# Vh and $A \rightarrow Zh$ ($h \rightarrow bb$) in ATLAS

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**GDR Terascale - Nantes - 24/05/2016**

# Overview of the talk: Two Analyses

## VH ($H \to bb$): SM Higgs search

- Run1(**7+8TeV**) analysis by ATLAS in 2014 [JHEP01(2015)069]

**Quick review:**
The Run1 lesson

- Run2(**13TeV**) analysis ongoing right now!
  - What is new for the SM VHbb @ 13TeV ?
  - What are the main learning points to keep from the Run1 search?

No public results today!

## $A \to Zh$ ($h \to bb$): 2HDM A boson search

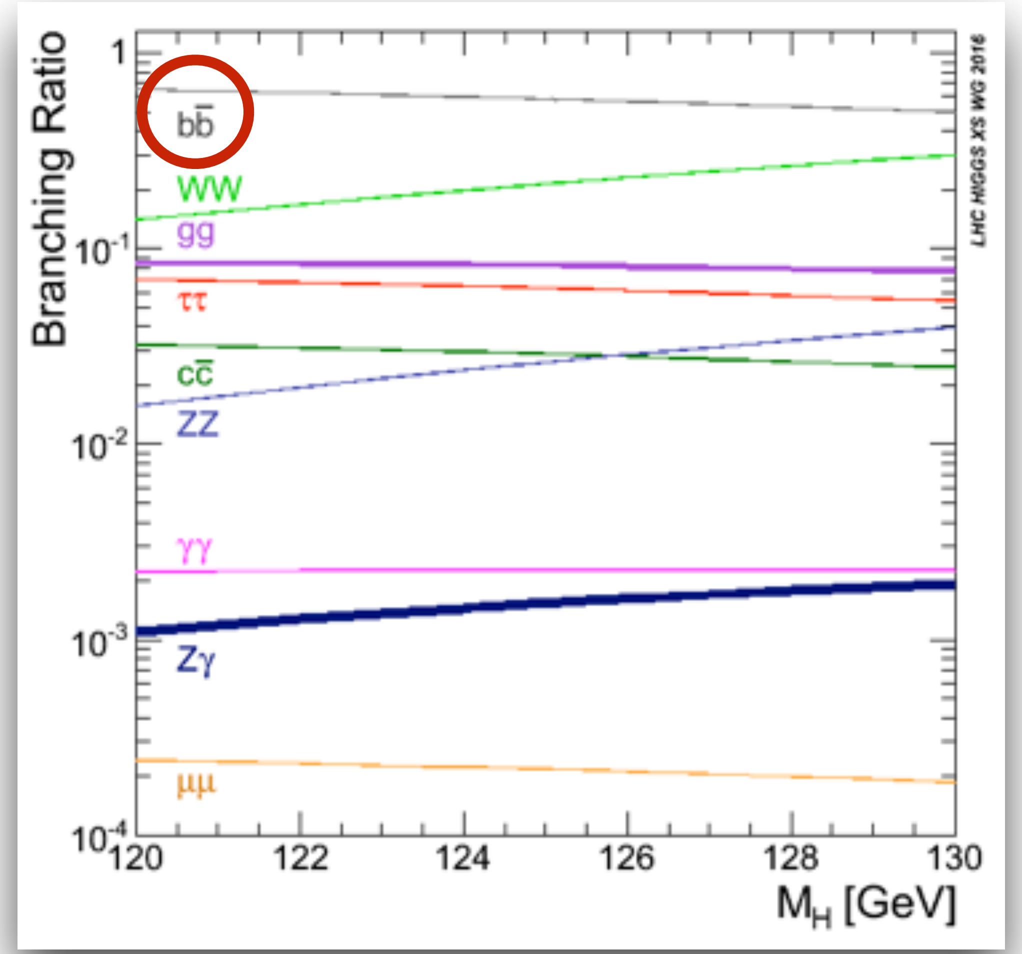
- Run2(**13TeV**) results presented for MoriondEW2016 [ATLAS-CONF-2016-015]

**The first look at the Zh(bb) phase space with 13TeV data (exploring the very high $p_T$ regime)**

# Run1 SM VHbb: The Higgs Signal

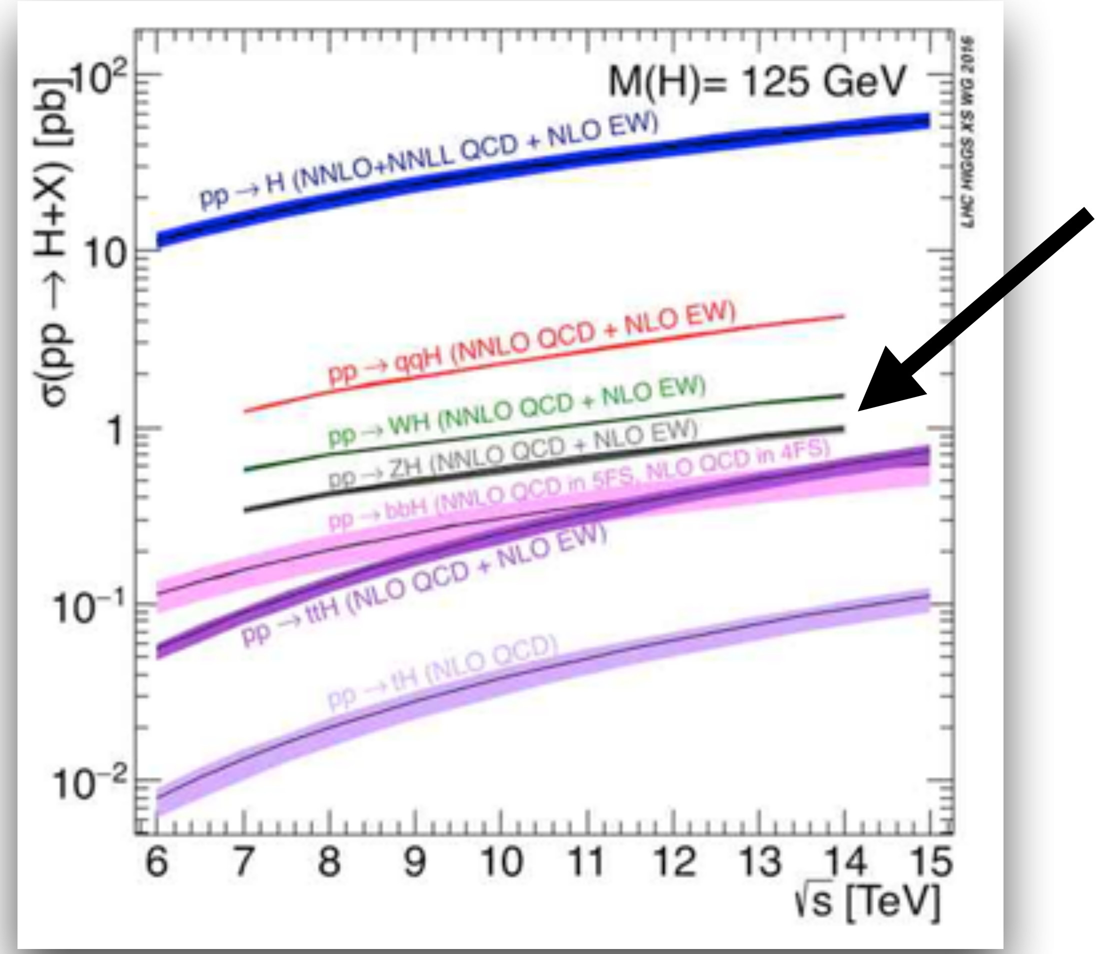
## VH→bb Motivations

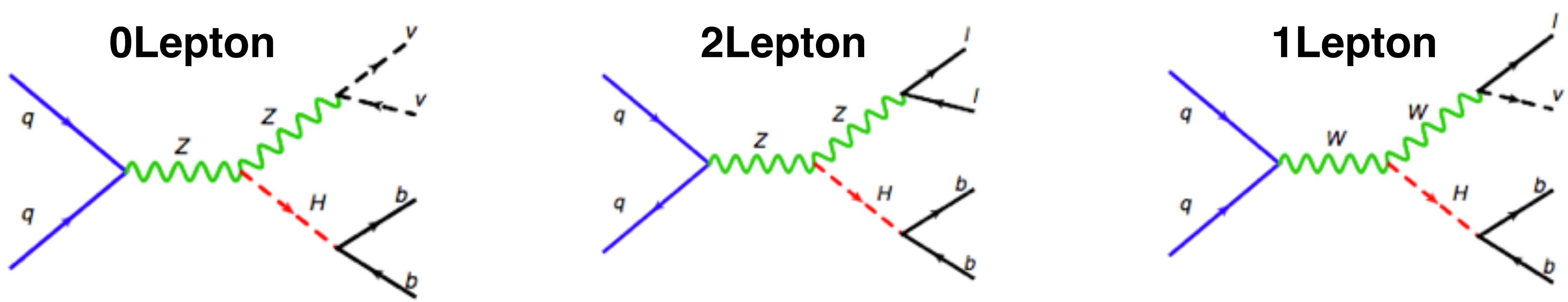
BR ~ 58% ($m_H$ = 125 GeV)
direct H coupling to down-type quark
sensitive to high $p_T$ Higgs production




## Production Mechanism

**VH production (~5%) V→leptons**
subdominant but cleanest vs QCD background

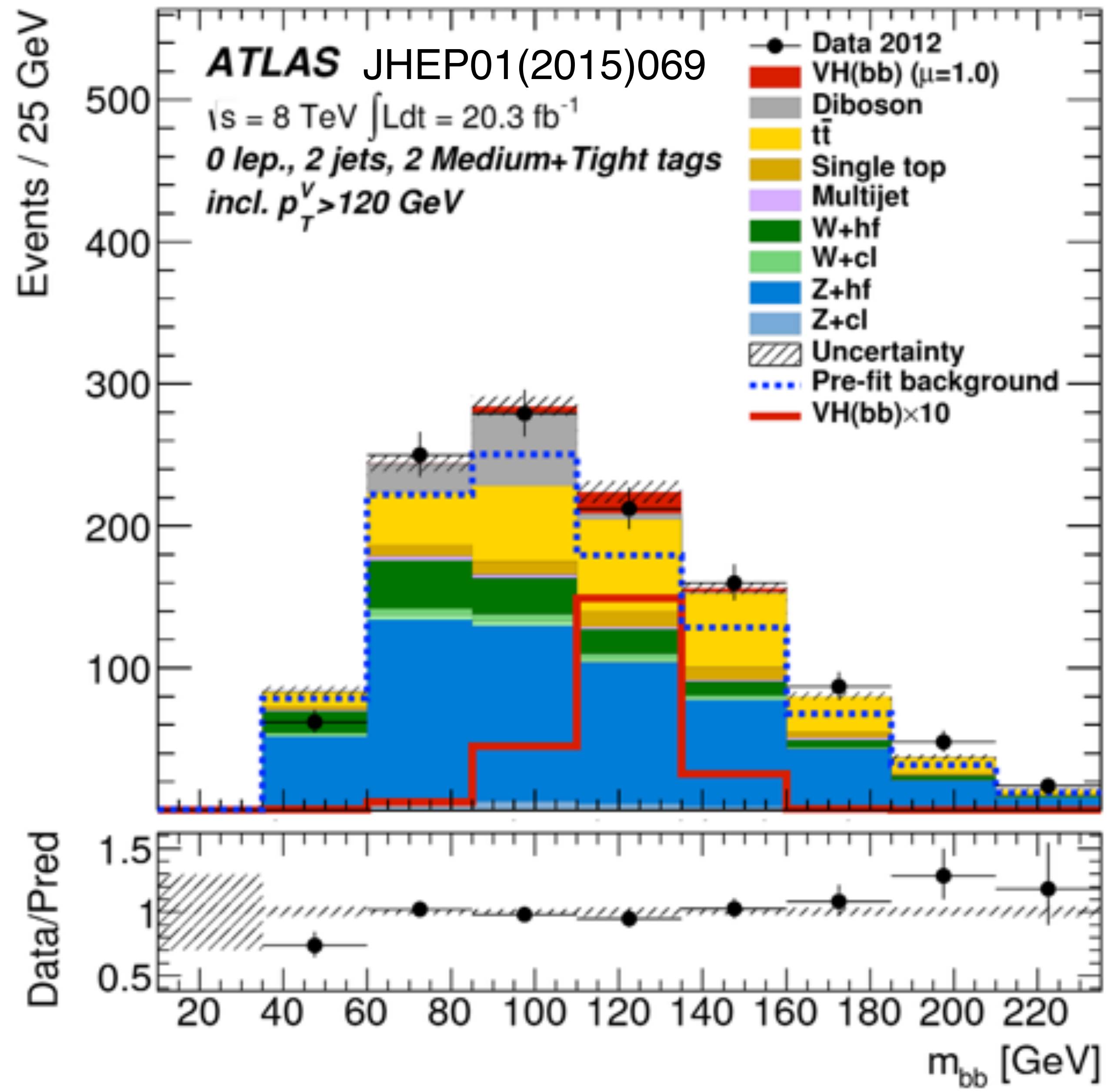


# Run1 SM VHbb: The Backgrounds

## Main Backgrounds

- Data
- VH(bb) (μ=1.0)
- Diboson
- $t\bar{t}$
- Single top
- W+hf
- W+cl
- W+l
- Z+hf
- Z+cl
- Z+l
- Multijet
- Uncertainty
- Pre-fit background




### Many SM processes contributing as backgrounds

- different kinematic and topologies
- resonant and non-resonant backgrounds

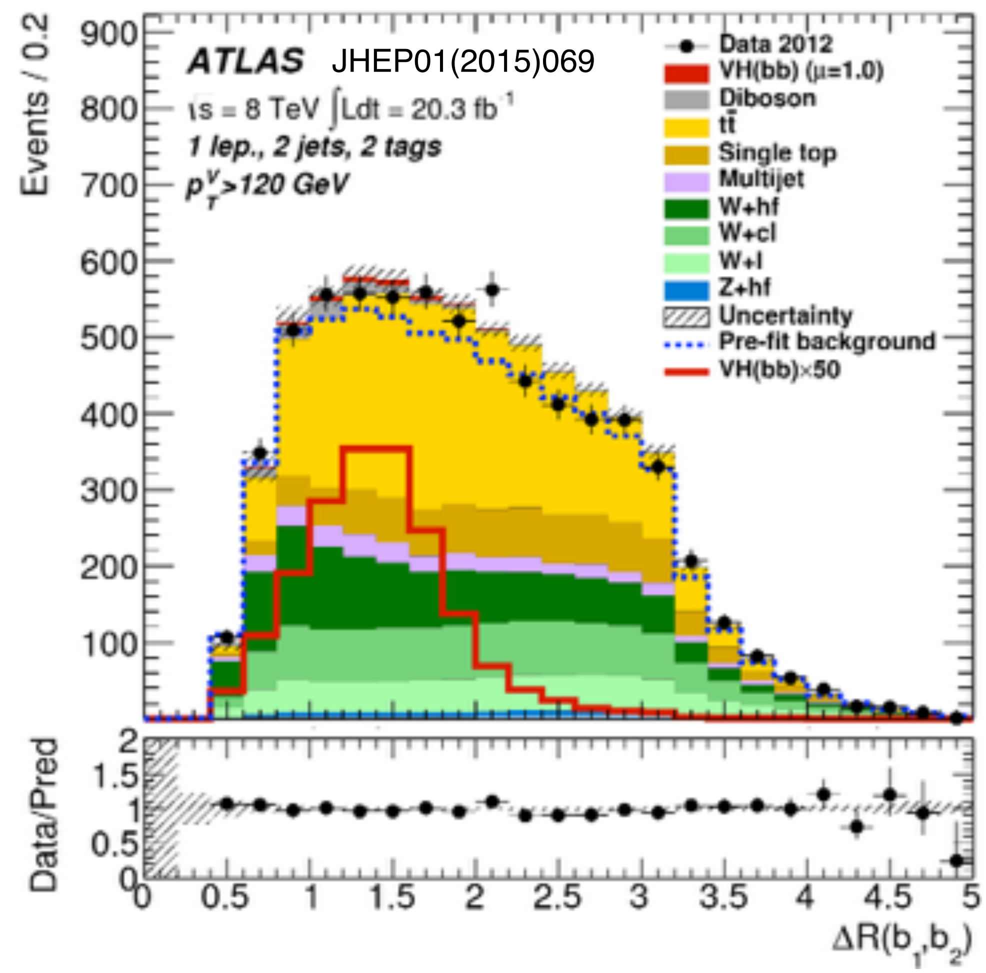
→

- most advanced available MC
- dedicated Control Regions
- global combined fit (CR+SR) to constrain the bkg modelling

# Run1 SM VHbb: Multivariate Discrimination

Separate a tiny signal from a complex background → multivariate techniques → **BDT**

| Variable | 0-Lepton | 1-Lepton | 2-Lepton |
|---|---|---|---|
| $p_T^V$ | | × | × |
| $E_T^{miss}$ | × | × | × |
| $p_T^{b_1}$ | × | × | × |
| $p_T^{b_2}$ | × | × | × |
| $m_{bb}$ | × | × | × |
| $\Delta R(b_1, b_2)$ | × | × | × |
| $\lvert\Delta\eta(b_1, b_2)\rvert$ | × | | × |
| $\Delta\phi(V, bb)$ | × | × | × |
| $\lvert\Delta\eta(V, bb)\rvert$ | | | × |
| $H_T$ | × | | |
| $\min[\Delta\phi(\ell, b)]$ | | × | |
| $m_T^W$ | | × | |
| $m_{\ell\ell}$ | | | × |
| $MV1c(b_1)$ | × | × | × |
| $MV1c(b_2)$ | × | × | × |
| | Only in 3-jet events | | |
| $p_T^{jet_3}$ | × | × | × |
| $m_{bbj}$ | × | × | × |




**MVA training variables:**

- as consistent as possible across lepton channels
- study of data/MC modelling and correlations
- most powerful: $\mathbf{m_{bb}}$, **ΔR(b,b)**, $\mathbf{p_T^V}$

We do not cut on the BDT output: the full BDT shape distribution is used as discriminating variable in a **combined Profile Likelihood Fit**

# Run1 SM VHbb: The Analysis Strategy

## 3 lepton channels (νν, lν, ll) according to the V decay

| | | | Variable |
|---|---|---|---|
| | | **1tag (CR)** | → **MV1c** |
| **$p_T^V$ < 120 GeV** | **2 jets** | **2tag LL (SR)** | → **MVA BDT** |
| **$p_T^V$ > 120 GeV** | **3 jets** | **2tag MM (SR)** | → **MVA BDT** |
| | | **2tag TT (SR)** | → **MVA BDT** |

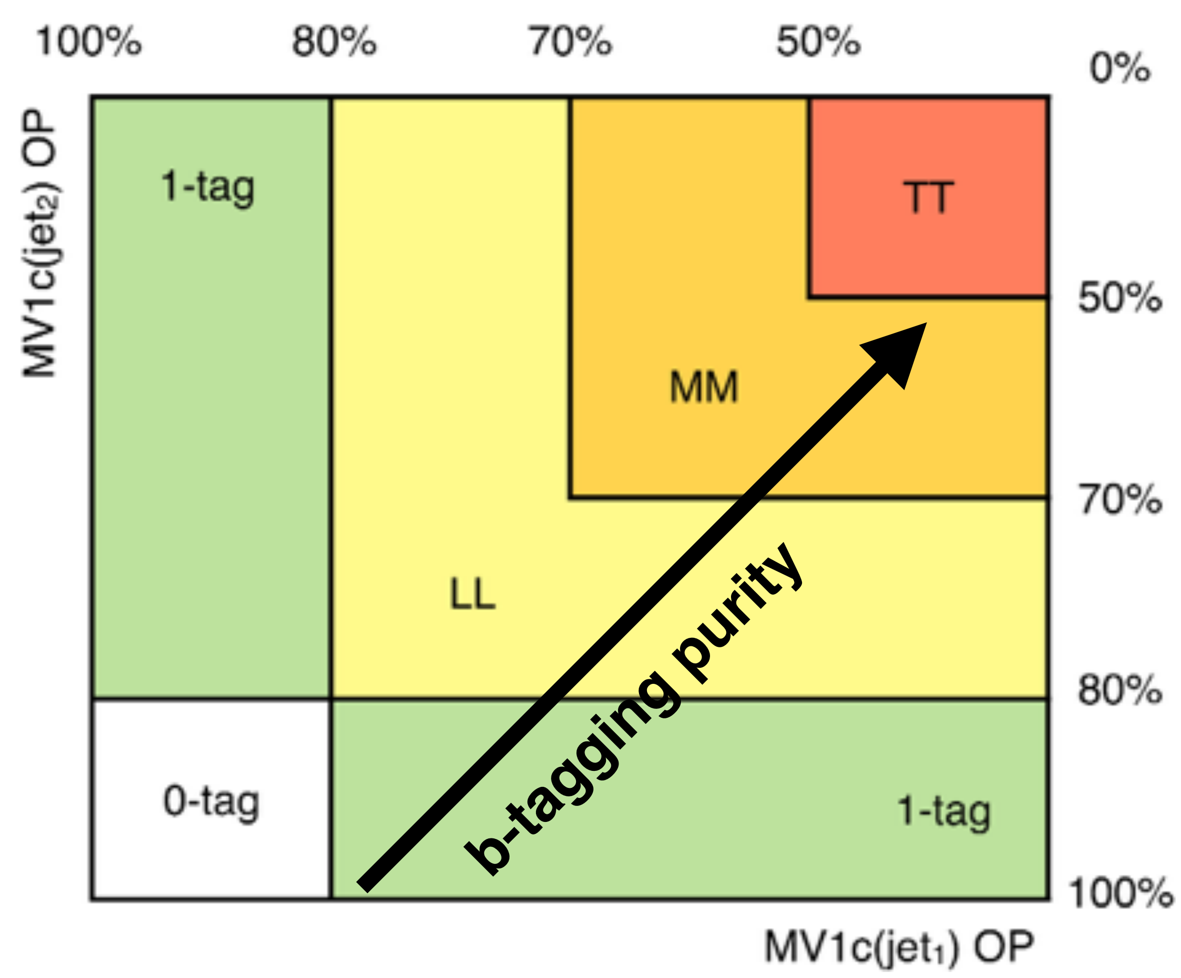
2 regions of transverse momentum of the vector boson **$p_T^V$**

2 regions in jet multiplicity

4 regions in number of b-tagged jets, and purity of the b-jet identification

## Total of 40-50 analysis regions

- additional selections specific to each lepton channel applied to reject backgrounds
- **BDT shape**, or **b-tagging discriminant**, used to fit the signal+background prediction to data
- **All regions** entering in a simultaneous **profile likelihood fit**



# Run1 SM VHbb: Results

Eur.Phys.J. C76 (2016)

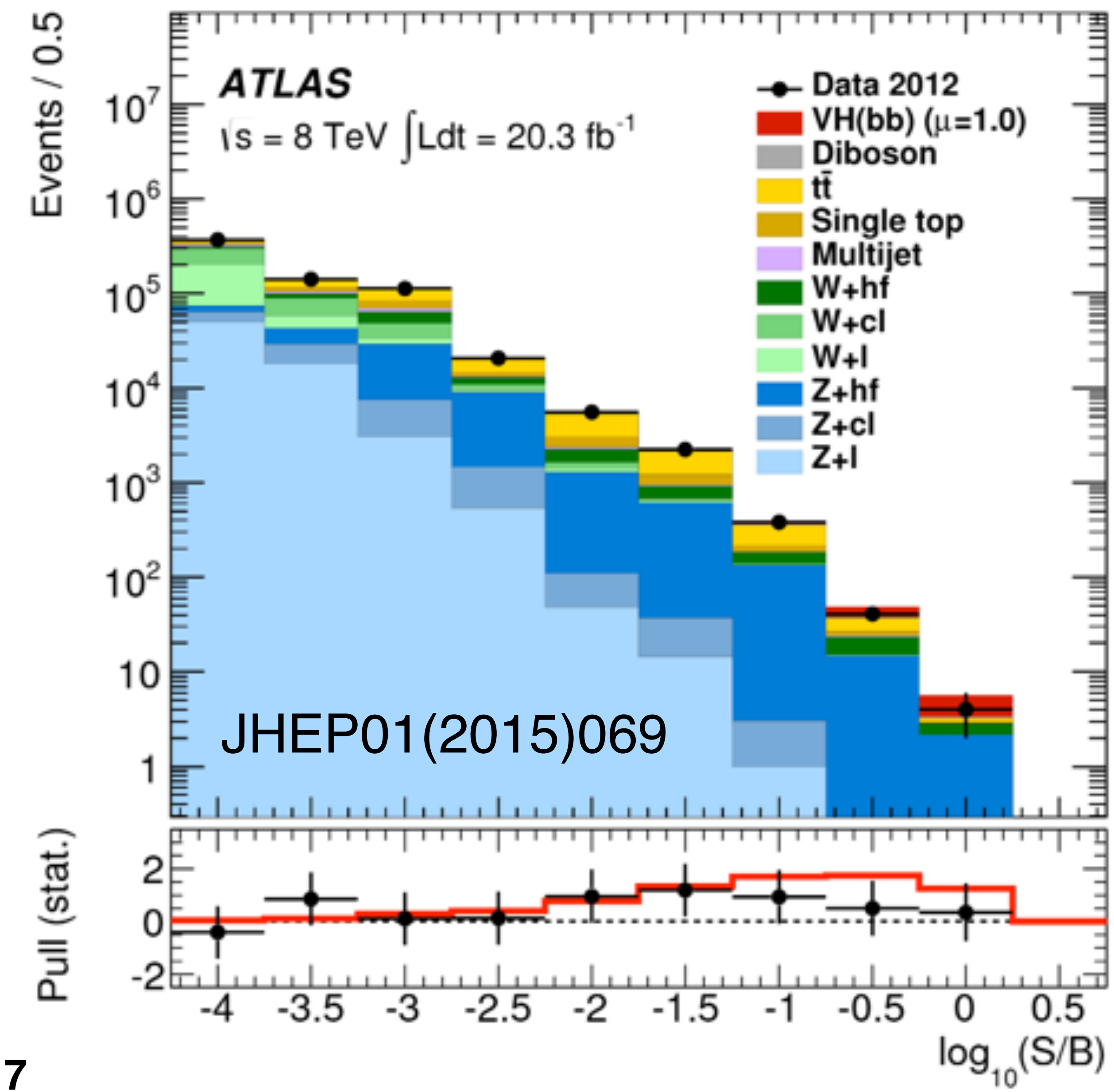
## VH→Vbb

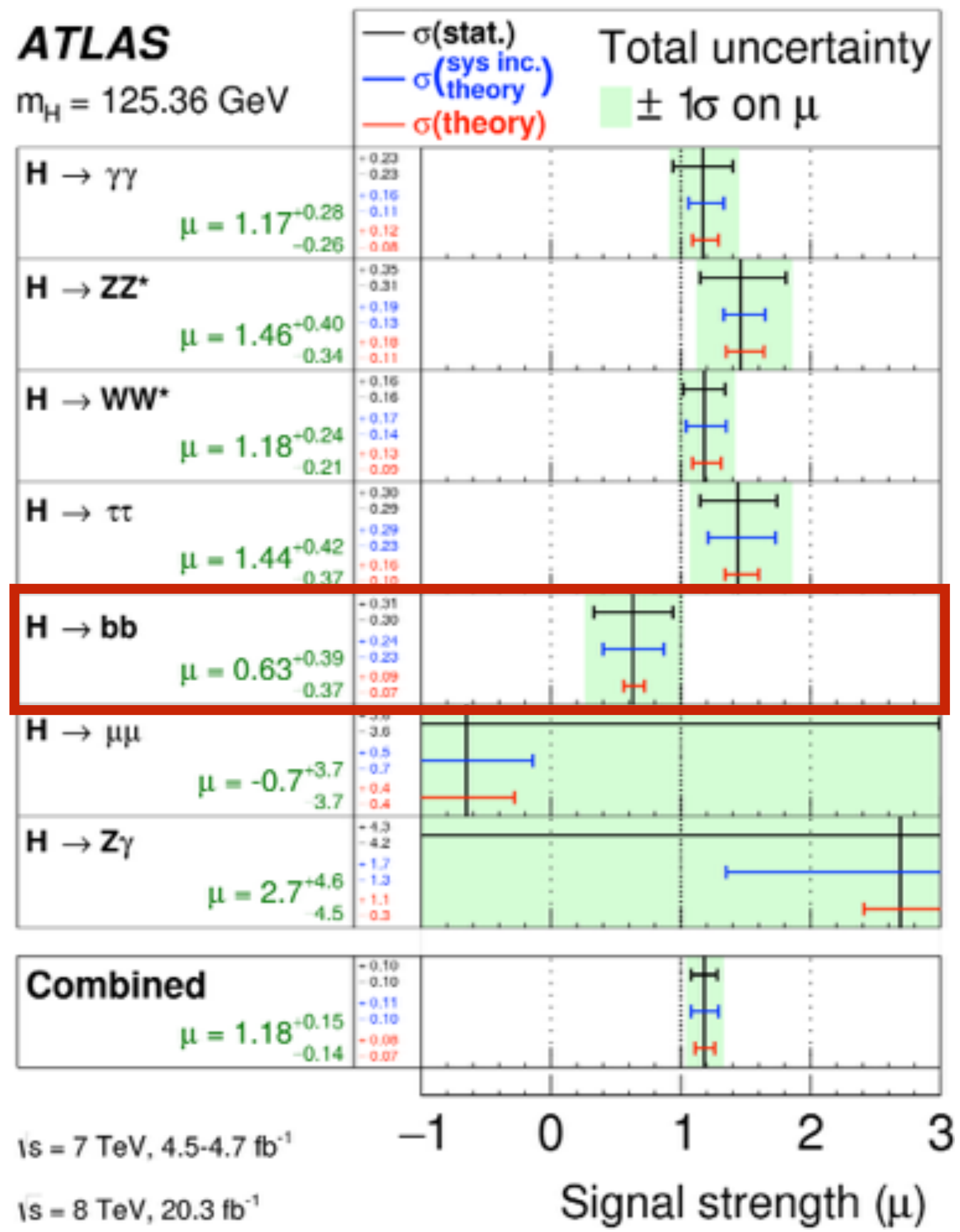
**expected significance $\sigma_{exp}$ = 2.6**

