EWK physics in Run2 at ATLAS:

from first Run2 results to HL-LHC projection

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MBI workshop 26-08-2016

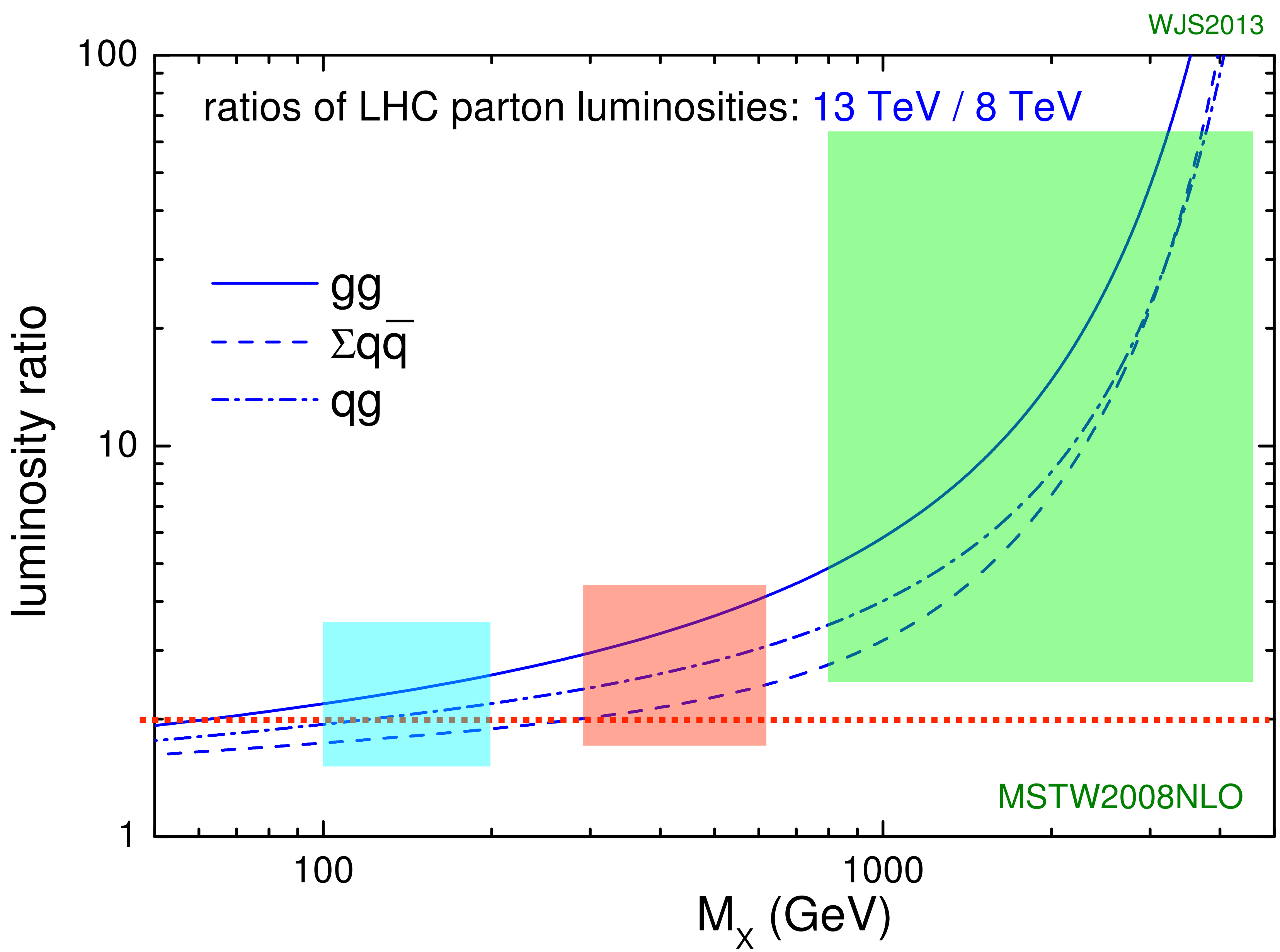
Run1 —> Run2

- **8 TeV —> 13 TeV:** *increase in cross section profits various processes in different ways*

- **Inclusive di-boson, Higgs production (ggF,VH):**
  - 13TeV/8TeV ~ 2
  - 20 fb^{-1} Run1 ~ 10 fb^{-1} Run2

- **top physics, VBS, ttH, HH:**
  - 13TeV/8TeV ~ 3-4
  - 20 fb^{-1} Run1 ~ 5-7 fb^{-1} Run2

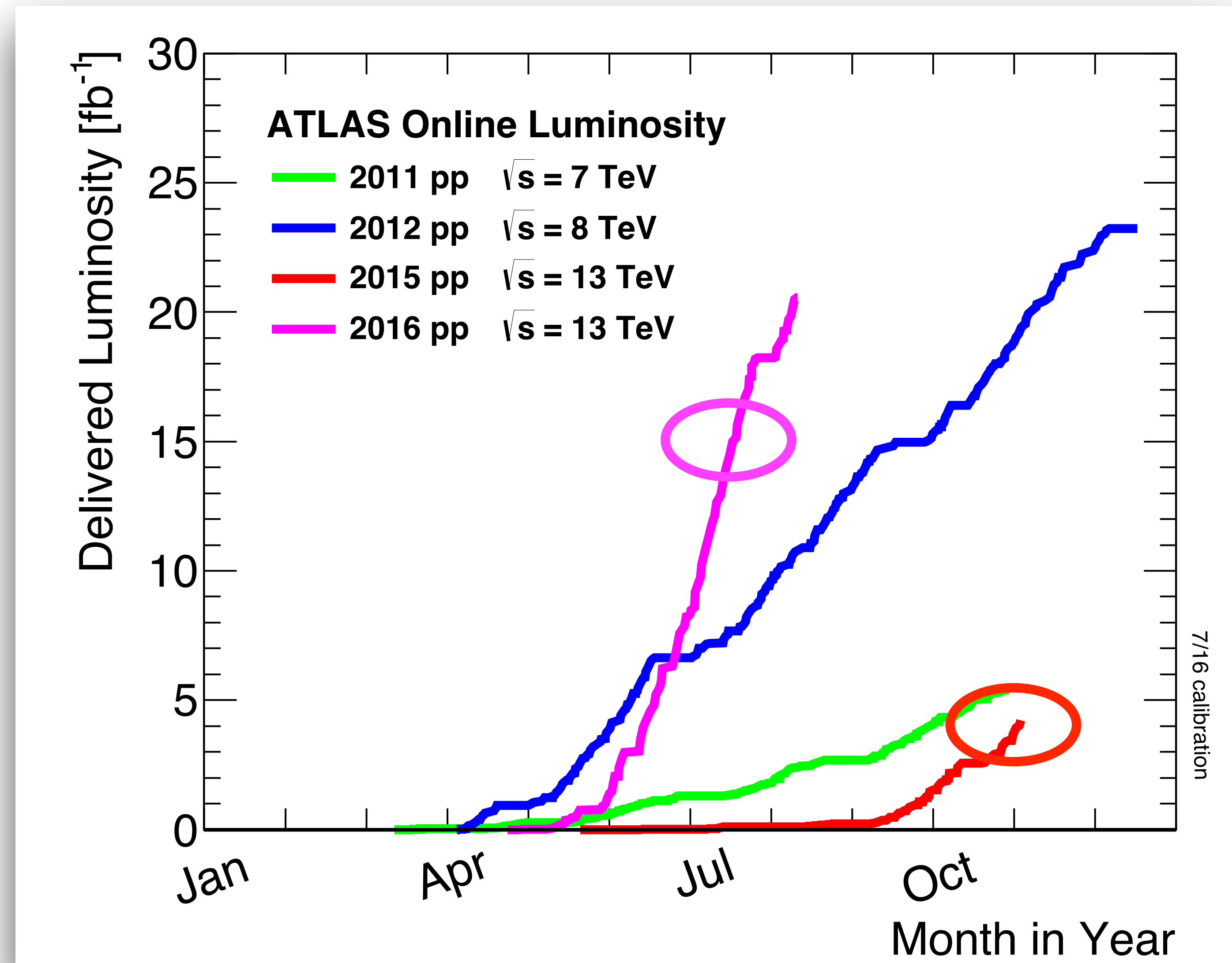
- **new physics state / new physics in tail of distributions:**
  - 13TeV/8TeV > 10
  - 20 fb^{-1} Run1 ~ few fb^{-1} Run2



Statistics is not everything: some time (and data) is needed to reach the same level of detector understanding we had in Run1

Overview

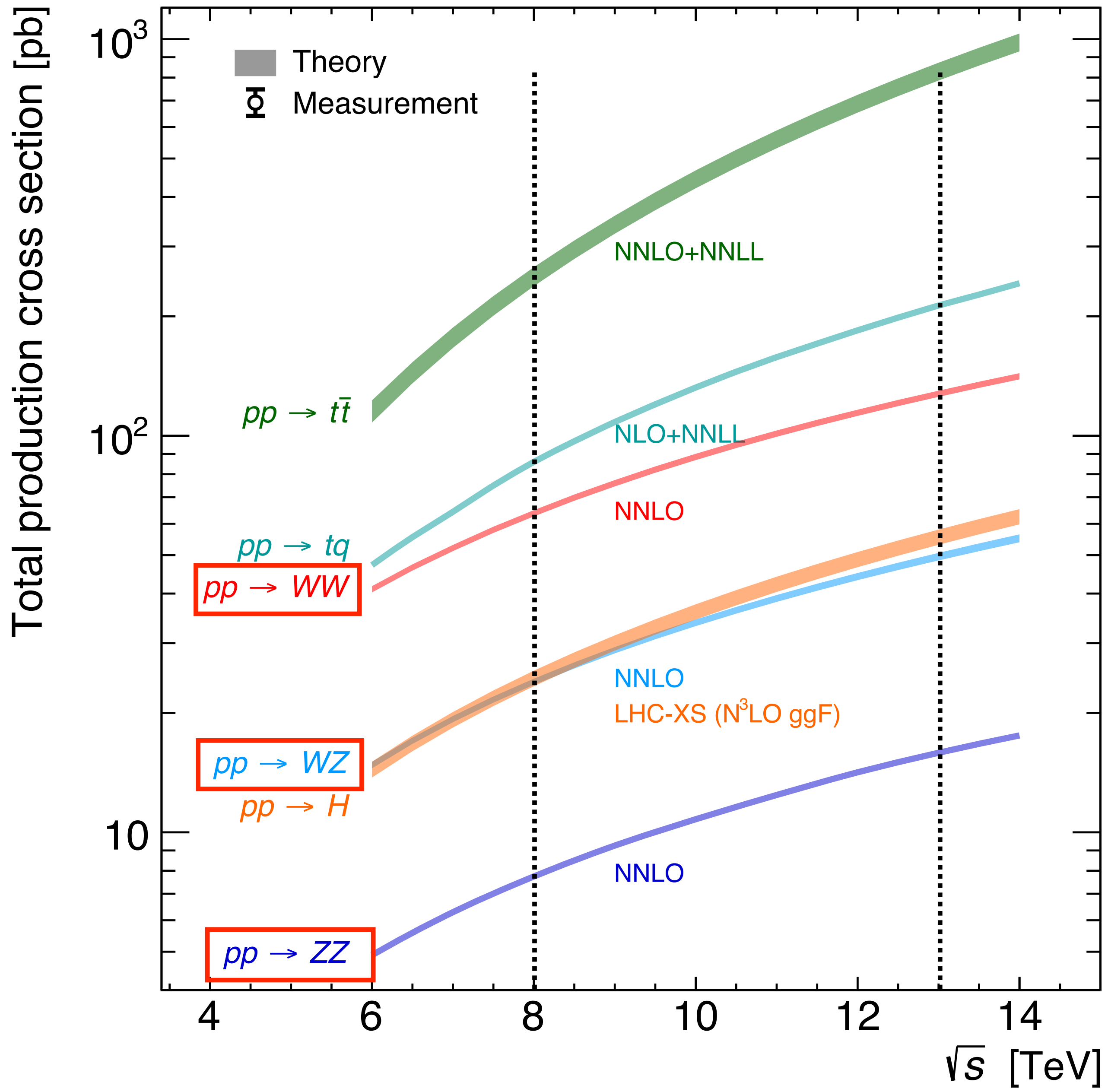
- **Concentrating effort in:**
  - searched for new physics: use as much luminosity as available
  - stat. limited measurements: repeating measurement when similar unc. is achieved
  - sys. limited analyses: trying to assess the impact of systematic uncertainties



- **2015 dataset: 3.2 fb^{-1}**
  - ZZ / WW inclusive cross section
  - HH->bb$\gamma\gamma$

- **2015+2016 (summer) dataset: ~13 fb^{-1}**
  - WZ analysis
  - VBF Higgs cross section
  - HH searches: bbbb, WW$\gamma\gamma$
  - direct search for di-boson resonances

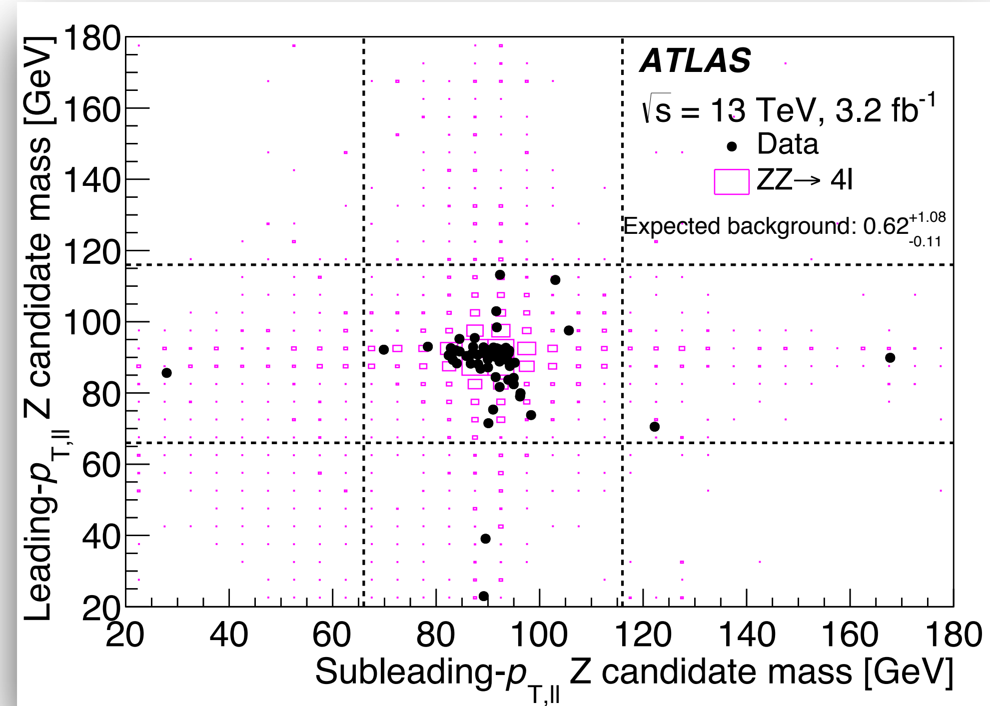
- **More results in Jan Stark's talk later today**

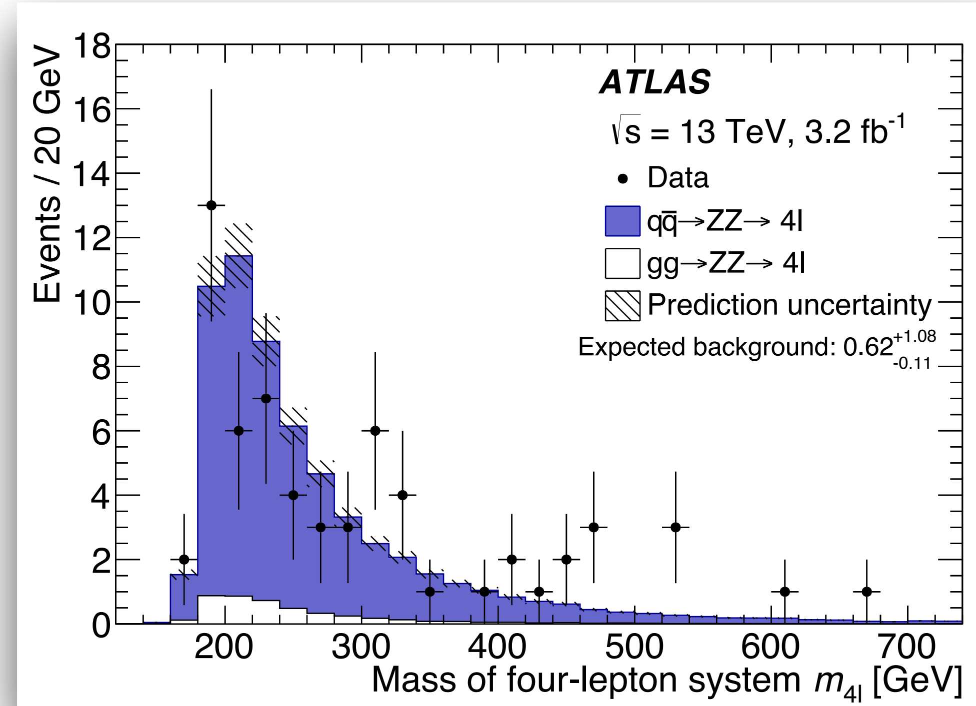


Di-boson physics

VERY first 13 TeV ATLAS EWK result

- **4 leptons** (electrons or muons), **2 on-shell Z bosons** —> very low Br but **exceptionally pure final state**





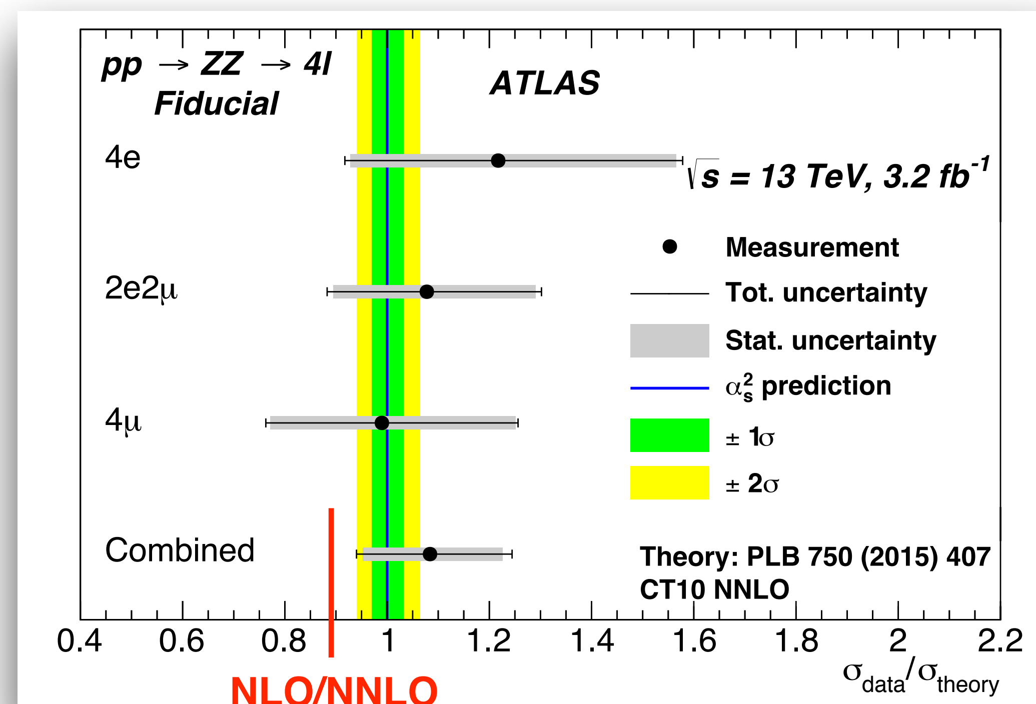
Signal composition in SR:

- qq->ZZ: ***93%*** **,** gg->ZZ: 7*%*

lepton ID

	13%	3%	5%
$\sigma^{\mathrm{fid}}_{ZZ\to\ell^+\ell^-\ell'^+\ell'^-}$ 29.7	$^{+3.9}_{-3.6}$(stat.)	$^{+1.0}_{-0.8}$(syst.)	$^{+1.7}_{-1.3}$(lumi.) fb
Run1 unc. :	***5.6%***	***3.2%***	***2.1%***

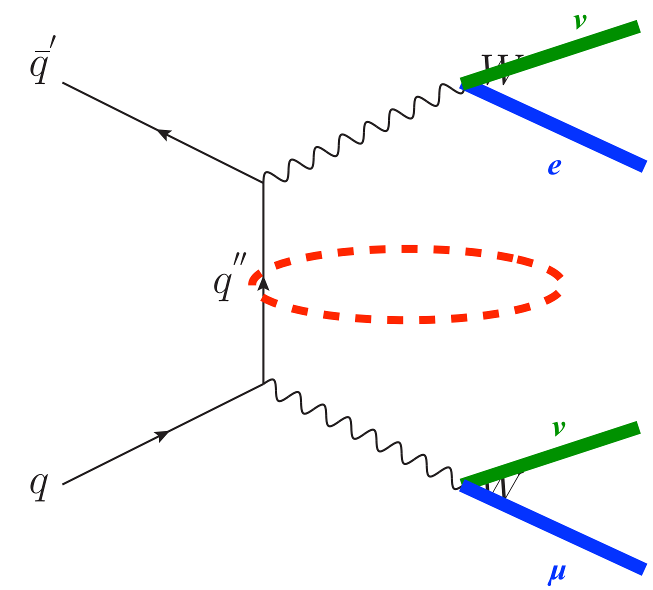
A lot of room for improvements: but mainly need to incorporate more statistics



ATLAS-CONF-2016-090

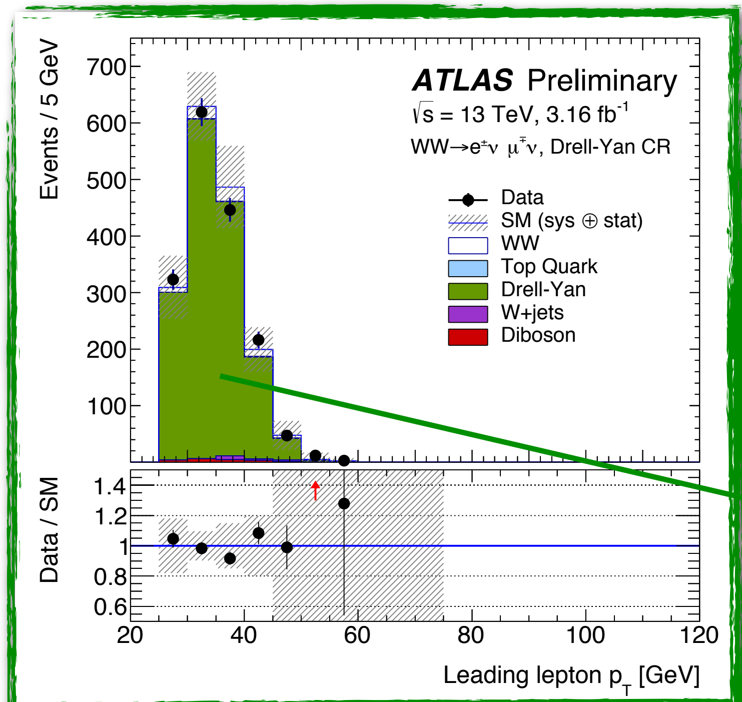
‘simplified’ version of Run1 analysis:

- **electron+muon only:** reduce Drell-Yann background
- **p_T>25GeV on both leptons:** strongly reduce DY and W+jets
- **vetoing on jets** (p_T>25/30 GeV for $|\eta|$<2.5/4.5) **and b-tagged jets** (p_T>20 GeV, $|\eta|$<2.5)



Cut & count analysis:

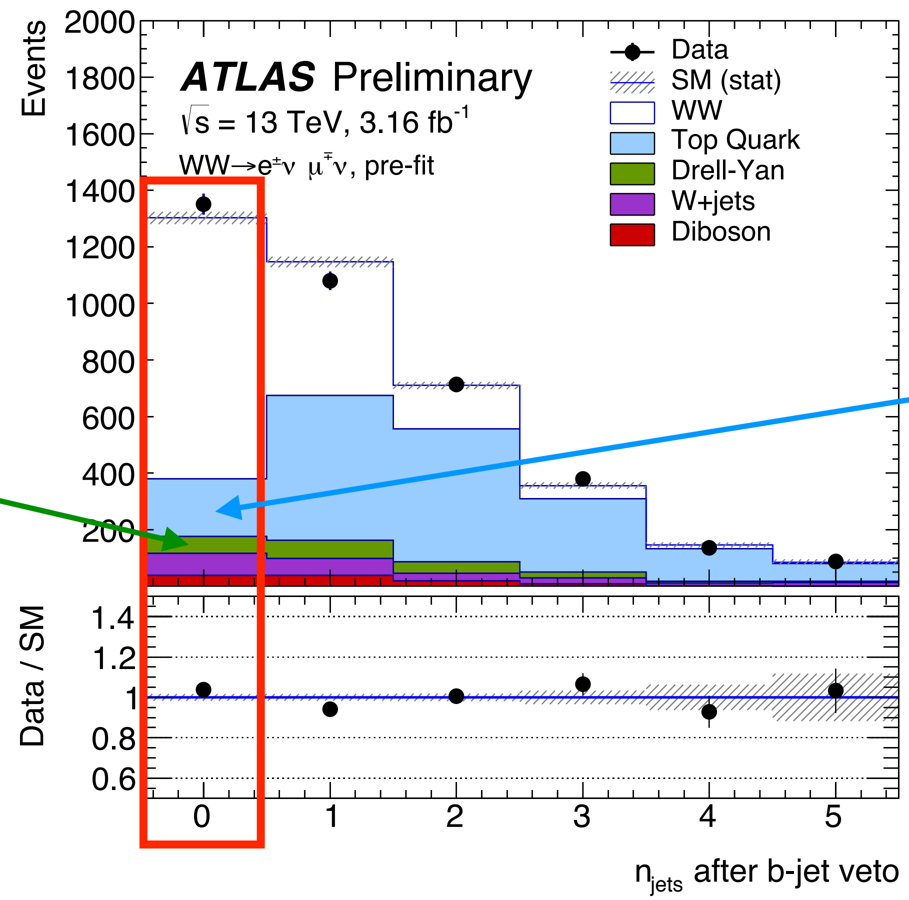
- leading backgrounds ***ttbar+single top***, ***DY(Z->$\tau\tau$)*** normalised in control regions
- small backgrounds ***W+jets*** (data-driven) and ***WZ/ZZ*** (from MC) checked in validation regions

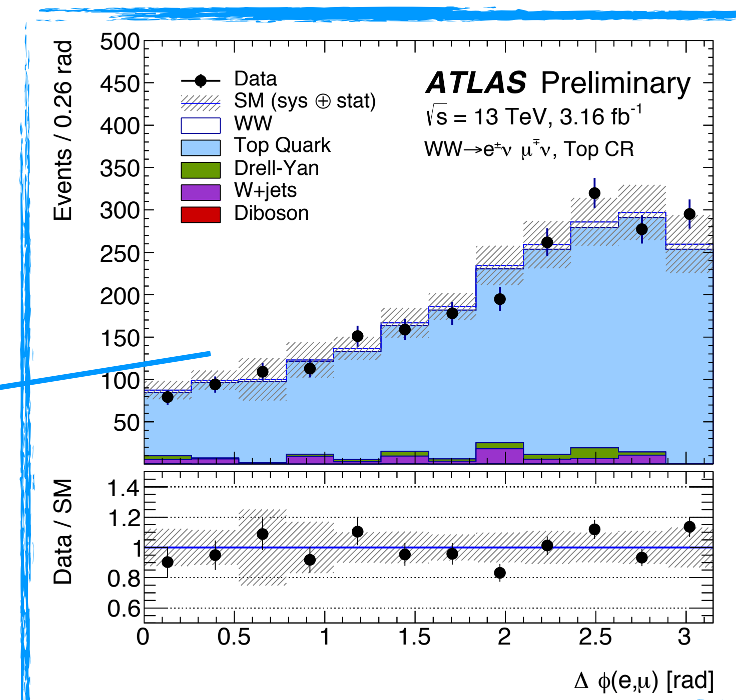


Drell-Yan CR:

45<m_{ll}<85 GeV, anti MET cuts

40% extrap. unc.[MET, MC mod]



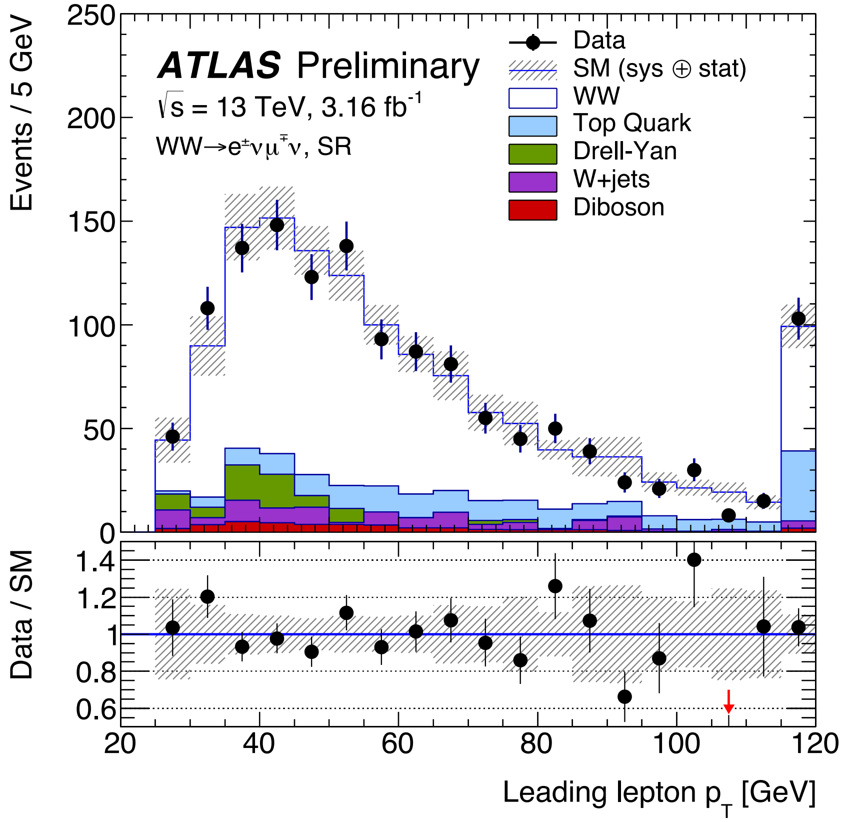


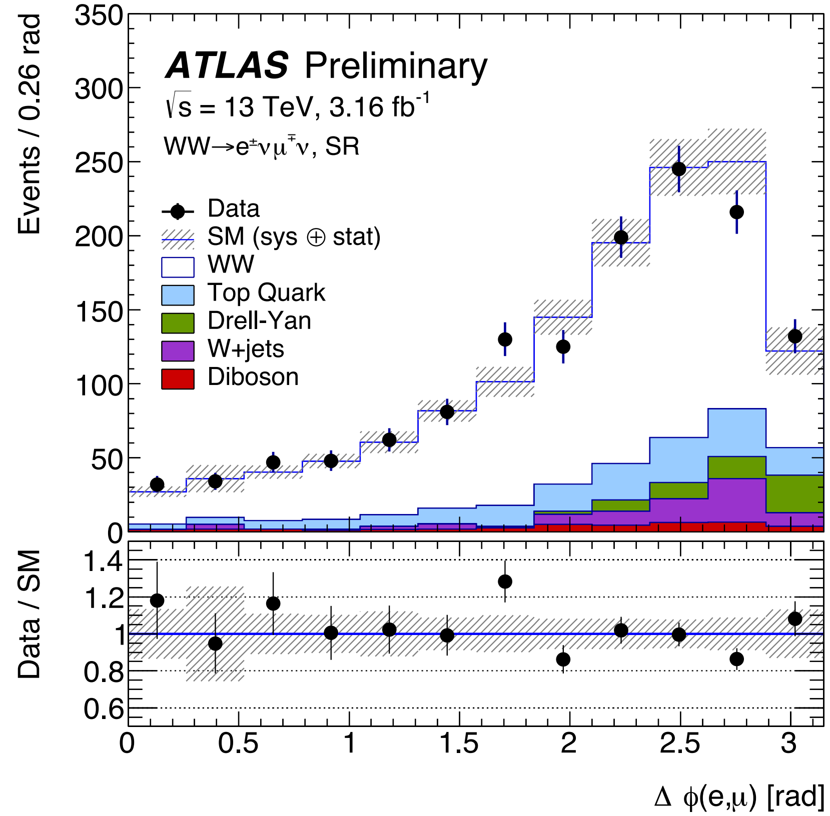
TOP CR:

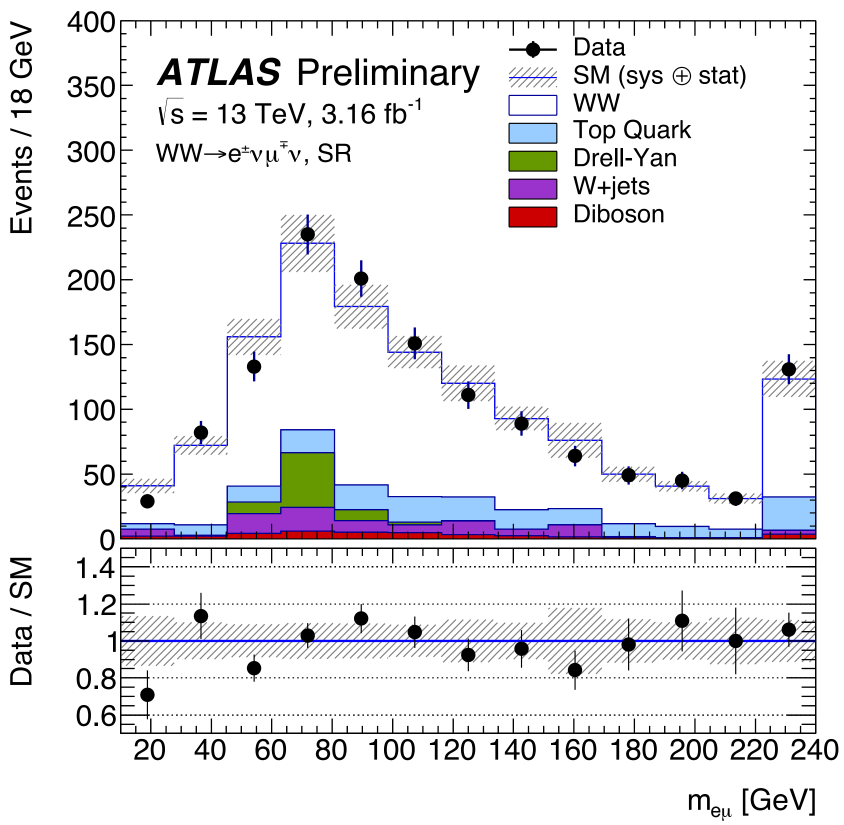
==1 jet, ≥1 b-tagged jet

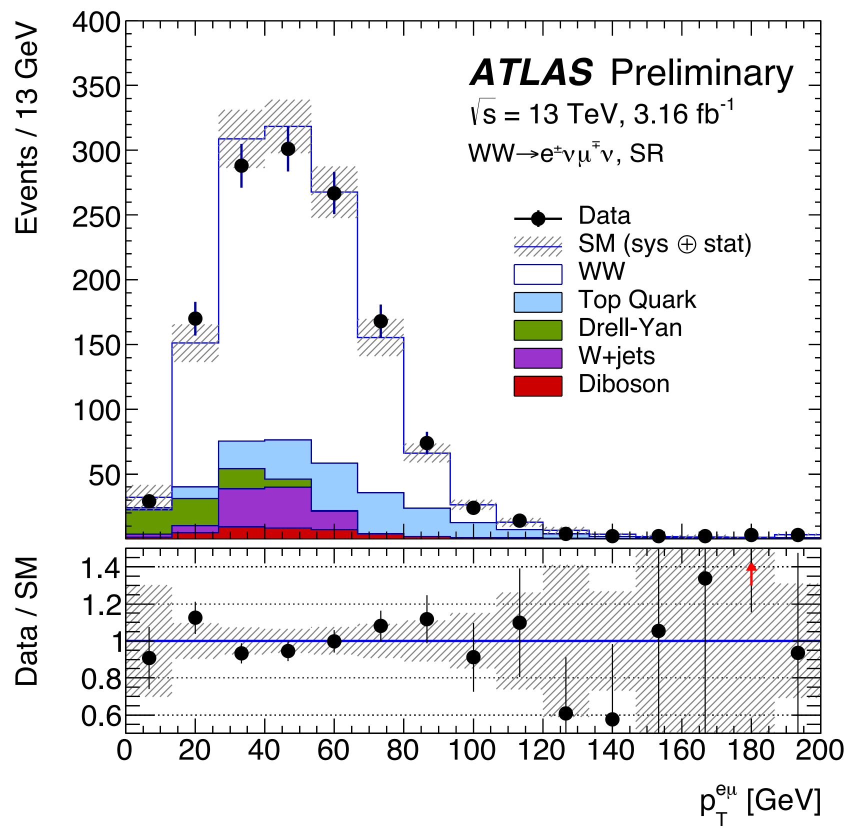
15% extrap. unc.[JES sys+MC mod]

