Prospects for Constraints on tZc Couplings Using Quantum Interference at Hadron Colliders

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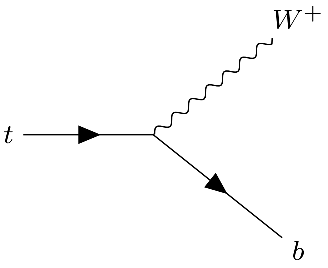
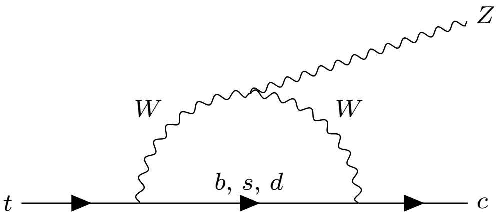
Top-Quark Decays in the Standard Model

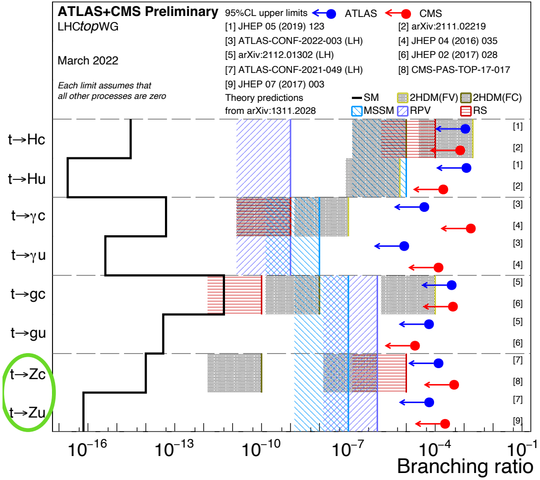
- Dominant top-quark decay mode: flavour-changing charged current $t \to W^+ b$
- Tree-level flavour-changing neutral currents (FCNCs) forbidden in SM
  $\to$ No decay $t \to qB$ possible with neutral boson B
- Branching Ratios of FCNC decays extremely small: GIM-suppression





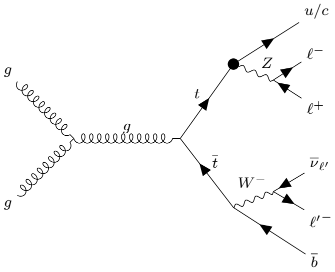
Searches for FCNCs in the Top-Quark Sector

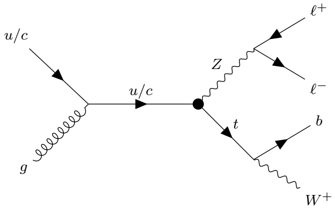
- LHC is a top-quark factory: more than 10^8 top-quark pairs produced in Run 2 alone!
  $\rightarrow$ Possibility to search for rare phenomena
- Experimental searches for FCNCs with top quarks important to probe BSM theories
- Any observed signal at the LHC: undeniable manifestation of BSM phyiscs!
- Tight upper limits allow to exclude various models that enhance FCNCs
- Aim to provide alternative approach to improve constraints



Traditional Searches for tZc FCNCs

- Analyes with Run 2 data by ATLAS (CONF-2021-049) and CMS (PAS-TOP-17-017)
  → Consider FCNC both in decay (top-quark pairs) and production (single top quark)
- Target leptonic decays of the Z boson: three-lepton final state
- 95% upper limits on $\mathrm{BR}(t \to qZ)$ in the range of $\mathcal{O}(10^{-4})$



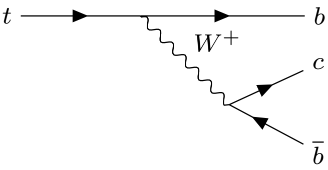


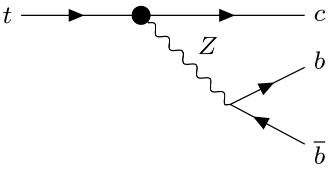
A Minimal Model to Describe tZc Couplings and Interference

