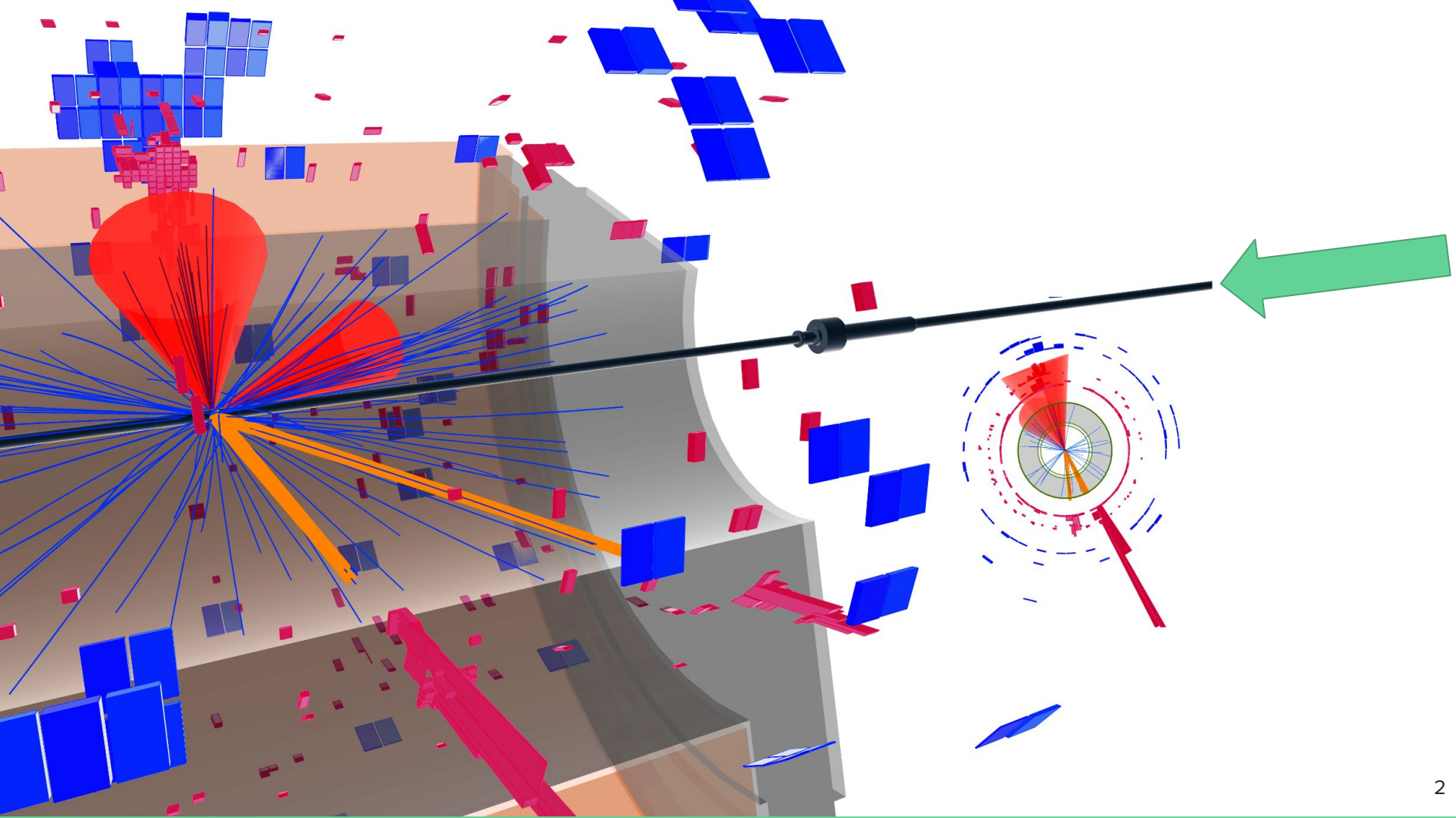
Precision measurements in HEP

Tommaso Cresta
Supervisor: Prof D. Rebuzzi,
Dott G. Manco,
Dott. F. Giuli

University of Pavia
INFN Pavia
ATLAS Collaboration
CERN

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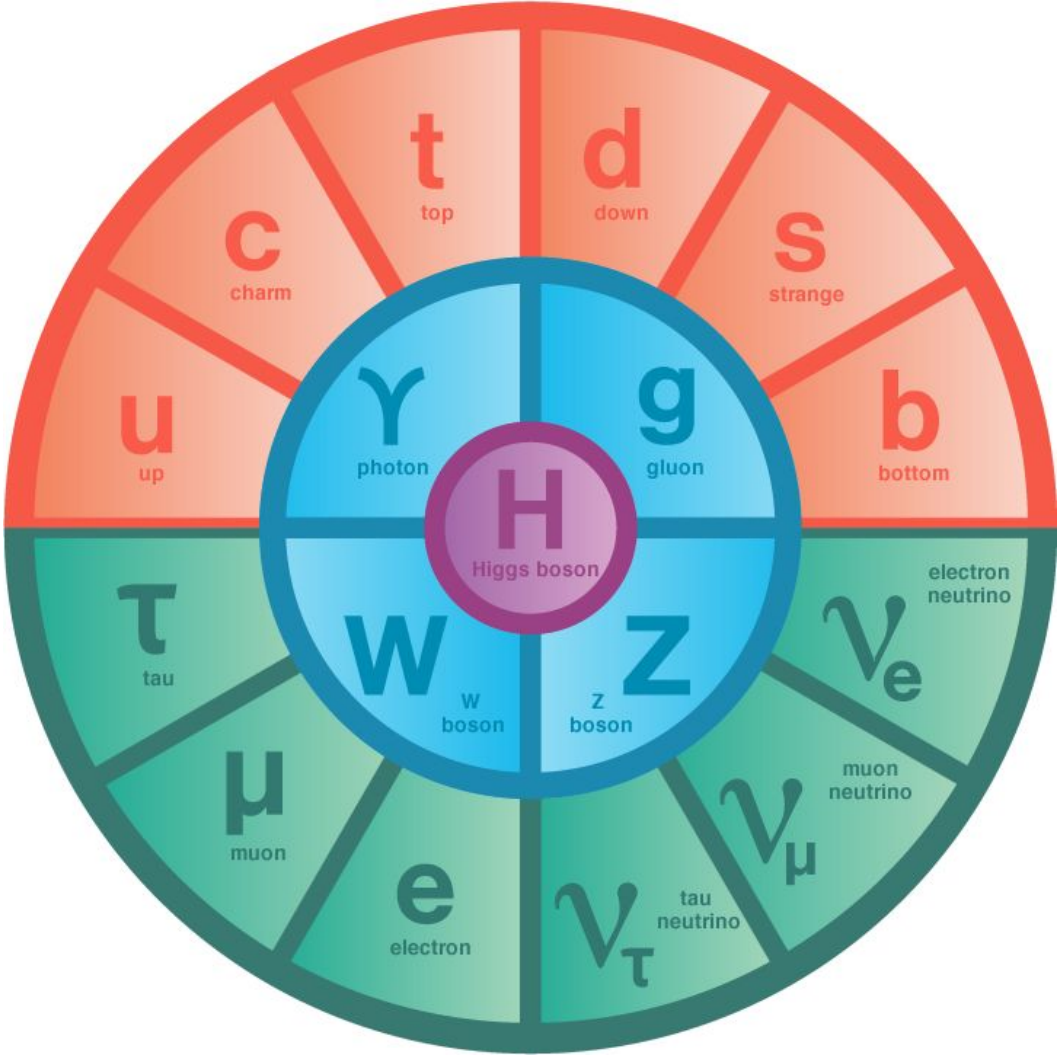
The Standard Model

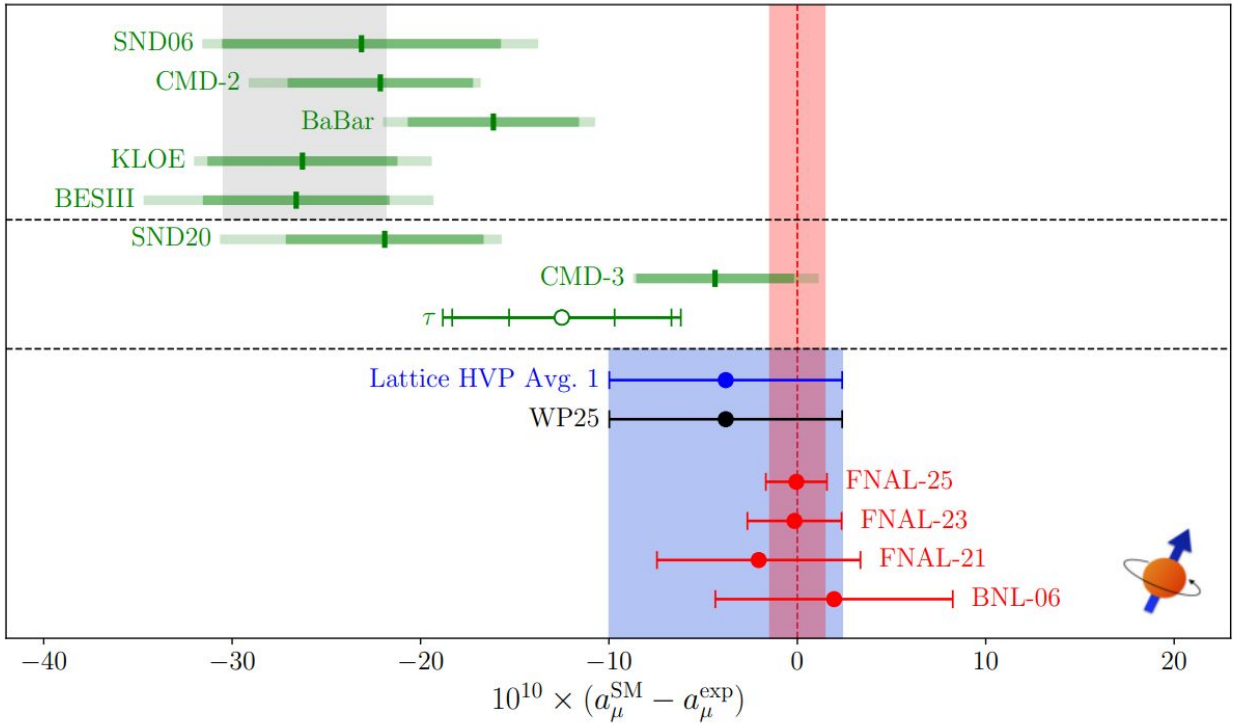


Precision measurements

It is fundamental to study the properties of the particles discovered.

New physics can be also discovered this way.

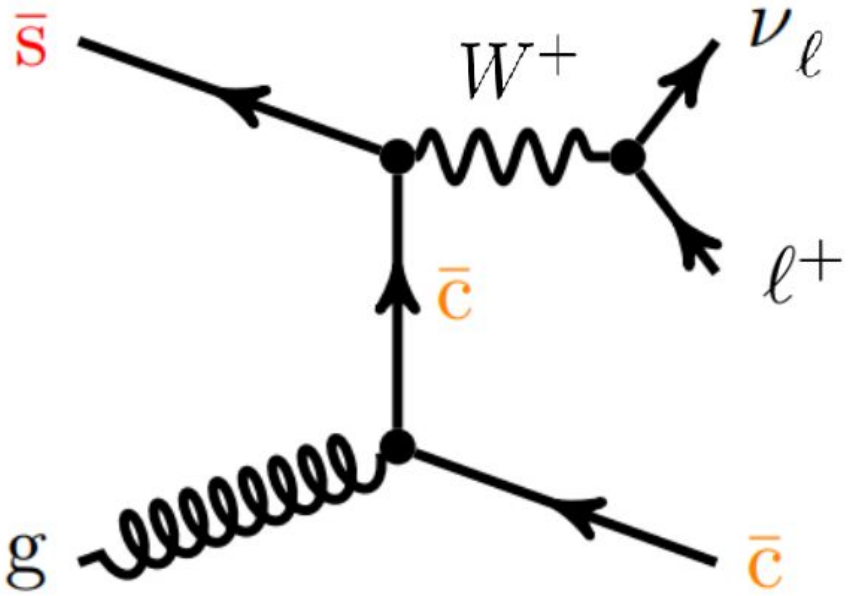
An example is the g-2 experiment.



What are we looking for?

We are looking for a W+c final state.

