Top Quarks Physics @ the LHC

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Course on Physics at the LHC, 19th March 2025, Lisbon

Main Topics in this Talk

- Global Fits of Data
- Invisible systems in $t\bar{t}$ events

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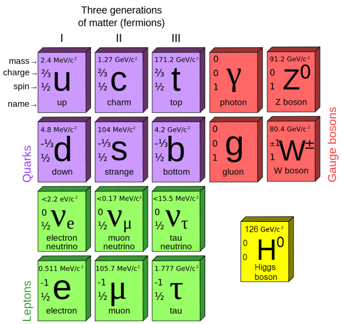
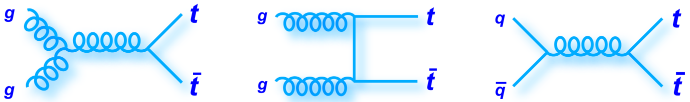
The top quark



- **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)
  - $\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}$s (D0, PRD **85** 091104, 2012)
    $\ll \Lambda_{QCD}^{-1} \sim (100\ \text{MeV})^{-1} \sim 10^{-23}$s (hadronization time)
    $\Rightarrow$ top decays before hadronization takes place

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

- Production at the LHC:

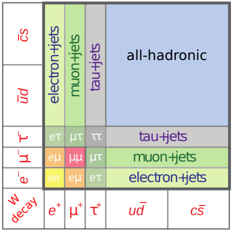


$\sigma(t\bar{t})$=177.3±9.9$^{+4.6}_{-6.0}$ pb @ 7 TeV, $\sigma(t\bar{t})$=252.9±11.7$^{+6.4}_{-8.6}$ pb @ 8 TeV,

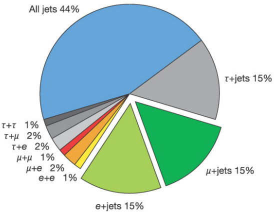
$\sigma(t\bar{t})$=832$^{+40}_{-46}$ pb @ 13 TeV, $\sigma(t\bar{t})$=924$^{+32}_{-40}$ pb @ 13.6 TeV

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).

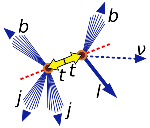
Top pair decay channels



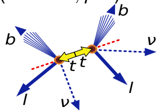
Top pair branching fractions



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

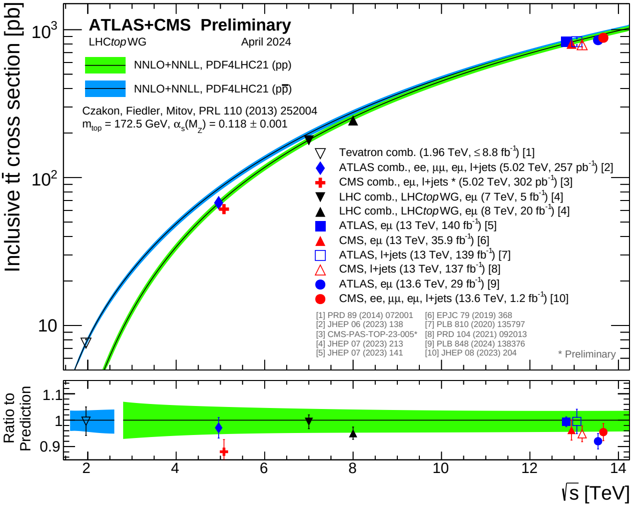


$\Longrightarrow$ Dilepton ($\sim$ 5%): ($\ell = e^{\pm}, \mu^{\pm}$)

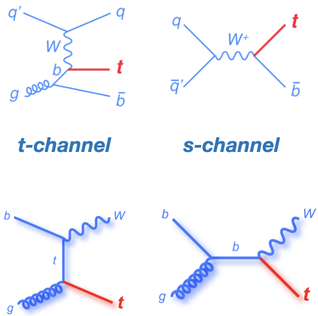


Cross-Section Measurements up to 13.6 TeV

☞ New ATLAS+CMS Results (April 2024)