WW @ 13TeV (2)









Signal composition in SR:

- qq->WW: ***92%***
- gg->WW (non res.): ***6%***
- gg->H->WW: ***2%***

- Signal / background scaled to fit predictions

Process	norm. factor
Drell-Yan	1.034 ± 0.030
Top	0.875 ± 0.035

- **Signal predictions scaled up by 8% with respect to MC predictions**

WW @ 13TeV: results

$$\sigma^{\text{fiducial}}_{WW} = \frac{N_{obs} - N_{bkg}}{C_{WW}\,\mathcal{L}}$$

6.6% unc.

$$\sigma^{\text{fid}}_{WW\to e\mu} = 529 \pm 20\,(\text{stat.}) \pm 50\,(\text{syst.}) \pm 11\,(\text{lumi.})\ \text{fb}$$

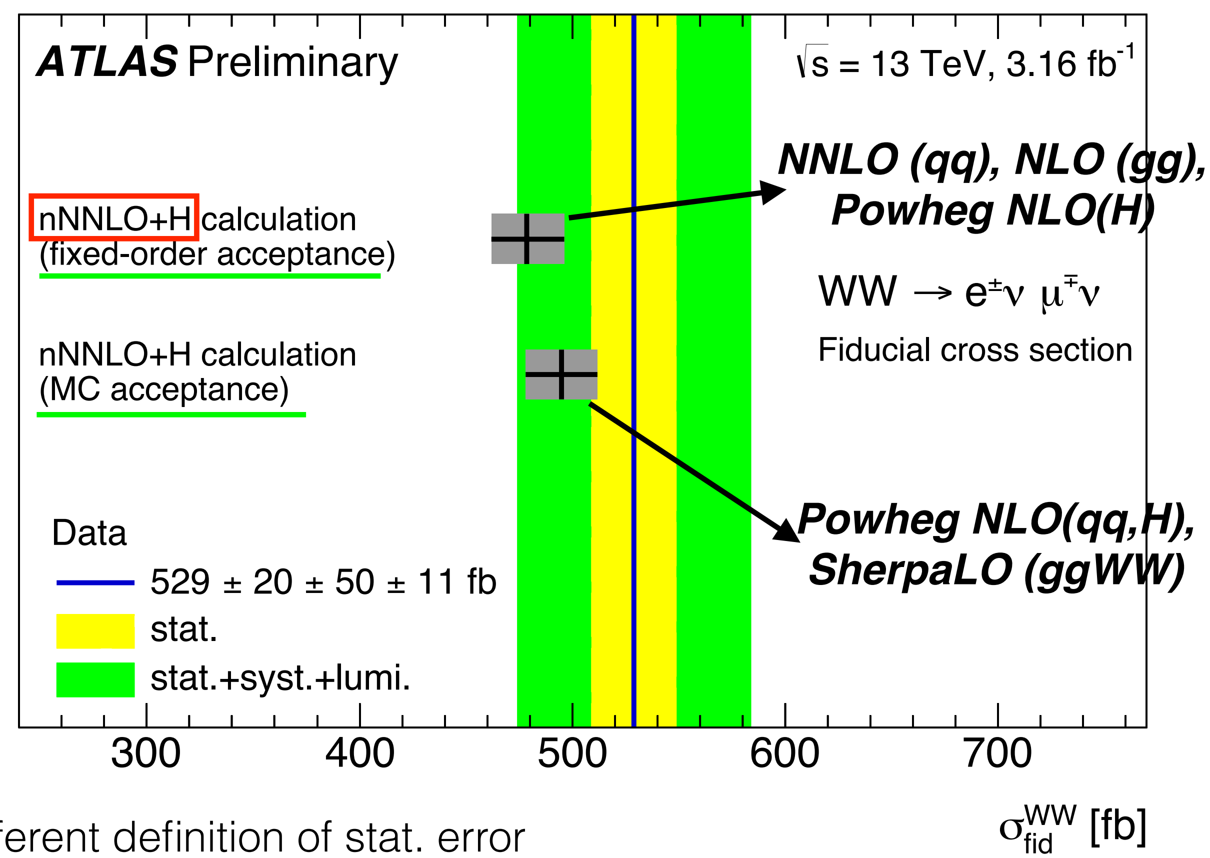
11% uncertainty on fiducial xSection

WW+0jets fid	stat. (*)	det.	bkg.	theo.	lumi
8 TeV	1.5%	5.1%	3.4%	4.5%	2.0%
13 TeV	3.7%	7.5%	4.9%	4.4%	2.1%

Dominant systematic sources: ***JES and W+jets/fake***

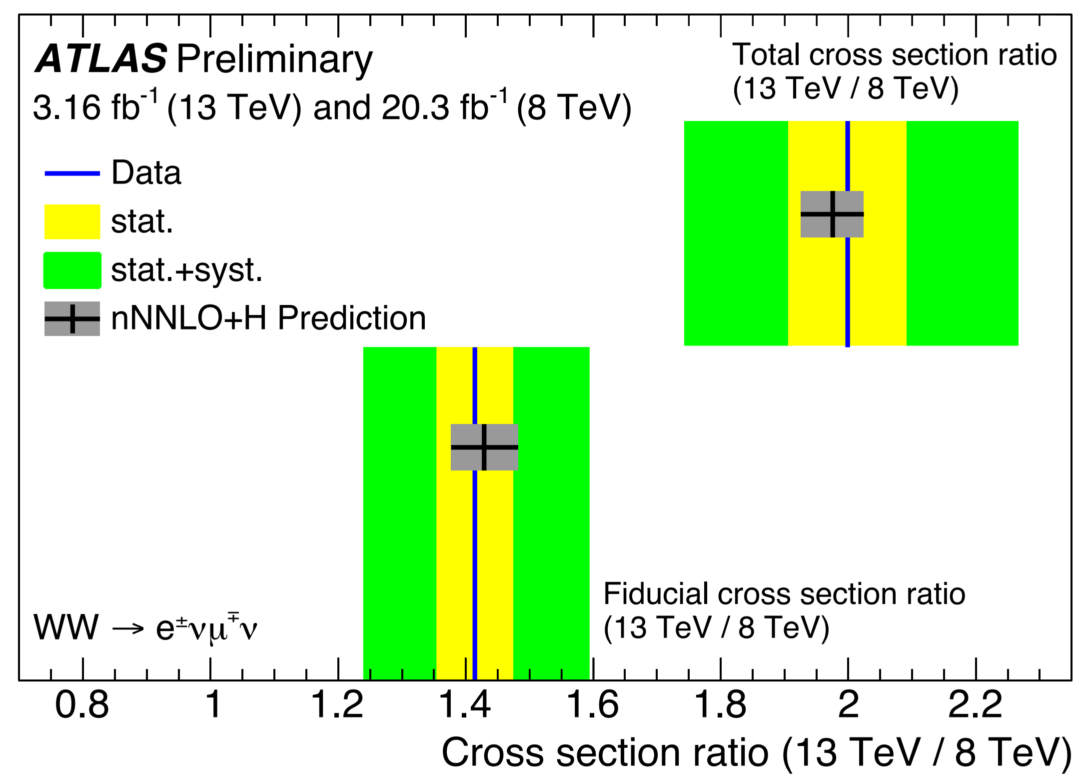
Inclusive nNNLO+H:

qq->WW (NNLO), gg->WW (NLO), H->WW (N3LO)



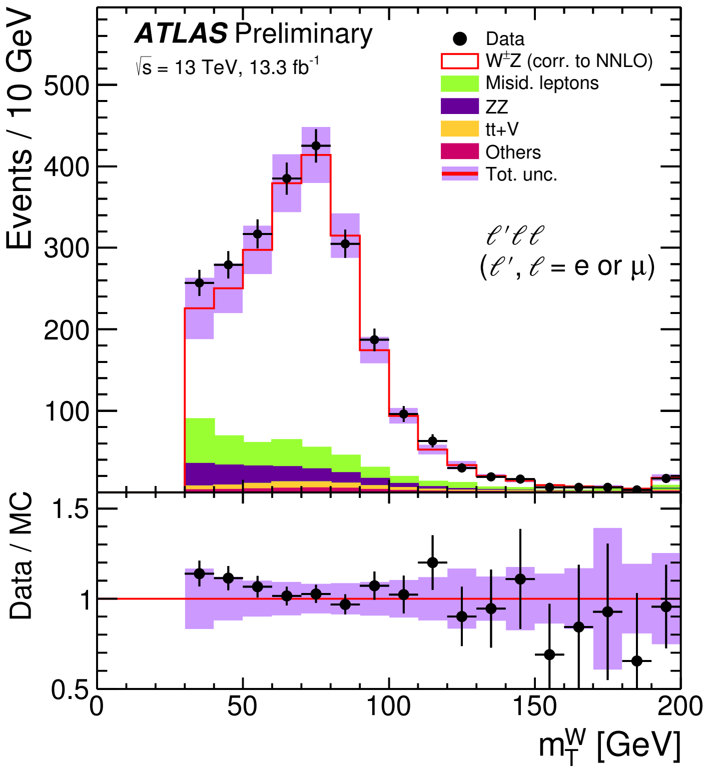
(*) different definition of stat. error

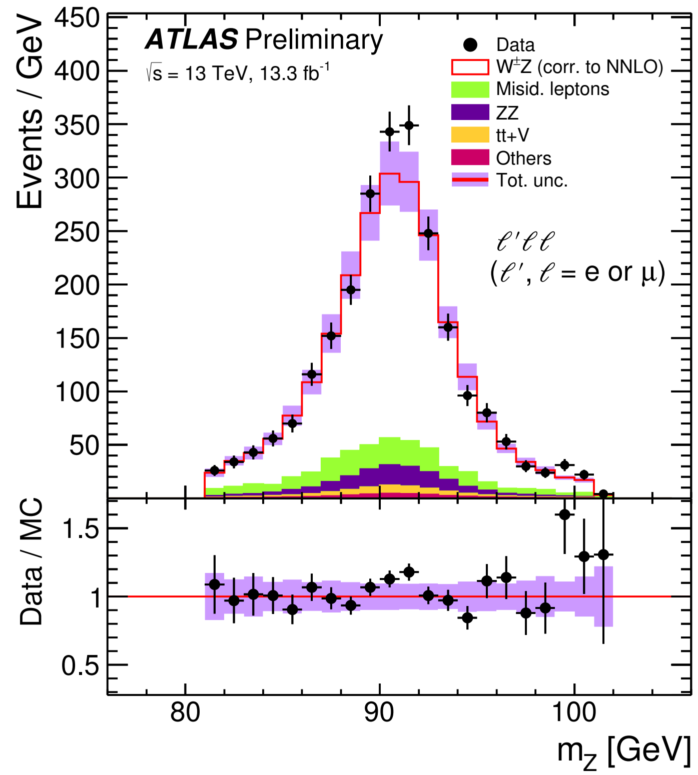
$$\frac{\sigma^{fid}_{13\text{TeV}}}{\sigma^{fid}_{8\text{TeV}}} = 1.41 \pm 0.06\,(\text{stat.}) \pm 0.16\,(\text{syst.}) \pm 0.04(\text{lumi.})$$



Caveat: (yet) no cancellation of detector systematics between 8TeV and 13TeV

WZ @13TeV





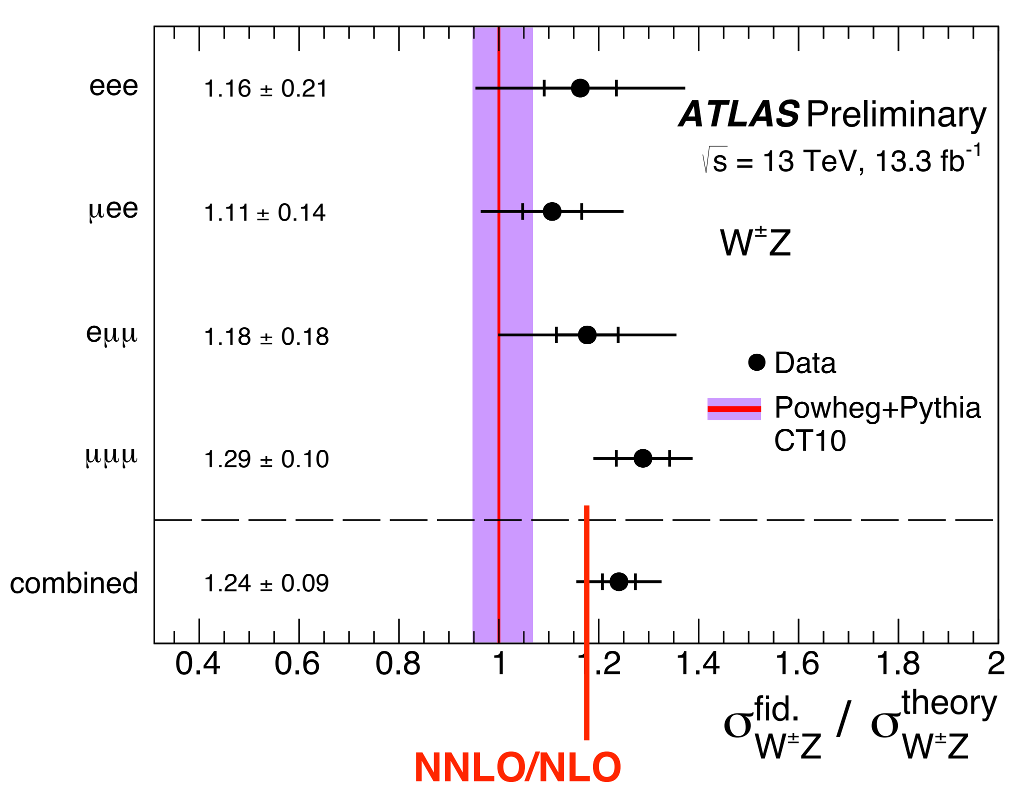
Very clean selection (same as Run1):

- 3 isolated leptons (p_T>25/15/15)
- 1 OSSF pair + M_T cut for 3rd lepton

Main backgrounds:

- ***fake leptons***: data-driven matrix method
- ***ZZ***: MC+ 4lepton validation region

NLO xSection + NLO acceptance



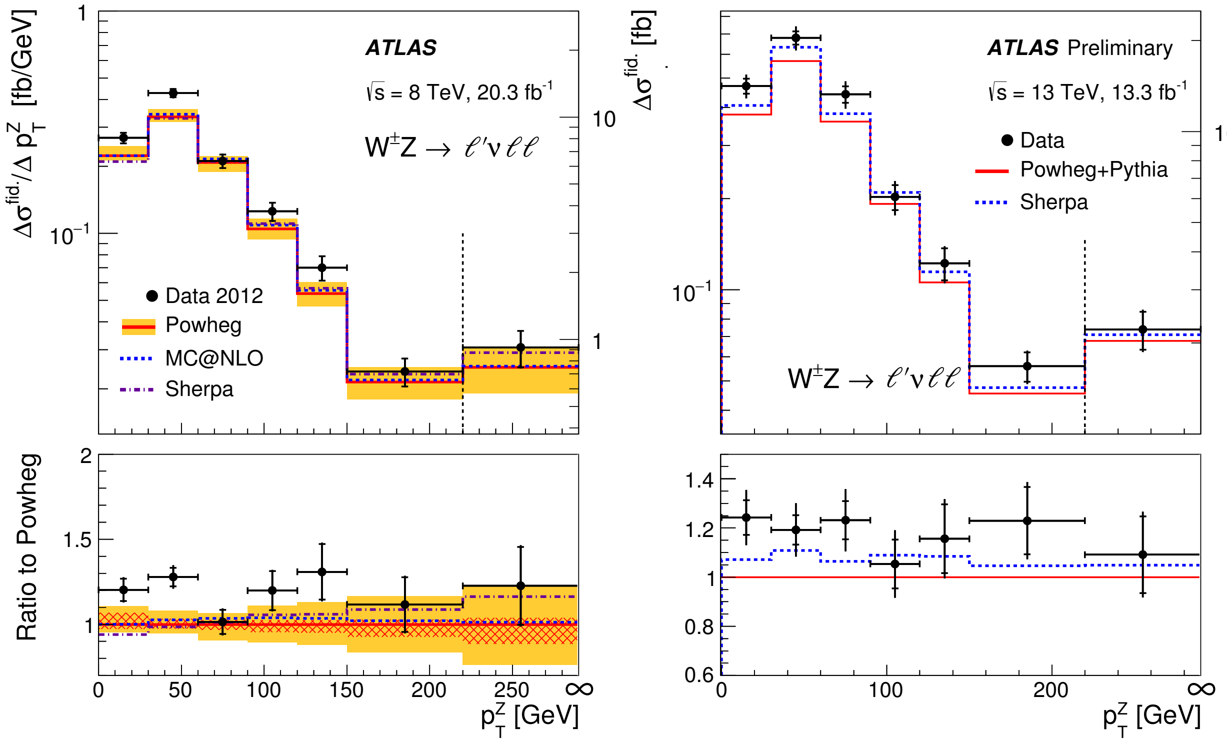
WZ fid.	stat.	sys.	lumi	*tot*
8 TeV	2.7%	2.4%	2.2%	*4.2%*
13 TeV	2.7%	5.5%	3.2%	*6.9%*

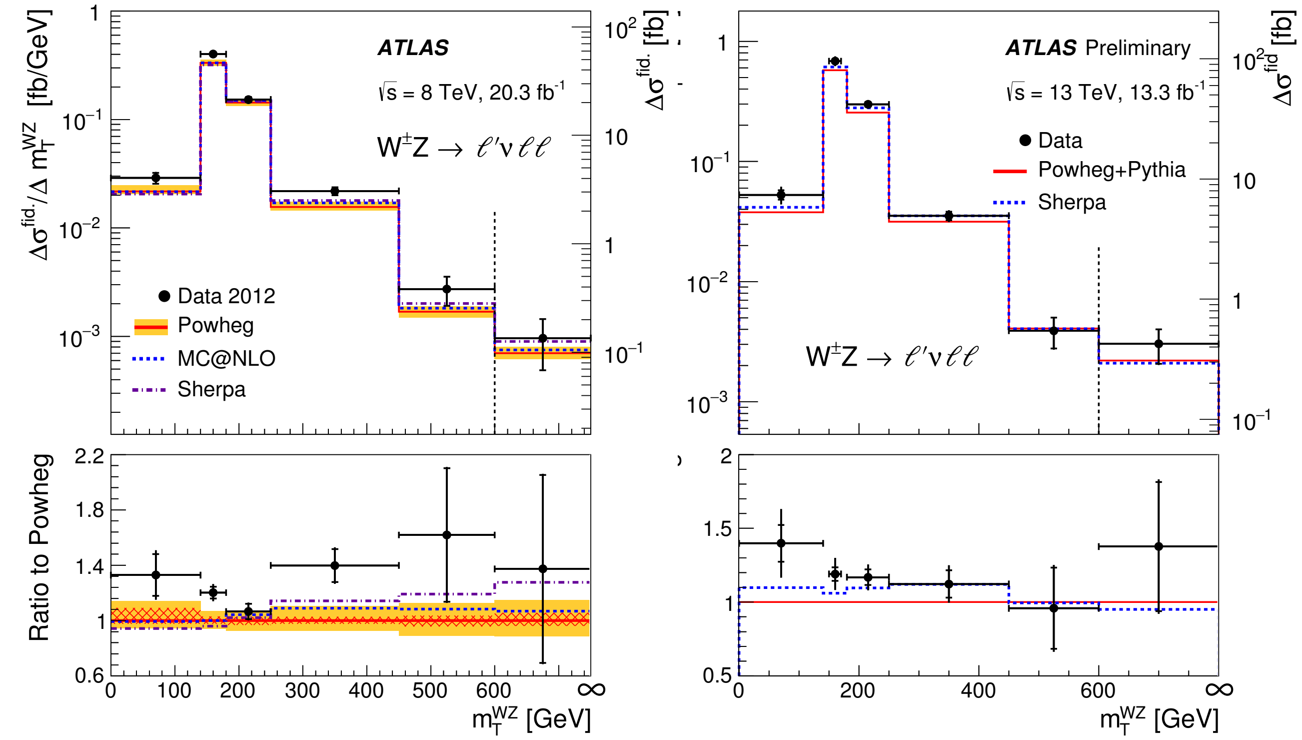
leading uncertainties from events with electrons:

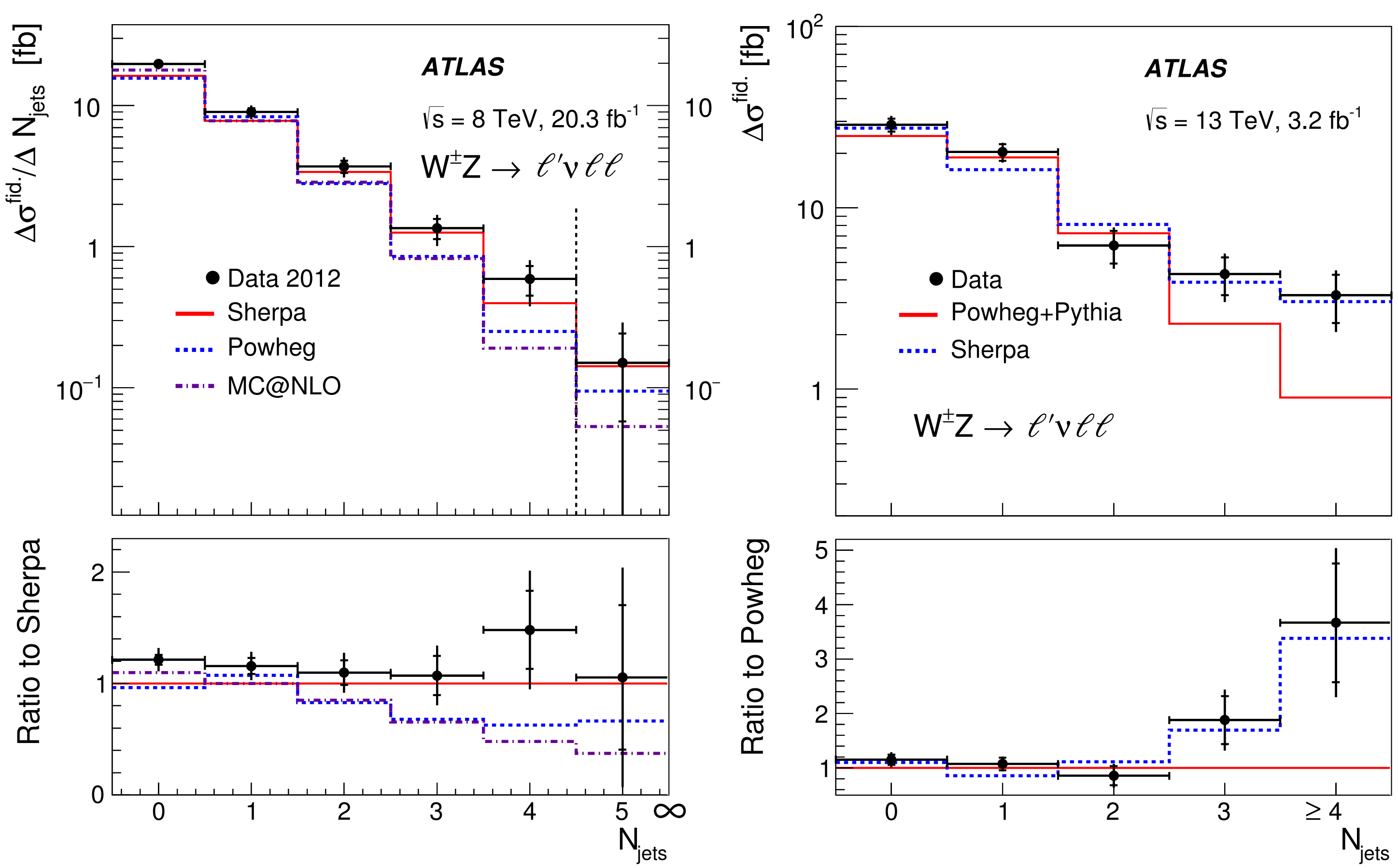
- electron ID, fake background

Excess w.r.t. NLO predictions largely mitigated when moving to NNLO inclusive cross section

WZ @13TeV: differential







Similar precision between Run1 and Run2:

- consistent trend in data/MC
- similar performance after generator changes:
  - Powheg V1->Powheg V2
  - Sherpa 1.4.5 —> Sherpa 2.1.1

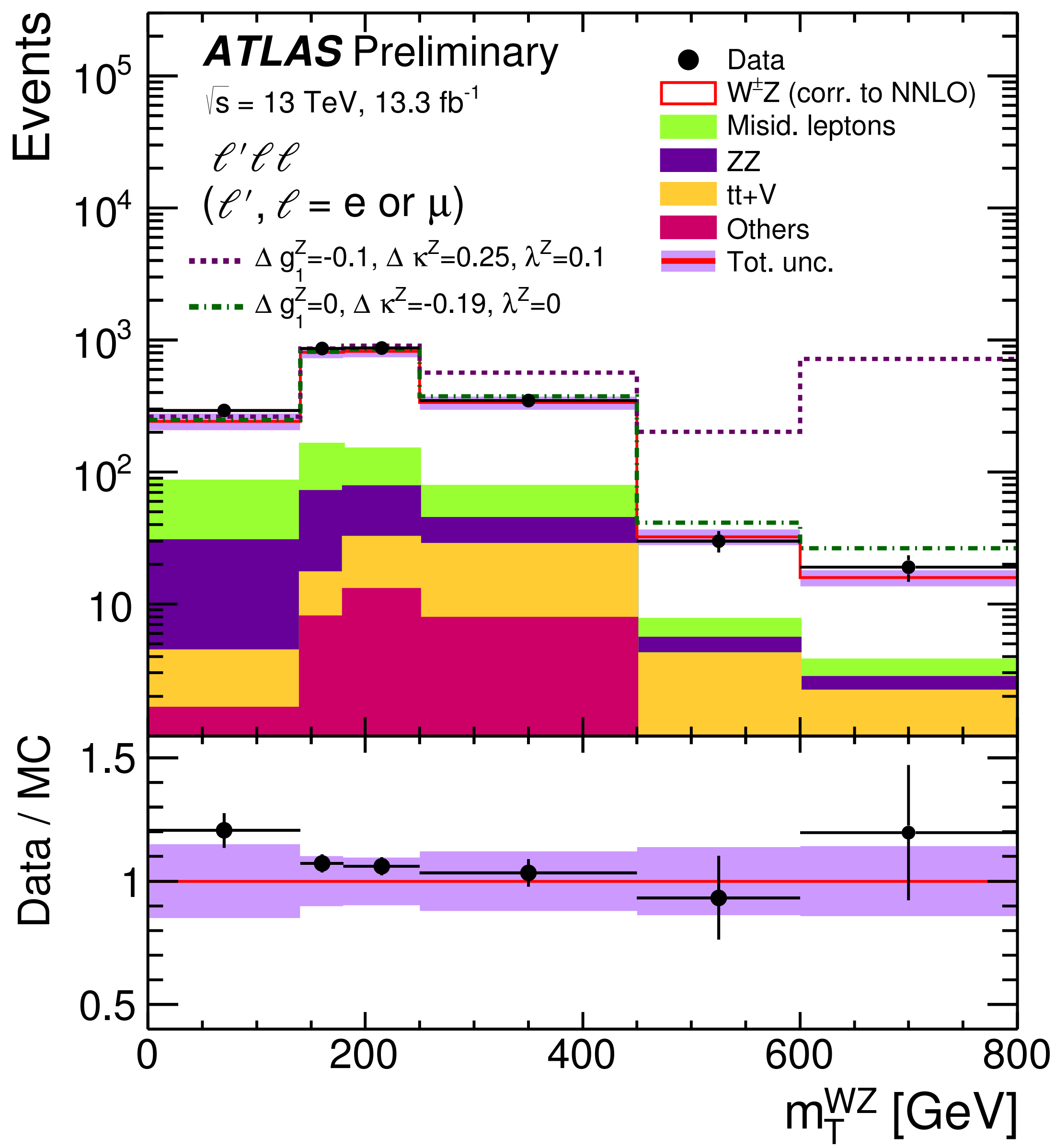
~~***Need multi-leg generators for N_{jet} description:***~~

- ~~jets: p_T>25 GeV, $|\eta|$<4.5~~

WZ @13TeV: aTGC

(As in Run1) extracting aTGC limit from template fit to m_T^{WZ} distribution:

- effects mainly in the tails
- up to 8% Powheg VS MC@NLO difference

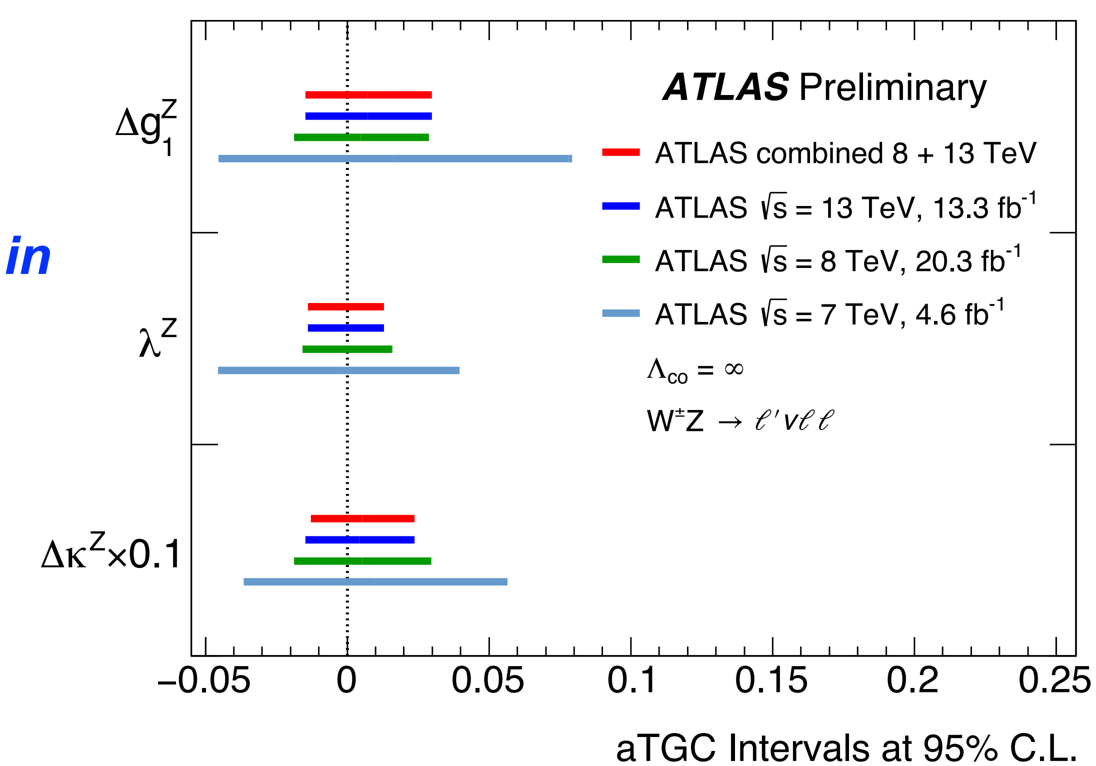


Similar performance between Run1 and Run2 analyses:

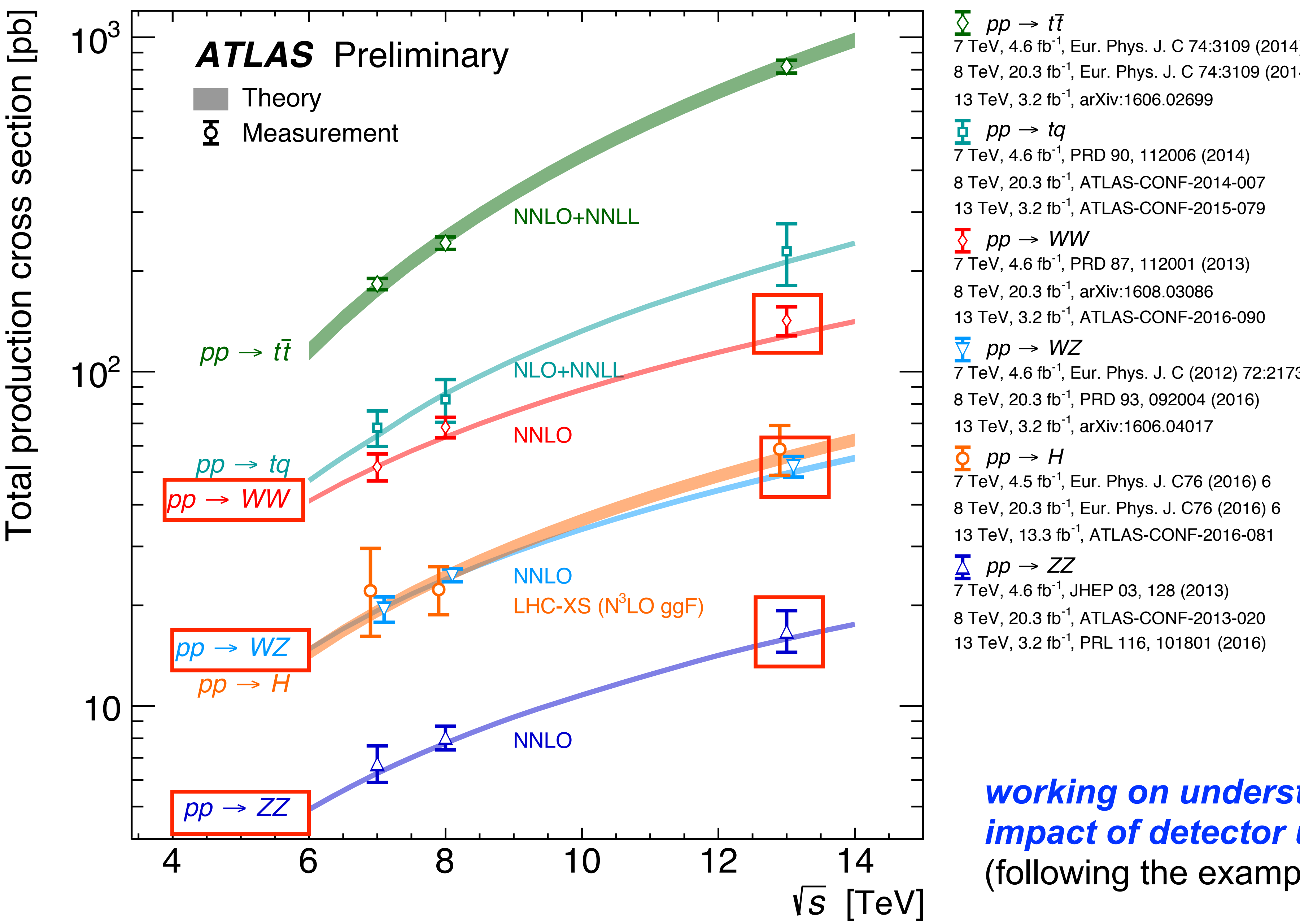
- combination performed by correlating theory sys and treating detector sys as uncorrelated

Dataset	Coupling	Expected $[\mathrm{TeV}^{-2}]$	Observed $[\mathrm{TeV}^{-2}]$
13 TeV	c_W/Λ^2_{NP}	[-4.1; 7.6]	[-3.8; 8.6]
	c_B/Λ^2_{NP}	[-261; 193]	[-280; 163]
	c_{WWW}/Λ^2_{NP}	[-3.6; 3.4]	[-3.9; 3.7]
8 and 13 TeV	c_W/Λ^2_{NP}	[-3.4; 6.9]	[-3.6; 7.3]
	c_B/Λ^2_{NP}	[-221; 166]	[-253; 136]
	c_{WWW}/Λ^2_{NP}	[-3.2; 3.0]	[-3.3; 3.2]

Up to 20% improvements in limit on aTGC from the combination



Di-boson physics in Run2: looking ahead



ZZ analysis is still statistically limited: already 6 times more statistics already recorded and ready to be analysed

WZ analysis starts to be limited by the knowledge of reducible background: more statistics will also increase the possibility of data-driven tests

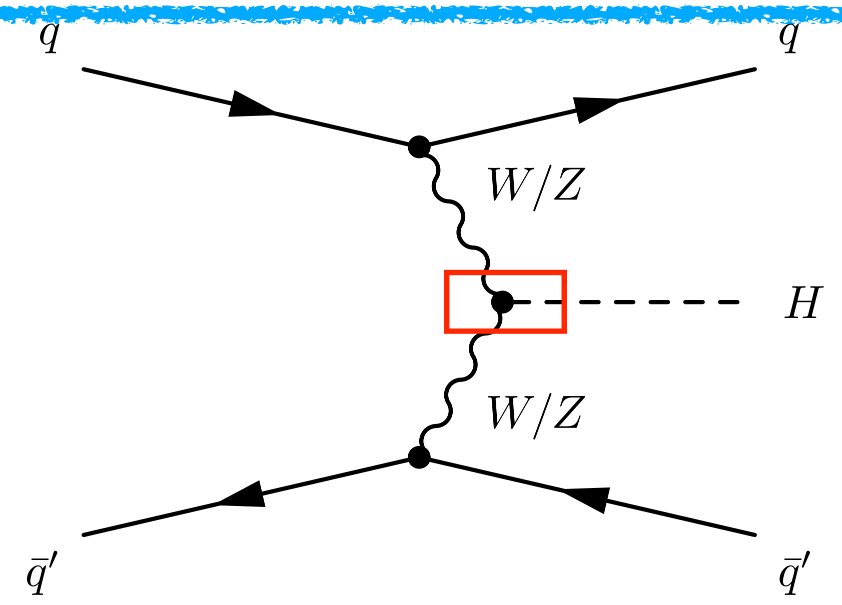
WW is limited by detector systematics (mainly by jet energy scale uncertainty and jet veto): increasing p_T cut, more sophisticated background estimation techniques

working on understanding correlation to reduce the impact of detector uncertainties in the 13TeV/8TeV (following the example of 7TeV/8TeV top mass combination)

