Latest Results on Di-Higgs Production at ATLAS

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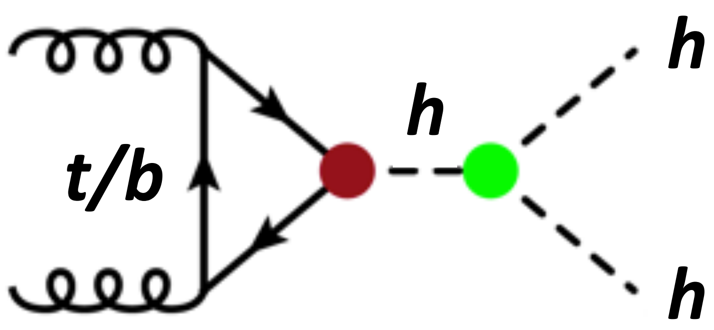
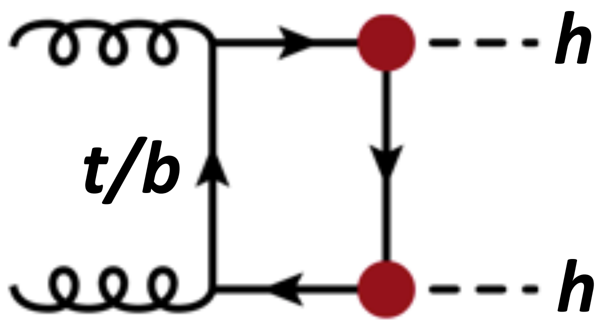
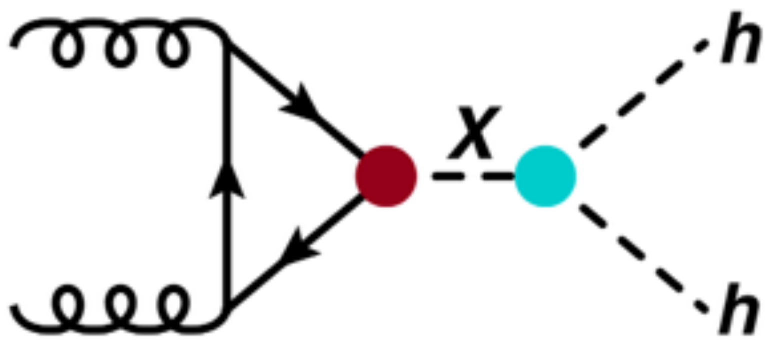
LHCP
Shanghai 17.5.2017

Theory







SM di-Higgs production (33fb) is **three order of magnitudes smaller** than single Higgs production (48pb)

destructive interference

The cross section is enhanced by **BSM contributions**

- non-resonant: **anomalous tri-linear coupling** (c_3) or other Higgs couplings (c_{2t}, c_{2g}, c_{2V}) or; **composite Higgs models**
- resonant: for example **2HDM** via heavy Higgs or Randall-Sundrum **gravitons**

Final states:

- **h→b$\bar{b}$** has the **highest branching ratio**
- **h→γγ** has the cleanest final state with a **good mass resolution**
- **h→WW** and **h→ττ** are good compromises

BR	b$\bar{b}$	WW
b$\bar{b}$	33%	
WW	25%	4.6%
ττ	7.4%	2.5%
ZZ	3.1%	1.2%
γγ	0.26%	0.10%

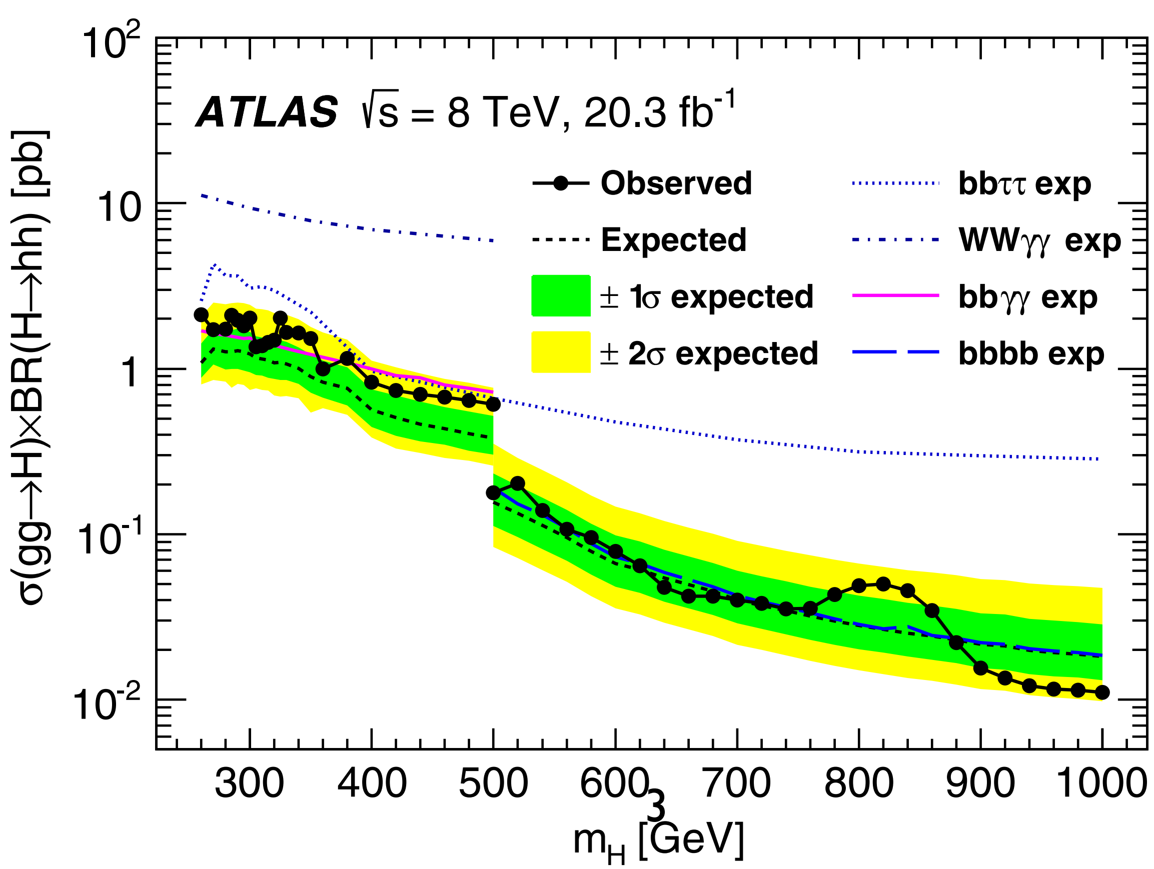
Run I 8TeV Combination

σ(HH) @ 8TeV ~10fb^{-1}

non-resonant limits:

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
	Upper limit on the cross section [pb]				
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
	Upper limit on the cross section relative to the SM prediction				
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

resonant limits:



PhysRevD.92.092004(1)

Run 2 13fb^{-1} **hh → $b\bar{b}b\bar{b}$**: Event selection

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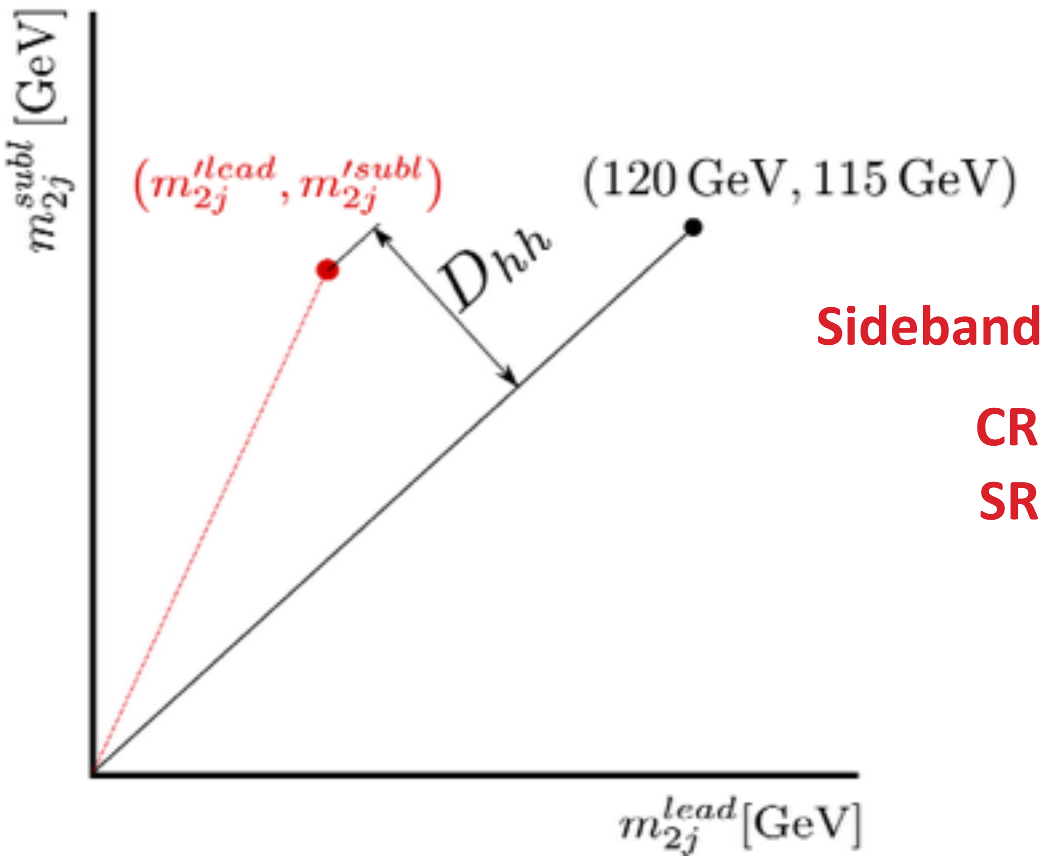
Boosted

- **> 1000 GeV**
- optimised for **resonant phenomena**
- **2 anti-k_T jets** with R=1.0
- **2-4 b-tags** in associated R=0.2 track-jets
- p_T>450-250 GeV, |η|<2.0, m_J>50GeV
- $|\Delta\eta_{hh}| < 1.7$

