Exploring CP violation in ttH events at the LHC

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1) ttH Yukawa Lagrangian L including CPV effects
2) Motivation for our approach in studying CPV effects using L
   → Overview of the different approaches and existing results
3) Based on all this → our motivation and first results
4) Outlook

Short preamble on CP transformation

When we write generically the SM Lagrangian as:

$L = \mathbf{\Sigma}\, a_i\, O_i + h.c.$ where a_i are parameters then O_i are called operators…

There are said to be of dimension 4 when they are homogeneous to M^4 etc.

Under CP: most of these operators follow: $O \rightarrow O^+ = (CP)^+ O\ (CP)$ (self adjoint-operators are CP invariant)
This is not trivial, the best is to prove this for each operator we select in L.
Remark: This will not be the case for operators of the form: $G \,.\, \widetilde{G}$

Then, L -> L if and only if a_i are real… in this case CP is a symmetry by definition.

And conversely CP is not a symmetry (violation of CP) <u>if there are some parameters which are complex</u>.
-> complex structure of L / or there are phases (arguments of the complex numbers) in L.

Reminder: top mass in the SM

After expanding $H(0, v+\phi/\sqrt{2})$ with $\phi \ll v$ ➔ $L_{mass} = -m_t/v\,(\bar{\psi}_t\ \psi_t\,\phi)$ ϕ is a scalar and ψ has 4 components

For more generality, let us multiply this by κ (with κ=1 in the SM)

$L_{mass} \simeq -\kappa_t\, m_t/v\,(\bar{\psi}_t\ \psi_t\,\phi)$

In extension of the SM, κ_t is not unity:
Example: here κ could be something like : $c\,\varphi^+\varphi/M^2 \sim c\,v^2/M^2$

Then, in general, let us write:

$L_{mass} = -\kappa_t\, y_t\,(\bar{\psi}_t\ \psi_t\,\phi)$ where κ_t is dimensionless (ϕ is often written X_0 is codes)

with CP-violating terms. In general, we can write

$$L_{mass}^{(all)} = -\kappa_t\, y_t\,(\bar{\psi}_t\ \psi_t\,\phi)\cos(\alpha) - i\,\kappa_t\, y_t\,(\bar{\psi}_t\,\gamma_5\,\psi_t\,\phi)\sin(\alpha).$$

with y_t the SM Yukawa coupling.

$L_{mass}^{(all)} = -\kappa_t\, y_t \{ (\bar{\psi}_t\ \psi_t \phi) \cos(\alpha) - i\, (\bar{\psi}_t \gamma_5\, \psi_t \phi) \sin(\alpha) \}$

Why L is not invariant under CP transformation (== it violates CP) ?

This is because, CP is violated when there is a complex structure in L (preamble):

Simple proof to arrive to the form above: Let us take C=a+ib (complex structure)

$$\mathcal{L}' = C\bar{\psi}_R\psi_L H + h.c. = a(\bar{\psi}_R\psi_L H + h.c.) + ib(\bar{\psi}_R\psi_L H - \bar{\psi}_L\psi_R H).$$

$$\mathcal{L}' = aH\bar{\psi}\psi + ibH(\bar{\psi}\psi(P_R - P_L)) = aH\bar{\psi}\psi + ibH\gamma^5(\bar{\psi}\psi) = H\bar{\psi}\psi(a + ib\gamma^5).$$

Note: as γ_5^2=Id (4x4 identity matrix) -> $\cos(\alpha) - i\,\gamma_5 \sin(\alpha)$ = $\exp(\, i\, \alpha\, \gamma_5\,)$…

There is a complication:

The modification with non zero $\boldsymbol{\alpha}$:

$$\cos(\alpha) - i\,\gamma_5 \sin(\alpha) = \exp(\, i\,\alpha\,\gamma_5\,)$$

will also impact all other terms in the SM Lagrangian involving the field: $\varphi(0, v+ \phi /\sqrt{2})$

For example, couplings for hWW, hZZ, hgg + effective couplings in H$\gamma\gamma$ HγZ etc.

The propagation of f(α) to all these terms is not simple…

Then, are we guaranteed that all SM symmetries are preserved?

SU(2) x U(1) + symmetries in the chiral limit

The answer seems to be Yes…

One (conceptual) remark:

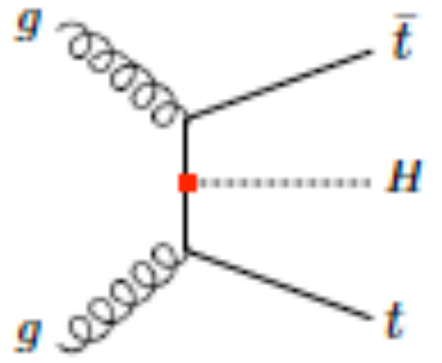
(i) SM with ***one*** *Higgs doublet is very special, since hermiticity makes all parameters in Higgs potential real.*

(ii) If there is more than one Higgs doublet, in general V_H may include CP-violating phases.
However, even then there are constraints…

(iii) Then, this is not immediate to justify CP violating phases in the Higgs sector (from first principles).

Now that we have something like:

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$



How can we observe effects of α ?

The first step is to compute $\boxed{d\boldsymbol{\sigma}/dO\ (pp\text{->}gg\text{->}ttH)}$ for an observable O.
This reads as:

$$\boxed{F(.)\cos^2\alpha + G(.)\sin^2\alpha} + \boxed{\left(\sum_k Q_k(.)\epsilon_k\right)\sin\alpha\cos\alpha.}$$

where F(.) and G(.) depend only of scalar products of momenta and therefore are even under P and CP.

The last term (linear in sin$\boldsymbol{\alpha}$) contain the “CP-odd” terms (not all of them are odd under CP).

We have: $\epsilon_k = \epsilon_{abcd}\, p_1^a\, p_2^b\, p_3^c\, p_4^d.$

$$\epsilon_k = \epsilon_{abcd}\, p_1^a\, p_2^b\, p_3^c\, p_4^d.$$

These are the famous trilinear products which are odd under P and for some of them under CP.

With 6 independent momenta , we can form in general 15 such terms and some of them are more interesting than others.

Then, there are 2 approaches:

(a) one approach is based on the first part of the xs: $F(.)\cos^2\alpha + G(.)\sin^2\alpha$

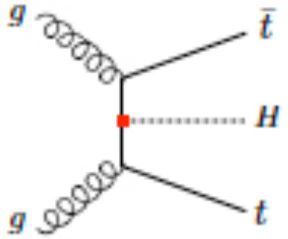
in physics configurations where the trilinear terms == 0.
This is essentially the approach followed by ATLAS/CMS and the one we describe later for our target studies

(b) a second approach is based on the trilinear couplings: $\epsilon_k = \epsilon_{abcd}\, p_1^a\, p_2^b\, p_3^c\, p_4^d.$

in other words: on the second part of the xs.

