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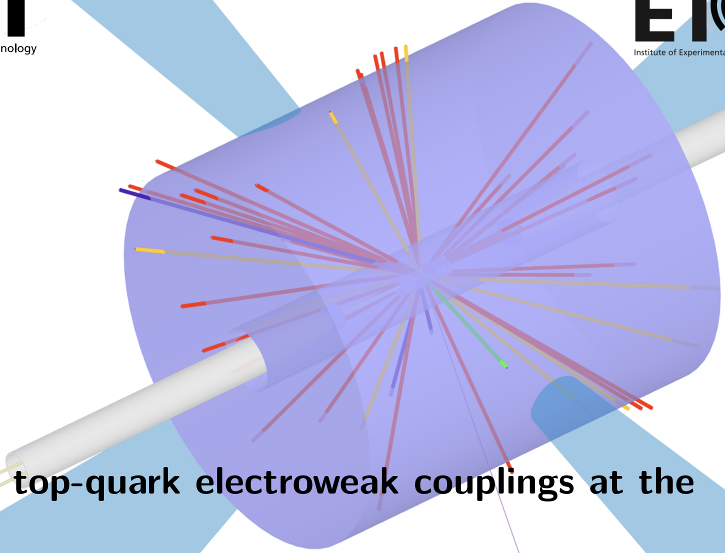
Institute of Experimental Particle Physics

FUTURE CIRCULAR COLLIDER

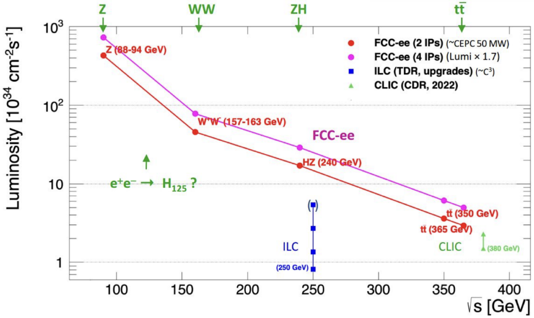


Probing top-quark electroweak couplings at the FCC-ee

Simon Keilbach, Jan Kieseler, Markus Klute, Matteo Presilla, Xunwu Zuo | 13.05.2024

FCC-ee

- Precision frontier lepton collider
- $\varnothing \approx 91\,\mathrm{km}$
- W,Z, Higgs and $t\bar{t}$ factory
- Offers unprecedented sensitivities to BSM physics, SM couplings and rare decays
- Infrastructure foreseen to be reused to house hadron collider (FCC-hh) after end of run



(M. Selvaggi at FCC WS)

$t\bar{t}$ EW couplings at FCC-ee

- Direct measurement of $tt\gamma$ and ttZ
  - modification of SM couplings via new physics feasible
  - predict potential sensitivity to couplings at $\sqrt{s} = 365\,\mathrm{GeV}$
- Access couplings by studying energy and angular information of leptons:

$$x_l = \frac{2E_l}{m_t}\sqrt{\frac{1-\beta}{1+\beta}}, \quad \beta \equiv \sqrt{1-4m_t^2/s}$$

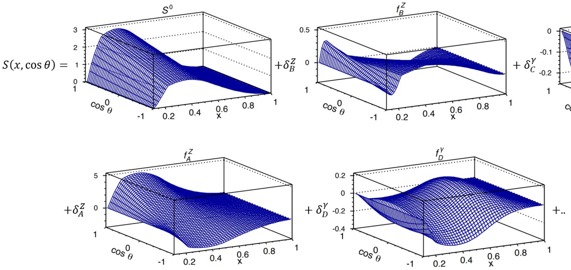
- Sufficient initial state polarisation deemed crucial for accessing γ/Z couplings at e^-e^+ colliders (arXiv:hep-ph/0004223v4)

  $\Rightarrow$ Substantial final state polarisation suffices to disentangle the couplings (arXiv:1503.01325v3)

Anomalous couplings

- Cross section $\frac{d^2\sigma}{dx_l d\cos\theta_l} \propto S(x, \cos\theta)$ can be linearised for supposedly small anomalous form factors δ_i:

$$S(x, \cos\theta) = S^0(x, \cos\theta) + \sum_{i=1}^{8} \delta_i f_i(x, \cos\theta), \; \delta_i \ll 1$$



adapted from(arXiv:1503.01325v3)