- Add dimension-four operators to SM Lagrangian to induce tZc FCNCs:

$$\mathcal{L}_{tZc} = \frac{1}{2}\bar{t}\left(g_{\mathrm{L}} \mathrm{e}^{\mathrm{i}\theta_{\mathrm{L}}}\gamma^{\mu}P_{\mathrm{L}} + g_{\mathrm{R}} \mathrm{e}^{\mathrm{i}\theta_{\mathrm{R}}}\gamma^{\mu}P_{\mathrm{R}}\right) c Z_{\mu} + \text{h.c.}$$

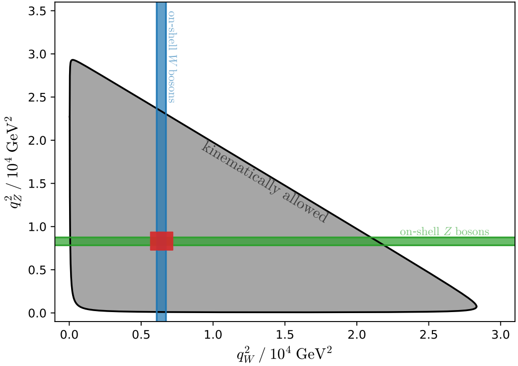
- Interference in top-quark decays when including hadronic $Z \to b\bar{b}$ decay!
- Choose $g_{\mathrm{R}} = 0$ and $\theta_{\mathrm{L}} = \pi$ to maximise positive interference
- Only consider charm quarks here: interference is CKM-enhanced compared to up quarks





Phase Space Region Enriched in Interference Contribution

- Kinematics of decay illustrated by variables $q_W^2 = (p_{\bar{b}} + p_c)^2$ and $q_Z^2 = (p_{\bar{b}} + p_b)^2$
- Interference contribution concentrated in narrow on-shell region in invariant mass plane
  → Allows for selections to separate SM, interference and FCNC contributions



Leveraging Quantum Interference for Small Couplings

- Assuming purely statistical uncertainties, exclusion limit of traditional search roughly scales as

$$g_{\text{excl}} \sim \frac{1}{\mathcal{L}^{1/4}}$$

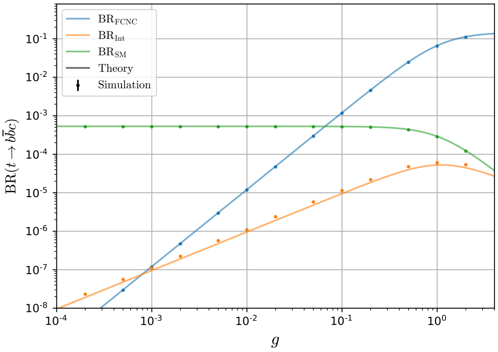
since $\mathrm{BR}(t \to cZ(\to \ell^+\ell^-)) \sim g^2$

- For interference-based approach and small couplings ($g^2 \ll g$), exclusion limit scales as

$$g_{\text{excl}} \sim \frac{1}{\mathcal{L}^{1/2}}$$

due to $\mathrm{BR}(t \to b\bar{b}c) \sim g$

$\Longrightarrow$ Interference-based approach benefits in realm of small couplings and large integrated luminosities!

