# Studying the CP nature of the Higgs couplings in $t\bar{t}H$ events @ the LHC

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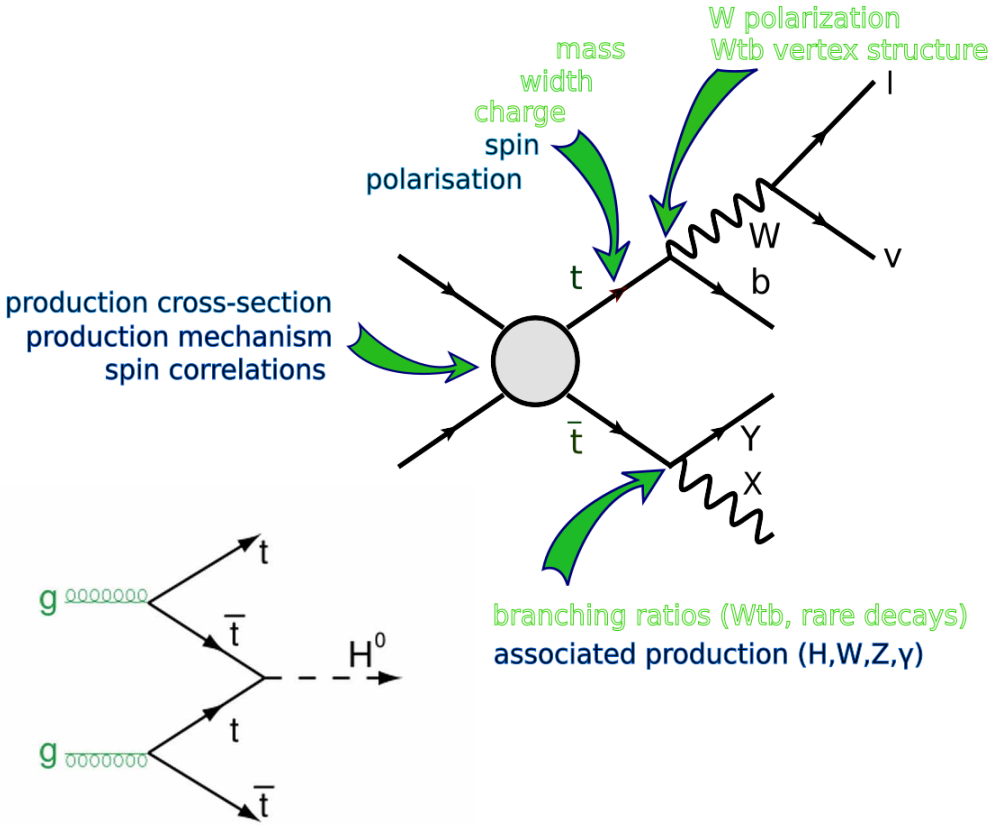
# The phenomenology of Top and Higgs Physics is very Rich. ☞ Understanding the interplay is quite important

## List of Topics Covered

☞ all about ....

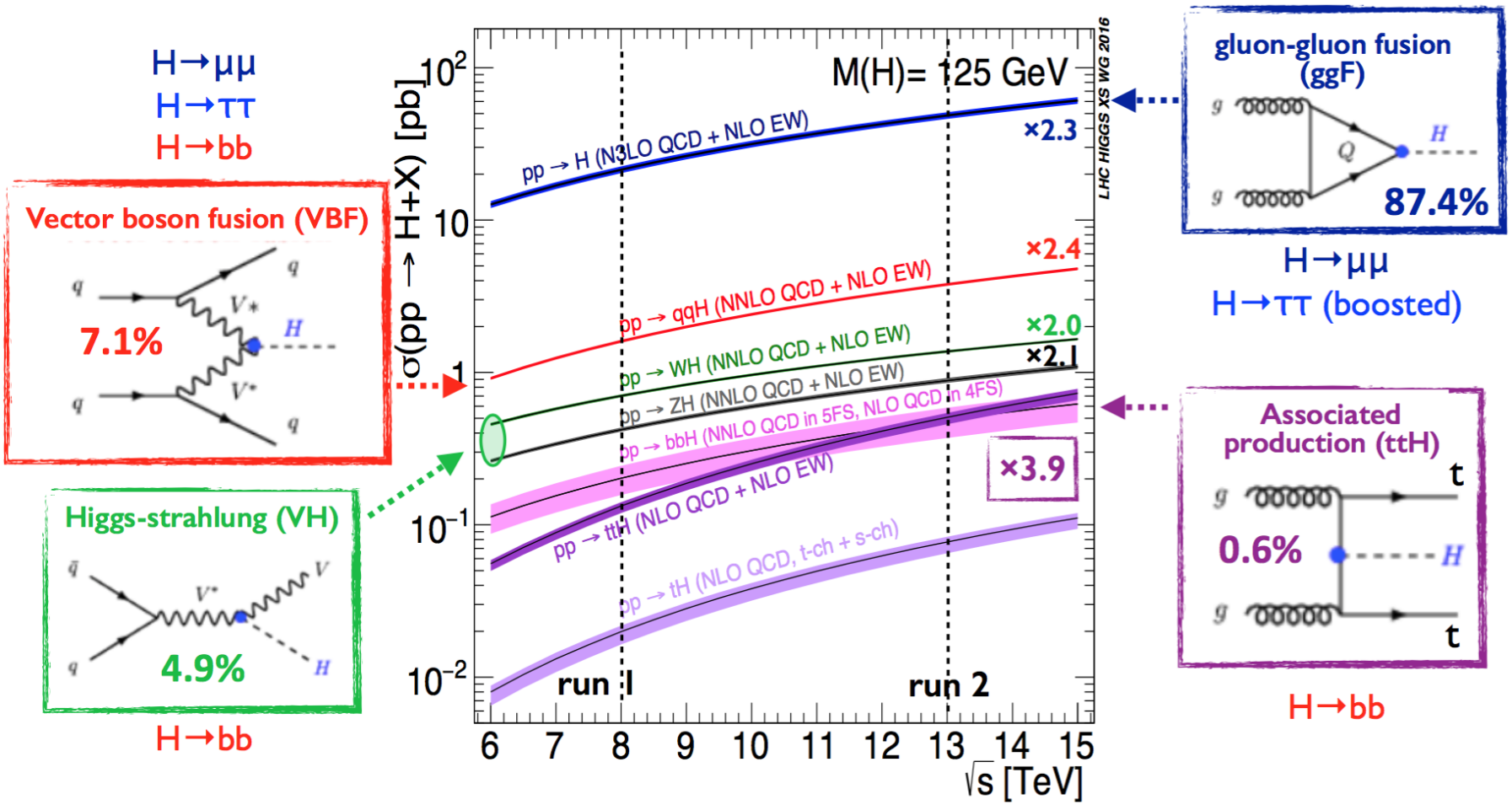
Top-Higgs Couplings!

- Introduction
- Experimental Results
- Studying $t\bar{t}H$ events @ LHC
  - Generation, Simulation and Analysis (MadGraph, MadAnalysis5@pheno)
  - Signal Reconstruction
  - Dealing with backgrounds (SM and combinatorial)
  - Observables Reconstruction
  - New Angular Distributions and Asymmetries (LO vs NLO)
- Conclusions



# Introduction

☞ thanks to E.Shabalina for this nice summary!

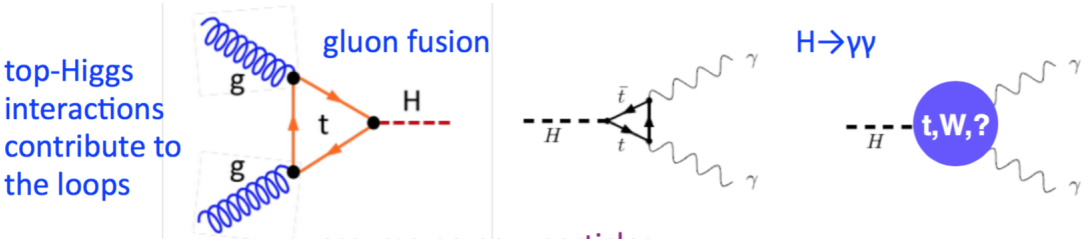



- VH and ttH production mechanisms haven't been observed yet
- These are the most promising channels to observe Higgs to bottom coupling

# Introduction

☞ all about top quark-Higgs Couplings!

- the top quark has the biggest coupling to the Higgs SM boson ($Y_t \sim 1.$)
- precision measurements of top quark Yukawa couplings are really important
- .....as well as deviations !!!
- need also to understand the nature of the coupling ($h = H, A$)
- indirect constraints are important (involve several contributions)




☞ probing CP-even($a$) -odd($d$) nature of couplings in $t\bar{t}H$, $L_{hf\bar{f}} \sim (a_f + ib_f\gamma_5)$

PRL **76**, 24 (1996)
J.F.Gunion, Xiao-Gang He

PRD **92**, 1 (2015)
F.Boudjema, R.M.Godbole, D.Guadagnoli, K.A.Mohan

$$a_1, a_2, b_1, b_2, b_3 \ldots b_4 = \frac{p_t^z p_{\bar{t}}^z}{|\vec{p}_t||\vec{p}_{\bar{t}}|}$$

$$\Delta\phi^{t\bar{t}}(l+, l-),\ \beta_{b\bar{b}}\Delta\theta^{lh}(l+, l-)$$

$$\beta \equiv \mathrm{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})\right) \qquad \cos(\Delta\theta^{\ell h}(\ell^+, \ell^-)) = \frac{(\vec{p}_h \times \vec{p}_{\ell^+}) \cdot (\vec{p}_h \times \vec{p}_{\ell^-})}{|\vec{p}_h \times \vec{p}_{\ell^+}||\vec{p}_h \times \vec{p}_{\ell^-}|}$$

- spin averaged $\sigma$ is proportional to $(a_f^2 - b_f^2) * m_f^2$ ☞ $t\bar{t}H$ will be very sensitive to $(a_f^2 - b_f^2)$
- $\sigma$ alone not enough to measure vertex completely ☞ need $t\bar{t}H$ production and decay kinematics