**observed significance $\sigma_{obs}$ = 1.4**

signal strength = **fitted $\sigma/\sigma_{SM}$**

**0.51 ± 0.31**(stat.) **± 0.24**(syst.)



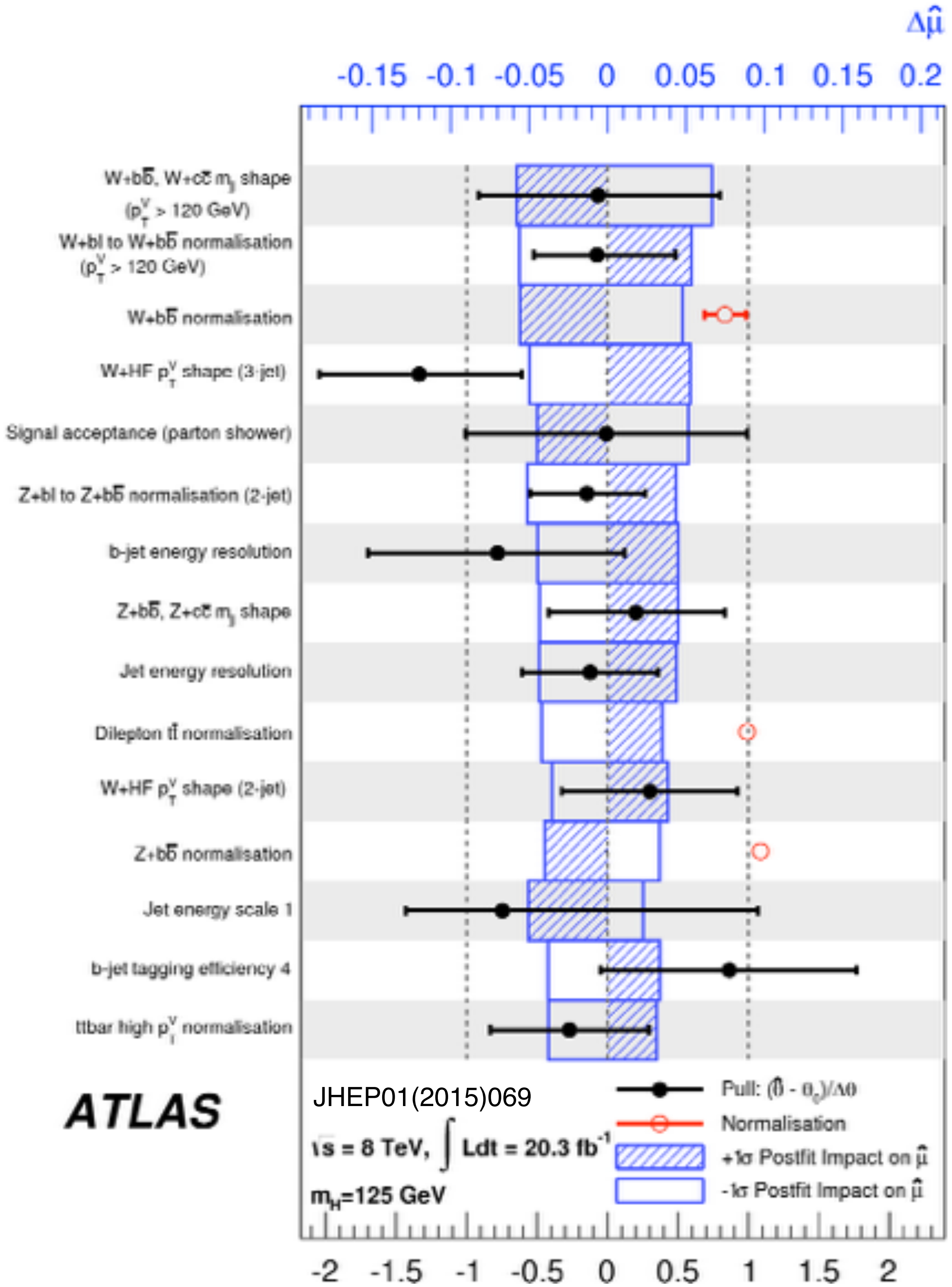

**Highest expected significance for Hbb searches**

Multivariate analysis brings **O(30%)** improvement in the expected significance

# Learning from Run1: Systematic Uncertainties (a hint)

signal strength = **fitted σ/σ$_{SM}$**

**0.51 ± 0.31**(stat.) **± 0.24**(syst.)




Several systematic sources, from background modelling and detector performance:

**systematics ranked according to their impact on the measured signal strength**

**W+jets** (heavy flavour) modelling

**Z+jets** (heavy flavour) modelling

Control over the modelling of **Z/W+heavy flavour** background is crucial for this analysis

| | |
|---|---|
| $Z$+jets | |
| $Zl$ normalisation, 3/2-jet ratio | 5% |
| $Zcl$ 3/2-jet ratio | 26% |
| $Z$+hf 3/2-jet ratio | 20% |
| $Z$+hf/$Zbb$ ratio | 12% |
| $\Delta\phi(\text{jet}_1, \text{jet}_2)$, $p_T^V$, $m_{bb}$ | S |
| $W$+jets | |
| $Wl$ normalisation, 3/2-jet ratio | 10% |
| $Wcl$, $W$+hf 3/2-jet ratio | 10% |
| $Wbl/Wbb$ ratio | 35% |
| $Wbc/Wbb$, $Wcc/Wbb$ ratio | 12% |
| $\Delta\phi(\text{jet}_1, \text{jet}_2)$, $p_T^V$, $m_{bb}$ | S |

# SM VHbb: Towards Run2 data

ATLAS collected **L~3.2/fb** of data at $\sqrt{s}$ = 13TeV and the 2016 data-taking is ongoing
**What can we (expect to) say with these data for VHbb?**

**Cross-section scaling: 13TeV/8TeV**

- **signal** and **EW backgrounds** scaling by ~ **2**
- **ttbar processes** increasing by ~ **3.3**

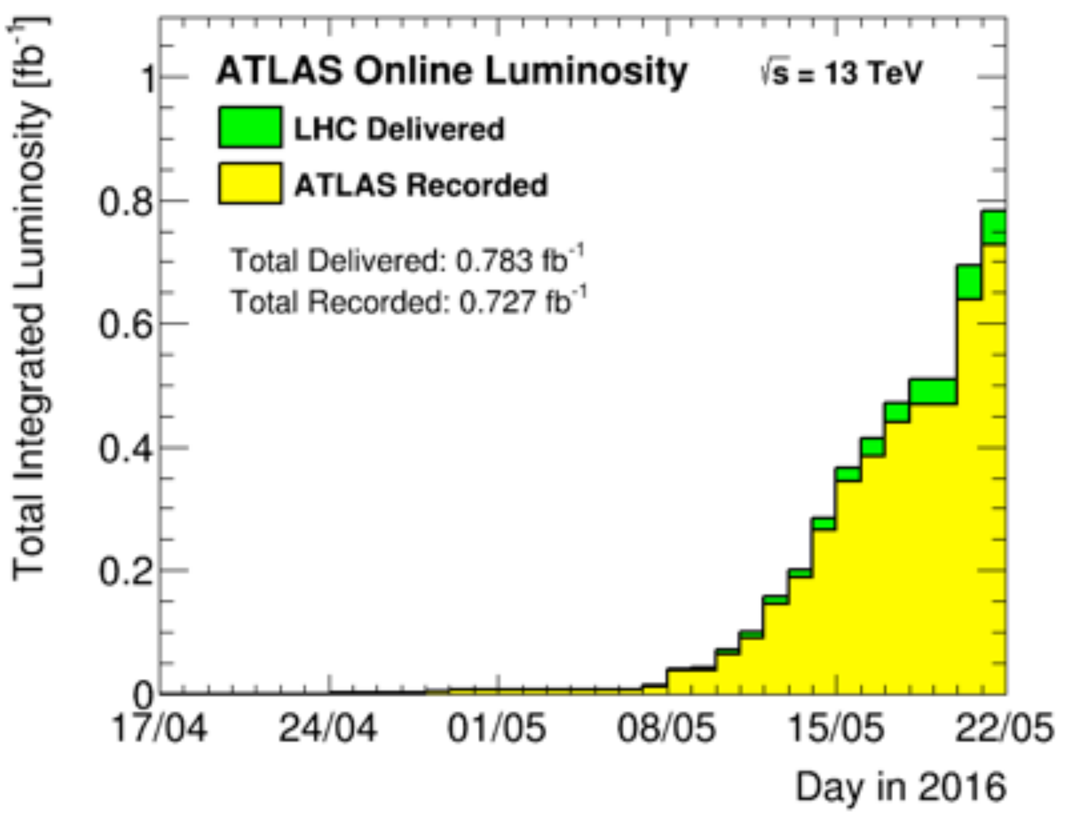
No public result yet: back-of-the-envelope considerations here

With a statistics of ~ half of the Run1 data the **sensitivity@13TeV** starts to be similar to the Run1 expected value

**From Run1**

| |
|---|
| $\sigma_{exp}$ = 2.6 |
| $\sigma_{obs}$ = 1.4 |

- Very exciting time to look at the **full Run2 dataset** (L~25/fb by December 2016?)
- Already *very interesting* to look at the first **10-15/fb of 13TeV** data,
  and **combine Run1+Run2** results

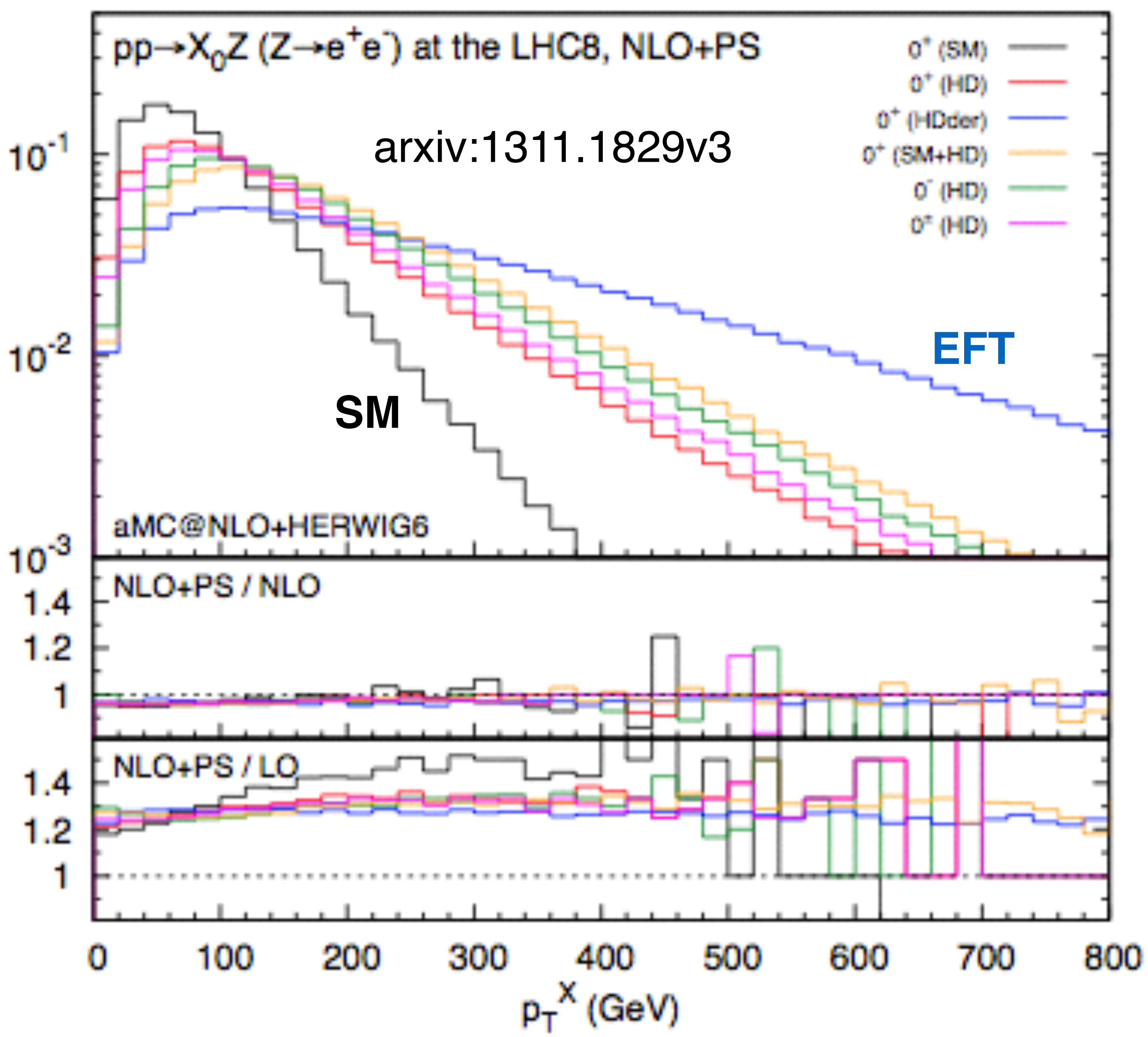


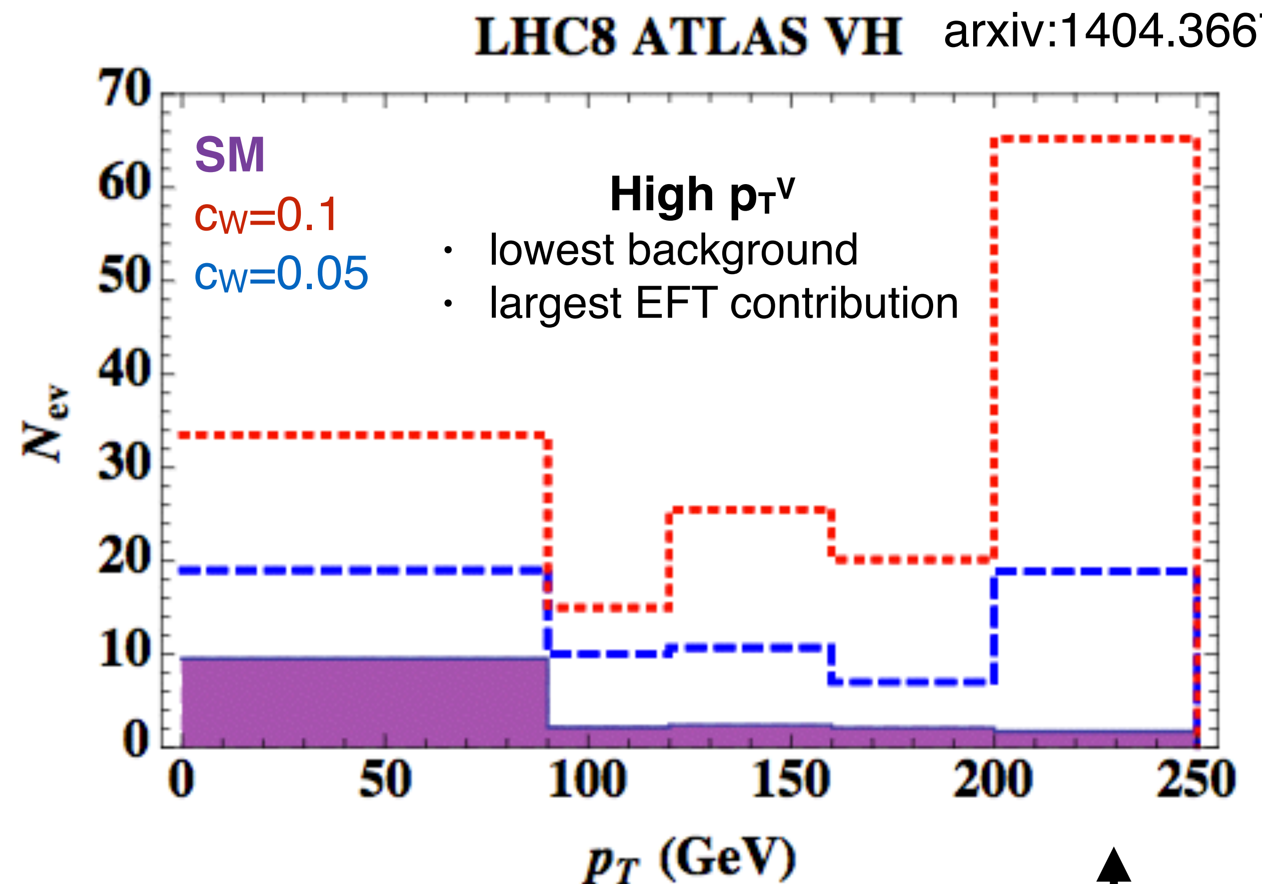
# ~SM VHbb: Towards Run2 data [EFT]

The VHbb channel is able to constrain some **combination of parameters** related to the dim-6 operators used to build the **EFT Lagrangian** (see arxiv:1404.3667 Ellis, Sanz, You)

**EFT samples already under study in ATLAS**:
**mg5_aMC** *Higgs Characterization Model*

*MonteCarlo generation at NLO(QCD)+PS*




$$\mathcal{L} \supset -\frac{1}{4} g^{(1)}_{HZZ} Z_{\mu\nu} Z^{\mu\nu} h - g^{(2)}_{HZZ} Z_{\nu} \partial_{\mu} Z^{\mu\nu} h - \frac{1}{2} g^{(1)}_{HWW} W^{\mu\nu} W^{\dagger}_{\mu\nu} h - \left[ g^{(2)}_{HWW} W^{\nu} \partial^{\mu} W^{\dagger}_{\mu\nu} h + \text{h.c.} \right]$$

EFT Lagrangian with VH anomalous couplings (mass basis, unitary gauge)

# Overview of the talk: Two Analyses

## VH ($H \to bb$): SM Higgs search

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**Quick review:**
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- Run2(**13TeV**) analysis ongoing right now!
  - What is new for the SM VHbb @ 13TeV ?
  - What are the main learning points to keep from the Run1 search?

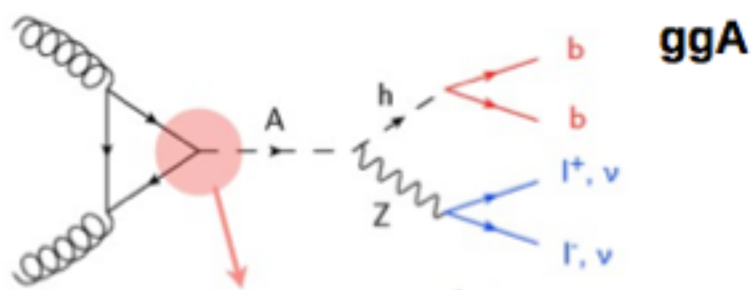
No public results today!

## $A \to Zh$ ($h \to bb$): 2HDM A boson search

- Run2(**13TeV**) results presented for MoriondEW2016 [ATLAS-CONF-2016-015]

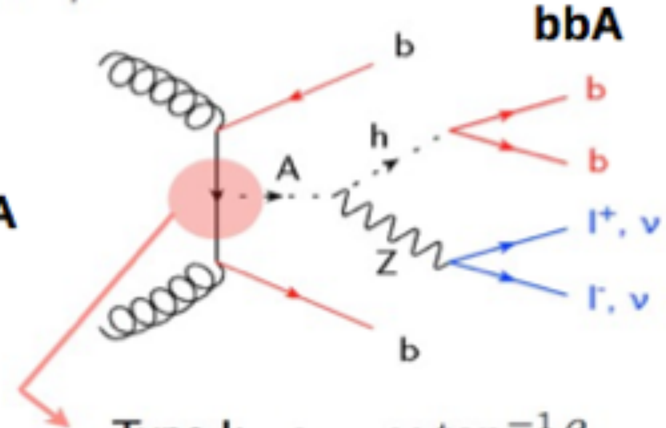
**The first look at the Zh(bb) phase space with 13TeV data (exploring the very high $p_T$ regime)**

# Run2: A→Zh(bb) search @ 13 TeV




Type-I: $c_{t\bar{t}A} \propto \tan^{-1}\beta$
Type-II: $c_{t\bar{t}A} \propto \tan^{-1}\beta$

Search for CP-odd scalar A boson through **ggA** or **bbA** production

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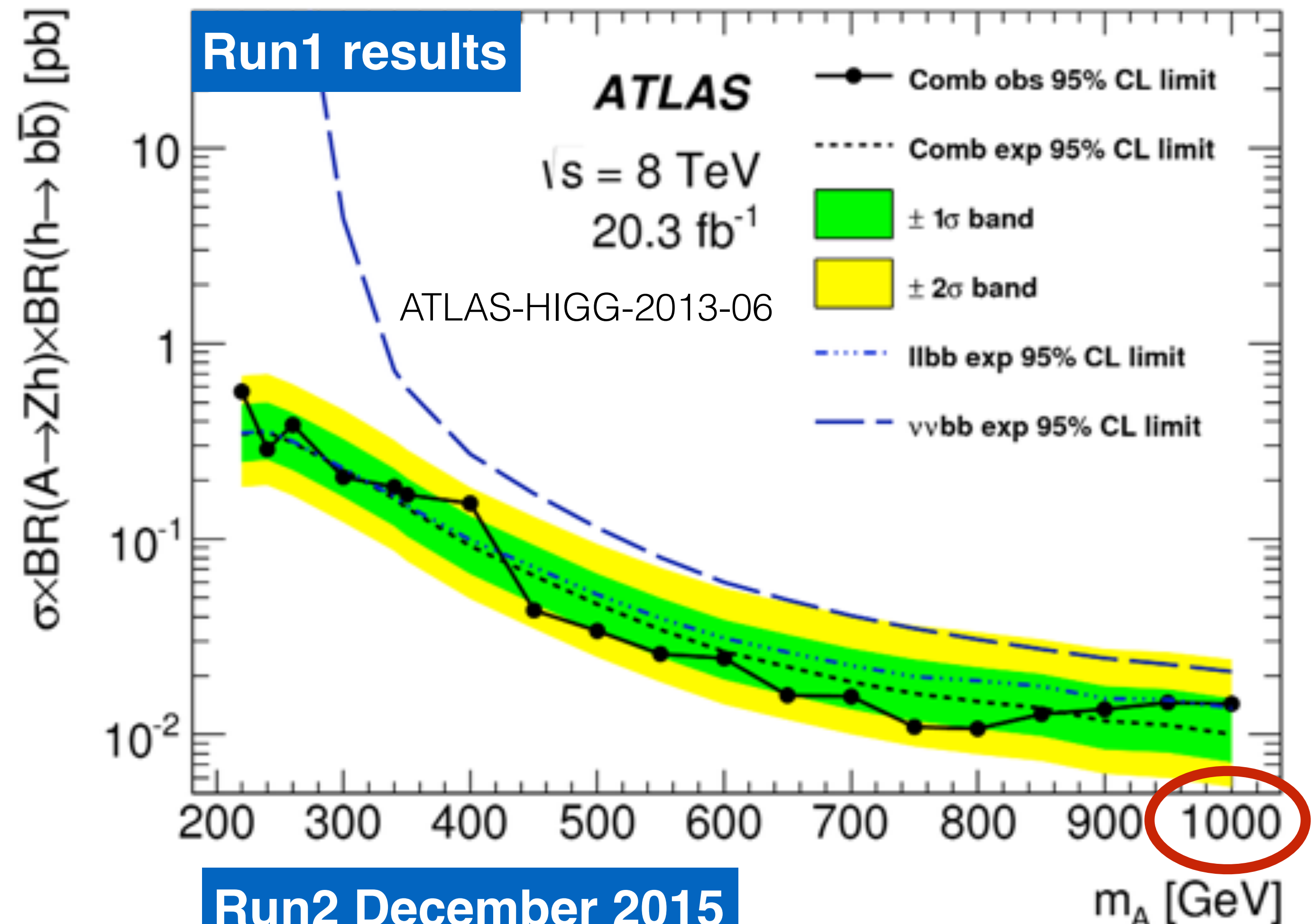


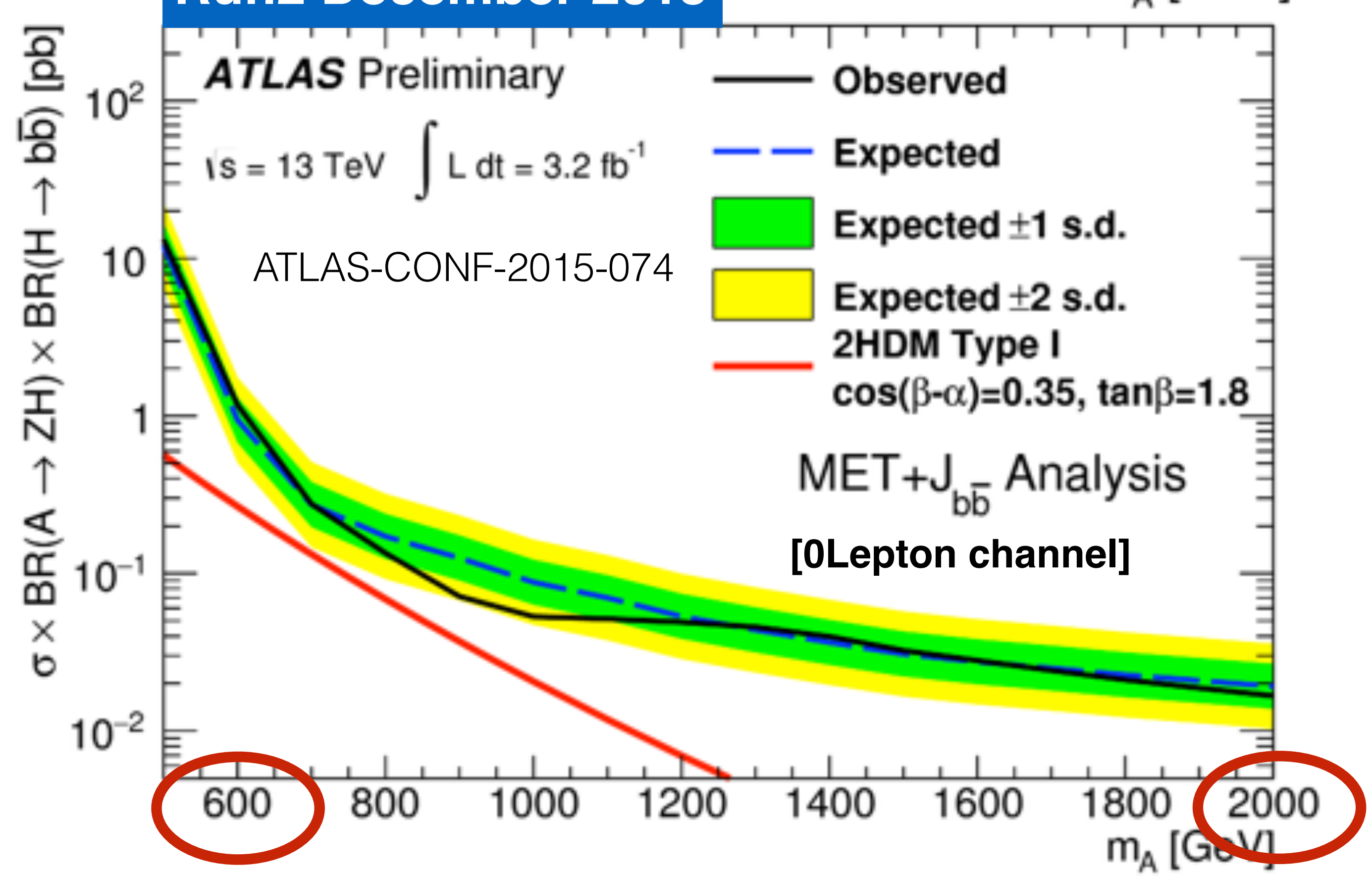


## Two main channels combined:

Zh→ννbb (dominant at **high** $m_A$)
Zh→$l^+l^-$bb (dominant at **low** $m_A$)

