New measurements of $t\bar{t}$ spin correlations

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Zoomland

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Jesús M. Moreno

Instituto de Física Teórica UAM/CSIC, Madrid

New measurements of $t\bar{t}$ spin correlations

- Top quark lifetime is one order of magnitude smaller than the typical hadronization time scale and much shorter than the spin decorrelation time

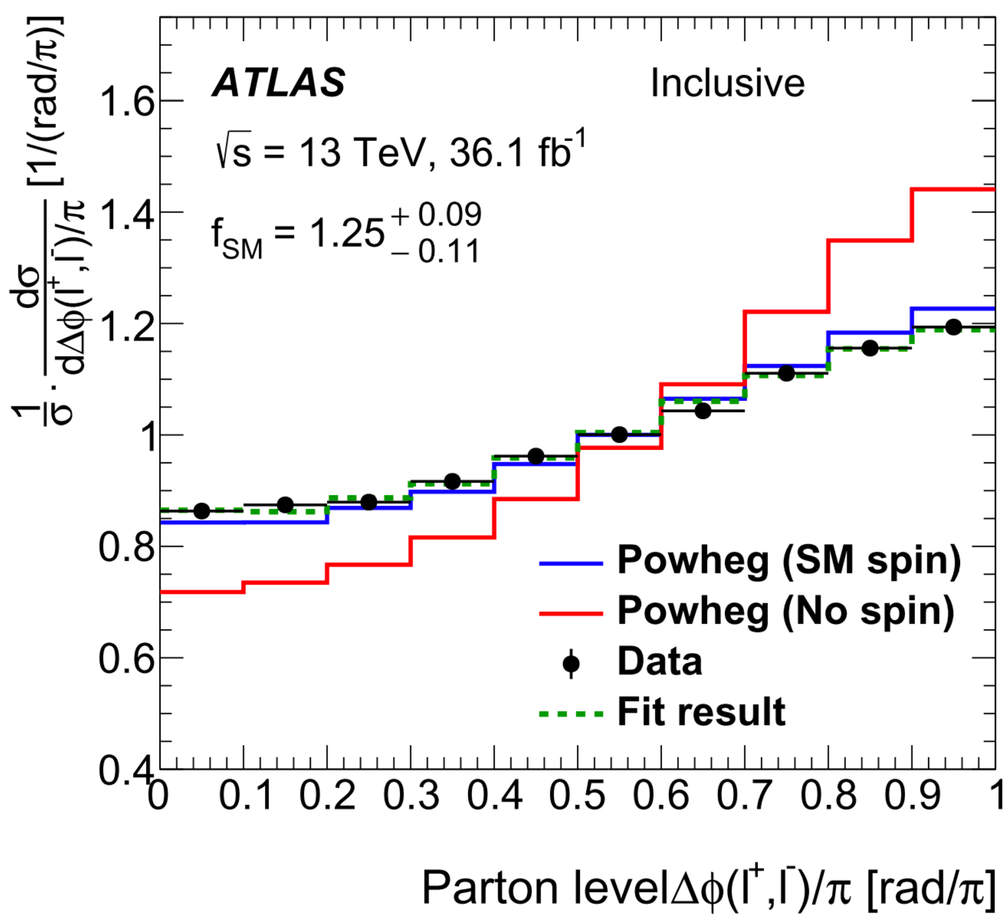
$\Longrightarrow$ top quark decays before the hadronization process can wipe out its spin information

- The top quark polarization can be extracted from the kinematical distributions of its decay products.

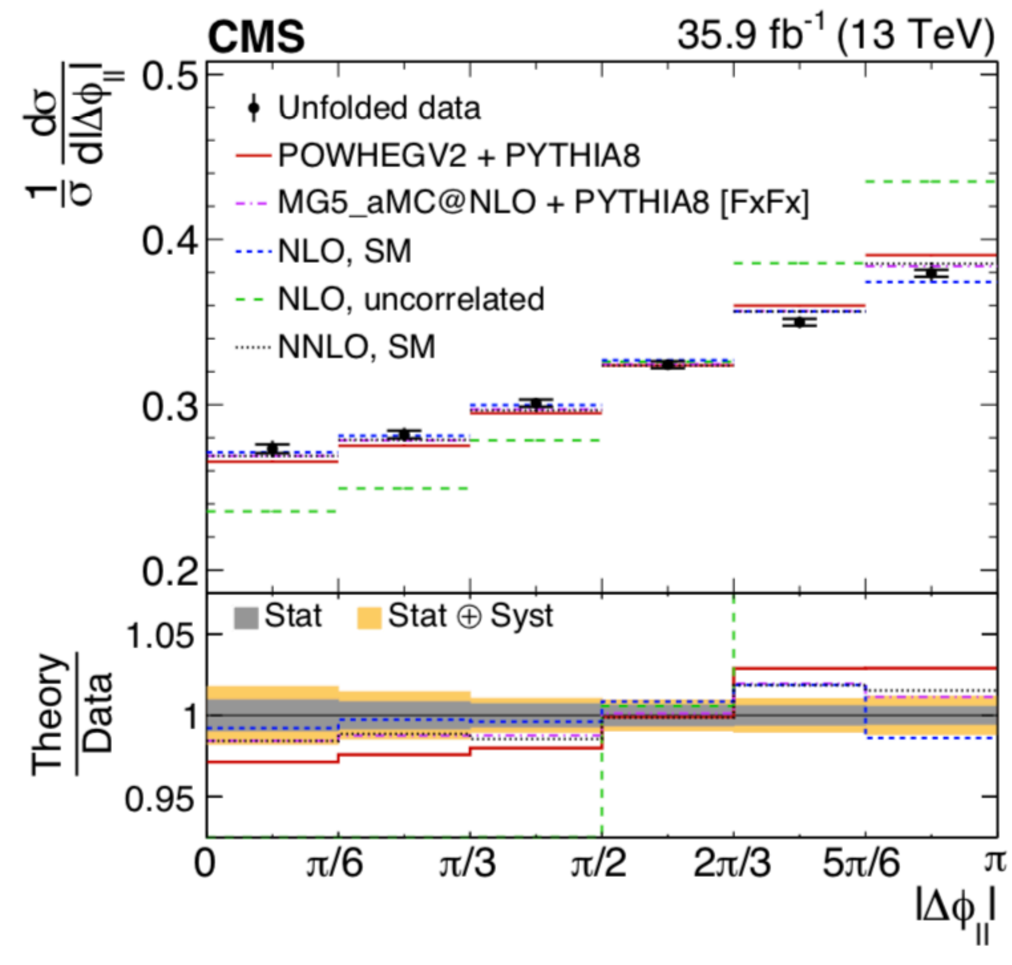
- ATLAS and CMS collaborations have measured the correlation of t and $\bar{t}$ in $t\bar{t}$ production at the LHC. The hypothesis of zero spin correlation has been excluded (> 6 standard deviations)

New measurements of $t\bar{t}$ spin correlations

Example: Dilepton azimuthal correlation in $t\bar{t} \rightarrow W^+b\, W^-\bar{b} \rightarrow l^+\nu b\, l^-\bar{\nu}\bar{b}$



