Università degli Studi di Bari

Dipartimento Interateneo di Fisica "M. Merlin"

PhD School in Physics XXXI Cycle

Activity report of the third year of the Doctoral School.

Phd Student: Adriano Di Florio

Supervisor: Dr. Alexis Pompili

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This report concerns the third year of the Doctoral School in Physics. The research work is presented in Section 1, the participation to conferences, workshops and schools in Section 2 and the list of publications in Section 3.

1 Research work

During the third year the research work has been mainly focused on the three following topics:

1. The inclusive search for the charmonium-like Y(4140) state and its partners in the $J/\psi\phi$ mass spectrum within CMS with Run II data.
2. The study and development of machine learning techniques for filtering the track seeds (pixel hit doublets) at CMS High Level Trigger.
3. The study and development of applications of the GPU-based analysis tool known as `GooFit` for the estimation of the global statistical significance of an unexpected physical signal.

1.1 Inclusive search in the $J\psi/\phi$ spectrum of charmonium-like states produced in pp collisions

Hadron Spectroscopy has experienced a renaissance in the last decade thanks to the experimental findings at *B-factories*, *Tevatron* and recently at the *LHC*. Quarkonium has became again a tool for discoveries of new phenomena in the complex realm of low-energy QCD. A new wide zoology of quarkonium-like states, many of them with manifestly exotic characteristics (the so-called XYZ states), still needs to be understood within a possibly consistent framework. The development of theoretical models, such as tetraquark or hadron molecule models, is not yet able to provide an unified explanation of these states. The analyses of LHC Run-I data provided (and are still providing) new experimental observations and measurements for exotic hadrons.

Even if LHCb is the most suitable experiment to contribute to this new spectroscopy, CMS has proven (see references [1] [2] [3] [4]) to be able to provide a few important results despite the absence of an hadronic identification. One of the neutral charmonium-like XYZ meson states is the Y(4140) state. The CDF collaboration at the Tevatron reported the first evidence for the $Y(4140)$ state in 2009 and confirmed it later in 2011 with higher statistics. The Y(4140) state was appearing as an intermediate state in the decay $B^+ \to Y(4140)K^+ \to J/\psi\phi K^+$, close the $J/\psi\phi$ kinematic threshold. Since then several interpretations have been proposed for the Y (4140) decaying into $J/\psi\phi$, none of them entirely convincing: $D_s^*\bar{D}_s^*$ molecule, compact tetraquark $cs\bar{c}\bar{s}$, threshold kinematic effect, hybrid charmonium, weak transition with $D_s\bar{D}_s$ rescattering.

In 2014, the CMS Collaboration observed (with a statistical significance much greater than 5σ) the $Y(4140)$ peaking structure in the $J/\psi\phi$ invariant mass spectrum. Later, in 2015, the D∅ collaboration found evidence of prompt and non prompt direct production of this state, in $p\bar{p}$ collisions ($p\bar{p} \to Y(4140) + X$ with $Y \to J/\psi\phi$), by studying inclusively the $J/\psi\phi$ mass spectrum [5]. On the other hand LHCb collaboration observed [7], by means of the first amplitude analysis of the decay $B^+ \to J/\psi\phi K^+$, even four $J/\psi\phi$ structures, each with a statistical significance greater than 5σ. The lightest of them appears to be possibly described by a cusp (kinematical threshold effect), even if a resonant interpretation is also possible with a mass consistent with, but a width much larger than, previous measurements of the claimed Y(4140) state. In [8] the authors proposed these structures to be interpreted as S-wave tetraquarks, with $[cs][\bar{c}\,\bar{s}]$ diquark-antidiquark composition. Given the latest experimental results it becomes crucial to confirm or refute the D∅ result for the inclusive search. In case of a positive confirmation this would rule out a cusp interpretation of the Y(4140) because a state that appears both as an intermediate state in a 3-body B meson decay and as a state promptly produced in pp collisions could definitely be considered as a genuine resonance.

1.1.1 Novel High Level Trigger paths development

The inclusive search strategy of a charmonium-like state in the $\mu\mu KK$ final state relies for both the full 2012 $\sqrt{s} = 8$ TeV Run-I pp collisions data sample and the $\sqrt{s} = 13$ TeV Run-II data collected in 2016, on inclusive J/ψ HLT triggers. Because of an increased dimuon p_T threshold, for the Run II data taking in 2017/2018, an alternative strategy has been explored, thanks to the development of two new specific High Level Trigger paths (*HLT_DoubleMu2_ Jpsi_ DoubleTrk1_Phi* and *HLT_DoubleMu2_ Jpsi_DoubleTkMu0 _Phi*). Since the $J/\psi\phi$ background is expected to be mainly combinatorial because of kaon track pair combinations, it would be interesting to investigate the $J/\psi\phi$ invariant mass spectrum also through the rare $\phi \to \mu\mu$ decay channel, namely in a much cleaner (but much rarer [6]) topology. Therefore $J\psi\phi$ system could be explored relying only on muons reconstruction, thus bypassing the issue related to the lack of particle identification for kaons. These new paths have been running since the last months of the 2017 data taking (from Run 305388). The path devoted to the $\mu\mu KK$ decay channel, due to the high rate estimated (see Table 1), has been put in production with a prescale factor $s = 2$ (i.e. the 50% of the events triggered are discarded) in 2017 data taking. For 2018 data taking several efforts have been done in order to reduce the trigger rate and then release the prescale factor, without loosing any possible interesting event. The main attempt has been focused on reducing the mass window range for the invariant mass of the two kaon tracks resulting from the decay $\phi \to KK$, namely $[0.65 - 1.30]$ in the original path. Thus a first preliminary study has

