Search for H→bb in the associated production in ATLAS

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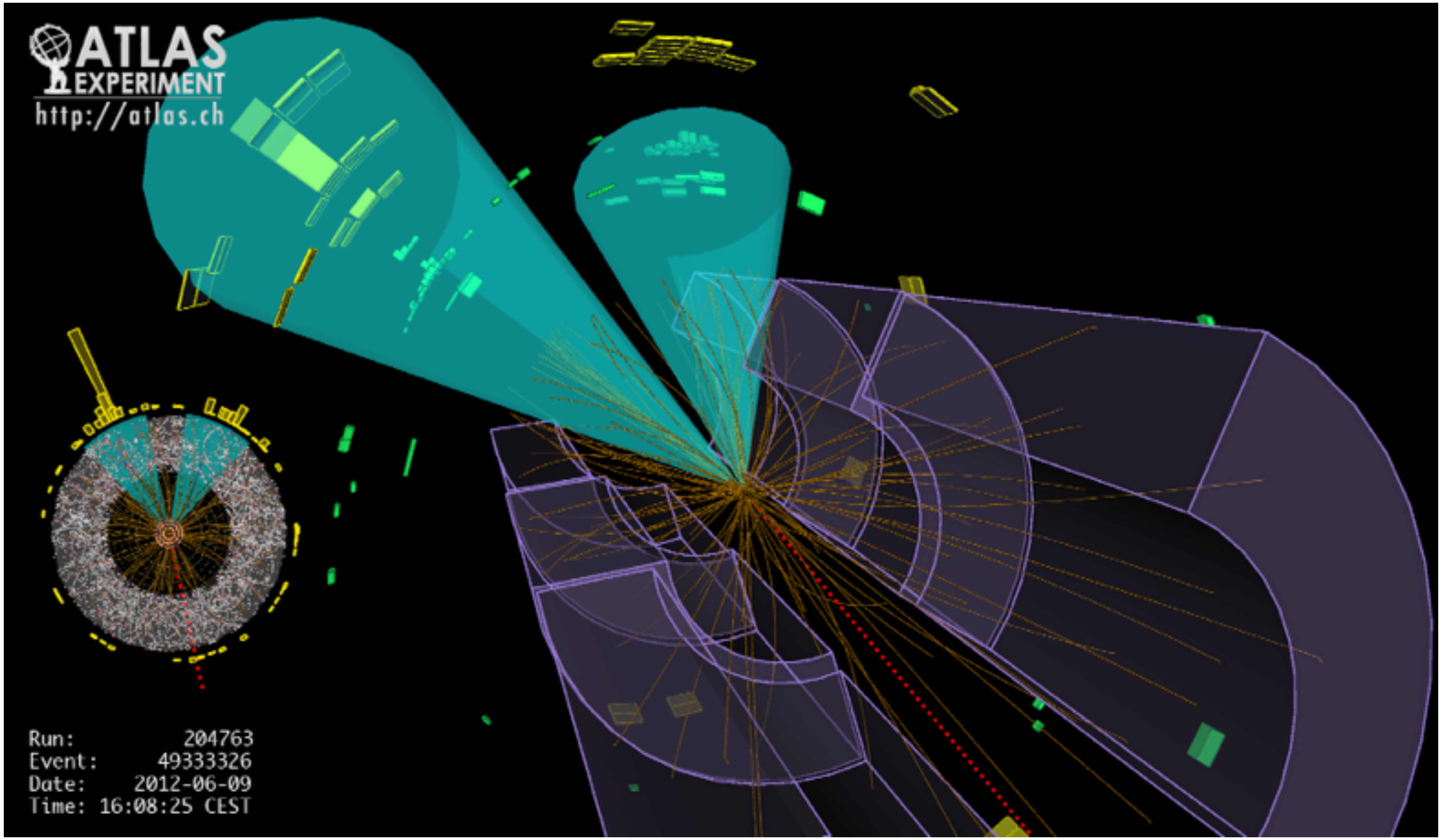


The Higgs Boson

Standard Model QFT $\Rightarrow$ Gauge Theory $\Rightarrow$ **renormalizability + high energy behaviour** $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

Mass Problems: including brute-force masses for fermions and bosons

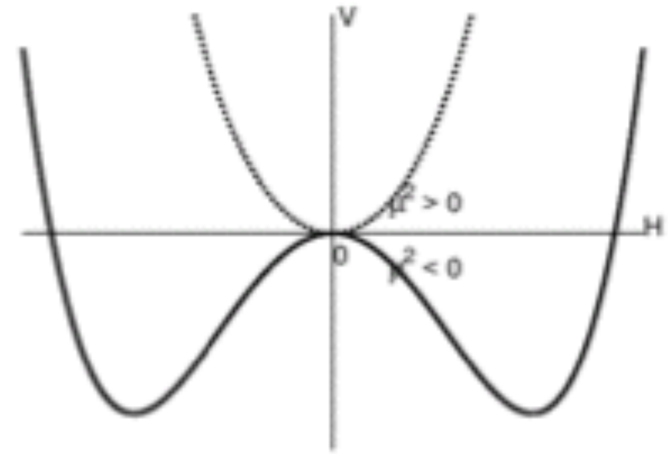
- gauge bosons mass terms violate gauge invariance $\Rightarrow \mu^2 B_\mu B^\mu$
- fermions mass terms break chiral invariance $SU(2)_L \Rightarrow m(\bar{\Phi}_L \Phi_R + \bar{\Phi}_R \Phi_L)$

Scalar Field: $\Phi = \begin{pmatrix} \phi^+ \\ \phi_1 + i\phi_2 \end{pmatrix}$

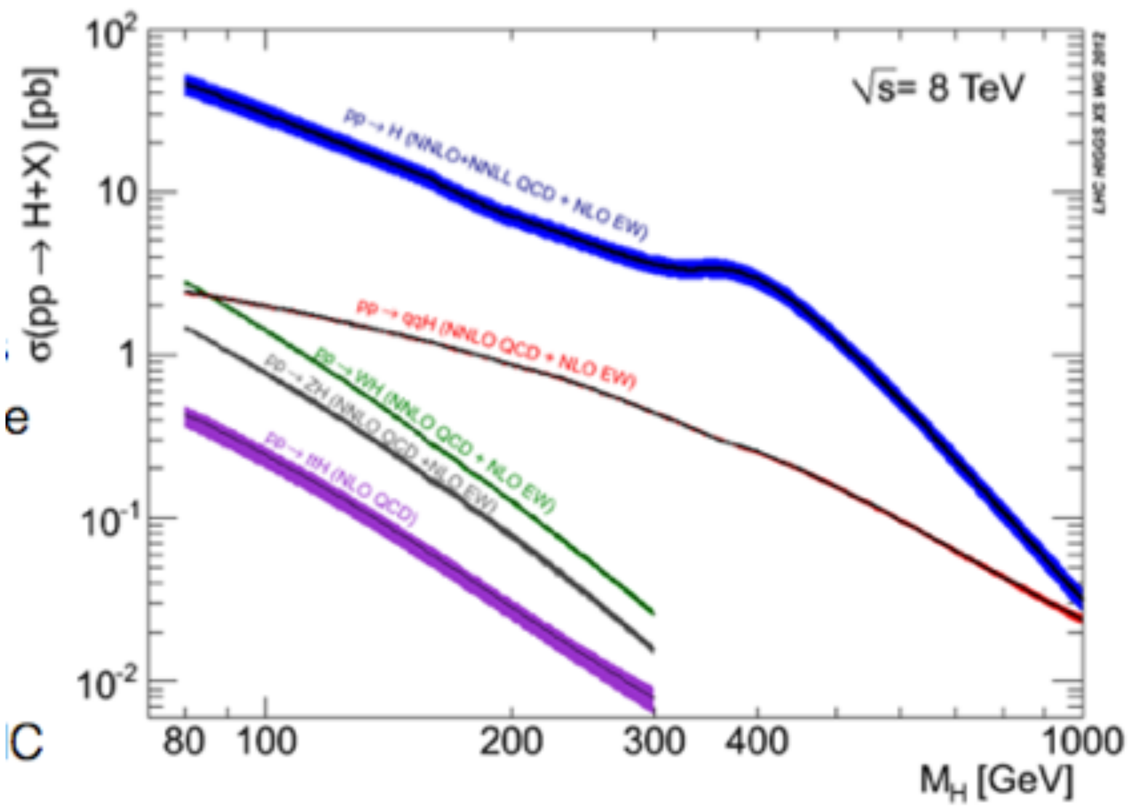
Scalar Lagrangian term:

$$L_\Phi = (D^\mu \Phi)^\dagger D_\mu \Phi - V(\Phi) = (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2$$

Vacuum Expectation Value: $v = < 0|\Phi|0 >$



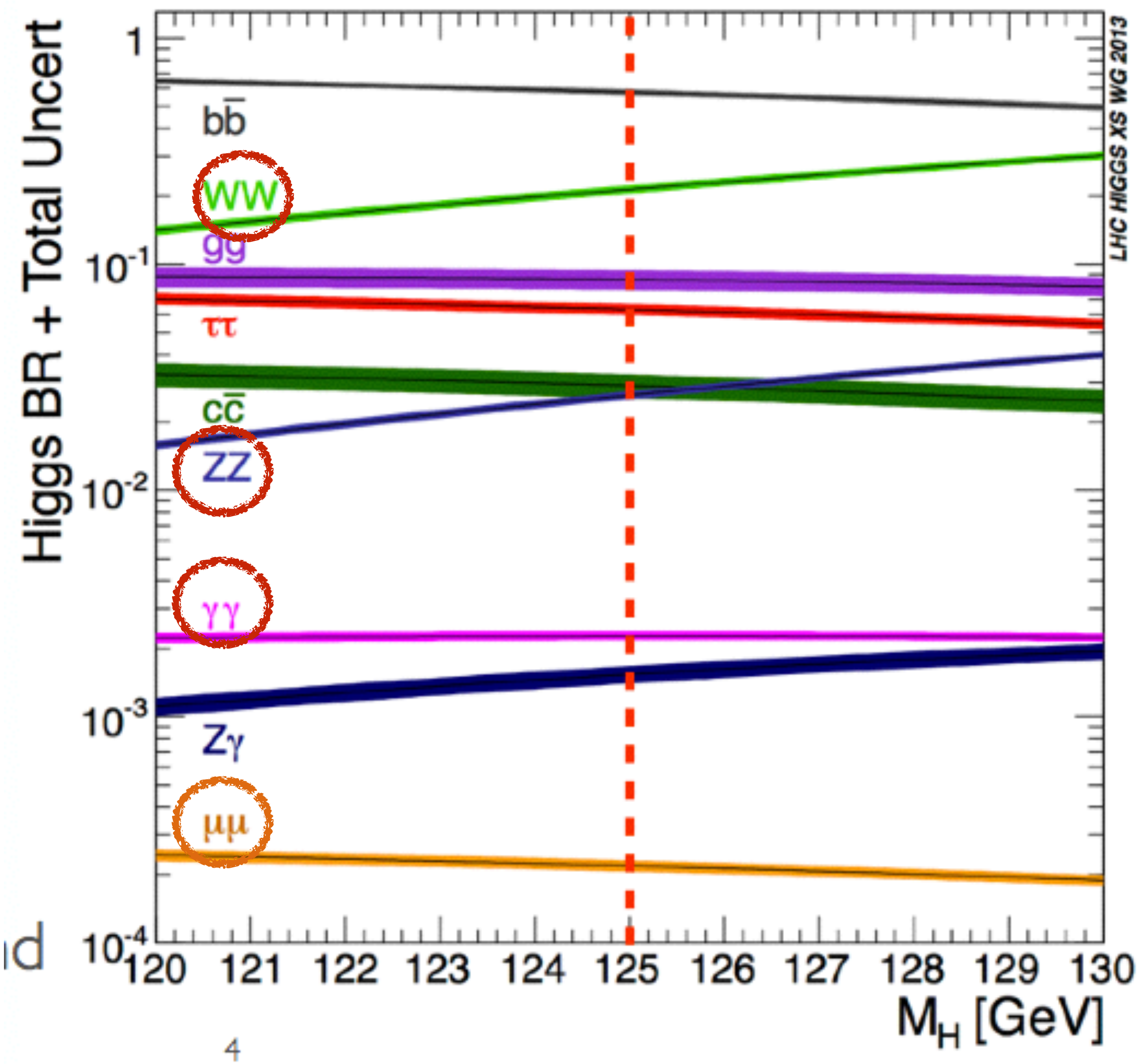
Multiple choices of *vev* possible $\Rightarrow$ SSB $\Rightarrow$ Expansion of Φ around the *vev*



$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \sigma \end{pmatrix} \qquad D_\mu \Phi = \left(\partial_\mu + ig\frac{\tau^i}{2} W^i_\mu + \frac{ig'}{2} B_\mu\right)\Phi$$

$$\begin{aligned} L_\Phi + L_{gauge} = \Bigg(& \frac{1}{2}(\partial_\mu \sigma)(\partial^\mu \sigma) + \mu^2 \sigma^2 - \lambda v \sigma^3 - \frac{\lambda}{4}\sigma^4 + \\ & +(\frac{gv}{2})^2 W^+_\mu W^\mu_- + \frac{1}{2}(\frac{g^2 + g'^2}{4})v^2 Z_\mu Z^\mu + \\ & +\frac{1}{2} g^2 v W^+_\mu W^\mu_- \sigma + \frac{g^2 v}{2} \frac{1}{2\cos(\theta_W)^2} + Z_\mu Z^\mu \sigma + \\ & +\frac{g^2}{4} W^+_\mu W^\mu_- \sigma^2 + \frac{g^2}{4} \frac{1}{2\cos(\theta_W)} Z_\mu Z^\mu \sigma^2 \Bigg) \end{aligned}$$

Higgs bosonic channels in ATLAS



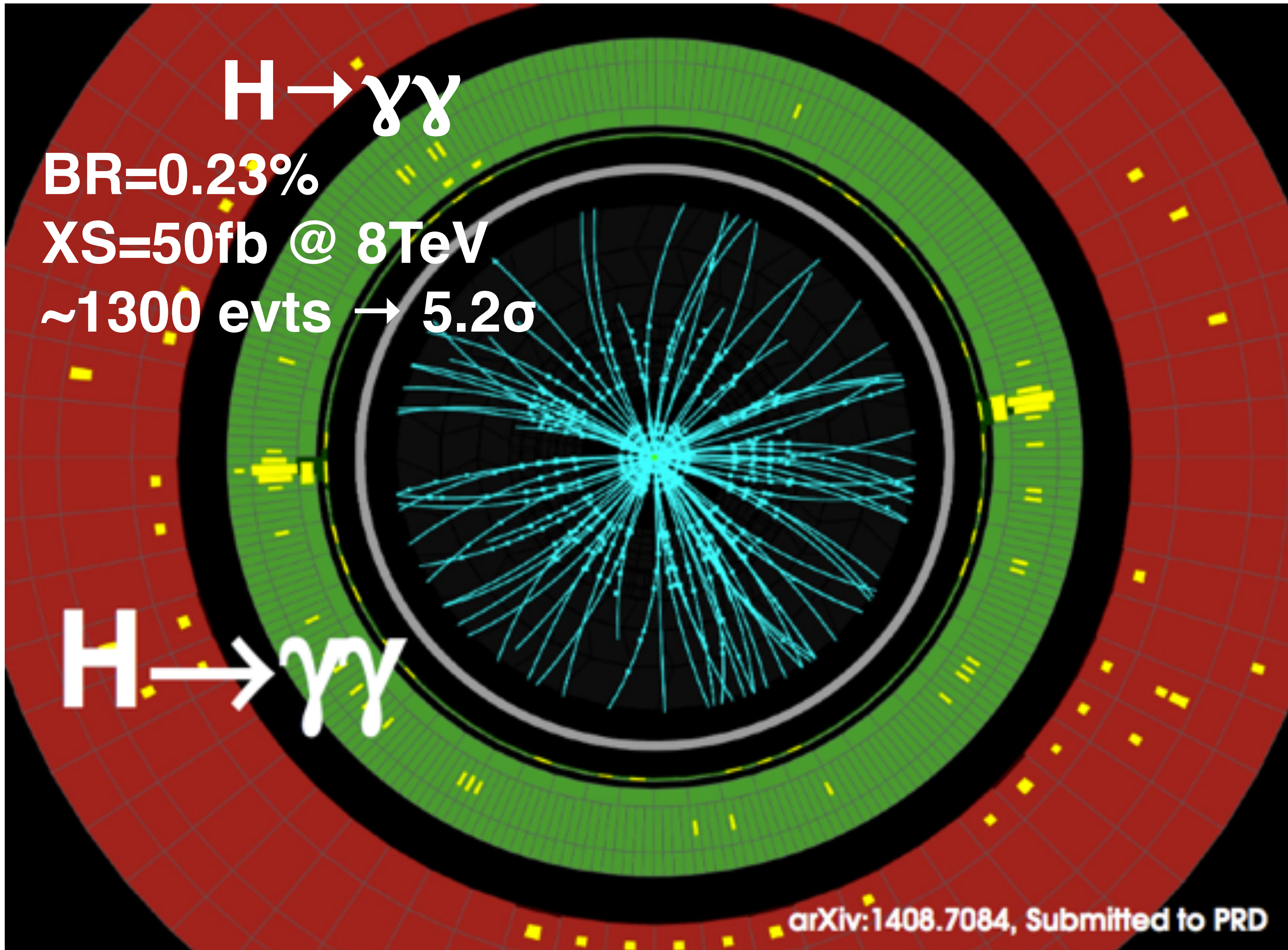
Bosonic **decay channels provide the cleanest experimental signatures**

- **major contribution to the discovery**
- **measurements sensitive to the H spin**

I will not cover these topics at all !