# Experimental Results

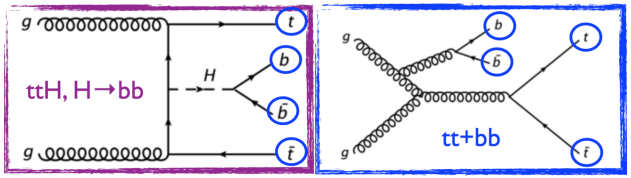
# Experimental Results

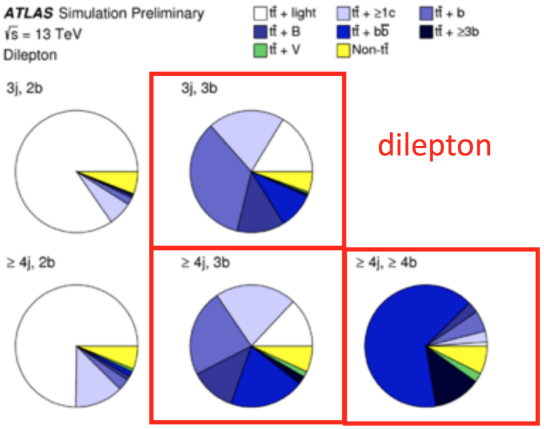
## Measurements by ATLAS @ 13 TeV

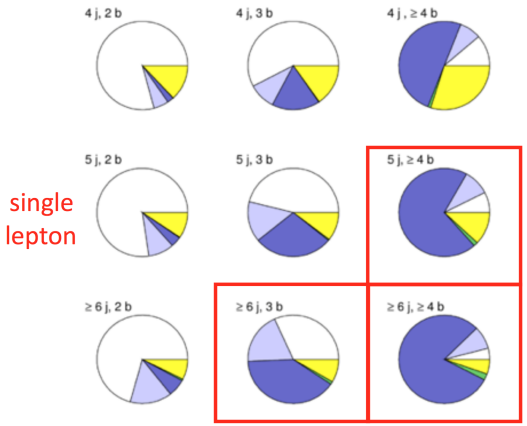
☞ $t\bar{t}H$: $H \to \gamma\gamma, WW, \tau\tau, ZZ, b\bar{b}$

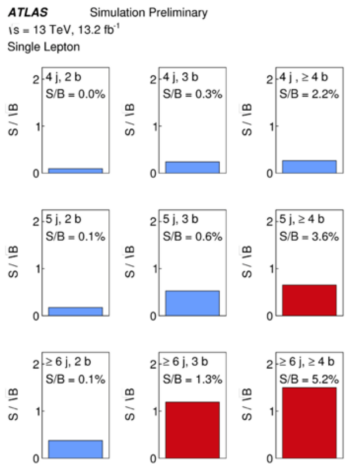
$H \to b\bar{b}$ [ATLAS-CONF-2016-068]

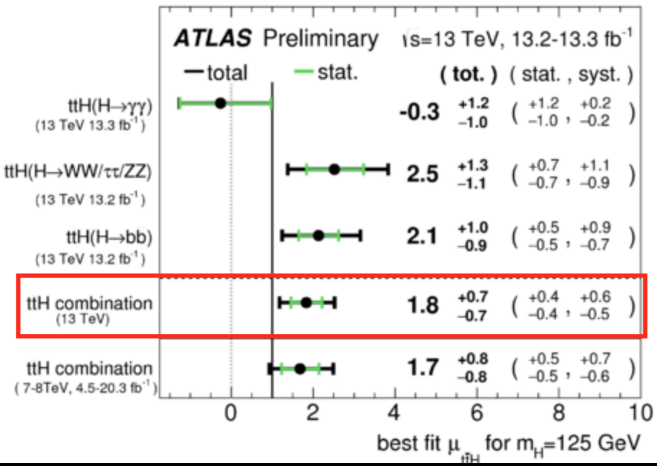
Signal Backg.

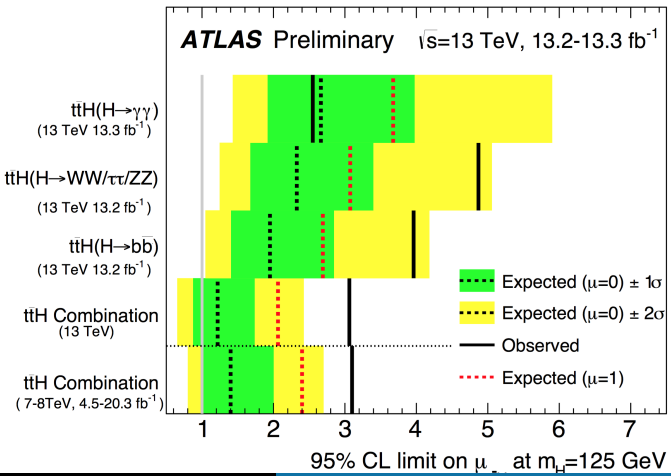


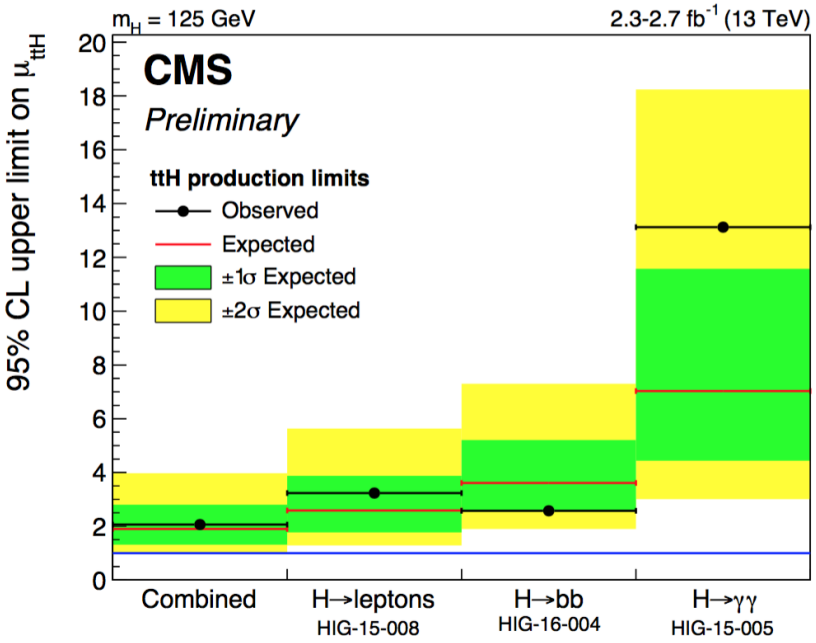




☞ Run 2 signif. already better then RUN I

## Measurements by CMS @ 13 TeV

☞ $t\bar{t}H$: $H \to \gamma\gamma$, *leptons*, $ZZ$, $b\bar{b}$

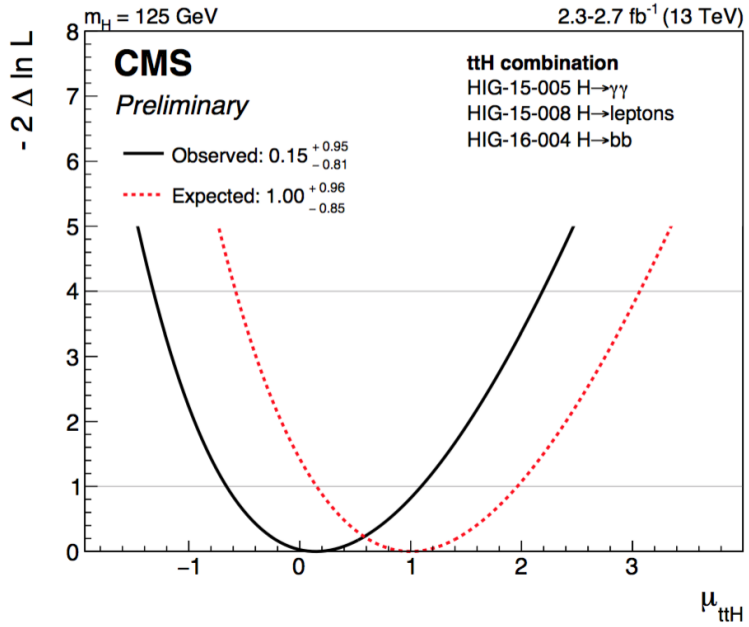
### 95% CL upper limit on $\mu_{ttH}$




**Observed limit on $\mu_{ttH}$ = 2.1 x SM**

Expected limit on $\mu_{ttH}$ = 1.9 x SM

### ttH signal strength




**Observed $\mu_{ttH}$ = 0.15 +0.95/-0.81**

Expected $\mu_{ttH}$ = 1.00 +0.96/-0.85

Other SM signal processes fixed to SM rates

**Run I results at 8 TeV:** **Obs. (Exp.) limit: 4.5 (2.7)** **Best fit μ = 2.8 +1.0/-0.9** JHEP 09 (214) 087

# Studying $t\bar{t}H$ events @ the LHC

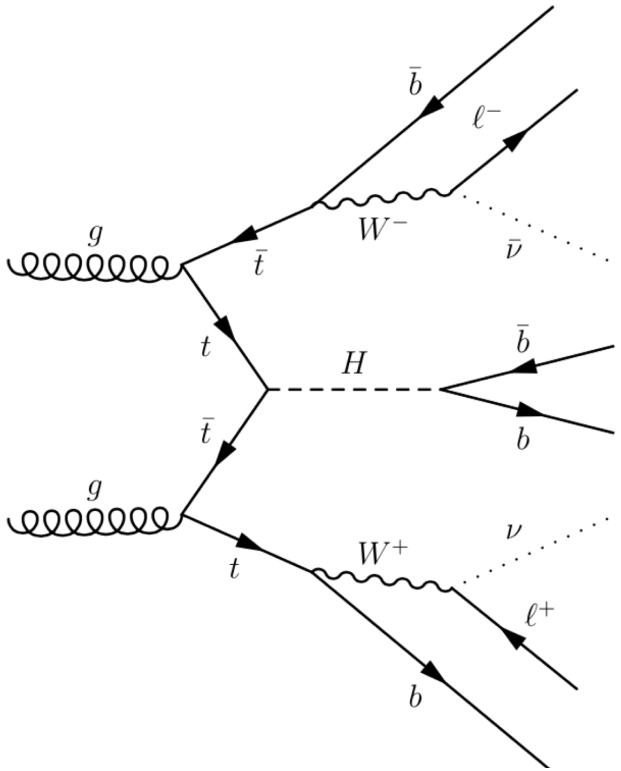
# Studying $t\bar{t}H$ events @ LHC

## Choice of a Particularly Challenging Final State Topology:

☞ $t\bar{t}H \to (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)(b\bar{b})$ **(dileptonic topology)**

☞ Event Generation @ 13 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 $t\bar{t}X, X = A, H$ and $t\bar{t}b\bar{b}$ (@ 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 $t \to bW^+ \to b\ell^+\nu_\ell$,
  $\bar{t} \to \bar{b}W^- \to \bar{b}\ell^-\bar{\nu}_\ell$, $H \to b\bar{b}$
  by MadSpin JHEP **1303**, 015 (2013) P. Artoisenet *et al.*
- Shower and hadronization by Pythia 6
  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

