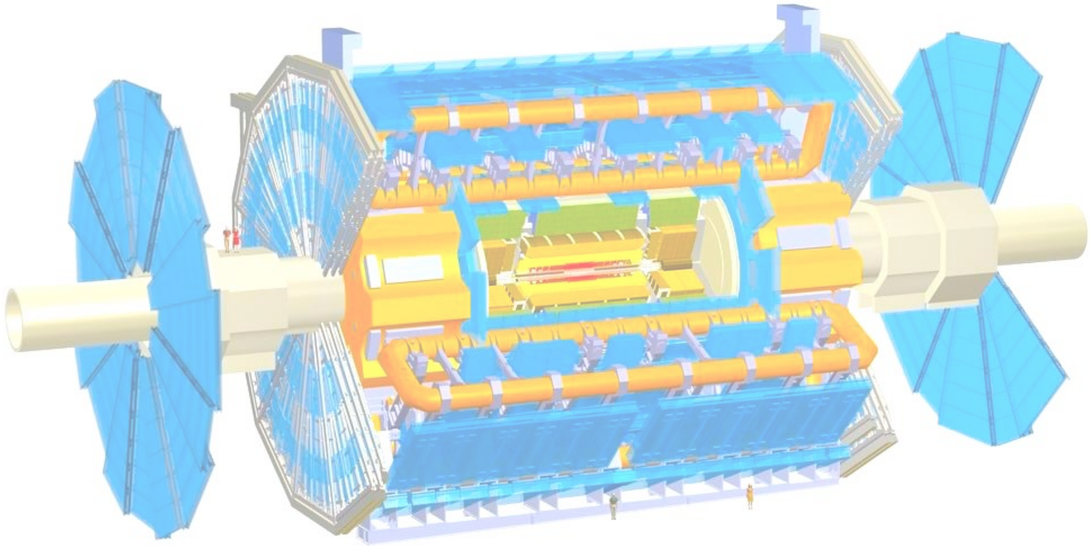
Search for rare and exotic Higgs Boson decay modes and Higgs Boson pair production with the ATLAS detector



2017 hh4b and hXX4l results

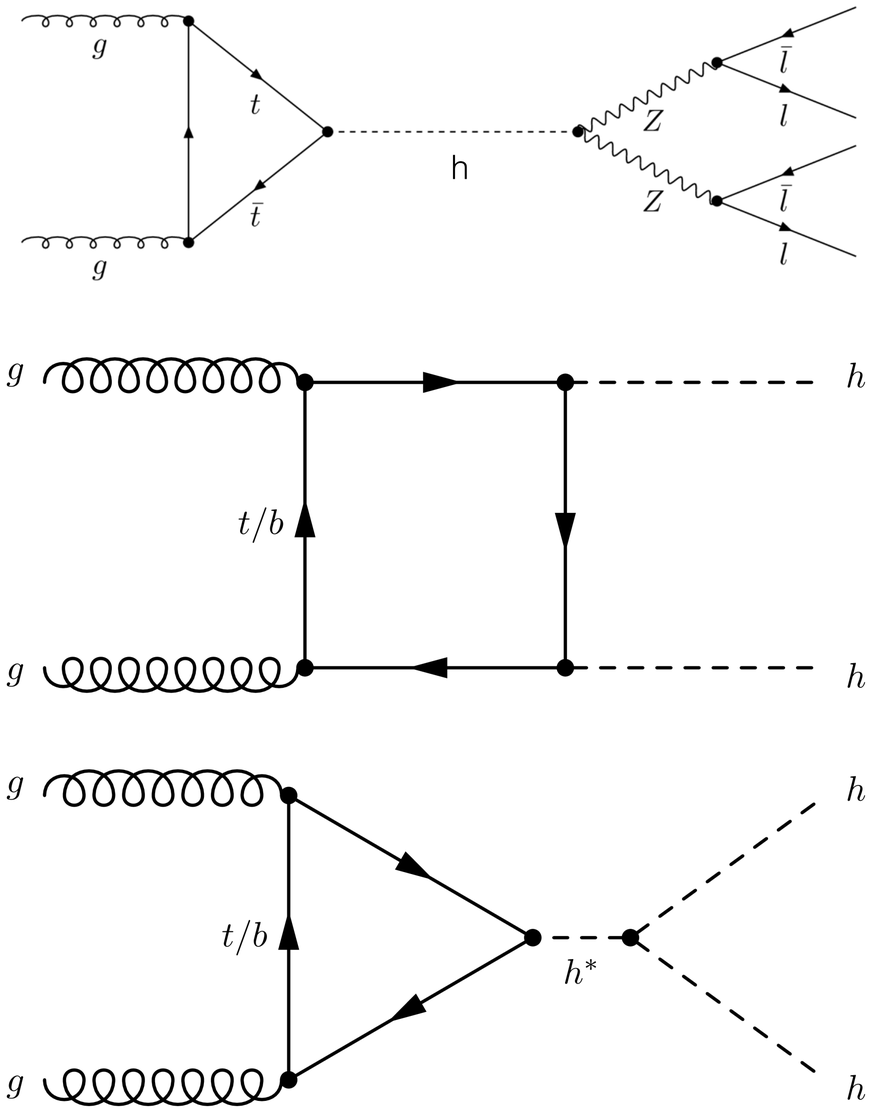
Arxiv1804.06174 Arxiv1802.03388

Tony(Baojia)Tong, Harvard University

Pheno, May 8, 2018

From the SM Higgs Boson

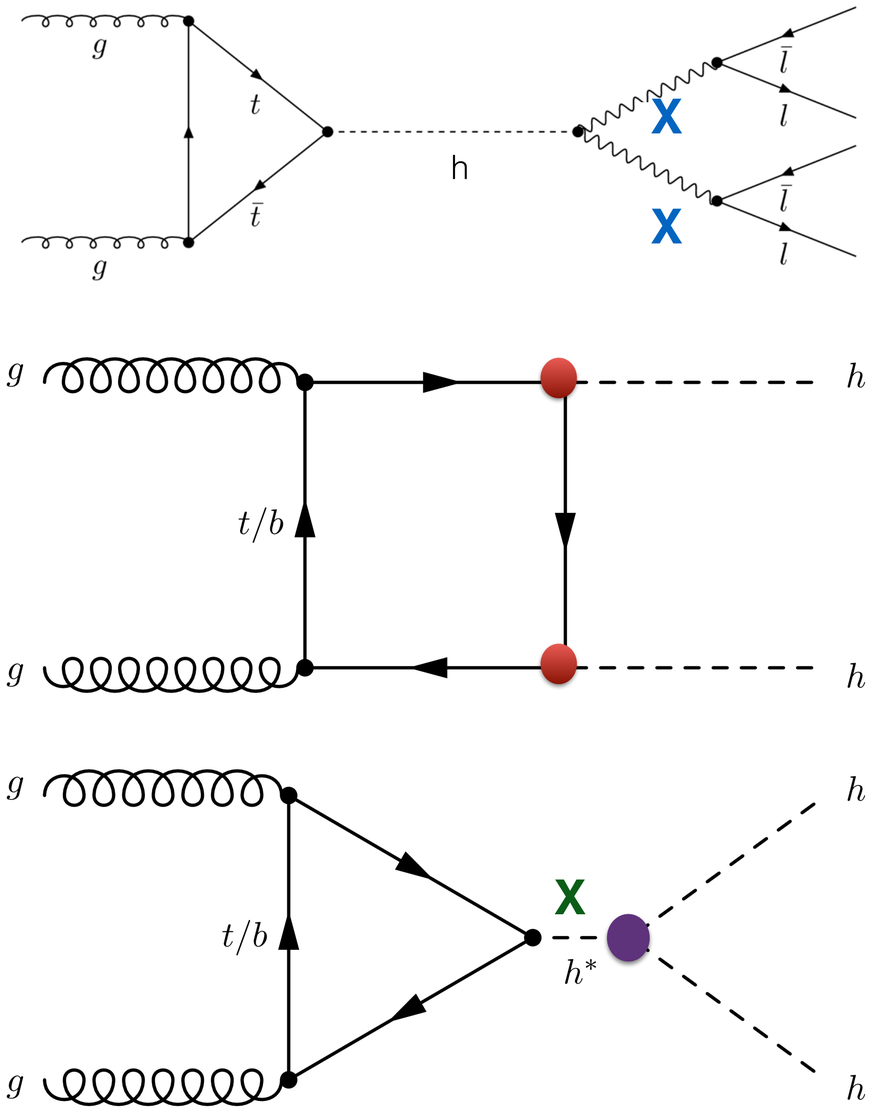
- Two rare yet known process
  - **h→ ZZ* → llll** — small branching ratio but very clean signature
  - **hh → bbbb** — small cross section at 13 TeV ~ 11.3 fb (NNLO + NNLL)



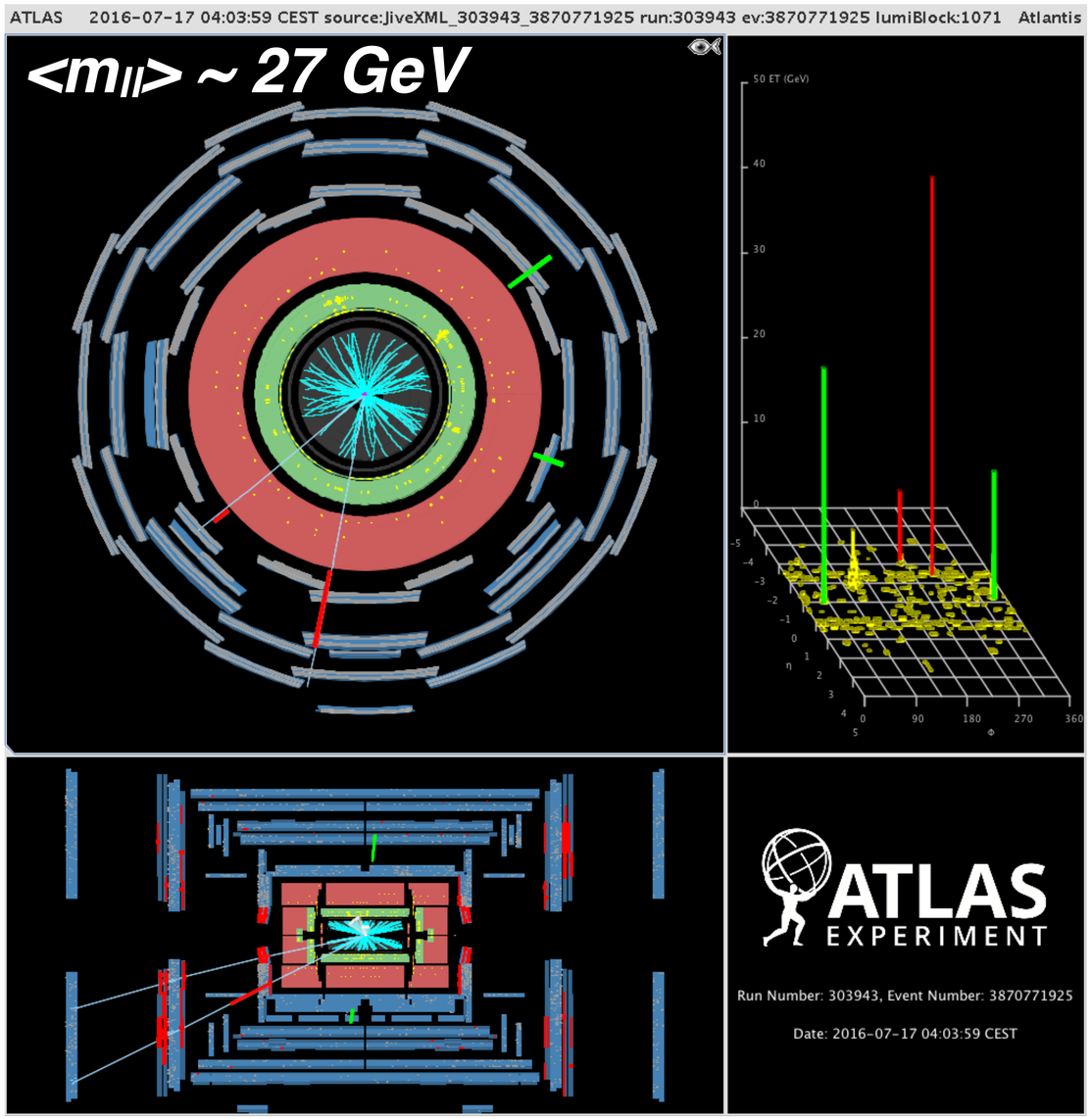
D.Florian,J.Mazzitelli, Arxiv1505.07122

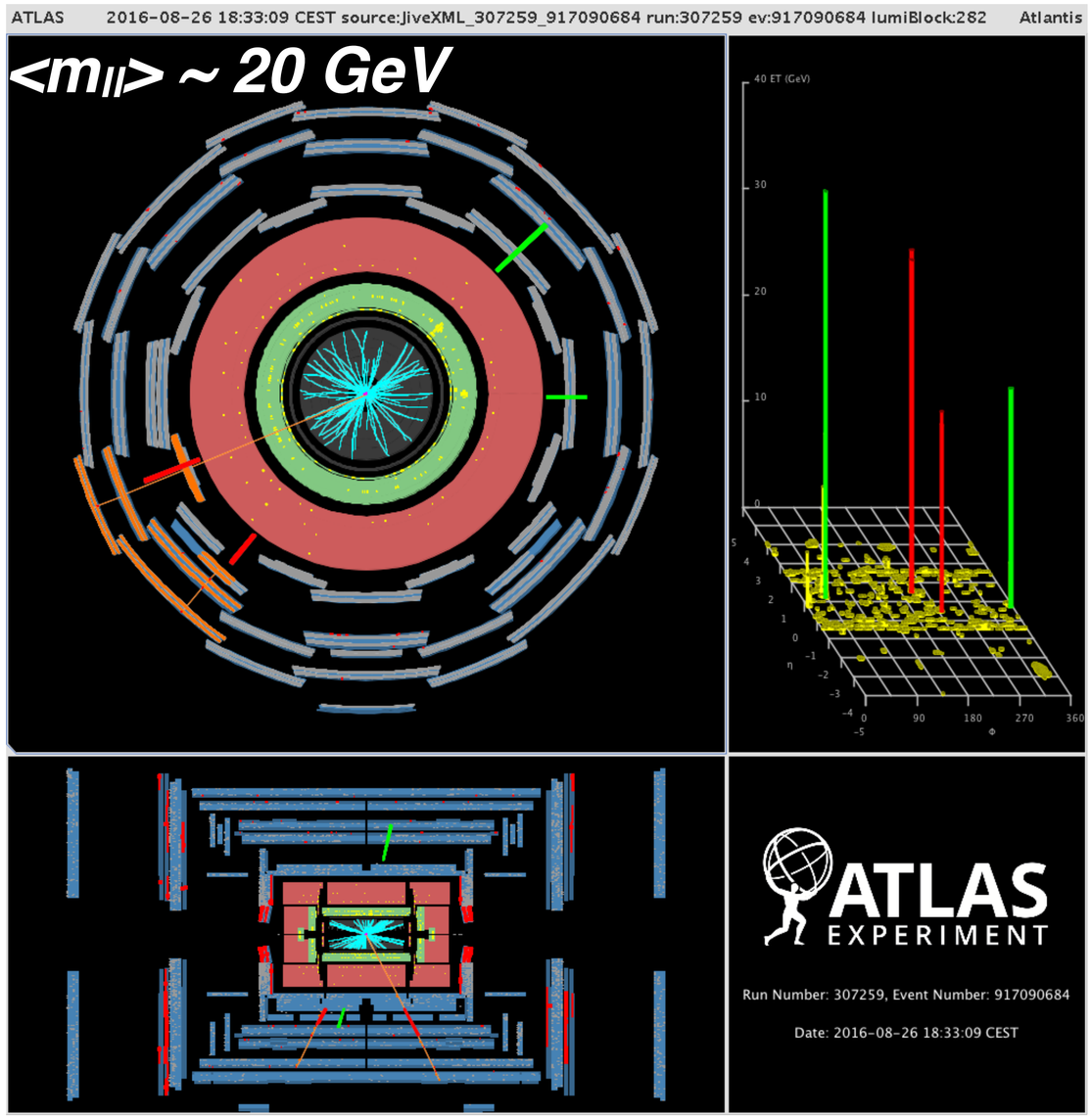
To beyond SM physics

- Two possible enhancements
  - **h→ XX → llll**
    - new vector boson **Z_d**
    - pseudo-scalar a_0
  - **hh → bbbb**
    - non resonant enhancements
      - tth vertex modifications
      - modified **λ_{hhh}** triple-Higgs coupling
    - resonant enhancements **X→ hh**
      - KK **Graviton**, spin 2
      - Heavy Higgs: 2HDM, spin 0



