Higgs Physics at ATLAS

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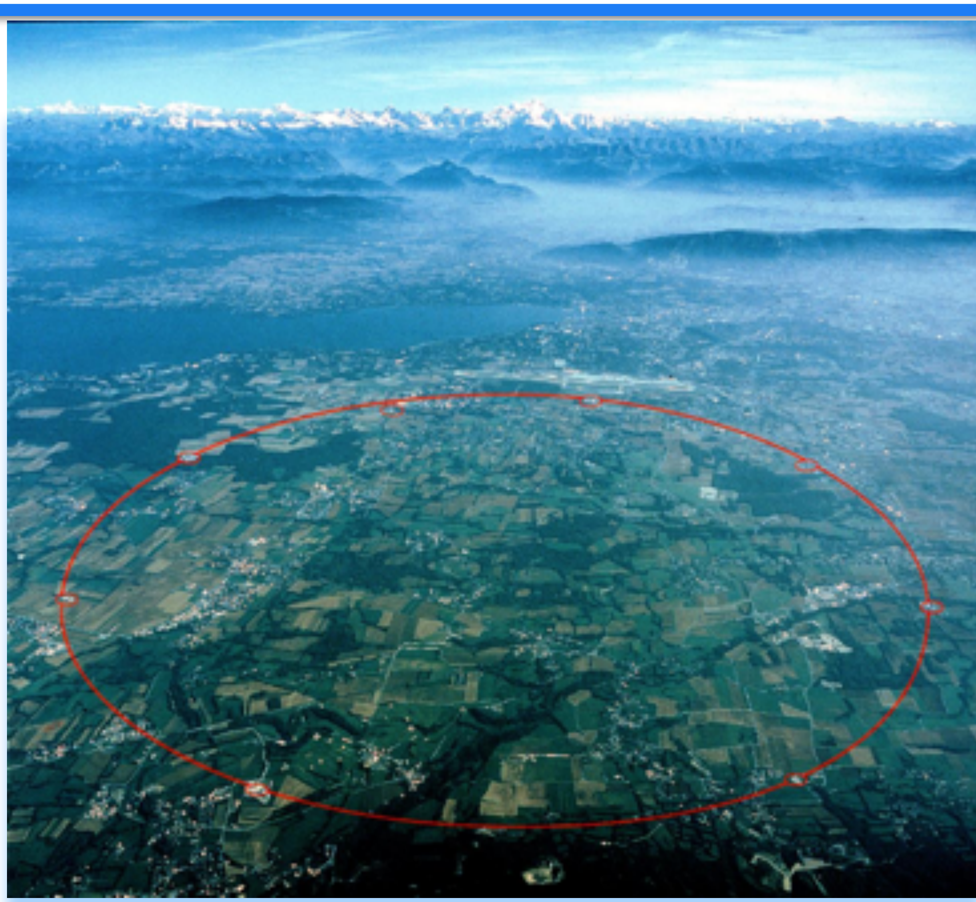
on behalf of the ATLAS collaboration

Talk outline

1) LHC and ATLAS in 2016/2017
2) Higgs physics motivation
3) run-1 Higgs measurement summary
4) updates from run-2
5) di-higgs search status
6) exotics searches with Higgs boson in the final state
7) conclusions

LHC status



2016

- Record instantaneous luminosity for p-p interactions **1.4×10^{34}** cm^{-2}s^{-1}
- Record delivered luminosity in one day **~ 613.1 pb^{-1}**
- Record delivered luminosity in one year **~ 40 fb^{-1}**
- Maximum colliding bunches **2208,** (96 per injection)

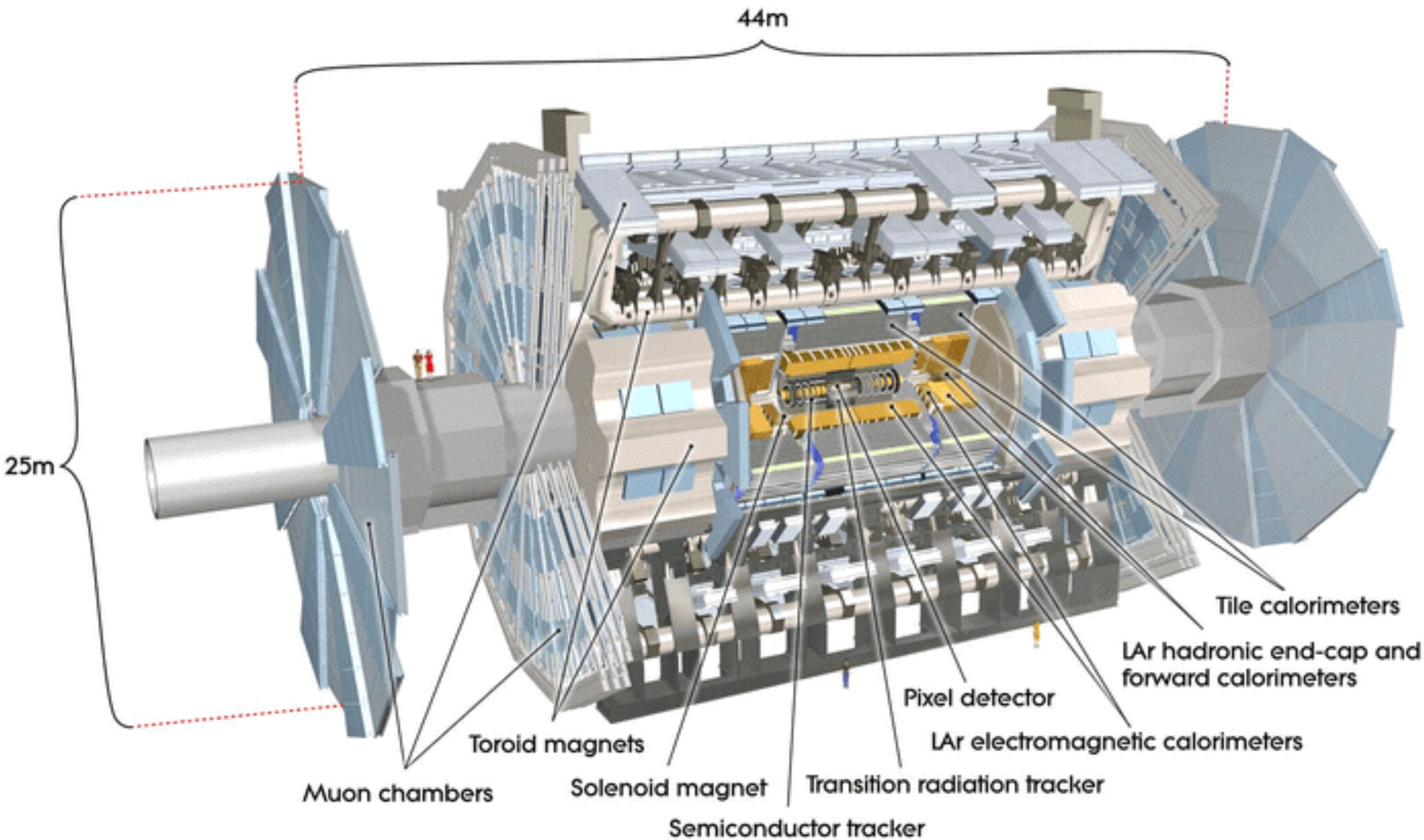
2017

- Record instantaneous luminosity for p-p interactions **1.46×10^{34}** cm^{-2}s^{-1}
- Record delivered luminosity in one day **~ 530.3 pb^{-1}**

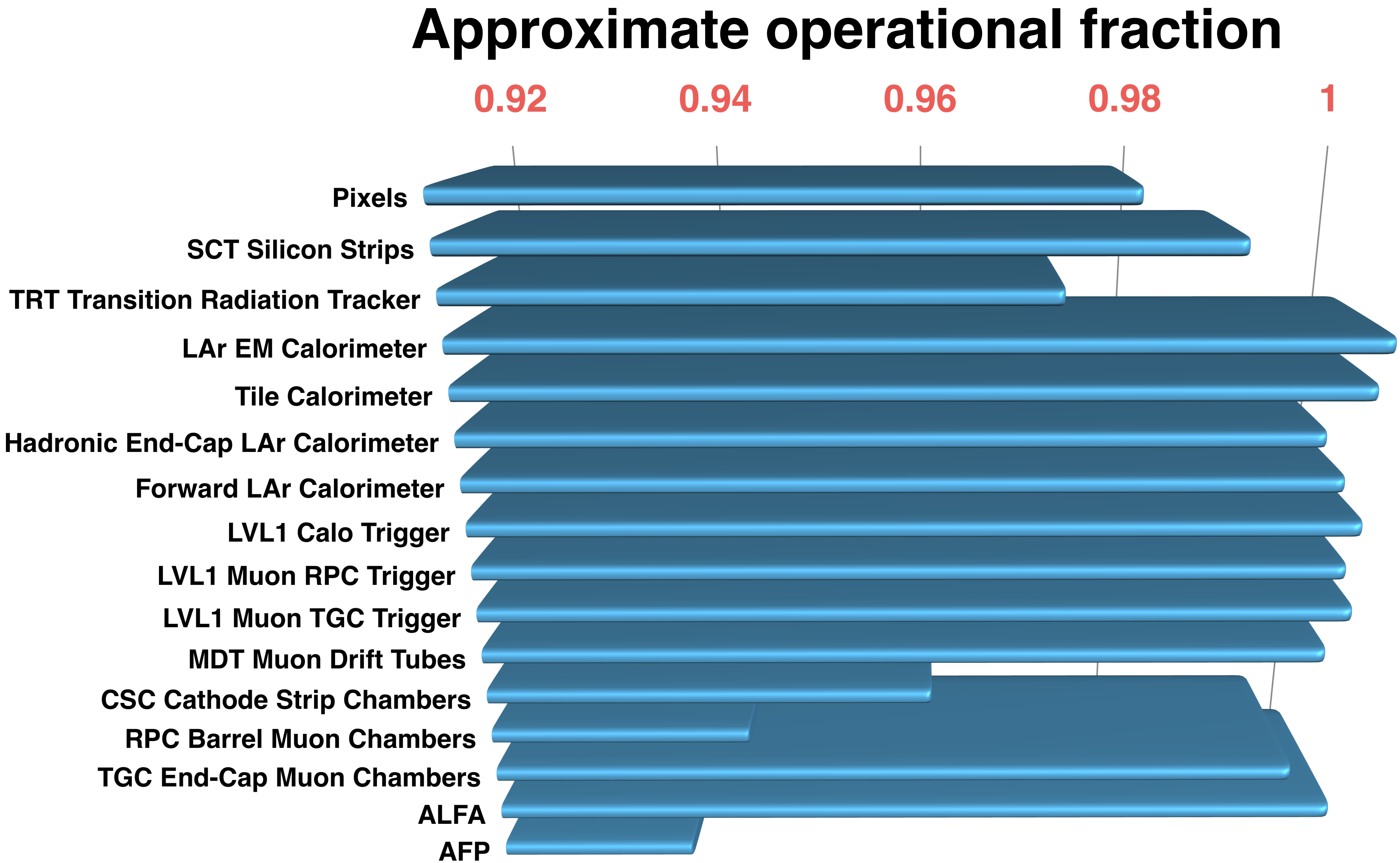
SPS beam dump replaced during winter shutdown,
allowing more bunch per injection, 144 (288) respect to 96.

- Maximum colliding bunches **2448**

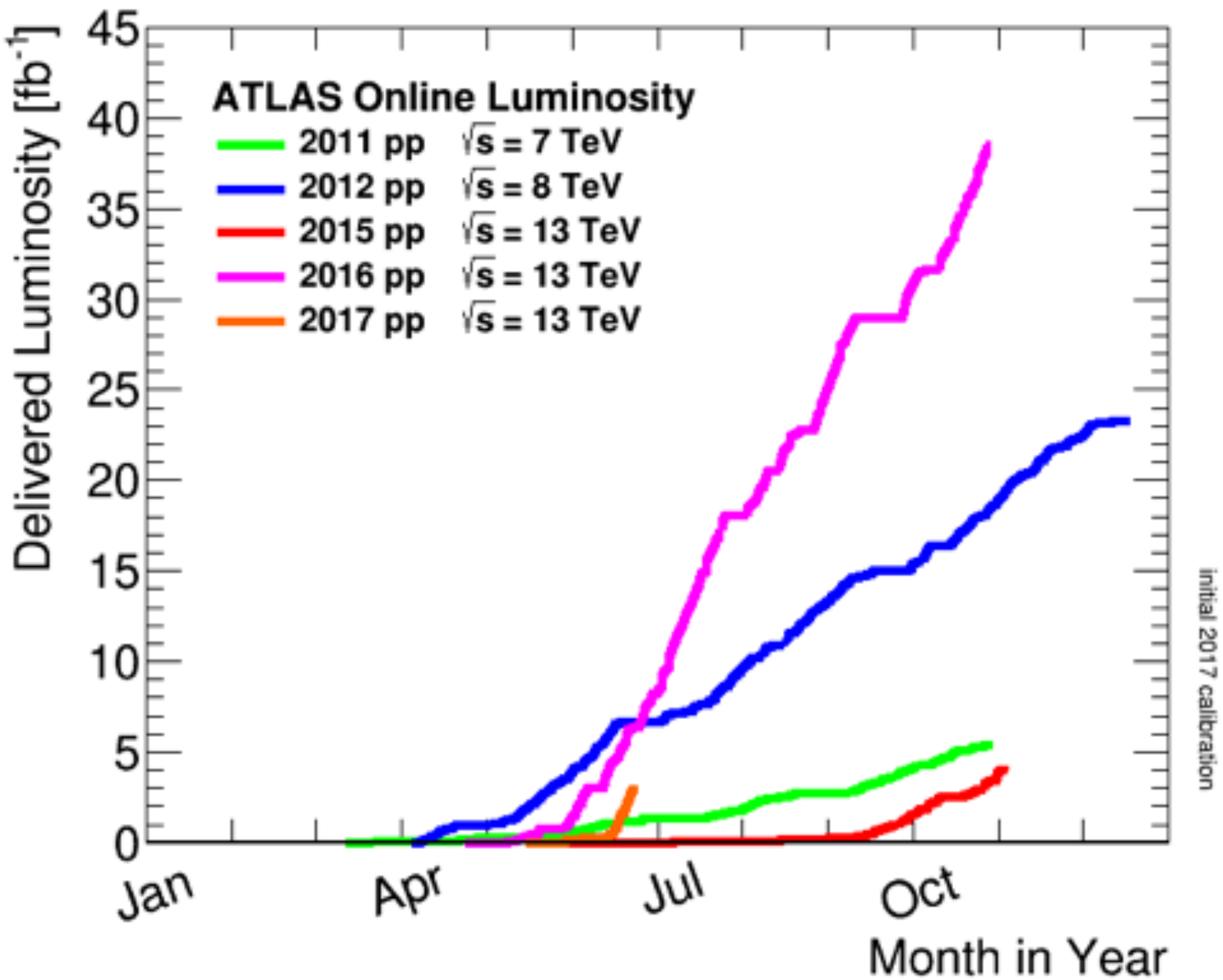
ATLAS detector

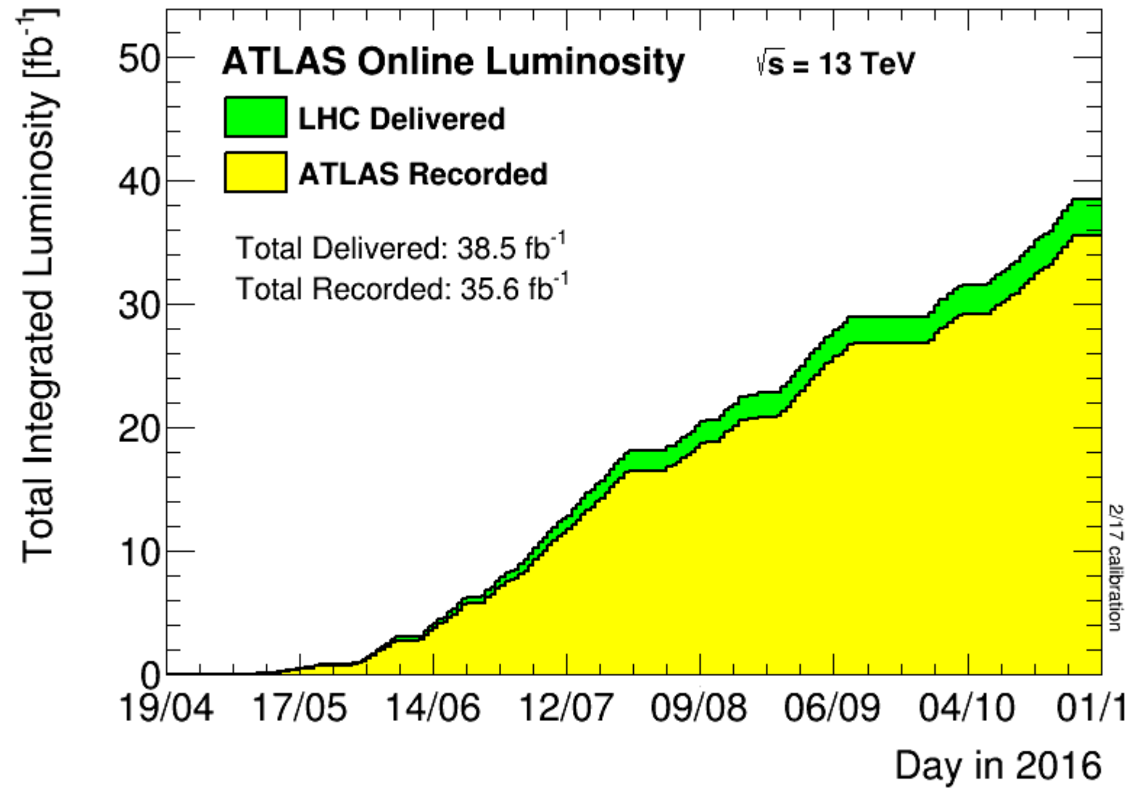


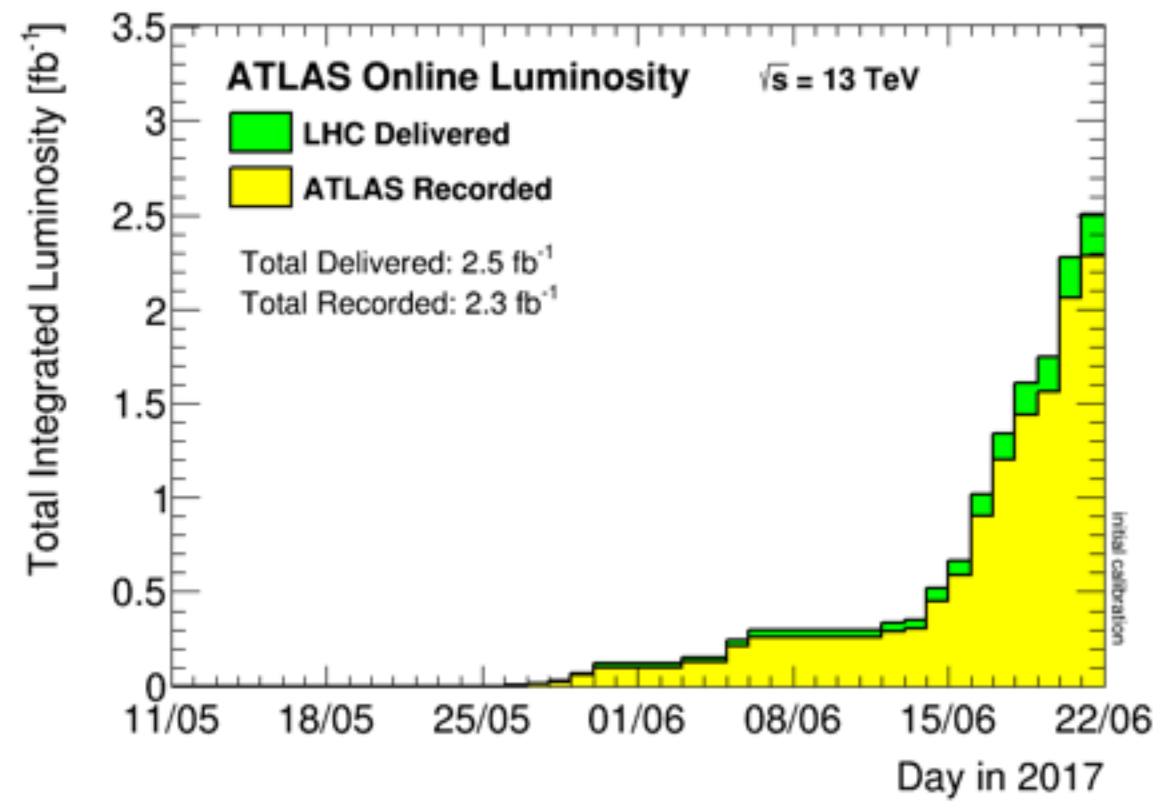
Detector status in 2017



Recorded data

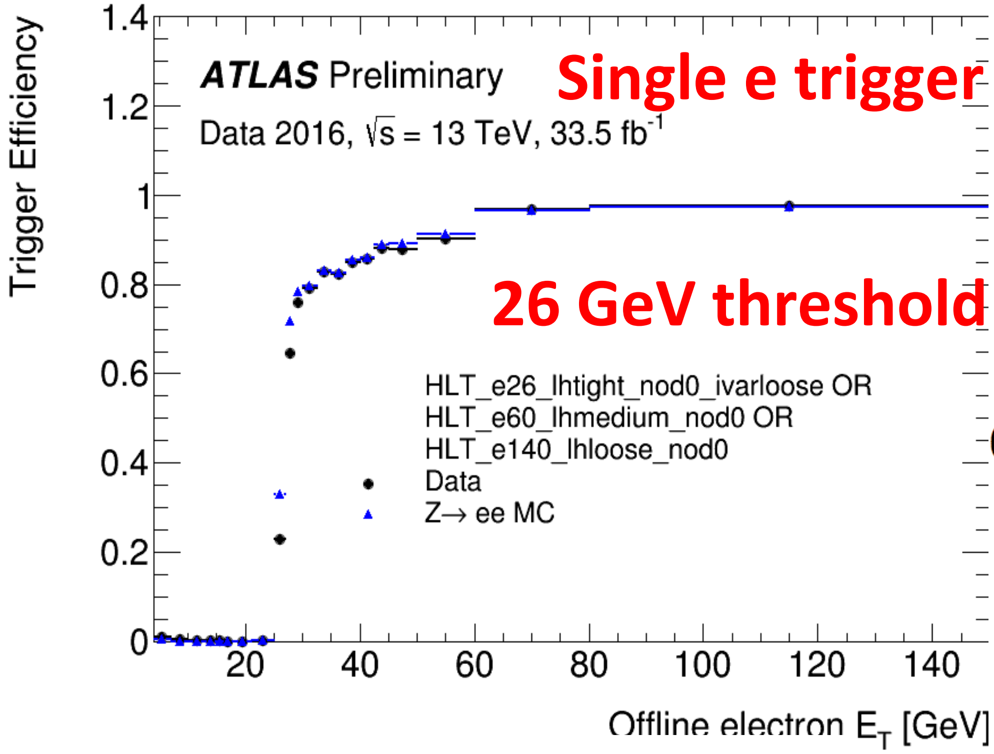


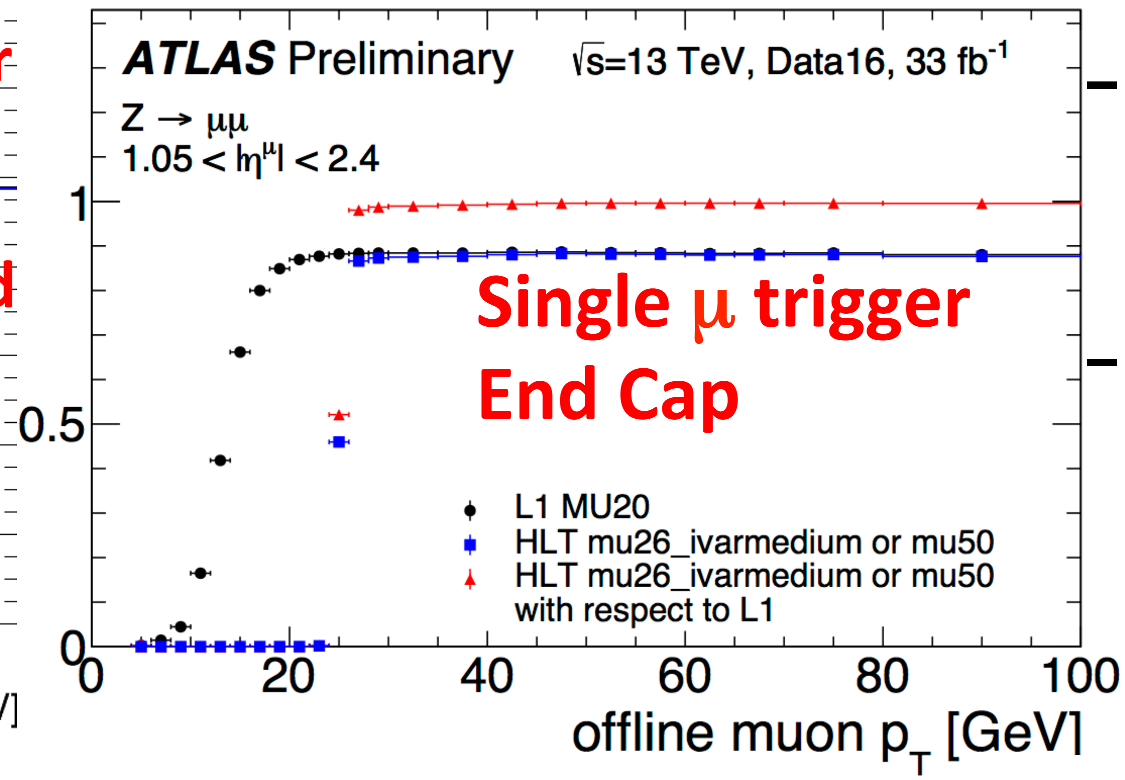




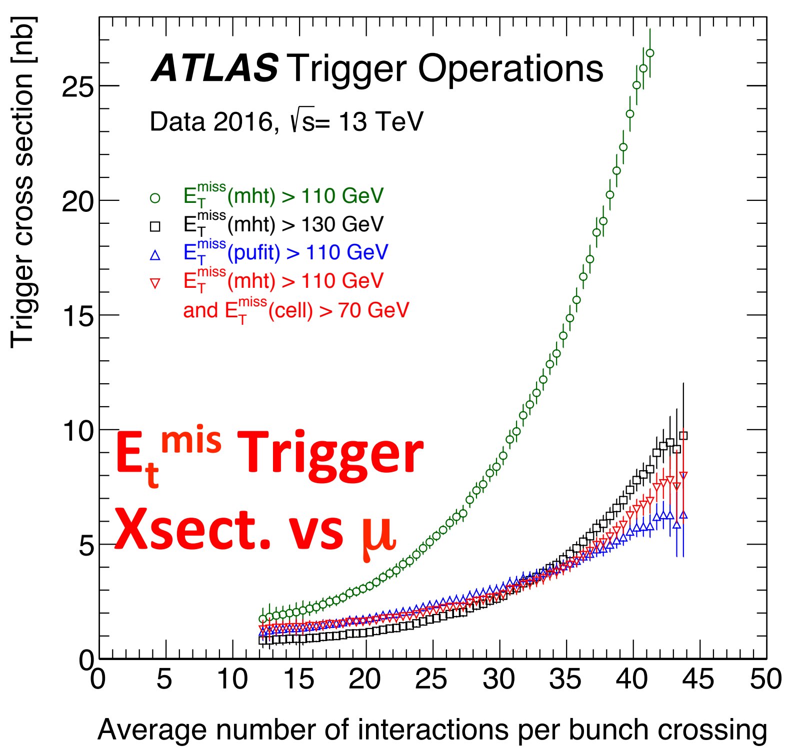
- Run-2 int. luminosity already exceeds Run-1 one
  - **2016** int. lumi: **35.6 fb^{-1}**
  - **2017** int. lumi: **2.5 fb^{-1}** (22-Jun)
  - DAQ efficiency **92%**

Trigger and reconstruciton

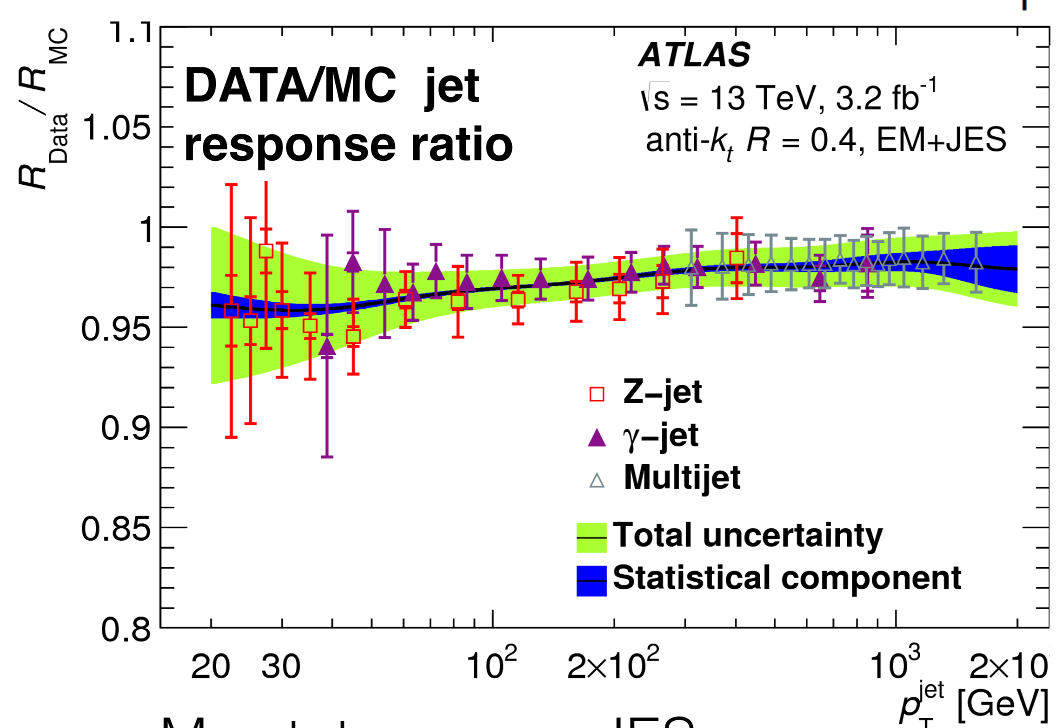




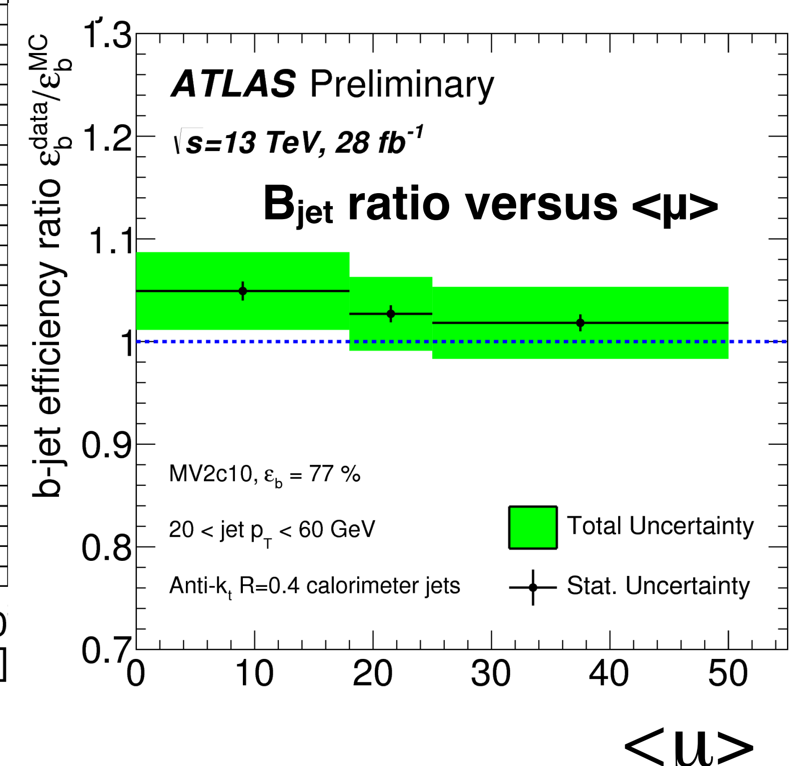
- accurate determination of the trigger turn-on curve;
- high HLT efficiency for both electrons and muons;



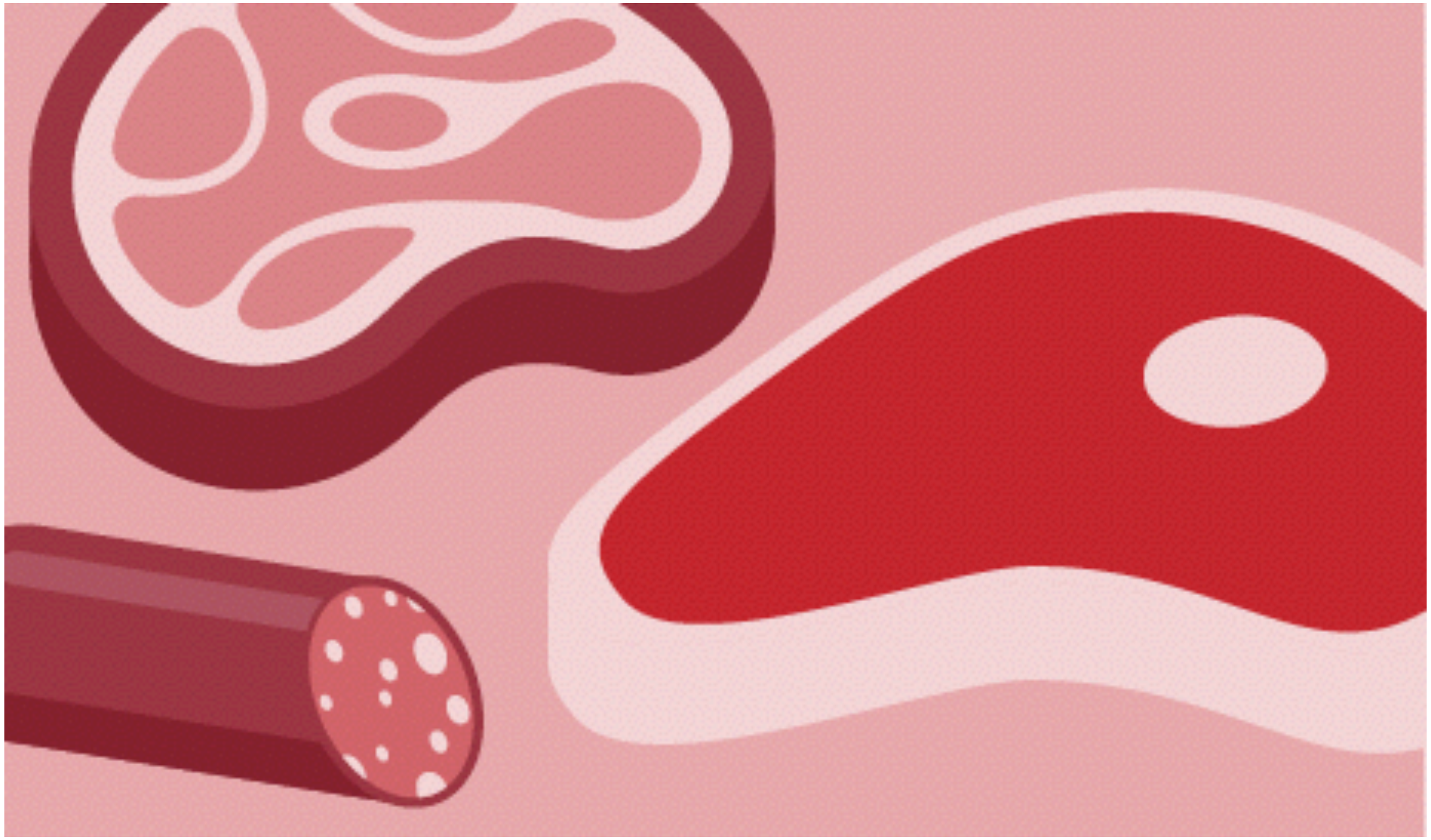
New E_T^{miss} algorithms stable respect to pile-up conditions



Max tot. unc. on JES ~ 4.5%



Let's go to the meat…



Why Higgs physics ?

Why Higgs physics ?

The Standard Model

$$\mathcal{L} =$$
$$-\frac{1}{4g'^4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{\mu\nu a} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a}$$
$$+\bar{Q}_i i\not{D} Q_i + \bar{u}_i i\not{D} u_i + \bar{d}_i i\not{D} d_i + \bar{L}_i i\not{D} L_i + \bar{\ell}_i i\not{D} \ell_i$$
$$+\left(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i \ell_j H + c.c.\right)$$
$$-\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H$$

$$-(D^\mu H)^\dagger D_\mu H \rightarrow -(\partial^\mu H)^\dagger \partial_\mu H - 2\frac{M_W^2}{v}W^{+\mu}W^-_\mu H - \frac{M_Z^2}{v}Z^\mu Z_\mu H + \ldots$$

ROMA TRE

The Standard Model

KNOWN

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$$+\bar{Q}_i i\not{D} Q_i + \bar{u}_i i\not{D} u_i + \bar{d}_i i\not{D} d_i + \bar{L}_i i\not{D} L_i + \bar{\ell}_i i\not{D} \ell_i$$

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$$-\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H$$

KNOWN

$$-(\partial^\mu H)^\dagger \partial_\mu H - 2\frac{M_W^2}{v}W^{+\mu}W^-_\mu H - \frac{M_Z^2}{v}Z^\mu Z_\mu H + \ldots$$

Why Higgs physics ?

ROMA TRE

The Standard Model

$$\mathcal{L} =$$

$$-\frac{1}{4g'^4}B_{\mu\nu}B^{\mu\nu} \ \ldots \ G^{\mu\nu a}$$

PARTIALLY KNOWN

$$+\bar{Q}_i i\not{D}Q_i + \ldots + \bar{\ell}_i i\not{D}\ell_i$$

$$+\left(Y_u^{ij}\bar{Q}_i u_j\tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i\ell_j H + c.c.\right)$$

$$-\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H$$

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Why Higgs physics ?