ATLAS, Eur. Phys.J.C 80 (2020) 8, 754



CMS, Phys.Rev.D 100 (2019) 7, 072002

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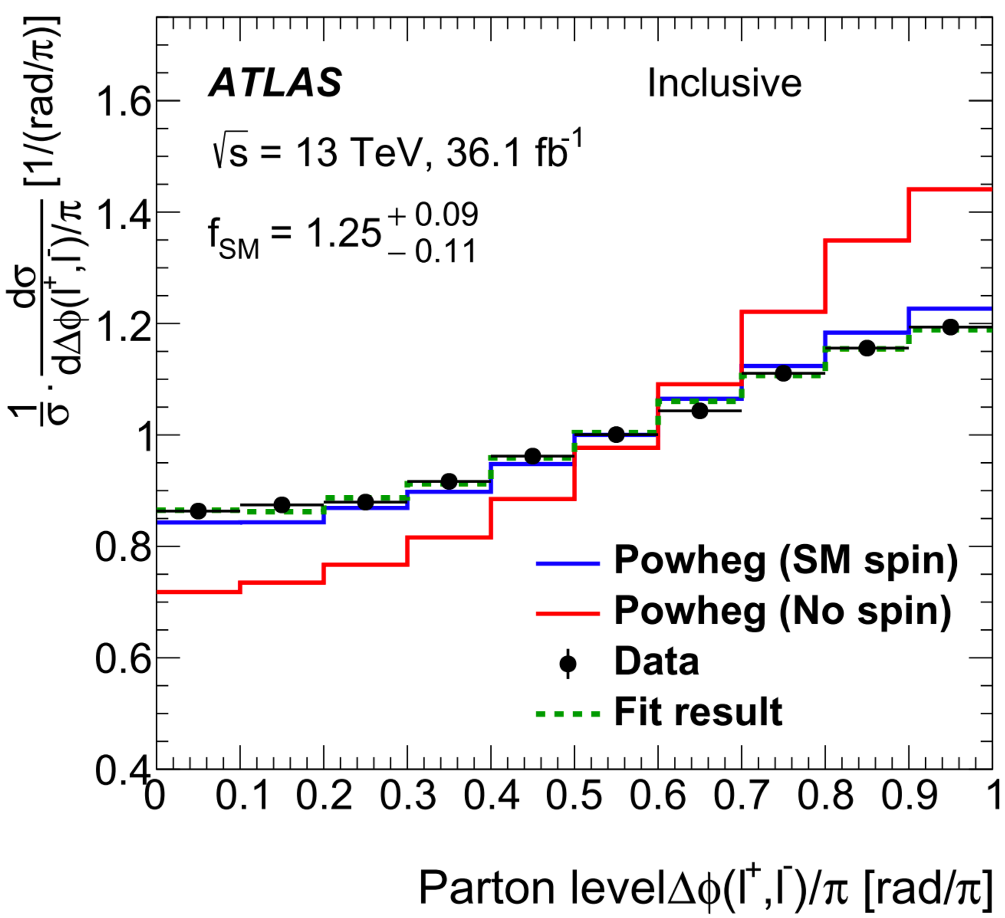

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Origin of the correlation?

G. Mahlon, S.J. Parke, Phys.Rev.D81:074024,2010

- At the LHC top quark pairs are mainly produced via gluon fusion: gg → tt
- They are unpolarized at leading order (LO)
- A small longitudinal polarization arises from electroweak corrections
- The spins of the top quarks and antiquarks are strongly correlated
- The configuration of spins depends on m_{tt}, the invariant mass of the tt pair with same (oposite) helicity pairs dominating at low (high) m_{tt}

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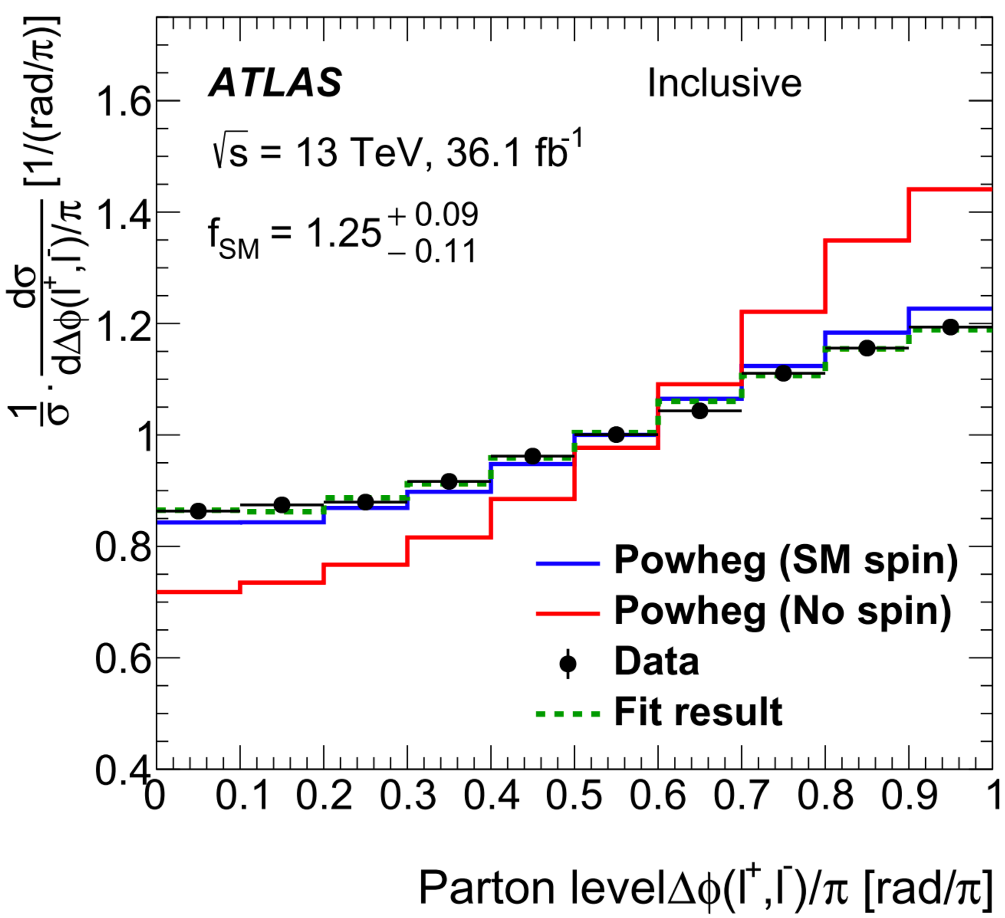

ATLAS measurements show a ~ 3.2σ deviation from the $\Delta(l^+, l^-)$ NLO predictions

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It is interesting:

- Perform other spin correlation measurements
- Explore different methods to extract the those correlations

New measurements of $t\bar{t}$ spin correlations

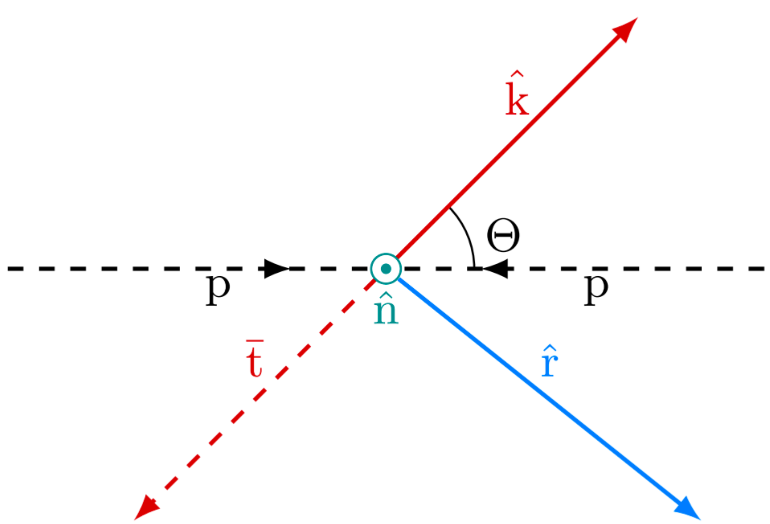
$\Delta(l^+, l^-)$ was evaluated in the LAB frame. It is useful to reconstruct the $t\bar{t}$ spin density matrix and compute their kinematic distributions in optimized frames.

$$|\mathcal{M}(q\bar{q}/gg \to t\bar{t} \to \ell^+\nu b\, \ell^-\bar{\nu}\bar{b})|^2 \propto \rho R \bar{\rho}.$$

Spin density matrix:

$$R \propto \tilde{A}\mathbb{1} \otimes \mathbb{1} + \tilde{B}_i^+ \sigma^i \otimes \mathbb{1} + \tilde{B}_i^- \mathbb{1} \otimes \sigma^i + \tilde{C}_{ij} \sigma^i \otimes \sigma^j$$

A convenient basis ($t\bar{t}$ CM frame)



$$\begin{aligned}
\tilde{B}_i^{\pm} &= b_k^{\pm}\hat{k}_i + b_r^{\pm}\hat{r}_i + b_n^{\pm}\hat{n}_i, \\
\tilde{C}_{ij} &= c_{kk}\hat{k}_i\hat{k}_j + c_{rr}\hat{r}_i\hat{r}_j + c_{nn}\hat{n}_i\hat{n}_j \\
&\quad + c_{rk}(\hat{r}_i\hat{k}_j + \hat{k}_i\hat{r}_j) + c_{nr}(\hat{n}_i\hat{r}_j + \hat{r}_i\hat{n}_j) + c_{kn}(\hat{k}_i\hat{n}_j + \hat{n}_i\hat{k}_j) \\
&\quad + c_n(\hat{r}_i\hat{k}_j - \hat{k}_i\hat{r}_j) + c_k(\hat{n}_i\hat{r}_j - \hat{r}_i\hat{n}_j) + c_r(\hat{k}_i\hat{n}_j - \hat{n}_i\hat{k}_j).
\end{aligned}$$

