ETH Institute for Particle Physics

Higgs boson production in association with a top quark pair: ttH(bb) with MEM

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First Annual Meeting of ITN HiggsTools

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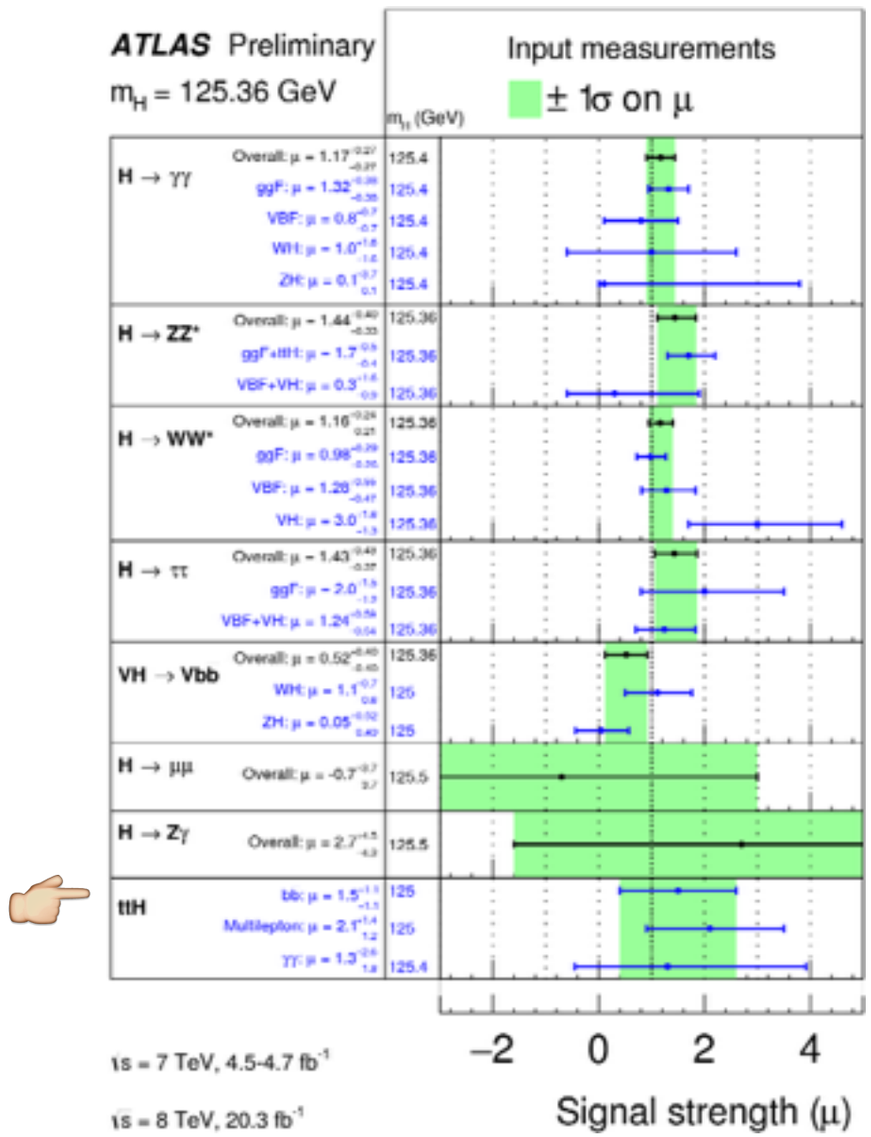
ETH zürich

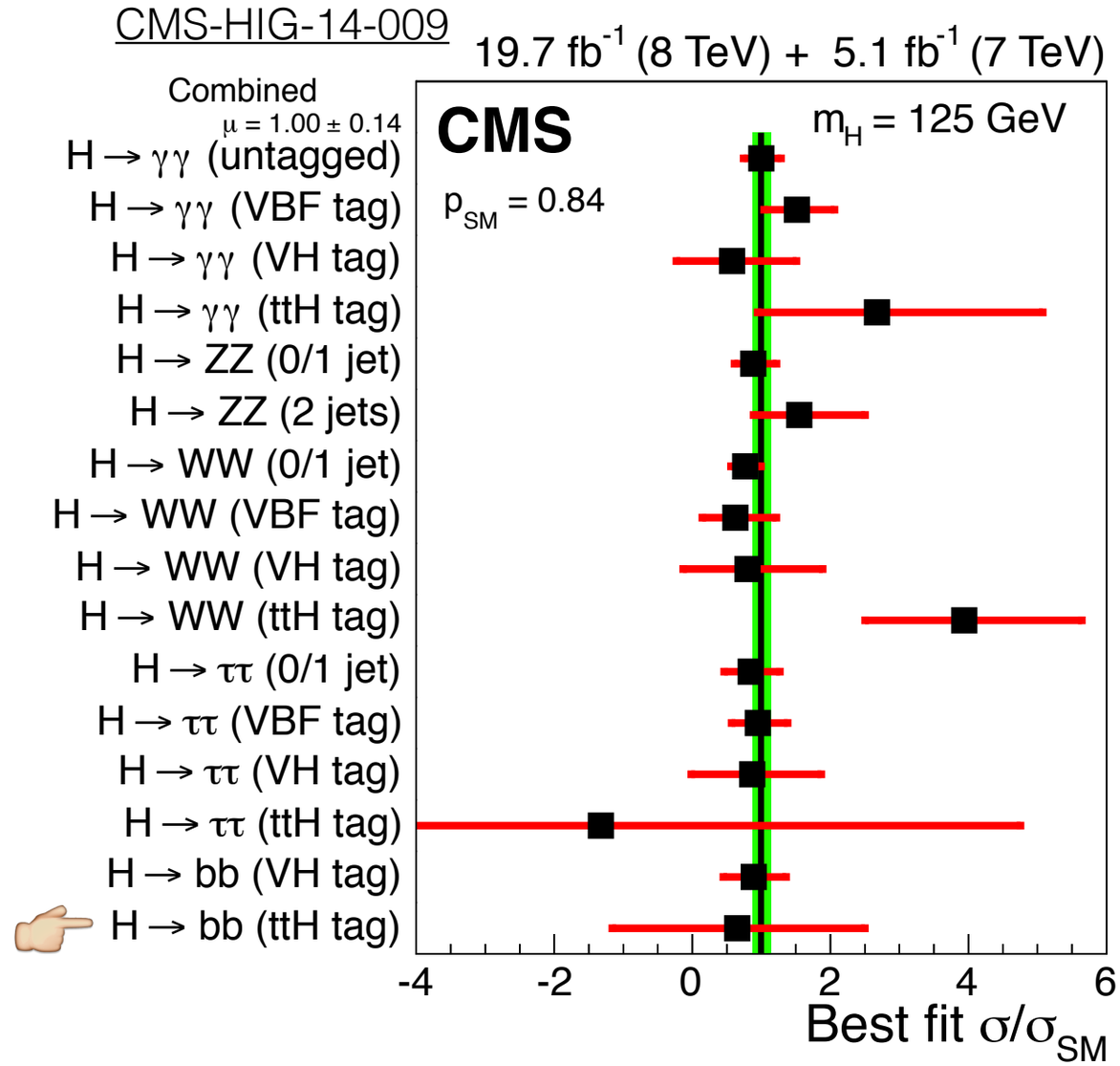
higgstools

What we know about H(125)

ATLAS-CONF-2015-007



CMS-HIG-14-009



H(125) coupling data mostly consistent with SM Higgs boson, but small differences could be very interesting!

