EFT studies in the same-sign WW VBS signature at the LHC

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SM Effective Field Theory (EFT)

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \frac{c^{(5)}}{\Lambda}\mathcal{O}^{(5)} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}_i^{(6)} + \ \dots \qquad (1)$$

Odd terms violate additional simmetries

Wilson coefficients

- Adding a single EFT operator (for example Q_W) the probability amplitude $A(v)$ (v is a generic observable) changes as:

$$A_{EFT}(v) = A_{SM}(v) + c_W A_{Q_W}(v)$$

If $f(v)$ is the probability distribution for the variable v, since $f(v) \sim |A(v)|^2$:

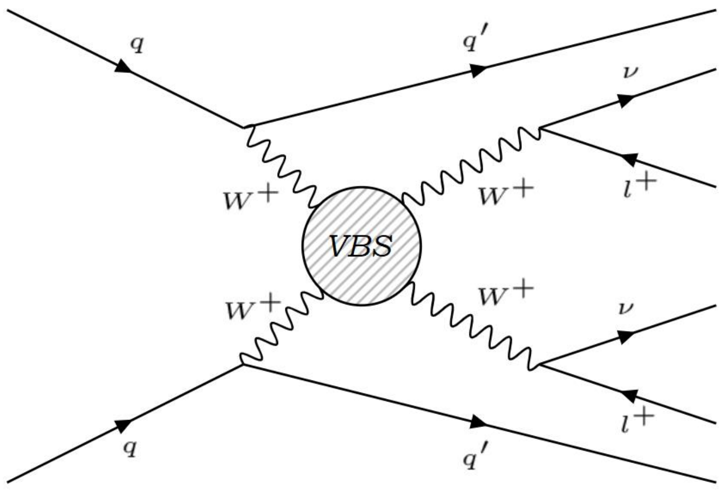
$$f_{EFT}(v) = f_{SM}(v) + c_W f_{LIN}(v) + c_W^2 f_{QUAD}(v)$$

- 6-th dimension EFT operators considered:

$$\left.\begin{aligned} Q_W &= \epsilon_{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu} \\ Q_{HW} &= H^\dagger H W_{\mu\nu}^i W^{i\mu\nu} \end{aligned}\right\} \longrightarrow \text{Wilson coefficients: } c_W \text{ , } \mathrm{c_{HW}}$$

MC generations and preselections

- Same-sign WW VBS:



Three distributions for each variable:

1. SM
2. Linear
3. Quadratic

- MadGraph, $\sqrt{s} = 13$ TeV

(EFT models from https://arxiv.org/abs/1709.06492)

- Variables and preselections:

(Source: Jasper Lauwer, *Study of Electroweak $W^{\pm}W^{\pm}jj$ production with the CMS detector*)

Variable	Selection
met	> 30 GeV
m_{jj}	> 500 GeV
m_{ll}	> 20 GeV
p_{tl1}	> 25 GeV
p_{tl2}	> 20 GeV
p_{tj1}	> 30 GeV
p_{tj2}	> 30 GeV
$\lvert\eta_{j1}\rvert$	< 5
$\lvert\eta_{j2}\rvert$	< 5
$\Delta\phi_{jj}$	> 2.5 GeV

Scaling relations and normalization

- **Test values** of c_W and c_{HW} :

0.05	0.1	0.3	0.4	1

Scaling relations

ex) $c_W = 0.1$ from the distribution with $c_W = 0.3$
- Linear term: histo->Scale(0.1/0.3)
- Quadratic term: histo->Scale(0.1∗0.1/0.3∗0.3)

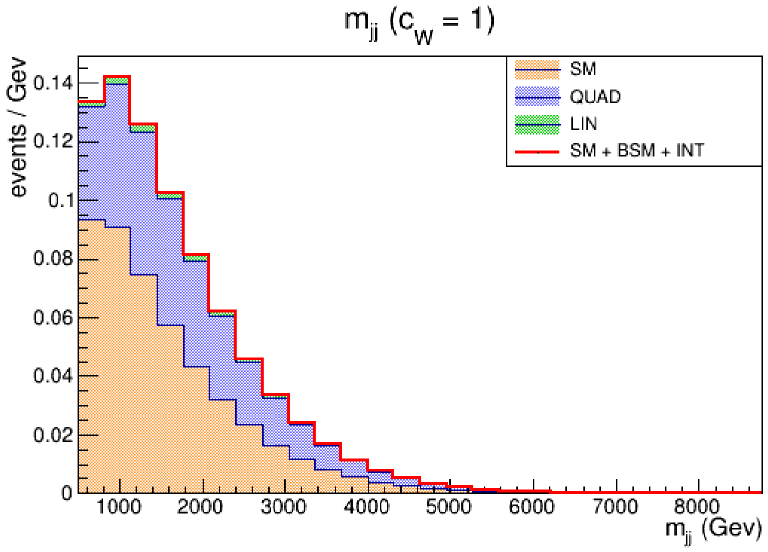
- **Normalization of the histograms** to the number of expected events at $L_{int} = 100\ \text{fb}^{-1}$:

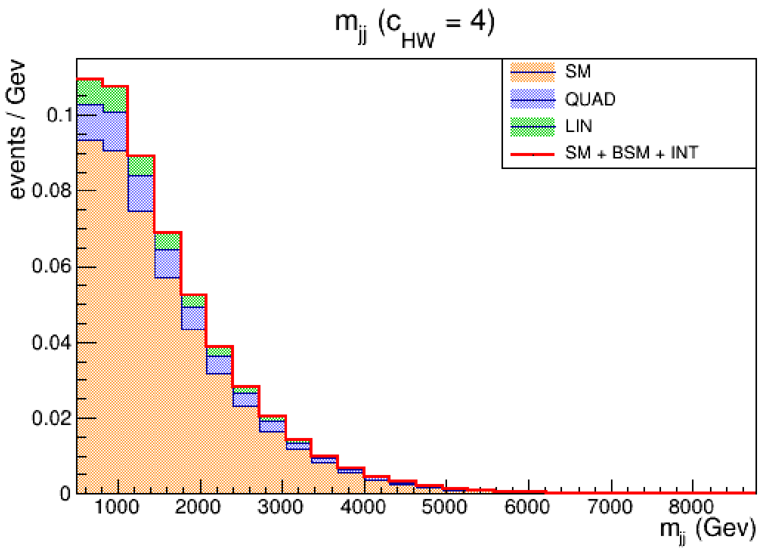
histo->Scale(cross_section*integrated_luminosity)

- **Choice of the binning**: bin width $= \frac{1}{3}$ RMS

Multiples in the tails (*variable width binning*):
- To reduce SM fluctuations
- To include the tails avoiding empty bins (requested by Combine for the likelihood scans)

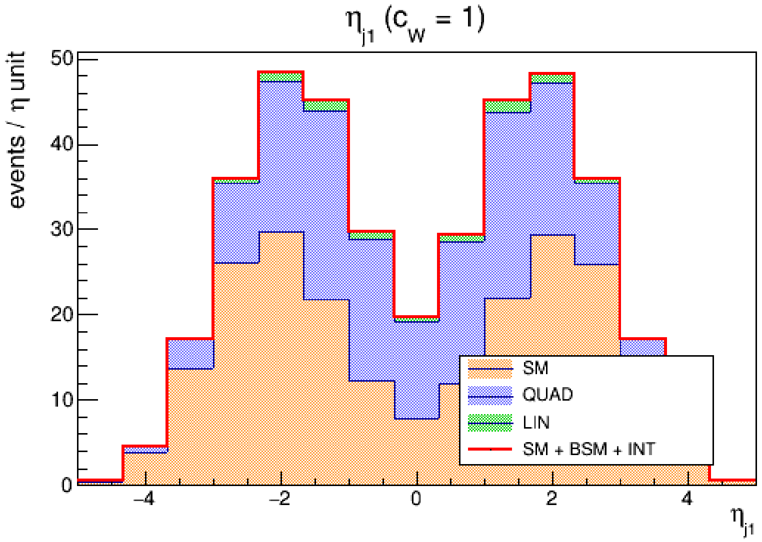
Comparison between Q_W and Q_{HW} distributions

