ETH Institute for Particle Physics

Higgs boson production in association with a top quark pair: ttH(bb) with the matrix element method

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PSI PhD seminar

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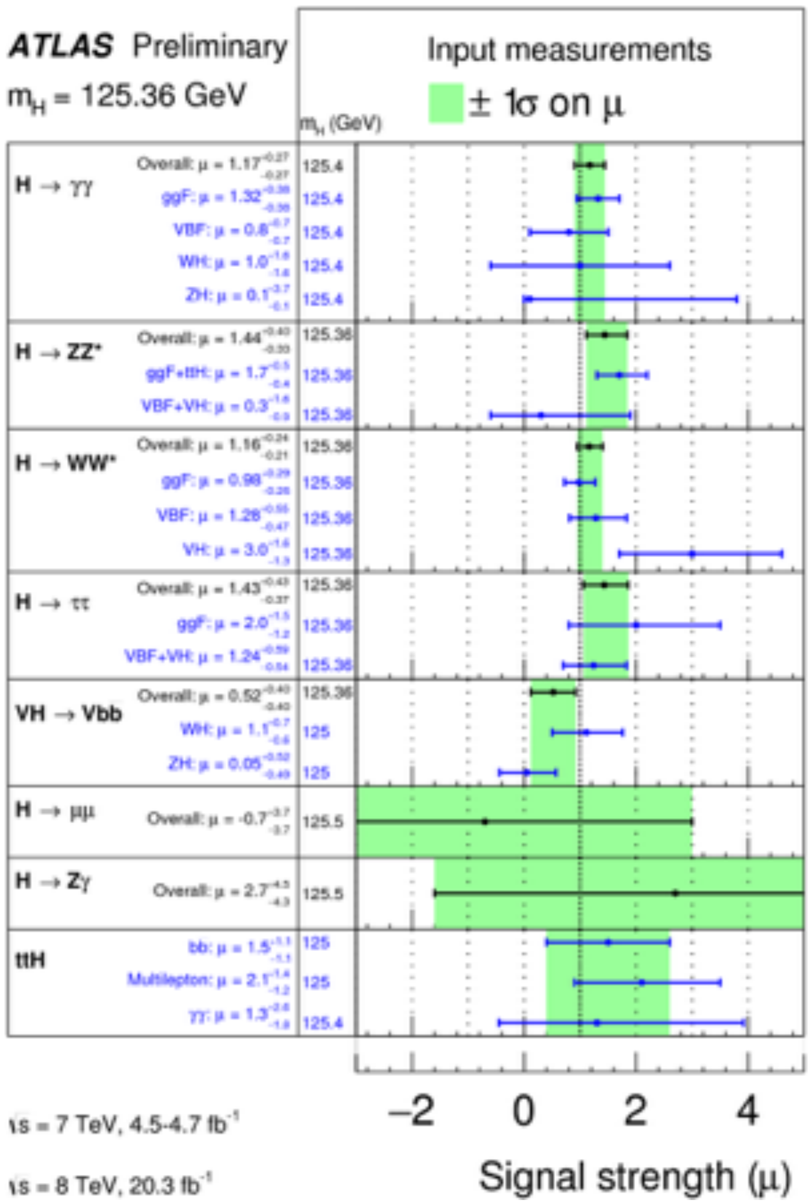
ETH Zürich

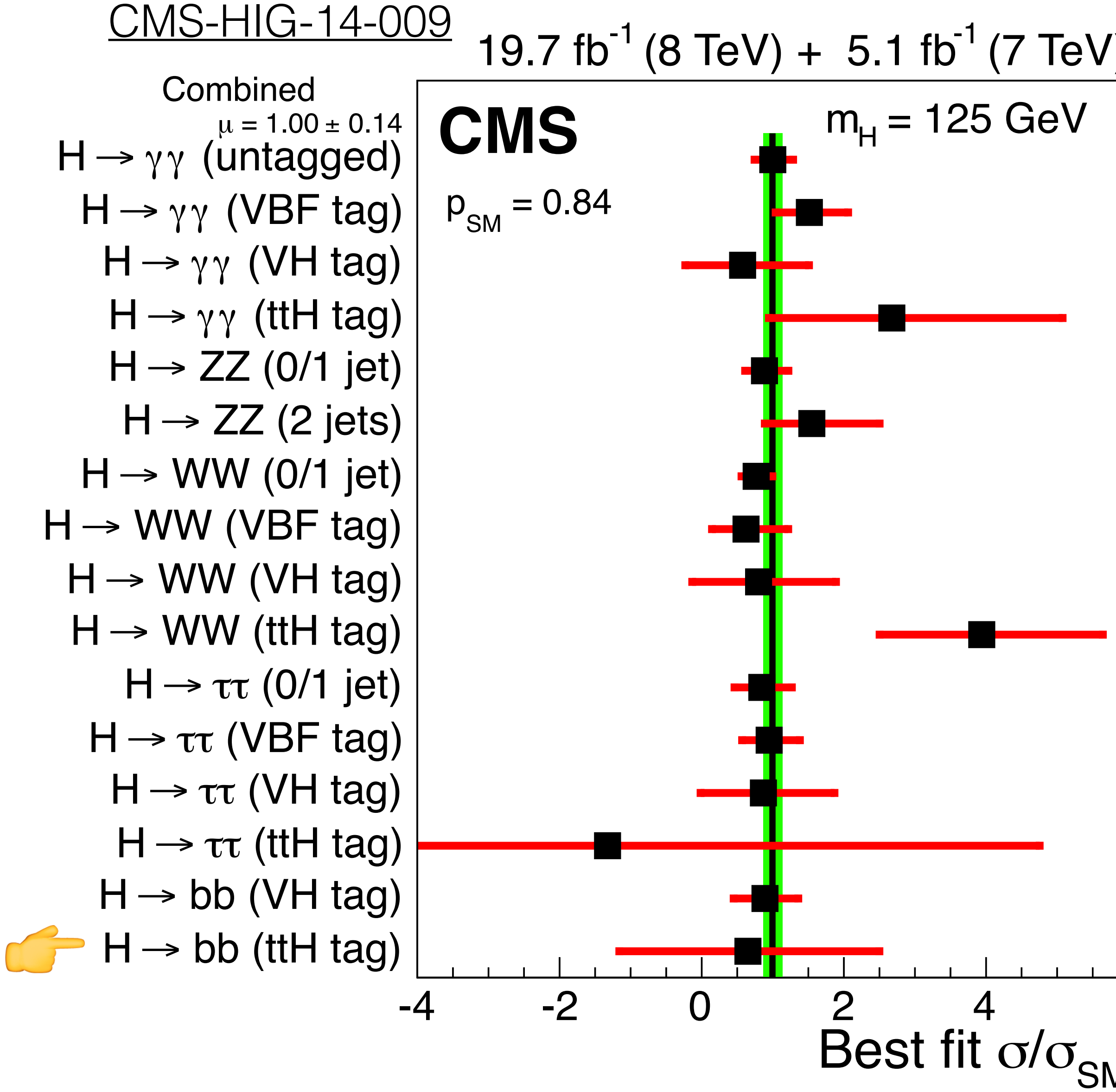
higgstools

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!

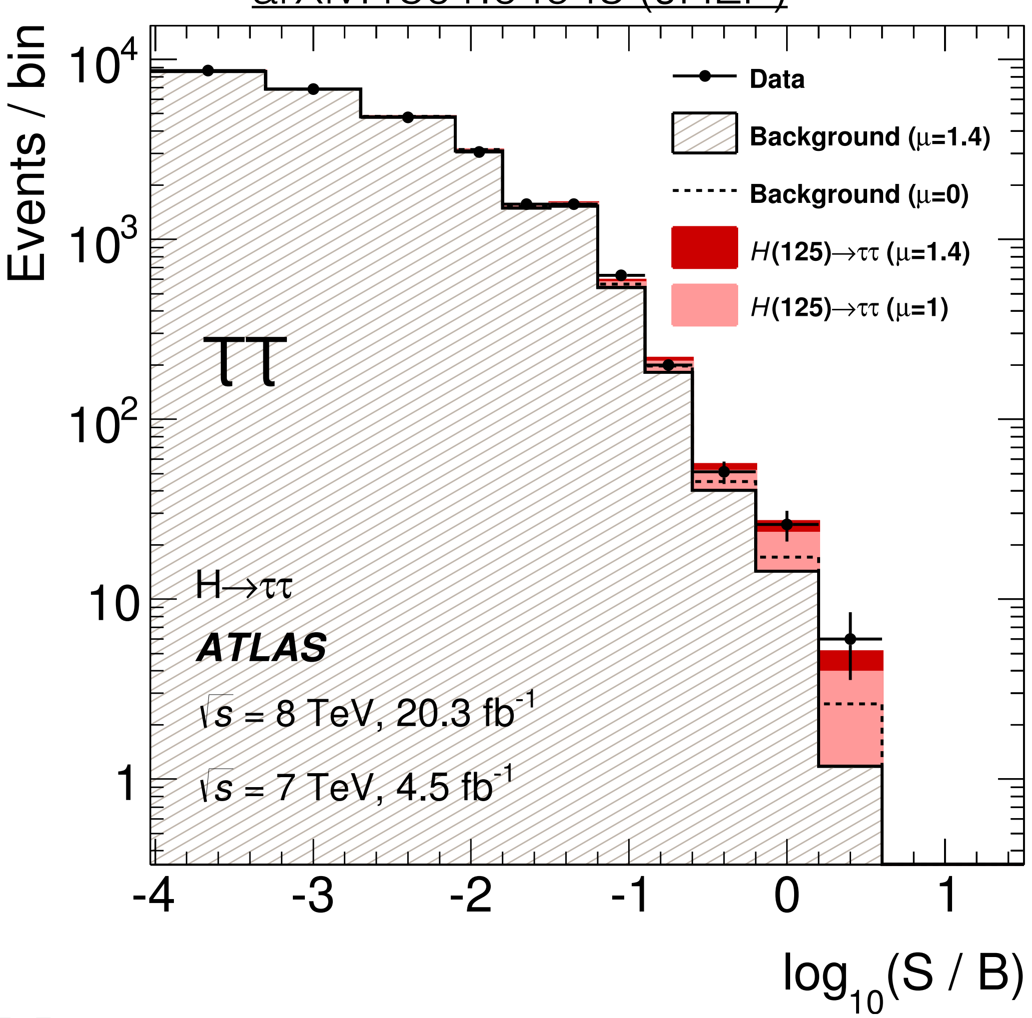
~15% uncertainty on top Yukawa with 300 fb^{-1} in Run II: **reaching the precision phase!**

