. t-decay **(Zhang 1404.1264)**, $t\bar{t}$ **(Franzosi et al. 1503.08841)**, single top **(Zhang 1601.06163)**, $t\bar{t}V$ **((Bylund et al. 1601.08193))**, $t\bar{t}H$ **(Maltoni et al. 1607.05330)** . . .
- Global C_i constraints available; PEWM operators **(Zhang et al. 1201.6670)** & **(de Blas et al. 1507.00757)**, FCNC operators **(Durieux et al. 1412.7166)**, $t\bar{t}$ + single top & more **(Buckley et al. 1506.08845, 1512.03360)** . . .
- Boosted $t\bar{t}$ investigations; A_C @ high $\beta_{t\bar{t}}$ **(Aguilar-Saavedra et al. 1109.3710)**, $\mathcal{O}^{33}_{uG}$ @ high $m_{t\bar{t}}$ **(Aguilar-Saavedra et al. 1412.6654v2)**, composite top operators (HEPTopTagger) **(Englert et al. 1401.1502v1)**. . .

TopFitter Constraints on $t\bar{t}$ Operators

- Fit MC to parton-level unfolded inclusive + differential top measurements
- Current global limits on C_i/Λ^2 extracted predominantly from Run I datasets utilizing resolved analyses
- Weak limits on C_i/Λ^2 inherently limit utility of EFT expansion: NP decoupled $\implies \Lambda > m_{t\bar{t}}^{\text{max}}$
- Strengthening constraints $\implies$ extend range of validity of EFT

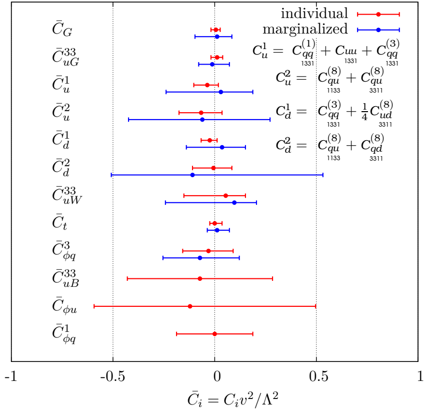
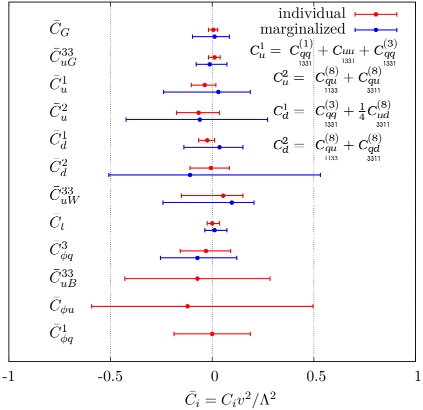


Figure : (TopFitter 95% CL **(Buckley et al. 1512.03360)**)

Improving Constraints in $t\bar{t}$ Production

- Capitalizing on higher $\mathcal{L}$ & $\sqrt{s}$ in Run II (and beyond) will require extracting information from boosted tops
- NP-sensitive phase space region subject to larger uncertainties; lower statistics, larger theory uncertainty. . .
- Top reconstruction at high p_T qualitatively different - jet substructure techniques necessary



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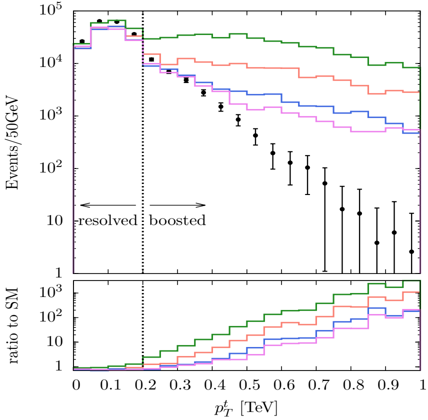

Figure : p_T^t spectrum @ 30 fb^{-1}, $C_u^1 = C_u^2 = C_d^1 = C_d^2 = 10\,\text{TeV}^{-2}$

