Spin Physics with Top Quarks @ the LHC

A. Onofre
(antonio.onofre@cern.ch)

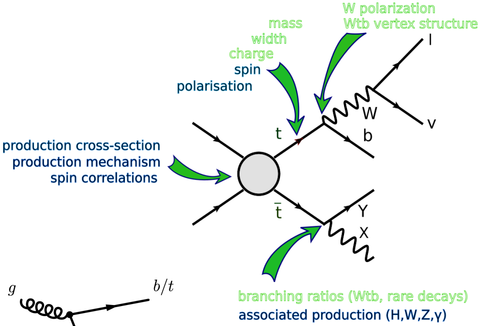
Course on Physics at the LHC, 2nd April 2024, Lisbon

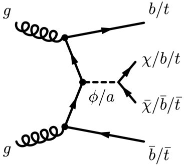
CERN/FIS-PAR/0029/2019 CERN/FIS-PAR/0037/2021

The top-quark and Higgs boson (ϕ) have a quite rich phenomenology. ☞ Understanding the couplings and the connection to BSM, DM etc., is quite important @ LHC

☞ All about t-quark Spin
$\oplus$ Spin Correlations !

- Introduction
- 1D distributions and
  $t\bar{t}$ Spin Correlations
- 2D distributions and
  new method to assess
  $t\bar{t}$ spin correlations, Interferences..
  [Eur.Phys.J.C 82 (2022) 2]
- The $t\bar{t}\phi$ DM searches
  via simplified models
  low to high mass



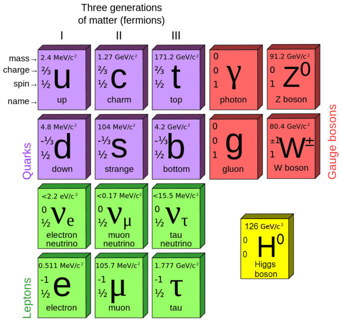


The top quark

The top quark

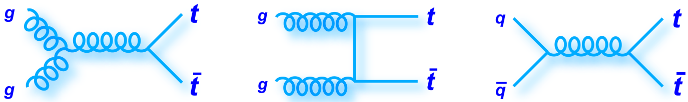
- **The top quark was discovered by CDF and D0 in 1995, almost 30 years ago**
  PRL**74** 2626-2631 (1995);
  PRL**74** 2632-2637 (1995).

- **Properties:**
  - belongs to 3^{rd} generation of quarks
  - the top quark is the weak-isospin partner of the *b*-quark
  - spin = $1/2$
  - charge = $+2/3\ |e|$
  - heaviest known fundamental fermion
    ($m_t = 173.34 \pm 0.76$ GeV, World comb.(2014), arXiv:1403.4427)
  - dominant decay mode: $t \to bW$
    $BR(t \to sW) \leq$0.18%, $BR(t \to dW) \leq$0.02%
  - $\Gamma_t^{SM} = 1.42$ GeV (including m_b, m_W, α_s, EW corrections)
  - τ_t=($3.29^{+0.90}_{-0.63}$) $\times 10^{-25}$s (D0, PRD **85** 091104, 2012)
    $\ll \Lambda^{-1}_{QCD} \sim$(100 MeV)$^{-1}$ $\sim 10^{-23}$s (hadronization time)
    $\Rightarrow$ top decays before hadronization takes place



$t\bar{t}$ production at the LHC

- Production at the LHC:

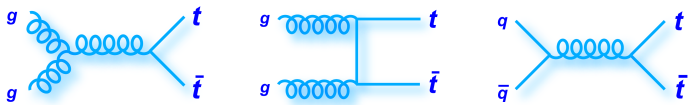


$\sigma(t\bar{t})$=177.3$\pm$9.9$^{+4.6}_{-6.0}$ pb @ 7 TeV, $\sigma(t\bar{t})$=252.9$\pm$11.7$^{+6.4}_{-8.6}$ pb @ 8 TeV,

$\sigma(t\bar{t})$=832$^{+40}_{-46}$ pb @ 13 TeV, $\sigma(t\bar{t})$=924$^{+32}_{-40}$ pb @ 13.6 TeV

NNLO+NNLL, m_t =172.5 GeV PLB **710** 612 (2012), PRL **109** 132001(2012), JHEP **1212** 054(2012), JHEP **1301** 080(2013), PRL**110** 252004 (2013).

- Production at the LHC:

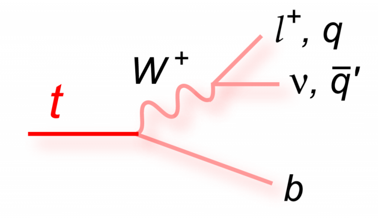


$\sigma(t\bar{t})$=177.3$\pm$9.9$^{+4.6}_{-6.0}$ pb @ 7 TeV, $\sigma(t\bar{t})$=252.9$\pm$11.7$^{+6.4}_{-8.6}$ pb @ 8 TeV,

$\sigma(t\bar{t})$=832$^{+40}_{-46}$ pb @ 13 TeV, $\sigma(t\bar{t})$=924$^{+32}_{-40}$ pb @ 13.6 TeV

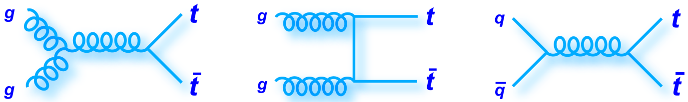
NNLO+NNLL, m_t =172.5 GeV PLB **710** 612 (2012), PRL **109** 132001(2012), JHEP **1212** 054(2012), JHEP **1301** 080(2013), PRL**110** 252004 (2013).

***t* quark decays**



$t\bar{t}$ production at the LHC

- Production at the LHC:

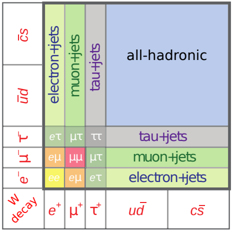


$\sigma(t\bar{t})$=177.3$\pm$9.9$^{+4.6}_{-6.0}$ pb @ 7 TeV, $\sigma(t\bar{t})$=252.9$\pm$11.7$^{+6.4}_{-8.6}$ pb @ 8 TeV,

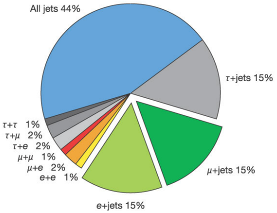
$\sigma(t\bar{t})$=832$^{+40}_{-46}$ pb @ 13 TeV, $\sigma(t\bar{t})$=924$^{+32}_{-40}$ pb @ 13.6 TeV

NNLO+NNLL, m_t =172.5 GeV PLB **710** 612 (2012), PRL **109** 132001(2012), JHEP **1212** 054(2012), JHEP **1301** 080(2013), PRL**110** 252004 (2013).

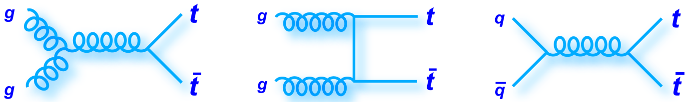
Top pair decay channels



Top pair branching fractions



- Production at the LHC:

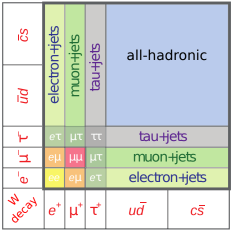


$\sigma(t\bar{t})$=177.3$\pm$9.9$^{+4.6}_{-6.0}$ pb @ 7 TeV, $\sigma(t\bar{t})$=252.9$\pm$11.7$^{+6.4}_{-8.6}$ pb @ 8 TeV,

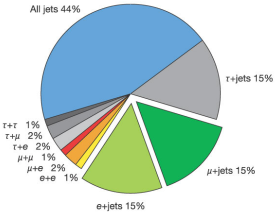
$\sigma(t\bar{t})$=832$^{+40}_{-46}$ pb @ 13 TeV, $\sigma(t\bar{t})$=924$^{+32}_{-40}$ pb @ 13.6 TeV

NNLO+NNLL, m_t =172.5 GeV PLB **710** 612 (2012), PRL **109** 132001(2012), JHEP **1212** 054(2012), JHEP **1301** 080(2013), PRL**110** 252004 (2013).