HLT Path	Rate [Hz]	Pure rate [Hz]	Prescale
DoubleMu2_Jpsi_DoubleTrk1_Phi	55.52 ± 1.50	10.74 ± 0.66	2
DoubleMu2_Jpsi_DoubleTkMu0_Phi	9.20 ± 0.61	1.62 ± 0.26	1

Table 1: Unprescaled rate and pure rate at $L = 2 \times 10^{34} cm^2 \cdot s^{-1}$ for the new HLT path.

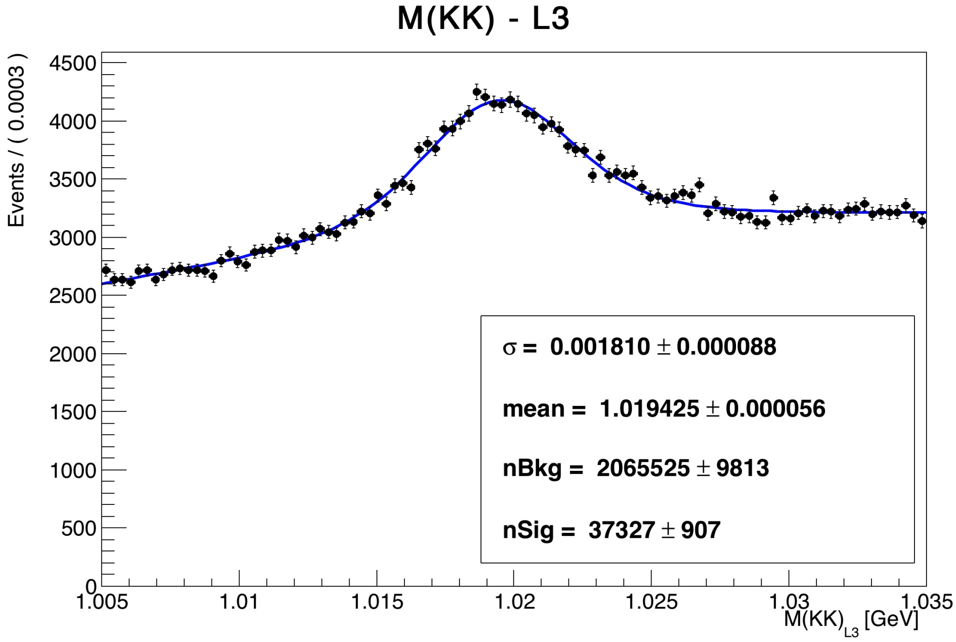

Figure 1: M(KK) for L3 HLT object fitted with a Voigtian p.d.f. for the signal and a Polynomial p.d.f. for the background. The σ_{tot} is calculated as $\sqrt{\Gamma^2 + \sigma_{res}^2}$ where Γ is fixed to the world average ϕ natural width ($\Gamma = 4.27$) taken from the PDG. [6].

been performed to estimate the $\phi(\rightarrow KK)$ system width for both high level trigger (L3) and final reconstructed (RECO) track objects. The ϕ peak is clearly visible and has been fitted (see Figure 1) with a Voigtian signal p.d.f. over a polynomial background. The total peak width has been so estimated as $\sigma_{tot} = 5.04 MeV$ allowing us to define the ϕ signal region as $S_\phi = [m_\phi - 3 * \sigma_\phi, m_\phi + 3 * \sigma_\phi] = [1.001, 1, 037]$. Three possible mass range configurations $R_{1,2,3}$ (so that $S_\phi \subset R_{1,2,3}$) has been tested for rate reduction, as shown in Table 2. The narrower has been chosen since it guarantees an higher rate reduction ($\simeq 80\%$).

Mass Ranges	[0.95-1.30]	[0.95-1.15]	[0.95-1.05]	Original
Rate [Hz]	31.86 ± 1.9	23.15 ± 1.2	10.55 ± 0.9	55.52 ± 1.5

Table 2: Unprescaled rate and pure rate at $L = 2 \times 10^{34} cm^2 \cdot s^{-1}$ for the new HLT path with different mass ranges for $M(KK)$.

1.1.2 Production upper limit calculation

The new paths have been in production ("online") for the whole 2018 data taking allowing us to collect more than $40 fb^{-1}$ of data without prescaling (data taking is still ongoing). The $J/\psi\phi$ invariant mass spectrum, for the whole 2018 data taking, resulting by the application

