Anomalous $\gamma\gamma \rightarrow t\bar{t}$ scattering at the LHC

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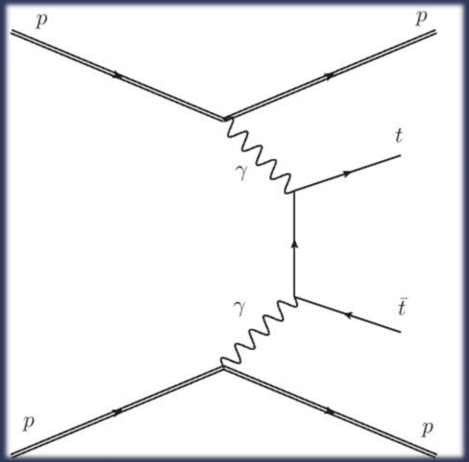
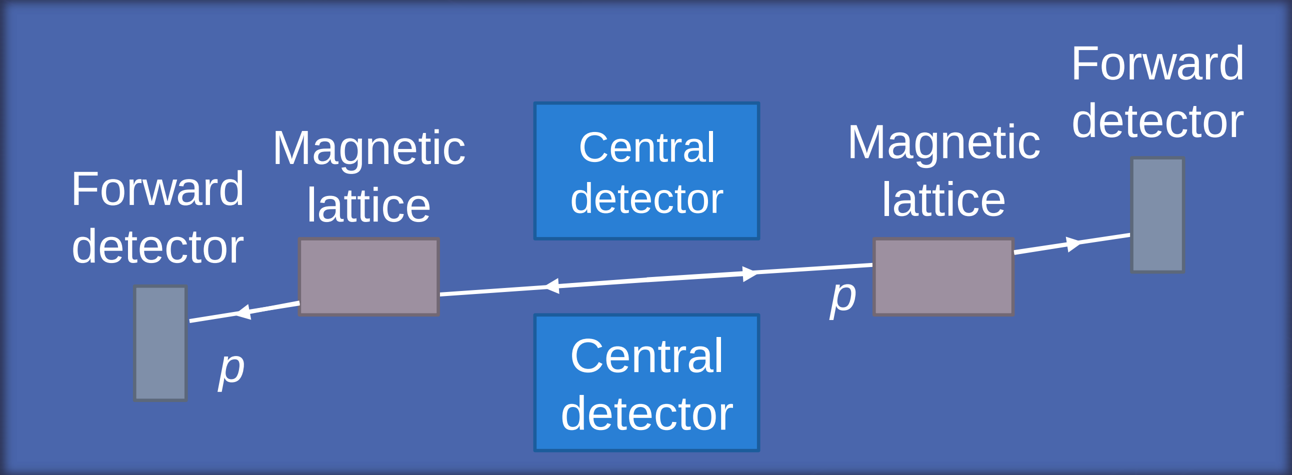
Introduction

- Peripheral pp collisions at the LHC produce quasi-real photons
  - LHC works as a $\gamma\gamma$ collider!
- QED $\gamma\gamma \rightarrow t\bar{t}$ process has never been measured so far
  - Central exclusive $t\bar{t}$ production has $\mathcal{O}(0.1)$ fb cross section ($\mathcal{O}(1)$ fb for semi-exclusive)
  - Can be measured with forward detectors
    - CMS PPS
    - ATLAS AFP



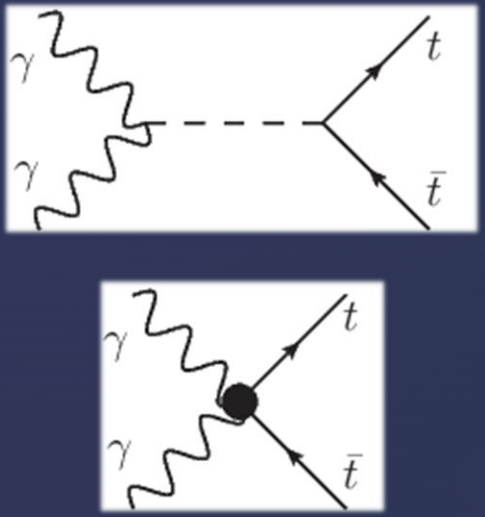


Introduction

- Recent studies:
  - V. P. Goncalves et al. (arxiv:2007.04565): SM exclusive and semi-exclusive $t\bar{t}$ production $\gamma\gamma$, $\gamma\mathbb{P}$, $\mathbb{P}\mathbb{P}$
  - M. Łuszczak et al. (arxiv:1810.12432): $\gamma\gamma \rightarrow t\bar{t}$ production with/without proton dissociation in k_T-factorisation approach
- SM $t\bar{t}$ production dominant at low mass. BSM contributions will modify the high-$m_{t\bar{t}}$ region
  - Anomalous $\gamma\gamma t\bar{t}$ couplings could give an indication of composite Higgs / extra dimensions
  - This approach could complement searches for on-shell BSM particles
- EFT approach (valid for $\Lambda_{BSM} \gg m_{t\bar{t}}$)
  - Model-independent way of addressing this question

Signal model

- Anomalous interactions modeled via dimension-8 EFT operators



CP-even, 2 derivatives

$\mathcal{O}_1 = \zeta_1 m_t F^{\mu\nu} F_{\mu\nu} t\bar{t}$ $\mathcal{O}_2 = \zeta_2 m_t F^{\mu\nu} \tilde{F}_{\mu\nu} \bar{t}\gamma_5 t$

CP-odd, 2 derivatives

$\mathcal{O}_3 = \zeta_3 m_t F^{\mu\nu} \tilde{F}_{\mu\nu} t\bar{t}$ $\mathcal{O}_4 = \zeta_4 m_t F^{\mu\nu} F_{\mu\nu} \bar{t}\gamma_5 t$

CP-even, 3 derivatives

$\mathcal{O}_5 = i\zeta_5 F^{\mu\rho} F^{\nu}_{\rho} \bar{t}\gamma_\mu \partial_\nu t$

CP-odd, 3 derivatives

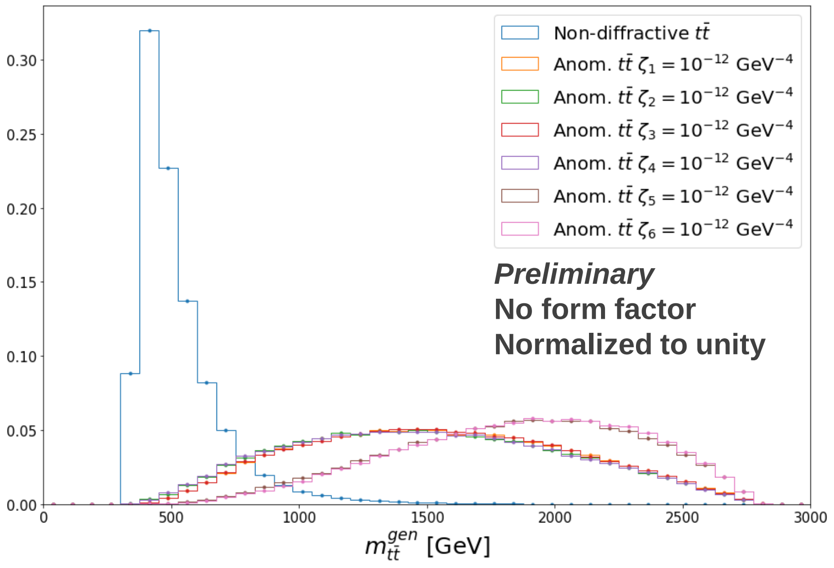
$\mathcal{O}_6 = i\zeta_6 F^{\mu\rho} F^{\nu}_{\rho} \bar{t}\gamma_5\gamma_\mu \partial_\nu t$

