Higgs boson production in association with a top quark pair: recent results from CMS

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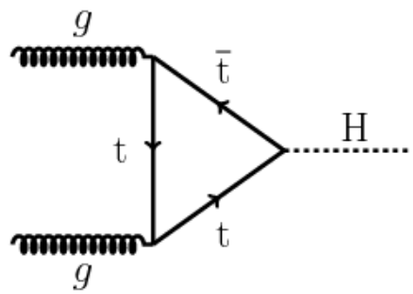
HiggsTools Second Annual Meeting
April 15, 2016

Outline

- What makes ttH(bb) interesting?
- What is the status and present difficulties?
- Closer look at a recently-published ttH(bb) search from the trenches
- Personal view, not for CMS
- Using only public information from HIG-16-004, BTV-15-001 where I have contributed

ttH→bb motivation

- Need direct experimental evidence for Higgs coupling to up-type fermions



- top mass → coupling near unity. Top quark is a Higgs probe!

- goal: verify top pair associated Higgs (ttH) production in Run II

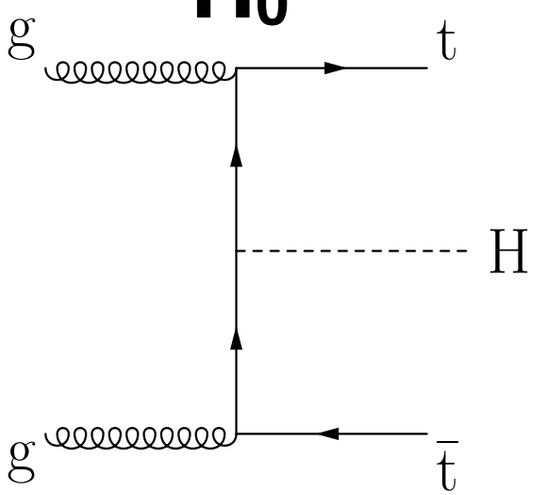
- measure **μ = σ(tt+H) / σ(tt+H in SM)**

- ttH cross-section crucial input for Higgs coupling fits

Challenges

- large background: mainly tt+jets production
  - σ(tt+jets) = **830 pb** vs. σ(tt+Hbb) = **0.3 pb**
- **tt+bb**: irreducible, multiscale process, difficulties in modelling, combinatorial self-background for H(bb)

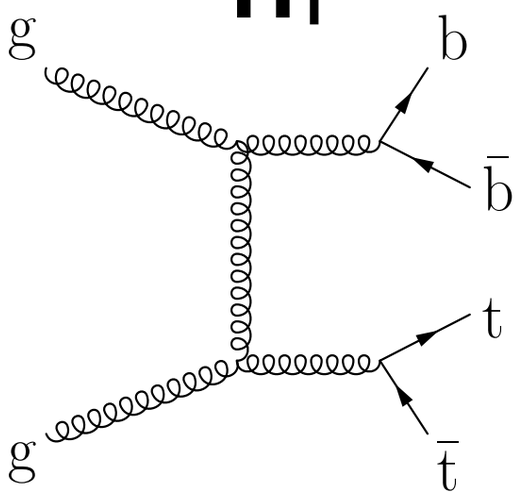
H0



signal

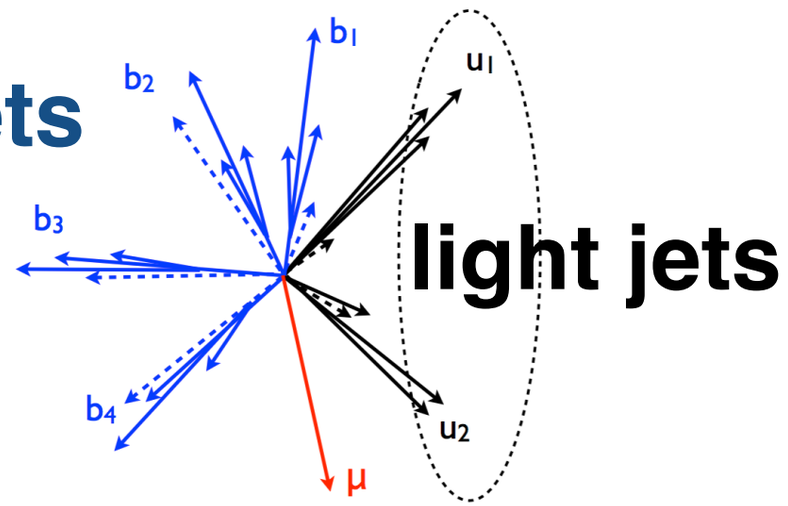
or

H1

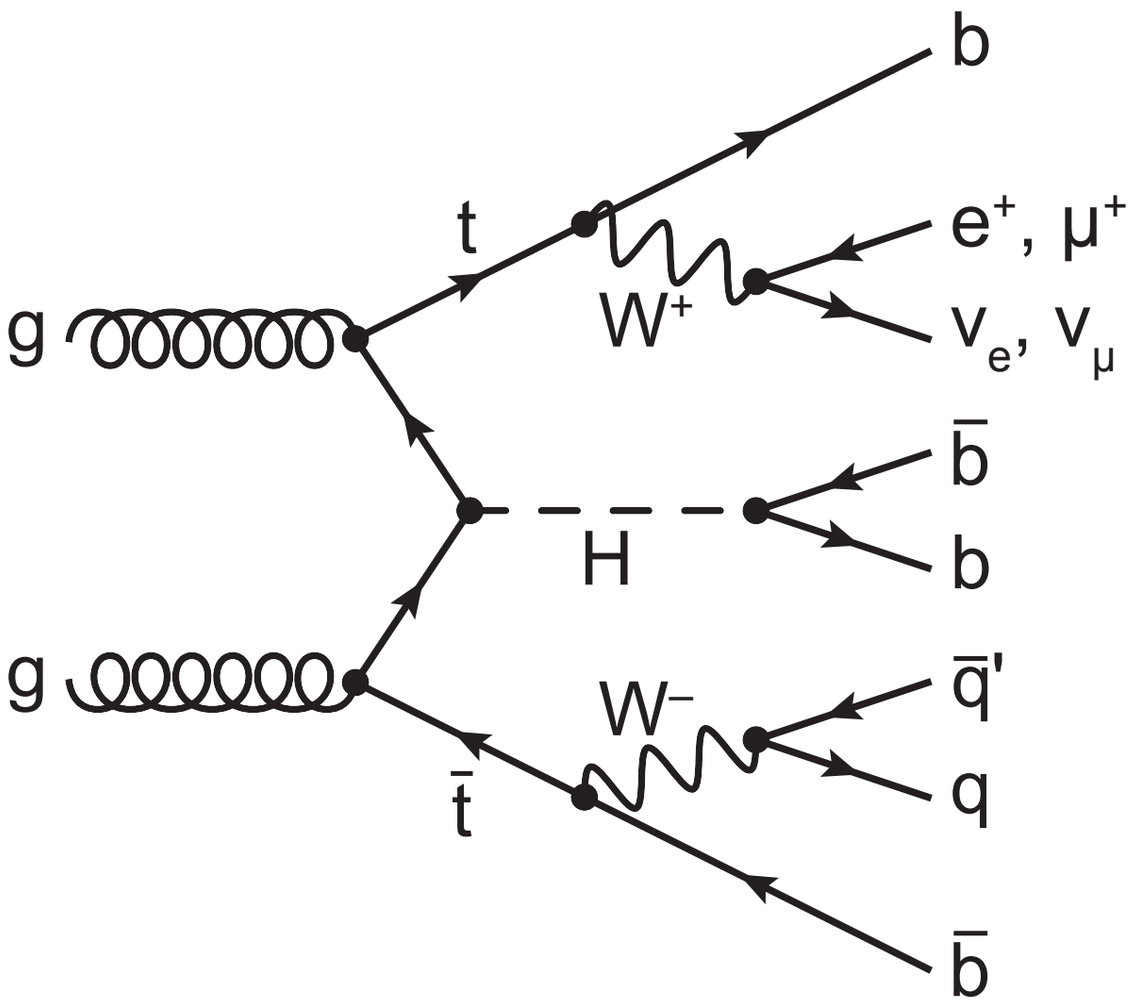


background

both have the same final state

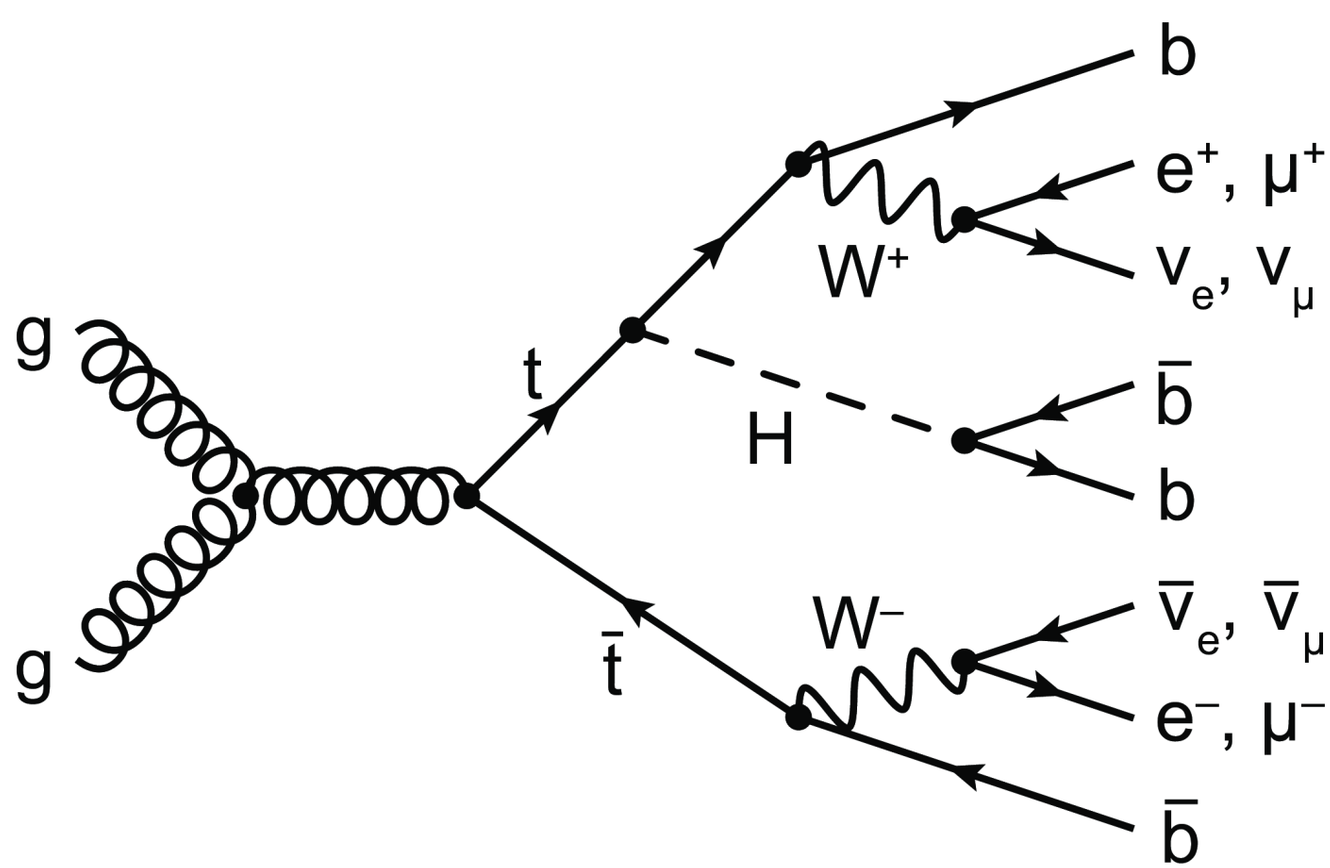


semileptonic



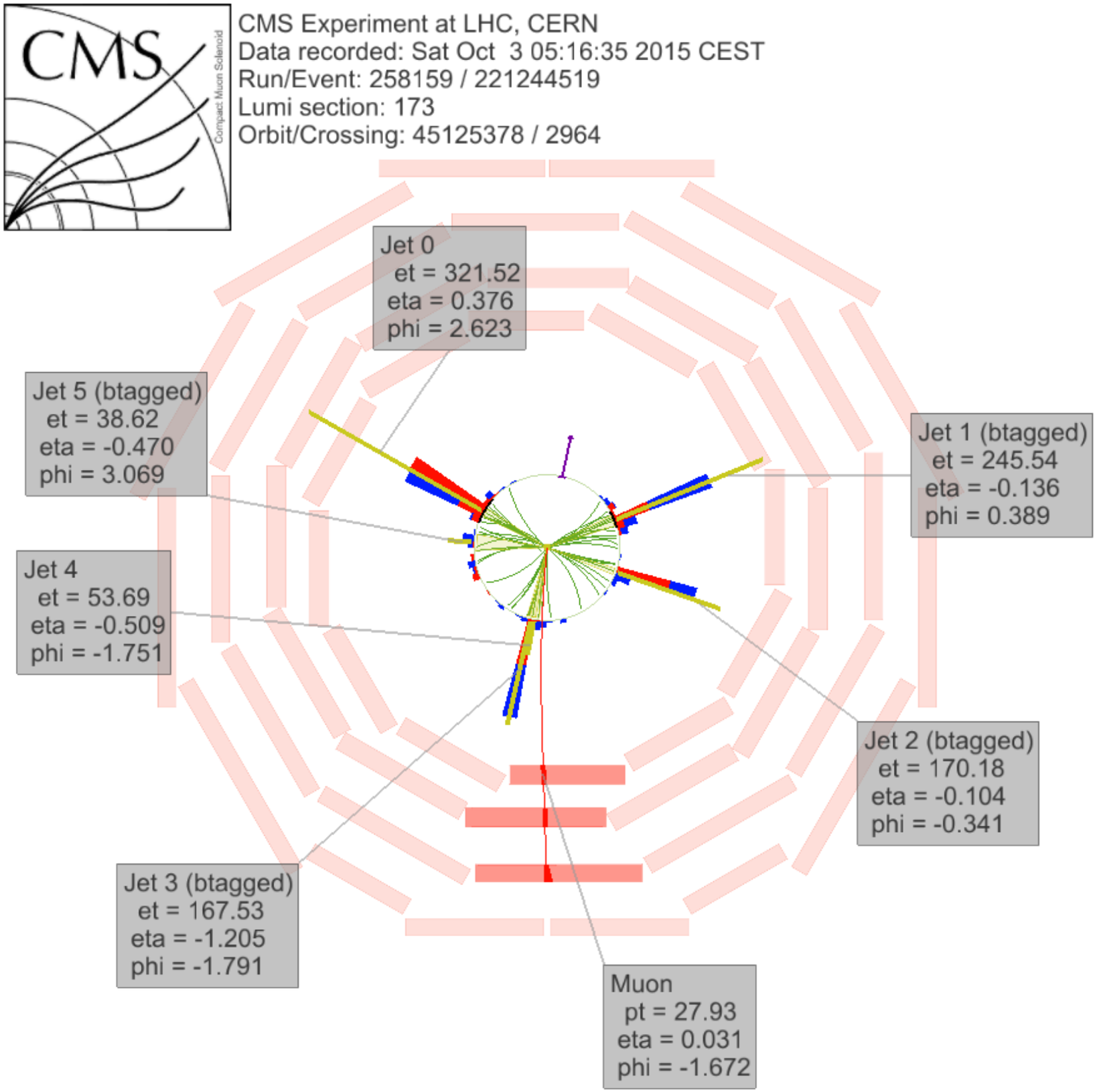
1 lepton, 6 jets, 4 b-tags

dileptonic



2 leptons, 4 jets, 4 b-tags

complicated final state with several b-jets, leptons, missing energy, combinatorial confusion, no clear resonant peak.


CMS Experiment at LHC, CERN
Data recorded: Sat Oct 3 05:16:35 2015 CEST
Run/Event: 258159 / 221244519
Lumi section: 173
Orbit/Crossing: 45125378 / 2964
Jet 0
et = 321.52
eta = 0.376
phi = 2.623
Jet 5 (btagged)
et = 38.62
eta = -0.470
phi = 3.069
Jet 1 (btagged)
et = 245.54
eta = -0.136
phi = 0.389
Jet 4
et = 53.69
eta = -0.509
phi = -1.751
Jet 2 (btagged)
et = 170.18
eta = -0.104
phi = -0.341
Jet 3 (btagged)
et = 167.53
eta = -1.205
phi = -1.791
Muon
pt = 27.93
eta = 0.031
phi = -1.672

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LHC analyses

higgstools

Run I analyses including the H → bb decay

Experiment	Analysis	Limit	reference
CMS, 7+8 TeV	H → bb+$\tau\tau$+$\gamma\gamma$, BDT	3.4 (3.7)	HIG-13-019
CMS, 8 TeV	H → bb, MEM	4.2 (3.3)	EPJC 75 (2015) 251
ATLAS, 8 TeV	H → bb, MEM+BDT	3.4 (2.2)	EPJC 75 (2015) 349
CMS, 7+8 TeV	ttH combined	4.5 (1.7)	JHEP 09 (2014) 087
ATLAS, 7+8 TeV	ttH fully hadronic	3.1 (1.4)	Moriond16

Analysis strategy well established by both experiments, Run II and 2016 has discovery potential.

