Search for VBF production of X→HH in the 4b final state at the HL-LHC

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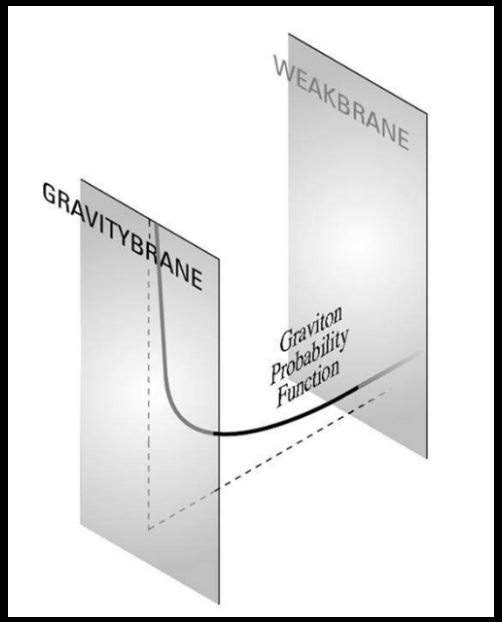
On behalf of the CMS Collaboration

Introduction

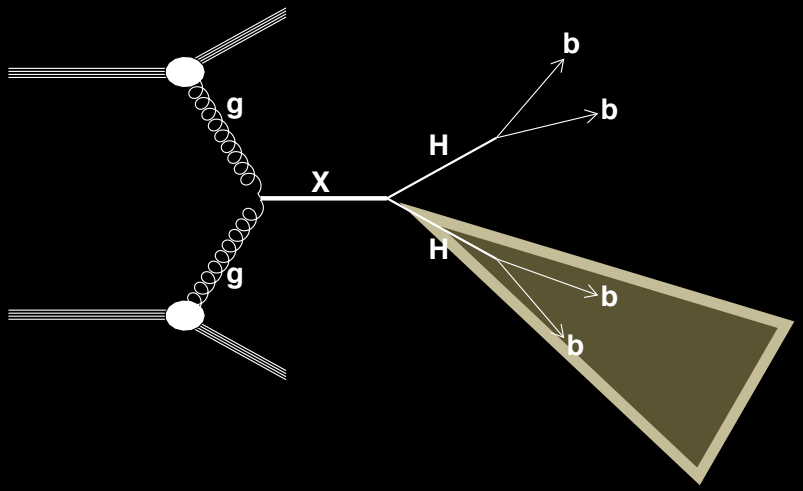
- Warped extradimension models as solution to the hierarchy problem.
- SM fields can propagate into the "bulk".



- Additional degrees of freedom
  - Graviton (spin 2) and radion (spin 0).
  - May have similar coupling strength to SM fermions and gauge bosons.
- Current searches look for s-channel resonances.

Planck scale $\overline{M_{\mathrm{Pl}}}$ Warp factor *k* Extradimension size *l*
κl ~35
Mass scale $\Lambda_R = \sqrt{6}e^{-\kappa l} \times \overline{M_{\mathrm{Pl}}}$ ~ TeV
Benchmarks of the model set by Λ_R and $\kappa/\overline{M_{\mathrm{Pl}}}$

Resonance ➔ HH



Boosted "Higgs jets"

Depending on the resonance mass m_X:

- H-> bb can be "resolved" – 4 b jets
- Both H->bb boosted: Higgs jets
- Only one boosted H->bb

CMS now covers all three topologies.

Putting constraints of warped extradimension models, 2HDM, etc.

