Search for Non-Resonant Higgs Boson Pair Production via Vector Boson Fusion in Boosted 4b Final State

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CLHCP 2021
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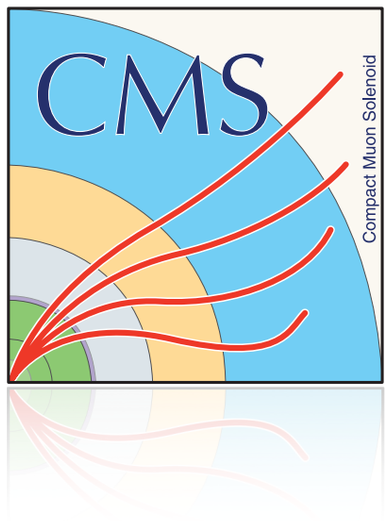
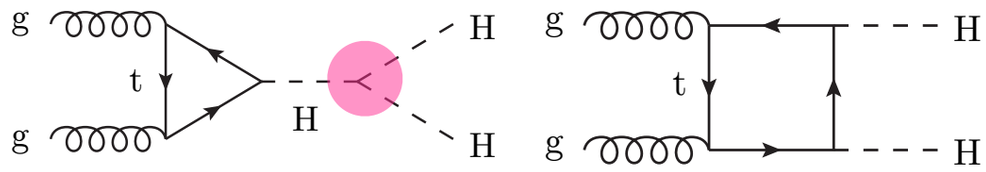
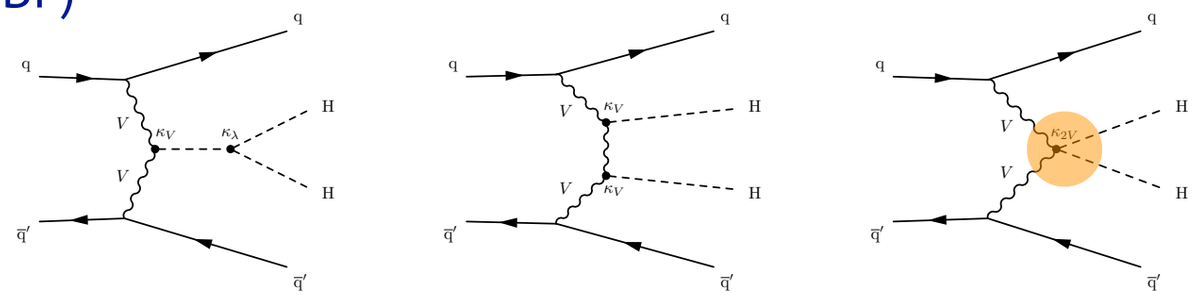


Introduction

- Higgs boson pair (HH) production: crucial to probe the Higgs potential in the Standard Model (SM)
- Dominant production mode: gluon-gluon fusion (ggF)
  - very rare process in the SM: σ_{ggF} ~ 31 fb
    - i.e., in total about 4300 HH events in the Run2 dataset
  - allows to directly probe the Higgs trilinear coupling λ_{HHH}

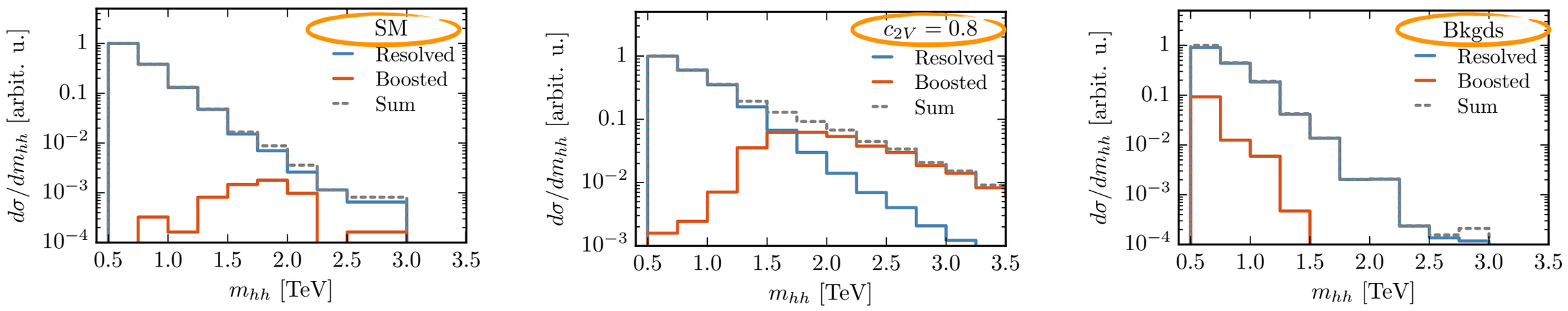


- Second production mode: vector boson fusion (VBF)
  - even more rare: σ_{VBF} ~ 1.7 fb
  - but: a unique channel to **probe the HHVV quartic coupling** (κ_{2V})



- moreover, if the HHVV coupling deviates from the SM ($\kappa_{2V} \neq 1$), a significant fraction of signal becomes highly Lorentz-boosted
  - -> **enhanced sensitivity using boosted objects for Higgs boson reconstruction**

Eur.Phys.J.C 77 (2017) 7, 481



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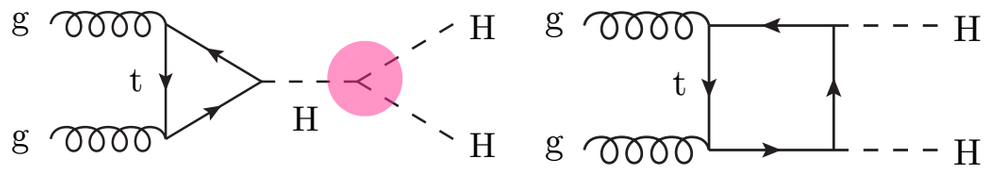

Topic of this talk!

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  - even more rare: σ_{VBF} ~ 1.7 fb
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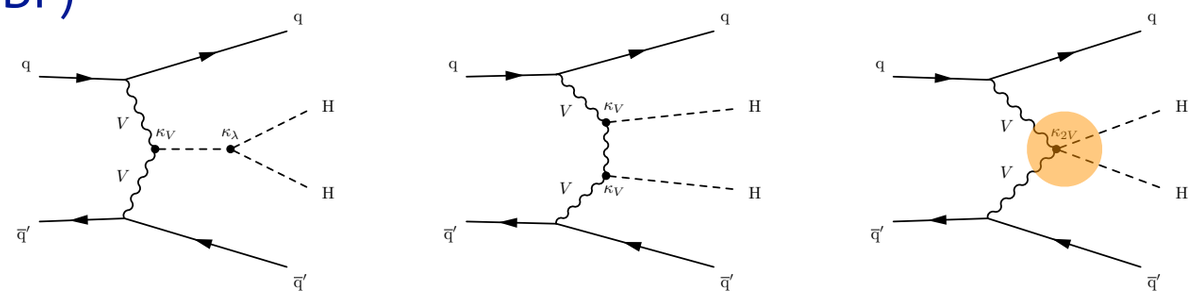

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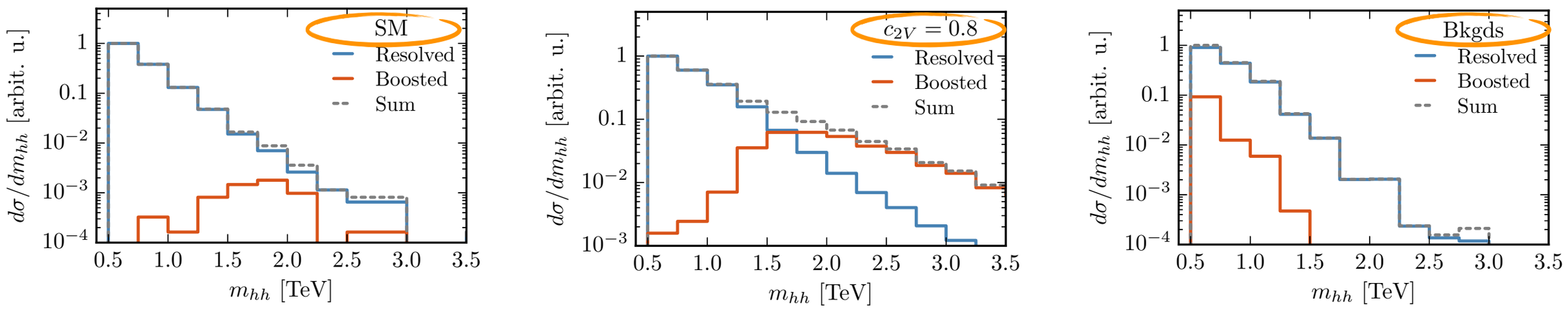
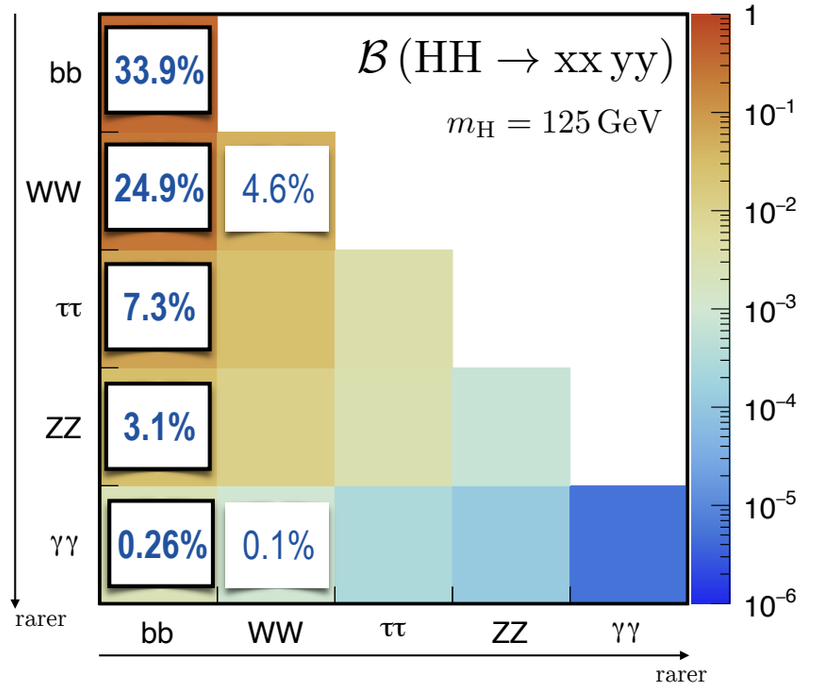
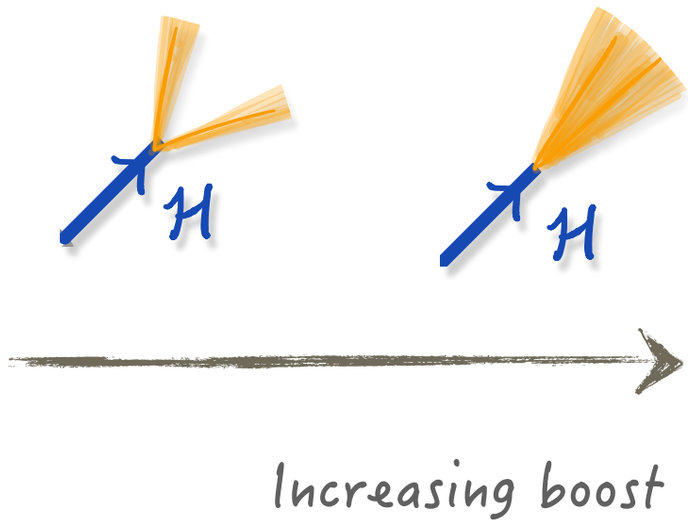