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Run II ttH(bb)

Search for $t\bar{t}H$ production in the $H \to b\bar{b}$ decay channel with $\sqrt{s} = 13$ TeV pp collisions at the CMS experiment

The CMS Collaboration

New in Run II

- combined discriminator approach
- boosted topologies included
- modelling with NLO generators (POWHEG)
- New tt+heavy-flavour treatment

- Very collaborative analysis, 40+ people, 5+ different institutes
- Presented by CMS at Moriond 2016

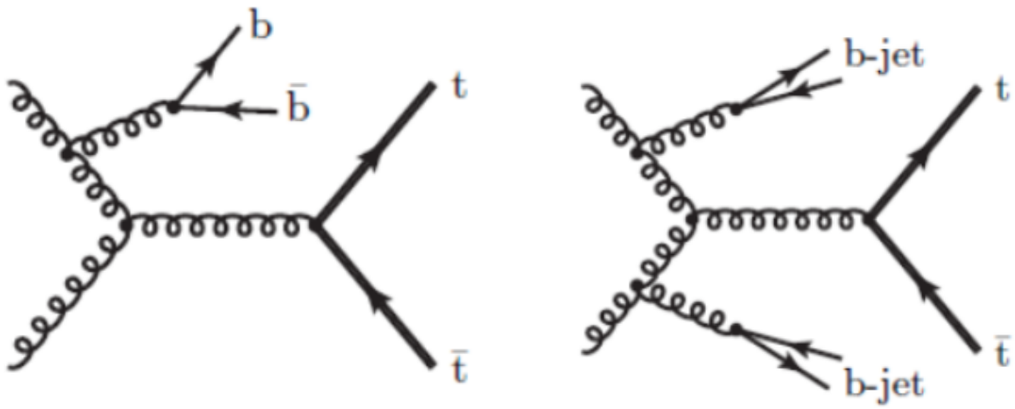
Analysis strategy

- **trigger**: rely on leptonic decay of top for triggering
- **selection**: events compatible with tt+H lepton+jets or dilepton channel and H→bb decay
- **categorization**: based on jet and b-tag multiplicity, presence of boosted top/higgs
- **shape analysis**: ttH vs. tt+jets (bb) against with multivariate tools: BDT or MEM
- **limit**: combined fit in all categories on discriminant shape

Data and simulation

- 2.7/fb of good data, (~50% of Run I stats for ttH)
- NLO modelling of backgrounds with POWHEG, tt+jets inclusive
- ttbar statistics a major issue, esp. for classifier training
- Minor backgrounds modelled by MC: single top (t, tW), diboson, W+jets, tt+W/Z, DY-jets

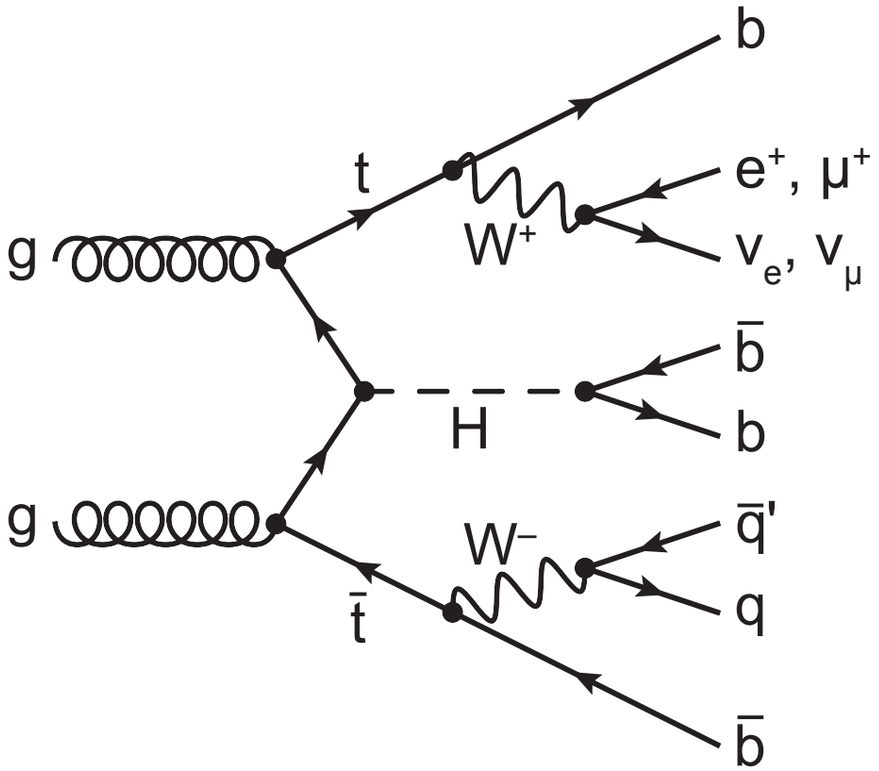
tt+jets subcomponents



tt+jets splitting via hadron matching

details in Tim's talk

Physics objects



leptons

- top pair decaying to lepton +jets: 1 tight muon (electron) with pt > 25 (30) GeV
- dileptonic decay: 1 tight, 1 loose opposite sign lepton

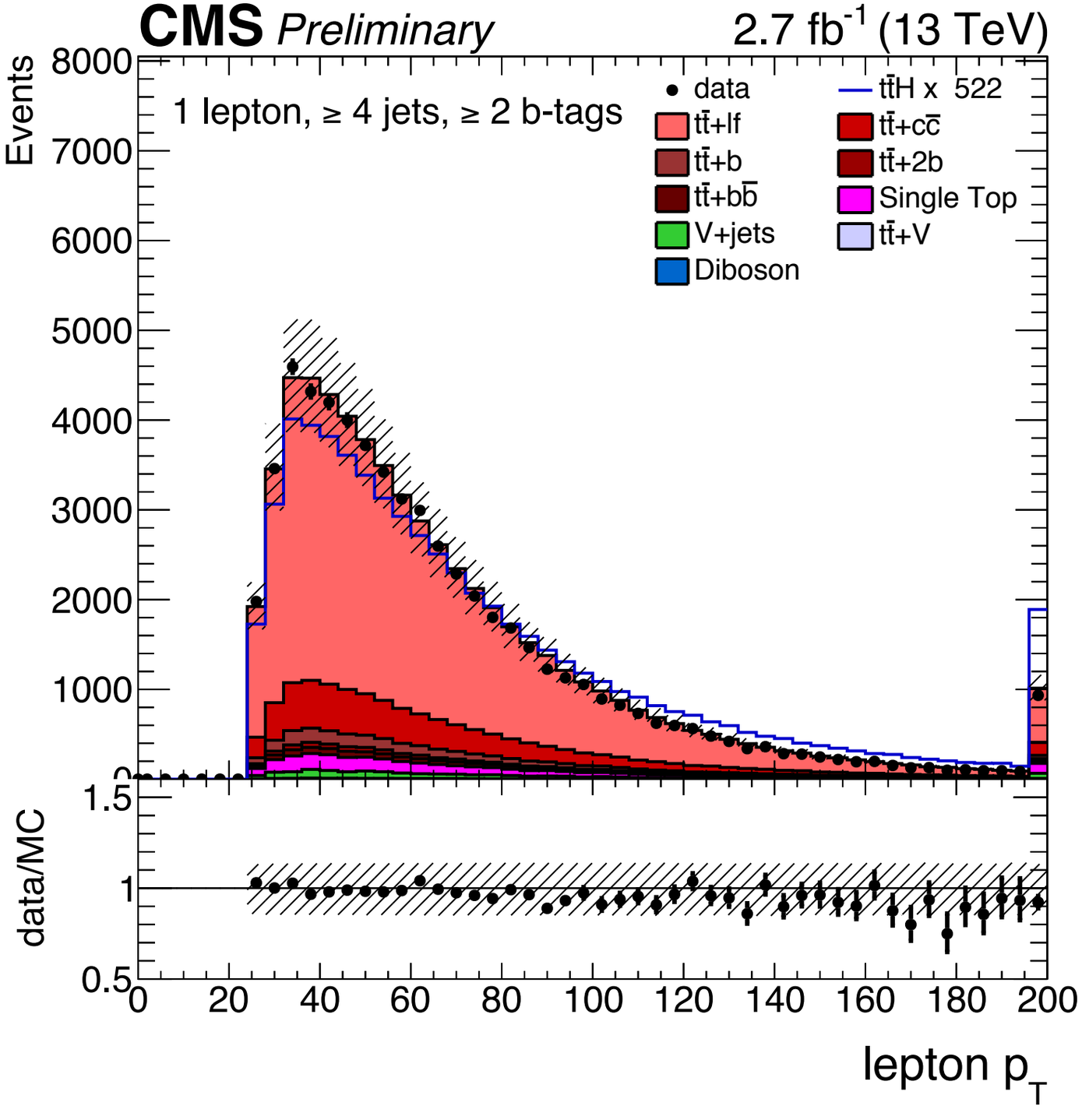
jets

- pt>30 GeV, |η|<2.4
- loosened pt for DL subleading jets

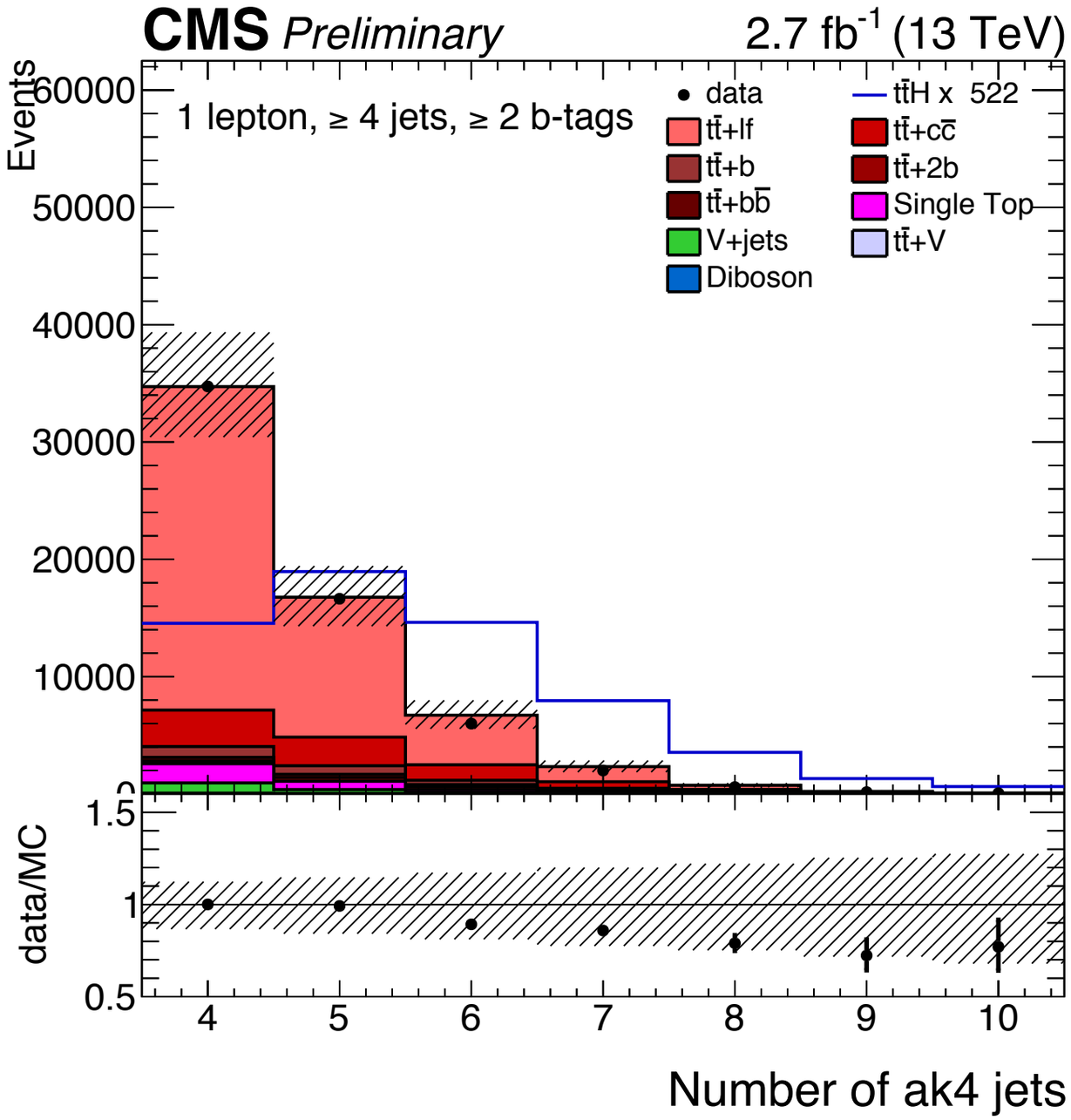
b-tagging

- # of b-tags as categorization
- b-discriminator shape as signal discriminator

Lepton kinematics



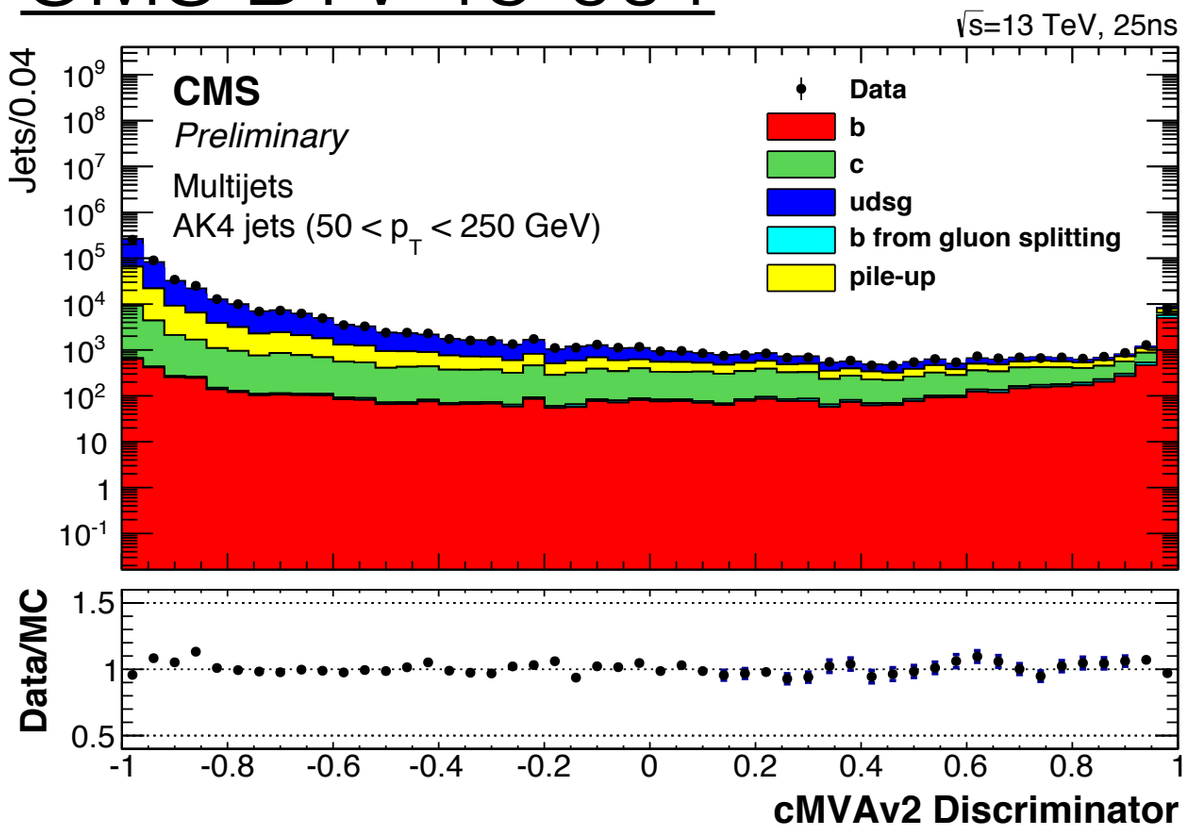
Jet multiplicity



Observe #jets overprediction, well known in CMS, connected to parton shower modelling

Improved b-tagging

CMS BTV-15-001

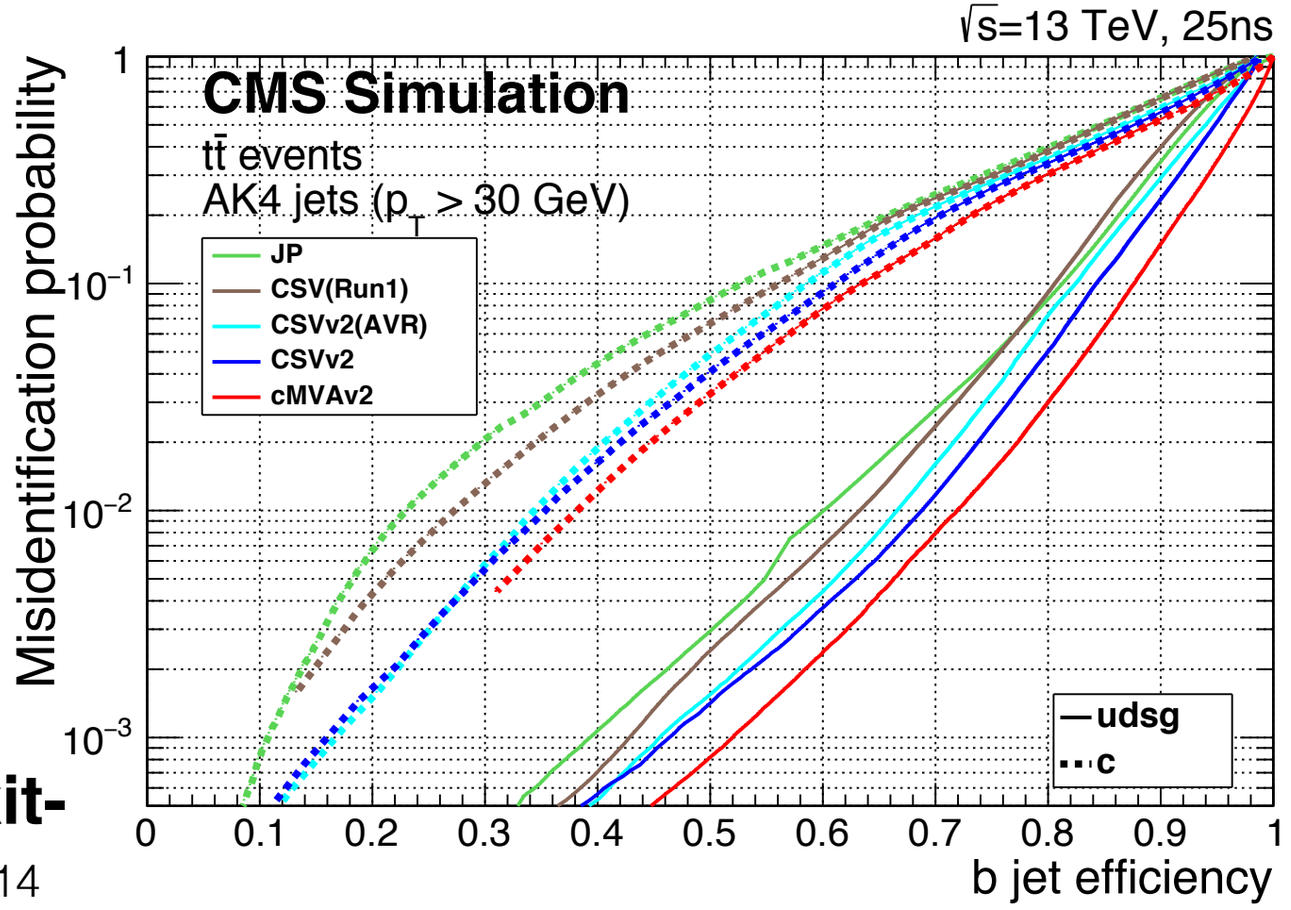


- Integrated into CMS software, deployed in 13 TeV data

- O(30%) better against fake b-quarks

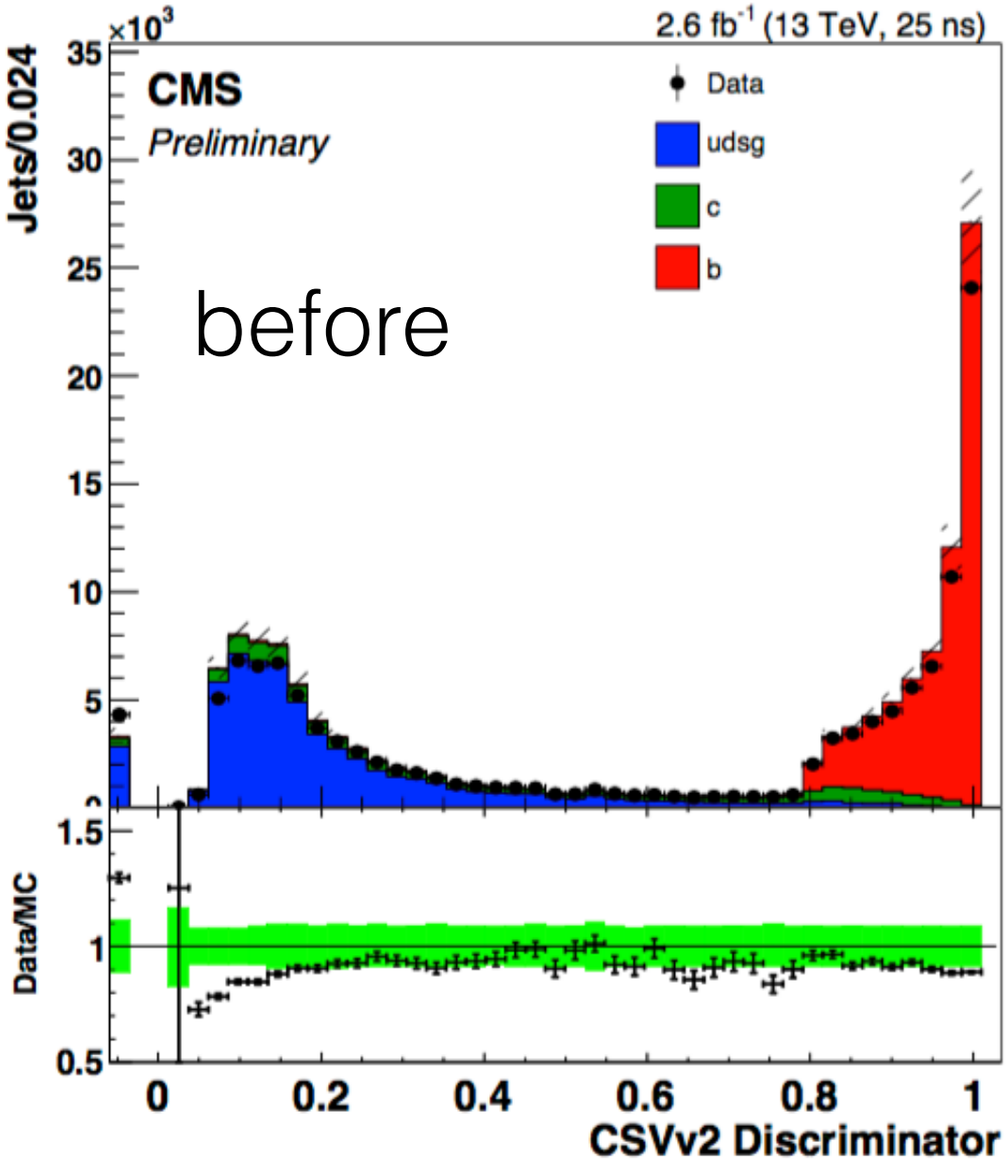
- As service task, developed a new b-discriminator algorithm for CMS