(b) based on trilinear couplings:

Let us consider the trilinear coupling built on the following momenta:

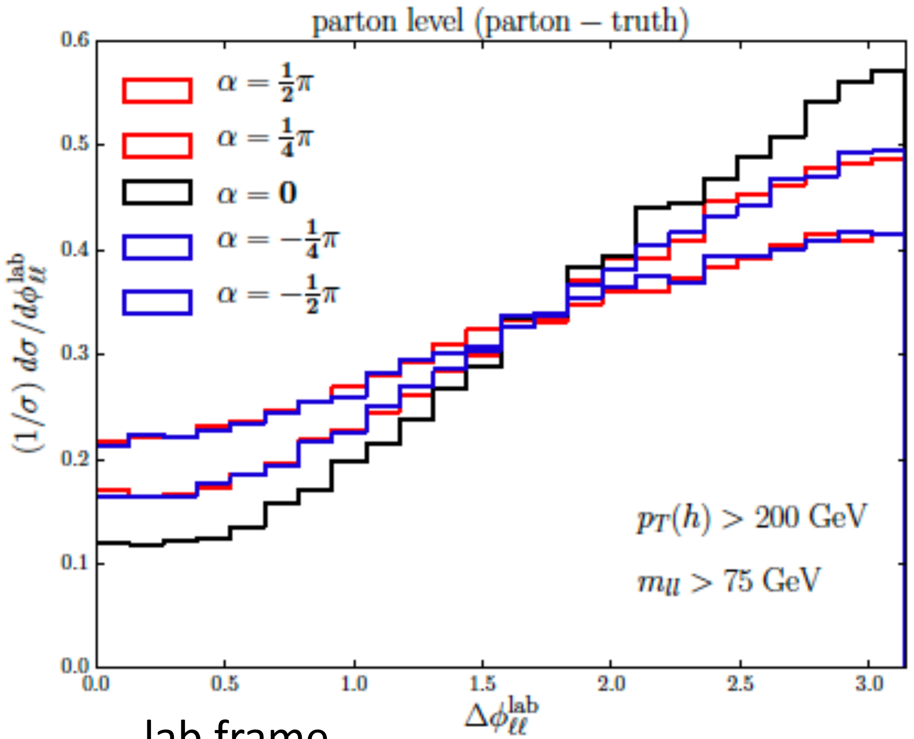


$$\epsilon(p_t, p_{\bar{t}}, p_{\ell+}, p_{\ell-})|_{t\bar{t}\ CM} \propto p_t \cdot (p_{\ell+} \times p_{\ell-})$$

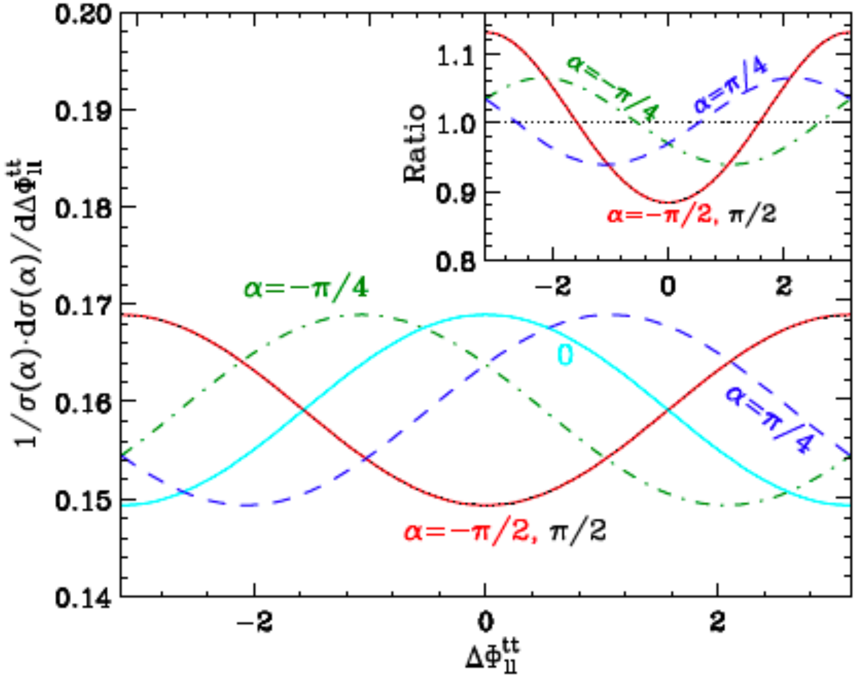
Then *it is easy* to build the CP-odd variable(s) following this →

$$\Delta\phi_{\ell\ell}^{t\bar{t}} = \mathrm{sgn}\left[\hat{p}_t \cdot (\hat{p}_{\ell+} \times \hat{p}_{\ell-})\right] \arccos\left[(\hat{p}_t \times \hat{p}_{\ell+}) \cdot (\hat{p}_t \times \hat{p}_{\ell-})\right]$$

This gives:



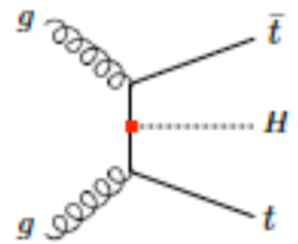
lab frame

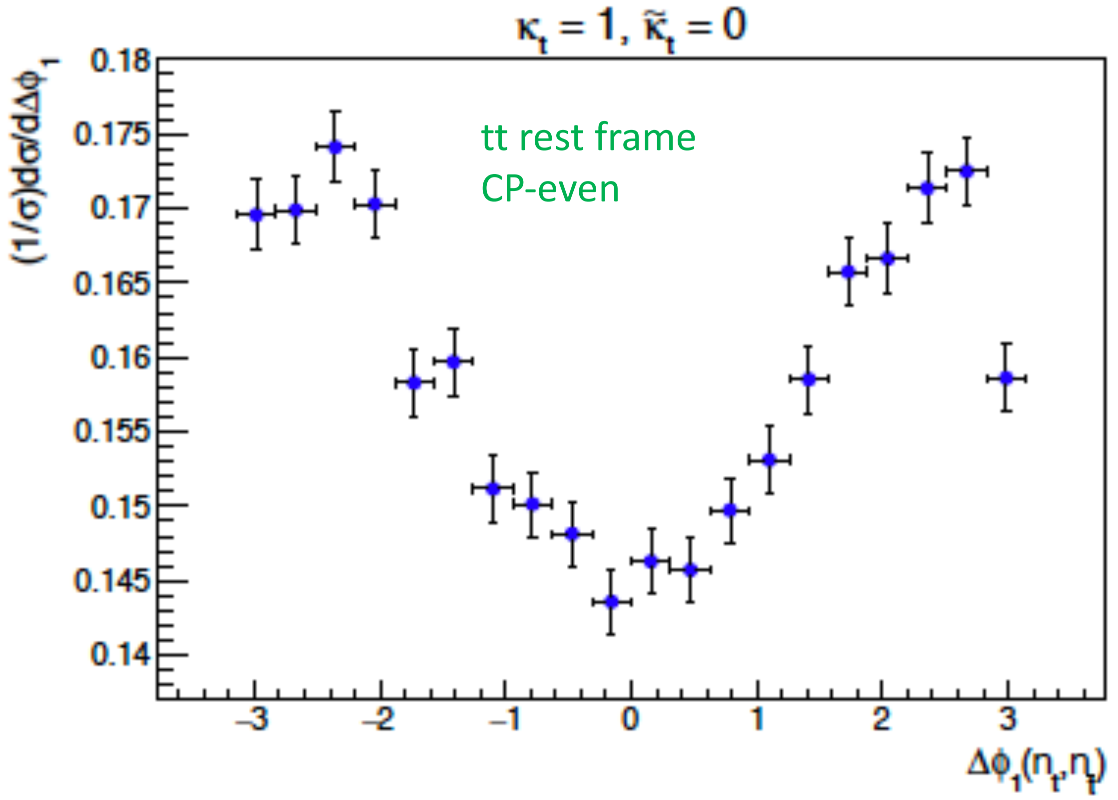


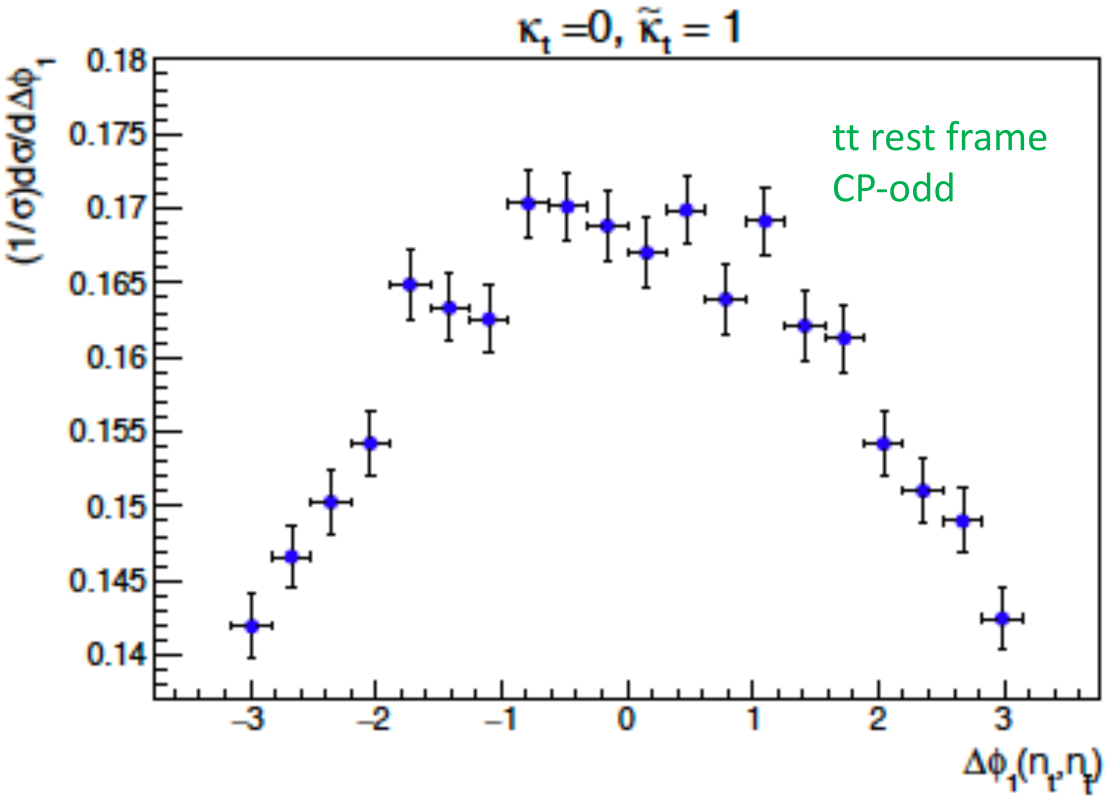
tt rest frame

(b) based on trilinear couplings (another example based on the spin vectors of the tops) :

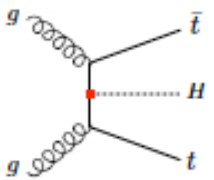
$$\epsilon(t+\bar{t},\bar{t},n_t,n_{\bar{t}}) = M_{t\bar{t}}\,|\vec{\bar{t}}|\,(\vec{n}_t \times \vec{n}_{\bar{t}})_z = M_{t\bar{t}}\,|\vec{\bar{t}}||\vec{n}_t||\vec{n}_{\bar{t}}|\sin\theta_{n_t}\sin\theta_{n_{\bar{t}}}\sin\boxed{\Delta\phi(n_t,n_{\bar{t}})}$$







(a) based on the first part of the xs // ATLAS and CMS results



ATLAS-CONF-2022-016
CMS PAS HIG-21-006

These analyses are based on spin-averaged cross sections for **ttH**, **then** on the expression: $F(.)\cos^2\alpha + G(.)\sin^2\alpha$ for the event yield in ttH.

ATLAS/CMS analyses are more refined with the **inclusion of tH yield**.

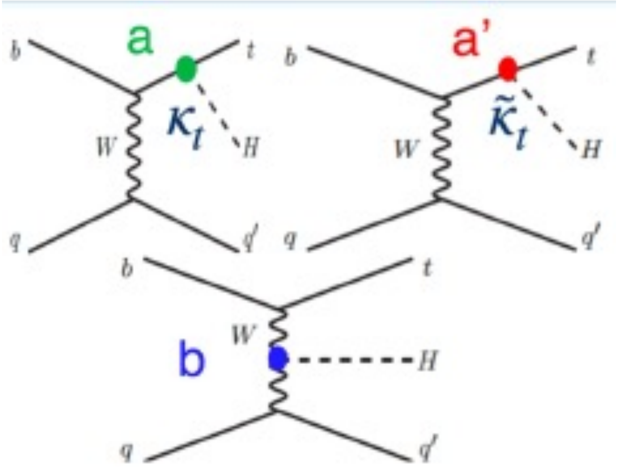
A general parameterization of the #events is taken to be of the form:

$$\text{ttH: } Ak_t'^2\cos^2(\alpha) + Bk_t'^2\sin^2(\alpha)$$

$$\text{tH: } \underbrace{Ak_t'^2\cos^2(\alpha)}_{a^2} + \underbrace{Bk_t'^2\sin^2(\alpha)}_{a'^2} + \underbrace{Ck_t'\cos(\alpha)}_{2\,\mathrm{Re}(a\,b)} + \underbrace{Dk_t'\sin(\alpha)}_{2\,\mathrm{Re}(a'\,b)} + \underbrace{Ek_t'^2\sin(\alpha)\cos(\alpha)}_{2\mathrm{Re}(a\,a')} + \underbrace{F}_{b^2}$$

where A(.),…,F(.) == terms that are the analogous to what I have noted F(.) and G(.) above and in the previous slide.

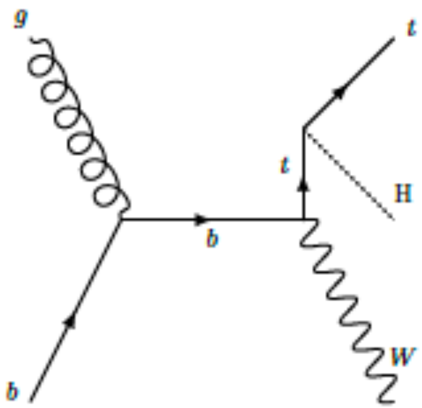
Here we keep also the possibility for a non unity κ_t.

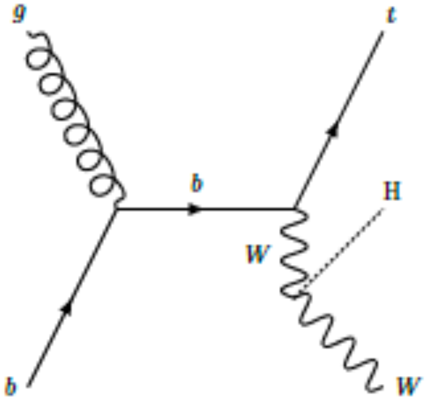


The idea to include tH final states in the analysis is of course interesting as it includes all possible ttH Yukawa couplings in the study.

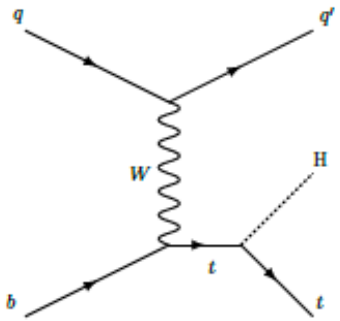
However, this makes everything more complicated because of the interference between (tH WH)

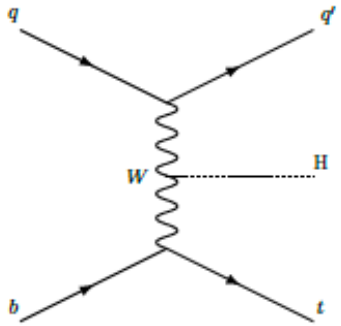
→ Therefore the analysis (related to tH final states) is considering also final states like:

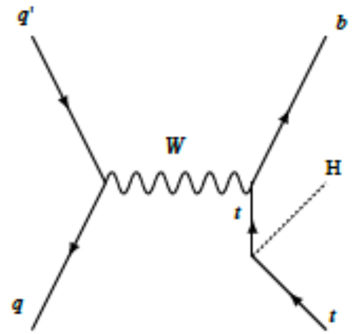




In addition to:







ATLAS and CMS strategies

ATLAS-CONF-2022-016
CMS PAS HIG-21-006

The idea of these analyses is to select events with high jets multiplicities, including b-quark jets expected in the final state of ttH and tH with H decaying in bb -ATLAS-.
and/or multi-leptons + jets, also tagging final states with H -> multi-leptons (WW, tautau, ZZ) –CMS-.

