W/Z production associated with a H or a Z boson decaying to a $b\bar{b}$ pair

Chiara Debenedetti
The University of Edinburgh

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Outline

Latest public results on the production of a vector boson decaying leptonically produced in association with a Z or a H boson decaying to a $b\bar{b}$ pair.

- Motivation
- Event selection and analysis strategy
  - Signal and background modeling
- Statistical treatment
  - Higgs fit ingredients
  - Validation on VZ($Z \to b\bar{b}$)
  - VH($H \to b\bar{b}$) results
- Summary and conclusions

public result: ATLAS-CONF-2012-161

Analysis performed on datasets:

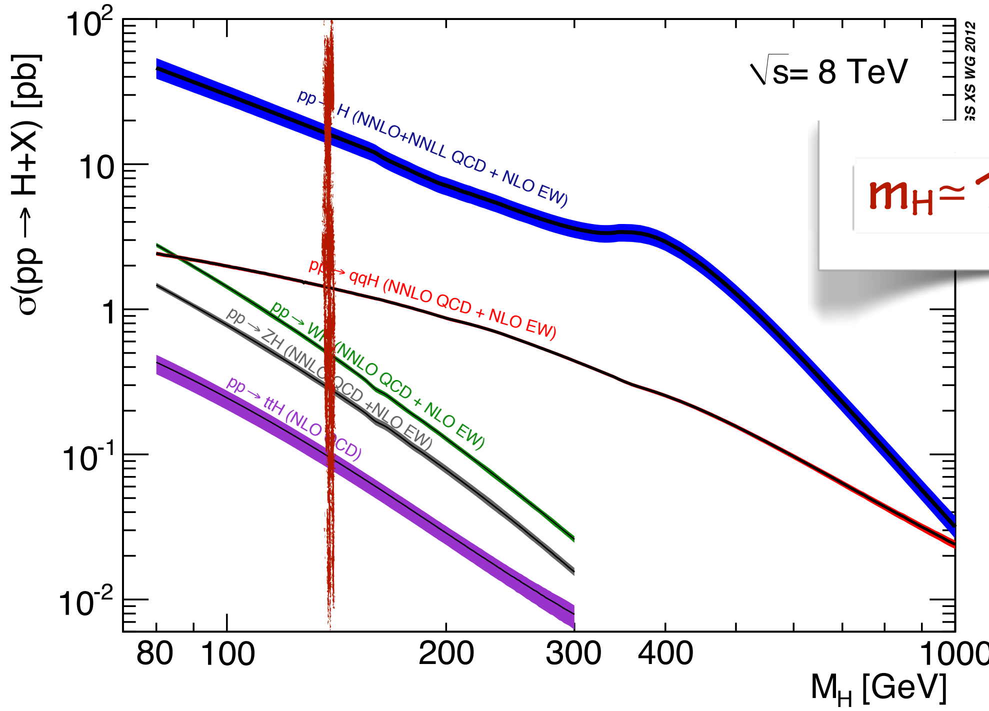
- 13.0 fb^{-1} for $\sqrt{s}$=8 TeV
- 4.7 fb^{-1} for $\sqrt{s}$=7 TeV

Motivation

Higgs mechanism explains **EW Symmetry breaking**
In SM coupling to the **scalar** Higgs field, vector bosons and fermions acquire mass

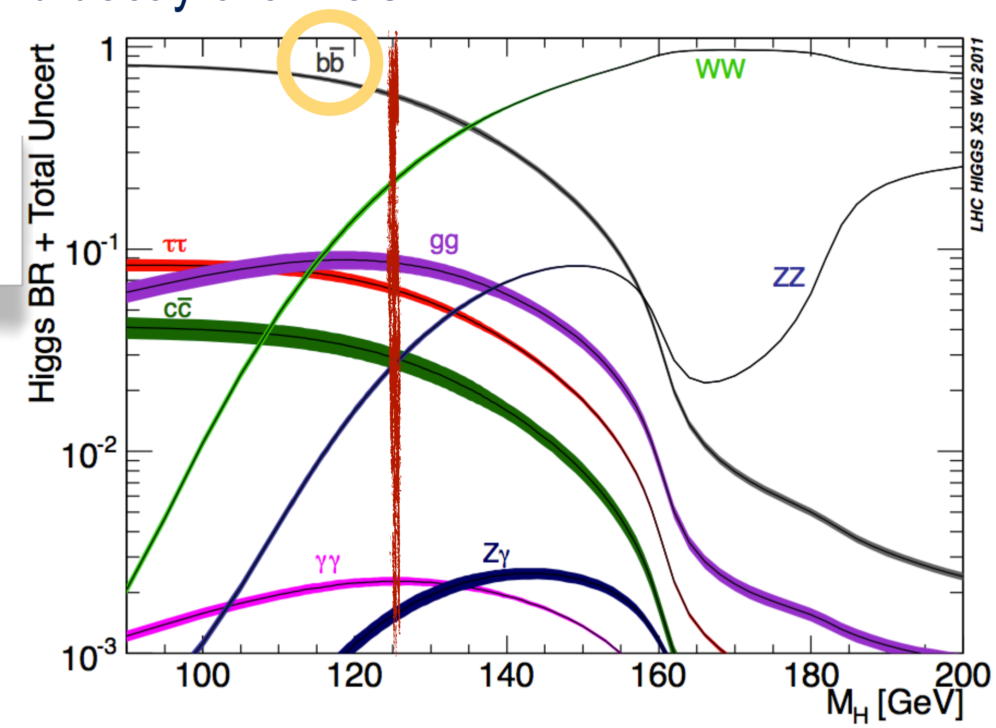
H⟶b$\bar{b}$ observation
⟶ test of direct **coupling with fermions**.

Several Production channels:

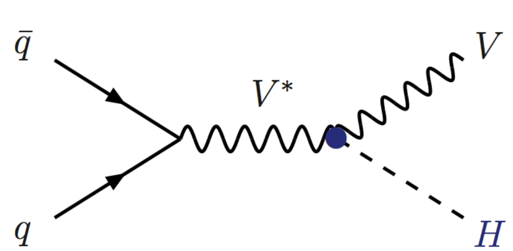


$m_H \simeq 125 GeV$

And decay channels:



ASSOCIATED PRODUCTION



with **W** or **Z**

other production mechanisms cannot be exploited because of QCD background ≈9 order of magnitudes larger

Method used in H⟶b$\bar{b}$ searches, look for associated production with:

W/Z and exploit **leptonic** vector bosons decays

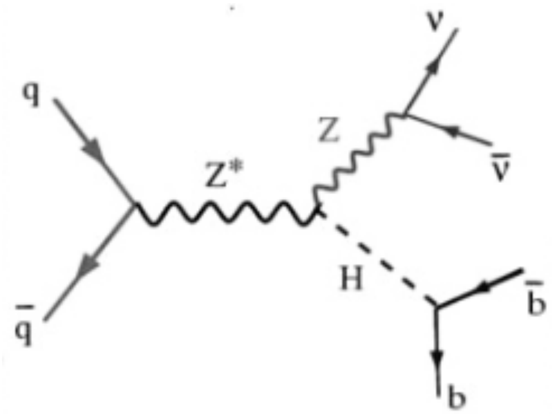
Exploit **distinct signature** in the detector.

Event selection strategy

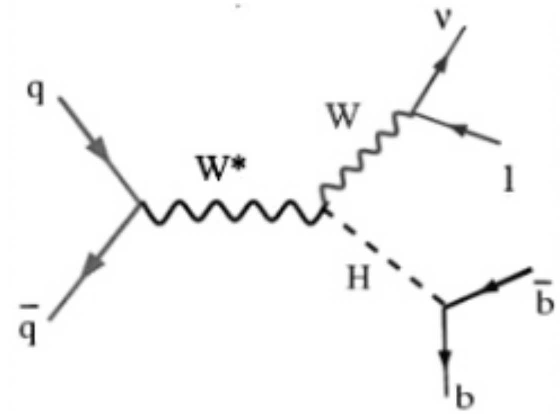
Three separate channels exploiting all possible leptonic V decays (naming convention: lepton = charged lepton):

0-lepton channel has significant contribution from $l\nu b\bar{b}$ events with undetected charged leptons

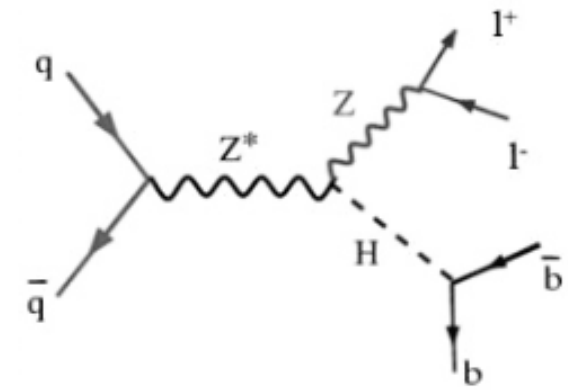
$ZH \rightarrow \nu\bar{\nu}b\bar{b}$ - "0 lepton"



$WH \rightarrow l\nu b\bar{b}$ - "1 lepton"



$ZH \rightarrow l^+l^-b\bar{b}$ - "2 lepton"



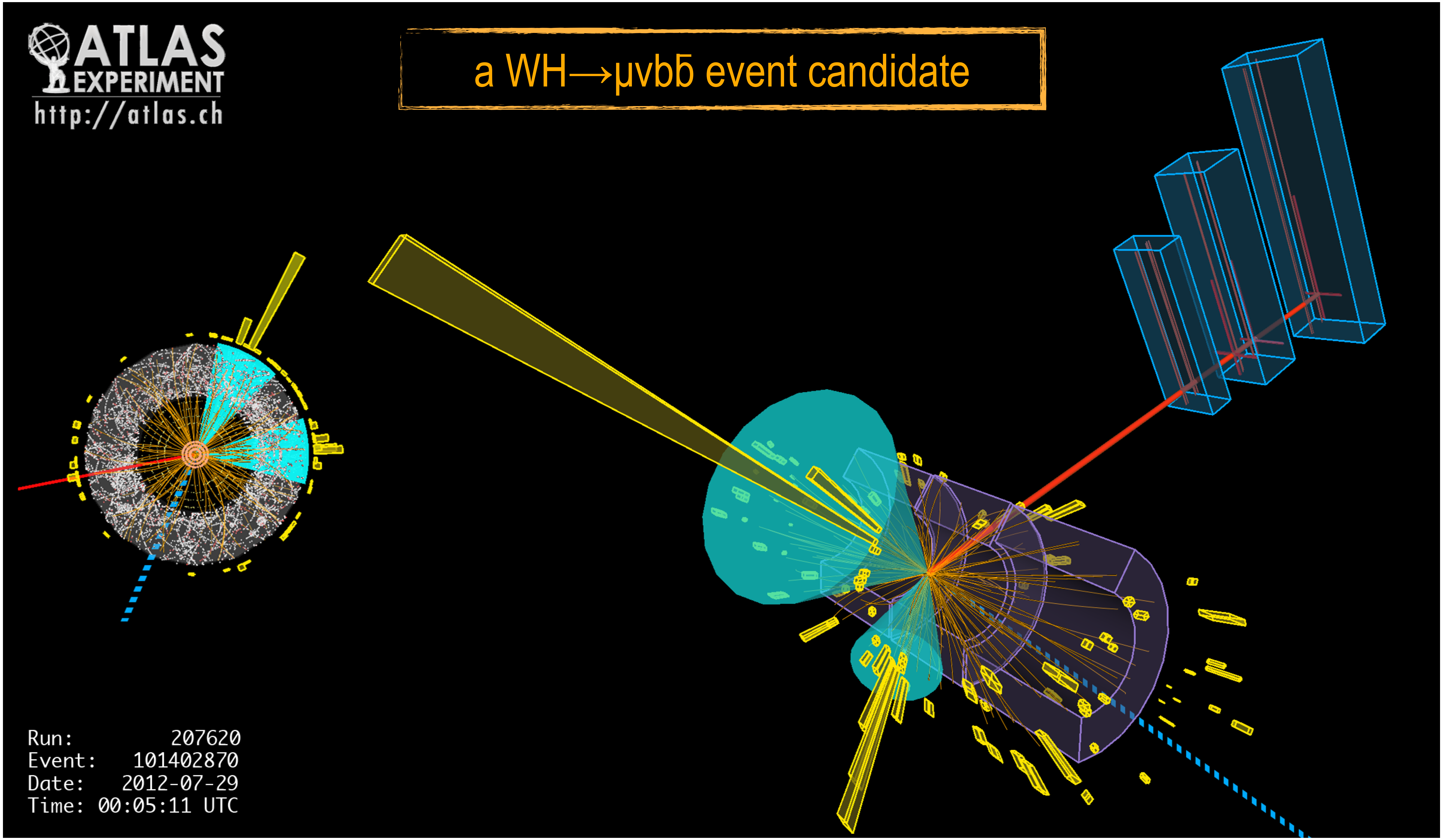
Tag signature via V→leptons

- ✫ *0-lepton → high E_t^{miss}*
- ✫ *1-lepton → identify W:*
  1 high-p_T lepton + E_t^{miss} + W m_T cut
- ✫ *2-lepton → identify Z:*
  2 high p_T leptons + Z mass cut

$H \rightarrow b\bar{b}$ - jet selection

- ✫ 2 or 3 jets final states
- ✫ 2 b-tagged jets
- ✫ b-tagging 70% efficient with 1% fake rate

WH candidate

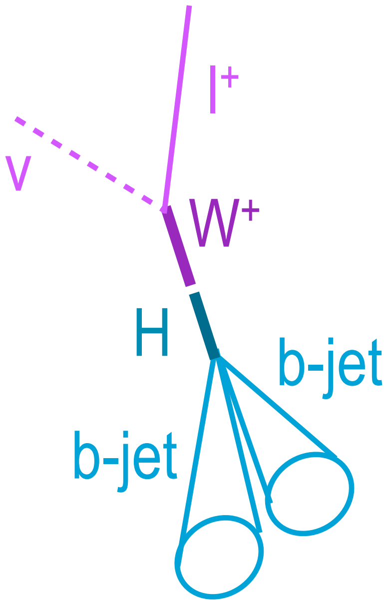


Analysis strategy

Strategy:

look for excess in $m_{b\bar{b}}$ (di-b-jet system invariant mass) distribution

☞ Exploit growth of S/√B as a function of recoiling V p_t



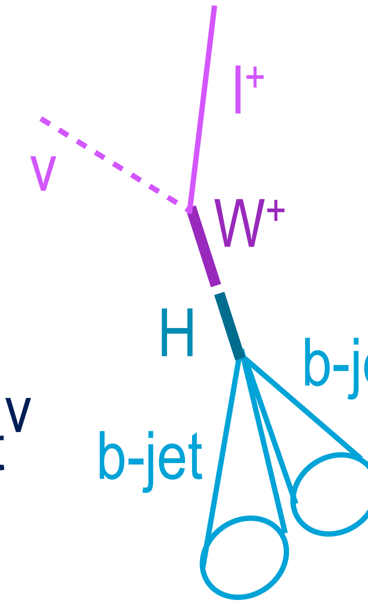
Analysis strategy

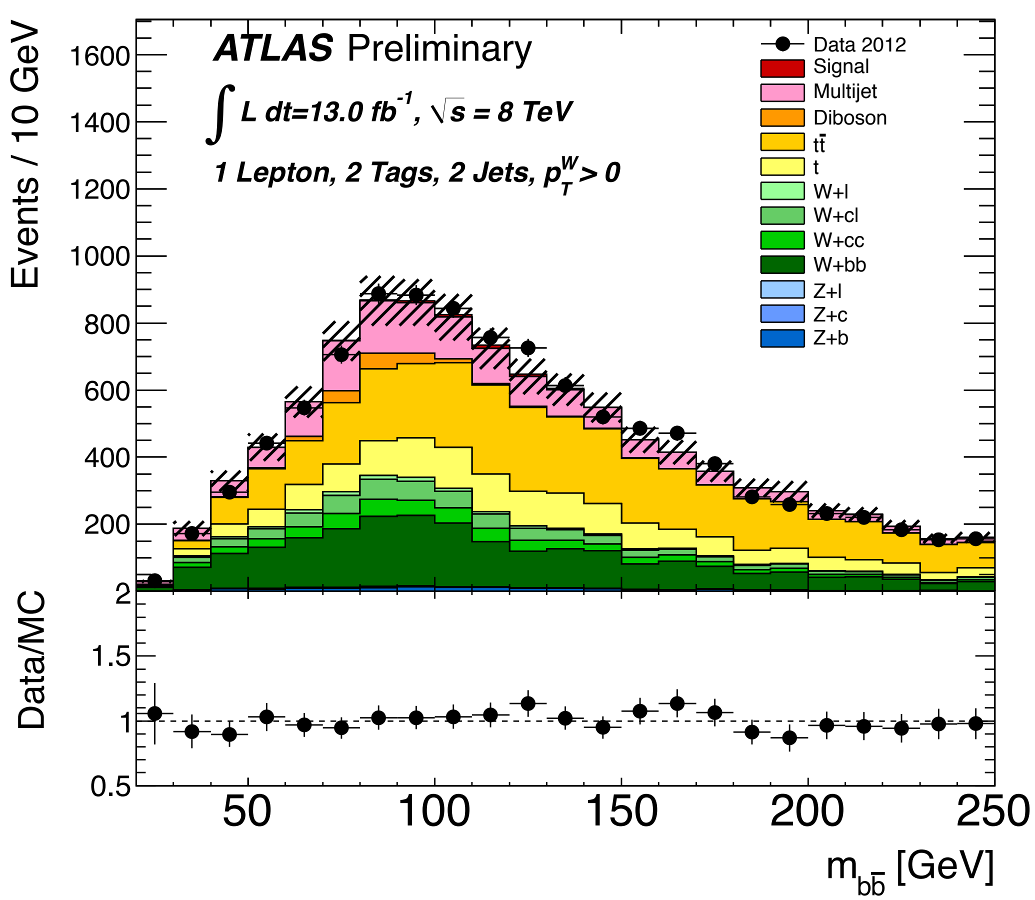
Strategy:

