Higgs boson measurements in hadronic final states at CMS

Nick Smith

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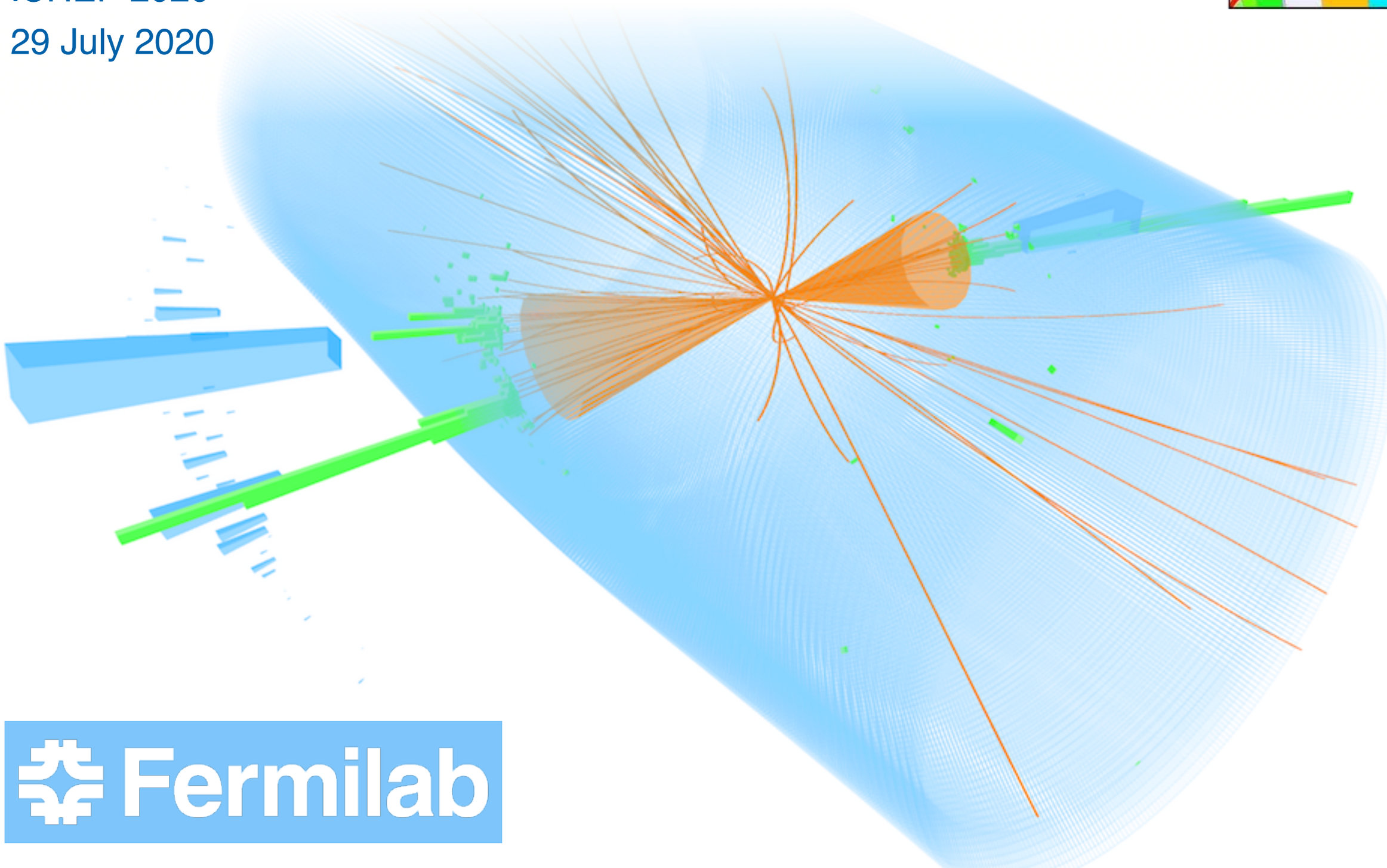
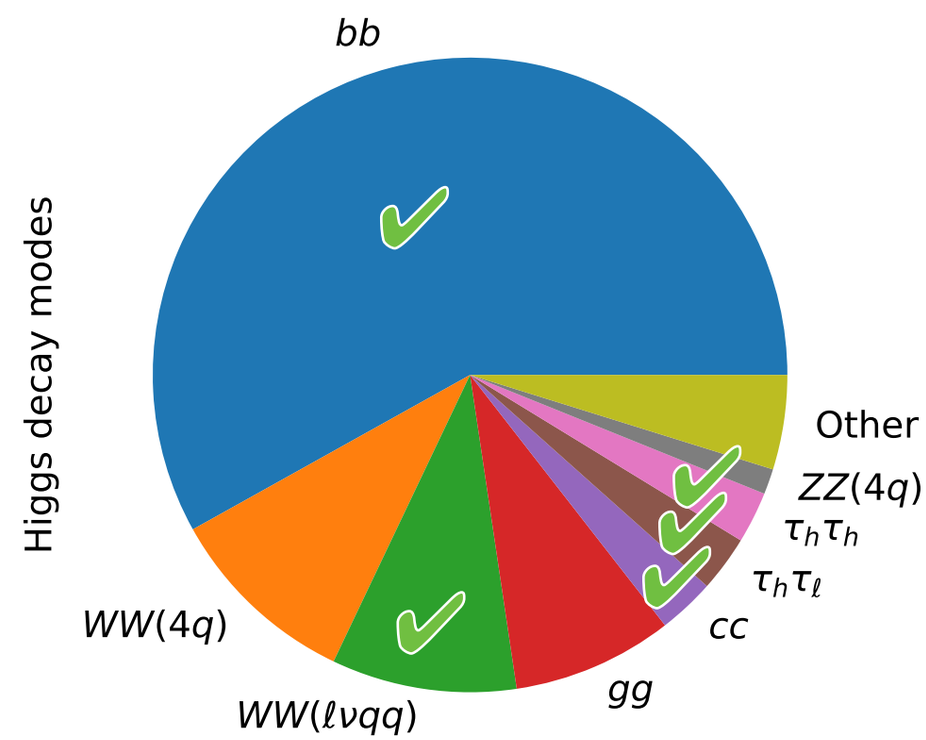


Fermilab

Hadronic Higgs decays

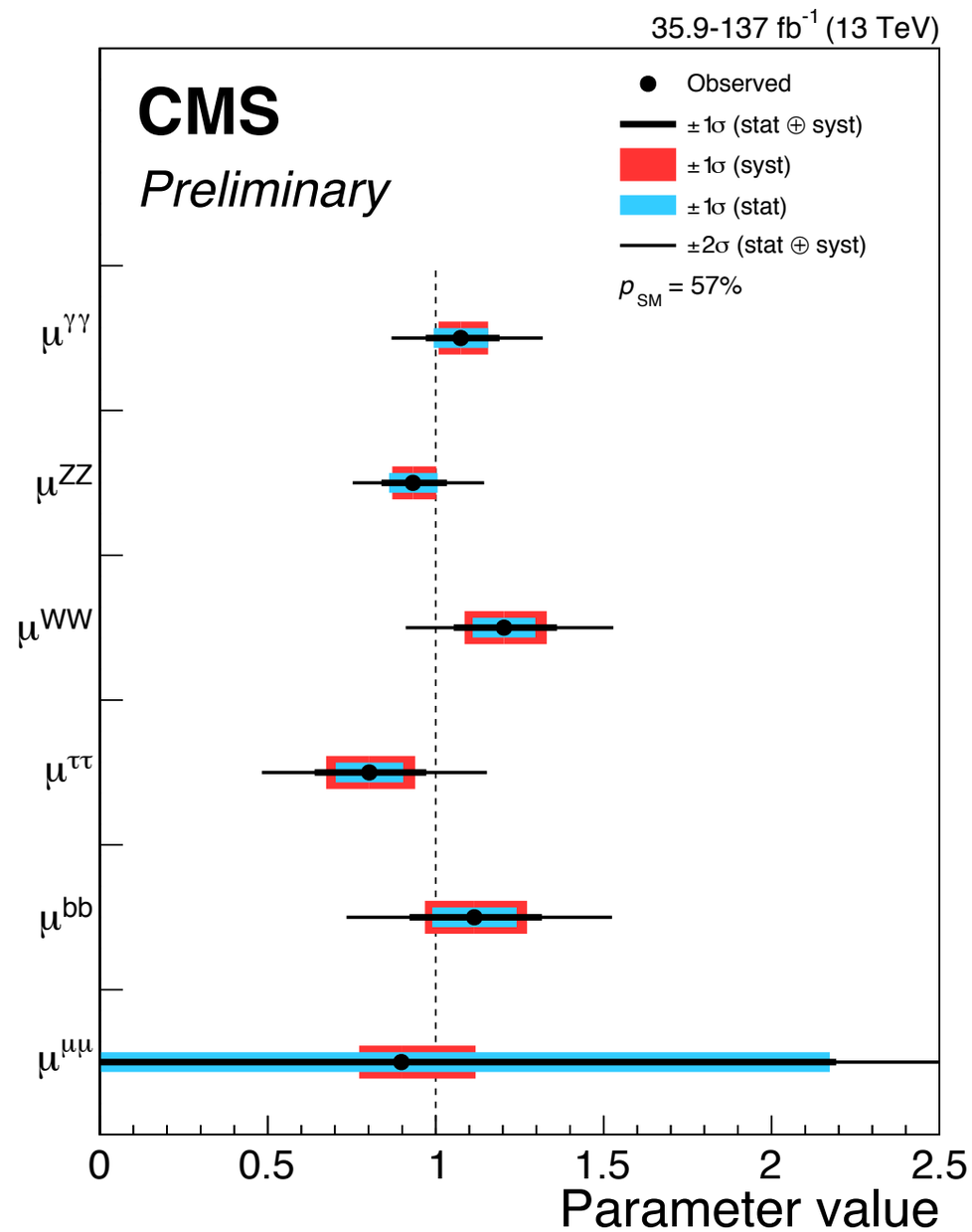
- Motivations:
  - Largest branching fractions
  - In some cases, direct probe of fermionic Higgs couplings
- Challenges:
  - Poor kinematic resolution
  - Seemingly insurmountable background rates
    - Both trigger-level and offline
  - Background simulation often untrustworthy

