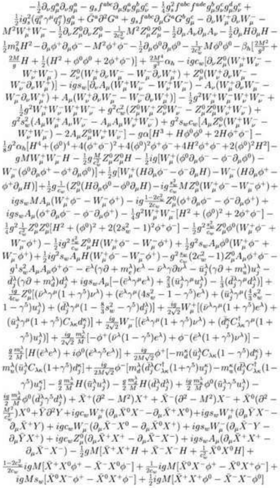
Probing anomalous interactions at the LHC

Matteo Maltoni

When the M meets the P

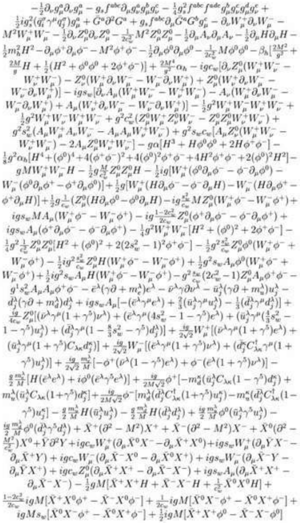
Louvain-la-Neuve, 20 January 2021

The SMEFT extends the SM by adding higher-dimensional operators



The SMEFT extends the SM by adding higher-dimensional operators

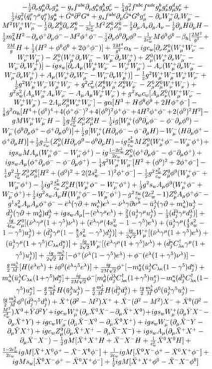
$\mathcal{L}_{SMEFT} =$



$$+\sum_i \frac{C_i}{\Lambda^{d-4}} O_i^d$$

The SMEFT extends the SM by adding higher-dimensional operators

$\mathcal{L}_{SMEFT} =$



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

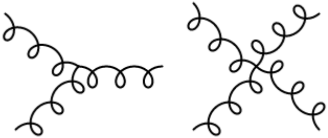
The O_G operator introduces new interactions

$$O_G = g_s f_{abc}\, G_{\nu}^{a,\mu} G_{\rho}^{b,\nu} G_{\mu}^{c,\rho}$$

The O_G operator introduces new interactions

$$O_G = g_s f_{abc}\, G_{\nu}^{a,\mu} G_{\rho}^{b,\nu} G_{\mu}^{c,\rho}$$

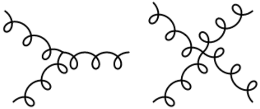
SM gluon interactions



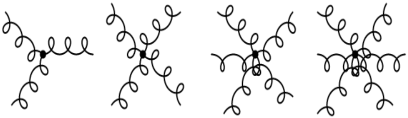
The O_G operator introduces new interactions

$$O_G = g_s f_{abc}\, G_{\nu}^{a,\mu} G_{\rho}^{b,\nu} G_{\mu}^{c,\rho}$$

SM gluon interactions



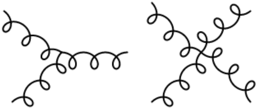
SMEFT gluon interactions



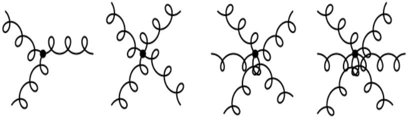
The O_G operator introduces new interactions

$$O_G = g_s f_{abc}\, G_{\nu}^{a,\mu} G_{\rho}^{b,\nu} G_{\mu}^{c,\rho}$$

SM gluon interactions



SMEFT gluon interactions



$$\sigma = \sigma^{SM} + \frac{C_G}{\Lambda^2}\, \sigma^{1/\Lambda^2} + \left(\frac{C_G}{\Lambda^2}\right)^2\, \sigma^{1/\Lambda^4} + \dots$$

We concentrate on three-jet production

- LHC is a proton accelerator: $pp \Rightarrow qq, gg, qg$

We concentrate on three-jet production

- LHC is a proton accelerator: $pp \Rightarrow qq, gg, qg$
- $pp > jj$ shows $\sigma^{1/\Lambda^2} = 0$

We concentrate on three-jet production

- LHC is a proton accelerator: $pp \ \Rightarrow \ qq, gg, qg$
- $pp \ > \ jj$ shows $\sigma^{1/\Lambda^2} = 0$
- $pp \ > \ jjj \quad @LO$

