Karlsruhe Institute of Technology

Hot TopHiggs @ LHC

Search for H $\rightarrow b\bar{b}$ in Association with Single Top Quarks in CMS

KSETA Plenary Workshop - Durbach

Simon Fink | 23.02.2016

INSTITUT FÜR EXPERIMENTELLE KERNPHYSIK

Higgs Introduction

Top Quark

- heaviest elementary particle
  $\Rightarrow \quad m_{\text{top}} = 173.2\,\text{GeV}$
- discovered in 1995 at Fermilab, Chicago

Higgs Boson

- second heaviest elementary particle
  $\Rightarrow \quad m_{\text{Higgs}} = 125.1\,\text{GeV}$
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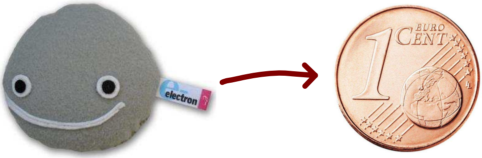
Particle Masses

Electron



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Bottom Quark

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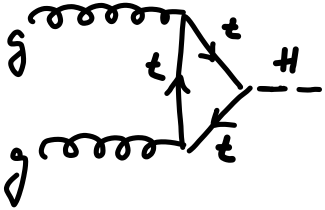
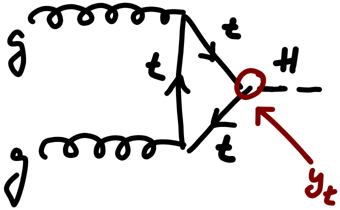


Indirect



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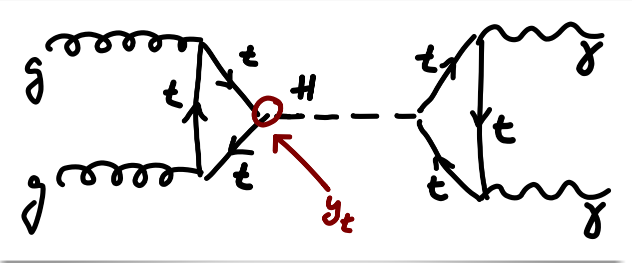

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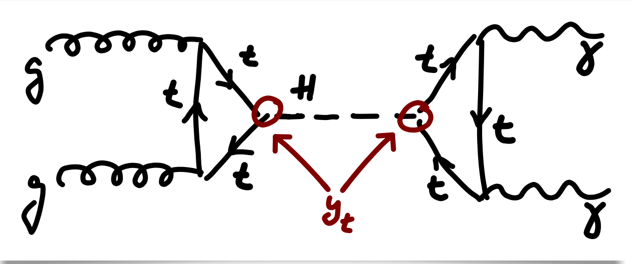

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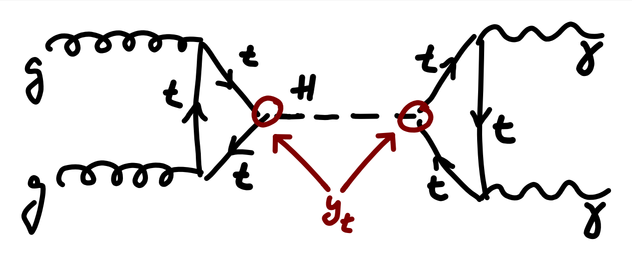

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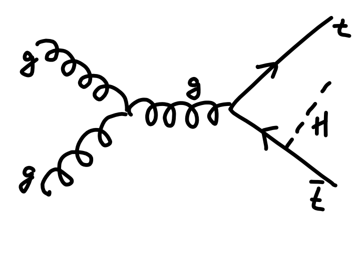
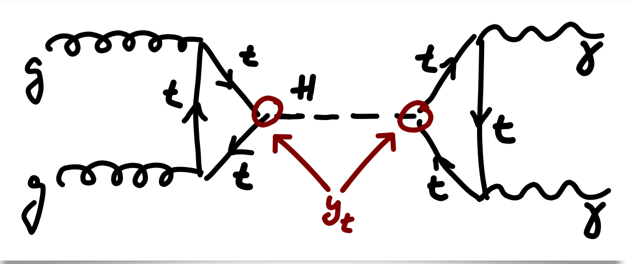


Direct: Absolute Value



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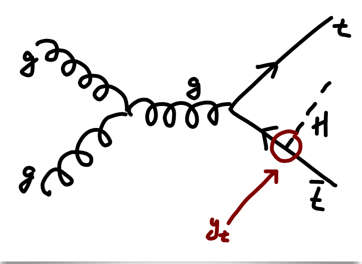

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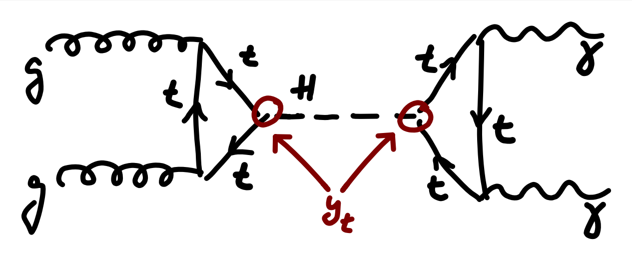

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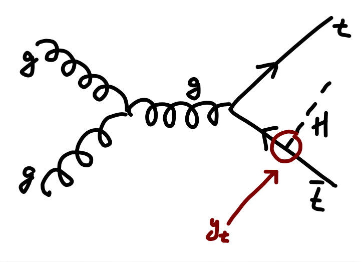

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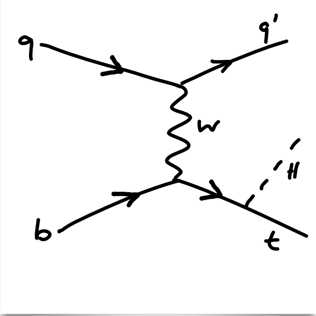

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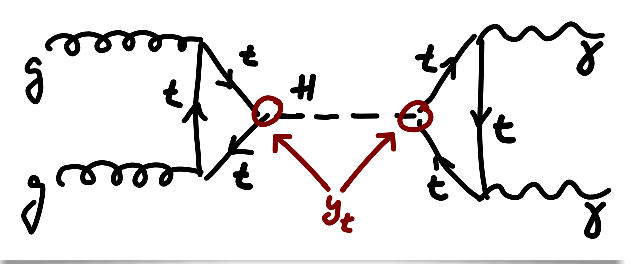

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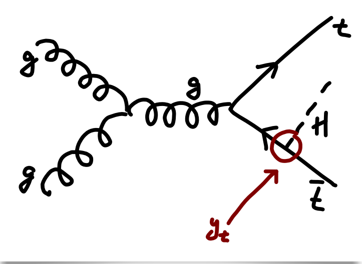

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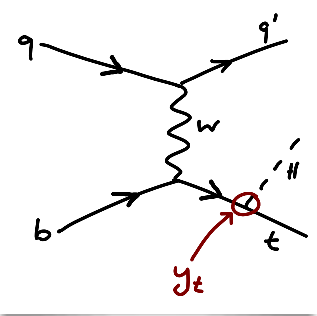

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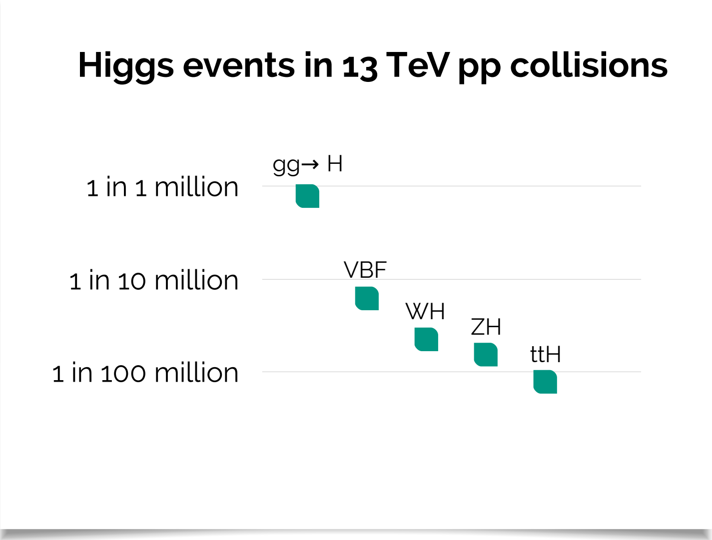

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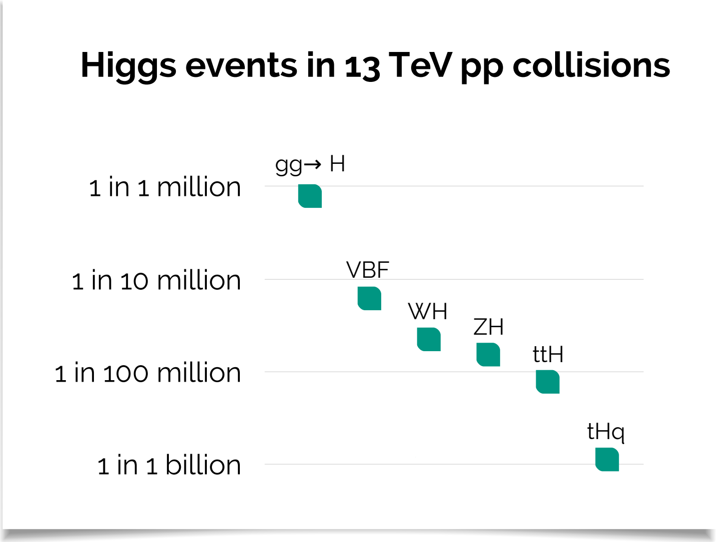

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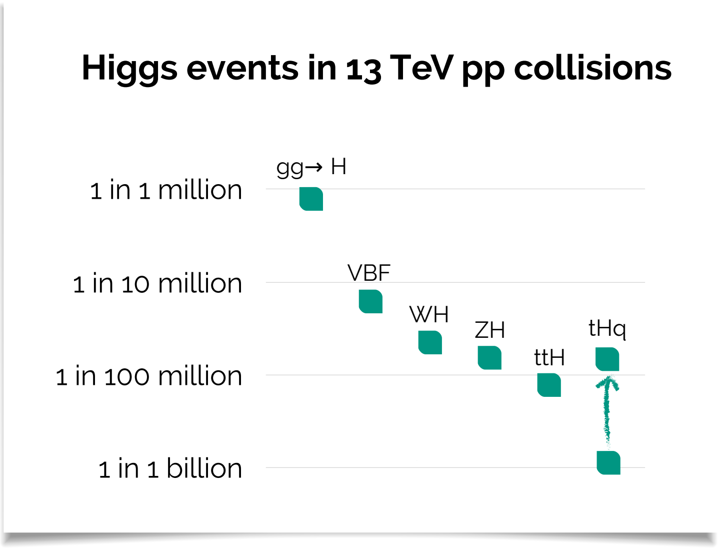
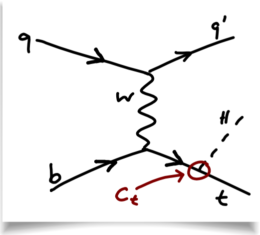