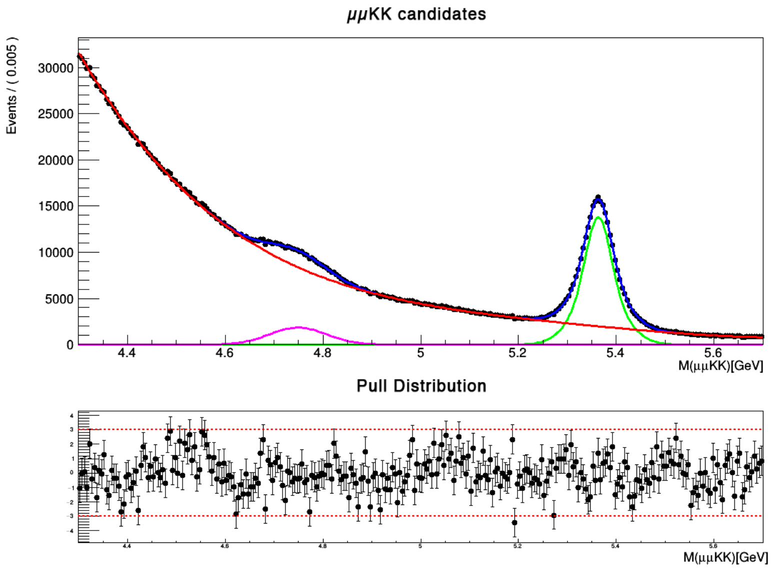

Figure 2: The B_s^0 signal for 2018 data. The signal is modelled as a single gaussian (green line). The combinatorial (red line) background is parametrized as a 5^{th} Chebychev polynomial p.d.f. The purple gaussian p.d.f. takes into account the misreconstructed B-mesons whose final state include two muons and two tracks and at least an extra not reconstructed track.

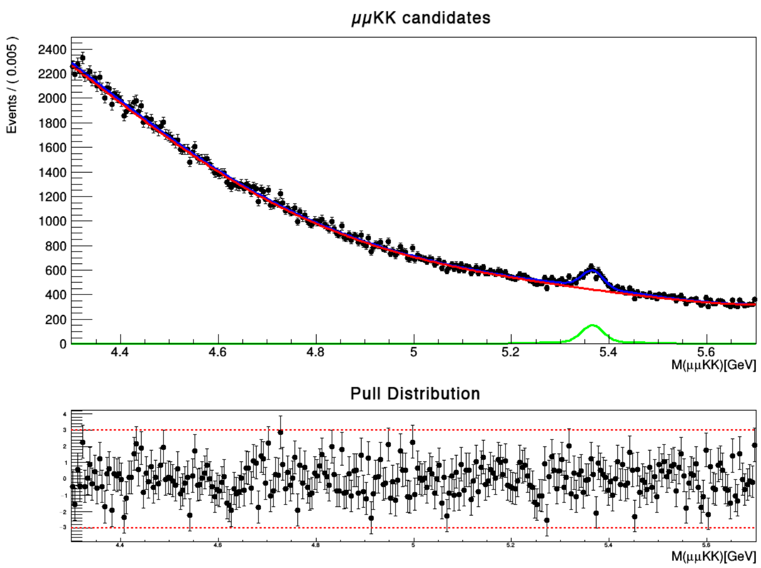

Figure 3: The B_s^0 signal fit for prompt region. The signal is modelled as a single gaussian (green line). The combinatorial (red line) background is parametrized as a 5^{th} Chebychev polynomial p.d.f..

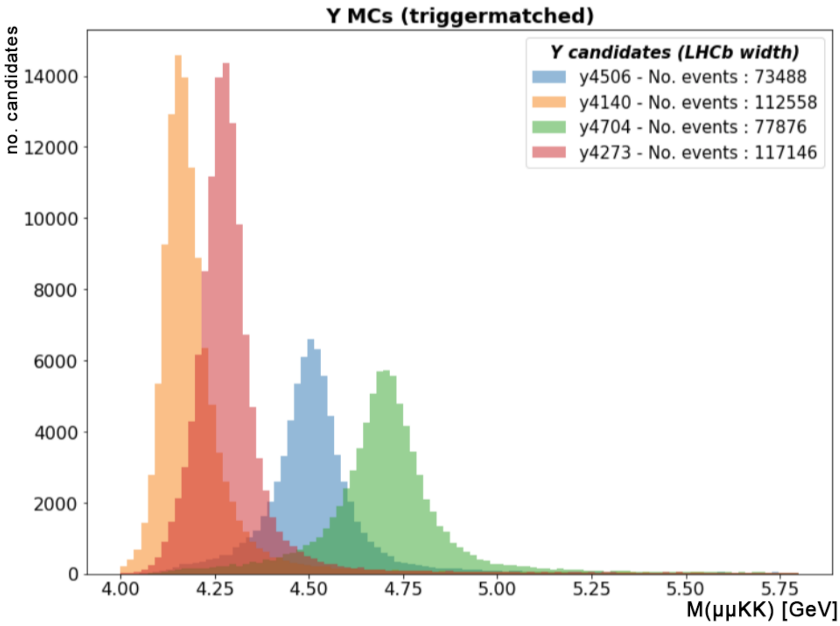

Figure 4: The reconstructed Y MC signals for the four masses reported in [7]: 4140, 4273, 4506, 4704 MeV.