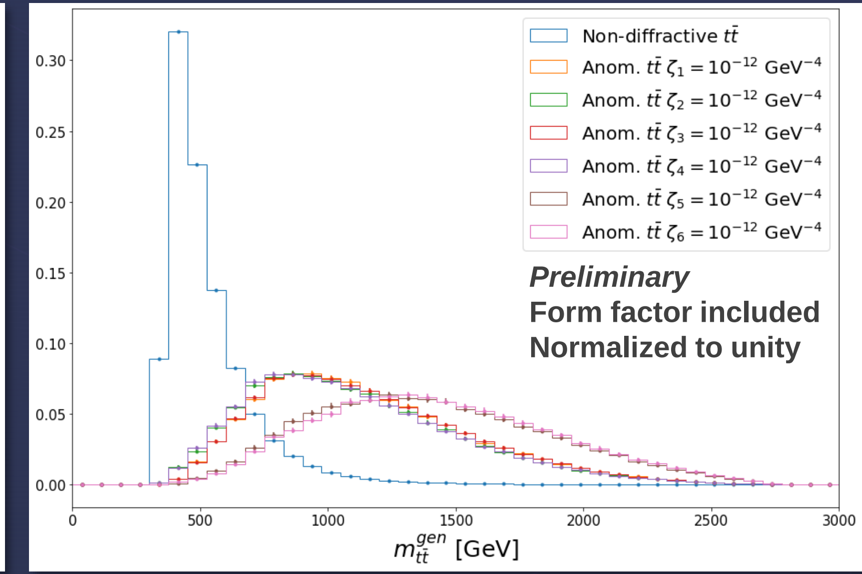
- $\zeta_i (i = 1, \dots, 6)$ are the anomalous coupling strengths (GeV^{-4})

Unitarity preservation

- Study performed both with and without a form factor to preserve unitarity:

$$\zeta_i \rightarrow \frac{\zeta_i}{\left(1+\frac{m_{t\bar{t}}^2}{\Lambda_{cutoff}^2}\right)^2}, \Lambda_{cutoff} = 2\ \mathrm{TeV}$$





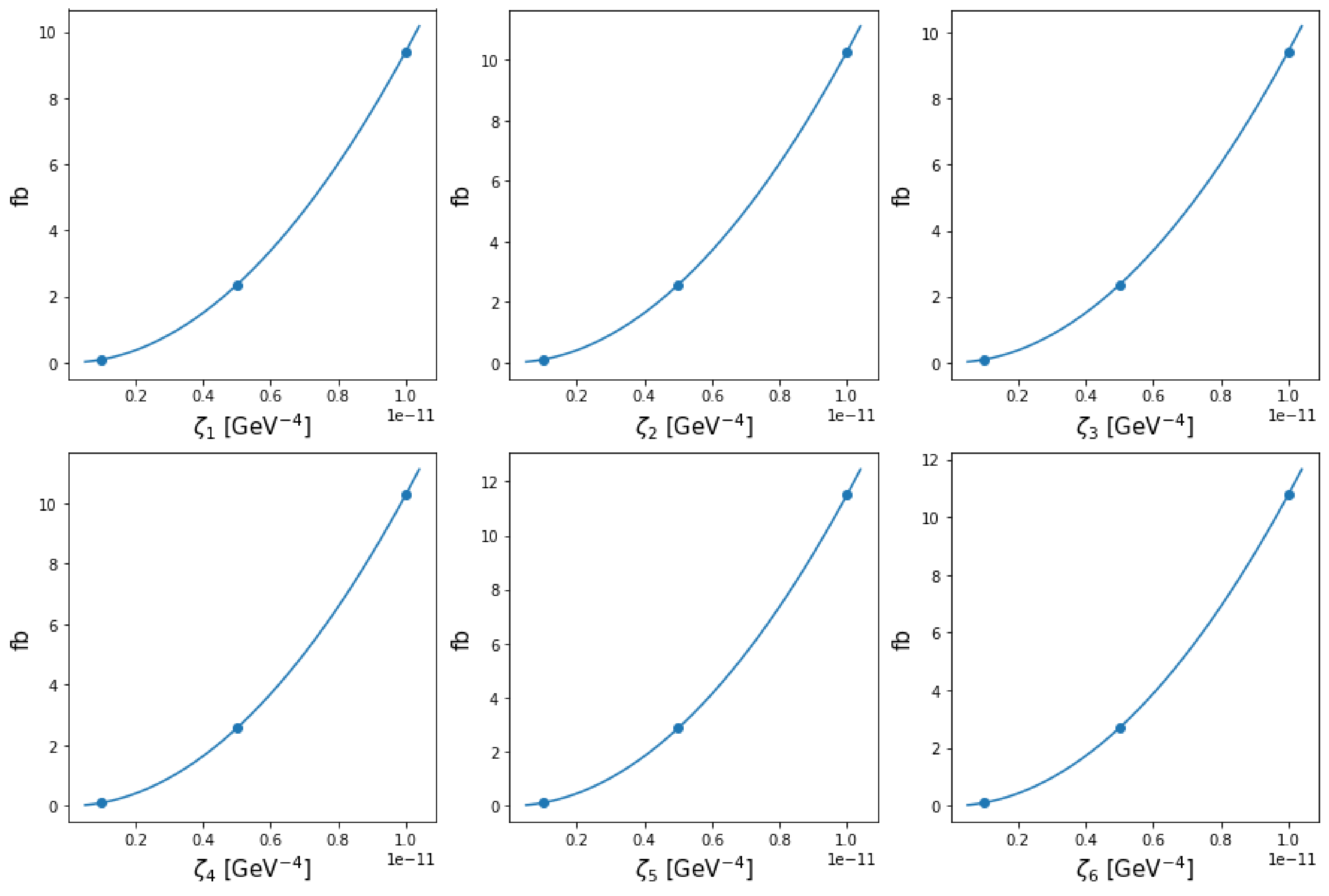
3-derivative operators grow faster at high-$m_{t\bar{t}}$ as expected