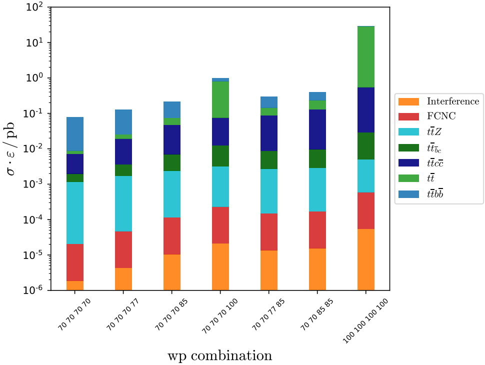


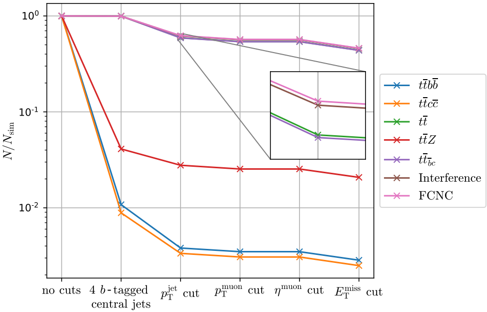
Simulation Setup and Sample Generation

- Use custom model in MadGraph5 that includes minimal FCNC tZc couplings
- Generating events at $\sqrt{s} = 14$ TeV at leading-order
- Simulate FCNC, interference, and SM contributions to $pp \to t\bar{t} \to b\bar{b}c\,\bar{b}\mu^-\bar{\nu}_\mu$ separately
- Reducible backgrounds: SM $t\bar{t}$, $t\bar{t}b\bar{b}$, $t\bar{t}c\bar{c}$, and $t\bar{t}Z(\to b\bar{b})$ (always lepton+jets)
- Do not include parton showering and extensive detector simulation for simplicity
  → Interpret parton-level objects directly as jets, muon and $E_{\mathrm{T}}^{\mathrm{miss}}$
- Include MC-based smearing of kinematic variables

Event Selection

- Require exactly four jets in central region
  $\rightarrow$ Suppresses the 8-particle final states very well ($t\bar{t}$ with additional jets)
- Optimised combination of b-tagging working points with MC methods: use $70\%\ 70\%\ 70\%\ 85\%$
  $\rightarrow$ Signal topology of $3b + 1c$ motivates three tight tags and one loose tag
- Further requirements to achieve realistic fiducial volume (trigger thresholds, $E_{\mathrm{T}}^{\mathrm{miss}}$ selection, ...)



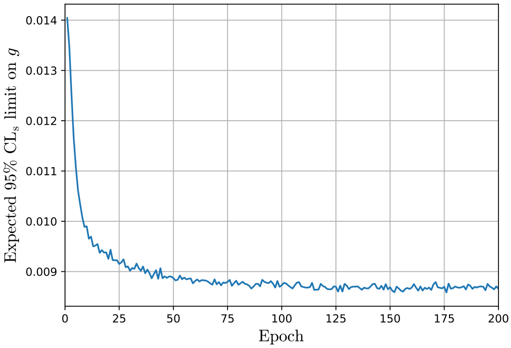


Separating Signal from Background with a Neural Network

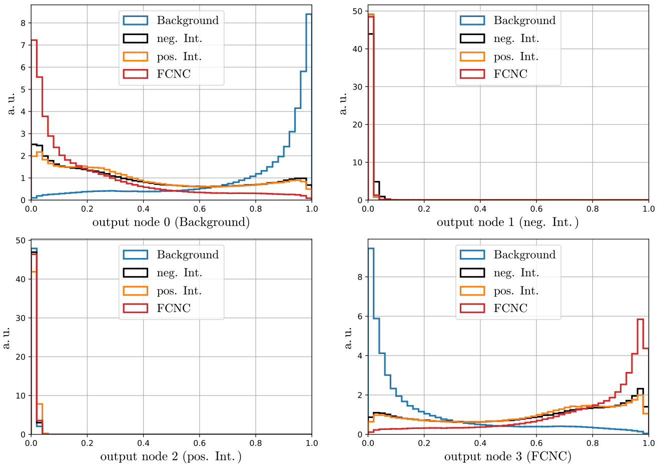
- Resolution and jet assignment issues motivate ML to enhance sensitivity
- Multiclass NN: split in pure FCNC, pos. int., neg. int., backgrounds
- Condense four outputs into one discriminant:

$$d = \frac{1 - \alpha_{\text{bkg}} - \alpha_{\text{negInt}} + \alpha_{\text{posInt}} + \alpha_{\text{FCNC}}}{2}$$