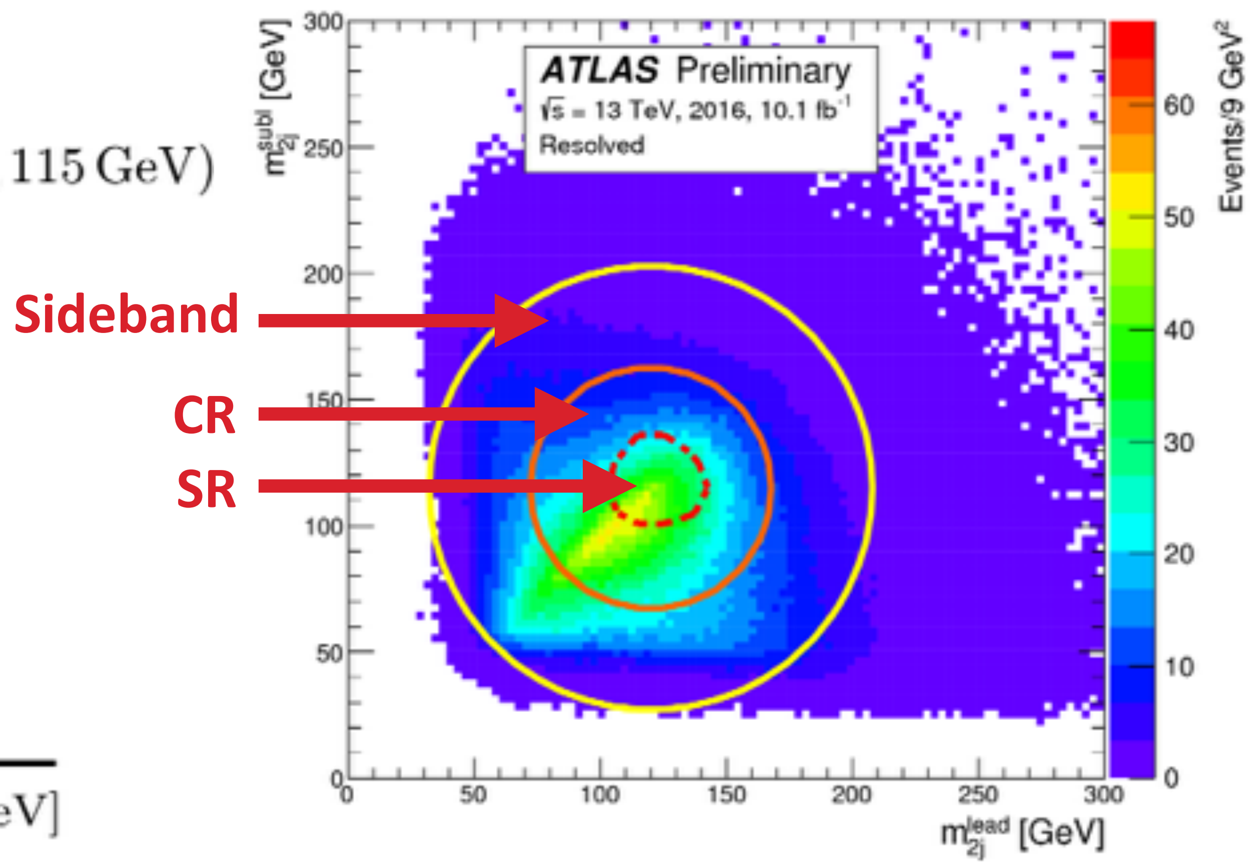
Resolved

- **300 to 1200 GeV**
- **resonant and non-resonant**
- **4 anti-k_T jets** with R=0.4
- **4 b-tags**; ε(b-tag) ≈ 70% in $t\bar{t}$
- m_{4j} dependent p_T cuts
- $|\Delta\eta_{hh}| <$ ~1.1 (m_{4j} dependent)

Jet combinatorics (resolved):



Resolved background model:



multi-jet background modelled in **sideband with 2-tags**

4/2-tag reweighting

- number of jets
- leading Higgs pT
- jet energies of sub-leading Higgs

ATLAS-CONF-2016-049

Run 2 13fb^{-1} **hh → $b\bar{b}b\bar{b}$**: Results

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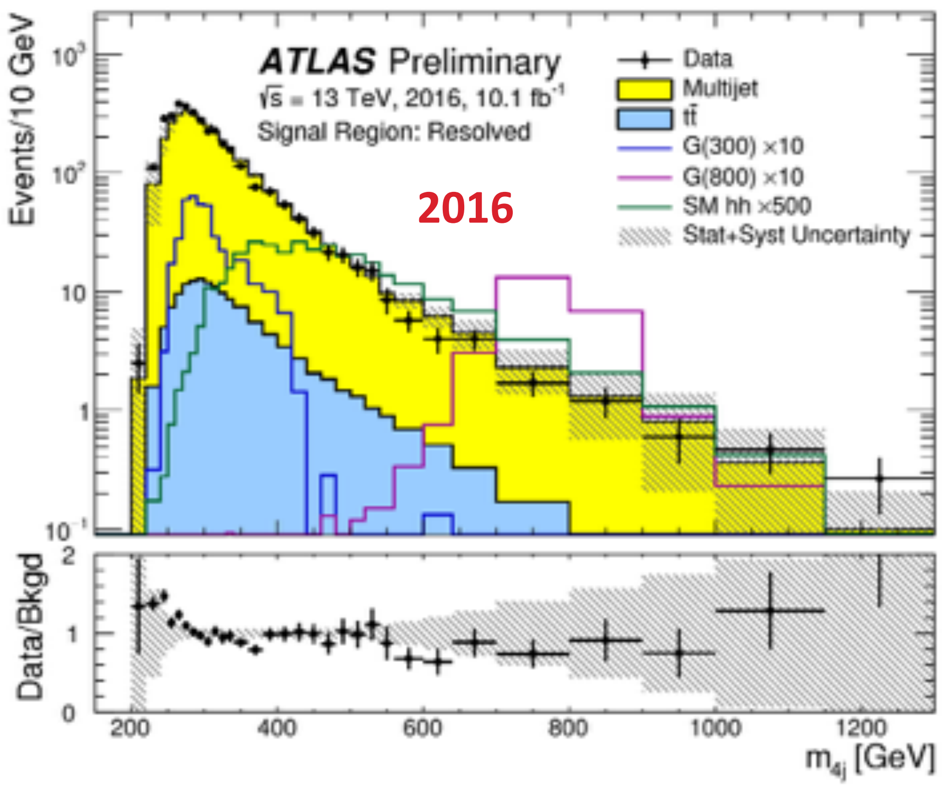
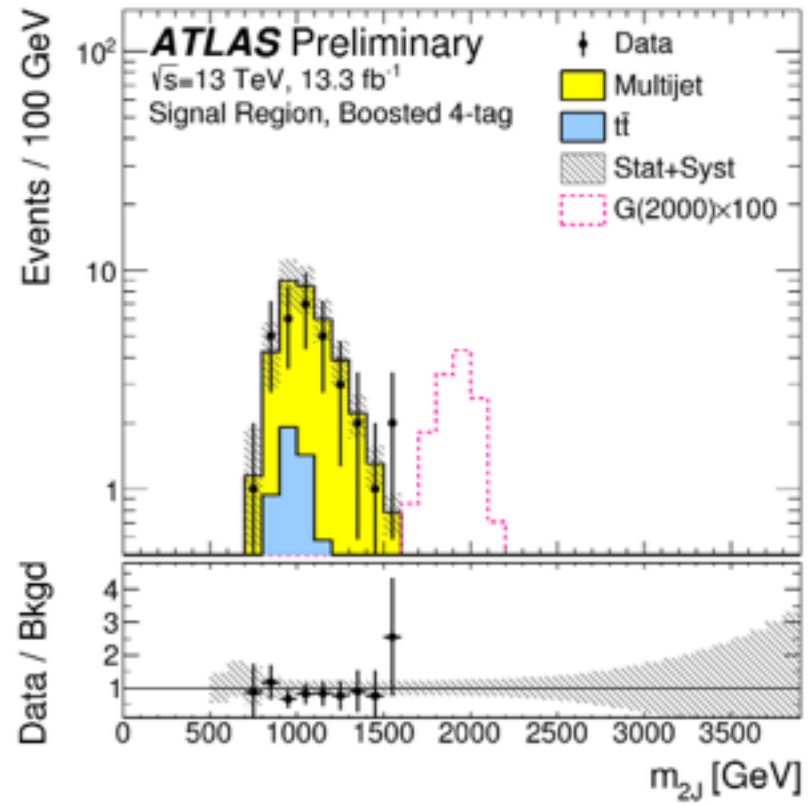
Resolved analysis:



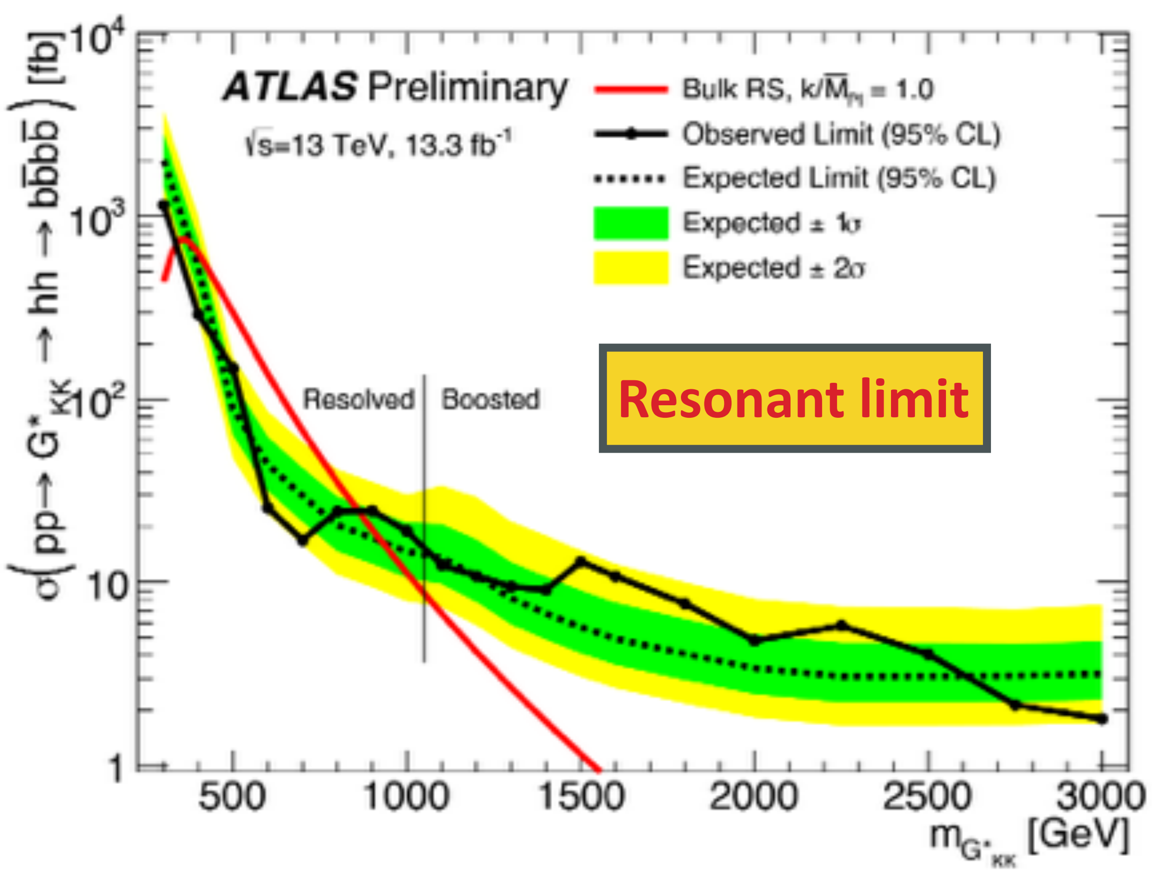
Boosted analysis:



Final discriminant:

- resolved: m_{4j}
- boosted: m_{2j}

non-resonant limit:
σ × BR < 330fb
(29×SM)



Systematics in %-yield in resolved analysis:

	2015			2016		
Source	Background	SM hh	G^*_{KK} (800 GeV)	Background	SM hh	G^*_{KK} (800 GeV)
Luminosity	–	2.1	2.1	–	3.7	3.7
JER	–	5.7	3.3	–	5.4	3.5
JES	–	6.4	1.3	–	6.6	1.3
b-tagging	–	23	35	–	23	35
Theoretical	–	9.7	4.2	–	9.7	4.2
Multijet	5	–	–	5	–	–
$t\bar{t}$	58	–	–	58	–	–
Total	5.5	26	35	5.5	27	36

hh → $b\bar{b}b\bar{b}$: Prospects for **HL-LHC**

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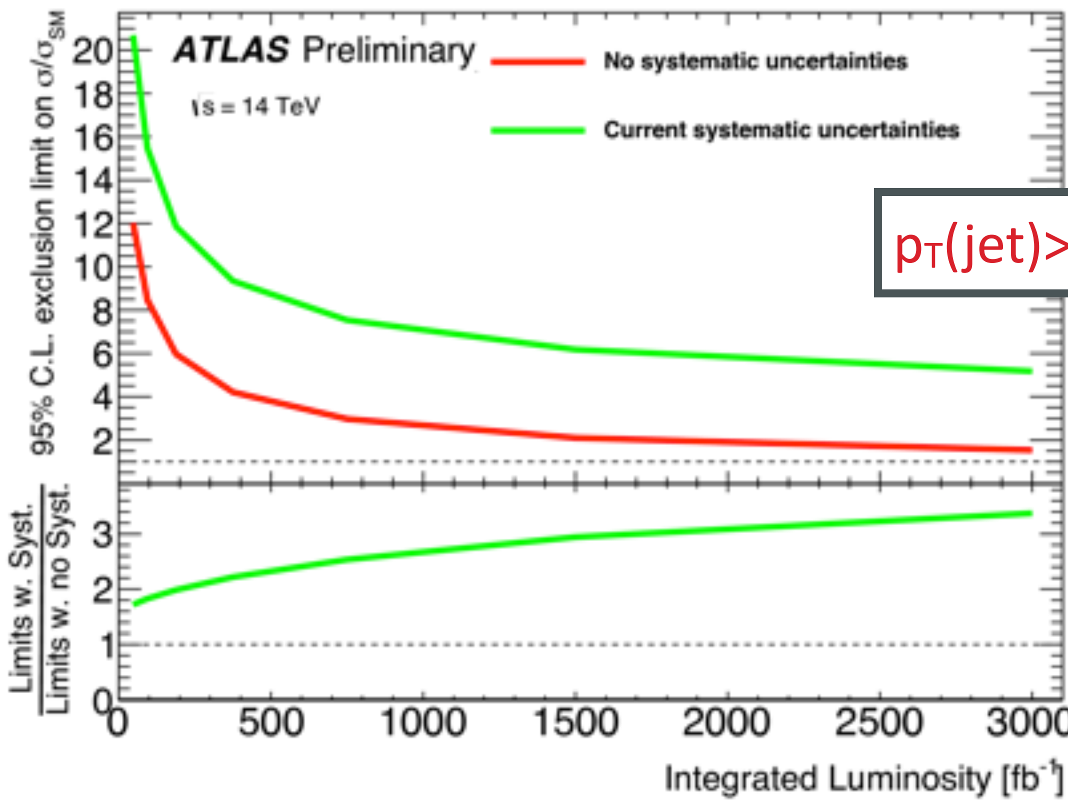
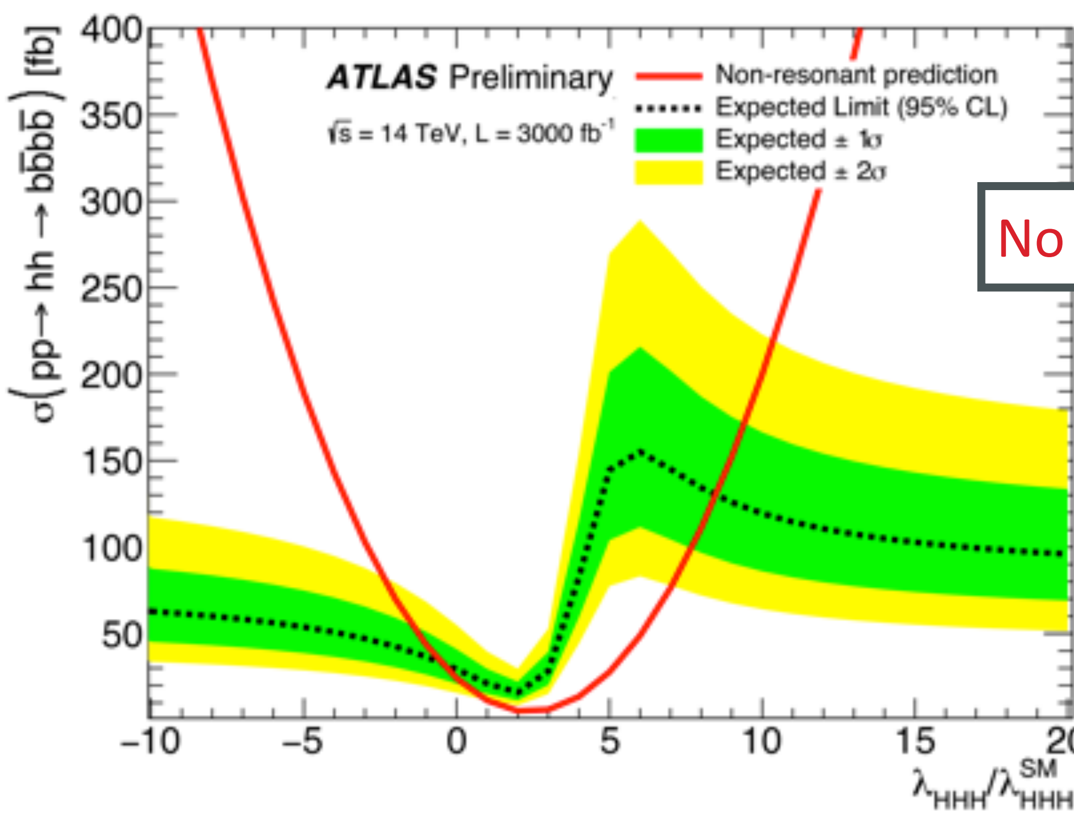
Extrapolating the resolved analysis limit on σ to **14TeV and 3000 fb^{-1}**:

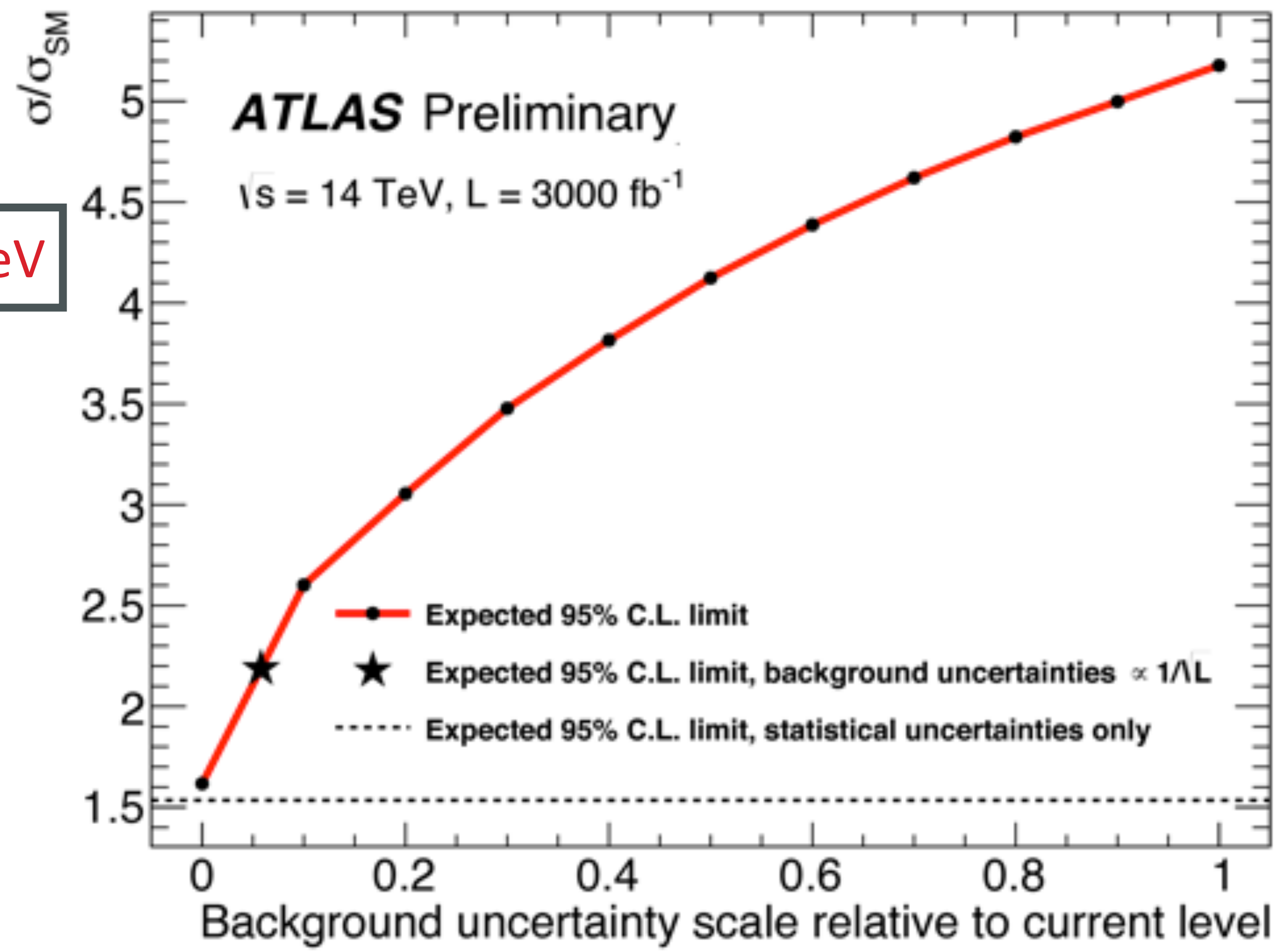


p_T(jet)>30GeV



No sys.

Adding improvement to **background understanding**:



Caveat: **pile-up** might require a higher cut on **jet-p_T** which would degrade the limit significantly.

expected HL-LHC limit on λ_{HHH}:

$0.2 < \lambda_{HHH}/\lambda_{SM} < 7.0$ @ 95% C.L.