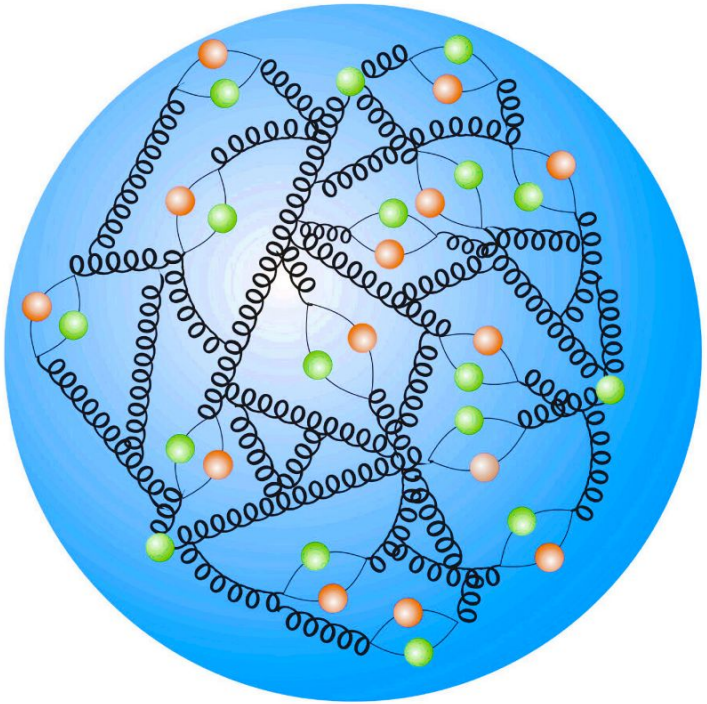
It is produced mainly via a single Feynman diagram.



Proton structure

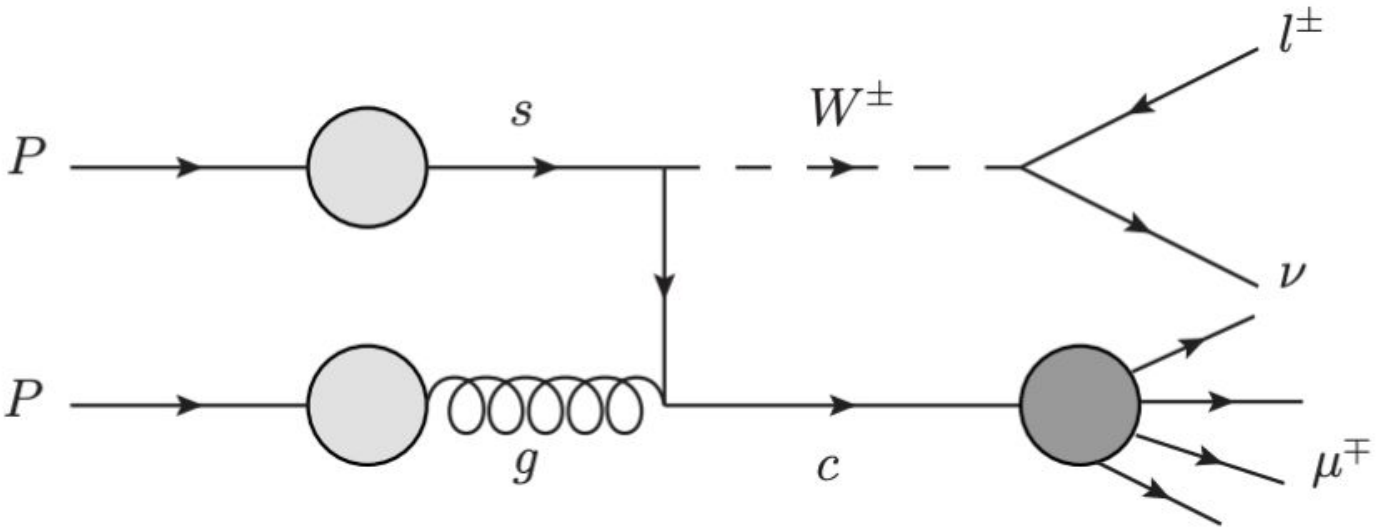
The proton is made up of quarks and gluons.

This internal structure is described by Parton Distribution Functions (PDFs).



Why is it interesting?

The W+c is directly sensitive to the strange quark PDF.



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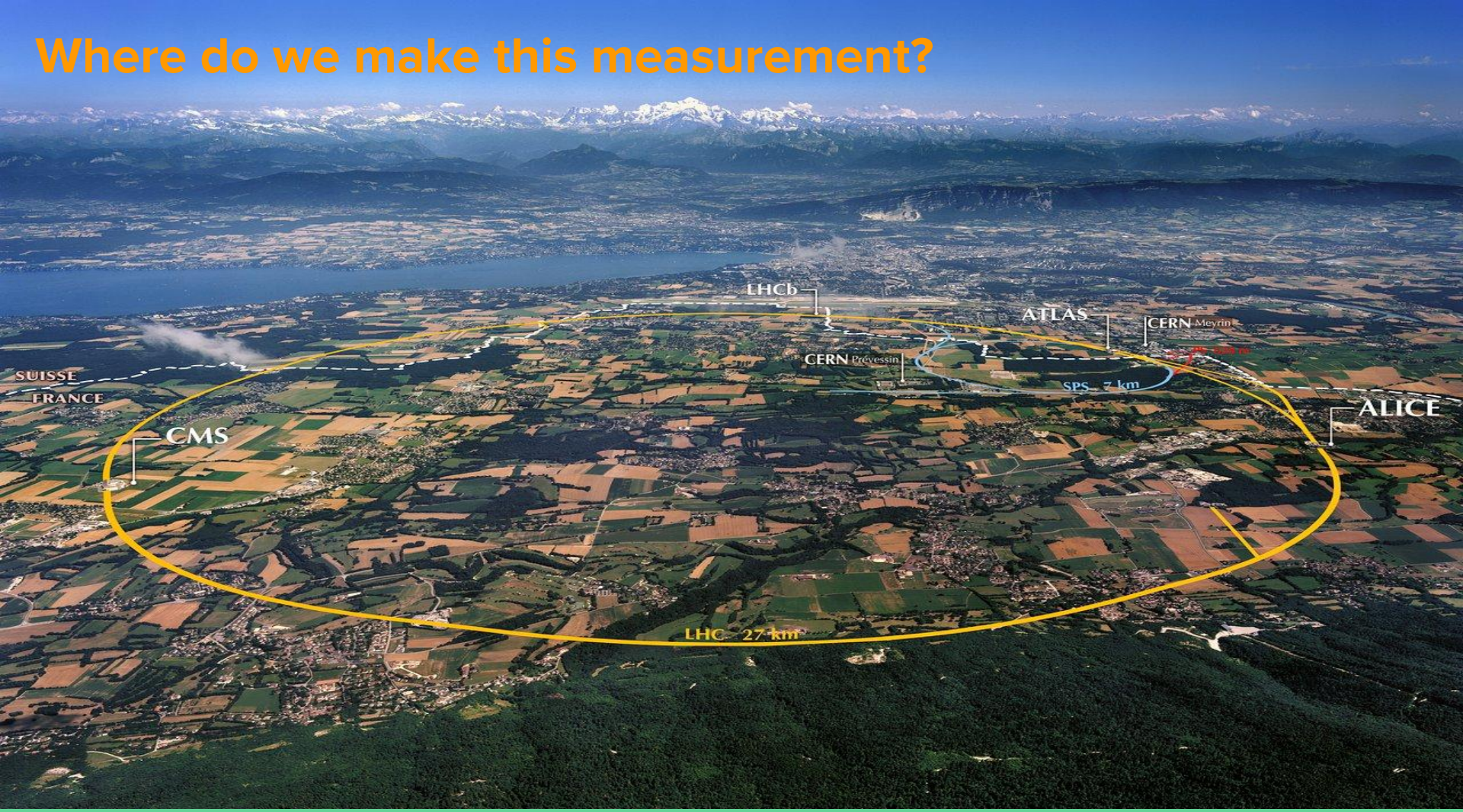

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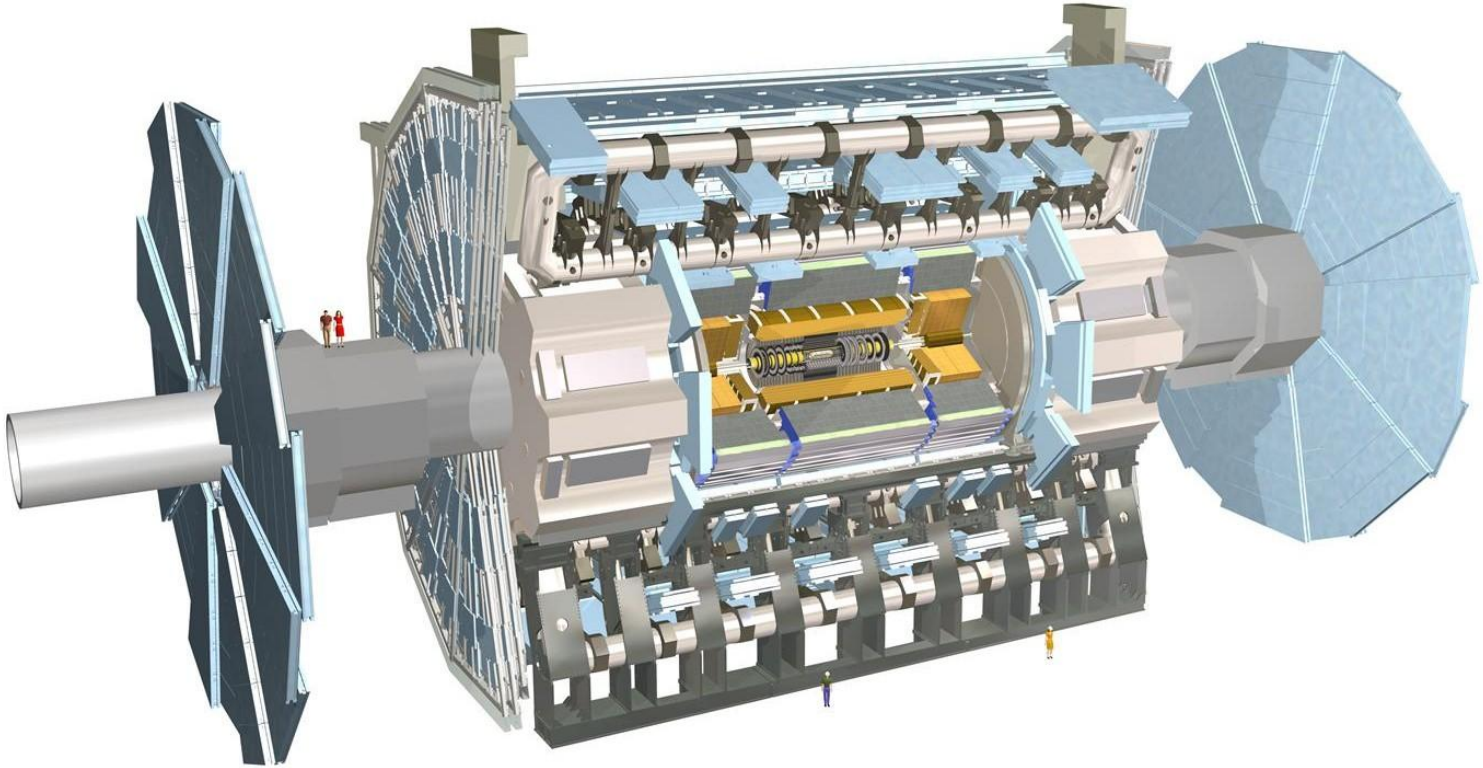
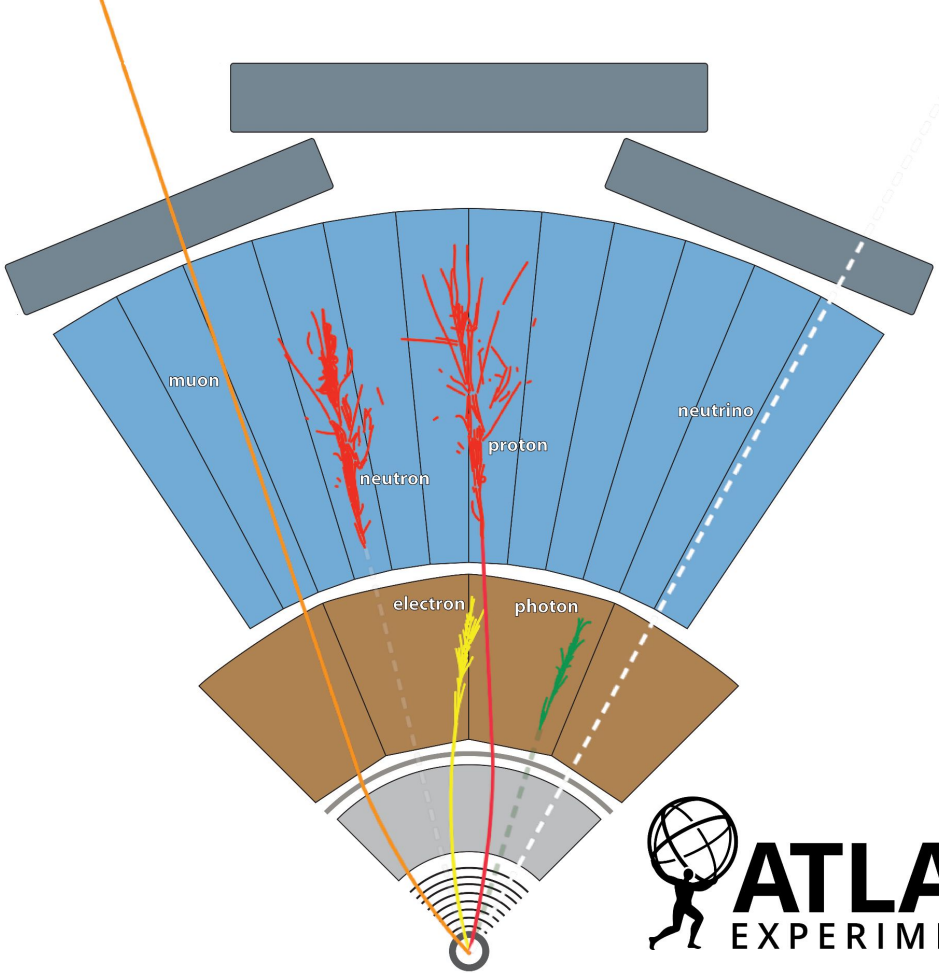


