ATLAS Higgs Pair Production studies.

Summary of Run 1 Searches and HL-LHC Prospects studies

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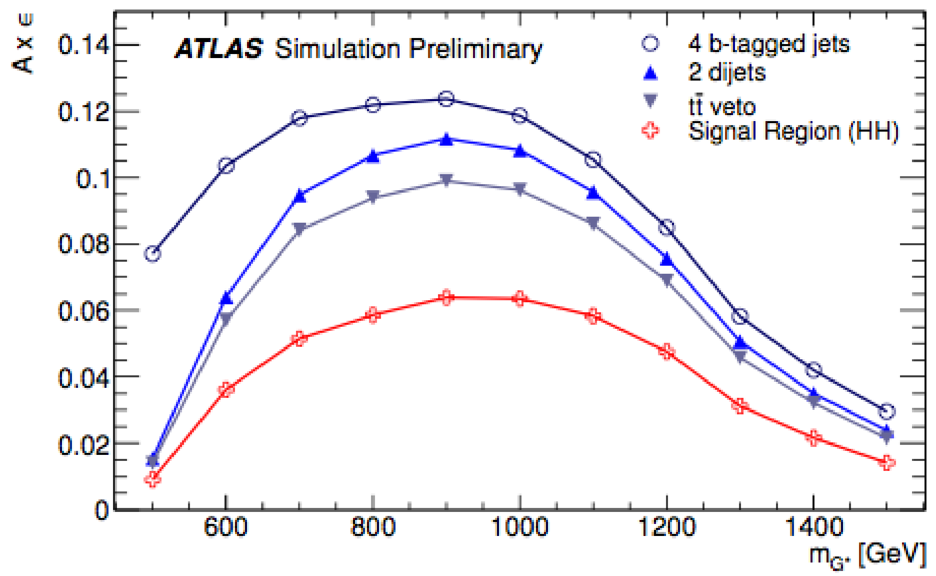
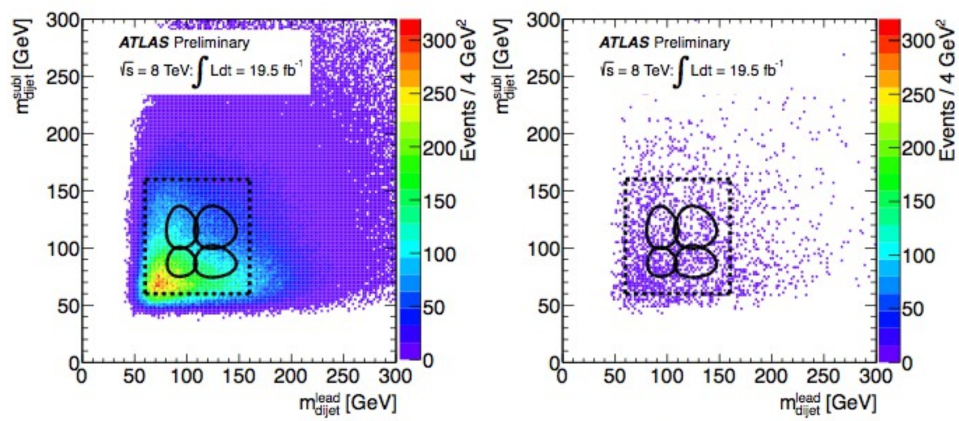
Introduction

- ATLAS has been studying Higgs pair production in 8TeV Run 1 LHC data
  - Used as a search channel with sensitivity to wide range of New Physics models
  - Consider both resonant and non-resonant contributions
  - Resonant: 2HDM, Graviton, Radion, Stoponium, Hidden sector mixing with Higgs...
  - Non-resonant: Modified self-coupling, direct ttHH vertex, light coloured scalars...
- Will summarise two Run 1 Studies:
  - "A search for resonant Higgs-pair production in the bb bb final state in pp collisions at s = 8 TeV" - ATLAS-CONF-2014-005
  - "Search for Higgs boson pair production in the b b final state using pp collision data at s = 8 TeV from the ATLAS detector" - Phys.Rev.Lett. 114 (2015) 081802
- Also looking at prospects of measuring SM Higgs pair production at HL-LHC
  - Sensitivity to Higgs self-interaction
  - Results of studies in 1 channel so far public
  - "Prospects for measuring Higgs pair production in the channel $H(\rightarrow \gamma\gamma)H(\rightarrow bb)$ using the ATLAS detector at the HL-LHC" - ATL-PHYS-PUB-2014-019

Run 1 HH→4b Analysis

- Studied in context of KK Graviton decaying to Higgs Pair
  - For 1 TeV Graviton mass, BR(HH)~7%
  - MadGraph5 v1.5.1, Pythia v8.175
- Events selection
  - Look for b-tagged di-jet pairs consistent with m_H
  - Acceptance reduced for high m_{G^*} due to jet merging
  - tt-veto applied by checking compatibility with W and t mass when 'additional jets' considered
  - Dominant multijet background estimated from data by reweighting '2-tag' category based on 4-tag distribution in sideband/control regions
  - tt background also largely estimated from data