look for excess in $m_{b\bar{b}}$ (di-b-jet system invariant mass) distribution

☞ Exploit growth of $S/\sqrt{B}$ as a function of recoiling V p_t

⇒ divide $m_{b\bar{b}}$ in bins of p_t^V





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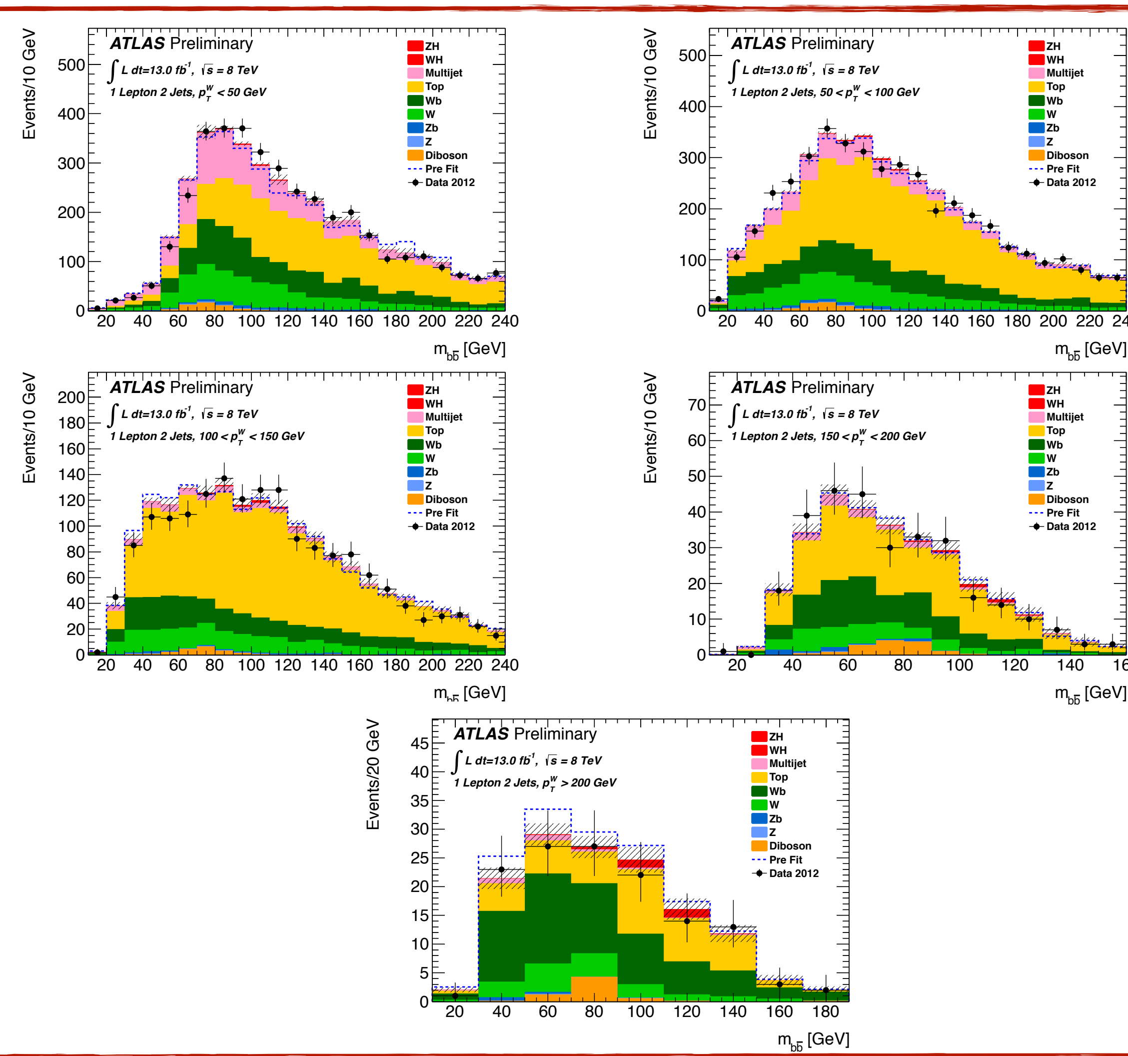


Signals and backgrounds

Data 2012	
Signal	✯ Signal: ZH and WH Pythia8
Multijet	✯ Multijet: data driven
Diboson	✯ Diboson: WW, WZ and ZZ Herwig
$t\bar{t}$	✯ ttbar: MC@NLO
t	✯ single top: AcerMc/MC@NLO
W+l	✯ W+light: Alpgen
W+c	✯ W+c: Alpgen
W+b	✯ W+b: Powheg
Z+l	✯ Z+light: Sherpa
Z+c	✯ Z+c: Sherpa
Z+b	✯ Z+b: Sherpa

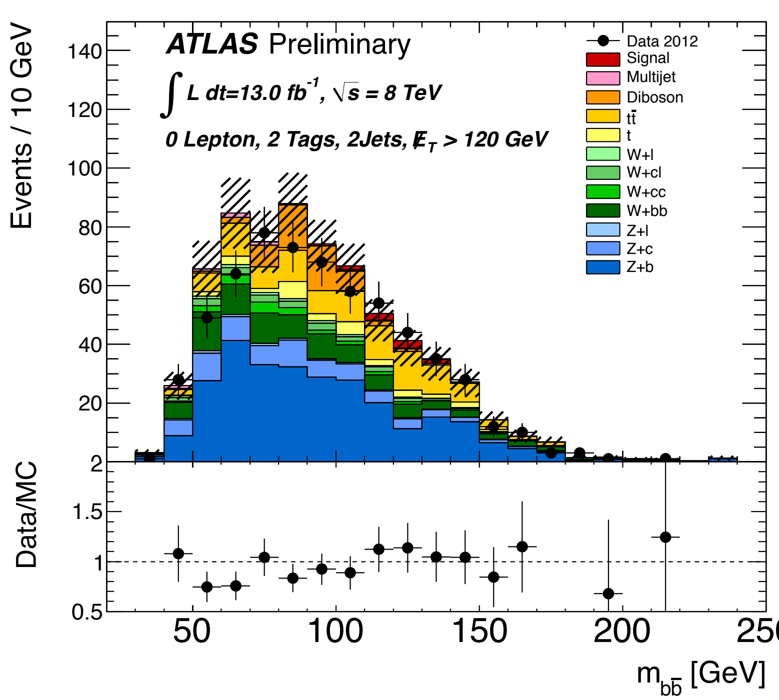
Background-dominated analysis

Rely on ***different techniques*** to estimate shape and normalisation

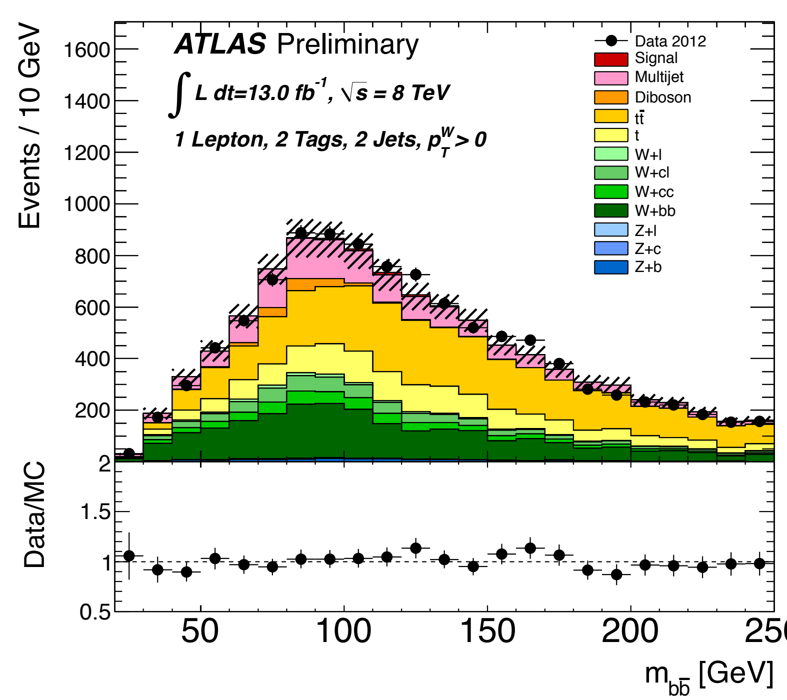
- ✯ QCD multijet ⟶ data-driven
- ✯ Diboson ⟶ MC prediction
- ✯ V+l/c ⟶ shape from MC and normalisation from data (template fit to extract V+jets flavor fraction)
- ✯ V+b,top ⟶ shape from MC and normalisation from data (profile likelihood fit)

Examples of background composition

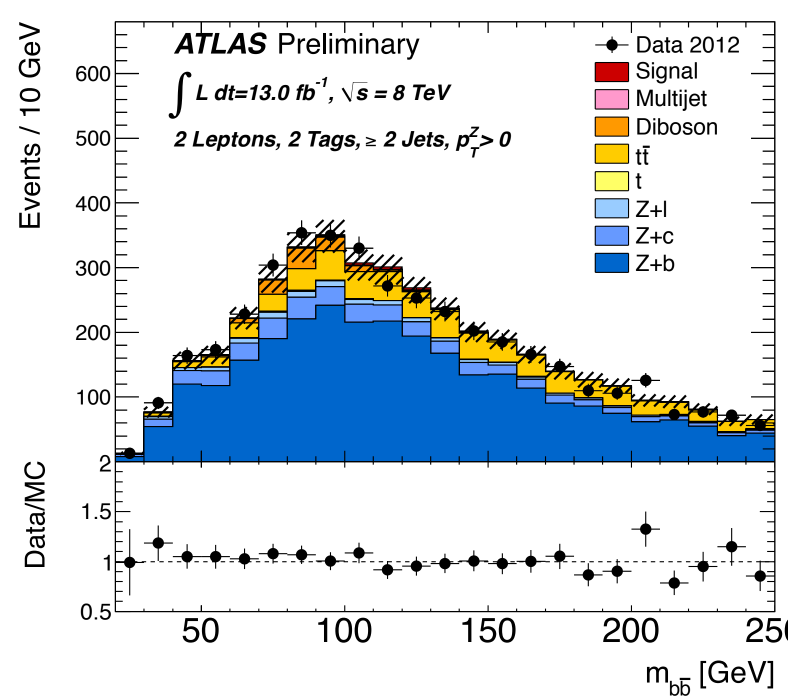
0 lepton - W+jets, Z+jets, top



1 lepton - W+jets, top



2 lepton - Z+jets



Statistical treatment - definitions

- **Profile likelihood fit** gives interpretation of result
- **Aim**: understand how much the data (dis)agree with the proposed model
- **Hypothesis testing:** signal+background hp vs null (background only) hp

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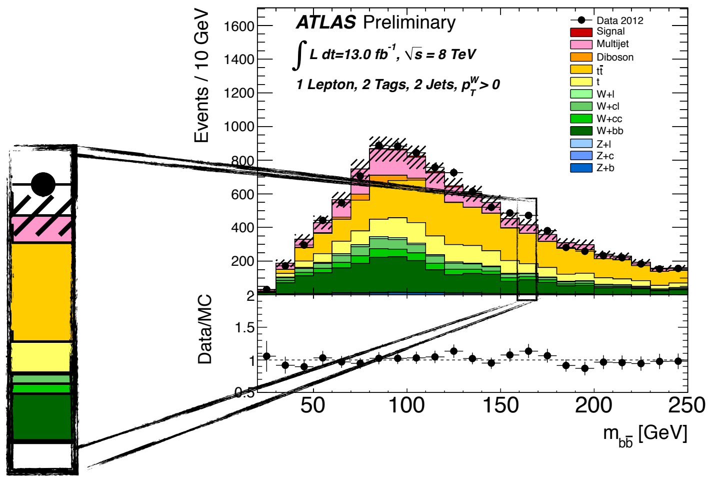

Each bin can be represented by a Poisson likelihood..

$$L(\mu) = \frac{(\mu s + b)^n}{n!} e^{-(\mu s + b)}$$

n → measurement (data, pseudodata..)

Useful definitions:

- **Parameter of interest** (μ) - specifies difference between null (μ=0) and test hypothesis (μ=1)

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..that can be extended to the full distribution (set of bins)

$$L(\mu, \boldsymbol{\theta}) = \prod_{i=1}^{N} \frac{(\mu s_i + b_i)^{n_i}}{n_i!} e^{-(\mu s_i + b_i)}$$

$$s_i = s_{tot} \int_{\text{bin } i} f_s(x; \boldsymbol{\theta}_s) dx$$

$$b_i = b_{tot} \int_{\text{bin } i} f_b(x; \boldsymbol{\theta}_b) dx$$

n_i: measurement (data, pseudodata..)

Useful definitions:

- **Parameter of interest** (μ) - specifies difference between null (μ=0) and test hypothesis (μ=1)
- **Nuisance parameters** (θ) - all additional parameters the model depends on (systematic errors)

Profile likelihood ratio

Profile likelihood ratio

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}})}{L(\hat{\mu}, \hat{\theta})}$$

NB: $0 \leq \lambda \leq 1$

Nuisance parameters for conditional and unconditional fit

- Numerator: ***conditional*** fit (μ is not determined by the fit - fixed)
- Denominator: ***unconditional*** fit (μ is a parameter of the ML fit)

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Define test statistic: $t_\mu = -2 \ln \lambda(\mu)$ (Log Likelihood Ratio)

Evaluated for 3 cases:

- ✯ n_i=background hp → distribution of t_μ
- ✯ n_i=signal+background hp → distribution of t_μ
- ✯ n_i=observed data → one value

$$L(\mu, \boldsymbol{\theta}) = \prod_{i=1}^{N} \frac{(\mu s_i + b_i)^{n_i}}{n_i!} e^{-(\mu s_i + b_i)}$$

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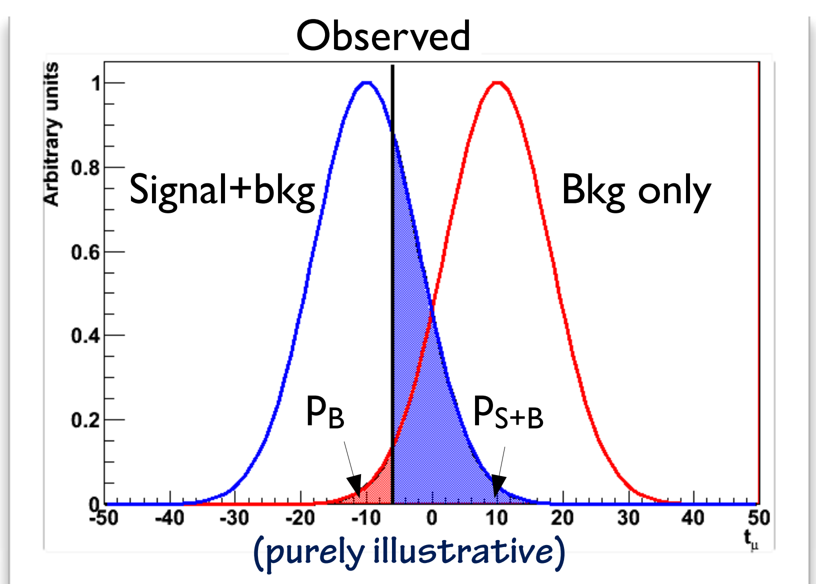
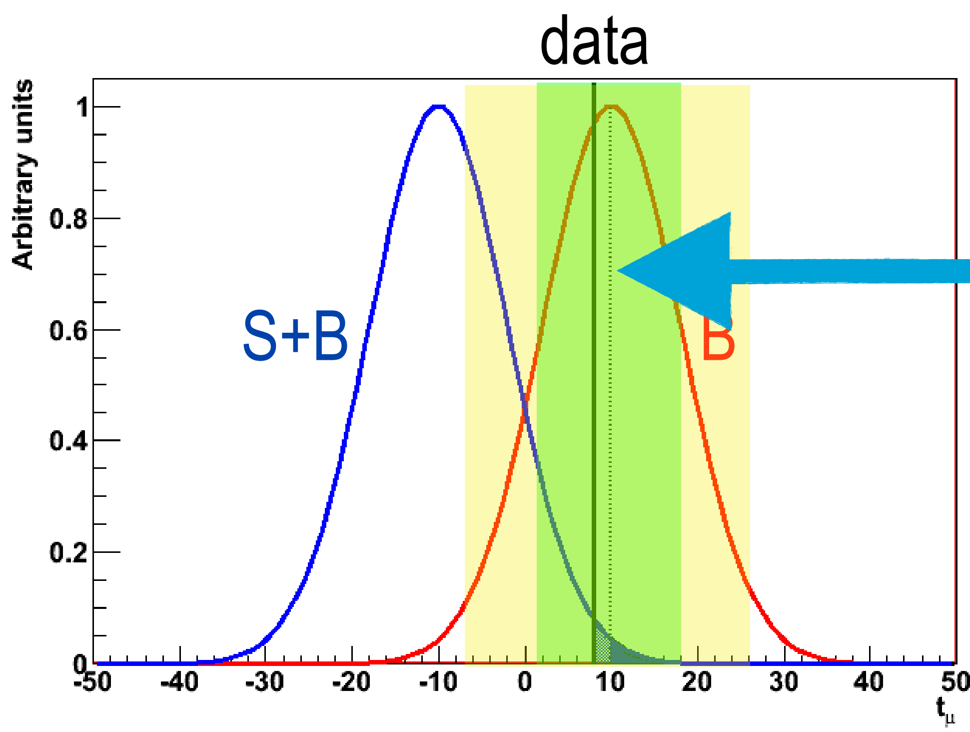
P-value: probability for a test to find a **more background-like** result than the observed data