- CMS has published results targeting:
  - H(bb) decays
  - H(cc) decays
  - Hadronic H($\tau\tau$) decays (not discussed here)
  - Semileptonic H(WW) decays (not discussed here)



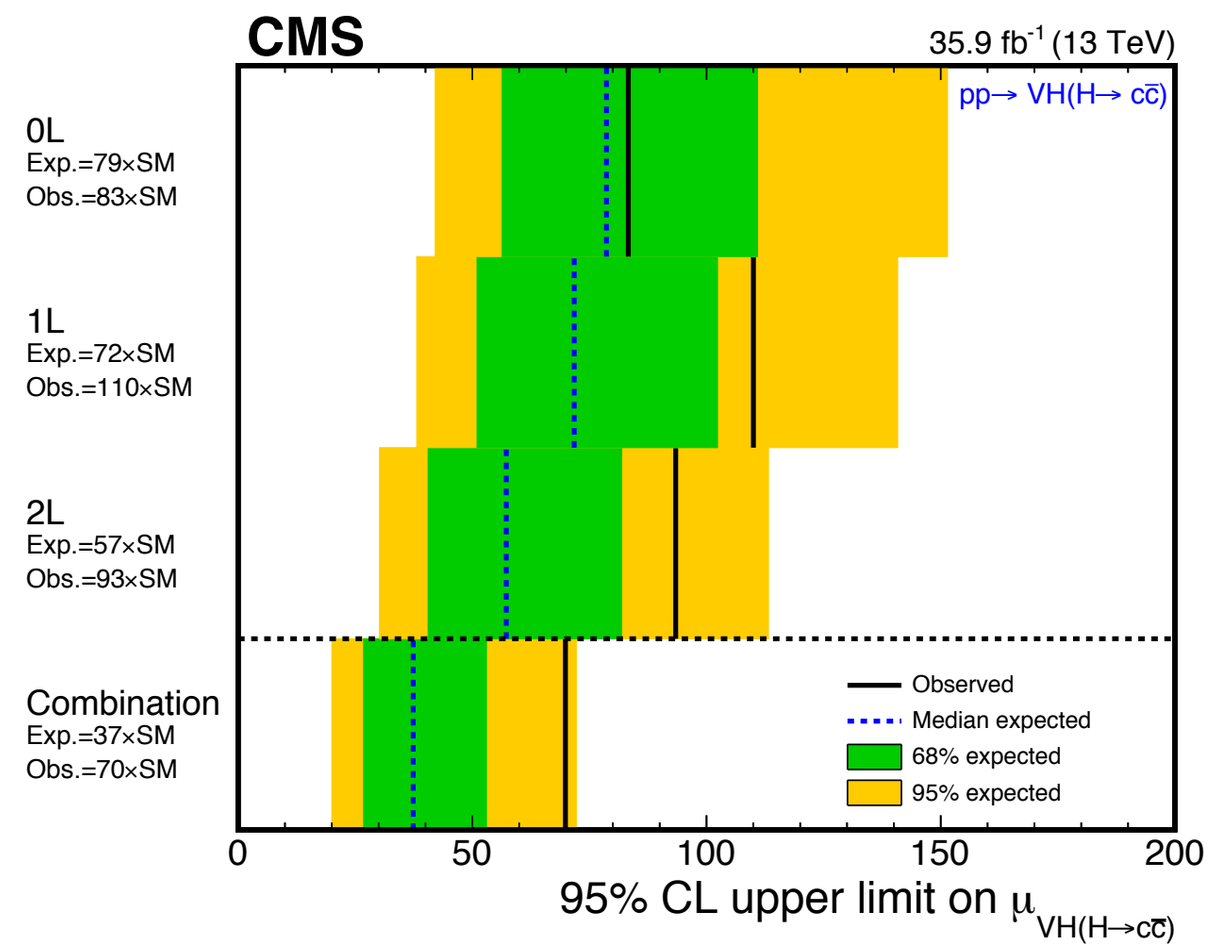
Current CMS H(bb) Results

- Recent CMS H(bb) measurements:
  - VH(bb) HIG-18-016
  - ttH(bb) HIG-18-030
  - Boosted ggH(bb) HIG-17-010 (superseded)
- Results use partial Run II data
  - Run I only: VBF H(bb) HIG-14-004
- Measurements combined in HIG-19-005
  - Several projections of combined likelihood
    - Decay rate modifiers
    - Coupling modifiers
    - Higgs EFT
  - Decay rate modifier constraint on bb is same order as “golden” modes



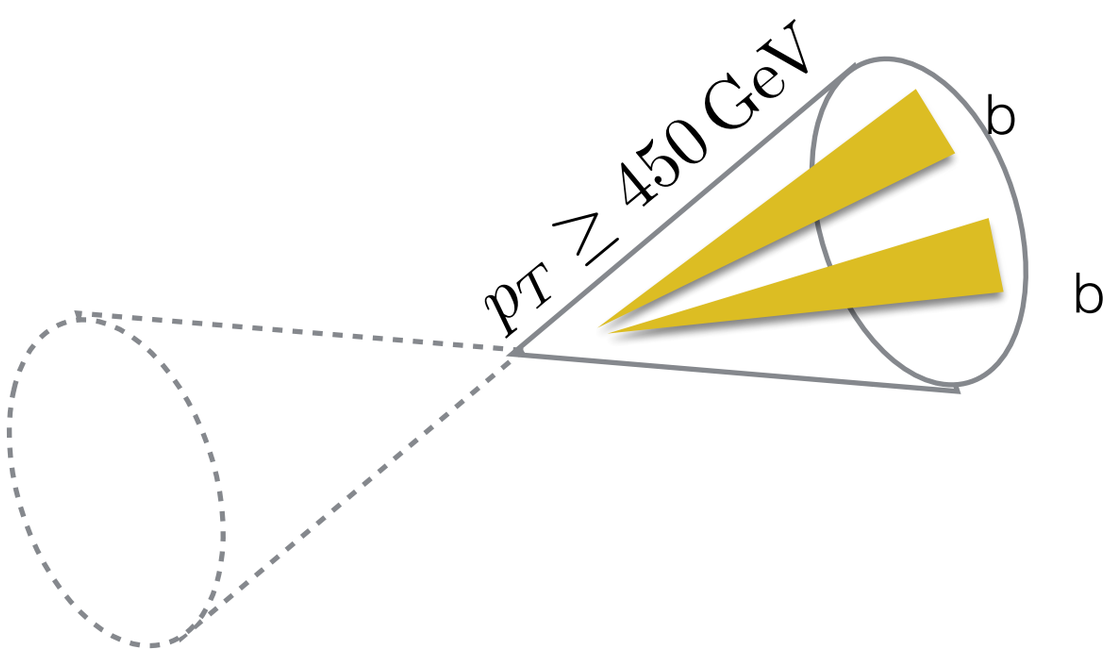
Current CMS H(cc) Results

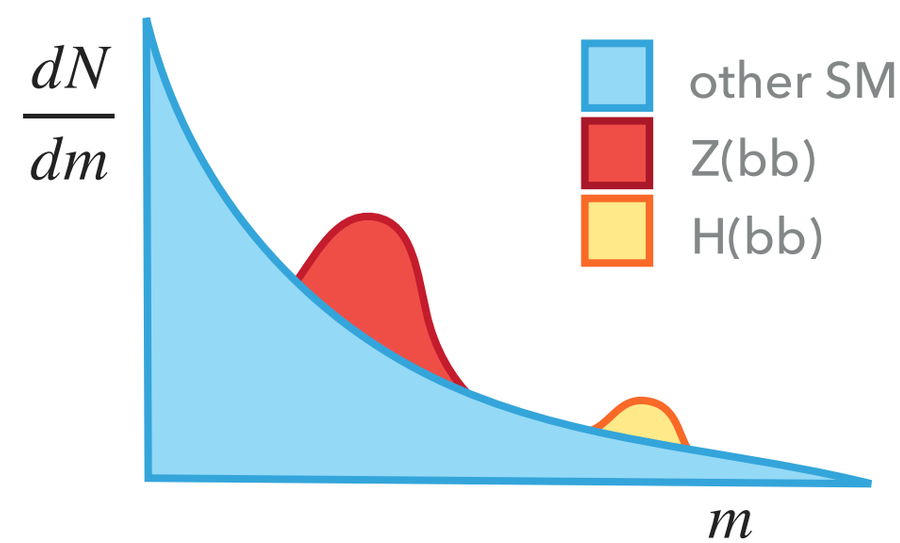
- First direct probe of VH(cc) in HIG-18-031 using combination of strategies
- Tag V boson based on lepton multiplicity categories
  - 0L ~ Z(νν), 1L ~ W(lν), 2L ~ Z(ll)
- Resolved strategy:
  - Require 2 DeepCSV c-tagged narrow-radius jets
  - Use kinematics of tag boson & jets to further reduce background
- Boosted strategy:
  - Select one double-c-tagged large-radius jet
    - Modified DeepAK8 tagger
  - Use kinematics of tag boson & jet to:
    - Reduce background
    - Construct control regions to evaluate deep tagger efficiency
- Observed UL on VH(cc): 70x SM