Introduction II

- two feynman diagrams for the tHq production in SM



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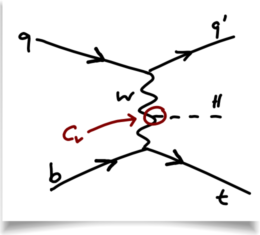

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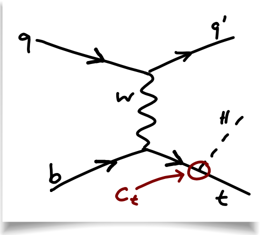

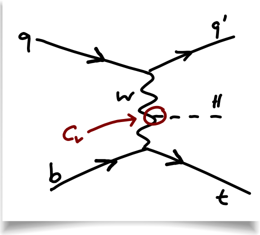

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- $\mathcal{A} \propto (C_V - C_t)$

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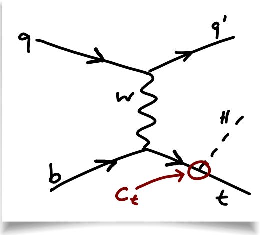

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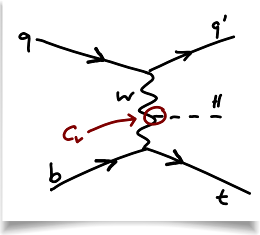

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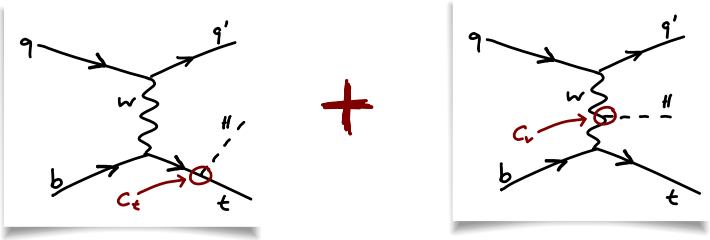

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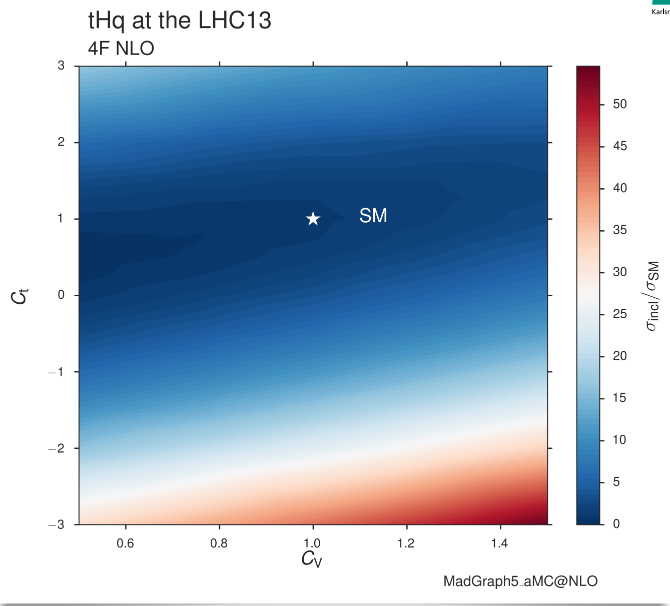
vastly different cross sections dependent on point in (C_V, C_f)

Introduction II

- two fe



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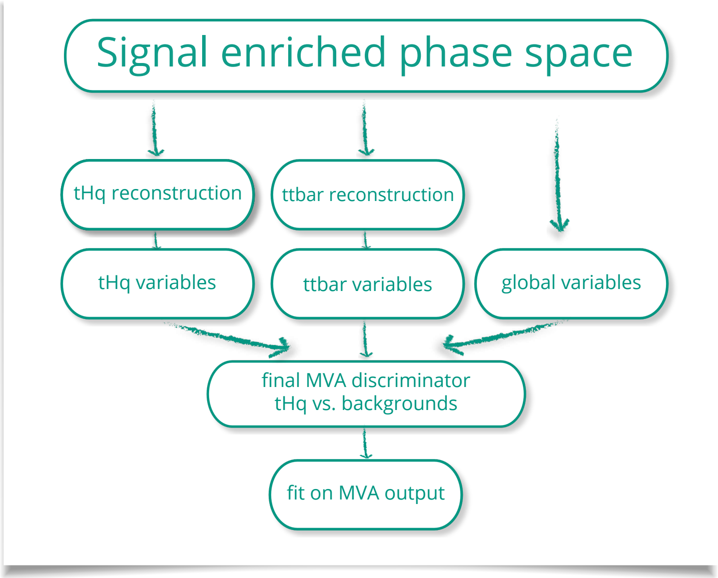
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ttbar reconstruction
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global variables
final MVA discriminator
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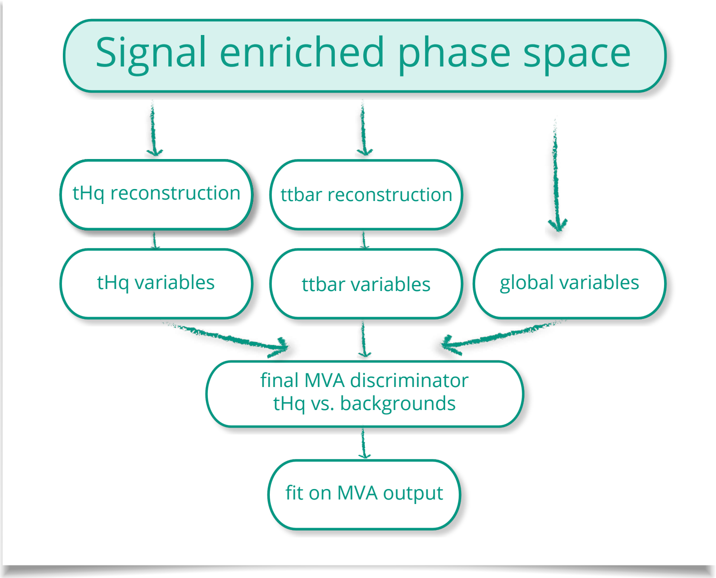
fit on MVA output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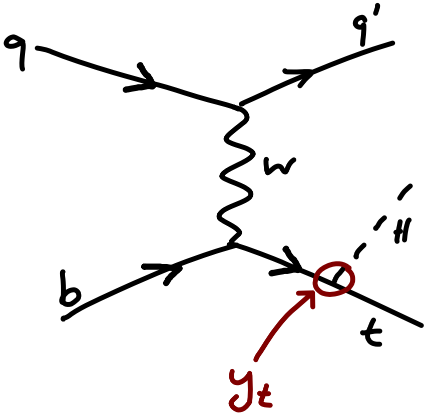

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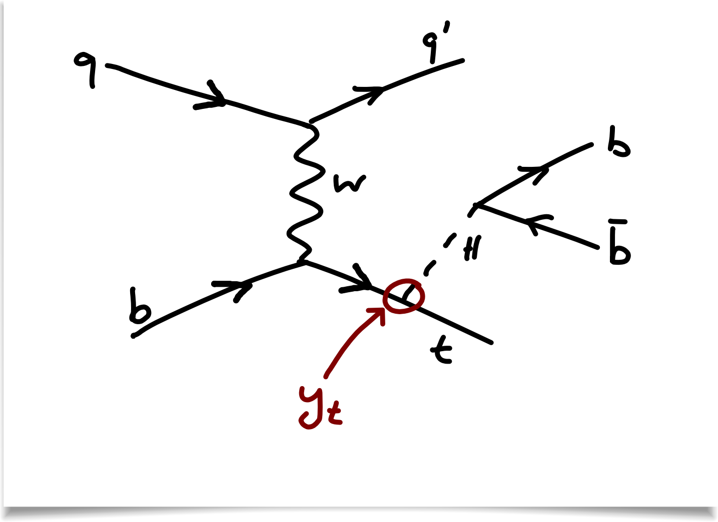

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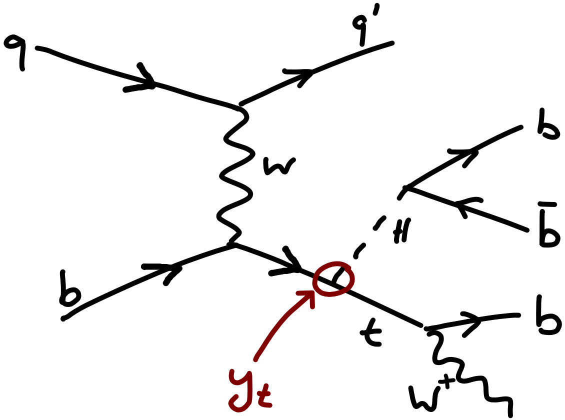

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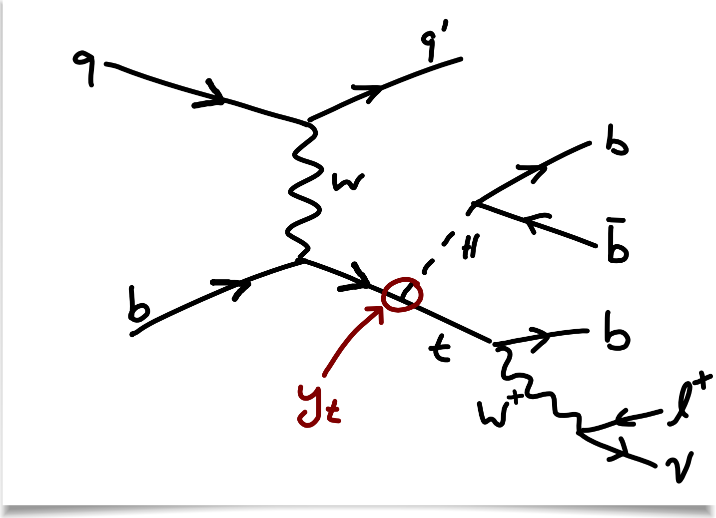

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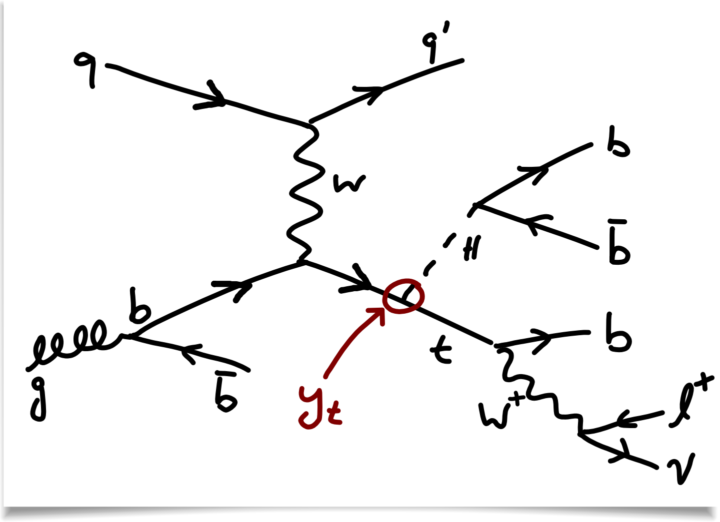

