



# Importance of the electron calibration in ATLAS and a case of study: the $VH$ , $H \rightarrow b\bar{b}$ analysis

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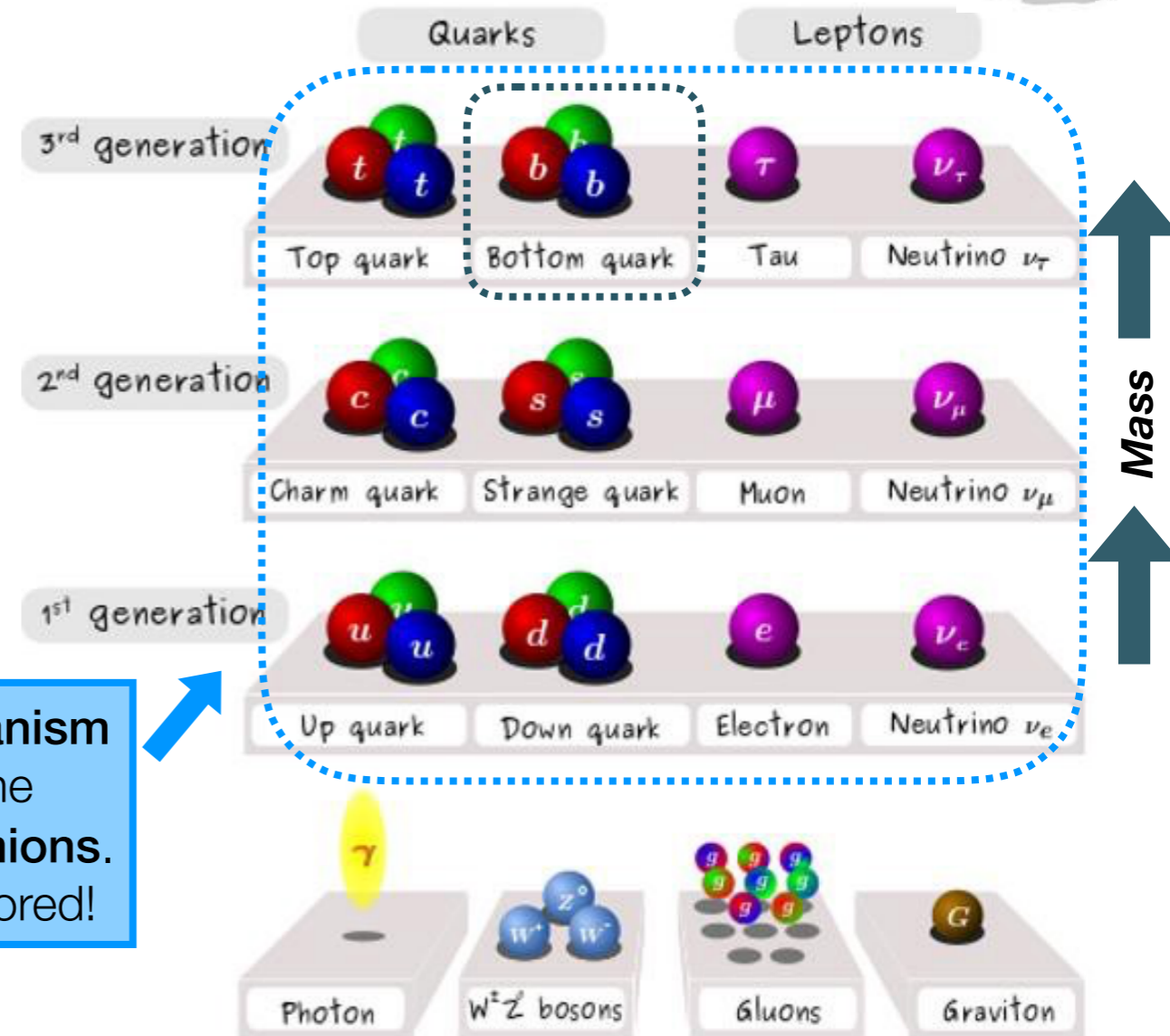
# The Higgs boson in the Standard Model

- In the Standard Model, the Higgs mechanism provides masses to bosons and fermions
- The Higgs boson discovery in 2012 opened the way to the study of new sectors of the SM Lagrangian

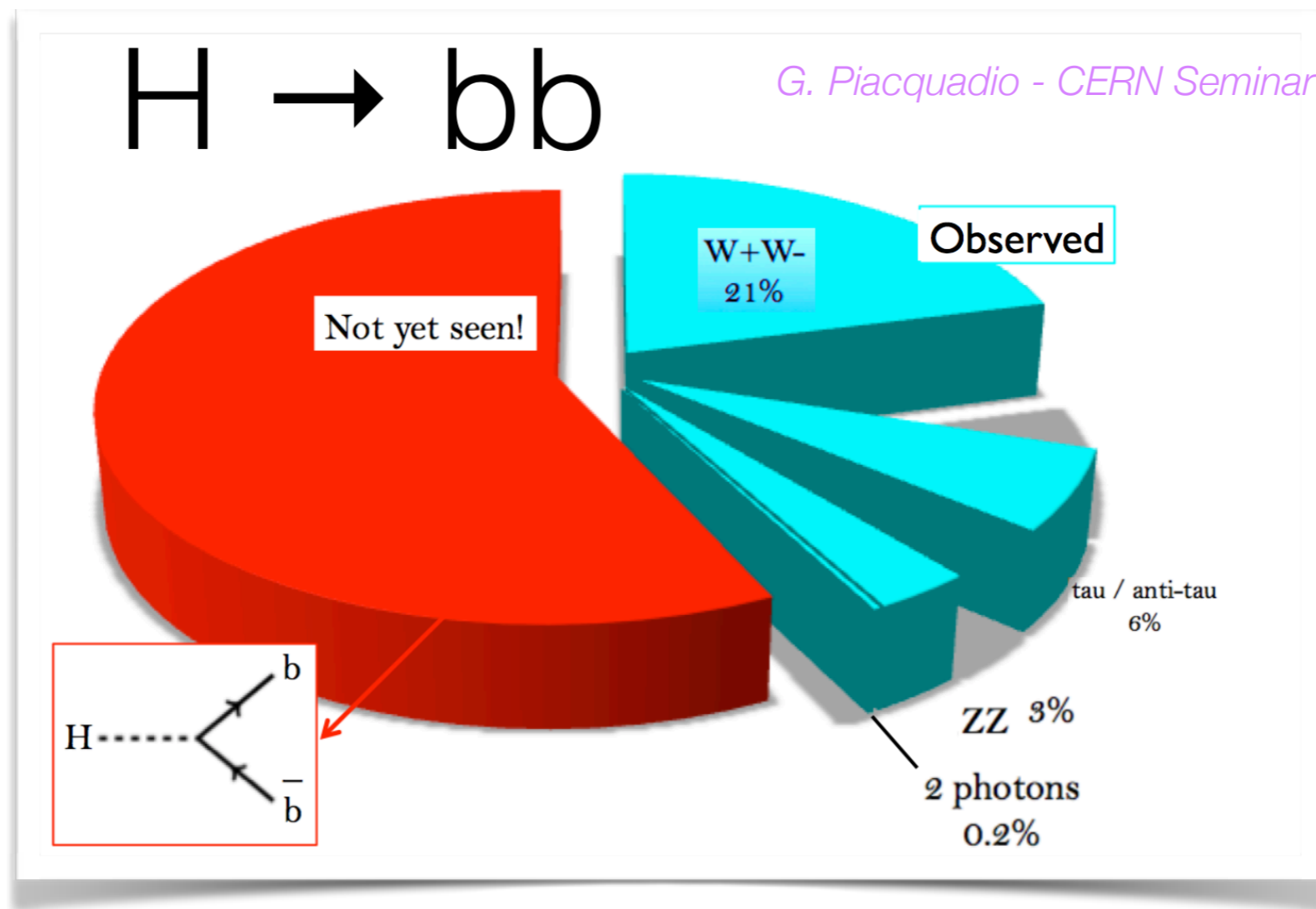


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

**Yukawa Mechanism**  
Explaining the coupling to **fermions**.  
Still barely explored!



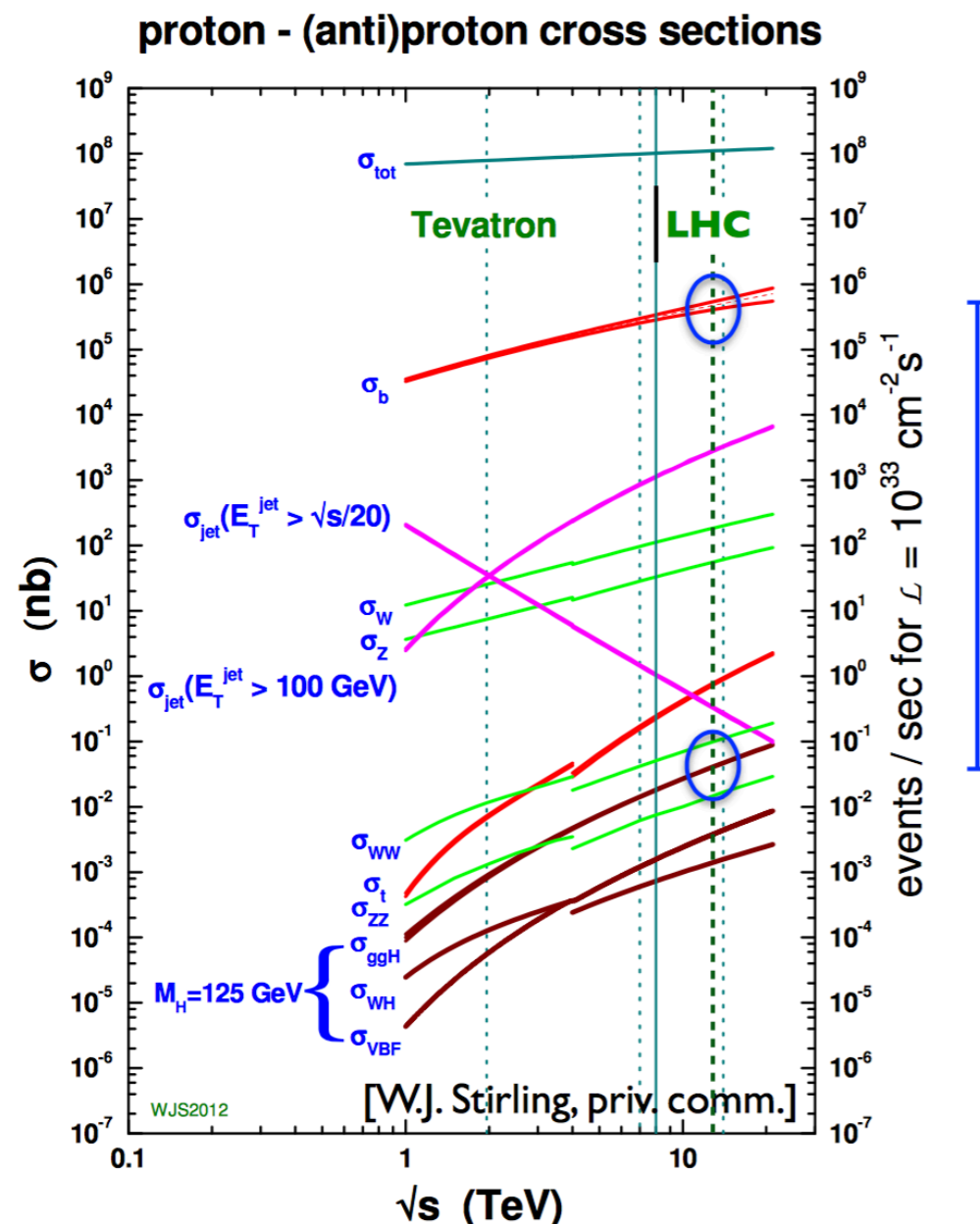
# $H \rightarrow b\bar{b}$ as missing piece of the Higgs “puzzle”



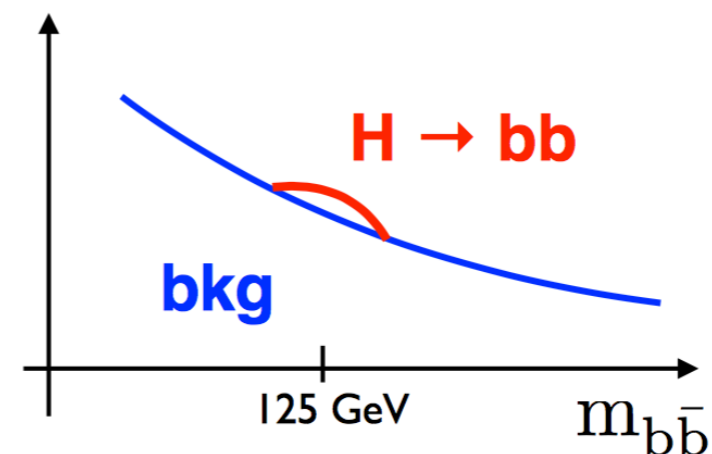
- The Higgs boson decays in  $b\bar{b}$  quarks 58% of the times.
- Most direct way to have access to the coupling to down type quarks.
- Still a lot of space for new physics hidden out there. The more Higgs boson decays we see, the less “space” for new physics we leave.

# Related problems

## Why is $H \rightarrow b\bar{b}$ so difficult?



- Jets containing b-hadrons are copiously produced at the Large Hadron Collider



- Without additional handles other than the two b-jets, signal overwhelmed by background by many orders of magnitude
- Production modes with additional signatures can help reduce the backgrounds

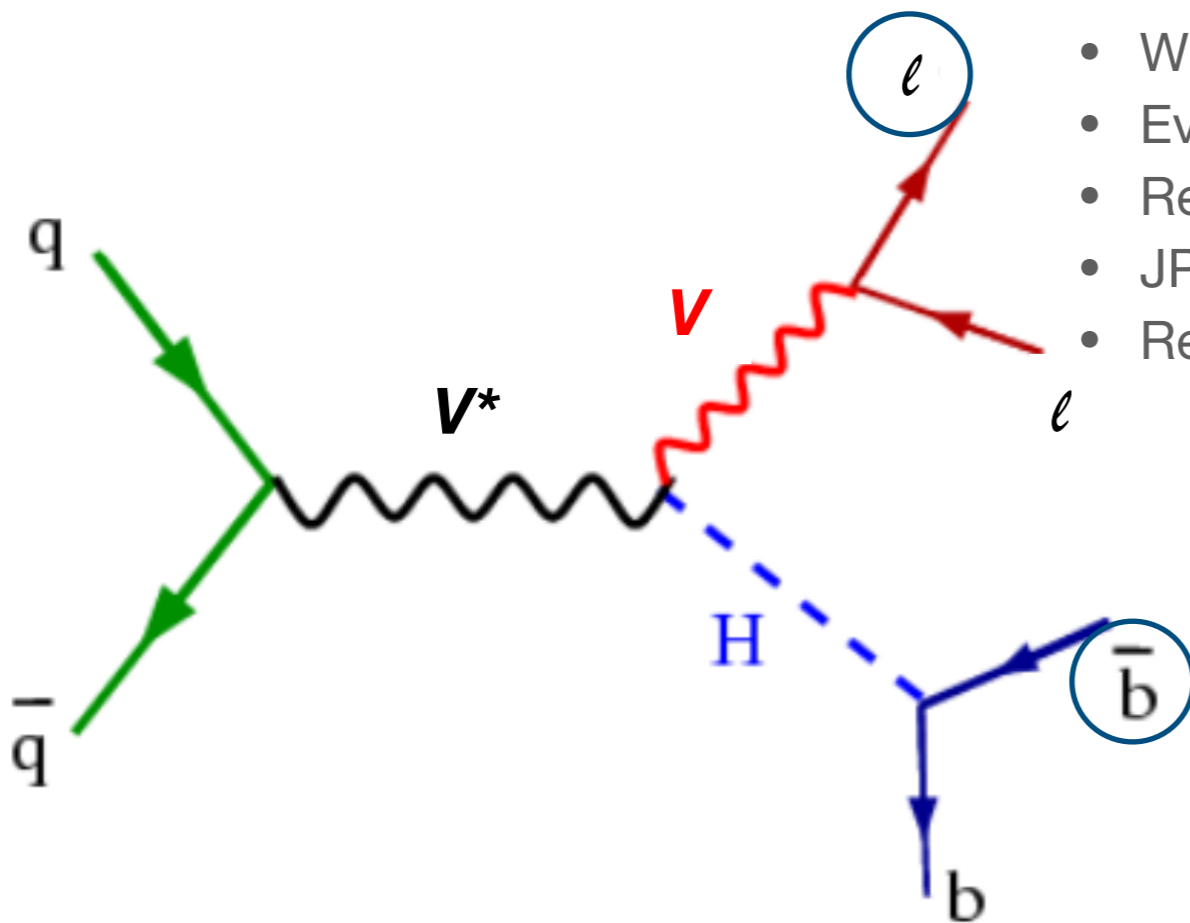
# VH, $H \rightarrow bb$ : a very special production mode

## Associated production with W/Z:

Exploit leptonic signatures for trigger, and suppression of multi-jet background.

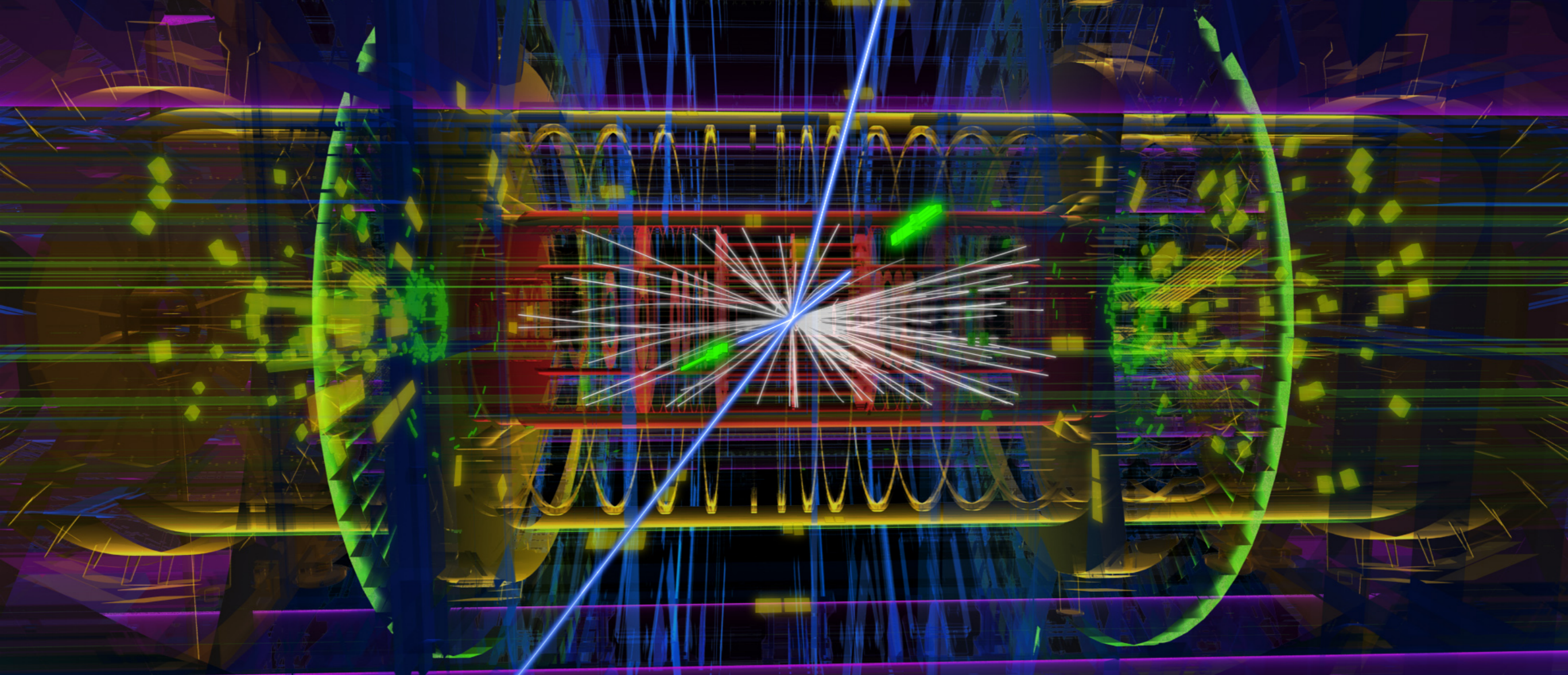
### First part: *Electron Calibration*

- Why we use  $J\psi \rightarrow ee$  peak for electron calibration
- Event selection and Methodology
- Residual energy scales measurements
- $J\psi \rightarrow ee$  to study the resolution term
- Residual resolution term measurements