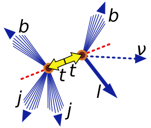
Top pair decay channels



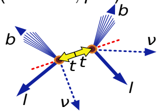
Top pair branching fractions



$\Longrightarrow$ Lepton+jets ($\sim$ 30%): ($\ell = e^{\pm}, \mu^{\pm}$)



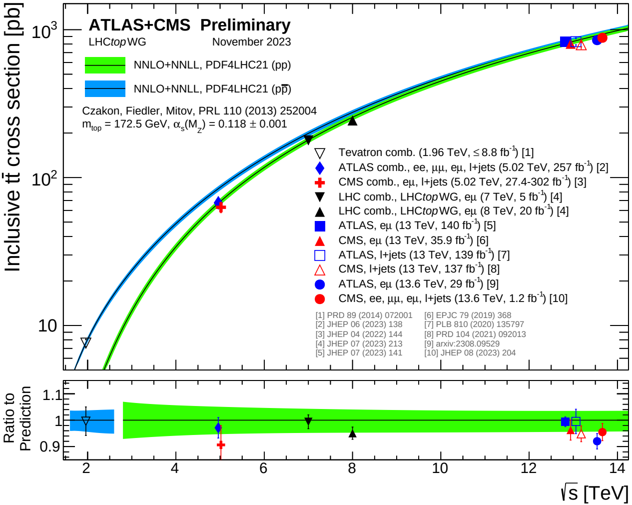
$\Longrightarrow$ Dilepton ($\sim$ 5%): ($\ell = e^{\pm}, \mu^{\pm}$)



$t\bar{t}$ production @ the LHC and Tevatron

Cross-Section Measurements up to 13.6 TeV

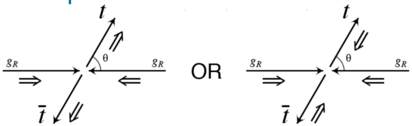
☞ New ATLAS+CMS Results (November 2023)



How to Probe New Physics @ the LHC?
whatever model, observables are needed...
Spin observables are quite powerful!

☞ Although produced unpolarised, the t spins are correlated in $t\bar{t}$ events

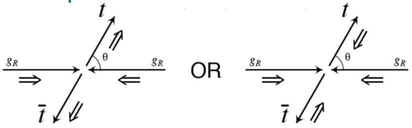
$$\sigma = \sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}$$



quantum interference effects between polarisation states exist

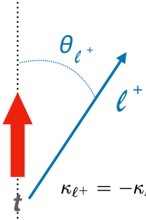
☞ Although produced unpolarised, the t spins are correlated in $t\bar{t}$ events

$$\sigma = \sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}$$



quantum interference effects between polarisation states exist

☞ Probe spin correlations using the $\ell^{\pm}$ i.e, $\cos\theta_{\ell^{\pm}}$

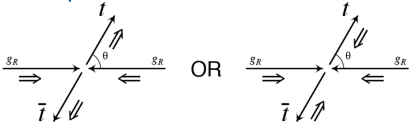


$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \kappa_\ell \cos\theta_\ell)$$

$\kappa_{\ell^+} = -\kappa_{\ell^-} = 1$ in the SM at leading order (LO)

- Although produced unpolarised, the t spins are correlated in $t\bar{t}$ events

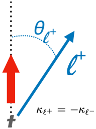
$$\sigma = \sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}$$



quantum interference effects between polarisation states exist

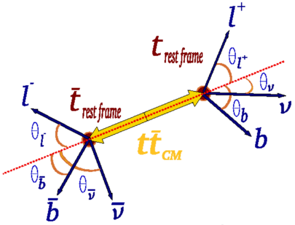
- Probe spin correlations using the $\ell^{\pm}$ i.e, $\cos\theta_{\ell^{\pm}}$ ($t\bar{t}$ dileptonic decays)

$$pp \to t + \bar{t} + X \to \ell^+\ell'^- + \text{ jets} + E_T^{\text{miss}}$$



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \kappa_\ell \cos\theta_\ell)$$

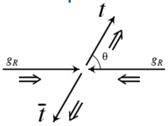
$\kappa_{\ell^+} = -\kappa_{\ell^-} = 1$ in the SM at leading order (LO)



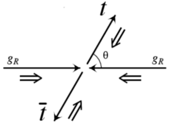
$t\bar{t}$ Production: Top spin correlations FACT 4

- Although produced unpolarised, the t spins are correlated in $t\bar{t}$ events

$$\sigma = \sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}$$



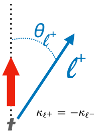
OR



quantum interference effects between polarisation states exist

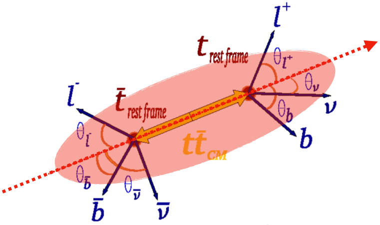
- Probe spin correlations using the $\ell^{\pm}$ i.e, $\cos\theta_{\ell^{\pm}}$ ($t\bar{t}$ dileptonic decays)

$$pp \to t + \bar{t} + X \to \ell^{+}\ell'^{-} + \text{ jets} + E_T^{\text{miss}}$$



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \kappa_\ell \cos\theta_\ell)$$

$\kappa_{\ell^+} = -\kappa_{\ell^-} = 1$ in the SM at leading order (LO)

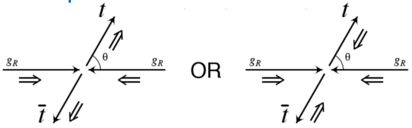


The use of the *tt* Centre-of-Mass is indeed quite convenient I.e., just one single direction!

$t\bar{t}$ Production: Top spin correlations FACT 4

☞ Although produced unpolarised, the t spins are correlated in $t\bar{t}$ events

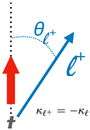
$$\sigma = \sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}$$



quantum interference effects between polarisation states exist

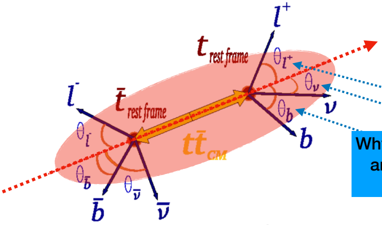
☞ Probe spin correlations using the $\ell^{\pm}$ i.e, $\cos\theta_{\ell^{\pm}}$ ($t\bar{t}$ dileptonic decays)

$$pp \to t + \bar{t} + X \to \ell^+ \ell'^- + \text{ jets} + E_T^{\text{miss}}$$



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \kappa_\ell \cos\theta_\ell)$$

$\kappa_{\ell^+} = -\kappa_{\ell^-} = 1$ in the SM at leading order (LO)



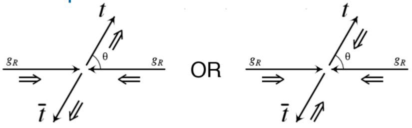
The use of the tt Centre-of-Mass is indeed quite convenient I.e., just one single direction!

Why using lepton/quarks angles in t Centre-of-Mass?