$N_{jets} \geq$**4 ($p_T \geq$20 GeV, $|\eta| \leq$2.5)** $\oplus$ $N_{lep} \geq$**2 ($p_T \geq$20 GeV, $|\eta| \leq$2.5)**

# Studying $t\bar{t}H$ events @ LHC

## Dileptonic Signal Reconstruction:

☞ $t\bar{t}H \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)(b\bar{b})$

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

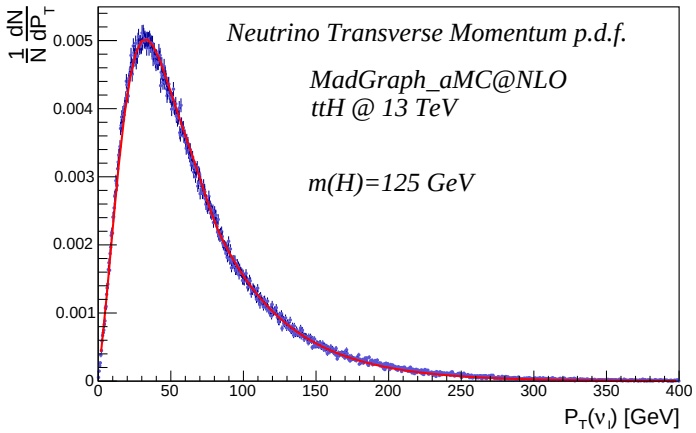
II- Missing Transverse Energy (use p.d.f.):

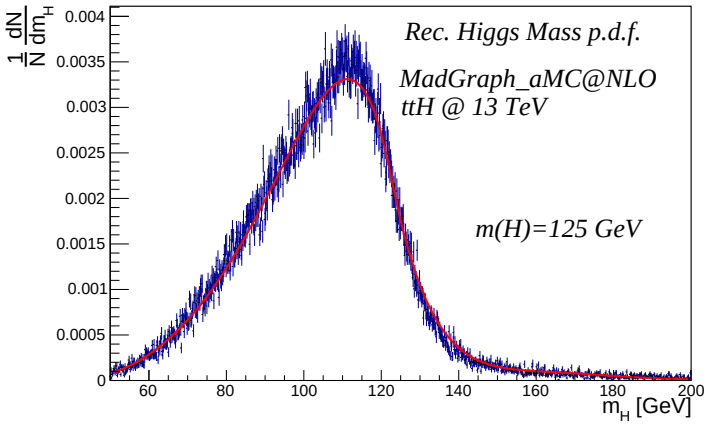
(1) $p_x^\nu + p_x^{\bar{\nu}} = \not{E}_x$

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

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

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



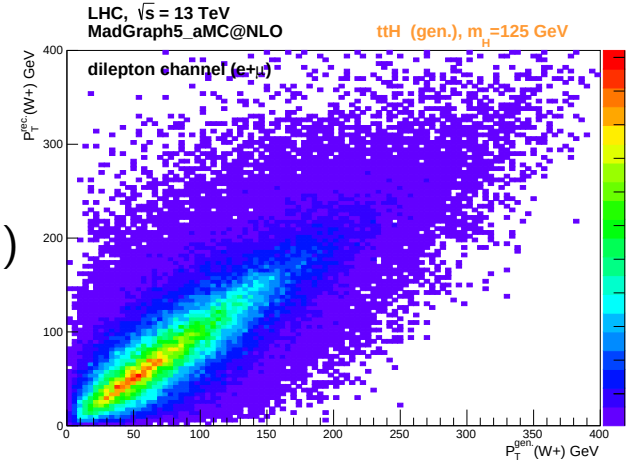




☞ Two steps: Reconstruction (1) with and (2) without Truth Match, i.e., imposing Reconstructed objects close to Parton objects (based on $\Delta R$) criteria

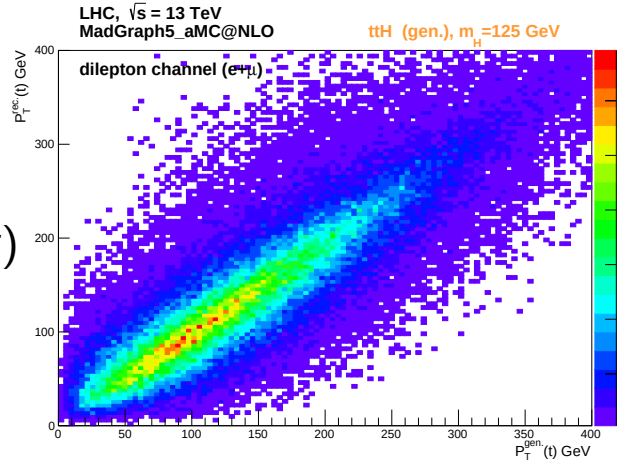
# Studying $t\bar{t}H$ events @ LHC

☞ (1) Reconstruction WITH Truth Match $|\Delta R(\ell_{parton}, \ell_{rec.})|<0.1$ and $|\Delta R(\ell_b, \ell_{iets})|<0.5$

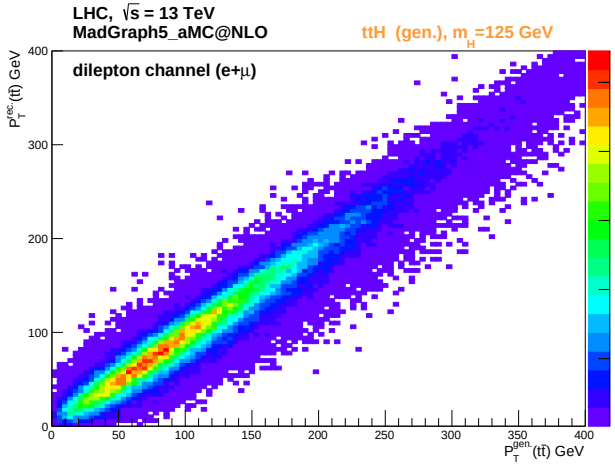
$p_T(W+)$




$p_T(t)$




$p_T(t\bar{t})$




$p_T(H)$

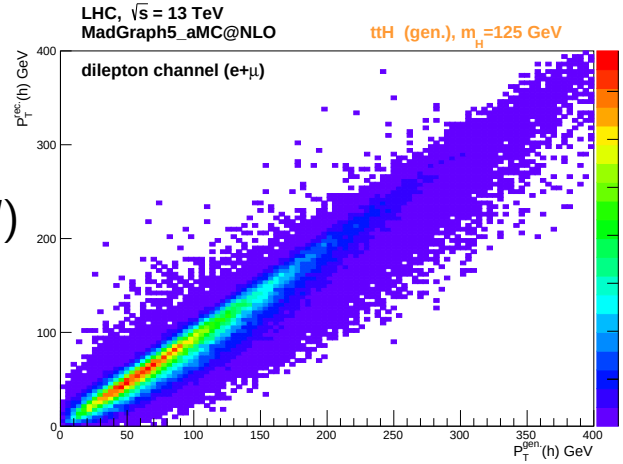
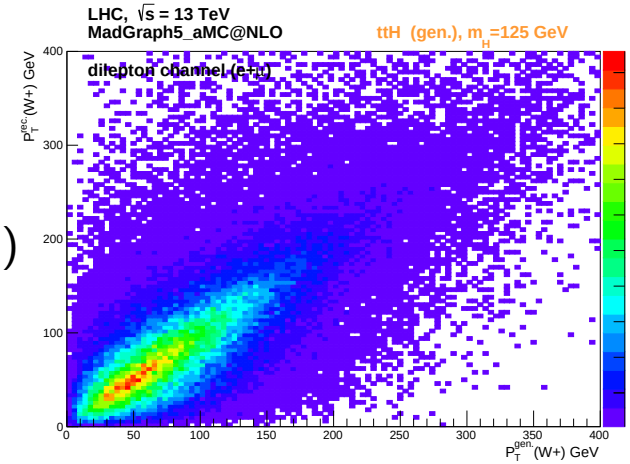



**Figure 2:** Two-dimensional distributions of $p_T$ in $t\bar{t}H$ events. The horizontal axes represent variables recorded at parton level, and the vertical axes represent the corresponding variables recorded at reconstruction level with truth-match. Upper-left: distribution for $W^+$. A similar distribution is obtained for $W^-$, but is not shown here. Upper-right: distribution for $t$. A similar distribution is obtained for $\bar{t}$, but is not shown here. Lower-left: distribution for $t\bar{t}$. Lower-right: distribution for $H$.

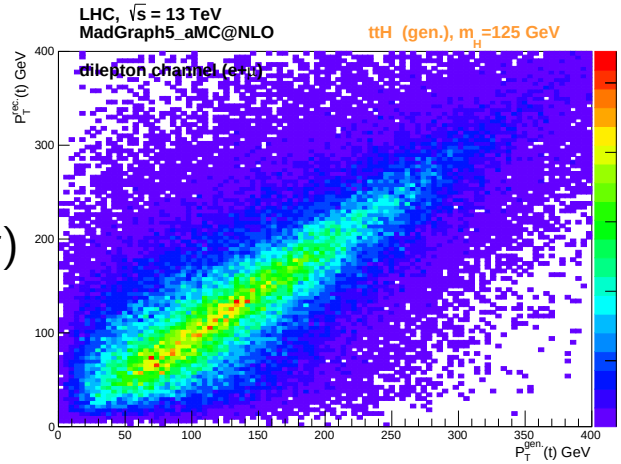
# Studying $t\bar{t}H$ events @ LHC

☞ (1) Reconstruction WITHOUT Truth Match

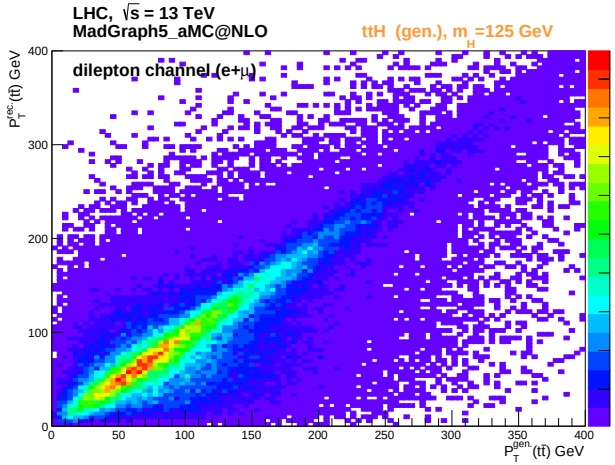
$p_T(W+)$




$p_T(t)$




$p_T(t\bar{t})$




$p_T(H)$

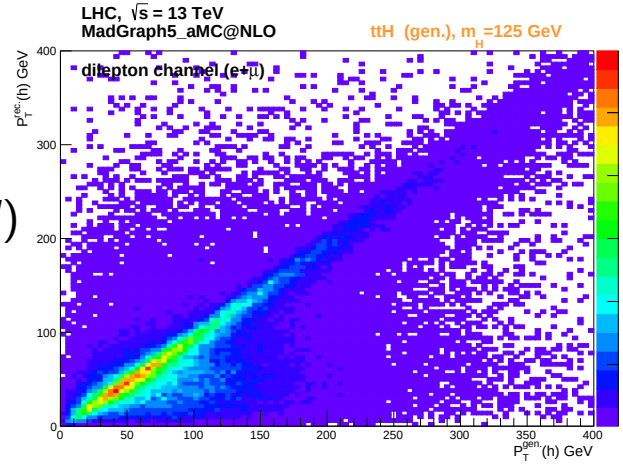



**Figure 3:** Two-dimensional distributions of $p_T$ in $t\bar{t}H$ events. The horizontal axes represent variables recorded at parton level, and the vertical axes represent the corresponding variables recorded at reconstruction level without truth-match. Upper-left: distribution for $W^+$. A similar distribution is obtained for $W^-$, but is not shown here. Upper-right: distribution for $t$. A similar distribution is obtained for $\bar{t}$, but is not shown here. Lower-left: distribution for $t\bar{t}$. Lower-right: distribution for $H$.

