CSI - Second year PhD presentation

Search in the dilepton final state in proton–proton collisions at $\sqrt{s}$=13 TeV with the ATLAS detector

Laboratoire d'Annecy de physique des particules
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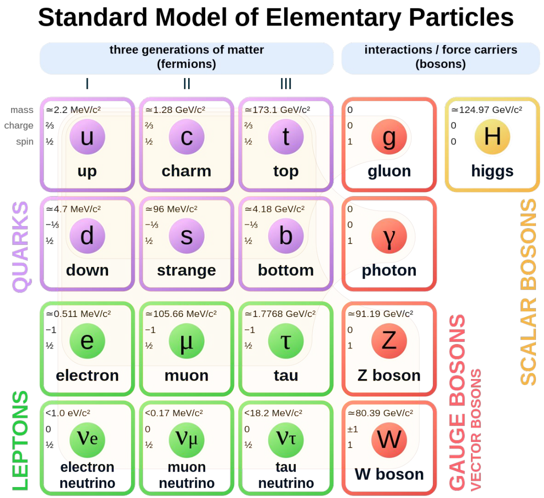
CSI : Fawzi Boudjema from LAPTH & Corinne Goy from LPSC

Introduction

★ Standard Model is only the piece of a more complete model



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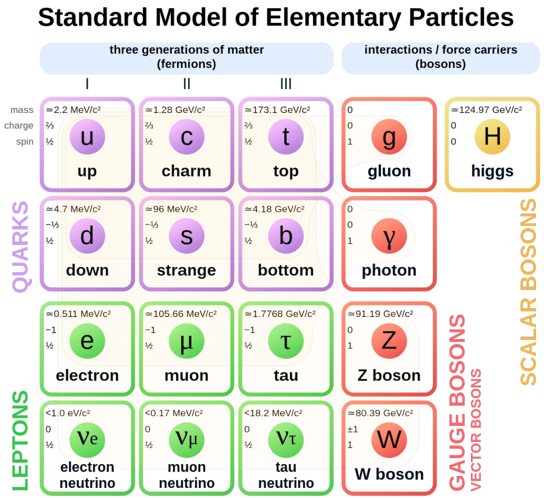

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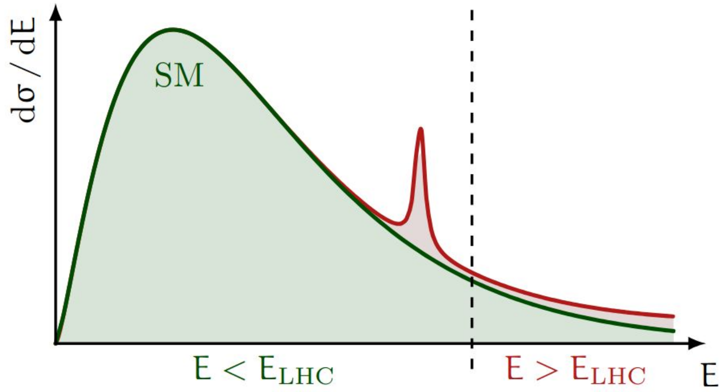
At LHC : Direct searches



Introduction

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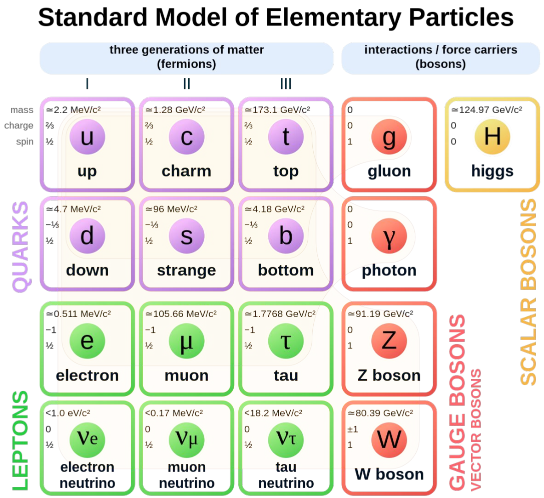

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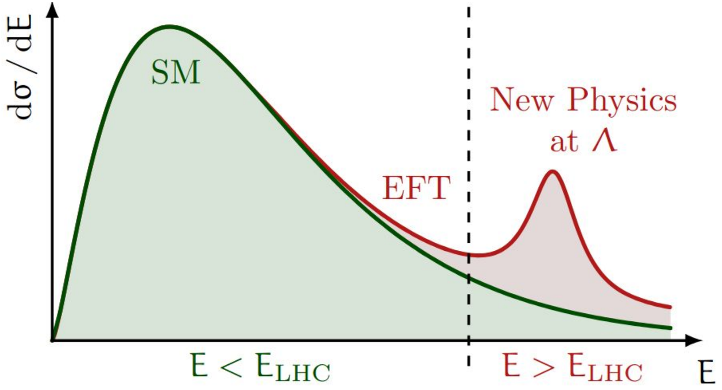
At LHC : Precision measurement + EFT interpretation



$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_{d,i}}{\Lambda^{d-4}} \mathcal{O}_{d,i}$$

OUTLOOK

- Search for new Z' resonances in the final state with two leptons + X
- High mass Drell-Yan double differential cross-section measurement in an exclusive final state with b-jets.

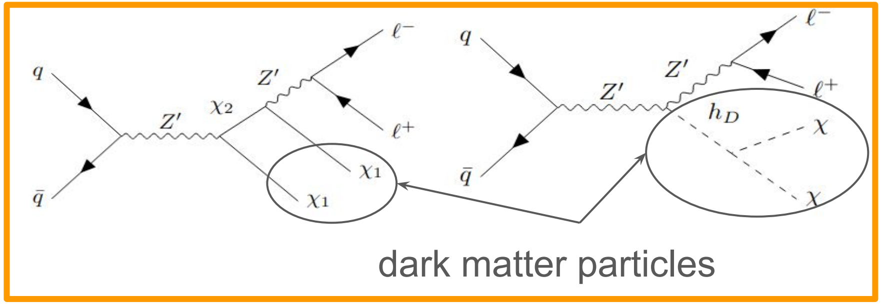
Direct searches

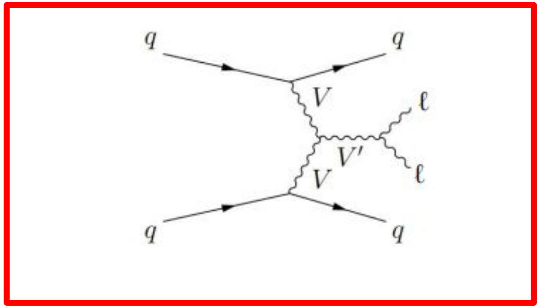
- Search for new Z’ resonances in the final state with two leptons + X

I contributed to 2 channels :

- Z’+MET*
- Z’+VBF* jets

MET* = Missing Transverse Energy
VBF* = Vector Boson Fusion





My main task was the development of statistical tools

Results for the **Z' + MET** channel were publicly released in August 2023 (ATLAS-CONF-2023-045)!

★ We set new limits on the **Z' cross-section** (1 order of magnitude better) and **lepton coupling**!

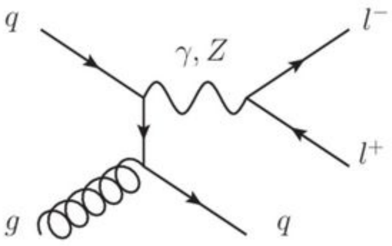
★ I presented the results at JRJC and wrote a proceeding on it.

Precision measurement

- High mass Drell-Yan double differential cross-section measurement in an exclusive final state with b-jets. (HMDY+b)

Precision measurement HMDY+b

- High mass Drell-Yan (DY) process at Next to-Leading Order (NLO)



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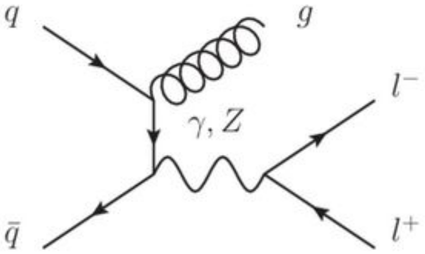


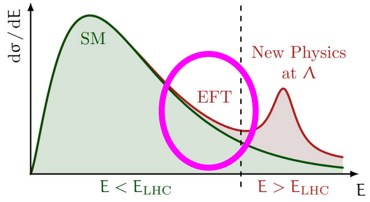
+ …

SM processes

+ BSM processes ?

➢ The **large cross-section of the Drell-Yan** process facilitates **precision measurements**, while the **high-mass region** is **sensitive to new physics**.

➢ Looking at final state with additional selection on number of b-jet
   - b-jet add sensitivity to new phenomena
   - Direct connection to b-anomalies (i.e. bsll vertex)



Analysis on-going!

Precision measurement HMDY+b

- Goals :

★ Double-differential cross-section measurement as function of dilepton (ee and mumu) mass and b-jet multiplicity

dilepton mass range : 130 GeV - 5 teV

b-jet multiplicity : 0 | 1 | ≥ 2

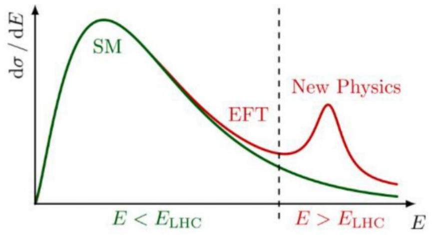
★ Lepton Flavor Universality test

Electroweak coupling of the gauge bosons to leptons is independent of the lepton flavour

⟶ Deviation to 1 of $R \frac{\sigma(DY \to ee)}{\sigma(DY \to \mu\mu)}$ could help probing new physics

★ Constraint of new physics effects with Effective Field Theory

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_{d,i}}{\Lambda^{d-4}} \mathcal{O}_{d,i}$$

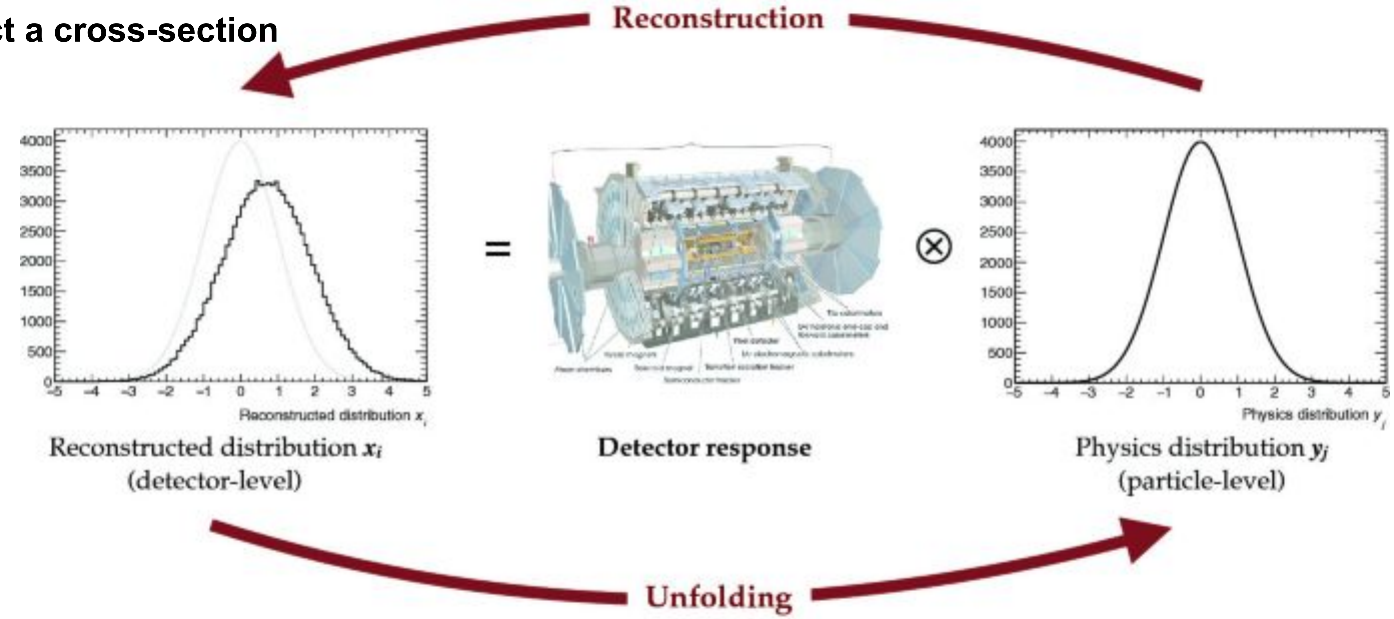


Precision measurement HMDY+b

- Unfolding

Unfolding is used to remove detector resolution effects from observed distribution in order to extract the underlying truth distribution.