### Second Part: *b-taggers for the VH, $H \rightarrow bb$*

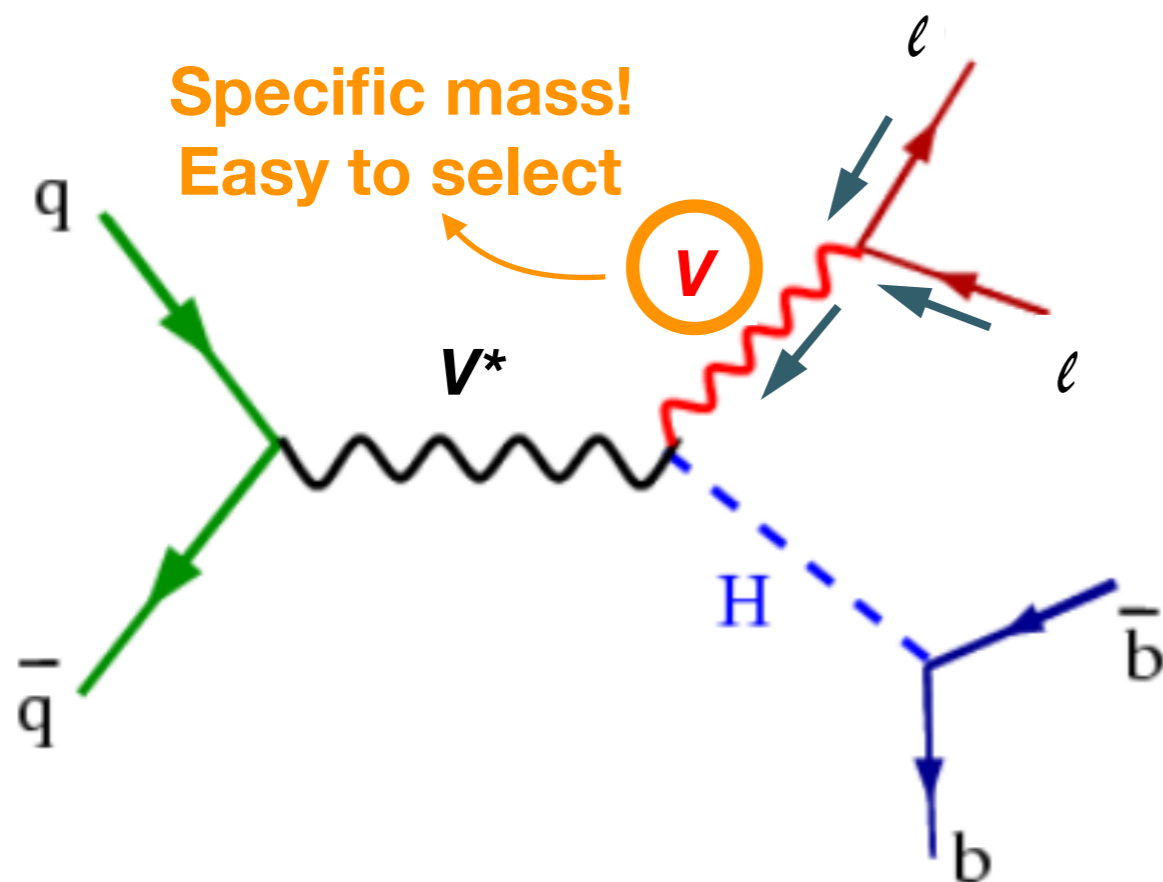
- *Summary of VH,  $H \rightarrow bb$  analysis*
- B-taggers in VH,  $H \rightarrow bb$
- Results and validation



Electron calibration with  $J/\psi \rightarrow ee$

# Why do we need a good energy calibration?

- The mass value is a good value to identify a particle (quite) uniquely.
- We reconstruct the properties (including the mass value) of short living particles going "back in time" from their decay products.



Useful quantity: **the invariant mass**  
( valid in the center of mass frame )

$$M_{12}^2 = (E_1 + E_2)^2 - \| \mathbf{p}_1 + \mathbf{p}_2 \|^2$$

$$m \sim 0 \rightarrow \mathbf{p}^2 = E$$

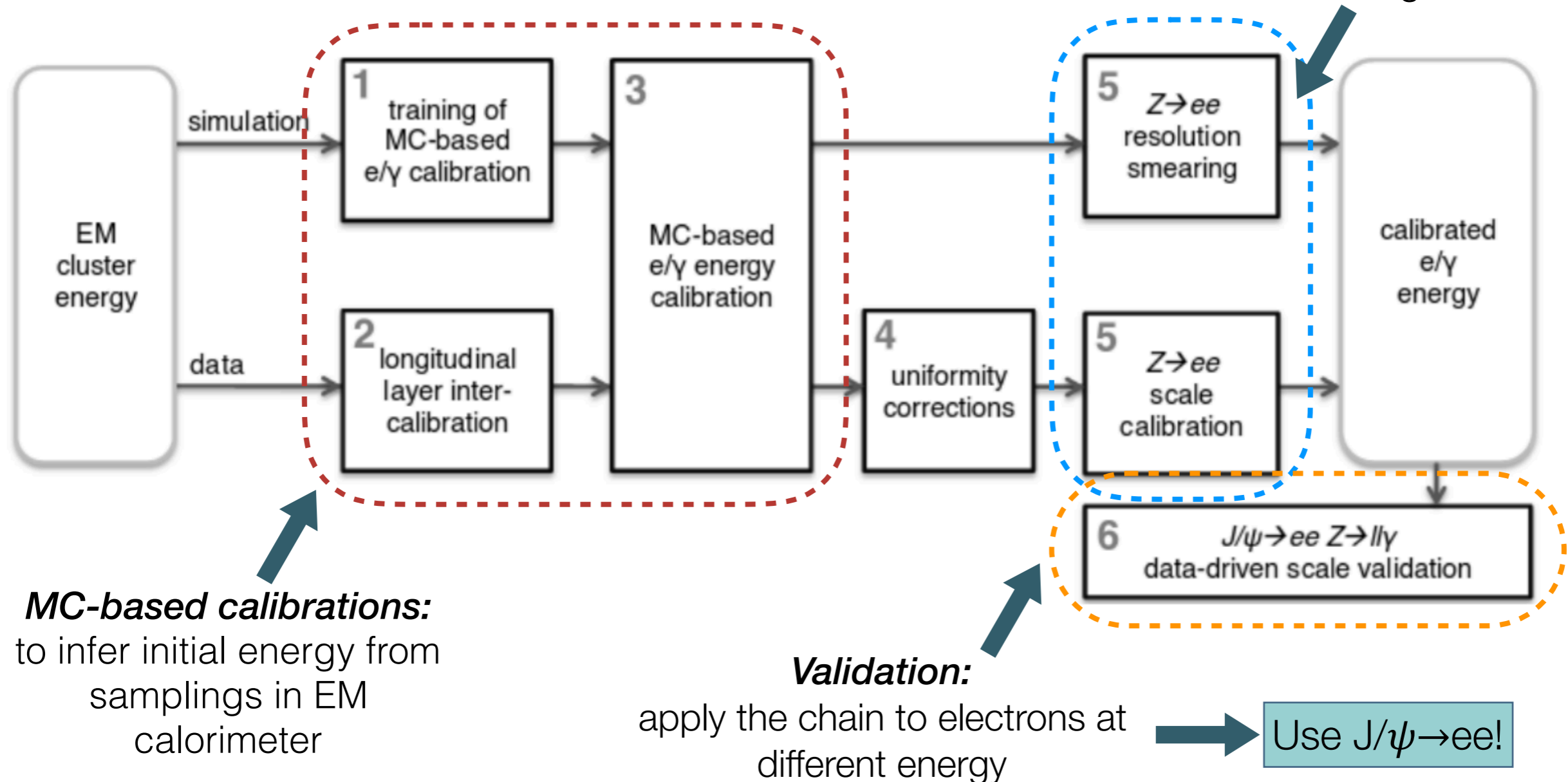
$$M_{12}^2 \sim 2E_1 E_2 (1 - \cos(\theta_{12}))$$

- The better we determine the energy of the “child” particles, the better we identify the mother.
- Detector used to measure the electron energy: **LAr EM calorimeter, Not perfect!**

# Electron calibration

Calibration chain used for all electrons and photons in ATLAS :

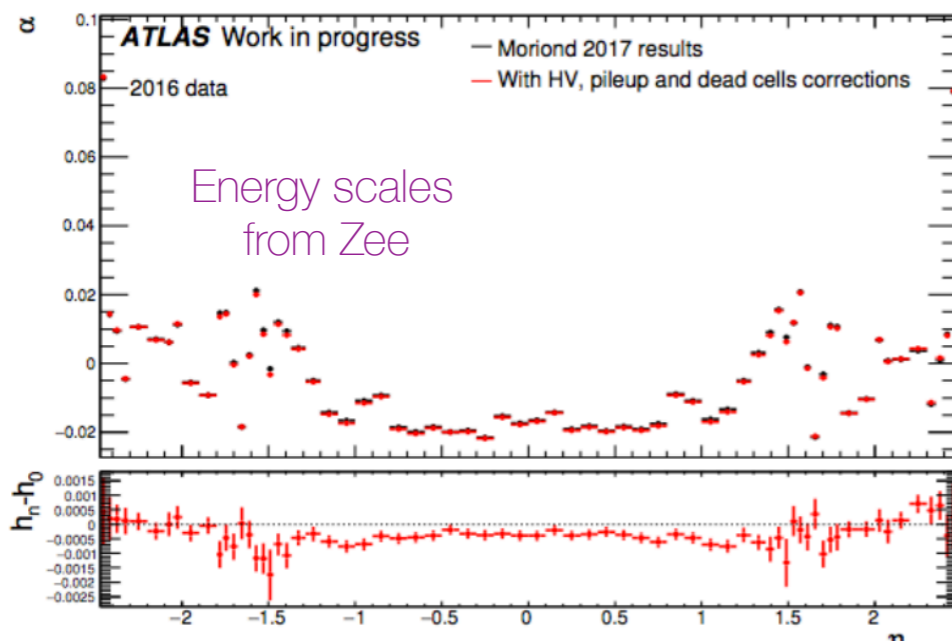
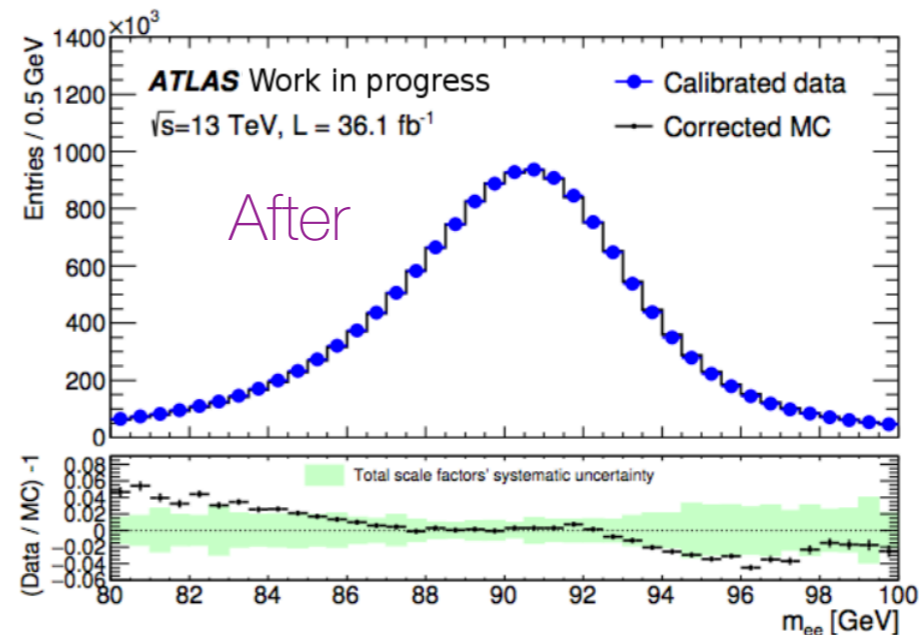
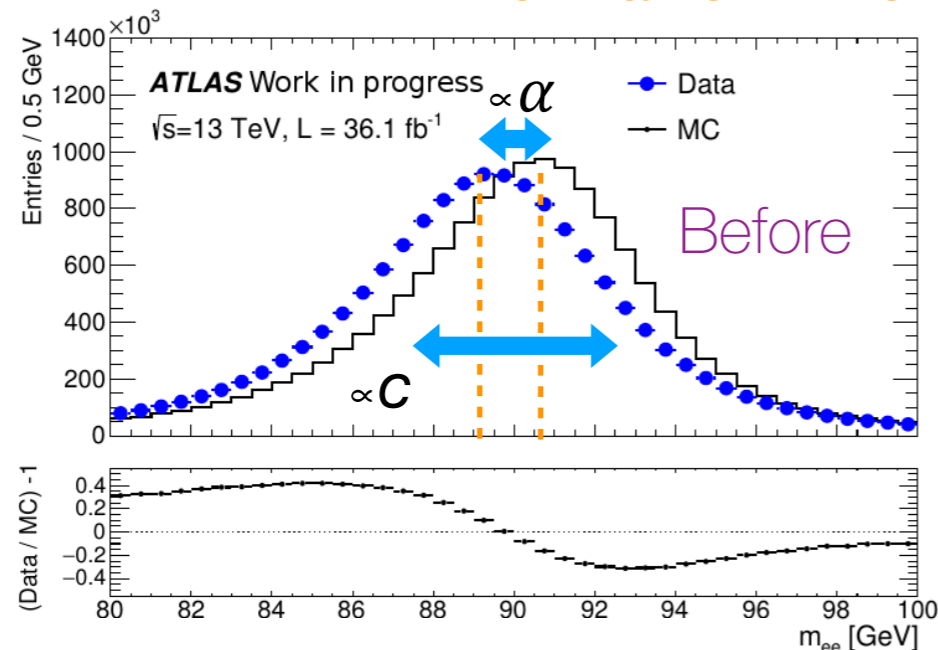
**Data-based calibrations:**  
To account for not perfect LAr modeling in simulations



# Z → ee based calibration

*The Zee based calibration is applied to all the electrons and photons in ATLAS, no matter which is their energy range*

Nominal  
Calibration:  
**Z → ee**



$$E_{\text{reco}}^{\text{Data}}(\eta) = E_{\text{reco}}^{\text{MC}}(1 + \alpha(\eta))$$

↓ Ignore 2nd order in α..

$$m_{\text{Reco}}^{\text{Data}}(\eta_i, \eta_j) \sim m_{\text{Reco}}^{\text{MC}}(\eta_i, \eta_j) \left( 1 + \frac{\alpha_i + \alpha_j}{2} \right)$$

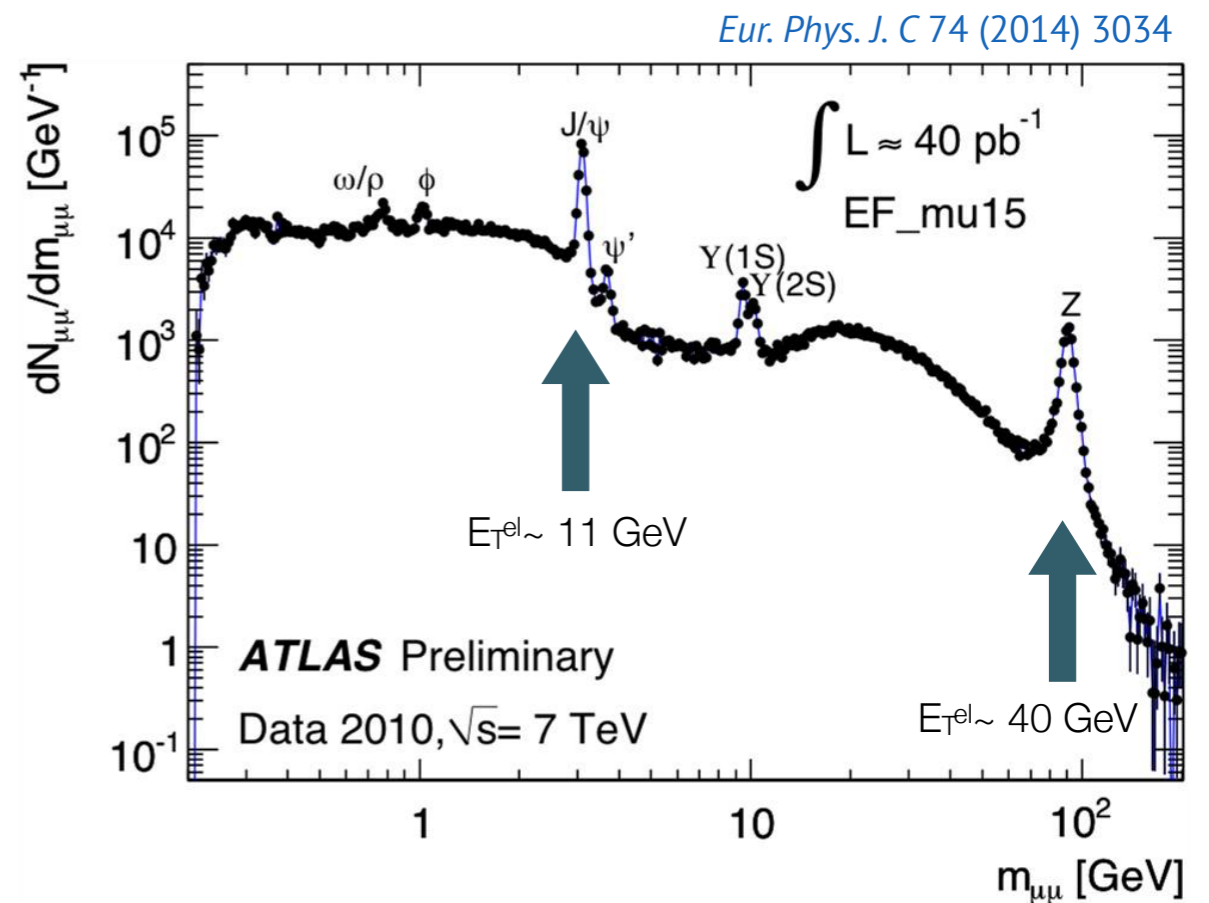
**α<sub>i</sub> determined from a simultaneous fit to several eta bins.**

# $J/\psi \rightarrow ee$ Event Selection

- At energies *far* from the Z peak we have a SM candle suitable for the simultaneous fit method: the  $J/\psi$  ( $m = 3.1$  GeV,  $\Gamma = 92$  keV).
- $J/\psi \rightarrow ee$  electrons (avg.  $E_T \sim 11$  GeV) *not* overlapping with  $Z \rightarrow ee$  (avg.  $E_T \sim 40$  GeV) ones.
- all the  $Z \rightarrow ee$  corrections applied prior to the measurement: Look for “**residual**” effects.

