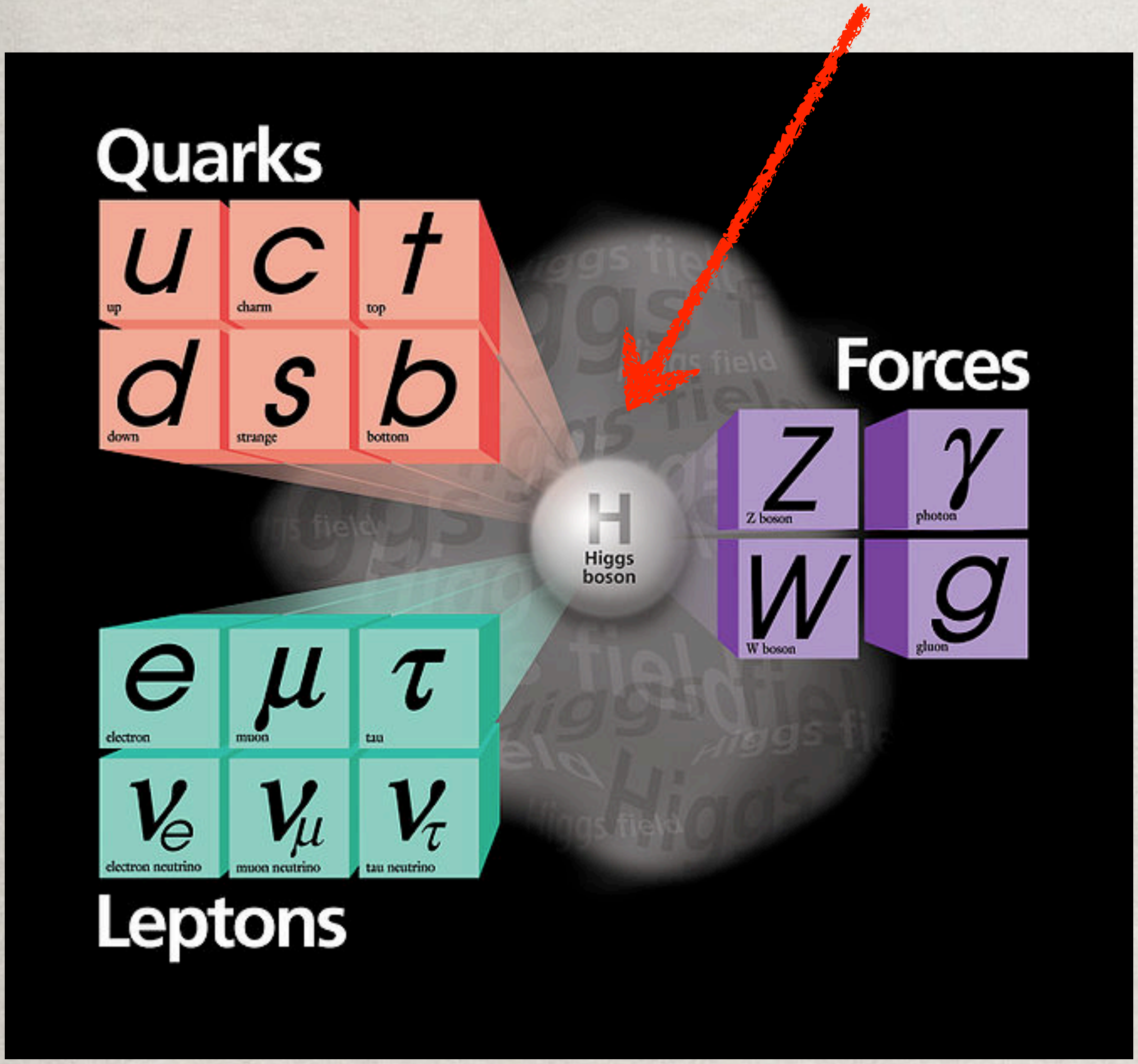
search for ttH(bb) @ CMS

Wuming Luo

WHAT IS IT?


Quarks
u
up
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Z boson
γ
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W
W boson
g
gluon
H
Higgs boson
e
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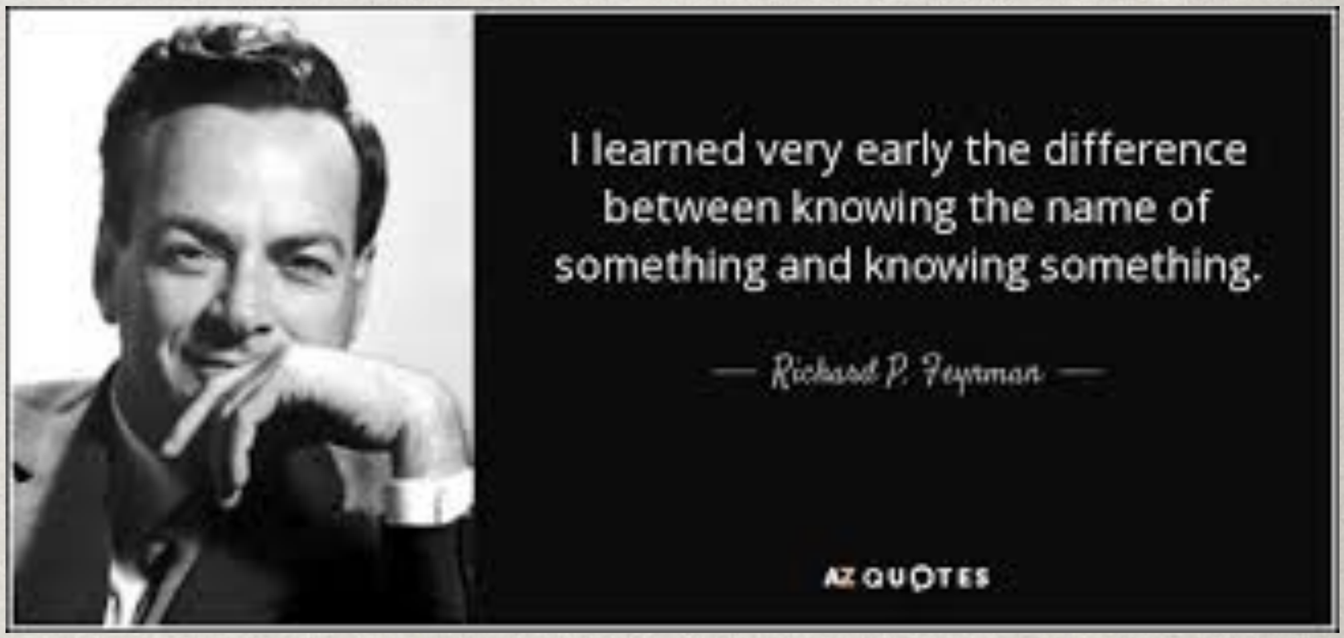
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons


I learned very early the difference between knowing the name of something and knowing something.
— Richard P. Feynman —
AZ QUOTES

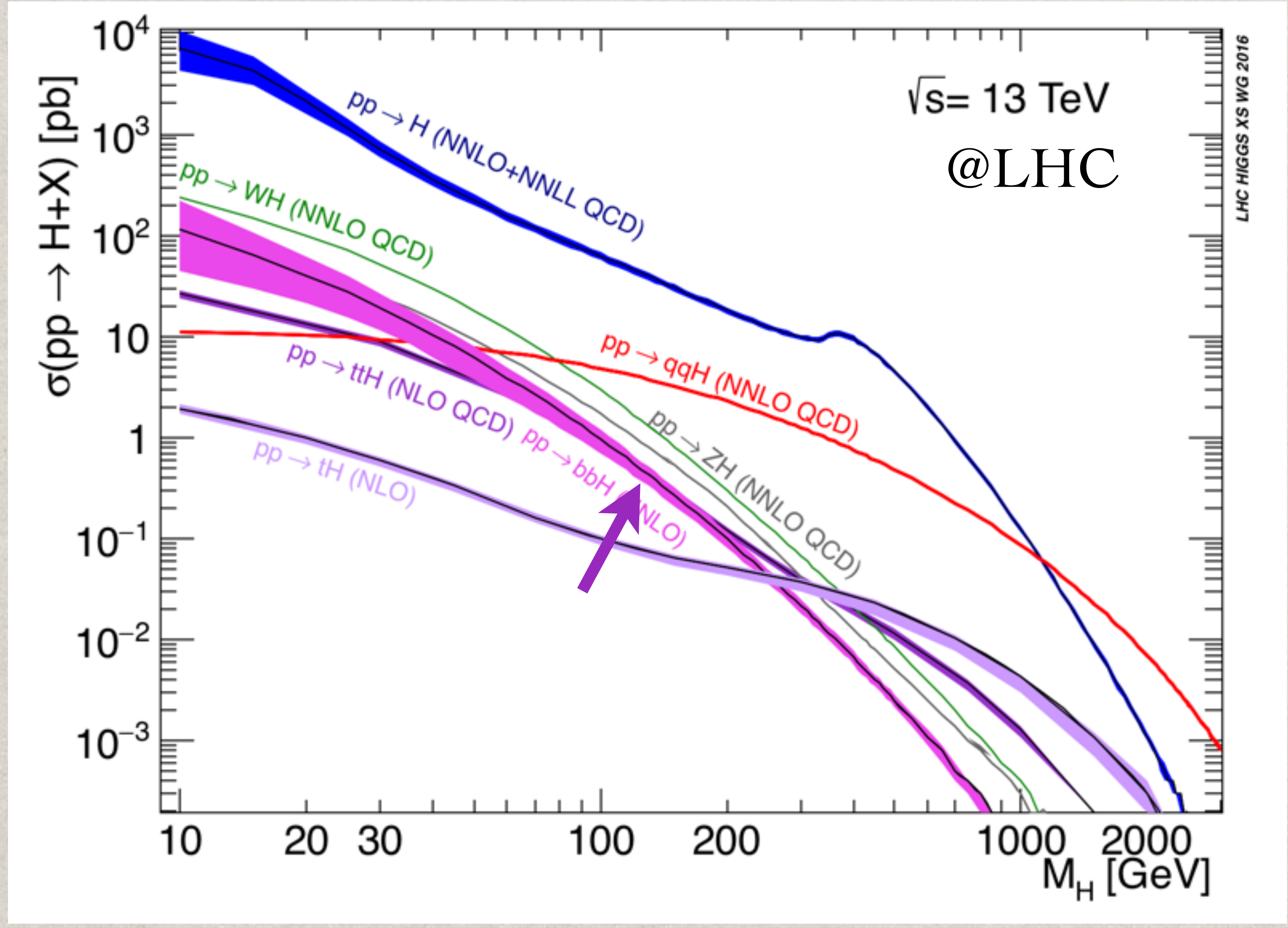
WHAT IS IT REALLY?

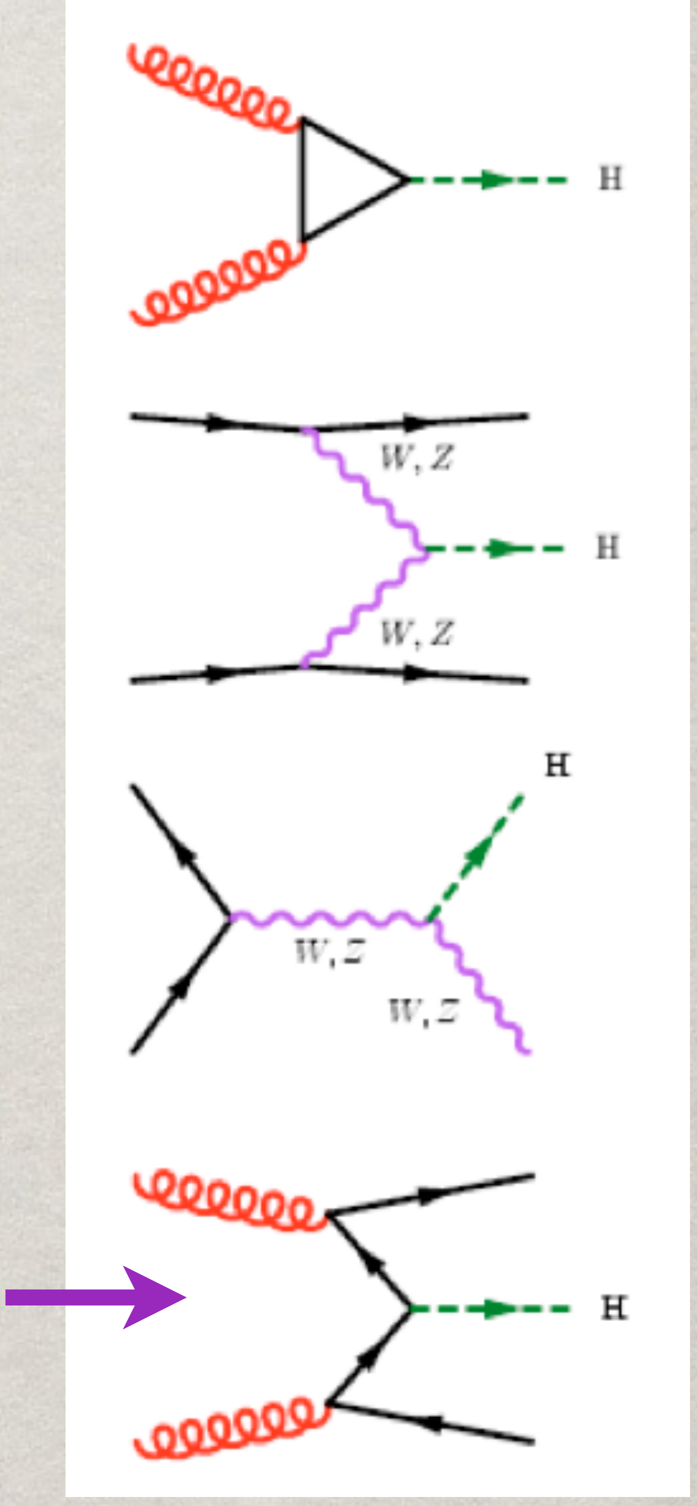
Mr. Somebody

Mr. Nobody

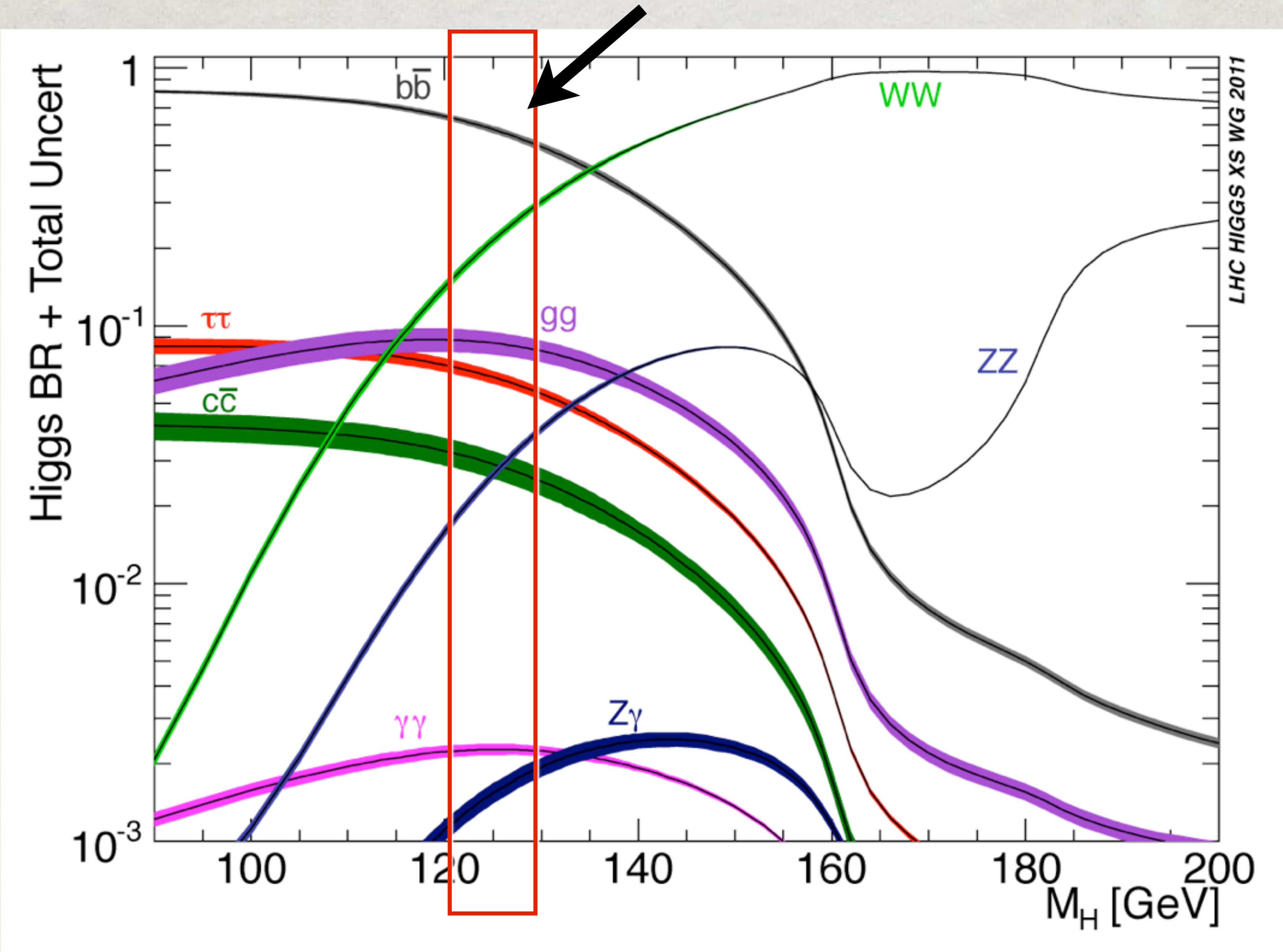
- Where do the masses of particles come from?
- Have been searching for the Higgs Boson for many years

