Karlsruhe Institute of Technology

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Measurement of $t\bar{t}H$ in the $H \to b\bar{b}$ decay channel at CMS

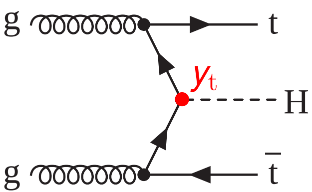
Rencontres de Blois

Michael Waßmer on behalf of the CMS collaboration | June 4, 2019

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (ETP)

$t\bar{t}H$ in a nutshell

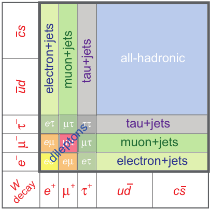
- SM: Yukawa-type coupling of Higgs boson to fermions ($y_f \propto m_f/v$)
  $\rightarrow$ expect largest coupling to top quark
- $\sigma_{\mathrm{SM}}(t\bar{t}H) \approx 0.5\,\mathrm{pb}$ at $\sqrt{s} = 13\,\mathrm{TeV}$
- $t\bar{t}H$: direct tree-level access to the coupling (instead of indirect by loop contributions)
- Final state signature determined by decay of $t\bar{t}$-system and Higgs boson



Observation in 2018 by
CMS: Phys. Rev. Lett. 120, 231801 (2018)
ATLAS: Phys. Lett. B 784 (2018) 173

$t\bar{t}H$ anatomy

Top Pair Decay Channels



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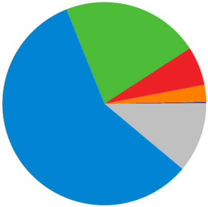
Higgs Boson Decay Channels



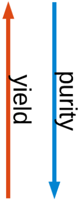
$H \to b\bar{b}$

$H \to WW^* / \tau\tau / ZZ^*$

“multi-lepton analysis”

$H \to \gamma\gamma$

$H \to ZZ^* \to 4l$



This talk will be focused on $t\bar{t}H$, $H \to b\bar{b}$.

$t\bar{t}H$, $H \rightarrow b\bar{b}$ analyses

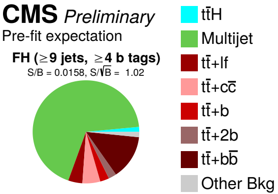
	leptonic	fully-hadronic
2016 dataset, 35.9 fb^{-1}	JHEP 1903 (2019) 026	JHEP 06 (2018) 101
2017 dataset, 41.5 fb^{-1} 2017+2016 results combined	NEW **CMS-PAS-HIG-18-030** NEW	

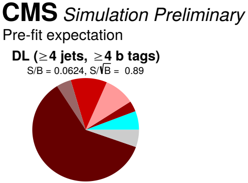
Improvements of 2017 analysis with respect to 2016:

- One more pixel layer, better algorithms $\rightarrow$ improved b-tagging
- Combination of all $t\bar{t}$ decay channels
- Improved modeling of parton shower (PS) uncertainties

Challenges

- Small signal $\sigma_{\text{SM},t\bar{t}H} \times \text{BR}_{\text{SM},H\to b\bar{b}} \approx 0.29\,\text{pb}$
- Complex multi-jet final state $\to$ no unambiguous event reconstruction
- Large (almost irreducible) backgrounds due to $t\bar{t}$ + b-jets production $\to$ small $S/\sqrt{B}$ even in signal-enriched categories
- Theoretical description of $t\bar{t}$ + b-jets very difficult $\to$ large uncertainties (20-30% @ NLO QCD)
- Large QCD contribution in channel with no leptons



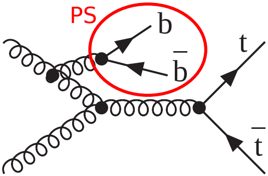


Need categorization, control regions and multivariate methods.

$t\bar{t}$ + b-jets

- PS has large impact on used simulation
- $t\bar{t}$ + b-jets signatures on particle level: $t\bar{t}$ + b/2b/$b\bar{b}$
- These signatures
  - contribute differently to different phase spaces (e.g. jet/b-tag multiplicity)
  - are affected by different PS uncertainties

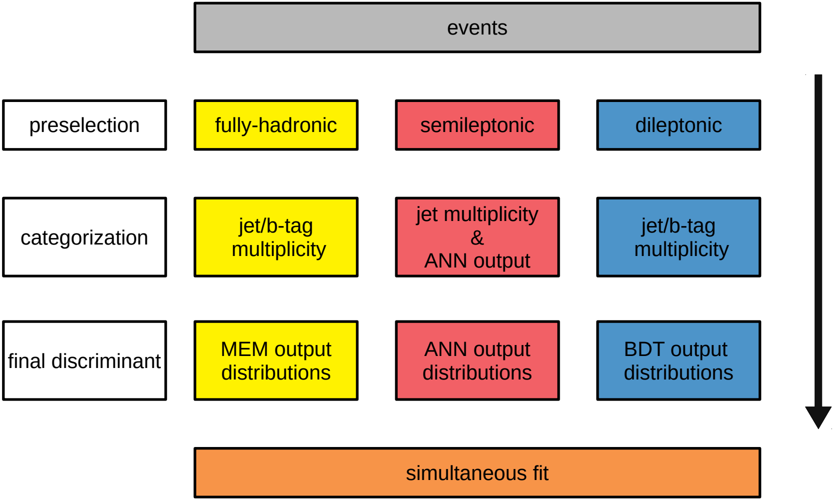
$\Rightarrow$ treat as **separate processes** with separate PS uncertainties



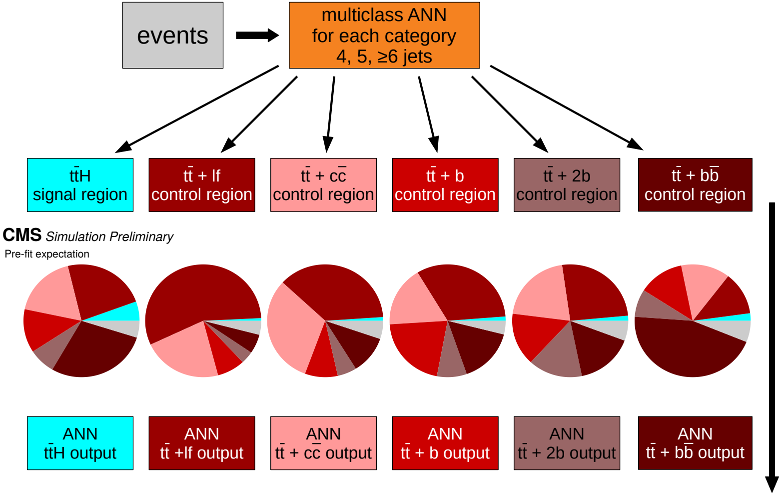
- Add additional 50% normalization uncertainties (separately to $t\bar{t}$ + b/2b/$b\bar{b}$) to PS (ISR, FSR, ME-PS matching, Tune) and matrix element (ME) scale uncertainties

$\Rightarrow$ **Flexible model** to account for remaining differences with alternative theoretical predictions