Coupling to fermions

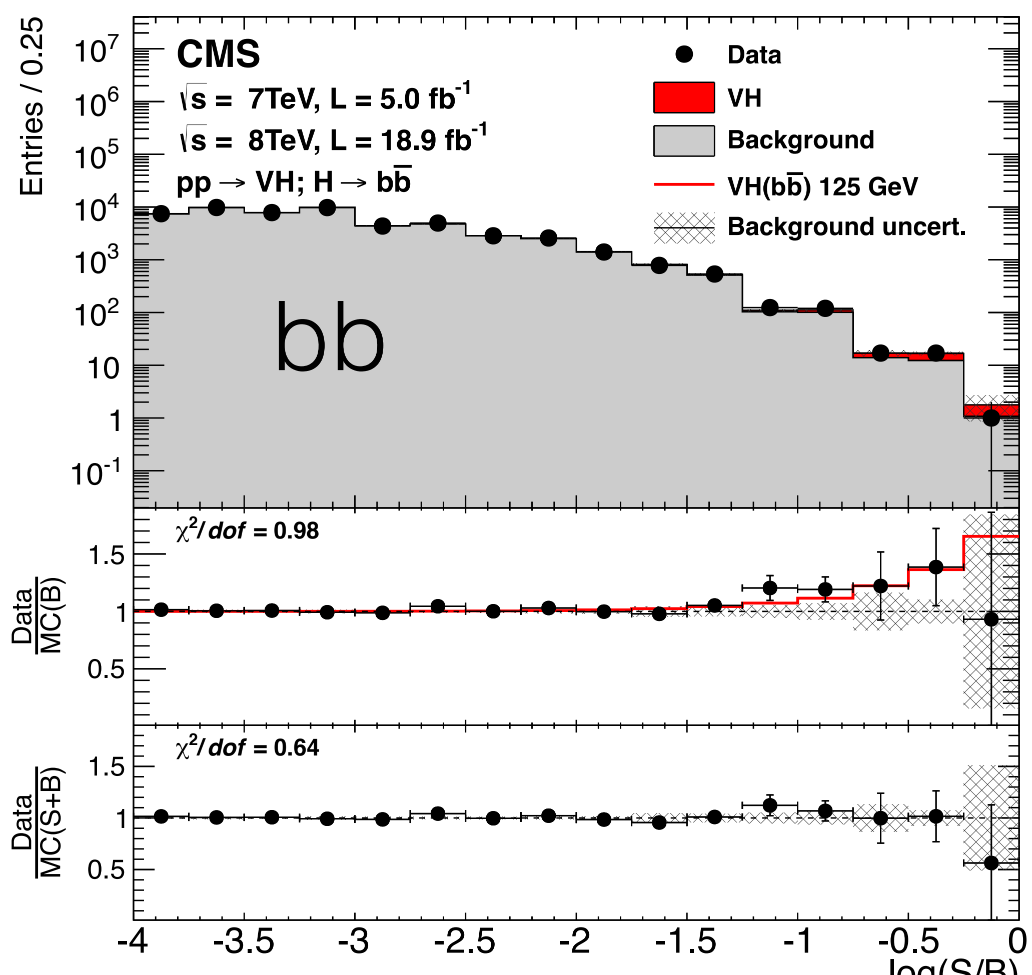
Verify EWSB mass generation by comparing **SM H decay to fermions to measurements**.

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

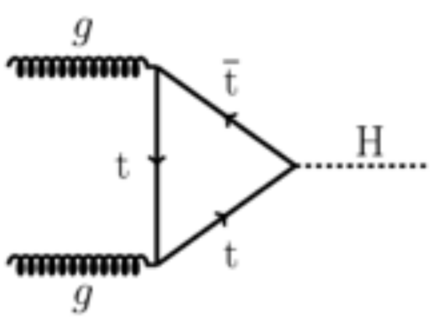
arXiv:1501.04943 (JHEP)



1310.3687 (PRD)

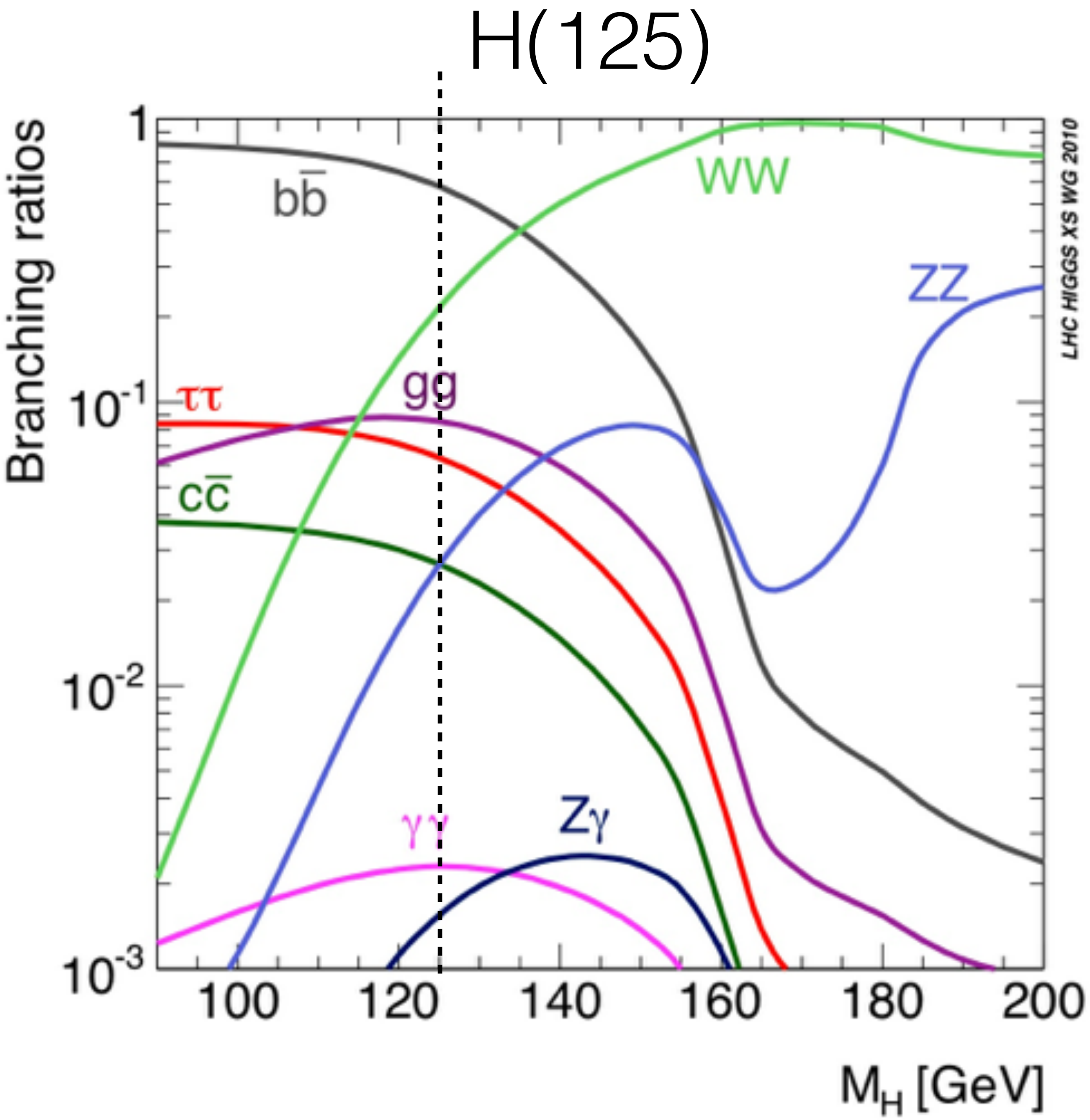


indirect evidence for coupling to tops through loop diagrams

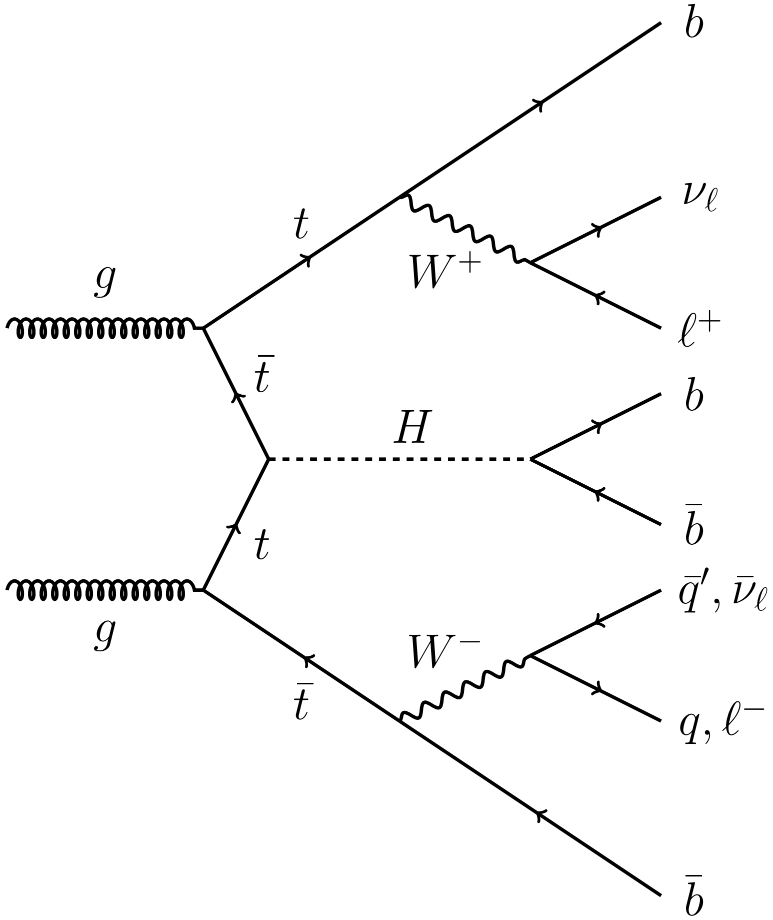


What to look for?