W. Bernreuther, D. Heisler and Zong-Guo Sib, 2015

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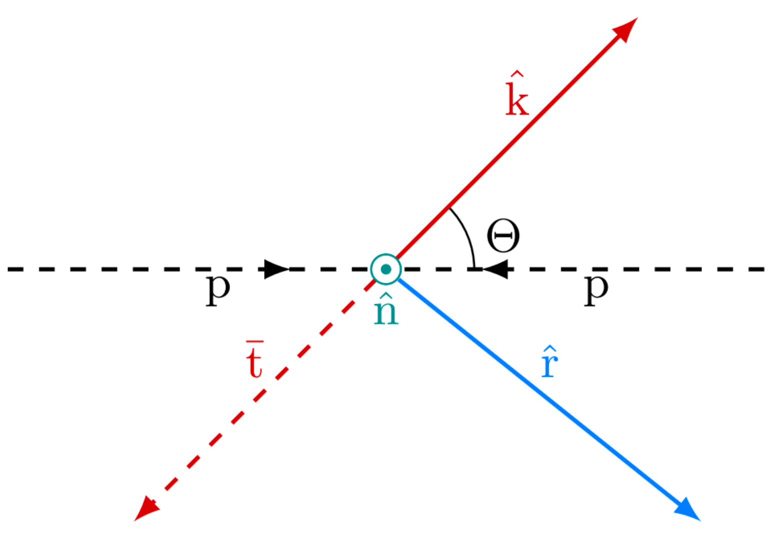


Orthogonal Polarization

Spin correlations

$$\tilde{B}_i^{\pm} = b_k^{\pm}\hat{k}_i + b_r^{\pm}\hat{r}_i + b_n^{\pm}\hat{n}_i,$$
$$\tilde{C}_{ij} = c_{kk}\hat{k}_i\hat{k}_j + c_{rr}\hat{r}_i\hat{r}_j + c_{nn}\hat{n}_i\hat{n}_j + c_{rk}(\hat{r}_i\hat{k}_j + \hat{k}_i\hat{r}_j) + c_{nr}(\hat{n}_i\hat{r}_j + \hat{r}_i\hat{n}_j) + c_{kn}(\hat{k}_i\hat{n}_j + \hat{n}_i\hat{k}_j) + c_n(\hat{r}_i\hat{k}_j - \hat{k}_i\hat{r}_j) + c_k(\hat{n}_i\hat{r}_j - \hat{r}_i\hat{n}_j) + c_r(\hat{k}_i\hat{n}_j - \hat{n}_i\hat{k}_j).$$

Asymmetries

W. Bernreuther, D. Heisler and Zong-Guo Sib, 2015

Extracting the spin correlations from angular distributions

Polarizations and spin correlations shape the angular distributions.
We will define the following angles:

$$\cos\theta_+ = \hat{\ell}_+ \cdot \hat{\mathbf{a}}$$

$$\cos\theta_- = \hat{\ell}_- \cdot \hat{\mathbf{b}}$$

θ are the lepton azimuthal angles respect to the chosen polarization axes, ($\hat{a}, \hat{b}$)

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}_1' \cdot \hat{\ell}_+ + \mathbf{B}_2' \cdot \hat{\ell}_- - \hat{\ell}_+ \cdot C' \cdot \hat{\ell}_-\right),$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 + B_1 \cos\theta_+ + B_2 \cos\theta_- - C \cos\theta_+ \cos\theta_-\right)$$

W. Bernreuther, D. Heisler and Zong-Guo Sib, 2015

Extracting the spin correlations from angular distributions

Table 3: Measured coefficients and asymmetries and their total uncertainties. Predicted values from simulation are quoted with a combination of statistical and scale uncertainties, while the NLO calculated values are quoted with their scale uncertainties [3, 4]. The NNLO QCD prediction for $A_{|\Delta\phi_{\ell\ell}|}$, with scale uncertainties, is $0.115\,^{+0.005}_{-0.001}$ [69].

CMS

Coefficient	Measured	POWHEGv2	MG5_aMC@NLO	NLO calculation
B_1^k	0.005 ± 0.023	$0.004\,^{+0.001}_{-0.001}$	$0.000\,^{+0.001}_{-0.001}$	$4.0\,^{+1.7}_{-1.2} \times 10^{-3}$
B_2^k	0.007 ± 0.023	$0.006\,^{+0.001}_{-0.001}$	$-0.002\,^{+0.001}_{-0.001}$	$4.0\,^{+1.7}_{-1.2} \times 10^{-3}$
B_1^r	-0.023 ± 0.017	$0.002\,^{+0.001}_{-0.001}$	$0.002\,^{+0.001}_{-0.001}$	$1.6\,^{+1.2}_{-0.9} \times 10^{-3}$
B_2^r	-0.010 ± 0.020	$0.003\,^{+0.001}_{-0.001}$	$0.000\,^{+0.001}_{-0.001}$	$1.6\,^{+1.2}_{-0.9} \times 10^{-3}$
B_1^n	0.006 ± 0.013	$-0.001\,^{+0.001}_{-0.001}$	$0.001\,^{+0.001}_{-0.001}$	$5.7\,^{+0.5}_{-0.4} \times 10^{-3}$
B_2^n	0.017 ± 0.013	$-0.001\,^{+0.001}_{-0.001}$	$0.000\,^{+0.001}_{-0.001}$	$5.7\,^{+0.5}_{-0.4} \times 10^{-3}$
B_1^{k*}	-0.016 ± 0.018	$-0.001\,^{+0.001}_{-0.001}$	$0.000\,^{+0.001}_{-0.001}$	$<10^{-3}$
B_2^{k*}	0.007 ± 0.019	$0.001\,^{+0.001}_{-0.001}$	$0.003\,^{+0.002}_{-0.001}$	$<10^{-3}$
B_1^{r*}	0.001 ± 0.017	$0.000\,^{+0.001}_{-0.001}$	$0.000\,^{+0.001}_{-0.001}$	$<10^{-3}$
B_2^{r*}	0.010 ± 0.017	$0.001\,^{+0.001}_{-0.001}$	$0.001\,^{+0.001}_{-0.001}$	$<10^{-3}$
C_{kk}	0.300 ± 0.038	$0.314\,^{+0.005}_{-0.004}$	$0.325\,^{+0.011}_{-0.006}$	$0.331\,^{+0.002}_{-0.002}$
C_{rr}	0.081 ± 0.032	$0.048\,^{+0.007}_{-0.006}$	$0.052\,^{+0.007}_{-0.005}$	$0.071\,^{+0.008}_{-0.006}$
C_{nn}	0.329 ± 0.020	$0.317\,^{+0.001}_{-0.001}$	$0.324\,^{+0.002}_{-0.002}$	$0.326\,^{+0.002}_{-0.002}$
$C_{rk} + C_{kr}$	-0.193 ± 0.064	$-0.201\,^{+0.004}_{-0.003}$	$-0.198\,^{+0.004}_{-0.005}$	$-0.206\,^{+0.002}_{-0.002}$
$C_{rk} - C_{kr}$	0.057 ± 0.046	$-0.001\,^{+0.002}_{-0.002}$	$0.004\,^{+0.002}_{-0.002}$	0
$C_{nr} + C_{rn}$	-0.004 ± 0.037	$-0.003\,^{+0.002}_{-0.002}$	$0.001\,^{+0.002}_{-0.002}$	$1.06\,^{+0.01}_{-0.01} \times 10^{-3}$
$C_{nr} - C_{rn}$	-0.001 ± 0.038	$0.002\,^{+0.002}_{-0.002}$	$0.001\,^{+0.003}_{-0.002}$	0
$C_{nk} + C_{kn}$	-0.043 ± 0.041	$-0.002\,^{+0.002}_{-0.002}$	$0.003\,^{+0.002}_{-0.002}$	$2.15\,^{+0.04}_{-0.07} \times 10^{-3}$
$C_{nk} - C_{kn}$	0.040 ± 0.029	$-0.001\,^{+0.002}_{-0.002}$	$-0.001\,^{+0.002}_{-0.002}$	0
D	-0.237 ± 0.011	$-0.226\,^{+0.003}_{-0.004}$	$-0.233\,^{+0.004}_{-0.006}$	$-0.243\,^{+0.003}_{-0.003}$
$A_{\cos\varphi}^{\mathrm{lab}}$	0.167 ± 0.010	$0.161\,^{+0.002}_{-0.002}$	$0.174\,^{+0.004}_{-0.003}$	$0.181\,^{+0.004}_{-0.003}$
$A_{\|\Delta\phi_{\ell\ell}\|}$	0.103 ± 0.008	$0.125\,^{+0.004}_{-0.005}$	$0.115\,^{+0.003}_{-0.005}$	$0.108\,^{+0.009}_{-0.012}$