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$$+\bar{Q}_i i\not{D}Q_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{L}_i i\not{D}L_i + \bar{\ell}_i i\not{D}\ell_i$$

$$+\left(Y_u^{ij}\bar{Q}_i u_j\tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i\ell_j H + c.c.\right)$$

$$-\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H$$

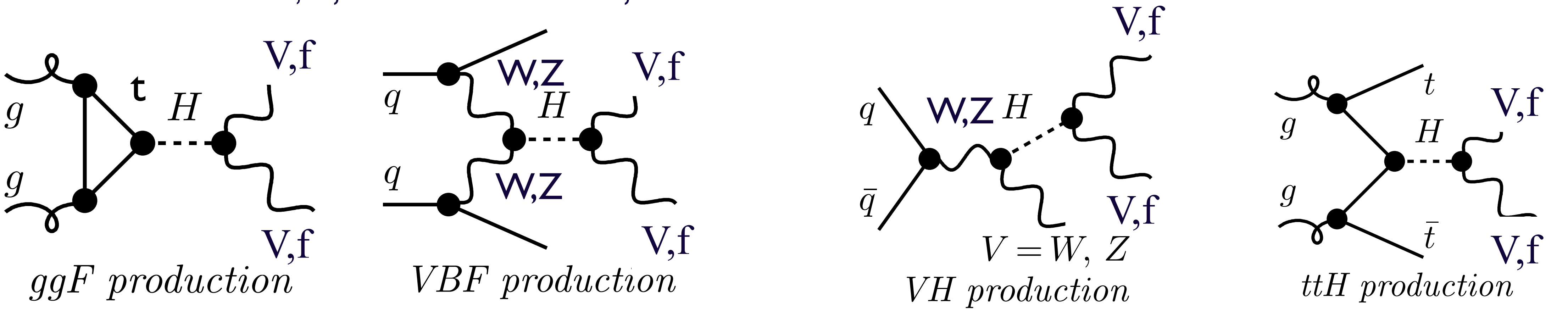
$$M^2 \quad \ldots W^{+\mu}W^-_\mu H - \frac{M_Z^2}{v}Z^\mu Z_\mu H + \ldots$$

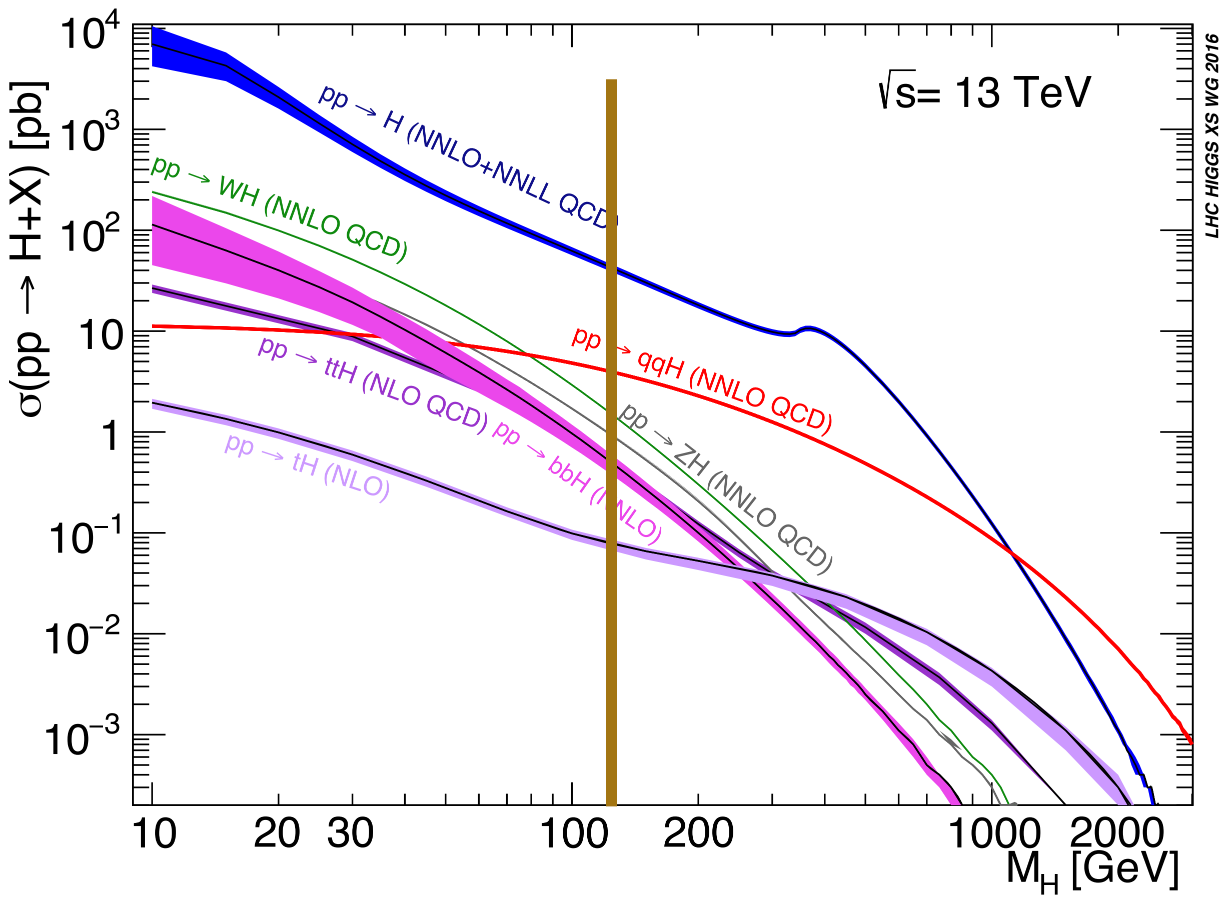
UNKNOWN

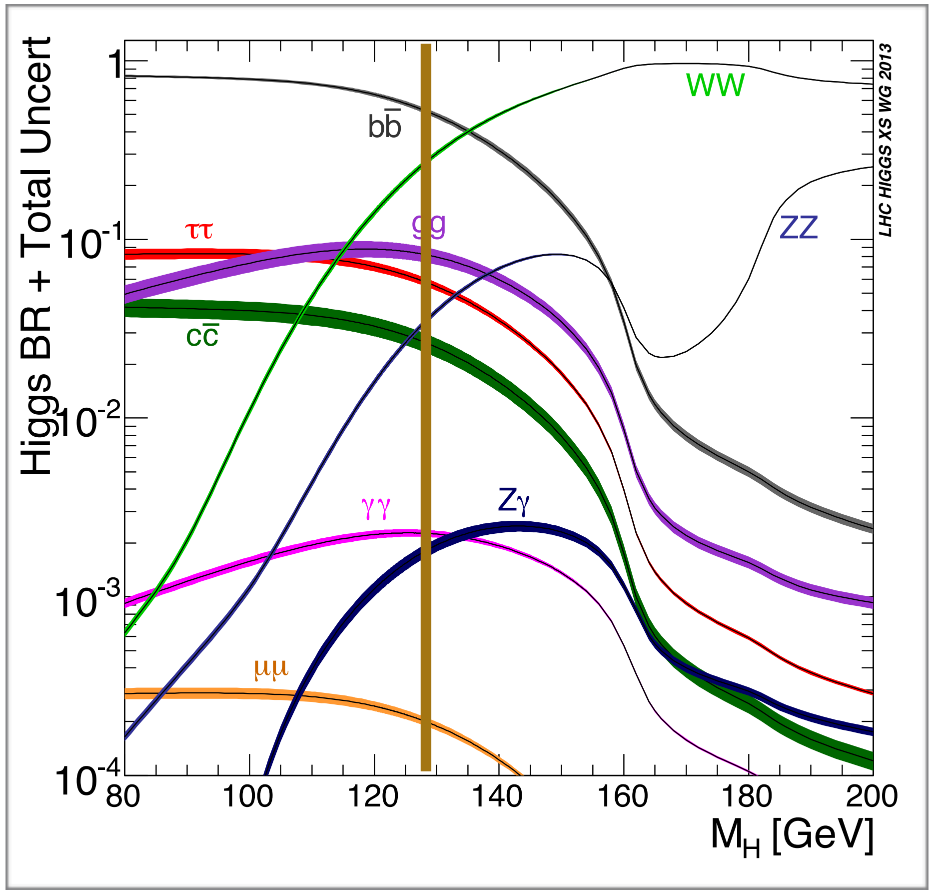
The Higgs sector is the most unknown piece of the SM, it is where new physics effects could be hidden

Higgs production and decay

V = Vector: W,Z; f = fermions: **b,τ**







Run1 ggF cross section computed at NNLO + NNLL, big effort from theory community in the last years to compute N3LO results, the baseline for Run2, +10% increase in ggF xs; resummation doesn't add much on top of N3LO

Higgs at Run-1 discovery

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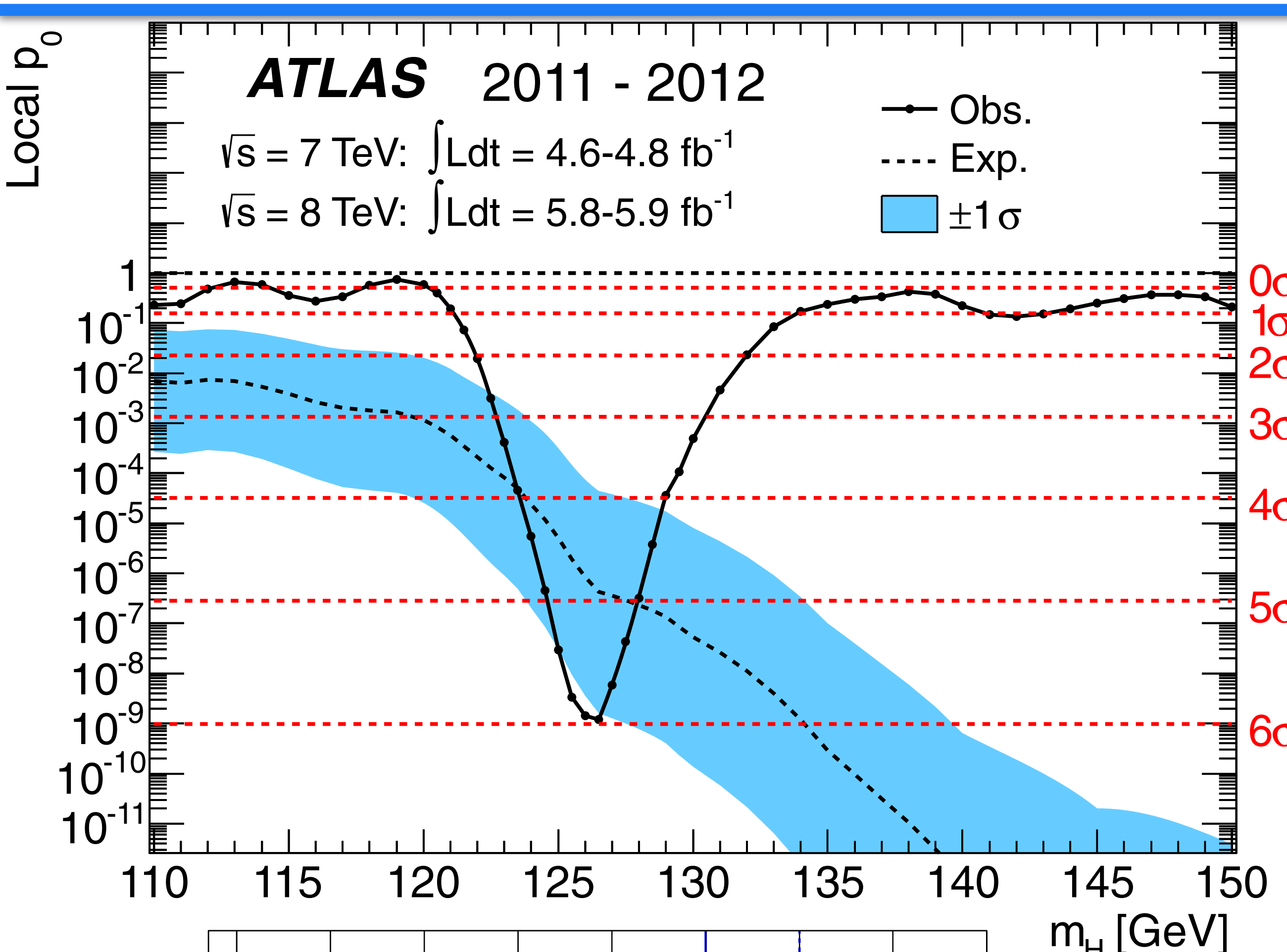
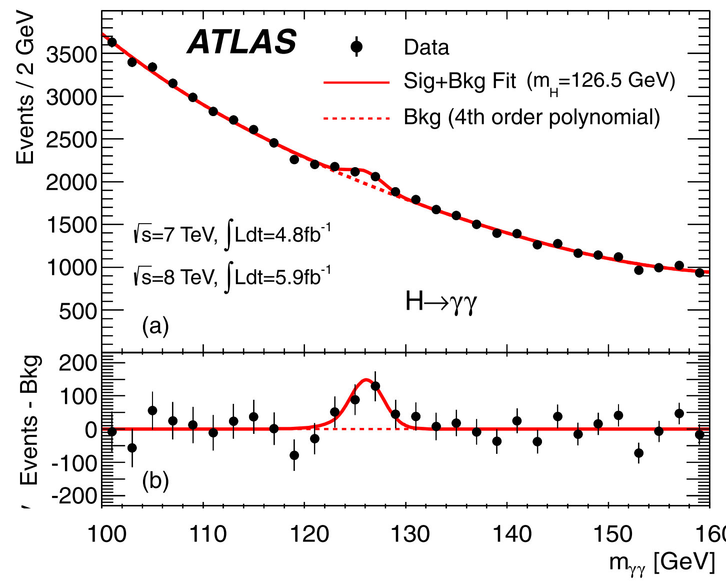
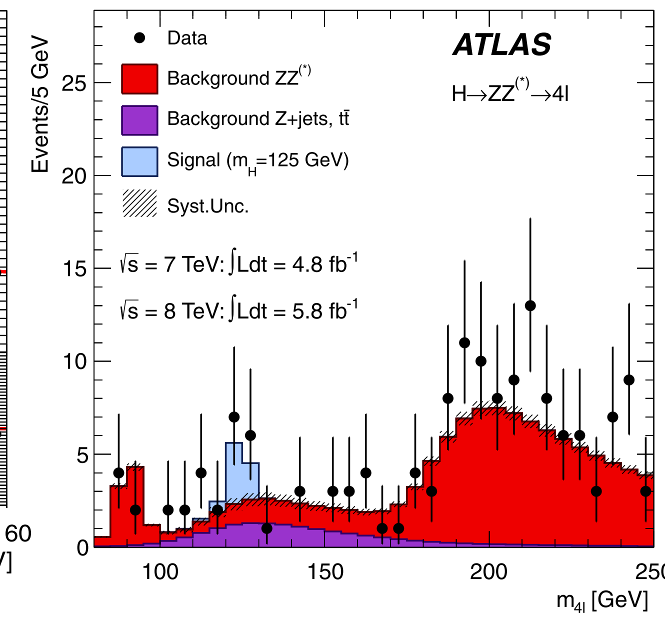
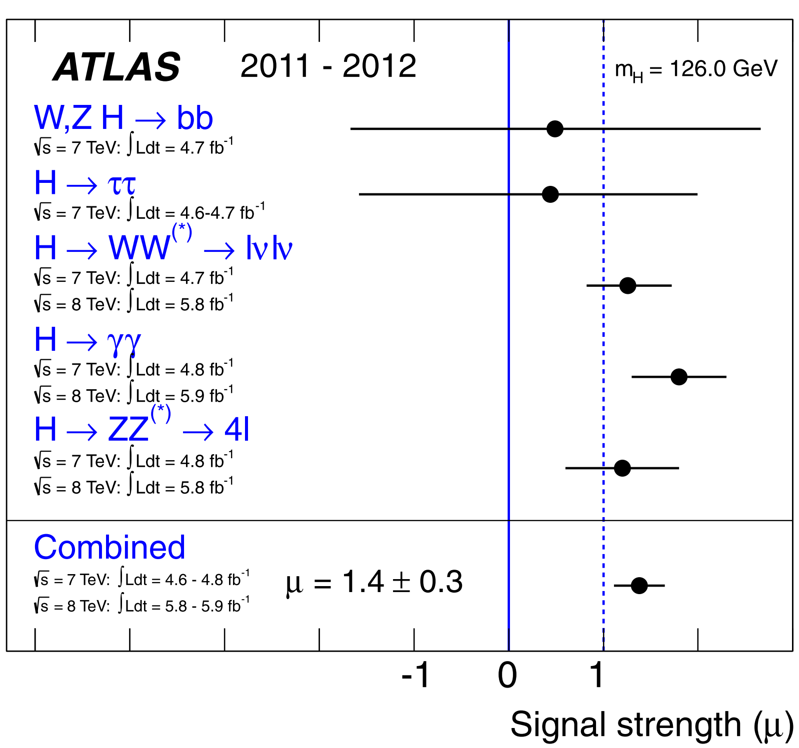
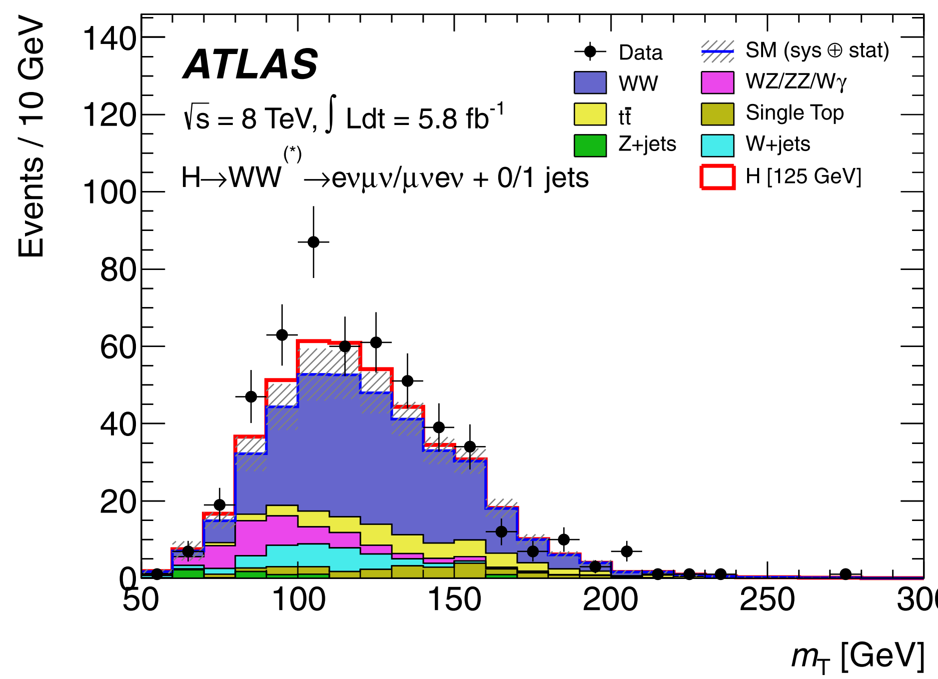




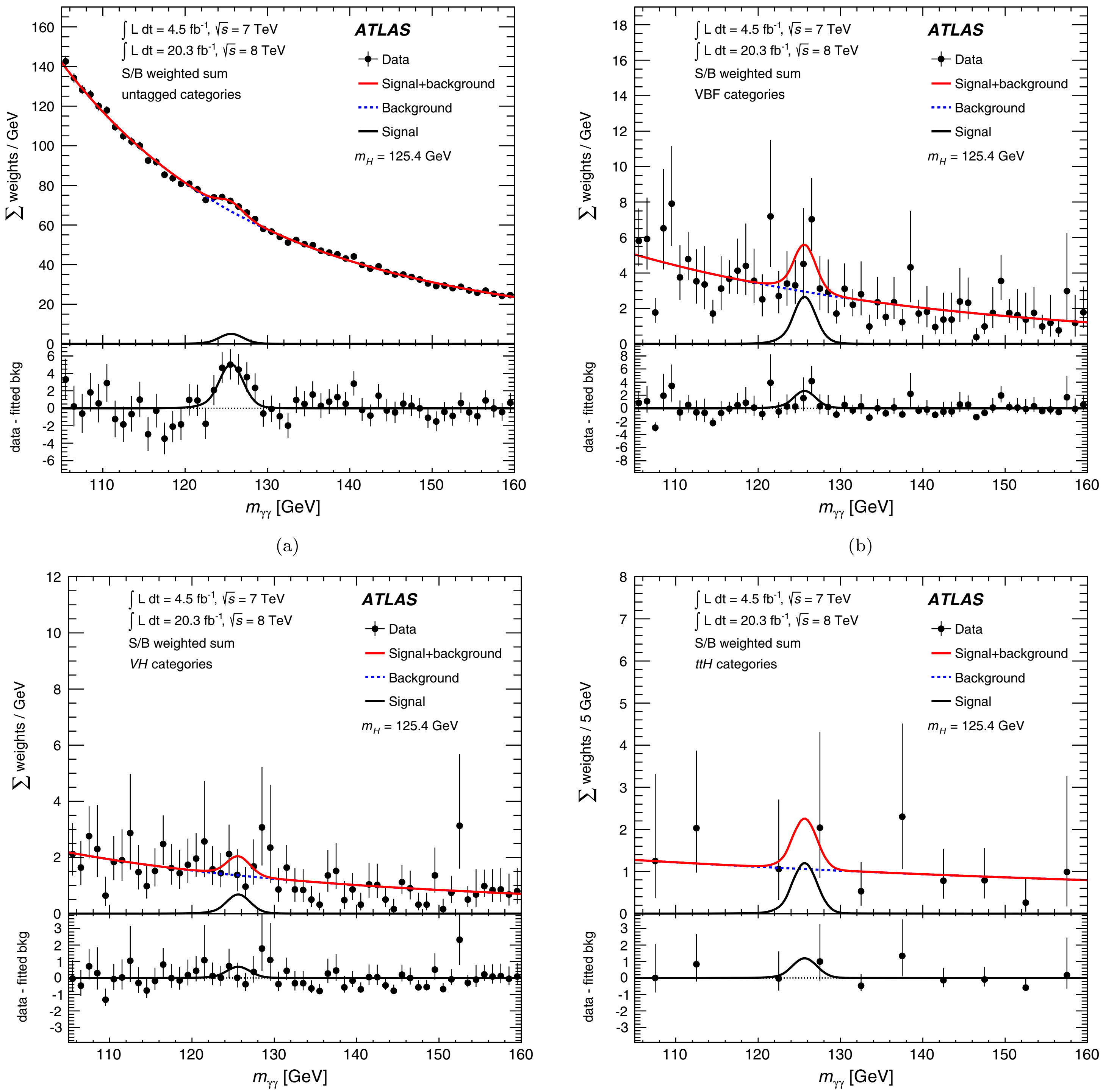




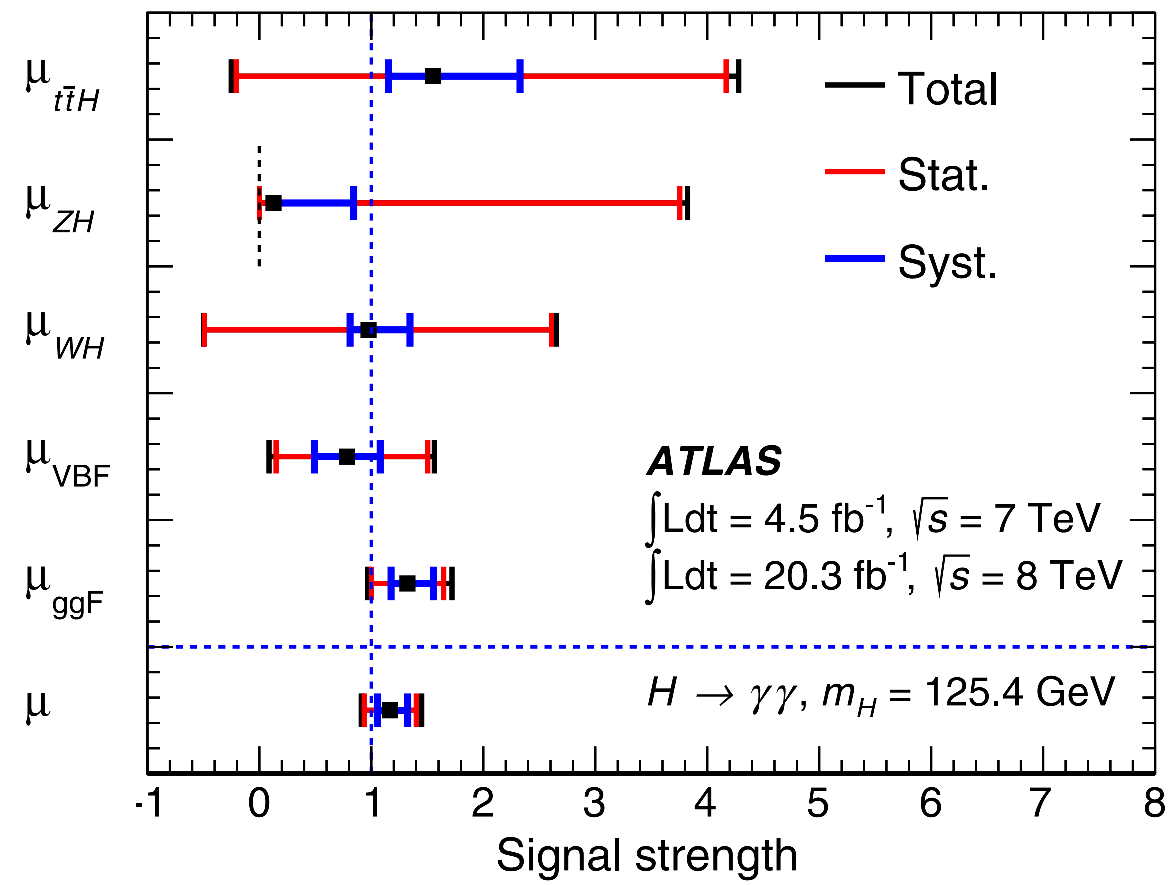


discovered in the bosonic decay channels

$\gamma\gamma$ low S/B but optimum invariant mass resolution, WW better S/B but poor mass resolution, ZZ optimum mass resolution and very high S/B, but low event yield



Signal strength summary



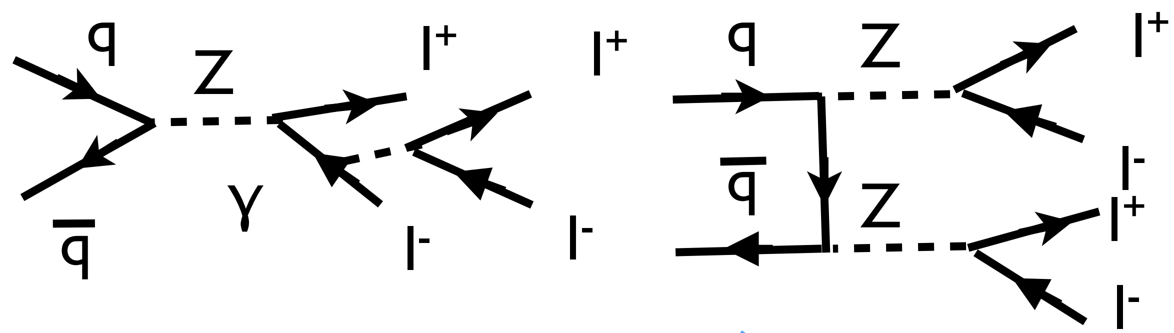
Observation in one single channel:

4.6 σ expected
5.2 σ observed

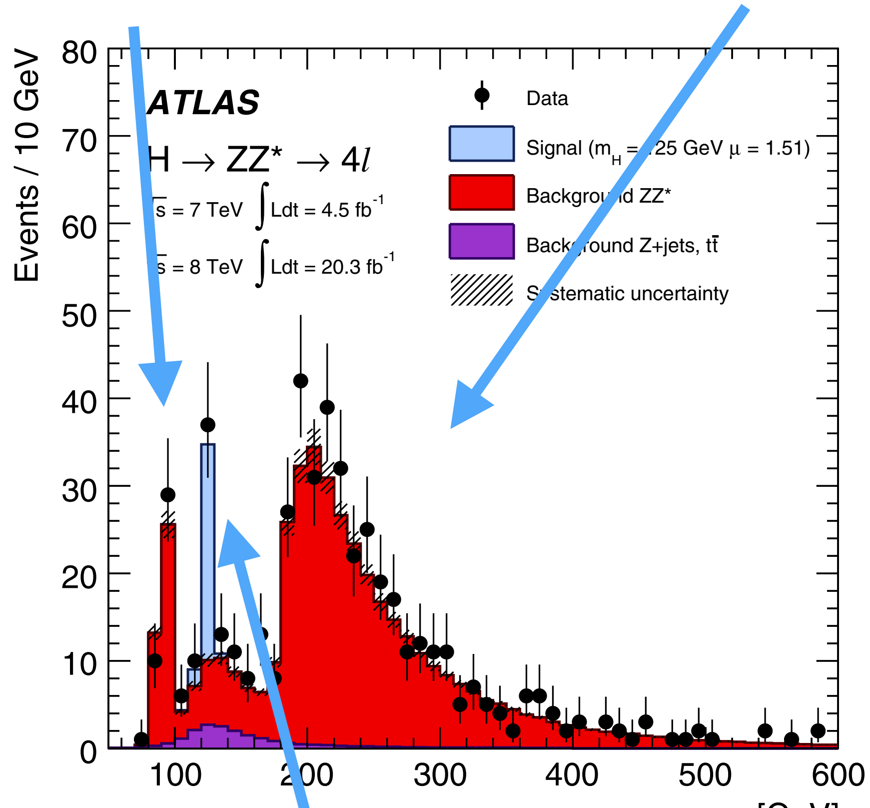
Low sensitivity to production modes other than ggF

h→ZZ→4l Run1 observation

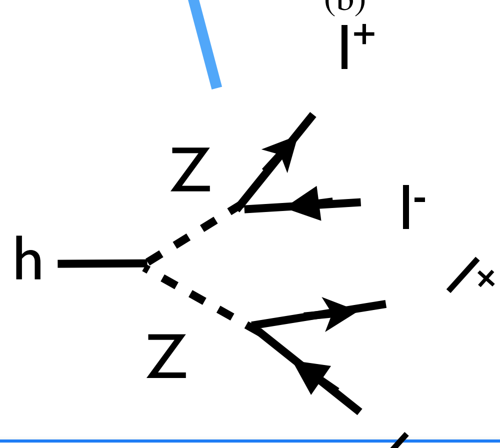
Phys. Rev. D91, 012006

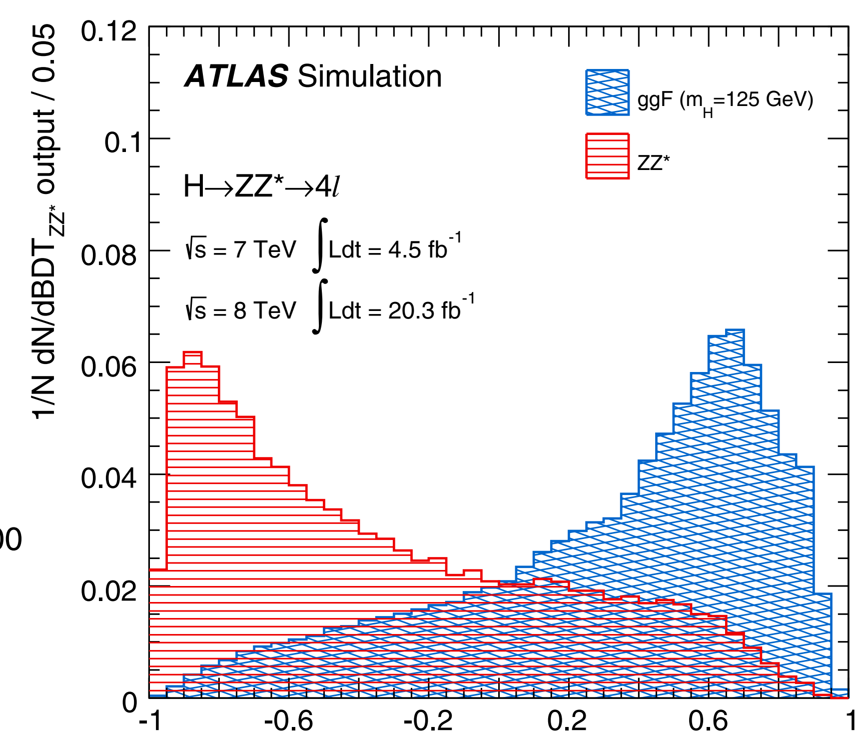


- very clean signal signature with S/B > 1
- double-resonant and continuum background well modelled, extreme evidence of the signal peak in the 125 GeV mass range
- signal yield a bit underpredicted (or data upper fluctuating)

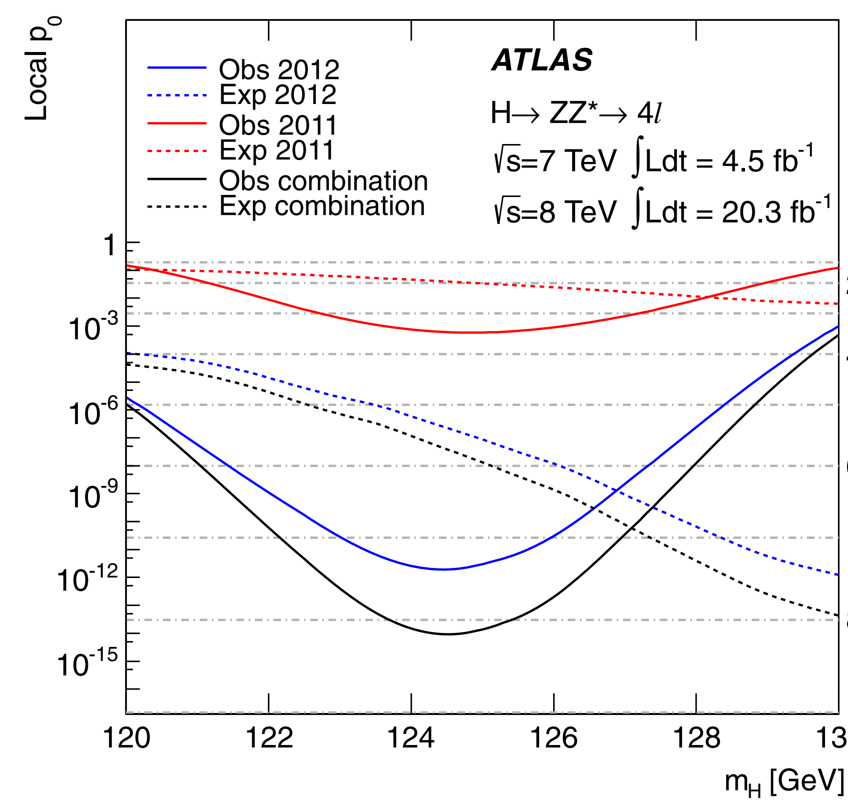


(b)





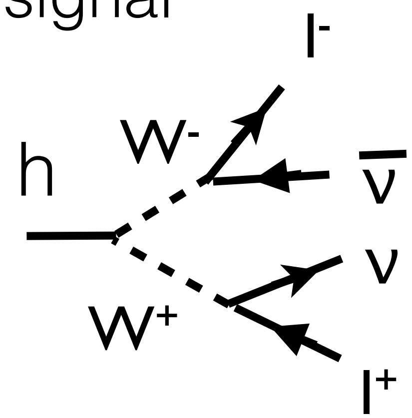
(d)



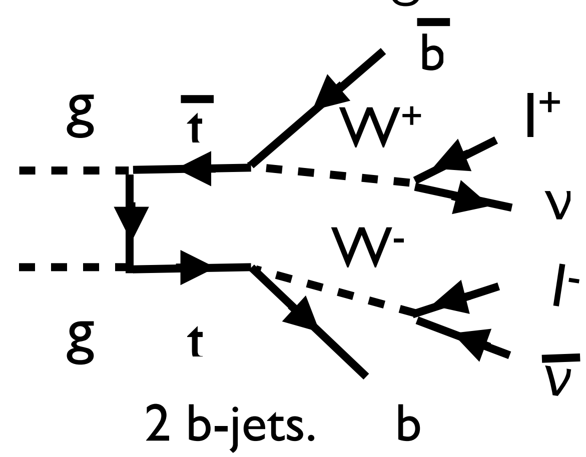
BDT exploits the spin-0 angular structure of the signal respect to the background: p_T^{4l}, η^{4l}, $D_{ZZ'}$

$$D_{ZZ^*} = \ln\left(\frac{|\mathcal{M}_{\rm sig}|^2}{|\mathcal{M}_{ZZ}|^2}\right)$$

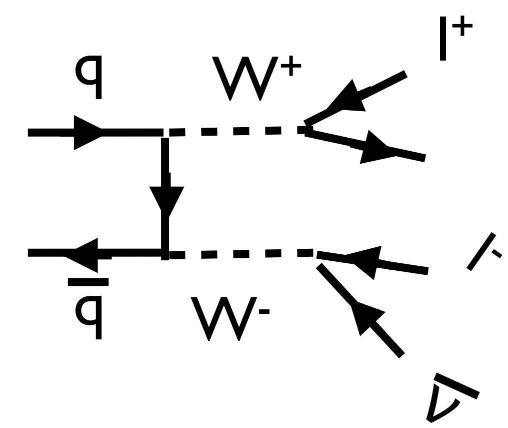
signal



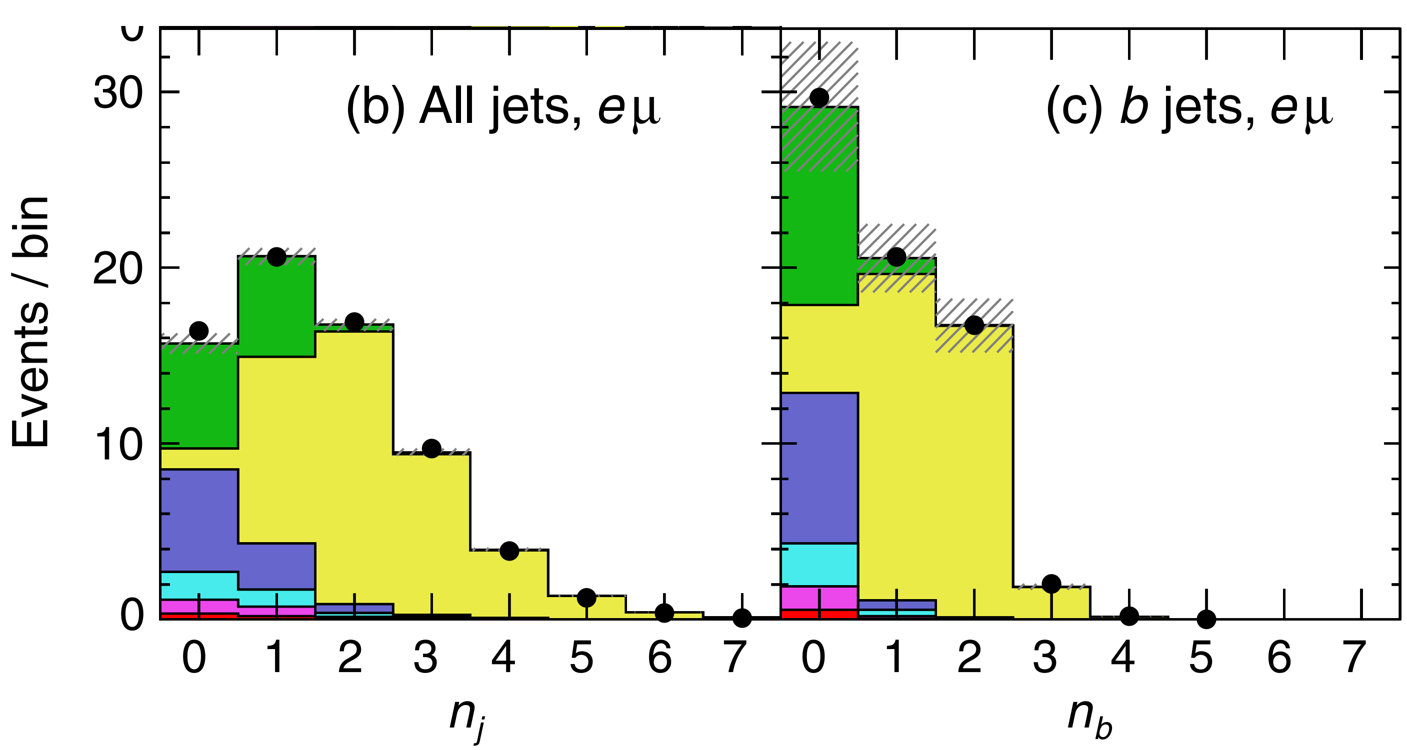
reducible background $t\bar{t}$

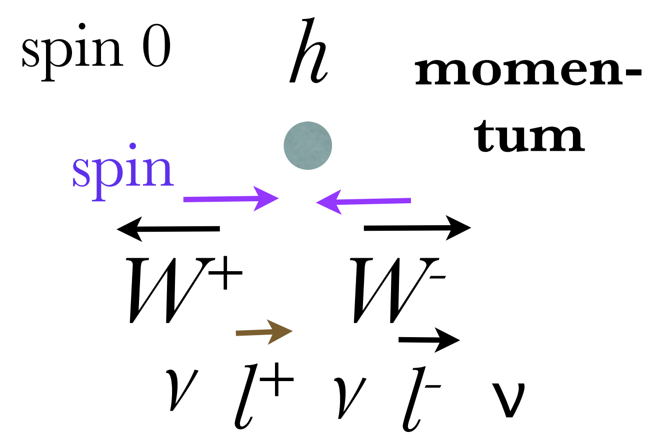


W^+W^-



analysis performed in jet bins and b-jet bins to reject top background





maximal parity violation (the charged leptons go in the direction of the spin. The anti-lepton opposite to it).