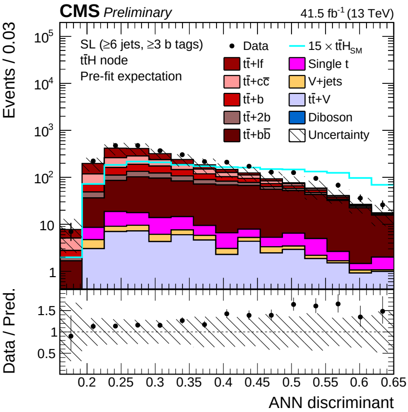
Analysis overview

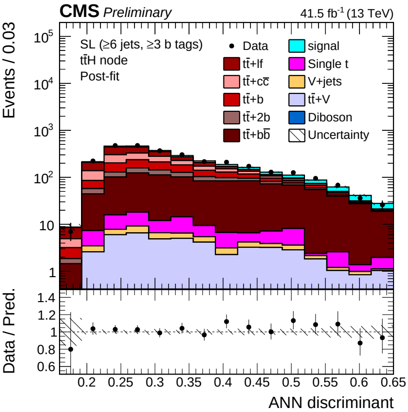


Semileptonic channel

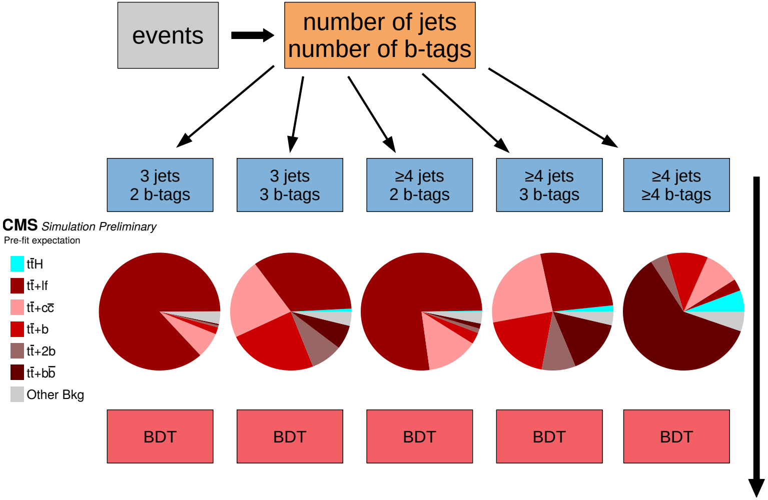


Semileptonic channel

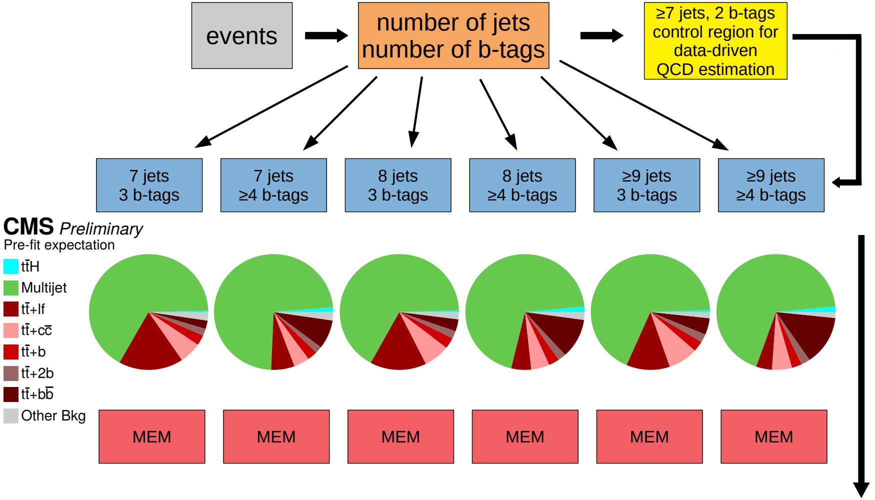




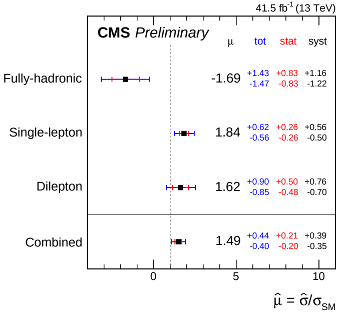
Dileptonic channel

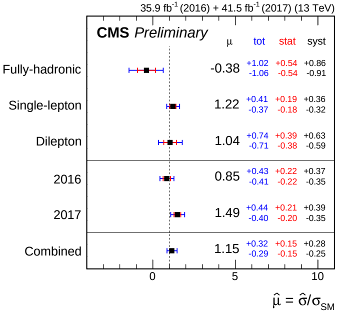


Fully-hadronic channel



Results





Channel & Analysis	Best-fit $\hat{\mu}$	obs. (exp.) Significance
2016 leptonic	$0.72^{+45\%}_{-45\%}$ (tot)	1.6 (2.2)σ
2017 only	$1.49^{+44\%}_{-40\%}$ (tot)	3.7 (2.6)σ
2017+2016 results combined	$1.15^{+32\%}_{-29\%}$ (tot)	3.9 (3.5)σ

Result is dominated by systematic uncertainties and compatible with the SM.

Systematic uncertainties

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Most important uncertainties for 2016+2017 combination in table below

Uncertainty source	$\Delta\hat{\mu}$ (observed)
Total experimental	+0.15/-0.13
b tagging	+0.08/-0.07
jet energy scale and resolution	+0.05/-0.04
Total theory	+0.23/-0.19
signal	+0.15/-0.06
$t\bar{t}$ + hf modeling	+0.14/-0.15
QCD background prediction	+0.10/-0.08
Size of simulated samples	+0.10/-0.10
Total systematic	+0.28/-0.25
Statistical	+0.15/-0.15
Total	+0.32/-0.29

$t\bar{t}$ + hf modeling: PS uncertainties (ISR, FSR, ME-PS matching, Tune), ME scale, additional normalization uncertainties

Summary

- Latest CMS result on $t\bar{t}H$, $H \rightarrow b\bar{b}$ with $41.5\,fb^{-1}$ of data
- Analysis relies heavily on b-tagging, description of $t\bar{t}$ + hf processes (dominant uncertainties), and machine learning techniques
- 2017 analysis combines all $t\bar{t}$ decay channels with improved b-tagging and better handling of parton shower uncertainties
- Combination of 2016 and 2017 results: Evidence for $t\bar{t}H$ production in the $H \rightarrow b\bar{b}$ decay channel

Thank you for your attention!

Backup

Baseline event selection

	FH channel	SL channel	DL channel
Number of leptons	0	1	2
p_T of leptons (e/μ) [GeV]	—	$> 30/29$	$> 25/25$ GeV
p_T of additional leptons [GeV]	< 15	< 15	< 15
$\lvert\eta\rvert$ of leptons	< 2.4	< 2.4	< 2.4
Number of jets	≥ 6	≥ 4	≥ 2
p_T of jets [GeV]	> 40	> 30	$> 30, 30, 20$
$\lvert\eta\rvert$ of jets	< 2.4	< 2.4	< 2.4
Number of b-tagged jets	≥ 2	≥ 2	≥ 1
p_T^{miss}	—	> 20 GeV	> 40 GeV

Best-fit values

	$\hat{\mu}$ ± tot (±stat ± syst)	significance obs (exp)
FH 3 b-tags	$1.36^{+3.57}_{-5.36}$ $\begin{pmatrix}+1.68 & +3.15 \\ -1.69 & -5.09\end{pmatrix}$	$0.3\,\sigma$ $(0.2\,\sigma)$
FH 4 b-tags	$-1.54^{+1.41}_{-1.45}$ $\begin{pmatrix}+0.91 & +1.08 \\ -0.90 & -1.13\end{pmatrix}$	— $(0.7\,\sigma)$
FH combined	$-1.69^{+1.43}_{-1.47}$ $\begin{pmatrix}+0.83 & +1.16 \\ -0.83 & -1.22\end{pmatrix}$	— $(0.7\,\sigma)$
SL 4 jets	$1.73^{+2.25}_{-2.21}$ $\begin{pmatrix}+0.88 & +2.07 \\ -0.87 & -2.04\end{pmatrix}$	$0.8\,\sigma$ $(0.5\,\sigma)$
SL 5 jets	$0.73^{+0.98}_{-0.97}$ $\begin{pmatrix}+0.47 & +0.86 \\ -0.46 & -0.86\end{pmatrix}$	$0.8\,\sigma$ $(1.0\,\sigma)$
SL $\geq$ 6 jets	$2.05^{+0.76}_{-0.69}$ $\begin{pmatrix}+0.31 & +0.69 \\ -0.31 & -0.62\end{pmatrix}$	$3.0\,\sigma$ $(1.6\,\sigma)$
SL combined	$1.84^{+0.62}_{-0.56}$ $\begin{pmatrix}+0.26 & +0.56 \\ -0.26 & -0.50\end{pmatrix}$	$3.3\,\sigma$ $(1.9\,\sigma)$
DL 3 jets	$-2.35^{+4.40}_{-2.65}$ $\begin{pmatrix}+2.13 & +3.85 \\ -2.06 & -1.66\end{pmatrix}$	— $(0.2\,\sigma)$
DL $\geq$ 4 jets	$1.57^{+1.02}_{-0.98}$ $\begin{pmatrix}+0.55 & +0.86 \\ -0.53 & -0.82\end{pmatrix}$	$1.6\,\sigma$ $(1.0\,\sigma)$
DL combined	$1.62^{+0.90}_{-0.85}$ $\begin{pmatrix}+0.50 & +0.76 \\ -0.48 & -0.70\end{pmatrix}$	$1.9\,\sigma$ $(1.2\,\sigma)$
FH+SL+DL combined	$1.49^{+0.44}_{-0.40}$ $\begin{pmatrix}+0.21 & +0.39 \\ -0.20 & -0.35\end{pmatrix}$	$3.7\,\sigma$ $(2.6\,\sigma)$
FH+SL+DL combined 2016+2017	$1.15^{+0.32}_{-0.29}$ $\begin{pmatrix}+0.15 & +0.28 \\ -0.15 & -0.25\end{pmatrix}$	$3.9\,\sigma$ $(3.5\,\sigma)$