## Search strategy: (h→bb) decay

**resolved regime ($p_T^Z$ < 500 GeV):**
calorimeter jets R=0.4 ('small-R')

**merged regime ($p_T^Z$ > 500 GeV):**
calorimeter jet R=1.0 ('large-R')
[b-tagging on *track-jets* R=0.2]

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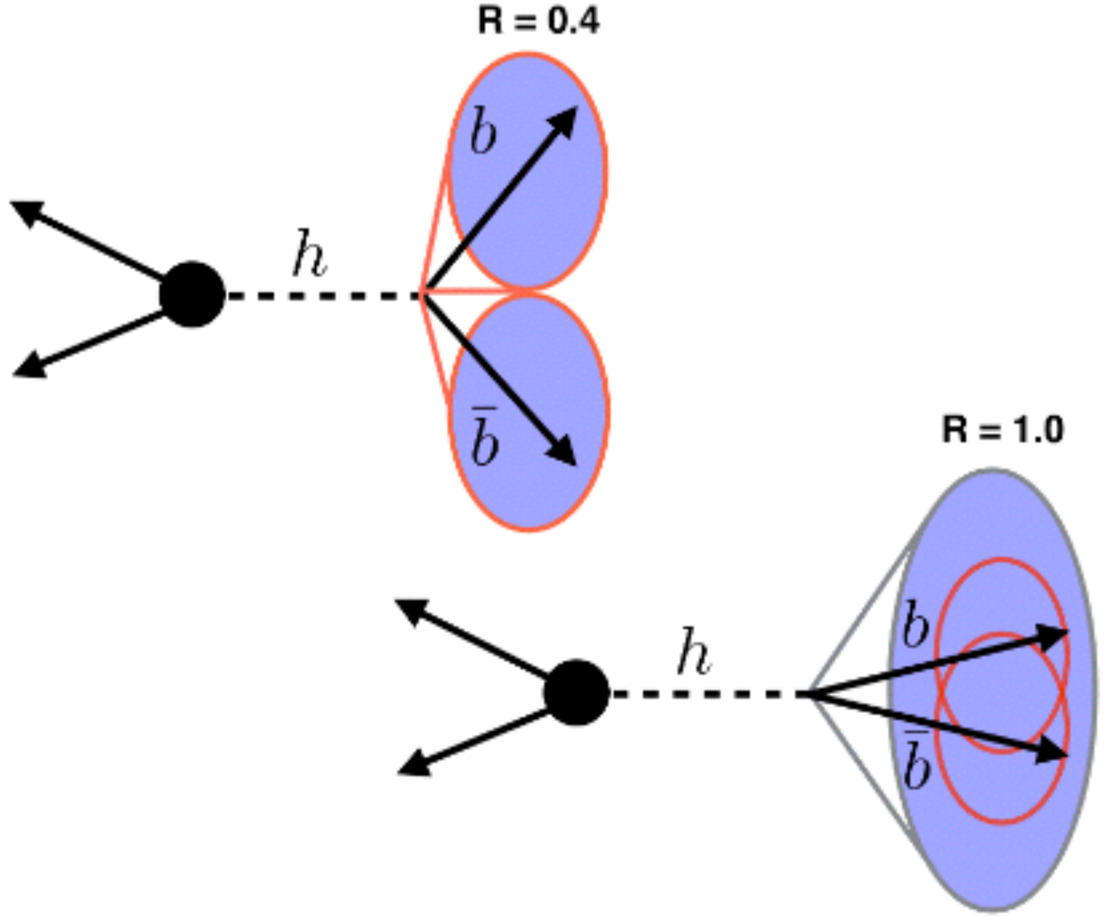


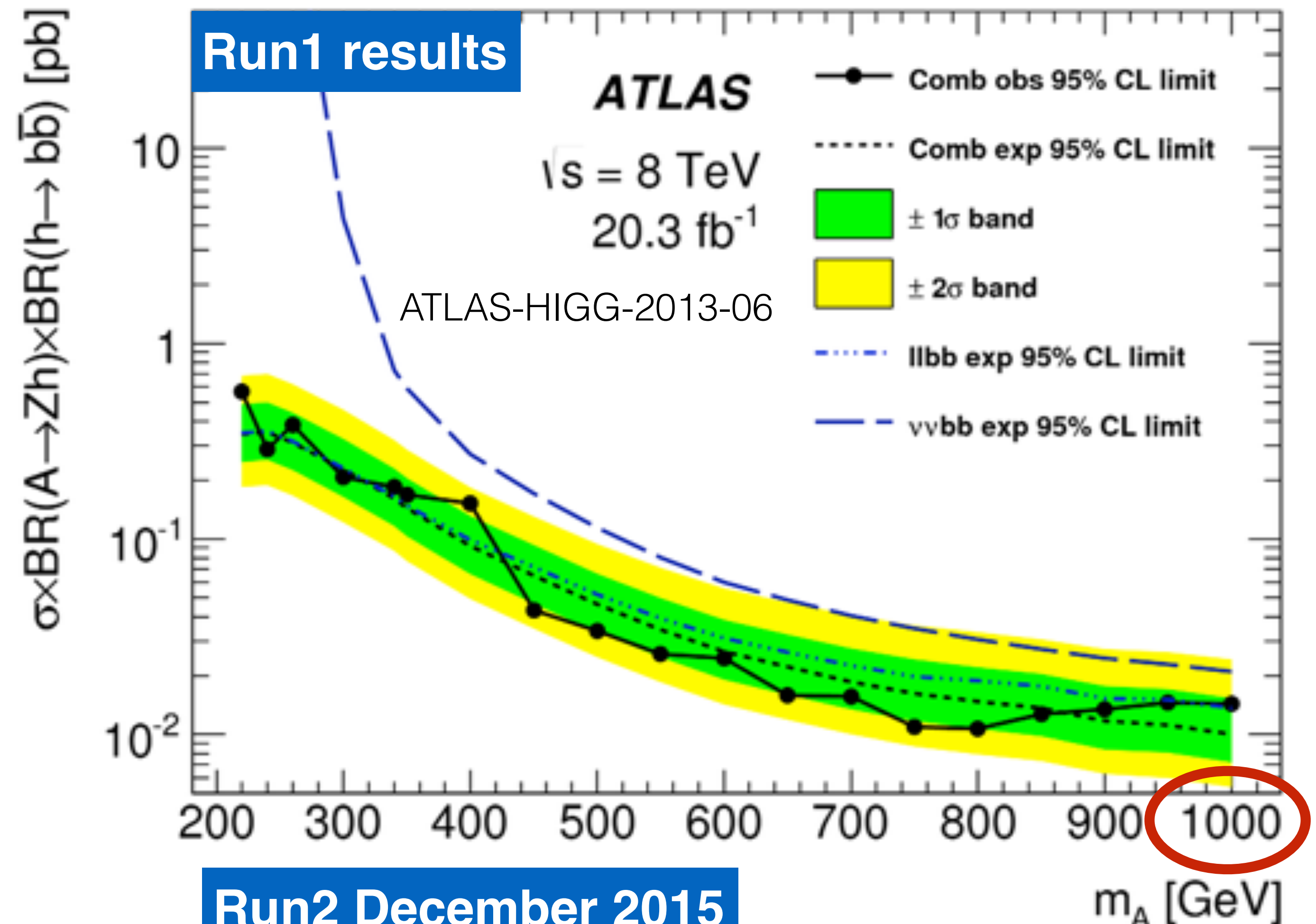


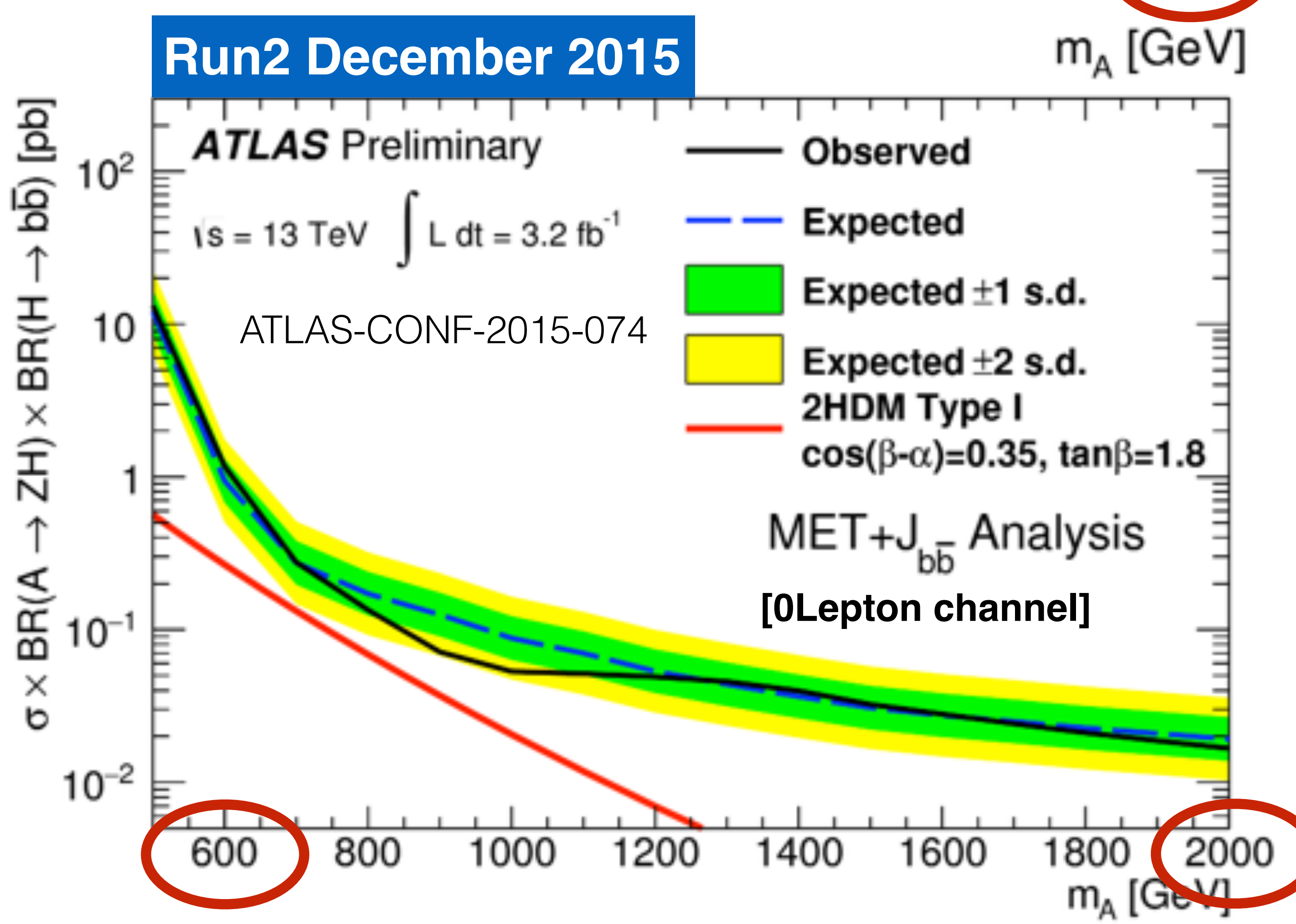


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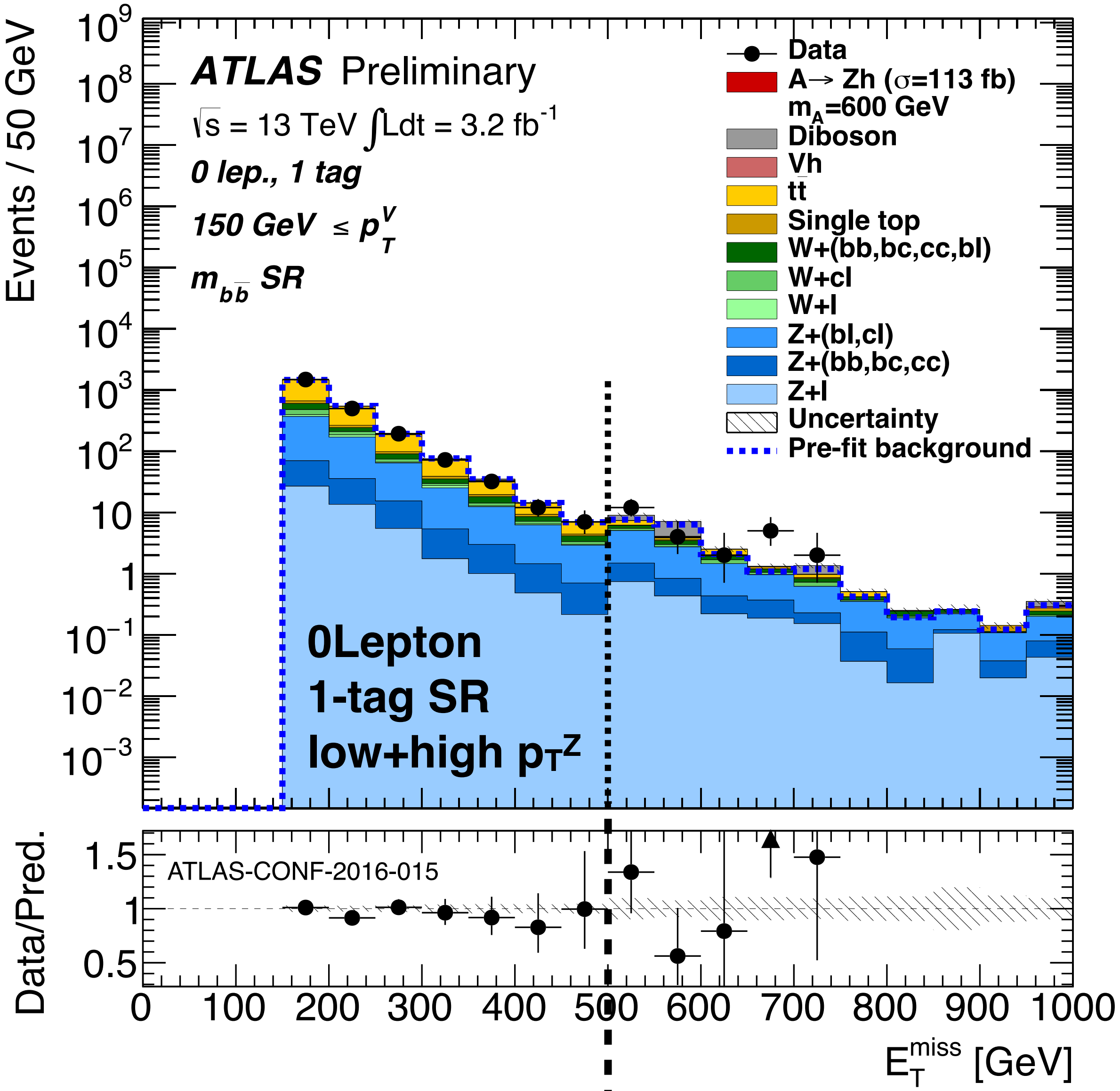
[b-tagging on *track-jets* R=0.2]

# A→Zh(bb): Analysis Overview and Selections

## SR Common Selection [Zh→(νν,l+l-)bb]




**Low $p_T^Z$**

#small-R jets ≥ 2
#b-tag jets = 1,2
$m_H \in$ [110-140] GeV

**Higgs candidate:**
2 leading small-R jets
(1/2 b-tag)

**High $p_T^Z$**

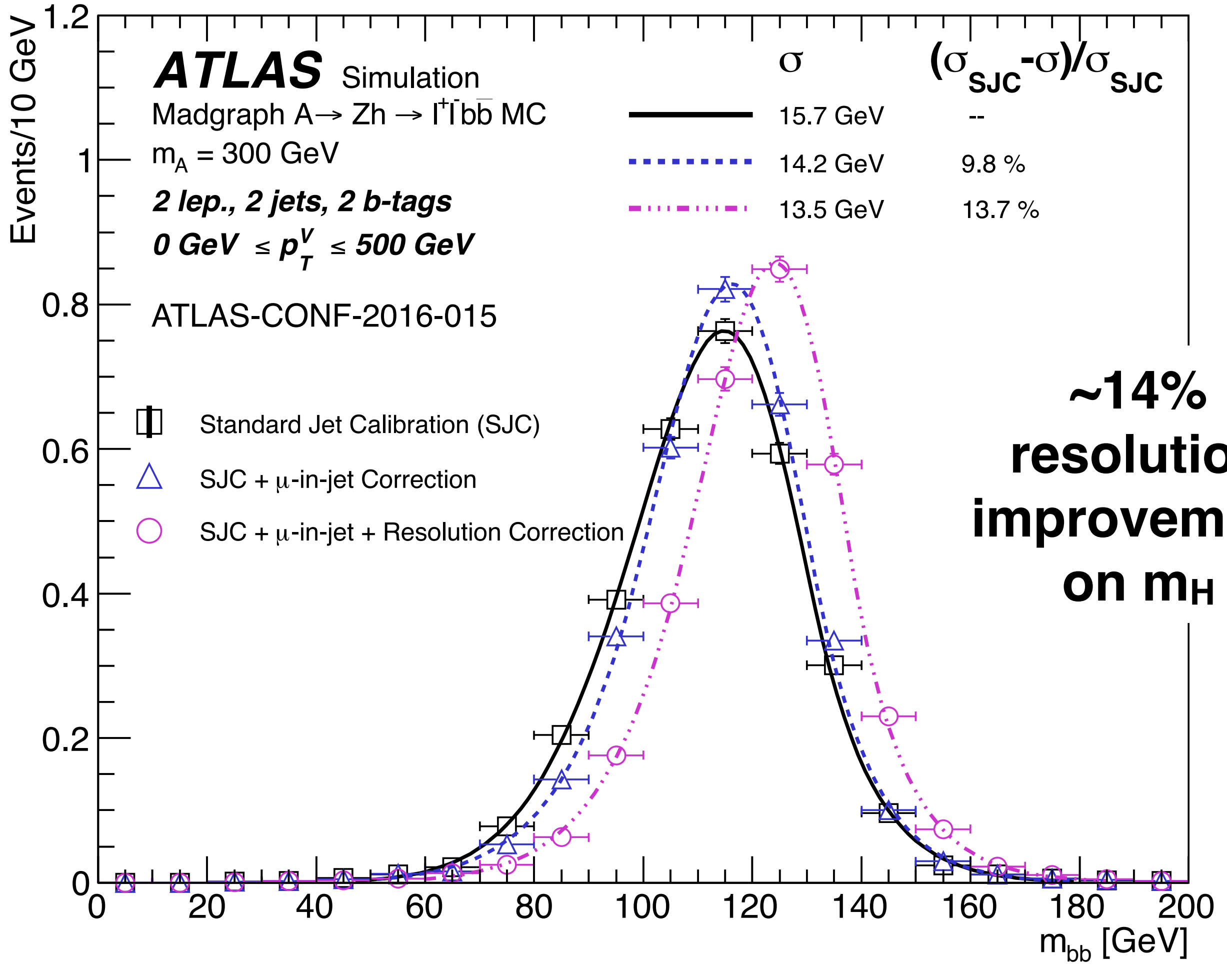
#large-R jets ≥ 1
#b-tag track-jets = 1,2
$m_H \in$ [75-145] GeV

**Higgs candidate:**
leading large-R jet
(1/2 b-tag track-jets)

$p_T^Z$ =500GeV

## b-jets Energy Corrections

- **semileptonic b-decays**
  add closest (ΔR) muon's energy to b-tagged jets
- **jet response correction** (small-R jets)
  multiplicative $p_T$ response factor on b-jet 4vector



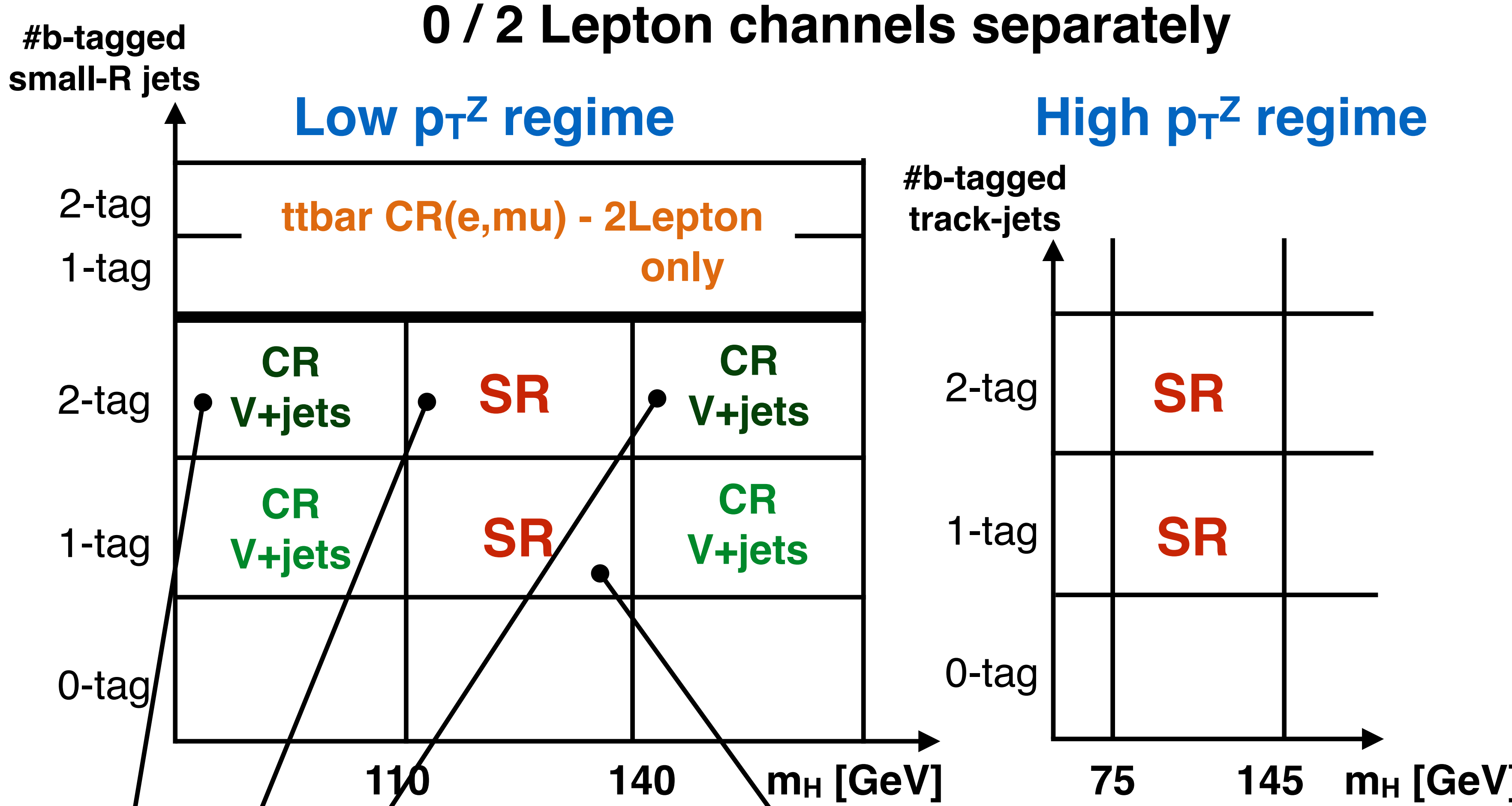

**~14% resolution improvement on $m_H$**

**0Lepton:**
- high $E_T^{miss}$ ( > 150 GeV)
- QCD-rejection cuts (topology + kinematic)

**2Lepton:**
- low $E_T^{miss}$ ( $E_T^{miss}/\sqrt{H_T} < 3.5$)
- $m_{ll}$-window around Z peak (l=e,mu)

# A→Zh(bb): Signal and Control Regions

## 0 / 2 Lepton channels separately




## 8 Signal Regions (SR)

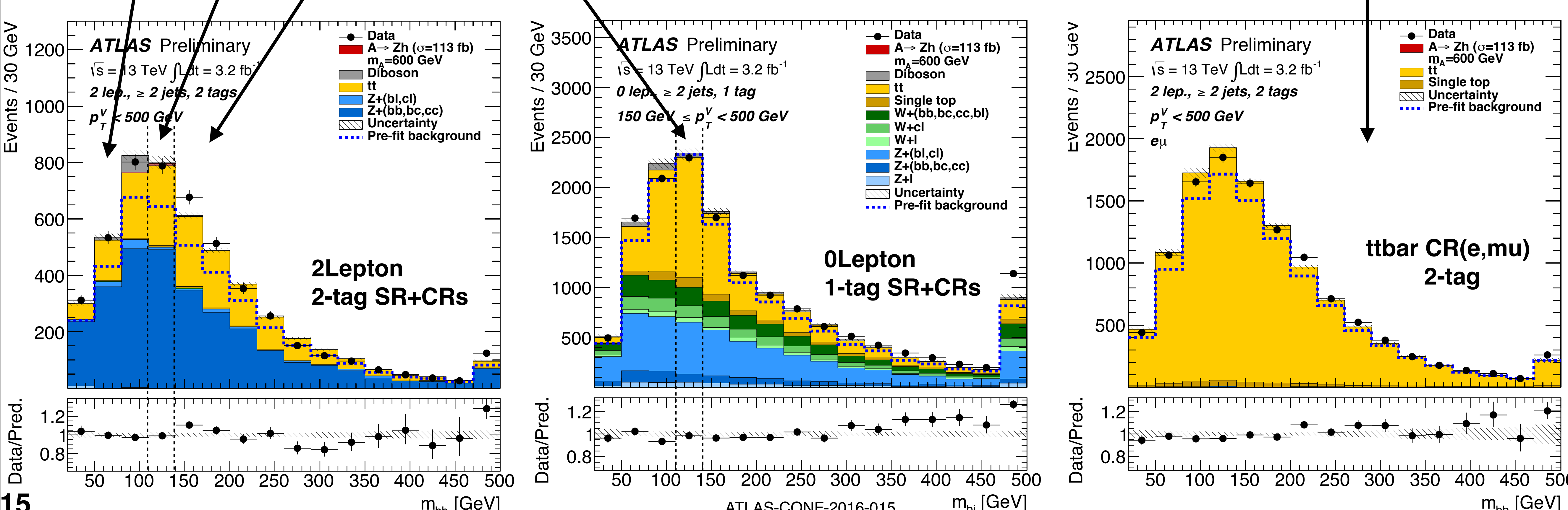
- 4 SRs x 2 leptonic channels

## 6 Control Regions (CR)

- 2 CRs for 0Lepton
- 4 CRs for 2Lepton (including ttbar (1,2)-tag CR)

low and high $m_H$ sidebands merged together

- **V+jets** modelling from $m_H$ sidebands
- **ttbar** modelling from 2Lepton CR(e,mu) [relaxed $m_{ll}$ cut]