Higgs to 4l event topology





Channels: low mass + high mass

Arxiv1802.03388

- Split because only muons are measured well at low momentum
- Require 2 pairs of same flavor opposite sign leptons, firing di/tri-lepton triggers
- Select quadruplet with smallest $\Delta m_{ll} = |m_{12} - m_{34}|$

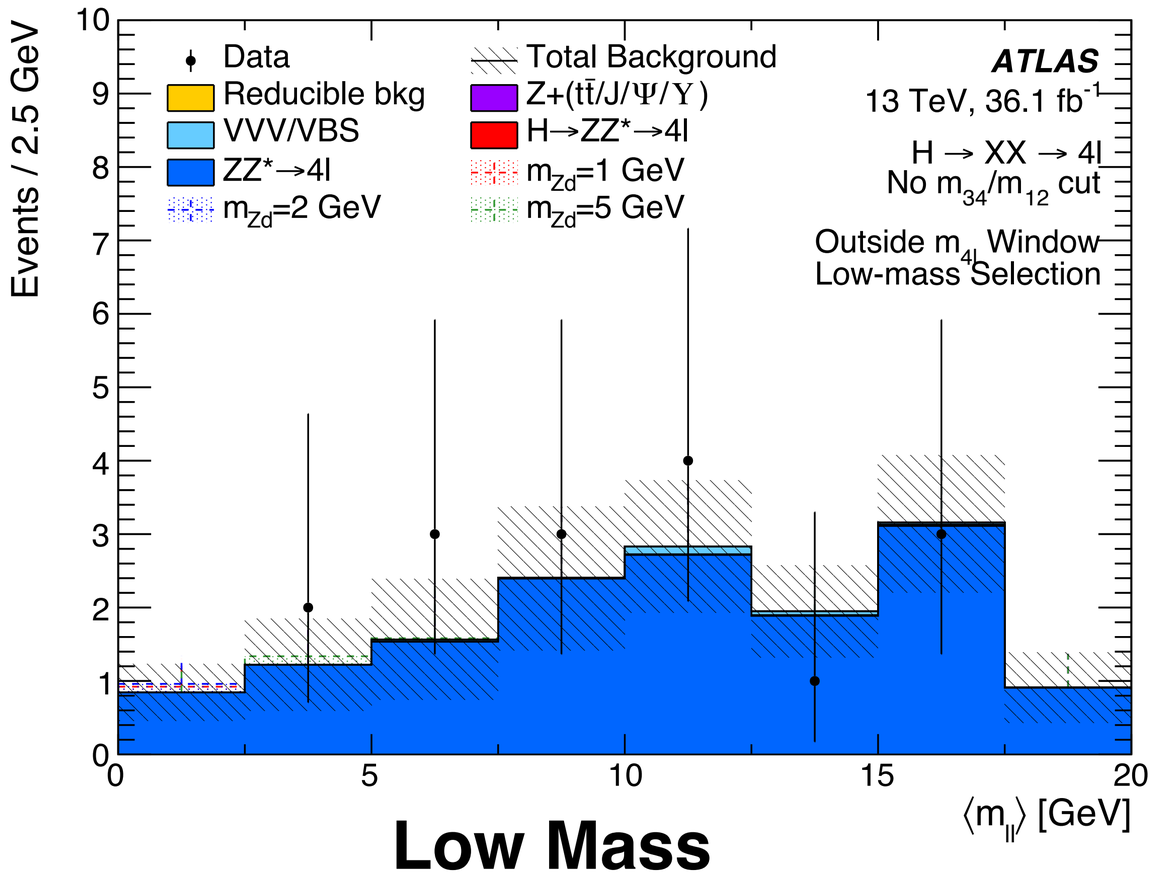
Selection	Low Mass (X 1–15 GeV)	High Mass (X 15-62 GeV)
Electron	—	$p_T > 7$ GeV
Muon	$p_T > 5$ GeV	$p_T > 5$ GeV
Higgs Mass Cut	$120 < m_{4l} < 130$ GeV	$115 < m_{4l} < 130$ GeV
Dilepton Mass Cut	$0.88 < m_{12,34} < 20$ GeV	$5 < m_{12,34} < 64$ GeV $5 < m_{14,32} < 75$ GeV

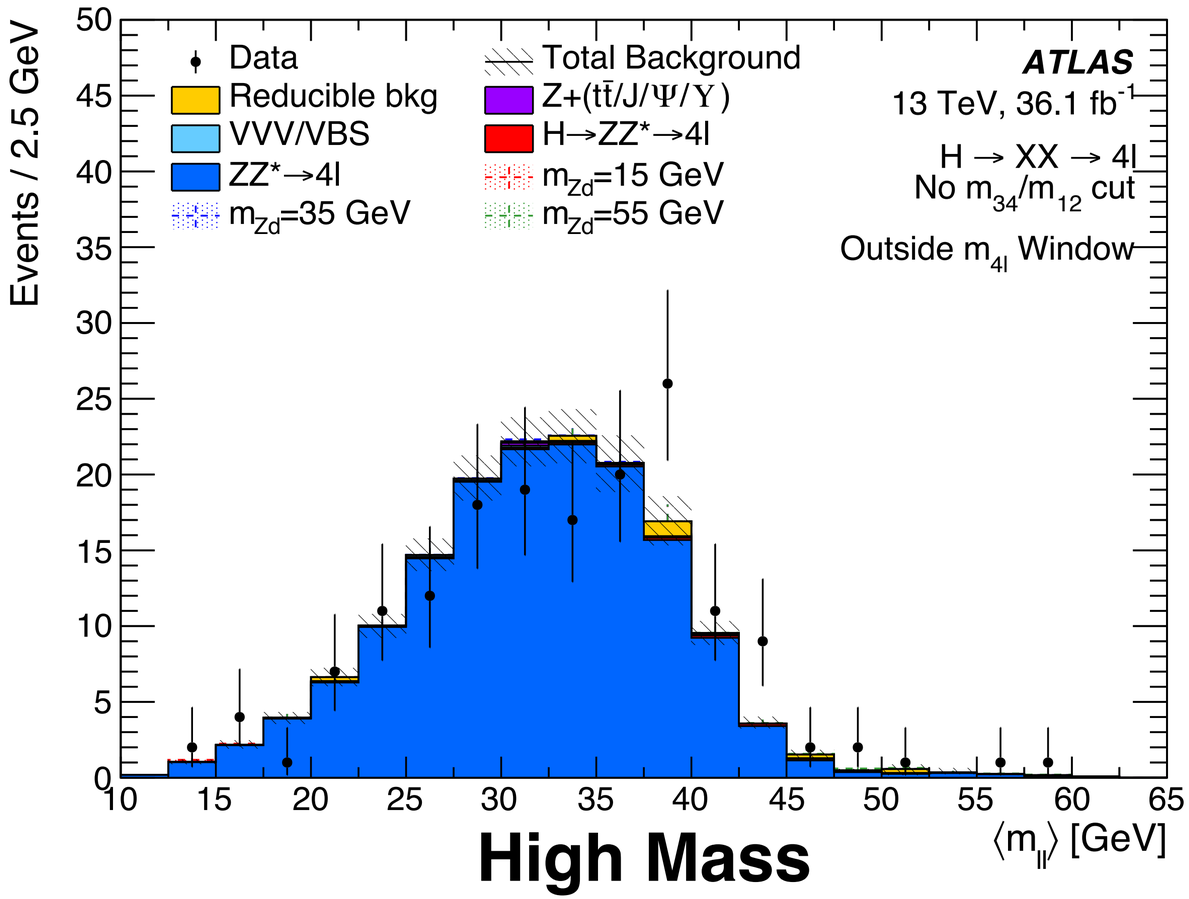
*m12 is defined to be the pair closer to m_Z.

Backgrounds and validation

Arxiv1802.03388

- Backgrounds are SM Higgs to ZZ* to 4l, or non-resonant ZZ* to 4l
- Validate with reversed m_{4l} requirements

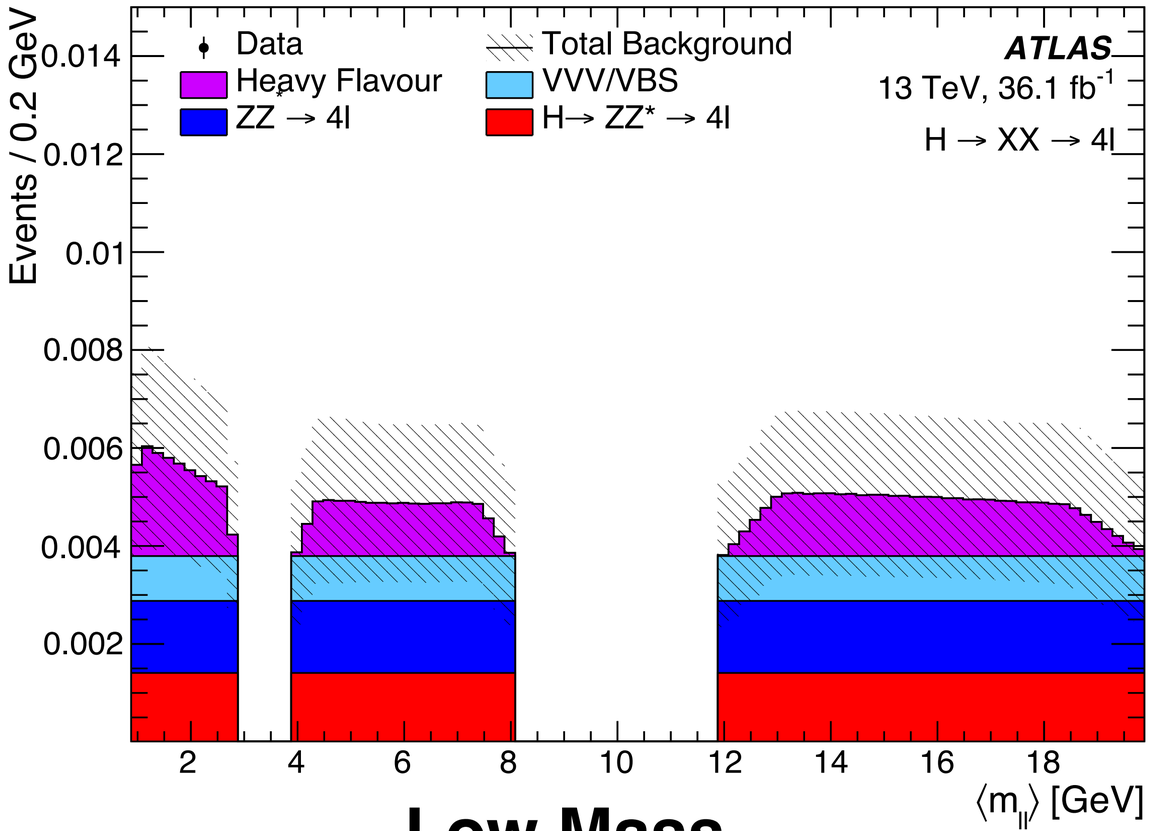




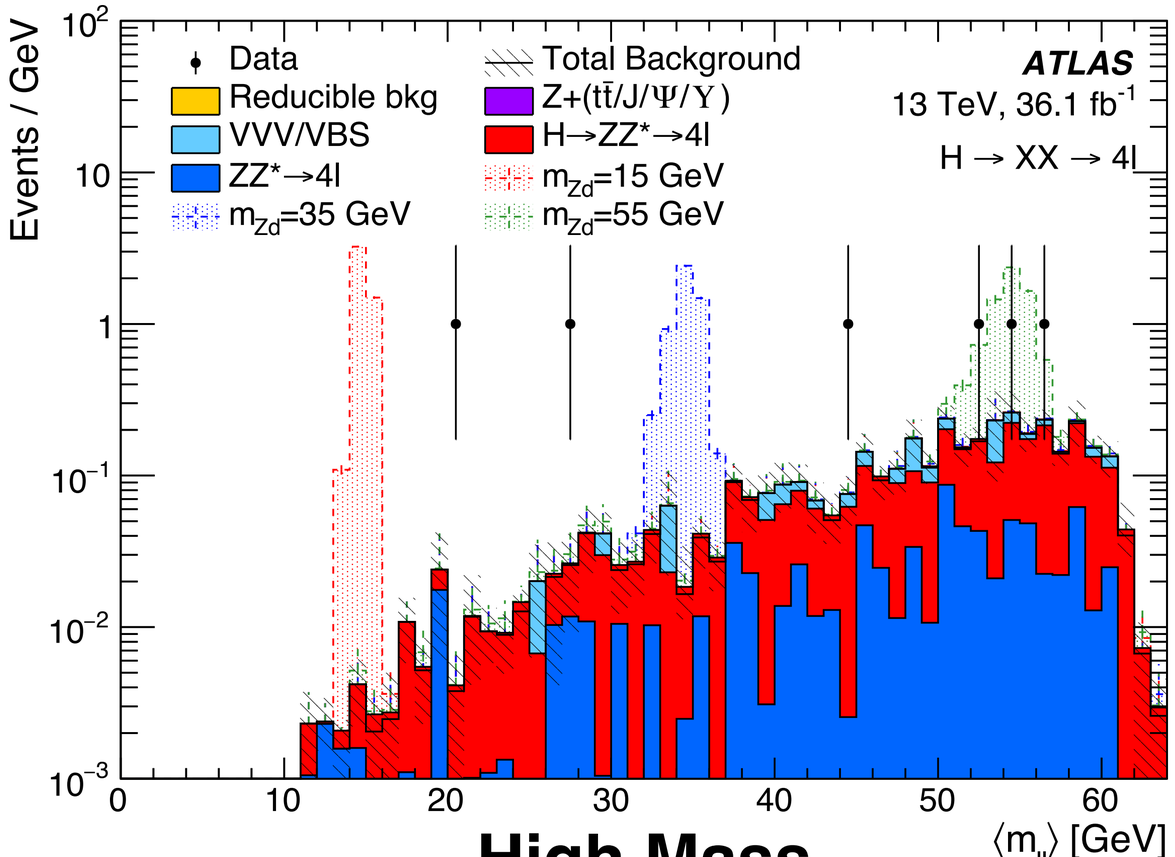
Signal region: $\langle m_{ll} \rangle = (m_{12} + m_{34})/2$