of a set of baseline selection criteria, is shown in Figure 2 and Figure 3. Figure 2 spectrum is the inclusive one while Figure 3 shows only the prompt spectrum. The latter includes only candidates whose four track vertex transverse distance from the primary vertex of the event $L_{xy}(\mu\mu kk)$ satisfies the requirement $L_{xy}(\mu\mu kk) < 2\sigma_{L_{xy}(\mu\mu kk)}$. In both cases the B_s^0 peak is visible and it will be used in order to estimate an upper limit on the ratio of cross-sections times the not common branching fractions

$$R = \frac{\sigma(pp \to Y + X) \times \mathcal{B}(Y \to J/\psi\phi)}{\sigma(pp \to B_s^0 + X) \times \mathcal{B}(B_s^0 \to J/\psi\phi)} = \frac{N_Y}{\in_Y} \times \frac{\in_{B_s^0}}{N_{B_s^0}}$$

where $N_Y(N_{B_s^0})$ and $\in_Y$ $(\in_{B_s^0})$ are the $Y(B_s^0)$ yields and reconstruction efficiencies and, of course,$\mathcal{B}(Y \to J/\psi\phi)$ is unknown. To estimate the reconstruction efficiency and the mass resolution, four MC samples with four Y states has been generated. The masses and the widths of the four generated signals are borrowed from LHCb (in Ref. [7]). In Figure 4 are reported the four simulated states reconstructed in the $\mu\mu KK$ decay channel. Also, to estimate $\in_{B_s^0}$ a dedicated MC for the B_s^0 meson has been generated. Therefore all the ingredients for the upper limit calculation are ready and this calculation is currently being finalized.

1.2 Convolutional Neural Network for Track Seed Filtering at the CMS High-Level Trigger

Future development projects for the Large Hadron Collider will allow to integrate higher luminosity than that already collected. The ultimate goal will be to reach a peak luminosity of $5 \cdot 10^{34} cm^{-2}s^{-1}$ for ATLAS and CMS experiments, as planned for the High Luminosity LHC (HL-LHC) phase. This will directly result in an increased number of simultaneous proton collisions (pileup), up to 200 per bunch crossing, that will pose new challenges for the CMS detector and, specifically, for track reconstruction in the Silicon Pixel Tracker.

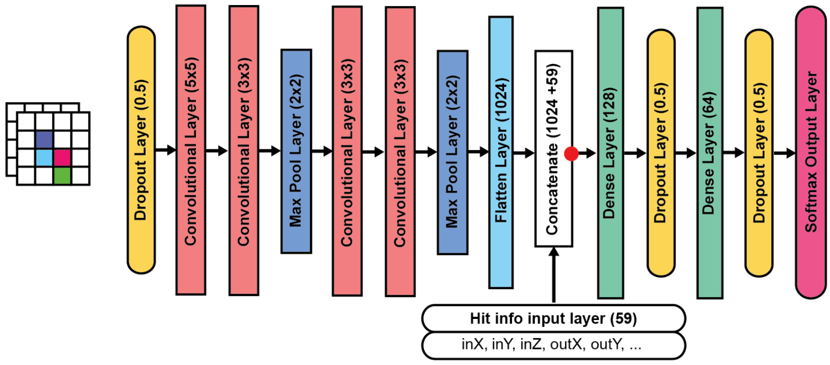

Figure 5: Layer map model architecture

One of the first steps of the track finding workflow is the creation of track seeds, i.e. compatible pairs of hits from different detector layers, that are subsequently fed to the higher level pattern recognition steps. However the set of compatible hit pairs is highly affected by combinatorial background that would have a strong impact onto the next steps of the tracking algorithm. To avoid the processing of a significant fraction of fake doublets a new method is being developed. It relies on taking into account the shape of the hit pixel cluster to check the compatibility between two hits. To each doublet a collection of two images is associated. These images are built with the ADC levels of the pixels forming the hit cluster. Thus the task of fakes' rejection can be considered as an image classification problem for which Convolutional Neural Networks (CNNs) have been widely proven to provide reliable results. To test the feasibility of this kind of approach, a Monte Carlo sample of $pp \rightarrow t\bar{t}$ events is generated, within the CMS software framework, at the center of mass energy of $\sqrt{s} = 13$ TeV, with average pileup $< PU >= 35$ and bunch time spacing of 25 ns. About 10^6 doublets are produced per each event and the ratio between *true* and *fake* doublets is between 300-400 (only about 3000 true doublets are produced per event by the seed generator). For each doublet 537 parameters are stored (450 pixels, 63 doublet info and 24 track parameters). The core structure for the doublet filtering classifier (*layer map model*) is shown in Figure 5 and it concatenates:

1. *CNN block*: conventional stack of convolutional layers (4) with 5×5 or 3×3 filters and max pooling layers (2) whose output is reduced to a one dimensional structure through a flatten layer that returns a 1024 element vector.

2. *Dense block*: stack of two fully connected layers that are fed with the one dimension reduced images from the previous block and 59 further doublets info (such as hits' detector layer and coordinates).

Overall 1000 events are simulated with 3 millions of doublets, 800 for the training dataset, 150 for testing and 50 for validation purposes. In the last year the efforts has been focused on the cross validation of the tool and its integration in the CMS Software Framework. For the first task the model has been tested under multiple conditions while retaining the same training sample.

- The ROC curves for different simulated processes and pile-ups is shown in Figure 6. The area under the curve is quite stable for all the configurations with the exception of very high pile-up configurations where the network performances are slightly worse but still very good.