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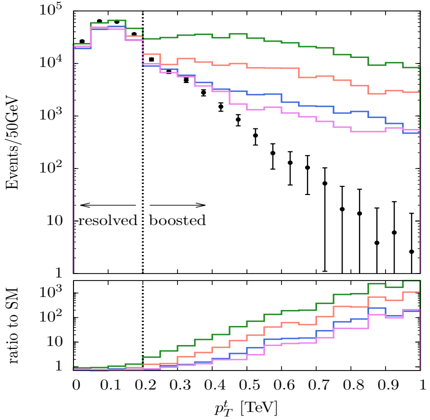

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Boosted vs. Resolved Top Kinematics

Figure : Resolved & Boosted topologies. Credit: **(CMS @ Universität Hamburg)**

$$d_{j_1 j_2} = \frac{\Delta R^2_{j_1 j_2}}{R^2_{\text{jet}}} \min(p^{2n}_{T j_1}, p^{2n}_{T j_2}), \quad n = \{1\,(k_T), 0\,(\text{C/A}), -1\,(\text{anti-}k_T)\}.$$

$$\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

- $\Delta R_{bjj} > R_{\text{jet}}$
- Isolated jets $\leftrightarrow$ hard partons
- Individually characterized by QCD $\rightarrow$ reconstruct traditional jets

- $\Delta R_{bjj} \sim R_{\text{jet}}$
- Merged 'fat' jets
- Individually QCD + massive decays $\rightarrow$ boosted top-tagging

Boosted vs. Resolved Top Kinematics

Figure : Resolved & Boosted topologies. Credit: **(CMS @ Universität Hamburg)**

- Boosted and resolved tops $\leftrightarrow$ distinct systematic uncertainties. $\sigma^{t\bar{t}}_{p_T^t > 200\text{GeV}} / \sigma^{t\bar{t}}_{\text{tot}} \sim 10\%$ @ 13 TeV - data-starved @ high p_T
- How does the relative weight of high p_T tops in constraining C_i/Λ^2 change with increasing $\mathcal{L}_{\text{int}}$ over the lifetime of the LHC, and as a function of experimental systematics and theory uncertainties?

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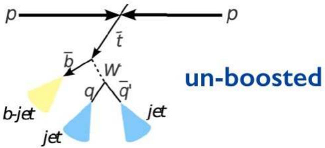

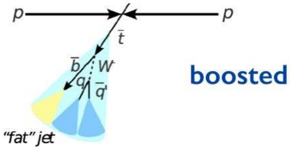

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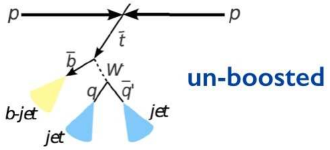

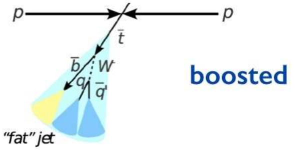

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Can investigate interplay of these factors by partitioning phase space by p^t_T and performing complementary resolved and boosted analyses on representative hadron-level pseudodata samples

Setup - Theory Samples (I)

- We implemented the 'Warsaw' Basis **(Grzadkowski et al. 1008.4884)** in FeynRules **(Alloul et al. 1310.1921)**, interfaced via UFO **(Degrande et al. 1108.2040)** to MG5_aMC **(Alwall et al. 1405.0301)** $\rightarrow$ parton-level $t\bar{t}$ events @ LO in SMEFT
- Reweight distributions to NLO QCD binwise with SM K-factors, obtained from MCFM **(Campbell et al. 1007.3492)** & cross-checked with with MC@NLO **(Alwall et al. 1405.0301)**
- Theory uncertainties: scales varied independently between $m_t/2 < \mu_{R,F} < 2m_t$. PDF uncertainties estimated by generating samples with CT14 **(Dulat et al. 1506.07443)**, MMHT14 **(Harland-Lang et al. 1412.3989)** and NNPDF3.0 **(Ball et al. 1410.8849)** PDFs as per PDF4LHC WG recommendations for Run II **(Butterworth et al. 1510.03865)**. Full scale + PDF envelope defines theory band. Treated as uncorrelated with $\epsilon^{\text{exp}}_{\text{syst}}$ & fixed with $\mathcal{L}$.