Full Run-II boosted H(bb) result

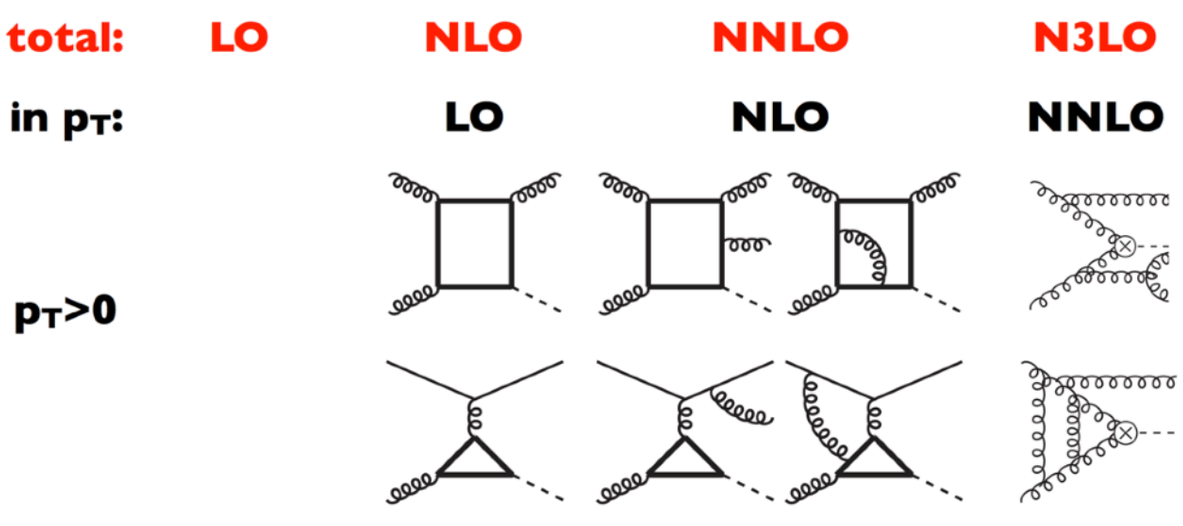
- HIG-19-003: a full Run-II analysis measuring high p_T H(bb) production
  - Supersedes HIG-17-010
- Overall strategy:
  - Preselect boosted large-radius jet with two-prong substructure
  - Use DeepDoubleB tagger to select bb-enriched events
  - Constrain QCD background via jet mass sideband + control region
  - Search for peak in jet mass distribution
- Next slides: a closer look

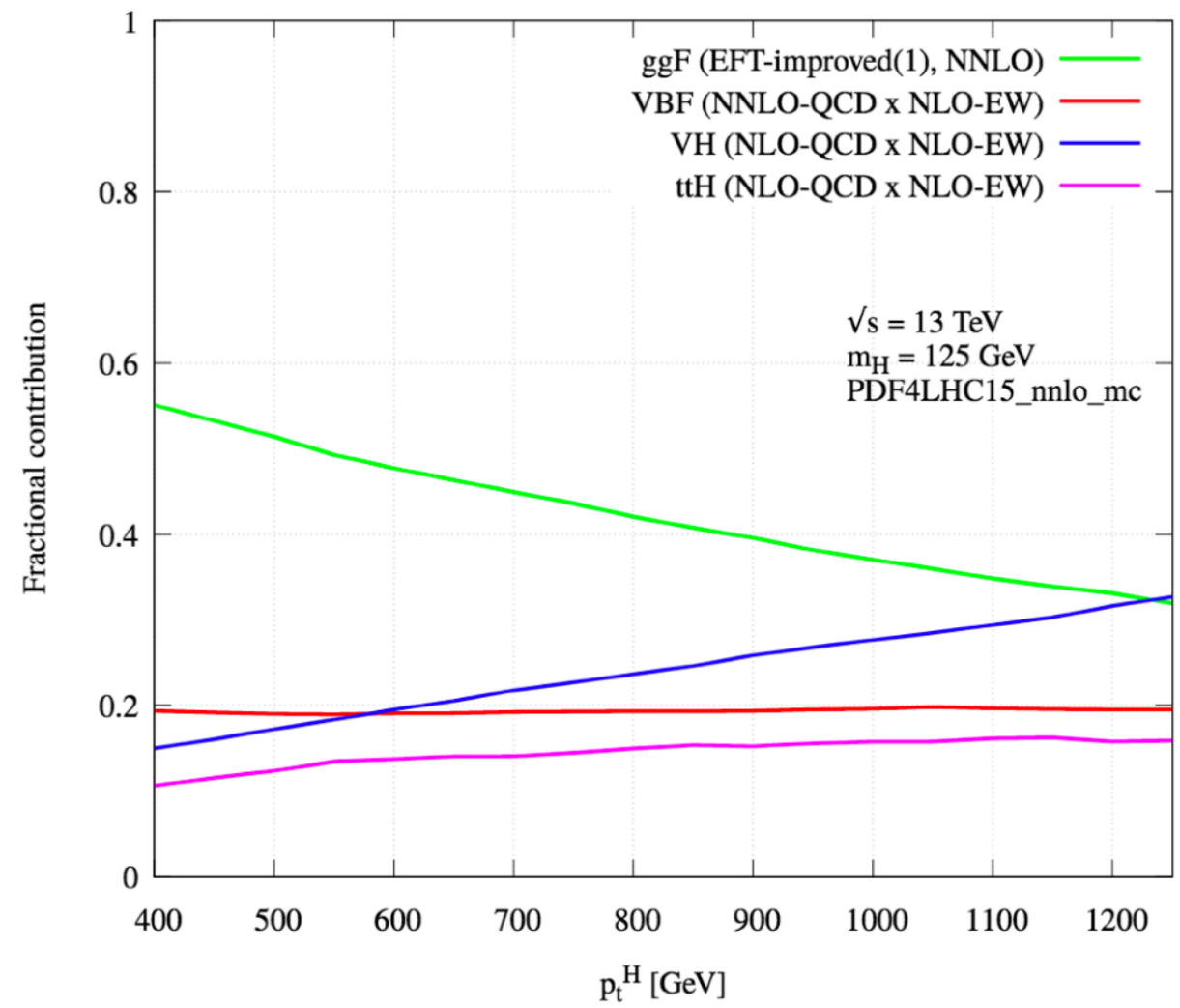




Boosted Higgs in theory

- Effort by theory community to provide precise predictions for boosted Higgs production: arXiv:2005.07762
  - ggH + 1j at quasi-NNLO QCD
  - VH, VBF, ttH at NLO QCD x NLO EW
- Dominant production mode is ggH
- Contribution from VH rises with p_T
- BSM couplings can easily change spectrum without spoiling inclusive XS
  - See e.g. arXiv:1612.00283



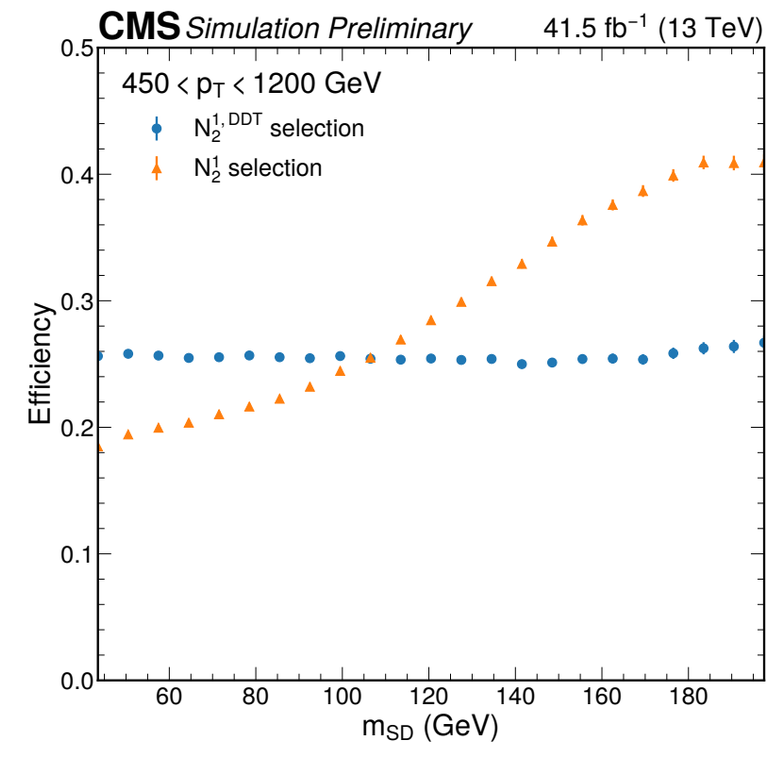


Event selection

- Trigger on high-p_T large-radius (AK8) jet and/or HT
- Select p_T-leading AK8 jet within kinematic region ➜

$$p_T \geq 450\,\mathrm{GeV}$$
$$|\eta| \leq 2.5$$
$$m_{\mathrm{softdrop}} \geq 47\,\mathrm{GeV}$$
$$\rho = 2\ln\frac{m_{\mathrm{softdrop}}}{p_T} \in (-6, -2.1)$$