The small angle between the two leptons imply small value of the di-lepton invariant mass m_{ll} and azimuthal angle $\Delta\Phi_{ll}$

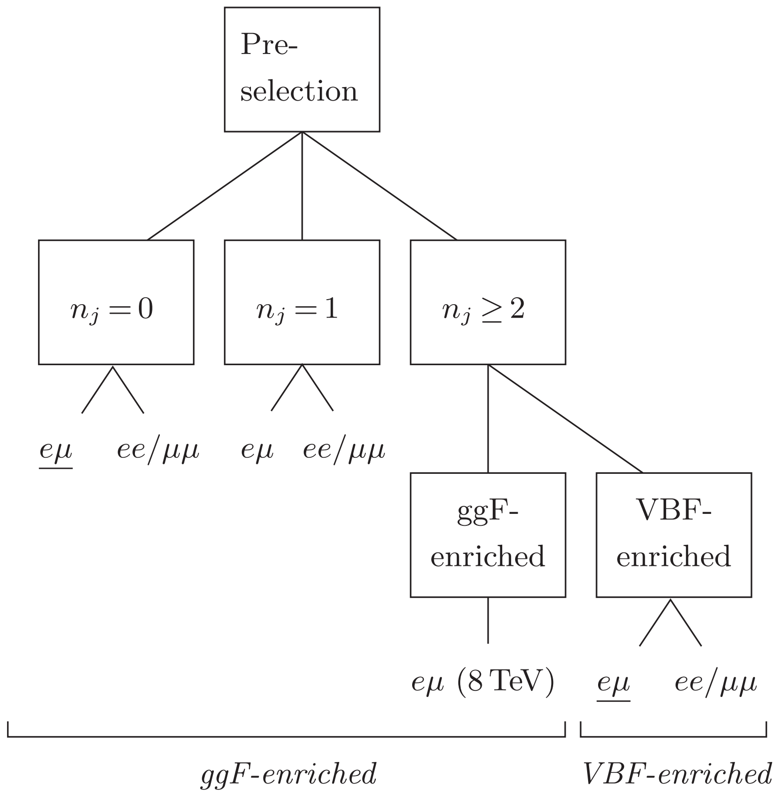
0-jet dominated by WW bkg.
1,2-jet by top background

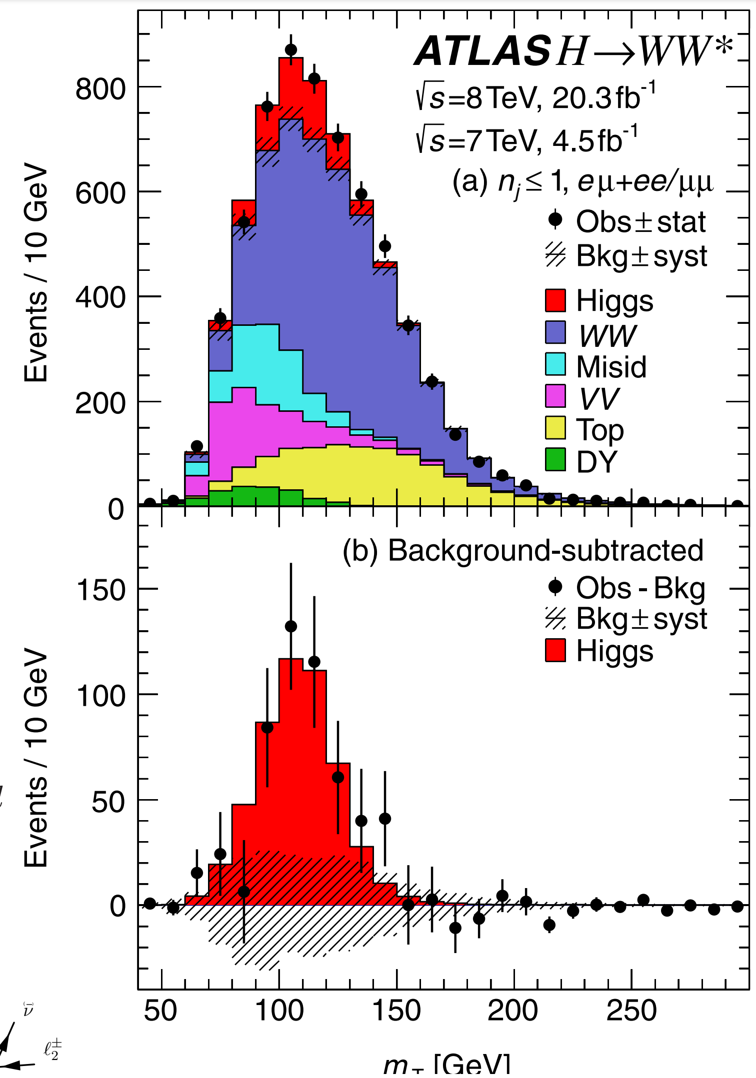
The transverse mass is defined to exploit sensitivity to the Higgs mass value

$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + p_{\mathrm{T}}^{\nu\nu})^2 - |\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{p}_{\mathrm{T}}^{\nu\nu}|^2}$$

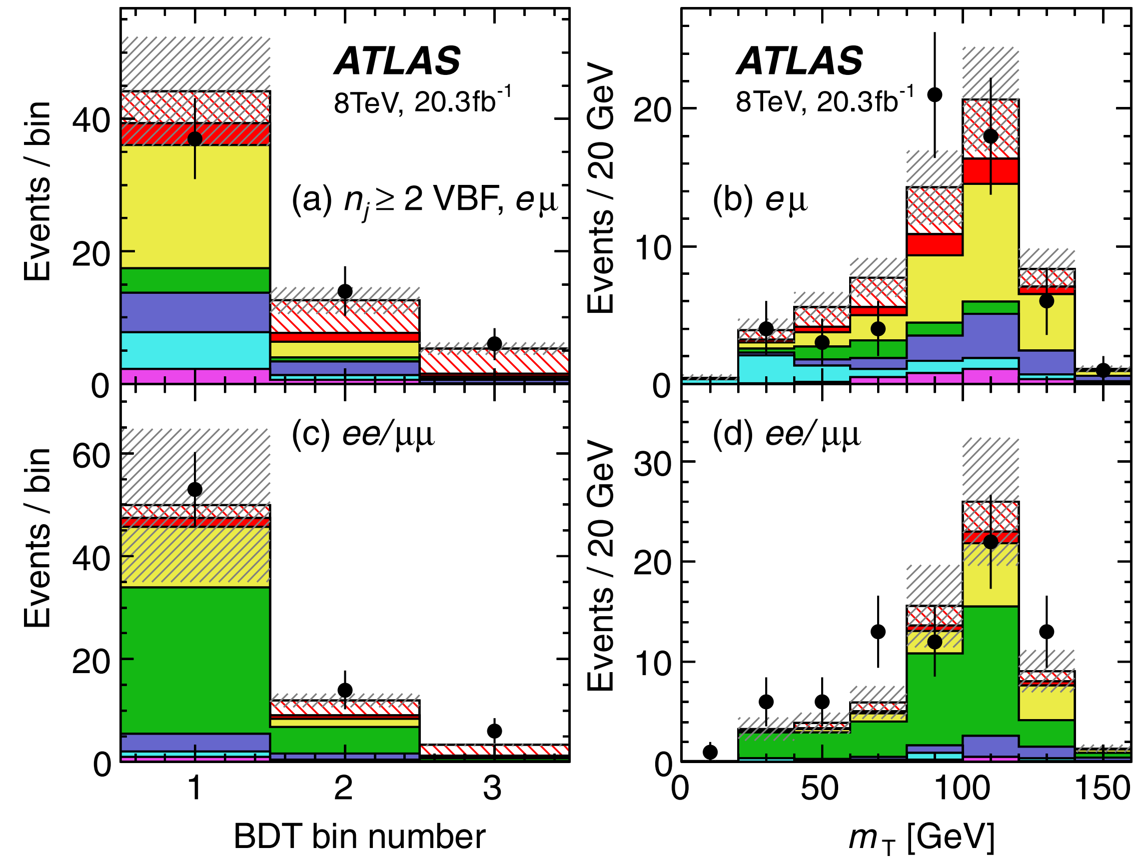
h→WW*→lνlν categorisation and result

Phys. Rev. D92, 012006

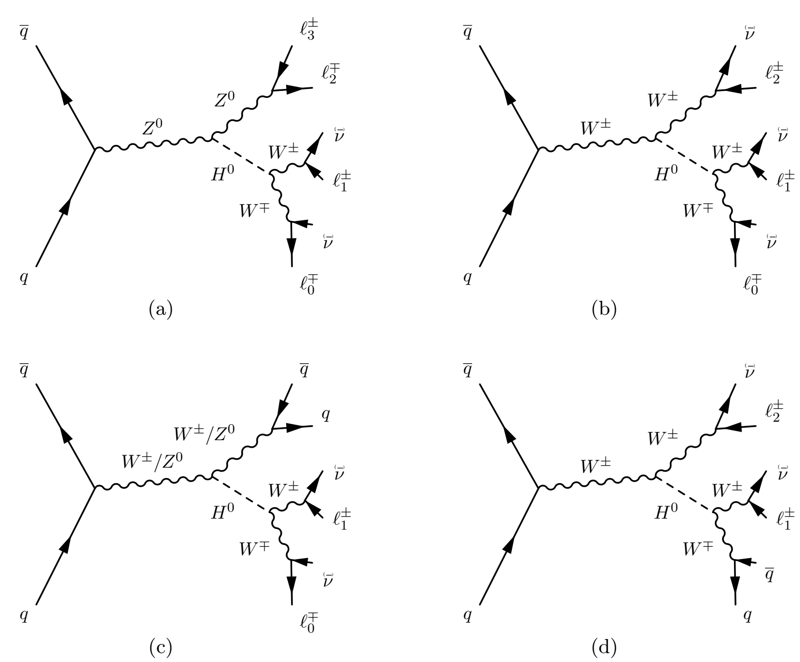


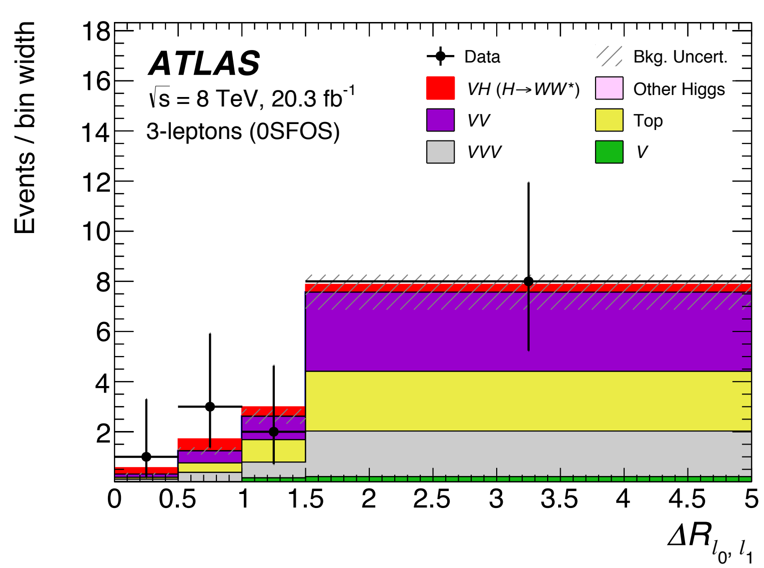


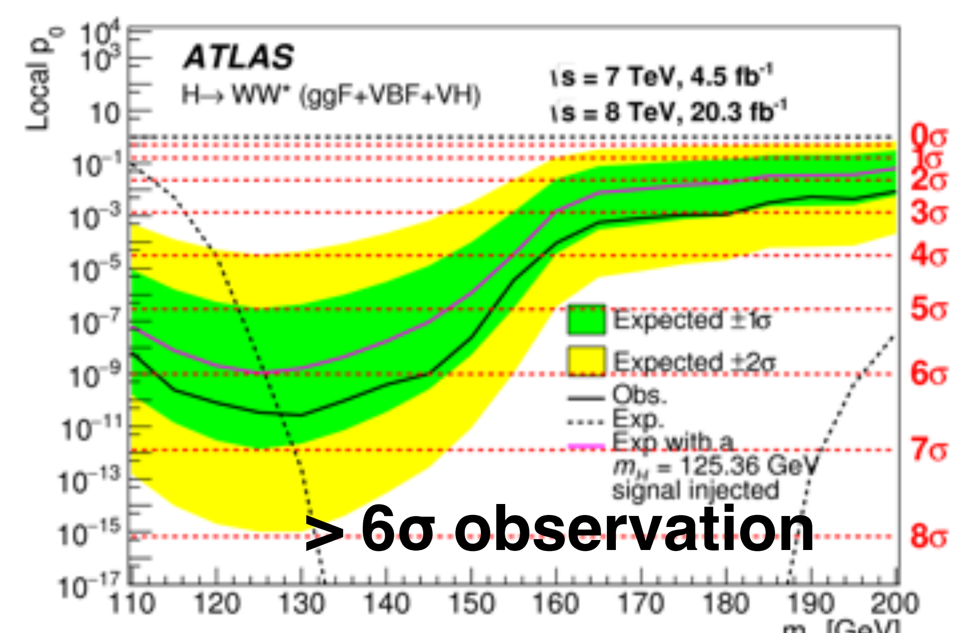
BDT used in VBF-like jet kinematics



W(Z)h

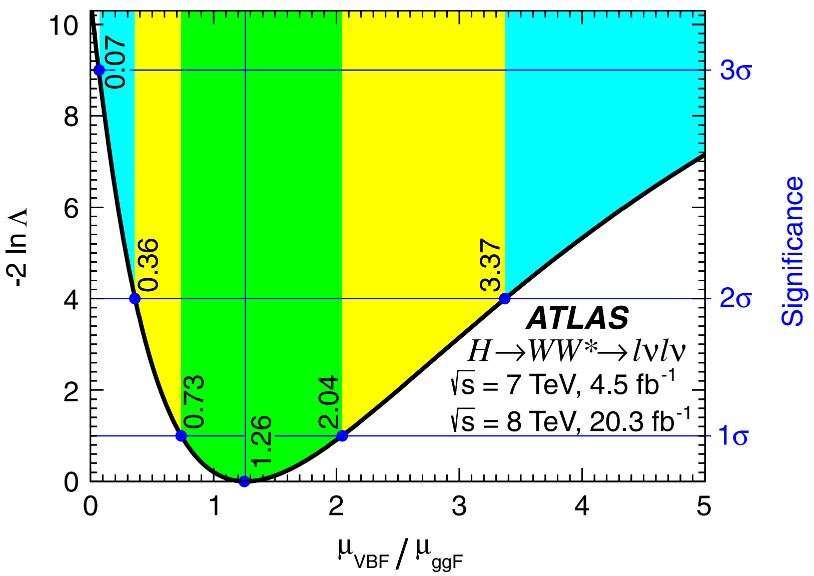


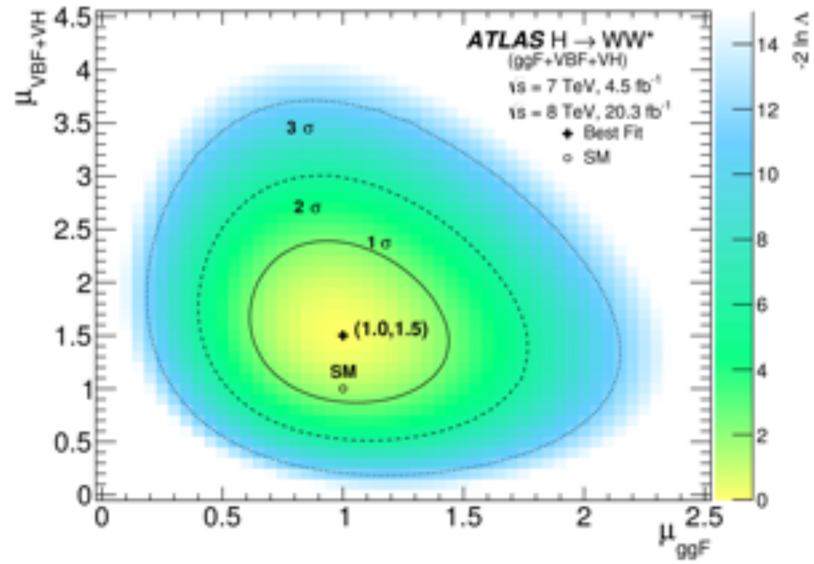




h→WW*→lνlν VBF evidence and couplings

Phys. Rev. D92, 012006





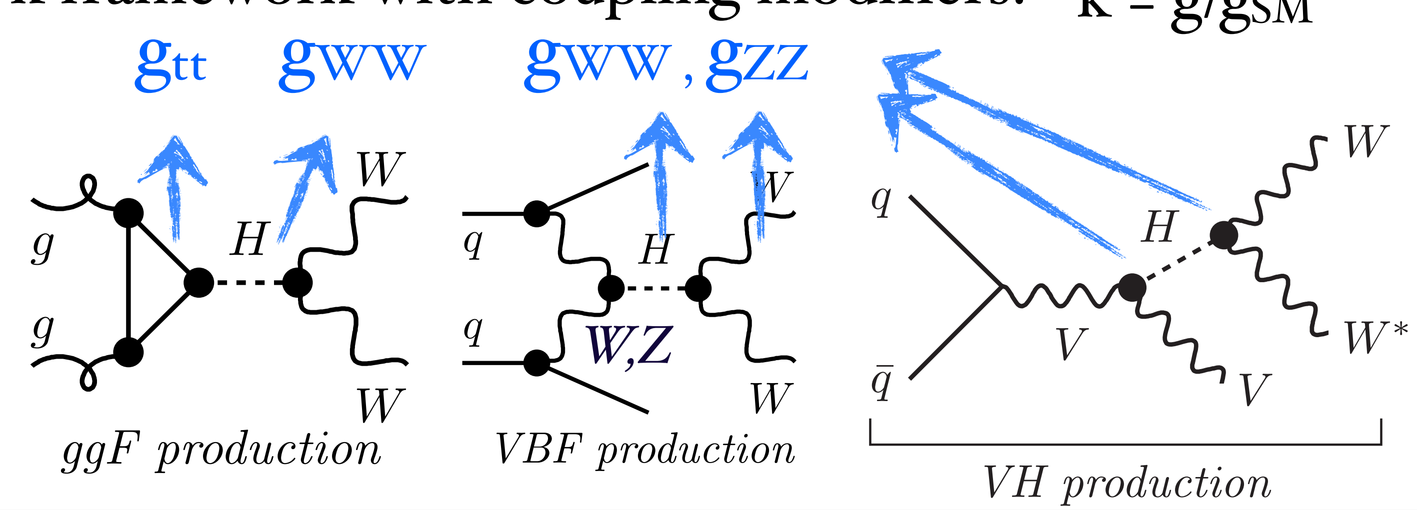
> 3σ evidence for VBF production, the only channel in Run-1

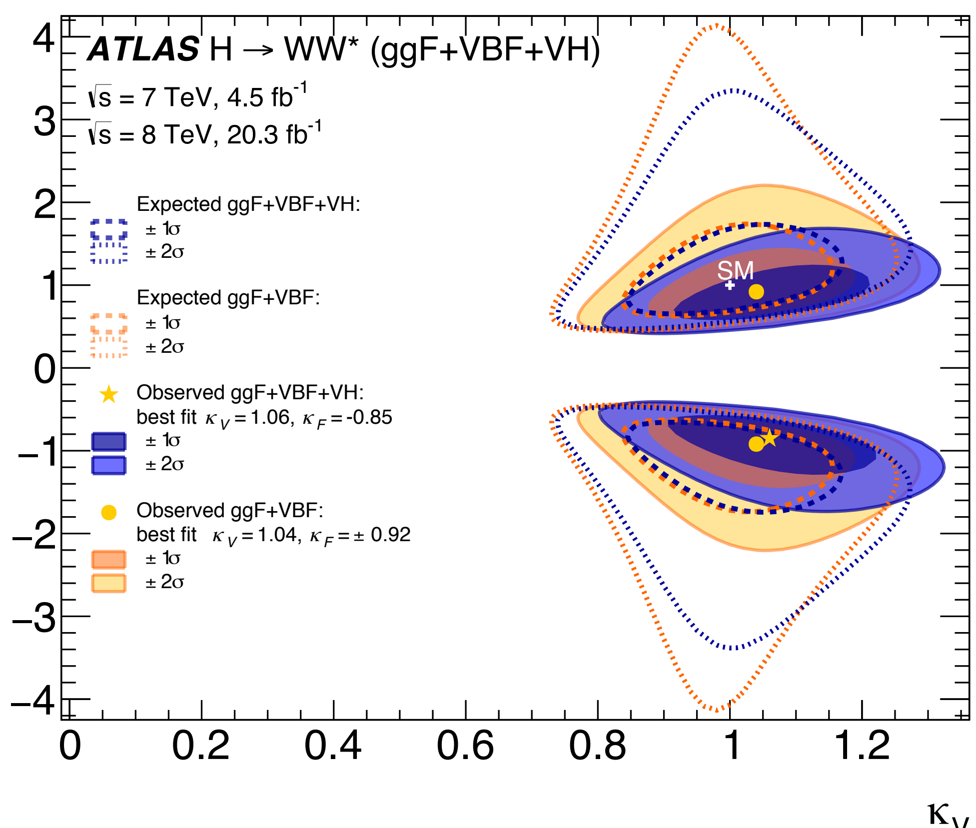
VH production ~2.5 σ observed, ~0.93 σ expected

Very difficult channel, but similar or better sensitivity than γγ and ZZ at Run-1

Category	Signal significance Z_0: Exp. Z_0	Obs. Z_0	Obs. Z_0	Observed signal strength μ: μ	Tot. err. +	Tot. err. −	Syst. err. +	Syst. err. −	μ
ggF	4.4	4.2		**0.98**	0.29	0.26	0.22	0.18	
VBF	2.6	3.2		**1.28**	0.55	0.47	0.32	0.25	
VH	0.93	2.5		**3.0**	1.6	1.3	0.95	0.65	
WH only	0.77	1.4		**2.1**	1.9	1.6	1.2	0.79	
ZH only	0.30	2.0		**5.1**	4.3	3.1	1.9	0.89	
ggF+VBF+VH	5.9	6.5		**1.16**	0.24	0.21	0.18	0.15	

k-framework with coupling modifiers: $k = g/g_{SM}$





$h \to \tau^+\tau^-$ @Run-1

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three prongs

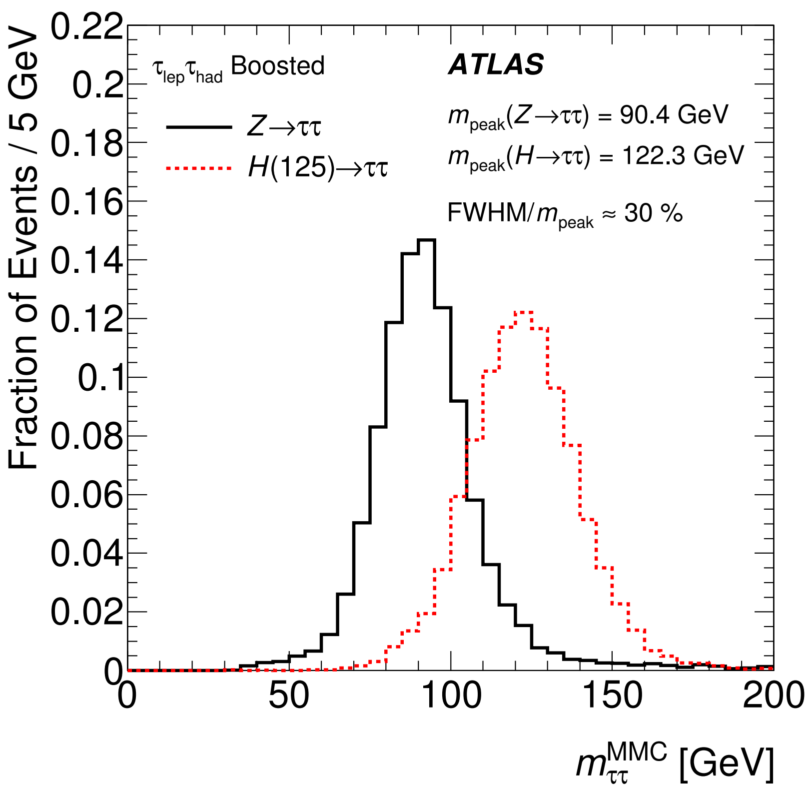
τ_{lep} : $\tau^\pm \to l^\pm \nu\nu$

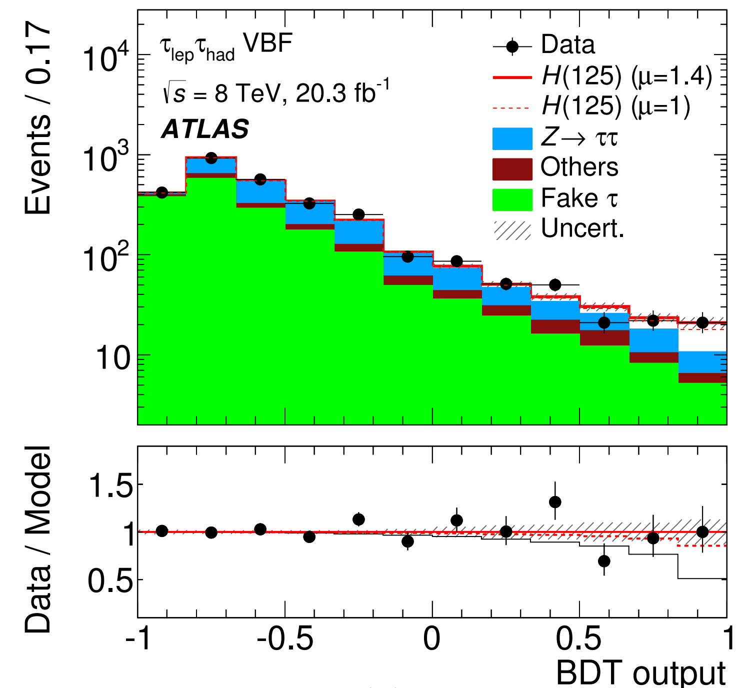
τ_{had} : $\tau^\pm \to \pi^\pm\nu$ $\tau^\pm \to \pi^\pm\pi^0\nu$ $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu$

one prong

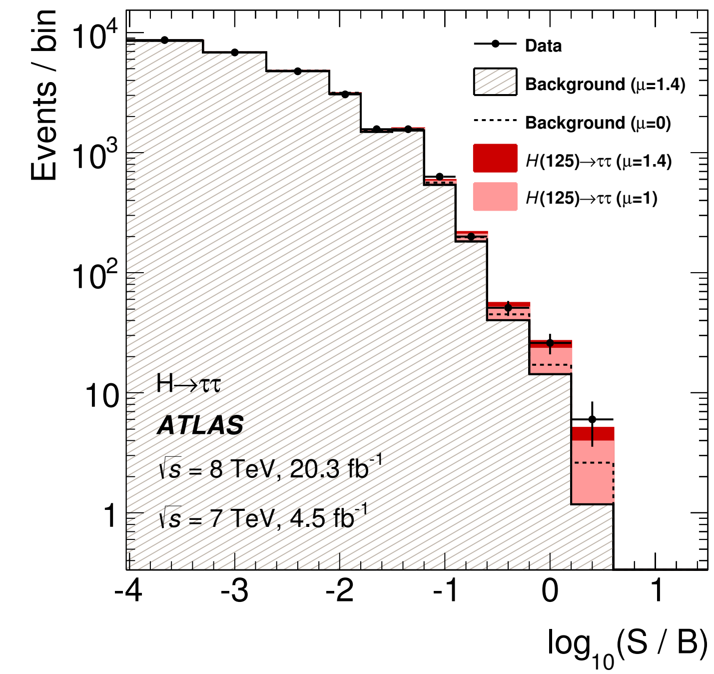
3 event categories: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_{lep}\,\tau_{lep}$

2 physics categories: VBF, boosted (p_T^h > 100 GeV)

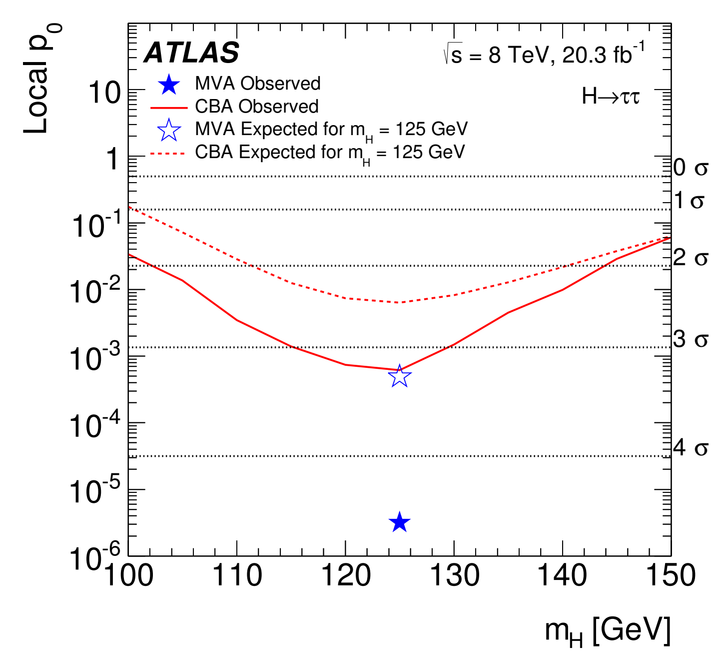


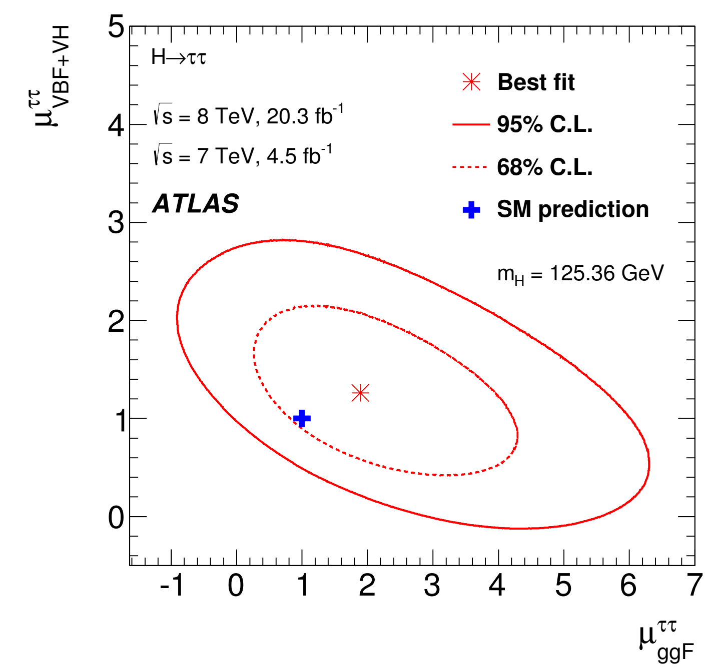


(c)



$m_{\tau\tau}$MC di-tau invariant mass computed using Missing Mass Calculator algorithm taking x,y,z component of each neutrino and $m_{\nu\nu}$, find the most likely configuration among those allowed by the measured constraints





Higgs ATLAS Run-1 combination

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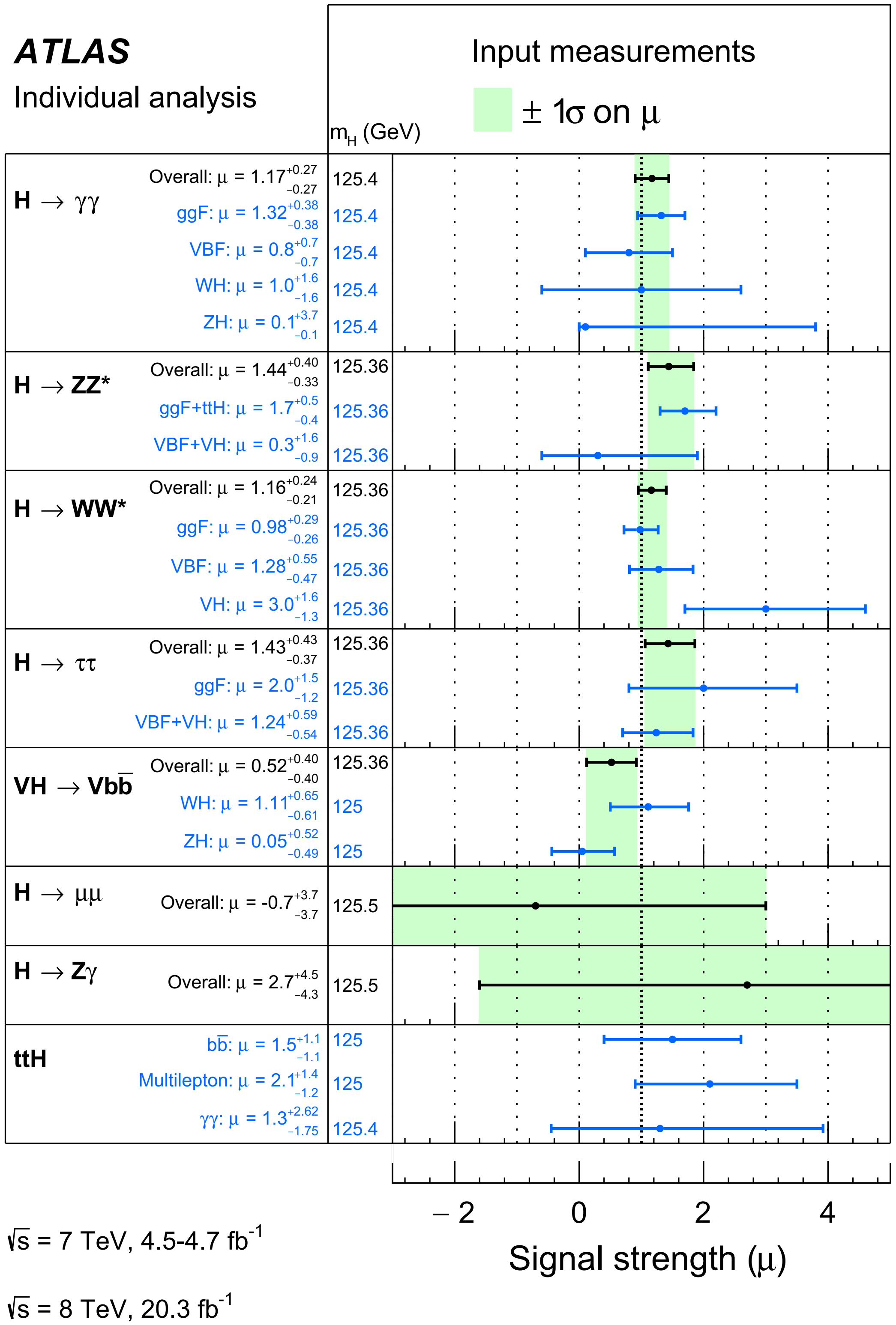
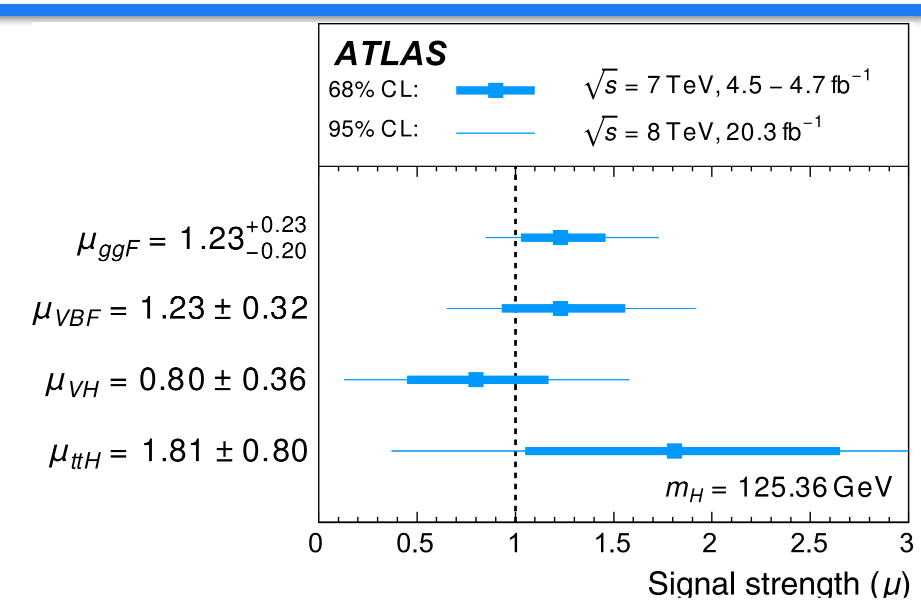
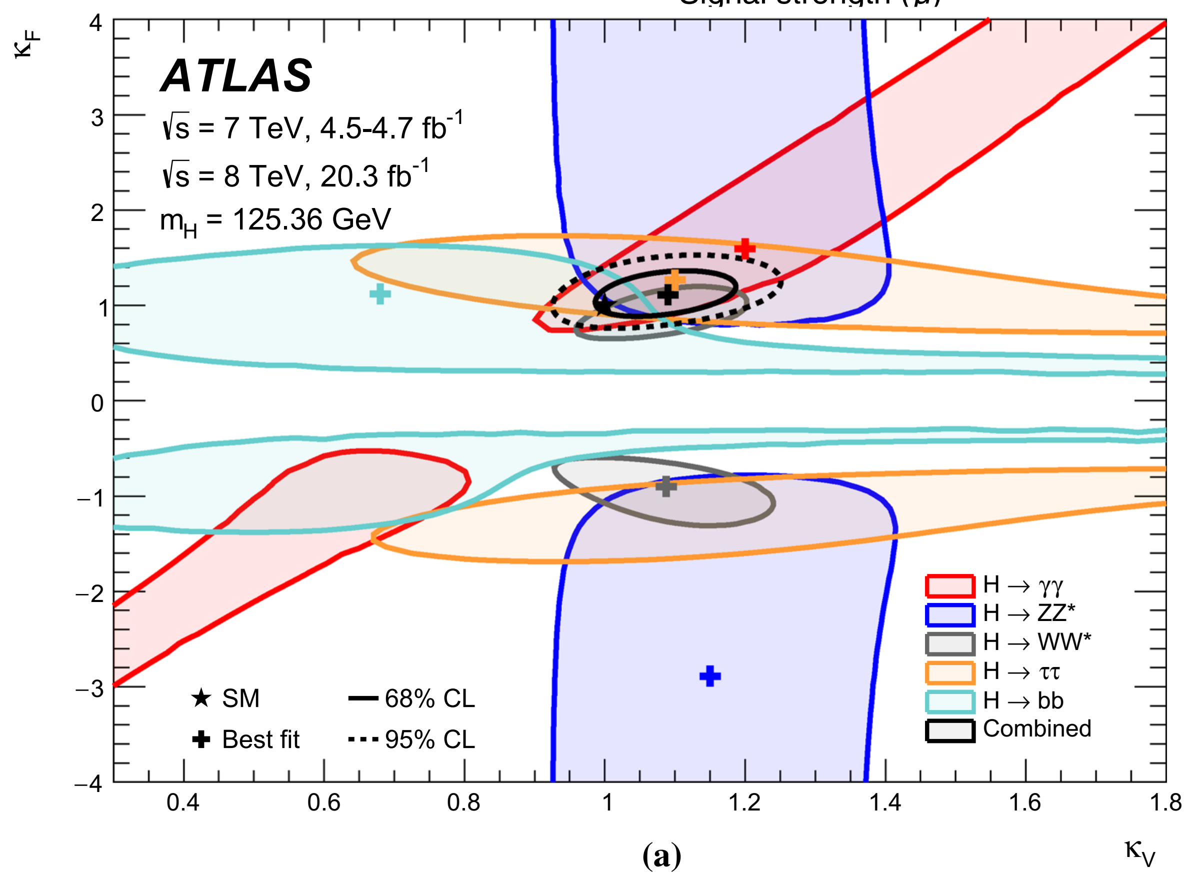