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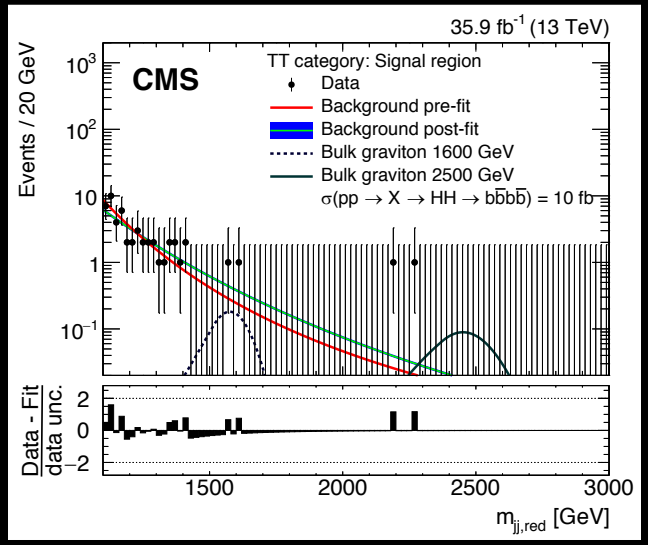
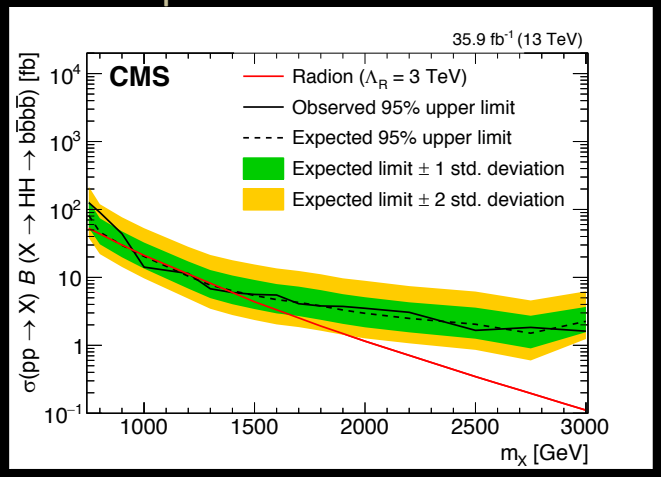
Run 2 high mass resonance

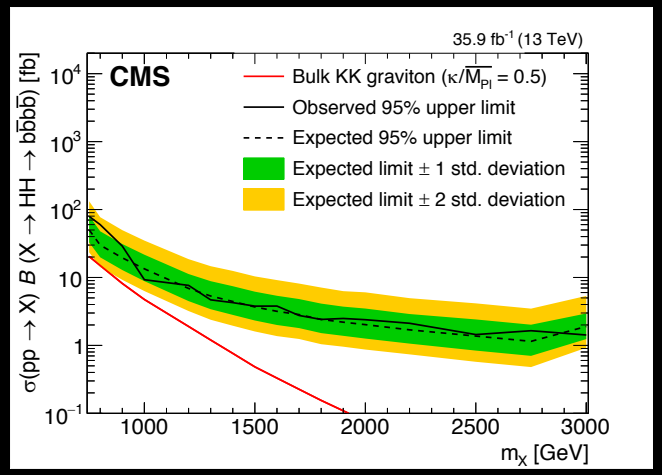


- Looking for a resonance X in the di-Higgs boson invariant mass.
- At high mass, used Higgs jet tagging:
  - H->bb system with large Lorentz boost
  - Reconstruct as one large-area jet.
- Limits were set on narrow radion (spin-0) and bulk graviton (spin-2) cross sections:
  - pp ->X ->HH->4b