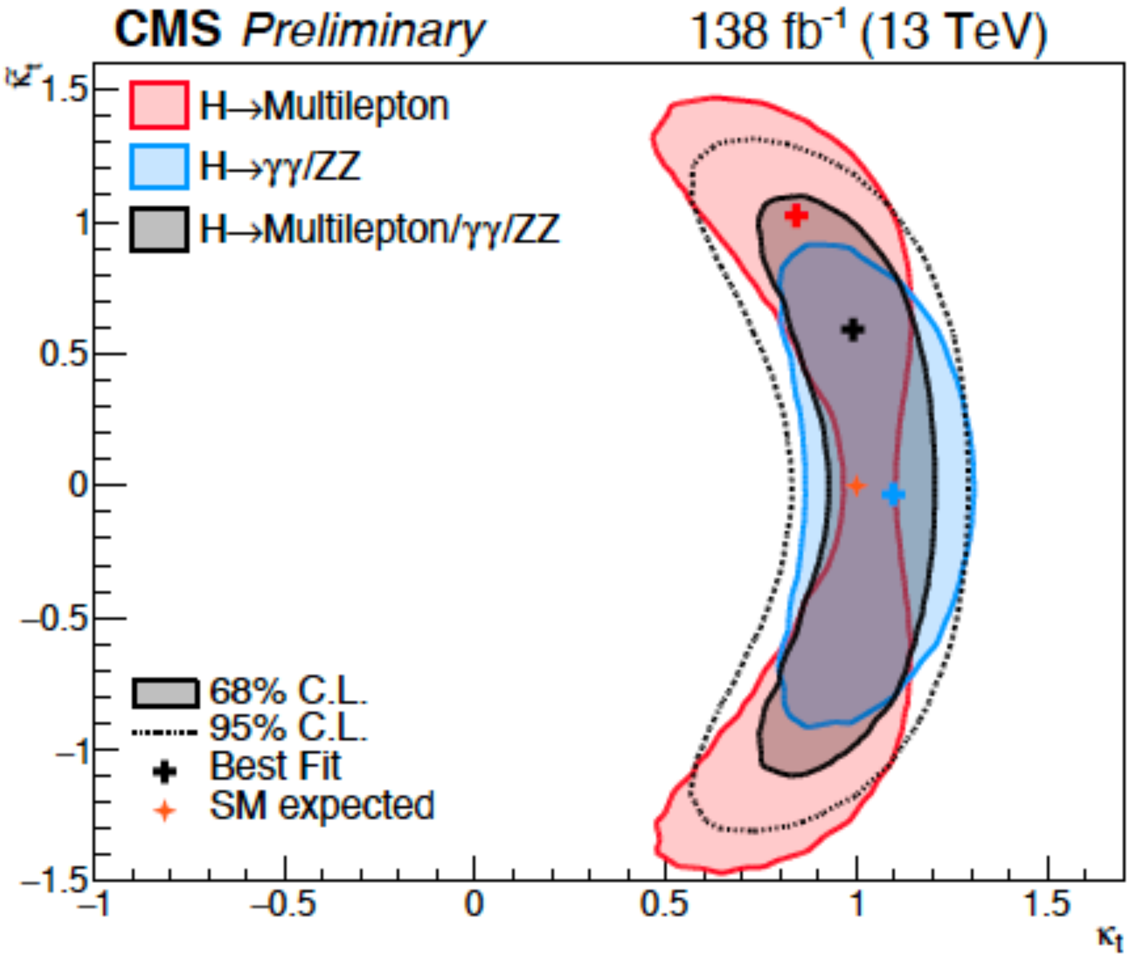
Then, a given set of kinematical variables are considered as discriminant between the different schemes ($\boldsymbol{\alpha}$,$\boldsymbol{\kappa}$) and included in a BDT:
depending of the final states, there can be up to 25 variables included.

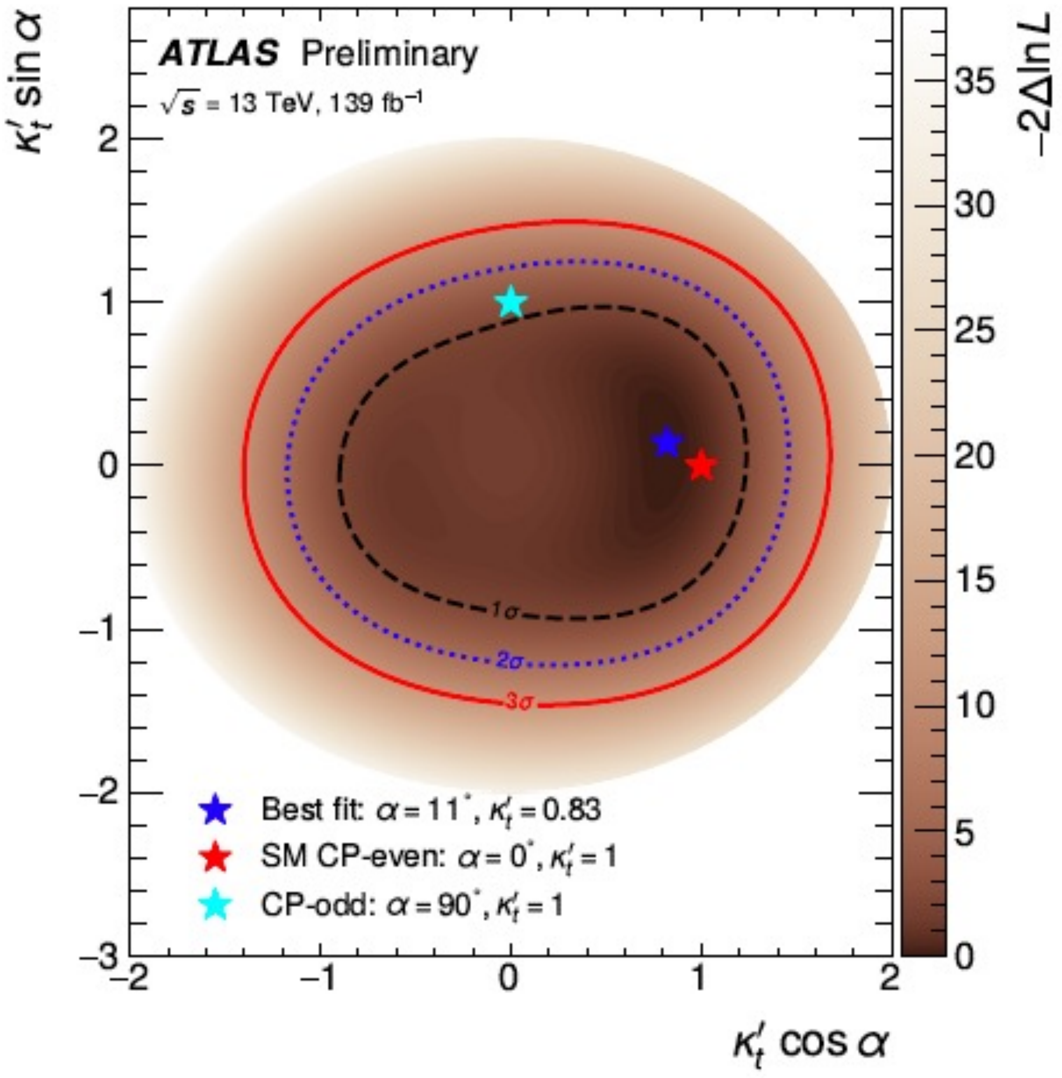
We can remark that each variable alone do not provide a clear discrimination and that’s why a combination is necessary.