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  - 4 *b* quarks
  - 1 isolated lepton
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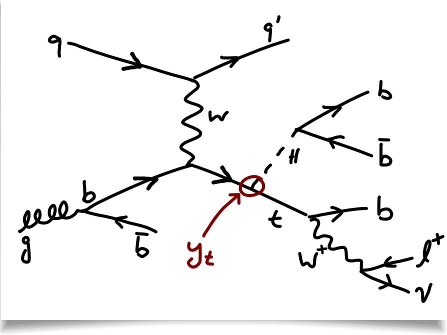

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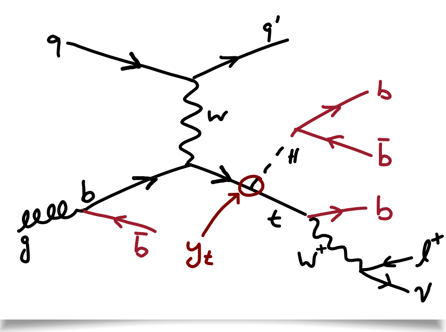

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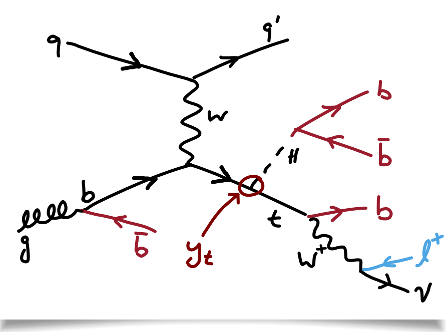

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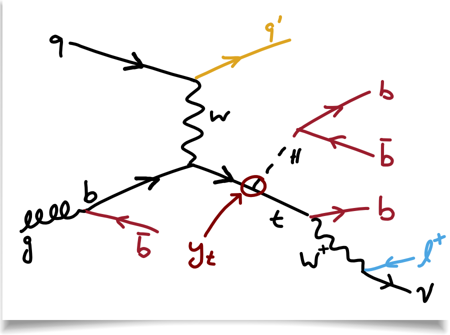

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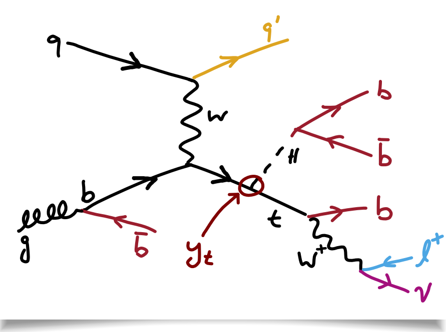

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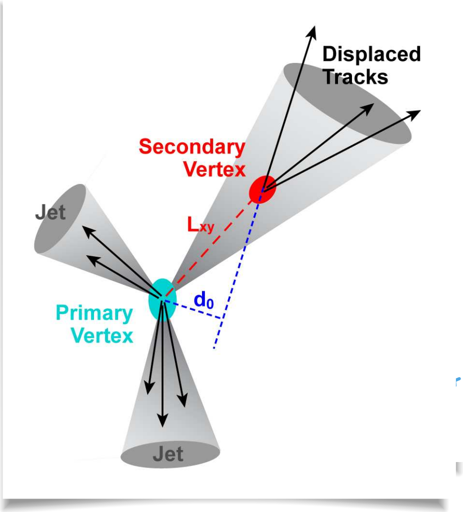

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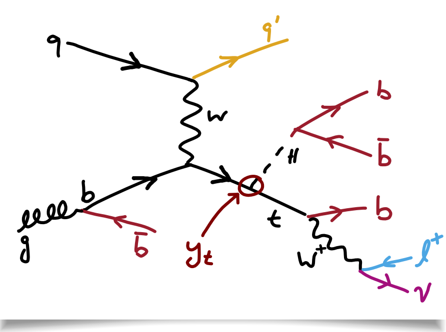

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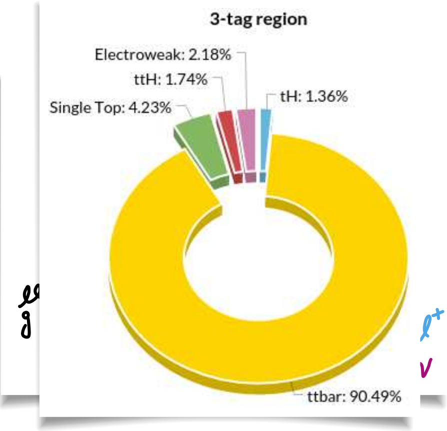

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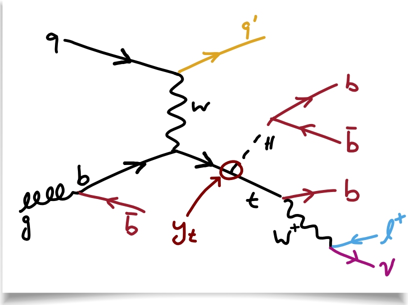
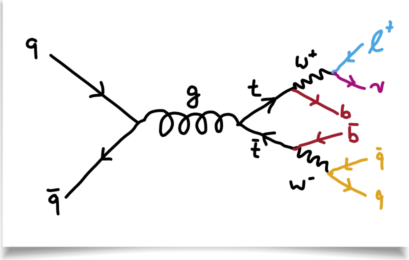


$t\bar{t}$



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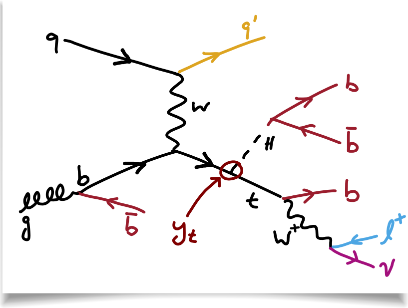

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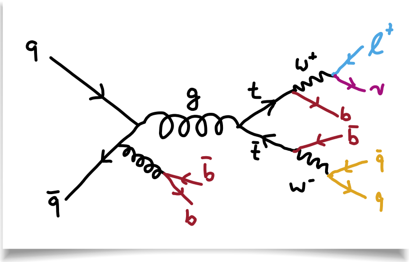

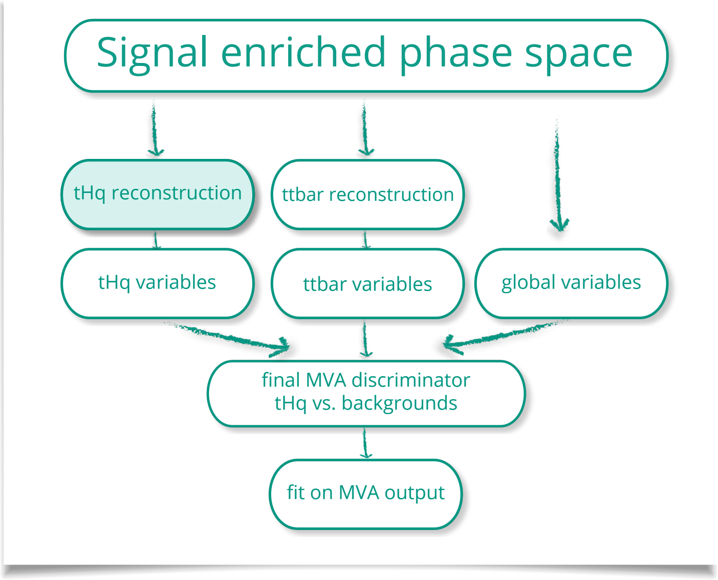
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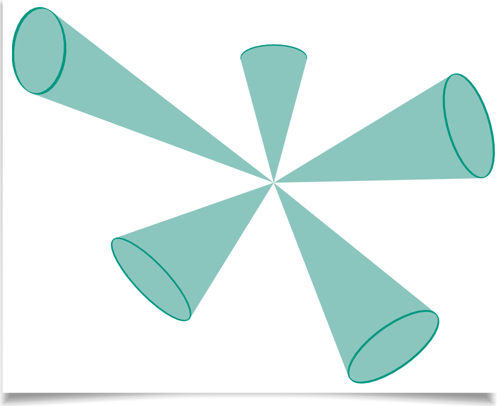
- use constraints to reduce number of possible permutations
- look at distributions for all possible assignments and all events
- use such variables to find right assignments



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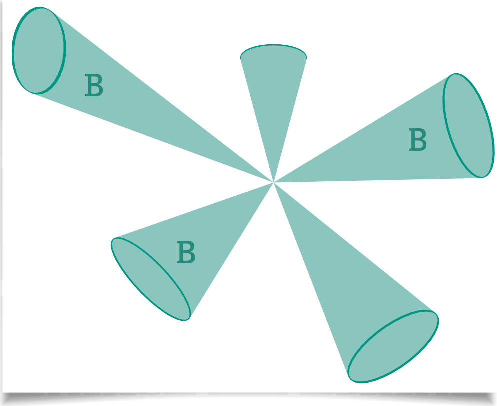

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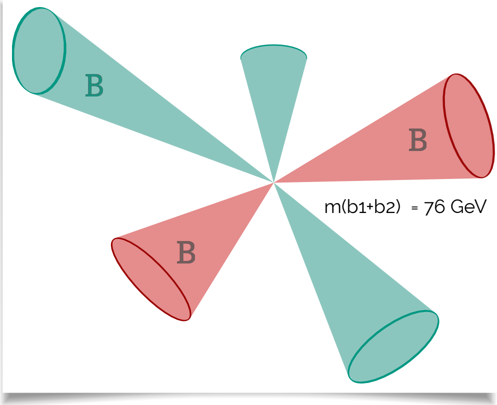

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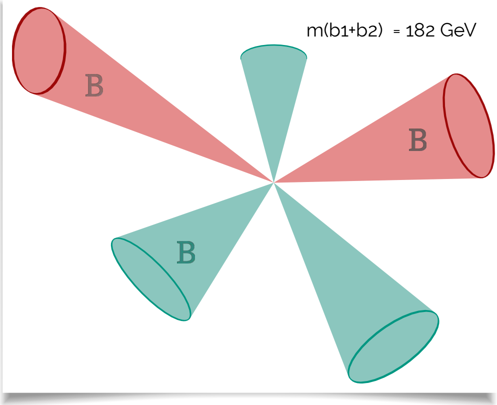

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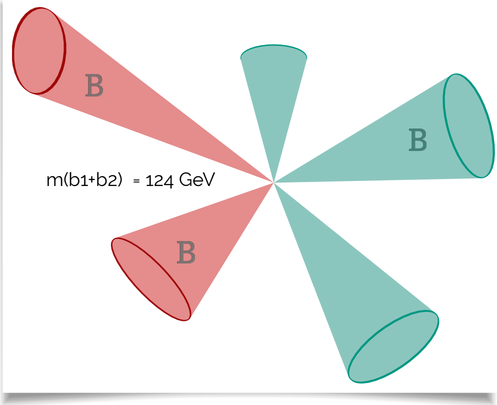

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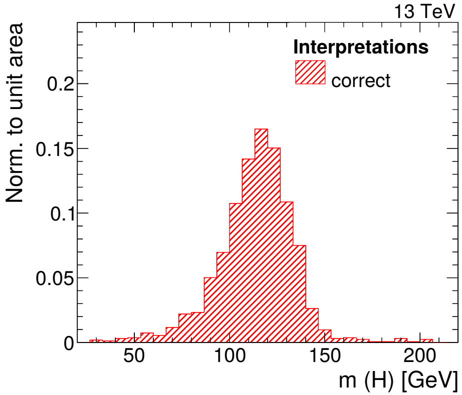