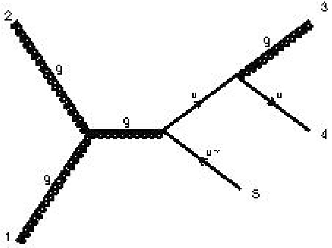
We concentrate on three-jet production

- LHC is a proton accelerator: $pp \Rightarrow qq, gg, qg$
- $pp > jj$ shows $\sigma^{1/\Lambda^2} = 0$
- $pp > jjj \quad @LO$

We use computer simulations to generate the events

$$p\,p\ >\ j\,j\,j\quad @LO$$

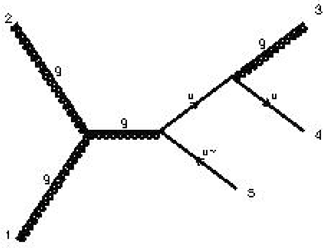
SM



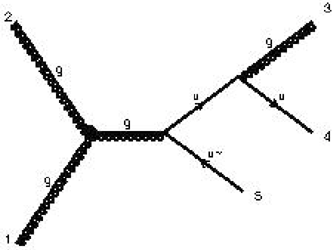
We use computer simulations to generate the events

$$p\,p\; > \; j\; j\; j \quad @LO$$

SM



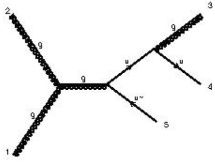
$\mathcal{O}(\Lambda^{-4})$



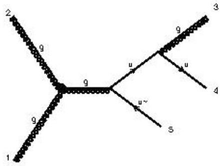
We use computer simulations to generate the events

$$p\ p\ >\ j\ j\ j \quad @LO$$

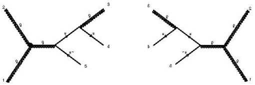
SM



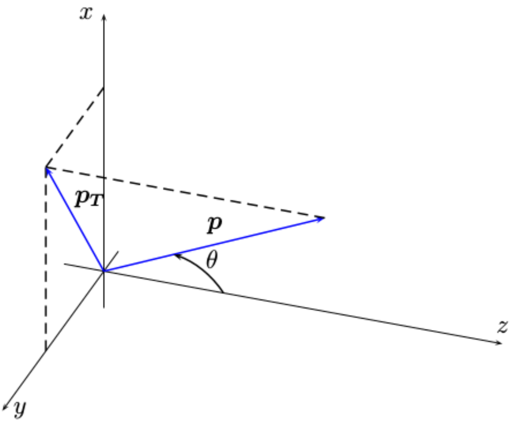
$\mathcal{O}(\Lambda^{-4})$



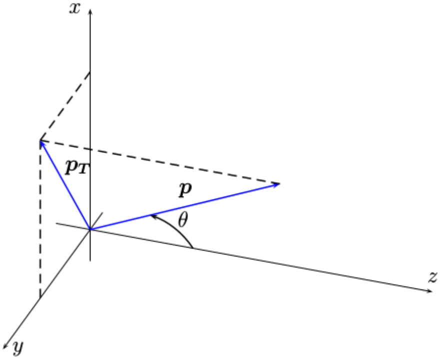
$\mathcal{O}(\Lambda^{-2})$



Some quantities used in jet analysis

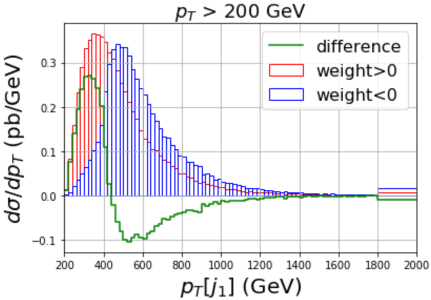


Some quantities used in jet analysis

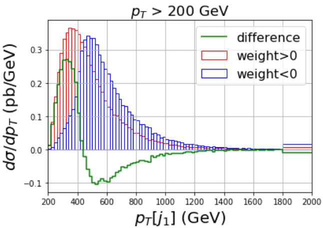


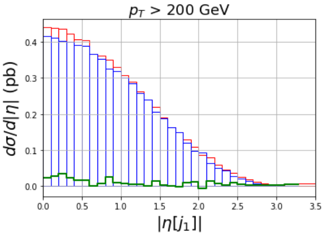
$$\eta = -\log\left(\tan\frac{\theta}{2}\right)$$

We focus on variables which separate the cross-section contributions with different sign