Signal simulation framework

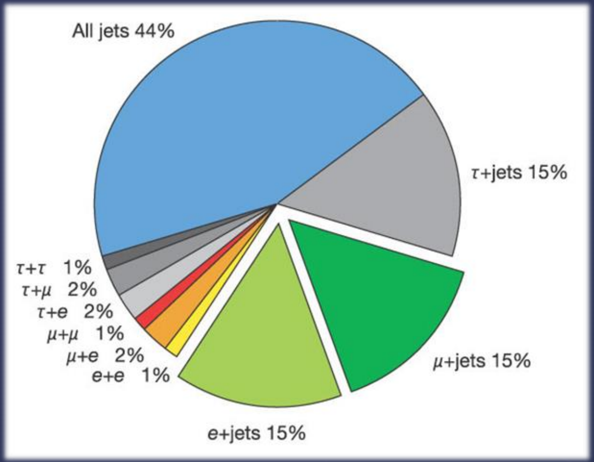
- EFT lagrangian implemented in MadGraph
- MadGraph matrix element calculation used in FPMC to generate exclusive events. Hadronization and parton shower with Herwig6
  - $\sqrt{s} = 14$ TeV
  - Proton ξ in the 0.015 - 0.2 range
    - Match forward detectors acceptance
- Detector simulation with Delphes (CMS reference datacard)
  - 2% gaussian smearing on ξ to account for detector uncertainties

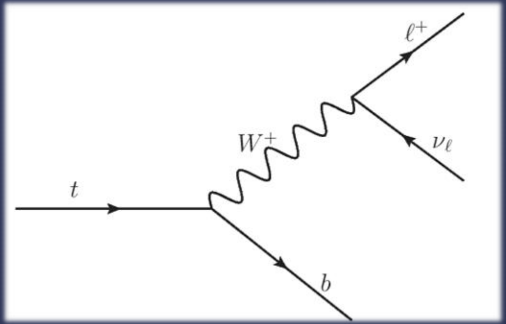
$$\xi = \frac{\Delta p}{p}$$

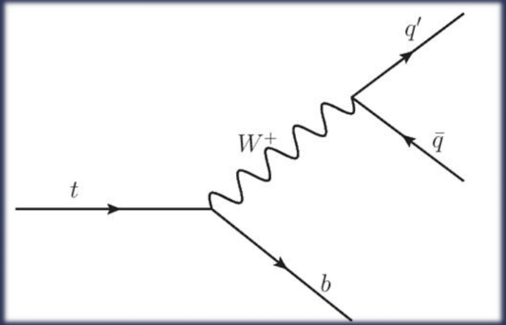
Coupling vs. Cross Section



$t\bar{t}$ decay channels

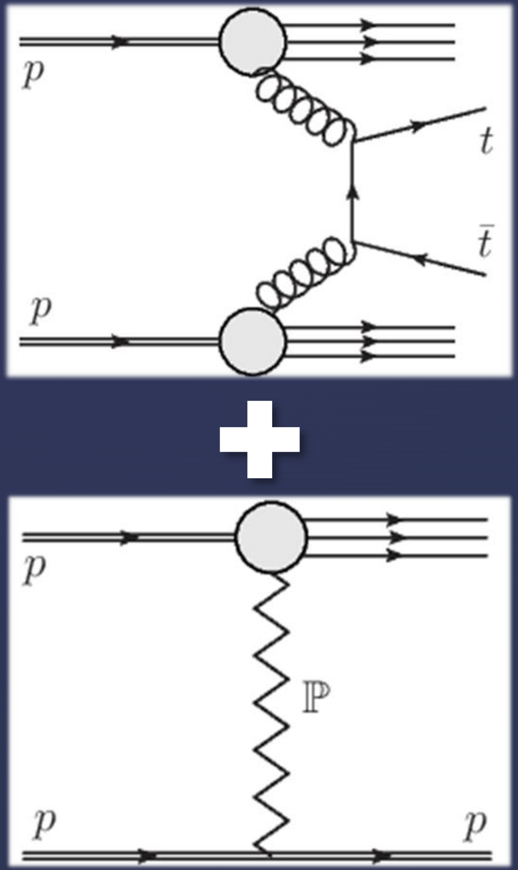






- 3 $t\bar{t}$ decay channels, depending on the W decay type
  - Fully-leptonic: lowest BR, two neutrinos make the top quark reconstruction less precise
  - Fully-hadronic: highest BR, although top quarks are harder to resolve in single large-R jets, higher backgrounds
  - Semi-leptonic (e/μ): good BR compromise, easy and precise reconstruction
- Preliminary results in semi-leptonic channel

Background

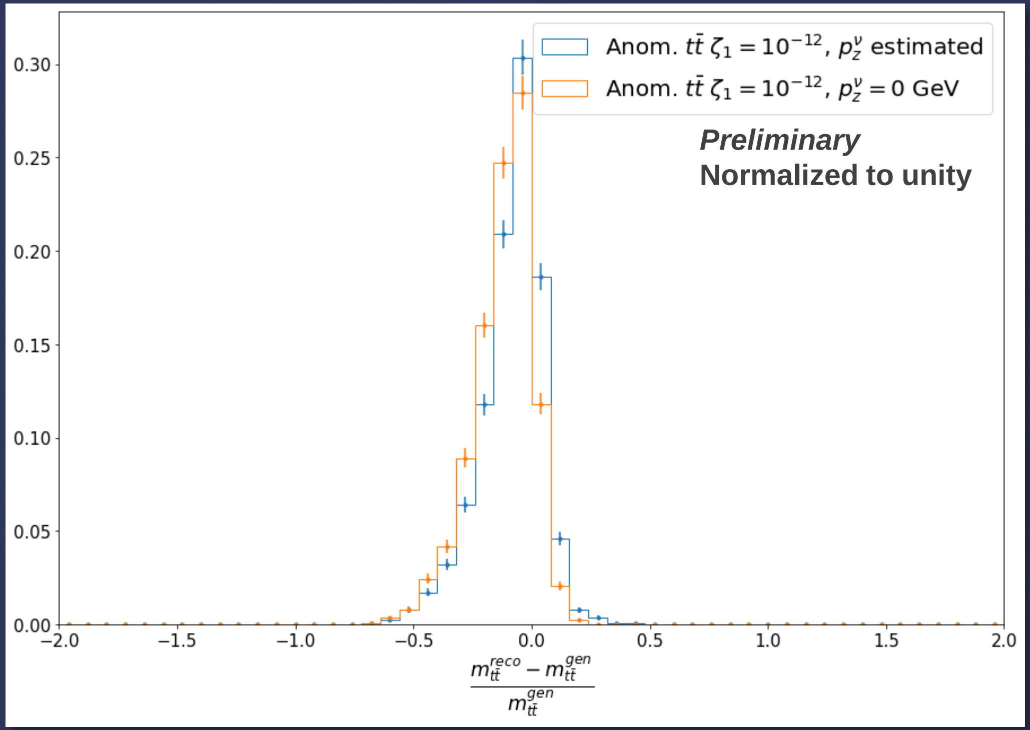


- Main contributions:
  - Non-diffractive $t\bar{t}$ + pileup protons from soft-diffractive events
  - Non-diffractive WW + pileup protons (mostly negligible)
  - SM exclusive $t\bar{t}$ → negligible
- Background events generated with MadGraph+Pythia8
- Identical detector simulation as for signal
- Pileup protons added sampling from a $\frac{1}{\xi}$ p.d.f. for an average conservative pileup of 50, in the 0.015 – 0.2 ξ range
  - ~28 % probability of having at least one pileup proton per side!!