Polarization Vectors

Largest spin correlation (spin polarization defined along the same axes)

CMS, Phys.Rev.D 100 (2019) 7, 072002

A new method to extract the $t\bar{t}$ spin correlation

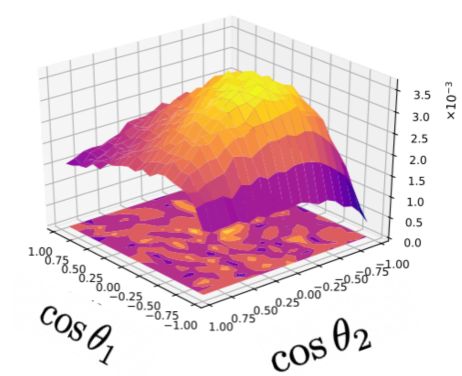
In collaboration with J.A. Aguilar-Saavedra, M. C.N. Fiolhais, P. Martin Ramiro, A. Onofre

IDEA:

- Choose the spin correlation coefficient that we want to extract (e.g. c_{kk}, c_{rr})
  That fixes the reference axes for the top (antitop) quark polarization (e.g. $\hat{k}\hat{k}$, $\hat{r}\hat{r}$)
  and for the evaluation of the lepton azimuthal angles (θ_1, θ_2)

- Generate $t\bar{t}$ simples along the <u>four possible spin</u> projections ($++$, $+-$, $-+$, $--$)
  For $\hat{k}\hat{k}$, they would correspond to (LL, LR, RL, RR) . This is done (@LO) using PROTOS

- Make them decay and obtain the <u>four templates</u> for the bidimensional angular distributions (and evaluate eficiencies)



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2}\Bigg|_{++,+-,-+,--}$$

- Reconstruct $t\bar{t}$ data (in our case, generated by MadGraph, @LO) and evaluate the data ($\cos\theta_1$, $\cos\theta_2$) distribution

- Use the <u>four templates</u> to extract the <u>four coefficients</u>
  $\Rightarrow$ evaluate the spin correlation $\quad c \equiv a_{++} + a_{--} - a_{+-} - a_{-+}$

$t\bar{t}$ reconstruction

Reconstruction

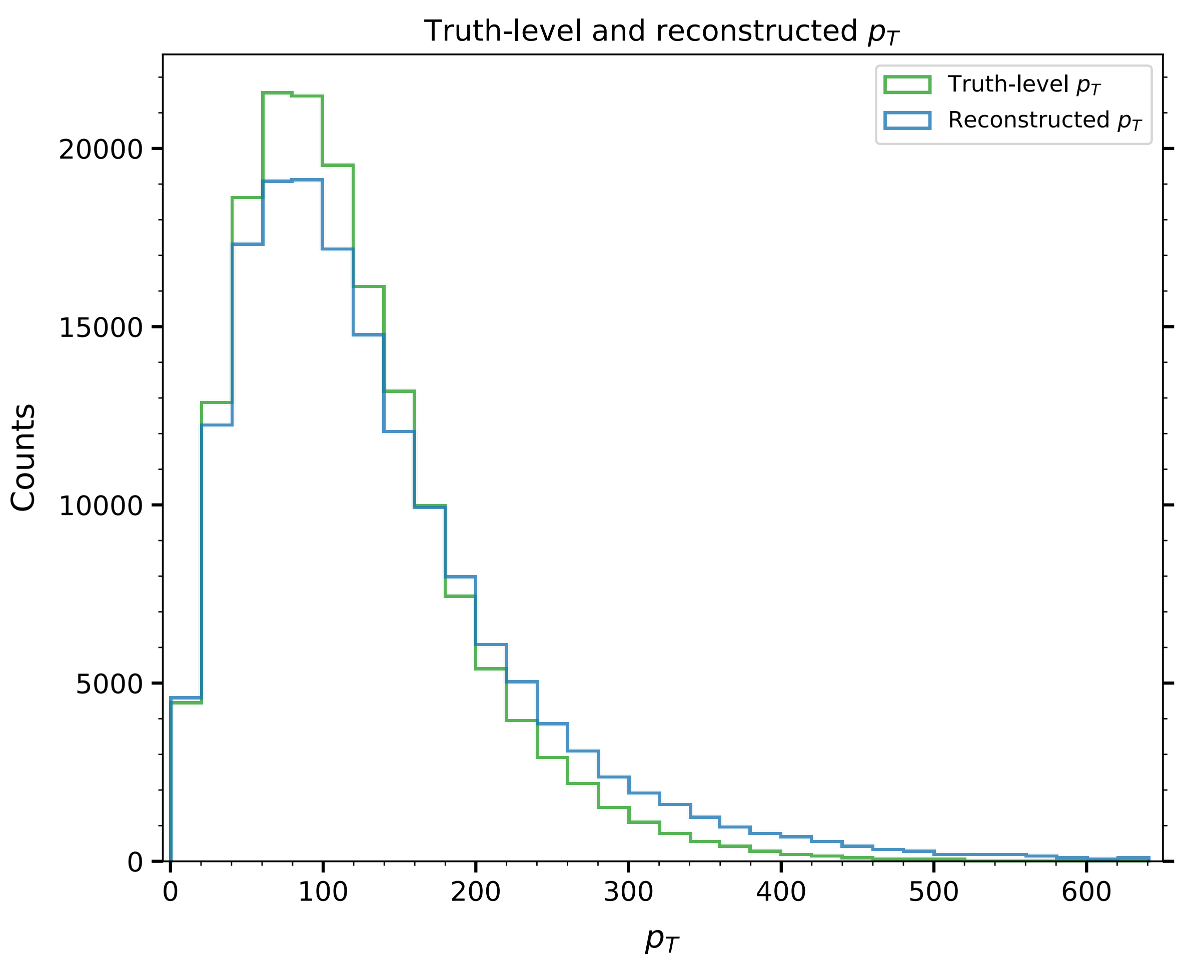
- 6 unknowns: $\vec{p}_\nu, \vec{p}_{\bar{\nu}}$
- 2 equations: $\{P^x, P^y\}=0$