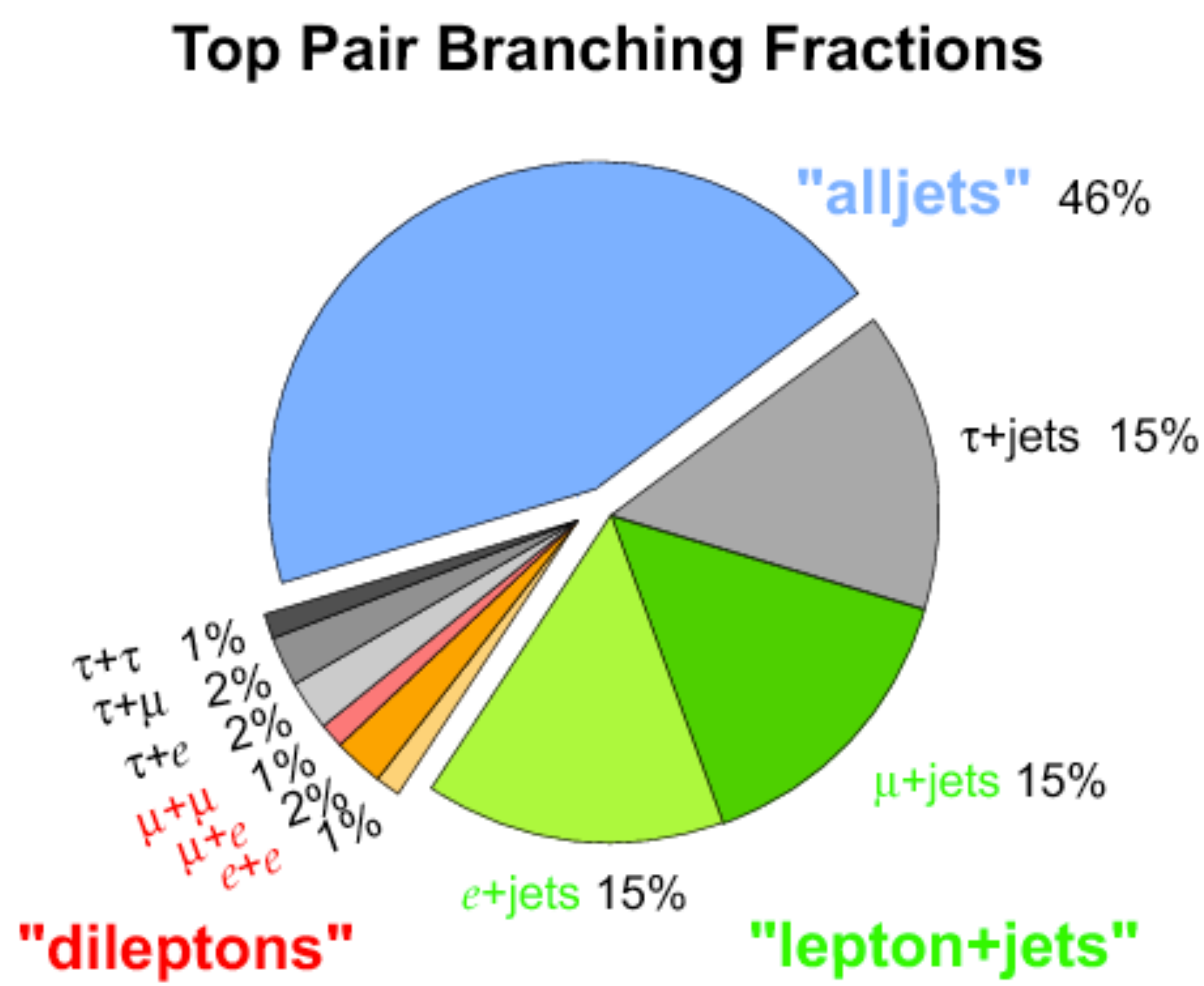
H(125) near-ideal for **bb** statistics-wise, but a very complicated final state.



Final state



1-2 leptons,
4-6 jets (4b),
MET



Reconstruction and selection

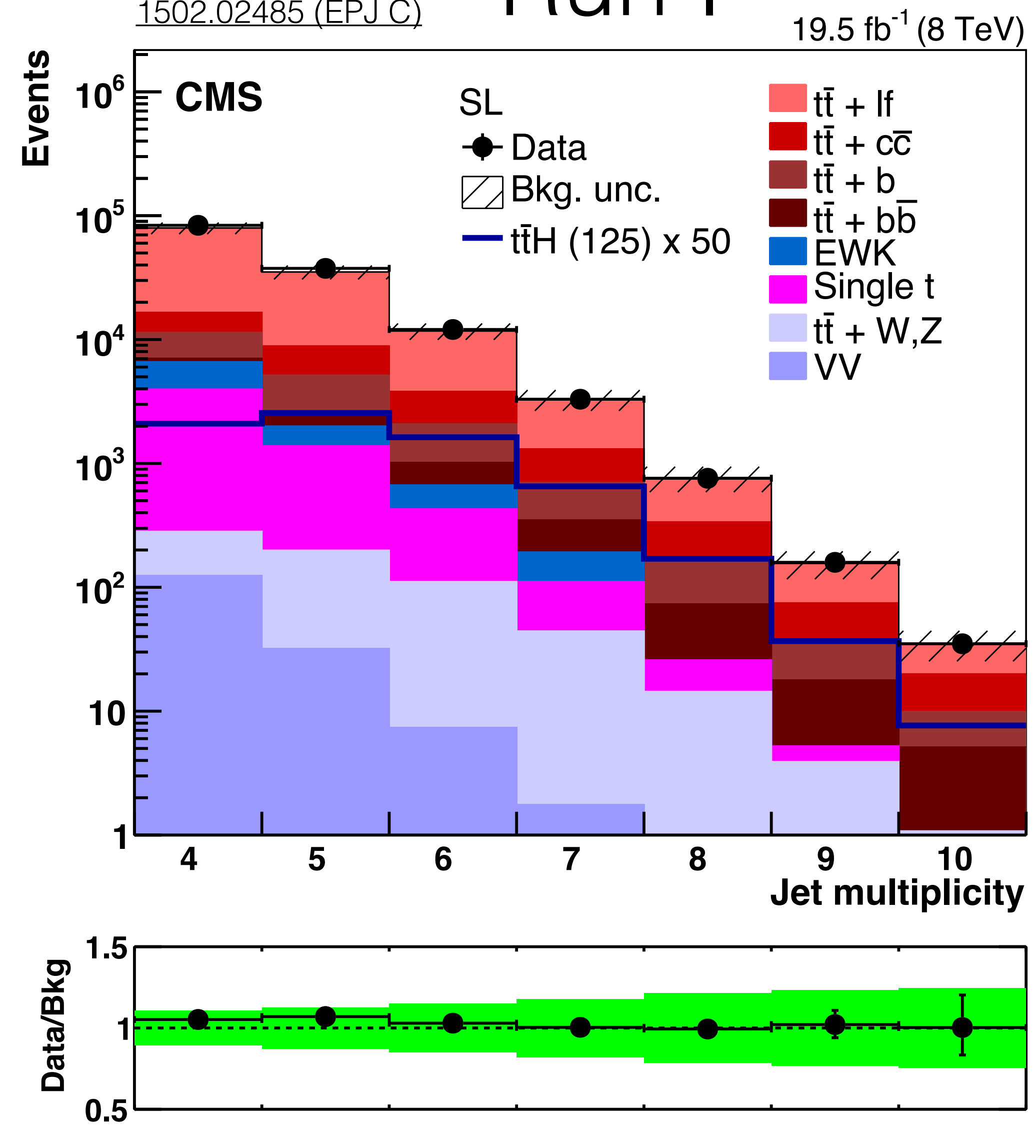
Require **1-2 isolated e/mu** → multi-jet QCD, but also fully-hadronic ttH(bb).

4 or more central jets p_t > 30(20) GeV, b-jets based on impact parameter and SV properties. → single top, EWK.

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

1502.02485 (EPJ C)

Run I



top quark background

Bevilacqua et al 2014

top quark pair background

$$\sigma^{\rm NLO}_{t\bar{t}b\bar{b}}({\rm LHC}_{13{\rm TeV}}, m_t = 173.5~{\rm GeV}, {\rm CT10}) = 1078.3^{+222.1(20\%)}_{-249.7(23\%)}~[{\rm fb}]\,,$$

$$\sigma^{\rm NLO}_{t\bar{t}jj}({\rm LHC}_{13{\rm TeV}}, m_t = 173.5~{\rm GeV}, {\rm CT10}) = 85.5^{-18.3(21\%)}_{-8.4(10\%)}~[{\rm pb}]\,.$$

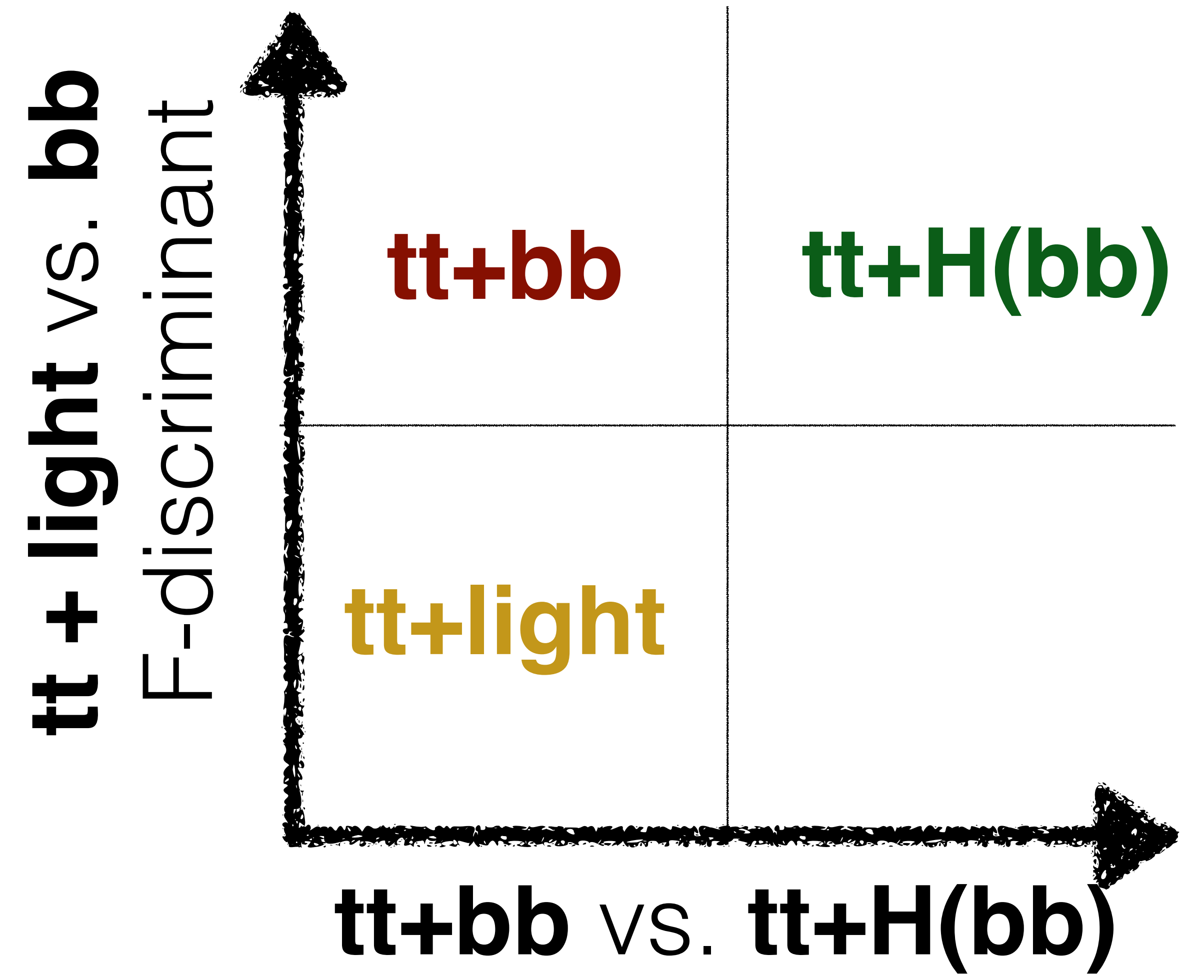
vs.