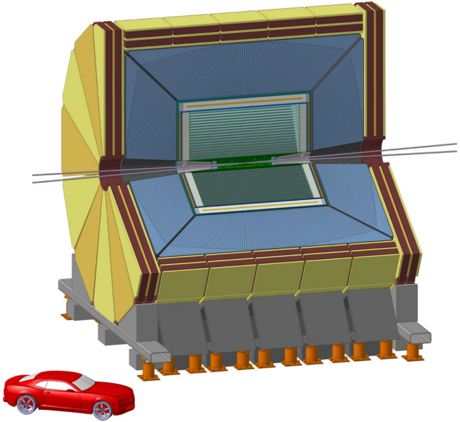
Anomalous couplings

- Sensitivity to anomalous top couplings arises from shape difference for SM and BSM scenarios $\Rightarrow$ vary coupling parameters by 5%

Coupling	Modification	Modification enforced by gauge invariance
`ta_ttA`	$+0.424237$ -0.424237	`ta_ttZ` $= -0.140487$ `ta_ttZ` $= +0.140487$
`tv_ttA`	$+0.010606$ -0.010606	`tv_ttZ` $= -0.003512$ `tv_ttZ` $= +0.003512$
`vr_ttZ`	$+0.17638$ -0.17638	–

Analysis

- Event generation with *WHIZARD+PYTHIA*
  - only one parameter allowed to differ from its SM value at a time
- Use *DELPHES* IDEA detector simulation for particle reconstruction
- Analyse semileptonic and full hadronic ntuples seperately (+ rescaling)
- Event selection + optimisation
- Template χ^2 fit



(doi:10.22323/1.414.0337)

Event selection

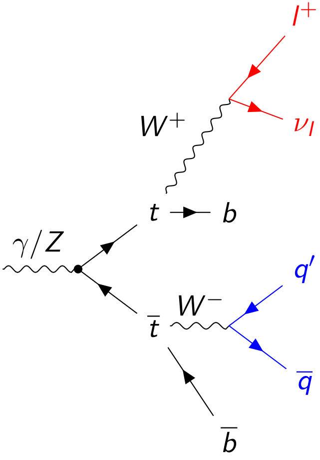
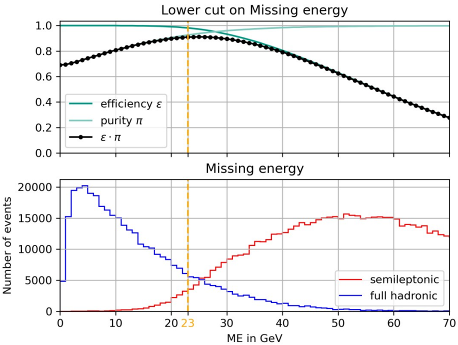
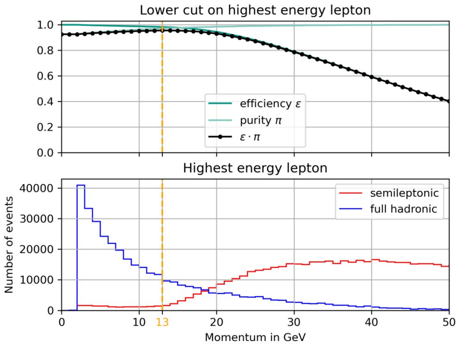


Figure: $e^- e^+ \to t\bar{t} \to b l^+ \nu_l \bar{b} q' \bar{q}$

- Cut1 (lepton isolation cut):
  $\Delta R > 0.4$ to all jets or $\frac{E_l}{E_{\text{jet}}} > 0.5$
- Cut2(sanity cut):
  $n_{\text{leptons}} > 0$
- Further restrictions on observables:
  - Missing energy $\not{E}$
  - $p_{\text{leading lepton}}$
  - Impact parameter d_0 (plus significance $d_0/\sigma(d_0)$)

Event selection optimisation





- Vary (upper/lower) cut limits calculating efficiency and purity each time
  $\rightarrow$ compare optimum of ϵ and π for respective cuts and choose best one