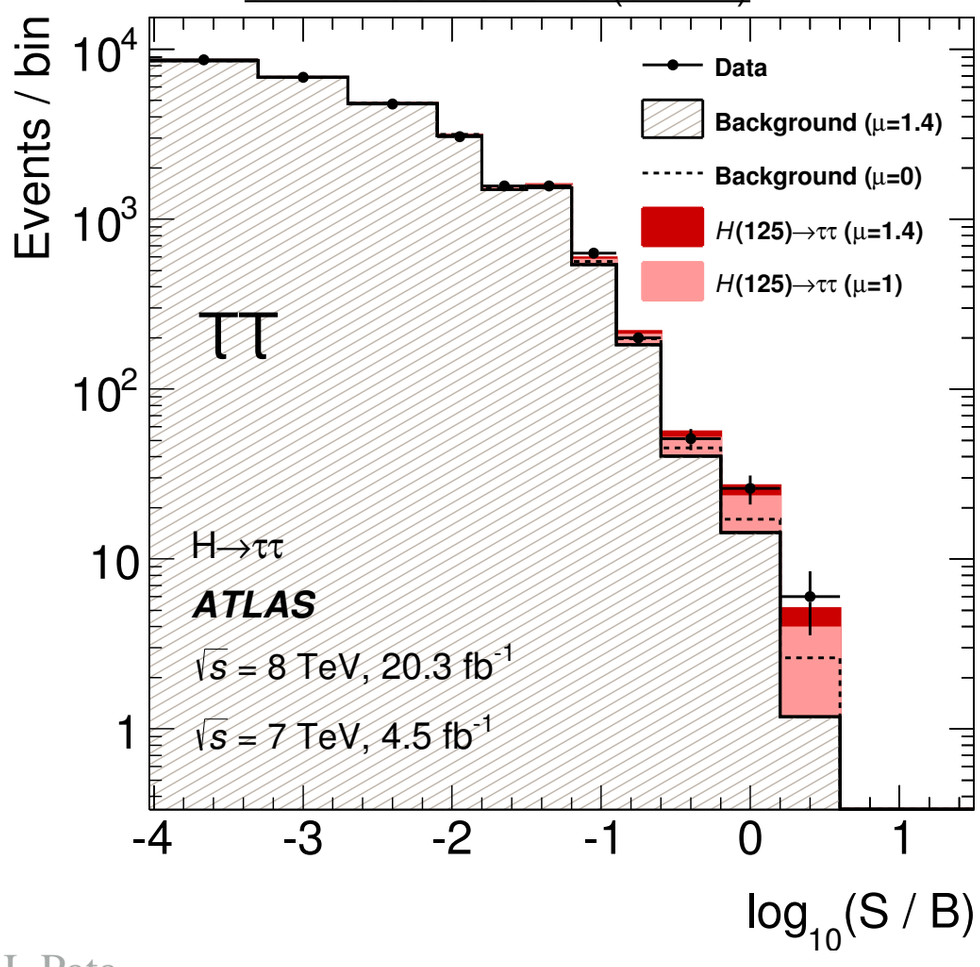
Reaching the precision measurement phase!

Coupling to fermions

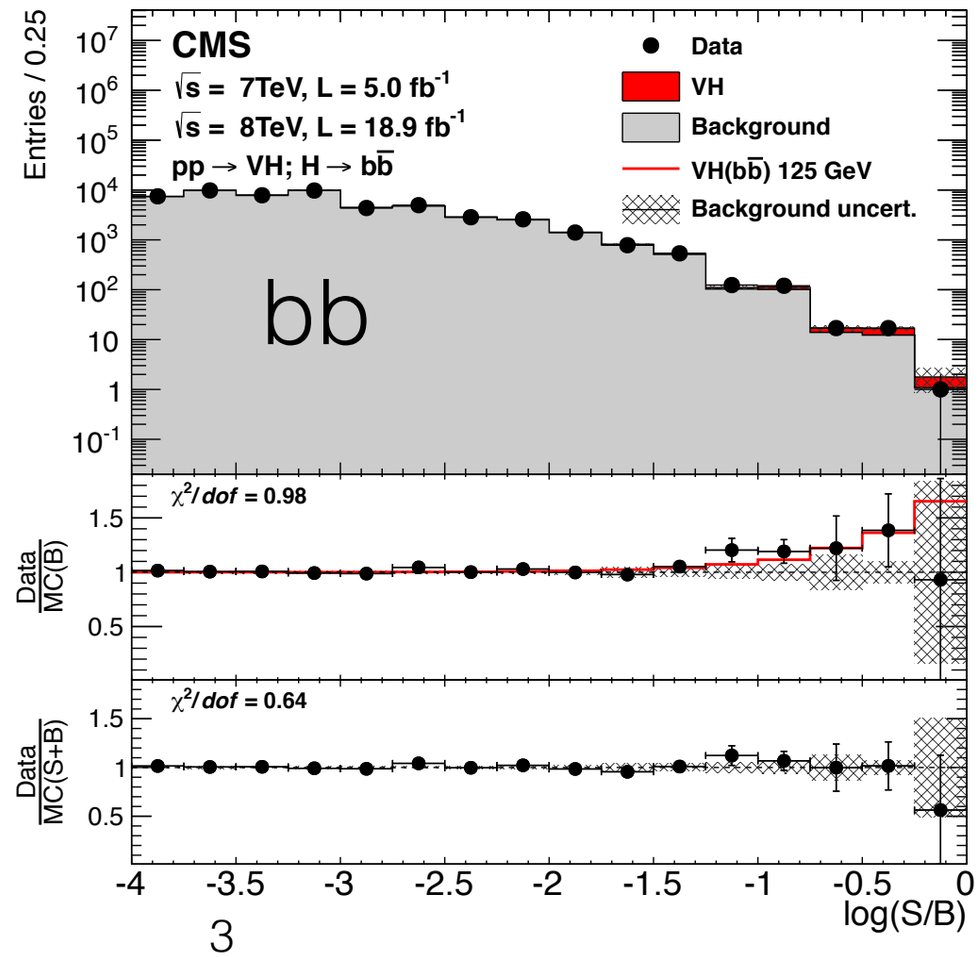
Verify EWSB mass generation by comparing **SM H decay to fermions to measurements**.

Direct evidence **down-type** (b, tau), indirect to **up-type** (top loops).

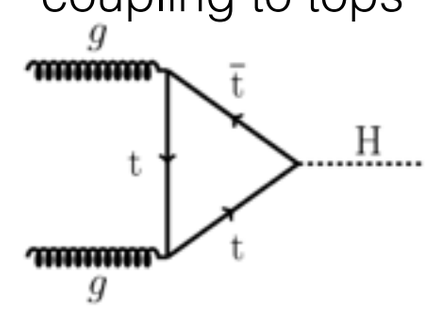
arXiv:1501.04943 (JHEP)



1310.3687 (PRD)

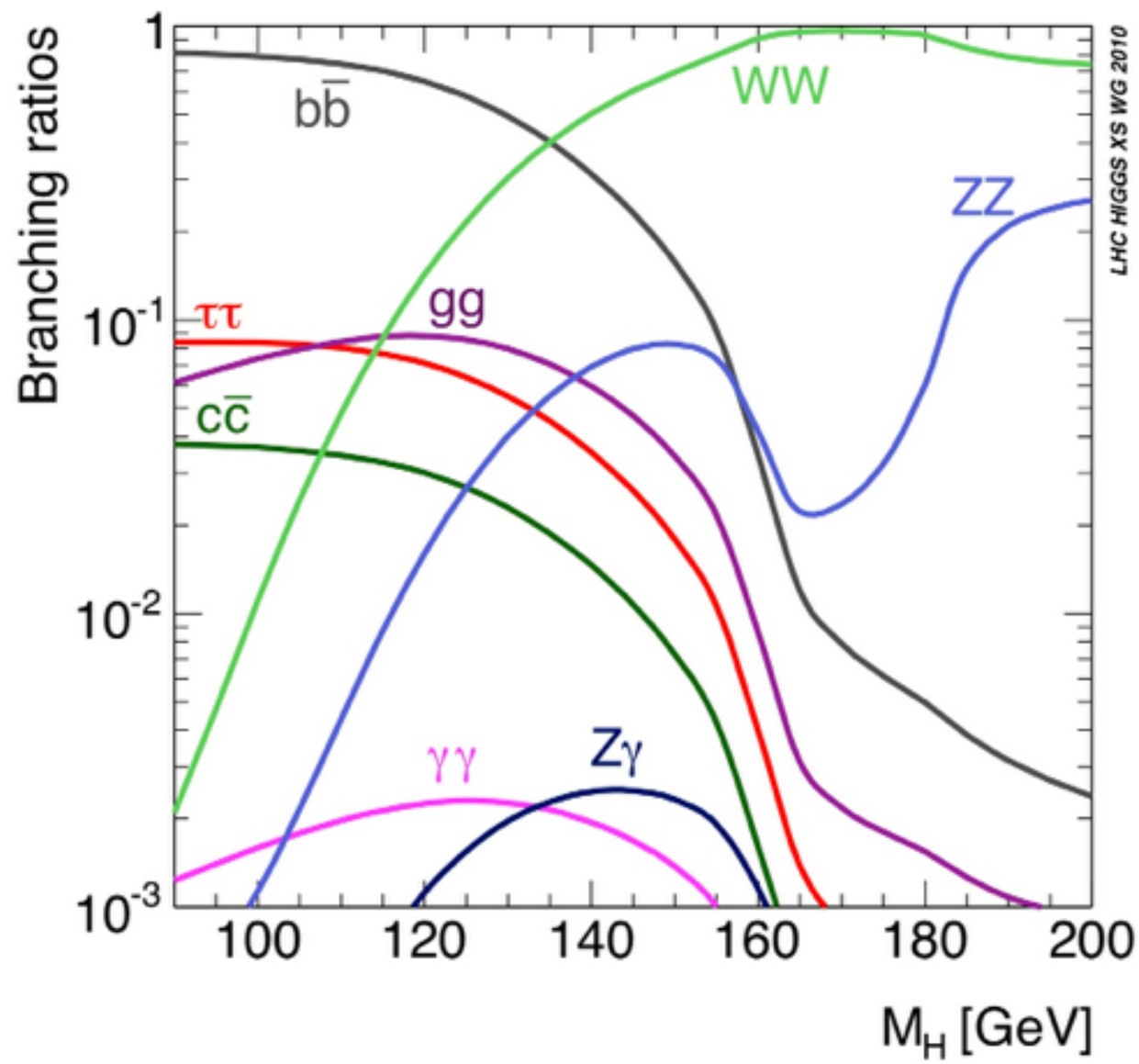


indirect evidence for coupling to tops



What to look for?