Systematic uncertainties part 1

Source	Type	Remarks
Integrated luminosity	rate	Signal and all backgrounds
Lepton identification/isolation	shape	Signal and all backgrounds
Trigger efficiency	shape	Signal and all backgrounds
Trigger prefiring correction	rate	Signal and all backgrounds
Pileup	shape	Signal and all backgrounds
Jet energy scale	shape	Signal and all backgrounds
Jet energy resolution	shape	Signal and all backgrounds
b tag hf fraction	shape	Signal and all backgrounds
b tag hf stats (linear)	shape	Signal and all backgrounds
b tag hf stats (quadratic)	shape	Signal and all backgrounds
b tag lf fraction	shape	Signal and all backgrounds
b tag lf stats (linear)	shape	Signal and all backgrounds
b tag lf stats (quadratic)	shape	Signal and all backgrounds
b tag charm (linear)	shape	Signal and all backgrounds
b tag charm (quadratic)	shape	Signal and all backgrounds
QGL reweighting	shape	Signal and all backgrounds
TF_{loose} correction	shape	QCD multijet estimate
H_T reweighting	shape	QCD multijet estimate
Multijet normalisation	rate	QCD multijet estimate
Renorm./fact. scales ($t\bar{t}H$)	rate	Scale uncertainty of NLO $t\bar{t}H$ prediction
Renorm./fact. scales ($t\bar{t}$)	rate	Scale uncertainty of NNLO $t\bar{t}$ prediction
$t\bar{t}$+hf cross sections	rate	Additional 50% rate uncertainty of $t\bar{t}$+hf predictions
Renorm./fact. scales (t)	rate	Scale uncertainty of NLO single t prediction

Systematic uncertainties part 2

Renorm./fact. scales (V)	rate	Scale uncertainty of NNLO W and Z prediction
Renorm./fact. scales (VV)	rate	Scale uncertainty of NLO diboson prediction
PDF (gg)	rate	PDF uncertainty for gg initiated processes except $t\bar{t}H$
PDF (gg $t\bar{t}H$)	rate	PDF uncertainty for $t\bar{t}H$
PDF ($q\bar{q}$)	rate	PDF uncertainty of $q\bar{q}$ initiated processes ($t\bar{t}$+W,W,Z)
PDF (qg)	rate	PDF uncertainty of qg initiated processes (single t)
PDF shape variations ($t\bar{t}H$, $t\bar{t}$)	shape	Based on the NNPDF replicas, same for $t\bar{t}H$ and additional jet flavours
μ_R scale ($t\bar{t}$)	shape	Renormalisation scale uncertainty of the $t\bar{t}$ ME generator (POWHEG), same for additional jet flavours
μ_F scale ($t\bar{t}$)	shape	Factorisation scale uncertainty of the $t\bar{t}$ ME generator (POWHEG), same for additional jet flavours
PS scale: ISR ($t\bar{t}$)	shape	Initial state radiation uncertainty of the PS (for $t\bar{t}$ events), same for additional jet flavours
PS scale: FSR ($t\bar{t}$)	shape	Final state radiation uncertainty of the PS (for $t\bar{t}$ events), same for additional jet flavours
ME-PS matching ($t\bar{t}$)	rate	NLO ME to PS matching, *hdamp* [**?**] (for $t\bar{t}$ events), independent for additional jet flavours
Underlying event ($t\bar{t}$)	rate	Underlying event (for $t\bar{t}$ events), independent for additional jet flavours
Bin-by-bin event count	shape	Statistical uncertainty of the signal and background prediction due to the limited sample size

Input variables part 1

Variable	Definition	SL (4 jets, $\geq$ 3 b-tags)	SL (5 jets, $\geq$ 3 b-tags)	SL ($\geq$ 6 jets, $\geq$ 3 b-tags)	DL (3 jets, 2 b-tags)	DL (3 jets, 3 b-tags)	DL ($\geq$ 4 jets, 2 b-tags)	DL ($\geq$ 4 jets, 3 b-tags)	DL ($\geq$ 4 jets, $\geq$ 4 b-tags)
MEM	maxtrix element method discriminant	+	+	+	−	−	−	+	+
BLR	likelihood ratio discriminating between events with 4 b quark jets and 2 b quark jets	+	−	+	−	−	−	−	−
$\mathrm{BLR}^{\mathrm{trans}}$	$\ln[\mathrm{BLR}/(1-\mathrm{BLR})]$	+	−	+	−	−	−	−	−
$p_{\mathrm{T}}(\text{jet } 1)$	p_{T} of the 1. jet, ranked in jet p_{T}	−	+	−	−	−	−	−	−
$p_{\mathrm{T}}(\text{jet } 3)$	p_{T} of the 3. jet, ranked in jet p_{T}	−	+	−	−	−	−	−	−
$H_{\mathrm{T}}^{\mathrm{b}}$	scalar sum of p_{T} of b-tagged jets	+	+	+	+	−	−	−	+
$\sum_{\mathrm{j,lep}} p_{\mathrm{T}}$	scalar sum of p_{T} of leptons and jets	−	−	−	+	+	−	+	−
$N_{\mathrm{b}}^{\mathrm{tight}}$	number of b-tagged jets at a working point with 0.1% probability of tagging gluon and light-flavour jets	+	+	−	−	−	−	−	−
$d(\text{jet } 4)$	b-tagging discriminant value of 4. jet,	+	−	−	−	−	−	−	−

Input variables part 2

	ranked in jet p_T								
d_2	2. highest b-tagging discriminant value of all jets	+	+	+	−	−	−	−	−
d_j^{avg}	average b-tagging discriminant value of all jets	+	+	+	+	−	+	+	−
d_b^{avg}	average b-tagging discriminant value of all b-tagged jets	+	+	+	−	+	−	+	+
d_b^{min}	minimal b-tagging discriminant value of all b-tagged jets	+	+	−	−	−	−	−	−
$\frac{1}{N_b}\sum_b^{N_b}\left(d - d_b^{avg}\right)^2$	squared difference between the b-tagged discriminant value of a b-tagged jet and the average b-tagging discriminant values of all b-tagged jets, averaged over all b-tagged jets	+	−	+	−	−	−	−	−
$m_j^{/}$	sum of the masses of all jets divided by the number of dijet pairs	−	−	+	−	−	−	−	−
$m_{b,b}^{\text{closest to 125}}$	mass of pair of b-tagged jets closest to 125 GeV	−	+	−	−	+	−	−	−
$m_{lep,b}^{min\Delta R}$	mass of pair of lepton and b-tagged jet closest in ΔR	−	−	+	−	−	−	−	−
$m_{j,j}^{min\Delta R}$	mass of pair of jets closest in ΔR	−	−	−	+	+	−	−	−
$m_{b,b}^{min\Delta R}$	mass of pair of b-tagged jets closest in ΔR	−	−	−	+	−	+	+	+