WHERE DOES IT COME FROM: HIGGS PRODUCTION



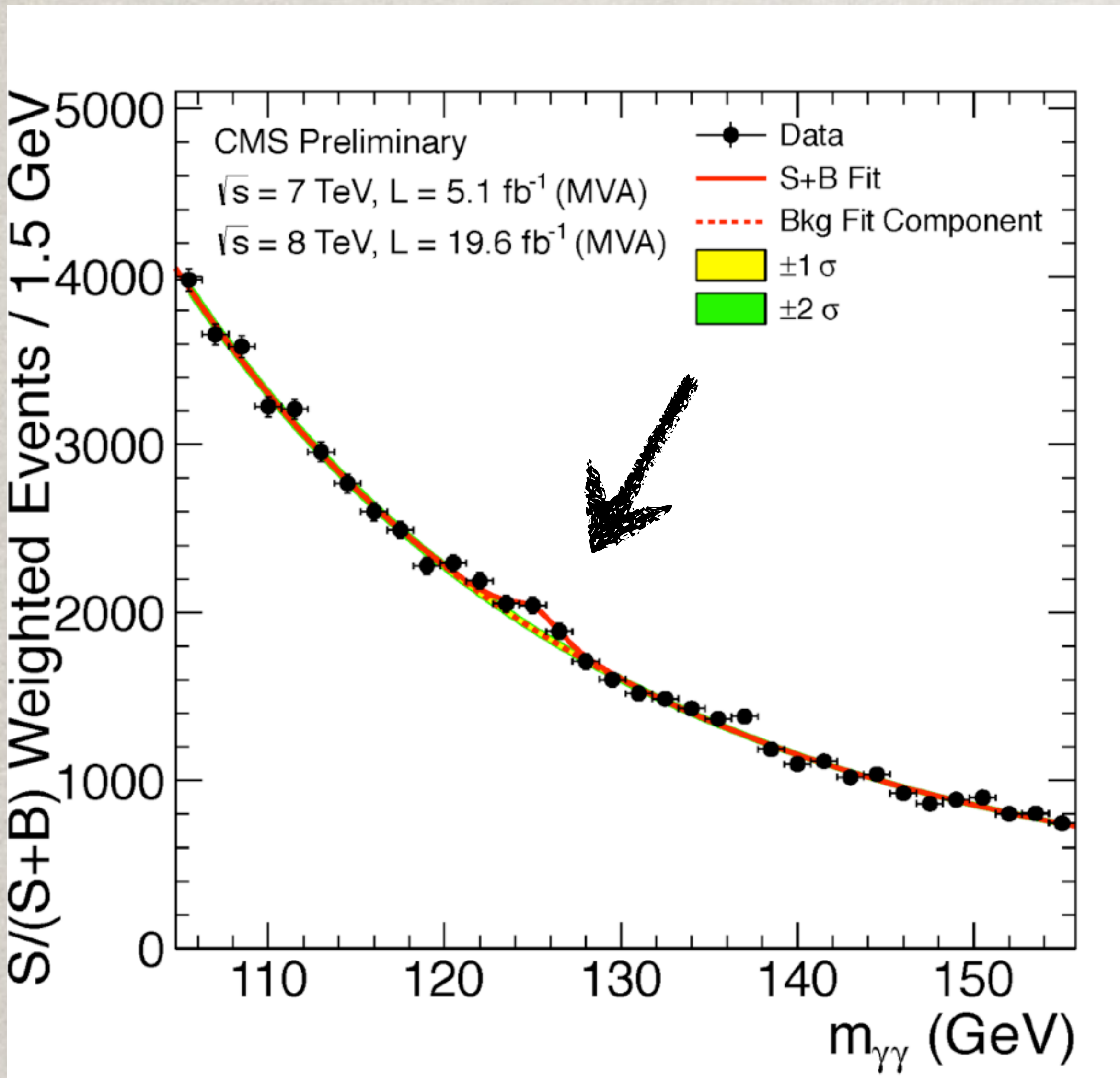


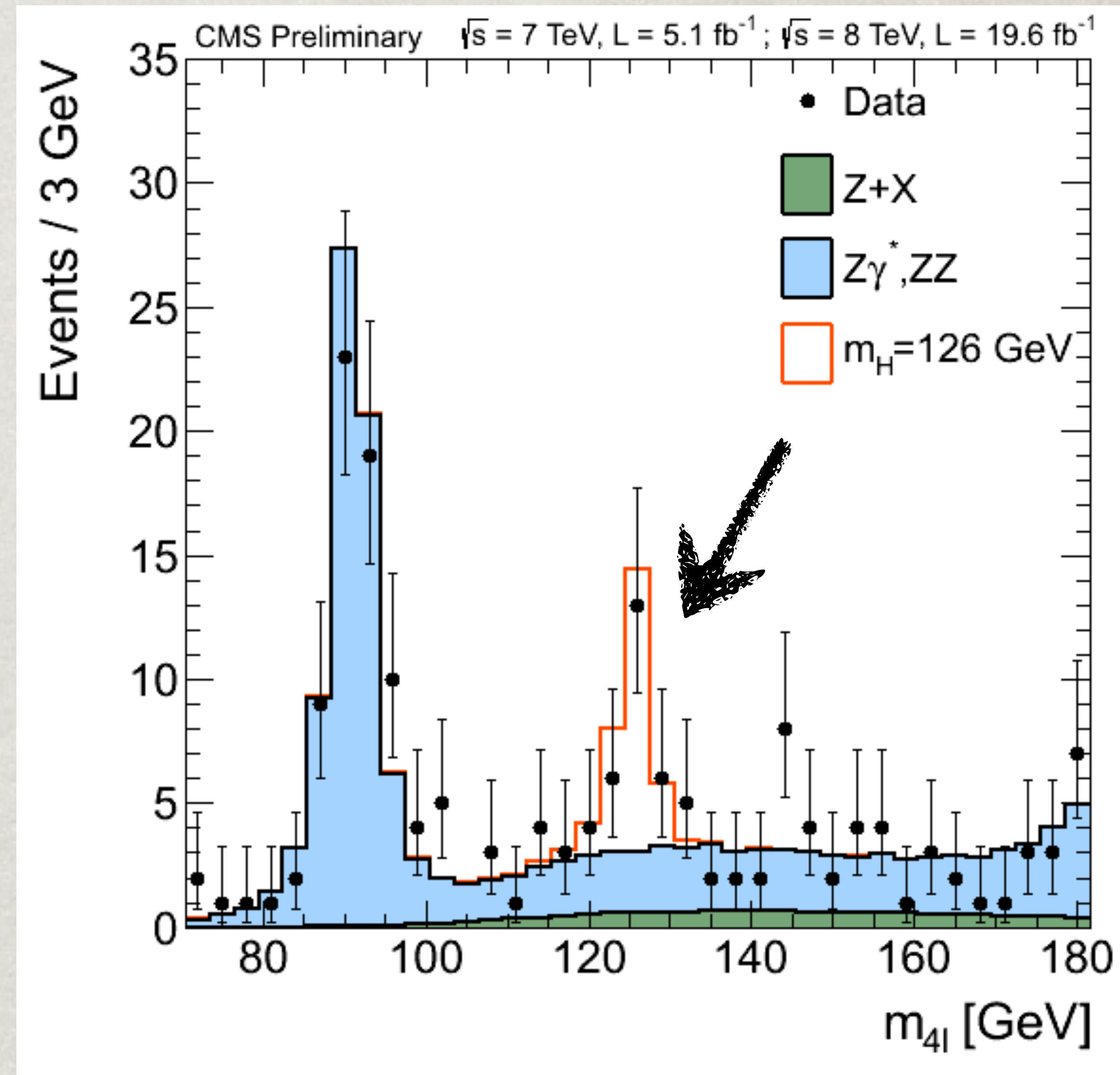
WHERE DOES IT GO: HIGGS DECAY



- At 125.7 GeV, H→bb dominates.
- Huge background makes direct search difficult.

HIGGS BOSON DISCOVERY



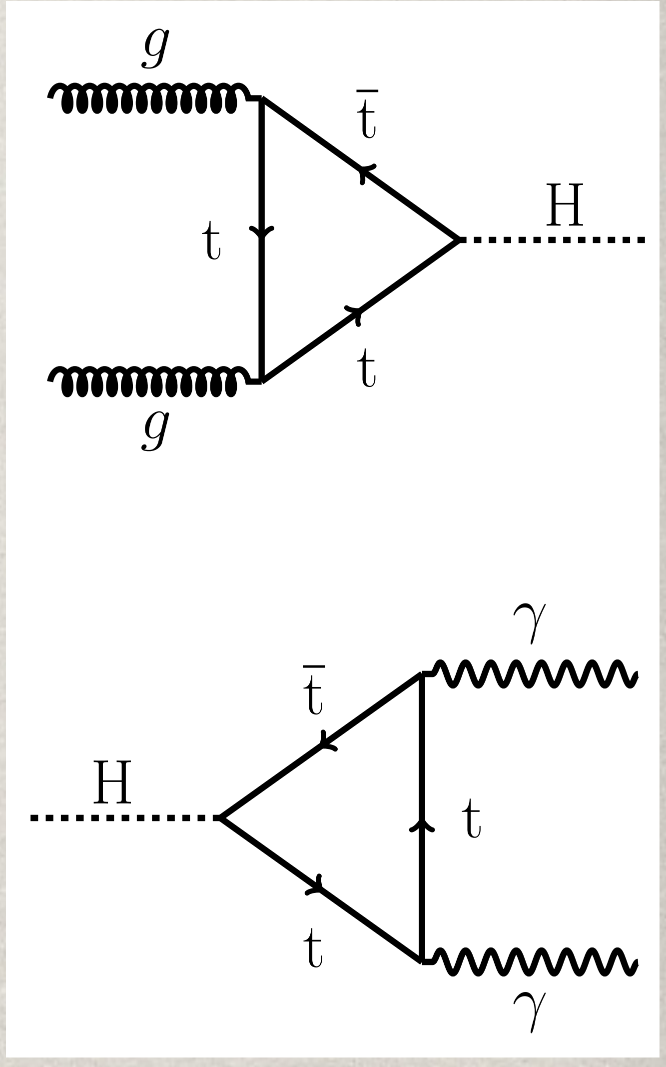


- We found "A" Higgs boson!

- Is it truly "The" SM Higgs Boson???

WHY TTH?

- Complementary to other H searches
- Directly probes the top-Higgs Yukawa coupling(Y_t)
  - Key component to evaluate the consistency of the new boson with SM expectations
- It could be sensitive to Beyond SM physics



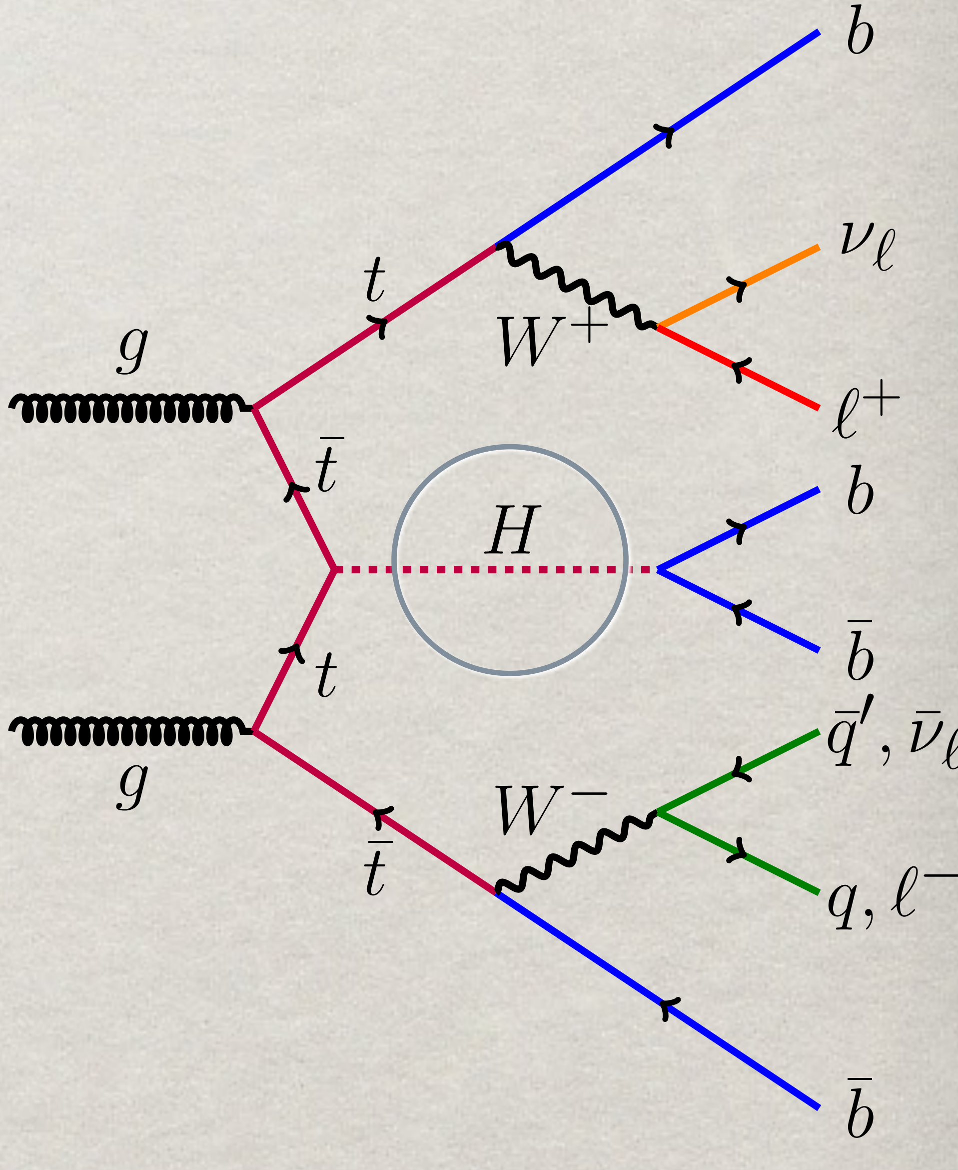
ttH @ CMS

	Decay Mode	No. of Institutes	Paper	Data(fb^{-1})
7TeV	bb	3	x	5
8TeV	bb/ $\tau\tau$/WW/ZZ/$\gamma\gamma$	3(bb) ≥4(non-bb)	1 bb* 1 combination	19.5
13TeV(2016)	bb/ $\tau\tau$/WW/ZZ/$\gamma\gamma$	11(bb) ≥7(non-bb)	1 bb 1 $\tau\tau$/WW/ZZ 1 comb.	35.9

- 13TeV paper in preparation, huge ttH groups
- This talk will focus on the ttH (H→bb) analysis

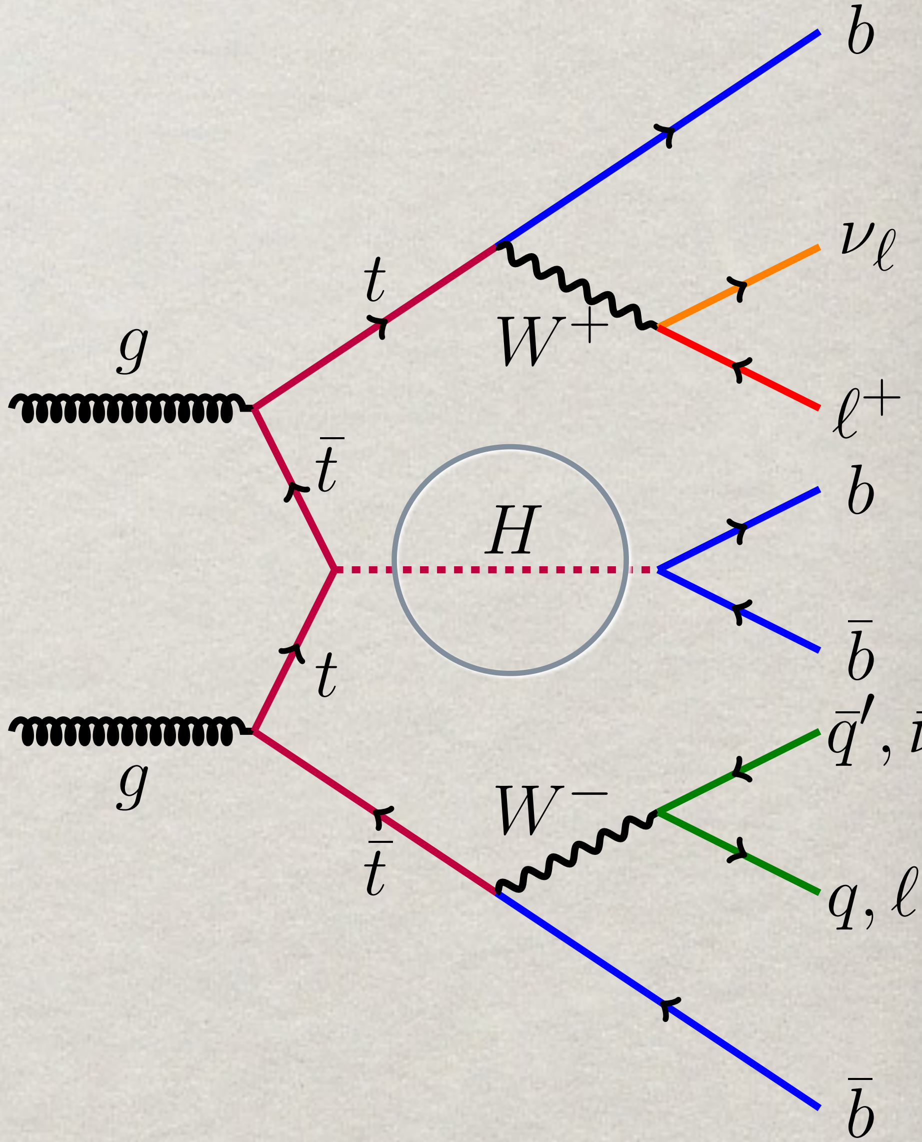
ttH(bb)

- Advantage:
  - Highest branching fraction
- Challenges:
  - Tiny production cross section
  - Higgs invariant mass hard to reconstruct
  - Difficult irreducible background ttbb



