Observation of Top Quark Pair Production in Association with a Higgs Boson at CMS

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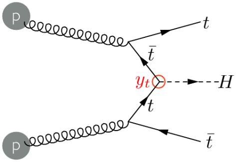
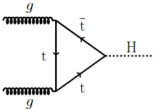
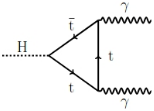
Top-Higgs coupling: the hunt for $t\bar{t}H$

Best direct probe of the top-Higgs Yukawa coupling, vital step towards verifying the SM nature of the Higgs boson

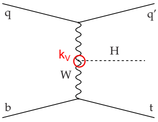
- Top quark is the most strongly-coupled SM fermion (y_t ∼1)
- Direct measurement of y_t in $t\bar{t}H$ production:
  - gluon-gluon fusion: assumes no BSM coupling
  - Allows probing new physics in gg→H and H→ $\gamma\gamma$ effective vertices

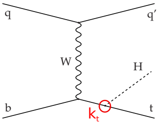






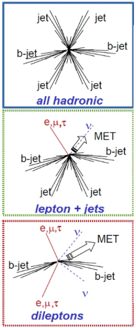
- y_t in tH production: access to sign of the coupling (→ Talk by B. Stieger)

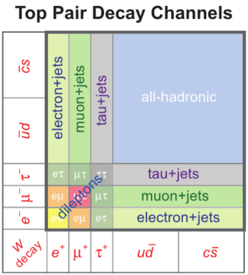




Top quark × Higgs decay channels

- Challenges: $\sigma_{t\bar{t}H} \approx 0.5$ pb, $\sigma_{t\bar{t}} \approx 830$ pb @13 TeV
  - Crucial to understand $t\bar{t}$+X (X = $b\bar{b}$, W, Z)
  - Large combinatorics of leptons and jets from top quark decays
- Exploiting all $t\bar{t}$ decay channels and Higgs decays to
  - bottom quarks → large BR, large background contributions *(→ Posters E31, E32)*
  - W, Z bosons, taus → smaller production rate, lower backgrounds *(→ Poster E28)*
  - photons → clean final state, very small rate





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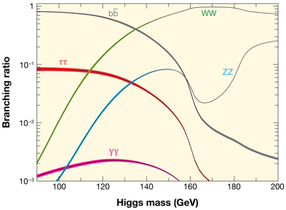
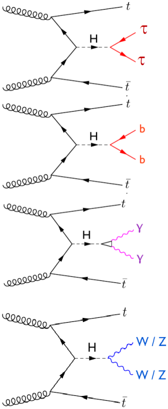
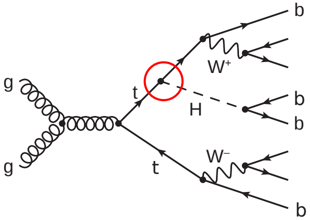
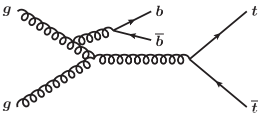




$t\bar{t}H(b\bar{b})$ Production

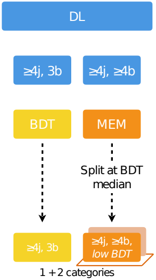
- Large $\mathcal{B}(H \to b\bar{b})$, access to coupling 3rd generation quarks
- Challenging final state
  - Huge combinatorics in event reconstruction
  - Poor $H \to b\bar{b}$ mass resolution
  - Large $t\bar{t} + b\bar{b}$ background of $\mathcal{O}(10)$pb with associated large theory uncertainties: from simulation
- Search channels
  - Leptonic $t\bar{t}$: higher purity
  - Fully-hadronic $t\bar{t}$: higher rate

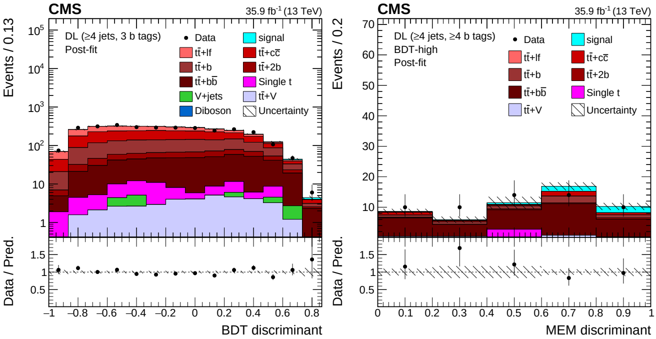




$t\bar{t}H(b\bar{b})$: **dilepton $t\bar{t}$ channel** arXiv:1804.03682, sub. to JHEP