ATL-PHYS-PUB-2016-024

hh → $b\bar{b}b\bar{b}$: Prospects for **HL-LHC**

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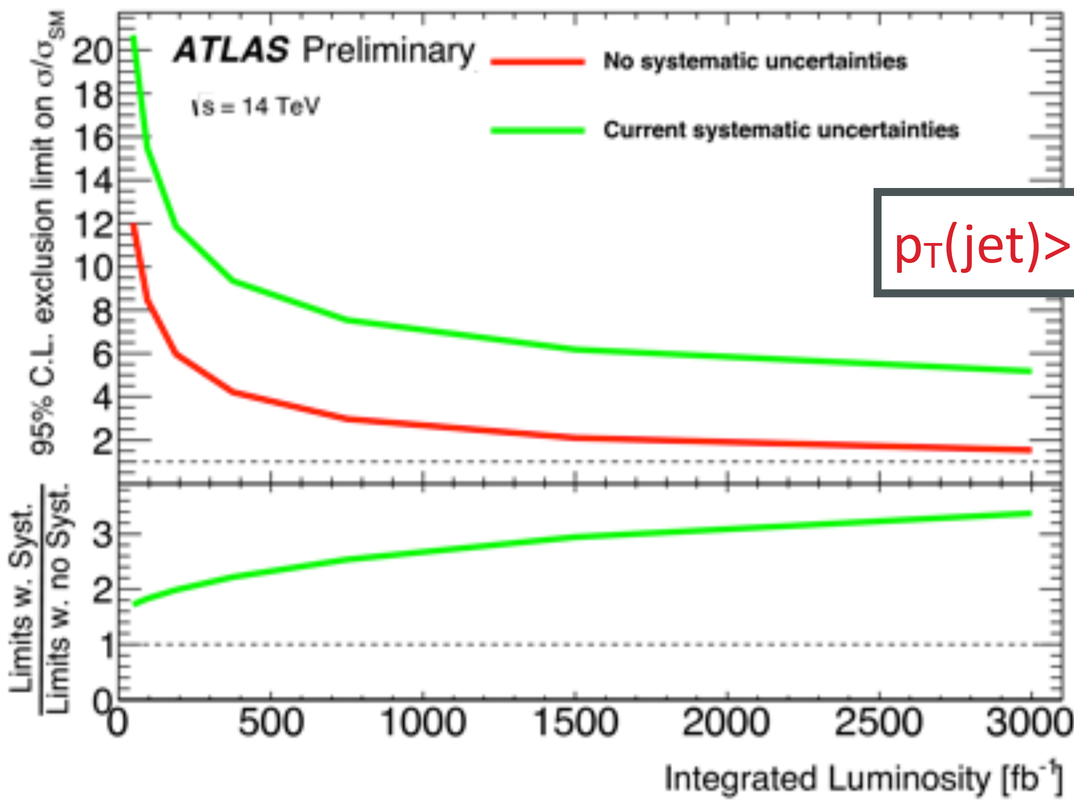
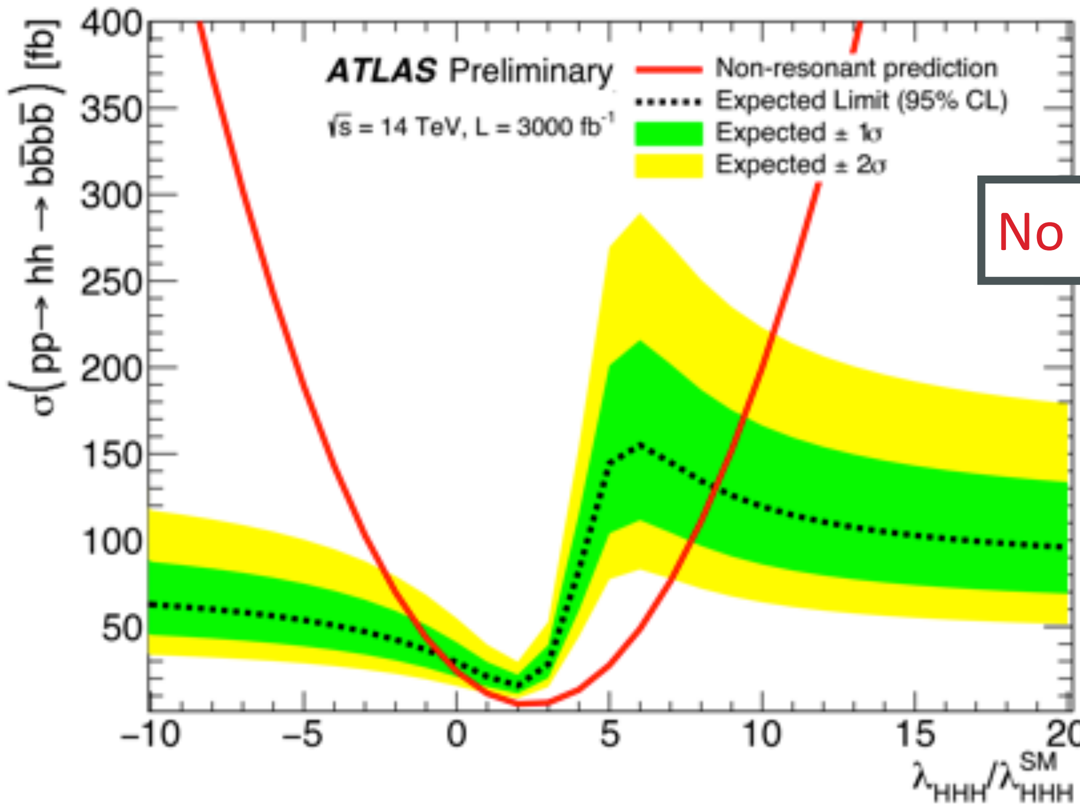
Extrapolating the resolved analysis limit on σ to **14TeV and 3000 fb^{-1}**:



p_T(jet)>30GeV



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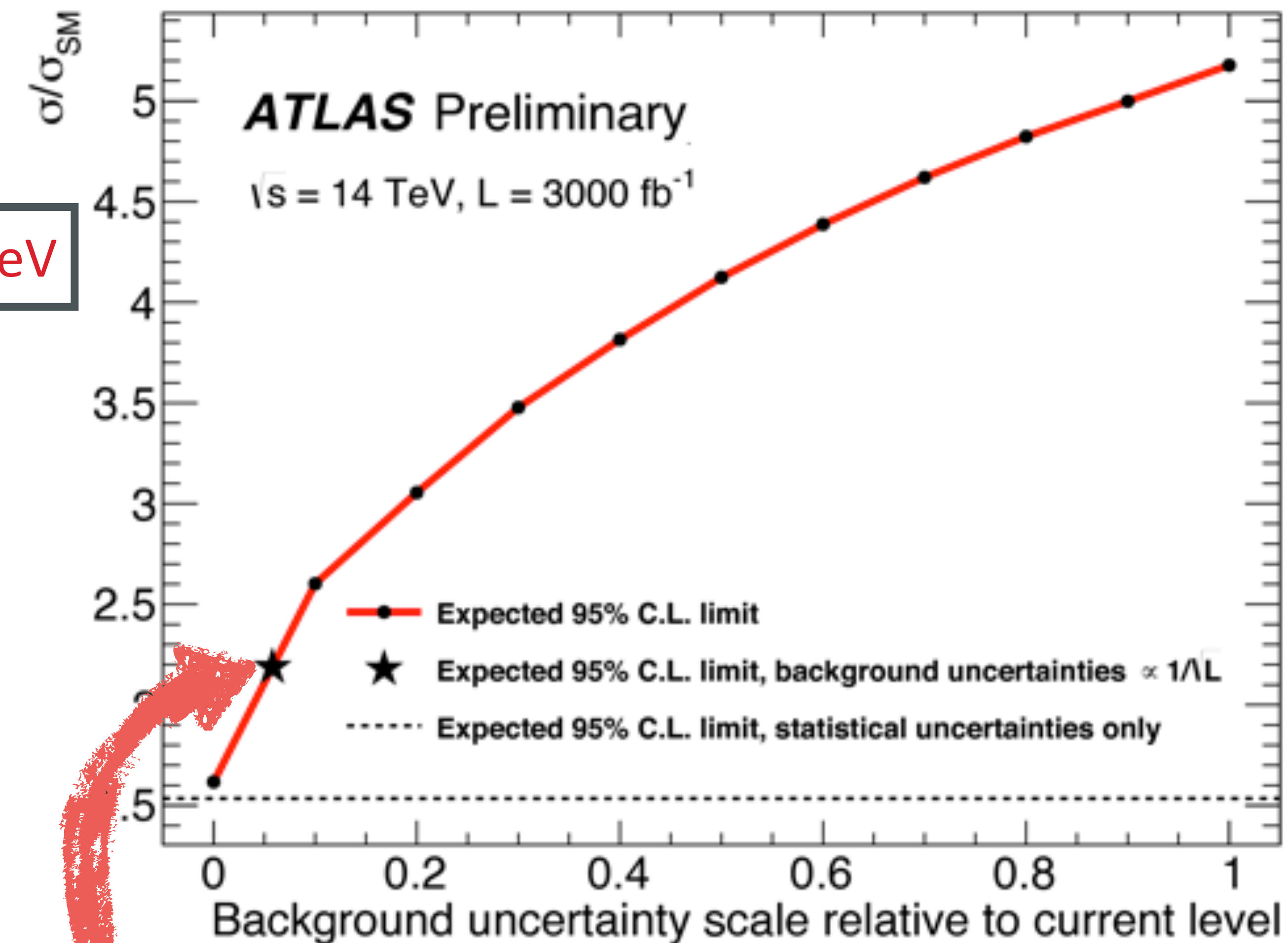


Extrapolated to 3000fb^{-1}

Caveat: **pile-up** might require a higher cut on **jet-p_T** which would degrade the limit significantly.

expected HL-LHC limit on λ_{HHH}:
$0.2 < \lambda_{HHH}/\lambda_{SM} < 7.0$ @ 95% C.L.

ATL-PHYS-PUB-2016-024

Run 2 13.3fb^{-1} hh → γγWW* (→ lν jj)

Signal selection:

1 lepton (p_T>10GeV)

2 jets (p_T>25GeV),

2 photons (p_T>35/25 GeV)

$|m(\gamma\gamma) - m_h| < 2\sigma_{hh}$,

σ_{hh} = 1.7 GeV

Data driven background modelling:

Sideband extrapolation. A transfer factor is measured using a second order exponential function in the **0-lepton control region**.