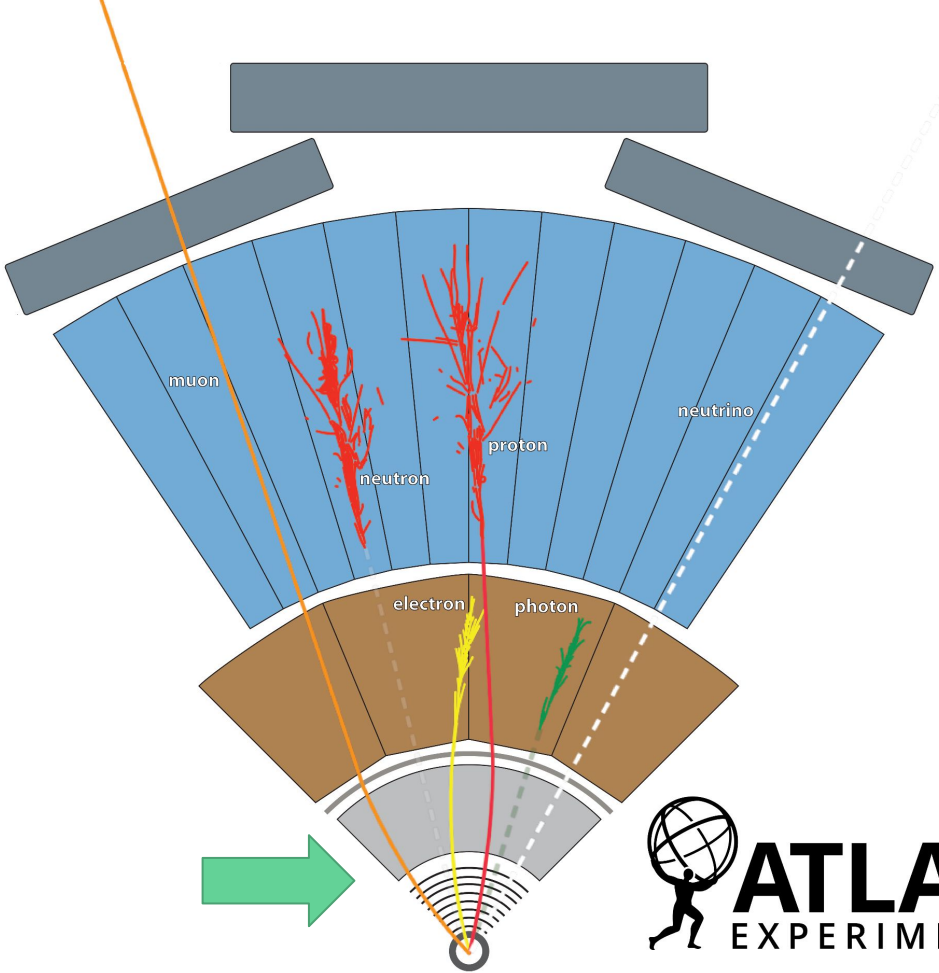
The structure of ATLAS



ATLAS EXPERIMENT

The structure of ATLAS

- **Tracker:** measures the trajectory of charged particles



ATLAS EXPERIMENT

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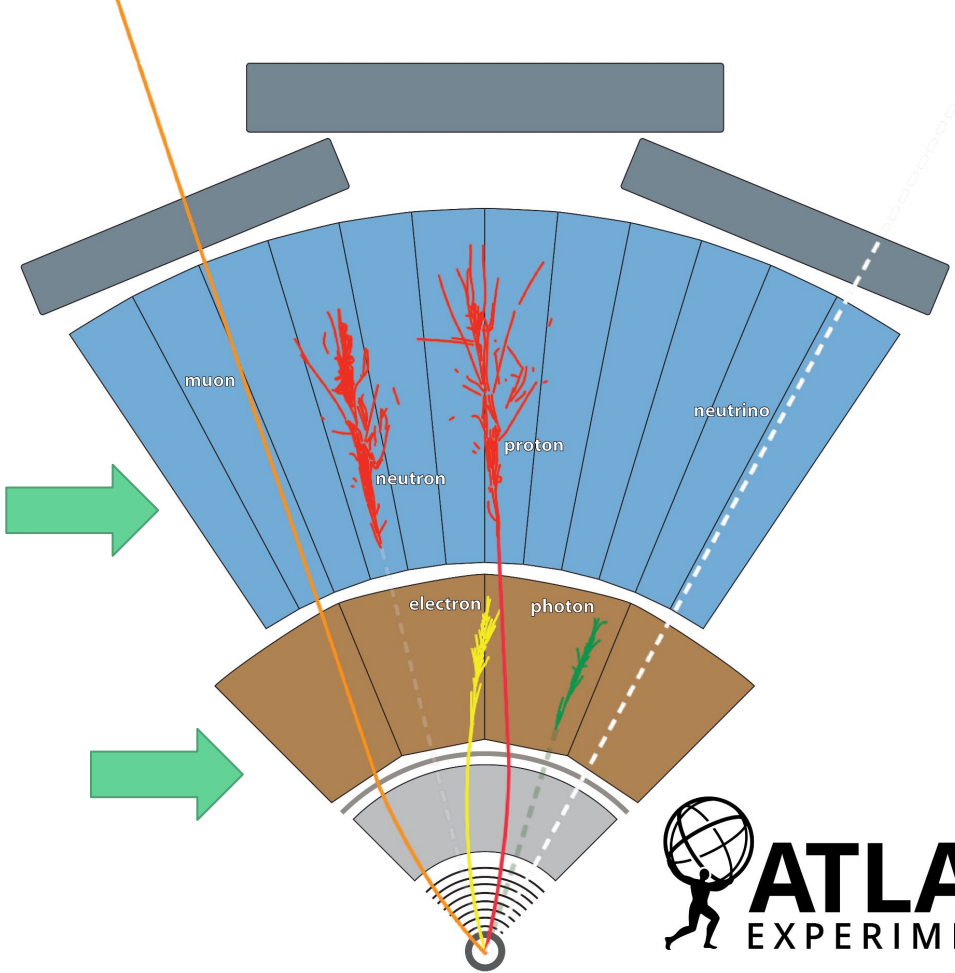
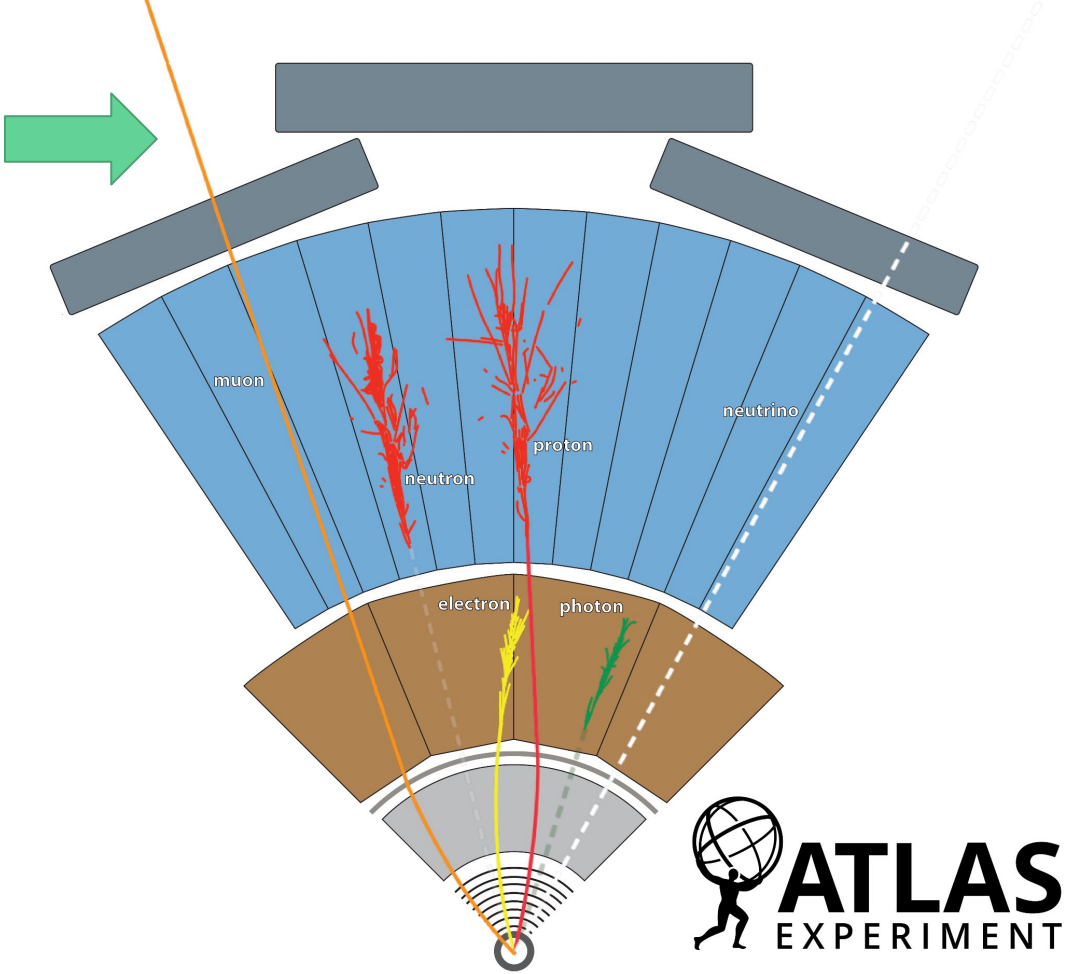
- **Tracker:** measures the trajectory of charged particles
- **Calorimeter:** measures the energy of particles. It is divided in electromagnetic and hadronic.



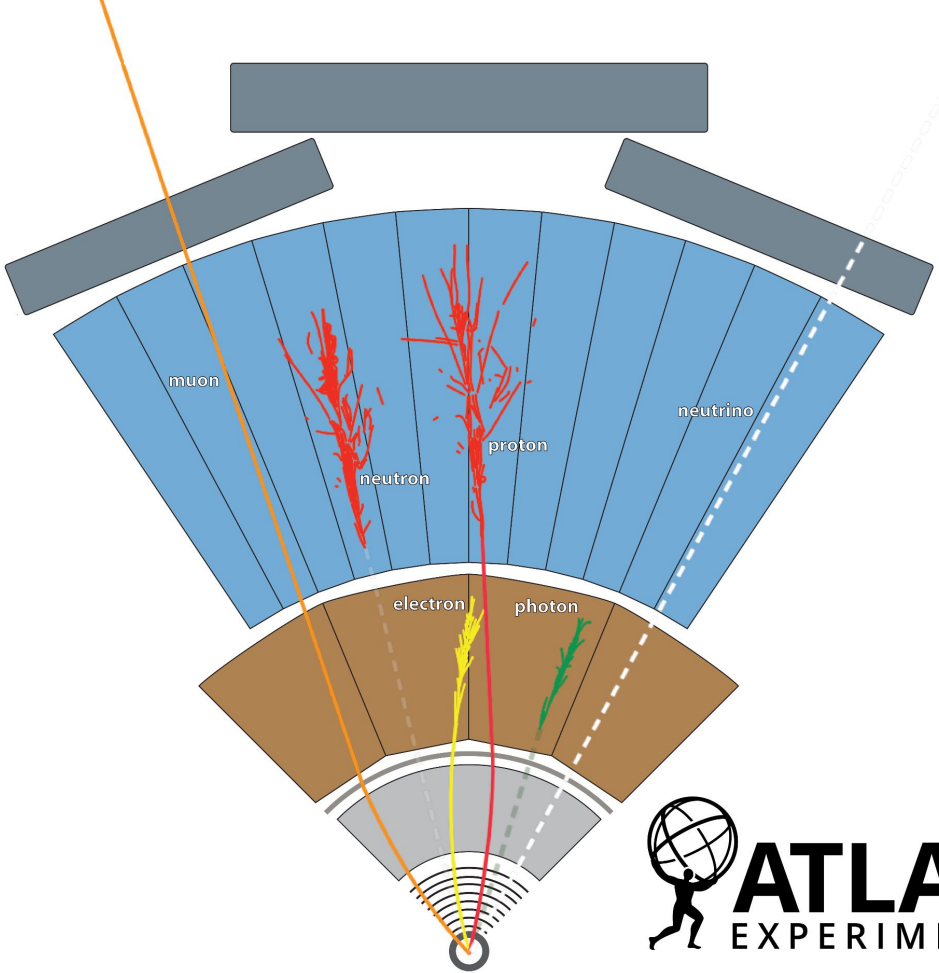
ATLAS EXPERIMENT

The structure of ATLAS

- **Tracker:** measures the trajectory of charged particles.
- **Calorimeter:** measures the energy of particles. It is divided in electromagnetic and hadronic.
- **Muon spectrometer:** measures the trajectory of muons specifically.