H(125) near-ideal for **bb** statistics-wise, but a very complicated final state.

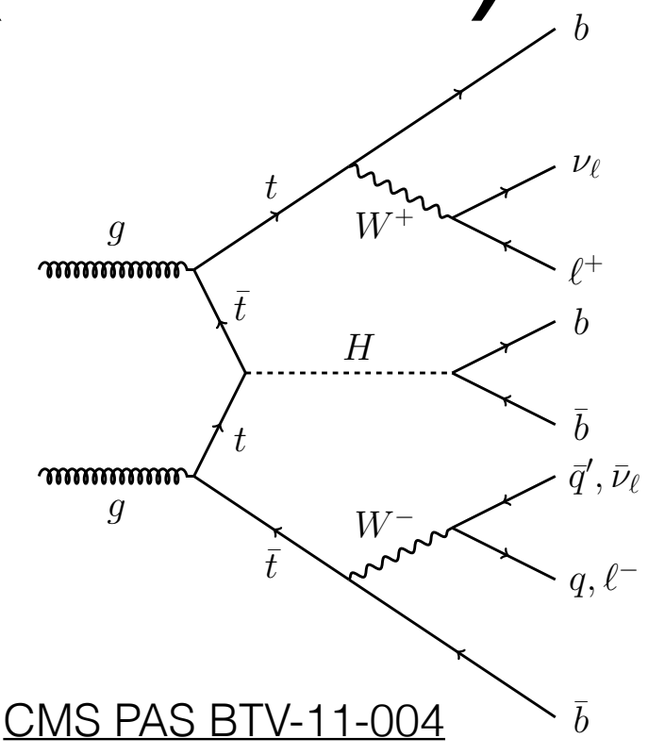


Case study: ttH(→bb)

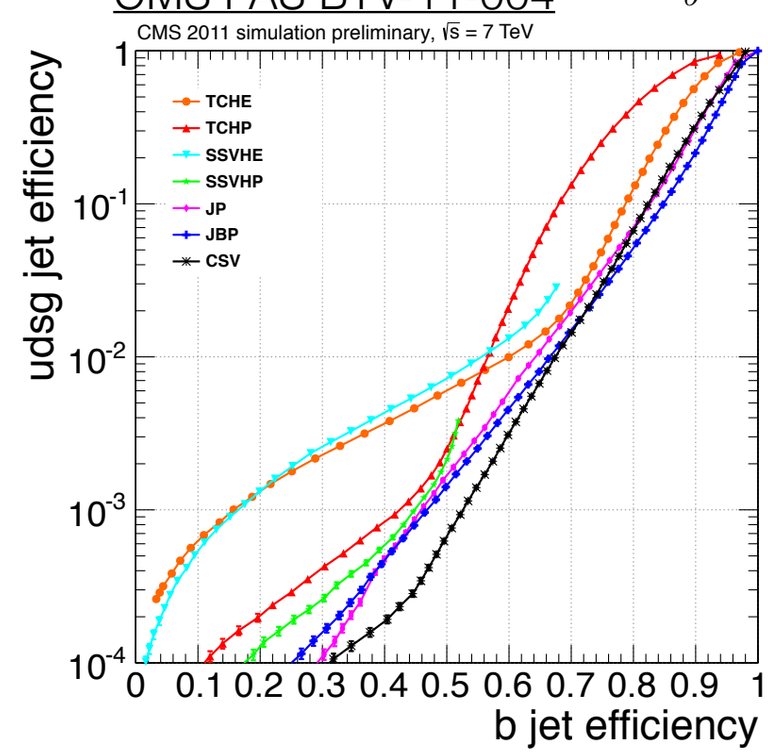
H(125) → decays to b-quarks most abundant.

Multi-jet events with high b-quark multiplicity are a prolific source of ttH.

The experiments are good at detecting jets from b-quarks: **1-2% udsg** fake rate with **70% b-quark** efficiency



CMS PAS BTV-11-004



Data & models

ATLAS and **CMS**: 5+20 fb^{-1} of 7 and 8 TeV collision data with lepton triggers -> 3.9 x 10^3 ttH events [CERN-2013-004], 55 (65) % gg->H at (N)LO in 8 TeV, more in 13 TeV

signal: LO->NLO simulation for tt+H, corrected to NNLO + leading log, Pythia (aMC@NLO at 13 TeV)

tt+bb: LO -> NLO, significant theoretical uncertainties, combine predictions from multiple generators, NLO recently available with Sherpa +OL

tt+cc, tt+light: LO (MG5), empirical corrections to top-antitop system and top quark kinematics.

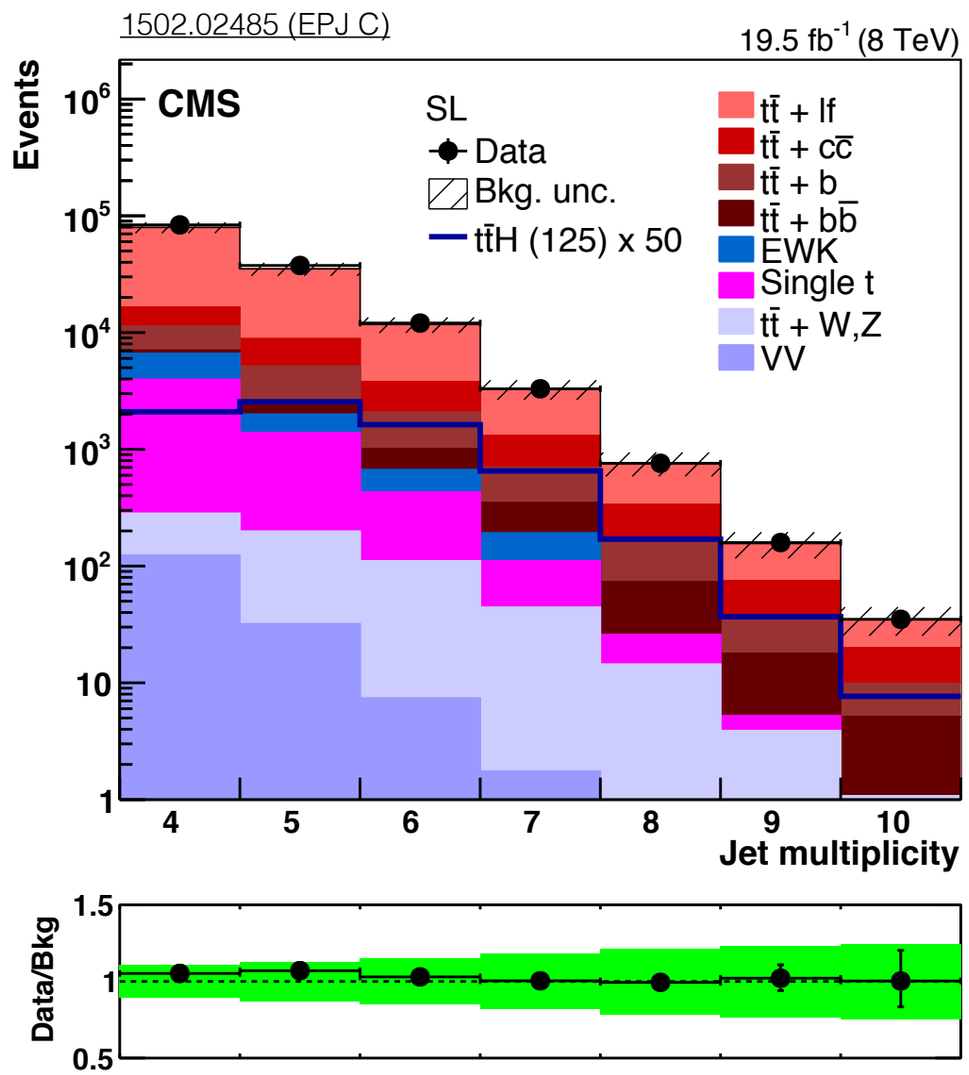
minor: single-top: NLO (aMC@NLO), W/Z+jets, diboson