$t\bar{t}$ Production: Top spin correlations FACT 5

- Although produced unpolarised, the t spins are correlated in $t\bar{t}$ events

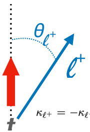
$$\sigma = \sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}$$



quantum interference effects between polarisation states exist

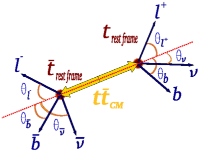
- Probe spin correlations using the $\ell^{\pm}$ i.e, $\cos\theta_{\ell^{\pm}}$ ($t\bar{t}$ dileptonic decays)

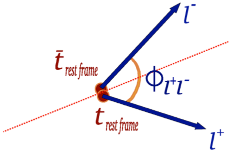
$$pp \to t + \bar{t} + X \to \ell^+ \ell'^- + \text{ jets} + E_T^{\text{miss}}$$



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \kappa_\ell \cos\theta_\ell)$$

$\kappa_{\ell^+} = -\kappa_{\ell^-} = 1$ in the SM at leading order (LO)



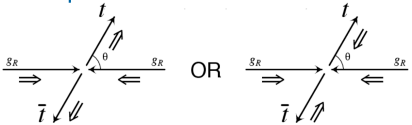


$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\Phi_{\ell\ell}} = \frac{1}{2}(1 - D\cos\Phi_{\ell\ell})$$

$t\bar{t}$ Production: Top spin correlations FACT 6

☞ Although produced unpolarised, the t spins are correlated in $t\bar{t}$ events

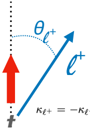
$$\sigma = \sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}$$



quantum interference effects between polarisation states exist

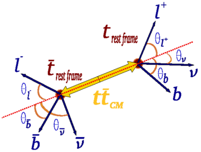
☞ Probe spin correlations using the $\ell^{\pm}$ i.e, $\cos\theta_{\ell^{\pm}}$ ($t\bar{t}$ dileptonic decays)

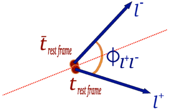
$$pp \to t + \bar{t} + X \to \ell^{+}\ell'^{-} + \text{ jets} + E_T^{\text{miss}}$$



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \kappa_\ell \cos\theta_\ell)$$

$\kappa_{\ell^+} = -\kappa_{\ell^-} = 1$ in the SM at leading order (LO)





$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\Phi_{\ell\ell}} = \frac{1}{2}(1 - D\cos\Phi_{\ell\ell})$$

☞ The $\Delta\Phi_{\ell^+\ell^-}$ also used in LAB frame
(does not require $t\bar{t}$ reconstruction)

Is the $t\bar{t}$ c.m. the only system of reference?
.....not really!

☞ Measurements with respect to $\{\hat{r}_t, \hat{k}_t, \hat{n}_t\}$ axis [JHEP12(2015)026]

The (four-fold) normalised cross section distribution:

$$\frac{1}{\sigma}\frac{d^4\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}(1 + \mathbf{B_1}\cdot\hat{\ell}_1 + \mathbf{B_2}\cdot\hat{\ell}_2 - \hat{\ell}_1\cdot C\cdot\hat{\ell}_2)$$

$d\Omega = d\cos\theta d\phi$ B1 (B2) = top (anti-top) vector spin polarisations C = spin correlation matrix

$\hat{\ell}_1$ ($\hat{\ell}_2$) = the $\hat{\ell}^+$ ($\hat{\ell}^-$) directions in the t($\bar{t}$) system

$t\bar{t}$ Production: Top spin correlations FACT 7

☞ Measurements with respect to $\{\hat{r}_t, \hat{k}_t, \hat{n}_t\}$ axis [JHEP12(2015)026]

The (four-fold) normalised cross section distribution:

$$\frac{1}{\sigma}\frac{d^4\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}(1 + \mathbf{B_1}\cdot\hat{\ell}_1 + \mathbf{B_2}\cdot\hat{\ell}_2 - \hat{\ell}_1\cdot C\cdot\hat{\ell}_2)$$

$d\Omega = d\cos\theta d\phi$ B_1 (B_2) = top (anti-top) vector spin polarisations C = spin correlation matrix

$\hat{\ell}_1$ ($\hat{\ell}_2$) = the $\hat{\ell}^+$ ($\hat{\ell}^-$) directions in the $t(\bar{t})$ system

Different polar axes $\hat{a}$ and $\hat{b}$ can be used, particles defined with respect to them:

$z_1 = \cos\theta_+ = \hat{\ell}_+.\hat{a}$ $z_2 = \cos\theta_- = \hat{\ell}_-.\hat{b}$

$t\bar{t}$ Production: Top spin correlations FACT 8

☞ Measurements with respect to $\{\hat{r}_t, \hat{k}_t, \hat{n}_t\}$ axis [JHEP12(2015)026]

The (four-fold) normalised cross section distribution:

$$\frac{1}{\sigma}\frac{d^4\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B_1}\cdot\hat{\ell}_1 + \mathbf{B_2}\cdot\hat{\ell}_2 - \hat{\ell}_1\cdot C\cdot\hat{\ell}_2\right)$$

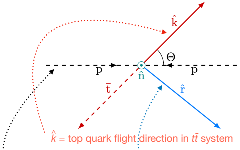
$d\Omega = d\cos\theta d\phi$ B_1 (B_2) = top (anti-top) vector spin polarisations C = spin correlation matrix

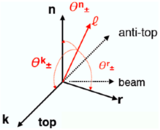
$\hat{\ell}_1$ ($\hat{\ell}_2$) = the $\hat{\ell}^+$ ($\hat{\ell}^-$) directions in the t($\bar{t}$) system

Different polar axes $\hat{a}$ and $\hat{b}$ can be used, particles defined with respect to them:

$z_1 = \cos\theta_+ = \hat{\ell}_+ . \hat{a}$ $\quad\quad$ $z_2 = \cos\theta_- = \hat{\ell}_- . \hat{b}$

The **B** and **C** functions are defined in the $\{\hat{r}, \hat{k}, \hat{n}\}$ basis:





$$\hat{\mathbf{p}}_p = (0,0,1)\,, \quad \hat{\mathbf{r}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p - y_p\hat{\mathbf{k}}) \quad \hat{\mathbf{n}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p \times \hat{\mathbf{k}})\,,$$

$$y_p = \hat{\mathbf{p}}_p \cdot \hat{\mathbf{k}}\,, \quad r_p = \sqrt{1 - y_p^2}\,.$$

$t\bar{t}$ Production: Top spin correlations FACT 9

☞ Measurements with respect to $\{\hat{r}_t, \hat{k}_t, \hat{n}_t\}$ axis [JHEP12(2015)026]

The (four-fold) normalised cross section distribution:

$$\frac{1}{\sigma}\frac{d^4\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B_1}\cdot\hat{\ell}_1 + \mathbf{B_2}\cdot\hat{\ell}_2 - \hat{\ell}_1 \cdot C \cdot \hat{\ell}_2\right)$$

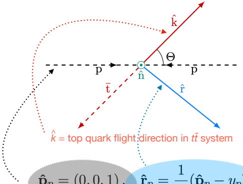
$d\Omega = d\cos\theta d\phi$ B1 (B2) = top (anti-top) vector spin polarisations C = spin correlation matrix

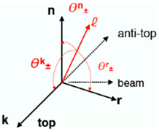
$\hat{\ell}_1$ ($\hat{\ell}_2$) = the $\hat{\ell}^+$ ($\hat{\ell}^-$) directions in the $t(\bar{t})$ system

Different polar axes â and b̂ can be used, particles defined with respect to them:

$z_1 = \cos\theta_+ = \hat{\ell}_+ . \hat{a}$ $\quad$ $z_2 = \cos\theta_- = \hat{\ell}_- . \hat{b}$

The **B** and **C** functions are defined in the $\{\hat{r}, \hat{k}, \hat{n}\}$ basis:





$$\hat{\mathbf{p}}_p = (0,0,1)\,, \quad \hat{\mathbf{r}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p - y_p\hat{\mathbf{k}}) \quad \hat{\mathbf{n}}_p = \frac{1}{r_p}(\hat{\mathbf{p}}_p \times \hat{\mathbf{k}})\,,$$

$$y_p = \hat{\mathbf{p}}_p \cdot \hat{\mathbf{k}}\,, \qquad r_p = \sqrt{1 - y_p^2}\,.$$

Why these axis choice?