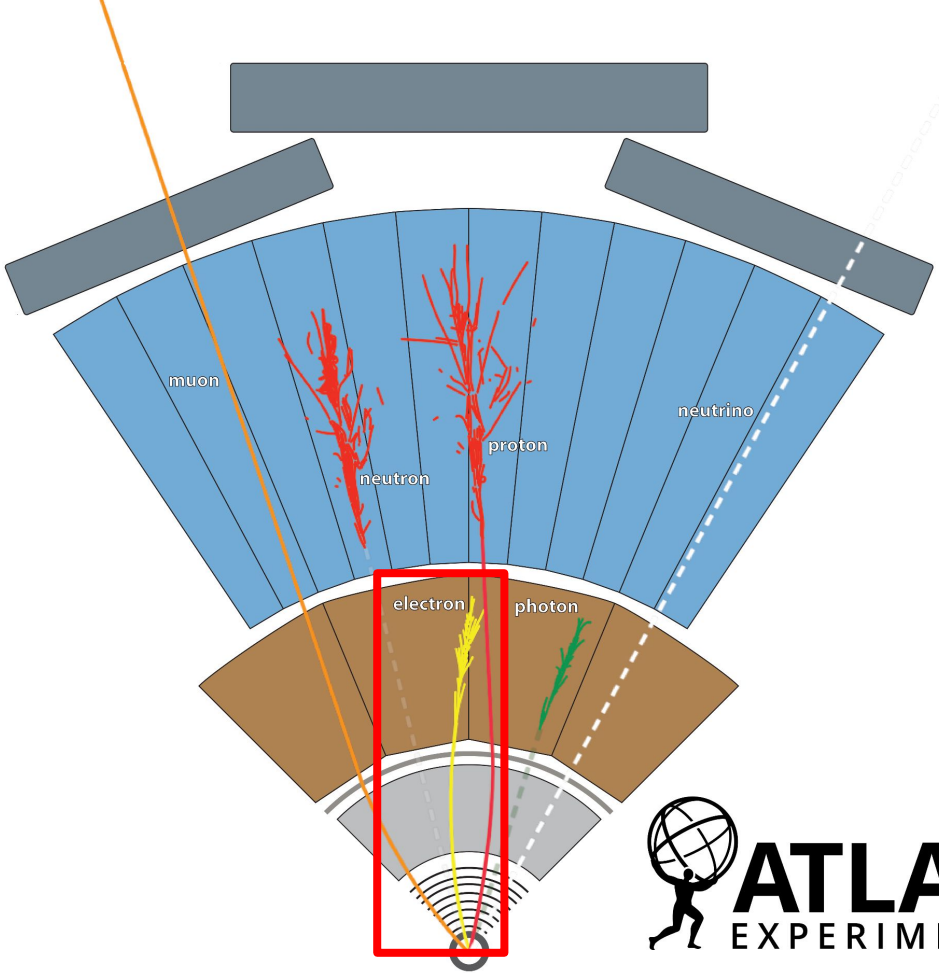
Object reconstruction



ATLAS EXPERIMENT

Object reconstruction

- **Electron:** it is detected in the tracker and is stopped in the <u>first</u> calorimeter.

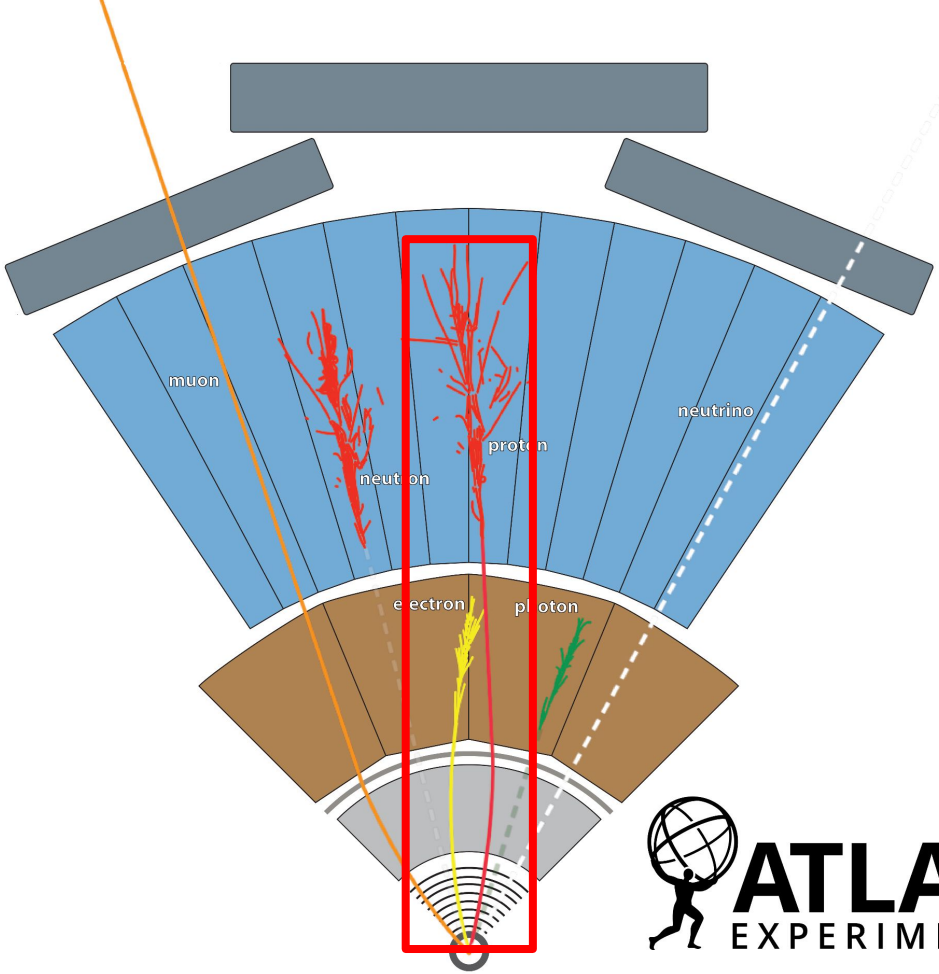


ATLAS EXPERIMENT

Object reconstruction

- **Electron:** it is detected in the tracker and is stopped in the <u>first</u> calorimeter.

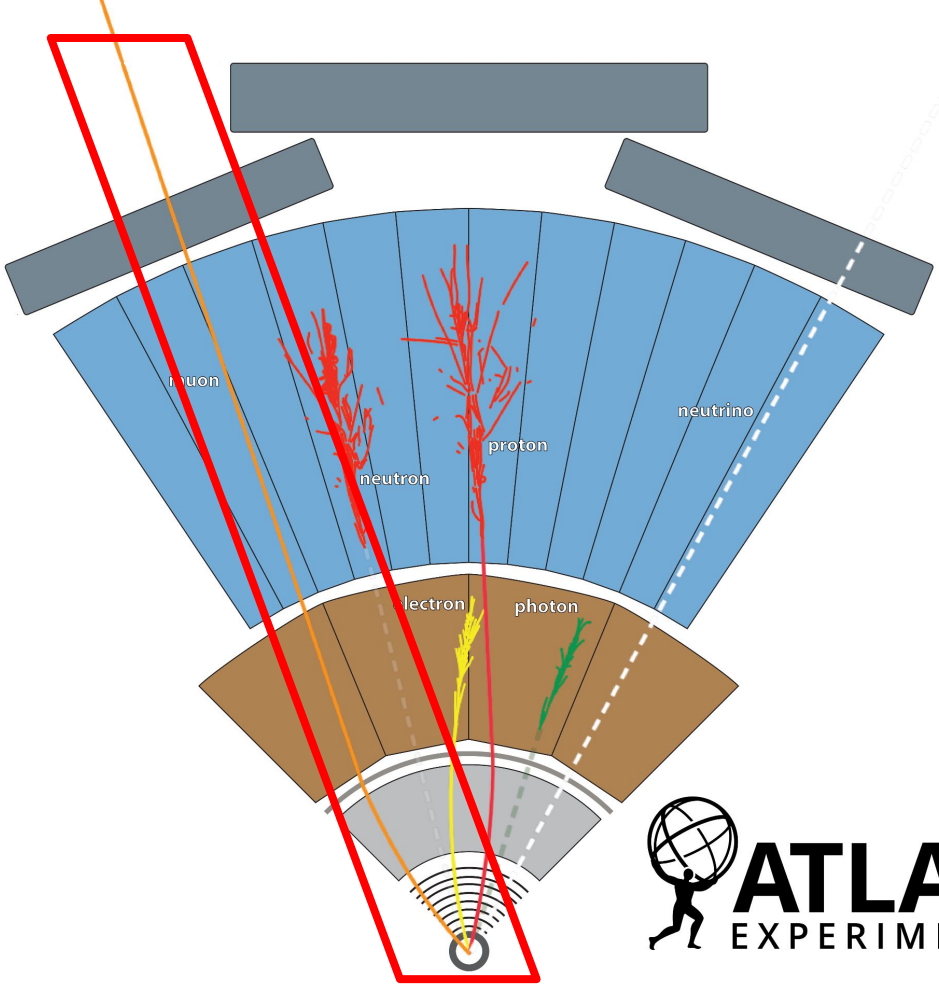
- **Hadron:** it is detected in the tracker and is stopped in the <u>second</u> calorimeter. Usually called <u>jet</u>.



ATLAS EXPERIMENT

Object reconstruction

- **Electron:** it is detected in the tracker and is stopped in the <u>first</u> calorimeter.
- **Hadron:** it is detected in the tracker and is stopped in the <u>second</u> calorimeter.Usually called <u>jet</u>.
- **Muon:** it is detected in the tracker and the muon spectrometer.



ATLAS EXPERIMENT

Which final state are we looking for?

We are looking for a **W boson** and single **charm quark** in the final state (W+c).

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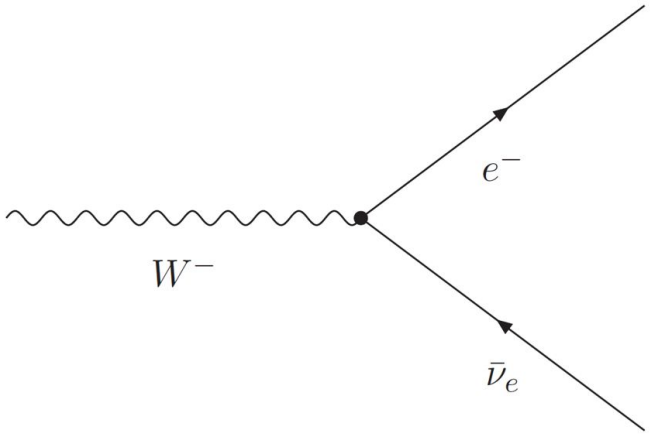
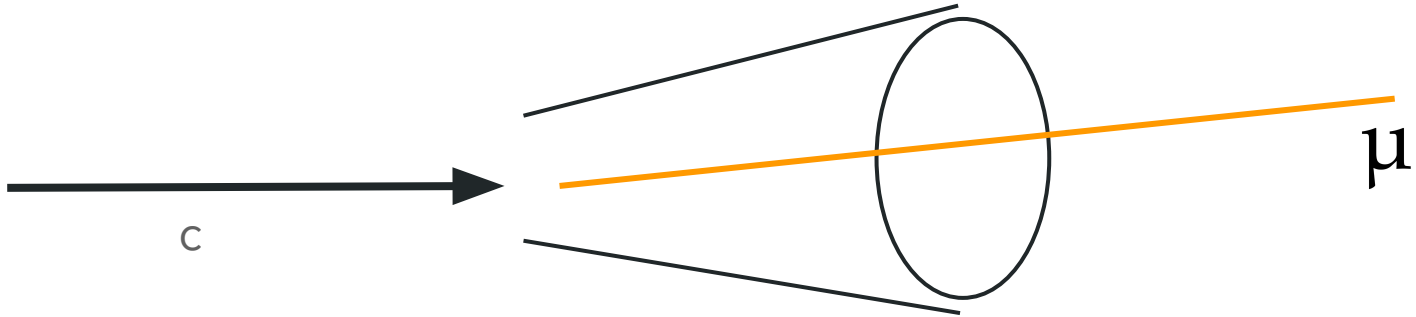
The W boson is reconstructed via its leptonic decay into an electron or muon and a neutrino.



Which final state are we looking for?

We are looking for a **W boson** and single **quark charm** in the final state (W+c).
The W boson is reconstructed via its leptonic decay into an electron or muon and a neutrino.
The quark charm is reconstructed as a jet with a muon inside of it.



How do we make the measurement?