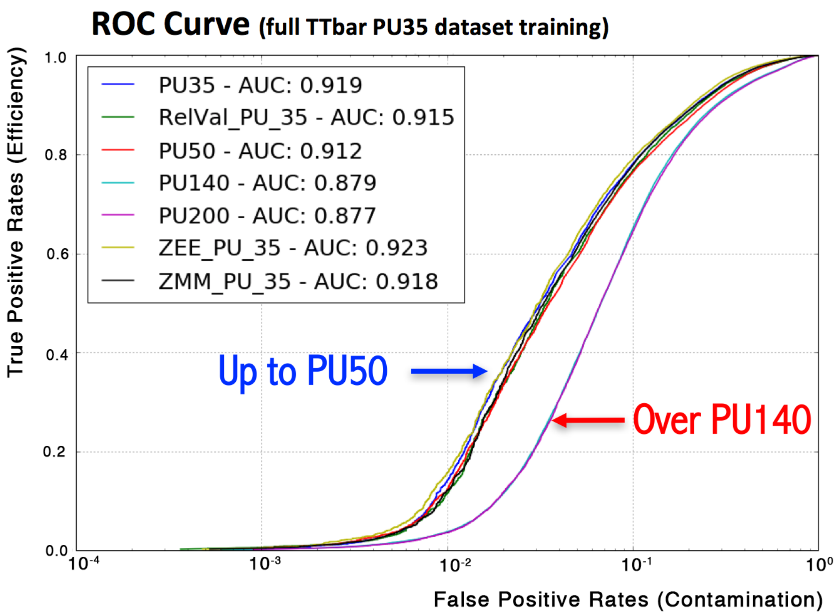

Figure 6: ROC curves for different pile up average values; event simulation recipes are given in the legend. Note the log scale for the contamination (x-axis).

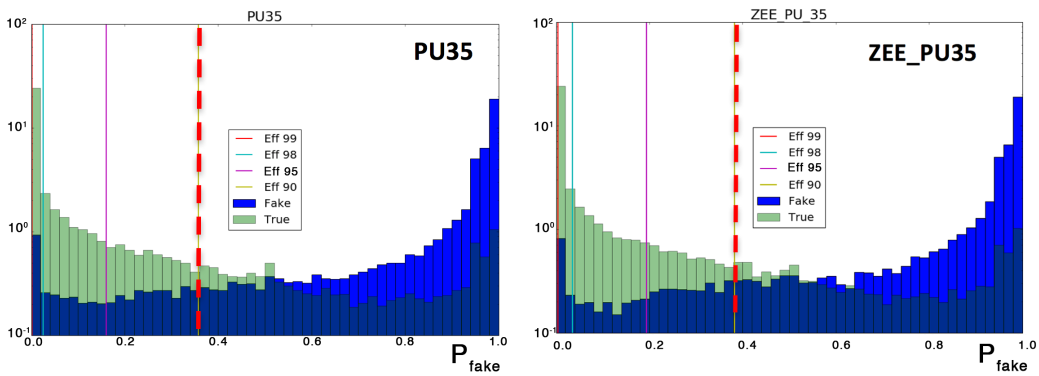

Figure 7: Example of the network output score, i.e. the probability p_{fake} that a doublet is fake, with $t\bar{t}$ and ZEE generation recipes. Each line shows the threshold that should be chosen to retain an efficiency values ranging from 90% to 99% (red dashed line).

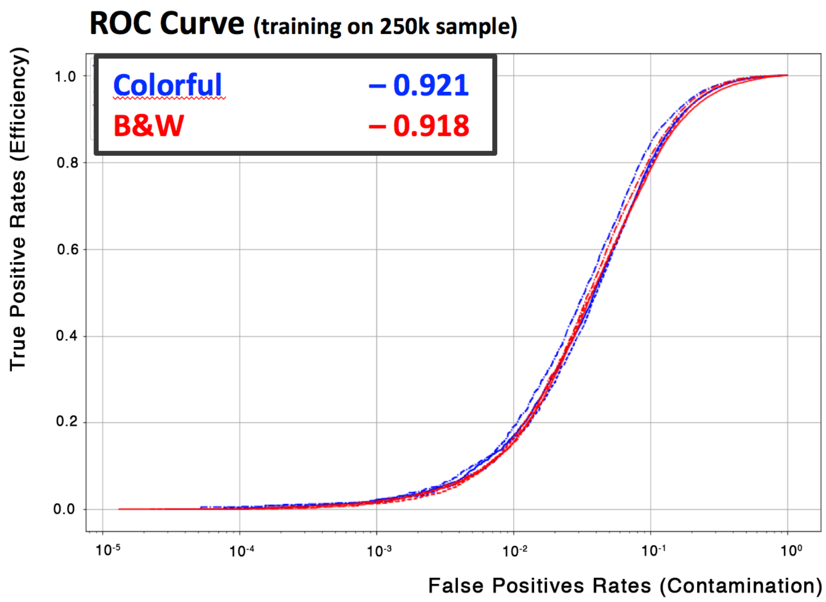

Figure 8: ROC curve comparison for "colorfull" 16bit model and "black and white" single bit model.

- The stability of the model output score has been tested with different recipes and pile-up conditions in order to determine the suitable thresholds for p_{fake}, i.e. the boundary value for the output scores defining the (fake) doublet rejection region. Figure 7 shows an example of the model output score for different simulation recipes and pile up conditions. It is clearly visible that both the output shape and the thresholds set for various values of target efficiency are very stable. This aspect is of paramount importance since it guarantees us great flexibility in the choice of the working point once the tool will be in production.
- A last test has been performed taking into account that, starting from Run III (2021-2022), the ADC readout for the Silicon Pixel detector is expected to become purely digital, i.e. each pixel will loose any information on the amount of charge collected reducing the output from 16 bits to 1 bit. Figure 8 shows that the network is performing equally well.

