THE MATRIX ELEMENT METHOD USED IN THE SEARCH FOR THE ASSOCIATED PRODUCTION OF THE HIGGS BOSON WITH TOP QUARKS AND DECAYING INTO TAU LEPTONS

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The ttH final state

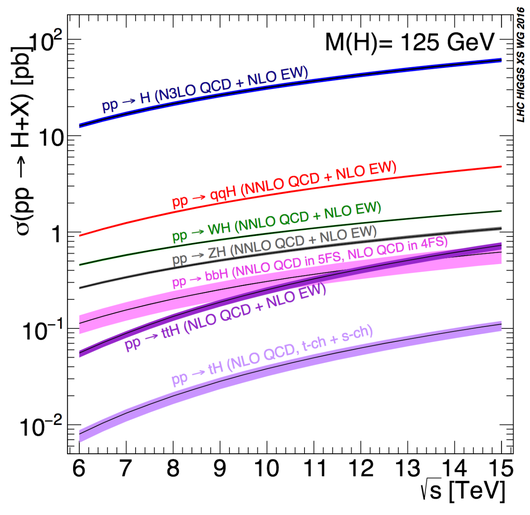
Motivation & Challenges

Motivations:
- **The ttH production mode is a direct probe to coupling of Higgs to top**
- **Increase LHC center-of-mass energy from 8 to 13 TeV, → x4 cross-section 0.51pb @ 13 TeV**
- **The ttH production has recently been observed** Phys. Rev. Lett. 120, 231801 (2018)

Challenges:
The study of the ttH production mode is challenging
→ *Looking for 2 tops + 1 Higgs* (w/ complex final states)

- ***Top decays:***
  t→blv : 1 b-jet + 1 lepton + MET
  t→bqq : 1 b-jet + 2 light jets

- ***Higgs decay:***
  H→bb : 2 b-jets
  H→$\tau\tau$: 1-2 τ_h (+ lepton + MET)
  H→WW/ZZ : leptons (+ jets + MET)
  H→$\gamma\gamma$: 2 photons
  H→ZZ->4l: 4 leptons



Final states with tau leptons: most sensitive final state to ttH H→$\tau\tau$ + 2 SS leptons. Signature with 2 b-jets + 2 light jets + 2 leptons + 1τ_h → almost every SM particle. Signal extraction makes extensive use of MVA discriminants

The Matrix Element Method

A powerful signal extraction method

The Matrix element method (MEM): The MEM is an alternative signal extraction method to Boosted Decision Trees, Neural Networks etc. It combines:
→ Variables from reconstructed objects (y) (such as leptons, taus, jets, MET)
→ Theoretical description in terms of particles in phase-space point (x) (such as quarks, neutrinos, tau before decay etc).
This combination is used to define event weights, which relates to how compatible the event is with a given physics process (signal and background weights are computed:

Parton density functions

Hard-scattering matrix element: computed at LO with MadGraph, OpenLoops…

$$w_\Omega(\mathbf{y}) \propto \sum_p \int d\mathbf{x} dx_a dx_b \frac{f(x_a,Q) f(x_b,Q)}{x_a x_b s} \delta^2(x_a P_a + x_b P_b - \sum p_k) |\mathcal{M}_\Omega(\mathbf{x})|^2 W(\mathbf{y}||\mathbf{x})$$

Numerical integration: performed with VEGAS, Markov chain integrator…

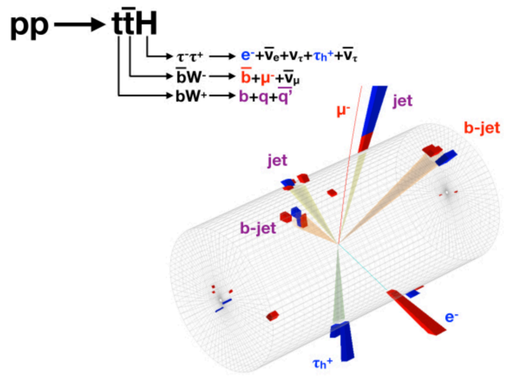
Momentum conservation (+ on-shell conditions): used to reduce dimensionality

Transfer functions: probability to measure y given a parton configuration x

The MEM: The event weight is computed for each hypothesis Ω (Ω=ttH, ttV…) using observables y as inputs and integrating over unmeasured (or poorly measured) quantities x. The final discriminant corresponds to:

$$\mathcal{L}(\mathbf{y}) = \frac{w_S(\mathbf{y})}{w_S(\mathbf{y}) + w_B(\mathbf{y})}$$