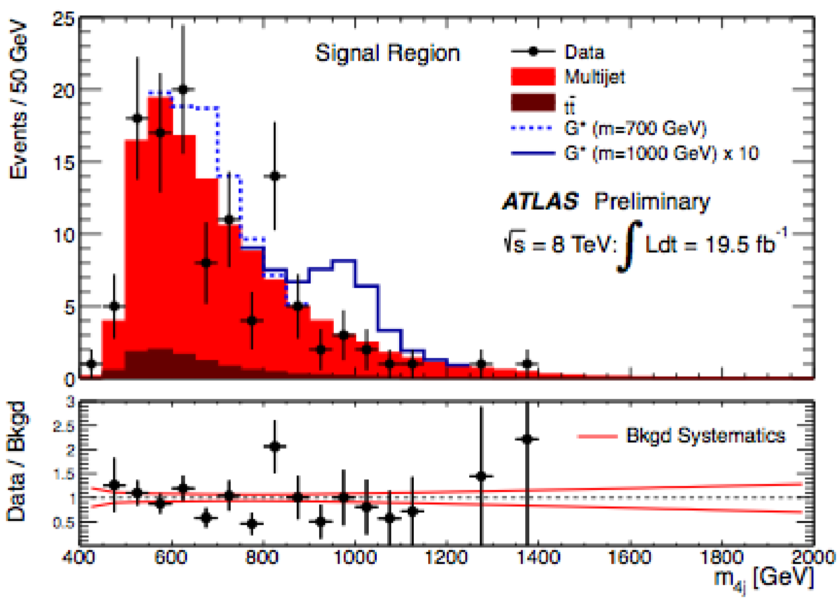


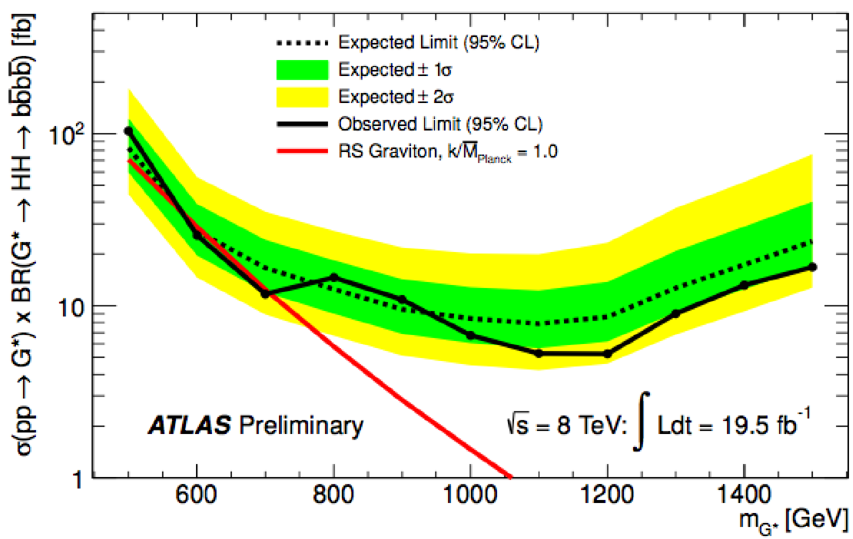
(a) 2-tag data sample (b) 4-tag data sample

Run 1 HH→4b Analysis - Results

- No excess observed
  - 19.5 fb^{-1} 2012 ATLAS data
  - 114 observed events compatible with 120+/- 8 background estimate
- Set limits on cross-section
  - from 100 fb (500 GeV m_{G^*}) to 7 fb (1 TeV m_{G^*})

Type	Signal Region
Multijet	109 ± 5
$t\bar{t}$	10 ± 6
Z+jets	0.7 ± 0.2
Total Bkgd	120 ± 8
Data	114
G^* (m_{G^*} = 500 GeV)	12.5 ± 0.4
G^* (m_{G^*} = 700 GeV)	12.5 ± 0.2





Run 1 HH→ b b Analysis

- Search for resonant and non-resonant enhancements to HH cross-section
  - Chosen channel has large branching ratio on H→bb side, clean trigger and excellent mass resolution on H→γγ side
  - Particularly useful on resonant search where $260<m_x<500$ GeV, where other channels suffer due to backgrounds and combinatorics
- Data-driven background estimates for non-Higgs backgrounds
  - VH and ttH backgrounds use Pythia8
  - ggF and VBF backgrounds use POWHEG+Pythia8
- MadGraph 5 + Pythia 8 used for both resonant benchmark signal models
  - Non-resonant: SM Higgs pair production
  - Resonant: 10 MeV width, m_x = 260,300,350,500 GeV

Run 1 HH→ b b – Selection and analysis procedure

Event Selection

- Pairs of b-tagged jets and γγ pairs consistent with m_H
- Additional mass constraint on 4-body mass for resonant search
- bb p_T correct by factor $125/m_{bb}$ (m_H =125 GeV in MC)
- mass window defined by 95% acceptance of MC signal

Control region with <2 b-tagged jets

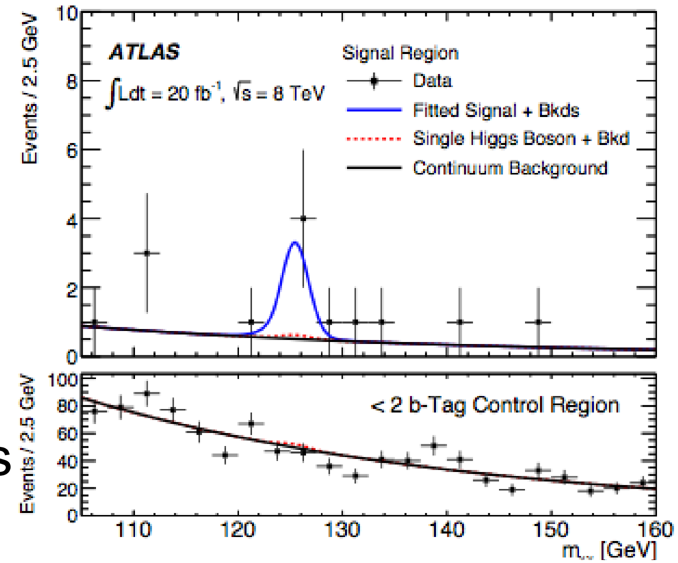
- For non-resonant case, exponential background distribution in $m_{\gamma\gamma}$ fit from control region
- For background acceptance of 4-body mass cut in resonant case, use $m_{\gamma\gamma}$ sidebands of control region fit with Landau distribution

