Study of a Kinematic Fit algorithm on the $b\bar{b}\gamma\gamma$ channel for the search of Higgs bosons pairs at the ATLAS detector

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Summary. — The research for Higgs bosons pairs, produced at the LHC, is a fundamental step for the study of the Higgs potential. The observation of this rare phenomenon would allow the measurement of its higher order terms, among which, the tri-linear Higgs self coupling. Due to the small number of expected events, many researches are focusing on developing analysis algorithms aimed at improving experimental sensitivity. This paper presents the implementation of one promising algorithm developed in the $HH \to b\bar{b}\gamma\gamma$ analysis at ATLAS: a Kinematic Fit. It will be shown how this algorithm is able to improve the energy resolution of the hadronic component of the channel by applying per-event kinematic constraints based on the balance of the total momentum in the transverse plane. This improvement results in a better rejection of the non-resonant $\gamma\gamma$+jets background, allowing to determine tighter confidence intervals on the tri-linear self coupling term.

1. – The $HH \to b\bar{b}\gamma\gamma$ analysis

The Higgs boson was discovered over 10 years ago by the ATLAS [1] and CMS [2] collaborations, but some predictions of the underlying mechanism [3, 4] still lack a proper confirmation. One example is the exact shape of the Higgs potential or, in other words, the value of the various Higgs self-coupling terms.

$$V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \supset \frac{1}{2}m_H^2H^2 + \lambda_3 H^3 + \frac{1}{4}\lambda_4 H^4 \tag{1}$$

Of these terms, the most accessible one is the tri-linear self-coupling (λ_3), which could be experimentally measured by a direct observation of a di-Higgs production at the LHC. Due to its small cross section ($\sim$ 33 fb @ 13 TeV with NNLO accuracy) however, this process is still far from being observed and thus many different analyses are currently competing to establish tighter confidence level (CL) bonds on the expected coupling value. This article describes the ATLAS $HH \to b\bar{b}\gamma\gamma$ analysis [5], which although affected by a branching ratio (BR) much smaller ($\sim$ 0.26%) with respect to the other decay channels, presents a much cleaner final state thus boosting its sensitivity and keeping its measurements competitive, one example being its latest 95% CL result on κ_λ ($-1.4 < \kappa_\lambda < 6.9$). However, this channel potential has not been fully exploited yet. An ad hoc Kinematic Fit (KF) algorithm is currently being developed with the main aim of improving the relatively poor b-jets energy resolution by balancing the event in the transverse plane with the much more accurately reconstructed photons.

2. – The Kinematic Fit algorithm

2·1. ***Principles & implementations.*** – The KF is an algorithm aimed at improving the resolution of specific observables by imposing appropriate kinematic constraints. In the $HH \to b\bar{b}\gamma\gamma$ production, the algorithm is applied on top of the analysis standard jets calibration (BCal) which consists in the combination of the muon-in-jet (which includes muons possibly originated from the jet to its energy) and p_T-Reco (which is a p_T dependent energy scale factor) corrections. At least two constraints can be imposed:

- **Total transverse momentum conservation:** The event total p_T is conserved, and it is in a range much smaller than the energy scales typical of the signal process. It is thus possible to improve the signal b-jets accuracy and resolution (and more crucially the m_{bb} invariant mass resolution) by balancing them with the photons'.
- **Higgs mass:** The invariant mass of the two b-jets can be constrained to that of the Higgs boson ($\sim$ 125 GeV).