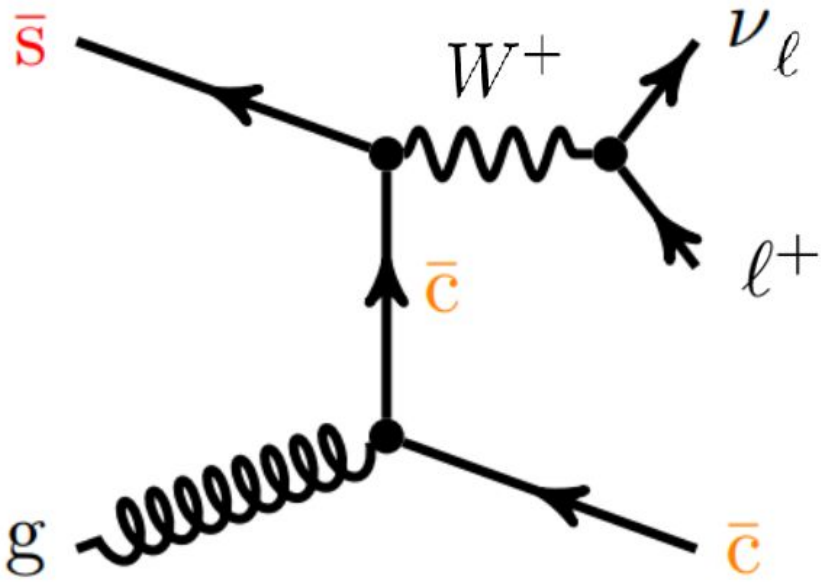
Ideally, we would like a signal region where there is most of the signal and only a small amount of background, but it is really hard to put in practice.

In particular for the W+c final state there are a 3 important background processes:

- **W+light**
- **W+b**
- **Multijet**

Charge exploitation

We can exploit the charge correlation between the lepton coming from the W decay and the muon inside the charm jet in order to reduce backgrounds.



Controlling the backgrounds

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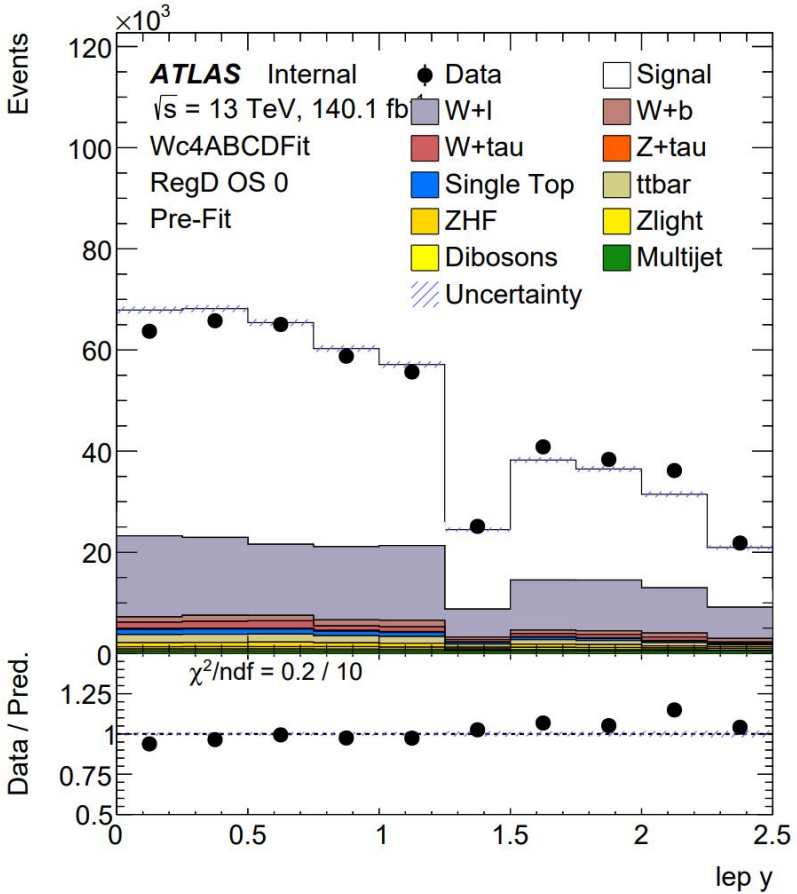
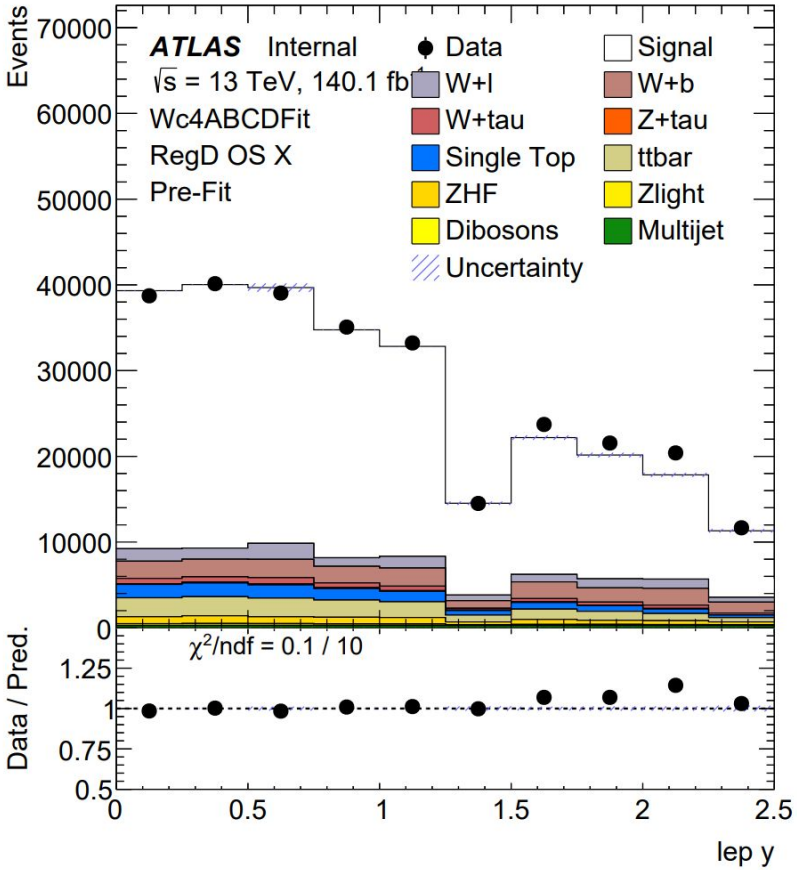
- **Bin 0:** for estimating W+light.



Controlling the backgrounds

In order to have a better handle on the backgrounds, we have constructed 3 different regions:

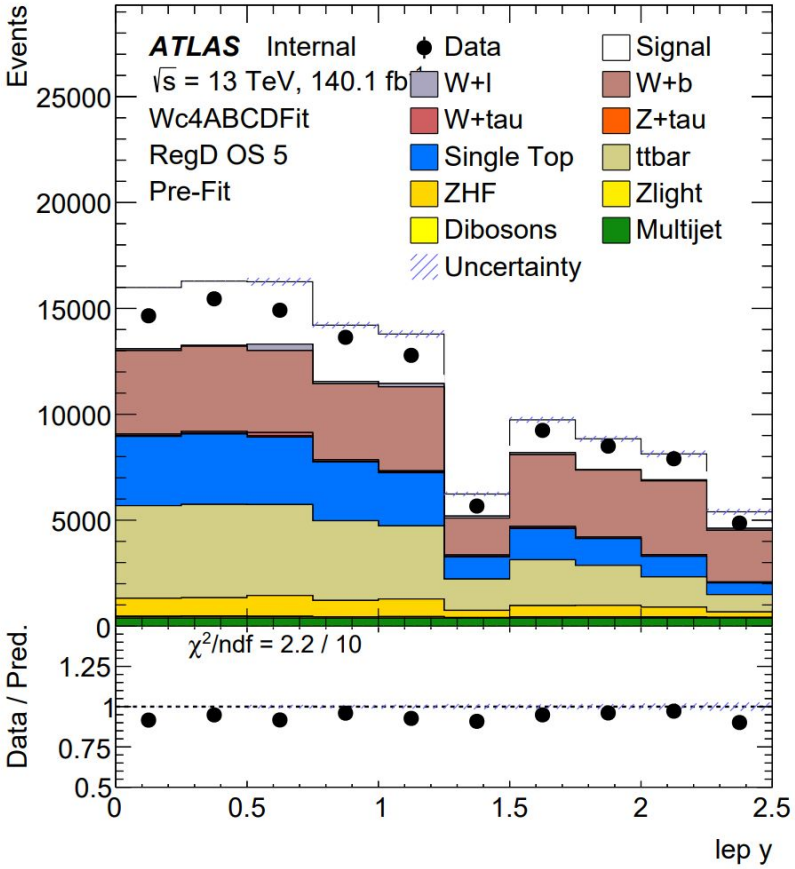
- **Bin 0:** for estimating W+light.
- **Bin X:** dominated by W+c.



Controlling the backgrounds

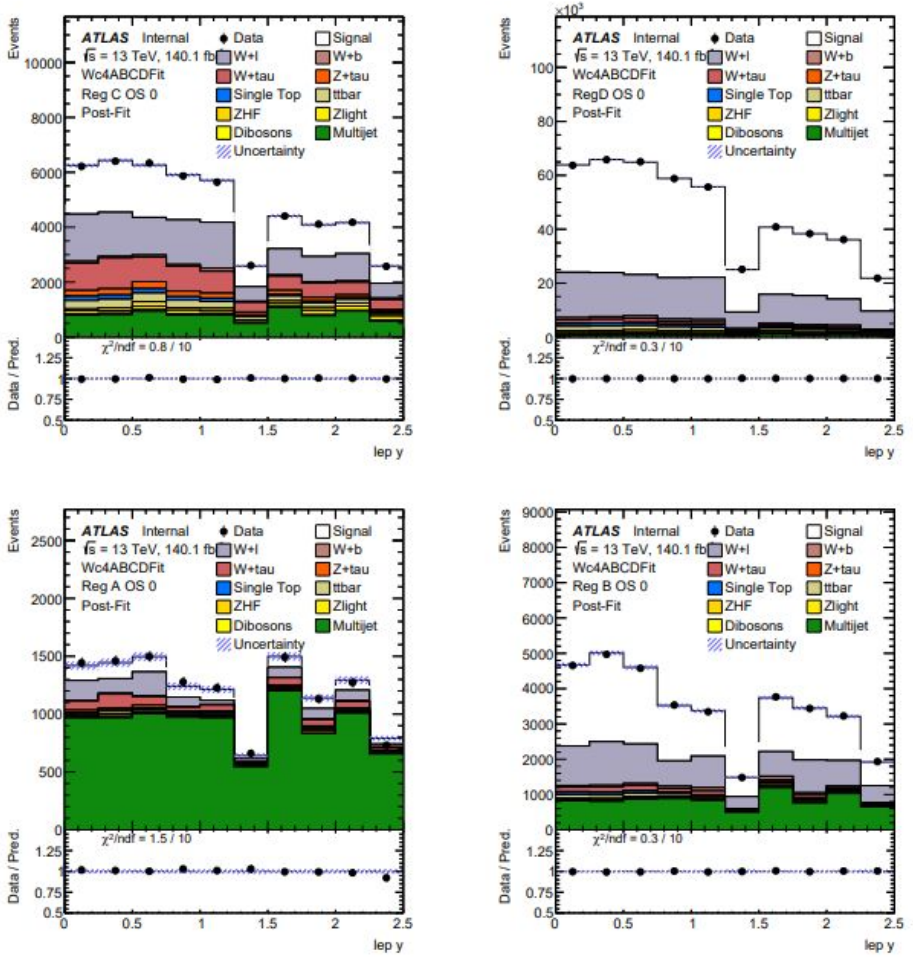
In order to have a better handle on the backgrounds, we have constructed 3 different regions:

- **Bin 0:** for estimating W+light.
- **Bin X:** dominated by W+c.
- **Bin 5:** for estimating W+b.



