Higgs searches at SLAC

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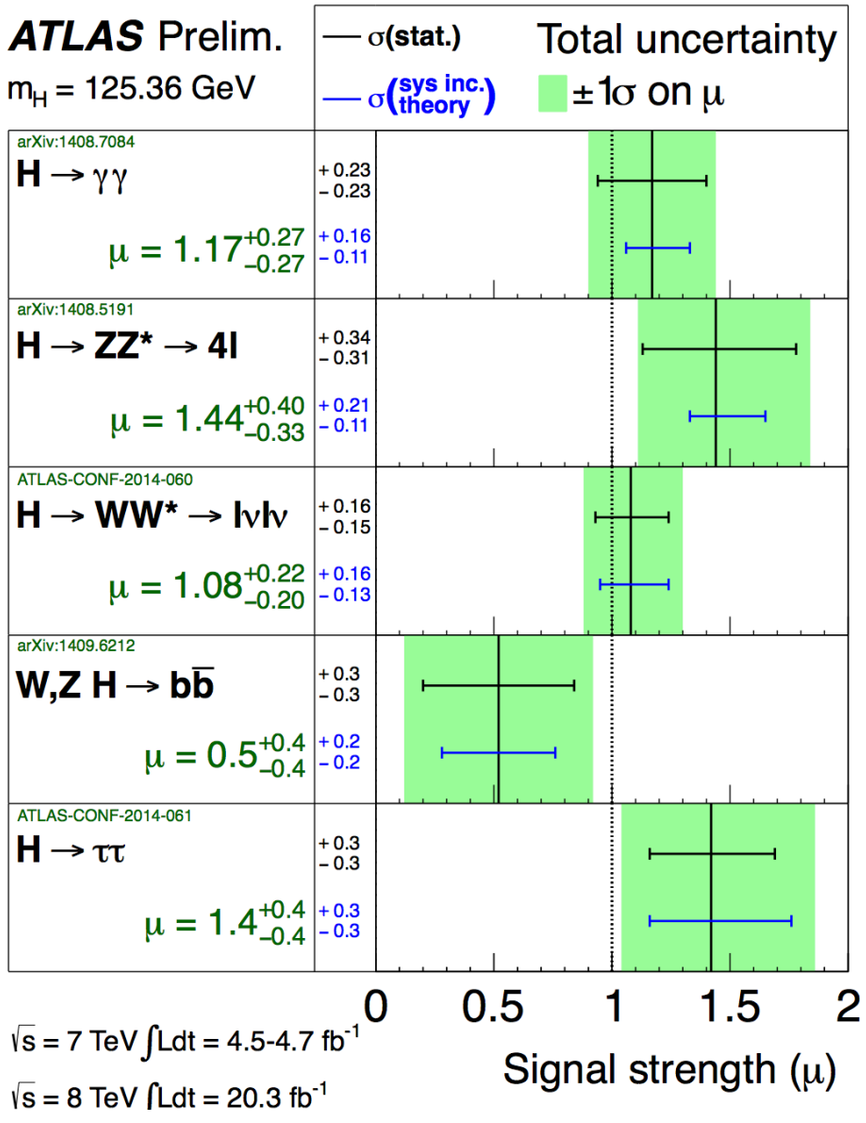
What we're looking for…

- SM H → bb, in Higgs-strahlung
  - One of the most elusive Higgs decay channel at LHC
  - But the one the Higgs boson (supposedly) most frequently decays into
- H/X → HH → 4 b-jets
  - In the future hope to access Higgs self-coupling
  - Now: look for BSM heavy X resonances to HH
- (b)bH, H → bb in (x)MSSM or 2HDM models
  - First analysis in ATLAS



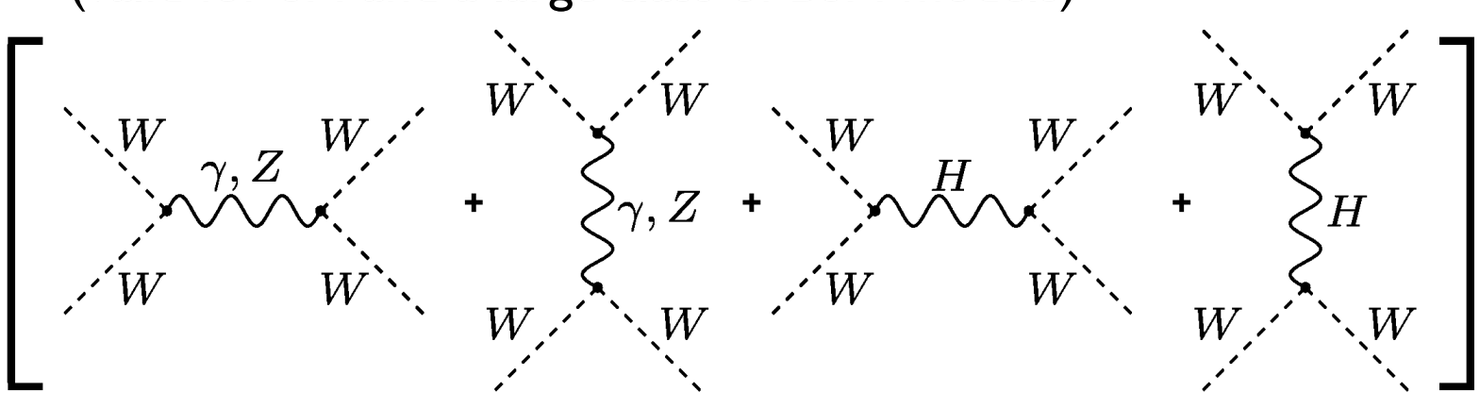
- Quite a few searches involving b-jets reconstruction, where we have >4 people very active also on the performance side (not covered in this talk).
- SM H → bb search now published, remaining ones still in ATLAS review.

One motivation for H to bb

- At the LHC the Higgs Higgs couplings can't be measured directly

$$\sigma_{YY\to H}\,\dot{BR}\left(H\to XX\right)\approx\Gamma_Y\frac{\Gamma_X}{\Gamma_H}$$

- A measurement of absolute couplings is possible if the total width is bound
  - Upper limit from fulfilling unitarity in WW scattering (valid for SM and a large class of BSM models)



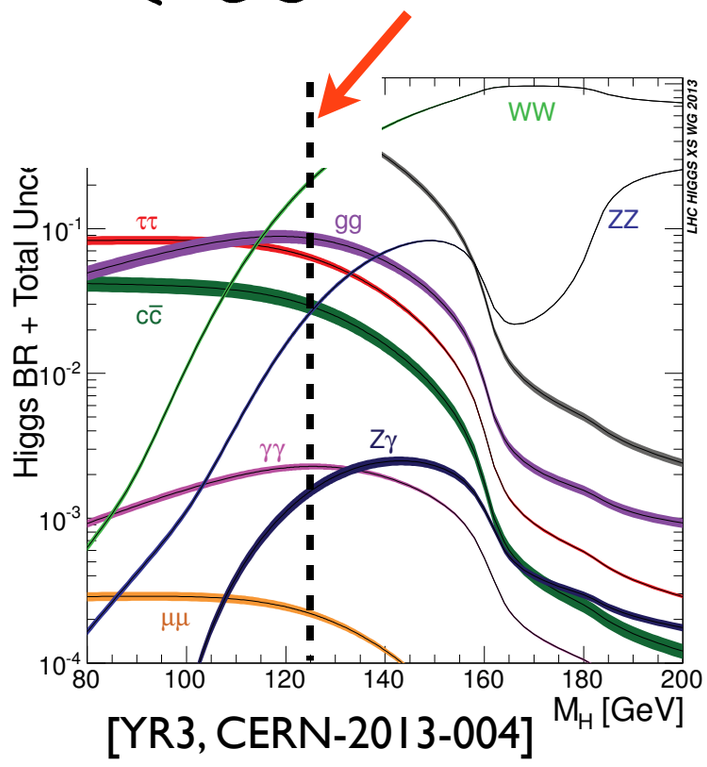
$$\kappa_W \leq 1,\ \kappa_Z \leq 1$$

  - Lower limit from sum of all "visible" decay modes

$$\Gamma_H \geq \Gamma_W+\Gamma_Z+\Gamma_g+\Gamma_\tau+\Gamma_b$$

- At ~125 GeV Higgs boson width is expected to be dominated by H to bb (BR ~ 60%)
  - Precise determination of H to bb important for extracting absolute couplings!

$$< \infty$$



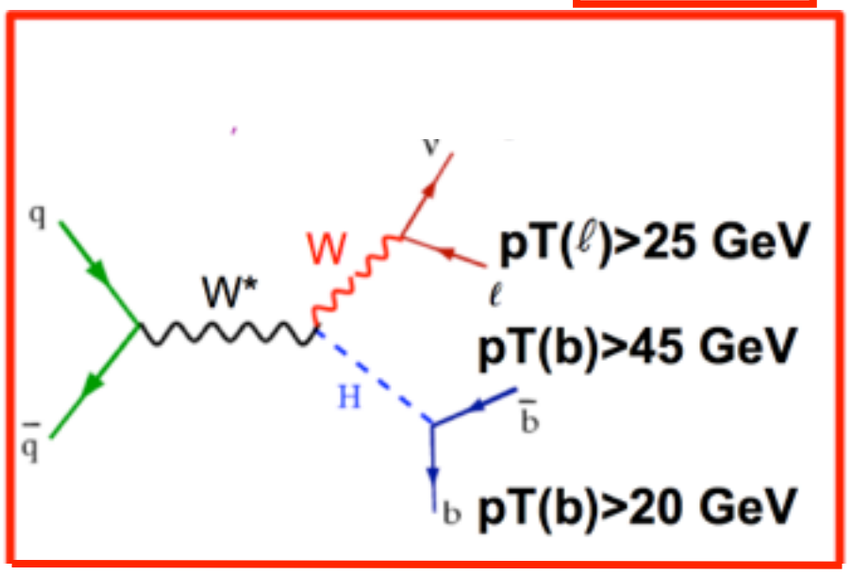
[YR3, CERN-2013-004]

The VH analysis

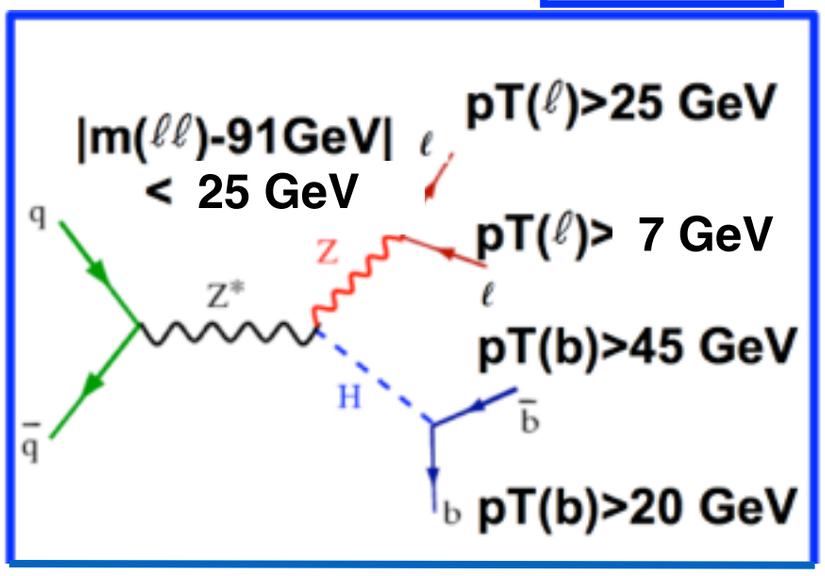
- Three leptonic signatures:
  - Missing ET $ZH \to \nu\bar{\nu}b\bar{b}$
  - 1-lepton + Missing ET $WH \to \ell\nu b\bar{b}$
  - 2-leptons $ZH \to \ell^+\ell^- b\bar{b}$
- Main analysis selection criteria:

- Jets reconstructed with an AntiKt4 jet algorithm.
- Leading two jets in pT used to form Higgs candidate.