Reconstruction and selection

Require 1-2 isolated e/mu → multi-jet QCD

4 or more jets, b-jets based on impact parameter and SV properties. → single top, EWK

b-tagging for tt+heavy vs. light: N_b, likelihood discriminant, MVA → tt+light



b-tagging
tt+heavy vs. tt+light

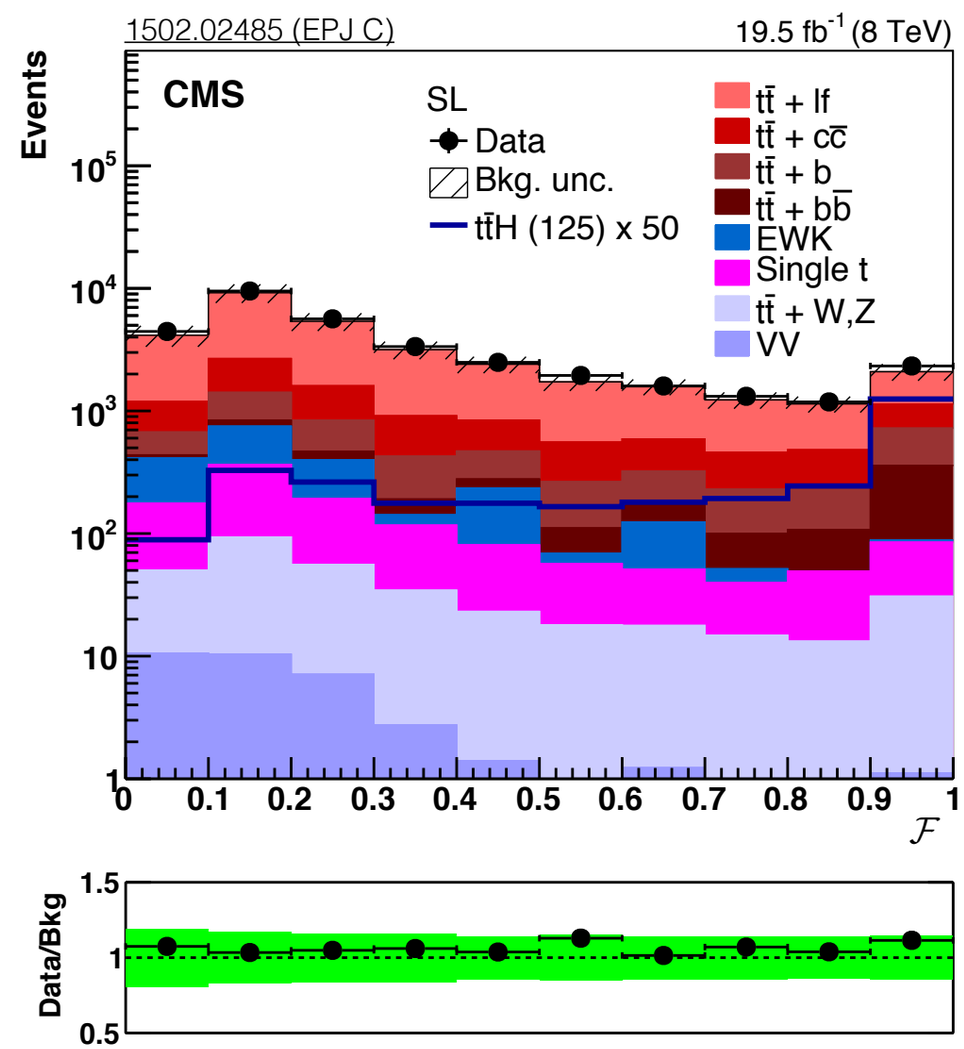
Assume uncorrelated jet b-discriminants → likelihood ratio

$$\mathcal{F}(\vec{\xi}) = \frac{f(\vec{\xi}|\mathrm{t\bar{t}+hf})}{f(\vec{\xi}|\mathrm{t\bar{t}+hf}) + f(\vec{\xi}|\mathrm{t\bar{t}+lf})}.$$

Optimal discriminant: sum over probabilities of possible permutations for associating 6 FS jets to 4(2) signal (background) b-quarks.

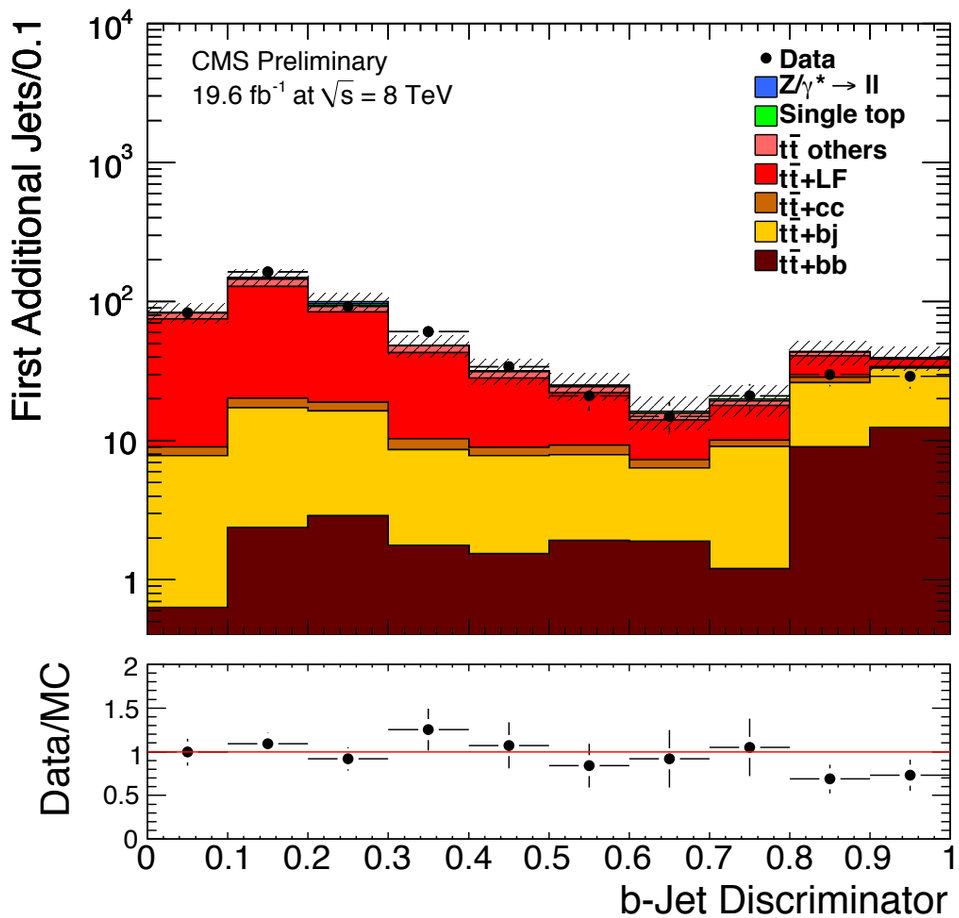
Use tt+jets enriched, signal poor regions to constrain uncertainties on the backgrounds.

MEM applied only on events compatible with signal final state topology.