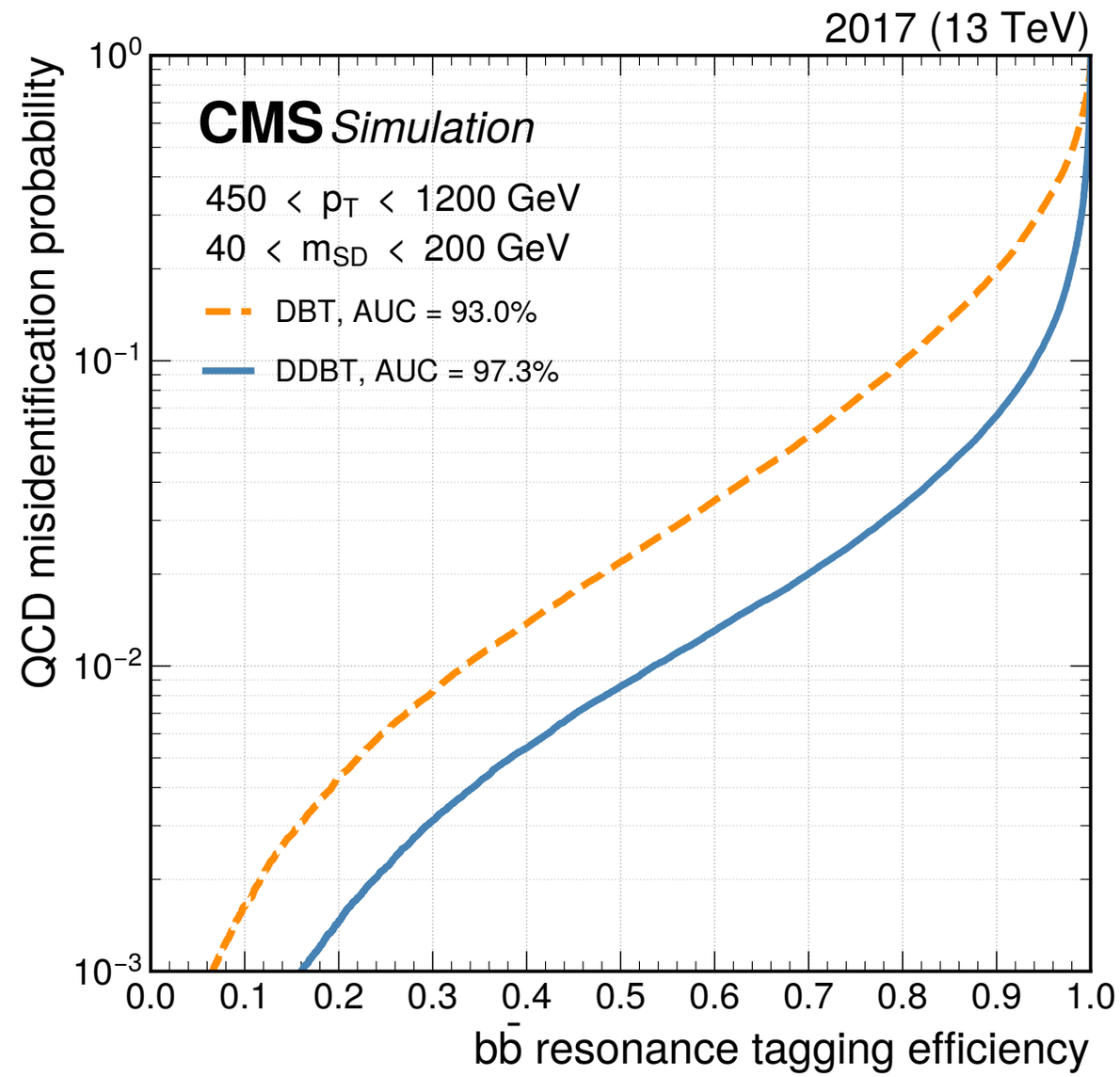
- Softdrop mass algorithm
  - Removes soft & wide-angle QCD radiation to improve mass resolution
- Require 2-prong substructure with N2 energy correlation variable
  - N2 is IRC-safe, relatively independent of jet mass, p_T
  - Residual dependence removed by DDT* procedure ➜
  - 26% QCD efficiency, 60% signal efficiency
- Apply lepton vetos and top rejection selections



* Designed Decorrelated Tagger, arXiv:1603.00027

Deep Double-B Tagger (DDBT)

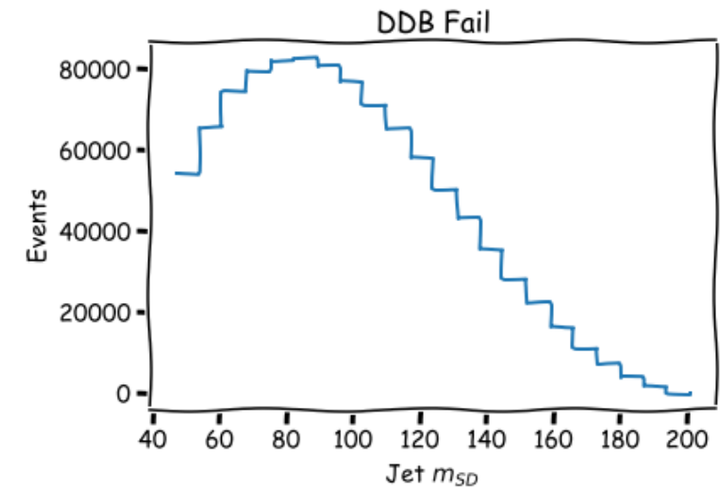
- Primary discriminant: 60% H(bb) efficiency at 1% QCD efficiency
- Inputs include:
  - 27 high-level features used in double-b BDT of HIG-17-010
  - Low-level variables for up to 60 tracks and 5 secondary vertices
- Net 1.3x H(bb) efficiency gain vs. double-b BDT at 1% QCD efficiency



DP2018_046

QCD background estimation

- Differential ABCD method
- Leave DDBT fail region QCD unconstrained
- Fix DDBT pass QCD by transfer factor
  - Classic ABCD: flat TF, mass sideband ➜ yield under peak
  - Here: correlation regulated by polynomial order



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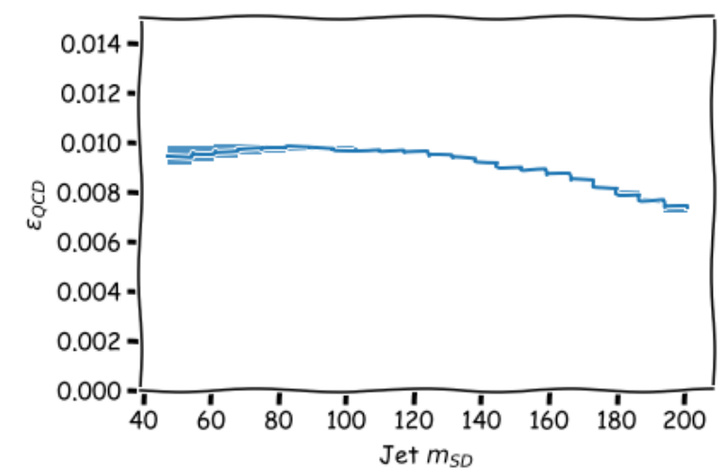

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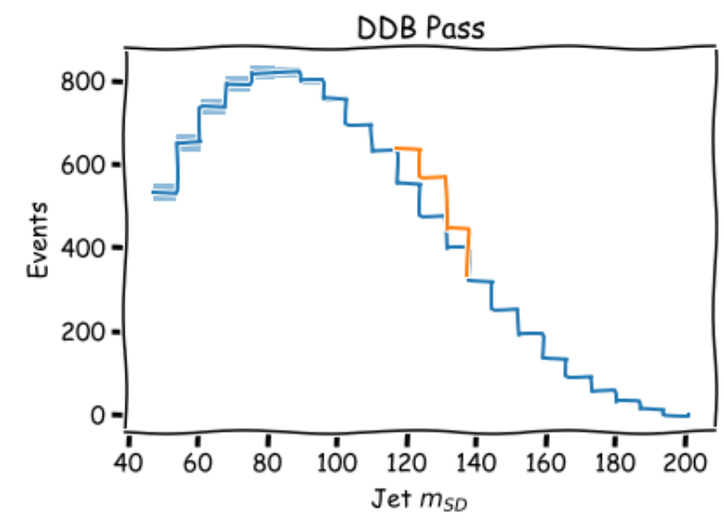