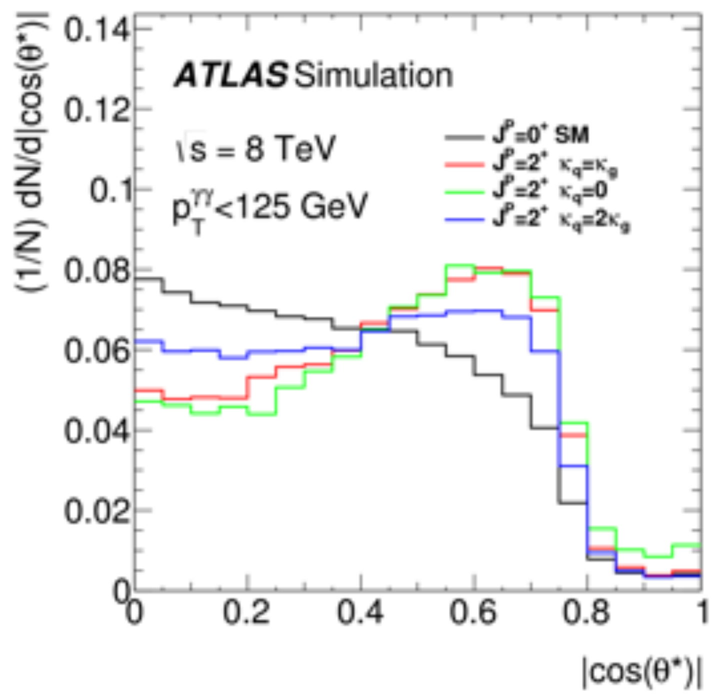


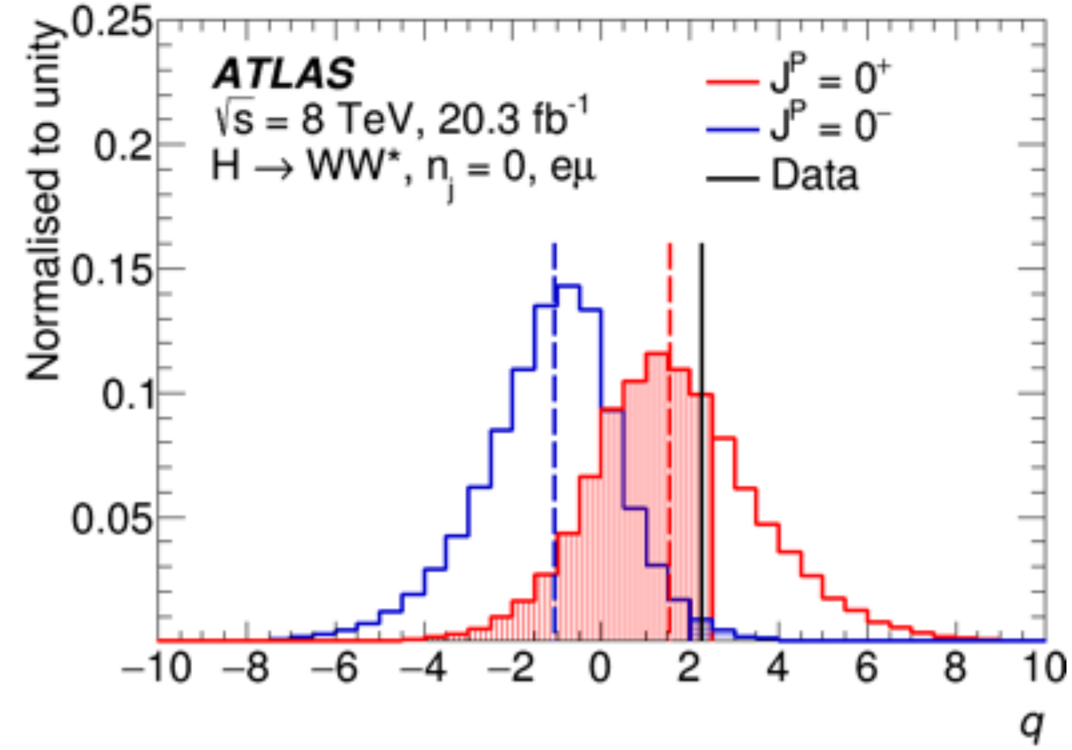


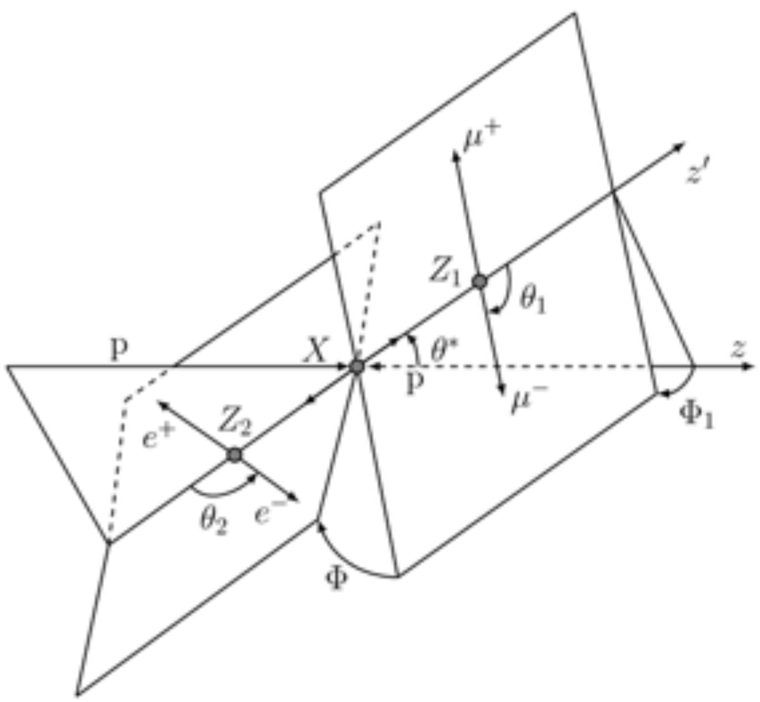
observation of: γγ, WW, ZZ decays
strong evidence of: ττ decay
observation of ggF production mode, evidence of VBF

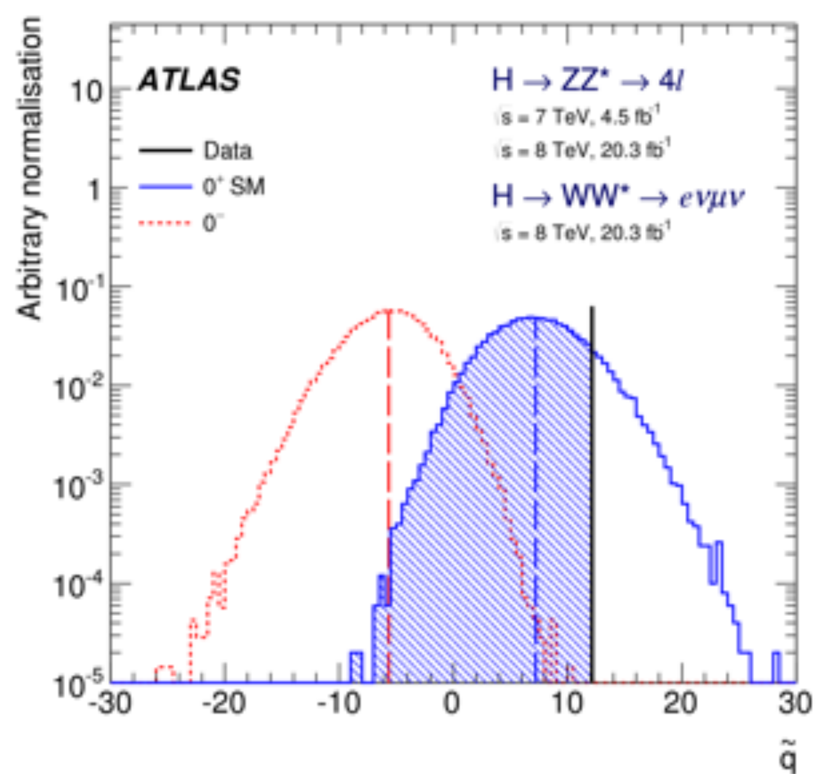
Spin and parity sensitivity through angular sensitive variables:
m_{ll} (WW), m_{12}, m_{34} for ZZ

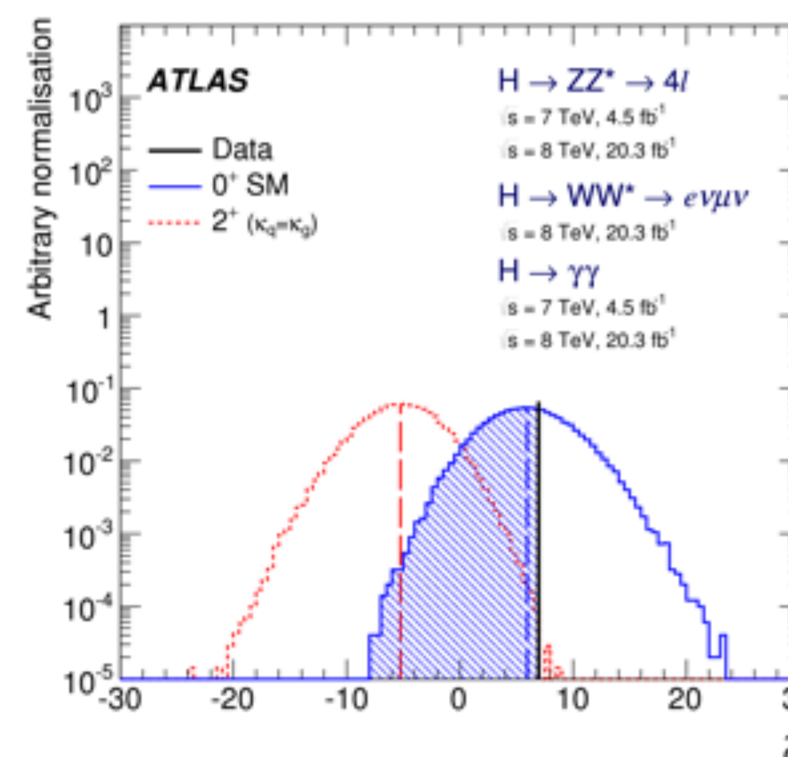
WW,ZZ: 0^+,0^- sensitivity
0-2 sensitivity dominated by WW,γγ









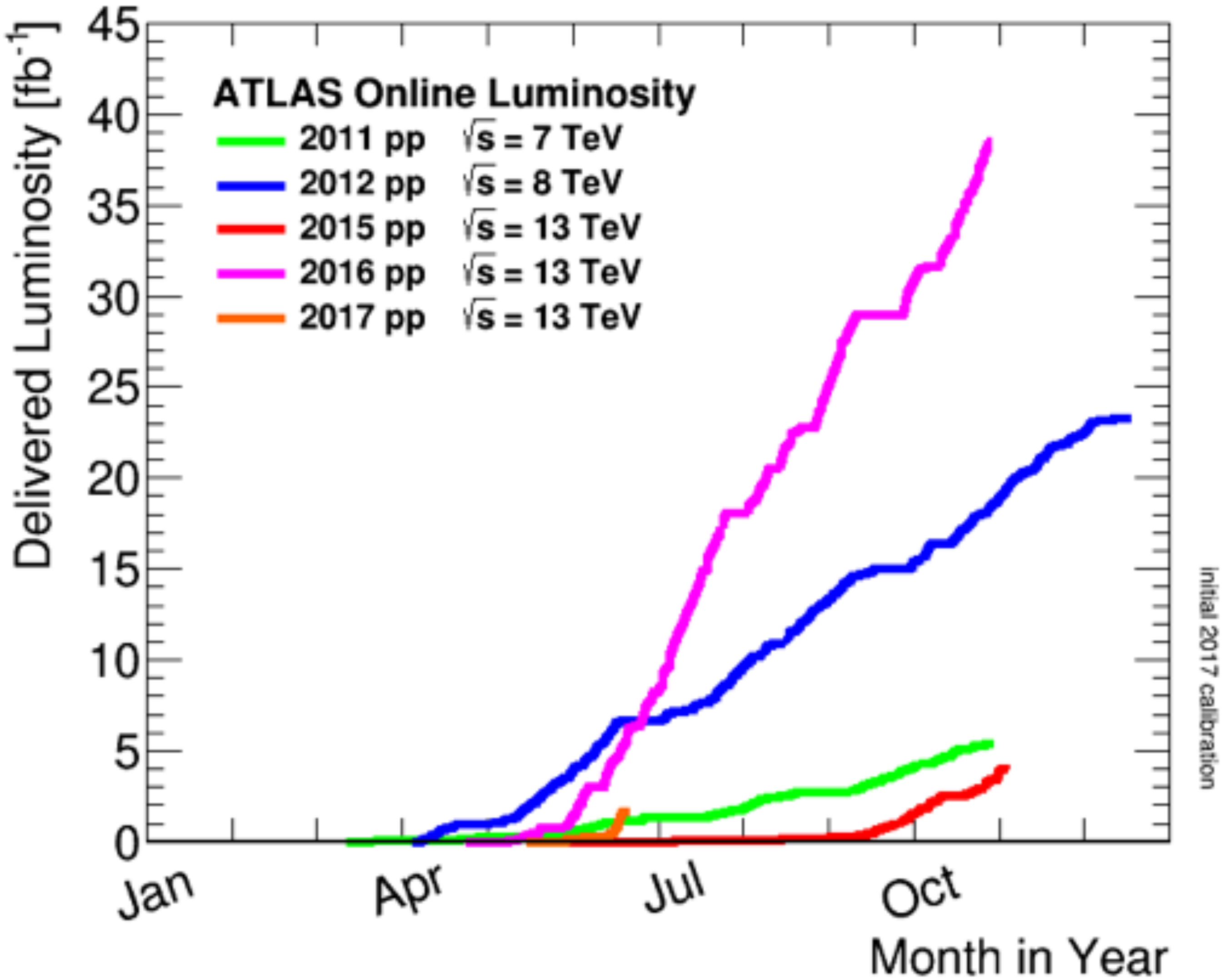


All spin and parity hypotheses different than the SM one are excluded at > 99.9% C.L

Higgs updates from Run-2

Many new results just going to be shown at EPS-2017, in 2 weeks from now, stay tuned!!

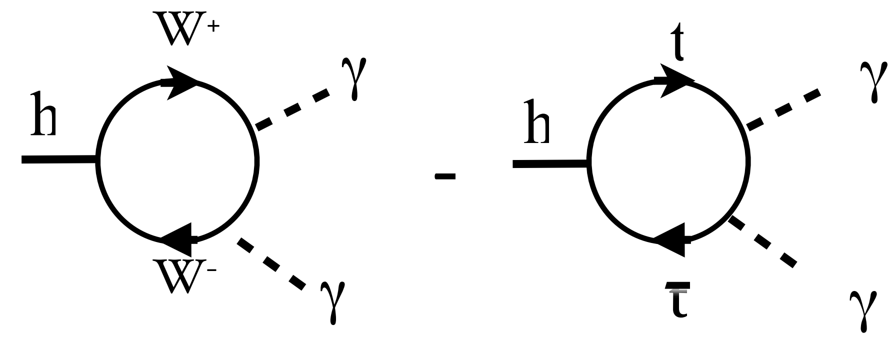
Here I'll summarise what came out from Run-2 up to now…, more details about couplings in Karri Folan Di Petrillo this afternoon in parallel session A

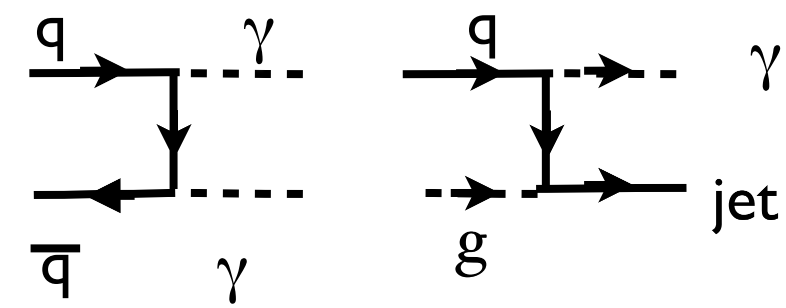


Higgs at Run-2 γγ

ATLAS-CONF-2016-067

- The Higgs boson couples at tree-level only with massive particles
- decay to γγ mediated by loop of massive charged particles (W,t)
- background dominated by non-resonant γγ production and γ−jet with a jet faking a photon
- event sample divided in sub-categories to exploit optimal S/B ratio and different production modes: ggF, VBF, W,Zh, tth
- use of p_{Tt} variable to further separate signal from non resonant background

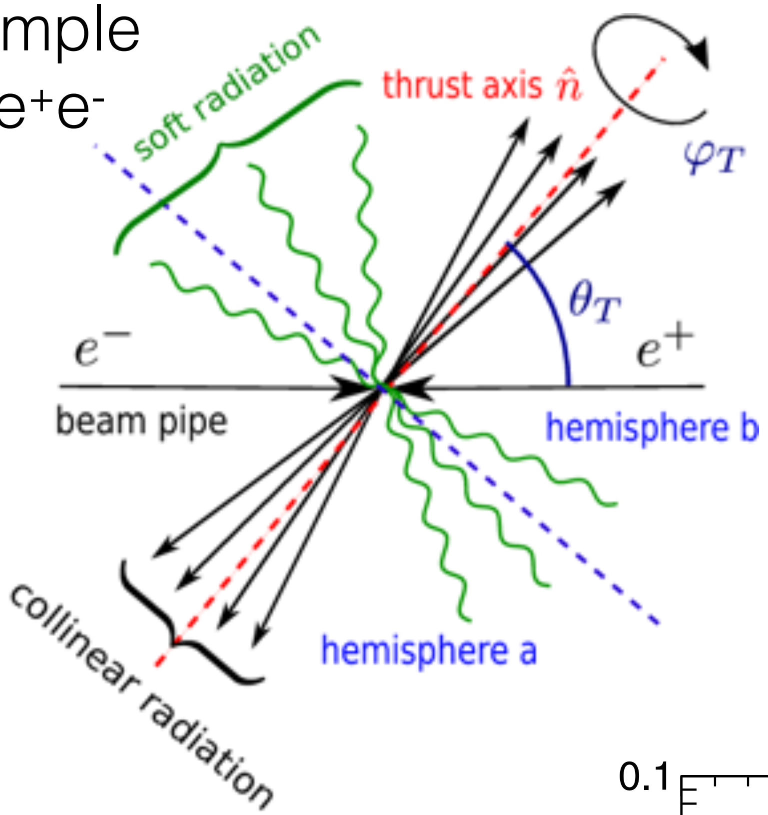




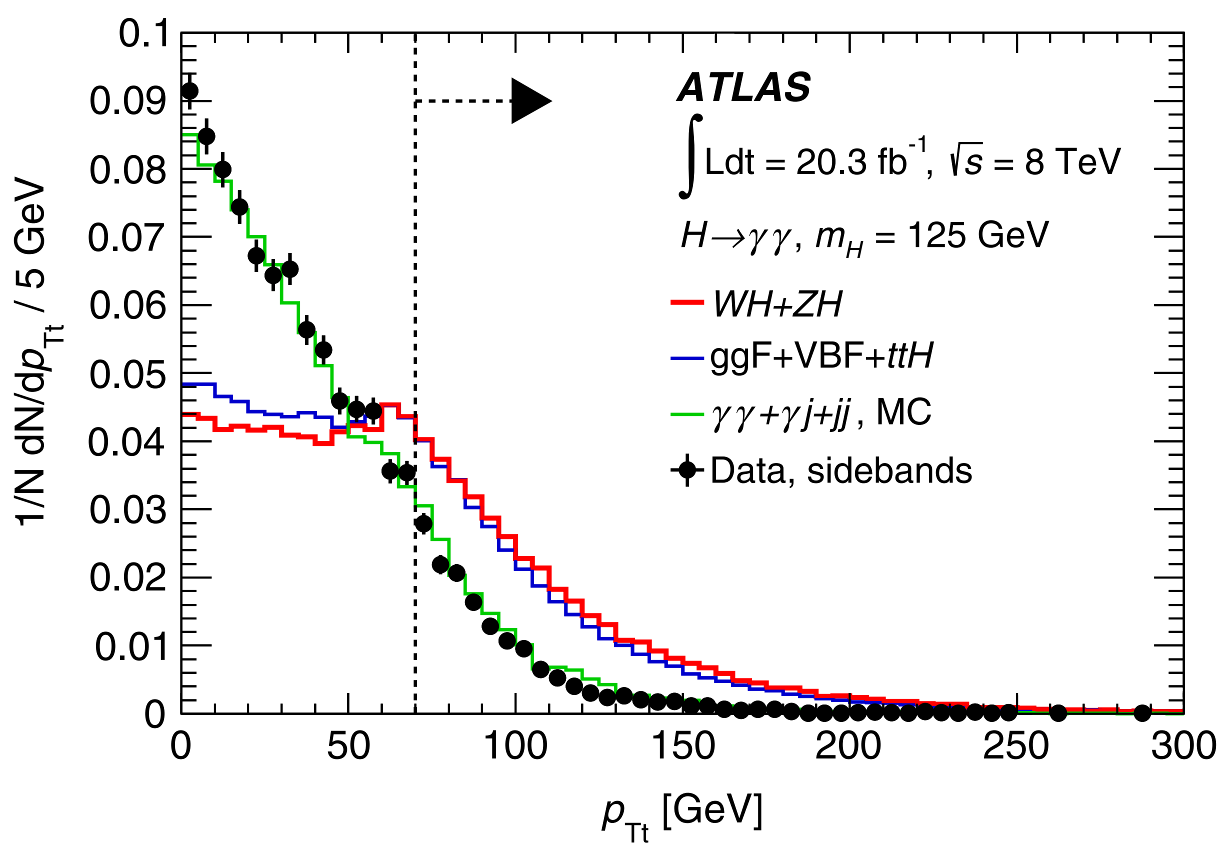
	ggH		VBF		WH		ZH		$t\bar{t}H$		$b\bar{b}H$		$tHjb$		tWH	
Category	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$
Central low-p_{Tt}	12.7	92.7	6.9	3.9	6.3	1.3	6.0	0.8	3.5	0.3	14.2	1.0	4.6	0.1	3.8	0.0
Central high-p_{Tt}	1.2	78.2	2.4	12.8	2.1	4.0	1.8	2.2	2.9	2.0	0.4	0.3	3.7	0.4	5.1	0.2
Forward low-p_{Tt}	22.0	92.1	12.5	4.1	13.0	1.5	12.7	1.0	5.1	0.2	24.9	1.0	9.5	0.1	4.8	0.0
Forward high-p_{Tt}	1.9	76.8	4.1	13.4	3.9	4.6	3.7	2.8	3.6	1.5	0.8	0.3	6.6	0.4	4.8	0.1
VBF loose	0.5	46.3	7.3	51.6	0.2	0.6	0.2	0.4	0.3	0.3	0.4	0.3	3.4	0.5	0.6	0.0
VBF tight	0.1	23.8	5.4	75.5	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	1.2	0.3	0.1	0.0
VH hadronic loose	0.4	64.6	0.4	4.3	3.9	16.5	4.1	11.0	1.7	2.6	0.5	0.6	1.0	0.2	2.2	0.2
VH hadronic tight	0.1	48.9	0.1	2.5	1.8	28.1	1.6	16.9	0.5	3.1	0.0	0.1	0.3	0.2	0.7	0.2
VH $E_{\mathrm{T}}^{\mathrm{miss}}$	0.0	2.4	0.0	0.6	0.6	28.5	1.9	55.8	0.6	10.9	0.0	0.0	0.3	0.7	1.2	1.0
VH one-lepton	0.0	0.2	0.0	0.0	1.3	83.7	0.1	3.0	0.4	10.4	0.0	0.0	0.4	1.3	1.1	1.3
VH dilepton	0.0	0.0	0.0	0.0	0.0	0.0	1.2	95.1	0.1	4.5	0.0	0.0	0.0	0.0	0.2	0.4
$t\bar{t}H$ hadronic	0.0	3.8	0.0	0.5	0.0	0.3	0.1	0.8	11.5	88.1	0.0	0.2	2.2	2.5	10.1	3.8
$t\bar{t}H$ leptonic	0.0	0.3	0.0	0.1	0.0	0.7	0.0	0.4	8.4	89.3	0.0	0.2	3.1	4.8	8.3	4.3
Total efficiency (%)	38.9	-	39.2	-	33.2	-	33.5	-	38.6	-	41.2	-	36.2	-	43.1	-
Events	568.8		44.6		13.7		8.9		5.9		5.6		0.8		0.3	

h→γγ, p_{Tt} categorisation

an example from e+e-



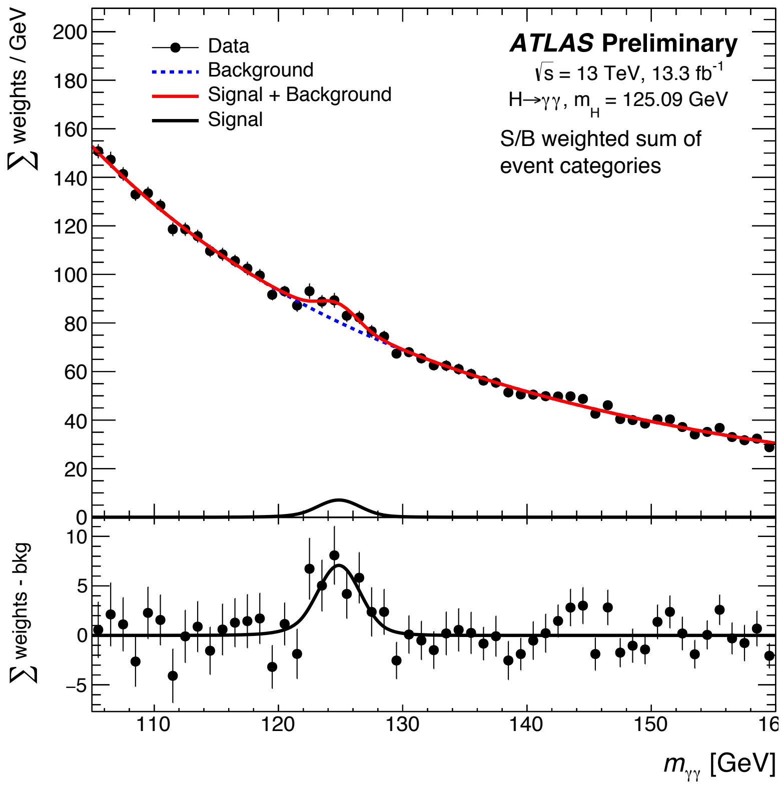
- The thrust axis is defined as the axis that maximises the projections of all produced particle momenta in the interaction
- it defines the direction of the soft event shape in pp collision (underlying event and initial state radiation will be mainly directed along the thrust axis of the event)
- ggF production has typically harder recoiling jets than qq production, therefore the produced Higgs boson will present harder p_{Tt}

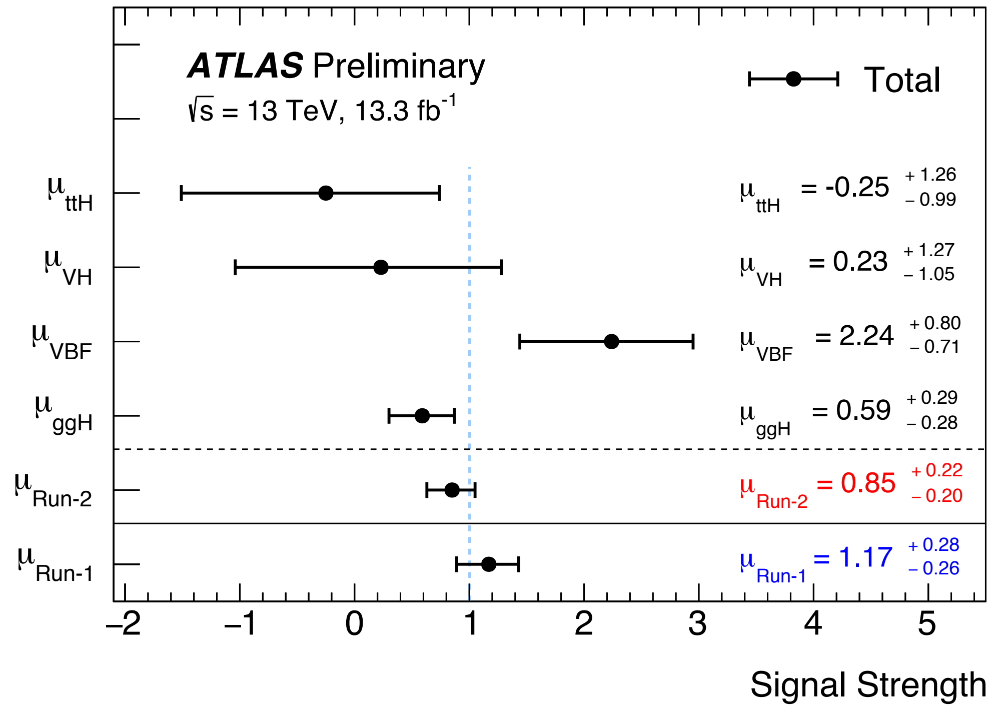


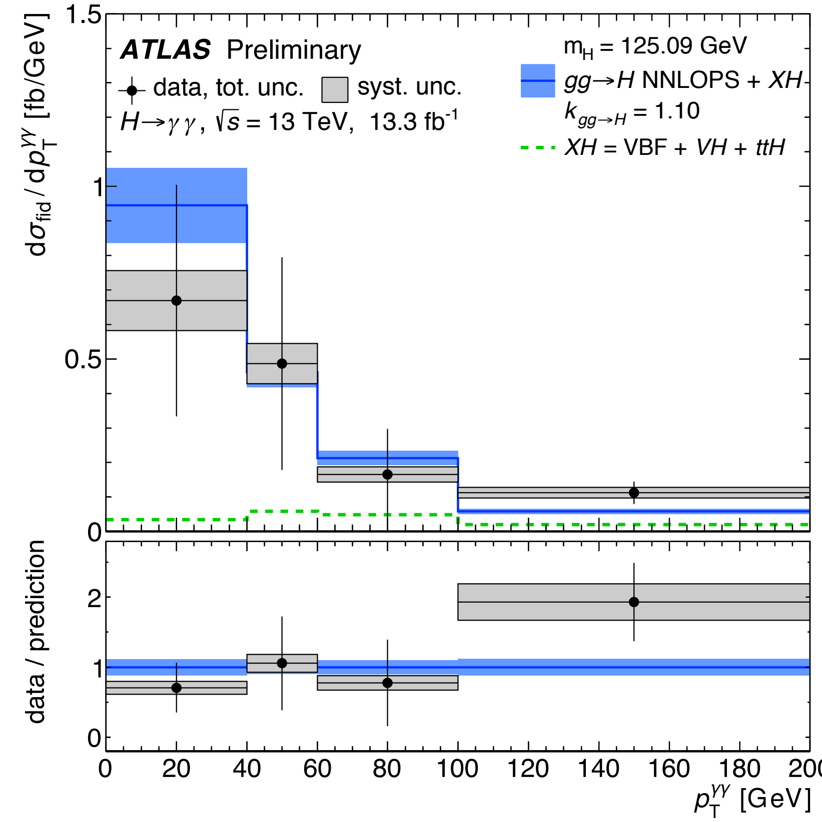
h→γγ update 13 fb^{-1}

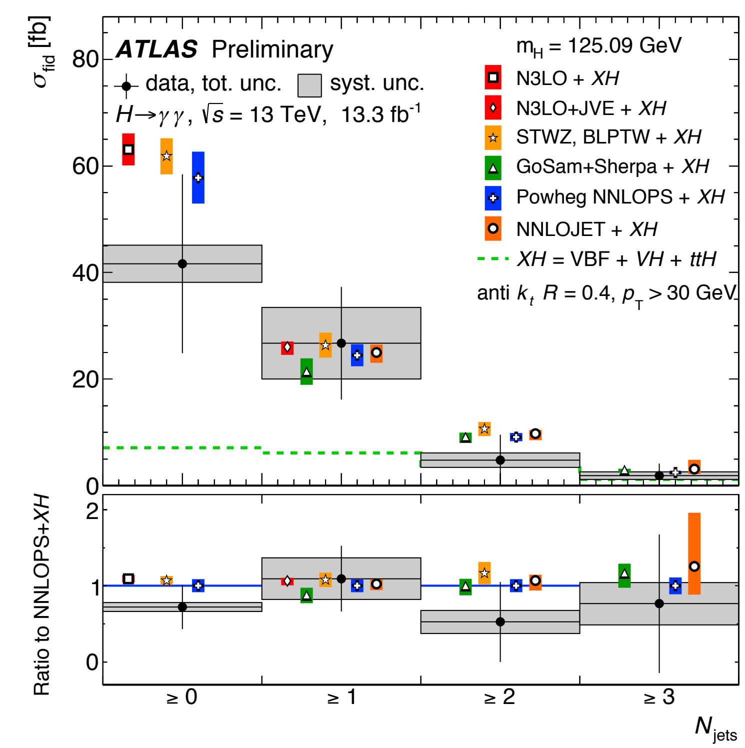
ATLAS-CONF-2016-067

- same analysis strategy and categorisation as Run-1
- profit of the higher ggF xs to reach same Run-1 accuracy with less integrated luminosity: σ_{ggF}: 19 pb (8 TeV)→ 49 pb (13 TeV)
- focus on signal properties: simplified xs and differential distributions









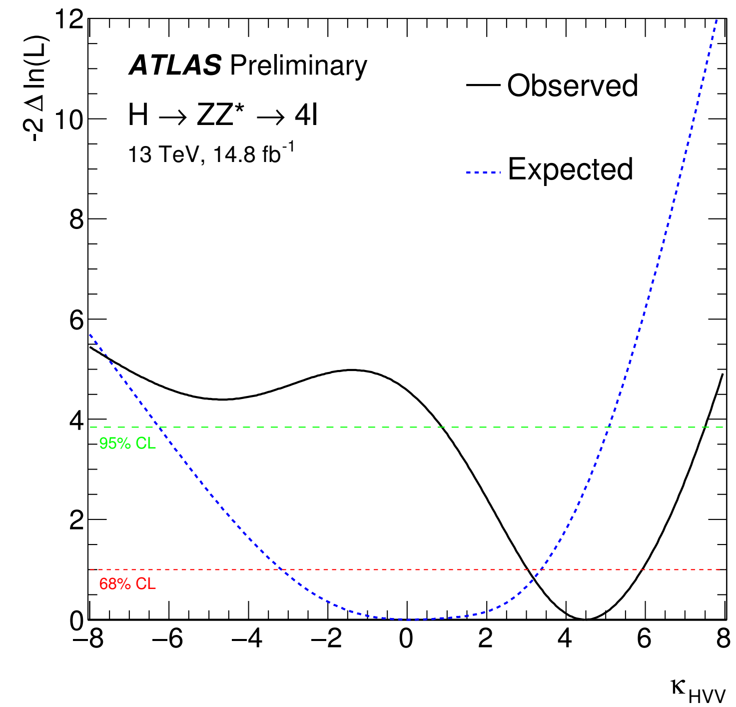
$$\sigma_{ggH} \times \mathcal{B}(H \to \gamma\gamma) = 63\ ^{+30}_{-29}\ \text{fb}$$
$$\sigma_{\text{VBF}} \times \mathcal{B}(H \to \gamma\gamma) = 17.8\ ^{+6.3}_{-5.7}\ \text{fb}$$
$$\sigma_{\text{VHlep}} \times \mathcal{B}(H \to \gamma\gamma) = 1.0\ ^{+2.5}_{-1.9}\ \text{fb}$$
$$\sigma_{\text{VHhad}} \times \mathcal{B}(H \to \gamma\gamma) = -2.3\ ^{+6.8}_{-5.8}\ \text{fb}$$
$$\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma\gamma) = -0.3\ ^{+1.4}_{-1.1}\ \text{fb}$$

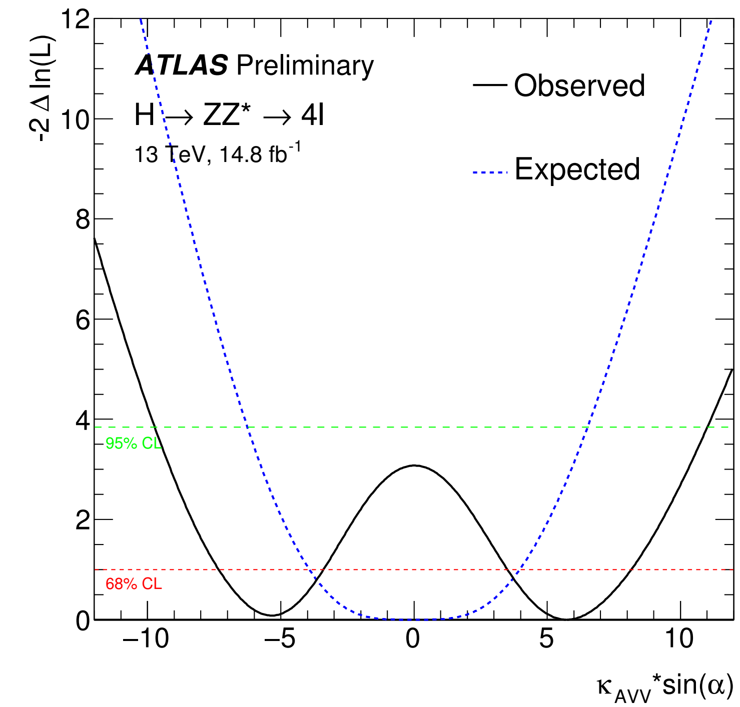
Simplified cross sections, measured in a fiducial volume closer to the analysis acceptance: $|y_H| < 2.5$, VH distinguished between hadronic and leptonic decays of the vector boson V

h→ZZ update 15 fb^{-1} couplings ATLAS-CONF-2016-079

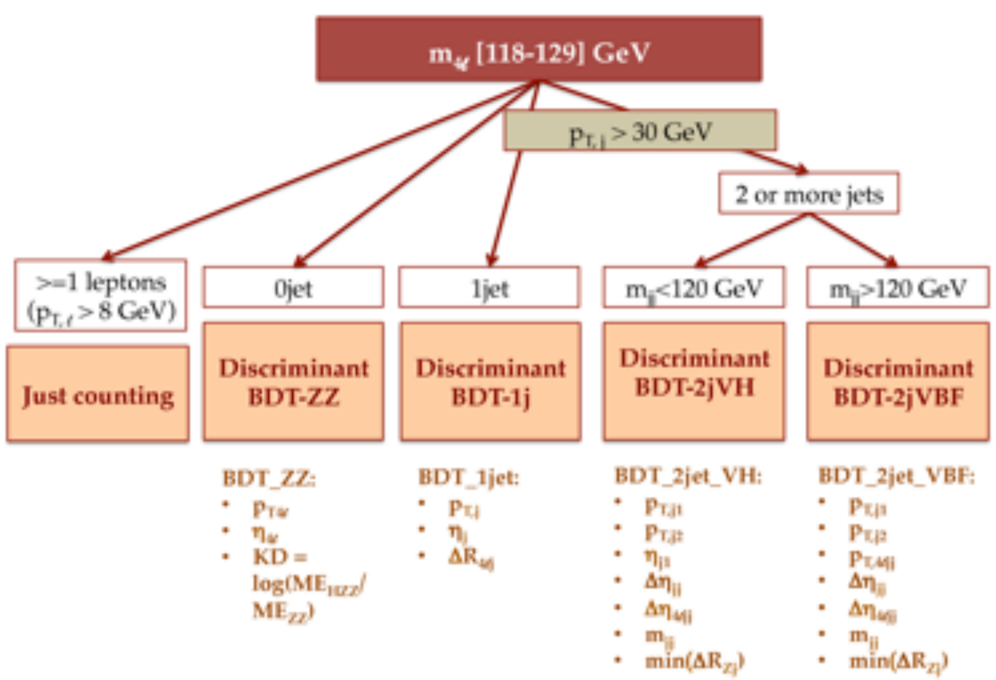
- coupling results with 15 fb^{-1}, probably going to be updated with ~40 fb^{-1} at EPS;
- inclusive results with 36.1 fb^{-1}, see next slide;
- k_{AVV} and k_{HVV} scalar and pseudo-scalar interactions with VV, sensitivity from VH and VBF production modes

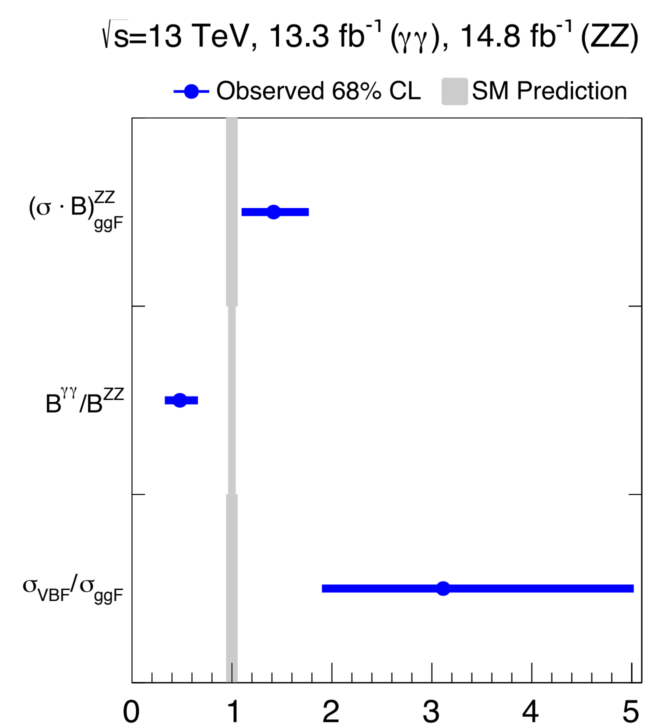
contribution of BSM physics altering the h -> VV coupling, Λ_{NP} = 1TeV (intringuing ~2σ effect , need to stay tuned)