- Events categorised by number of jets and b-tagged jets

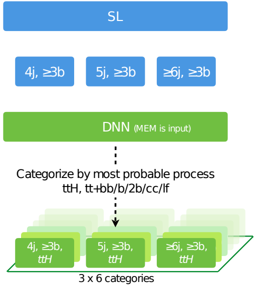


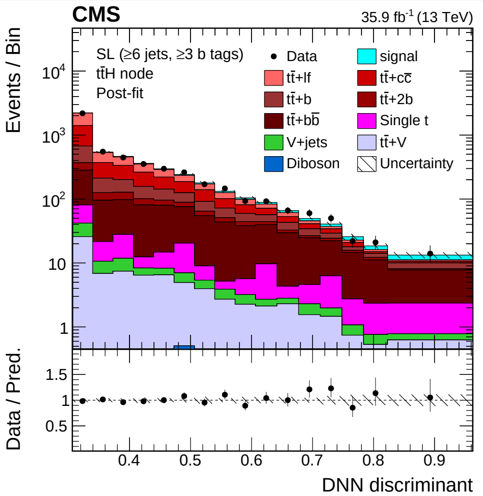


- $\geq$ 4j, 3b: BDT separating signal and inclusive $t\bar{t}$ + jets background
- $\geq$ 4j, $\geq$ 4b: low/high BDT sub-categories + Matrix Element Method (MEM) separating against $t\bar{t} + b\bar{b}$ background

$t\bar{t}H(b\bar{b})$: **lepton+jets $t\bar{t}$ channel** arXiv:1804.03682, sub. to JHEP

- Search in single-lepton $t\bar{t}$ channel
- Events categorised by number of jets: 4, 5, ≥ 6

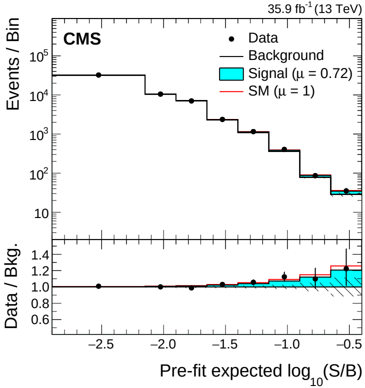


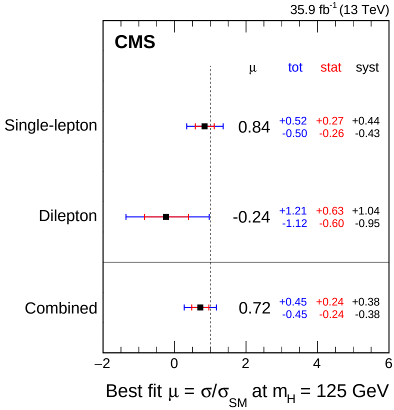


- Deep Neural Network (DNN) per jet category: multi-classification as signal or any of 5 $t\bar{t}$ + jets bkgs. ($t\bar{t}+b\bar{b}$, $t\bar{t}+2b$, $t\bar{t}+b$, $t\bar{t}+c\bar{c}$, $t\bar{t}+LF$)
- Final discriminant: DNN output of chosen process node

tt̄H(bb̄) Leptonic: Results

arXiv:1804.03682, sub. to JHEP





Best-fit $\mu = 0.72^{+0.45}_{-0.45}$, at 1.6 (2.2) σ obs. (exp.) significance

tt̄H(bb̄) Leptonic: Results

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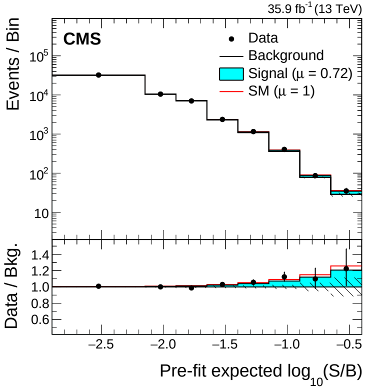
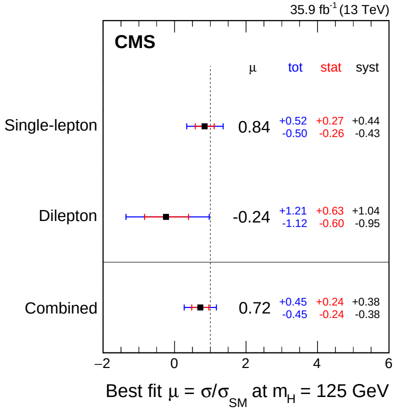