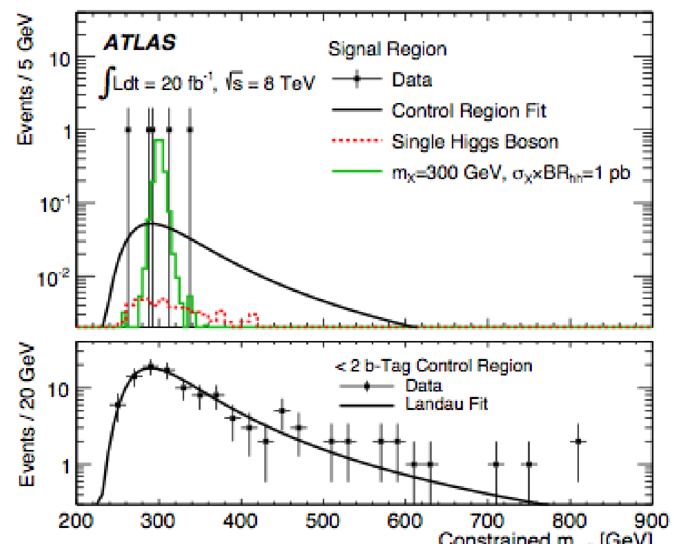
Fit 3 components to $m_{\gamma\gamma}$ spectrum in non-resonant search

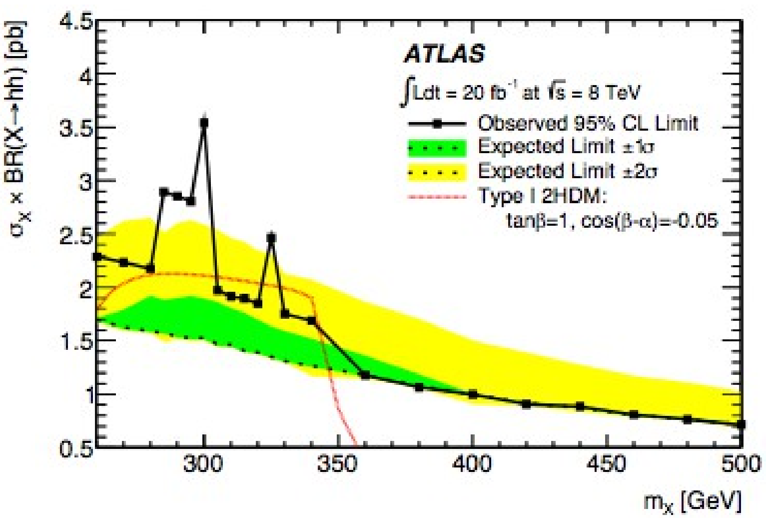
- Signal, continuum, and resonant single Higgs backgrounds
- Resonant search carried out as counting experiment, due to statistical limitations imposed by 4-body mass cut

Run 1 HH→ b b – Results

- Results in 20.3 +/- 0.6 fb^{-1} 2012 data
- Non-resonant search observes 5 events, 2.4σ excess over background-only hypothesis
  - 2.2 pb observed upper limit on HH production, compared to $1.0^{+0.5}_{-0.2}$ pb expected limit
- Observed exclusion in resonant search ranges from 0.7 – 3.5 pb
  - weaker than expected exclusion for m_x < 350 GeV