→ **e.g. extract a cross-section**



Precision measurement HMDY+b

- Fiducial phase space to unfold to

Electrons

- p_t > 40, 30 GeV
- $|\eta| < 2.5$

Muons

- p_t > 40, 30 GeV
- $|\eta| < 2.5$

Jet

- pt > 20 GeV
- B-tagging via ghost association

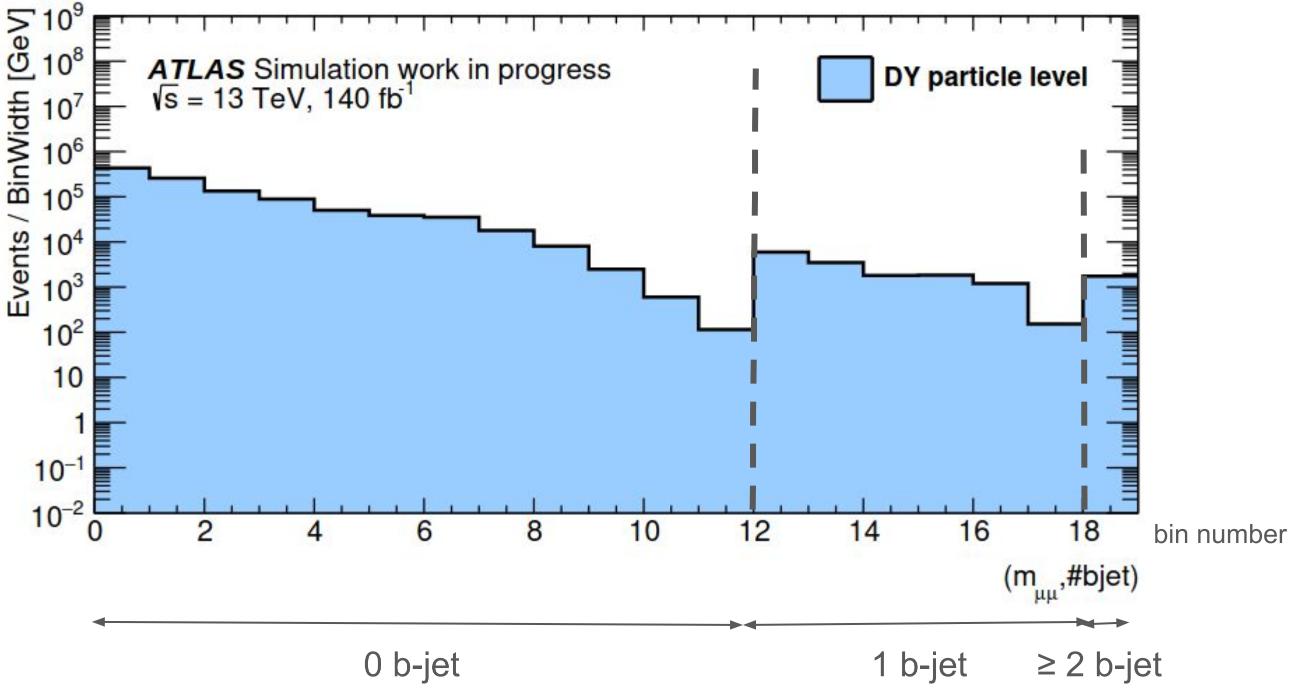
Event

- Exactly two opposite sign, same flavour leptons
- mll > 130 GeV
- **MET < 30 GeV***

Precision measurement HMDY+b

- Observable to unfold : 2D Observable : (m_ll,#b-jet)

particle (truth) level



Precision measurement HMDY+b

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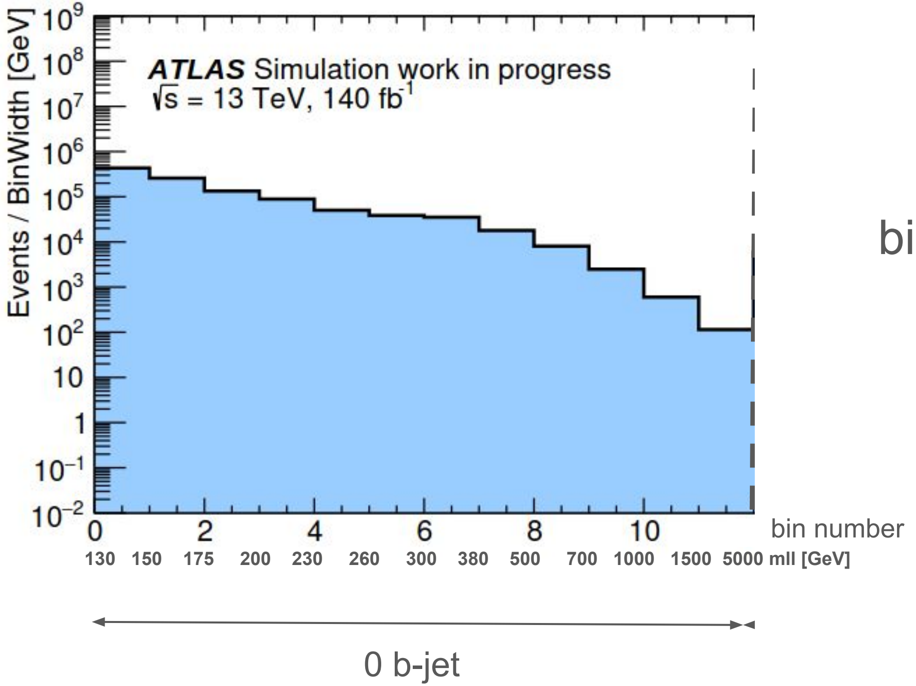
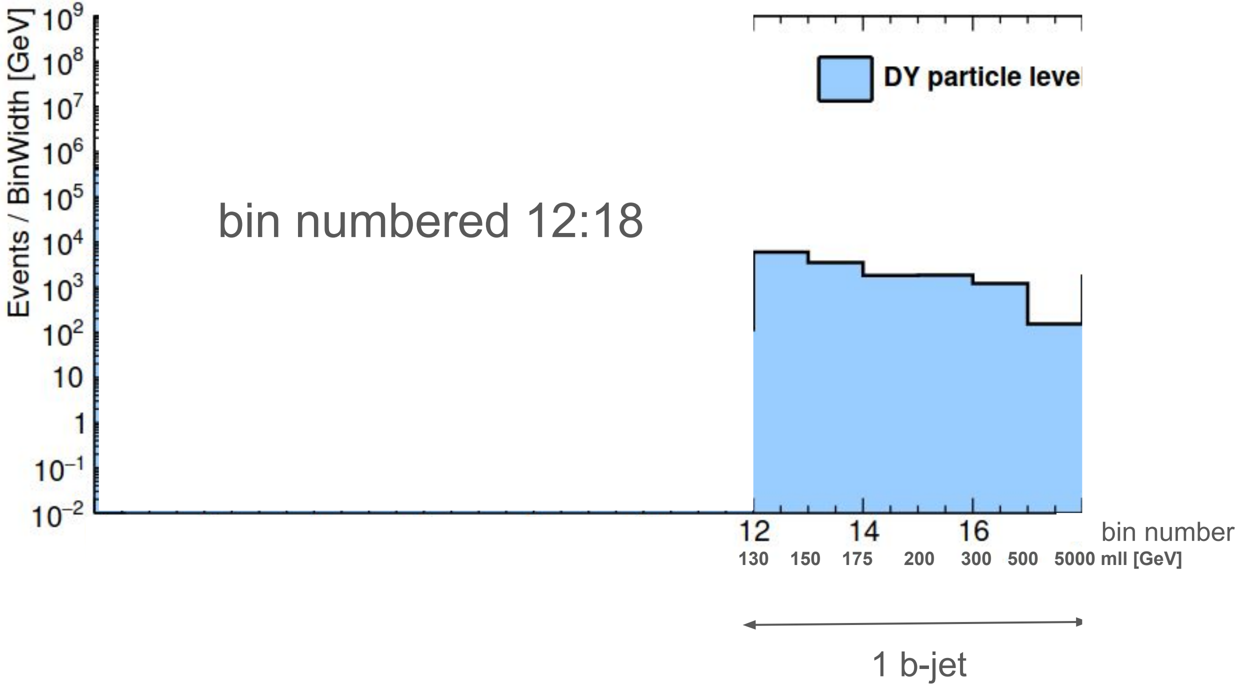


bin numbered 0:11

Precision measurement HMDY+b

- Observable to unfold : 2D Observable : (m_ll,#b-jet)



Precision measurement HMDY+b

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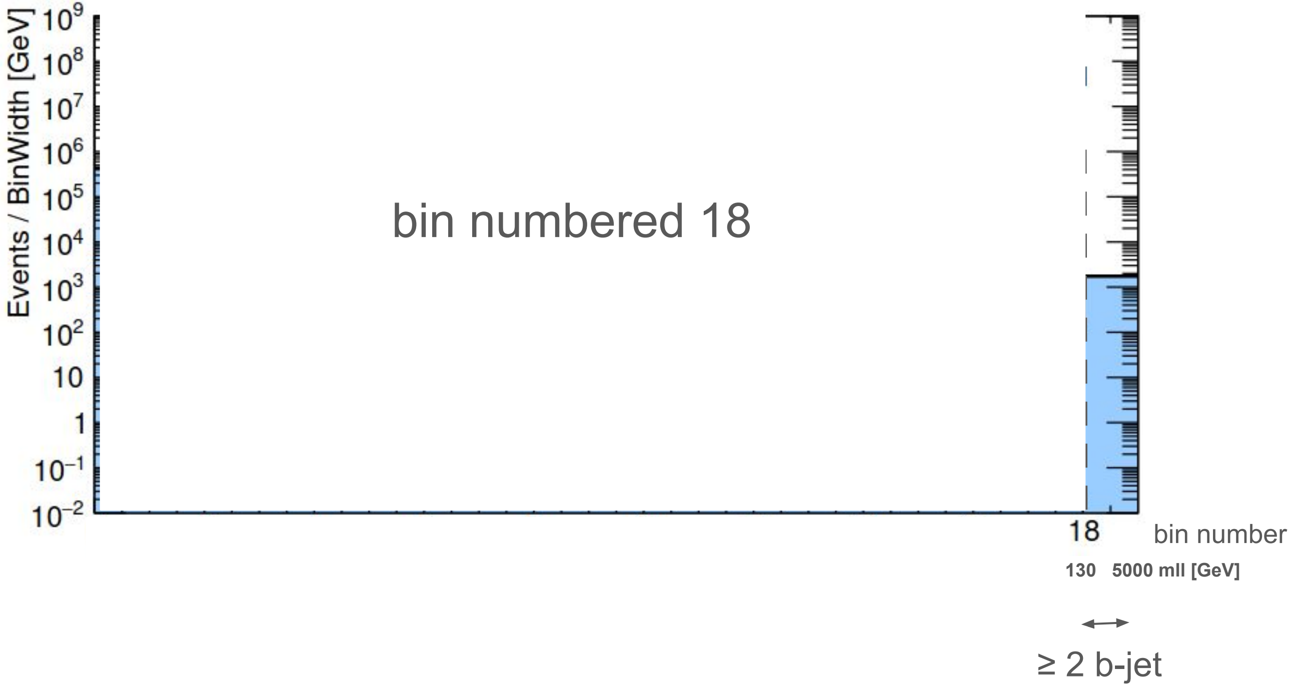