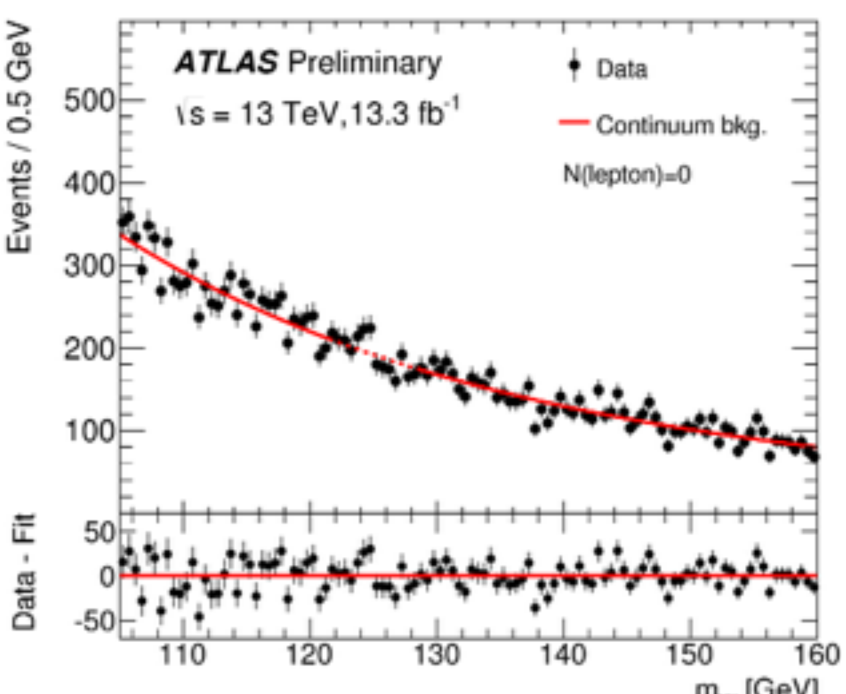
Background modelling is the main systematics (17%)

Event numbers in SR:

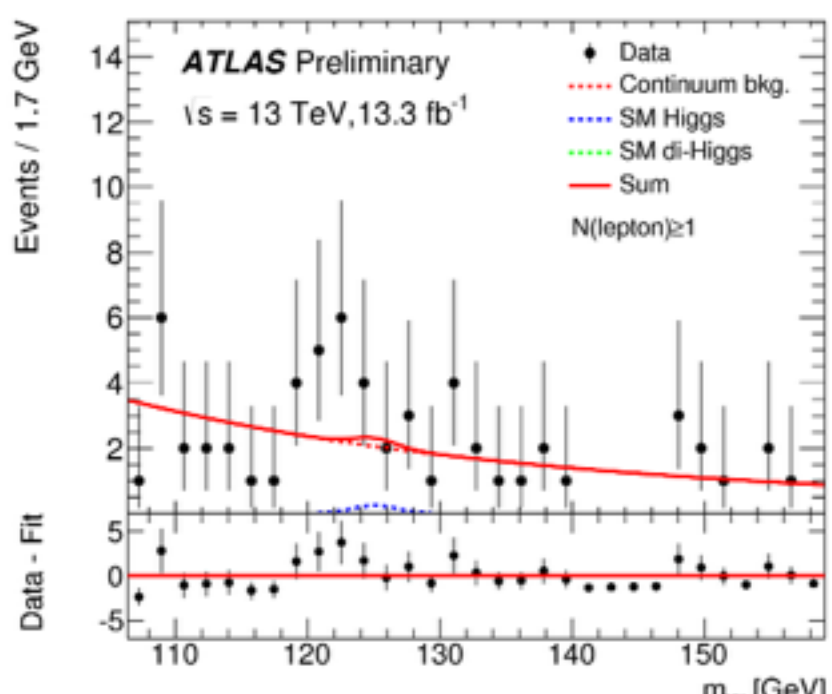
Process	Number of events	
Continuum background	7.26	± 1.23
SM single-Higgs	0.616	± 0.115
SM di-Higgs	0.0187	± 0.00224
Observed		15

non-resonant limit:
σ_{HH} < 25pb
(749 × SM)

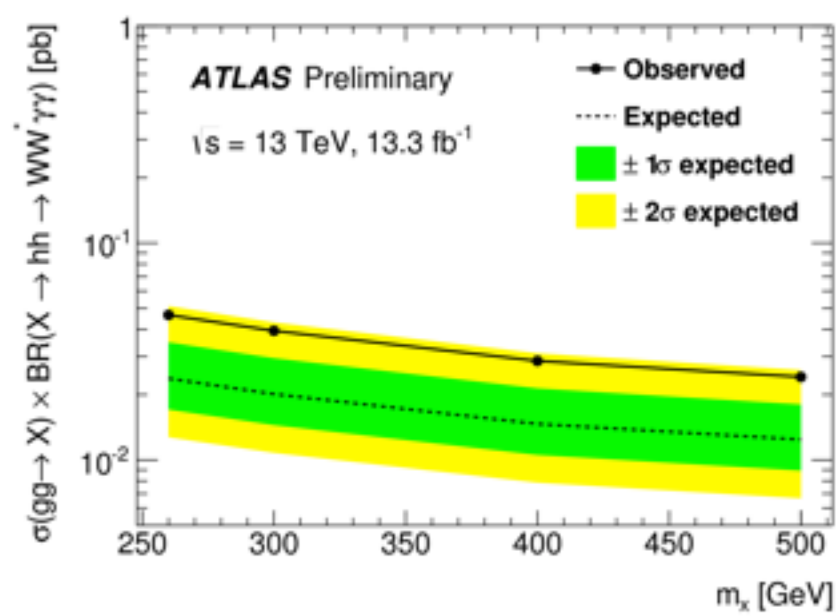
Control region (0 lepton):



Signal region (1 lepton):



Limit for resonant hh production:



ATLAS-CONF-2016-071

Run 2 3.2fb^{-1} **hh → $b\bar{b}\gamma\gamma$**

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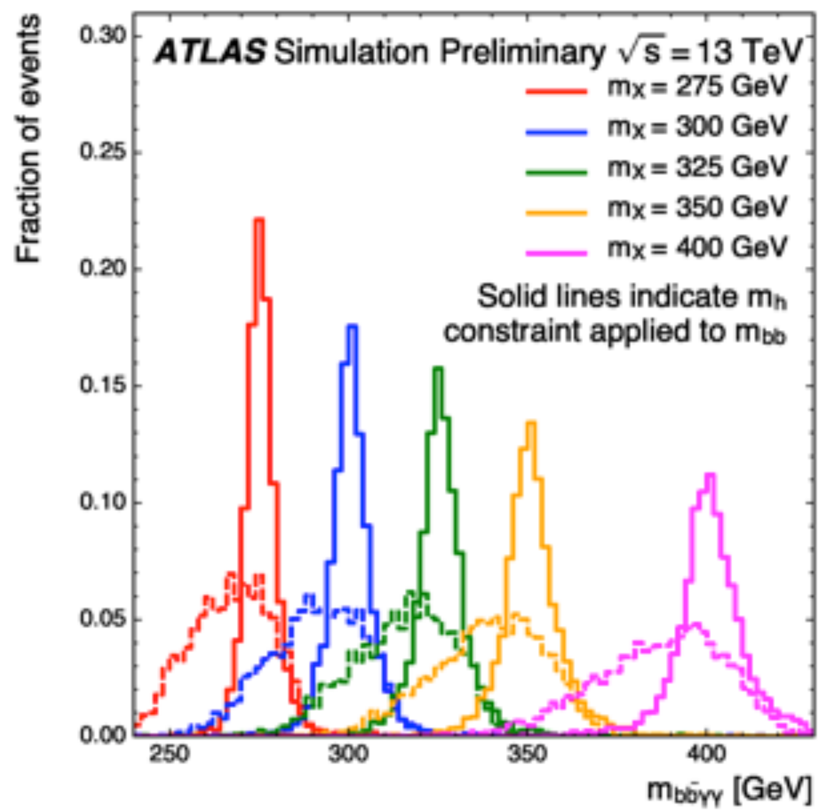
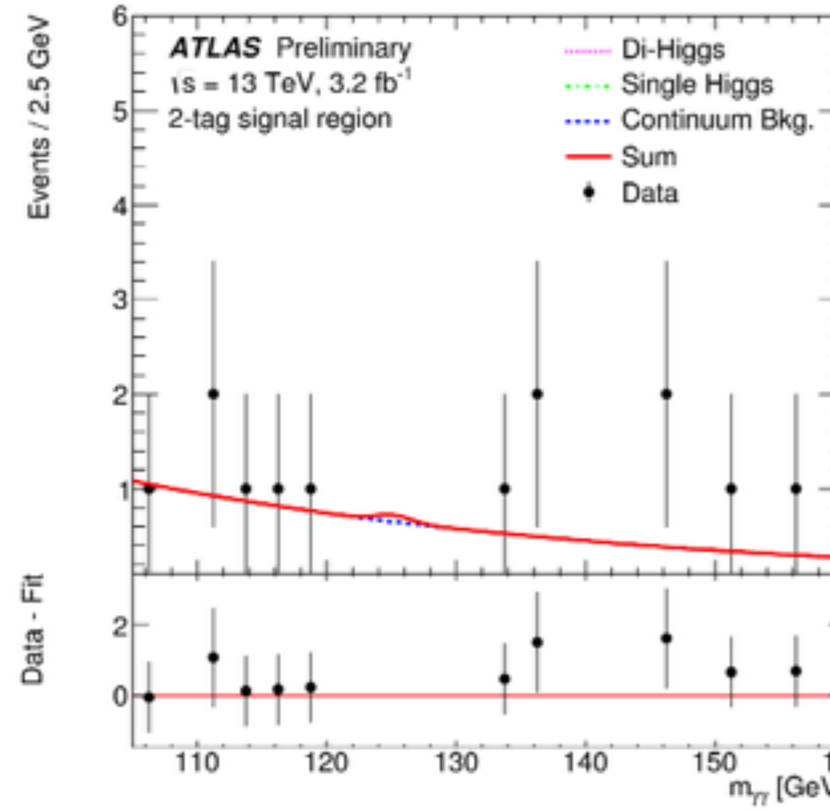
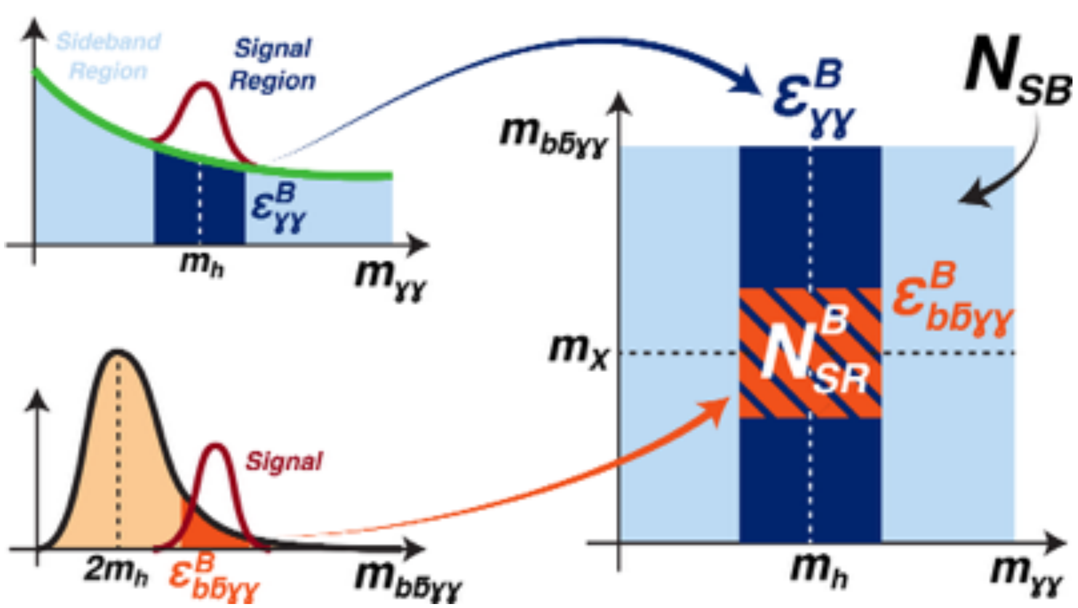
Event selection:

- **2 isolated photons**, $E_T/m_{\gamma\gamma} > 0.35$ (0.25)
- **2 b-jets**, p_T>55/35 GeV, ε=85%, removal of pile-up jets
- **m_h/m_{bb} scaling** to improve the $m_{hh\gamma\gamma}$ resolution is used
- **$|m_{\gamma\gamma} - m_h| < 2\sigma(m_{hh})$**; $\sigma(m_{hh})$=1.55GeV
- **$m_{b\bar{b}\gamma\gamma}$** containing 95% of di-Higgs events

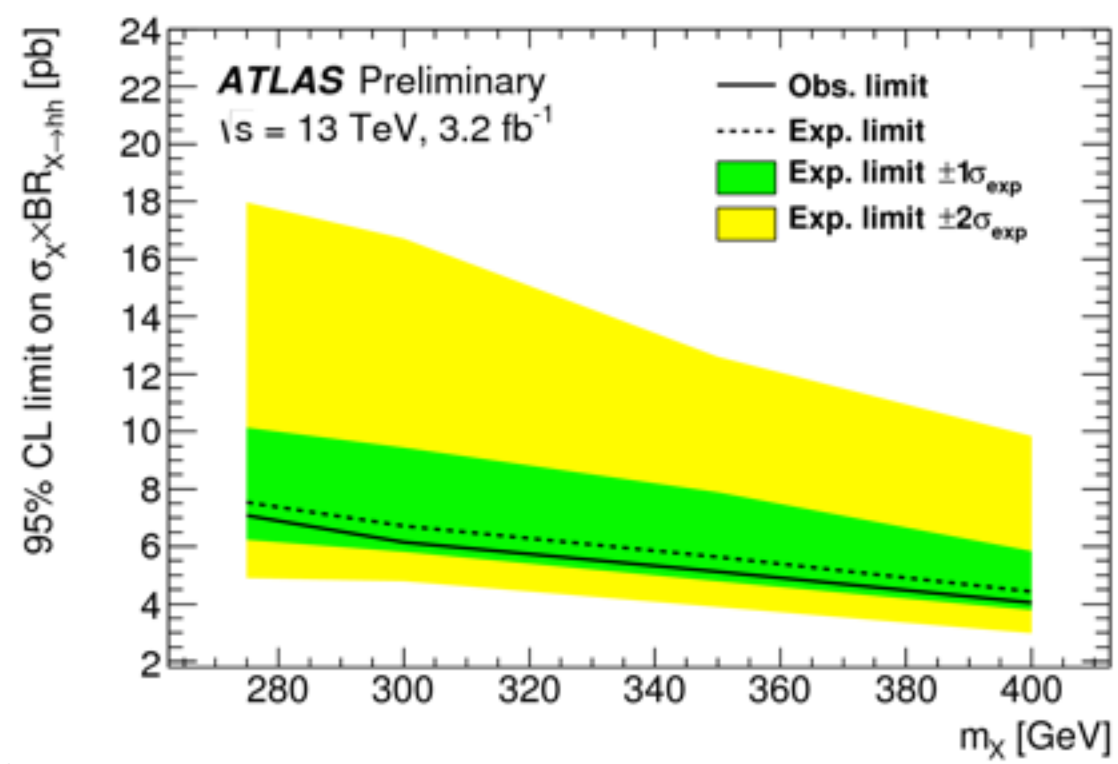






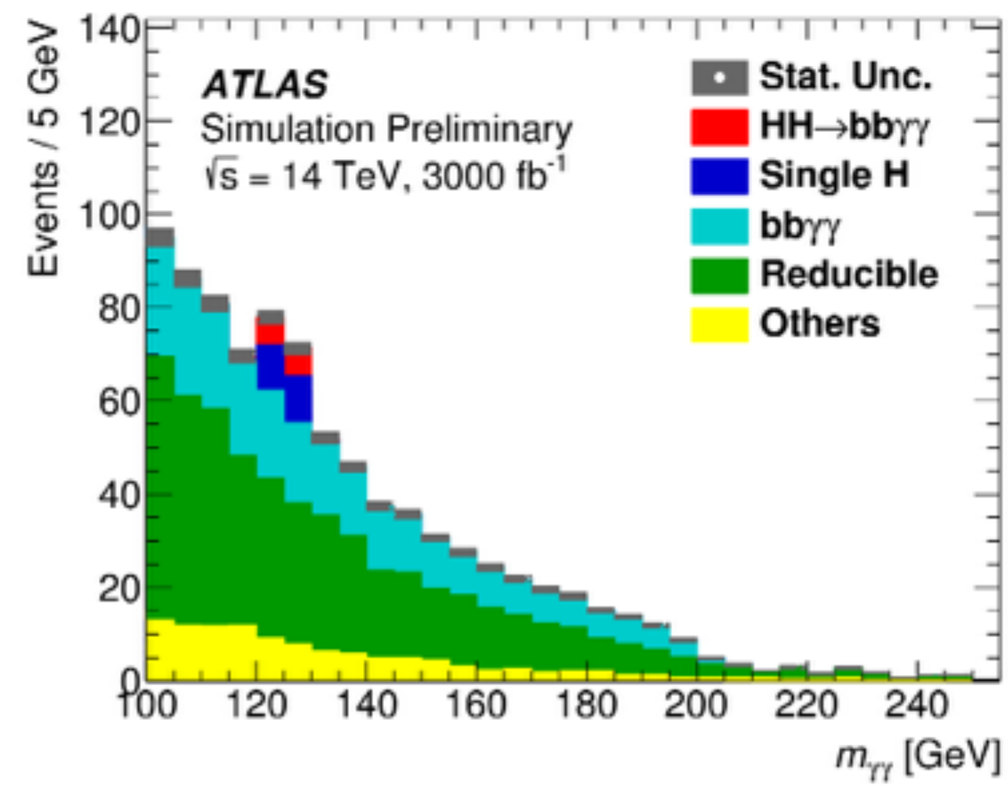
Non-resonant limit:
σ < 3.9pb (117 × SM)

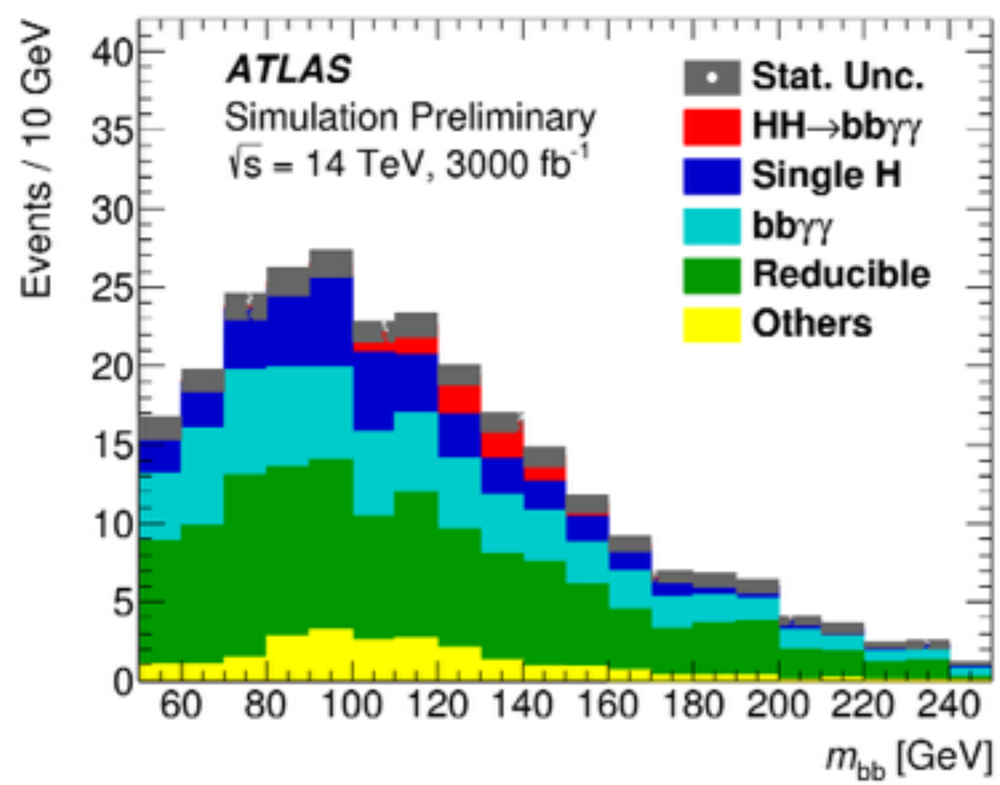
Resonant limit:

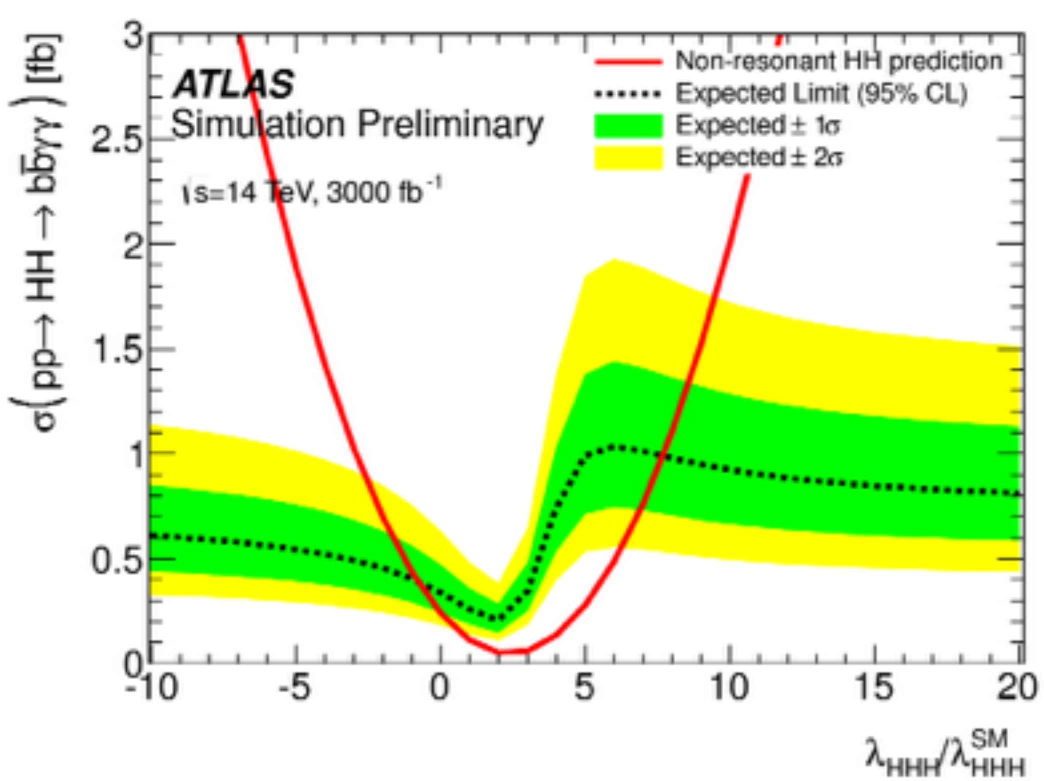


$hh \rightarrow b\bar{b}\gamma\gamma$: HL-LHC

Simplified analysis for √s=14TeV and a luminosity of 3000 fb^{-1}







S/B=9.5 / 91 giving a 1σ significance

expected HL-LHC limit on λ_{HHH}:
$-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$ @ 95% C.L.

