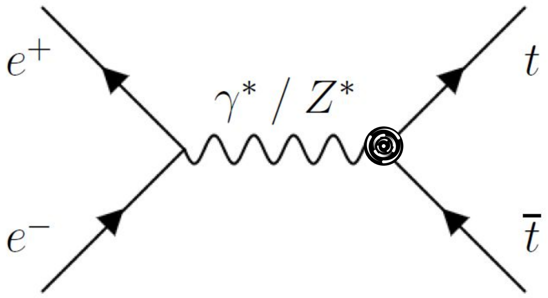
Top-antitop pair production in electron-positron collisions with an Effective Field Theory perspective

(**Pablo Villaseñor Inda**, Cristina Oropeza Barrera, Oscar Ochoa Valeriano and Mateo Ramírez García)[1]



IBERO CIUDAD DE MÉXICO
Física y Matemáticas /

[1] Departamento de Física y Matemáticas
Universidad Iberoamericana
Ciudad de México

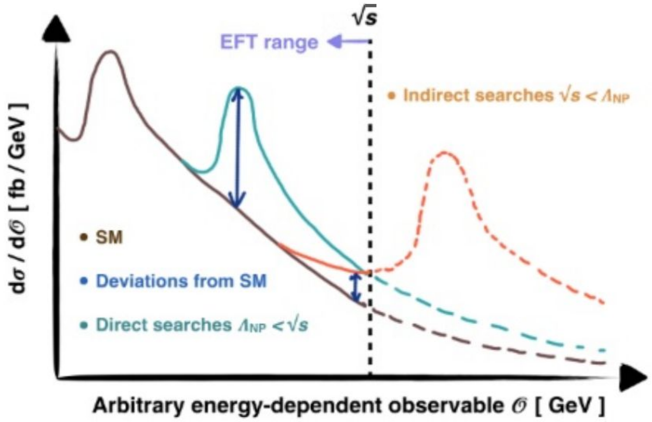
DPC-SMF
UNIVERSIDAD DE GUANAJUATO

Mexican Workshop on Particles and Fields
Universidad de Guanajuato, Campus León
22/oct/2025

The Standard Model as an Effective Field Theory (SMEFT)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{D\geq 5,i} \frac{c_i^{(D)}}{\Lambda_{\mathrm{NP}}^{D-4}} \mathbb{O}_i^{(D)}$$

* $\Lambda_{\mathrm{NP}} \sim 10\ \mathrm{TeV}$



- At mass-dimension 6 (D=6), we use the Warsaw Basis:

$$\mathbb{O}_i^{(6)} \sim \{F_{\mu\nu}^3,\ \phi^2 F_{\mu\nu}^2,\ \phi^4 D_\mu^2,\ \phi^6;\quad \psi^2\phi^3,\ \underbrace{\psi^2\phi F_{\mu\nu}}_{2},\ \underbrace{\psi^2\phi^2 D_\mu}_{3};\quad \psi^4\}$$

*epem → ttbar @ tree-level

- With one D6 operator, amplitudes have the following structure:

$$|\mathcal{M}_{\mathrm{EFT}}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\,\mathcal{R}e\left\{\frac{c_i}{\Lambda^2}\mathcal{M}_{(6)}^*\mathcal{M}_{\mathrm{SM}}\right\} + \frac{c_i^{\ 2}}{\Lambda^4}|\mathcal{M}_{(6)}|^2$$

- Low energy (EW scale) measurements can be used to set bounds on Wilson coefficients.

$$|c_i| < c_{i0}\sqrt{\frac{\chi_\alpha^2}{\chi_{\mathrm{sim}}^2(c_{i,0})}}$$

D6 operators in epem → ttbar

$\psi^2 \phi F_{\mu\nu}$

$$\mathbb{O}_{tW} := (\bar{q}_{L3}\, \sigma^{\mu\nu}\, t_R)\, \tau^I\, \tilde{\phi}\, W^I_{\mu\nu}$$

$$\mathbb{O}_{tB} := (\bar{q}_{L3}\, \sigma^{\mu\nu}\, t_R)\, \tilde{\phi}\, B_{\mu\nu}$$