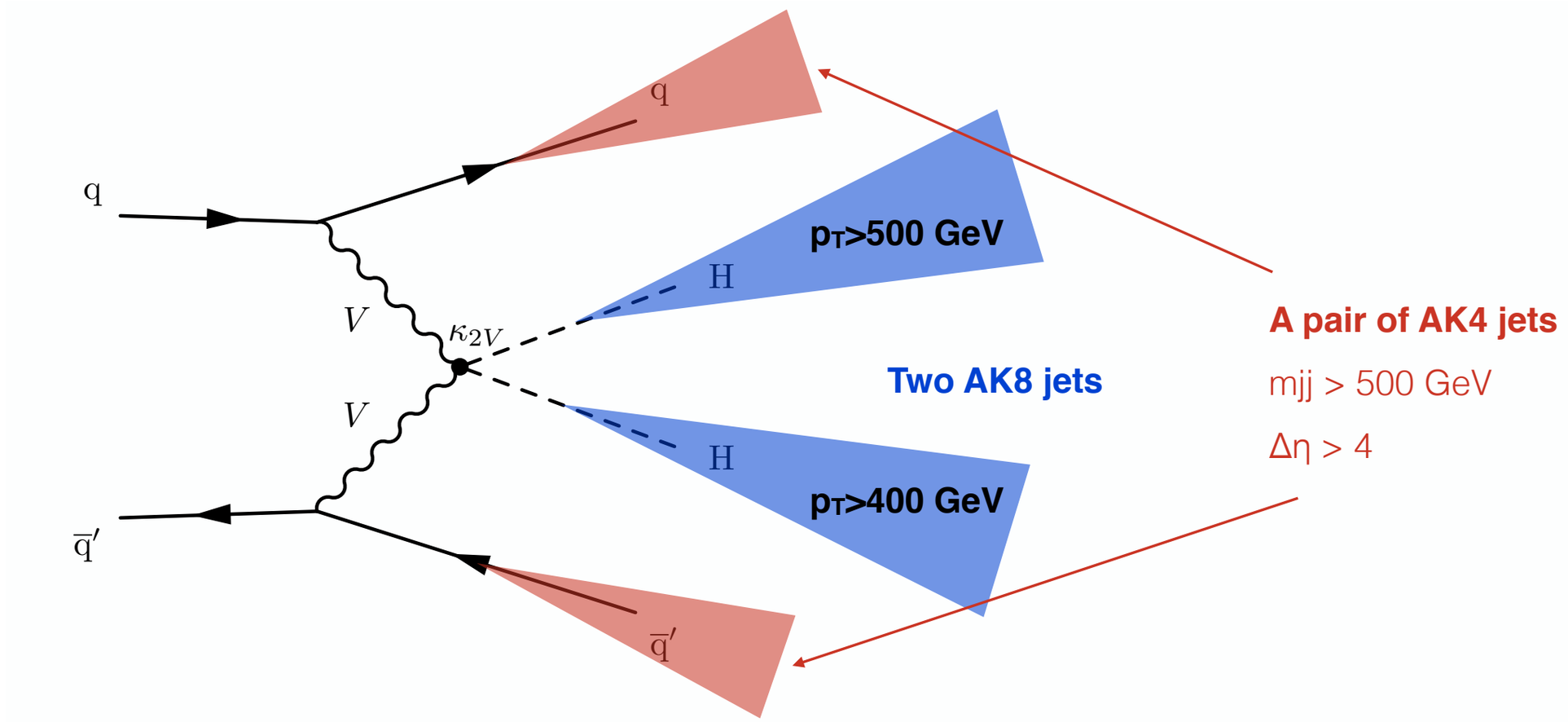
Analysis Overview

- First search of VBF HH production with boosted objects [CMS-PAS-B2G-21-001]
- Both Higgs bosons required to decay to a pair of bottom quarks
  - largest branching fraction, though high QCD multijet background
- Focus on the regime where both Higgs bosons are highly boosted
  - decay products becomes highly collimated and therefore reconstructed as one merged jet instead of two separate jets
  - enhanced sensitivity for anomalous HHVV quartic coupling
- Identification and reconstruction of the boosted H→bb decay is the key of this analysis
  - advanced machine learning techniques exploited to improve the performance





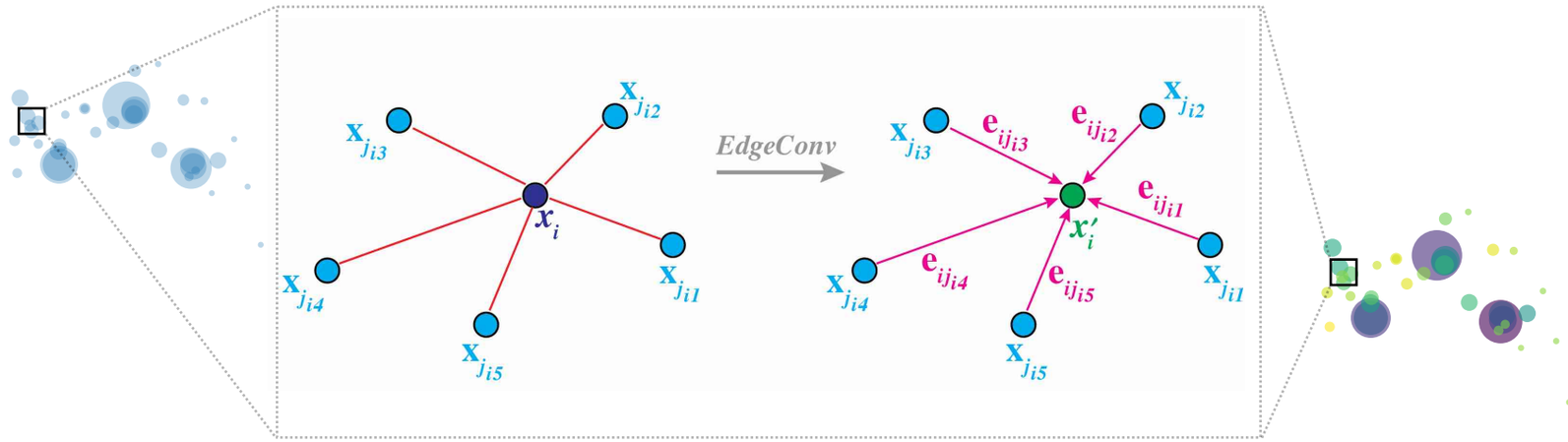
Analysis Strategy



- **VBF topology**: two small-R jets with dijet mass > 500 GeV and $|\Delta\eta| > 4$
- Higgs bosons reconstructed as two **high p_T large-R jets** (p_T > 500/400 GeV)
  - **H→bb identification** with the ParticleNet algorithm
  - Higgs jet mass reconstructed with the **ParticleNet mass regression**