The KF is simply a negative log likelihood (NLL) minimization algorithm. The likelihood function itself is a product of Transfer Functions (*i.e.* PDFs encapsulating the resolution of specific observables such as jet energy or momentum) and Constraints. This NLL takes the following form:

$$
\begin{aligned}
-2\ln(\mathcal{L}) = &\sum_{j=jets}\Big[-2\ln\big[f_E\big(\frac{E^j_{Fit}-E^j_{Reco}}{E^j_{Fit}}\big)\big] - 2\ln\big[f_{p_T}\big(\frac{p^j_{T,Fit}-p^j_{T,Reco}}{p^j_{T,Fit}}\big)\big]\Big] + ...\\
&... + \sum_{j=\gamma}\Big[\frac{E^j_{Fit}-E^j_{Reco}}{\sigma_E}\Big] - 2\lambda_{pT}\ln\big[f_2(p_X^{HH})\big] - 2\lambda_{pT}\ln\big[f_2(p_Y^{HH})\big] + ...\\
&... + \lambda_m(m_{bb}^{fit}-m_H)^2
\end{aligned}
\tag{2}
$$

where:

- $f_{E/pT}$ are the Transfer Functions for jets energy and transverse momentum. The remaining observables η and ϕ are fixed at their reconstructed values.
- $\lambda_{pT/m}$ are the constraints weights. These are estimated empirically through a scan on a ggF signal MC sample; the chosen values are those maximizing the m_{bb} resolution and $m^*_{bb\gamma\gamma}$ accuracy respectively.

2·2. ***Transfer functions & constraints parameterizations.*** – The actual parameterization of jets Transfer Functions and constraints is estimated through a sample of 30k Monte Carlo (MC) generated gluon-gluon Fusion (ggF) signal events. In order to keep these PDFs parameterizations C^∞, while still being able to represent the complicated observed distributions, a series of ad-hoc functions obtained by combining of continuous step-functions is used to build the PDFs.

2˙2.1. **Transfer Functions**. Given the wide variability of the b-jets distributions both in energy range and detector regions, a total of 24 different parameterizations have been evaluated to encode this dependence both for E and p_T Transfer Functions:

- 6 $\log(p_T$ [GeV]) bins, namely [2.0, 3.7]; [3.7, 4.0]; [4.0, 4.5]; [4.5, 5.0]; [5.0, 5.3], [5.3, 6.0].
- 4 η regions representing the Barrel ($1.37 < \eta < 1.37$), Crack ($1.37 \leq |\eta| < 1.52$), End-cap ($1.52 \leq |\eta| < 2.5$) and No-Track ($2.5 \leq |\eta| < 4.4$) detector regions.

The chosen parametrization for all these bins (with specific parameters for each region) is the following expression (example in fig 1):

$$f(x) = N \cdot \Big(\frac{1}{\pi}\big(\tan^{-1}(a(x-m)) + \frac{\pi}{2}\big)\Big)^{\alpha} \cdot e^{\frac{(x-\mu)^2}{2\sigma^2}} \cdot \Big(\frac{1}{\pi}\big(\tan^{-1}(-b(x-n)) + \frac{\pi}{2}\big)\Big)^{\beta} \quad (3)$$

where x can either be $\frac{E^{jet}_{Fit} - E^{jet}_{Reco}}{E^{jet}_{Fit}}$ or $\frac{pT^{jet}_{Fit} - pT^{jet}_{Reco}}{pT^{jet}_{Fit}}$.

2˙2.2. **Constraints**. Similarly, the transverse momentum constraints are parameterized starting from the expected signal distribution. These depend on the number of additional jets, which in the analysis range from 0 up to a maximum of 3. The parameterization is also similar, albeit a bit simpler (example in fig 1):

$$f_2(x) = N \cdot \Big(\frac{1}{\pi}\big(\tan^{-1}(a(x-m)) + \frac{\pi}{2}\big)\Big)^{\alpha} \cdot \Big(\frac{1}{\pi}\big(\tan^{-1}(-b(x-n)) + \frac{\pi}{2}\big)\Big)^{\beta} \quad (4)$$

where x is either p_X or p_Y (*i.e.* the total p_T components in the ATLAS coordinate system).