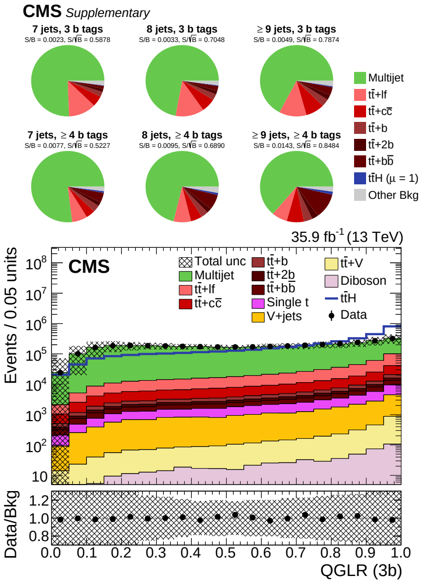
Best-fit $\mu = 0.72^{+0.45}_{-0.45}$, at 1.6 (2.2) σ obs. (exp.) significance

- Limited by $t\bar{t}+$HF and b-tagging uncertainties

tt̄H(bb̄) Hadronic

arXiv:1803.06986, sub. to JHEP

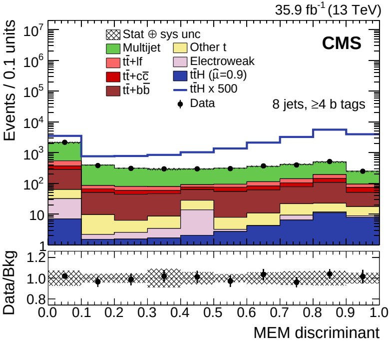
- ≥ 7 jets, ≥ 3 b-tagged jets, $H_{\mathrm{T}} > 500\,\mathrm{GeV}$, no leptons
- Events categorised by number of jets and b-tagged jets
- Dominant background: QCD-multijet production
    - Shape from low b-tag multiplicity control region in data
    - Rate from final fit to data



$t\bar{t}H(b\bar{b})$ hadronic

arXiv:1803.06986, sub. to JHEP

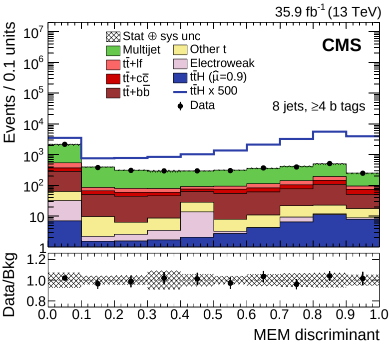
- Final discriminant: MEM (discriminate $t\bar{t}H$ signal and $t\bar{t}+b\bar{b}$)
- Also performs well against the $t\bar{t}$ + LF jets and QCD multijets backgrounds

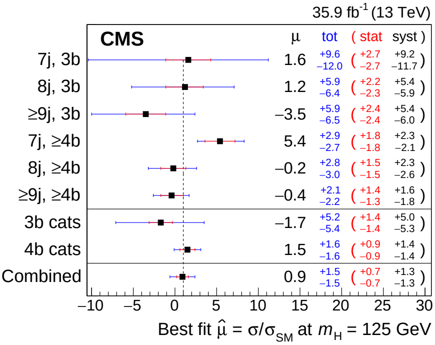


tt̄H(bb̄) hadronic

arXiv:1803.06986, sub. to JHEP

- Final discriminant: MEM (discriminate tt̄H signal and tt̄ + bb̄)
- Also performs well against the tt̄ + LF jets and QCD multijets backgrounds