# Studying $t\bar{t}H$ events @ LHC

☞ (1) Reconstruction WITHOUT Truth Match

Combinatorial Background is a major concern !!!

☞ Use BDTs to discriminate wrong from right combinations:

$\Delta R(\ell^+, b_t)$, $\Delta\theta(\ell^+, b_t)$, $\Delta\phi(\ell^+, b_t)$, $m(\ell^+, b_t)$ use also $(\ell^-, \bar{b})$ and $(b_H, \bar{b}_H)$

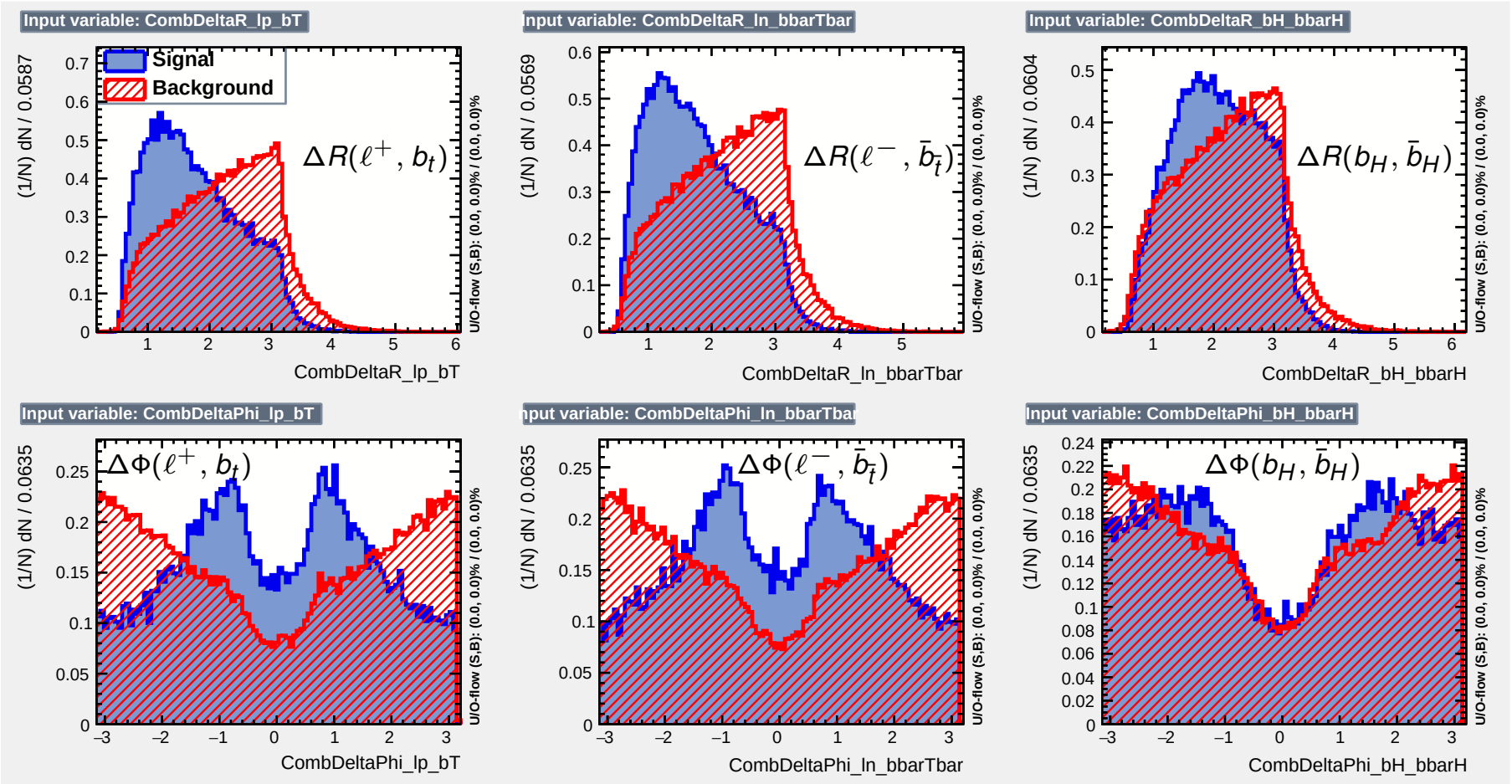


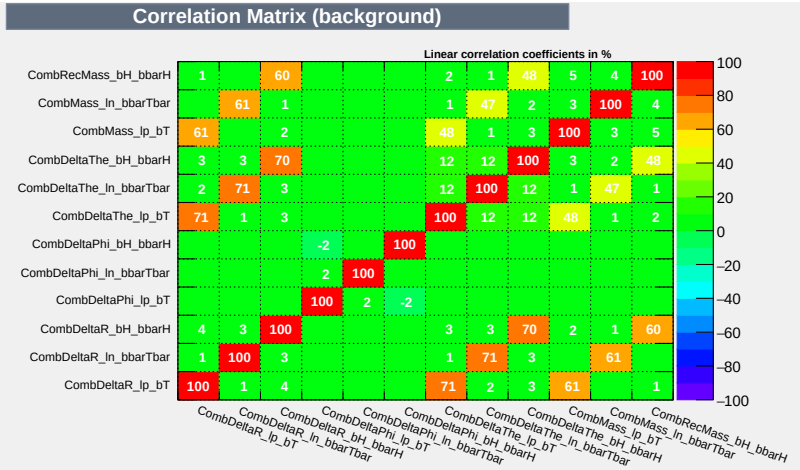

**Figure 3:** Distributions of the input variables for the signal and combinatorial background test samples.

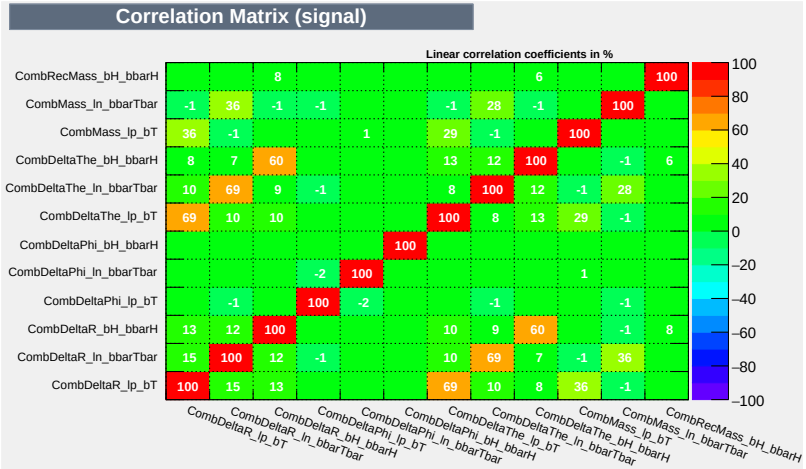
# Studying $t\bar{t}H$ events @ LHC

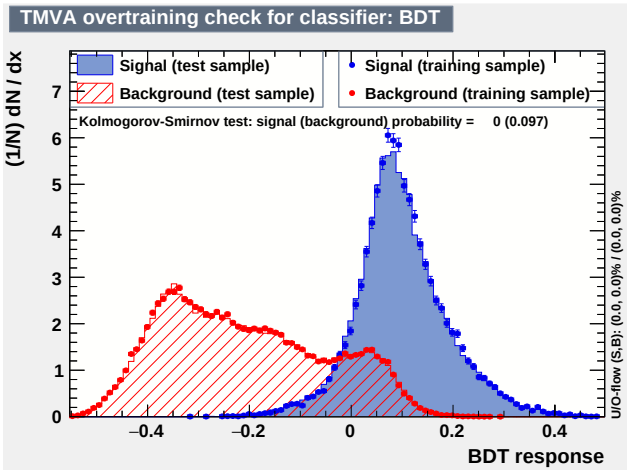
☞ (1) Reconstruction WITHOUT Truth Match

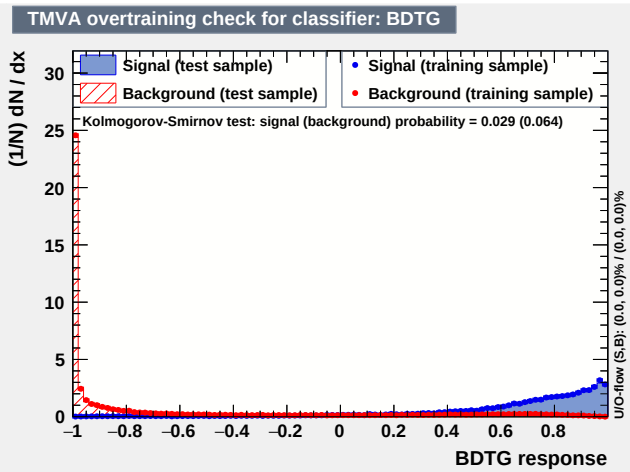
Combinatorial Background is a major concern !!!