1.3 GooFit applications in the context of exotic QCD searches

1.3.1 Introduction to `GooFit`

The word heterogeneous computing refers to an enhancement of application performances that can be obtained by offloading compute-intensive portions to the GPU, while the remaining code still runs on the CPUs. In the context of High Energy Physics (HEP) analysis application, `GooFit` is an under development open source data analysis tool used in applications for parameters' estimation, that interfaces ROOT/RooFit to the CUDA parallel computing platform on nVidia's GPUs. `GooFit` acts as an interface between the MINUIT minimisation algorithm and a parallel processor which allows a Probability Density Function (PDF) to be evaluated in parallel. Fit parameters are estimated at each negative-log-likelihood (NLL)

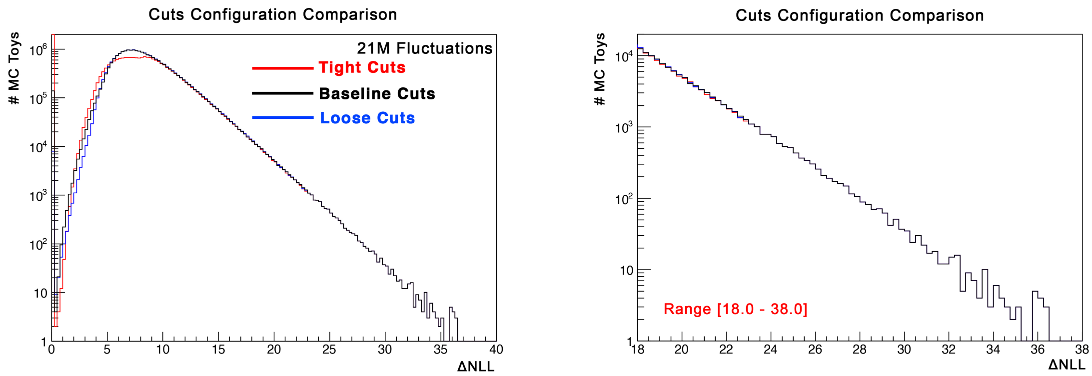

Figure 9: Left ΔNLL distributions for 21 millions of common fluctuations for the three configurations: baseline cut in black, tight in red and loose in blue. Right: zoom on the range 18.0-38.0.

Local Significance	**4.0σ**	**4.5σ**	**5.0σ**	**5.5σ**	**6.0σ**
Tight	2.21	2.91	3.58	4.23	5.19
Baseline	2.20	2.91	3.58	4.23	5.19
Loose	2.19	2.92	3.58	4.23	5.19

Table 3: MCToys stimated global significance for the three configurations with respect to different local significance values associated to different pseudo-data distributions.

minimisation step on the *host side* (CPU) while the PDF/NLL is evaluated on the *device side* (GPU).

1.3.2 Global statistical significance estimation by MC toys with GooFit

A high-statistics toy Monte Carlo technique has been implemented both in ROOT/RooFit and `GooFit` frameworks with the purpose to estimate the *local* statistical significance of an already known signal. The optimised `GooFit` application running on GPUs has provided striking speed-up performances with respect to the RooFit application parallelised on multiple CPUs by means of PROOF-Lite tool.

The work done in the third year has concerned the extension of this `GooFit` MC toys significance estimation method when a new unexpected signal (such as an exotic QCD state) is reconstructed and a global significance must be considered. In this case the Look Elsewhere Effect must be taken into account and a scanning technique needs to be implemented in order to consider any relevant random peaking activity with respect to the background model over the whole mass spectrum within the same fluctuation. Thus a scanning technique has been developed on the basis of a clustering approach. In order to test this procedure a pseudo-data invariant mass distribution of 15K candidates in a generic mass region of interest [1-18GeV] has been generated according to an invented background model (7th order polynomial) on the top of which a fake signal, mimicked with a Voigtian fucntion, is added close to 8 GeV (as shown in Figure 10); the local statistical significance of this peak is 5.5σ.

Three clustering configurations have been tuned in order to test the behavior of the clustering procedure and to estimate the systematic uncertainty associated to the clustering technique. After some tests with different cuts three configurations have been chosen: a set of tight, baseline and loose selection criteria for the cluster building. The three configurations are run on the same common set of 21 millions fluctuations and the three resulting ΔNLL