Then a template likelihood fit is supposed to provide a determination of ($\boldsymbol{\alpha}$,$\boldsymbol{\kappa}$).

This is extremely complex in practice.

ATLAS and CMS results

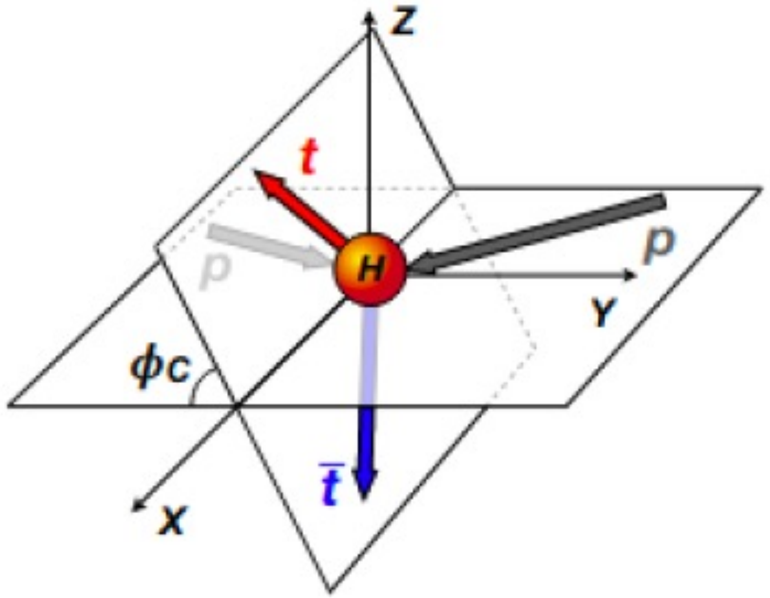


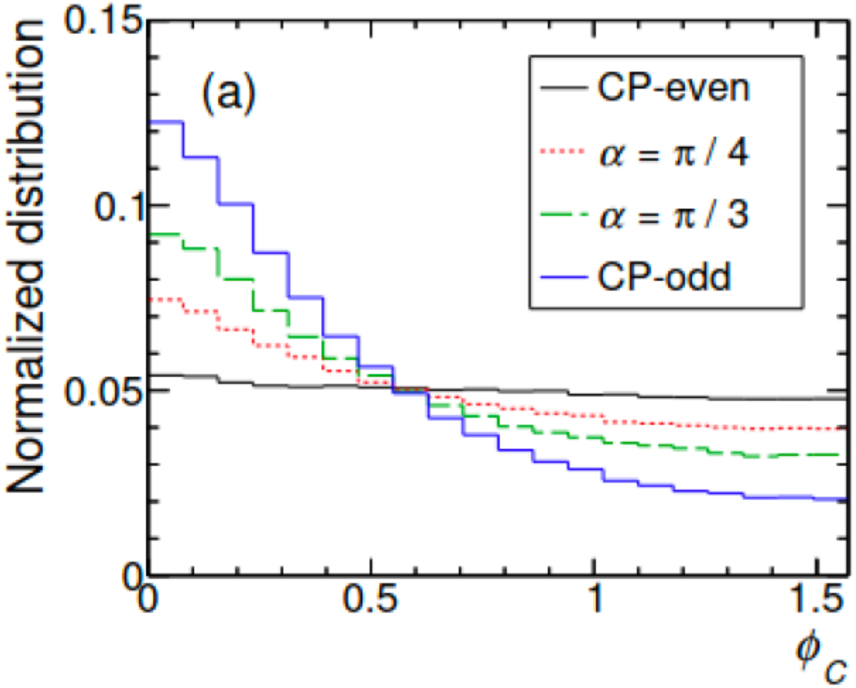


(a) Continuing through this approach but with a new motivation

The goal is to search for a set of variables that are discriminant on their own between the different schemes… (if possible)

arXiv:2008.13442v1





CP-even $\alpha=0$
CP-odd $\alpha=\pi/2$

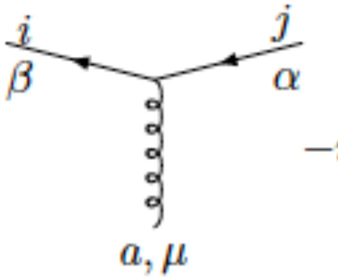
$$\cos\Phi_c = \frac{|(\vec{p}_1 \wedge \vec{p}_2).(\vec{p}_t \wedge \vec{p}_{\bar{t}})|}{|(\vec{p}_1 \wedge \vec{p}_2)||(\vec{p}_t \wedge \vec{p}_{\bar{t}})|} \; (H r.f.)$$

We observe clearly the effect of f($\boldsymbol{\alpha}$)

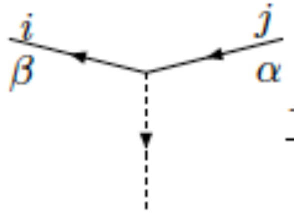
As an exercise, this is interesting to find $\Phi_c(\boldsymbol{\alpha})$ from algebra that

Start of the exercise

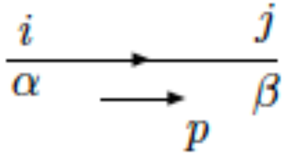
Building blocks:



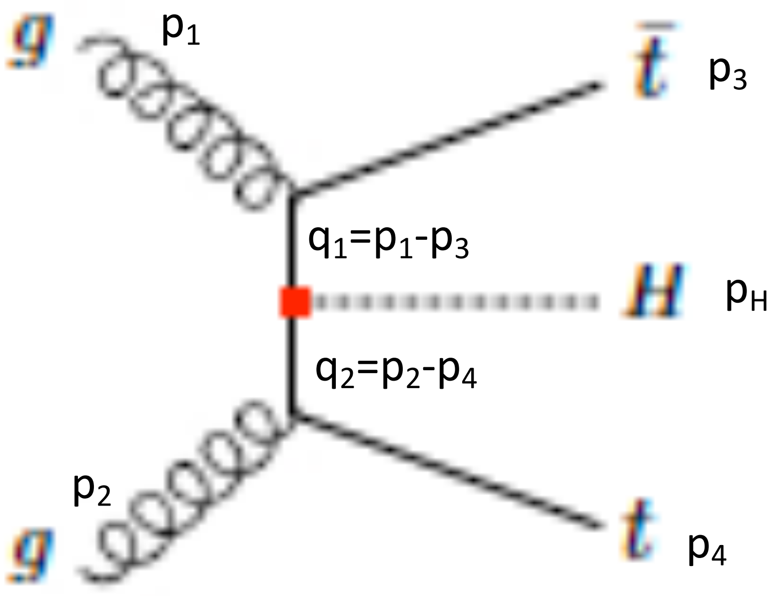
$-ig_s\gamma^{\mu}_{\beta\alpha}\,[t^a]_{ji}$



$\dfrac{-iy_t\delta_{ij}\delta_{\alpha\beta}}{\sqrt{2}}$. exp(i $\alpha\,\gamma_5$)



$\dfrac{i(\not{p}+m)_{\beta\alpha}\delta_{ij}}{p^2-m^2+i\epsilon}$



Then, let us start with (this will not be the full story)

$$-i\,M = -ig_s^2\; y_t/\sqrt{2}\;\epsilon_\mu^{a}(p_1,s_1)\;\;\epsilon_\nu^{b}(p_2,s_2)$$
$$.\; T^a\;\; T^b$$
$$.\; \bar{u}(p_3)\,\gamma^\mu\,\frac{\not{q}_1+m}{q_1^2-m^2}\;\exp(\,i\,\alpha\,\gamma_5\,)\,\frac{\not{q}_2+m}{q_2^2-m^2}\;\gamma^\nu\;\;v(p_4)$$

This is a product of 4x4 matrices

The idea is then to compute $|M|^2$ and <u>sum over colors and gluon polarizations</u>
This looks bad but this is not so much…

The square of IMI gives color terms in: $Tr(T^a\ T^b\ T^a\ T^b)$ which is a constant ($N\ c_F^2$)

$|\epsilon_\mu^a(p_1,s_1)\ \epsilon_\nu^b(p_2,s_2)|^2$ summed over polarizations leads to $g_{\mu\nu}$ when we keep also the unphysical polarizations.