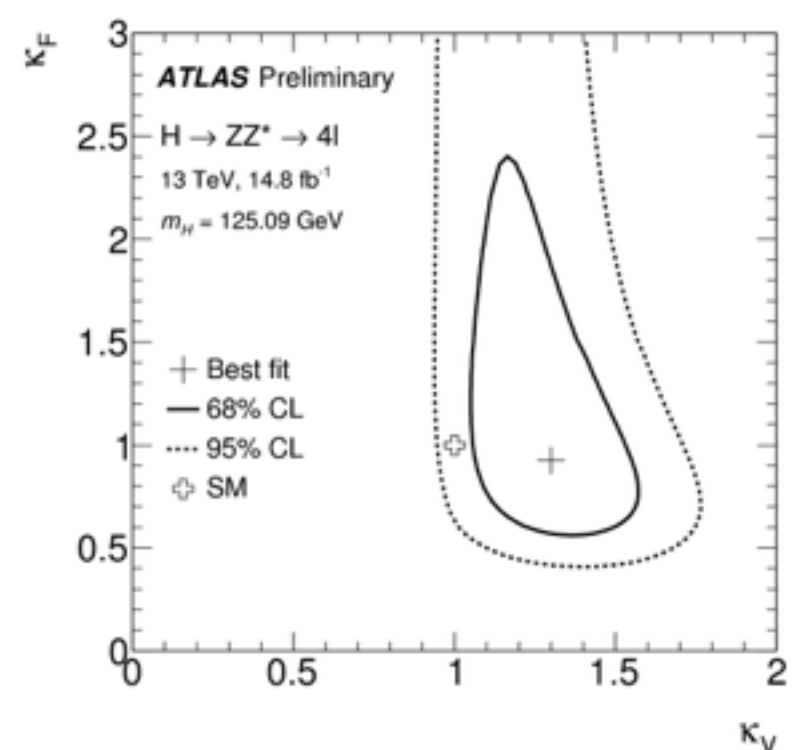




Event categorisation similar at Run-1







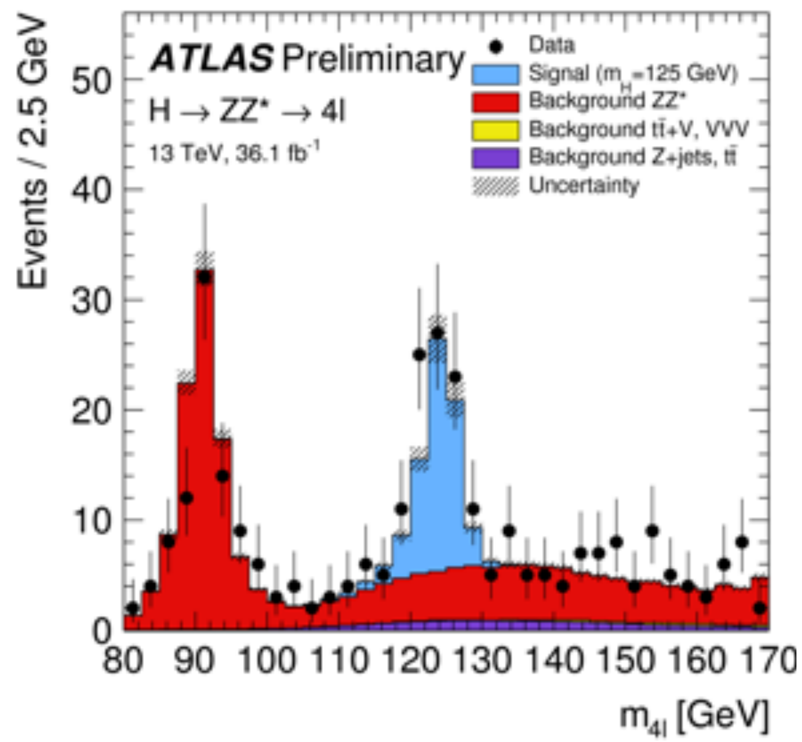
h→ZZ update 36 fb^{-1} fiducial cross section

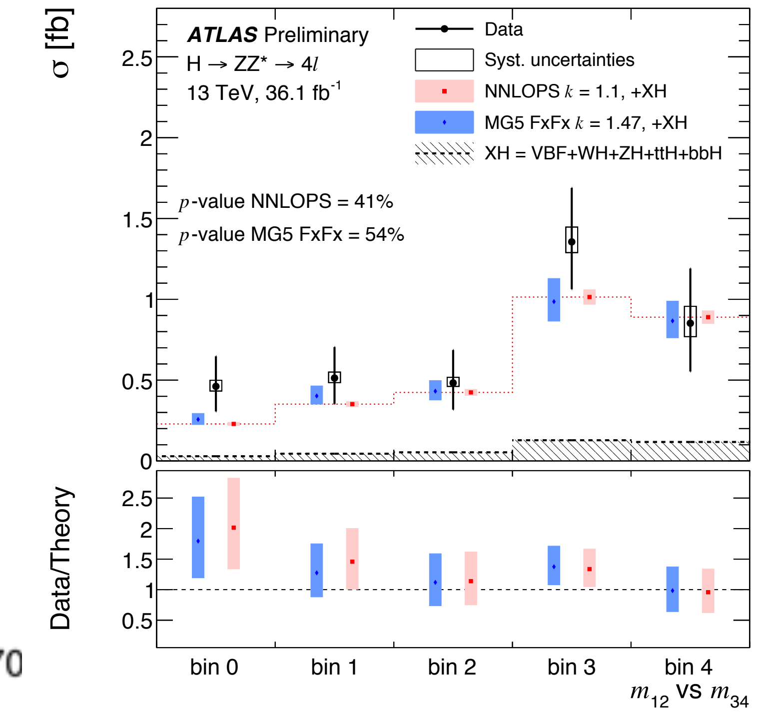
ATLAS-CONF-2017-032

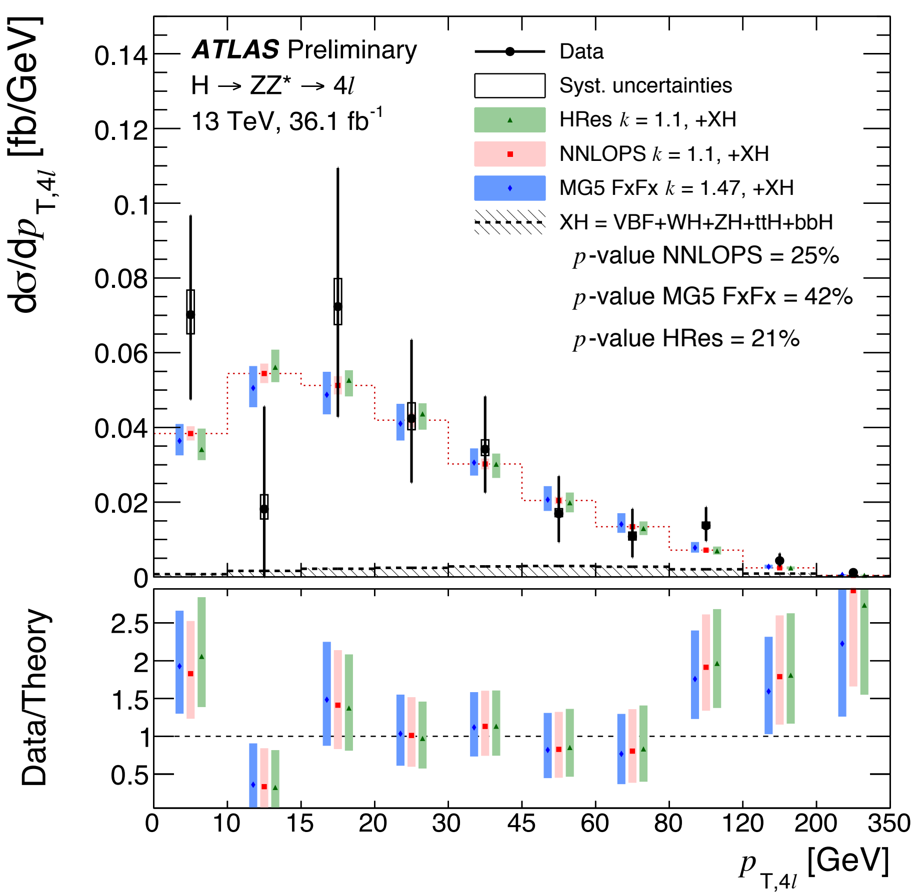
- analysis performed without production mode categorisation;
- focus on differential distributions and fiducial cross sections

$$\sigma_{\rm fid} = 3.62^{+0.53}_{-0.50}({\rm stat})^{+0.25}_{-0.20}({\rm sys})\,{\rm fb}$$

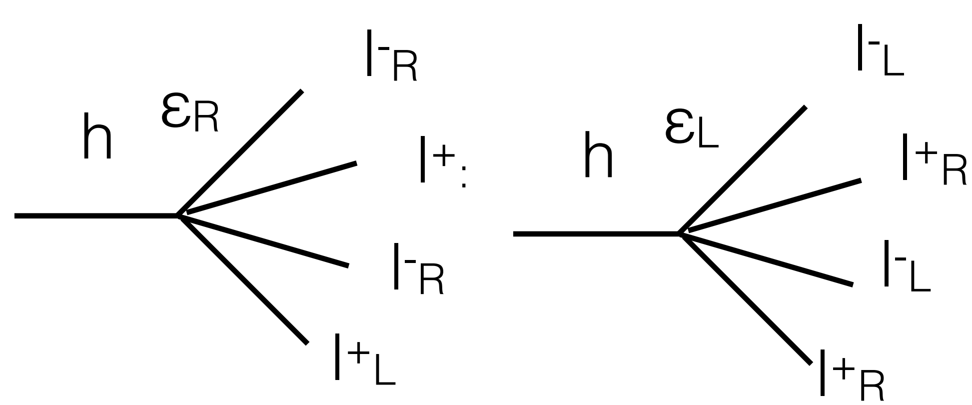
$$\sigma_{\rm SM} = 2.91 \pm 0.13\,{\rm fb}$$

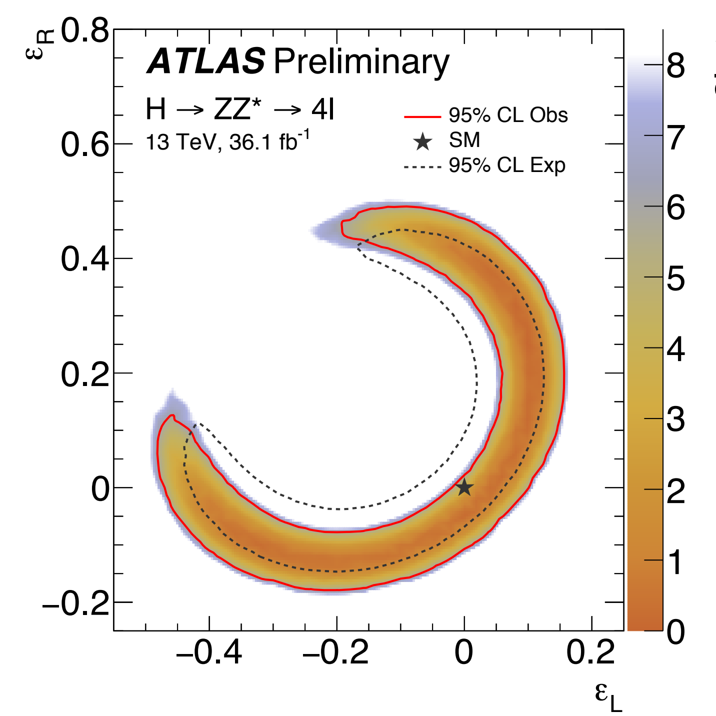




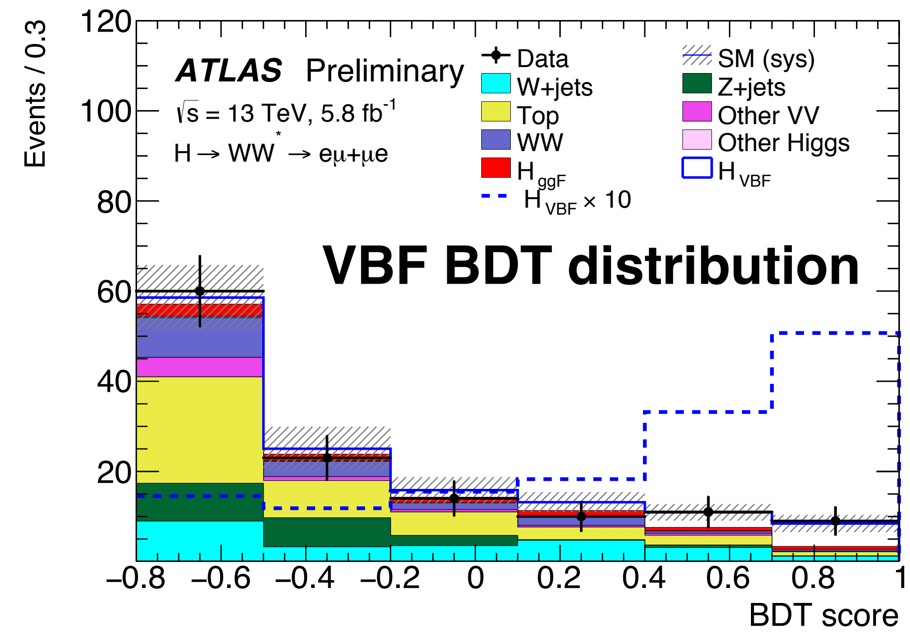


m_{12}, m_{34} used to extract left-handed and right-handed effective couplings to leptons

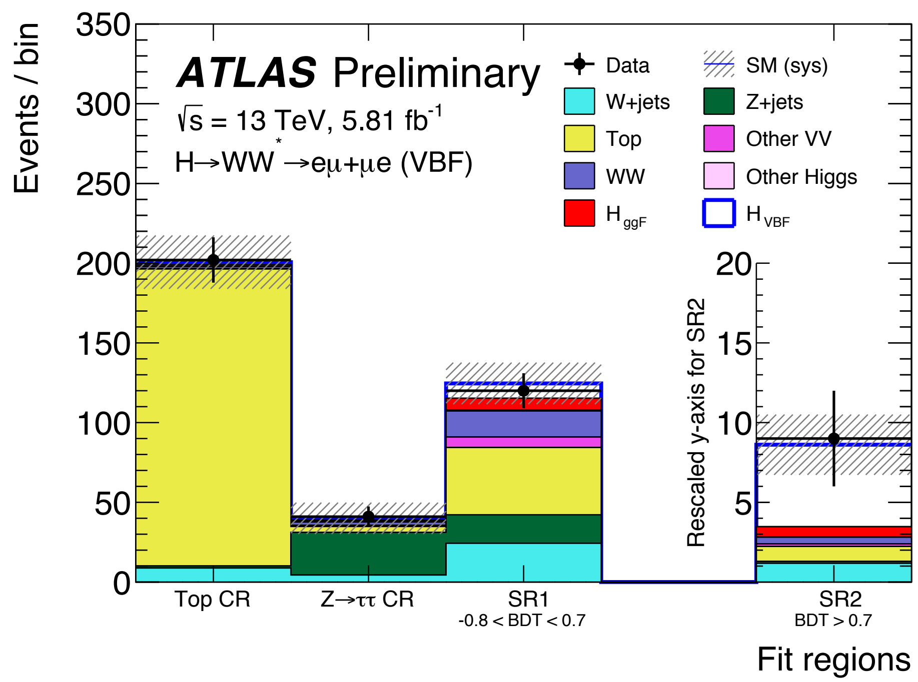


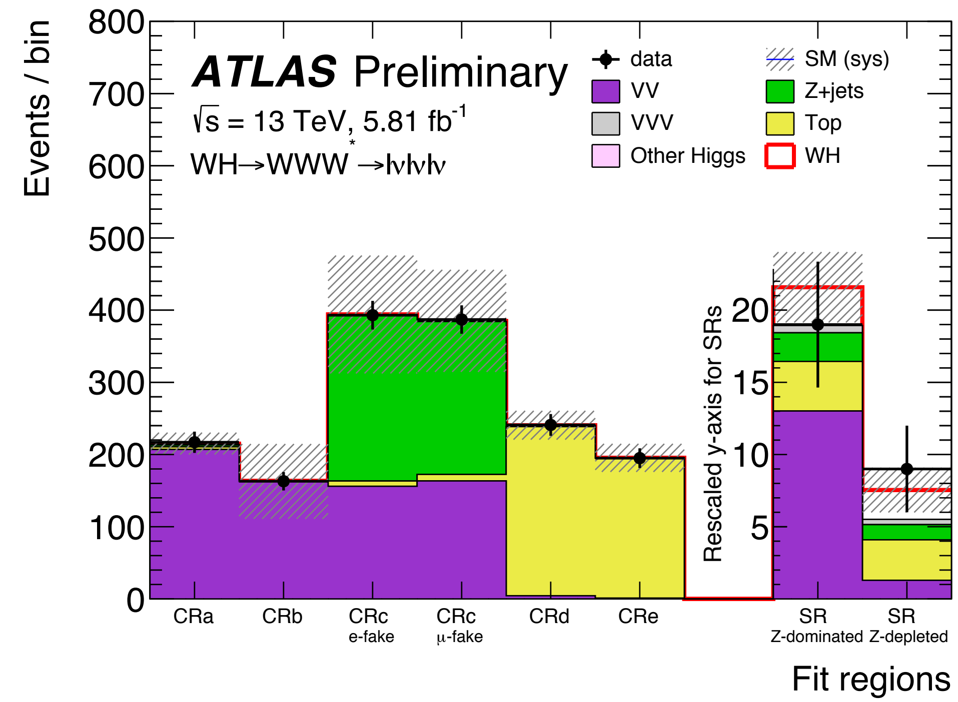


- analysis performed only in the VBF and VH final state, due to the complexity of the fake background estimation in ggF that needs more careful evaluation;
- integrated luminosity 5.8 fb^{-1};
- difference respect to Run-1: cut and count analysis for VH only in the 3-lepton channel, no SF channel for VBF



VBF ~ 2σ





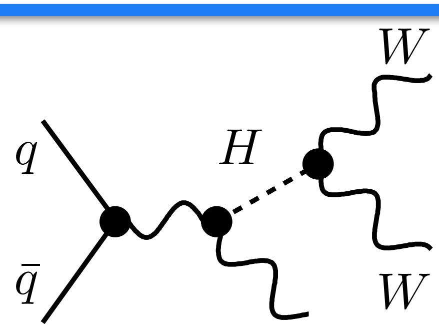
$$\mu_{\mathrm{VBF}} = 1.7^{+1.0}_{-0.8}(\mathrm{stat})^{+0.6}_{-0.4}(\mathrm{sys})$$

$$\mu_{WH} = 3.2^{+3.7}_{-3.2}(\mathrm{stat})^{+2.3}_{-2.7}(\mathrm{sys})$$

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 1.4^{+0.8}_{-0.6}(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{sys})\ \mathrm{pb}$$

$$\sigma_{WH} \cdot \mathcal{B}_{H\to WW^*} = 0.9^{+1.1}_{-0.9}(\mathrm{stat})^{+0.7}_{-0.8}(\mathrm{sys})\ \mathrm{pb}$$

h→bb @Run2



$V = W, Z$
VH production

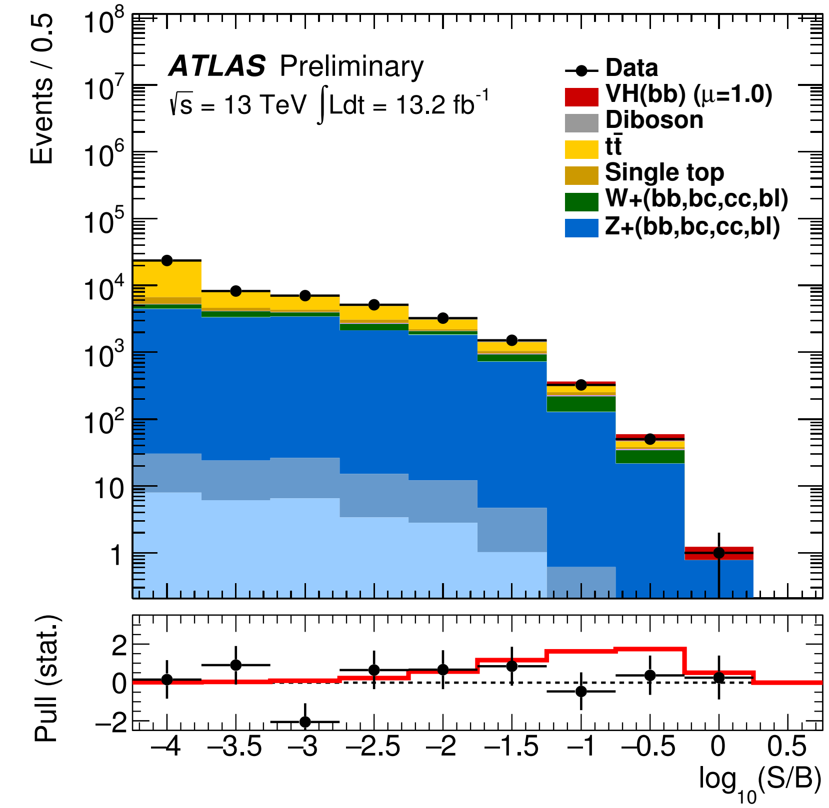
analysis based on categorisation in number of leptons and BDT

Channel	Categories					
	2 *b*-tagged jets					
	$p_T^V < 150$ GeV			$p_T^V > 150$ GeV		
	2 jets	3 jets	≥ 3 jets	2 jets	3 jets	≥ 3 jets
0-lepton	-	-	-	BDT	BDT	-
1-lepton	-	-	-	BDT	BDT	-
2-lepton	BDT	-	BDT	BDT	-	BDT

Main backgrounds:
Top; V+bb, V+jets; WZ, Z→bb

Typically low S/B ratio:
0.002-0.02

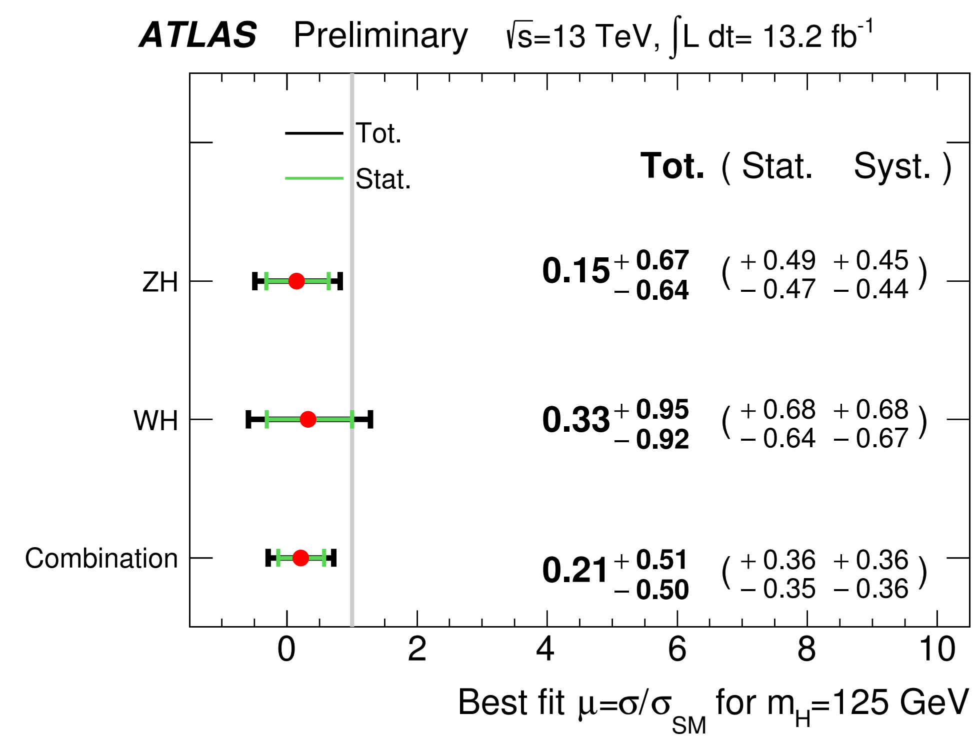
Run-1 results: 1.4 σ observed
2.6 σ expected



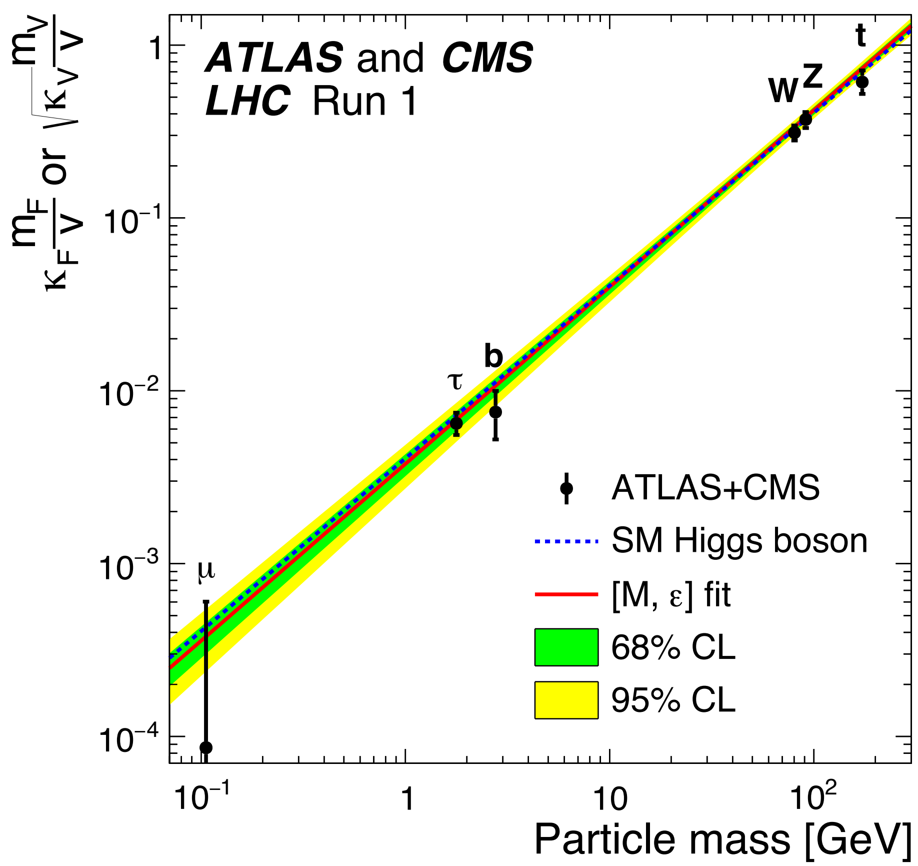
Run-2 results

Dataset	Limit		p_0		Significance	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
0-lepton	$1.4^{+0.6}_{-0.4}$	2.0	0.07	0.15	1.45	1.02
1-lepton	$2.0^{+0.8}_{-0.6}$	2.1	0.15	0.46	1.04	0.10
2-lepton	$1.8^{+0.7}_{-0.5}$	1.7	0.13	0.57	1.14	−0.17
Combined	$1.0^{+0.4}_{-0.3}$	1.2	0.03	0.34	1.94	0.42

still missing evidence of bb up to now, results going to be updated soon with full 2016 statistics

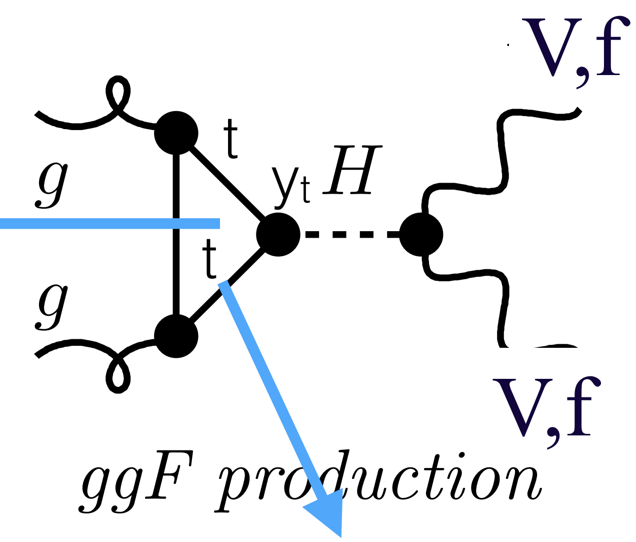


ttH motivation



Run-1 fit to Higgs production and decay shows a clear coupling to top, can we say to have observed top coupling?

h→tt coupling
(sc. factor to SM coupling)

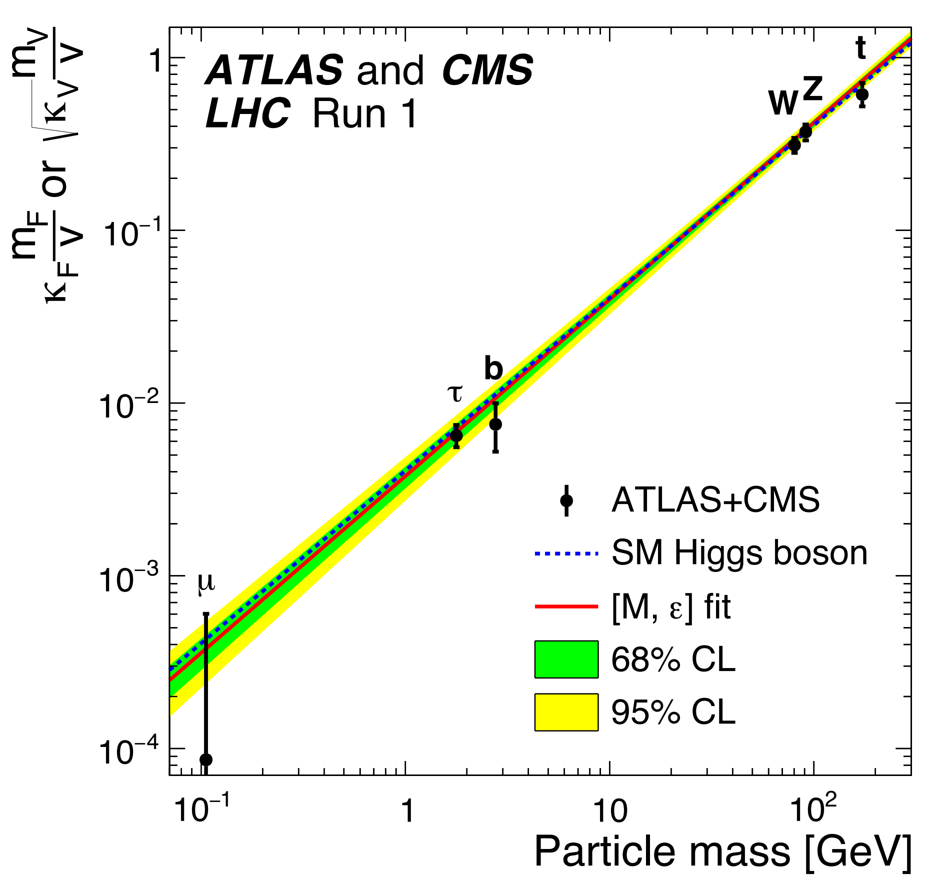


$$m_t \propto h_{tt} \langle VEV \rangle = y_t h_{tt}^{\mathrm{SM}} \langle VEV \rangle \quad 1/m_t \sim 1/y_t$$

The values of the ggF xs is barely sensitive to top coupling, due to the cancellation between the m_t dependence of the loop and the Higgs coupling to the top

V,f

ttH motivation



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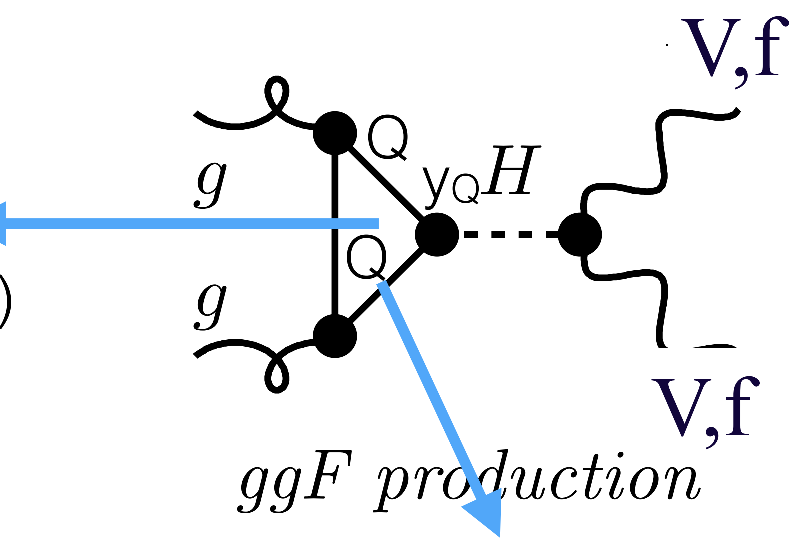
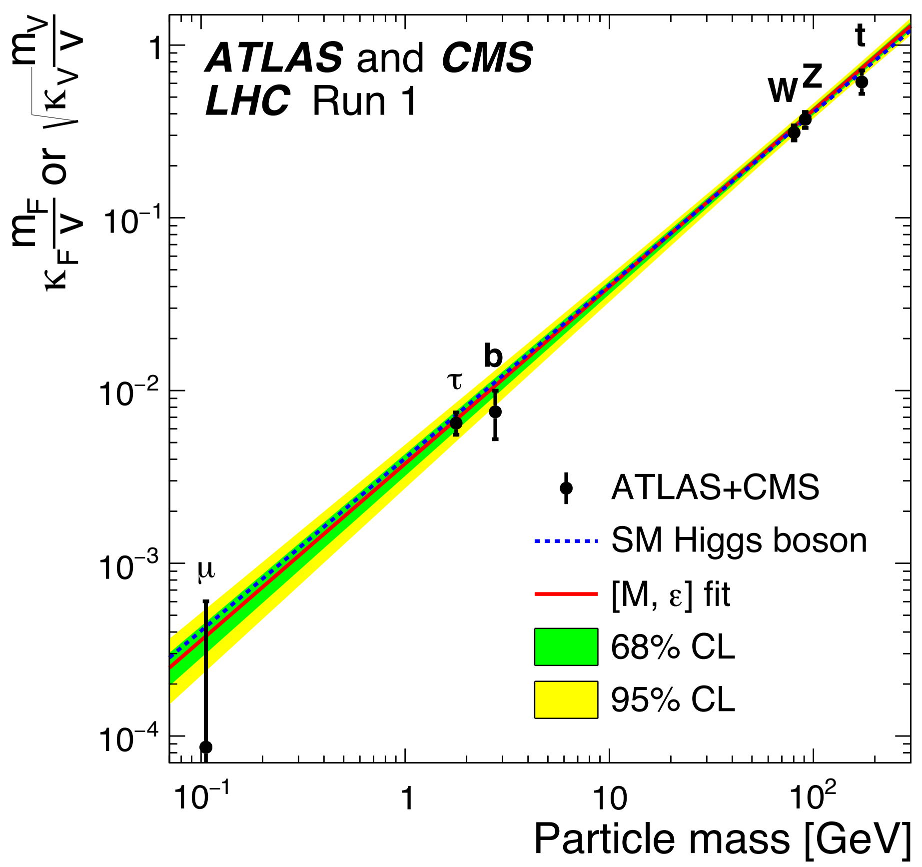


$m_t \propto h_{tt} \langle VEV \rangle = y_t h_{tt}^{SM} \langle VEV \rangle$ $1/m_Q \sim 1/y_Q$

What if an unknown heavy quark Q were running in the loop instead of top?

ttH motivation



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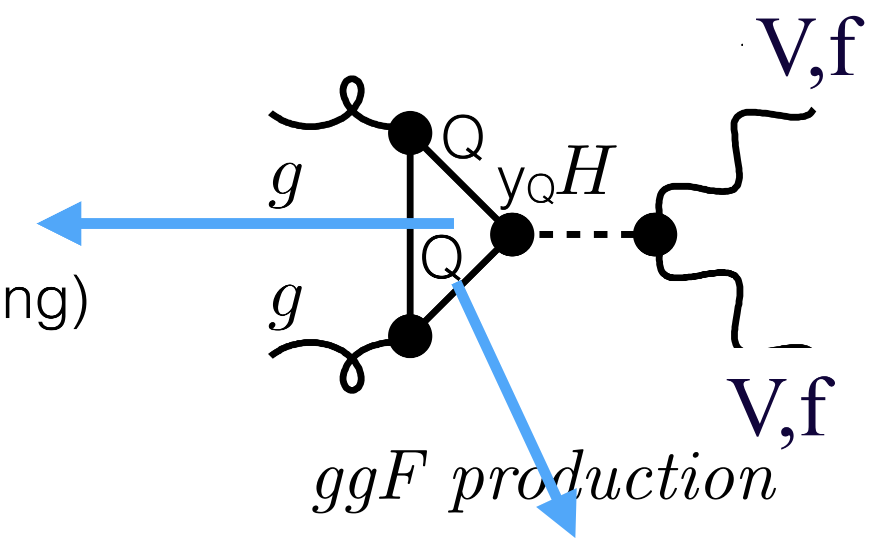
h→tt coupling
(sc. factor to SM coupling)

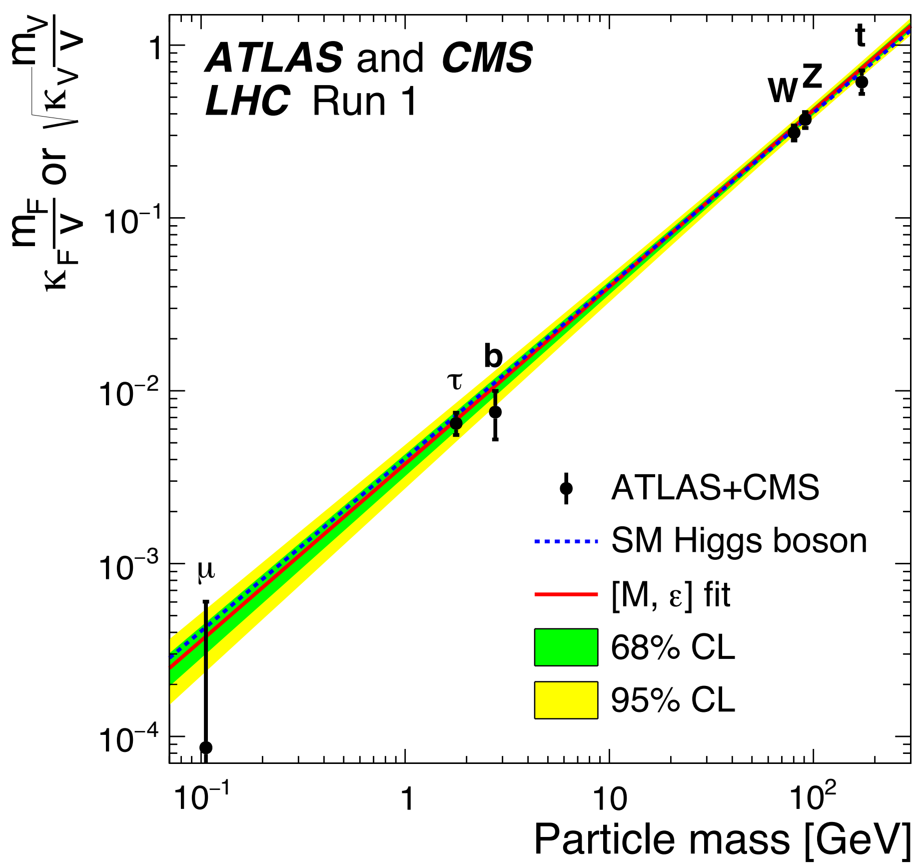


$m_t \propto h_{tt} \langle VEV \rangle = y_t h_{tt}^{SM} \langle VEV \rangle$ $1/m_Q \sim 1/y_Q$

What if an unknown heavy quark Q were running in the loop instead of top?