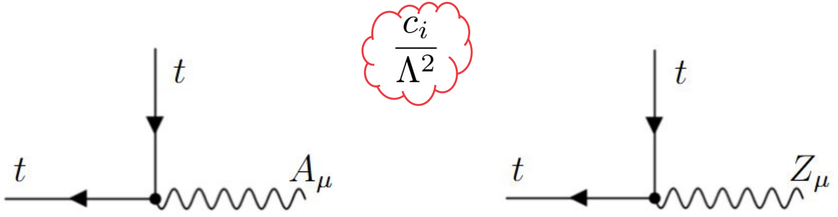
$\psi^2 \phi^2 D_\mu$

$$\mathbb{O}_{\phi t} := (\phi^\dagger\, i\overleftrightarrow{D}_\mu\, \phi)\, (\bar{t}_R\, \gamma^\mu\, t_R)$$

$$\mathbb{O}_{\phi q(1)} := (\phi^\dagger\, i\overleftrightarrow{D}_\mu\, \phi)\, (\bar{q}_{L3}\, \gamma^\mu\, q_{L3})$$

$$\mathbb{O}_{\phi q(3)} := (\phi^\dagger\, i\overleftrightarrow{D}^I_\mu\, \phi)\, (\bar{q}_{L3}\, \tau^I\, \gamma^\mu\, q_{L3})$$

Feynman rules



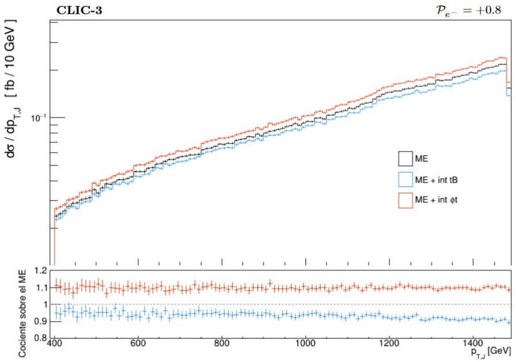
$\mathbb{O}_i^{(6)}$	vev	A_μ	Z_μ	P_L	P_R	cin.
$\mathbb{O}_{tW}$	$v\sqrt{2}$	$s\theta_w$	$c\theta_w$	✓✓	✓	$p^\nu \sigma_{\mu\nu}$
$\mathbb{O}_{tB}$	$v\sqrt{2}$	$c\theta_w$	$s\theta_w$	✓	✓	$p^\nu \sigma_{\mu\nu}$
$\mathbb{O}_{\phi t}$	$v^2/2$	·	g_z	·	✓	γ^μ
$\mathbb{O}_{\phi q(1)}$	$v^2/2$	·	g_z	✓✓	·	γ^μ
$\mathbb{O}_{\phi q(3)}$	$v^2/2$	·	$-g_z$	✓✓	·	γ^μ

SMEFT cross section

- Remember the amplitude is given by: $|\mathcal{M}_{\mathrm{EFT}}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\,\mathcal{R}e\left\{\frac{c_i}{\Lambda^2}\,\mathcal{M}^*_{(6)}\mathcal{M}_{\mathrm{SM}}\right\} + \frac{{c_i}^2}{\Lambda^4}\,|\mathcal{M}_{(6)}|^2$

Differential XS (2→2)

$$\frac{d^2\sigma}{dK\,d\Omega} = \frac{\langle|\mathcal{M}|^2\rangle_{\mathrm{dof}}}{64\pi^2 s}\cdot\frac{|\vec{p}_f|}{|\vec{p}_i|}$$



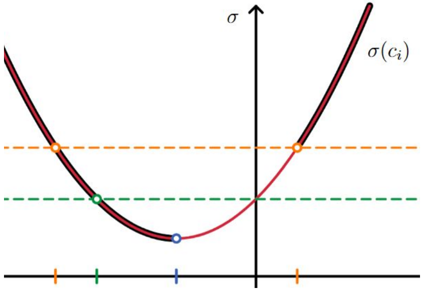
Total XS

$$\sigma(c_i) := \sigma_{\mathrm{ME}} + \underbrace{B_i\frac{c_i}{\Lambda^2_{\mathrm{NF}}}}_{\sigma_{\mathrm{int}}(c_i)} + \underbrace{A_i\left(\frac{c_i}{\Lambda^2_{\mathrm{NF}}}\right)^2}_{\sigma_{(6)}(c_i)}$$

$$c_{i,0}\mid\Delta\sigma \le 0.1\sigma_{\mathrm{SM}}$$
$$|c_{i,0}| < |c_{i,\mathrm{v}}|$$

$$\sigma_{\mathrm{int}}(c_{i,0}) \equiv B_i\frac{c_{i,0}}{\Lambda^2_{\mathrm{NF}}}$$