Precision measurement HMDY+b

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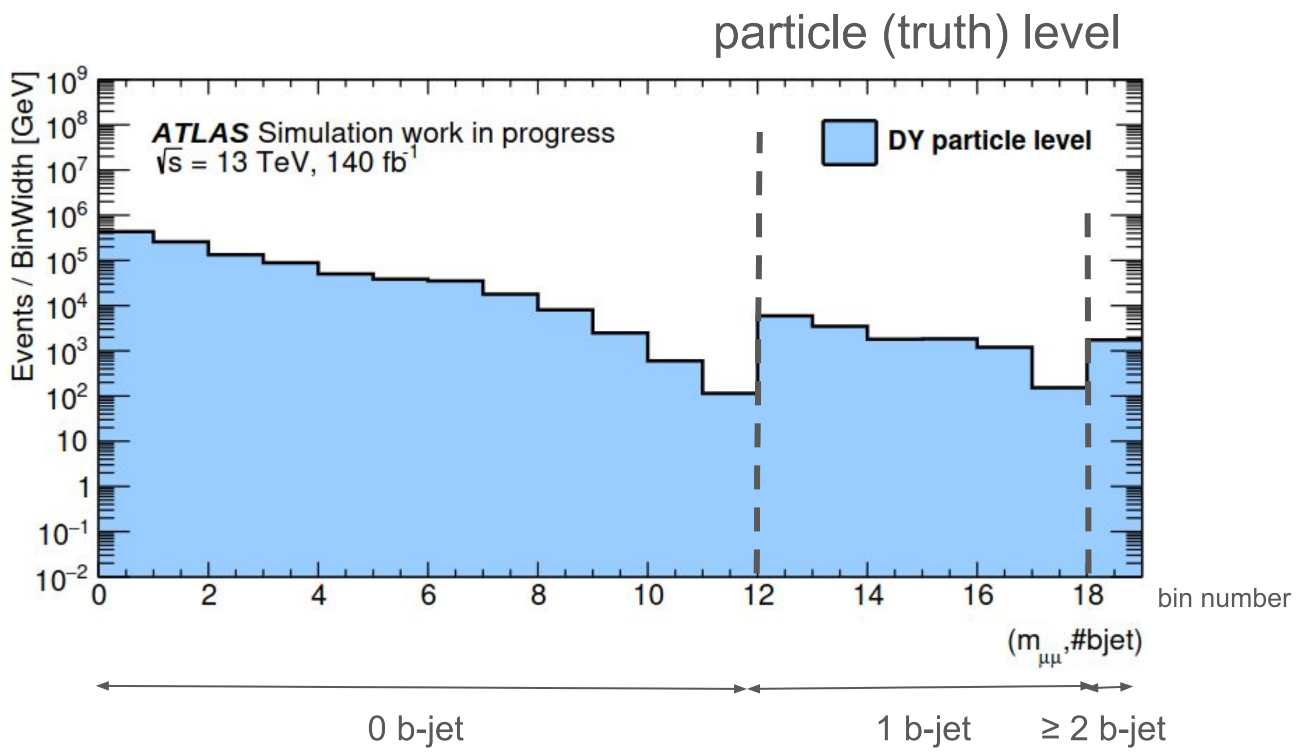
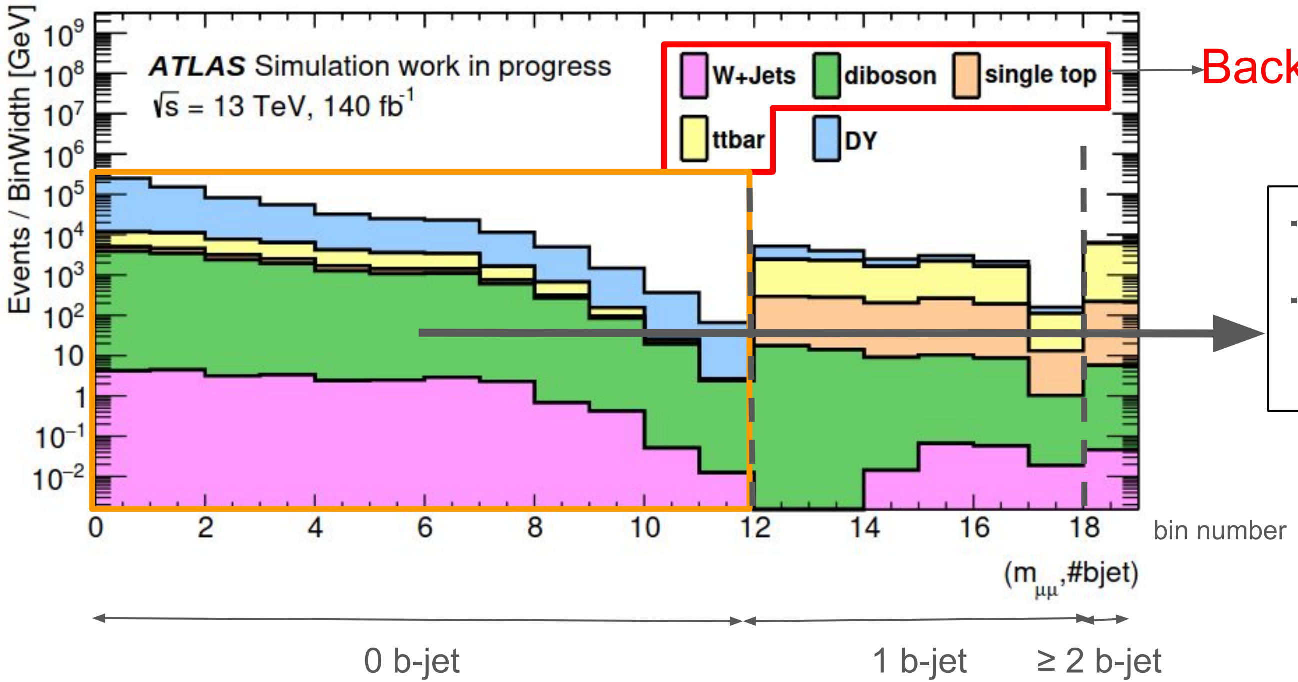


Precision measurement HMDY+b

- Observable to unfold : 2D Observable : (m_ll,#b-jet)

Reconstructed level (particle level + detector effect)

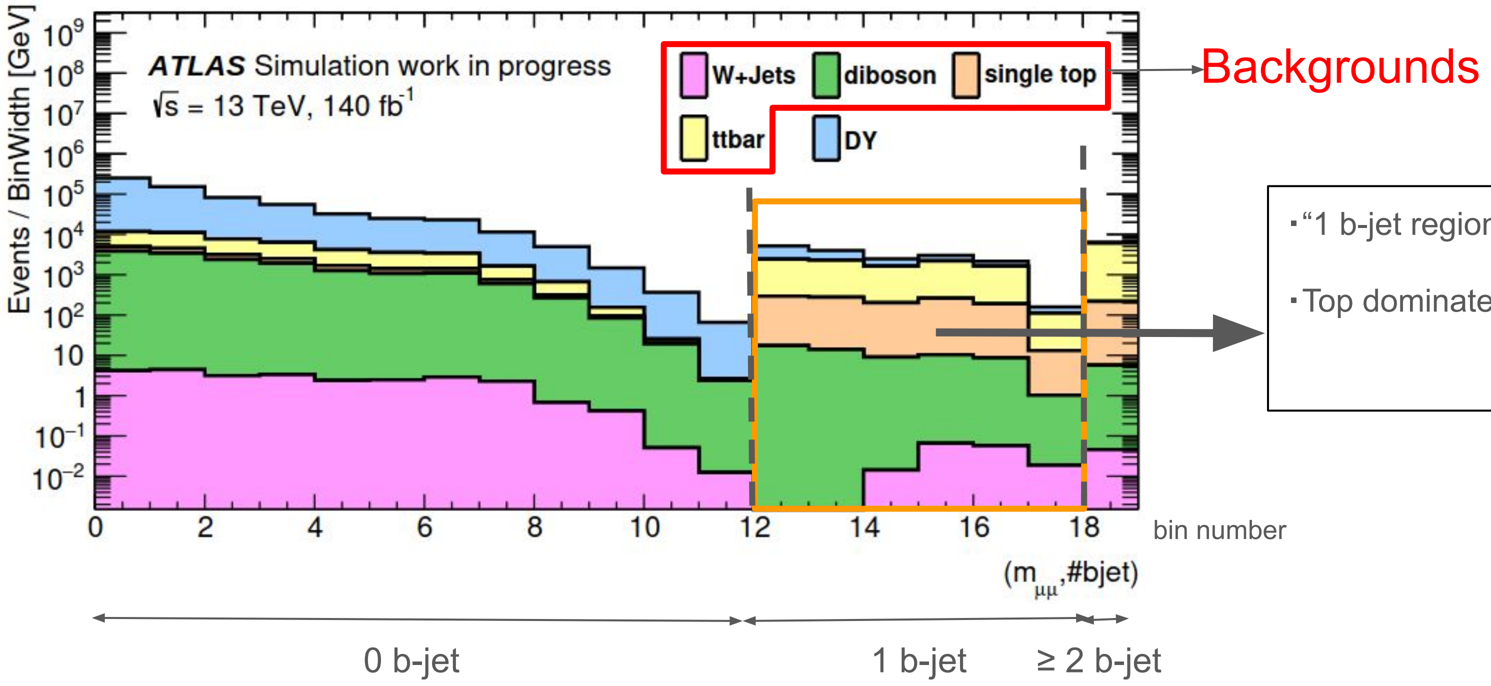


- "0 b-jet region"
- DY dominated.