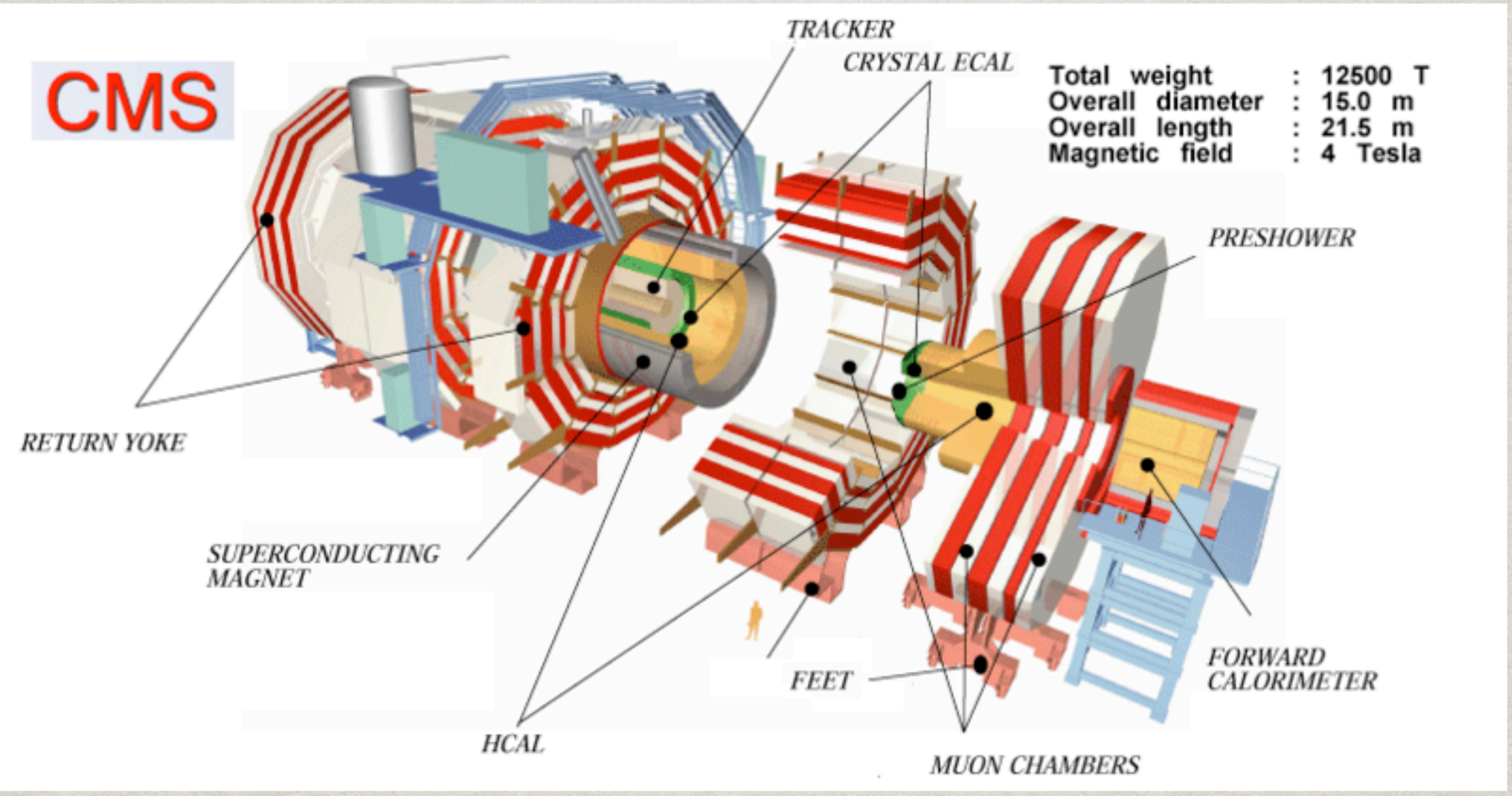
OVERVIEW

- Split channels by top pair decay
  - Lepton + jets (e, μ): LJ channel
  - Dilepton: DIL channel
- For each channel, separate events into categories
- Use MVA* to separate S/B and fit simultaneously all categories to data to extract signal



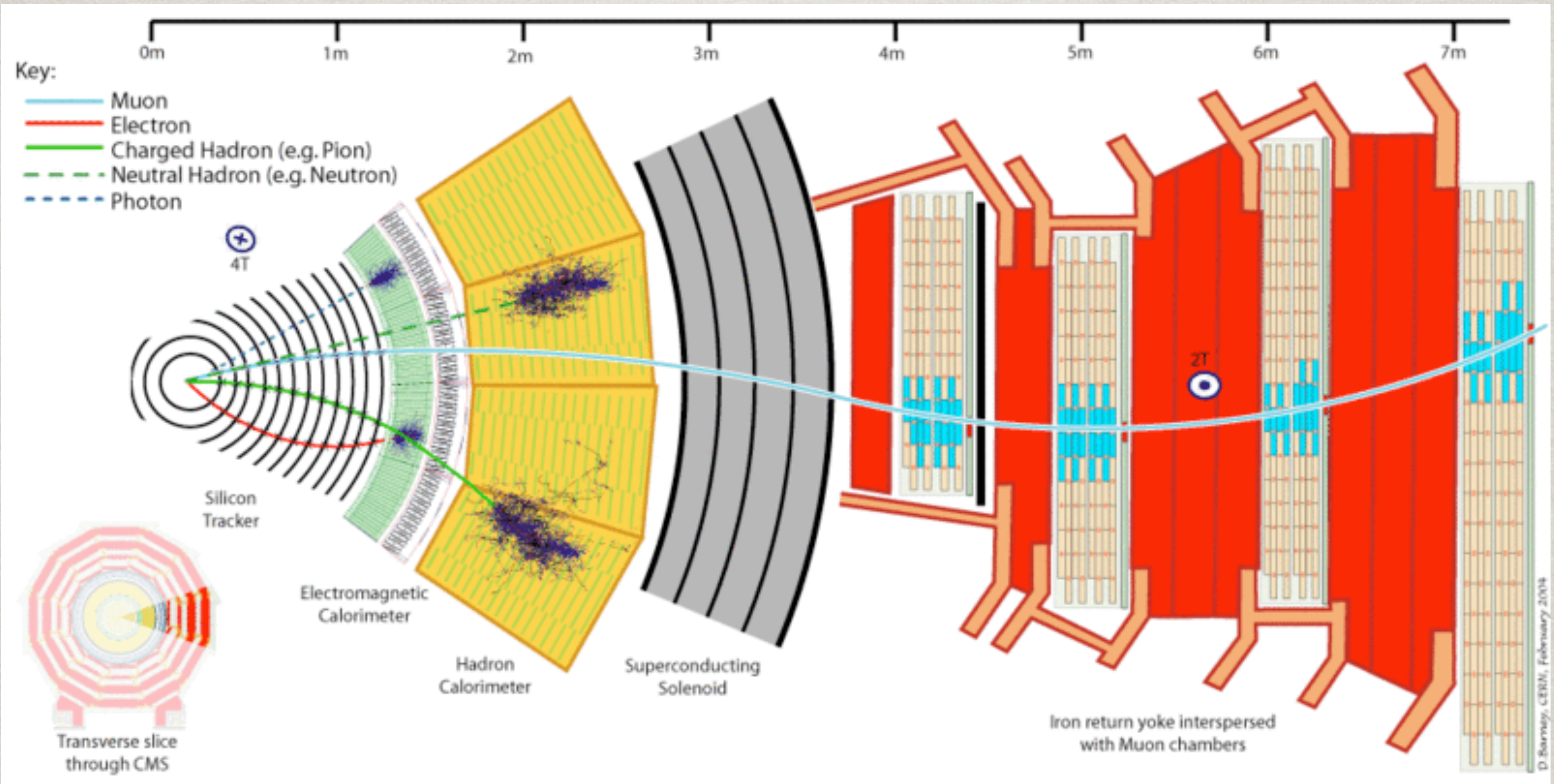
*MVA: Multi-Variate-Analysis method using various machine learning techniques

Compact Muon Solenoid



Tracker, ECAL, HCAL, Magnet, Muon Chamber

DETECTOR SIGNATURES



Particle Flow: combine the info in different sub-detectors to identify particle types

SAMPLES AND SELECTION

DATA SAMPLES

- Full 2016 Data, $\sqrt{s}$ = 13TeV
- The total integrated luminosity is: L = 35.9/fb

lepton+jets triggers

Dataset	Trigger Name
SingleMu	HLT_IsoMu22_v*
SingleMu	HLT_IsoTkMu22_v*
SingleEle	HLT_Ele27_eta2p1_WPTight_Gsf_v*

dilepton triggers

Channel	Trigger Name
$\mu^+\mu^-$	HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v*
$\mu^+\mu^-$	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v*
e^+e^-	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*
$\mu^\pm e^\mp$	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*
$\mu^\pm e^\mp$	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v*

SIGNAL AND BACKGROUND

- Signal ttH samples
  - All Higgs and top decays allowed
  - ttH(bb) sample and ttH(non-bb) sample
- $t\bar{t}$+Jets is the main background
  - Dedicated samples by ttbar decay mode
  - Separated by extra jet content: tt+lf/bb/b/B/cc
- Other relevant bkg MC
  - tt+Z/W, WJets, ZJets, WW, WZ, ZZ, single top

*XS from CERN Yellow Report Page

SELECTION: LEPTON

Muons	Single Muon Channel ID	Leading ID Dilpeton	Sub-Leading Dilepton ID Veto ID for Single Muon
p_T [GeV] $>$	25	25	15
$\|\eta\| <$	2.1	2.4	2.4
ID	tight	tight	tight
$\mathrm{Iso}_{\delta\beta}/p_T <$	0.15	0.25	0.25

Electrons	Single Electron Channel ID	Leading ID Dilpeton	Sub-Leading Dilepton ID Veto ID for Single Electron
p_T [GeV] $>$	30	25	15
$\|\eta\| <$	2.1	2.4	2.4
ID	80% eff. non-trig. MVA ID	80% eff. non-trig. MVA ID	80% eff. non-trig. MVA ID
$\mathrm{Iso}_{\rho A}/p_T <$	0.15	0.15	0.15

$\mu^+\mu^-$ and e^+e^- Channel:
$m_{\ell\ell} > 20$ GeV
$m_{\ell\ell} < 76$ GeV or $m_{\ell\ell} > 106$ GeV
MET > 40 GeV

- Lepton Pt > trigger thresholds
- Tight ID and isolation to suppress multi-jet events
- Veto Z+jets events for DL

SELECTION: JETS

Jets	Single Lepton Channel Leading 2 Jets Dilepton	Dilepton Channel Subleading Jets Dilepton
Type	PFJets, CHS	PFJets, CHS
Algorithm	anti-k_T 0.4	anti-k_T
p_T [GeV] $>$	30	20
$\|\eta\| <$	2.4	2.4
Lepton cleaning	Require $\Delta R(\ell, j) > 0.4$	Require $\Delta R(\ell, j) > 0.4$

- Jet multiplicity:
  - ≥4 jets in LJ channel
  - ≥2 jets in DL channel
- b-tags: jets originating from b quarks
  - use CSV(Combined Secondary Vertex) algorithm
  - identify as b-jets if passing Medium working point
  - 1(2) b-tags for DL(LJ) inclusive selection

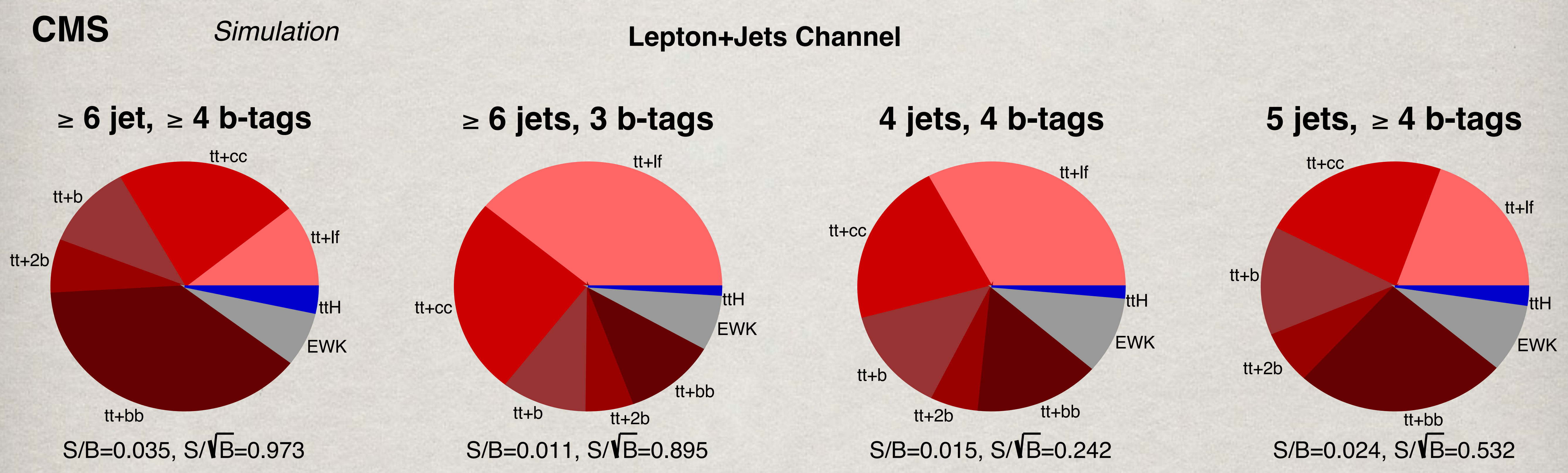
EVENT CATEGORIZATION

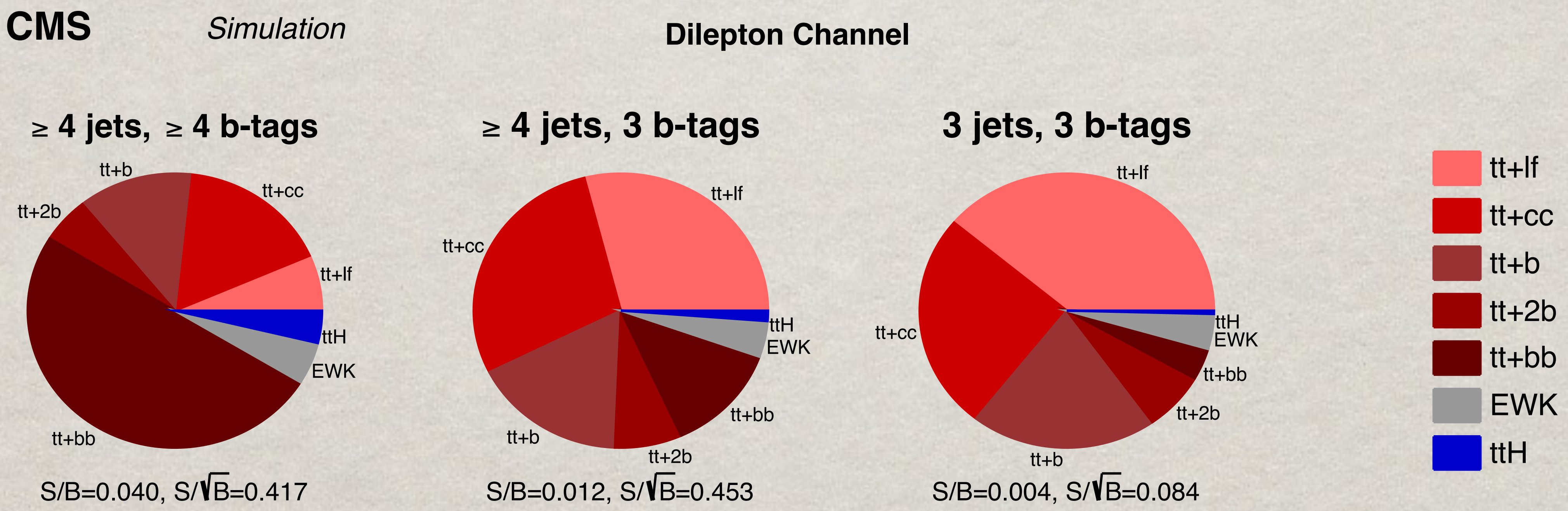
- Different channels based on top pair decay
  - LJ channel and DIL channel
- For each channel, categorize events based on number of jets and number of b-tags (alternative scheme later*)