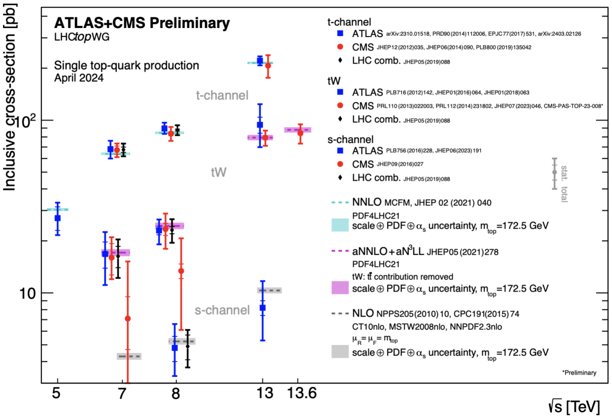


Single top quark production @ LHC



t-channel ***s-channel***

Wt associated production



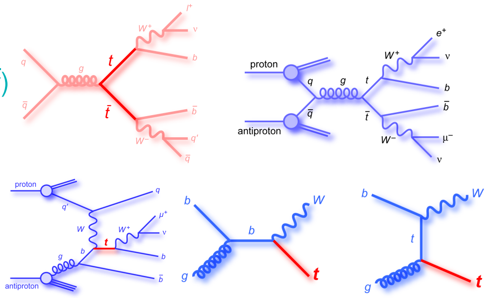
Why is it necessary a precise model-independent measurement of the Wtb vertex structure?

- It may reveal physics beyond the Standard Model
  - V_{tb} could be different from the Standard Model value
  - Anomalous couplings may appear at the vertex
- It may help understand possible other new physics beyond the Standard Model
  - top quarks decay almost exclusively to $t \to W^+ b$
  - understanding the structure of the Wtb vertex helps revealling possible non-standard $t\bar{t}$ production at LHC, $Zt\bar{t}/\gamma t\bar{t}$ couplings at ILC, etc.
  - important for B and K physics (indirect limits on anomalous couplings, see later)

Main objective: perform a global fit of data @ LHC on top quark Anomalous/SMEFT Couplings in $t \to Wb$ decays

Several processes under study to probe the *Wtb* vertex[1]:

- Top quark pair production ($t\bar{t}$)
  - (i) semileptonic channel
  - (ii) dileptonic decays
- single top quark physics
  - (i) *t*-channel (single lepton)
  - (ii) *Wt*-channel (dilep. decay)
- SMEFT/Anomalous coupling studied associated to the *Wtb* vertex



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[1] JHEP**1206**(2012)088, EPJC**77**(2017)264, JHEP**04**(2017)124, JHEP**04**(2016)023, JHEP**12**(2017)017, PLB**717**(2012)330, PRD**90**(2014)112006, PLB**716**(2012)142, PLB**756**(2016)228, EPJC**77**(2017)531, JHEP**01**(2016)064, JHEP**04**(2017)086, JHEP**01**(2018)63, EPJC**78**(2018)186

Global Fits of Data

General Wtb vertex

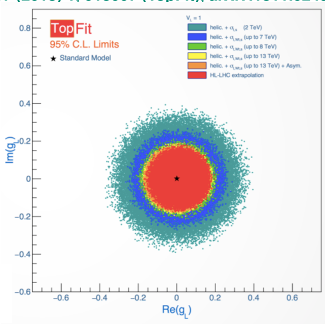
Eur.Phys.J. C50 (2007) 519-533

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-}$$

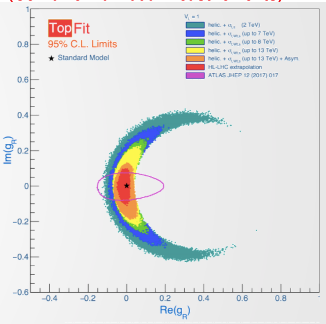
vector (V_R) and tensor like couplings (g_L, g_R) zero @ tree level in SM

☞ SMEFT parameters: anomalous couplings described by effective operators $\mathcal{O}_{uW}$,$\mathcal{O}_{dW}$, $\mathcal{O}_{\phi q}^{(3)}$ and $\mathcal{O}_{\phi ud}$ i.e., constraints on anomalous couplings equivalent to constraints on SMEFT parameters (a more integrating framework) [arXiv:1802.07237]

PRD 97 (2018) 1, 013007 (TopFit), arXiv:1811.02492



(Combine Individual Measurements)