LHC XSWG

ttH: 508.5 [fb] ± ~10%

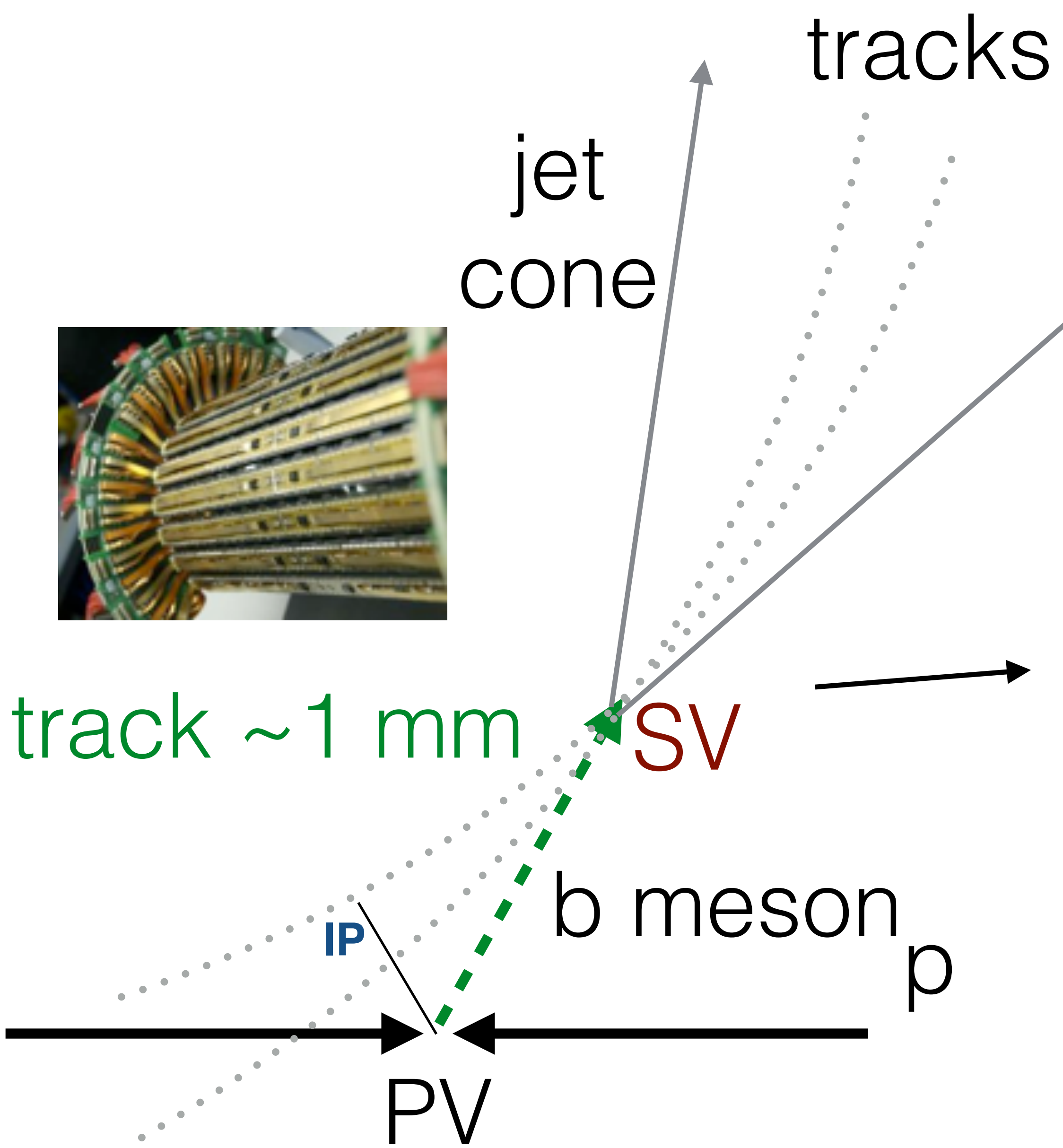
ttbb uncertainties cover expected signal!

Modelling uncertainties of tt+bb (gluon splitting).



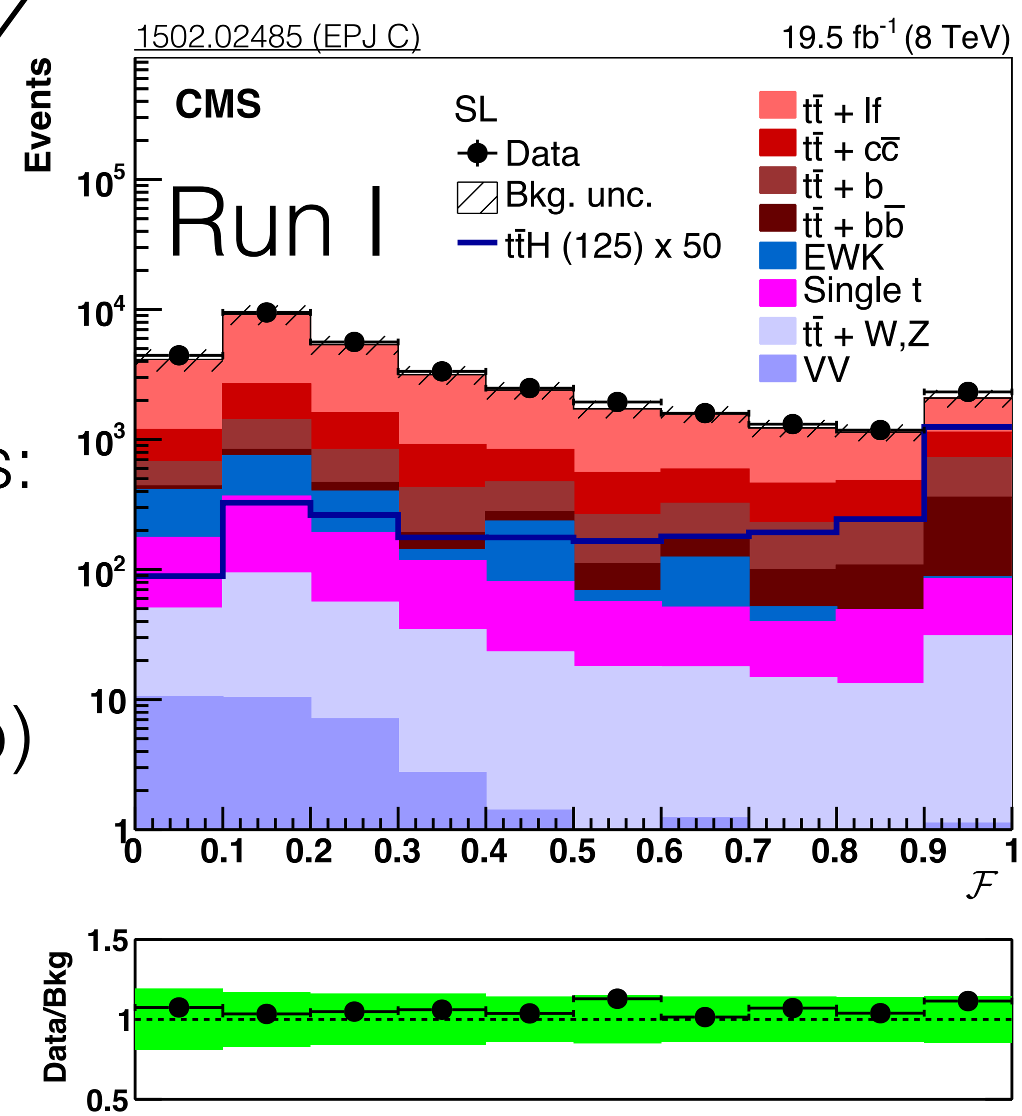
combined fit in σ(ttH) vs. σ(ttbb)/σ(ttjj) space!

b-tagging: tt+heavy vs. tt+light



in multi-jet, combine probabilities: p(jet | b) & p(jet | non-b)

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

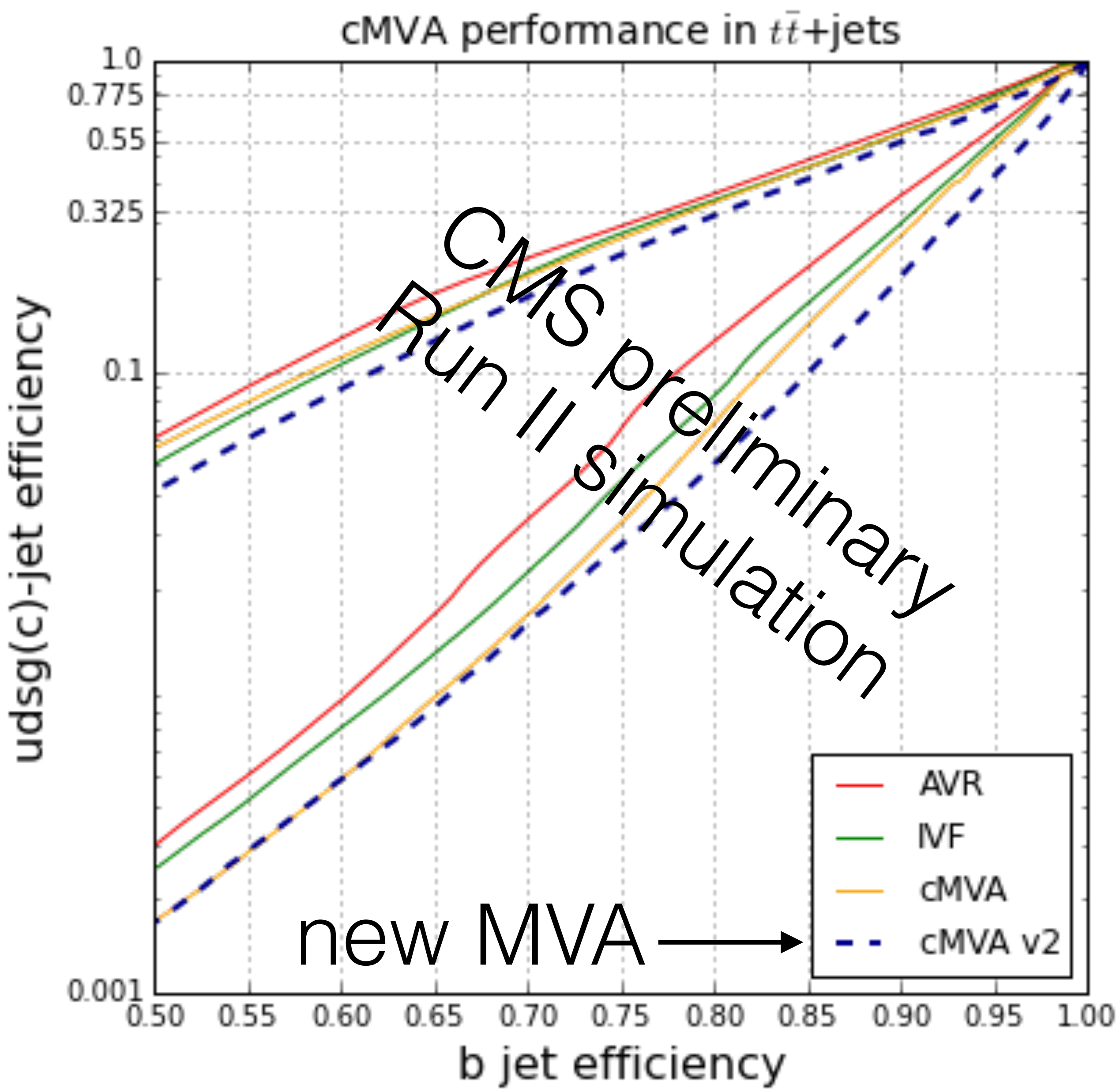


b-tagging in Run II

Studying a new “super-MVA” for b vs. light.