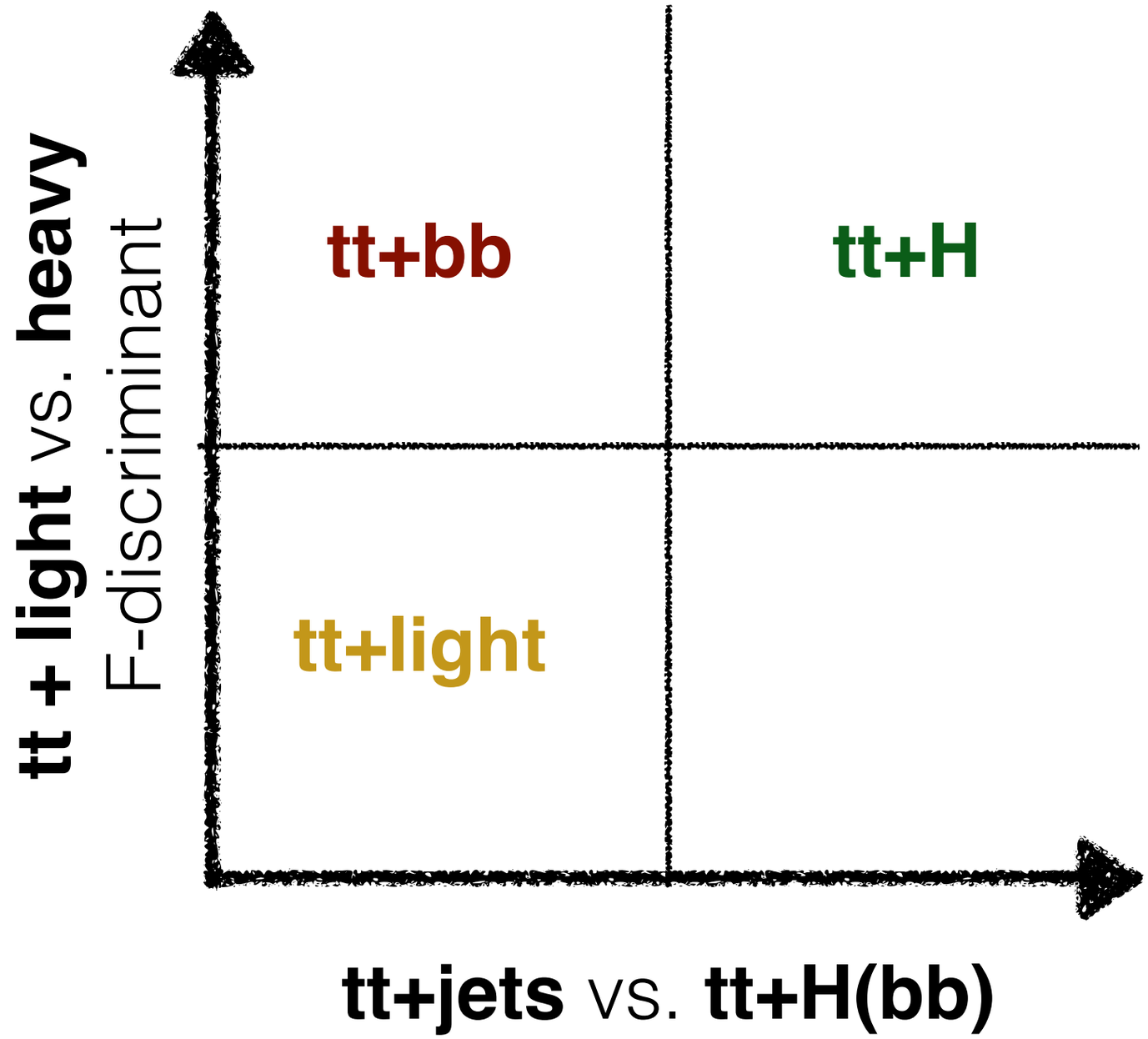
Combined discrimination

CMS-TOP-13-010



$\sigma(ttbb)/\sigma(ttjj)$

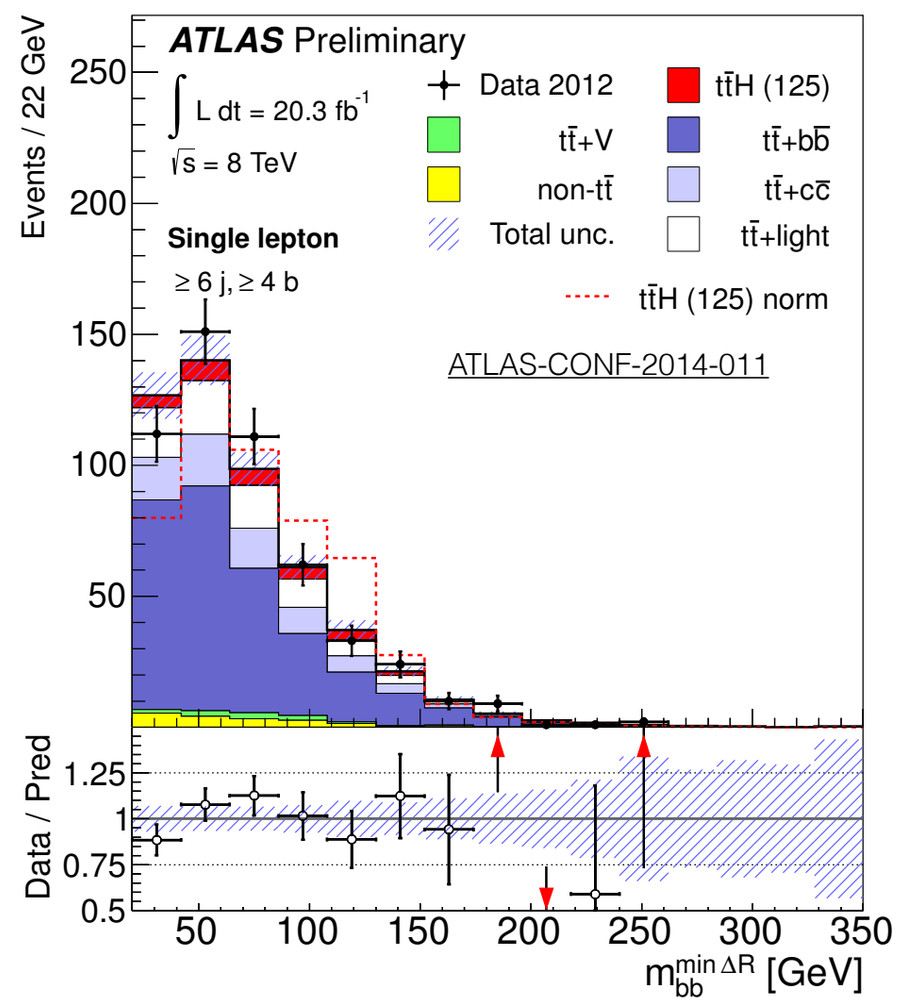
$0.023 \pm 0.003 \pm 0.005$



Dijet mass

We could reconstruct H(→bb) system invariant mass, but how to choose the right b-jet candidates?

H(→bb) smeared out due to combinatorics.



Main problems

tt+jets without H resonance dwarfs the signal by several orders of magnitude.

Not all particles are measured, need to account for unknown neutrino momenta, jet resolution.

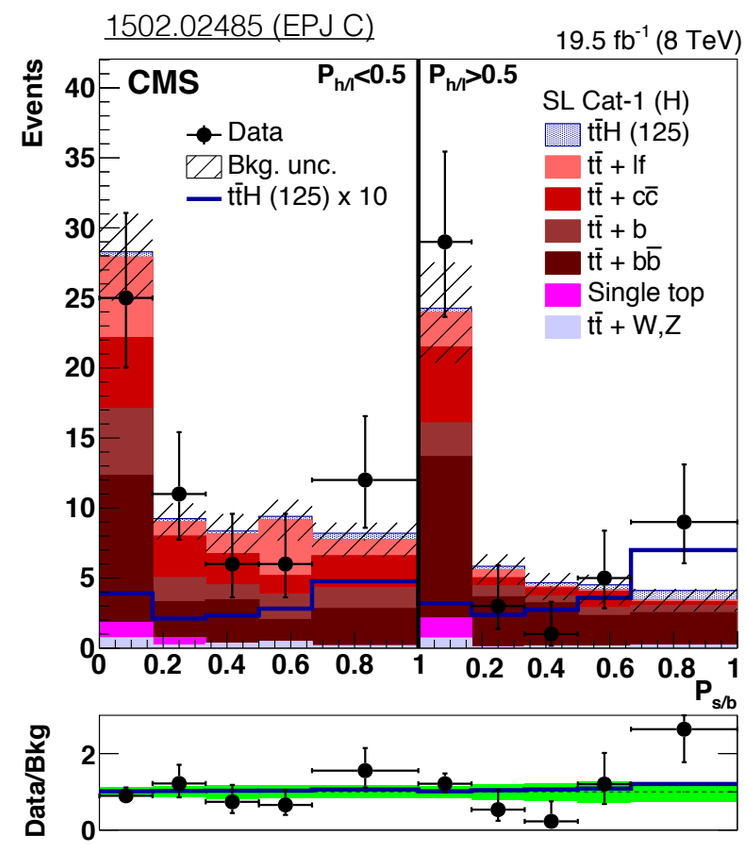
Extracting the signal

Reconstructed event → probability density value from theoretical models: Matrix Element Method (MEM), **full use of kinematics** in LO.

Unknown, poorly measured quantities → integrated out directly.

- **combinatorics** for associating the multi-particle final state to the theoretical model.

High-level features: **neural networks** (NN) or **boosted decision tree** (BDT) -> exploit best simulation (NLO), but little physical insight, need high statistics.

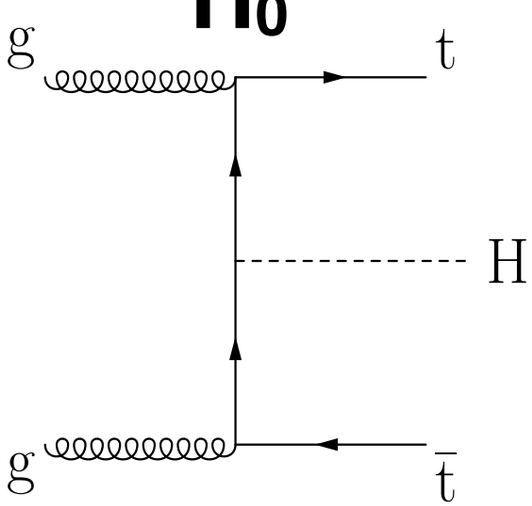


Matrix Element Method

Y - measured event properties

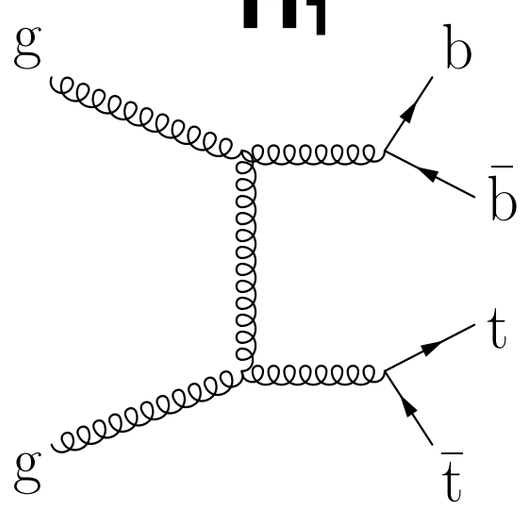
X - "true" parton-level quantities

H_0



or

H_1



likelihood ratio

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

$$f(Y \mid H_0, \lambda) = 1/\sigma(H_0, \lambda) \int dX \int dx_a dx_b\, \Phi(x_a, x_b)\, |\mathcal{M}(X \mid H_0, \lambda)|^2\, W(Y,X)$$

PDF

amplitude

exp. resolution

ME details

OpenLoops-based.