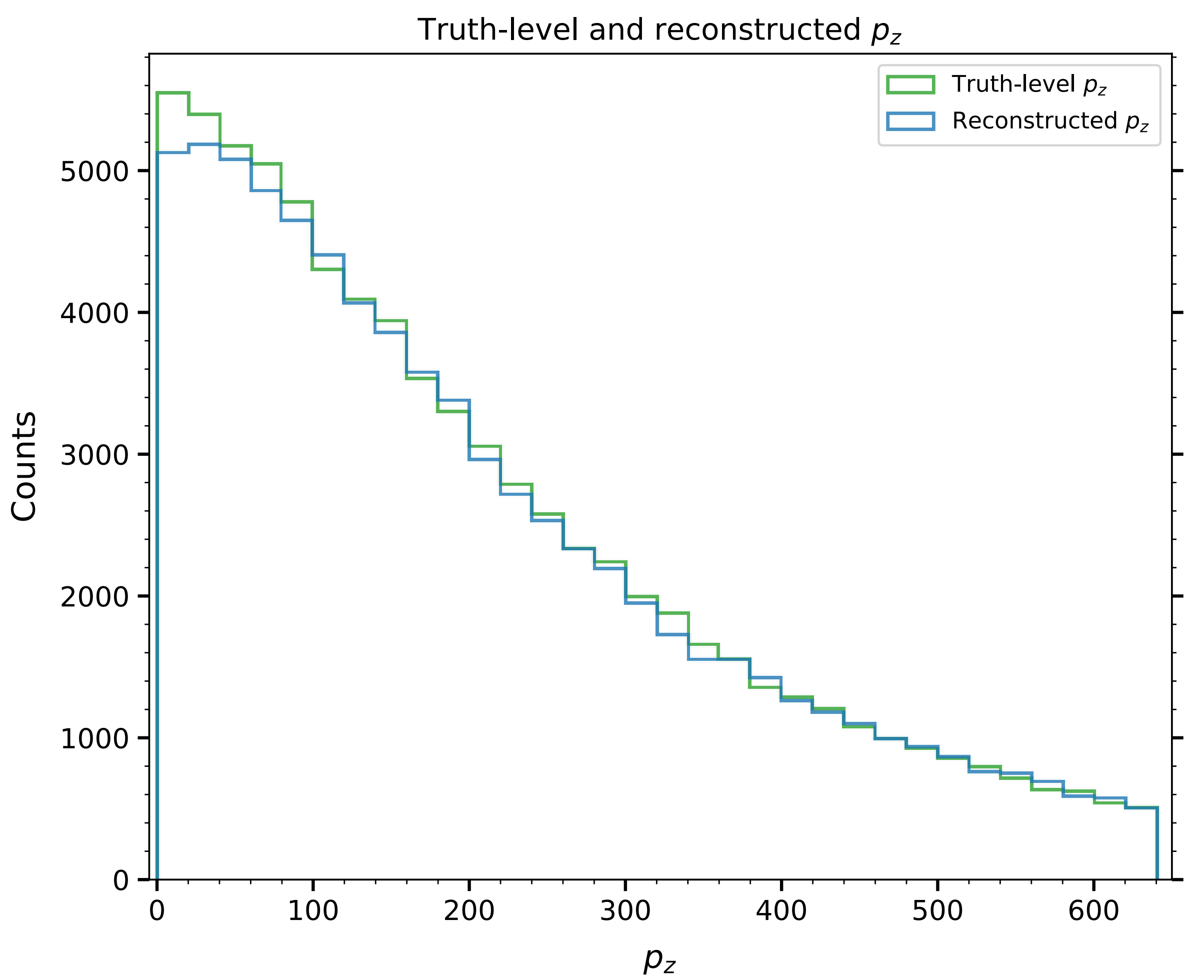
} 4 more inputs are needed

- W bosons assumed on shell

- We scan on neutrino pseudorapidities $(\eta, \bar{\eta})$ for several m_t values (similar to the Neutrino Weighting Method)
- We infer $\not{E}_T$ the value and compare to the observed value.
- A weight is introduced in order to quantify this agreement, and the solution with the largest weight is selected.

$t\bar{t}$ reconstruction





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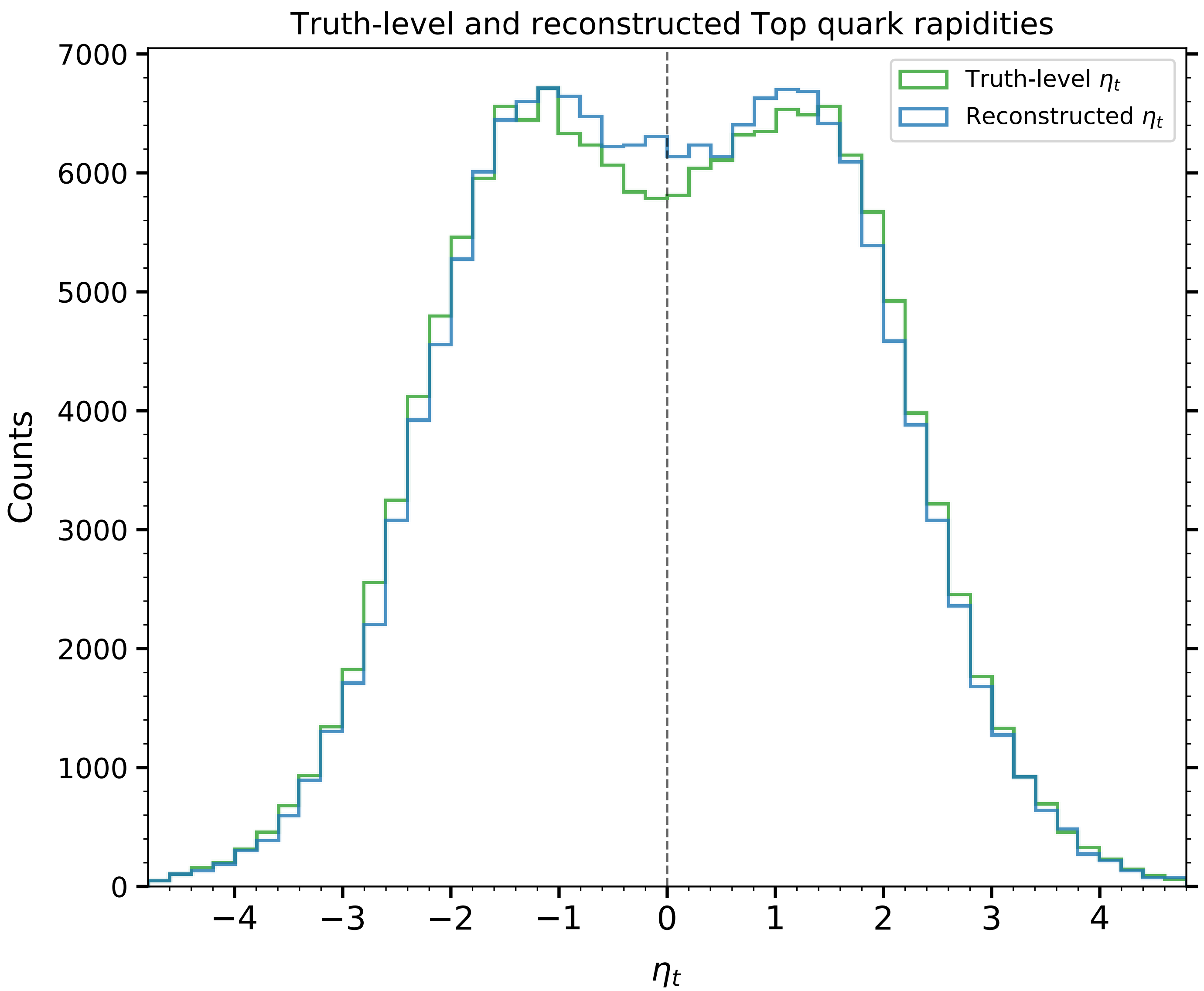