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Setup - SMEFT Theory Samples (II)

- Construct a logarithmically random-sampled parameter space for C_i/Λ^2 centred about $\{C_i\} = 0$, and generate theory predictions and uncertainties as described at each point
- Fit an interpolation-based parameterizing function to supply predictions for arbitrary values of $\{C_i\}$ for each bin

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- Fit an interpolation-based parameterizing function to supply predictions for arbitrary values of $\{C_i\}$ for each bin

This takes the form of a fourth order polynomial in the coefficients $\{C_i\}$ for each bin b:

$$f_b(\{C_i\}) = \alpha_0^b + \sum_i \beta_i^b C_i + \sum_{i \leq j} \gamma_{i,j}^b C_{i,j} + \dots$$

Once f_b is constructed, all that remains is to define a χ^2 goodness of fit function between theory and (pseudo-)data, and minimise it to obtain exclusion contours for $\{C_i\}$.

Setup - SM Pseudodata Samples

- Simulate hadron-level $t\bar{t}$ events in the semileptonic decay channel by showering $\{C_i\} = 0$ point in HERWIG++ **(Bahr et al. 0803.0883, Bell et al. 1512.01178)**
- Extract event samples corresponding to representative LHC integrated luminosity scenarios $\mathcal{L}_{\text{int}} = \{30\text{fb}^{-1}, 300\text{fb}^{-1}, 3\text{ab}^{-1}\}$
- $p_T^t \geq 200\text{GeV}$ chosen as threshold above which an event qualifies for boosted reconstruction (based on top-tagging efficiency **(Plehn et al. 1112.4441)**)
- Resolved and boosted analyses for each p_T^t region implemented in RIVET **(Buckley et al. 1003.0694)**

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Analysis Strategy

- We require a single charged lepton with $p_T > 30\text{GeV}$, and missing transverse energy vector with magnitude $E_T^{\text{miss}} > 30\text{GeV}$. The leptonic W-boson is reconstructed from these by assuming it was produced on-shell. We do not consider the τ decay mode
- Jets are then clustered using the anti-k_T algorithm **(Cacciari et al. 0802.1189)** using FastJet **(Cacciari et al. 1111.6097)** in two separate groups with $R = (0.4, 1.2)$ requiring $p_T > (30, 200)\text{GeV}$ respectively, and jets which overlap with the charged lepton are removed.
- The $R = 1.2$ fat jets are required to be within $|\eta| < 2$, and the $R = 0.4$ small jets are b-tagged within the same η range with an efficiency of 70% and fake rate of 1%

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Analysis Strategy - Boosted

If $n_{\text{fat}} \geq 1$ and $n_{\text{b-tagged}} \geq 1 \implies$ boosted top-tag of the leading fat jet using HEPTopTagger **(Plehn et al. 1006.2833, Kasieczka et al. 1503.05921)** and reconstruct t_{lept} using the leading, non-overlapping b-tagged small jet and the reconstructed leptonic W.

$m_{\text{subjet}}^{\text{max}} = 30\text{GeV}$
$\mu_{\text{drop}} = 0.8$
$R_{\text{filt}} = 0.3$
$n_{\text{filt}} = 5$
$p_{T\,subjet}^{\text{min}} = 30\text{GeV}$
$f_W = 15\%$
$150\text{GeV} < m_t^{\text{rec}} < 200\text{GeV}$

