Di-Higgs Production in ATLAS

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Young Scientist Symposium Series (ANL)

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Motivation

July 4, 2012 -

Standard Model-like Higgs particle discovered by ATLAS and CMS!

- Mass reconstructed at ~125 GeV
- Observed in multiple channels with rates consistent with the Standard Model (SM)

NYTimes

But, plenty of outstanding questions! Among these…

- Does the discovered Higgs boson couple as predicted by the SM?
- Are there any additional Higgs bosons?
- Do particles beyond those predicted by the SM exist? If so, how do they couple to the Higgs boson?

Searching for di-Higgs production gives insight into these questions

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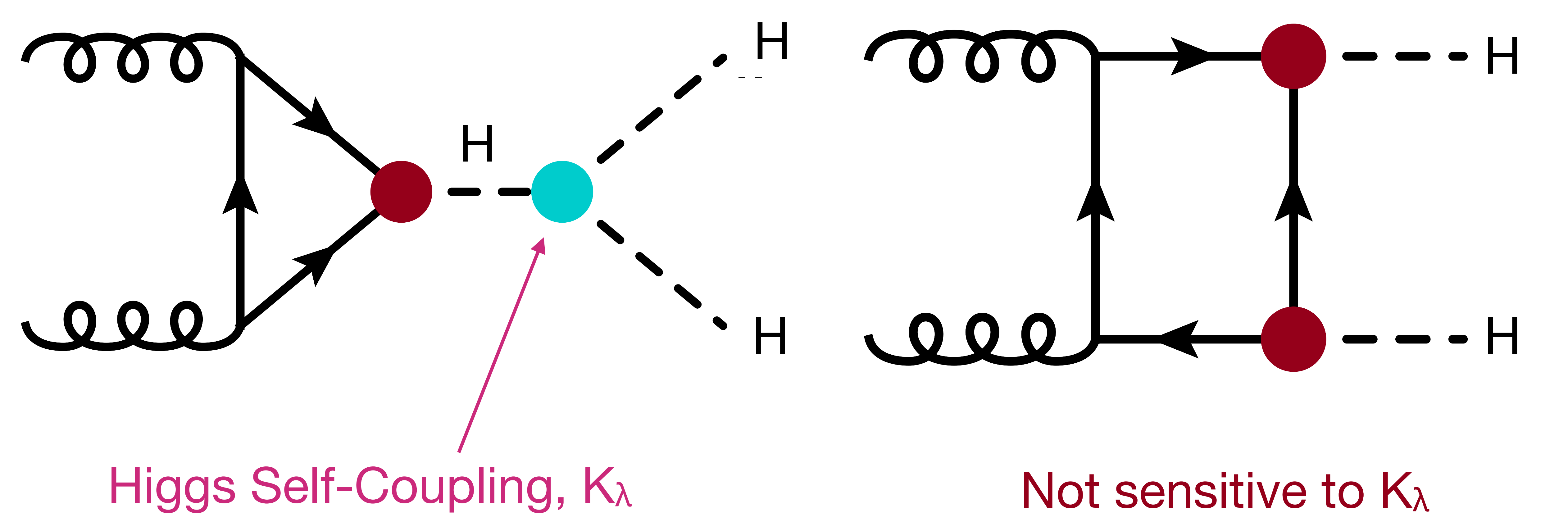
Di-Higgs Production in the SM

Gluon-gluon fusion (ggF) is the dominant di-Higgs production mode, accounting for ~87% of di-Higgs events at 13 TeV, current analyses target this production mode

SM non-resonant HH Production via gluon-gluon fusion



Occurs through two diagrams which interfere destructively, which causes a very small cross section

$$\sigma(gg \rightarrow HH)_{SM} \approx 33 \text{ fb @ 13 TeV}$$

Expect ~4600 HH events produced in the 139 fb^{-1} collected in Run-2

di-Higgs production is a rare process, which will test the limits of the LHC

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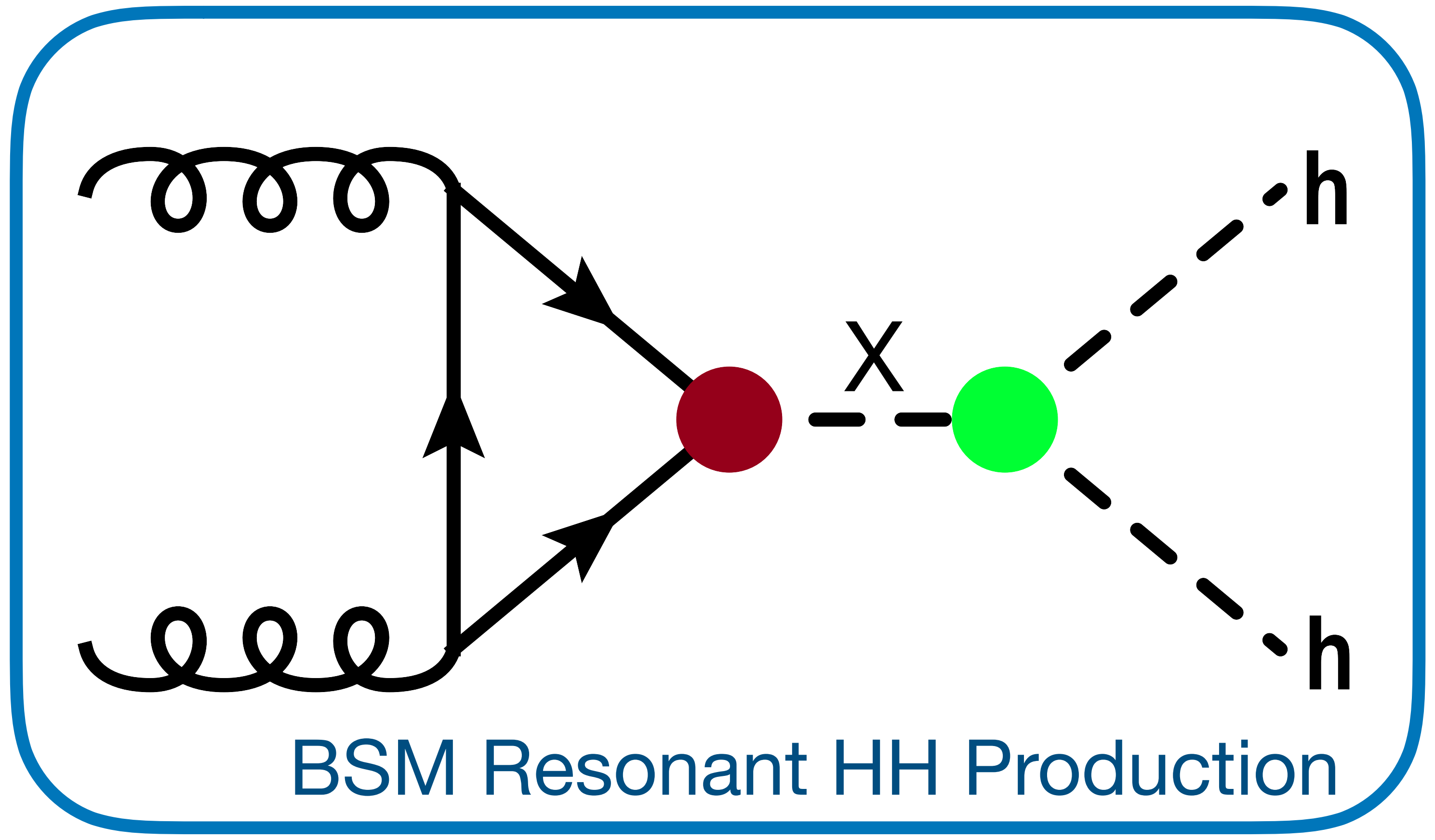
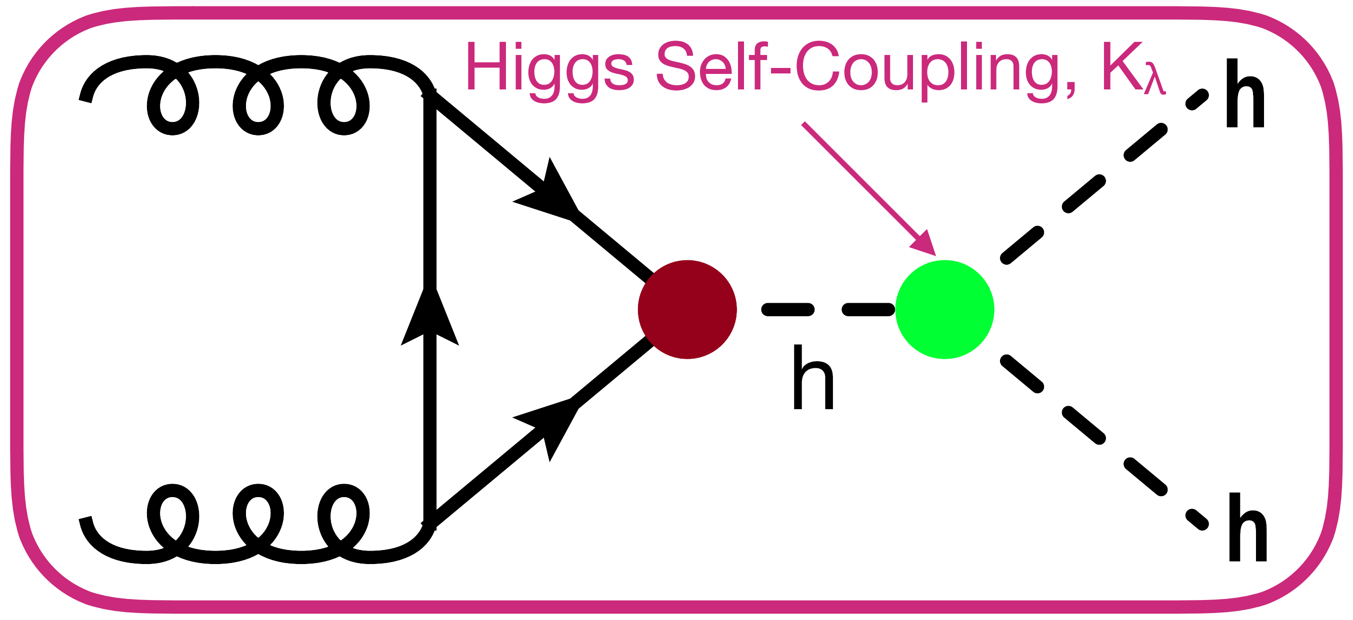
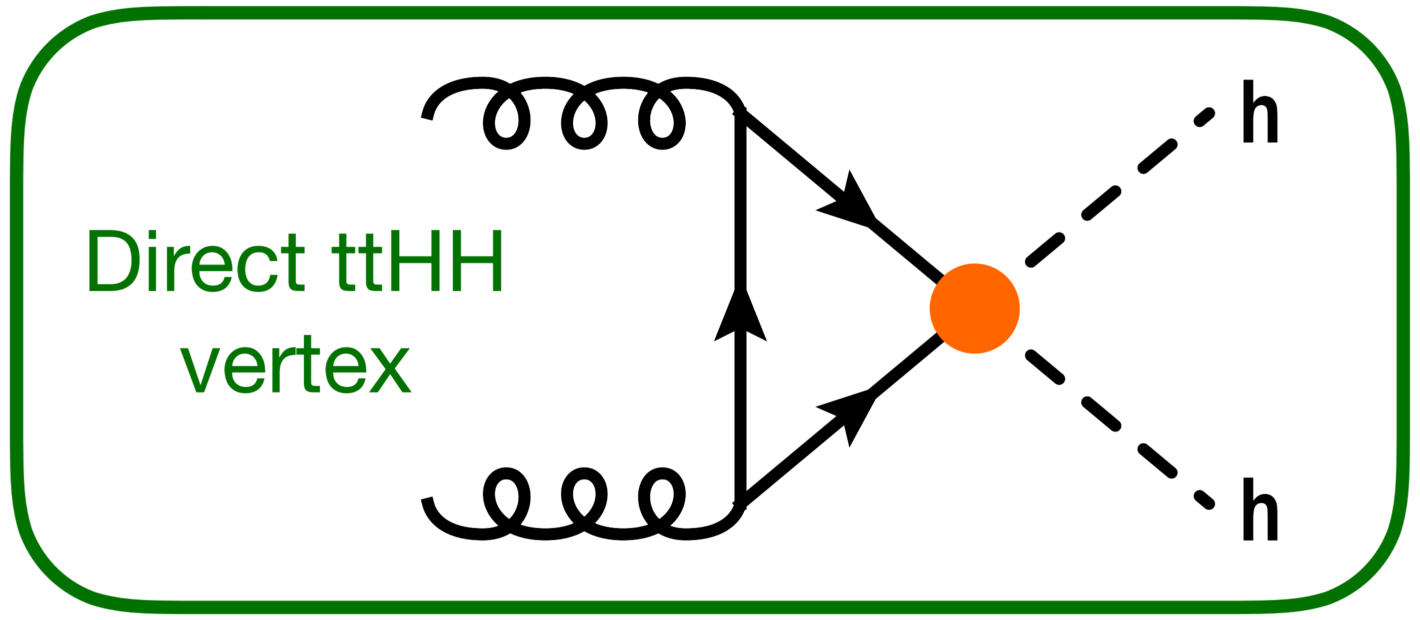
BSM Di-Higgs Production