Arxiv1802.03388

Obs	**0**	**6**
Exp	0.35 ± 0.12	4.1 ± 0.35



Low Mass

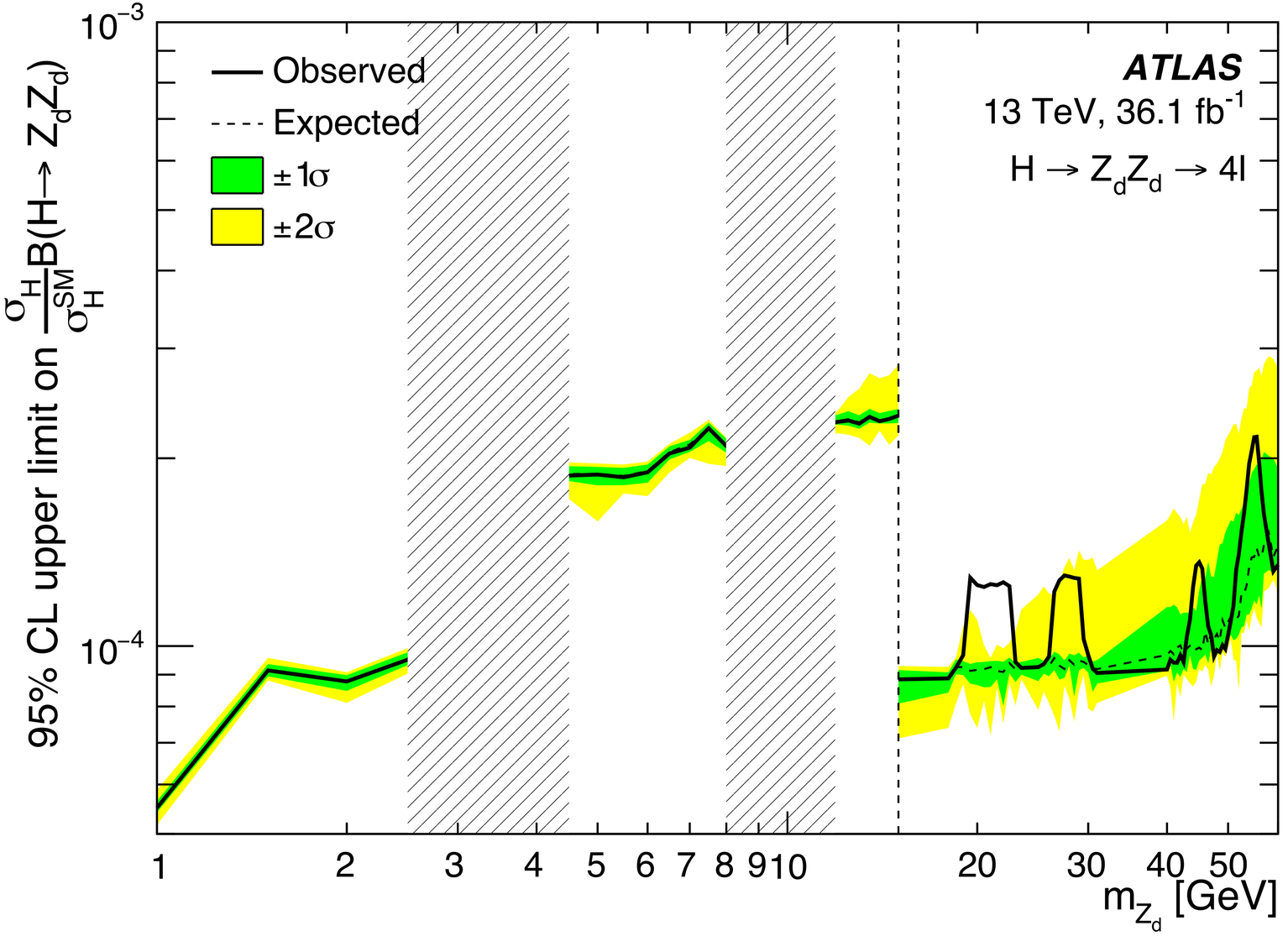


High Mass

Limits for Higgs to Z_dZ_d

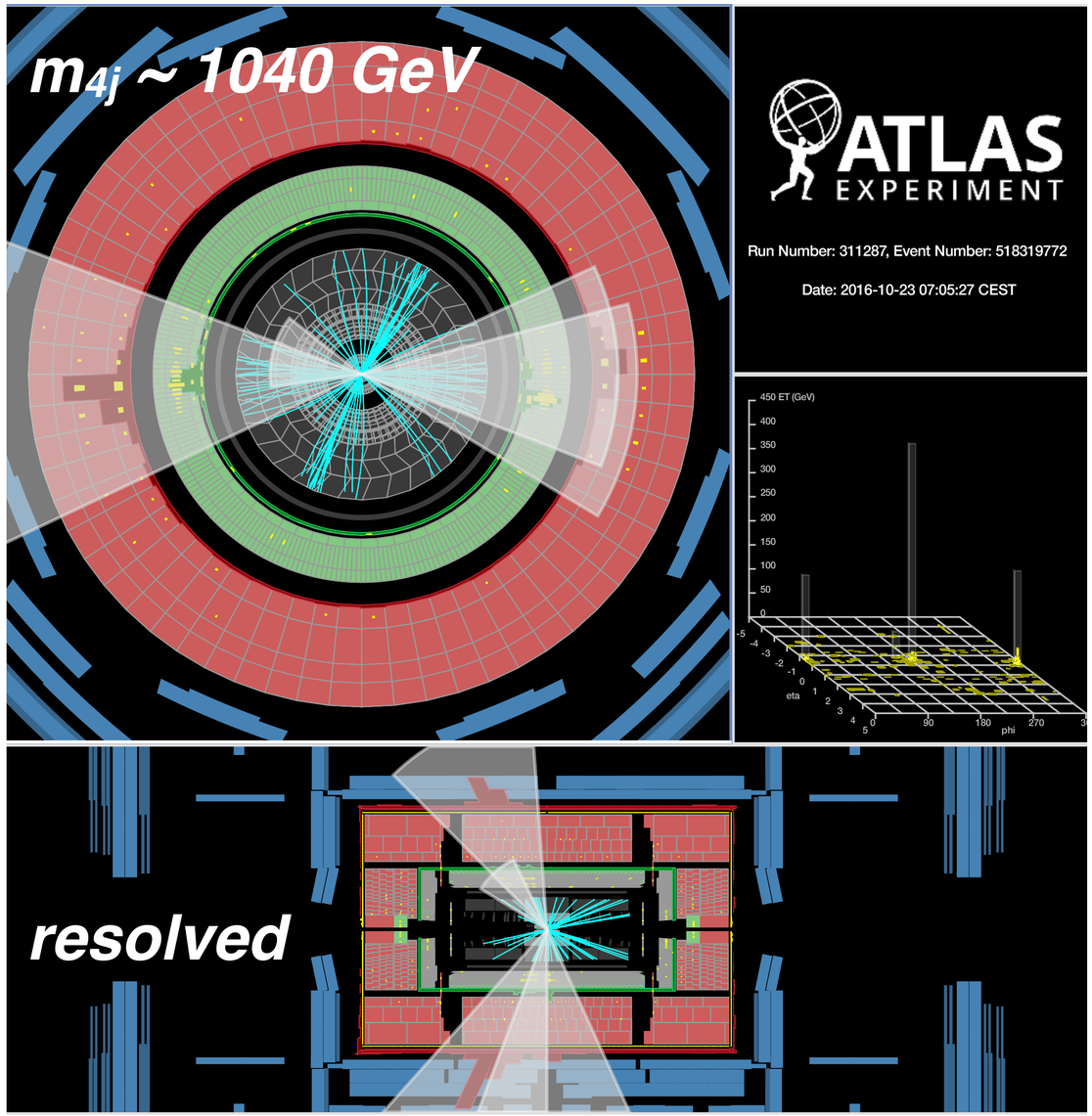
Arxiv1802.03388

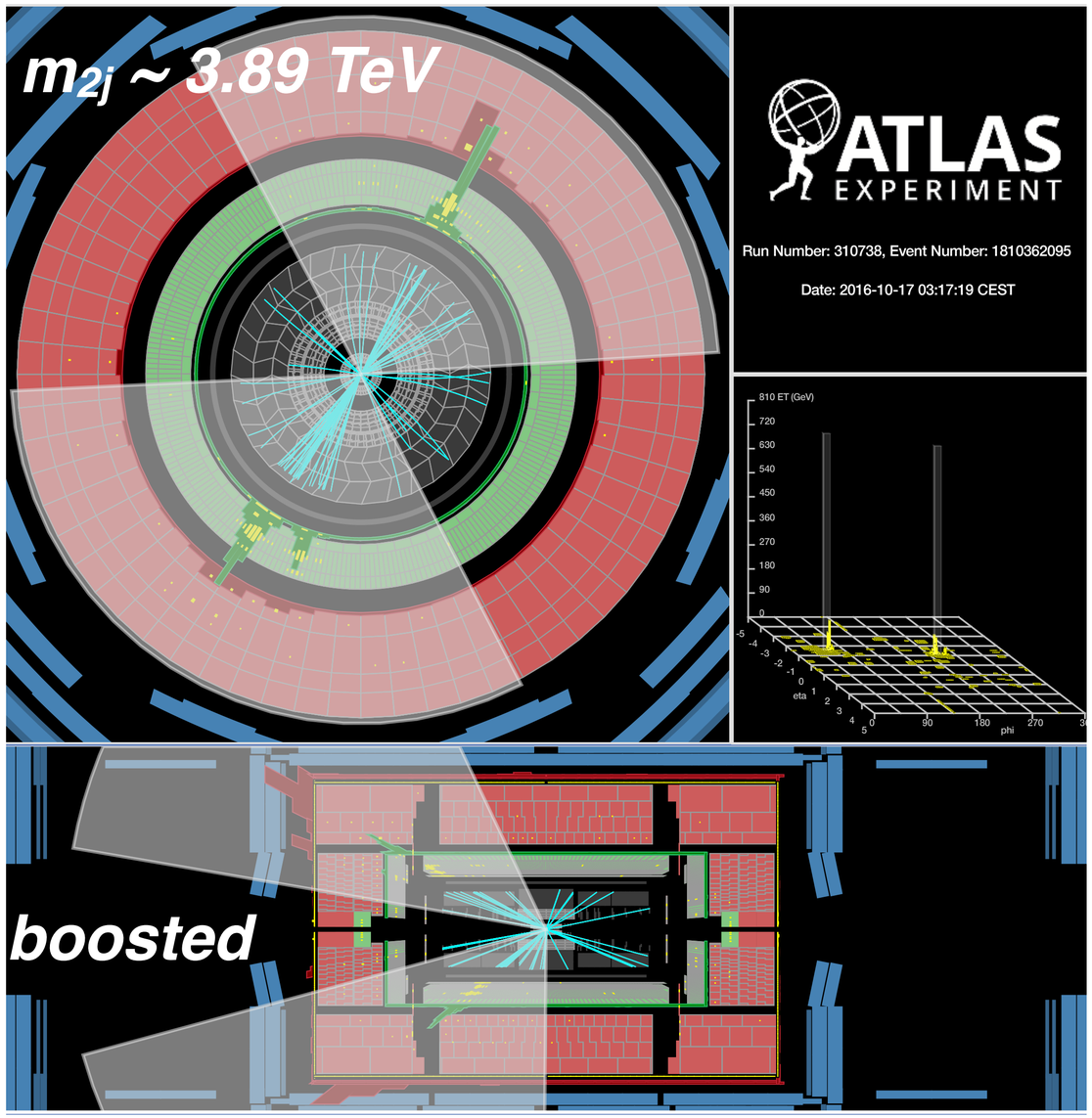
- Discontinuity due to the addition of sensitivity to 4e and 2e2μ final states (lowering the limit).
- The shaded areas are the quarkonia veto regions.
- Need more data!



di-Higgs to 4b event topology

Arxiv1804.06174

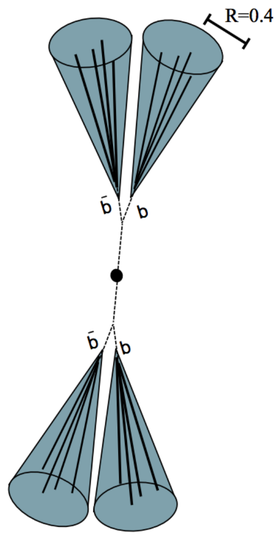




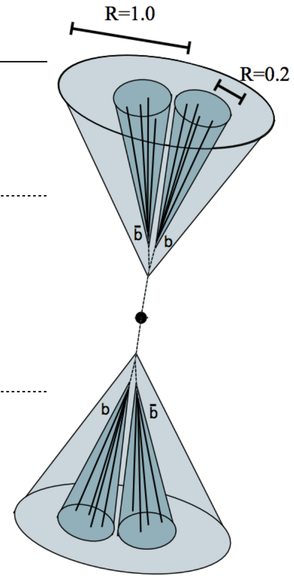
Channels: Resolved + Boosted

Arxiv1804.06174

- Standard resolved 4b jets for the low mass range
- **1.5 TeV** resonance → ~ 600 GeV Higgs → $\Delta R_{bb} \sim 2m_h/p \sim$ **0.4**

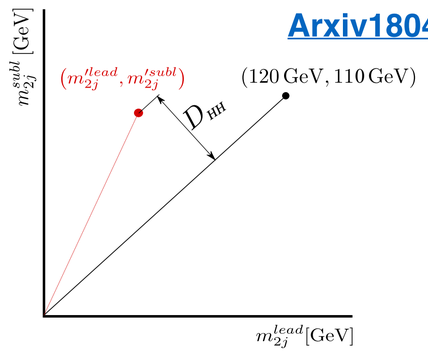


Objects/ Final State	Resolved (260–1400 GeV)	Boosted (1000-3000 GeV)
Trigger	Mixed b Trigger	Large R-jet Trigger
Jets	Four R=**0.4** Jets	Two R=**1.0** trimmed Jets
pT cuts	Jet pT > **40** GeV	Leading > **450** GeV Subleading > **250** GeV
B-tagging	70% WP	70% WP on R=**0.2** track-jets



Resolved: Jets Pairing and Cuts

- Select hh pair that has the minimal distance to a diagonal line on the 2D mass plane
- m_{4j} dependent requirements on h **pT, eta, and dR_{jj}**
- **Fine** signal efficiency across **large** mass ranges