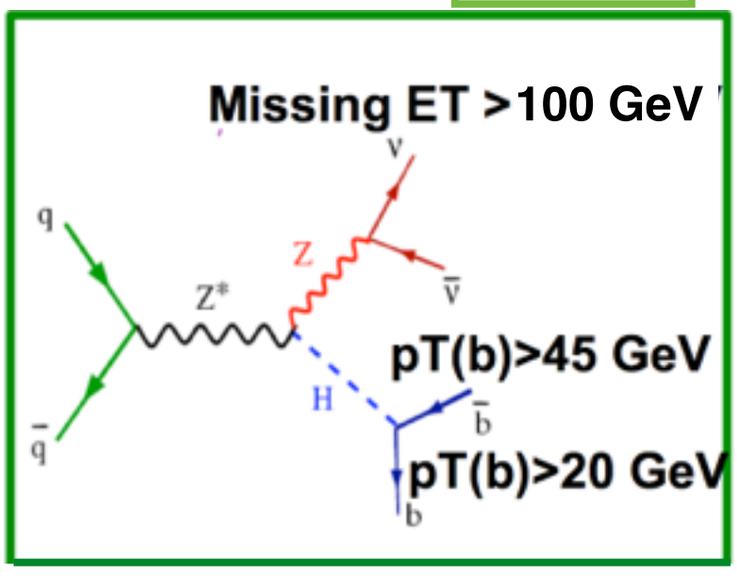
1-lepton



2-lepton



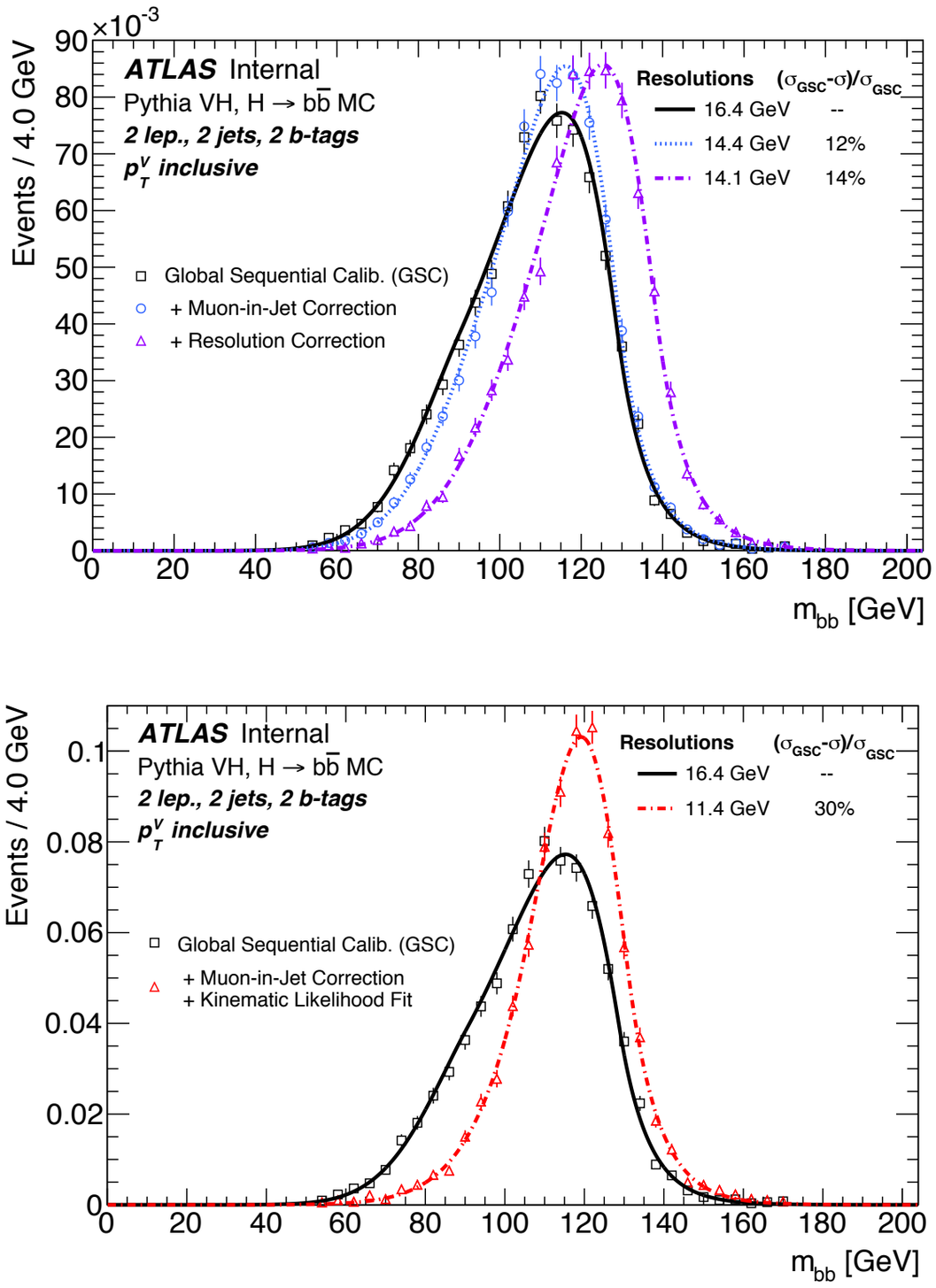
0-lepton



- Categories with no or one additional jets.

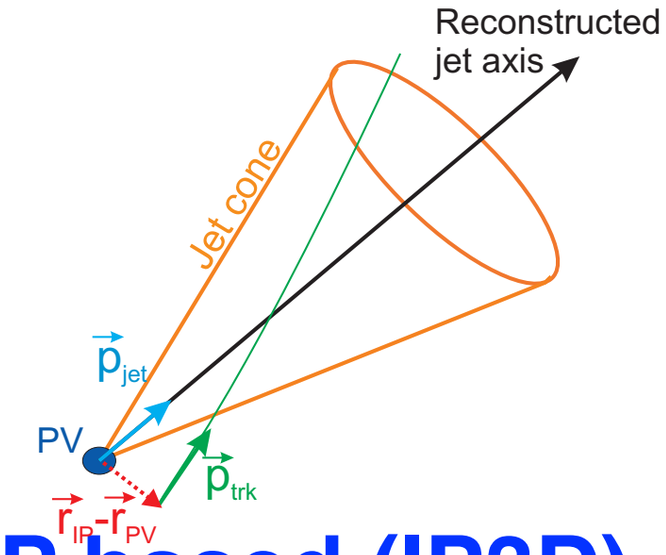
Acceptance: ~4.2% ~13.4% ~4.0%

Ingredients: (1) mass

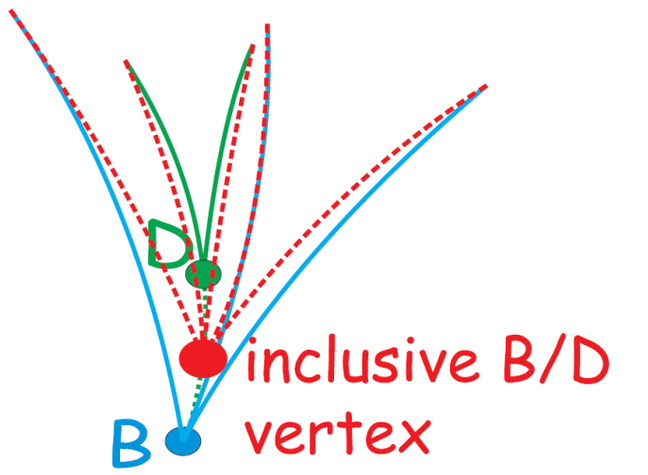


- Std antiKt R=0.4 jets
- Use Global Sequential Calibration as basis (already ~5% improvement w.r.t. EM jets)
- Then add muon-in-jet
- For 2-lepton channel, run full kinematic fit
  - Exploit closed kinematics of llbb system (maximize likelihood)

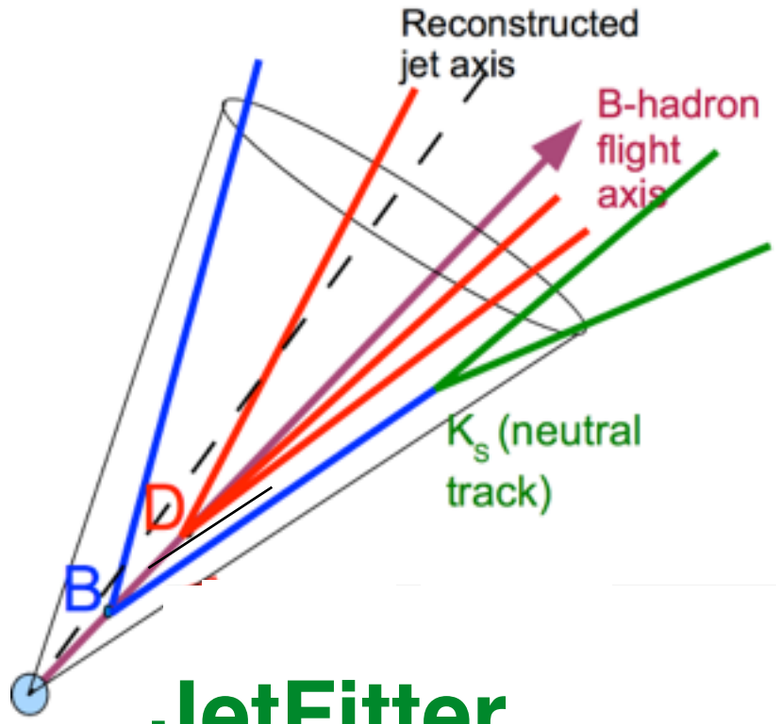
Ingredients: (2) b-tagging



IP based (IP3D)



One vertex (SV1)



JetFitter

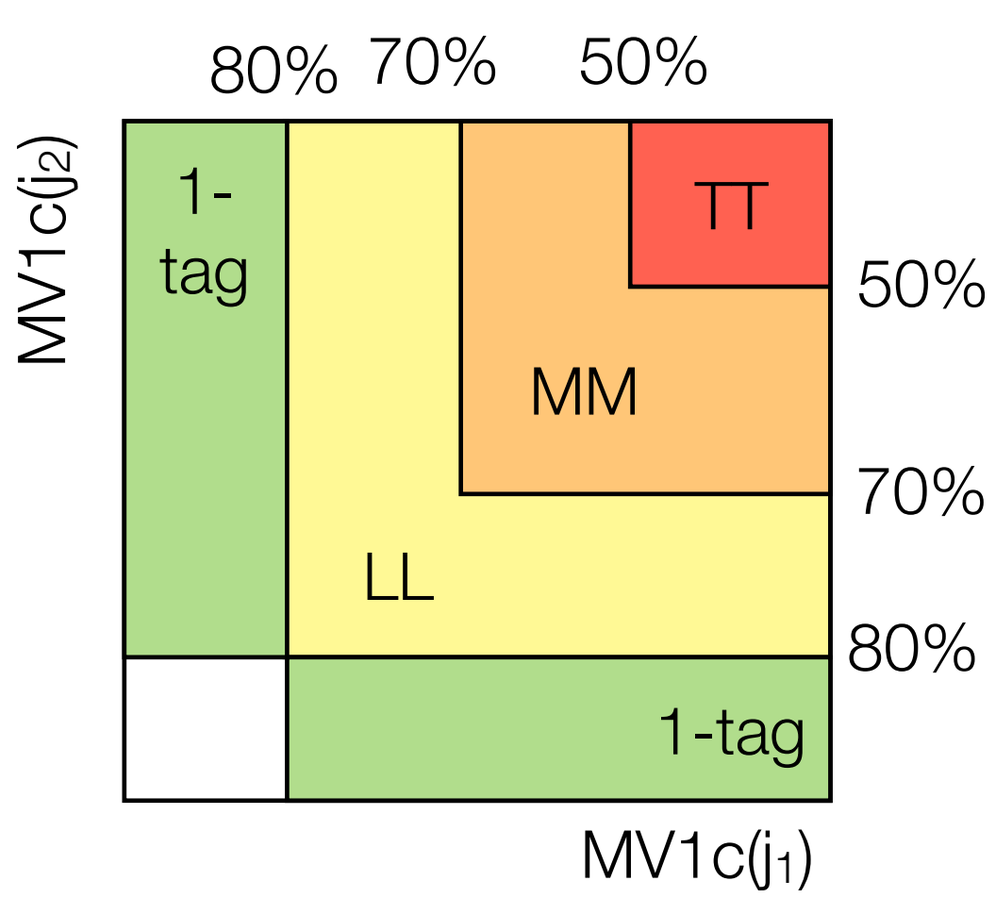
NN (MV1c)

ε(B)	R(c)	R(light)
80%	~3	~29
70%	~5.3	~136
60%	~10.5	~450
50%	~26	~1400

- R = 1 / efficiency
- Optimized to reject c-jets
- Simultaneous use of several working points.
- Dedicated calibration with reduced uncertainties (~2-3%).

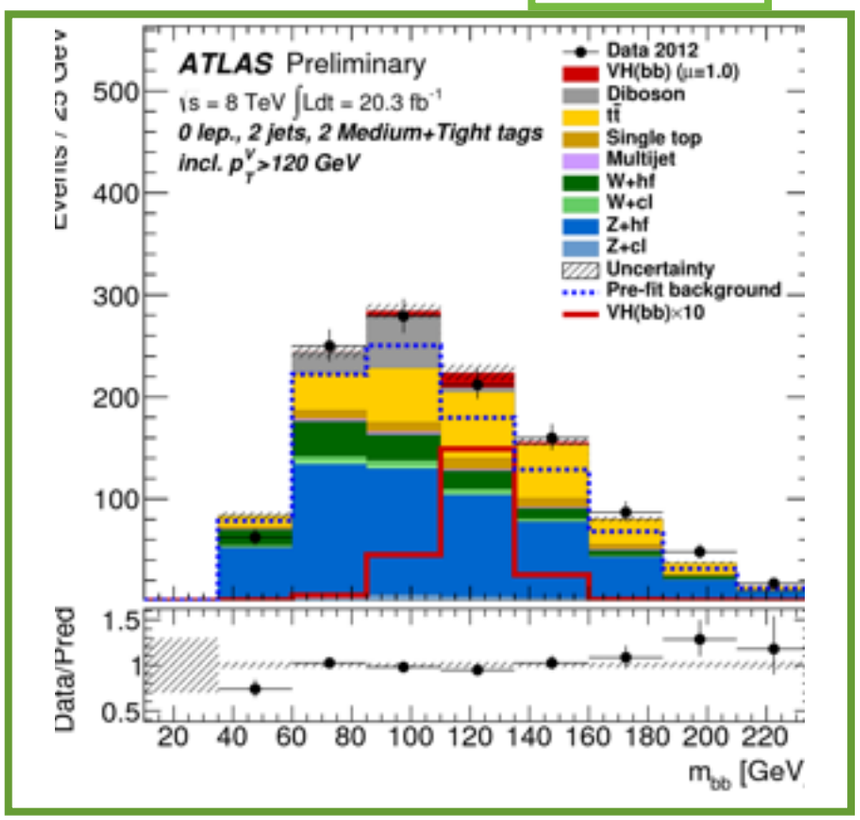
Analysis categories

- Three channels: **0-lepton**, **1-lepton** and **2-lepton**
- **Two** pT(W/Z) regions
  - <120, >120 GeV
- **Four** b-tag regions (1-tag, LL,MM,TT)
- **Two** jet bins (2 and 3 jets)
- Discriminating variables in fit
  - 1-tag: **MV1c**
  - 2-tag: **BDT**