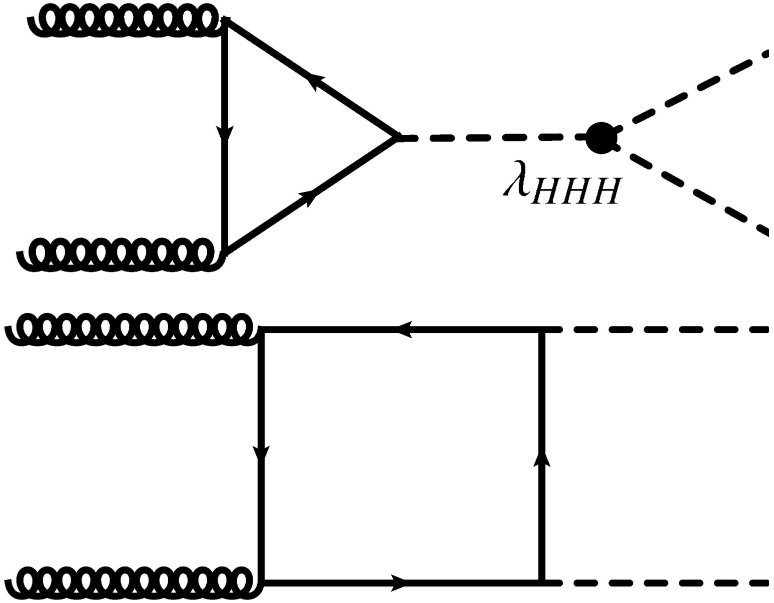


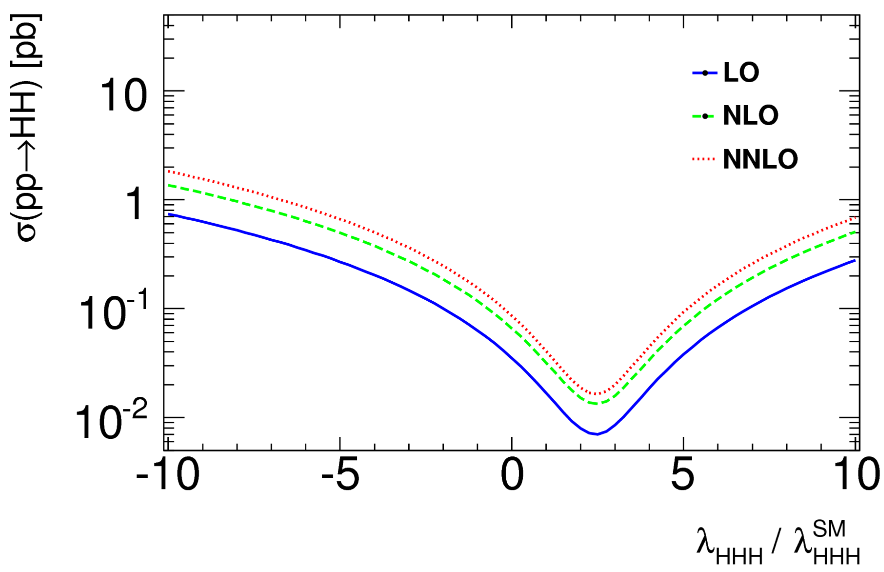


DESY

Prospects Studies - HL-LHC

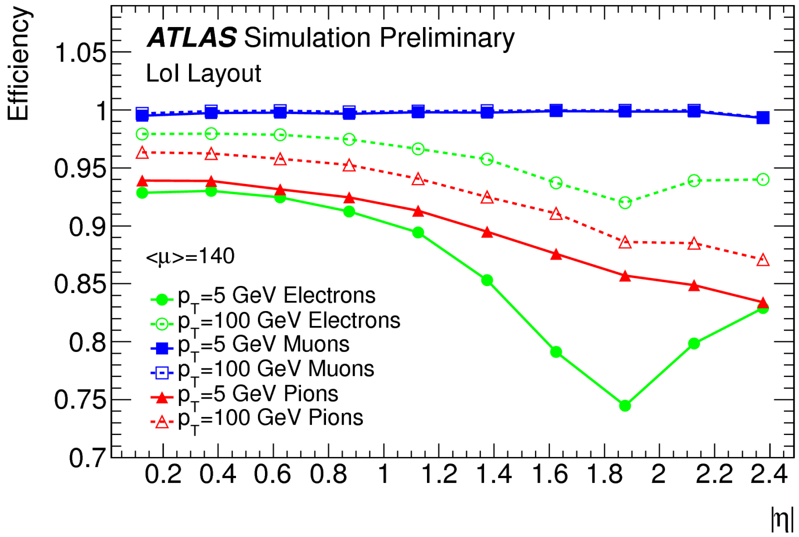
- Self coupling is a fundamental property of the SM Higgs field
  - To understand if observed Higgs boson is really SM, must measure this coupling as well as its coupling to other particles
- Self-coupling strength can be determined by measuring Higgs pair production cross-section
  - Destructive interference between diagrams with and without self-interaction
- NB Analysis is not currently optimised specifically for sensitivity to λ_{HHH}
  - Focus on extracting a signal

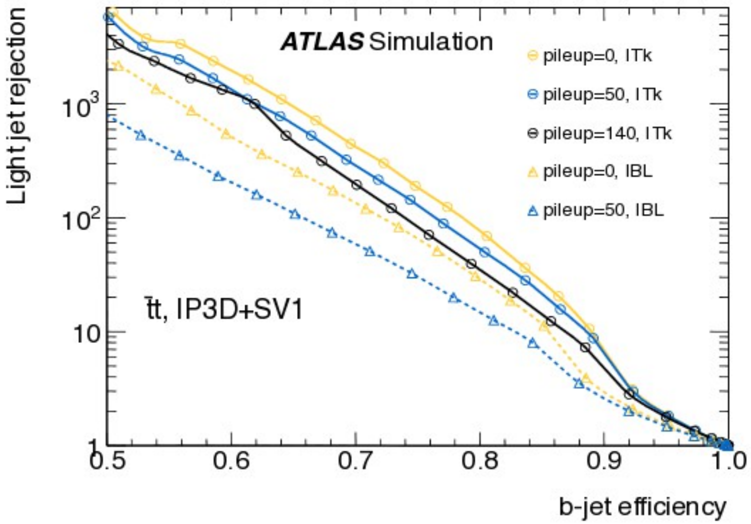




Aside: HL-LHC and ATLAS Phase 2 Upgrade

- High Luminosity LHC planned to begin operation ~2025
  - Aims to provide 3000 fb^{-1} 14 TeV pp data
  - Peak instantaneous luminosity 5 - 7 $\times 10^{34} cm^{-2} s^{-1}$
  - Implies events with pile-up 140-200
- ATLAS detector will receive significant upgrades
  - Including full replacement of tracking detector
- ATLAS 'Phase 2' upgrade simulation performed
  - Inserts baseline design for replacement tracker in current calorimeter/muon systems
  - Upgrades to other systems not yet available in these full-simulation samples





Self Coupling at HL-LHC

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

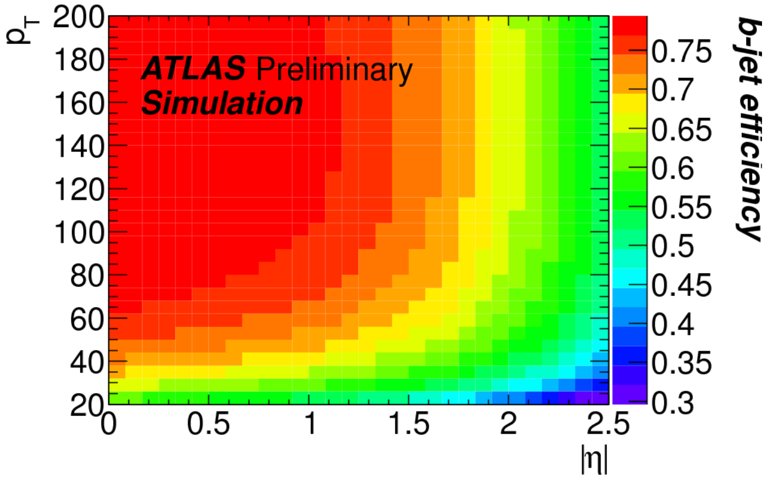
- Total (SM) NNLO cross-section 40.8 fb^{-1}
  - Need large HL-LHC data sample to have a good chance of measuring this process
- A wide variety of final states available
  - High branching fraction modes also have large backgrounds
  - As for Run 1 study, $bb\gamma\gamma$ chosen as promising mode for study due to clean $\gamma\gamma$ signature (clean trigger, excellent mass resolution)
- Final measurement will use combination of final states
  - $bb\tau\tau$, 4b and others are also under study, not yet approved within ATLAS

