The 15th International Workshop on Top Quark Physics

Searching for anomalous top quark interactions with proton tagging and timing detectors at the LHC

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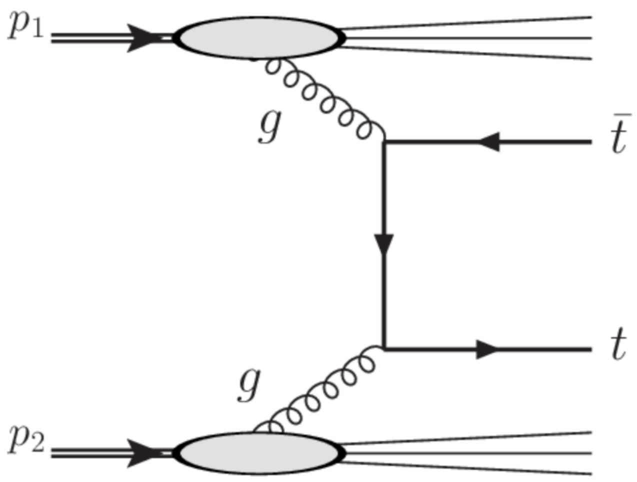
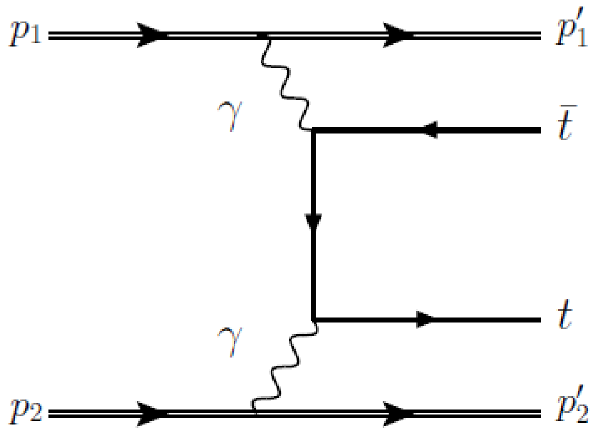
Introduction – ttbar production at the LHC

- The dominant production of ttbar is via ggF:
  - ttbar produced by QCD interactions
  - Protons dissociate into multiparticle final states
  - A large number of energetic particles are produced (ISR)



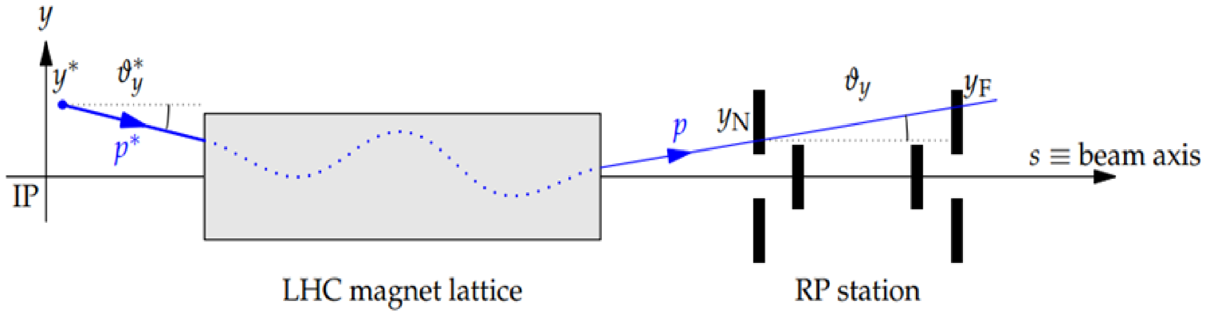
- Rarely, top quarks can be produced in Ultra-Peripheral collisions:
  - ttbar produced via photon fusion
  - Low track activity due to exchange of color singlets
  - Protons could remain intact
  - **LHC works as a photon collider**



Introduction – LHC as a photon collider

○ At high masses, intact protons → photon fusion

- At the LHC, intact protons that lose a fraction of their momentum ($\xi = \Delta p/p$) and are scattered at small angles (θ^*_x, θ^*_y) , are deflected away from the proton beam by LHC magnets
- These protons can be measured by very-far near-beam detectors (AFP/PPS located ~200 m from the ATLAS/CMS detectors)



- Displacement of the protons from the beam determines the proton momentum loss ξ and p_T
- At the 200 m stations forward protons can be measured in the range of ξ ~ 1.5% –20% and p_T up to a few GeV

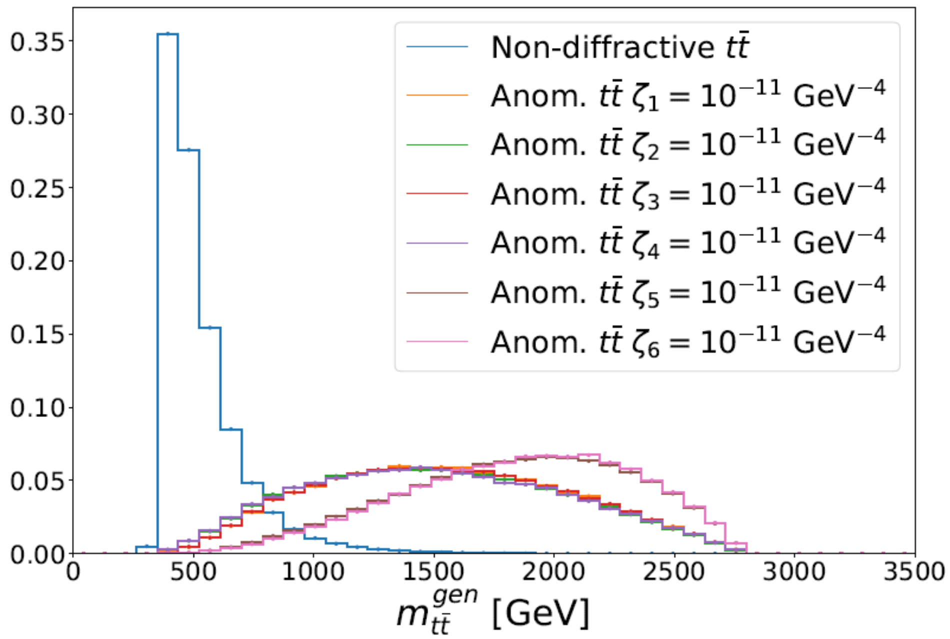
Introduction – SM predictions

- The SM $\gamma\gamma \rightarrow t\bar{t}$ processes have been discussed in the literature:
  - V. P. Goncalves et al. (arXiv:2007.04565): SM exclusive and semi-exclusive $t\bar{t}$ production via $\gamma\gamma$, $\gamma\mathbb{P}$, $\mathbb{P}\mathbb{P}$
  - J. Howarth (arXiv:2008.04249): Elastic production of top quarks
  - M. Łuszczak et al. (arXiv:1810.12432): $\gamma\gamma \rightarrow t\bar{t}$ production with/without proton dissociation in kT-factorization approach

- SM **cross-section** with tagged protons within the acceptance of LHC experiments ~ **0.3 fb** → accessible at the HL-LHC phase (arXiv:2103.02752).

Looking beyond the SM

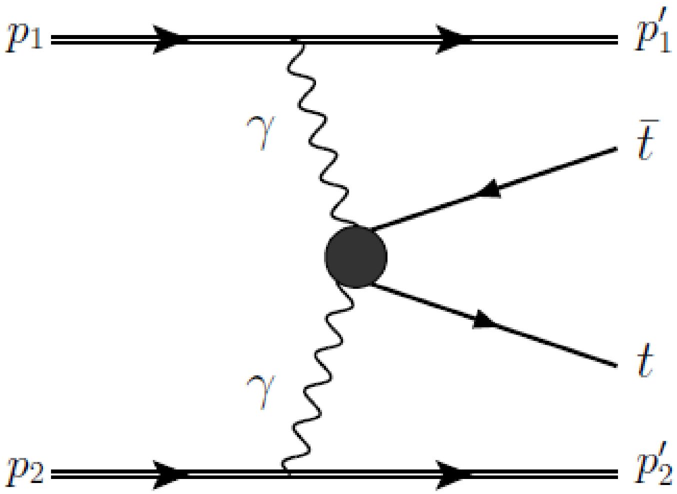
- SM $\gamma\gamma \rightarrow t\bar{t}$ processes dominant at m_{tt} threshold, while any modifications of γ-top coupling will affect the high m_{tt} region
  - Anomalous couplings indicate of BSM signal
  - This approach could complement searches for on-shell BSM particles



- EFT approach (valid for $\Lambda_{BSM} \gg \mathrm{m}_{t\bar{t}}$)
  - Model-independent way of addressing this question

Signal Model

Anomalous interactions are modeled via dimension-8 EFT operators



CP-even (2 derivatives)

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

CP-odd (2 derivatives)

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

CP-even (3 derivatives)

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

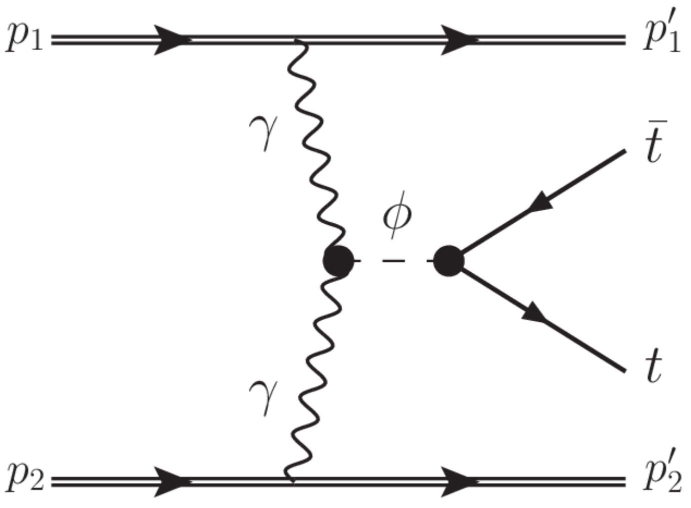
CP-odd (3 derivatives)