$CL_S = p_{S+B}/(1-p_B)$
confidence interval for limit calculation



Exclusion and discovery

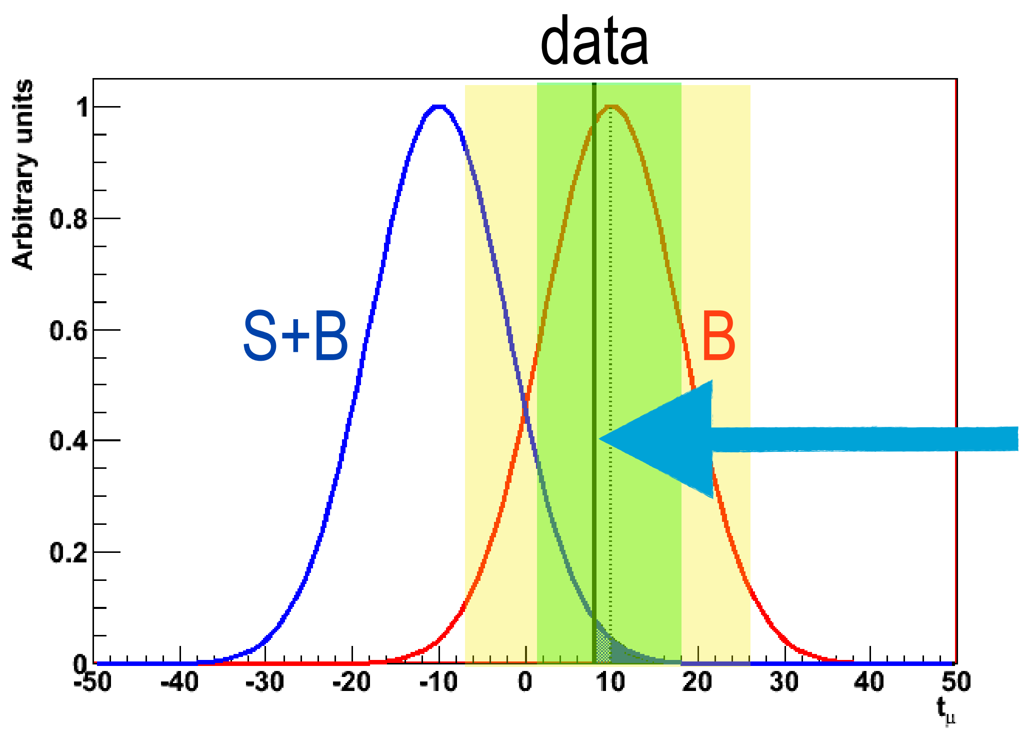


Exclusion (at 95% CL)

aka how to obtain the "brazilian band" plot:

- **expected** limit: calculate CL_S using median of null hp (B)
- **observed** limit: CL_S calculated using measured data
- **CL_S<0.05** => reject test hypothesis at 95% confidence Level
- to calculate limit, **μ is varied** to satisfy CL_S=0.05

Exclusion and discovery



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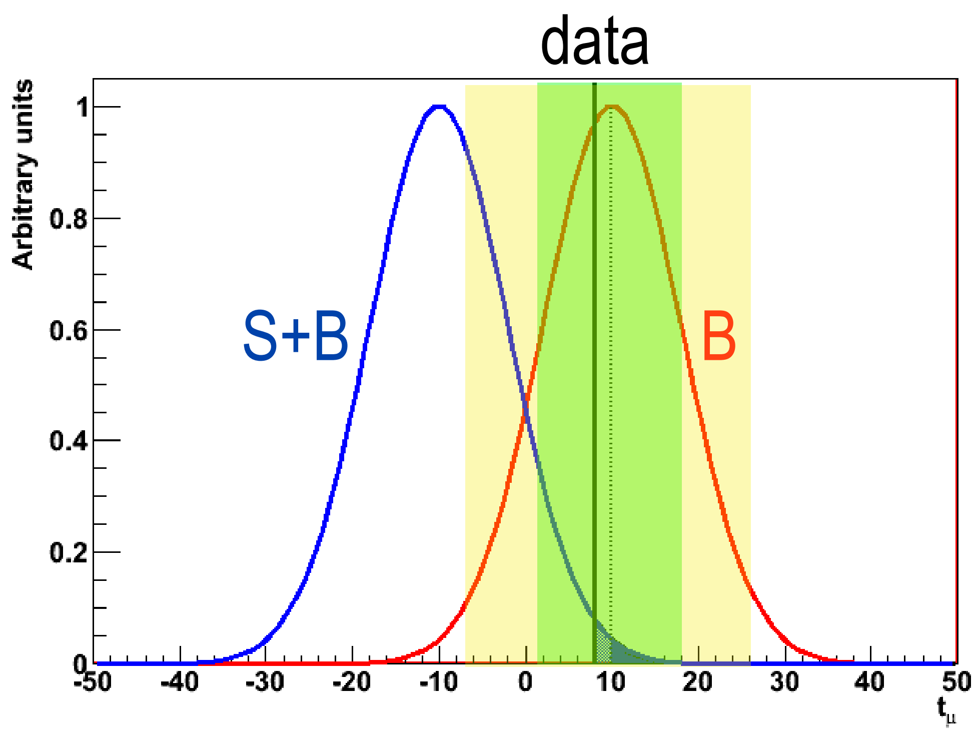

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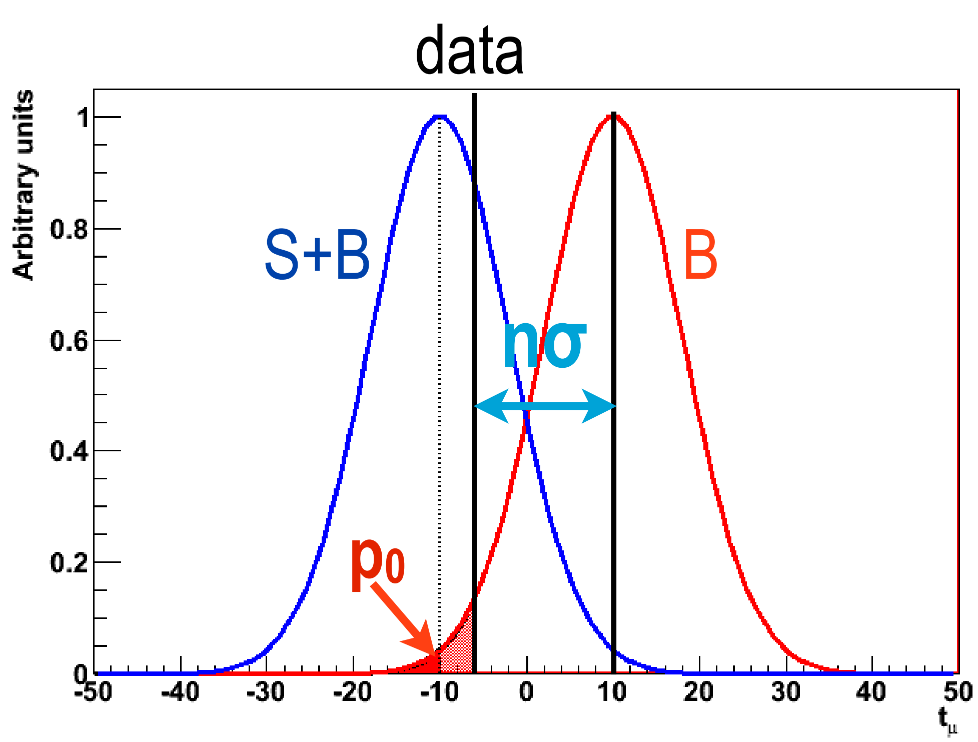
Discovery p_0(=p_B) and gaussian significance (σ):

- **expected** p_0 calculated using median of test hypothesis
- **observed** p_0 using observed data
- **nσ**=distance from median of null hypothesis

  3σ ⟶ evidence

  5σ ⟶ discovery



Higgs fit ingredients

Input to VH($b\bar{b}$) profile likelihood fit: $m_{b\bar{b}}$ distributions split into ***categories***

Discriminant variables:

- number of leptons
- number of jets
- V p_T intervals

Different regions of $S/\sqrt{B}$

Total: 16 categories + control regions
⇒ complex fit

Validation needed!!

Use known signal to cross-check:
VZ(Z→$b\bar{b}$)

VZ($b\bar{b}$) observation

- ✯ Similar signature to VH($b\bar{b}$) and ~5 times larger cross section
- ✯ Excellent way to **validate** background estimate and Higgs search strategy
- ✯ Performed profile likelihood fit with a mixture of **WZ($b\bar{b}$) and ZZ($b\bar{b}$)** as **signal**
- ✯ **WH and ZH with m_H=125 GeV** considered as **backgrounds**

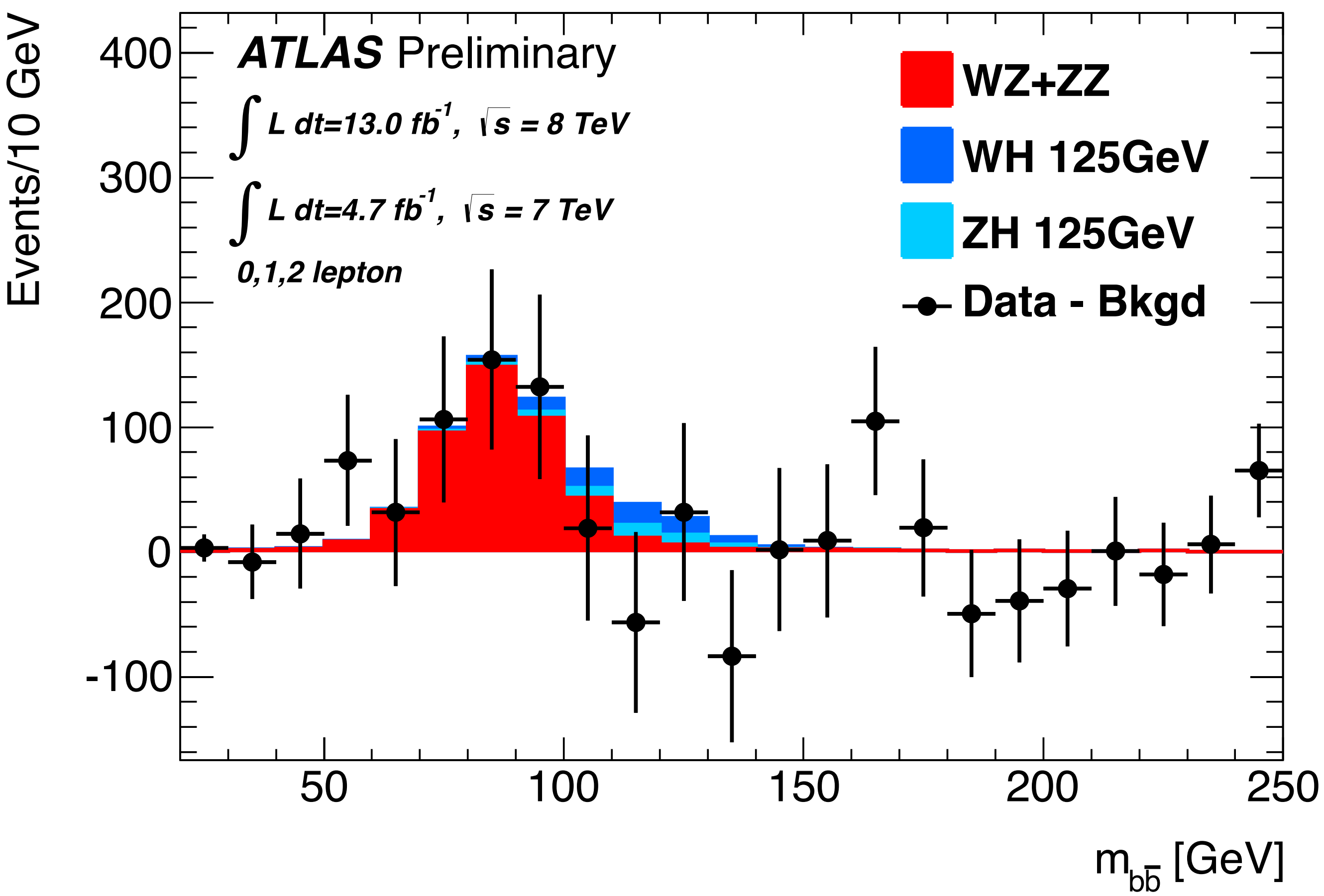
Observed VZ($b\bar{b}$) signal with

$$\hat{\mu}=1.09$$

±0.20(stat)±0.22(syst)

and **4σ significance**

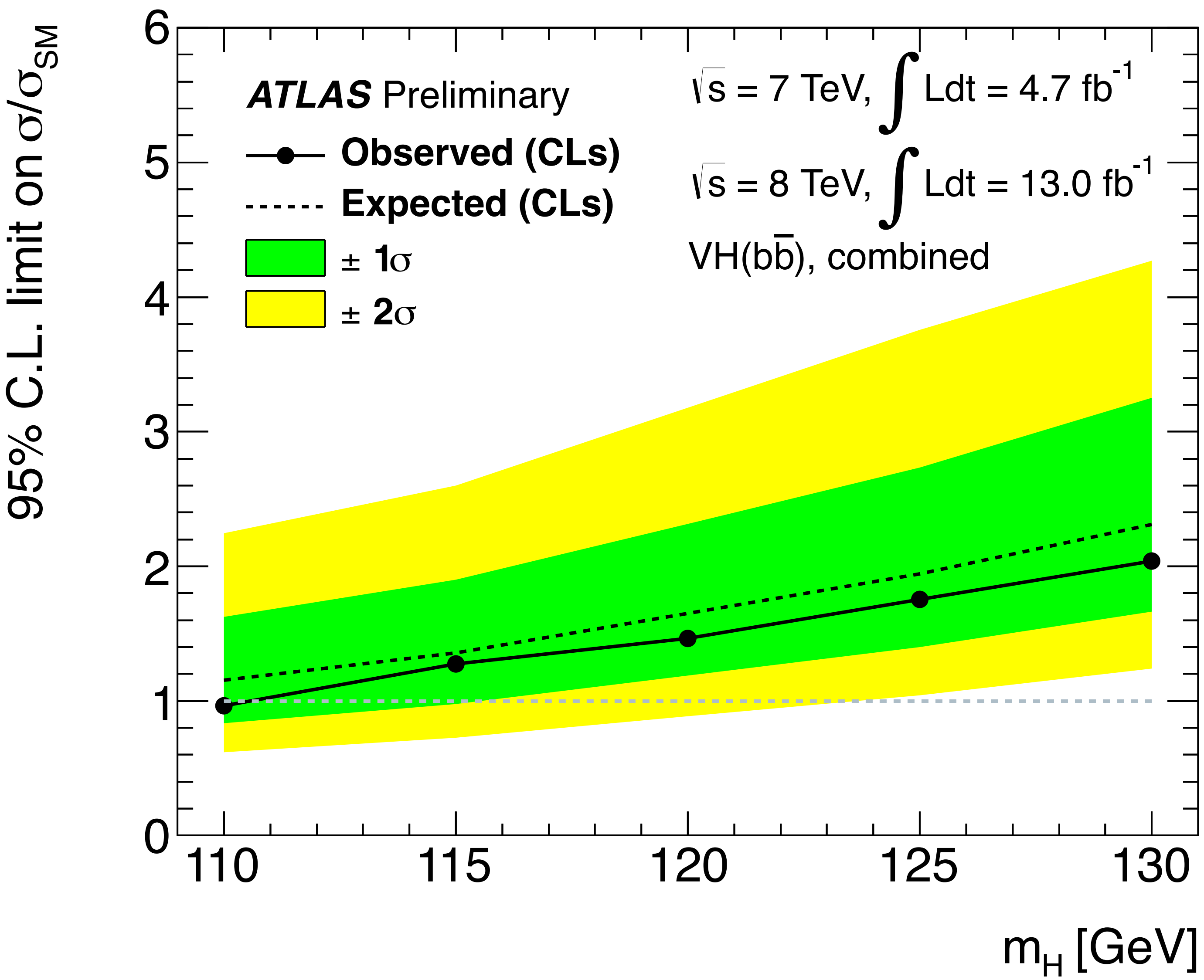
Clear observation of an excess in MC-subtracted data compatible with SM prediction