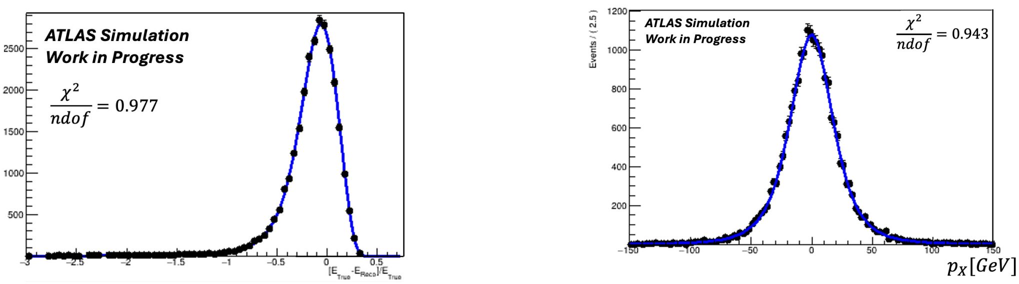

Fig. 1.: Examples of the jet energy transfer function for Barrel in the 2.0-3.7 $\log(p_T)$ bin (left) and of the total p_X constraint in the case with no additional jets (right).

2˙3. ***Results***. – The actual Kinematic Fit is currently applied in two independent stages.

- **No-mass KF**: At this stage the Higgs mass constraint is excluded ($\lambda_m = 0$) while the transverse momentum constraint is applied ($\lambda_{pT} = 3.05$). This KF has the main objective of improving the signal m_{bb} resolution without affecting (or smearing) that of the background.
- **Full KF**: This implementation adds the mass constraints ($\lambda_m = 0.1$). In this case, m_{bb} actually loses its discriminating power between signal and background (since

the variable peaks at 125 GeV in both samples) but this is not the case for $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ (a crucial variable in the analysis strategy presented in ref. [5]), which improves reconstruction accuracy while retaining some discriminating power (since bb and $\gamma\gamma$ are uncorrelated in the continuum background) by applying the KF.

The results of both these fits are shown in fig. 2. In particular, fitting the distributions allows to estimate both the improvements for the m_{bb} resolution ($\sim 13\%$) and the $m^*_{bb\gamma\gamma}$ Truth-Reco accuracy ($\sim 42\%$) with respect to the latest jet correction used in the $bb\gamma\gamma$ analysis (*i.e.* the BCal correction explained in sect. **2**˙1).

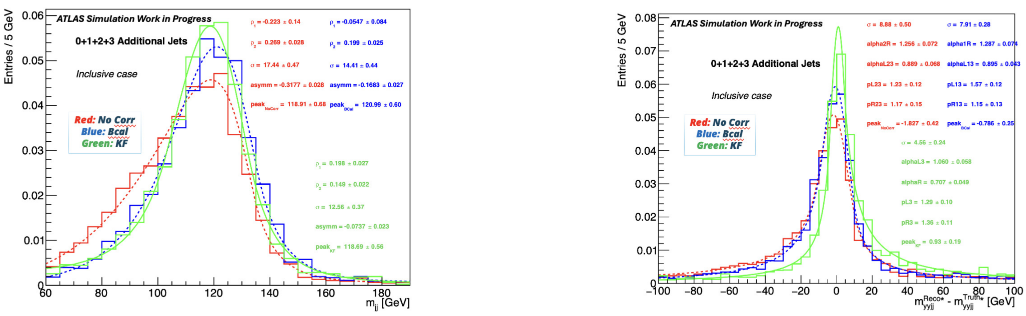

Fig. 2.: On the left (right), MC ggF signal m_{bb} (Truth-Reco $m^*_{bb\gamma\gamma}$) distribution with no correction in red, BCal correction in blue and No-Mass (Full) KF applied in green. Fitted with a Bukin (DSCB) distribution.

3. – Conclusions

The study presented in this article shows a possible strategy to improve the sensitivity to $HH \to b\bar{b}\gamma\gamma$ signal events reconstructed with the ATLAS detector by exploiting a kinematic fit. Applying the method brings improvements both in the m_{bb} resolution ($\sim 13\%$) and m^*_{bbyy} signal reconstruction accuracy ($\sim 42\%$), but its impact on the analysis sensitivity is still under study.

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