Deployment of a Matrix Element Method code for the $ttH$ channel analysis on GPU's platform

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**Recent discovery of H boson in \(ttH\) channel**

- Higgs decays into \(\gamma\gamma\), \(ZZ\), \(WW\) and \(\tau\tau\) final states have been observed (discovery 2012) and there is evidence for the direct decay to the \(bb\) final state
- In the Standard Model, the Higgs boson couples to fermions with a strength proportional to the fermion mass (Yukawa coupling)
- The decay to the \(tt\) final state is not kinematically possible
- Probing the coupling of the Higgs boson to the \(t\) quark, the heaviest known fermion, is a high priority
- The Higgs boson in association with \(tt\) final state can result from the fusion of a \(tt\) pair or through a radiation of \(t\) quark

- **We (CMS@LLR) contributed to the \(ttH \rightarrow \tau\tau\) sub-channel**

- First observation* of the simultaneous production of a Higgs boson with a \(tt\) pair (channel) April 2018

Matrix Element Method (MEM)

MEM is an unsupervised method (theory-driven) which is important to have among the supervised ones (Machine Learning, ...)

Principle:
- select a Signal final state $S_{\text{sig}}$: $b\bar{b}, q\bar{q}, \tau_{\text{had}}, 2$ leptons same sign
- compute a weight quantifying the probability that an observed event matches a theoretical model
- vary the theoretical model (Signal, background(s))
- deduce a likelihood ratio

$$w_i(y) = \frac{1}{\sigma_i} \sum_p \int dx_1 dx_2 dx_3 \frac{f(x_1, Q)f(x_2, Q)}{x_1 x_2 x_3} \delta^2(x_a P_a + x_b P_b - \sum p_k) |M_i(x)|^2 W(y|x)$$
MEM: time-consuming computations

- Multiple scenarios to consider (compute one integral for each): the signal process and the background processes

- For each scenario: 4 permutations (green arrows)

Irreducible background

One background: one non-prompt lepton produced in a b decay

Only one quark not reconstructed (blue) → loop on all “light-jets”

\((1+3) \times 4 \times [\text{#Light-jets}]\) Integrals with a dimension from 3 to 7. They are computed if they are kinematically possible
The MEM Code

- The processing time for a typical data set (2395 evts) 55 days (14 hours / 96 cores)
- MEM code features: MPI/OpenCL/Cuda to aggregate numerous computing resources (HPC)
- Main kernel (one Vegas iteration)
  - developed a MadGraph extension to generate the OCL/Cuda kernel codes
  - LHAPDF lib.: Fortran to C-kernel translation
  - ROOT tools: Lorentz/geometric arithmetic's
  - \( \rightarrow \) big kernels (10-20 x 10^3 lines)
- OpenCL / Cuda bridge (IBM+NVidia)
MEM code performance

- MPI C++ version versus MPI / OpenCL / CUDA - compilation -O 3, nvcc
- 1 node @CC-IN2P3:
  - Intel Xeon 2 x E5-2640, 2 x 8 cores@2.6 GHz
  - 2 NVidia K80 cards -> 4 Kepler GPUs per node
- Good scalability (MPI & kernels asynchronous mechanisms ok)

- Computing time of a data set with 2395 evts:
  - 55 days on 1 core (or 3.5 days on a node)
  - 450 sec. on 32 GPUs (8 nodes)

- Gains:
  - C++ → C kernel (careful) rewriting
  - CPU → GPU, the use of GPUs
Conclusion / perspective

- The MEM has proven to be an efficient method for signal extraction and our (CMS@LLR) results were combined to achieve the \( ttH \) production mode observation in 2018 *Phys. Rev. Lett.* 120, 231801 (2018)

Gain
- Restitution time: several days against \( \sim 10 \) mn
- Computing efficiency (cost, power supply, cooling, ...)
  - 1 K80-GPUs is equivalent - for C++ MEM case - to \( \sim 20 \) nodes (2x8 cores)
- In HL-LCG computing challenge, save the computing resources for other jobs.

Physic program
- For 2017 and 2018 data, new computations only with GPUs for \( ttH(\tau\tau) \) analysis

New developments
- if we get the funding, project to have one code for CPU and GPUs, with the principles used by the MadGraph code generator
- Optimizations: improve the computing load on GPUs

2 lepton same sign and 1 tau channel

\[
\begin{align*}
pp & \rightarrow t\bar{t}H \\
\rightarrow & \tau^+\tau^- + e^+\nu_e + \tau^+\bar{\nu}_e + bW \\
\rightarrow & bW + b\mu + \nu_e \\
\rightarrow & bW + b + q + q^* \\
\rightarrow & jet + b-jet + \mu^+ \\
\rightarrow & jet + b-jet + e^-
\end{align*}
\]
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