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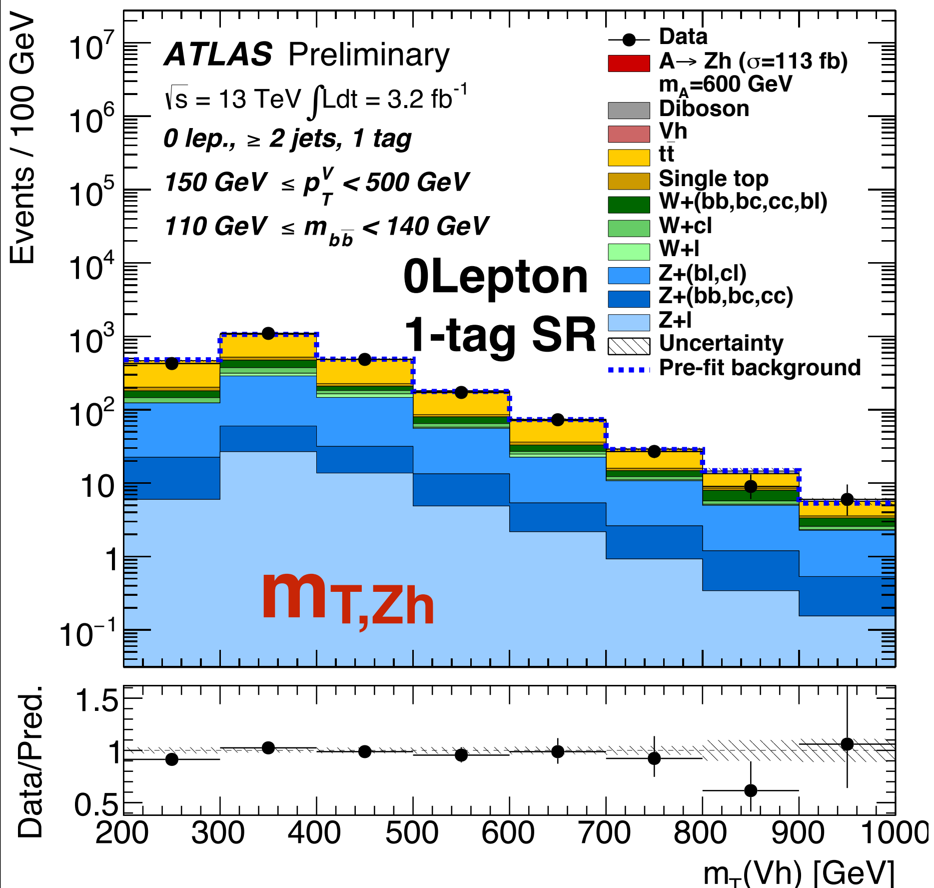
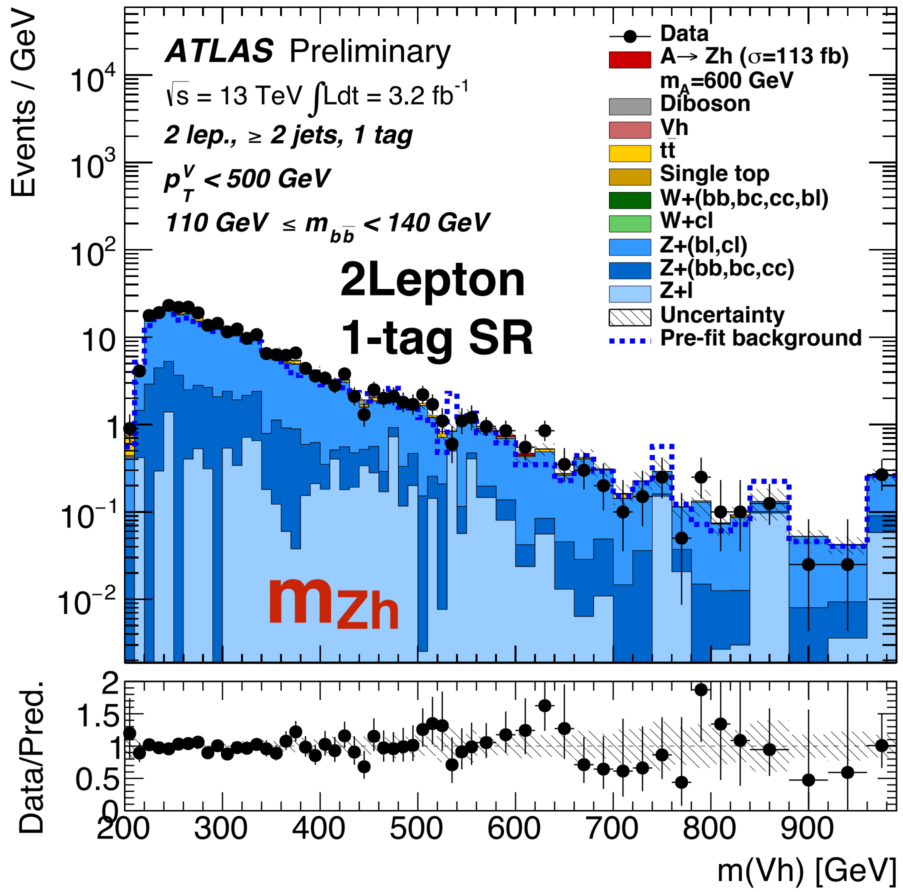
# A→Zh(bb): Systematic Uncertainties and Fit Model

**Data fitted to MC prediction with binned profile likelihood ratio test statistic**

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**Discriminating variable:**

**$m_{Zh}$** invariant mass (2Lepton)

**$m_{T,Zh}$** transverse mass (0Lepton)

$$m_{T,Zh} = \sqrt{(E_T^h + E_T^{miss})^2 - (\vec{p}_T^{\,h} + \vec{E}_T^{miss})^2}$$

- **dominant experimental systematics**:
  calibration/resolution of small-R and large-R jets energy, large-R jets mass (high $p_T^Z$), b-tagging efficiency and mistag rate

- **theoretical systematics & background normalisation**:

ttbar (0Lepton / 2Lepton)
**Z+(bb,bc,cc) / Z+(bl,cl) / Z+l**
**W+(bb,bc,cc,bl) / W+cl / Z+l**
➜
- overall normalisation freely floating
  (gaussian prior for the smaller contributions: Z+l, W+jets)
- relative acceptance variations across analysis categories
- systematic variation on the shape of **$m_{Zh}$** (or **$m_{T,Zh}$**)

Acceptance and/or shape systematics for the smaller backgrounds (diboson, single-top) and signals

**After the maximum likelihood fit to data, the total uncertainty on the signal cross-section ($m_A$=600GeV) is dominated by data statistics (~80%)**

# A→Zh(bb): Results & Conclusions

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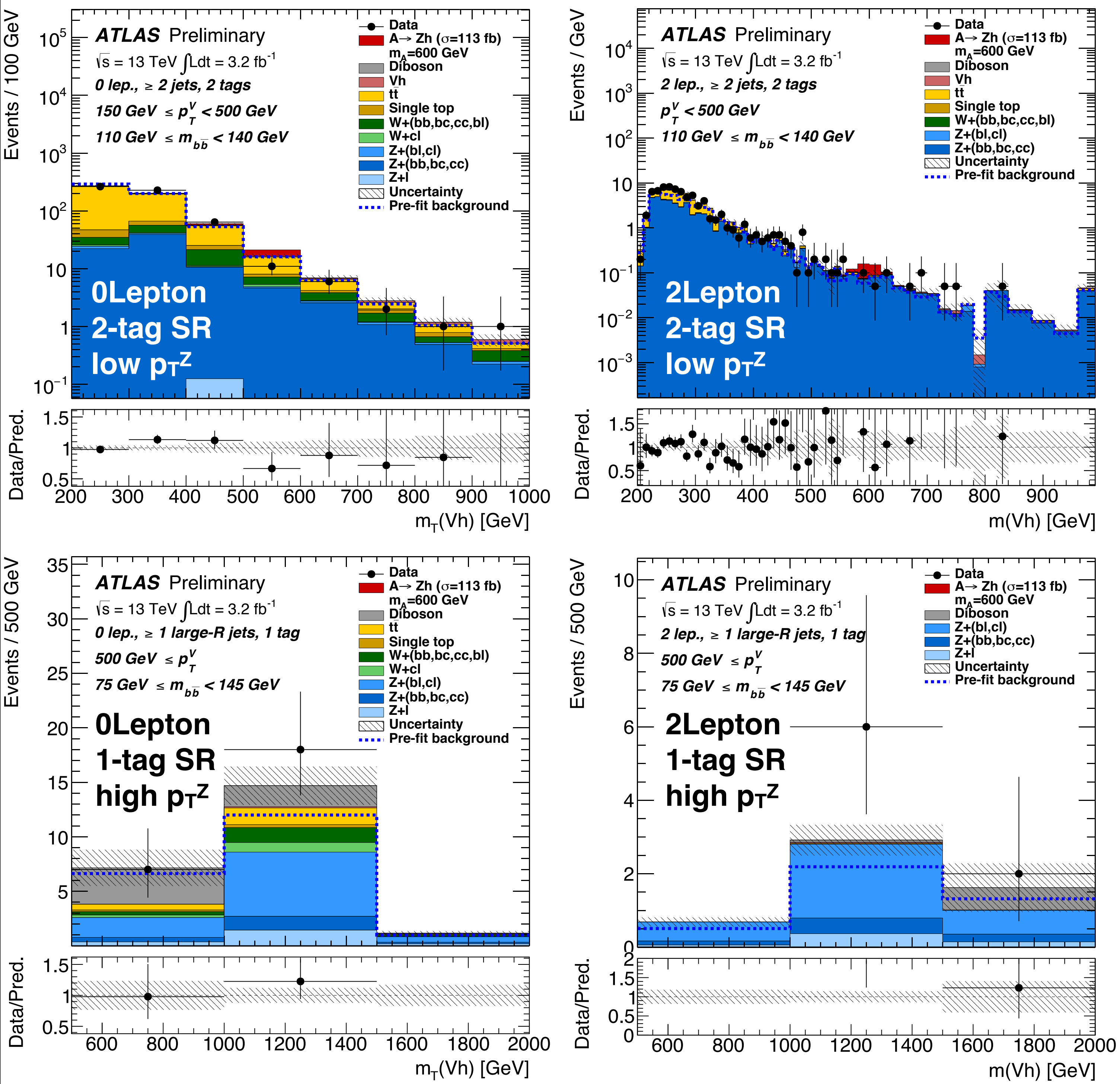
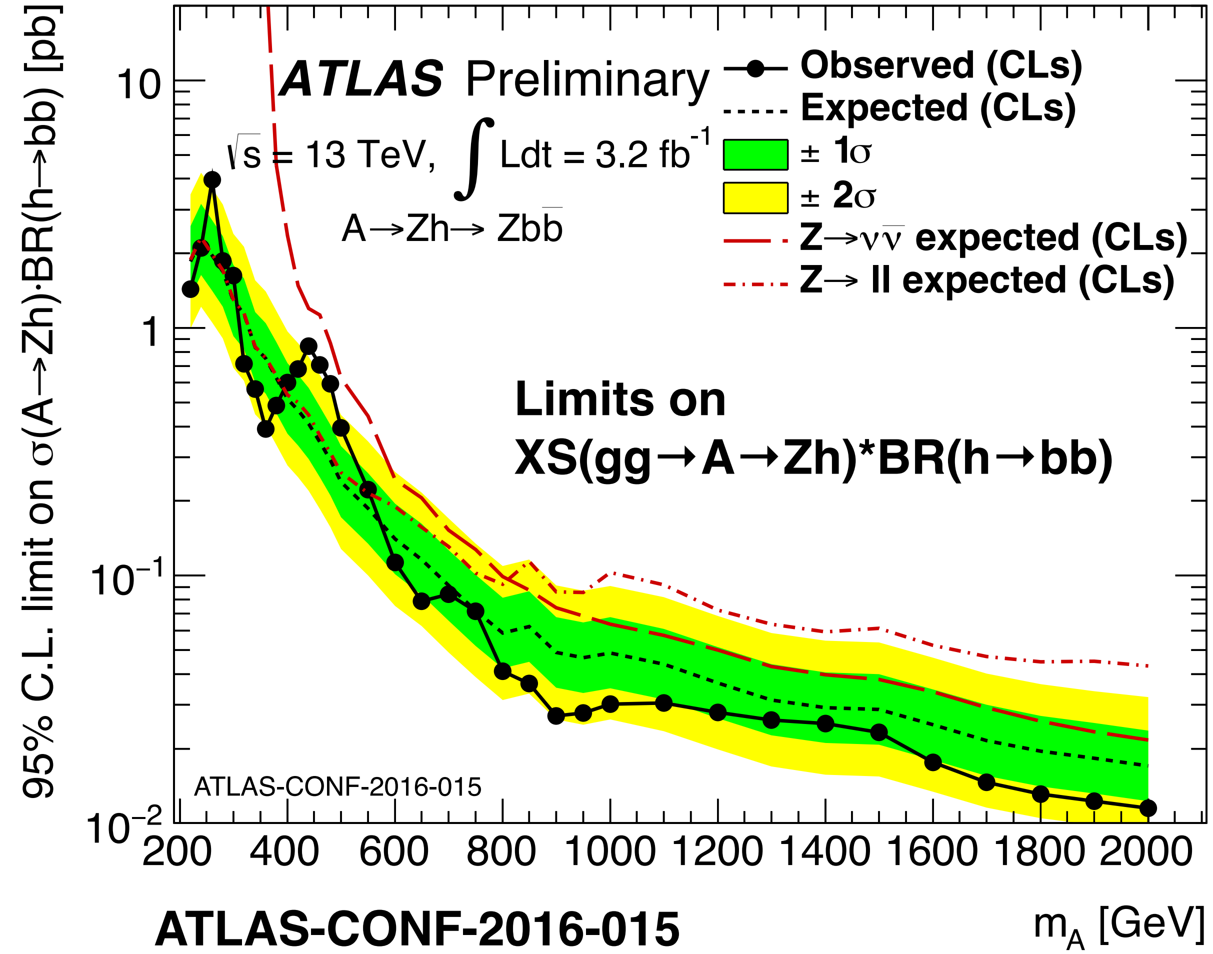



**First Run2 combined result**

(low+high $p_T^Z$, 0+2Lepton channels)

**Run1 exclusion limits improved for $m_A \gtrsim$ 800 GeV**




**No significant excess over the background prediction is observed**

exclusion limits set on the A →Zh XS

**Two upward deviations from the background-only hypothesis $m_A$=260,440 GeV**

[ local significance ~ 2σ ]

# A→Zh(bb): 2 Higgs Doublet Models Interpretation

The results can be interpreted in the framework of **Type-I** and **Type-II** 2HD models:

exclusion limits are shown for $m_A$=600 GeV in the tan(β) / cos(β-α) plane, for points in the parameter space with $\Gamma_A/m_A < 5\%$

**2HDMs**
1 charged-scalar
1 pseudo-scalars
2 neutral-scalars

**tan(β) = v2/v1**
(β = rotation angle that diagonalises the squared mass matrices of charged scalars and pseudo scalars)

**cos(β-α)**
(α = rotation angle that diagonalises the squared mass matrix of the scalars)

Avoid tree-level FCNC imposing discrete symmetries:

- **Type I**: all quarks couples to 1 of the doublets
- **Type II**: Q=2/3 RH and Q=-1/3 RH couple to different doublets

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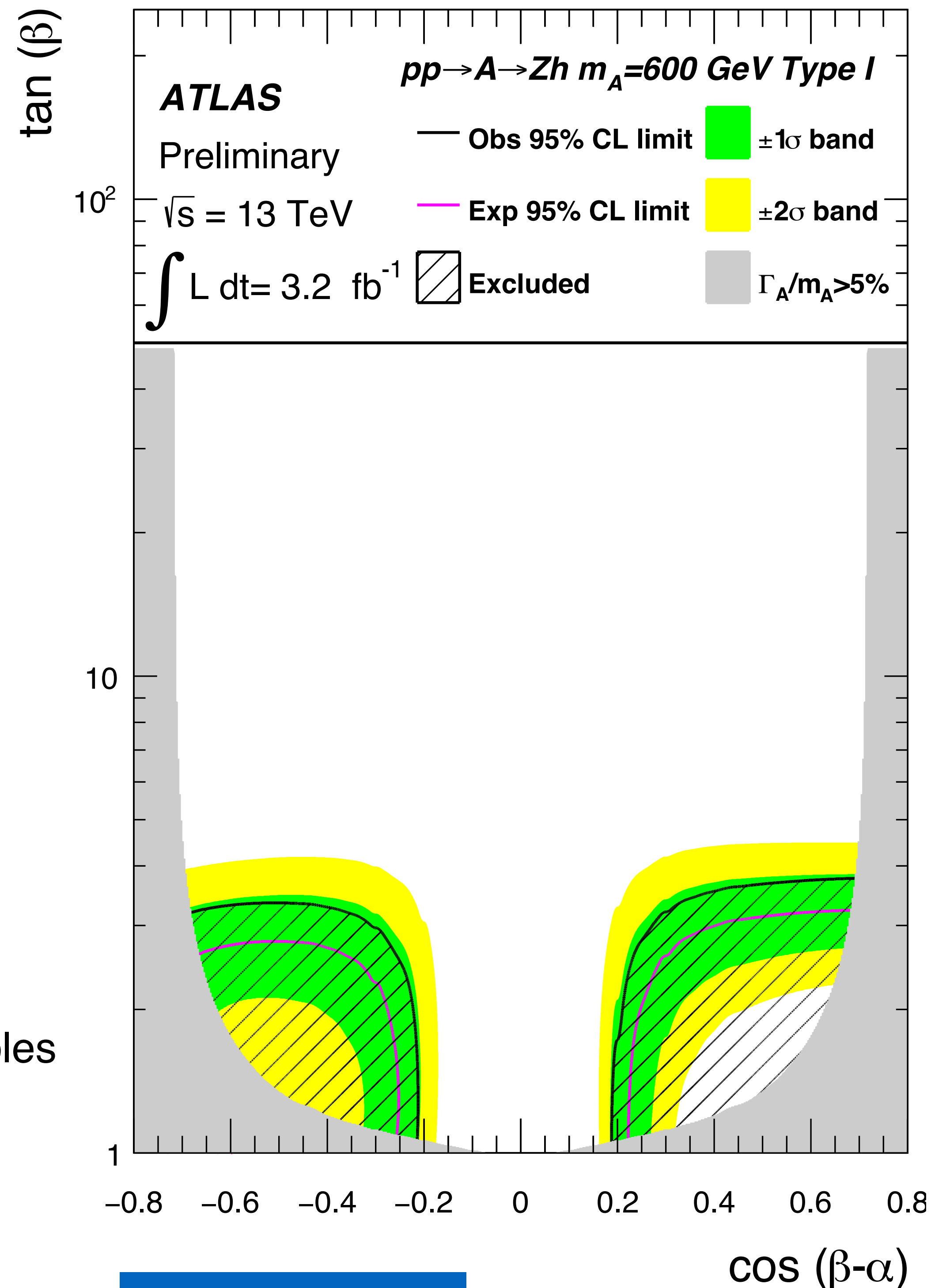
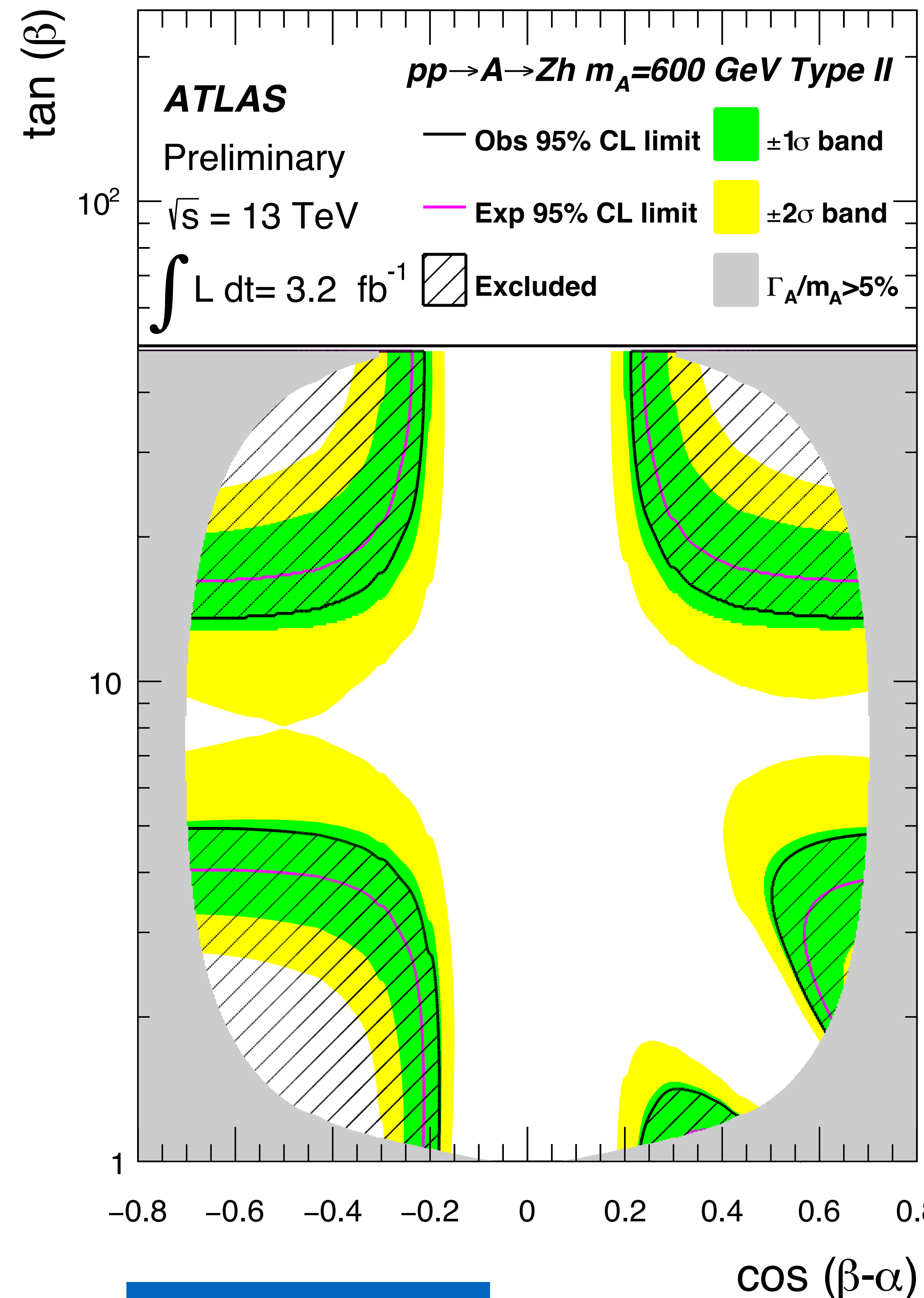



Type-I 2HDM




Type-II 2HDM

# Conclusions and Outlook

## VH ($H\to bb$): SM Higgs search

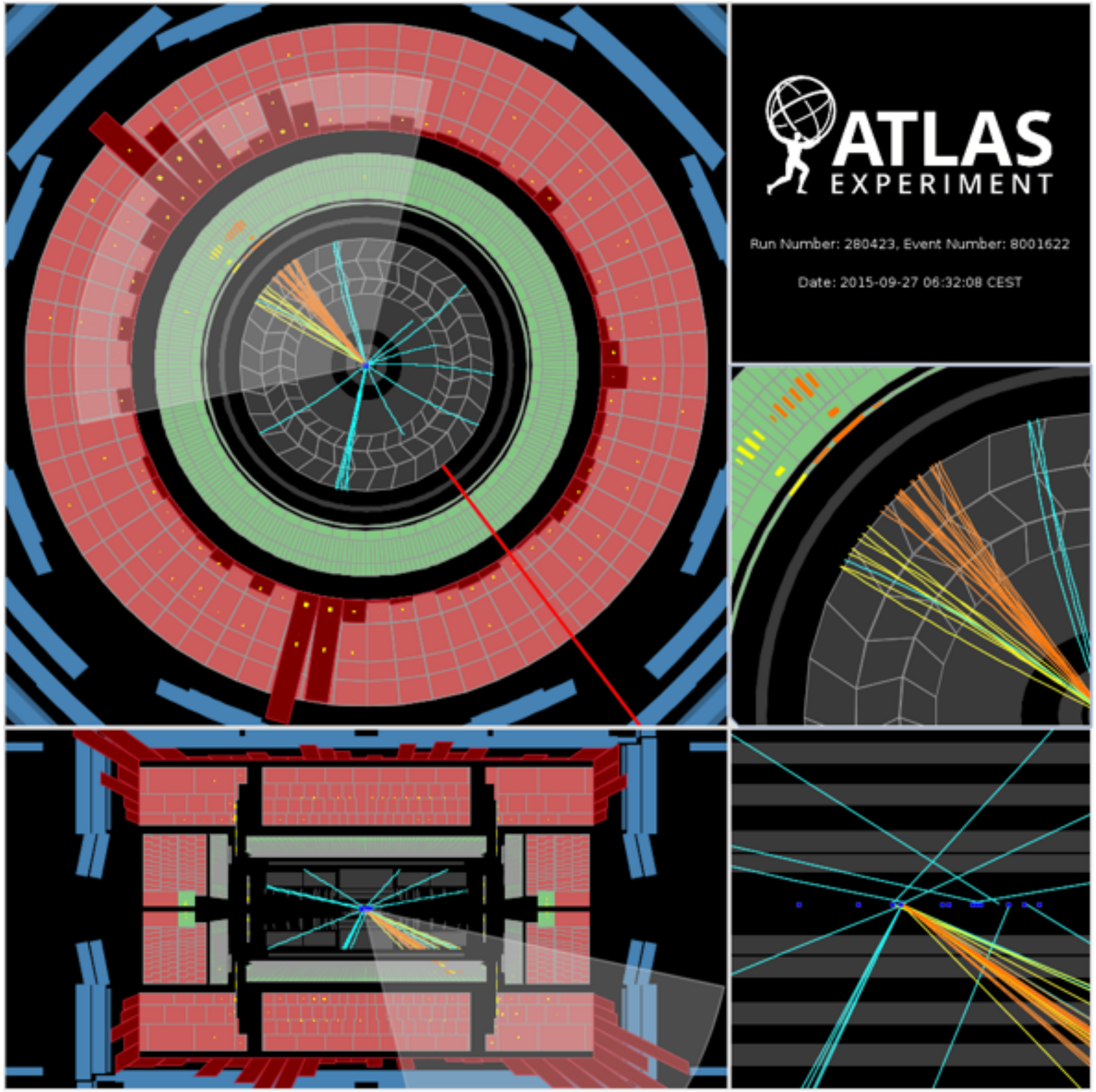
- We do have a very solid Run1 analysis, from which we learnt the fundamental aspects of this search: starting from a solid ground
- Moving **now** to look at the 13TeV data:
  - very promising prospects for the Run2 dataset
  - HEFT good candidate for an interesting interpretation

Looking forward to the 13TeV results!