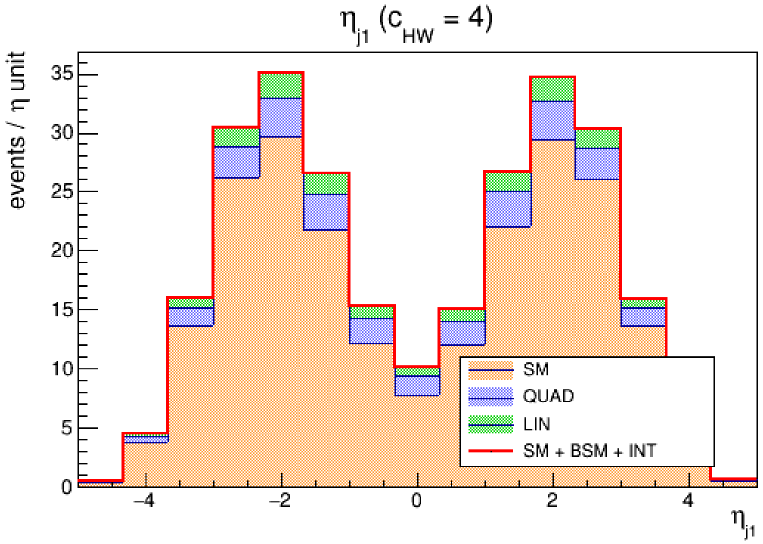




Results:

1. The BSM deviations are more significant for Q_W than for Q_{HW} (larger integrals)
2. The relative contribution of the linear term is greater for Q_{HW} than for Q_W





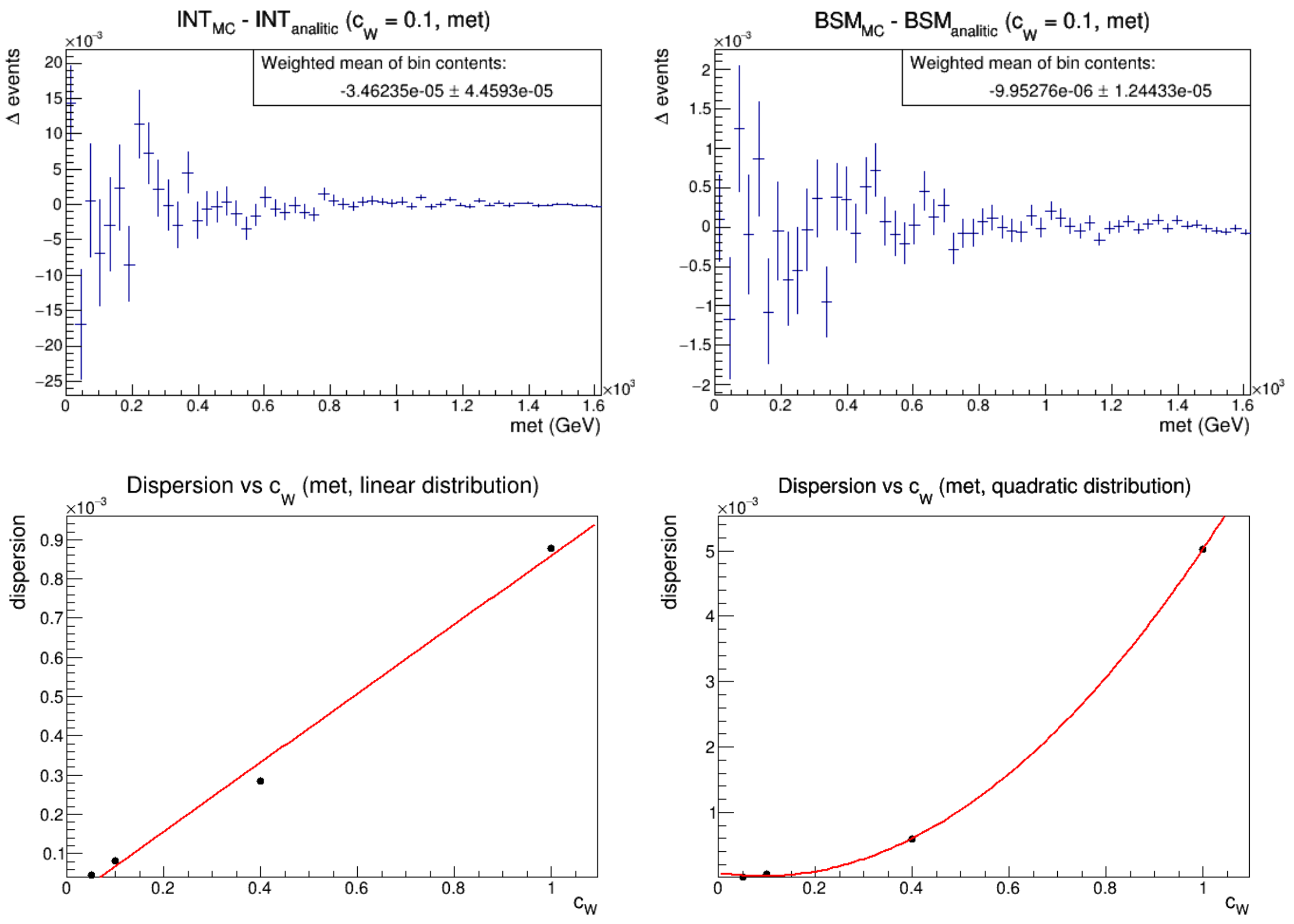
Cross sections:

Coefficient	$c_W = 0.3$	$c_{HW} = 0.3$
SM	3.95 fb	
Linear	0.04 fb	0.13 fb
Quadratic	0.27 fb	0.02 fb

Consistency checks of the MC generations

➢ Plot of the difference between MC distributions and the distributions generated through scaling relations

Expected behaviour: fluctuations around 0

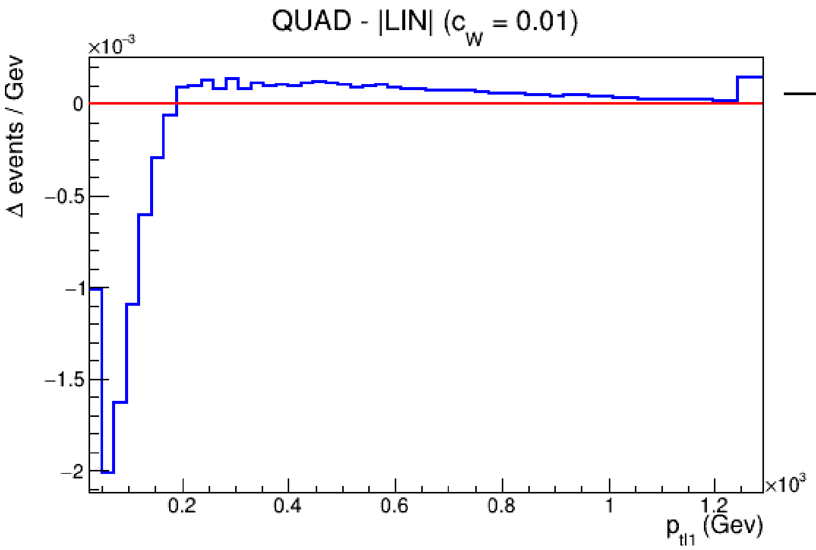


<u>Results</u>: scaling relations verified (for every c_W and every variable)

- Weighted mean of bin contents compatible with 0
- Dispersion (standard error of the weighted mean of bin contents) vs c_W:
  - linear trend for the difference between the linear distributions
  - quadratic trend for the difference between the quadratic distributions

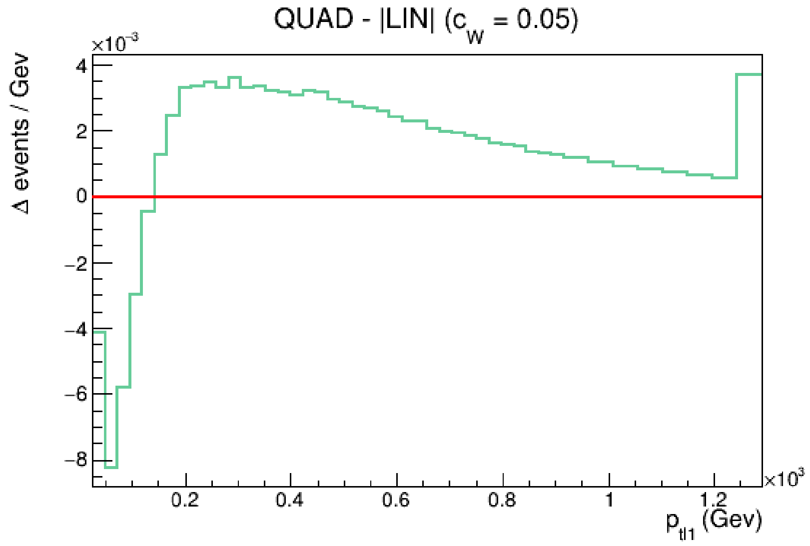
Comparison between linear and quadratic terms

- Plot of the difference between quadratic and linear distributions: $f_{QUAD}(v) - |f_{LIN}(v)|$



When the plot is under the red line the linear term is preponderant

N.B. The linear term is an interference term, so it is not positive definite



Results:

With small values of c_W, the linear term prevails in a limited region at the beginning of the distribution

Explanation: the linear distribution is concentrated in a smaller and initial region, while the tails of the quadratic term spread in a wider range.