H→BB IDENTIFICATION

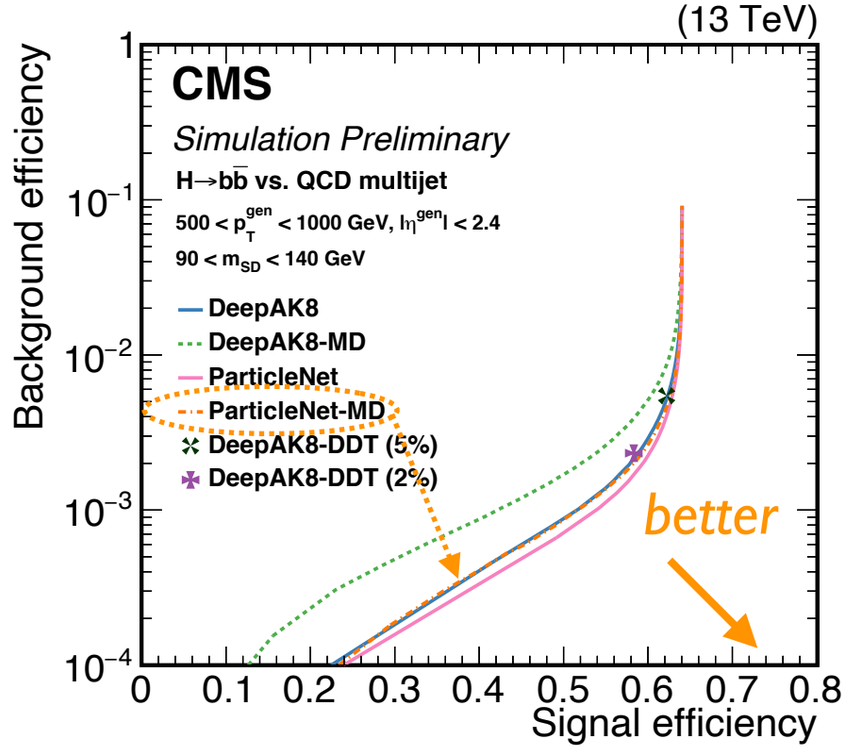
- The ParticleNet algorithm used to identify the H→bb decay
  - ParticleNet [Phys. Rev. D 101, 056019 (2020)]
    - treating a jet as an **unordered set of particles** in space
    - using permutation-invariant **graph neural networks**



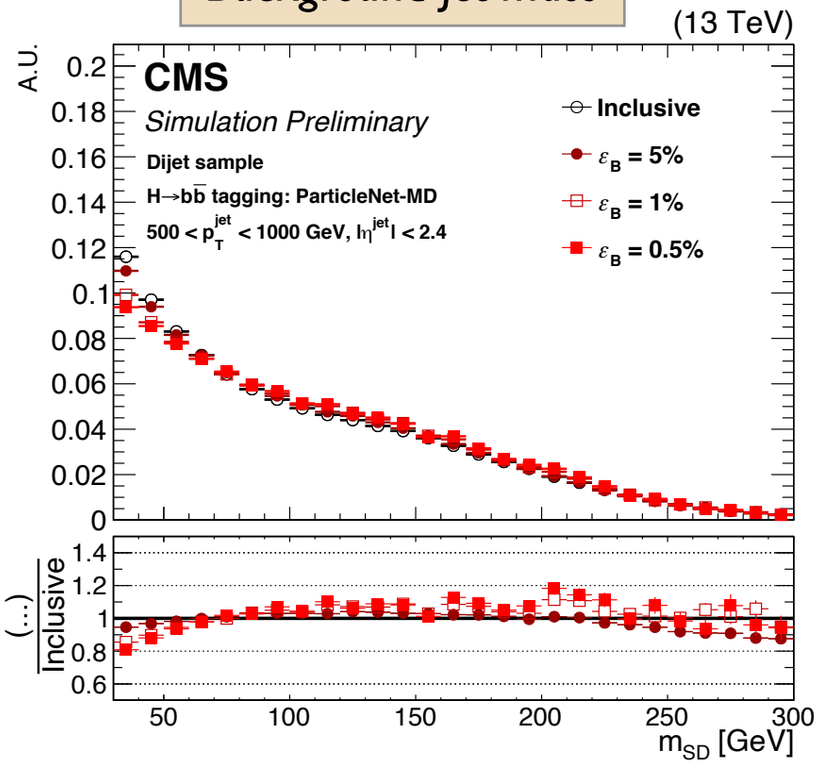
- mass-decorrelated version (ParticleNet-MD) used in this analysis
  - mass decorrelation archived by training on a signal sample with variable Higgs boson masses (flat spectrum ranging between 15 to 250 GeV)
- **~3-4x better background rejection than previous DNN tagger**

CMS DP-2020/002

H→bb tagging performance

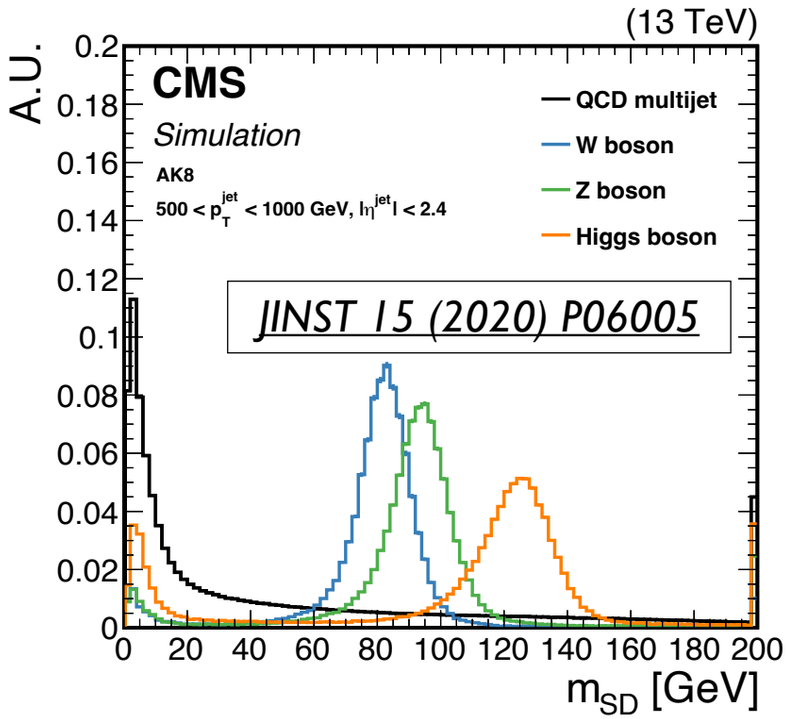


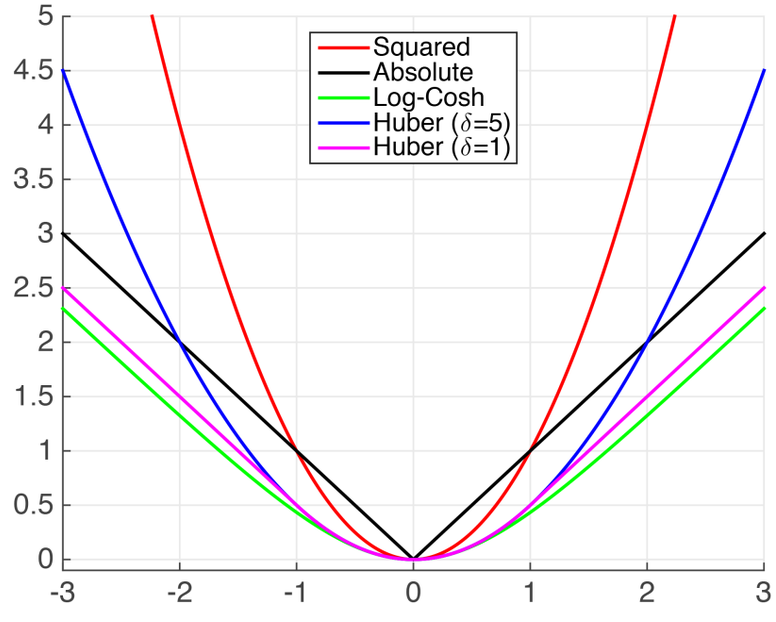
Background jet mass



Mass Regression

- Jet mass: one of the most powerful observables to distinguish jets from different origins
  - soft drop grooming applied to reduce sensitivity to unrelated radiations (initial-state radiation, underlying event, pileup, etc.)
  - overall good performance, but still some limitations (e.g., tails near 0 for H->bb signal jets in soft drop mass)
- Dedicated mass regression algorithm developed to improve the jet mass reconstruction
  - exploit the ParticleNet architecture to predict the jet mass directly from jet constituents
  - similar setup as the ParticleNet-MD tagger (inputs, training samples, etc.)
  - regression target
    - signal (H->bb/cc/qq): generated particle mass (pole mass) of H [flat spectrum ranging from 15 – 250 GeV]
    - background (QCD): soft drop mass of the particle-level jet
  - loss function
    - LogCosh: $L(y, y^p) = \sum_{i=1}^{n} \log(\cosh(y_i^p - y_i))$