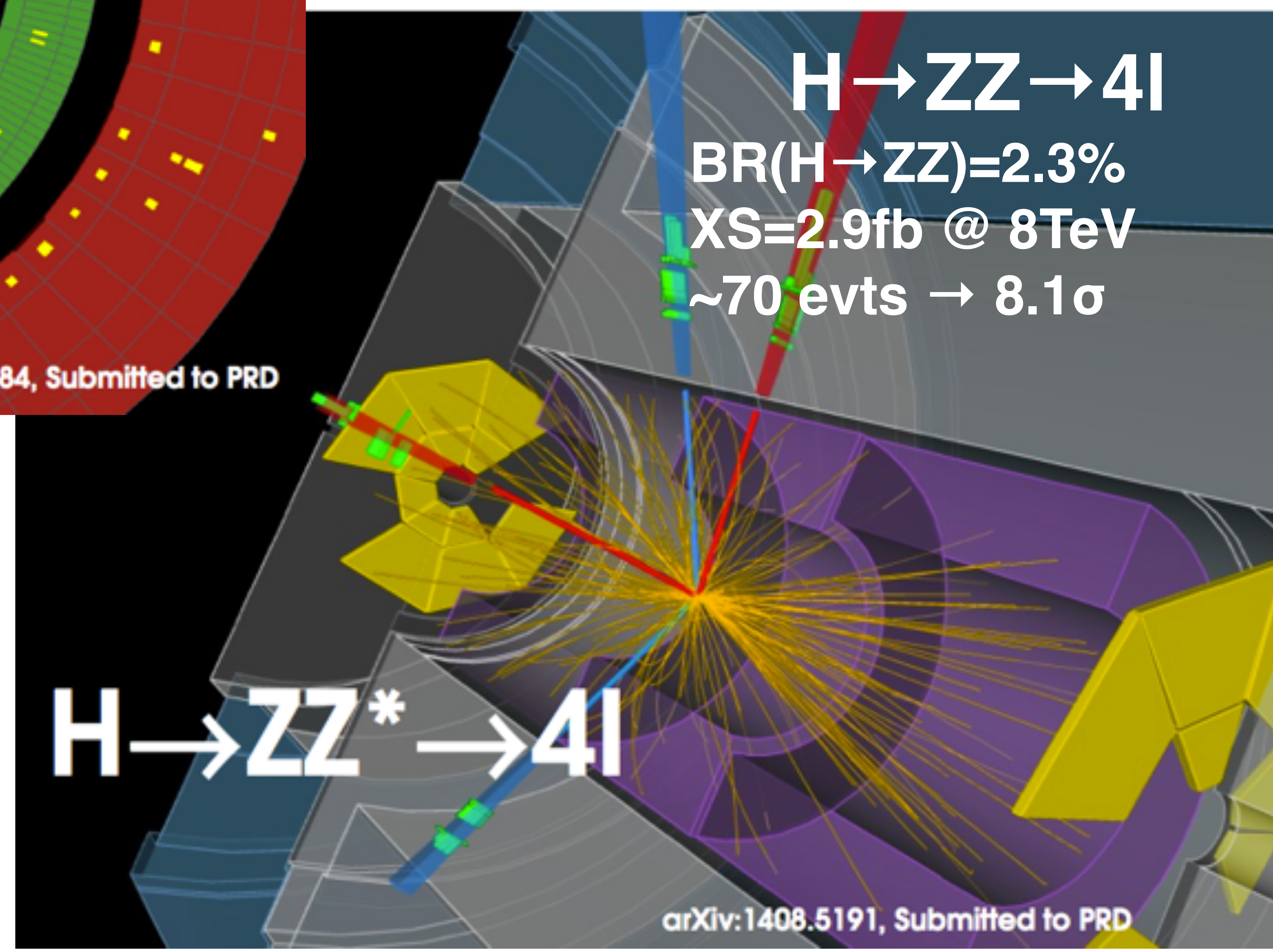
Just a very quick overview of the Higgs searches results in ATLAS

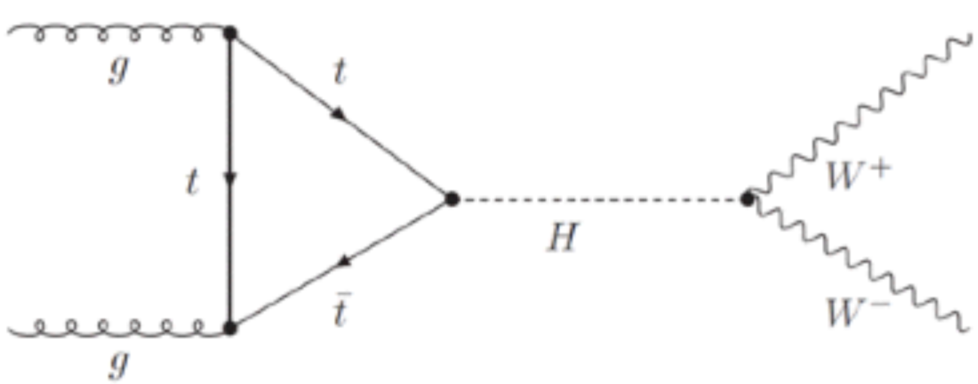
Higgs bosonic channels in ATLAS



H→WW→lνlν

BR(H→WW)=22%
XS=240fb @ 8TeV
→ 6.1σ





Higgs fermionic channels in ATLAS

Fermionic decay channels have a much more complex experimental signature .. However:

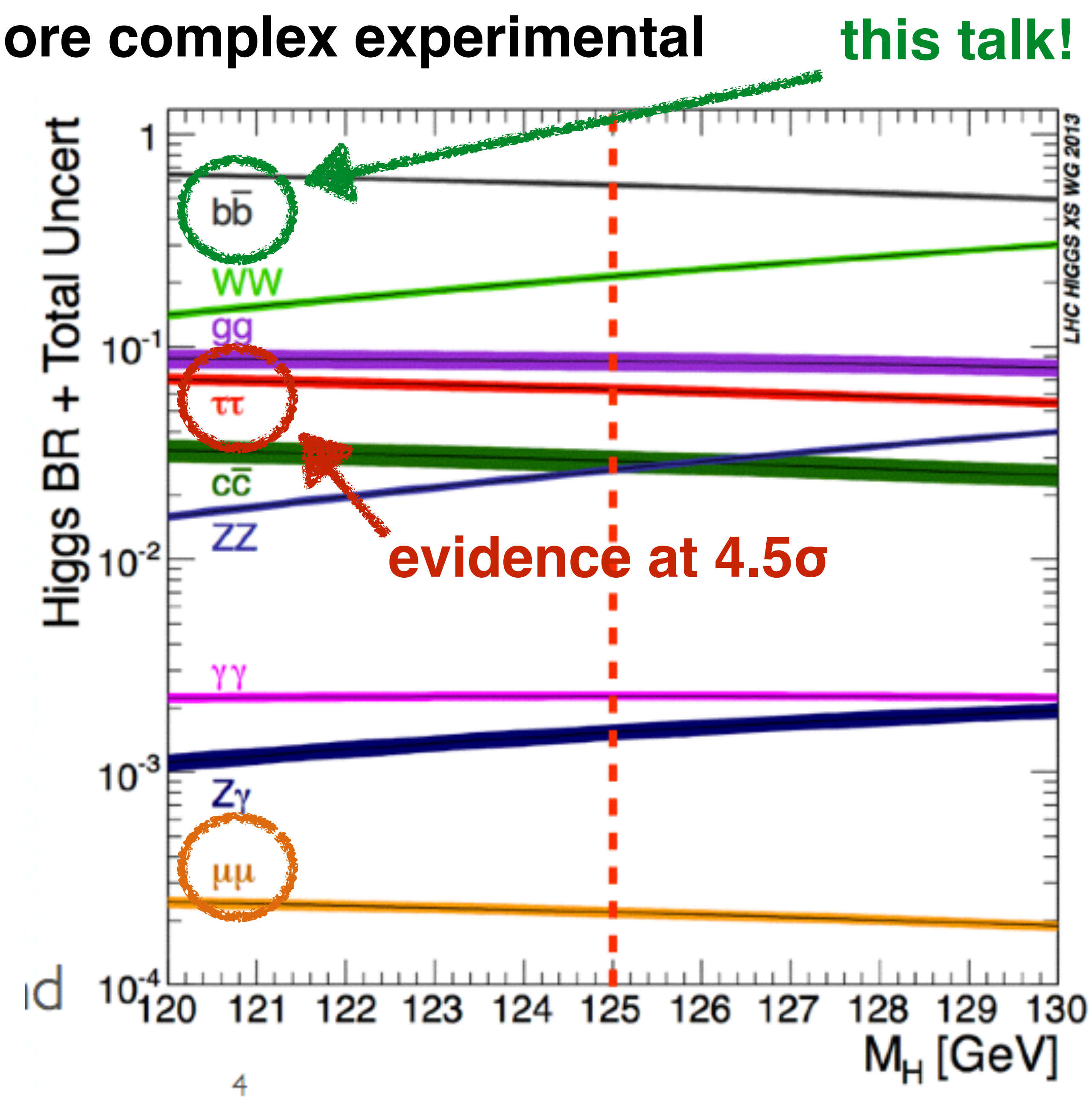
-> probe the direct coupling to fermions

(NOTE: indirectly already from $H\rightarrow\gamma\gamma$ loop induced)

-> possible deviations from SM H couplings ?

-> probe lepton universality ($H\rightarrow\tau\tau$ vs $H\rightarrow\mu\mu$)

-> sensitive to specific Higgs production modes



NOTE: It's not the branching ratio that limits these searches, but the the complex objects in the final state (→low mH resolution) and the competing background processes

H→bb : motivations

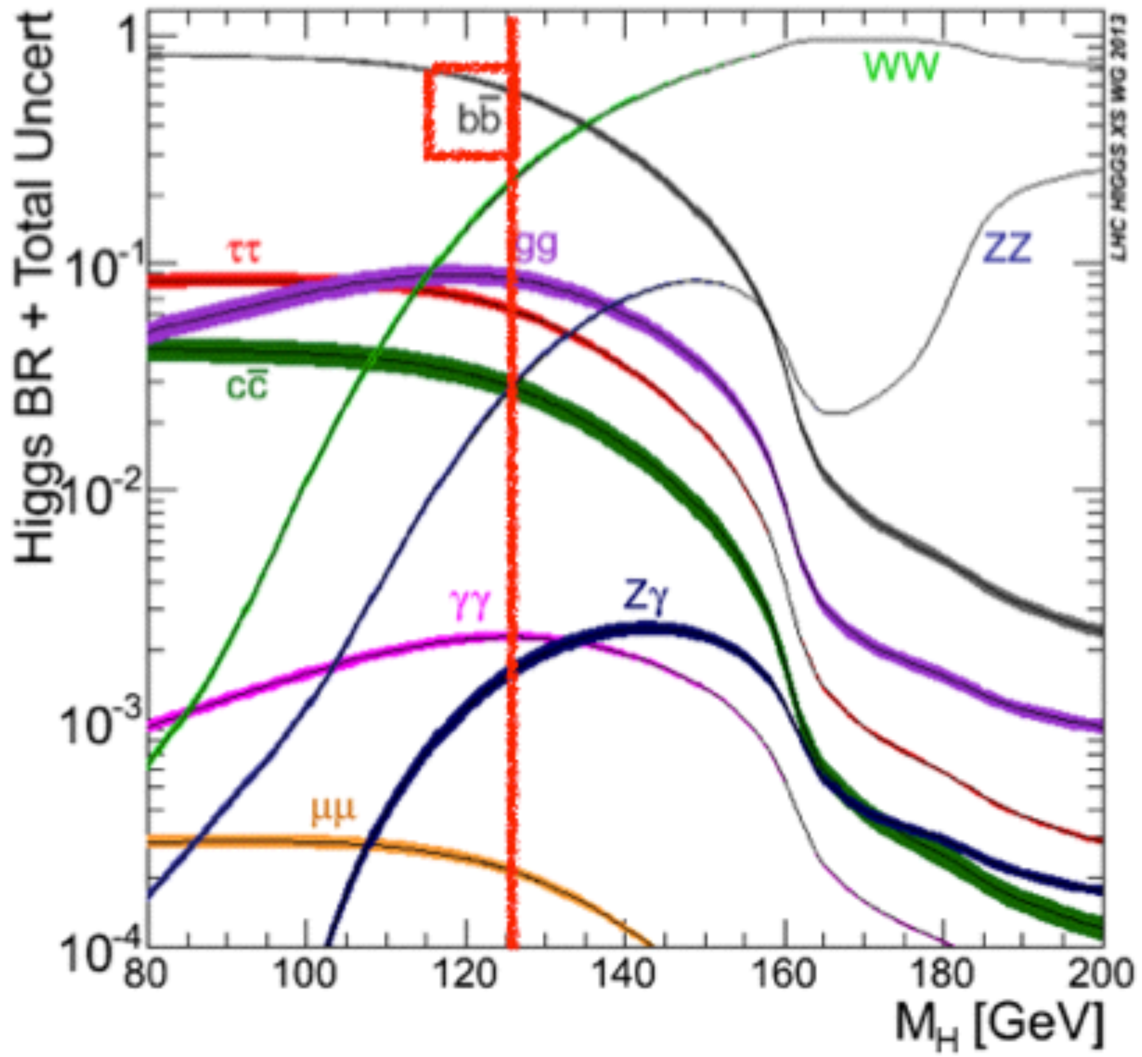
-> BR(H→bb) = 0.57 @ mH = 125 GeV
highest for the SM channels

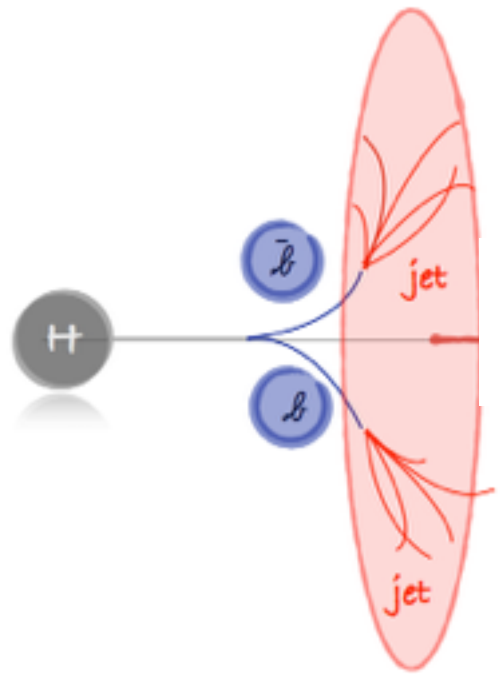
-> provides direct evidence of coupling
to (down-type) quarks

-> sensitive to high pT Higgs production
(boosted Higgs)

-> good sensitivity to new physics
at LHC

NOTE: very large BR → can provide
good statistics for rare processes
SM / SUSY / exotics
(i.e. HH production, …)



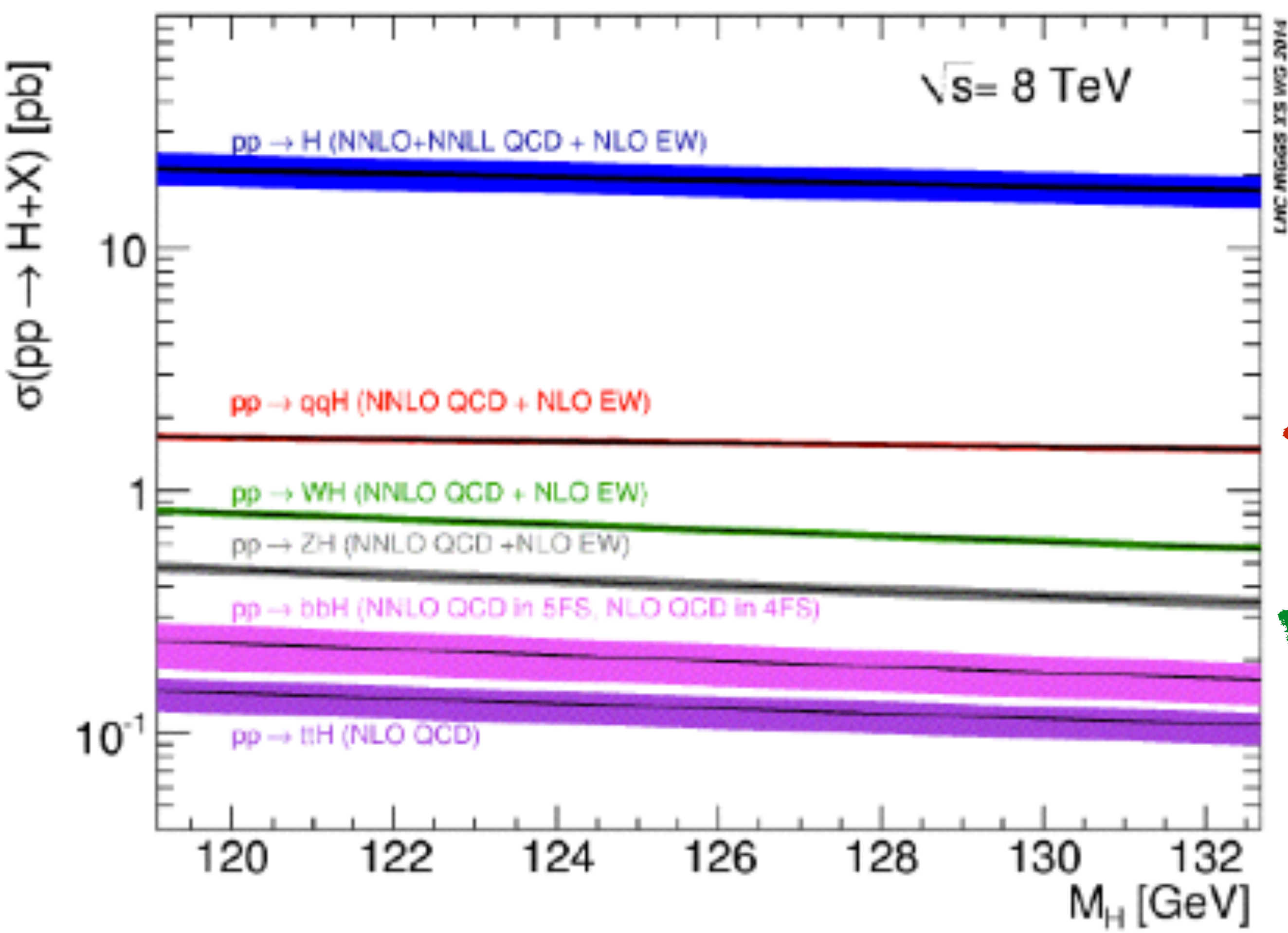


Challenging object reconstruction

low invariant mass resolution

(V)H→bb : motivations

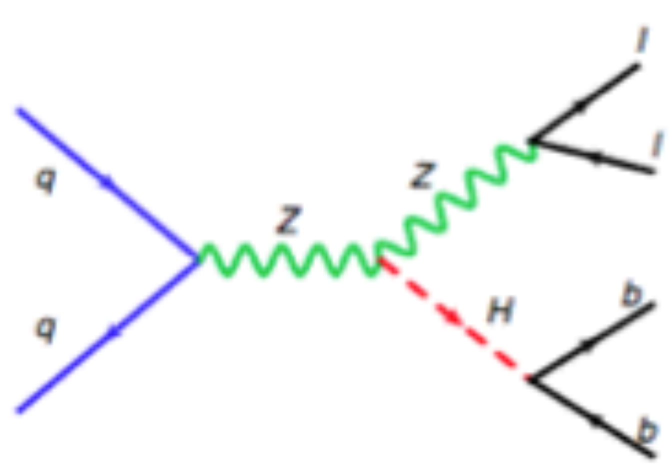
However … the experimental signature of the H→bb process is NOT clean —> completely overwhelmed by QCD background



Gluon fusion production gg→H
(87%)
(dominant production mode)
S/B (LHC) ~ 10^{-4}-10^{-5}
challenge for brave people

Vector boson fusion VBF→H
(7%)
(subdominant)
better S/B → under study for Run2

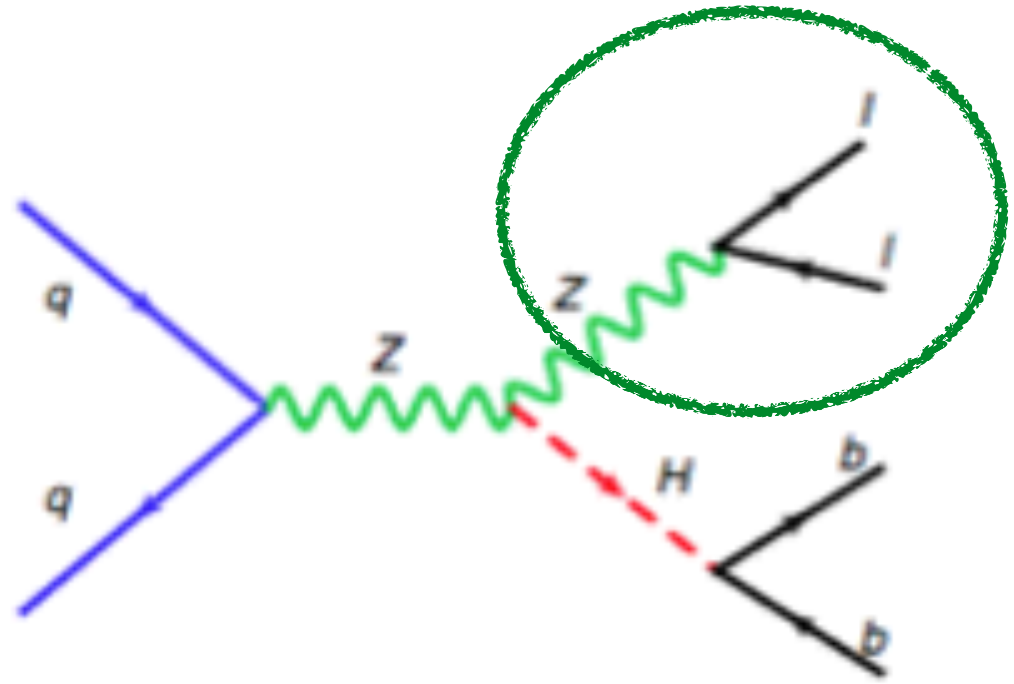
Associated production VH
(5%)
(not really dominant …)
cleaner experimental signature



Exploit leptonic decay of the Z (or W) boson to kill the multijet background originated by QCD processes

→ highest sensitivity at LHC
→ main contribution for Tevatron results

(V)H→bb : what are we looking for ?