Likelihood Scans

- For a counting experiment (all the observations in one bin):

$$\mathcal{L} = Poisson(n \mid \underbrace{n^{SM} + c_W\, n^{LIN} + c_W^2\, n^{QUAD}}_{\text{theoretical model, } c_W\text{: Parameter Of Interest (POI)}}) \qquad (2)$$

likelihood

countings (observations)

where $Poisson(n \mid \theta) = \frac{e^{-\theta}}{n!}\theta^n$

- Considering several bins ($i = 1, \ldots, N_{bin}$):

$$\mathcal{L} = \prod_{i=1}^{N_{bin}} Poisson(n_i \mid n_i^{SM} + c_W\, n_i^{LIN} + c_W^2\, n_i^{QUAD}) \qquad (3)$$

where in this case $n_i = n_i^{SM}$

Likelihood Scans

- Best estimation of the POI (Wilson coefficient), i.e. higher probability that the model describes the observations:

maximization of $\mathcal{L} = \mathcal{L}(c_W)$ $\Longleftrightarrow$ minimization of $-2\Delta \log \mathcal{L}$ (Δ: shift to have $\min(\log \mathcal{L}) = 0$)

- Profile of $\mathcal{L} = \mathcal{L}(c_W)$: depends on the sensibility to the Wilson coefficient:

higher sensibility $\Longleftrightarrow$ best estimation of the Wilson coefficient

- Cramér-Rao theorem:
  - $-2\Delta \log \mathcal{L} < \mathbf{1}$ defines the 68% confidence range in the estimation of the Wilson coefficient
  - $-2\Delta \log \mathcal{L} < \mathbf{3.84}$ defines the 95% confidence range in the estimation of the Wilson coefficient

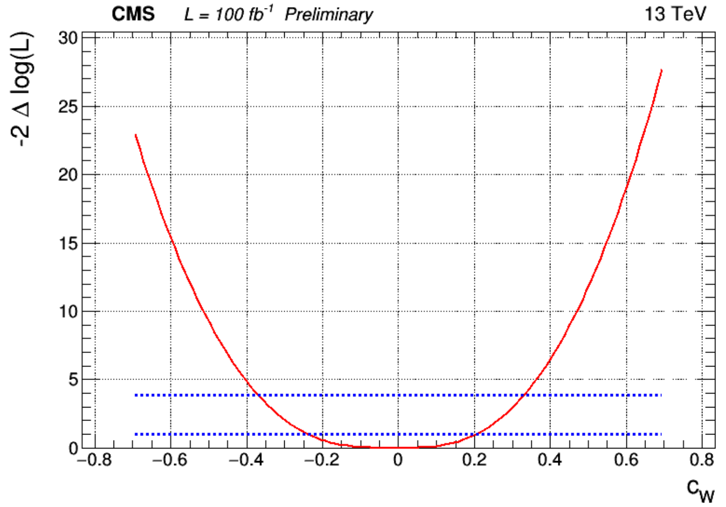
Red horizontal lines in the plots

Narrower intervals = more discriminant variables

Likelihood Scans

Examples:

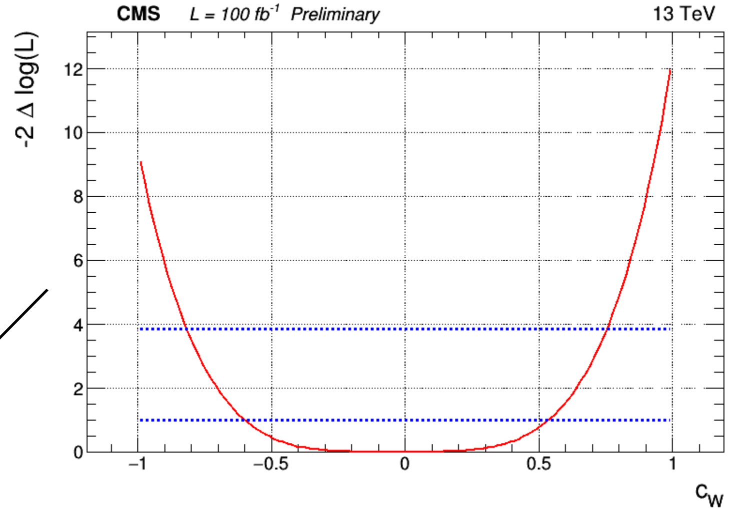
$p_{tj1}(\mathrm{Q_W})$



More discriminant

Less discriminant

$m_{\mathrm{jj}}(Q_{HW})$



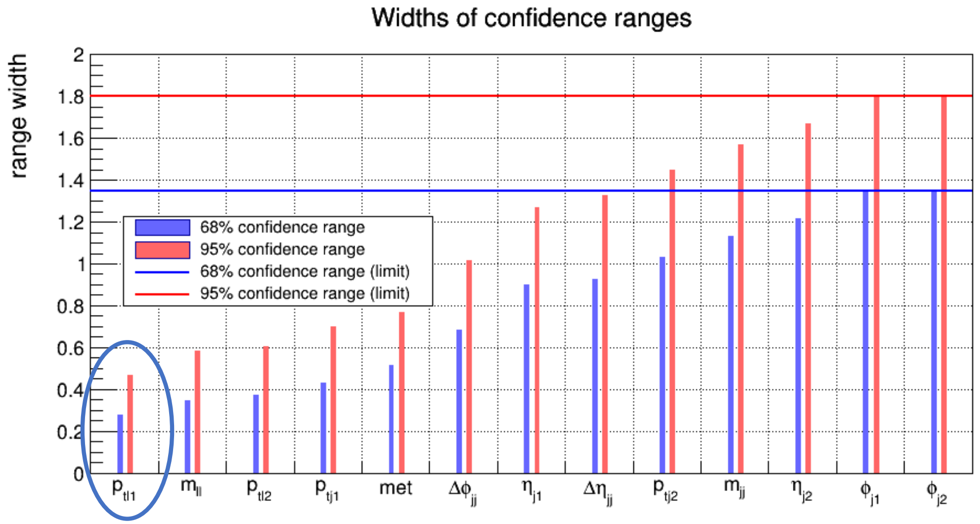
Minimum:

$c_W \sim 10^{-2} - 10^{-3}$

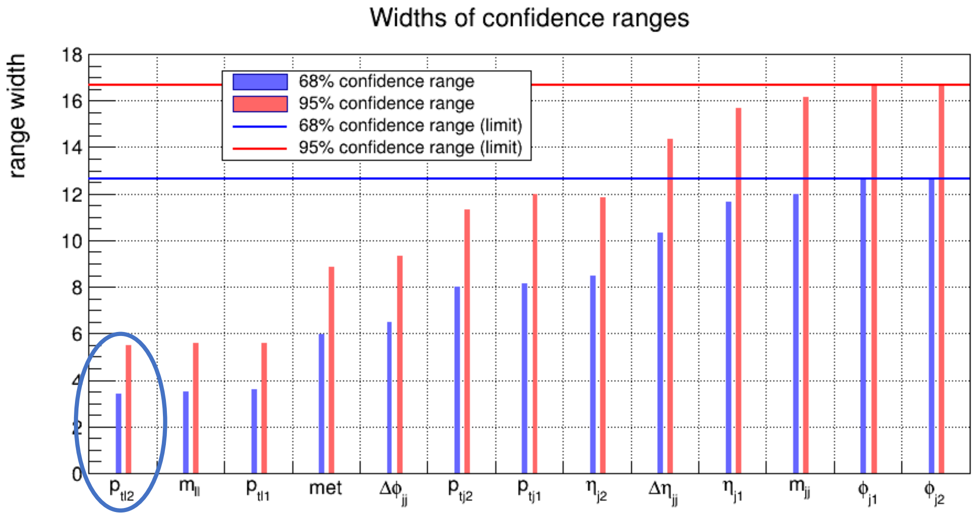
Results (best variables):