- based on subdetector combination

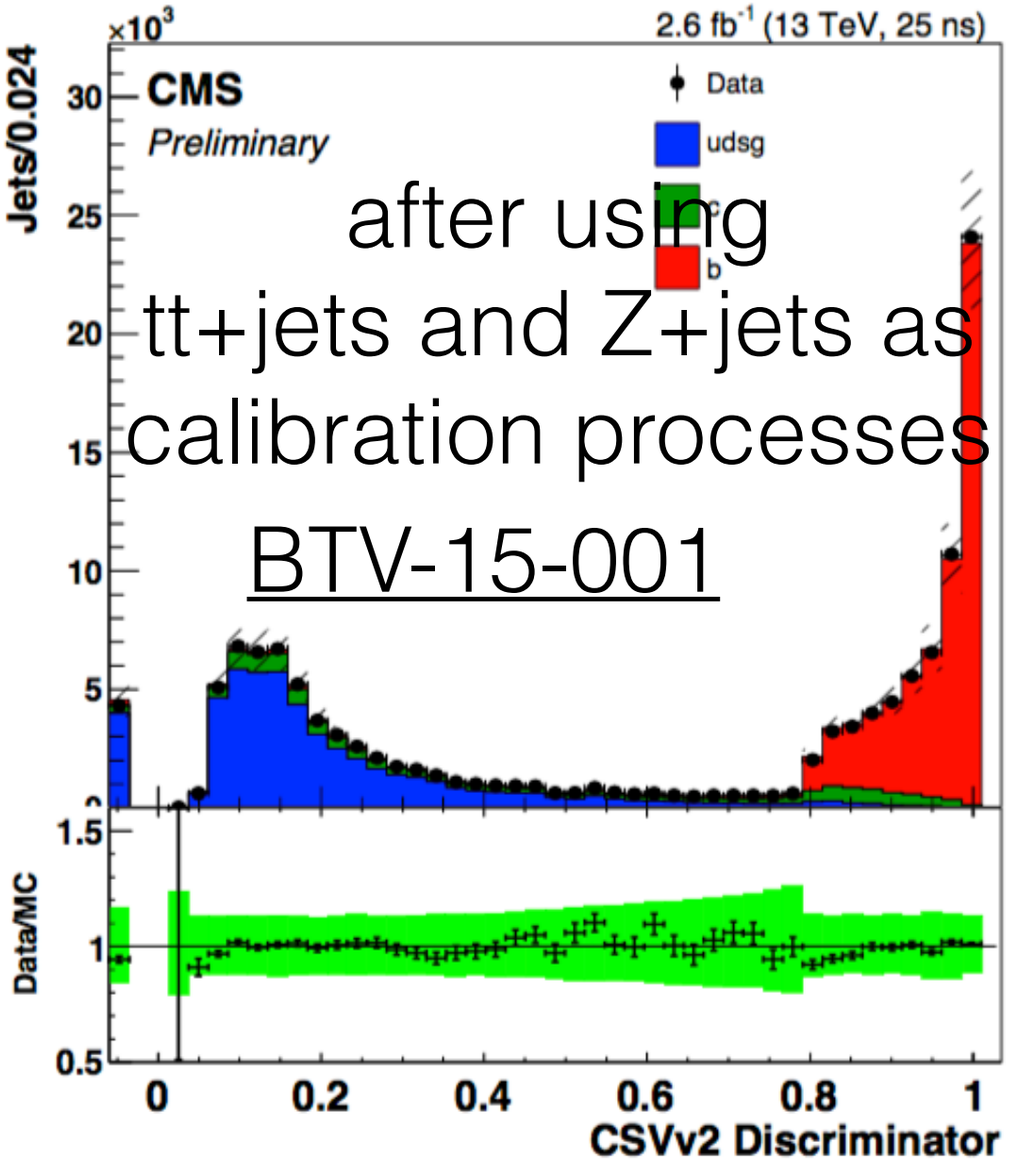


First major use of scikit-learn in LHC!

CSV reshaping



before



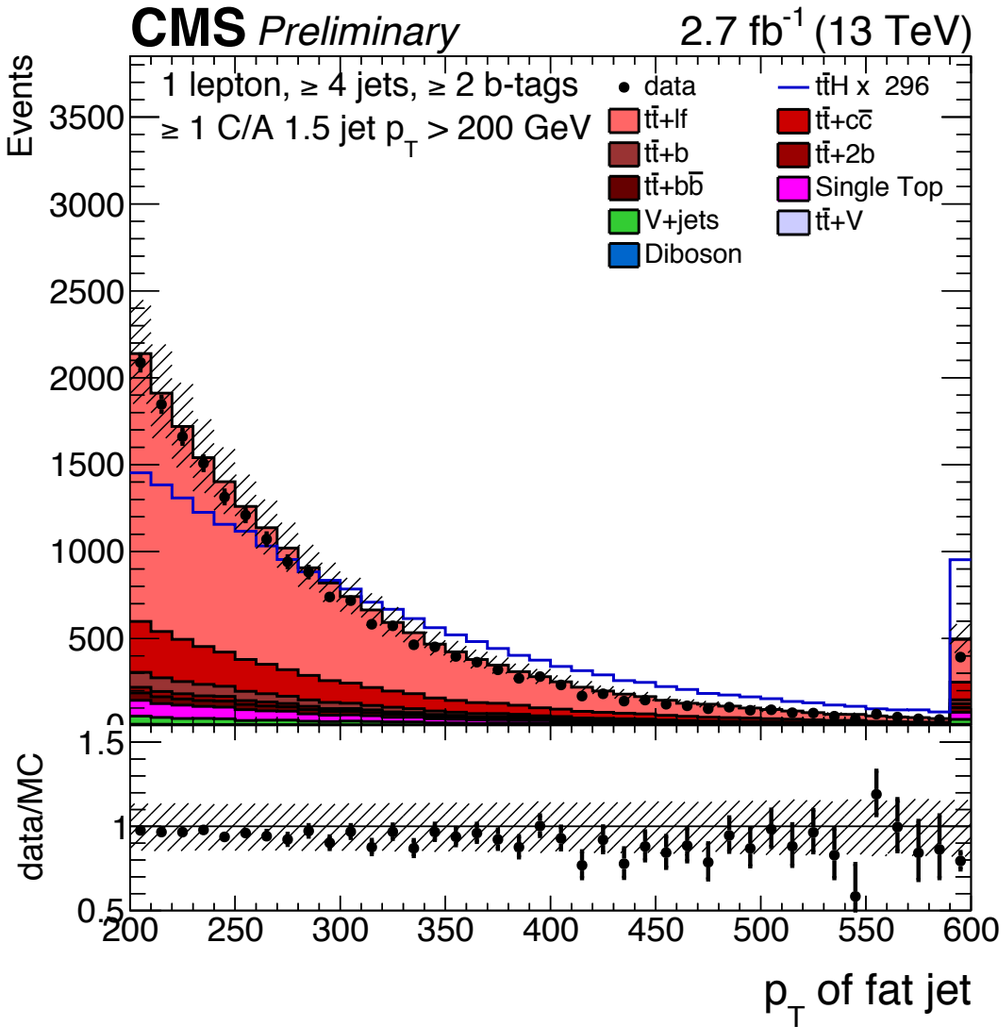
after using tt+jets and Z+jets as calibration processes

BTV-15-001

- Need to reshape CSV distribution, major systematic

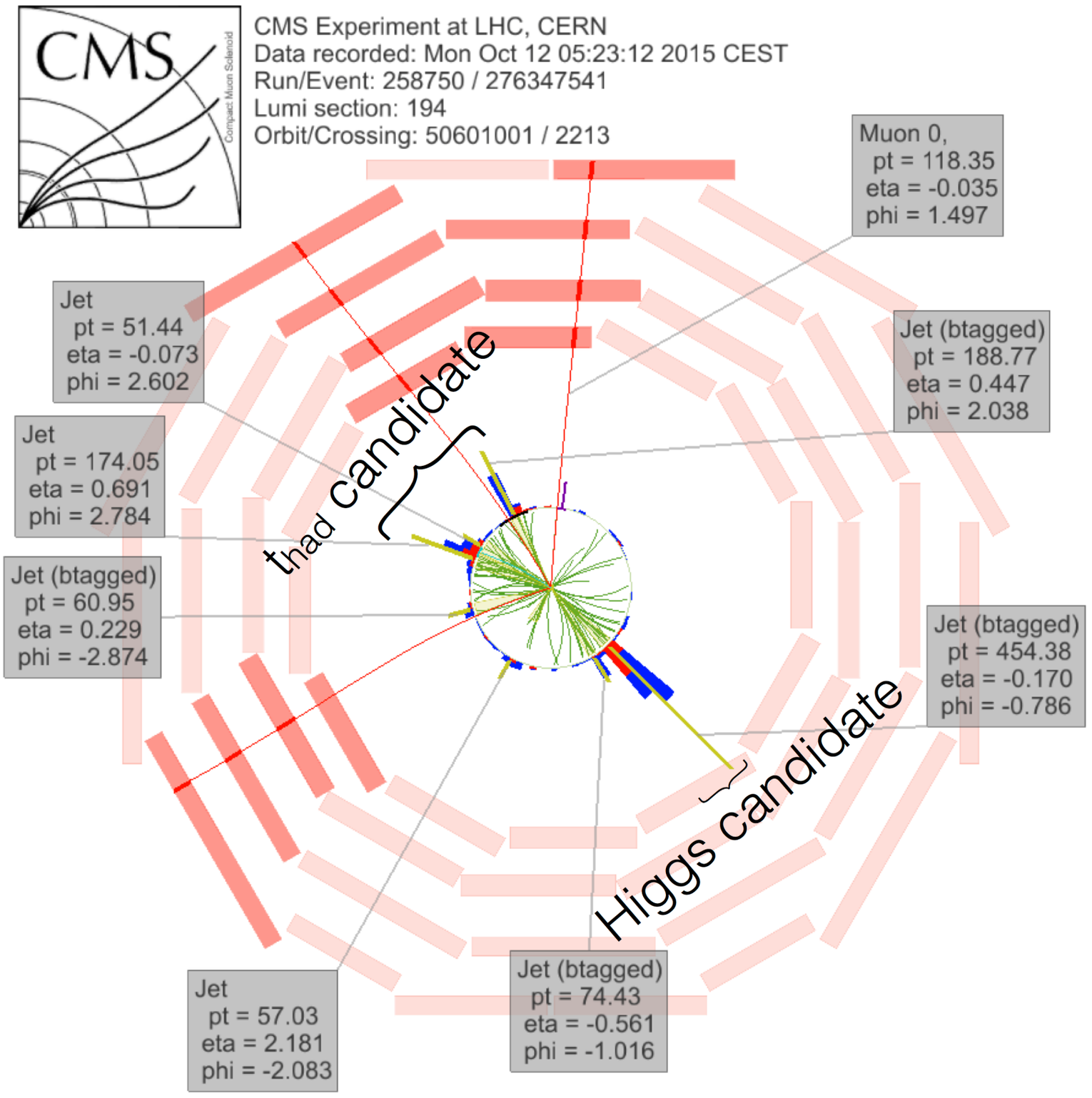
Boosted objects

- CA R=1.5 jets, excluding tight leptons, pt>200 GeV, |η| < 2.0
- use a dedicated MVA based on HepTopTaggerV2 for top-tagging
- Same b-discriminant as for resolved jets on subjets
- Details in Gregor's talk



We have already hundreds of high-momentum boosted jets!

Boosted candidate

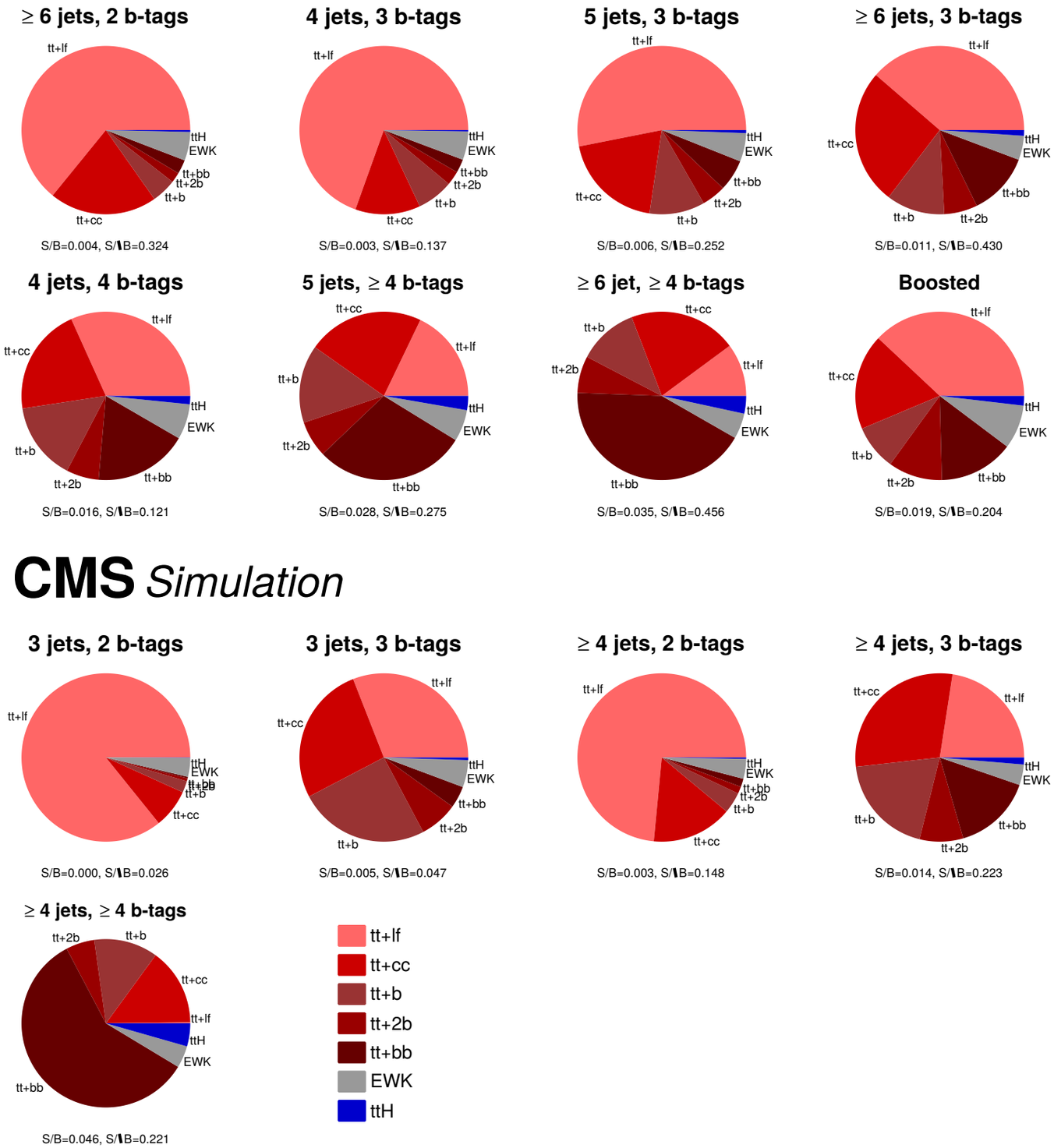


Now that we have some events, how to optimally use them in the analysis?

Currently, create categories with different background components based on jet/b-tag multiplicity

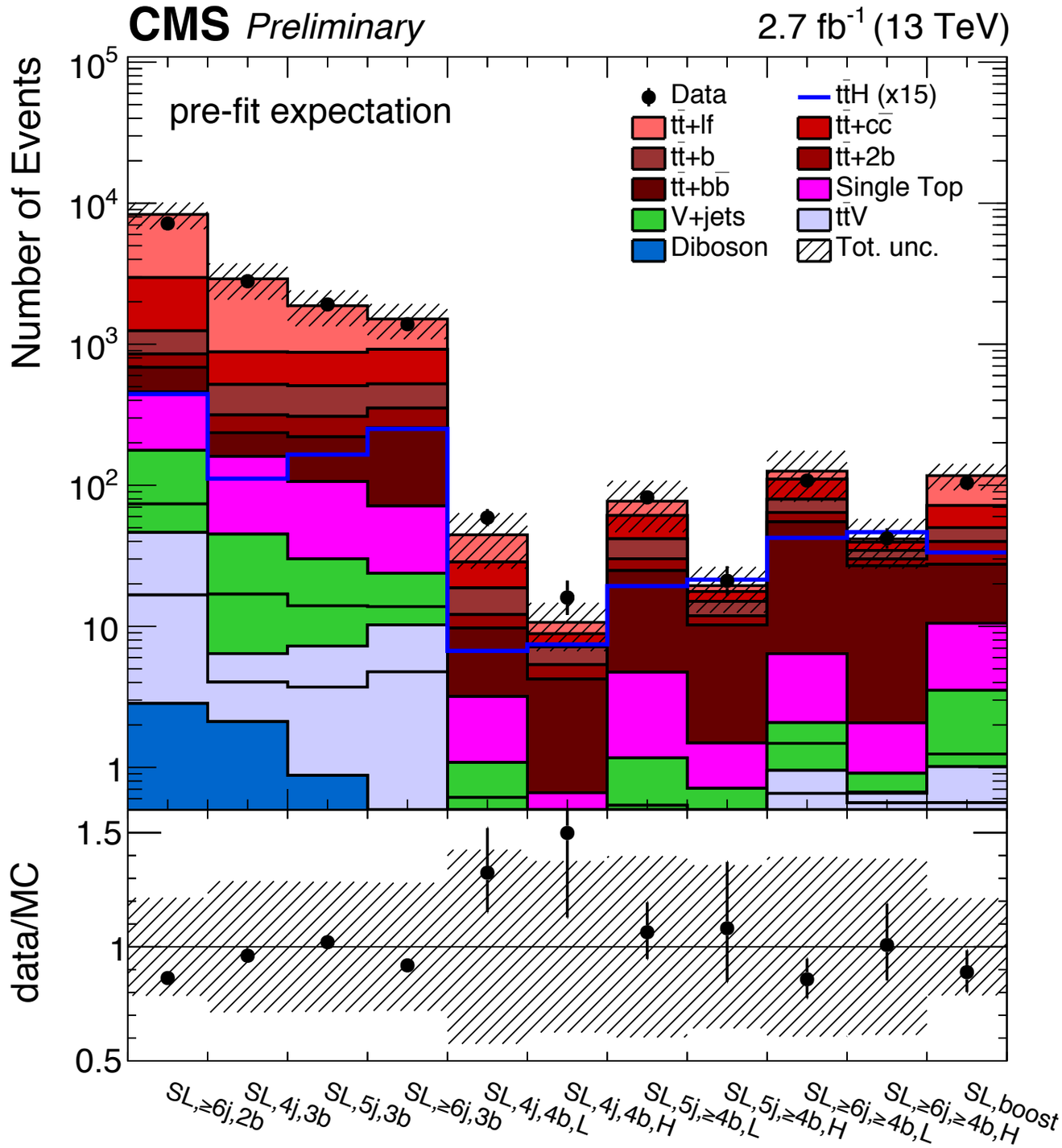
Analysis channels

- 13 final categories
- **Lepton+jets:** exactly 1 tight lepton, veto loose, ≥4j ≥3t or ≥6j ≥2t, 7 baseline categories
- **Boosted**: if l+j and ≥4j ≥2t and both boosted Higgs and top present
- **Dilepton:** exactly 2 opposite sign leptons (1loose + 1tight), 4 baseline categories (3j2t, 3j 3t, ≥4j 2t, ≥4j 3t, ≥4j ≥4t)
- categories defined to be non-overlapping (also SL & DL)



lepton + jets

- Subdivide to 7 jet/tag categories + 1 boosted category
- Evaluate MEM and BDT discriminators, tuned category-by-category
- Study correlations of discriminators
- combined discriminators if motivated