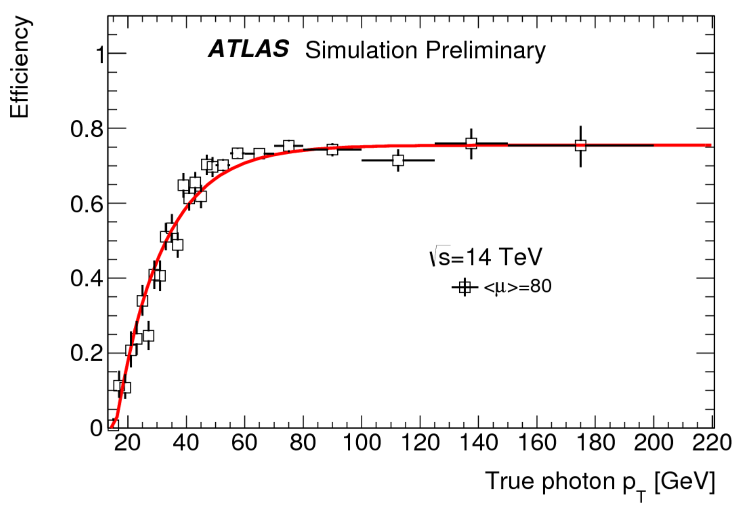
What about bbWW?

- Have seen in earlier talk that bbWW may still provide some sensitivity
- This was looked at in 2012 by ATLAS ahead of `European Strategy for Particle Physics' preparation
  - Looked at semi-leptonic channel
  - Require exactly 1 lepton, at least 4 jets (at least one b-tagged). missing transverse momentum
  - Chi^2 fit technique to reconstruct W and Higgs masses, then apply mass requirements
- Before any smearings or efficiencies applied S/B is of order 10^{-5}
  - Final state identical to tt
  - Looks very prohibitive
- Analysis cuts can reduce backgrounds by ~2 orders of magnitude
  - ...but signal also suffers
- Concluded from these studies that no reasonable sensitivity is possible

HL-LHC performance & object definitions

- Full simulation not available for signal plus all backgrounds under HL-LHC conditions
  - Performance parameterisations extracted from benchmark samples, and applied to generator-level particle 4-vectors
  - ATL-PHYS-PUB-2013-009, ATL-PHYS-PUB-2013-004
  - Momentum smearings, efficiency functions, fake rates, etc...
- Probabilities for e→γ fakes not described in notes
  - After discussion, took assumption that performance will be ~similar to today
  - Apply 2/5 % for barrel/endcap