Table : HEPTopTagger setup

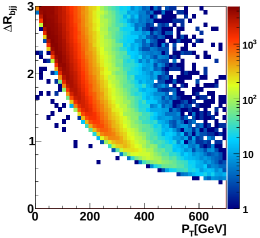

Figure : $\Delta R_{bjj}^{SM}(p_T^t)$ **(1112.4441 Plehn et al.)**

Analysis Strategy - Resolved

- If no satisfactory fat jet exists $\implies$ require $n_{\text{b-tagged}} \geq 2$ and $n_{\text{light}} \geq 2$
- Reconstruct hadronic W-boson by finding the light small jet pair that best reconstructs the W mass
- Reconstruct top candidates by similarly finding the pairs of reconstructed W-boson and b-tagged small jet that best reconstruct the top mass

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Finally, regardless of the approach used, we require both top candidates to have $|m_{\text{cand}} - m_{\text{top}}| < 40\text{GeV}$. If this requirement is fulfilled the event passes the analysis.

Analysis Summary

Leptons	$p_T > 30$ GeV
	$\lvert\eta\rvert < 4.2$
Missing energy	$E_T^{\text{miss}} > 30$ GeV
Small jets	anti-k_T $R = 0.4$
	$p_T > 30$ GeV , $\lvert\eta\rvert < 2$
Fat jets	anti-k_T $R = 1.2$
	$p_T > 200$ GeV , $\lvert\eta\rvert < 2$
Resolved	$\geq$ 4 jets w/ $\geq$ 2 b-tags
Boosted	$\geq$ 1 fat jet, $\geq$ 1 w/ b-tag

Table : Summary of Rivet event selection criteria

- We chose the benchmark scenarios $\mathcal{L}_{\text{int}}=\{30, 300, 3000\}$ fb^{-1} with $\varepsilon_{\text{syst}} = \{10\%, 20\%\}$
- Systematics inserted by defining a flat percentage interval associated with each bin
- Bounds presented here are 'one-at-a-time', i.e. not marginalised over the full operator set.

Analysis Summary

Leptons	$p_T > 30$ GeV
	$\lvert\eta\rvert < 4.2$
Missing energy	$E_T^{\text{miss}} > 30$ GeV
Small jets	anti-k_T $R = 0.4$
	$p_T > 30$ GeV , $\lvert\eta\rvert < 2$
Fat jets	anti-k_T $R = 1.2$
	$p_T > 200$ GeV , $\lvert\eta\rvert < 2$
Resolved	≥ 4 jets w/ ≥ 2 b-tags
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95% $C.L.$ @ $\mathcal{L}_{\text{int}} = 30\ \text{fb}^{-1}$, $\epsilon_{\text{syst}} = 20\%$

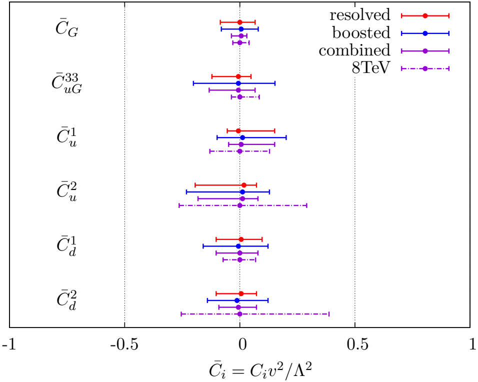

Figure : 1-dimensional 95% confidence intervals on C_i/Λ^2 for both selections using $\mathcal{L} = 30\ \text{fb}^{-1}$ and $\varepsilon_{\text{syst}} = 20\%$, displayed together with TopFitter constraints from unfolded 8 TeV p_T^t distributions.

Resolved - Relative Improvements w/ $\mathcal{L}_{\text{int}}$ and ϵ_{syst}

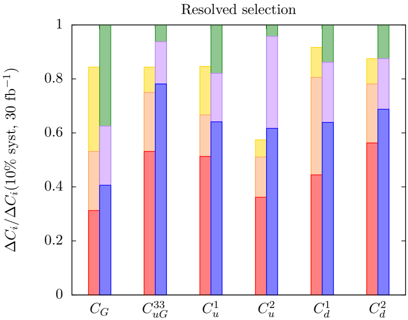

Figure : Fractional improvement on the 95% C.I., with each choice of ϵ_{syst} and $\mathcal{L}_{\text{int}}$, normalized to $\epsilon_{\text{syst}} = 20\%$ and $\mathcal{L}_{\text{int}} = 30\text{fb}^{-1}$.
$\{30\text{fb}^{-1}, 300\text{fb}^{-1}, 3\text{ab}^{-1}\}$ of data at at **20% systematics**.
$\{30\text{fb}^{-1}, 300\text{fb}^{-1}, 3\text{ab}^{-1}\}$ of data for **10% systematics**.