Lepton + Jets(LJ)			
	4jets	5jets	≥6jets
2tags	x	x	x
3tags	x	x	✓
≥4tags	✓	✓	✓

Dilepton(DIL)		
	3jets	≥4jets
2tags	x	x
3tags	x	✓
≥4tags	✓	✓

CATEGORIZATION





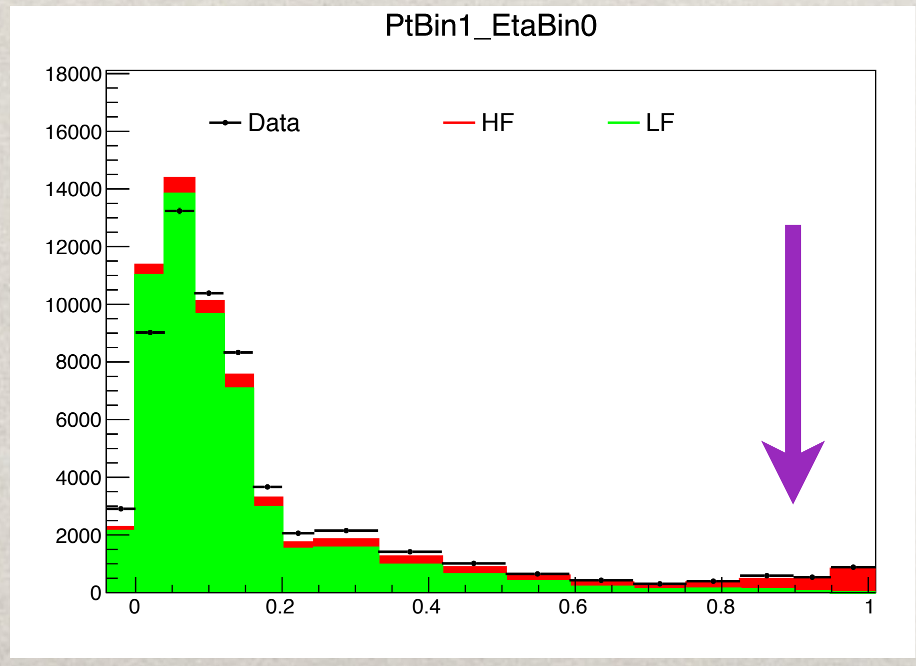
BACKGROUND MODELING

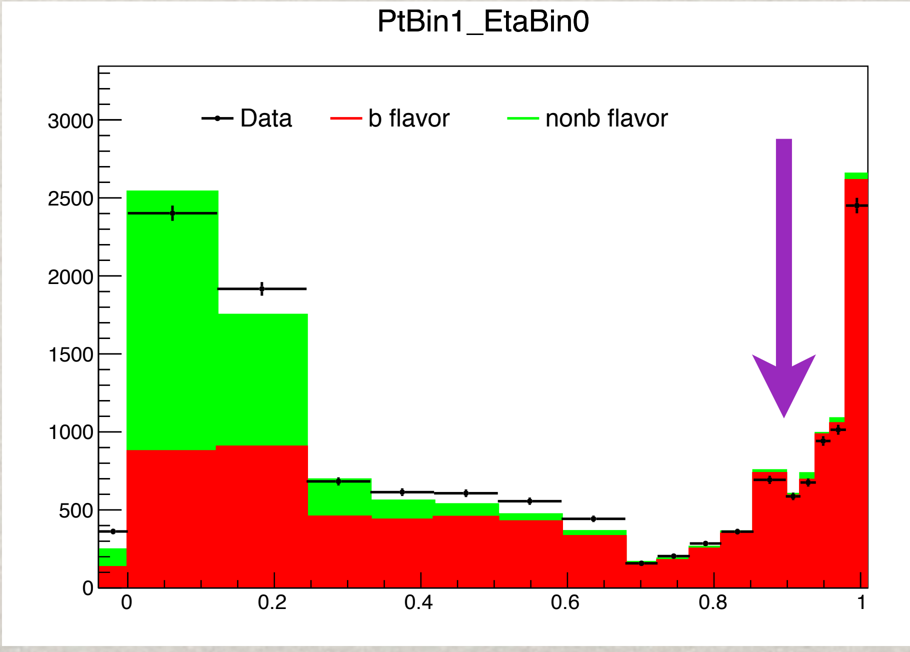
CORRECTIONS TO MC

- MC samples were created based on certain theory assumptions
  - Need corrections to match Data
- Pileup vertex reweighting
  - Reproduce number of PU interactions
- Jet energy calibration: jet energy resolution/scale
- Lepton data/MC scale factor
  - Based on lepton P_T and η
- B-tag CSV reweighting
  - Correct MC b-tag efficiency as a function of the CSV discriminator

B-TAG CSV REWEIGHTING

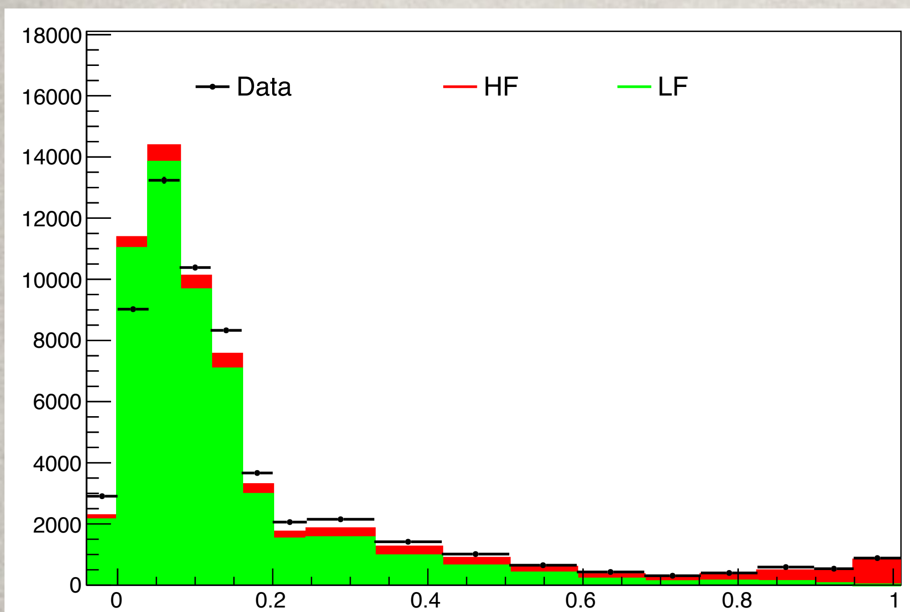
- We need to model CSV b-tagging correctly:
  - Use CSV medium working point to identify b-tagged jets
  - Use CSV distributions to separate signal from background
- We require corrections to CSV shape bin-by-bin
- We derive a reweighting of CSV discriminant shape for both light and heavy flavor jets

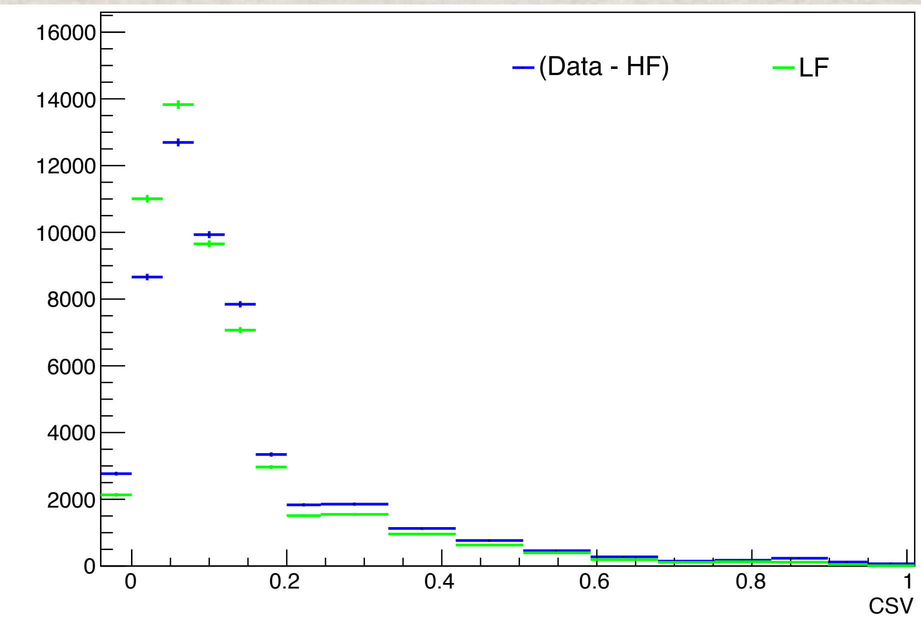


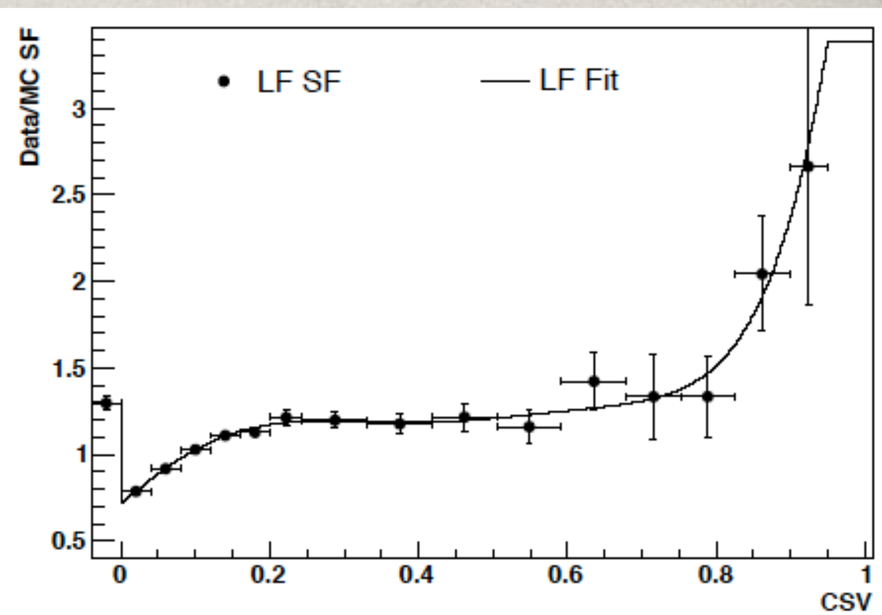


TAG AND PROBE

- Use Tag-and-Probe method to calculate CSV scale factors bin-by-bin from independent control samples not used in analysis
  - Heavy flavor SF: DIL ttbar enriched sample
  - Light flavor SF: DIL Z+jets enriched sample
- Require one jet to be (anti) tagged, account for LF(HF) contamination, correct probe jet CSV shape in MC to match data
- Scale Factor is defined as: $SF(CSV, p_t, \eta) = \frac{Data - MC_A}{MC_B}$ (A/B=HF/LF)

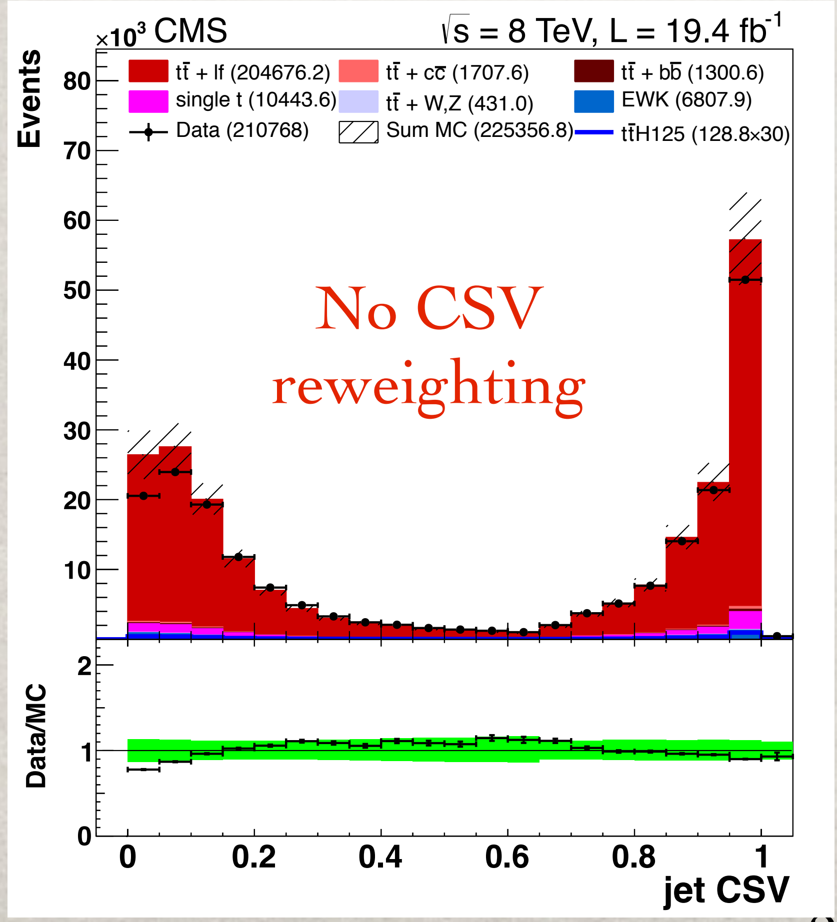


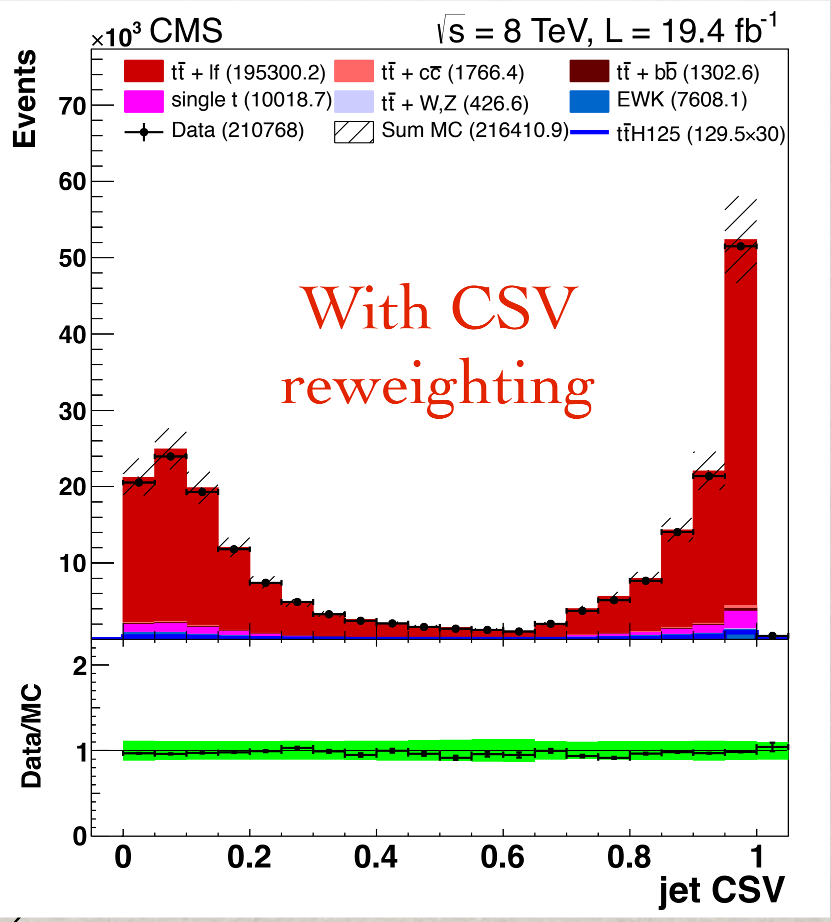




CSV SF

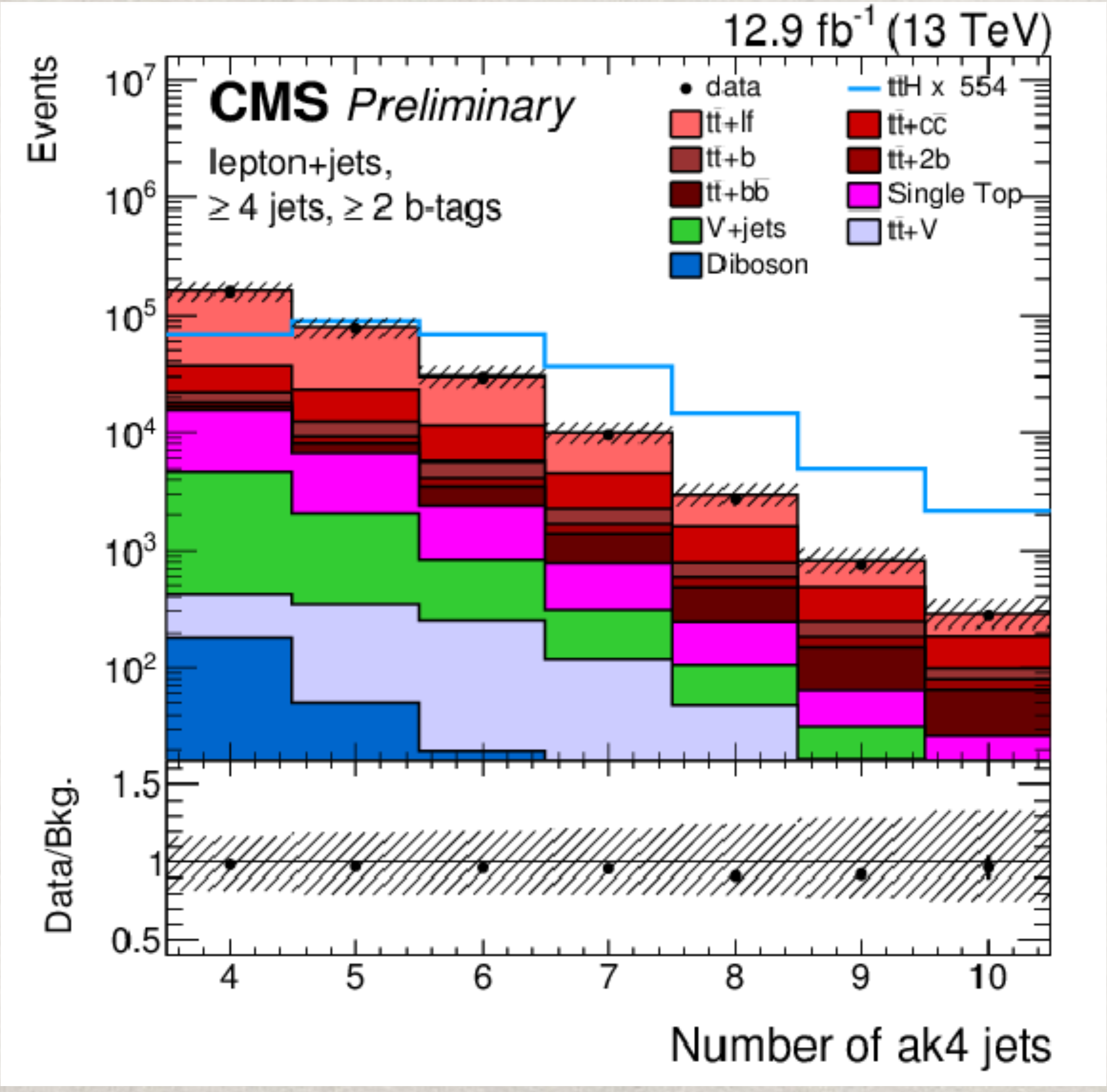
- Apply the CSV Scale Factors(SFs) based on jet flavor:
  - for b jets, assign heavy flavor SF
  - for light jets, assign light flavor SF
  - for c jets, no correction
- Final scale factor for each event is: $SF_{total} = SF_{jet1} * SF_{jet2} * \ldots$
- Significant improvement for CSV shapes