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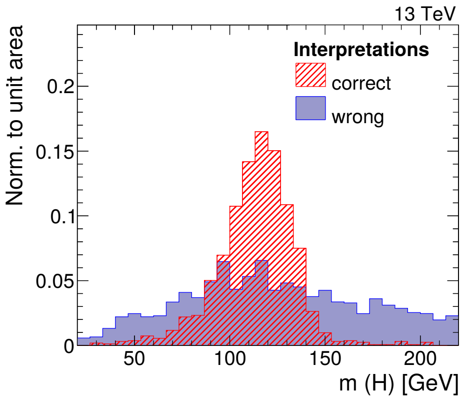
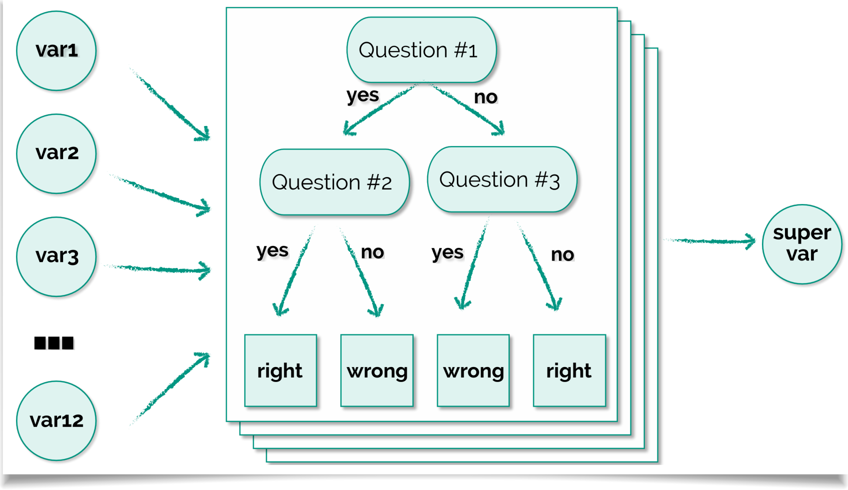
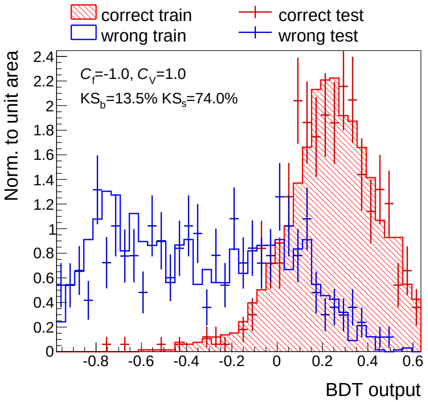


Boosted Decision Trees



tHq reconstruction

- assignment with highest MVA output gets chosen
- build your new objects
- look at object distributions
- variables distinguish between signal and background



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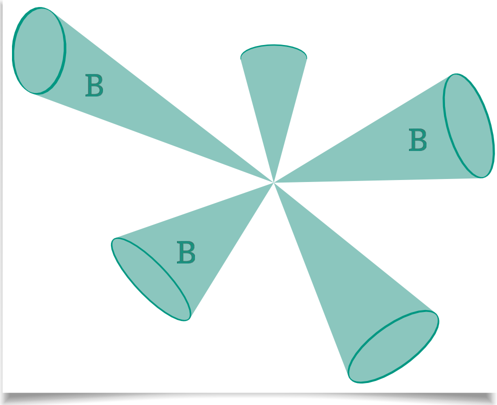

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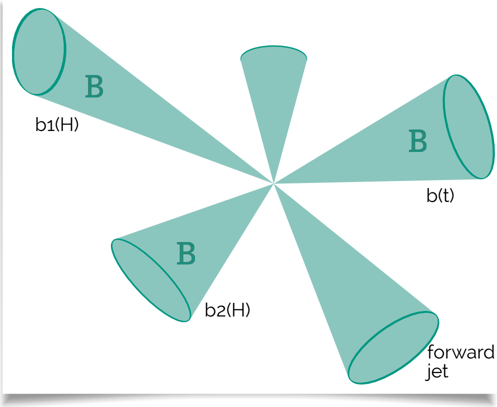

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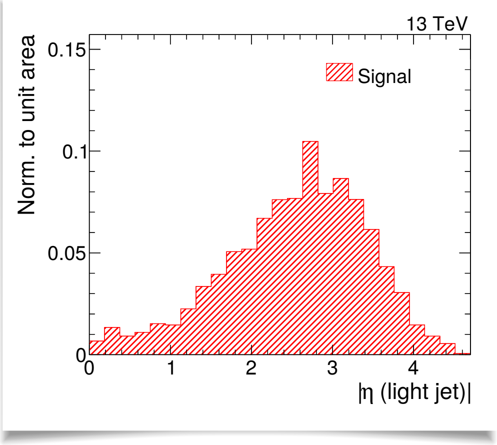
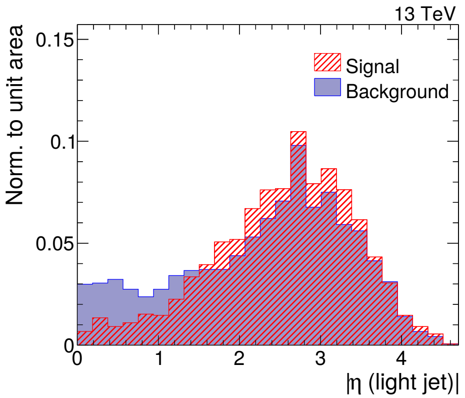
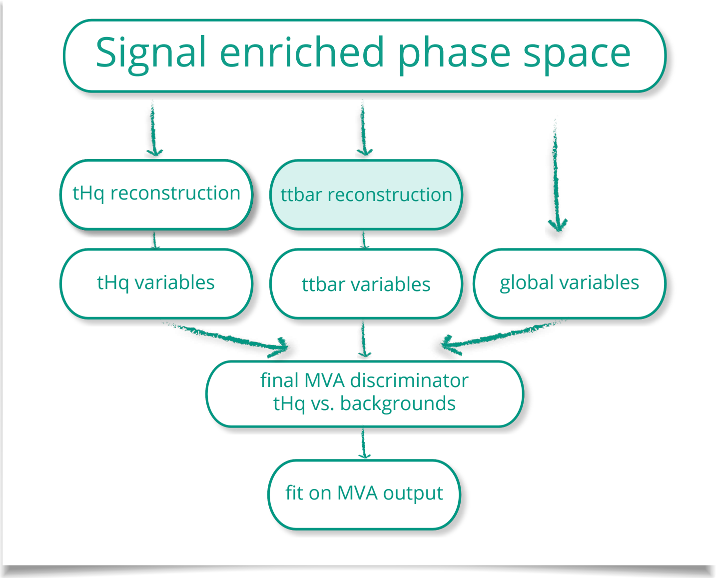


tHq reconstruction

- assignment with highest MVA output gets chosen
- build your new objects
- look at object distributions
- variables distinguish between signal and background





Signal enriched phase space
tHq reconstruction
ttbar reconstruction
tHq variables
ttbar variables
global variables
final MVA discriminator
tHq vs. backgrounds
fit on MVA output

$t\bar{t}$ reconstruction

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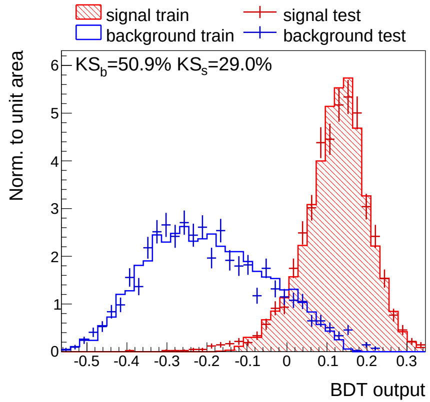

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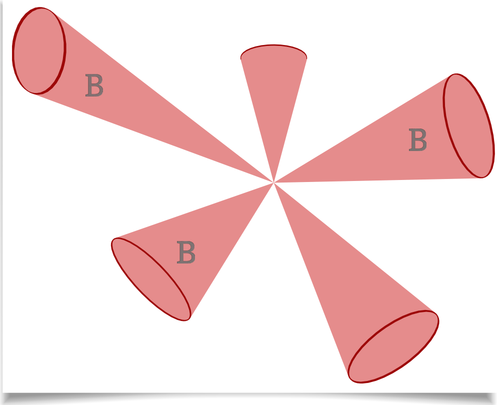

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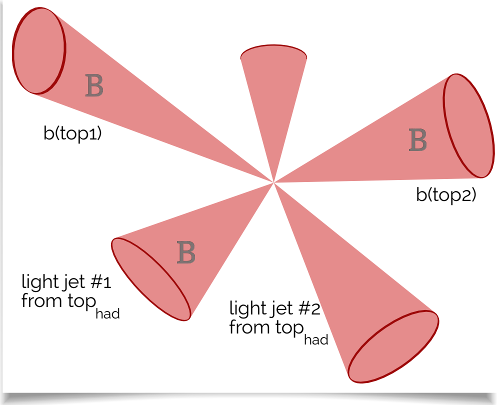

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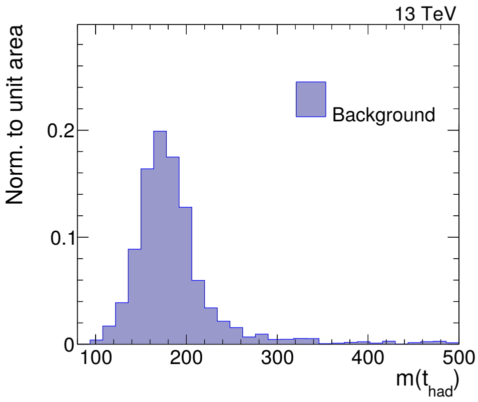

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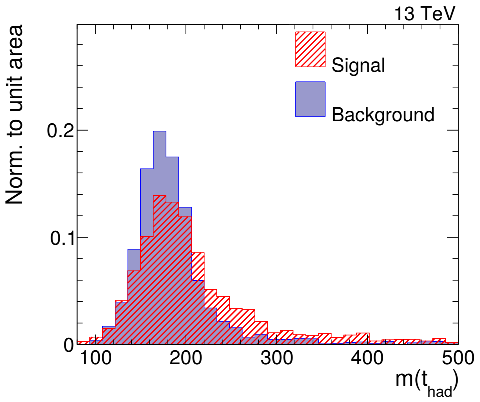
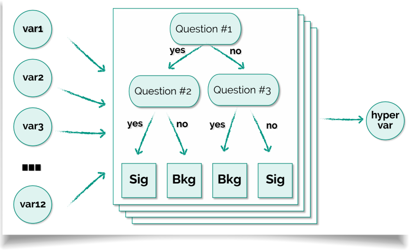
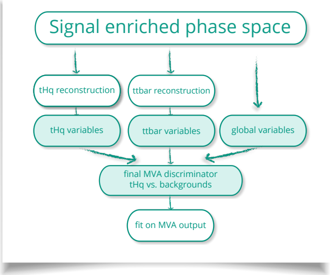