Limits spin 0



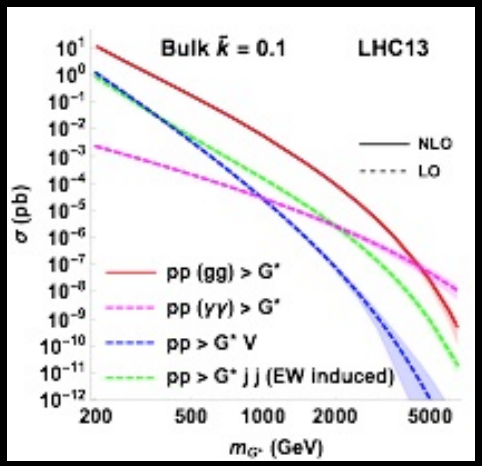
Limits spin 2



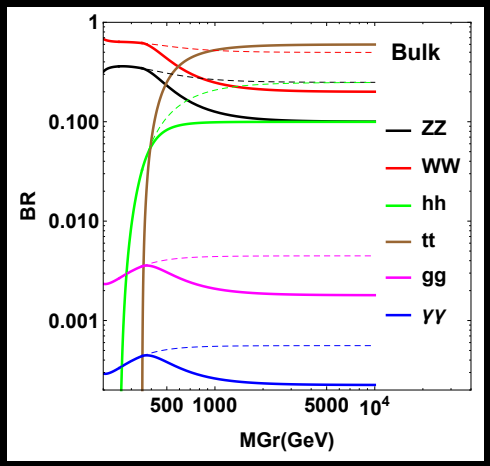
VBF search: Motivation

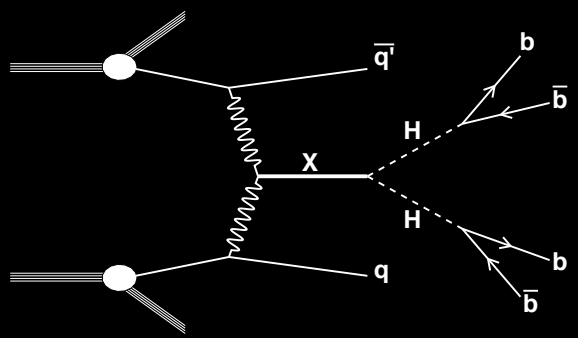
A. Oliveira arXiv:1404.0102

VBF production cross section about 1/10 of gluon-gluon fusion cross section



Branching fraction to HH depends on mass: ~ 10% for high masses





Searching for a resonance X->HH in the 4b final state:

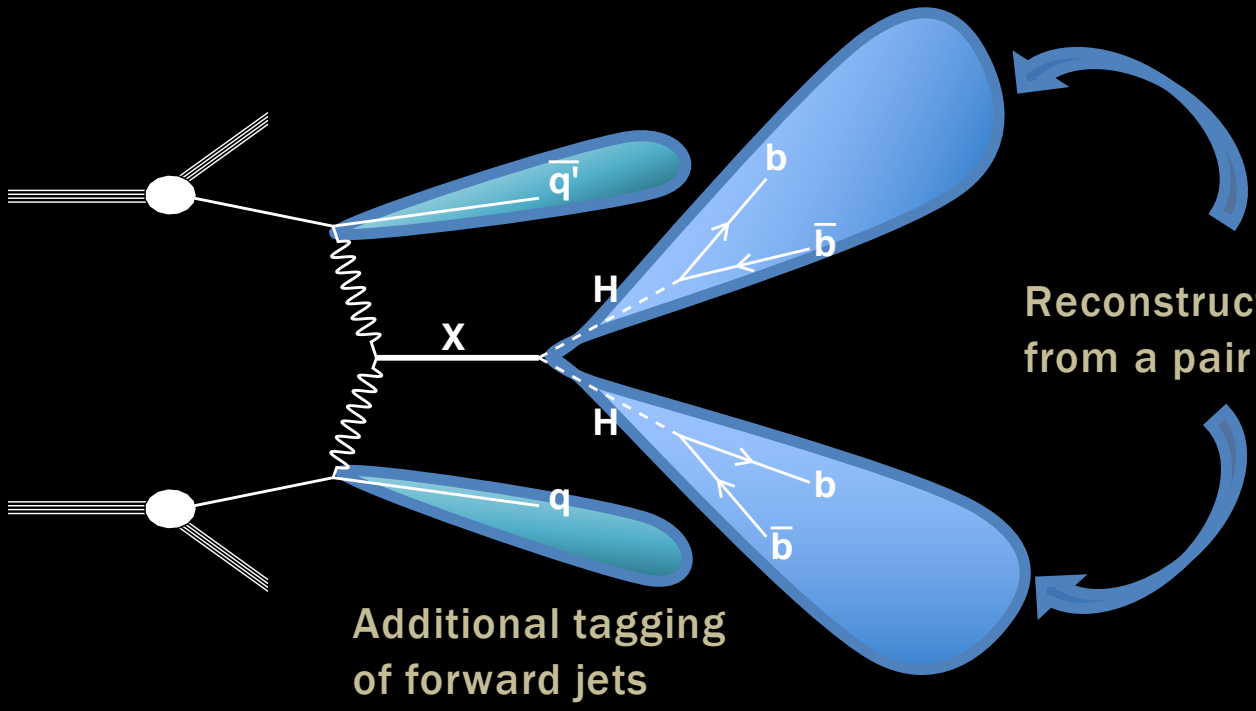
- Largest Higgs boson branching fraction: ~58%
- Substructure + boosted b-tagging helps to suppress large QCD multijets background.

Brand new search: Not done in Run 1 or 2.
Highlights the possibilities of the HL-LHC physics programme.

Analysis approach

CMS-FTR-18-003

We are looking for a narrow resonance X.