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

In terms of the EFT operators $\mathcal{L} = \mathcal{L}_{SM} + \Sigma \zeta_i O_i$, where ζi are the anomalous coupling strengths

Signal Model

Neutral particles coupled to photons can be classified to ϕ is CP-even scalar, a (or $\tilde{\phi}$) is CP-odd scalar and $h^{\mu\nu}$ is CP-even spin-2 field :



Coupling to photons

$$\mathcal{L}_{\text{eff}}^{\gamma\gamma} = \frac{1}{f_{0^+}^{\gamma\gamma}}\varphi(F_{\mu\nu})^2 + \frac{1}{f_{0^-}^{\gamma\gamma}}aF_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{1}{f_{2}^{\gamma\gamma}}h^{\mu\nu}\left(-F_{\mu\rho}F^{\rho}_{\ \nu} + \frac{1}{4}\eta_{\mu\nu}(F_{\rho\sigma})^2\right)$$

Coupling to top quarks

$$\mathcal{L}_{\text{eff}}^{\bar{t}t} = \frac{m_t}{f_{0^+}^{\bar{t}t}}\varphi\bar{t}t + i\frac{m_t}{f_{0^-}^{\bar{t}t}}a\bar{t}\gamma_5 t + i\frac{1}{f_{2}^{\bar{t}t}}h^{\mu\nu}\bar{t}\gamma_\mu D_\nu t$$

Matching to EFT couplings:

- Spin-0, CP-even scalar ϕ $\quad \zeta_1 = \frac{1}{f_{0^+}^{\gamma\gamma} f_{0^+}^{\bar{t}t} m^2},\qquad \zeta_{i\neq 1} = 0$
- Spin-0, CP-odd scalar $\tilde{\phi}$ $\quad \zeta_2 = \frac{1}{f_{0^-}^{\gamma\gamma} f_{0^-}^{\bar{t}t} m^2},\qquad \zeta_{i\neq 2} = 0$
- Spin-2, field $h_{\mu\nu}$ $\quad \zeta_1 = \frac{1}{4 f_{2}^{\gamma\gamma} f_{2}^{\bar{t}t} m^2}, \zeta_5 = -\frac{1}{f_{2}^{\gamma\gamma} f_{2}^{\bar{t}t} m^2},\qquad \zeta_{i\neq 1,5} = 0$

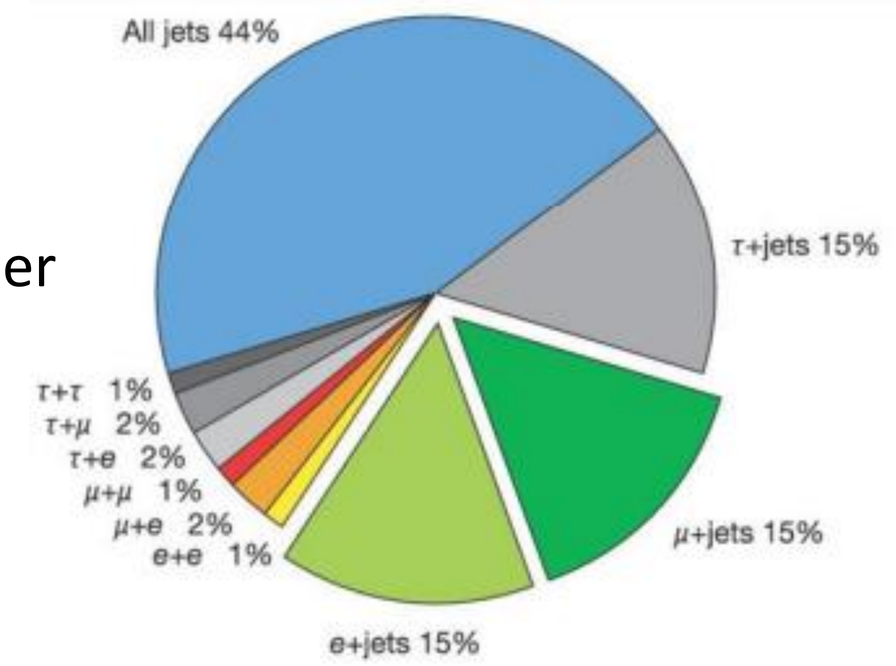
Signal simulation framework

- EFT lagrangian implemented in MadGraph: **import model AAttbar_UFO**
- MadGraph matrix element calculations are implemented in Forward Physics MC (FPMC) to generate exclusive events: https://github.com/fpmc-hep/fpmc
- Hadronization and parton shower with Herwig6
  - $\sqrt{s}$ = 14 TeV
  - Proton momentum loss, ξ, in the 0.015 - 0.2 range
    - Match LHC forward detectors acceptance
- Detector simulation with Delphes (CMS reference datacard)
  - 2% gaussian smearing on ξ to account for detector uncertainties

$t\bar{t}$ 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**



Results are shown for the semi-leptonic channel

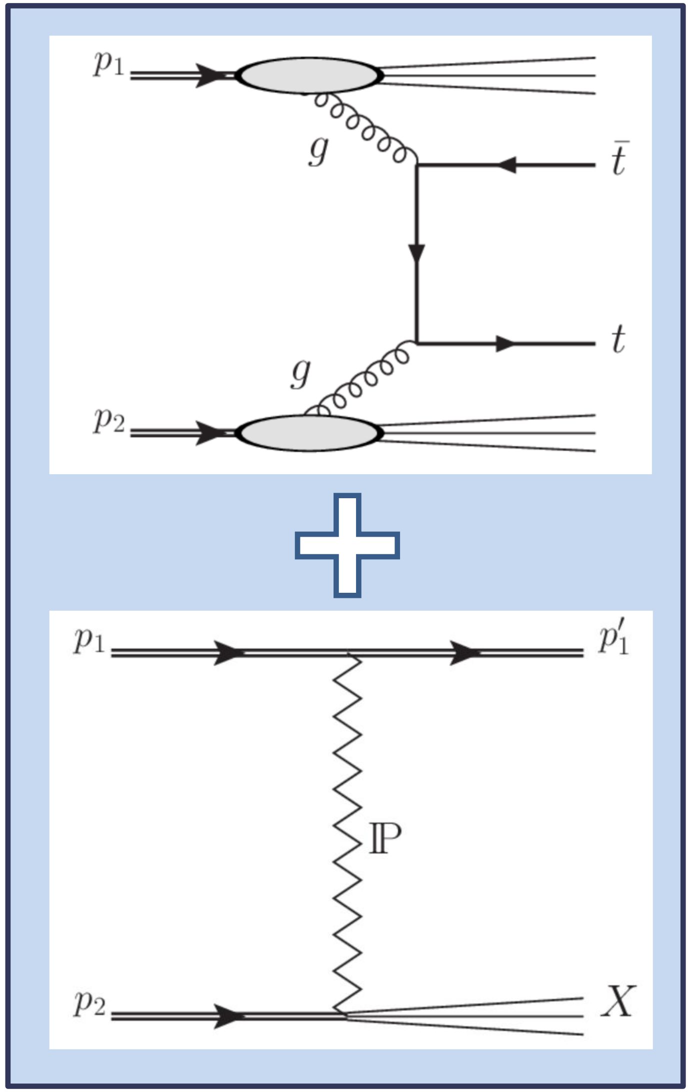
Background

At the LHC, with ~50 average interactions / bunch crossing the dominant background is SM processes + pileup protons

<u>Main contributions</u>:

- Non-diffractive $t\bar{t}$ + pileup protons from soft-diffractive events
- Non-diffractive WW + pileup protons (mostly negligible)
- SM exclusive $t\bar{t} \rightarrow$ negligible (see next selection cuts)

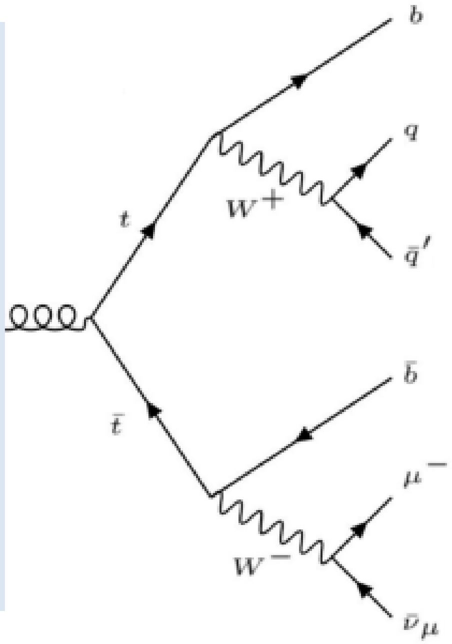
- Background events generated with MadGraph+Pythia8
- Same detector simulation as for signal
- Pileup protons added by sampling from a $P \propto 1/\xi$ for an average conservative pileup of 50, in the 0.015 – 0.2 ξ range
  - ➢ ~28 % probability of having at least one pileup proton per side!!