Precision measurement HMDY+b

- Observable to unfold : 2D Observable : (m_ll,#b-jet)

Reconstructed level (particle level + detector effect)

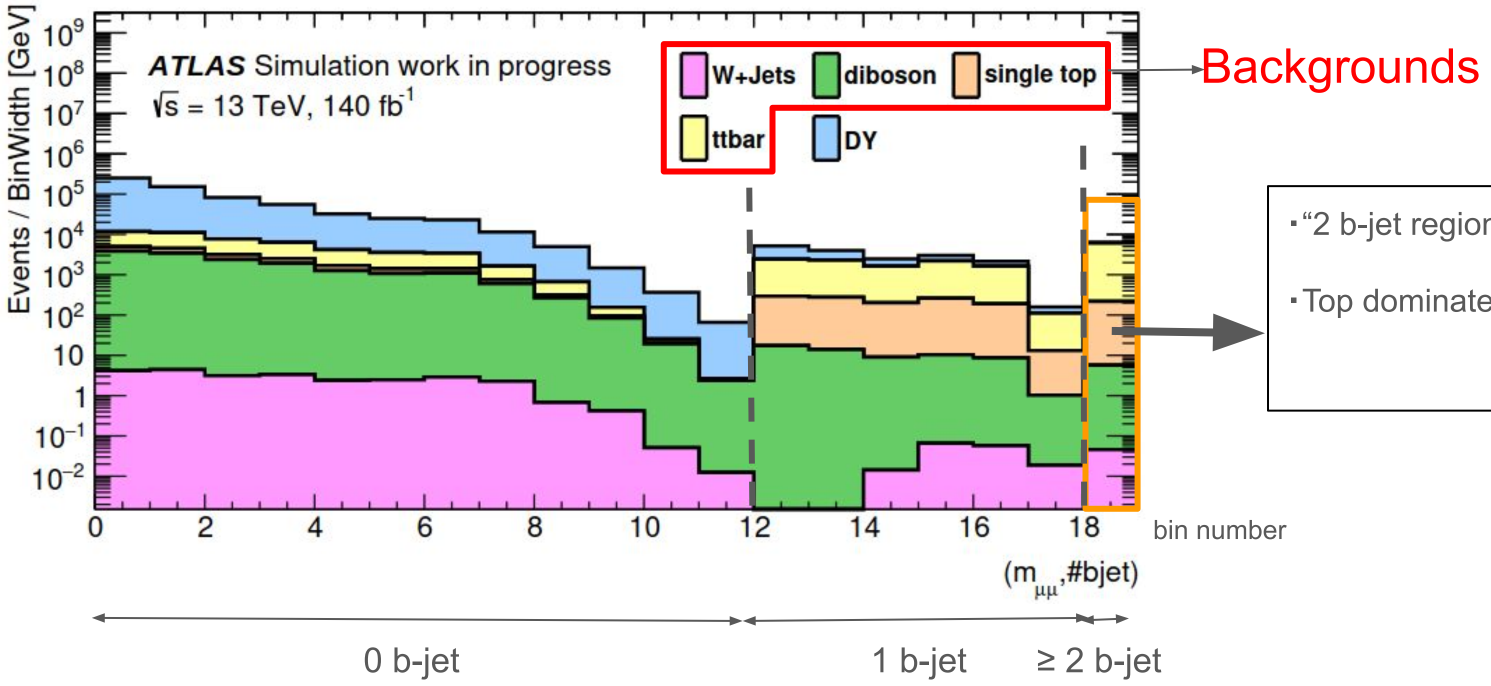


- "1 b-jet region"
- Top dominated.

Precision measurement HMDY+b

- Observable to unfold : 2D Observable : (m_ll,#b-jet)

Reconstructed level (particle level + detector effect)



- "2 b-jet region" (but means "≥ 2")
- Top dominated.

Precision measurement HMDY+b

- Binning optimization

Starting point : Muon channel

- Estimation of **rel. stat. uncertainties** with the formula **: √(DY+ttbar)/DY** for the **muon channel**
- Started with optimized 0 b-jet region binning and merge bins from **right to left** in order to achieve an acceptable rel. stat. uncertainties

130 150 175 200 230 260 300 380 500 700 1000 1500 5000

Inclusive	<	<	<	<	<	<	<	0.01	0.01	0.02	0.05	0.13
exclusive 1 bjet	0.04	0.06	0.08	0.12	0.17	0.20	0.22	0.29	0.37	0.49	0.72	1.07
											0.62	
										0.40		
				0.09			0.17		0.29			
				0.10		0.13			0.29			

rel. stat. uncertainties

100% statistical uncertainty !

Chosen one. 6 bins (n12:17)
Allows to keep a correct binning multiplicity to stay sensitive to EFT effects.

Precision measurement HMDY+b

- Binning optimization

Starting point : Muon channel

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- Started with optimized 0 b-jet region binning and merge bins from **right to left** in order to achieve an acceptable rel. stat. uncertainties

	130–150	150–175	175–200	200–230	230–260	260–300	300–380	380–500	500–700	700–1000	1000–1500	1500–5000
Inclusive	<	<	<	<	<	<	<	0.01	0.01	0.02	0.05	0.13
exclusive ≥2 bjet	0.46	0.75	0.91	1.30	1.93	2.16	2.07	2.40	3.10	4.25	4.17	5.13
											3.52	
										3.13		
									2.35			
	0.34											

rel. stat. uncertainties

500% statistical uncertainty !

Chosen one : single bin (n18) top background contamination makes it very challenging in this region.

Precision measurement HMDY+b

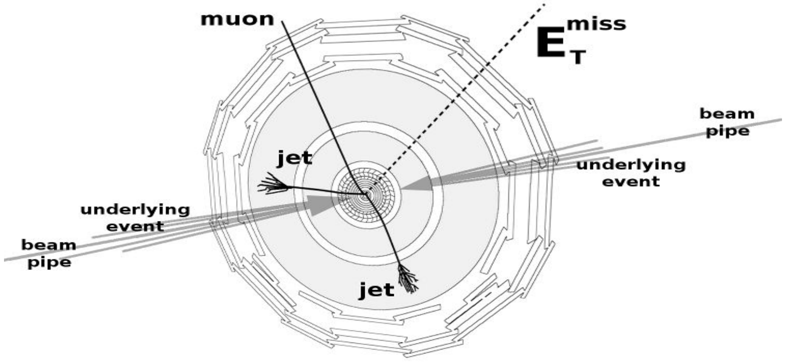
- Selection

Would a cut on missing transverse energy (MET) could improve signal purity in b-jet region dominated by top background ?

In ATLAS, MET primarily arises from neutrinos. In this channel, neutrinos are mainly produced by the decay of W bosons, which themselves originate from the decay of top quarks.

$$t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow (\ell^+ \nu b)(\ell^- \bar{\nu} \bar{b}) \quad (\ell = e, \mu)$$

No neutrino should be produced at LO by DY process.



Precision measurement HMDY+b

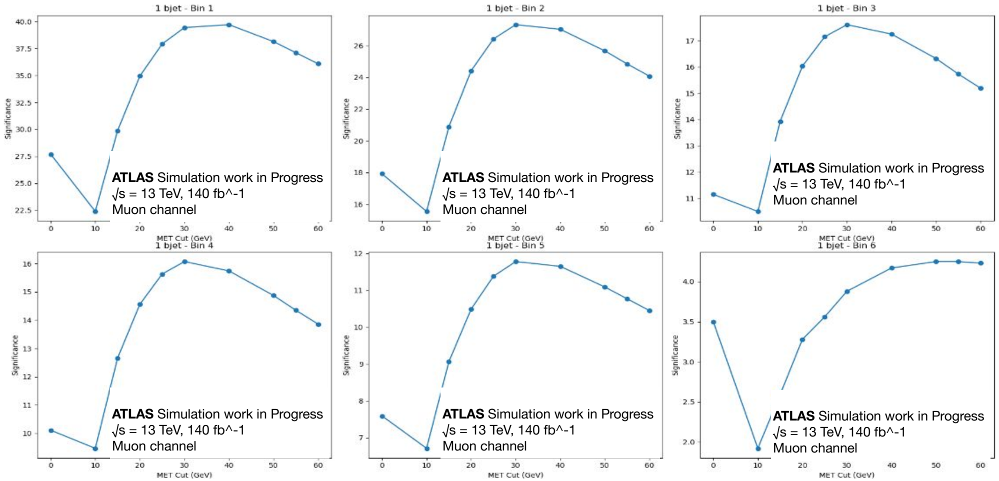
- Selection

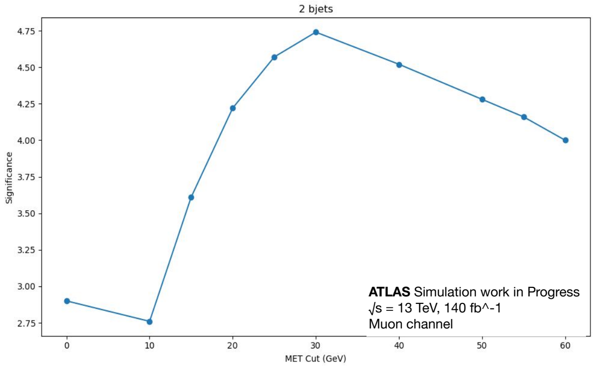
- Study different cutting values : ≥ 10 - ≥15 - ≥20 - ≥25 - ≥30 - ≥40 - ≥50 - ≥55 - ≥60 GeV
- Stat only - **S=DY** & **B=ttbar**
- Look at **significance** & **efficiency**

Significance : S/√(S+B)

≥2 bjet

1 bjet





➔ **30 GeV** cut achieves best performances with better sensitivity across all bins compare to the configuration without any cut on MET

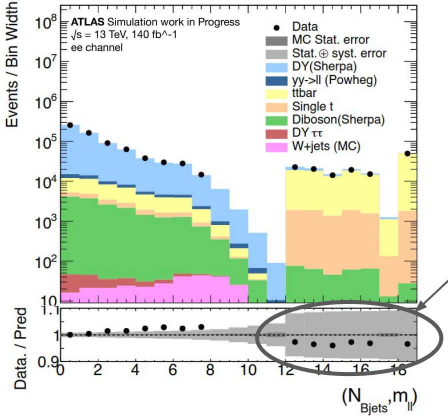
Precision measurement HMDY+b

- ttbar estimation

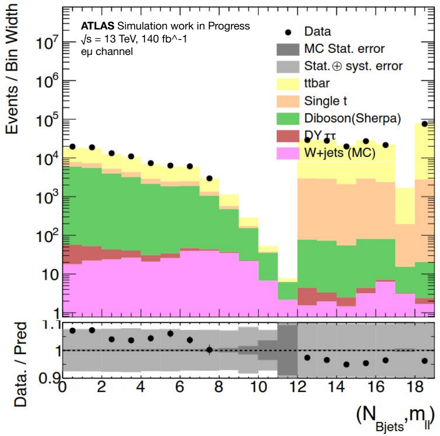
➔ **(partially) Data-driven method** using emu region
  - Overall agreement is fine within large modelling uncertainties
  - The goal is to **constraint** the **ttbar** background in the **1 & 2b-jet** region where it is dominant
  - Use **transfer factor** method to address this

➢ Uncertainties
  - Huge reduction in experimental and modelling uncertainties in the transfer factors R
  - Data statistical uncertainty from the emu CR yields
  - MC stat uncertainty from both SR and emu regions

$$N^{t\bar{t}}_{ee/\mu\mu} = N^{t\bar{t}}_{e\mu} \times R_{e\mu \rightarrow ee/\mu\mu} = N^{t\bar{t}}_{e\mu} \times \frac{N^{t\bar{t},MC}_{ee/\mu\mu}}{N^{t\bar{t},MC}_{e\mu}}$$



- In ttbar-dominated regions (1b&2b), flat uncertainty of ~10% primarily driven by scale uncertainty
- ttbar yield slightly overestimated in 1b and 2b region



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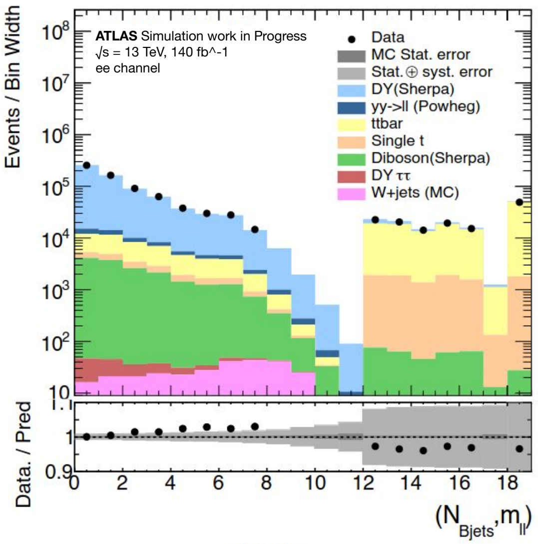
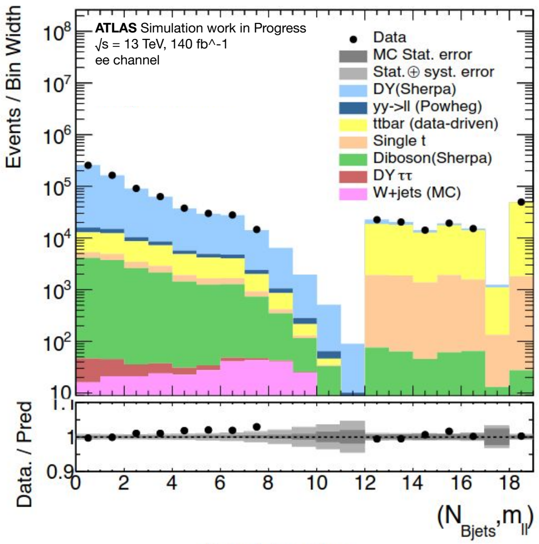
Precision measurement HMDY+b