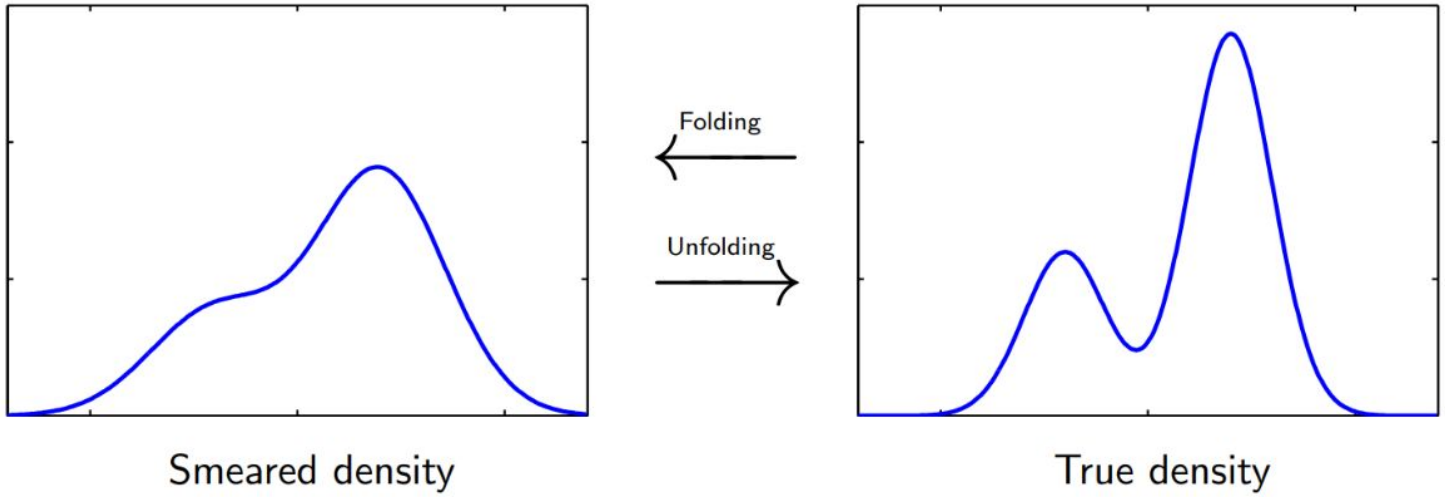
Fit strategy

The end result is a fit strategy with 12 signal regions and 36 control regions.



Unfolding step

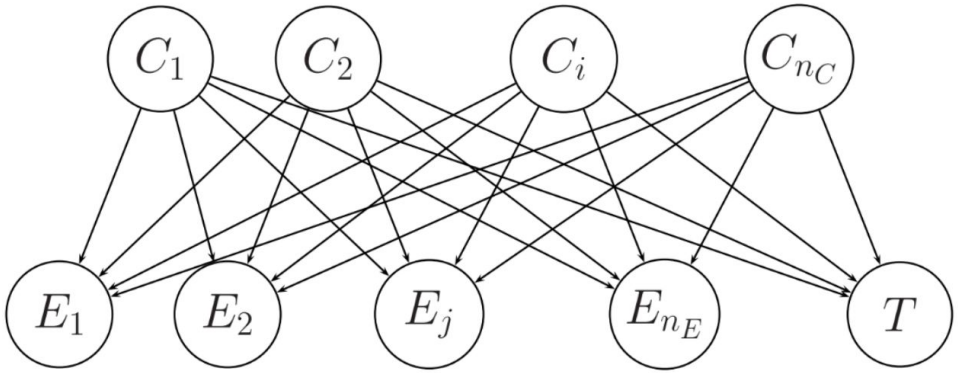
The result of the fit is the experimentally measured distribution for W+c. This is however the convolution between a true distribution and the response of the detector.
We can recover the true physics distribution with **Unfolding**.



Iterative Bayesian Unfolding

The most used algorithm is **Iterative Bayesian Unfolding (IBU)** and it is based on a probabilistic approach.

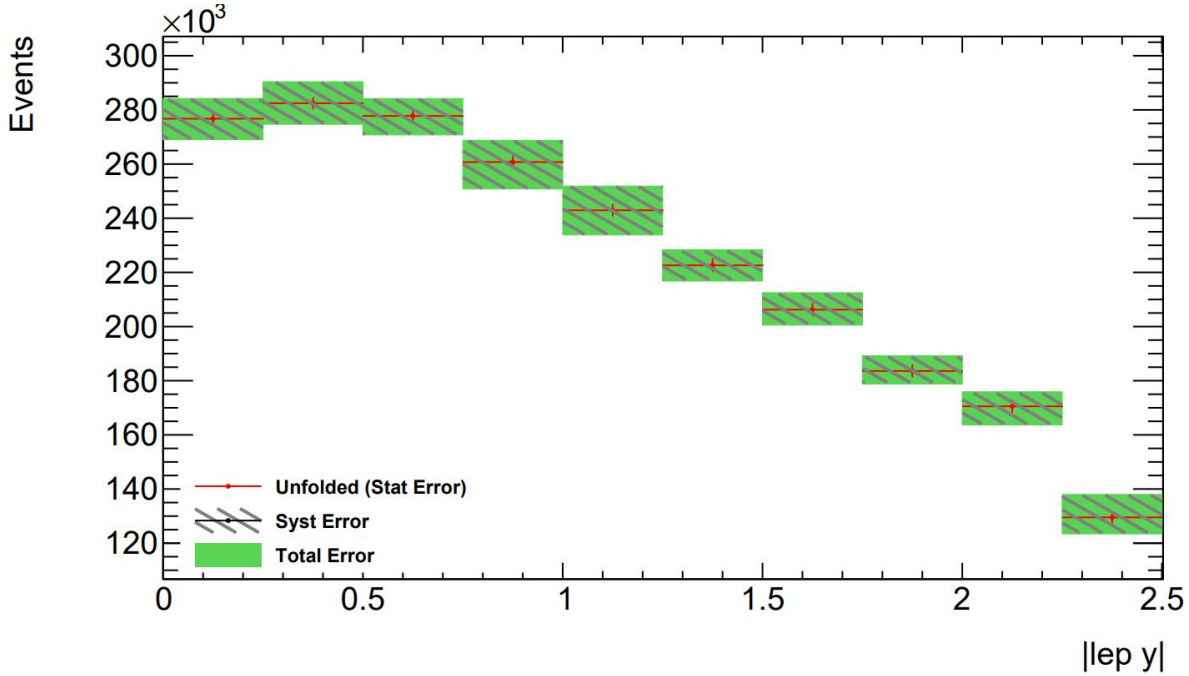
$$P(C_i \mid E_j) = \frac{P(E_j \mid C_i) \cdot P(C_i)}{\sum_i P(E_j \mid C_i) \cdot P(C_i)}$$



Improved iterative Bayesian unfolding, G. D'Agostini, arXiv:1010.0632v1

Cross section

Only after this last step it is possible to estimate the cross section for the production of W+c, opening up to a PDF interpretation of the result.



Conclusions

Precision measurements in HEP are complementary to searches for new particles.
In particular the W+c final state is sensitive to the s-quark PDF.
The main difficulty for this analysis is developing a robust and effective strategy, which has been the core of this year of my PhD.

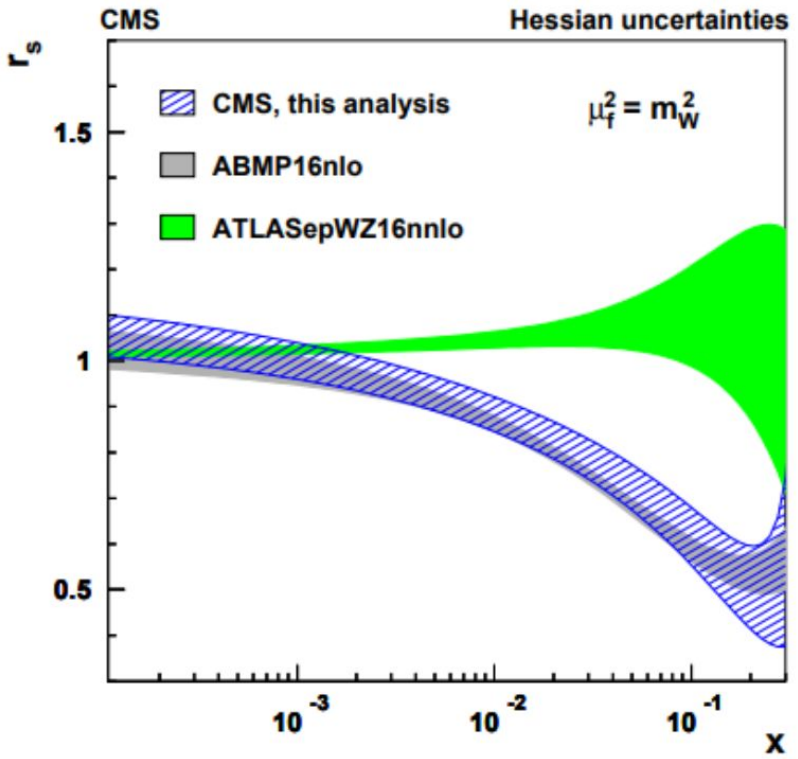
This is only the main line of research: additional work has been put into testing prototypes for Low Voltage and High Voltage electronics for ATLAS.

Backup

s-quark PDF

The s-quark PDF is usually defined by the **strangeness suppression factor**, defined as:

$$r_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$



Selections

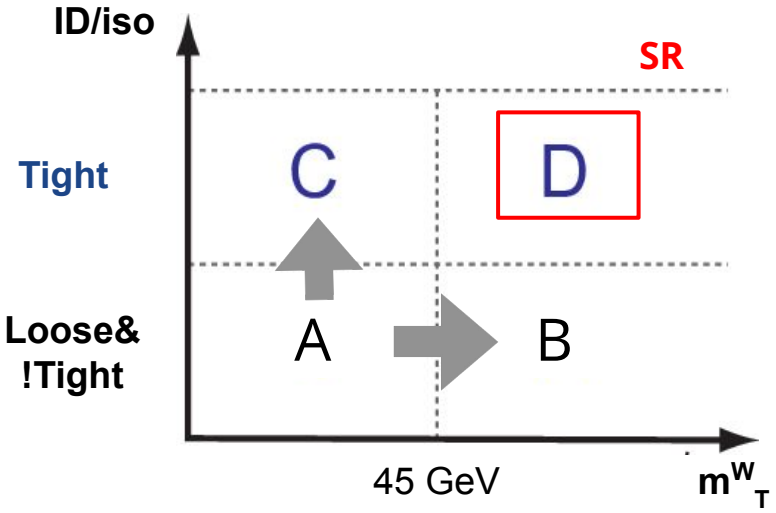
- **Electron selection:**
  - Single lepton trigger
  - **1 electron, p_T > 27 GeV, tight Iso and ID**, match trigger object, $|\eta| < 2.47$ (excluding crack region)
  - dilepton veto on prompt loose electrons (Medium LH, FC Loose Iso, $p_T > 15$ GeV)
  - Overlap removal
- **Muon selection:**
  - **1 muon with p_T > 27 GeV** (veto additional isolated muons with $p_T > 10$ GeV), $|\eta| < 2.5$
  - **Isolation: PflowTight_FixedRad**
  - **Medium quality at least**
  - 2015 trigger requirement: mu20_iloose_L1MU15_OR_mu50
  - 2016/2017/2018 trigger requirement: mu26_ivarmedium_OR_mu50
  - dilepton veto on loose muons (Medium, PFlow Loose Fixed Rad Iso, p_T>10 GeV)
  - Overlap removal
- **MET > 30 GeV and m_T^W> 45 GeV**
- **Jet selection (P-Flow jets):**
  - **1 <= Njets <= 2**
  - **p_T > 20 GeV**, $|\eta| < 2.5$,
  - ΔR(jet,electron/muon) > 0.4
  - pass JVT Tight WP
- **Soft-muon selection:**
  - **Tight identification**
  - **p_T >4 GeV**, $|\eta| < 2.5$
  - ΔR(jet,muon) < 0.4
  - $|d_0|, |z_0 \sin\theta| < 3$ mm
- **Only muon channel:**
  - m(SMT,Wlep) < 4, 8-11 and 80-100 GeV vetoed
  - pTbal = p_T Z / (p_T lep + p_TSMT) > 0.4
  - (EMFrac < 0.8 || Ntracks > 2)
  - (smtmu_ptvarcone30_TightTTVA_pt500+0.4* smtmu_neflowisol20)/smtmu_pt > 0.16

Multijet

- 3 **CONTROL** regions (A, B and C)
- **SIGNAL region (D)**

Default variables:

- m^{T}_{W} (regions A, C < 45 GeV, region B, D > 45 GeV)
- Lepton isolation (iso)



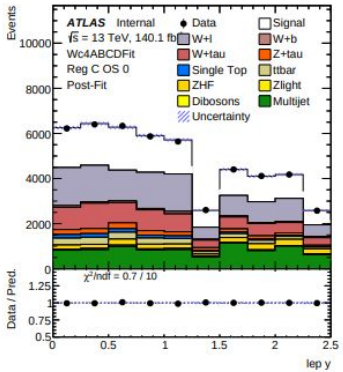
D = A x (B/A) x (C/A)

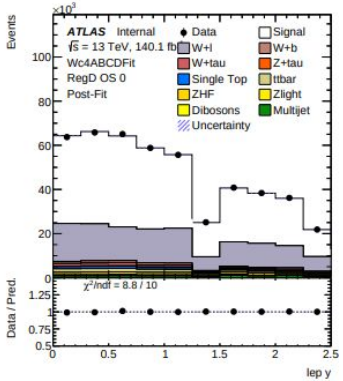
Cross section

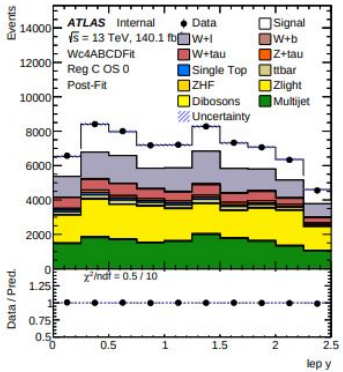
ELE	Cross section $[pb]$		
Variable	Sum	$W+$	$W-$
LY	16.5 ± 0.6	8.1 ± 0.3	8.5 ± 0.4
JY	16.5 ± 0.7	8.1 ± 0.2	8.4 ± 0.4
SMY	16.5 ± 0.6	8.1 ± 0.2	8.4 ± 0.4