## Sample Selection:

- Pass dedicated low energies di-electron triggers.
- **2 opposite charge** electrons
- Electrons pass tight identification requirement
- $p_T > 5$  GeV
- $|\eta| < 1.37$  or  $1.52 < |\eta| < 2.47$
- from primary vertex
- invariant mass in  $[2.1, 4.1]$  GeV



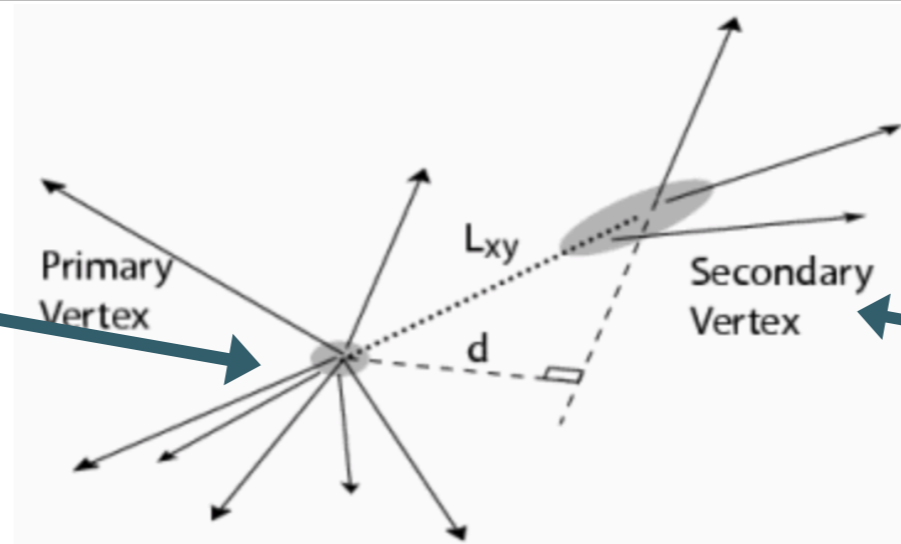
**60k events collected in total in 2015+2016 13TeV data.**

# Pseudo proper time fit

$J/\psi$  can be produced in:

**“prompt mode”**

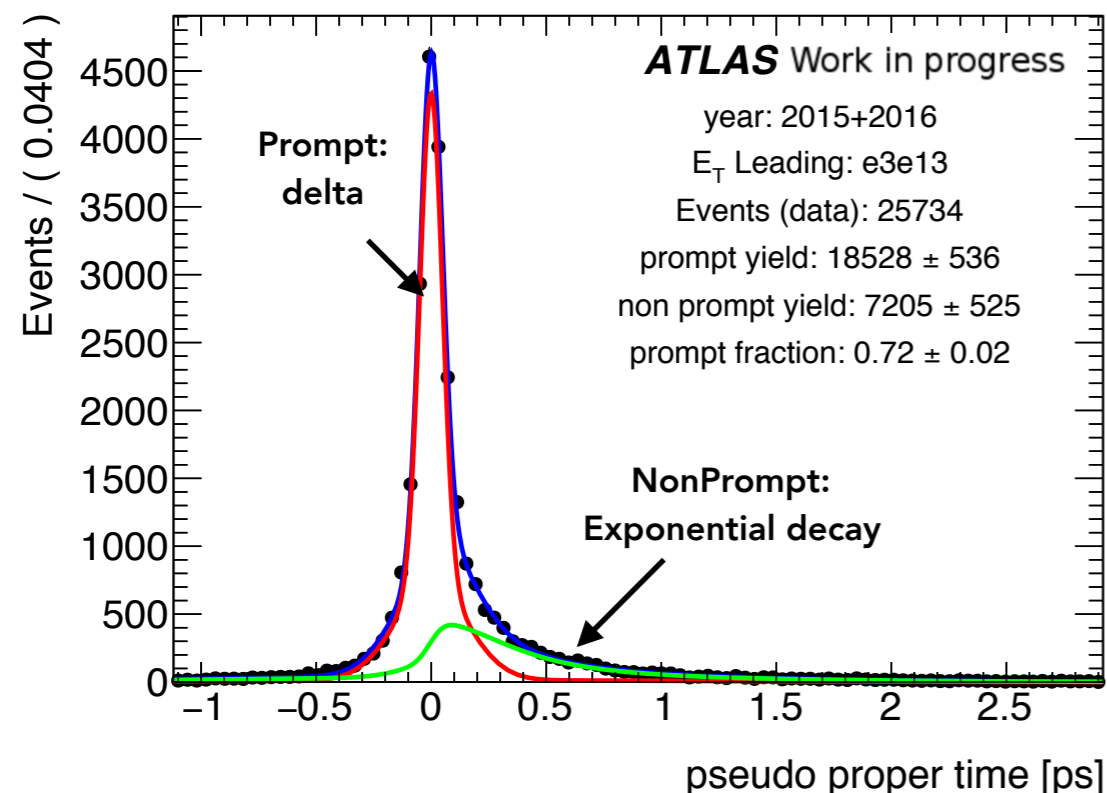
Coming from the hard collision.  
(Primary Vertex)



**“Non-prompt mode”**

Coming from a b-decay.  
(Secondary Vertex)

- Need to extract the fraction of the two components directly from data.
- Main discriminant: **Pseudo-proper time**



$$\tau := \frac{L_{xy} m^{J/\psi}}{p_T^{J/\psi}}$$

Leading $E_T$ [GeV]	$f_{\text{prompt}}$ [%]
[5,7]	$0.83^{+0.09}_{-0.09} {}^{+0.08}_{-0.11}$
[7,9]	$0.76^{+0.04}_{-0.04} {}^{+0.10}_{-0.06}$
[9,14]	$0.68^{+0.03}_{-0.03} {}^{+0.02}_{-0.05}$
[14,30]	$0.68^{+0.01}_{-0.01} {}^{+0.01}_{-0.04}$

# The invariant mass fit

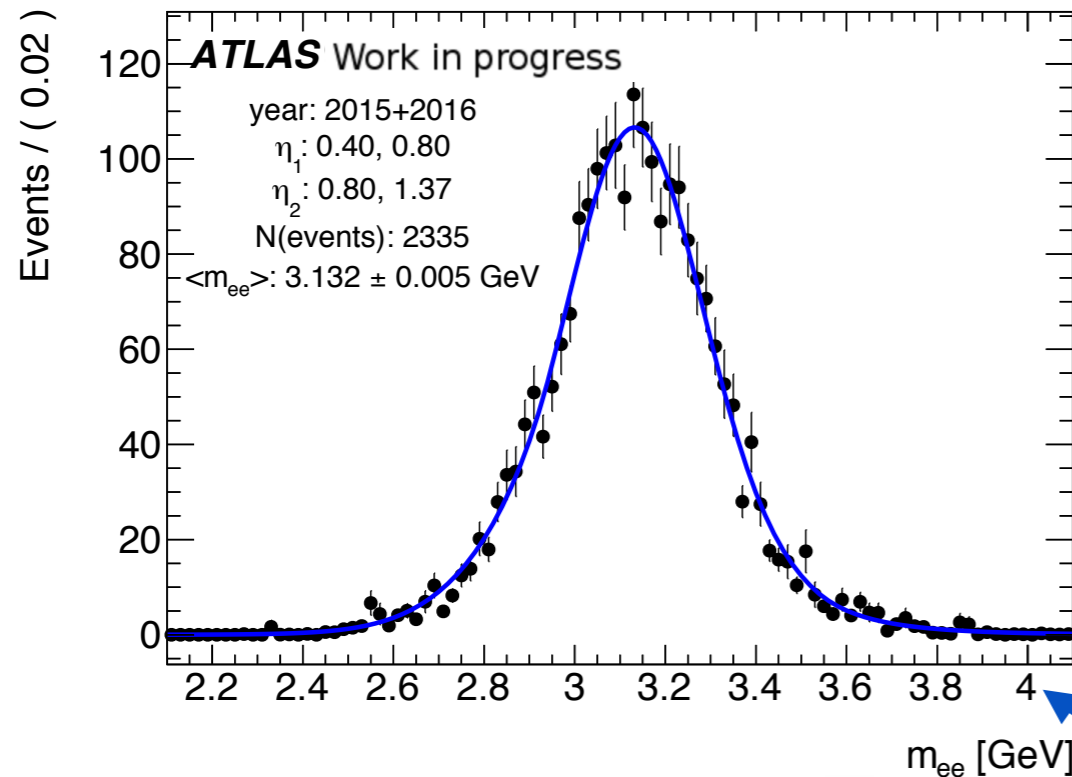
*N.B. MC is simulating  $J/\psi$  peak only.  
Background shape extracted from the fit.  
 $\psi(2s)$  parameters rescaled from  $J/\psi$  ones*

- Divide the samples in  $(\eta_1, \eta_2)$  categories
- Fit the MC ee invariant with a **Double Sided Crystal Ball\*** to fix the  $MC_{reco}$  shapes.
- Fit the data  $m_{ee}$  spectrum:

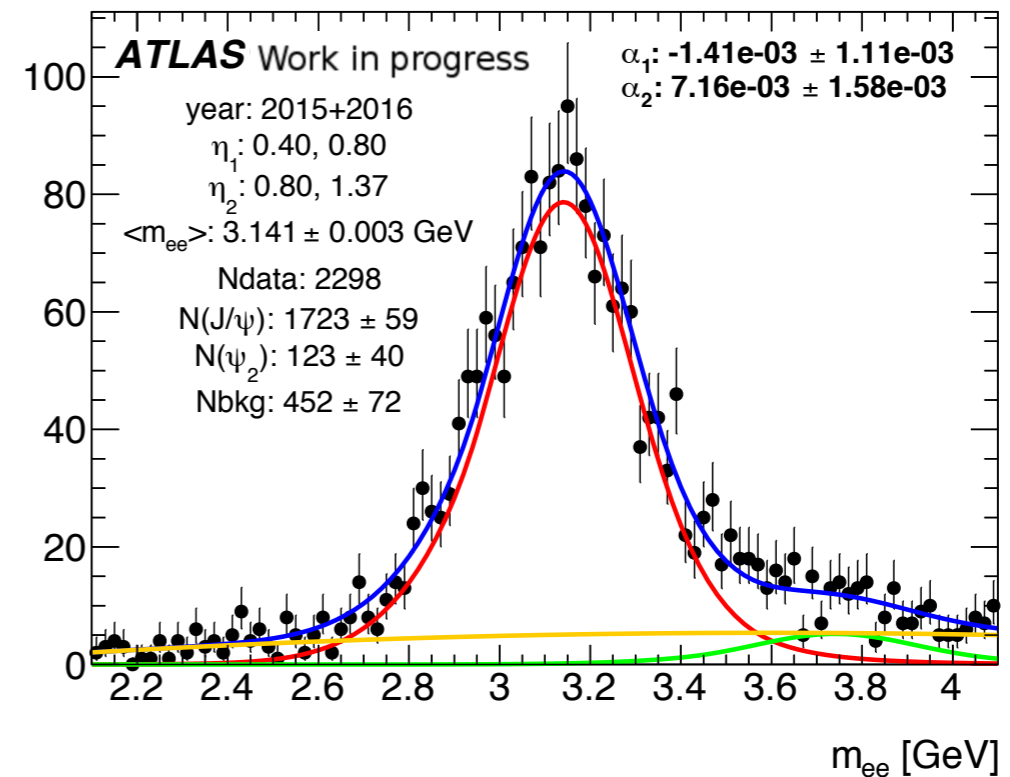


**DSCB( $J/\psi$ ) + DSCB( $\psi(2s)$ ) + bkg (Pol2)**

*Fit to MC to find the signal shape*



*Fit to data to extract the energy scales*



$$m_{Reco}^{Data}(\eta_i, \eta_j) \sim m_{Reco}^{MC}(\eta_i, \eta_j) \left( 1 + \frac{\alpha_i + \alpha_j}{2} \right)$$

\* Double Sided Crystal Ball = Gaussian + Polynomial tails

# The invariant mass fit

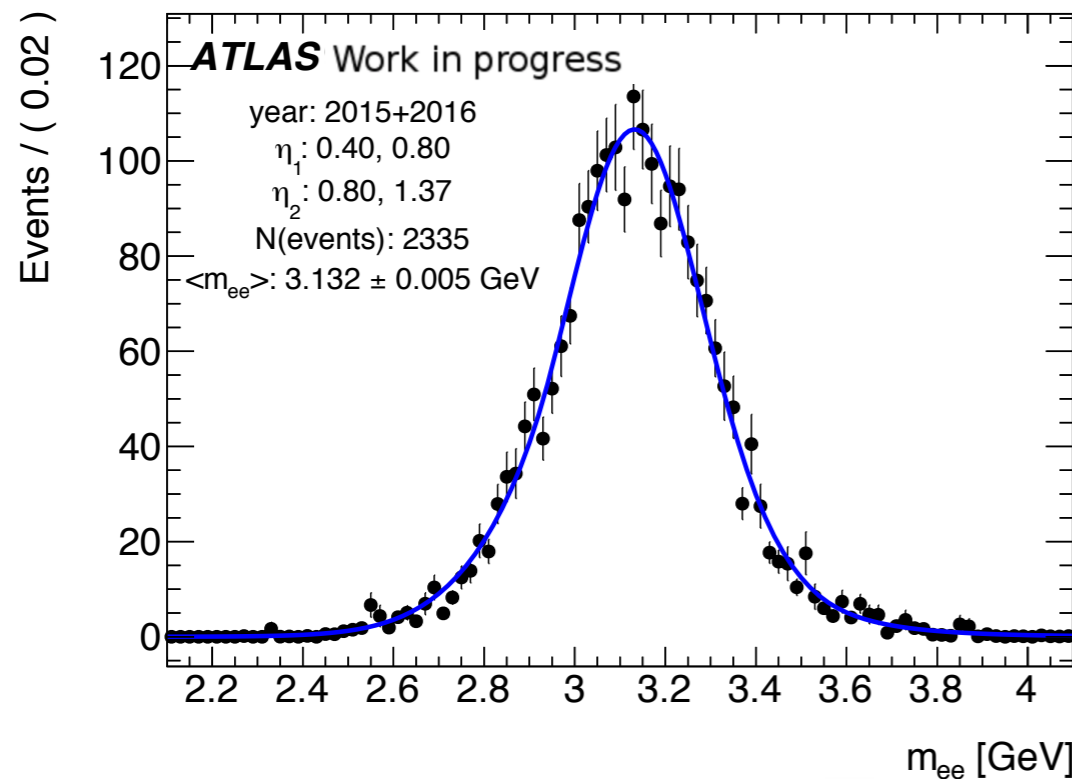
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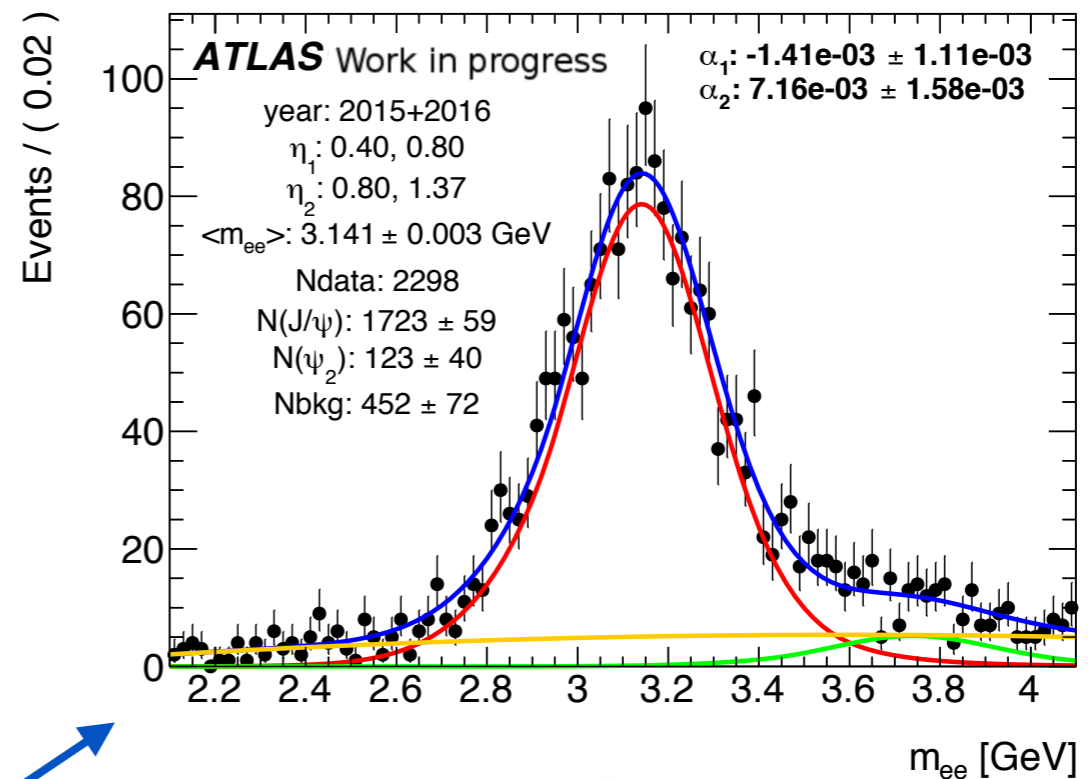


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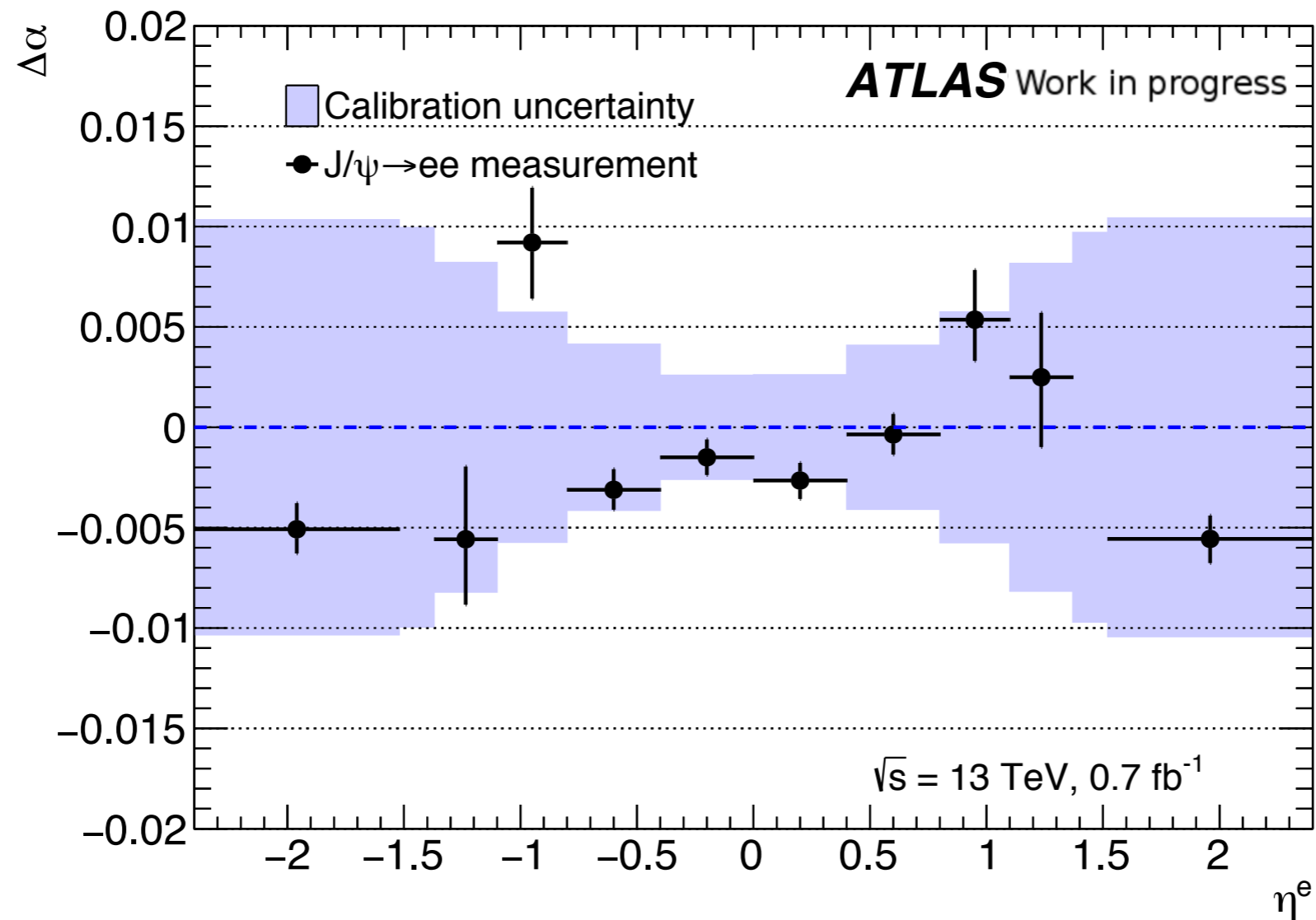


$$m_{Reco}^{Data}(\eta_i, \eta_j) \sim m_{Reco}^{MC}(\eta_i, \eta_j) \left( 1 + \frac{\alpha_i + \alpha_j}{2} \right)$$

\* Double Sided Crystal Ball = Gaussian + Polynomial tails

# Results

Comparison between  $J/\psi \rightarrow ee$  energy scales and uncertainties obtained from  $Z \rightarrow ee$  calibration.



Residual energy scale miscalibration in  $\eta$  is up to 0.9% in  $\eta = [0.8, 1.37]$ .