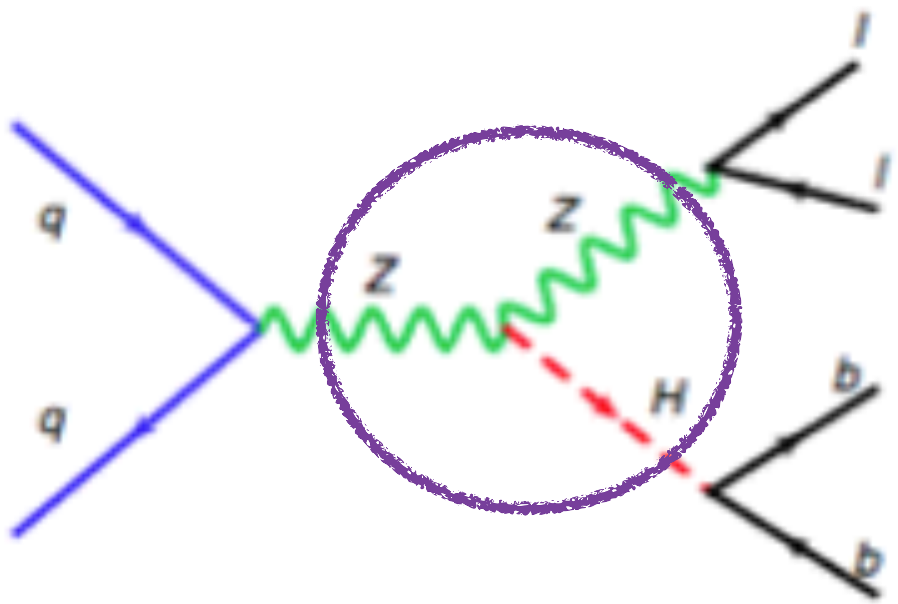


Z boson decay →2 leptons

Z boson decay →2 neutrinos

W boson decay →1 leptons + 1 neutrino

(V)H→bb : what are we looking for ?



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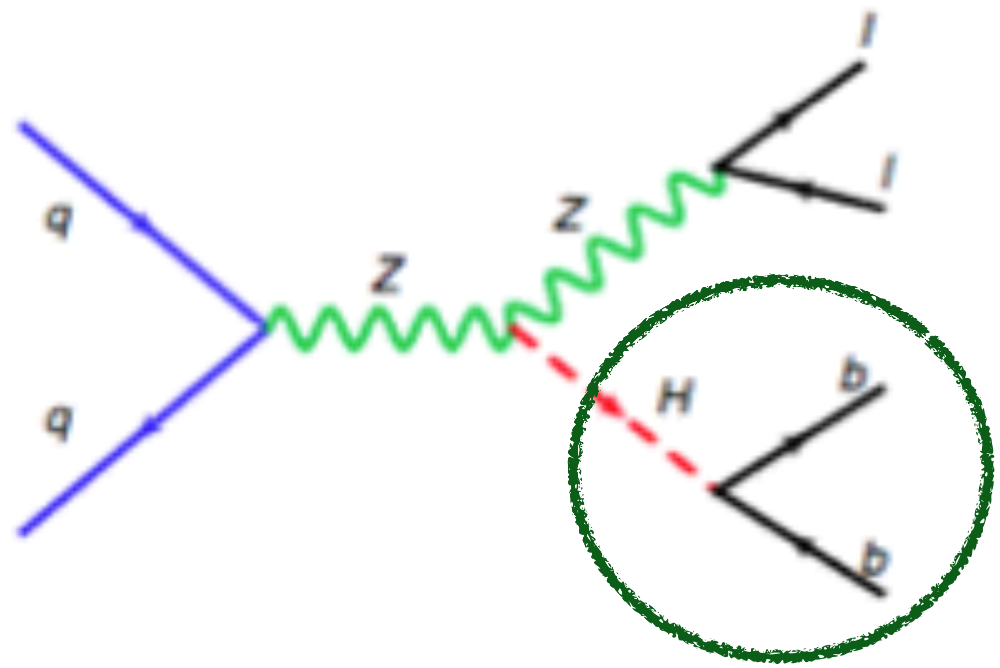
Z boson decay →2 neutrinos

W boson decay →1 leptons + 1 neutrino

Higgs-stralhung

- the Higgs is "radiated" from the Z boson
- kHZZ coupling (proportional to mZ)

(V)H→bb : what are we looking for ?



Higgs decay → bbar quark pair

Z boson decay →2 leptons

Z boson decay →2 neutrinos

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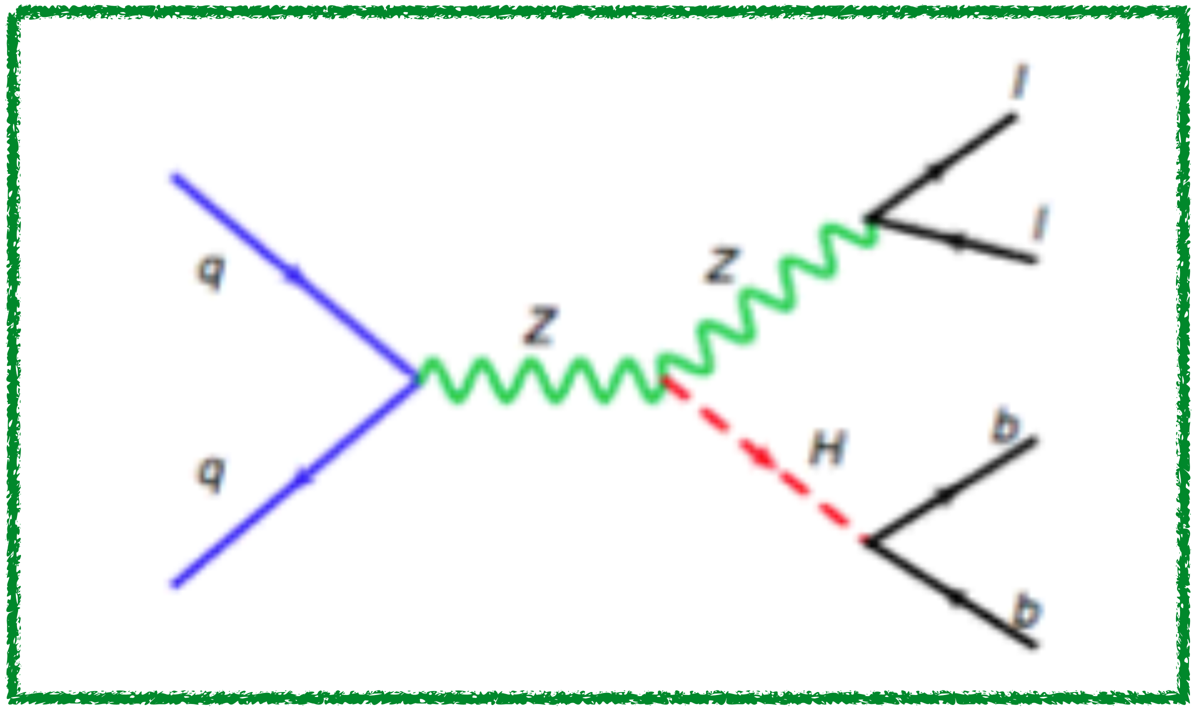
(V)H→bb : what are we looking for ?

LO-only picture



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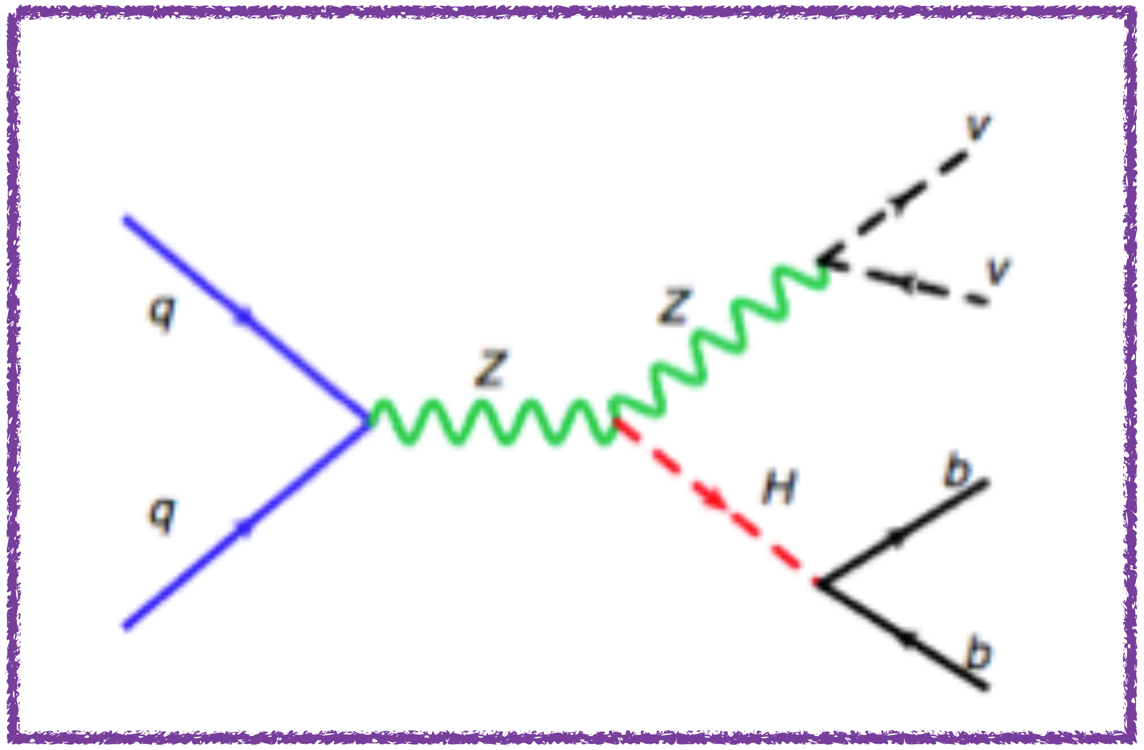
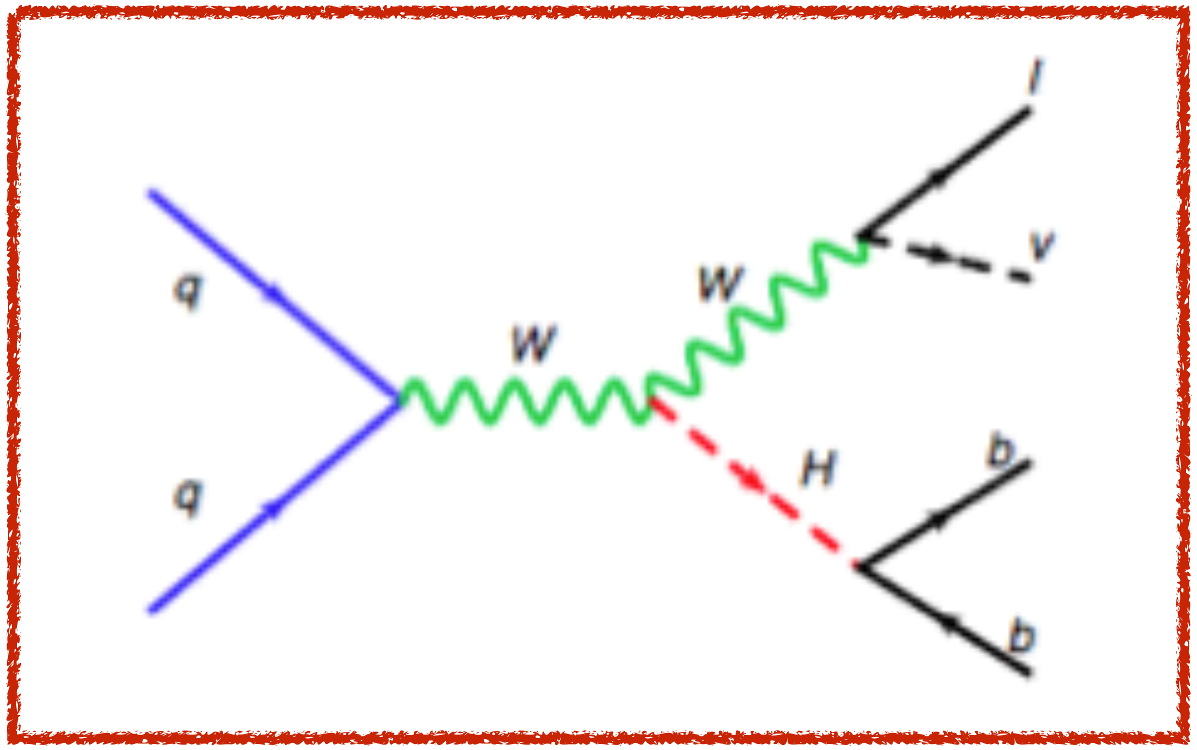
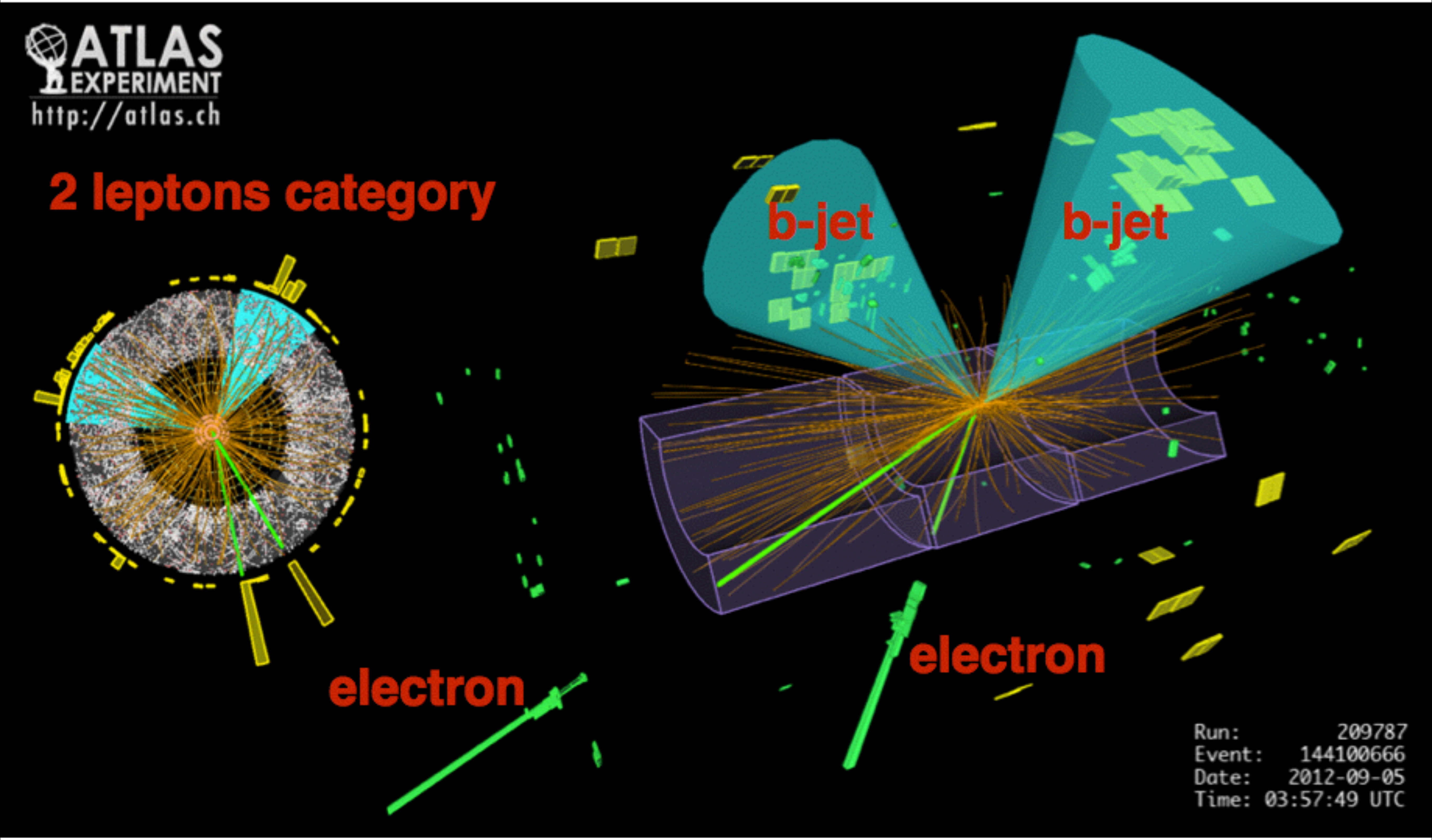
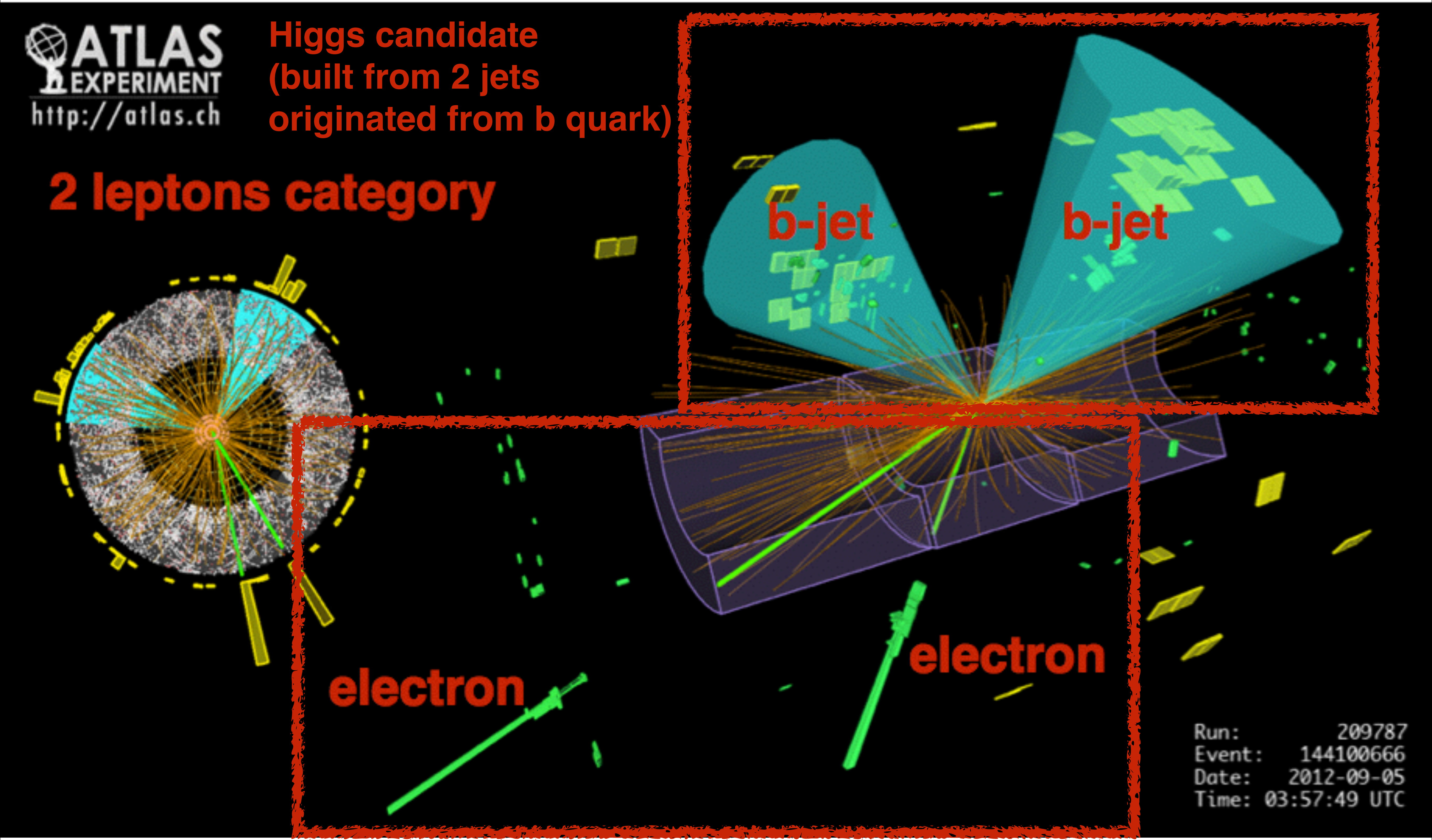




(V)H→bb : what are we (really) looking for ?