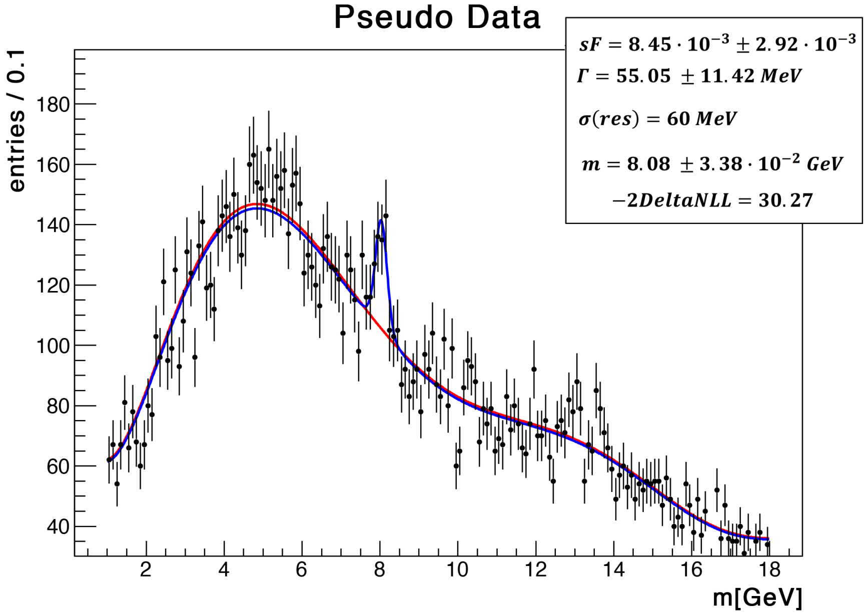

Figure 10: Pseudo-data simulated invariant mass distribution. In red the null hypothesis H0 fit, in blue the alternative hypothesis H1 fit.

distributions are shown superimposed in Figure 9. The right plot in Figure 9 focussing on the region of interest for the estimation of the statistical significance, i.e. the tail of the ΔNLL distribution ($\Delta NLL > 20$). From Table 3 it is evident that there is no sensitive difference by inspecting either the three distribution tails and the estimates of the *global* significance. Thus the systematic uncertainties associated with the method are negligible. Specifically the global significance for the pseudo-data signal presented in Figure 10 results to be 4.23σ for all the three configurations.

1.3.3 Comparison with Gross-Vittels method

In addition the results have been compared to the results of the paper by E. Gross and O. Vittels [9]. The authors proposed a method to estimate an upper limit for the global p-value when the signal hypothesis (H_1) depends on s nuisance parameters ($\vec{\theta}$) that don't exist under the null hypothesis (H_0). In our case $\vec{\theta} = (m; \Gamma)$ and we denote as $q(\vec{\theta})$ the ΔNLL test statistics. Thus, to estimate the p-value taking into account the LEE, we are interested in the maximum of $q(\vec{\theta})$ over $q(\hat{\theta}) = \max_{\vec{\theta}}(q(\vec{\theta}))$ with reference to a desired threshold c:

$$P(q(\vec{\theta}) > c) \leq P(\chi^2_s > c) + < N(c) >$$

.

The $N(c)$ function depends specifically on the details of the statistical model and can be difficult to calculate it analytically. In [9], it is instead proposed to estimate the number of *upcrossings* with respect to a low enough reference level c_0

$$P(q(\vec{\theta}) > c) \leq P(\chi^2_s > c) + < N(c_0) > (\frac{c}{c_0})^{s-1} e^{-(c-c_0)/2}$$

.

Therefore, a procedure to estimate $< N(c_0) >$ has has been implemented in *GooFit* for our sample pseudo-data and, after 10^4 toys, the result was:

Local Sig.	**4.0σ**	**4.5σ**	**5.0σ**	**5.5σ**	**6.0σ**
GV Method (upperlmit)	2.09	2.82	3.48	4.10	4.71
MC Toys	2.20	2.91	3.58	4.22	4.87

Table 4: The upper limit estimated with the G-V method is compared with the exact function extrapolated from the MC toys, with baseline clustering configuration.

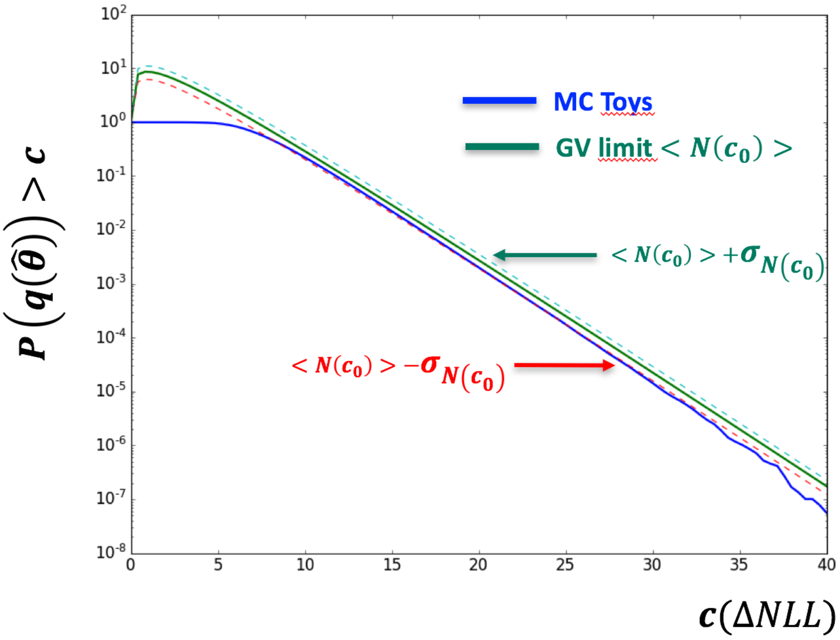

Figure 11: Estimated global significance with respect to different local significance. The upper limit estimated with the G-V method is compared with the exact function extrapolated from the baseline configuration MC toys.

$$< N(c_0) >= 7.3, \quad \sigma_{N(c_0)} = 2.4, \quad , c_0 = 1.0$$

.

