Constraining higher-order operators in $t\bar{t}$ production using a Matrix Element Method

Vincent Lemaître, Sébastien Brochet, Sébastien Wertz

Université catholique de Louvain
Center for Cosmology, Particle Physics and Phenomenology

December 1st, 2015

Introduction

- LHC RunI:
  - Standard Model Higgs discovered
  - No evidence for New Physics at the EW scale
- LHC RunII has just started! Entering new territory!
- What if new degrees of freedom out still of reach of direct searches?
  $\rightarrow$ look for indirect effects: precision measurements of SM observables
  $\rightarrow$ compass for future direct searches
- Where to look? This work: $t\bar{t}$ production:
  - Special role of the top in EWSB? (Yuwaka $\sim 1 \ldots ?$)
  - Many NP models predict deviations in the top sector
  - Only quark decaying before hadronizing
  - Abundant process at the LHC
- How to parametrise & search for possible deviations?

Effective Field Theory

- Effective Field Theory:

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{d=4} + \sum_{d>4,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

  - $\mathcal{O}_i$ are operators satisfying SM symmetries, with "couplings" c_i
  - Λ is a New Physics scale
  - Some operators can be removed $\rightarrow$ define minimal subset
  - Global fit necessary
- In $t\bar{t}$ production, dominant effect expected from interference of dim. 6 operators with SM amplitude:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \sum_i \frac{c_i}{\Lambda^2} 2\,\mathfrak{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\mathcal{O}_i^{(6)}}) + \mathcal{O}(\Lambda^{-4})$$

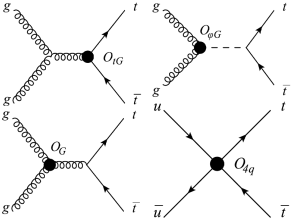
- *Partial* Λ^{-4} term can be used to assess validity of expansion

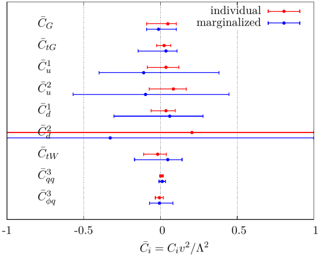
[S.Weinberg (1979)], [W.Buchmuller et al. (1986)], [C.N.Leung et al. (1986)], [B.Grzadkowski et al. - 0310159,1008.4884], [J.A.Aguilar-Saavedra et al. - 0811.3842], ...

Top Effective Field Theory

- For now, exclude operators affecting top decay
- Some (reasonable) simplifying assumptions:
  - Consider only leading color structure
  - Flavour universal in first two generations
  - No CP violation

  $\Rightarrow$ 10 interfering dim. 6 operators
- $\mathcal{O}_{tG}$ $(gt\bar{t}, ggt\bar{t})$, $\mathcal{O}_G$ $(ggg, \dots)$, $\mathcal{O}_{\phi G}$ $(ggh, \dots)$
- Seven four-fermion operators (variations of $q\bar{q}t\bar{t}$)
- Implemented in MadGraph (LO)
- Proof-of-principe global fit at parton level using σ, unfolded differential $p_T(t)$, $|y(t)|, |y(t\bar{t})|, M_{t\bar{t}}$ $\longrightarrow$





[C.Zhang et al. - 1008.3869], [C.Degrande et al. - 1010.6304], [D.B. Franzosi et al. - 1503.08841], [A.Buckley et al. - 1506.08845], ...

Signal generation (1)

- Aim: constrain operators in a global fit
  → how to disentangle operators' effects?
  → generate events, use all final state information?
- Probe parameter space: for each operator, generate *only* interference
  → "signals" linear in c_i/Λ^2 (real), #samples = #operators
- Want to keep spin correlations in the decays
  → For now, use full matrix element in MadEvent
  → Use of MadSpin (necessary at NLO) being investigated
  → Focus on dileptonic $t\bar{t}$ final state
- Not possible out-of-the-box:
  - In MadGraph, generate matrix element:
    $|\mathcal{M}(c_i)|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2c_i\Lambda^{-2}\,\mathfrak{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\mathcal{O}_i}) + (c_i\Lambda^{-2})^2\,|\mathcal{M}_{\mathcal{O}_i}|^2$
  - Hack matrix elements to return $(|\mathcal{M}(c_i)|^2 - |\mathcal{M}(-c_i)|^2)/2$
  - Validated by checking $\tilde{\sigma}_i \propto c_i/\Lambda^2$