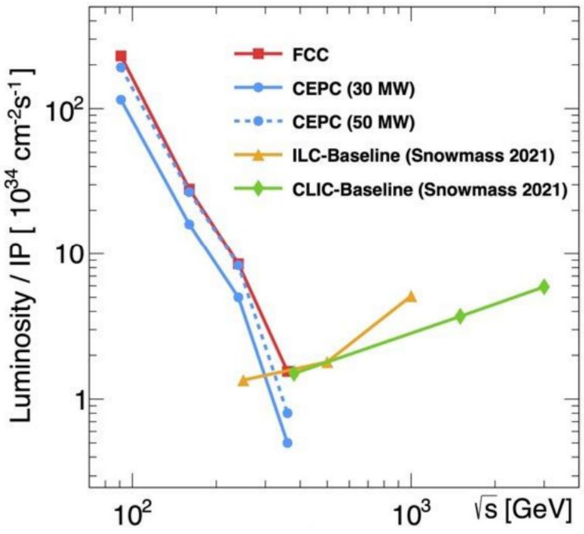
$$\sigma_{(6)}(c_{i,0}) \equiv A_i\left(\frac{c_{i,0}}{\Lambda^2_{\mathrm{NF}}}\right)^2$$

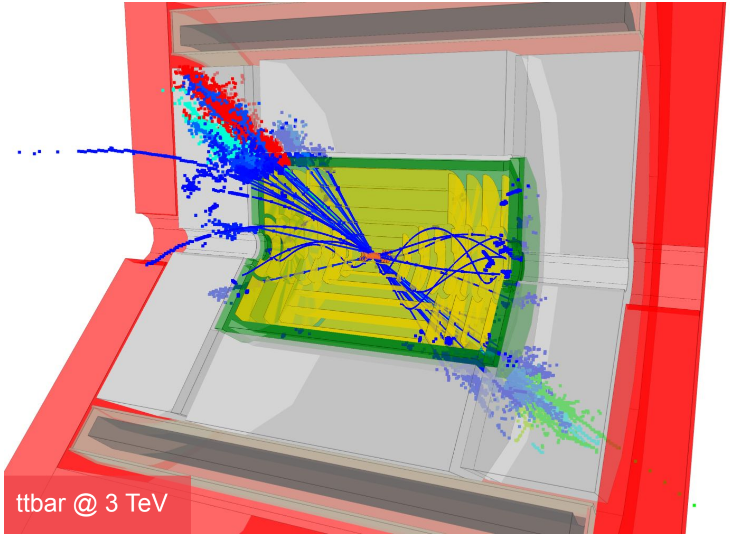


CLIC: Compact Linear Collider / CERN

$$\sqrt{s} \in \{380,\ 1500,\ \boxed{3000}\} \quad [\mathrm{GeV}]$$

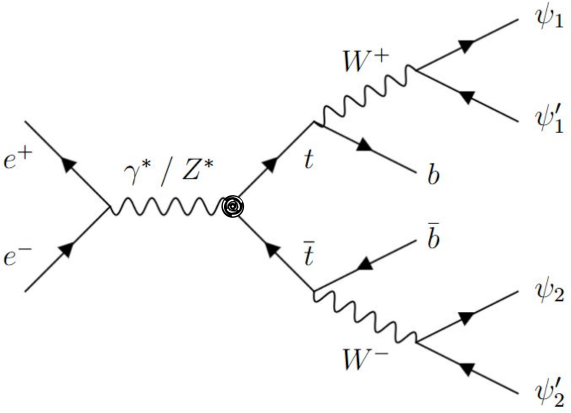
$$\mathcal{P}_{e^-} = \pm 80\,\% \quad \& \quad \mathcal{P}_{e^+} = 0\,\%$$





Our analysis (in general)