Resolved - Relative Improvements w/ $\mathcal{L}_{\text{int}}$ and ϵ_{syst}

- We find that the limits on the coefficient C_G can be improved by 40% by going from 30 fb^{-1} to 300 fb^{-1}, and by a further 20% at 3 ab^{-1}.
- Systematics have a more modest effect: at 3 ab^{-1} limits marginally improved by 10% reduction. Improvements in the threshold region require collecting enough data to overcome the lack of sensitivity.

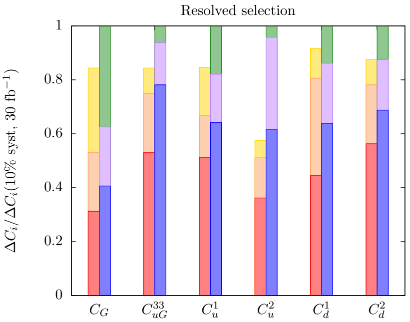

Figure : Relative 95% C.I., w/ $\{30, 300, 3000\}$fb^{-1} @ **20% systematics**. $\{30, 300, 3000\}$fb^{-1} @ **10% systematics**.

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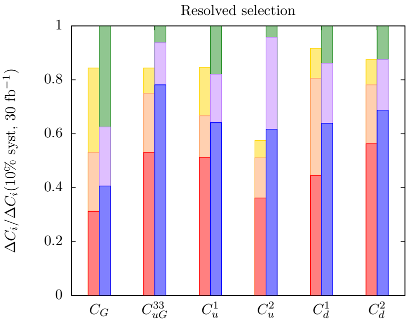

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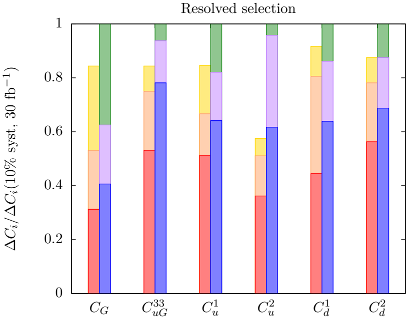
For the chromomagnetic dipole operator Q_{uG}^{33}, improving the experimental systematics plays much more of role. A 10% improvement in systematics, coupled with an increase in statistics from 30 fb^{-1} to 300 fb^{-1} leads to stronger limits that maintaining current systematics and collecting a full 3 ab^{-1} of data.



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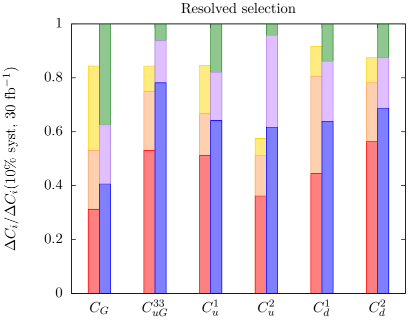
- Similar conclusions apply for the four-quark operators, to varying degrees, i.e. reducing systematic uncertainties can provide comparable improvements to collecting much larger data samples
- The Wilson coefficients C_1^u and C_2^u contributing to the $u\bar{u}$ channel benefit more from reduced systematic uncertainties than their $d\bar{d}$ counterparts



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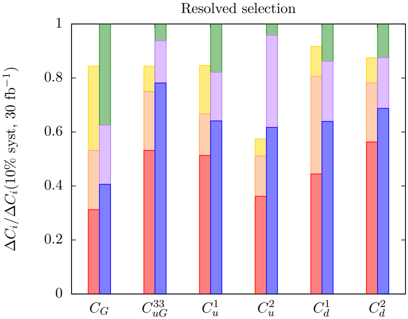