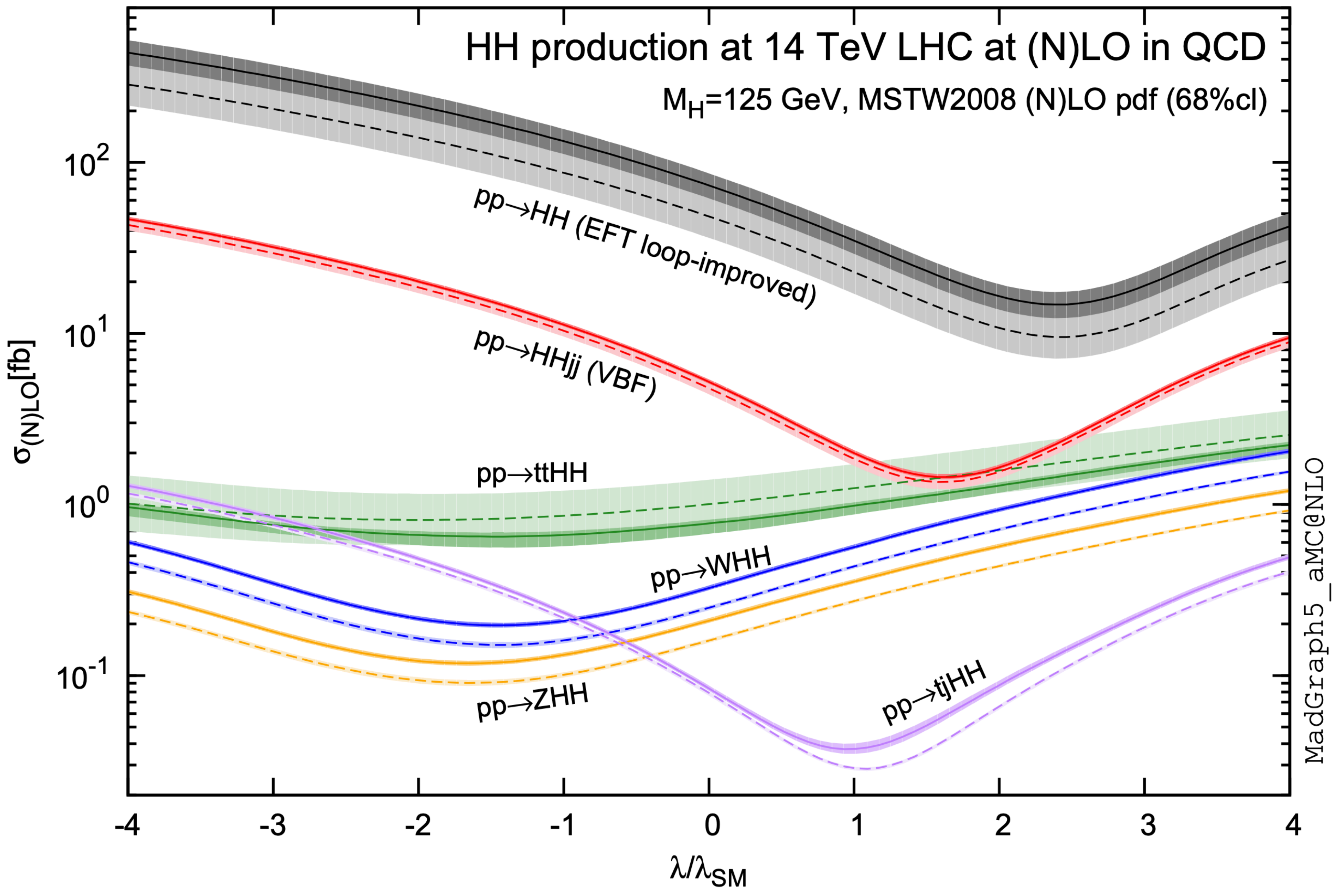


Resonant enhancements:
Enhancements can occur through a resonance that decays to to two Higgs bosons
- Two-Higgs-doublet model (THDM) - Resonance is a heavy scalar
- Randall-Sundrum Model - Resonance is a Spin-2 Kaluza-Klein graviton

Non-Resonant enhancements:
Can also look toward enhanced production caused by couplings that differ from the SM
- Higgs Self-Coupling (K_λ) - strength of coupling deviating from SM value can lead to enhanced production
- Additional couplings not predicted by the SM, e.g. direct ttHH vertex







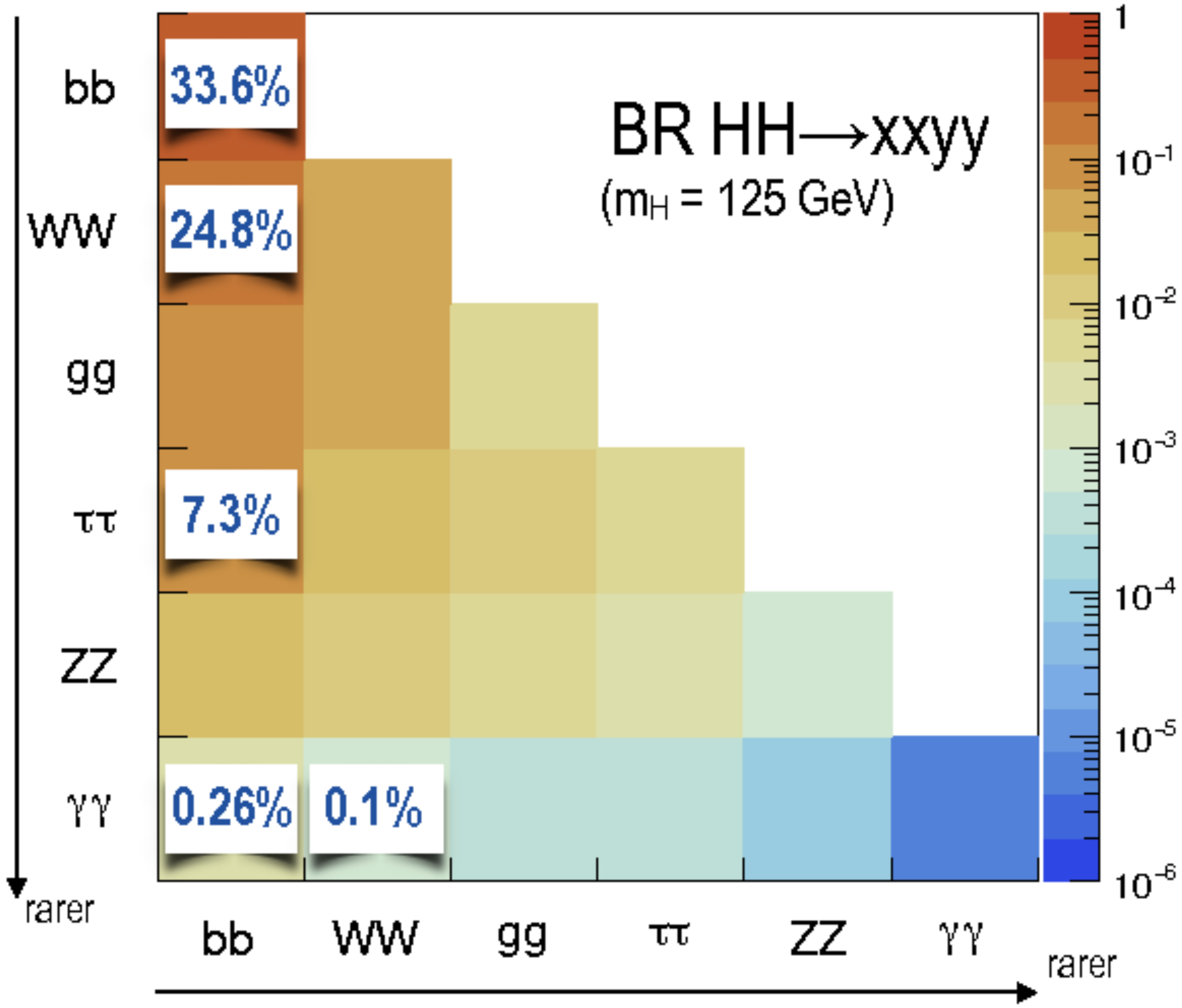
Models with enhanced production make di-Higgs already interesting to study with Run-2 data

Decay Modes

Strong motivation to look at certain channels based on properties of decay products

Strongest contribution to current limits:
- $b\bar{b}b\bar{b}$: Fully takes advantage of high bb branching ratio, but suffers from large multijet background
- $\gamma\gamma b\bar{b}$: Excellent trigger and mass resolution for photons, high bb branching ratio - **my thesis :)**
- $b\bar{b}\tau\tau$: Taus are relatively clean while still having a large branching ratio, high bb branching ratio

Morse



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Analysis Approach

$HH \rightarrow b\bar{b}\gamma\gamma$

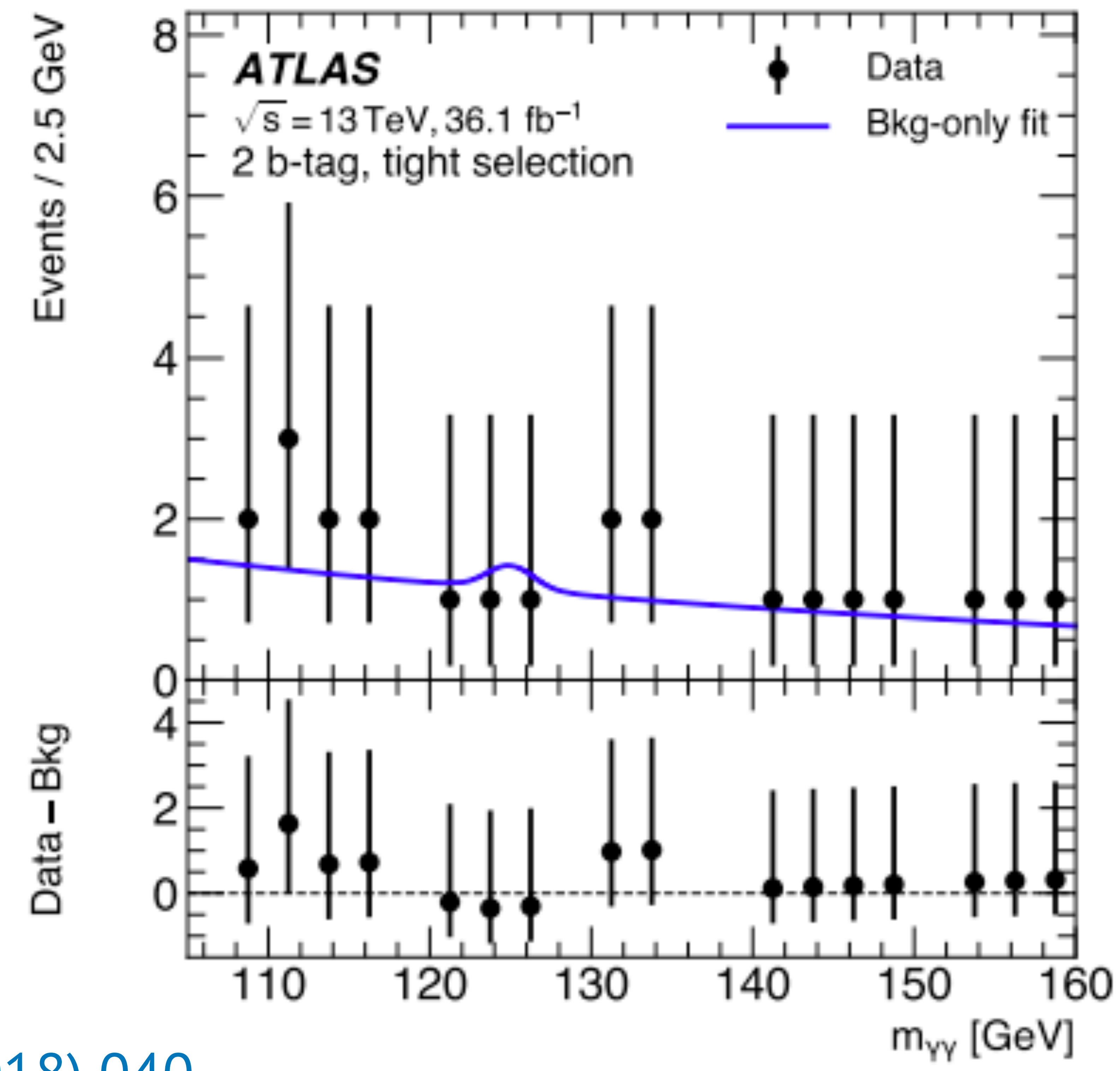
Define tight and loose selections based on kinematics, apply requirements on b-tagged jets