Fortunately(/unfortunately) results are very consistent between Run1 and Run2***: confirming agreement between data and MC when higher order calculation are considered***

VBF Higgs production

5.4 observed significance with Run1 data (ATLAS+CMS)



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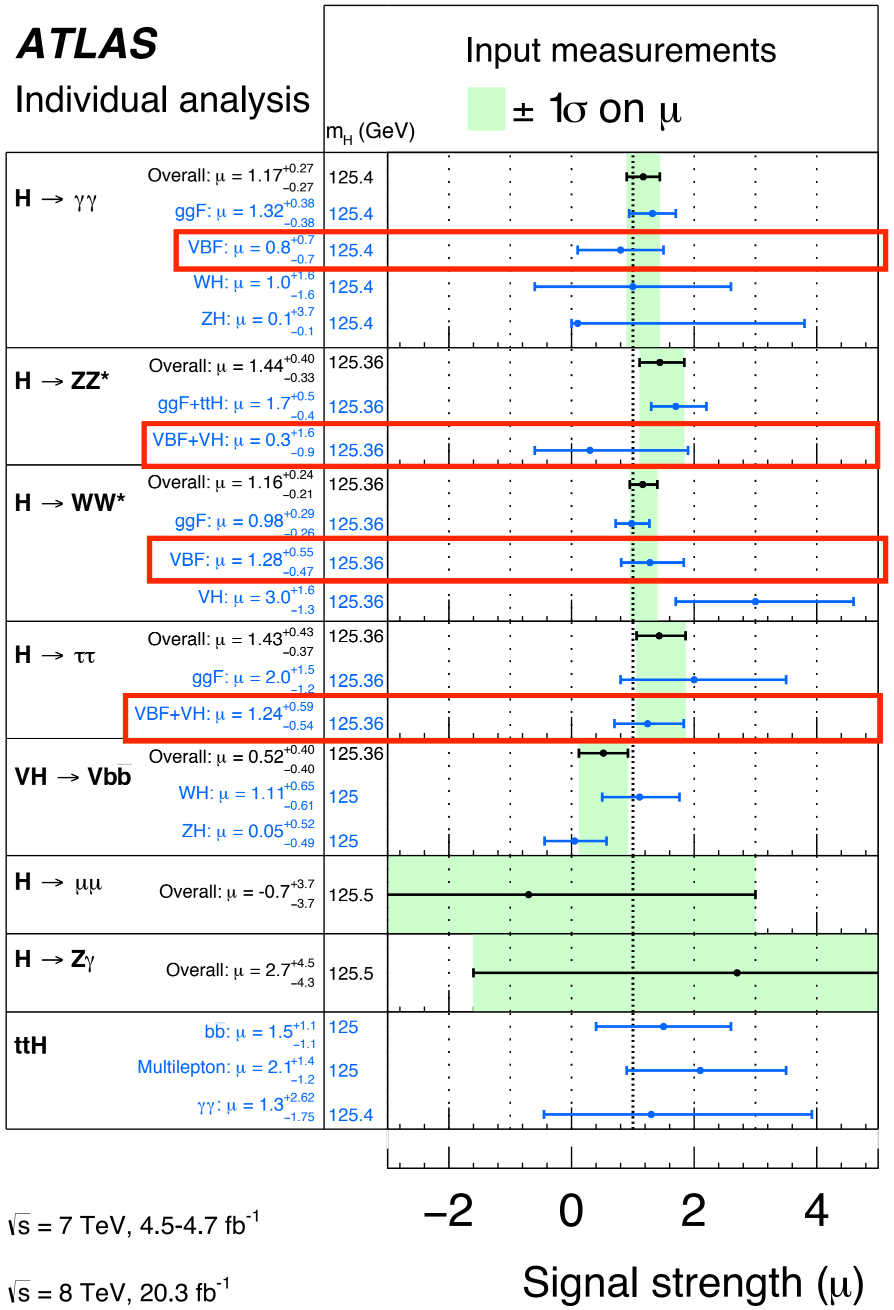
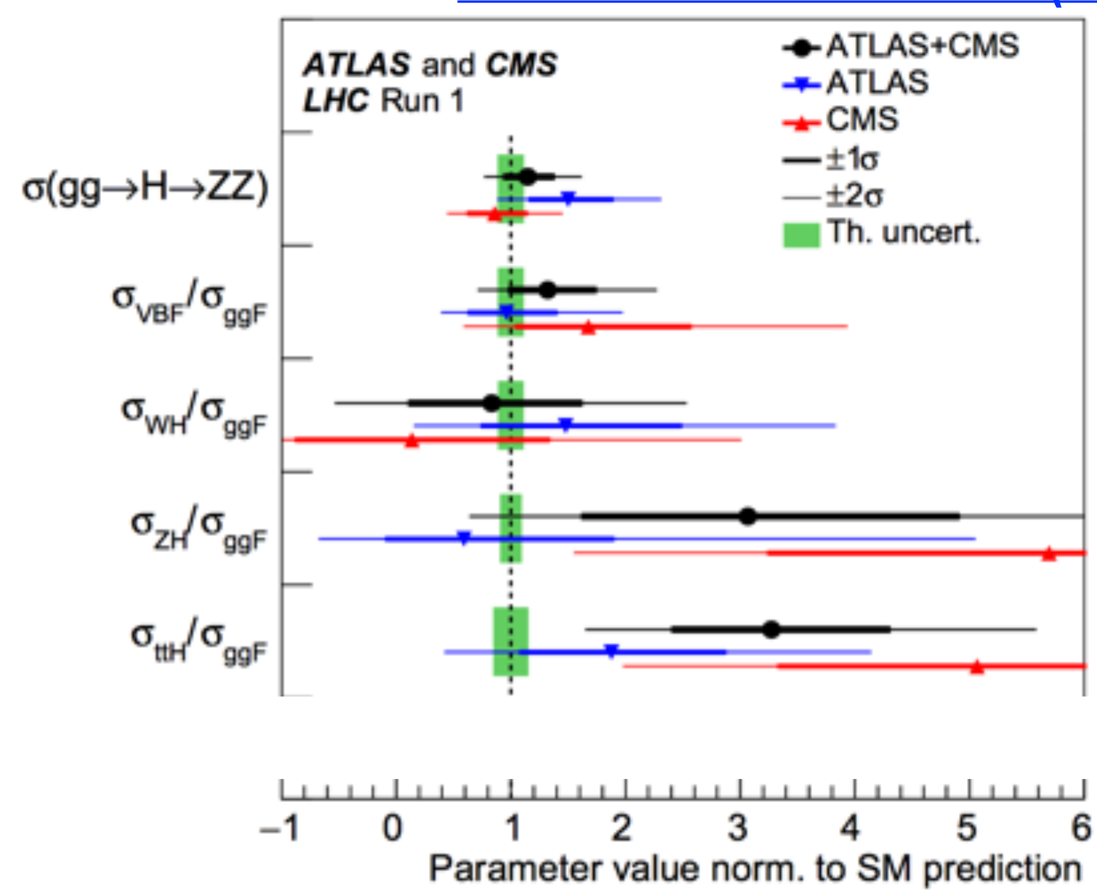


[ATLAS-CMS combination (1606.02266)]

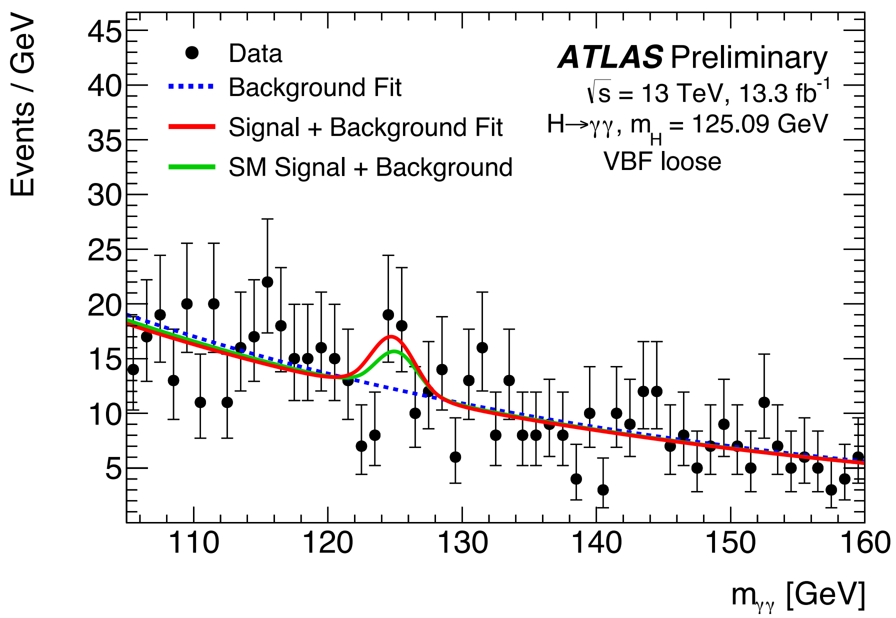


VBF Higgs production

Standard selection for Higgs candidate + ***optimised categories for VBF***: at least 2 jets, large ΔY_{jj} and large m_{jj}

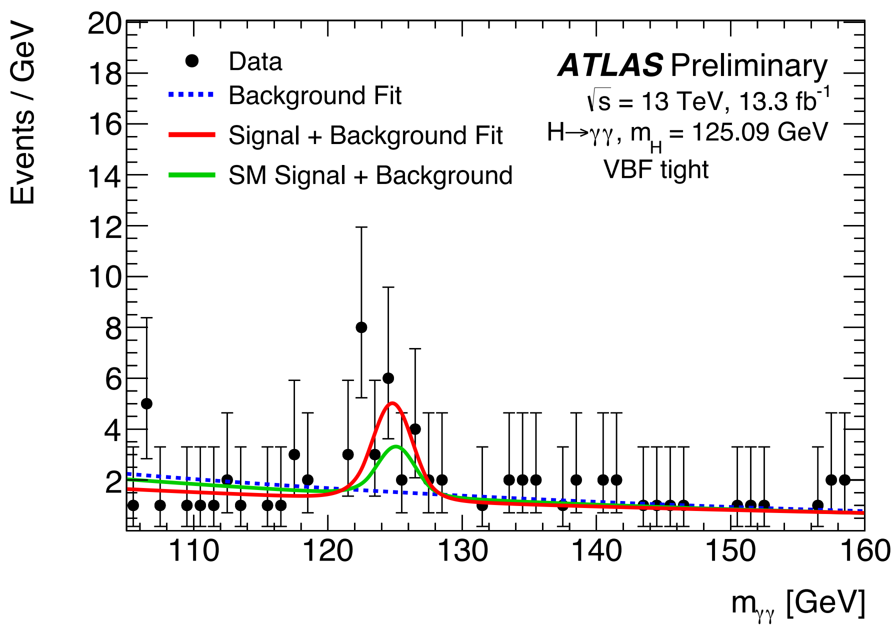
H->γγ (ATLAS-CONF-2016-067)

≥2jets BDT: m_{jj}, $|\Delta y_{jj}|$, $|\Delta\varphi_{\gamma\gamma,jj}|$, …



50% VBF in signal

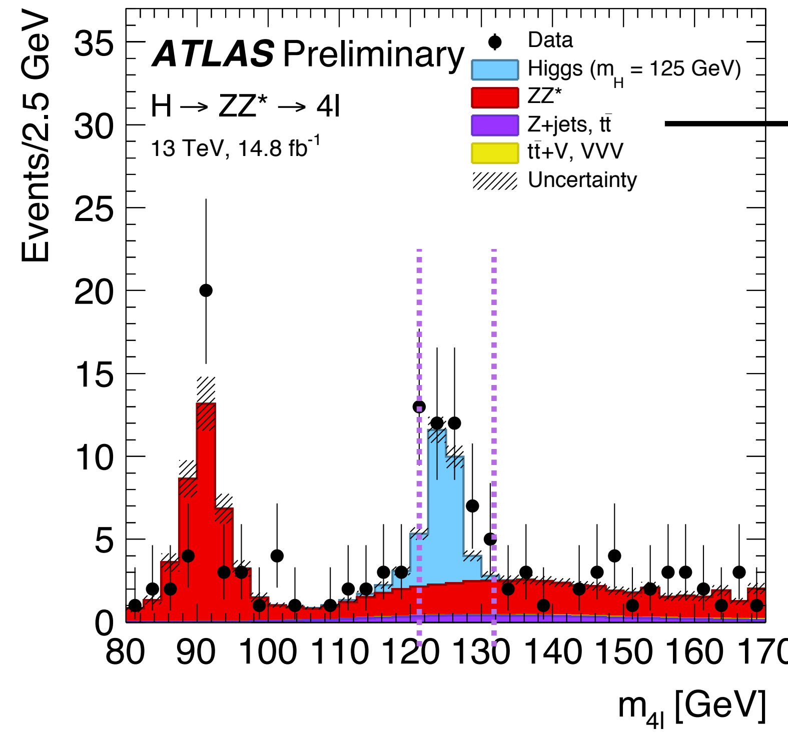
increasing BDT cut



75% VBF in signal

fit to $m_{\gamma\gamma}$ in BDT bins

H->ZZ (ATLAS-CONF-2016-079)



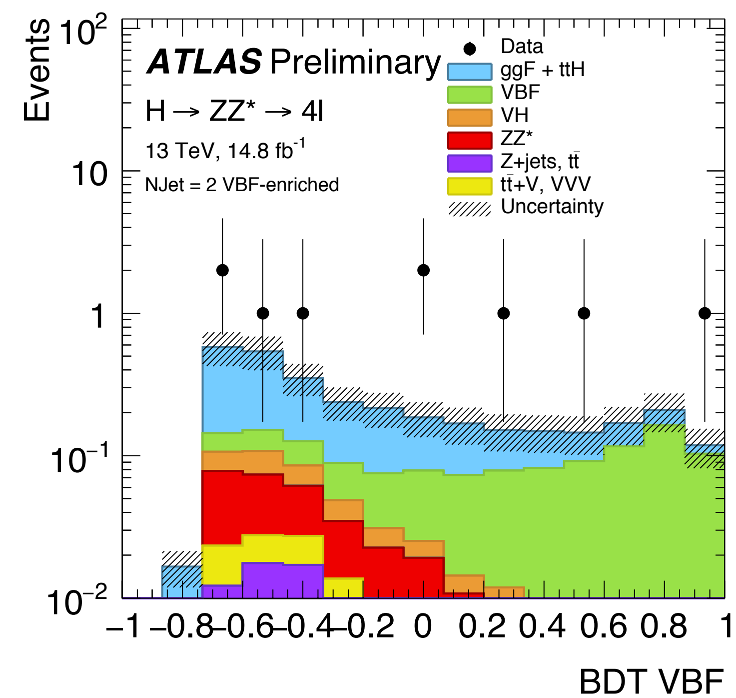
inclusive

≥2jets (p_T>30GeV), m_{jj}>120 GeV

Discriminant BDT-2jVBF

BDT_2jet_VBF:

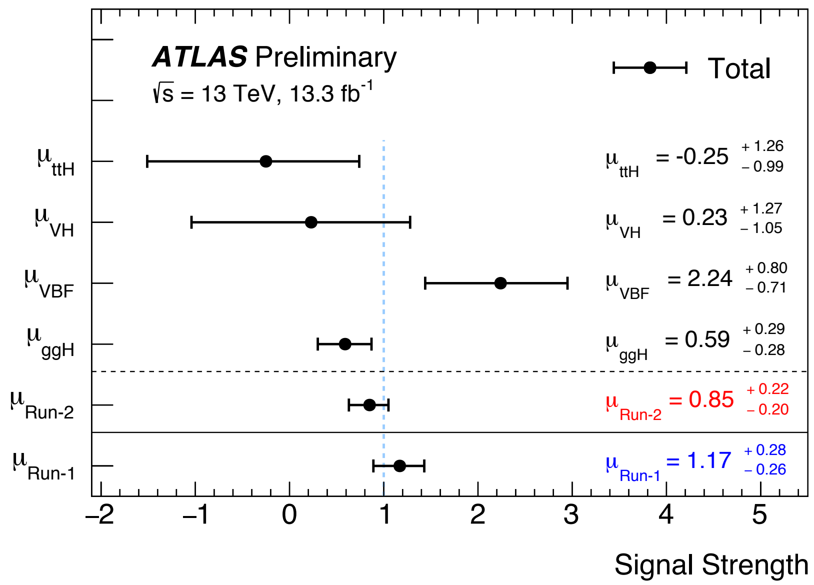
- $p_{T,j1}$
- $p_{T,j2}$
- $p_{T,4\ell jj}$
- $\Delta\eta_{jj}$
- $\Delta\eta_{4\ell j}$
- m_{jj}
- $\min(\Delta R_{Zj})$



template fit to BDT discriminant

VBF Higgs production: results

H->$\gamma\gamma$ (ATLAS-CONF-2016-067)

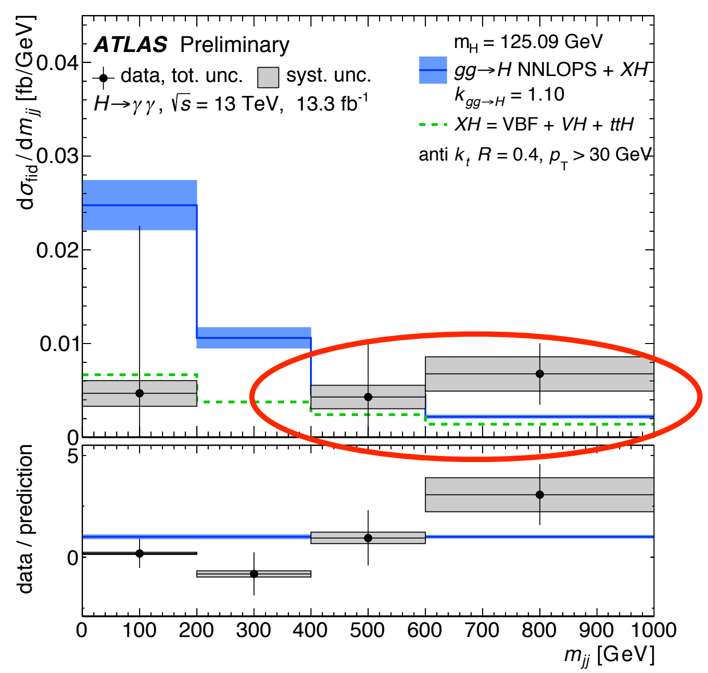


$$\boxed{\text{VBF-enhanced} \;\; | \;\; 4.0 \pm 1.4\,(\text{stat.}) \pm 0.7\,(\text{syst.})\ \text{fb}}$$

$$\text{SM prediction (fb)} \;\; | \;\; 2.04 \pm 0.13 \quad [\text{NNLOPS} + \text{XH}] \;\; |$$

$$p_T > 30\,\text{GeV},\ |y| < 4.4$$
$$m_{jj} > 400\,\text{GeV},\ |\Delta y_{jj}| > 2.8$$
$$|\Delta\phi_{\gamma\gamma,jj}| > 2.6$$

Exercising machinery for differential cross section extraction



H->ZZ (ATLAS-CONF-2016-079)

In VBF-enhanced region:

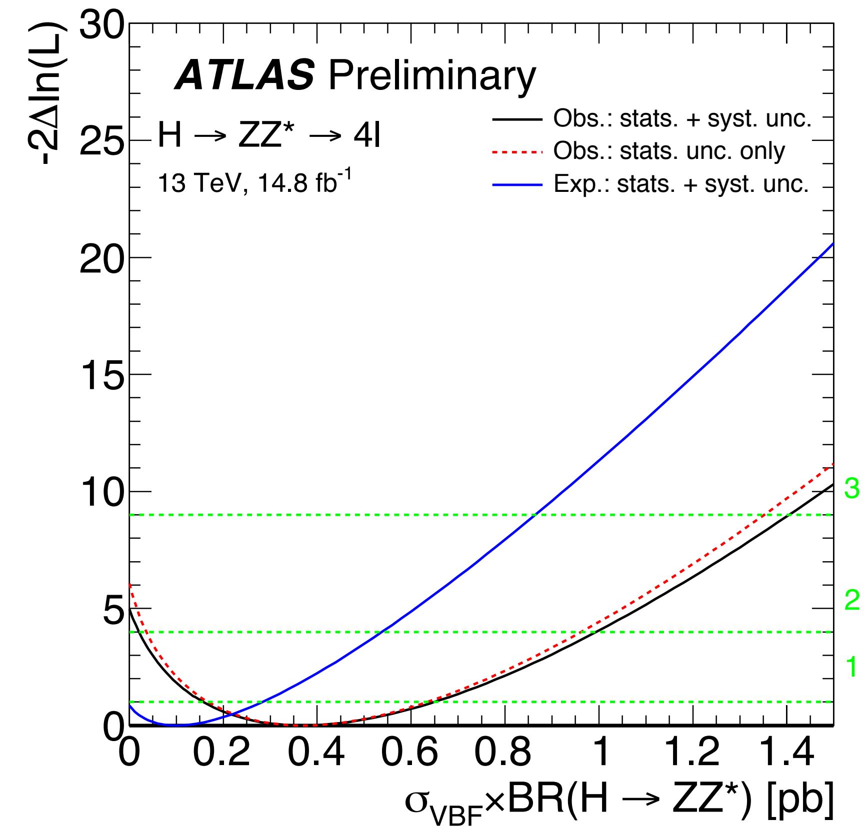
- ~ 1 VBF event, ~2ggF events:
- *3.4 events expected , 9 observed*

$$\boxed{\sigma_{\text{VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}\ \text{pb}}$$

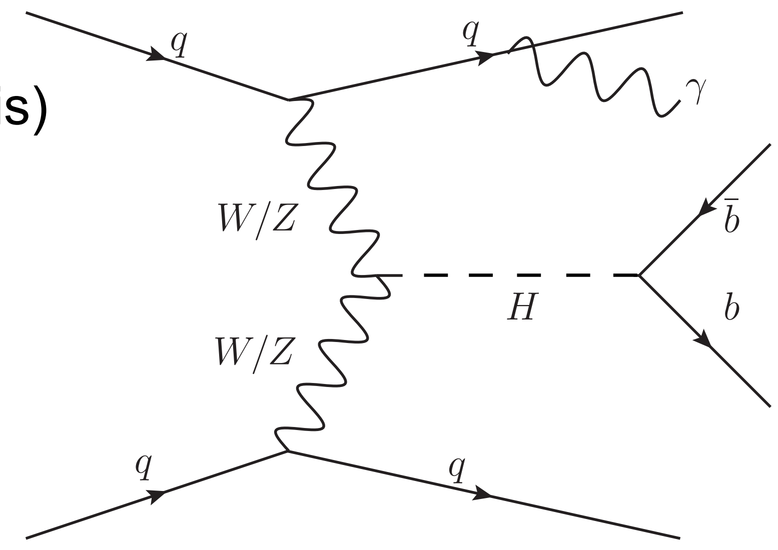
$$\sigma_{\text{SM,VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.100 \pm 0.003\ \text{pb}$$

2 s.d. excess observed, 1.s.d. expected

also interpreted in terms of anomalous H->ZZ couplings



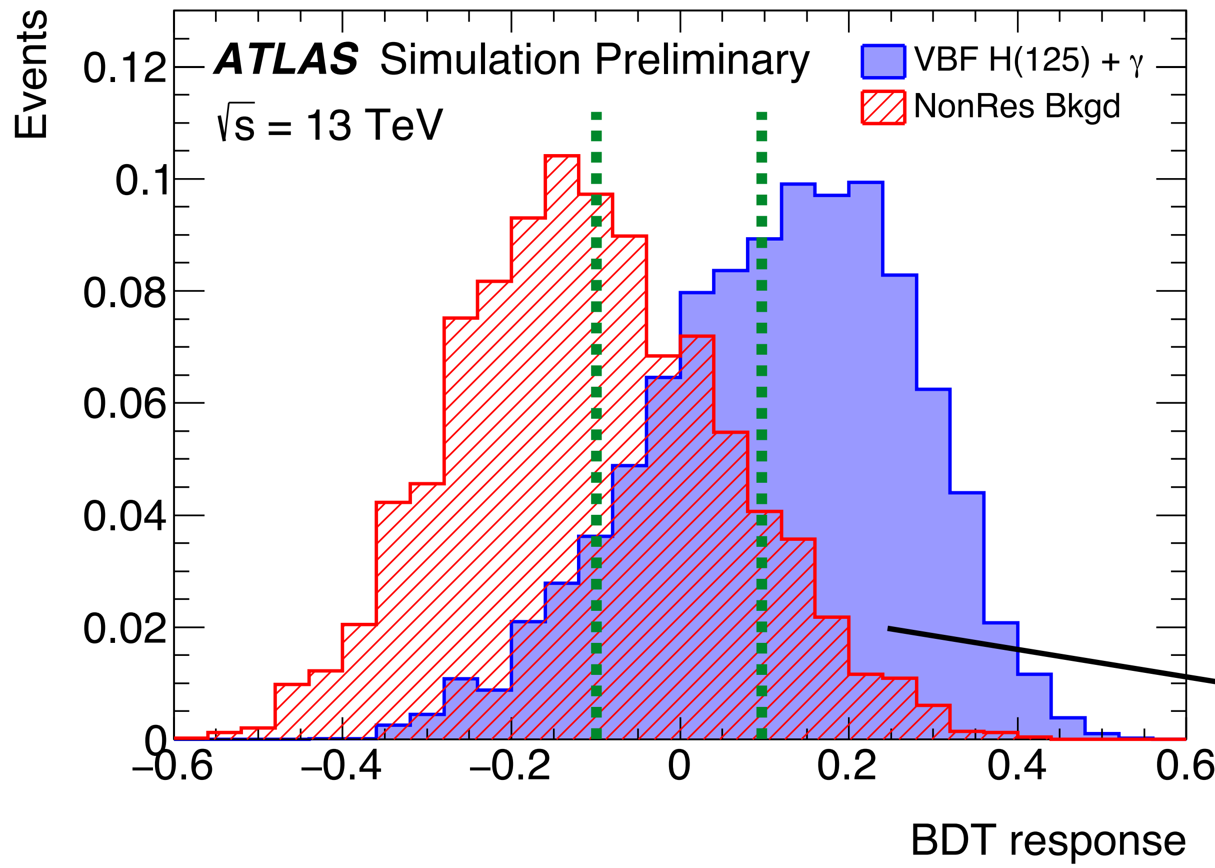
Results are still completely statistically limited

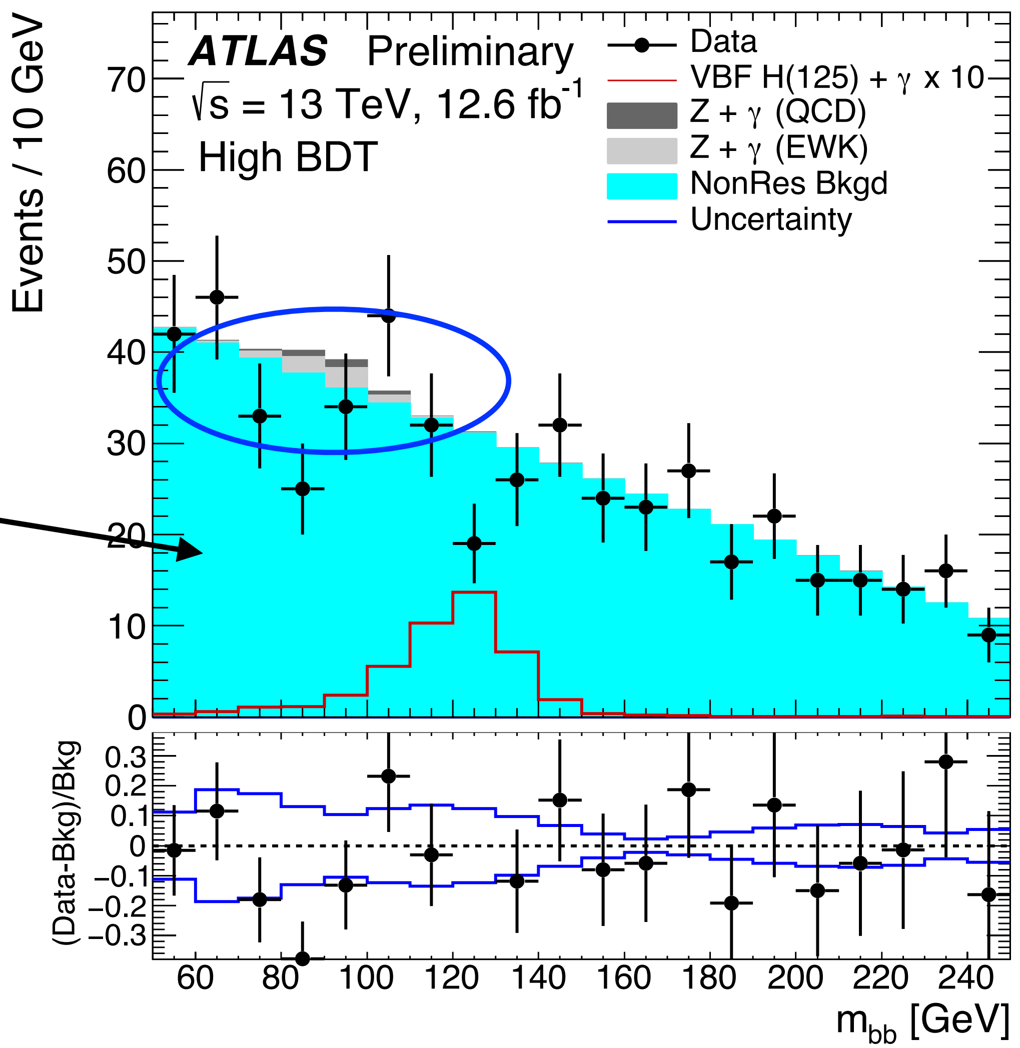


Photon coming to the rescue of VBF (H->bb) analysis:

- **provide clean source of trigger** (biggest limitation in inclusive VBF analysis)
- reduces gluon-initiated background

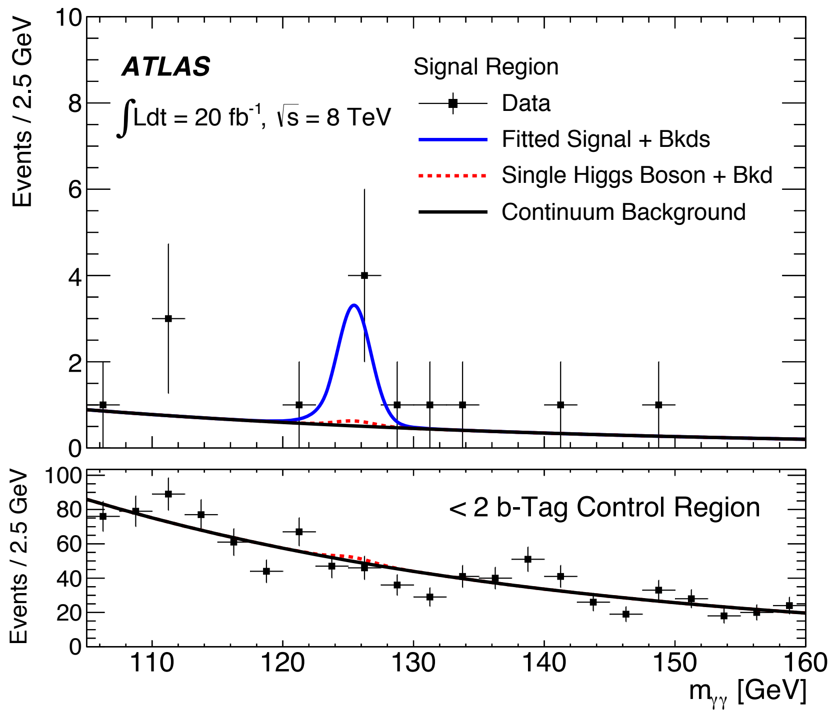
BDT trained with di-jet and photon+jets quantities (m_{jj}, $|\Delta y_{jj}|$ …)



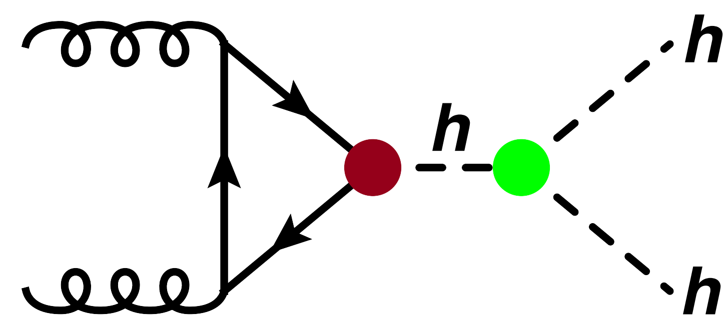


obs/exp σ*BR/(σ*BR)$_{SM}$ < 4.0/6.0

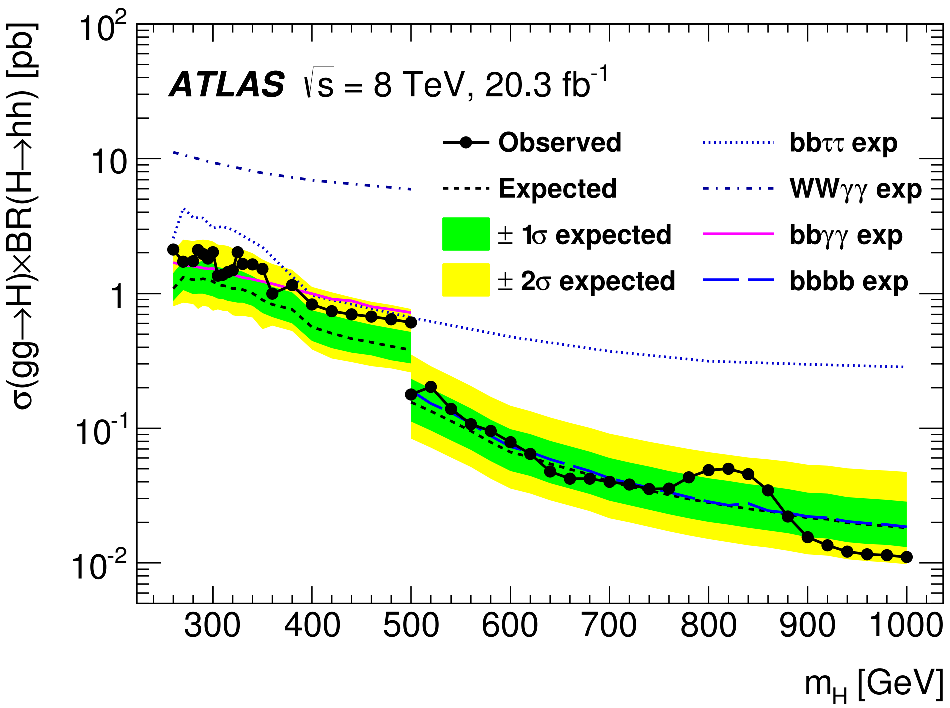
Using ***Z+gamma*** as "calibration signal": 0.3 ± 0.8