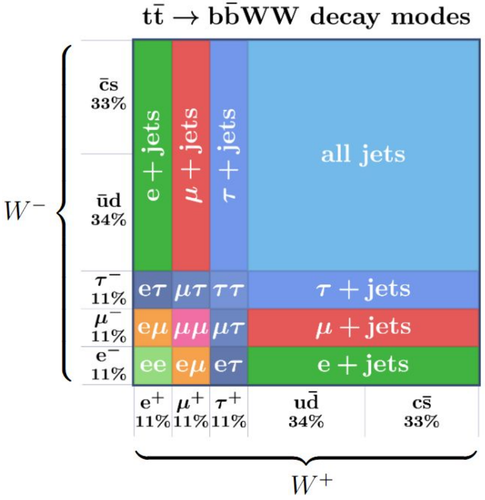
General structure of the process:



$$m^2_{\text{rec},J} := (s + m_J^2) - 2\sqrt{s}E_J$$

Recoil mass

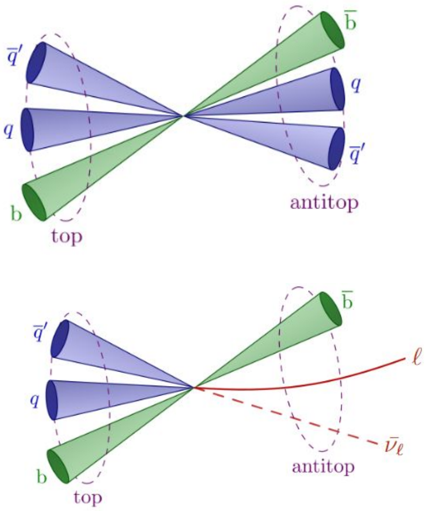
Final states matrix:



$$\mathbb{P}_{qX} \equiv \mathbb{P}_{qq} + \mathbb{P}_{q\ell} = 89.38\ \%$$

Fully- and semi- hadronic events

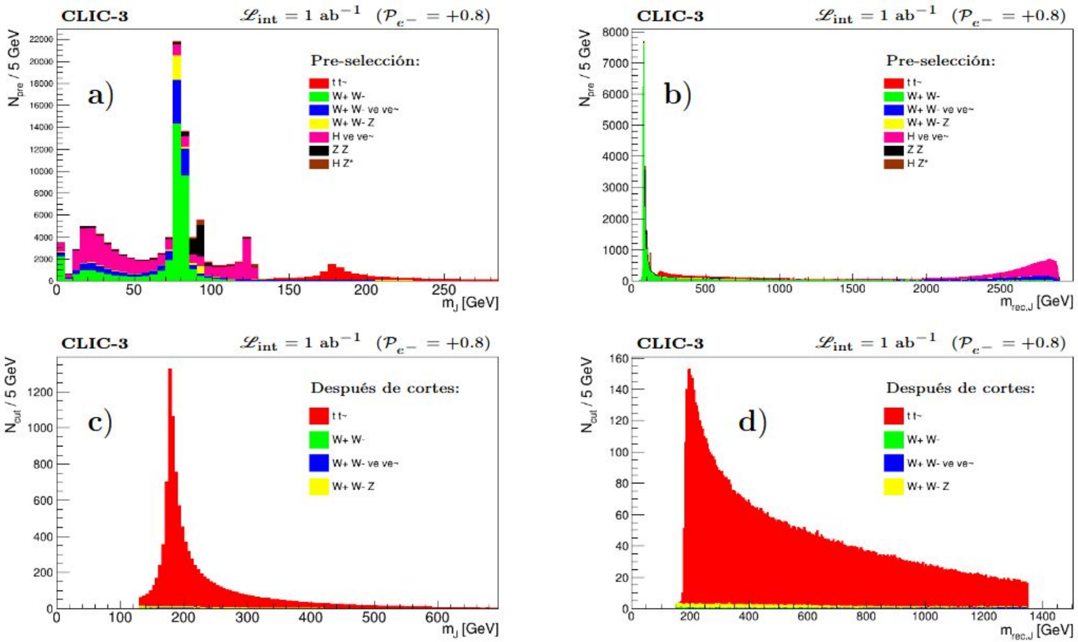
Pre-selection topologies:



$$N_J \geq 1 \quad \& \quad N_\ell \leq 1$$

Our analysis (bkgs and cuts)

- $p_{T,J} > 400$ GeV, $m_J > 130$ GeV y $m_{\text{rec},J} \in (150,\ 1350)$ GeV



- Cross sections without BSM operators.