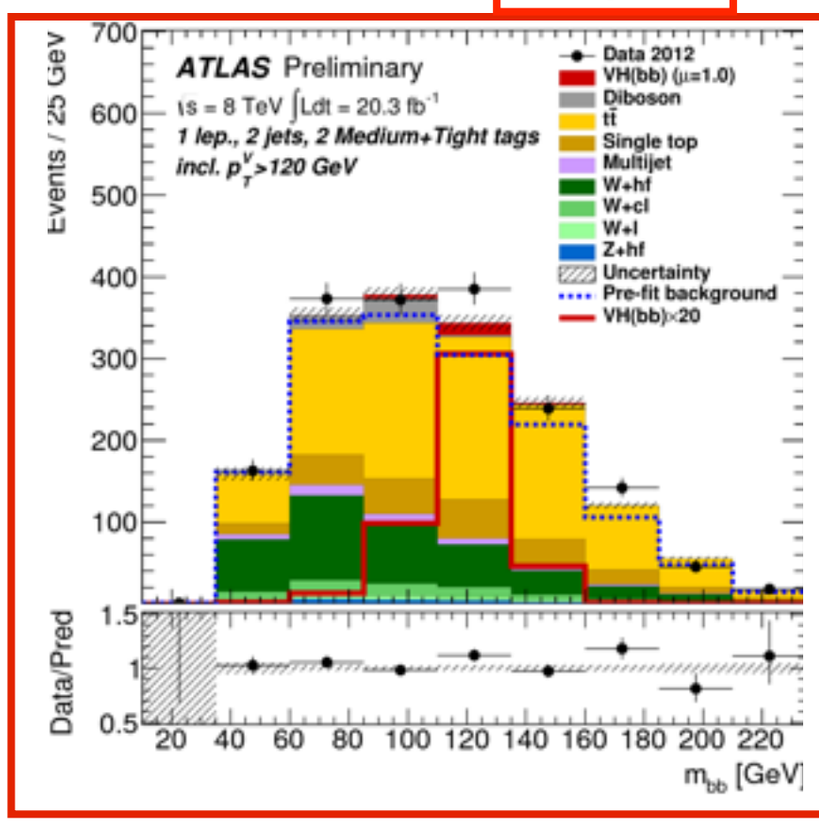


Main backgrounds

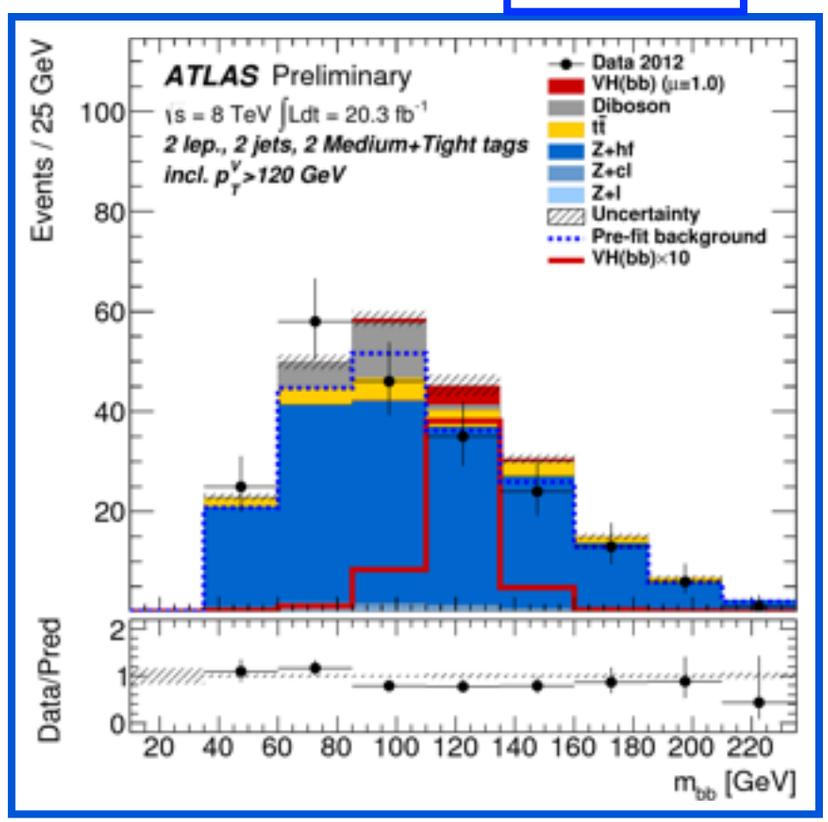
0-lepton



1-lepton



2-lepton

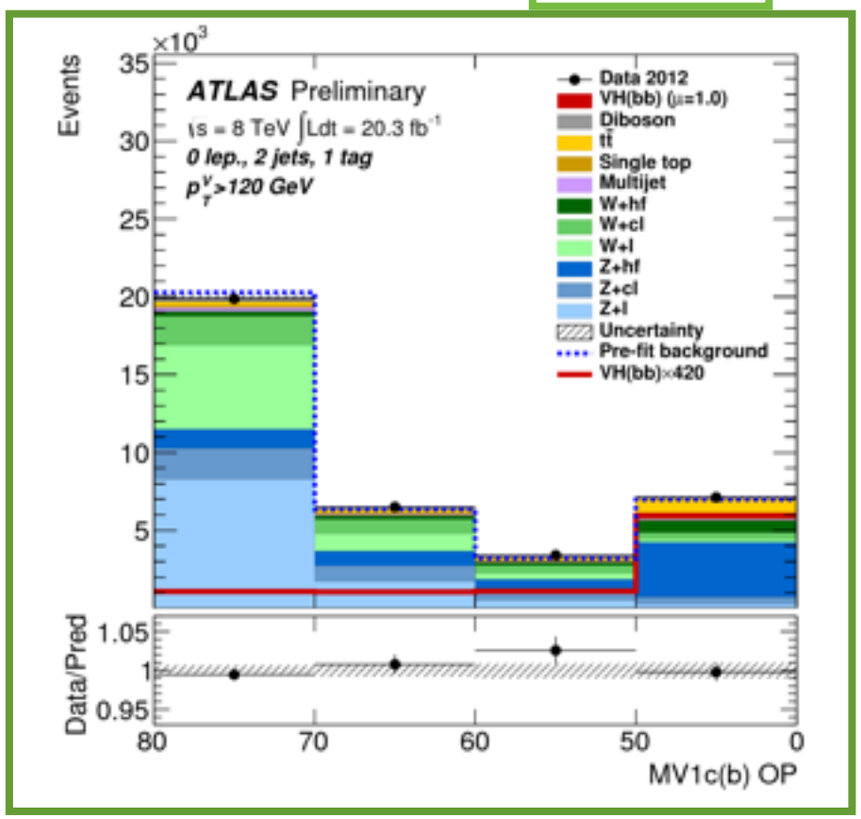


- W/Z+jets (mainly +bb/cc/cl)
- Top background (especially 1- and 0-lepton)
- Diboson (W/Z+Z to bb)
- QCD (data-driven estimates)

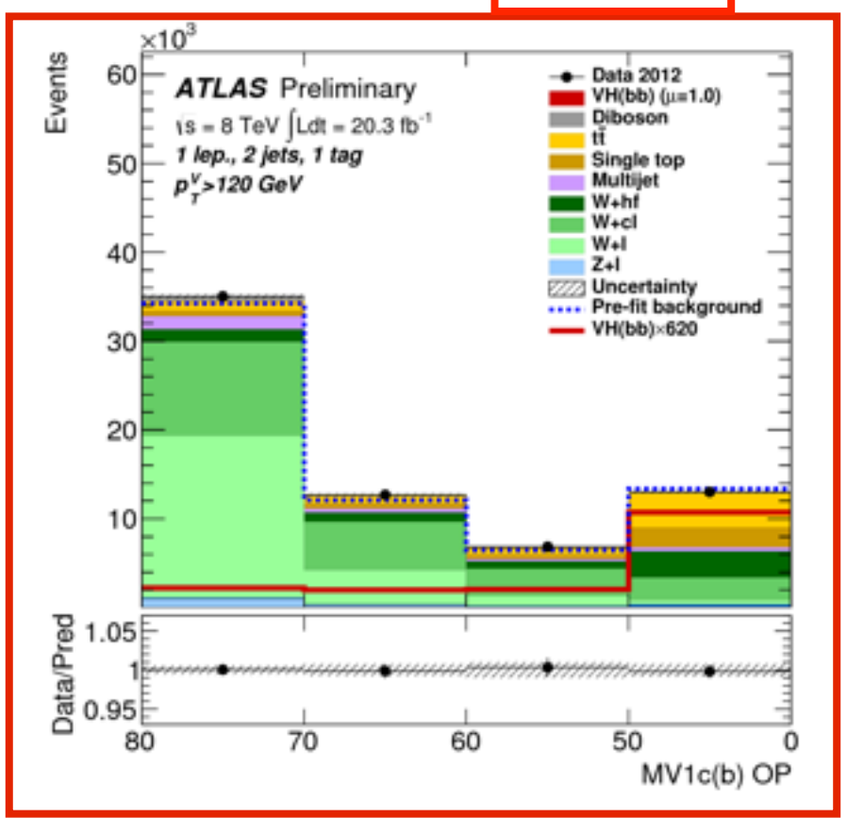
W+jet, Z+jet backgrounds

- High statistics control regions are the 0- and 1-tag regions
- Residual contamination from top bkg in 0- and 1-lepton

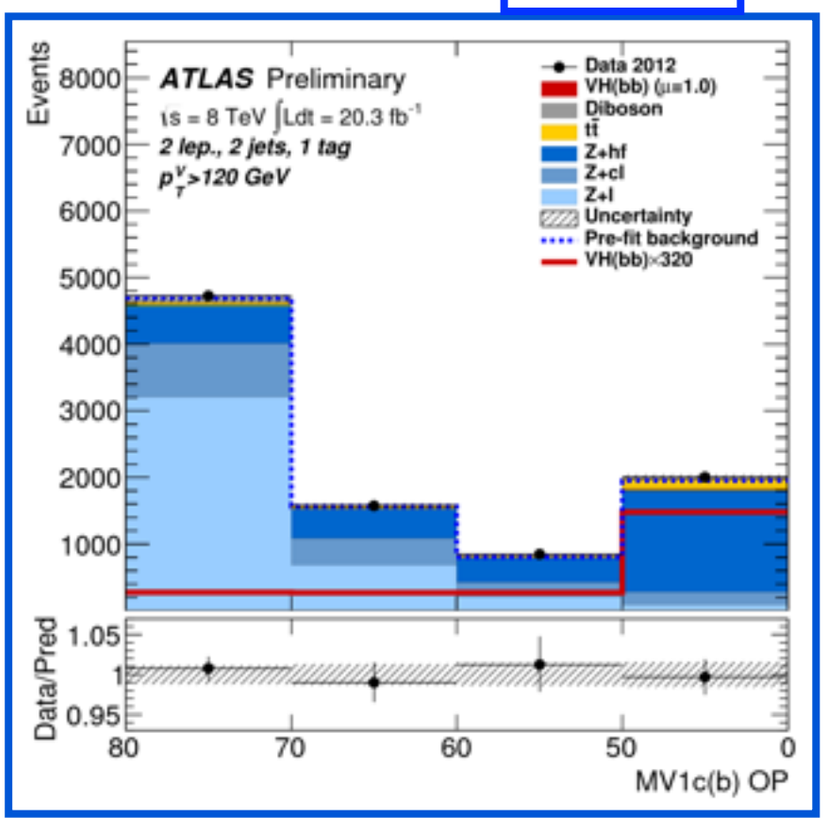
0-lepton



1-lepton



2-lepton

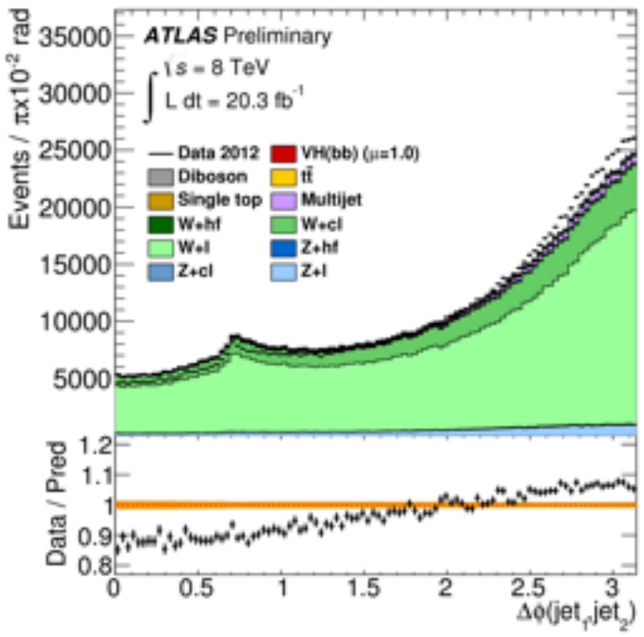


- The MV1c distribution in the 1-tag regions is used to obtain the fractions of W+ and Z+cl, cc/cb/bb from data.