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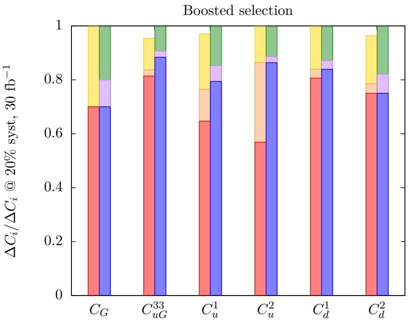
Boosted - Relative Improvements w/ $\mathcal{L}_{\text{int}}$ and ϵ_{syst}

- In the boosted selection, improving systematics by 10% has virtually no effect on the improvement in the limits $\implies$ statistics dominated @ 30 fb^{-1}
- For C_G, at 300 fb^{-1} some improvement can be made if systematics are reduced, beyond which systematics saturate the sensitivity to C_G, i.e. there is no improvement to be made by collecting more data.



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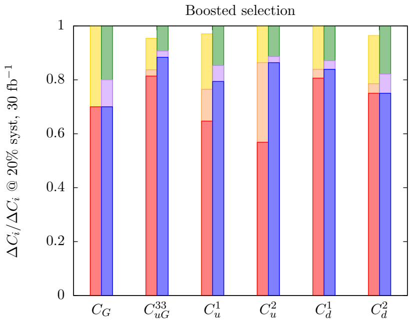

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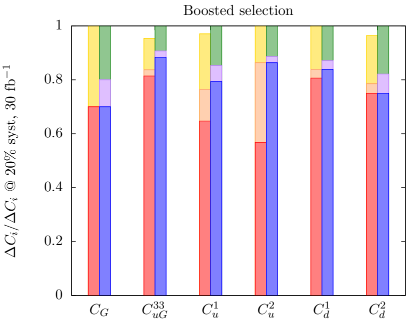

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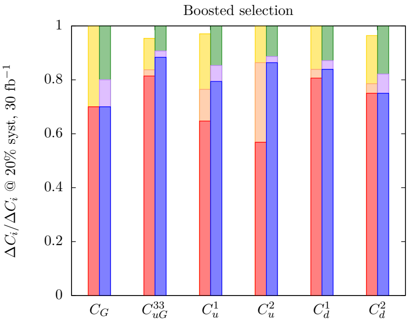

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The Role of Theoretical Uncertainties (I)

- The scale and PDF variation procedure outlined typically leads to uncertainties in the 10-15% range.
- Recently, differential K-factors for top pair production at NNLO QCD have become available, which have substantially reduced the scale uncertainties **(Czakon et al. 1601.05375, 1511.00549)**. These are presently limited to the range $p_T^t < 400$ GeV, applicable to the TeVatron and 8 TeV LHC
- NLO + RGE effects in EFT important for measurements at LEP-level precision **(Berthier et al. 1508.05060)**. At LHC, we find them to be numerically insignificant compared to the sources of uncertainty studied here.
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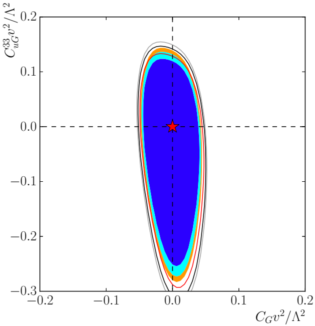
The Role of Theory Uncertainties (II)

Can get a feel for improvements given similar precision @ 13 TeV;



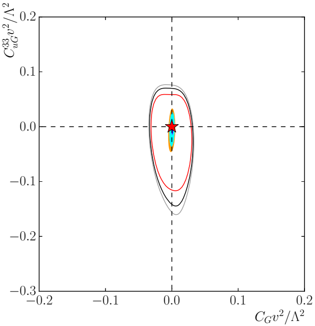


Figure : Left: 68%, 95% and 99% C.I. for C_G & C_{uG}^{33}, **Lines**: ($\epsilon_{\text{syst}} = 20\%$, $\mathcal{L}_{\text{int}} = 30$ fb^{-1}) **with** NLO theoretical uncertainties. **Filled contours**: likewise, with **no** theoretical uncertainties. Right: Likewise, w/ ($\epsilon_{\text{syst}} = 10\%$, $\mathcal{L}_{\text{int}} = 3$ ab^{-1}).