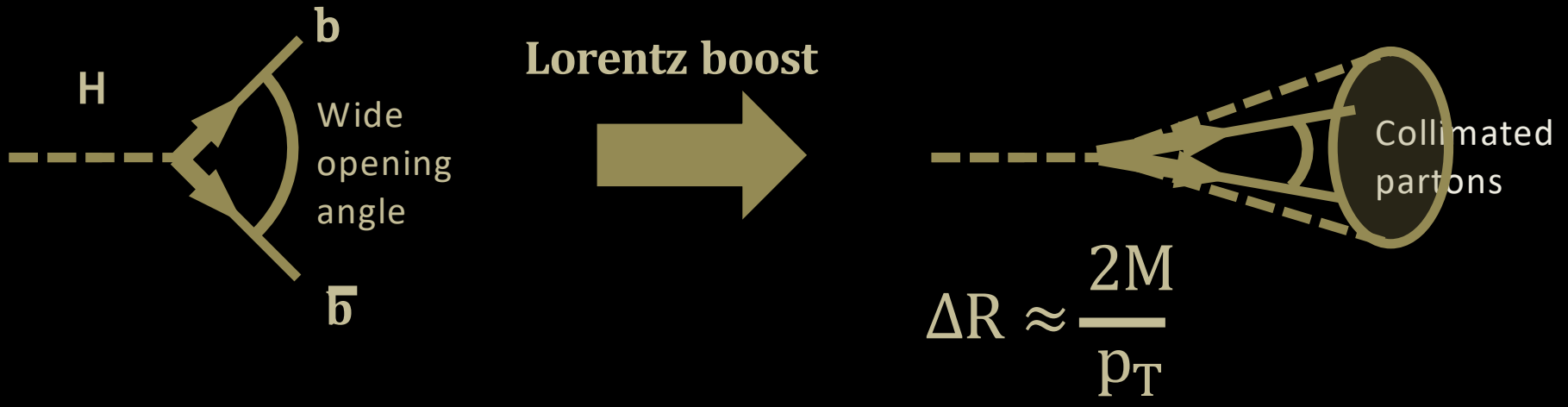


Reconstruct resonance mass mX
from a pair of boosted H-tagged jets

Additional tagging
of forward jets

Events simulated at LO using MADGRAPH5_aMC@NLO.
Processed using simulation of the CMS Phase 2 detector.

Jets from boosted particles



- Seek to exploit techniques o identify a boosted boson decay:
  - Jet substructures
  - B-tagging

Jet groomed mass

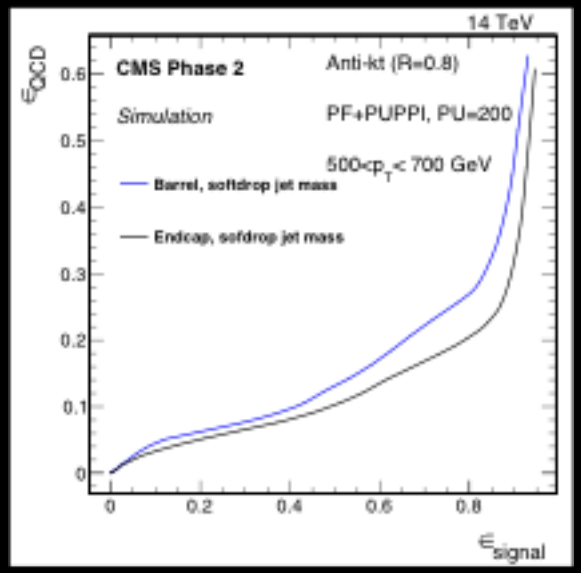
- Soft drop: Discard soft component if

JHEP 05 (2014) 146

$$\frac{\min(p_{T1}, p_{T2})}{P_{T1} + p_{T2}} < z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

  - Angular exponent parameter $\beta = 0$
    Soft radiation parameter $z_{cut} = 0.1$