$$\frac{dN}{dt} = \varepsilon\sigma\mathscr{L}(t),$$

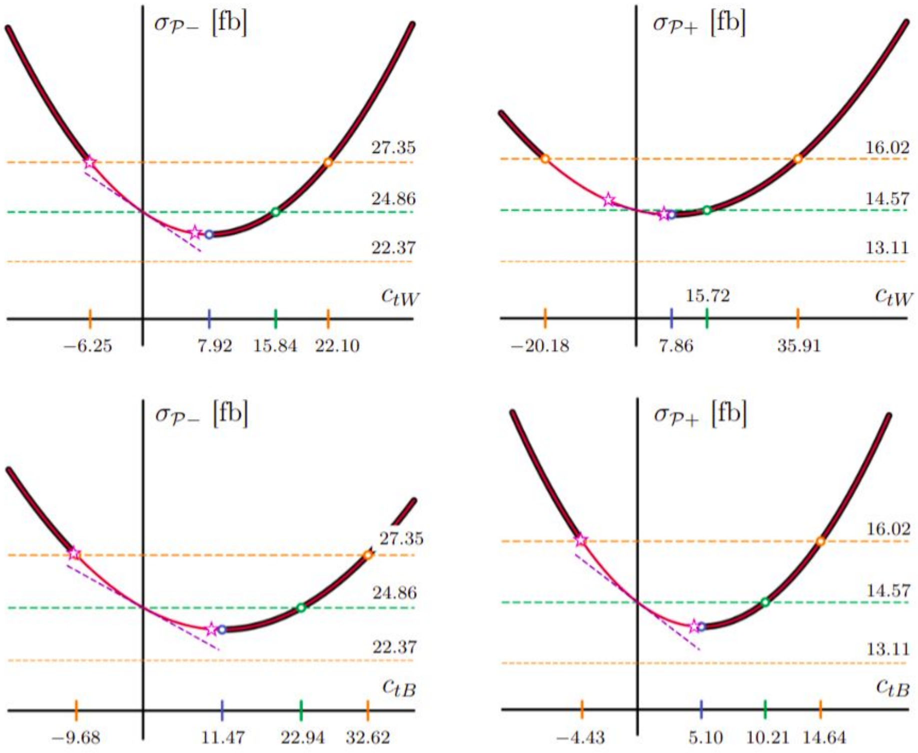
	$\mathcal{P}-$		$\mathcal{P}+$		
σ[fb]	MG	cortes	MG	cortes	ε
$t\bar{t}$	24.86	18.437	14.57	10.820	0.74
W^+W^-	816.68	0.427	91.81	0.005	5×10^{-4}
$W^+W^-\nu_e\bar{\nu}_e$	220.59	0.550	24.53	0.006	2.5×10^{-3}
W^+W^-Z	55.98	2.946	6.38	0.338	5×10^{-2}
$H\nu_e\bar{\nu}_e$	872.13	0	96.97	0	0
ZZ	30.04	0	19.78	0	0
HZ	1.40	0	1.14	0	0
S/B	0.01	4.70	0.06	24.1	

SMEFT cross section parabolae

- Remember:

$$\sigma(c_i) := \sigma_{\mathrm{ME}} + \underbrace{B_i \frac{c_i}{\Lambda_{\mathrm{NF}}^2}}_{\sigma_{\mathrm{int}}(c_i)} + \underbrace{A_i \left(\frac{c_i}{\Lambda_{\mathrm{NF}}^2}\right)^2}_{\sigma_{(6)}(c_i)}$$