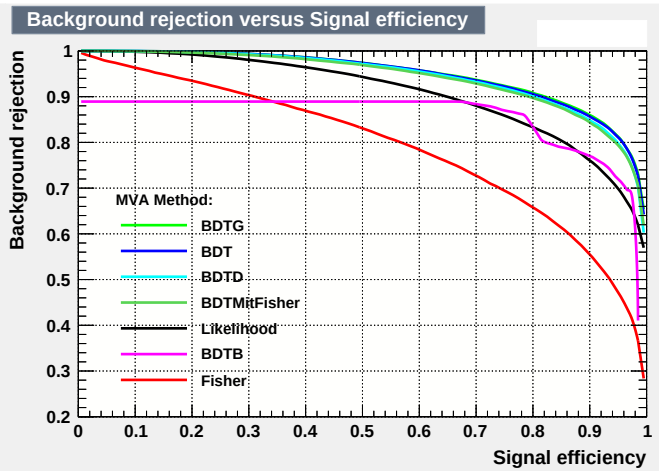
☞ Some correlations (diff. signal and back.) but significant association power



## Observables Reconstruction @ the LHC

parton level, after selection and full reconstruction...

# Studying $t\bar{t}H$ events @ LHC

☞ (1) PARTON LEVEL observables NO CUTs

no cuts whatsoever i.e.,

partons from MadGraph5_aMC@NLO ⊕ Pythia 6 event record

PRD **92**, 1 (2015)

F.Boudjema, R.M.Godbole, D.Guadagnoli, K.A.Mohan

PRL **76**, 24 (1996)

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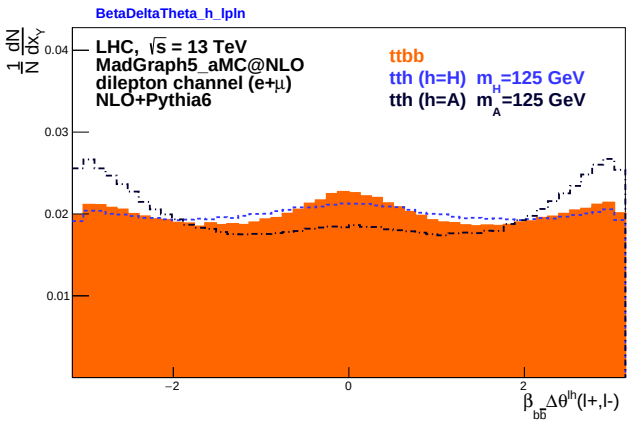


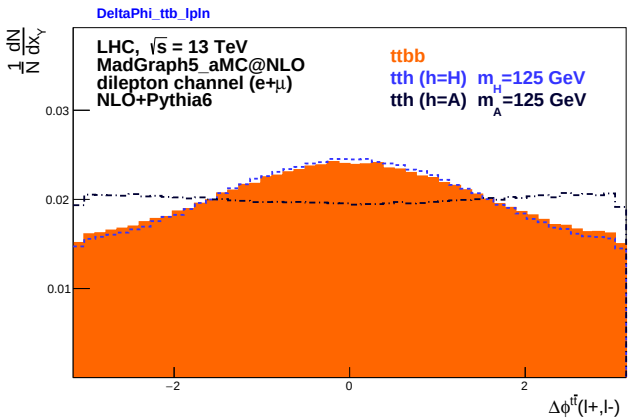


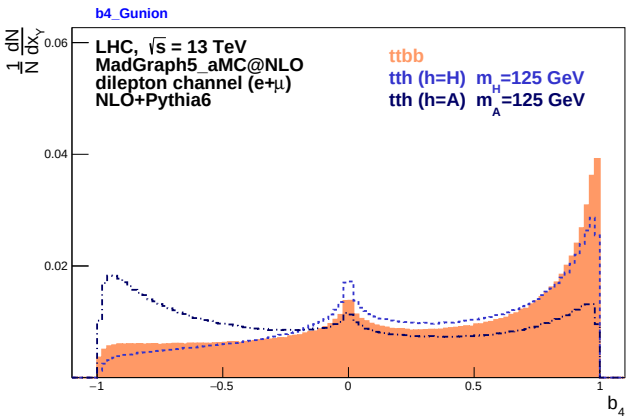


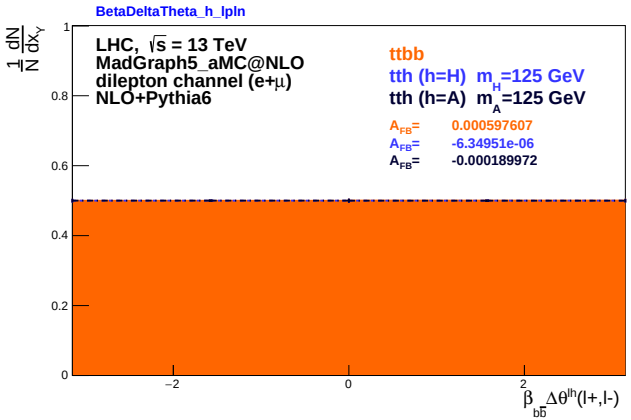


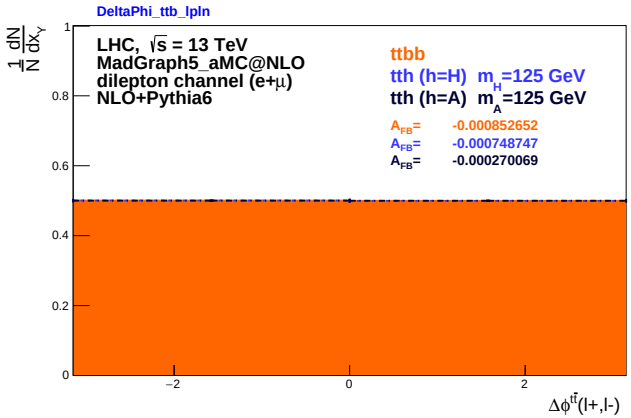


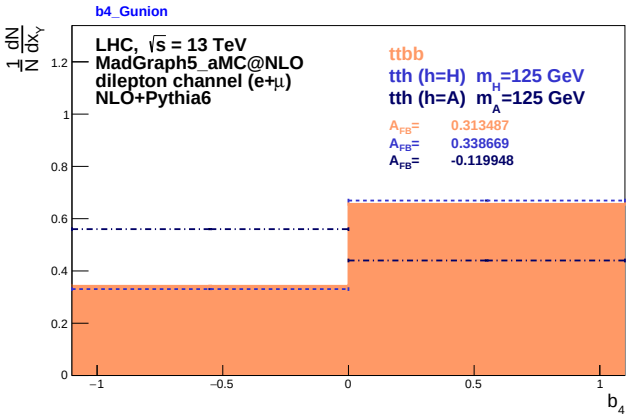

# Studying $t\bar{t}H$ events @ LHC

☞ (2) PARTON LEVEL observables WITH CUTs

AFTER SELECTION (no reconstruction)

check distortions from phase space constraints ($p_T$ and $|\eta|$ cuts)

PRD **92**, 1 (2015)

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PRL **76**, 24 (1996)

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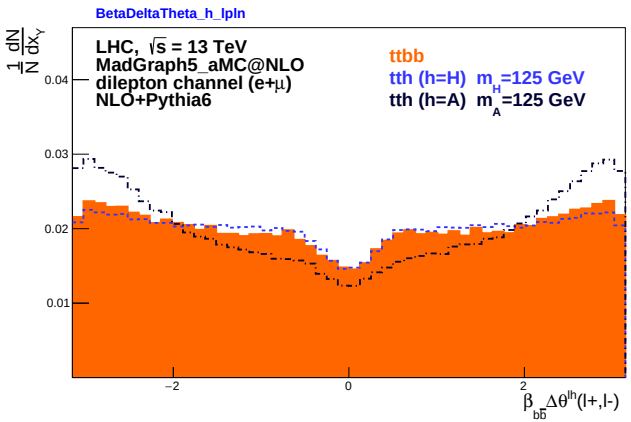
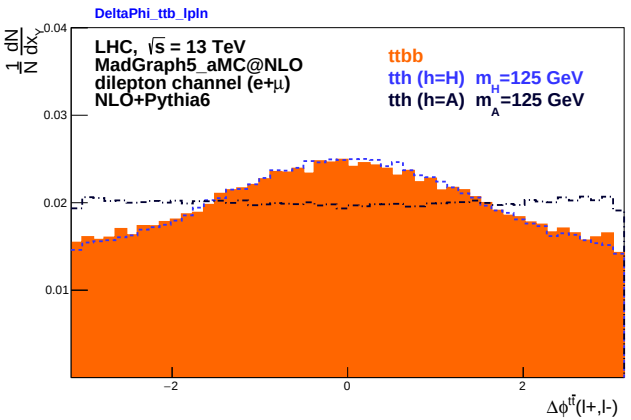
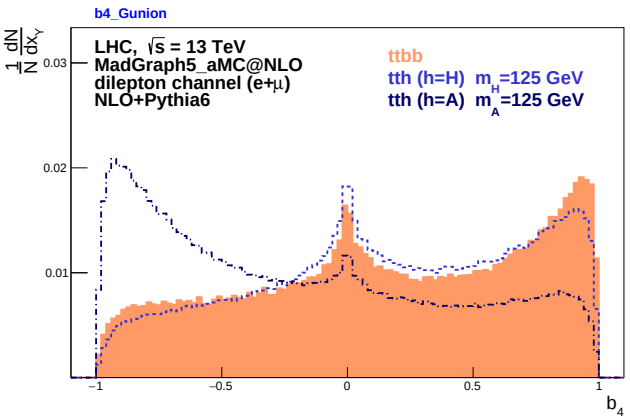
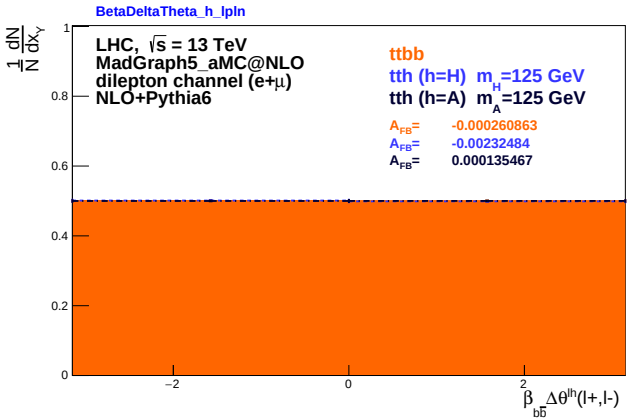
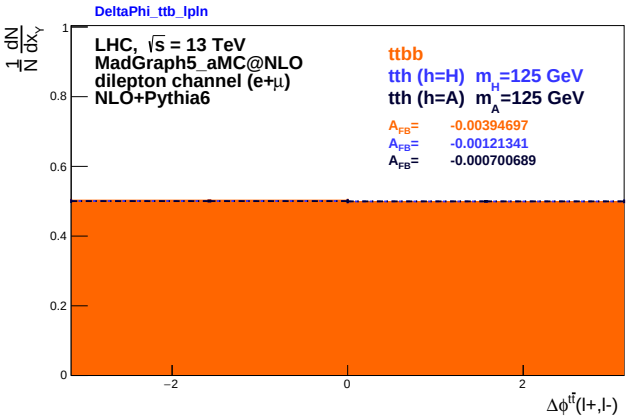
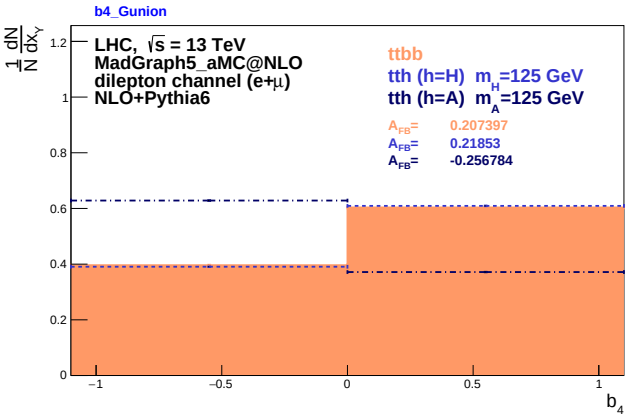