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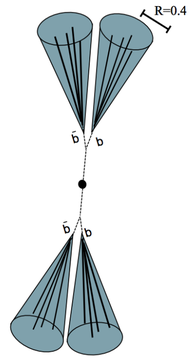
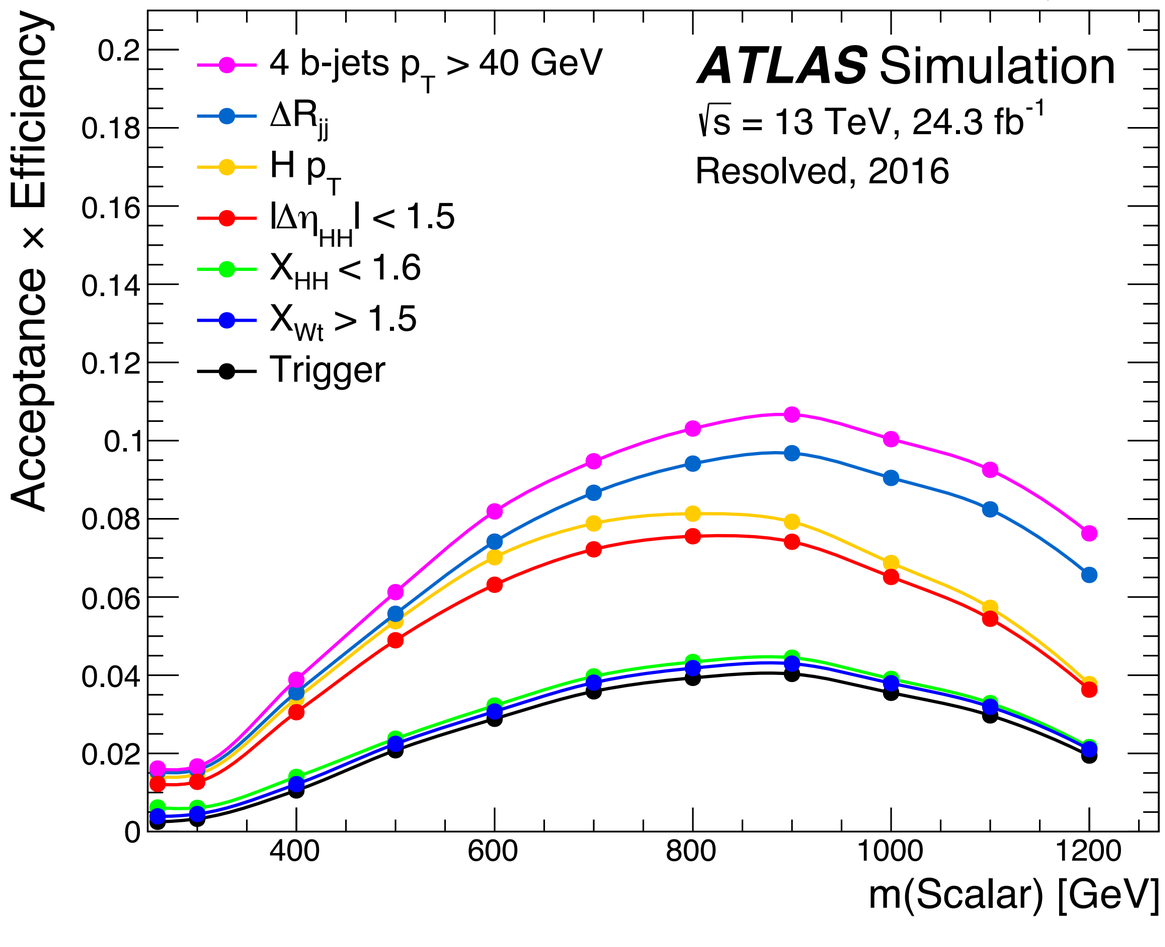
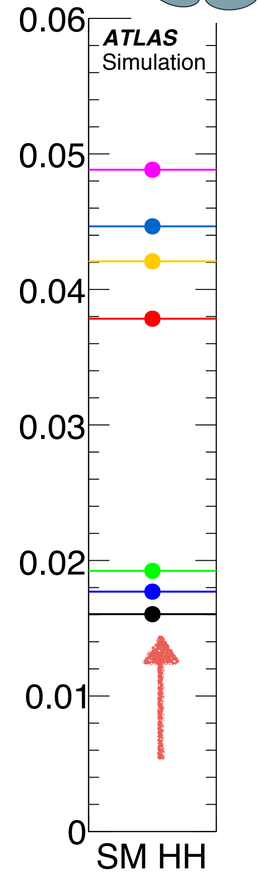


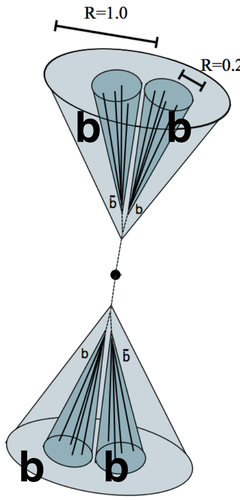




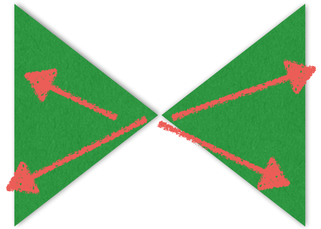
non-res

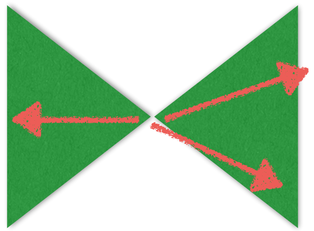
Boosted: Number of b-tagging

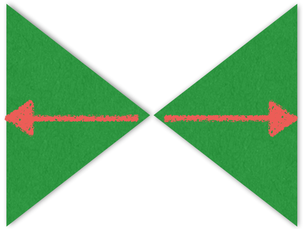
Arxiv1804.06174

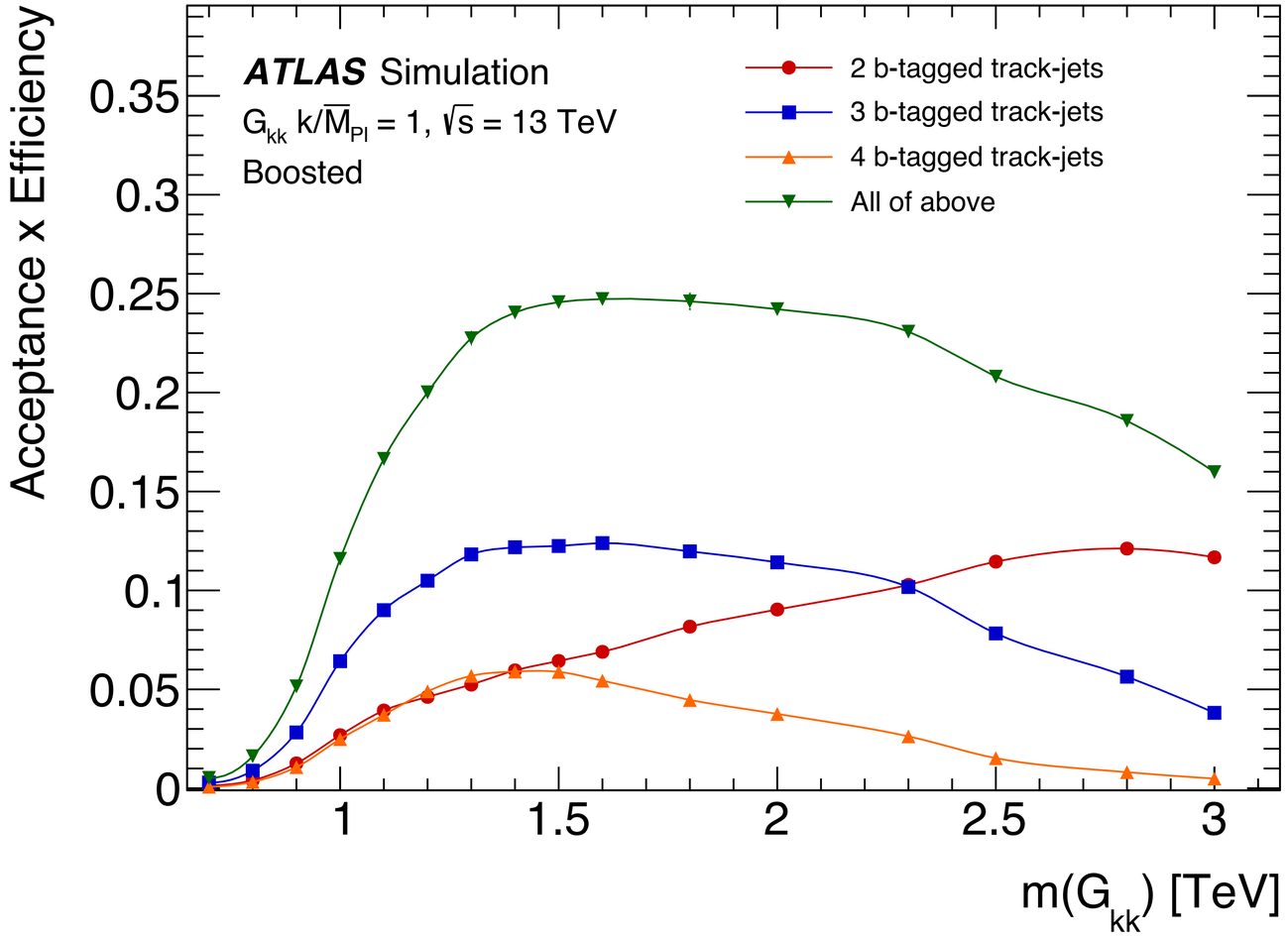


- Three Signal Regions:
  - 4b
  - 3b: (recover efficiency)
  - 2b split (merging of track-jets)







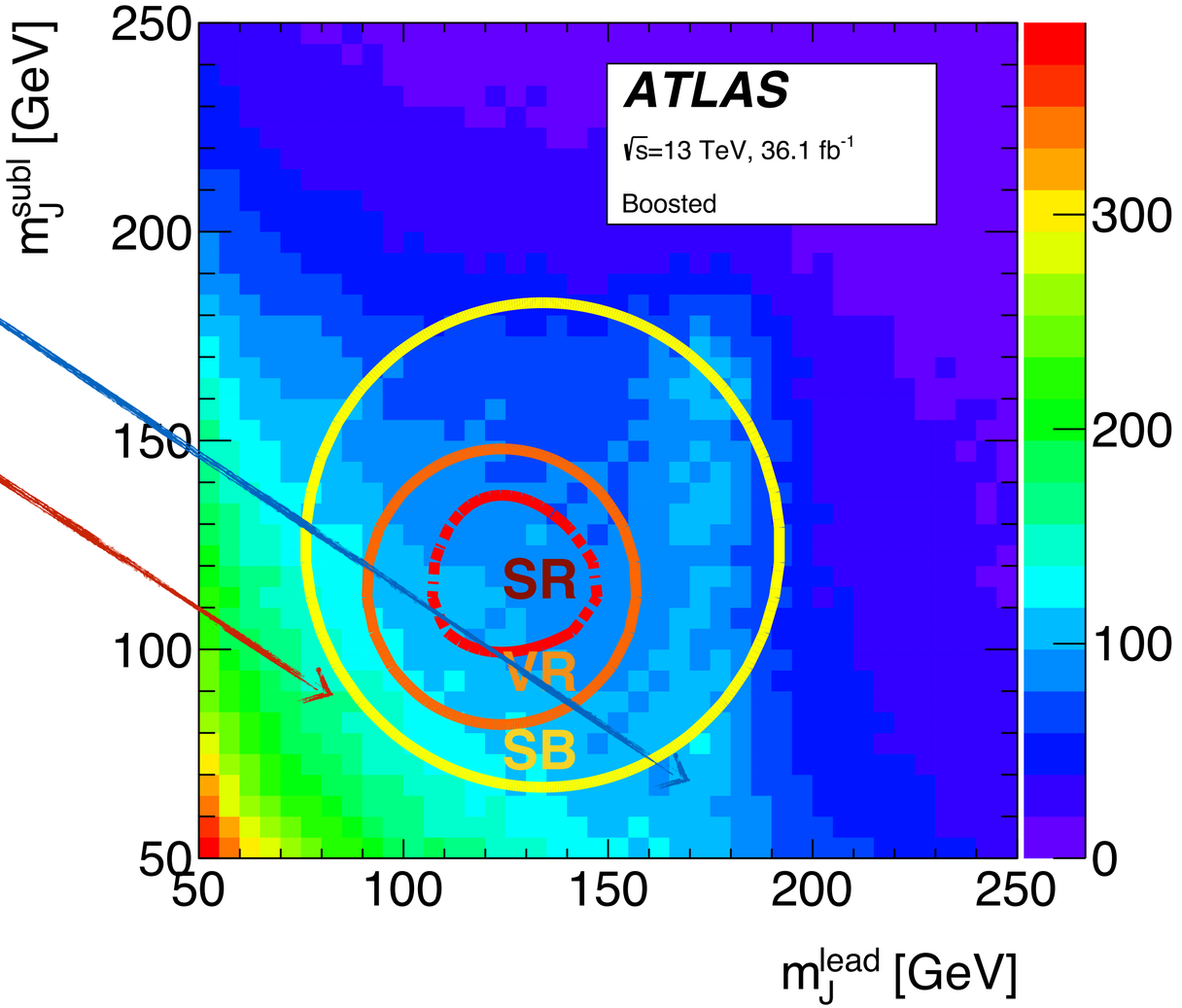


Backgrounds

Arxiv1804.06174

- Background:
  - 10-15% **ttbar**—MC
  - 90-85% **qcd**—data driven
- Data driven because heavy flavor MC is hard to simulate
- Generalized ABCD method: Use lower-b-tag, lower-signal yield region to model higher-b-tag regions