Continuum $m_{\gamma\gamma}$ spectra background estimated from data

Particularly sensitive at low masses

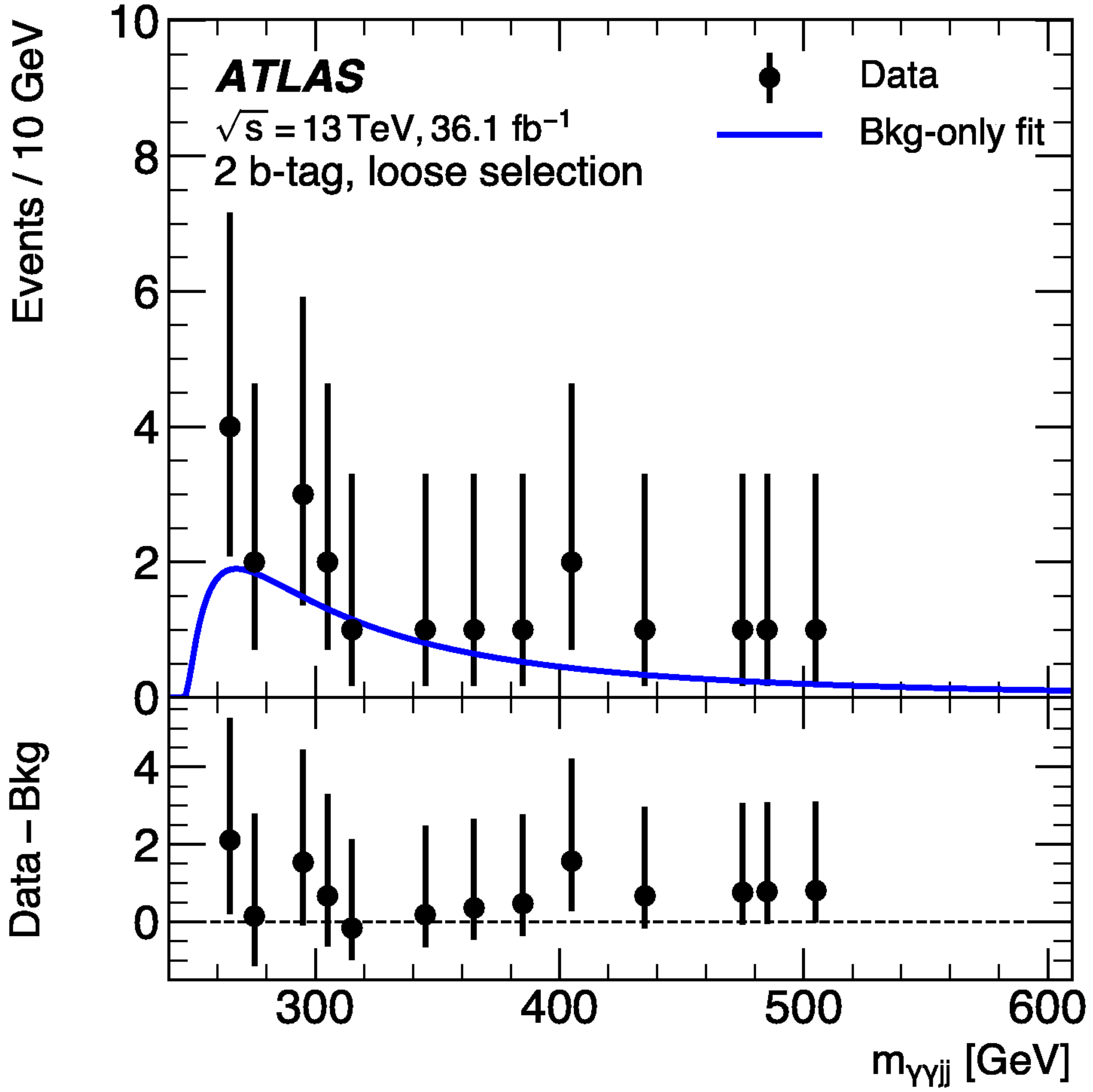
Non-resonant:

Fit $m_{\gamma\gamma}$ spectrum between 105 and 160 GeV



Resonant:

Fix m_{bb} to 125 GeV, cut $m_{\gamma\gamma}$ between 120 and 130 GeV, perform fit in $m_{\gamma\gamma jj}$



JHEP 11 (2018) 040

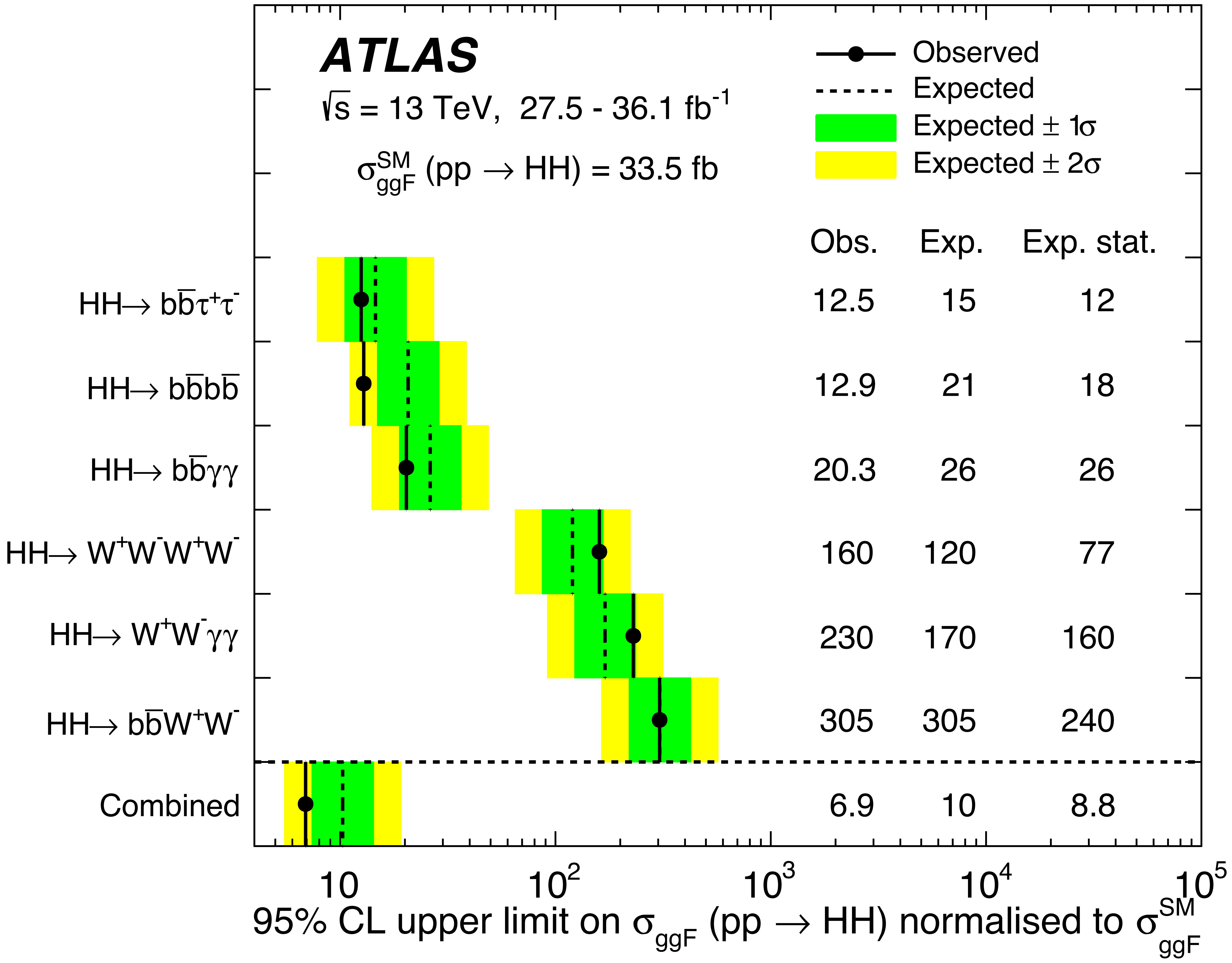
Early Run 2 Results - 36 fb^{-1}

Results shown today from early Run 2 publications, corresponding to 36.1 fb^{-1}, the 2015+2016 dataset

Combined observed limit of 6.9*SM expectation on HH→ggF cross section

Best single channel limit by bbττ at 12.5*SM observed

Aforementioned channels (bbττ, bbbb, $\gamma\gamma$bb) driving limit



[1906.02025](1906.02025)

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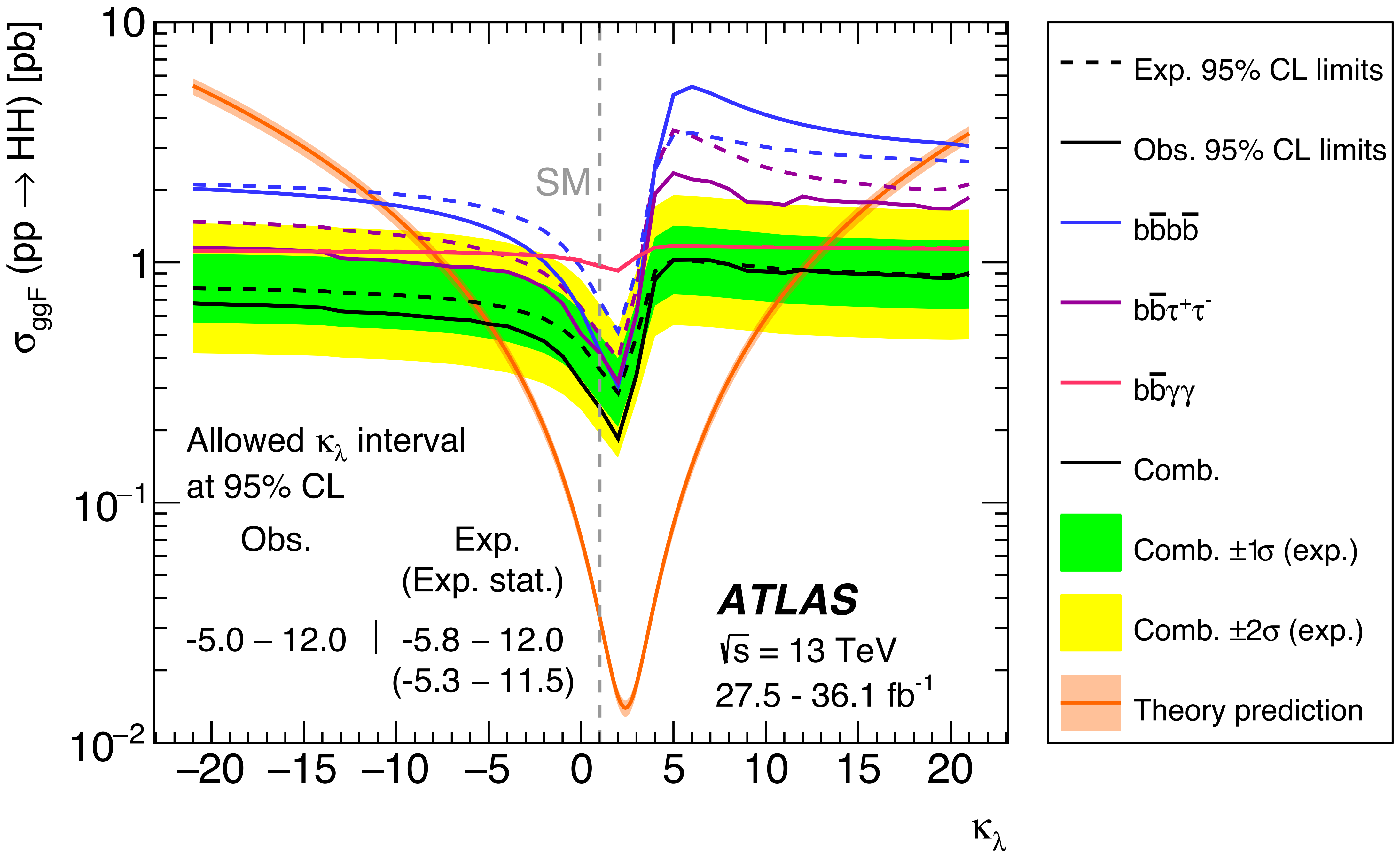
Early Run 2 Results - 36 fb^{-1}

Trilinear Coupling:
Expected: $-5.8 < K_\lambda < 12.0$
Observed: $-5.0 < K_\lambda < 12.0$

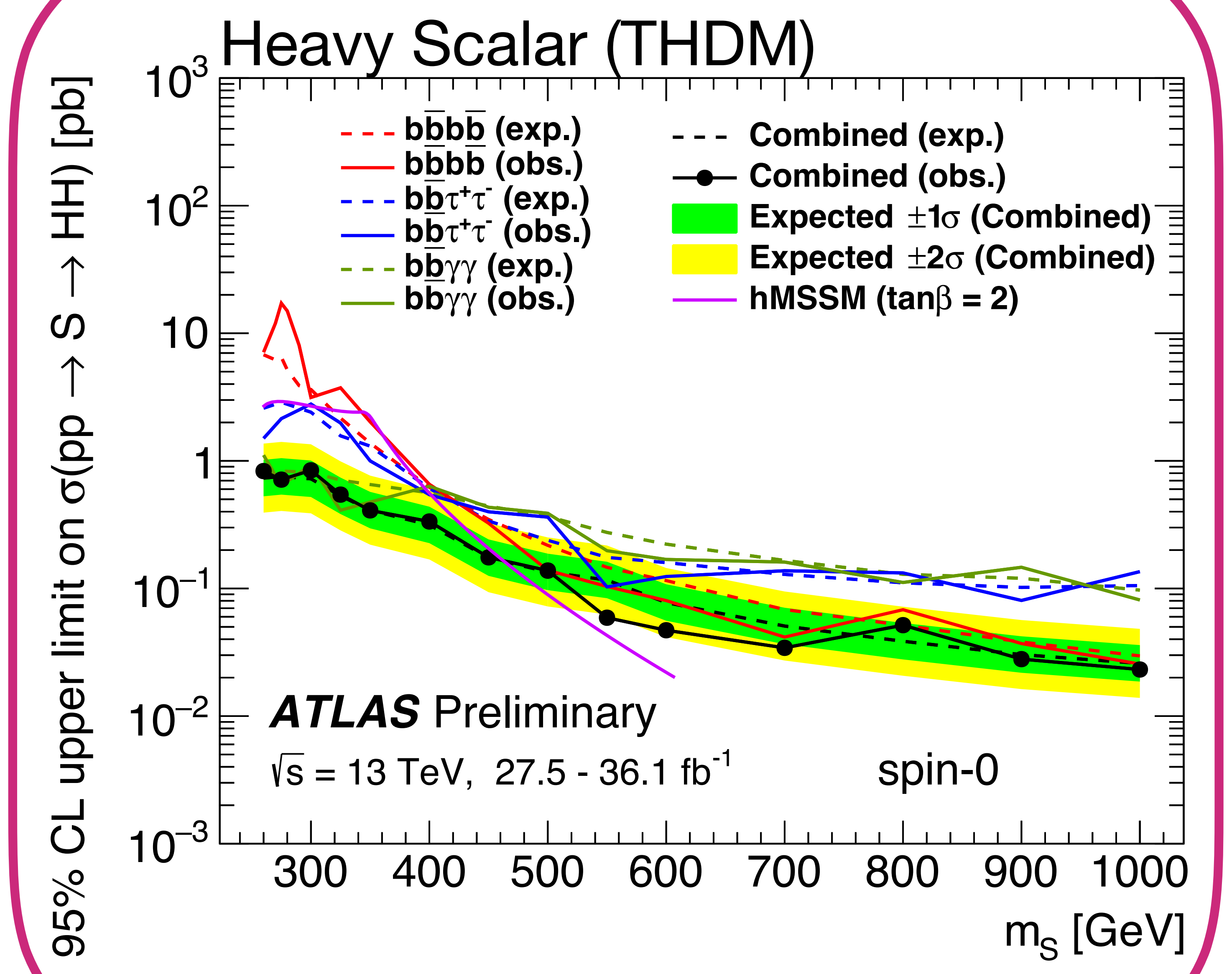


Two-Higgs Doublet Model
mX < 462 GeV @ 95% CL in hMSSM

Randall-Sundrum Model
k/M_{Pl} =1.0 constraints: $307 < m_G < 1362$ GeV
k/M_{Pl} =2.0 constraints: $m_G < 1744$ GeV

tanβ = 2: ratio of the vacuum expectation values of the two Higgs doublets

k: curvature of the warped extra dimension
M̄ Pl: the effective four-dimensional Planck scale