Event selection optimisation

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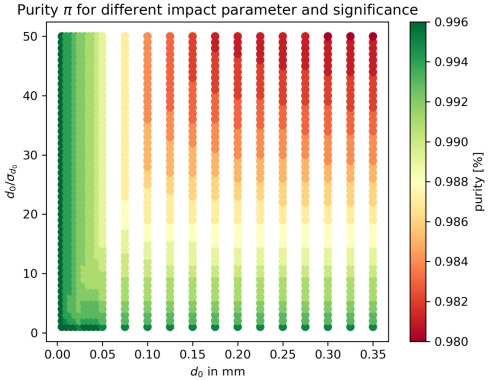
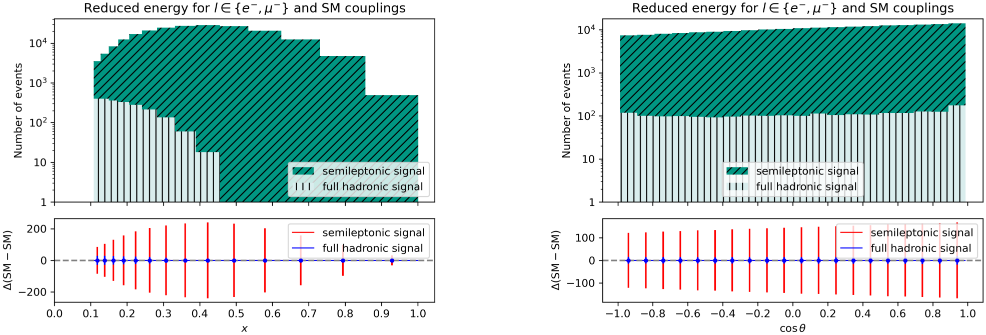
- Optimised event selection
  1. $\Delta R > 0.4$ to all jets or $E_l/E_{\text{jet}} > 0.5$ for all reconstructed leptons (Isolation criteria)
  2. $n_{\text{leptons}} > 0$
  3. $\not{E} > 23\,\text{GeV}$
  4. $p_{\text{lead}} > 13\,\text{GeV}$
  5. $d_0 < 0.05\,\text{mm}$, $d_0/\sigma(d_0) < 50$ and $p > 13\,\text{GeV}$ for all prompt lepton candidates



Event selection: results



- $\epsilon = \frac{n}{k}$ (efficiency)
- $\pi = \frac{k}{k+k'}$ (purity)

	ϵ [%]	π [%]
semileptonic	47.083 ± 0.055	98.886 ± 0.017
full hadronic	0.514 ± 0.008	$1.114 \pm 4.3 \cdot 0.001$

Template χ^2 fit

- PDF to observe n_i amount of events in bin i for source j is:

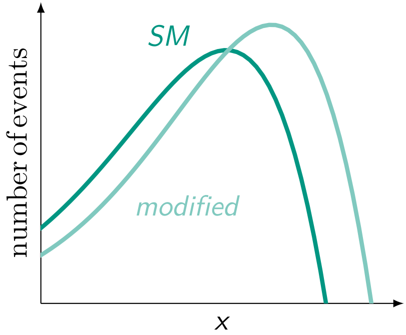
$$\mathcal{P}(n_i|\mu_i) = \frac{\mu_i^{n_i}}{n_i!}e^{-\mu_i}, \quad \mu_i = \sum_{j=1}^{n_{source}} \mathcal{L}_{\mathrm{int}}\sigma_j\epsilon_{ij} = n_{\mathrm{SM},i} + \delta \cdot (n_{\mathrm{mod},i} - n_{\mathrm{SM},i})$$

- Likelihood function with fit (scaling) parameter δ:

$$\mathcal{L}(D,\mu(\delta)) = \prod_{i=1}^{N} \mathcal{P}(n_i|\mu_i(\delta)) = \prod_{i=1}^{N} \frac{\mu_i^{n_i}}{n_i!}e^{-\mu_i}$$

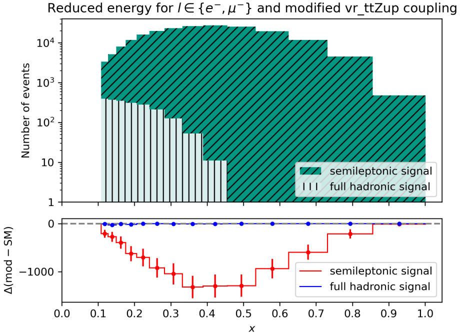
- Minimise $-\ln(\mathcal{L})$ to determine $\delta = \hat{\delta} \pm \sigma_\delta$