Combines different vertexing algorithms, likelihood-based jet probability, soft lepton taggers.

c mistag, high-eff b-tagging improved by **~20-30% (rel.)**.

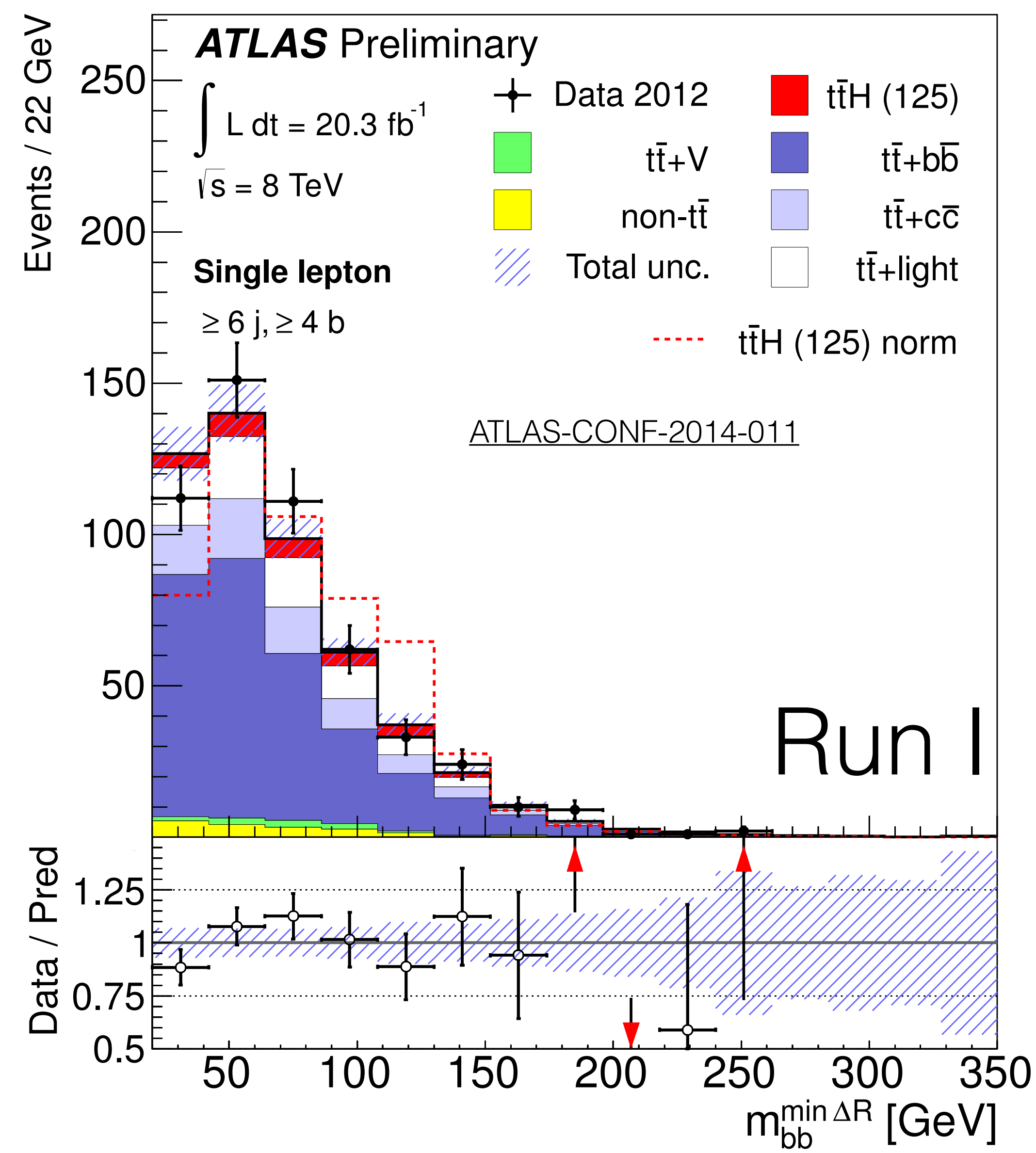


tt+bb vs. tt+H(bb)

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

H(→bb) smeared out due to combinatorics, cannot observe "Higgs peak".

Need to exploit H resonance properties experimentally.



Main problems

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

complicated final state: multi-jet, missing energy

Extracting the signal

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

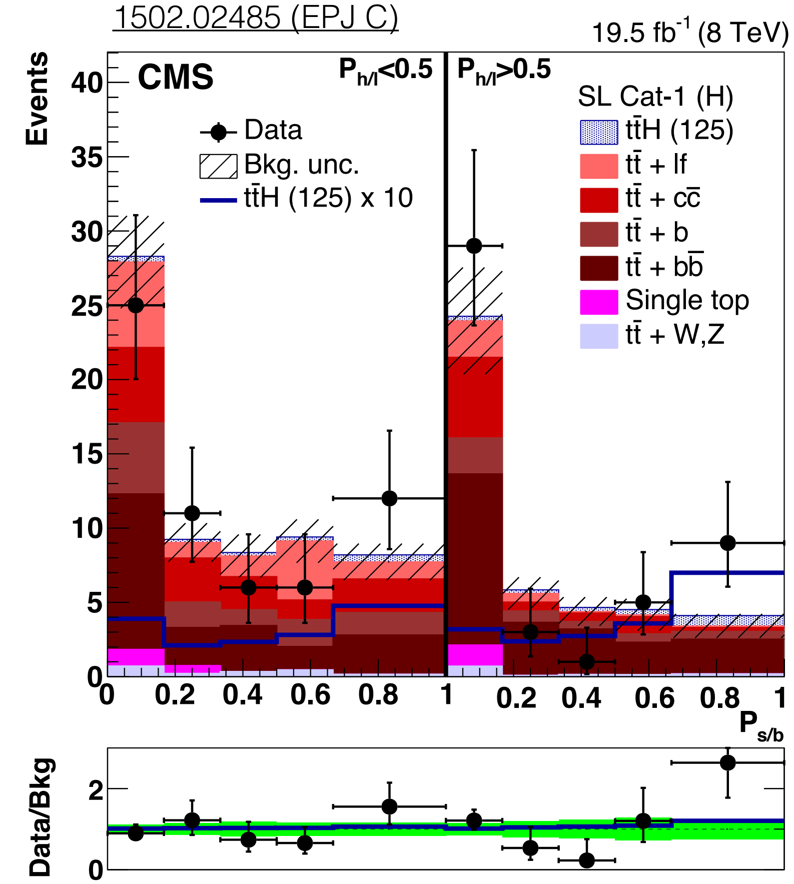
Unknown, poorly measured quantities → integrated out directly.

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.

Run I

1502.02485 (EPJ C)

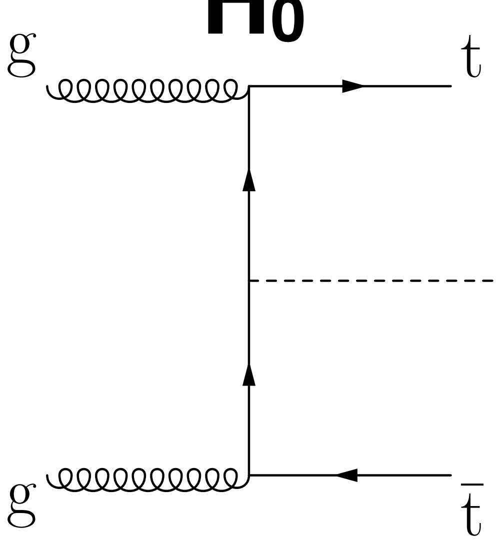


Matrix Element Method

Y - measured event properties

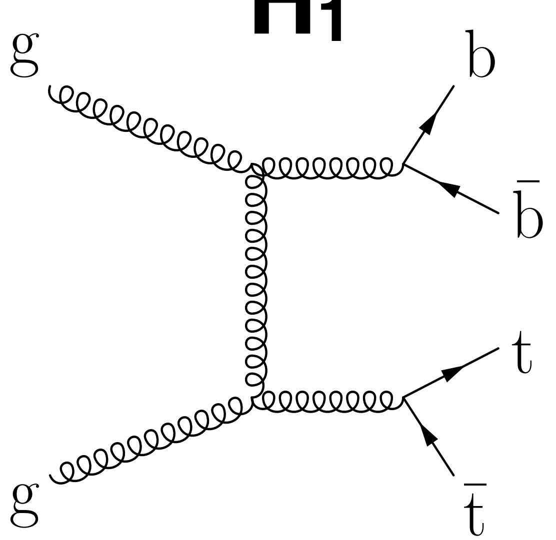
X - "true" parton-level quantities

H_0



or

H_1



likelihood ratio

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

parton level → reconstruction level

$$f(Y \mid H_0, \lambda) = 1/\sigma(H_0, \lambda) \int dX \int dx_a dx_b \; \Phi(x_a, x_b) \rightarrow \textbf{PDF}$$