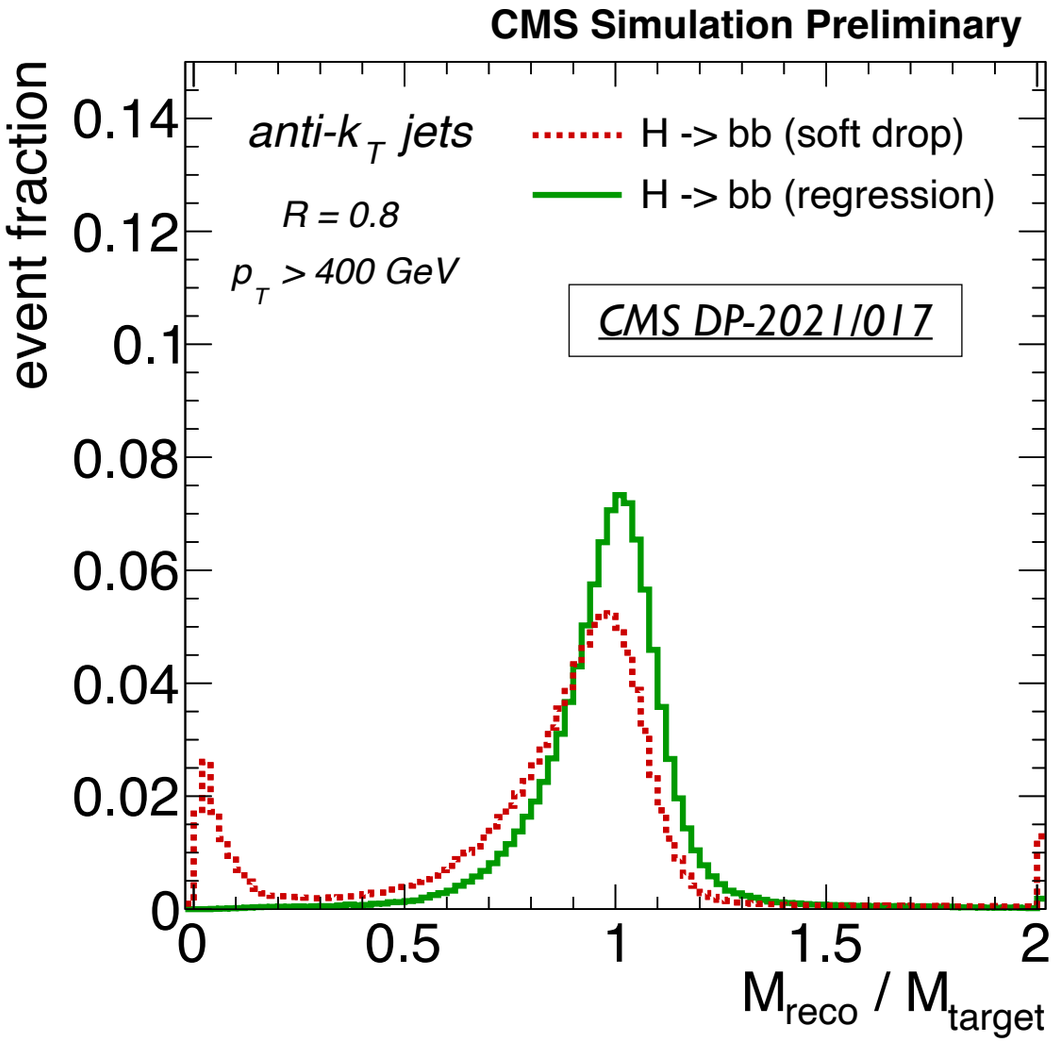




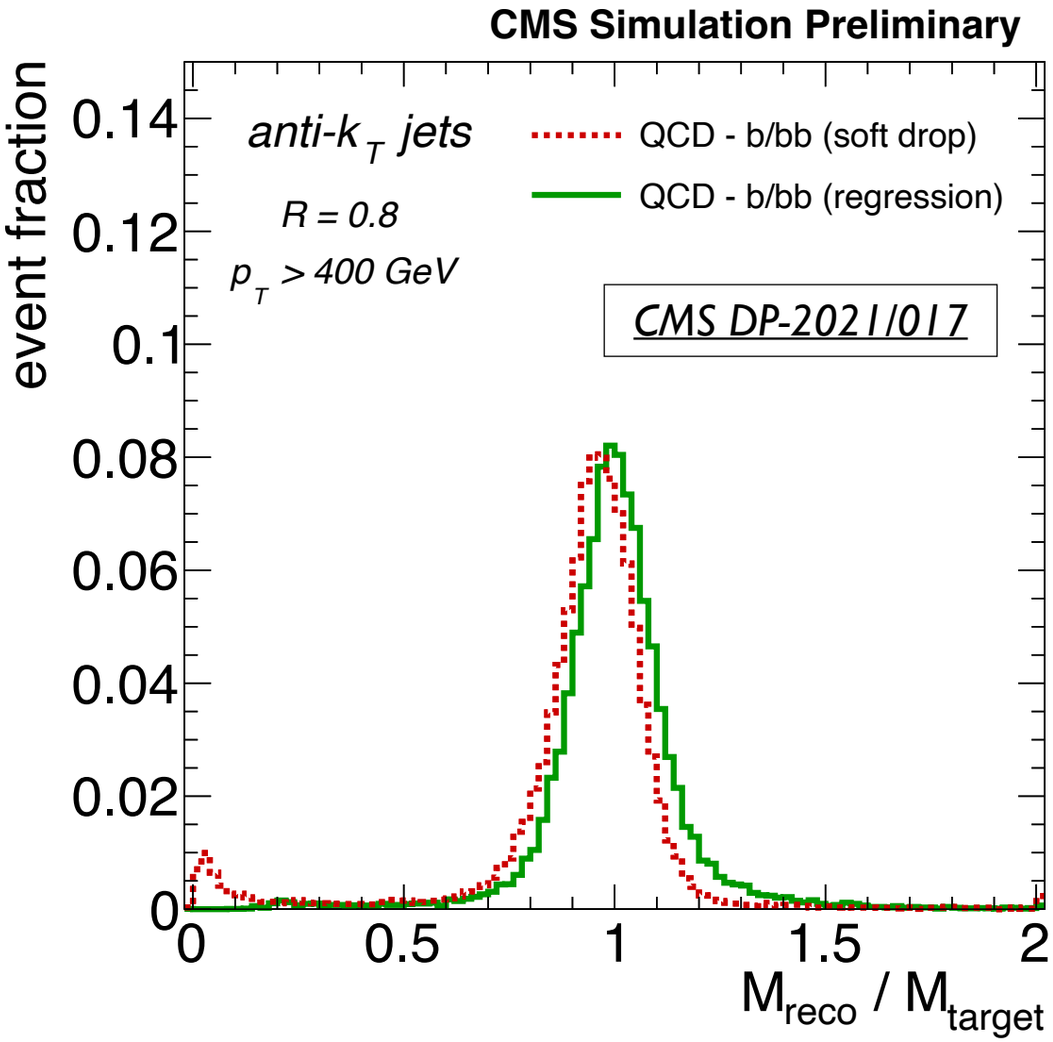
https://www.cs.cornell.edu/courses/cs4780/2015fa/web/lecturenotes/lecturenote10.html