## $A\to Zh$ ($h\to bb$): 2HDM A boson search

- We had a first comprehensive look at the Zh(bb) phase space, combining both resolved and merged regimes
- So far no significant excess, but important to keep looking with the new data (since **statistics** is the largest limitation), and identify the aspects of the analysis that can be further improved

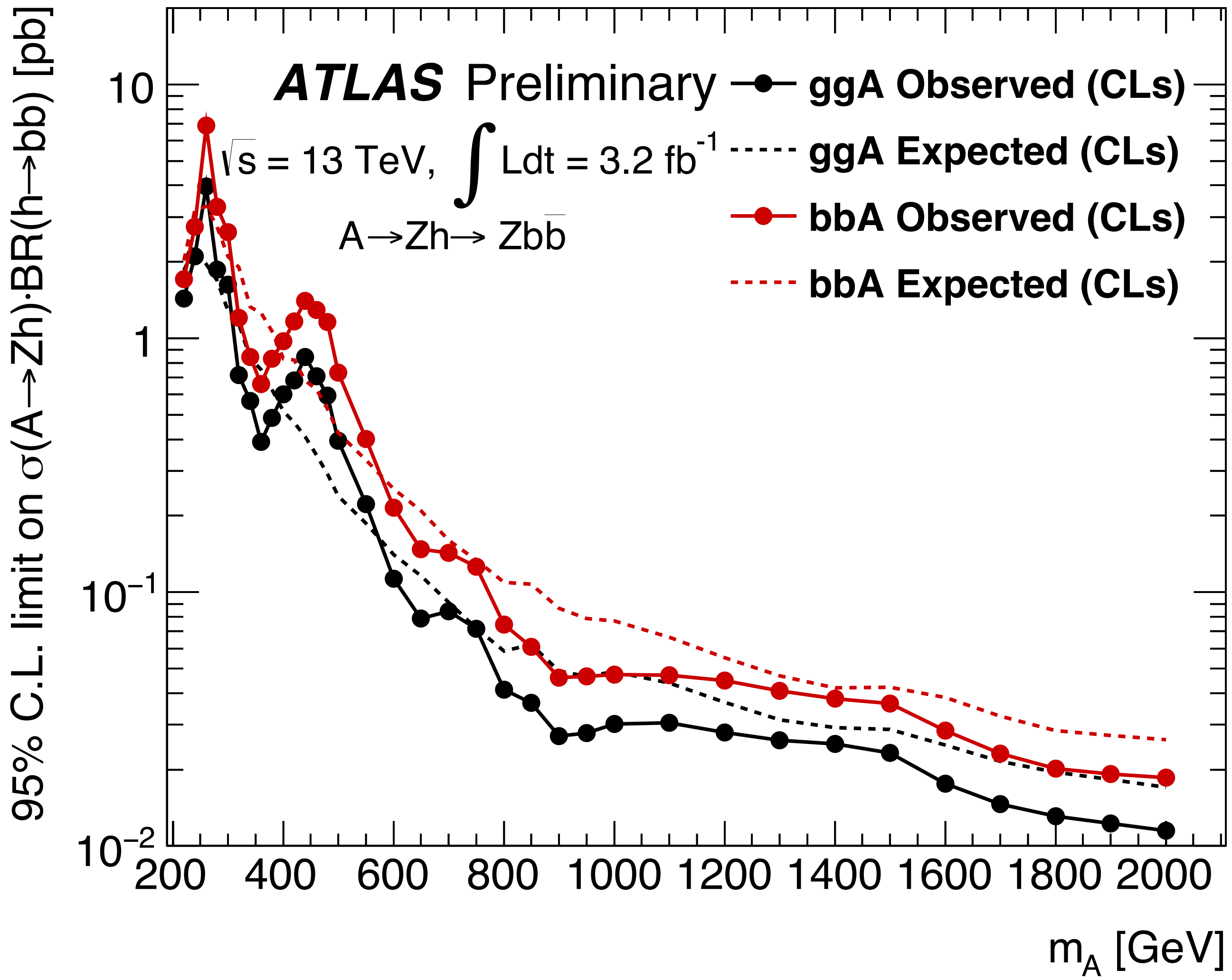
# Back-Up




**0Lepton**
**2-tag SR**
**high $p_T^Z$ event**

**$m_{T,Zh}$ = 985 GeV**

# Cross-Section Limits: bbA vs ggA production

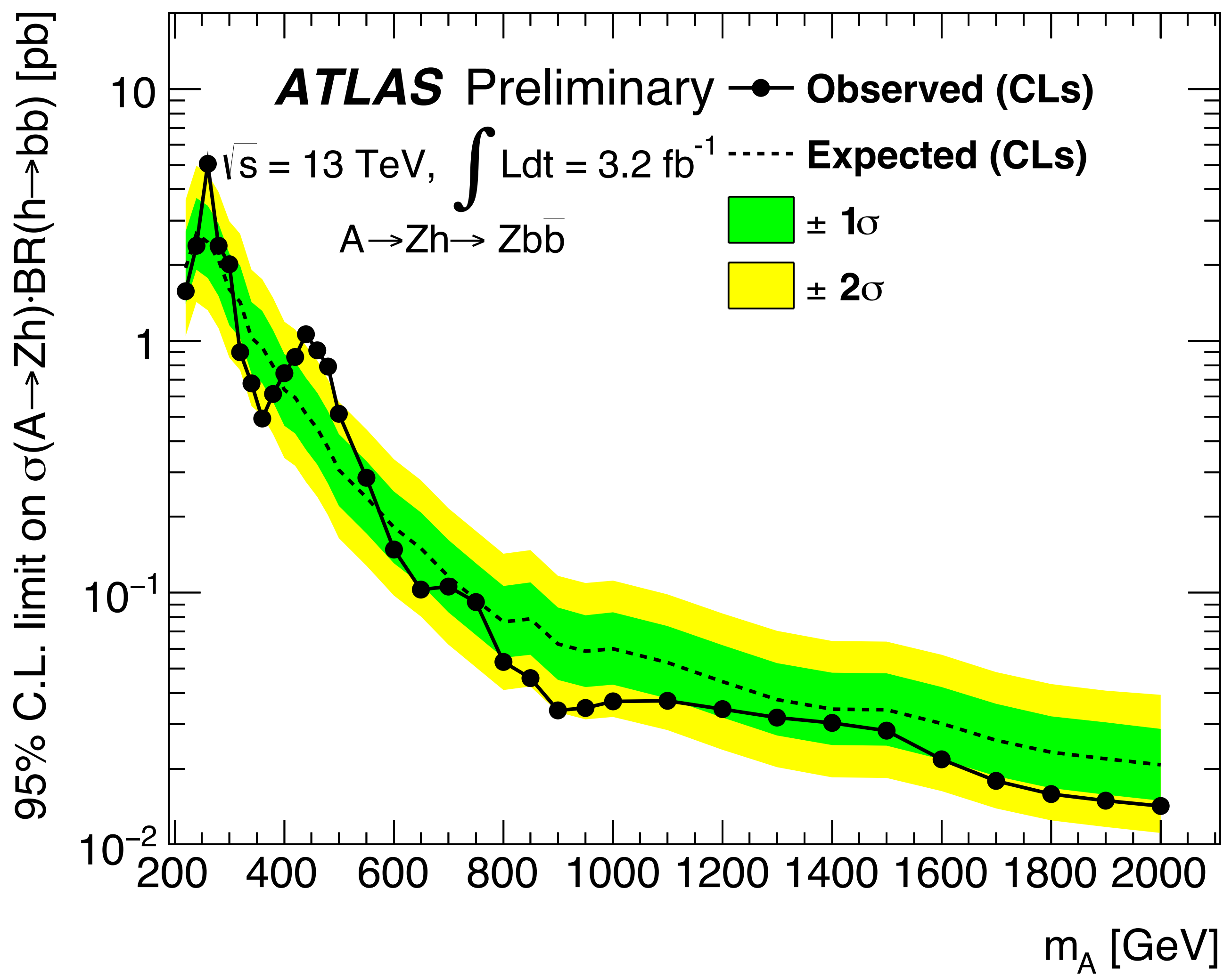



**Limits on**

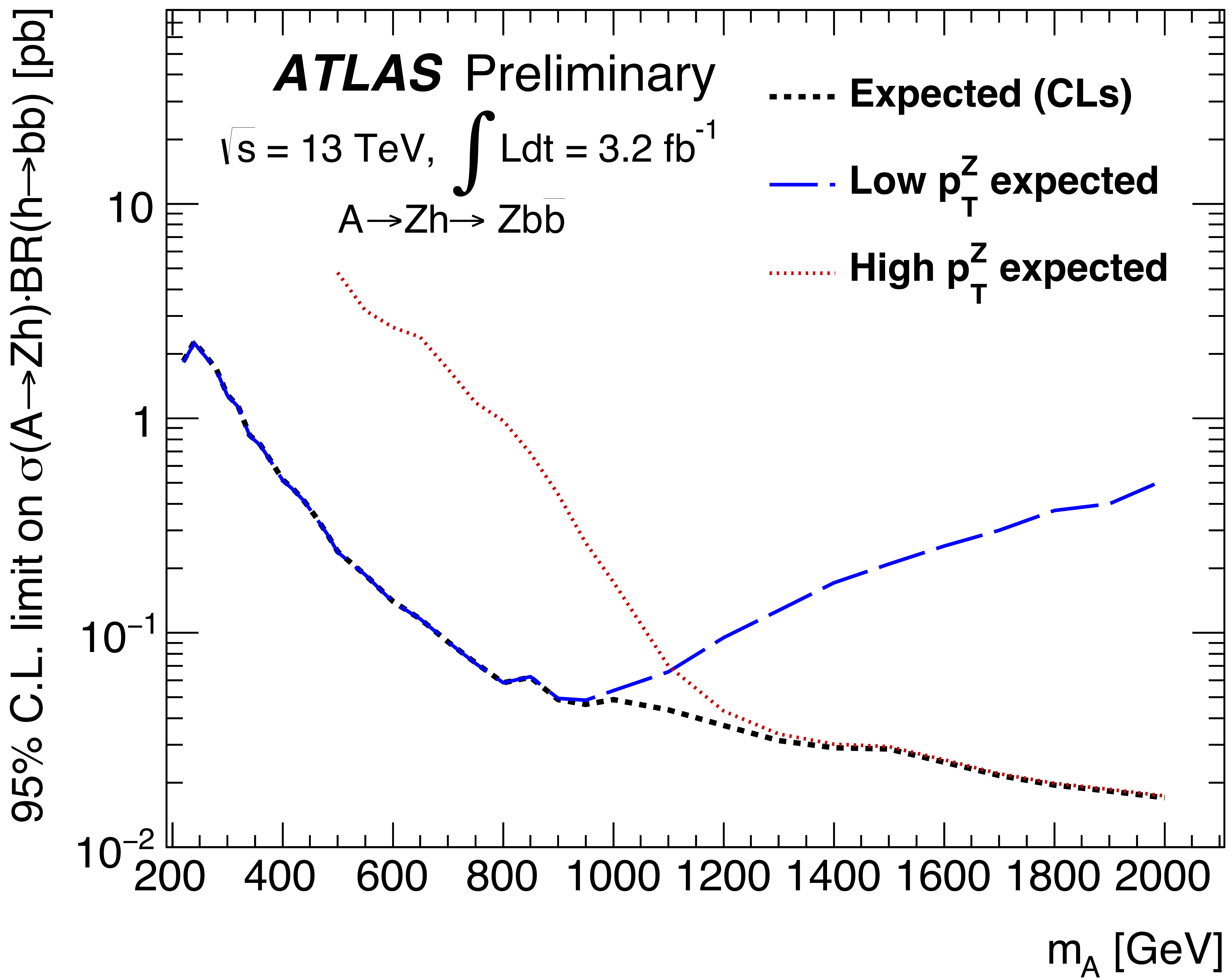
- **XS(bb→A→Zh)*BR(h→bb)**
- **XS(gg→A→Zh)*BR(h→bb)**

**Limits on an equal mixture of gluon-fusion and b-quark associated production**

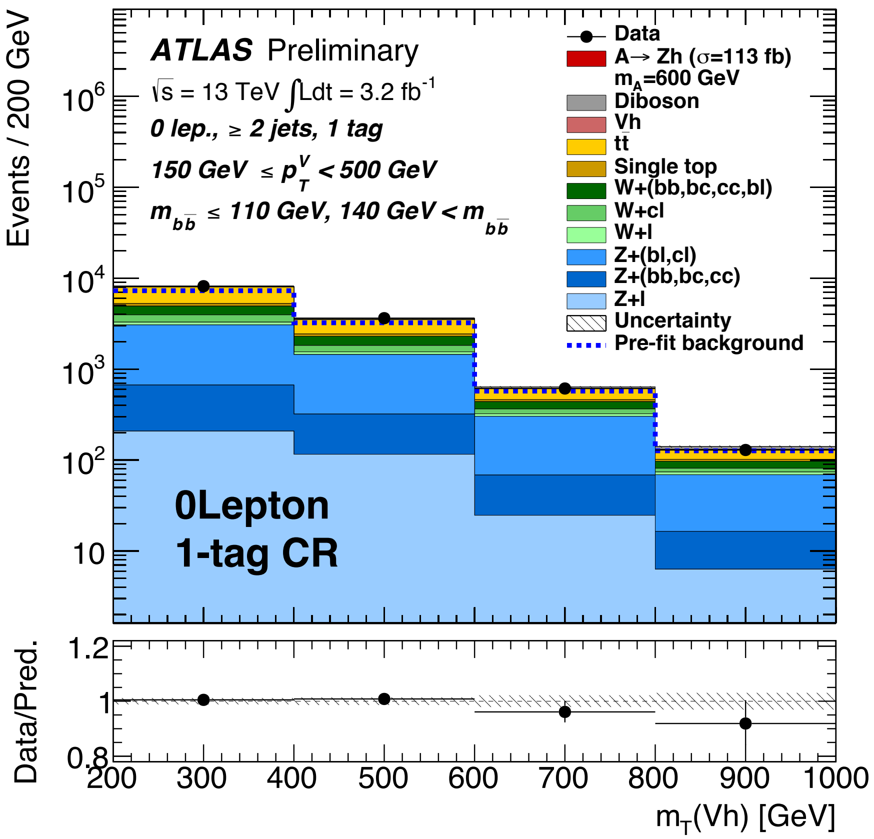
- **50%[bb→A→Zh] + 50%[gg→A→Zh]**

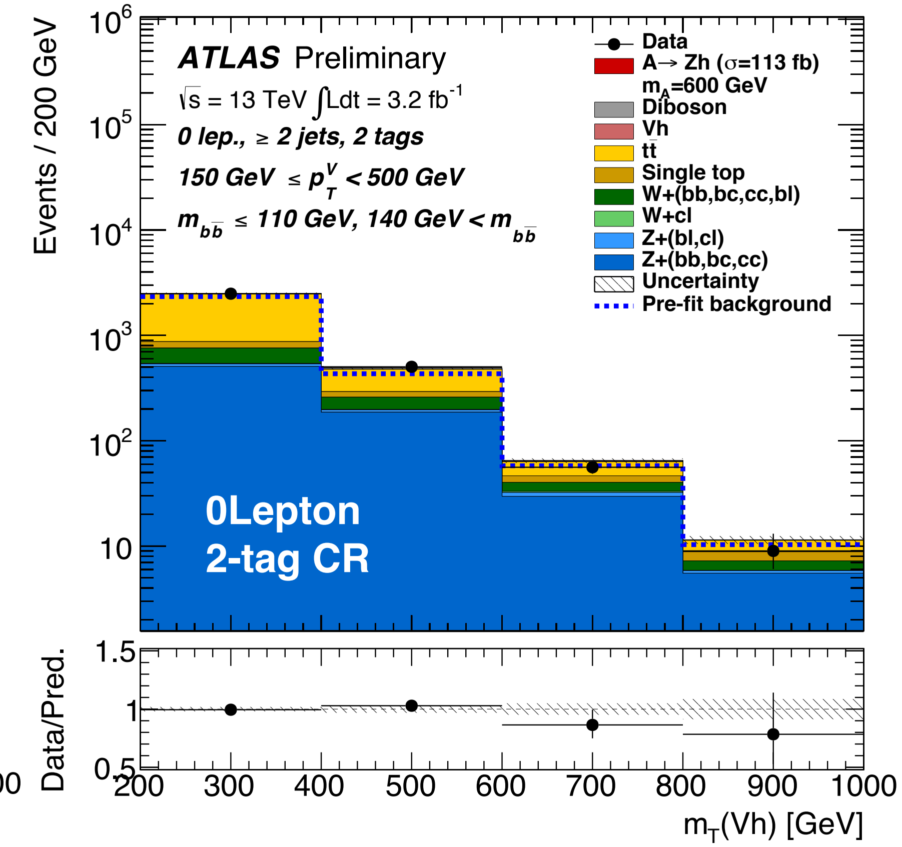


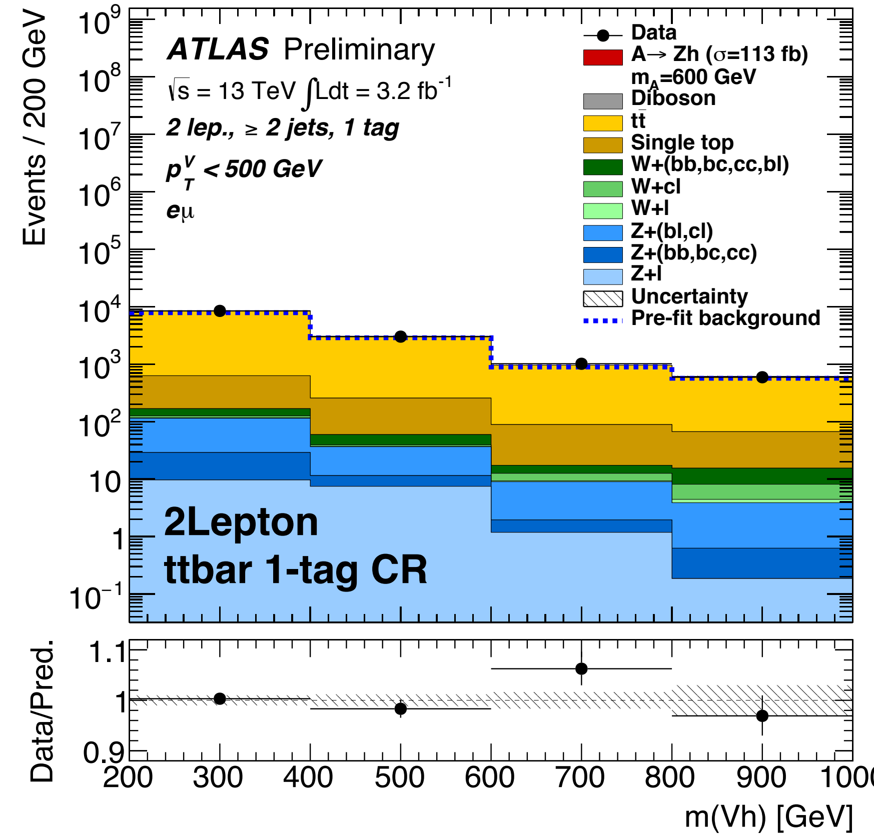
# Cross-Section Limits: resolved vs merged regimes