Process	Scale factor
Wbb	0.83 ± 0.15
Wcl	1.14 ± 0.10
Zbb	1.09 ± 0.05
Zcl	0.88 ± 0.12

Data driven corrections

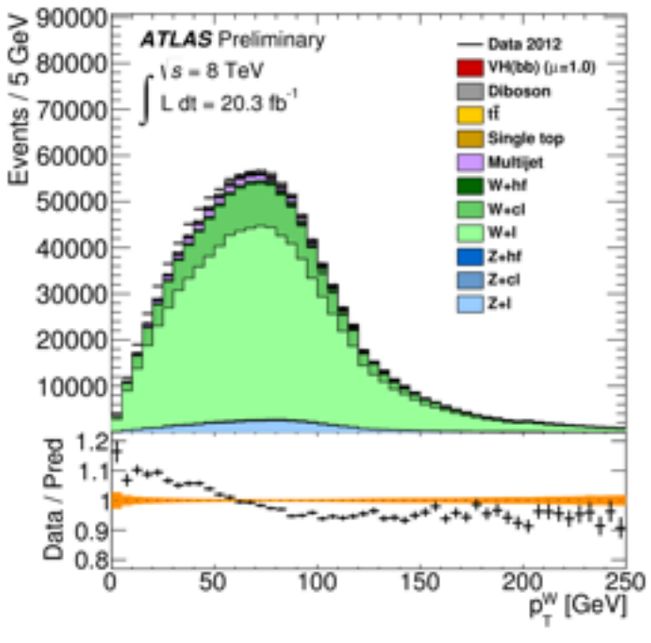
- In both 0- and 1-tag regions, a significant discrepancy between data and MC is seen in both the DeltaPhi(j,j) and pT(V) distributions.

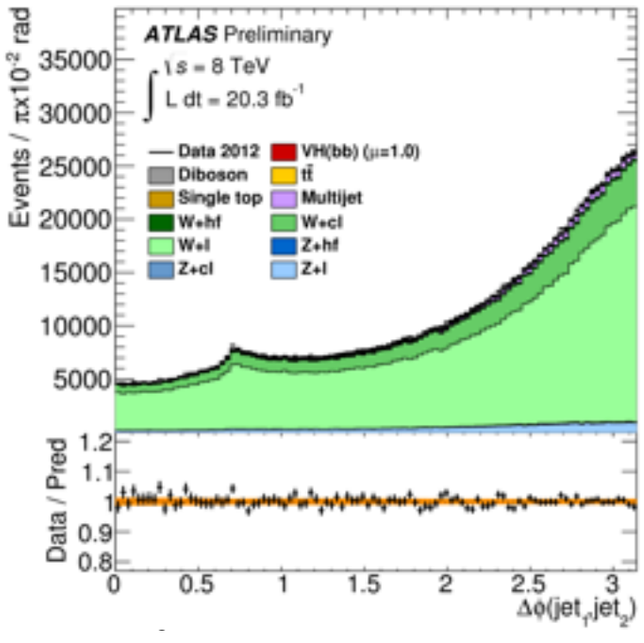


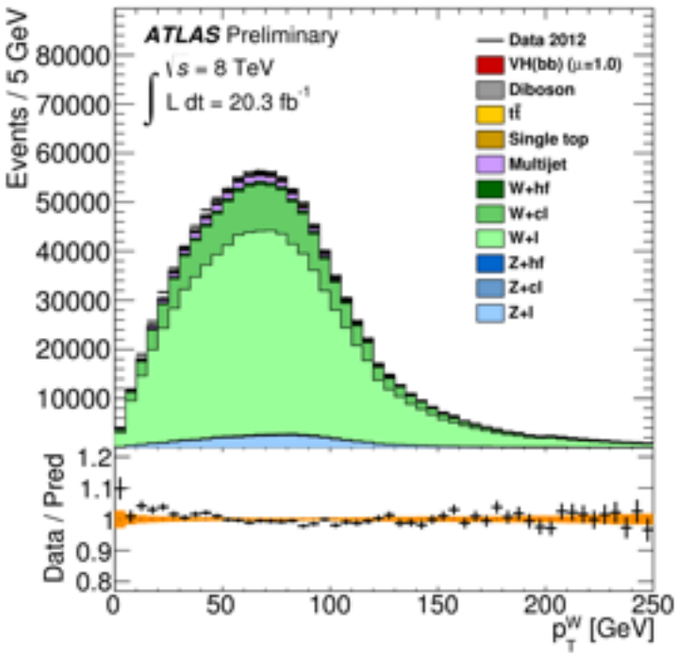
- A data/MC correction is derived using 0-tag events based on DeltaPhi, and applied to MC. The low and high pT(V) bins are separately corrected.

- The correction works well also in 1-tag events, which means W+cl needs the same correction. But hard to conclude on W+cc/bb: no correction applied there.

- Half of the correction as systematic uncertainty. The full W+light/cl correction as systematics on W+bb/cc.







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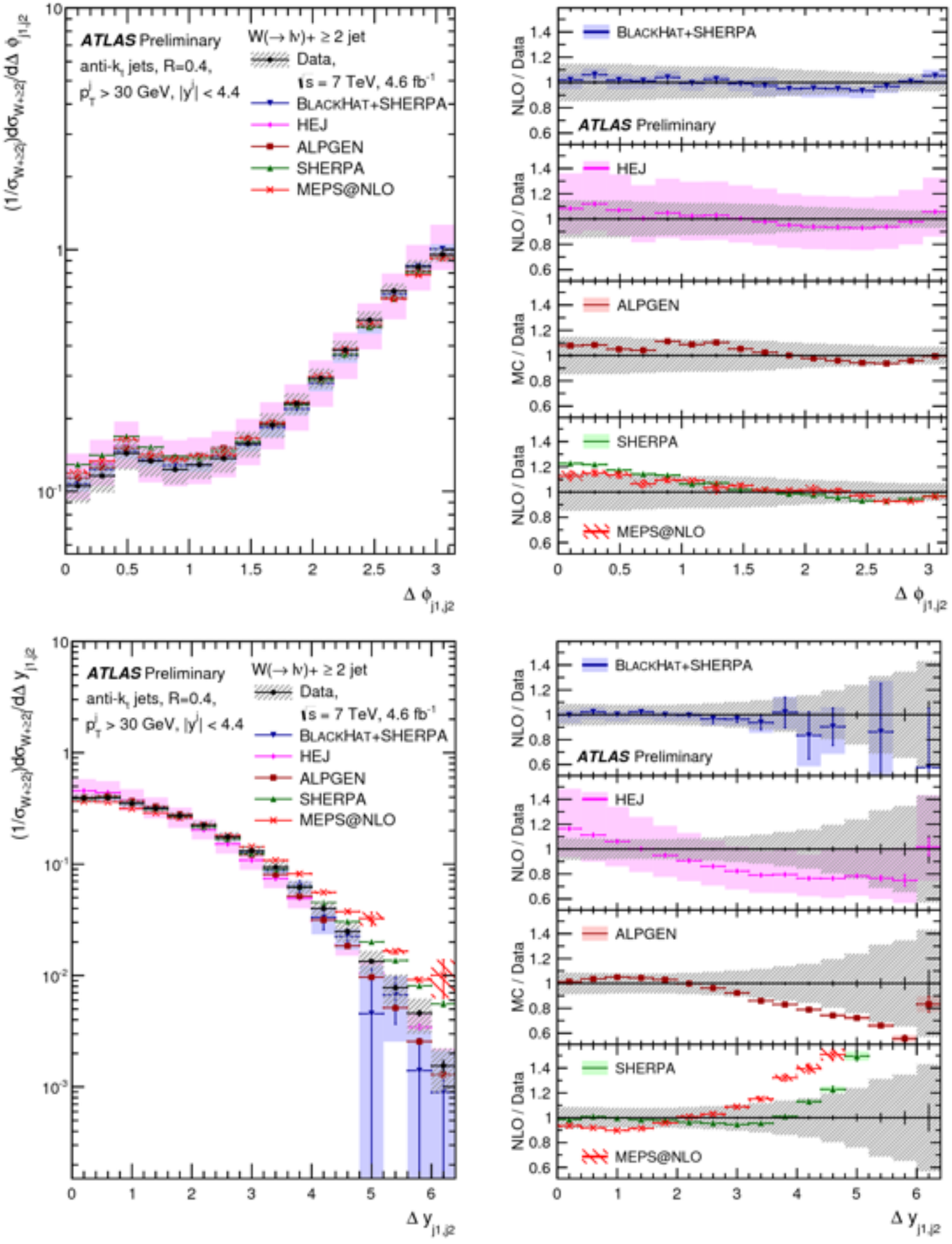
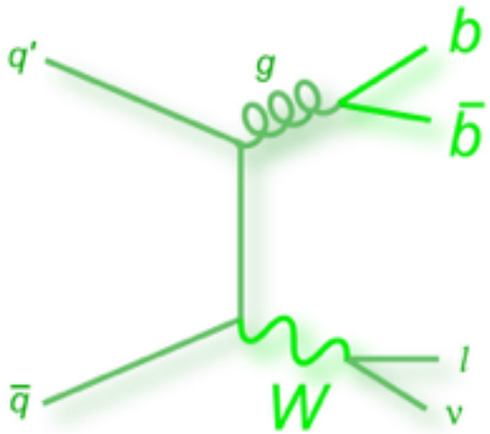


SM measurement

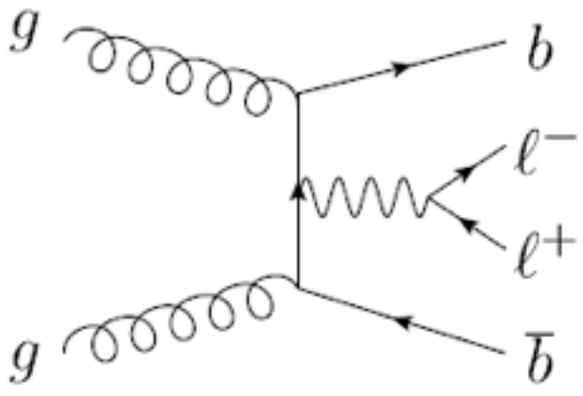
- Despite the different cuts, the same effect is seen in the unfolded W+jet measurement, for N(jets)≥2.
- NLO for W+2 jets (BlackHat +Sherpa) gets closest to data.
- For Run-II, hopefully we can establish a good modelling for W+jets first, before the fun with heavy flavor starts!
  - First indications based on Sherpa 2.1.x are not so promising.
  - Some NLO codes give slightly improved modelling, is the matching to the parton shower the problem?

W+bb/Z+bb processes

- For heavy flavor processes additional systematic uncertainties are considered.

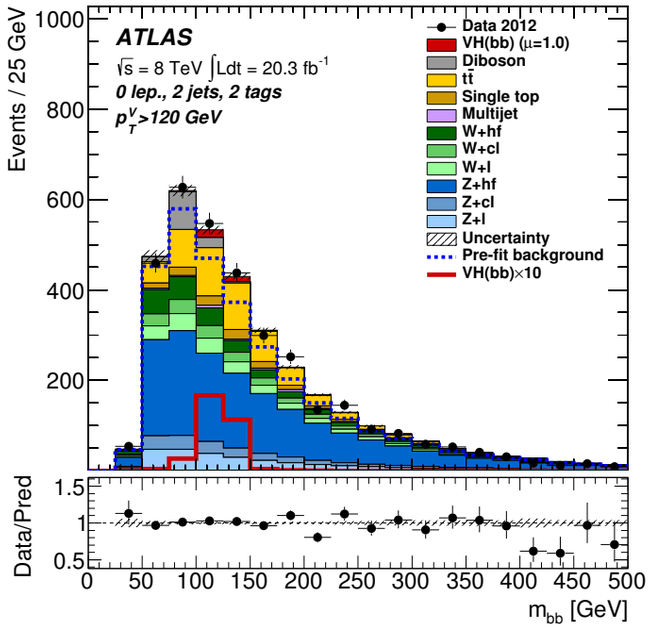


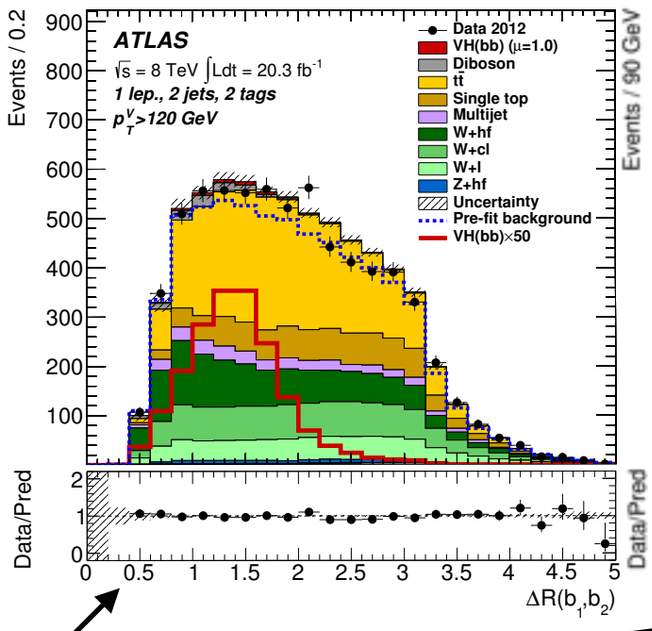
- **W+bb** is hard to control with data (top/single-top backgrounds). Different generators / models are considered:
  - 1. Powheg+Pythia/Herwig
  - 2. aMC@NLO
  - 3. Sherpa
- Variations of O(20%) on m(bb), ΔR(bb)! (gluon splitting? NLO corrections?)
- Really hoping in theory improvements in this area…
  - Sherpa 2? Powheg MiNLO Wbb? (needs W+bbj @ NLO)? aMC@NLO (needs extension of FxFx to b-jets)?