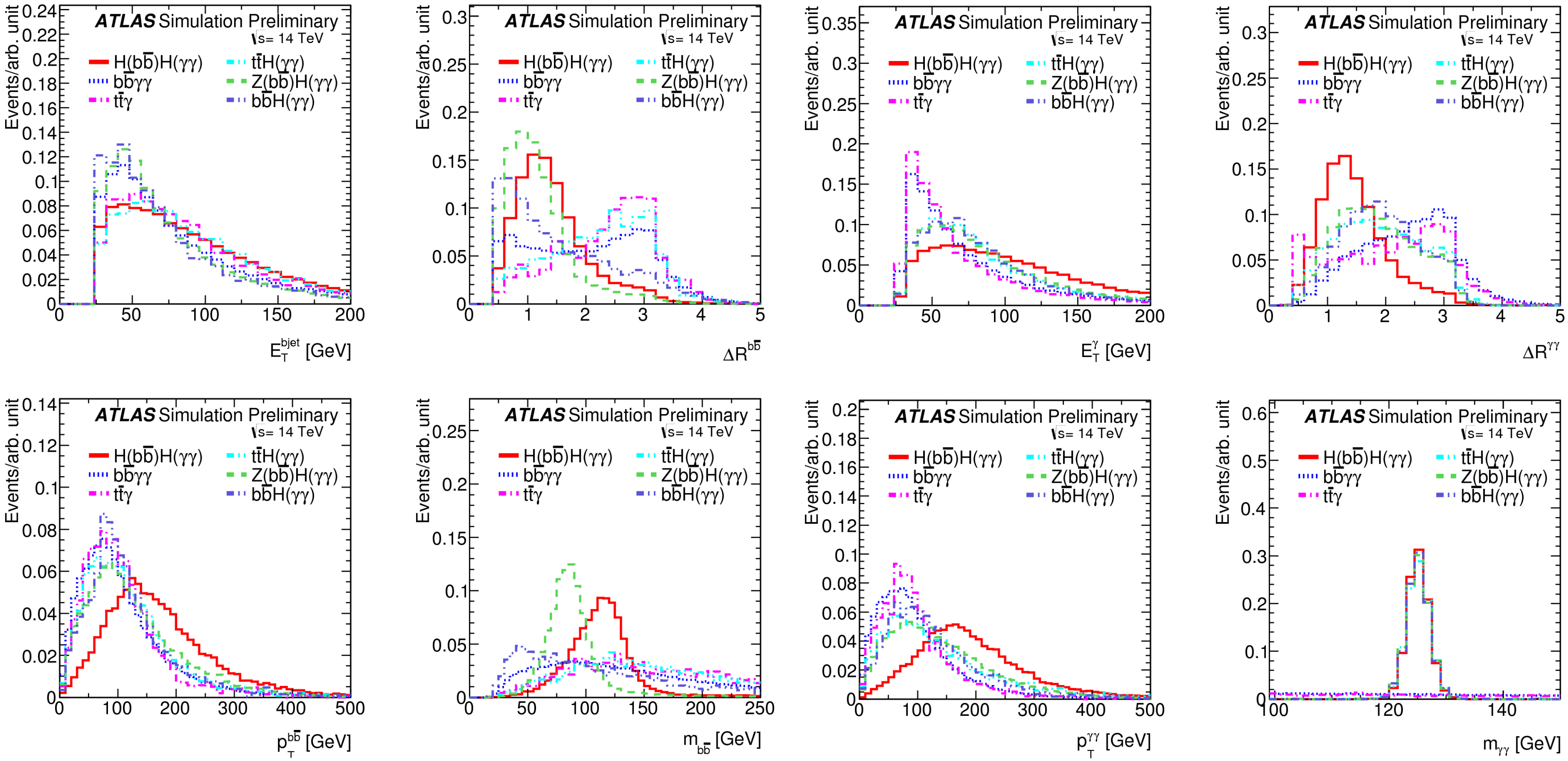


Monte Carlo Samples

Samples	Generated/ Showered With	$\sigma \cdot BR$ (fb)	Order pQCD	Generated Events	Equivalent Lum. (fb^{-1})
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM} = 1)$	MadGraph5/Pythia8	0.11	NNLO	3×10^5	2.8×10^6
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM} = 0)$	MadGraph5/Pythia8	0.23	NNLO	3×10^5	1.3×10^6
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM} = 2)$	MadGraph5/Pythia8	0.05	NNLO	3×10^5	6.1×10^6
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM} = 10)$	MadGraph5/Pythia8	1.81	NNLO	3×10^5	0.2×10^6
$b\bar{b}\gamma\gamma$	MadGraph5/Pythia8	338	LO	4.0×10^6	1.2×10^4
$c\bar{c}\gamma\gamma$	MadGraph5/Pythia8	1.6×10^3	LO	1.8×10^7	1.2×10^4
$b\bar{b}\gamma j$	MadGraph5/Pythia8	2.6×10^5	LO	1.9×10^7	72
$b\bar{b}jj$	MadGraph5/Pythia8	9.4×10^7	LO	4.9×10^5	5.2×10^3
$jj\gamma\gamma$	MadGraph5/Pythia8	2.2×10^4	LO	4.6×10^7	2×10^3
$t\bar{t}(\geq 1$ lepton)	MC@NLO/Herwig	5.3×10^5	NNLO	1.5×10^7	280
$t\bar{t}\gamma$	MadGraph5/Pythia8	3.3×10^3	LO	6.2×10^6	1.9×10^3
$t\bar{t}H(\gamma\gamma)$	POWHEG/Pythia8	1.39	NLO	1.2×10^5	8.4×10^4
$Z(b\bar{b})H(\gamma\gamma)$	Pythia8	0.304	NLO	1.0×10^6	3.3×10^6
$b\bar{b}H(\gamma\gamma)$	MadGraph5/Pythia8	1.32	NLO	7.5×10^5	5.6×10^5

- Signal under several self-coupling scenarios
  - Unless otherwise stated, talking about SM scenario
- 4 main background categories
  - irreducible continuum, reducible continuum, top, and single Higgs