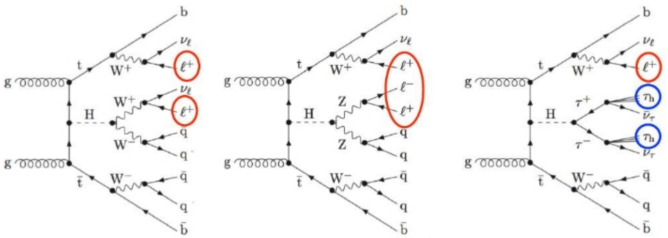
Best-fit $\mu = 0.9^{+1.5}_{-1.5}$, upper 95% C.L. limit 3.8 (3.1) obs. (exp.) $\times$ SM

- Major systematic uncertainties: Multijet estimation, tt̄ + HF prediction, b-tagging and JES etc.

$t\bar{t}H$ multilepton

arXiv:1803.05485, sub. to JHEP

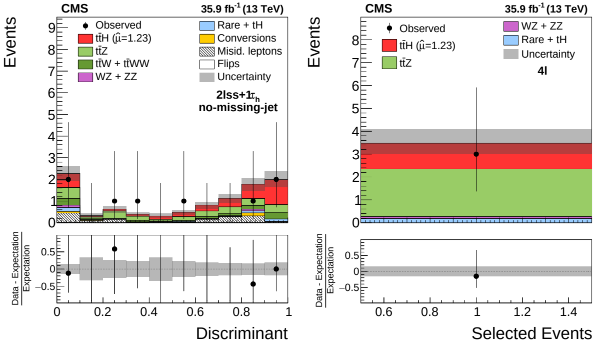
- Multilepton final states: Higgs decay to W^+W^-, ZZ, and $\tau\tau$
- Events categorised based on number of leptons and τ_h candidates



- $1\ \ell + 2\ \tau_h$, 2 same-sign ℓ + 0, $1\ \tau_h$, $3\ \ell$ + 0, $1\ \tau_h$, $4\ \ell$
- Additional requirements on jets, b-tagged jets
- Major backgrounds
  - Irreducible: $t\bar{t} + V$ and diboson, predicted from simulation and control regions
  - Reducible: non-prompt leptons in $t\bar{t}$ + jets events, estimated from data
  - Large $t\bar{t}$ + fake τ_h for $1\ \ell + 2\ \tau_h$
- BDT and MEM discriminants to separate signal from backgrounds

$t\bar{t}H$ multilepton: analysis strategy **arXiv:1803.05485, sub. to JHEP**

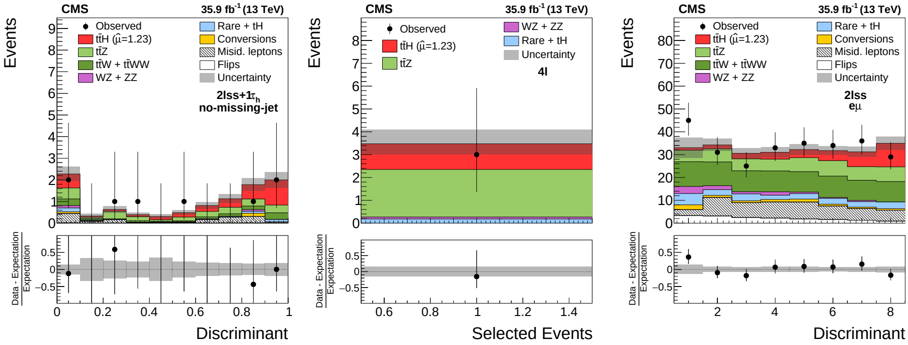
- Event categorisation in lepton flavor, and b-jet multiplicity
- Discriminating variables
  - MEM against $t\bar{t}Z$ (2 ℓ same-sign + 1 τ_h)
  - Yield in 4-leptons (low stats.)