Pre-selection

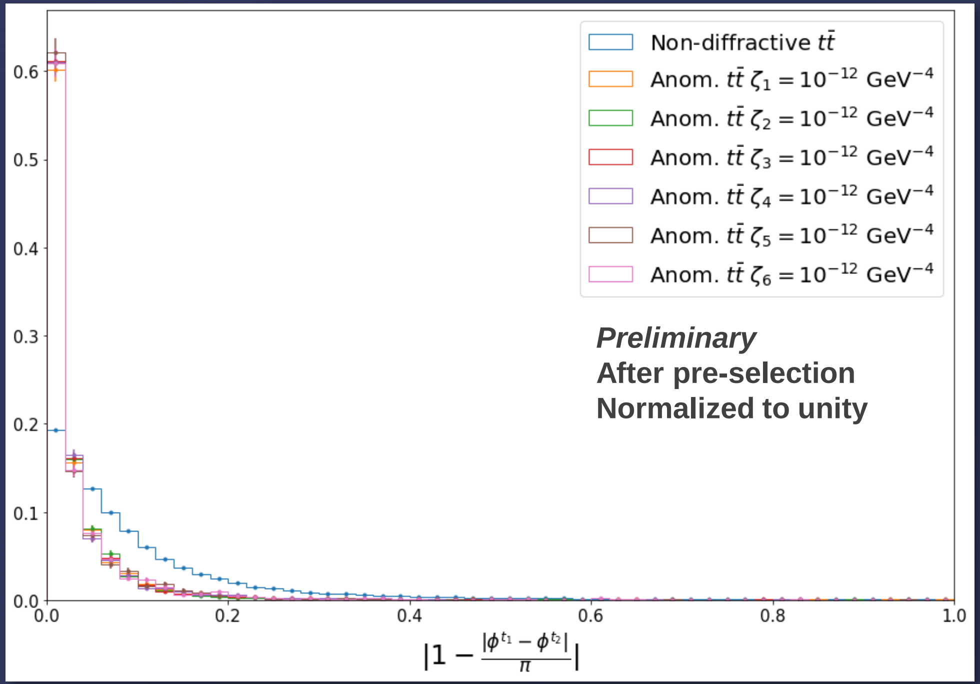
- Enhance semi-leptonic decay channel and select particles for reconstruction:
  - Leptons ≥ 1
  - b-tagged jets ≥ 2 (j_1^b, j_2^b)
  - Non-b-tagged jets ≥ 2 (j_1, j_2)
  - MET ≥ 20 GeV
  - At least one tagged proton per side
- Highest-p_T (ξ for protons) particles are always chosen, to favor anomalous production (high-$m_{t\bar{t}}$)

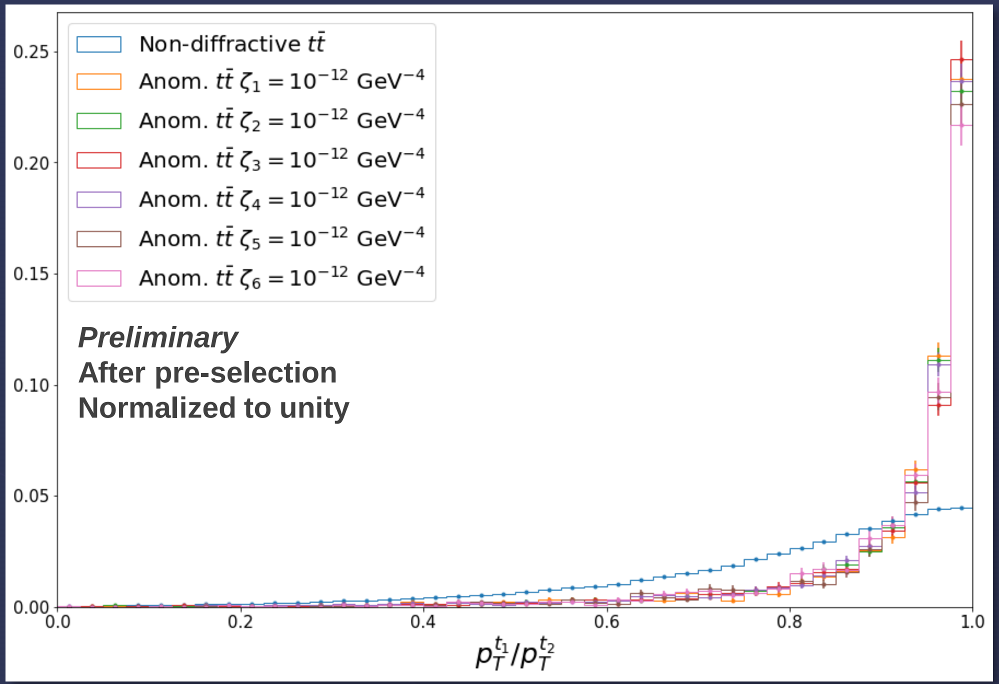
Reconstruction



- b-jet assignment: check the mass of $j_1^b + j_1 + j_2$ and $j_2^b + j_1 + j_2$
  - Assign to the hadronic-decaying top j_i^b ,based on which yields the result closest to the top quark mass
- Assume $p_T^{\nu} = MET$ and estimate p_z^{ν} by imposing mass of $\ell + \nu = m_W$
  - Analytically solved
- ✓ Reconstructed $m_{t\bar{t}}$ is more accurate
- ✓ Better match with $m_{t\bar{t}}$ reconstructed with tagged protons!