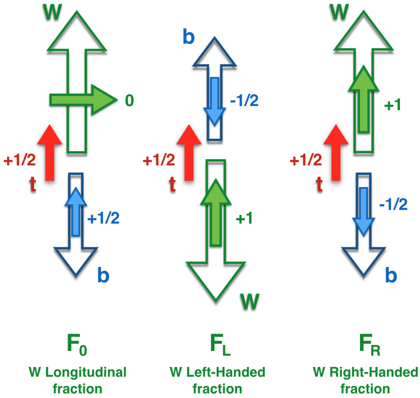
Fits Using:

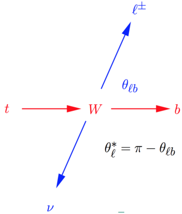
σ, W_{hel}, A_{FB} @ 7,8,13 TeV

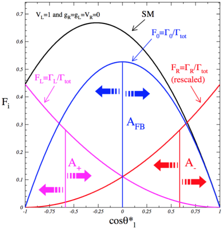
How do we probe these SMEFT/Anomalous Couplings?

How do we probe these SMEFT/Anomalous Couplings?
.....by measuring observables that depend on them!

☞ Example of Decay Observable: $\cos\theta^*_\ell$ $[F_0, F_L, F_R]$

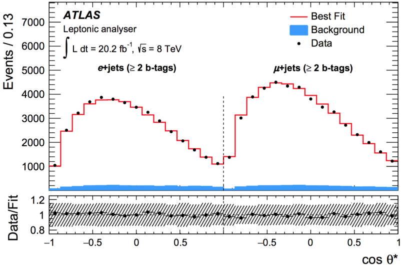






$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*_\ell} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta^*_\ell}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\theta^*_\ell}{2}\right)^2 + F_R\left(\frac{1+\cos\theta^*_\ell}{2}\right)^2\right]$$

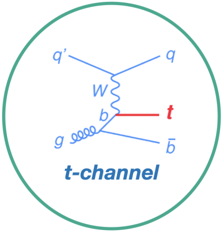
EPJC**77**(2017)264



$$F_0^{\rm SM} = 0.687 \pm 0.005$$
$$F_L^{\rm SM} = 0.311 \pm 0.005$$
$$F_R^{\rm SM} = 0.0017 \pm 0.0001$$

@ NNLO QCD calculation, PRD**81**(2010)111503
$(F_0 + F_L + F_R = 1)$

Single top quark production @ LHC

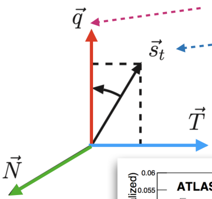


New Reference System

(W momentum)

(*t* spin direction)

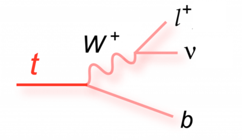
Spectator quark direction

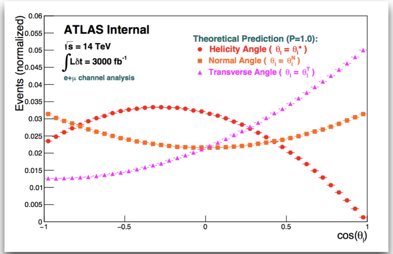


$$\vec{N} = \vec{s}_t \times \vec{q}\,, \qquad \vec{T} = \vec{q} \times \vec{N}\,,$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^{T,N}} = \frac{3}{8}(1+\cos\theta_\ell^{T,N})^2\, F_+^{T,N} + \frac{3}{8}(1-\cos\theta_\ell^{T,N})^2\, F_-^{T,N} + \frac{3}{4}\sin^2\theta_\ell^{T,N}\, F_0^{T,N}$$

t quark decays





Angular Distributions and Helicity Fractions (F_i):