Kinematics

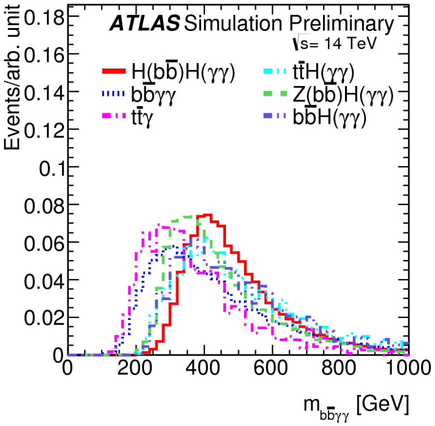


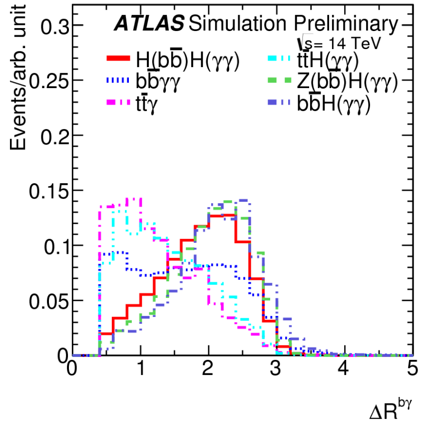
bb system

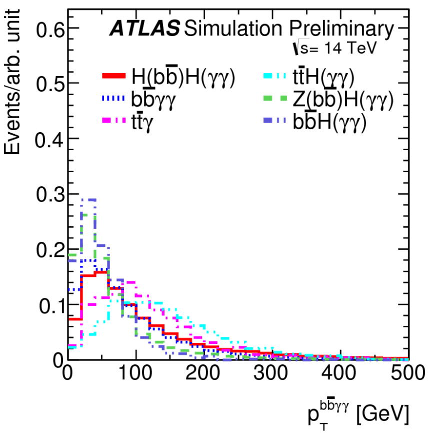
γγ system

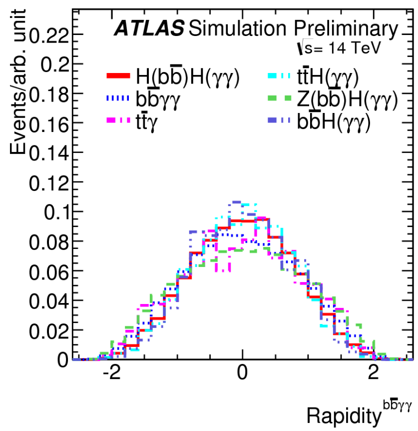
DESY

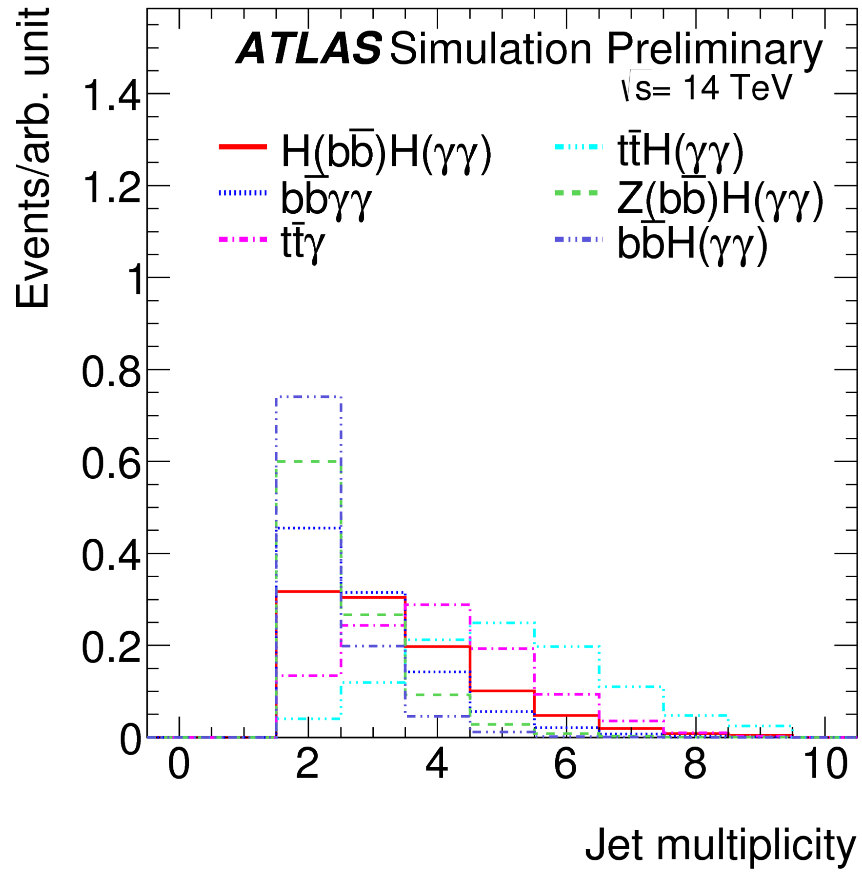
Kinematics











bbγγ system

Selection Criteria

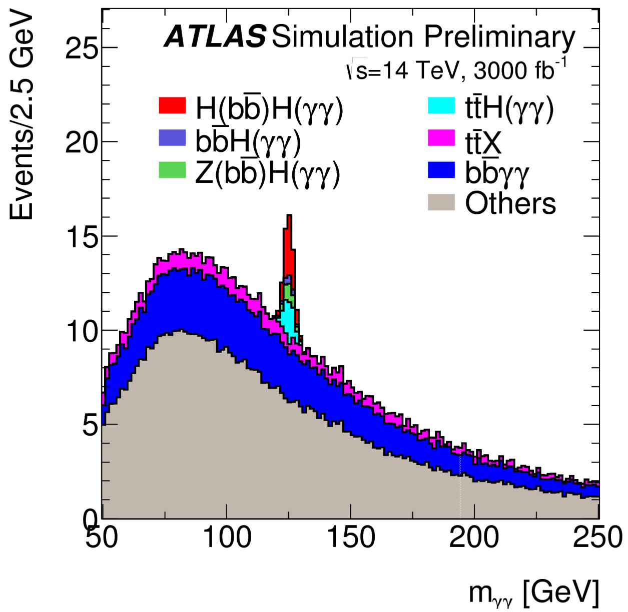
- The following event selection was arrived at following optimisation
  - Mostly optimised S/√(B), but tried to avoid overly tight cuts on parameters where it could reduce sensitivity to self-coupling through restricting the phase space

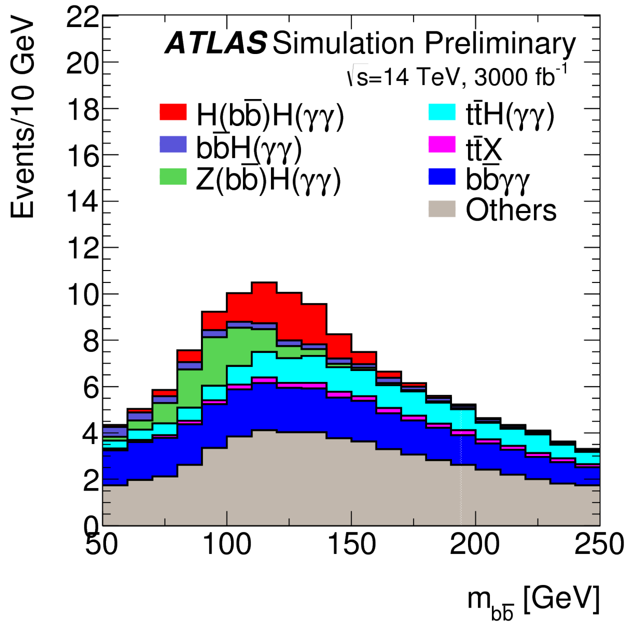
Event Selection Criteria
≥ 2 isolated photons, with $p_T > 30$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$
≥ 2 jets identified as b-jets with leading/subleading $p_T > 40/25$ GeV, $\lvert\eta\rvert < 2.5$
No isolated leptons with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
< 6 jets with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
$0.4 < \Delta R^{b\bar{b}} < 2.0$, $0.4 < \Delta R^{\gamma\gamma} < 2.0$, $\Delta R^{\gamma b} > 0.4$
$100 < m_{b\bar{b}} < 150$ GeV, $123 < m_{\gamma\gamma} < 128$ GeV
$p_T^{\gamma\gamma}$, $p_T^{b\bar{b}} > 110$ GeV

- Also performed cross-check, using selection compatible with Run 1 study
  - After appropriate scalings applied, reasonable agreement with background estimate from Run 1 study