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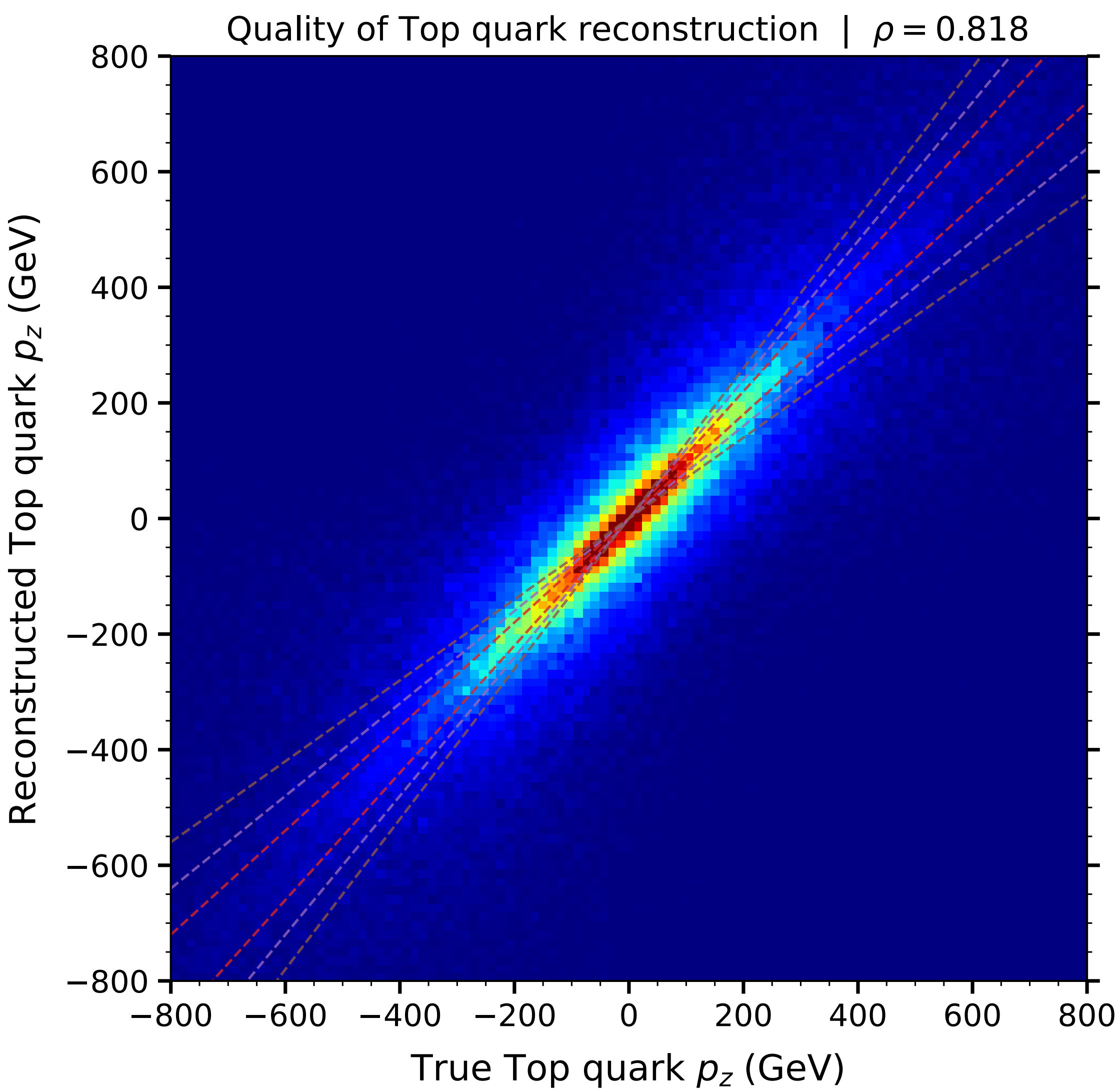
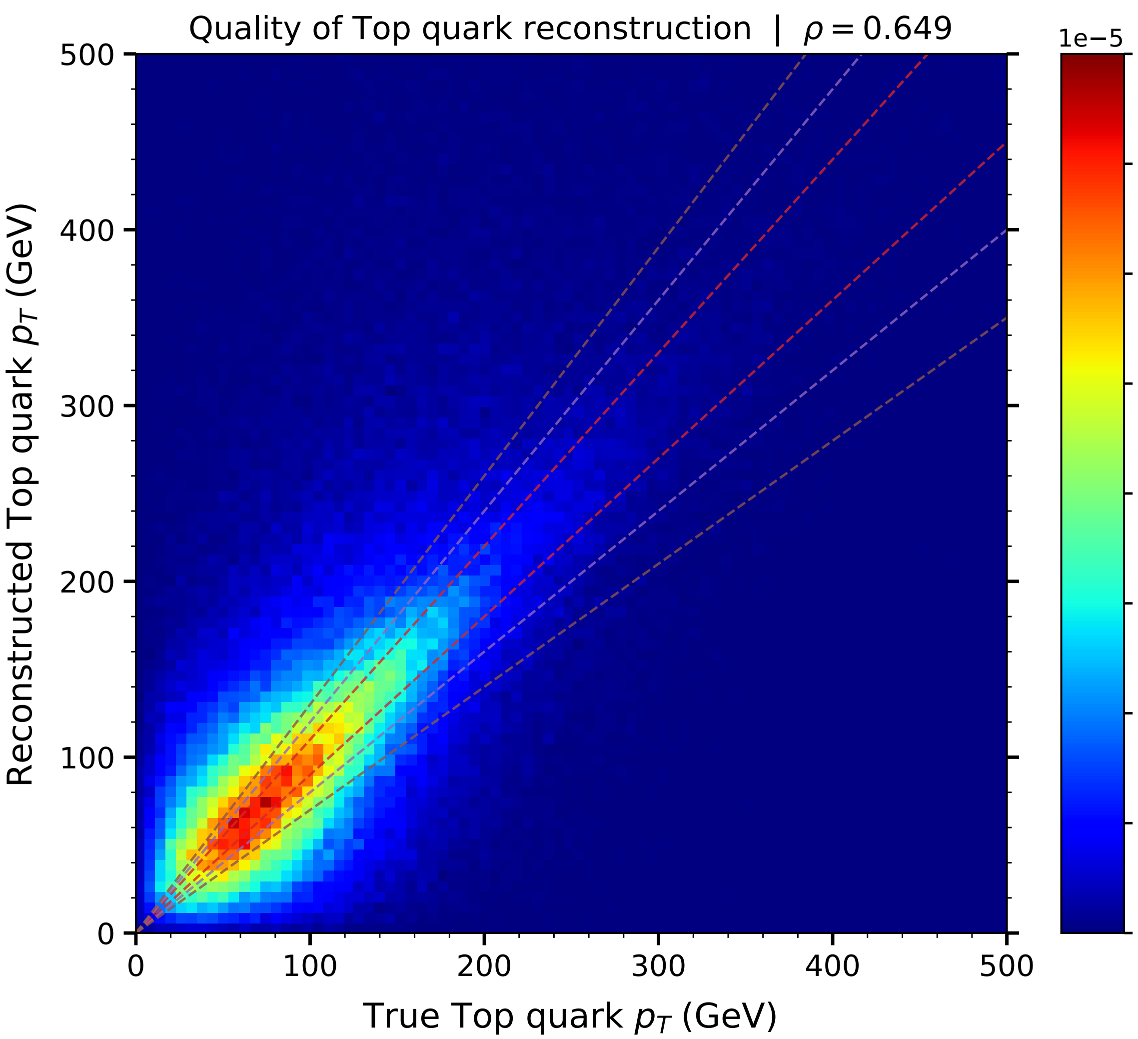
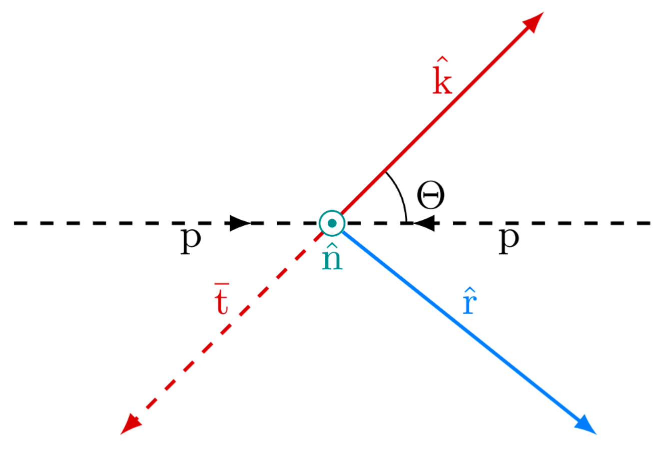




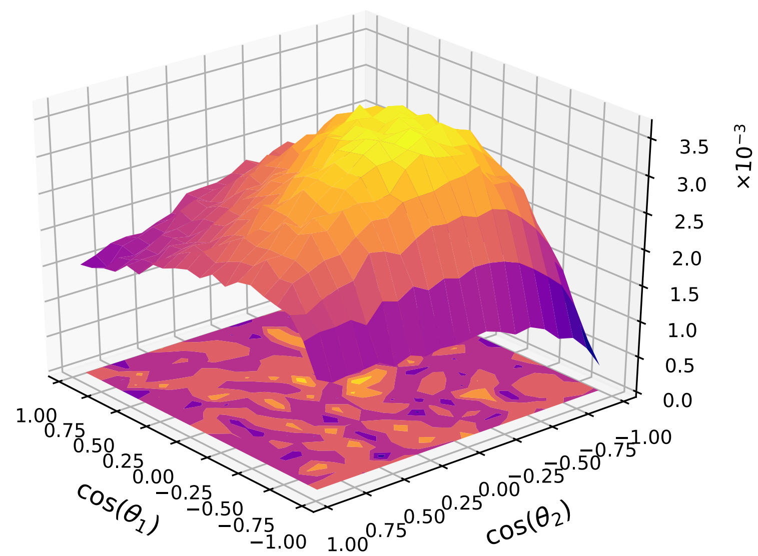
Standard Model : Extracting C_{kk}

C_{kk}



From the reconstructing $t\bar{t}$ data (SM, MadGraph, @LO)

We get the $(\cos\theta_1, \cos\theta_2)$ distribution



	a_{LL}	a_{RR}	a_{LR}	a_{RL}
SM Prediction	0,337	0,337	0,163	0,163
Fit	0,331 ± 0,006	0,341 ± 0,006	0,166 ± 0,006	0,164 ± 0,006