Then:

$|M|^2 \sim C\ 1/P\ \mathbf{Tr}\ [\ (\not{p}_3+m)\ \gamma^\mu\ (\not{q}_1+m)\ \exp(\ i\ \alpha\ \gamma_5\ )\ (\not{q}_2+m)\ \gamma^\nu\ (\not{p}_4-m)\ \gamma_\nu\ (\not{q}_2+m)\ \exp(\ i\ \alpha\ \gamma_5\ )\ (\not{q}_1+m)\ \gamma_\mu\ ]$

If $\boldsymbol{\alpha}$=0, there are 10, 8, 6… γ matrices in the trace… this is a bit of algebra to write everything… but not difficult.
The result will be <u>a function of product of pairs of momenta.</u>
Note: there are some tricks: $\gamma^\nu\ (\not{p}_4)\ \gamma_\nu = -2\not{p}_4 \quad \not{a}\not{b} = -\not{b}\not{a} + 2ab$ *etc.*

<u>At the end</u>, in the rest frame of the H, there is no term left in $\mathbf{p_1.p_3}$ or $\mathbf{p_2.p_4}$ (vectors – momenta - scalar product)
(warning there is still a Φc dependence hidden in the propagators P)

The full story consists in doing that also for the change 3<->4 + the interference between both… no change.
(only the order of γ matrices is changing)
+ correcting from non physical polarizations of the gluons: Here I am not sure but I found no change which seems to be correct as we know the result (no Φc dependence).

What is changing with $\boldsymbol{\alpha}$ non zero in:

Tr $[\ (\not{p}_3+m)\ \gamma^{\mu}\ (\not{q}_1+m)\ \exp(\ i\ \boldsymbol{\alpha}\ \gamma_5\ )\ (\not{q}_2+m)\ \gamma^{\nu}\ (\not{p}_4-m)\ \gamma_{\nu}\ (\not{q}_2+m)\ \exp(\ i\ \boldsymbol{\alpha}\ \gamma_5\ )\ (\not{q}_1+m)\ \gamma_{\mu}\ ]$

→There will be terms with 1 γ_5 and 2 γ_5.

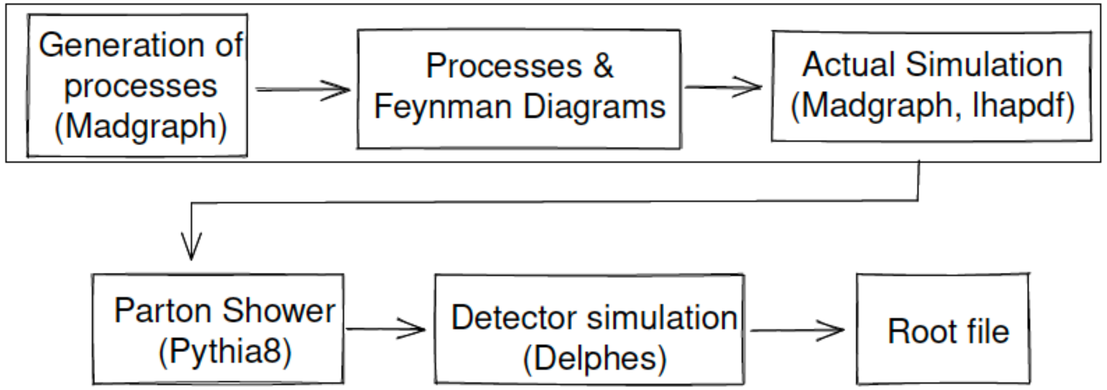
Terms with 2 γ_5 does not change anything… we can make the γ_5 sliding in the trace as it anti-commutes with all other γ's.

But terms with 1 γ_5 will give several Levi-Civita tensors ϵ_{abcd} in terms with 10, 8, 6… γ's.
due to relations like: $\mathrm{Tr}(\gamma_5\ \gamma_a\ \gamma_b\ \gamma_c\ \gamma_d) = -4\ i\ \epsilon_{abcd}$

This will make all the difference!

<u>by mixing initial and external momenta… leading to an explicit Φc dependence.</u>