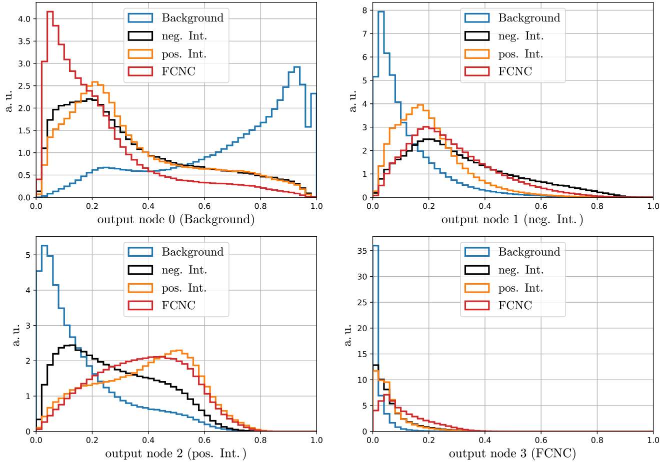
- Choose best model based on $95\%\ \text{CL}_s$ expected upper limit on g
- Parametrise neural network in g
  $\rightarrow$ Aim to retain sensitivity over large range of couplings



Output Distributions for Large Coupling Value $g = 0.2$



Output Distributions for Small Coupling Value $g = 0.0002$

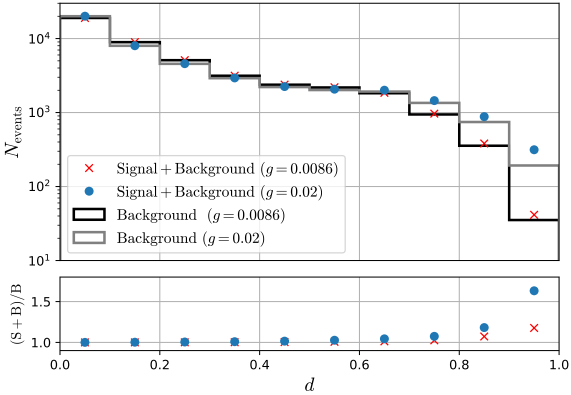


Expected Limit at the HL-LHC

- Expected events for $3000\,\text{fb}^{-1}$
- Distribution of background-only expected data changes with g
- Only consider stat. uncertainty on upper limit

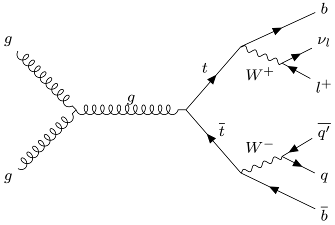
$$g_{\text{excl}}^{\text{HL-LHC}} = 8.6^{+1.5}_{-1.3} \cdot 10^{-3}$$

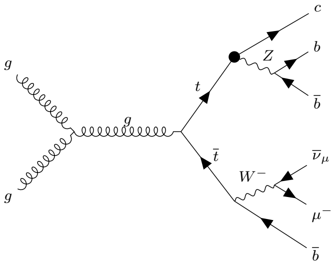
- Same order of magnitude as scaled traditional search ($5.9 \cdot 10^{-3}$)



Conclusions and Outlook

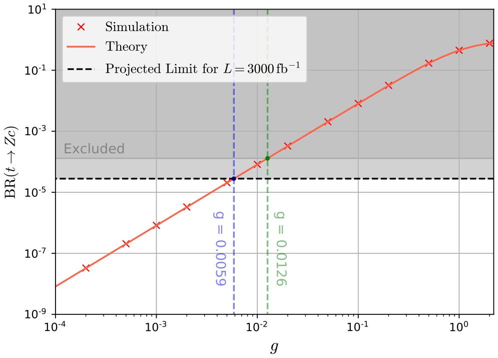
- Presented prospects of interference-based searches for $t \to Zc$ transitions at HL-LHC
  $\longrightarrow$ Heavy-flavour enriched $t\bar{t}$ phase space, using mutliclass parametrised neural network
- Method benefits from high statistics: exp. limit at FCC-hh comparable to traditional search
- Rough projection with $20\,\mathrm{ab}^{-1}$ and $t\bar{t}$ cross section at $\sqrt{s} = 100$ TeV: $g_{\text{excl}}^{\text{FCC-hh}} = 1.8^{+0.3}_{-0.3} \cdot 10^{-3}$
- Finishing studies and preparing journal submission