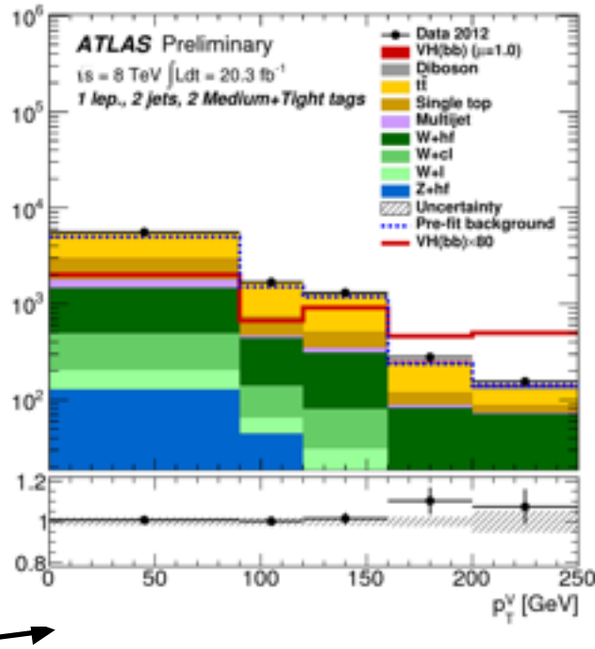


- **Z+bb** can be controlled a bit easier from m(bb) sidebands, but signal region lacks statistics
  - Systematic variation on m(bb) derived in 0- and 1-tag region, and cross-checked in 2-tag region.

BDT



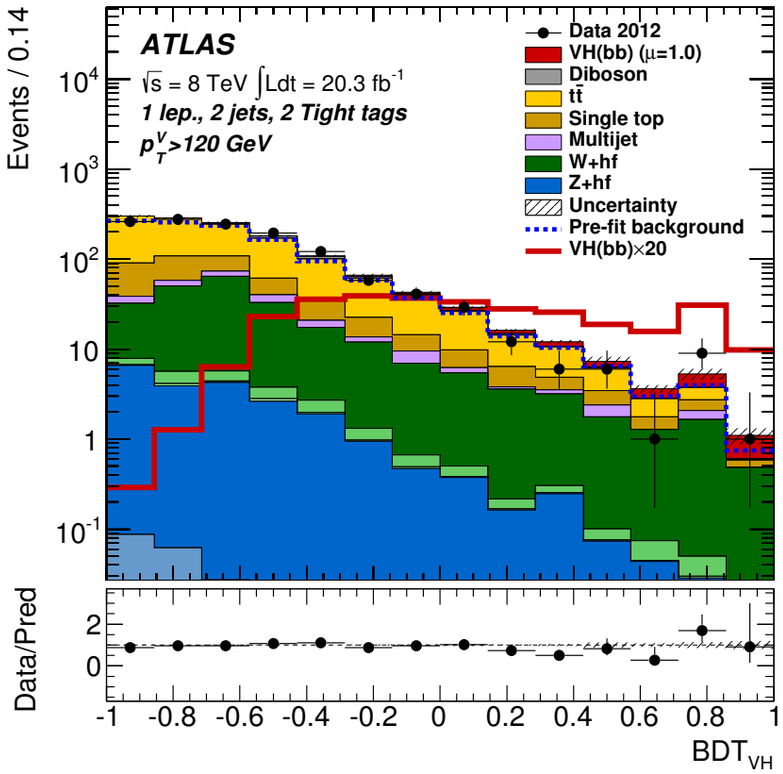




Variable	0-Lepton	1-Lepton	2-Lepton
p_{T}^{V}		×	×
$E_{\mathrm{T}}^{\mathrm{miss}}$	×	×	×
$p_{\mathrm{T}}^{b_1}$	×	×	×
$p_{\mathrm{T}}^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\lvert\Delta\eta(b_1, b_2)\rvert$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\lvert\Delta\eta(V, bb)\rvert$			×
H_{T}	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_{T}^{W}		×	
$m_{\ell\ell}$			×
$MV1c(b_1)$	×	×	×
$MV1c(b_2)$	×	×	×
	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	×	×	×
m_{bbj}	×	×	×

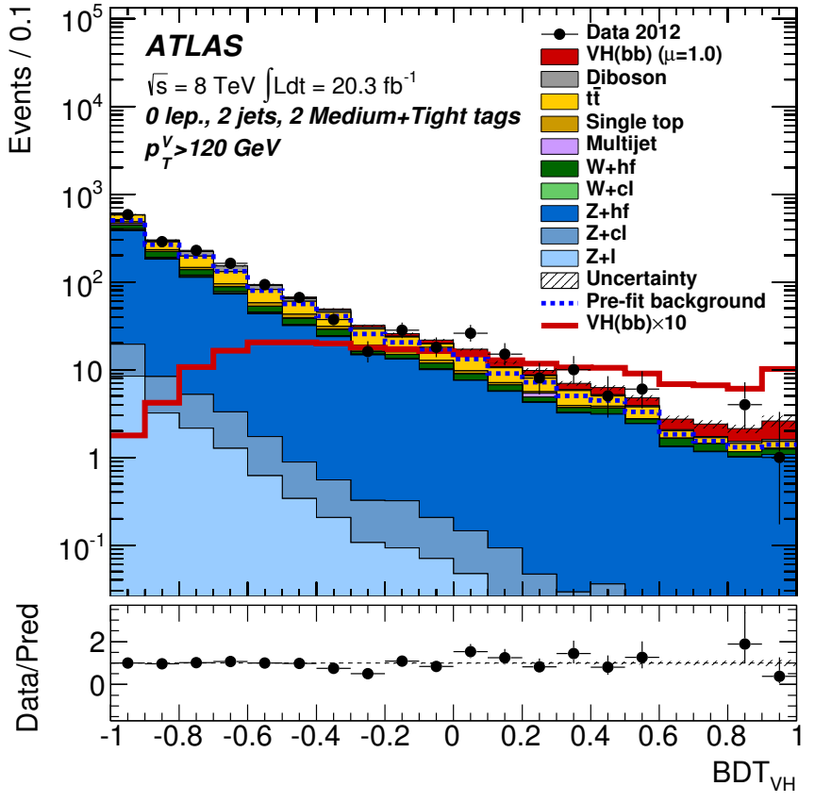
- Good description of input variables & correlations.
- Main improvements from EPS 2013:
  - MVA based on BDT (+15%)
  - “Continuous” b-tagging (+15%)
  - GSC for jets / kinematic fit in 2-lepton
  - Re-optimization of cuts
- >50% improvement in sensitivity
  - SLAC goal was to improve H to bb by >20%. Exceeded!!