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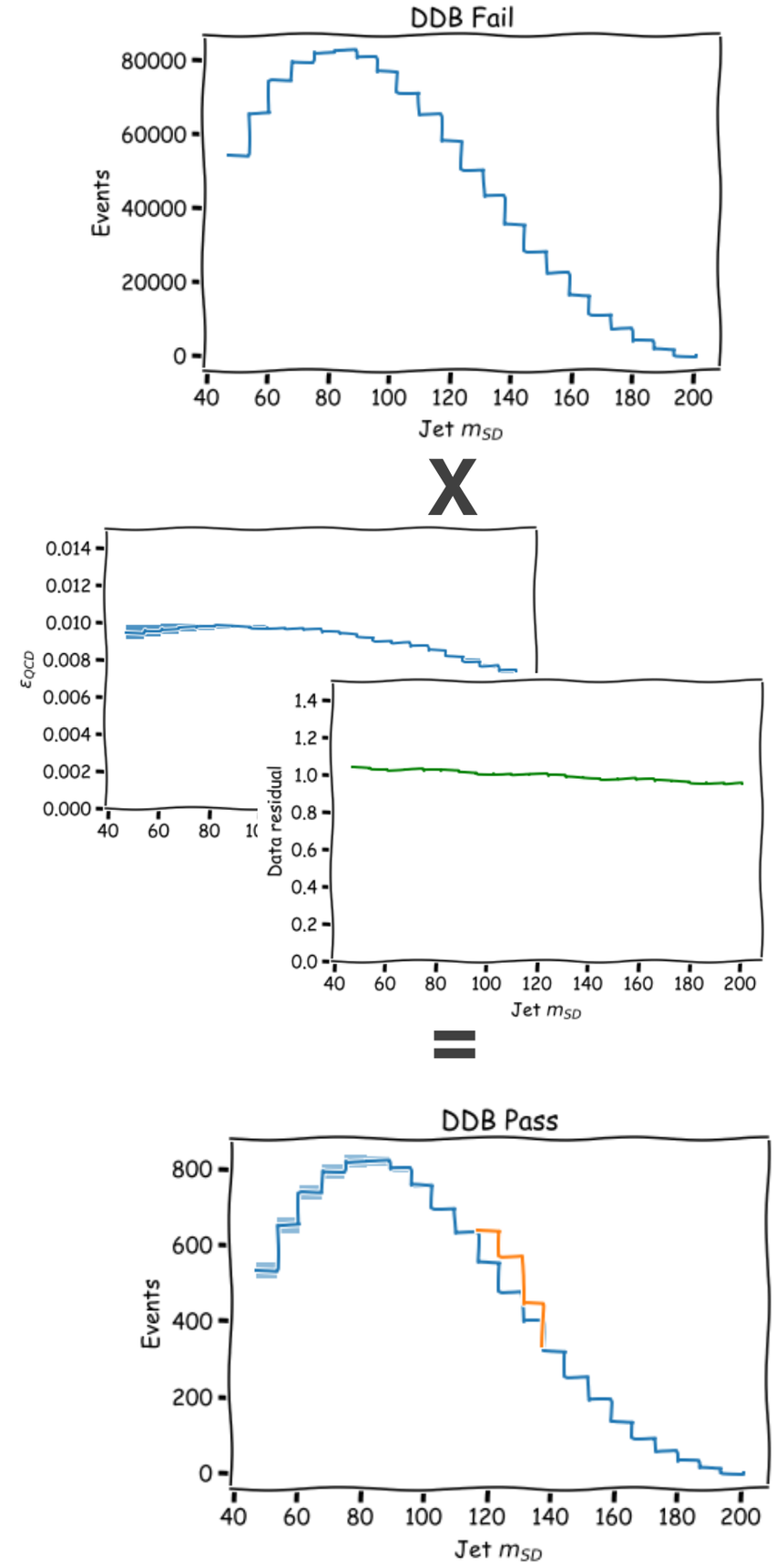
- TF factorized into:
  - Polynomial with constrained parameters defined by separate fit to QCD simulation
    - Captures residual tagger-kinematics correlation
  - Data residual polynomial with free parameters
    - Captures data-simulation discrepancies



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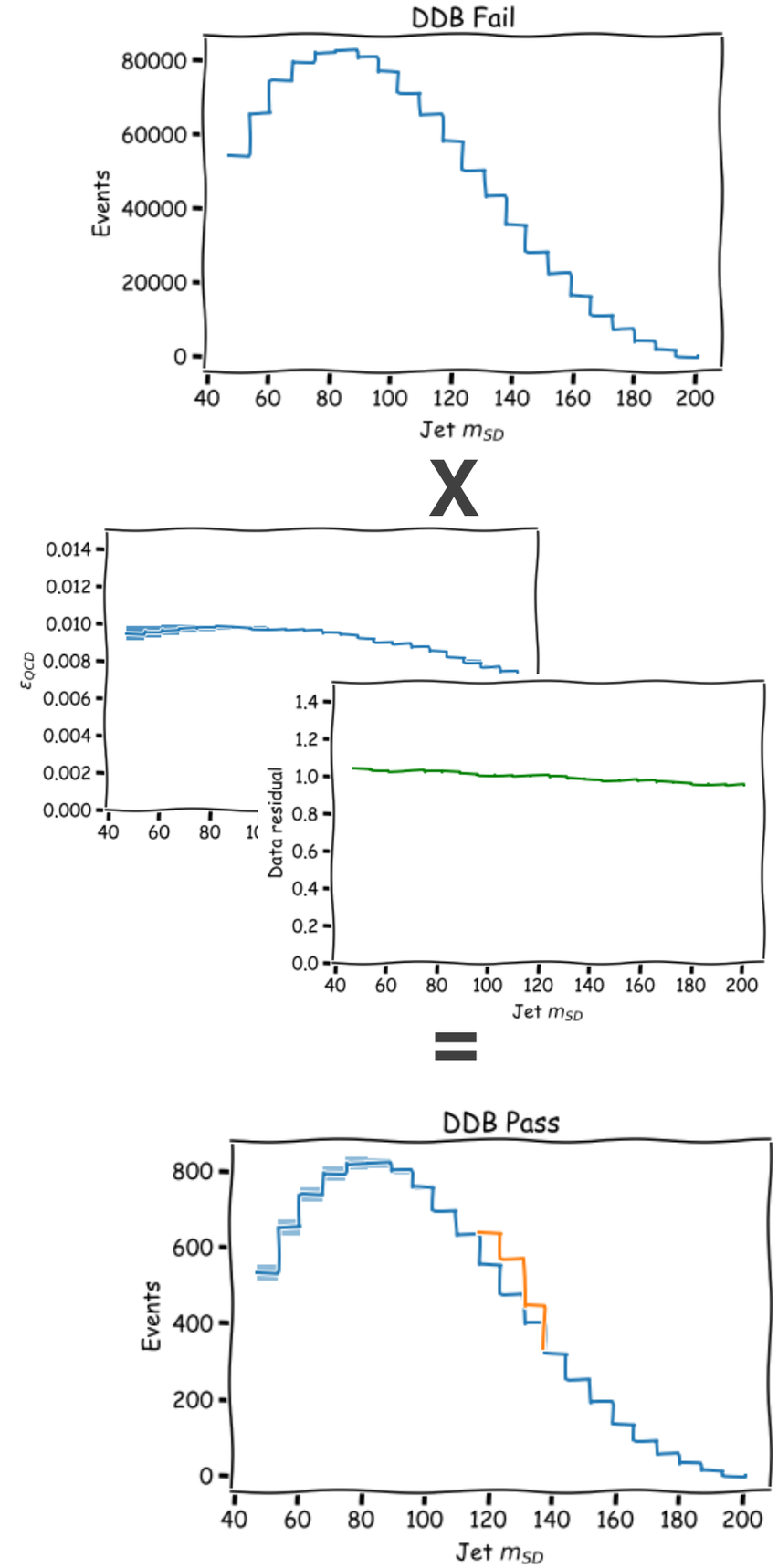
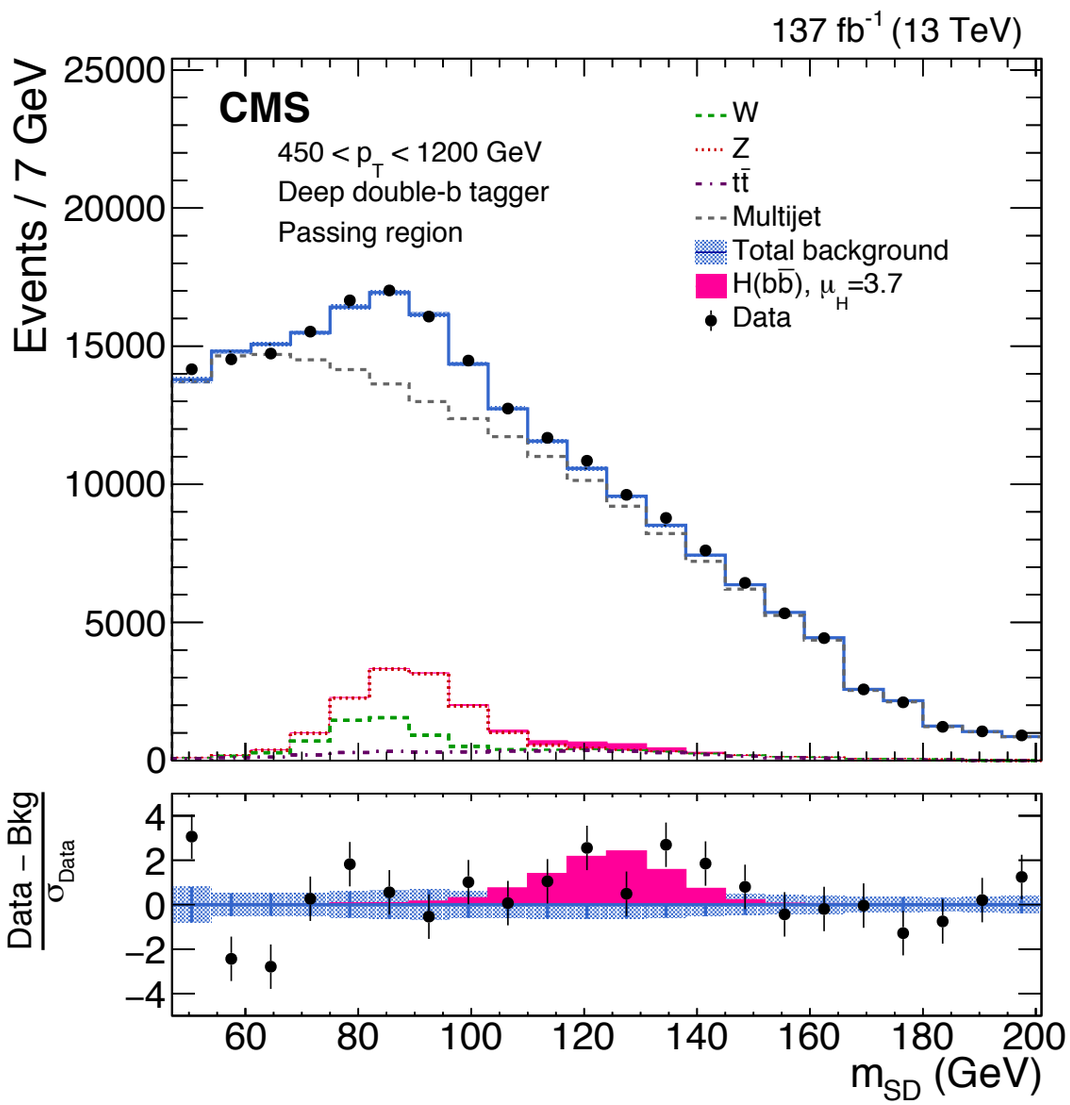
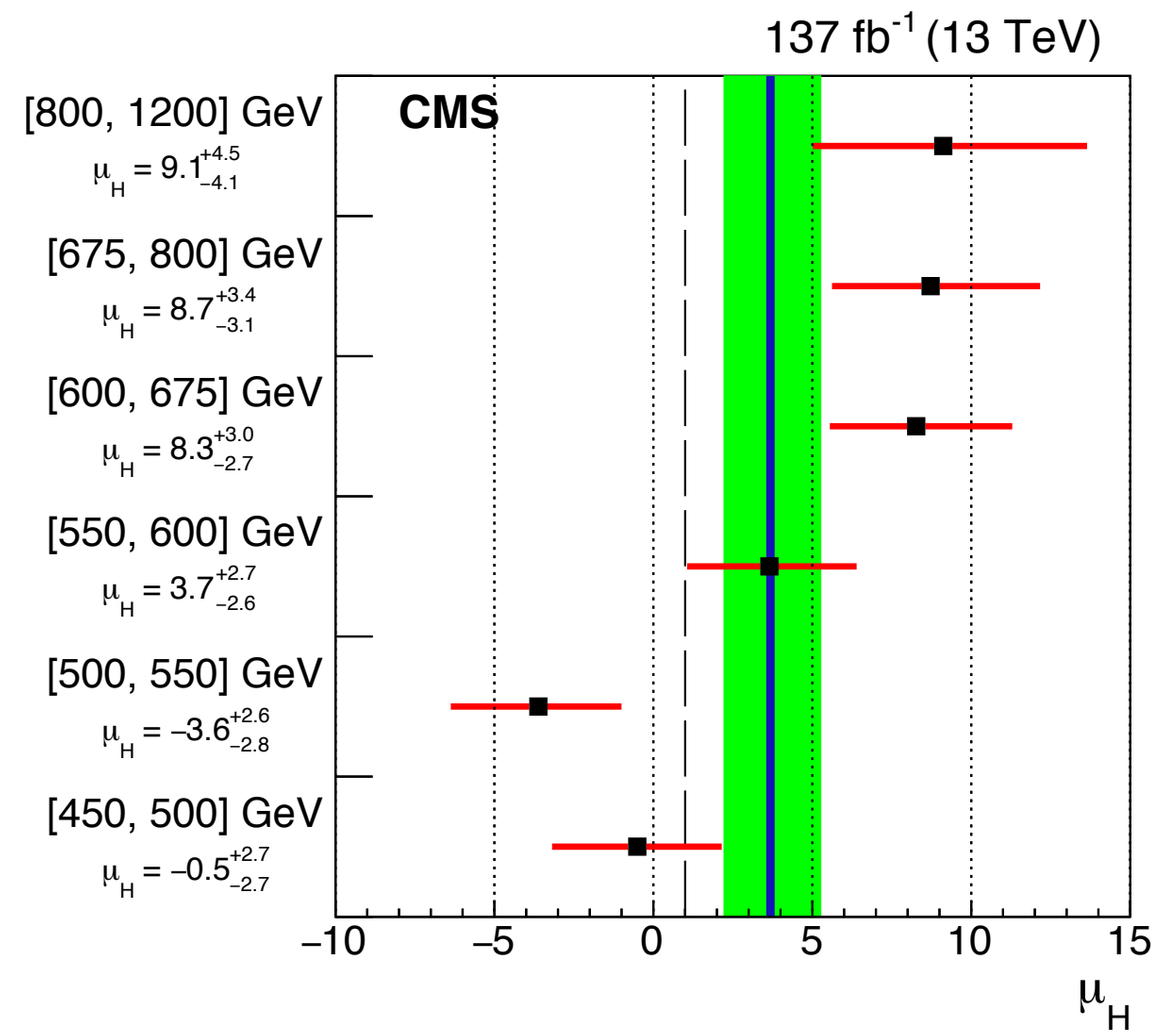
    - Captures residual tagger-kinematics correlation
  - Data residual polynomial with free parameters
    - Captures data-simulation discrepancies
- Polynomial order determined by F-test