Modified mass drop
JHEP 09 (2013) 029



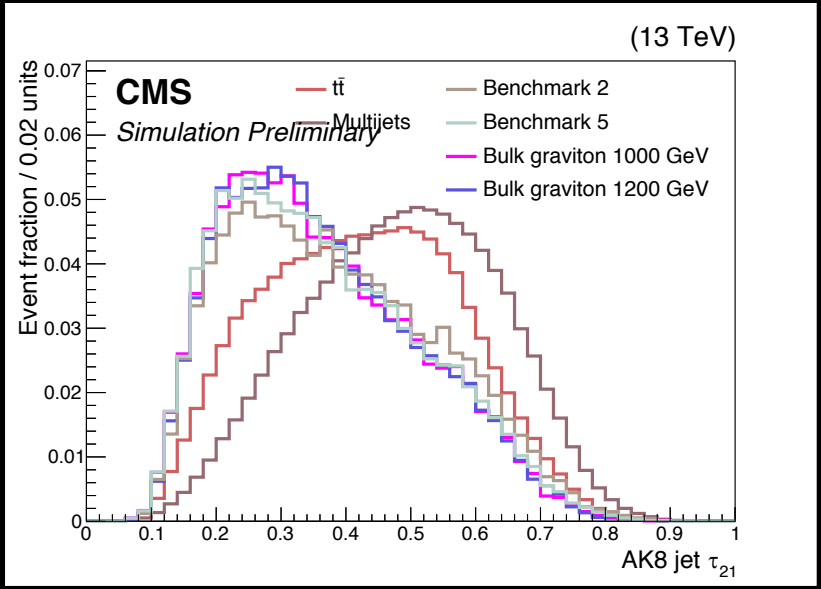
CERN-LHCC-2017-023/ CMS-TDR-019

N-subjettiness

- N-subjettiness $\tau_N = \frac{1}{d_o} \sum_k p_{T,k} \min\{\Delta R_{1k}, \Delta R_{2k}, \ldots, \Delta R_{Nk}\}$
  - 2-prong jet: $\tau_2 << \tau_1$ (τ_2/τ_1 for W/Z/ Higgs tagging)