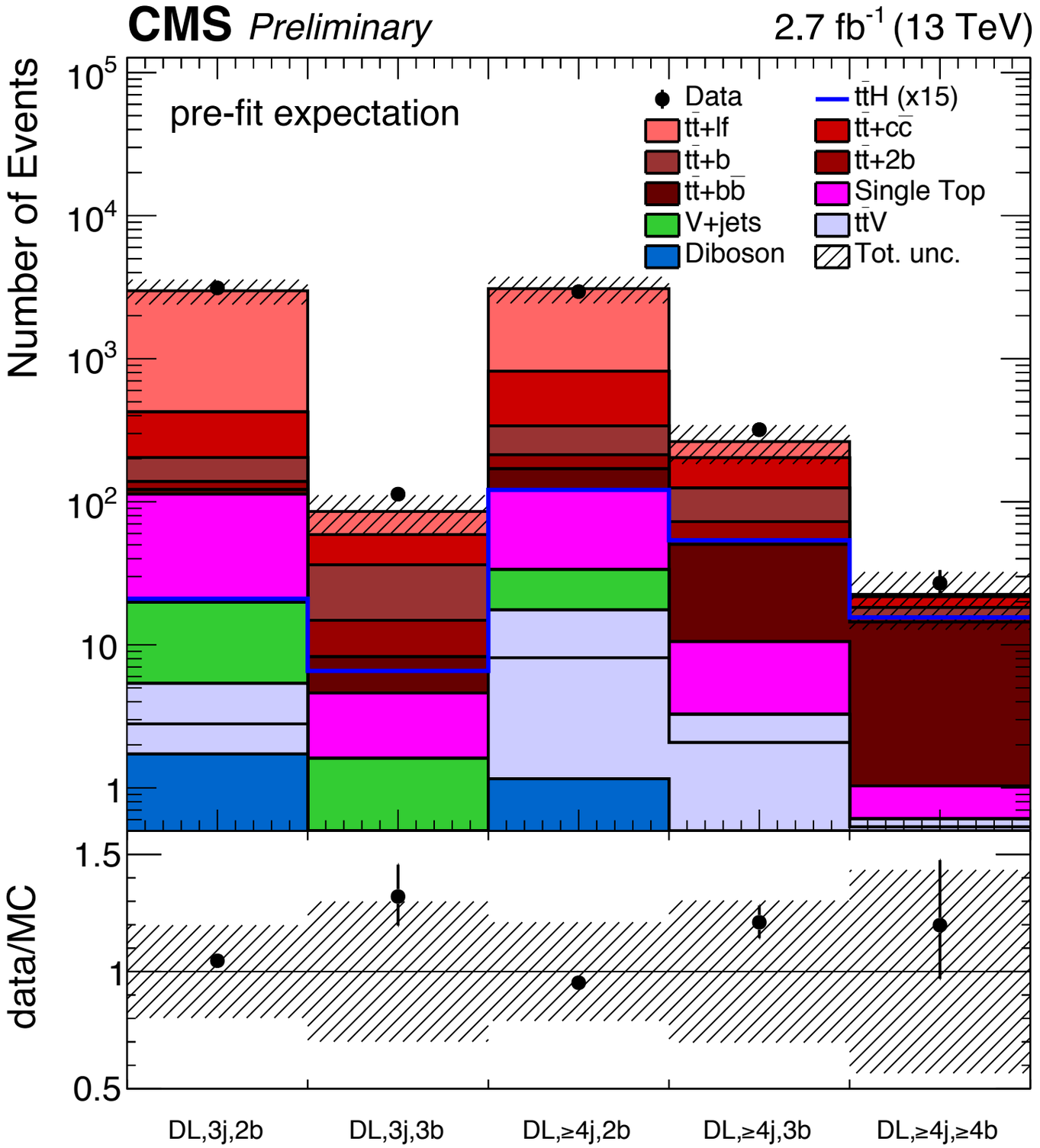
prefit yields

dilepton channel

- **5 categories**: 3j2t, 3j 3t, 3j ≥4t, ≥4j 2t, ≥4j ≥4t

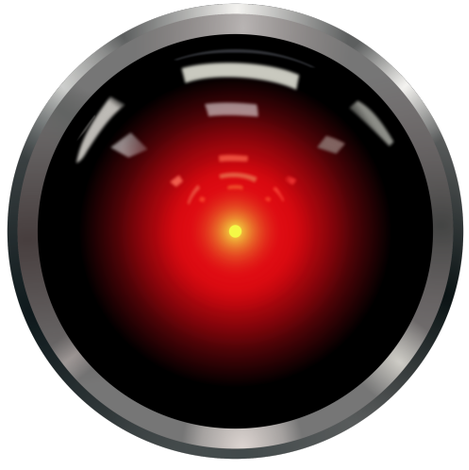
- Low data statistics (also MC), S/√B ~ 0.2 in best category

- Same approach for discriminators as in lepton+jets



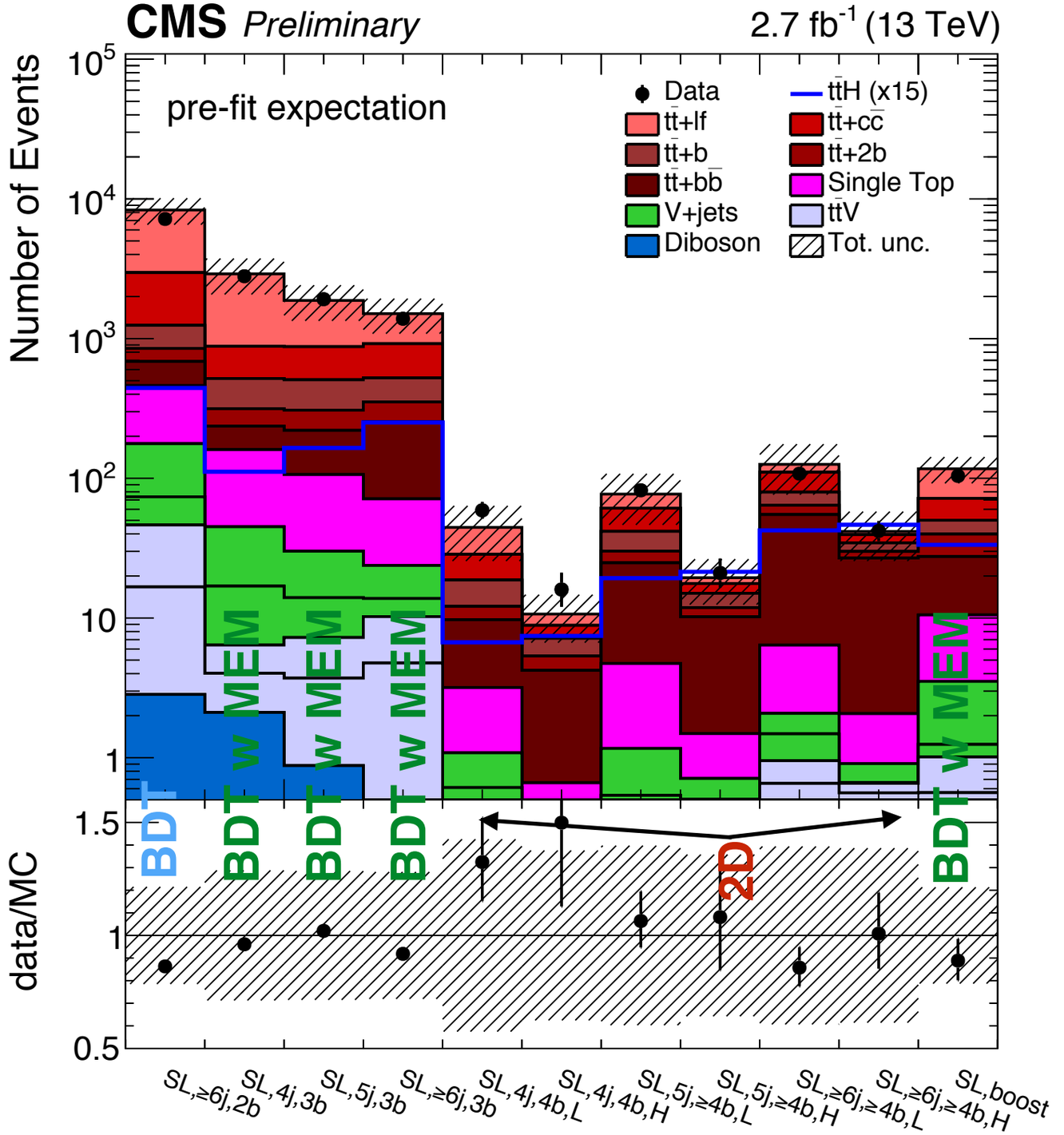
tt+H discrimination

- Purest category has 3.5% signal
- Need an MVA to separate out ttH(bb) from tt +bb
- **BDT** trained category-by-category to separate ttH(bb) from tt+jets: **need 500M+ fully simulated NLO events**
- **MEM@LO** using leptons and b-quark kinematics to separate ttH(bb) from tt+bb: **O(30) CPU-years to evaluate**



Combined discriminant

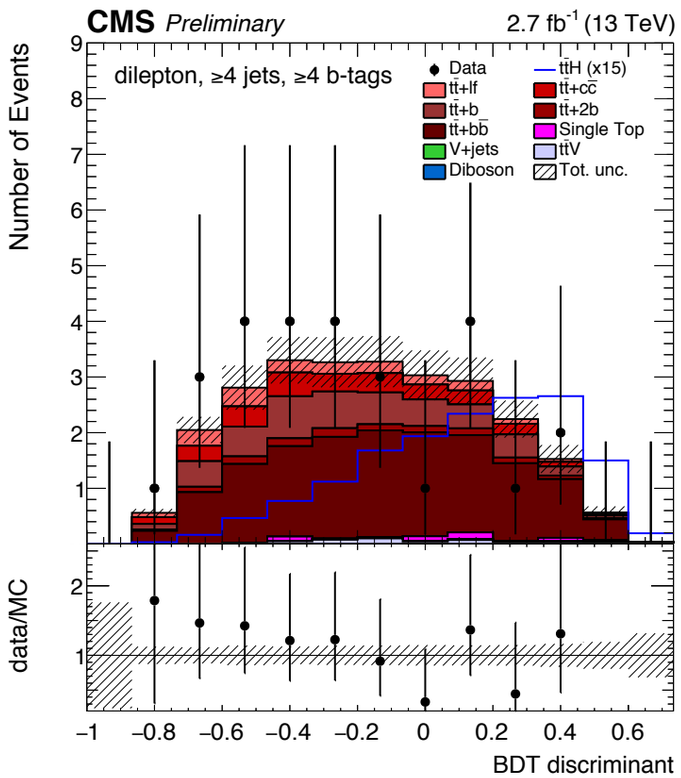
- Adopted combination scheme:
  - **BDT deployed in 2-tag events**: light flavour dominated, no MEM needed
  - **MEM included in BDT in 3-tag for events with high BLR**: can deploy both MEM & BDT, stats for training
  - **2D MEM vs. BDT in 4t:** low MC stats, but MEM applicable for all events
- Limit changes of ~5-10% expected from binning effects: statistical variability of the procedure
- Expected without combination (BDT only or MEM+BLR only) stand around 4.7… 5.0 depending on the used binning. **Combination improves noticeably!**

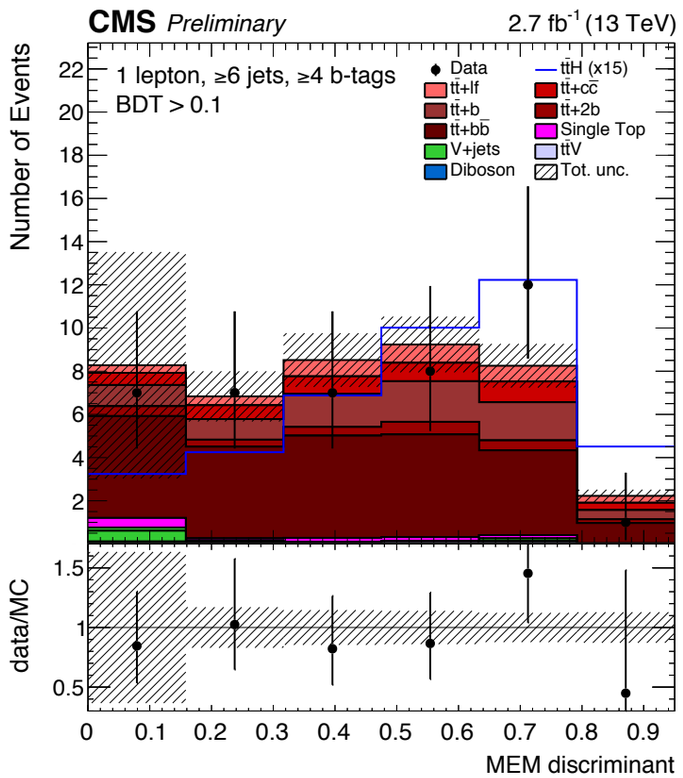


nota bene: MEM-only analysis possible but ~20% less sensitive

Limit procedure

- Fit the signal and background scale factors across all categories simultaneously
- Systematic uncertainties, MC stats as nuisance parameters, correlated between all categories as appropriate
- Quote median expected limit on $\mu=\sigma/\sigma_{SM}$ @ 95% CL





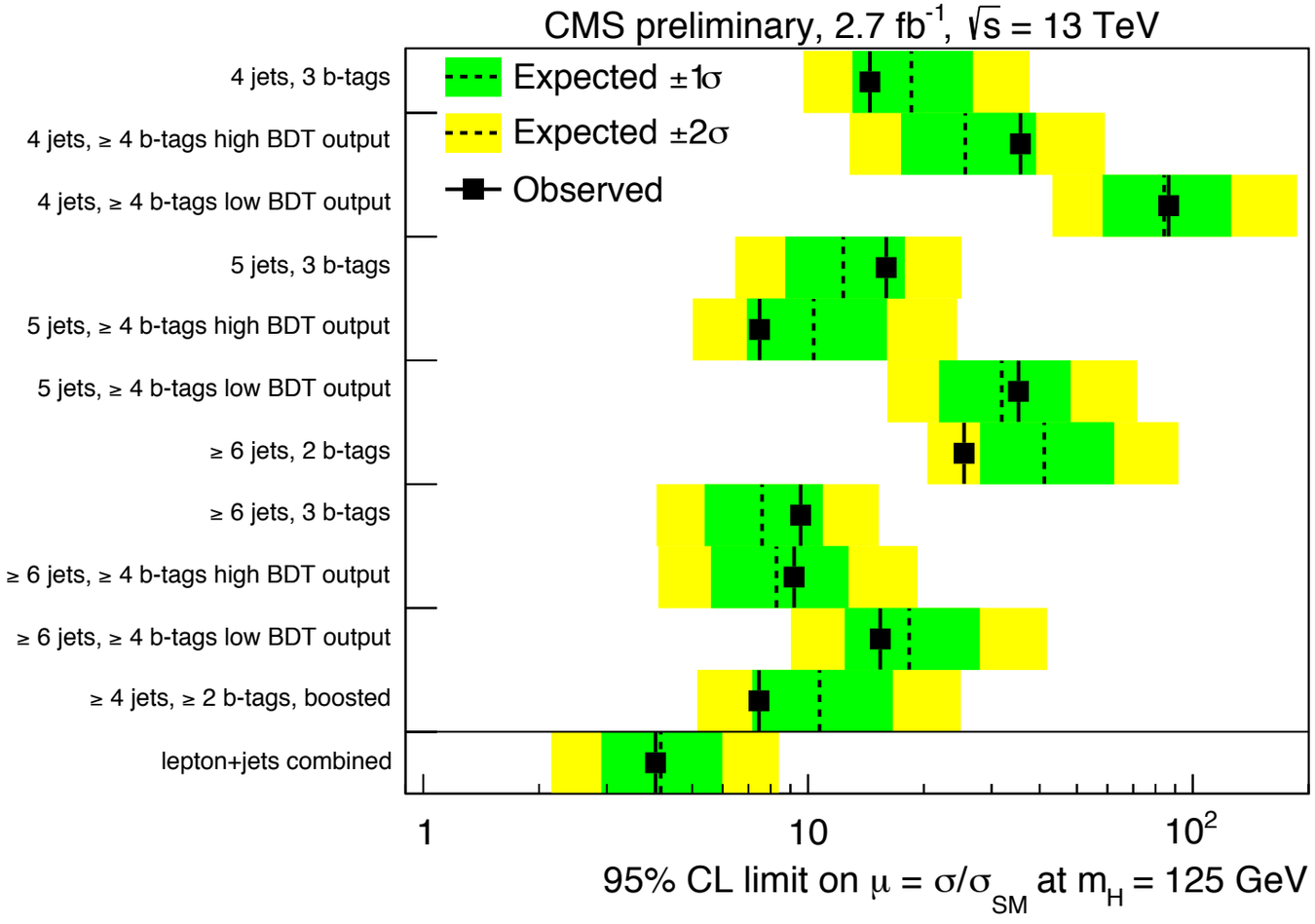
Systematic uncertainties

- b-tagger shape calibration
- rate and shape of tt+jets components (QCD scale)
  - 50% uncorrelated priors on tt+heavy
  - 30% on tt+light
- Rate of ttH from QCD scale
- jet energy scale, resolution (changes acceptance)

Limits

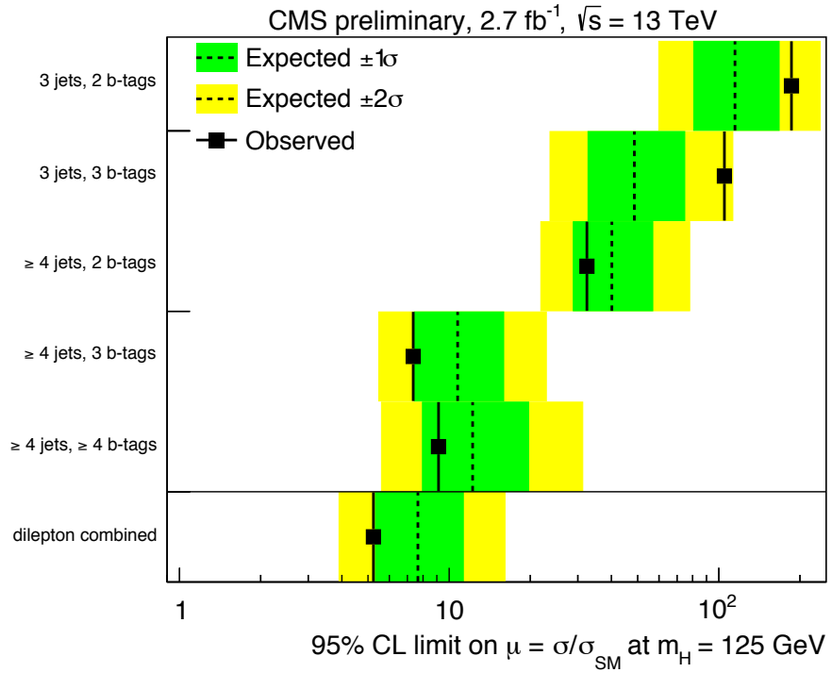
lepton+jets

Category	Observed	Expected
4 jets, 3 b-tags	14.5	$18.6^{+8.2}_{-5.5}$
4 jets, $\geq$ 4 b-tags high BDT output	35.7	$25.6^{+13.4}_{-8.1}$
4 jets, $\geq$ 4 b-tags low BDT output	86.6	$84.2^{+41.3}_{-25.8}$
5 jets, 3 b-tags	16.0	$12.3^{+5.5}_{-3.6}$
5 jets, $\geq$ 4 b-tags high BDT output	7.5	$10.3^{+5.6}_{-3.4}$
5 jets, $\geq$ 4 b-tags low BDT output	35.2	$31.9^{+16.1}_{-9.9}$
$\geq$ 6 jets, 2 b-tags	25.4	$41.1^{+21.1}_{-13.1}$
$\geq$ 6 jets, 3 b-tags	9.6	$7.6^{+3.3}_{-2.2}$
$\geq$ 6 jets, $\geq$ 4 b-tags high BDT output	9.2	$8.3^{+4.4}_{-2.7}$
$\geq$ 6 jets, $\geq$ 4 b-tags low BDT output	15.4	$18.3^{+9.6}_{-5.8}$
$\geq$ 4 jets, $\geq$ 2 b-tags, boosted	7.5	$10.7^{+5.9}_{-3.5}$
lepton+jets combined	4.0	$4.1^{+1.8}_{-1.2}$