$$|\mathscr{M}(X \mid H_0, \lambda)|^2 \; W(Y,X)$$

ME amplitude @ LO

exp. resolution

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Reconstruction categories

Reconstructed event

Interpretation

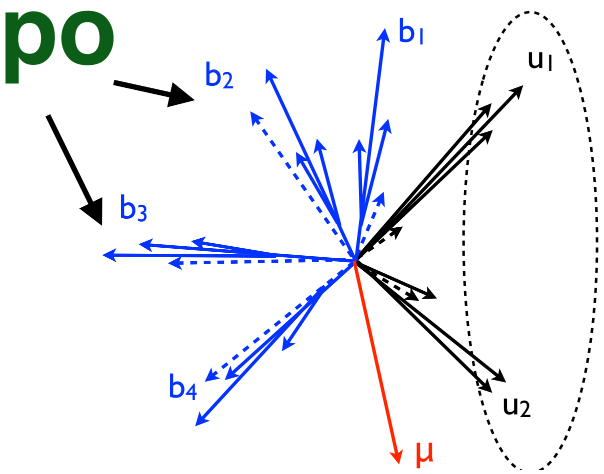
Integration

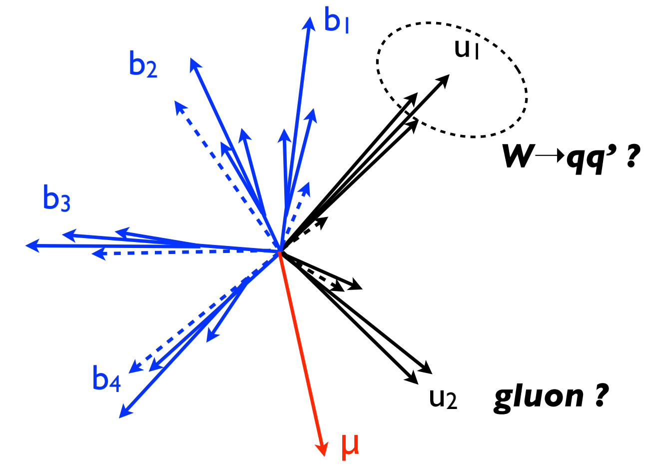
Discriminant **P**

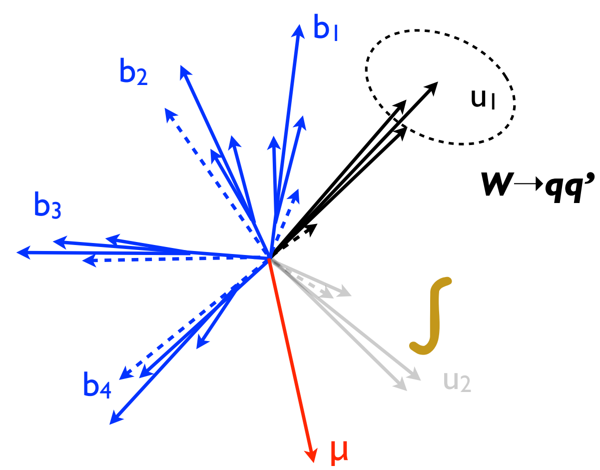
W→qq' in acceptance

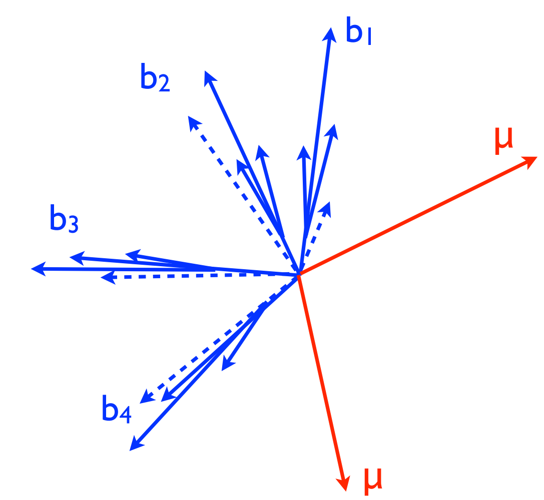
one light quark not reconstructed

hypo







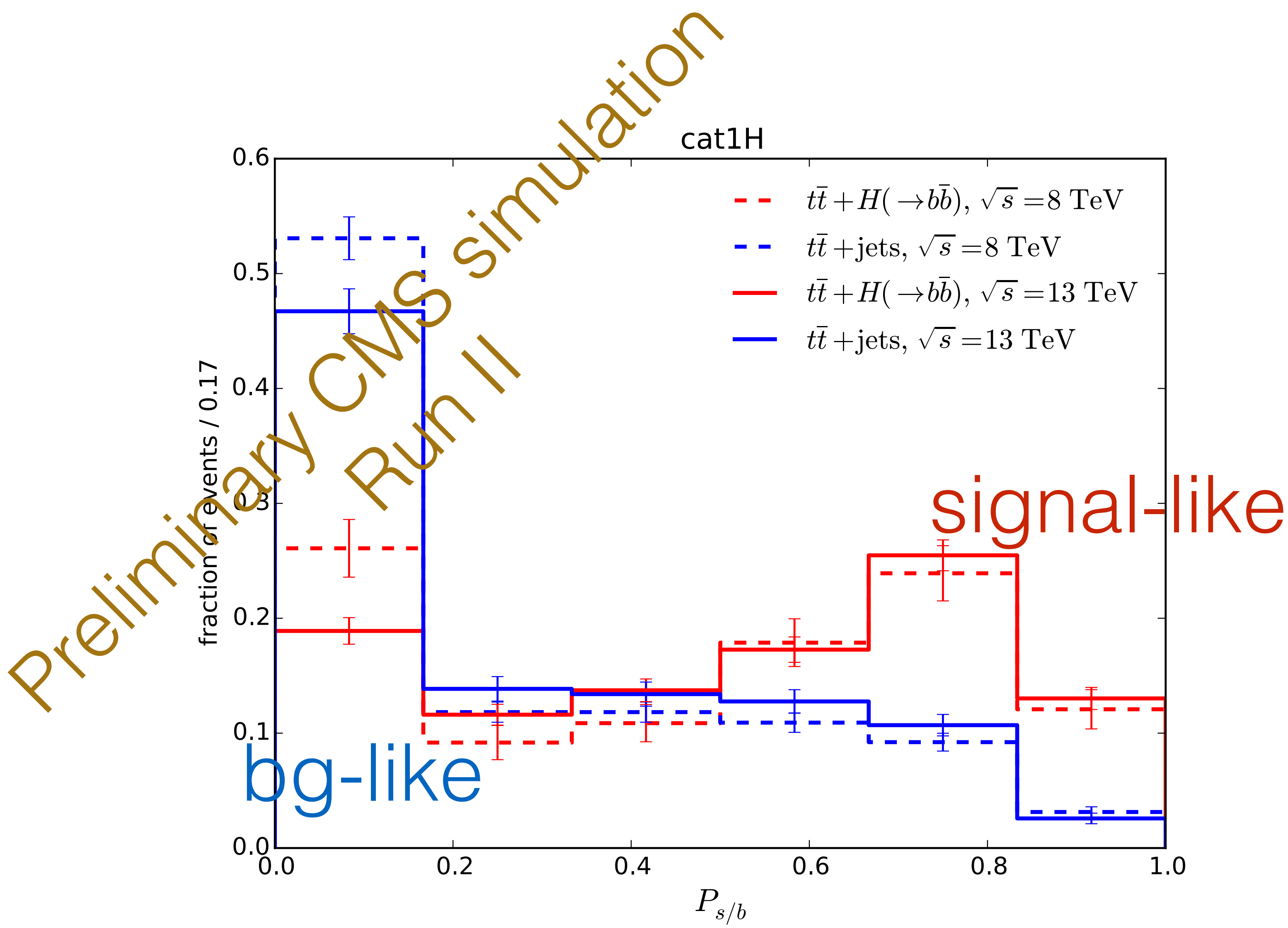


SL

DL

ME is just a discriminator, no need to be fully theoretically sound.

An approximation already does a very good job.



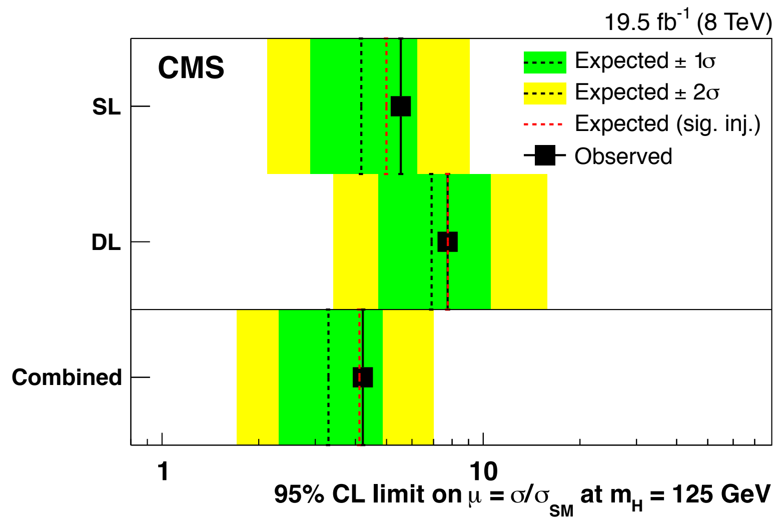
Results from LHC run I

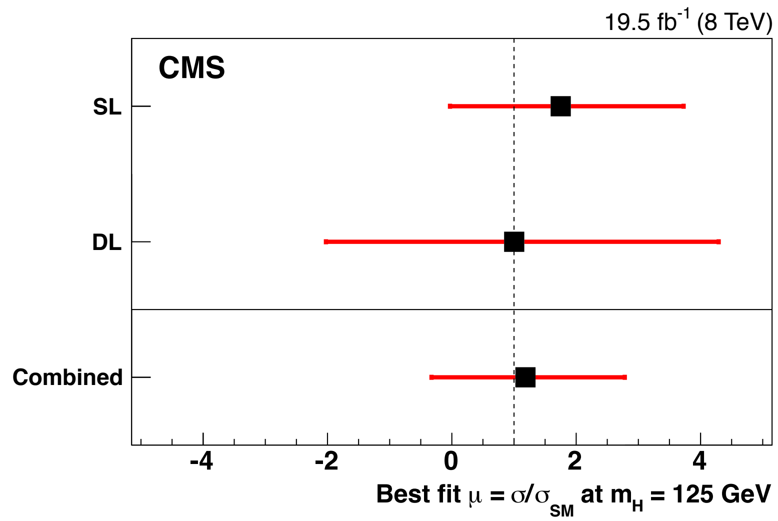
👉**CMS** ttH(bb) with **MEM** 20/fb: μ < 4.2 (3.3) obs (exp) @ 95%CL

CMS with **NN** 5+5/fb: μ < 5.8 (5.2)

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

in Run II, first limits with ~10/fb.