Conclusion

Three **ATLAS Run 2 analyses** searching for di-Higgs decays at $\sqrt{s}$ = 13 TeV have been presented.

No BSM physics has been observed - **yet**.

Run 2 limits with 13.3fb^{-1} already **improve on the Run 1** limits

HL-LHC may be able to **constrain tri-linear Higgs** couplings.

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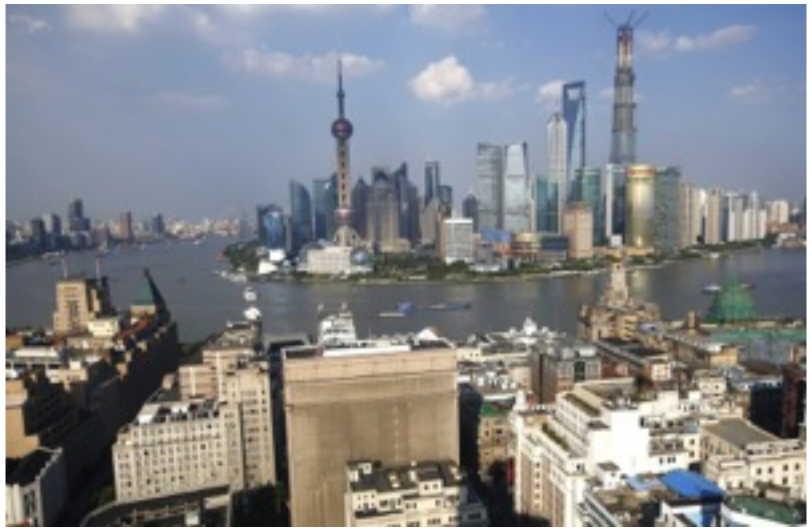
Shanghai 1987

Shanghai 2013



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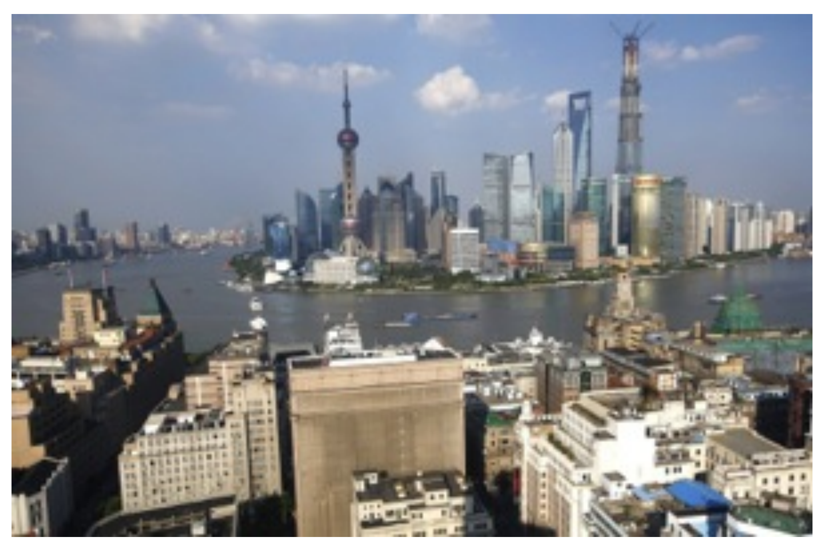

Shanghai 20xx?

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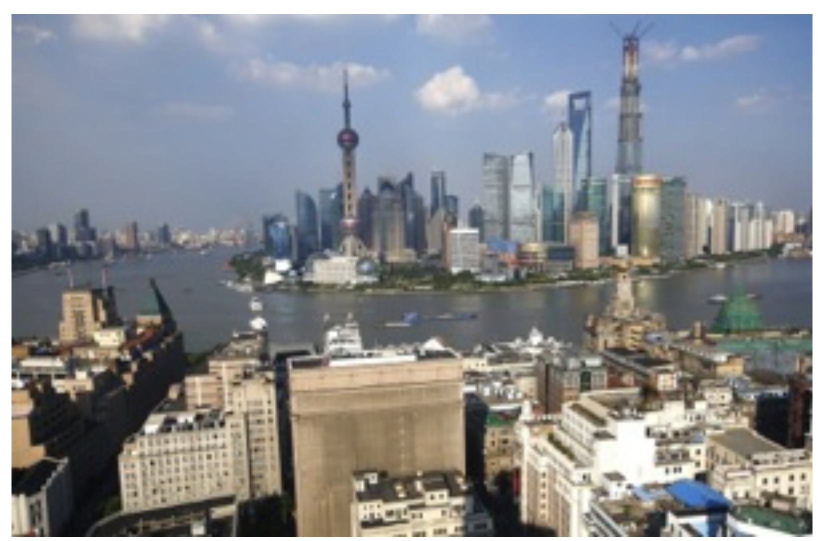
e^- π^0 μ^+

ν_e e^-

Shanghai 1987

Shanghai 2013



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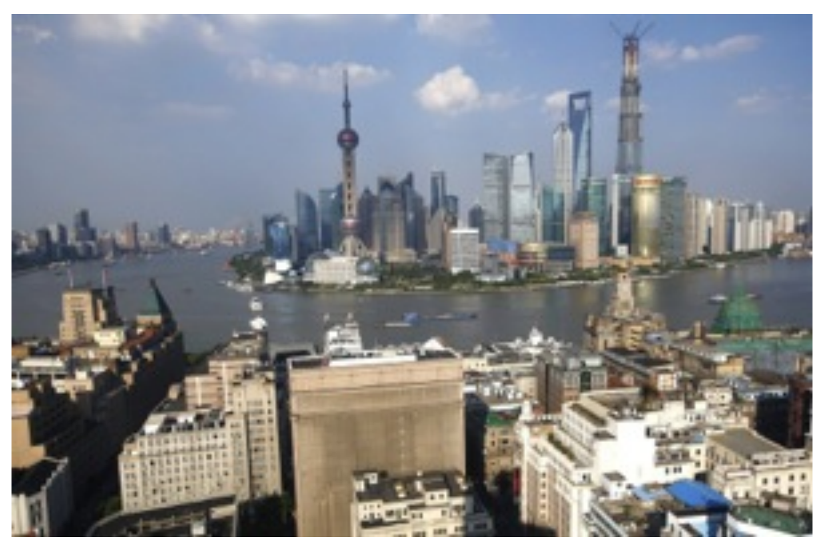
e^- μ^+ π^0 ν_e e^-

Shanghai 1987

e^- μ^+ π^0 H ν_e e^-

Shanghai 2013



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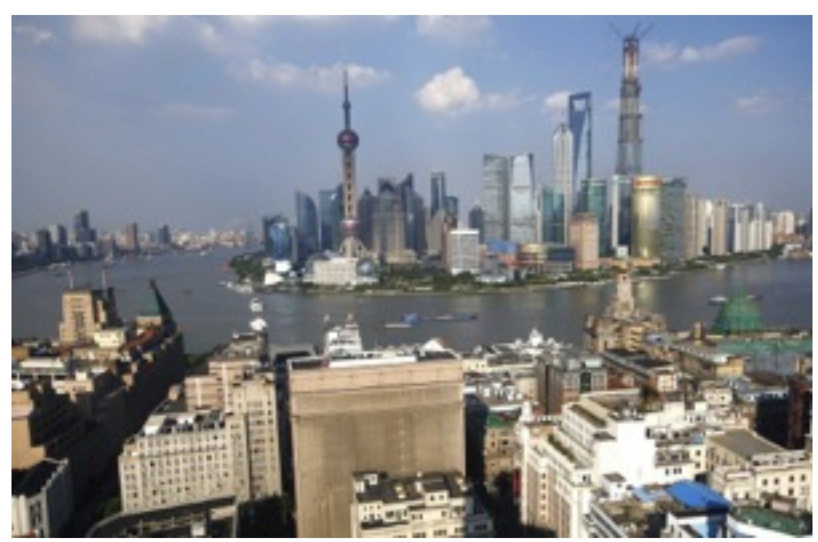
Shanghai 1987

e^- π^0 μ^+ ν_e e^- H

Shanghai 2013

HH

Shanghai 20xx?