Fit model

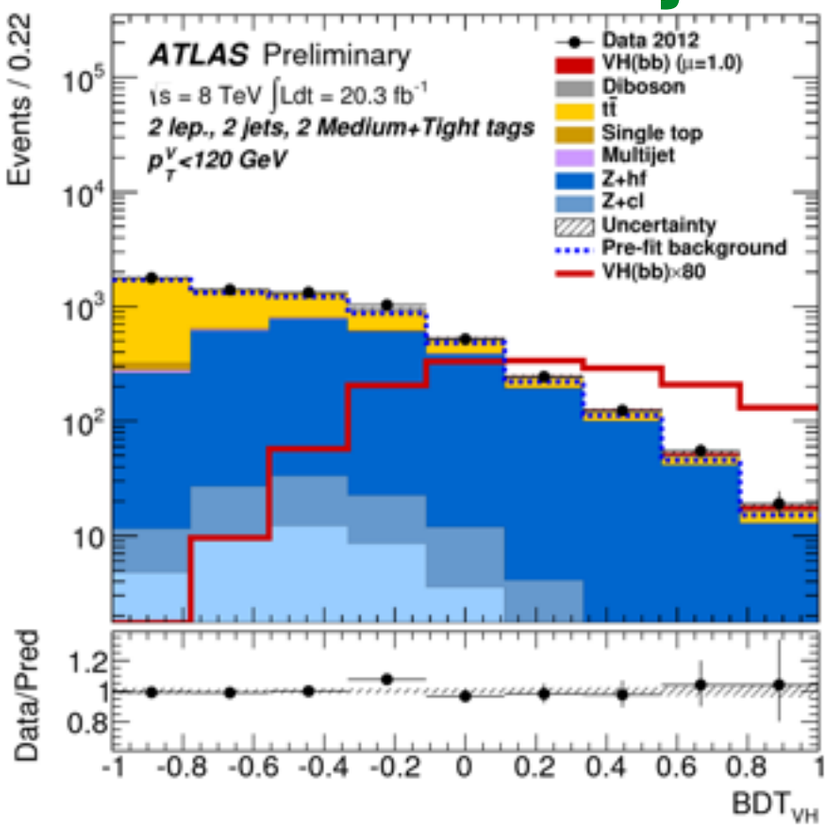


1-lepton
TT 2 jets

0-lepton
MM+TT 2 jets

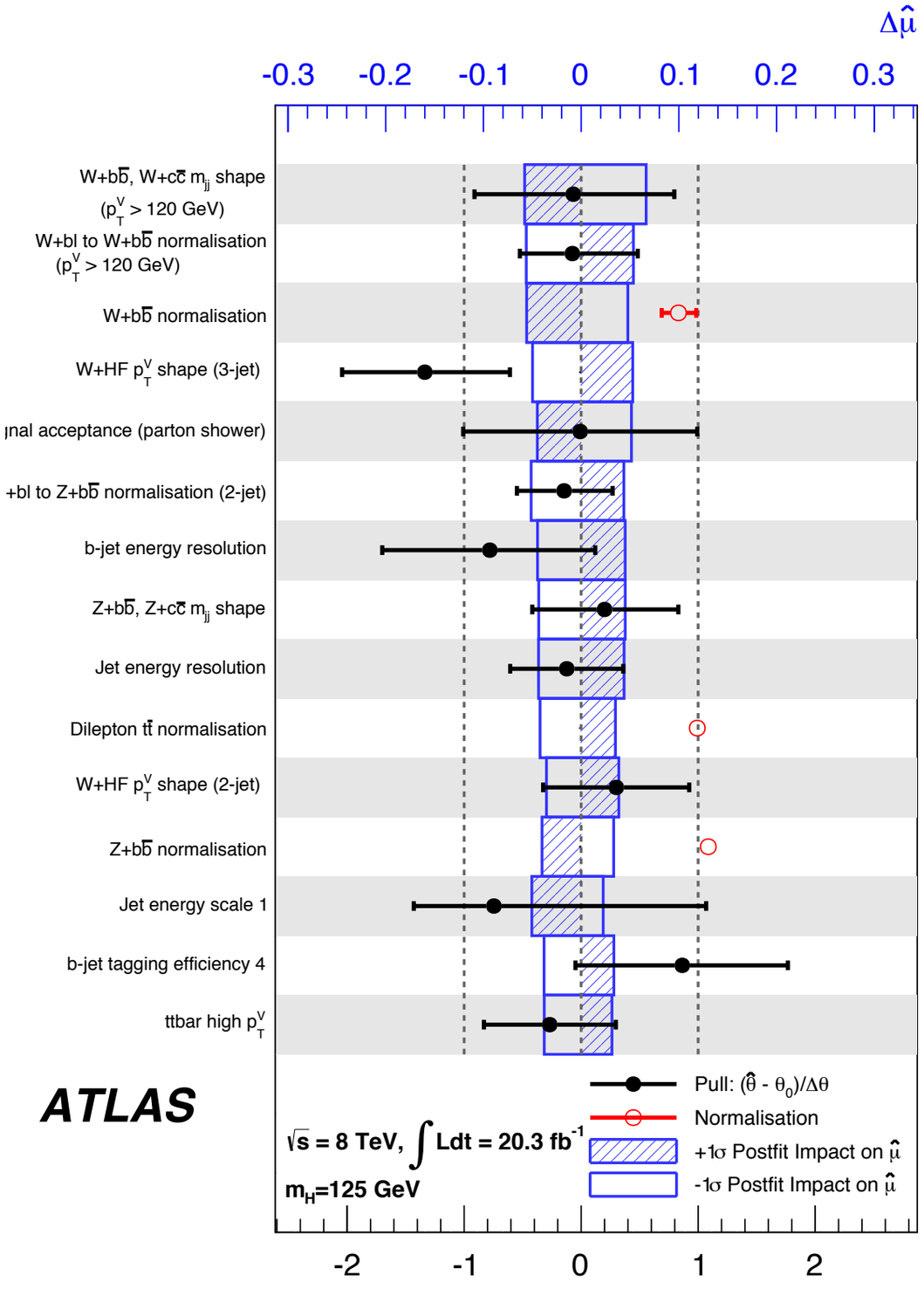


2-lepton
MM+TT 2 jets

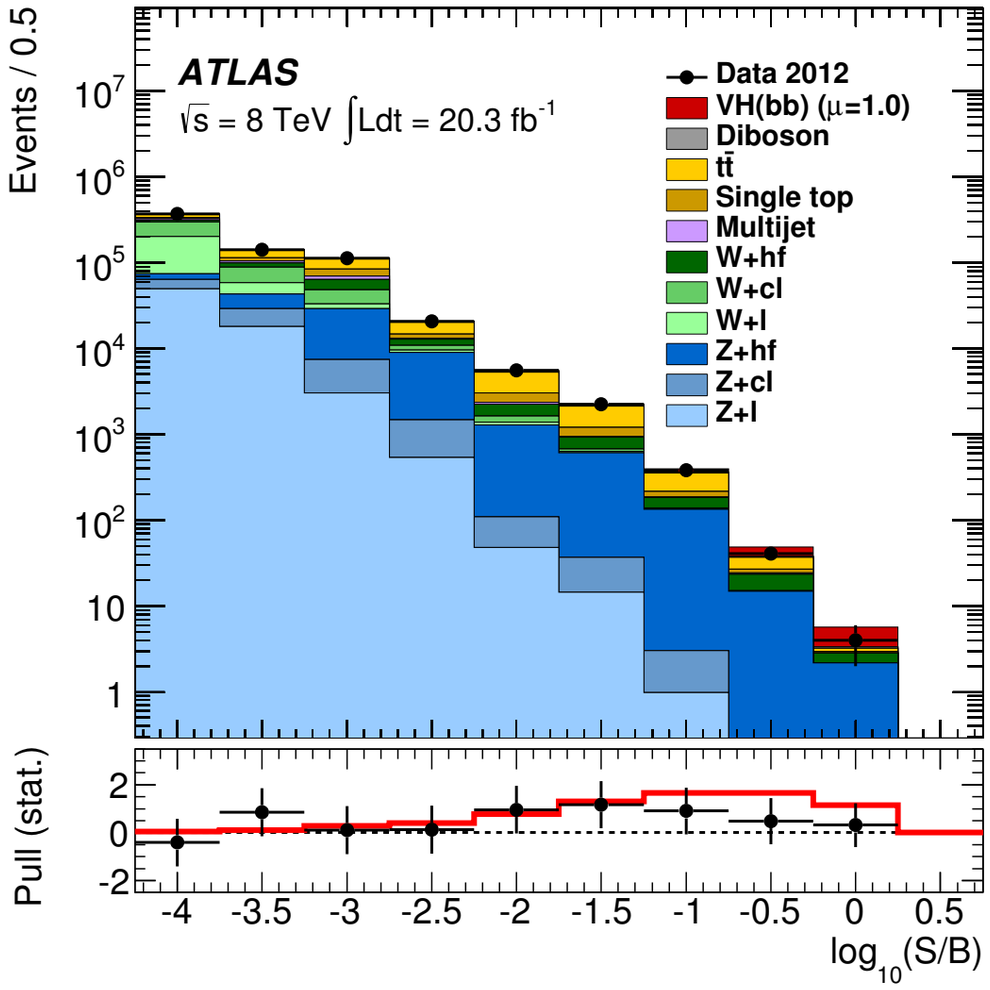


- Simultaneous profile likelihood fit to:
  - **2-tag**: 27 signal regions
  - **1-tag**: 11 control regions
- constraining backgrounds & extracting μ
- ~170 NPs to account for systematic effects

Systematic uncertainties

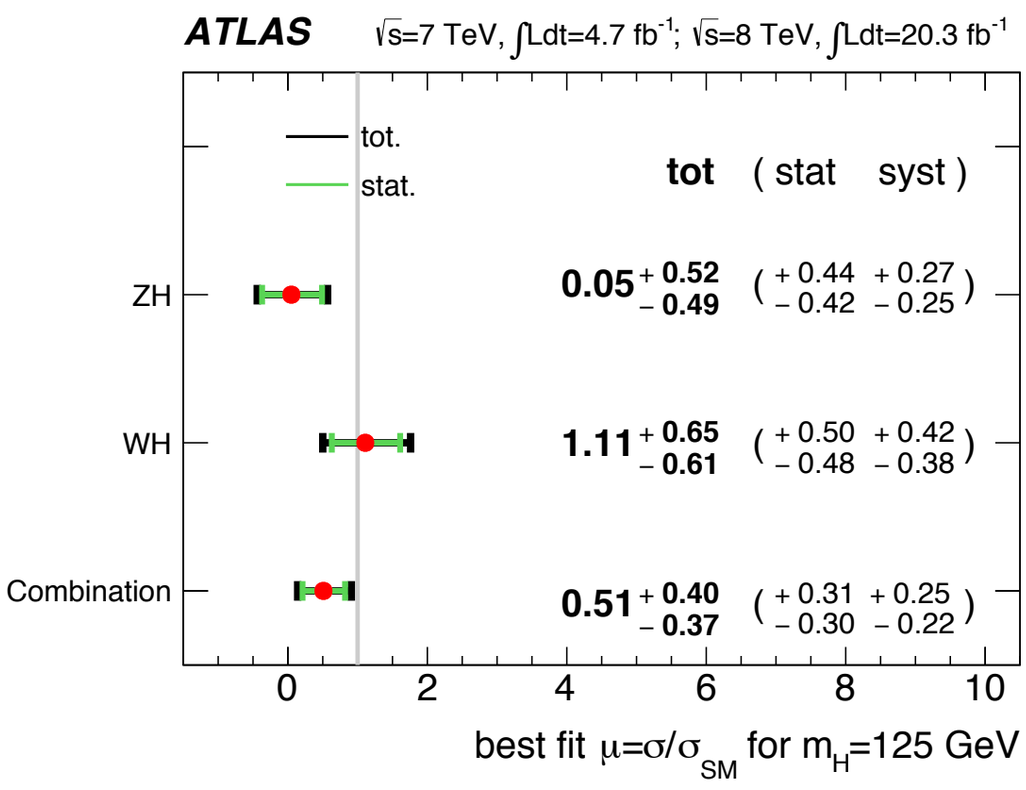


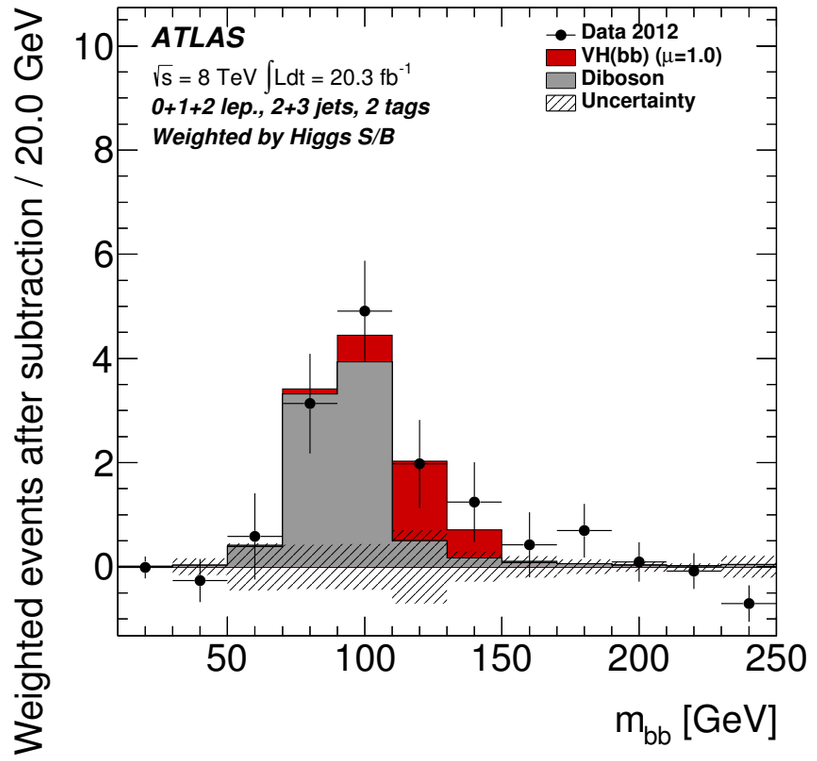
- Leading uncertainties:
  - W+b/c theory (shapes + flavor composition)
  - signal theory (parton shower)
  - jet energy resolution
- Important message for Run-II
  - Need to urgently improve our MC modeling (gluon splitting, heavy flavor fractions,…)



Main result

- Uncertainty on μ decreased from ~0.65 to ~0.4!
- Expected sensitivity 2.6σ, observ. 1.4σ
  - μ = 0.5 ± 0.4
- No evidence for H to bb yet, but no incompatibility either……





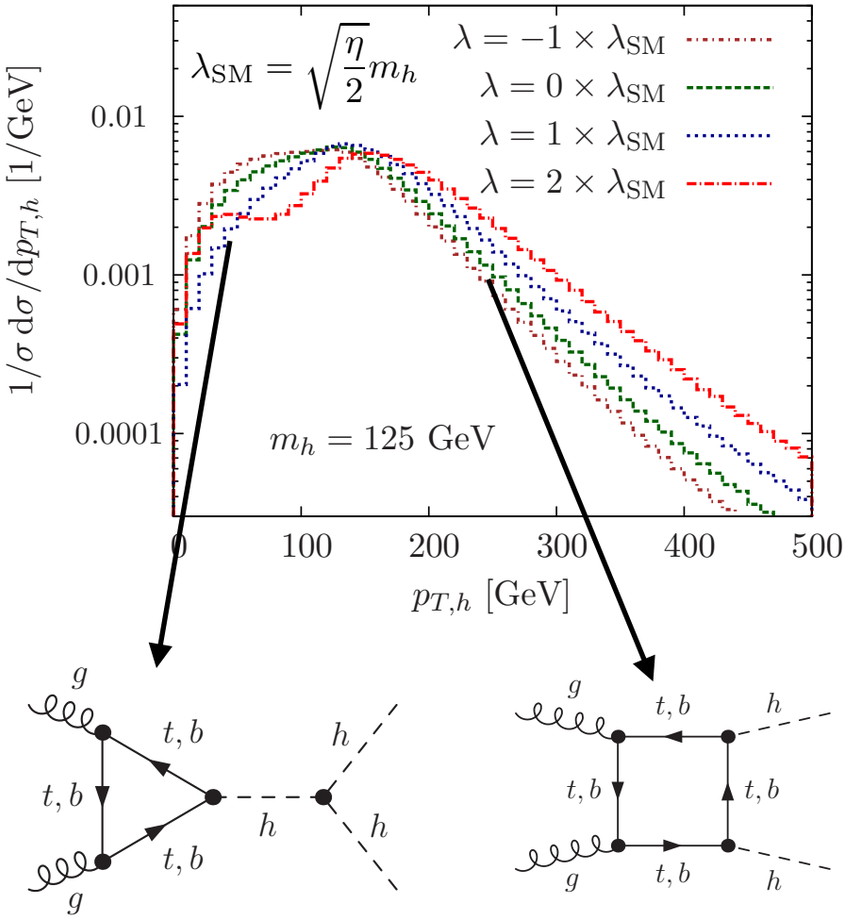
H to hh to 4b

- Measurement of Higgs self-coupling crucial for full characterization of EW sector

$$V(H^\dagger H) = \mu^2 H^\dagger H + \eta (H^\dagger H)^2$$
$$\supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4$$

- Very challenging at the LHC! (even with L=3000 inv. fb.)

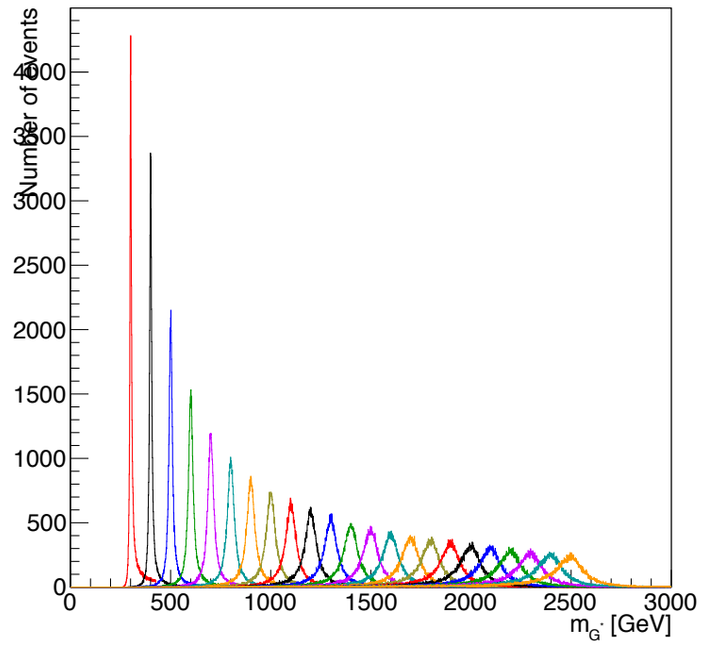
$$2\eta = g^2 m_h^2 / m_W^2 \quad ?$$



- Di-Higgs production does not only involve triple Higgs vertex.
- Variation of coupling result in variation of differential pT(H) cross section.
- Important to finalize sensitivity studies now, since we **already** need to finalize the main detector design choices for Phase-II!!