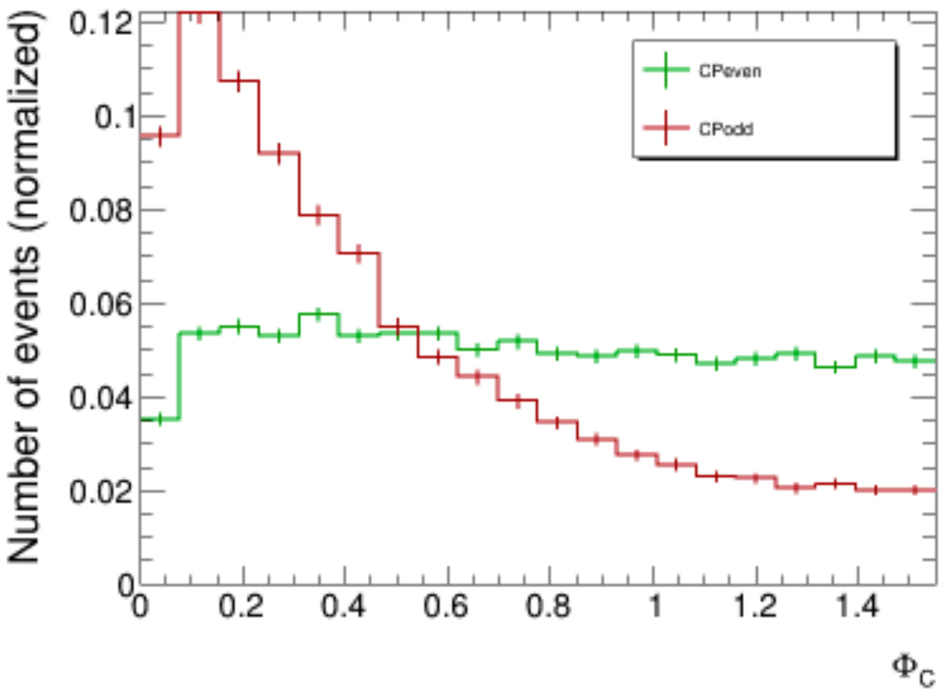
We have reproduced the result using MG5



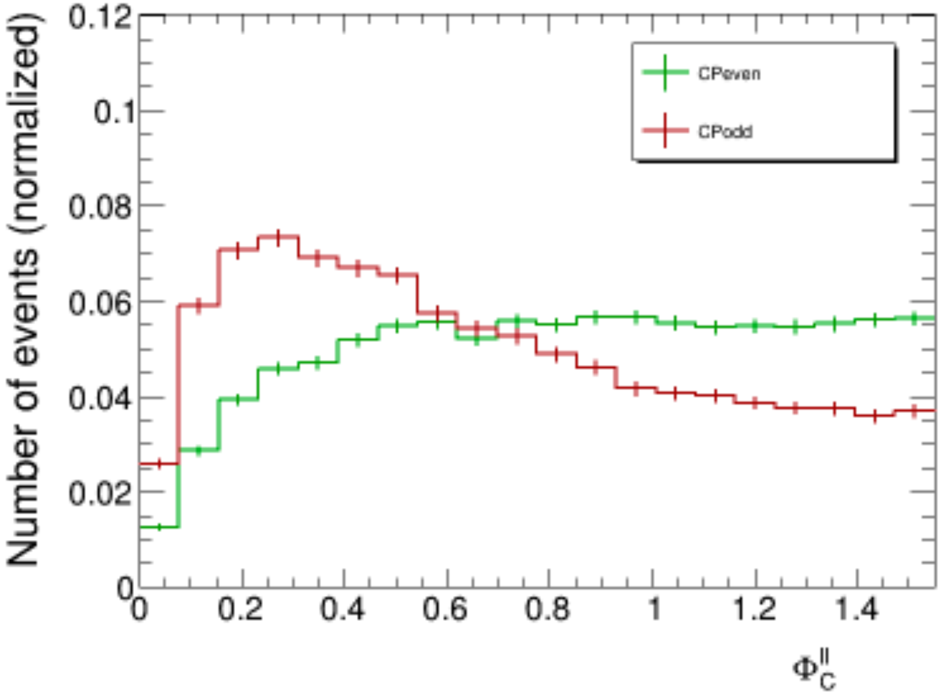
First results at generated level

$$\cos \Phi_c = \frac{|(\vec{p}_1 \wedge \vec{p}_2).(\vec{p}_t \wedge \vec{p}_{\bar{t}})|}{|(\vec{p}_1 \wedge \vec{p}_2)||(\vec{p}_t \wedge \vec{p}_{\bar{t}})|} \; (Hr.f.)$$

computed from the generated tops

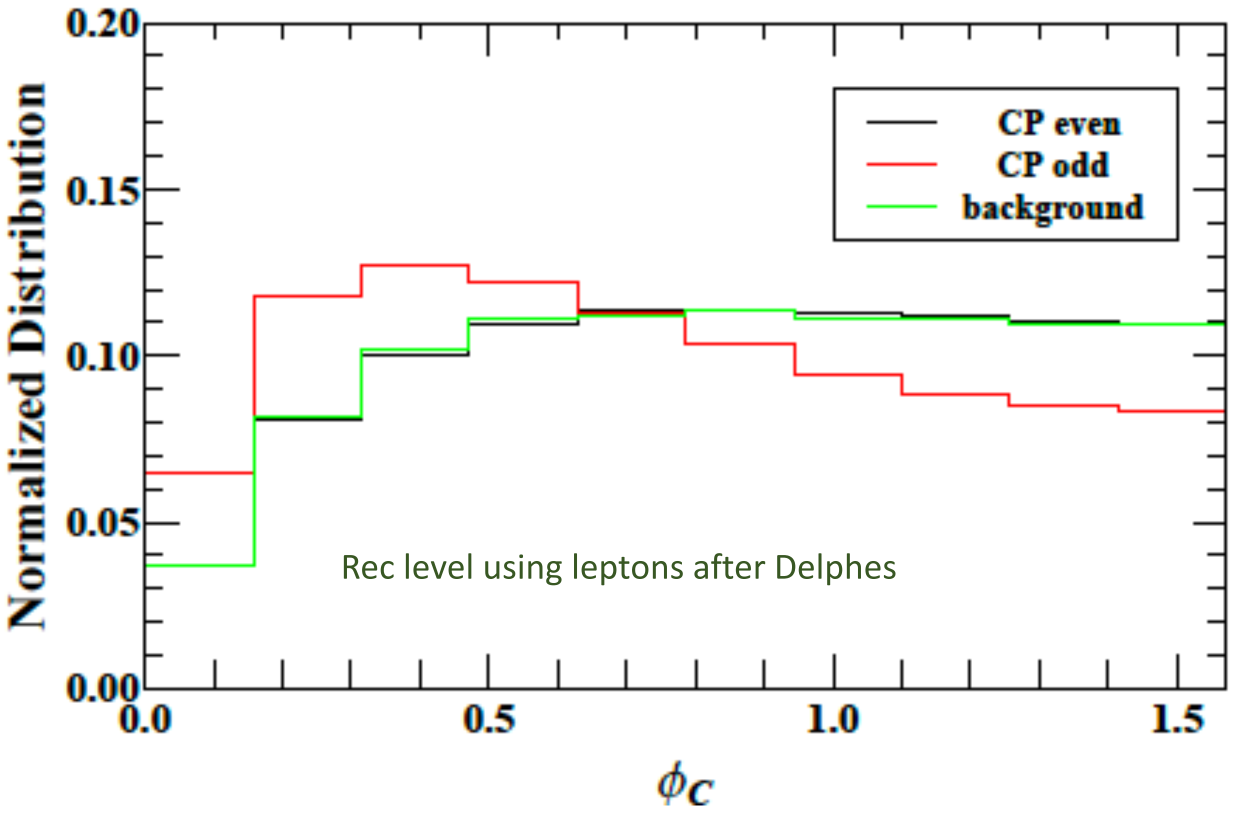


computed from the generated leptons (from tops)

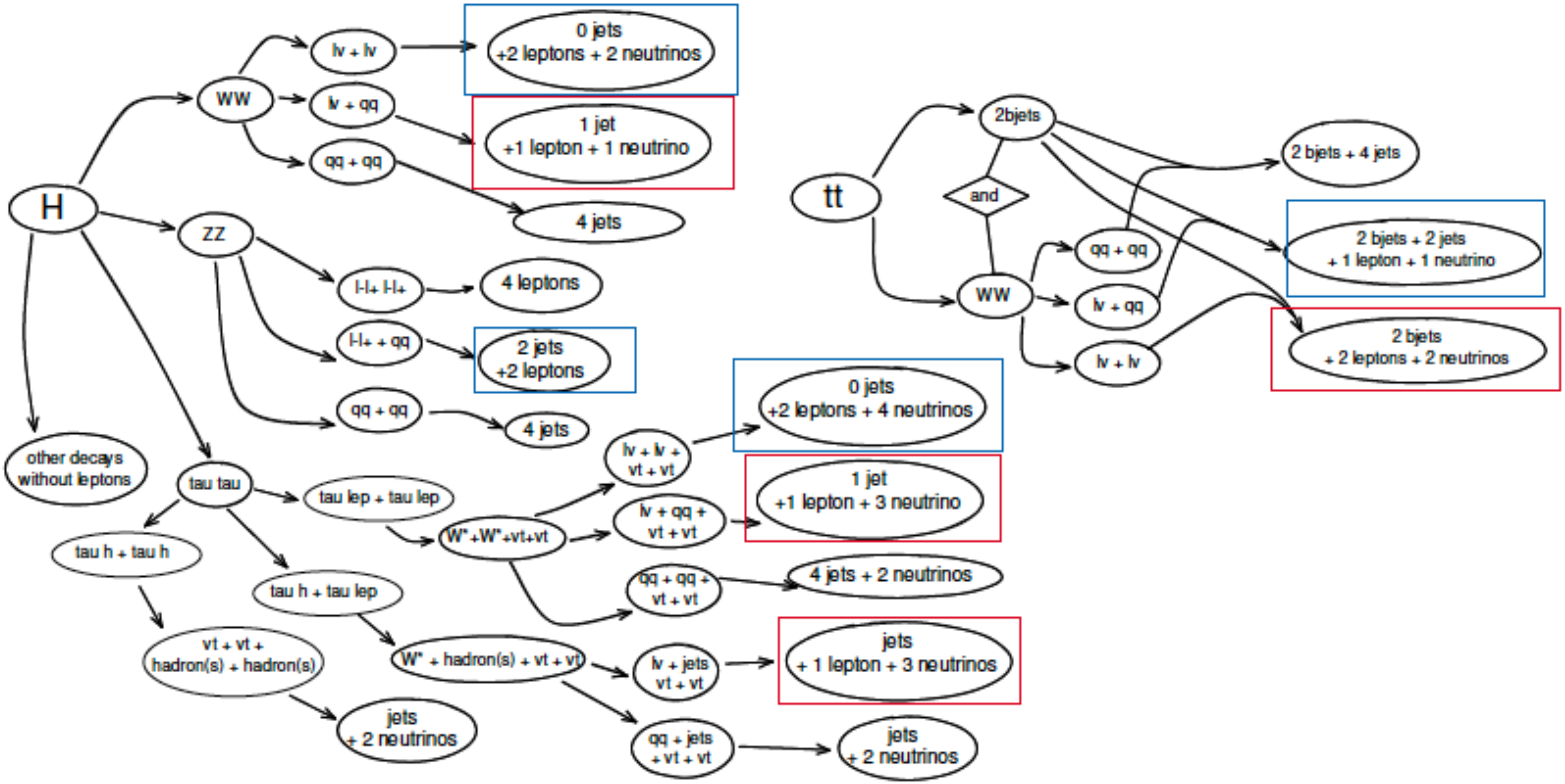


At Rec level, things are more complicated (this is ongoing)