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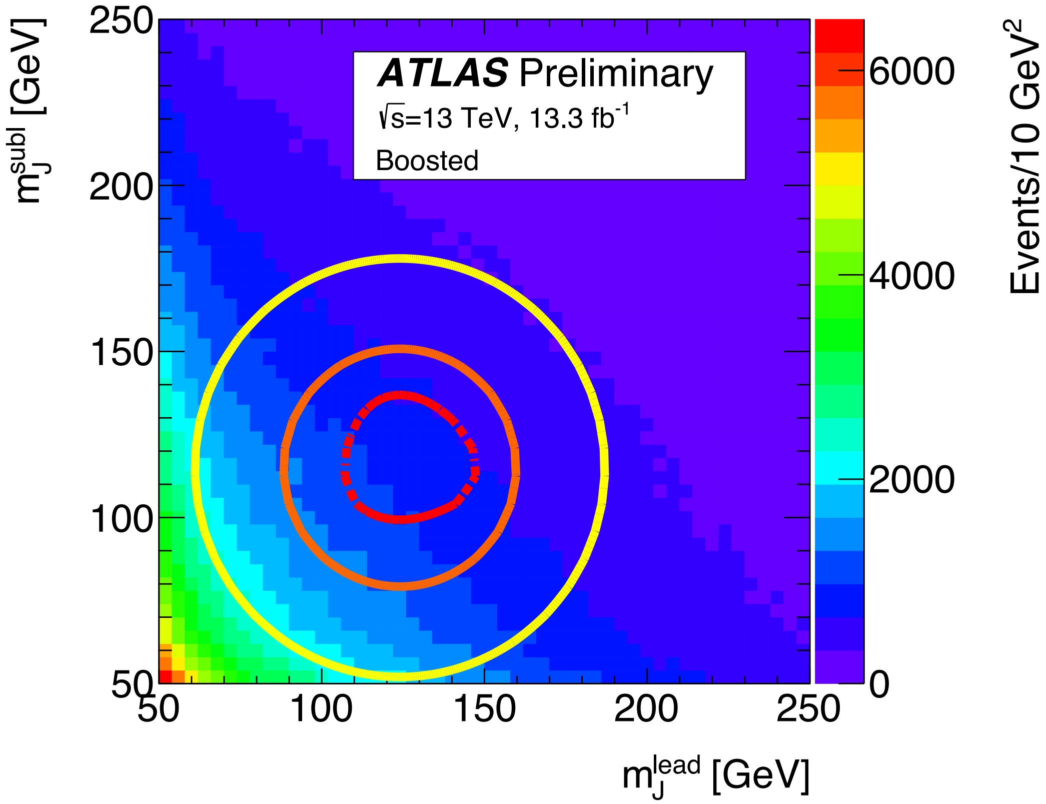
Backup

Run 2 13fb^{-1} **hh → $b\bar{b}b\bar{b}$**: Event selection

$$p_{\mathrm{T}}^{\mathrm{lead}} > 0.5 m_{4\mathrm{j}} - 90\ \mathrm{GeV}$$

$$p_{\mathrm{T}}^{\mathrm{subl}} > 0.33 m_{4\mathrm{j}} - 70\ \mathrm{GeV}$$

$$|\Delta\eta_{hh}| < \begin{cases} 1.1 & \text{if } m_{4\mathrm{j}} < 850\ \mathrm{GeV} \\ 2\times 10^{-3} m_{4\mathrm{j}} - 0.6 & \text{if } m_{4\mathrm{j}} > 850\ \mathrm{GeV} \end{cases}$$



Sample	2-tag-split	3-tag	4-tag
Multijet	2 310 ± 240	515 ± 41	32.6 ± 7.6
$t\bar{t}$	460 ± 170	81 ± 37	5.7 ± 5.2
Total	2 770 ± 130	596 ± 39	38.3 ± 9.0
Data	2 813	671	32
G^*_{KK} (2 TeV), $k/\bar{M}_{\mathrm{Pl}} = 1$	0.17 ± 0.10	0.31 ± 0.06	0.15 ± 0.06

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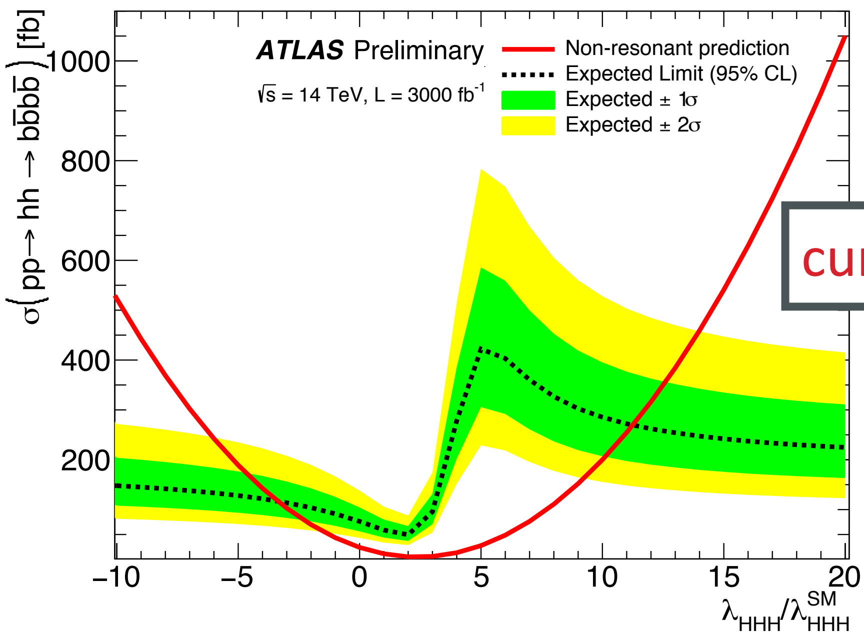
Table 3: The number of predicted background events in the signal region for the resolved analysis compared to the data, for the 2015 and 2016 datasets. The yields for two potential signals, SM non-resonant Higgs pair production and an 800 GeV G^*_{KK} resonance with $k/\bar{M}_{\mathrm{Pl}} = 1$ are shown. The quoted errors include both the statistical and systematic uncertainties.

Sample	2015 Signal Region	2016 Signal Region
Multijet	1 131 ± 68	3 670 ± 200
$t\bar{t}$	57 ± 34	190 ± 110
Total	1 189 ± 76	3 860 ± 230
Data	1 231	3 990
SM hh	0.47 ± 0.12	1.5 ± 0.4
G^*_{KK} (800 GeV), $k/\bar{M}_{\mathrm{Pl}} = 1$	8 ± 3	24 ± 8

	2-tag-split		3-tag		4-tag	
Sample	Sideband	Control Reg.	Sideband	Control Reg.	Sideband	Control Reg.
Multijet	19 400 ± 200	5 917 ± 62	4 294 ± 89	1 318 ± 27	258 ± 22	84.3 ± 7.1
$t\bar{t}$	3 860 ± 160	1 038 ± 45	720 ± 68	189 ± 19	36 ± 16	10.1 ± 4.5
Total	23 260 ± 160	6 954 ± 52	5 014 ± 73	1 507 ± 24	294 ± 17	94.4 ± 5.8
Data	23 277	7 200	5 007	1 529	291	81

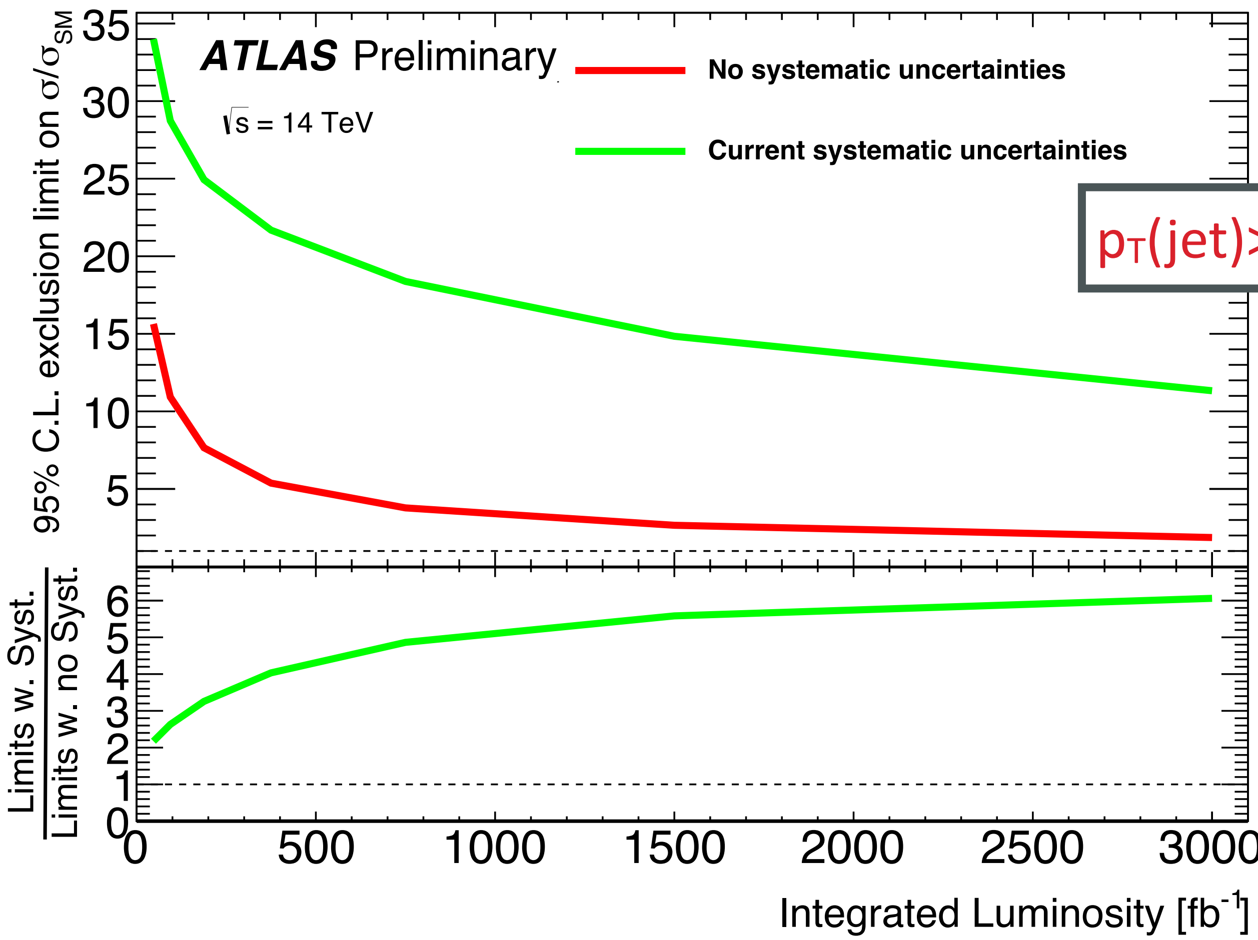
	2-tag-split		3-tag		4-tag	
Source	Background	G^*_{KK} (2 TeV)	Background	G^*_{KK} (2 TeV)	Background	G^*_{KK} (2 TeV)
Luminosity	-	2.9	-	2.9	-	2.9
JER	-	0.1	-	0.1	-	0.3
JMR	-	12	-	12	-	12
JES/JMS	-	4.5	-	4.2	-	3.3
b-tagging	-	58	-	15	-	38
Theoretical	-	2.7	-	2.3	-	2.4
Bkg Estimate	4.4	-	4.6	-	21	-
Statistical	0.5	1.4	1.1	1.0	1.2	1.3
$t\bar{t}$	1.6	-	4.7	-	10	-
Total Sys	4.7	59	6.6	20	24	40

hh → b$\bar{b}$b$\bar{b}$: Prospects for **HL-LHC**



current sys.

expected HL-LHC limit on λ_{HHH}:
$-3.5 < \lambda_{HHH}/\lambda_{SM} < 11.0$ @ 95% C.L.



p_T(jet)>75GeV

Jet Threshold [GeV]	Background Systematics	σ/σ_{SM} 95% Exclusion	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Lower Limit	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Upper Limit
30 GeV	Negligible	1.5	0.2	7
30 GeV	Current	5.2	-3.5	11
75 GeV	Negligible	2.0	-3.4	12
75 GeV	Current	11.5	-7.4	14