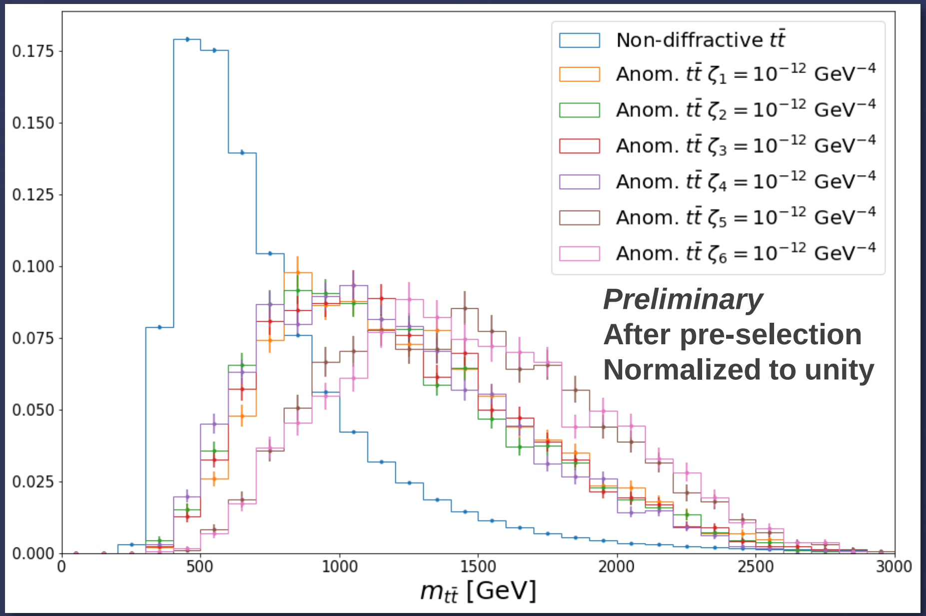
Central selection: exclusivity cuts

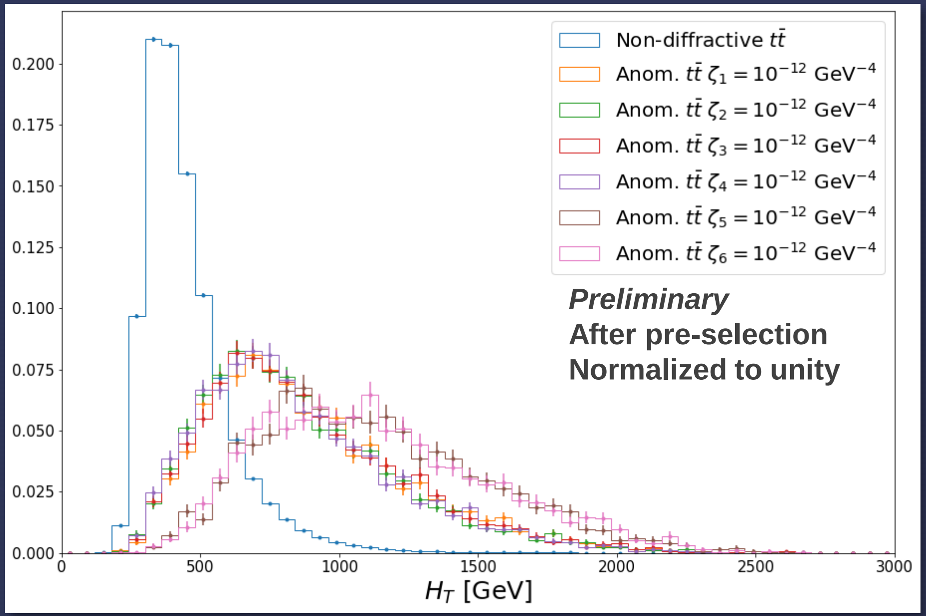




- Exploit exclusivity of signal, top quarks emitted back-to-back:
  - Low acoplanarity: $|1 - \frac{|\Phi^{t_1} - \Phi^{t_2}|}{\pi}| < 0.01$
  - Top quarks balanced in p_T: $p_T^{t_1}/p_T^{t_2} > 0.88$
- Selection optimized for best significance