(V)H→bb : what are we (really) looking for ?

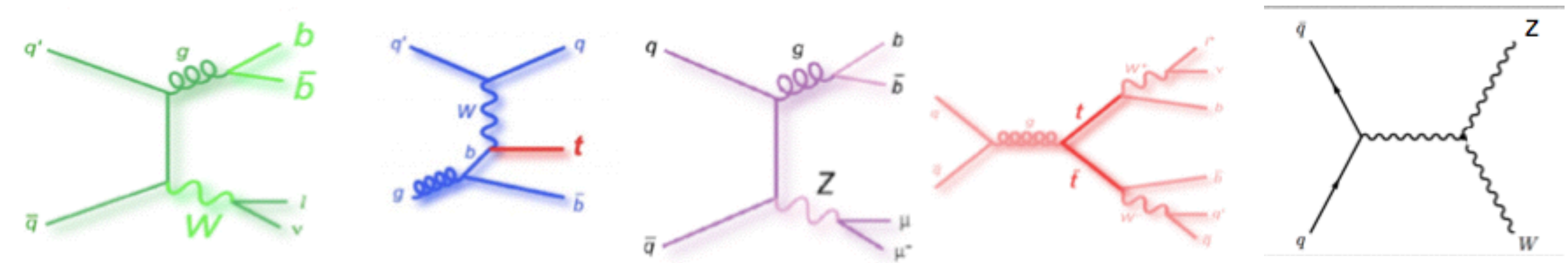


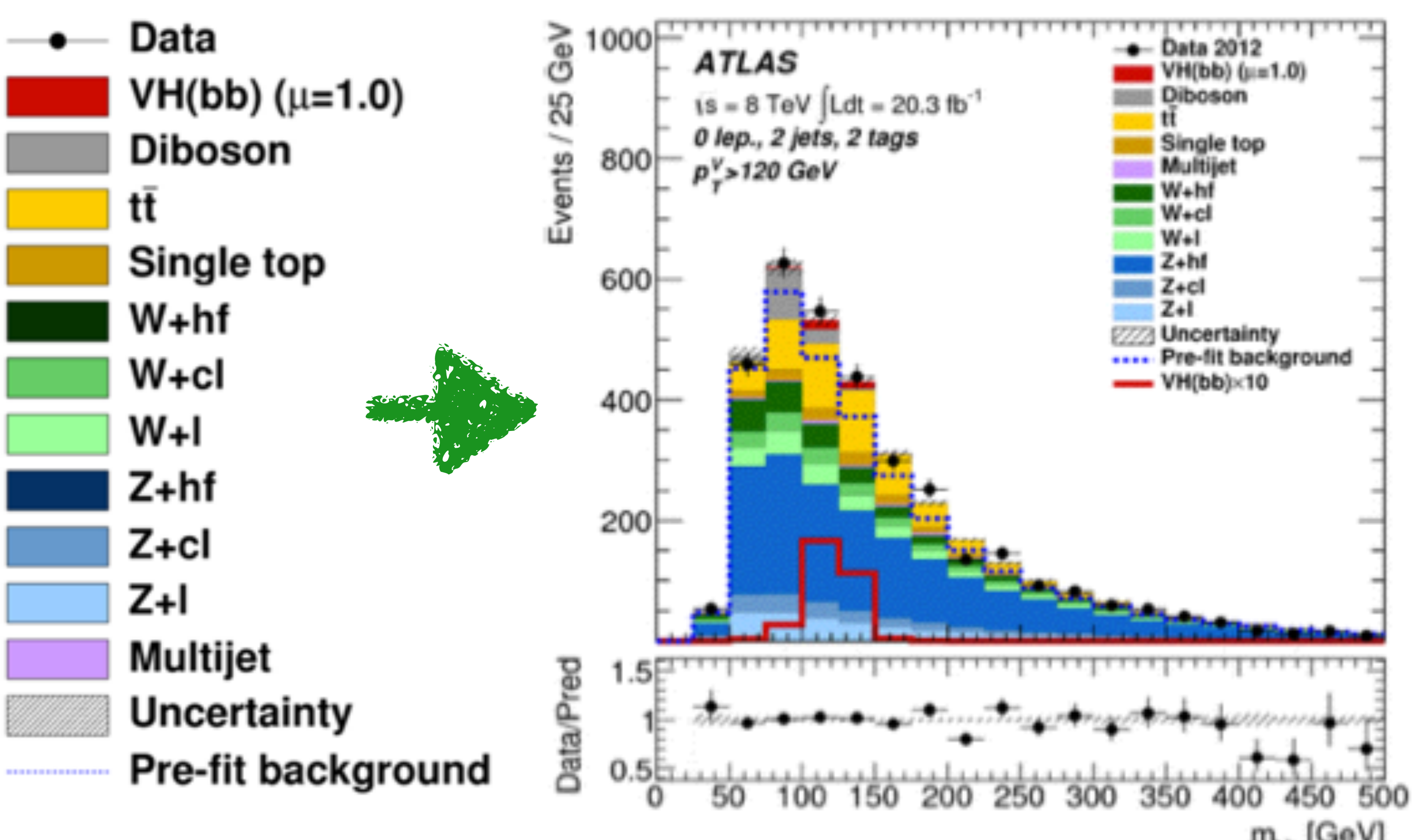
Z boson candidate (reconstructed from 2 electrons)

(V)H→bb : main SM background processes

Backgrounds: **every SM process that can mimic the VH→bb signature**

- **2 jets originate by bottom quarks**
- **(2 leptons) (0 / 1 lepton + missing energy)**





All these processes enter in our phase space and cannot be neglected

- different topologies and kinematics
- resonant & non resonant bkgs

Multijet QCD background

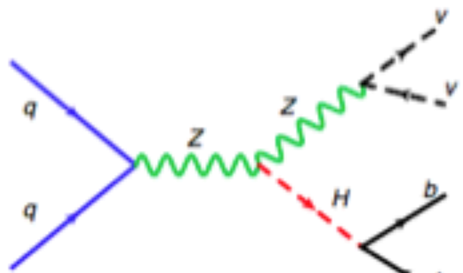
- no MC prediction to rely on
- data driven estimate from CRs
- mostly relevant in the 1 lepton channel

very hard to model properly !

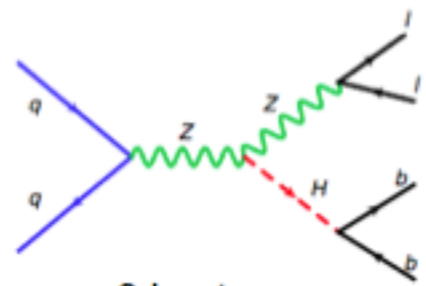
The Analysis Strategy: probing a huge phase space ...

… to find a very tiny signal !

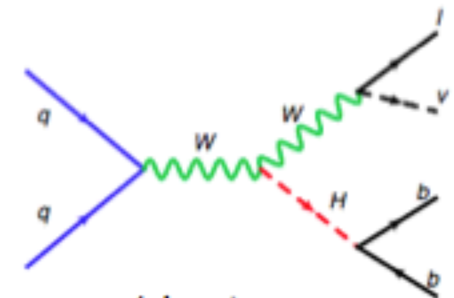
Three lepton channels:



0 Lepton



2 Lepton



1 Lepton

Analysis Phase Space

		1 tag (CR)
VpT > 120GeV	2 jets	2 tag LL (SR)
VpT < 120GeV	3 jets	2 tag MM (SR)
		2 tag TT (SR)

2 regions of transverse momentum of the vector boson V

2 "jet-bins": categories defined counting the number of jets in the event

4 "b-tagging" regions: defined by counting the number of jets originate by bottom quark (with different degrees of likelihood)

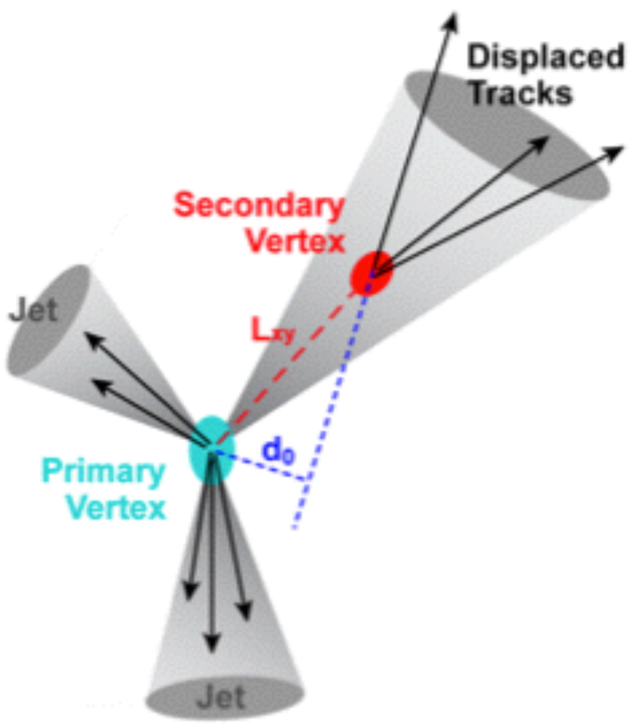
- **2 "b-jets" → Signal Region SR (we use this region to measure the signal)**
- **1 "b-jet" → Control Region SR (used to constrain the bkgs prediction)**

Why such a "splitted" phase space?

- **different background contribution**: the many regions select different kinds of events with different kinematics
- **Signal Regions vs Control Regions**: different sensitivity and background constraining power

Total: 40-50 analysis regions **(all of them enter in a simultaneous fit to extract the signal and constrain the backgrouns)**

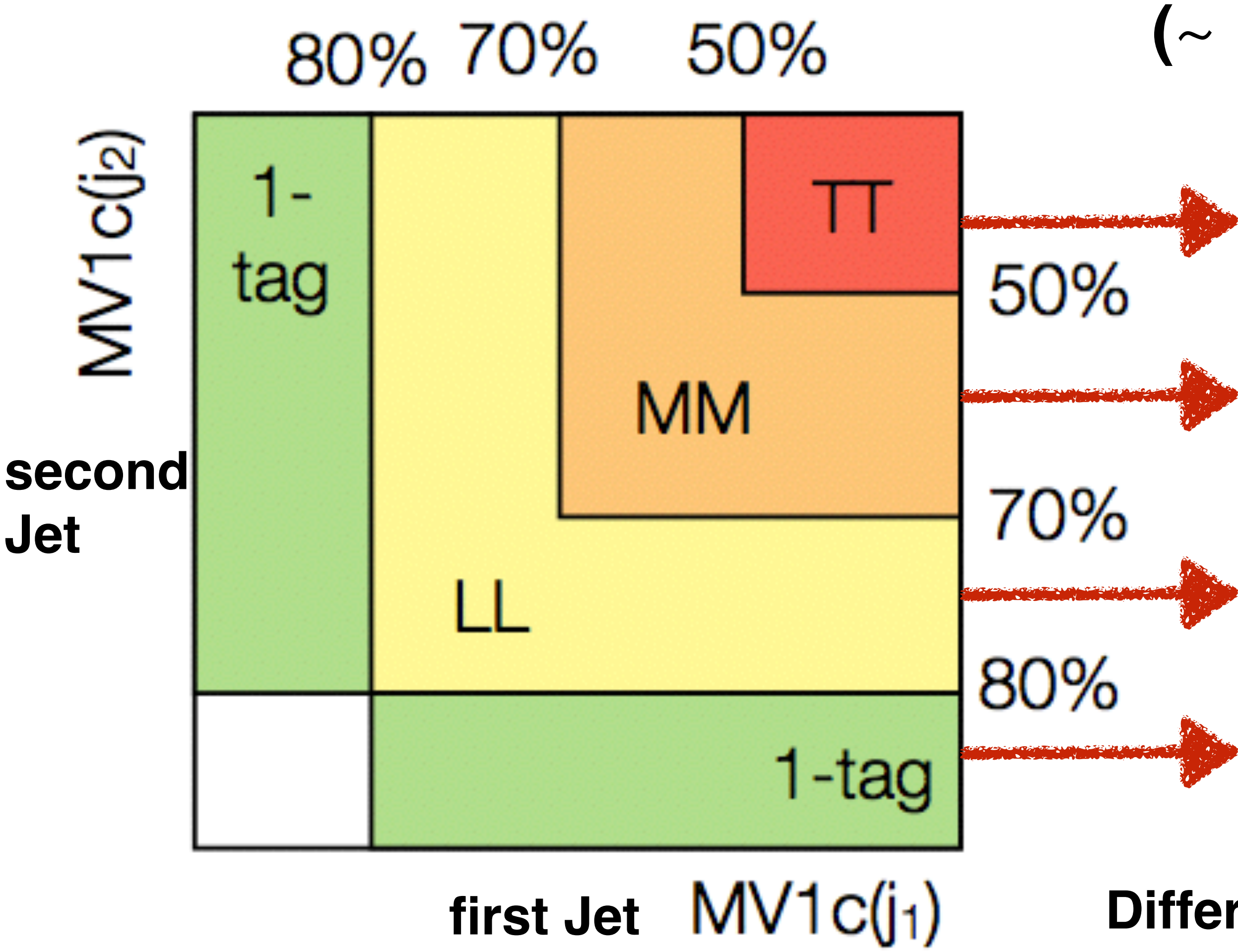
B-tagging: Bottom quark → B-jets



B-tagging = label the jet according to the flavour of the parton originating it
(already covered in previous talk)

Strongly dependent on the b-tagging performances
(we build our Higgs candidate from b-jets!)

MV1c algorithm = output a weight for each jet according to the likelihood of it being a b-jet
(~ MVA-like) [3 working points]



2 "tight" b-tagged jets: 50% efficiency

2 "medium" b-tagged jets: 70% to 50%

2 "loose" b-tagged jets: 80% to 70%

1 "loose" b-tagged jet

Different backgrounds and signal composition in each bin

The Analysis Strategy: probing a huge phase space ...

Event Selection → suppress the backgrounds & slice the phase space

Variable	Multivariate analysis	
	common selection	
p_T^V (GeV)	0-120	> 120
$\Delta R(\text{jet}_1, \text{jet}_2)$	> 0.7 (p_T^V<200 GeV)	
	0 lepton selection	
p_T^{miss} (GeV)	NU	> 30
$\Delta\phi(\boldsymbol{E}_T^{\text{miss}}, \boldsymbol{p}_T^{\text{miss}})$		$< \pi/2$
$\min[\Delta\phi(\boldsymbol{E}_T^{\text{miss}}, \text{jet})]$		> 1.5
$\Delta\phi(\boldsymbol{E}_T^{\text{miss}}, \text{dijet})$		> 2.8
$\sum_{i=1}^{N_{\text{jet}}=2(3)} p_T^{\text{jet}_i}$ (GeV)		> 120 (150)
		–
	1 lepton selection	
m_T^W (GeV)	–	
H_T (GeV)	> 180	–
E_T^{miss} (GeV)	–	> 20
	2 lepton selection	
$m_{\ell\ell}$ (GeV)	71-121	
E_T^{miss} (GeV)	–	

Common selection (0,1,2 lepton channel)

pTV slicing (2 pTV regions)
jet separation for non-boosted events

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Common selection (0,1,2 lepton channel):

pTV slicing (2 pTV regions)

jet separation reduces V+jets background

0 Lepton (Z → neutrinos) selection:

large missing transverse energy (> 100 GeV)

angular cuts to suppress multijet background (e.g. neutrino system back-to back wrt di-jet system)

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1 Lepton (W → lepton+neutrino) selection:

HT cut to suppress multi jet background (sum of the transverse energy of all the objects)

note: only muon channel used for pTV < 120 GeV (electron channel dominated by MJ background)

The Analysis Strategy: probing a huge phase space ...

Event Selection → suppress the backgrounds & slice the phase space

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jet separation reduces V+jets background

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angular cuts to suppress multijet background (e.g. neutrino system back-to back wrt di-jet system)

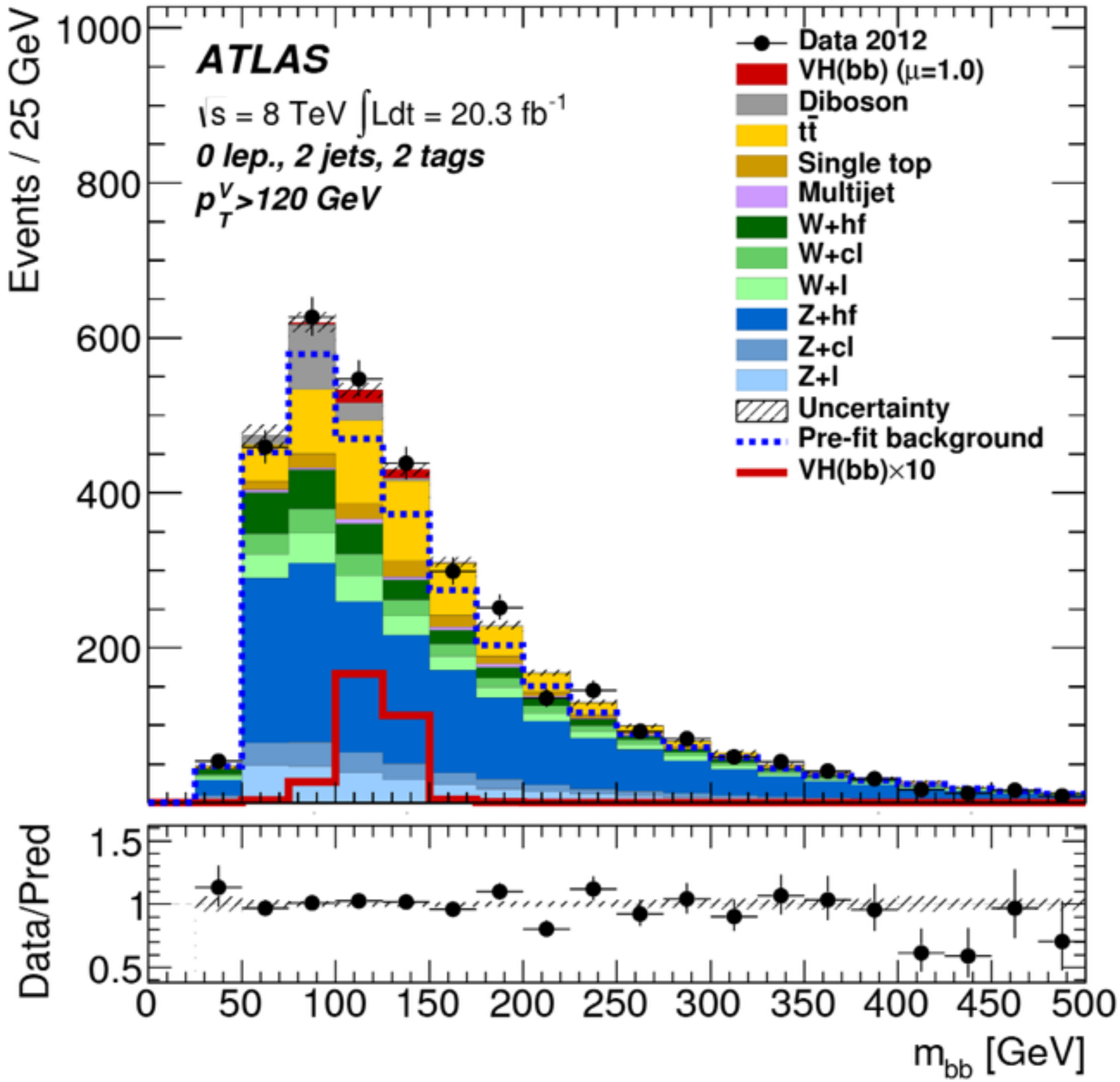
1 Lepton (W → lepton+neutrino) selection:

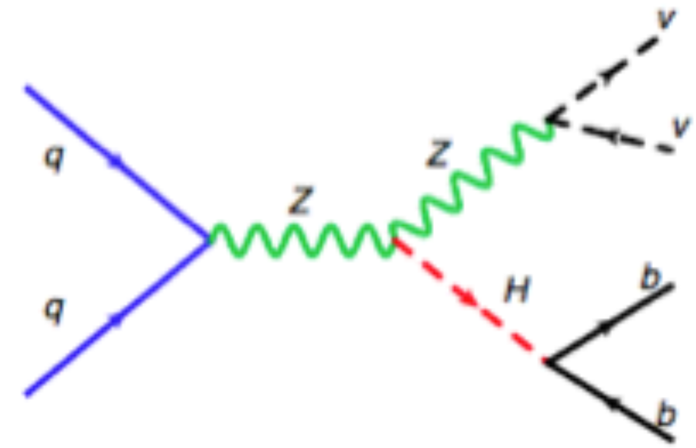
HT cut to suppress multi jet background (sum of the transverse energy of all the objects)

2 Lepton (Z → lepton+lepton) selection:

di-lepton invariant mass selects the Z peak

(tiny) signal vs (very large) backgrounds: 0 Leptons





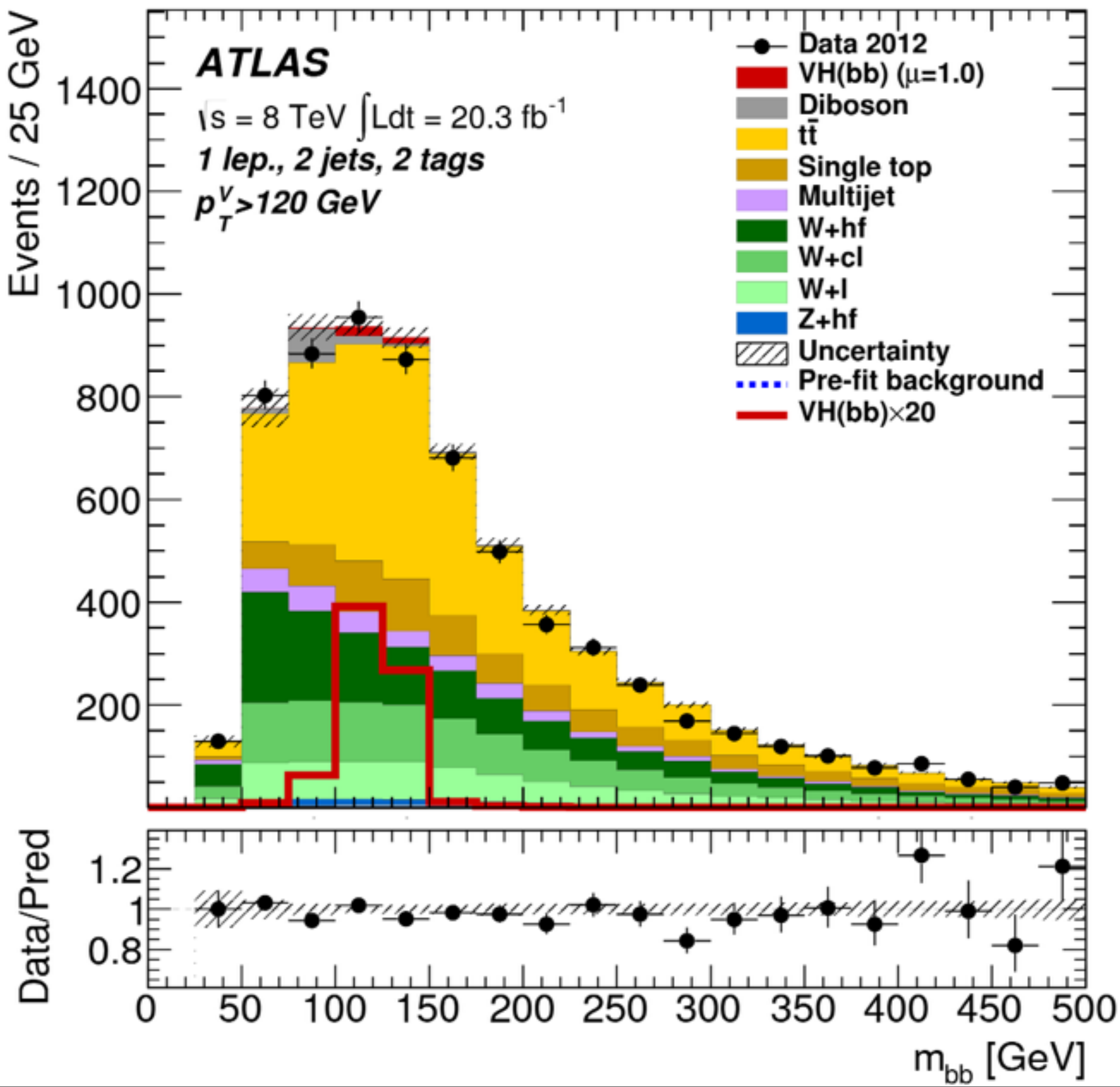
Background Composition:

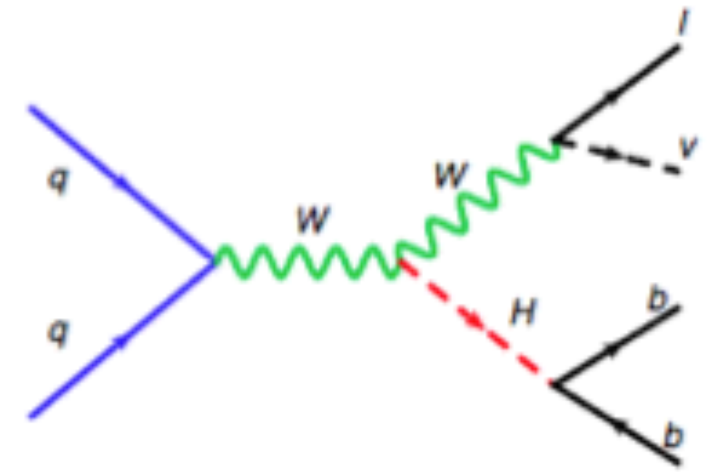
- dominated by **Z(→νν) + heavy flavor**
- relevant contribution from ttbar, W+heavy flavor, diboson

Features:

- **diboson** invariant mass peak ~ very close to signal
- very small multijet contribution

(tiny) signal vs (very large) backgrounds: 1 Lepton





Background Composition:

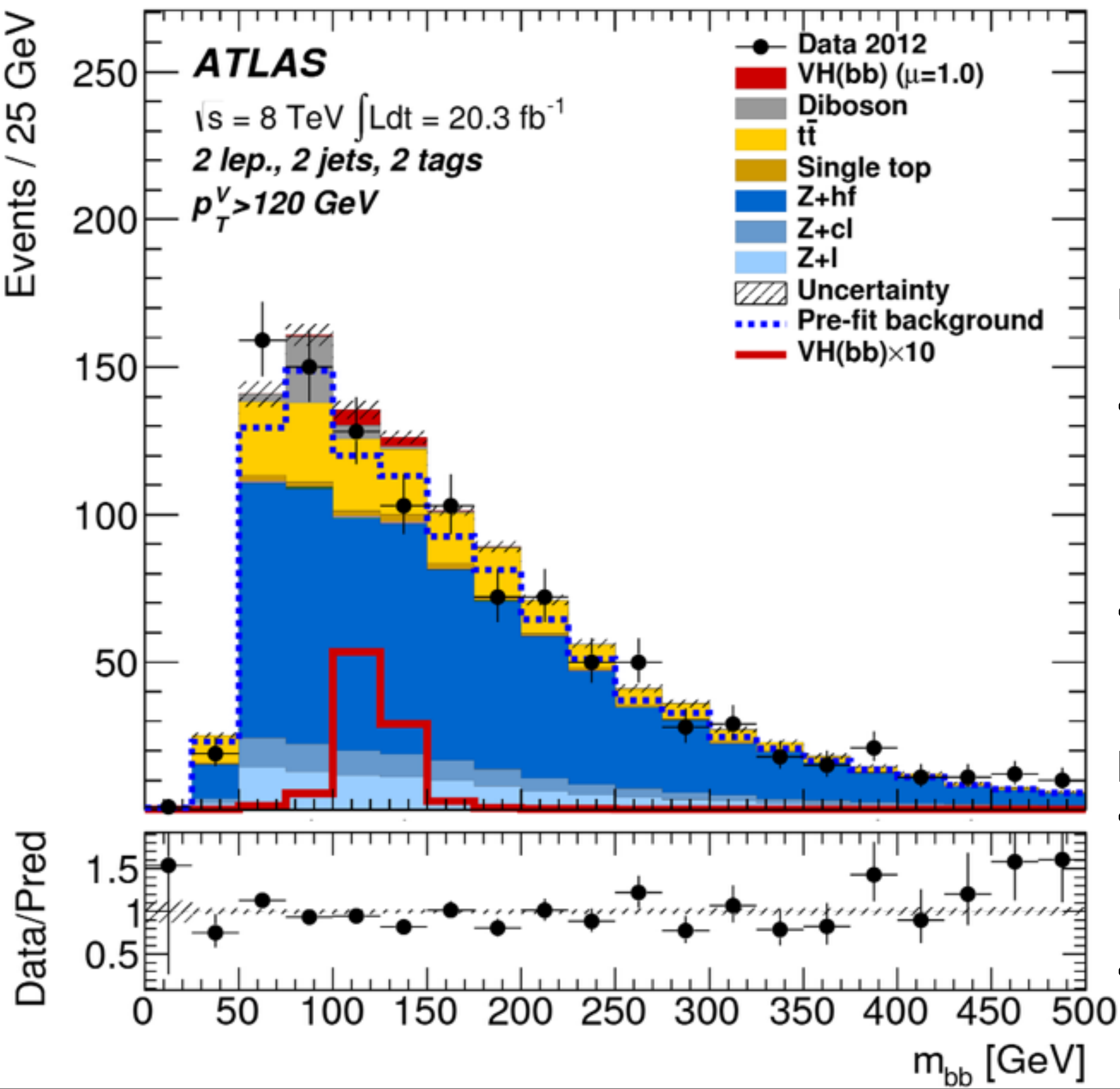
- dominated by
  ttbar
  W(→lν) + heavy flavor

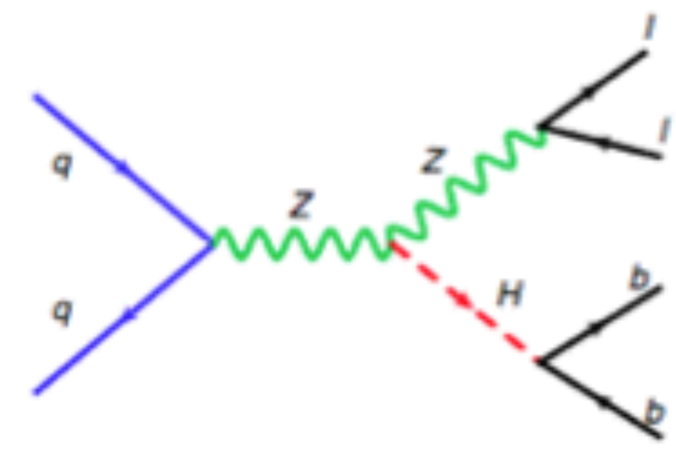
- relevant contribution from
  single top
  multijet

Features:

- **diboson** invariant mass peak ~ very close to signal
- non negligible **multijet** contribution (very painful in this channel !)

(tiny) signal vs (very large) backgrounds: 2 Lepton





Background Composition:

- dominated by
  ttbar
  Z(→ll) + heavy flavor

- relevant contribution from diboson

Features:

- **diboson** invariant mass peak ~ very close to signal

- very small multijet contribution

MVA Analysis: Boosted Decision Trees

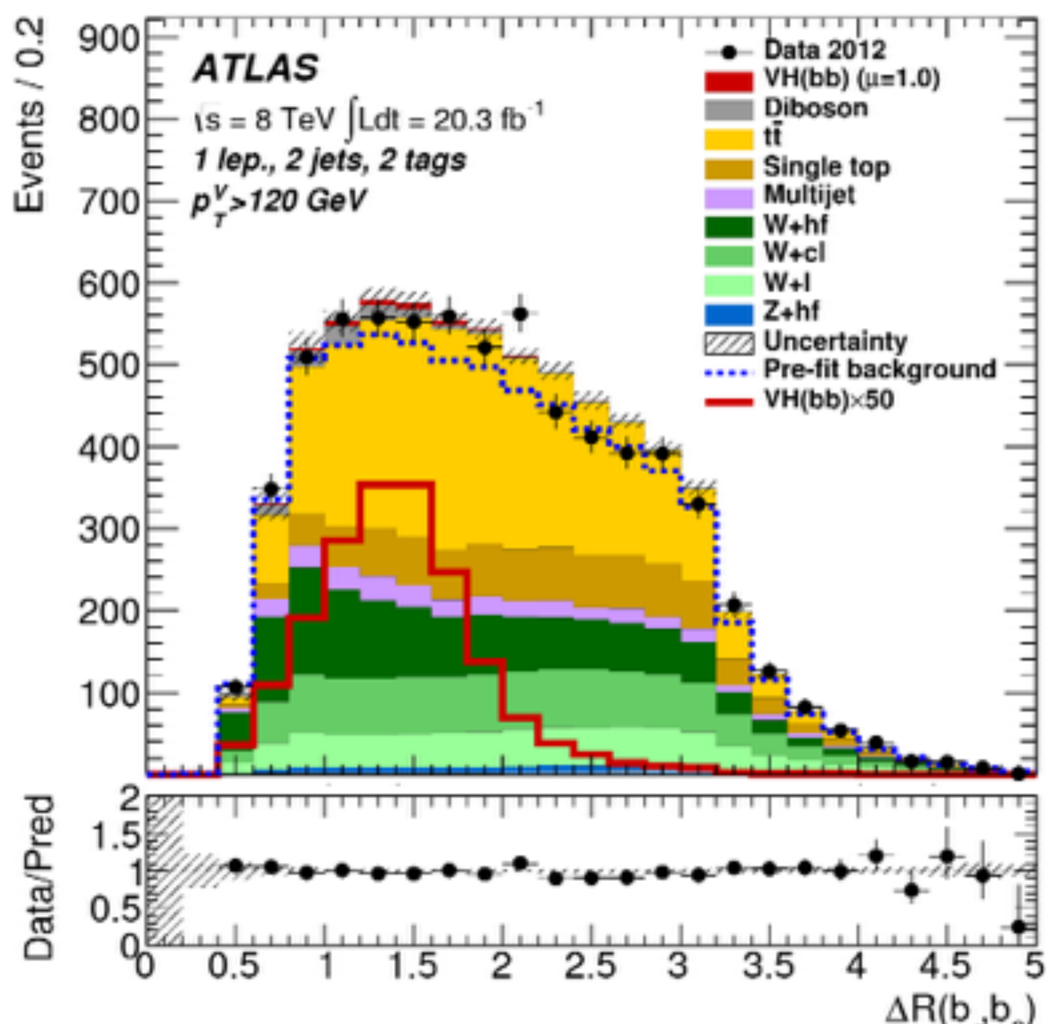
BDT training variables (exploit discriminating power coming from signal topologies)

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}	×	×	×

As coherent as possible across lepton channels and high/low pTV regions

MVA training

- starting from a minimal set of variables (mbb, dR(b,b))
- keep the set with the better discriminating power
- check the modelling / correlations of all the variables (data/MC)



MVA Analysis: Boosted Decision Trees

BDT training variables (exploit discriminating power coming from signal topologies)

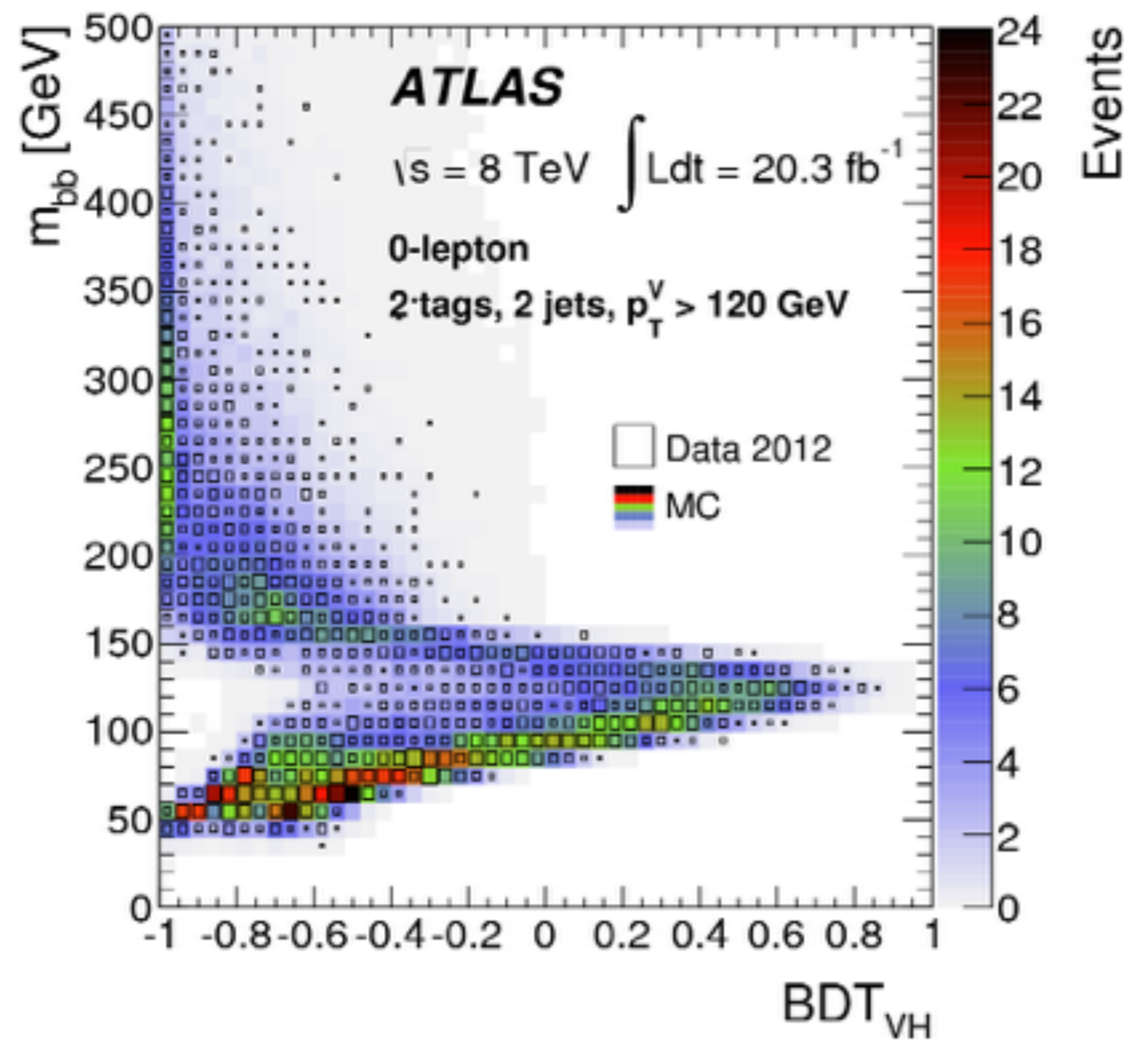
Variable	0-Lepton	1-Lepton	2-Lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\|\Delta\eta(b_1, b_2)\|$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\|\Delta\eta(V, bb)\|$			×
H_T	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$MV1c(b_1)$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