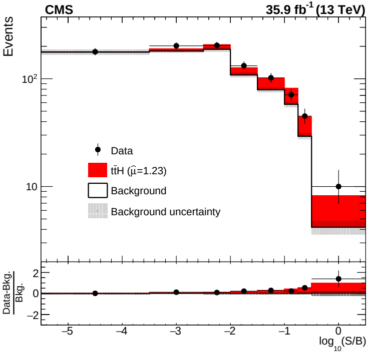
tt̄H multilepton: analysis strategy

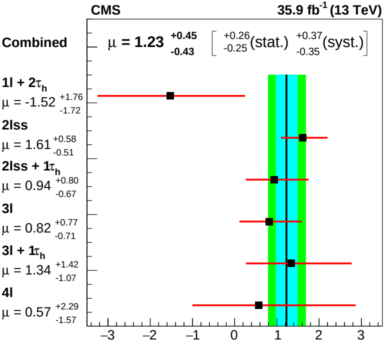
arXiv:1803.05485, sub. to JHEP

- Event categorisation in lepton flavor, and b-jet multiplicity
- Discriminating variables
  - MEM against tt̄Z (2 ℓ same-sign + 1 τ_h)
  - Yield in 4-leptons (low stats.)
  - BDTs against tt̄ + jets (1l+2 τ_h) and tt̄ + jets, tt̄ + V (2 ℓ same-sign, 3 ℓ)



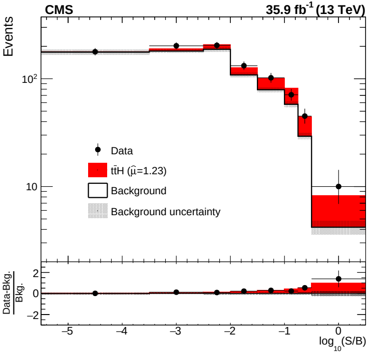
tt̄H multilepton results arXiv:1803.05485, sub. to JHEP

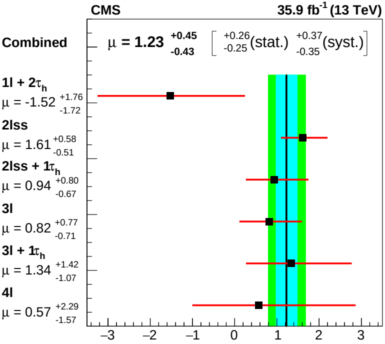




Best-fit $\mu = 1.23^{+0.45}_{-0.43}$, at 3.2 (2.8) σ obs. (exp.) significance

$t\bar{t}$H multilepton results arXiv:1803.05485, sub. to JHEP





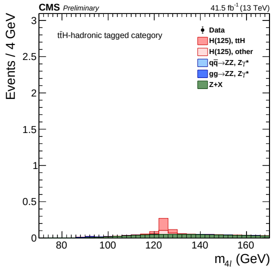
Best-fit $\mu = 1.23^{+0.45}_{-0.43}$, at 3.2 (2.8) σ obs. (exp.) significance

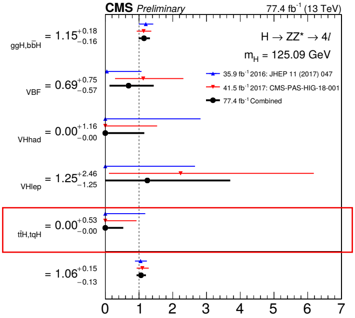
- Limited by non-prompt lepton estimation and tau identification, JES, $t\bar{t}$H and $t\bar{t}+V$ modelling
- Several channels limited by statistics

$t\bar{t}H \to ZZ^{*} \to 4\ell$

PAS-HIG-18-001

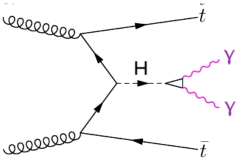
- Analysis with full 2017 dataset
- Very clean final state, but tiny branching fraction
- Dedicated tt̄H channel part of the global $H \to ZZ^{*}$ analysis
- tt̄ hadronic and leptonic channels
    - ≥ 4 jets, ≥ 1 b-tagged jet and additional 0/1 leptons
- Combined fit (relying on $m_{4\ell}$ and a kinematic discriminant) with analysis of 2016 data (doi:10.1007/JHEP11(2017)047)