MASS REGRESSION: PERFORMANCE

Signal jets: H→bb



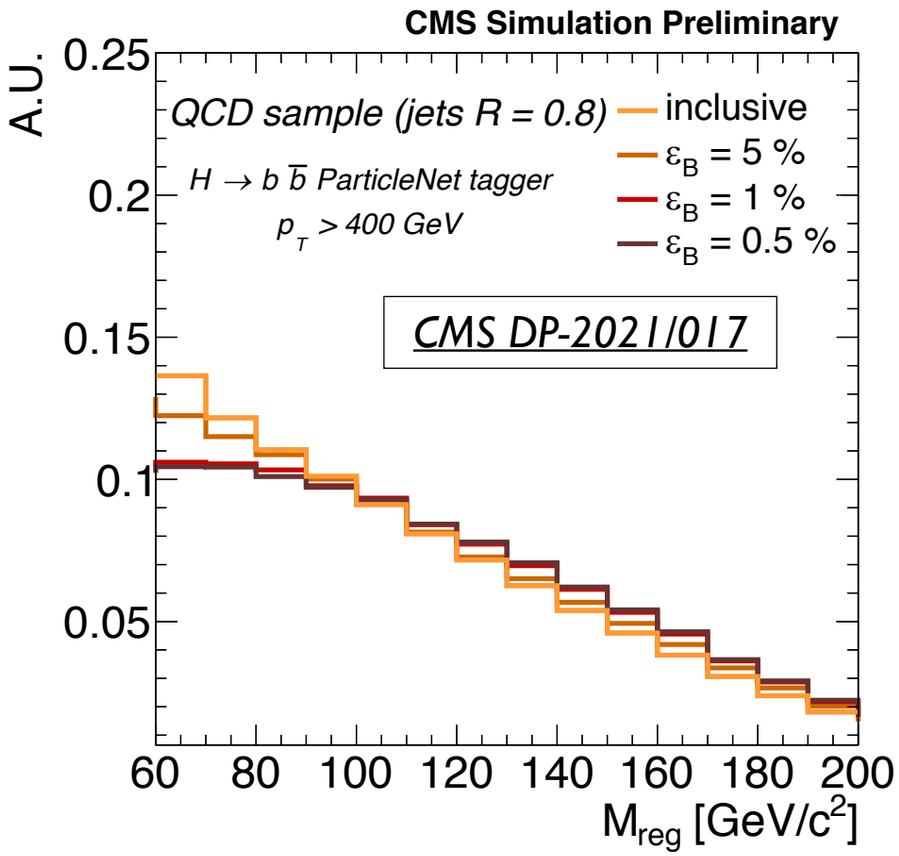
Background jets: QCD



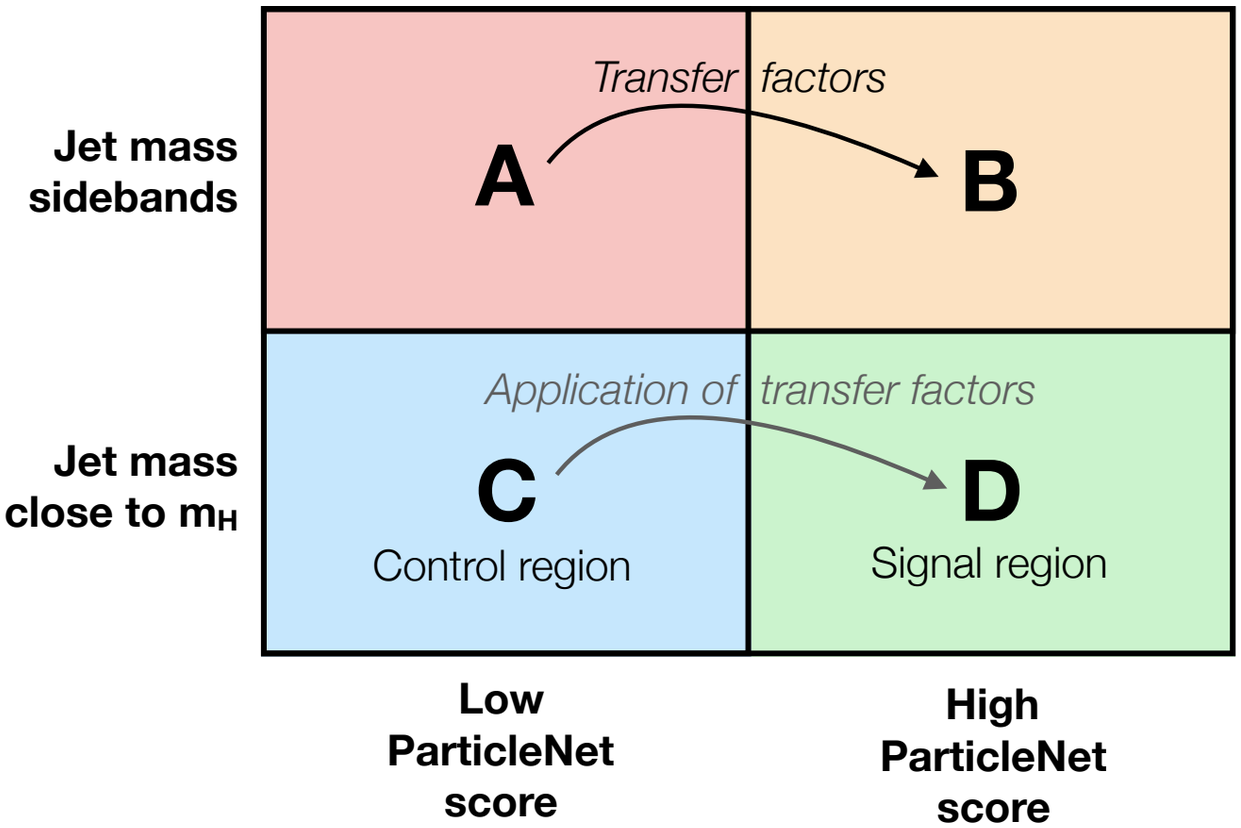
- Substantial improvement in both mass scale and resolution, especially for signal jets
  - tails in m_{SD} also significantly reduced
- Up to ~20-25% improvement in analysis sensitivity

BACKGROUND ESTIMATION

- **QCD multijet background** estimated with a data-driven method
  - using QCD-enriched "fail" region by inverting the ParticleNet bb-tagging selections



No mass sculpting: ***ParticleNet tagger and jet mass largely independent***



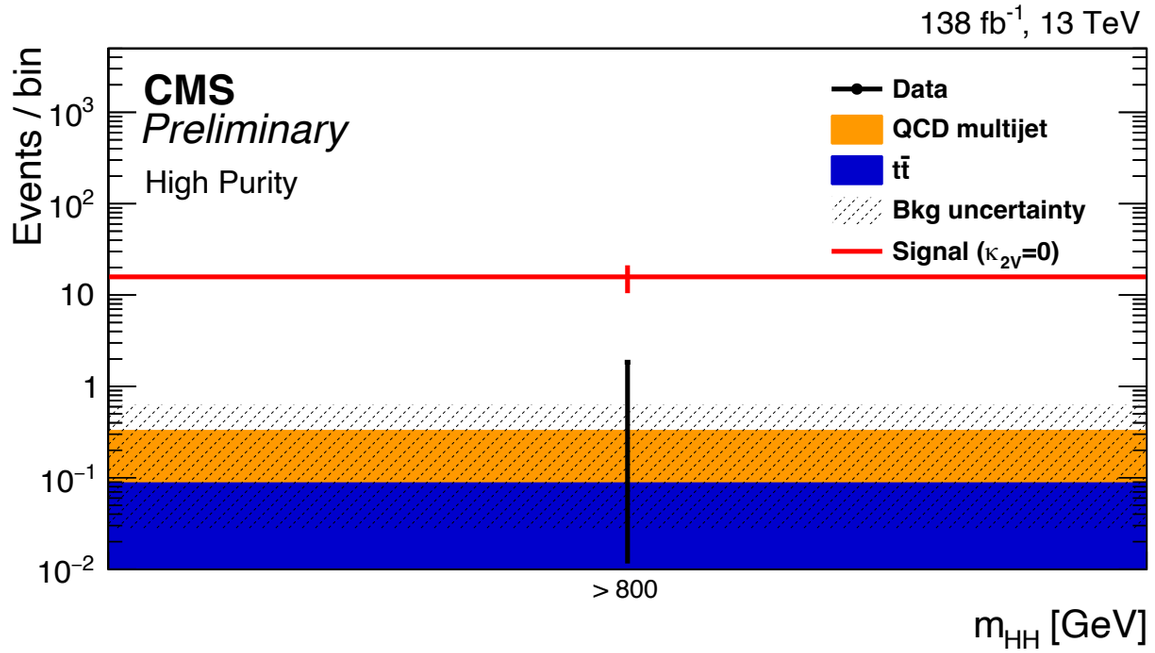
Straightforward to use the ABCD method for the QCD background estimation

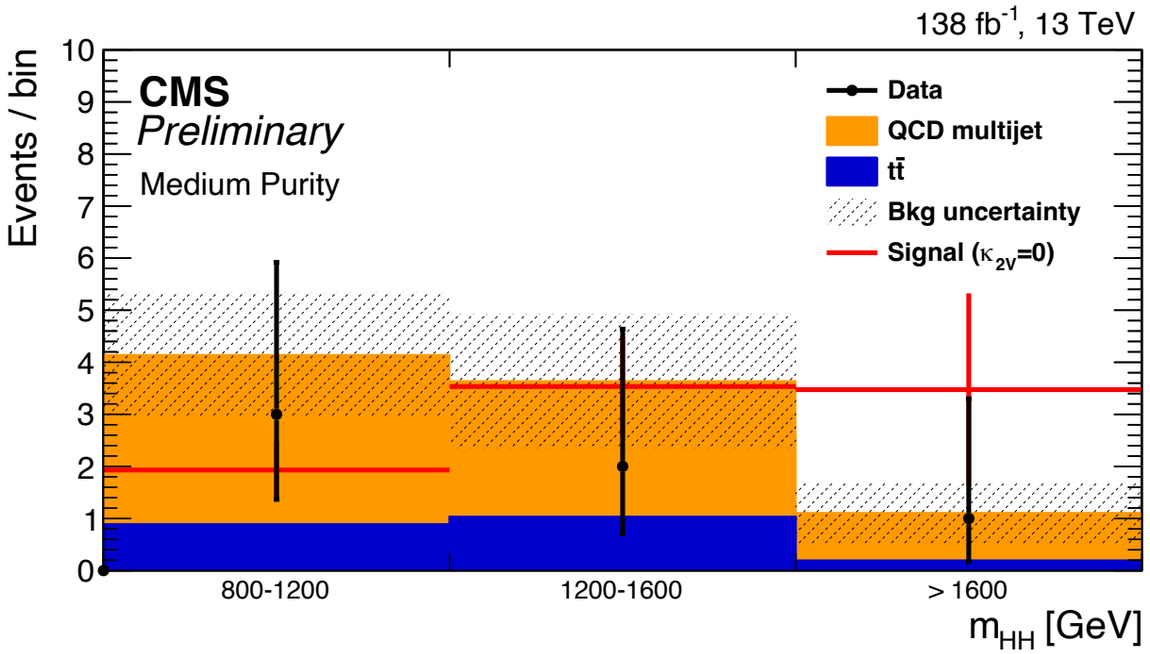
- **ttbar background** estimated from simulation, with corrections derived from a top-enriched region