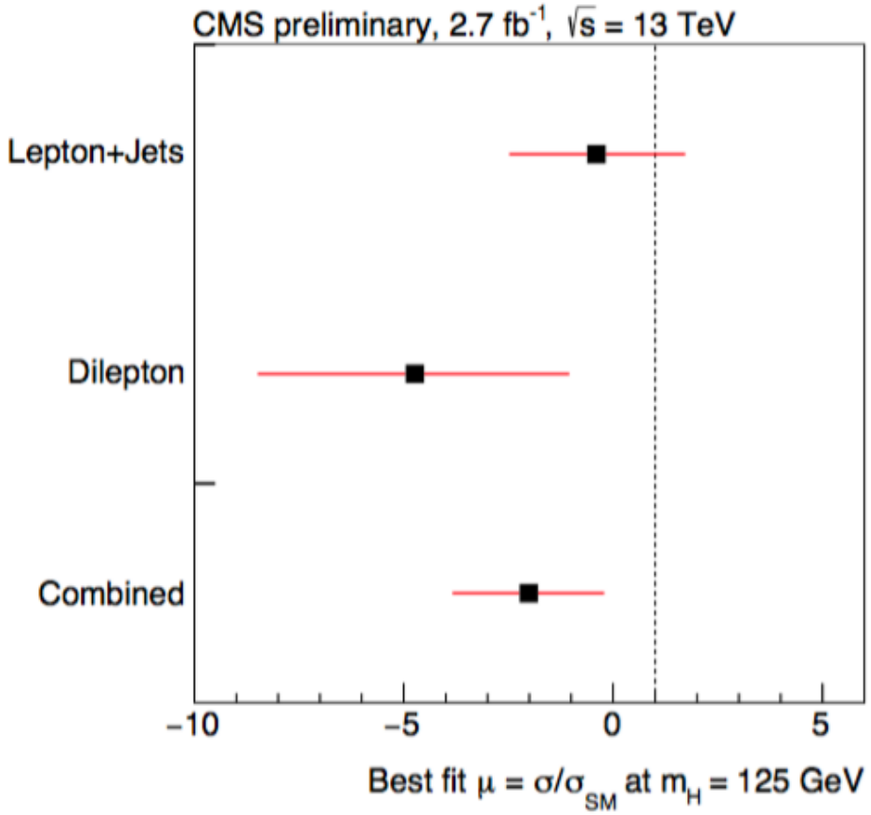


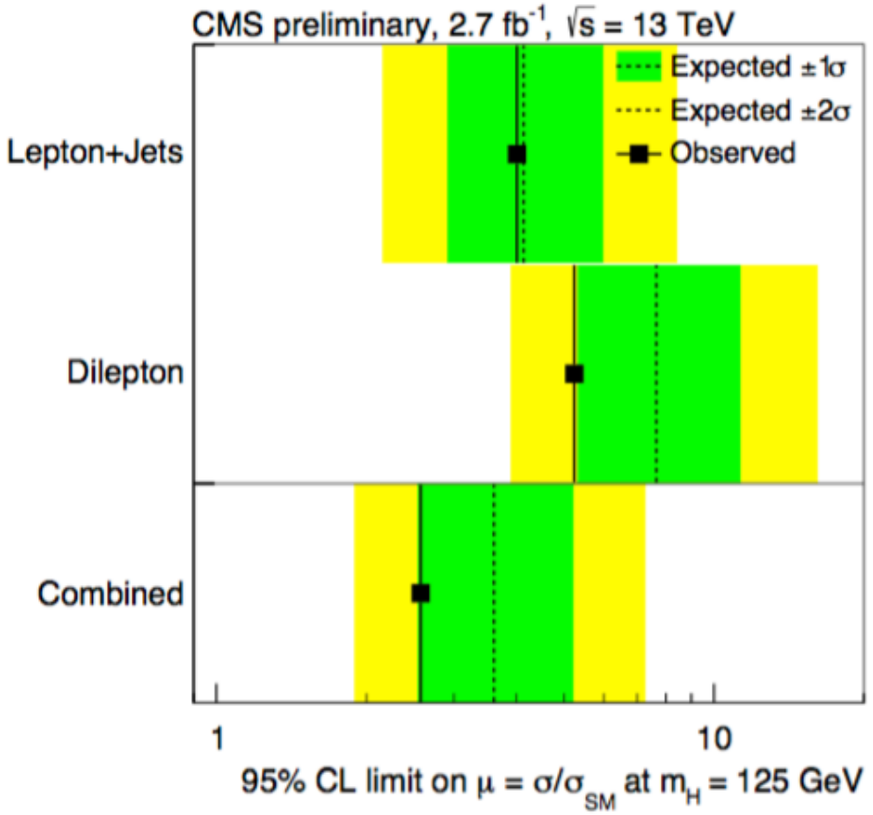
di-lepton

Category	Observed	Expected
3 jets, 2 b-tags	186.0	$114.8^{+52.6}_{-34.1}$
$\geq$ 3 jets, 3 b-tags	104.9	$48.6^{+26.2}_{-15.9}$
$\geq$ 4 jets, 2 b-tags	32.4	$40.1^{+16.8}_{-11.3}$
$\geq$ 4 jets, 3 b-tags	7.4	$10.8^{+5.2}_{-3.3}$
$\geq$ 4 jets, $\geq$ 4 b-tags	9.1	$12.2^{+7.5}_{-4.3}$
dilepton combined	5.2	$7.7^{+3.6}_{-2.3}$



Combined limits





Channel	Best-fit μ	Observed UL	Expected UL
Lepton+jets	$-0.4^{+1.0}_{-1.0}(\text{stat})^{+1.9}_{-1.9}(\text{syst})$	4.0	$4.1^{+1.8}_{-1.2}$
Dilepton	$-4.7^{+2.1}_{-1.9}(\text{stat})^{+3.0}_{-3.3}(\text{syst})$	5.2	$7.7^{+3.6}_{-2.3}$
Combined	$-2.0^{+0.9}_{-0.8}(\text{stat})^{+1.6}_{-1.6}(\text{syst})$	2.6	$3.6^{+1.6}_{-1.1}$

Summary

- **First results on ttH(bb) with 13 TeV data**

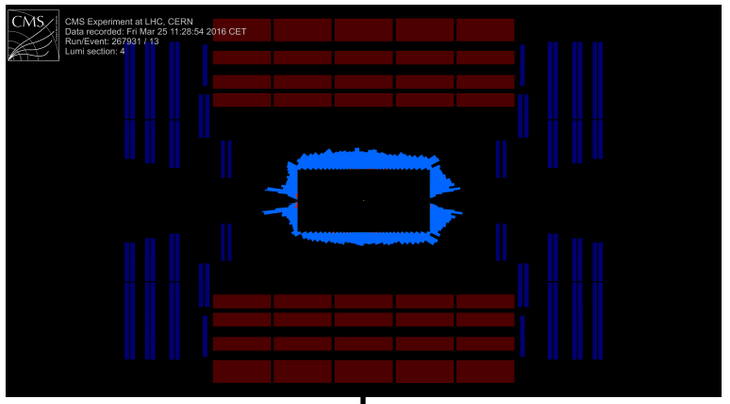
- Build on existing run I analyses, combining several techniques:

  - improved tt+bb discrimination, MEM deployed on additional expensive final states, BDT optimized

  - MEM+BDT combination methods explored

  - set up first boosted analysis

- Ready for 2016 data taking with 30/fb expected



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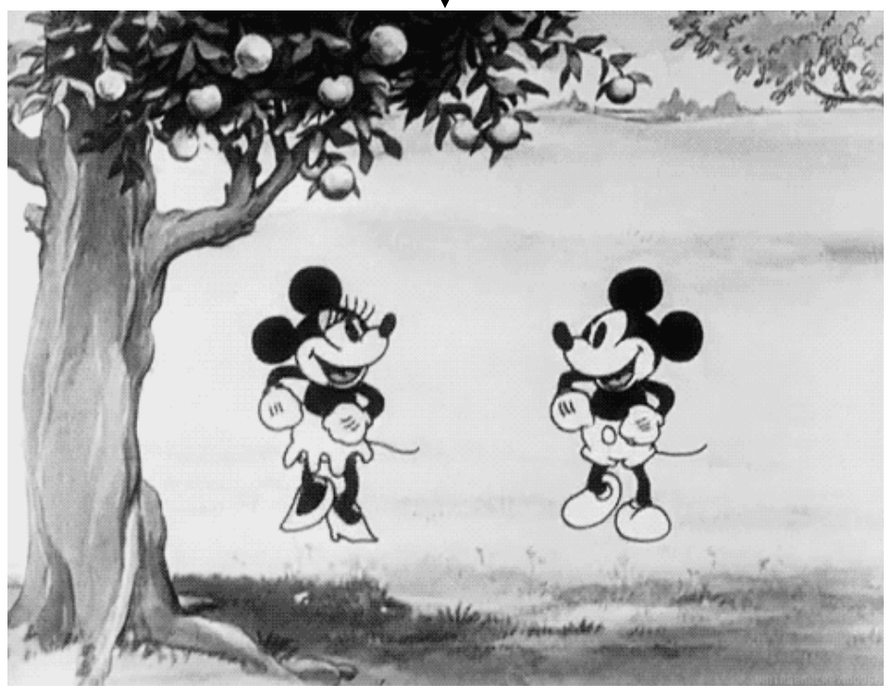


Many thanks to the organizers for a wonderful conference!

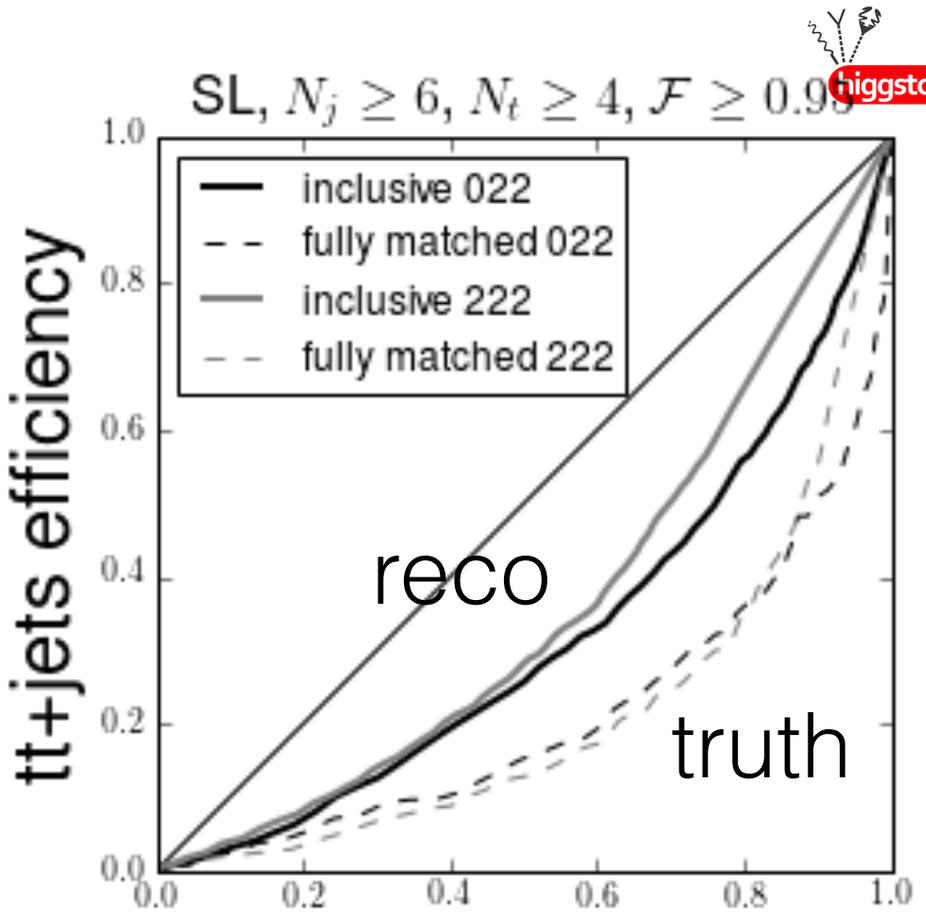
Bonus slides

ETH Institute for Particle Physics

MEM

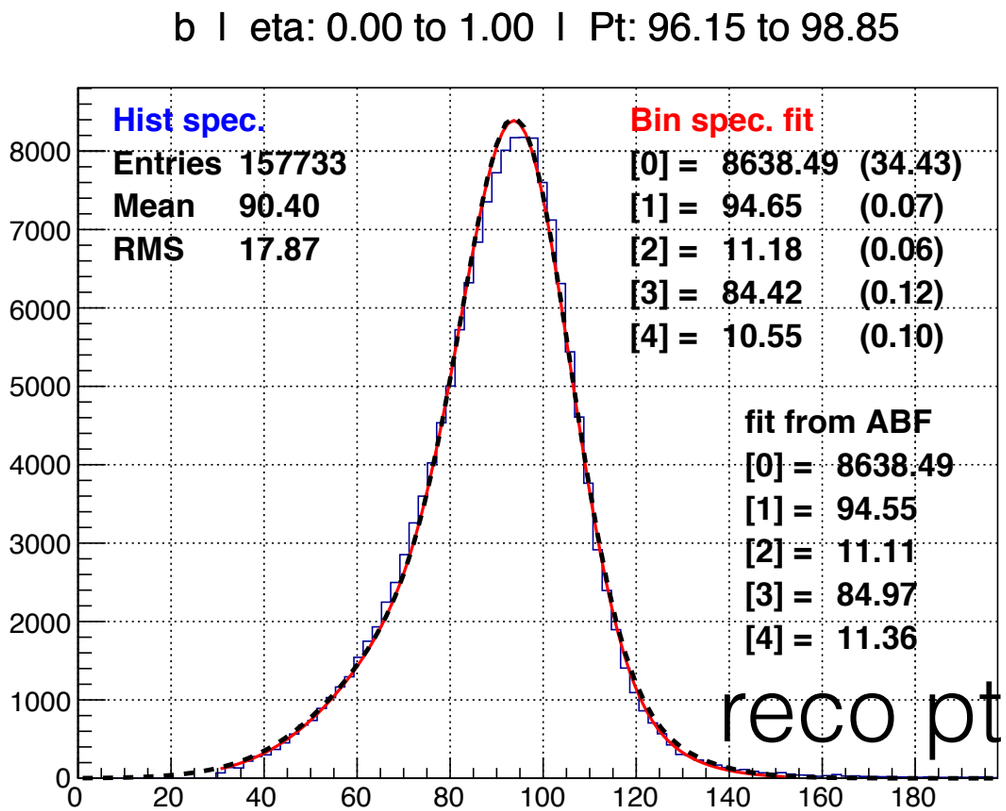
$$P_{\mathrm{s/b}} = \frac{w(\vec{y}|\mathrm{t\bar{t}H})}{w(\vec{y}|\mathrm{t\bar{t}H}) + k_{\mathrm{s/b}} w(\vec{y}|\mathrm{t\bar{t}+b\bar{b}})}$$

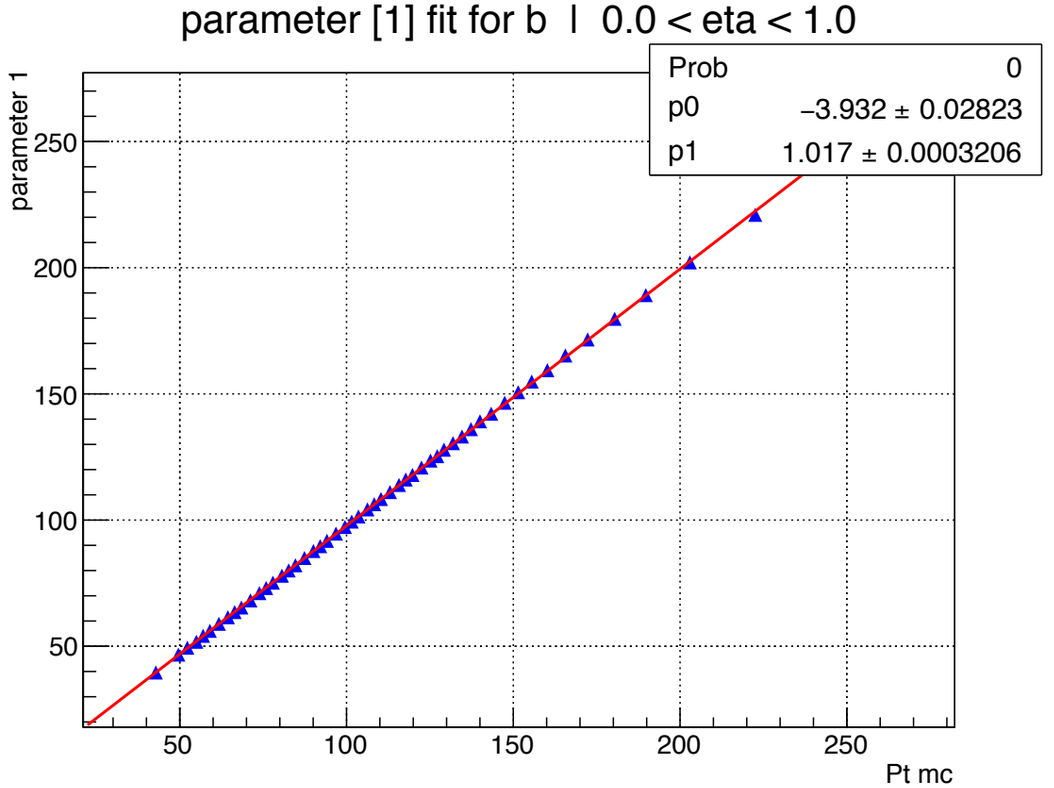
- Based on Run I approach, new validated code
- event interpretation × detector description
- Uses LO hard scattering from OpenLoops, gluon fusion only
- consider only b-quarks, integrate over light quarks
- Unresolved events from incompatible kinematics, resolve with BDT



Transfer functions

- Derived from ttH(bb) simulation
- double-gaussian fit in bins of generated pt, parameter dependence on pt polynomial





$$F(p_T|p_{T,\text{gen}}) = p_0\left[0.7\exp\left(\frac{p_T - p_1}{p_2}\right)^2 + 0.3\exp\left(\frac{p_T - p_3}{p_2 + p_4}\right)^2\right]$$

BDT base variables (SL)

- **Inputs:** O(30) baseline + 8 (boosted) + 2 (MEM, BLR) variables, optimized from Run I
- **Object and event kinematics:** pt of 4 hardest jets, sum of all jet transverse momenta and energies, MET, invariant mass of jet+lepton+MET, M3 (inv. mass of 3 hardest jets)
- **angular:** mean, min ΔR; mean η of (b-tagged) jets, ΔR(lep, closest jet), inv. mass of two closest (ΔR) b-tagged jets, inv. mass of b-tagged jets closest to 125 GeV
- **event shape:** Fox-Wolfram moments 0-3
- **best Higgs mass, geom. mean of top-higgs rapidity differences:** χ2-based reco of leptonic & hadronic top, Higgs in 6j4t events
- In case of 5 jets, promote highest jet with pt>20, similarly in 3t, promote jet with 4th highest CSV

Table 8: BDT input variable assignment per category in the lepton+jets channel.