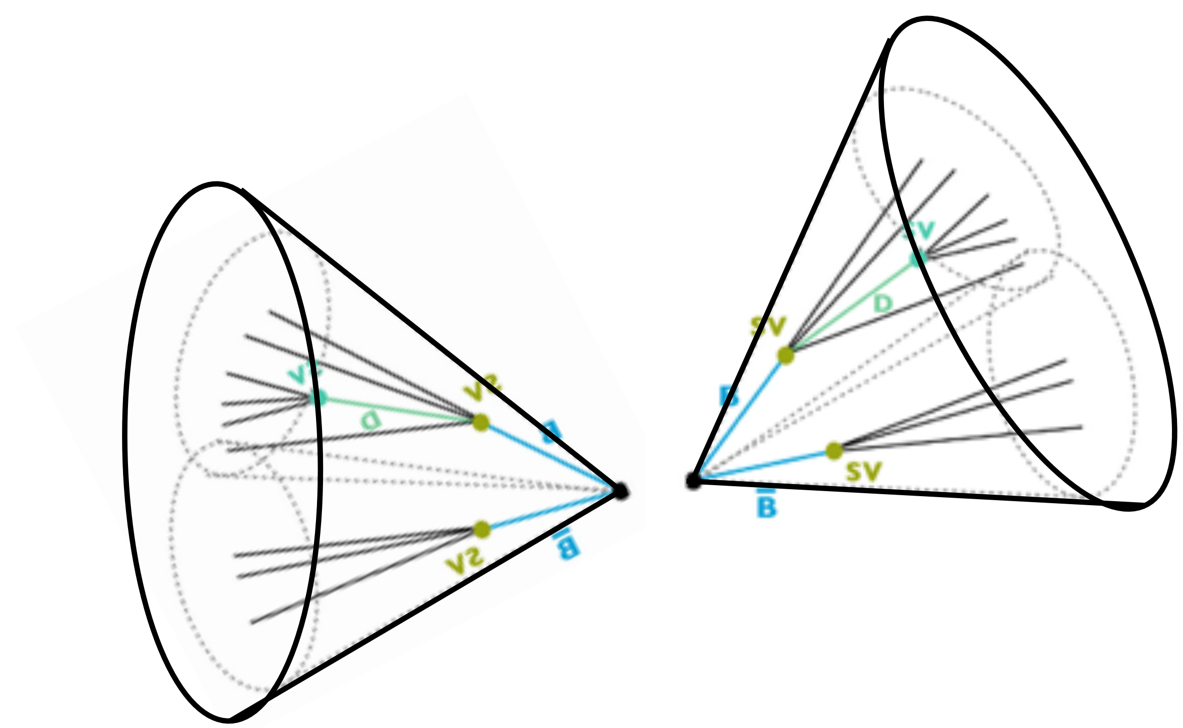


Phys. Rev. D 92, 092004 (2015)



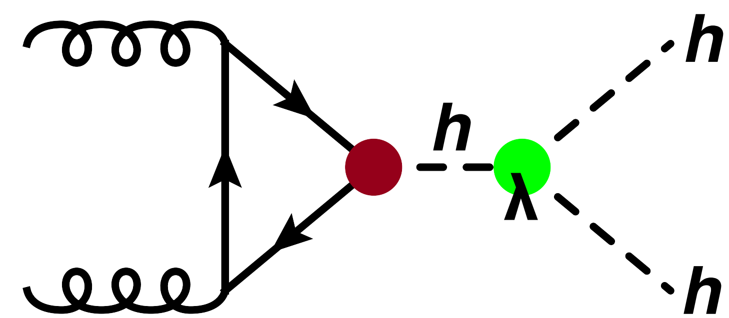
Di-Higgs searches





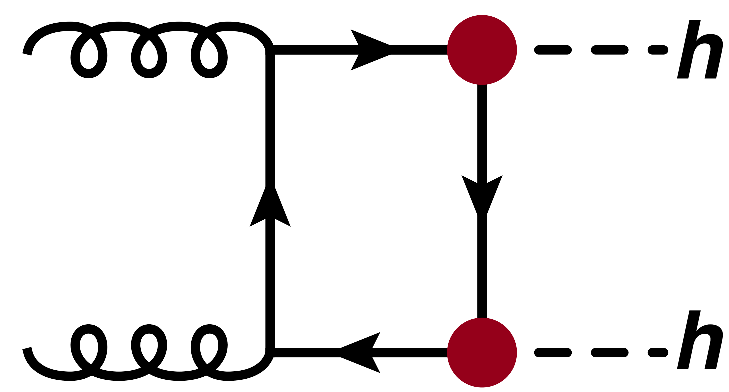
Ultimate goal is the measurement of Higgs boson self coupling:

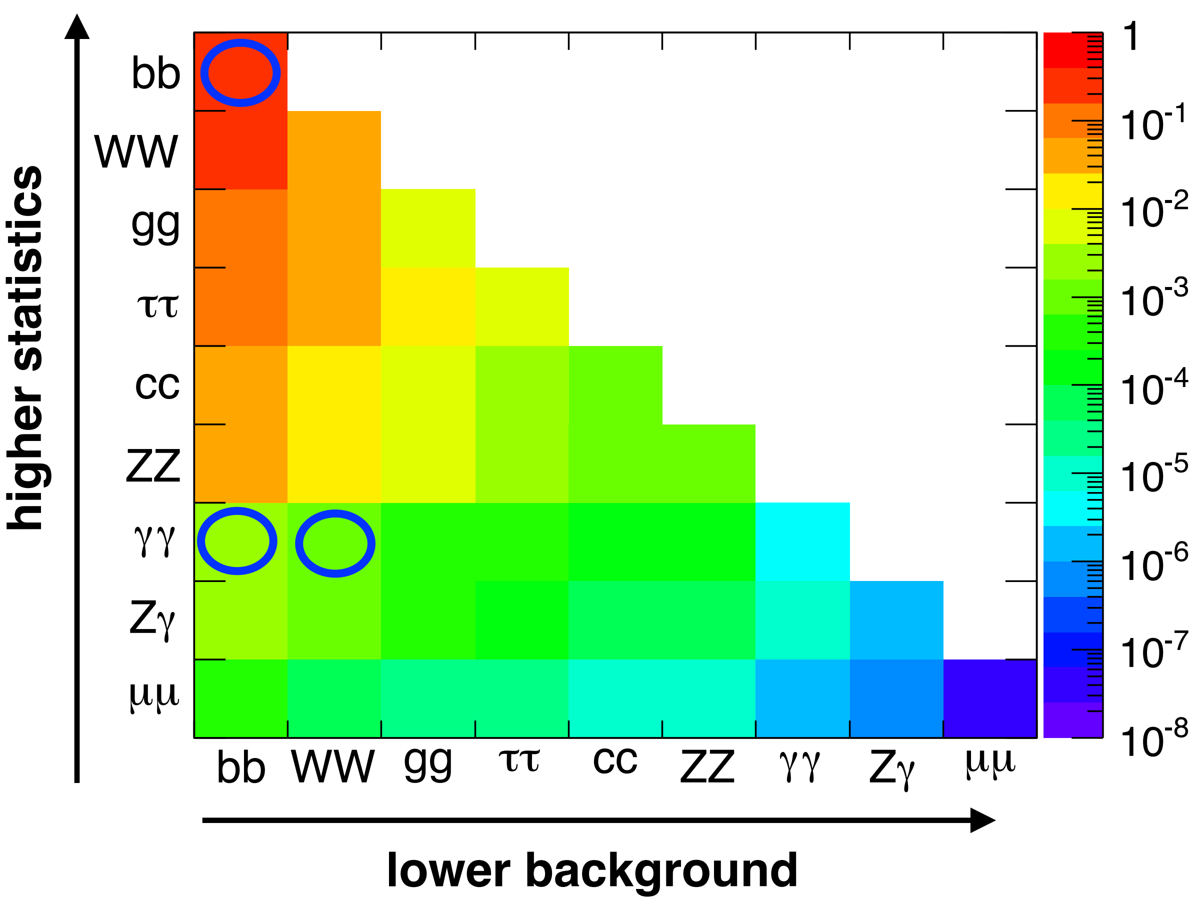
- SM process (σ_{HH}**=33fb**) way out of reach for current analyses also due to negative interference with “non resonant” production
- Run1 result: σ_{HH}<690 fb



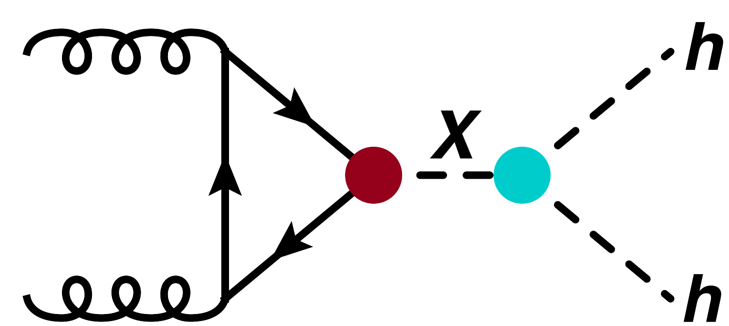
Still many new physics models (2HDM, graviton) *predict resonant and non resonant enhancement of di-Higgs production:*

- SM Higgs boson as extra handle to assess presence of new physics
- sensitivity to anomalous triboson coupling: λ





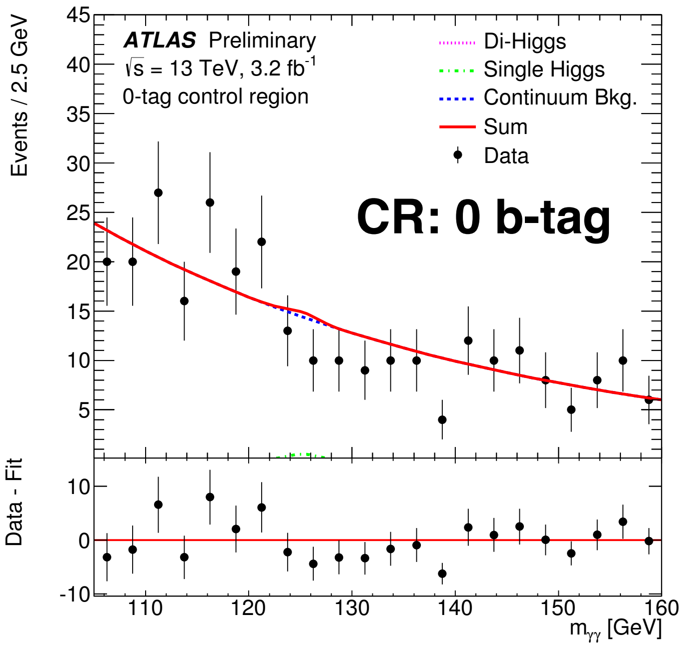
Given the extremely low cross section: ***need to rely to at least one high statistic decay mode***



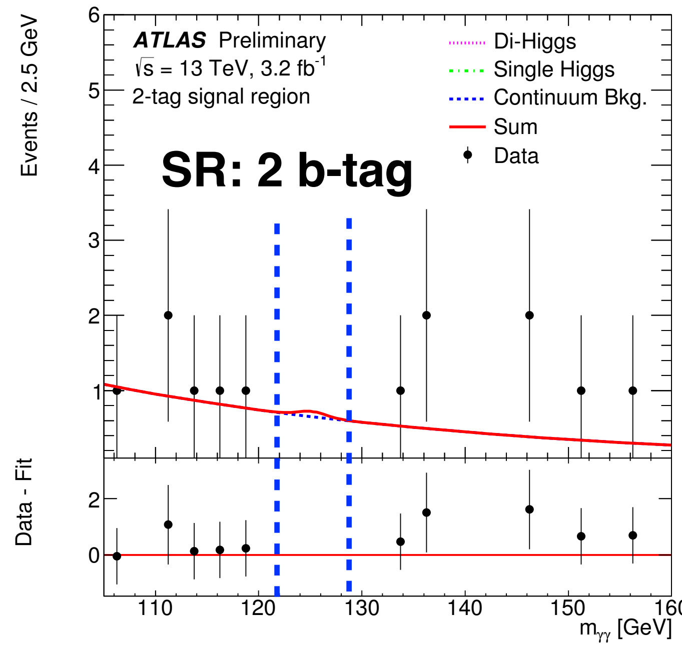
Di-Higgs searches: γγ+X

Despite the very low Br, ***di-photon peak in final state is a key ingredient to boost the sensitivity***

HH->γγbb (ATLAS-CONF-2016-004)



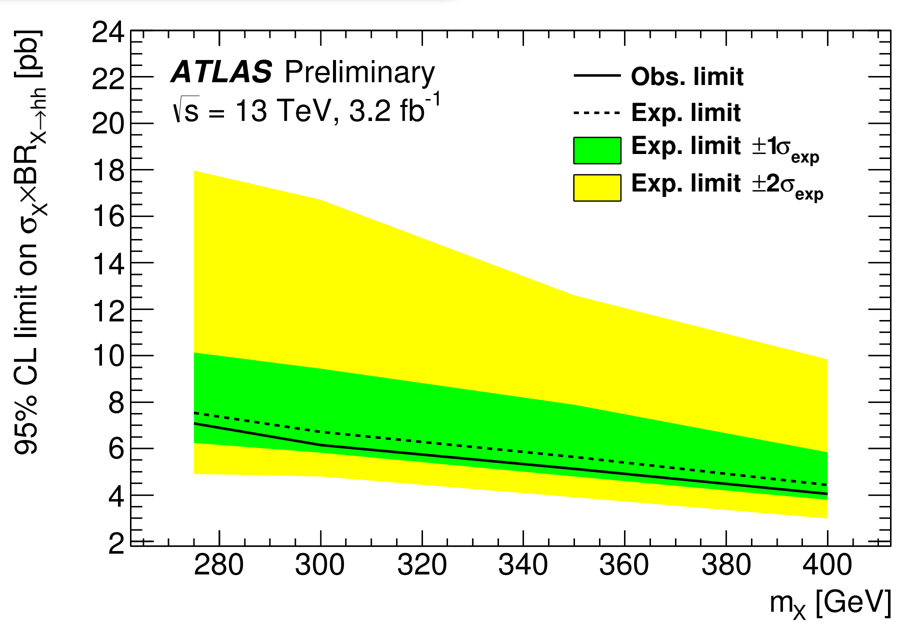
shape for continuous bkg



signal extraction

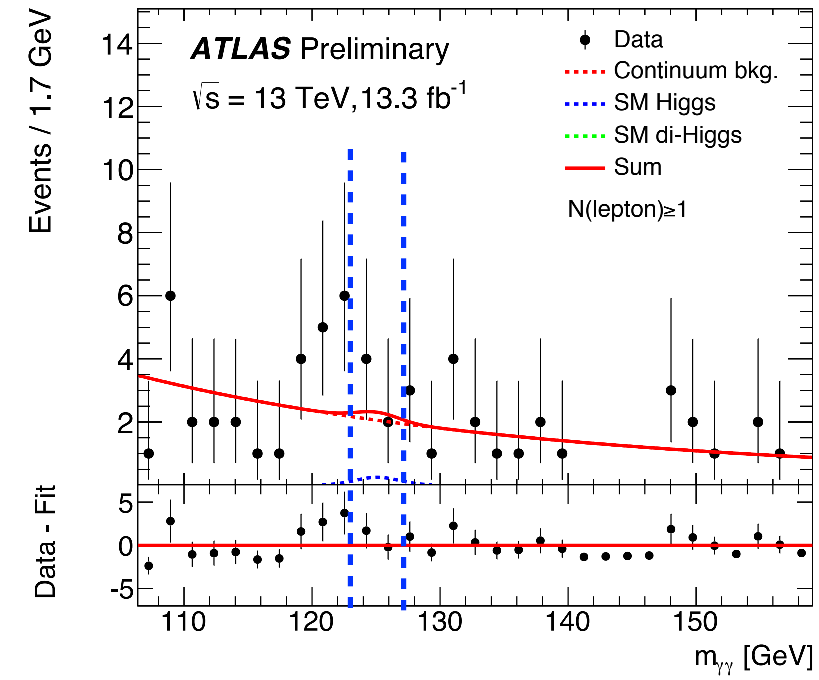
obs/exp σ_{hh}<3.9/5.4 pb (120/160 σ_{hh}^{SM})

Excellent mass resolution: *select narrow window in $m_{\gamma\gamma bb}$ for every mx hypothesis*



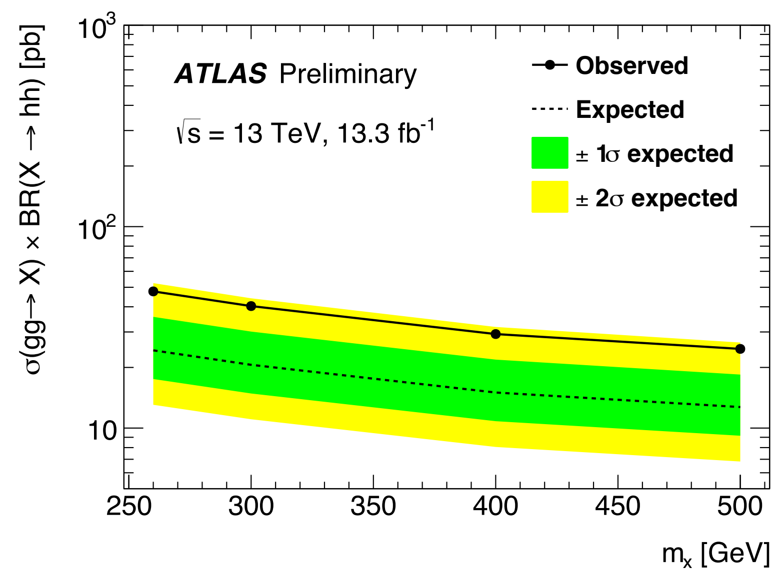
HH->γγWW*->γγlνqq (ATLAS-CONF-2016-071)

2 photons + 1lepton (e/μ) + 0b-jets



obs/exp σ_{hh}<25/19 pb (770/580 σ_{hh}^{SM})

Cut&count analysis: same cuts for each mass points



Di-Higgs searches: 4b (ATLAS-CONF-2016-049)

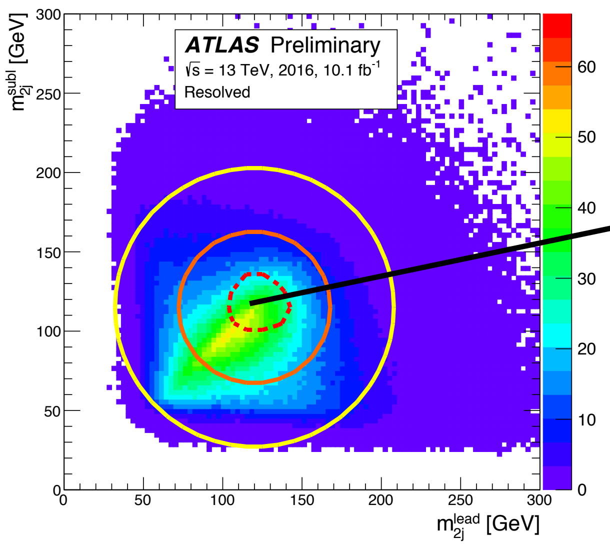
Largest Br, perfect for High mass searches (but triggering is a delicate issue)

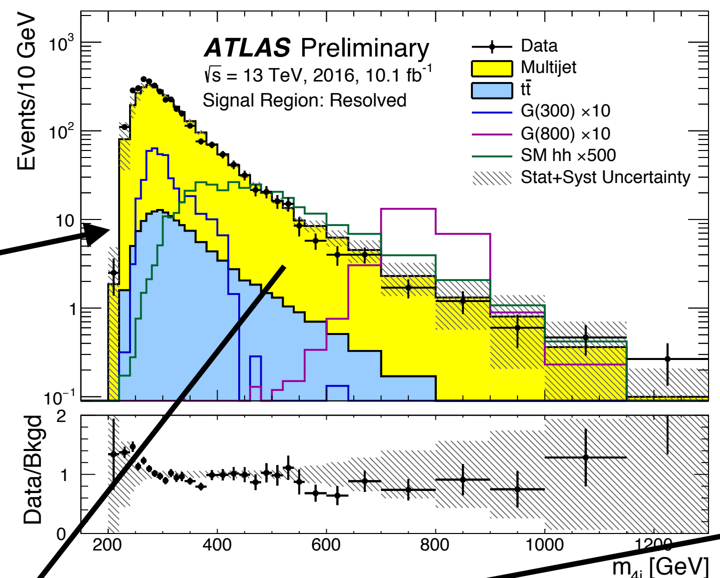
Resolved analysis

≥4 b-tagged jets in final state

optimised set of requirements for best pairing

multi-jet background estimated from mjj sidebands in 2 b-tagged

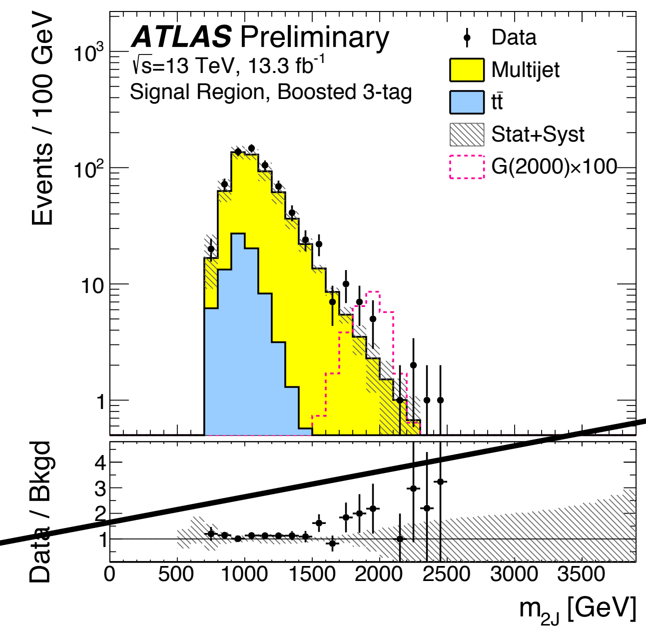


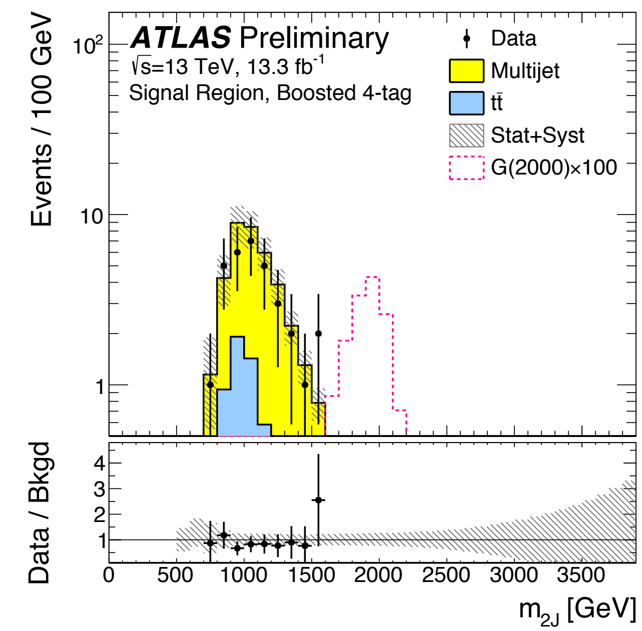


Boosted analysis

Higgs identified as R=1.0 jet. Better efficiency at high p_T, easier combinatorics

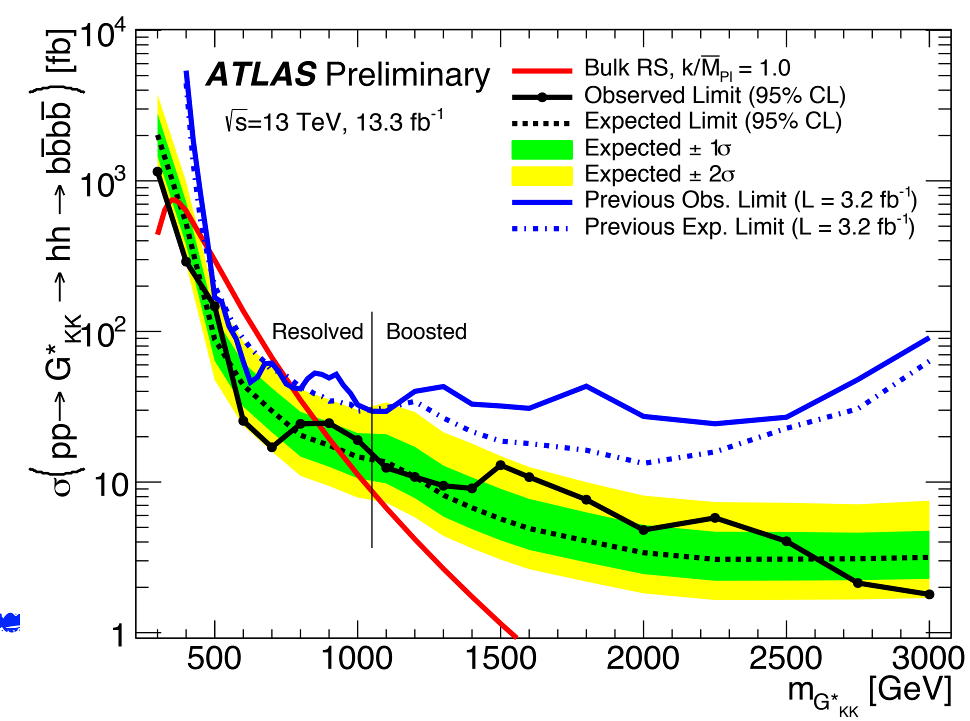
Requiring R=0.2 subnets to pass b-tagging requirement: classify events according to the number of tagged subjects in the 2 pairs





m_{4j} / m_{2J} fit for signal extraction

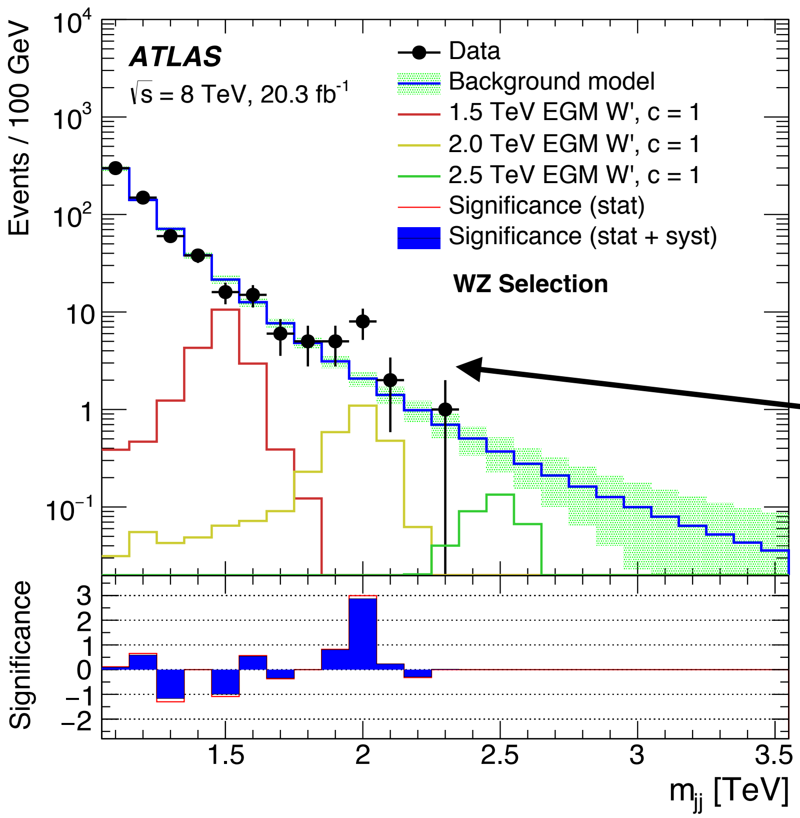
obs σ_{hh}<0.96 pb (29 σ_{hh}^{SM})

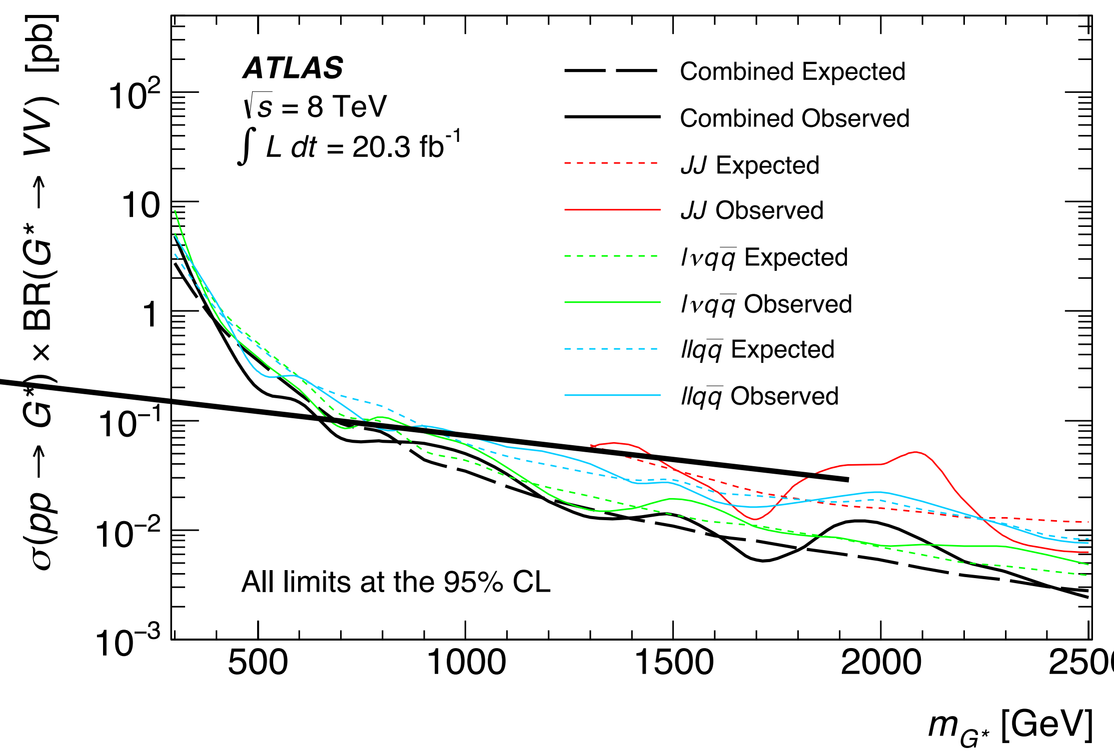


Very high mass still statistically dominated

Low mass will soon be sensitive background modelling

Di-boson resonance searches (a.k.a. direct searches for new physics)





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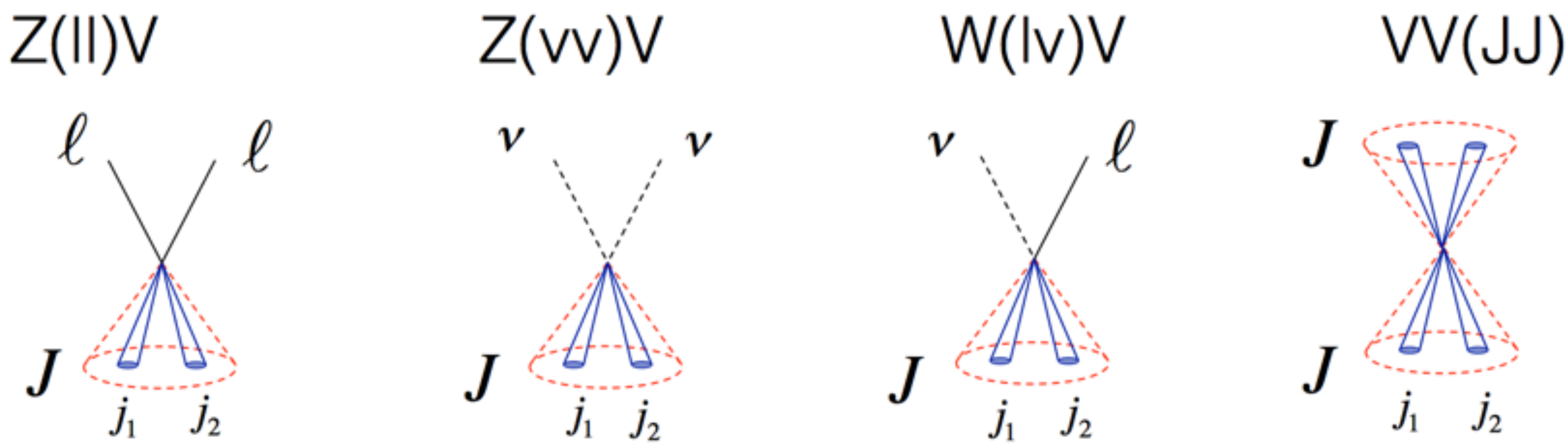
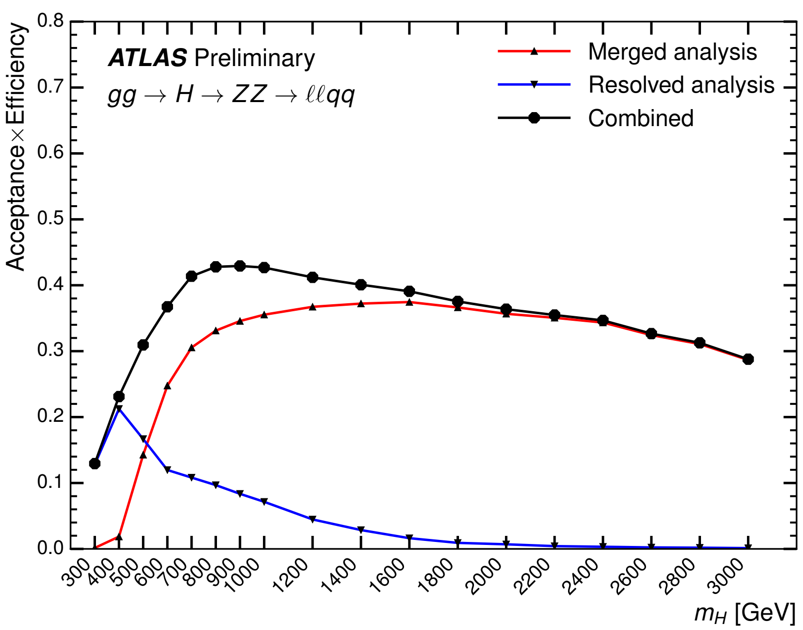
Here V=W/Z … see Jan Stark's talk for VH

Di-boson resonance searches

- **Large variety of final states:**
  - different composition of WW/WZ/ZZ
  - leptonic states: lower background, easier to trigger ….. but low Branching ratio
  - hadronic states: larger branching ratio …. generally larger background (not well described by MC)

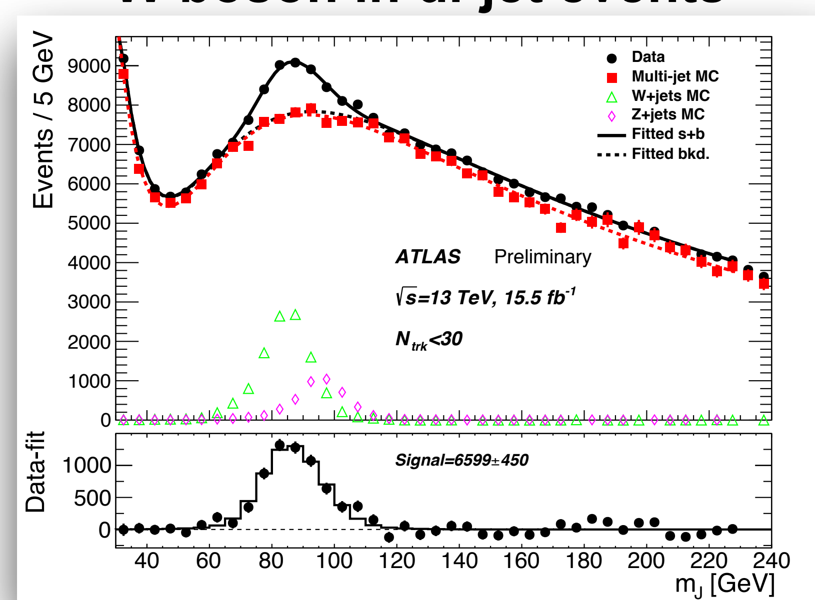




***J VS jj*:**

- boosted topologies rescue the high p_T case
- well understood substructure techniques allow to significantly reduce the background