Then the upper limit for $P(q(\vec{\theta}) > c)$ may be readily calculated. In Figure 11 and Table 4 the upper limit estimated with the G-V method is compared with the exact function extrapolated from the MC toys. The results are rather compatible.

2 Schools, Conferences and Workshops

The learning activity concerning schools and workshops attended during the first year is reported in this section.

2.1 Participation to Schools/Hackatons

- 3rd Patatrack Hackaton, CERN Geneva (Switzerland), 22-25 May 2018
- CMS Machine Learning Workshop, CERN Geneva (Switzerland), 2-4 July 2018

2.2 Participation to Workshops and Conferences

- IFAE2018: XVII Incontri di fisica delle alte energie, Milano (Italy), 4-6 Apr 2018 - Oral presentation with title : "Reti Neurali Convoluzionali per il seeding nella ricostruzione delle tracce a CMS, applicazioni e prospettive".
- 2nd IML Machine Learning Workshop, CERN, Geneva (Switzerland), 9-12 Apr 2018. Invited talk : "Convolutional Neural Network for Track Seed Filtering at the CMS HLT".
- The 23nd International Conference on Computing in High Energy and Nuclear Physics, CHEP 2018, Sofia, 9-13 Jul 2018 - Oral presentation with title: "Track Seed Filtering using Convolutional Neural Network at the CMS High Level Trigger"
- The 6th Annual Conference on Large Hadron Collider Physics, LHCP 2018, Bologna, 4-9 Jun 2018 - Oral presentation with title: "Heavy Flavour production at ATLAS and CMS".
- XIIIth Quark Confinement and the Hadron Spectrum (QCHS)", Maynooth University (Ireland), 31 Jul - 6 Aug 2018 - Oral presentation with title: "Estimation of global statistical significance of a new signal within the GooFit framework on GPUs".

3 List of publications

- A.Pompili and A. Di Florio (on behalf of CMS collaboration), *GPUs for statistical data analysis in HEP: a performance study of GooFit on GPUs vs. RooFit on CPUs*, J.Phys.Conf.Ser. 762 (2016), 012044, Proceedings of "17th International workshop on Advanced Computing and Analysis Techniques (ACAT-2016)".
- A.Di Florio et al. *Statistical significance estimation of a signal within the GooFit framework on GPUs*", J.Phys.Conf.Ser. 762 (2016), 012044 Proceedings of "12th Conference on Quark Confinement and the Hadron Spectrum (Confinement XII)".
- A. Di Florio, *Performance studies of GooFit on GPUs versus RooFit on CPUs while estimating the statistical significance of a new physical signal*, Proceedings of "22nd International Conference on Computing in High Energy and Nuclear Physics (CHEP-2016)".
- A. Di Florio et al., *Convolutional Neural Network for Track Seed Filtering at the CMS High-Level Trigger*, Proceedings of "18th International workshop on Advanced Computing and Analysis Techniques in physics research (ACAT-2017)".
- A. Di Florio et al., *Performance studies of GooFit on GPUs versus RooFit on CPUs while estimating the global statistical significance of a new physical signal*, Proceedings of "18th International workshop on Advanced Computing and Analysis Techniques in physics research (ACAT-2017)".
- A. Di Florio, *Heavy Flavour production at ATLAS and CMS*, Proceedings of "6th Annual Conference on Large Hadron Collider Physics (LHCP 2018)" Bologna, 4-9 Jun 2018 (ACAT-2017).
- A. Di Florio et al., *Track Seed Filtering using Convolutional Neural Network at the CMS High Level Trigger*, Proceedings of "23nd International Conference on Computing in High Energy and Nuclear Physics, CHEP 2018" Sofia, 9-13 Jul 2018.
- A. Di Florio et al., *Estimation of global statistical significance of a new signal within the GooFit framework on GPUs*, Proceedings of "XIIIth Quark Confinement and the Hadron Spectrum (QCHS)", Maynooth University (Ireland), 31 Jul - 6 Aug 2018 in preparation.
- CMS Collaboration, *Studies of* $B^{*}_{s2}(5840)^0$ *and* $B_{s1}(5830)^0$ *mesons including the observation of the* $B^{*}_{s2}(5840)^0 \to B^0 K^0_S$ *decay in proton-proton collisions at* $\sqrt{s} = 8$ *TeV*, [arXiv:1809.03578].
- CMS Collaboration, *Angular analysis of the decay* $B^+ \to K^+\mu^+\mu^-$ *in proton-proton collisions at* $\sqrt{s} = 8$ *TeV*, [arXiv:1806.00636].
- CMS Collaboration, *Observation of the* χ_{b1}*(3P) and* χ_{b2}*(3P) and measurement of their masses*, Phys. Rev. Lett. **121** (2018) 092002 [arXiv:1805.11192]
- CMS Collaboration, *Observation of the* $Z \to \psi\ell^+\ell^-$ *decay in pp collisions at* $\sqrt{s} = 13$ *TeV*, Phys. Rev. Lett. **121** (2018) 141801 [arXiv:1806.04213]
- Author of 98 publications as member of CMS collaboration.

Adriano Di Florio

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