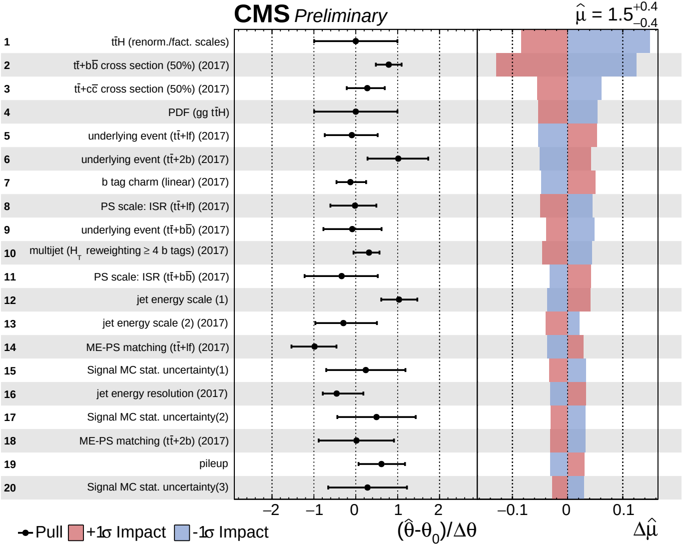
Input variables part 3

Variable	Definition	SL (4 jets, $\geq$ 3 b-tags)	SL (5 jets, $\geq$ 3 b-tags)	SL ($\geq$ 6 jets, $\geq$ 3 b-tags)	DL (3 jets, 2 b-tags)	DL (3 jets, 3 b-tags)	DL ($\geq$ 4 jets, 2 b-tags)	DL ($\geq$ 4 jets, 3 b-tags)	DL ($\geq$ 4 jets, $\geq$ 4 b-tags)
$m_{\mathrm{j,b}}^{\mathrm{min}\Delta R}$	mass of pair of jet and b-tagged jet closest in ΔR	−	−	−	−	−	+	−	+
$m_{\mathrm{b,b}}^{\mathrm{avg}}$	average mass of all pairs of b-tagged jets	+	−	−	−	−	−	−	−
$m_{\mathrm{b,b}}^{\mathrm{max}\,m}$	mass of pair of b-tagged jets with largest mass	−	−	−	−	+	−	+	−
$m_{\mathrm{j,j,j}}^{\mathrm{max}\,p_{\mathrm{T}}}$	mass of tri-jet system with highest p_T	−	−	−	+	−	−	−	+
$p_{T;\mathrm{b,b}}^{\mathrm{min}\,\Delta R}$	sum p_{T} of pair of closest b-tagged jets	−	−	−	+	−	+	+	+
$p_{T;\mathrm{j,j}}^{\mathrm{min}\,\Delta R}$	sum p_{T} of pair of closest jets	−	−	−	−	+	+	−	−
$\Delta R_{\mathrm{j,j}}^{\mathrm{max}}$	largest ΔR between any two jets	−	+	−	−	−	−	−	−
$\Delta R_{\mathrm{b,b}}^{\mathrm{avg}}$	average ΔR between b-tagged jets	−	+	+	−	−	−	+	+
$\Delta R_{\mathrm{j,j}}^{\mathrm{avg}}$	average ΔR between two jets	−	−	−	+	+	+	−	−
$\Delta R_{\mathrm{j,b}}^{\mathrm{avg}}$	average ΔR between a jet and a b-tagged jets	−	−	−	−	−	+	−	−

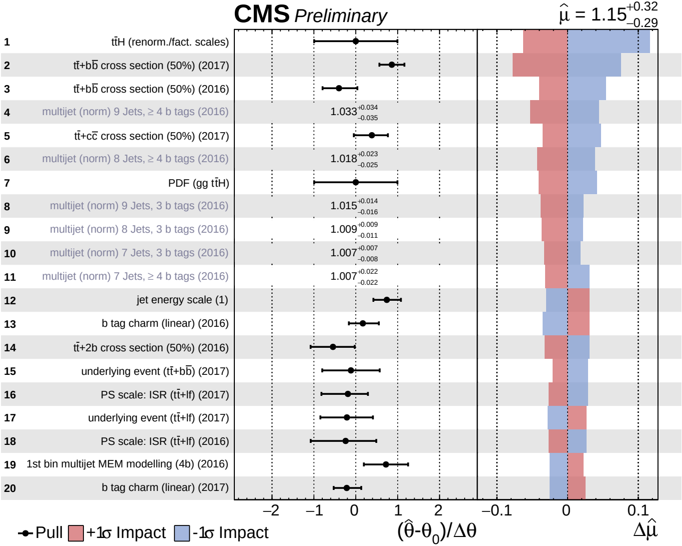
Input variables part 4

$\Delta R^{\text{min}}_{\text{j,j}}$	minimal ΔR between any two jets	−	−	−	+	+	−	−	−
$\Delta R^{\text{min}}_{\text{b,b}}$	minimal ΔR between any two b-tagged jets	−	−	−	−	−	−	+	+
$\Delta R^{\text{min}}_{\text{lep,b}}$	minimal ΔR between lepton and b-tagged jet	−	+	−	−	−	−	−	−
$\Delta \eta^{\text{max}}_{\text{j,j}}$	largest $\Delta \eta$ between any two jets	−	−	−	+	+	+	−	+
$\Delta \eta^{\text{max}}_{\text{b,b}}$	largest $\Delta \eta$ between any two b-tagged jets	−	−	−	−	−	−	+	+
S^{j}	$\frac{3}{2}(\lambda_2 + \lambda_3)$, with λ_i the eigenvalues of the momentum tensor computed with jets	+	+	−	−	−	−	−	−
S^{b}	$\frac{3}{2}(\lambda_2 + \lambda_3)$, with λ_i the eigenvalues of the momentum tensor computed with b-tagged jets	−	+	−	−	−	−	−	−
S^{j}_{T}	$\frac{2\lambda_2}{\lambda_2+\lambda_1}$, with λ_i the eigenvalues of the momentum tensor computed with jets	+	−	−	−	−	−	−	−
$C^{\text{j,lep}}$	scalar sum of the jet and lepton p_{T} divided by the sum of the energies of all jets and leptons	−	−	−	+	+	+	−	−
C^{b}	scalar sum of the b-tagged jet p_{T} divided by the sum of the energies of all b-tagged jets	−	−	−	+	−	+	−	−
H_0	0th Fox–Wolfram moment computed with all jets	−	−	−	+	−	−	+	−
R_1	ratio H_1/H_0 of 0th and first Fox–Wolfram moment computed with all jets	−	−	−	−	+	−	−	−

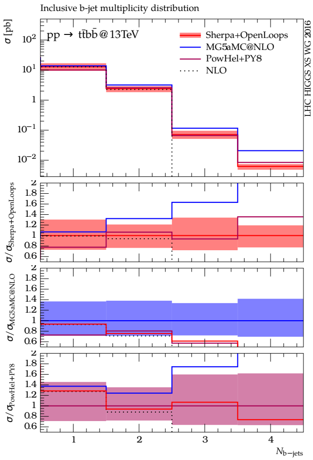
Post-fit pulls and impacts 2017



Post-fit pulls and impacts 2016+2017



$t\bar{t}$ + additional b-jets



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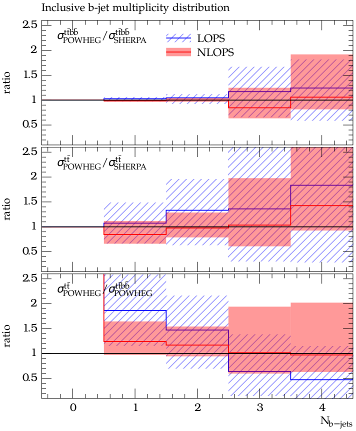


[1]

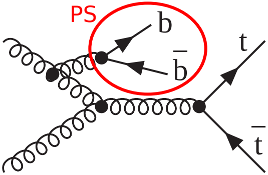
Conclusion: account for uncertainties of around 30% (left plot) and consider differences between inclusive $t\bar{t}$ and $t\bar{t}$ +$b\bar{b}$ simulation (right plot) $\Rightarrow$ 50% uncertainties on $t\bar{t}$ +hf processes

$t\bar{t}$ + additional b-jets

- QCD multi-scale problem
- LO $t\bar{t}$ +$b\bar{b}$ renormalisation uncertainty $\approx 70 - 80\%$
- NLO $\approx 20 - 30\%$
- 5FS with massless b-quarks: collinear g$\rightarrow b\bar{b}$ singularities $\rightarrow$ generation cuts to phase space
- 4FS considering b-mass effects applicable to complete b-quark phase space
- matching & shower effects have a large impact

$t\bar{t}$ + b-jets

- $t\bar{t}$ events with additional initial or final state radiation (ISR,FSR) and g$\rightarrow$b$\bar{b}$ splitting
- Using 5FS inclusive $t\bar{t}$ + jets simulation $\rightarrow$ additional b-jets (not from top decay) modeled by parton shower (PS)
- PS has large impact on this simulation
  $\rightarrow$ uncertainties on PS parameters essential
- Considering PS parameter variations in (ISR, FSR, ME-PS matching and Tune) and QCD scale variations