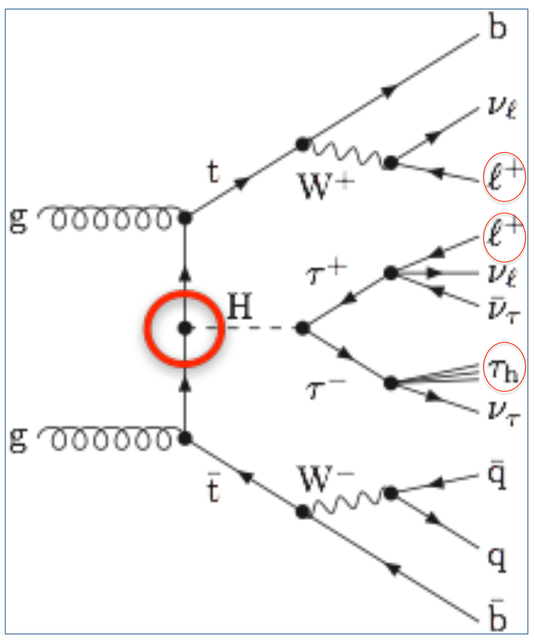
The use of the MEM is very CPU intensive and methods to implement a GPU-based derivation is actively ongoing @ LLR.



The ttH multilepton Analysis

Focus on the two same sign leptons and tau category

The categories with ttH → tau + X are part of the ttH multilepton analysis (CMS PAS HIG-17-018) including final states with more than or one hadronic tau lepton. Using here a dedicated tau identification with a smaller isolation cone size (ΔR=0.3) optimized for high multiplicity events

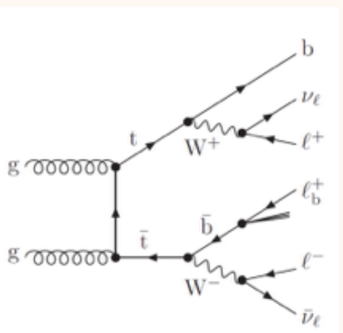


A good case for MEM:
2lSS+1τ_h + ≥ 3 jets (≥ 1 b-tag medium or ≥ 2 b-tag loose)

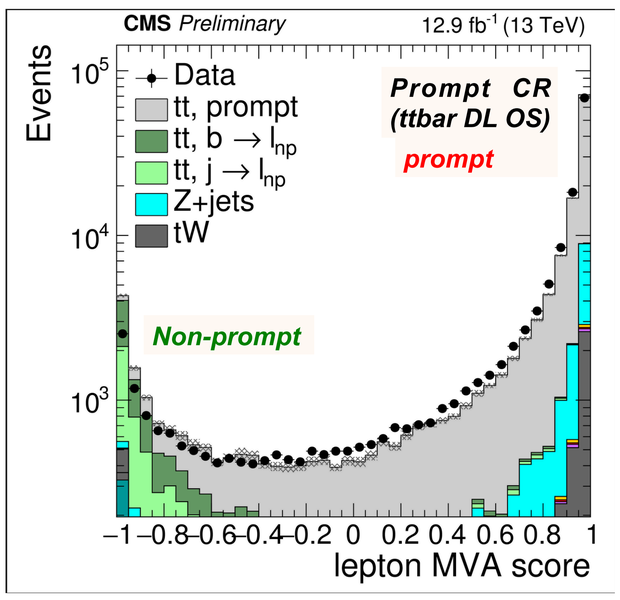
Main sources of background:
- ***Irreducible: ttV, di-boson (evaluated from MC)***
- ***Reducible: non-prompt leptons and charge mis-ID (from data)***

In the analysis presented, the leptons are selected with a MVA, trained to discriminate prompt leptons (from W, Z or τ decays) from non-prompt leptons (from b-jets and mis-identified hadrons)

Inputs to the MVA used:
- ***Isolation***
- ***vertex***
- ***Lepton Identification***
- ***jet variables (…)***



The performance of the MVA was validated in control regions directly using the CMS data.