The cancellation would hold as well and coupling results would not change much (at least with the present precision)

ttH motivation



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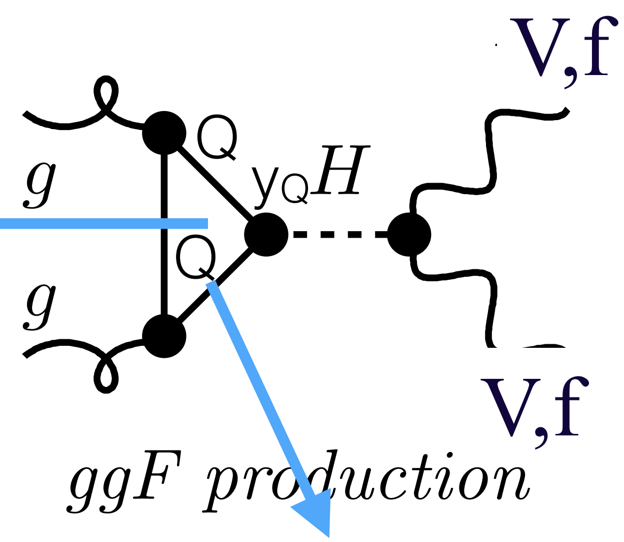
h→tt coupling
(sc. factor to SM coupling)



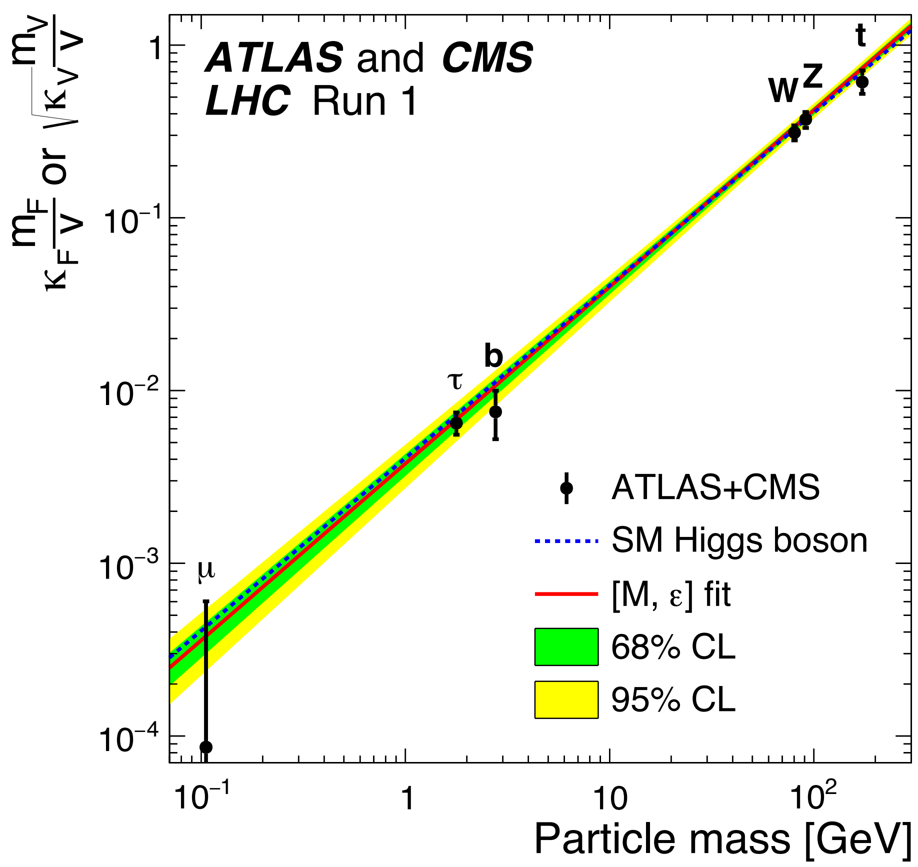
$m_t \propto h_{tt} \langle VEV \rangle = y_t h_{tt}^{\rm SM} \langle VEV \rangle$ $1/m_Q \sim 1/y_Q$

What if an unknown heavy quark Q were running in the loop instead of top?

The cancellation would hold as well and coupling results would not change much (at least with the present precision)

Nevertheless, assuming that what is in the loop is the top quark, we really measure the h-top coupling because the m_t values is given by the measured top mass value

ttH motivation



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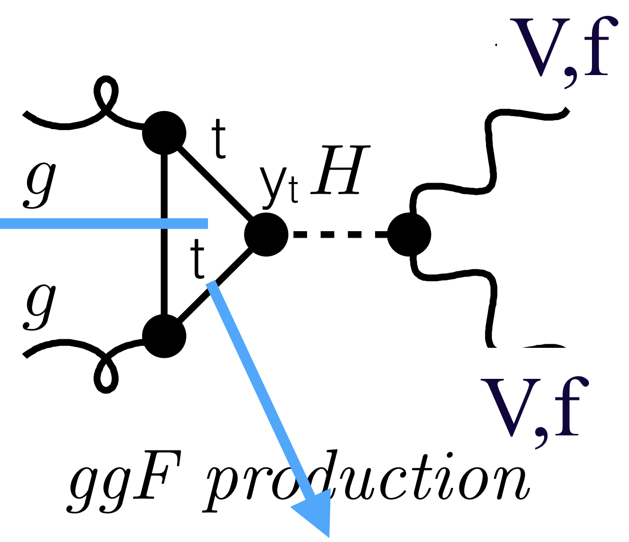
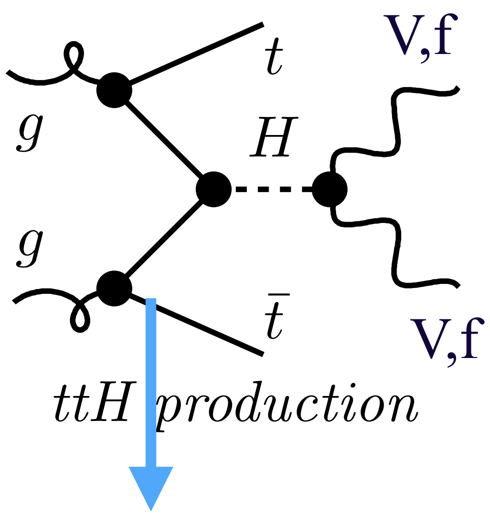
h→tt coupling
(sc. factor to SM coupling)



$m_t \propto h_{tt} \langle VEV \rangle = y_t h_{tt}^{SM} \langle VEV \rangle$ $1/m_t \sim 1/y_t$

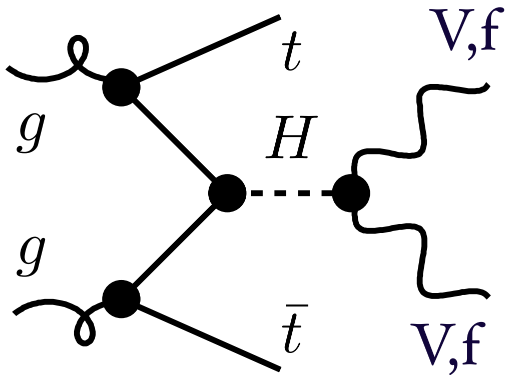
ttH is absolutely needed to certify that the Higgs boson couples to top



direct coupling

ttH results @Run2

ATLAS-CONF-2016-068



ttH production

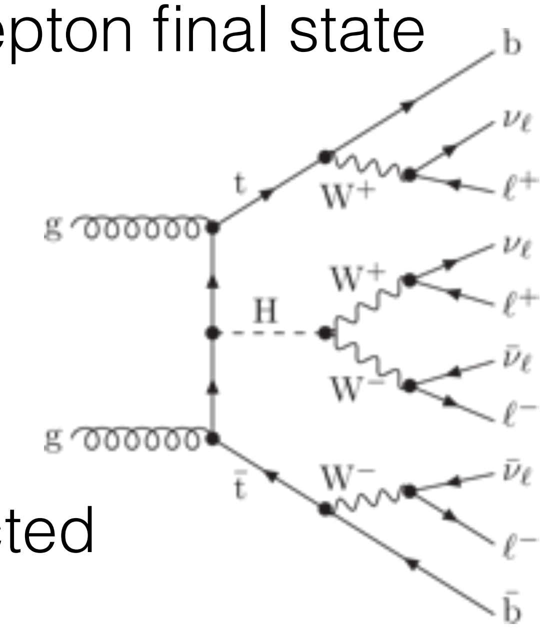
gg→ttH (H→bb)→WbWb bb→ lν lνbb, lνqqbb

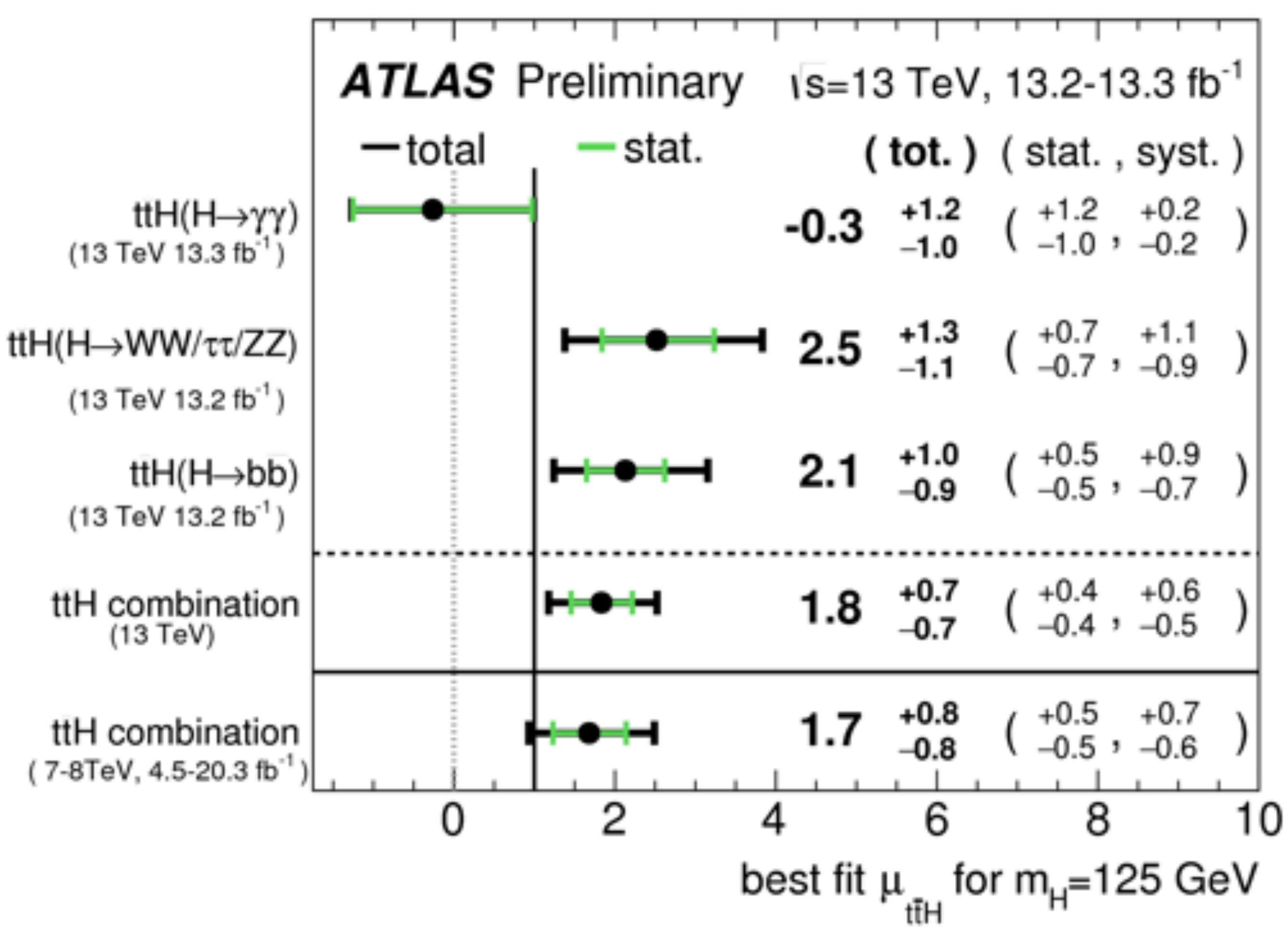
(H→γγ)→WbWb γγ→ lν lνγγ, lνqqγγ

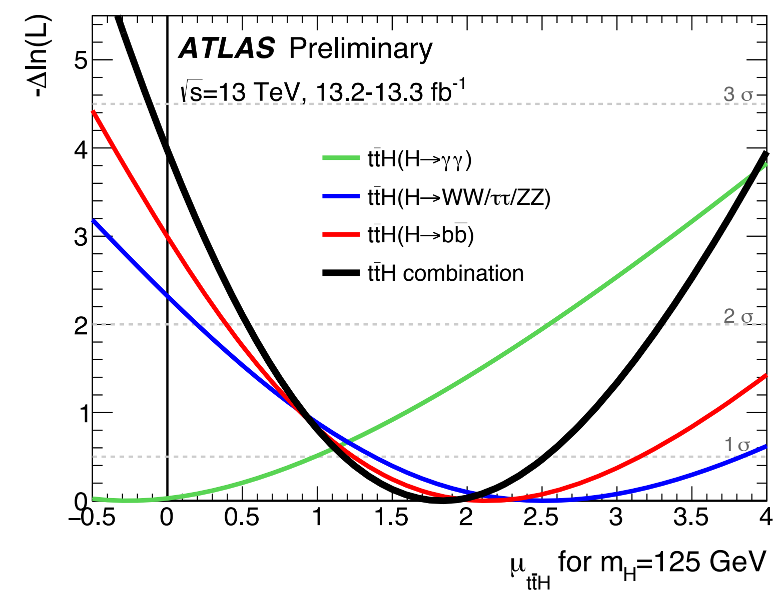
(H→WW/ZZ)→ multi-lepton

@Run-1 significance 2.33 σ observed, 1.53 expected

multi-lepton final state







Channel	Significance	
	Observed [σ]	Expected [σ]
$t\bar{t}H, H \to \gamma\gamma$	−0.2	0.9
$t\bar{t}H, H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H, H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

h→μμ 36 fb-1

arXiv:1705.54082
acc. by Phys. Rev. Lett.

- First probe of coupling to second generation fermions, very low branching fraction: Br(h→μμ) = 2.19×10^{-4}
- comparable to Br(h→ZZ→4l) but with a much larger background from $Z/\gamma^*\to\mu\mu$

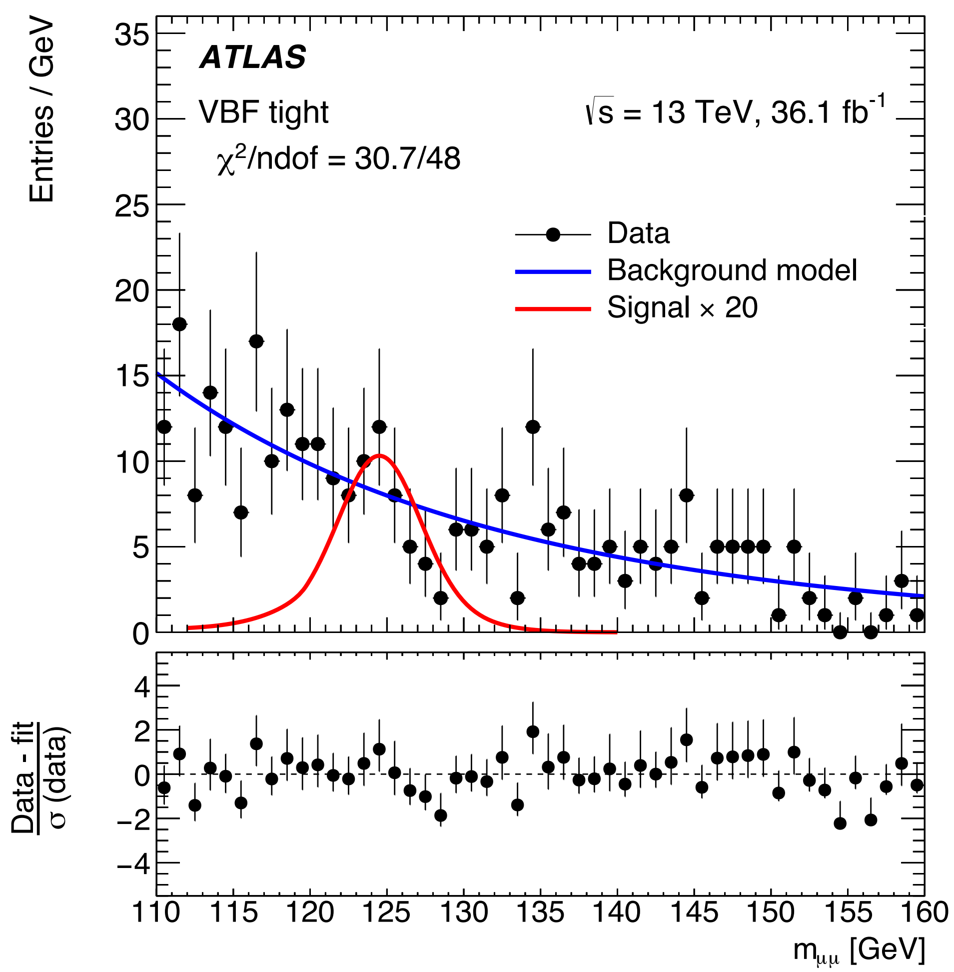
signal extraction through di-muon inv. mass fit to a signal peak plus a continuum exponentially falling background

$$P_S(m_{\mu\mu}) = f_{CB}\cdot CB(m_{\mu\mu}, m_{CB}, \sigma_{CB}, \alpha, n) + (1-f_{CB})\cdot GS\left(m_{\mu\mu}, m_{GS}, \sigma^S_{GS}\right)$$

$$P_B(m_{\mu\mu}) = f\cdot[BW(m_{BW}, \Gamma_{BW})\otimes GS(\sigma^B_{GS})](m_{\mu\mu}) + (1-f)\cdot e^{A\cdot m_{\mu\mu}}/m^3_{\mu\mu},$$

categorisation exploiting ggF Higgs p_T and VBF topologies

	S	B	$S/\sqrt{B}$	FWHM	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6 GeV	7885
Non-central low $p_T^{\mu\mu}$	32	38000	0.16	7.0 GeV	38777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7 GeV	6585
Non-central medium $p_T^{\mu\mu}$	66	31000	0.37	7.1 GeV	31291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3 GeV	3160
Non-central high $p_T^{\mu\mu}$	40	13000	0.35	7.7 GeV	12829
VBF loose	3.4	260	0.21	7.6 GeV	274
VBF tight	3.4	78	0.38	7.5 GeV	79



Run-2

$\mu_S = -0.1 \pm 1.5$

$\mu_S < 3.0$ 95% C.L.

Run-1 + Run-2

$\mu_S = -0.1 \pm 1.4$

$\mu_S < 2.8$ 95% C.L.

HL-LHC naive extrapolation

Δμ = 0.15

Difficult to observe it at Run-2, one of the strongest motivation for HL-LHC

hh-the last missing piece

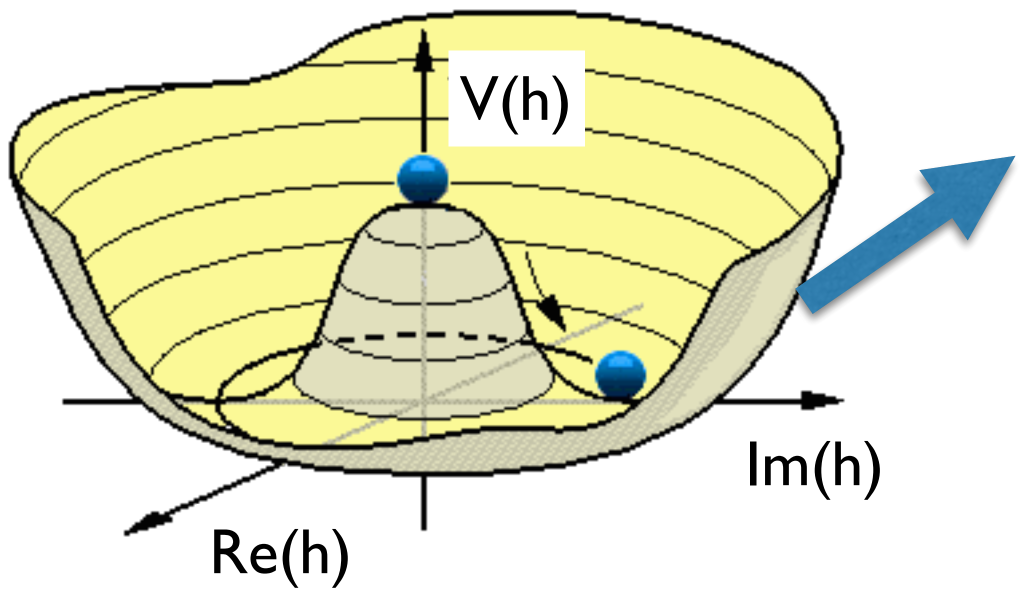
$$\mathcal{L} =$$
$$-\frac{1}{4g'^4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{\mu\nu a} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a}$$
$$+\bar{Q}_i i\not{D} Q_i + \bar{u}_i i\not{D} u_i + \bar{d}_i i\not{D} d_i + \bar{L}_i i\not{D} L_i + \bar{\ell}_i i\not{D} \ell_i$$
$$+\left(Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i \ell_j H + c.c.\right)$$
$$-\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H$$
$$\ldots W^{+\mu}W^-_\mu H - \frac{M_Z^2}{v}Z^\mu Z_\mu H + \ldots$$

UNKNOWN

The Higgs potential term is completely unmeasured.
It is the only potential term of the SM lagrangian and it is fundamental to determine the vacuum structure

The Higgs potential: how to probe it

$$V(h) = \mu^2 \frac{h^2}{2} + \lambda \frac{h^4}{4}$$



After spontaneous symmetry breaking

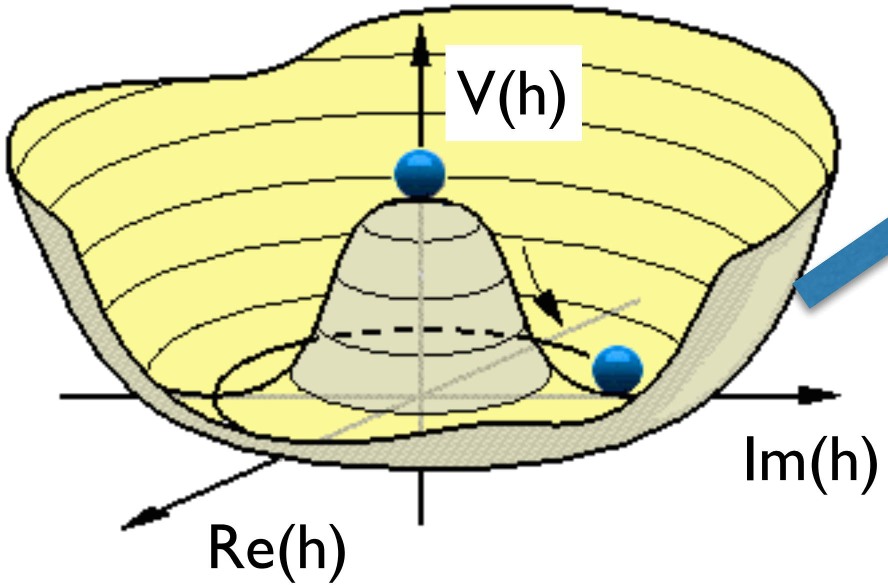
$$h_0 =< 0|\phi|0 >= \sqrt{\frac{-\mu^2}{\lambda}} \quad h = h_0 + \eta$$

$$\mu^2 \frac{\eta^2}{2} + \mu^2 \eta h_0 + \frac{\lambda}{4}\eta^4 + \lambda h_0 \eta^3 + \lambda \frac{3}{2} h_0^2 \eta^2 + \lambda h_0^3 \eta$$

replacing μ^2

$$\lambda h_0^2 \eta^2 + \frac{\lambda}{4}\eta^4 + \lambda h_0 \eta^3$$

$$V(h) = \mu^2 \frac{h^2}{2} + \lambda \frac{h^4}{4}$$



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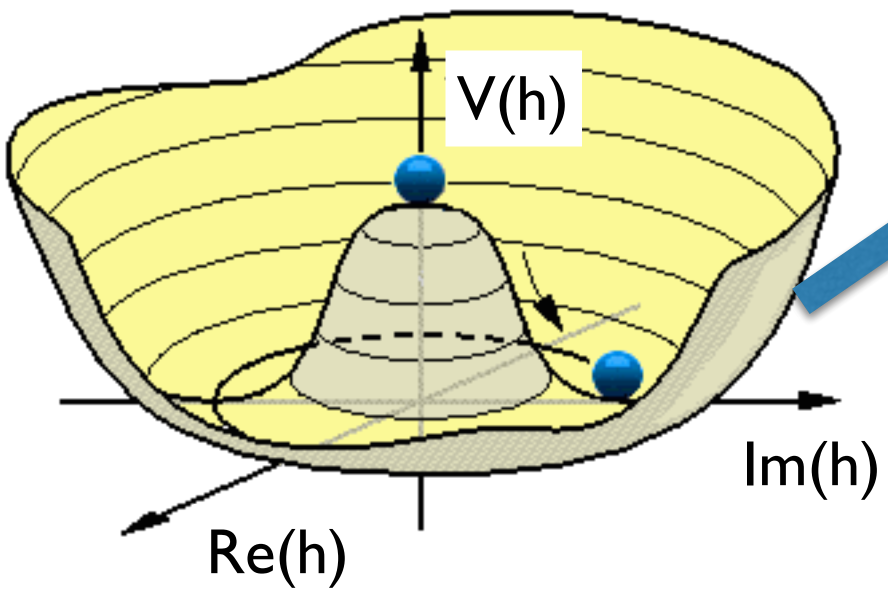
replacing μ^2

$$\lambda h_0^2 \eta^2 + \frac{\lambda}{4}\eta^4 + \lambda h_0 \eta^3$$

$$m_h^2 = 2\lambda h_0^2$$

The Higgs potential: how to probe it

$$V(h) = \mu^2 \frac{h^2}{2} + \lambda \frac{h^4}{4}$$



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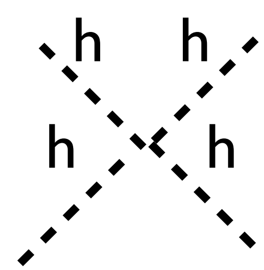
$$h_0 =< 0|\phi|0 >= \sqrt{\frac{-\mu^2}{\lambda}} \quad h = h_0 + \eta$$

$$\mu^2 \frac{\eta^2}{2} + \mu^2 \eta h_0 + \frac{\lambda}{4}\eta^4 + \lambda h_0 \eta^3 + \lambda \frac{3}{2} h_0^2 \eta^2 + \lambda h_0^3 \eta$$

replacing μ^2

$$\lambda h_0^2 \eta^2 + \frac{\lambda}{4}\eta^4 + \lambda h_0 \eta^3$$

$$m_h^2 = 2\lambda h_0^2$$



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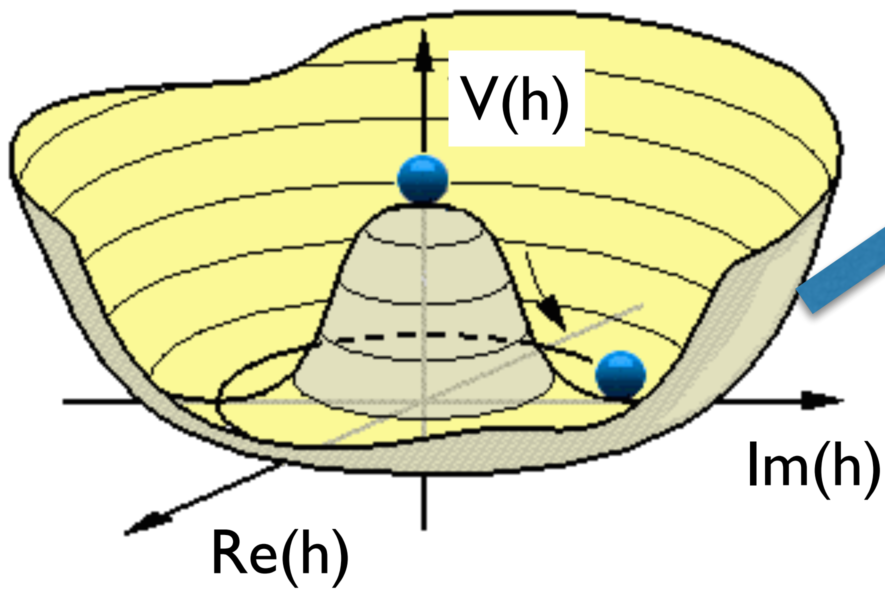


After spontaneous symmetry breaking

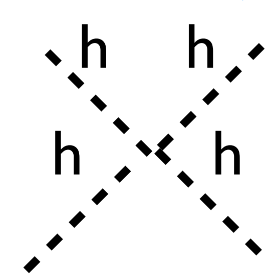
$$h_0 = <0|\phi|0> = \sqrt{\frac{-\mu^2}{\lambda}} \quad h = h_0 + \eta$$

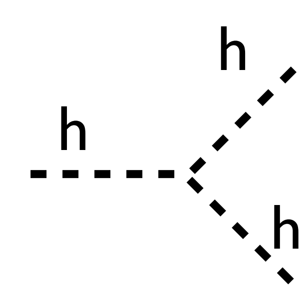
$$\mu^2 \frac{\eta^2}{2} + \mu^2 \eta h_0 + \frac{\lambda}{4}\eta^4 + \lambda h_0 \eta^3 + \lambda \frac{3}{2} h_0^2 \eta^2 + \lambda h_0^3 \eta$$

replacing μ^2

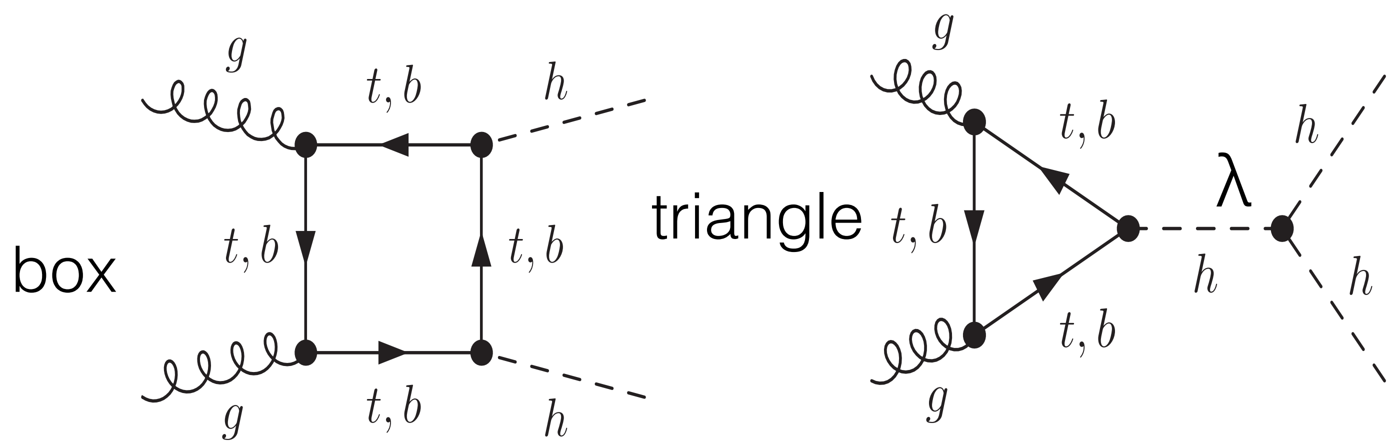
$$\lambda h_0^2 \eta^2 + \frac{\lambda}{4}\eta^4 + \lambda h_0 \eta^3$$

$$m_h^2 = 2\lambda h_0^2$$

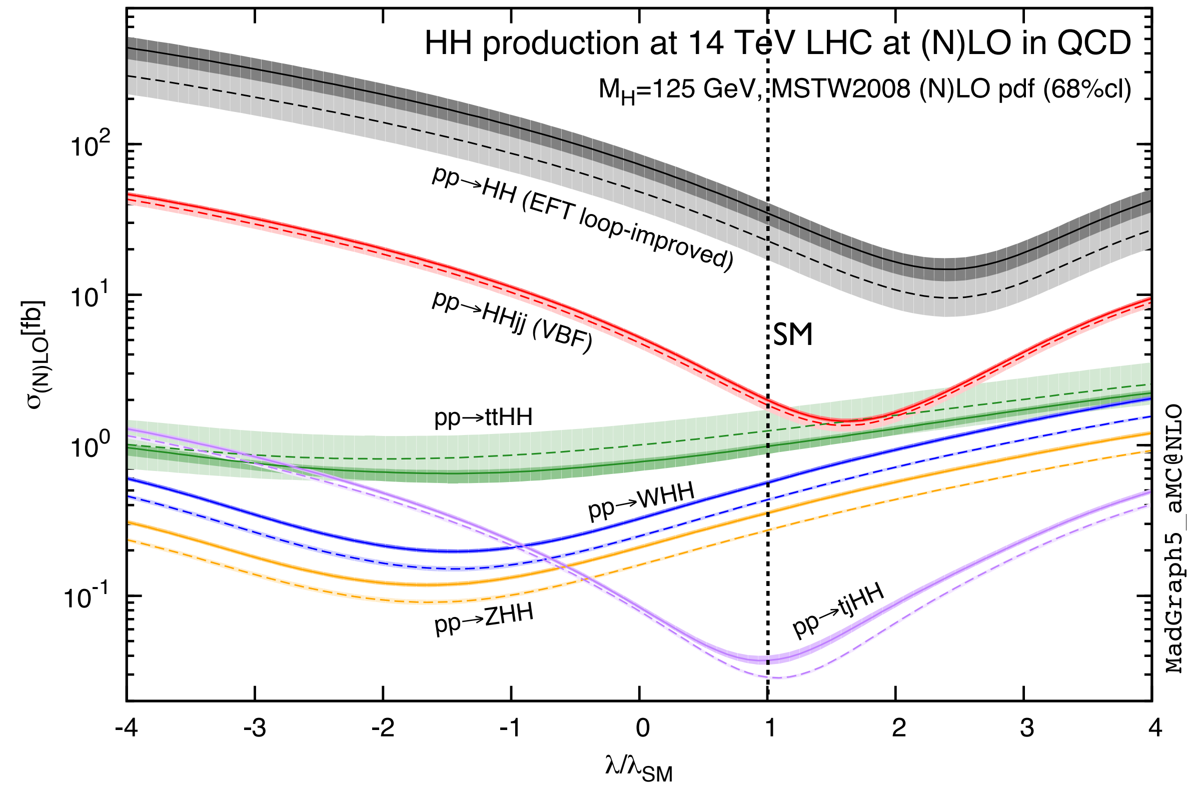




Standard Model



Negative interference between box and triangle reduces further the production cross section

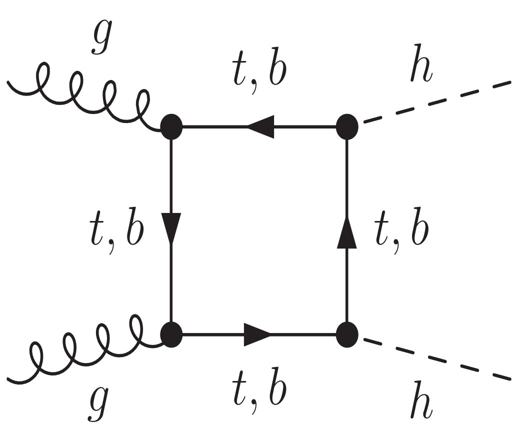


$$\sigma(pp \to hh) = 33.45^{+4.3\%}_{-6.0\%}\,(\text{scale}) \pm 5\%\,(\text{Th.}) \pm 2.3\%(\alpha_s) \pm 2.1\%\,(\text{PDF})\,\text{fb}$$

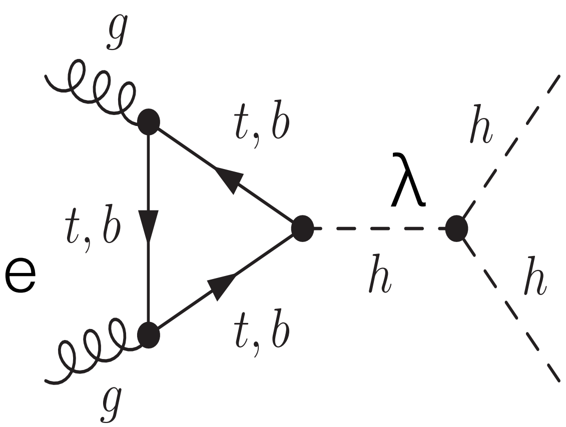
hh production

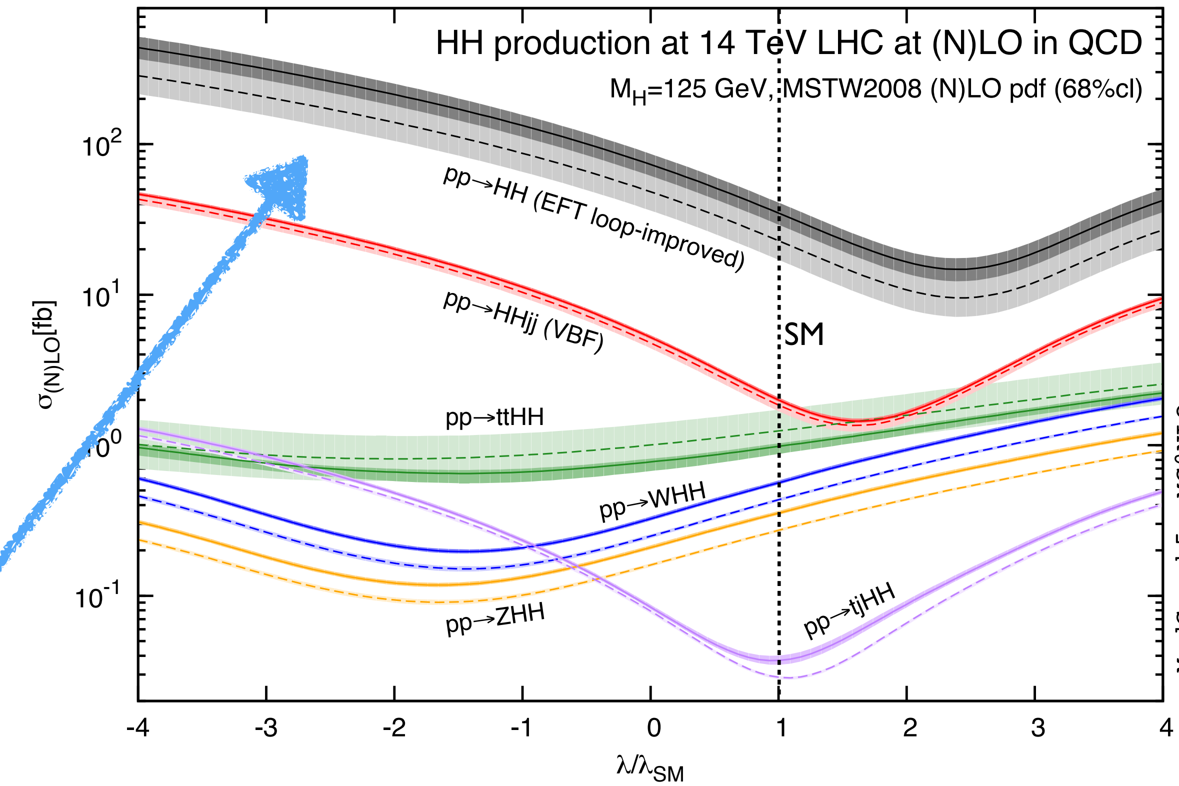
Standard Model

box



triangle





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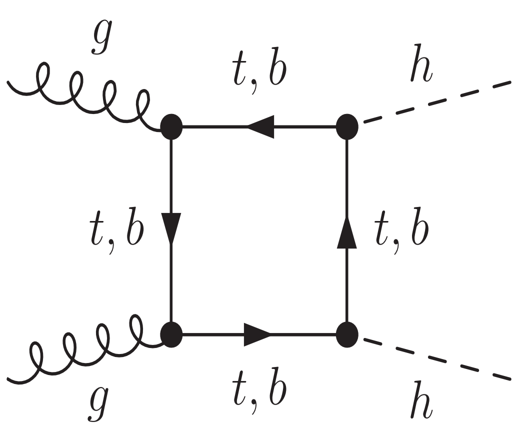
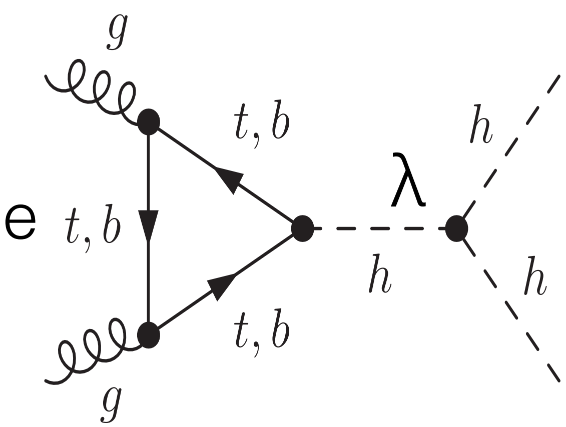
huge cross section enhancement is allowed even in the non resonant case, it makes sense to measure hh cross section at Run-2