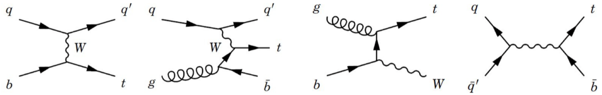
$$
\begin{aligned}
A_0 = {} & \frac{m_t^2}{M_W^2}\left[|V_L|^2+|V_R|^2\right]\left(1-x_W^2\right)+\left[|g_L|^2+|g_R|^2\right]\left(1-x_W^2\right) \\
& -4x_b\,\mathrm{Re}\left[V_L V_R^*+g_L g_R^*\right]-2\frac{m_t}{M_W}\mathrm{Re}\left[V_L g_R^*+V_R g_L^*\right]\left(1-x_W^2\right) \\
& +2\frac{m_t}{M_W}x_b\,\mathrm{Re}\left[V_L g_L^*+V_R g_R^*\right]\left(1+x_W^2\right)\,, \\
A_1 = {} & \frac{m_t^2}{M_W^2}\left[|V_L|^2-|V_R|^2\right]-\left[|g_L|^2-|g_R|^2\right]-2\frac{m_t}{M_W}\mathrm{Re}\left[V_L g_R^*-V_R g_L^*\right] \\
& +2\frac{m_t}{M_W}x_b\mathrm{Re}\left[V_L g_L^*-V_R g_R^*\right]\,, \\
B_0 = {} & \left[|V_L|^2+|V_R|^2\right]\left(1-x_W^2\right)+\frac{m_t^2}{M_W^2}\left[|g_L|^2+|g_R|^2\right]\left(1-x_W^2\right) \\
& -4x_b\,\mathrm{Re}\left[V_L V_R^*+g_L g_R^*\right]-2\frac{m_t}{M_W}\mathrm{Re}\left[V_L g_R^*+V_R g_L^*\right]\left(1-x_W^2\right) \\
& +2\frac{m_t}{M_W}x_b\,\mathrm{Re}\left[V_L g_L^*+V_R g_R^*\right]\left(1+x_W^2\right)\,,
\end{aligned}
$$

$$
\Gamma_0=\frac{g^2|\vec{q}|}{32\pi}A_0 \qquad \Gamma_\pm=\frac{g^2|\vec{q}|}{32\pi}\left(B_0\pm 2\frac{|\vec{q}|}{m_t}B_1\right)
$$

$$
\boxed{F_i \equiv \Gamma_i/\Gamma}
$$

$$
\begin{aligned}
\Gamma_0^T = \Gamma_0^N &= \frac{g^2|\vec{q}|}{32\pi}B_0\,, \\
\Gamma_\pm^T &= \frac{g^2|\vec{q}|}{32\pi}\left(\frac{A_0+B_0}{2}\pm\frac{\pi}{4}\frac{m_t}{M_W}C_0\right) \\
\Gamma_\pm^N &= \frac{g^2|\vec{q}|}{32\pi}\left(\frac{A_0+B_0}{2}\pm\frac{\pi}{4}\frac{|\vec{q}|}{M_W}D_1\right)
\end{aligned}
$$

Single top quark Cross Sections:

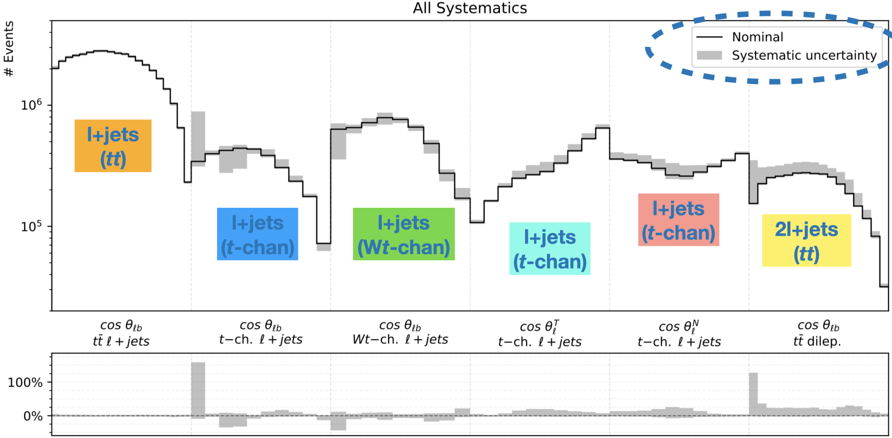


$$
\sigma=\sigma_{\mathrm{SM}}\left(V_{\mathrm{L}}^2+\kappa^{V_{\mathrm{R}}}\,V_{\mathrm{R}}^2+\kappa^{V_{\mathrm{L}}V_{\mathrm{R}}}\,V_{\mathrm{L}}V_{\mathrm{R}}+\kappa^{g_{\mathrm{L}}}\,g_{\mathrm{L}}^2+\kappa^{g_{\mathrm{R}}}\,g_{\mathrm{R}}^2+\kappa^{g_{\mathrm{L}}g_{\mathrm{R}}}\,g_{\mathrm{L}}g_{\mathrm{R}}+\ldots\right)
$$

Ready to Perform the Global Fit with Experimental Data!