Correlation		sensitive to
$C(n, n)$	c^I_{nn}	P-, CP-even
$C(r, r)$	c^I_{rr}	P-, CP-even
$C(k, k)$	c^I_{kk}	P-, CP-even
$C(r, k) + C(k, r)$	c^I_{rk}	P-, CP-even
$C(n, r) + C(r, n)$	c^I_{rn}	P-odd, CP-even, absorptive
$C(n, k) + C(k, n)$	c^I_{kn}	P-odd, CP-even, absorptive
$C(r, k) - C(k, r)$	c^I_{n}	P-even, CP-odd, absorptive
$C(n, r) - C(r, n)$	c^I_{k}	P-odd, CP-odd
$C(n, k) - C(k, n)$	$-c^I_{r}$	P-odd, CP-odd
$B_1(n) + B_2(n)$	$b^{I+}_n + b^{I-}_n$	P-, CP-even, absorptive
$B_1(n) - B_2(n)$	$b^{I+}_n - b^{I-}_n$	P-even, CP-odd
$B_1(r) + B_2(r)$	$b^{I+}_r + b^{I-}_r$	P-odd, CP-even
$B_1(r) - B_2(r)$	$b^{I+}_r - b^{I-}_r$	P-odd, CP-odd, absorptive
$B_1(k) + B_2(k)$	$b^{I+}_k + b^{I-}_k$	P-odd,CP-even
$B_1(k) - B_2(k)$	$b^{I+}_k - b^{I-}_k$	P-odd, CP-odd, absorptive
$B_1(k^*) + B_2(k^*)$	$b^{I+}_k + b^{I-}_k$	P-odd,CP-even
$B_1(k^*) - B_2(k^*)$	$b^{I+}_k - b^{I-}_k$	P-odd, CP-odd, absorptive
$B_1(r^*) + B_2(r^*)$	$b^{I+}_r + b^{I-}_r$	P-odd, CP-even
$B_1(r^*) - B_2(r^*)$	$b^{I+}_r - b^{I-}_r$	P-odd, CP-odd, absorptive

$t\bar{t}$ Production: Top spin correlations

☞ CMS Measurements [Phys. Rev. D 100 (2019) no.7, 072002]

for each 15 coefficient **B_1,B_2, C** single differential distributions are used

Integrating over the azimuthal angles (for each axis ***i,j***)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1^i\, d\cos\theta_2^j} = \frac{1}{4}(1 + B_1^i\cos\theta_1^i + B_2^j\cos\theta_2^j - C_{ij}\cos\theta_1^i\cos\theta_2^j)$$

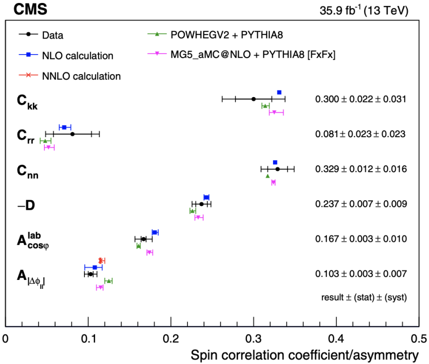
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i} = \frac{1}{2}(1 + B_1^i\cos\theta_1^i),$$

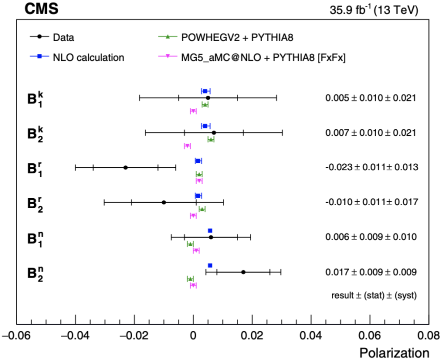
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_2^i} = \frac{1}{2}(1 + B_2^i\cos\theta_2^i),$$

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 - C_{ij}x)\ln\left(\frac{1}{|x|}\right),$$

$$x = \cos\theta_1^i\cos\theta_2^j.$$

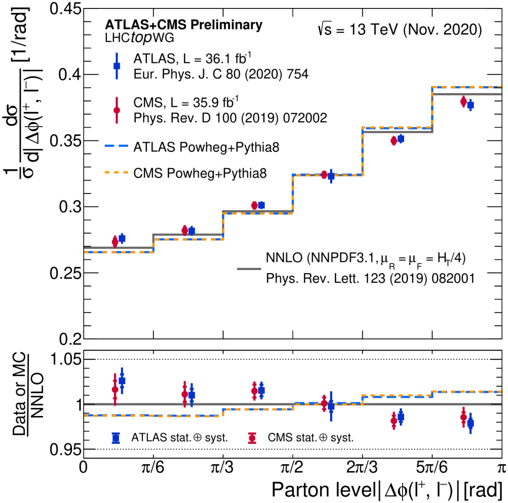
θ_1^i (θ_2^j) = ℓ^+ (ℓ^-) directions in the $t(\bar{t})$ system, with respect to $i(j)$ axis ($\hat{r},\hat{k},\hat{n}$)





$t\bar{t}$ Production: Top spin correlations FACT 6 Measurement

☞ Using the Normalized Differential $|\Delta\phi_{\ell^+\ell^-}|$ Distribution (LAB system)



☞ ATLAS and CMS data compared to calculations at NNLO.

(https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots)

Are the $t\bar{t}$ 1D observables the only ones?
.....not really! (2D observables OK)

☞ Double Differential Normalized Distributions [Eur.Phys.J.C 82 (2022) 2]

Defining (with respect to any of the axis ***i,j={r̂,k̂,n̂}***)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1^i\, d\cos\theta_2^j} = \frac{1}{\sigma}\frac{d\sigma}{dz_1 dz_2} = f(z_1, z_2) \quad \text{and} \quad f_{XX'}(z_1, z_2) = \frac{1}{\sigma_{XX'}}\frac{d\sigma_{XX'}}{dz_1 dz_2} \quad \text{with} \quad X, X' = L, R$$

θ_1^i (θ_2^j) = ℓ^+ (ℓ^-) directions in the t($\bar{t}$) system, with respect to i(j) axis (r̂,k̂,n̂)

☞ Double Differential Normalized Distributions [Eur.Phys.J.C 82 (2022) 2]

Defining (with respect to any of the axis ***i,j={r̂,k̂,n̂}***)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1^i\, d\cos\theta_2^j} = \frac{1}{\sigma}\frac{d\sigma}{dz_1 dz_2} = f(z_1, z_2) \quad \text{and} \quad f_{XX'}(z_1, z_2) = \frac{1}{\sigma_{XX'}}\frac{d\sigma_{XX'}}{dz_1 dz_2} \quad \text{with} \quad X, X' = L, R$$

θ_1^i (θ_2^j) = ℓ^+ (ℓ^-) directions in the t($\bar{t}$) system, with respect to i(j) axis (r̂,k̂,n̂)

the **Normalised Double Differential Distribution** can be defined (at parton level)

$$f(z_1, z_2) = \sum_{XX'} a_{XX'} f_{XX'}(z_1, z_2) \quad \text{with} \quad \sum_{XX'} a_{XX'} = 1$$

☞ Double Differential Normalized Distributions [Eur.Phys.J.C 82 (2022) 2]

Defining (with respect to any of the axis ***i,j*={$\hat{r},\hat{k},\hat{n}$}**)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1^i\, d\cos\theta_2^j} = \frac{1}{\sigma}\frac{d\sigma}{dz_1 dz_2} = f(z_1, z_2) \quad \text{and} \quad f_{XX'}(z_1, z_2) = \frac{1}{\sigma_{XX'}}\frac{d\sigma_{XX'}}{dz_1 dz_2} \quad \text{with} \quad X, X' = L, R$$

θ_1^i (θ_2^j) = ℓ^+ (ℓ^-) directions in the t($\bar{t}$) system, with respect to i(j) axis ($\hat{r},\hat{k},\hat{n}$)

the **Normalised Double Differential Distribution** can be defined (at parton level)

$$f(z_1, z_2) = \sum_{XX'} a_{XX'} f_{XX'}(z_1, z_2) \quad \text{with} \quad \sum_{XX'} a_{XX'} = 1$$

Phase Space cuts (p_T, η, etc.) affect the Polarizations differently

$$\frac{d\bar{\sigma}}{dz_1 dz_2} = \sum_{X,X'} \frac{d\bar{\sigma}_{XX'}}{dz_1 dz_2} + \ldots$$