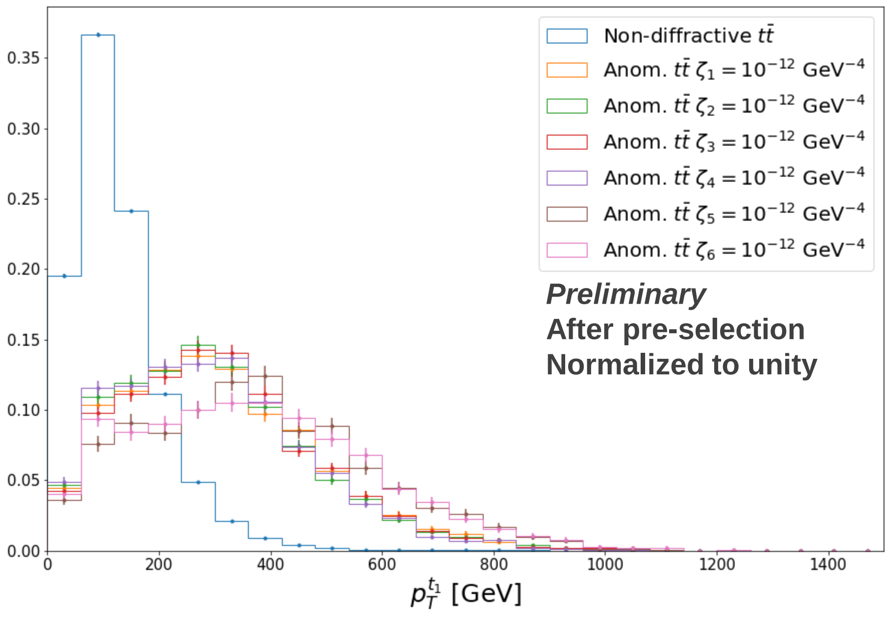
Central selection: high-mass cuts

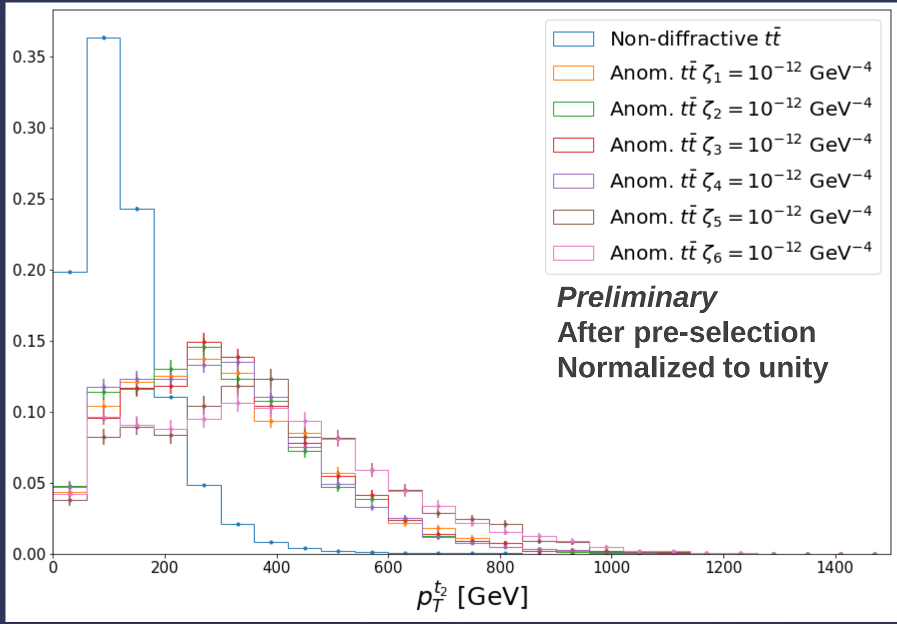




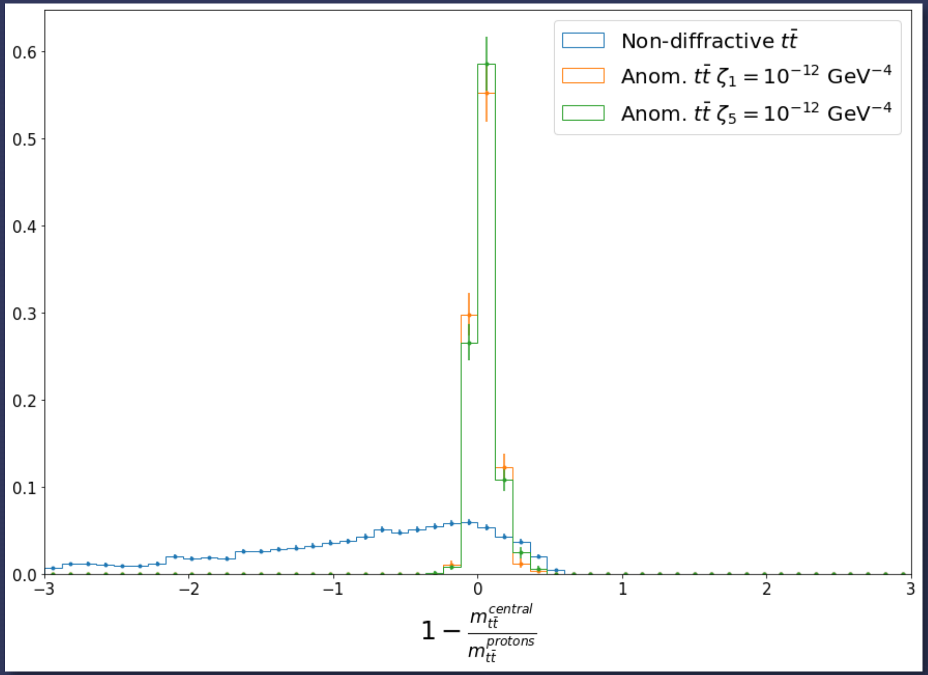
- Favor anomalous production by selecting high-$m_{t\bar{t}}$ events:
  - Reconstructed mass of the $t\bar{t}$ system: $m_{t\bar{t}} > 960$ GeV
  - $H_T = p_T^{\ell} + p_T^{\nu} + p_T^{j_1} + p_T^{j_2} + p_T^{j_1^b} + p_T^{j_2^b} > 1100$ GeV
- Selection optimized for $\mathcal{O}_1$ - $\mathcal{O}_4$

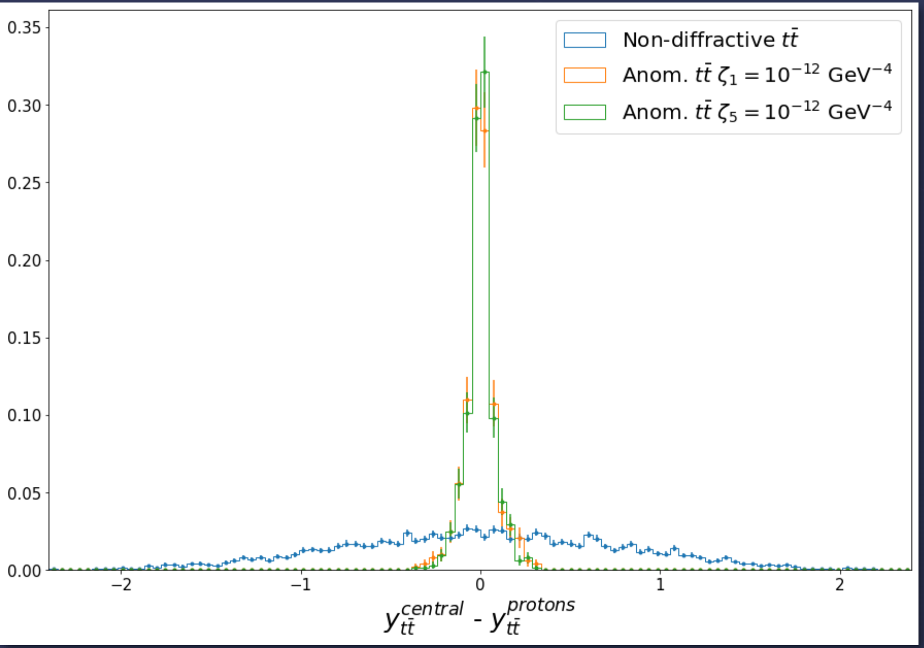
Central selection: top quark p_T





- Favor anomalous production by selecting events with high top quarks p_T:
  - $p_T^{t_i} > 425$ GeV





Proton matching

- Four-momentum conservation in $p\,p \to p\,t\bar{t}\,p$ $\to$ kinematic correlations between forward protons and central system
  - $m_{t\bar{t}}^{p} = \sqrt{s\xi_1\xi_2} \to \left|\frac{m_{t\bar{t}}^{p} - m_{t\bar{t}}^{c}}{m_{t\bar{t}}^{p}}\right| < 0.08$
  - $y_{t\bar{t}}^{p} = \frac{1}{2}\log\left(\frac{\xi_1}{\xi_2}\right) \to \left|y_{t\bar{t}}^{c} - y_{t\bar{t}}^{p}\right| < 0.05$

Results & predictions

Selection step	$\zeta_1 = 10^{-11}[\mathrm{GeV}^{-4}]$	$\zeta_5 = 10^{-11}[\mathrm{GeV}^{-4}]$	Non-exclusive $t\bar{t}$	Non-exclusive WW
Pre-selection	106.3	88.6	$5\cdot10^{6}$	$3.0\cdot10^{3}$
Central selection	13.3	21.2	$1.2\cdot10^{4}$	25.2
Proton selection	9.45	14.2	96.7	~0

	$\zeta_1 = 1\cdot10^{-11}[\mathrm{GeV}^{-4}]$	$\zeta_5 = 1\cdot10^{-11}[\mathrm{GeV}^{-4}]$	SM $t\bar{t}$	SM WW
Cross section	9.42 fb	11.5 fb	903 pb	131.3 pb

- Results shown for a single coupling point and 300 fb^{-1} integrated luminosity, passing fractions do not strongly depend on coupling value
- Very strong background rejection provided by proton tagging
  - Could be further improved by using timing detectors
- Only SM $t\bar{t}$ really contributes to background

Results & predictions

Coupling [10^{-11} GeV^{-4}]	5σ No form factor	95 % CL No form factor	5σ With form factor	95 % With form factor
ζ_1	2.4	1.5	3.1	1.9
ζ_2	2.3	1.4	3.1	1.9
ζ_3	2.3	1.4	2.9	1.8
ζ_4	2.3	1.4	3.1	1.9
ζ_5	1.9	1.2	2.2	1.3
ζ_6	2.1	1.3	2.3	1.4

- Preliminary sensitivities to anomalous couplings extracted for 300 fb^{-1} integrated luminosity and $\sqrt{s} = 14$ TeV
- Assuming similar object reconstruction performance and acceptance at the HL-LHC with 3000 fb^{-1}, would expect at most an improvement on the projections by a factor of $\sim$3

Summary & Outlook

- EFT model for anomalous $\gamma\gamma t\bar{t}$ coupling implemented in FPMC
  - Available soon in MadGraph and FPMC!
- Anomalous exclusive $t\bar{t}$ production in semi-leptonic decay channel studied and analyzed
- Preliminary anomalous coupling sensitivities extracted for 300 fb^{-1} at $\sqrt{s} = 14$ TeV:
  - 95 % CL at $\zeta \sim 2 \cdot 10^{-11}$ GeV^{-4}
- Next steps:
  - Finalization of the paper and submission!