Consequences on EFT Validity

- Strength of constraints $\iff$ range of EFT validity
- Match $\frac{C_i}{\Lambda^2} = \frac{g_*^2}{M_*^2}$
- Impose $M_* > m_{t\bar{t}}^{\text{max}} = 2\text{TeV}$
- Weak constraint $\implies$ larger g_*, higher-order corrections to BSM important
- Truncation at e.g. $\mathcal{O}(\Lambda^{-2})$ less reliable

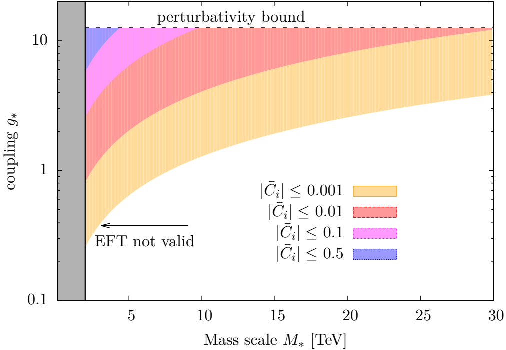


Figure : Areas in the $g_* - M_*$ plane. Coloured areas constrained in perturbative models subject to condition $C/\Lambda^2 = g_*^2/M_*^2$. Shaded grey area: mass scales $M_* < m_{t\bar{t}}^{\text{max}}$

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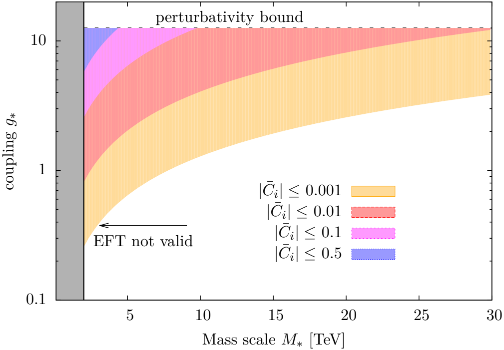

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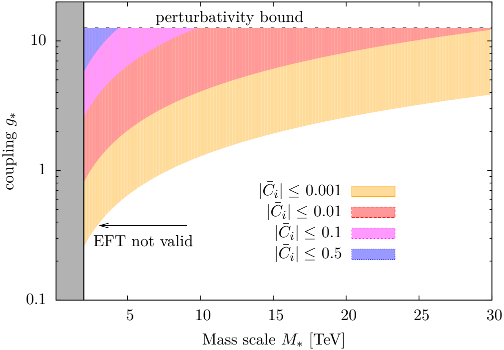

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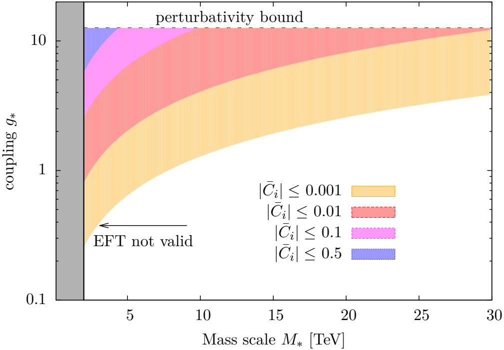

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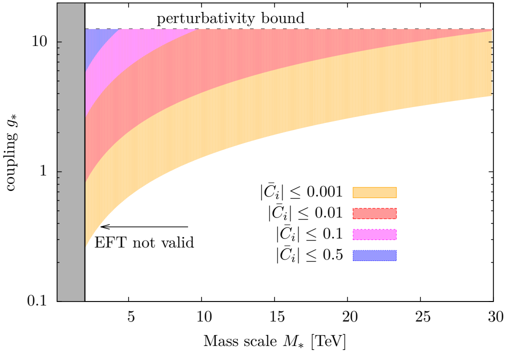