Verified against MadWeight at discriminator-level.

10-100 CPU-sec / event.

Integration via VEGAS, PDF using LHAPDF.

Detector effects encoded in transfer functions.

assumptions

No spin correlations.

Leading order only - no p_t etc.

Narrow-width t, W, H.

Only ggH.

Require b-tagging of b-quarks (F-discriminant).

ME is just a discriminator, need not be fully theoretically sound.

An approximation already does a very good job.

Categories

Reconstructed event

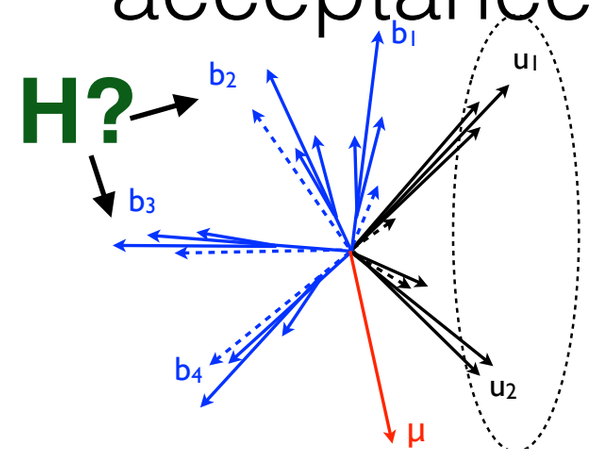
Interpretation

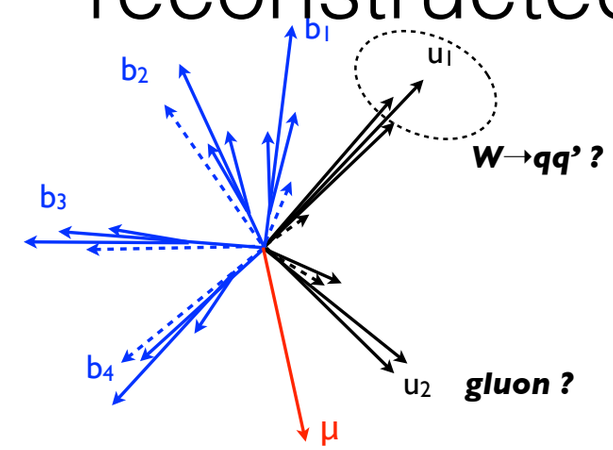
Integration

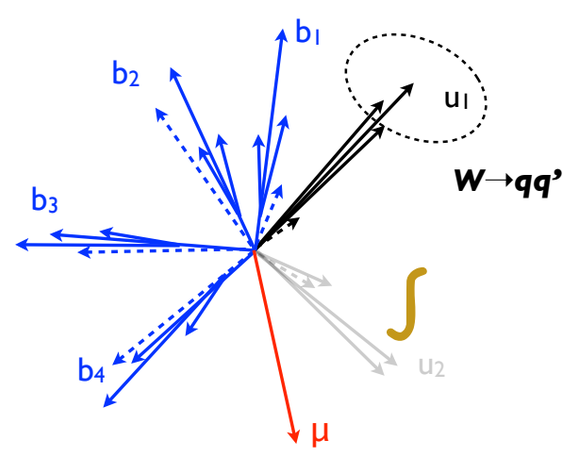
Discriminant **P**

W→qq' in acceptance

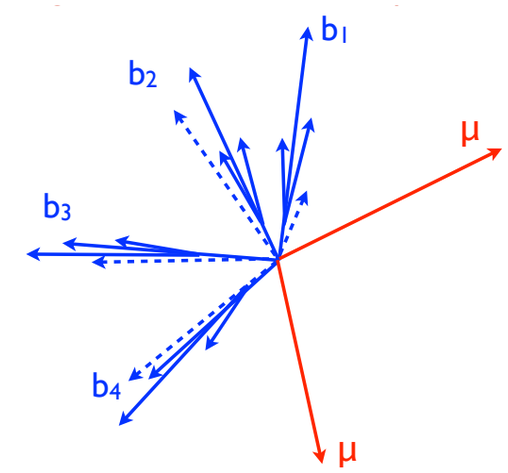
one light quark not reconstructed







SL



DL 4!/2!2!

Yields

after selecting the high-purity heavy flavour region

S/B ~ 2-3%, ~15 tt+H(bb) events

	SL Cat-1 (H)	SL Cat-2 (H)	SL Cat-3 (H)	DL (H)
b-tagging selection	$0.995 \leq \mathcal{F} \leq 1.000$	$0.993 \leq \mathcal{F} \leq 1.000$	$0.995 \leq \mathcal{F} \leq 1.000$	$0.925 \leq \mathcal{F} \leq 1.000$
$t\bar{t}H$	3.5 ± 0.7	5.9 ± 1.1	7.5 ± 1.4	4.5 ± 0.7
+lf	17 ± 3	70 ± 13	152 ± 21	84 ± 11
$+c\bar{c}$	22 ± 8	66 ± 20	81 ± 24	85 ± 24
+b	16 ± 8	44 ± 23	70 ± 32	47 ± 23
$+b\bar{b}$	43 ± 11	75 ± 17	69 ± 18	50 ± 13
+W/Z	3.2 ± 0.8	4.4 ± 1.1	4.2 ± 1.0	5.1 ± 1.1
Single t	3.1 ± 1.4	5.3 ± 2.2	14 ± 4	5.9 ± 1.7
W/Z+jets	—	0.3 ± 2.2	—	6 ± 5
Total background	103 ± 11	265 ± 24	390 ± 28	283 ± 24
Data	107	272	401	279
S/B ($S/\sqrt{B}$)	3.4% (0.34)	2.2% (0.36)	1.9% (0.38)	1.6% (0.27)

Uncertainties

Differential (shape) and **inclusive** (normalization) cross-sections affected.
Fit **μ** within uncertainties. CL based on profile likelihood q(μ) properties

$$q(\mu) \;=\; -2\ln\left[\mathcal{L}\left(\mu,\hat{\theta}_{\mu}\right)/\mathcal{L}\left(\hat{\mu},\hat{\theta}\right)\right]$$

tt+jets modelling: tt+heavy flavour cross-section (data → 15-20%), renormalization, factorization and resummation scale and functional form, shower recoil, PDF choice, MPI, FSR, top quark and top pair kinematics.

Jet energy **scale** and **resolution**: study constraining in-situ.

B-tagging: discriminator distributions, not only total efficiencies need to be modelled well -> differential corrections.

Theory uncertainties on tt+H and tt+jets discriminant shape - work on NLO tools. → **collaboration within HiggsTools with S. Pozzorini.**

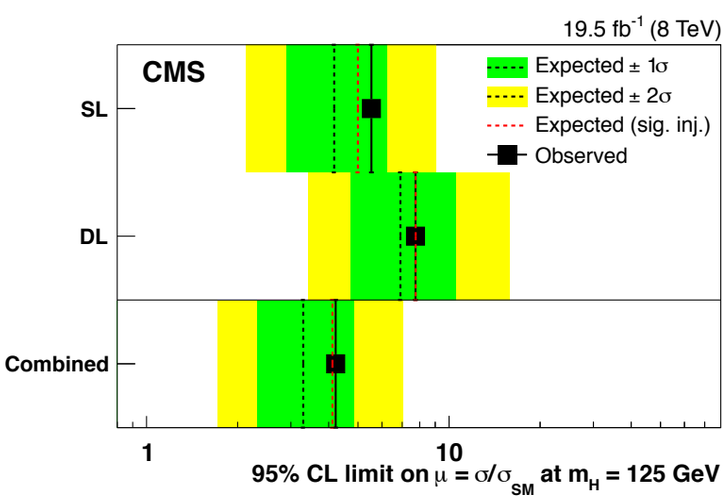
Results from LHC run I

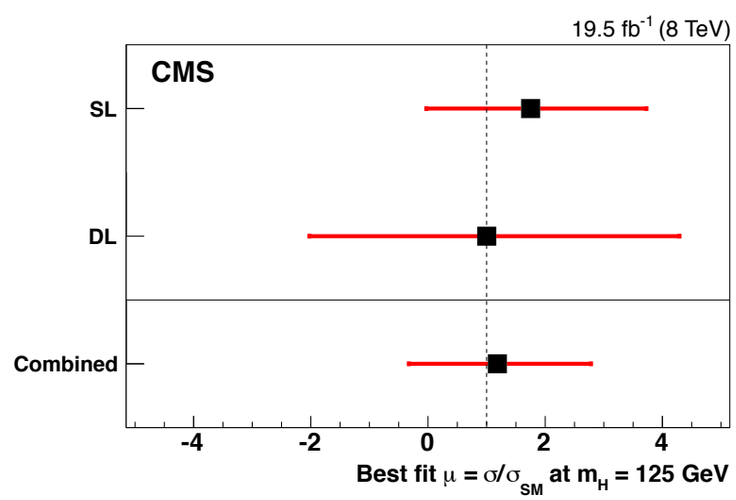
👉**CMS** ttH(bb) with **MEM** 20/fb: μ < 4.2 (3.3) obs (exp) @ 95%CL