Event preselection

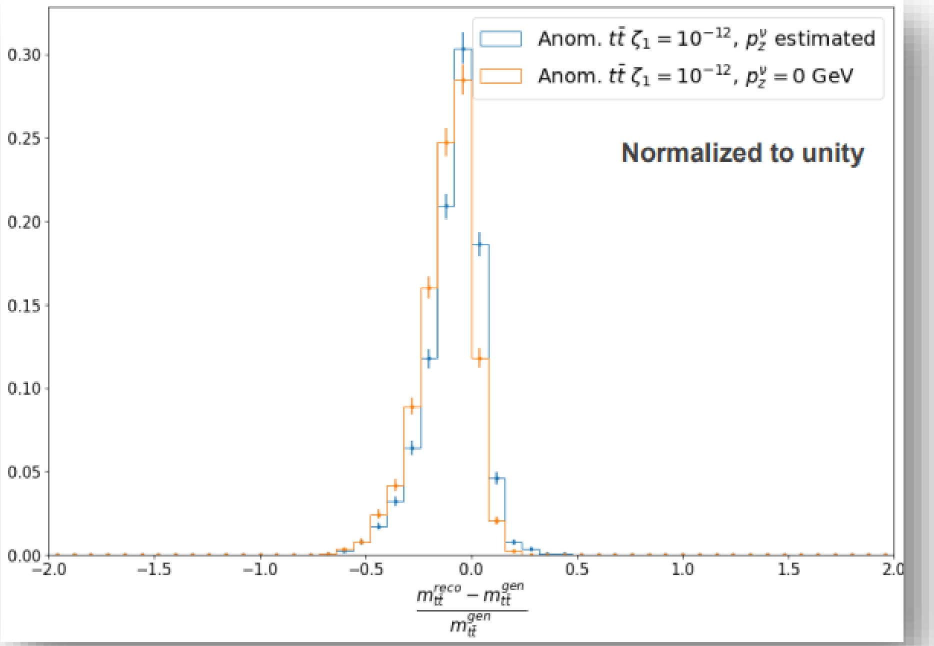
- Enhance semi-leptonic decay channel and select particles for reconstruction

  - b-tagged jets ≥ 2
  - Non-b-tagged jets ≥ 2
  - Leptons ≥ 1
  - MET ≥ 20 GeV
  - At least one tagged proton per side



- Highest-pT (ξ for protons) particles are always chosen, to favor anomalous production (high-$\mathrm{m}_{t\bar{t}}$)

Reconstruction



b-jet assignment:

- Compute masses $m_1 = b_1+j_1+j_2$ and $m_2 = b_2+j_1+j_2$
- Assign b_i to hadronic top satisfy $\min\{|m_i - m_{top}|\}$

Leptonic top reconstruction

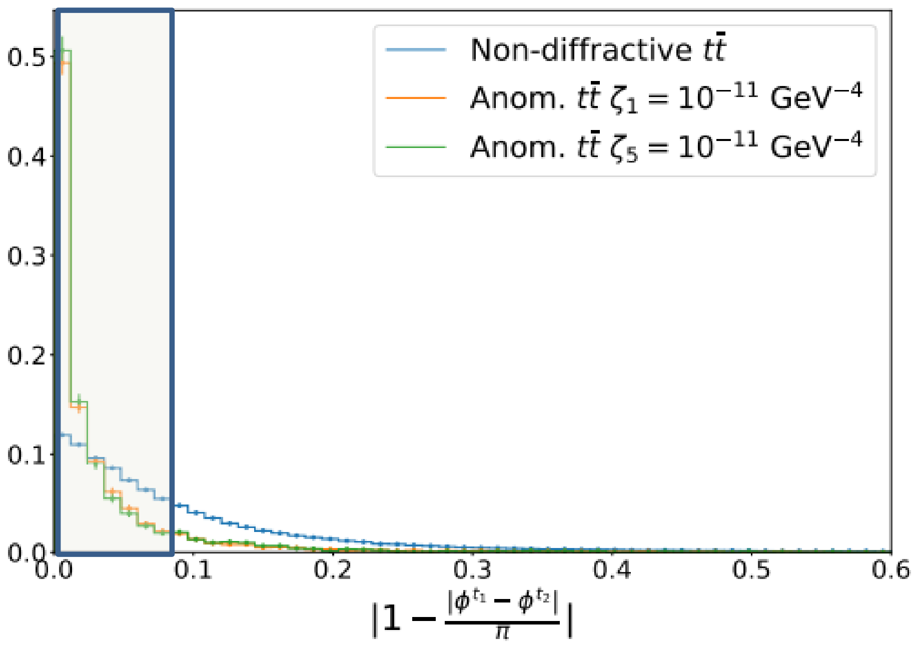
- Assume pT of neutrino = MET and estimate pZ by imposing W mass constraint

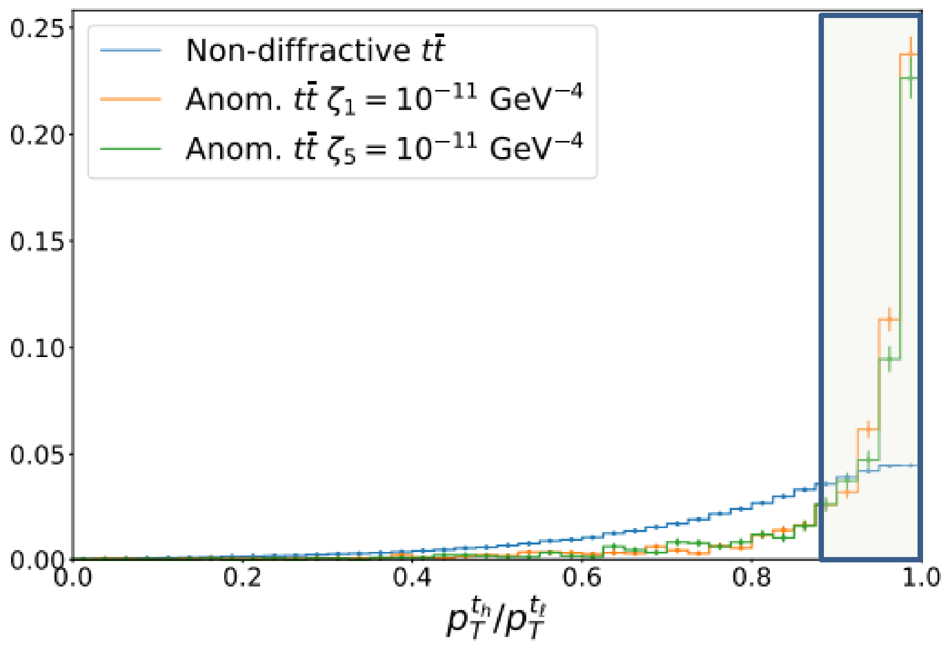
✓ **Reconstructed $m_{t\bar{t}}$ is more accurate**

✓ **Better match with $m_{t\bar{t}}$ reconstructed with tagged protons (next slide)**

Central selection: exclusivity cuts

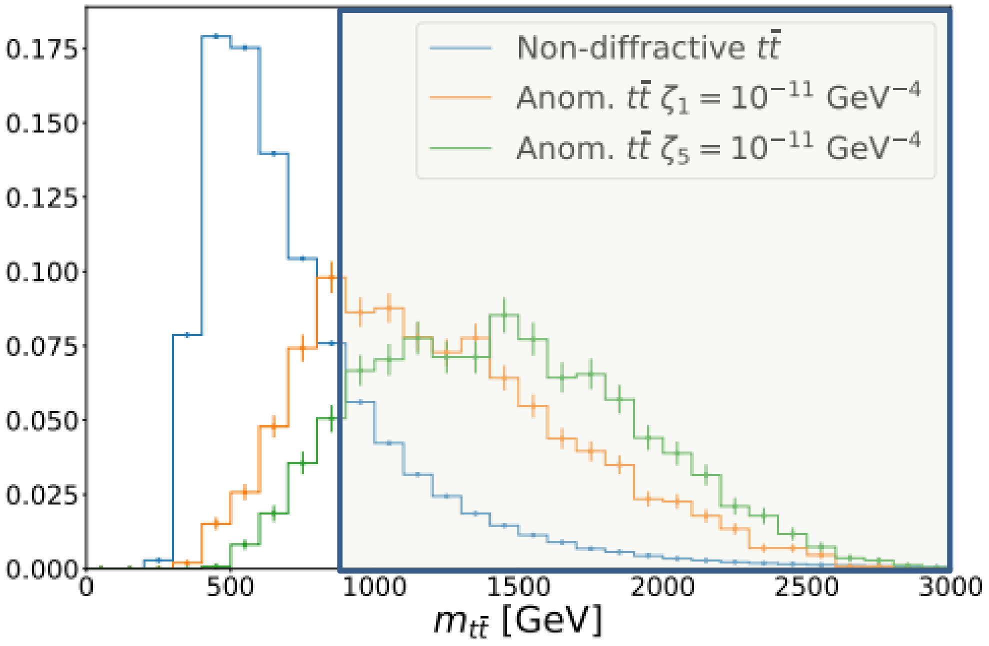
- Exploit exclusivity of signal, top quarks emitted back-to-back
  - Low acoplanarity: $\left|1 - \frac{\Delta\phi_{tt}}{\pi}\right| < 0.09$
  - Top quakrs balanced in pT: $\frac{p_T^{t_h}}{p_T^{t_l}} > 0.88$