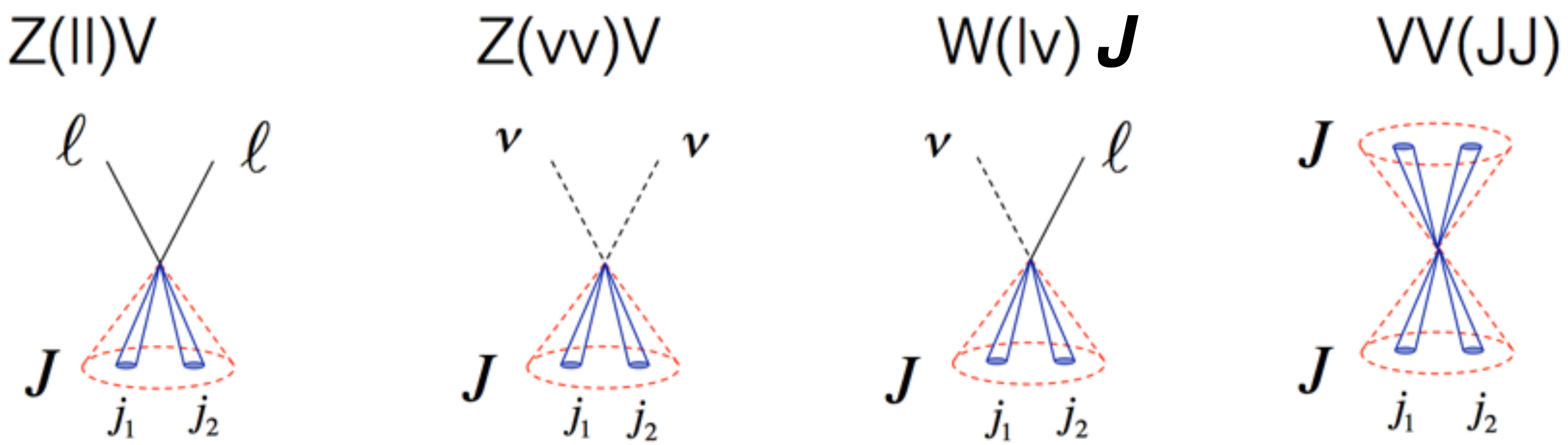
W boson in di-jet events



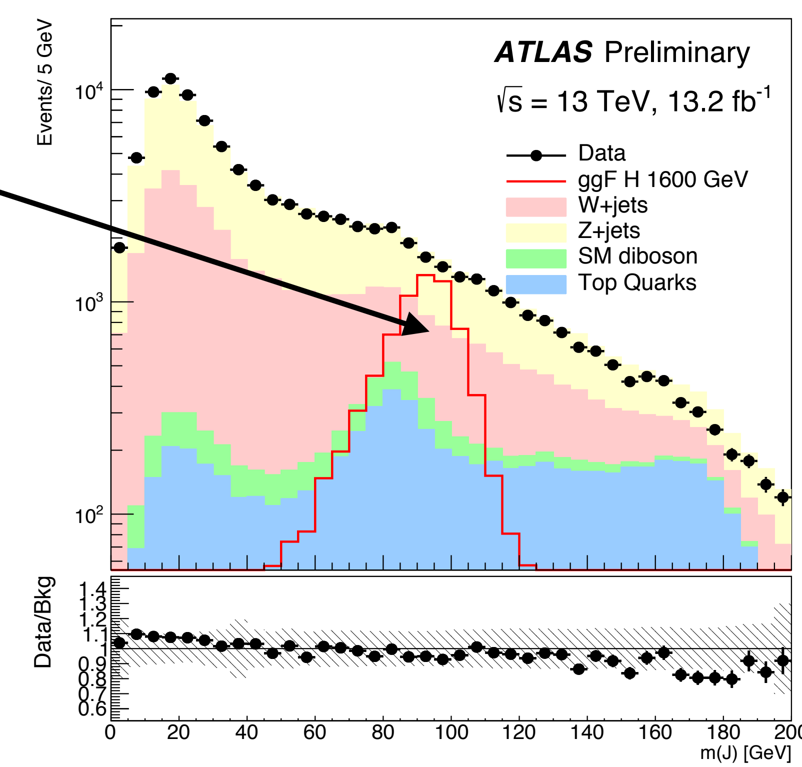
ATLAS-CONF-2016-082 **ATLAS-CONF-2016-062** **ATLAS-CONF-2016-055**

for ll: jj and J

for vv: J only



- ✦ **Select V boson through mass related cuts** (different window for W and Z):
  - *ll, jj —> easy , lv: using MET+M_T*
  - *vv: using MT (vvJ)*
  - *J: V contained in a single R=1.0 jet (using substructure to reduce bkgd)*



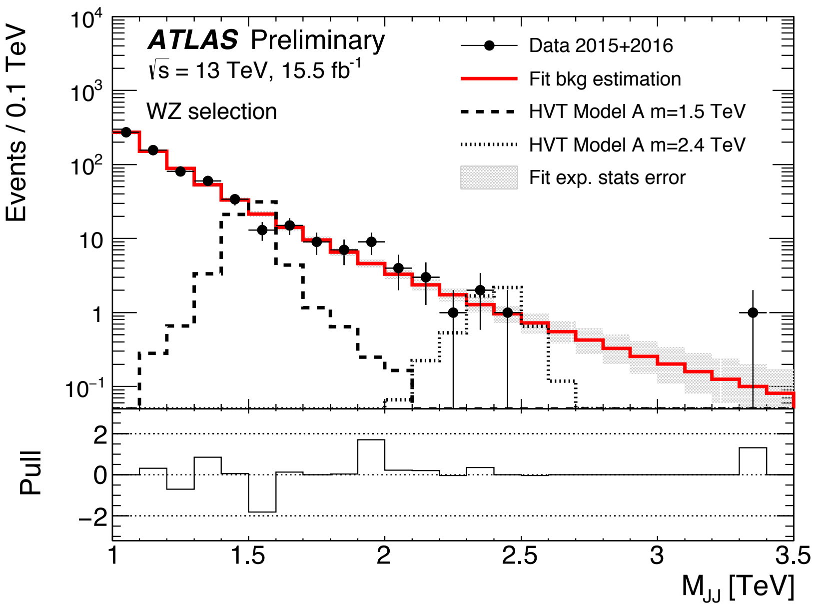
- ✦ **Apply extra selection for boost sensitivity:**
  - *mass dependent cut on p_TV, p_T balance of the bosons*
  - *VBF region for llV*

- ✦ **define CRs/VRs** *for background normalisation (if MC) and/or shape check (using mV sidebands)*

- ✦ **Extract signal from VV mass proxy: m(lvJ), m(JJ), m(lljj) ….**

Di-boson resonance searches: money plots

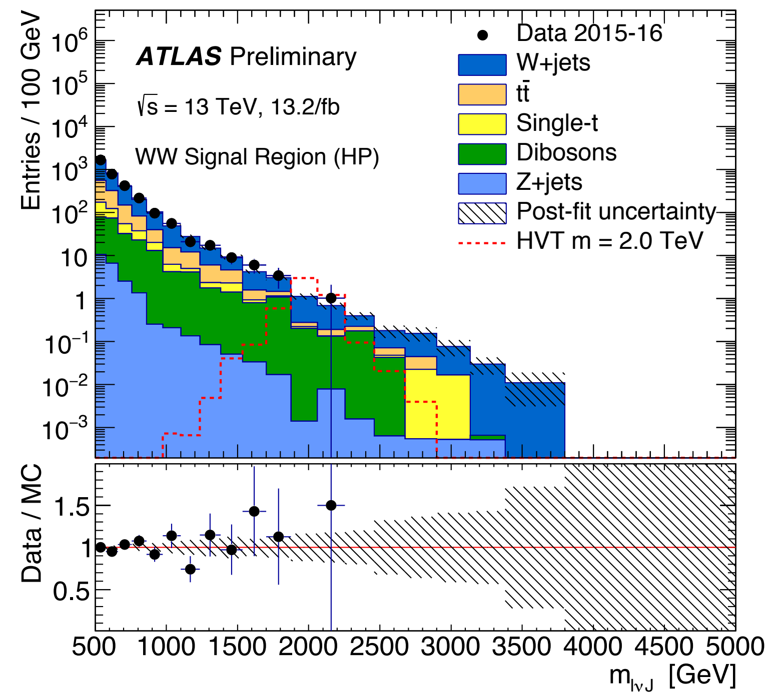
VV->JJ

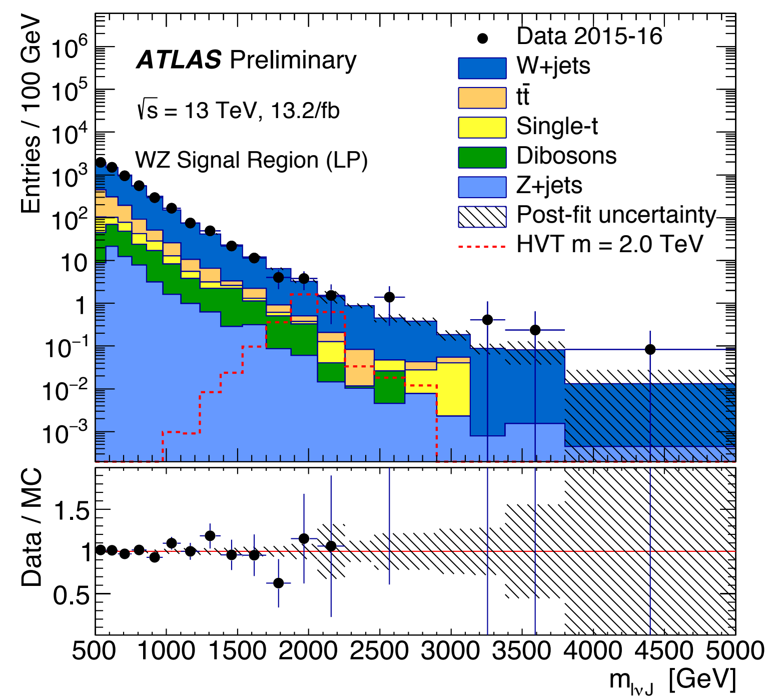


analytical shape for background
(checked in control regions)

Run1 excess not confirmed

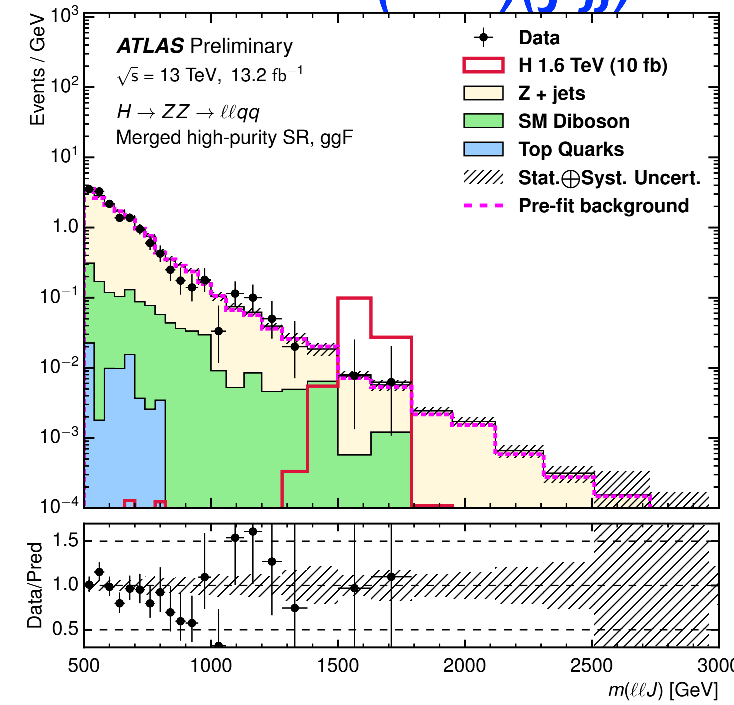
WV->lvJ

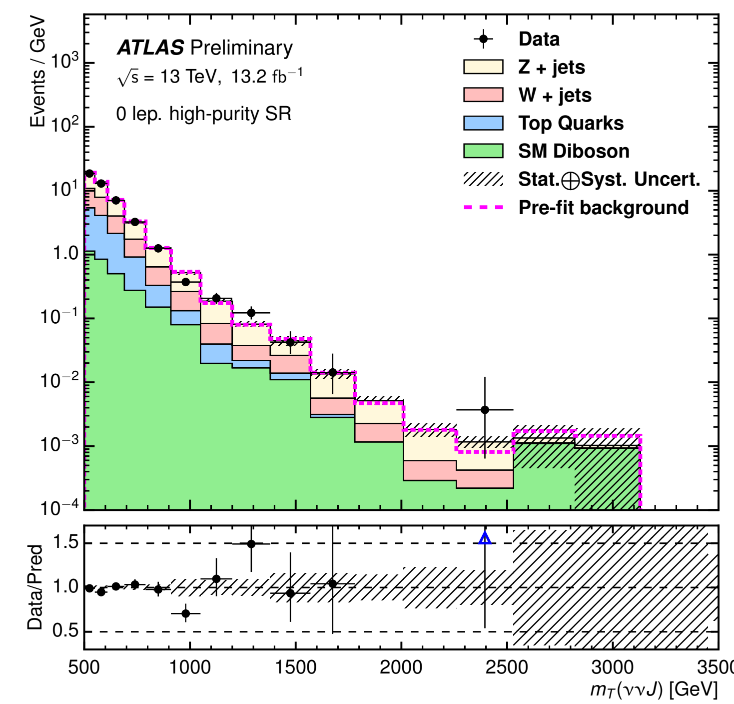




***W+jets* / *top* are the leading background [shape from MC, normalisation from CR]**

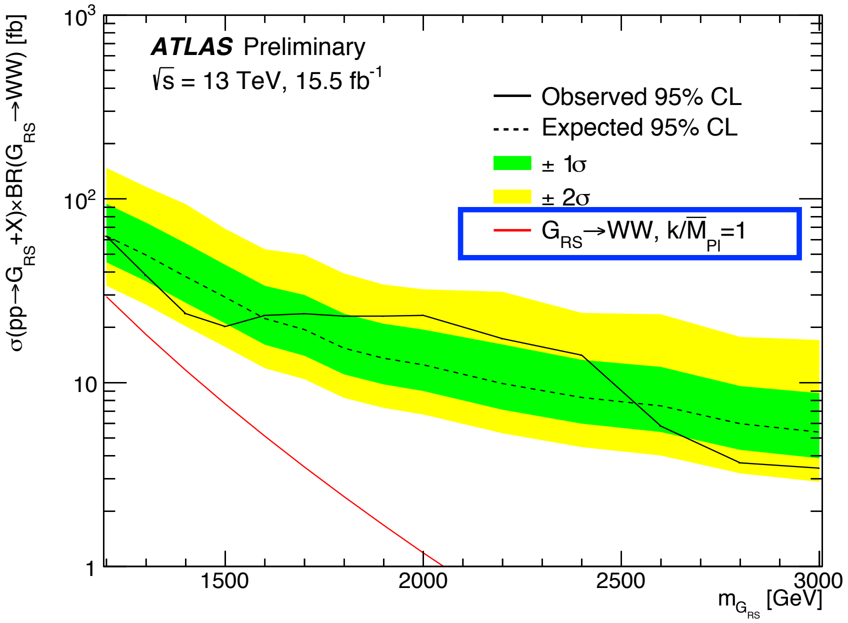
ZZ->(ll/vv)(J/jj)

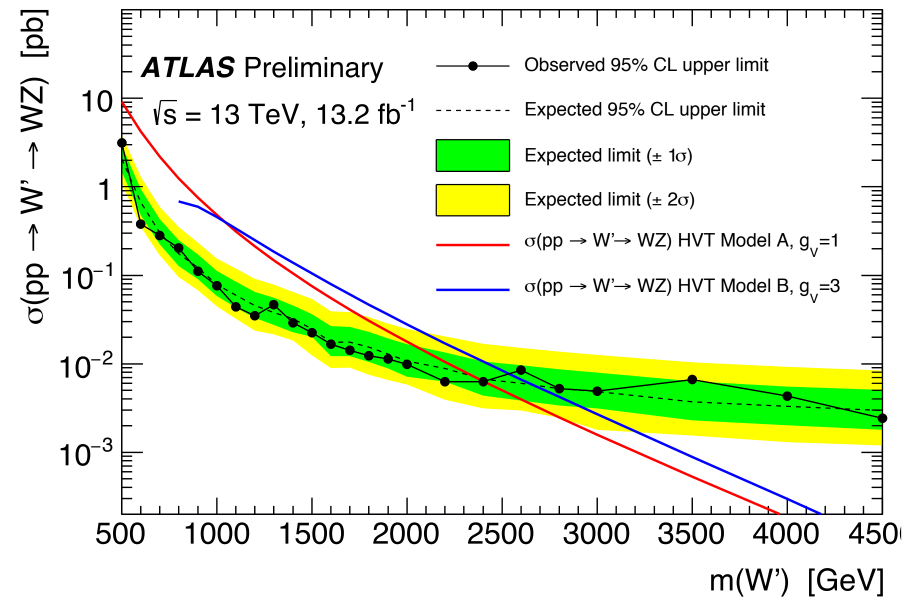


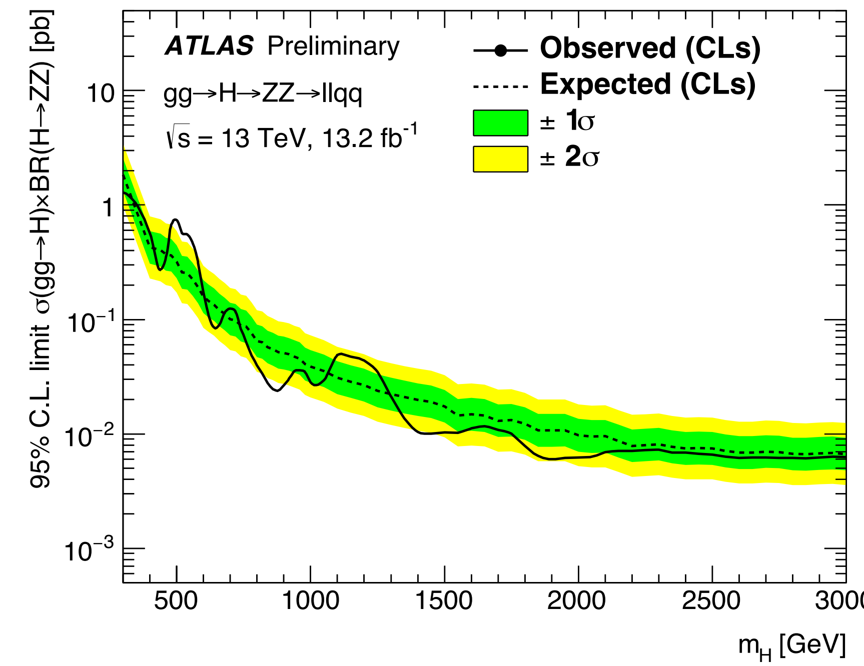


Z+jets (and W+jets for 0 lepton) is the leading background [shape from MC, normalisation from CR]

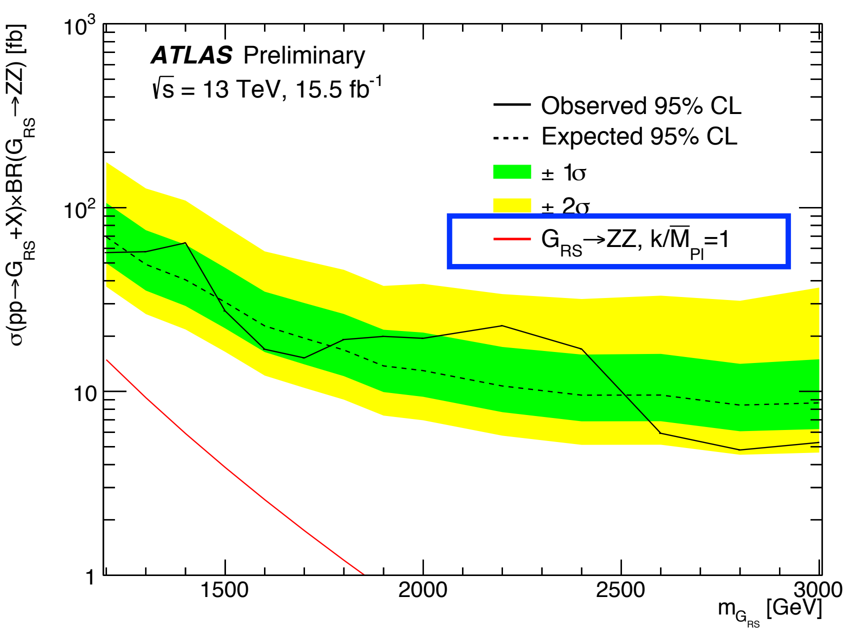
- **Large variety of interpretations:**
  - high mass Higgs boson, Graviton, Z', W', heavy vector triplets (HVT)

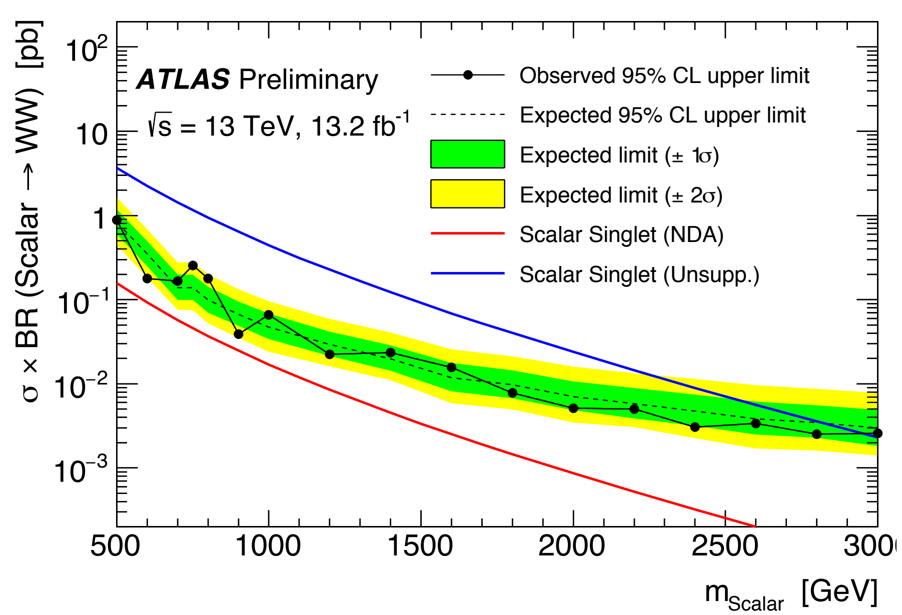


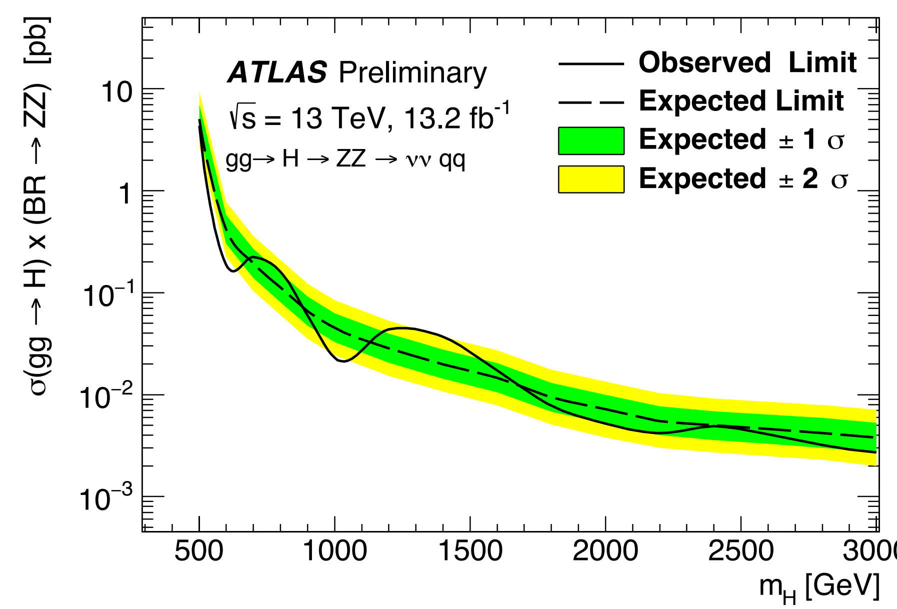




VV->JJ *WV->lvJ* *ZZ->(ll/vv)(J/jj)*

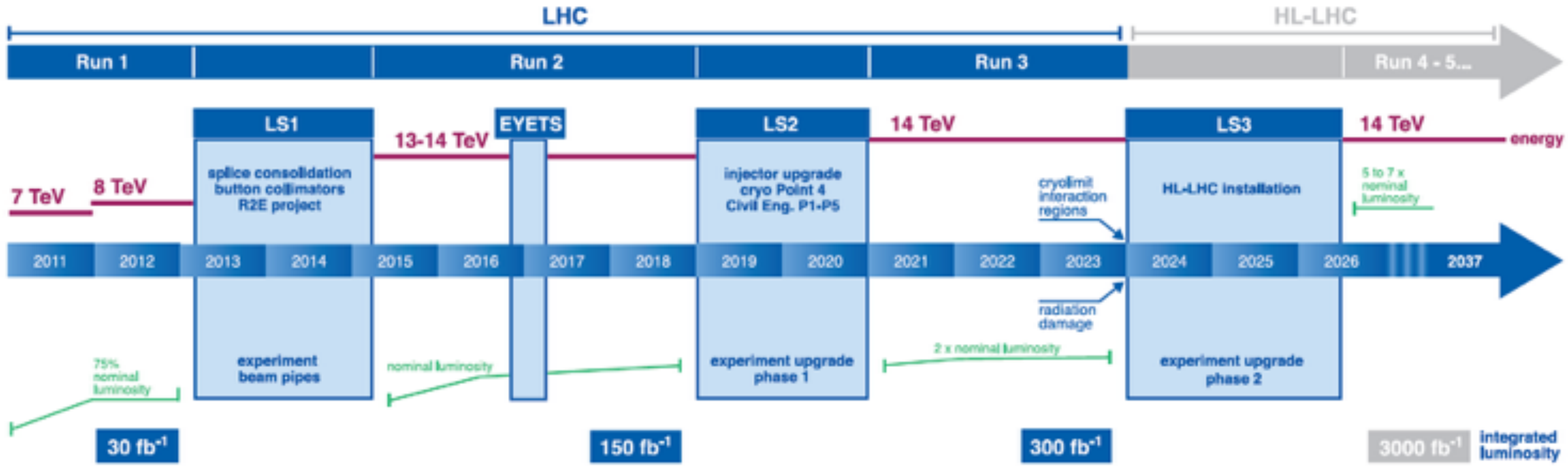






- **… still no combination yet**


BRACE YOURSELF
DATA IS COMING

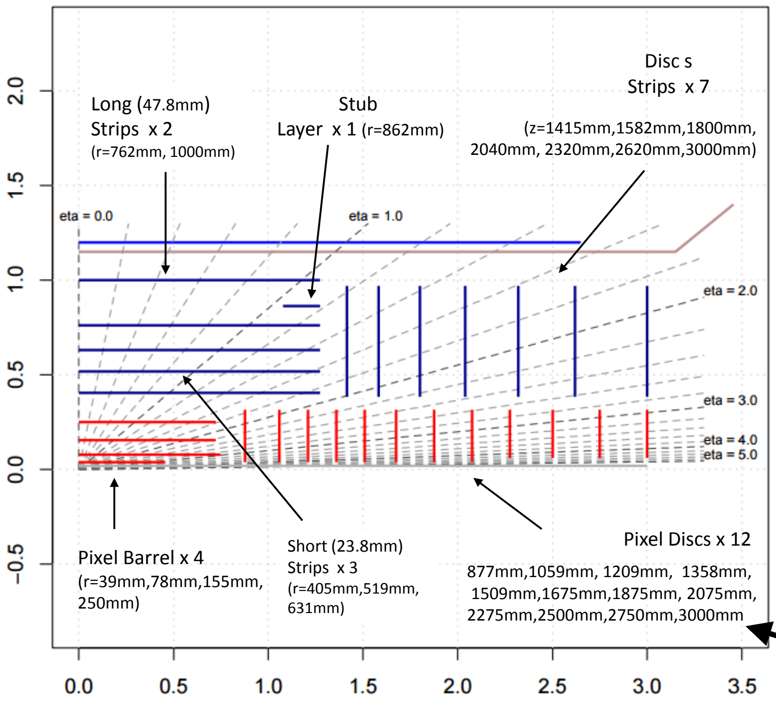


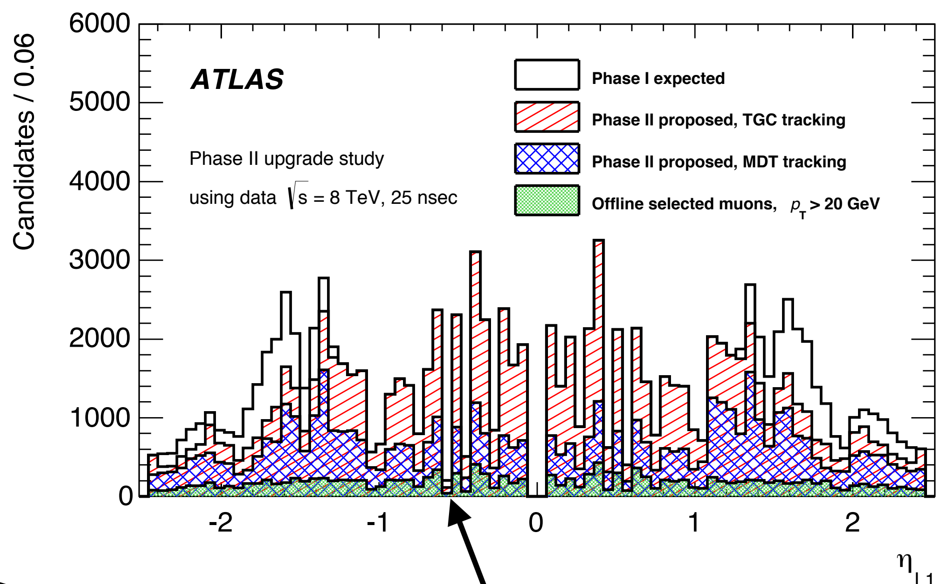
HighLuminosity LHC

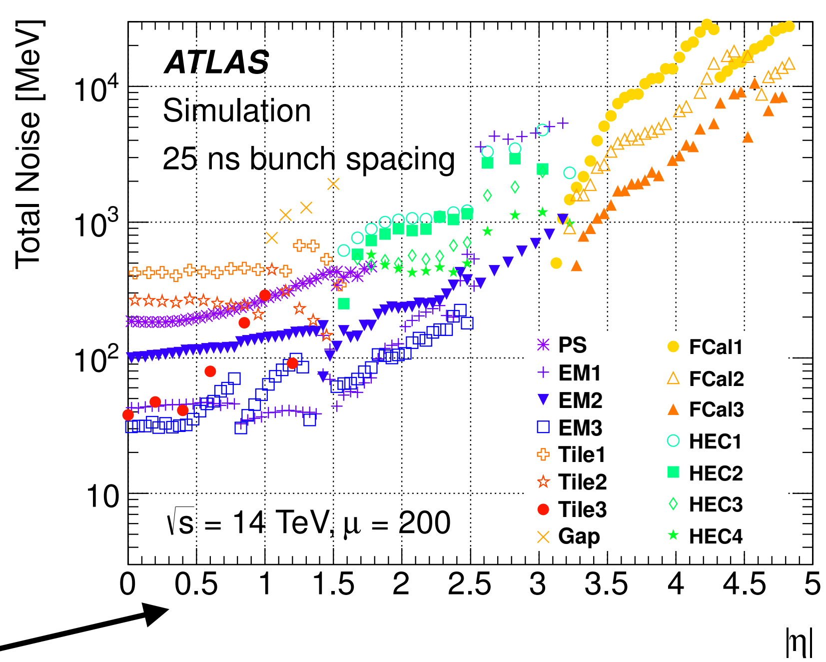
tracking

trigger

calorimeter







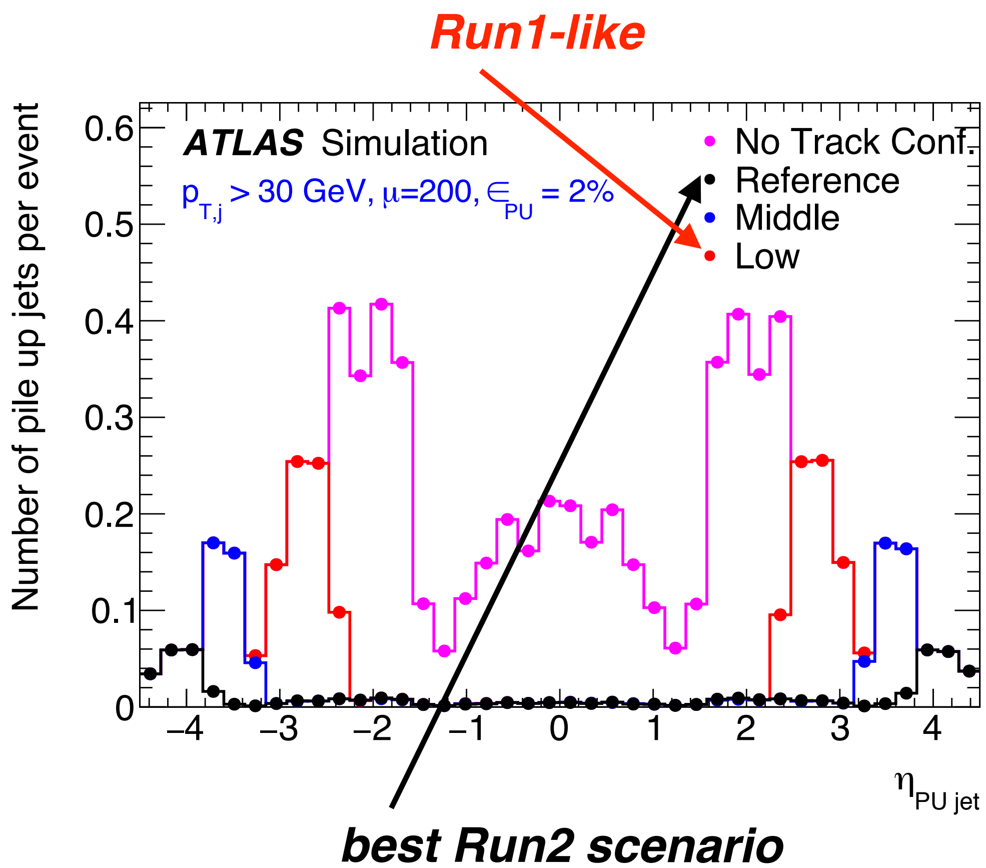
LHCC-G-166

warning: speaker's personal opinion

- **Prospects studies are a tricky business ….**
  - usually require a lot of assumptions on performance of detector not already built
  - relies of some approximation: parameterisation of performance applied on truth quantities
  - clearly NOT suited for convoluted analyses (easy to get overoptimistic scenarios).