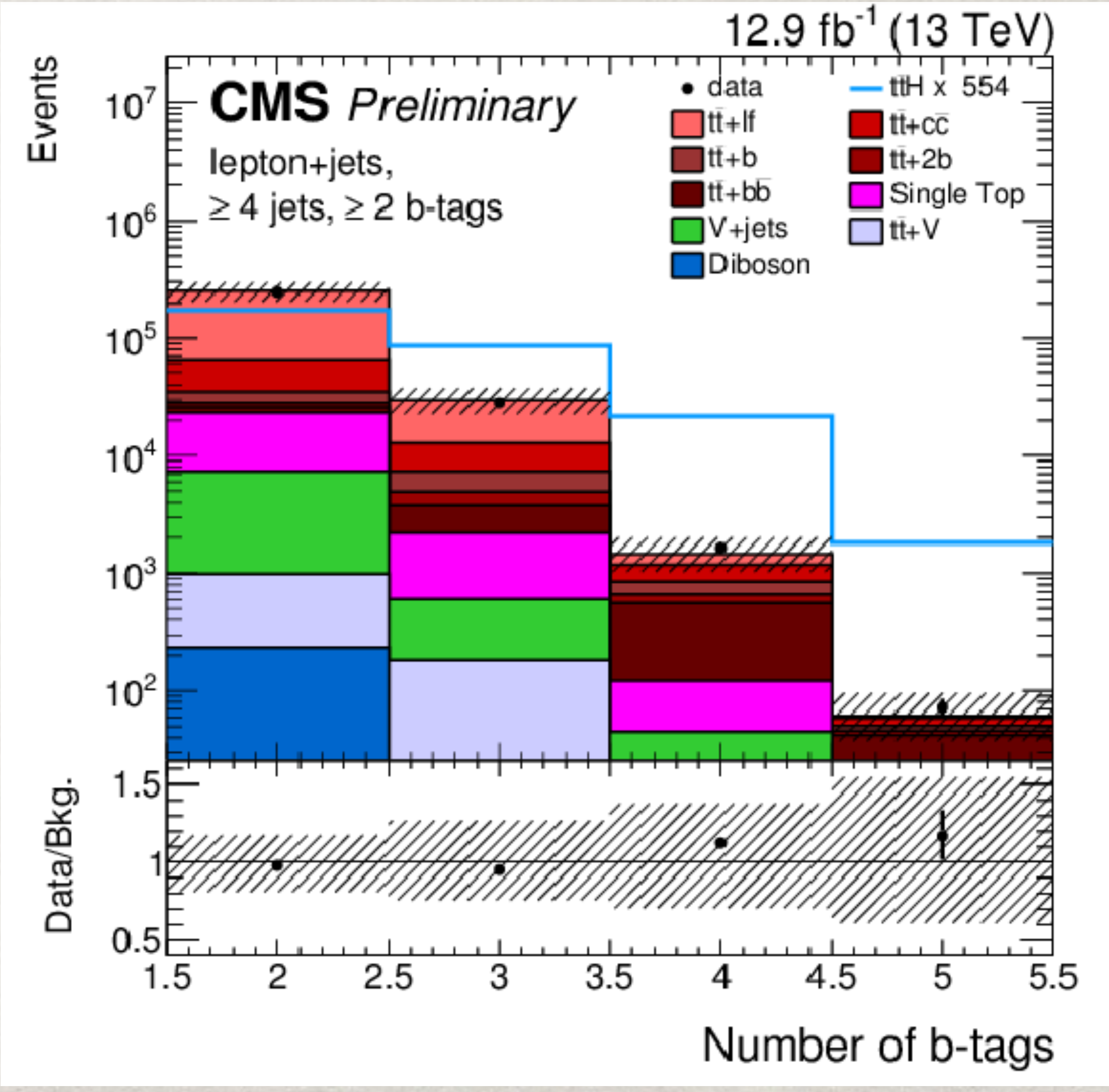




DATA/MC AGREEMENT: LJ

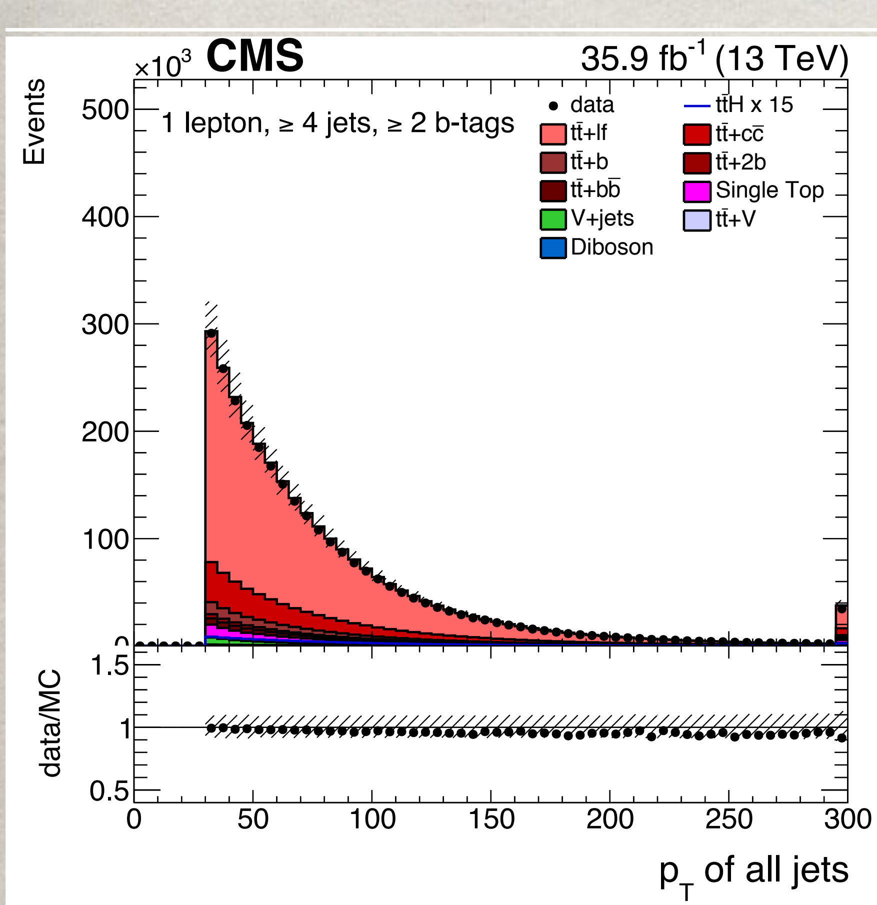
- All corrections to MC applied
- Good agreement between Data and MC