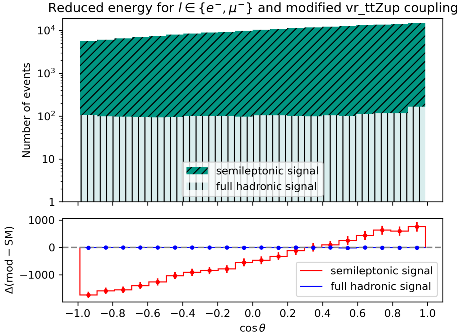
- $$\chi^2 = \sum_{i=1}^{N} \frac{(n_i - (n_{\mathrm{SM},i} + \delta\cdot(n_{\mathrm{mod},i} - n_{\mathrm{SM},i}))^2}{n_i}$$



Results

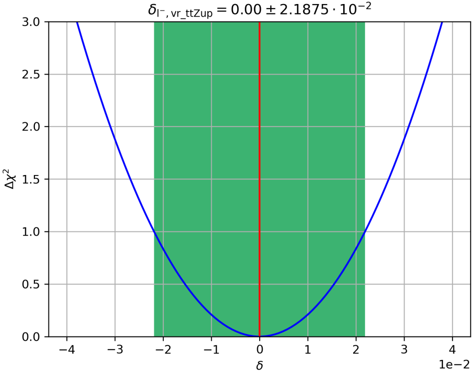
- Verify that shape difference is genuine and not statistical noise
- Choose appropriate binning:
  - reject outliers with $x > 1$, i.e. enforce $p_{\text{lepton}} < 120\,\text{GeV}$
  - non-uniform binning accounting for areas with less and more statistics
  - $min(n_i) = 20$ to justify applying the central limit theorem

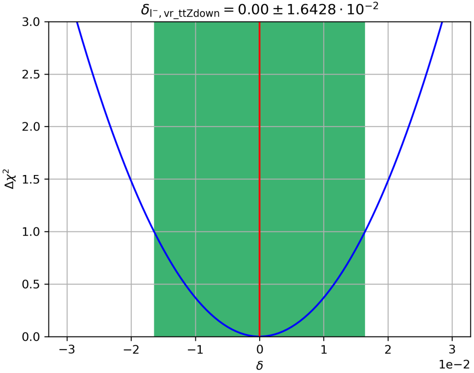




Template χ^2 fit results

- Fit results using n_{SM} as experimental data n_i:





Precision on anomalous couplings

- Expected precision on anomalous couplings for $2.5\,\mathrm{ab}^{-1}$ of l^{-1} at $\sqrt{s} = 365\,\mathrm{GeV}$ assuming contributions from `tv/ta_ttZ` to be negligible:

Coupling	Modification	Modification enforced by gauge invariance	Precision
`ta_ttA`	$+0.424237$	`ta_ttZ` $= -0.140487$	$+1.46 \times 10^{-2}$
	-0.424237	$+0.140487$	-1.40×10^{-2}
`tv_ttA`	$+0.010606$	`tv_ttZ` $= -0.003512$	$+4.20 \times 10^{-4}$
	-0.010606	$+0.003512$	-3.92×10^{-4}
`vr_ttZ`	$+0.17638$	–	$+3.86 \times 10^{-3}$
	-0.17638		-2.89×10^{-3}

Conversion scheme

$$F_{1V}^{\gamma} = 0$$
$$F_{1A}^{\gamma} = 0$$
$$F_{1V}^{Z} = -\frac{1}{4 s_W c_W}\left(\texttt{vl\_ttZ} + \texttt{vr\_ttZ} - \frac{8}{3} s_W^2\right)$$
$$F_{1A}^{Z} = \frac{1}{4 s_W c_W}(\texttt{vl\_ttZ} - \texttt{vr\_ttZ})$$
$$F_{2V}^{\gamma} = -2 \cdot \texttt{tv\_ttA}$$
$$F_{2A}^{\gamma} = 2 \cdot \texttt{ta\_ttA}$$

- A direct comparison with (arXiv:1503.01325v3) cannot be performed in general
  - correlation between `vl_ttZ` and `vr_ttZ` unknown
  - `tv/ta_ttA` not independent in `WHIZARD` but fixed to `tv/ta_ttZ` by gauge invariance
  - Janot uses different constraints on form factors, e.g. CP-violating form factor F_{2A}^{γ} vanishes

Conclusion

- Comparison only possible for F_{2V}^{γ} and only if one of the two `WHIZARD` parameters is assumed to be predominant