MVA input variables

- obtain variables dependent on the reconstruction, e.g.:
  - $|\eta_{q'}|$ - pseudorapidity of the light forward jet
  - $m_{t_{had}}$ - mass of the hadronically decaying top quark
  - . . .
- additional reconstruction-independent lepton charge used
- train MVA to separate signal from background





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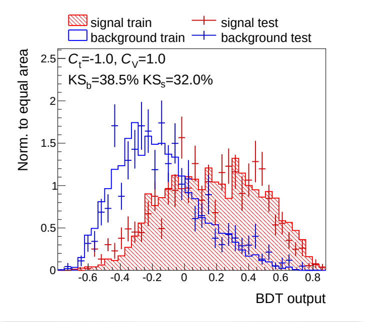
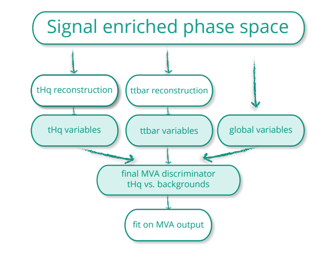
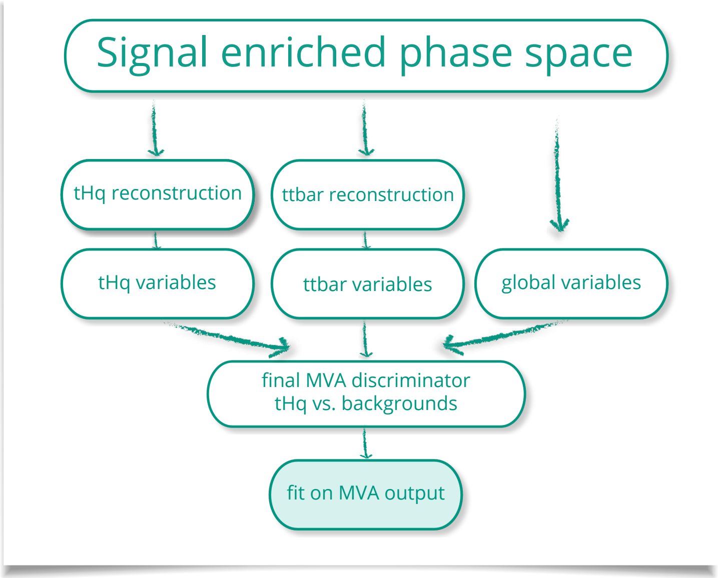
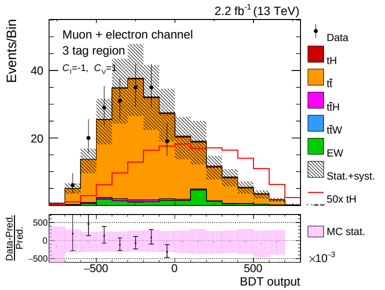


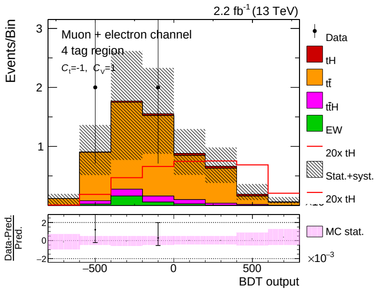


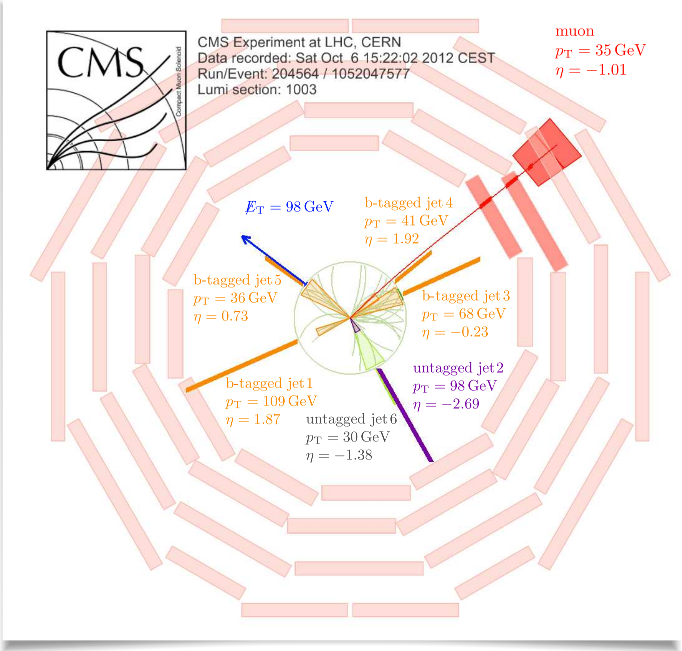

Signal enriched phase space
tHq reconstruction
ttbar reconstruction
tHq variables
ttbar variables
global variables
final MVA discriminator
tHq vs. backgrounds
fit on MVA output

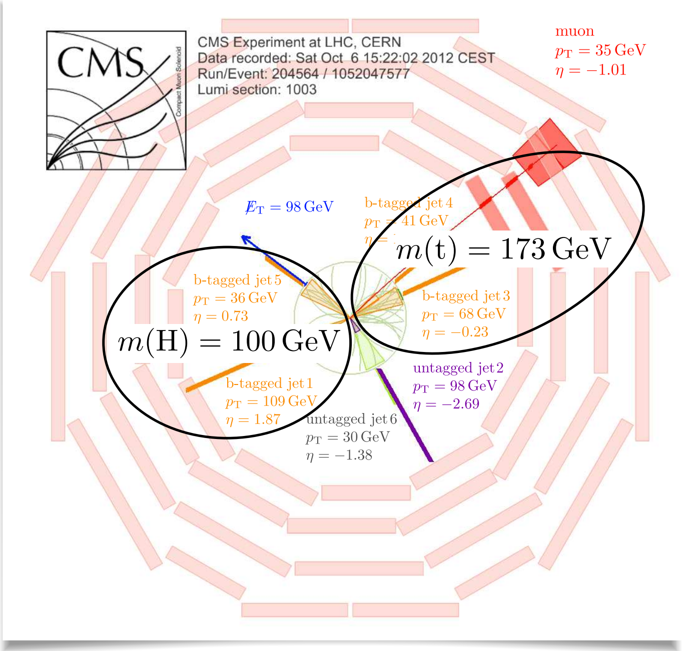
Classification MVA

- subject all samples (MC and Data) to the classification training
- systematic uncertainties implemented either as rate or shape uncertainties
- blinded at hight BDT output regions to not bias ourselves






CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Sat Oct 6 15:22:02 2012 CEST
Run/Event: 204564 / 1052047577
Lumi section: 1003
muon
$p_T = 35\,\mathrm{GeV}$
$\eta = -1.01$
$\not{E}_T = 98\,\mathrm{GeV}$
b-tagged jet 4
$p_T = 41\,\mathrm{GeV}$
$\eta = 1.92$
b-tagged jet 5
$p_T = 36\,\mathrm{GeV}$
$\eta = 0.73$
b-tagged jet 3
$p_T = 68\,\mathrm{GeV}$
$\eta = -0.23$
untagged jet 2
$p_T = 98\,\mathrm{GeV}$
$\eta = -2.69$
b-tagged jet 1
$p_T = 109\,\mathrm{GeV}$
$\eta = 1.87$
untagged jet 6
$p_T = 30\,\mathrm{GeV}$
$\eta = -1.38$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$p_T = 68$ GeV
$\eta = -0.23$
$m(H) = 100$ GeV
untagged jet 2
$p_T = 98$ GeV
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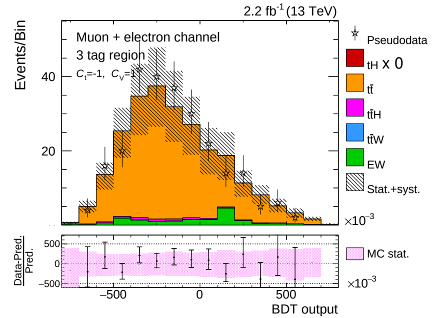
$p_T = 109$ GeV
$\eta = 1.87$
untagged jet 6
$p_T = 30$ GeV
$\eta = -1.38$

How to Calculate Expected Limits?

- get random “toys” from your background-only distribution
- see what signal strength factor you can exclude
- go down to the first signal strengh not excludable
- do this a lot of times ...
  $\Rightarrow$ expected limit



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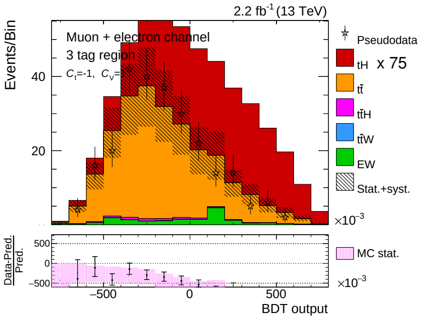

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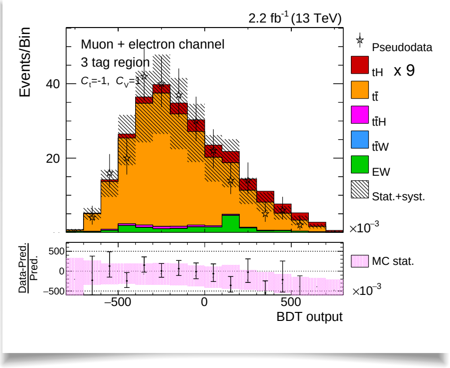

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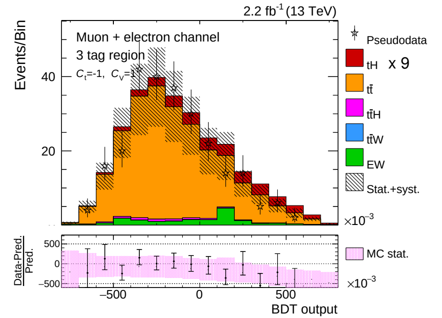
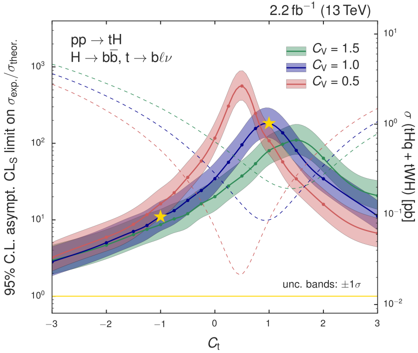


Expected Limits

- expected limits calculated for 51 points in (C_t,C_V) plane
- most systematic uncertainties included

(C_t,C_V)	Expected Limit @ 95% C. L.
(-1 , 1.0)	**10.95**
(+1 , 1.0)SM	182.25

- not yet able to exclude points in (C_t,C_V) plane
- still very early in LHC Run II



Conclusions

- presented search for tHq with $H \rightarrow b\bar{b}$
- presented pioneering use of reconstruction techniques
- 8 TeV combination paper submitted to journal
- 13 TeV analysis currently going through the approval process in CMS
- more data $\Rightarrow$ first exclusions!!!