$t\bar{t}$ + heavy flavor splitting

$t\bar{t}$ sample split further according to gen-jets containing additional b/c hadrons with CMSSW GenHFHadronMatcher tool

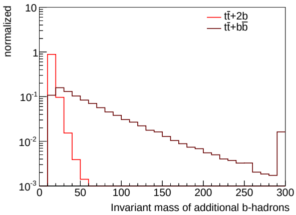
- gen-jets: clustered from final state generator particles, $p_T > 20$, $|\eta| < 2.4$
- containing hadrons: jets into which b/c hadrons (before decay) that are injected as "ghosts" (energy scaled $\rightarrow 0$) are clustered
- additional hadrons: cannot be traced back to top-decay products

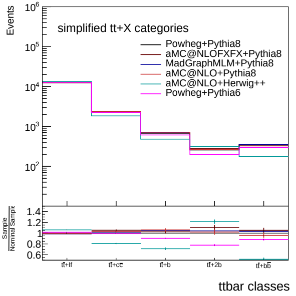
$t\bar{t}$ +HF classes:

$t\bar{t} + b\bar{b}$: at least two add. b-jets
$t\bar{t}$ + b: one add. b-jet from a single b hadron
$t\bar{t}$ + 2b: one add. b-jet from two or more overlapping b hadrons
$t\bar{t} + c\bar{c}$: at least one add. c-jet, no add. b-jets
$t\bar{t}$ + lf : does not belong to any of the above

$t\bar{t}$ + heavy flavor splitting

- Physics motivation
  - $t\bar{t} + b\bar{b}$ and $t\bar{t} + b$ in principle same process, well separated jets $\Rightarrow$ can be treated perturbatively
    $t\bar{t} + b\bar{b}$ signal-like in terms of jets and tags
  - $t\bar{t} + 2b$ different: collinear gluon splitting within one jet $\Rightarrow$ depends on parton shower tuning
  - $t\bar{t} + c\bar{c}$ Similar issues, but less signal-like
- Scheme developed in coordination with ATLAS
- Assigning 50% rate uncertainty for $t\bar{t}$ subprocesses





Matrix Element for ttH(bb) vs ttbb

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- Signal extraction via Matrix Element Methods (MEM):
  - Event-by-event discriminator build upon matrix elements, combined with reconstruction-level information.

Numerical integration — Momentum conservation — Resolution function (allow ISR)

$$w(\vec{y}|\mathcal{H}) = \sum_{i=1}^{\mathrm{N_C}} \int \frac{dx_a dx_b}{2x_a x_b s} \int \prod_{k=1}^{8} \left(\frac{d^3\vec{p}_k}{(2\pi)^3 2E_k} \right) (2\pi)^4 \delta^{(E,z)} \left(p_a + p_b - \sum_{k=1}^{8} p_k \right) \mathcal{R}^{(x,y)} \left(\vec{\rho}_T, \sum_{k=1}^{8} p_k \right)$$
$$\times g(x_a, \mu_F) g(x_b, \mu_F) |\mathcal{M}(p_a, p_b, p_1, \ldots, p_8)|^2 W(\vec{y}, \vec{p})$$

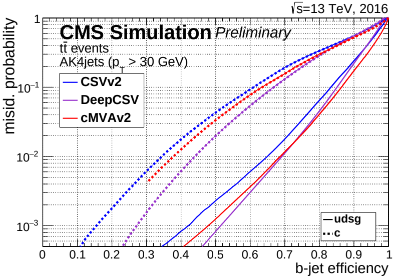
Parton density functions — LO scattering amplitude (Open Loops) — Detector transfer function

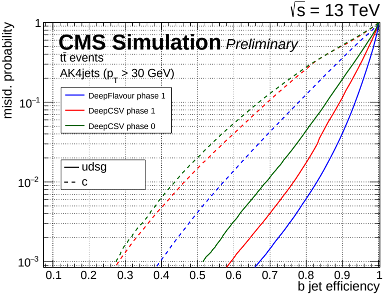
- Construct per-event signal/background probability using full kinematic information in an analytic approach

$$P_{s/b} = \frac{w(\vec{y}|t\bar{t}H)}{w(\vec{y}|t\bar{t}H) + k_{s/b} w(\vec{y}|t\bar{t}+b\bar{b})}$$

- $t\bar{t}$ +$b\bar{b}$ taken as background hypothesis, permuting over all jet assignments

B-tagging performance





Dileptonic channel

- Split events according to number of jets and btags: (3j,2b), (3j,3b), ($\geq$ 4j,2b), ($\geq$ 4j,3b), ($\geq$ 4j,4b)
- Construct BDT separately for each category
- BDTs to separate signal ($t\bar{t}H$) from background ($t\bar{t}$ +X)
- BDT uses kinematic, event-shape and b-tagging variables
- For ($\geq$ 4j,3b),($\geq$ 4j,4b) also the output of the matrix element method is used as an input variable

Details on BDT training

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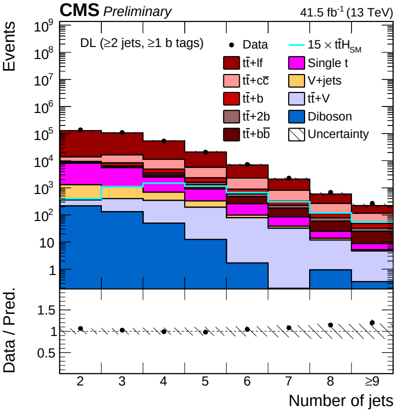
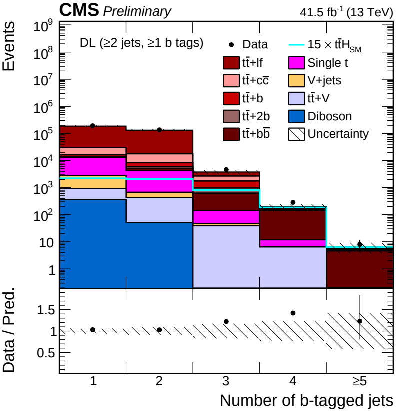
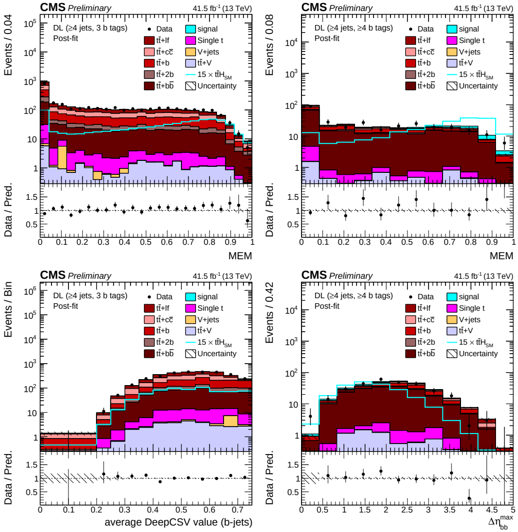
- separate BDTs for each of the 5 categories
- implemented in TMVA package
- gradient boosting algorithm
- 50% of $t\bar{t}$ DL sample used to construct BDT (splitted in half for training and testing)
- dedicated $t\bar{t}H$, $H \to b\bar{b}$ DL sample used for signal (splitted in half for training and testing)
- at least 1750 events per process and category available for training
- only well modeled variables considered (quality measure?) and best 12 variables chosen
- hyperparameters optimized by particle swarm algorithm
- inclusion of MEM improved sensitivity around 10%