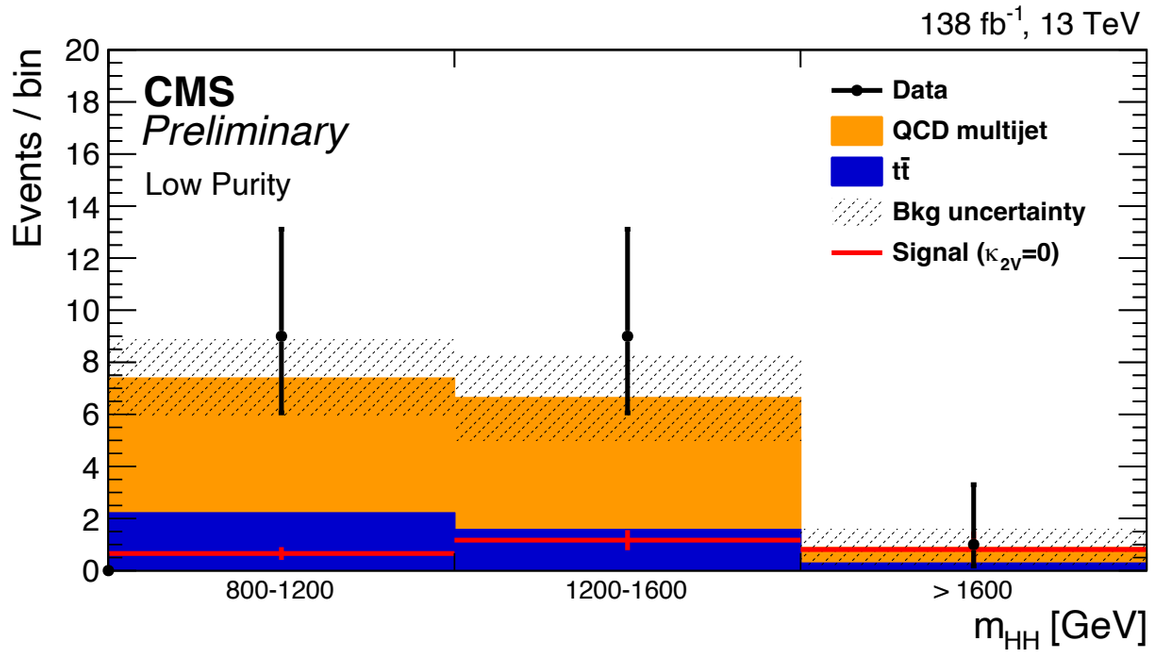
RESULTS

- Signal extraction
  - by fitting to m_{HH} in three search categories of increasing purity
    - signal efficiencies ~ 60%, 80%, 90% at QCD mis-id. rate ~0.3%, 1% and 2%
- **No significant excess observed**

CMS-PAS-B2G-21-001

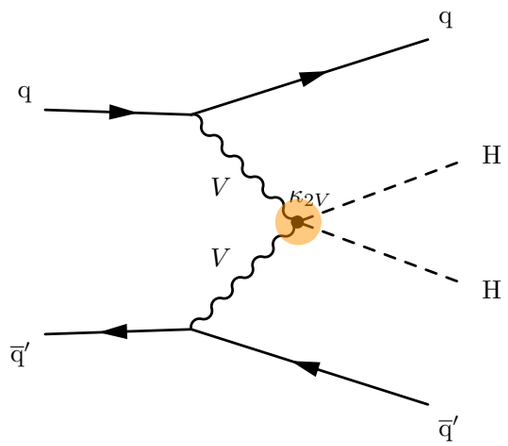




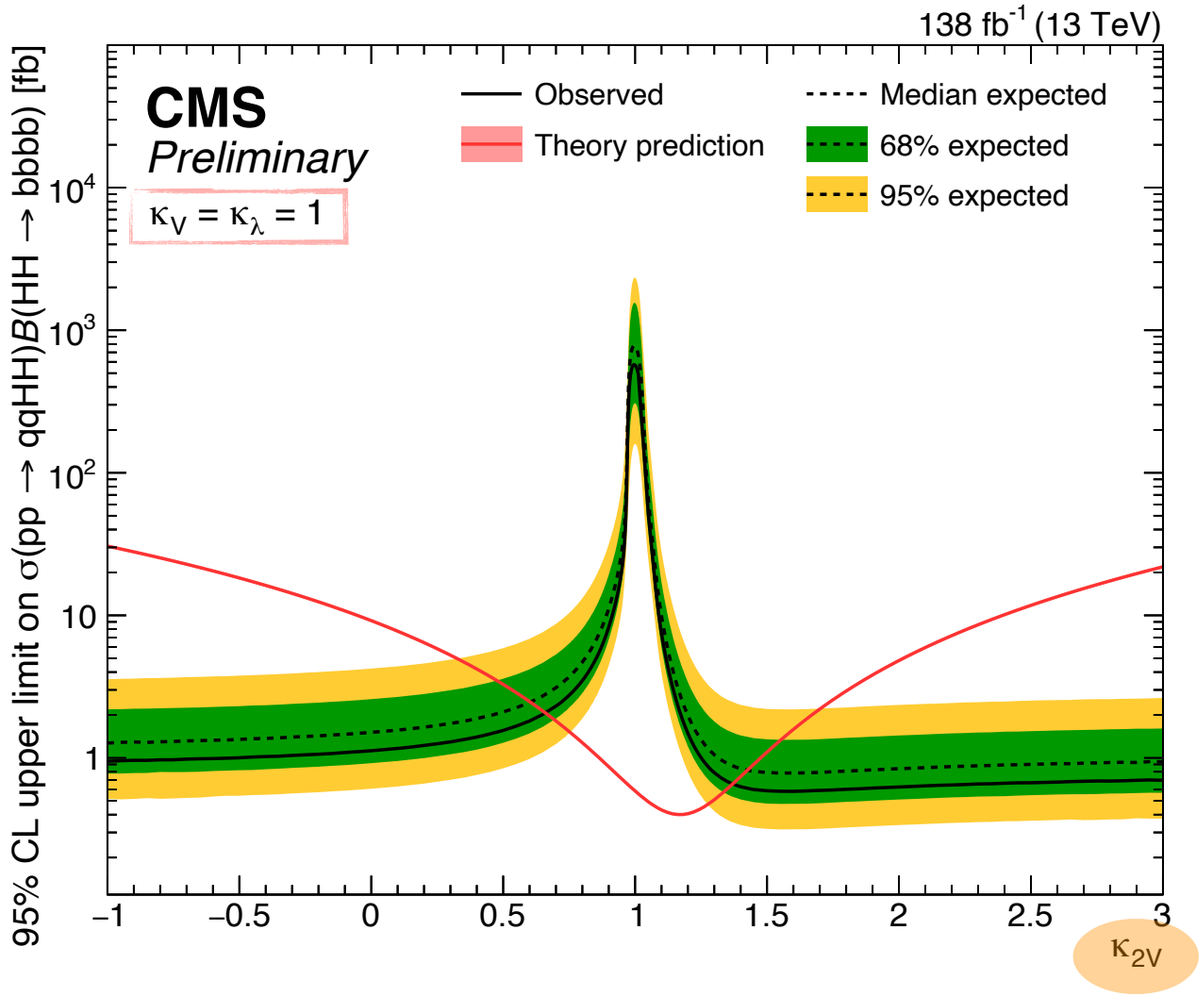


LIMITS

CMS-PAS-B2G-21-001



Upper limits on σ(VBF HH) × B(HH→bbbb)



- Most stringent constraint on κ_{2V} to date: **$0.6 < \kappa_{2V} < 1.4$**
  - $\kappa_{2V} = 0$ **excluded for the first time!**
  - cf. ATLAS [JHEP 07 (2020) 108]: -0.43 (-0.55) < κ_{2V} < 2.56 (2.72) obs. (exp.)

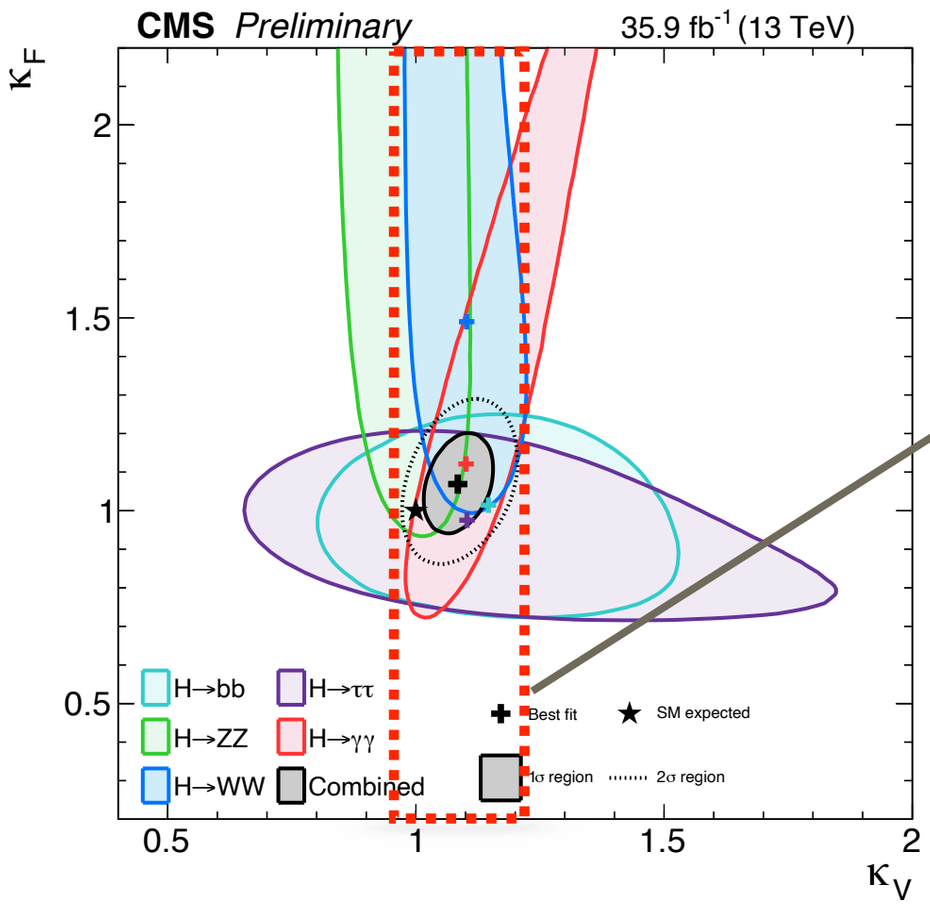
SUMMARY

- First search of VBF HH production in the 4b final state with boosted objects
  - advanced graph neural networks used for H→bb identification and jet mass reconstruction, leading to significant improvement in the sensitivity
- The search set the most stringent constraint on the HHVV coupling to date
  - the hypothesis of a vanishing HHVV coupling ($\kappa_{2V} = 0$) is excluded for the first time, assuming all other Higgs couplings are at their standard model values