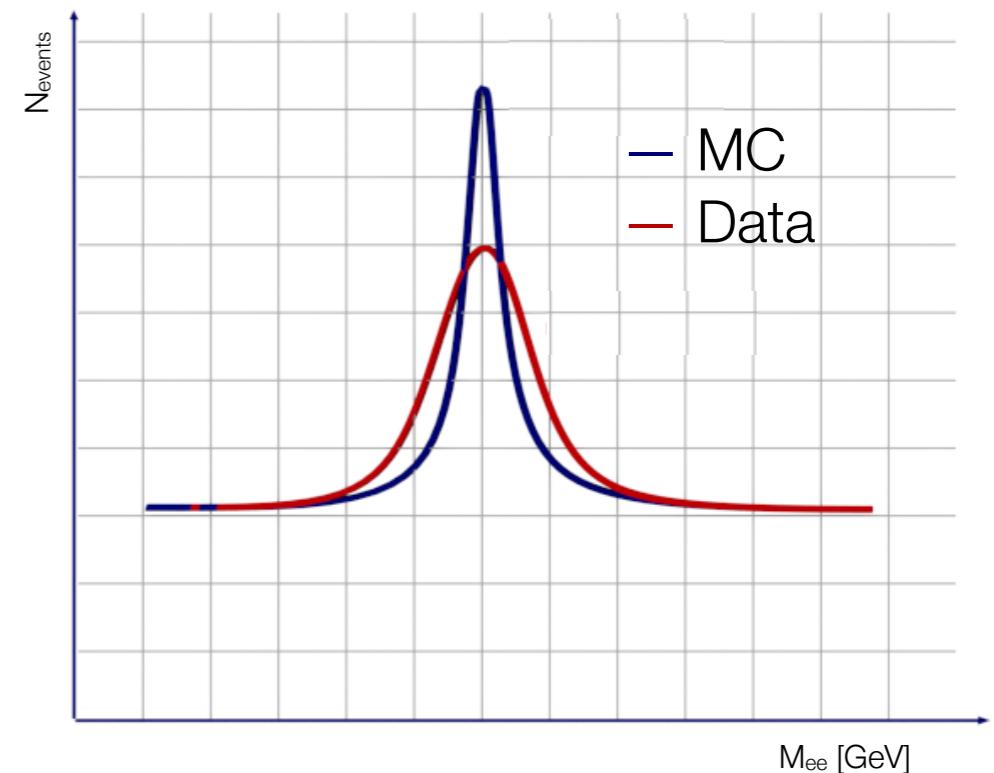
**The residual energy scales are within the Zee systematic uncertainties.**

# Energy resolution studies with $J/\psi \rightarrow ee$

The EM calorimeter resolution has three terms. But **not all** of them contribute significantly @  $J/\psi \rightarrow ee$  energies:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

$\frac{a}{\sqrt{E}}$  is **Dominating @  $J/\psi$  energies**  
 $\frac{b}{E}$  is measured with **pile-up only events**  
 $c$  is Measured with  $Zee$



If we consider **c** and **b** as well known from other measurements, the **residual** resolution term can be interpreted as:

$$\frac{\sigma_{data}}{E} = \frac{\sigma_{MC}}{E} \oplus \frac{\Delta a}{\sqrt{E}}$$

$\frac{\Delta a}{\sqrt{E}}$  is the **Residual sampling term**

We have a **direct access to miscalibrations in the sampling term**, which are not accessible with  $Z \rightarrow ee$  or *pile-up only* events.

# Methodology

- **Idea:** include the resolution variables as free parameters in the  $m_{ee}$  fit
- Process in **two steps**, first we extract the scales and then the residual term
- Signal + background PDF changed to:

$$\text{BW} \otimes 2\text{Gaussians} + \text{DSCB}(\psi 2s) + \text{Pol}(2)$$

- **Caveat:** sensitive only to positive values of  $\Delta a$ :  $\rightarrow$  when data resolution  $>$  MC resolution
- **Technical details:**
  - The resolution Gaussians param. are defined as:

$$\mu_{data} = \left(1 + \frac{\alpha_i + \alpha_j}{2}\right) \mu_{MC}$$

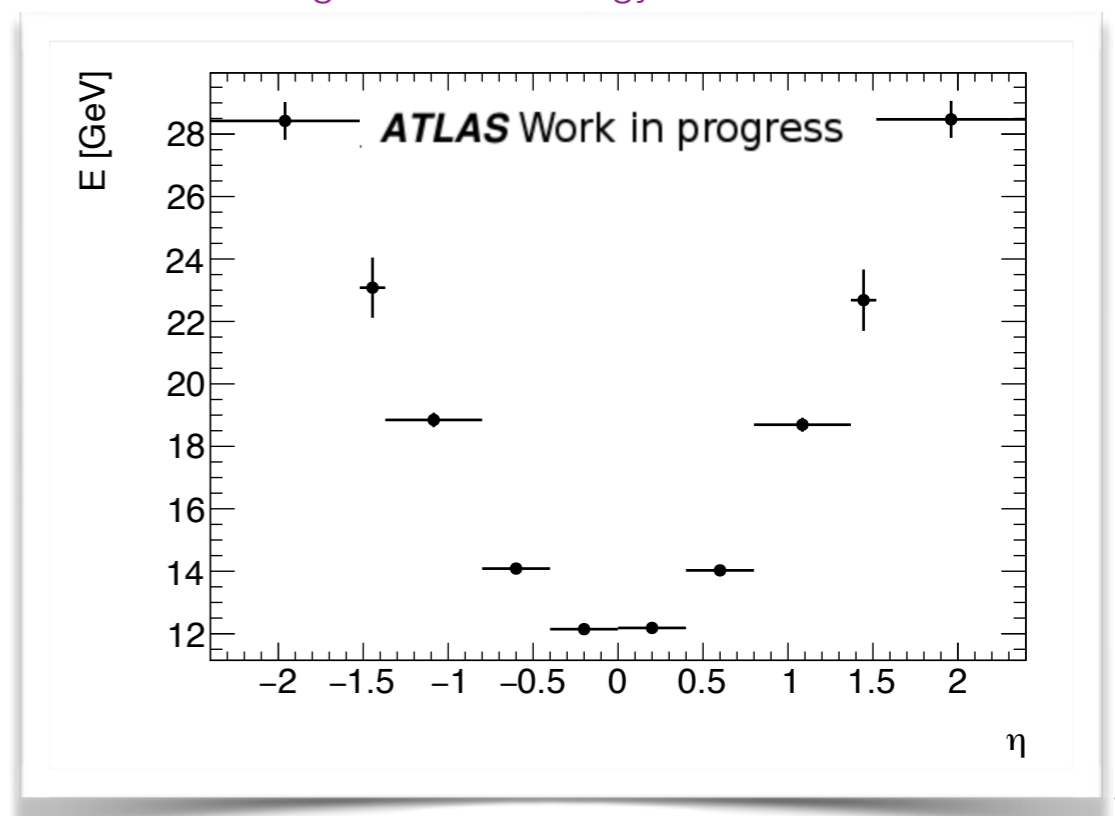
$$\sigma_{data} = \left(1 + \frac{\alpha_i + \alpha_j}{2}\right)^2 \left(\sigma_{MC}^2 + \mu_{MC}^2 \frac{c_i^2 + c_j^2}{4}\right)$$

- With:  $c_j^2 = \frac{a_j^2}{\langle E \rangle}$

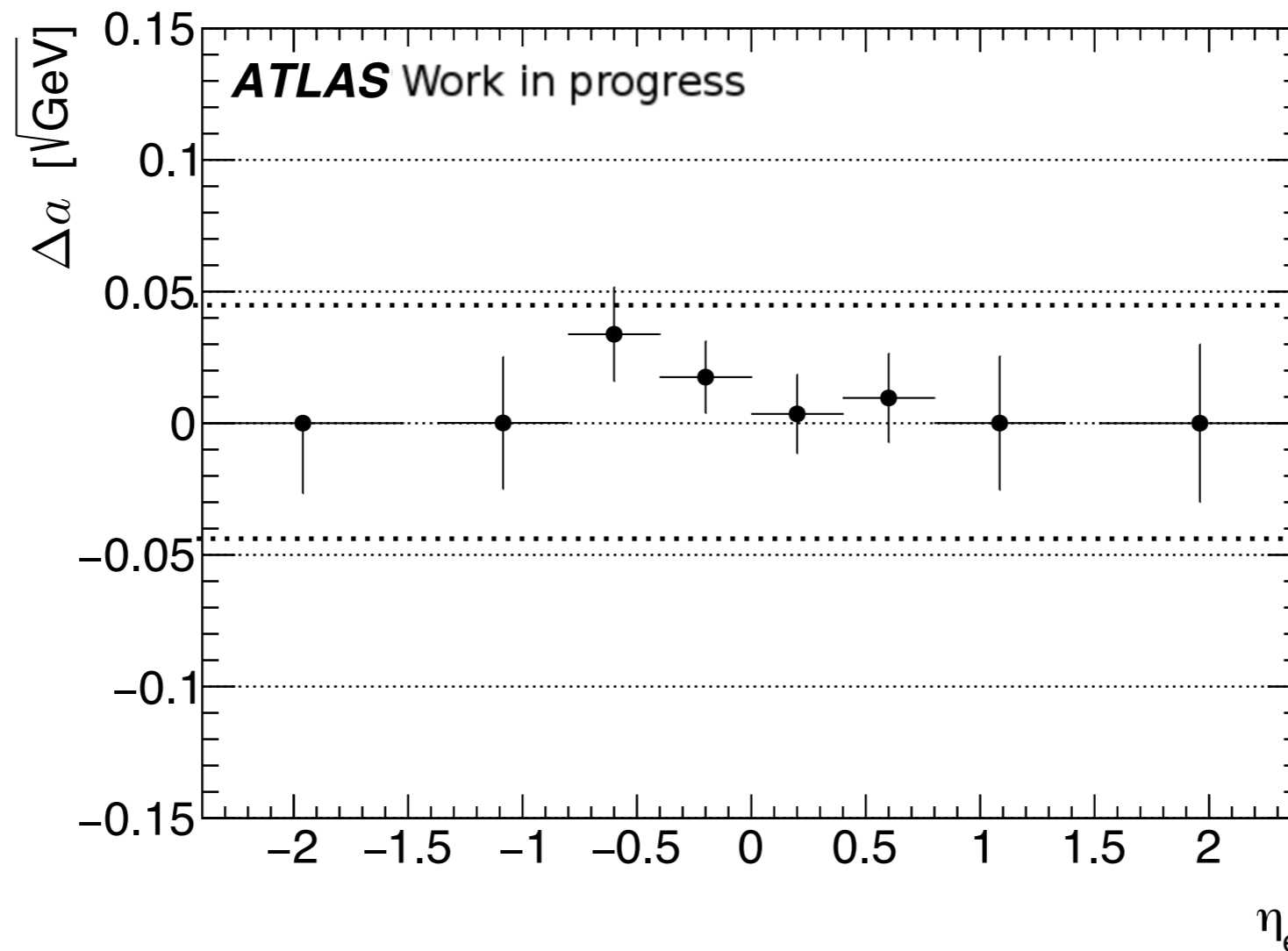
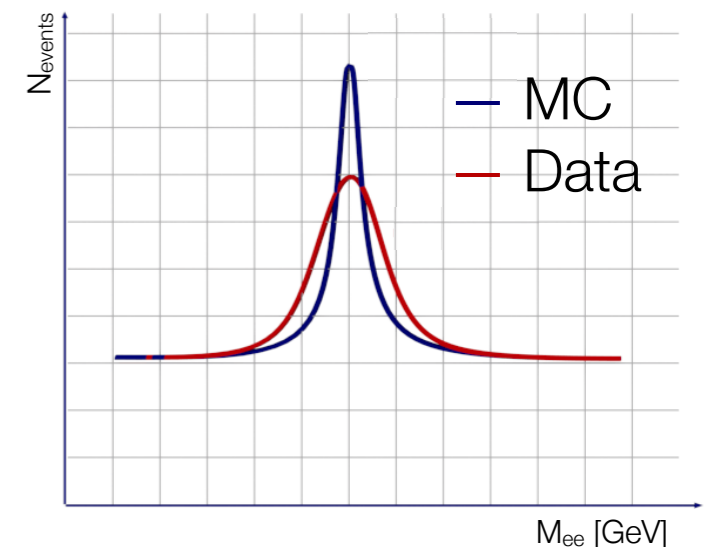
- $a_i$  extracted from  $c_i^2$  **averaging** the energy distribution per eta bin



Average electron Energy distribution vs eta



# Results

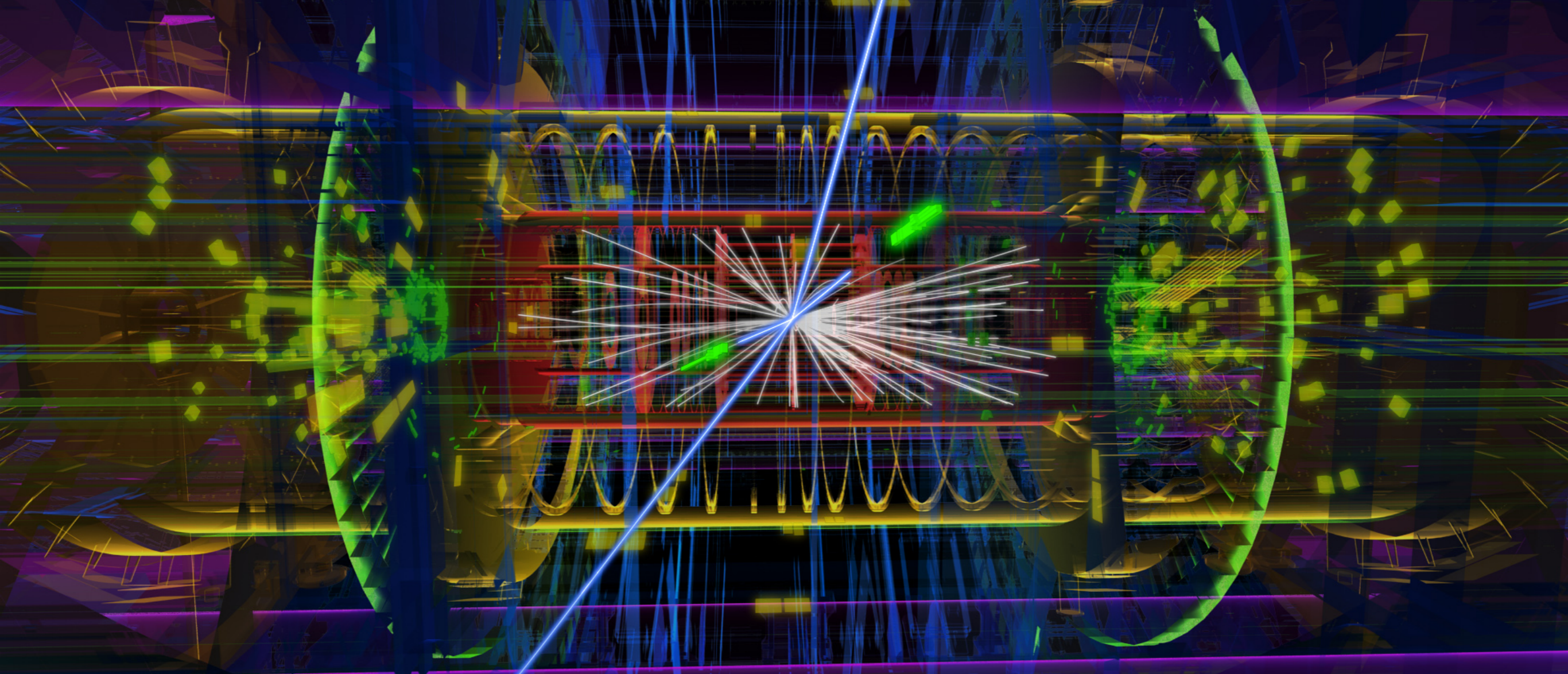


Residual resolution term generally compatible with **zero**.

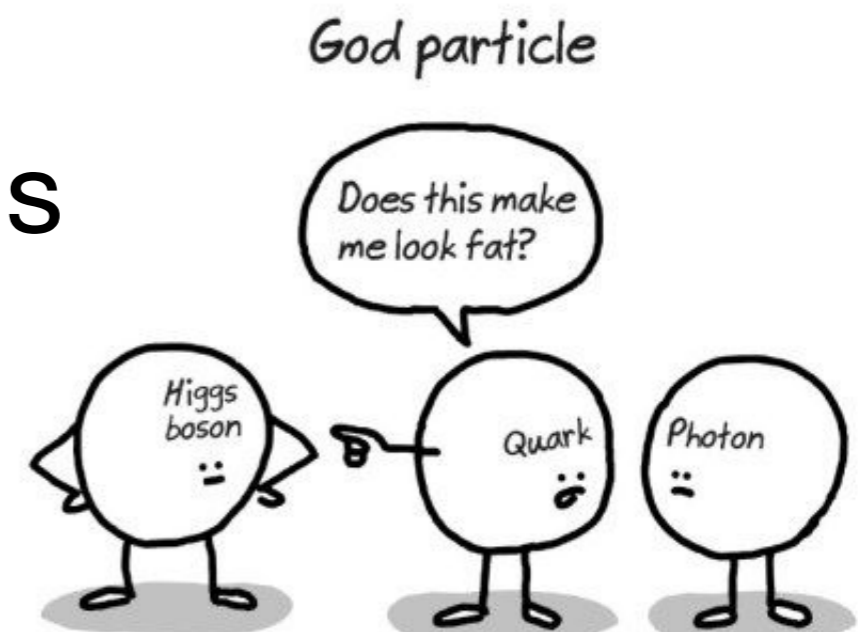
With uncertainties rising up to 4% (5.5%) in barrel (EC) including the ***b*** term uncertainty (100MeV/ $E_T$ ).