DL channel jet/b-tag multiplicity pre-fit

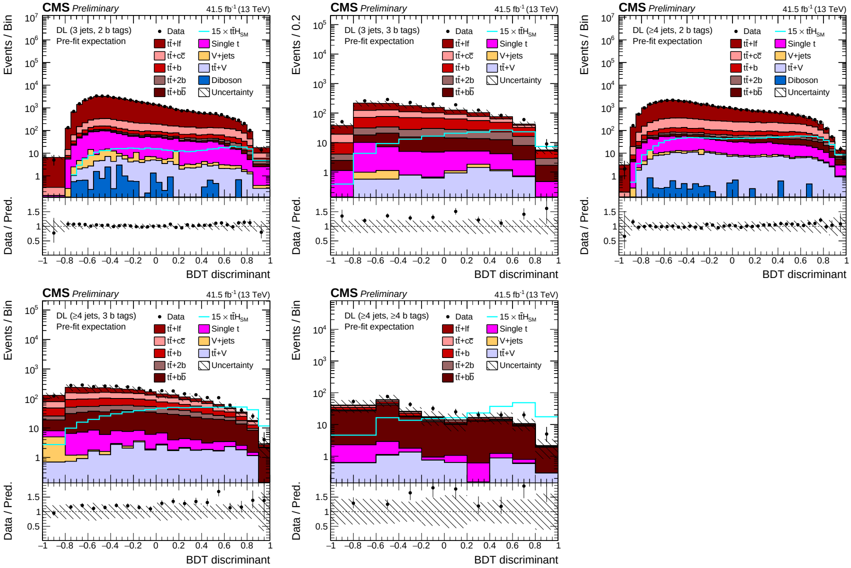




Examples of BDT input variables post-fit



BDT discriminants pre-fit



BDT discriminants post-fit

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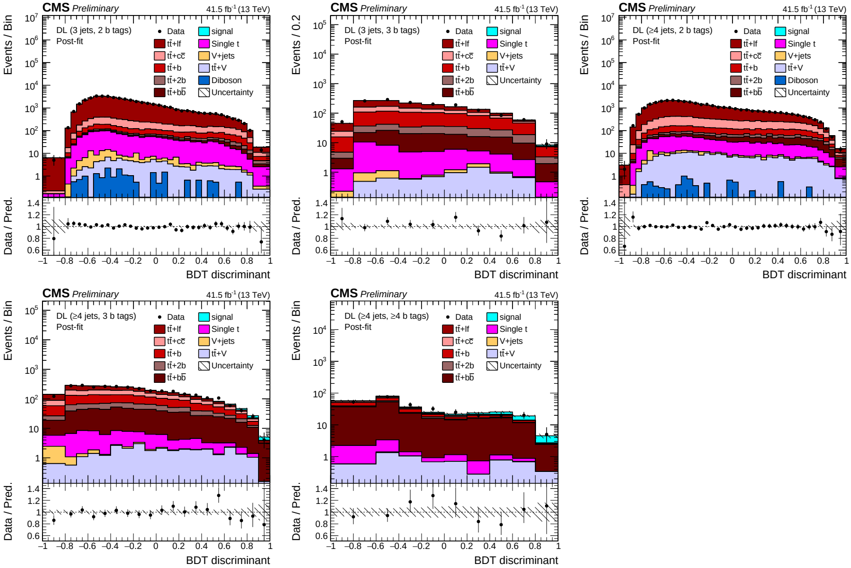
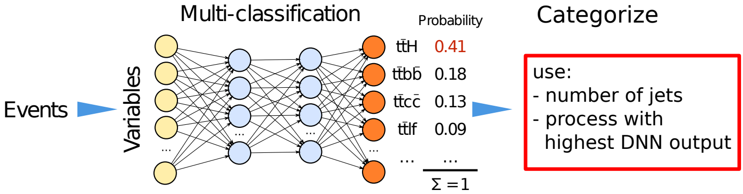


Semileptonic channel

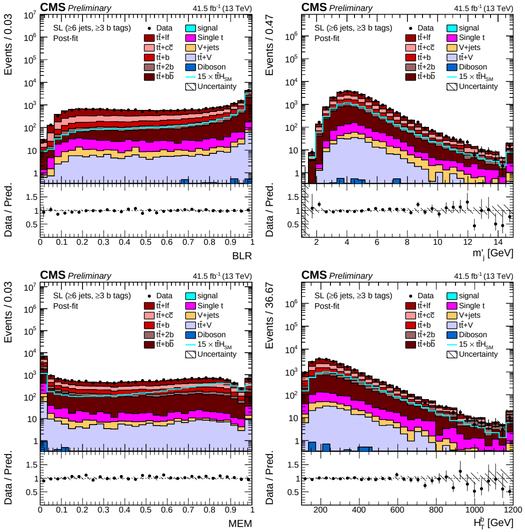
- Split events according to number of jets (4, 5, $\geq$ 6)
- Multi-class ANN classifies events into classes corresponding to
  - Main $t\bar{t}$ +X backgrounds
  - $t\bar{t}H$ signal
- ANN uses kinematic, event-shape and b-tagging variables as well as output of matrix element method
- $t\bar{t}H$ node: signal enriched category
- Background nodes (control regions): constrain systematic uncertainties, especially on $t\bar{t}$ +hf processes



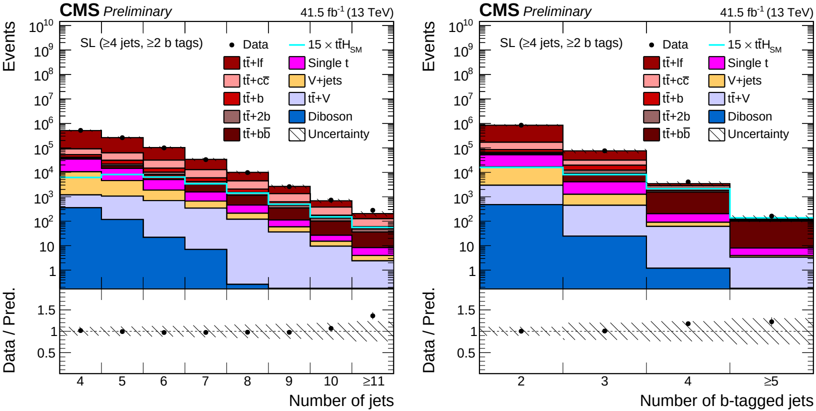
Details on ANN training

- input variable validation with goodness-of-fit tests in 1D and 2D
  - fit 1D and 2D distributions to data in each category with complete uncertainty model
  - calculate p-value from post-fit uncertainty model,
  - only allow variables with p-value ≥ 0.05 in all combinations
- implemented in Keras
- feedforward NN with 3 hidden layers of 100 nodes each
- at least 2100 training events in each of the final categories
- events weighted that each process has the same number of effective events in each jet-multiplicity category
- 500 epochs with early stopping
- cross-entropy loss function
- L2 regularisation and dropout used