	`WHIZARD` framework	framework of (arXiv:1503.01325v3)
F_{2V}^{γ}	-8.40×10^{-4} $+7.85 \times 10^{-4}$	$\pm 8.1 \times 10^{-4}$
F_{2A}^{γ}	$+2.91 \times 10^{-2}$ -2.81×10^{-2}	–

- Event selection optimisation procedure highly beneficial tool to boost signal event rate for constraints on set of observables
- Findings agree with Janot on order of magnitude of the precision

  $\Rightarrow$ precision sufficient to measure top EW couplings with unprecedented accuracy

Outlook

- Account for different parametrisation scheme to compare more than one parameter
  - interpret `WHIZARD` parameters in terms of SMEFT directly
- Top polarisation also transferred to b quarks $\Rightarrow$ analogous analysis of $(x, \cos\theta)$ of b-jets possible
- Include dileptonic channel to enhance amount of leptons available to study
- ML approach to improve final sensitivities imaginable

Thank you for your time

Any questions?

Jet Algorithm

- At least 4 jets from hadronising quarks are expected per event
  $\Rightarrow$ proper choice of jet algo crucial
- Exclusive $k_\perp$ jet algo with $R = 0.4$ used preliminarily:
  - $d_{ij} = \min(E_{\perp,i}^2, E_{\perp,j}^2)\frac{\Delta R_{ij}^2}{R^2}$, $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$
  - $d_i = E_{\perp,i}^2$
  - collinear emission and infrared safe $\Rightarrow$amply used at hadron colliders
- Full jet performance study (including jet algos tailored to lepton colliders like *valencia*) pending

Efficiency and purity uncertainties

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- Common method of calculating uncertainty of cut efficiency $\epsilon \equiv k/n$ is flawed (arXiv:physics/0701199v1)
  - both poissonian and binomial treatment of errors leads to incorrect predictions
  - e.g.: $\sigma^2(\epsilon) = \epsilon^2 \left(\frac{1}{k} + \frac{1}{n}\right)$ gives unreasonable result for $k = 0$ and $n \geq 1$
- Correct treatment with Bayesian ansatz:

$$P(\epsilon; k, n) = \frac{P(k;\epsilon,n)P(\epsilon;n)}{N}, \quad P(\epsilon; n) \begin{cases} 1 & \text{if } 0 \leq \epsilon \leq 1 \\ 0 & \text{otherwise} \end{cases}$$

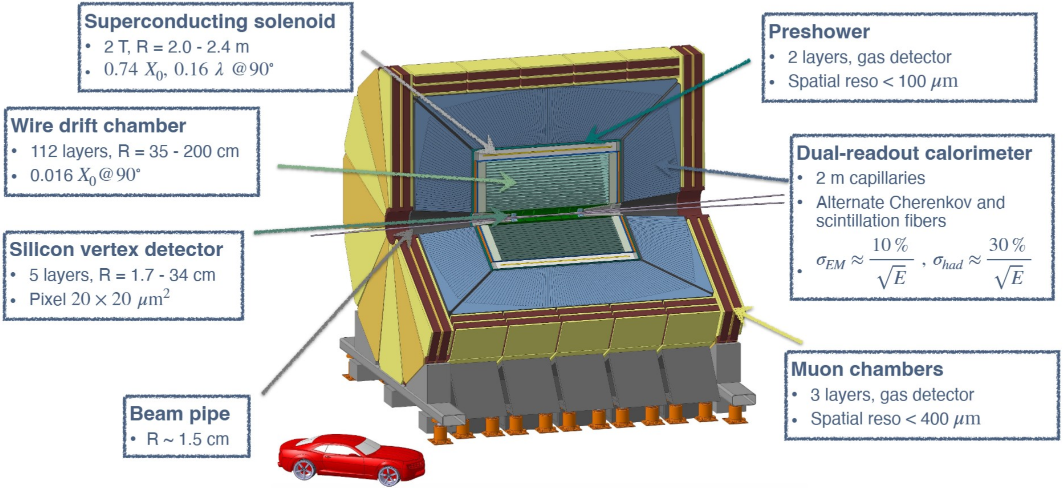
- For a $P(k; \epsilon, n)$ binomially distributed:

$$\Rightarrow \boldsymbol{\sigma(k) = \sqrt{\frac{(k+1)(k+2)}{(n+2)(n+3)} - \frac{(k+1)^2}{(n+2)^2}}}$$