- ttbar estimation
  - **(partially) Data-driven method** results :



MC ttbar



Data-driven ttbar

- The estimation in the 1 & 2 b-jet regions is much more precise.
  - Significant uncertainties reduction (factor ~10)

Precision measurement HMDY+b

- Profile likelihood Unfolding (PLU)
  - Allows to transform the unfolding problem into a standard problem of fitting normalisation of distributions. →**Likelihood**

$$L(n|\theta,\mu) = \prod_i P(n_i|S_i(\theta,\mu),B_i(\theta)) \times \prod_j G(\theta_j)$$

n = Data (Asimov data = perfect prediction of S and B events)
B = Background (fixed) S
S = Signal (free floating)
μ = Parameter of interest(s) (POI)
θ = Nuisance parameter(s) (NP) Systematics uncertainties that affect both S & B estimation

The μ is estimated by maximizing the Likelihood function (or minimizing the -log(L))

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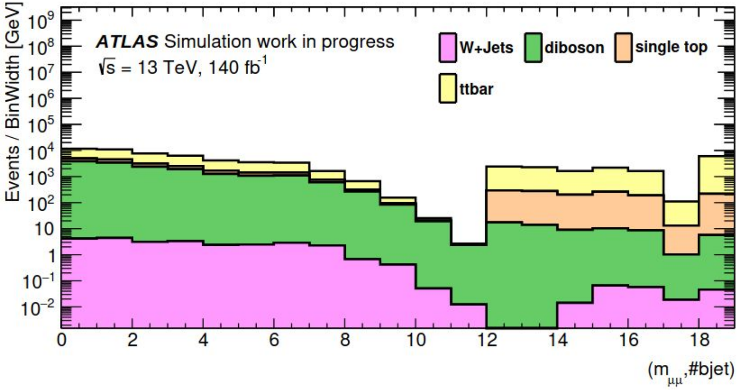

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Systematics uncertainties:
- Electron, Muon, JET (Identification, Energy resolution…)
- Flavor tagging (b-tagging..)
- MET (soft tracks..)
- emu CR (from ttbar estimation)
- theory (PDF..)

Precision measurement HMDY+b

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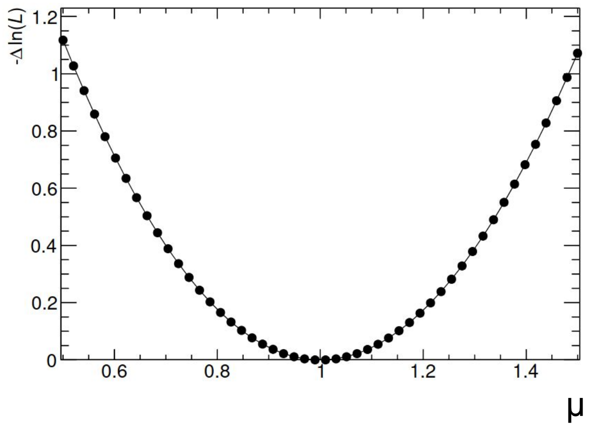
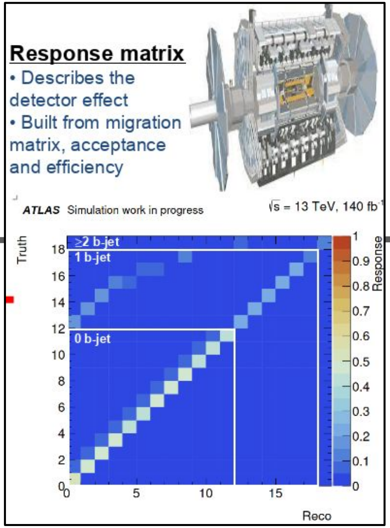


Precision measurement HMDY+b

- Folding of signal inputs

Particle level

Monte-Carlo
DY process



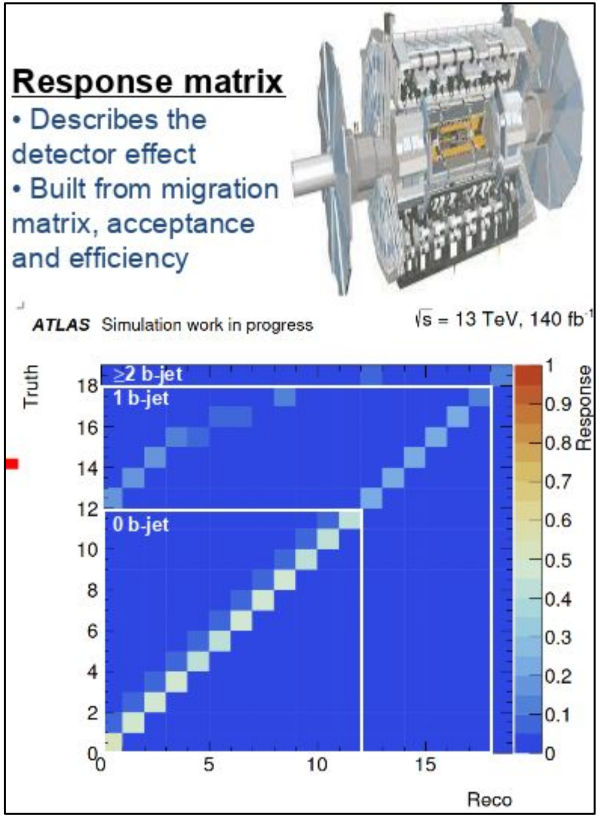
Reconstructed level

Folded
Monte-Carlo
DY process + systematics

Backgrounds + systematics

Precision measurement HMDY+b

- Response matrix



▪Built from the acceptance (α), efficiency (ε) and the migration matrix (M)

$$R = \frac{1}{\vec{\alpha}} \cdot M \cdot \vec{\epsilon}$$

▪acceptance (α) : correcting for events that are outside the fiducial region but still selected as part of the detector-level events.

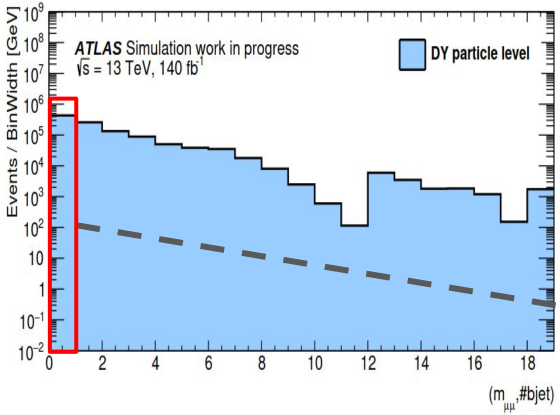
▪efficiency (ε) : correcting for events that are inside the fiducial region but that are not reconstructed.

▪Migration Matrix (M) : Account for events from a truth bin_i reconstructed in a bin_j.

Precision measurement HMDY+b

- Folding of signal inputs

Particle level



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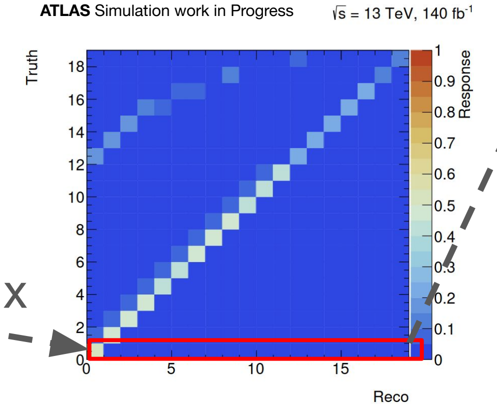

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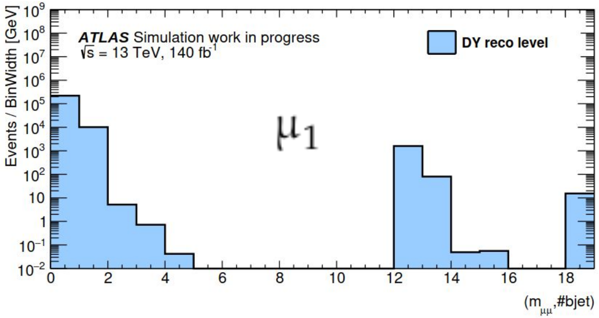
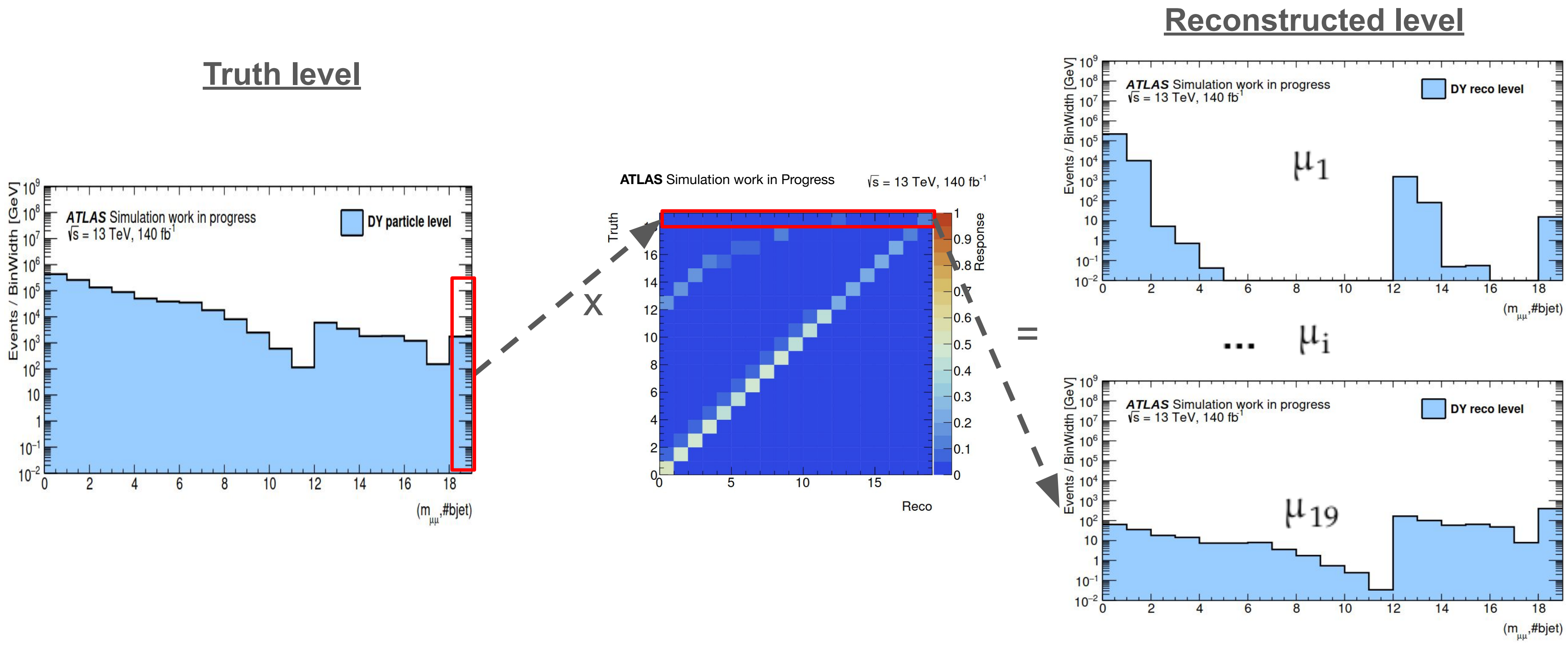
Reconstructed level



- Ni sub-reco DY distributions are built from the multiplication of each truth bin by each row of the response matrix.