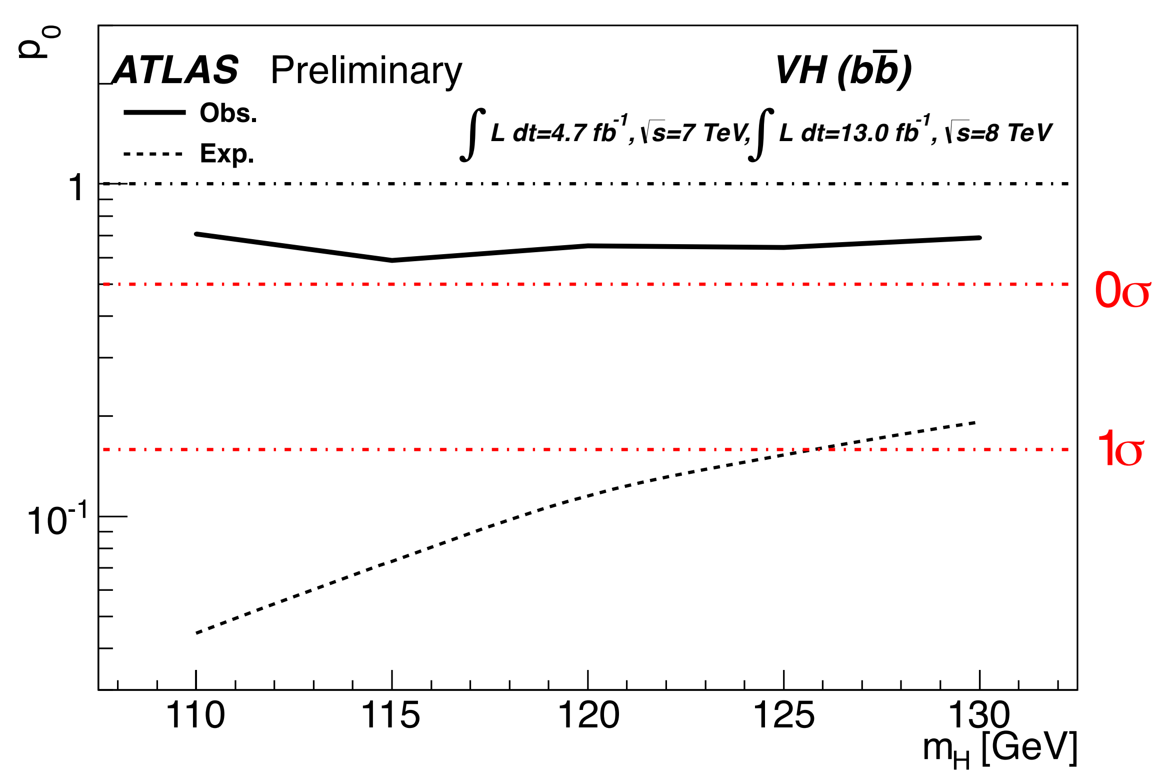


VH(H→$b\bar{b}$) results

- Observed limit at m_H=125 GeV: **1.8×SM** (expected 1.9)
- Signal strength $\hat{\mu}$**=-0.4**±0.7(stat)±0.8(syst)
- Observed **p_0: 0.64** (expected 0.15)
- **Excluded** a Higgs of mass **~110 GeV**

Reached sensitivity more than 2 times that of previous publication (Phys. Lett. B 718 (2012) 369-390)
1.8 vs 4.6 obs at m_H=125 GeV





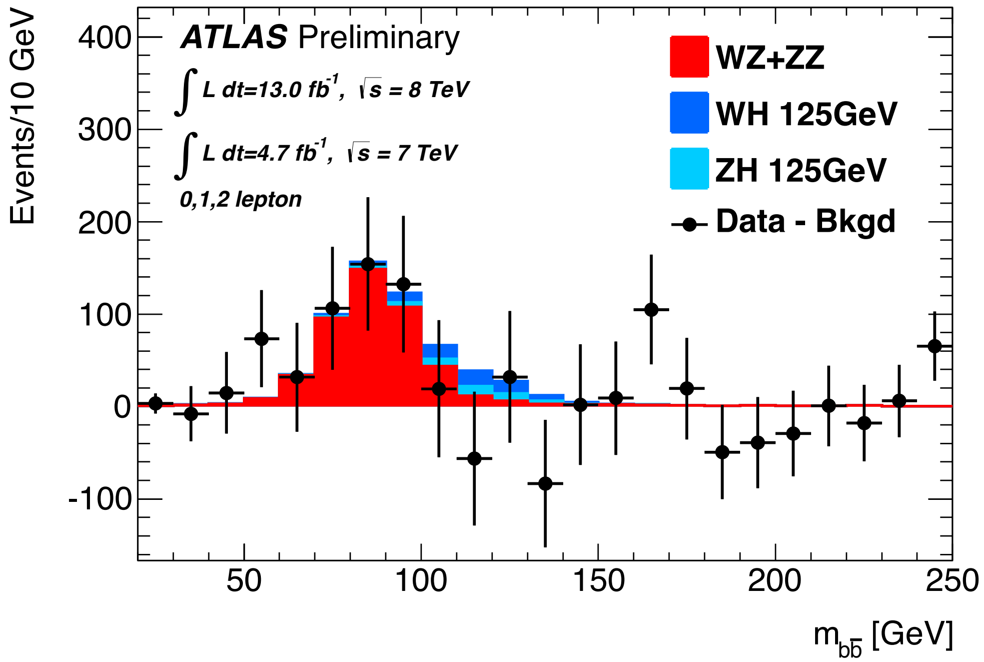
Summary and conclusions

- Looking for the Higgs in difficult **H⟶b$\bar{b}$** topology
  ⇓
  highest BR for $m_H \simeq 125$GeV

- Exploit **associated production with a vector boson**
  ⟶ tag on leptonic final states

- Perform complicated **profile likelihood fit** to test signal+background hp

- Search method validated on VZ(Z⟶b$\bar{b}$) ⇒ **4σ observation**



Summary and conclusions

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  $\Downarrow$

  highest BR for $m_H \simeq 125$GeV

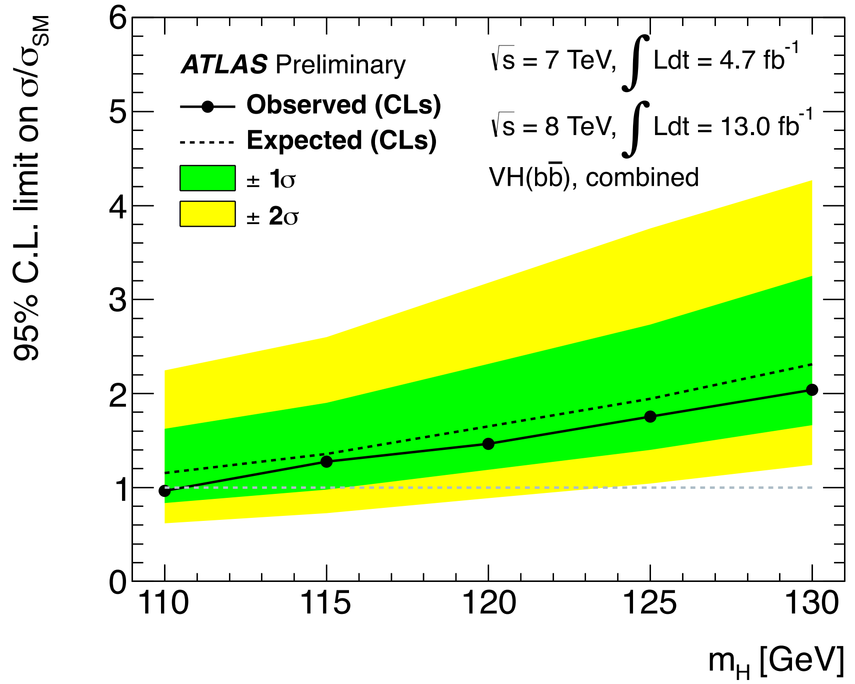
- Exploit **associated production with a vector boson**
  $\longrightarrow$ tag on leptonic final states

- Perform complicated **profile likelihood fit** to test signal+background hp

- Search method validated on $VZ(Z \longrightarrow b\bar{b}) \Rightarrow$ **4σ observation**

- **Excluded** a Higgs of **m=110GeV**

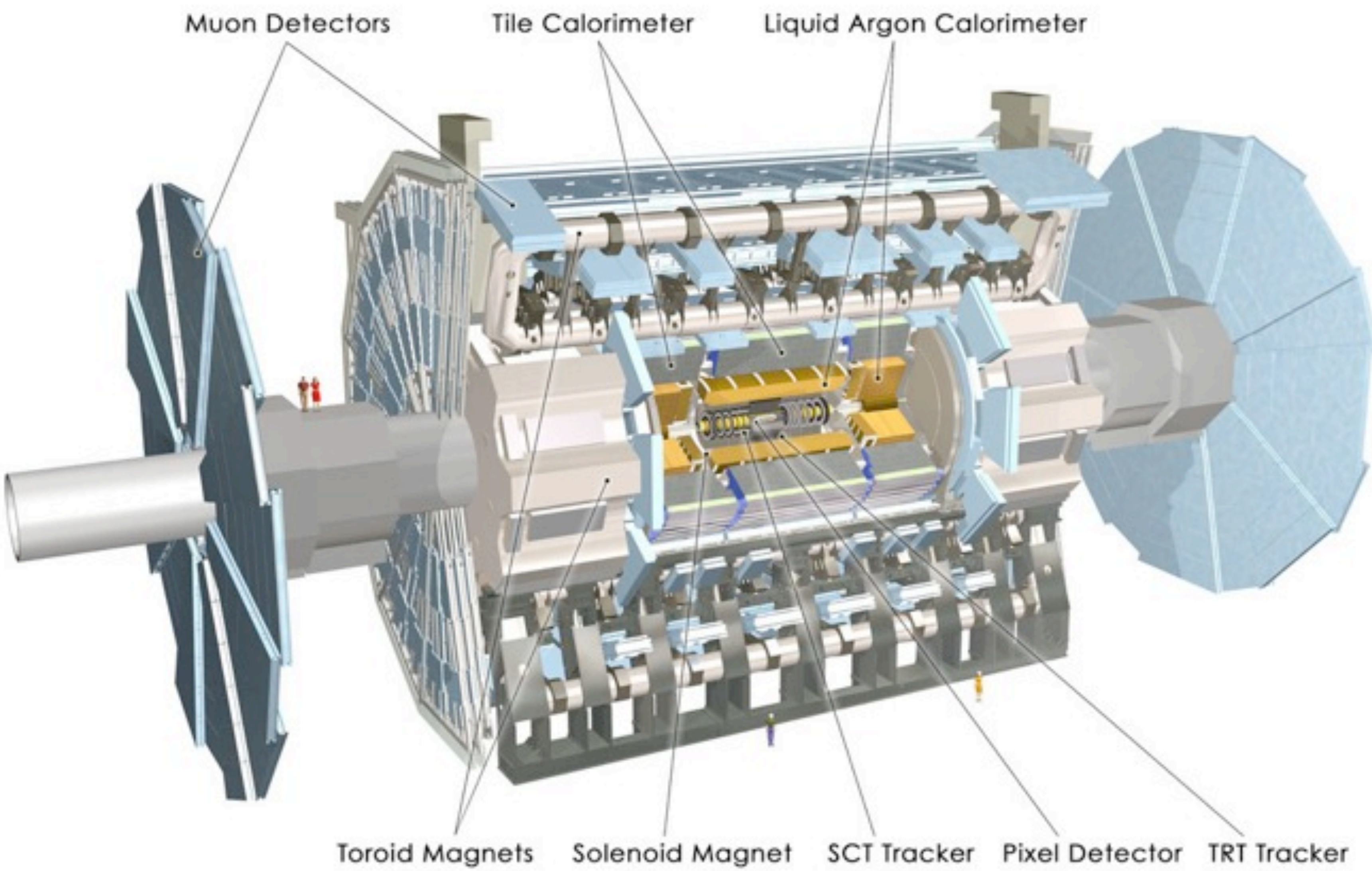
- Observed (expected) a 95% CL limit of **1.8 (1.9)×SM**



..thanks a lot for your attention!!

Backup

The ATLAS detector



Calorimeters

- Pb/LAr accordion structure for **EM**
- provides e/γ energy measurement with $\sigma/E \sim 10\%/\sqrt{E(GeV)} \oplus 0.7\%$
- Iron scintillator tiles for **hadronic**
- provides jet and E_t^{miss} measurement with $\sigma/E \sim 50\%/\sqrt{E\ (GeV)} \oplus 3\%$
- Forward calorimeter: FCAL covers up to $|\eta|<4.9$

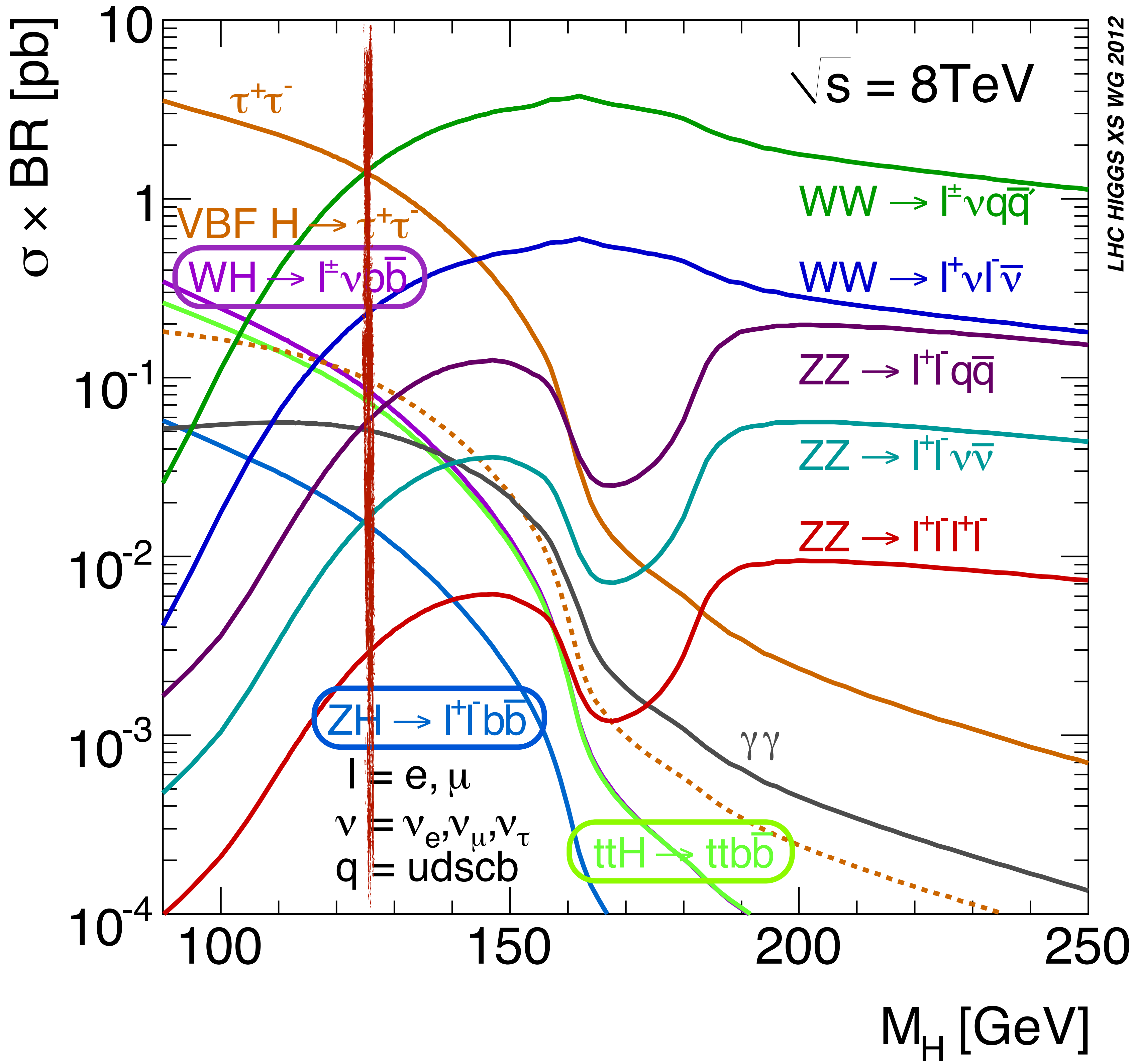
Inner detector

- for $\eta=0$, track has typically 3 Pixel, 8 SCT and 30 TRT hits
- magnetic field (~2 T) produced by solenoid
- coverage: $|\eta|<2.5$ (2.0 for TRT)
- resolution: $\sigma(p_t)/p_t=0.05\% \oplus 1\%$

Muon spectrometer

- coverage: $|\eta|<2.7$
- magnetic field (~0.5 T) produced by toroids
- $\sigma(p_t)/p_t \approx 10\%$ for $p_t=1$TeV