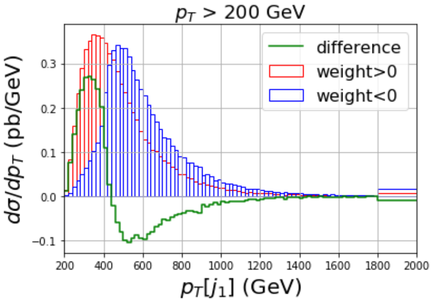


We focus on variables which separate the cross-section contributions with different sign

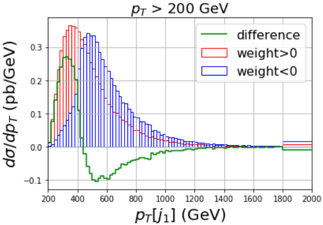




The chi-square function sets bounds on the coefficient

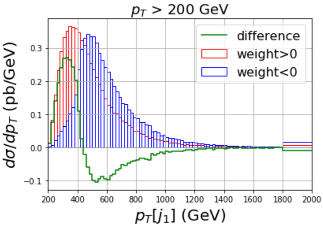


The chi-square function sets bounds on the coefficient



$$\chi^2 = \sum_i \left(\frac{x_i^{exp} - x_i^{th}}{\Delta_i} \right)^2$$

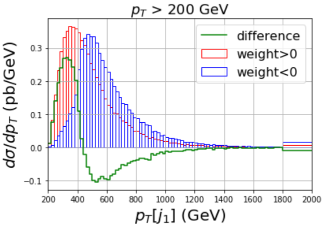
The chi-square function sets bounds on the coefficient



$$\chi^2 = \sum_i \left(\frac{x_i^{exp} - x_i^{th}}{\Delta_i} \right)^2$$

- The LHC data we are interested in is not public yet

The chi-square function sets bounds on the coefficient

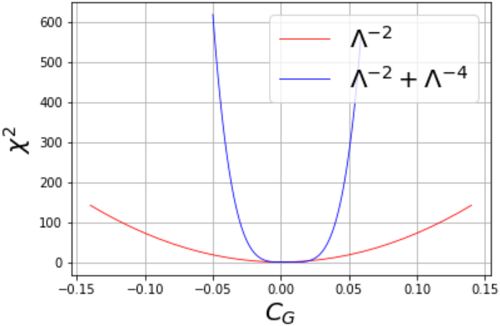


$$\chi^2 = \sum_i \left(\frac{x_i^{exp} - x_i^{th}}{\Delta_i} \right)^2$$

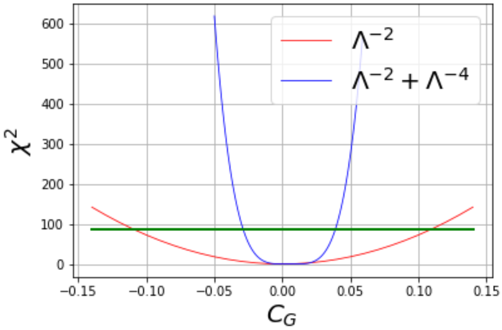
$$= \sum_i \left(\frac{\frac{C_G}{\Lambda^2} \sigma_i^{1/\Lambda^2} + \left(\frac{C_G}{\Lambda^2}\right)^2 \sigma_i^{1/\Lambda^4}}{\Delta_i} \right)^2$$

- The LHC data we are interested in is not public yet

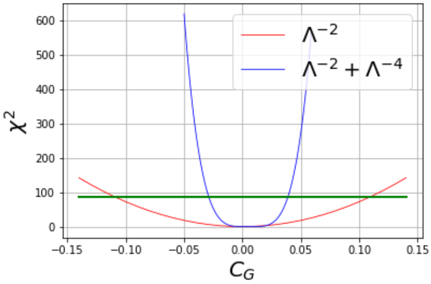
The chi-square function sets bounds on the coefficient