(the ***bar*** = quantities **after cuts**)

☞ Double Differential Normalized Distributions [Eur.Phys.J.C 82 (2022) 2]

Defining (with respect to any of the axis ***i,j={r̂,k̂,n̂}***)

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1^i\,d\cos\theta_2^j} = \frac{1}{\sigma}\frac{d\sigma}{dz_1 dz_2} = f(z_1,z_2) \text{ and } f_{XX'}(z_1,z_2) = \frac{1}{\sigma_{XX'}}\frac{d\sigma_{XX'}}{dz_1 dz_2} \text{ with } X,X' = L,R$$

θ_1^i (θ_2^j) = ℓ^+ (ℓ^-) directions in the $t(\bar{t})$ system, with respect to $i(j)$ axis (r̂,k̂,n̂)

the **Normalised Double Differential Distribution** can be defined (at parton level)

$$f(z_1,z_2) = \sum_{XX'} a_{XX'} f_{XX'}(z_1,z_2) \text{ with } \sum_{XX'} a_{XX'} = 1$$

Phase Space cuts (p_T, η, etc.) affect the Polarizations differently

$$\frac{d\bar{\sigma}}{dz_1 dz_2} = \sum_{X,X'} \frac{d\bar{\sigma}_{XX'}}{dz_1 dz_2} + \dots$$

(the ***bar*** = quantities **after cuts**)

which implies

$$\varepsilon \bar{f}(z_1,z_2) = \sum_{XX'} a_{XX'} \varepsilon_{XX'} \bar{f}_{XX'}(z_1,z_2) + \Delta_{\text{int}}(z_1,z_2)$$

Interference Term (small but not zero!)

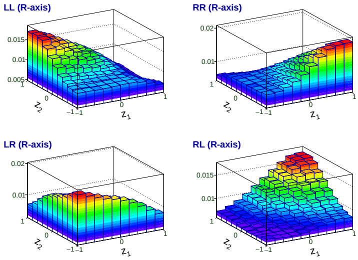
with $\varepsilon = \bar{\sigma}/\sigma$

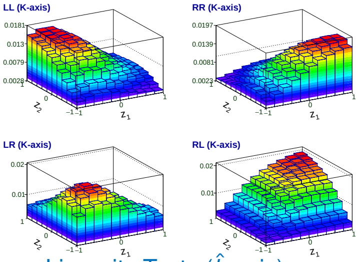
$\varepsilon_{XX'} = \bar{\sigma}_{XX'}/\sigma_{XX'}$

$\bar{f}_{XX'}(z_1,z_2)$, $\bar{f}(z_1,z_2)$ } **2D Templates after cuts**

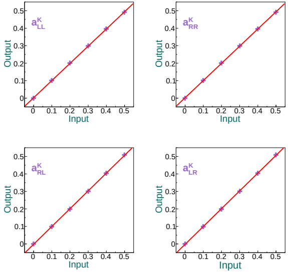
$a_{XX'}$ = a_{RR}, a_{LL}, a_{RL} and a_{LR} are the Parton Level spin correlation fractions (no need for unfolding!)

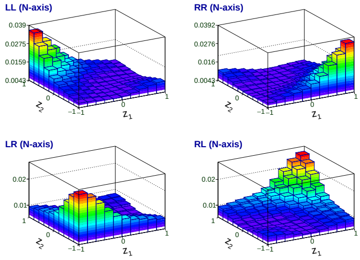
☞ Double Differential Normalized Templates in $\{\hat{r},\hat{k},\hat{n}\}$ axes



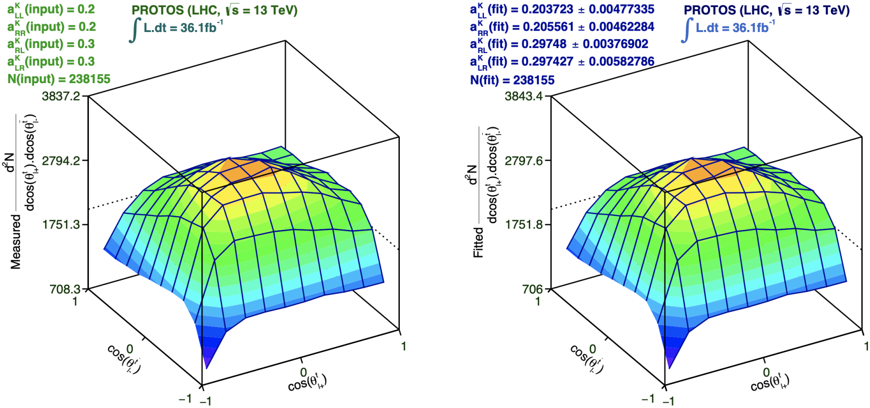


Linearity Tests ($\hat{k}$ axis)





☞ Template 2D fit example in $\hat{k}$ axis (from linearity tests)

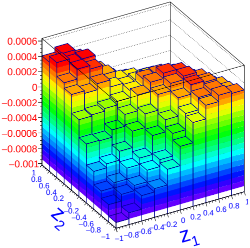


$t\bar{t}$ Production: 2D Template top spin correlations FACT 11 test

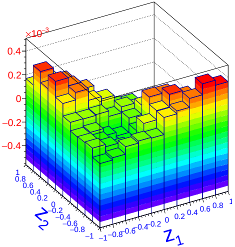
☞ Interference effects can also be measured in all axes $\{\hat{r},\hat{k},\hat{n}\}$

$$\varepsilon\bar{f}(z_1,z_2)=\sum_{XX'} a_{XX'}\varepsilon_{XX'}\bar{f}_{XX'}(z_1,z_2)+\Delta_{\rm int}(z_1,z_2)$$

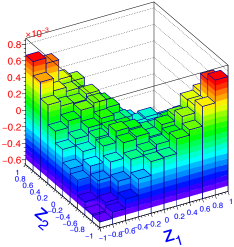
R-axis



K-axis



N-axis



☞ BSM interference effects are different from the SM in all $\{\hat{r},\hat{k},\hat{n}\}$ axes

☞ Results for the SM in all $\{\hat{r},\hat{k},\hat{n}\}$ axes

2D Template Fit Results

Spin correlations parameter $C_{ii} = a_{RR} + a_{LL} - a_{RL} - a_{LR}$

Top quark Polarizations

$P_t = a_{RR} + a_{RL} - a_{LR} - a_{LL}$

$P_{\bar{t}} = a_{RR} + a_{LR} - a_{RL} - a_{LL}$

K	SM	
	Prediction	Fit
a_{LL}	0.335 ± 0.001	0.337 ± 0.006
a_{RR}	0.336 ± 0.003	0.330 ± 0.005
a_{LR}	0.165 ± 0.003	0.167 ± 0.007
a_{RL}	0.165 ± 0.002	0.160 ± 0.004
C_{kk}	0.340 ± 0.002	0.340 ± 0.019
P_t	0.001 ± 0.002	-0.014 ± 0.008
$P_{\bar{t}}$	0.001 ± 0.002	0.000 ± 0.008

What happens if $t\bar{t}$ is accompanied with additional bosons (e.g. Higgs, Dark Matter mediators, etc.) ?
arXiv:2208.04271, JHEP 4 (2014), JHEP 01 (2022) 158

☞ Probing the top quark - Higgs boson vertex CP nature

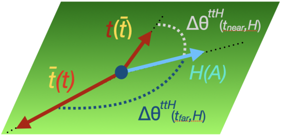
Effective Lagrangian for top quark Higgs boson interaction

$$\mathcal{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\,(\kappa + \mathrm{i}\tilde{\kappa}\gamma_5)\,\psi_t\,H,$$ $k(\tilde{k})$ = CP-even (CP-odd) components

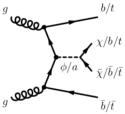
SM (pure CP-even): $k=1$ and $\tilde{k}=0$ BSM, pure CP-odd: $k=0$ and $\tilde{k}=1$