**No significant degradation of the value of *a*, determined in test beams\* :**

$$a = 10\% \pm 0.1$$

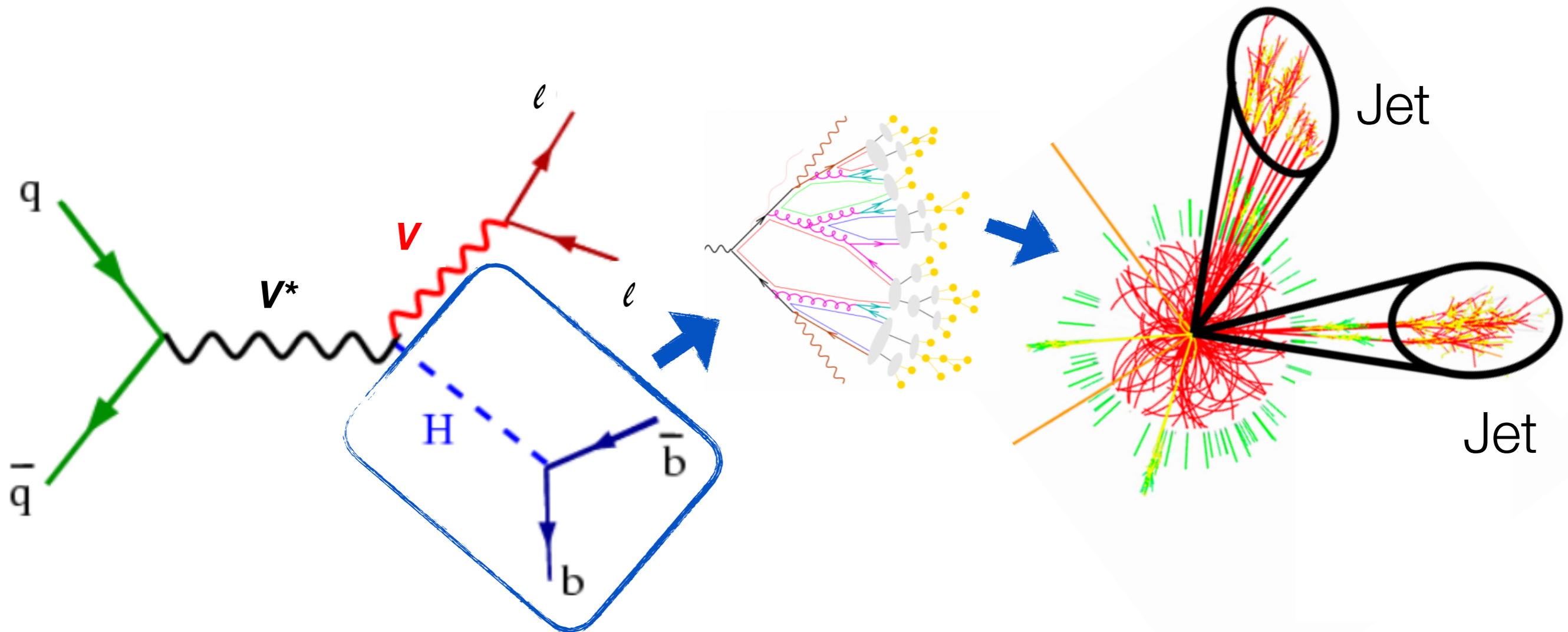


## VH, $H \rightarrow b\bar{b}$ analysis



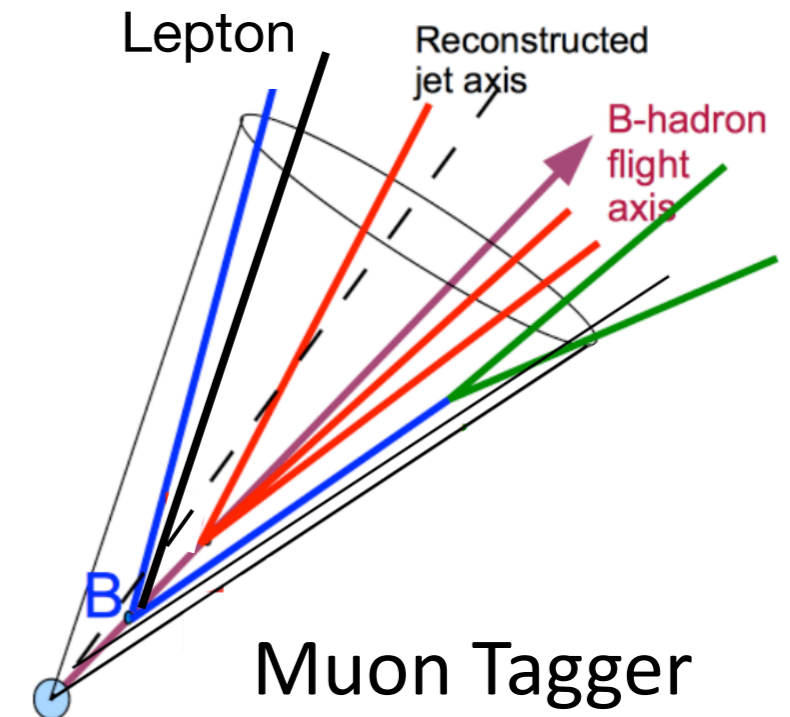
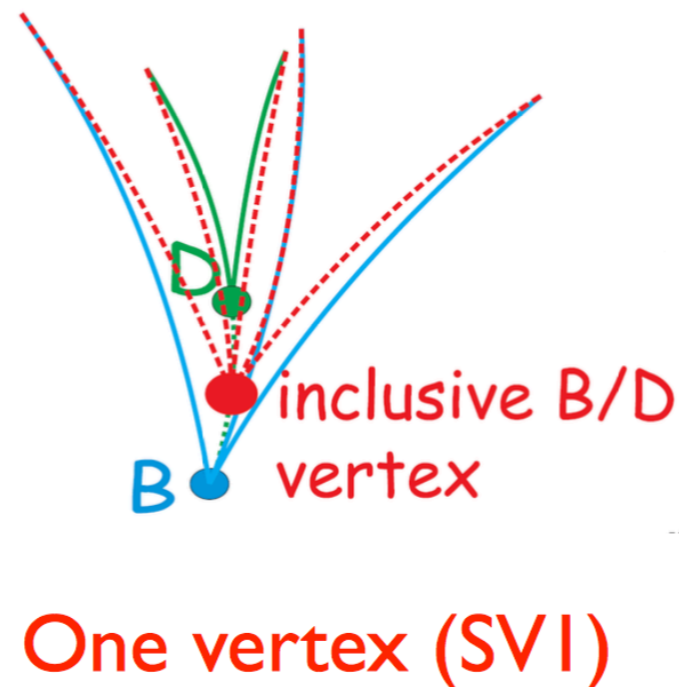
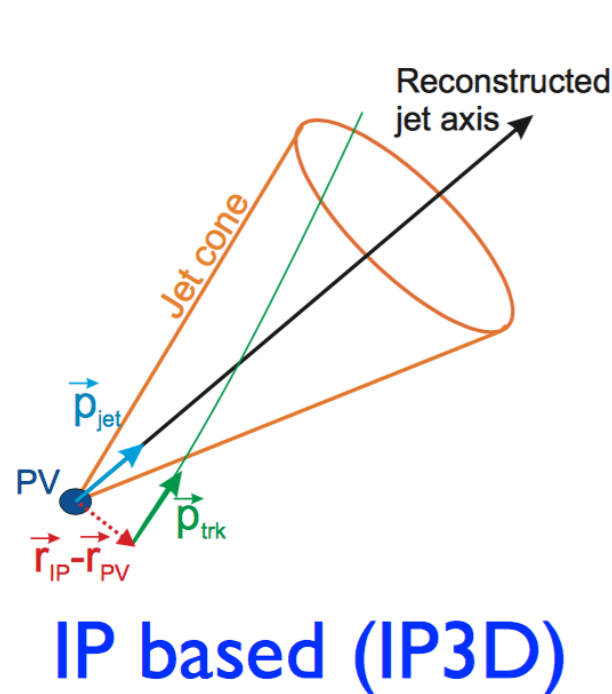
# How do we reconstruct the Higgs?

- Again, starting from the invariant mass of the decay products.
- Quarks are complicated objects to see in the detector. Nasty property: **hadronization**!



- We need a way to recognize if jets are coming from a  $b$ ,  $c$  or  $t$  quark.
- In this case we need a “b-tagger”: an algorithm to distinguish  $b$  from the other jets.

# “B-tagging” in ATLAS :

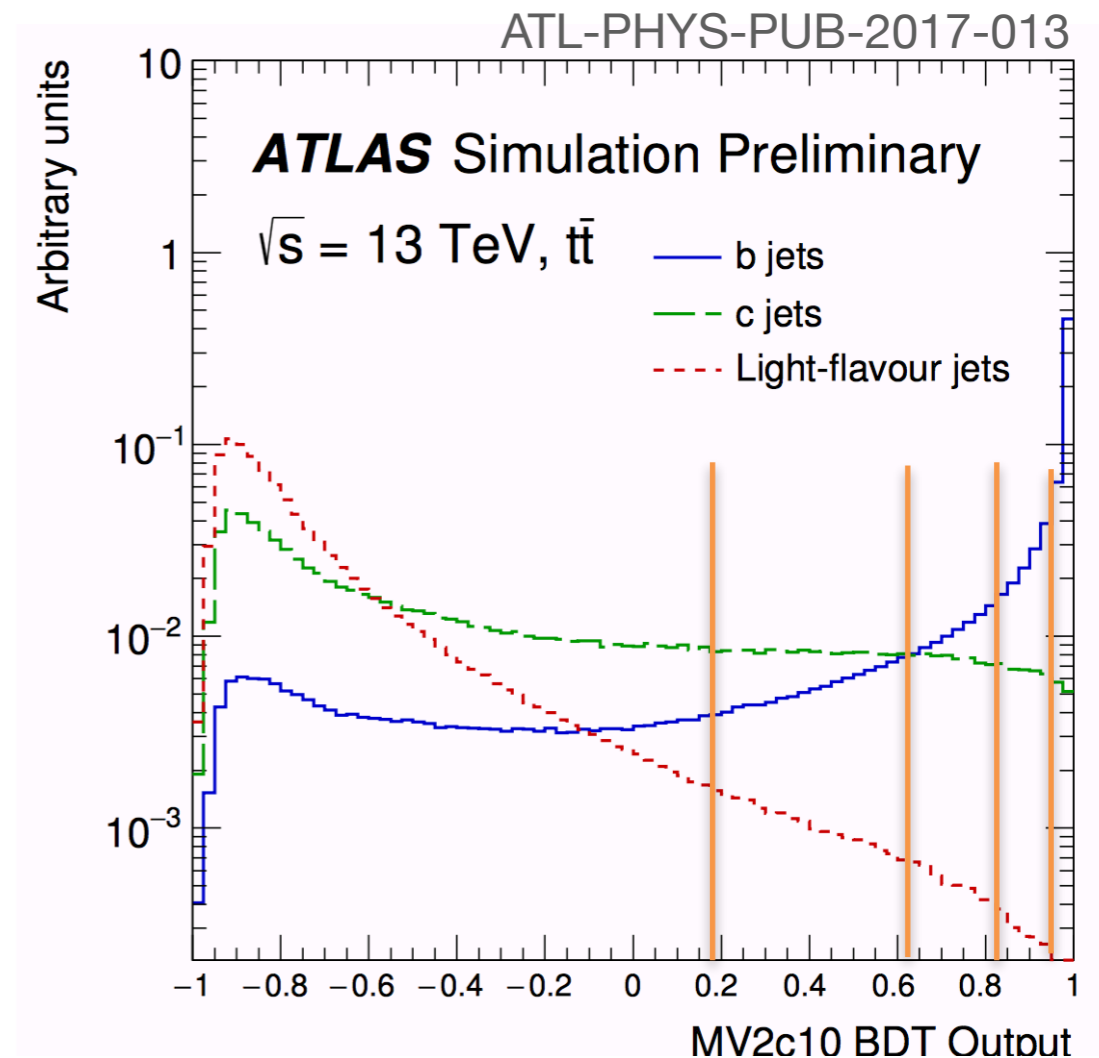


- Separate b-jets from light (u,d,s,g) and charm jets using specific b-hadron properties:
  - Mass of b-hadrons (5 GeV)
  - **Large lifetime (~1.5 ps) → Secondary Vertex and tracks with large IP.**
  - In ~42% of the cases the b-hadron **decays semi-leptonically**, in ~11% directly ( $b \rightarrow \ell$ ) and in ~10% indirectly ( $b \rightarrow c \rightarrow \ell$ ) where  $\ell=e$  or  $\mu$ . → search for “soft” muons in the SV

**Information from different low-level taggers (exploiting different properties) combined into a single high-level one**

# Intermezzo: What is a “Working point” ?

- **Problem:** the b-tagger is distributed from  $[-1,1]$ , but we need to convert this information in a bool: “is tagged? yes, no!” **Solution:** cut on a certain value of this distribution (if  $> \rightarrow$  is tag!).
- **How do we define a WP?** Find the b-tagger score for which the b-jet is identified with a X% efficiency\* (i.e. cut at 0.8244 to have 70% WP, at 0.9349 for 60% WP etc..)



BDT Cut Value	<i>b</i> -jet Efficiency [%]	<i>c</i> -jet Rejection	Light-jet Rejection	$\tau$ Rejection
0.9349	60	34	1538	184
0.8244	70	12	381	55
0.6459	77	6	134	22
0.1758	85	3.1	33	8.2

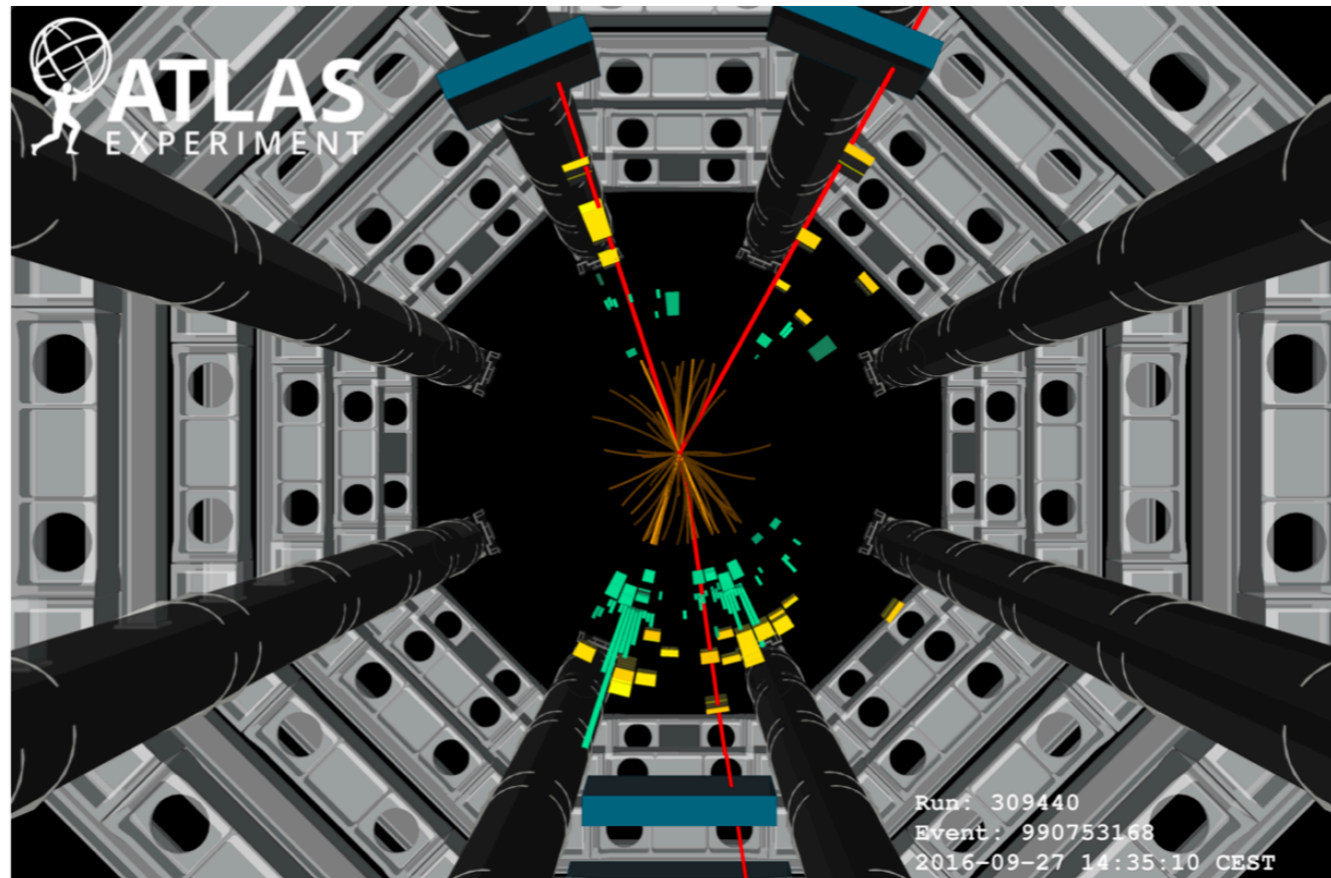
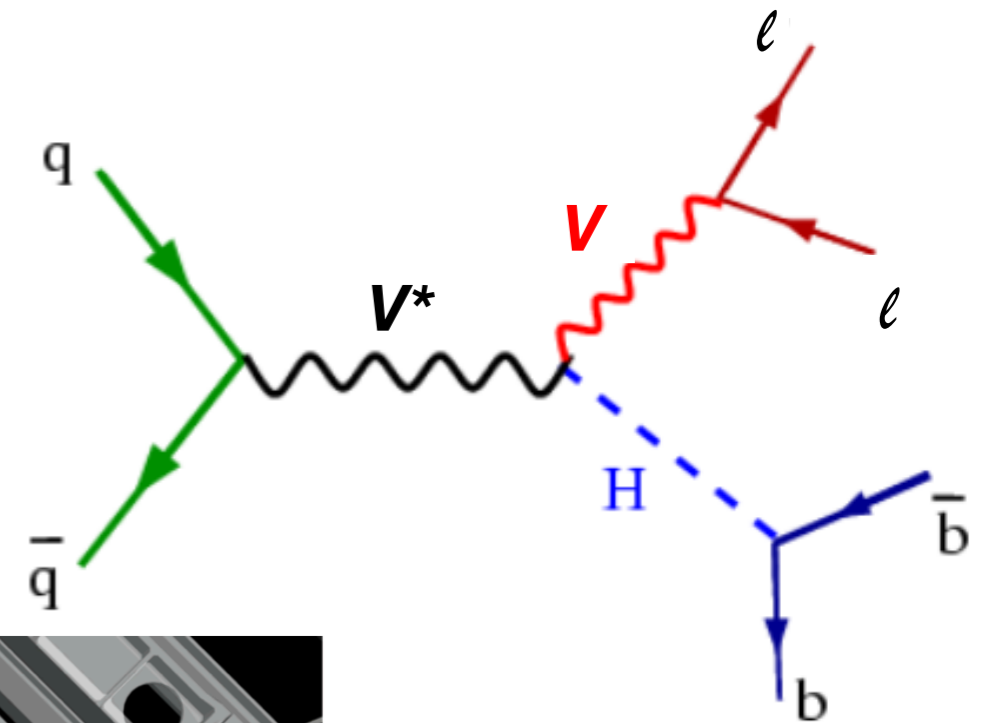
# VH, $H \rightarrow b\bar{b}$ event selection

## Associated production with W/Z:

Exploit leptonic signatures for trigger, and suppression of multi-jet background.

- Exactly 2 b-tagged jets as Higgs candidate (2 or  $\geq 3$  in 2lep)
- Channels denoted by the number of charged leptons (e or  $\mu$ )

2-lepton channel:



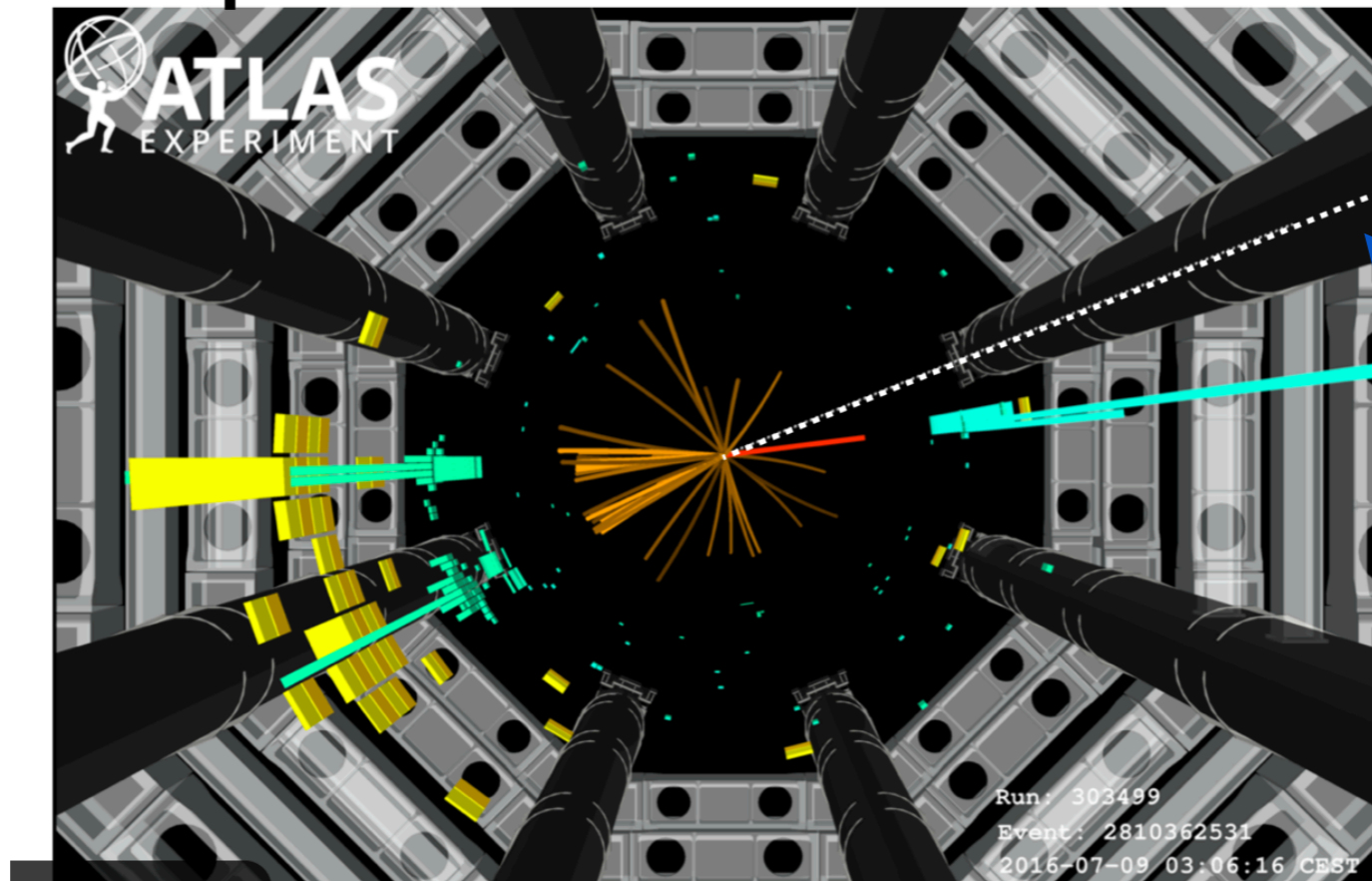
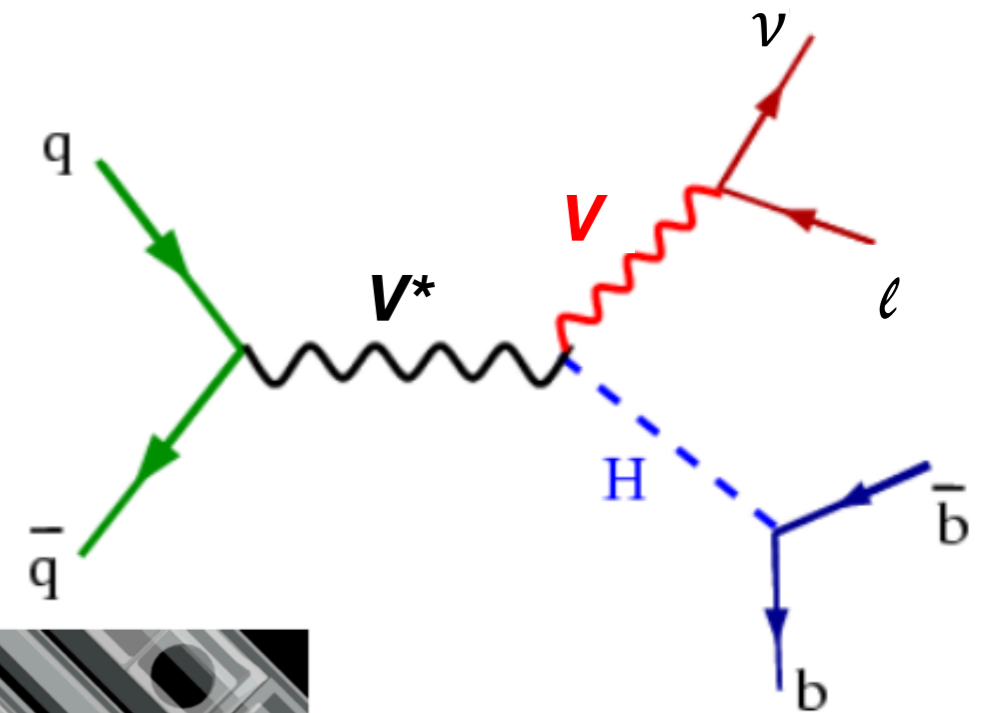
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1-lepton channel:



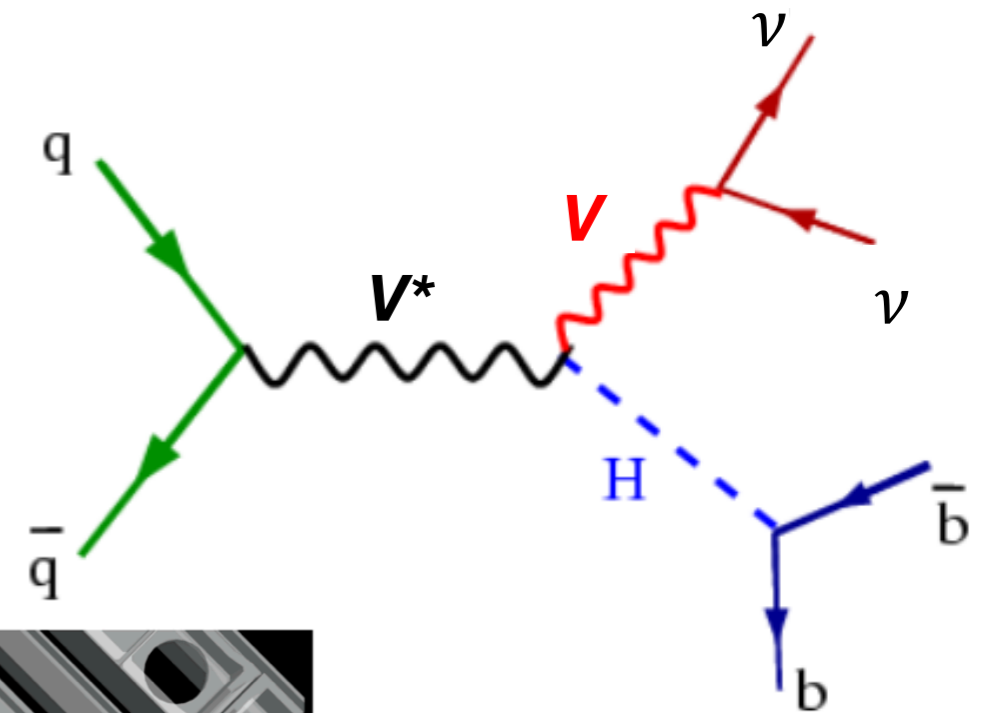
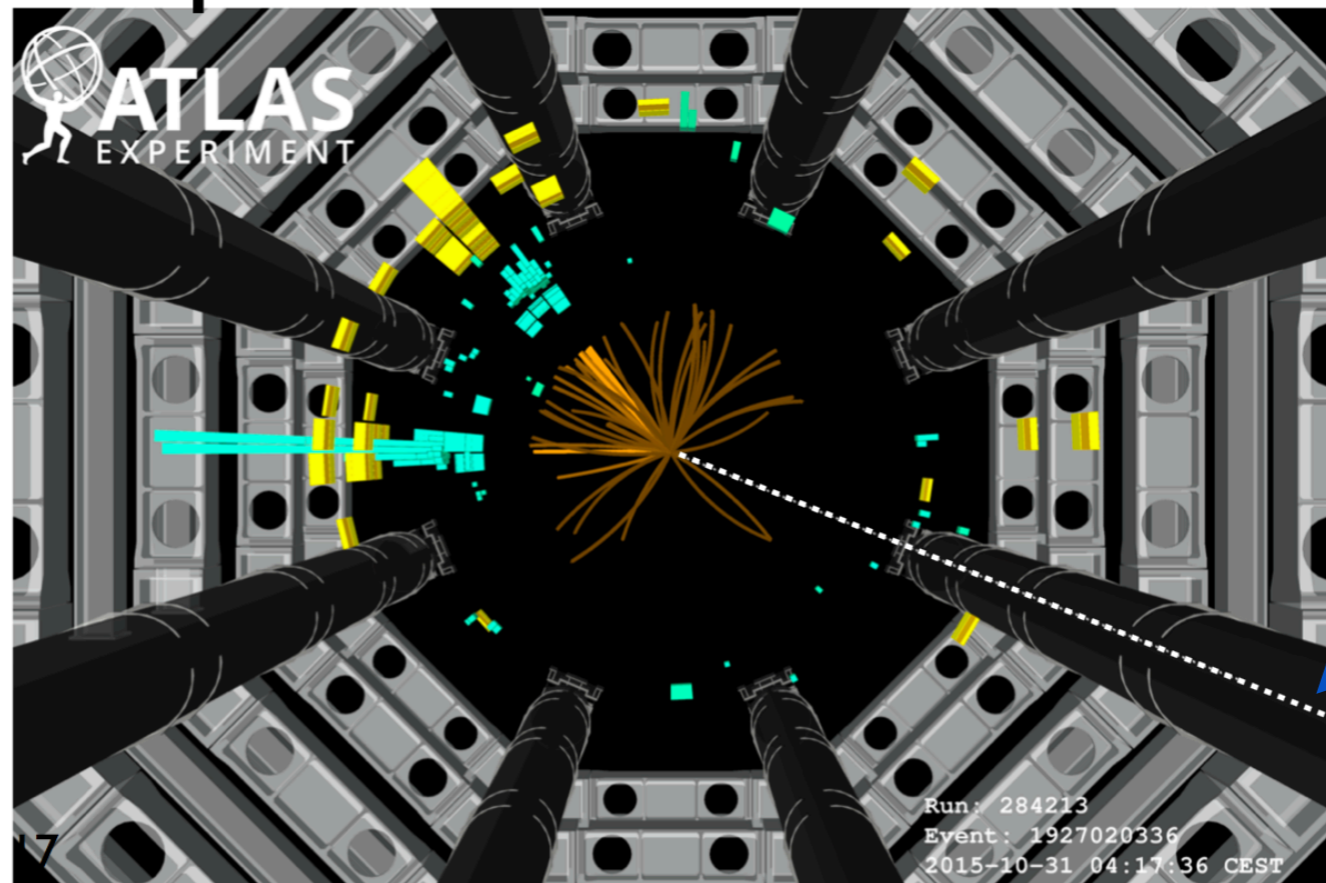
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- Exactly 2 b-tagged jets as Higgs candidate (2 or  $\geq 3$  in 2lep)
- Channels denoted by the number of charged leptons (e or  $\mu$ )

0-lepton channel:

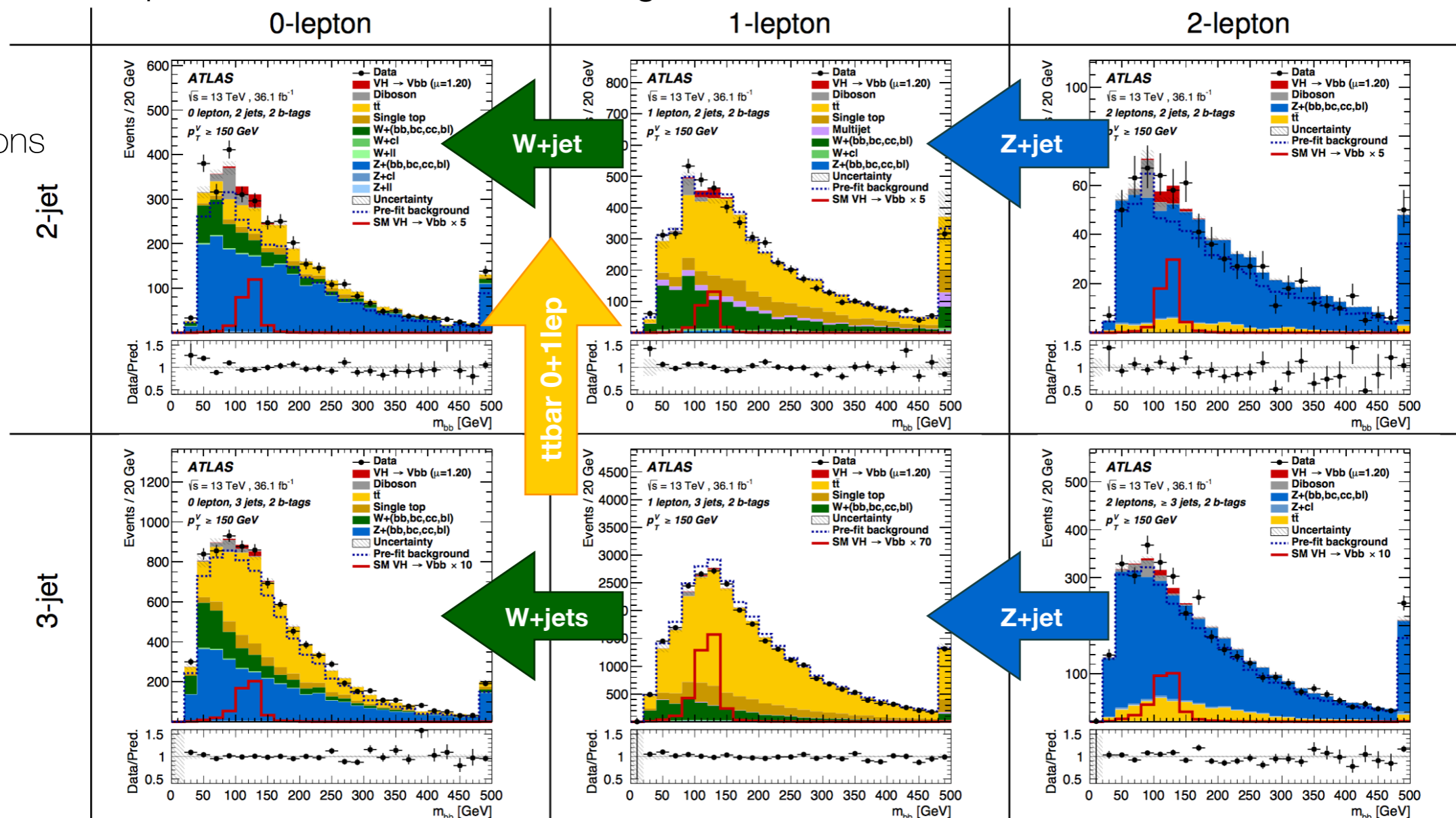


# Backgrounds:

ATL-PHYS-PUB-2007-011

- Normalization driven by a region, with appropriate extrapolation uncertainties
- Main backgrounds:  $t\bar{t}$ ,  $W+HF$ ,  $Z+HF$ .
- $t\bar{t}$  contribution is very different in 0- and 1- lepton to 2-lep case:
  - In 0- and 1- lepton, we have missed and object (jet or lepton)  $\rightarrow$  one common normalization
  - In 2-lepton  $\rightarrow$  we need a control region

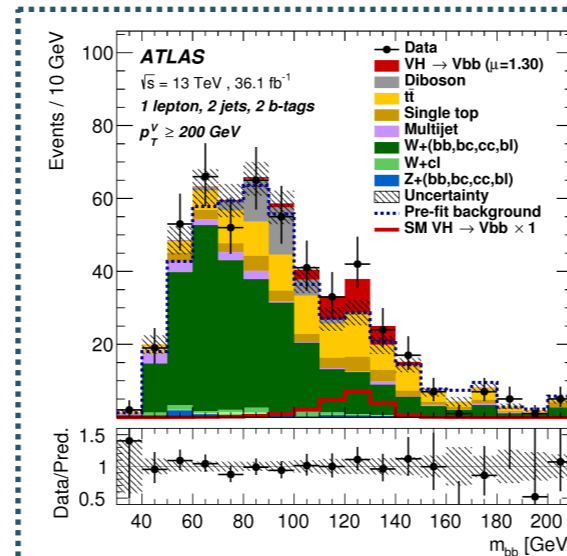
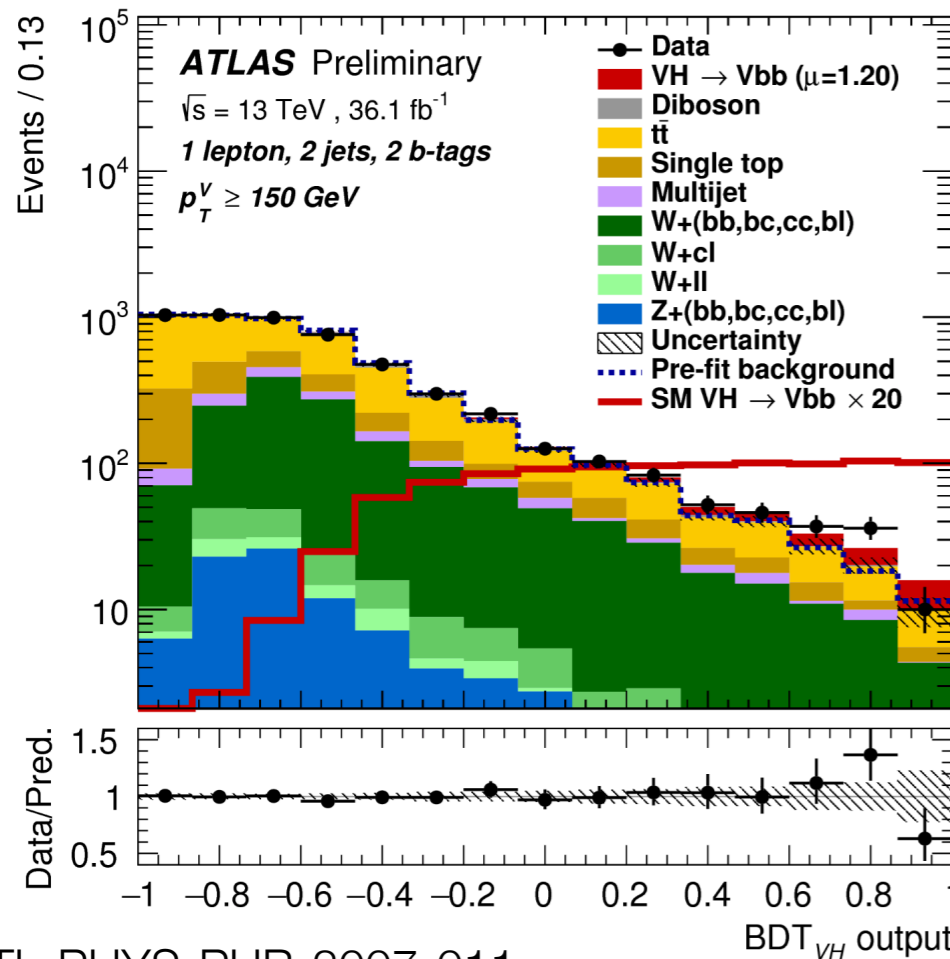
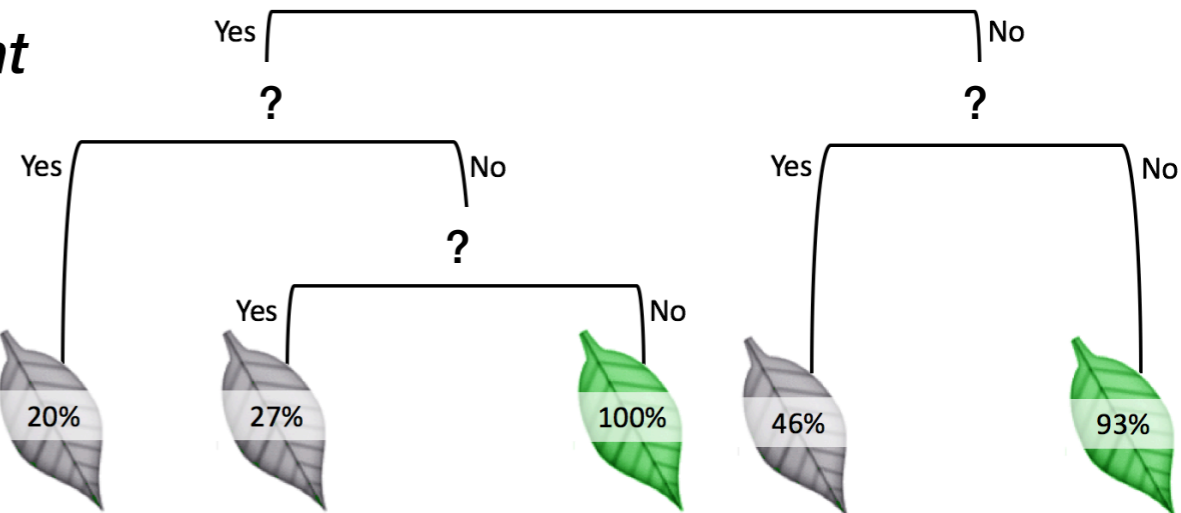
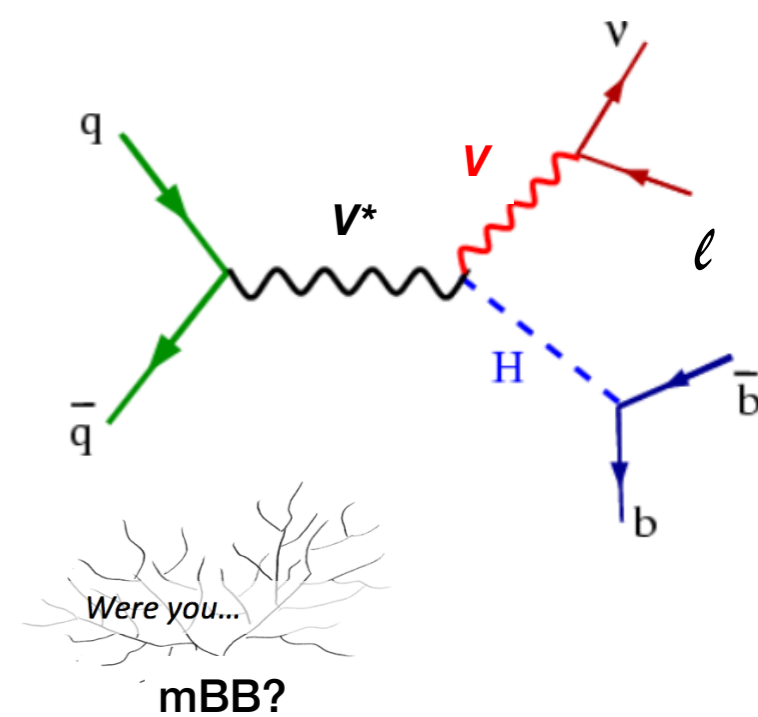
mBB  
distributions



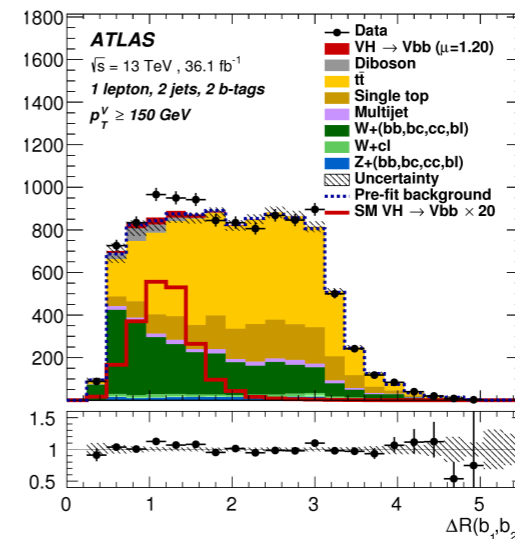
# Signal extraction (MVA)

$m_{bb}$  is the most discriminating variable for  $VHbb$  signal:

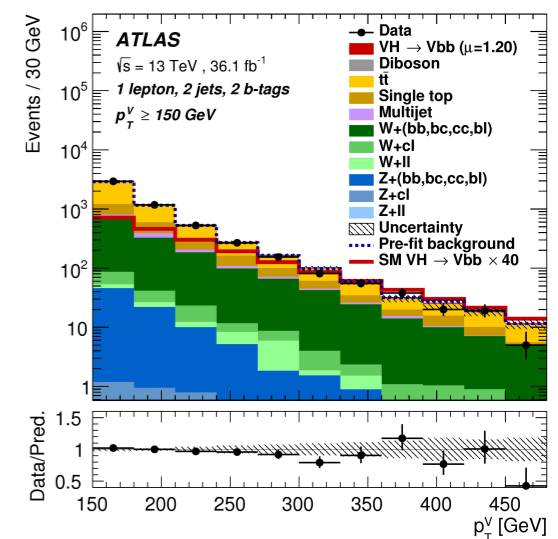
- Construct BDT of **several variables** to have better discrimination (141 BDT bins in 14 regions.)
- **$m_{bb}$ ,  $dR_{BB}$  and  $P_T^V$  are in order the most important variables**
- Separate trainings for each region