Boosted 2Tag Background Prediction

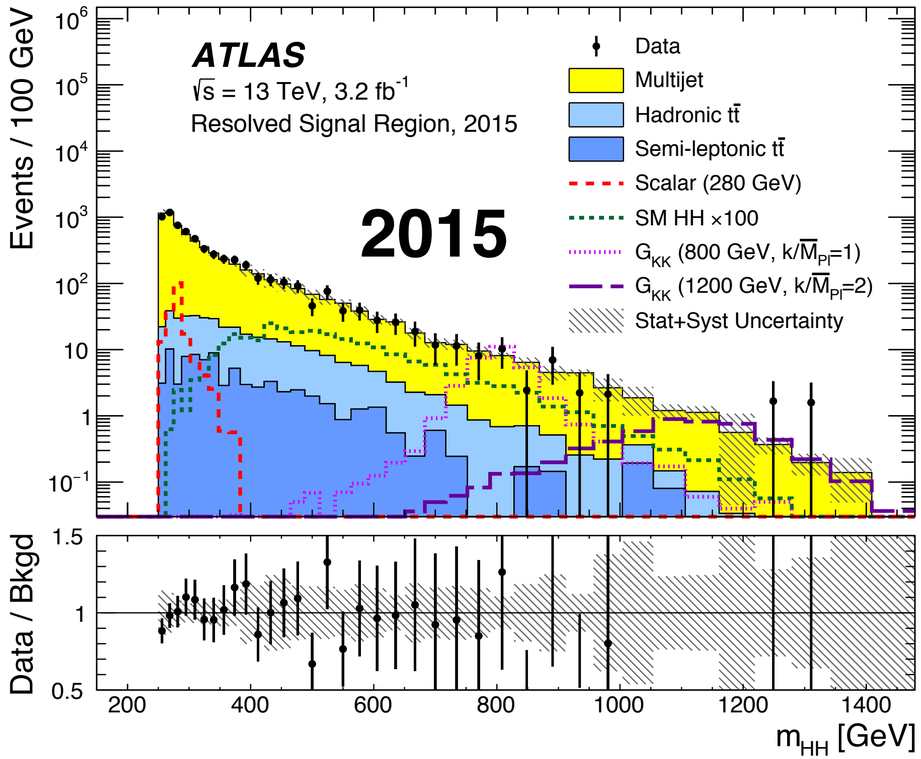


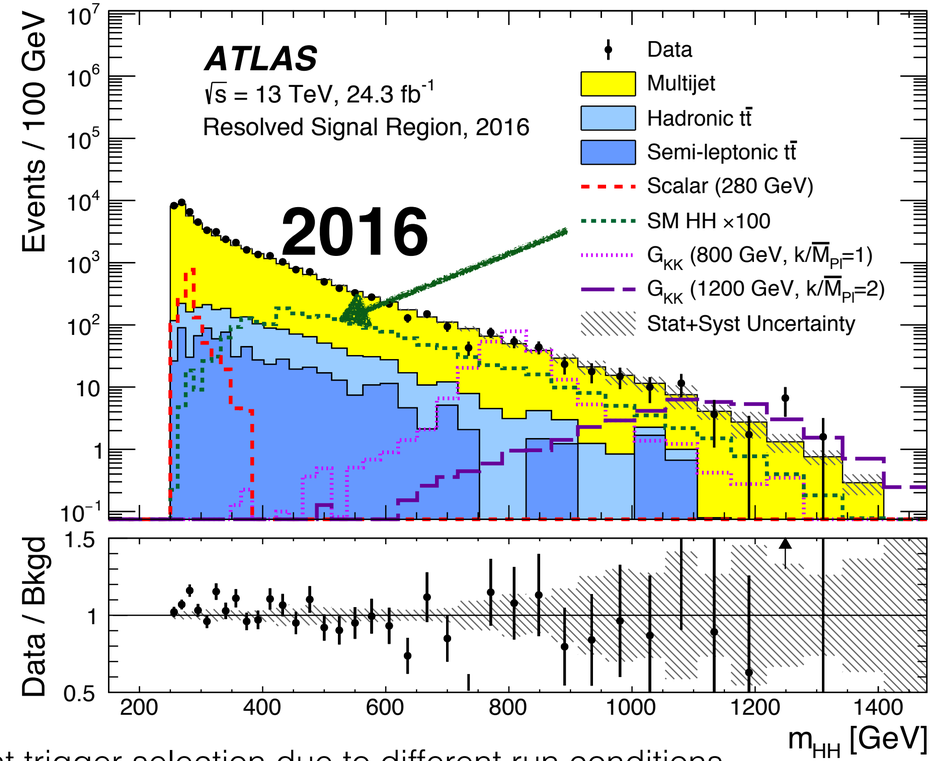
Signal Region: Resolved

Arxiv1804.06174

- Final discriminant: **m4j**, **four jets's invariant mass**; no significant excess observed

Data	2015	2016
Obs	928	7430
Exp	930 ± 70	7130 ± 130





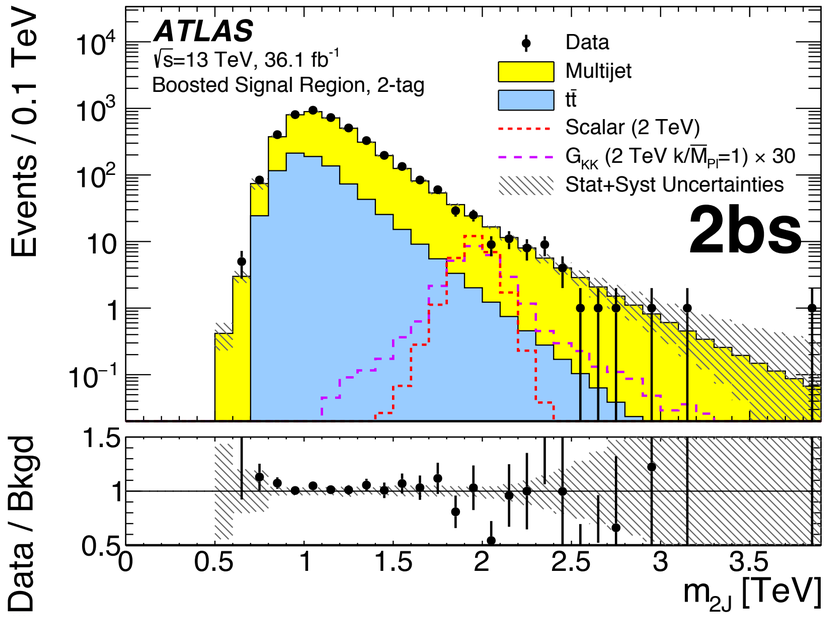
*2015 and 2016 have different trigger selection due to different run conditions

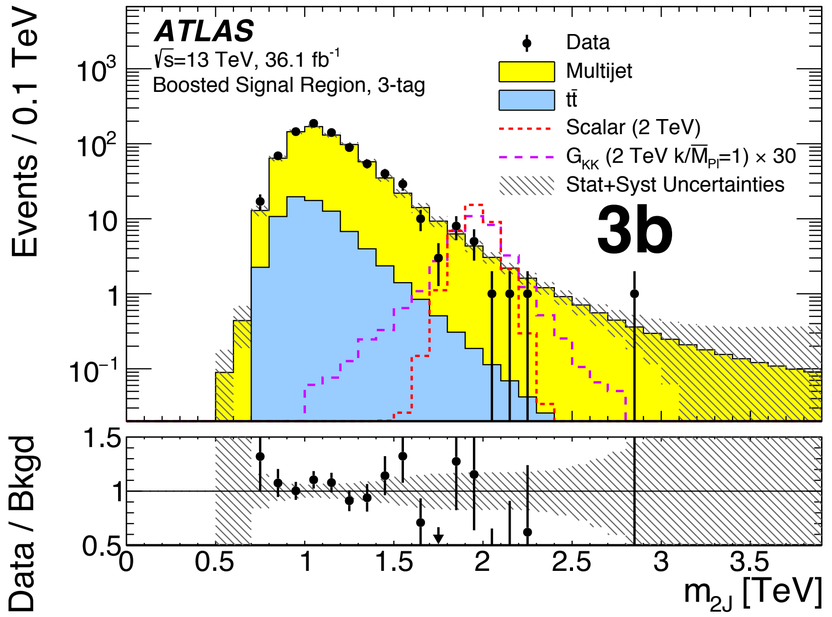
Signal Region: Boosted

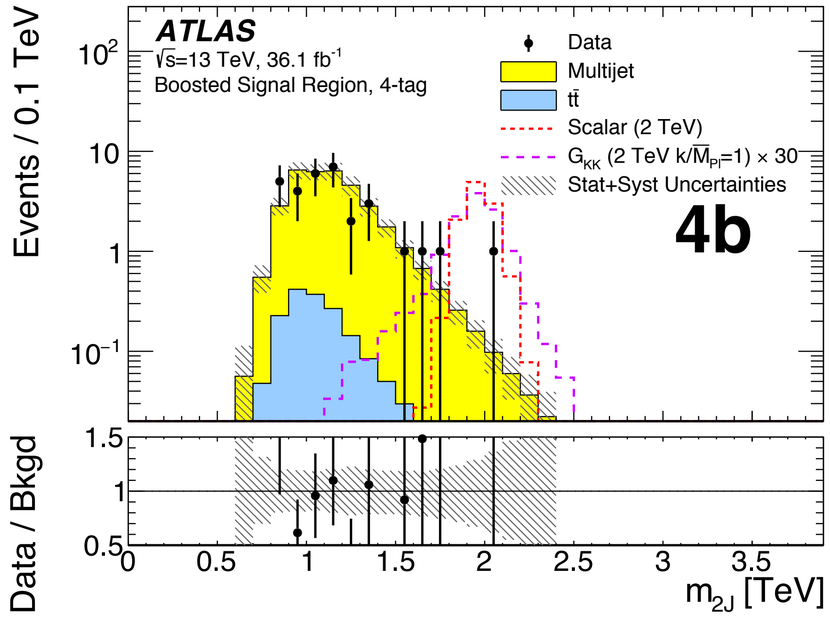
Arxiv1804.06174

- Final discriminant: **m2j**, **dijet invariant mass**; no significant excess observed

Channel	2bs	3b	4b
Obs	4376	801	31
Exp	4250 ± 130	782 ± 51	35 ± 6





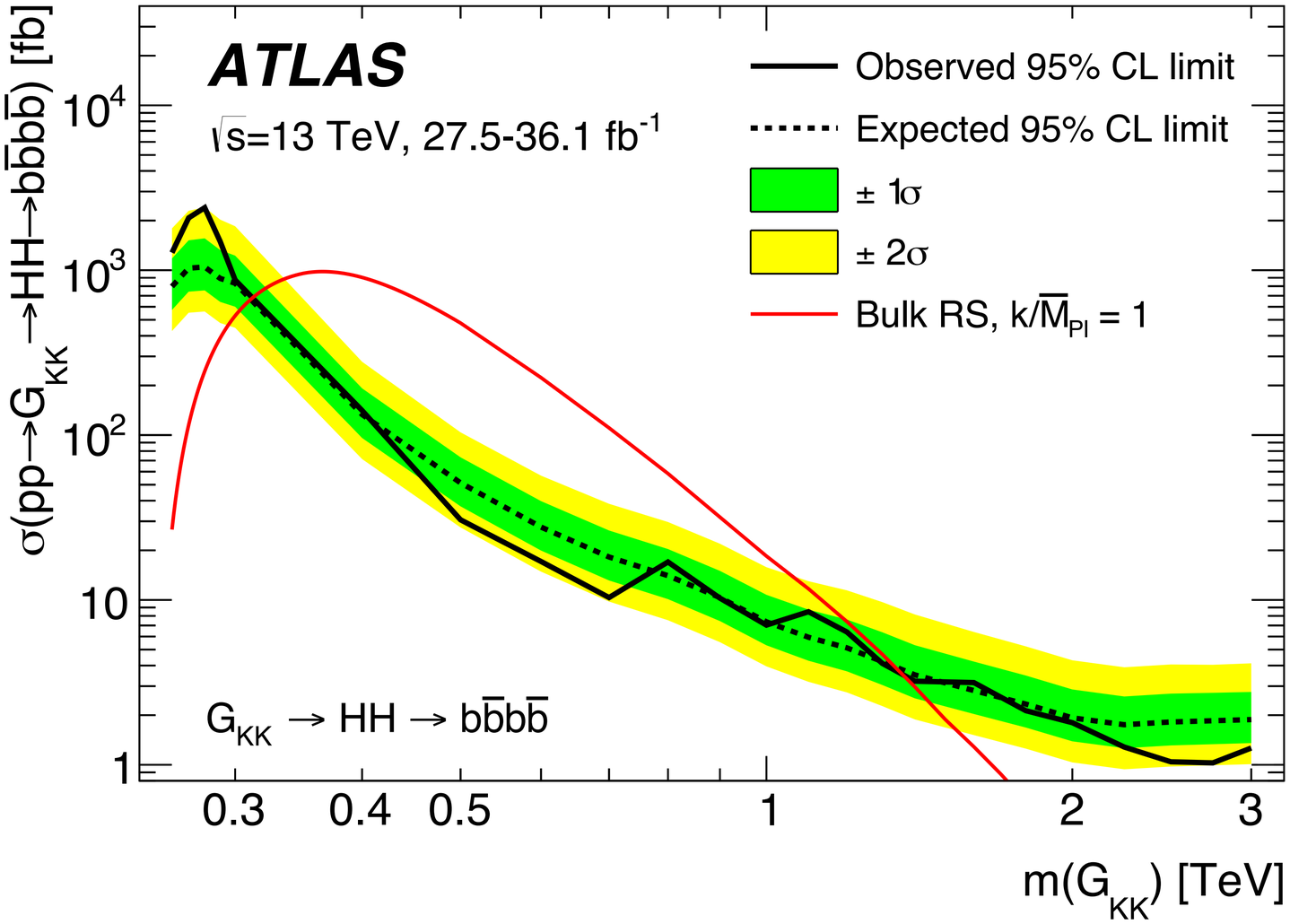


Combined Limits

Arxiv1804.06174

- No significant excess
- Non-Resonant **hh → bbbb** cross section limit:
  - **147 fb**
  - **$\mu = \sigma/\sigma_{SM} \sim 13$**

    (20.7 expected)



Conclusion

- Two very different searches in exotic Higgs sector
  - Search for **h→ Z_dZ_d → llll** for low and high mass Z_d
  - Search for **hh → bbbb** for non-resonant and resonant
- So far **no significant excess observed**, 13 TeV non-resonance di-Higgs limit at **13** times the SM prediction
- **Check out and stay tuned for more results!**
  - Rare decays: h→ aa → ɣɣgg and h→ρɣ/Φɣ
  - di-Higgs: other channels with 36 ifb will come soon!