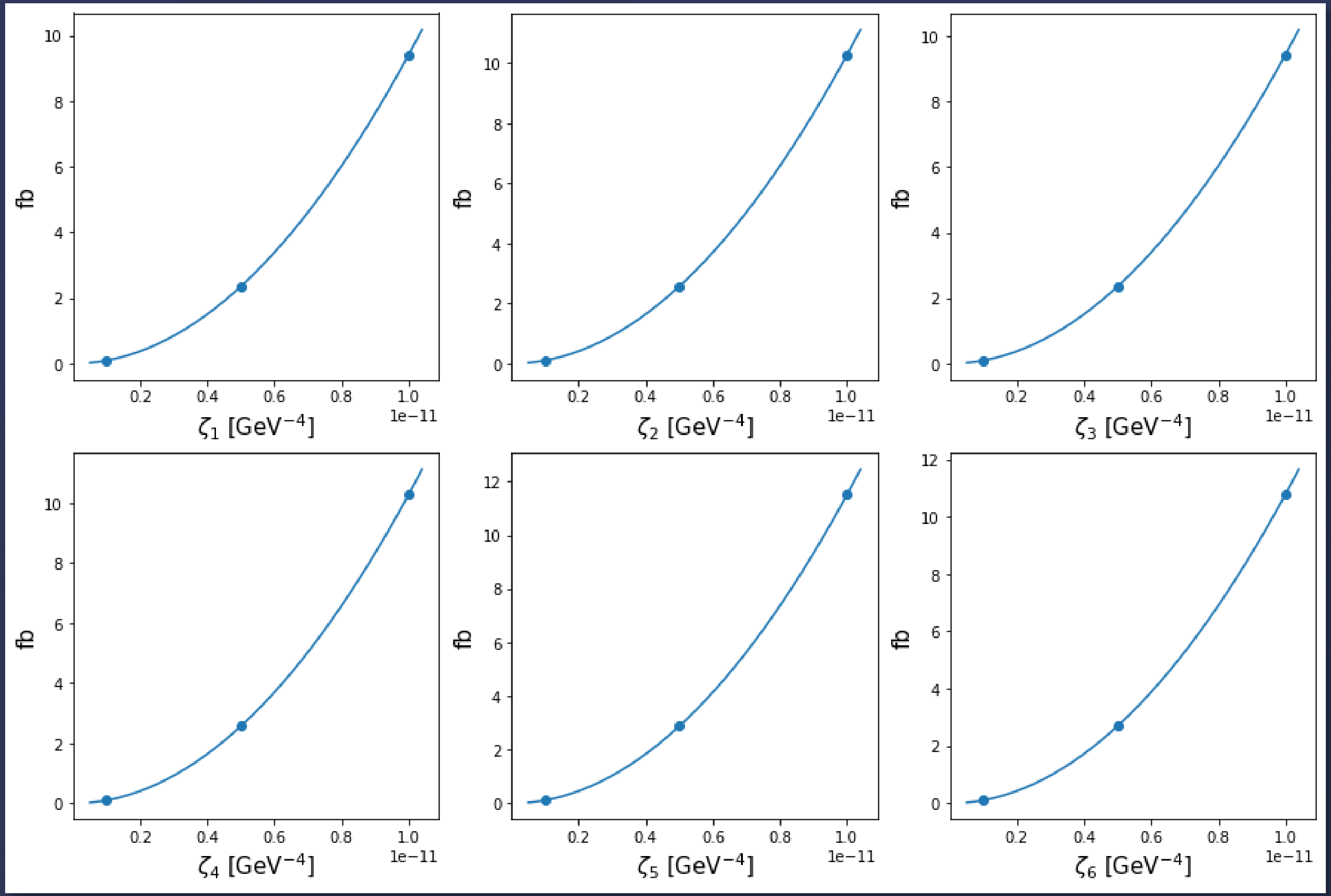
Thanks for your attention!