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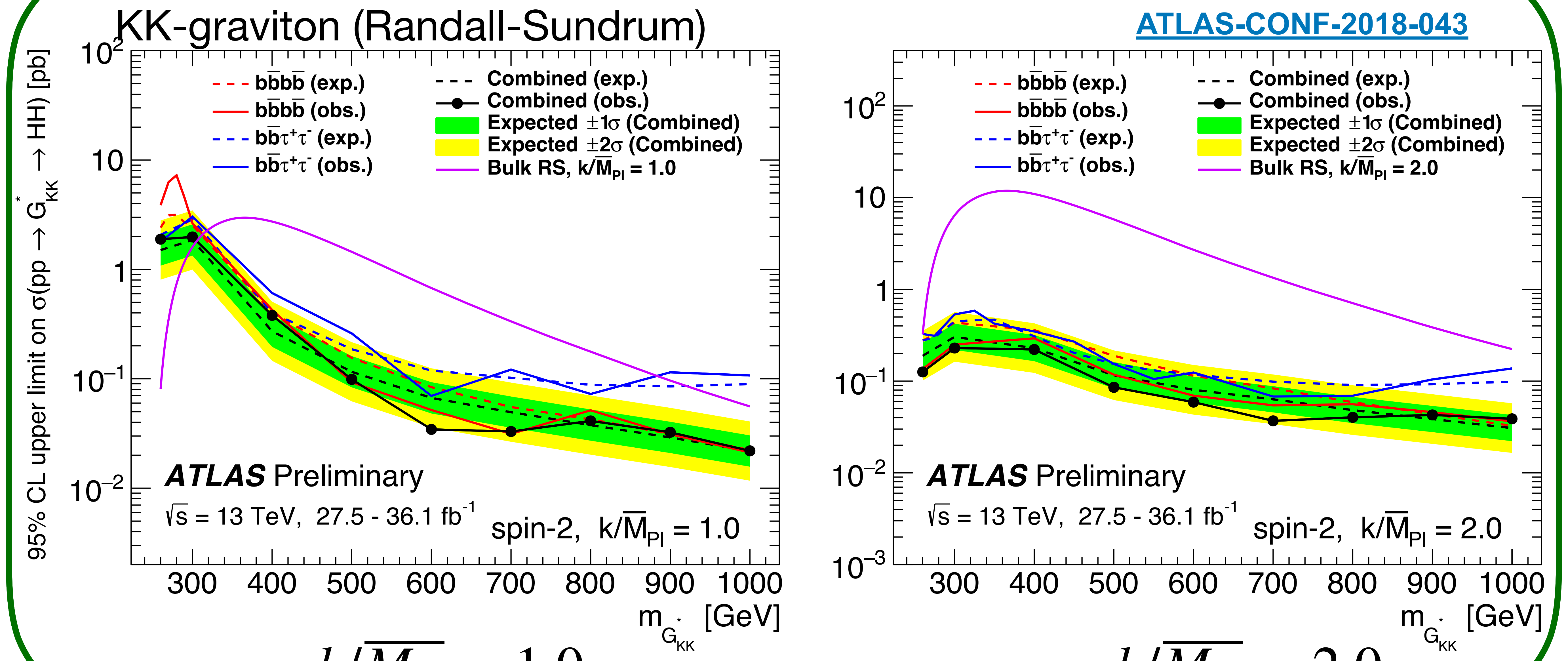

$k/\overline{M}_{Pl} = 1.0$ $k/\overline{M}_{Pl} = 2.0$

Moving Forward - Toward Full Run 2 Analyses

Full Run 2 analyses will present on 139 fb^{-1}. Beyond the additional data, how can we improve the analyses moving into the future?

Many ways! Considerations in $\gamma\gamma$bb:

- More sophisticated signal selection via machine learning methods
- Consider 2D fit approach, fitting both m_{bb} and $m_{\gamma\gamma}$
- Investigate new production modes beyond just ggF
  - Vector Boson Fusion (VBF) - the remainder of this talk

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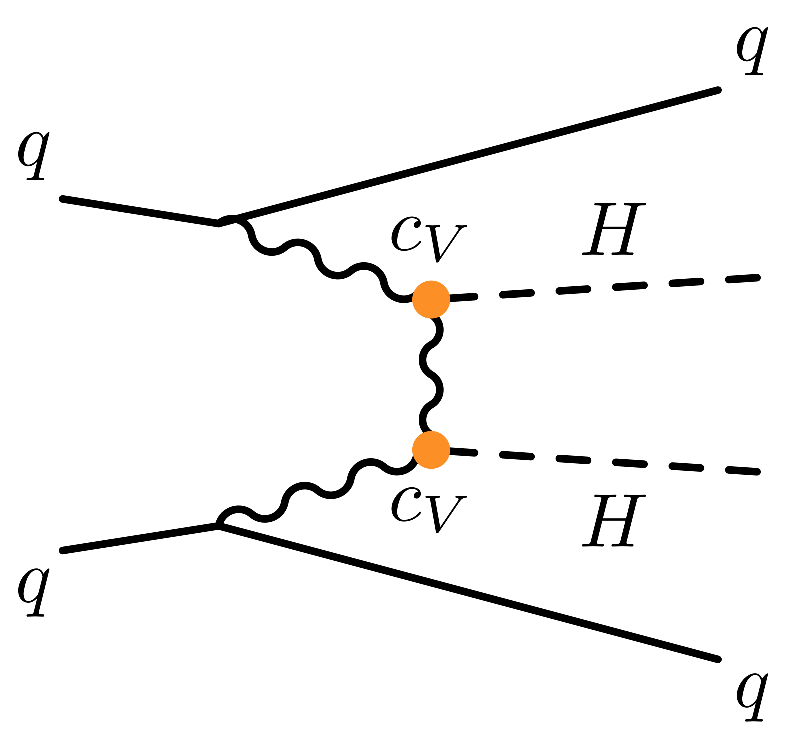
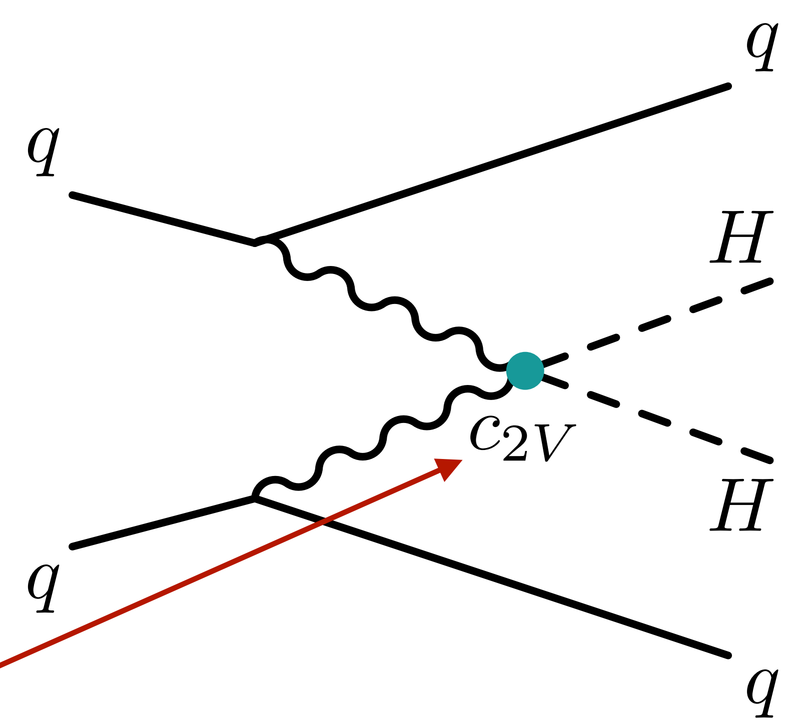
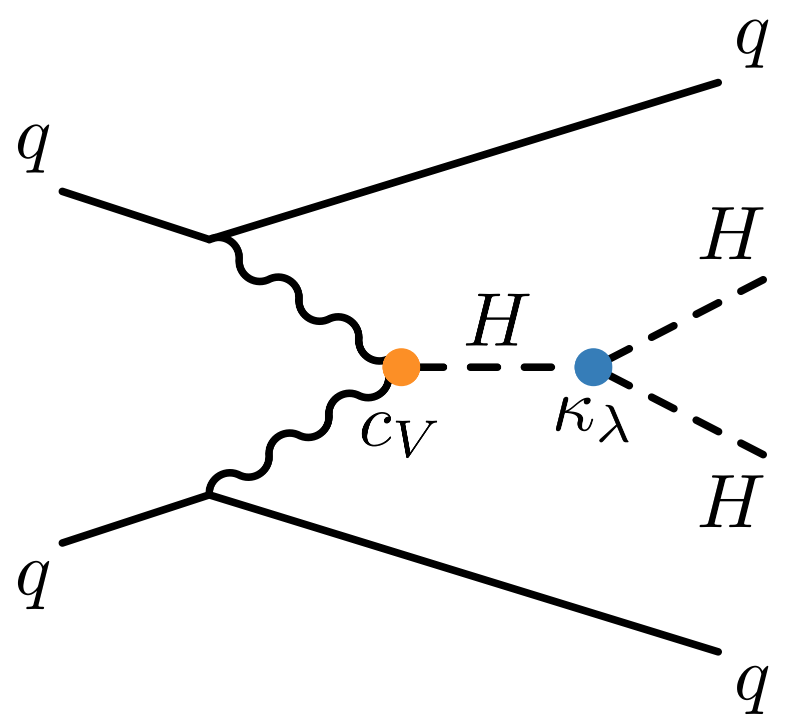
Vector Boson Fusion HH Production

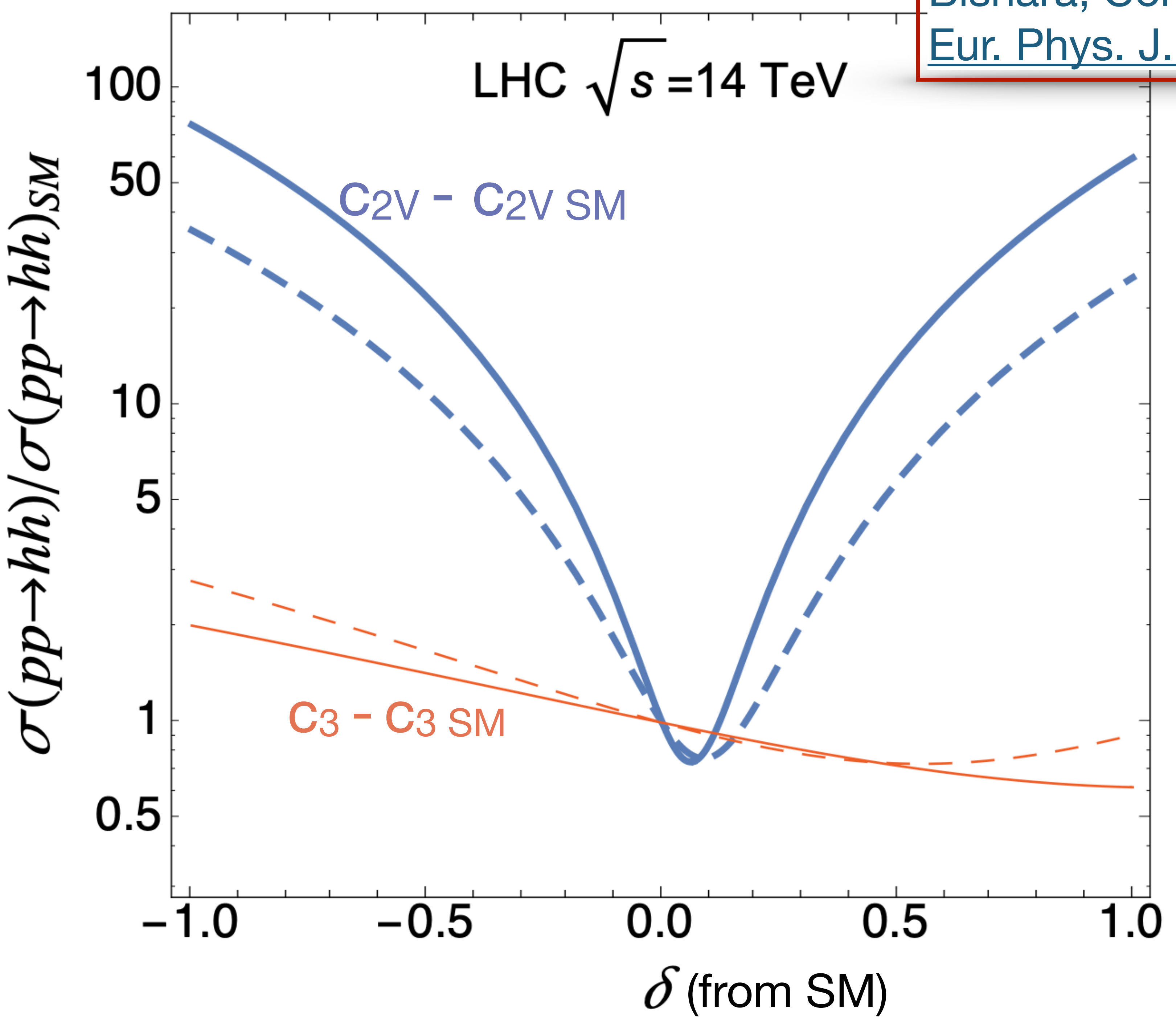
Second most dominant production mode, diagrams shown