Signal generation (2)

Details on generation:

- SM $t\bar{t}$, $\mathcal{O}_{tG}$ at LO for now; more detailed studies using NLO planned
- PDF: NNPDF2.3LO
- Scale, PDF uncertainties not (yet) included ($\rightarrow$ reweighting)
- $m_t = 173.2$ GeV, investigations ongoing on propagation of uncertainty
- Showered using PYTHIA 8.2, tune CUETP8M1
- DELPHES 3.3.0 fast detector simulation: CMS, <PU>=50

Event selection:

- "Standard" selection yielding almost pure $t\bar{t}$ sample
- Two opposite charge leptons:
  $p_T > 20$ GeV, $|\eta| < 2.4$, RelIso $< 0.12(0.25)$, $m_{ll} > 20$ GeV
- At least two b-jets, $p_T > 30$ GeV, $|\eta| < 2.4$, $\Delta R_{lb} > 0.3$
- For $ee/\mu\mu$ channels: $76 > m_{ll} > 106$ GeV, MET > 40 GeV

Signal generation: cross sections

Total cross sections (branching fraction to $\mu\mu/ee/\mu e$: 4.9%):

“Process”	σ (pb) ($c_i\Lambda^{-2} = 1$ TeV^{-2}), 13 TeV
SM $t\bar{t}$	815.96 @NNLO
$\mathcal{O}_{tG}$	275.47
$\mathcal{O}_{G}$	22.74
$\mathcal{O}_{\phi G}$	-7.49
$\mathcal{O}_{qq}^{(8,1)}$	5.23
$\mathcal{O}_{qq}^{(8,3)}$	1.04
$\mathcal{O}_{ut}^{(8)}$	3.13
$\mathcal{O}_{dt}^{(8)}$	2.08

3 four-fermion operators not yet included (proof of principle)

Parton level distribution examples

As expected, operators' relative contributions tend to be larger at high energies:

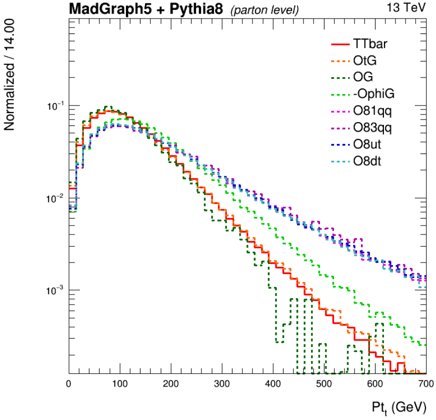


Figure : Top p_T

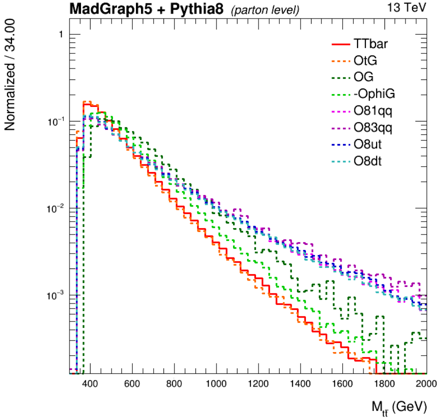


Figure : $t\bar{t}$ invariant mass

Analysis level distribution examples

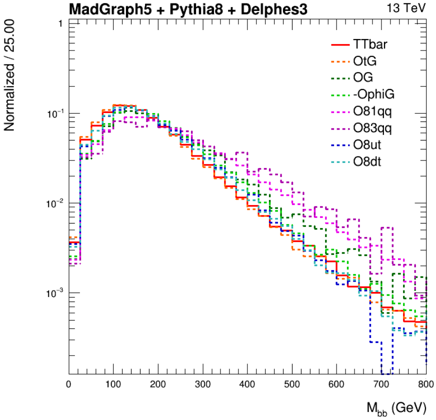


Figure : bb invariant mass

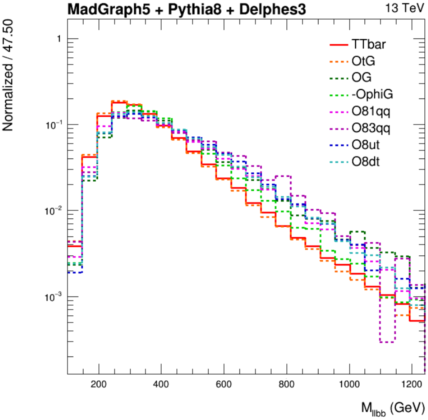
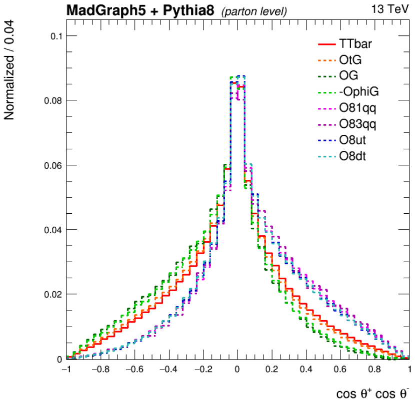
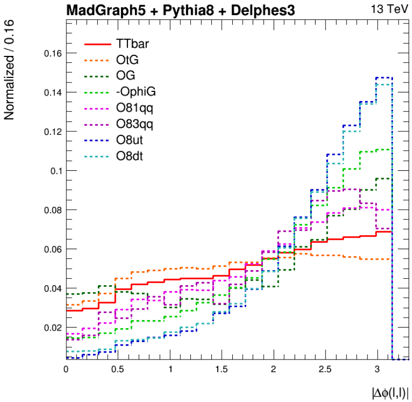


Figure : llbb invariant mass

- Define $\theta^{+(-)}$ as the angle between the direction of the (anti-)top in the $t\bar{t}$ restframe, and the direction of the positive (negative) lepton in the (anti-)top rest frame
  $\rightarrow \cos\theta^{+} \times \cos\theta^{-}$ sensitive to spin correlations between t, $\bar{t}$
- $\Delta\phi(l^{+}, l^{-})$ is also sensitive, without the need to reconstruct the tops





Matrix Element Method

- Compute a likelihood to observe event $\mathbf{x}$ under a theoretical hypothesis α (=LO matrix element of a chosen process)

$$P(\mathbf{x}|\alpha) = \frac{1}{\sigma_\alpha} \int \mathrm{d}x_1 \mathrm{d}x_1 \, \mathrm{d}\Phi(\mathbf{y}) \, f(x_1) f(x_2) \, |\mathcal{M}_\alpha(\mathbf{y})|^2 \, T(\mathbf{x}|\mathbf{y}) \equiv \frac{W_\alpha}{\sigma_\alpha}$$

  - Normalization using *visible* cross-section σ_α s.t. P is a likelihood
  - f: PDFs, x_i: Björken-x, $\mathrm{d}\Phi(\mathbf{y})$: phase-space density & flux factor
  - $|\mathcal{M}_\alpha(\mathbf{y})|^2$: matrix element for hypothesis α, evaluated on partonic event $\mathbf{y}$
  - Transfer Function $T(\mathbf{x}|\mathbf{y})$: probability density to reconstruct event $\mathbf{x}$, given partonic configuration $\mathbf{y}$. Usually, one assumes

$$T = \prod_{i \in \text{vis.objects}} \delta(\phi_i^{\text{gen}} - \phi_i^{\text{rec}}) \, \delta(\eta_i^{\text{gen}} - \eta_i^{\text{rec}}) \, T_i(E_i^{\text{rec}} | E_i^{\text{gen}})$$

- Average over jet assignment permutations

Matrix Element Method & effective operators

- Use MEM to construct variables most sensitive to the operator's effects $\rightarrow$ use all the available information
- Distributions $\rightarrow$ template fits, propagate systematics
- In principle, most discriminating variable between hypotheses "SM $t\bar{t}$" and "SM modified by operator i with coef. c_i/Λ^2" is:

$$\mathfrak{R}(c_i) = \frac{(W_{t\bar{t}} + \frac{c_i}{\Lambda^2} W_i)/(\sigma_{t\bar{t}}^{\text{vis}} + \frac{c_i}{\Lambda^2}\tilde{\sigma}_i^{\text{vis}})}{W_{t\bar{t}}/\sigma_{t\bar{t}}^{\text{vis}}}$$