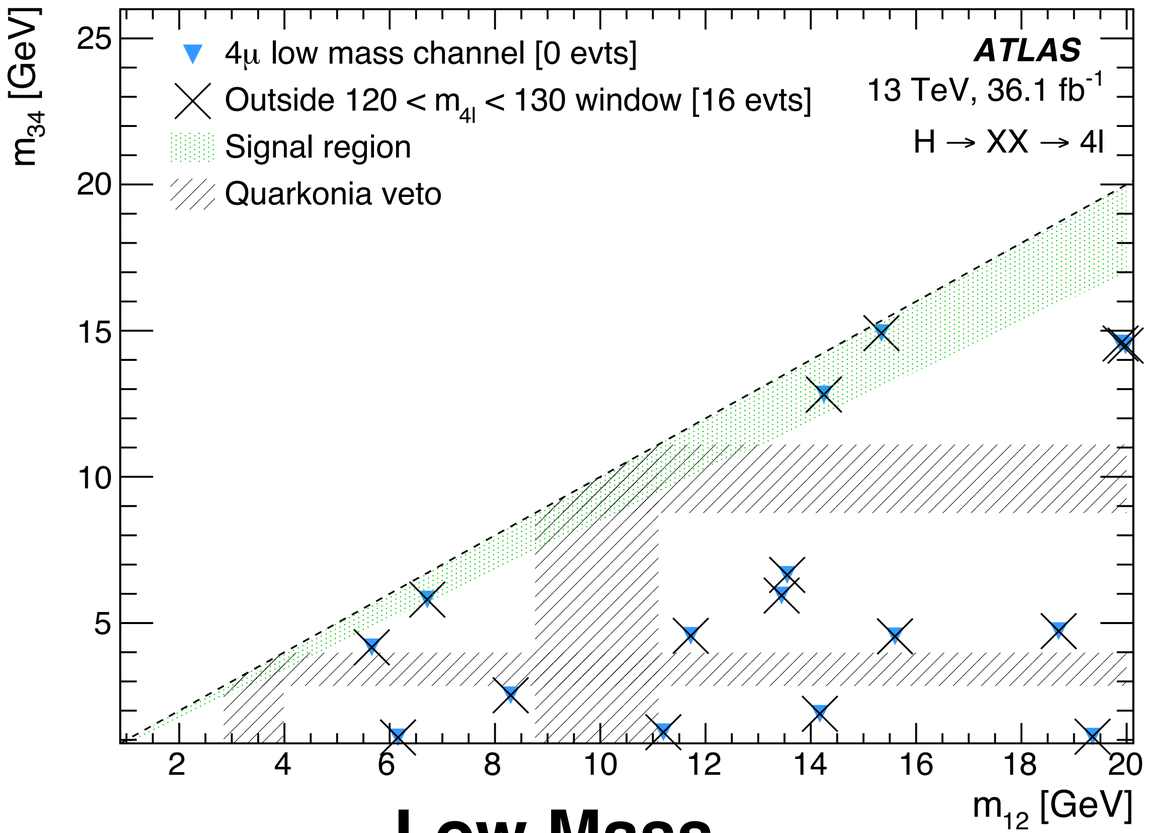
Arxiv1803.11145

Arxiv1712.02758

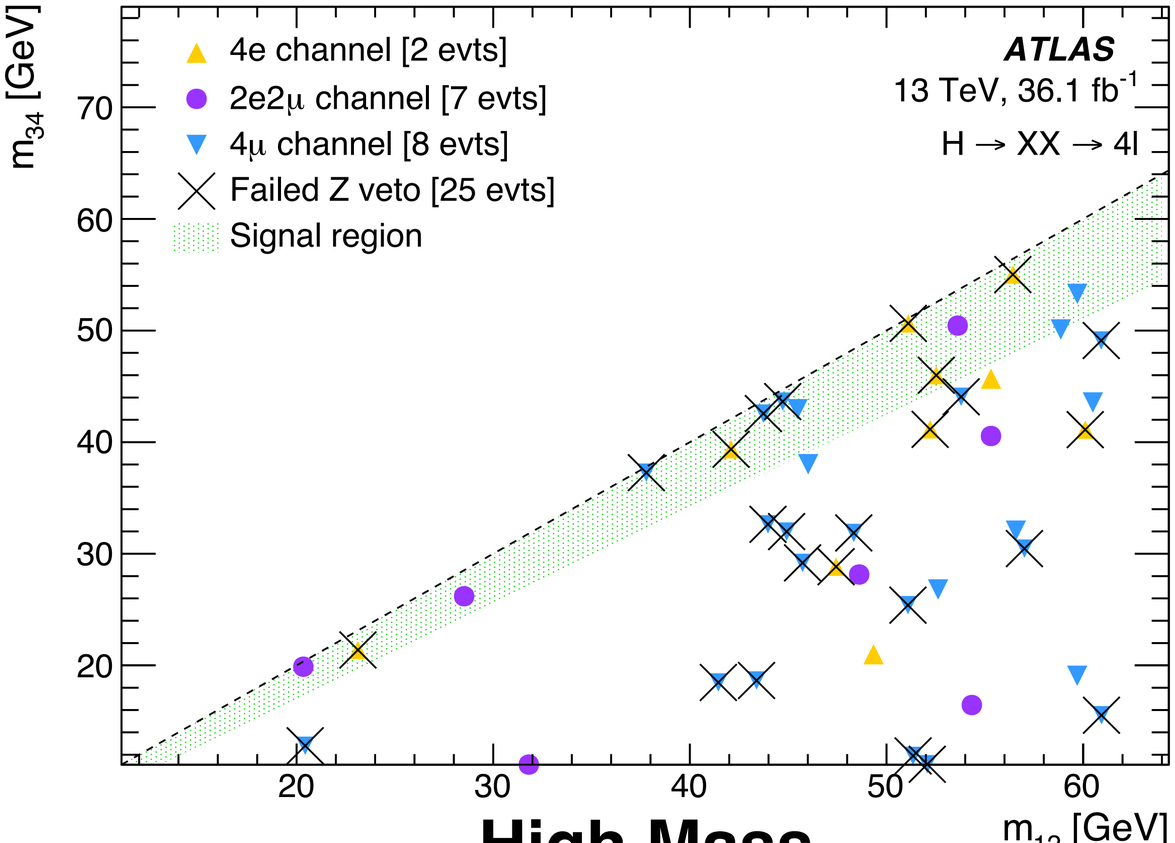
Back up Slides

Signal region: $\langle m_{ll} \rangle = (m_{12} + m_{34})/2$

Obs	**0**	**6**
Exp	0.35 ± 0.12	4.1 ± 0.35



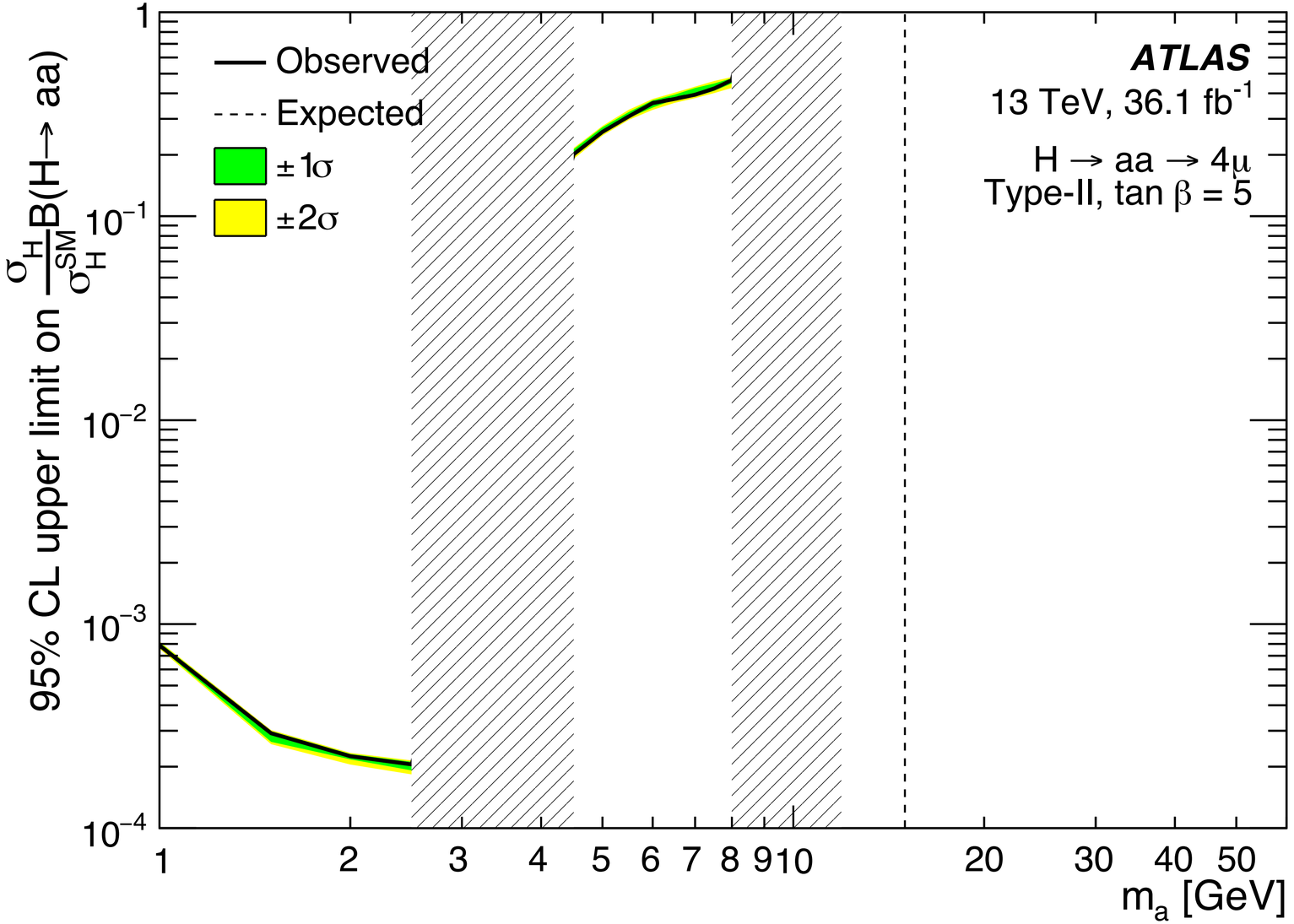
Low Mass



High Mass

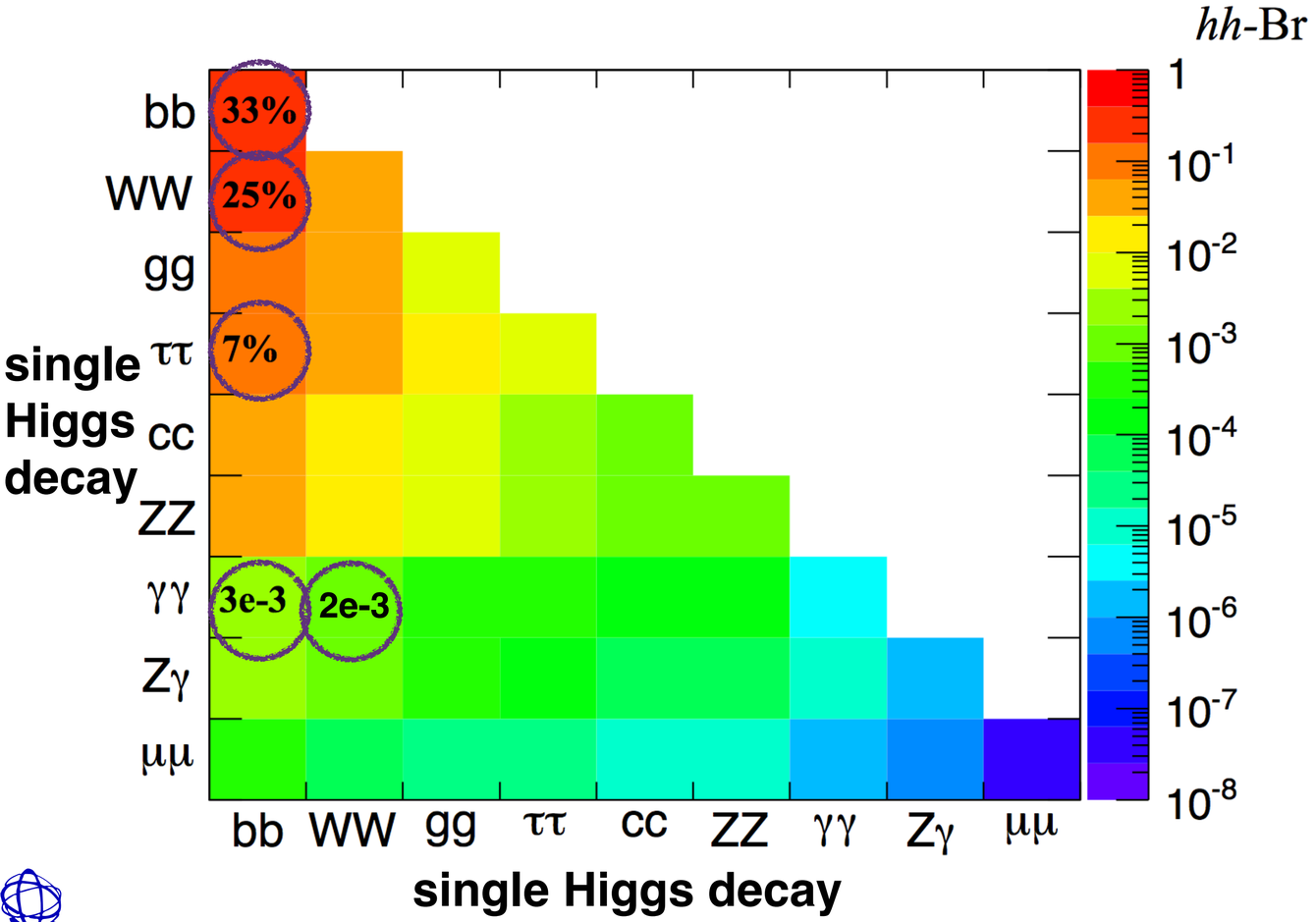
Limits for Higgs to aa

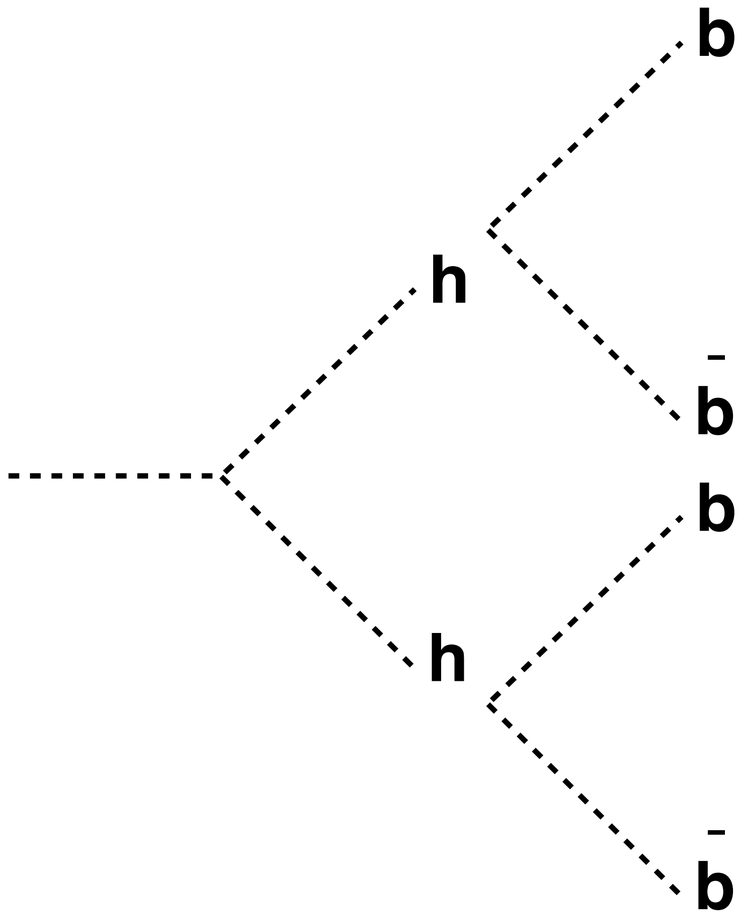
- The shaded areas are the quarkonia veto regions.
- Need more data!