# Studying $t\bar{t}H$ events @ LHC

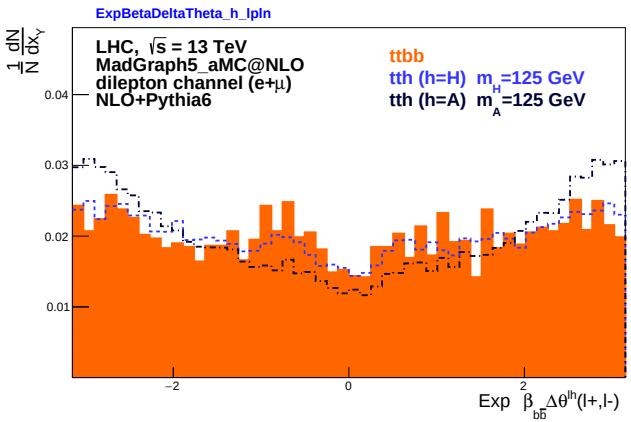
☞ (3) REC. LEVEL observables WITH CUTs $\oplus$ RECONSTRUCTION
AFTER SELECTION and KINEMATICAL RECONSTRUCTION
(just like in a regular experiment)

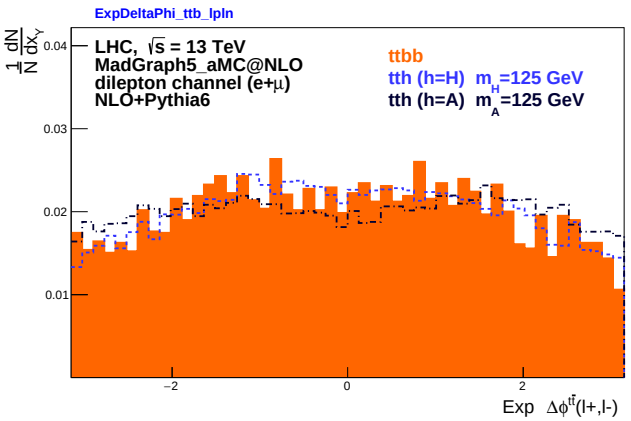
PRD **92**, 1 (2015)

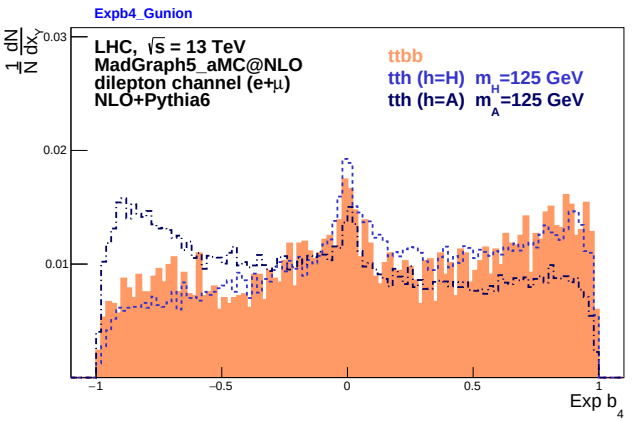
F.Boudjema, R.M.Godbole, D.Guadagnoli, K.A.Mohan

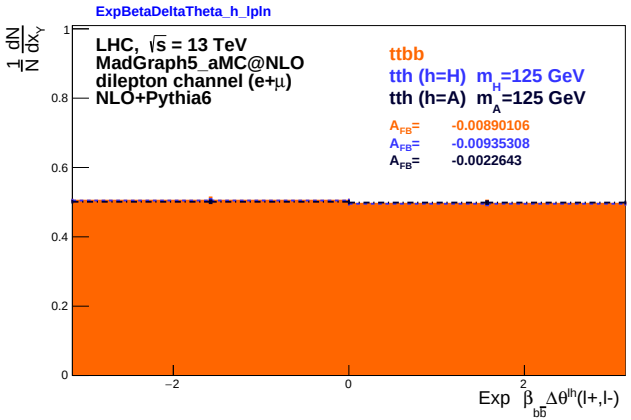
PRL **76**, 24 (1996)

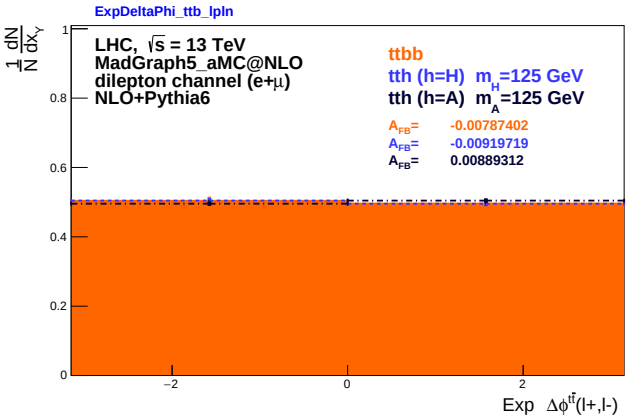
J.F.Gunion, Xiao-Gang He

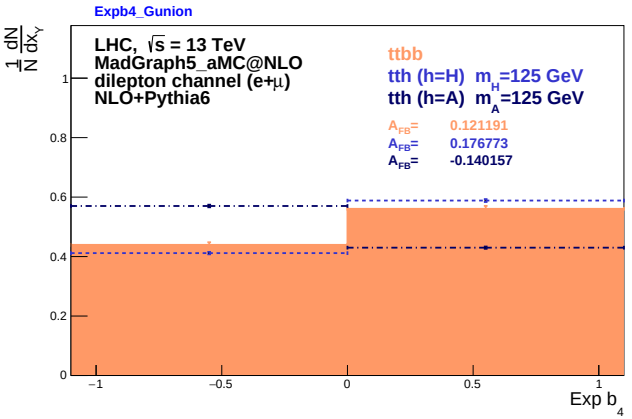


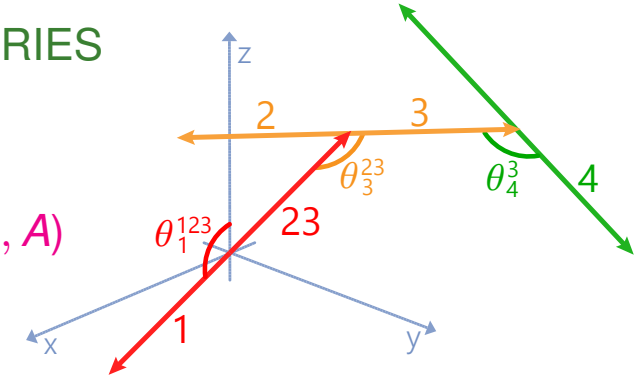
# Studying $t\bar{t}H$ events @ LHC

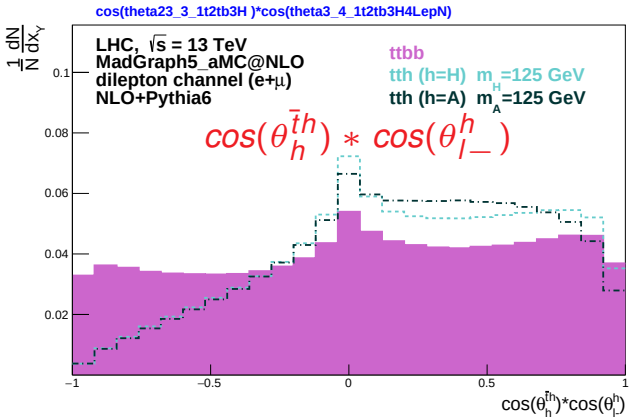
NEW ANGULAR DISTRIBUTIONS AND ASYMMETRIES

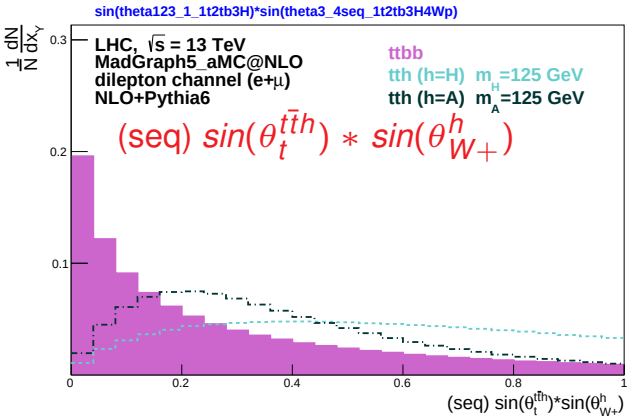
☞ (1) PARTON LEVEL observables NO CUTs

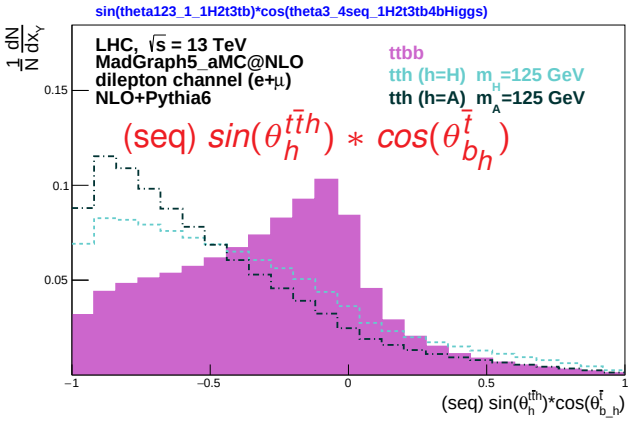
motivated by spin helicity formalism

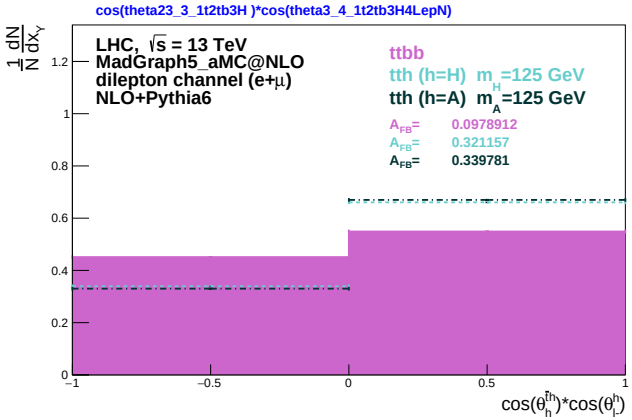
are there good discriminators to separate signals ($H$, $A$) from dominant backgrounds? Yes!