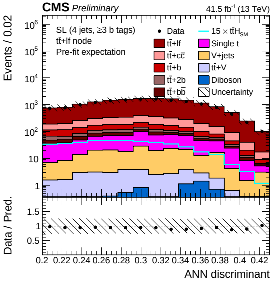
Examples of ANN input variables

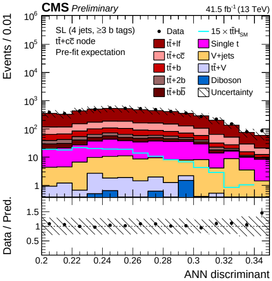


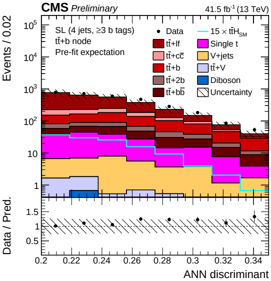
SL channel jet/b-tag multiplicity

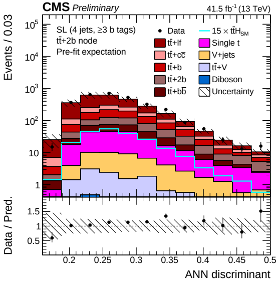


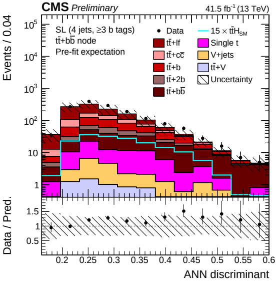
ANN discriminants pre-fit

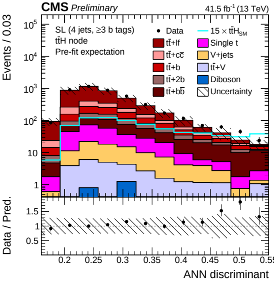












ANN discriminants post-fit

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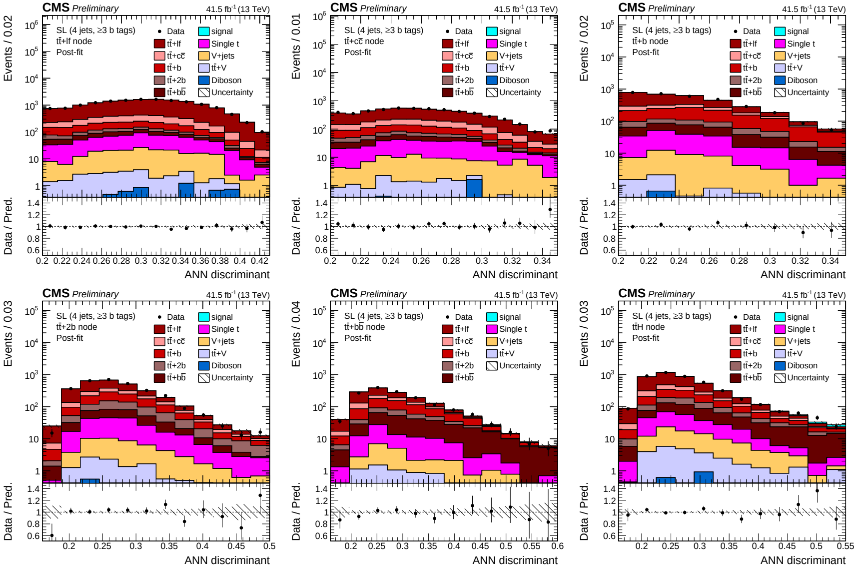
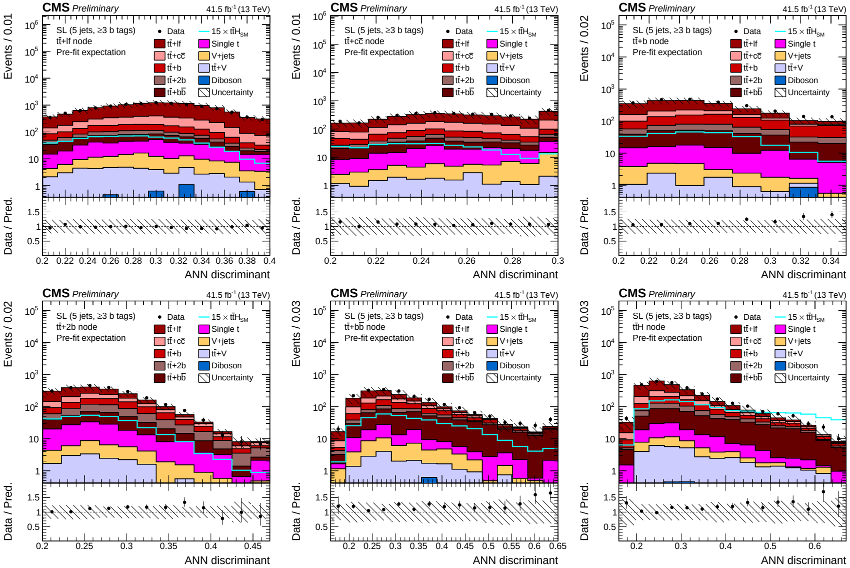
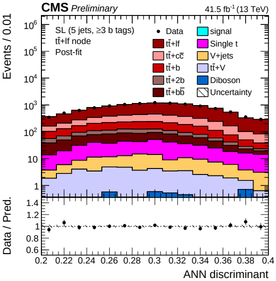
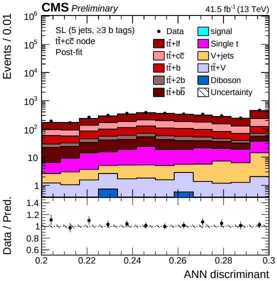