Run I

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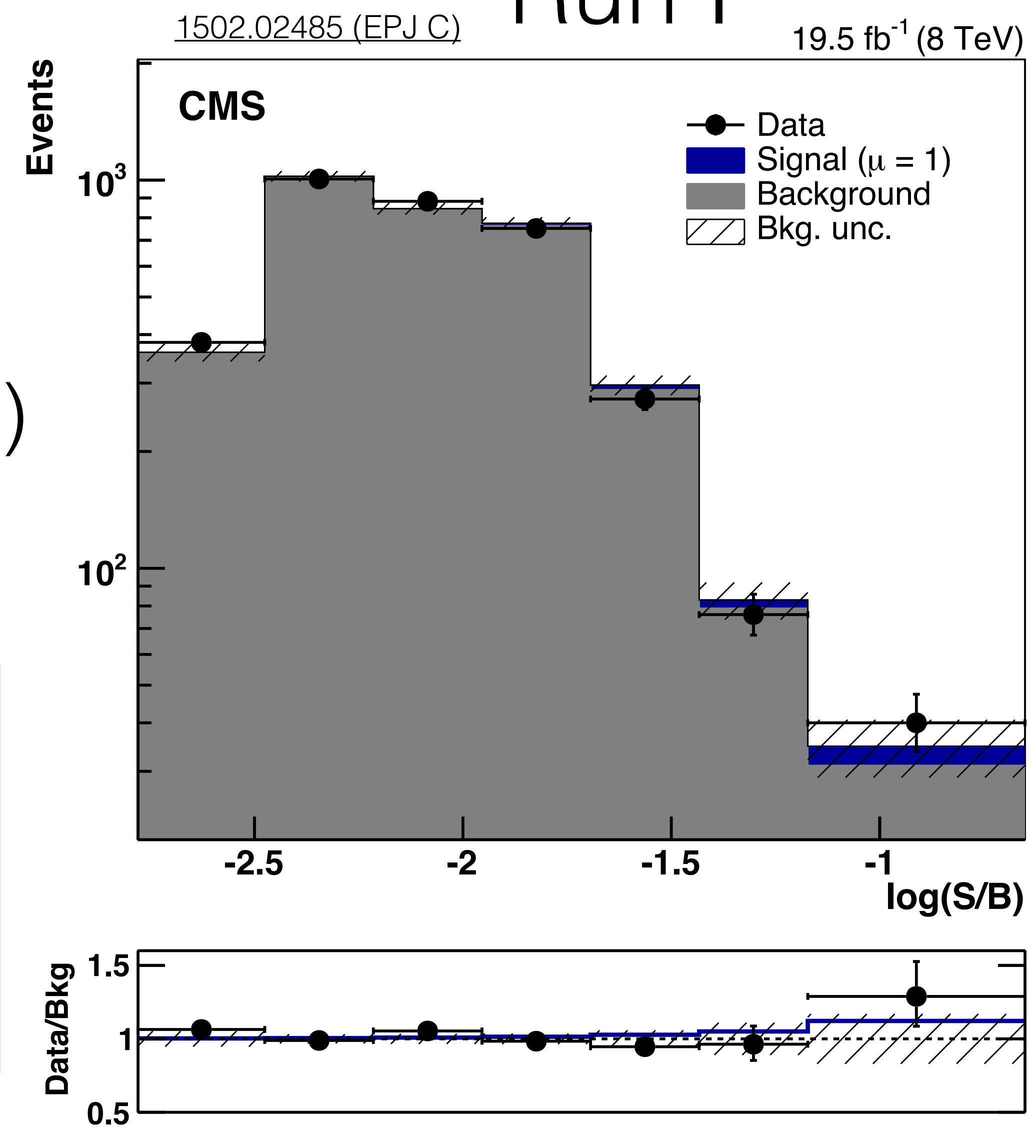


Ongoing work

Improve MEM categorization: less constrained hypotheses - more separation at the cost of CPU time.

Combination of MEM discrimination with **NLO-based machine learning**.

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).

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

Moving to LHC Run II

gg-dominated

ttH ~0.5085 pb (3.9x) favoured over

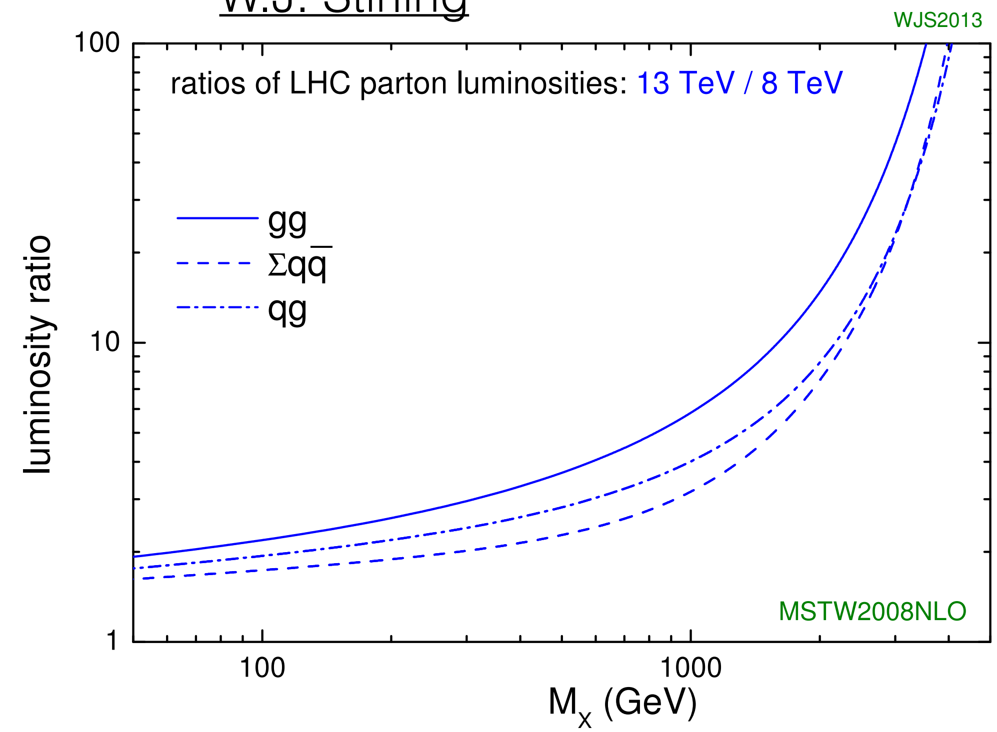
tt+jets ~832 pb (3.3x)

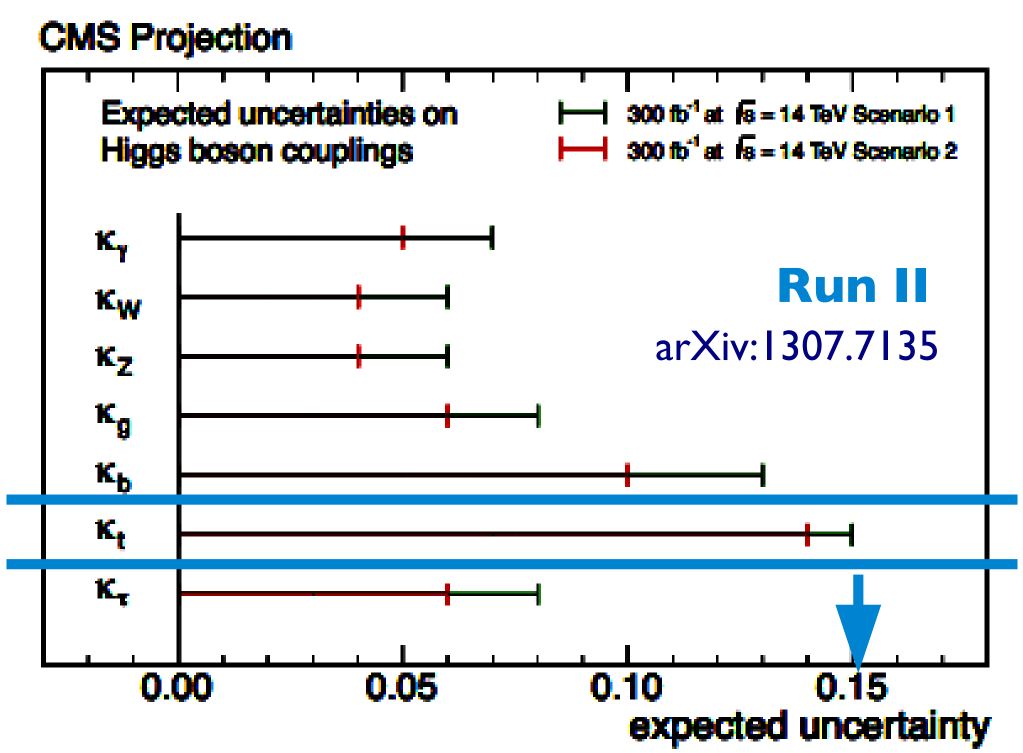
With 300/fb, coupling scale factor κ_t uncertainty 0.15.

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

But crucial to keep b-tagging performance with high pile-up, exploit jet substructure.

W.J. Stirling





Summary & outlook

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

Need the **best possible interpretation of data** : matrix element method natural for high jet multiplicities, complements machine learning.

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

Extend to additional reco. hypotheses, use of jet substructure information.

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

Backup

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.

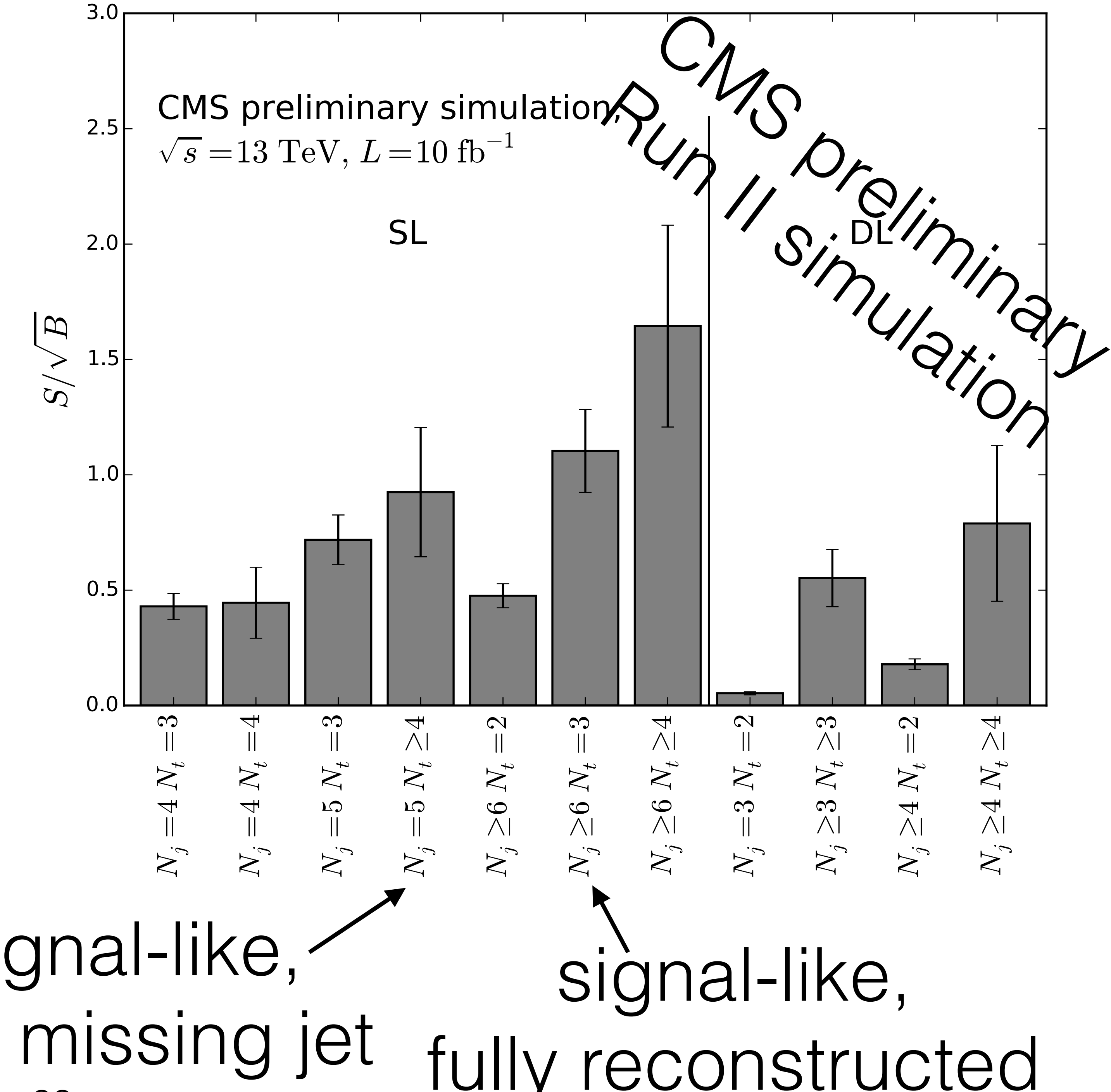
Require b-tagging of b-quarks (F-discriminant).