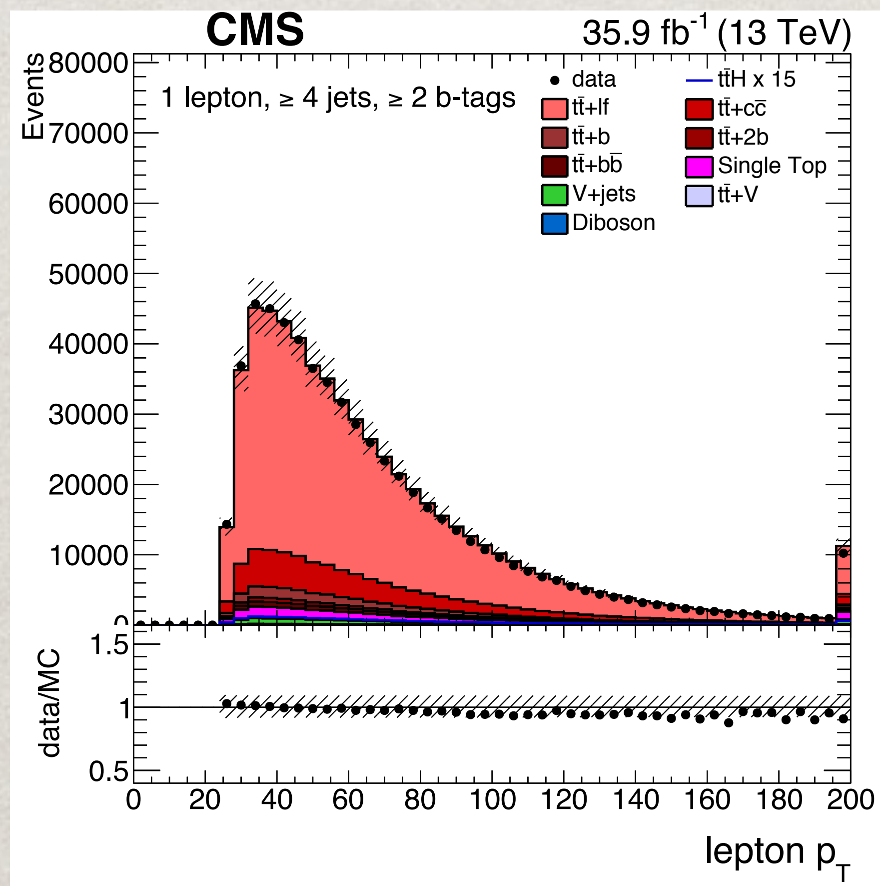


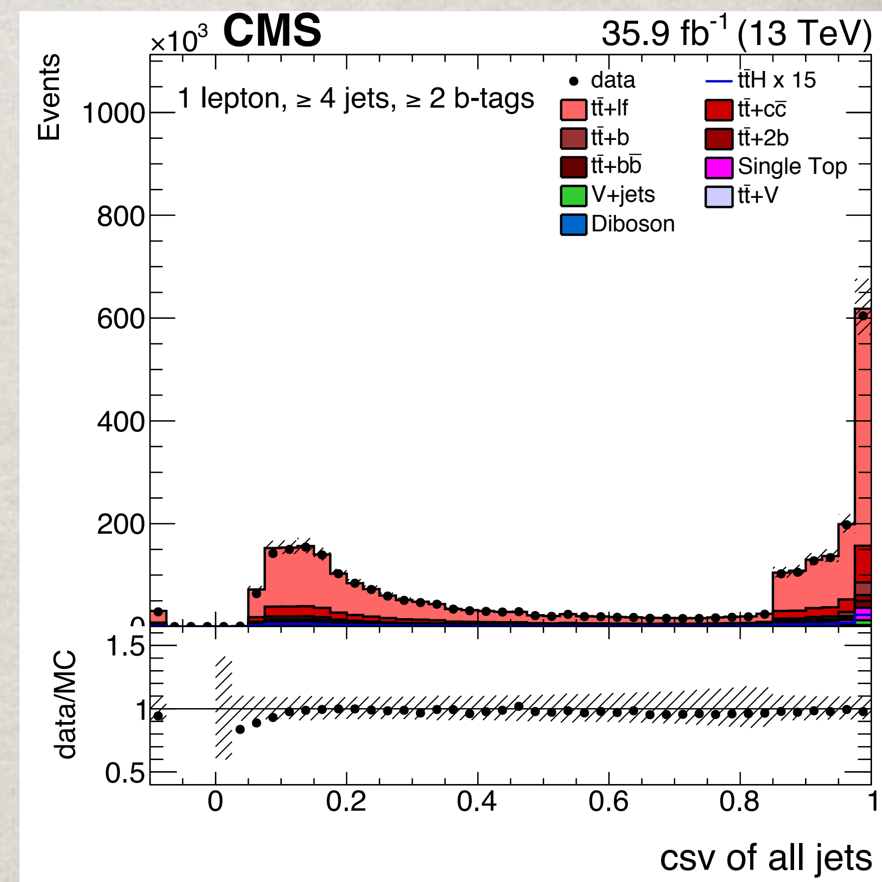


DATA/MC AGREEMENT: LJ

- All corrections to MC applied
- Good agreement between Data and MC

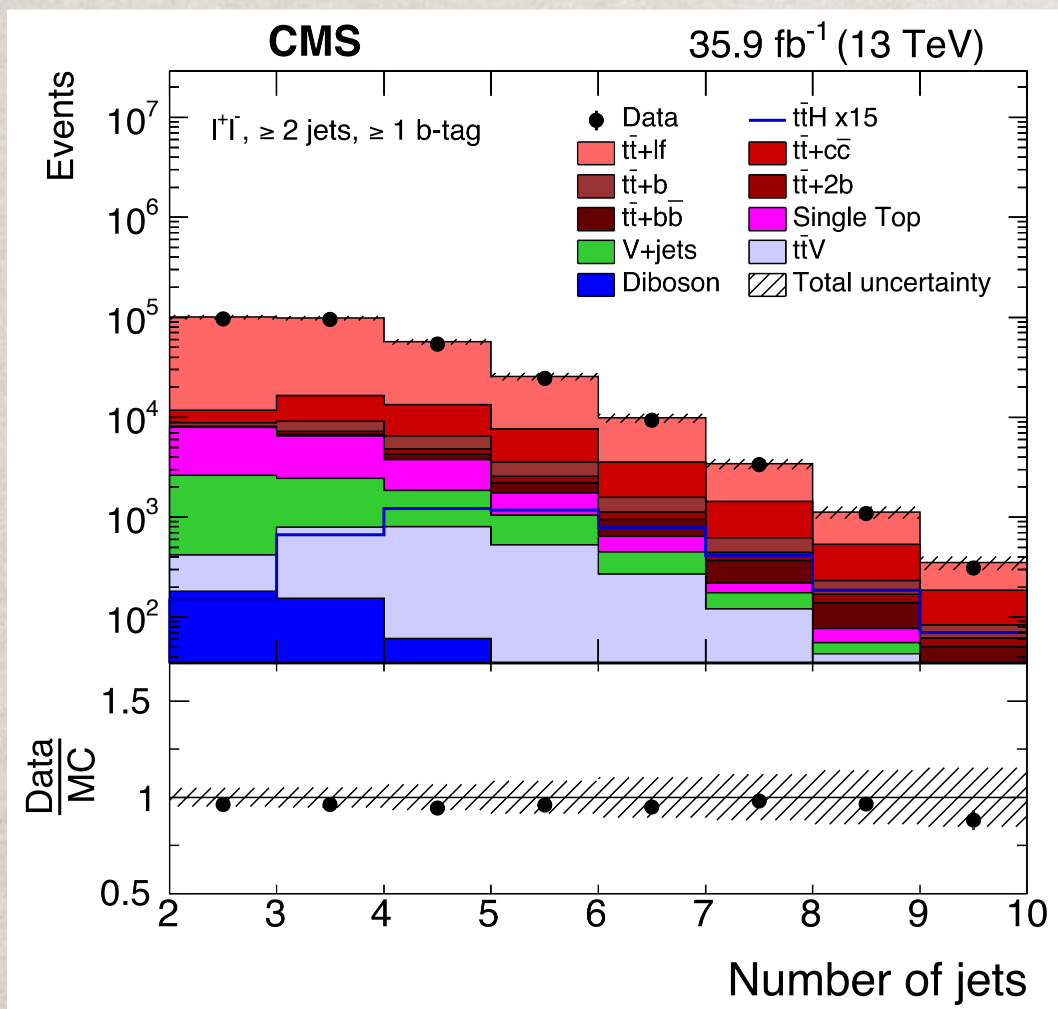


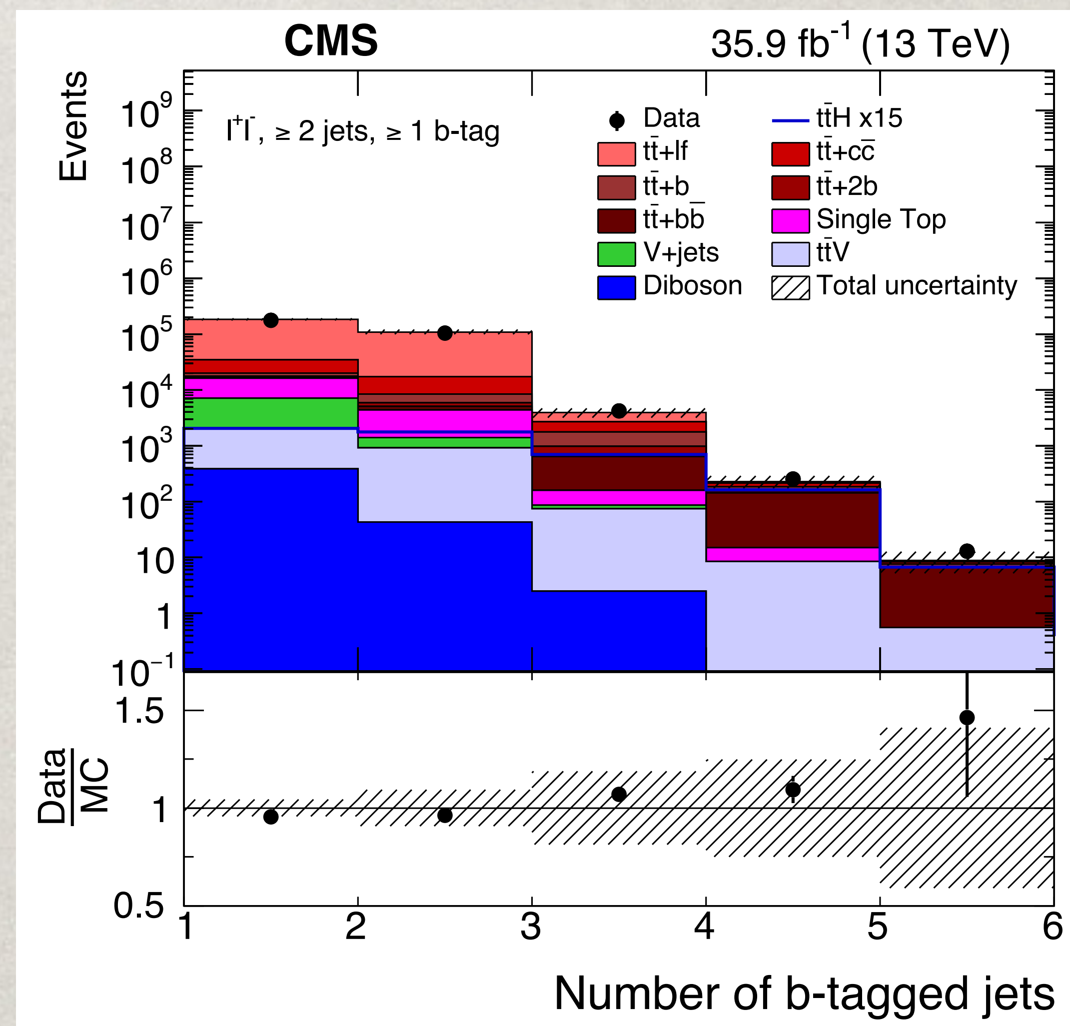




DATA/MC AGREEMENT: DIL

- All corrections to MC applied
- Good agreement between Data and MC



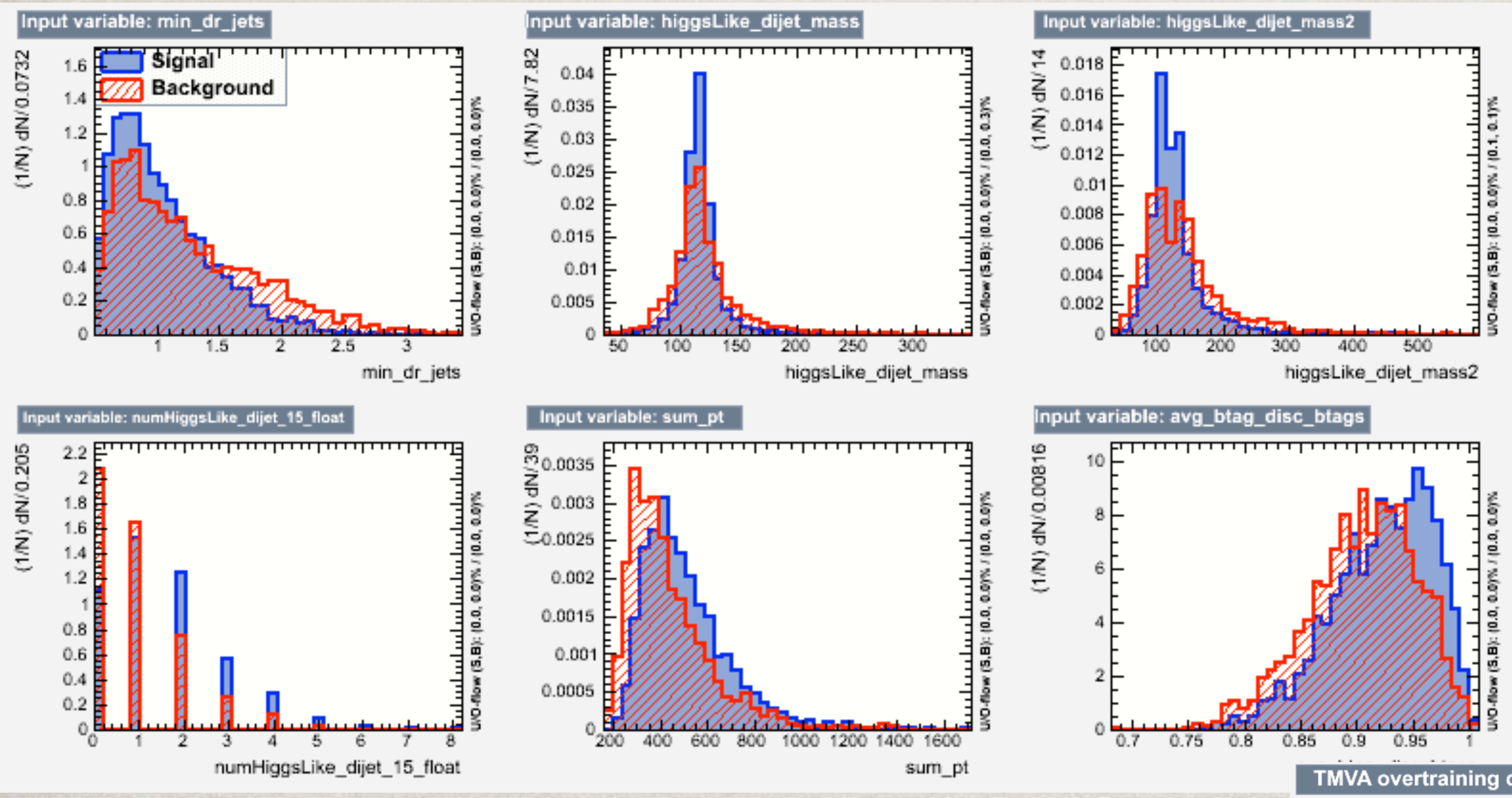


SIGNAL EXTRACTION

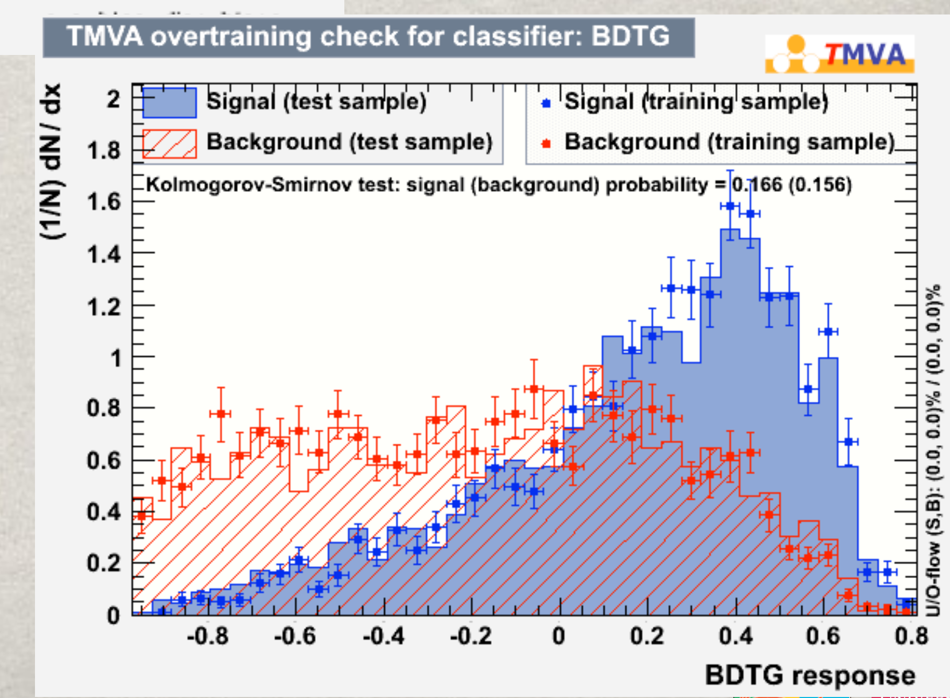
MULTIVARIATE ANALYSIS

- Can't use Higgs invariant mass as discriminant like other analyses ($H\rightarrow\gamma\gamma$ or $H\rightarrow ZZ\rightarrow 4l$).
- Background very similar to Signal
- Multi-Variate Analysis:
  - Combine several variables' discriminating power
  - Use Boosted Decision Tree (BDT) or Deep Neural Network(DNN)
- Train separate BDT/DNN for each category
- Fit BDT/DNN discriminators from all categories simultaneously to extract signal

BDT EXAMPLE



input variables



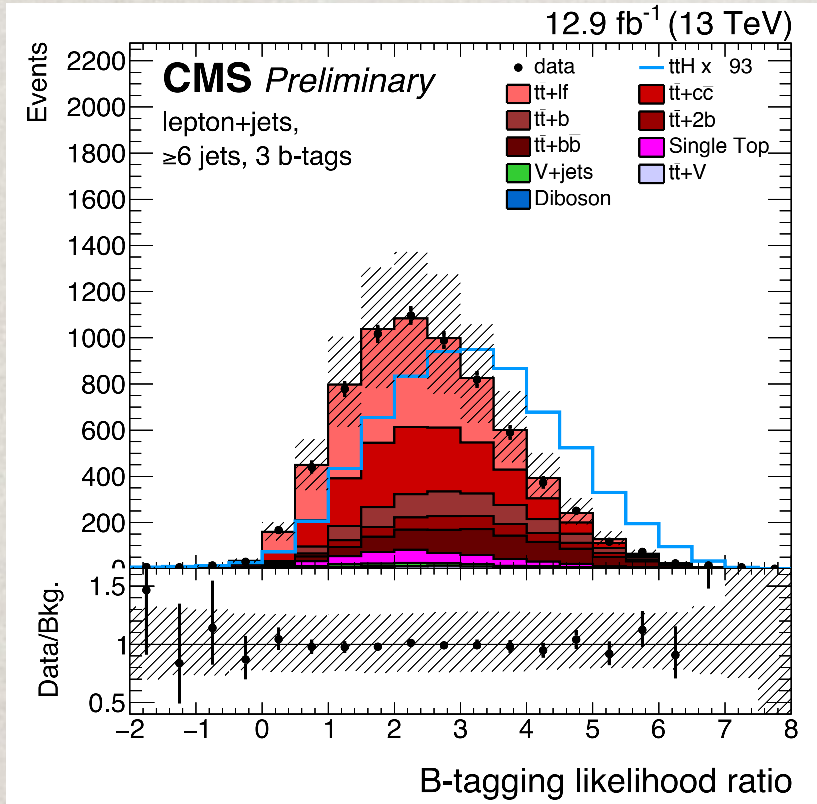
output discriminator

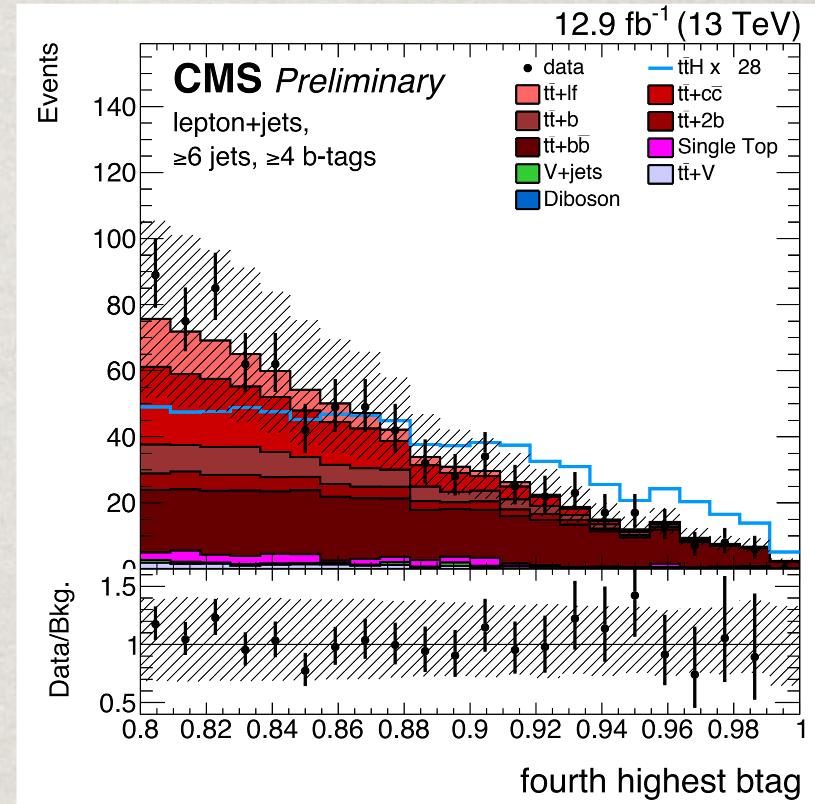
BDT

- BDT training is a machine learning process
  - Aim to classify/separate signal or background
- For the BDT training in each jet/tag category
  - ttH as signal(S) and ttjets as background(B)
- Input variables: CSV tagging, invariant mass, angular correlations, event shapes, and jet Pt variables