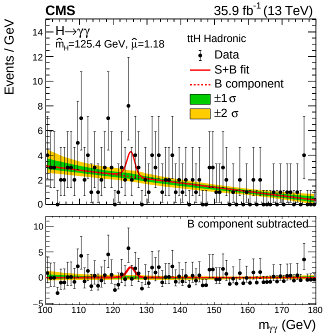


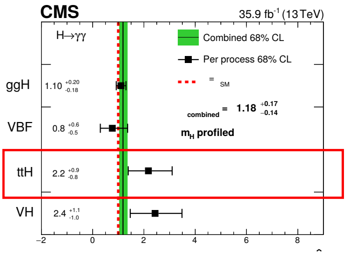
t$\bar{t}$H($\gamma\gamma$)

arXiv:1804.02610, sub. to JHEP



- Clear signature coming from the photons
- Higgs boson can be reconstructed as a narrow peak
- Dedicated t$\bar{t}$H channel part of the global H $\to \gamma\gamma$ analysis
- t$\bar{t}$ hadronic and leptonic channels
- Signal extracted from fit to $m_{\gamma\gamma}$





Combination: First observation of tt̄H

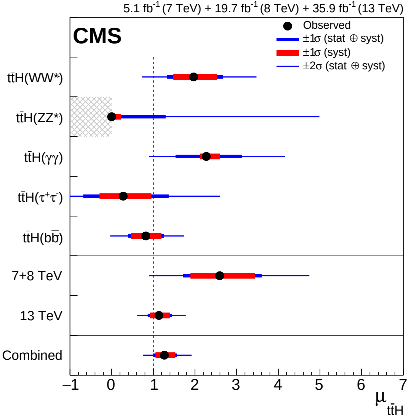
PRL 120 (2018) 231801

Contributing analyses

- All tt̄H analyses with 2016 data
- 7 TeV (up to 5.1 fb^{-1}) + 8 TeV (up to 19.7 fb^{-1}):

  Dedicated analyses targeting the bb and multilepton final states

  The tt̄H categories of the H$\rightarrow \gamma\gamma$ analysis

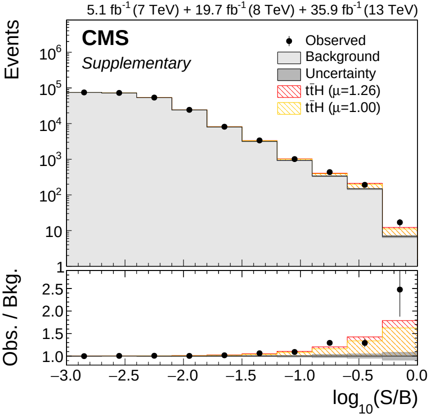


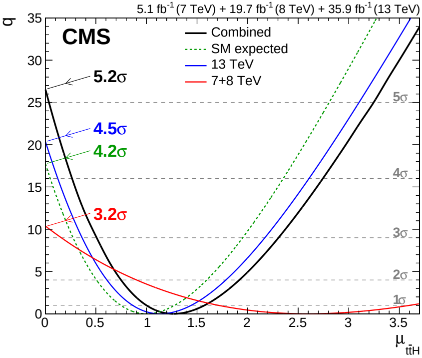
Correlations between Run-1 and Run-2 analyses

- Inclusive signal theory and some background theory uncertainties correlated
- Experimental uncertainties largely uncorrelated

Combination: First observation of $t\bar{t}$H **PRL 120 (2018) 231801**

- Observed significance is 5.2σ (4.2σ exp.) with respect to the $\mu_{t\bar{t}H} = 0$ hypothesis
- First observation of the $t\bar{t}$H production process





$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat})^{+0.17}_{-0.15}(\text{expt})^{+0.14}_{-0.13}(\text{Th. bkg})^{+0.15}_{-0.07}(\text{Th. sig})$$

Summary and outlook

- Results presented for $t\bar{t}H$ searches with 36 fb^{-1} of pp collision data @ 13 TeV (2016 data)
  - Improvements in analysis techniques compared to Run 1 (e.g. DNN)
  - Addition of new challenging final states: fully hadronic mode, final states with hadronically decaying τ leptons
  - Work ongoing to reduce limitations of systematic uncertainties of results with full Run-2 lumi.(signal and background modeling ($t\bar{t}+b\bar{b}$, $t\bar{t}+V$), improve non-prompt lepton estimation, jet flavor tagging...)
- First observation of $t\bar{t}H$ production, combining 7, 8, and 13 TeV analyses
- New data...
  - More statistics helpful for developing more sophisticated strategy for background control
  - Statistic limited channels will become more and more relevant