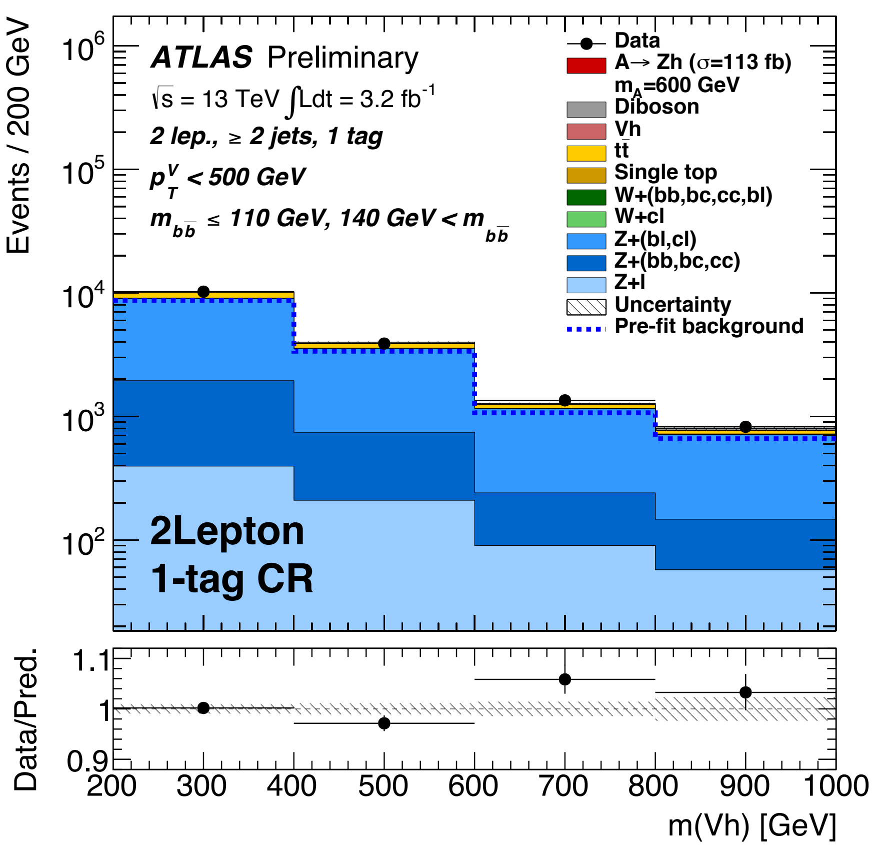


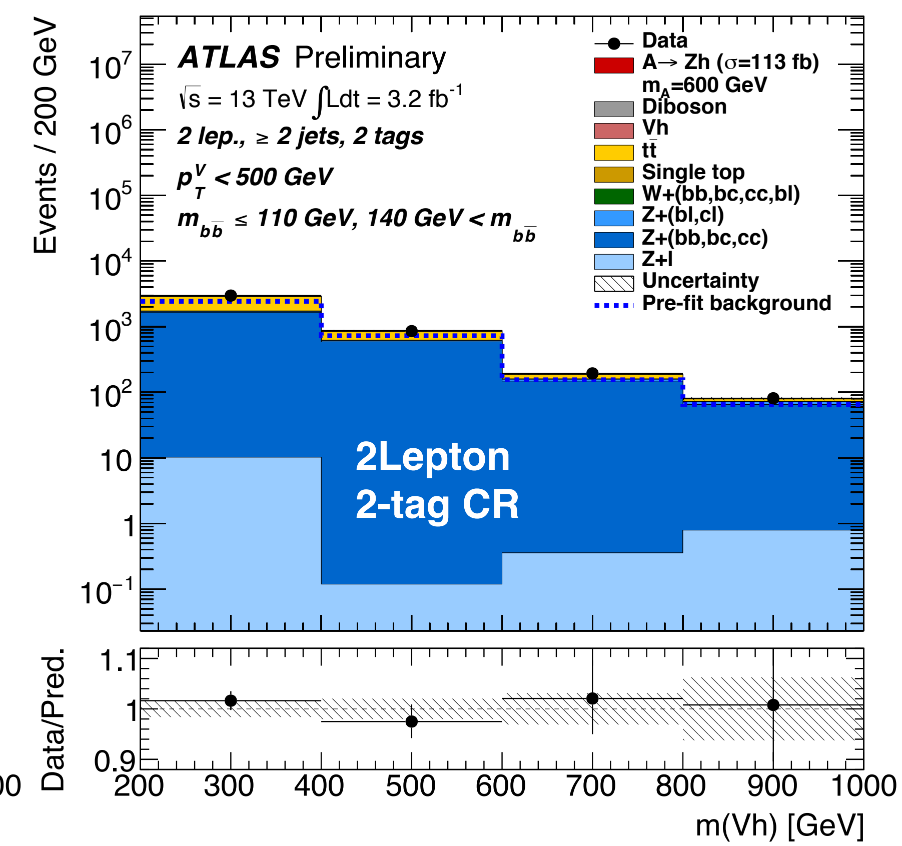
# Control Regions: low $p_T^Z$

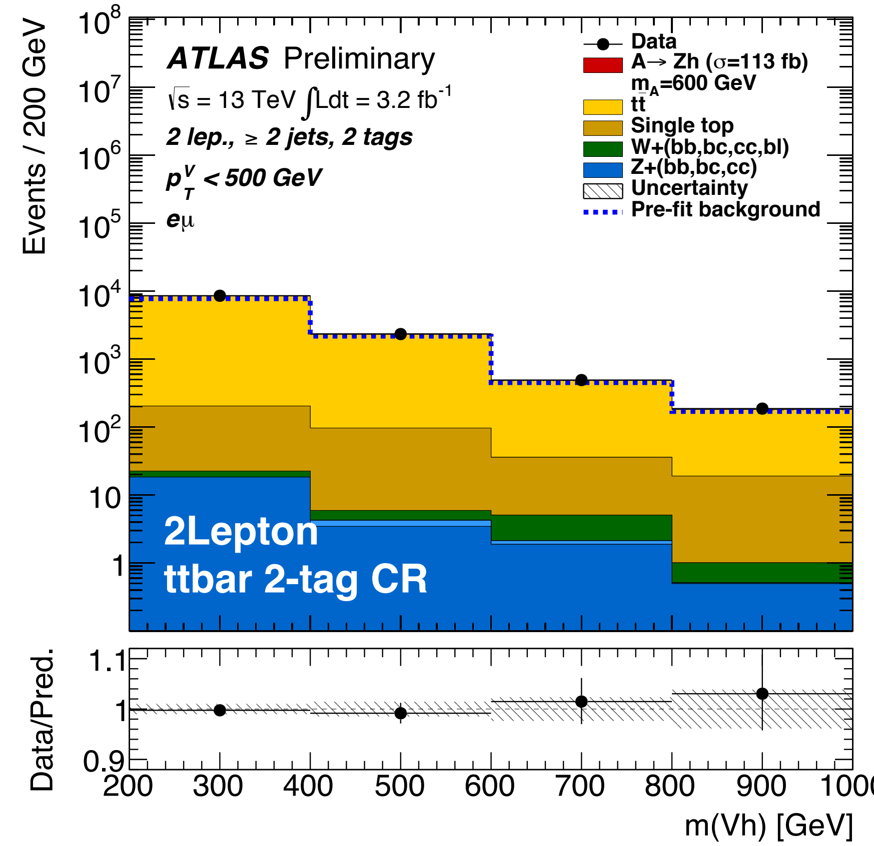


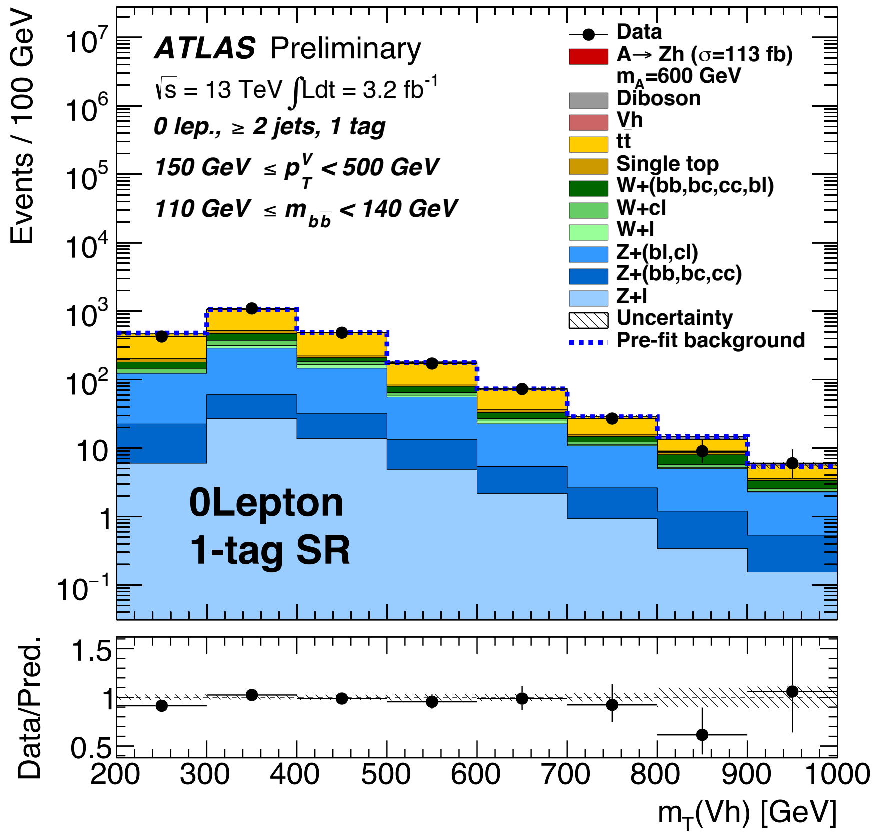



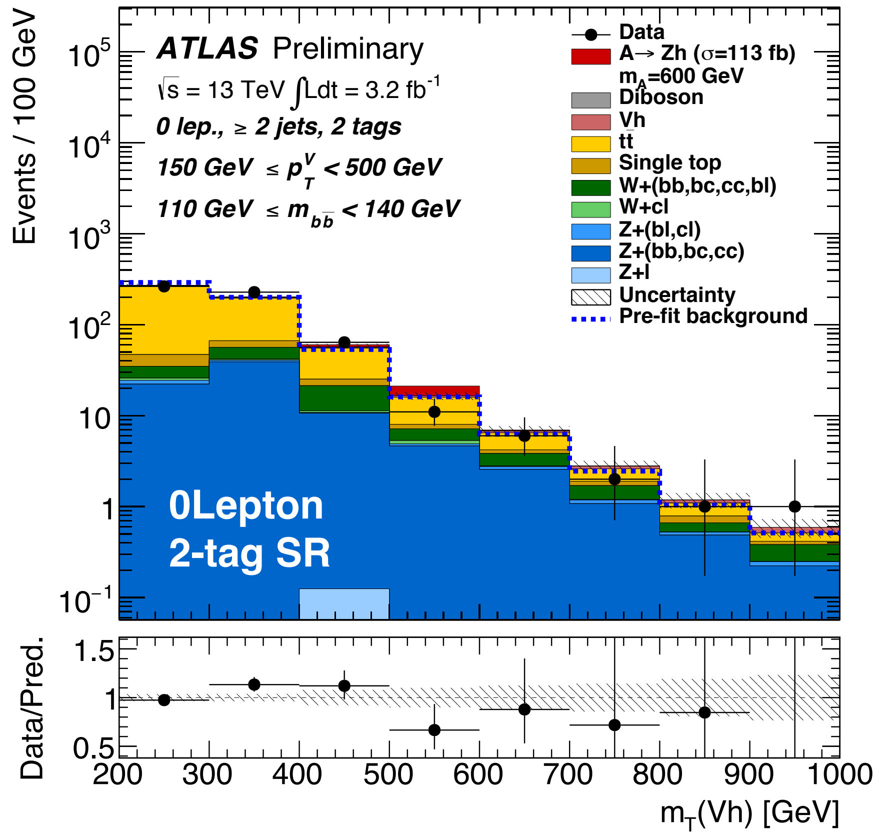



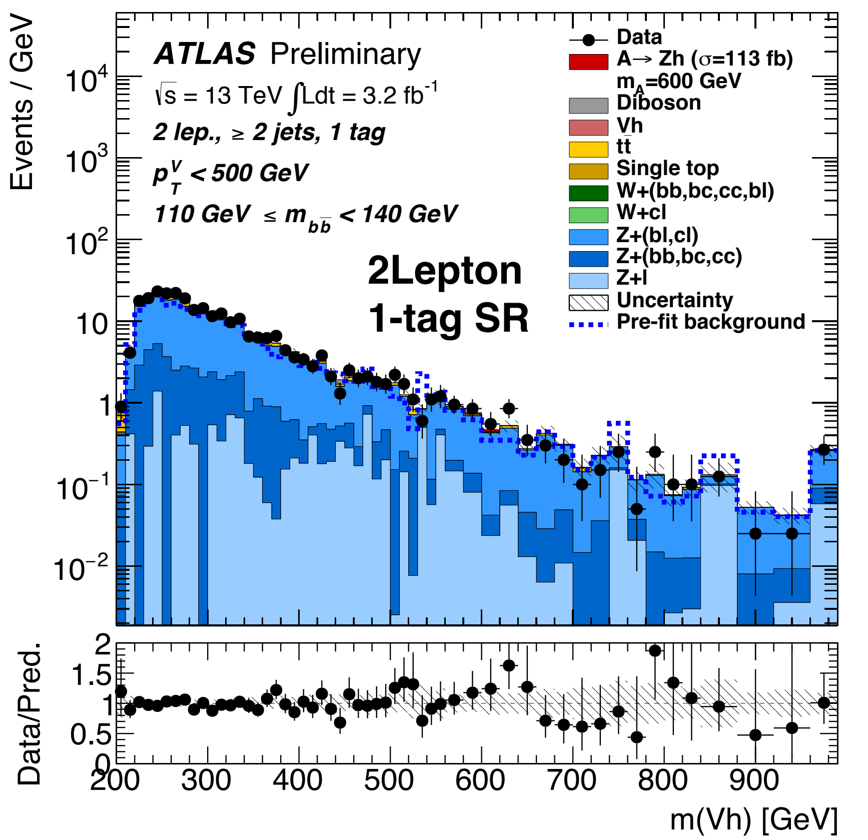



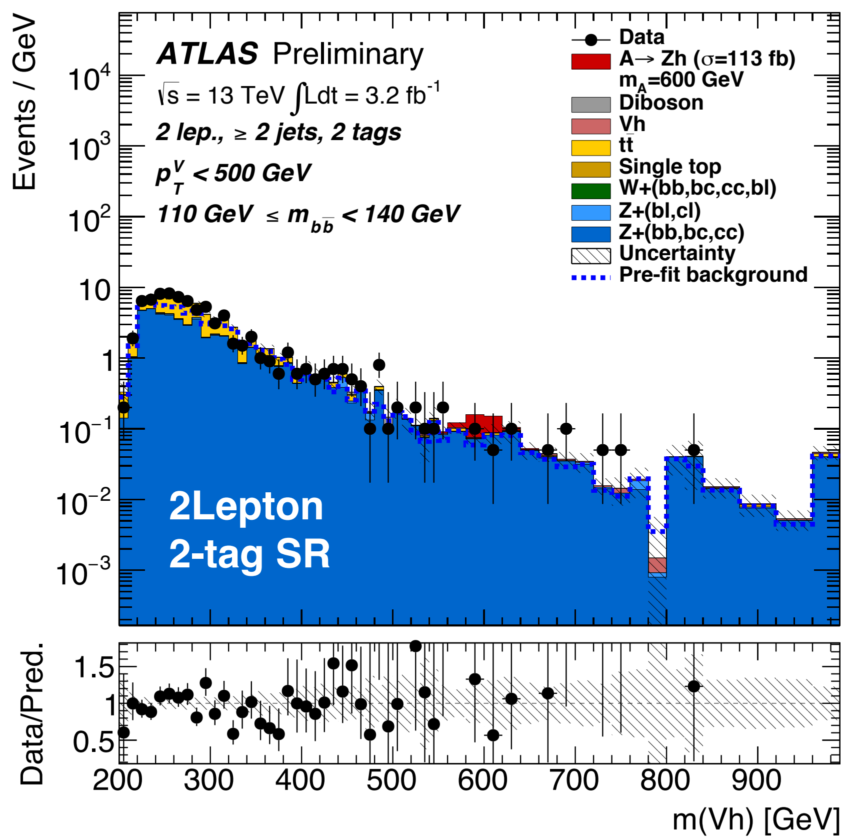



# Signal Regions: low $p_T^Z$

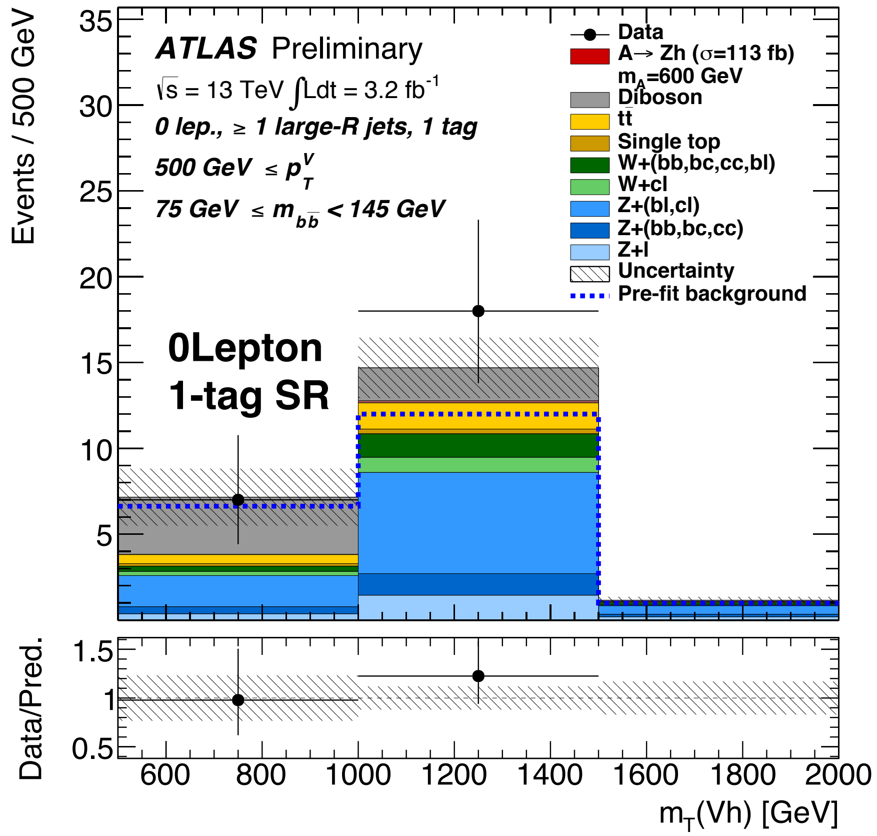


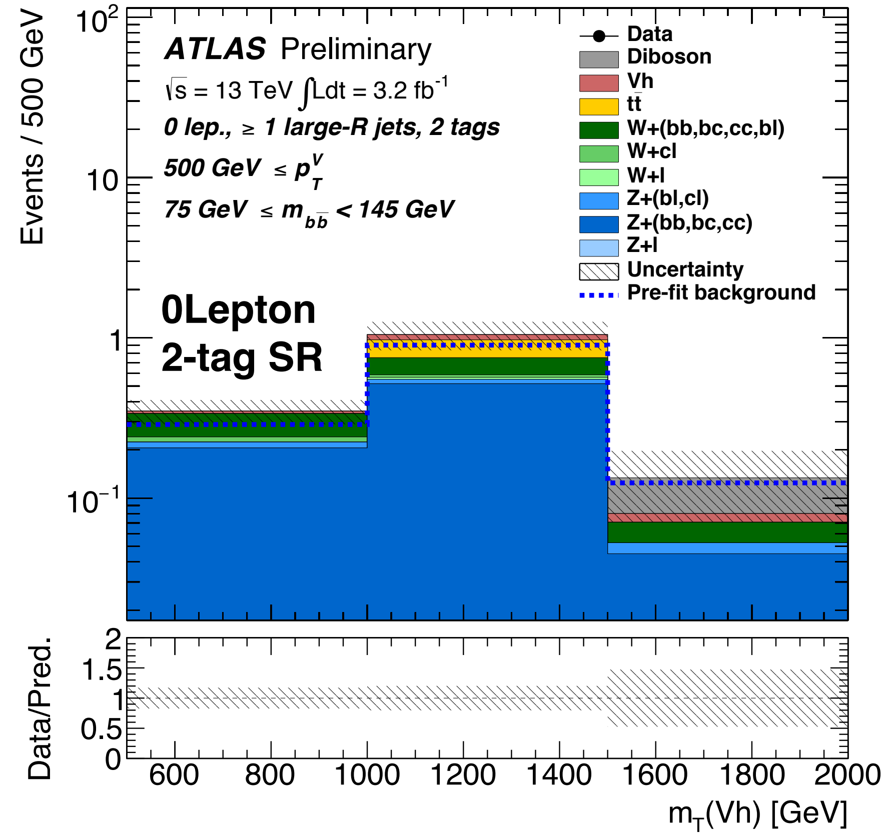



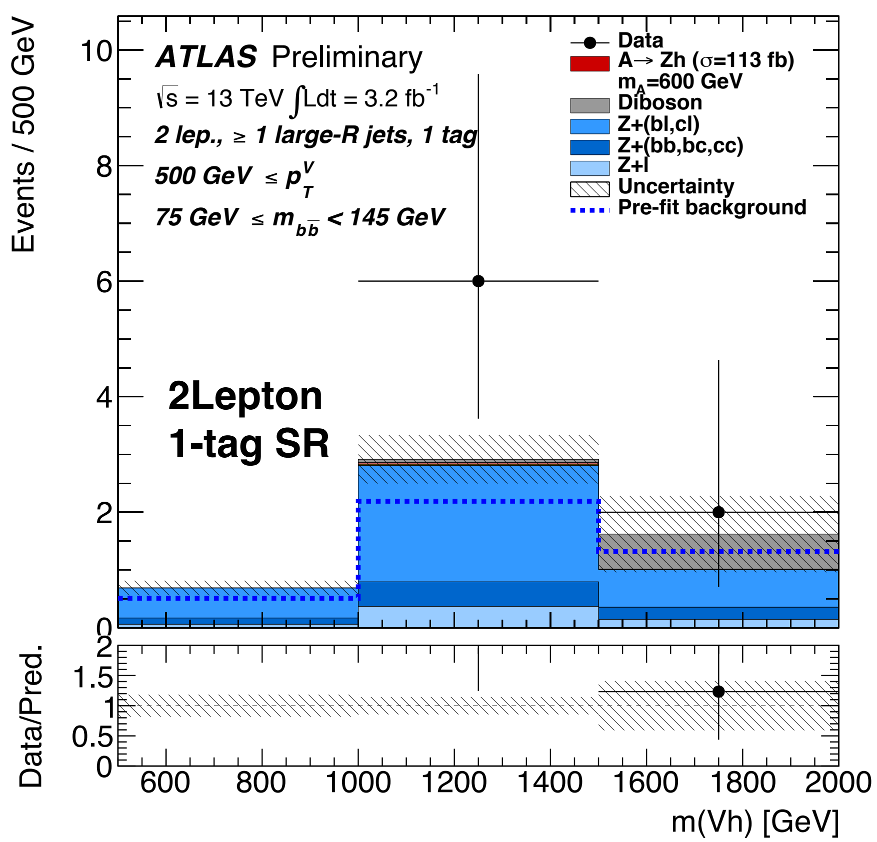



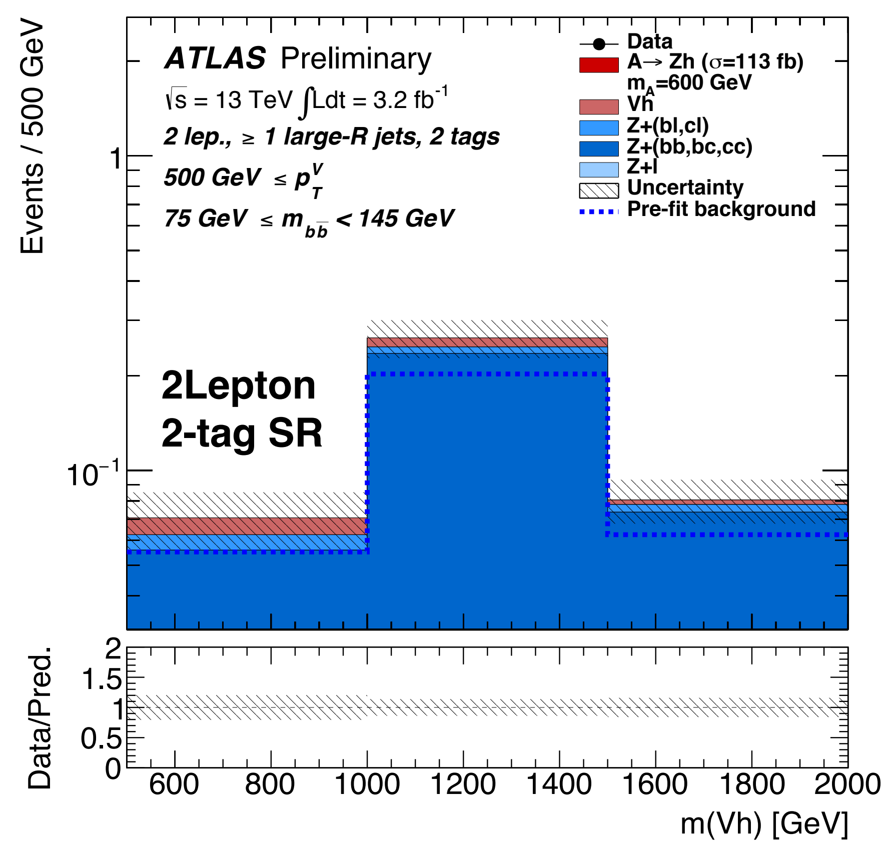



# Signal Regions: high $p_T^Z$

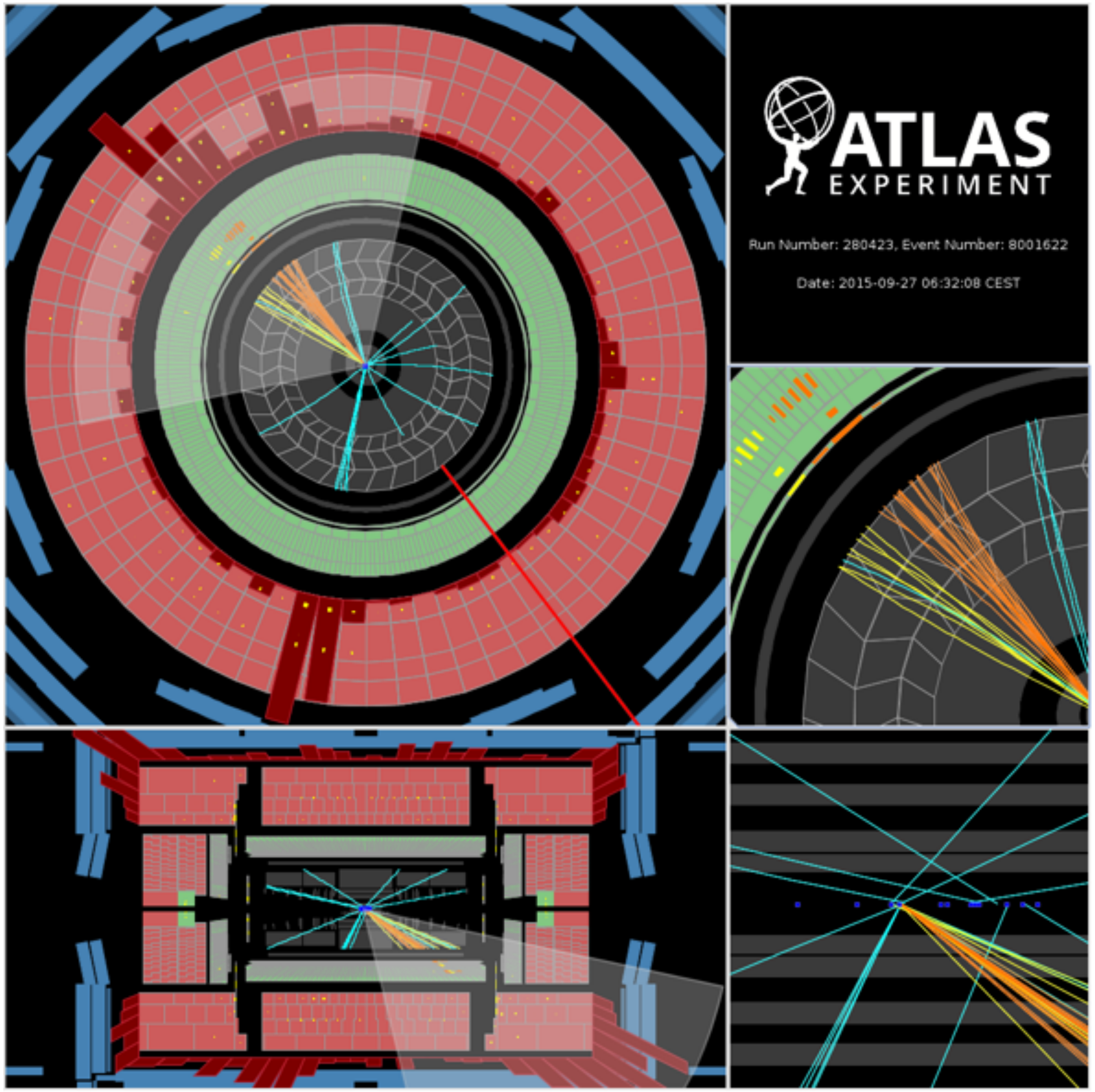


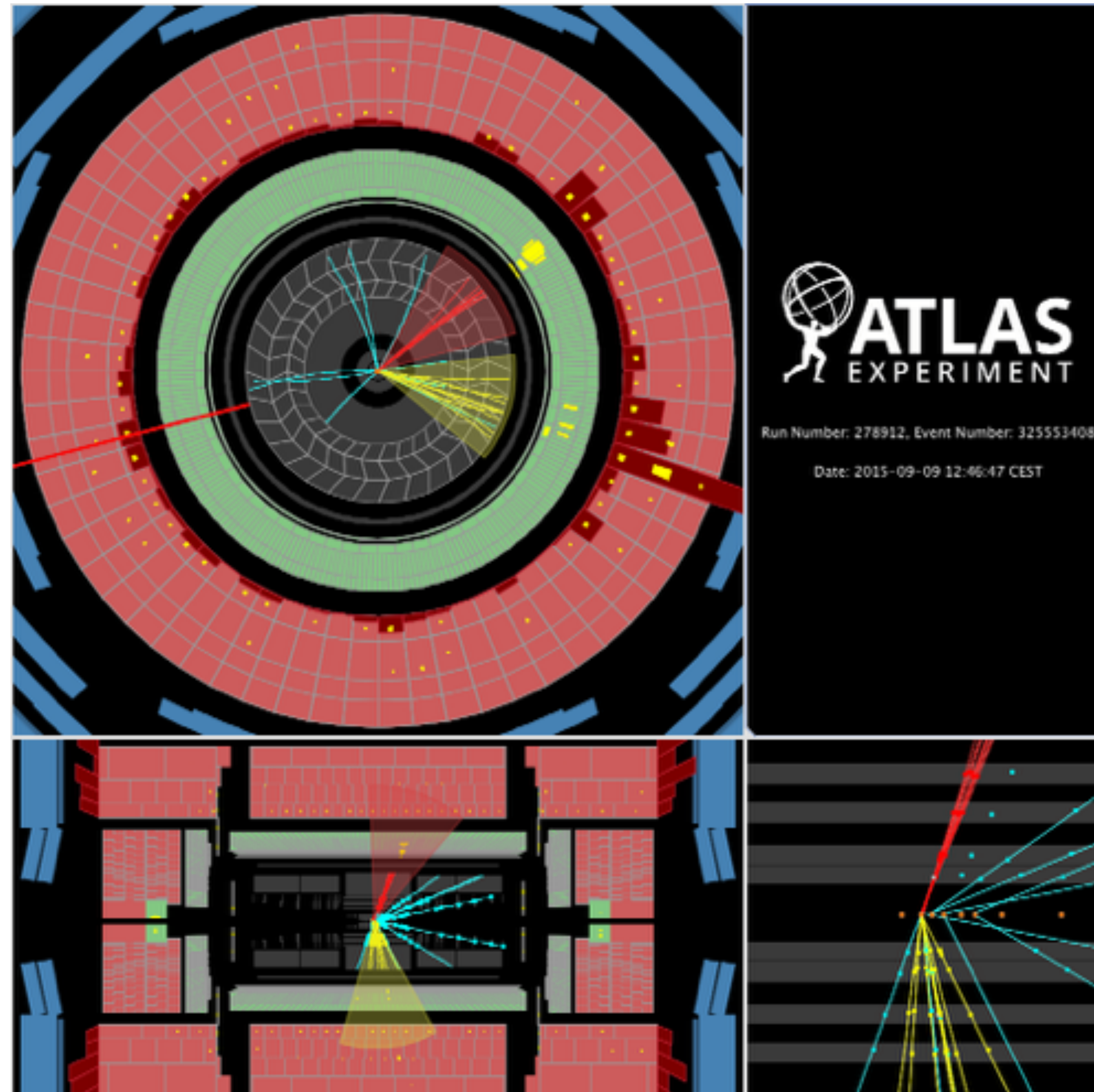



# 0Lepton Event Displays

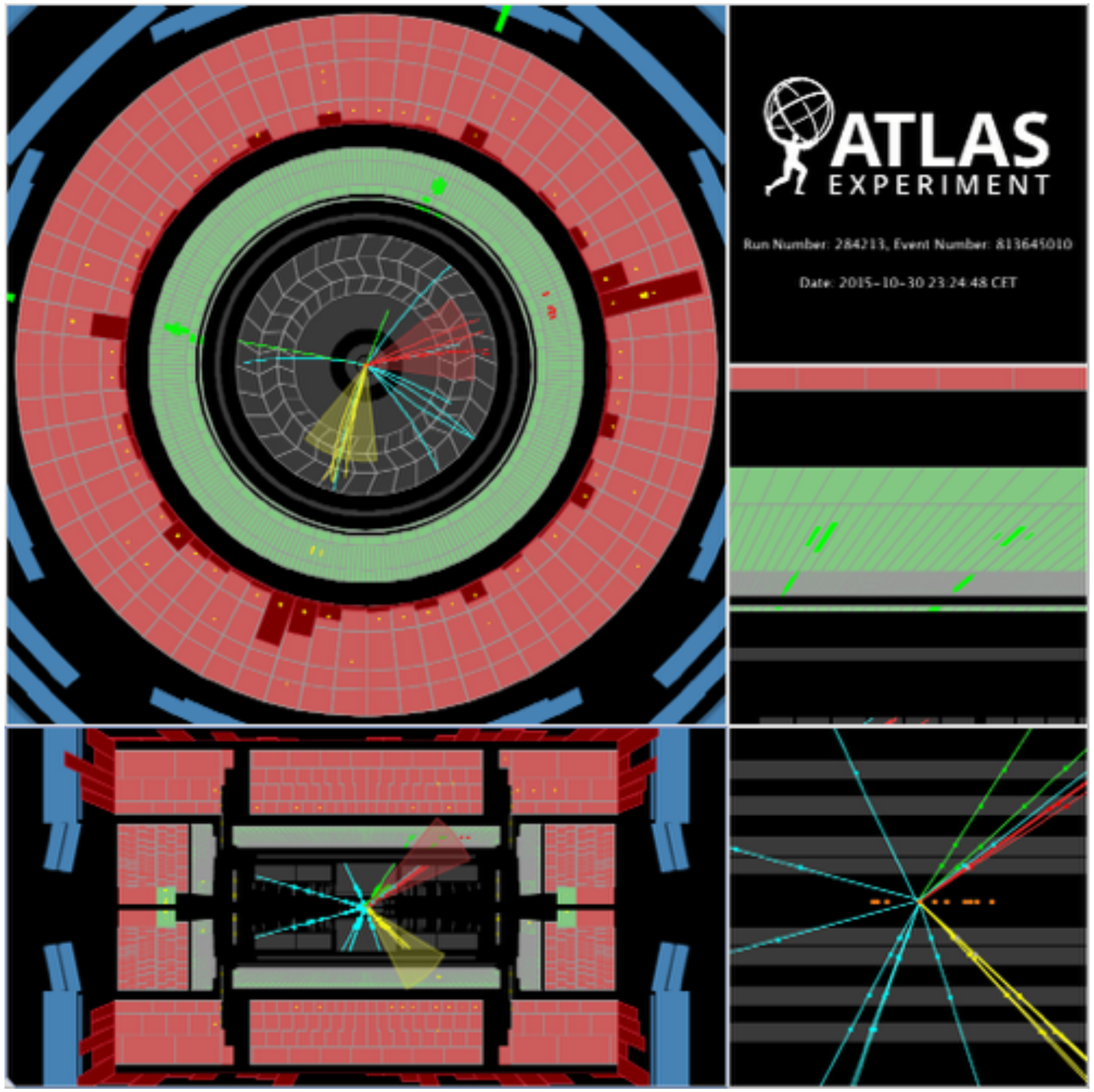


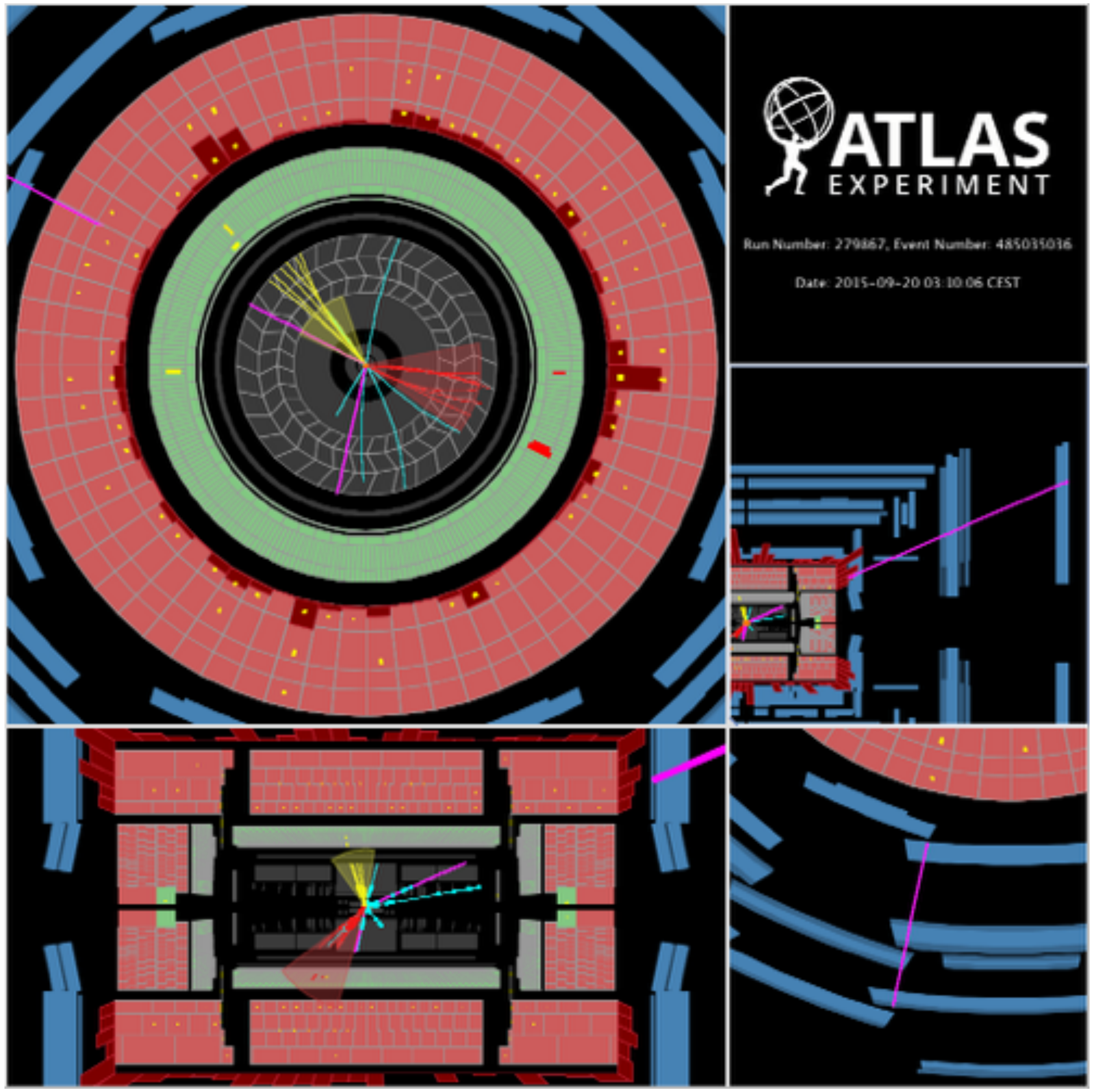

**High $p_T^Z$**

**Low $p_T^Z$**

# 2Lepton Event Displays

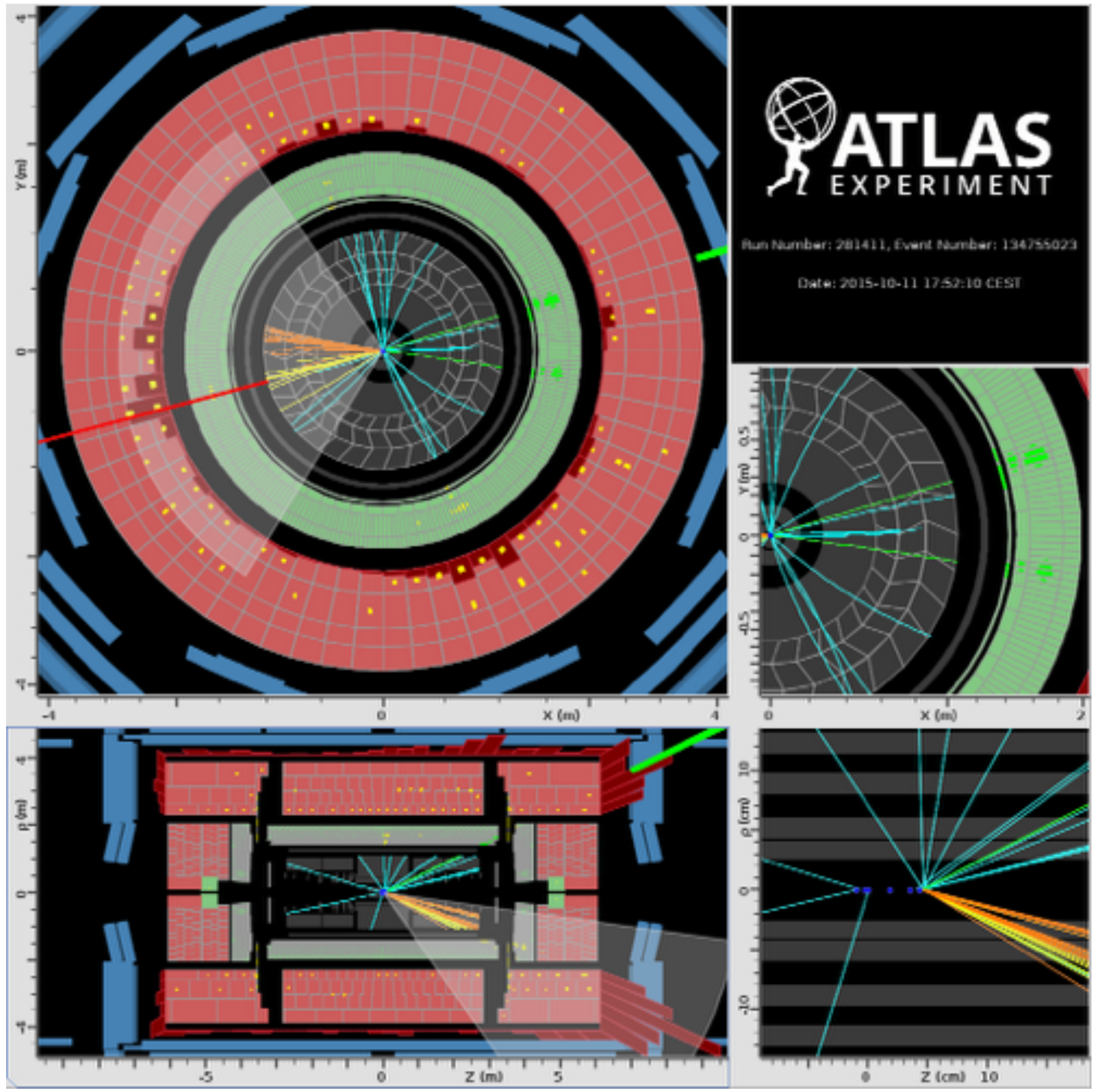



Low $p_T^Z$




Low $p_T^Z$

# 2Lepton Event Displays

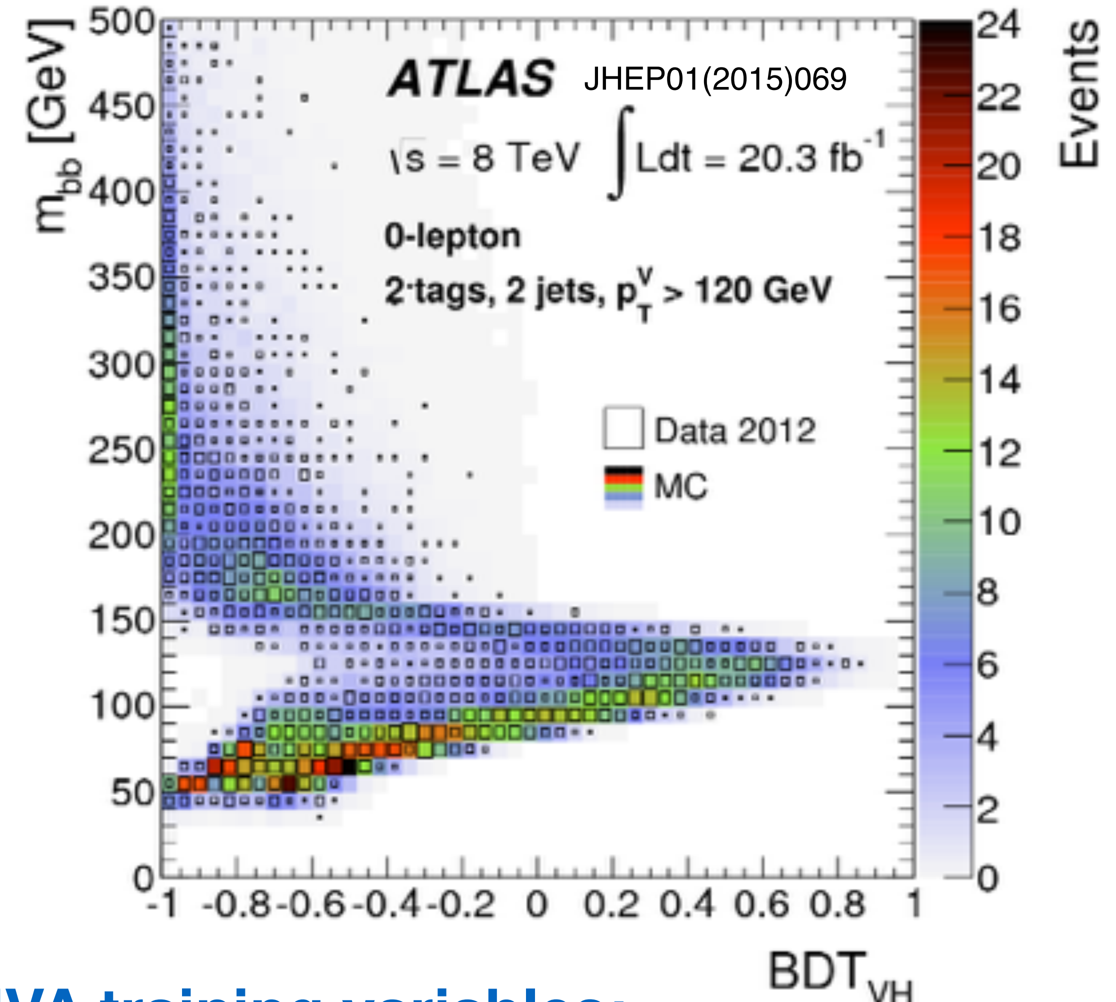



**High $p_T^Z$**

# Run1 SM VHbb: Multivariate Discrimination

Separate a tiny signal from a complex background → multivariate techniques → **BDT**

| Variable | 0-Lepton | 1-Lepton | 2-Lepton |
|---|---|---|---|
| $p_T^V$ | | × | × |
| $E_T^{miss}$ | × | × | × |
| $p_T^{b_1}$ | × | × | × |
| $p_T^{b_2}$ | × | × | × |
| $m_{bb}$ | × | × | × |
| $\Delta R(b_1, b_2)$ | × | × | × |
| $\|\Delta\eta(b_1, b_2)\|$ | × | | × |
| $\Delta\phi(V, bb)$ | × | × | × |
| $\|\Delta\eta(V, bb)\|$ | | | × |
| $H_T$ | × | | |
| $\min[\Delta\phi(\ell, b)]$ | | × | |
| $m_T^W$ | | × | |
| $m_{\ell\ell}$ | | | × |
| $MV1c(b_1)$ | × | × | × |
| $MV1c(b_2)$ | × | × | × |
| | Only in 3-jet events | | |
| $p_T^{jet_3}$ | × | × | × |
| $m_{bbj}$ | × | × | × |




**MVA training variables:**

- as consistent as possible across lepton channels
- study of data/MC modelling and correlations
- most powerful: $\mathbf{m_{bb}}$, **ΔR(b,b)**, $\mathbf{p_T^V}$

We do not cut on the BDT output: the full BDT shape distribution is used as discriminating variable in a **combined Profile Likelihood Fit**

# $H \to bb$ @ LHC

## The global picture looking at ATLAS & CMS (Run1)

**ATLAS Hbb combination (VH+ttH)**
significance = 1.7 $\sigma_{obs}$ (2.7 $\sigma_{exp}$),
signal strength $\mu = 0.63 \pm 0.4$

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**CMS Hbb combination (VH+ttH+VBF)**
significance = 2.6 $\sigma_{obs}$ (2.7 $\sigma_{exp}$),
signal strength $\mu = 1.0 \pm 0.4$

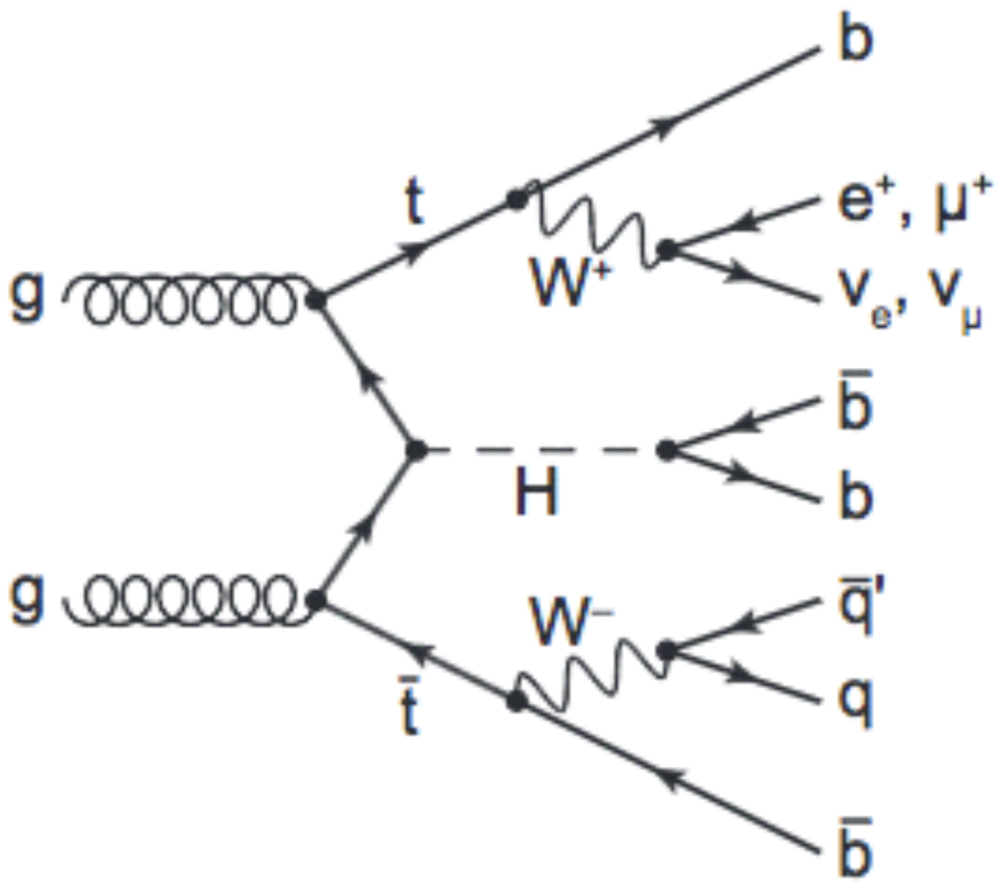
**CMS VHbb standalone**
significance = 2.08 $\sigma_{obs}$ (2.52 $\sigma_{exp}$),
signal strength $\mu = 0.89 \pm 0.43$

| $H \to b\bar{b}$ | Best fit (68% CL) | Upper limits (95% CL) | | Signal significance | |
|---|---|---|---|---|---|
| Channel | Observed | Observed | Expected | Observed | Expected |
| VH | $0.89 \pm 0.43$ | 1.68 | 0.85 | 2.08 | 2.52 |
| $t\bar{t}H$ | $0.7 \pm 1.8$ | 4.1 | 3.5 | 0.37 | 0.58 |
| VBF | $2.8^{+1.6}_{-1.4}$ | 5.5 | 2.5 | 2.20 | 0.83 |
| Combined | $1.03^{+0.44}_{-0.42}$ | 1.77 | 0.78 | 2.56 | 2.70 |

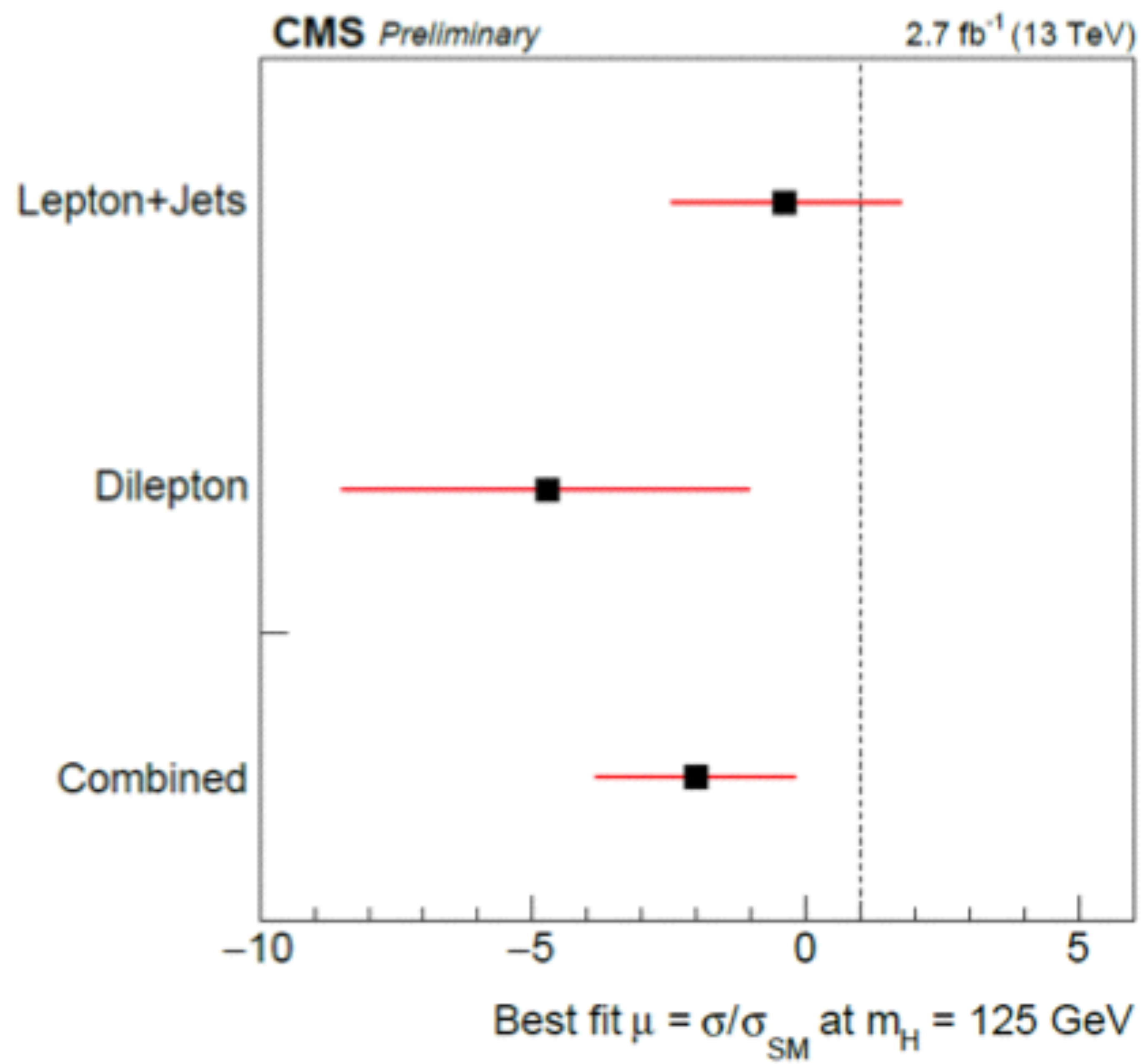
**ttH(bb) from Run1**

# H→bb @ LHC

## The first Run2 results from CMS : ttH(bb)




CMS-PAS-HIG-16-004




$$\hat{\mu}_{obs} = -2.0^{+1.8}_{-1.8}$$

# b-tagging: Run1 vs Run2

"b-tagged jets" with MV1c:
Identify if there are originated from b-quark fragmentation

| b-jets efficiency | 80% | 50% |