HOT TOPHIGGS


BACKUP

tHq input variables

Electric charge of b-quark jet from decay of top quark, multiplied by lepton's charge. The jet charge is defined as in Eq. (1) in Ref. [37], with $\kappa = 1$
ΔR between the two jets from decay of Higgs boson
ΔR between b-quark jet and W boson from decay $t \rightarrow bW$
ΔR between reconstructed top quark and Higgs boson
Pseudorapidity of recoil jet
Invariant mass of b-quark jet from decay of top quark and charged lepton
Mass of reconstructed Higgs boson
Pseudorapidity of the most forward jet from decay of H
Tranverse momentum of the softest jet from decay of H
Number of b-tagged jets among the two jets from decay of H
Boolean variable that equals 1 if the b-quark jet from decay of t is b-tagged, 0 otherwise
Relative H_T, $(p_T(t) + p_T(H))/H_T$

$t\bar{t}$ input variables

Karlsruhe Institute of Technology

Difference of electric charges of b-quark jets from decays of t_{had} and t_{lep}, multiplied by lepton's charge
ΔR between the two light-flavor jets from decay of t_{had}
ΔR between b-quark jet and W boson from decay $t_{had} \rightarrow bW$
ΔR between b-quark jet and W boson from decay $t_{lep} \rightarrow bW$
Difference between masses of t_{had} and W from decay of t_{had}
Pseudorapidity of t_{had}
Invariant mass of b-quark jet from decay of t_{lep} and charged lepton
Mass of W from decay of t_{had}
Number of b-tagged jets among the two light-flavor jets from decay of t_{had}
Boolean variable that equals 1 if the b-quark jet from decay of t_{had} is b-tagged, 0 otherwise
Boolean variable that equals 1 if the b-quark jet from decay of t_{lep} is b-tagged, 0 otherwise
Transverse momentum of t_{had}
Transverse momentum of t_{lep}
Relative H_T, $(p_T(t_{had}) + p_T(t_{lep}))/H_T$
Sum of electric charges of the two light-flavor jets from decay of t_{had}, multiplied by lepton's charge

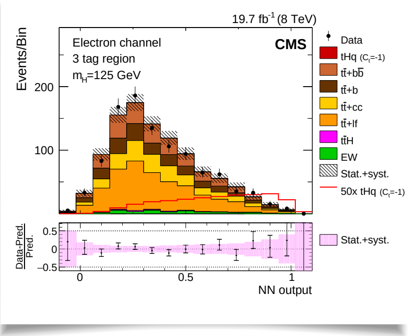
MVA input variables

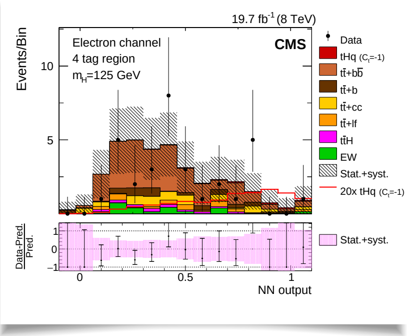
Electric charge of the lepton
Pseudorapidity of the recoil jet
Number of b-tagged jets among the two jets from the Higgs boson decay
Transverse momentum of the Higgs boson
Transverse momentum of the recoil jet
ΔR between the two light-flavor jets from the decay of t_{had}
Mass of t_{had}
Number of b-tagged jets among the two light-flavor jets from the decay of t_{had}

impact of systematic sources

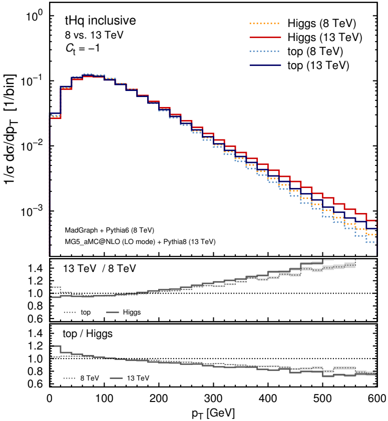
Source	Type	impact as exclusive source on final limit [%]	improvement of final limit after removal [%]
JES	shape	17	3
JER	shape	< 1	< 1
BTag light flavor	shape	13	< 1
BTag heavy flavor	shape	17	< 1
Pile up	normalization	< 1	< 1
Unclustered energy	shape	3	1
Lepton efficiency	normalization	5	< 1
Luminosity	normalization	10	< 1
Cross section (PDF)	normalization	8	< 1
Cross section (Scale)	normalization	9	< 1
MC Bin-by-Bin unc.	shape	< 1	< 1
Q^2 scale ($tHq + t\bar{t}$)	shape	20	4
Matching	shape	2	2
Top p_T reweighting	shape	19	2
$t\bar{t}$ HF rates (b)	normalization	13	< 1
$t\bar{t}$ HF rates ($b\bar{b}$)	normalization	15	< 1
$t\bar{t}$ HF rates (c / $c\bar{c}$)	normalization	13	1

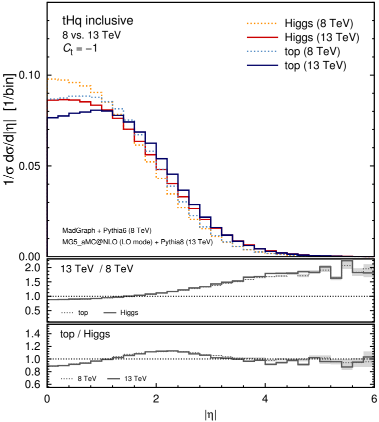
post-fit electron channel





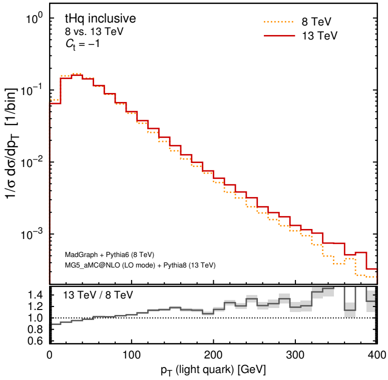
How objects behave at 13 TeV





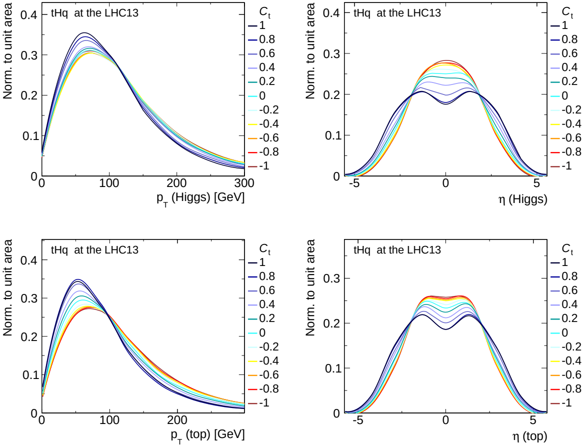
- Harder p_T spectra, objects tend to fly more often in forward directions than at 8 TeV

How objects behave at 13 TeV



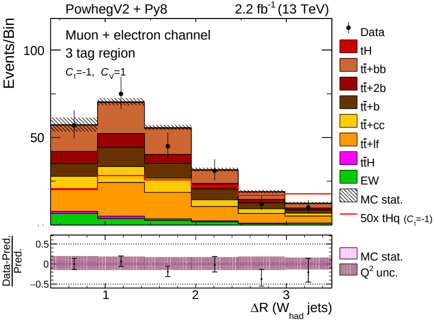
- Light quark is particularly relevant in discriminating against backgrounds
- Will be even more important because it is much more forward at 13 TeV
- But why only focus on $C_t = -1$?

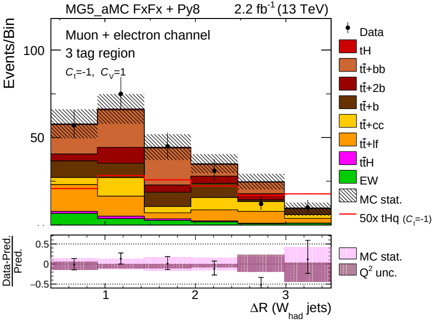
Differential distributions for different C_t



- Kinematics differs for different hypotheses. Expect different performances in BDTs
- Cross section differences might not translate linearly into exclusion limit differences

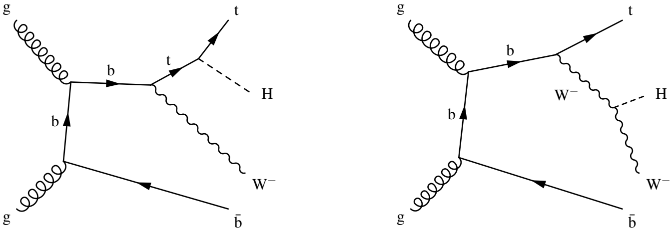
$t\bar{t}$ modelling: Powheg vs. FxFx





- In variables sensitive to additional radiation the FxFx provides a more accurate description, since more jets are modelled at NLO
- But statistical uncertainties are huge due to negative event weights

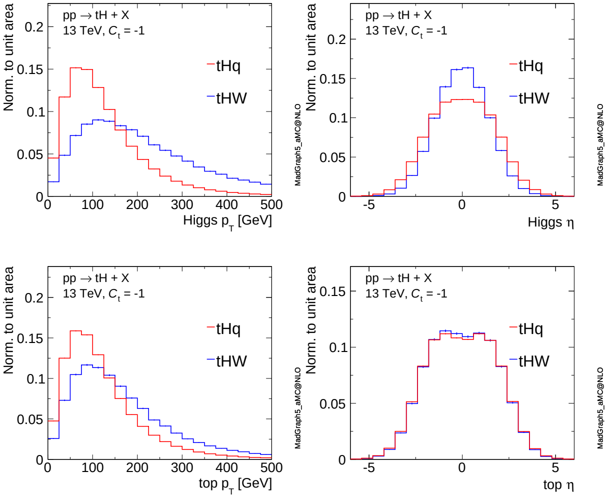
Another new thing in Run-II: tWH



We finally also now consider tWH. Will not train tWH against backgrounds, but just plug it into the analysis optimized for tHq. Notably, tWH has the same interference patterns as tHq!