Backups

LIMITS

Eur. Phys. J. C 79 (2019) 421



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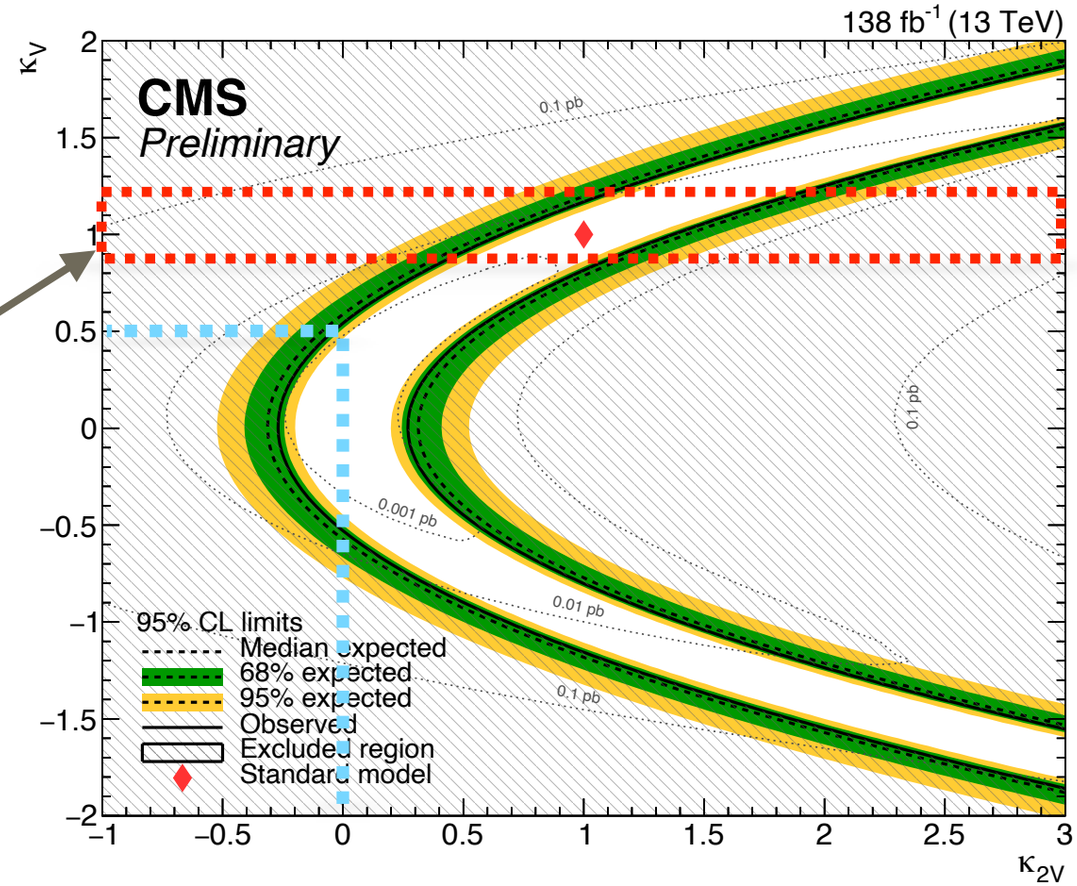
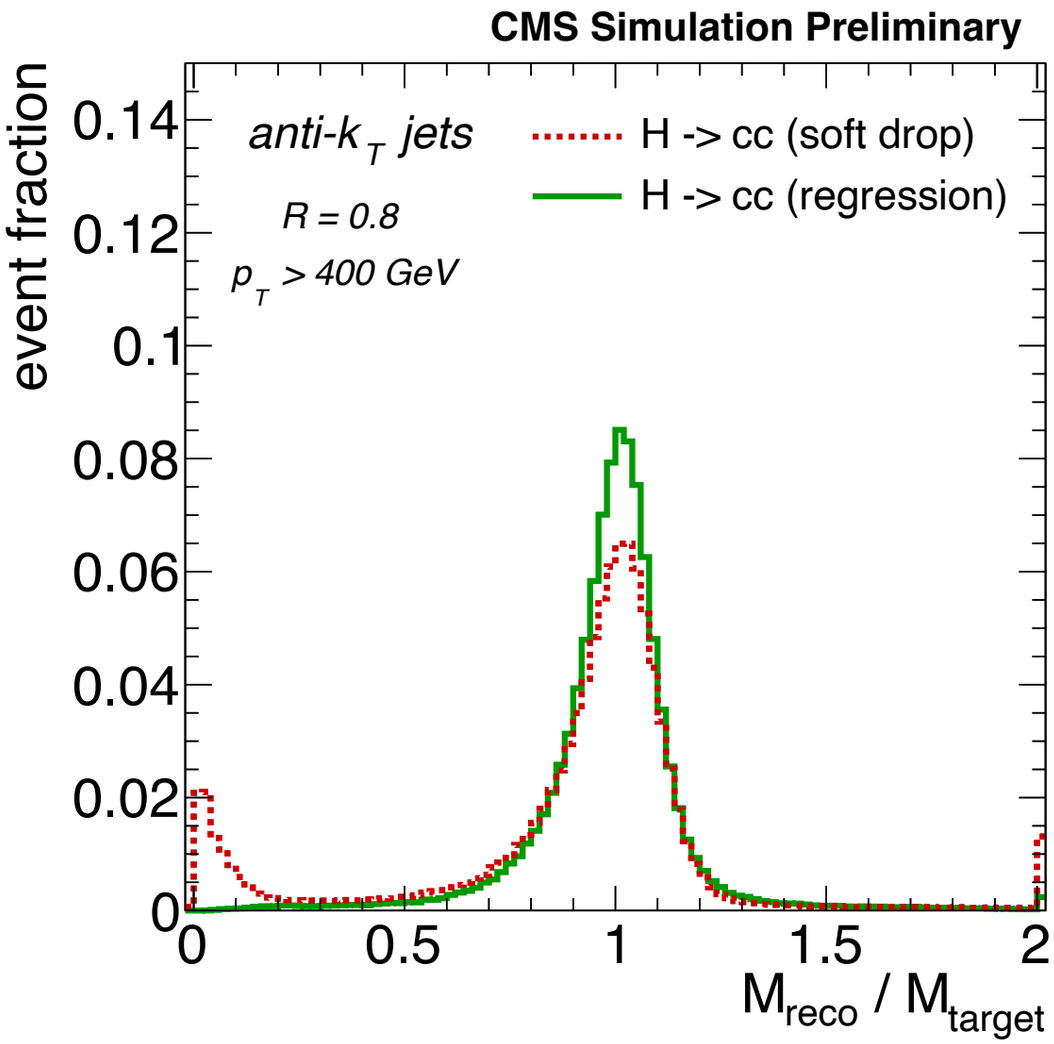


- 2D limit scan excludes $\kappa_{2V} = 0$ for $\kappa_V > 0.5$ (with other couplings fixed to SM values)
  - previous (single-Higgs) results suggest that κ_V is close to 1

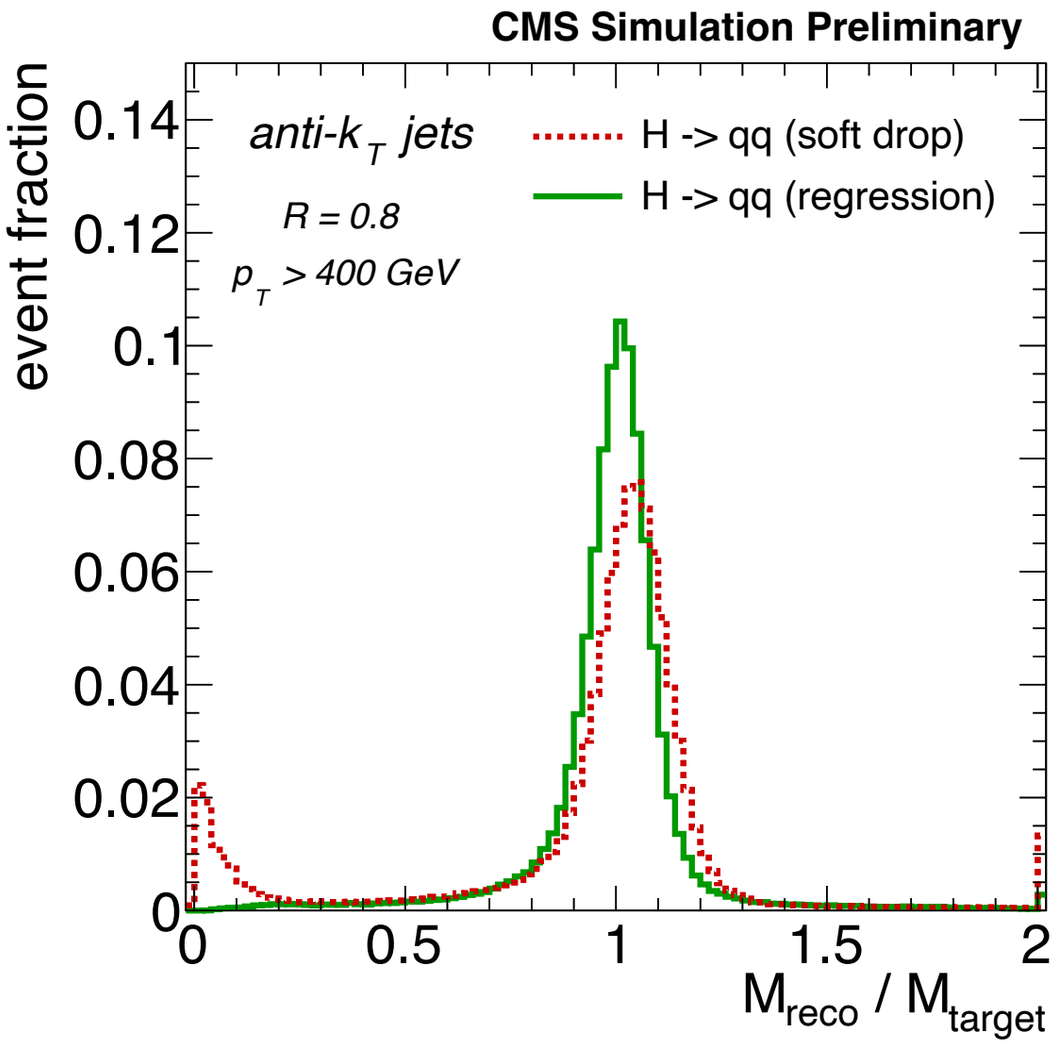
MASS REGRESSION: PERFORMANCE (II)