Inclusive Results

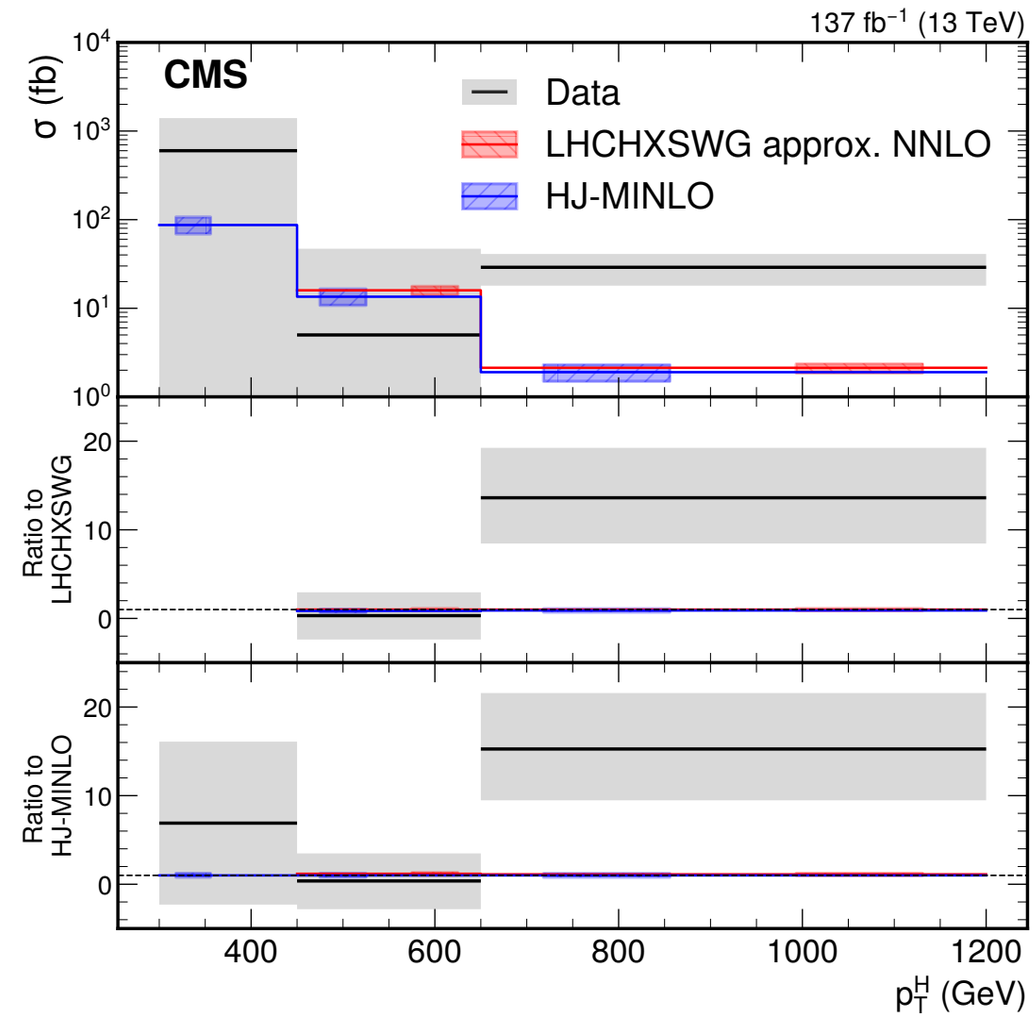
- Observed $\mu_H = 3.7 \pm 1.2\ (\text{stat})\ ^{+0.6}_{-0.7}\ (\text{syst})\ ^{+0.8}_{-0.5}\ (\text{theo})$
- Observed significance: 2.5σ
- Alternative fit: independent signal strength per p_T category (right)