|---|---|---|
| c-jets rejections | 3 | 26 |
| light-jets rejections | 30 | 1400 |

**Mv2c Run2 b-tagging algorithm**

| **b-jets efficiency** | **77%** | **50%** |
|---|---|---|
| **c-jets rejections** | 6 | 106 |
| **light-jets rejections** | 134 | 5700 |

# ~SM VHbb: Towards Run2 data [EFT]

CP-even dim-6 Lagrangian

$$\mathcal{L} \supset \frac{\bar{c}_H}{2v^2}\partial^\mu[\Phi^\dagger\Phi]\partial_\mu[\Phi^\dagger\Phi] + \frac{g'^2\,\bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\,\bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G^{\mu\nu}_a$$
$$+ \frac{2ig\,\bar{c}_{HW}}{m_W^2}[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi]W^k_{\mu\nu} + \frac{ig'\,\bar{c}_{HB}}{m_W^2}[D^\mu\Phi^\dagger D^\nu\Phi]B_{\mu\nu}$$
$$+ \frac{ig\,\bar{c}_W}{m_W^2}[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi]D^\nu W^k_{\mu\nu} + \frac{ig'\,\bar{c}_B}{2m_W^2}[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi]\partial^\nu B_{\mu\nu}$$
$$+ \frac{\bar{c}_t}{v^2}y_t\Phi^\dagger\Phi\,\Phi^\dagger\cdot\bar{Q}_L t_R + \frac{\bar{c}_b}{v^2}y_b\Phi^\dagger\Phi\,\Phi\cdot\bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2}y_\tau\,\Phi^\dagger\Phi\,\Phi\cdot\bar{L}_L\tau_R\,.$$

Independent set of parameters for Higgs physics

$$\bar{c}_i \equiv \{\bar{c}_H, \bar{c}_{t,b,\tau}, \bar{c}_W, \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g\}$$

Effetive Lagrangian in terms of anomalous Higgs couplings (in mass basis, unitary gauge)

$$\mathcal{L} \supset -\frac{1}{4}g^{(1)}_{HZZ}Z_{\mu\nu}Z^{\mu\nu}h - g^{(2)}_{HZZ}Z_\nu\partial_\mu Z^{\mu\nu}h$$
$$-\frac{1}{2}g^{(1)}_{HWW}W^{\mu\nu}W^\dagger_{\mu\nu}h - \left[g^{(2)}_{HWW}W^\nu\partial^\mu W^\dagger_{\mu\nu}h + \text{h.c.}\right]$$

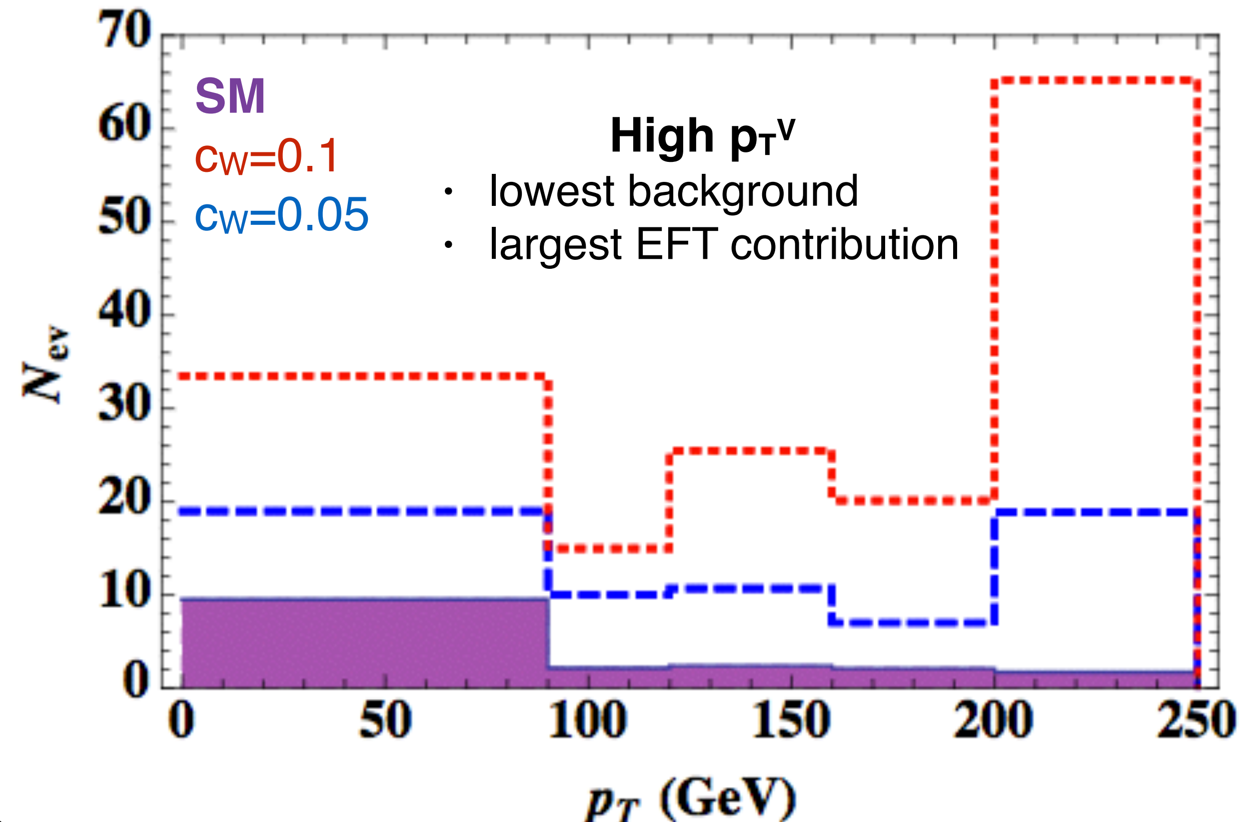
Constraint on $c_W$ from ATLAS & CMS signal strength global fit, including (ggF,VBF) (Hττ,Hww,Hzz,Hγγ,Hγz):

$$\bar{c}_W \in [-0.05, 0.06]$$

Including VHbb differential fit (VpT from ATLAS, mVH from D0):

$$\bar{c}_W \in [-0.03, 0.01]$$

LHC8 ATLAS VH arxiv:1404.3667




$$g^{(1)}_{hzz} = \frac{2g}{c_W^2 m_W}\left[\bar{c}_{HB}s_W^2 - 4\bar{c}_\gamma s_W^4 + c_W^2\bar{c}_{HW}\right]$$
$$g^{(2)}_{hzz} = \frac{2g}{c_W^2 m_W}\left[(\bar{c}_{HW}+\bar{c}_W)c_W^2 + (\bar{c}_{HB}+\bar{c}_B)s_W^2\right]$$
$$g^{(1)}_{hww} = \frac{2g}{m_W}\bar{c}_{HW}$$
$$g^{(2)}_{hww} = \frac{g}{m_W}(\bar{c}_W + \bar{c}_{HW})\,.$$

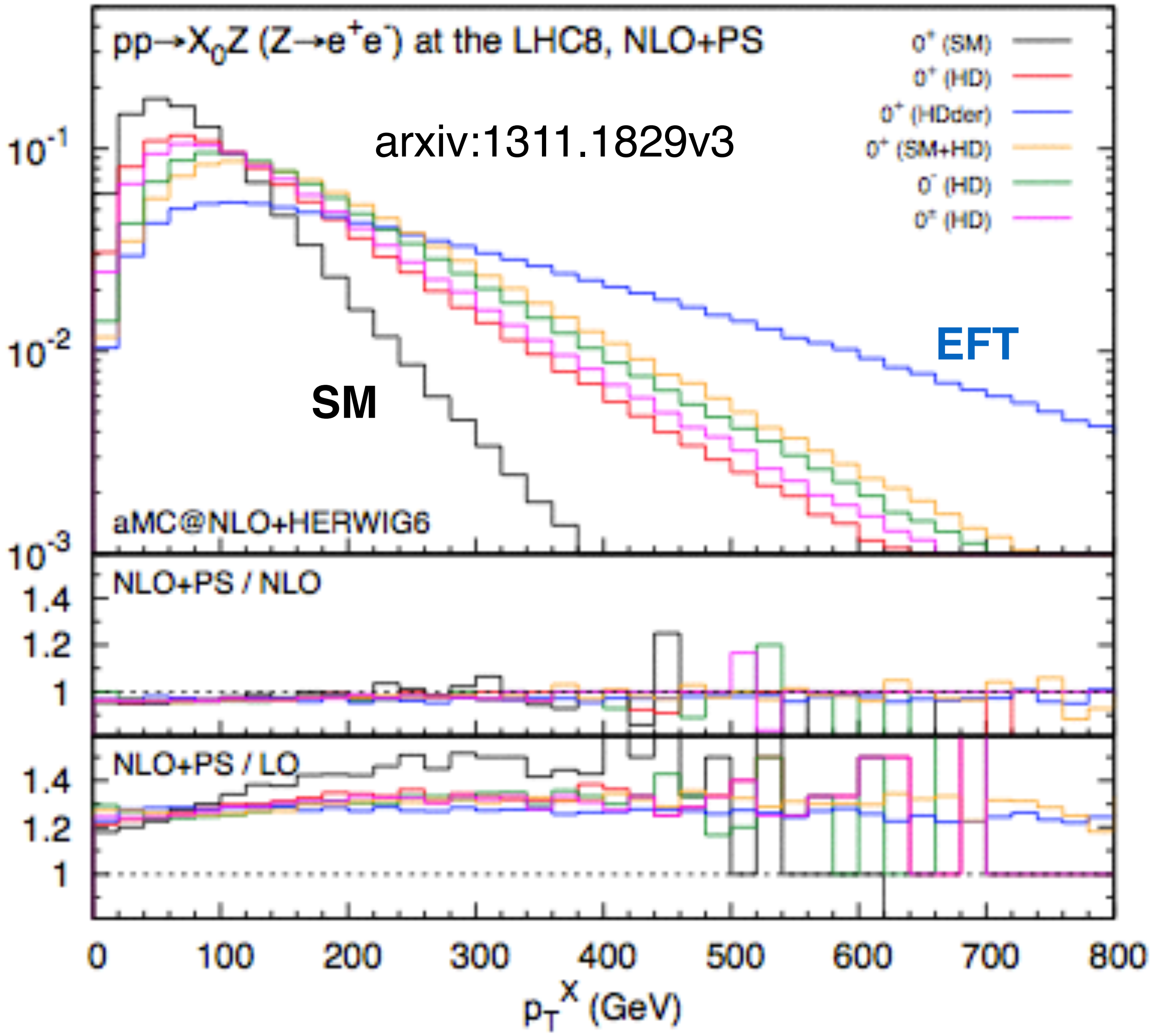
Considerable improvement for single operator fit
Even more important when fitting multiple operators

# ~SM VHbb: Towards Run2 data [EFT]

arxiv:1311.1829v3

**EFT samples already under study in ATLAS**:
**mg5_aMC** *Higgs Characterization Model*

*MonteCarlo generation at NLO(QCD)+PS*




SM

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\big]$$

CP-even | CP-odd

$$- \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\big]$$

$$- \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu}\big]$$

derivative operators

$$- \frac{1}{\Lambda} c_\alpha \big[\, \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu}$$

$$+ \big(\kappa_{H\partial W} W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\big)\big]$$

| parameter | description |
|---|---|
| $\Lambda$ [GeV] | cutoff scale |
| $c_\alpha$ ($\equiv \cos\alpha$) | mixing between $0^+$ and $0^-$ |
| $\kappa_i$ | dimensionless coupling parameter |