Phenomenological studies on interference with ttH at NLO still ongoing. For this reason, samples have been produced at 5F LO (= no overlap).

tHq vs. tWH


pp → tH + X
13 TeV, C_t = -1
tHq
tHW
Norm. to unit area
Higgs p_T [GeV]
Higgs η
top p_T [GeV]
top η
MadGraph5_aMC@NLO

Monte Carlo Samples

/THW_Hincl_13TeV-madgraph-pythia8_TuneCUETP8M1/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v2
/THQ_Hincl_13TeV-madgraph-pythia8_TuneCUETP8M1/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1

/ST_t-channel_top_4f_leptonDecays_13TeV-powheg-pythia8_TuneCUETP8M1/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1
/ST_t-channel_antitop_4f_leptonDecays_13TeV-powheg-pythia8_TuneCUETP8M1/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1
/ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v2
/ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1

/TT_TuneCUETP8M1_13TeV-powheg-pythia8/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1
/TT_TuneCUETP8M1_13TeV-powheg-pythia8/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2_ext3-v1
/TTJets_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v3 (cross check)

/ttHTobb_M125_13TeV_powheg_pythia8/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1//

/TTWJetsToQQ_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1
/TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v1

/WJetsToLNu_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1

/WW_TuneCUETP8M1_13TeV-pythia8/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1
/WZ_TuneCUETP8M1_13TeV-pythia8/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1
/ZZ_TuneCUETP8M1_13TeV-pythia8/RunIISpring15MiniAODv2-74X_mcRun2_asymptotic_v2-v1

/QCD_Pt-*_EMEnriched_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v*
/QCD_Pt_*_bcToE_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v*
/QCD_Pt-*_MuEnrichedPt5_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt25ns_MCRUN2_74_V9-v*

*(QCD not in plots due to very limited statistics, possible data-driven QCD background in the future)

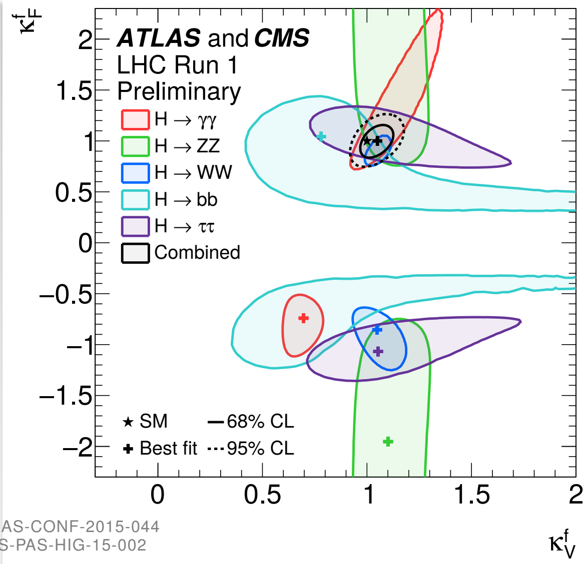
Data Samples

```
/SingleElectron/Run2015D-05Oct2015-v1/MINIAOD
/SingleElectron/Run2015D-PromptReco-v4/MINIAOD

/SingleMuon/Run2015D-05Oct2015-v1/MINIAOD
/SingleMuon/Run2015D-PromptReco-v4/MINIAOD

JSON : Cert_246908-260627_13TeV_PromptReco_Collisions15_25ns_JSON.txt
```

- delivered Luminosity: 2.2907 fb^{-1}
- recorded Luminosity: 2.2152 fb^{-1}

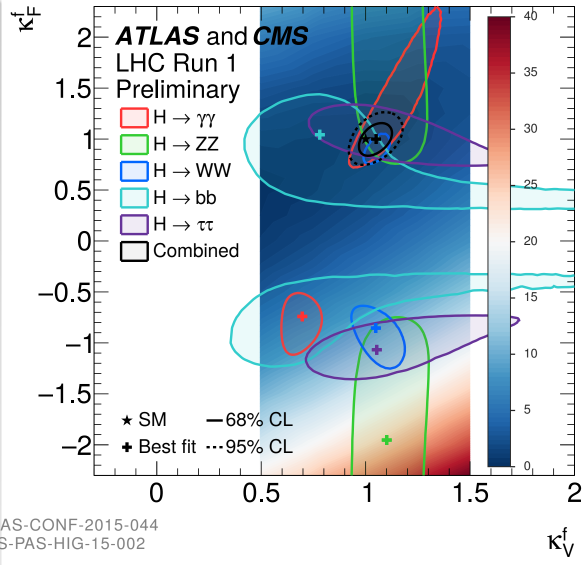
- actual recorded lumi a little bit lower due wrong run range

Couplings



ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

Couplings



ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

Object Selection - Leptons

Electrons

- $p_{\mathrm{T}} > 30\,\mathrm{GeV}$
- $|\eta| < 2.5$
- isolation ≤ 0.15
- tight Non-Triggering MVA ID WP80 (will change to triggering)

Muon

- $p_{\mathrm{T}} > 26\,\mathrm{GeV}$
- $|\eta| < 2.1$
- isolation < 0.15
- tight MuonPOG ID

- Object selections are based on ttH(bb) analysis' objects

Jet Definition and Selection

Jets

- AK4 jets (”slimmedJets”)
- pt $> 20\,\mathrm{GeV}$
- $|\eta| < 4.7$
- Lepton cleaning in dR < 0.4
- ak4PFchsL1L2L3 corrections

Selection:

- exactly **one** muon or electron
- **three** or **four** b-tagged jets
- at least **one** untagged jet
- at least **four** jets with $> 30\,\mathrm{GeV}$
- $\not{E}_T > 45\,\mathrm{GeV}$ (e) / 35 GeV (muon)

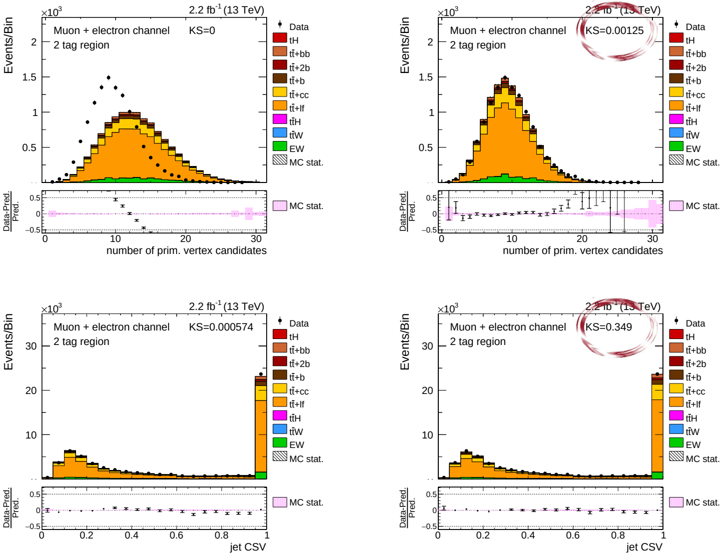
Setup details

- Global tags:
  - 74X_mcRun2_asymptotic_v4
  - 74X_dataRun2_v5
- CMSSW_7_4_15_patch1
- Triggers
  - MC:
    - HLT_Ele27_WP85_Gsf_v*
    - HLT_IsoMu17_eta2p1_v*
  - Data:
    - HLT_Ele27_eta2p1_WPLoose_Gsf_v*
    - HLT_IsoMu18_v*

Implemented Weights

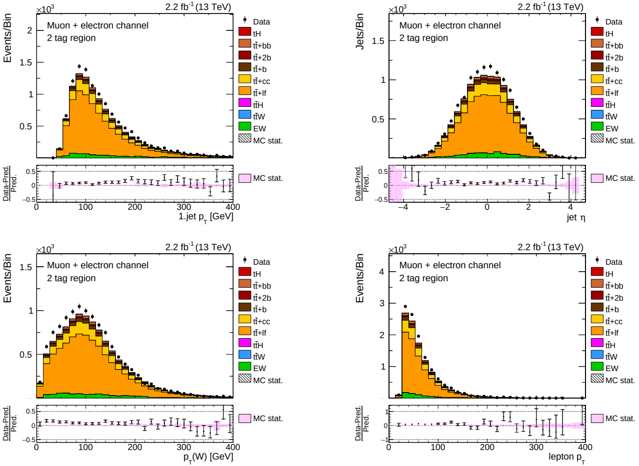
- LHE event weights
- CSV reweighting (as done by ttH groups)
  - fixes shape of CSV output, not limited to working points
- PU reweighting

Impact of PU and CSV weights



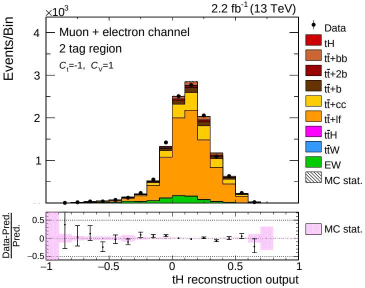
TTbar control Region

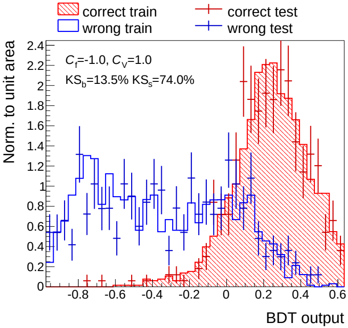
- exactly one charged lepton (electron/muon)
- exactly two tight btags (CSVv2T WP $\rightarrow$ 0.97)

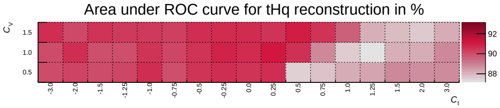


tHq reconstruction

- One reconstruction BDT is trained per available point in the (C_t, C_V) plane
  $\Rightarrow$ 51 BDT's with possible 51 different jet assignments

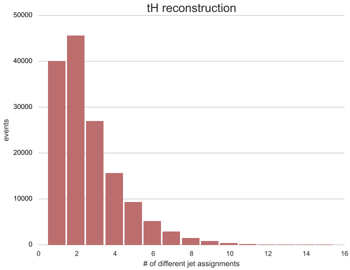


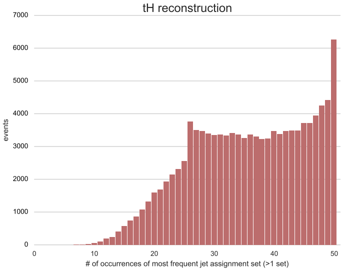




tHq reconstruction II

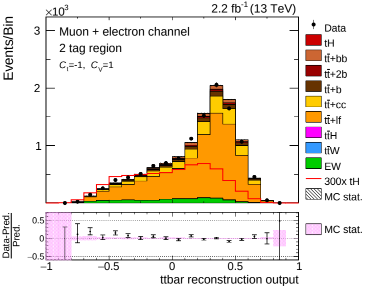
- Are 51 BDTs really necessary?
- In $\sim$ 30% of events all (51) BDTs or all but one (50) choose the same jet assignment
- In $\sim$ 70% different BDT are necessary!

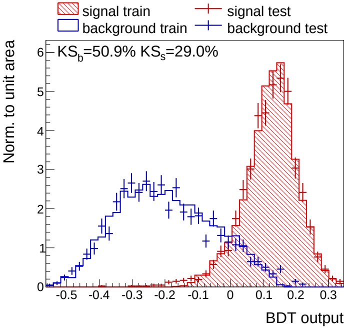




TTbar reconstruction

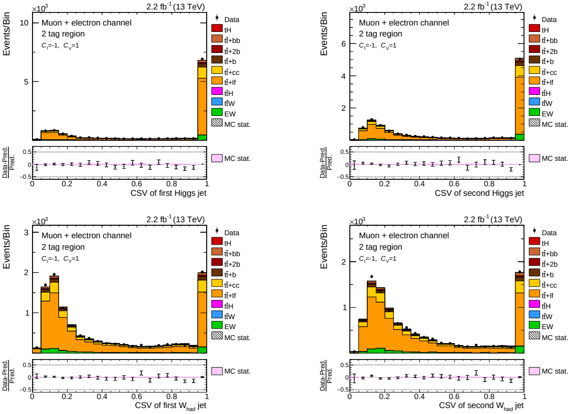
- One reconstruction BDT is trained
- assign jets under hypothesis of a ttbar event
- concept same as in 8 TeV analysis