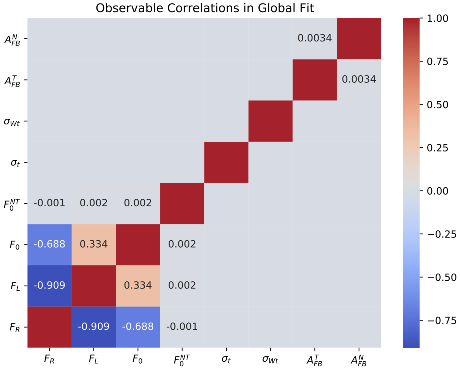
Global Fits of Data

Angular Distributions Fits with Systematics (JES,JER,Lumi,Xsec):

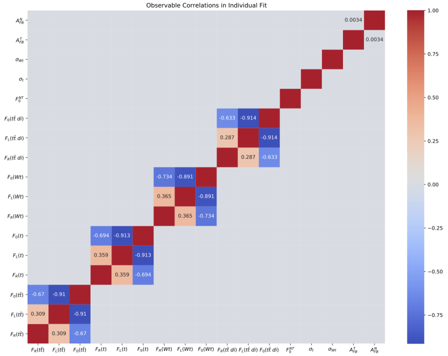


☞ Observables Correlations

Correlations for Global Fit

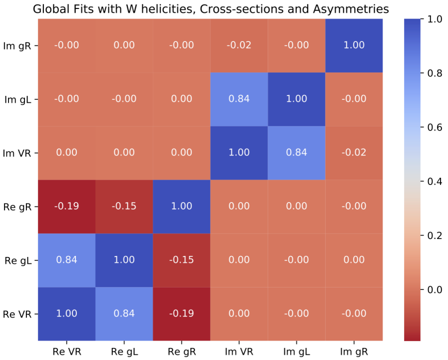


Correlations for Individual Fits

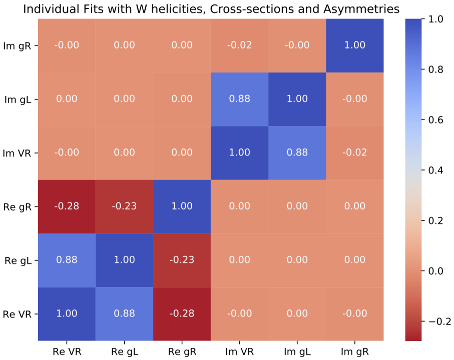


☞ Couplings Correlations (after fits, complex couplings)

Correlations for Global Fit



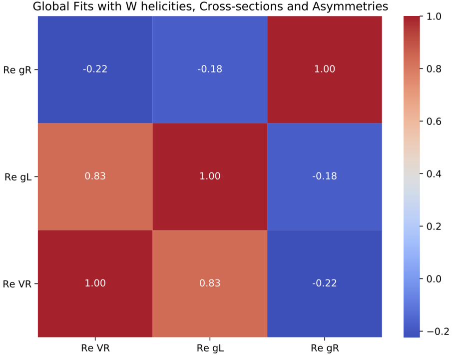
Correlations for Individual Fits



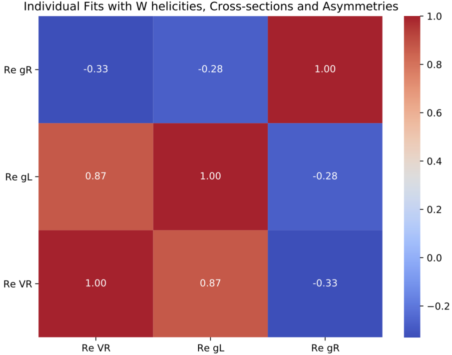
Global Fits of Data

☞ Couplings Correlations (after fits, real couplings)