We do **not cut** on the BDT output, but instead we **FIT** the score distribution

Profile Likelihood Fit

MVA training

- starting from a minimal set of variables (mbb, dR(b,b))
- keep the set with the better discriminating power
- check the modelling / correlations of all the variables (data/MC)



Extracting the Signal: Profile Likelihood Fit

$$L(\mu,\boldsymbol{\theta}) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k} .$$

Poisson distribution for **n_j** number of measured events

Signal prediction scaled by **μ** **signal strength**

Background prediction

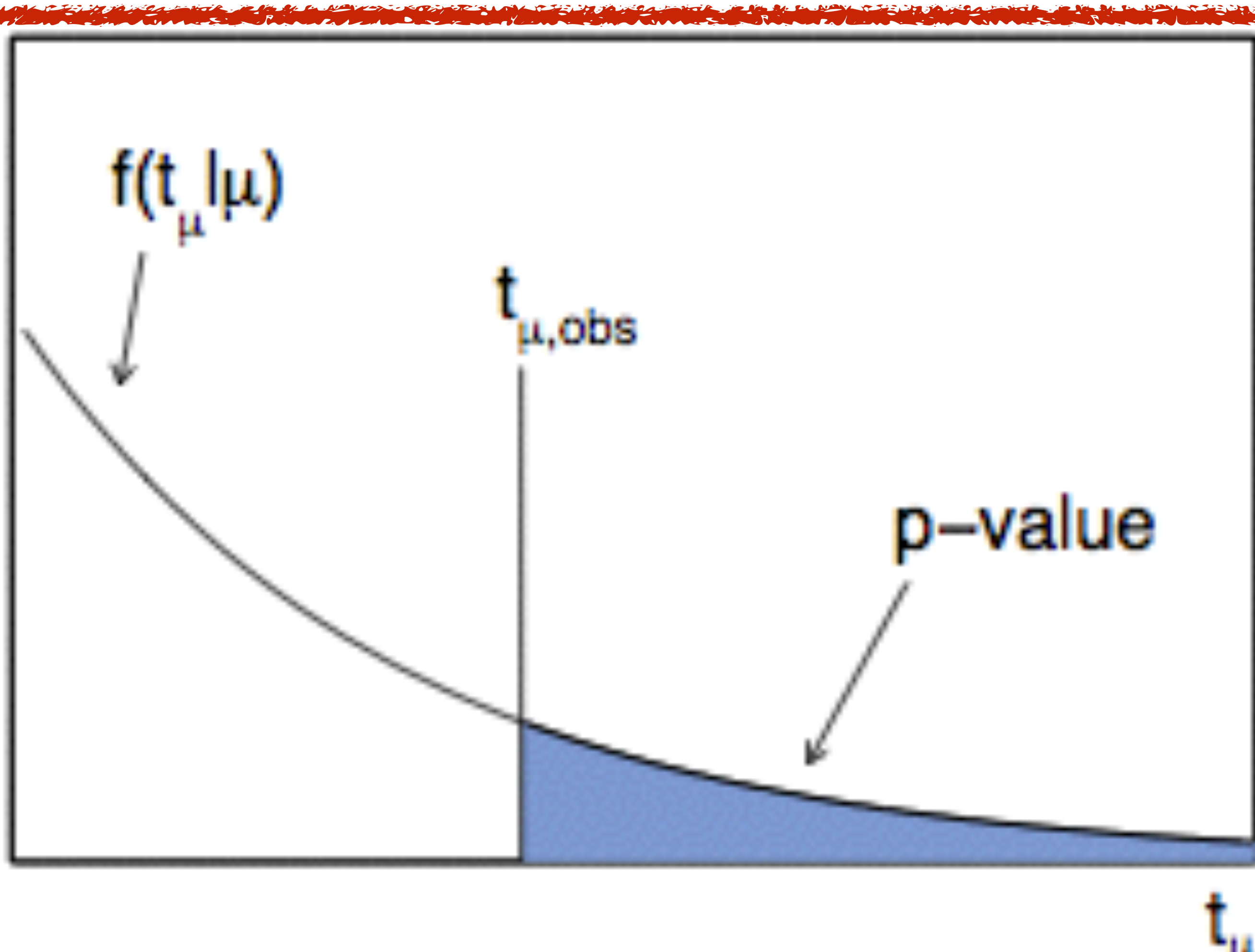
Constraint measurements (Control Regions)

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

Profile Likelihood Ratio PLR

$$t_\mu = -2 \ln \lambda(\mu)$$

test statistic



$$p_\mu = \int_{t_{\mu,\mathrm{obs}}}^{\infty} f(t_\mu|\mu)\, dt_\mu$$

The (in)famous p-value

p=2.87 x 10-7

Z(significance) = 5σ (discovery!)

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$$L(\mu,\boldsymbol{\theta}) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k} .$$

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Profile Likelihood Ratio **PLR**

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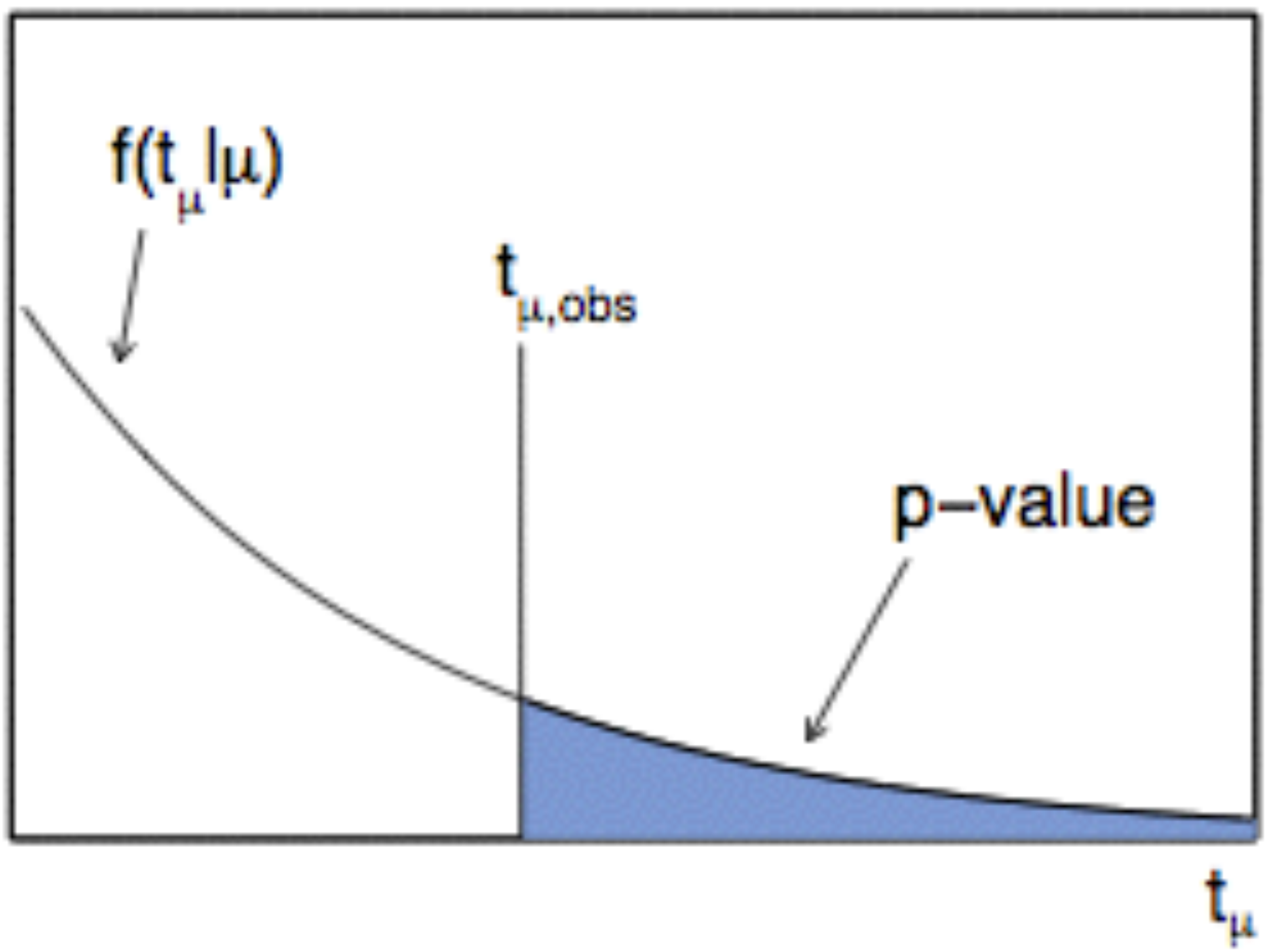

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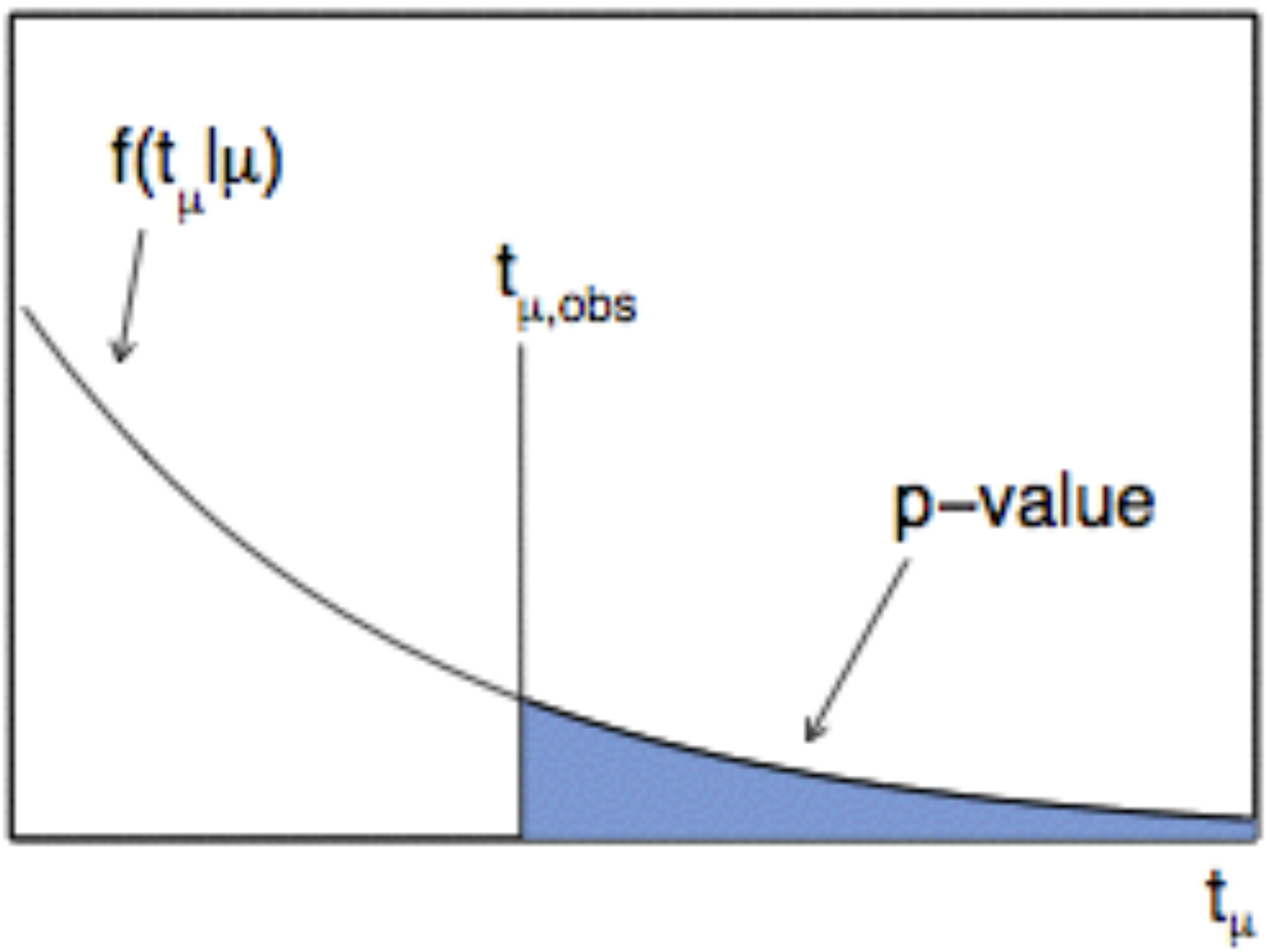
Profile Likelihood Ratio PLR

$$\boxed{t_\mu = -2\ln\lambda(\mu)}$$

test statistic



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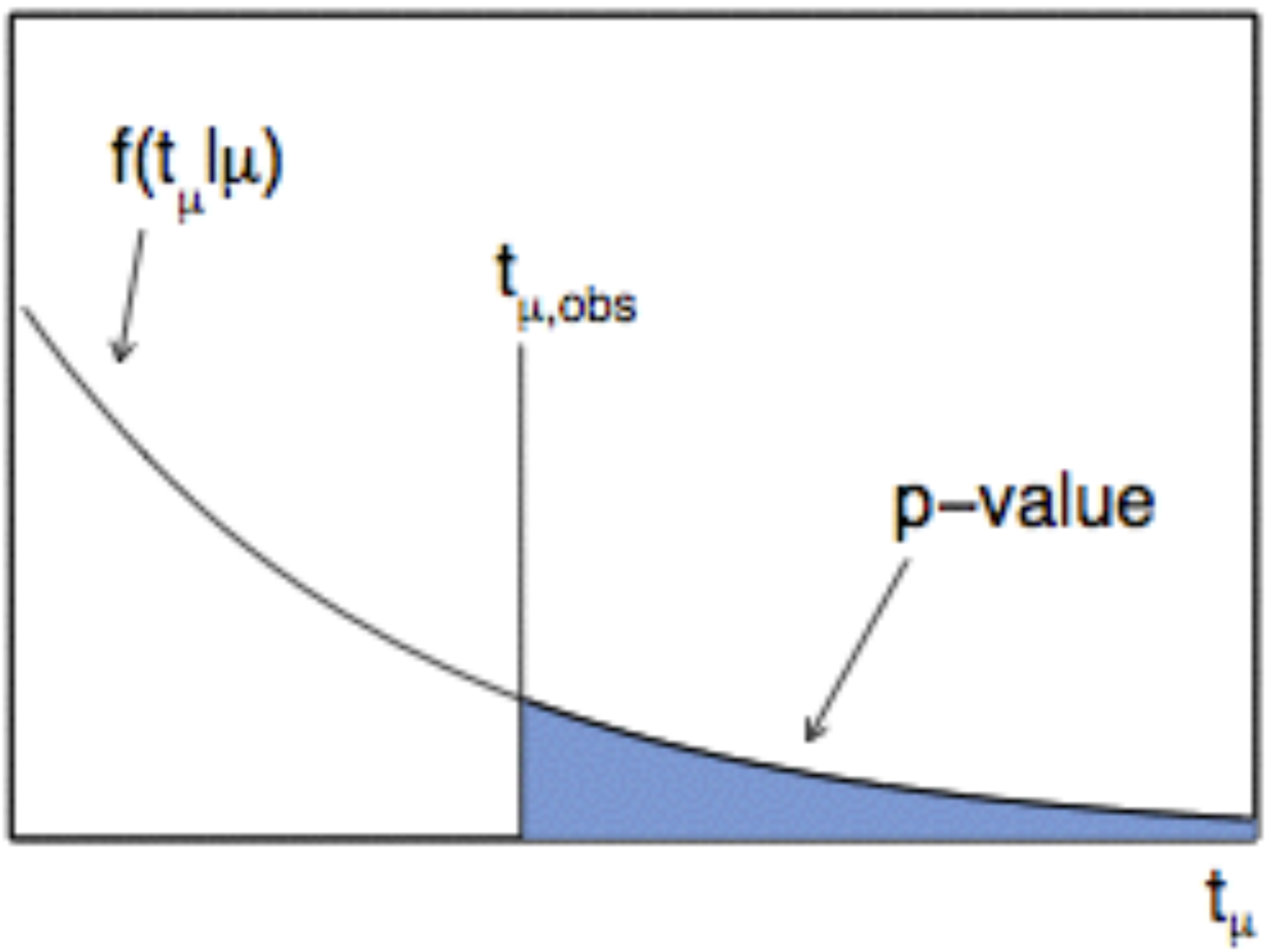

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The (in)famous p-value

p=2.87 x 10-7

Z(significance) = 5σ (discovery!)