Higgs σxBR @ 8TeV



Jet clustering anti-kt algorithm

From topoclusters to jets

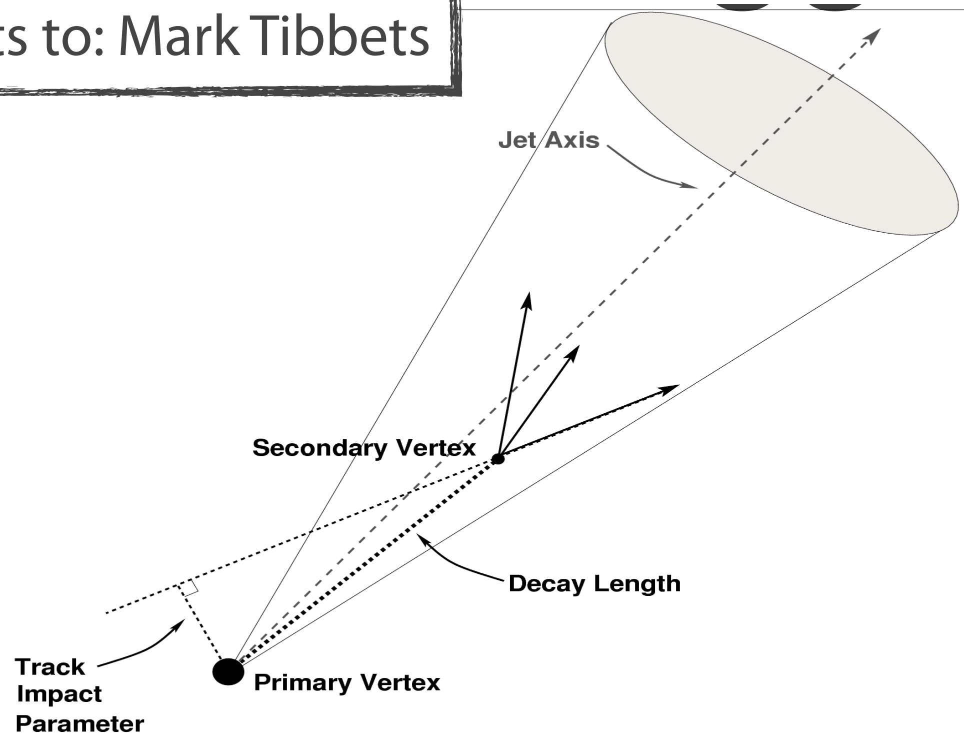
$\{t_i\} \rightarrow$ reconstruction algorithm $\rightarrow \{j_k\}$

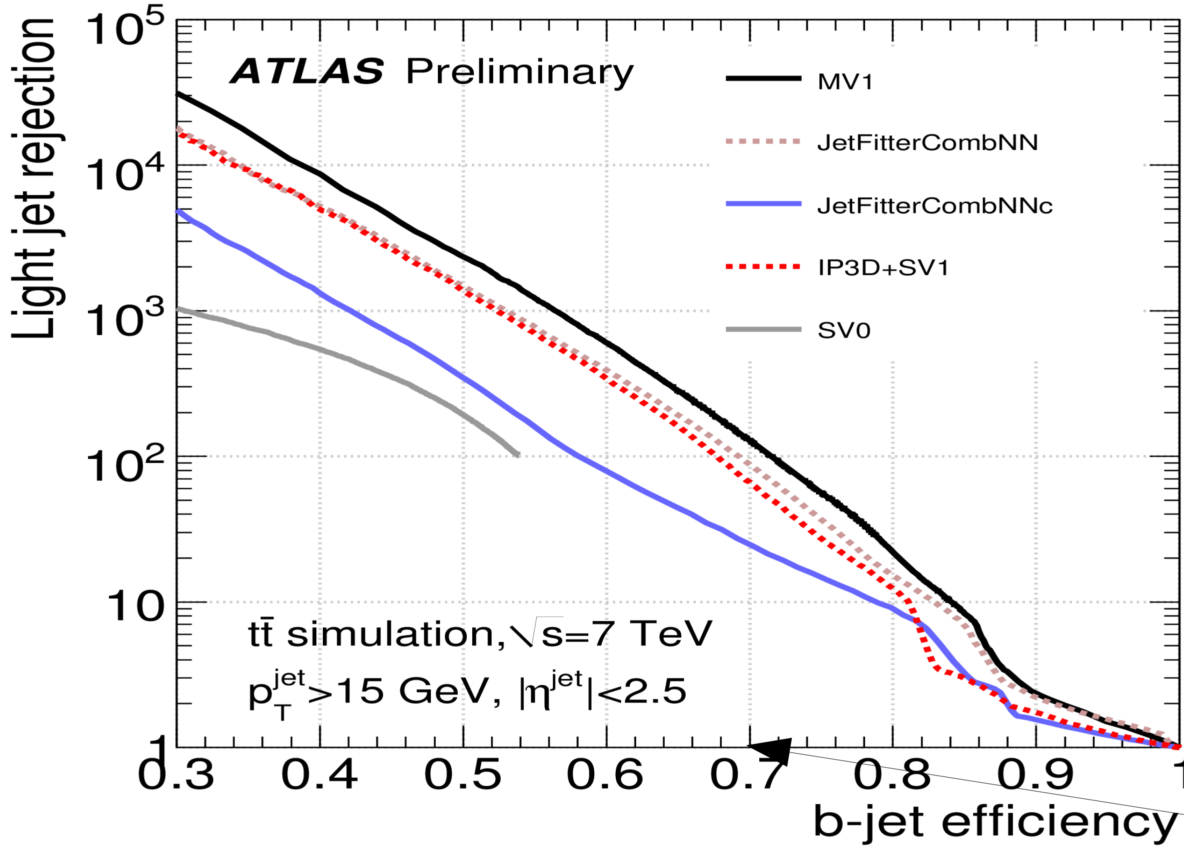
Anti-kt algorithm

- default for ATLAS jet reconstruction
- recursive algorithm - combines sequentially pairs of constituents
- combination dependent on p_t, (η,φ) distance
- clustering starts from most energetic constituents
- advantage: high-p_t anti-kt jets have regular shapes guaranteeing stability against pile-up

b-tagging in ATLAS

Credits to: Mark Tibbets

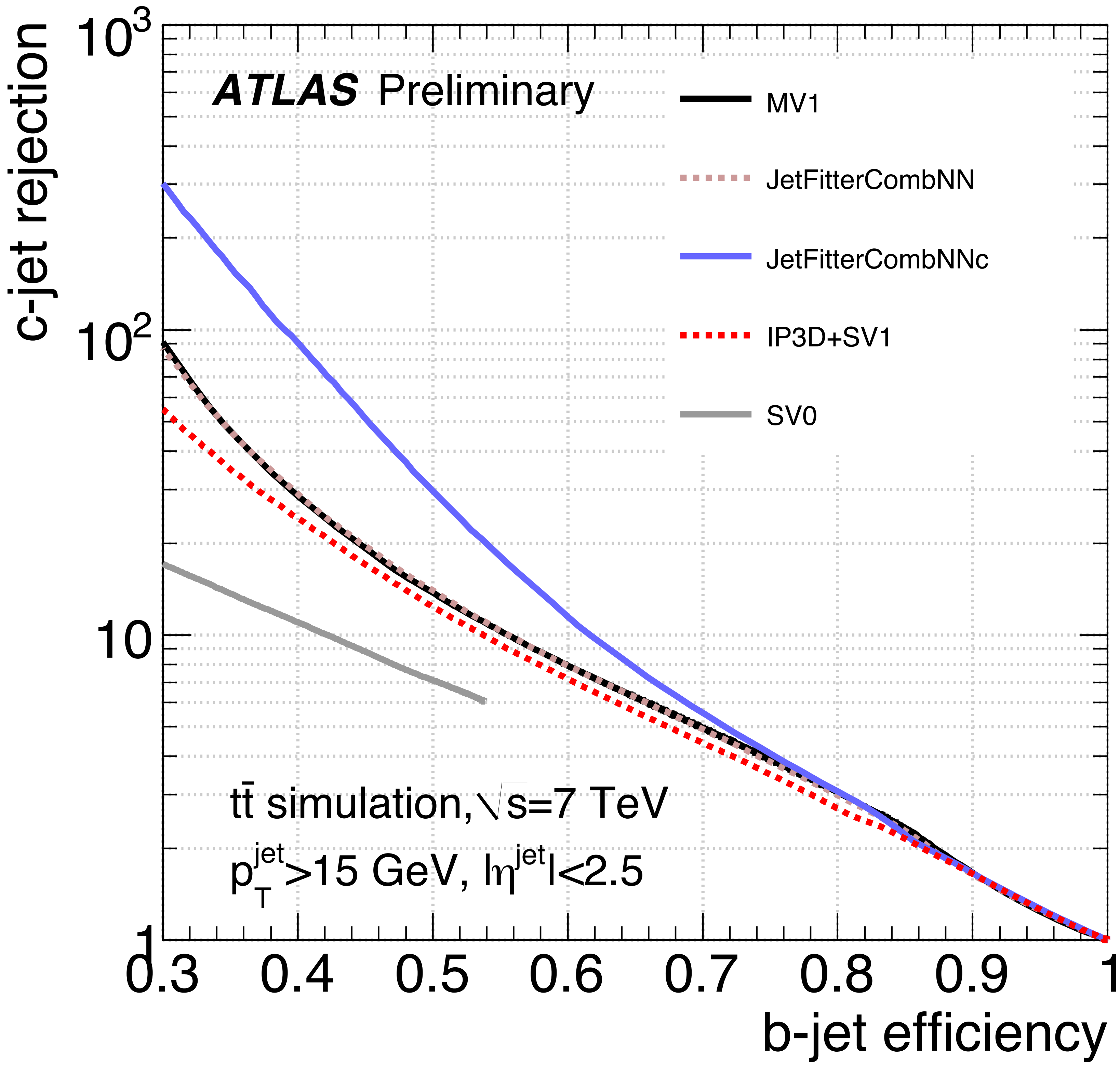




- Algorithms to identify heavy flavour content in reconstructed jets
- Impact parameter of tracks in jet
  - **IP3D** uses track weights based on longitudinal and transverse IP significance
- Displaced secondary vertex
  - **SV1** reconstructs inclusive displaced vertex
  - **JetFitter** reconstructs multiple vertices along implied b-hadron line of flight
    - Cascade decay topologies
- Advanced NN based algorithms
  - **JetFitterCombNN**: IP3D+JetFitter
  - **MV1**: IP3D+JetFitterCombNN+SV1

MC calibration results illustrated with MV1 @ 70% b-jet efficiency

b-tagging in ATLAS - c mistag rate



calibrated on tt̄ events at 7TeV

Flavour fit

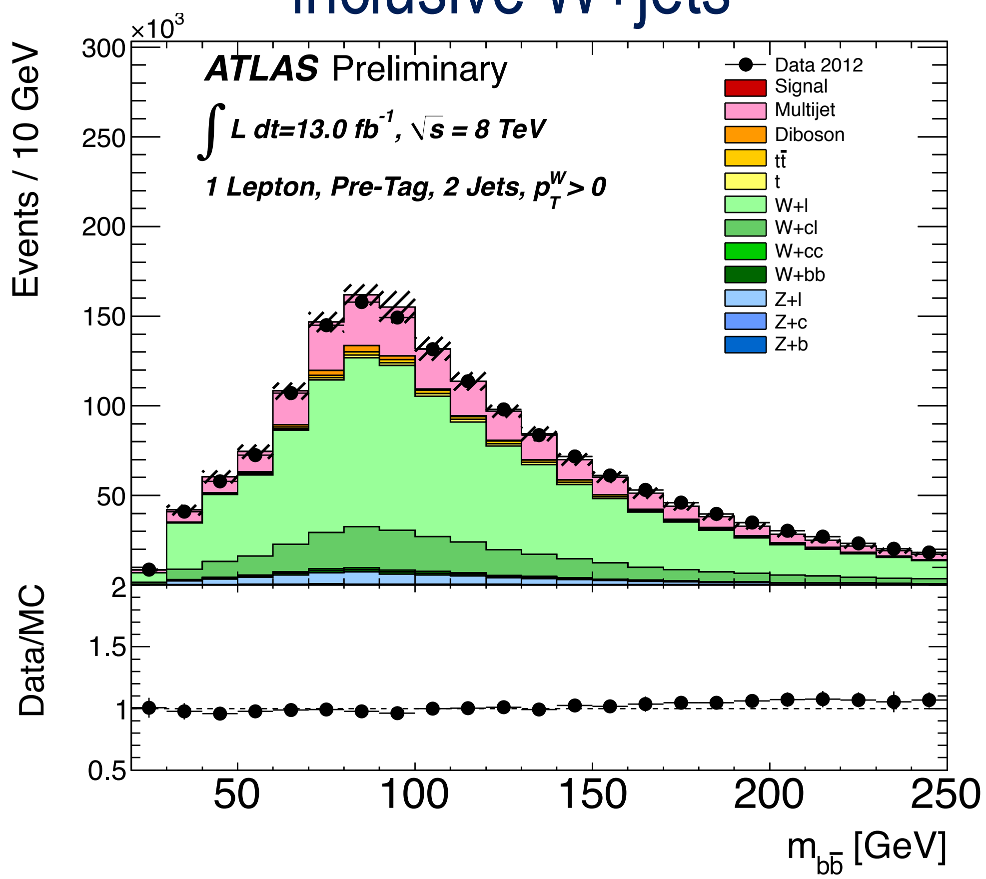
- ✧ Maximum likelihood fit for jet flavour fraction evaluation in V+jets background
- ✧ Aim: calculation of W/Z+l/c scale factors for normalisation
- ✧ Performed on 12 regions (with different Vjets composition and top enriched)

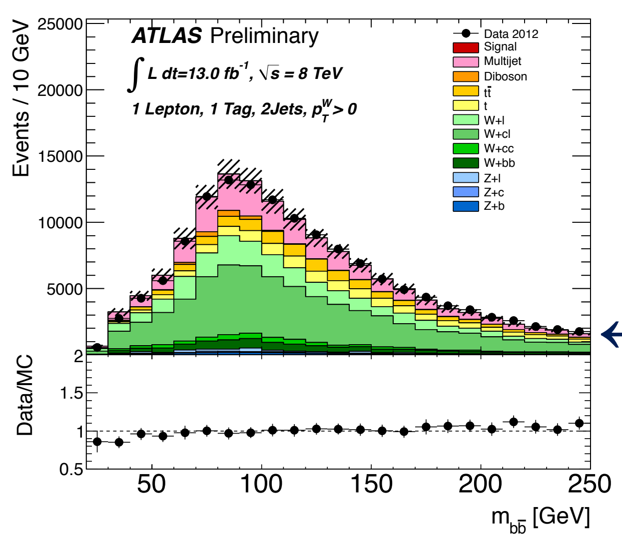
$$\text{Vjets} = \alpha_1 \times Wl + \alpha_2 \times Wc + \alpha_3 \times Wb + \beta_1 \times Zl + \beta_2 \times Zc + \beta_3 \times Zb$$

Want to evaluate α_i and β_i, α_3 and β_3 will be re-calculated in the profile likelihood fit

Example input regions

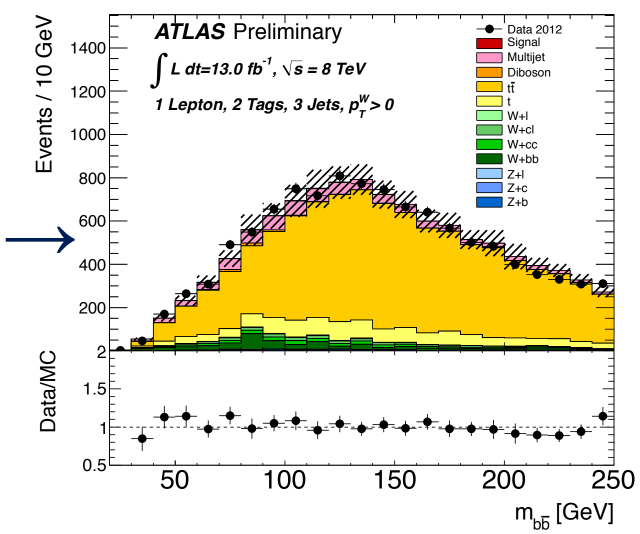
inclusive W+jets





← 1 b-tag region

top enriched region →



p_t^V dependence and final fit

- Steeper fall for background in p_t^V distribution in data than MC ⇒ good news!
- Need to correct for this in the MC. Affects both V+jets and top.