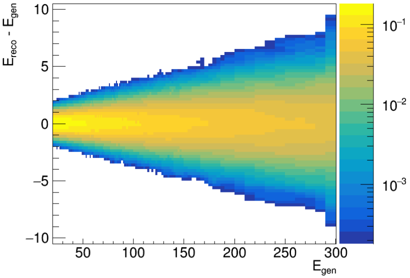
  - $W_{t\bar{t}}$ is the weight under the SM $t\bar{t}$ hypothesis
  - W_i is the unphysical "weight" from integrating the interference of operator i with the SM
- In practice, all that counts is $W_i/W_{t\bar{t}}$. So, define:

$$D_i = (\arctan(\log(|W_i|/W_{t\bar{t}})) + \pi/2)/\pi$$

(arctan $\rightarrow$ normalize output between 0 and 1)

Matrix Element Method: implementation

- Private C++ code (MEM++)
- CUBA, LHAPDF, MADWEIGHT's phase-space mappings
- Using CUBA's vector integrand capabilities → 8 weights at once
- New MADGRAPH C++ matrix element exporter
- Edited C++ matrix element by hand → keep interference part only, minimise unnecessary operations (re-using diagrams)
- Validated by checking that $W_i \propto c_i$, $W_{t\bar{t}}$ independent of c_i
- Binned transfer functions on electrons, muons, b-jets from SM $t\bar{t}$ sample
- Example: electron transfer function:



Weights and discriminants

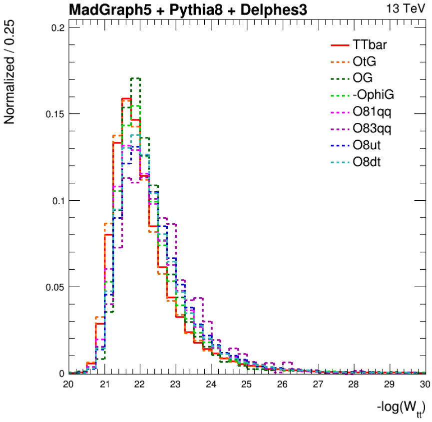


Figure : SM $t\bar{t}$ weight (unnormalized)

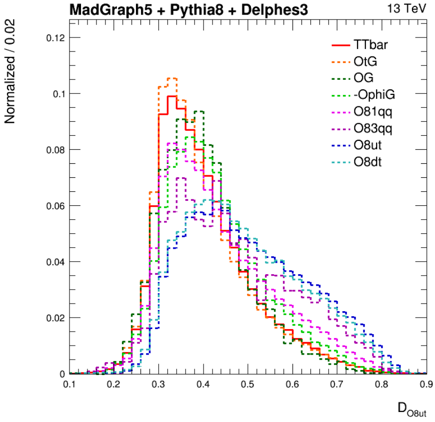


Figure : Discriminant for $\mathcal{O}_{ut}^{(8)}$

Discrimination power

- Compare constraining power of different variables using binned maximum likelihood fit
- Consider statistical uncertainties only (assuming 100 fb^{-1})
- SM $t\bar{t}$ fixed, float one operator at a time:

Operator	Uncertainty on $c_i\Lambda^{-2}$ (TeV^{-2})		
	Yields only	$\Delta\phi(l^+, l^-)$	Variable D_i
$\mathcal{O}_{tG}$	0.0057	0.0057	0.0057
$\mathcal{O}_{G}$	0.072	0.071	0.049
$\mathcal{O}_{\phi G}$	0.19	0.18	0.17
$\mathcal{O}_{qq}^{(8,1)}$	0.32	0.31	0.24
$\mathcal{O}_{qq}^{(8,3)}$	2.23	2.06	1.29
$\mathcal{O}_{ut}^{(8)}$	0.55	0.46	0.36
$\mathcal{O}_{dt}^{(8)}$	0.73	0.63	0.50