Results

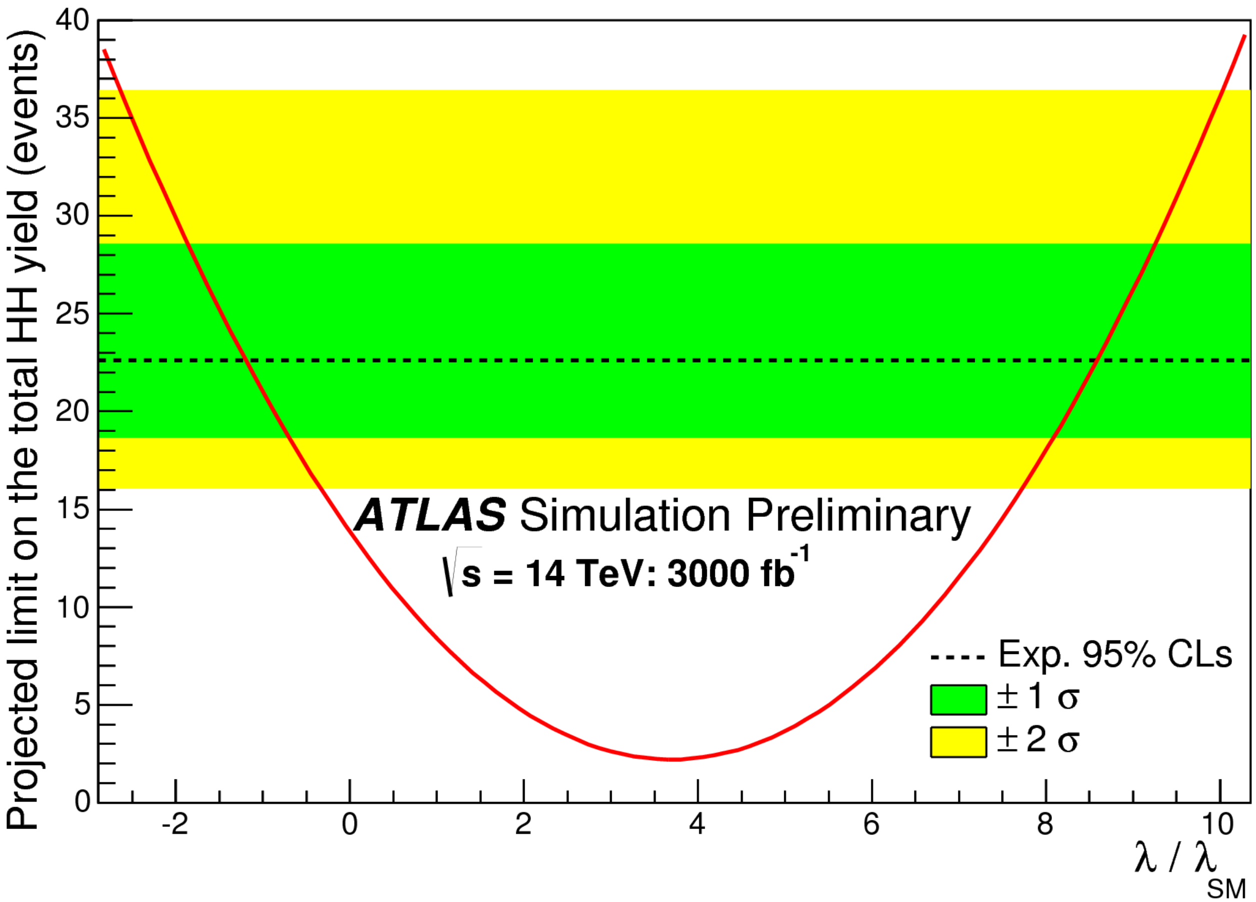
Expected yields (3000 fb^{-1}) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=1)$	8.4±0.1	6.7±0.1	1.8±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=0)$	13.7±0.2	10.7±0.2	3.1±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=2)$	4.6±0.1	3.7±0.1	0.9±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=10)$	36.2±0.8	27.9±0.7	8.2±0.4
$b\bar{b}\gamma\gamma$	9.7±1.5	5.2±1.1	4.5±1.0
$c\bar{c}\gamma\gamma$	7.0±1.2	4.1±0.9	2.9±0.8
$b\bar{b}\gamma j$	8.4±0.4	4.3±0.2	4.1±0.2
$b\bar{b}jj$	1.3±0.2	0.9±0.1	0.4±0.1
$jj\gamma\gamma$	7.4±1.8	5.2±1.5	2.2±1.0
$t\bar{t}(\geq 1$ lepton)	0.2±0.1	0.1±0.1	0.1±0.1
$t\bar{t}\gamma$	3.2±2.2	1.6±1.6	1.6±1.6
$t\bar{t}H(\gamma\gamma)$	6.1±0.5	4.9±0.4	1.2±0.2
$Z(b\bar{b})H(\gamma\gamma)$	2.7±0.1	1.9±0.1	0.8±0.1
$b\bar{b}H(\gamma\gamma)$	1.2±0.1	1.0±0.1	0.3±0.1
Total Background	47.1±3.5	29.1±2.7	18.0±2.3
$S/\sqrt{B}(\lambda/\lambda_{SM}=1)$	1.2	1.2	0.4





- Split events into barrel/endcap categories
  - If one photon has 1.37<|eta|<2.37, endcap
- Overall significance 1.3 σ
  - ('total' column means 'only one category')

Limit Setting



- Based on these results, we should be able to exclude values of the self-coupling strength larger than 8.7xSM, and smaller than -1.3xSM

Summary of Prospects study

- Projected signal significance ~1.3 σ in this channel, for 3000 fb^{-1} of 14 TeV p-p data
  - Tried to make as realistic a projection as possible, including as many major effects as feasible
  - More realistic pile-up treatment now available; can be included for future studies
  - Not very inspiring on its own, but can form a component of a measurement that uses multiple channels (combining results across ATLAS and CMS)
  - Work is ongoing on these other channels
- Number of places where we can potentially improve matters
  - Different b-tagging working points (including specialization for c-jet rejection)
  - Look at Multi-Variate Analysis techniques; very preliminary look suggests ~30% improvement
  - Being considered within context of High-eta extensions of ATLAS tracker upgrade
  - Very open to other suggestions of improvements we could try!

Conclusions

- ATLAS has studied Higgs pair production in Run 1 data as BSM searches
  - No excess found in 4b final state
  - b b final state observes small excess (2σ4) compared to background-only hypothesis in non-resonant search
  - Look forward to Run 2 to see how these results develop in 13 TeV dataset
- Prospect studies for HL-LHC have been undertaken
  - Aim to observe SM Higgs pair production and measure Higgs self-coupling in 3000 fb^{-1} of 14 TeV pp data
  - Important part of foreseen HL-LHC physics program
  - b b study currently available; other channels with which this will form combined measurement under study and results hopefully available soon
  - Use Run 1 and Run 2 experience to improve these studies
  - Suggestions for new avenues to to explore to improve sensitivity, increase realism of projection, or other suggestions, would all be highly welcomed