Precision measurement HMDY+b

- Folding of signal inputs

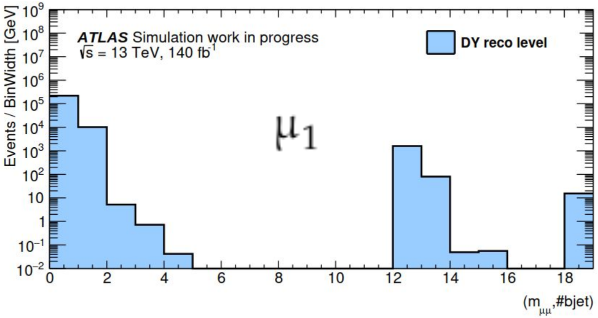


Precision measurement HMDY+b

- Likelihood components

$$L(n|\theta,\mu_1) = \prod_i P(n_i|S_i(\theta,\mu_1),B_i(\theta)) \times \prod_j G(\theta_j)$$

Asimov Data 1 =



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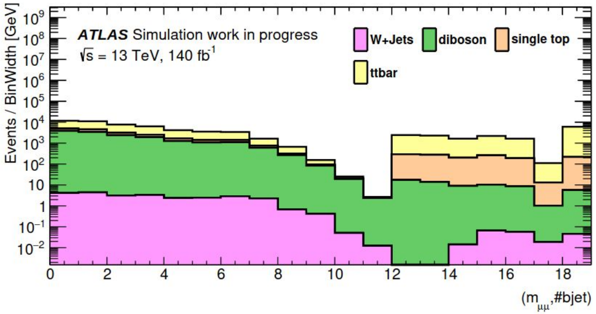


\+ Folded systematics distributions

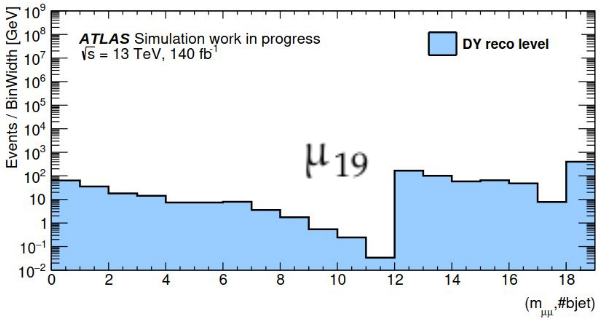
\+ systematics distributions

Precision measurement HMDY+b

- Likelihood components

$$L(n|\theta,\mu_{19}) = \prod_i P(n_i|S_i(\theta,\mu_{19}),B_i(\theta)) \times \prod_j G(\theta_j)$$

Asimov Data 19 =



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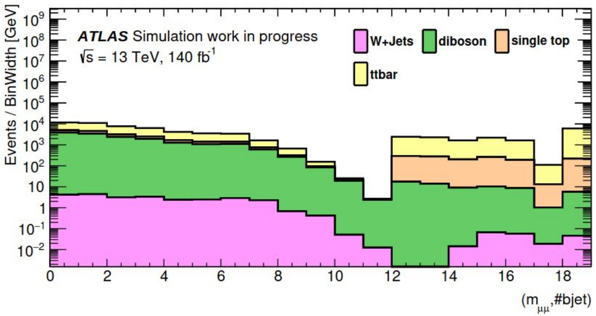


\+ Folded systematics distributions

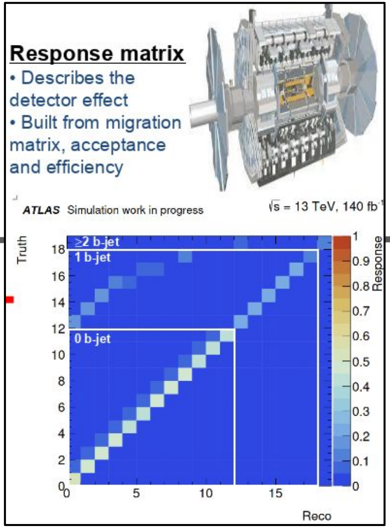
\+ systematics distributions

Precision measurement HMDY+b

- Unfolding of DY process

Particle level

Monte-Carlo
DY process



Reconstructed level

Monte-Carlo
DY process +
Background

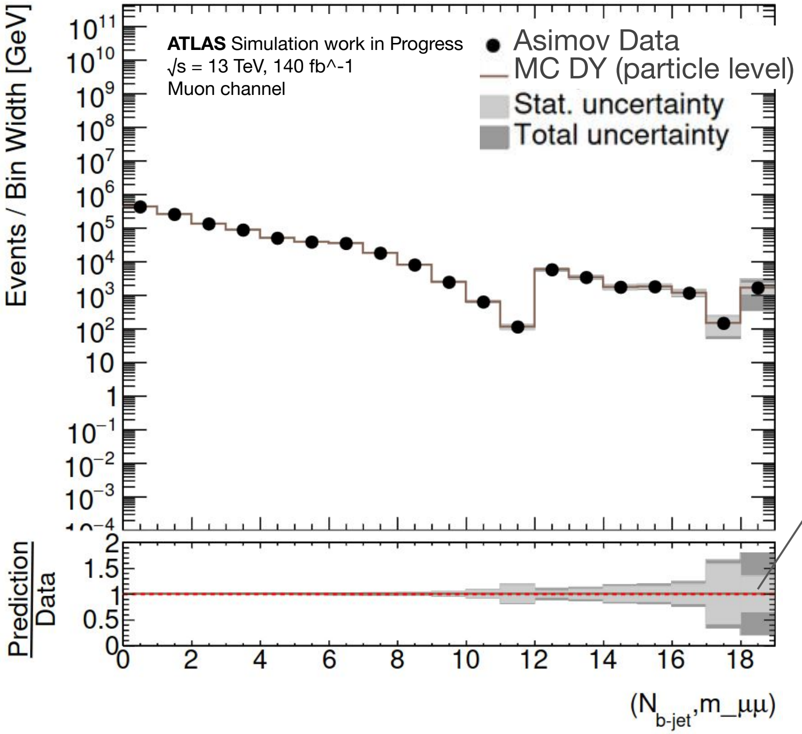
likelihood fit

Data

Unfolded
DY process

Precision measurement HMDY+b

- Unfolded results

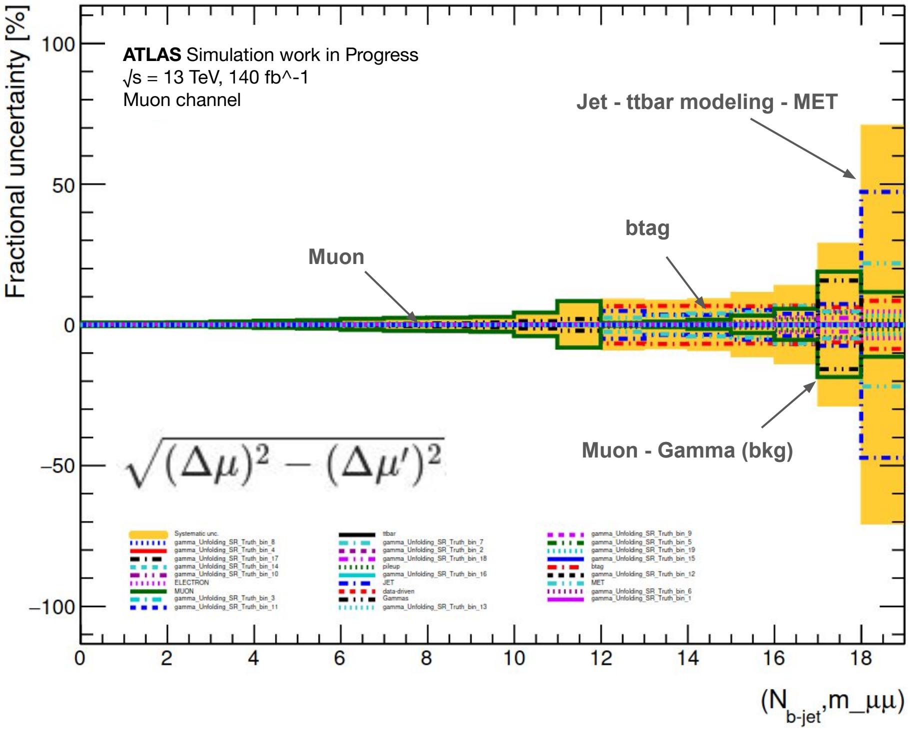


▪The MC DY (particle level) process is fully retrieved via the PLU method.

▪Effects of the statistical and systematics uncertainties can be studied from this results.

Precision measurement HMDY+b

- Systematics study



▪Impact of each Nuisance Parameter (NP) on each 19 POI μi

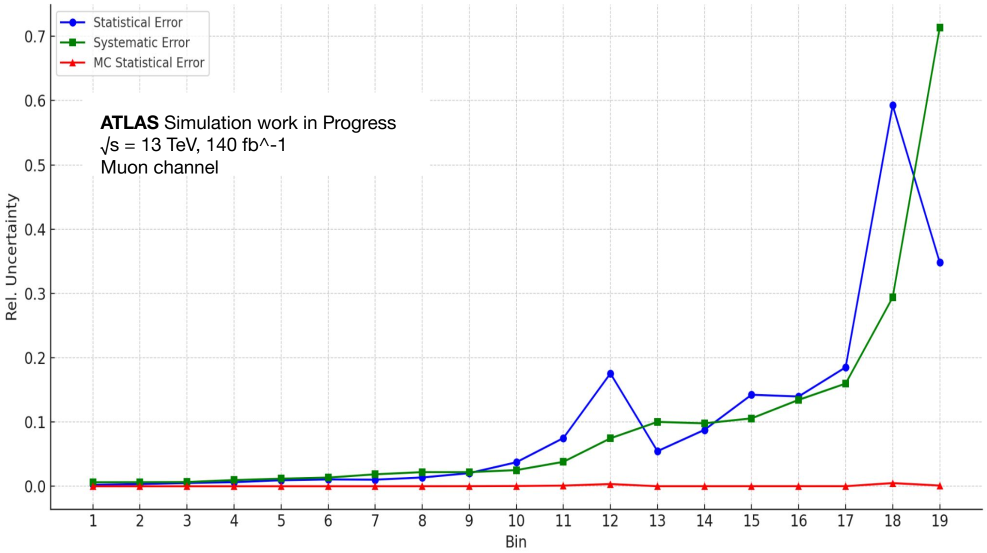
- In 0 b-jet region, Muon object systematics are the most impactful

- In 1 bjet region, b-tagging systematics show the highest impact across the first 5 bins, and Muon and MC stat from background in the last bin

- The POI in the 2 b-jet region define by a single bin is most impacted by Jet object, ttbar modeling and MET systematics