Correlations for Global Fit

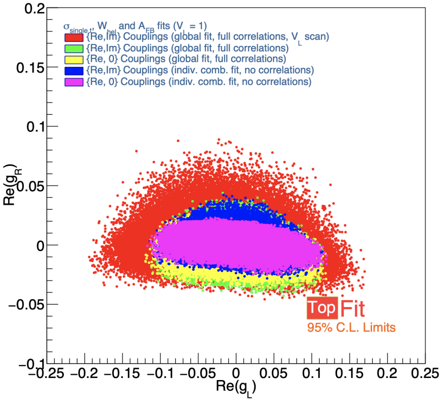


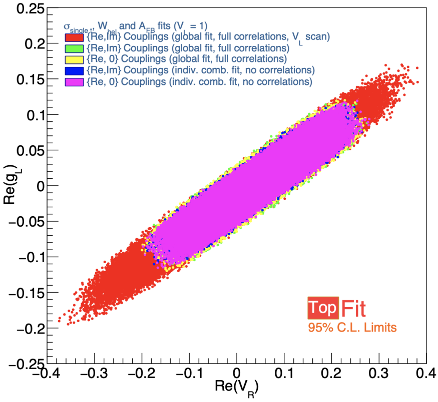
Correlations for Individual Fits



☞ Couplings Results (complex couplings)

Couplings Fit Results





Main Topics in this Talk

- Global Fits of Data
- Invisible systems in $t\bar{t}$ events

The LHC is a *t*-quark factory:

$t\bar{t} + \phi \; (\phi = H, \gamma, W, Z, DM, DE, 2HDM...)$

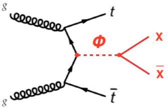
☞ precision SM tests $\oplus$ BSM

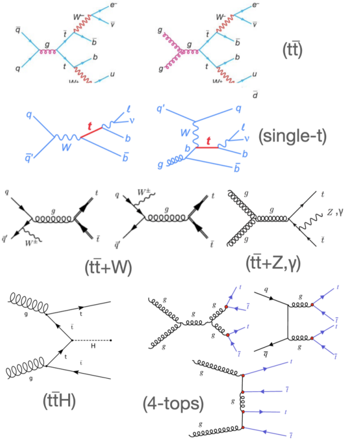
The goals:

☞ see if (invisible) BSM particles spoil $t\bar{t}$ Kine. Reconstruction and Precision Measurements

☞ take advantage of the fact that (invisible) BSM particles change $t\bar{t}$ Kine.

- Reconstruct the $t\bar{t}$ system (2ℓ)
- Explore Spin Physics Observables ($t\bar{t}$ angular dist., $m_{t\bar{t}}$, $p_T(t\bar{t})$,...)
- $t\bar{t} + \phi$ production @ LHC
  [JHEP 11 (2023) 125 ($\phi = \phi_{DM}$)]
  [Phys.Rev.D 110 (2024) 7]
  [JHEP 09 (2022) 246 ($\phi = h_{SM}$)]
  [recently in the context of a 2HDM: $\phi = H2 \oplus H3$]

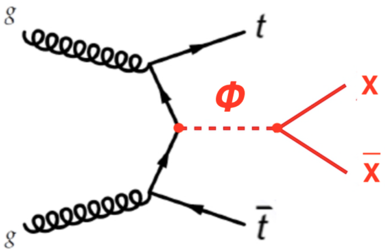




Final State Topology: ☞ $t\bar{t}\phi_{DM} \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)\phi_{DM}$

☞ Event Generation @ 13.6 TeV:

- MadGraph5_aMC@NLO JHEP **1407**, 079 (2014) J.Alwall *et al.*
  $\oplus$ NNPDF2.3 PDF NPB **867** 244 (2013) R.D.Ball *et al.*
  for $t\bar{t}\phi_{DM}$ (@ NLO)
  other backgrounds @ LO with MLM:
  $t\bar{t}+jets$, $t\bar{t}V+jets$, Single t,
  $W(Z)$+jets, $W(Z)b\bar{b}$+jets, VV+jets
- Full spin correlation of $t \rightarrow bW^+ \rightarrow b\ell^+\nu_\ell$,
  $\bar{t} \rightarrow \bar{b}W^- \rightarrow \bar{b}\ell^-\bar{\nu}_\ell$, ϕ_{DM} (invisible)
  by MadSpin JHEP **1303**, 015 (2013) P. Artoisenet *et al.*
- Shower and hadronization by Pythia
  JHEP **0605**, 026 (2006) T. Sjostrand, S.Mrenna, P.Z.Skands



☞ Simulation: DELPHES 3 (default ATLAS cards)

JHEP **1402**, 057 (2014)

J. de Favereau, C.Delaere, P. Demin, A.Giammanco, V. Lemaître, A.Mertens, M.Selvaggi

☞ MadAnalysis5 and Event Selection:

EPJC **74, no. 10, 3103 (2014)** E.Conte, B.Dumont, B.Fuks, C.Wymant

N_{jets} **≥2 (p_T ≥20 GeV, $|\eta|$ ≤2.5)** $\oplus$ N_{lep} **≥2 (p_T ≥20 GeV, $|\eta|$ ≤2.5)**

Final State Topology: ☞ $t\bar{t}\phi_{DM} \to (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)\phi_{DM}$

☞ A- Before Reconstruction pair Jets and Leptons from correct $t(\bar{t})$

☞ B- Constrained Kinematic fit

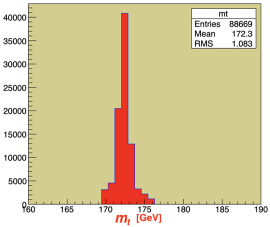
I- Mass constraints (2D-distributions):

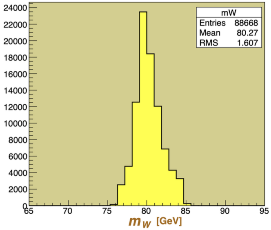
(1) $(p_{W^+} + p_b)^2 = m_t^2$

(2) $(p_{W^-} + p_{\bar{b}})^2 = m_{\bar{t}}^2$

(3) $(p_{\ell^+} + p_\nu)^2 = m_{W^+}^2$

(4) $(p_{\ell^-} + p_{\bar{\nu}})^2 = m_{W^-}^2$





II- Missing Transverse Energy (use p.d.f.):

(1) $p_x^\nu + p_x^{\bar{\nu}} = \not{E}_x$

(2) $p_y^\nu + p_y^{\bar{\nu}} = \not{E}_y$

III- Likelihood probability (use p.d.f.):

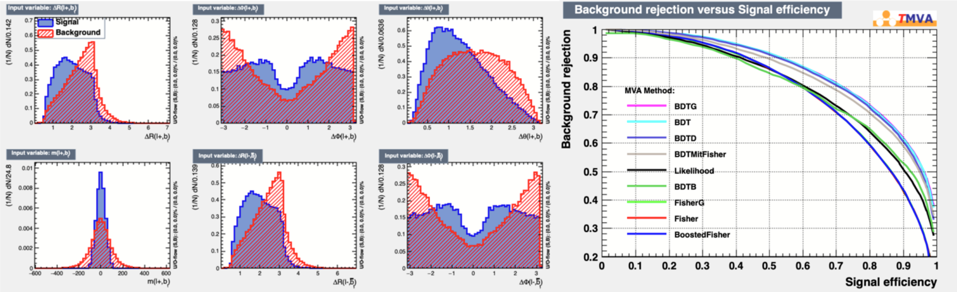
(1) $L_{t\bar{t}H} = \frac{1}{p_{T_\nu} p_{T_{\bar{\nu}}}} P(p_{T_\nu}) P(p_{T_{\bar{\nu}}}) \times P(p_{T_t}) P(p_{T_{\bar{t}}}) P(m_t, m_{\bar{t}}) P(p_{T_{t\bar{t}}})$

Invisible systems in $t\bar{t}$ events

Final State Topology: ☞ $t\bar{t}\phi_{DM} \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)\phi_{DM}$

☞ A- Before Reconstruction pair Jets and Leptons from correct $t(\bar{t})$

Use TMVA with Jets,Leptons Angular Distributions [13 distributions]

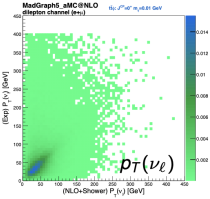


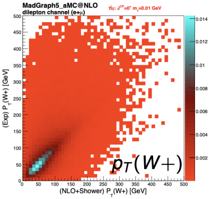
Invisible systems in $t\bar{t}$ events

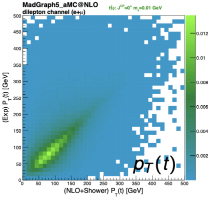
Final State Topology: ☞ $t\bar{t}\phi_{DM} \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)\phi_{DM}$