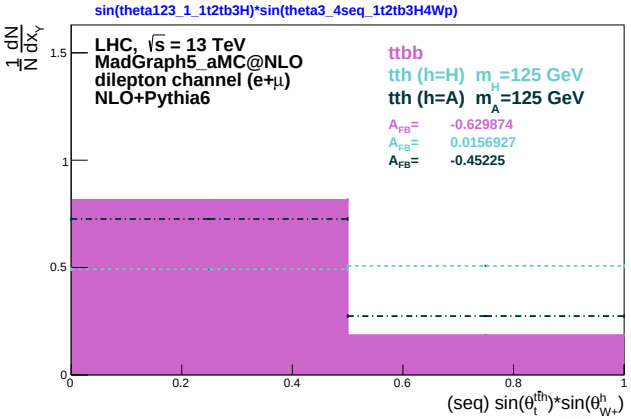


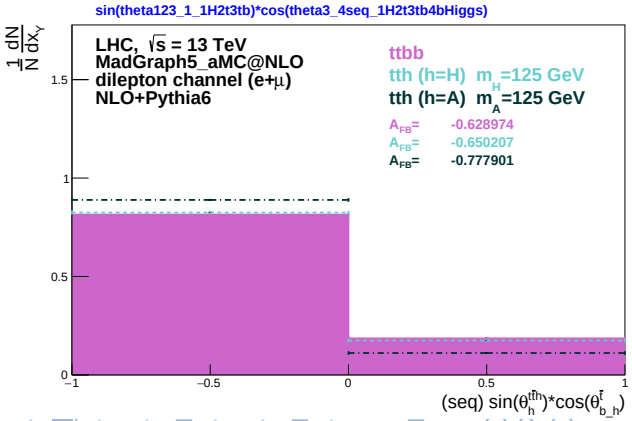



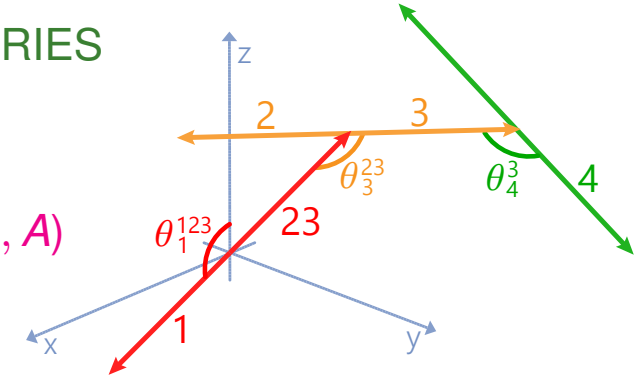
# Studying $t\bar{t}H$ events @ LHC

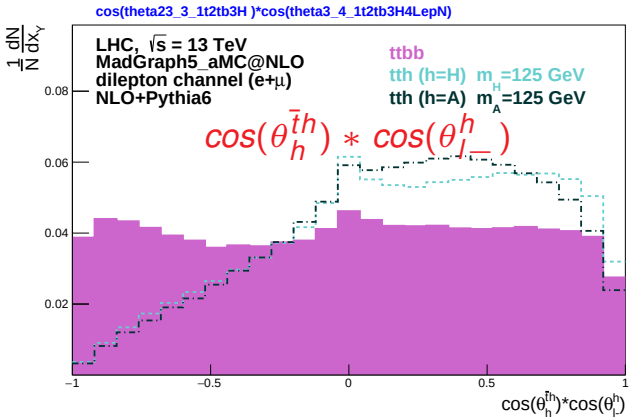
NEW ANGULAR DISTRIBUTIONS AND ASYMMETRIES

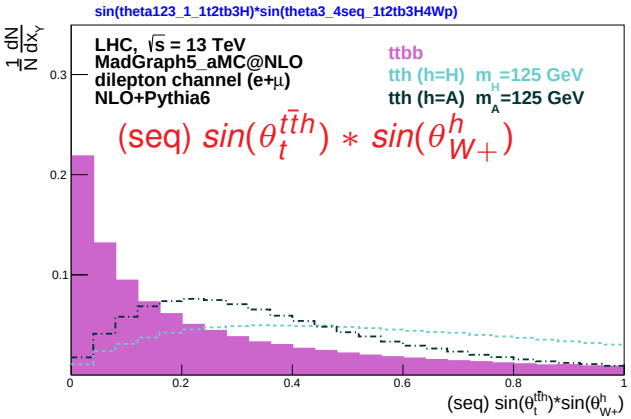
☞ (2) PARTON LEVEL observables WITH CUTs

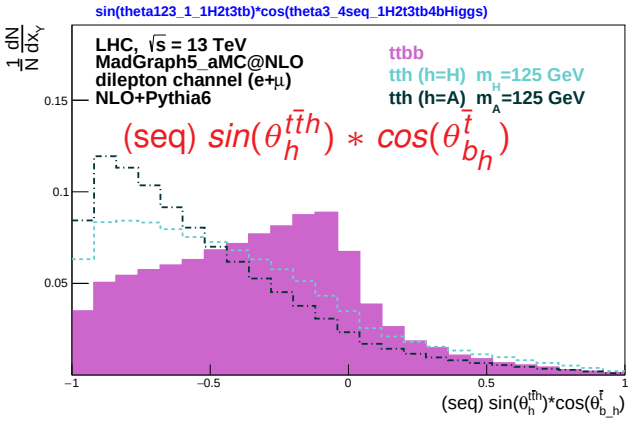
motivated by spin helicity formalism

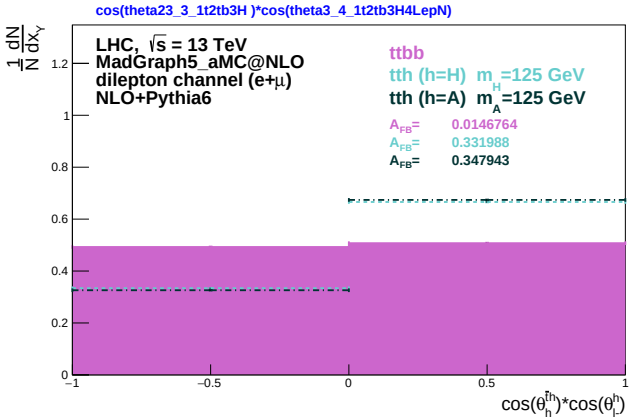
are there good discriminators to separate signals ($H$, $A$) from dominant backgrounds? Yes!