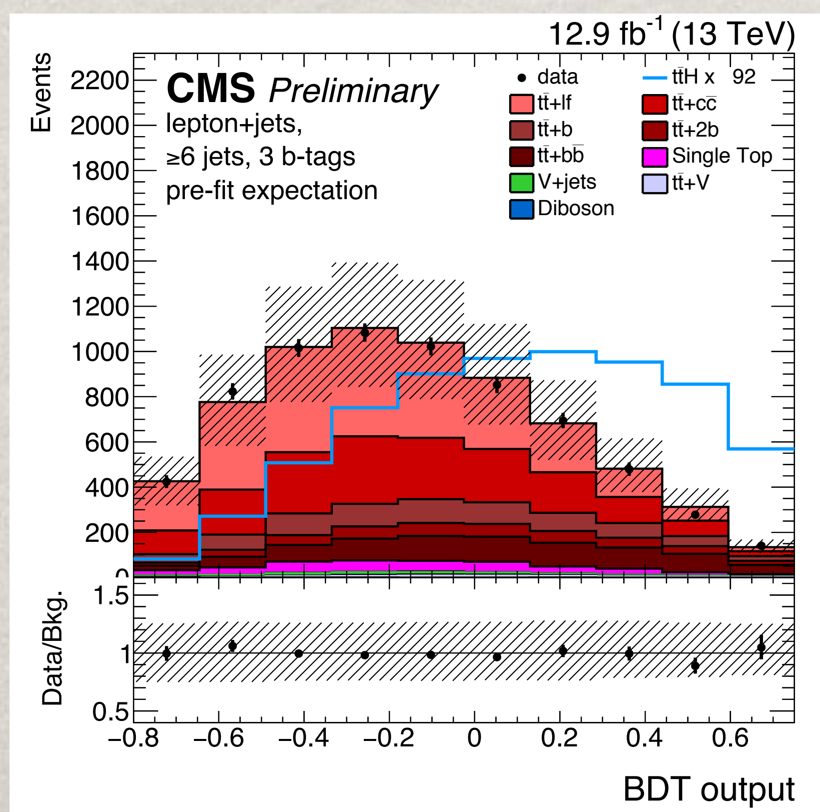
BDT INPUT/OUTPUT

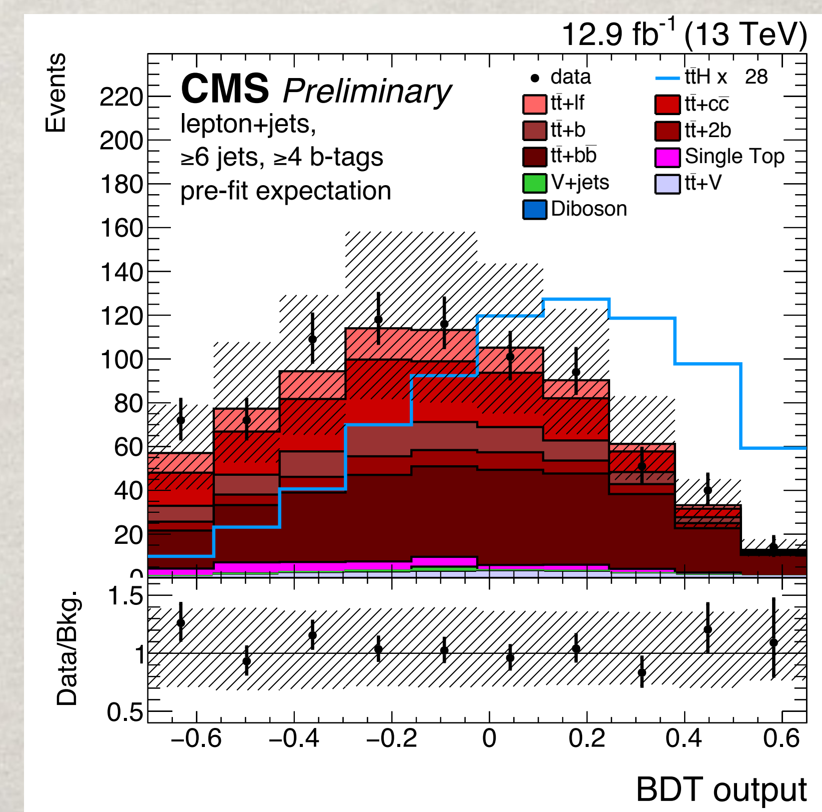
Input variables





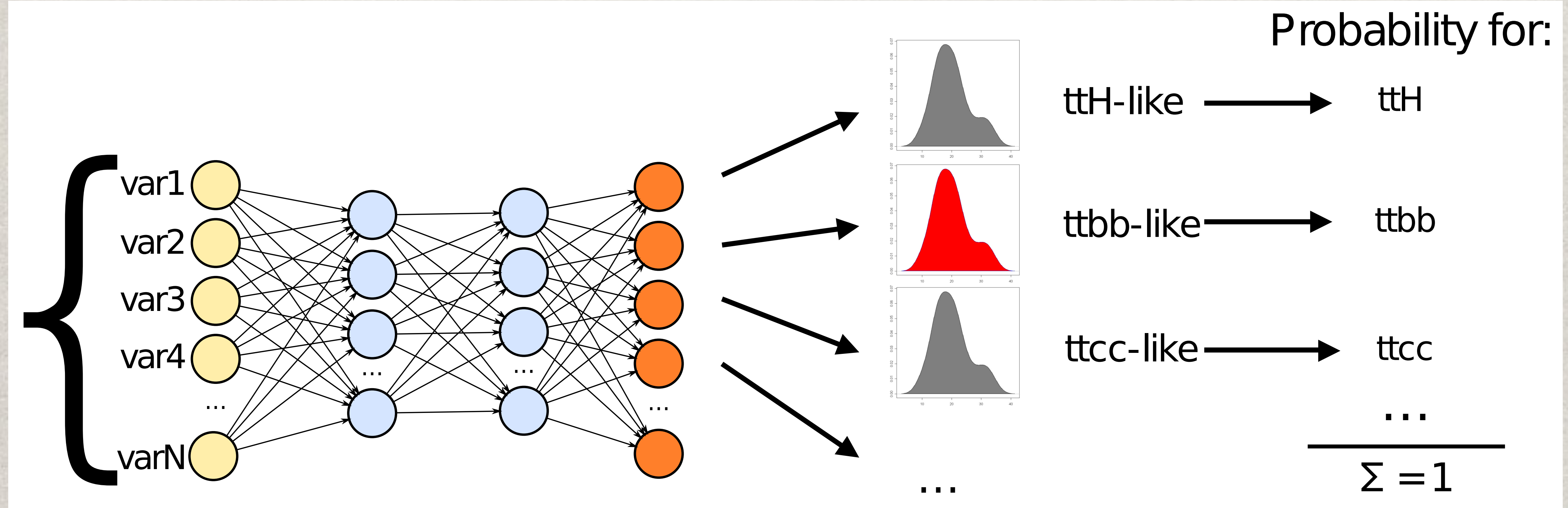
Output variable





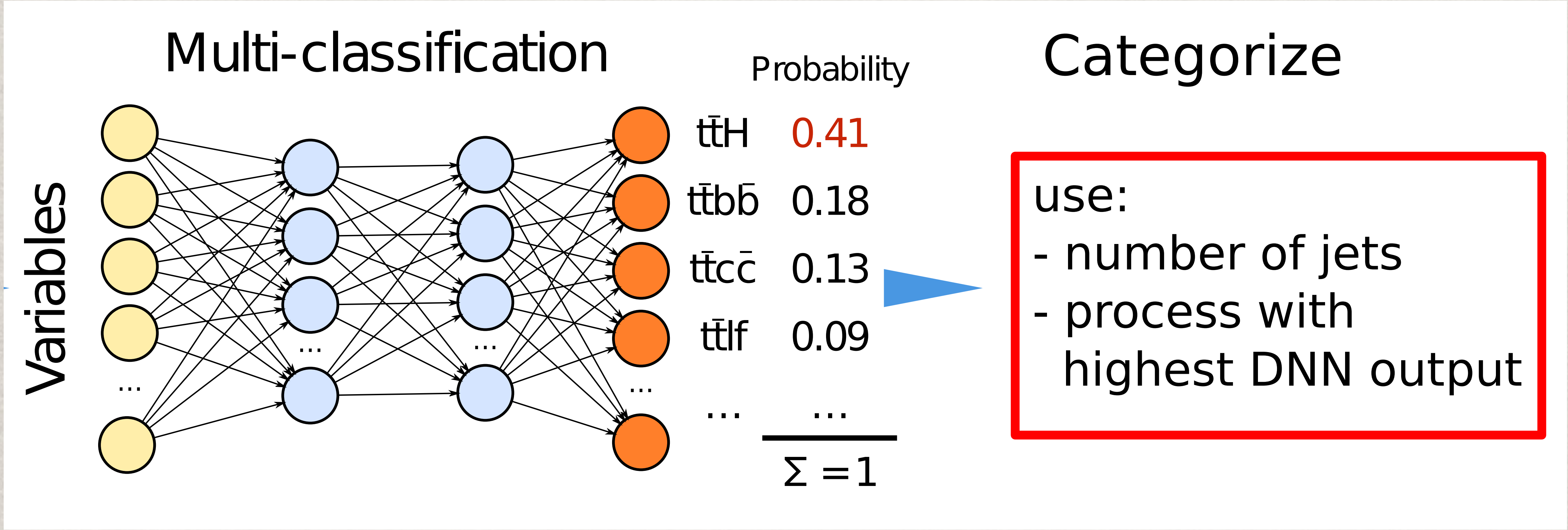
Deep Neural Networks

- Deep Neural Networks(DNNs) is very good at multi-classification:
  - split dominant bkg ttjets into all components
  - BDT only separates ttH from INCLUSIVE ttjets

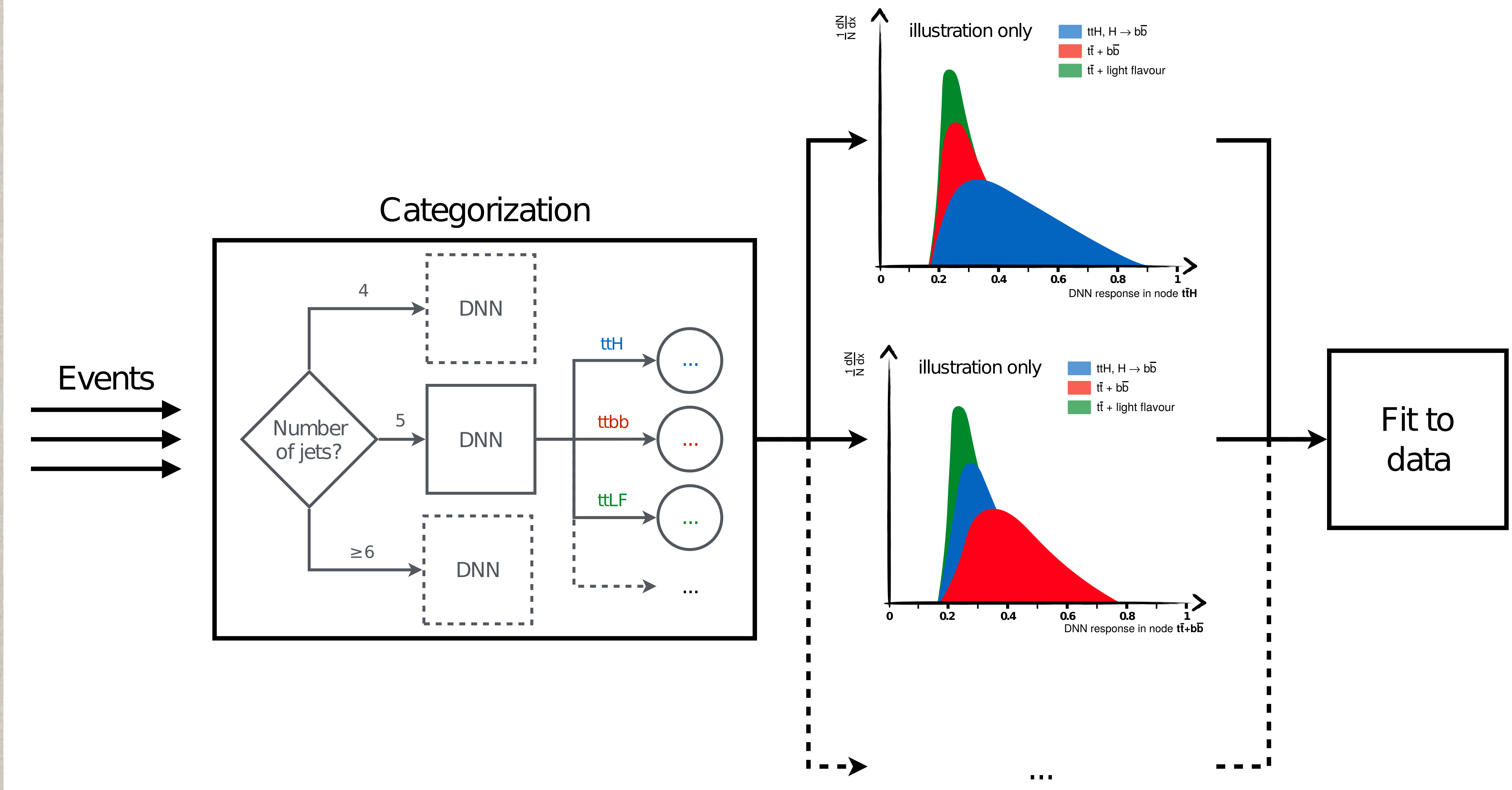


DNN

- Use DNN for alternative categorization, instead of the nJet-nTag scheme
- Use DNN output as final fit discriminant



DNN WORKFLOW



TTBAR+HF

MATRIX ELEMENT METHOD

- Irreducible background ttbb
- Use Matrix Element Method(MEM) to further distinguish ttbb from ttH

Numerical integration

Momentum conservation

Resolution function (allow ISR)

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

Parton density functions

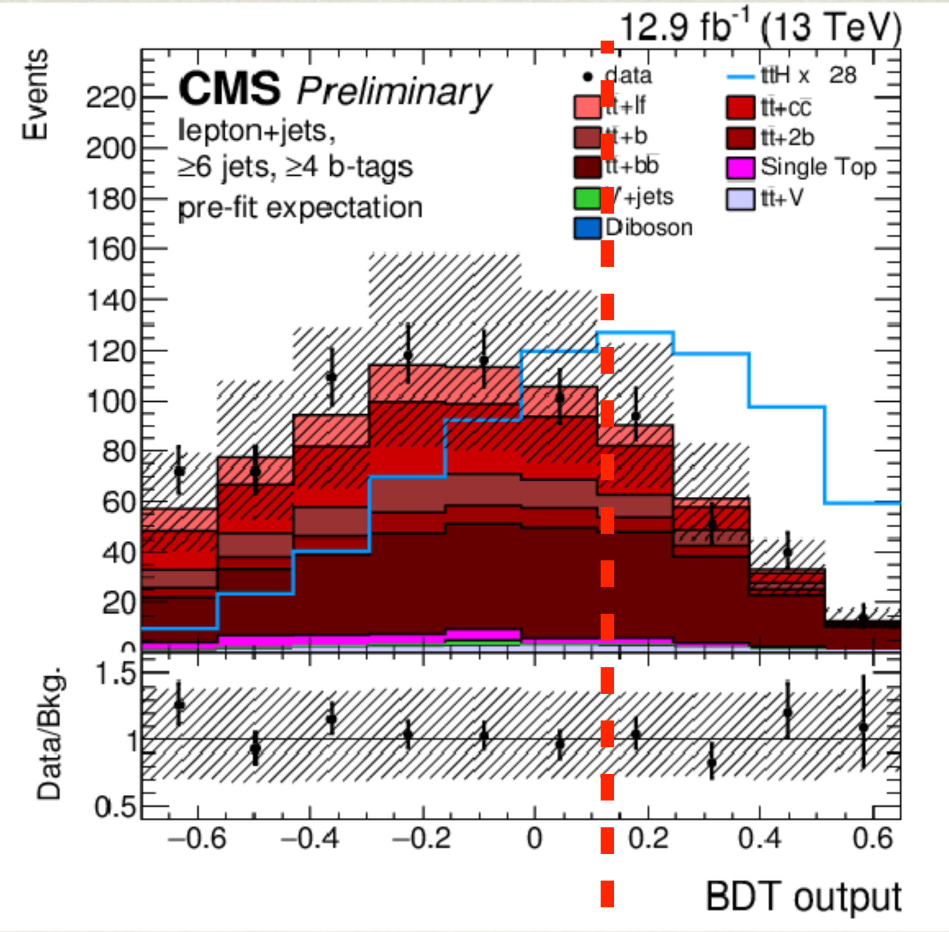
LO Scattering amplitude (Open Loops)

Detector transfer function

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

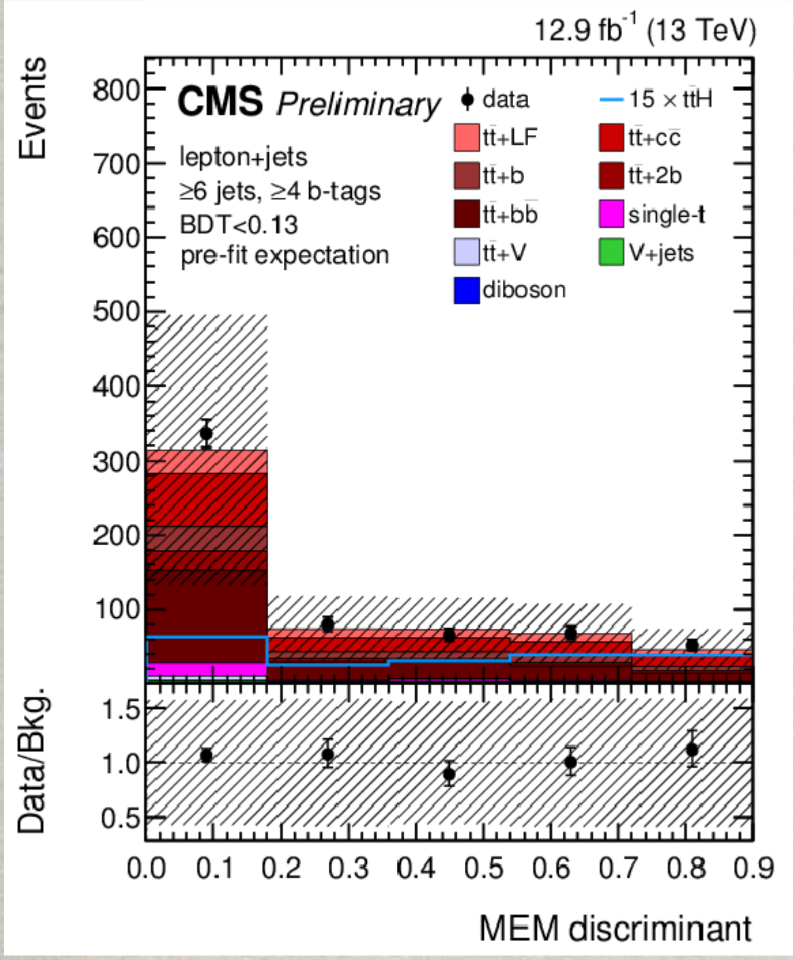
BDT/MEM 2D APPROACH

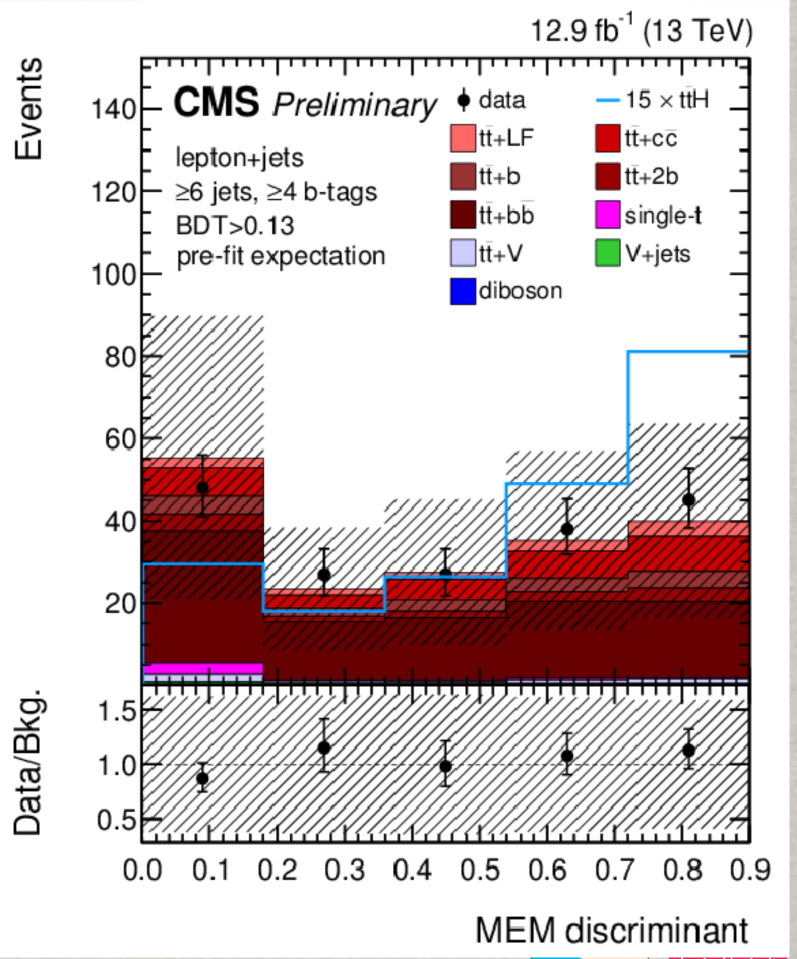
split category at the median of ttH BDT output



low purity

high purity





ADDITIONAL TT+HF UNCERTAINTY

- Contribution from tt+HF very similar to signal
  - uncertainty on rate/shape has a big impact on our search
- Due to lack of more accurate higher order theory predictions, we obtained tt+HF estimate and uncertainty based on the inclusive ttbar sample
- On top of other uncertainty, assign an extra 50% rate uncertainty for tt+bb/b/B/cc independently

RESULTS

FINAL STRATEGY

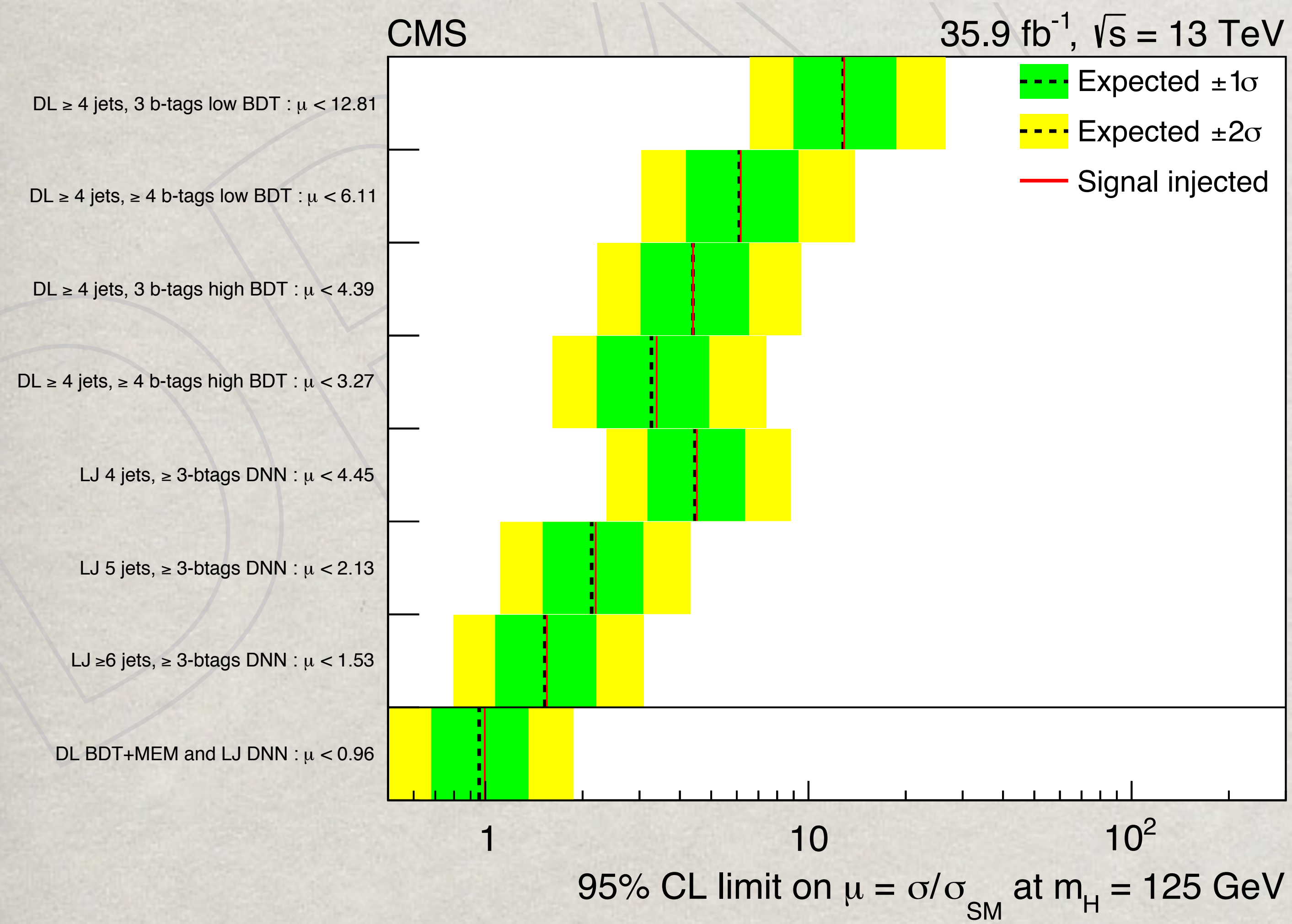
Categorization	Discriminant
nJet-nTag	BDT
nJet-DNN_process	DNN
	MEM