- $p_{tl1}(Q_W)$
- $p_{tl2}(Q_{HW})$

Q_W



Q_{HW}

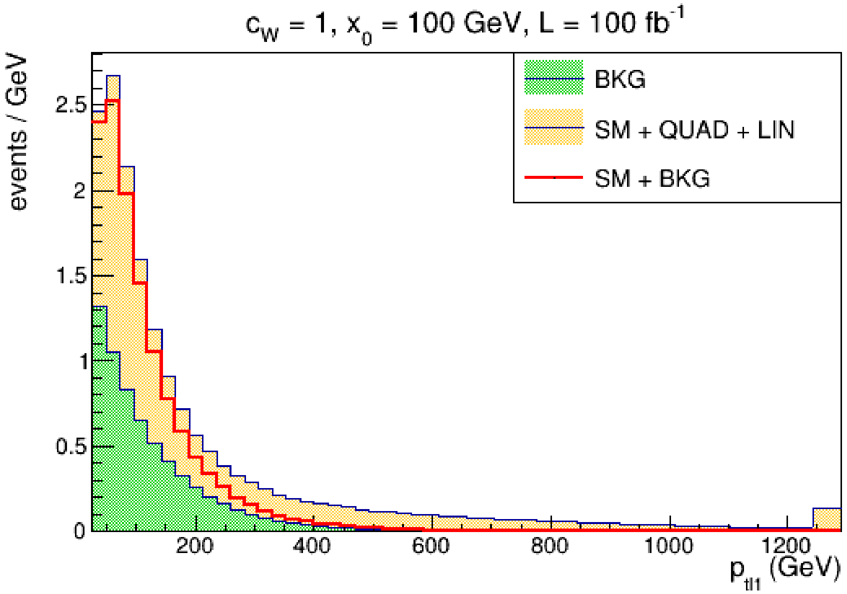


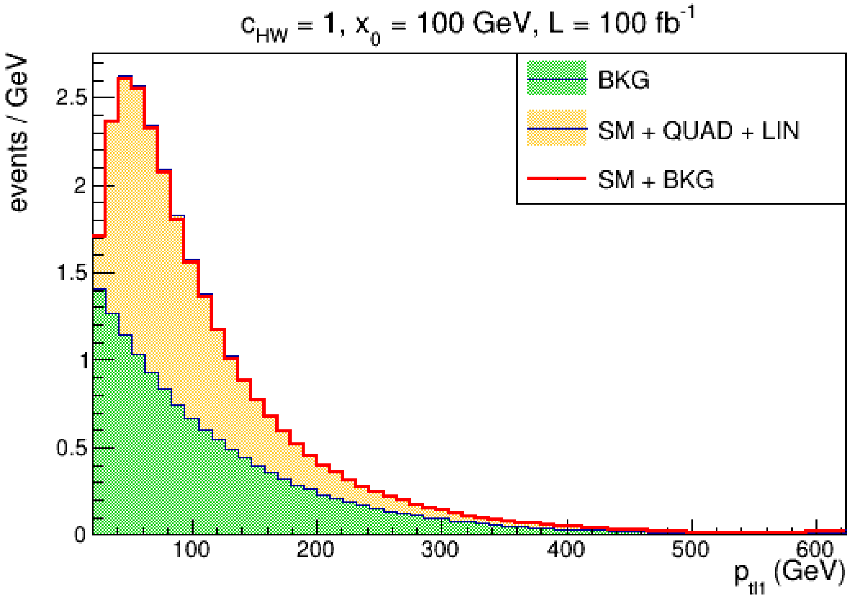
Background generation

- Model used (from previous studies at CMS, https://arxiv.org/abs/1709.05822):
  - Generation of 10^6 events with the distribution e^{-x/x_0}
  - Normalization: ratio 1:1 between the integrals of the background and the signal
  - Best choice of x_0: ratio 1:1 between the partial integrals (contents of the single bins), $x_0 = 100$ GeV

- Examples:

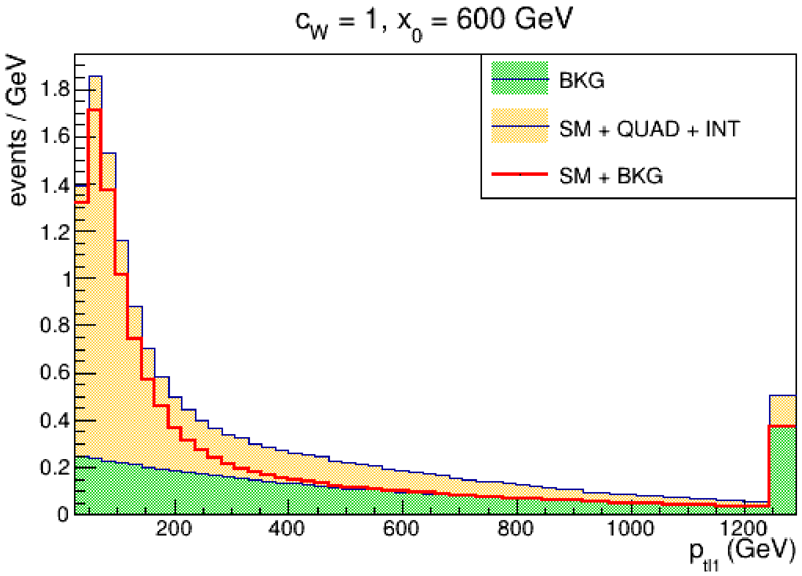
$(c_W = 0.05)$





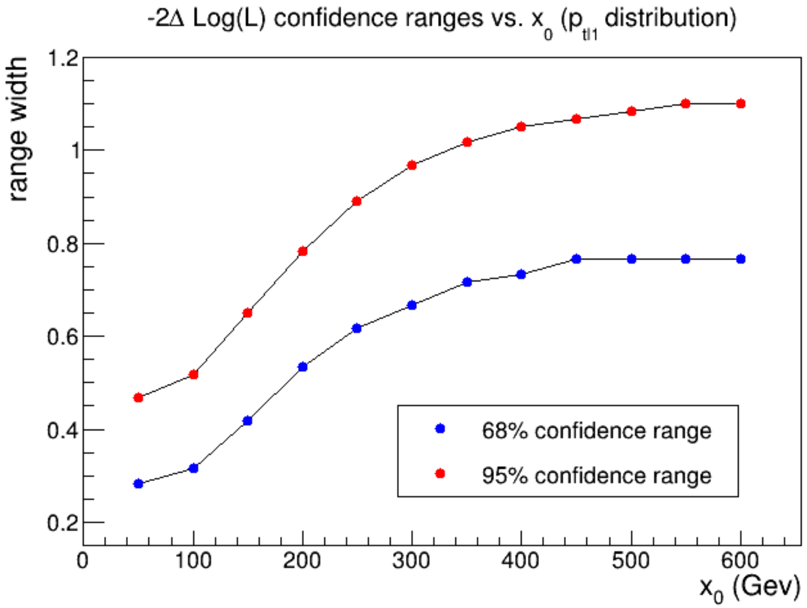
Confidence ranges vs x_0

➢ Variation of x_0 in the range [100 GeV, 600 GeV]



Increasing x_0 the backround contribution in the tail becomes predominant

The sensibility to the Wilson coefficient is expected to decrease; this trend is verified



<u>Results</u>:

- Likelihood scans seem mostly affected by the tails of the distributions
- $x_0 = 100$ GeV is a reasonable choice

Asymptotic study of systematic errors

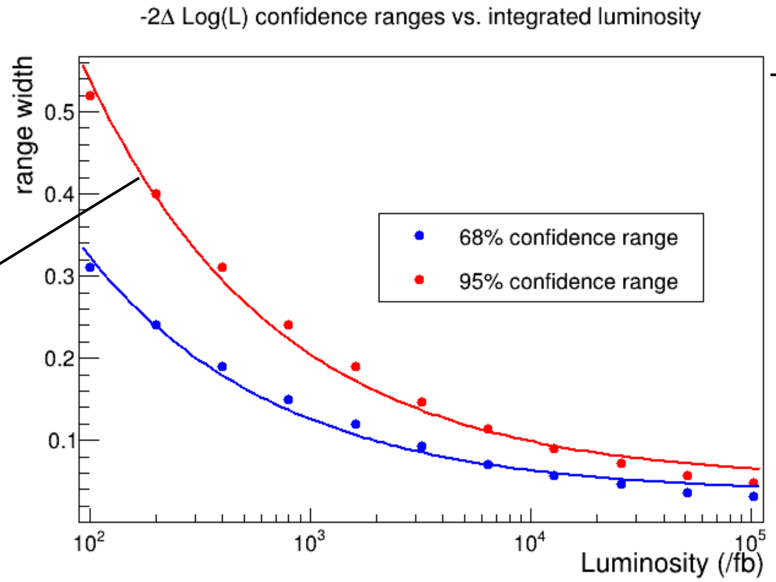
- Background systematic error: 5%
- Increasing the integrated luminosity L $\Longleftrightarrow$ Reducing the statistical errors, since $N = \sigma L$ and the relative error on N is $1/\sqrt{N}$ (N: expected event at the luminosity L, σ: cross section of the process)

When L is high enough, only systematic errors contribute to the confidence ranges

Variation of L with a logarithmic trend to study this asymptotic behaviour

- Plot:

p_{tl1}, EFT operator: Q_W



Fit function: $A + B/\sqrt{L}$

(similar plot for p_{tl2}, $\mathrm{Q_{HW}}$)

- Fit results (parameter A):

Wilson coefficient	c_W (p_{tl1})	c_{HW} (p_{tl2})
68% confidence range	0.034 ± 0.005	0.95 ± 0.09
95% confidence range	0.050 ± 0.006	1.32 ± 0.13

Future perspectives

- Applying the same methods on other EFT operators
- Multivariate analysis considering both of the operators at the same time
- Comparing the results with the Full Simulation
- Application to the data analysis