JHEP 03 (2011) 015

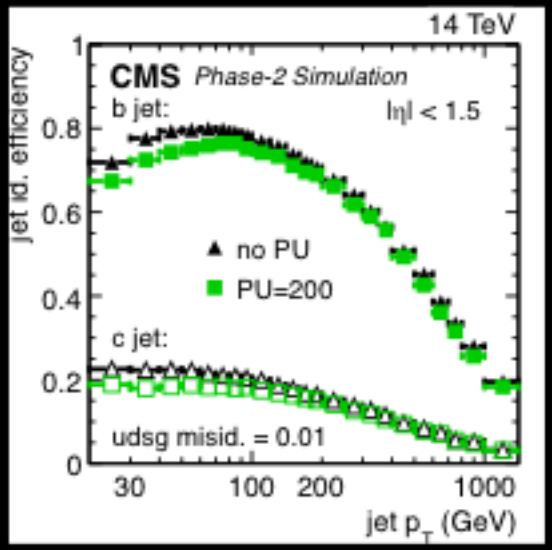
CMS-B2G-17-019

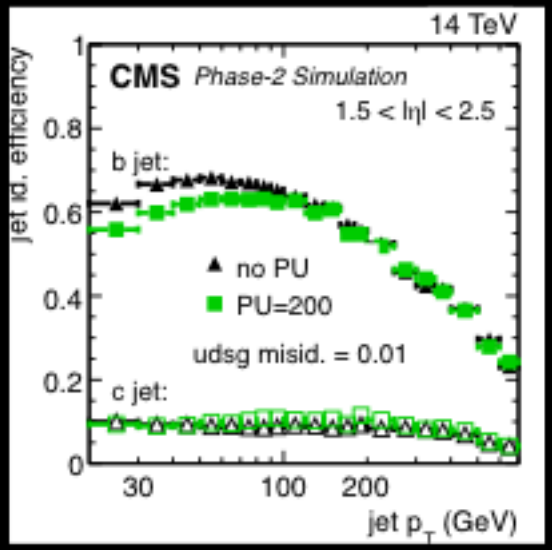


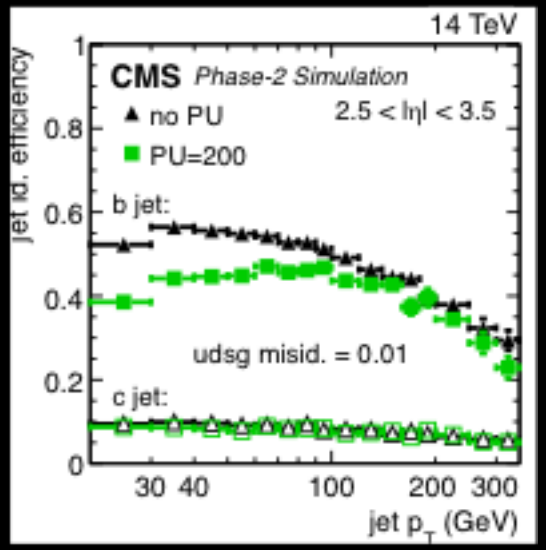
Jet b-tagging

- Four hadronized b quarks merged into two boosted H->bb jets.
- Substructure b-tagging helps to suppress multijets background.
  - Tag at least 3 subjets out of 4 using DeepCSV algorithm.
  - Light flavour rate fixed at 1% per subjet

CERN-LHCC-2017-023/ CMS-TDR-019

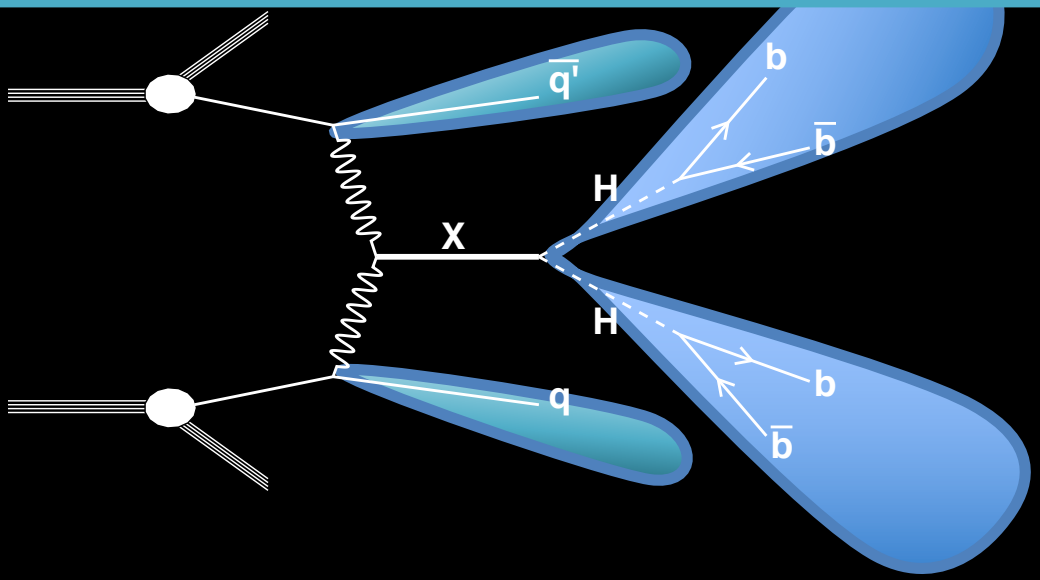






Event selection

- AK4 jets separated from H jets by $\Delta R > 1.2$: $p_T > 50$ GeV $|\eta| < 5$
- Large pseudorapidity separation: $|\Delta\eta(j_1, j_2)| > 5$
- $m_{jj} > 300$ GeV
- In opposite sides of the detector: $\eta_{j1} \times \eta_{j2} < 0$



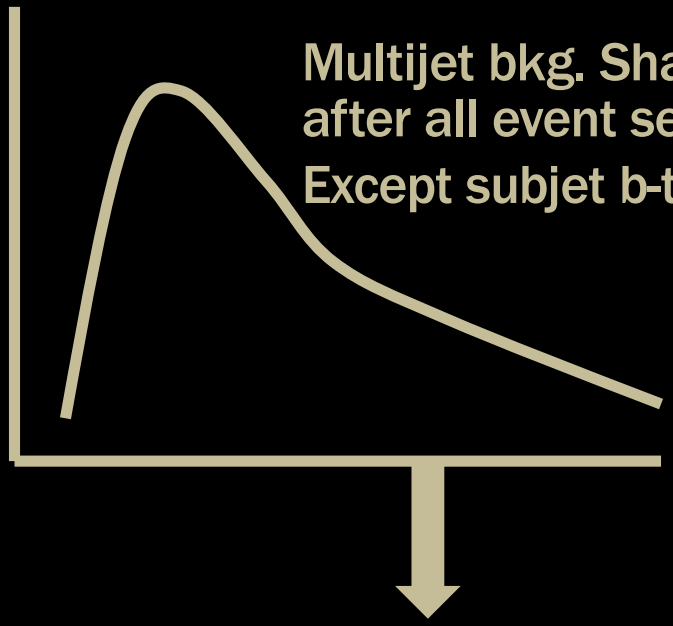
- Central AK8 jets: **$p_T > 300$ GeV $|\eta| < 3$**