Corrections applied per p_t^V bin:

- V+jets ranging between 5 and 10%
- top ~15%

In final fit 16 signal region categories and top control regions

- Profile likelihood fit L(μ,θ) to signal strength $\mu=\sigma/\sigma_{SM}$
- θ represent statistical and systematic nuisance parameters
- W/Z+b and top normalisations left floating in the fit

Floating backgrounds scale factors:

	$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV
Top	1.10 ± 0.14	1.29 ± 0.16
$Z+b$	1.22 ± 0.20	1.11 ± 0.15
$W+b$	1.19 ± 0.23	0.79 ± 0.20

Treatment of systematics

Systematic errors = nuisance parameters θ

Different type of systematic ⇒ different statistical treatment

$$s_i = s_{tot} \int_{\text{bin } i} f_s(x; \boldsymbol{\theta}_s) dx$$

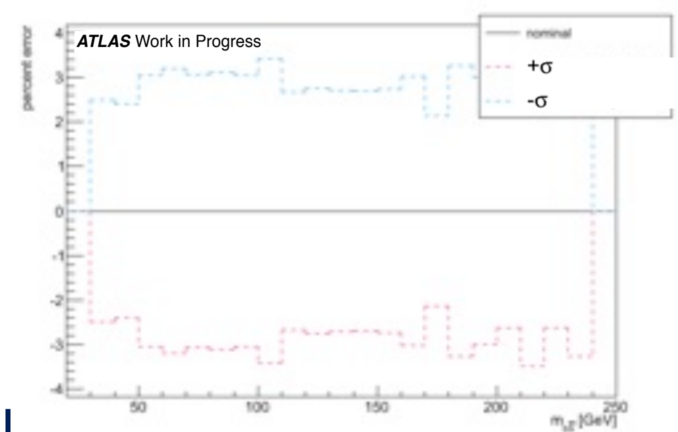
$$b_i = b_{tot} \int_{\text{bin } i} f_b(x; \boldsymbol{\theta}_b) dx$$

Shape systematic

Gaussian distributed

Systematic variation is different for each bin of $m_{b\bar{b}}$ distribution but is correlated ⟶ if one bin varies, the others vary as well

relative Jet energy scale variation on WH $m_{b\bar{b}}$



Floating normalisation

no prior

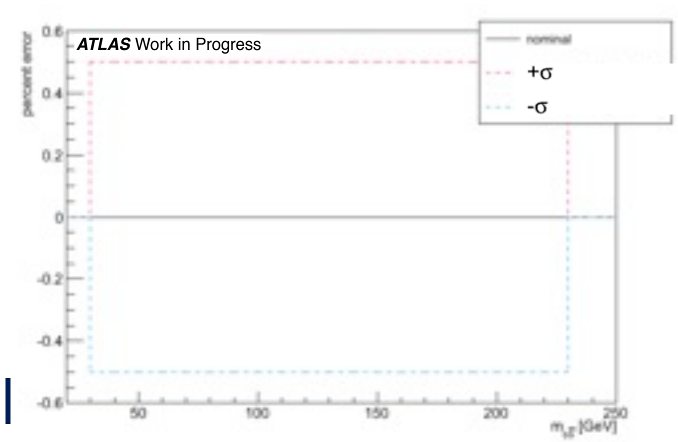
Normalisation in bin left free to float within very loose constraints. Allows to calculate normalisations for top and $Wb\bar{b}$ backgrounds

Normalisation systematic

log-normal distributed

Systematic variation is the same for each bin of $m_{b\bar{b}}$ distribution and is correlated ⟶ if one bin varies, the others vary as well

relative muon resolution variation on ZH $m_{b\bar{b}}$



Statistical parameters

Poisson distributed

MC statistical uncertainty per bin.
Bin-by-bin **uncorrelated**.
Mean of Poisson is number of events per bin - less than 5% statistical uncertainty per bin ⟶ 400 events ⟶ gaussian

Systematic uncertainties

- Enter in the fit as nuisance parameters both for signal and backgrounds
- Shrunk considerably by profile likelihood fit
- Illustrate **values after cuts** in tables

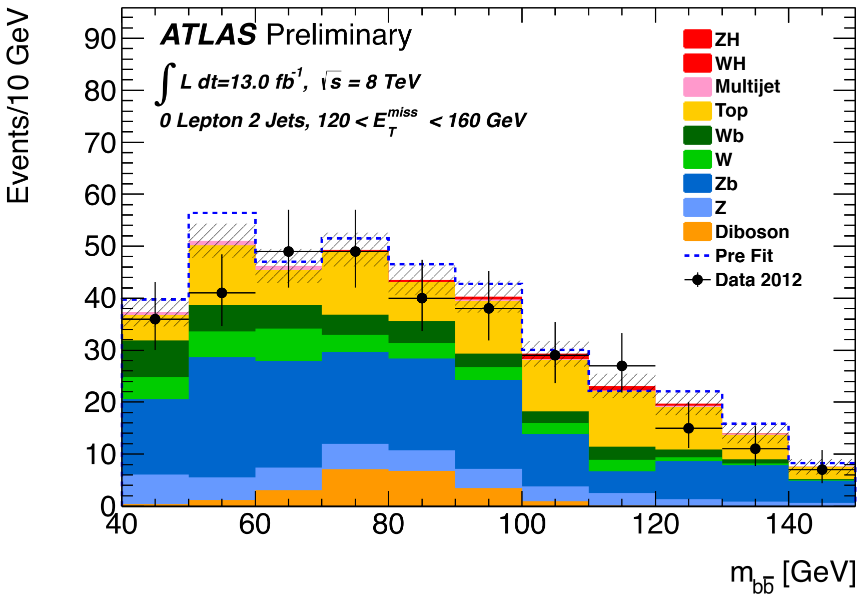
Background

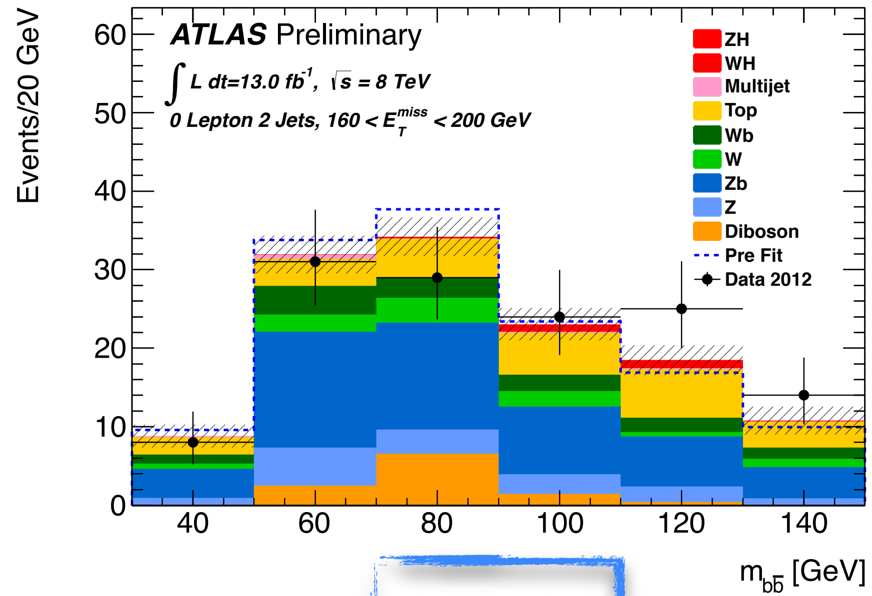
Uncertainty [%]	0 lepton	1 lepton	2 leptons
b-tagging	6.5	6.0	6.9
c-tagging	7.3	6.4	3.6
light tagging	2.1	2.2	2.8
Jet/Pile-up/$E_{\mathrm{T}}^{\mathrm{miss}}$	20	7.0	5.4
Lepton	0.0	2.1	1.8
Top modelling	2.7	4.1	0.5
W modelling	1.8	5.4	0.0
Z modelling	2.8	0.1	4.7
Diboson	0.8	0.3	0.5
Multijet	0.6	2.6	0.0
Luminosity	3.6	3.6	3.6
Statistical	8.3	3.6	6.6
Total	25	15	14

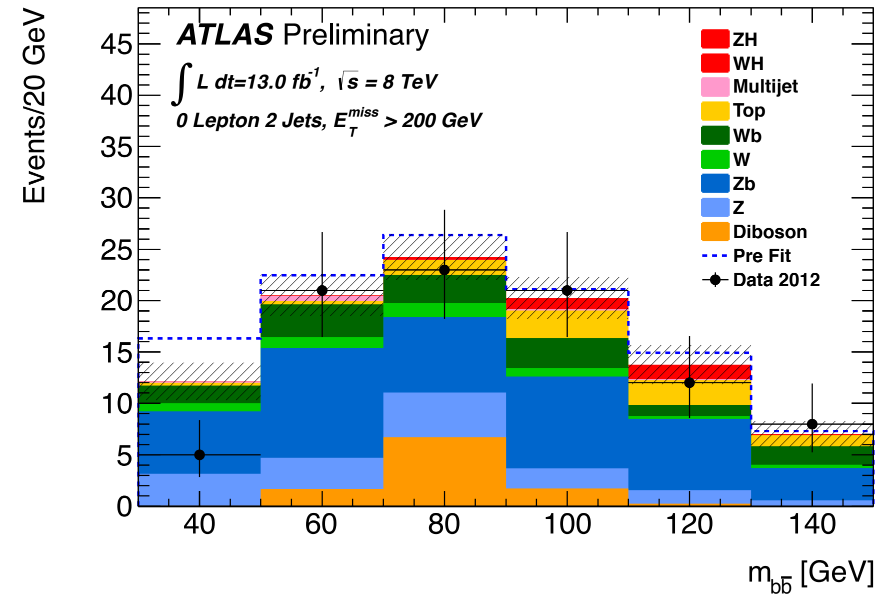
Signal

Uncertainty [%]	0 lepton		1 lepton	2 leptons
	ZH	WH	WH	ZH
b-tagging	8.9	9.0	8.8	8.6
Jet/Pile-up/$E_{\mathrm{T}}^{\mathrm{miss}}$	19	25	6.7	4.2
Lepton	0.0	0.0	2.1	1.8
$H \to bb$ BR	3.3	3.3	3.3	3.3
VH p_T-dependence	5.3	8.1	7.6	5.0
VH theory PDF	3.5	3.5	3.5	3.5
VH theory scale	1.6	0.4	0.4	1.6
Statistical	4.9	18	4.1	2.6
Luminosity	3.6	3.6	3.6	3.6
Total	24	34	16	13