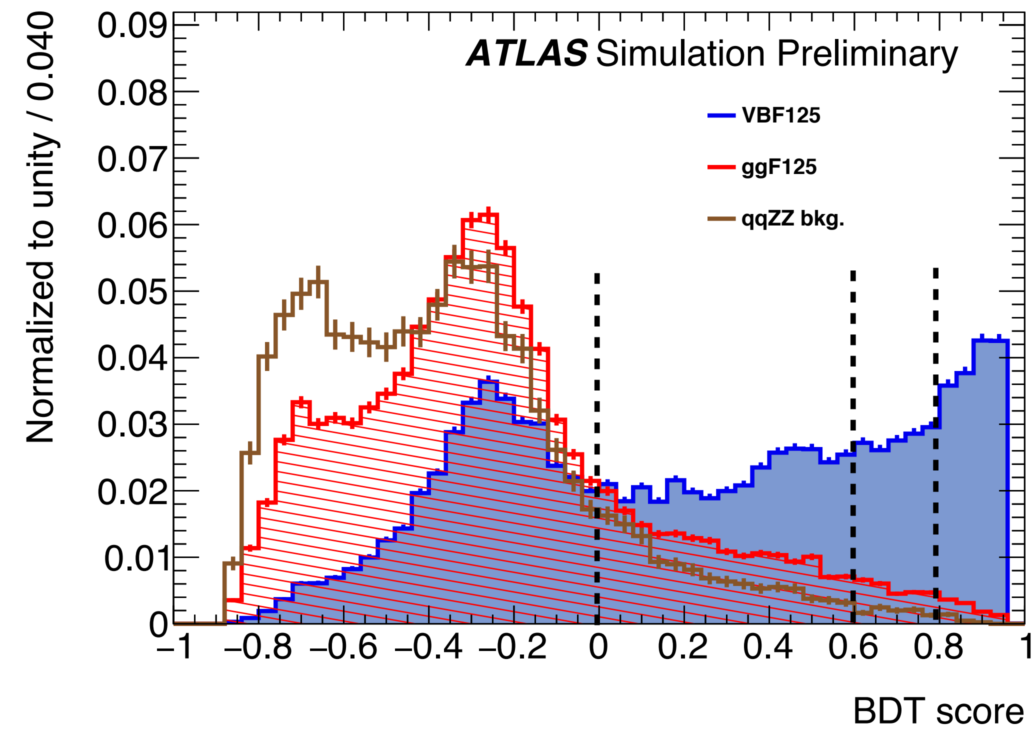
- **… at the same time experimentalists usually surpass their own expectations:** new algorithms, new techniques … etc …

- **Concentrating on latest results based on *Phase2 Upgrade scoping document*:**
  - more "reliable" results: *more recent MC production, more stable detector layout*
  - using as benchmark analyses which are currently statistically limited but also that are strongly dependent on detector design choices
  - critical detector design component: ***η coverage of the inner tracker*** (2.7 —> 4.0)
    - impact acceptance/veto for charged lepton (e,mu,tau) reconstruction
    - impact capabilities of rejecting pileUp jets at large rapidity



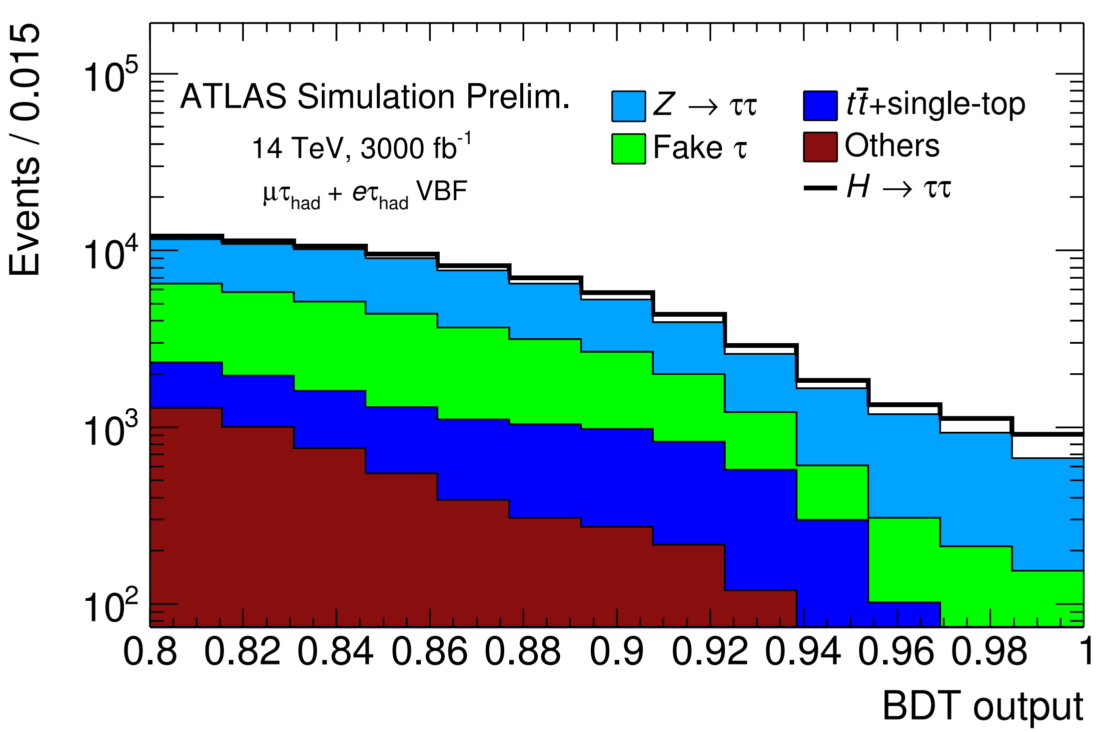
HL-LHC prospects: VBF Higgs

- The golden channel ***H->ZZ->4l*** :
  - *+20% acceptance with forward lepton reconstruction*
  - very clean Higgs selection (m_{4l} window), concentrate on separating VBF from ggF contribution
  - BDT variables:
  - PU contribution in ggf ~ 25%/50% (even with large eta tracker)



- **Expected performance with 3 ab^{-1}:**
  - cut & count analysis in 3 BDT bins
  - ***13% / 17% uncertainty on μ_{VBF} without / with theory uncertainties***

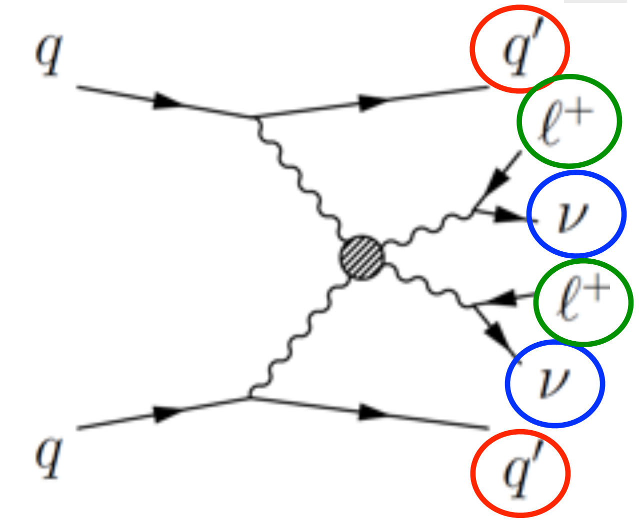
ATL-PHYS-PUB-2014-018



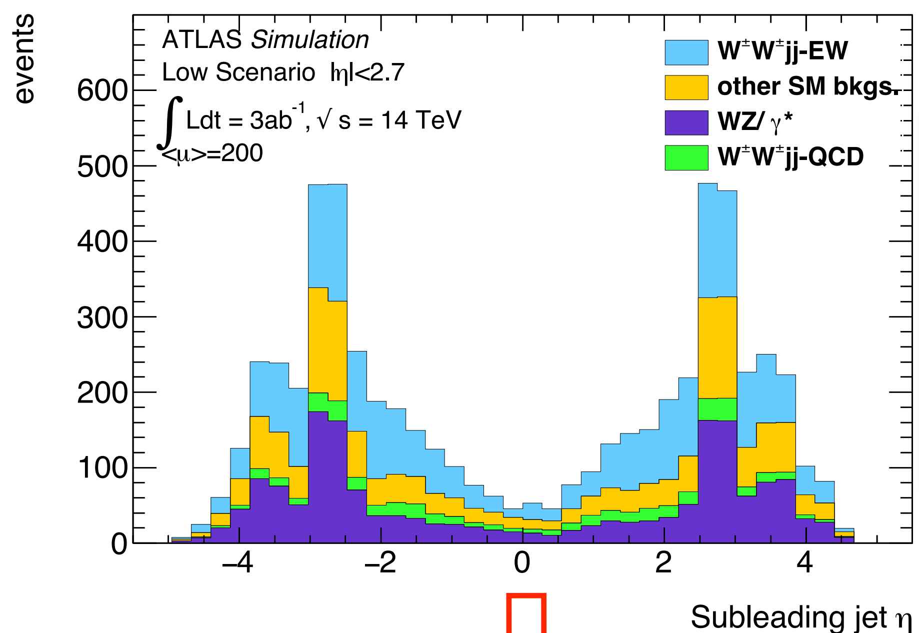
- A tougher case HVBF ***H->$\tau\tau$*** (l+τ final state):
  - *BDT to separate signal from background* (S/B=0.4 in best BDT bin)
  - only assessing effect of PU rejection from extended tracker: ***up to factor 2*** improvement in performance

- **Expected performance with 3 ab^{-1}:**
  - no theory uncertainty, 10% bgk unc., 5% detector sys on signal
  - 75% PU rejection in the forward region
  - ***12% uncertainty on μ_{VBF}***

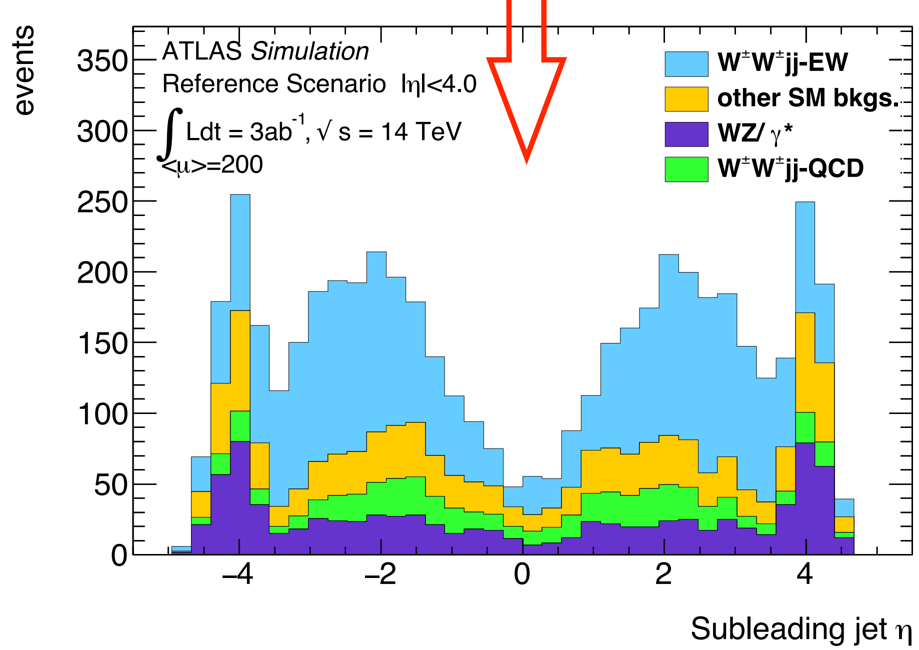
LHCC-G-166



- **Using ssWW as benchmark analysis:**
  - *good compromise between available statistics and amount of background:* likely the first VBS final state that will enter the precision realm
  - characteristic experimental features: 2 SS leptons + MET + 2 forward jets with high m_{jj}
  - Run1 analysis strategy: cut and count with mjj>500 GeV, $\Delta\eta_{jj}$>2.4
  - main MC bkgd (WZ/ssWW QCD) scaled by 1.6 to account for experimental backgrounds



- **Several advantages from increasing tracker acceptance:**
  - better signal efficiency: 10 %
  - factor 2 better rejection of WZ events from 3rd lepton veto
  - reducing events where “tagging” jets originates from PileUp: 27% —> 18%

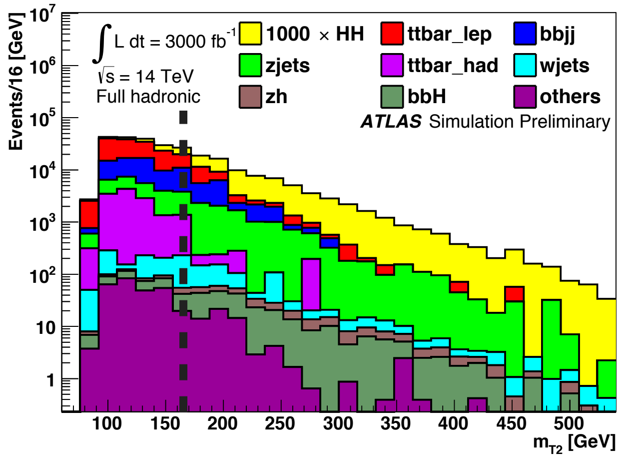


- **Expected performance** *(assuming 15% background uncertainty):*
  - precision on ***ssWW fiducial xSection for 3 ab^{-1}: 6%***
  - 13% with Run1 acceptance

- Higher statistics allows application of ***more sophisticated methods*** as well as ***better precision on NP effects*** (old studies):
  - ***5 σ discoveries for f_{S0}/Λ^2>4.5 TeV^{-2}***

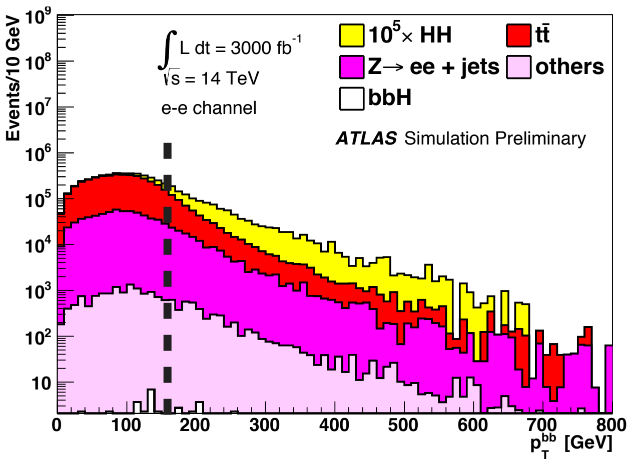
HL-LHC prospects: di-Higgs

HH->ττbb (ATL-PHYS-PUB-2015-046)



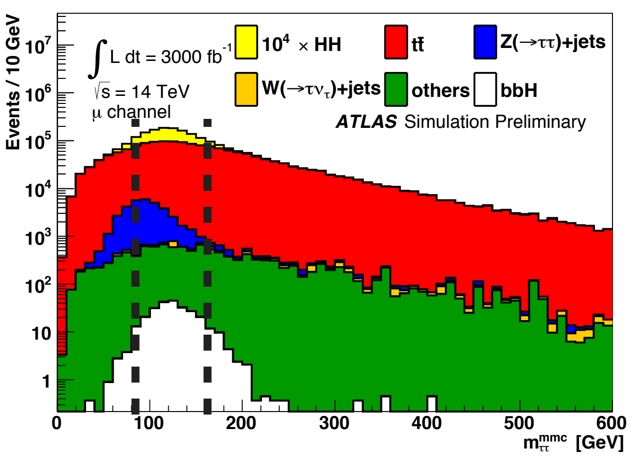
had-had + bb:

- p_T^{bb}>180 GeV, m_{T2}>180 GeV
- ***~13 sig. events (S/B~1.6%)***



lep-lep + bb:

- huge ttbar background
- dR_{bb}<1.0, p_T^{bb}>160 GeV
- ***~6 sig. events (S/B<<1%)***



lept-had + bb:

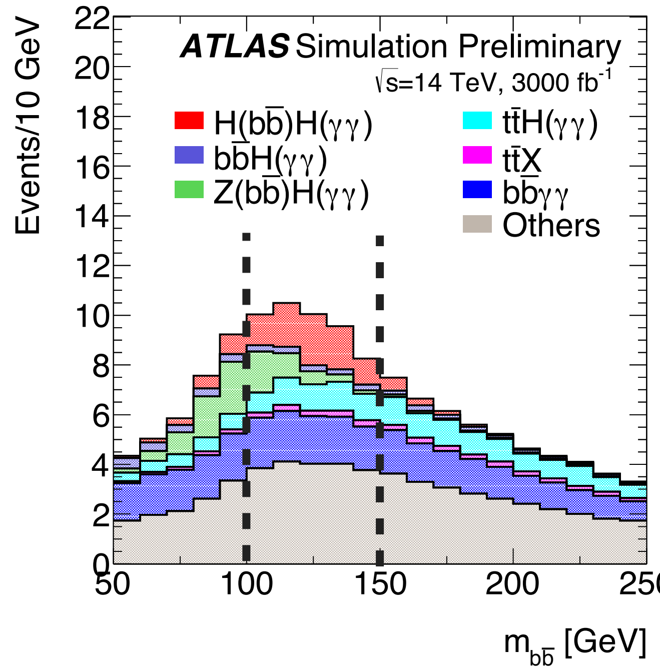
- p_T^{bb}>200 GeV, m_{T2}>220 GeV
- kinematic reconstruction to reduce top background
- ***~14 sig. events (S/B~1.5%)***

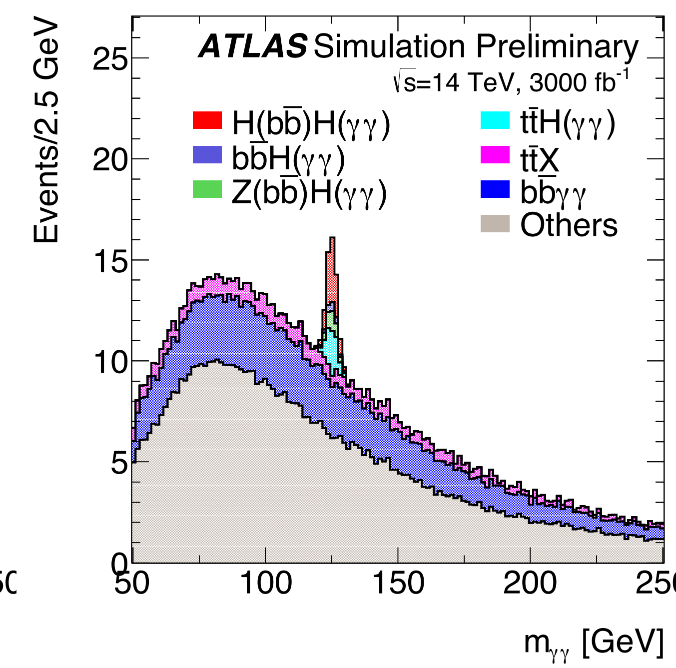
σ_{HH}/σ^{SM} < 4.3 @ 95% C.L.

- Extracting also confidence interval tri-linear coupling:
  - ***-4 < $\lambda_{HHH}/\lambda^{SM}_{HHH}$ < 12***

HH->γγbb (ATL-PHYS-PUB-2014-019)

- ==2 photons, ≥2 b-tagged jets (70%) efficiency:
  - optimised kinematic cuts on dR among objets

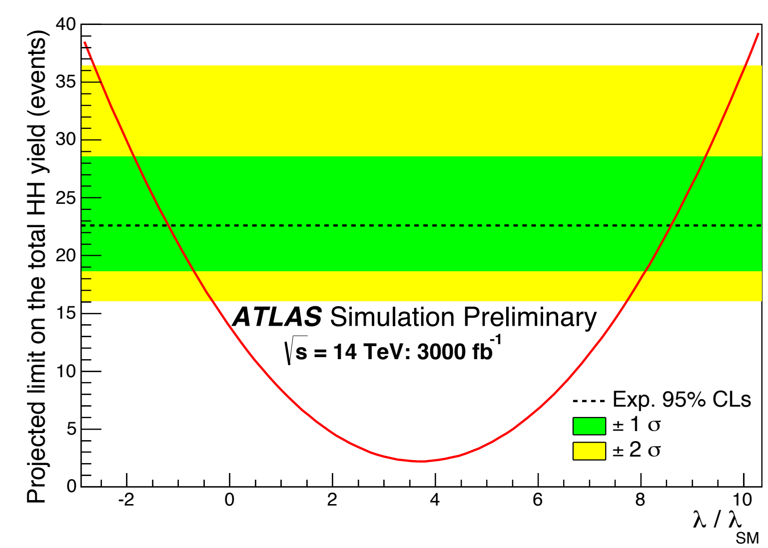




- With 3 ab^{-1} @ 14TeV:
  - ***8.4 signal events, 47 bkgd. events (S/B~20%)***

1.3 s.d. expected significance

σ_{HH}/σ^{SM} < 3 @ 95% C.L.

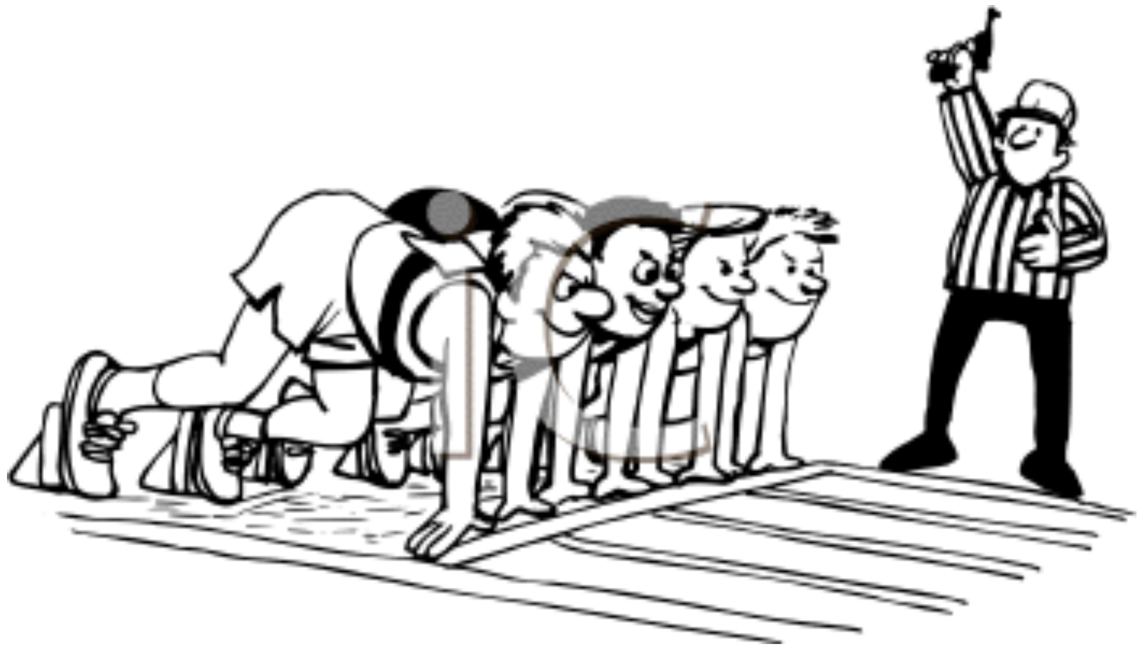


Summary and conclusions

✦ The start …….

- 13 TeV LHC Run2 is in full swing ….
- first preliminary EWK result being produced: inclusive cross section, VBF Higgs, searches for di-Higgs and di-boson resonances
- confirming results from Run1, no major surprised
- the summer dataset allows similar performance as Run1, more refined and complete analyses expected by the end of the year

STAY TUNED



✦ ….. the finish(?)

- while HL HLC is still far away, intensive work is already ongoing
- constantly refining our projections with more detailed and precise simulation
- improvement in detector component proved to have a strong impact on analyses sensitivities (especially on VBS/VBF channels): better acceptance, better background rejction

Thank you for your attention

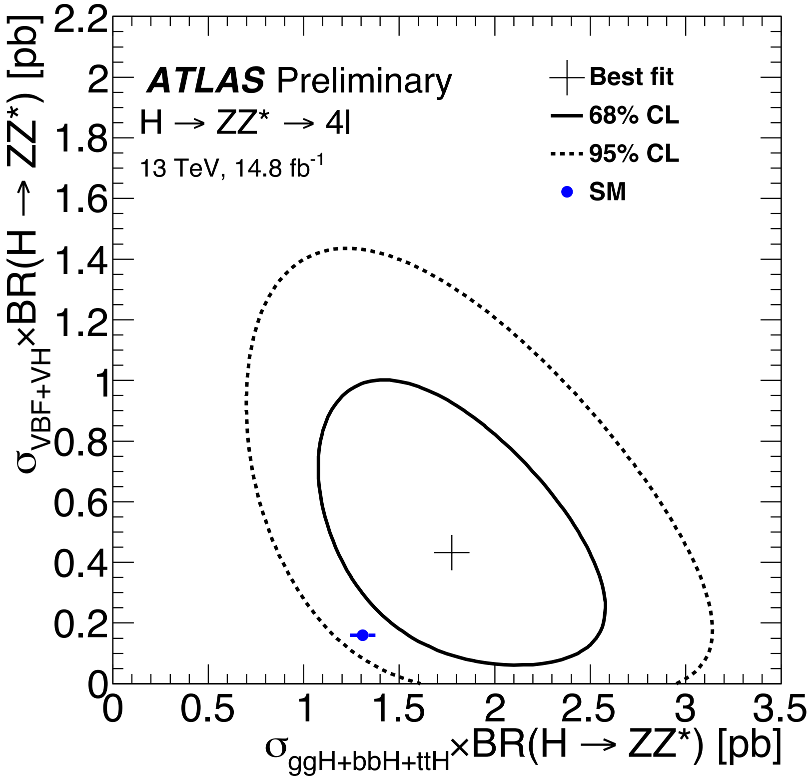
BackUp

WW theoretical predictions

$pp \to WW$ sub-process	order of $\mathcal{O}(\alpha_s)$	σ_{WW}^{tot} [pb]	A [%]	$\sigma_{WW\to e\mu}^{fid}$ [fb]
$q\bar{q}$ [10,14]	$\mathcal{O}(\alpha_s^2)$	111.1 ± 2.8	16.20 ± 0.13	422^{+12}_{-11}
gg (non-resonant) [16]	$\mathcal{O}(\alpha_s^3)$	$6.82^{+0.42}_{-0.55}$	$28.1^{+2.7}_{-2.3}$	44.9 ± 7.2
$gg \to H \to WW$ [17][31]	$\mathcal{O}(\alpha_s^5)$ tot. / $\mathcal{O}(\alpha_s^3)$ fid.	$10.45^{+0.61}_{-0.79}$	4.5 ± 0.80	11.0 ± 2.1
$q\bar{q} + gg$ (non-resonant) $+ gg \to H$	nNNLO+H	$128.4^{+3.5}_{-3.8}$	$15.87^{+0.17}_{-0.14}$	478 ± 17

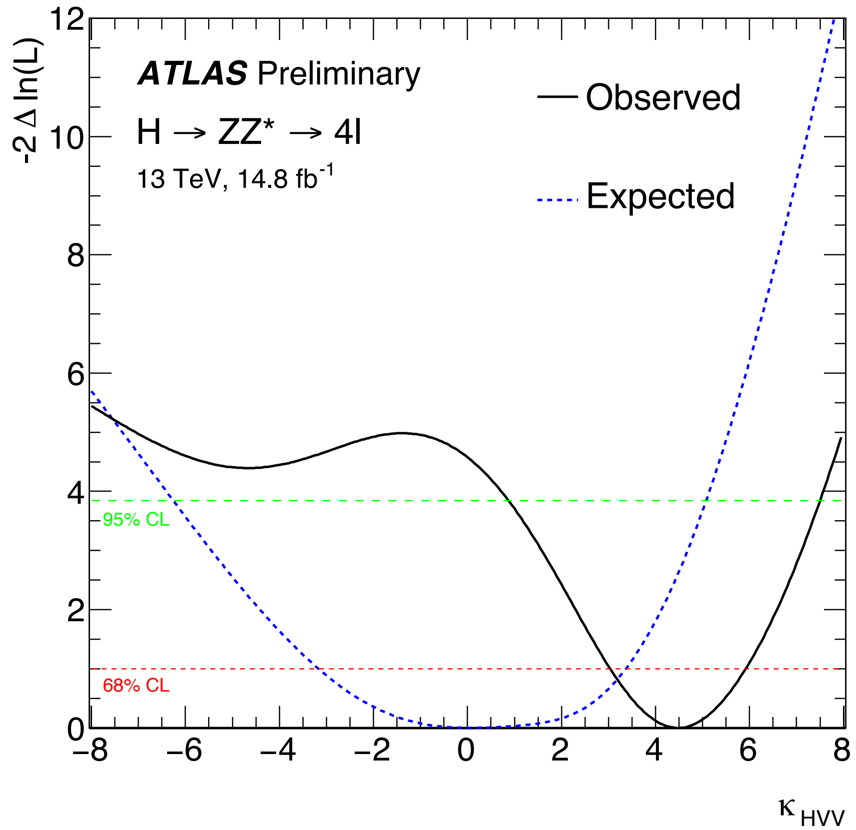
Detailed explanation of the xSection ratio plot.

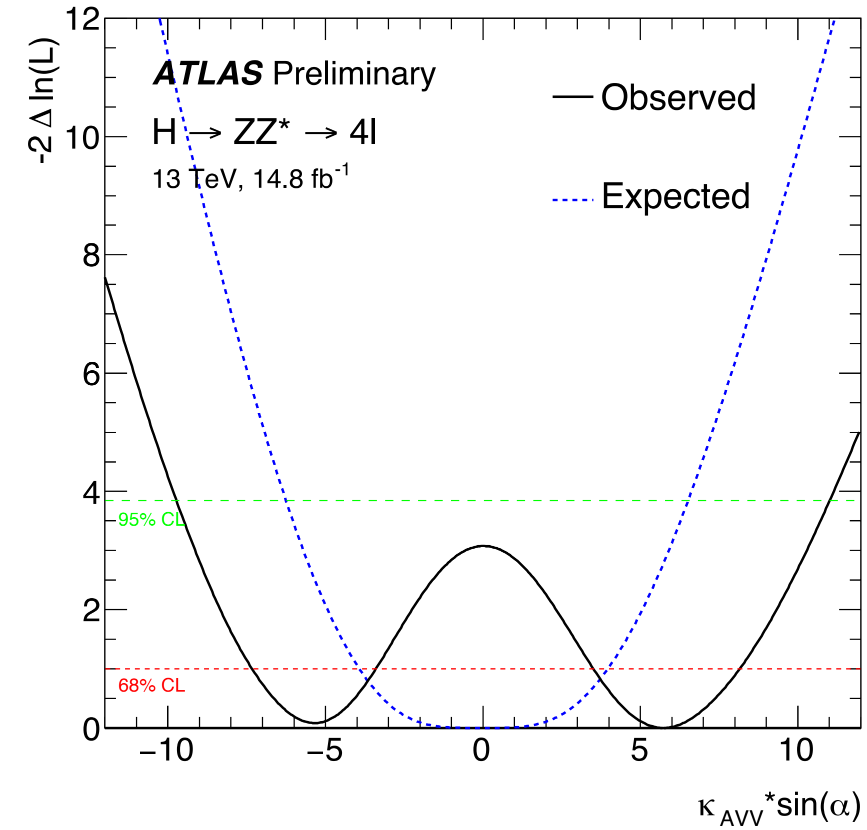
VBF H->ZZ @ 13 TeV



$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{\rm SM}\big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\big] \\
& - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big] \\
& - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big] \\
& - \frac{1}{\Lambda}c_\alpha\big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \big(\kappa_{H\partial W}\, W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\big)\big]\Big\} X_0\,,
\end{aligned}
$$

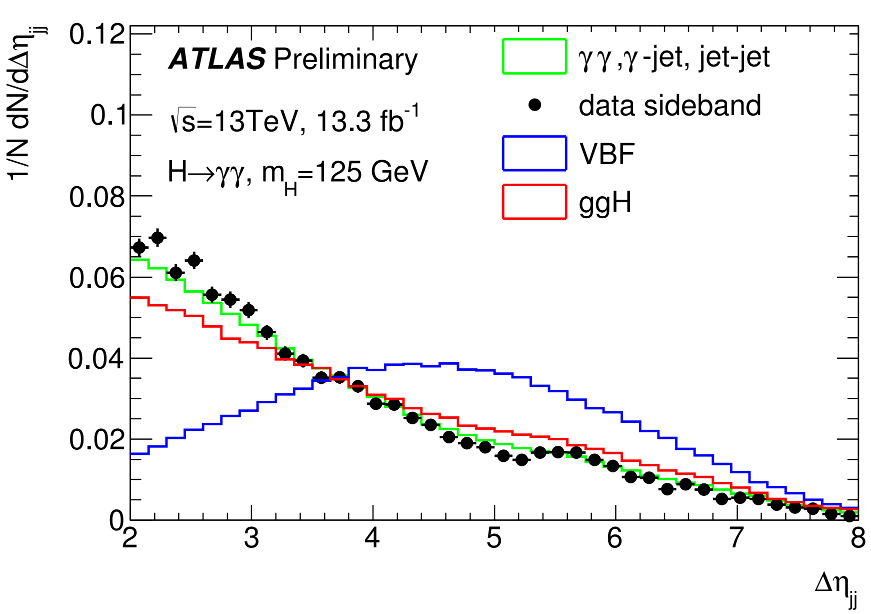
Not excluded range at 95% CL	κ_{HVV}		$\kappa_{AVV} \cdot \sin\alpha$	
	expected	observed	expected	observed
	[−6.3, 5.1]	[0.9, 7.5]	[−6.3, 6.5]	[−9.7, 11.0]

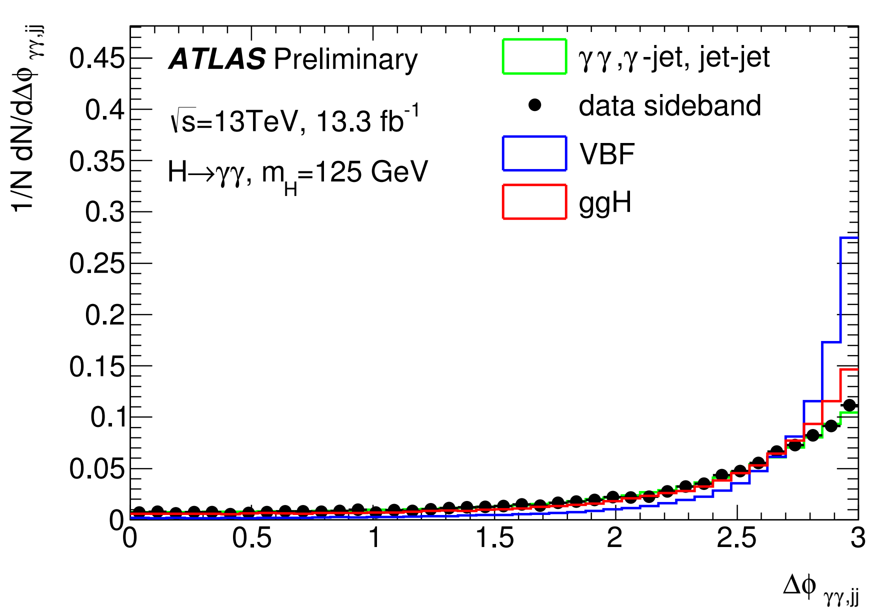




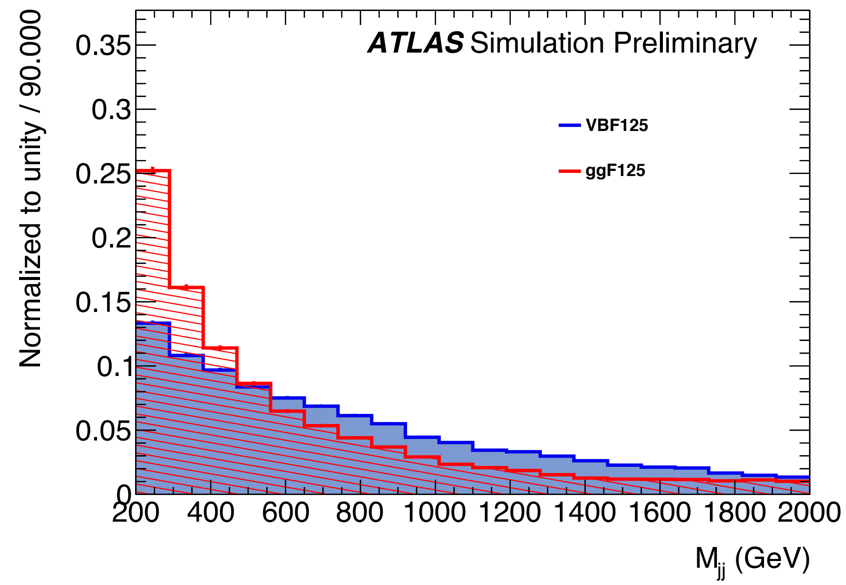
typical VBF variables

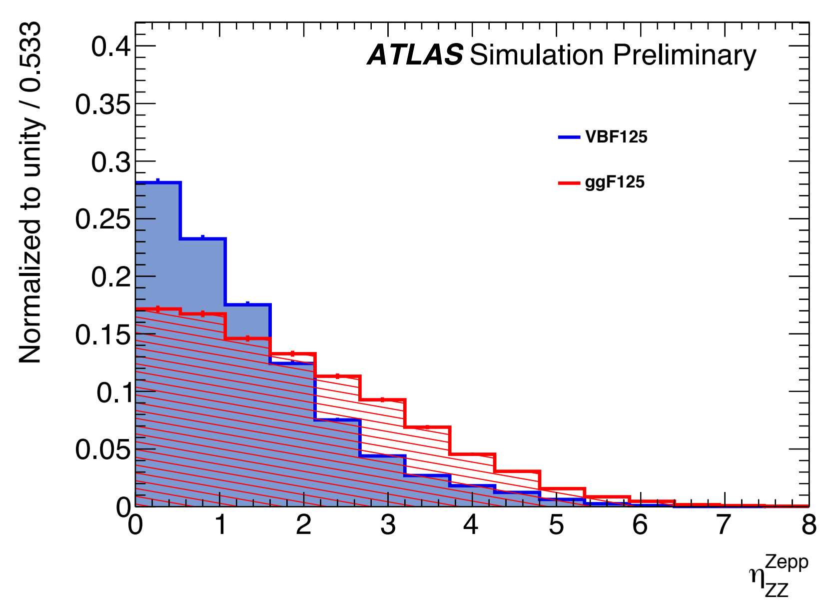
H->γγ





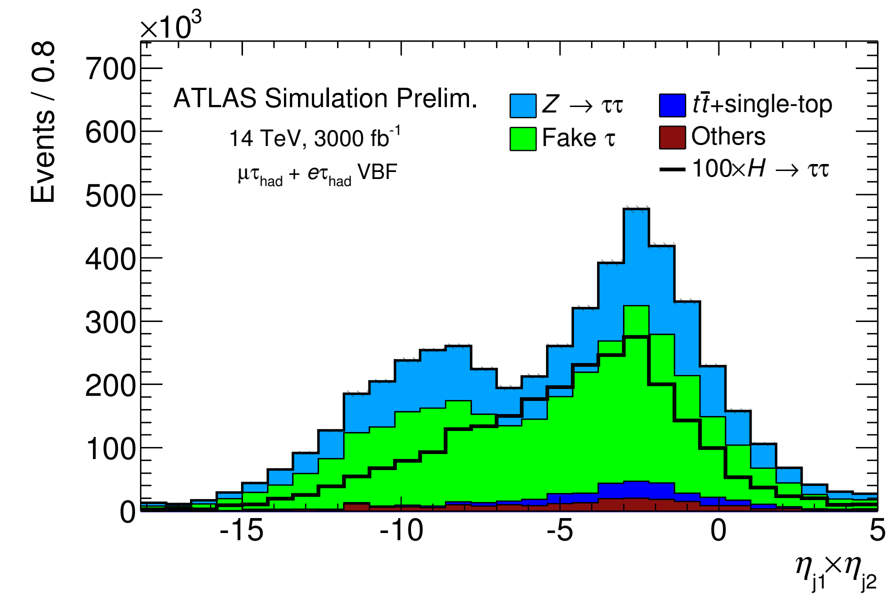
H->ZZ

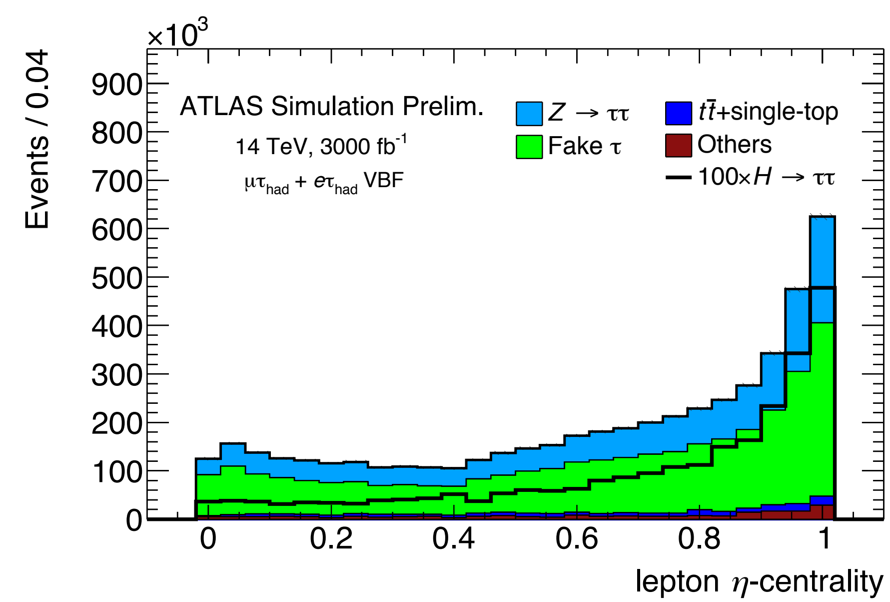




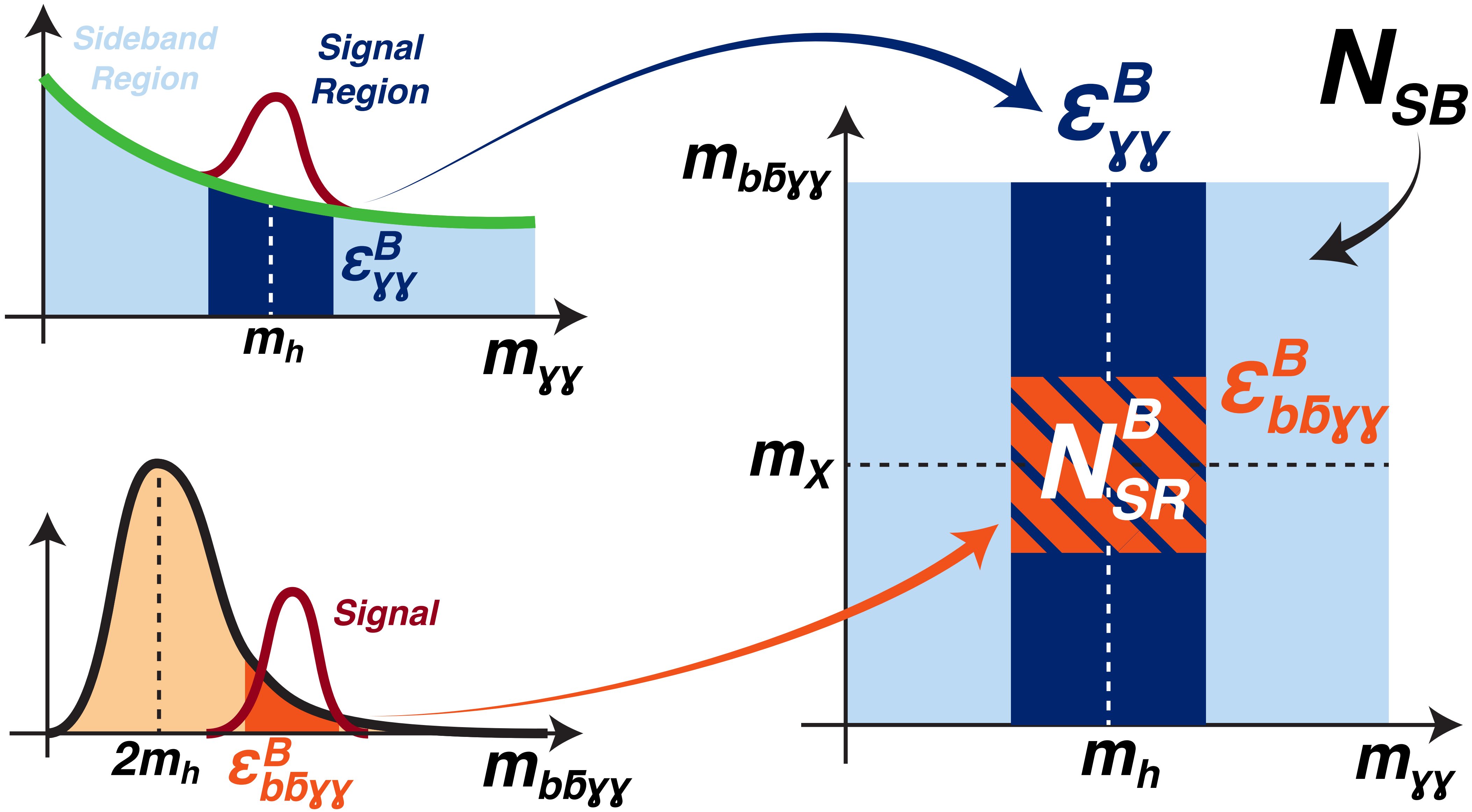
$$\eta_H^{\text{Zepp}} = \eta_H - \left\langle \eta_{(\text{jet 1})},\ \eta_{(\text{jet 2})} \right\rangle$$