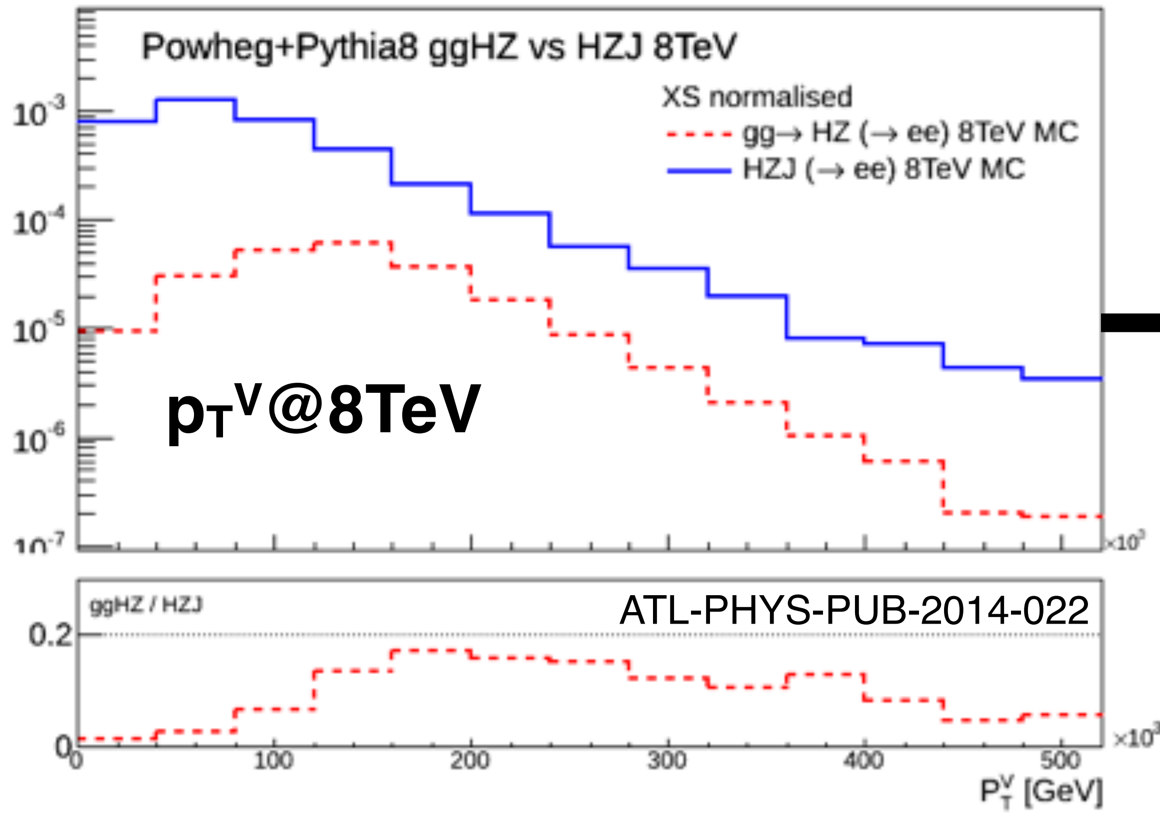
*Benchmark scenarios* →

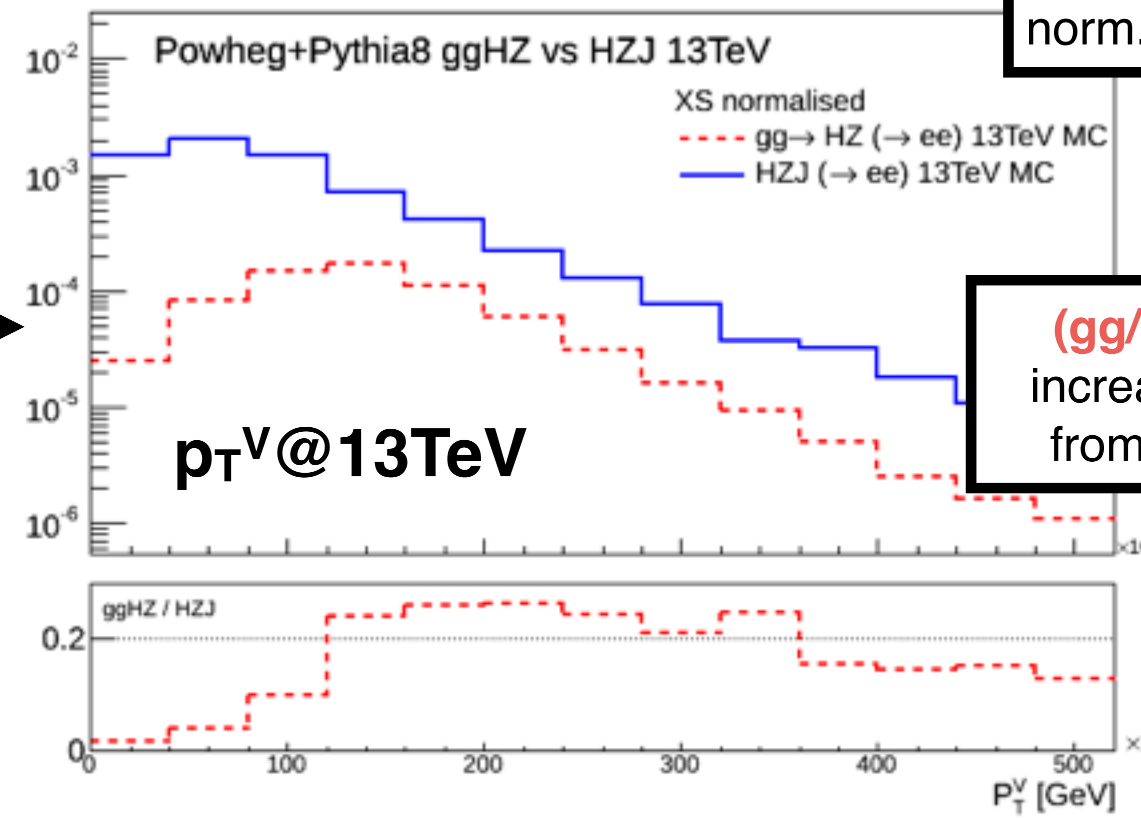
| scenario | HC parameter choice |
|---|---|
| $0^+$(SM) | $\kappa_{SM} = 1$ ($c_\alpha = 1$) |
| $0^+$(HD) | $\kappa_{HZZ,HWW} = 1$ ($c_\alpha = 1$) |
| $0^+$(HDder) | $\kappa_{H\partial Z,H\partial W} = 1$ ($c_\alpha = 1$) |
| $0^+$(SM+HD) | $\kappa_{SM,HZZ,HWW} = 1$ ($c_\alpha = 1$, $\Lambda = v$) |
| $0^-$(HD) | $\kappa_{AZZ,AWW} = 1$ ($c_\alpha = 0$) |
| $0^\pm$(HD) | $\kappa_{HZZ,AZZ,HWW,AWW} = 1$ ($c_\alpha = 1/\sqrt{2}$) |

# SM VHbb: ZH Signal @ 13 TeV

From 8 to 13 TeV: **XS(qq→ZH) increases by ~ 2.2**
**XS(gg→ZH) increases by ~ 3.3** (larger at high $p_T^V$)

gg→ZH(eebb)
norm. Powheg XS



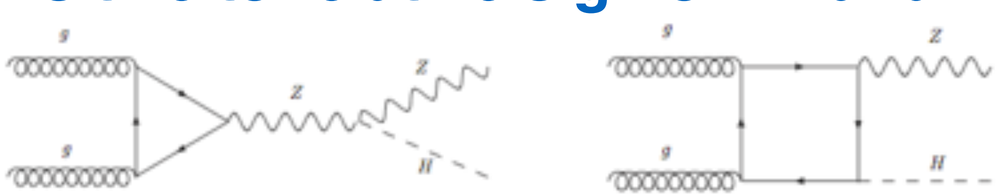



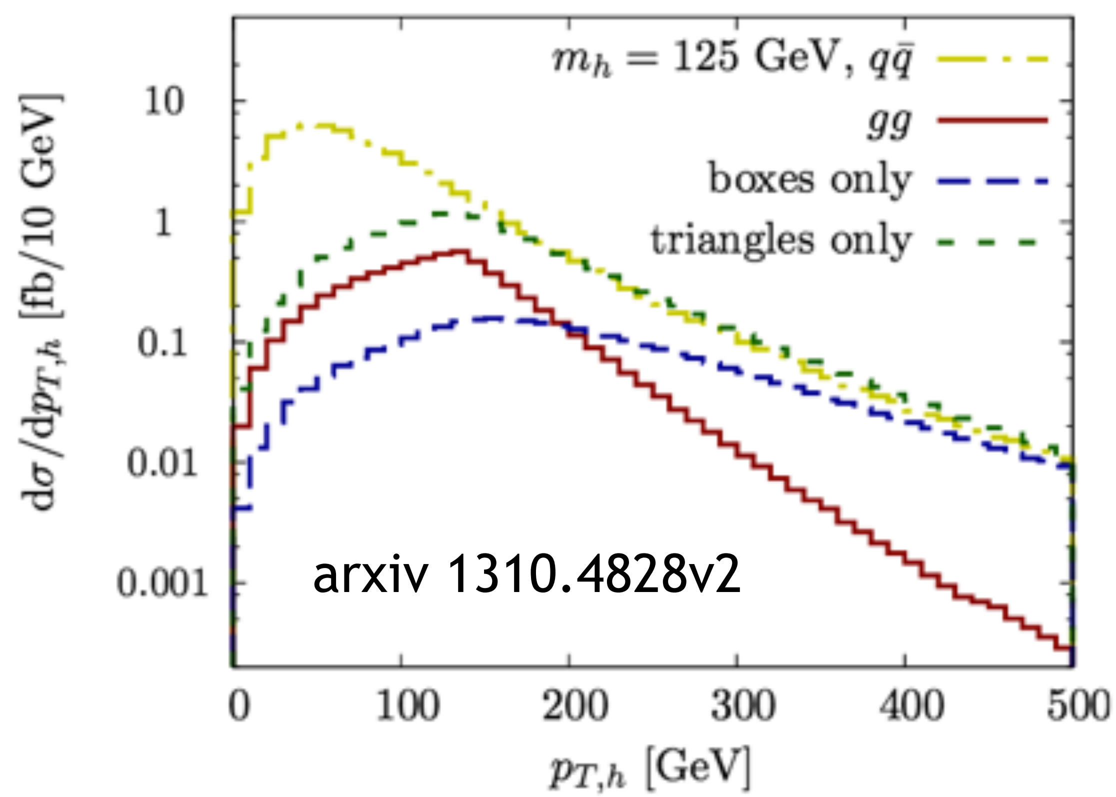

**(gg/qq)** fraction
increases by 70%
from 8 to 13TeV

## gg→ZH at LO QCD [ O($\alpha_S^2$) ] Powheg

- **large theory uncertainty** (scale unc. ~50% Run1)
- **NLO computation** in the ∞ $m_{top}$ limit: **kNLO~2**
- **gg→ZH+1jet** merged prediction mg5_aMC [arXiv:1503.01656v1]

## Sensitive to relative sign of kZ and kT





# Backup

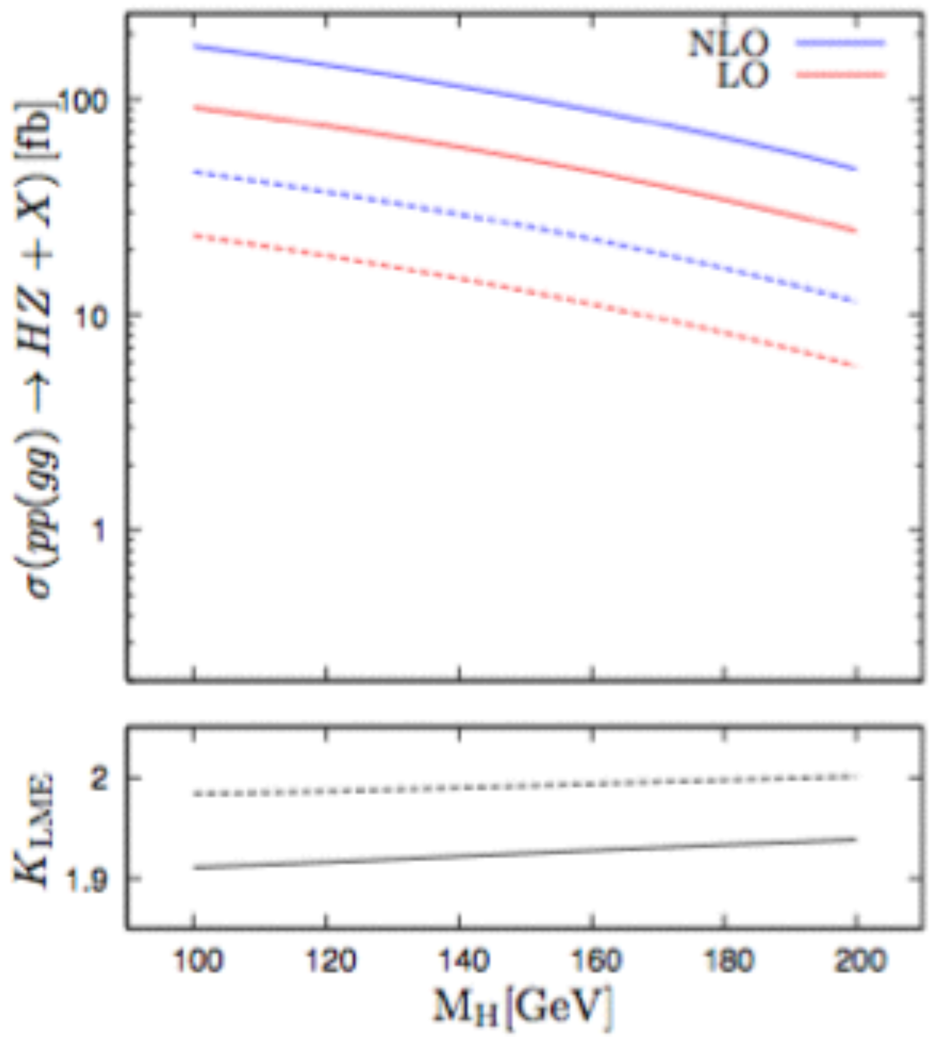
**(qq+qg)+(gg)→ ZH at 13TeV**: estimate of the **gluon-gluon** contribution at 13TeV vs 8TeV

$\sigma$(qq→HZ) (⇒ 14 TeV) increases by ∼ **2.3**

$\sigma$(gg→HZ) (⇒ 14 TeV) increases by ∼ **3.8-4**

Some interesting notes:

- ⊕ gg→HZ begins to contribute at LO (O($\alpha_S^2$)) (**as implemented in POWHEG**)
- ⊕ **NLO corrections** to gg→HZ ⇒ **K-factor** ∼ **2** (fairly flat across $m_H$)



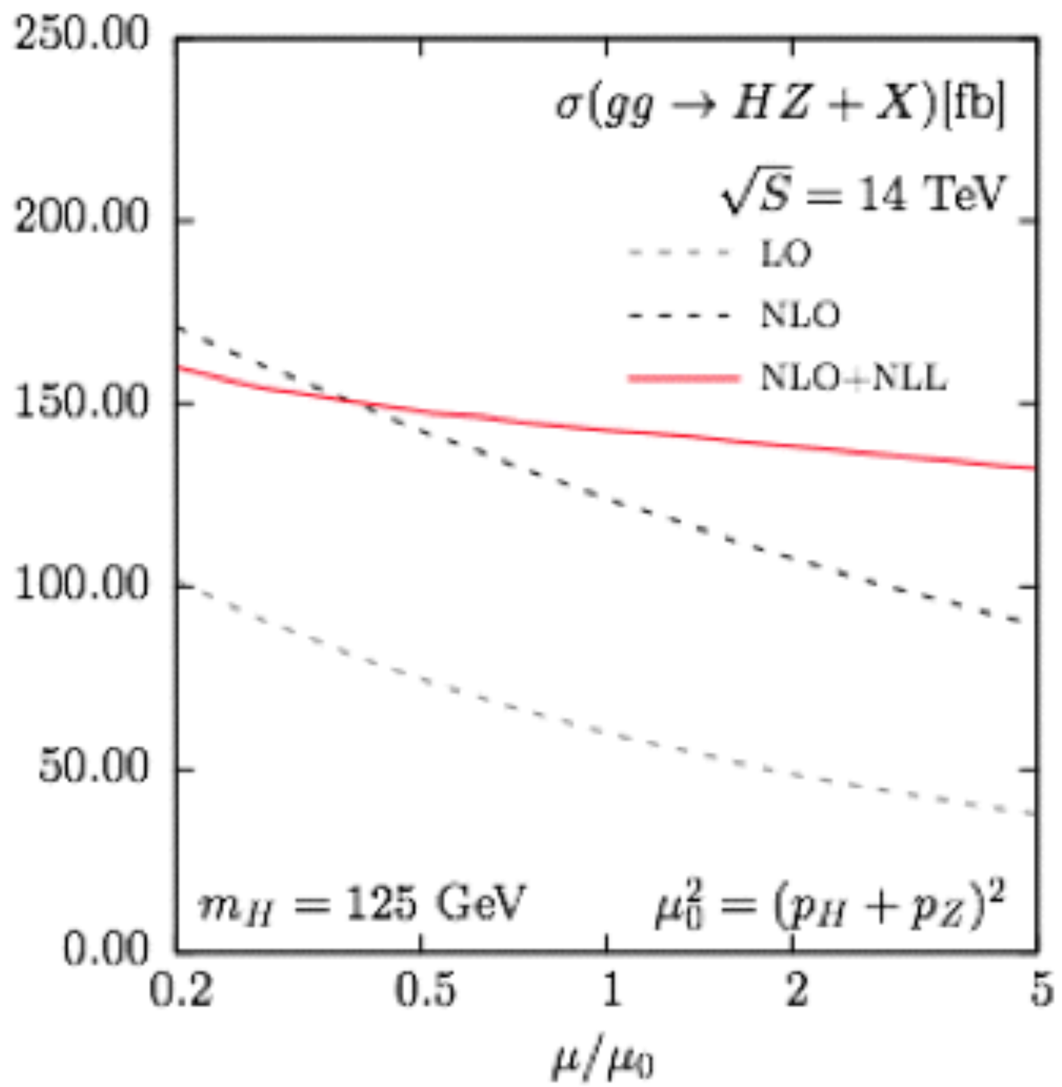

| $\sqrt{s}$ [TeV] | $M_H$[GeV] | $\sigma_{gg}^{LO}$[fb] | $\sigma_{gg}^{NLO}$[fb] |
|---|---|---|---|
| no $p_{T,H}$ cut | | | |
| 8 | 115 | $19.8^{+61\%}_{-34\%}$ | $39.3^{+32\%}_{-24\%}$ |
| 8 | 120 | $18.7^{+61\%}_{-34\%}$ | $37.2^{+32\%}_{-24\%}$ |
| 8 | 125 | $17.7^{+61\%}_{-34\%}$ | $35.1^{+32\%}_{-24\%}$ |
| 8 | 130 | $16.7^{+61\%}_{-34\%}$ | $33.1^{+32\%}_{-24\%}$ |
| 14 | 115 | $79.1^{+51\%}_{-31\%}$ | $152^{+27\%}_{-21\%}$ |
| 14 | 120 | $75.1^{+51\%}_{-31\%}$ | $144^{+27\%}_{-21\%}$ |
| 14 | 125 | $71.1^{+51\%}_{-31\%}$ | $136^{+27\%}_{-21\%}$ |
| 14 | 130 | $67.2^{+51\%}_{-31\%}$ | $129^{+27\%}_{-21\%}$ |
| $p_{T,H} > 200$ GeV | | | |
| 8 | 115 | $1.41^{+65\%}_{-36\%}$ | $2.94^{+34\%}_{-25\%}$ |
| 8 | 120 | $1.33^{+65\%}_{-36\%}$ | $2.79^{+33\%}_{-26\%}$ |
| 8 | 125 | $1.26^{+65\%}_{-36\%}$ | $2.63^{+34\%}_{-25\%}$ |
| 8 | 130 | $1.19^{+65\%}_{-36\%}$ | $2.48^{+33\%}_{-25\%}$ |
| 14 | 115 | $6.86^{+55\%}_{-32\%}$ | $13.8^{+29\%}_{-22\%}$ |
| 14 | 120 | $6.53^{+55\%}_{-32\%}$ | $13.1^{+28\%}_{-22\%}$ |
| 14 | 125 | $6.19^{+55\%}_{-32\%}$ | $12.5^{+29\%}_{-22\%}$ |
| 14 | 130 | $5.87^{+55\%}_{-32\%}$ | $11.8^{+29\%}_{-22\%}$ |

arXiv:1211.5015v1 [hep-ph] 21 Nov 2012

# Backup

**(qq+qg)+(gg)→ ZH at 13TeV**: estimate of the **gluon-gluon** contribution at 13TeV vs 8TeV

⊕ **NLL resummation** for to gg→HZ : reduction of scale dependence + **increase in XS**
arXiv:1410.0217v1 [hep-ph] 1 Oct 2014




| $\sqrt{s}$ [TeV] | $M_H$ [GeV] | $\sigma_{pp\to HZ}$ incl. $gg$ @ NLO [pb] | [%] | incl. $gg$ @ NLO+NLL [pb] | [%] |
|---|---|---|---|---|---|
| 8.00 | 125.0 | 0.4157 | $^{+3.1}_{-2.8}$ | 0.4217 | $^{+1.5}_{-1.5}$ |
| 8.00 | 125.5 | 0.4104 | $^{+3.1}_{-2.8}$ | 0.4165 | $^{+1.5}_{-1.5}$ |
| 8.00 | 126.0 | 0.4054 | $^{+3.2}_{-2.8}$ | 0.4114 | $^{+1.5}_{-1.6}$ |
| 13.0 | 125.0 | 0.8696 | $^{+3.8}_{-3.8}$ | 0.8859 | $^{+1.6}_{-2.0}$ |
| 13.0 | 125.5 | 0.8594 | $^{+3.8}_{-3.8}$ | 0.8757 | $^{+1.7}_{-1.9}$ |
| 13.0 | 126.0 | 0.8501 | $^{+3.8}_{-3.9}$ | 0.8663 | $^{+1.6}_{-2.1}$ |
| 13.5 | 125.0 | 0.9190 | $^{+3.9}_{-3.8}$ | 0.9366 | $^{+1.6}_{-2.0}$ |
| 13.5 | 125.5 | 0.9085 | $^{+3.8}_{-3.8}$ | 0.9259 | $^{+1.6}_{-2.0}$ |
| 13.5 | 126.0 | 0.8988 | $^{+3.8}_{-3.9}$ | 0.9162 | $^{+1.5}_{-2.0}$ |
| 14.0 | 125.0 | 0.9690 | $^{+4.0}_{-3.9}$ | 0.9878 | $^{+1.7}_{-2.0}$ |
| 14.0 | 125.5 | 0.9574 | $^{+4.0}_{-3.9}$ | 0.9761 | $^{+1.7}_{-2.0}$ |
| 14.0 | 126.0 | 0.9465 | $^{+4.1}_{-3.9}$ | 0.9652 | $^{+1.7}_{-2.0}$ |

**At** $\mu = \mu_R = \mu_F =$ **Q** central scale value:

$\sigma$(gg→HZ) **8TeV** increases by ∼ **18%**

$\sigma$(gg→HZ) **14TeV** increases by ∼ **15%**

# SM Candle Process: Diboson VZ→bb

VZ→ $b\bar{b}$ as standard candle to validate VH production

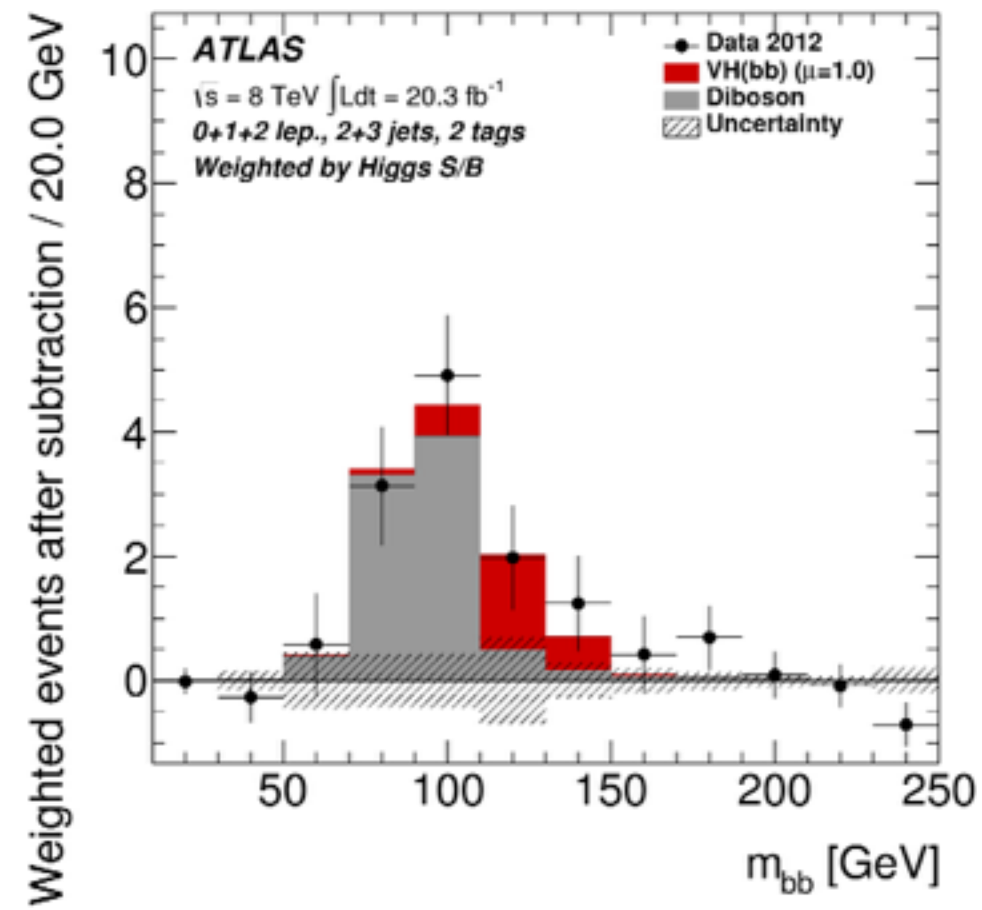
→ cross section ~ 5 times larger than VH

→ almost identical final state

⊗ **Expected Significance → 6.3**

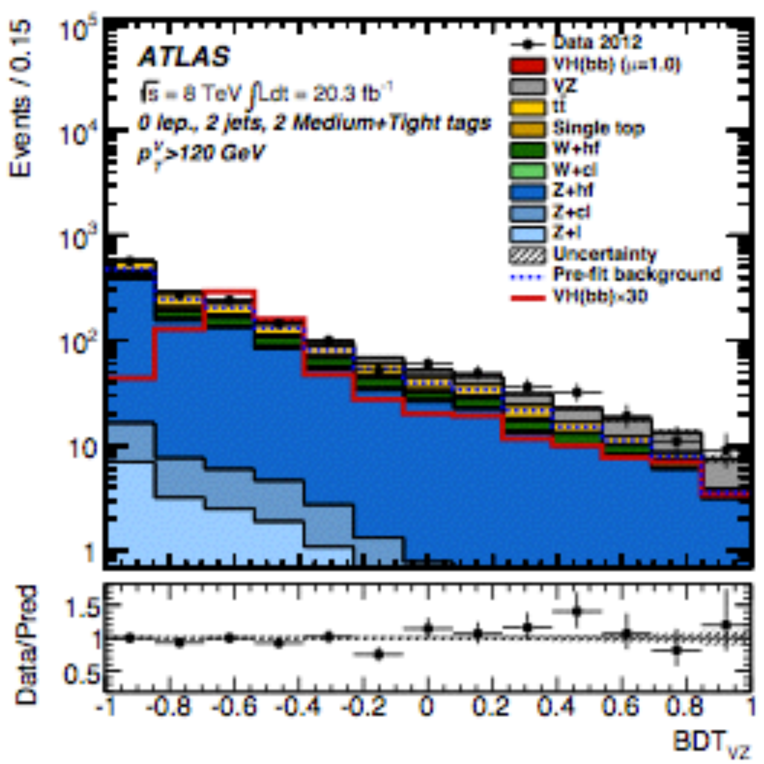
⊗ **Observed Significance → 4.9**

**VH($b\bar{b}$)** $\hat{\mu} = 0.74 \pm 0.09(stat.) \pm 0.14(syst.)$

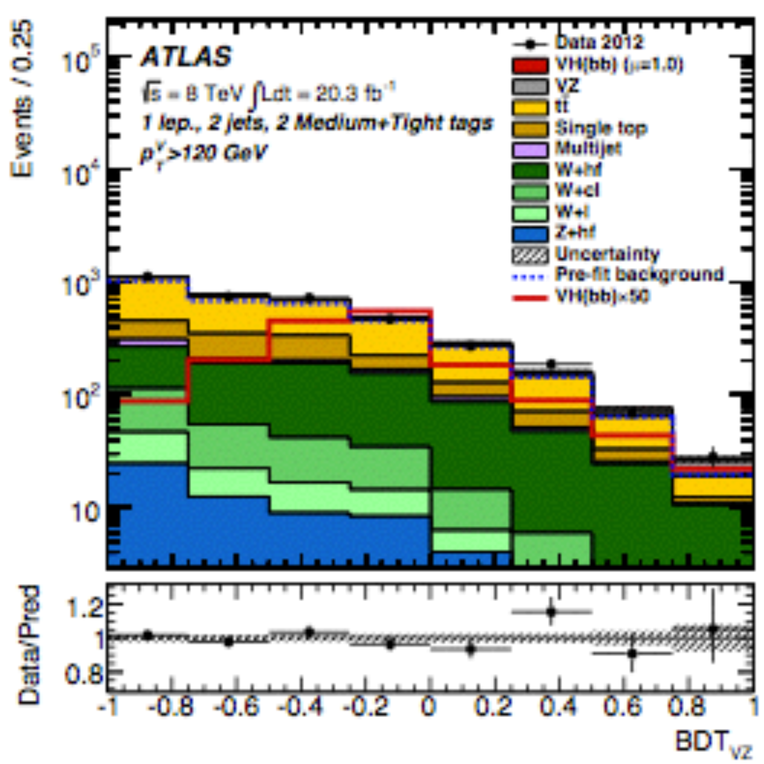



**MVA analysis re-trained to select VZ processes**

0lepton




1lepton




2lepton