Cut-flow efficiency and purity

	semileptonic		full hadronic	
	ϵ [%]	π [%]	ϵ [%]	π [%]
$n_{\mathrm{leptons}} > 0$	97.486 ± 0.017	69.212 ± 0.027	42.029 ± 0.053	30.789 ± 0.004
$\not{E} > 23\,\mathrm{GeV}$	95.686 ± 0.022	92.602 ± 0.026	7.409 ± 0.028	7.398 ± 0.002
$p_{\mathrm{lead}} > 13\,\mathrm{GeV}$	94.035 ± 0.026	97.139 ± 0.018	2.684 ± 0.017	2.861 ± 0.001
PV selection	47.083 ± 0.055	98.886 ± 0.017	0.514 ± 0.008	1.114 ± 0.001

IDEA



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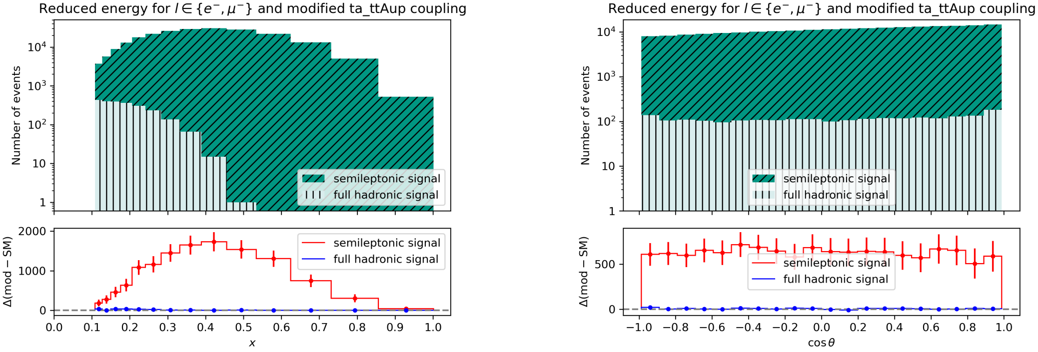
more $(x, cos\theta)$ plots



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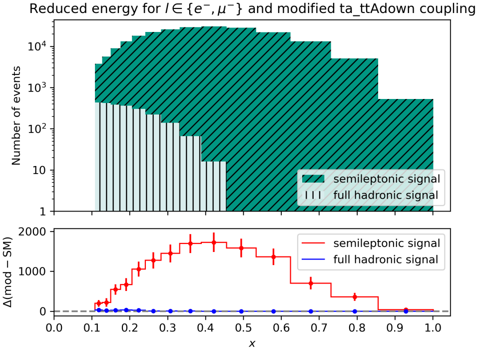

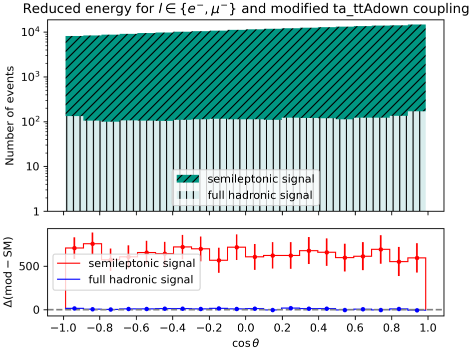

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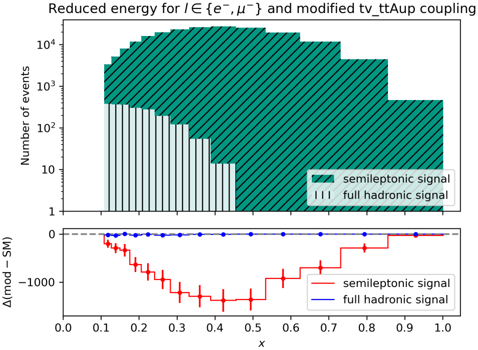

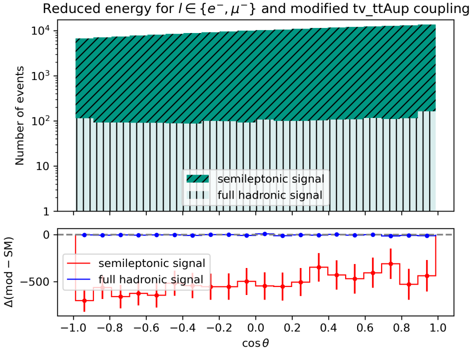

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