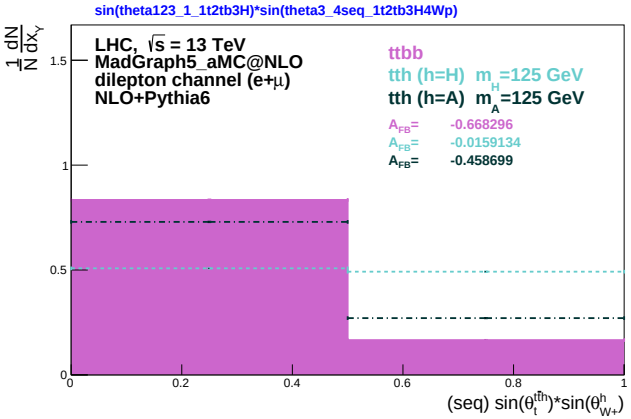


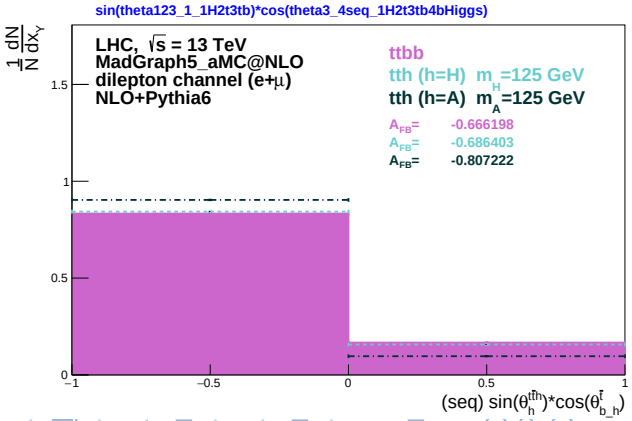



# Studying $t\bar{t}H$ events @ LHC

NEW ANGULAR DISTRIBUTIONS AND ASYMMETRIES

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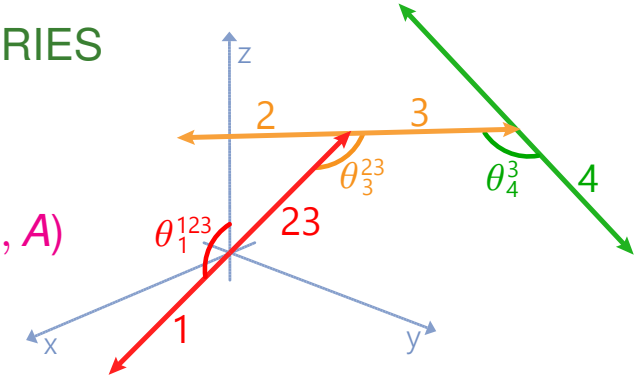
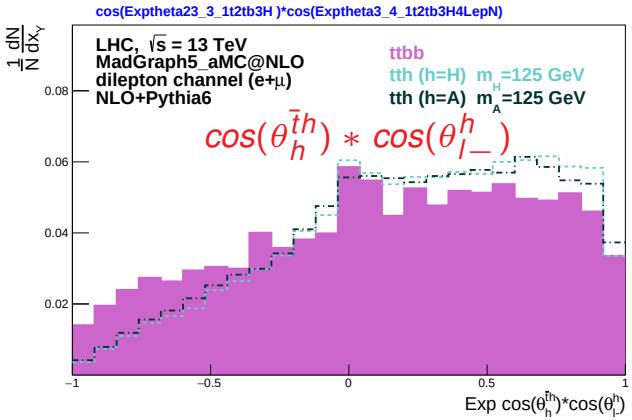
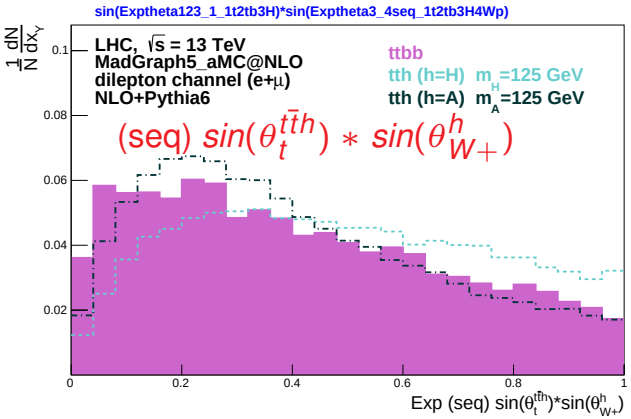
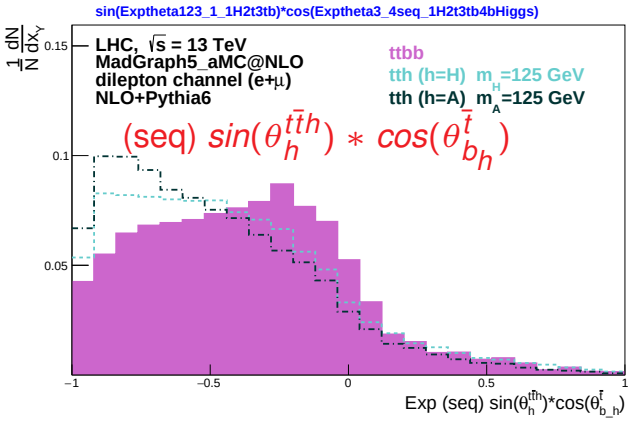
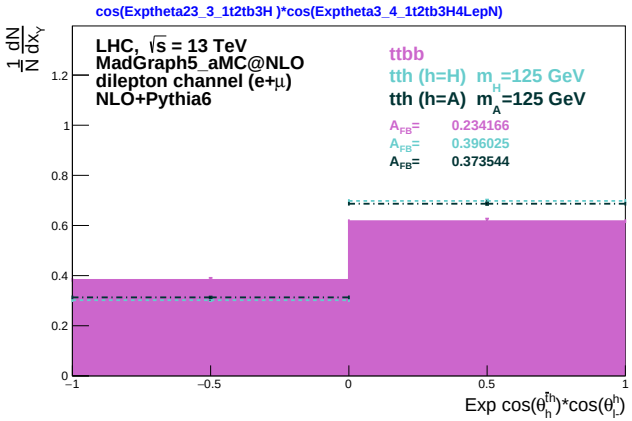
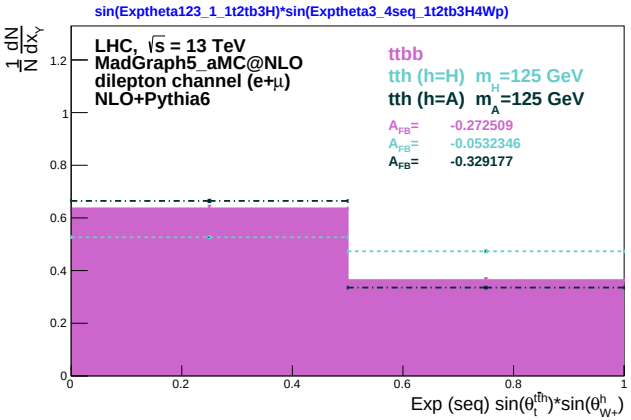


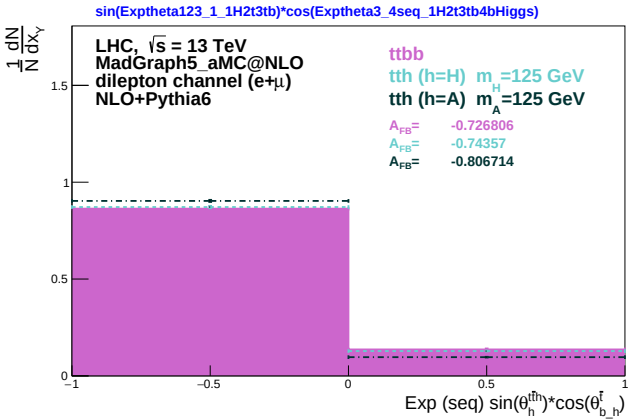



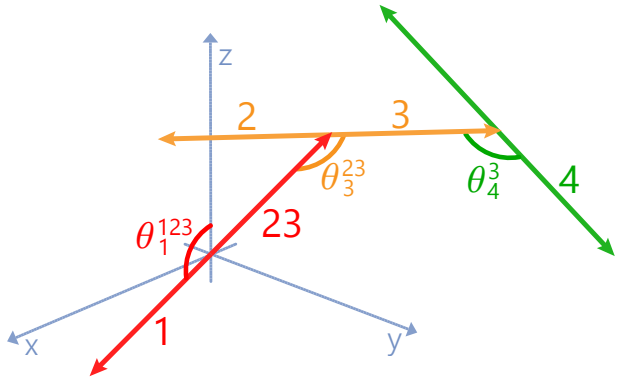



## NLO vs LO COMPARISON

☞ PARTON LEVEL and REC. observables

Angular Distributions and Asymmetries
not too much distorted by NLO corrections

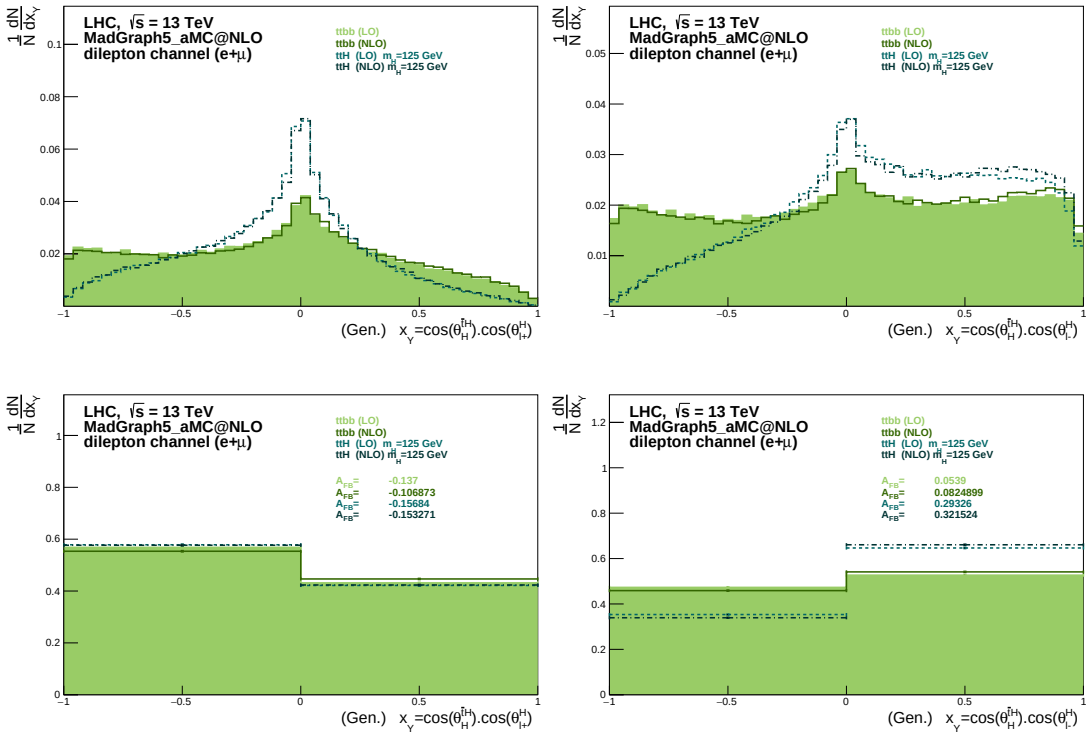



PRD **92**, no.3, 034021 (2015)

S.P.Amor dos Santos, J.P. Araque, R. Cantrill, N.F.Castro, M.C.N. Fiolhais, R.Frederix, R.Gonçalo, R.Martins, R.Santos, J.Silva, A.Onofre, H.Peixoto A.Reigoto

| (Asymmetries @ LO) | Parton level | | Reconstruction | |
|---|---|---|---|---|
| | $t\bar{t}H$ | $t\bar{t}b\bar{b}$ | $t\bar{t}H$ | $t\bar{t}b\bar{b}$ |
| $A_{FB}^{Y=\ell+}$ | −0.157 | −0.137 | −0.141 | −0.268 |
| $A_{FB}^{Y=\ell-}$ | +0.291 | +0.056 | +0.331 | +0.118 |
| $A_{FB}^{Y=W+}$ | −0.154 | −0.119 | −0.119 | −0.275 |
| $A_{FB}^{Y=W-}$ | +0.317 | +0.067 | +0.348 | +0.127 |
| $A_{FB}^{Y=b}$ ($b$ from $t$) | −0.155 | −0.141 | −0.179 | −0.306 |
| $A_{FB}^{Y=\bar{b}}$ ($\bar{b}$ from $\bar{t}$) | +0.293 | +0.053 | +0.334 | +0.117 |
| $A_{FB}^{Y=b}$ ($b$ from $H$) | +0.000 | +0.001 | +0.086 | −0.048 |
| $A_{FB}^{Y=\bar{b}}$ ($\bar{b}$ from $H$) | +0.000 | −0.001 | −0.086 | +0.048 |

TABLE I. Values for the asymmetry for $t\bar{t}H$ and $t\bar{t}b\bar{b}$ events at the LHC. The second and third column show the observed asymmetries at the parton level (without any cuts), while the fourth and last column show same asymmetries after applying the selection cuts and the kinematical reconstruction (without truth match).



# Conclusions

- At RUN I ☞ things went really well for top quark and Higgs physics i.e., the Higgs was discovered and the top quark measurements became a World reality (CDF, D0, ATLAS and CMS) with the best precision ever observed...RUN 2 looks even more promising!
- Need to measure the nature of the top quark Higgs boson couplings
- This is a particularly challenging task that will need a significant amount of luminosity
- It is quite important to monitor the parameter phase space and find angular distributions that can help distinguishing background from signal and also between different signals (probably of combination of those would be best.....)
- Asymmetries may play an important role.....

The phenomenology interplay of top quark and higgs physics needs precision and .....observables