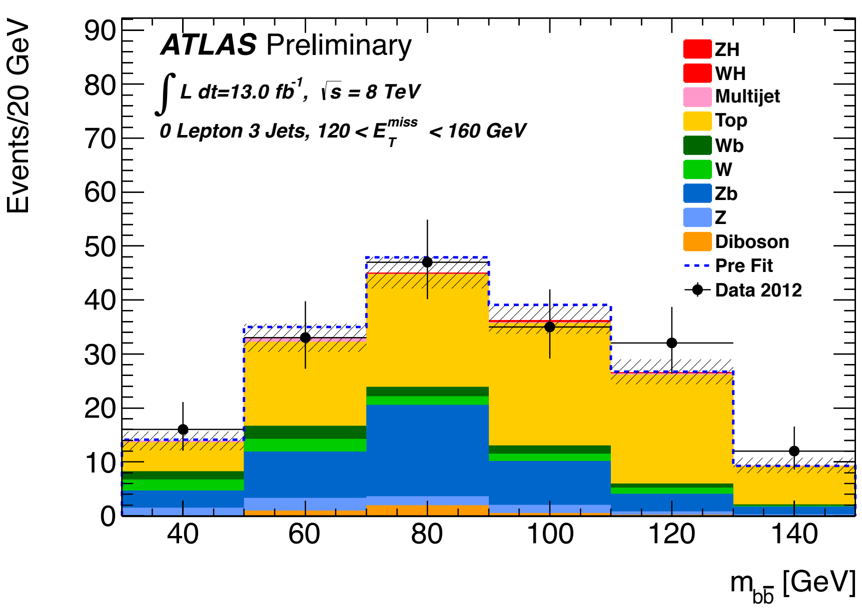
Final plots - 0 lepton

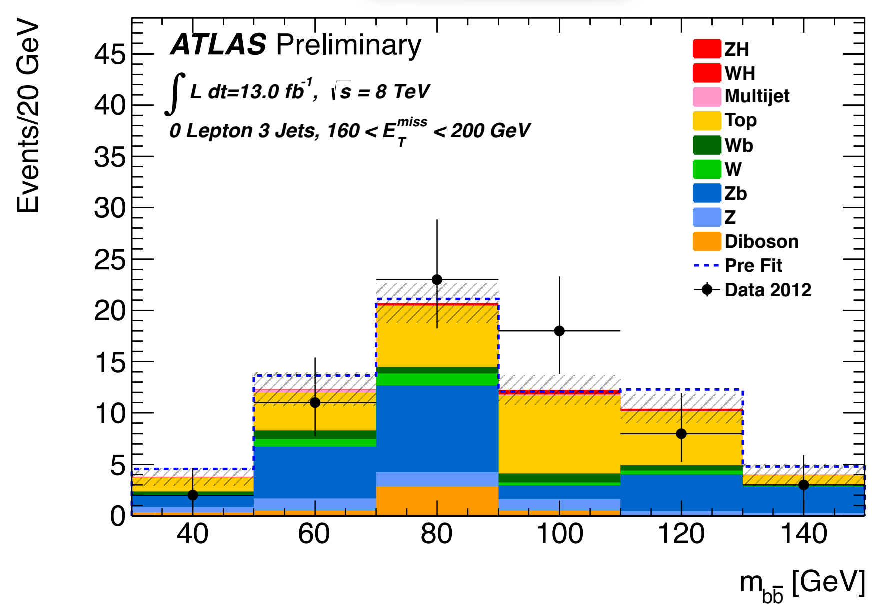


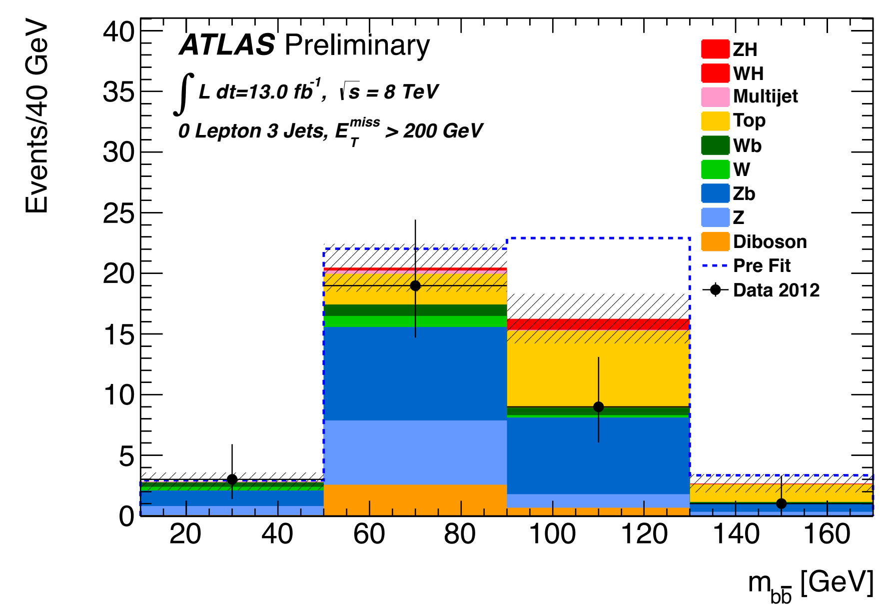




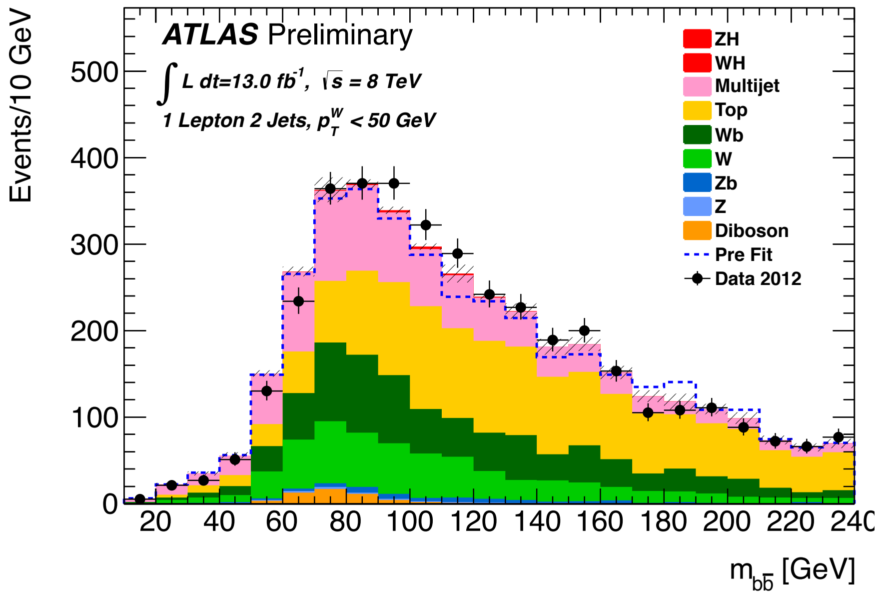
8TeV

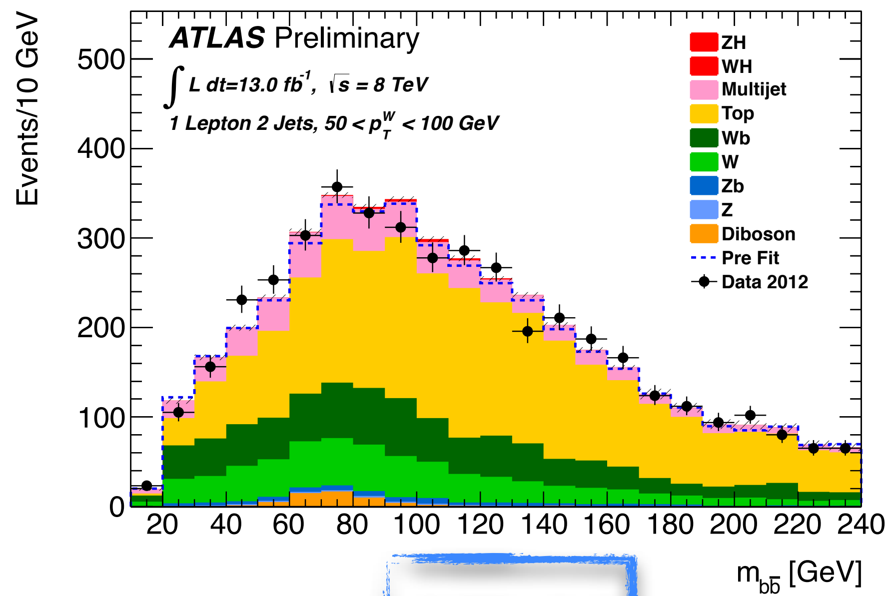


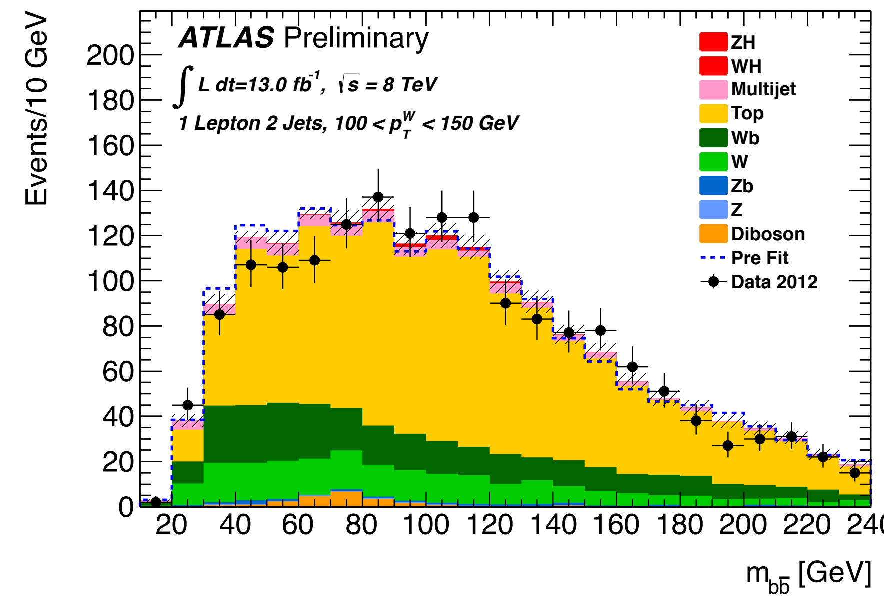




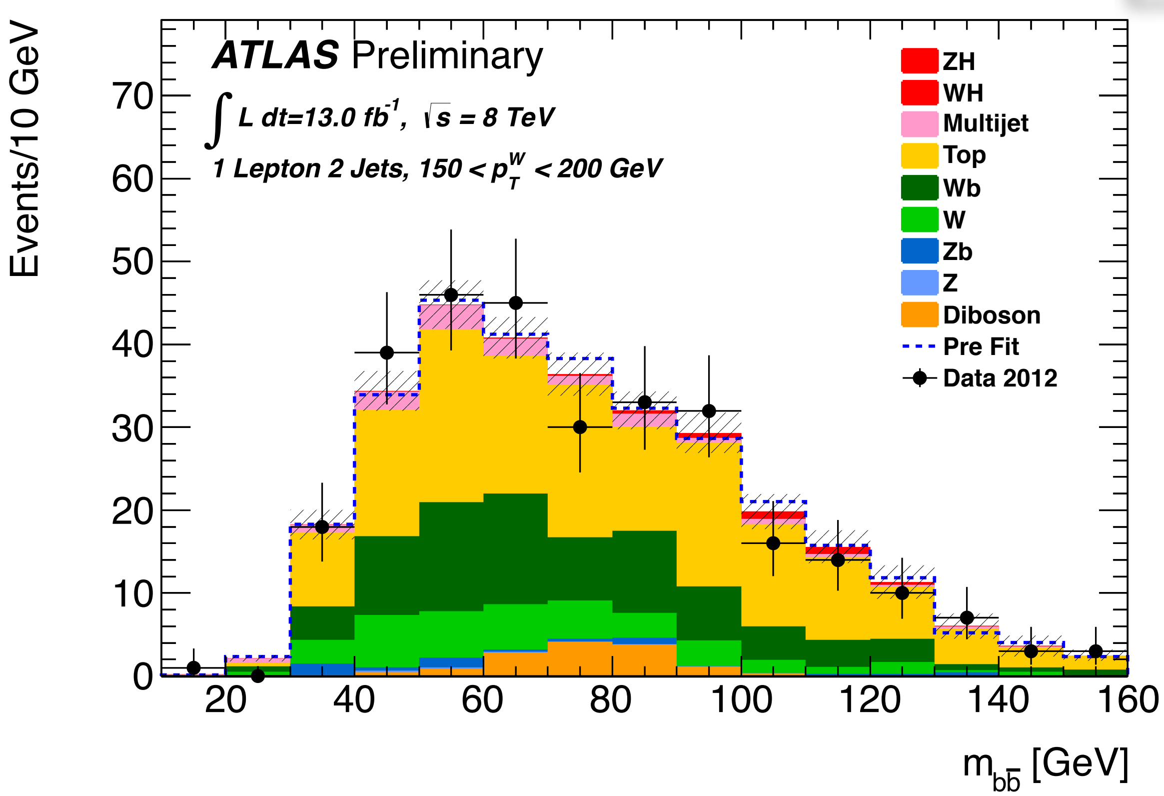
Final plots - 1 lepton

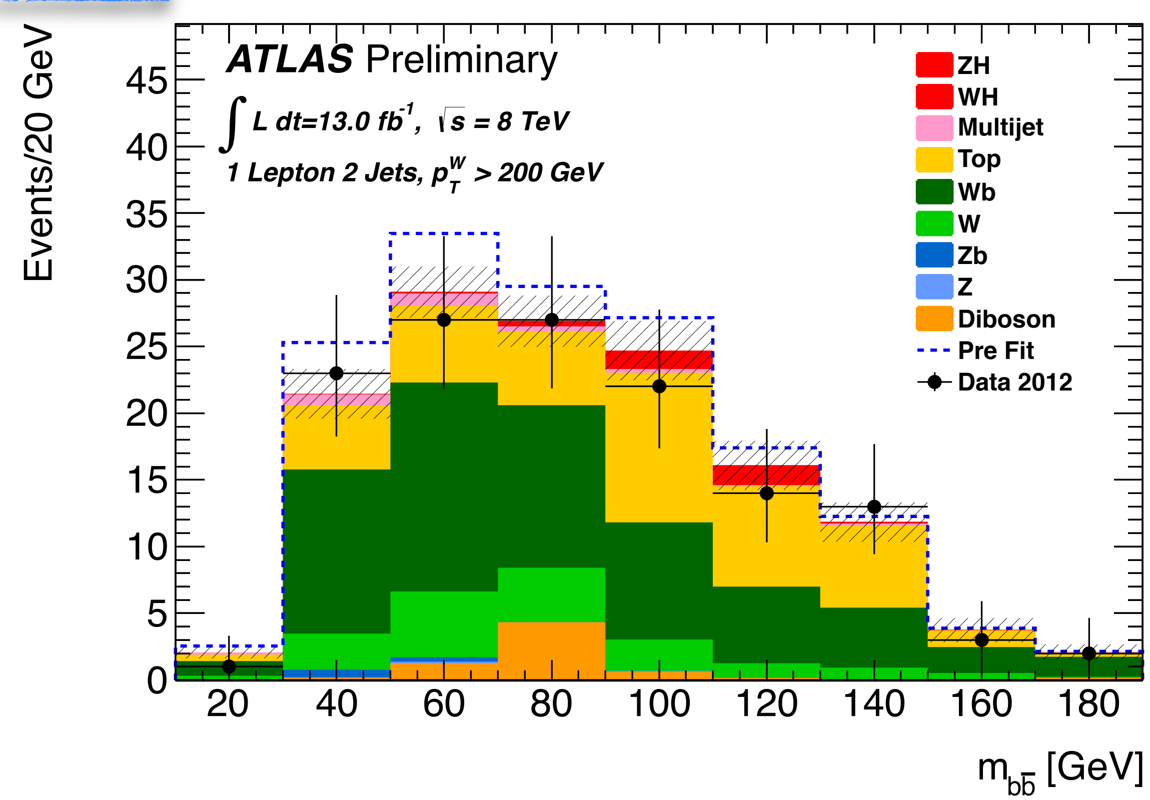




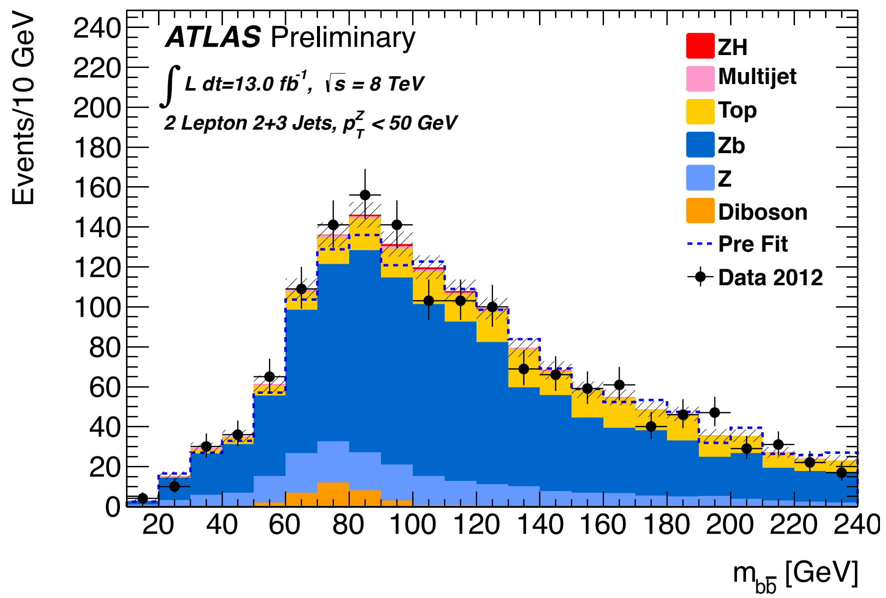


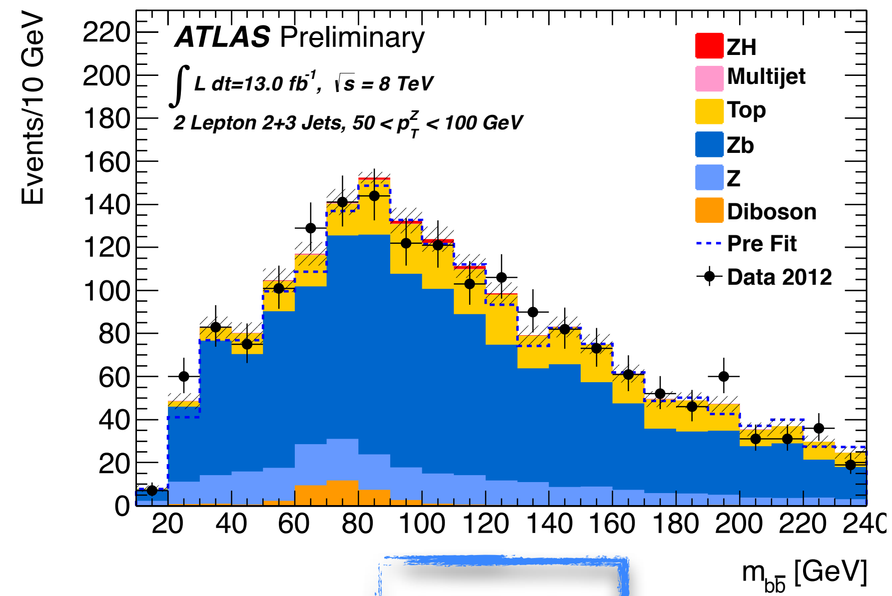
8TeV

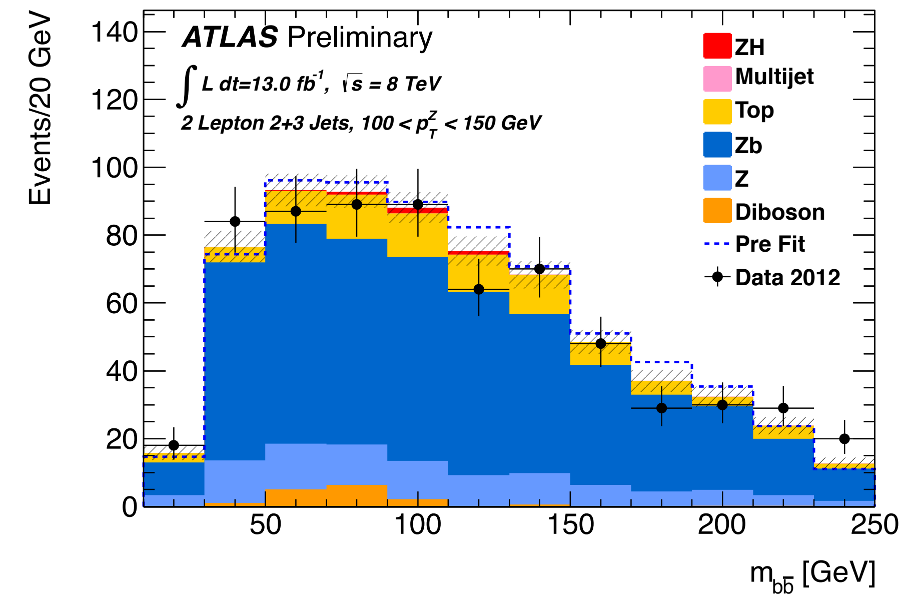




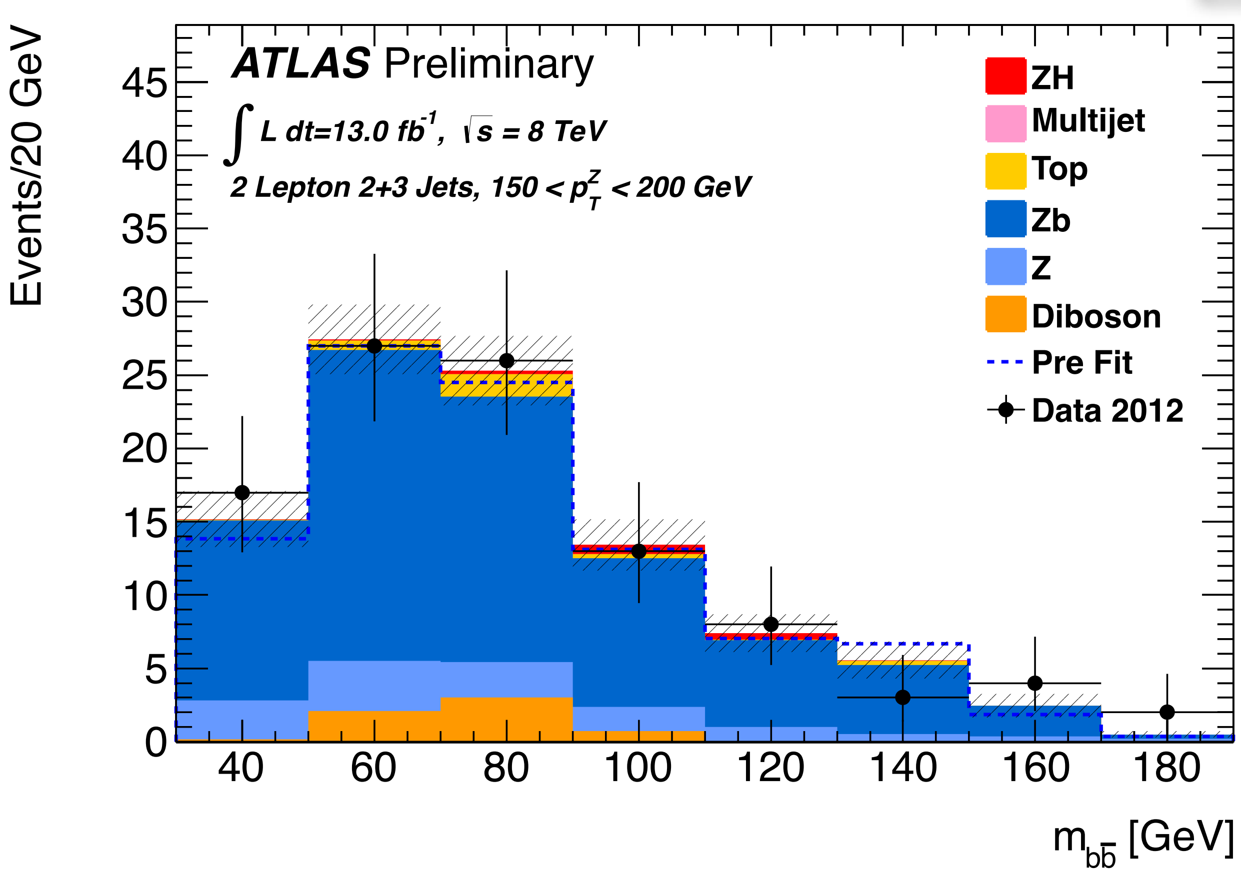
Final plots - 2 lepton

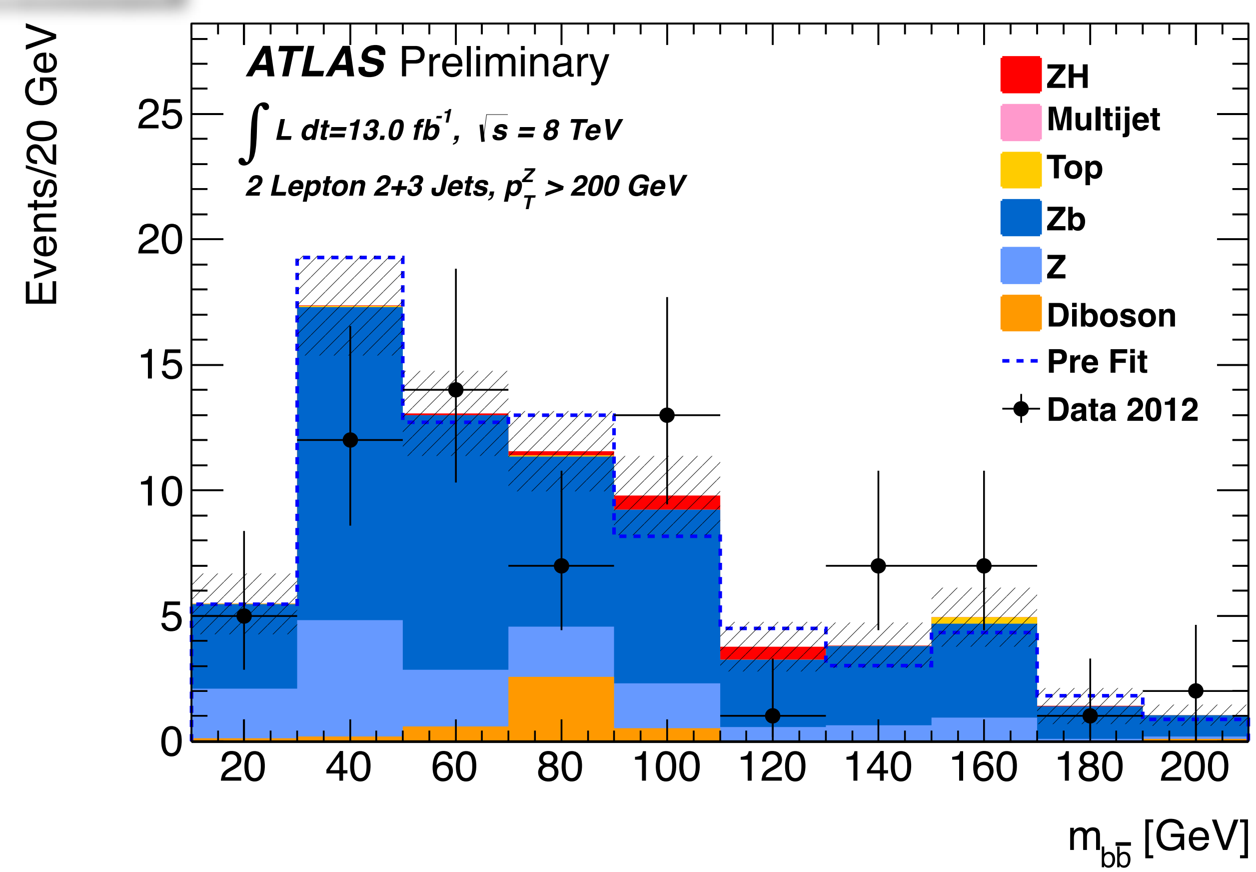






8TeV





Final event yields

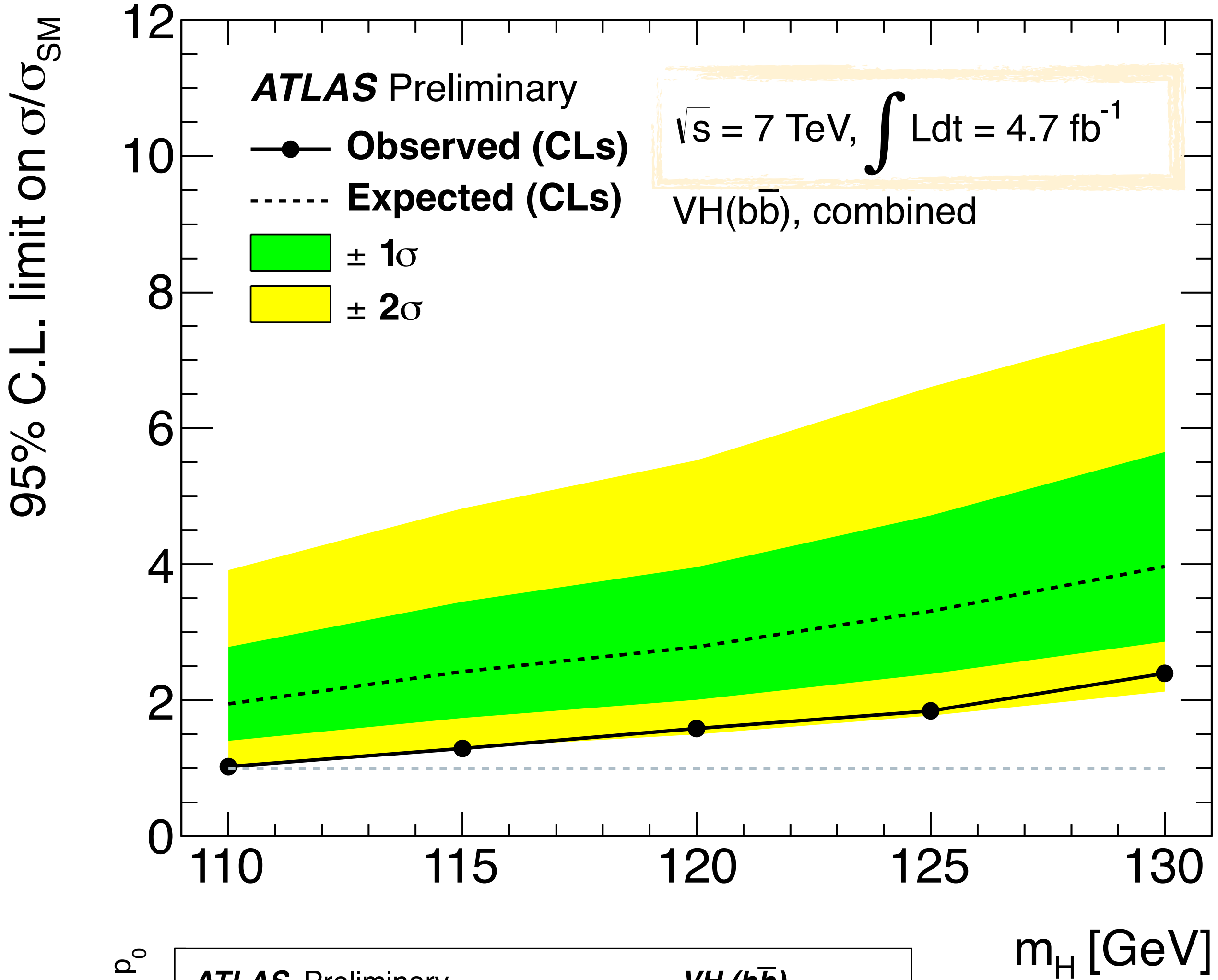
8TeV

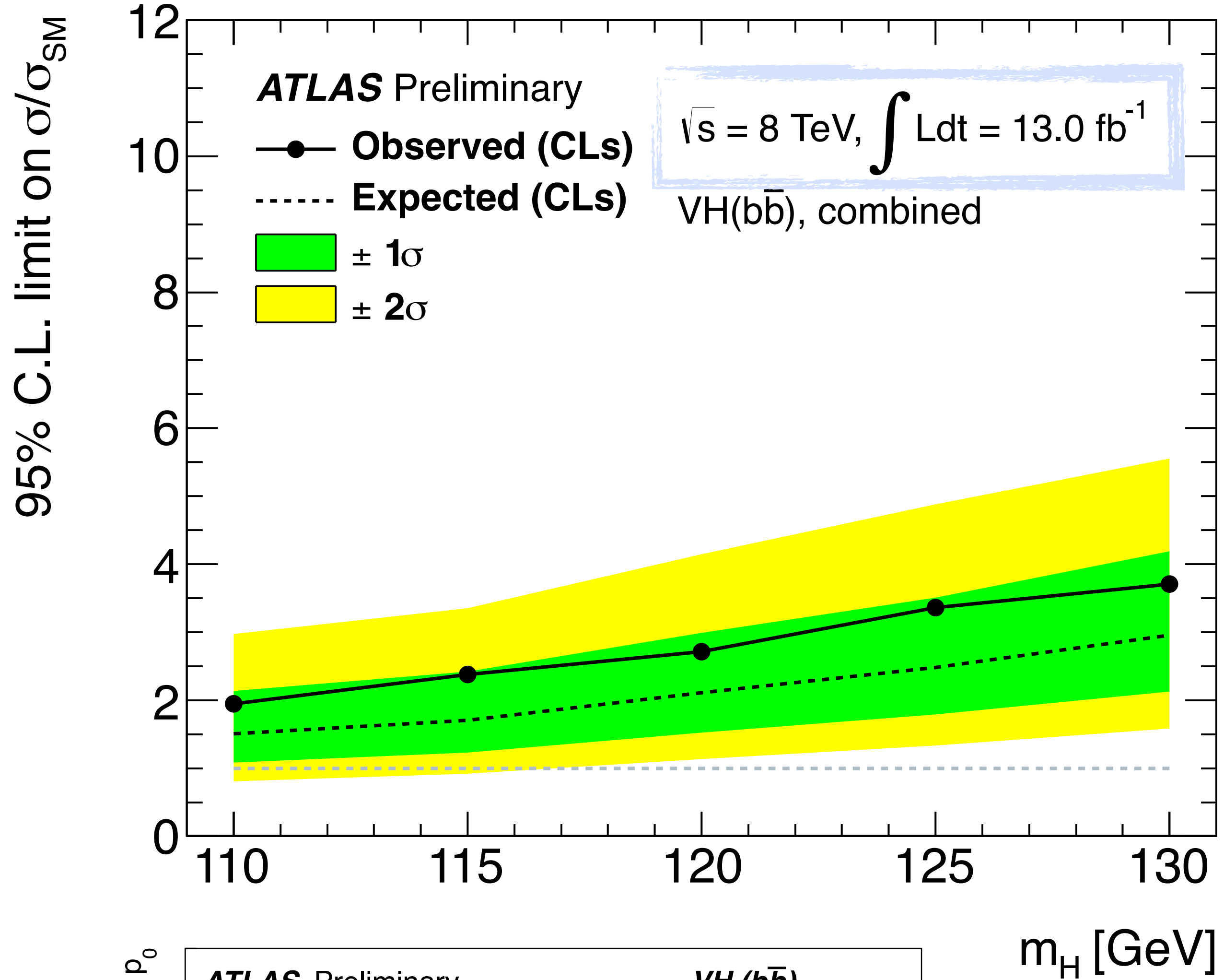
Bin	0-lepton, 2 jet			0-lepton, 3 jet			1-lepton					2-lepton				
	E_T^{miss} [GeV]						p_T^W[GeV]					p_T^Z[GeV]				
	120-160	160-200	>200	120-160	160-200	>200	0-50	50-100	100-150	150-200	> 200	0-50	50-100	100-150	150-200	>200
ZH	2.9	2.1	2.6	0.8	0.8	1.1	0.3	0.4	0.1	0.0	0.0	4.7	6.8	4.0	1.5	1.4