Di-Higgs decay

larger branching ratio—higher yield





Di-Higgs decay

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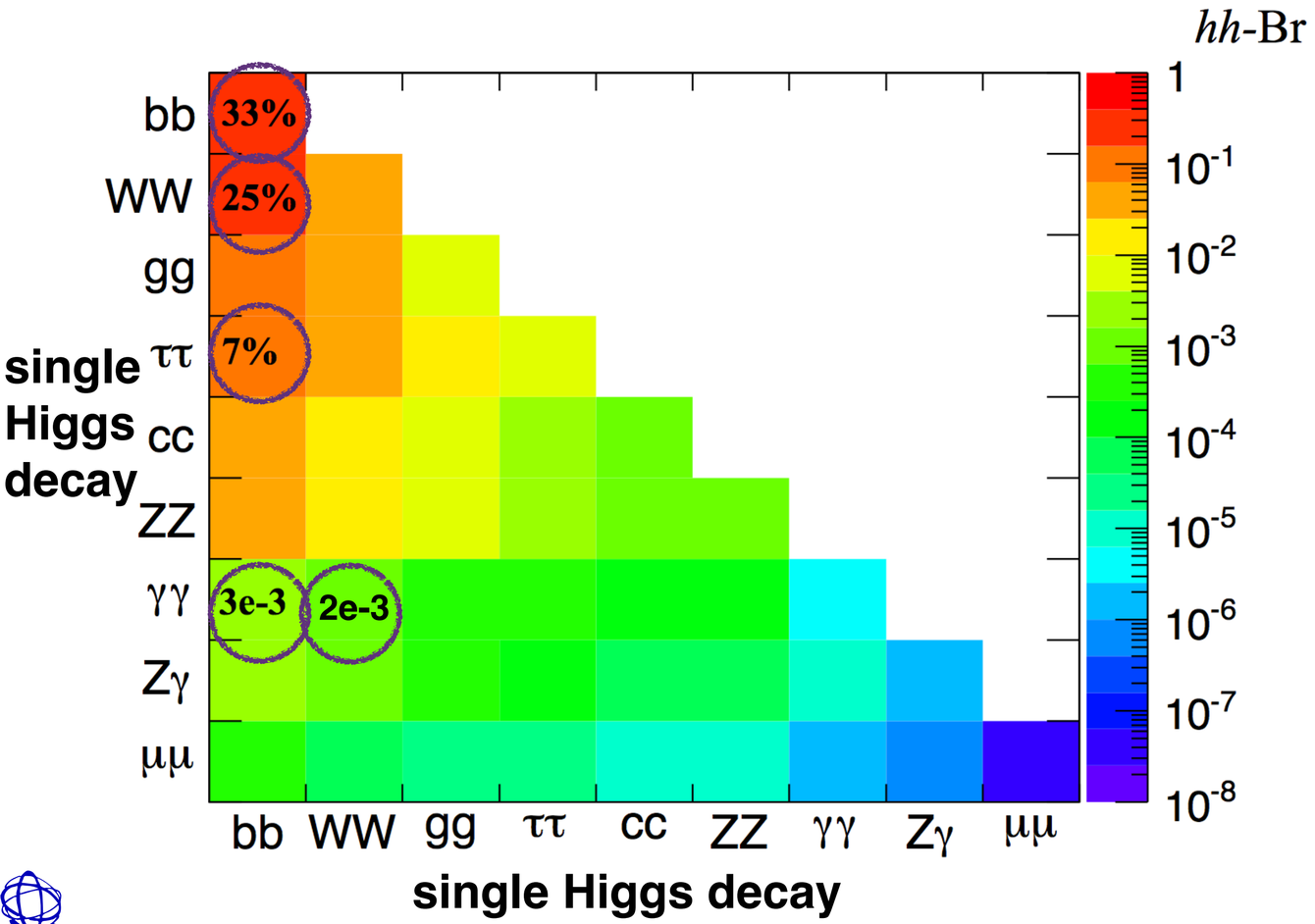
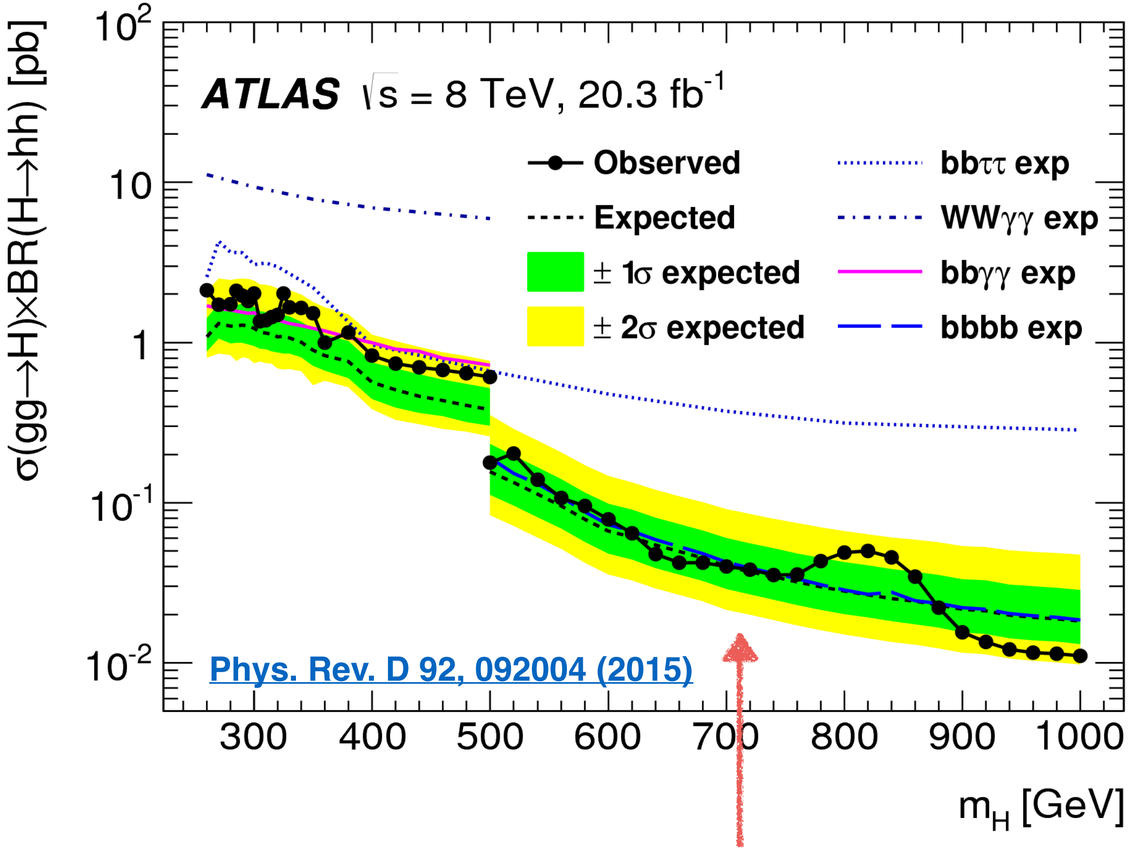




4b better limit for higher mass

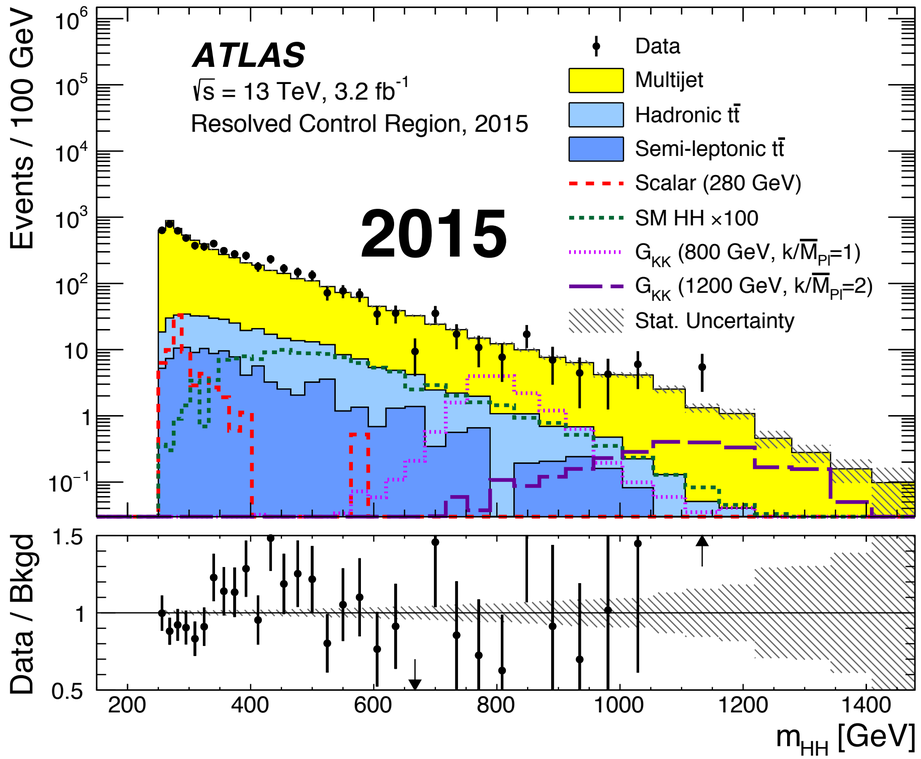
Summary of HH ATLAS Results

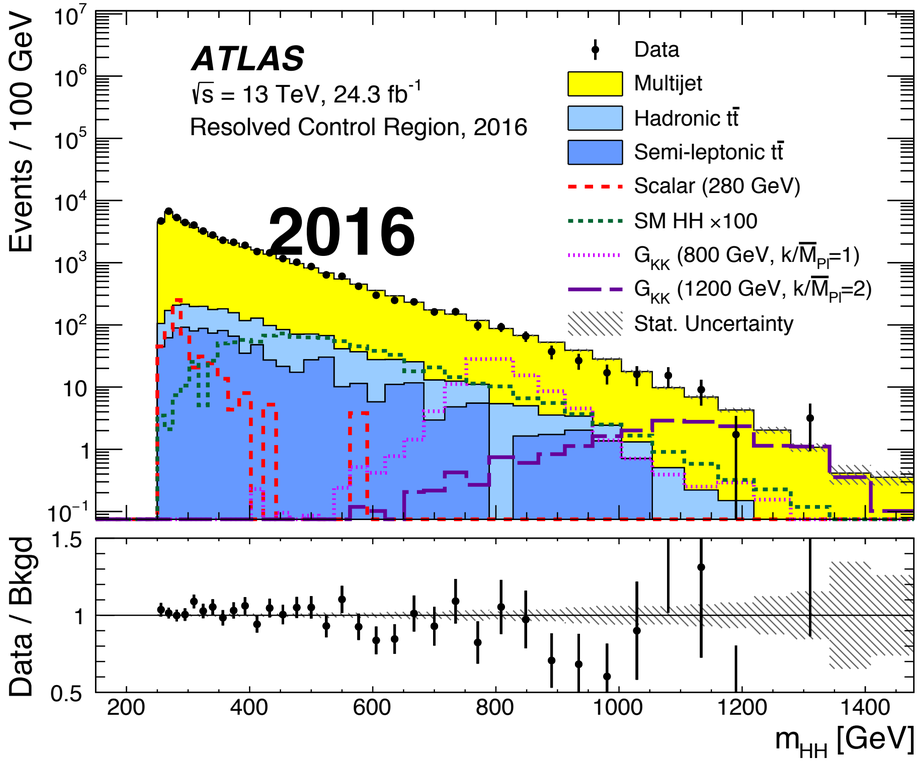
ATLAS Search Results	8TeV, fb^{-1}	13TeV, fb^{-1}	HL-LHC
bbbb	20	3 / 13 / 36	prospect
bb$\tau\tau$	20		prospect
bbγγ	20	3	prospect
WW*γγ	20	13	
Combination	20		