A first result using leptons from tops to build Φ_c after Delphes
(here the change of Ref frame is still done using the 4-vector of the generated H)

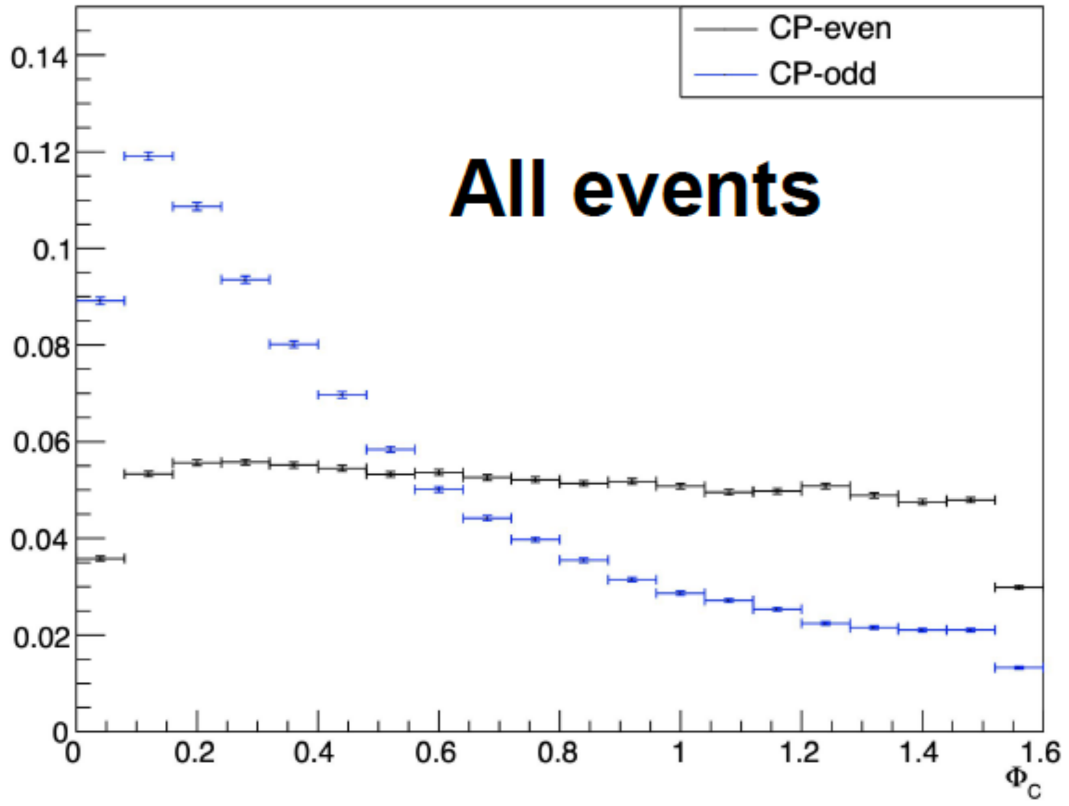


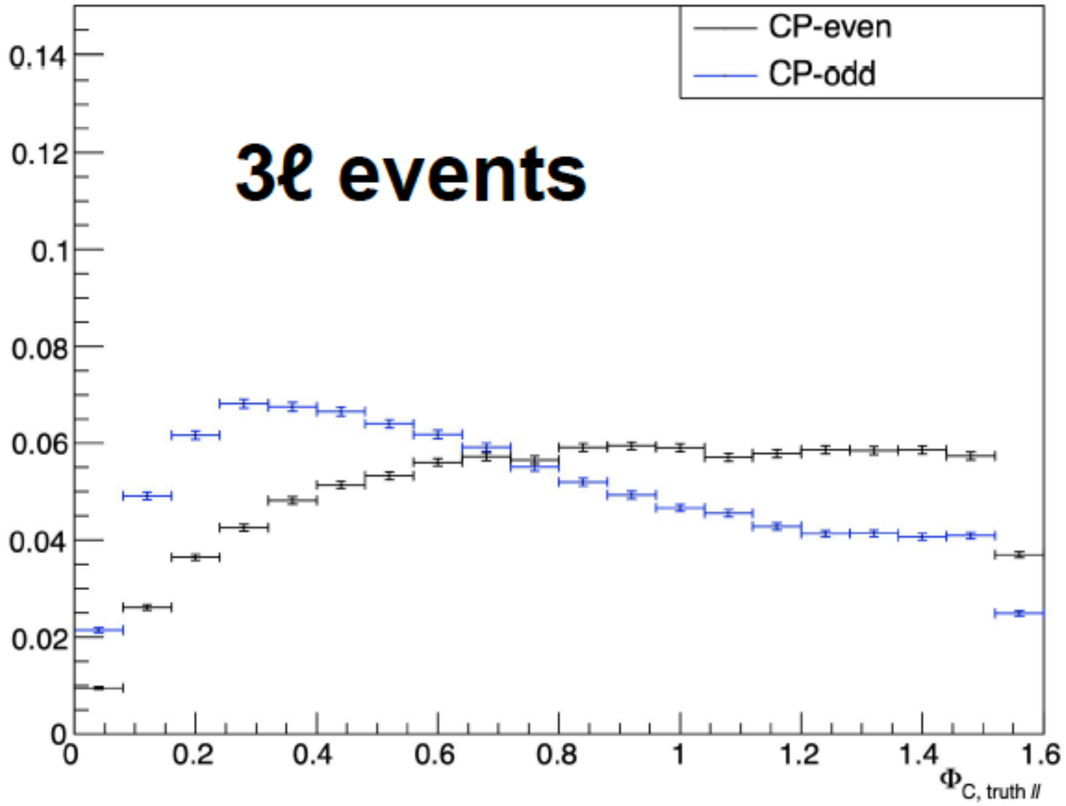
We have also developed an in situ analysis chain to make the data (and/or MC) analysis…
Here the sequence for 3-leptons+X in the final state.



This leads to something like this at generated level when the sequence is applied

$$\cos\Phi_c = \frac{|(\vec{p}_1 \wedge \vec{p}_2).(\vec{p}_t \wedge \vec{p}_{\bar{t}})|}{|(\vec{p}_1 \wedge \vec{p}_2)||(\vec{p}_t \wedge \vec{p}_{\bar{t}})|}\ (Hr.f.)$$





Outlook

Our present work consists in developing a personal code in order to be able to make all studies locally first and then in ATLAS.
The group is thus also involved in the new ATLAS data analysis (starting by defining the framework for it)
There are still a lot of steps ahead but we are progressing…

Other variables are also under study (also in the CP-even approach)… + all ideas that we have in hands but not exploited yet
++ we will follow what the intermediate results tell us… ("Naturam si sequimur ducem, nunquam aberrabimus")

$$b_4 = \frac{p_t^z p_{\bar{t}}^z}{|\vec{p}_t||\vec{p}_{\bar{t}}|}$$