- Tag AK8 jets as H → bb:
  - -- **Soft drop mass within 90-140 GeV**
  - -- **N-sub $\tau_2/\tau_1 < 0.6$**
  - -- **B-tagged subjets (DeepCSV)**

Events categorized by number of b-tagged subjets: 3b or 4b

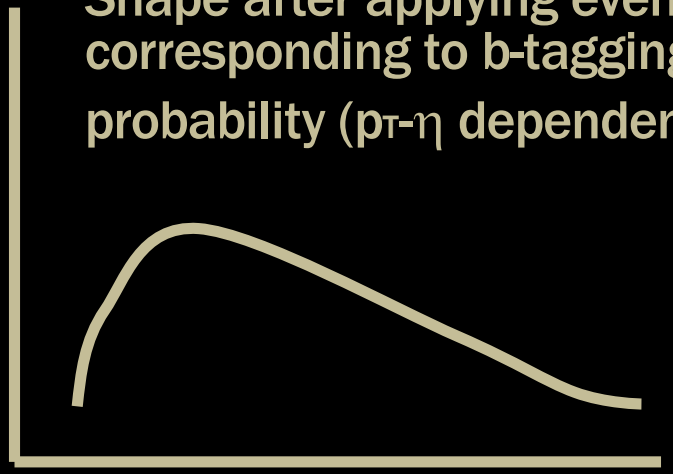
Background estimation

- Expected that most > 90% backgrounds will be from QCD multijets.
- The di-Higgs jet invariant mass m_{JJ} corresponds to the resonance mass m_X.
- Background m_{JJ} estimated from simulations.
- To get a smooth background shape, a reweighting method is used, based on b-tagging efficiency.
  - Events are not thrown away, merely reweighted.



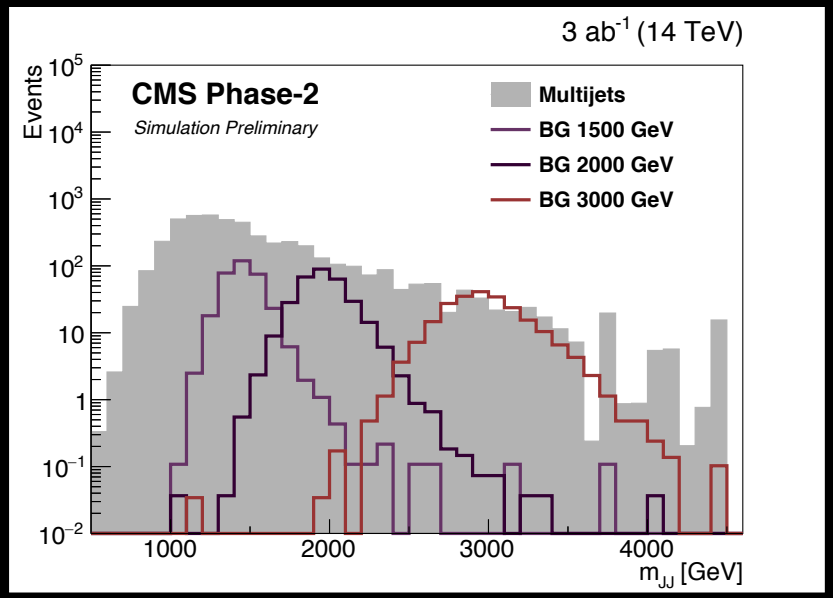
Multijet bkg. Shape after all event selection Except subjet b-tagging