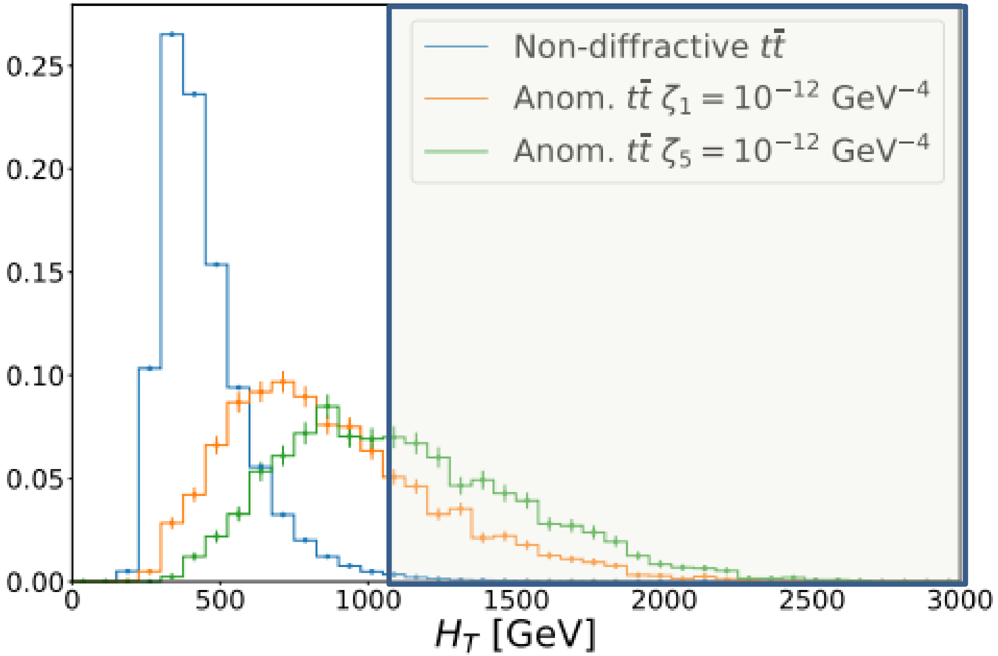




Central selection: high-mass / HT cuts

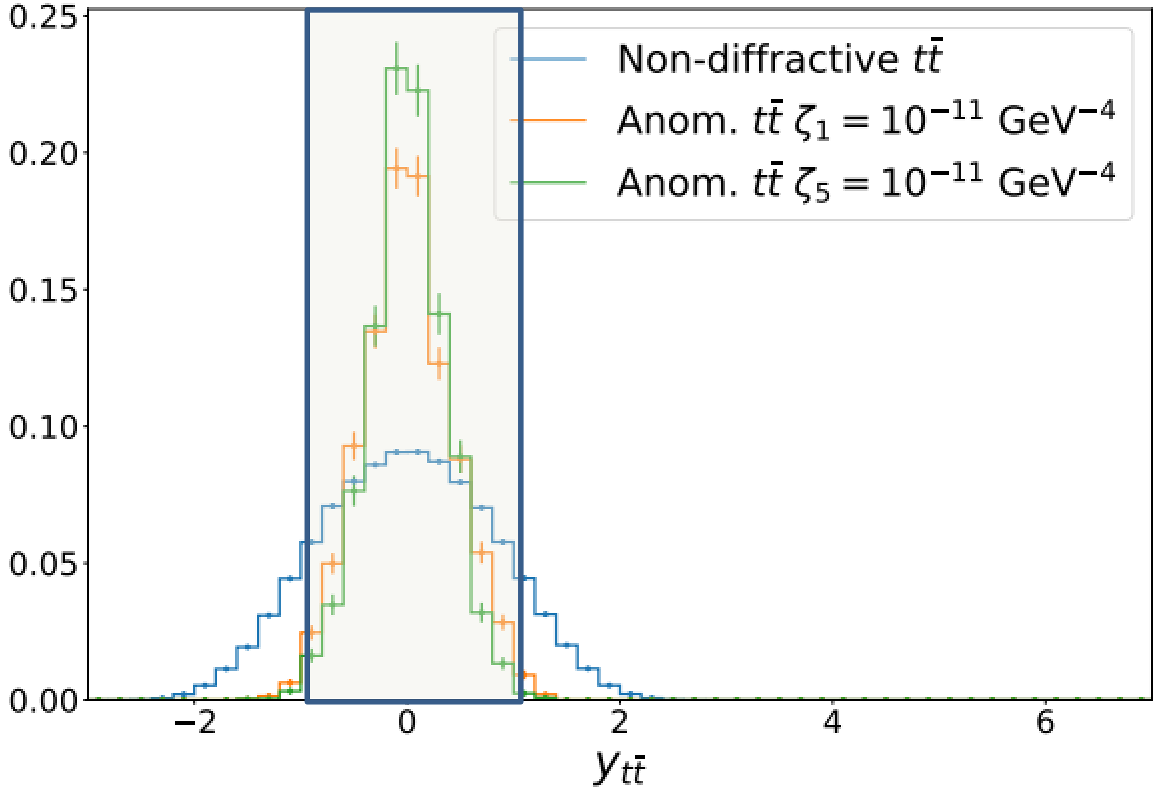
- Favor anomalous production by selecting high-m_{tt} events
  - Reconstructed mass of the tt system: m_{tt} > 960 GeV
  - H_T > 1100 GeV
- Selection optimized for $\mathcal{O}_1$- $\mathcal{O}_4$





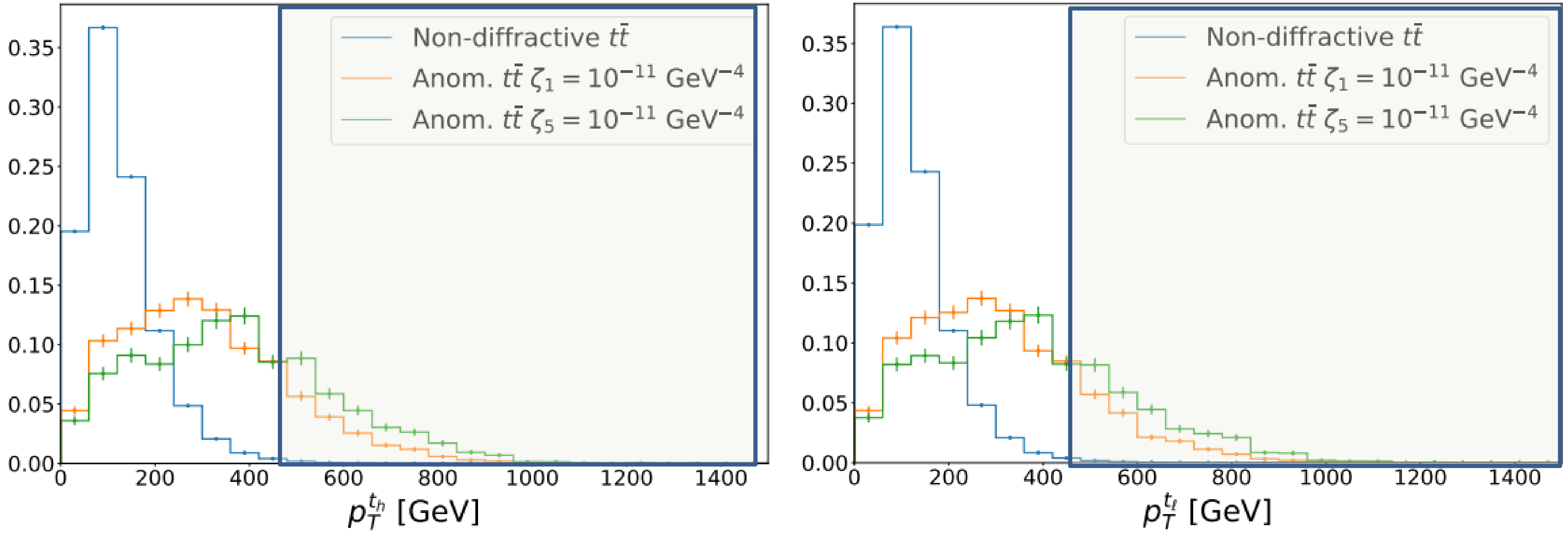
Central selection: $t\bar{t}$ rapidity

- Top quark reconstruction → Rapidity of ttbar system
- BSM contributions are more centrally produced
  - Select central events with $|Y_{tt}| < 0.72$

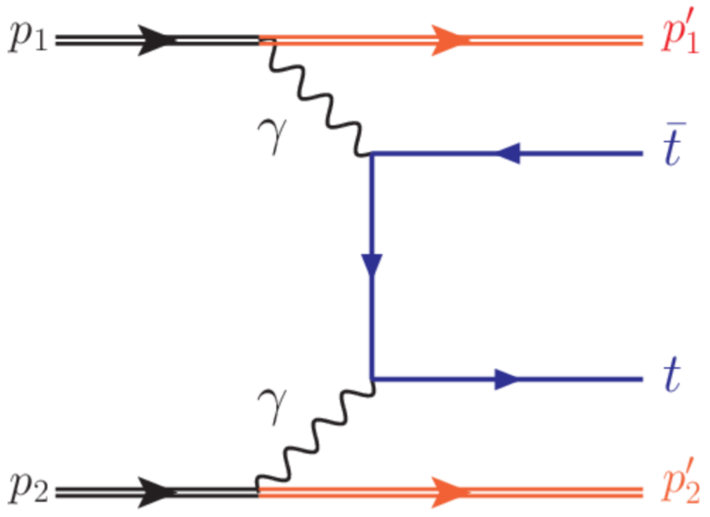


Central selection: top quark p_T

- Top quark reconstruction → Rapidity of ttbar system
- Favor BSM contribution by selection events with high top pT
  - $p_T^t > 425$ GeV



Proton matching



- Four-momentum conservation:
  - In Central Exclusive production of ttbar:

    ttbar kinematics = Proton kinematics

  - For given proton momentum loss $\xi = \Delta p/p$:

Proton kinematics can be inferred from the ttbar:

$$\xi_{\pm} = \frac{\sum E \pm p_Z}{\sqrt{s}}$$

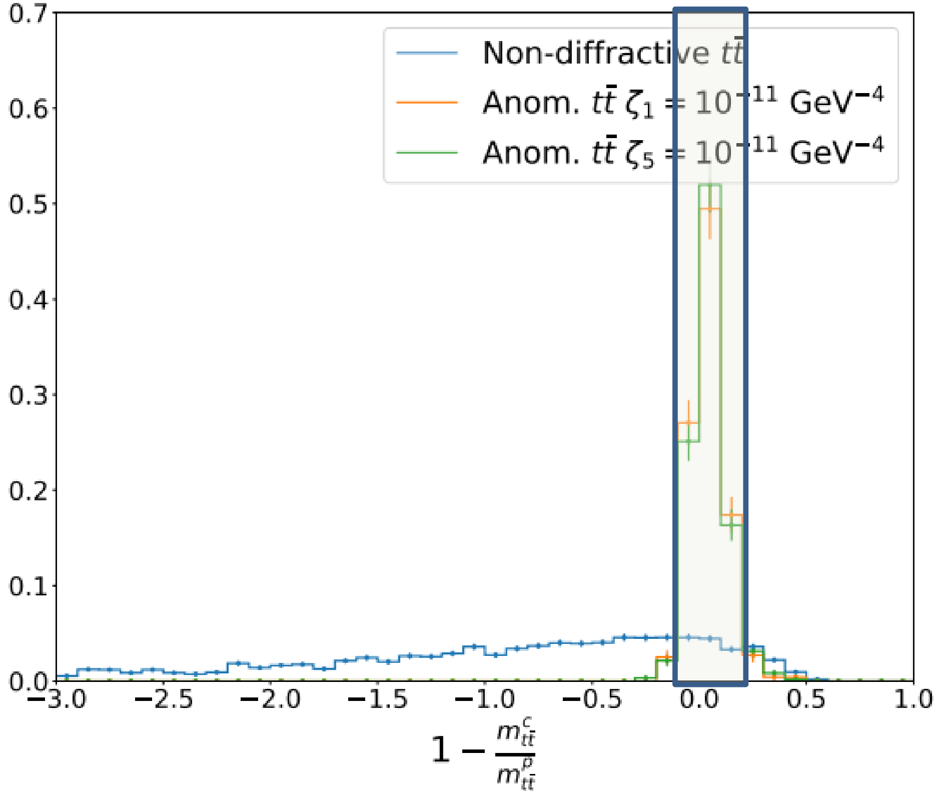
ttbar kinematics can be inferred from the protons:

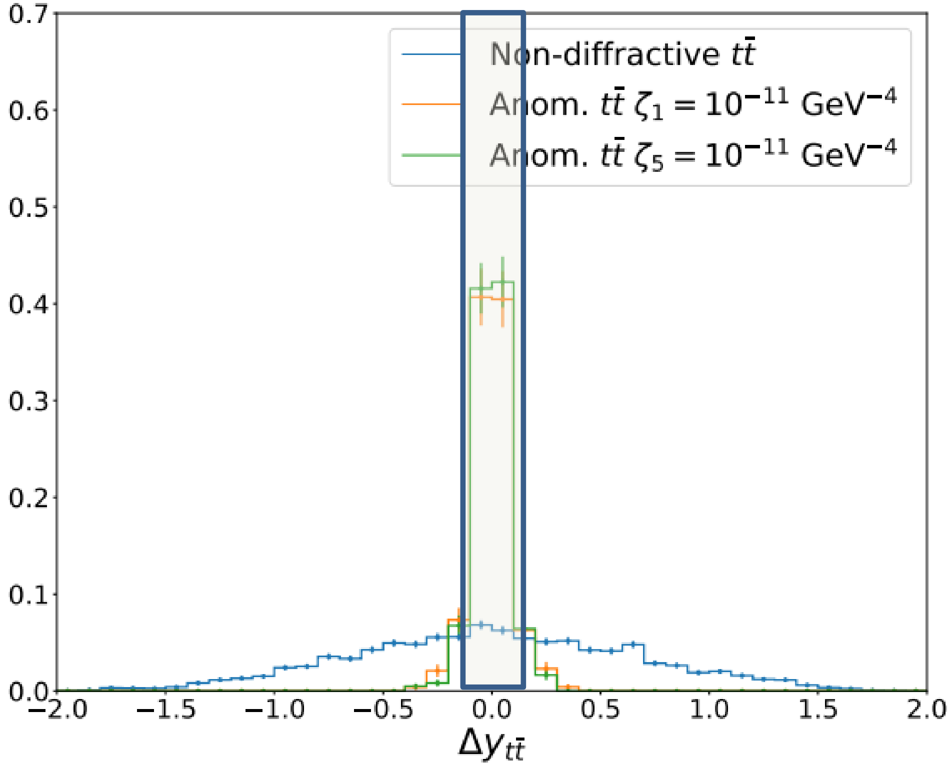
$$m_{tt} = \sqrt{s\xi_{+}\xi_{-}}$$

$$Y_{tt} = \frac{1}{2} log\left(\frac{\xi_{+}}{\xi_{-}}\right)$$

Proton matching

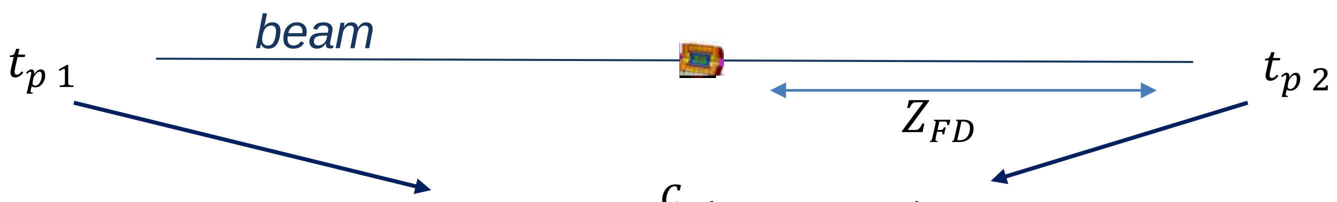
- Four-momentum conservation:
  - Matching kinematics to select CEP candidates $\frac{|\Delta m|}{m} < 0.08, \;\; |\Delta Y_{tt}| < 0.05$





Proton matching

- Vertex z-coordinate is reconstruction using ToF form forward proton detectors (FD):



$$V_{Z,FD} = \frac{c}{2}\left(t_{p\,1} - t_{p\,2}\right)$$

- Vertex time coordinate is reconstructed:

$$V_{t,FD} = \frac{\Sigma t_{p,i}}{2} - \frac{Z_{FD}}{c}$$

Timing
$\lvert z^p - z^c \rvert < 1.5\sigma$
$\lvert t_+ + t_- - \frac{2\times 200\mathrm{m}}{c} \rvert < 1.5\sigma$

Depends on timing resolution

Results

Selection step	Signal		Background		
	$\zeta_1 = 5 \cdot 10^{-11}$ GeV^{-4}	$\zeta_5 = 5 \cdot 10^{-11}$ GeV^{-4}	$t\bar{t}$ (non-diffractive)	WW (non-diffractive)	CEP $t\bar{t}$ (diffractive)
Pre-selection	$2.6 \cdot 10^3$	$2.2 \cdot 10^3$	$5.0 \cdot 10^6$	$3.0 \cdot 10^3$	13
Central selection	341	487	$5.5 \cdot 10^3$	25	0
Proton matching	246	355	95	0	0
Timing (60 ps)	224	323	13.8	0	0
Timing (20 ps)	224	323	1.7	0	0

- 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 tt really contributes to background

Cross sections:

$\sigma_{\zeta=5\cdot10^{-11}[GeV^{-4}]} \sim 250$ fb

$\sigma_{tt} \sim 903$ fb

$\sigma_{WW} \sim 131$ fb

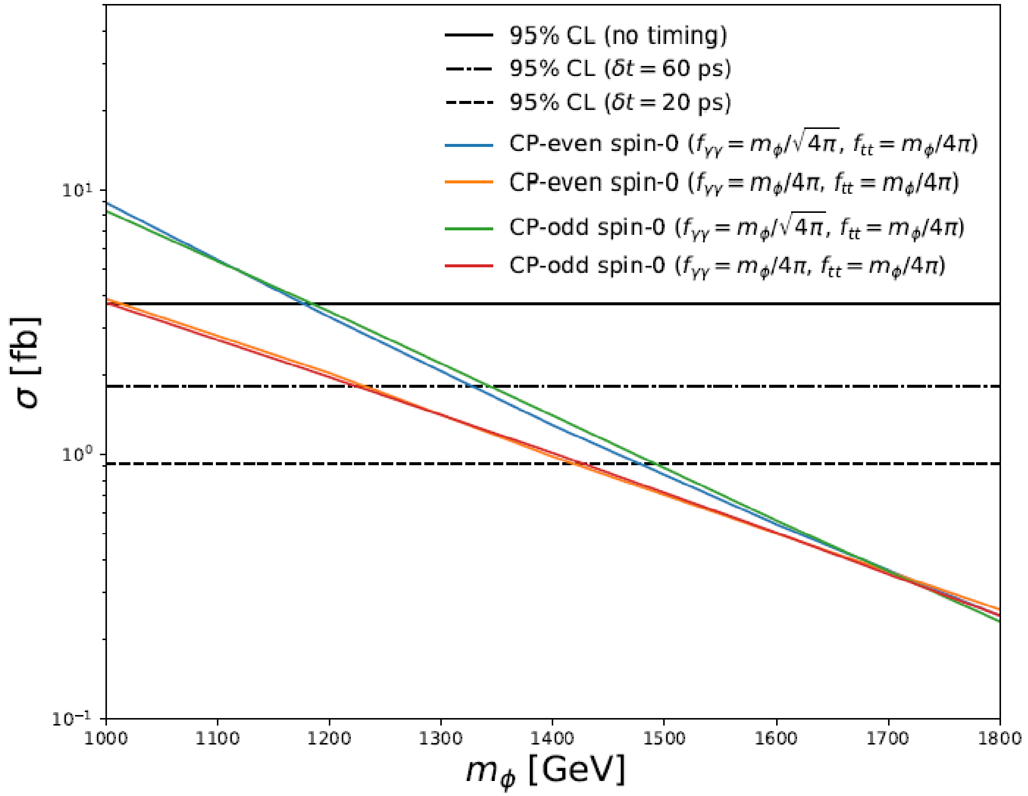
Results

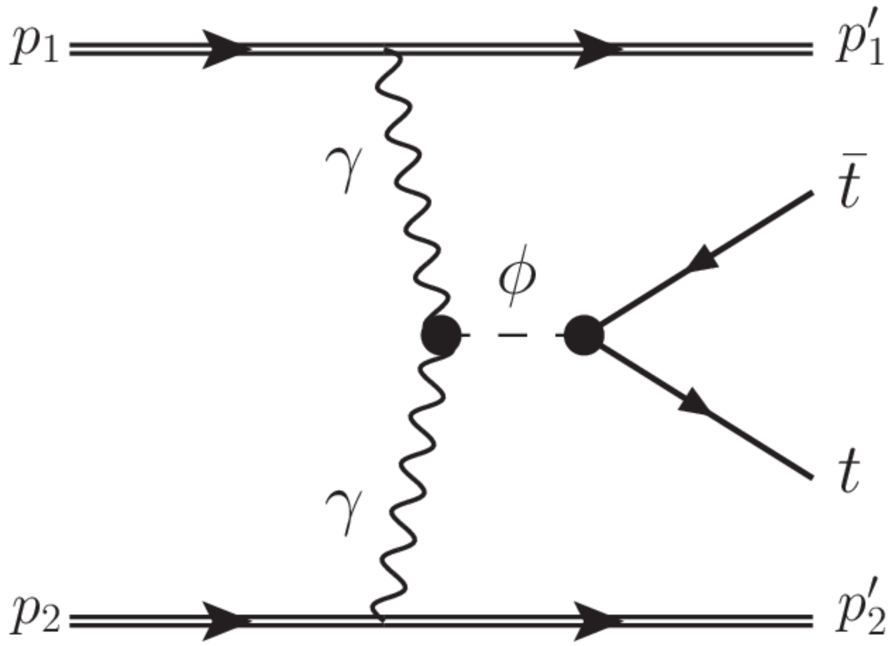
Coupling $[10^{-11}\,\mathrm{GeV}^{-4}]$	95% CL	5σ	95% CL (60 ps)	5σ (60 ps)	95% CL (20 ps)	5σ (20 ps)
ζ_1	1.5	2.5	1.1	1.9	0.74	1.5
ζ_2	1.4	2.4	1.0	1.7	0.70	1.4
ζ_3	1.4	2.4	1.0	1.7	0.70	1.4
ζ_4	1.5	2.5	1.0	1.8	0.73	1.4
ζ_5	1.2	2.0	0.84	1.5	0.60	1.2
ζ_6	1.3	2.2	0.92	1.6	0.66	1.3

- Sensitivities to anomalous couplings extracted for 300 fb^{-1} of integrated luminosity and $\sqrt{s}$= 14 TeV
- Assuming similar object reconstruction performance and acceptance at the HL-LHC with 3000 fb^{-1} and PU~200 , we would expect an improvement on the projections by a factor of ~3.

Results

- In the hypothesis of a discovery of the neutral scalar in the $\gamma\gamma \rightarrow \gamma\gamma$ channel, sensitivity to scalar's coupling to top quarks





Summary & outlook

- The EFT model for anomalous $\gamma\gamma t\bar{t}$ coupling implemented in FPMC
- Available both in Madgraph (**AAttbar_UFO**) and FPMC (dataQED_anomttbar)
- CEP with modified $\gamma\gamma t\bar{t}$ couplings in semi-leptonic decay channel was analyzed, and expected sensitivities extracted for 300 fb^{-1} and $\sqrt{s}$ = 14 TeV:
  - 95% CL at in range $\zeta \sim 1.5 \cdot 10^{-11} - 0.7 \cdot 10^{-11}$ GeV^{-4}
- Sensitivity to new scalars coupled to $\gamma\gamma$ and $t\bar{t}$ was analyzed, under hypothesis of $\gamma\gamma \to \varphi \to \gamma\gamma$, analysis sensitive to scalar masses up to 1.5 TeV

Backup

Delphes Simulation

Standard CMS datacard:

- pT- and η-dependent tracking efficiency ($\sim$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

Event selection

Selection step	Signal $\zeta_1 = 5 \cdot 10^{-11}$ GeV^{-4}	Signal $\zeta_5 = 5 \cdot 10^{-11}$ GeV^{-4}	Background $t\bar{t}$ (non-diffractive)	Background WW (non-diffractive)	Background CEP $t\bar{t}$ (diffractive)
Pre-selection	$2.6 \cdot 10^3$	$2.2 \cdot 10^3$	$5.0 \cdot 10^6$	$3.0 \cdot 10^3$	13
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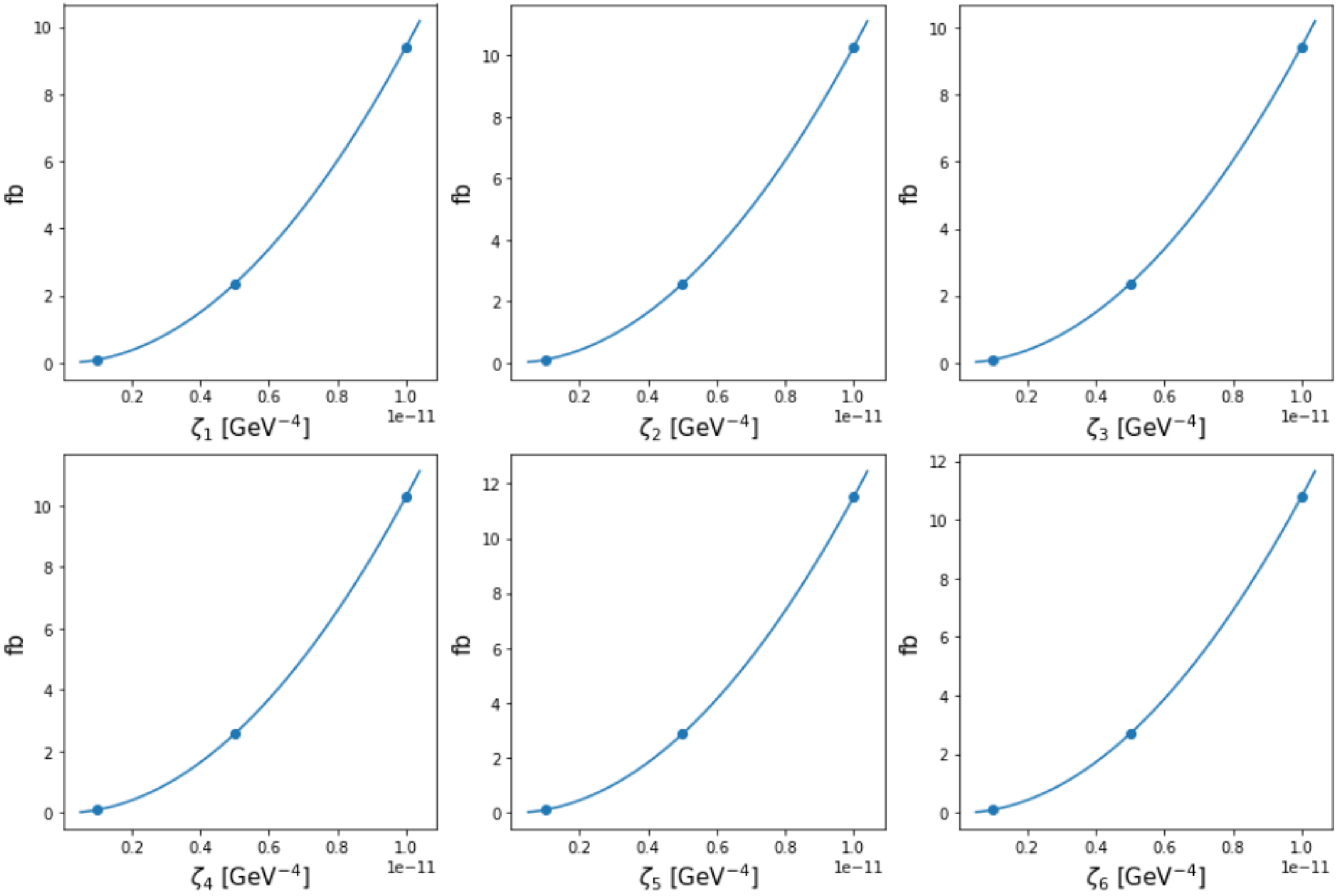
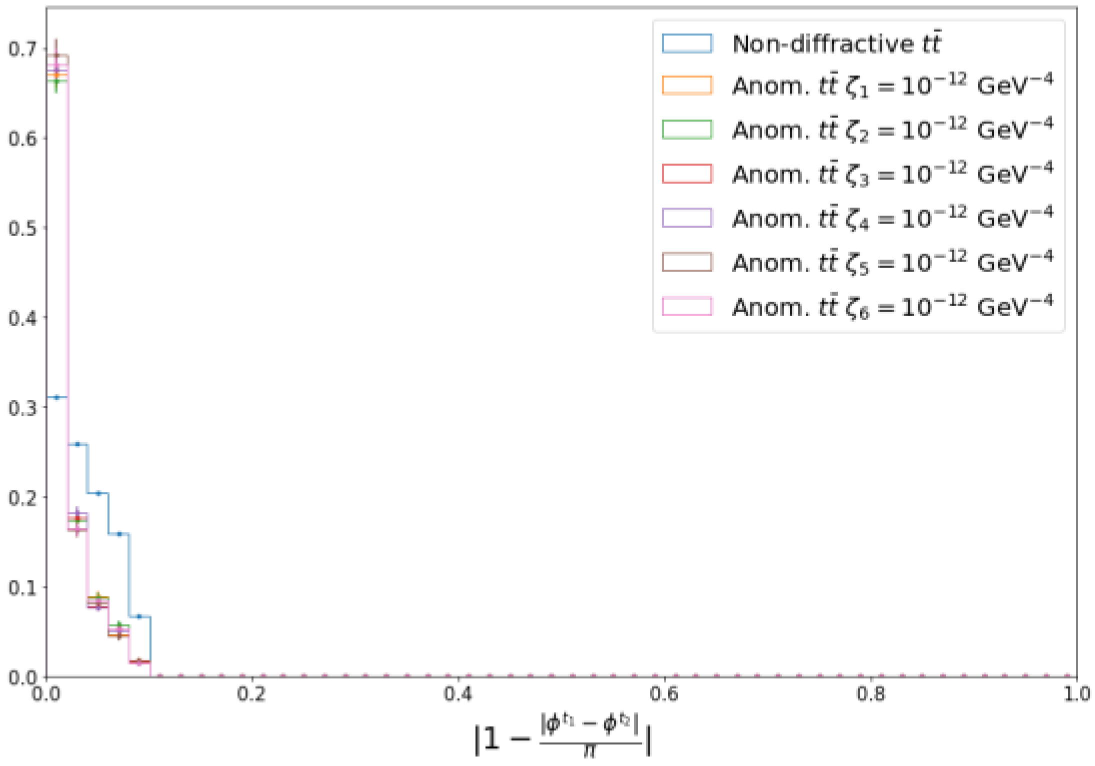
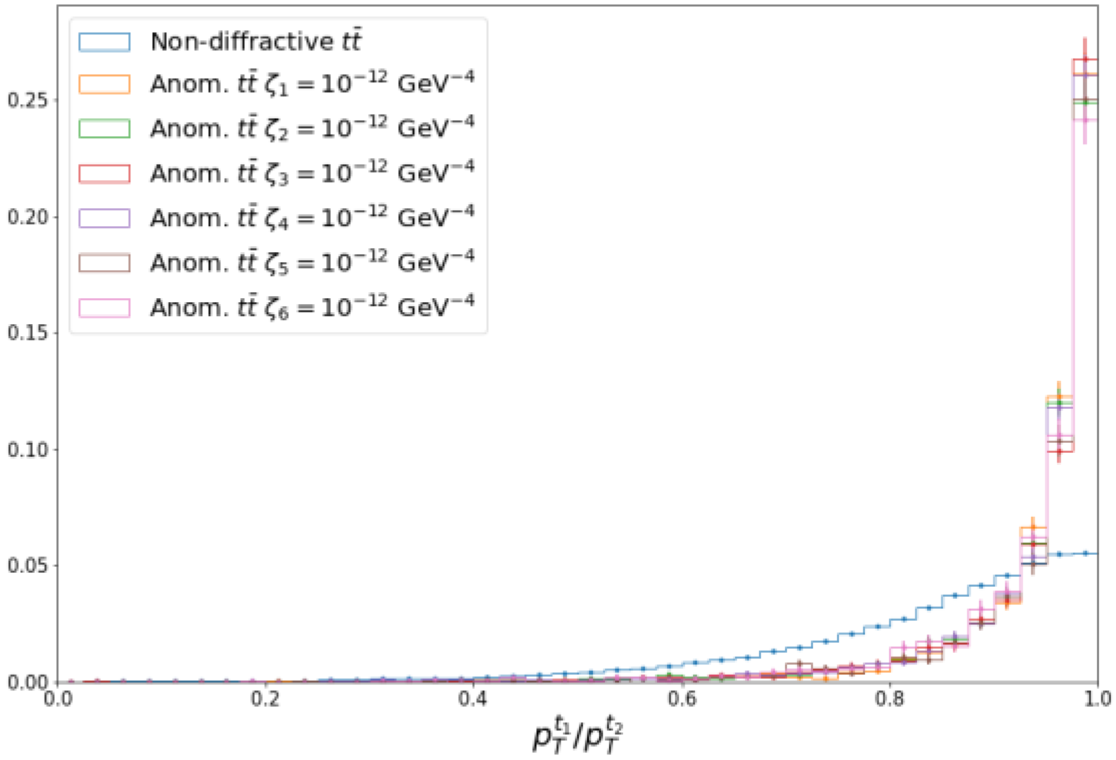
Table 2. Expected events for 300 fb^{-1} at each of the selection steps, for the representatives of the operator sets $\mathcal{O}_{1\ldots4}$, $\mathcal{O}_{5\ldots6}$ and for backgrounds. All other couplings are fixed to zero.