Extracting the Signal: Our Fit Model

$$L(\mu,\boldsymbol{\theta}) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \quad \prod_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k} \, .$$

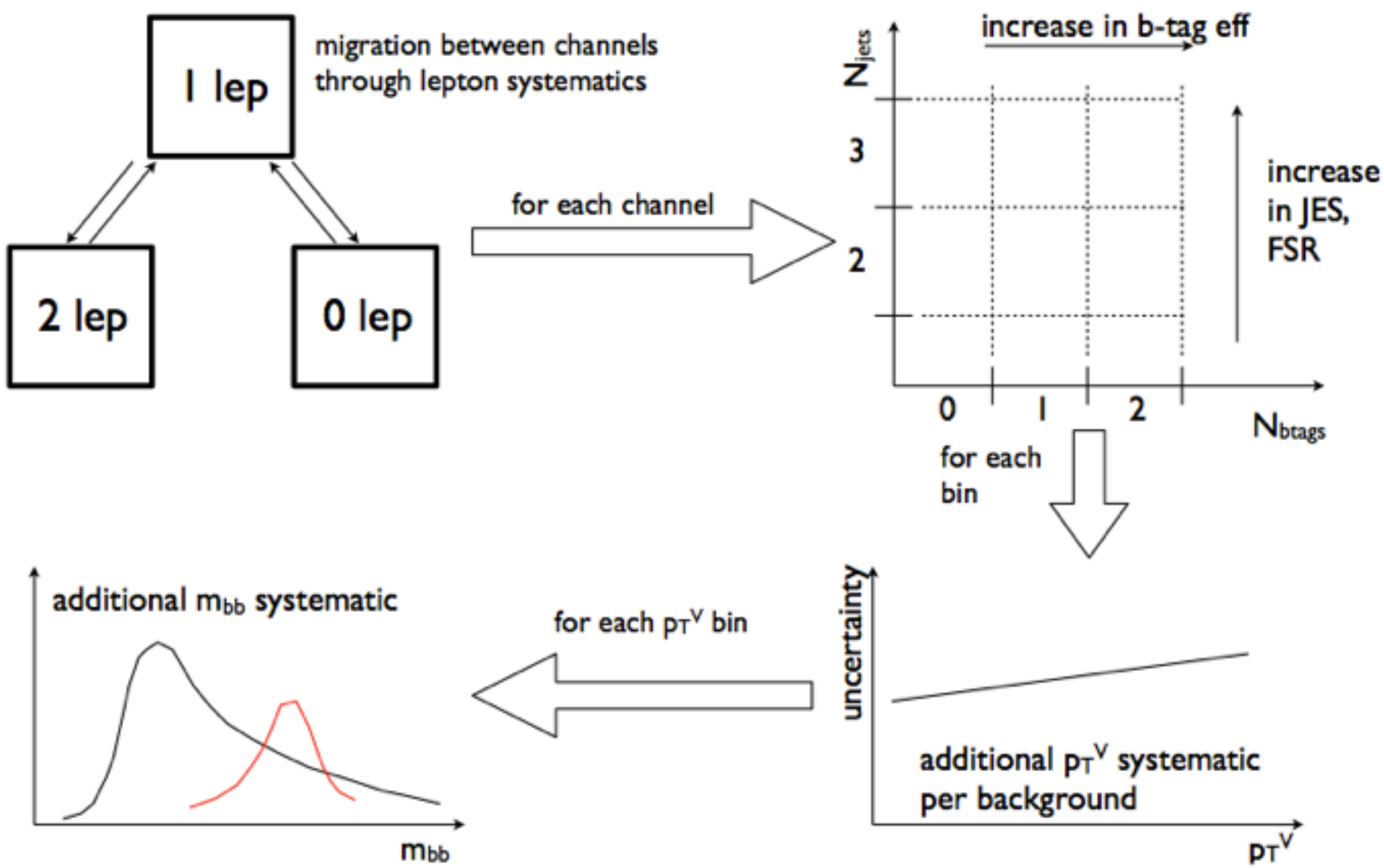
Very large and complex phase space, with several background contributions:

extremely complex fit model

- systematic uncertainties

    1. leptons
    2. jets
    3. b-tagging
    4. pTV-dependent

  can cause migration across different regions

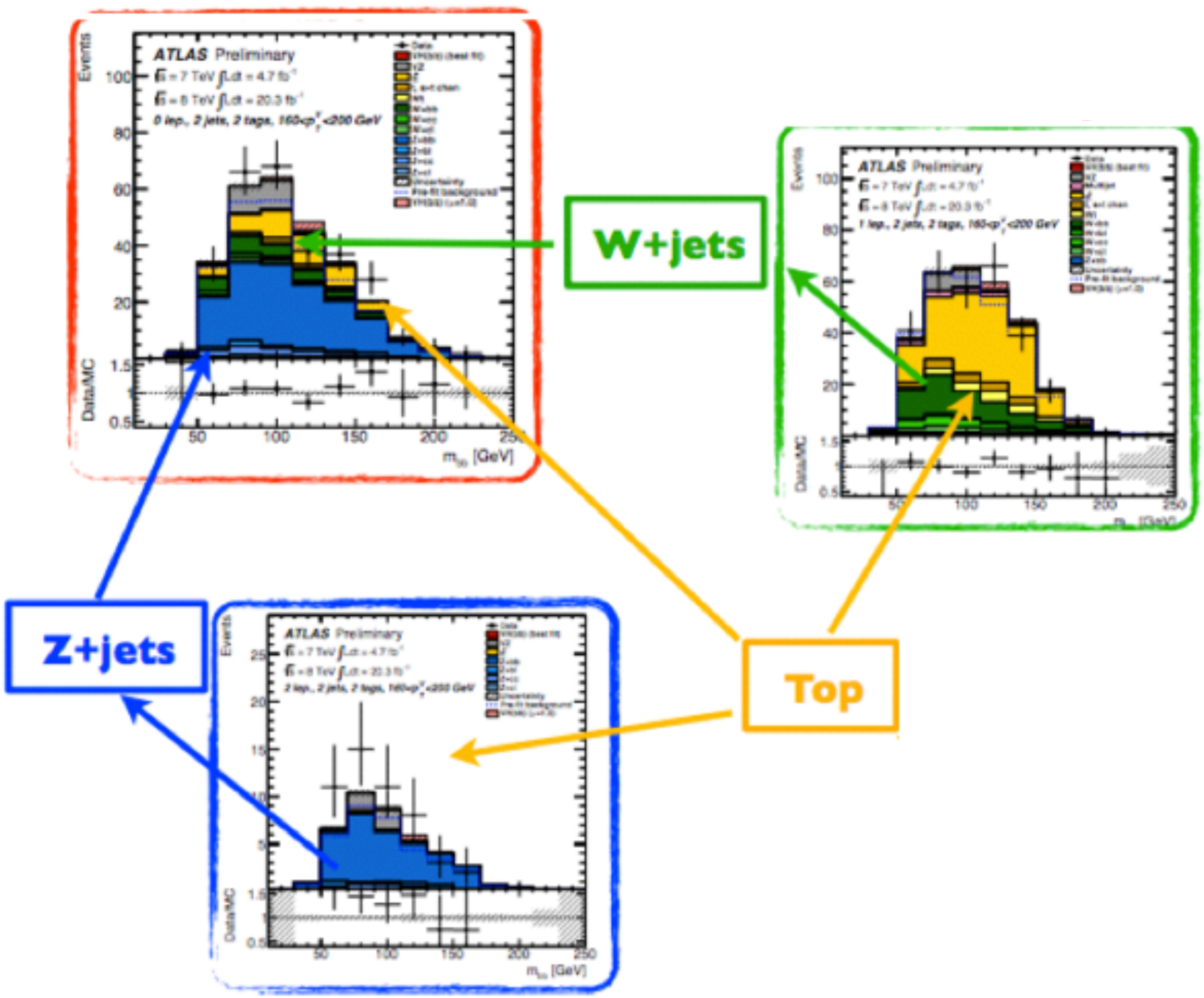


Extracting the Signal: Our Fit Model

$$L(\mu,\boldsymbol{\theta}) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k} \,.$$

It allows us to:

- "learn" the background modelling from on region, and "export" it to an other
- combine the discriminating power of several signal regions

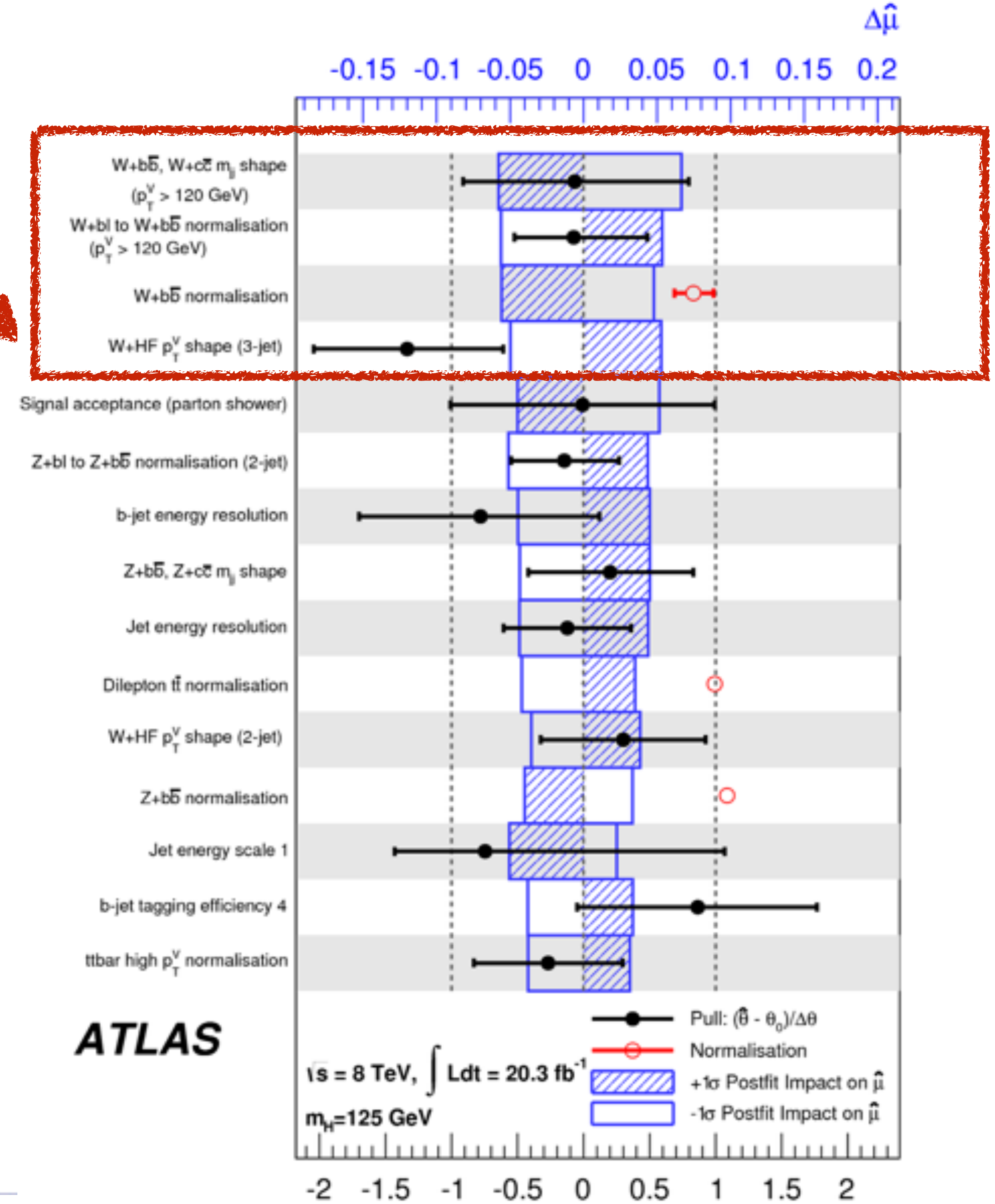


Process	Scale factor
$t\bar{t}$ 0-lepton	1.36 ± 0.14
$t\bar{t}$ 1-lepton	1.12 ± 0.09
$t\bar{t}$ 2-lepton	0.99 ± 0.04
Wbb	0.83 ± 0.15
Wcl	1.13 ± 0.10
Zbb	1.09 ± 0.05
Zcl	0.88 ± 0.12

Fit Model: Systematic Uncertainties (just a hint)

Signal	
Cross section (scale)	1% (qq), 50% (gg)
Cross section (PDF)	2.4% (qq), 17% (gg)
Branching Ratio	3.3 %
Acceptance (scale)	1.5–3.3%
3-jet acceptance (scale)	3.3–4.2%
p_T^V shape (scale)	S
Acceptance (PDF)	2–5%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)	8–13%
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
$t\bar{t}$	
3/2-jet ratio	20%
high/low-p_T^V ratio	7.5%
top p_T, m_{bb}, E_T^{miss}	S
Single top	
Cross section	4% (s-,t-channel), 7% (Wt)
Generator	3–52%
m_{bb}, $p_T^{b_2}$	S
Diboson	
Cross section and acceptance (scale)	3–29%
Cross section and acceptance (PDF)	2–4%
m_{bb}	S
Multijet	
0-, 2-lepton channels normalisation	100%
1-lepton channel normalisation	2–60%
Template variations, reweighting	S

Systematic ranking from the 8TeV MVA profile likelihood fit
on the full channel combination (0+1+2 leptons):



SM Candel Process: Diboson VZ→bb

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

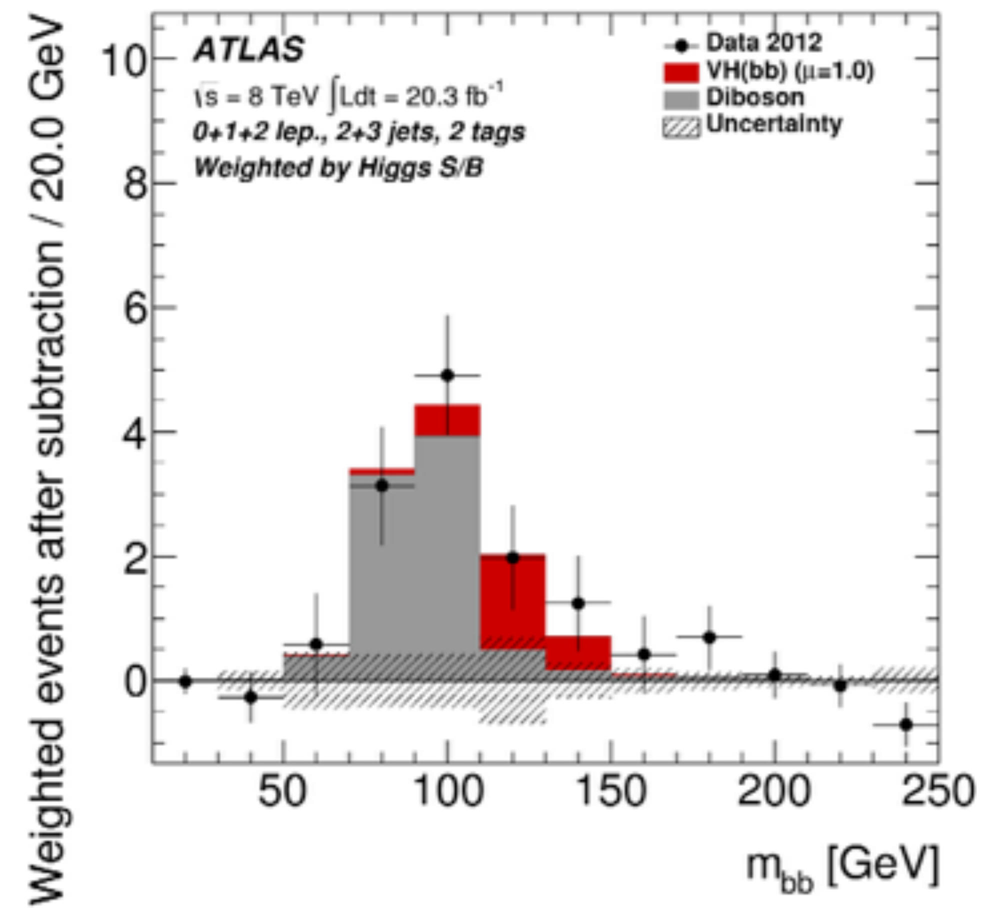
→ cross section ~ 5 times larger than VH

→ almost identical final state

⊗ **Expected Significance → 6.3**

⊗ **Observed Significance → 4.9**

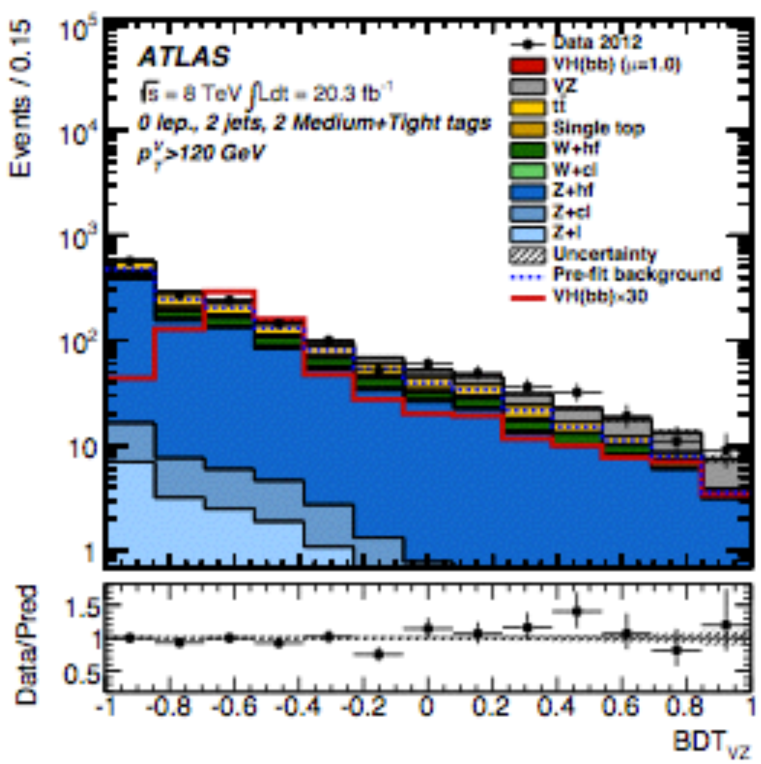
VH($b\bar{b}$) $\hat{\mu} = 0.74 \pm 0.09(stat.) \pm 0.14(syst.)$

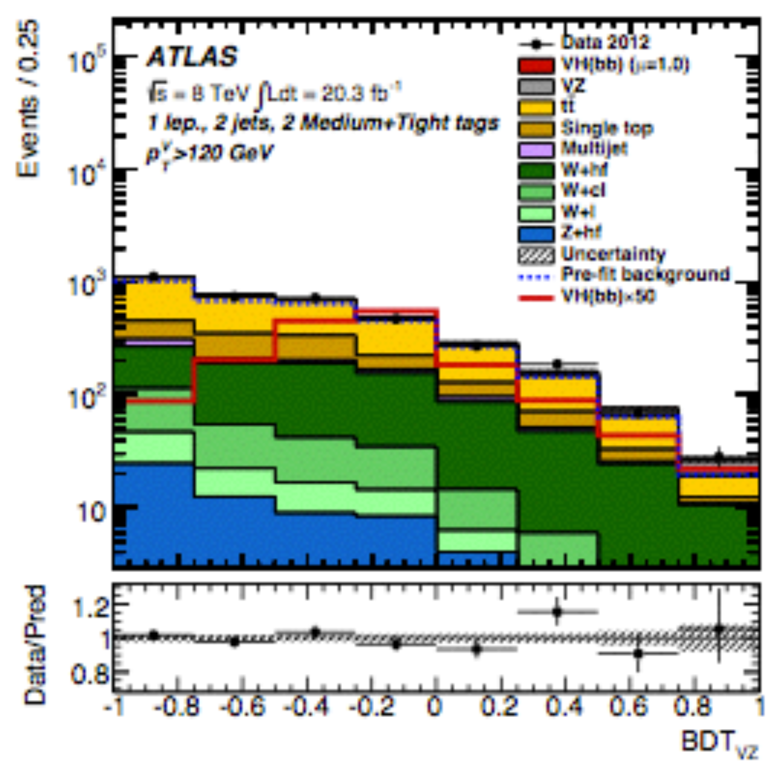


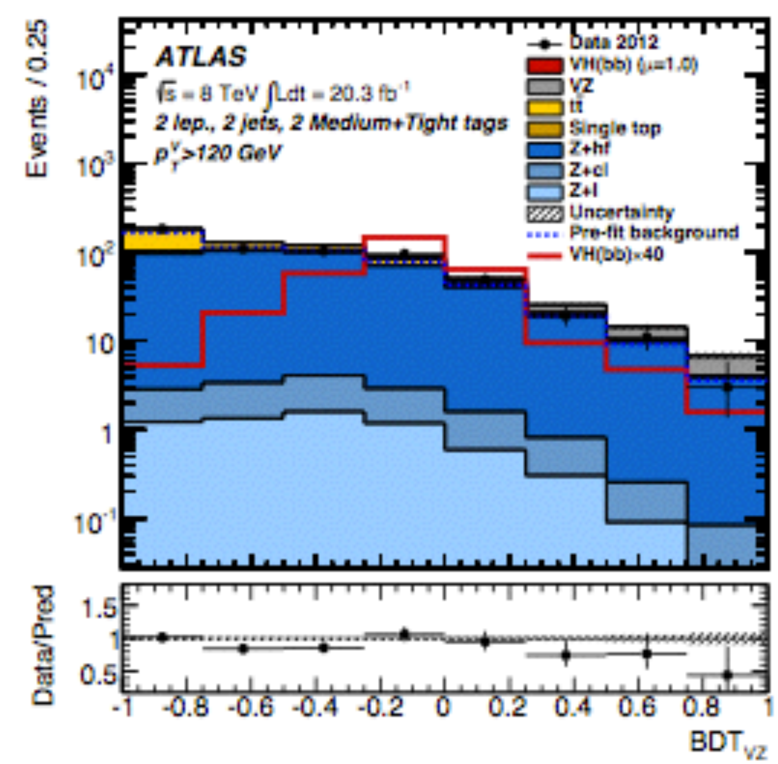
MVA analysis re-trained to select VZ processes