CMS DP-2021/017

Signal jets: H→cc



Signal jets: H→qq

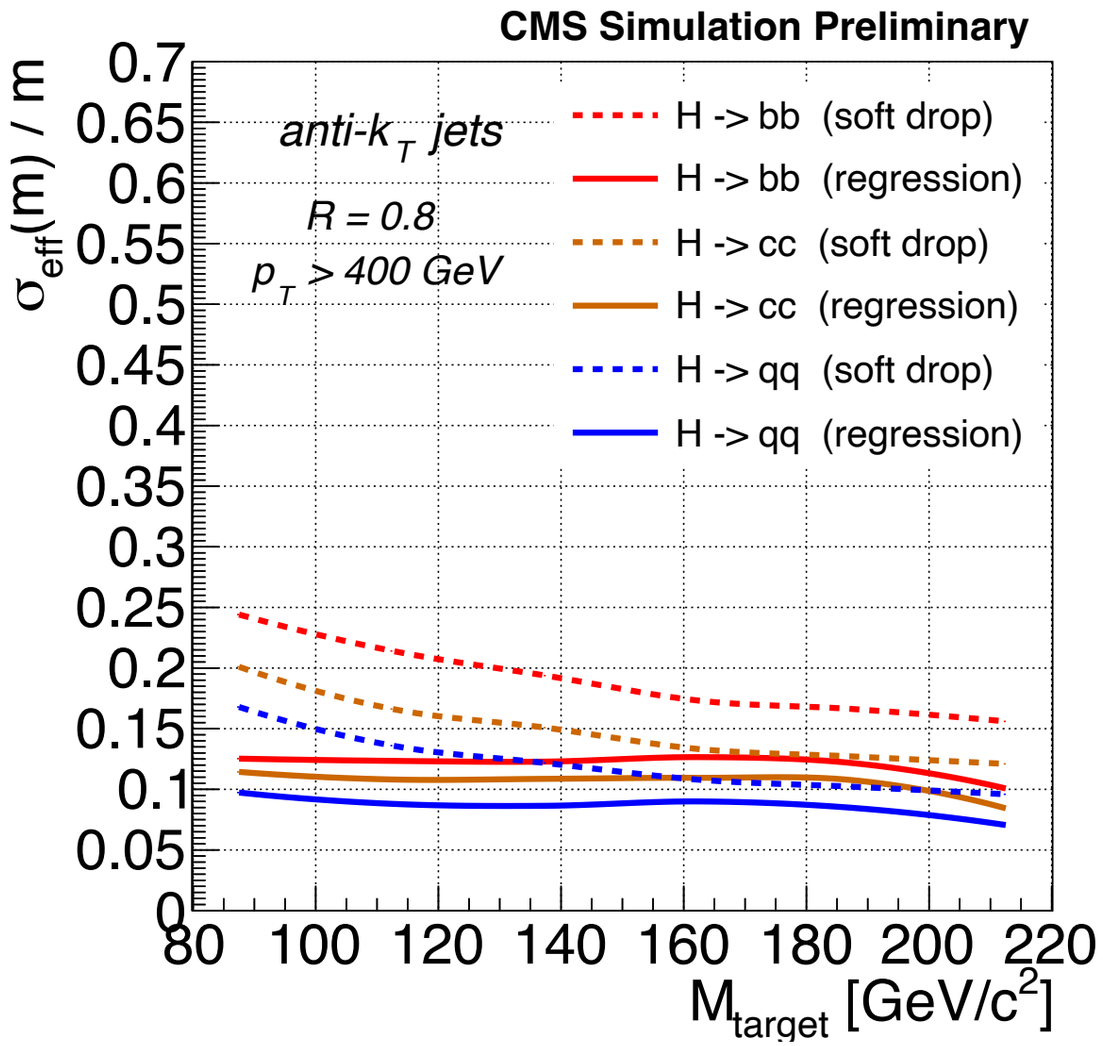


- Consistent improvements in all jet flavors

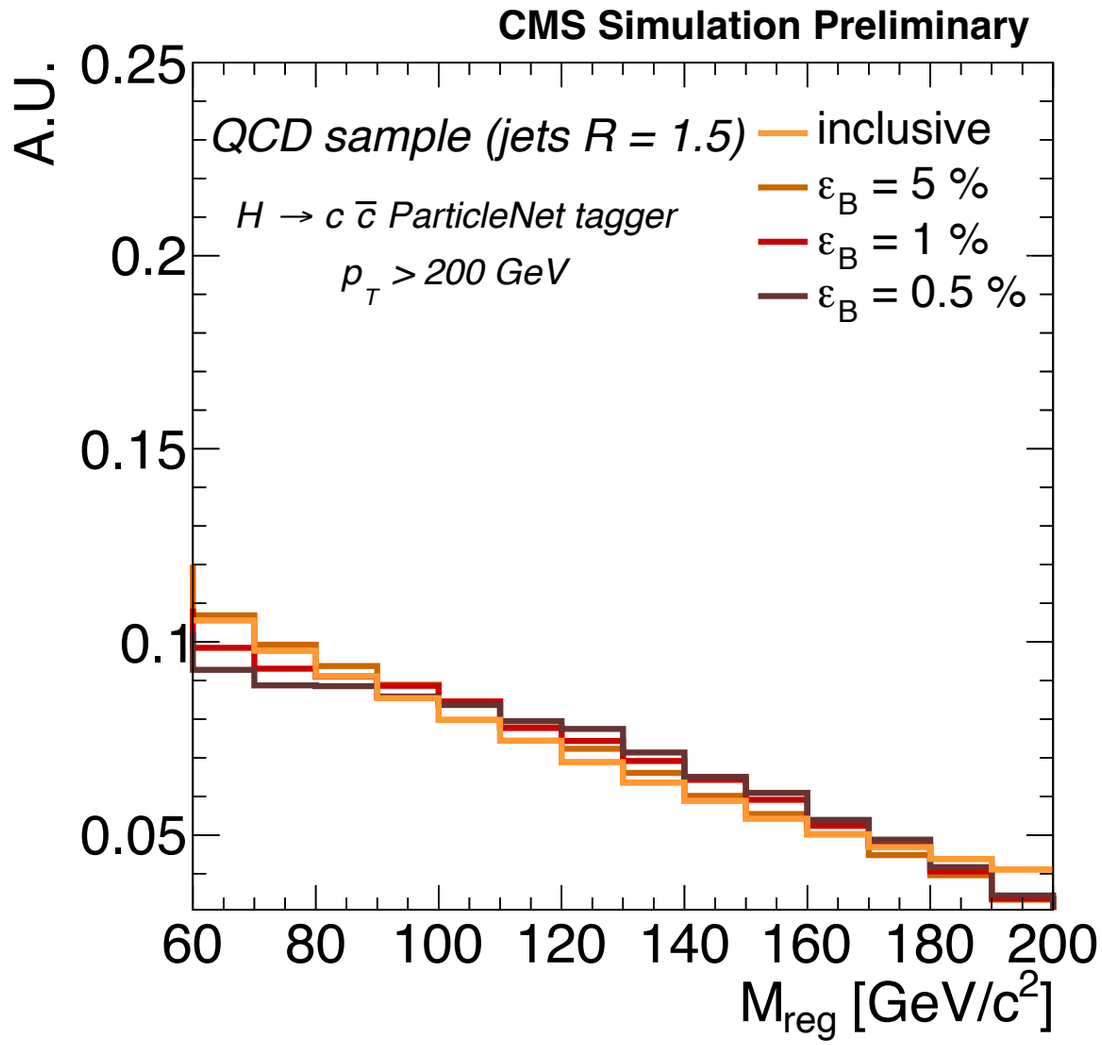
MASS REGRESSION: PERFORMANCE (III)

CMS DP-2021/017

Mass resolution vs m_X



Regressed mass vs Tagger WP



- Mass resolution more stable vs m_X compared to soft drop
- No signs of mass sculpting – even for very tight tagger selections