X to hh to 4b

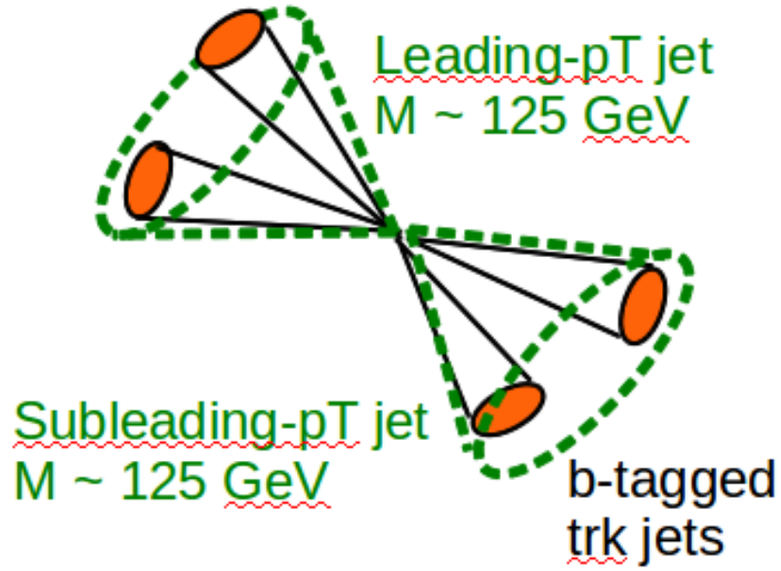
- Well before, we can start to investigate di-Higgs production in several BSM scenarios:
  - Spin-2 KK graviton in the Randall-Sundrum model with warped extra-dimensions
    - Search for masses up to ~2 TeV
  - SUSY H to hh
  - … and many other models

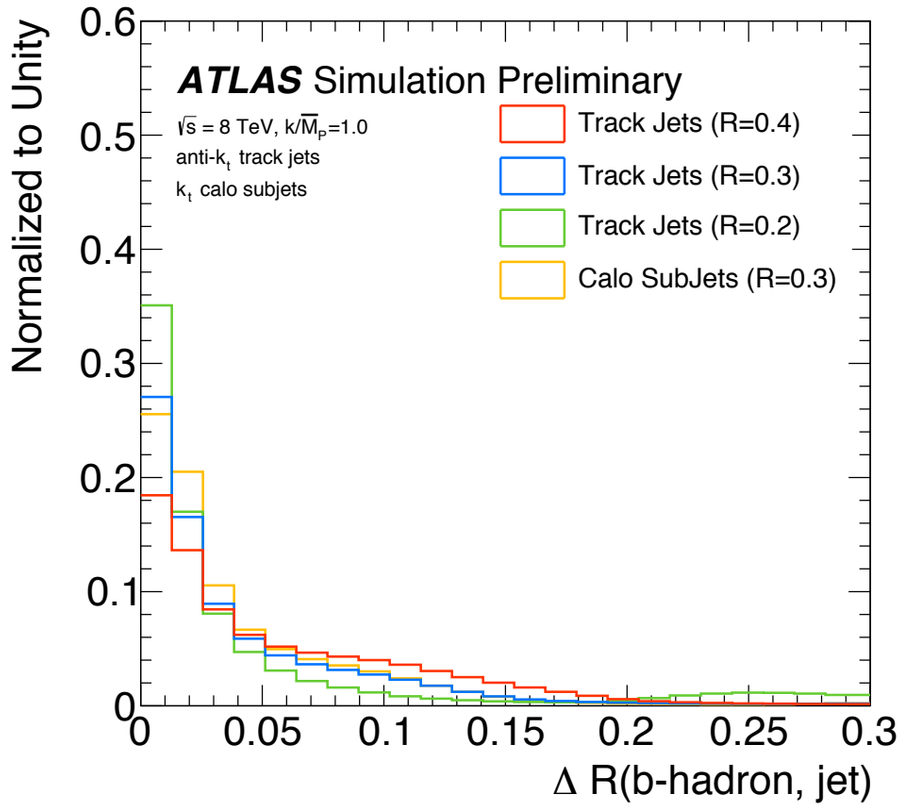


- For resonances above ~400 GeV, pairs of b-jets from two Higgses start to be very collimated
  - Challenging for reconstruction algorithms !

Reconstruction strategy

- Trigger based on multi-jet and multi-jet + b-jets signatures.
- Reconstruct two Anti-Kt R=1.0 calorimeter jets and trim them
  - Leading pT>350 GeV, sub-leading pT>250 GeV
- Then match these two jets to four Anti-Kt R=0.3 track-jets.
- Allows to resolve jets into sub-structure.
- Results in better alignment of "subjets" along true b-hadron direction (crucial for b-tagging!).

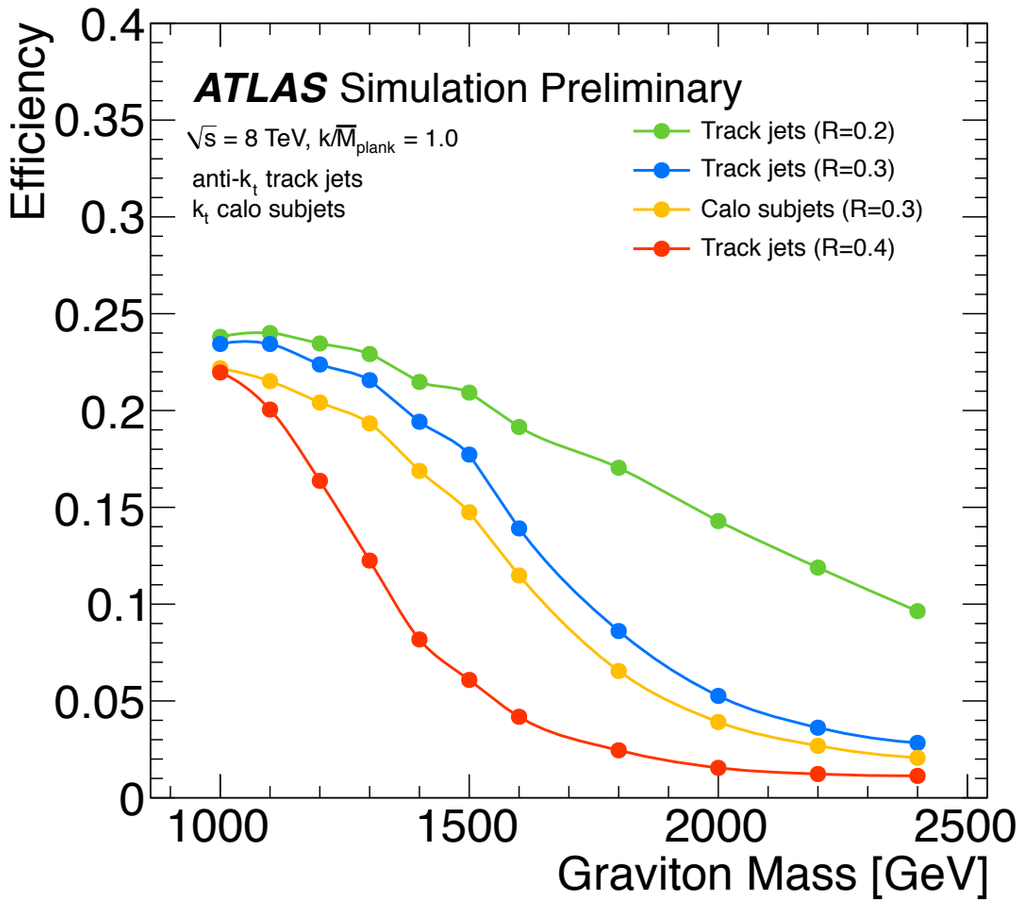




B-tagging the 4 b-jets…

- A proof of the concept is described in the ATLAS pub note ATL-PHYS-PUB-2014-13 and shown at Boost 2014.

- The new technique has the potential to significantly improve the sensitivity to a high mass resonance w.r.t. previous analyses.



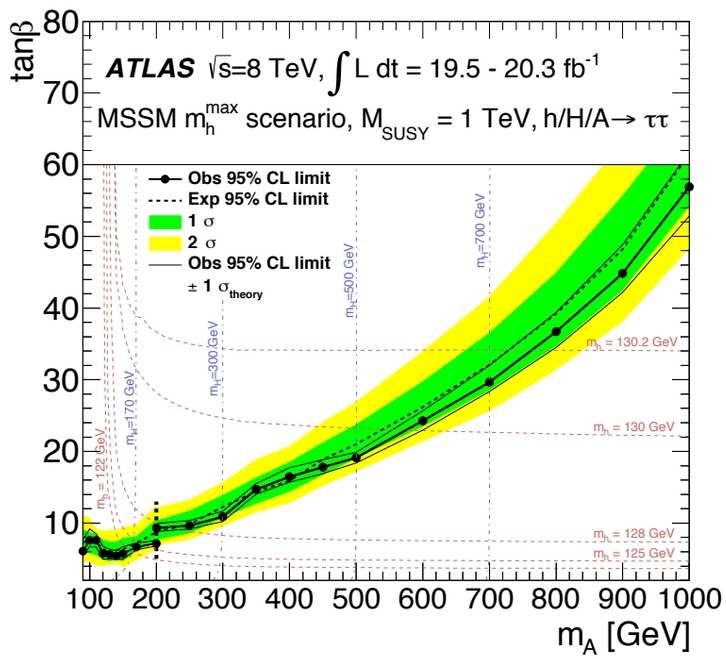
- Track-jets are now being calibrated with data.

- X to 4b analysis progressing well

- Plan is to publish full Run-I result on a few months timescale.

bH to bbb analysis

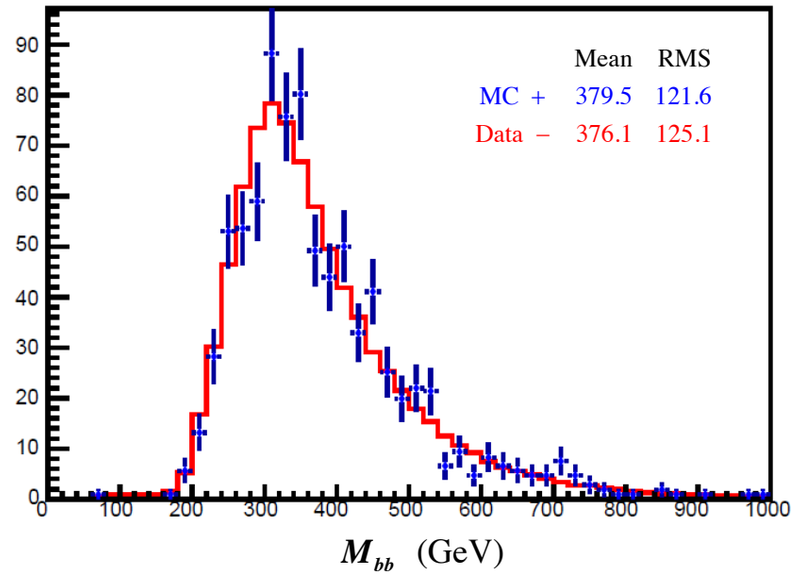
- Together with H → ττ, main search channel for heavy A/H Higgs boson in MSSM scenarios with large tan(β).
- Very challenging analysis because of pure hadronic environment and relatively soft b-jet from associated. production



- Select events with at least 3 b-tagged jets.
- Look for di b-jet peak over large bbb continuum background.
- Determine background shape from simultaneous likelihood fit to m(bb) in control region (bb + anti-tag).
  - Assumption that m(bb) is nearly independent on flavor of third jet crucial. Need theory and simulations to back this up!

Background simulation

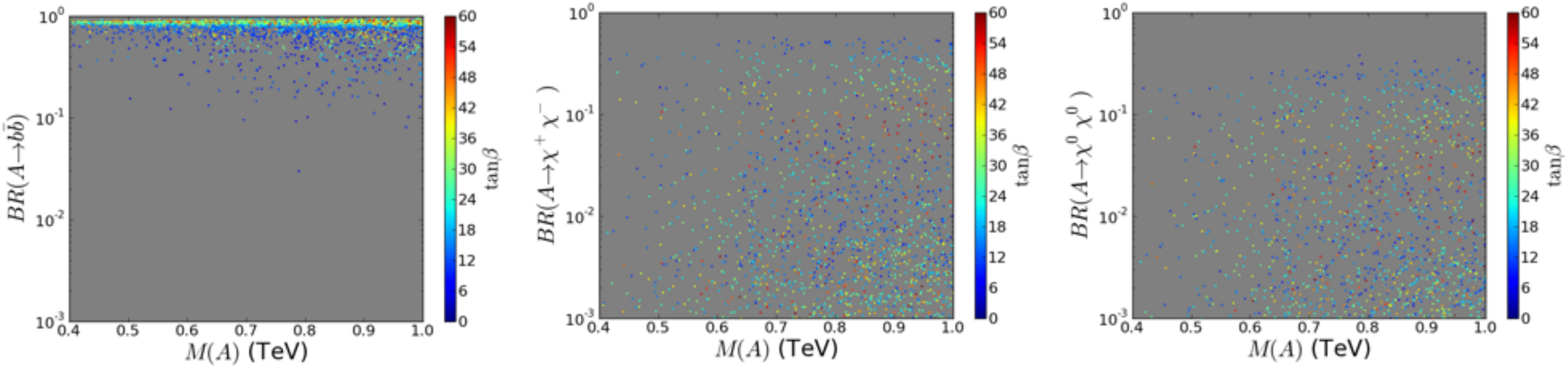
- Background mainly from multi-jet production of ≧ 3 b-jets difficult process to simulate
  → help from Stephan to produce realistic Sherpa sample (thanks!!)
  - Replaces more simplistic model based on Pythia (2-to-2 scattering ME only)
  - Of general interest for studying multi-b production in ATLAS
- After quite some validation, got the MC request finally approved.
- Plan to finalize analysis soon, and have public results to show!



subprocess	cross section (pb)
$jj \to b\bar{b}jj$	58531
$jj \to b\bar{b}j$	33411
$bj \to bjj \;+\; \bar{b}j \to \bar{b}jj$	22147
$bj \to bjjj \;+\; \bar{b}j \to \bar{b}jjj$	16282
$bj \to bj \;+\; \bar{b}j \to \bar{b}j$	12135
$jj \to b\bar{b}$	1672
$cj \to cb\bar{b}j \;+\; \bar{c}j \to \bar{c}b\bar{b}j$	1602
$bj \to bb\bar{b}j \;+\; \bar{b}j \to \bar{b}b\bar{b}j$	997
$jj \to b\bar{b}c\bar{c}$	776
$cj \to cb\bar{b} \;+\; \bar{c}j \to \bar{c}b\bar{b}$	681
$bj \to bb\bar{b} \;+\; \bar{b}j \to \bar{b}b\bar{b}$	387
$jj \to b\bar{b}b\bar{b}$	376
$b\bar{c} \to b\bar{c}j \;+\; \bar{b}c \to \bar{b}cj$	206
$bc \to bcj \;+\; b\bar{c} \to b\bar{c}j$	194
$b\bar{c} \to b\bar{c}jj \;+\; \bar{b}c \to \bar{b}cjj$	143
$bc \to bcjj \;+\; b\bar{c} \to b\bar{c}jj$	136
$bc \to bc \;+\; b\bar{c} \to b\bar{c}$	122
$b\bar{c} \to b\bar{c} \;+\; \bar{b}c \to \bar{b}c$	121
$b\bar{b} \to b\bar{b}j$	62
$bb \to bbj \;+\; b\bar{b} \to \bar{b}\bar{b}j$	53
$b\bar{b} \to b\bar{b}jj$	44
$bb \to bbjj \;+\; b\bar{b} \to \bar{b}\bar{b}jj$	39
$b\bar{b} \to b\bar{b}$	37
$bb \to bb \;+\; b\bar{b} \to \bar{b}\bar{b}$	30

MSSM Models

- Benchmark models defined within Higgs cross section working group (https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGMSSMNeutral).
- Most of these have very low BR(H/A →bb) < 50%.
- We were wondering why and have asked Tom and JoAnne for advice.