C_{KK}
0,347
0,341 ± 0,022

$c_{kk} = a_{LL} + a_{RR} - a_{LR} - a_{RL}$

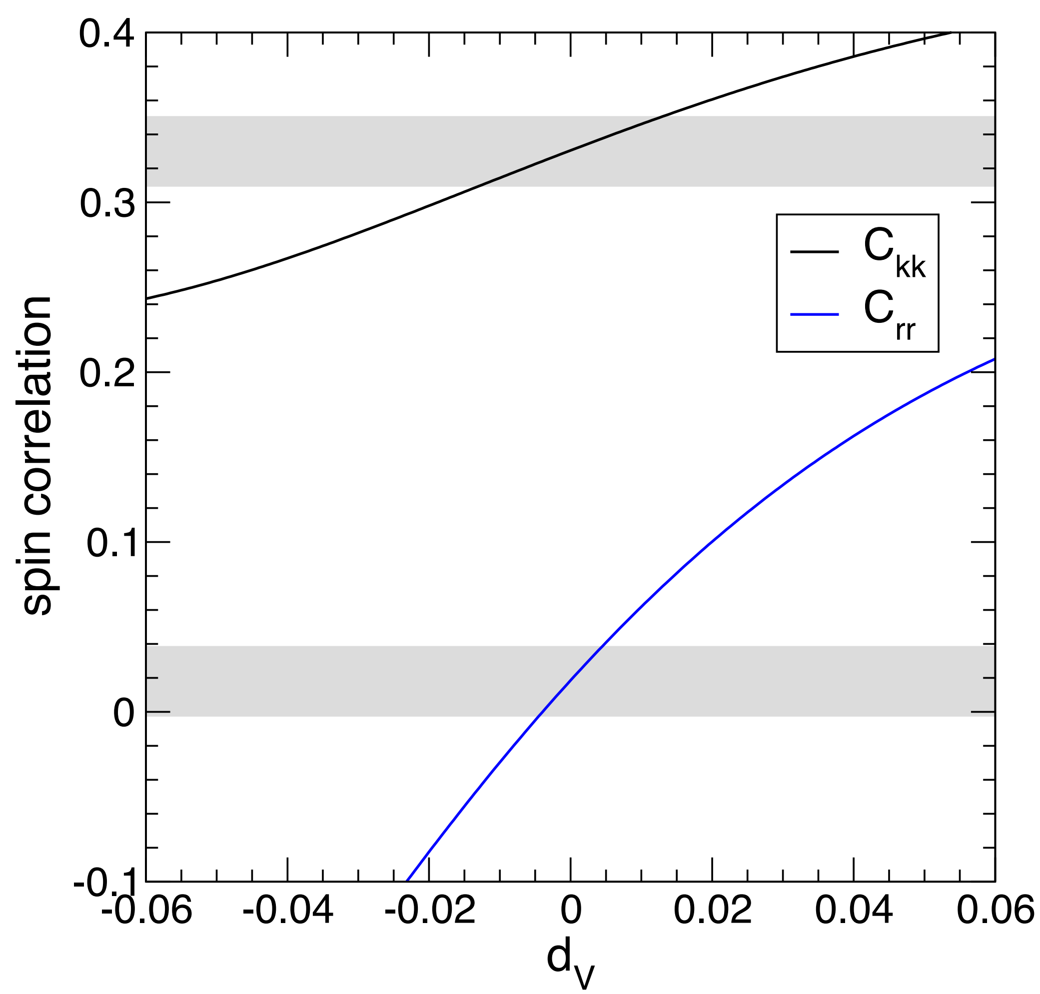
C_{rr}

Work in progress!

New Physics effects on $t\bar{t}$ spin correlation

EXAMPLE : Chromomagnetic dipole moment (CMDM)

$$\mathcal{L}_{gt\bar{t}} = -g_s \bar{t}\frac{\lambda^a}{2}\gamma^\mu t G^a_\mu - g_s \bar{t}\frac{\lambda^a}{2}\frac{i\sigma^{\mu\nu}}{m_t}(d^g_V + i d^g_A \gamma_5) t G^a_{\mu\nu},$$



SM Value: $-5.6\ 10^{-2} = -6.4\ 10^{-2}$ (EW) + $7.5\ 10^{-3}$ (QCD)

ATLAS: $-6.4\ 10^{-2} < d_V < 7.5\ 10^{-3}$

Standard Model + d_V : Extracting C_{kk}

C_{kk}

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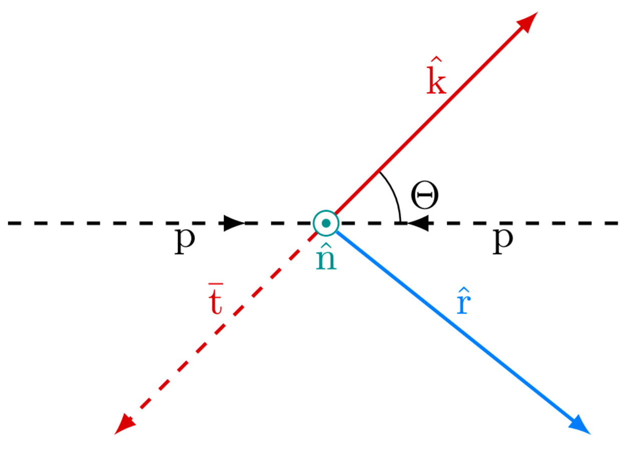
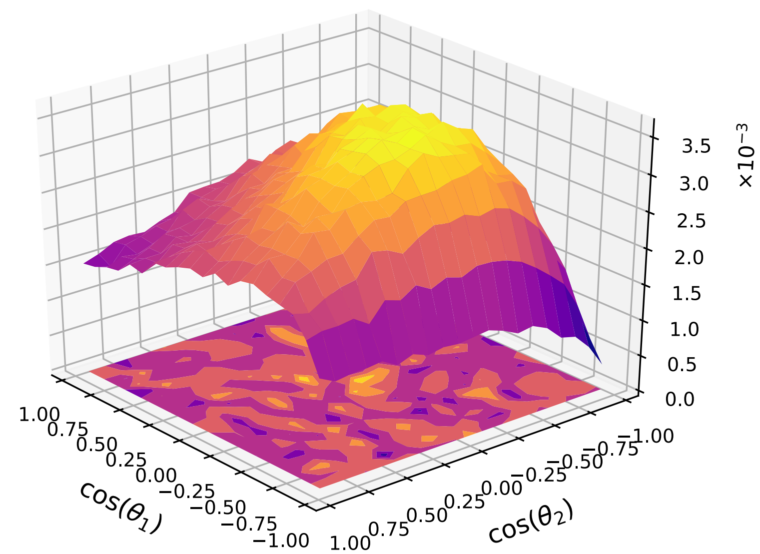
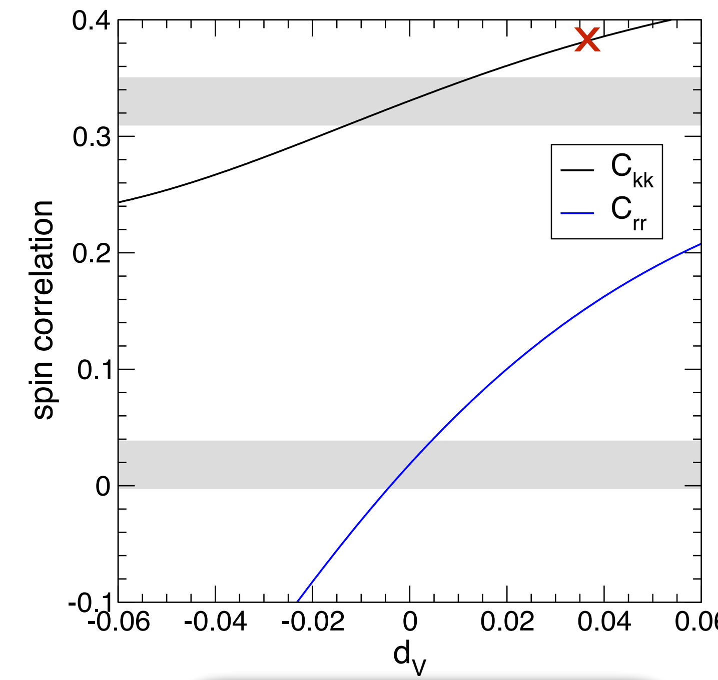
We get the $(\cos\theta_1, \cos\theta_2)$ distribution

Closure Test



dV = 0.036





	a_{LL}	a_{RR}	a_{LR}	a_{RL}
SM	0,337	0,337	0,163	0,163
SM + dV(0,036)	0,348	0,348	0,152	0,152
Fit	0,348 ± 0,006	0,347 ± 0,006	0,166 ± 0,006	0,139 ± 0,006

C_{KK}
0,347
0,392
0,391 ± 0,023

$C_{kk} = a_{LL} + a_{RR} - a_{LR} - a_{RL}$

C_{rr}

Work in progress!