H->$\tau\tau$

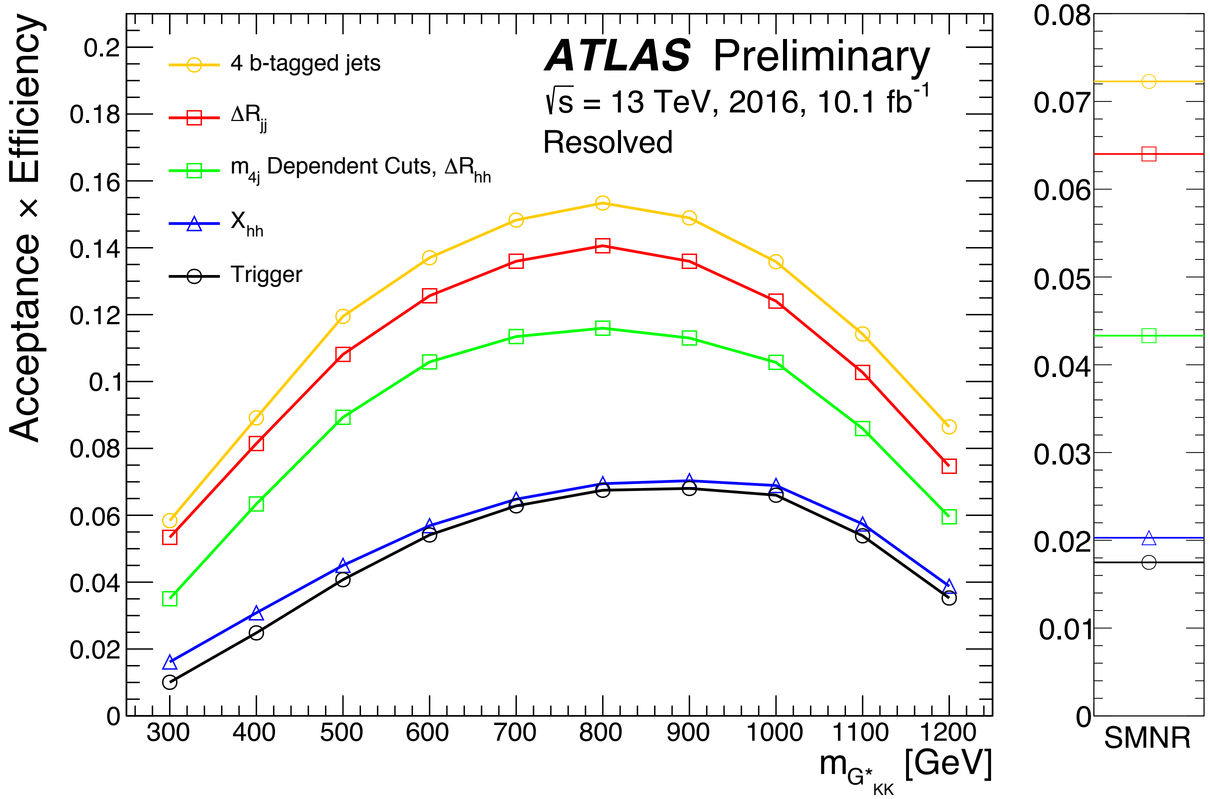




HH->$\gamma\gamma bb$

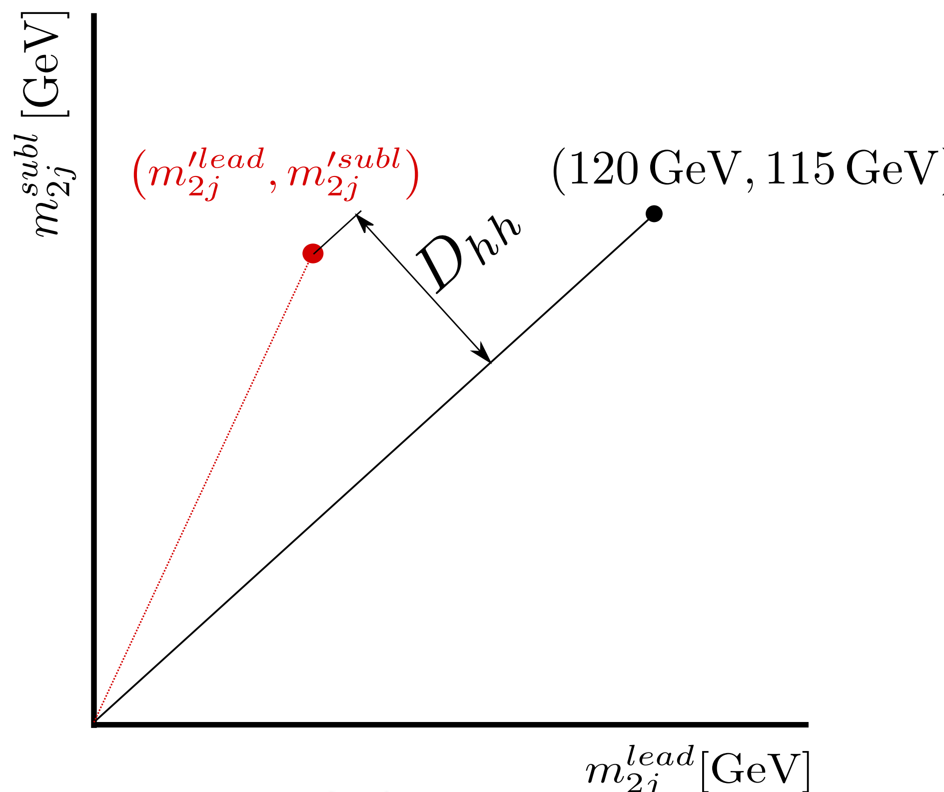


HH->bbbb: resolved



$$\left.\begin{array}{r}\dfrac{360}{m_{4j}} - 0.5 < \Delta R_{jj,\mathrm{lead}} < \dfrac{655}{m_{4j}} + 0.475 \\ \dfrac{235}{m_{4j}} < \Delta R_{jj,\mathrm{subl}} < \dfrac{875}{m_{4j}} + 0.35\end{array}\right\} \text{if } m_{4j} < 1250 \text{ GeV}$$

$$\left.\begin{array}{r}0 < \Delta R_{jj,\mathrm{lead}} < 1 \\ 0 < \Delta R_{jj,\mathrm{subl}} < 1\end{array}\right\} \text{if } m_{4j} > 1250 \text{ GeV}$$



$$X_{hh} = \sqrt{\left(\frac{m_{2j}^{\mathrm{lead}} - 120 \text{ GeV}}{0.1 m_{2j}^{\mathrm{lead}}}\right)^2 + \left(\frac{m_{2j}^{\mathrm{subl}} - 115 \text{ GeV}}{0.1 m_{2j}^{\mathrm{subl}}}\right)^2} < 1.6$$

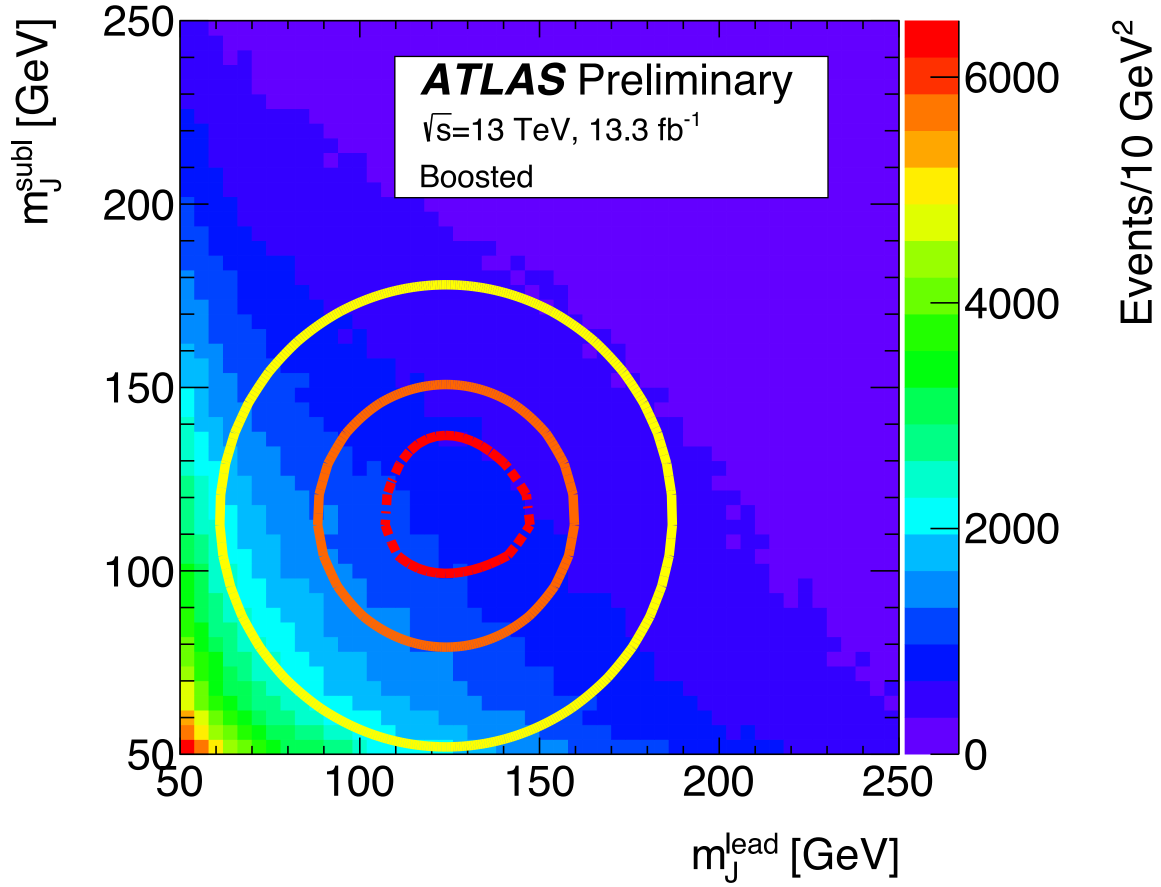
$$p_{\mathrm{T}}^{\mathrm{lead}} > 0.5 m_{4j} - 90 \text{ GeV}$$

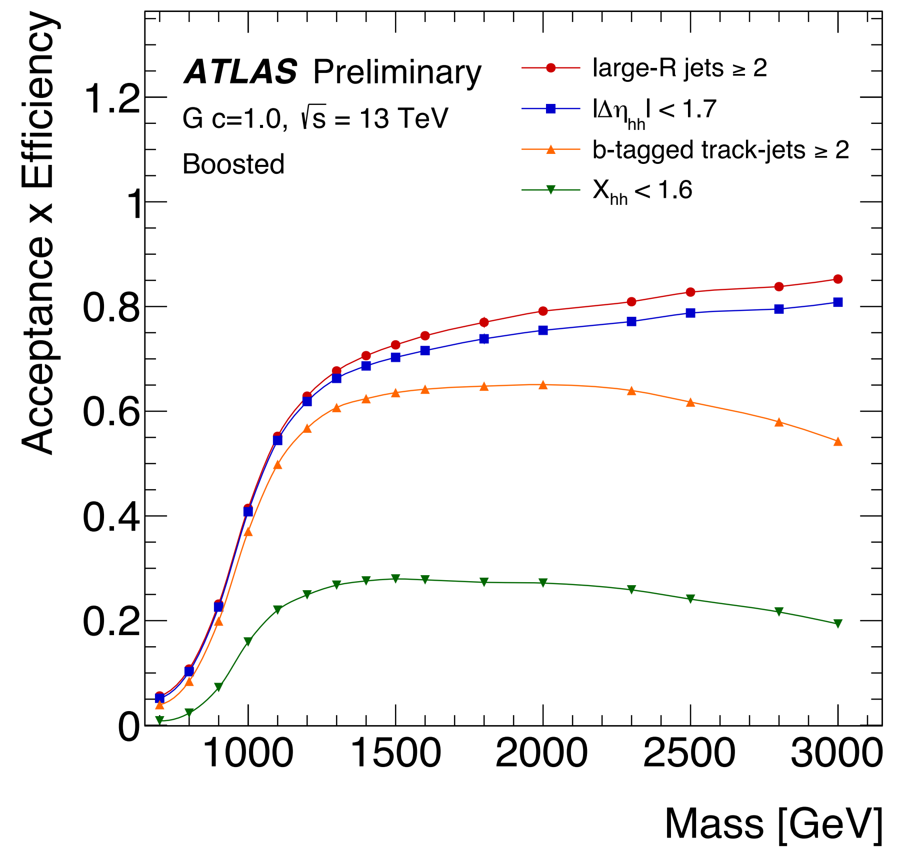
$$p_{\mathrm{T}}^{\mathrm{subl}} > 0.33 m_{4j} - 70 \text{ GeV}$$

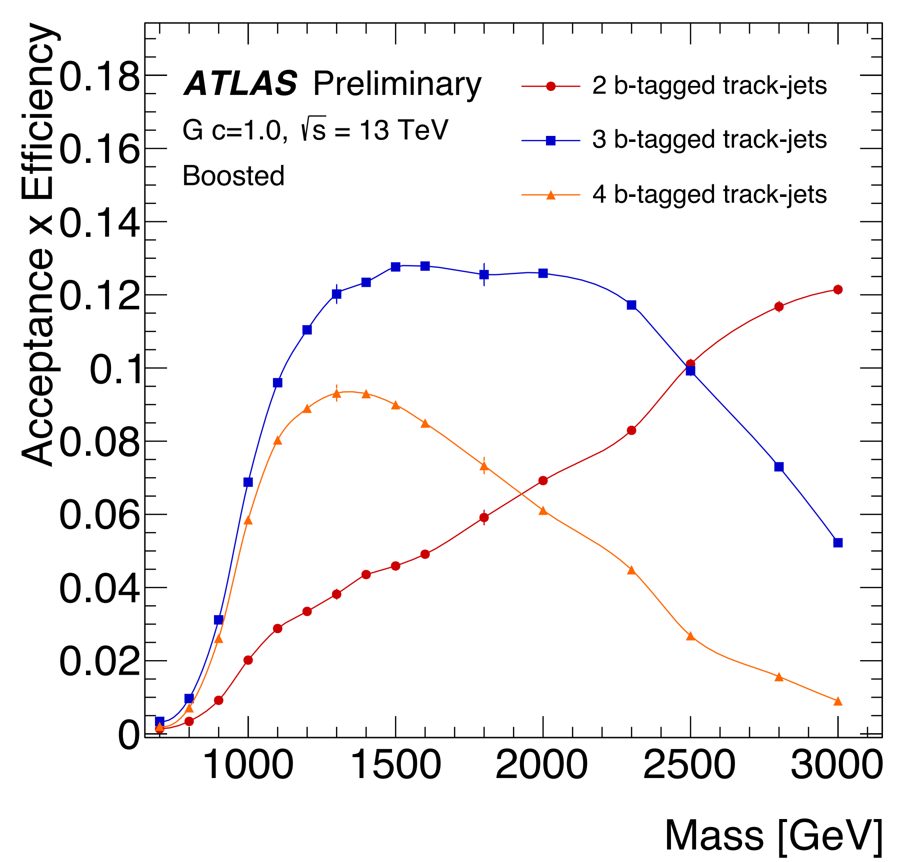
$$|\Delta\eta_{hh}| < \begin{cases} 1.1 & \text{if } m_{4j} < 850 \text{ GeV} \\ 2 \times 10^{-3} m_{4j} - 0.6 & \text{if } m_{4j} > 850 \text{ GeV}\end{cases}$$

HH->bbbb: boosted

$$X_{hh} = \sqrt{\left(\frac{m_J^{lead} - 124\ \text{GeV}}{0.1 m_J^{lead}}\right)^2 + \left(\frac{m_J^{subl} - 115\ \text{GeV}}{0.1 m_J^{subl}}\right)^2} < 1.6$$







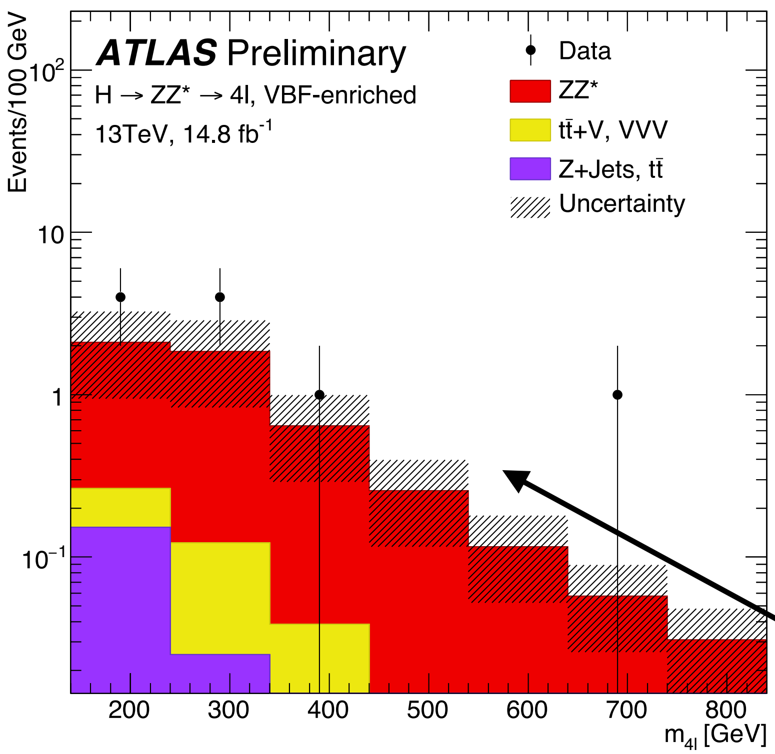
H->ZZ selection

Leptons and Jets requirements	
Electrons	
Loose Likelihood quality electrons with hit in innermost layer, $E_T > 7$ GeV and $\|\eta\| < 2.47$	
Muons	
Loose identification $\|\eta\| < 2.7$	
Calo-tagged muons with $p_T > 15$ GeV and $\|\eta\| < 0.1$	
Combined, stand-alone (with ID hits if available) and segment tagged muons with $p_T > 5$ GeV	
Jets	
anti-k_t jets with $p_T > 30$ GeV, $\|\eta\| < 4.5$ and passing pile-up jet rejection requirements	

Event Selection	
Quadruplet Selection	Require at least one quadruplet of leptons consisting of two pairs of same flavour opposite-charge leptons fulfilling the following requirements: p_T thresholds for three leading leptons in the quadruplet - 20, 15 and 10 GeV Maximum of one calo-tagged or standalone muon per quadruplet Select best quadruplet to be the one with the (sub)leading dilepton mass (second) closest the Z mass Leading dilepton mass requirement: 50 GeV $< m_{12} <$ 106 GeV Sub-leading dilepton mass requirement: $12 < m_{34} < 115$ GeV Remove quadruplet if alternative same-flavour opposite-charge dilepton gives $m_{\ell\ell} < 5$ GeV $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same(different)-flavour leptons in the quadruplet
Isolation	Contribution from the other leptons of the quadruplet is subtracted Muon track isolation ($\Delta R \leq 0.30$): $\Sigma p_T/p_T < 0.15$ Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T/p_T < 0.30$ Electron track isolation ($\Delta R \leq 0.20$) : $\Sigma E_T/E_T < 0.15$ Electron calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.20$
Impact Parameter Significance	Apply impact parameter significance cut to all leptons of the quadruplet. For electrons : $\|d_0/\sigma_{d_0}\| < 5$ For muons : $\|d_0/\sigma_{d_0}\| < 3$
Vertex Selection	Require a common vertex for the leptons χ^2/ndof < 6 for 4μ and < 9 for others.

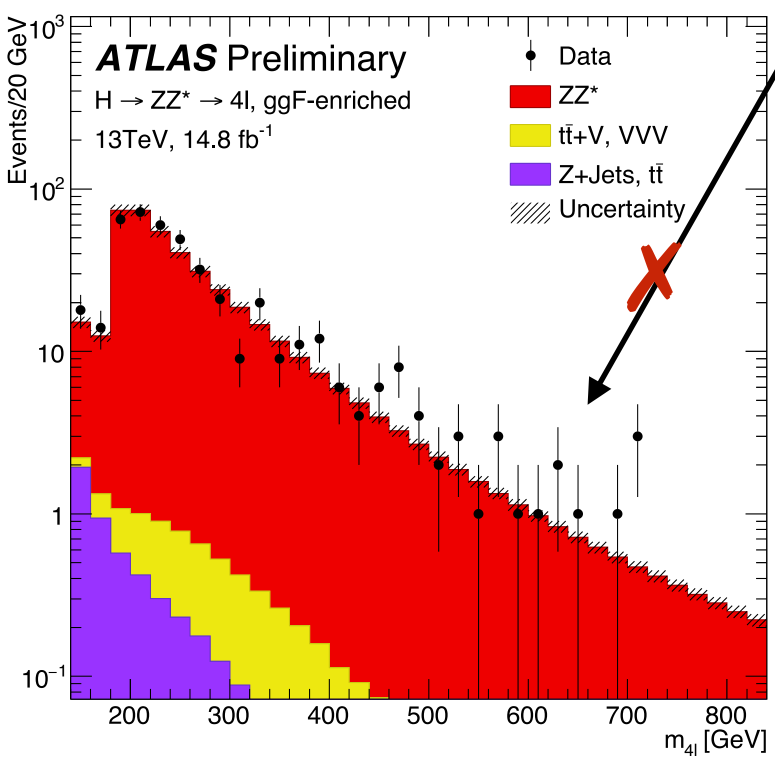
High mass H->WW/ZZ

H->ZZ (ATLAS-CONF-2016-079)



2 on-shell Z:

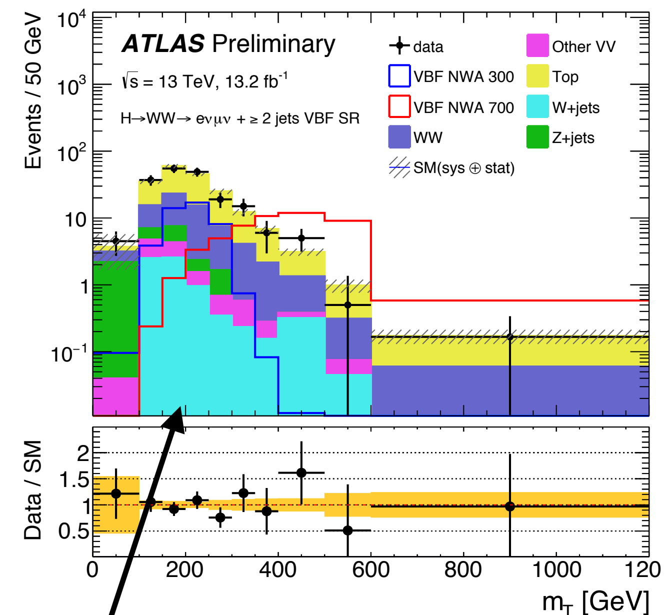
- 2 jets
- m_{jj}>400 GeV
- $|\Delta\eta_{jj}|$>3.3

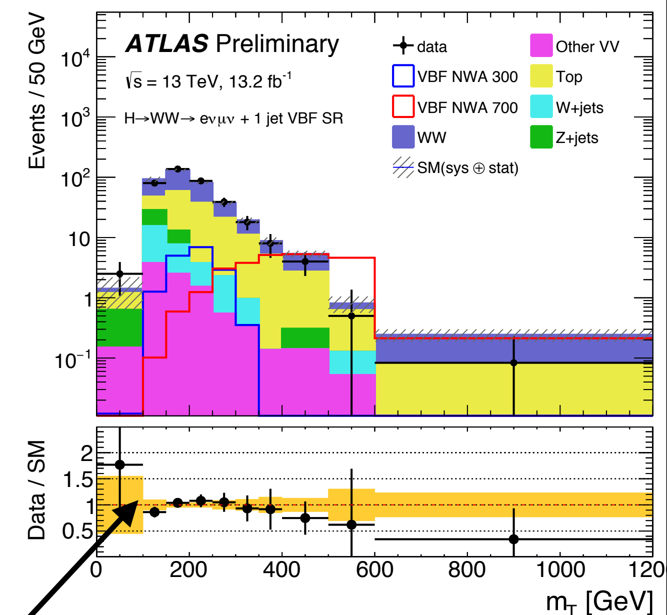


analytical shape description of signal (Gaussian+CB) and background

H->WW (ATLAS-CONF-2016-074)

eνμν final state: 2 on-shell W (m_{ll}>55 GeV)



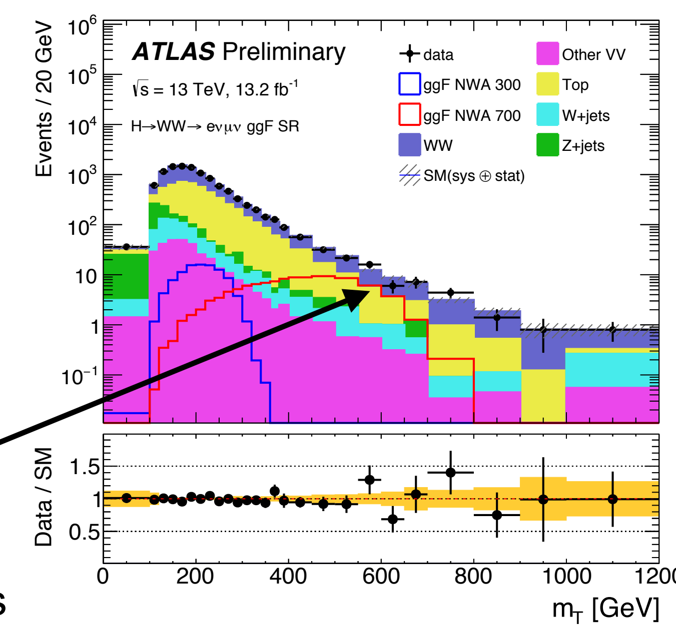


VBF 2jets:

- m_{jj}>400 GeV, $|\Delta\eta_{jj}|$>4
- top dominated

VBF 1jets:

- jet η>2.4,
- min($|\Delta\eta_{jl}|$)>1.5



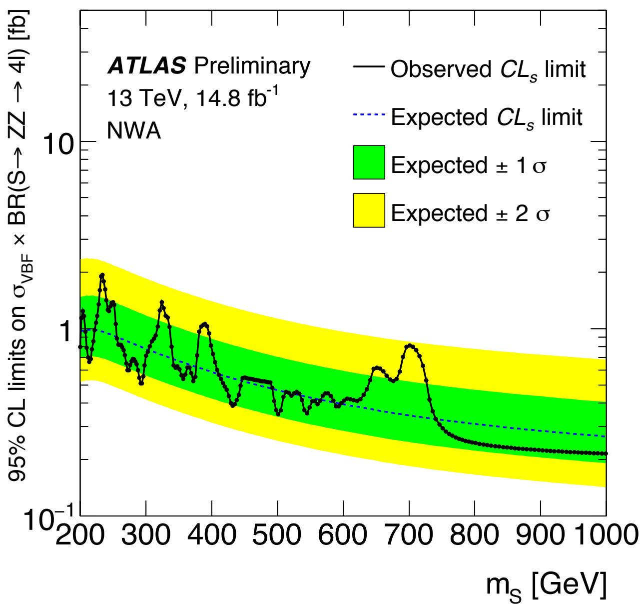
ggF:VBF 2jets:

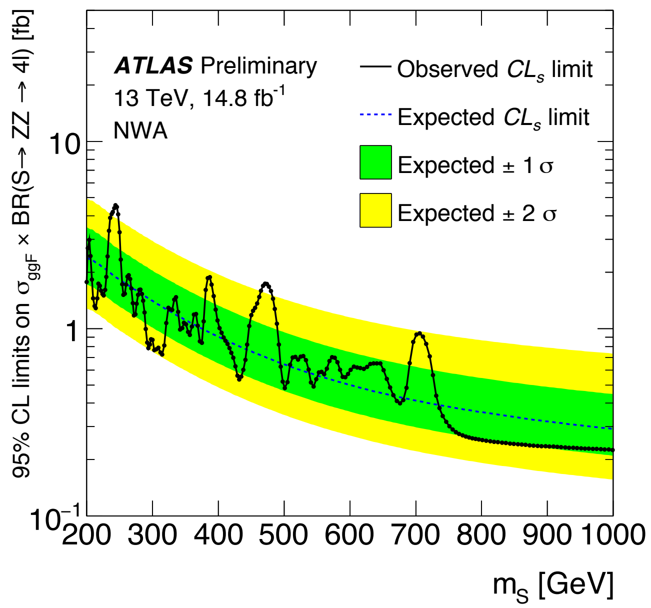
- inclusive minus VBF categories
- WW dominated

High mass H->WW/ZZ (2)

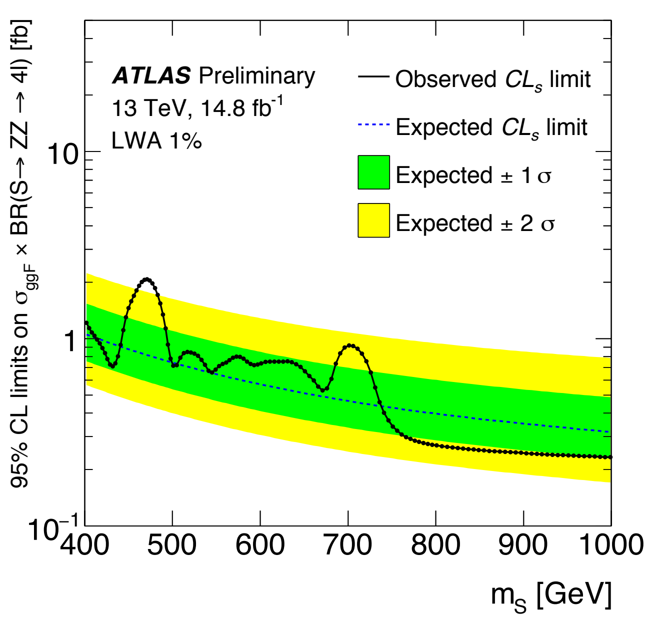
H->ZZ (**ATLAS-CONF-2016-079**)

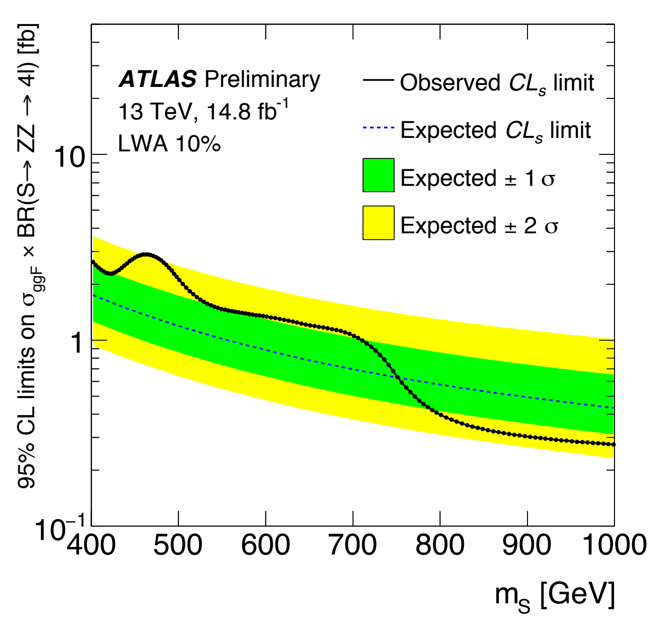
***NWA**: same width as SM Higgs boson (peak width dominated by detector resolution)*