Unfolding

- Result is unfolded to ggH differential cross section in 3 particle-level p_T bins
  - STXS 1.2 binning *
- Fix other production modes to SM expectation
- For $p_T \geq 650$ GeV, the observed excess over SM Higgs production rate has a local significance of 2.6σ



Cross section in fb:

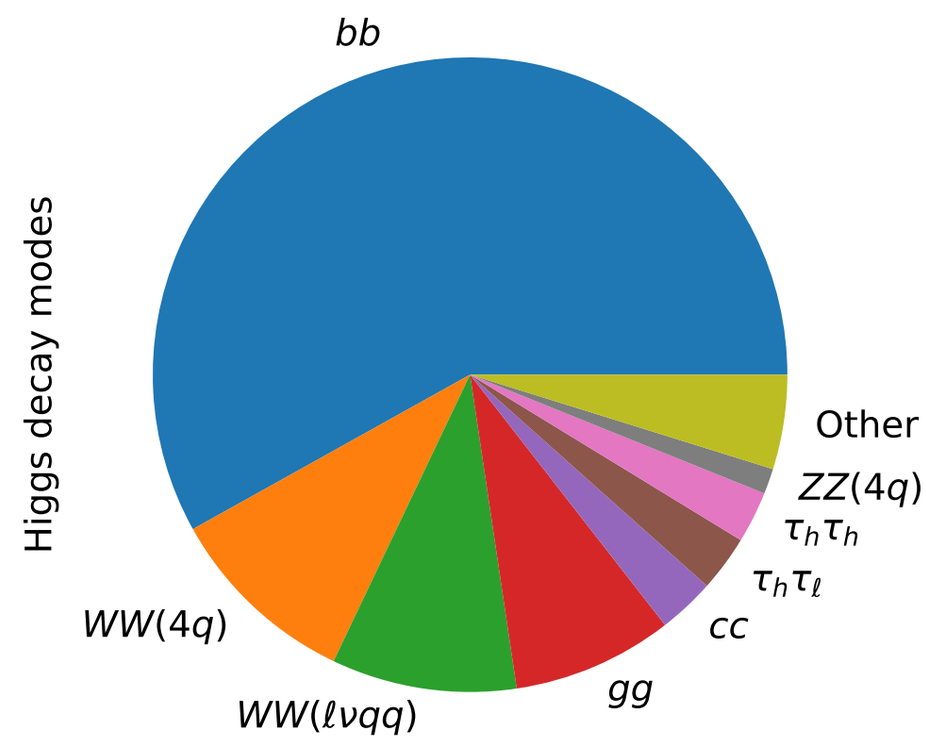
p_T^H (GeV)	300–450		450–650		>650	
Measured	580	±790	5	±43	29	±11
		±720 (stat) ± 350 (syst)		±37 (stat) ± 22 (syst)		±9 (stat) ± 7 (syst)
LHCHXSWG		—	16.0	$^{+1.7}_{-2.0}$	2.1	$^{+0.2}_{-0.3}$
HJ-MINLO	89	$^{+20}_{-18}$	13.5	$^{+3.0}_{-2.7}$	1.9	±0.4

* See talk by M. Bonanomi tomorrow

Conclusions

- CMS continues to overcome the challenges of hadronic Higgs decays
- Recent success via:
  - Advancements in deep neural networks for b and c quark tagging
  - New or improved background estimation techniques
- A new kinematic regime in Higgs production is now being explored
  - Made possible by the large H(bb) branching fraction
  - Other boosted hadronic modes may help probe high-p_T Higgs production

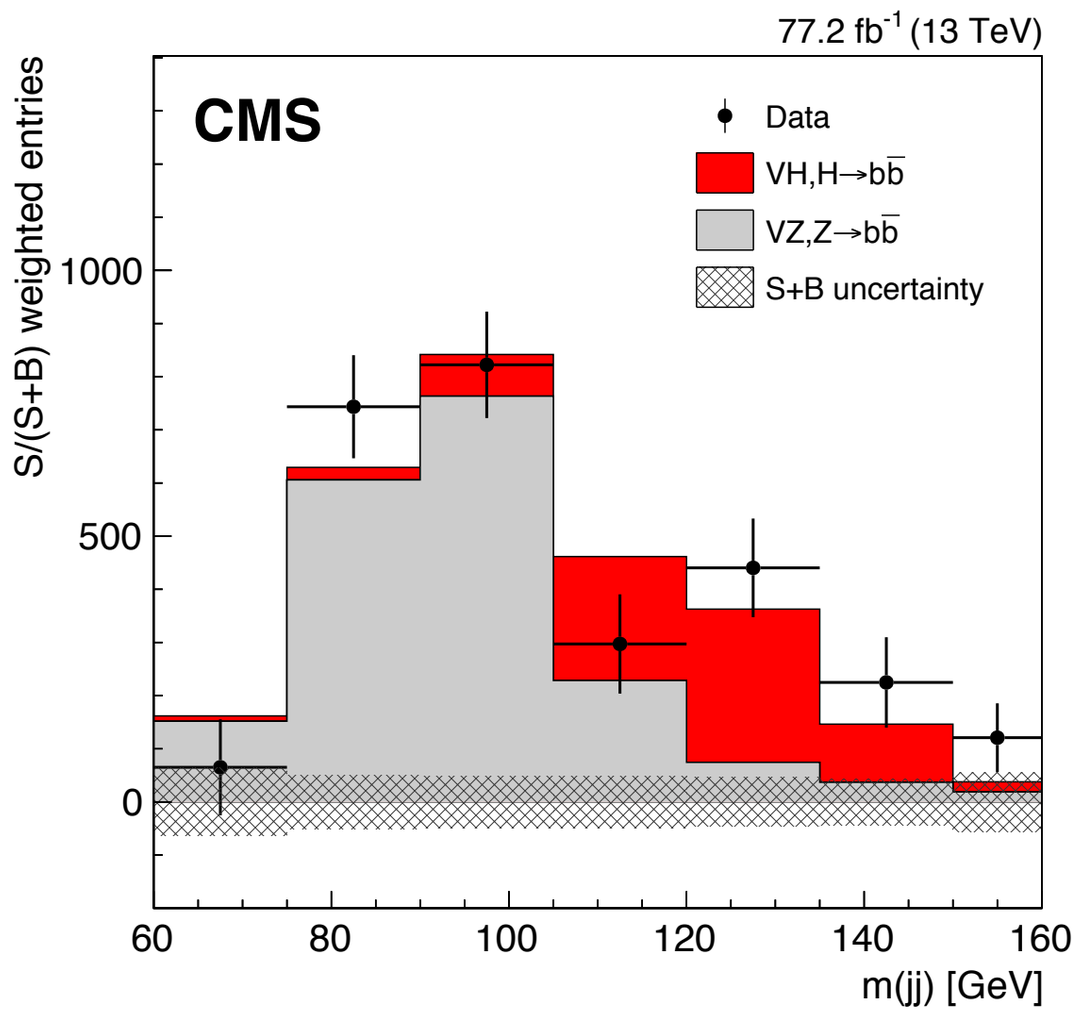
- Thanks for your interest!