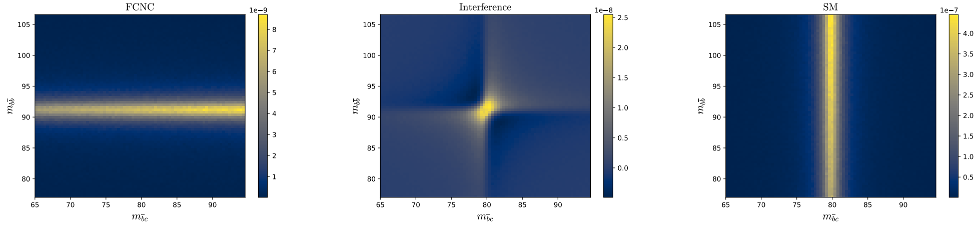
Branching ratio and Traditional Limits as a Function of g

- $95\%\ \mathrm{CL}_s$ limit from ATLAS full Run 2 analysis: CONF-2021-049
- Extrapolated limit for HL-LHC assuming total uncertainty scales as statistical uncertainty



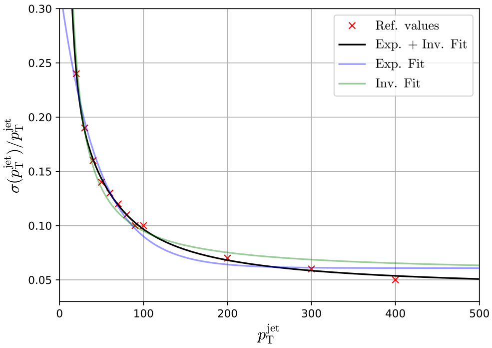
Validation of Sample Generation: Dalitz Plots

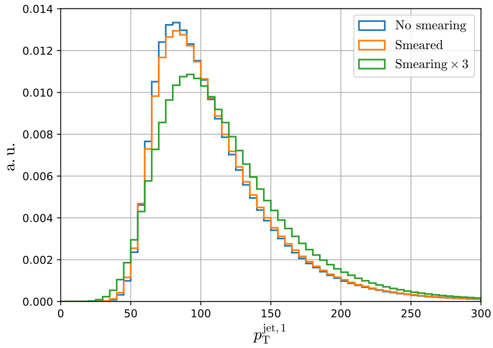
- Numerical Simulation with MadGraph5 of different contributions to $t \to b\bar{b}c$
- Validates model: reproduction of analytical expectations



Smearing of Transverse Momentum of Jets

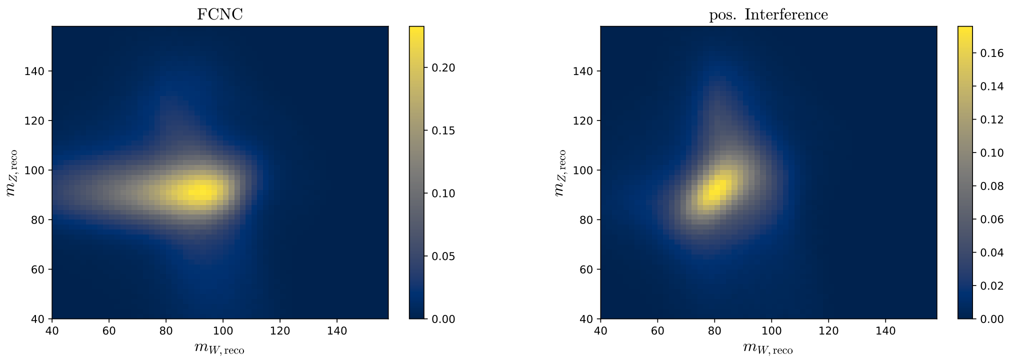
- Left: Fit of exponential plus inverse function to ATLAS jet resolution values from 2007.02645
- Allows to describe low- and high-p_{T} regions well
- Right: Validation of impact of smearing on leading jet p_{T}