- Cross section at 13 TeV = 1.7 fb
  - Just ~5% of HH events
- Final state includes 2 very forward, high-pT jets, which can be used to identify VBF production and separate from background - clean signature









Bishara, Contino, Rojo
Eur. Phys. J. C 77 (2017) 481

Direct handle on HHVV vertex, previously unprobed

- Deviations from SM value can lead to striking increase in HH cross-section

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Vector Boson Fusion HH Study

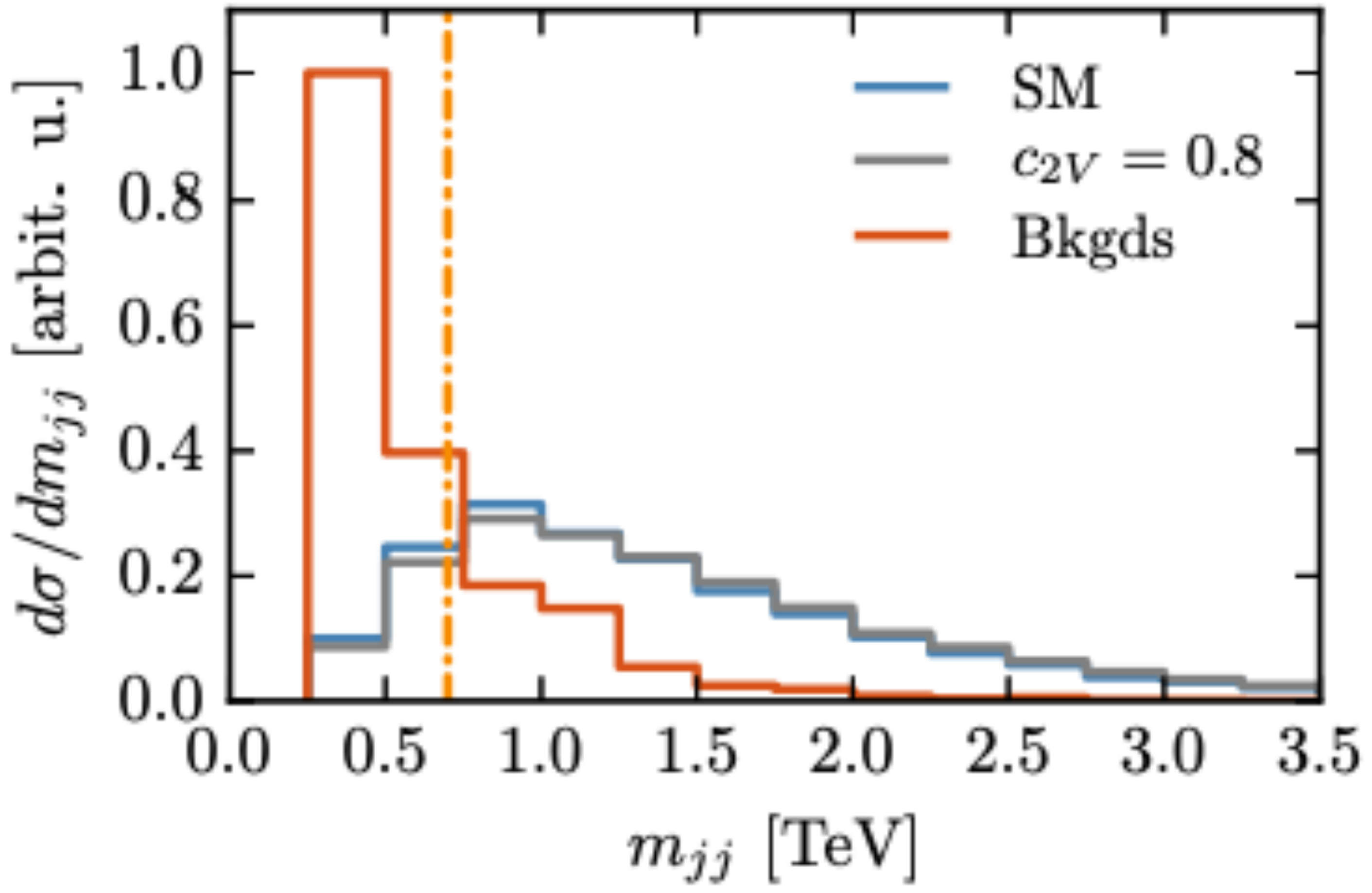
Pheno study in 4b channel with VBF specific cuts are on m_{jj}, rapidity, central jet veto

- Reduces ggF contamination by a **factor of 25**
- **55%** relative signal efficiency for VBF production

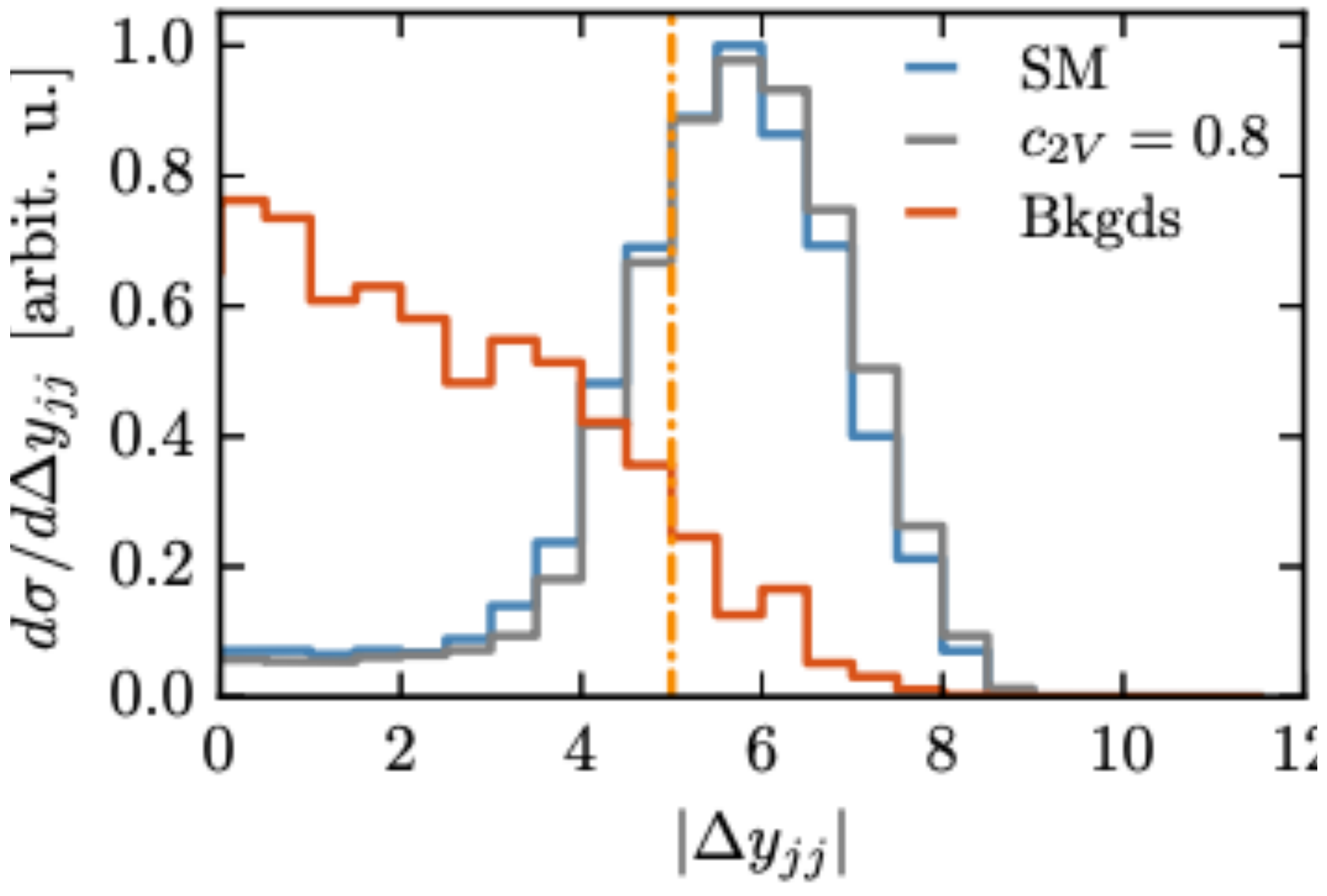
Background contributions

	Acceptance	VBF	Higgs reco.	m_{hh} cut
$4b$	1.18×10^4	613	54	4.45
$2b2j$	1.14×10^5	4.31×10^3	514	42.6
$t\bar{t}jj$	150	4.75	0.732	0.0706
$gg \to hh$	0.98	0.0388	0.0223	0.00857
Total	1.3×10^5	4.9×10^3	569	47