Backup

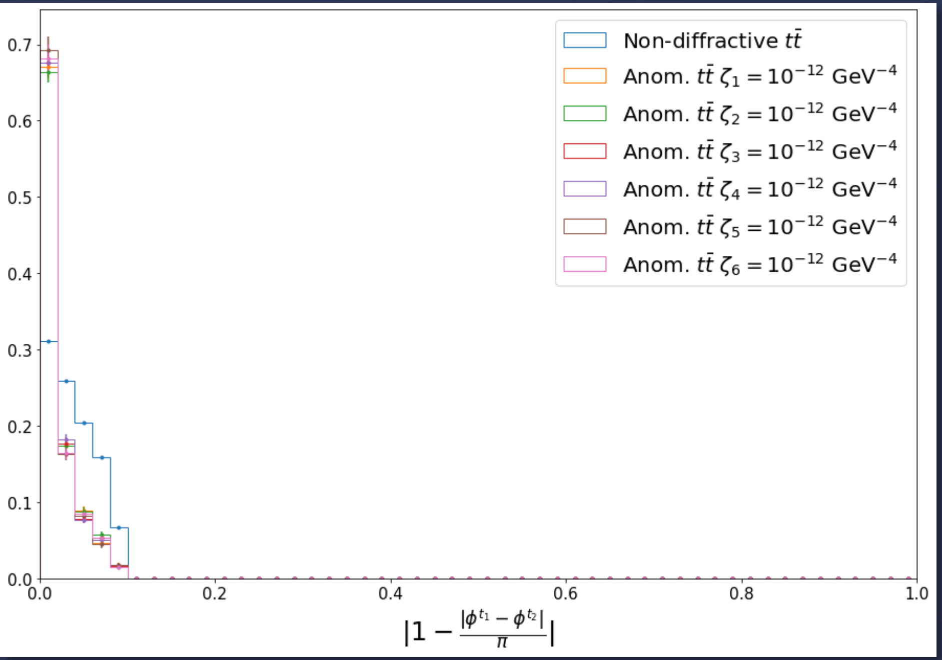
Delphes Simulation

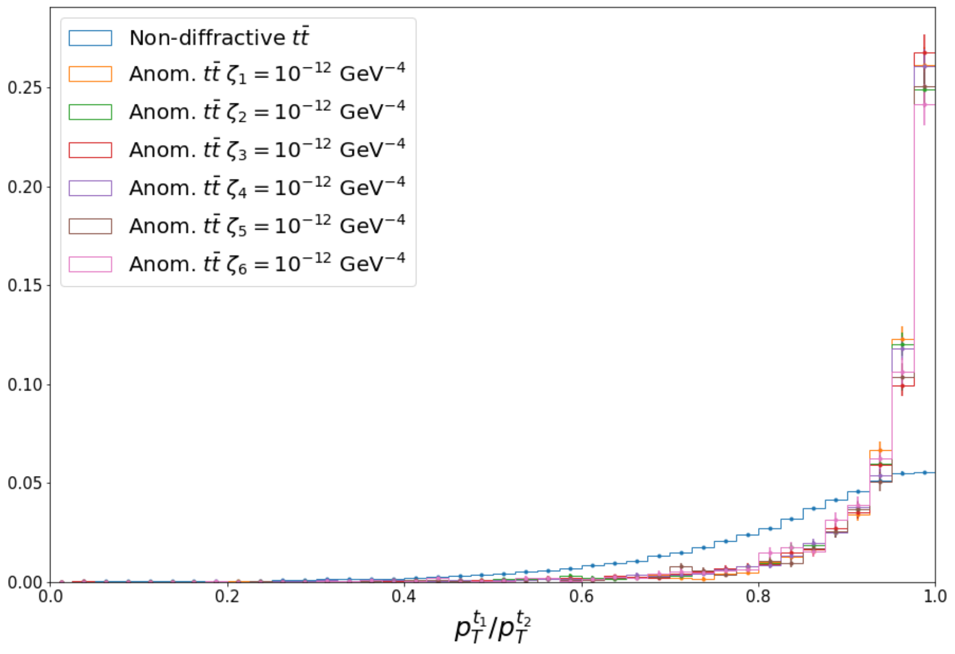
- Standard CMS datacard:
  - p_T- and η-dependent tracking efficiency (~95 % in the most populated region)
  - Momentum resolution based on arXiv:1405.6569 and arXiv:1502.02701 formulas
  - ECAL resolution formula based on hep-ex/1306.2016 and hep-ex/1502.02701
    - Also η-dependent
- Jet clustering with FastJet:
  - Anti-kt, R = 0.5, JetPTMin = 20 GeV
- MET from Particle Flow approach
- b-tagging based on arXiv:1211.4462

Coupling vs. Cross Section



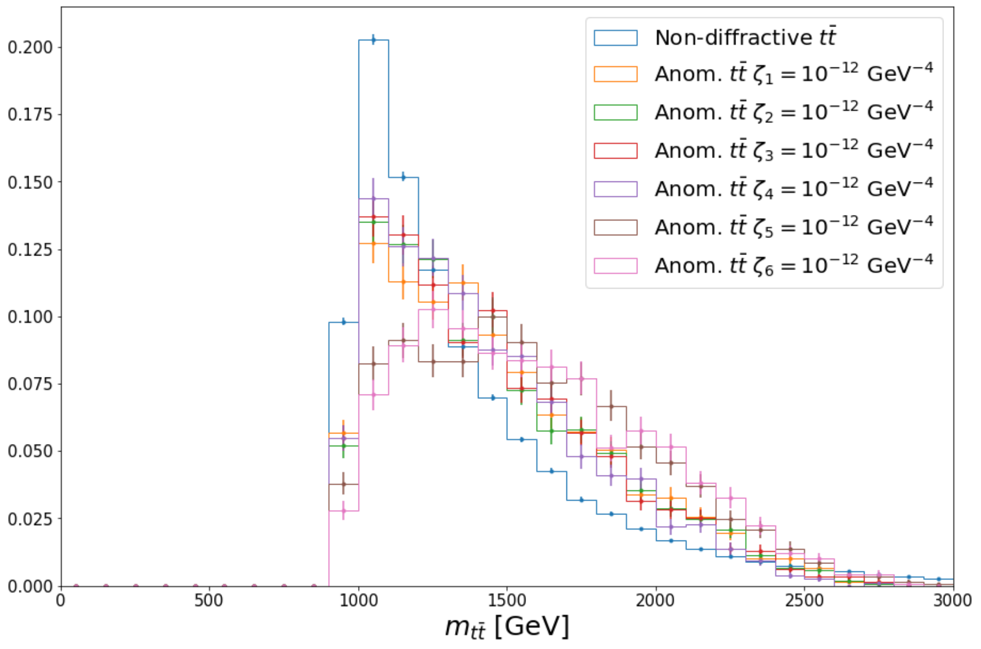
Correlation cross-checks

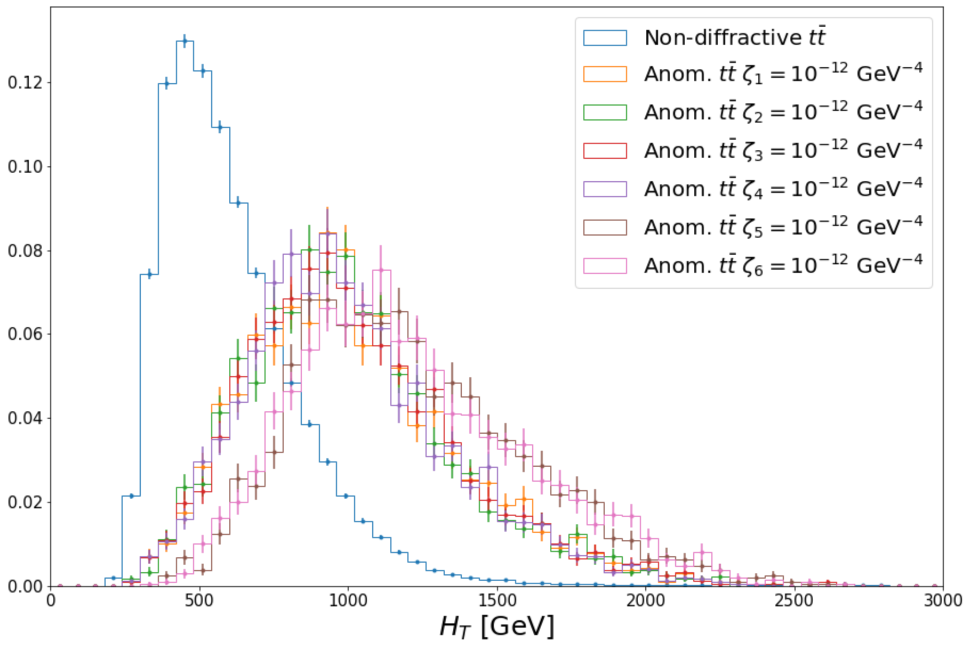




- p_T balance distribution not very affected by the acoplanarity cut

Correlation cross-checks





- H_T distribution not significantly affected by $m_{t\bar{t}}$ cut