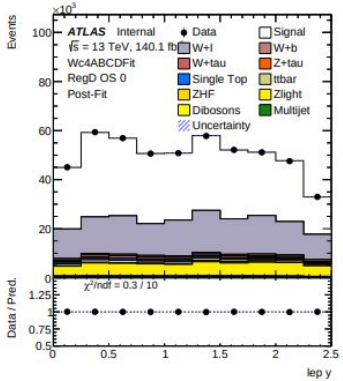
MUO	Cross section $[pb]$		
Variable	Sum	$W+$	$W-$
LY	16.1 ± 0.5	7.9 ± 0.2	8.3 ± 0.3
JY	16.1 ± 0.5	7.9 ± 0.2	8.2 ± 0.3
SMY	16.1 ± 0.5	7.9 ± 0.2	8.2 ± 0.3

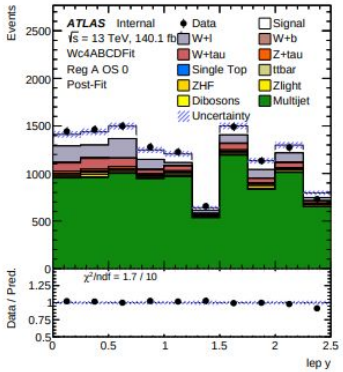
OS Bin 0 - Ele left - Muo right

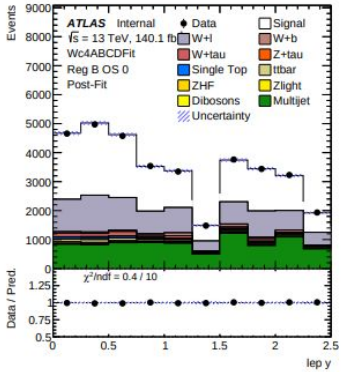


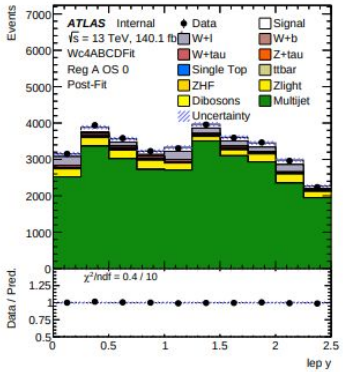


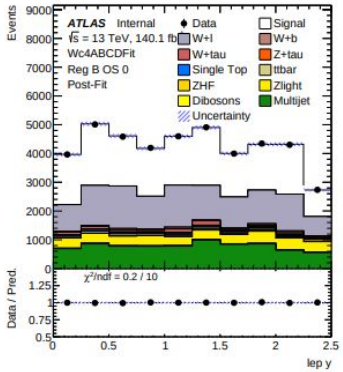




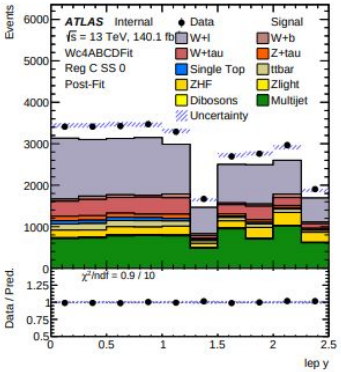


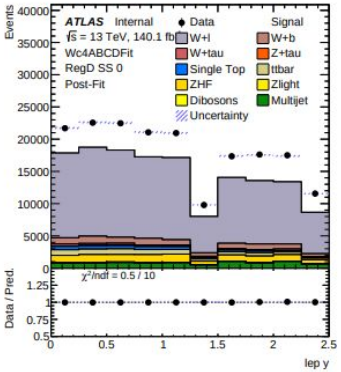


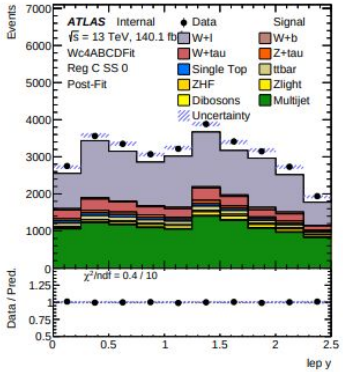


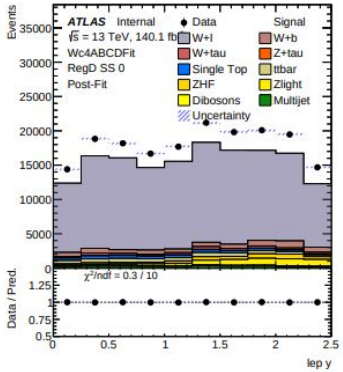


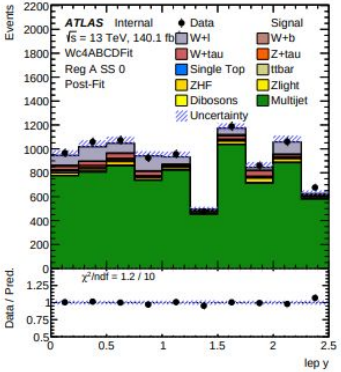
SS Bin 0 - Ele left - Muo right

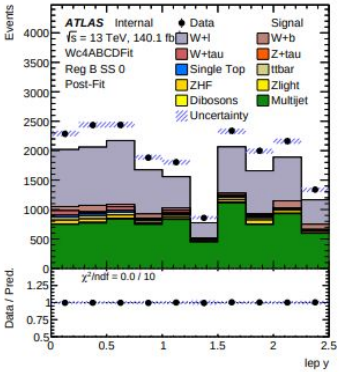


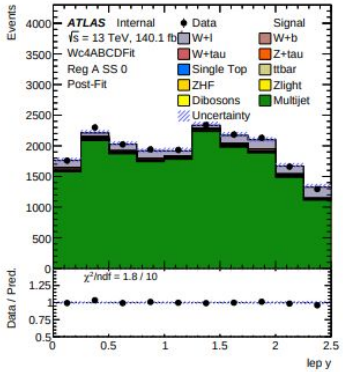


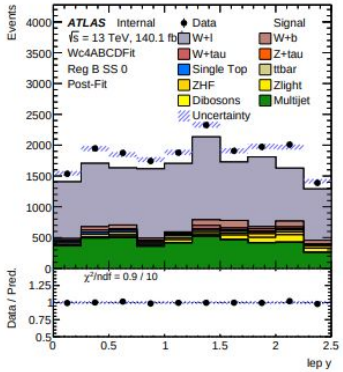




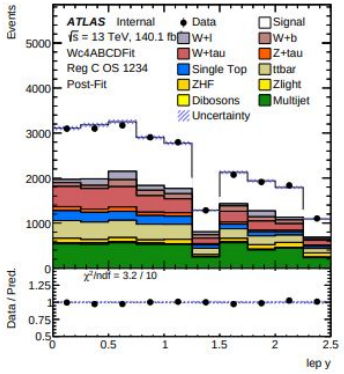


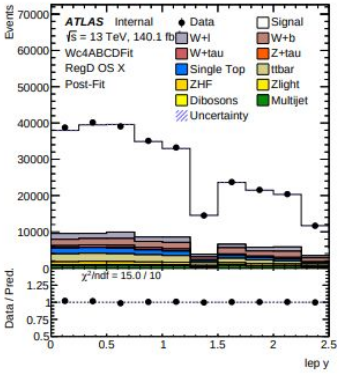


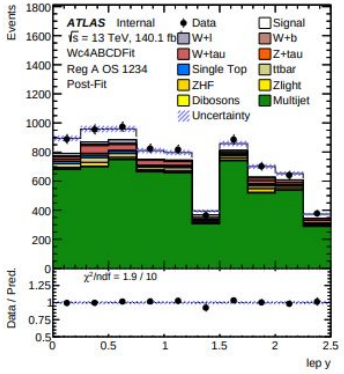


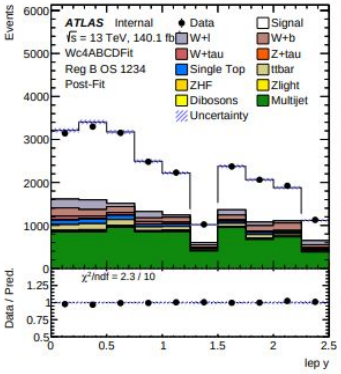


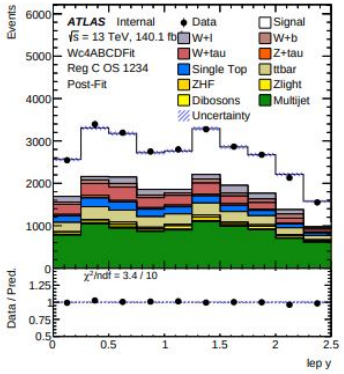
OS Bin X - Ele left - Muo right

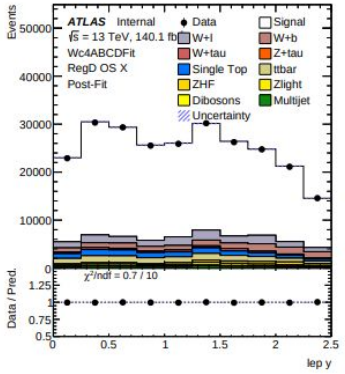


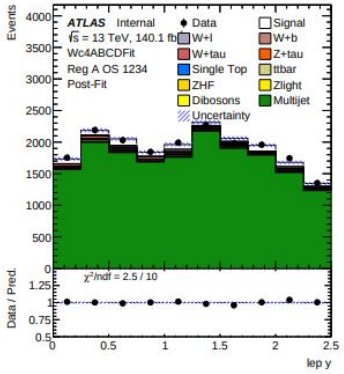


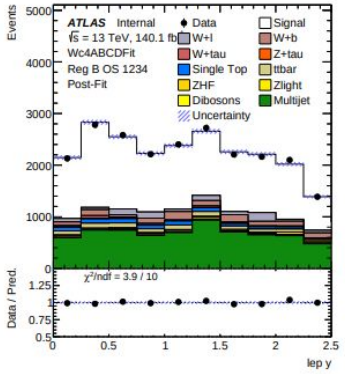




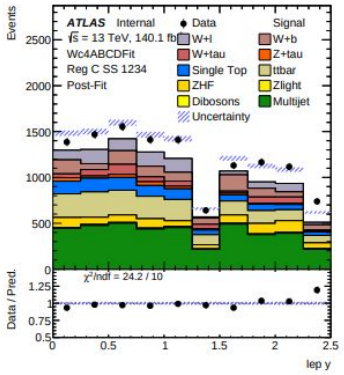


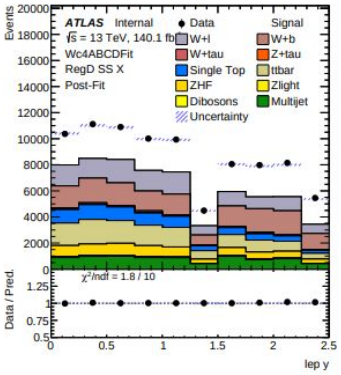


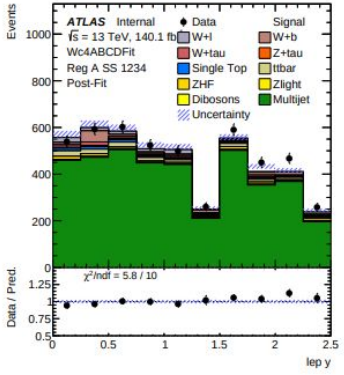


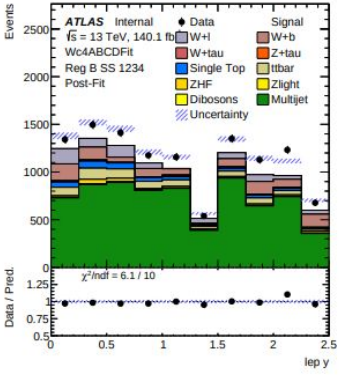


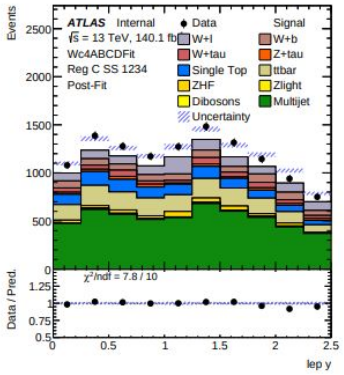
SS Bin X - Ele left - Muo right

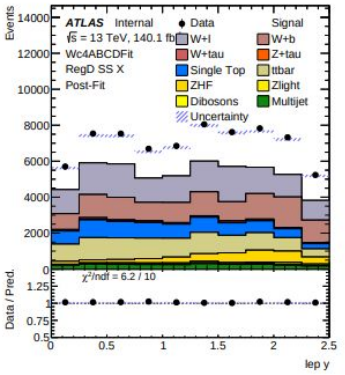


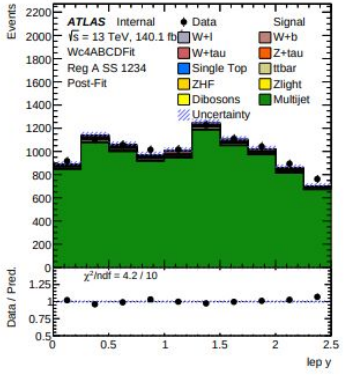


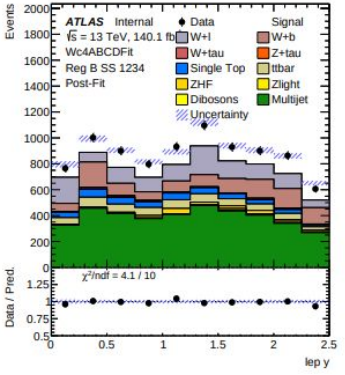




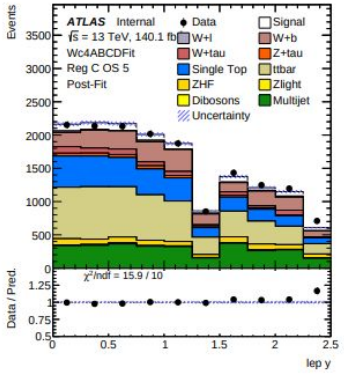


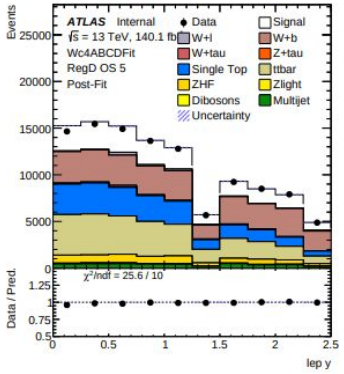


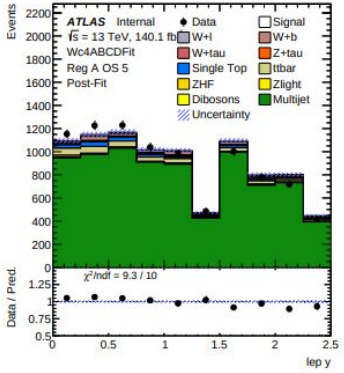


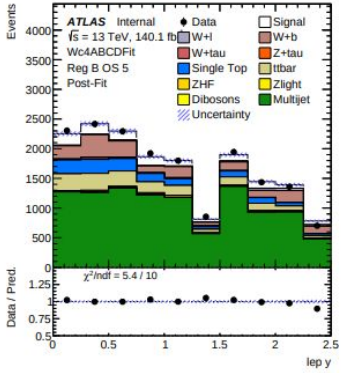


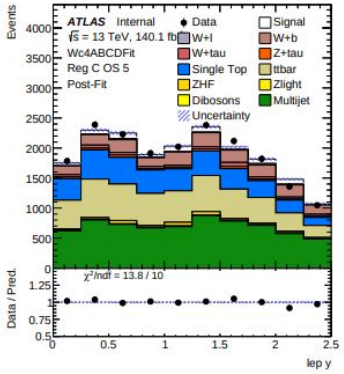
OS Bin 5 - Ele left - Muo right

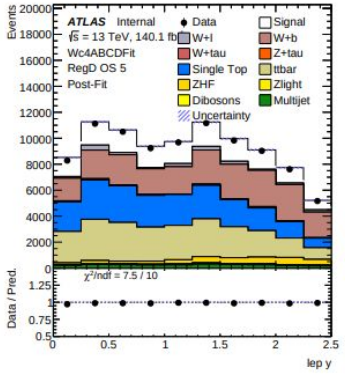


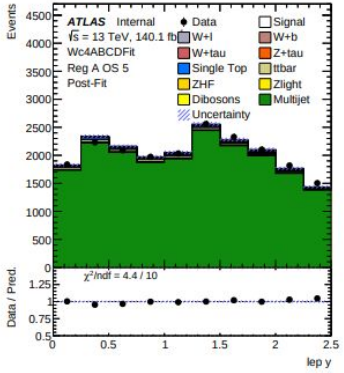