The chi-square function sets bounds on the coefficient



The chi-square function sets bounds on the coefficient



$\Lambda = 1$ TeV, 68% CL

- Interference contribution $\mathcal{O}(\Lambda^{-2})$

$$C_G \in [-0.136, 0.136]$$

- New Physics contribution $\mathcal{O}(\Lambda^{-4})$

$$C_G \in [-0.032, 0.041]$$

The procedure can be repeated using any distribution

$\Lambda = 1$ TeV, 68% CL

Distribution	Upper bound on C_G	Lower bound on C_G
$p_T[j_1]$	$1.36 \cdot 10^{-1}$ ($4.06 \cdot 10^{-2}$)	$-1.36 \cdot 10^{-1}$ ($-3.19 \cdot 10^{-2}$)
$\frac{\lvert(\boldsymbol{p_1} \times \boldsymbol{p_2}) \cdot \boldsymbol{p_3}\rvert}{\lvert\boldsymbol{p_1} \times \boldsymbol{p_2}\rvert \lvert\boldsymbol{p_3}\rvert}$	$6.29 \cdot 10^{-1}$ ($2.11 \cdot 10^{-1}$)	$-6.29 \cdot 10^{-1}$ ($-2.45 \cdot 10^{-1}$)
$\lvert\eta[j_3]\rvert$	1.11 ($2.62 \cdot 10^{-1}$)	-1.11 ($-2.44 \cdot 10^{-1}$)
$\lvert\eta[j_1]\rvert$	3.33 ($2.55 \cdot 10^{-1}$)	-3.33 ($2.60 \cdot 10^{-1}$)

Takeaways

- The interference of SM and O_G operator is small, for multijet production, because a cancellation occurs between phase space regions with different cross-section signs

Takeaways

- The interference of SM and O_G operator is small, for multijet production, because a cancellation occurs between phase space regions with different cross-section signs
- Some variables can separate the different regions quite well with simple cuts

Takeaways

- The interference of SM and O_G operator is small, for multijet production, because a cancellation occurs between phase space regions with different cross-section signs
- Some variables can separate the different weights with simple cuts
- These variable distributions over the interference can be used to set constraints on the C_G coefficient

Takeaways

- The interference of SM and O_G operator is small, for multijet production, because a cancellation occurs between phase space regions with different cross-section signs
- Some variables can separate the different weights with simple cuts
- These variable distributions over the interference can be used to set constraints on the C_G coefficient
    - The bounds from variables which are sensitive to the sign changes are, by more than one order of magnitude, better than the bounds from the other ones

Takeaways

- The interference of SM and O_G operator is small, for multijet production, because a cancellation occurs between phase space regions with different cross-section signs
- Some variables can separate the different weights with simple cuts
- These variable distributions over the interference can be used to set constraints on the C_G coefficient
  - The bounds from variables which are sensitive to the sign changes are, by more than one order of magnitude, better than the bounds from the other ones
  - The best bounds are comparable to the ones from the $\mathcal{O}(\Lambda^{-4})$ contribution

Takeaways

- The interference of SM and O_G operator is small, for multijet production, because a cancellation occurs between phase space regions with different cross-section signs
- Some variables can separate the different weights with simple cuts
- These variable distributions over the interference can be used to set constraints on the C_G coefficient
  - The bounds from variables which are sensitive to the sign changes are, by more than one order of magnitude, better than the bounds from the other ones
  - The best bounds are comparable to the ones from the $\mathcal{O}(\Lambda^{-4})$ contribution
- This precision should be available with current LHC data

Takeaways

- The interference of SM and O_G operator is small, for multijet production, because a cancellation occurs between phase space regions with different cross-section signs
- Some variables can separate the different weights with simple cuts
- These variable distributions over the interference can be used to set constraints on the C_G coefficient
    - The bounds from variables which are sensitive to the sign changes are, by more than one order of magnitude, better than the bounds from the other ones
    - The best bounds are comparable to the ones from the $\mathcal{O}(\Lambda^{-4})$ contribution
- This precision should be available with current LHC data
- The procedure is general and can be applied to any other process with interference suppression

Takeaways

- The interference of SM and O_G operator is small, for multijet production, because a cancellation occurs between phase space regions with different cross-section signs
- Some variables can separate the different weights with simple cuts
- These variable distributions over the interference can be used to set constraints on the C_G coefficient
  - The bounds from variables which are sensitive to the sign changes are, by more than one order of magnitude, better than the bounds from the other ones
  - The best bounds are comparable to the ones from the $\mathcal{O}(\Lambda^{-4})$ contribution
- This precision should be available with current LHC data
- The procedure is general and can be applied to any other process with interference suppression

---

C. Degrande, M. Maltoni, *"Reviving the interference: framework and proof-of-principle for the anomalous gluon self-interaction in the SMEFT"*, arXiv:2012.06595 [hep-ph]