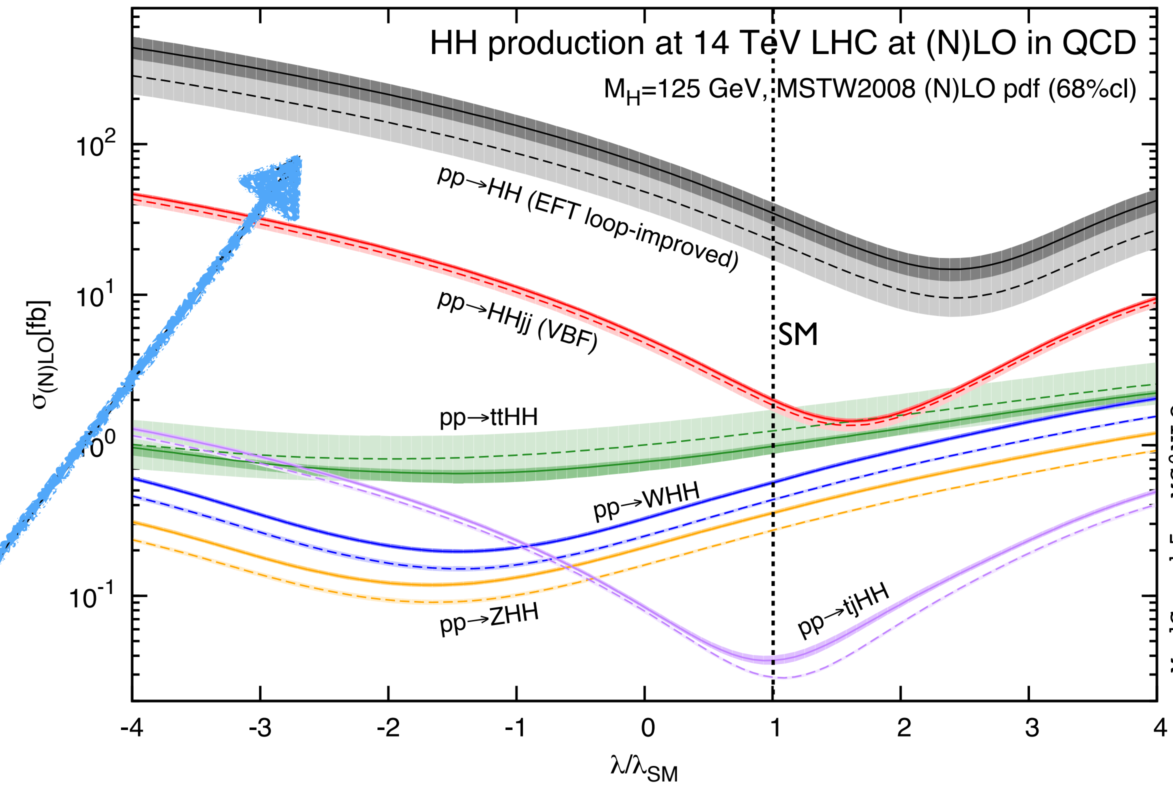
Standard Model

box



triangle





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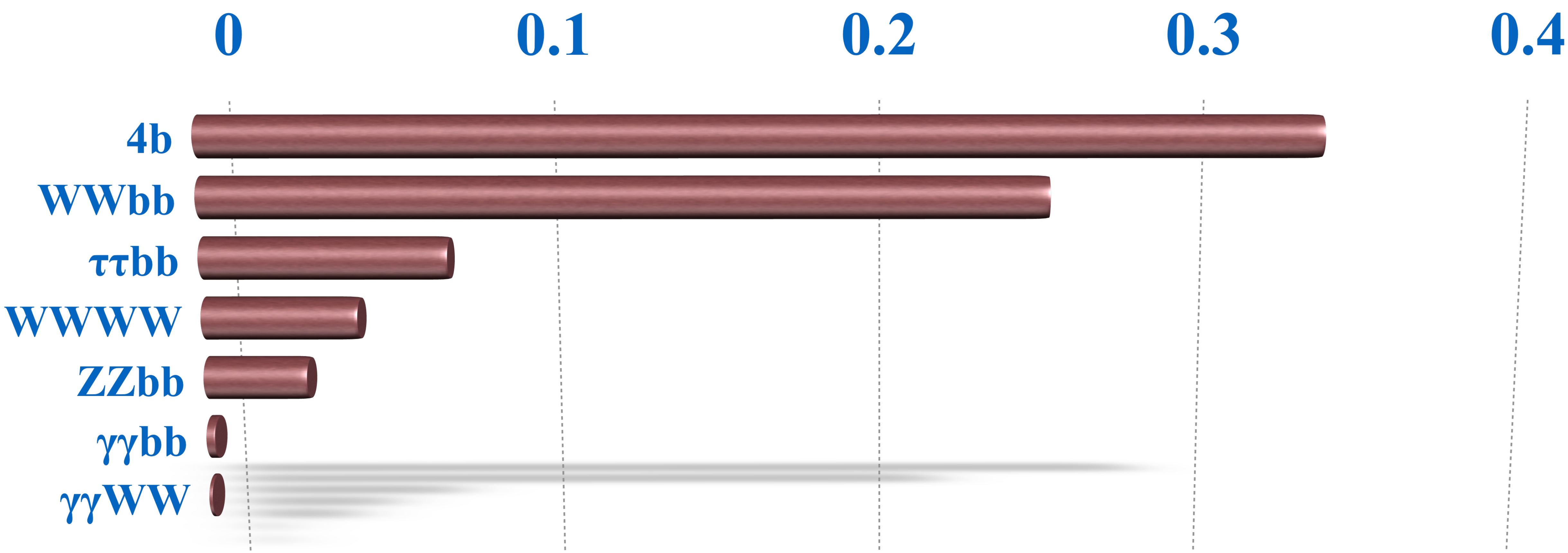
huge cross section enhancement is allowed even in the non resonant case, it makes sense to measure hh cross section at Run-2

The only available constraints are from Higgs couplings [arXiv:1607.04251]

$$\frac{\lambda}{\lambda_{SM}} = -0.24^{+11.21}_{-5.65}$$

di-higgs branching fractions

Higgs decay branching fraction

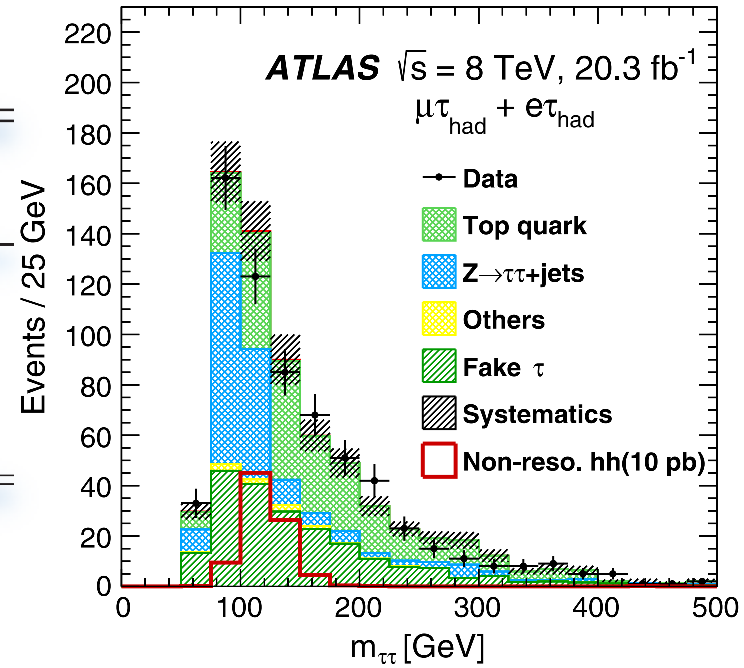


1. many decay modes, signal yield divided among many rivers;
2. typically higher S/B channel have lower signal yield;
3. need to exploit all possible decay topologies and combine them to boost the sensitivity

hh Run-1 results

Phys. Rev. D 92, 092004

hh Final state	Nonresonant search Categories	Discriminant
$\gamma\gamma b\bar{b}$	1	$m_{\gamma\gamma}$
$\gamma\gamma WW^*$	1	event yields
$b\bar{b}\tau\tau$	4	$m_{\tau\tau}$
$b\bar{b}b\bar{b}$	1	event yields



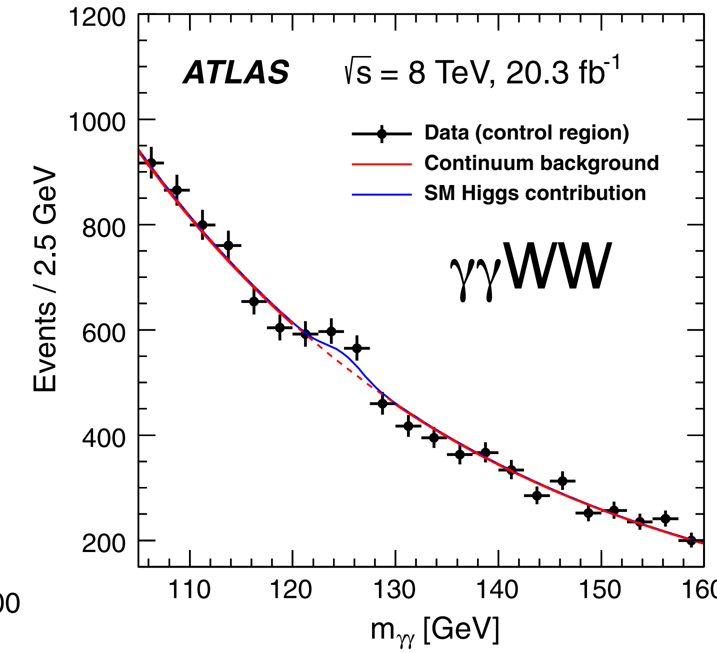


TABLE IV. The expected and observed 95% C.L. upper limits on the cross sections of nonresonant $gg \to hh$ production at $\sqrt{s} = 8$ TeV from individual analyses and their combinations. SM values are assumed for the h decay branching ratios. The cross-section limits normalized to the SM value are also included.

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

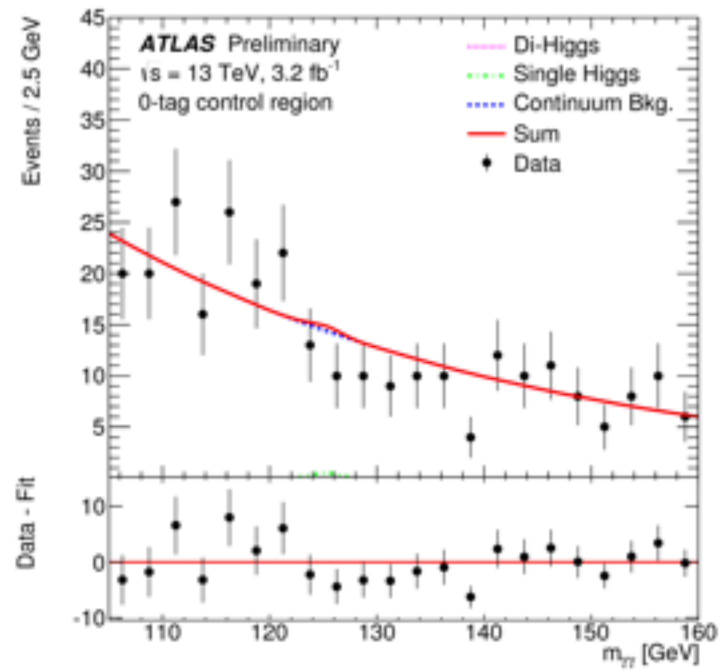
excess in Run-1

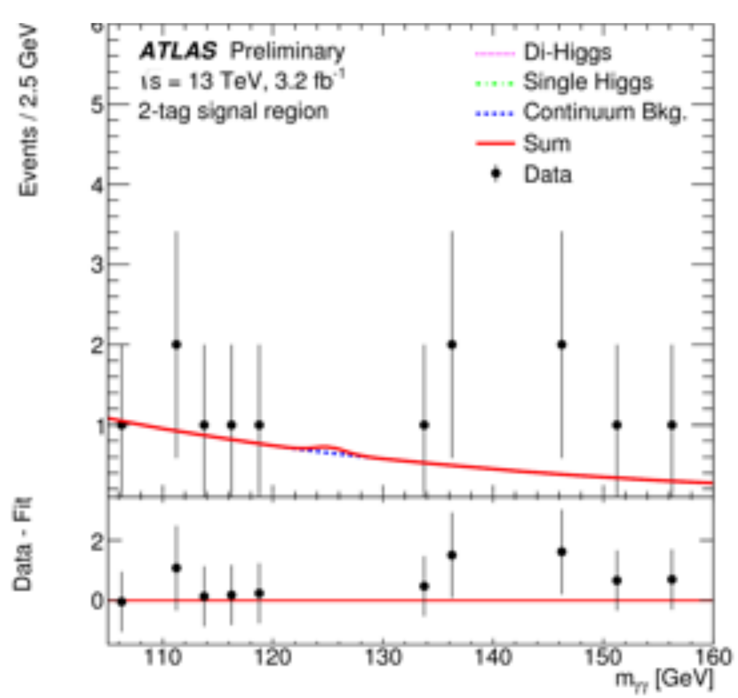
most sensitive in Run-1

interesting sensitivity in Run-1 already

hh Run-2 updates, γγ channels

hh→bbγγ

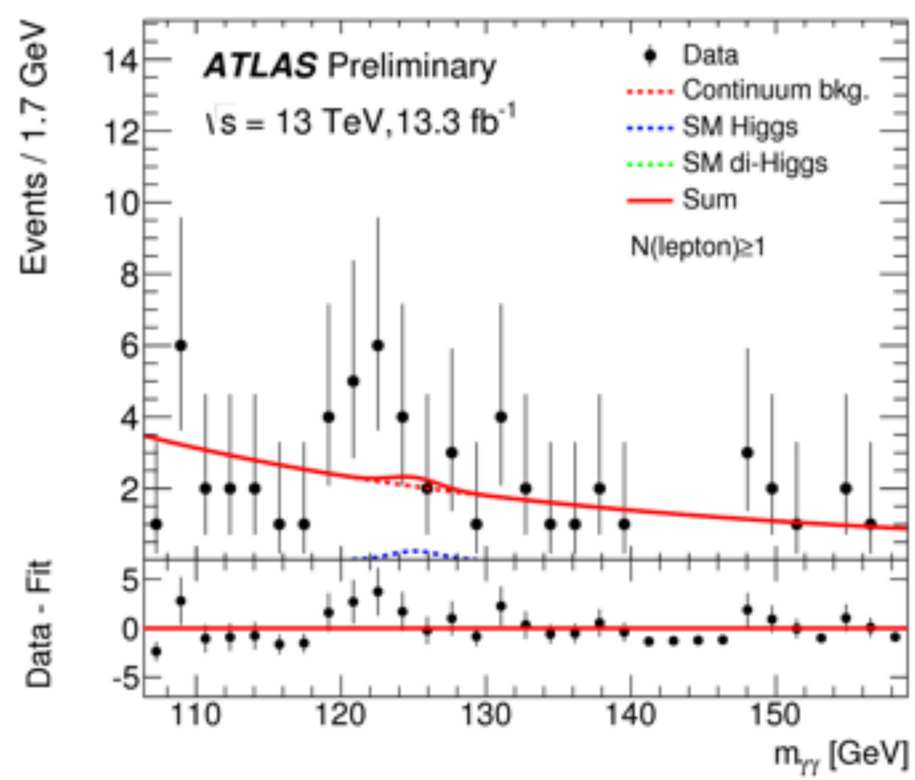




$$\sigma(pp \to hh) < 3.9\,\text{pb}$$
$$\sigma(pp \to hh) < 116 \times \sigma_{\text{SM}}$$

hh→WW(→lνjj)γγ

Process	Number of events	
Continuum background	7.26	±1.23
SM single-Higgs	0.616	±0.115
SM di-Higgs	0.0187	±0.002 24
Observed		15



$$\sigma(pp \to hh) < 25\,\text{pb}\,(15\,\text{exp})$$
$$\sigma(pp \to hh) < 743\,\sigma_{\text{SM}}(446\,\text{exp.})$$

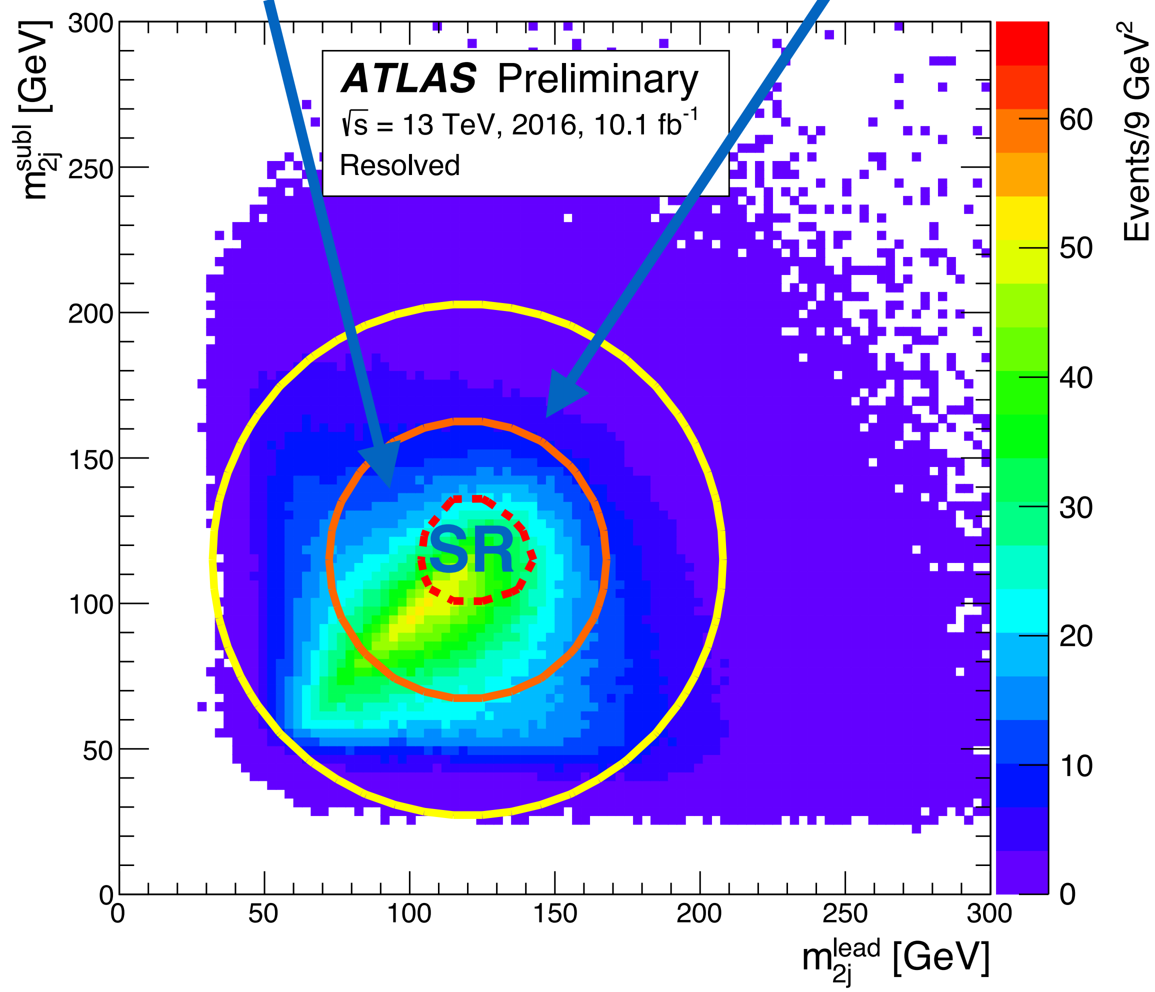
ATLAS-CONF-2016-071
ATLAS-CONF-2016-004

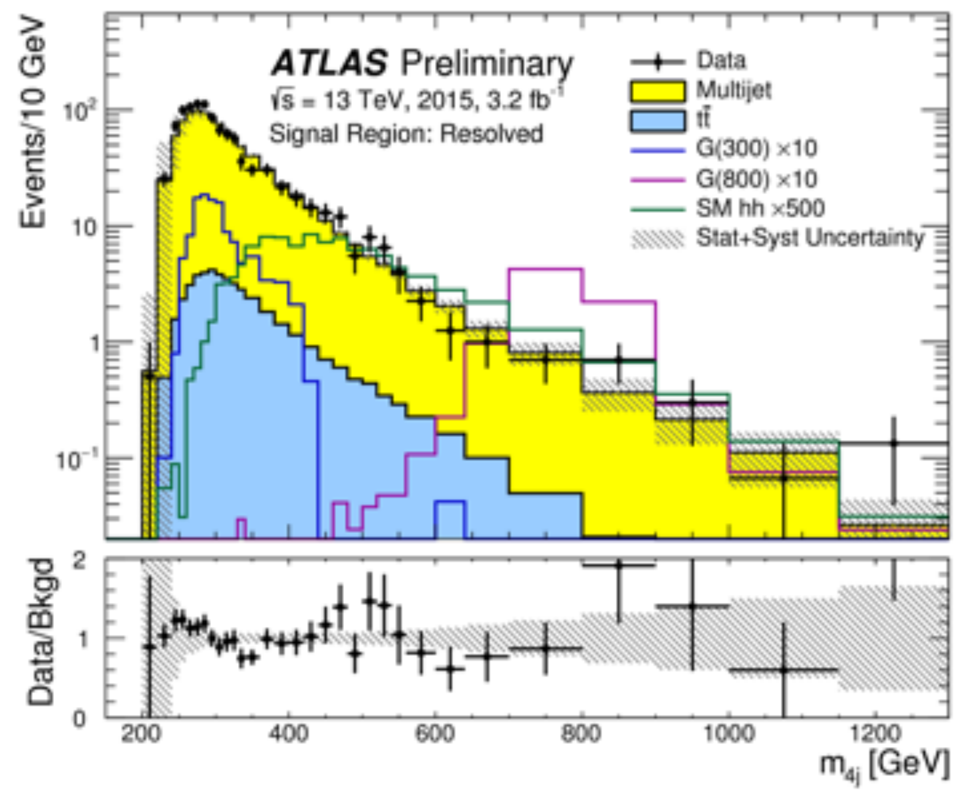
- similar strategy for both channels, after a topological selection, look for γγ mass peak on a smoothly falling background
- excess in bbγγ not confirmed, still excess in WWγγ
- updates on 2015+2016 statistics expected this summer

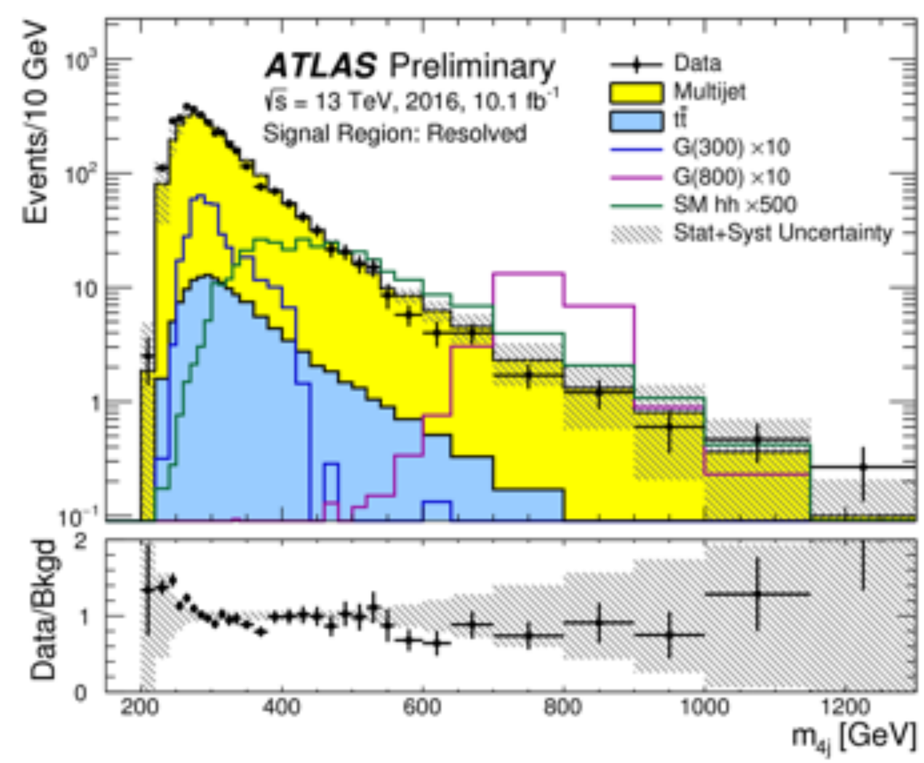
hh→4b run-2 updates

ATLAS-CONF-2016-049

- main background: multi-jet background
- background estimated from side-band region and validated in CR







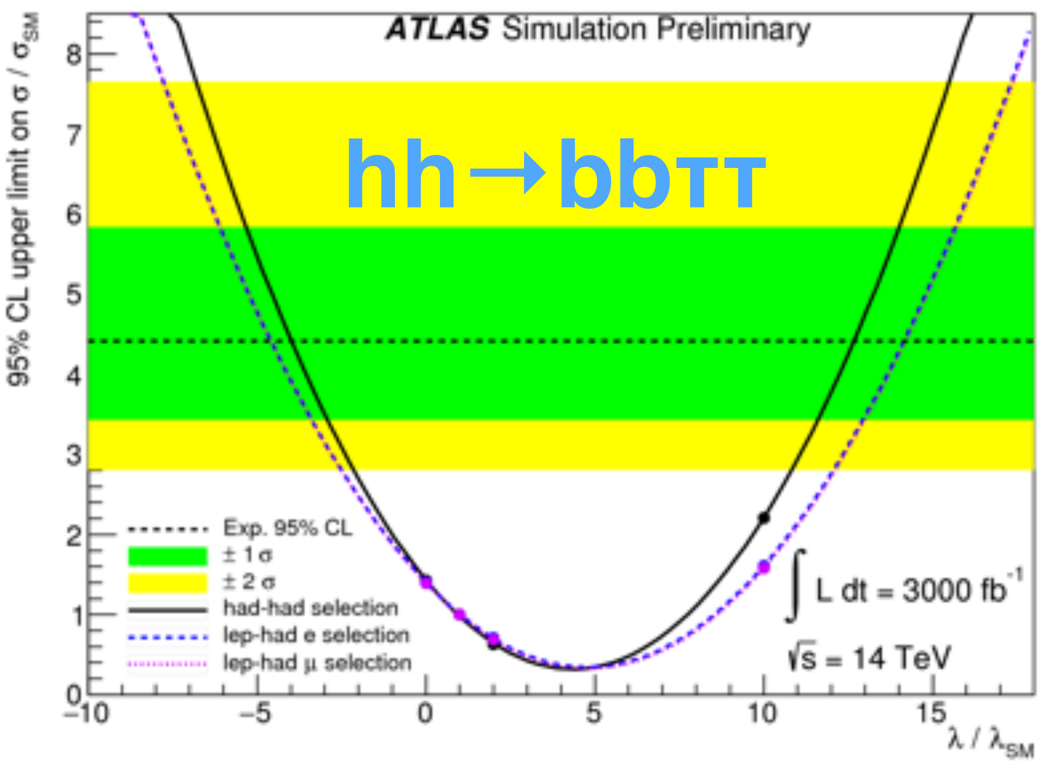
- use of multi-jet triggers with b-tagging at HLT
- main discriminant m_{hh}

$$\sigma(pp \to hh) \times Br(hh \to 4b) < 330\,\text{fb}$$
$$< 29 \times \sigma_{\text{SM}}$$

hh prospects @HL-LHC

ATL-PHYS-PUB-2017-001, ATL-PHYS-PUB-2016-024, ATL-PHYS-PUB-2015-046

σ / σ_{SM} as a function of λ / λ_{SM}



Study performed assuming flat acceptance as a function of λ

HL-LHC $\sqrt{s}$ = 14 TeV, L = 3000 fb^{-1}	Exp. sign	λ/λ_{SM} 95% C.L.	exp σ/σ_{SM}
ATLAS: $bb\gamma\gamma$	1.05 σ	[-0.8, 7.7]	< 1.7 [recalc.]
ATLAS: 4b		$[0.2, 7.0]_{stat.}$, [-3.5, 11]	< $1.5_{stat.}$, 5.2
ATLAS: $bb\tau\tau$	0.6 σ	[-4, 12]	< 4.3

1. The most sensitive channel alone are not able to claim evidence of hh production, their sensitivity to the Higgs self-coupling is also very mild

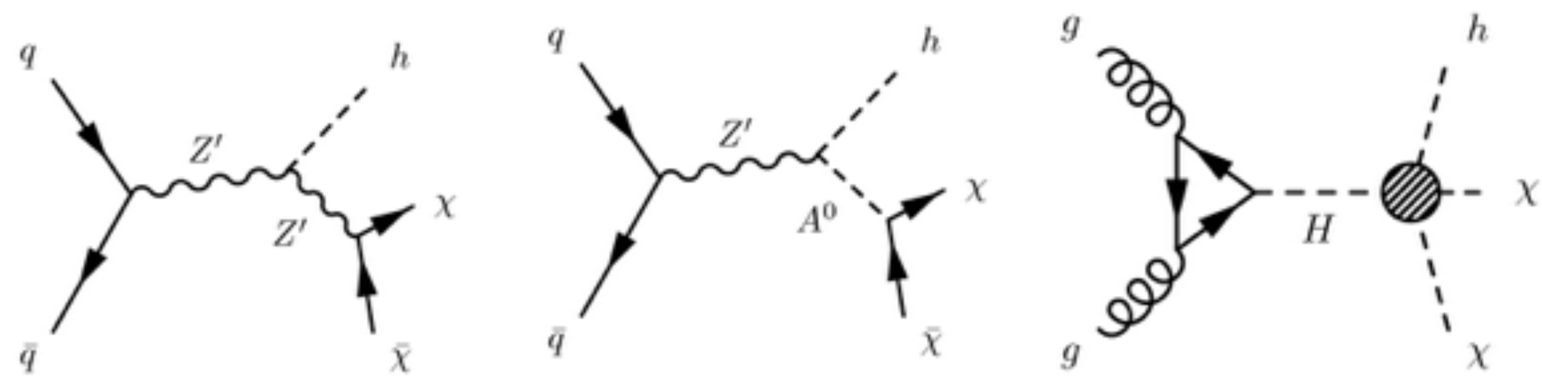
2. It is important to push the analysis techniques as much as possible forward now, to make possible an observation of this channel at HL-LHC

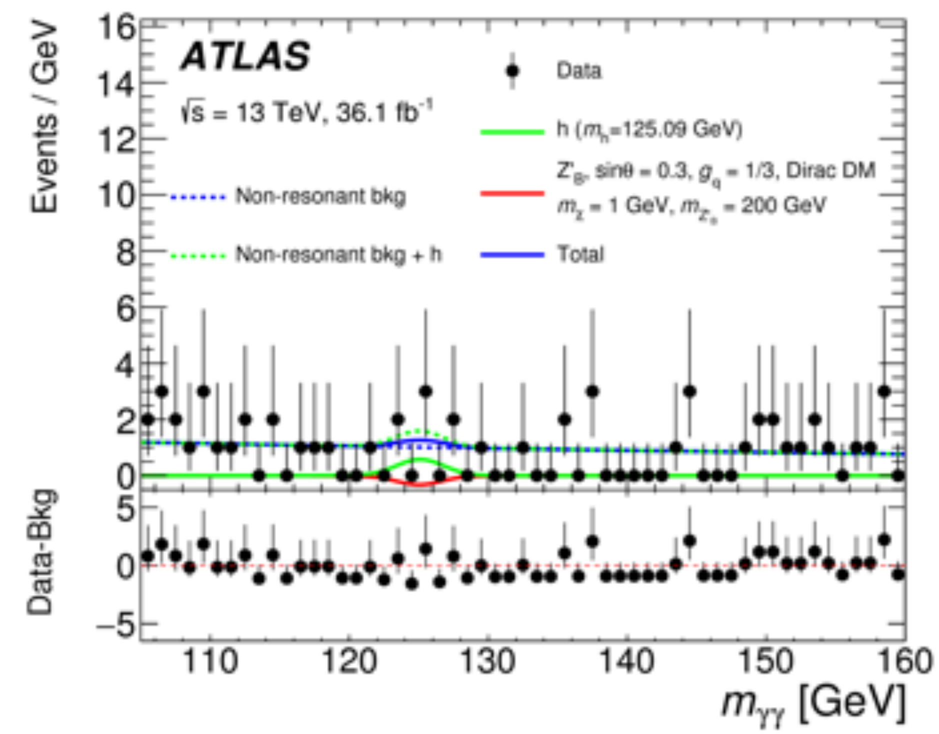
Exotic searches

- The Higgs boson is moving from object to search, to object to study, but it is also a tool for discovery.
- many searches are performed where the Higgs boson is among the final state particles
- here we select only the most recent results

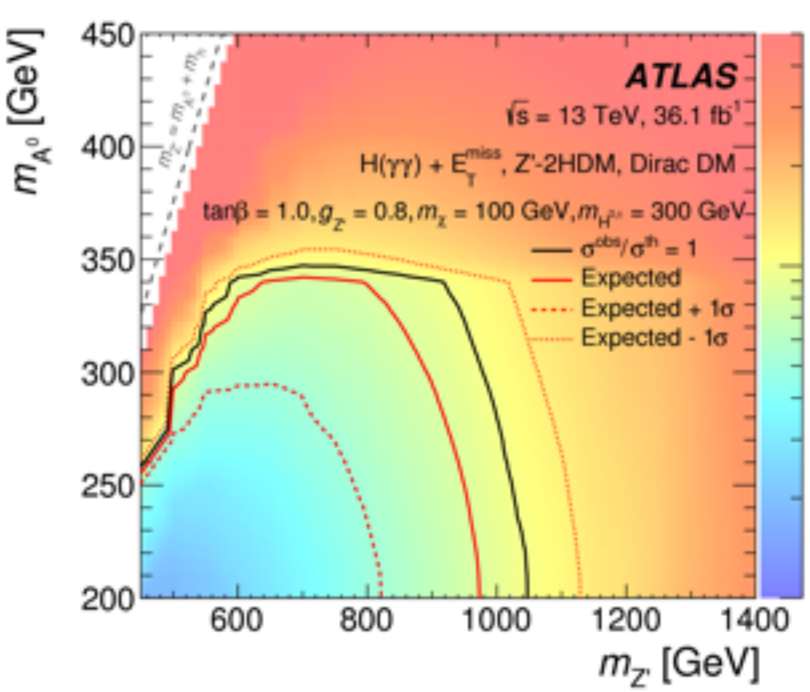
h-DM, h→γγ search

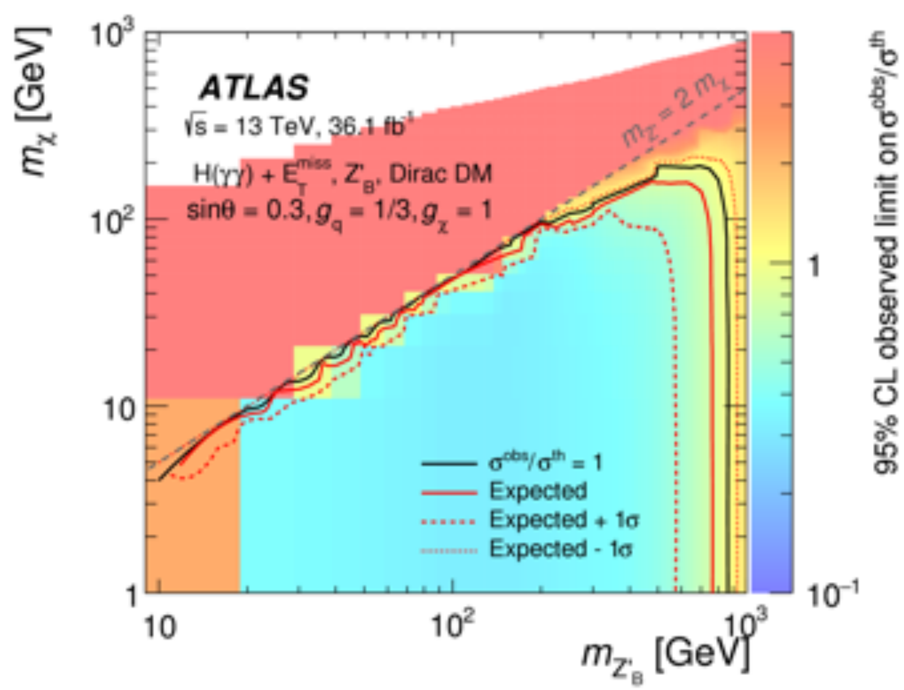
arXiv:1706.03948
sub. to Phys. Rev. D

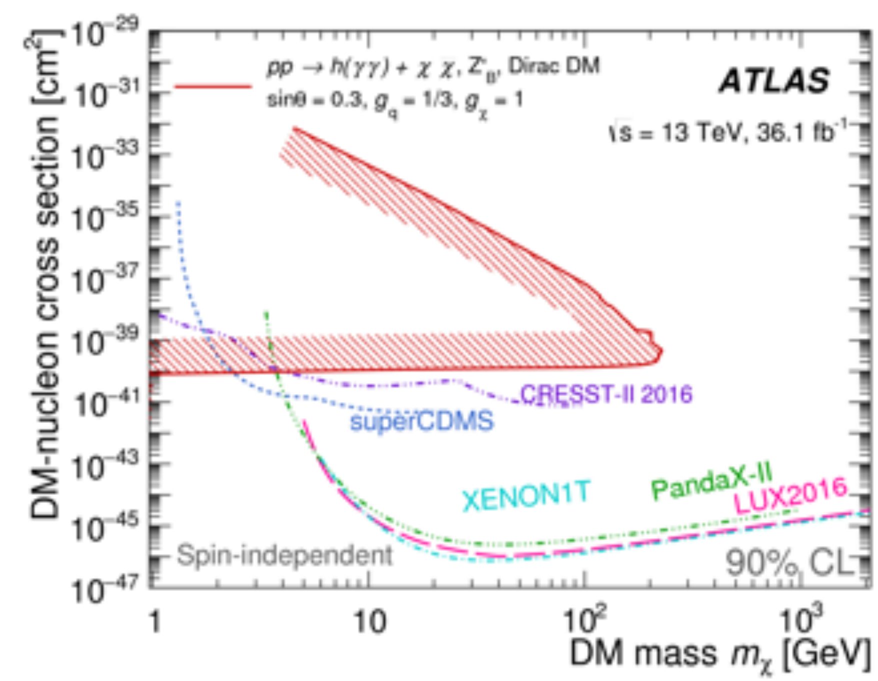




Category	Requirements
Mono-Higgs	$S_{E_T^{miss}} > 7\ \sqrt{\text{GeV}}$, $p_T^{\gamma\gamma} > 90$ GeV, lepton veto
High-E_T^{miss}	$S_{E_T^{miss}} > 5.5\ \sqrt{\text{GeV}}$, $\lvert z_{PV}^{highest} - z_{PV}^{\gamma\gamma}\rvert < 0.1$ mm
Intermediate-E_T^{miss}	$S_{E_T^{miss}} > 4\ \sqrt{\text{GeV}}$, $p_T^{hard} > 40$ GeV, $\lvert z_{PV}^{highest} - z_{PV}^{\gamma\gamma}\rvert < 0.1$ mm
Different-Vertex	$S_{E_T^{miss}} > 4\ \sqrt{\text{GeV}}$, $p_T^{hard} > 40$ GeV, $\lvert z_{PV}^{highest} - z_{PV}^{\gamma\gamma}\rvert > 0.1$ mm
Rest	$p_T^{\gamma\gamma} > 15$ GeV