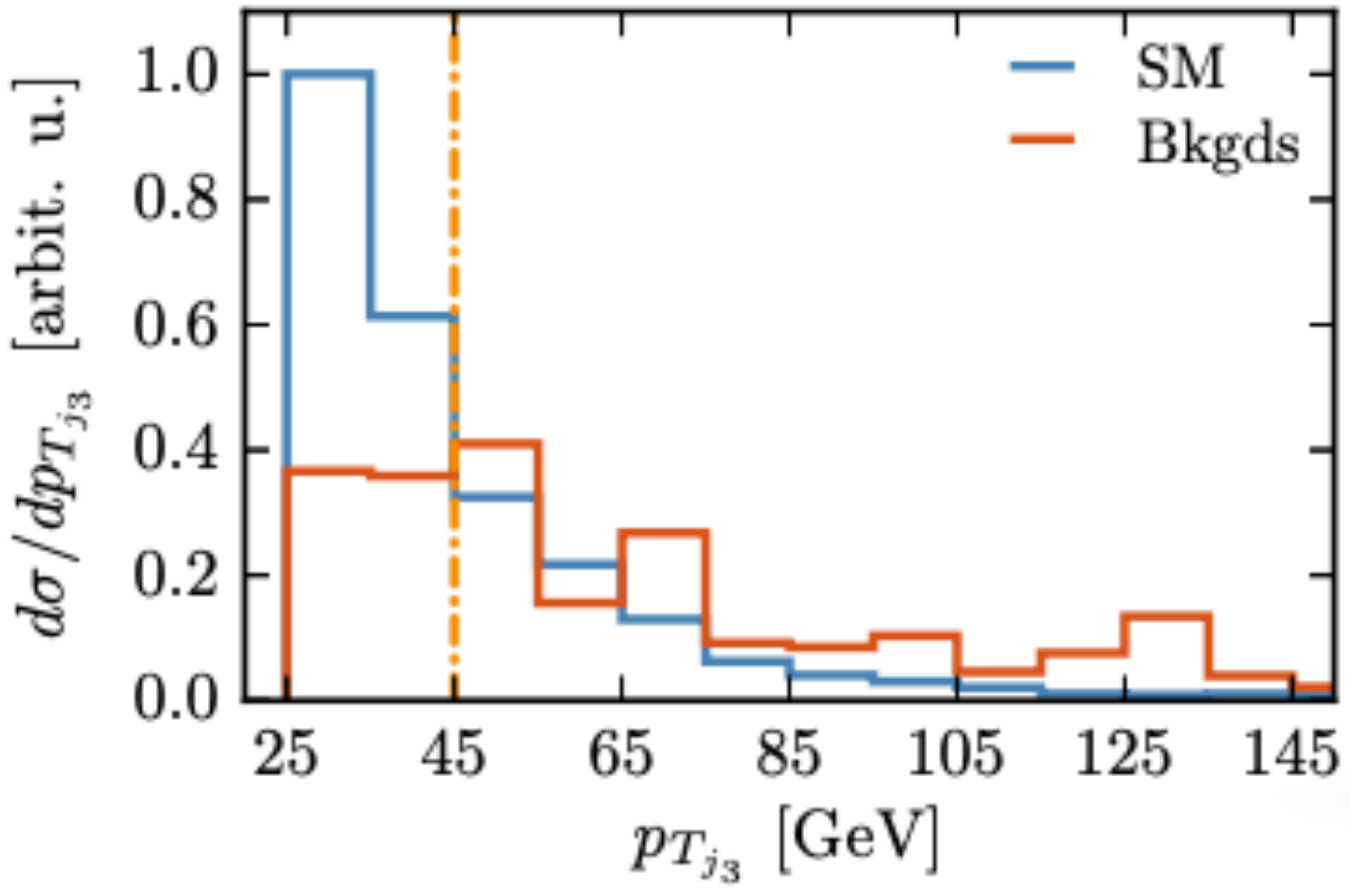
m_{jj} Selection



Rapidity Selection



Central Jet Veto



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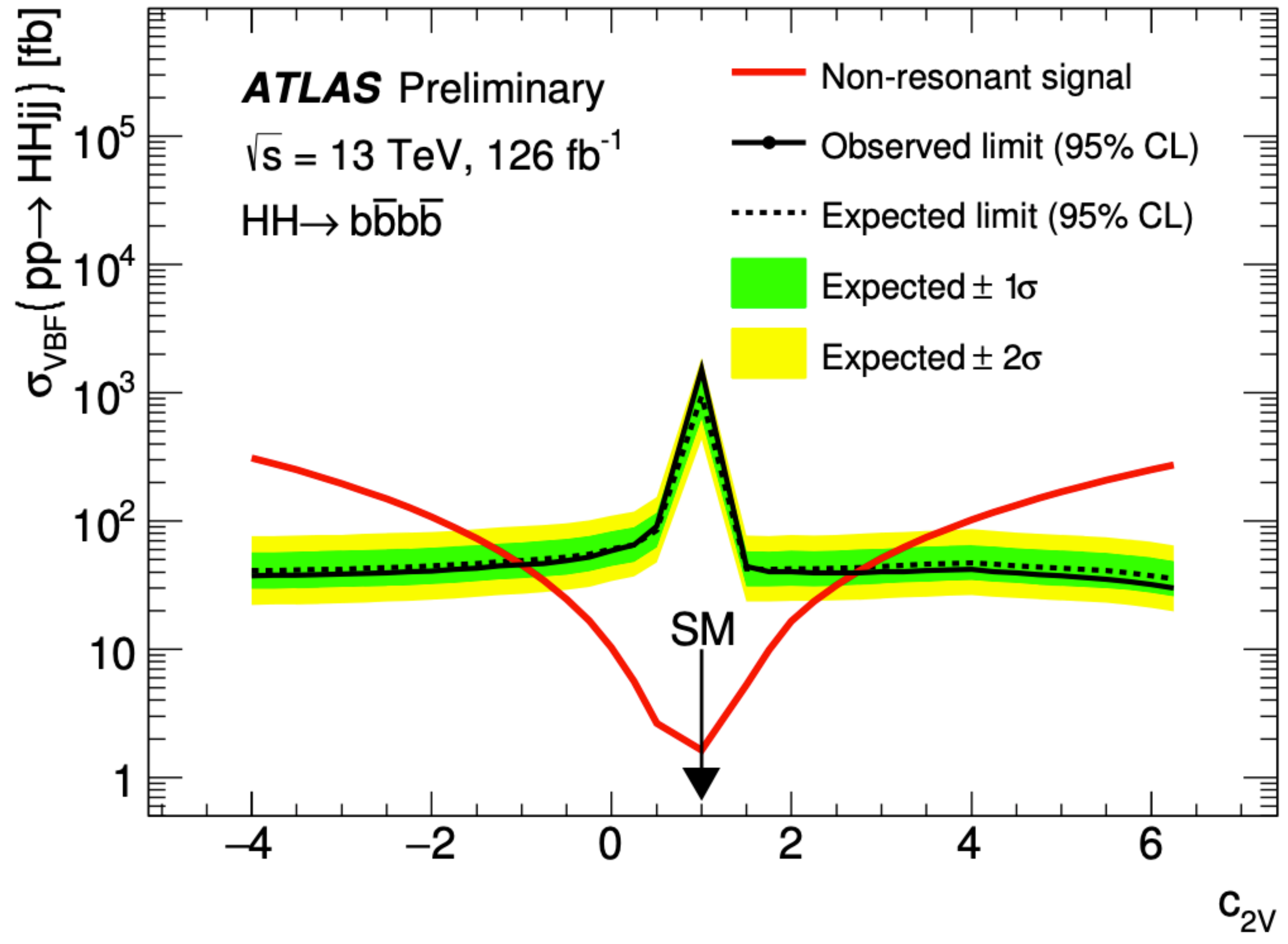
Vector Boson Fusion HH Results

ATLAS 4b VBF publication

Full Run 2 VBF HH publication out in 4b channel, setting limits on σ(pp→HHjj)

- Analysis strategy similar to ggF 4b analysis, fit m_{4b}
  - Cuts on $|\Delta\eta| < 5$, $m_{jj} > 1000$ GeV used for VBF topology
- Expected 1000*SM, observed 1600*SM
- First ever limits on c_{2V}:
  - Expected: $-1.09 < c_{2V} < 2.82$
  - Observed: $-1.02 < c_{2V} < 2.71$



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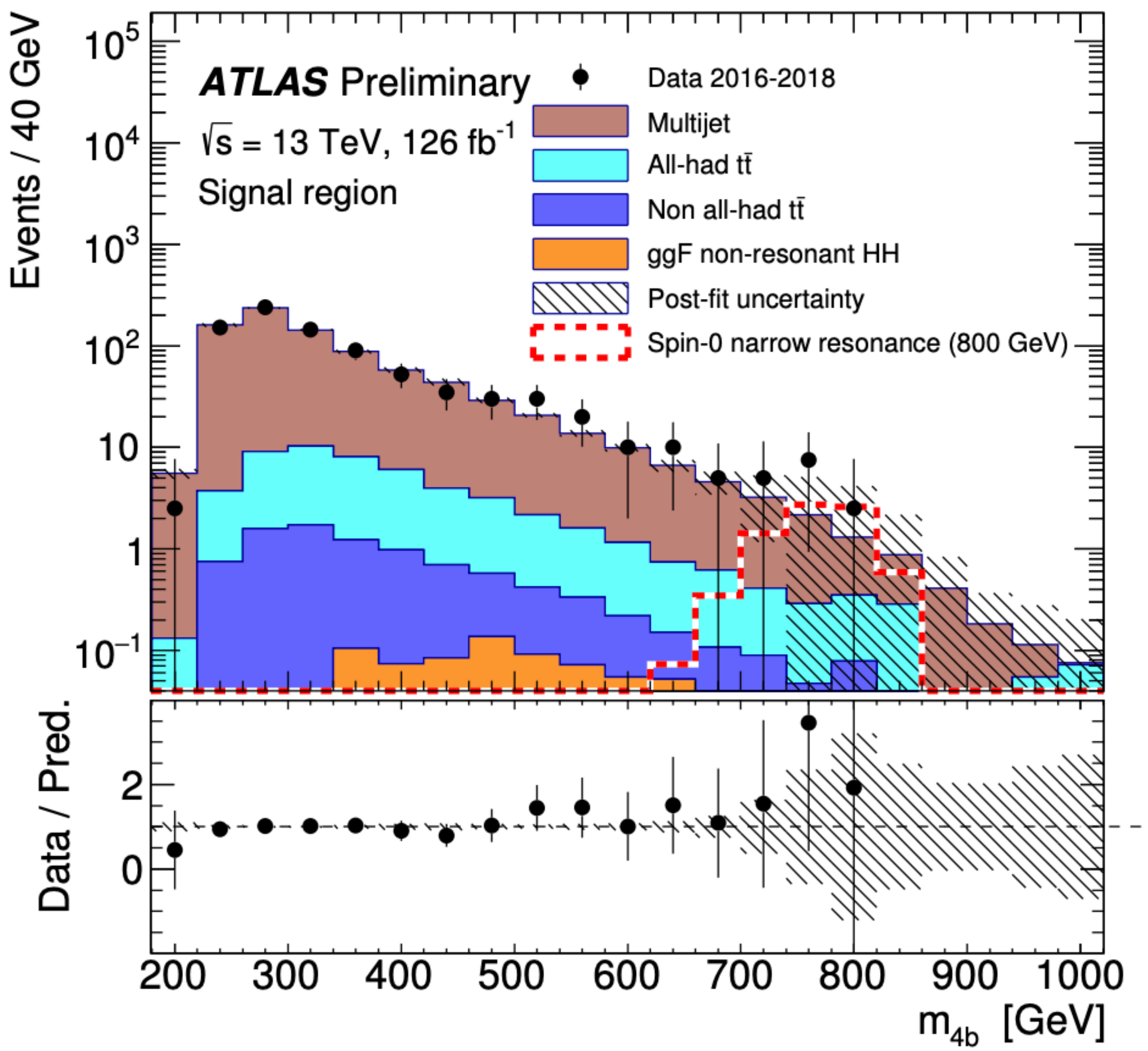

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Summary

Searches for di-Higgs production seek to answer important outstanding questions still surrounding the discovered Higgs boson

Measuring the Higgs trilinear coupling helps understand if the discovered Higgs couples as predicted by the SM

- Provides insight into Electroweak Symmetry Breaking, a long-term goal of the LHC

Searching for enhanced di-Higgs production targets BSM physics

- Opportunity to discover additional Higgs bosons or new BSM particles
- Due to small SM HH cross section, BSM enhancements may be noticeable even with the full Run-2 dataset

ATLAS is hard at work studying di-Higgs in the Run 2 dataset

- Early results presented, corresponding to 2015+2016 dataset
- Full Run 2 publications in progress! Working to improve our analysis techniques in addition to the increase in data
  - The VBF production mode provides a unique signature, interesting for study on its own or through a dedicated VBF-enriched signal region
- With more data and improved analysis techniques, evidence for di-Higgs production *may* be possible with full LHC dataset

Channel	Exclusion (95% CL)	Discovey Significance
$\gamma\gamma bb$	N/A	1.5σ
$bb\tau\tau$	$4.3*\sigma_{SM}$	0.6σ
bbbb	$1.5*\sigma_{SM}$	N/A

Combination Projection:
3.5σ Stat-only
3.0σ Stat+Systematic

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Backup

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Prospect Projections

Channel	Exclusion @ 95% CL
$HH\to bbbb$	$-4.1 < \kappa_\lambda < 8.7$
$HH\to \gamma\gamma bb$	$0.2 < \kappa_\lambda < 6.9$
$HH\to bb\tau\tau$	$-4.0 < \kappa_\lambda < 12.0$