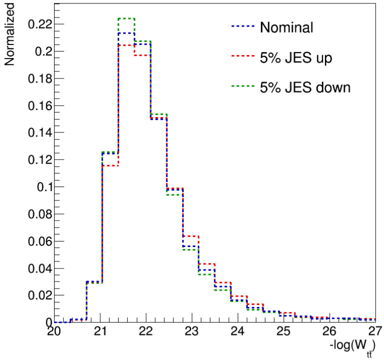
- Already substantial improvements using MEM-based discriminants
- Expect real gain to be seen in global fit

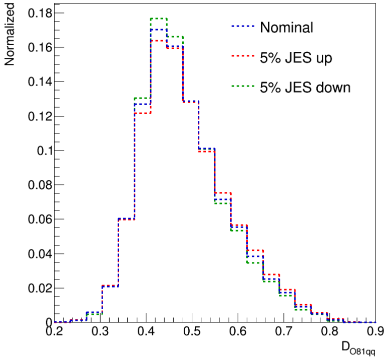
Weights and systematics

- Propagation of Jet Energy Scale uncertainty to the weights
- Weights for nominal & up/down variations computed simultaneously:

$$\int \mathrm{d}E_{gen}\, |\mathcal{M}(E_{gen})|^2 \times \begin{bmatrix} T(E^{+}_{rec}|E_{gen}) \\ T(E_{rec}|E_{gen}) \\ T(E^{-}_{rec}|E_{gen}) \end{bmatrix} \times \dots$$

- Impact of (pessimistic) 5% variation of JES on shapes:





Conclusion and prospects

- EFT: complete description of indirect New Physics effects
- Define strategy to search for/fit effective operators in $t\bar{t}$ production, in the dileptonic final state
- $1/\Lambda^2$ expansion $\rightarrow$ consider only interferences with Dim6 operators
  $\rightarrow$ Limited number of samples to generate
- Generation of "interference samples" feasible
- Matrix Element-based approach using new `C++` implementation
  $\rightarrow$ build variables most sensitive to operators' effects
- Work in progress: recursive subdivision of phase-space based on ME discriminants $\rightarrow$ global fit of operators, minimizing correlations

Backup

Backup!

List of perators

List of dimension 6 operators interfering with the SM in $t\bar{t}$ production (1):

$$\mathcal{O}_{tG} = (\overline{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu}$$

$$\mathcal{O}_G = f_{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$$

$$\mathcal{O}_{\phi G} = \frac{1}{2}(\phi^\dagger\phi)G^A_{\mu\nu}G^{A\mu\nu}$$

$$\mathcal{O}^{(8,1)}_{qq} = \frac{1}{4}(\overline{q}^i\gamma_\mu\lambda^A q_j)(\overline{q}\gamma^\mu\lambda^A q)$$

$$\mathcal{O}^{(8,3)}_{qq} = \frac{1}{4}(\overline{q}^i\gamma_\mu\tau^I\lambda^A q_j)(\overline{q}\gamma^\mu\tau^I\lambda^A q)$$

$$\mathcal{O}^{(8)}_{ut} = \frac{1}{4}(\overline{u}^i\gamma_\mu\lambda^A u_j)(\bar{t}\gamma^\mu\lambda^A t)$$

$$\mathcal{O}^{(8)}_{dt} = \frac{1}{4}(\overline{d}^i\gamma_\mu\lambda^A d_j)(\bar{t}\gamma^\mu\lambda^A t)$$

$$\mathcal{O}^{(1)}_{qu} = (\overline{q}u^i)(\overline{u}^j q)$$

$$\mathcal{O}^{(1)}_{qd} = (\overline{q}d^i)(\overline{d}^j q)$$

$$\mathcal{O}^{(1)}_{qt} = (\overline{q}^i t)(\bar{t}q^j)$$

- q^i (u^i, d^i) are the left-handed doublets (right-handed singlets) of the first two generations
- q (t) is the left-handed doublet (right-handed singlet) of the third generation
- ϕ is the Higgs doublet
- Considering only $t\bar{t}$ total & differential cross sections, reduction to 4 linear combinations of the 4-fermion operators