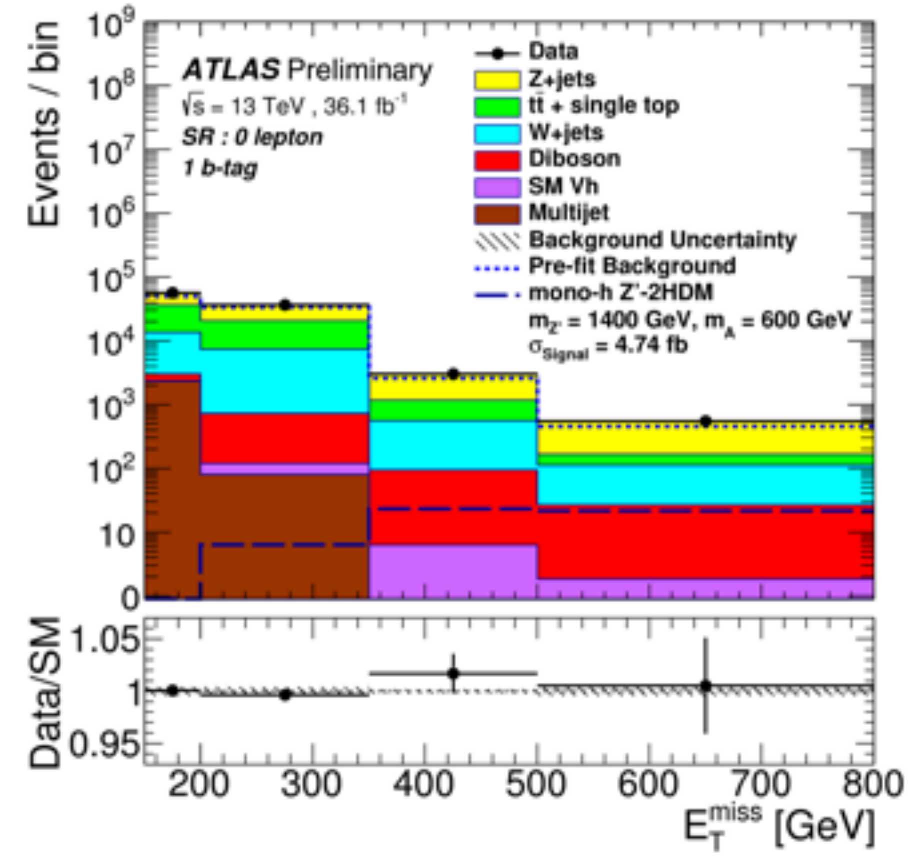


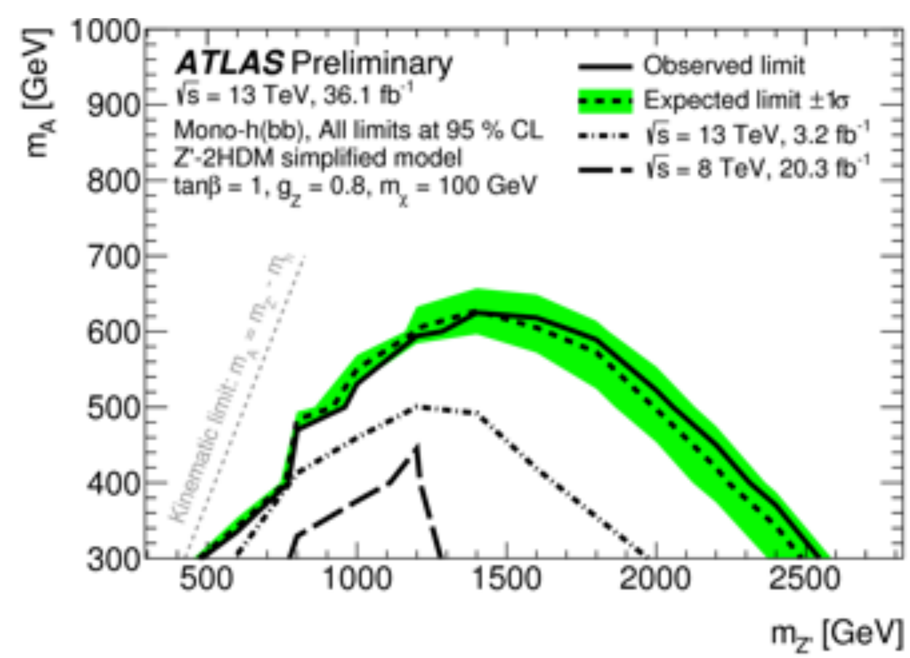




CR defined to normalise tt$_{bar}$, W+HF and Z+HF

Region	SR	1μ-CR	2ℓ-CR
Trigger	E_T^{miss}	E_T^{miss}	Single lepton
Leptons	No e or μ	Exactly one μ	Exactly two e or μ 83 GeV $< m_{ee} <$ 99 GeV 71 GeV $< m_{\mu^\pm\mu^\mp} <$ 106 GeV
Resolved	$E_T^{miss} \in [150, 500]$ GeV	$p_T(\mu, E_T^{miss}) \in [150, 500]$ GeV	$p_T(\ell, \ell) \in [150, 500]$ GeV
	$p_T^{miss} > 30$ GeV (1 b-tag only)	$p_T(\mu, p_T^{miss}) > 30$ GeV	–
	$\min\left[\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{jet}\right)\right] > \pi/9$	$\min\left[\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{jet}\right)\right] > \pi/9$	–
	$\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss}\right) < \pi/2$	$\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss}\right) < \pi/2$	–
	–	–	$E_T^{miss} \times \left(\sum_{jets,leptons} p_T\right)^{-1/2} < 3.5$ GeV$^{1/2}$
	Number of central small-R jets ≥ 2 Leading Higgs candidate small-R jet $p_T > 45$ GeV $H_{T,2\,jets} > 120$ GeV for 2 jets, $H_{T,3\,jets} > 150$ GeV for > 2 jets $\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_{T,h}\right) > 2\pi/3$ Veto on τ-leptons $\Delta R\left(\vec{p}_h^{\,jet\,1}, \vec{p}_h^{\,jet\,2}\right) < 1.8$ Veto on events with > 2 b-tags Sum of p_T of two Higgs candidate jets and leading extra jet $> 0.63 \times H_{T,all\,jets}$ b-tagging : one or two small-R calorimeter jets **Final discriminant = Dijet mass**		
Merged	$E_T^{miss} > 500$ GeV	$p_T(\mu, E_T^{miss}) > 500$ GeV	$p_T(\ell, \ell) > 500$ GeV
	$p_T^{miss} > 30$ GeV	$p_T(\mu, p_T^{miss}) > 30$ GeV	–
	$\min\left[\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{jet}\right)\right] > \pi/9$	$\min\left[\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{jet}\right)\right] > \pi/9$	–
	$\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss}\right) < \pi/2$	$\Delta\phi\left(\vec{E}_T^{miss}, \vec{p}_T^{miss}\right) < \pi/2$	–
	Number of large-R jets ≥ 1 Veto on τ-lepton not associated to large-R jet Veto on b-jets not associated to large-R jet H_T-ratio selection (<0.57) b-tagging : one or two ID track jets matched to large-R jet **Final discriminant = Large-R jet mass**		





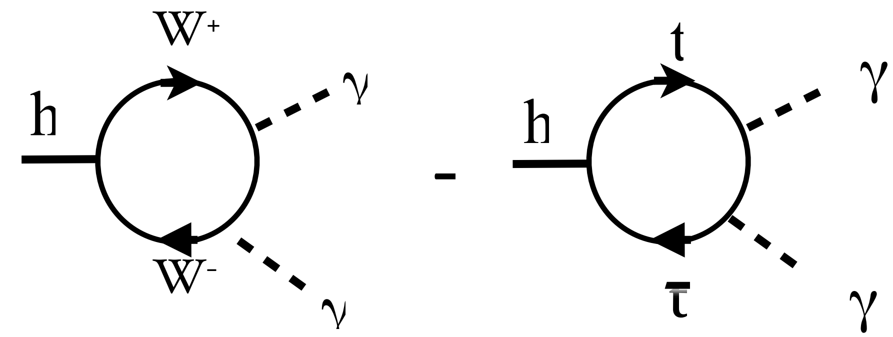
Higgs shopping list for the future

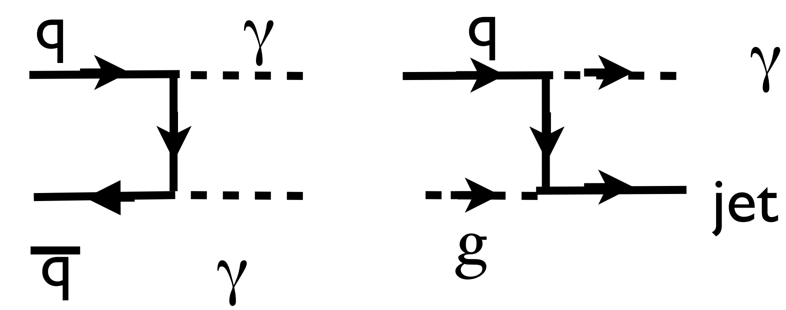
1) The Higgs boson from particle to tool for discovery
2) look for evidence of all its couplings as predicted by SM (they are all SM fundamental parameters, practically without theoretical constraints)
3) discover the last piece of SM, the Higgs potential through hh production
4) look for unexpected: i.e. Higgs coupled dark-matter through Higgs portal models
5) more and more accuracy with the coming data at Run-2

Спасибо!

Higgs at Run-1 single channel observation

- The Higgs boson couples at tree-level only with massive particles
- decay to $\gamma\gamma$ mediated by loop of massive charged particles (W,t)
- background dominated by non-resonant $\gamma\gamma$ production and γ–jet with a jet faking a photon
- event sample divided in sub-categories to exploit optimal S/B ratio and different production modes: ggF, VBF, W,Zh, tth
- use of p_{Tt} variable to further separate signal from non resonant background





	ggF		VBF		WH		ZH		$t\bar{t}H$		$b\bar{b}H$		$tHbj$		tHW		
Category	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	$\epsilon(\%)$	$f(\%)$	N_S
Central-low p_{Tt}	14.1	92.3	7.5	4.0	6.5	1.5	7.2	1.0	2.9	0.1	14.1	1.0	...	...	...	...	135.5
Central-high p_{Tt}	0.9	73.3	2.5	15.7	1.9	5.5	2.0	3.4	2.4	1.3	0.9	0.8	...	...	...	...	11.3
Forward-low p_{Tt}	21.6	91.7	11.9	4.1	12.3	1.9	13.0	1.2	3.8	0.1	21.6	1.0	...	...	...	...	208.6
Forward-high p_{Tt}	1.3	71.9	3.6	16.2	3.2	6.4	3.3	3.9	2.5	0.9	1.3	0.8	...	...	...	...	16.1
VBF loose	0.4	41.9	7.2	56.5	0.2	0.6	0.2	0.4	0.2	0.1	0.4	0.4	...	...	...	...	9.3
VBF tight	0.1	19.0	6.4	80.5	< 0.1	0.2	< 0.1	0.1	0.1	0.1	0.1	0.2	...	...	...	...	5.7
VH hadronic	0.2	45.9	0.1	3.2	3.0	30.3	3.1	18.8	0.7	1.3	0.2	0.5	...	...	...	...	3.2
VH E_T^{miss}	< 0.1	2.3	< 0.1	0.3	1.3	36.9	3.0	51.0	1.8	9.5	< 0.1	< 0.1	...	...	...	...	1.1
VH one-lepton	< 0.1	0.5	< 0.1	0.2	4.8	89.8	0.6	6.3	1.0	3.3	< 0.1	< 0.1	...	...	...	...	1.7
VH dilepton	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	1.3	99.1	< 0.1	0.9	< 0.1	< 0.1	...	...	...	...	0.3
$t\bar{t}H$ hadronic	< 0.1	7.3	< 0.1	1.0	< 0.1	0.7	< 0.1	1.3	6.9	84.1	< 0.1	< 0.1	2.1	3.4	4.8	2.1	0.5
$t\bar{t}H$ leptonic	< 0.1	1.0	< 0.1	0.2	0.1	8.1	0.1	2.3	7.9	80.3	< 0.1	< 0.1	4.1	5.5	7.1	2.6	0.6
Total efficiency (%)	38.7	...	39.1	...	33.3	...	33.8	...	30.2	...	38.7	...					38.5%
Events	342.8		28.4		10.7		6.4		1.8		3.6		< 0.1		< 0.1		393.8

h→ZZ→4l @Run1 1/2

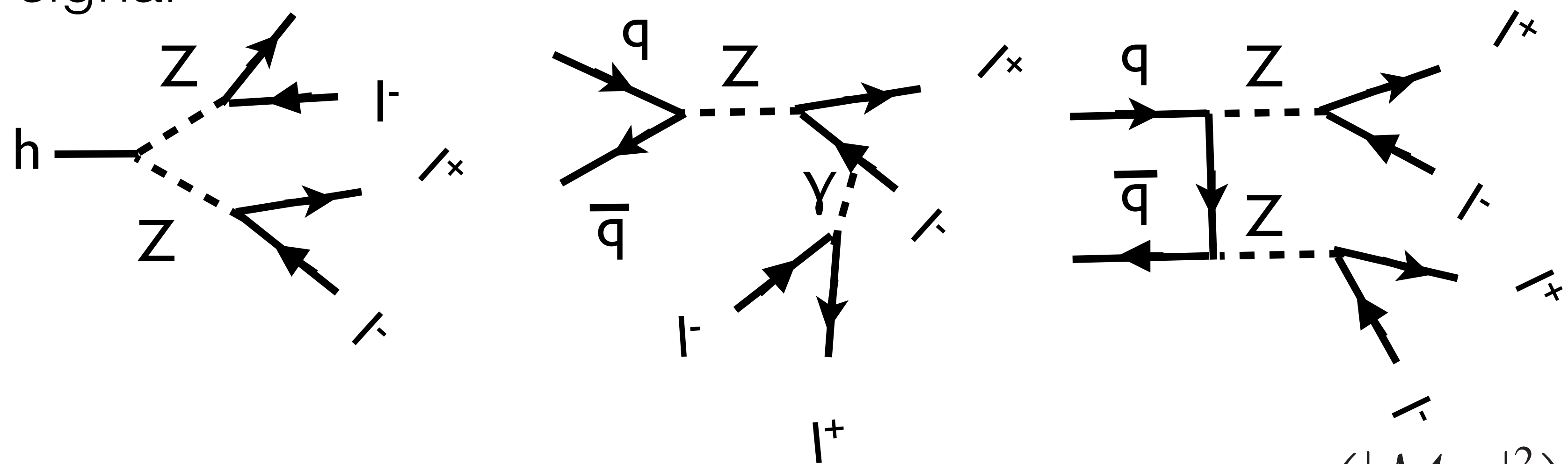
Event categorisation

BDT used to separate h signal from ZZ^* background, and VBF, VH from ggF

$H \to ZZ^* \to 4l$

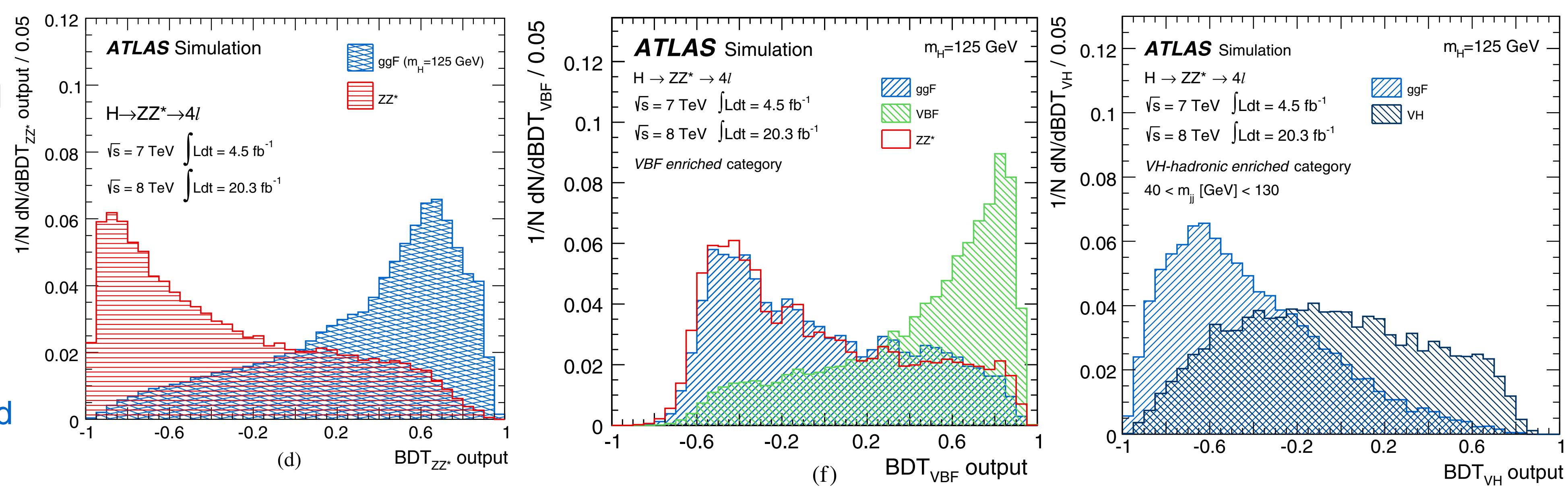
4l selection
↓
High mass two jets — VBF — VBF enriched
↓
Low mass two jets — W(→ jj)H, Z(→ jj)H — VH enriched
↓
Additional lepton — W(→ $l\nu$)H, Z(→ ll)H — VH enriched
↓
ggF — ggF enriched

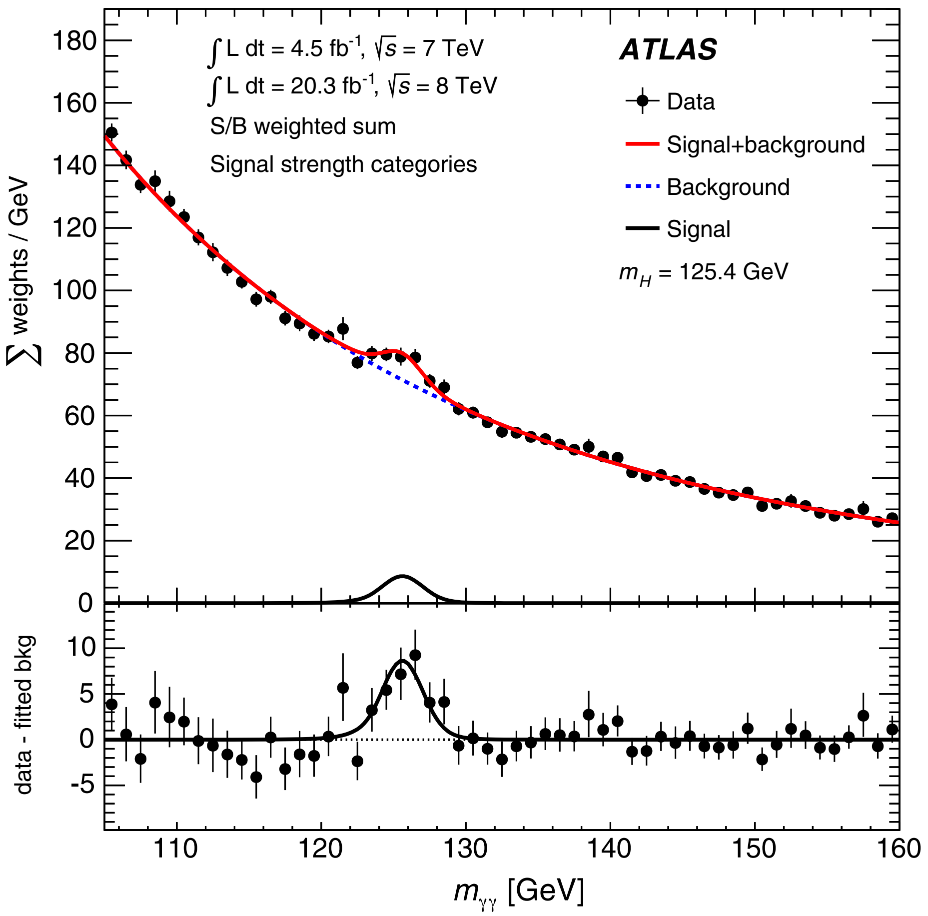
signal | double resonant | continuum.



BDT exploits the spin-0 angular structure of the signal respect to the background: p_T^{4l}, η^{4l}, $D_{ZZ'}$

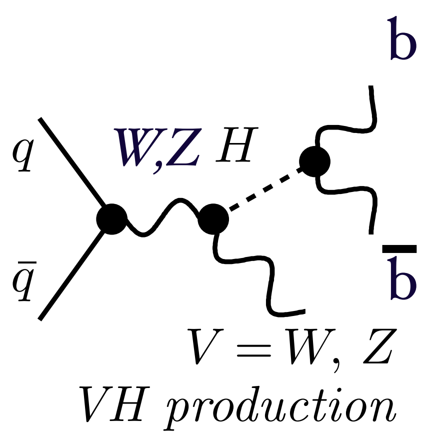
$$D_{ZZ^*} = \ln\left(\frac{|\mathcal{M}_{sig}|^2}{|\mathcal{M}_{ZZ}|^2}\right)$$

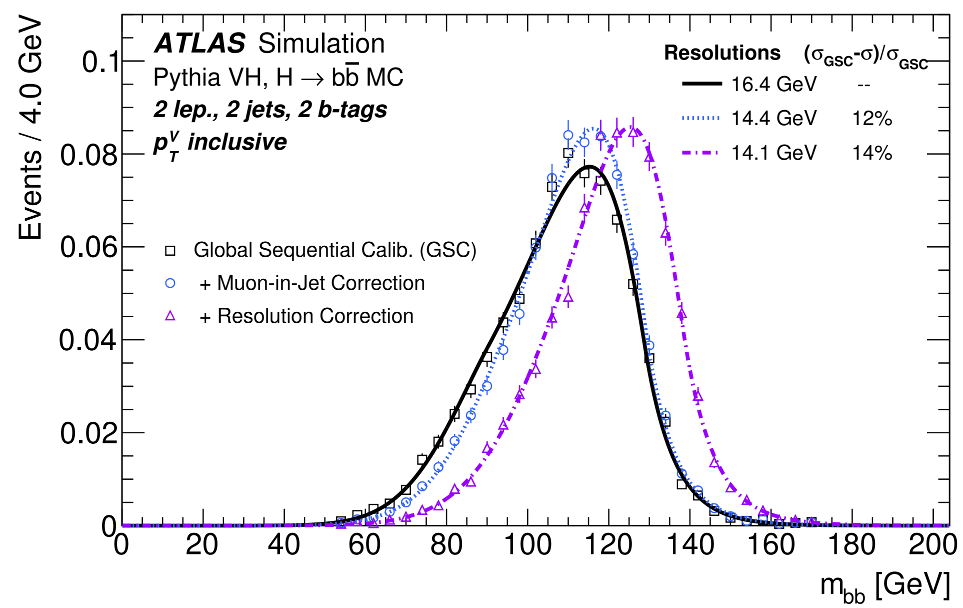


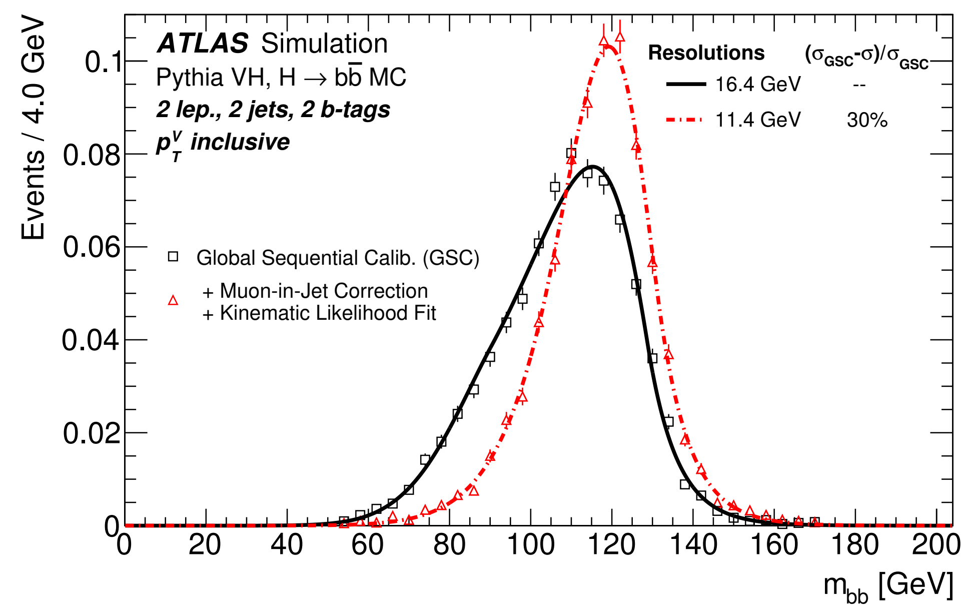


∫L dt = 4.5 fb^-1, √s = 7 TeV
∫L dt = 20.3 fb^-1, √s = 8 TeV
S/B weighted sum
Signal strength categories
ATLAS
Data
Signal+background
Background
Signal
m_H = 125.4 GeV
∑ weights / GeV
data - fitted bkg
m_γγ [GeV]

h→bb @Run-1



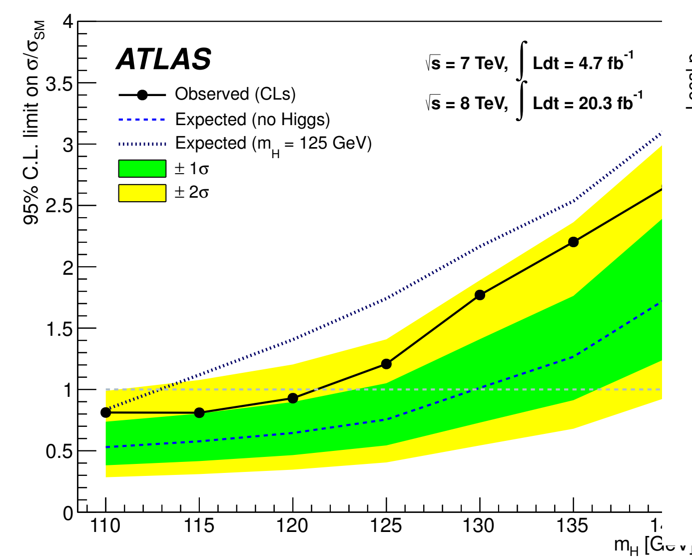


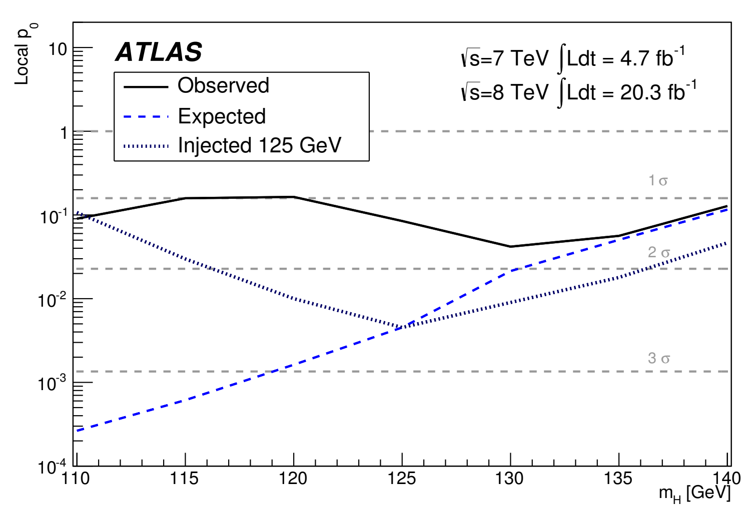


The VH production with W→lv, Z→ll, Z→vv allows to reduce the background by large factors.

Event classification

Channel	Categories					
	2 *b*-tagged jets					
	p_T^V < 150 GeV			p_T^V > 150 GeV		
	2 jets	3 jets	≥ 3 jets	2 jets	3 jets	≥ 3 jets
0-lepton	-	-	-	BDT	BDT	-
1-lepton	-	-	-	BDT	BDT	-
2-lepton	BDT	-	BDT	BDT	-	BDT

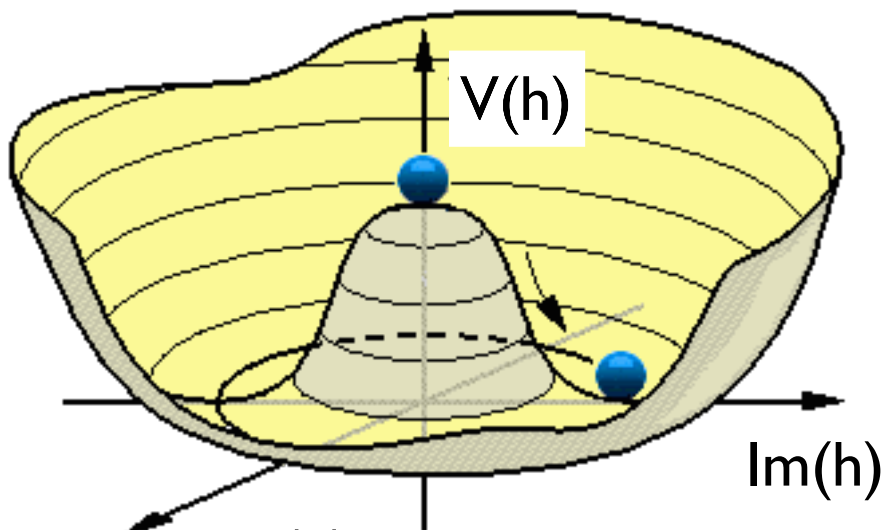




Main backgrounds: Top; Z+bb; WZ, Z→bb
Typically low S/B ratio: 0.002-0.02

The Higgs potential: how to probe it

$$V(h) = \mu^2 \frac{h^2}{2} + \lambda \frac{h^4}{4}$$

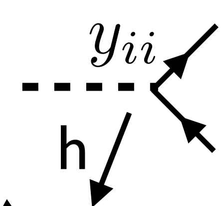


After spontaneous symmetry breaking:

$$\bar{\psi}_i y_{ii} \psi_i h_0 + \bar{\psi}_i y_{ii} \psi_i \eta \qquad h_0 =< 0|\phi|0 >= \sqrt{\frac{-\mu^2}{\lambda}}$$

$$m \sim y_{ii} h_0$$

mass term



coupling term

Fermion couplings are proportional to their mass

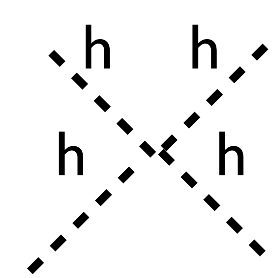
$$\mu^2 \frac{\eta^2}{2} + \mu^2 \eta h_0 + \frac{\lambda}{4}\eta^4 + \lambda h_0 \eta^3 + \lambda \frac{3}{2} h_0^2 \eta^2 + \lambda h_0^3 \eta$$

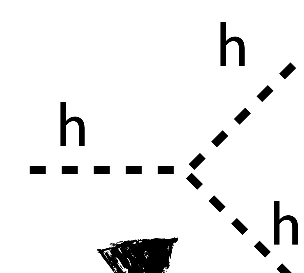
replacing μ^2

$$\to -\lambda h_0^2 \frac{\eta^2}{2} - \lambda h_0^3 \eta + \frac{\lambda}{4}\eta^4 + \lambda h_0 \eta^3 + \lambda \frac{3}{2} h_0^2 \eta^2 + \lambda h_0^3 \eta$$

$$\to \lambda h_0^2 \eta^2 + \frac{\lambda}{4}\eta^4 + \lambda h_0 \eta^3$$

$$m_h^2 = 2\lambda h_0^2$$





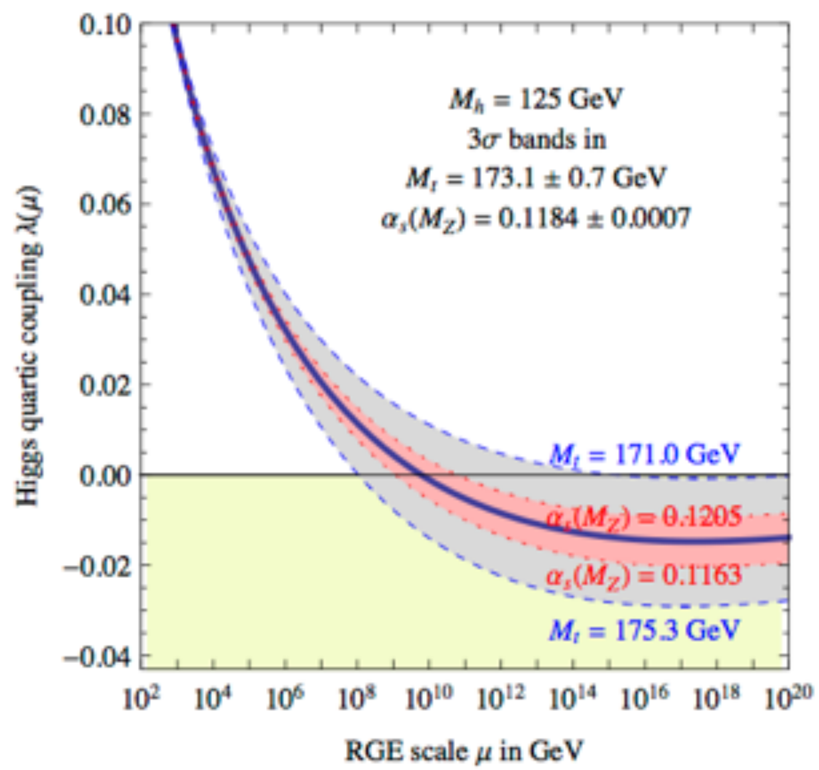
Implications of the Higgs potential

$$V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\Lambda(scale)\Phi^4$$

+ ...

arXiv:1307.3536v2

Dario Buttazzo[a,b], Giuseppe Degrassi[c], Pier Paolo Giardino[a,d], Gian F. Giudice[a], Filippo Sala[b,e], Alberto Salvio[b,f], Alessandro Strumia[d]

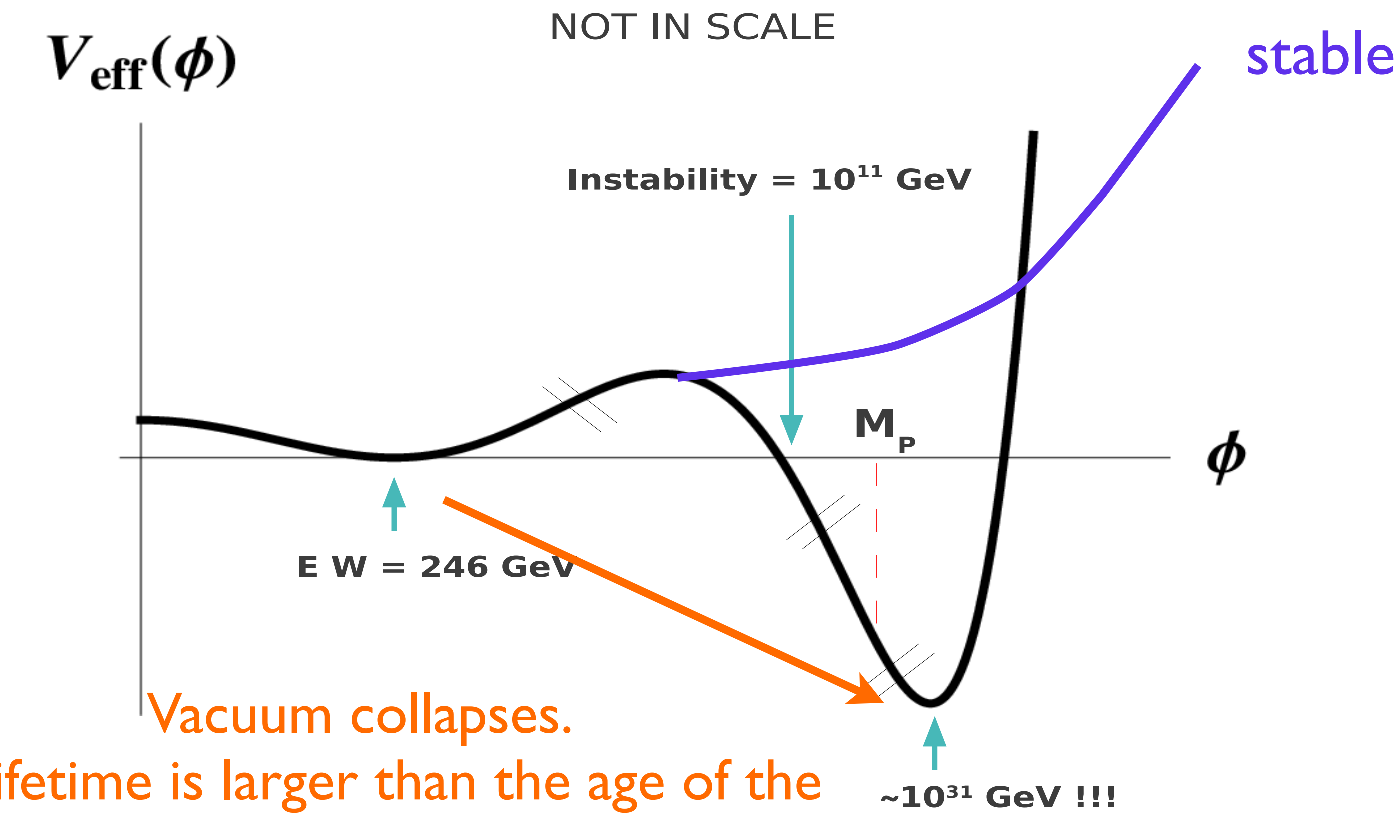


The modification of λ with the energy implies a dependence Λ(Φ). The Higgs potential has a shape that is more complex than just $\lambda\Phi^4$.

$$\lambda(\mu) \sim F(y_t, \lambda(m_H)) = F'(m_t, m_H)$$

$$\lambda(m_H) = \frac{m_H^2}{2v^2} = 0.1301 \pm 0.0007$$

See Buttazzo *et al.* and talk from V. Branchina (Moriond QCD 2014)



Vacuum collapses.
If the lifetime is larger than the age of the universe we call it metastable otherwise it is unstable. What's the shape of the Higgs potential?

Higgs boson as inflaton

Gravitational action coupled to the SM sector

$$S = \int \left[\frac{1}{2}M_{\rm pl}^2 R + \mathcal{L}\right] d^4x\sqrt{-g} = \int \left[\frac{1}{2}M_{\rm pl}^2 R - \frac{1}{2}\partial_\mu h \partial^\mu h + V(h) + \ldots\right] d^4x\sqrt{-g}$$

Inflation model

- need a scalar field (h is a scalar field)
- need a well shaped potential, with a slow-roll condition

$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \longrightarrow H^2 = \frac{8\pi G}{3}V(\phi) \simeq const. \longrightarrow a(t) \simeq e^{Ht} \quad \left(H(t) = \frac{\dot{a}}{a}\right)$$

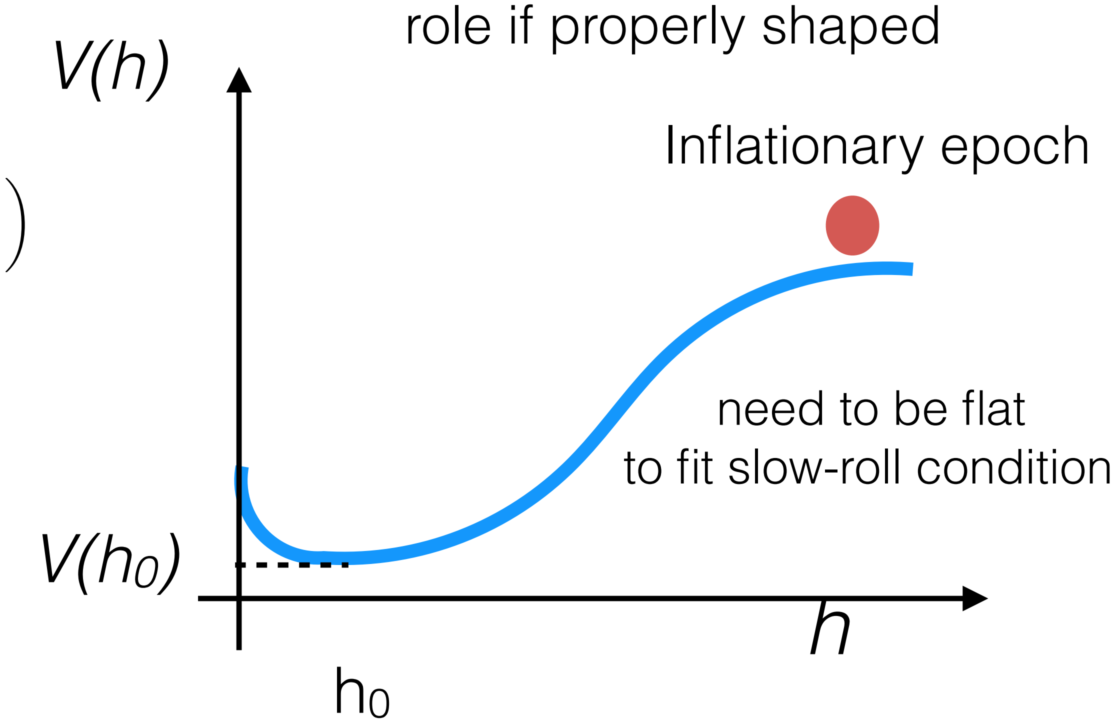
universe radius, exponentially expanding during inflation

In order to make this to work

$$h >> h_0 \;\; V(h) \sim \lambda h^4 \;\; \lambda \sim 10^{-13}$$

Intringuing, λ nearly vanishes for high h value with the present value of top and Higgs mass.

The Higgs potential could have such role if properly shaped



The Higgs potential could have fundamental cosmological implications.