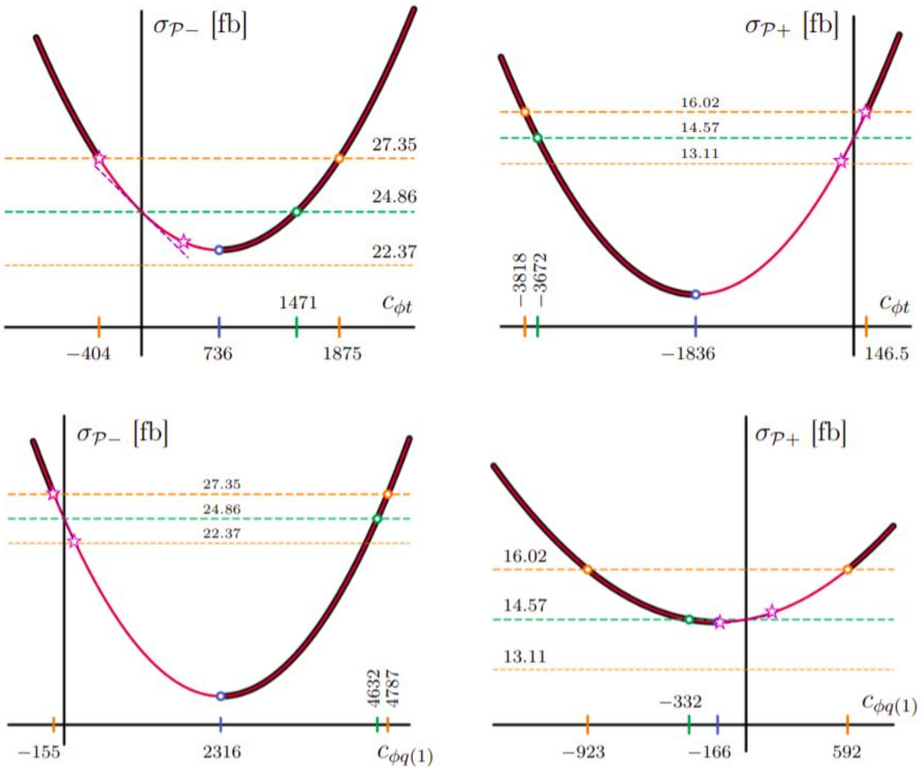
	$\mathcal{P}-$		$\mathcal{P}+$	
$\mathbb{O}_i^{(6)}$	B_i	A_i	B_i	A_i
$\mathbb{O}_{tW}$	−28.488	179.840	−3.16	20.096
$\mathbb{O}_{tB}$	−18.065	78.750	−22.933	224.691
$\mathbb{O}_{\phi t}$	−0.482	0.033	0.956	0.026
$\mathbb{O}_{\phi q(1)}$	−1.552	0.033	0.088	0.027
$\mathbb{O}_{\phi q(3)}$	1.552	0.033	−0.088	0.027



SMEFT cross section parabolae

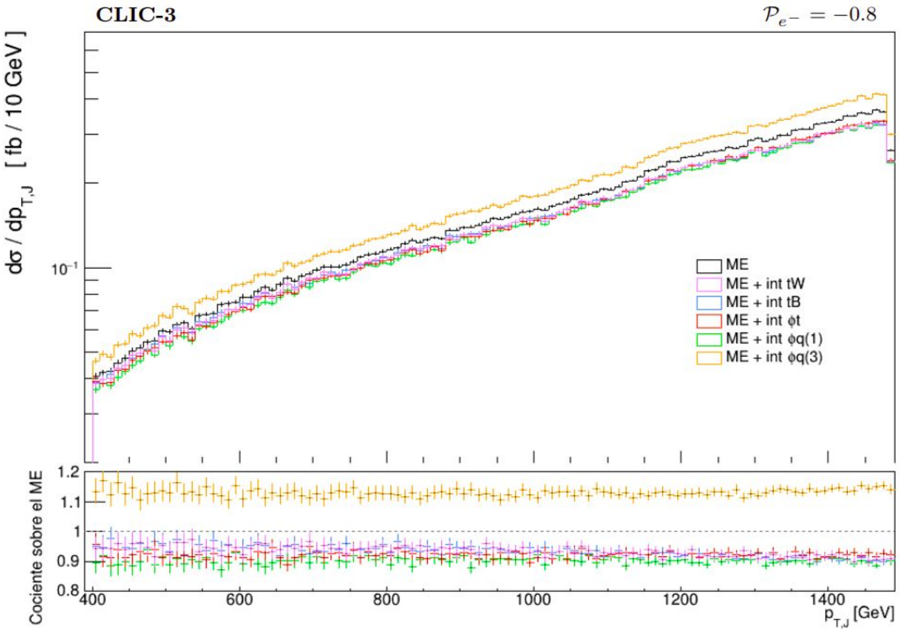
	$c_{tW,0}$	$c_{tB,0}$	$c_{\phi t,0}$	$c_{\phi q(1),0}$	$c_{\phi q(3),0}$
$\mathcal{P}-$	6.25	10	400	155	155
$\mathcal{P}+$	6.25	4.5	146	155	155