Expected rates

S/√B ~ 2% after lepton and jet selection.

Validate analysis in different jet / b-tag categories, combined fit.

MEM hypotheses optimized per category.



Uncertainties

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

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

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**:

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: crucial to describe gluon splitting.

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

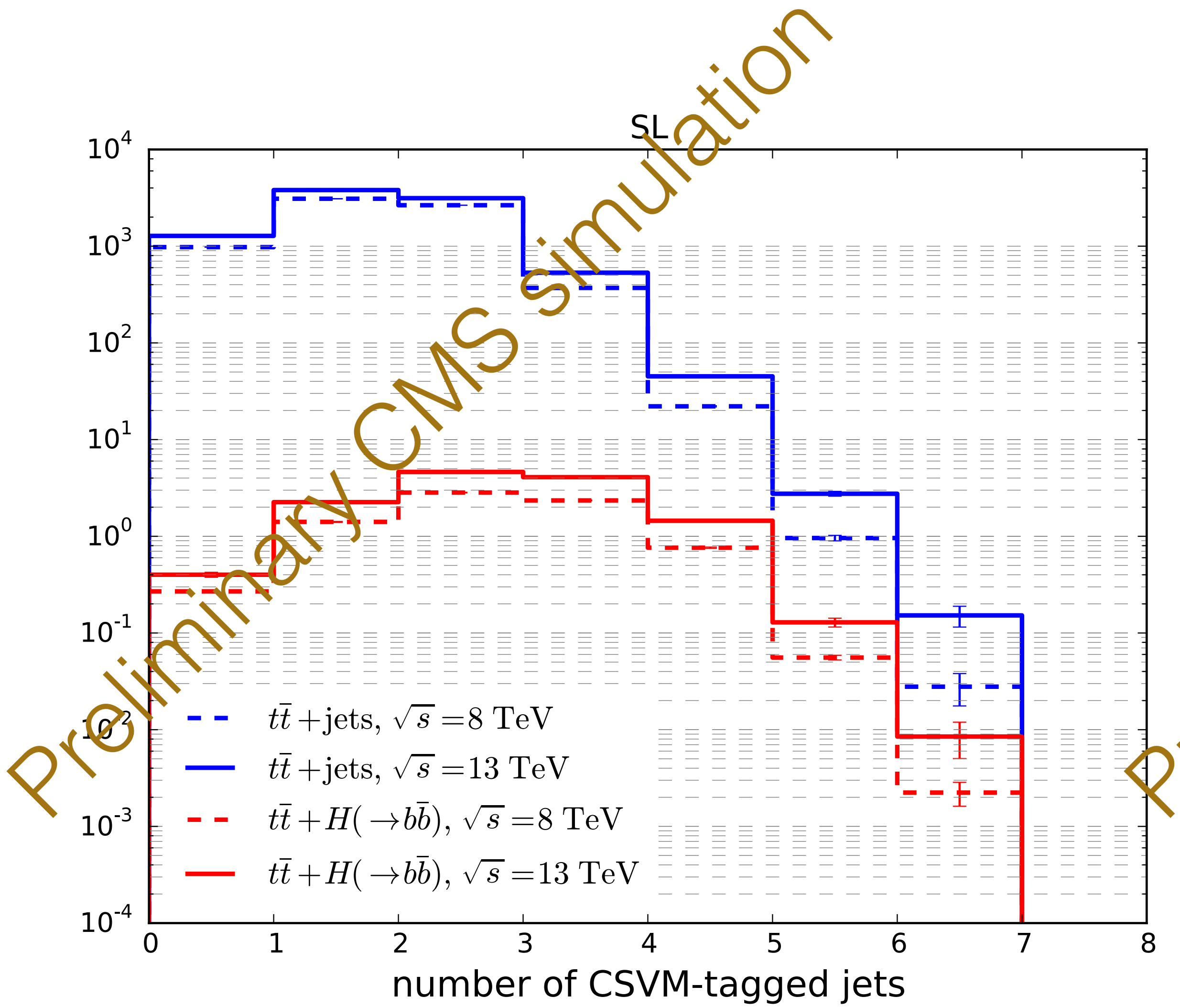
signal: LO->NLO simulation for tt+H, corrected to NNLO + leading log, Pythia (aMC@NLO at 13 TeV)

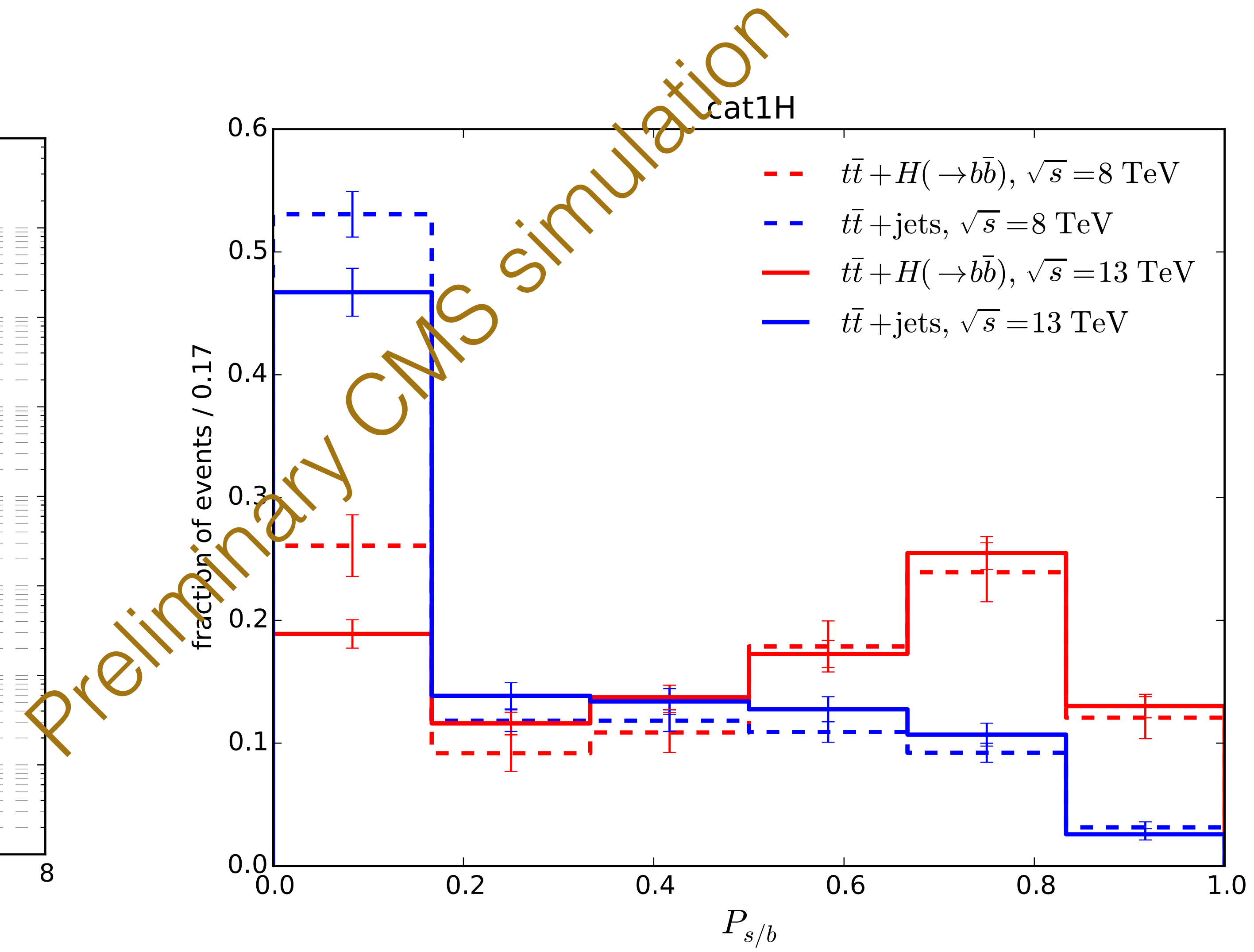
tt+bb: LO -> NLO, significant theoretical uncertainties, combine predictions from multiple generators, NLO recently available with Sherpa +OL

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

First look at 13 TeV simulation



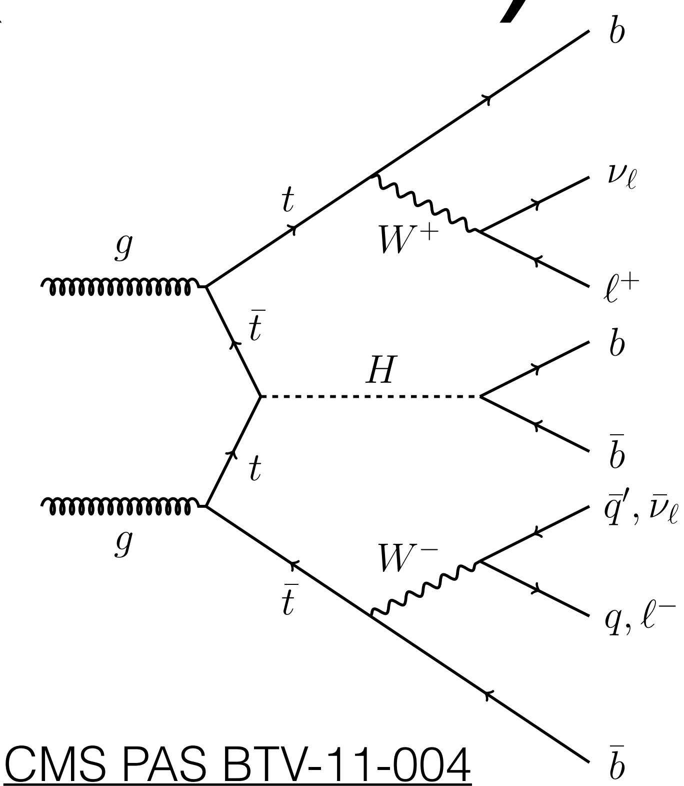


Case study: ttH(→bb)

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