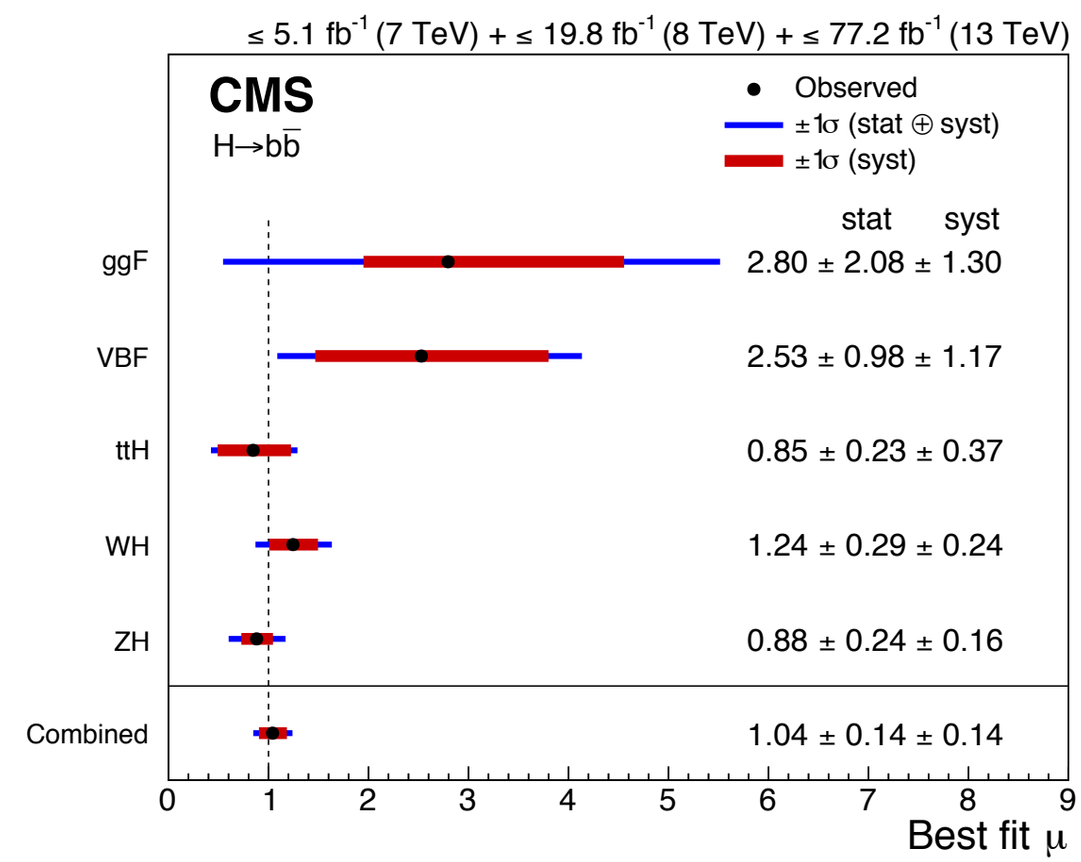


Backup

VH(bb) result

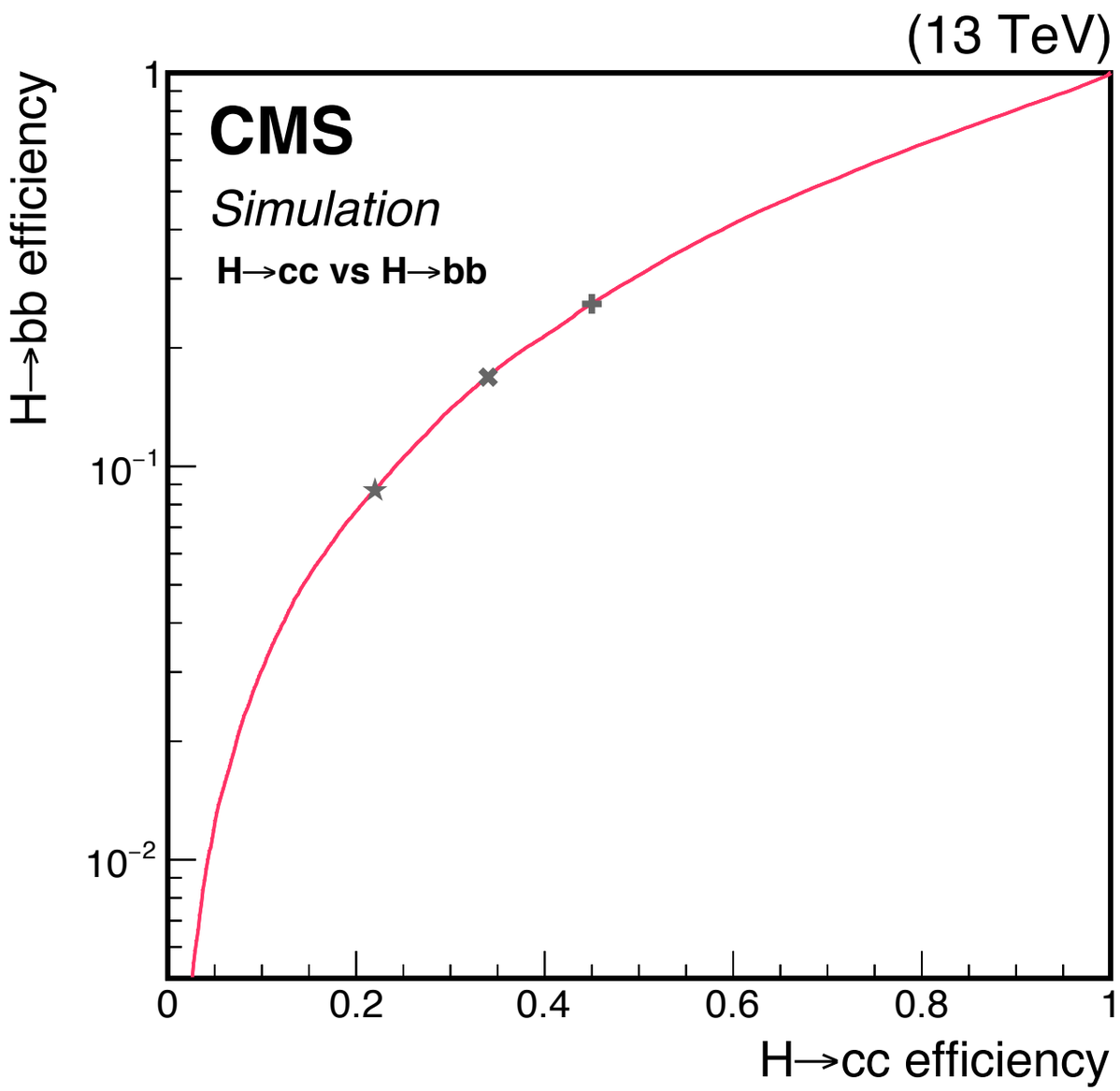
- In combination with all results at the time (Aug. 2018), observed (expected) significance increases to 5.6 (5.5) s.d.

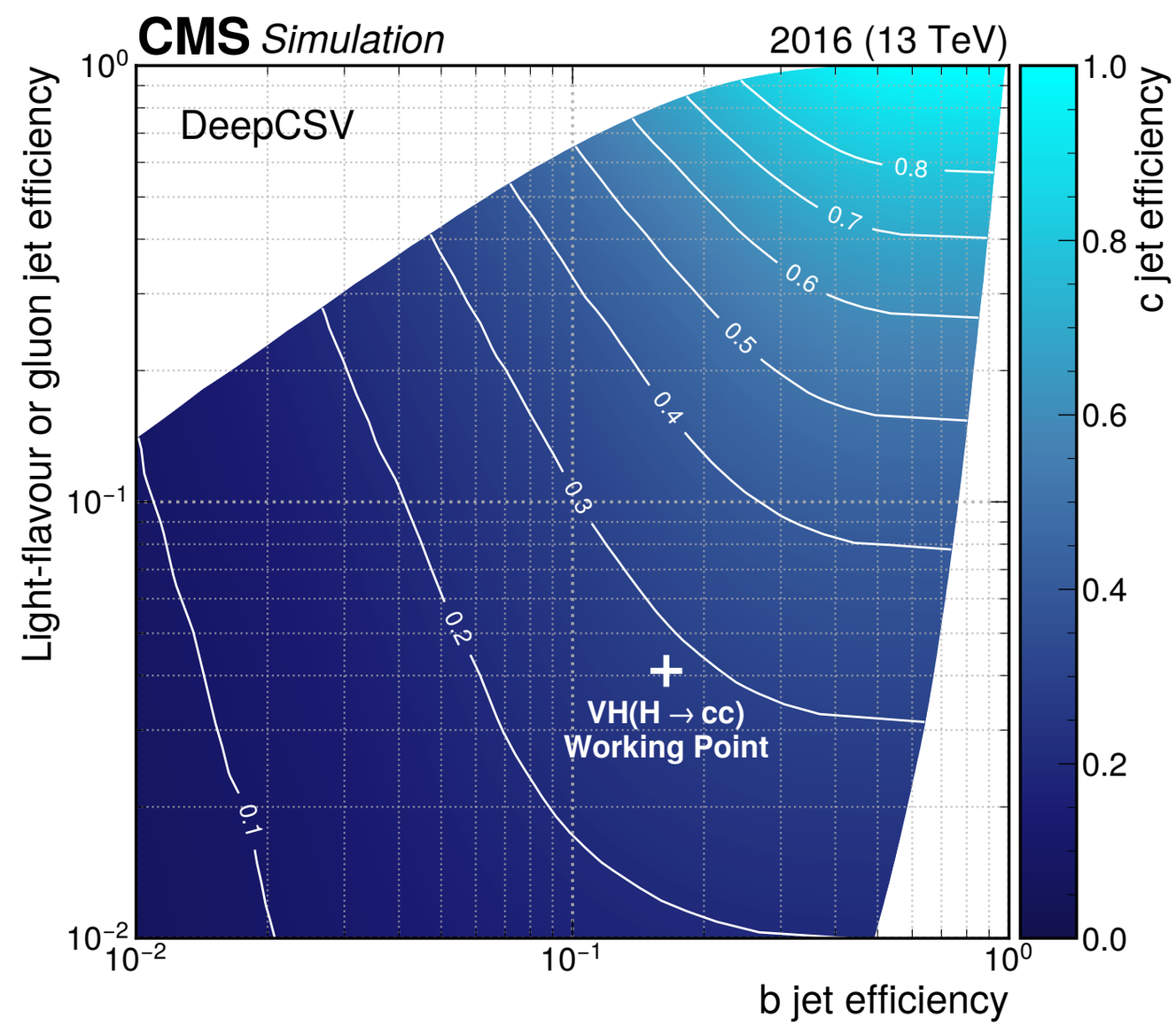




VH(cc) taggers

- Boosted double-c tagger (left), DeepCSV c-tagger (right)





Gluon fusion at NNLO

- H+1j in heavy-top EFT computed to NNLO
- H+1j with resolved top loop computed to NLO
- K-factors in EFT and full theory consistently flat in pT
  - Rescale NNLO EFT result by NLO EFT/full ratio

$$\frac{d\sigma^{\text{EFT-improved (1), NNLO}}}{dp_\perp} = \frac{\frac{d\sigma^{\text{QCD, NLO}}}{dp_\perp}}{\frac{d\sigma^{\text{EFT, NLO}}}{dp_\perp}} \frac{d\sigma^{\text{EFT, NNLO}}}{dp_\perp}$$