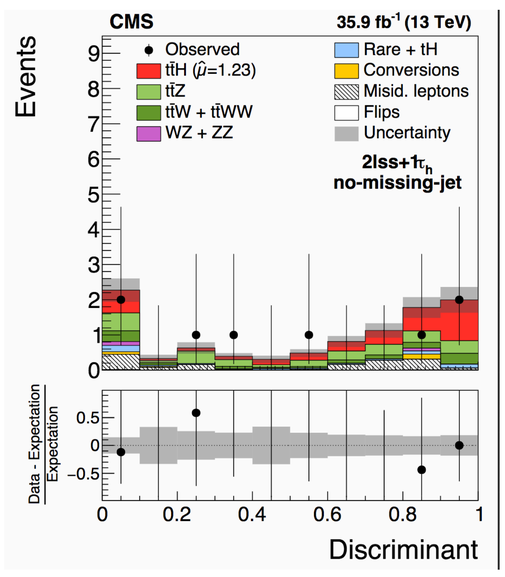


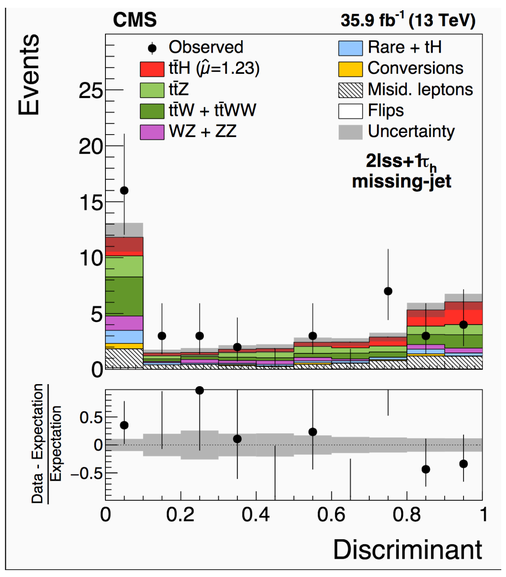
The residual background coming from non-prompt leptons was evaluated using tight-to-loose fake rate method

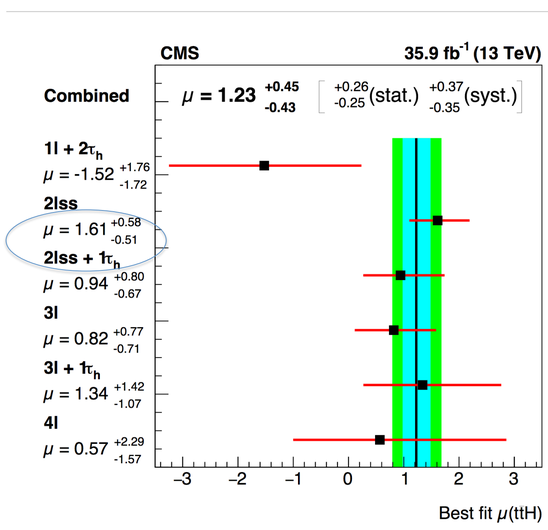
Analysis Results

Based on 2016 CMS data

The impact of the use of the MEM in the 2lSS + 1τ_h
- ***2lSS+1τ_h channel: MEM optimized to discriminate ttH H→$\tau\tau$ signal from ttZ → $\tau\tau$ + ttZ Z→ ll + tt w/ non-prompt lepton***
- ***The events are split between two subcategories based on presence of jets compatible with the W→ qq decay: MEM integration performed on direction of missing jet if needed***

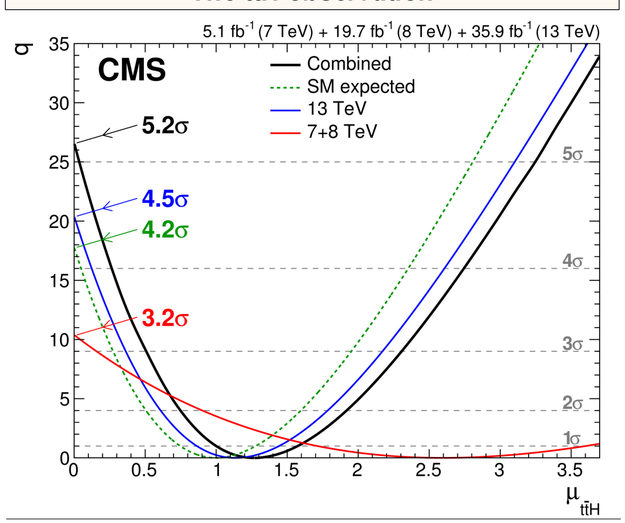






An excess has been observed with respect to the background-only hypothesis in the multilepton final states: 3.2σ observed significance (2.8σ expected). The combined results obtained are compatible with the Standard Model expectation.

The ttH observation



The 2lSS+1τ_h category used as input to the CMS ttH combination→ First observation of the ttH production mode!

CONCLUSION:
- ***In the search for the ttH production mode, the channels involving the presence of τ complement the coverage of the accessible phase space in CMS***
- ***Dedicated signal extraction methods optimized for final states with τ has been used: the MEM has proven to be a powerful tool.***
- ***Final combination with LHC Run I (8 TeV) has allowed to observe the ttH production mode with a significance of 5.2σ (4.2σ expected)***
  Phys. Rev. Lett. 120, 231801 (2018)