Control Region: Resolved

- **Good** agreement in shape and normalization

Data	2015	2016
Obs	969	7656
Exp	956 ± 50	7550 ± 130

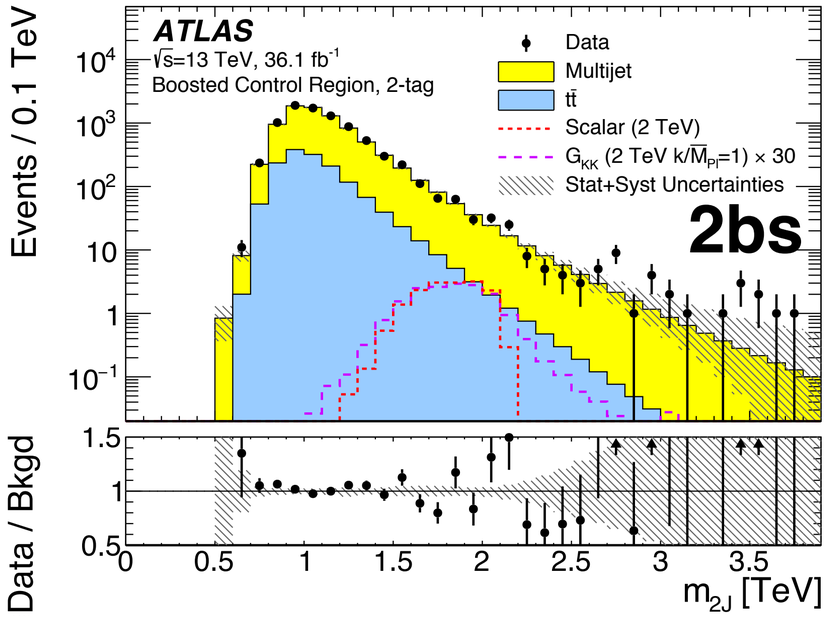


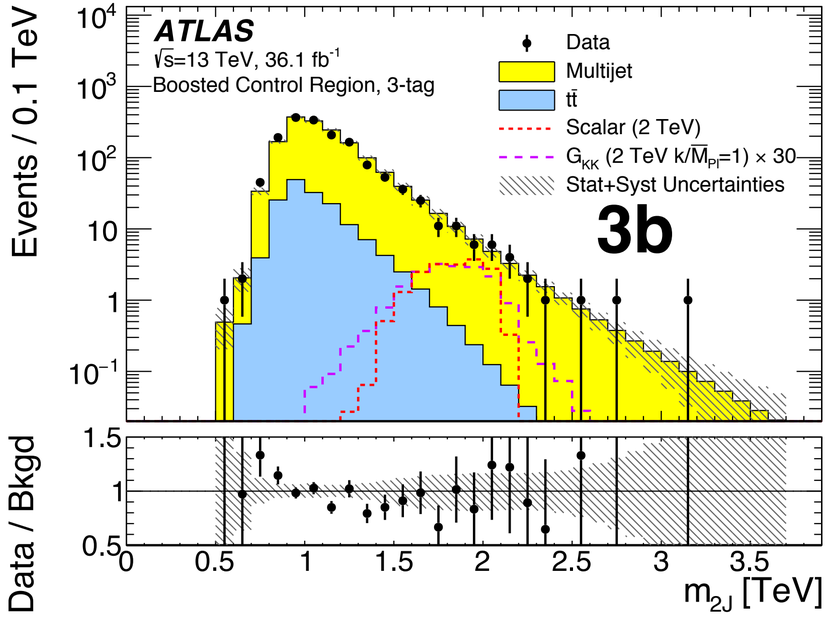


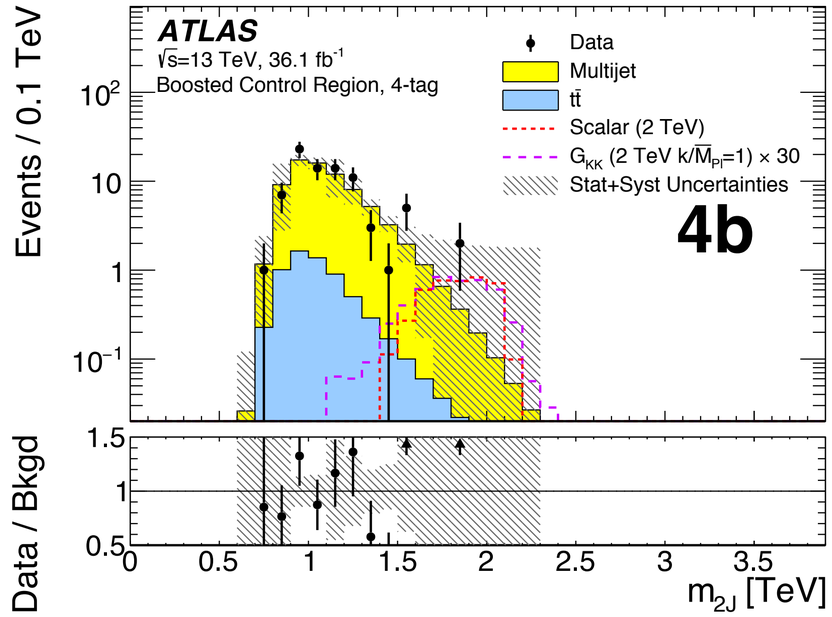
Control Region: Boosted

- **Good** agreement in shape and normalization

Channel	2bs	3b	4b
Obs	**8486**	**1553**	**81**
Exp	8333 ± 67	1587 ± 36	77 ± 8

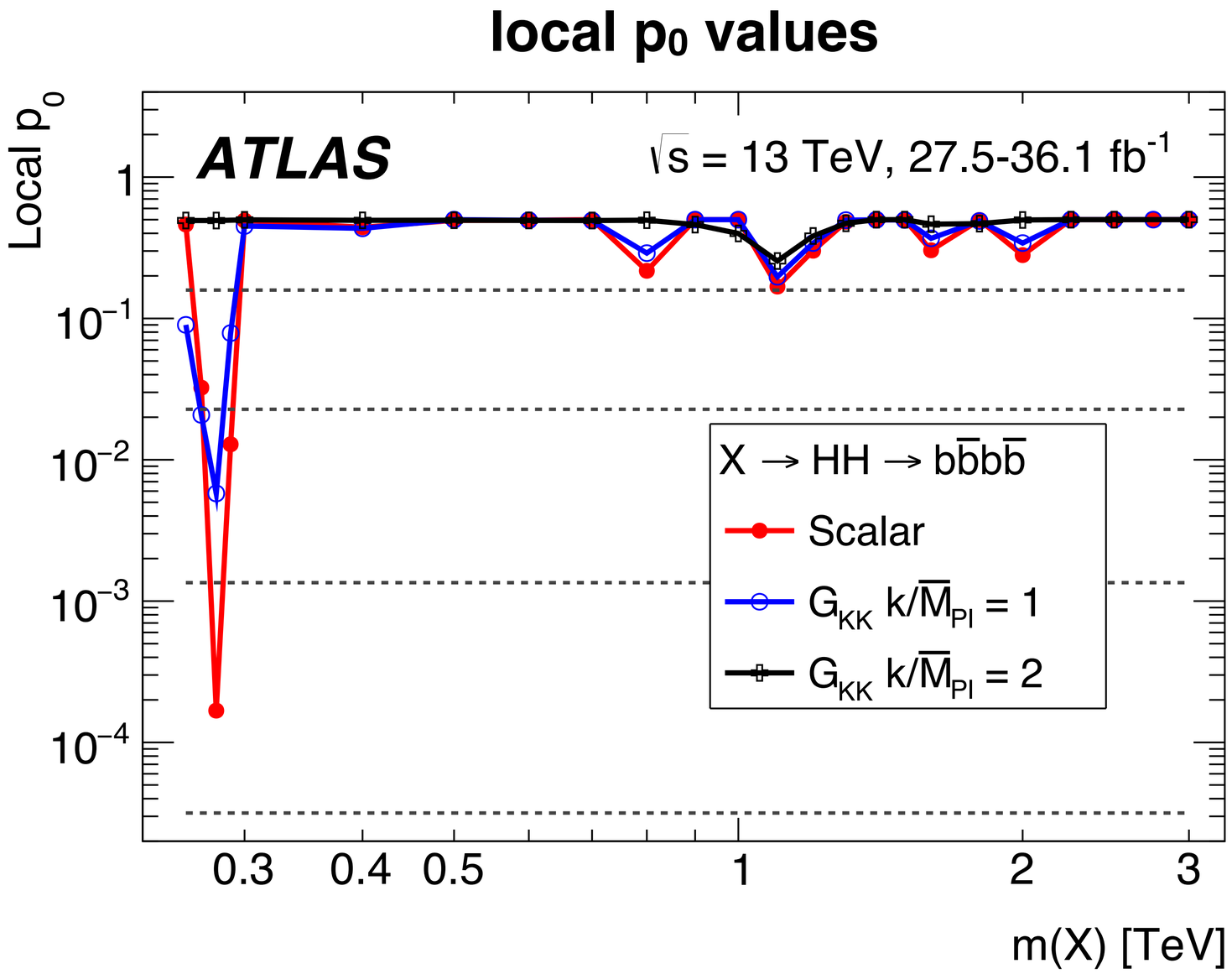






di-Higgs p-values

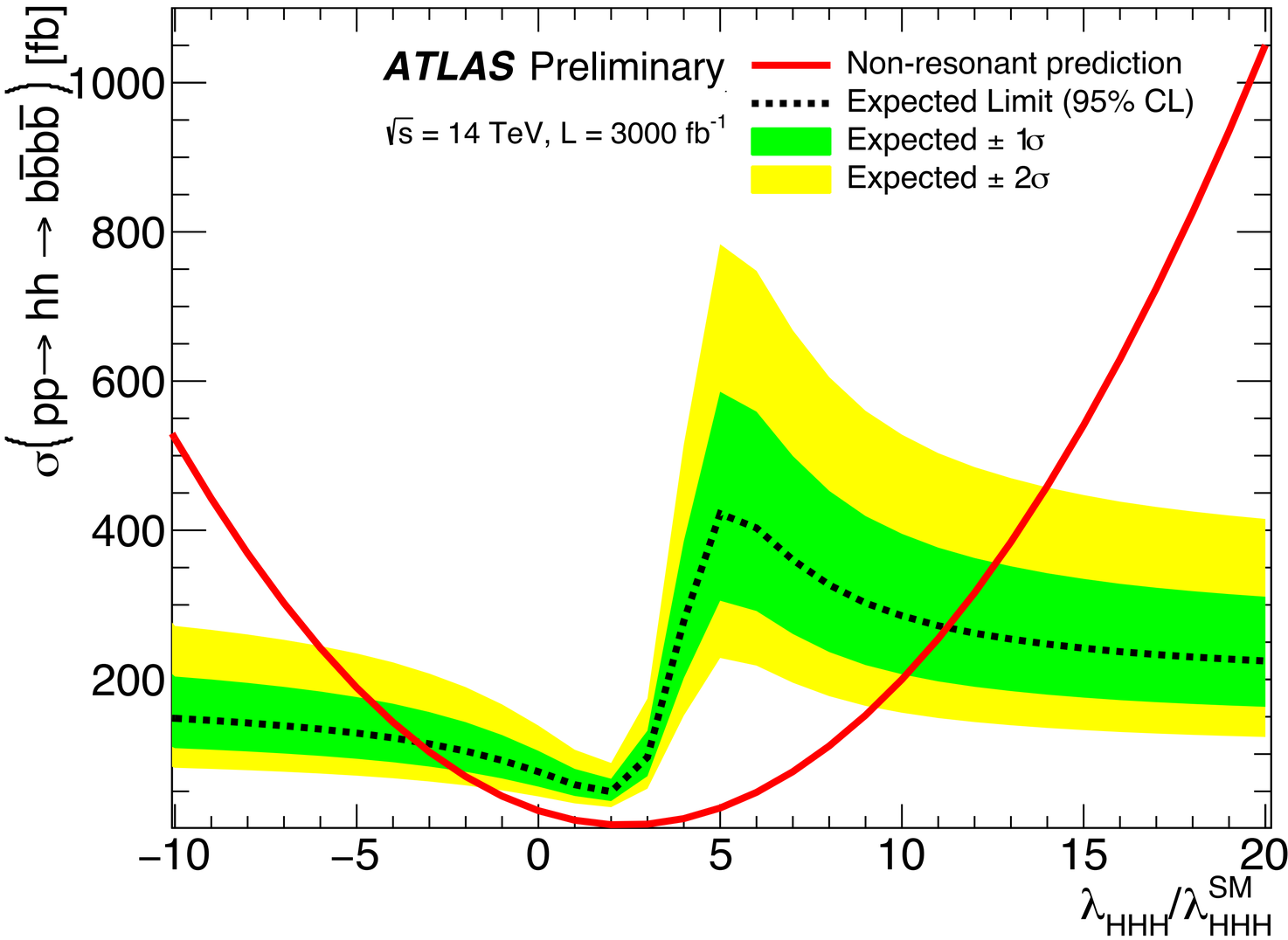
- The smallest p_0 is found for the narrow-width scalar at 280 GeV and corresponds to 3.6 (2.3 global) standard deviations from the background-only hypothesis.
- The p_0 value for the G_{KK} model with $k/\bar{M}_{Pl}=1$ at the same mass is 2.5 standard deviations, the G_{KK} model with $k/\bar{M}_{Pl}=2$ is too wide to fit the excess.



Future Perspectives

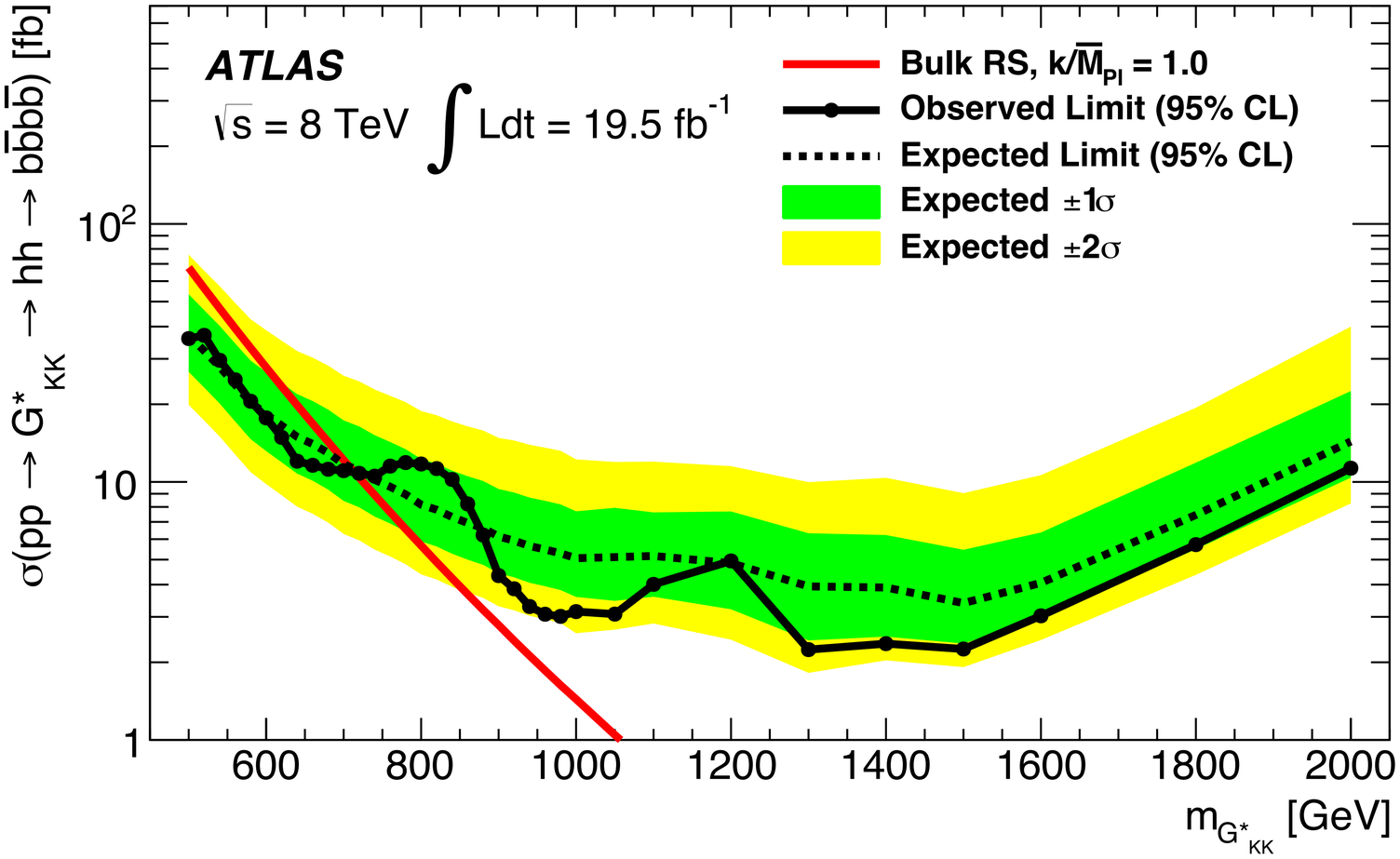
ATLAS-CONF-2016-024

- Extrapolation of current 2016 results
- Limit: $-3.5 < \lambda_{hhh} < 11$



Combined Limit

Eur. Phys. J. C (2015) 75:412



Run I non-res limit comparison

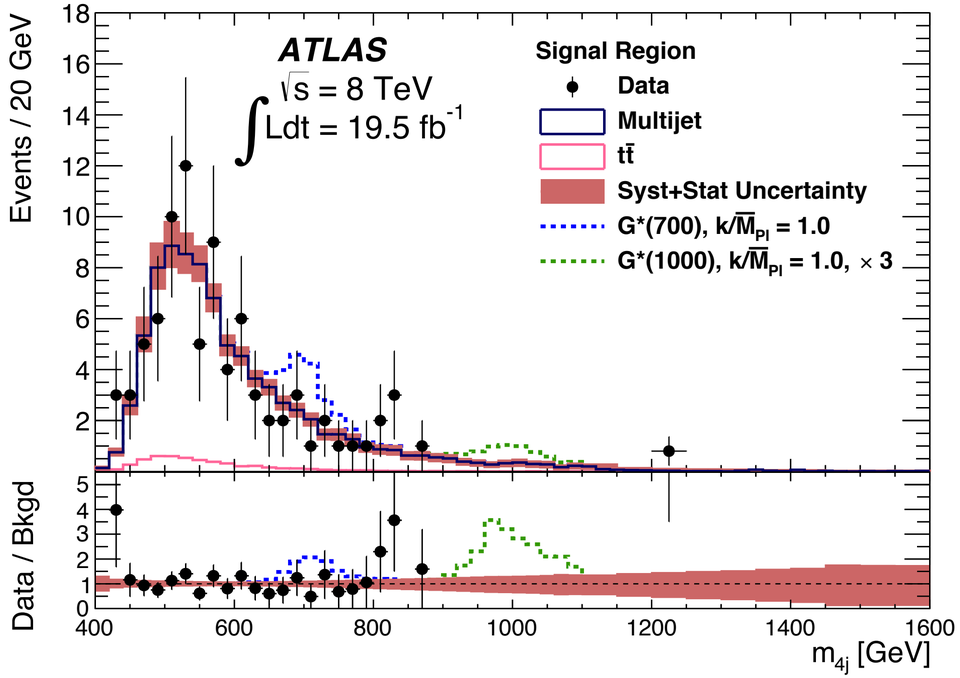
Phys. Rev. D 92, 092004 (2015)

RunI non-res limits rel to SM	Obs(**Exp**)
bb$\tau\tau$	160 (**130**)
WW*γγ	1150 (**680**)
bbγγ	220 (**100**)
bbbb	63 (**63**)
Combination	70 (**48**)

Resolved and Boosted Results

Eur. Phys. J. C (2015) 75:412

Sample		Signal Region Yield
Multijet	**Resolved**	81.4 ± 4.9
$t\bar{t}$		5.2 ± 2.6
Z+jets		0.4 ± 0.2
Total		87.0 ± 5.6
Data		87
SM hh		0.34 ± 0.05
G^*_{KK} $(500\,GeV)$, $k/\bar{M}_{\mathrm{Pl}} = 1$		27 ± 5.9



Sample		Signal Region Yield
Multijet	**Boosted**	23.5 ± 4.1
$t\bar{t}$		2.2 ± 0.9
Z+jets		0.14 ± 0.06
Total		25.7 ± 4.2
Data		34
G^*_{KK} $(1000\,GeV)$, $k/\bar{M}_{\mathrm{Pl}} = 1$		2.1 ± 0.6