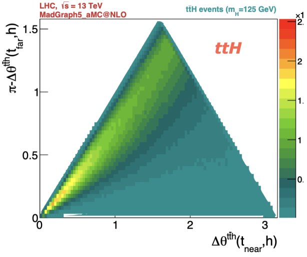
Mixing angle (α) parametrisation: $k=k_t\cos(\alpha)$ and $k=\tilde{k}_t\sin(\alpha)$

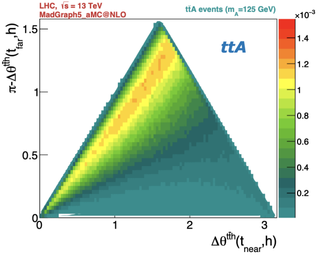
The role of *ttH* CM system is quite important [Phys. Rev. D**100**, 075034 (2019)]



ttH centre-of-mass system







$t\bar{t}H$, tH Production @ the LHC FACT 14

☞ Probing the top quark - Higgs boson vertex CP nature

Effective Lagrangian for top quark Higgs boson interaction

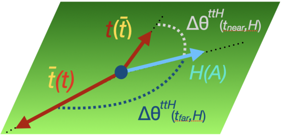
$$\mathcal{L}(Htt) = -\frac{m_t}{v}\bar{\psi}_t\,(\kappa + \mathrm{i}\,\tilde{\kappa}\gamma_5)\,\psi_t\,H,$$

k ($\tilde{k}$) = CP-even (CP-odd) components

SM (pure CP-even): $k=1$ and $\tilde{k}=0$ BSM, pure CP-odd: $k=0$ and $\tilde{k}=1$

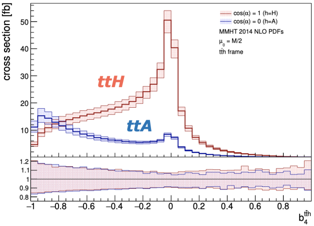
Mixing angle (α) parametrisation: $k=k_t\cos(\alpha)$ and $k=\tilde{k}_t\sin(\alpha)$

The role of *ttH* CM system is quite important [Phys. Rev. D**100**, 075034 (2019)]



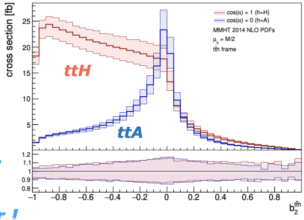
ttH centre-of-mass system

$$b_4^f(i,j) = \frac{p_{i,z}^f\;p_{j,z}^f}{|\vec{p}_i^{\,f}||\vec{p}_j^{\,f}|}$$



The role of *top quarks* is also very important

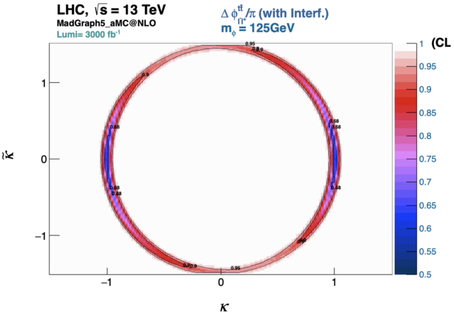
$$b_2^f(i,j) = \frac{(\vec{p}_i^{\,f}\times\hat{k}_z).(\vec{p}_j^{\,f}\times\hat{k}_z)}{|\vec{p}_i^{\,f}||\vec{p}_j^{\,f}|}$$

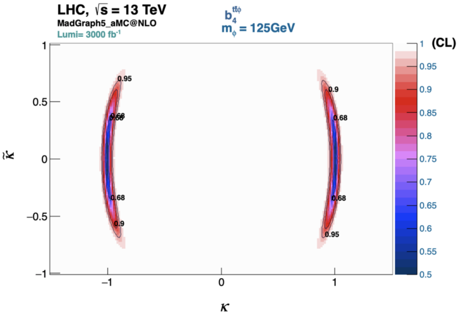


Spin-parity sensitivity is clear !

☞ Probing the top quark - Higgs boson vertex CP nature (Interf. Terms)

Expected Exclusion CLs using Differential Distributions w/ Interference



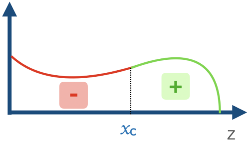


☞ $d\sigma_{t\bar{t}\phi}$ with Interference term:

$$d\sigma_{t\bar{t}\phi} = \kappa^2\ d\sigma_{\text{CP-even}} + \tilde{\kappa}^2\ d\sigma_{\text{CP-odd}} + \kappa\tilde{\kappa}\ d\sigma_{\text{int}}$$

☞ Idea for RUN 3: use Asymmetries

Asymmetries from angular distributions, defined as:



$$A_c[Z] = \frac{\sigma(Z > x_c) - \sigma(Z < x_c)}{\sigma(Z > x_c) + \sigma(Z < x_c)}$$

$$= \frac{+ \; - \; -}{+ \; + \; -}$$

$$A_c[Z] = A\kappa^2 + B\tilde{\kappa}^2 + \ldots$$

$$A \propto \int_{x_c}^{+1} d\sigma_{\text{CP-even}} - \int_{-1}^{x_c} d\sigma_{\text{CP-even}} \quad \text{and} \quad B \propto \int_{x_c}^{+1} d\sigma_{\text{CP-odd}} - \int_{-1}^{x_c} d\sigma_{\text{CP-odd}}$$

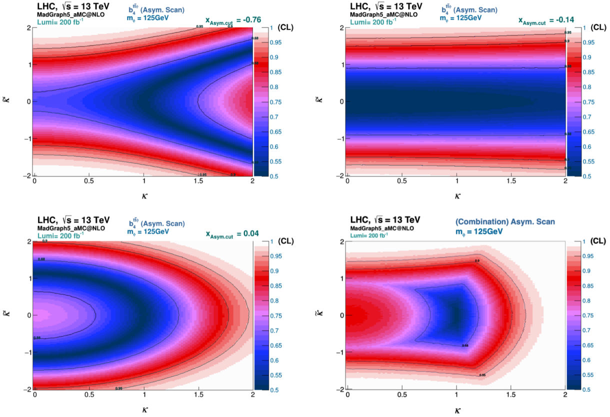
Choose x_c when ttH/ ttA $A_c[z]$ differences are maximum:

Asymmetries	x_c	MadGraph5 @ NLO+Shower (no cuts applied) $t\bar{t}\phi$ signal mixing angle α (deg.)							
		0.0°	22.5°	45.0°	67.5°	90.0°	135.0°	180.0°	$t\bar{t}b\bar{b}$
$A_c[b_2^{t\bar{t}\phi}]$	−0.30	−0.35	−0.31	−0.15	+0.15	+0.34	−0.14	−0.36	−0.17
$A_c[b_4^{t\bar{t}\phi}]$	−0.50	+0.41	+0.37	+0.22	−0.04	−0.22	+0.22	+0.41	+0.33
$A_c[\sin(\theta_\phi^{t\bar{t}\phi}) * \sin(\theta_{\bar{t}}^{t\bar{t}})]$	+0.70	−0.27	−0.26	−0.20	−0.09	−0.03	−0.20	−0.27	−0.56
$A_c[\sin(\theta_\phi^{t\bar{t}\phi}) * \sin(\theta_{b_{\bar{t}}}^{\bar{t}})]$ (seq. boost)	+0.60	+0.05	+0.05	+0.07	+0.09	+0.11	+0.06	+0.05	−0.38

Table 1: Asymmetries for the $t\bar{t}\phi$ signal as a function of the mixing angle α, as well as for the dominant background $t\bar{t}b\bar{b}$ at NLO+Shower (without any cuts), are shown for several observables. Significant differences between the asymmetries for the pure scalar ($\alpha = 0.0°$) and pseudo-scalar ($\alpha = 90.0°$) cases are observed for several asymmetries.