≥ 4 jets, ≥ 2 b-tags boosted	4 jets, 3 b-tags	4 jets, ≥ 4 b-tags
avg ΔR(tag,tag) τ_2/τ_1 of Higgs cand. third-highest CSV fourth-highest CSV $\Delta\eta$(top,Higgs) aplanarity m(Higgs, di-filterjet) min ΔR(tag,tag) avg CSV (all) MEM discriminator (using subjets) b-tagging likelihood ratio	H_1 b-tagging likelihood ratio $\sum p_T$(jets,leptons,MET) MEM discriminator avg CSV (tags) avg CSV (all) jet 2 p_T jet 4 p_T	closest tagged dijet mass b-tagging likelihood ratio $\sum p_T$(jets,lepton,MET) avg ΔR(tag,tag) H_3 jet 1 p_T
	5 jets, 3 b-tags	5 jets, ≥ 4 b-tags
	MEM discriminator avg ΔR(tag,tag) min ΔR(lepton,jet) b-tagging likelihood ratio fourth-highest CSV H_1 dev from avg CSV (tags) avg $\Delta\eta$(jet,jet) avg CSV (tags) avg CSV (all) max $\Delta\lvert\eta\rvert$ (tag, avg jet $\lvert\eta\rvert$)	b-tagging likelihood ratio jet 3 p_T tagged dijet mass closest to 125 avg $\Delta\eta$(jet,jet) avg ΔR(tag,tag) H_1 fifth-highest CSV $(\Sigma$ jet $p_T)/(\Sigma$ jet E)
≥ 6 jets, 2 tags	≥ 6 jets, 3 tags	≥ 6 jets, ≥ 4 tags
avg $\Delta\eta$(tag,tag) avg ΔR(tag,tag) ΔR(jet1, jet2) b-tagging likelihood ratio max $\Delta\lvert\eta\rvert$ (tag, avg tags $\lvert\eta\rvert$) third-highest CSV sphericity fourth-highest CSV max $\Delta\lvert\eta\rvert$ (tag, avg jet $\lvert\eta\rvert$) min ΔR(tag,tag)	b-tagging likelihood ratio $\sqrt{\Delta\eta(t^{lep}, bb) \times \Delta\eta(t^{had}, bb)}$ HT MEM discriminator $\sum p_T$(jets,lepton,MET) H_1 fourth-highest CSV avg CSV (tags) max $\Delta\lvert\eta\rvert$ (tag, avg jet $\lvert\eta\rvert$)	$\sum p_T$(jets,leptons,MET) H_3 best Higgs mass b-tagging likelihood ratio tagged dijet mass closest to 125 fifth-highest CSV $(\Sigma$ jet $p_T)/(\Sigma$ jet E) jet 4 p_T sphericity max $\Delta\lvert\eta\rvert$ (tag, avg tag $\lvert\eta\rvert$) second-highest CSV

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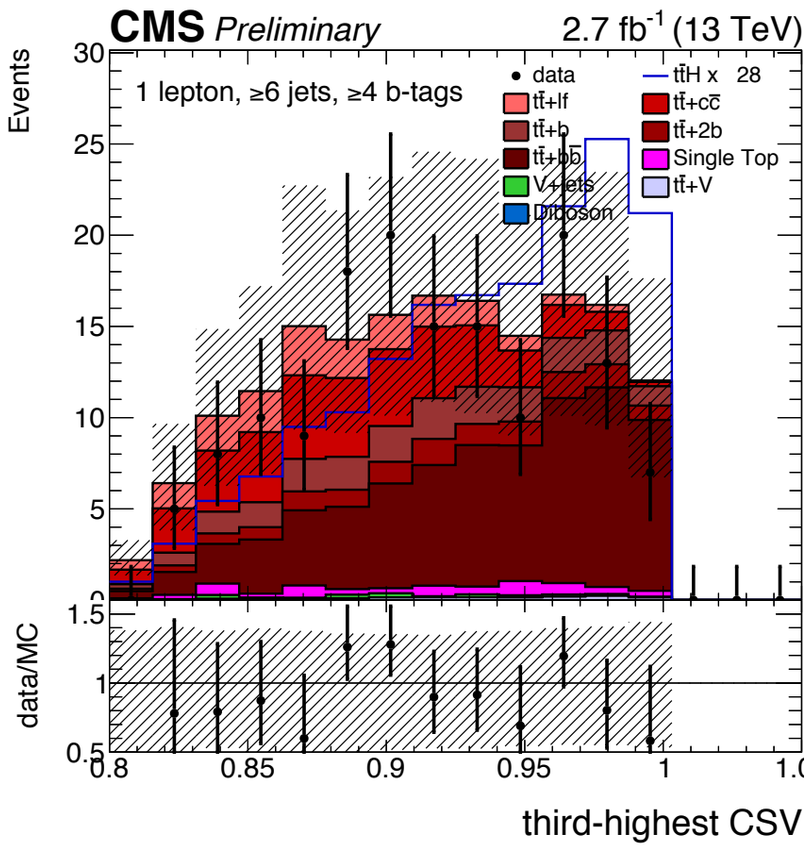
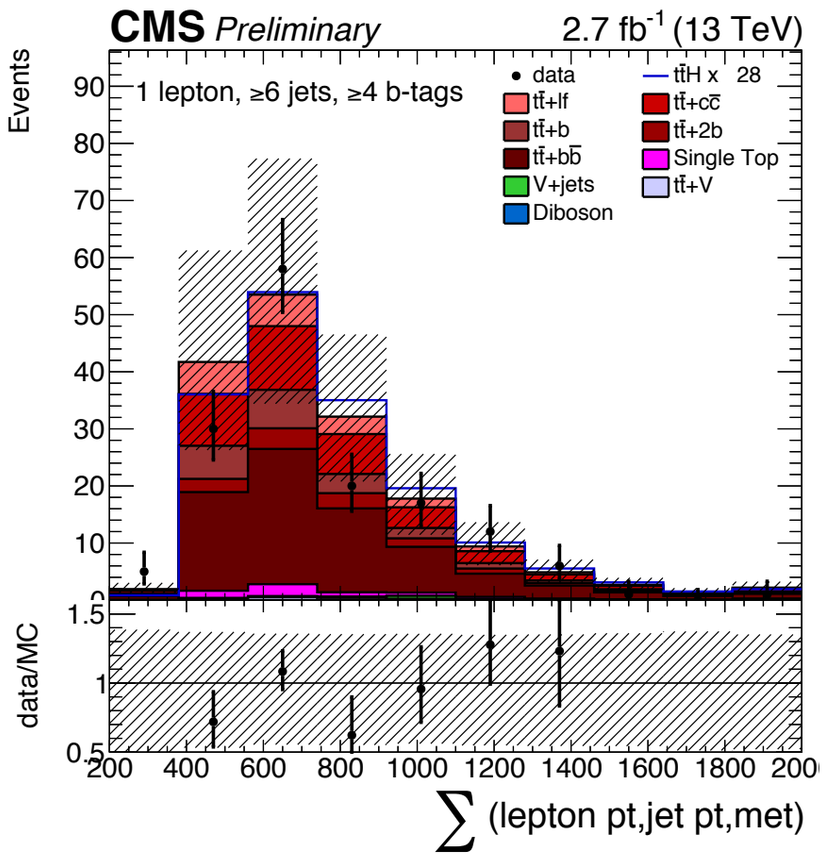
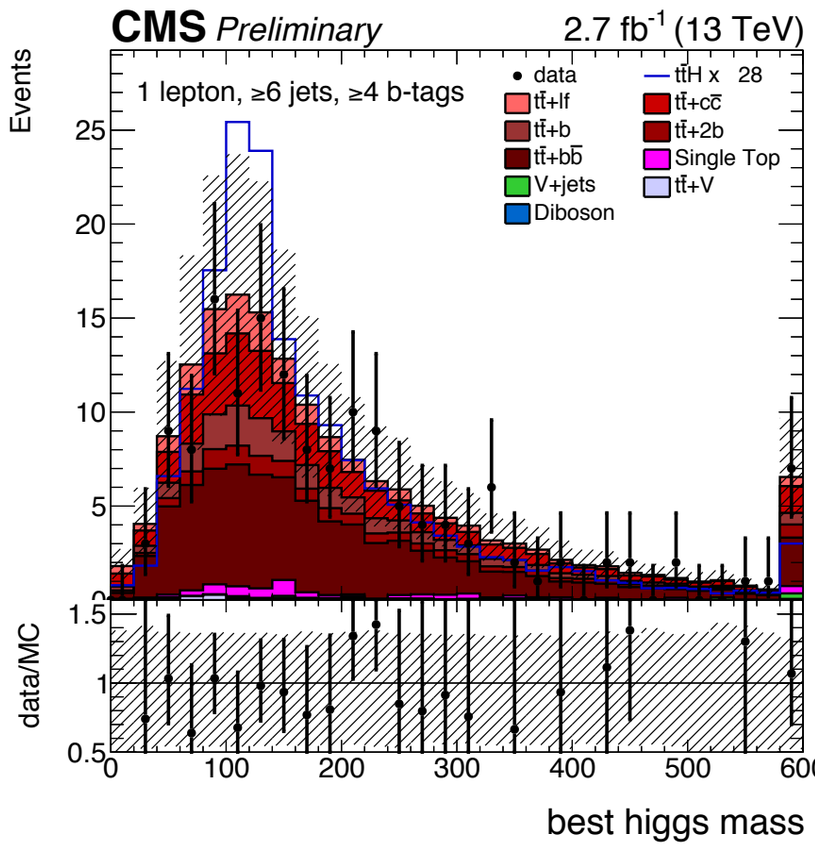
higgstools

BDT variables in 6j4t







- Example BDT input variables in the SL channel

Dilepton BDT

- O(20) variables

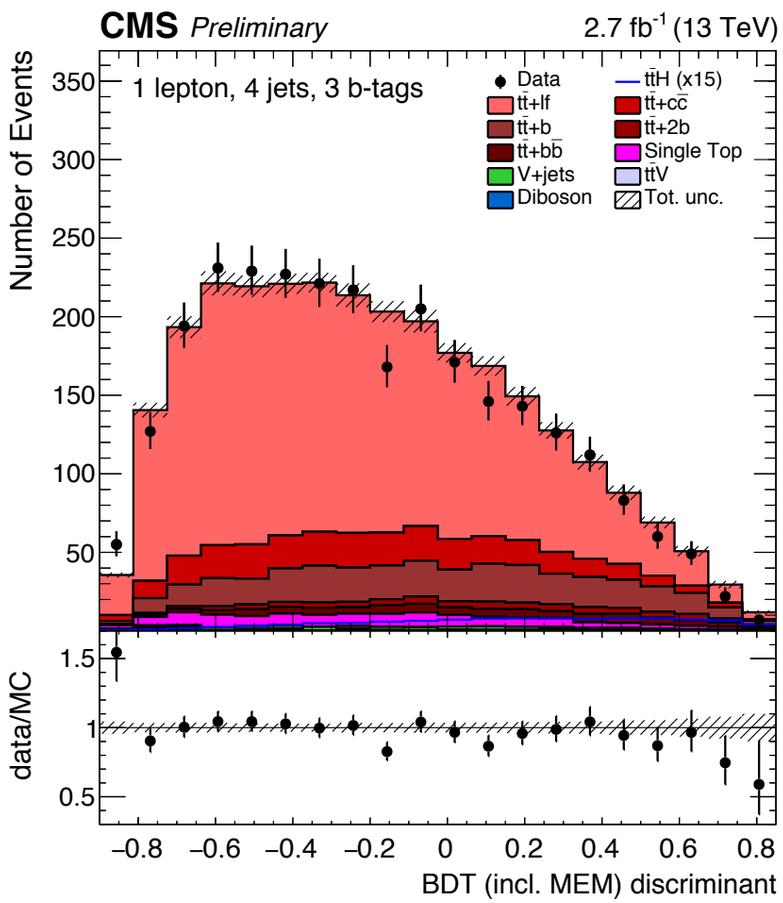
- **Object and event kinematics:** sum pt(jets, leptons), centrality(b-tags), inv. mass of jet pair closest to 125 GeV, mass, sum pt of closest b-tag pair, median mass of all jet pairs, mass, sum pt(jet, tag) with min ΔR

- **angular:** mean ΔR of all b-tags; min ΔR(closest b-tags, jets), max Δη(furthest b-tags), twist angle

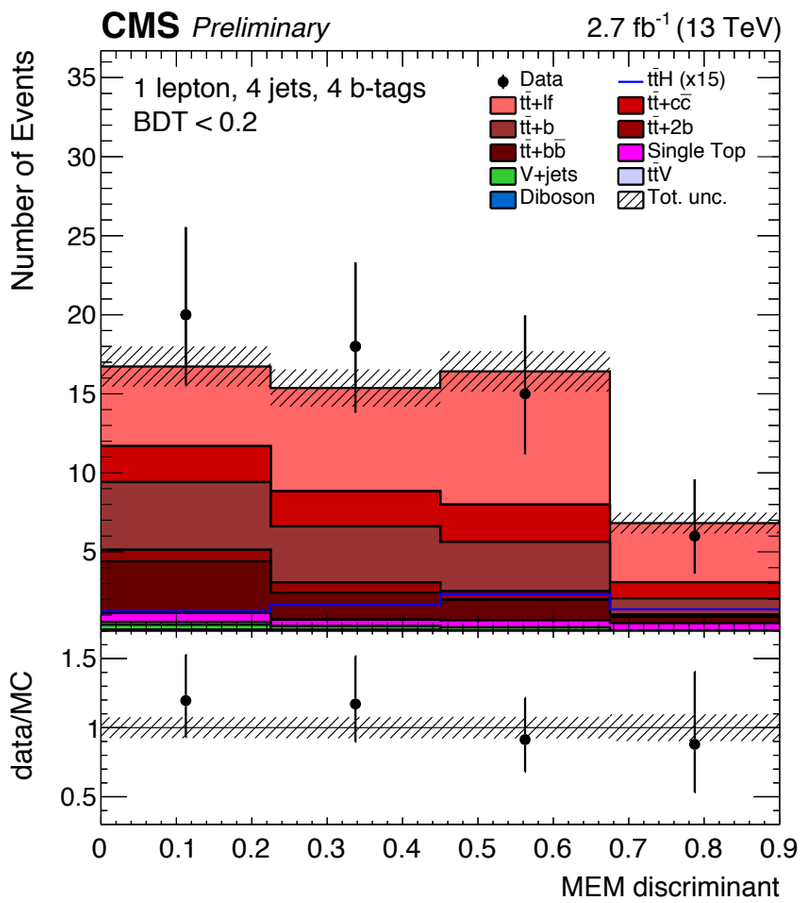
- **Event properties:** number of jets, average b-discriminant for (b-tagged) jets, Fox-Wolfram moments