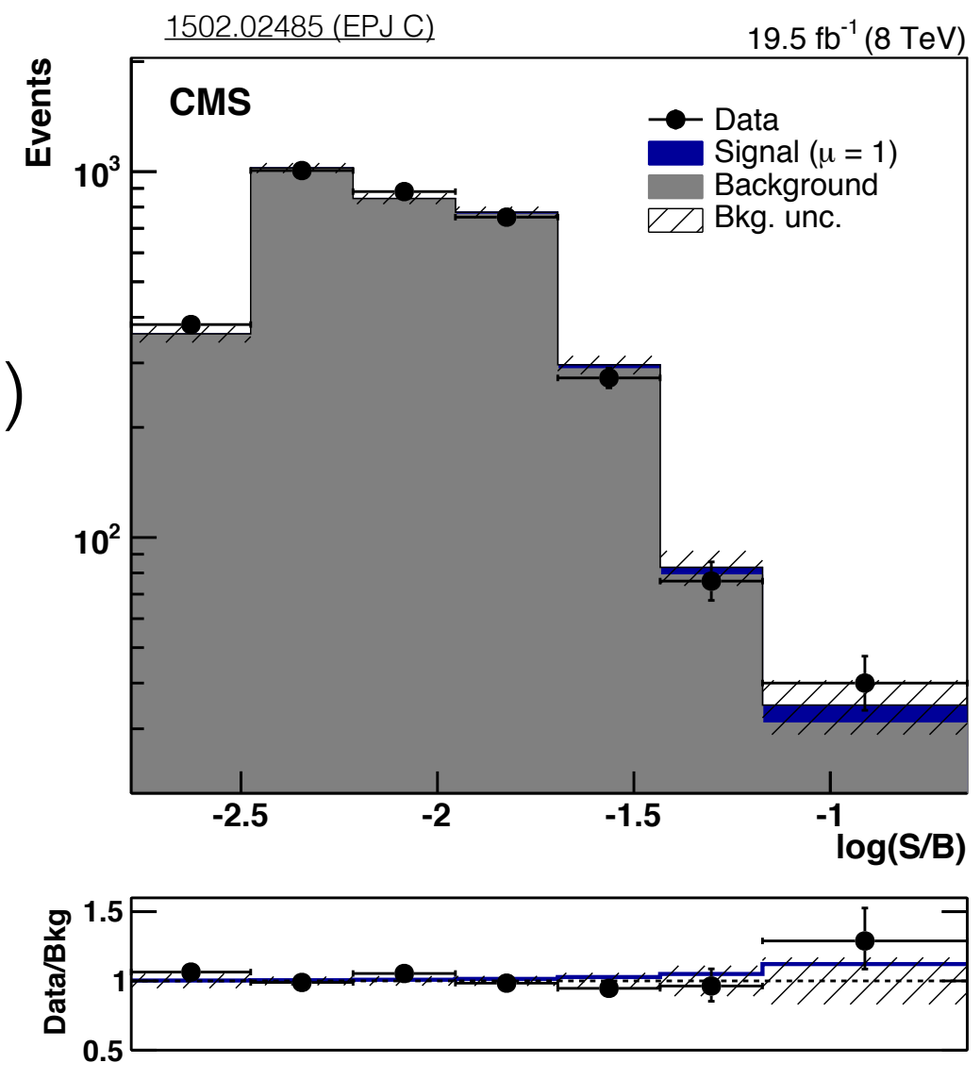
CMS with **NN** 5+5/fb: μ < 5.8 (5.2)

ATLAS MEM(SL) + **NN** 20/fb: μ < 3.4 (2.2)

Very competitive!







State of the art

Jet substructure can improve already existing limits: top tagging [1503.05921], higgs tagging of fat jets [1402.2657], direct integration with MEM/MVA.

Deploy MEM in **additional topologies**: H(ττ), fully-hadronic ttH(bb).

Improve MEM categorization: additional hypotheses - more separation at the cost of time.

Fully exploit and improve **b-tagging to constrain tt+bb/cc/light**, quark-gluon discrimination.

Moving to LHC Run II

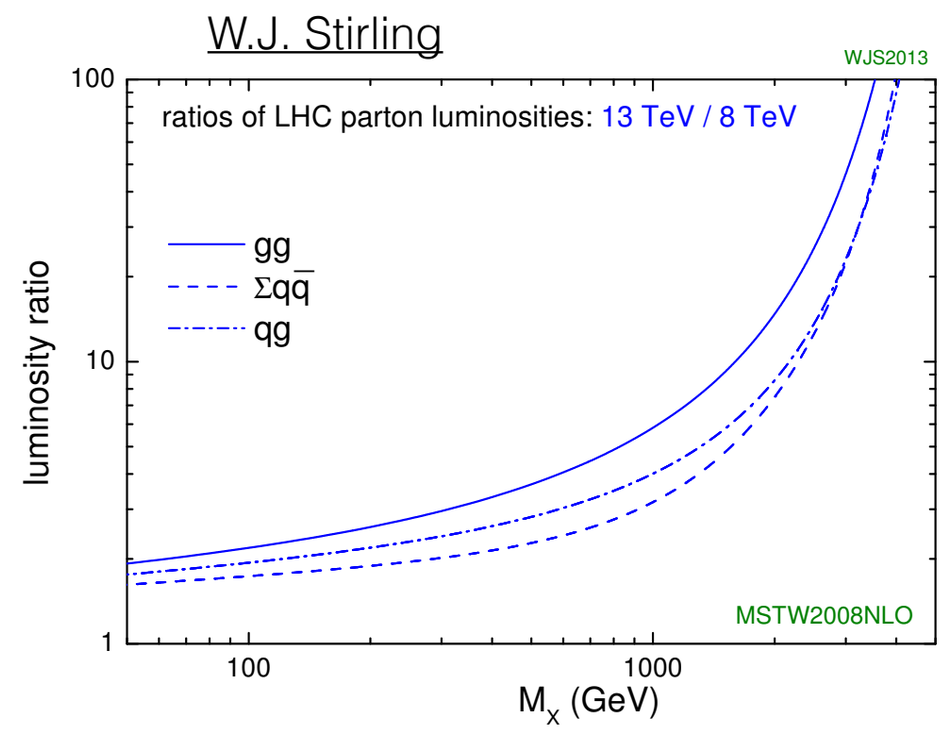
ttH 0.5085 pb (3.9x)

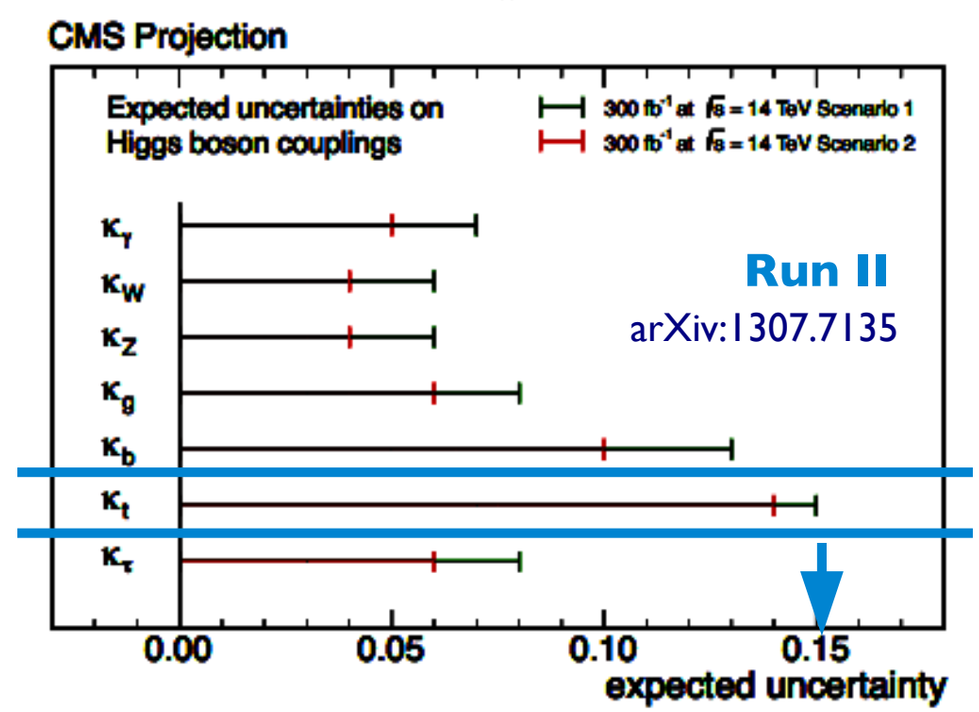
tt+jets 832 pb (3.3x)

With 300/fb, κ_t uncertainty 0.15.