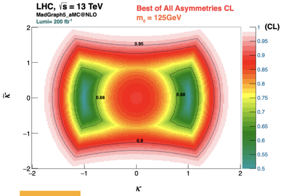
☞ Idea for RUN 3: use Asymmetries

CLs change with the cut-off definition for the asymmetry x_c (200 fb^{-1})

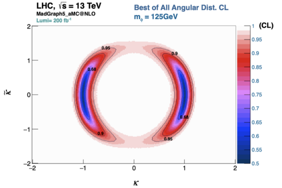


CLs using Asym. vs Ang.Dist. (200 fb^{-1})

Asym



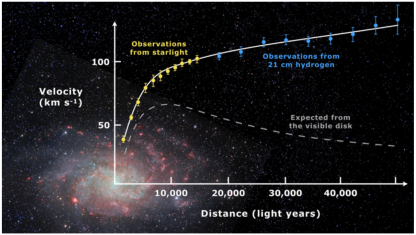
Angular



Are Spin Observables sensitive to Dark Matter?

Dark Matter

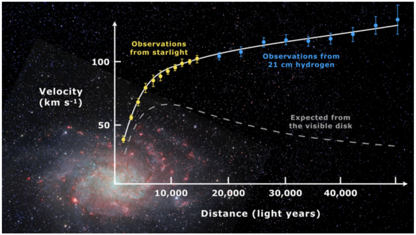
Galaxy Rotation Curves



Rotation curve of spiral galaxy **Messier 33** (yellow and blue points with error bars), and a predicted one from distribution of the visible matter (gray line). The discrepancy between the two curves can be accounted for by adding a dark matter halo surrounding the galaxy.

Dark Matter

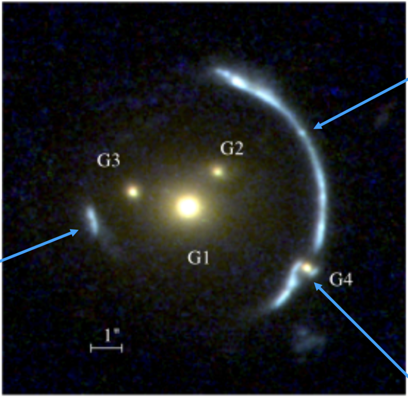
Galaxy Rotation Curves



Rotation curve of spiral galaxy **Messier 33** (yellow and blue points with error bars), and a predicted one from distribution of the visible matter (gray line). The discrepancy between the two curves can be accounted for by adding a dark matter halo surrounding the galaxy.

Strong gravitational lenses give rise to multiple images of the same source

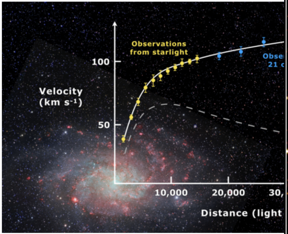
Vegetti et al. 2010



even low-mass perturbers cause deflections and magnifications

Dark Matter

Galaxy Rotation Curves

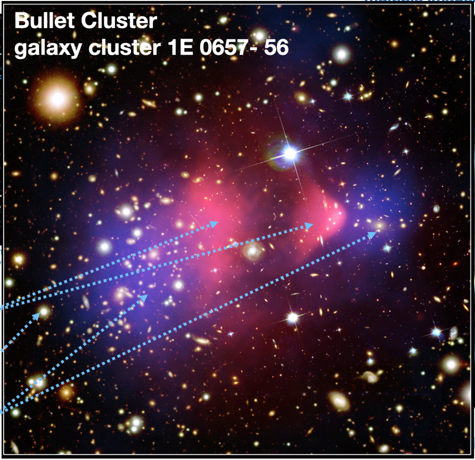


Rotation curve of spiral galaxy **Messier 33** (yellow and blue points with
from distribution of the visible matter (gray line). The discrepancy betw
accounted for by adding a dark matter halo surrounding the galaxy.

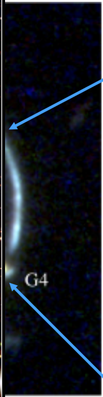
(pink regions) Hot gas detected by Chandra in X-rays "normal" or baryonic matter

(bright points) Magellan and Hubble stars

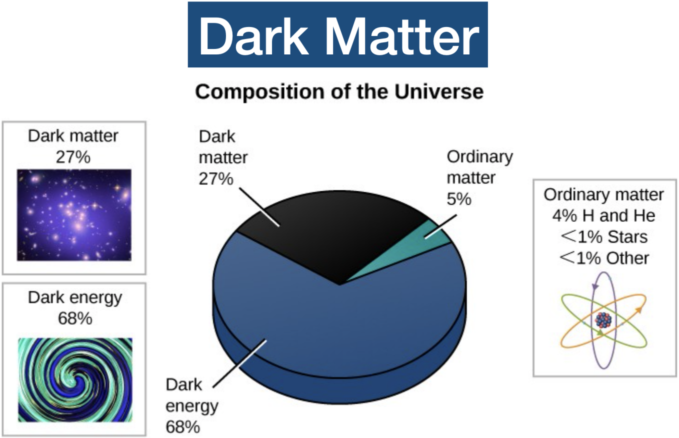
(blue areas) where most of the (DM) mass is, determined with Gravitational Lensing



Strong gravitational lenses give rise to multiple images of the same source

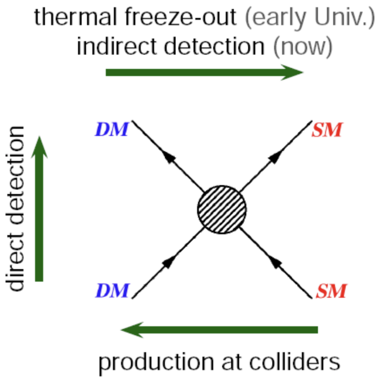


ions and magnifications


Dark Matter
Composition of the Universe
Dark matter
27%
Dark energy
68%
Dark
matter
27%
Ordinary
matter
5%
Dark
energy
68%
Ordinary matter
4% H and He
<1% Stars
<1% Other

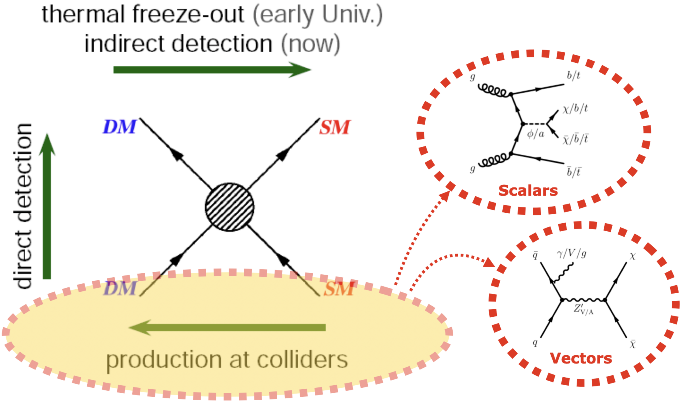
Dark Matter

Complementarity of Measurements in Many Environments



Dark Matter

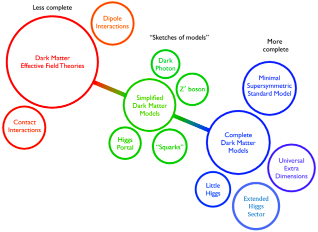
Complementarity of Measurements in Many Environments

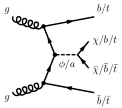


How, with all previous methods, can we say something about Dark Matter and its properties?
[arXiv:2308.00819 (hep-ph)]

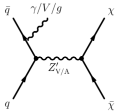
DM in $t\bar{t}$ Production @ LHC

DM Effects in $t\bar{t}$ Spin Observables





Scalar/pseudo-scalar



Vector/Axial-vector

Note: reconstruct only the $t\bar{t}$ system and study spin-parity effects in exp. observables