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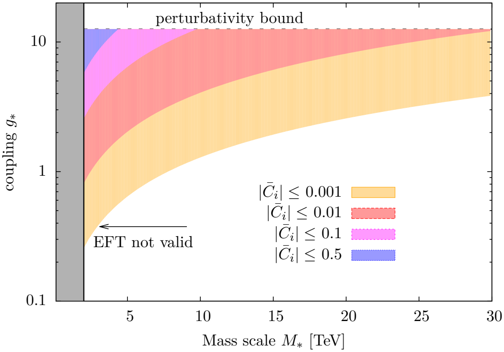

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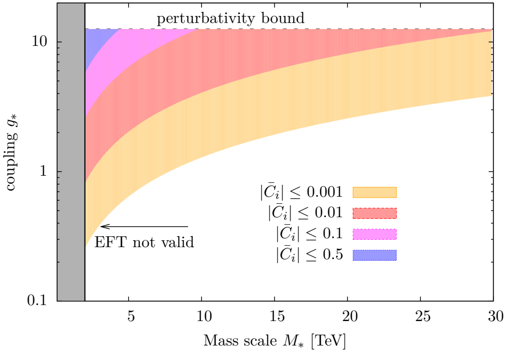

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- For representative experimental scenarios we performed a dedicated analysis for events with transverse momenta $p_T^t \geq 200$ GeV where top-tagging becomes relevant
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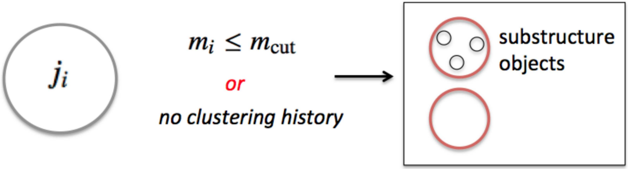
Backup - HEPTopTagger



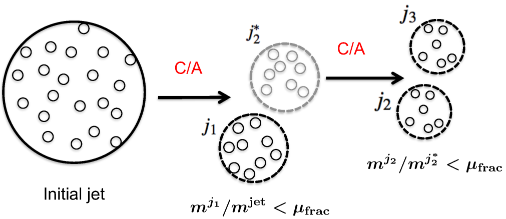
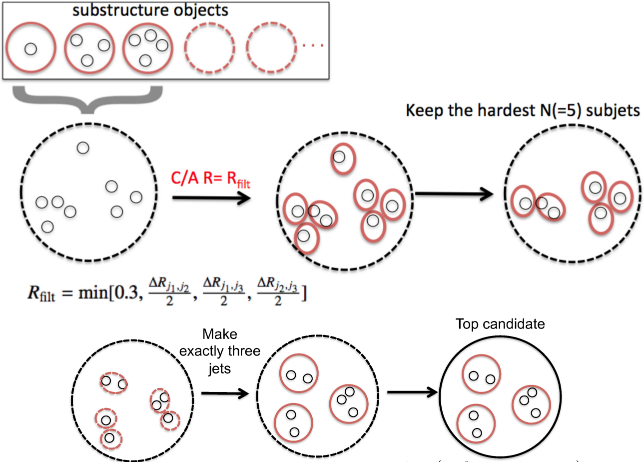


Figure : HEPTopTagger Illustration - Image: **(Aad et al. 1306.4945)**

Backup - HEPTopTagger



$$R_{\text{filt}} = \min[0.3, \frac{\Delta R_{j_1,j_2}}{2}, \frac{\Delta R_{j_1,j_3}}{2}, \frac{\Delta R_{j_2,j_3}}{2}]$$

$$m_{ab} = m_W(1 \pm 0.15) \quad (a, b = j_1, j_2, j_3)$$

Figure : HEPTopTagger Illustration - Image: **(Aad et al. 1306.4945)**