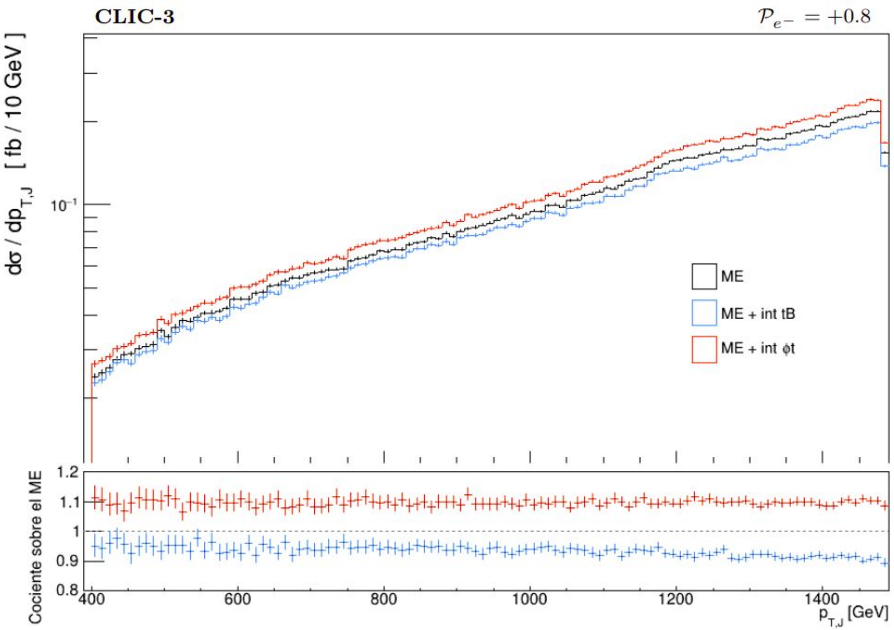
	$\mathcal{P}-$		$\mathcal{P}+$	
$\mathbb{O}_i^{(6)}$	B_i	A_i	B_i	A_i
$\mathbb{O}_{tW}$	−28.488	179.840	−3.16	20.096
$\mathbb{O}_{tB}$	−18.065	78.750	−22.933	224.691
$\mathbb{O}_{\phi t}$	−0.482	0.033	0.956	0.026
$\mathbb{O}_{\phi q(1)}$	−1.552	0.033	0.088	0.027
$\mathbb{O}_{\phi q(3)}$	1.552	0.033	−0.088	0.027



SMEFT cross section differential distributions with respect to p_T

- Adding only D6-SM interference.





Bounds on Wilson coefficients

- Simple chi-square test.

$$\chi^2(c_i) := \sum_{k\in bins} \frac{\left[N(c_i)_k - N_k^{\rm ME}\right]^2}{\Delta_k}$$

$$\approx \left(\frac{\mathscr{L}_{\rm int} B_i c_i}{\Lambda_{\rm NF}^2}\right)^2 \sum_{k\in bins} \frac{\varepsilon_{i,k}^2}{\Delta_k}$$

$$\therefore \quad |c_i| < c_{i0}\sqrt{\frac{\chi_\alpha^2}{\chi_{\rm sim}^2(c_{i,0})}}$$

Our results for the dimension-full Wilson coefficients

	$\mathcal{P}-$		$\mathcal{P}+$	
i	$g_{i,0}^{(6)}$	$g_{i,\rm bound}^{(6)}$	$g_{i,0}^{(6)}$	$g_{i,\rm bound}^{(6)}$
tW	0.0625	0.0550	0.0625	0.6330
tB	0.100	0.087	0.045	0.101
ϕt	4.000	3.398	1.460	2.535
$\phi q(1)$	1.550	1.052	1.550	19.752
$\phi q(3)$	1.550	0.945	1.550	9.927

Outlook

- The SMEFT framework is a model-agnostic bottom-up paradigm for BSM searches. We analyzed the BSM effects of D6 operators on epem→ttbar and set bounds on their Wilson coefficients.
- Top Physics is crucial for both SM and BSM studies. We focused on the top-EW sector.
- A future e^+e^- collider will be essential for EW and BSM precision measurements. We studied CLIC’s environment.
- With the mostly negative polarization our method has good sensitivity for detecting linear SMEFT effects in CLIC-3.
- With the mostly positive polarization (even though the ttbar S/B is enhanced) the selected D6 operators we studied have very small linear contributions to be detected with our analysis.

Thanks to the organizing committee!

Dr. Roig, Pablo
Dr. Barranco, Juan
Prof. Pedraza, Isabel
Dr. Maury Cuna, Humberto
Dr. Hernandez-Arellano, Haydee
Dr. Vaquera Araujo, Carlos Alberto

Thanks to everyone for your attention. Enjoy the rest of the Workshop!

MWPF2025 a.k.a. Guanajuato Unification Tour?