Coupling vs. Cross Section



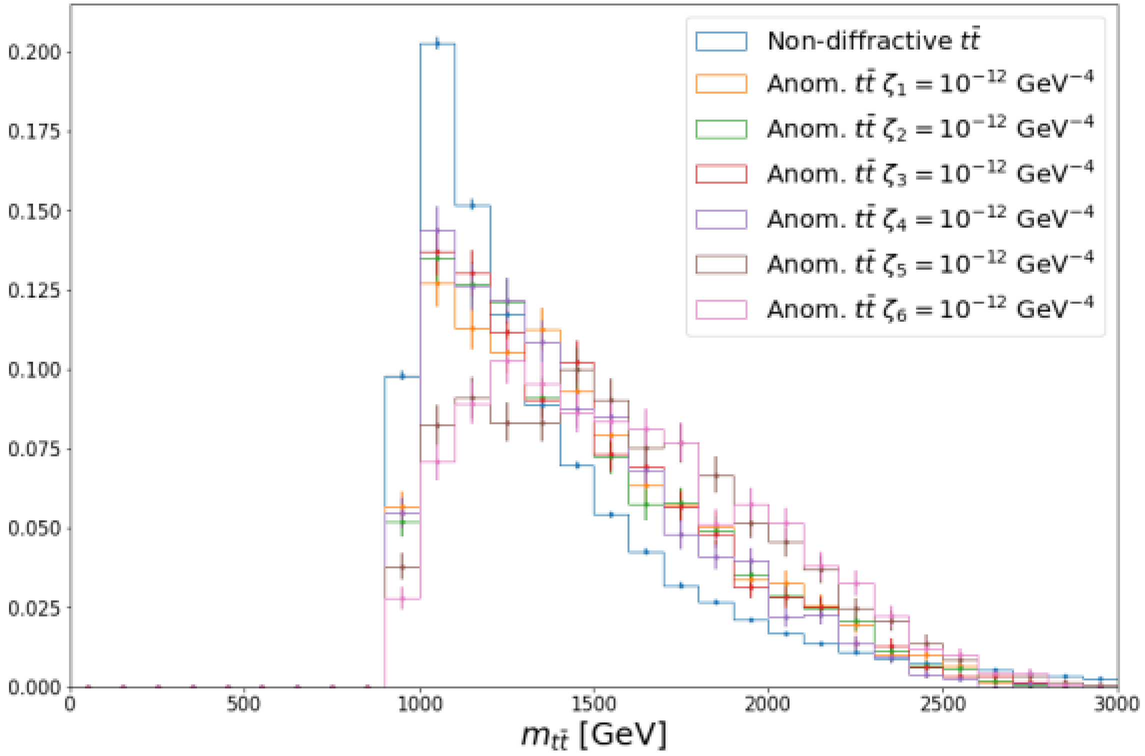
Correlation cross-checks

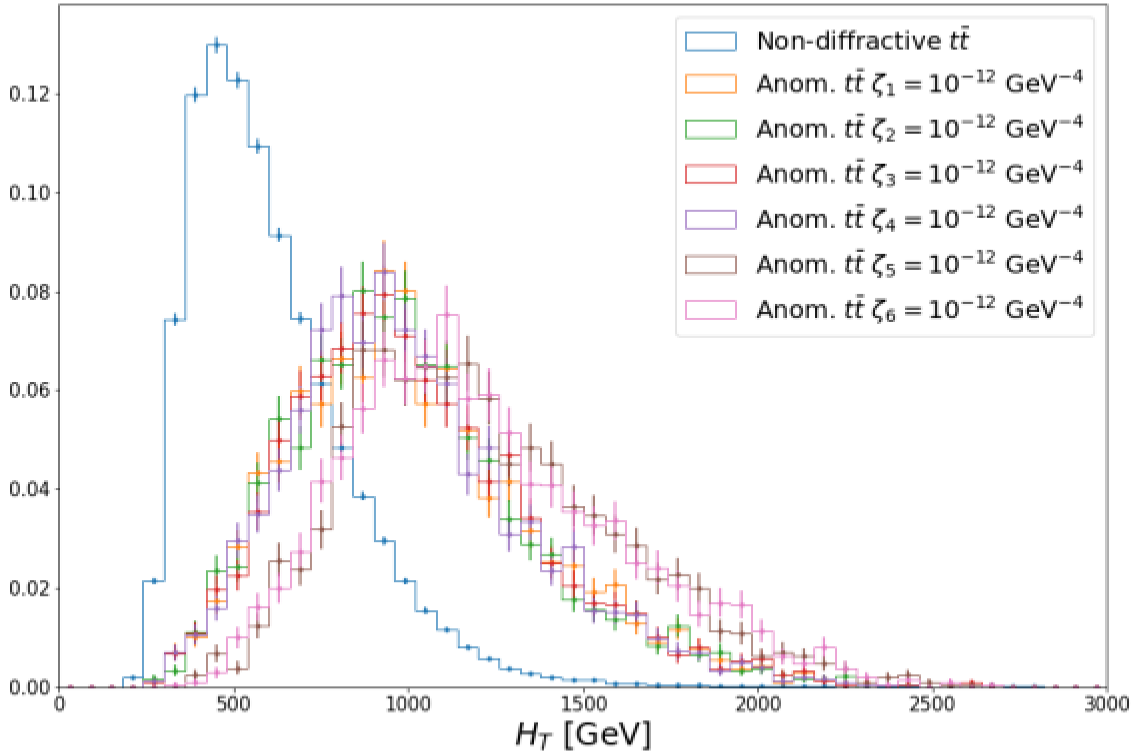




p_T balance distribution not very affected by the acoplanarity cut

Correlation cross-checks



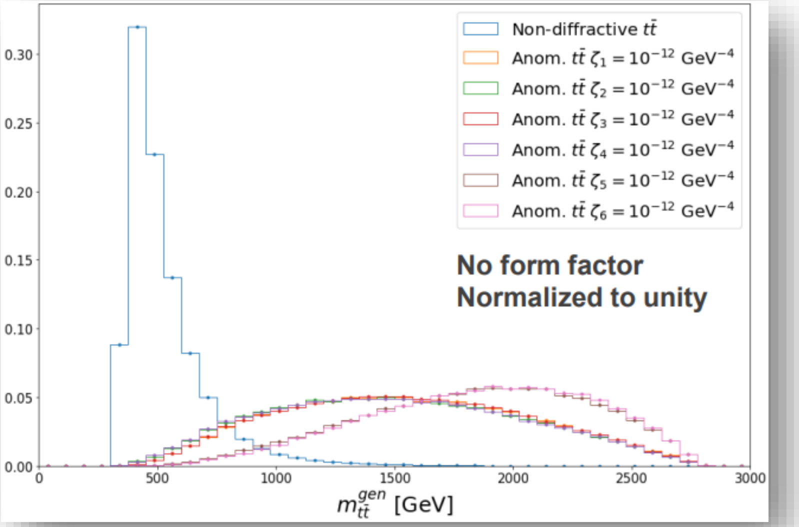


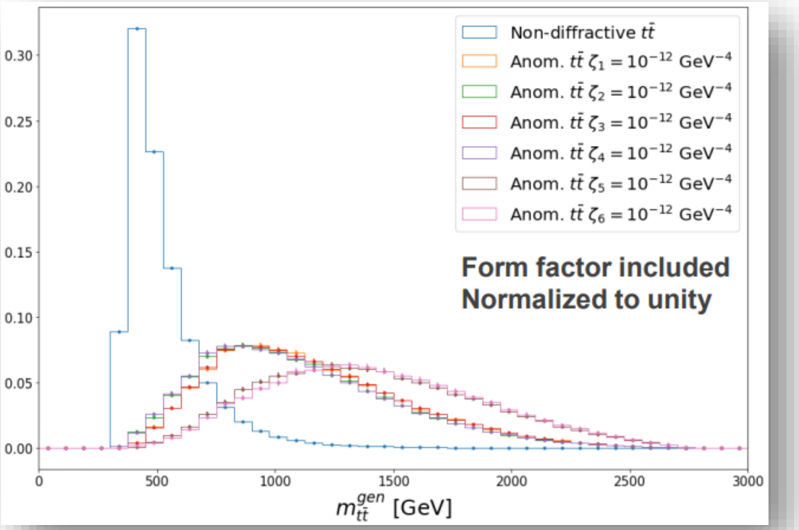
H_T distribution not significantly affected by m_{tt} cut

Unitarity preservation

Study performed both with and w/o a form factor to preserve unitarity:

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





Results

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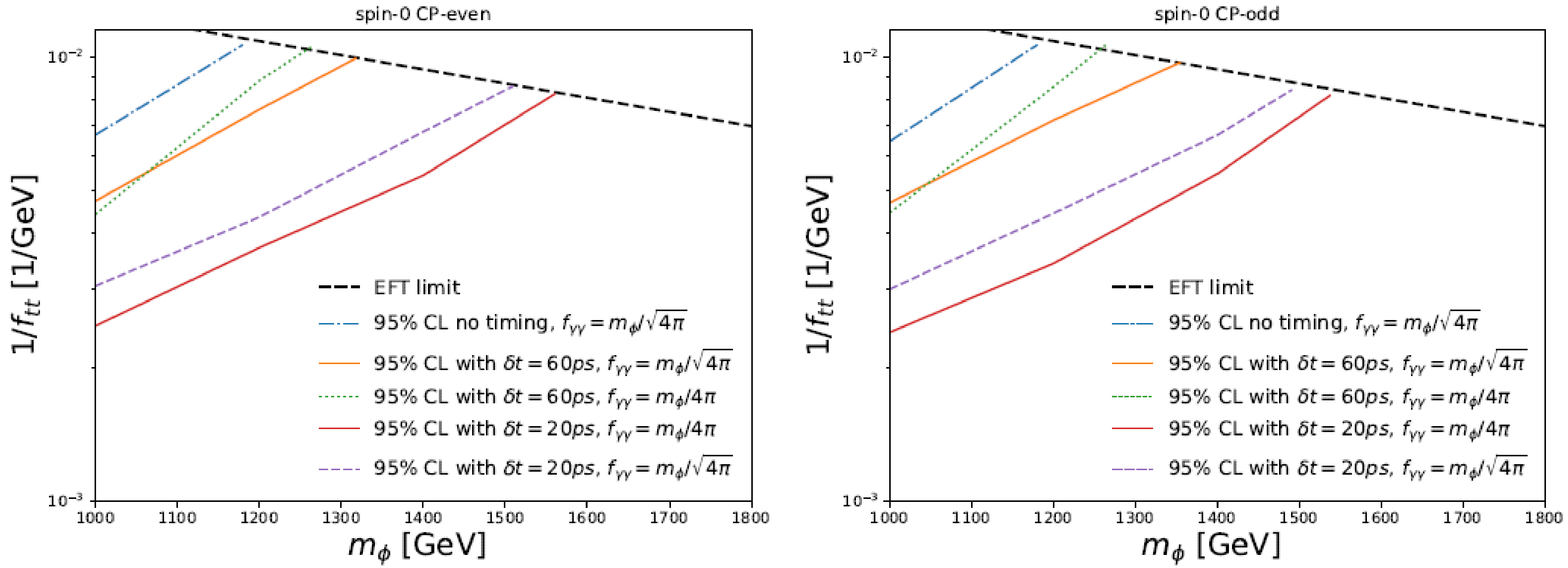
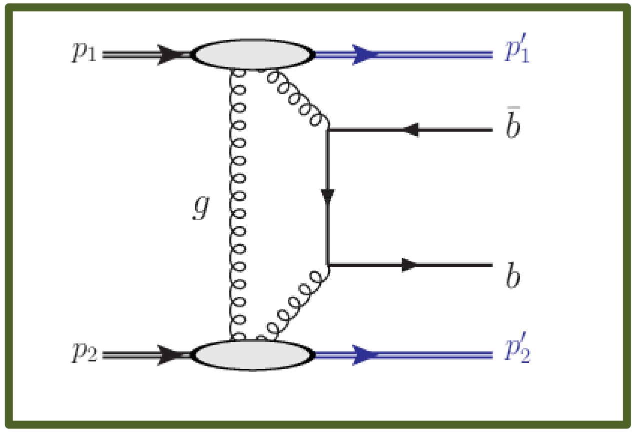
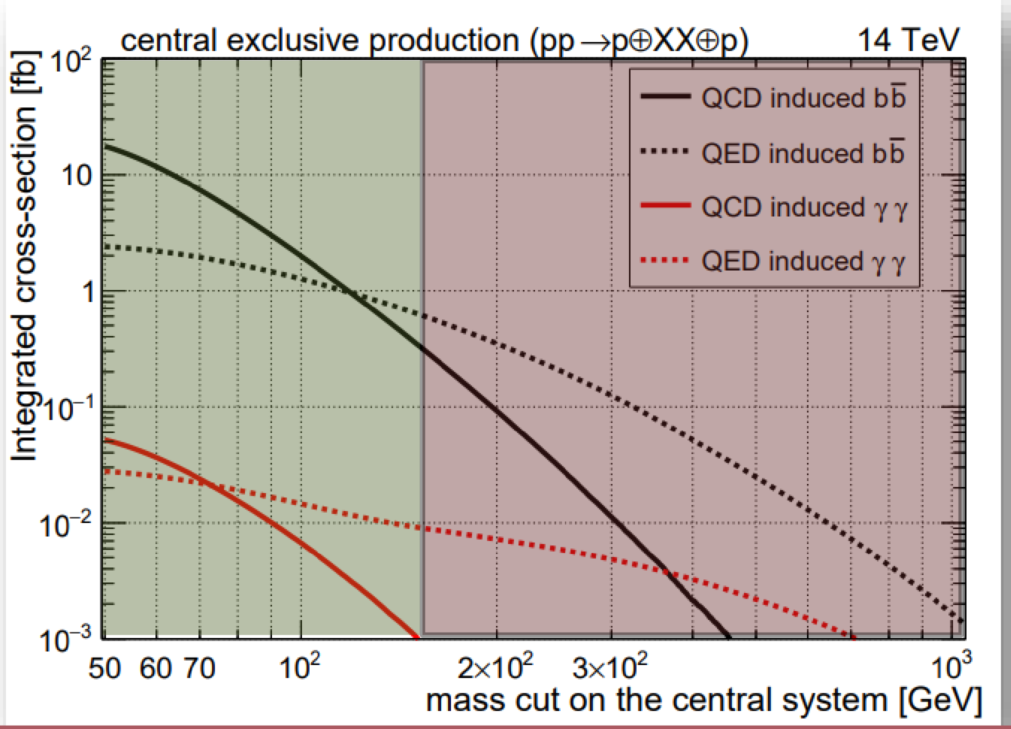
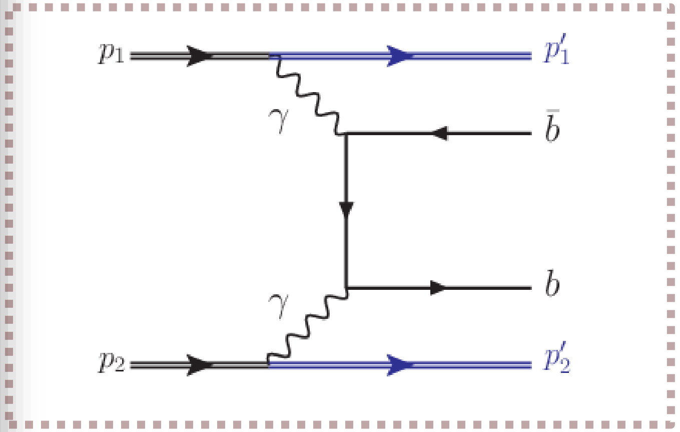


$pp \rightarrow p \oplus X \oplus p$

- In rare cases of pp collisions:
- Protons remain intact (**tagged by forward proton detectors**)
- Low track activity due to exchange of color singlets via **QCD (Pomeron)** or **QED (γ)**







High mass range is dominated by photon-photon interactions