Conclusions

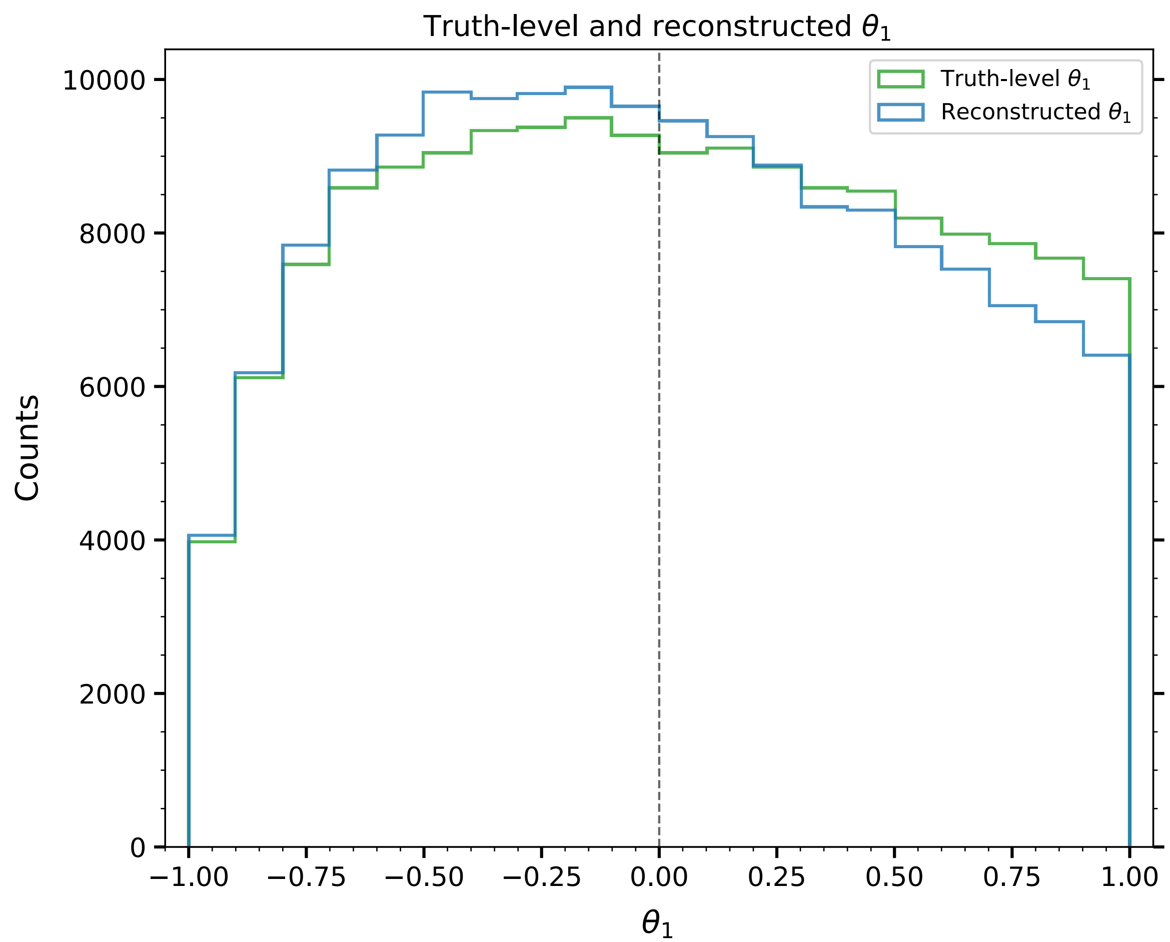
- We have proposed a new method to measure the $t\bar{t}$ spin correlations at the LHC

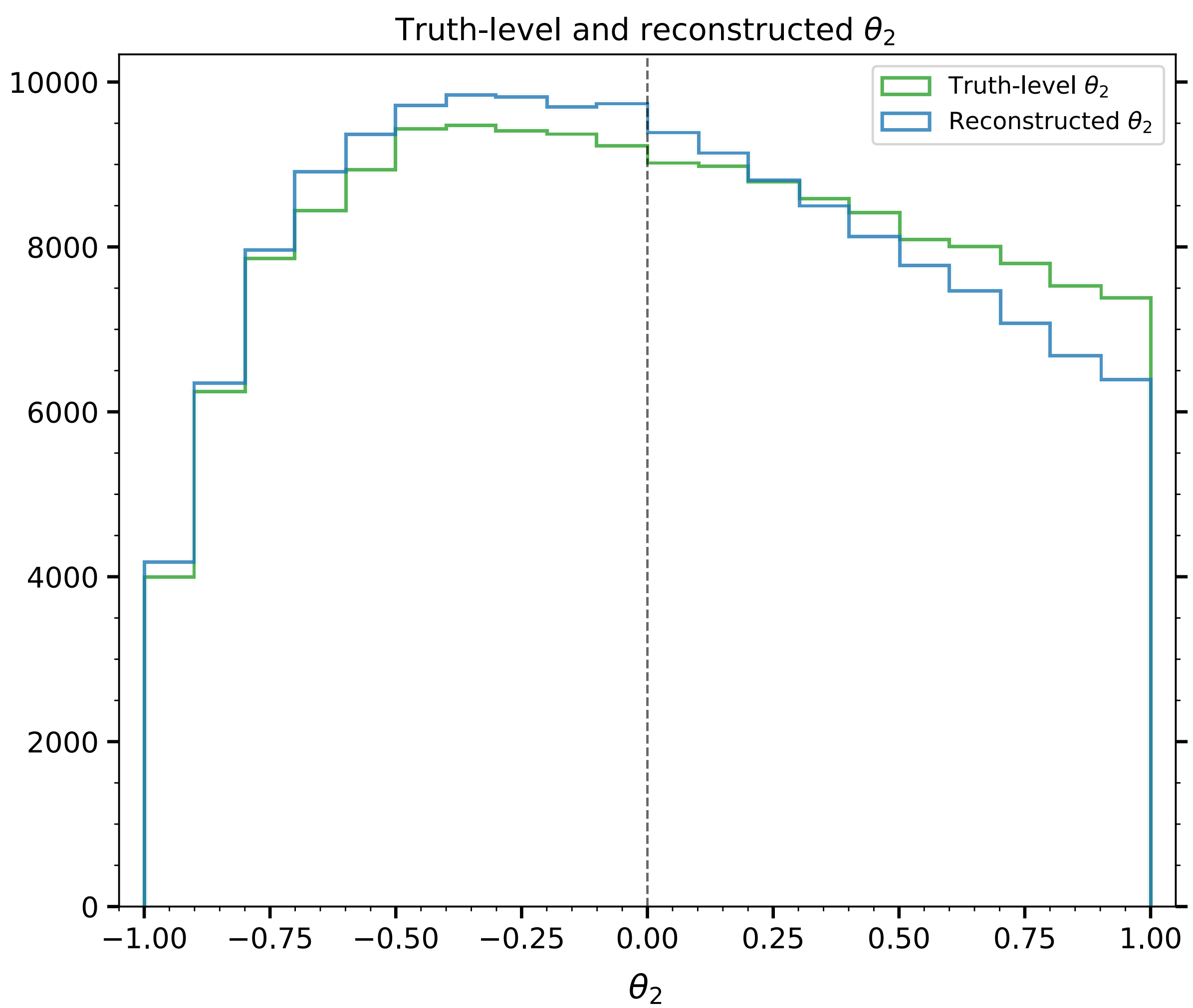
- It could be useful to explore / analyze the $\Delta(l^+, l^-)$ deviation found by ATLAS

- The method uses bidimenisonal templates to extract the $t\bar{t}$ spin correlations at the LHC, providing an alternative to unfolding methods

- We have tested it on a sample of Monte Carlo SM generated events, extracting C_{kk} . Also we have shown the sensitivity to New Physics (e.g. Top Chromomagnetic Dipole Moment) that could modify the spin correlations of $t\bar{t}$

$t\bar{t}$ reconstruction





cos(Theta_1), SM, eje K (top)