$m_{BB}$



$dR_{BB}$



$P_T^V$

# Signal extraction (MVA)

BDT  
distributions

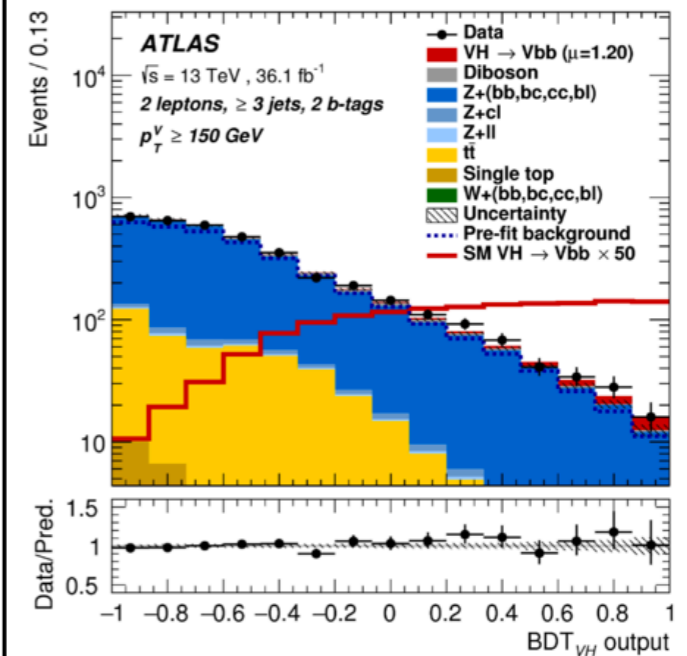
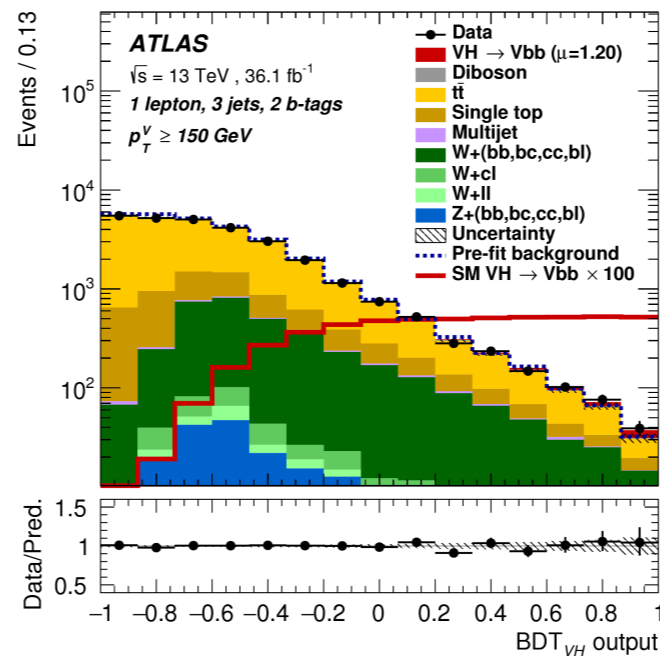
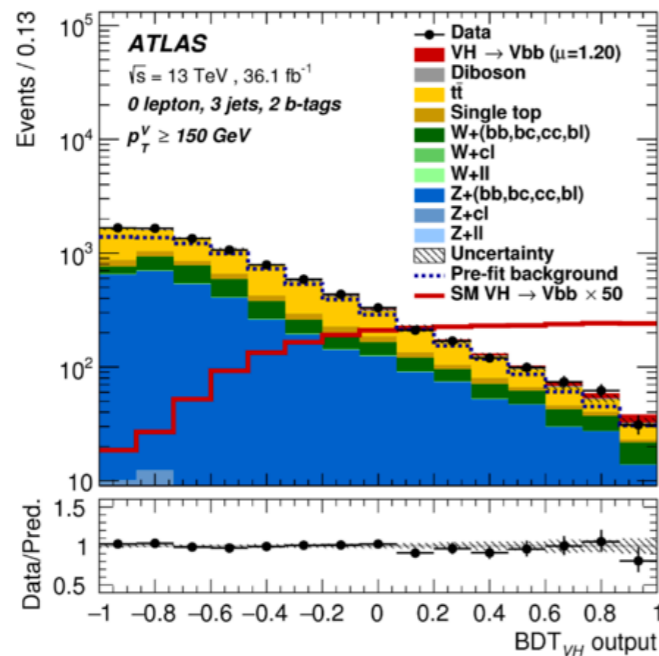
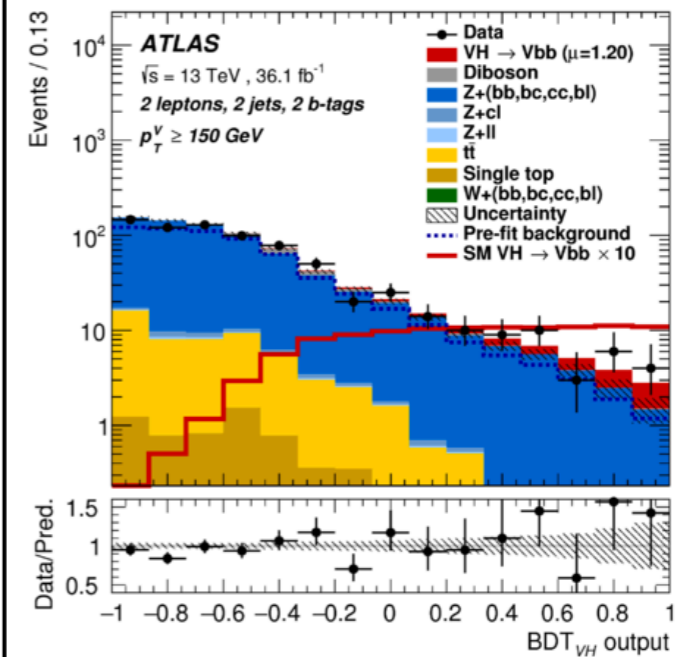
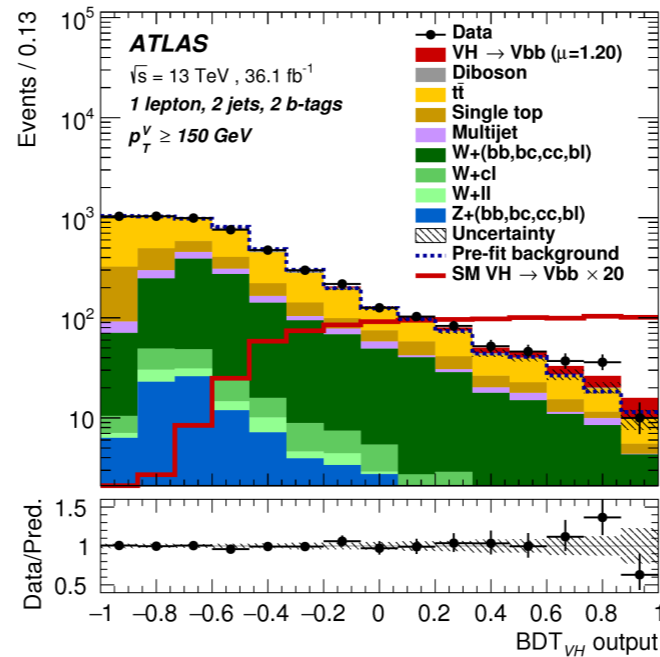
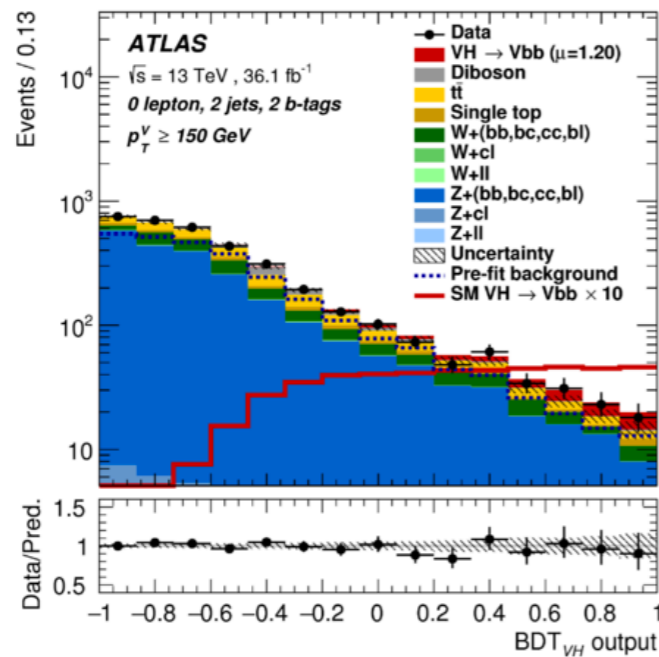
2-jet

3-jet

0-lepton

1-lepton

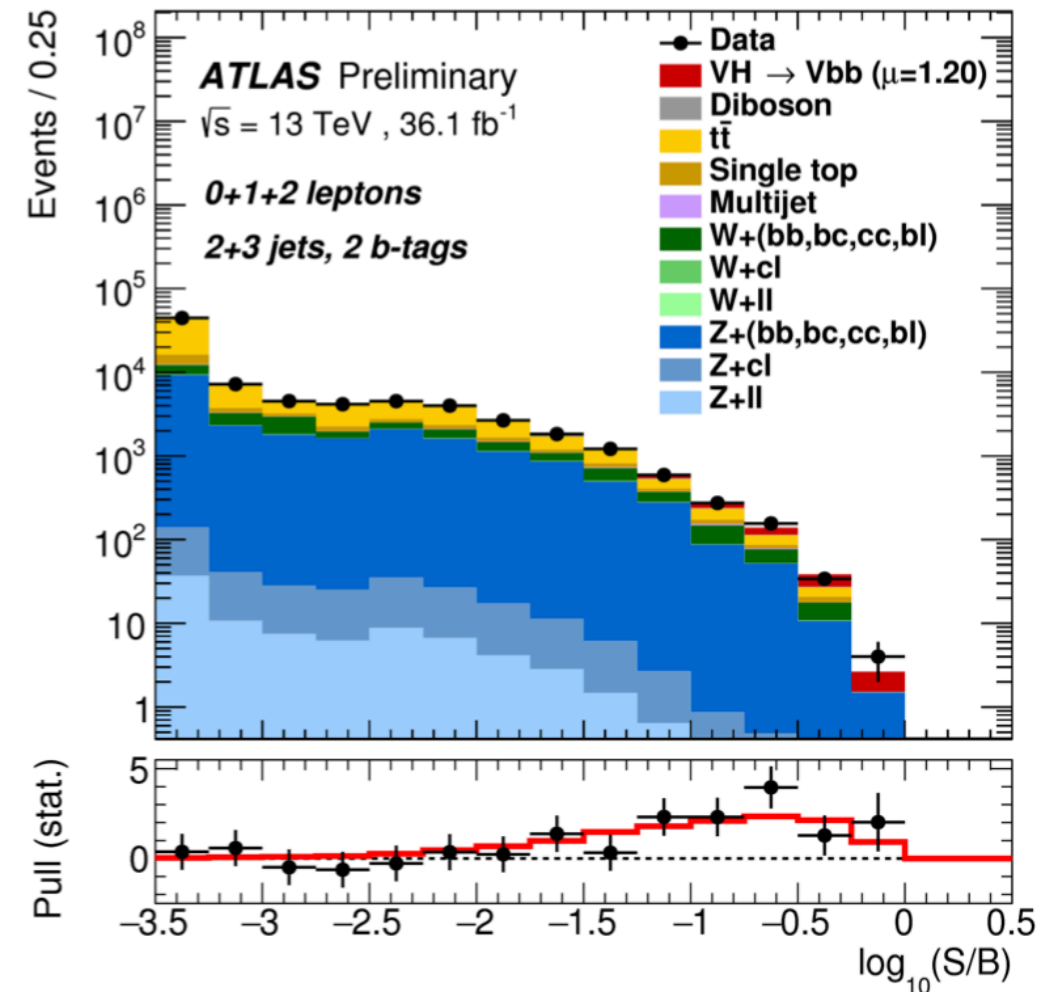
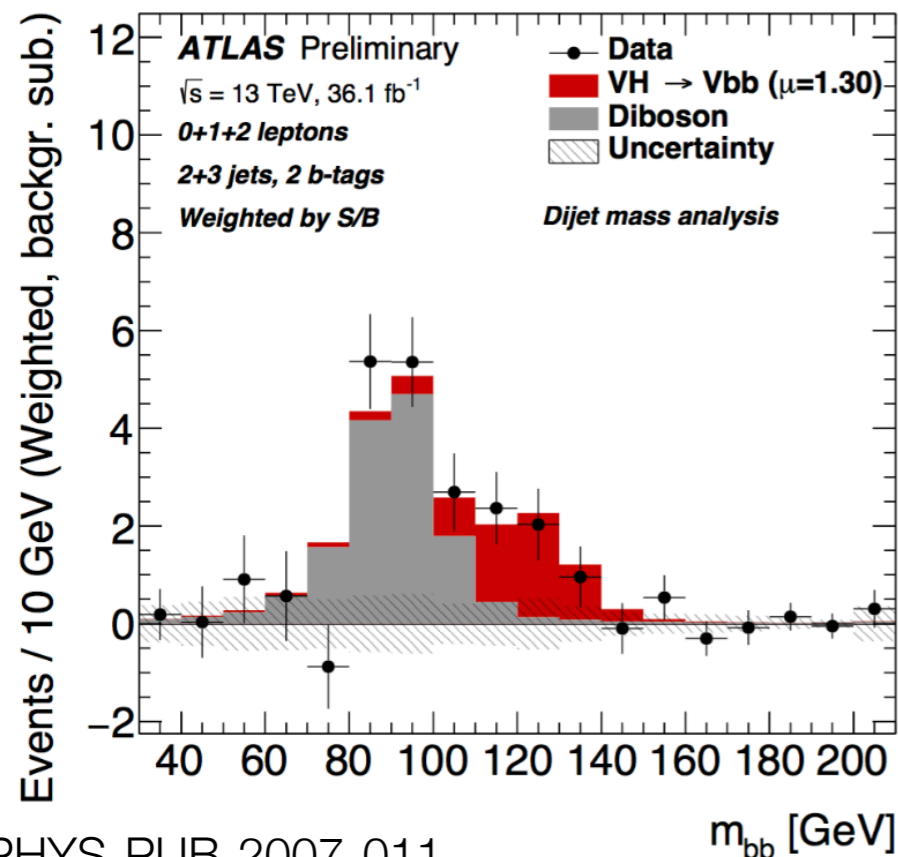
2-lepton



# The Analysis in a nutshell

## Main steps:

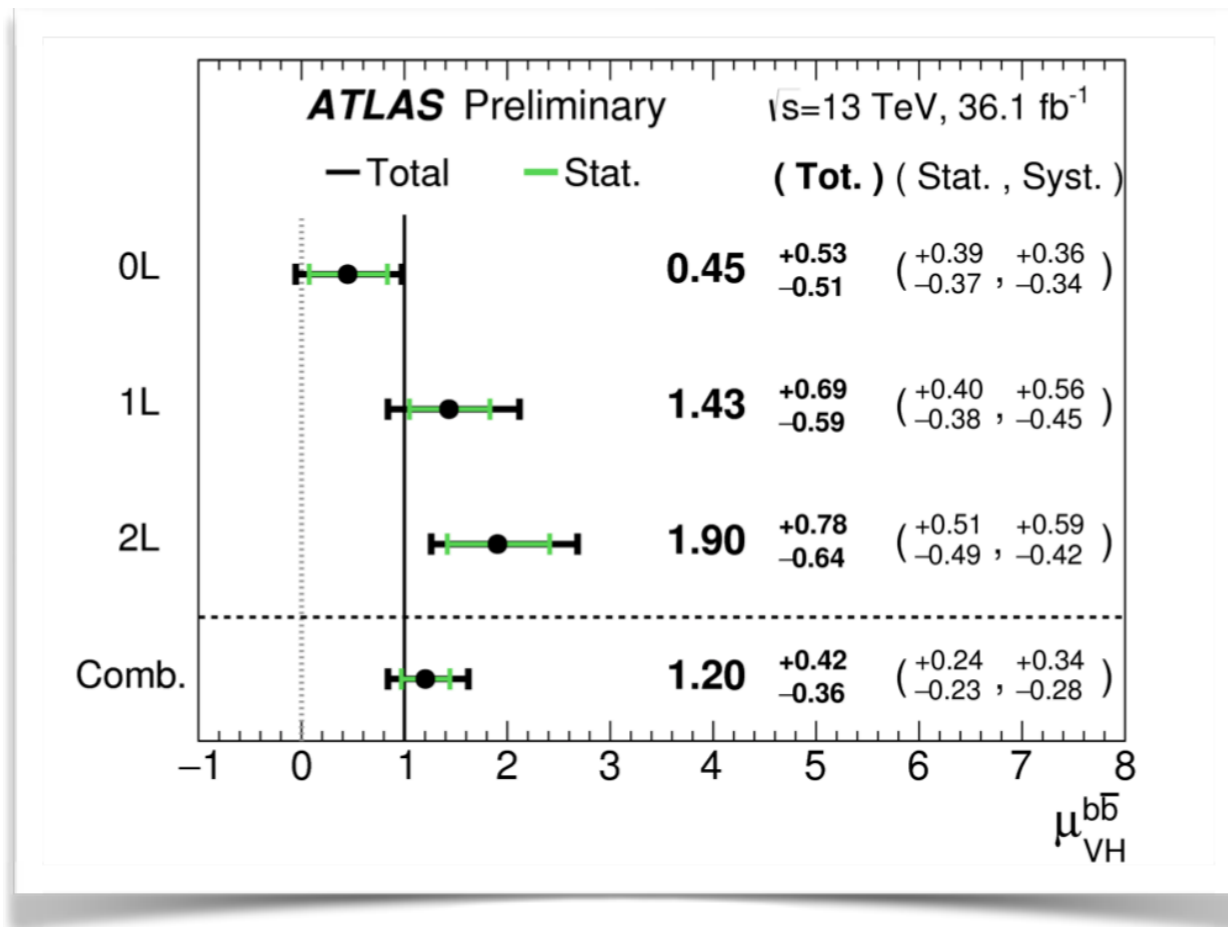
- Use **Multivariate Analysis** (BDT) to combine a set of observables. (mBB, dRBB and pTV the most powerful)
- Use **control regions** enriched in one of the backgrounds to constrain the normalizations.
- Use a **binned likelihood fit on the BDT** distribution to extract the significance.



## Validation:

- Cross check using a cut-based approach on mBB. (No BDT)
- Validate the BDT analysis with VZ(bb) events. Same chain, but different cuts: observed at  $5.8\sigma$

# 2017 Results : Evidence @ 13 TeV!



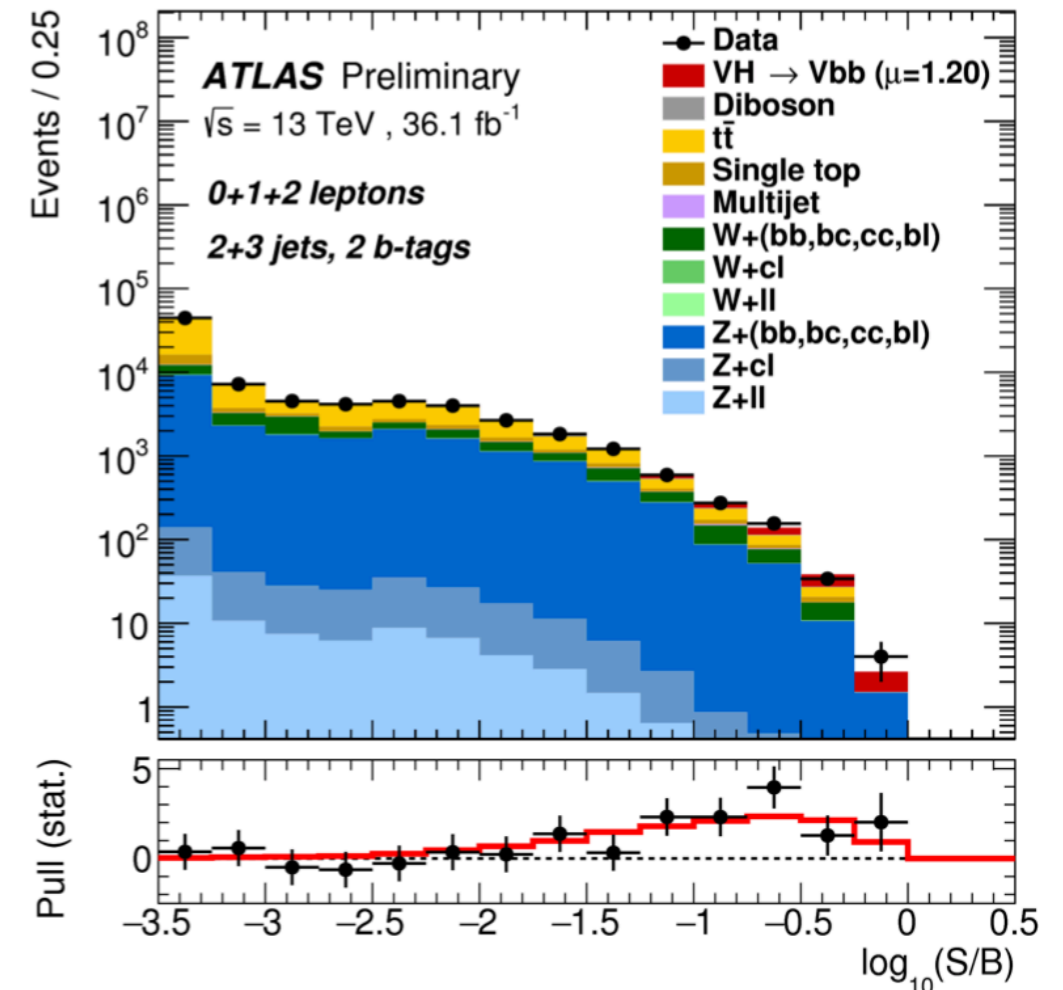
Note: what is the “expected” significance?