0lepton

1lepton







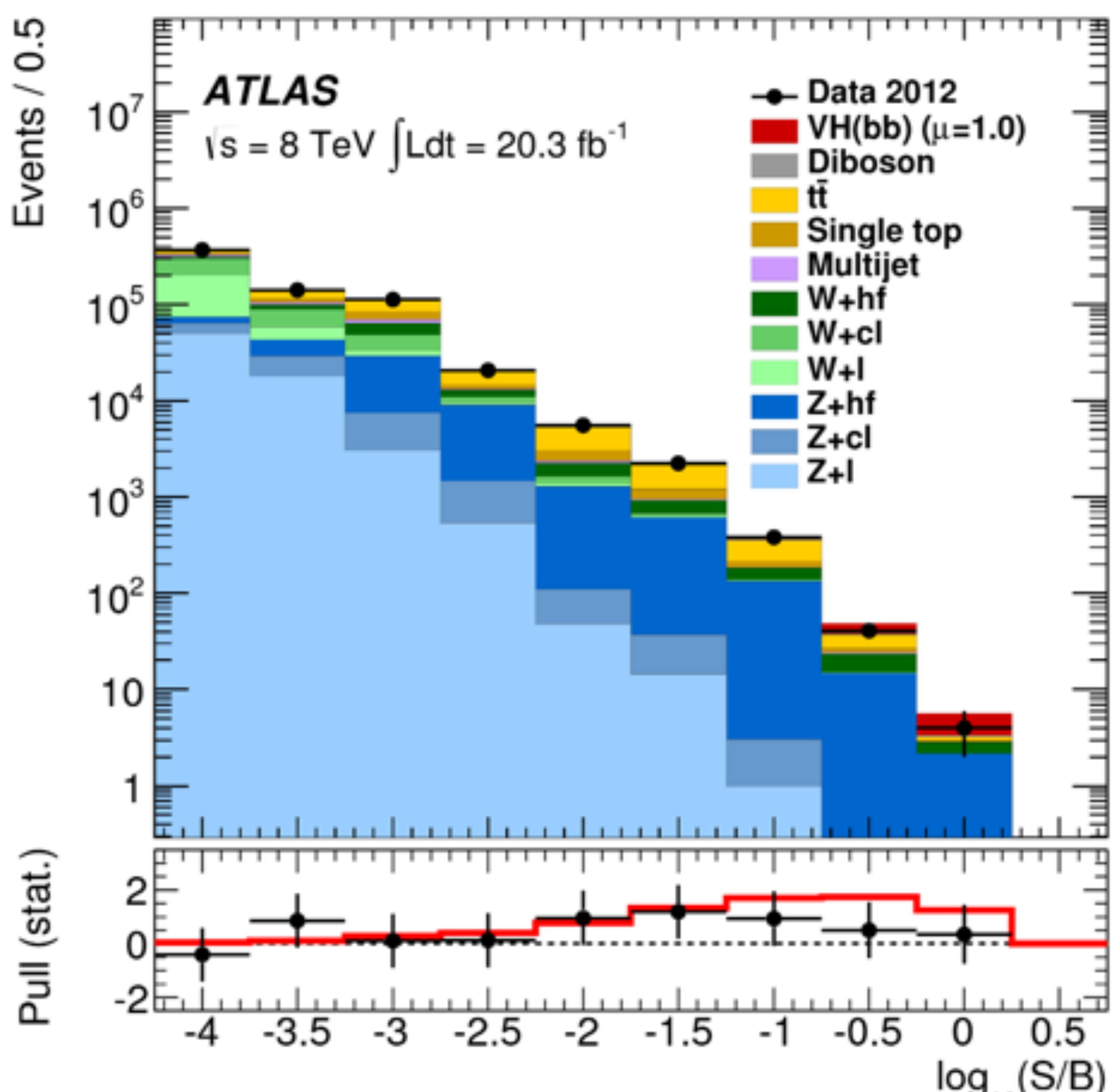
VH→bb Results from the LHC Run1 dataset

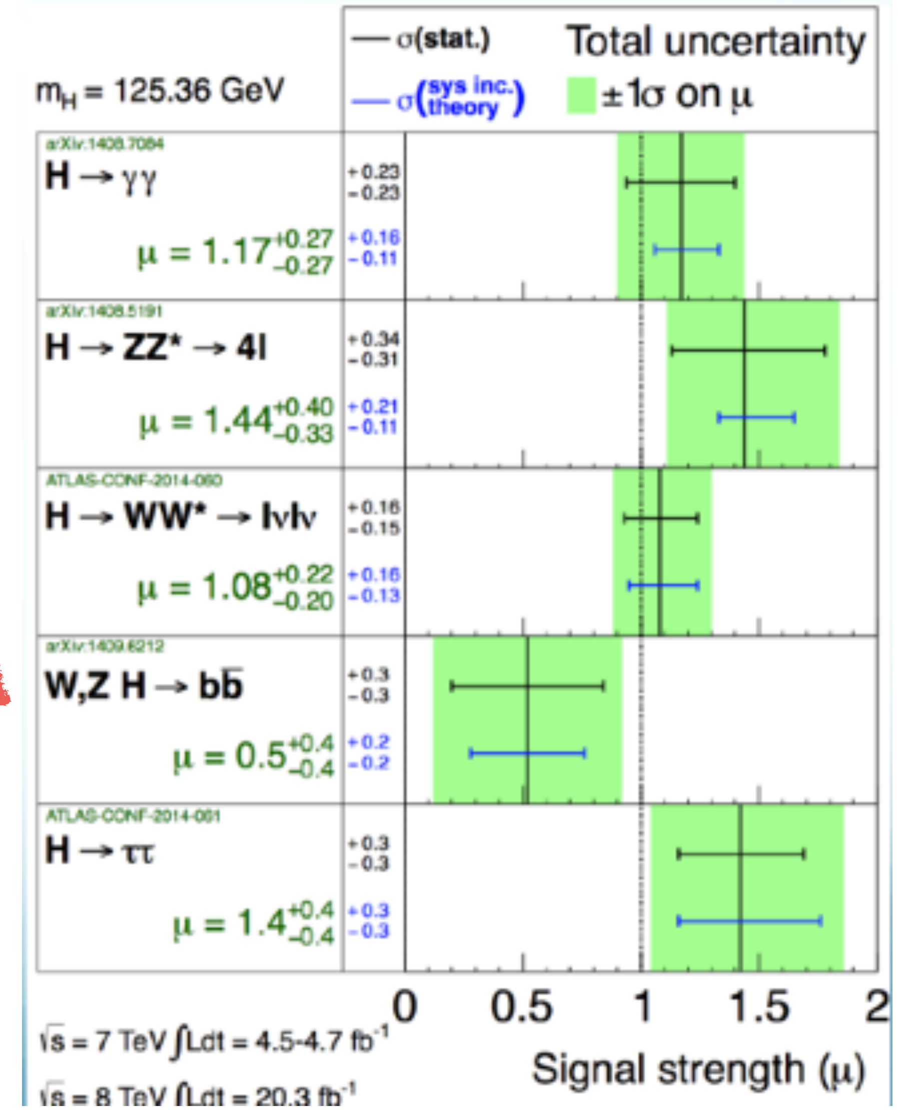
VH→ $b\bar{b}$ ATLAS-HIGG-2013-23

⊗ **Expected Significance** → **2.6**

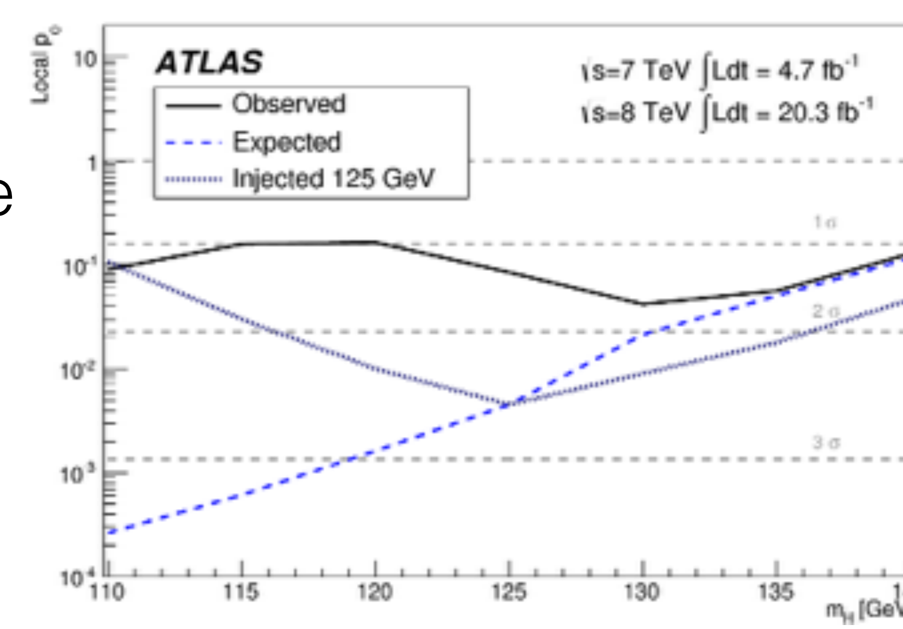
⊗ **Observed Significance** → **1.4**

VH($b\bar{b}$) $\hat{\mu} = 0.51 \pm 0.31(stat.) \pm 0.24(syst.)$

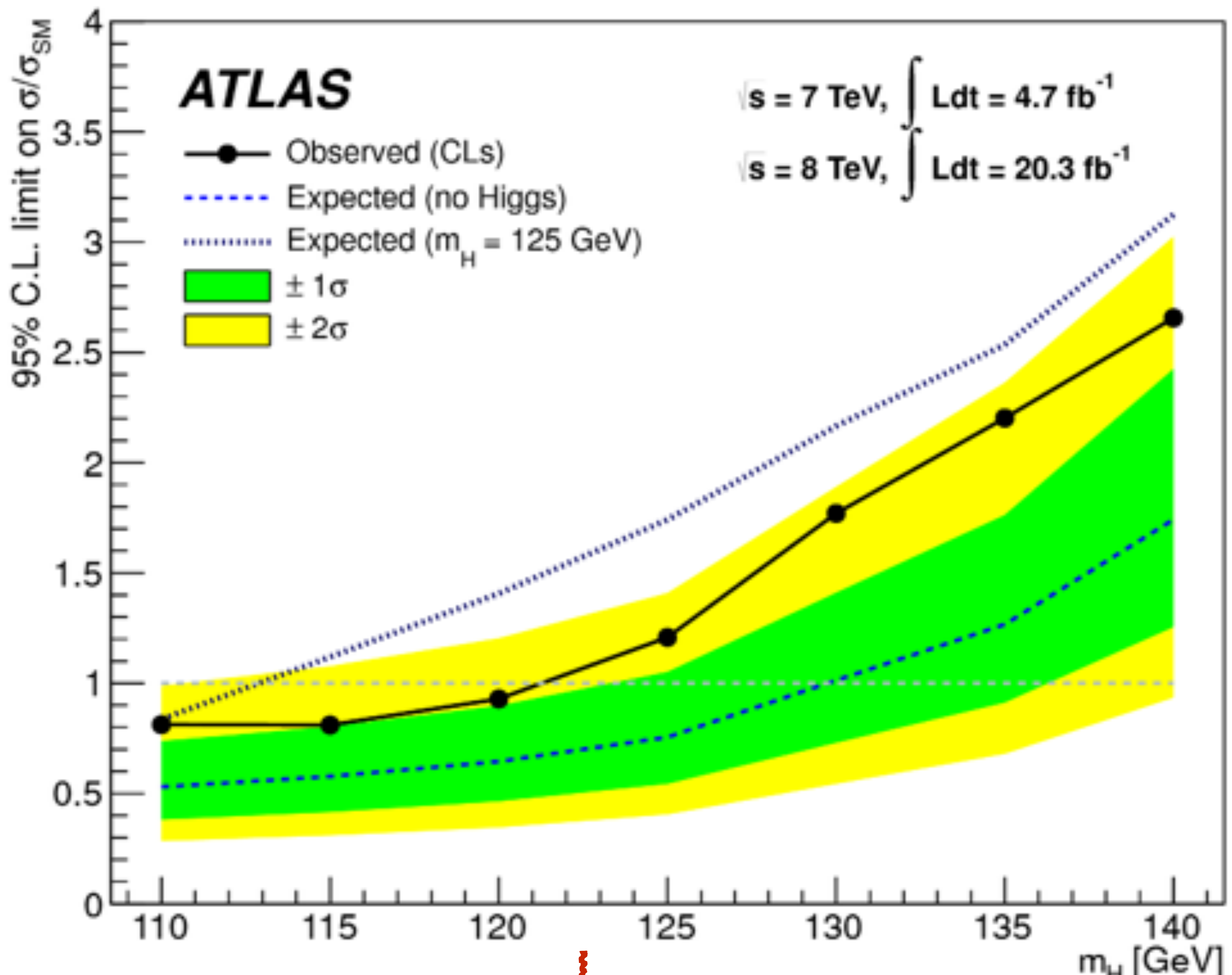


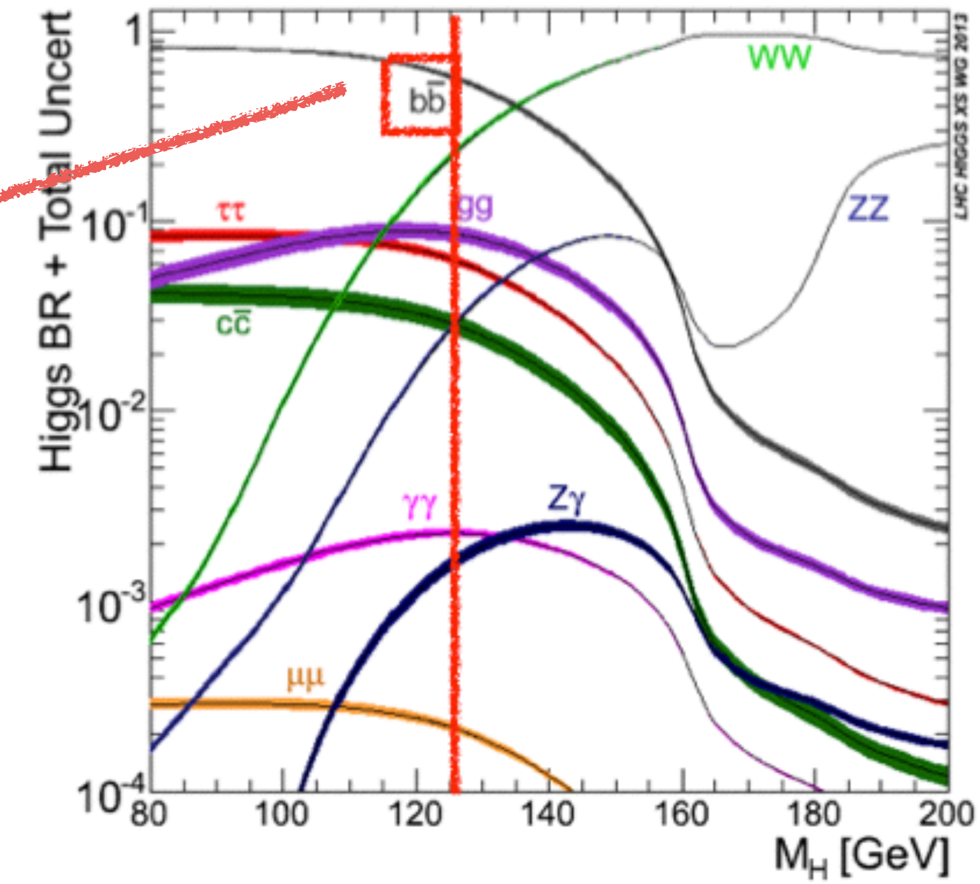


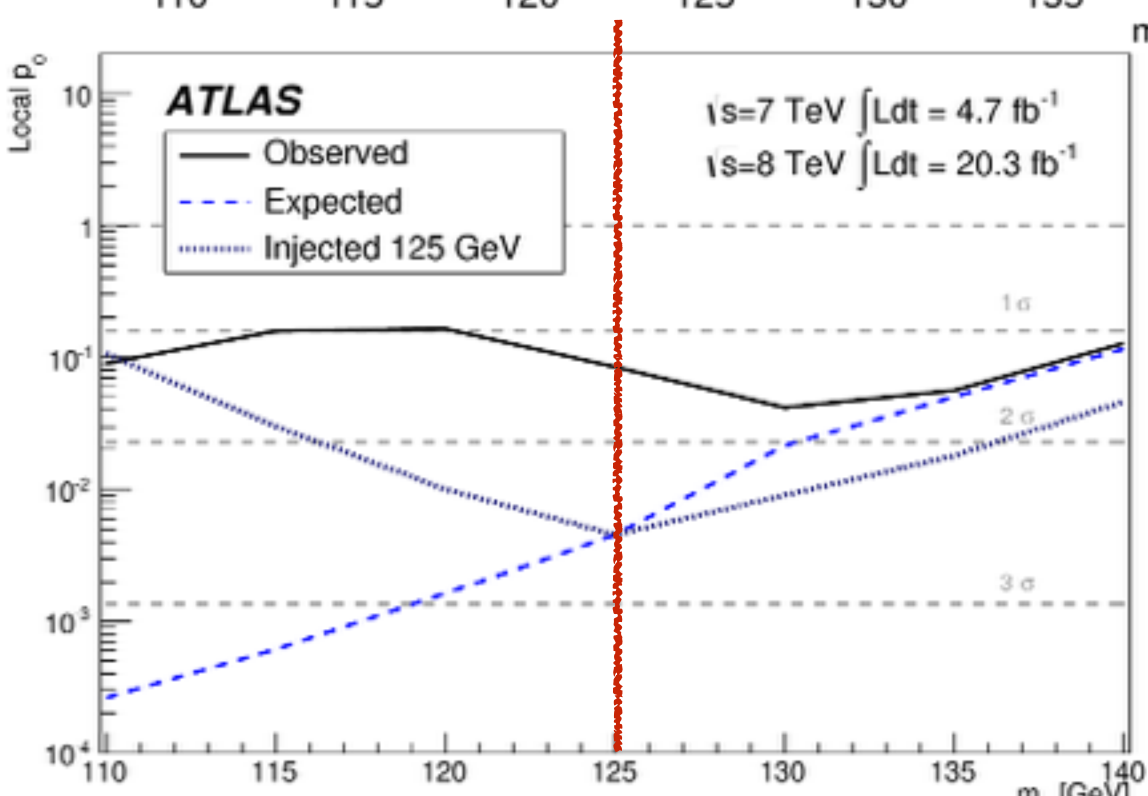
p-value across the mH range



VH→bb Results from the LHC Run1 dataset







Falling BR results in the shape of the expected limit / p-value (dotted blue lines)

Main changes wrt 2013 analysis:

- MVA analysis (BDT)
- MV1c b-tagging
- (same dataset analysed)

> 50% improvement

Significance = 1.4 (2.6) obs.(exp.)

highest expected significance for H→bb searches

Conclusions

VH→bb : promising but very complex analysis

- **Run1: no evidence, but good confidence with the analysis model and the background modelling (**crucial for this search**)**
- **Starting to work towards Run2: (**approximately**) expect to reach ~Run1 sensitivity after first 10 inverse femtobarn (~~~)**

pb	8 TeV	13 TeV	ratio
ggF	19	44	2.3
VBF	1.6	3.7	2.3
VH	1.1	2.2	2
ttH	0.13	0.5	3.8

note: background processes are increasing too (ttbar ~x4)

- **will benefit from the detector upgrade (IBL) and the increase center of mass energy**
- **very interesting to combine Run1+Run2 results (~) early**
- **will pursue also other production modes (VBF, VBF+gamma)**
- **start to test BSM physics ? (EFT models parameters can be constrained by VH)**

Thank you !