Stefania Gori

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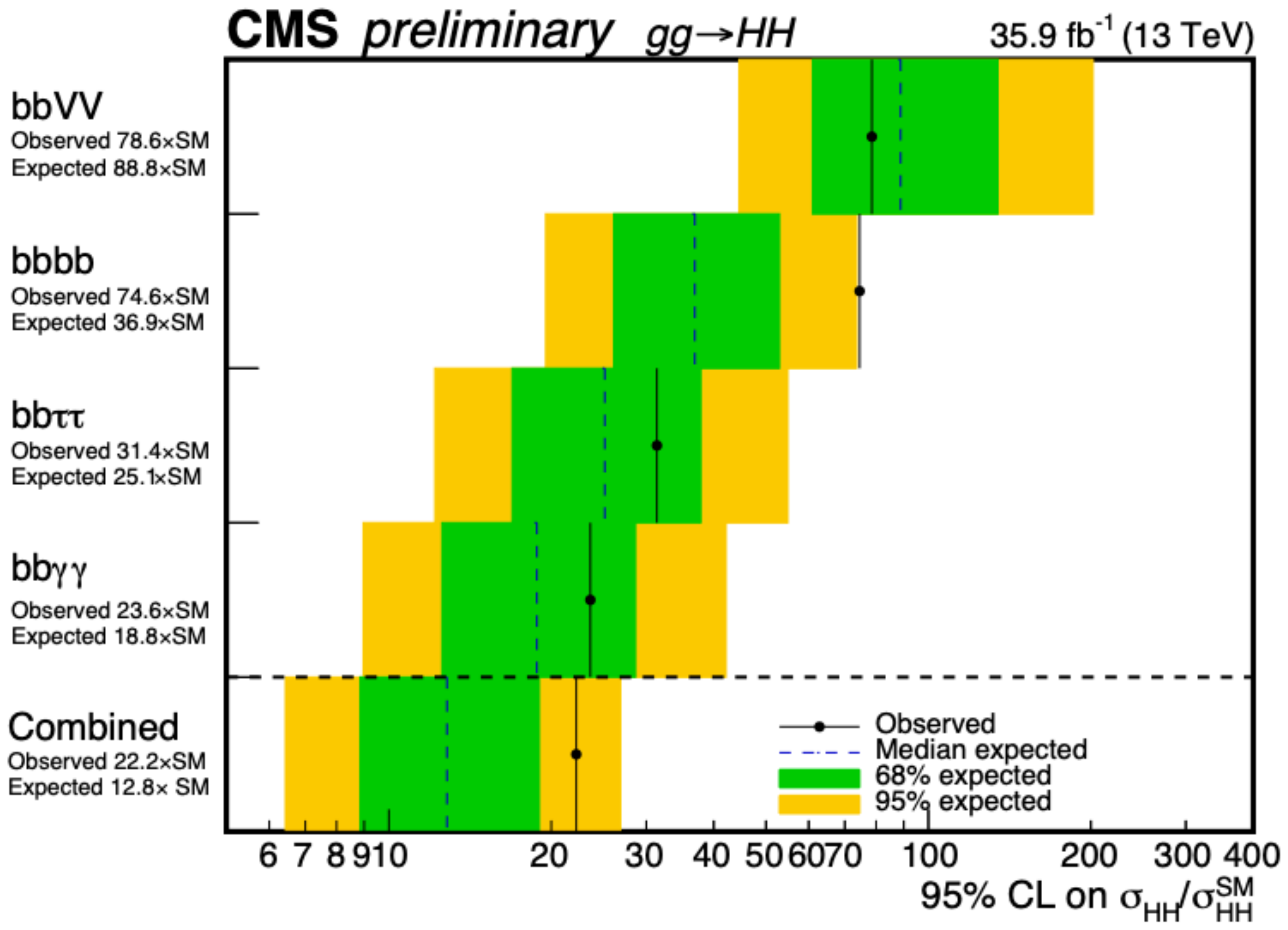
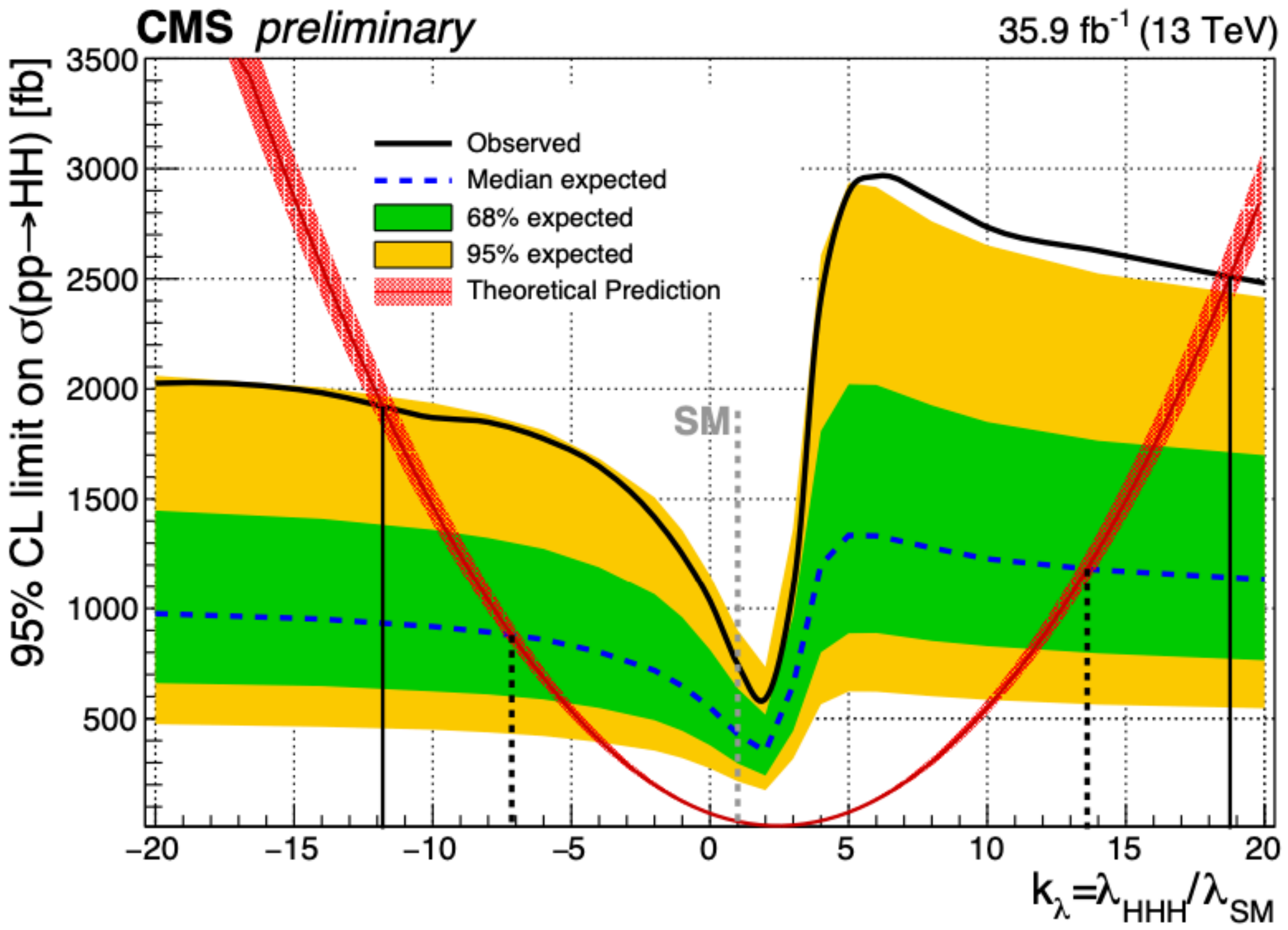
CMS Results

Luca Cadamuro





Combined limit on σ / σ_{SM}
Observed : 22.2
Expected : 12.8

Constraint on $k_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$
Observed : $-11.8 < k_\lambda < 18.8$
Expected : $-7.1 < k_\lambda < 13.6$

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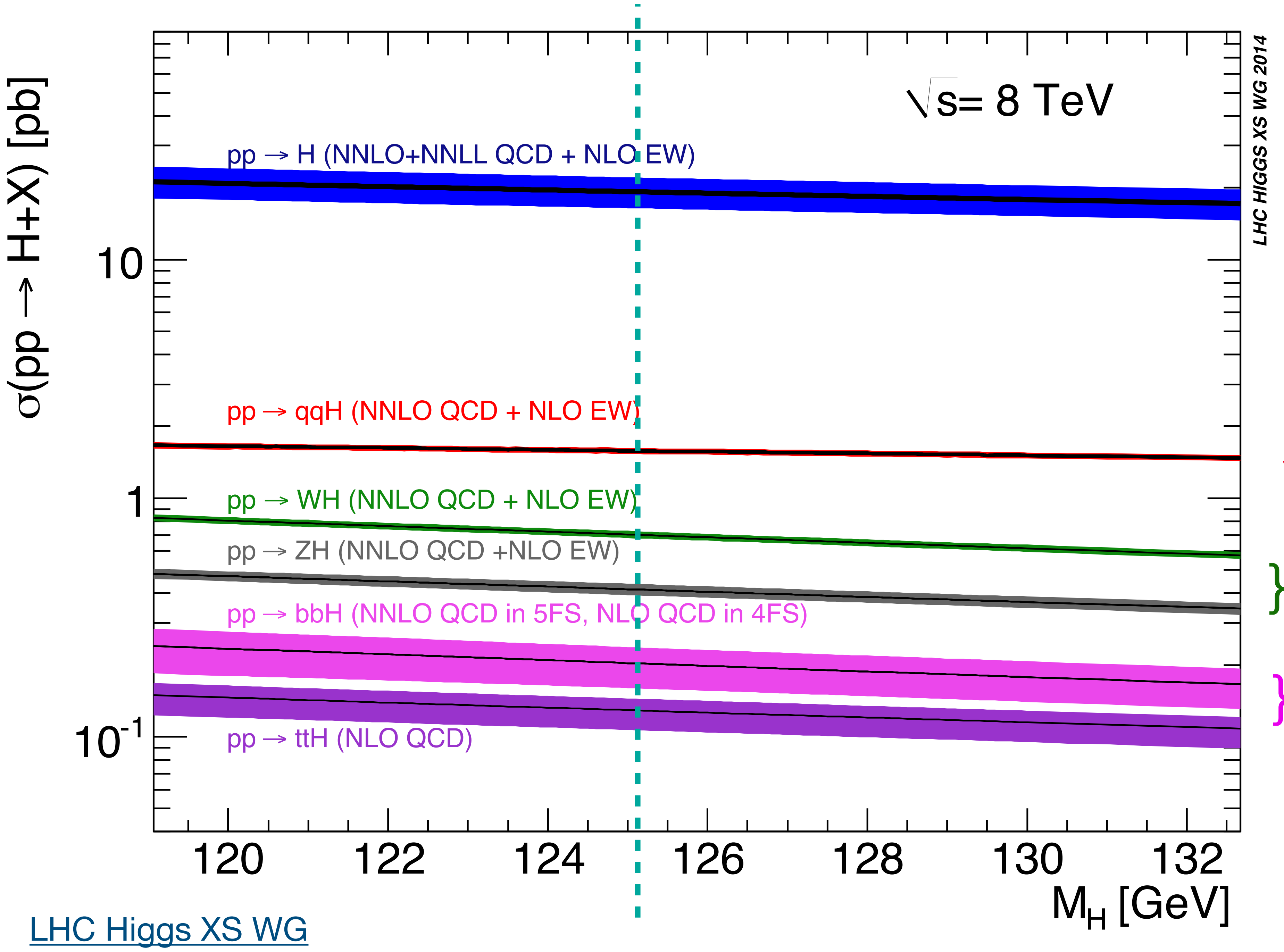
Higgs Production Modes



LHC Higgs XS WG

(for 13 TeV)

ggF = 87.3 %

VBF = 6.8%

} VH = 4.1%

} ttH + bbH = 1.8%

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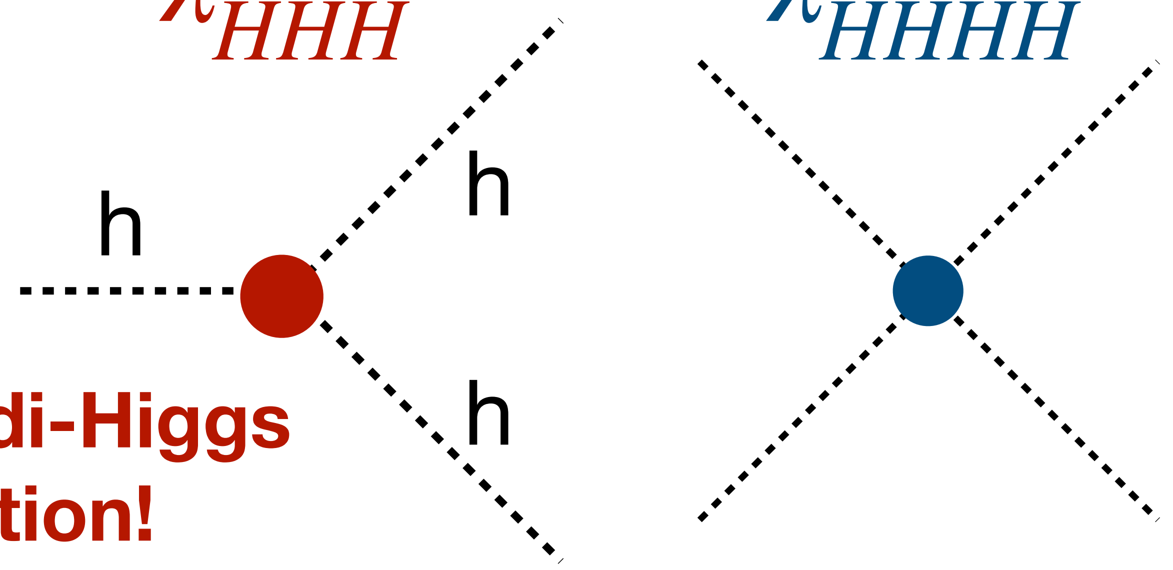
Motivation

Familiar Higgs potential shown, with nonzero vacuum expectation.

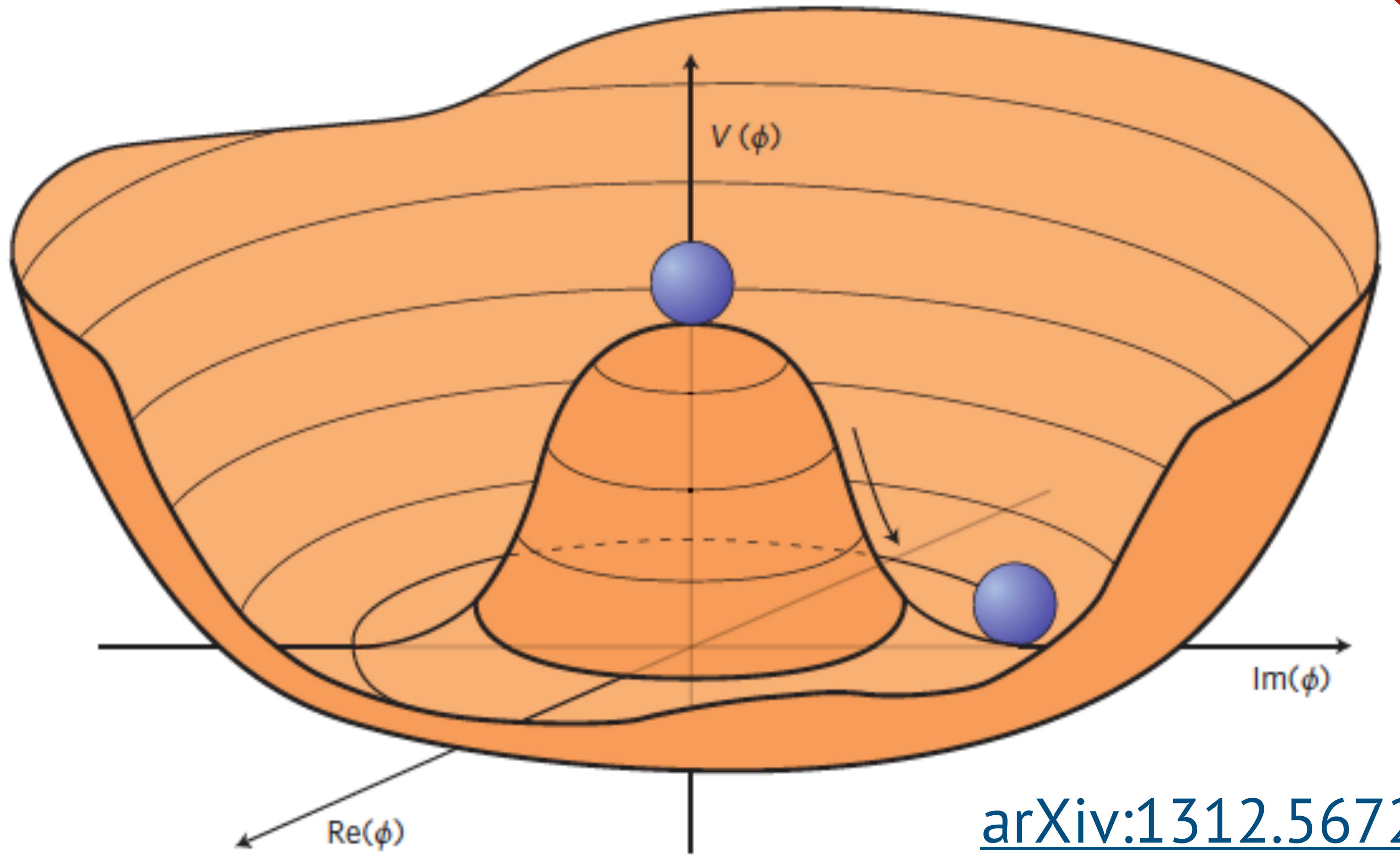
For fluctuations about the minima, $\phi \rightarrow v + h,$ can expand potential as:

$$V = V_0 + \frac{m_h^2}{2}h^2 + \underbrace{\frac{m_h^2}{2v^2}}_{\lambda_{HHH}^{SM}} vh^3 + \underbrace{\frac{m_h^2}{8v^2}}_{\lambda_{HHHH}^{SM}} h^4$$