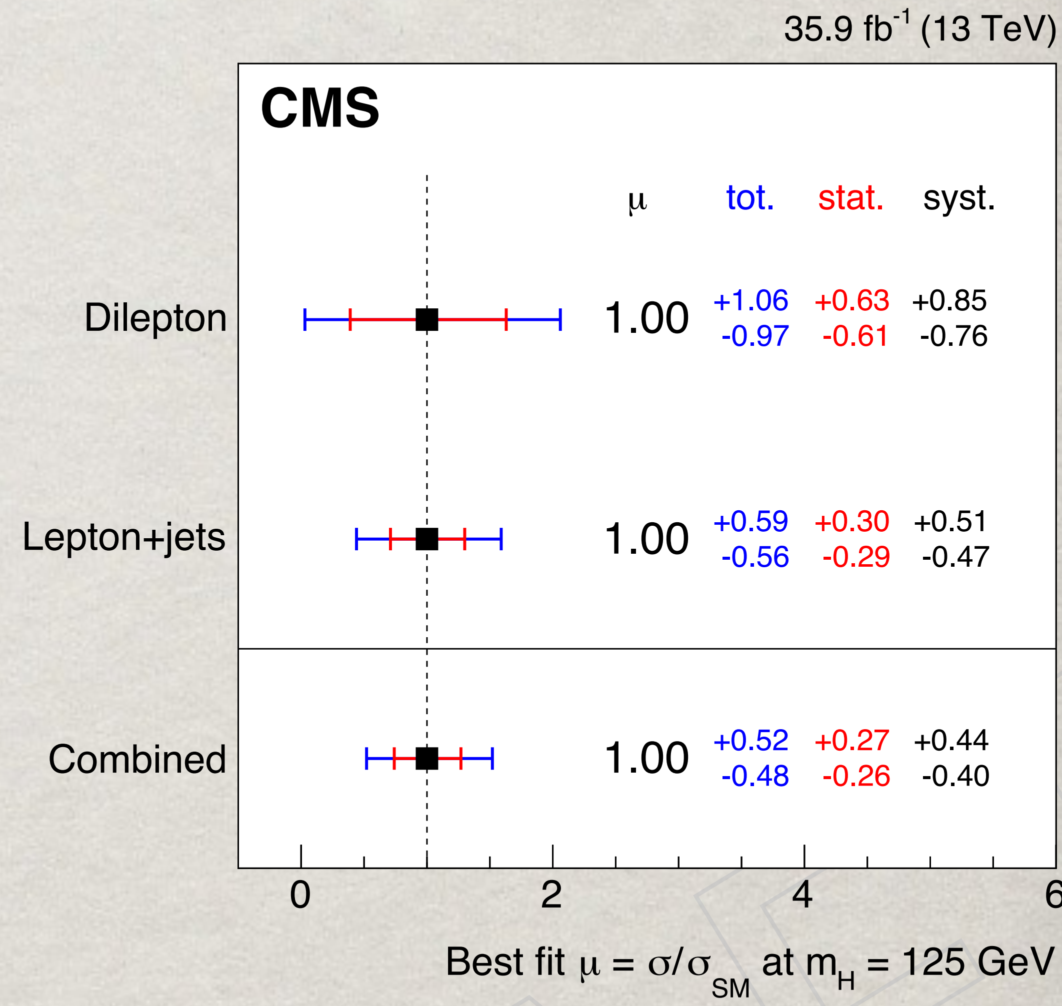
- Various strategies when combining the above steps
- Choose the one with the best sensitivity and robustness
- Use the other strategies as cross-checks

RESULTS SUMMARY

Channel	Analysis	Expected Limit	Best-fit μ	Significance
dilepton	MEM+BLR	$2.93^{+3.44}_{-1.46}$	$1.0^{+1.33}_{-1.50}$	
dilepton	2D BDT+MEM	$2.02^{+0.96}_{-0.61}$	$1.0^{+1.06}_{-0.97}$	1.02
dilepton	DNN	$2.59^{+1.12}_{-0.77}$	$1.0^{+1.34}_{-0.69}$	0.92
single lepton	MEM+BLR	$1.71^{+1.72}_{-0.96}$	$1.0^{+0.86}_{-0.90}$	
single lepton	2D BDT+MEM	$1.29^{+0.55}_{-0.36}$	$1.0^{+0.67}_{-0.66}$	1.49
single lepton	DNN	$1.14^{+0.48}_{-0.33}$	$1.0^{+0.61}_{-0.57}$	1.77
combined	MEM+BLR	$1.43^{+1.43}_{-0.68}$	$1.0^{+0.73}_{-0.76}$	1.38
combined	2D BDT+MEM	$1.07^{+0.45}_{-0.3}$	$1.0^{+0.57}_{-0.55}$	1.8
combined	DNN	$1.04^{+0.44}_{-0.3}$	$1.0^{+0.56}_{-0.53}$	1.99
single-lepton DNN + dilepton 2D BDT+MEM		$0.97^{+0.41}_{-0.28}$	$1.0^{+0.53}_{-0.5}$	2.04

LIMIT AND SIGNAL STRENGTH





Blinded

Channel	Observed UL	Expected UL	Best-fit μ
Dilepton	X.X	$2.0^{+1.0}_{-0.6}$	$1.00^{+1.06}_{-0.97}(\text{tot.})\ ^{+0.63}_{-0.61}(\text{stat.})\ ^{+0.85}_{-0.76}(\text{syst.})$
Lepton+jets	X.X	$1.1^{+0.5}_{-0.3}$	$1.00^{+0.59}_{-0.56}(\text{tot.})\ ^{+0.29}_{-0.29}(\text{stat.})\ ^{+0.59}_{-0.56}(\text{syst.})$
Combined	X.X	$1.0^{+0.4}_{-0.3}$	$1.00^{+0.52}_{-0.48}(\text{tot.})\ ^{+0.27}_{-0.26}(\text{stat.})\ ^{+0.44}_{-0.40}(\text{syst.})$

TTH@LHC

- Most recent $t\bar{t}H$ results by ATLAS and CMS (significance, $\mu_{t\bar{t}H} = \sigma_{t\bar{t}H}/\sigma_{SM}$)

	ATLAS 36.1 fb^{-1}	CMS
Run-1 combination	JHEP **1608** (2016) 045 4.4σ (exp: 2.0σ) $\mu_{t\bar{t}H} = 2.3^{+0.7}_{-0.6}$	
$t\bar{t}H(b\bar{b})$	**ATLAS-CONF-2017-076** 1.4σ μ= 0.84 $^{+0.64}_{-0.61}$	CMS-PAS-HIG-16-038 (13 fb^{-1}) $\mu_{t\bar{t}H} = -0.19 \pm 0.8$
$t\bar{t}H$ multilepton	**ATLAS-CONF-2017-077** 4.1σ μ= 1.6 $^{+0.5}_{-0.4}$	CMS-PAS-HIG-17-004 (ℓ only) 3.3σ (exp: 2.5σ) $\mu_{t\bar{t}H} = 1.5 \pm 0.5$ CMS-PAS-HIG-17-003 (τ_{had}) 1.4σ (exp: 1.8σ) $\mu_{t\bar{t}H} = 0.72^{+0.62}_{-0.53}$
$t\bar{t}H(ZZ \to 4\ell)$	ATLAS-CONF-2017-043 $\mu_{t\bar{t}H} < 7.7$	arXiv:1706.09936 $\mu_{t\bar{t}H} < 1.18$
$t\bar{t}H(\gamma\gamma)$	ATLAS-CONF-2017-045 1.8σ (exp: 1.0σ) $\mu_{t\bar{t}H} = 0.5 \pm 0.6$	CMS-PAS-HIG-16-040 3.3σ (exp: 1.5σ) $\mu_{t\bar{t}H} = 2.2^{+0.9}_{-0.8}$

SUMMARY

- ttH(bb) directly probes directly top-Higgs coupling
- It also has a few challenges:
  - Small production XS: split events to channels/categories
  - Higgs invariant mass not applicable: use BDT/MEM to extract signal
  - Difficult tt+HF bkg: MEM, extra uncertainty
- Latest results are approaching SM sensitivity
- Expecting '5σ' significance for combined 13TeV ttH searches with both 2016 and 2017 data

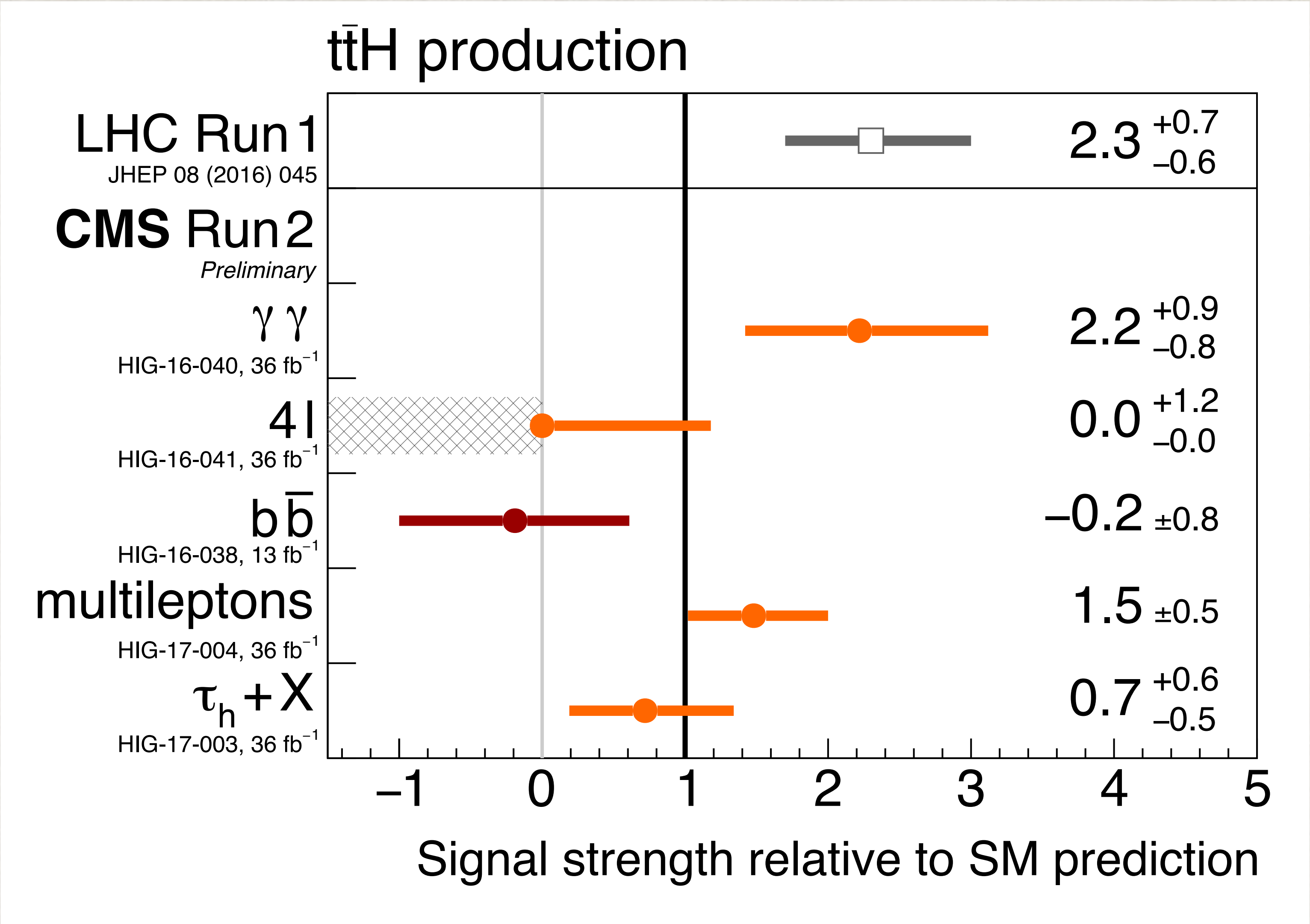
BACK UP

BDT TRAINING

- BDT training is a machine learning process
- Aim to classify/separate signal or background
- For the BDT training in each jet/tag category
  - ttH as signal(S) and ttjets as background(B)
  - events split in half: one for training and one for testing of overtraining

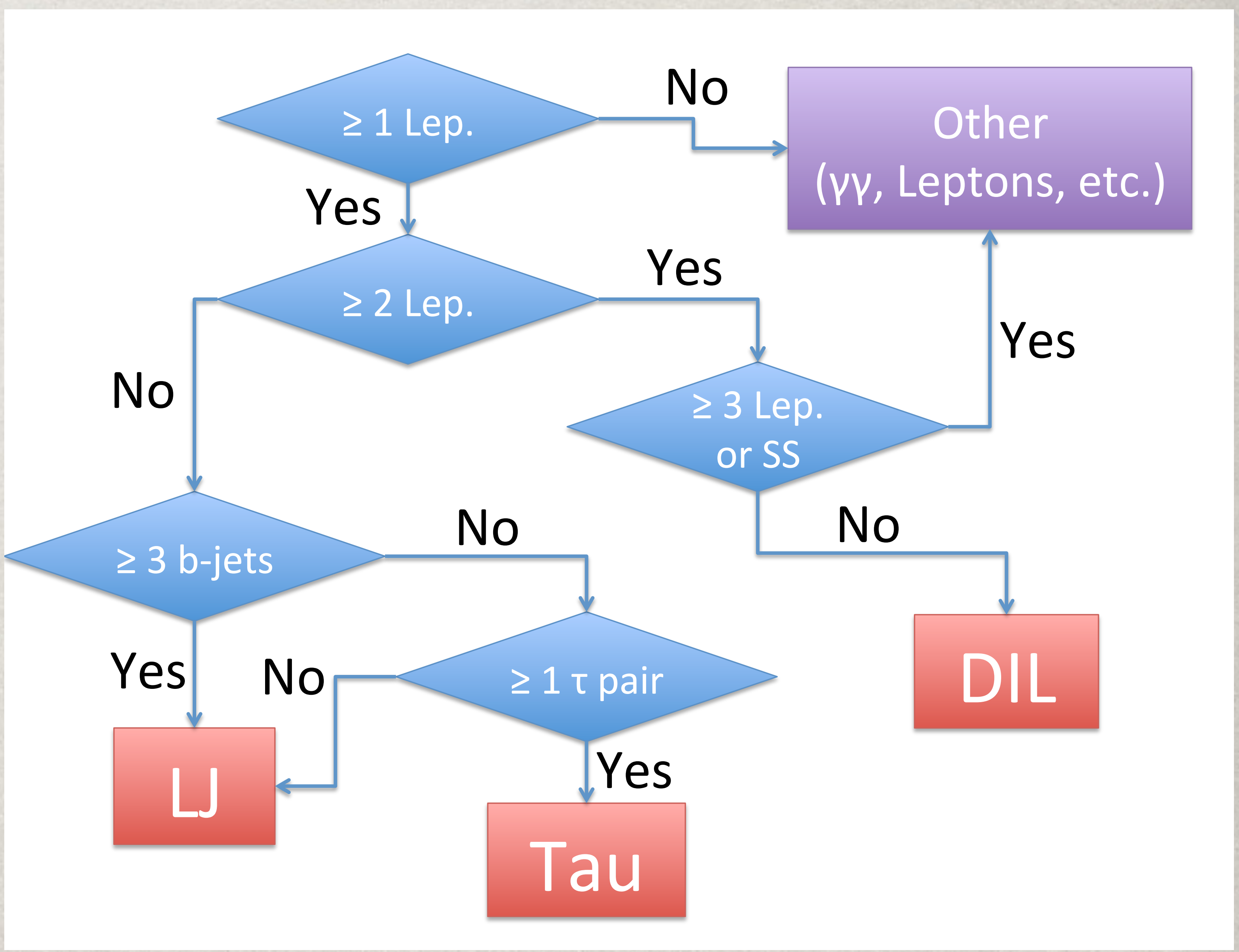
OUTLOOK

- Updated ttH(bb) results with 36/fb data come out soon
- Combined 13 TeV ttH searches(all decay modes) might yield interesting findings



SEARCH CHANNELS

- Different channels based on top pair decay(number of leptons) and Higgs decay(number of b-jets)



III: Matrix Element

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

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

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

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

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

Ideal for final states with many reconstructed objects.

Built for ttH(bb) vs ttbb

SYSTEMATIC UNCERTAINTIES

- PileUp re-weighting: use 69.4 mb ± 7%
- Lepton SF
  - independently vary id and HLT efficiency
- b-tag SF
- top Pt reweighting
- JER and JES
  - JER has a negligible effect on shape or normalization
- Luminosity: 4.4%
- Cross section
  - Use CMS standard model cross section uncertainties
- MC statistics
- Q^2 scale for MadGraph ttjets
- extra 50% rate uncertainty for tt+HF
- Tau efficiency, Tau fake-rate and Tau energy scale

DATA/MC AGREEMENT: LJ

- All corrections to MC applied
- Good agreement between Data and MC