Parton level distributions

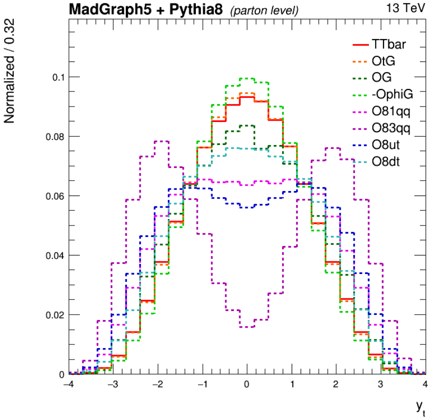


Figure : Top rapidity

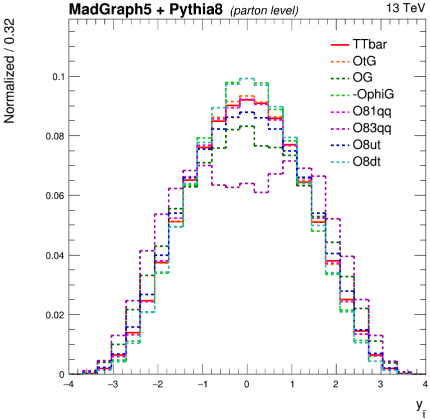


Figure : Anti-top rapidity

Parton level distributions

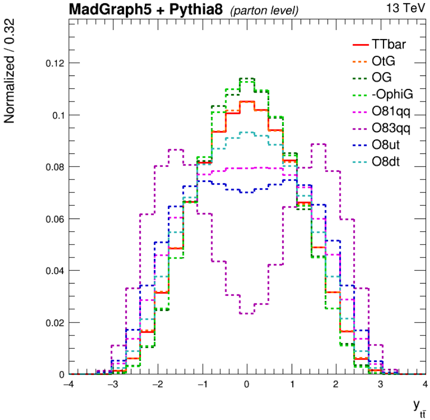


Figure : $t\bar{t}$ rapidity

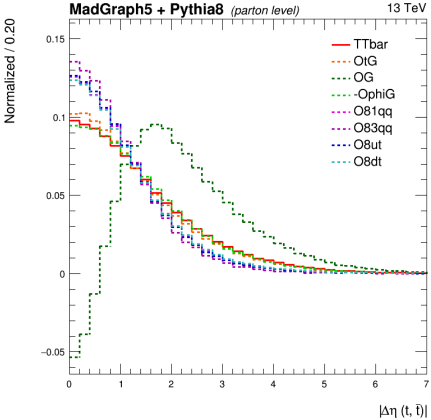


Figure : $|\Delta\eta(t, \bar{t})|$

Analysis level distributions

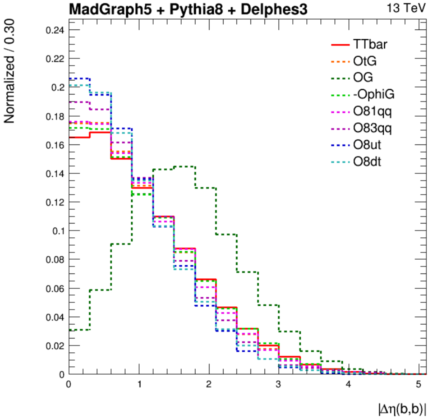


Figure : $|\Delta\eta(b,b)|$

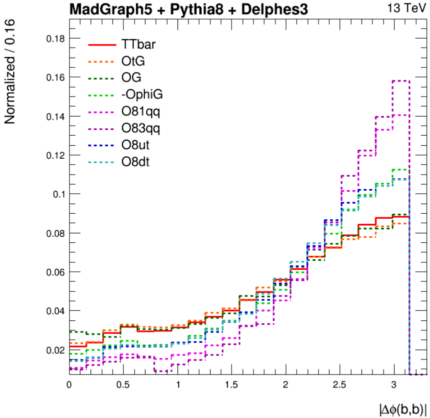


Figure : $|\Delta\phi(b,b)|$

Analysis level distributions