Jet, lepton spectra harder in pt, higher multiplicity, increased acceptance.

But crucial to keep b-tagging performance with high pile-up.





Summary & outlook

ttH(bb) proof of concept at 8 TeV: **μ < 4.2 (3.3) @ 95%**.

Need the **best possible interpretation of data** - MEM + machine learning.

tt+bb NLO crucial, MEM naturally suited for systematically dominated (LHC 300/fb).

Extension to additional hypotheses, interpretations, use of jet substructure information.

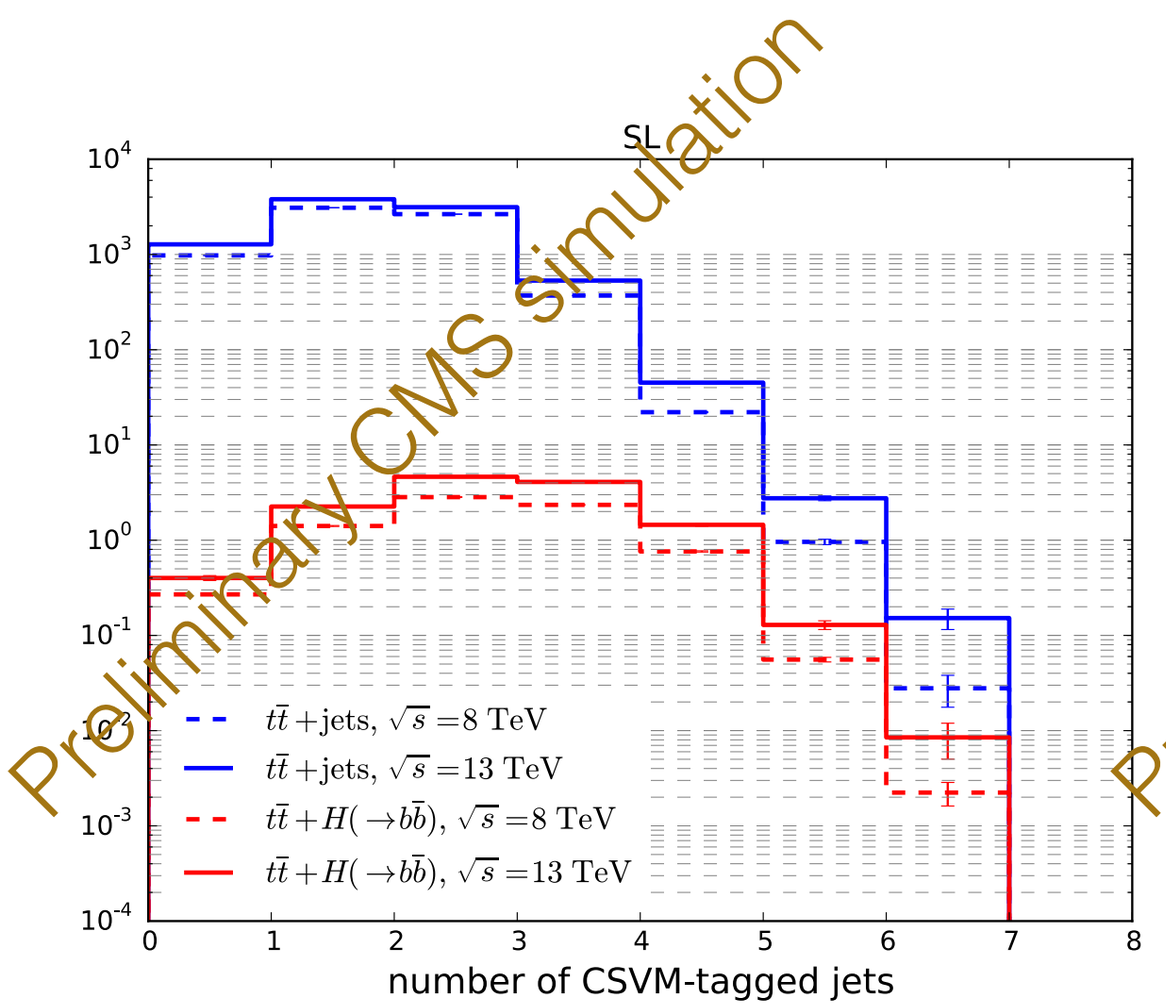
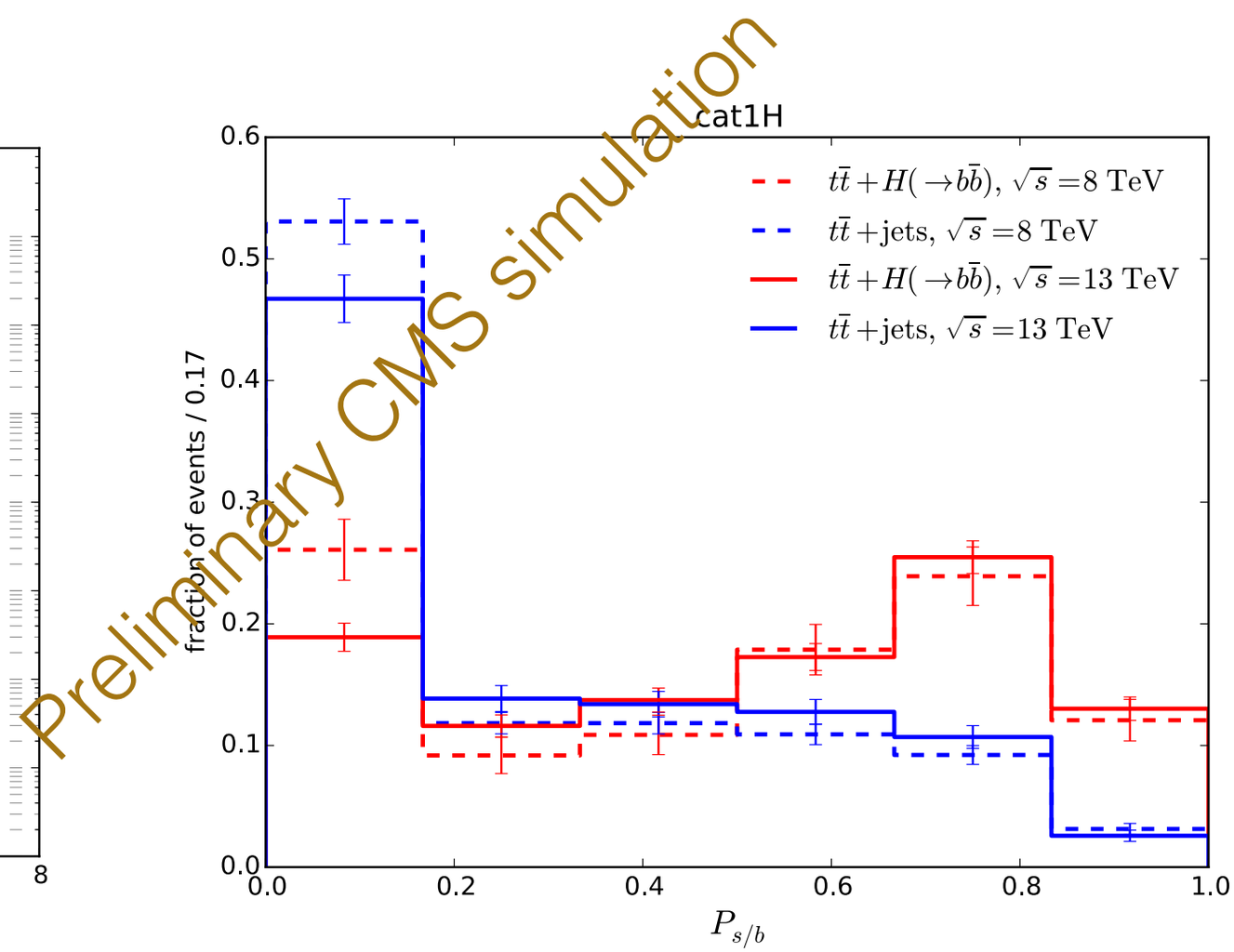
LHC has only started to speak up about the Higgs, Run II will be crucial!

HiggsTools collaboration opportunities:

tt+bb modelling and uncertainties.

MEM as a general tool for busy final states.

Inclusion and calibration of substructure.

Backup

First look at 13 TeV simulation