Precision measurement HMDY+b

- Systematics study

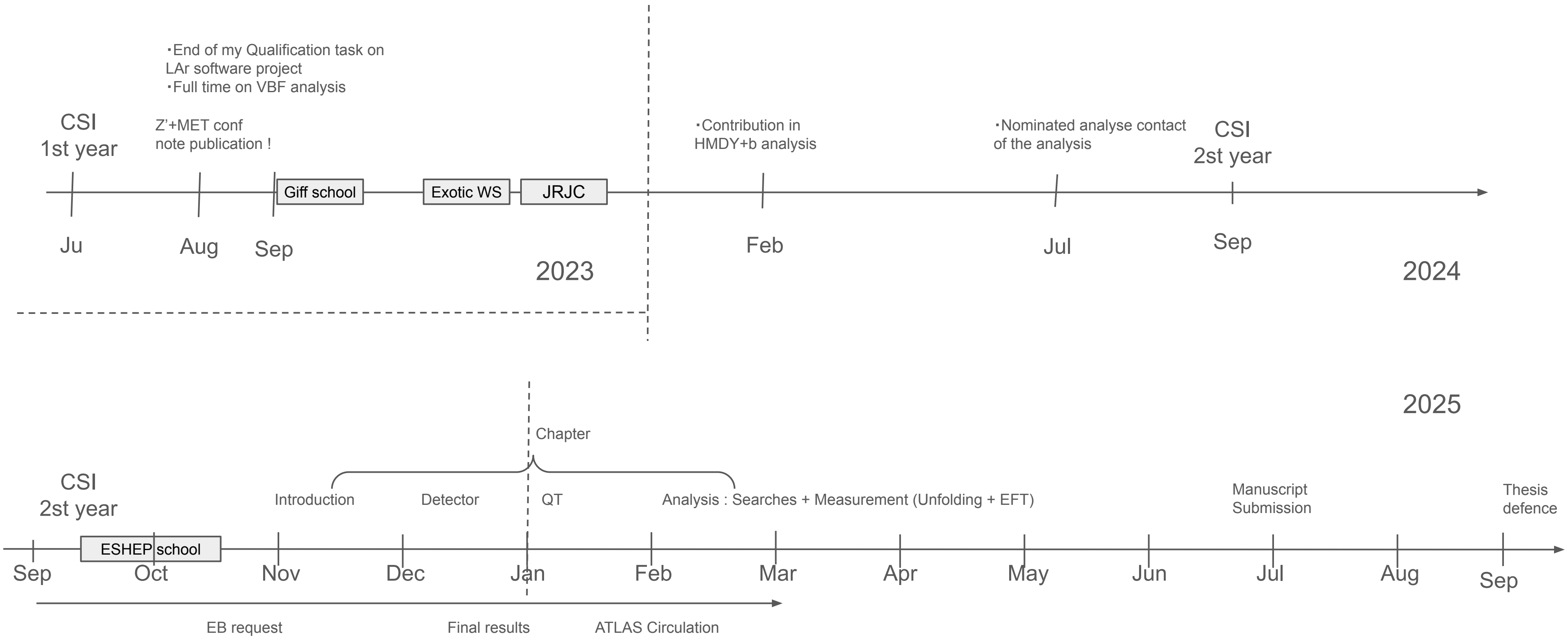


▪ Check if the uncertainties of each POI are statistically or systematically dominated.

Precision measurement HMDY+b

- Status of the analysis
  - Status report was given early July.
  - A second one is planned next week.
  - Internal note has been written.
  - ATLAS internal review on-going

Conclusion



・End of my Qualification task on LAr software project
・Full time on VBF analysis
CSI 1st year
Z'+MET conf note publication !
Giff school
Exotic WS
JRJC
・Contribution in HMDY+b analysis
・Nominated analyse contact of the analysis
CSI 2st year
Ju
Aug
Sep
Feb
Jul
Sep
2023
2024
2025
Chapter
CSI 2st year
Introduction
Detector
QT
Analysis : Searches + Measurement (Unfolding + EFT)
Manuscript Submission
Thesis defence
ESHEP school
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
EB request
Final results
ATLAS Circulation

Back-up

Inclusive Z' search

★ **Theoretical motivation :**

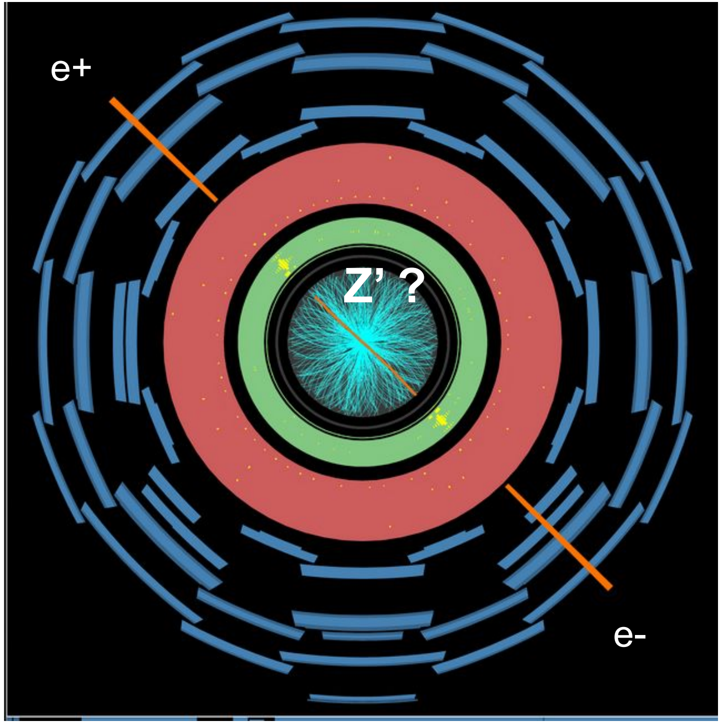
- New Z' gauge boson in BSM theories.
  - Additional SU(2) or U(1) gauge symmetry.
  - TeV scale.

ATLAS EXPERIMENT

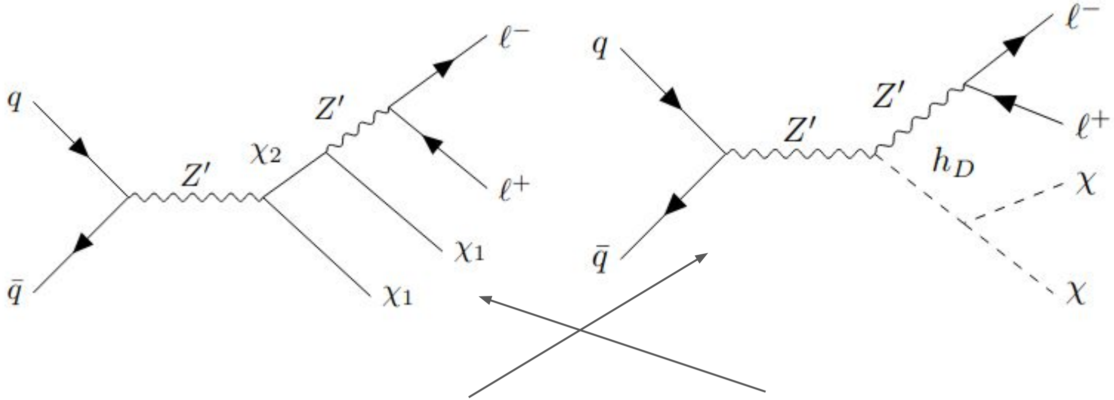
Run Number: 336852, Event Number: 1440436043

Date: 2017-09-29 11:44:35 CEST

m_ee = 4.06 TeV



Exclusive Z'+MET search

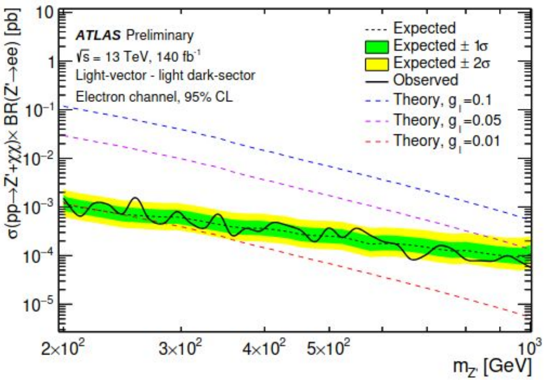


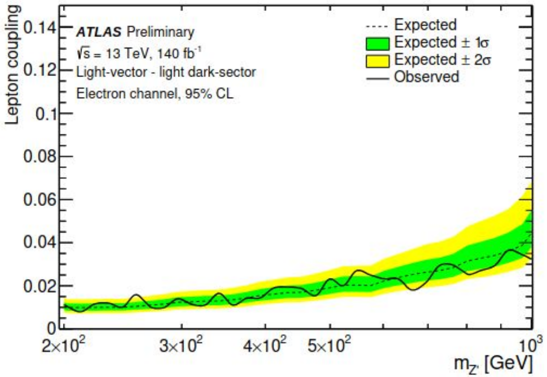
benchmark

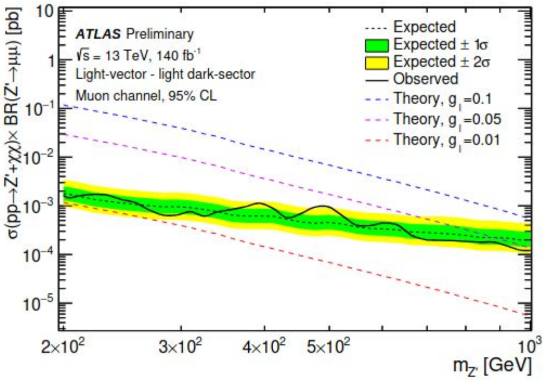
	Dark Higgs	Light Vector
Z'	$m'_Z > 180GeV$ $g_D = 1, g_q = 0.1, g_l = 0.01$	
Light dark sector	$m_\chi = 5GeV$ $m_{h_D} = 125GeV$	$m_{\chi 1} = 5GeV$ $m_{\chi 2} = m_{\chi 1} + m_{Z'}$ $+25GeV$
Heavy dark sector	$m_\chi = 5GeV$ $m_{h_D} = m_{Z'}$	$m_{\chi 1} = 5GeV$ $m_{\chi 2} = 2m_{Z'}$