Results in di-Higgs production!

$$V(\phi^*\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$$



arXiv:1312.5672

minimum corresponds to:

$$\frac{\mu}{\sqrt{\lambda}} \equiv v$$

~246 GeV

Higgs Vacuum expectation value (vev)

- Probes the trilinear coupling - providing another check that this is the SM Higgs boson
- Measurement of λ_{HHH} checks that Electroweak Symmetry Breaking follows from the Higgs' ϕ^4 potential

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Analysis Approaches

$HH \rightarrow b\bar{b}\gamma\gamma$

Fix m_{bb} to 125 GeV, cut $m_{\gamma\gamma}$ between 120 and 130 GeV, perform S+B fit in $m_{\gamma\gamma jj}$

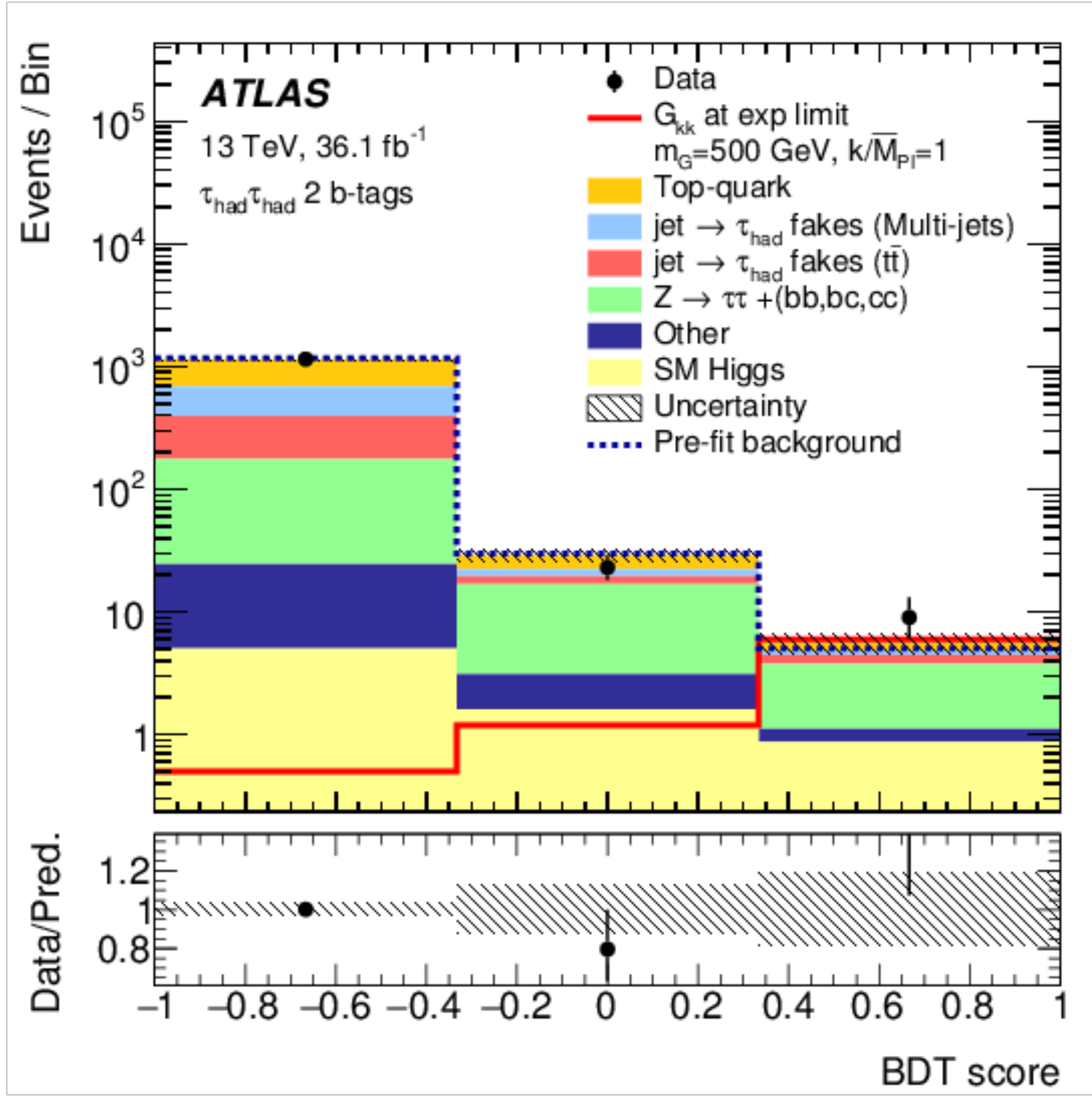
Continuum $m_{\gamma\gamma}$ spectra background estimated from data

Particularly sensitive at low masses

$HH \rightarrow b\bar{b}\tau\tau$

Train BDT to discriminate signal from backgrounds, fit BDT score distributions

- Dominant backgrounds: multijet, $t\bar{t}$, $Z \rightarrow \tau\tau$
- Separate BDT for each mass hypothesis



Phys. Rev. Lett. 121 (2018) 191801

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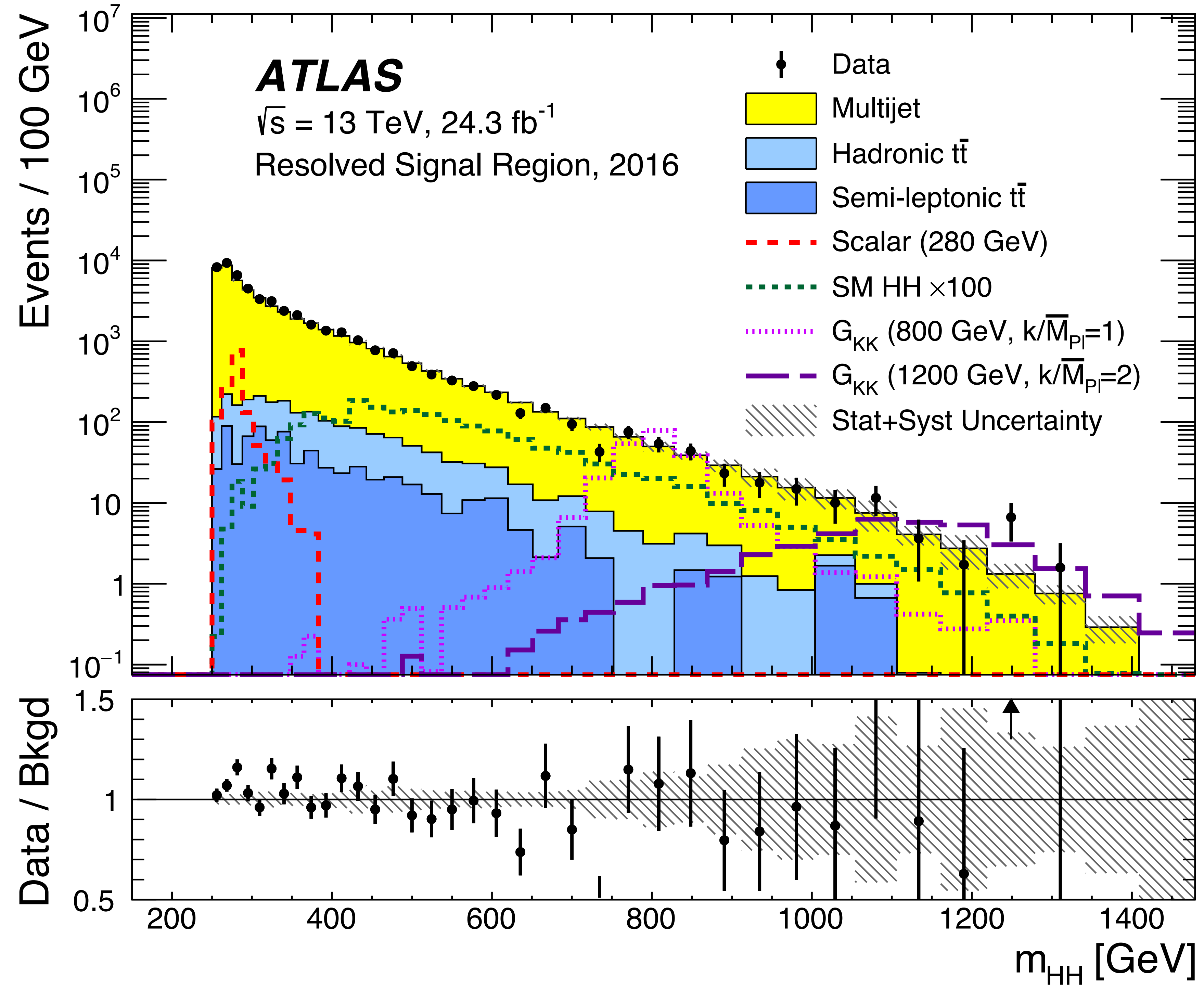
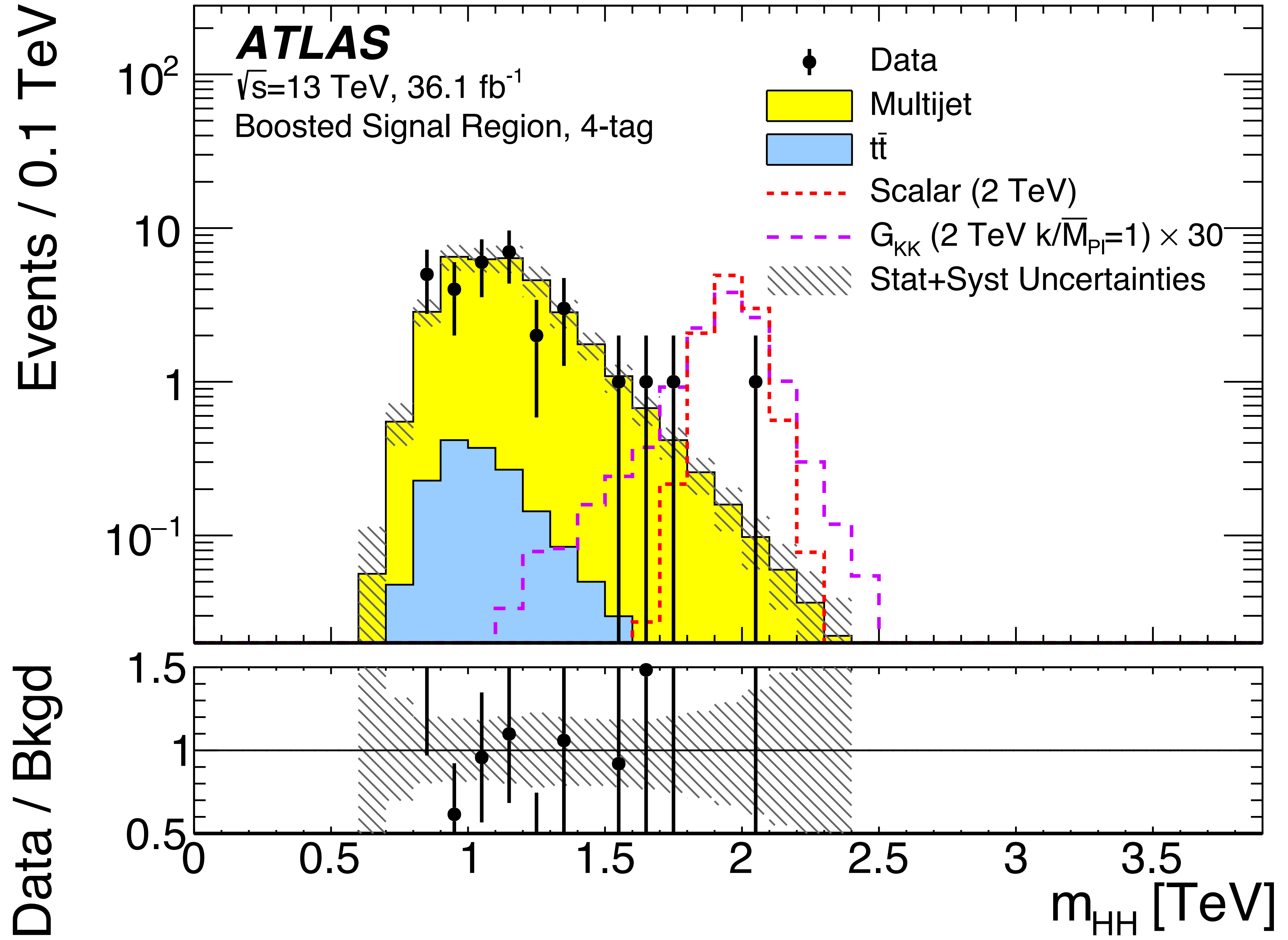
$HH \rightarrow b\bar{b}b\bar{b}$

S+B fit to m_{4j} (m_{2J}) in the resolved (boosted) selection

Multijet background estimated from data

Especially sensitive in high mass region





JHEP 01 (2019) 030