WH	0.8	0.4	0.4	0.2	0.2	0.2	10.6	12.9	7.5	3.6	3.6	0.0	0.0	0.0	0.0	0.0
Top	89	25	8	92	25	10	1440	2276	1120	147	43	230	310	84	3	0
$W + c$,light	30	10	5	9	3	2	580	585	209	36	17	0	0	0	0	0
$W + b$	35	13	13	8	3	2	770	778	288	77	64	0	0	0	0	0
$Z + c$,light	35	14	14	8	5	8	17	17	4	1	0	201	230	91	12	15
$Z + b$	144	51	43	41	22	16	50	63	13	5	1	1010	1180	469	75	51
Diboson	23	11	10	4	4	3	53	59	23	13	7	37	39	16	6	4
Multijet	3	1	1	1	1	0	890	522	68	14	3	12	3	0	0	0
Total Bkg.	361	127	98	164	63	42	3810	4310	1730	297	138	1500	1770	665	97	72
	± 29	± 11	± 12	± 13	± 8	± 5	± 150	± 86	± 90	± 27	± 14	± 90	± 110	± 47	± 12	± 12
Data	342	131	90	175	65	32	3821	4301	1697	297	132	1485	1773	657	100	69

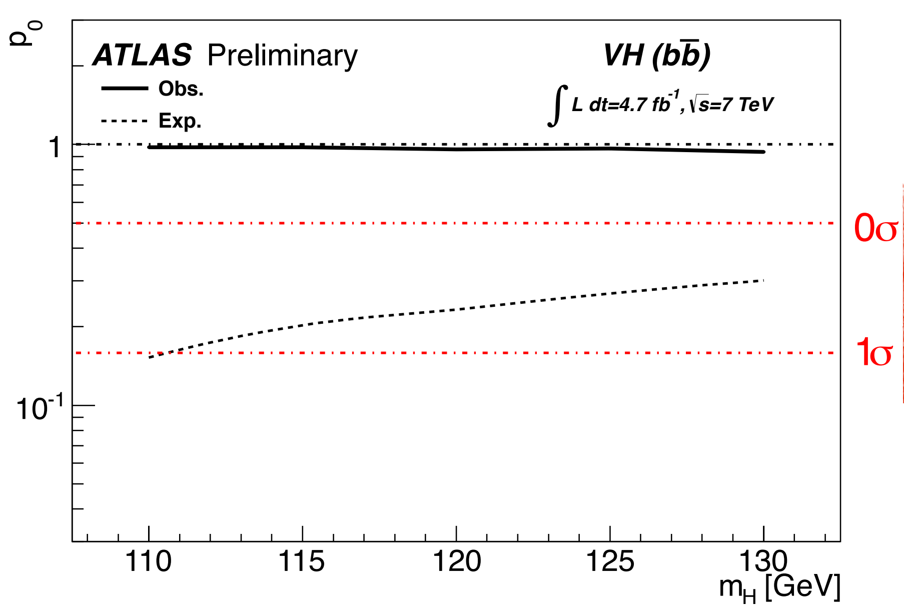
Calculated in range $0<m_{b\bar{b}}/\mathrm{GeV}<250$

Results for 7 and 8 TeV datasets

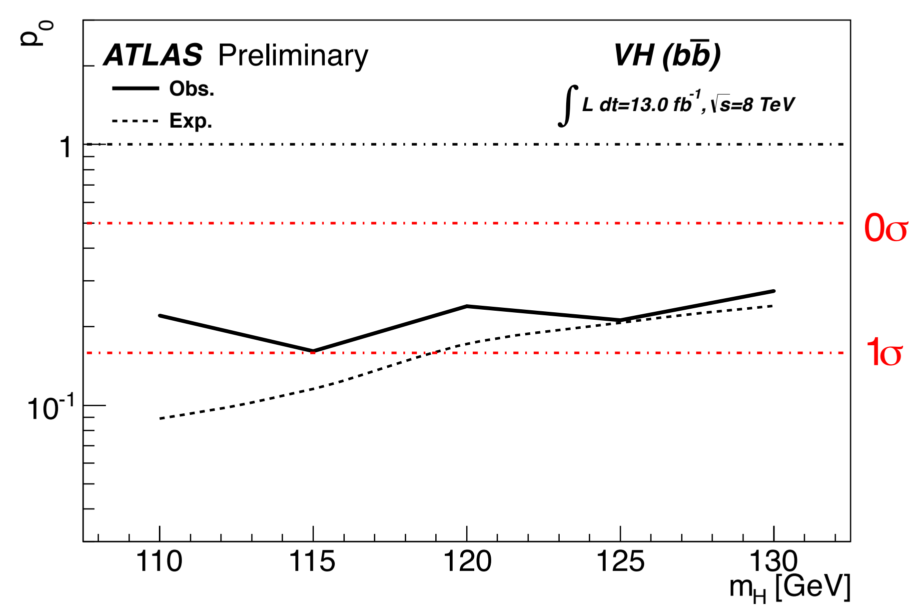
Result of profile likelihood fit for 7 and 8TeV dataset separately







μhat=-2.7
±1.1(stat)
±1.1(syst)



μhat=1.0
±0.9(stat)
±1.1(syst)

VZ($b\bar{b}$) - 8TeV channel breakdown