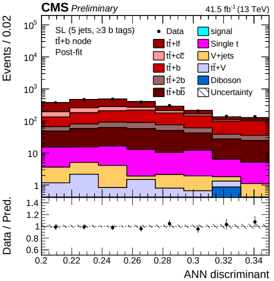
ANN discriminants pre-fit

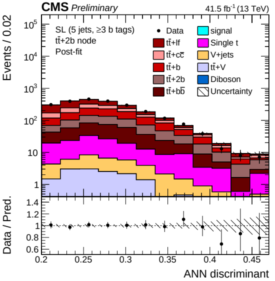


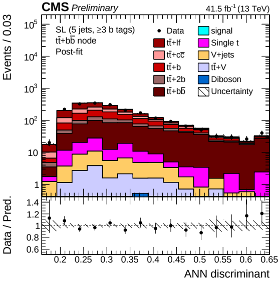
ANN discriminants post-fit

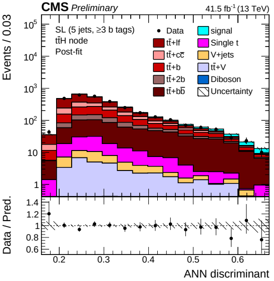




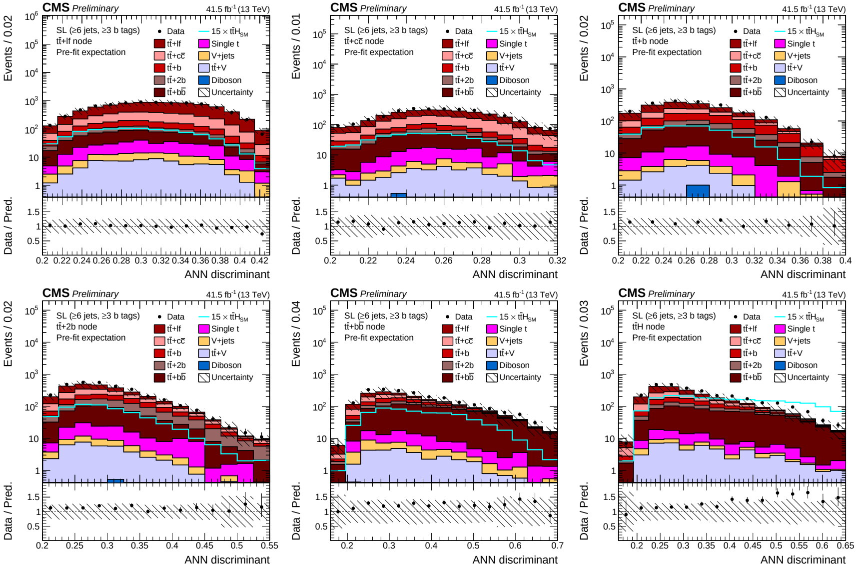




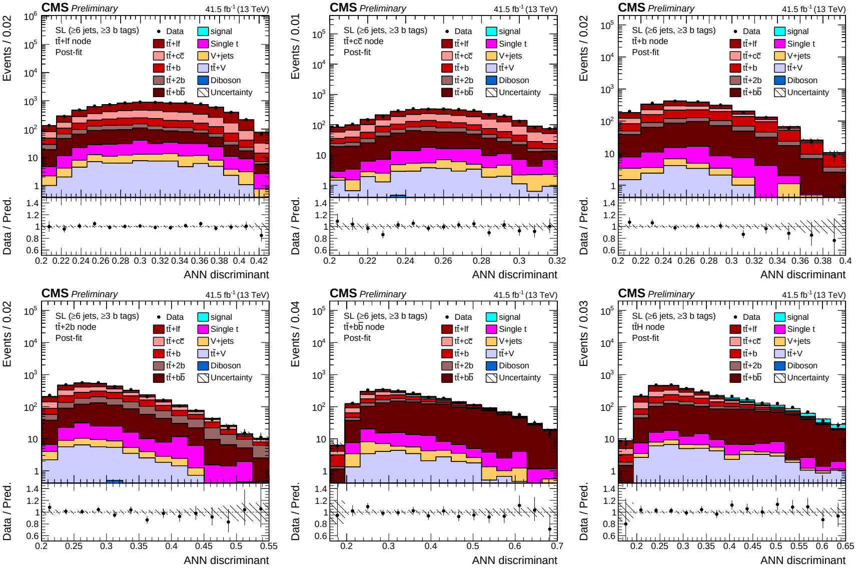




ANN discriminants pre-fit



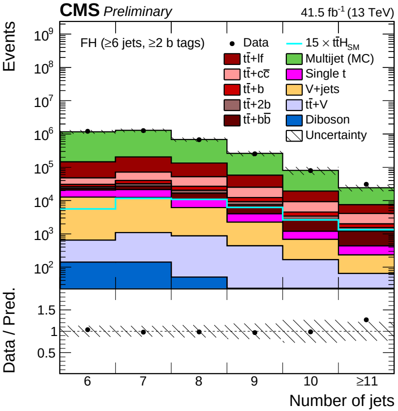
ANN discriminants post-fit

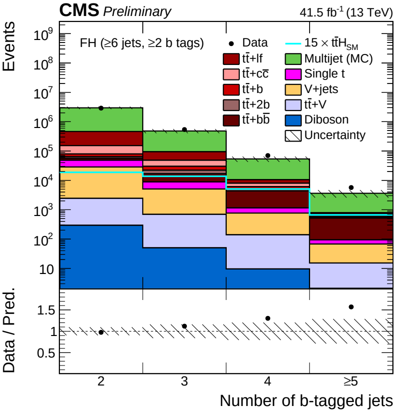


$t\bar{t}H$, $H \rightarrow b\bar{b}$ hadronic

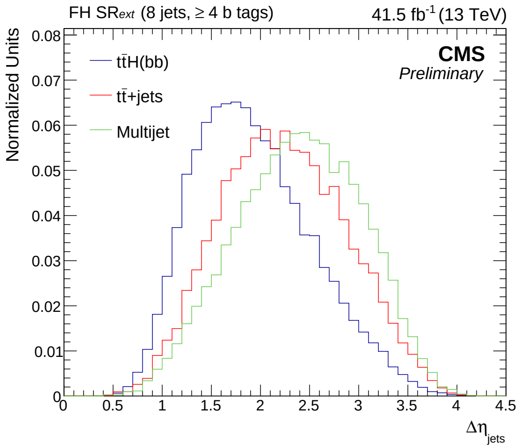
- Selection: $\geq$ 7 jets, $\geq$ 3 b-tagged jets, $H_T \geq$ 500 GeV, lepton veto
- Categorization: jet and b-tag multiplicity
- 2 main backgrounds: QCD multijet and $t\bar{t}$
- Data-driven QCD multijet determination:
  - Kinematic cuts to reject QCD events
  - Discriminate against QCD multijet with Quark-Gluon-Likelihood-Ratio
  - Estimate shape from controlregion with low number of b-tags
  - Rate is obtained during final fit to data
- $t\bar{t}$:
  - Estimated from MC simulation (same as in leptonic analysis)
  - Difficult contribution: $t\bar{t} + b\bar{b}$
- Final discrimination with matrix element method separating $t\bar{t}H, H \rightarrow b\bar{b}$ with $t\bar{t} + b\bar{b}$

FH channel jet/b-tag multiplicity

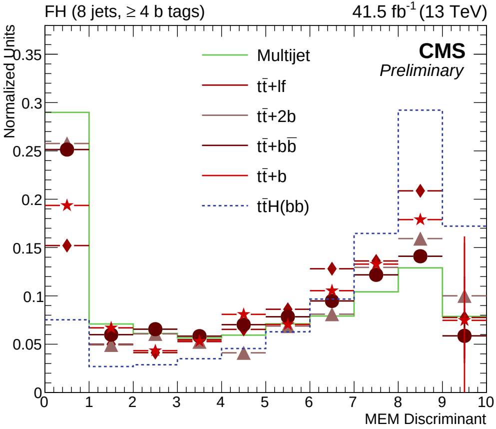




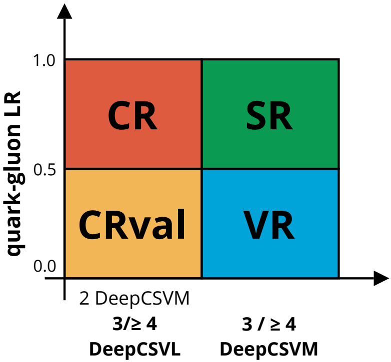
FH channel $\Delta\eta_{jets}$

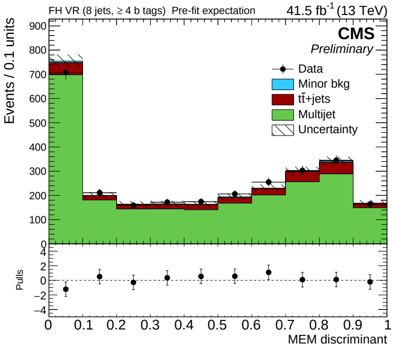


FH channel MEM example

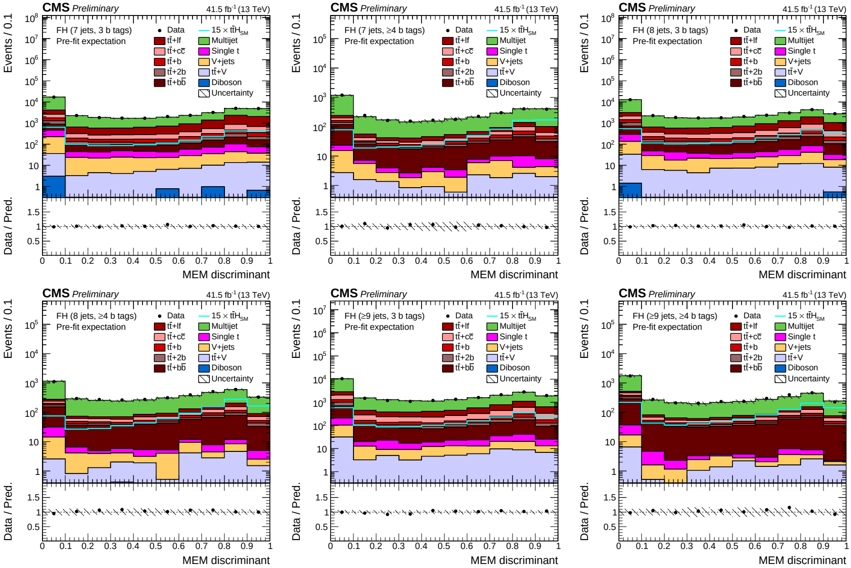


FH channel data-driven QCD determination

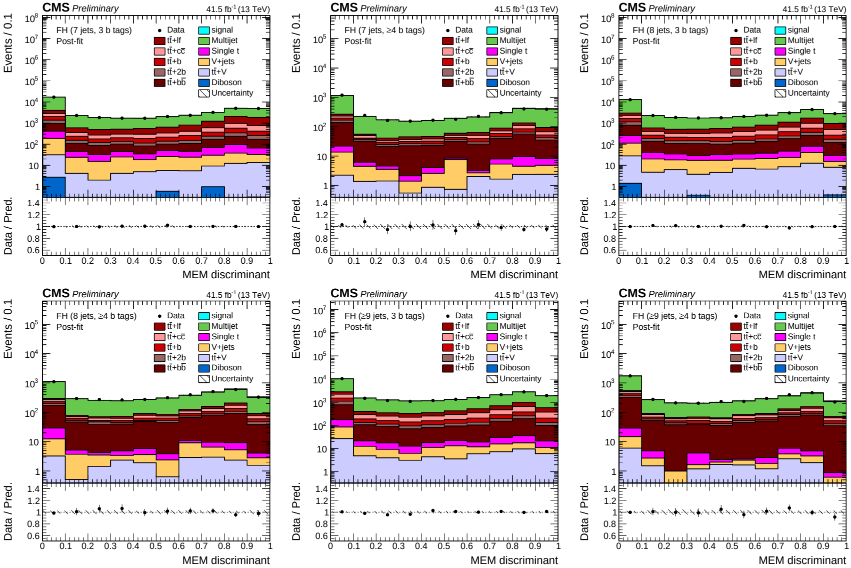




MEM discriminants pre-fit



MEM discriminants post-fit



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[1] D. de Florian et al. *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*. Tech. rep. FERMILAB-FN-1025-T. 869 pages, 295 figures, 248 tables and 1645 citations. Working Group web page: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG. Oct. 2016. URL: `https://cds.cern.ch/record/2227475`.

[2] Tomáš Ježo et al. "New NLOPS predictions for $t\bar{t} + b$ -jet production at the LHC". In: *Eur. Phys. J.* C78.6 (2018), p. 502. DOI: `10.1140/epjc/s10052-018-5956-0`. arXiv: `1802.00426 [hep-ph]`.