lepton+jets categories

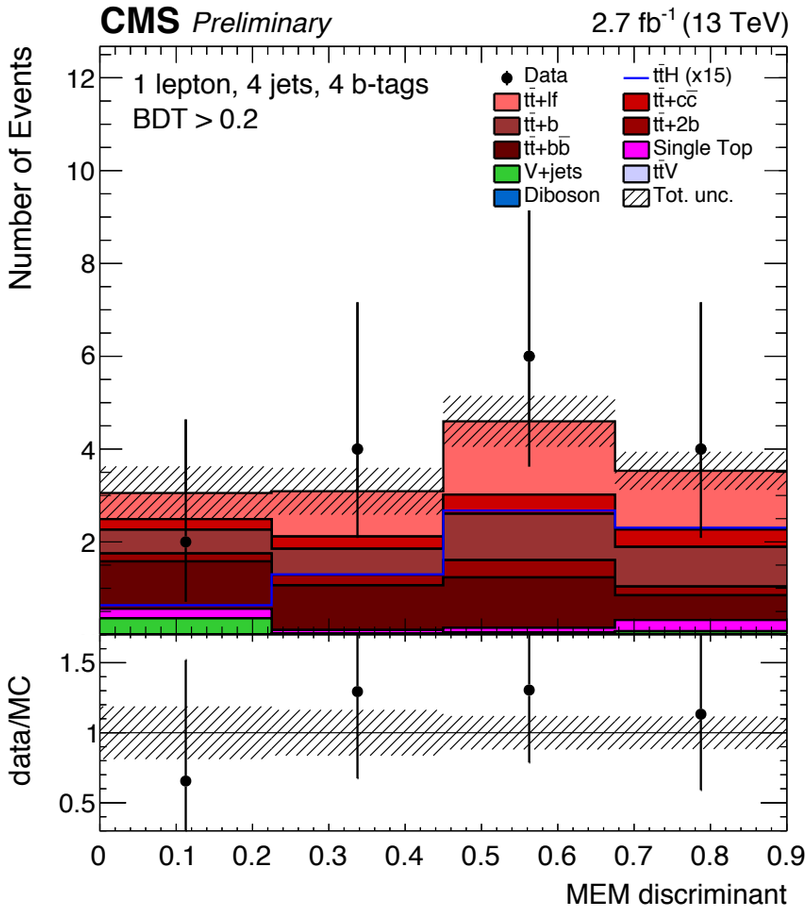
4j3t



4j4t BDT low

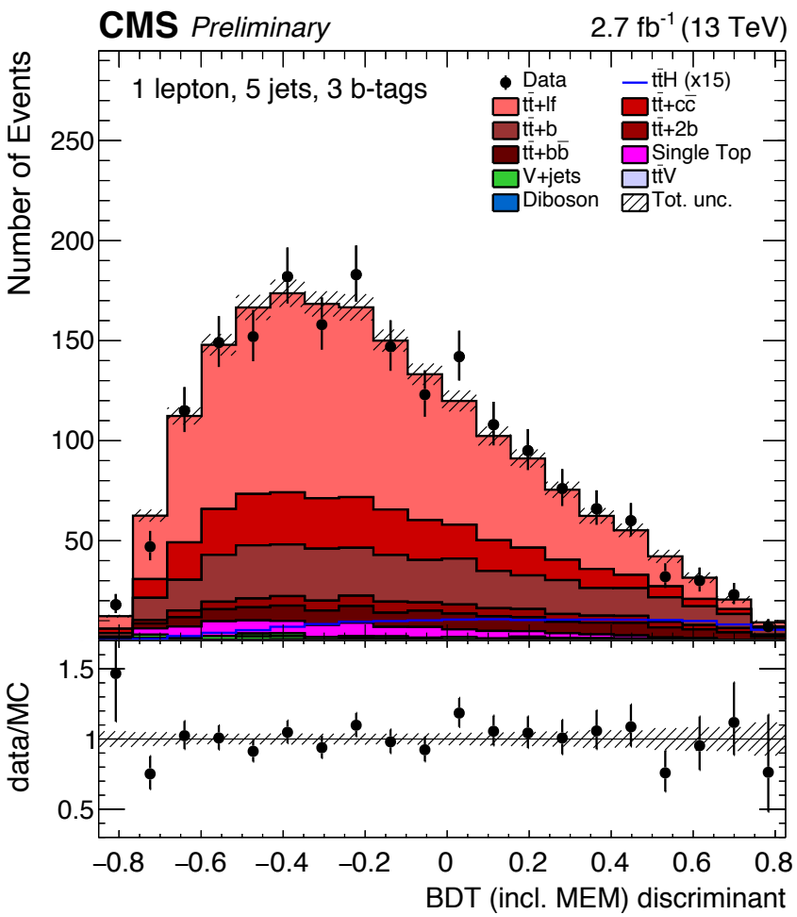


4j4t BDT high

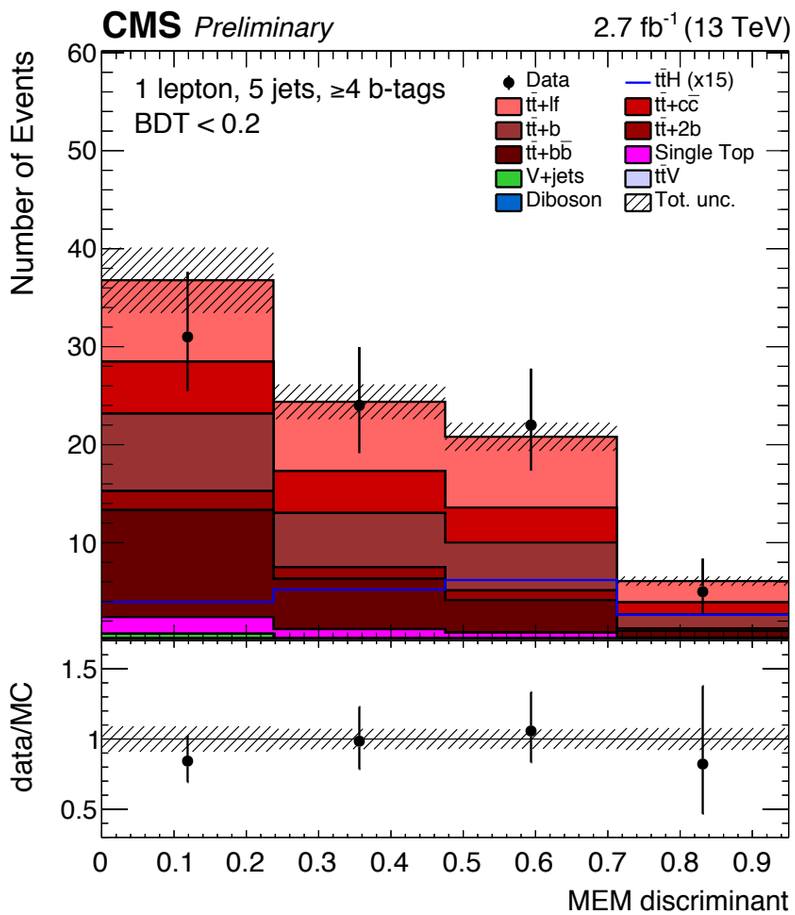


lepton+jets categories

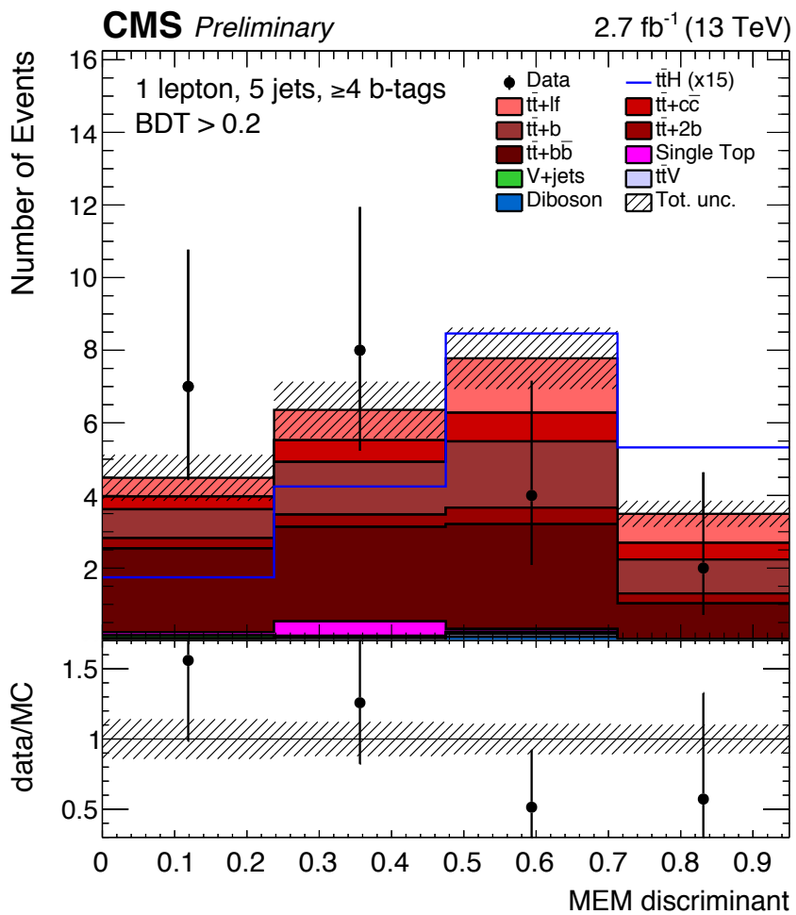
5j3t



5j4t BDT low

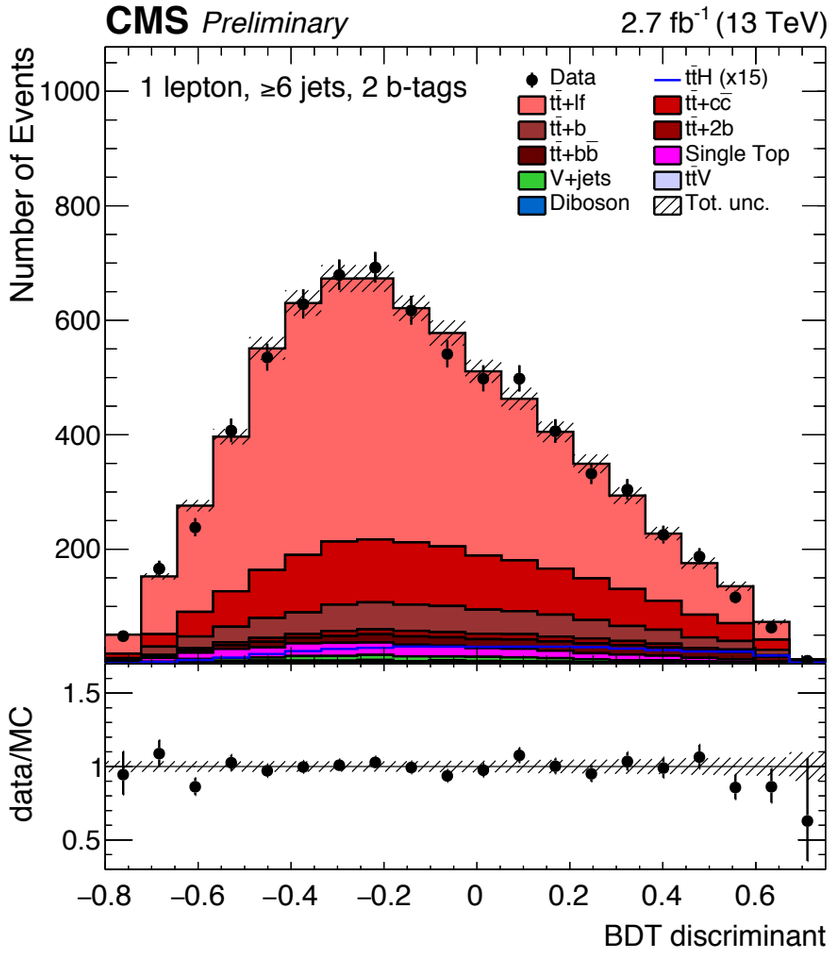


5j4t BDT high

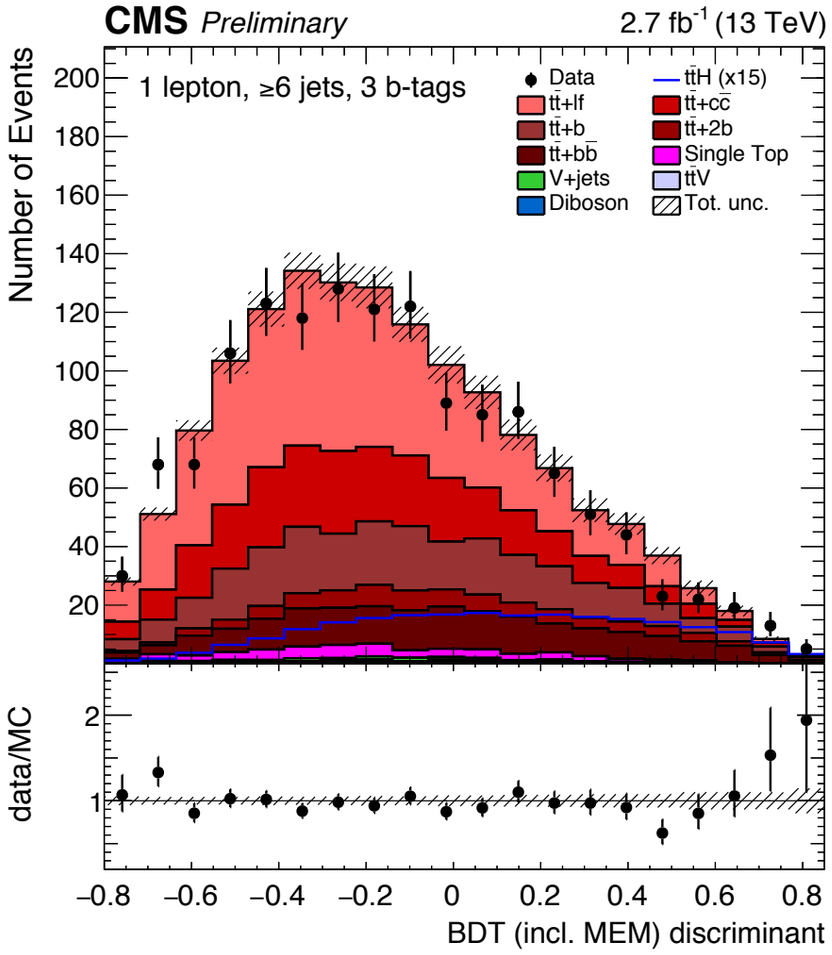


lepton+jets categories

6j2t BDT low

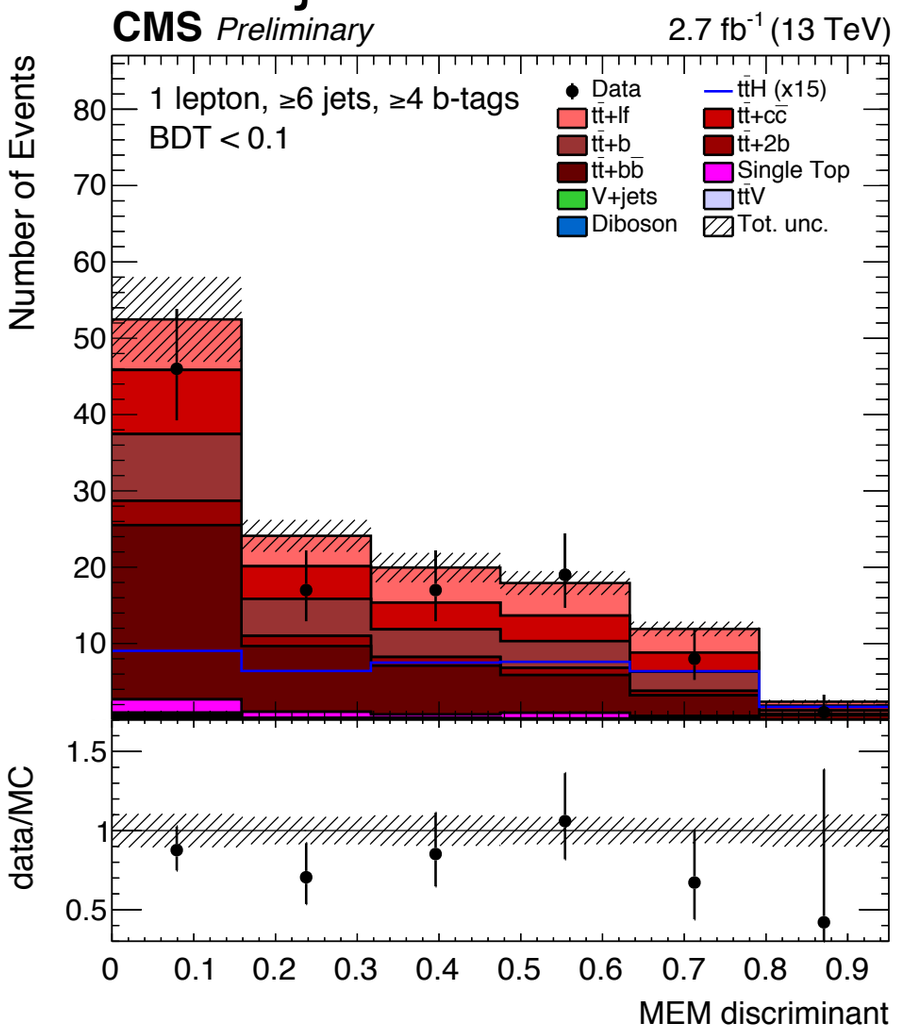


6j3t BDT high

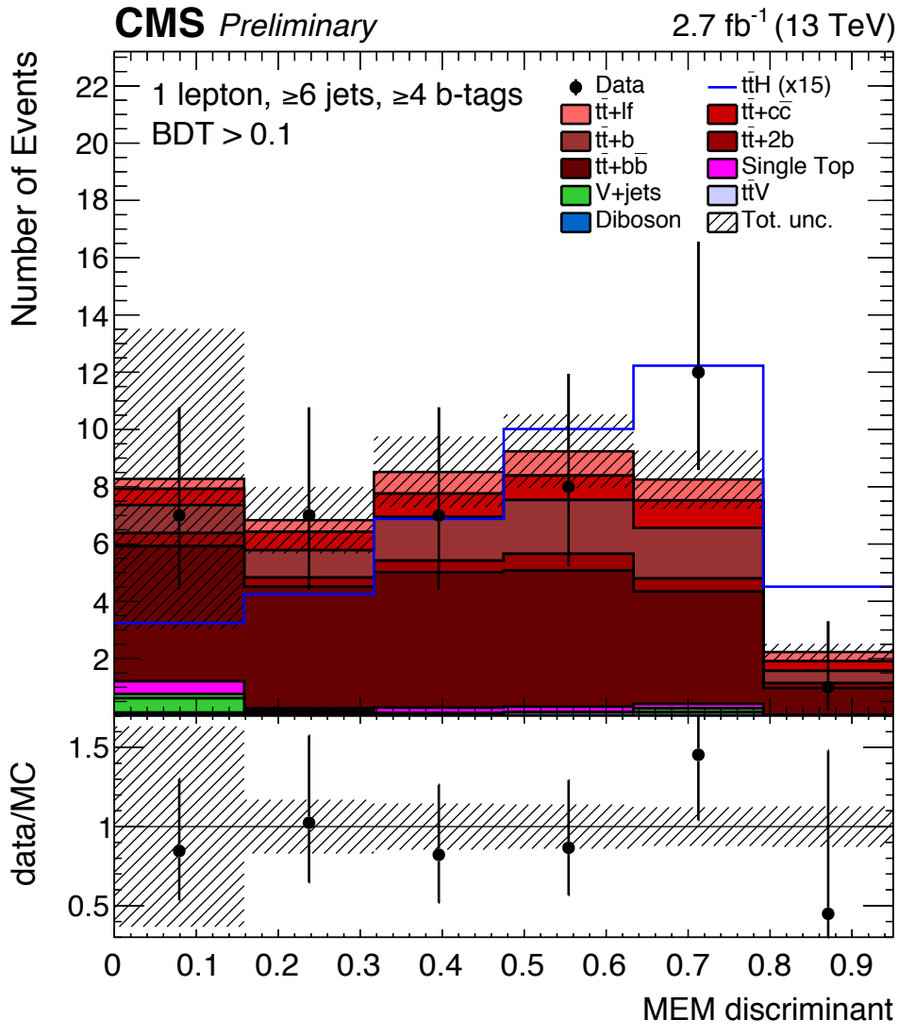


lepton+jets categories

6j4t BDT low



6j4t BDT high



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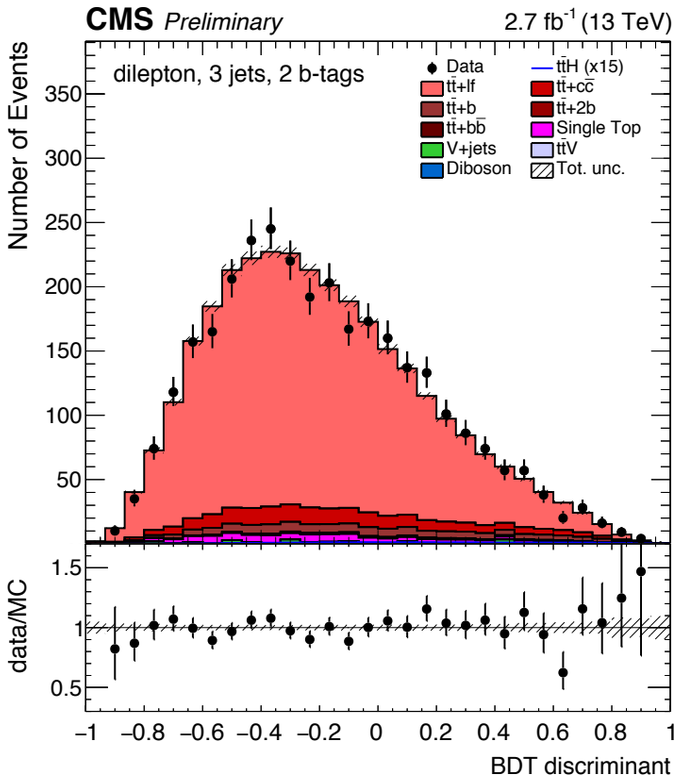
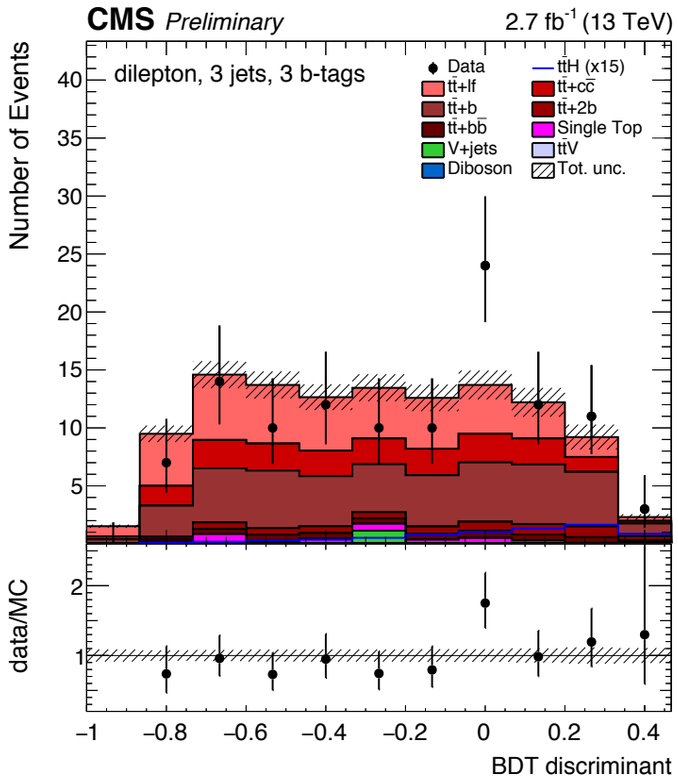
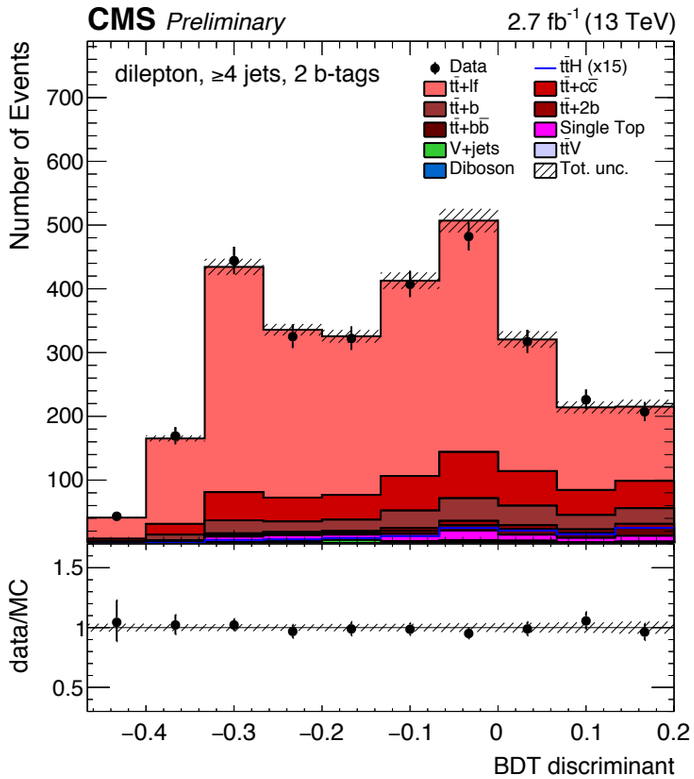
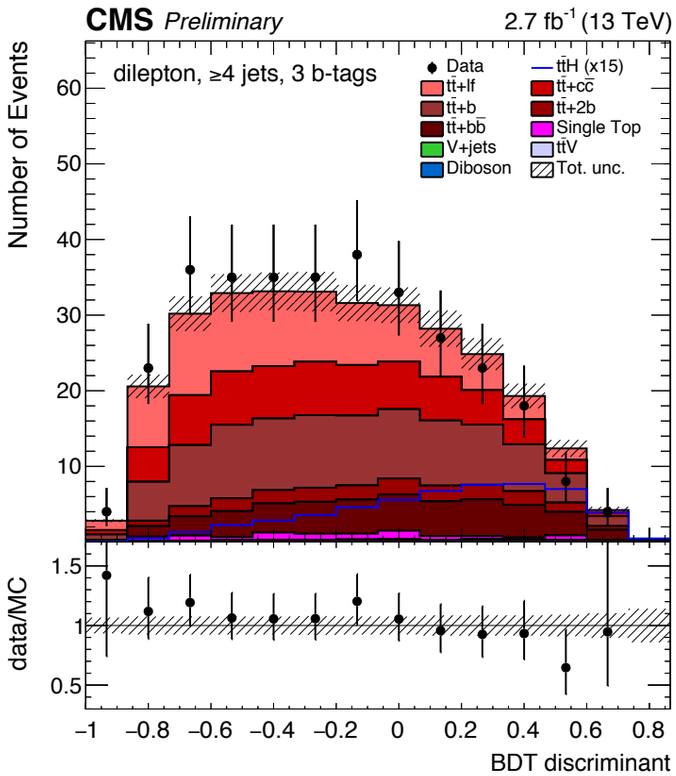
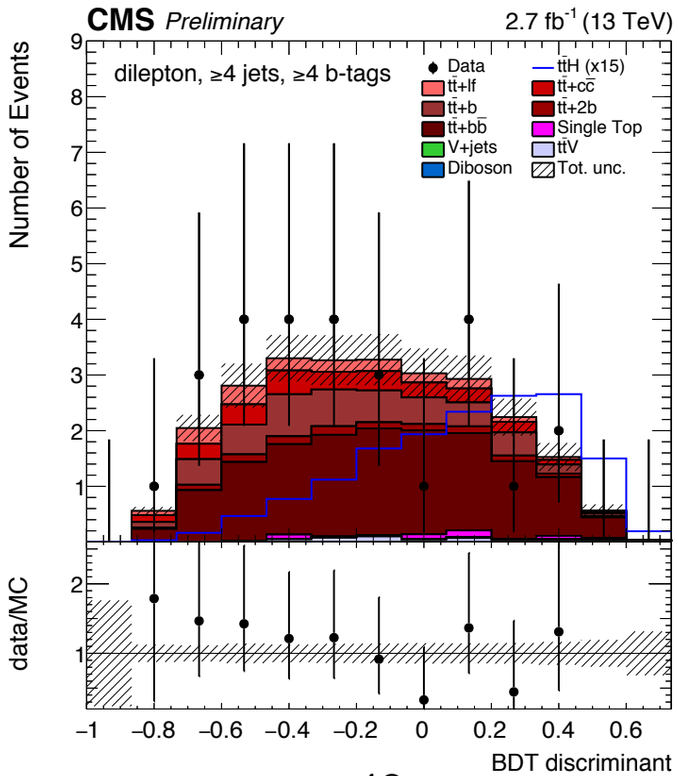
dilepton categories





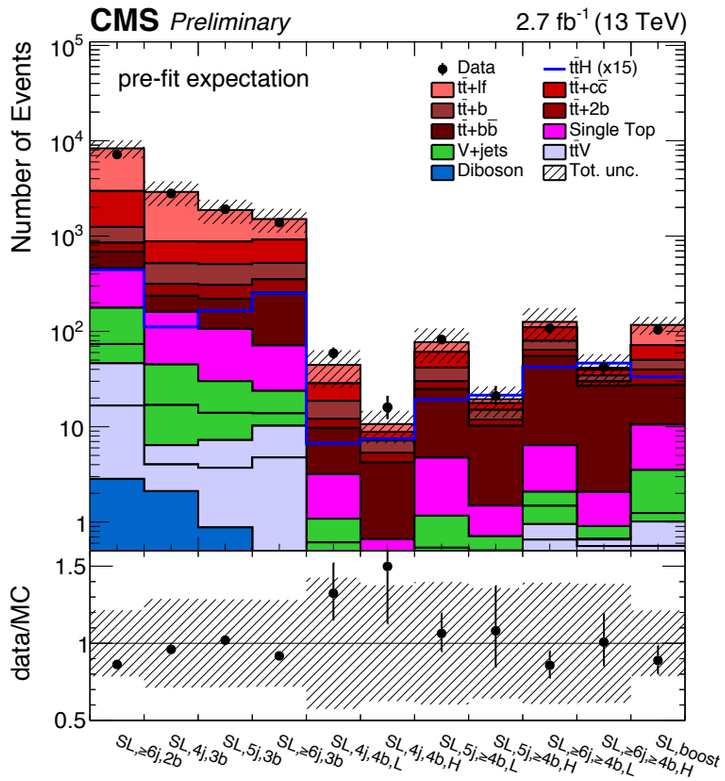


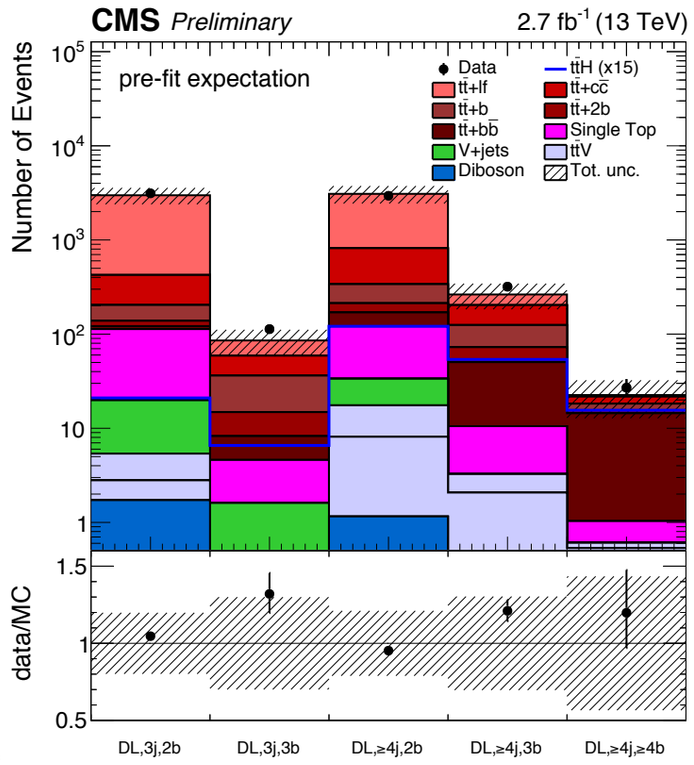




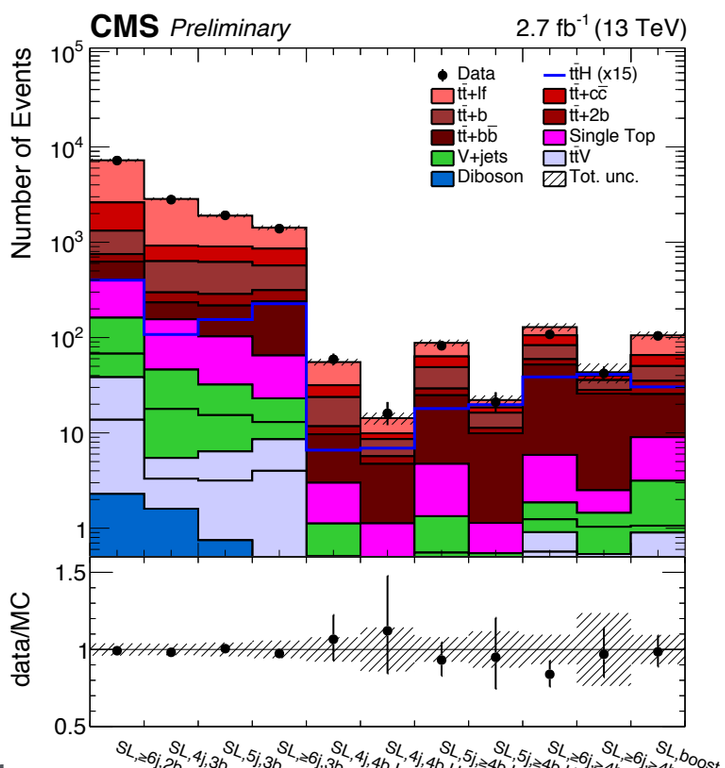
Pre-fit vs. post-fit yields

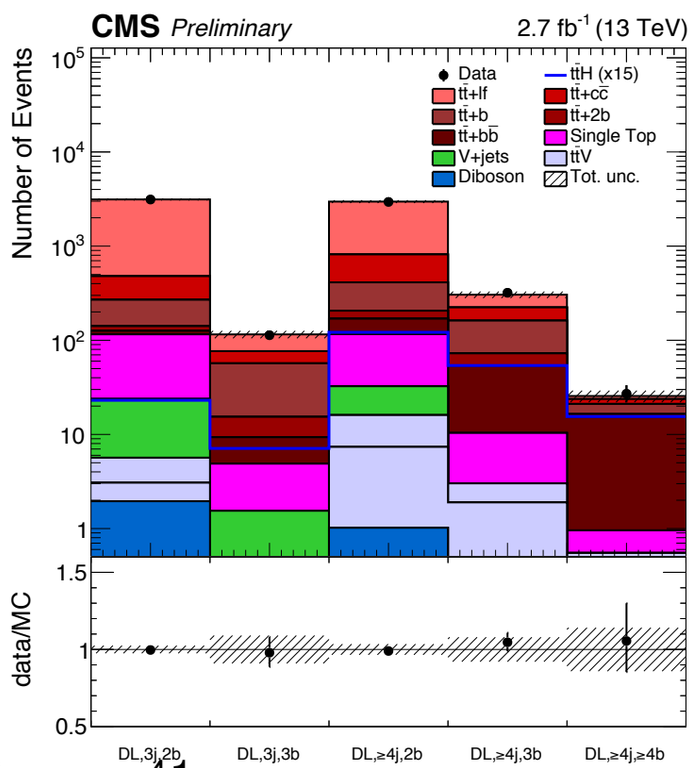
prefit





postfit

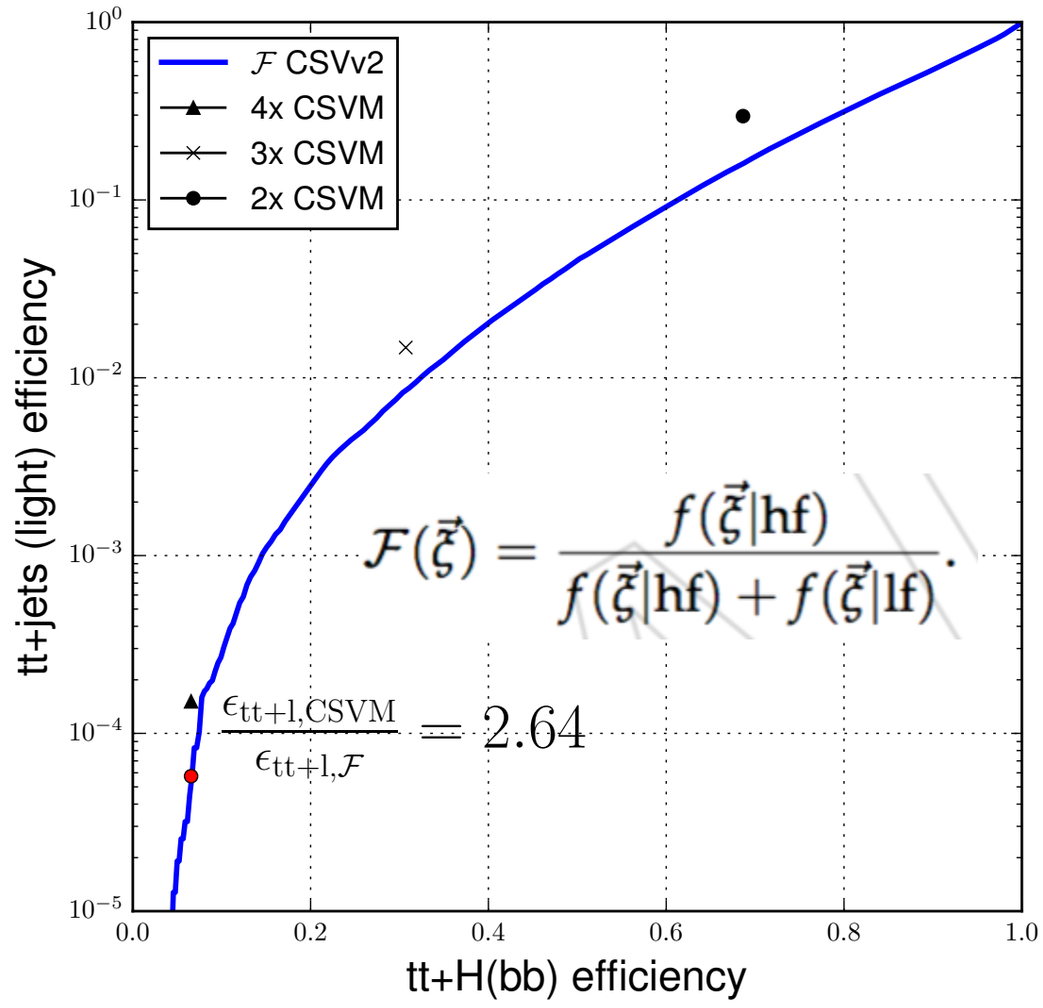




- Fit is able to accommodate observed yields without overt tension

b-tagging likelihood

- Separate tt+bb (4b -quark) from tt+lf (2 b-quark)
- Sum over permutations of associating 4 (2) b-quarks to jets, defined for ≥4 jet events
- Constructed from CSVv2 distributions extracted from tt+jets single-leptonic events
- Observe ~2x better tt+light rejection than flat N CSVM cut
- **Use blr cut to choose 4-b compatible events in 3-tag categories to deploy MEM**
- **Possible training input to BDT**



$$f(\vec{\xi}|\mathrm{t\bar{t}} + \mathrm{hf}) = \sum_{i_1} \sum_{i_2 \neq i_1} \cdots \sum_{i_6 \neq i_1,\ldots,i_5} \left\{ \prod_{k \in \{i_1,i_2,i_3,i_4\}} f_{\mathrm{hf}}(\xi_k) \prod_{m \in \{i_5,i_6\}} f_{\mathrm{lf}}(\xi_m) \right\},$$