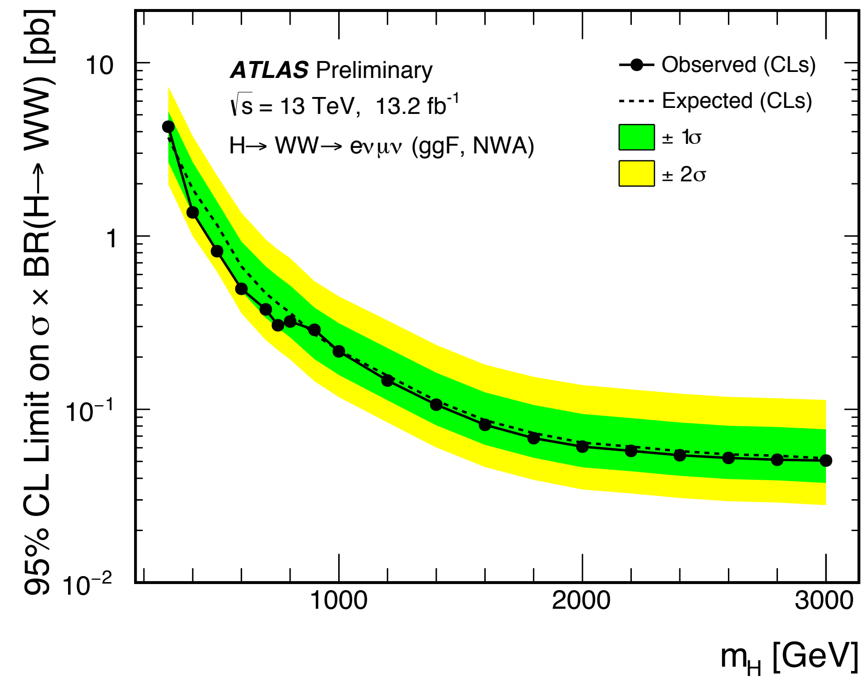


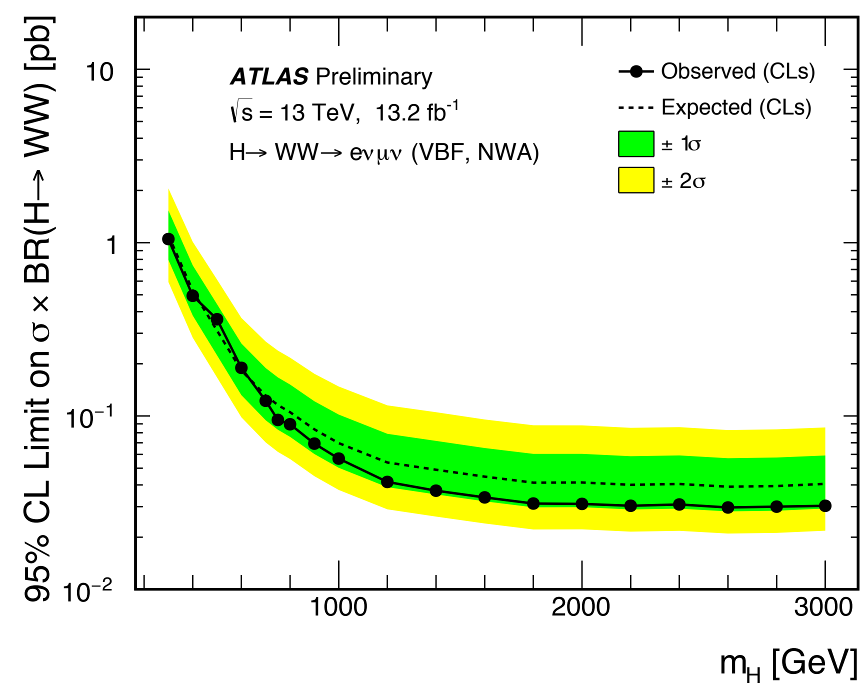
***LWA**: different assumptions on the width*



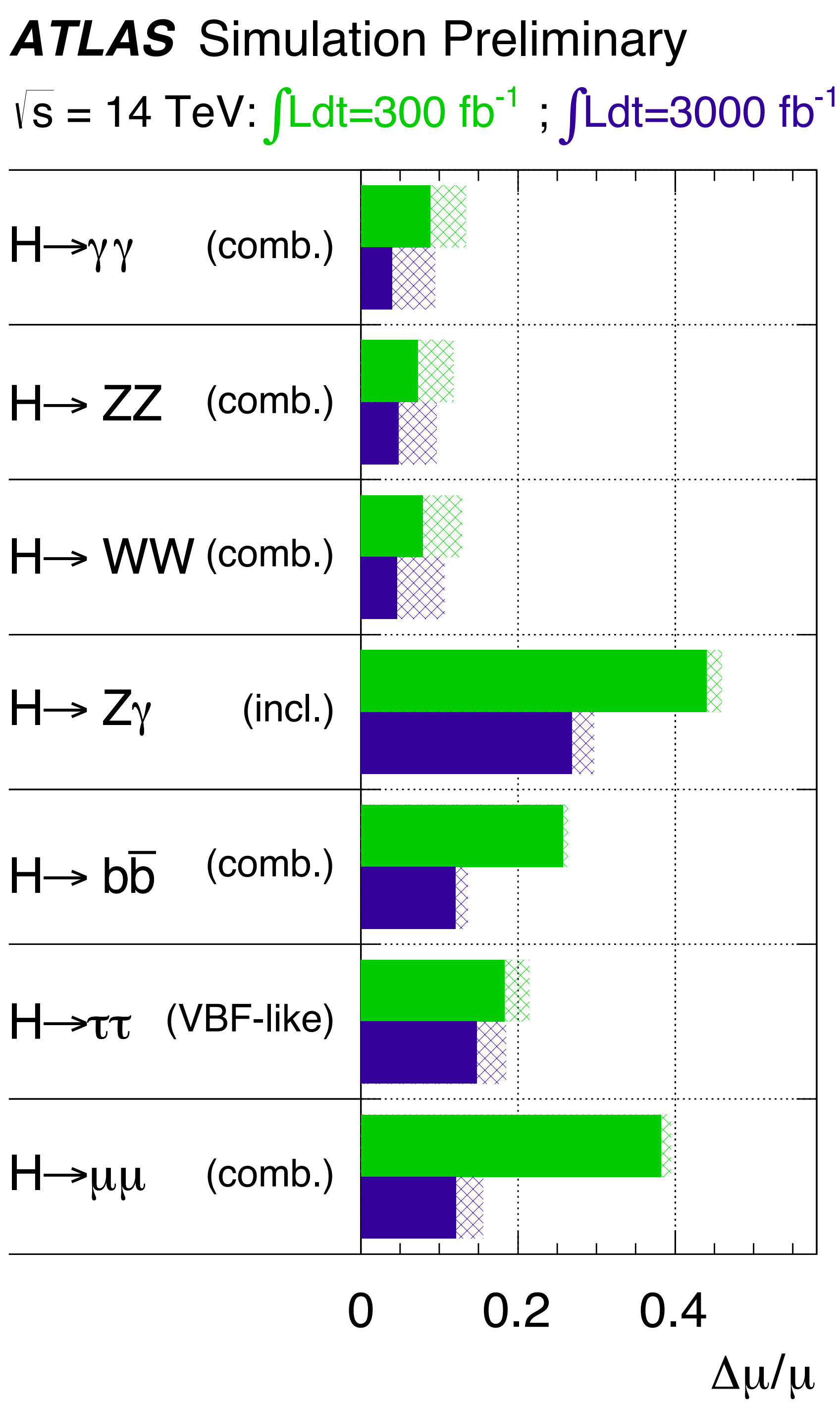


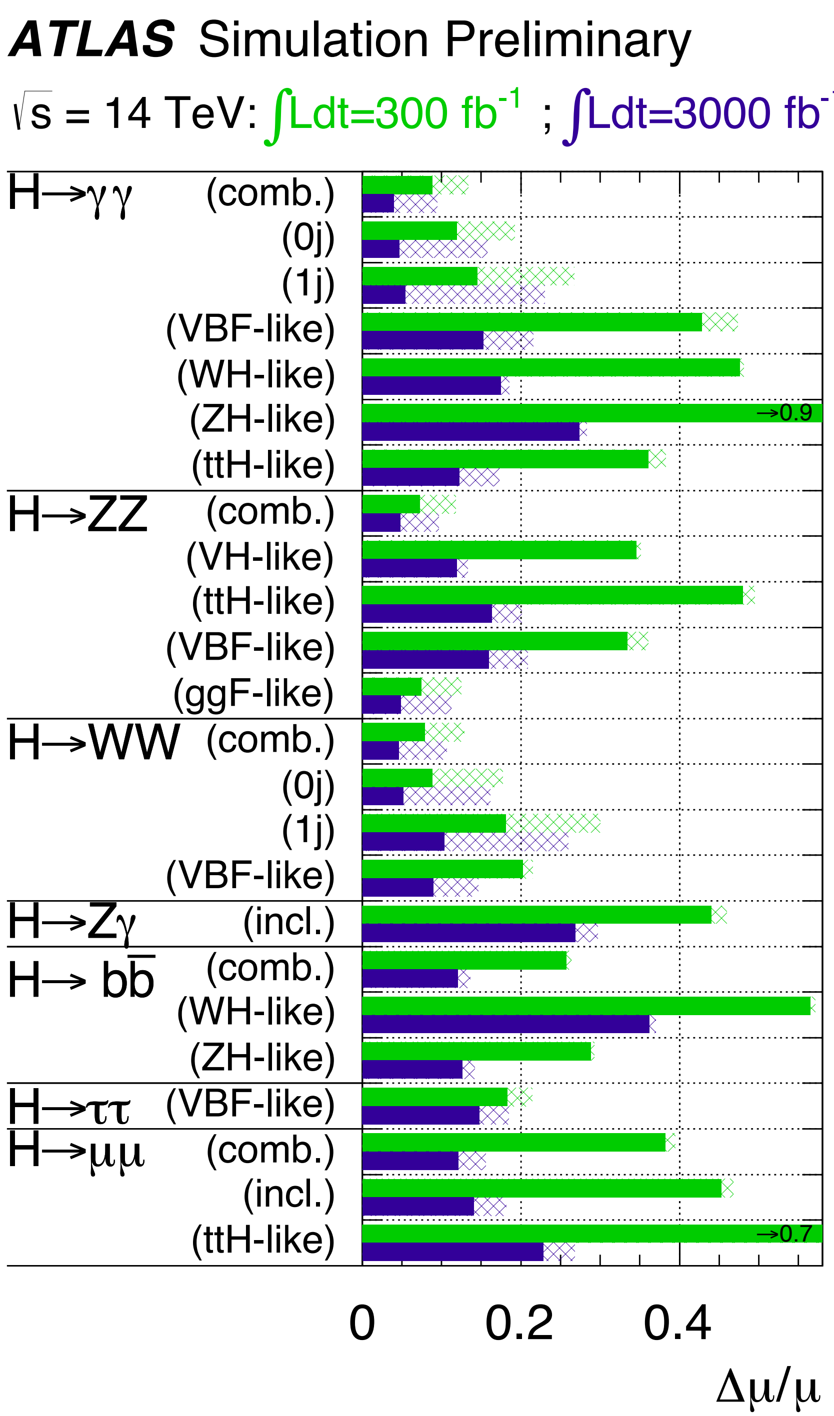
H->WW (**ATLAS-CONF-2016-074**)





A bit out-dated studies: ***ATL-PHYS-PUB-2014-016***



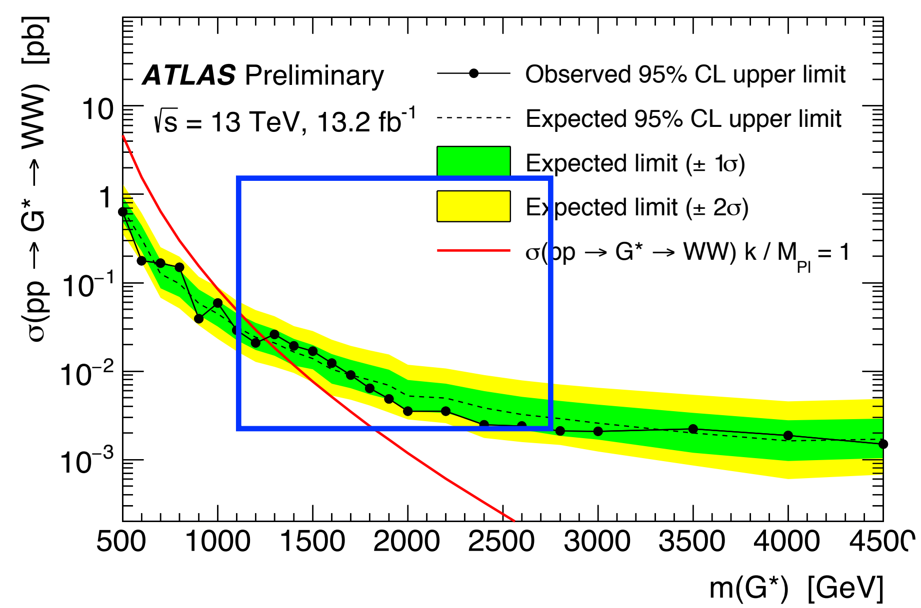


Prospects for VBS:

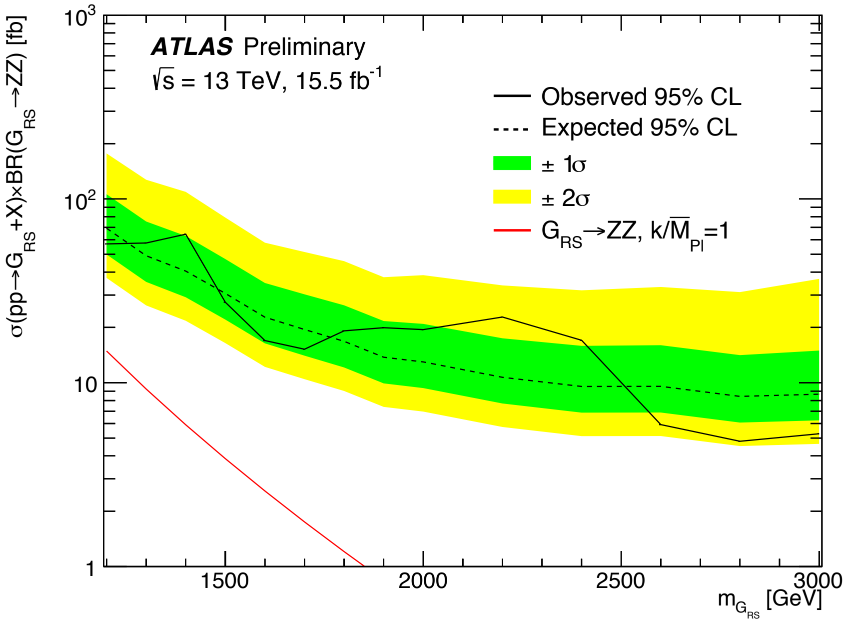
https://cds.cern.ch/record/1558703/files/ATL-PHYS-PUB-2013-006.pdf

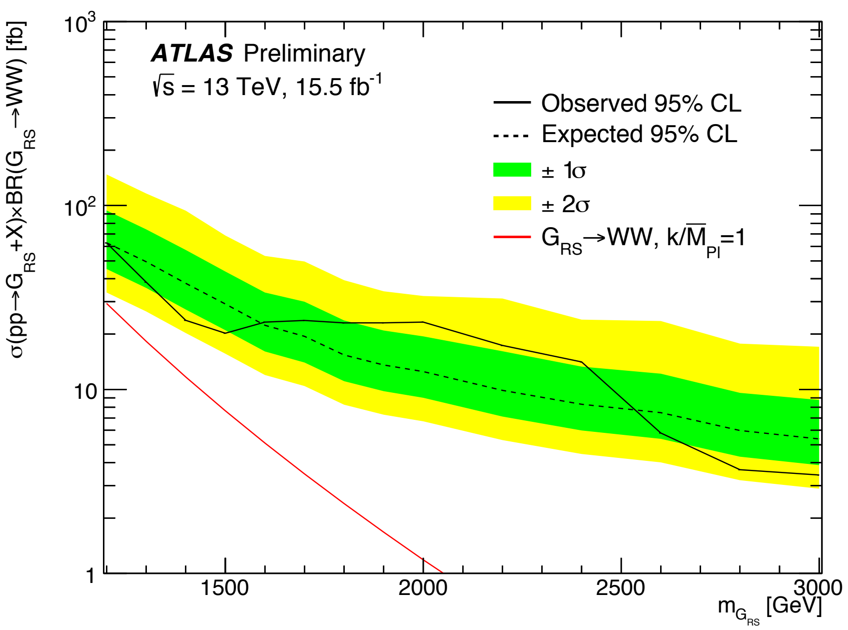
VV resonances: RS interpretations

WV->lvJ

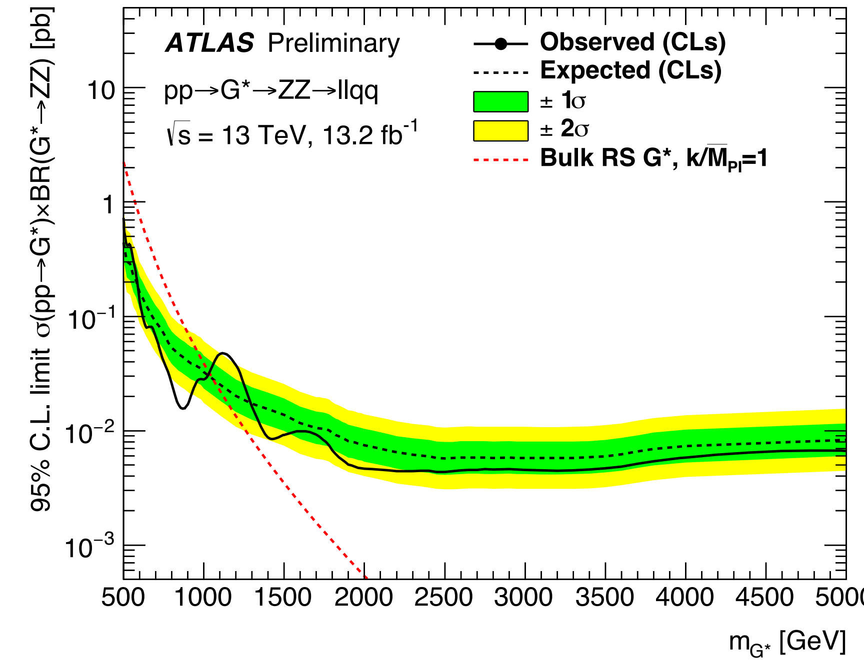


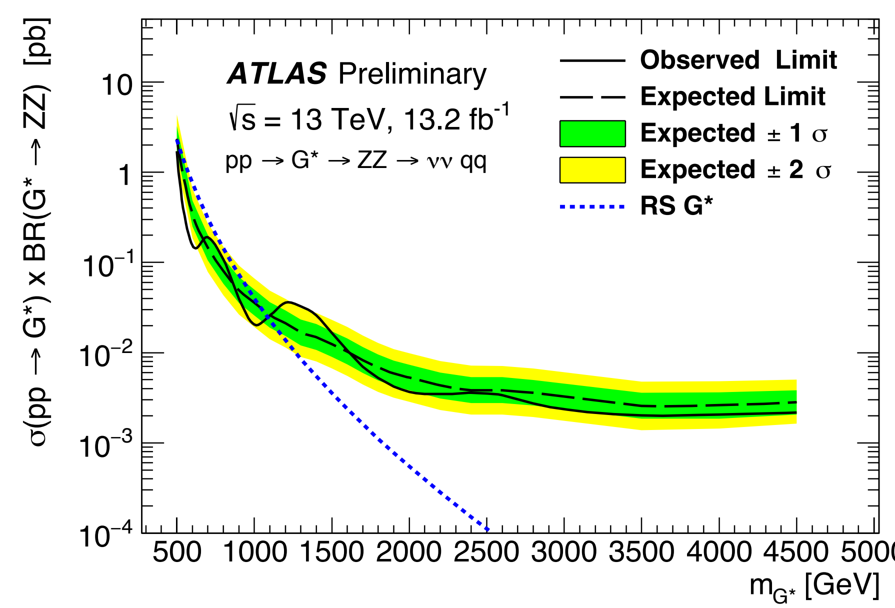
VV->JJ



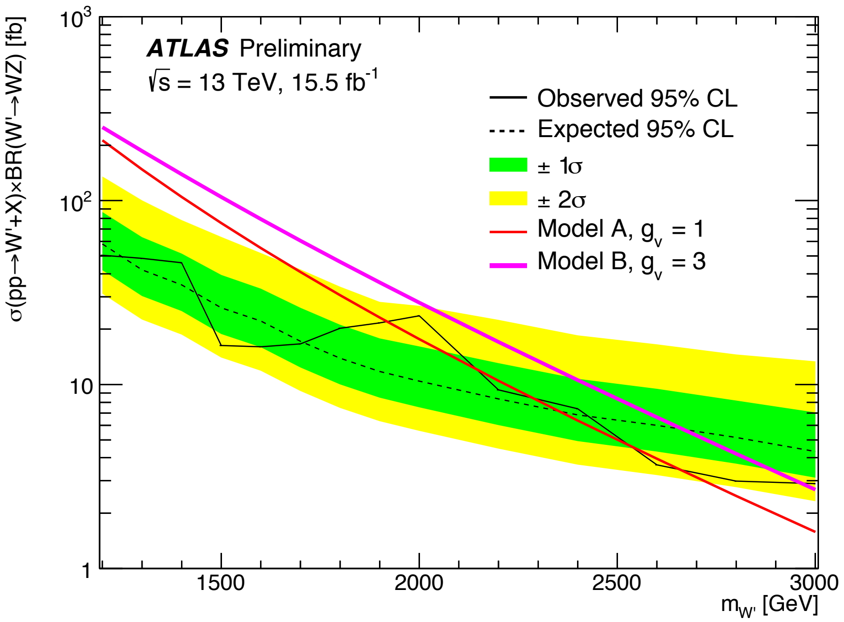


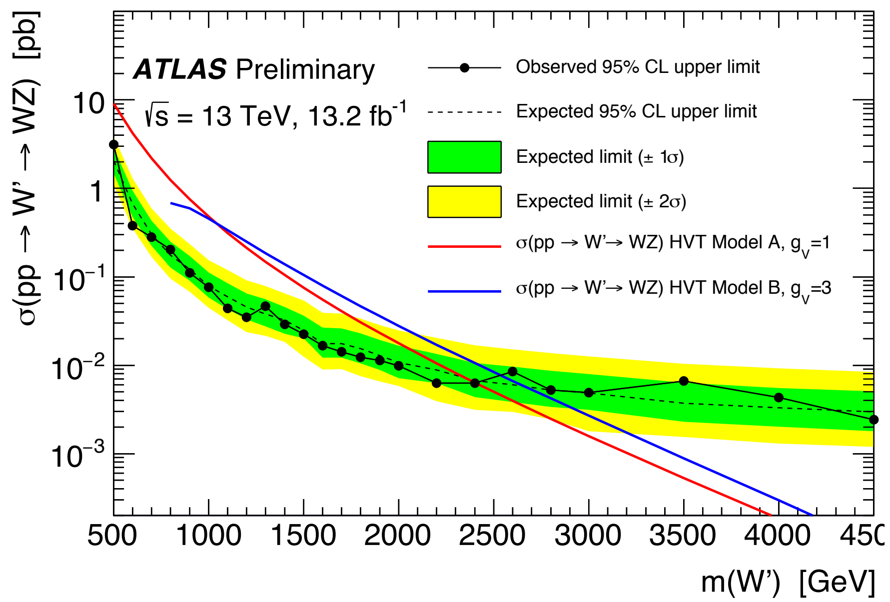
ZZ->(ll/vv)(J/jj)

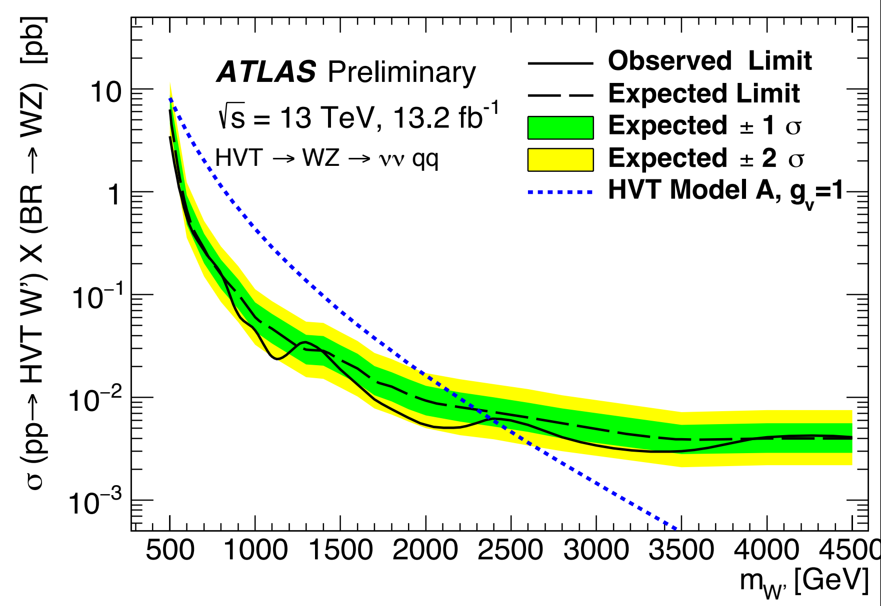




VV resonances: W'/Z'RS interpretations



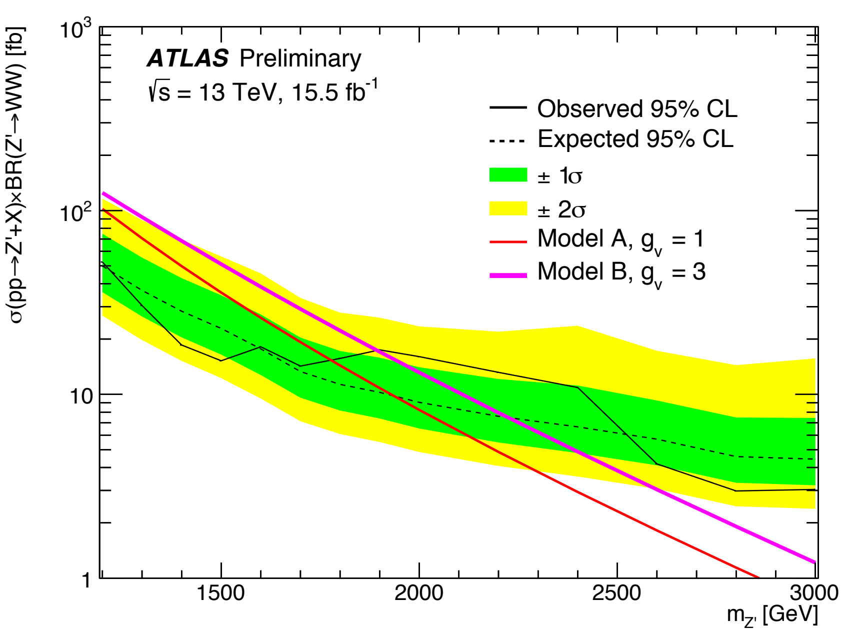


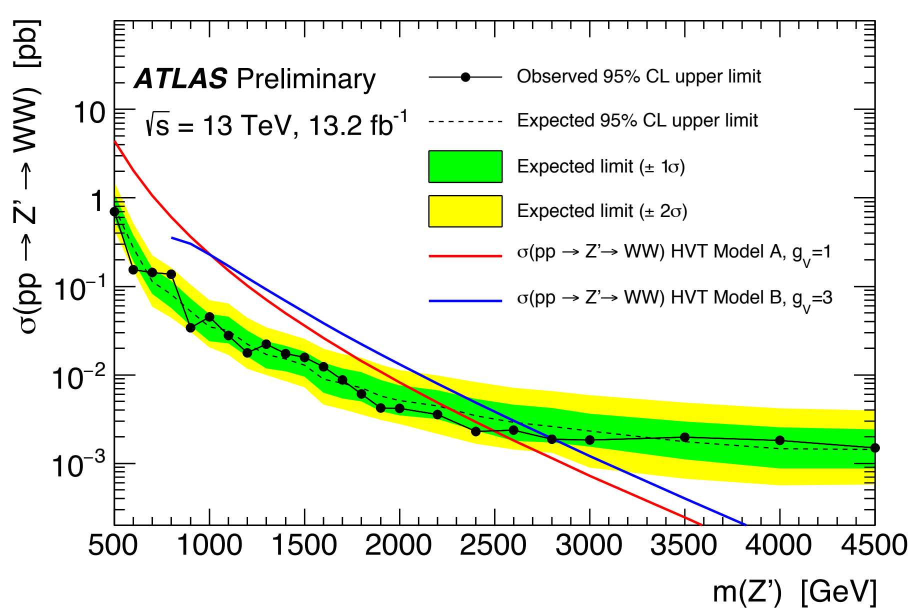


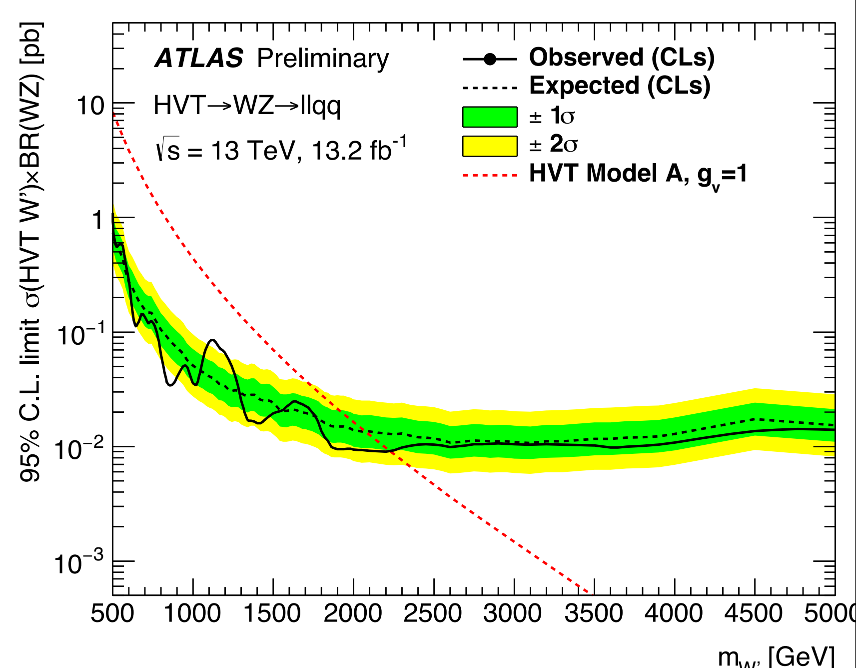
VV->JJ

WV->lvJ

ZZ->(ll/vv)(J/jj)

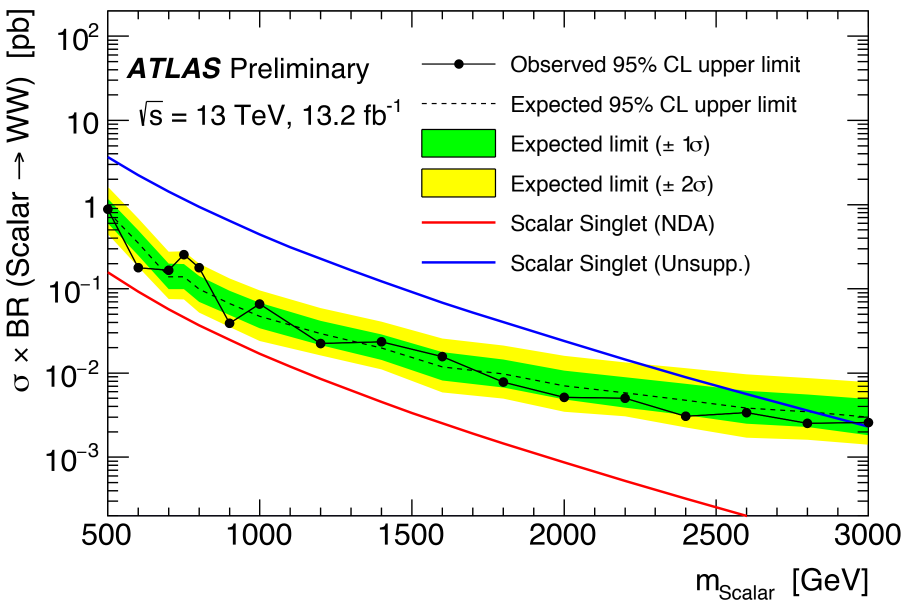


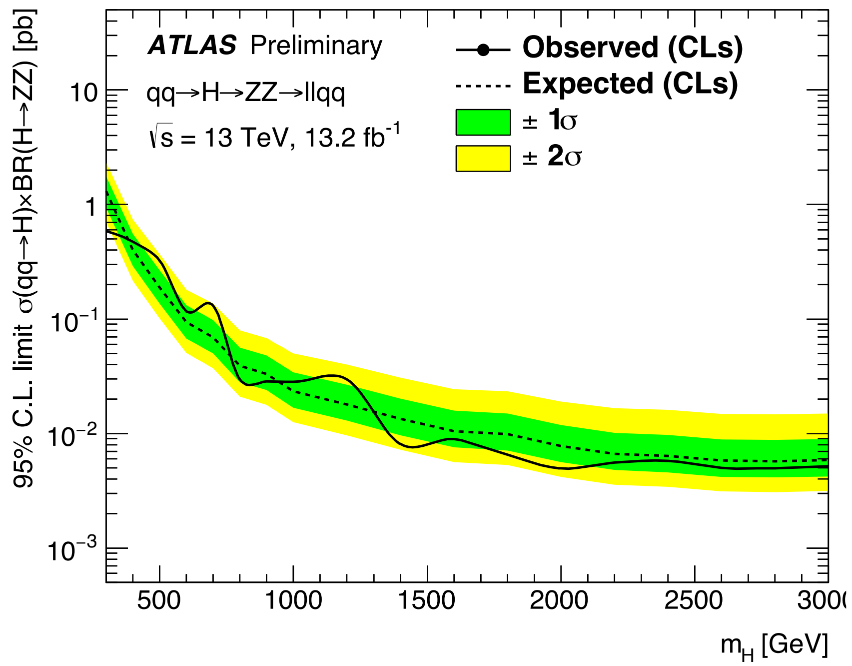


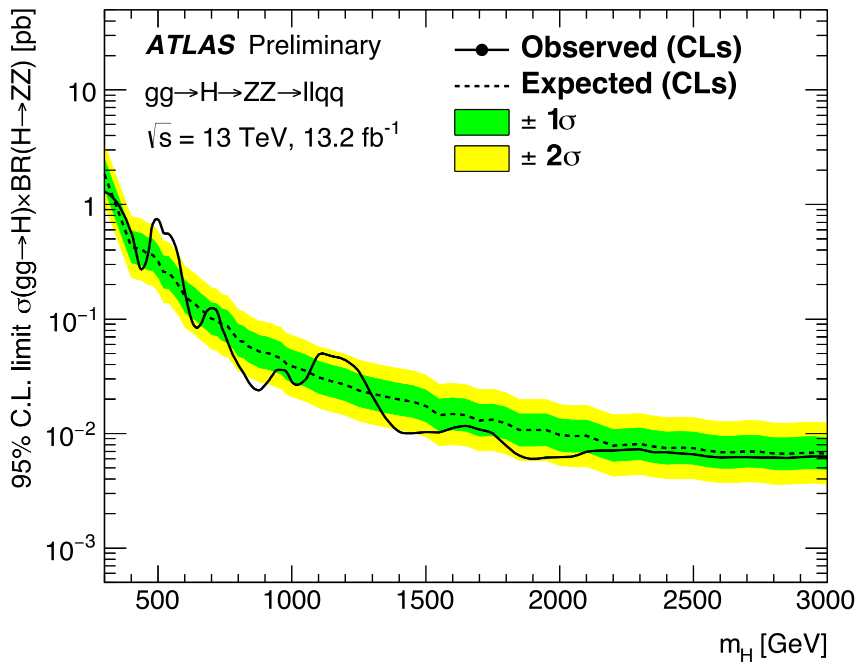


VV resonances: Scalar

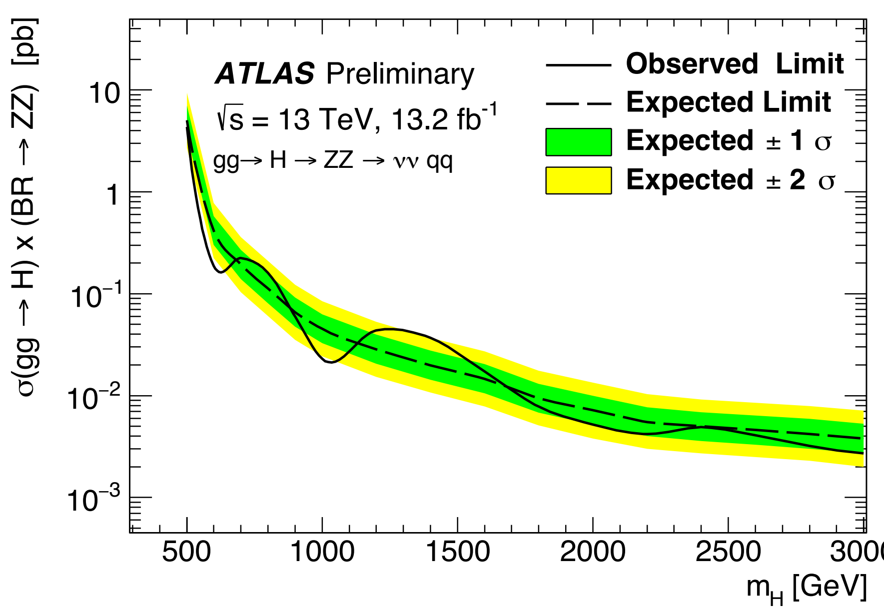
WV->lvJ







ZZ->(ll/vv)(J/jj)



llqq analysis