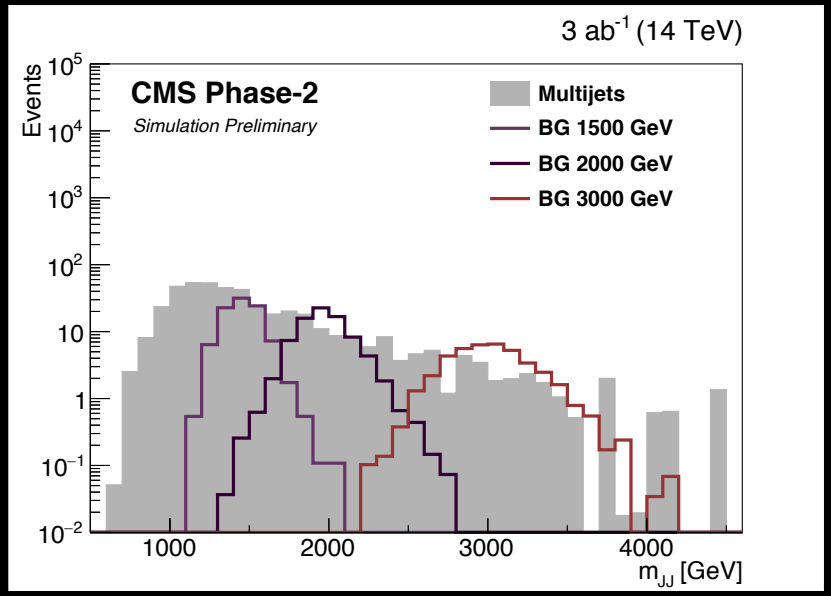
Shape after applying event weights corresponding to b-tagging probability (p_T-η dependent).



Background estimation

- We perform a “bump hunt” using the background and the signal m_{JJ} shapes.
  - An actual background estimation technique should be able to predict both the shapes and the yields of the background.
  - Used in CMS analyses: B2G-16-026 B2G-17-019

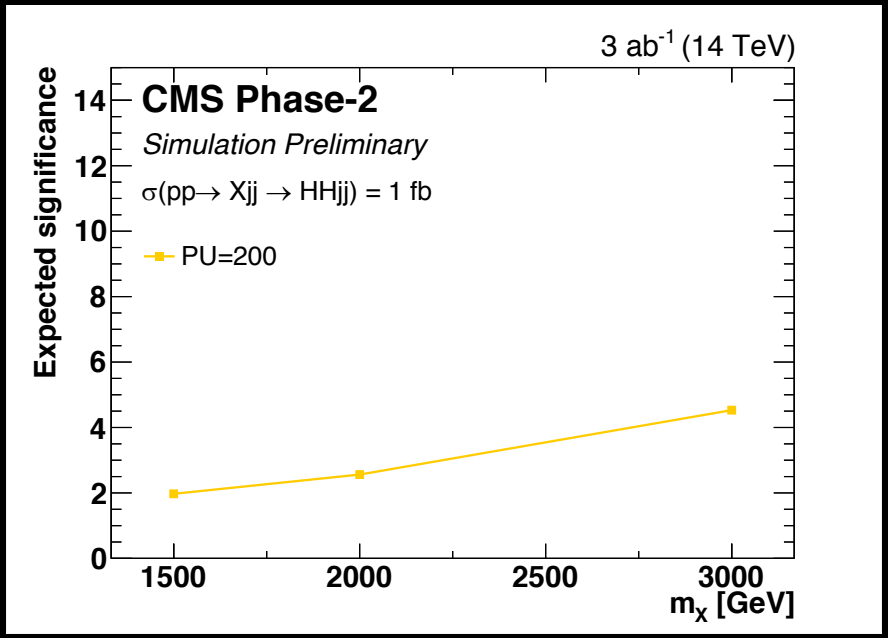




Systematic uncertainties

Uncertainties	Values (%)	Obtained from
H jet mass scale and resolution	1	CMS Run 2 Di-Higgs resonance searches, scaled by 1/2
H jet t_{21} selection	13	
H-tagging correction factor	3.5	
Pileup modelling	1	
Parton distribution functions and QCD scales	1	
Luminosity	1	CMS HL-LHC projections
Jet energy scale	1	
B-tagging	1	

Results



- With 3 ab^{-1}, we can reach a sensitivity of up to four for very massive resonances decaying to HH.
- Expect even greater improvements from jet substructures, b-tagging.

Summary

- Analysis proposed to showcase the feasibility of searching for a resonance decaying to HH in VBF production mode at the HL-LHC.
  - Important part of parameter space of extradimensional models. Difficult to access at the LHC Run 2 and 3.
- With present techniques and a simulation of the CMS Phase 2 detector we may be able to find evidence for VBF production of bulk gravitons in the mass range 1500–3000 GeV.
- A dedicated search in the future will definitely improve over this projection:
  - Newer techniques for physics object reconstruction, pileup removal, event selections

backup