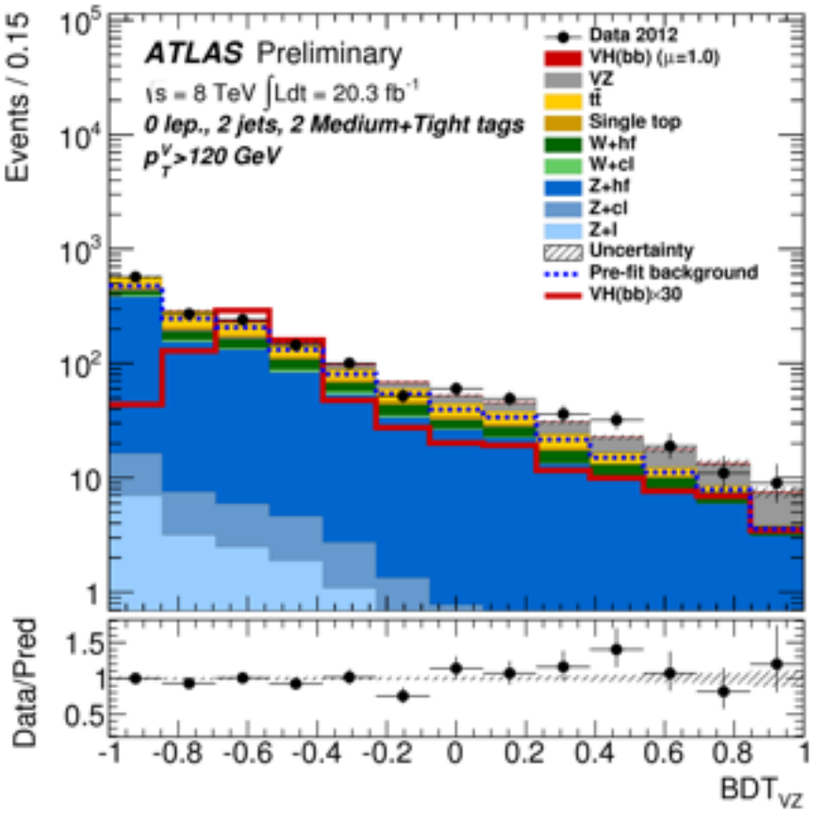
- From their findings (thanks!), most of the allowed A/H decays to SUSY are in charginos and neutralinos, but scenarios with BR(H/A → bb) < 50% remain very unusual.
- Time to add more representative SUSY scenarios?
- An interesting question remains how much BR(bb)/BR(tt) varies from model to model. This determines the relative sensitivity of the ττ and bb searches.

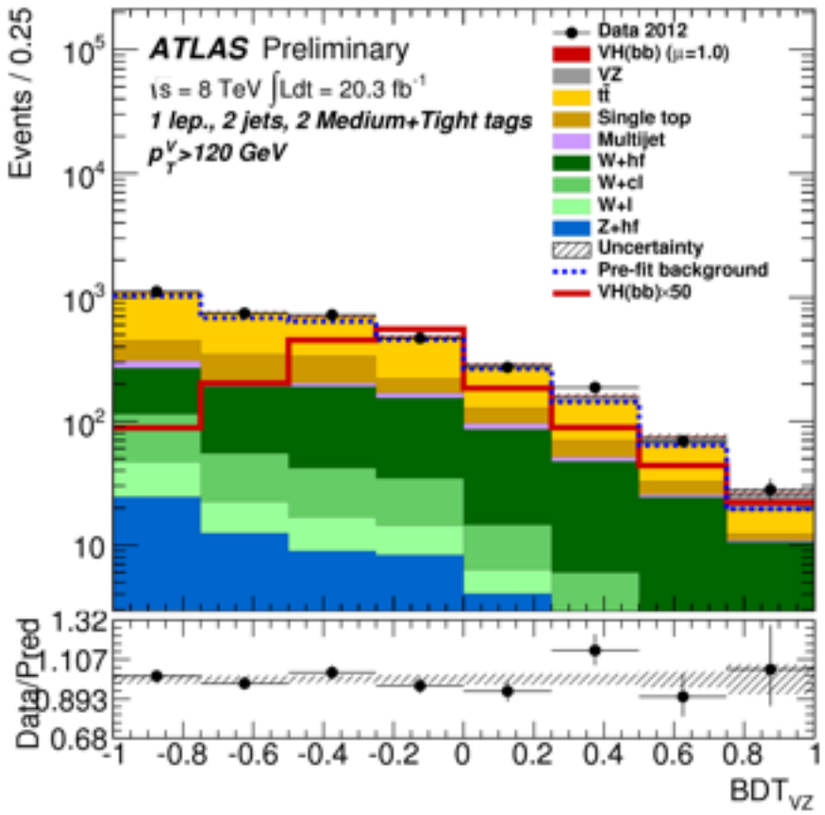
Plans for the future

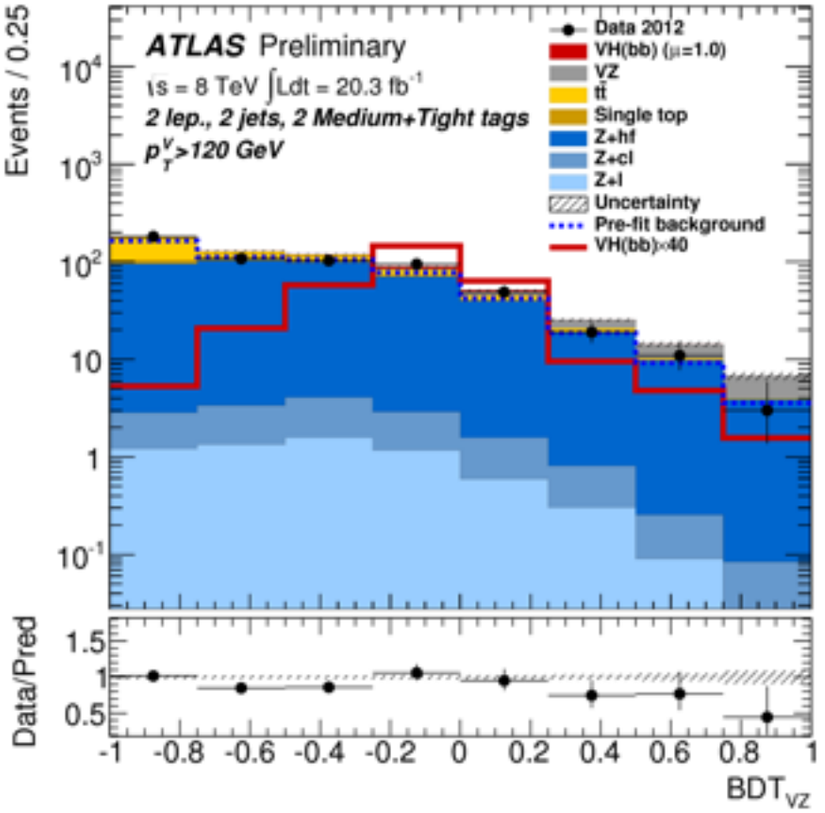
- Observe a clear H → bb signal
  - But need to reduce uncertainties, including theory:
    - SM measurement of W+bb background, in particular challenging region with g → bb splitting?
- Look in early data for resonances decaying into two or 4 b-jets
  - We are now able to access phase space regions with very close-by b-jets: this will extend our reach in many models!
- In 13 TeV data, triggering on bH will be more challenging, but we plan continuing looking into this channel.

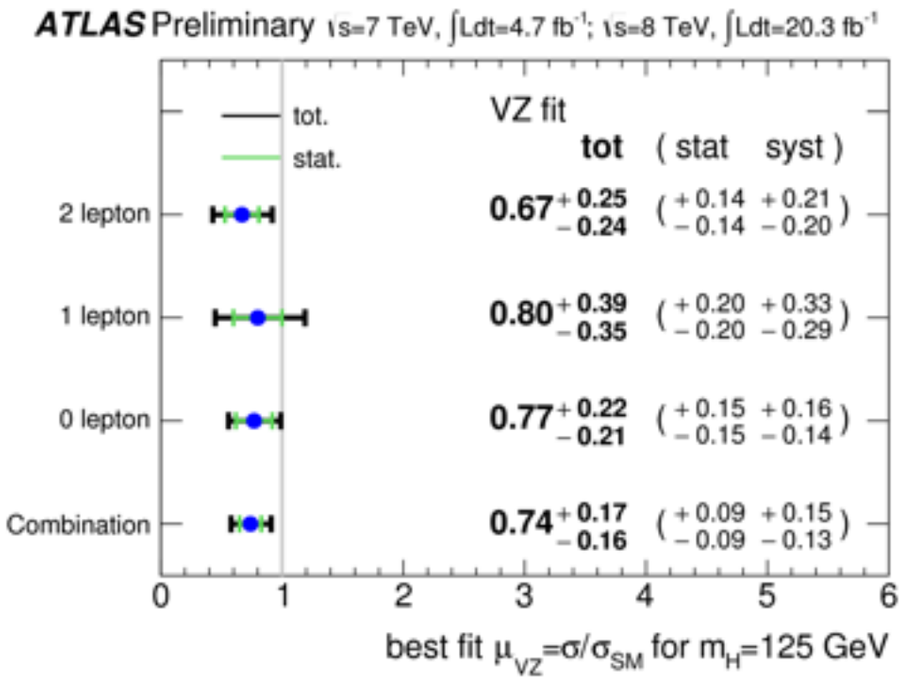
Backup

Cross-check (1): VZ to Vbb







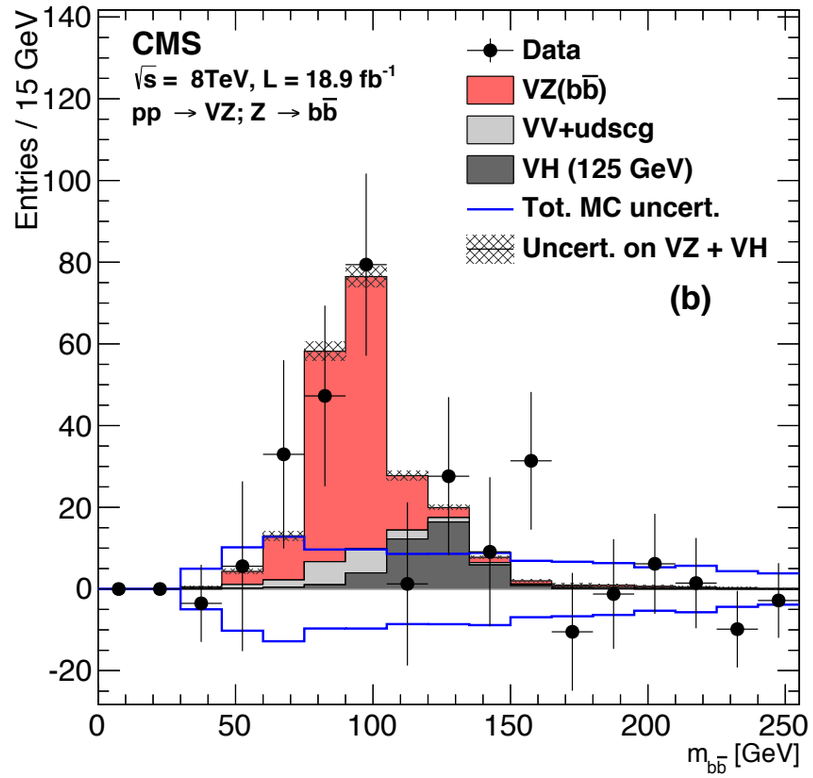


- Train MVA to extract diboson signal
- Clear signal found, all channels well compatible
- ~1.5σ low

Comparison to CMS

ATLAS		CMS	
σ [exp]	σ [obs]	σ [exp]	σ [obs]
2.6	1.4	2.1*	2.1

* neglects pT dependence of gg to ZH contribution, 10% increase in sensitivity?



- New ATLAS analysis has slightly better sensitivity, but observed signal lower
- Combining ATLAS and CMS won't get us to evidence: will need to wait for some good Run-II data
- In the meantime, hope the coupling fits will profit from increased precision of H to bb signal strength