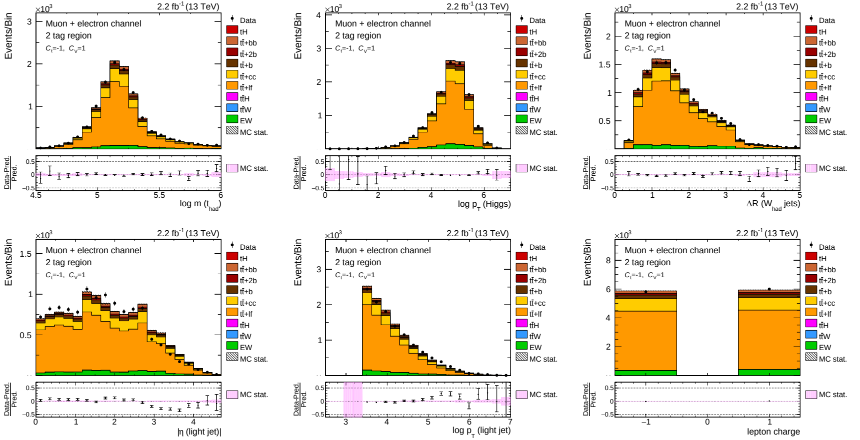


Input variables – TTbar CR

- almost same set as in 8 TeV analysis, but using full CSV shape now, instead of number of b-tags
- tHq-reco dependent variables differ for the 51 coupling points
- train 51 different classification BDTs

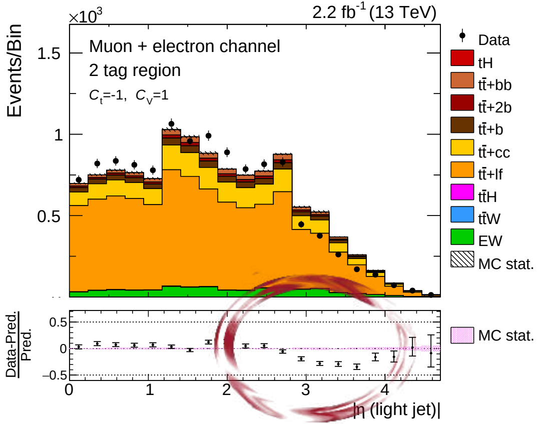


Input variables II – TTbar CR

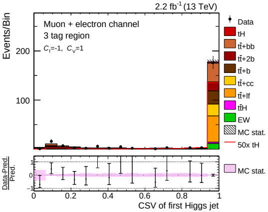


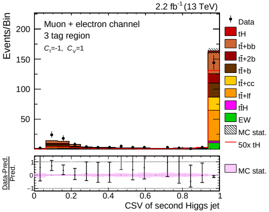
Forward jet problem

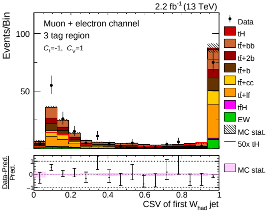
- problem in MC with HF
- $|\eta_{\text{light jet}}|$ is the most discriminating variable against background
- appears to be fixed in 76x samples

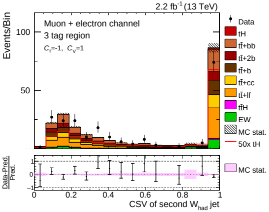


Input variables – 3 Tag Region

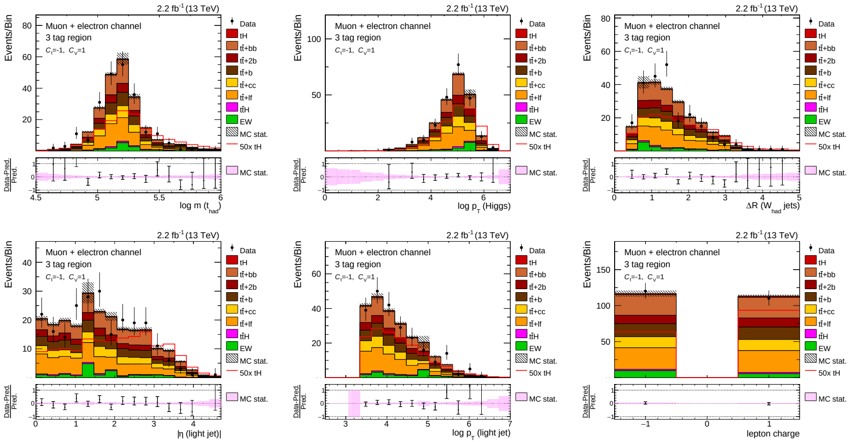








Input variables II – 3 Tag Region



Input variables – 4 Tag Region

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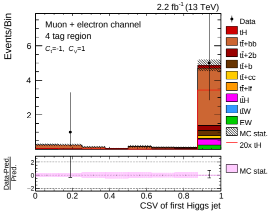
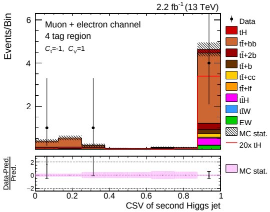
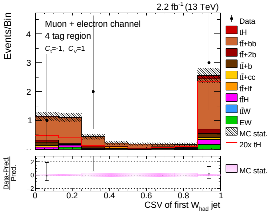
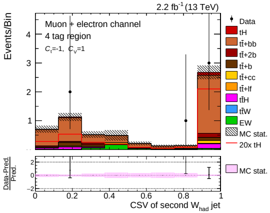
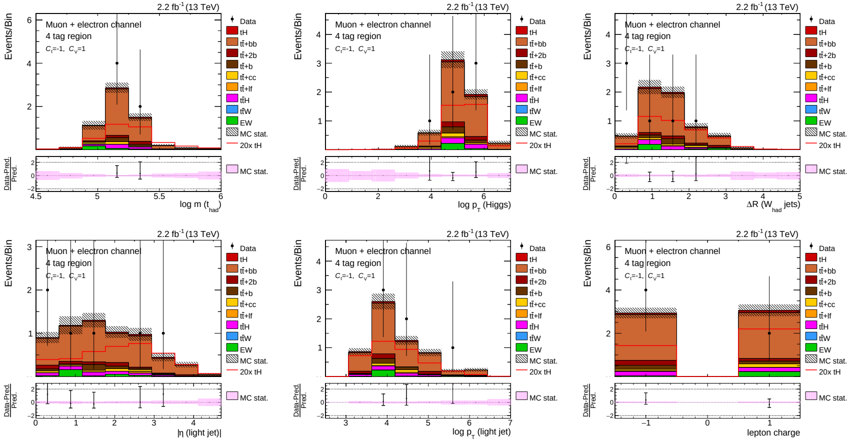






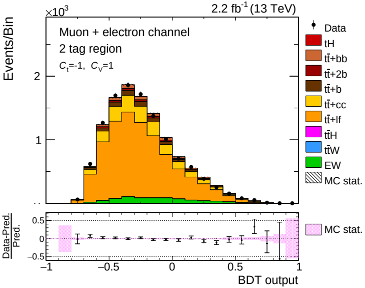


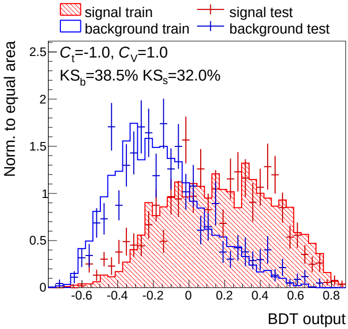
Input variables II – 4 Tag Region

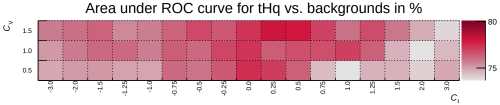


Classification

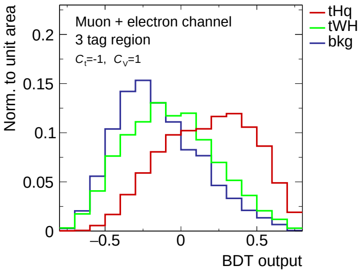
- Still only one reconstruction BDT is trained
- assign jets under hypothesis of a ttbar event

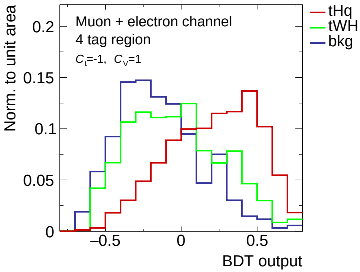






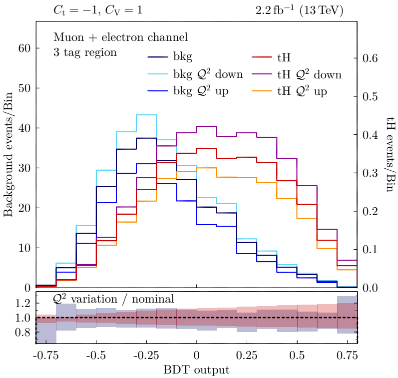
Classification

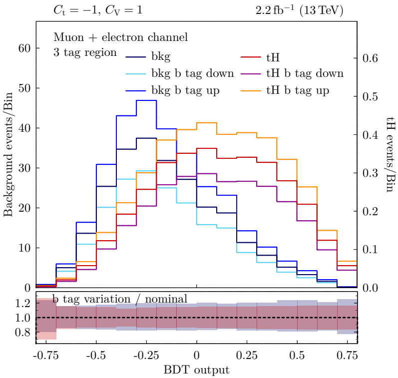




- As expected, tWH looks a bit more like $t\bar{t}$
- Room for improvement: dedicated training tWH vs. $t\bar{t}$

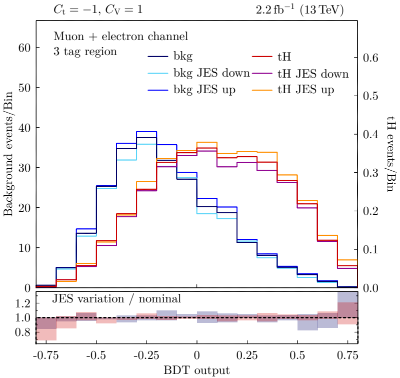
Systematics

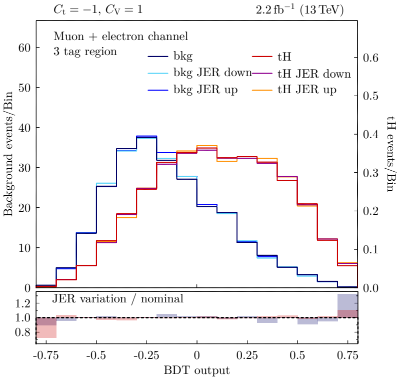




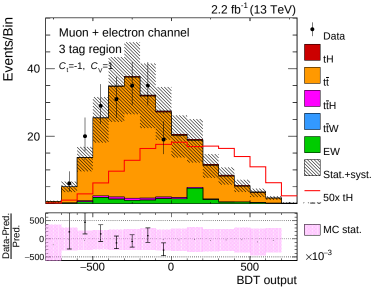
- Consider not only shape but also normalization difference for scale systematics
- CSV reweighting brings large b tag systematics

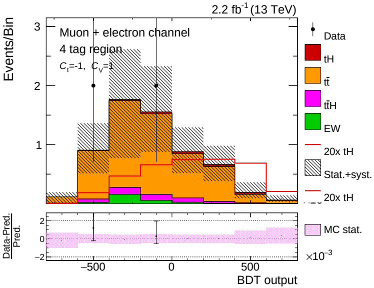
Systematics





Classification





- Pre-fit distributions from which the limit will be derived
- Of course, still blinded at high BDT scores
- tH includes tHq and tWH

Expected Limits