"heavy" "light"

event yields

	6j2t	4j3t	5j3t	6j3t	boosted
$t\bar{t}$+lf	3989.4 ± 18.1	988.5 ± 8.6	520.4 ± 6.3	308.1 ± 4.8	52.2 ± 2.0
$t\bar{t} + c\bar{c}$	1378.3 ± 11.4	213.8 ± 4.0	225.2 ± 4.3	230.7 ± 4.3	26.8 ± 1.4
$t\bar{t}$+b	349.8 ± 5.9	129.9 ± 3.2	121.4 ± 2.9	112.2 ± 2.9	11.7 ± 0.9
$t\bar{t}$+2b	149.2 ± 3.7	47.7 ± 1.8	52.3 ± 1.9	64.9 ± 2.1	12.6 ± 1.0
$t\bar{t} + b\bar{b}$	223.1 ± 5.1	46.6 ± 1.8	77.5 ± 2.5	135.2 ± 3.5	16.9 ± 1.1
Single Top	220.8 ± 8.7	59.5 ± 4.2	38.6 ± 3.3	32.1 ± 3.1	5.6 ± 1.3
V+jets	92.8 ± 13.4	18.9 ± 4.4	11.5 ± 5.6	15.5 ± 6.2	5.0 ± 1.0
$t\bar{t}$+V	46.2 ± 1.5	3.8 ± 0.3	6.8 ± 0.5	10.2 ± 0.7	2.1 ± 0.3
Diboson	0.2 ± 0.1	0.5 ± 0.3	0.4 ± 0.3	0.4 ± 0.2	0.0 ± 0.0
Total bkg	6449.7 ± 28.1	1509.3 ± 12.0	1054.0 ± 10.9	909.4 ± 10.7	133.0 ± 3.4
$t\bar{t}H$	26.3 ± 0.2	4.6 ± 0.1	7.4 ± 0.1	12.0 ± 0.1	2.5 ± 0.1
Data	6161.0 ± 78.5	1422.0 ± 37.7	996.0 ± 31.6	894.0 ± 29.9	122.0 ± 11.0

	4j4tl	4j4th	5j4tl	5j4th	6j4tl	6j4th
$t\bar{t}$+lf	4.9 ± 0.6	1.0 ± 0.3	6.7 ± 0.7	0.9 ± 0.3	5.7 ± 0.6	1.8 ± 0.6
$t\bar{t} + c\bar{c}$	3.1 ± 0.4	0.4 ± 0.2	5.5 ± 0.6	1.0 ± 0.2	12.3 ± 1.0	2.9 ± 0.5
$t\bar{t}$+b	2.5 ± 0.4	0.6 ± 0.2	5.4 ± 0.6	1.0 ± 0.2	7.0 ± 0.7	1.7 ± 0.3
$t\bar{t}$+2b	0.6 ± 0.2	0.3 ± 0.1	2.7 ± 0.5	0.6 ± 0.2	4.7 ± 0.5	1.3 ± 0.3
$t\bar{t} + b\bar{b}$	2.4 ± 0.4	1.0 ± 0.2	10.9 ± 0.8	3.7 ± 0.5	26.5 ± 1.4	9.7 ± 0.8
Single Top	0.2 ± 0.1	0.2 ± 0.1	1.8 ± 0.7	1.0 ± 0.5	2.3 ± 0.7	0.1 ± 0.1
V+jets	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.5 ± 0.3	0.1 ± 0.1
$t\bar{t}$+V	0.1 ± 0.1	0.0 ± 0.0	0.4 ± 0.1	0.2 ± 0.1	1.2 ± 0.2	0.4 ± 0.1
Diboson	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.4 ± 0.4
Total bkg	13.9 ± 1.0	3.6 ± 0.5	33.5 ± 1.6	8.5 ± 0.9	60.2 ± 2.1	18.2 ± 1.2
$t\bar{t}H$	0.2 ± 0.0	0.2 ± 0.0	0.7 ± 0.0	0.7 ± 0.0	1.5 ± 0.0	1.6 ± 0.0
Data	23.0 ± 4.8	5.0 ± 2.2	41.0 ± 6.4	6.0 ± 2.4	60.0 ± 7.7	12.0 ± 3.5