The “Expected” sensitivity quantifies how sensitive is the experiment to see the signal, under assumption of a SM Higgs ( $\mu = 1$ ).

The “observed” significance is what we actually measure.

Note: Why 3“sigma” is so important?

The null hypothesis to have a background fluctuation as great or greater than the observed number of signal events is “really” unlikely (probability of  $1.35 \cdot 10^{-3}$ ), which expressed in Gaussian statistic corresponds to 3 standard deviations from the mean value. Reaching this value is commonly defined as “**observation**”, the “**discovery**” is reached at “5sigma”, which corresponds to a probability of  $1.23 \cdot 10^{-7}$ .



**Significance:**  
**3.5 $\sigma$  observed**  
**3.0 $\sigma$  expected**

**Results:**

- Cut based analysis: 3.5 $\sigma$  (3 $\sigma$  exp.)
- Combination with Run1: 3.6 $\sigma$  (4 $\sigma$  exp.)

# Conclusions

## Electron Calibration with $J/\psi \rightarrow ee$ :

- We validated the calibration chain with another SM “candle” at low energies. Useful to all the analyses involving electrons.
- Es: Higgs mass CONF Note is including  $J/\psi \rightarrow ee$  validation plots:
  - <https://cds.cern.ch/record/2271145>

## VH, $H \rightarrow bb$ Analysis:

- An example of complex analysis in which electrons (and muons) are fundamental to reduce the QCD background.
- Observation reached just recently, because of the different challenges of the final state (es. b-tagging).
- First look to the coupling with fermions: it seems compatible with Standard Model predictions!
- Stay tuned: looking forward to reach  $5\sigma$ ..

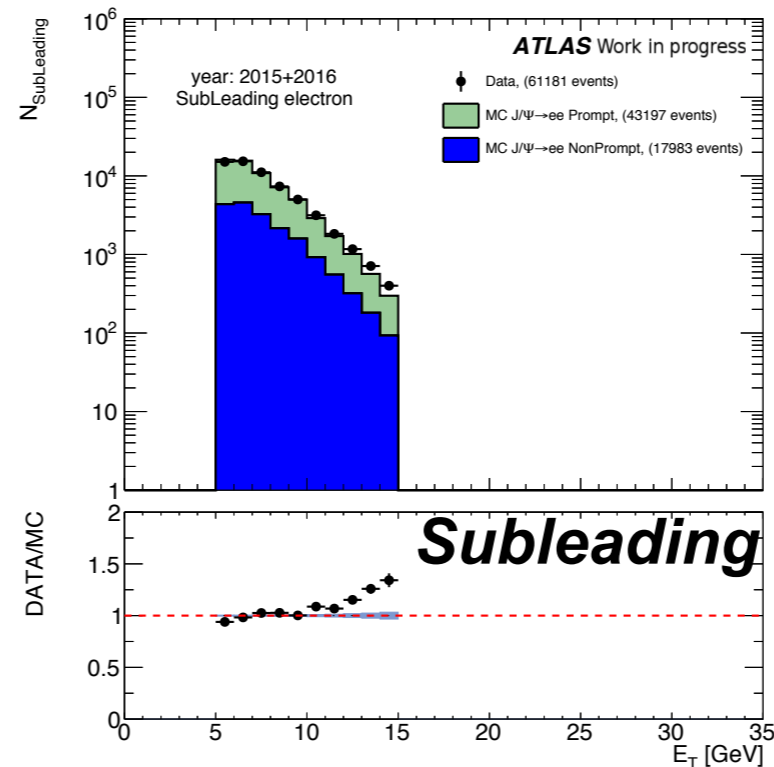
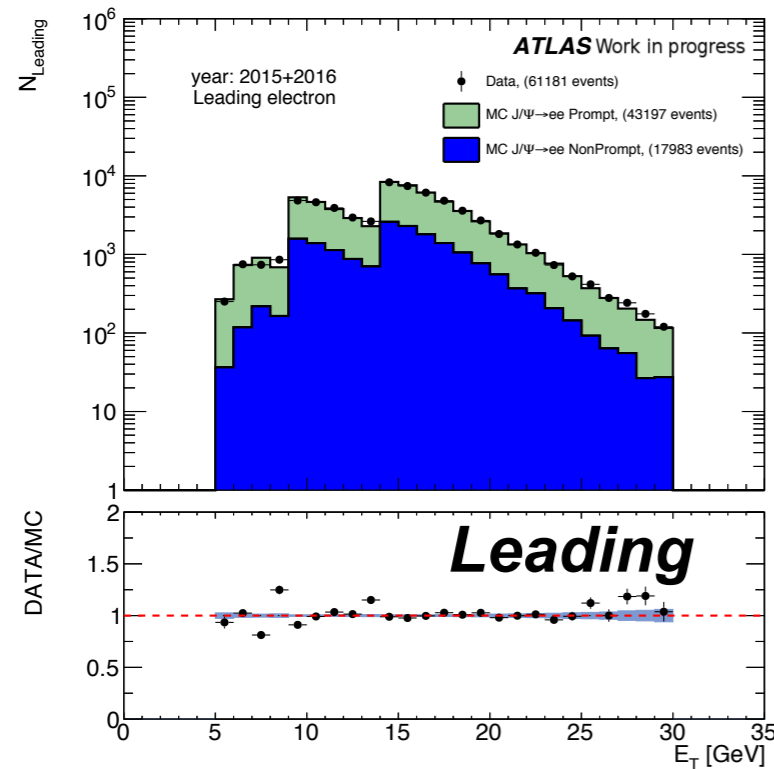


# Backup

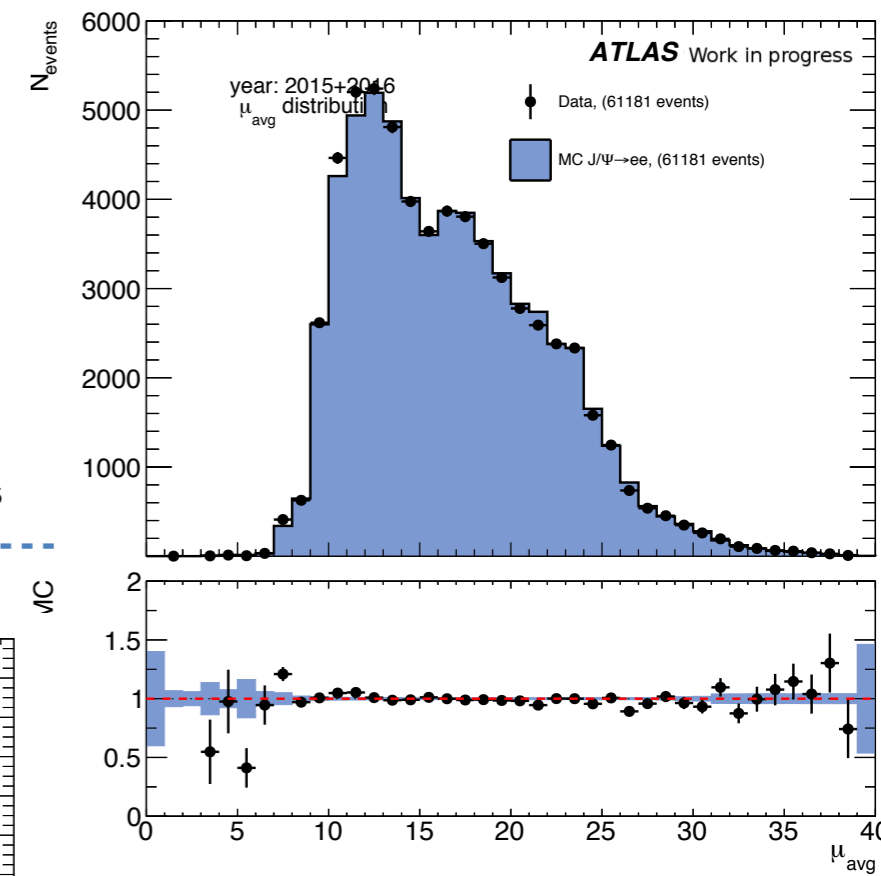
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# $J/\psi \rightarrow ee$ kinematic distributions

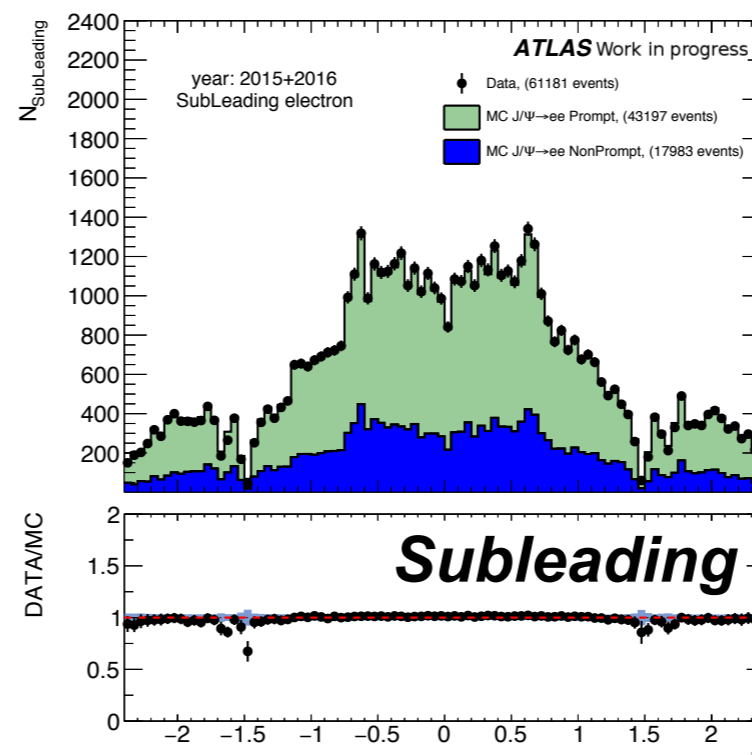
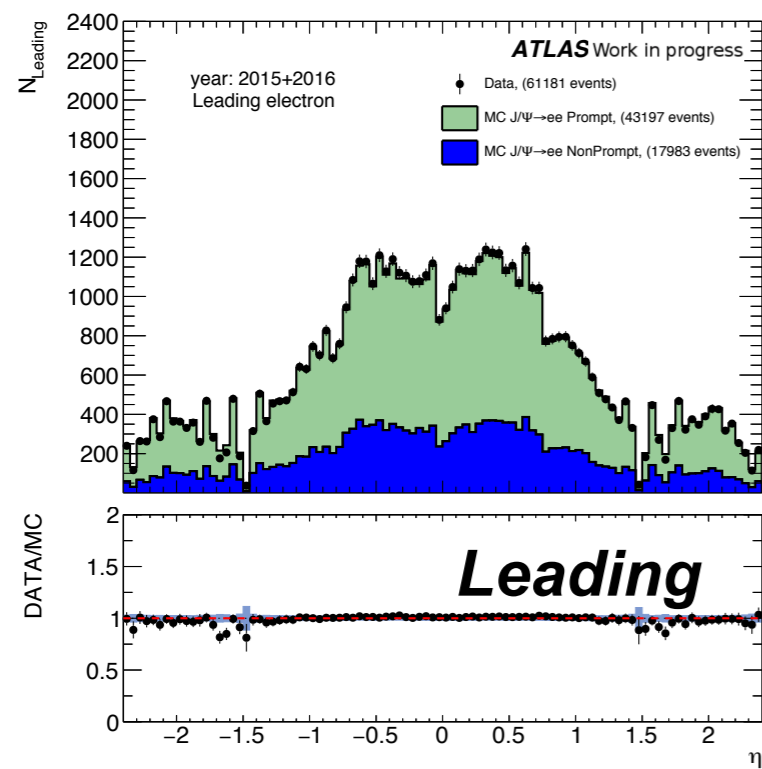
$E_T$



**Pile-up**



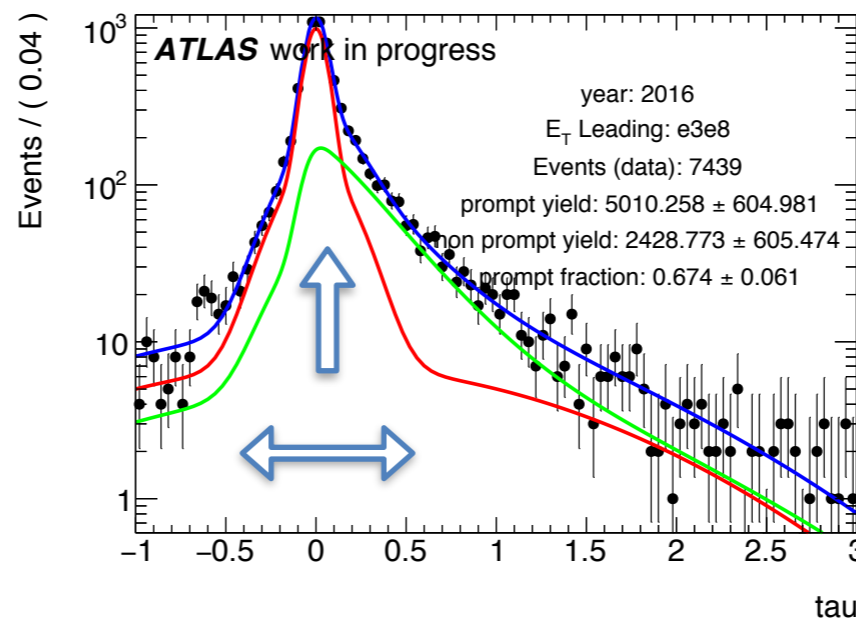
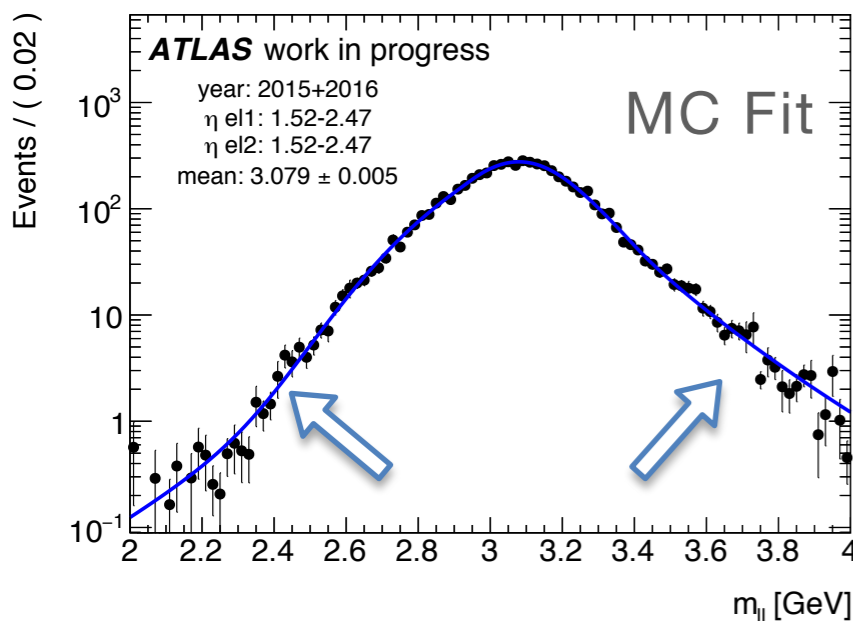
$E_{\eta}$



# $J/\psi \rightarrow ee$ systematic uncertainties

We varied the parameters involved in the fit to estimate the **systematic uncertainties**

- pseudo proper time settings
- eta reweighting
- PDF shapes
- ranges



## Mass Fit Variations:

- Thresholds

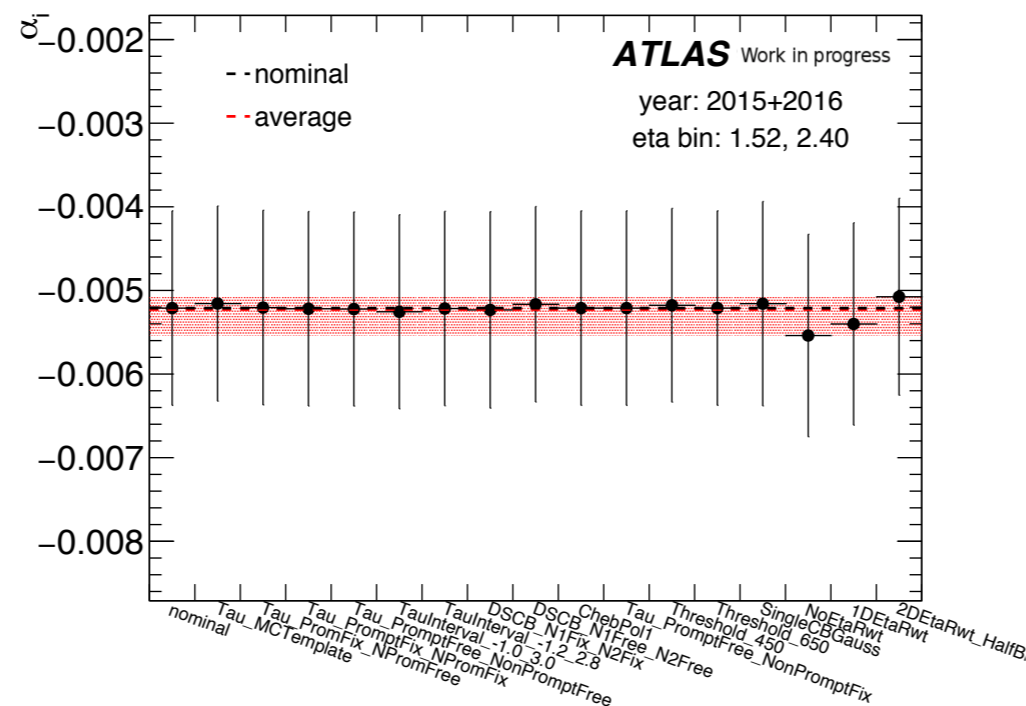
## Signal Shape:

- N1 in Crystal Ball 1
- N2 in CrystalBall 2
- CB + Gauss

## Background Shape:

- Chebychev Pol1
- Expo Background

We recompute the scales applying just **one** variation:



## Tau Fit Variations:

- Fit Ranges
- PDF Model (4 cases)
- MC Template

## Reweighting variations:

- NoEtaRwt
- 1DEtaRwt
- 2DEtaRwt

# Sampling term: Error calculation

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- An eventual change in the sampling term value equal to the uncertainty on the residual sampling term would have a relative impact of:

$$\Delta = \frac{\sqrt{d\Delta a^2 + a^2}}{a}$$

- Assuming  $a = 10\%$ , this is relative change quantified to be: **1%** in the barrel and **7%** in the endcaps.
- Another source of uncertainty is coming from the uncertainty on the noise term (100 MeV/  $E_T$ , 200 MeV/  $E_T$  in the region [1.4, 1.8]). The equivalent uncertainty on the sampling term is:

$$\frac{\Delta a}{\sqrt{E}} = \frac{\Delta b}{E_T} \Rightarrow d\Delta a = \frac{100 \text{ MeV}}{E_T} \sqrt{E}$$

- Considering an  $E_T \sim 12 \text{ GeV}$  (14 GeV) in the barrel (endcaps), and  $E$  as in slide 11 ( $\sim 12 \text{ GeV}$  and 28 GeV) we get: 2.9% (3.8%) respectively.
- Summing in quadrature these effects we have an **overall uncertainty on the relative sampling term of 4% (5.5%)**, which translates in a **8% (14%) possible relative change on  $a$** .