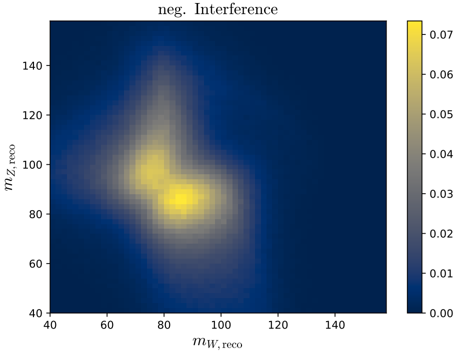


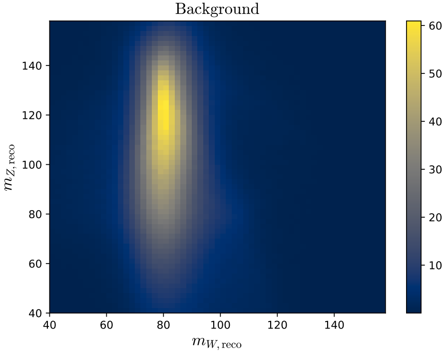
Dalitz Plots After Smearing: FCNC and Positive Interference

- Results for full process $pp \to t\bar{t} \to b\bar{b}c\,\bar{b}\mu^-\bar{\nu}_\mu$ with invariant mass reconstruction
- Basic idea: choose three quarks as top candidate with three-jet mass closest to m_t
- Then: jet with loosest b-tag interpreted as c-jet, remaining two jets form Z-system
- Finally, m_W given by lowest m_{cb_i}



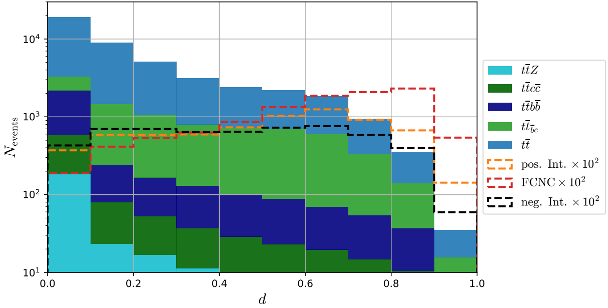
Dalitz Plots After Smearing: Negative Interference Backgrounds





Showing Separation with Distributions of Discriminant

- Condensation of outputs into single discriminant is successful
- Irreducible SM $t\bar{t} \to b\bar{b}c\,\bar{b}\mu^-\bar{\nu}_\mu$ appears to be most difficult background
- Reducible $t\bar{t}$ remains most important background in signal-enriched region



Distributions for Discriminant of the Four Classes

- Definition: $d = (1 - \alpha_{\text{bkg}} - \alpha_{\text{negInt}} + \alpha_{\text{posInt}} + \alpha_{\text{FCNC}})/2$
- Distributions shown for $g_{\text{excl}}^{\text{HL-LHC}} = 8.6 \cdot 10^{-3}$

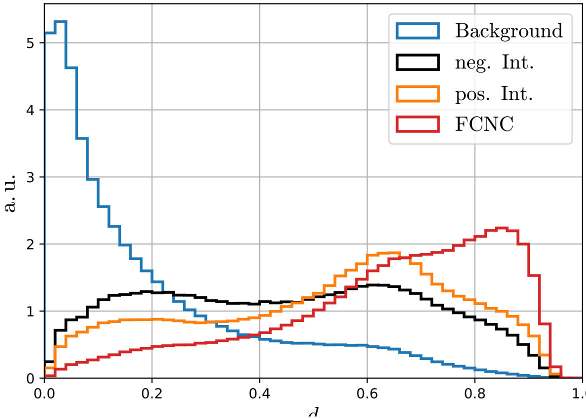


Illustration of 95% CL_s Expected Upper Limit Calculation

- Left: illustration of $\mathrm{CL}_s = \frac{\mathrm{CL}_{s+b}}{\mathrm{CL}_b}$ calculation
- Right: calculation of expected upper limit from CL_s value as a function of g