Interaction Lagrangians for Spin 0 and 1 Mediators

Spin-0 mediator model

$$\mathcal{L}_{X_D}^{Y_0} = \bar{X}_D(g^S_{X_D} + i g^P_{X_D}\gamma_5)X_D\, Y_0$$

pure scalar: $g^S{}_{XD}$= $g^S{}_{u33}$=1, $g^P{}_{XD}$= $g^P{}_{u33}$=0

pure pseudo-scalar: $g^S{}_{XD}$= $g^S{}_{u33}$=0, $g^P{}_{XD}$= $g^P{}_{u33}$=1

Spin-1 mediator model

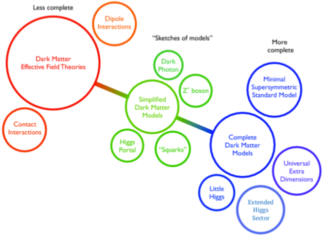
$$\mathcal{L}_{X_D}^{Y_1} = \bar{X}_D\gamma_\mu(g^V_{X_D} + g^A_{X_D}\gamma_5)X_D\, Y_1^\mu$$

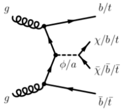
pure vector: $g^V{}_{XD}$=1, $g^V{}_{u33}$=0.25, $g^A{}_{XD}$= $g^A{}_{q33}$=0

pure axial-vector: $g^V{}_{XD}$= $g^V{}_{q33}$=0, $g^A{}_{XD}$=1, $g^A{}_{q33}$=1

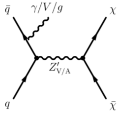
☞ Normalized Differential Distributions

DM Effects in $t\bar{t}$ Spin Observables





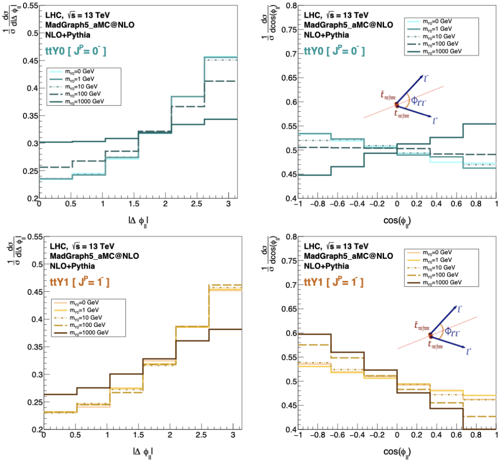
Scalar/pseudo-scalar



Vector/Axial-vector

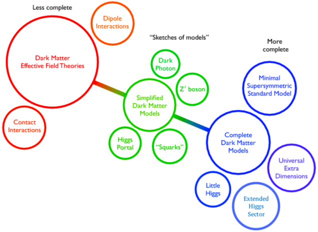
Note: reconstruct only the $t\bar{t}$ system and study spin-parity effects in exp. observables

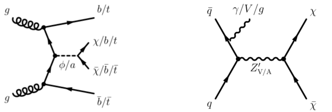
Spin Correlations Observables in $t\bar{t}$ Events @ LHC



☞ CLs exclusions

Just one simple example

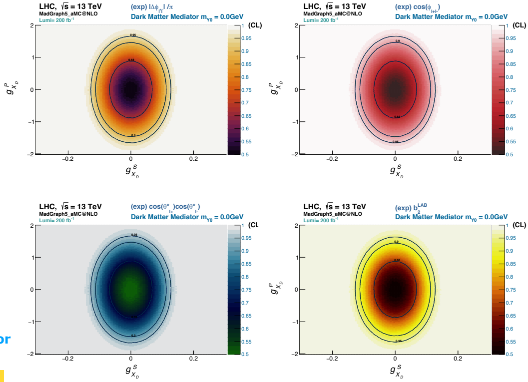




Note: use $m_\phi=0$, and $m_{DM}=0$

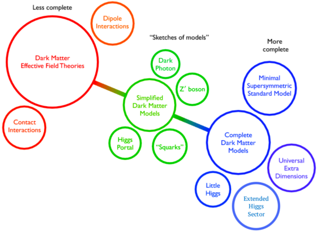
Exclusion Limits for tt Events @ LHC (analysis)

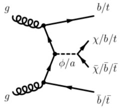
SM (Null Hyp.)



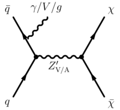
☞ CLs exclusions

Just one simple example





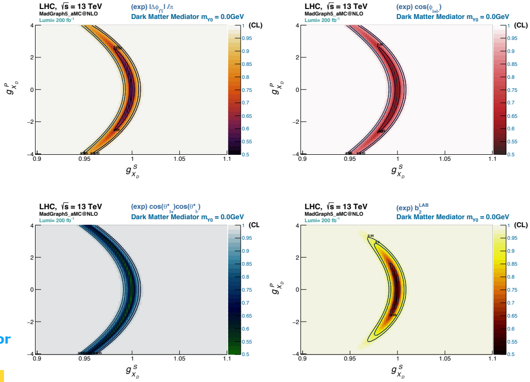
Scalar/pseudo-scalar



Vector/Axial-vector

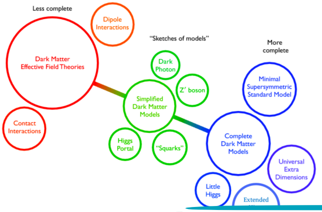
Note: use $m_{\phi}=0$, and $m_{DM}=0$

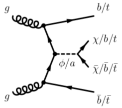
Exclusion Limits for tt Events @ LHC (analysis)
SM + $J^P=0^+$ (Null Hyp.)



☞ CLs exclusions

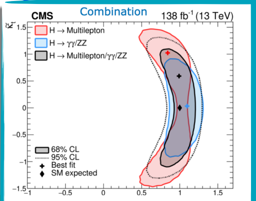
Just one simple example





Scalar/pseudo-scalar

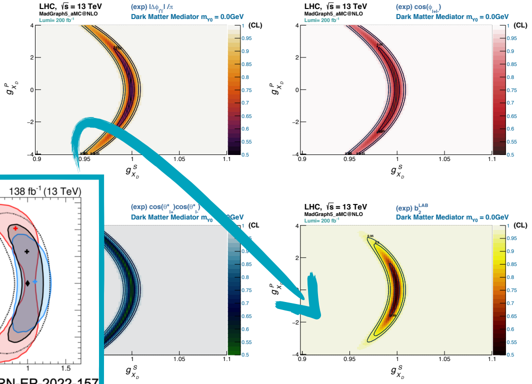
Note: use m_ϕ=0



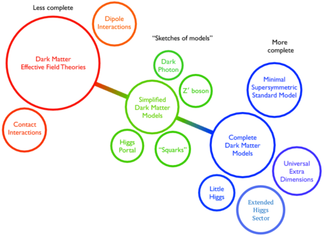
CMS-HIG-21-006 ; CERN-EP-2022-157

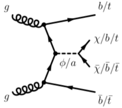
Exclusion Limits for *tt* Events @ LHC (analysis)

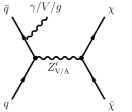
SM + $J^P=0^+$ (Null Hyp.)



Just one simple example







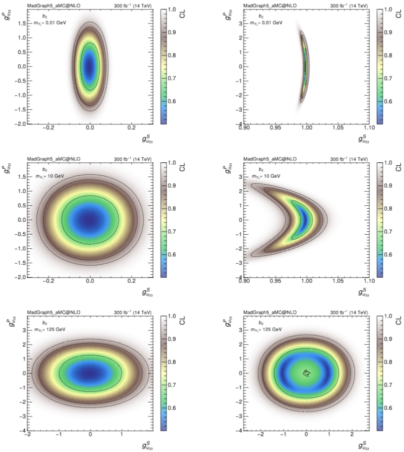
Scalar/pseudo-scalar **Vector/Axial-vector**

Note: use $m_\phi=0$, and $m_{DM}=0$

Using FB Asymmetries

Mediator Mass Dependence

SM (Null Hyp.) **SM+$J^P=0^+$ (Null Hyp.)**



Conclusions

- Top quark spin observables are indeed quite powerful to probe New Physics
- Asymmetries can play an important role at the LHC
- A lot to be done for DM @ LHC: observables exist, they need to be studied phenomenologically i.e. the 2D angular correlations, the asymmetries, etc.