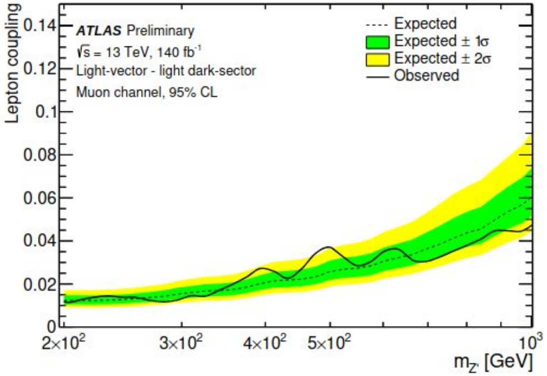
Exclusive Z'+MET public results

★





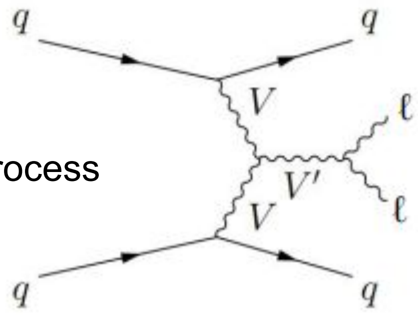


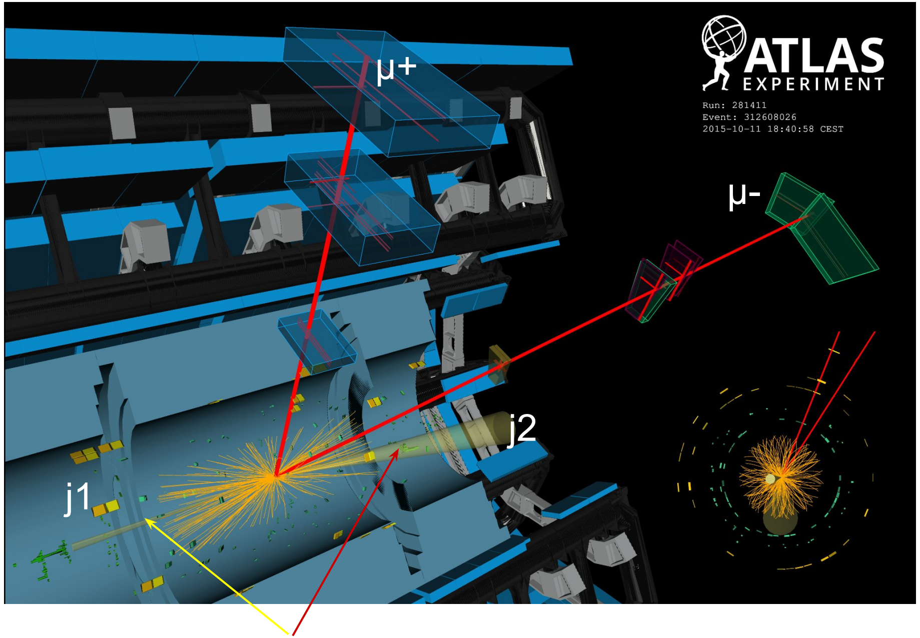


Exclusive Z'+VBF jets search

★ *VBF topology*

VBF Process



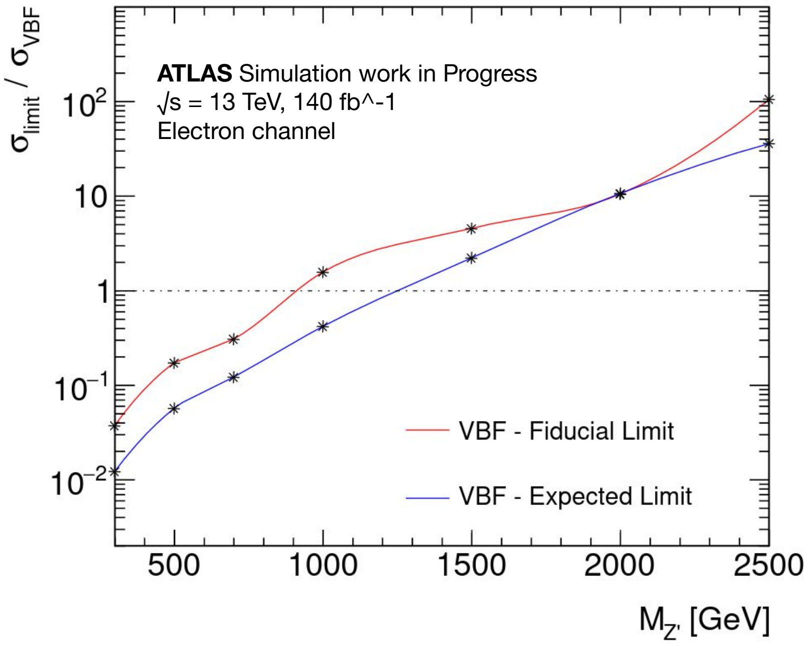


forward jets

Exclusive Z'+VBF jets preliminary results

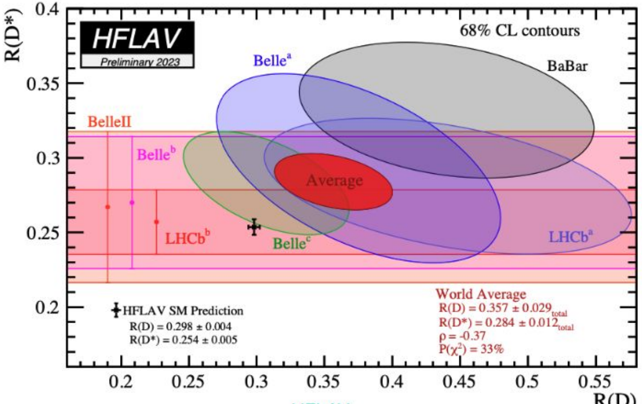
★ Preliminary **stats-only** expected limits produced for both channels.

- Increase the sensitivity compared to the inclusive search

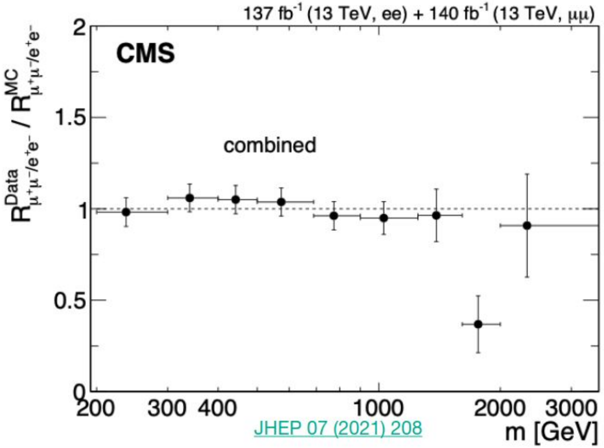


Lepton flavour universality

- Tensions with SM have been observed in LHCb/Belle
- Also in CMS HMDY measurement
- Important to also look with ATLAS



HFLAV



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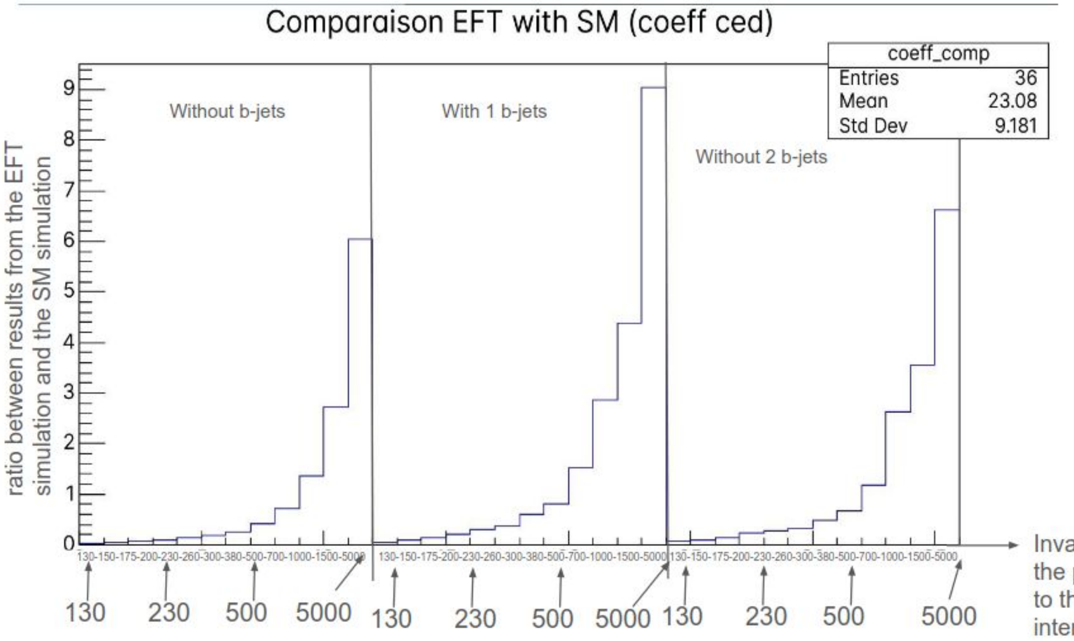
Back-up

- EFT sensitivity

Study done by **Ariane Arnaud** during her internship this summer



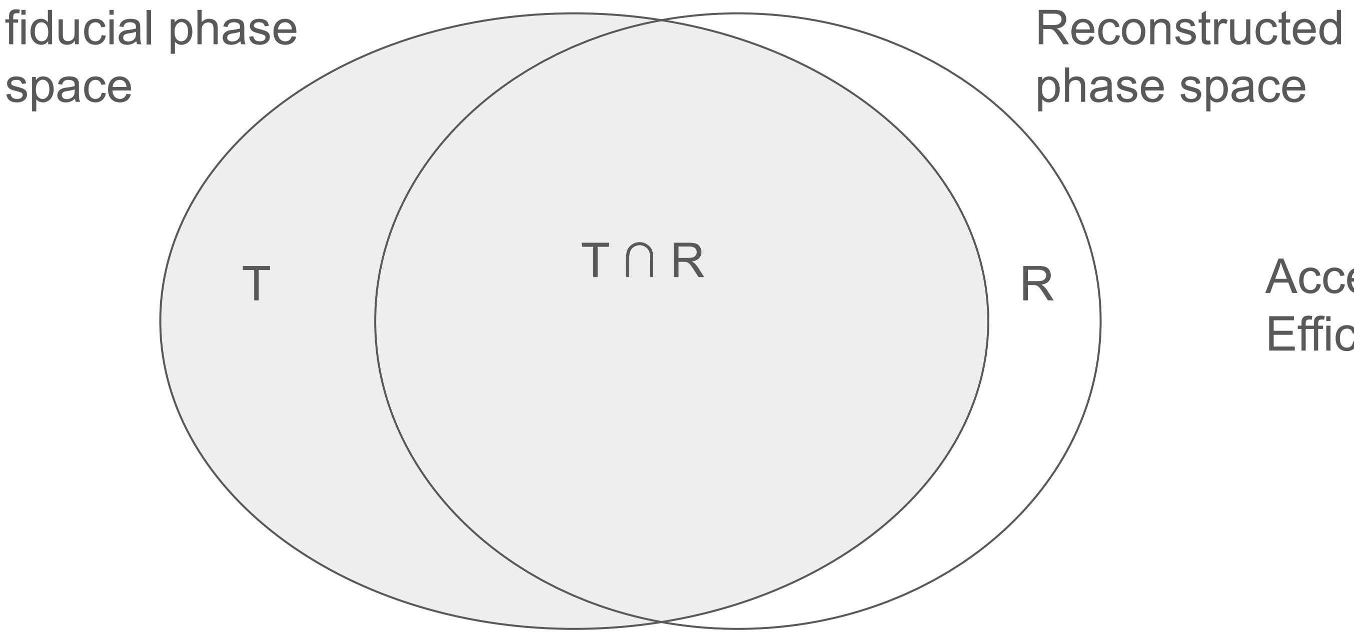
Invariant mass of the particles (linked to the energy of the interaction) GeV

11

The greater the ratio between results from the EFT simulation and the SM simulation
=> greater difference between those two theories
=> greater chance to find new physic studying the process

Back-up

- Acceptance & Efficiency



Acceptance = T ∩ R / R
Efficiency = T ∩ R / T

Electron Reconstruction

Inner Detector (ID):

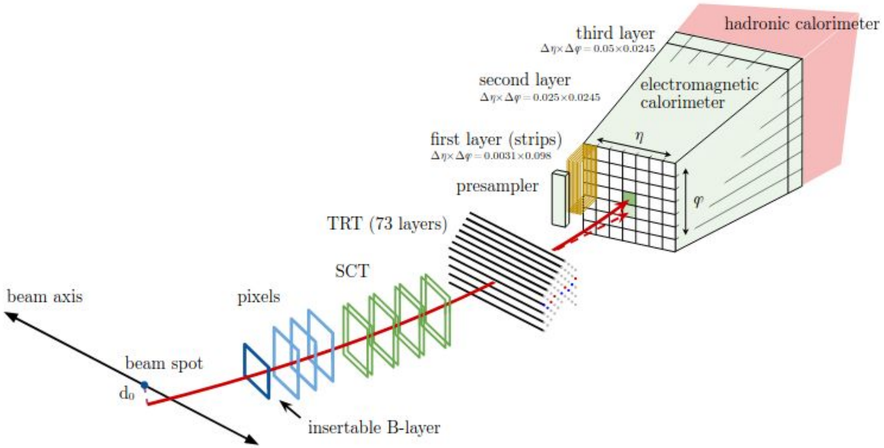
- **Pixel Detector & SCT**: Tracks the electron's trajectory and measures momentum.
- **TRT**: Distinguishes electrons from other particles using transition radiation.

Electromagnetic Calorimeter (ECAL):

- **LAr Calorimeter**: Measures electron energy via electromagnetic showers.

Hadronic Calorimeter (HCAL):

- Confirms minimal energy deposit, verifying the electron ID.



Muon Reconstruction

Inner Detector (ID):

- Tracks the muon's trajectory and measures momentum.

Hadronic Calorimeter (HCAL):

- Muons pass through with minimal energy loss.

Muon Spectrometer (MS):

- Measures the muon’s momentum with high precision