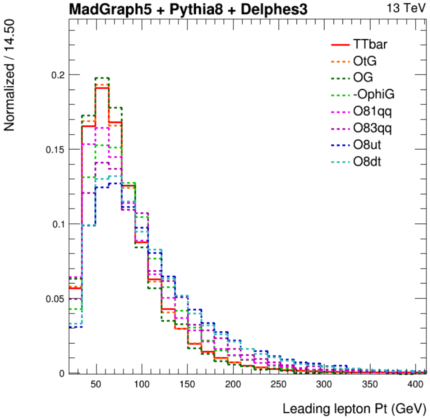


Figure : Leading lepton p_T

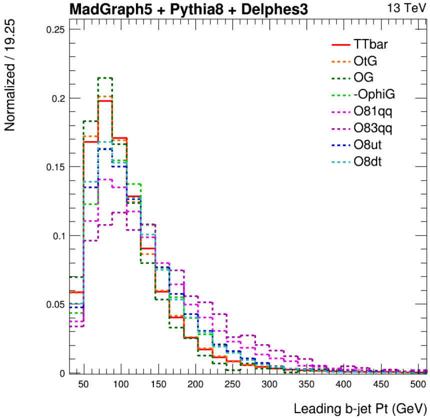


Figure : Leading b-jet p_T

Weights & discriminants

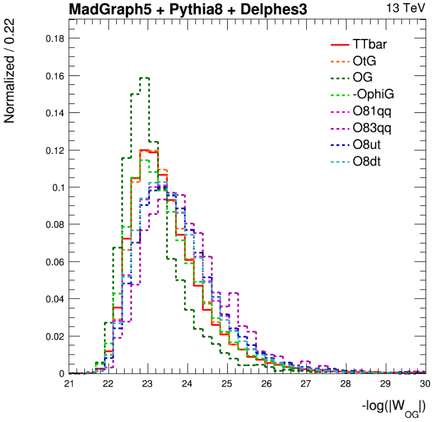


Figure : "Weight" for $\mathcal{O}_G$

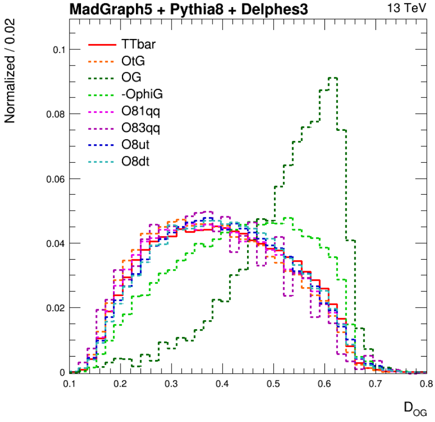


Figure : Discriminant for $\mathcal{O}_G$

Weights & discriminants

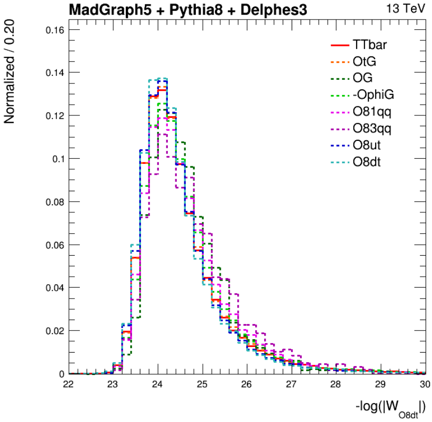


Figure : “Weight” for $\mathcal{O}_{dt}^{(8)}$

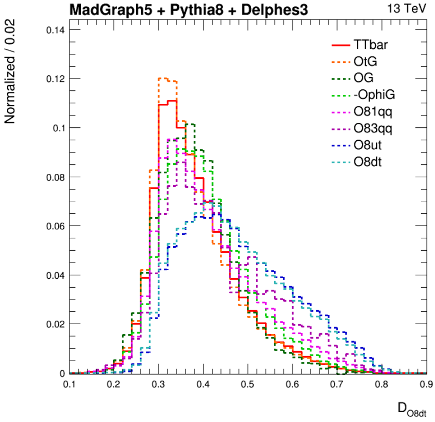


Figure : Discriminant for $\mathcal{O}_{dt}^{(8)}$