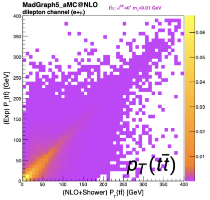
☞ B- Constrained Kinematic fit

$m_\phi = 0.01\,GeV$

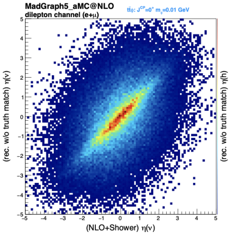




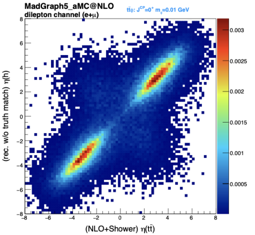




$\eta(\nu_\ell)$

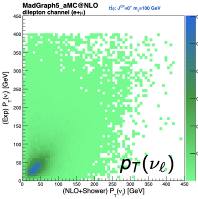


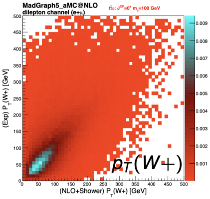
$\eta(t\bar{t})$



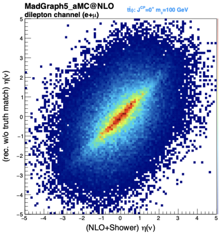
Final State Topology: ☞ $t\bar{t}\phi_{DM} \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)\phi_{DM}$

☞ B- Constrained Kinematic fit $m_\phi = 100GeV$

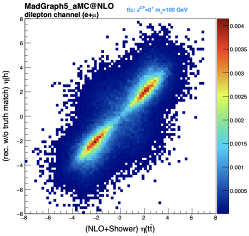


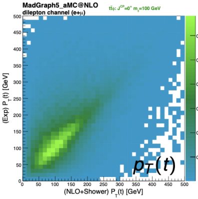


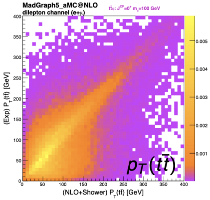
$\eta(\nu_\ell)$



$\eta(t\bar{t})$



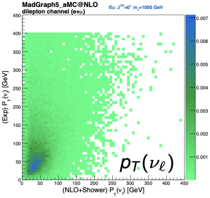


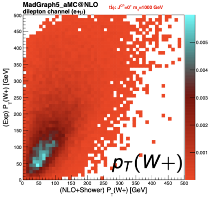


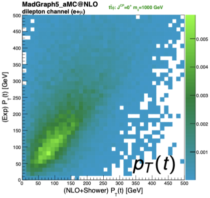
Final State Topology: ☞ $t\bar{t}\phi_{DM} \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)\phi_{DM}$

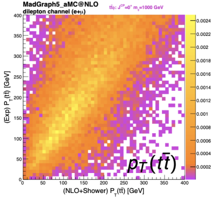
☞ B- Constrained Kinematic fit

$m_\phi = 1000\,GeV$

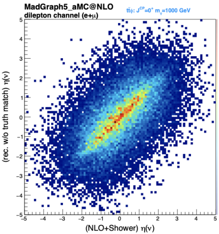




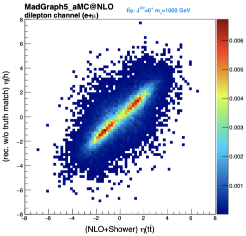




$\eta(\nu_\ell)$



$\eta(t\bar{t})$

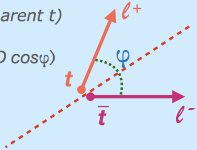


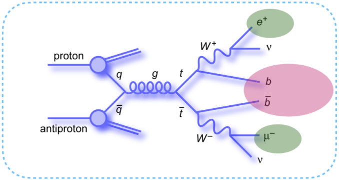
Spin Observables May Be Used to Probe Invisible Particles

i) opening angle (leptons in their parent t)

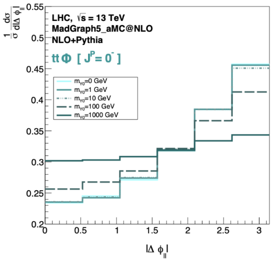
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

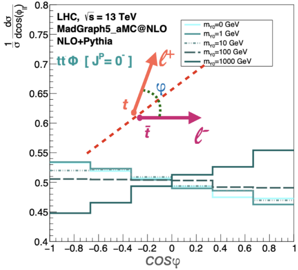
ii) $\Delta\phi_{ll}$ in LAB frame





Leptons azimuthal angle difference (LAB)





END