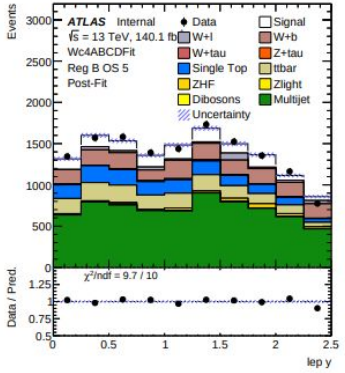




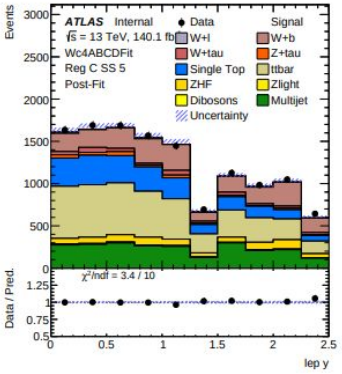


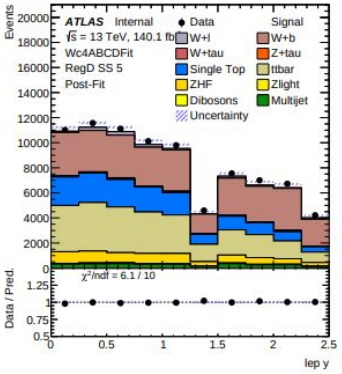


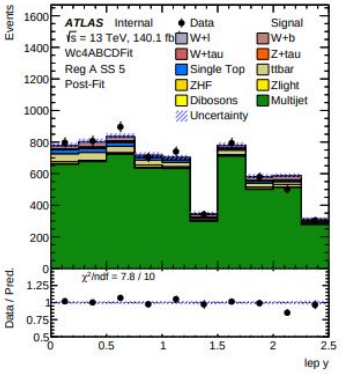


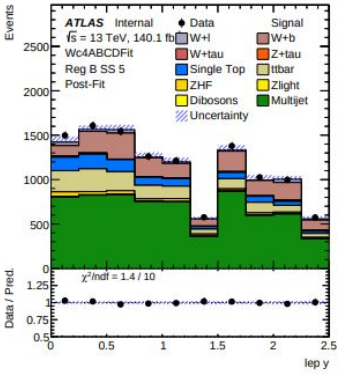


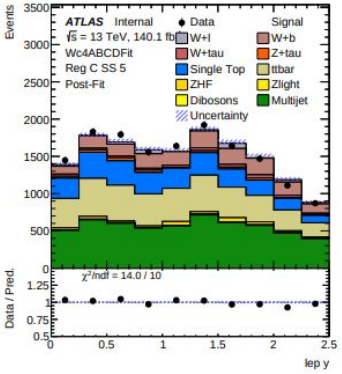
SS Bin 5 - Ele left - Muo right

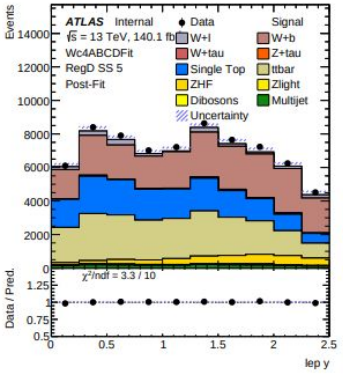


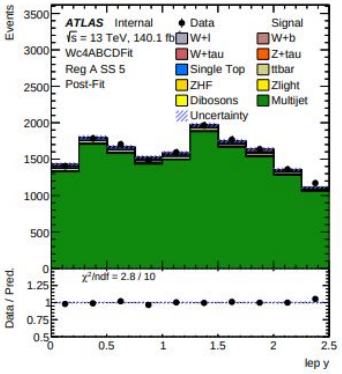


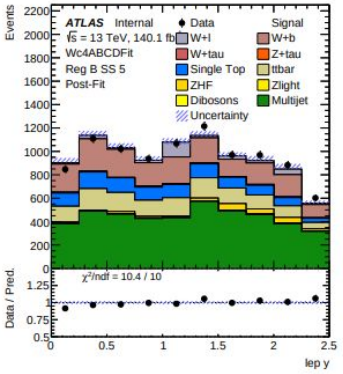












Current results - ELE

ELE	Post fit		
Variable	Sum	Wp	Wm
LY	451589	221806	230094
JY	454310	223800	230289
SMY	454924	224657	230939

Sum - (Wp + Wm) %
Post fit
-0,069
0,049
-0,148

ELE	Post unfold		
Variable	Sum	Wp	Wm
LY	2316461	1132527	1187635
JY	2309248	1133770	1174090
SMY	2311735	1137801	1177293

Sum - (Wp + Wm) %
Post unfold
-0,160
0,060
-0,145

	Post fit			Post unfold		
Diff to average %	Sum	Wp	Wm	Sum	Wp	Wm
LY	-0,445	-0,723	-0,150	0,172	-0,191	0,675
JY	0,155	0,170	-0,066	-0,140	-0,082	-0,473
SMY	0,290	0,553	0,216	-0,032	0,273	-0,202

Current results - MUO

MUO	Post fit		
Variable	Sum	Wp	Wm
LY	439908	216073	224648
JY	435772	214795	220724
SMY	436293	215624	221299

Sum - (Wp + Wm) %
Post fit
-0,185
0,058
-0,144

MUO	Post unfold		
Variable	Sum	Wp	Wm
LY	2257742	1105558	1156017
JY	2251606	1107042	1143271
SMY	2253852	1109721	1146310

Sum - (Wp + Wm) %
Post unfold
-0,170
0,057
-0,097

	Post fit			Post unfold		
Diff to average %	Sum	Wp	Wm	Sum	Wp	Wm
LY	0,591	0,267	1,091	0,148	-0,170	0,652
JY	-0,355	-0,326	-0,675	-0,124	-0,036	-0,458
SMY	-0,236	0,059	-0,416	-0,024	0,206	-0,194

Fit and unfold VS MC

The difference between post-fit and post-unfold has been calculated by averaging over the 3 different variables (LY, JY and SMY).

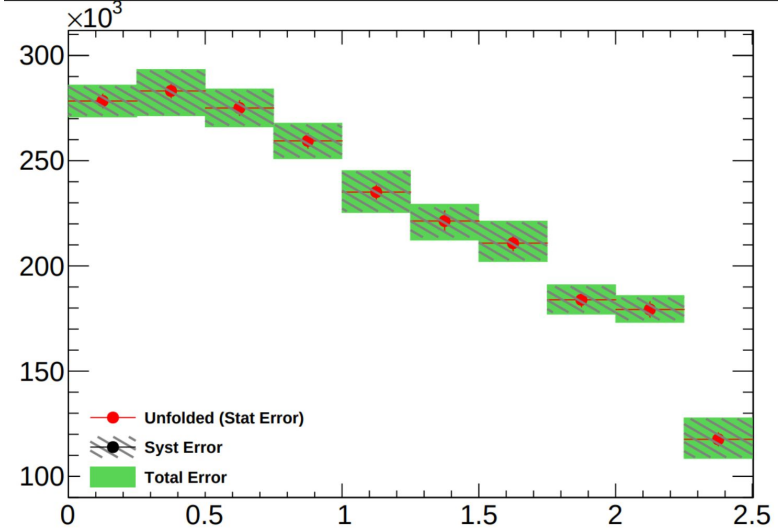
Data - MC [%]	Sum	Wp	Wm
ELE Post-fit	+4.4	+4.1	+4.8
ELE Post-unfold	+4.7	+4.4	+5.1
MUO Post-fit	+3.6	+3.2	+4.1
MUO Post-unfold	+3.3	+3.0	+3.8

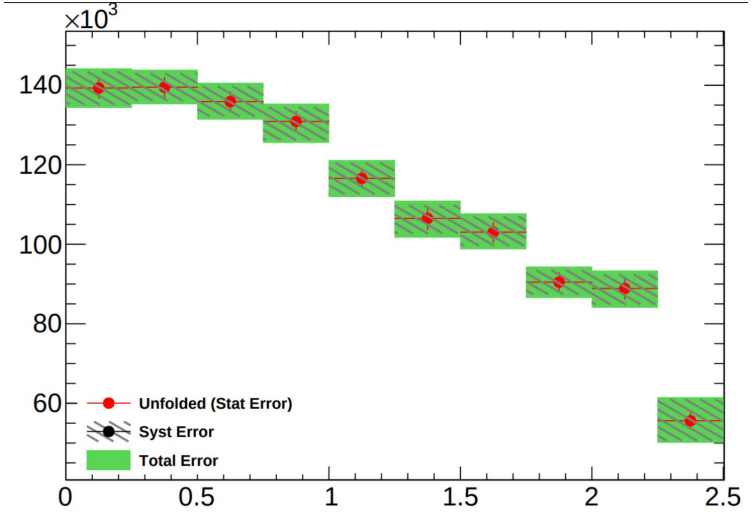
ELE - LY

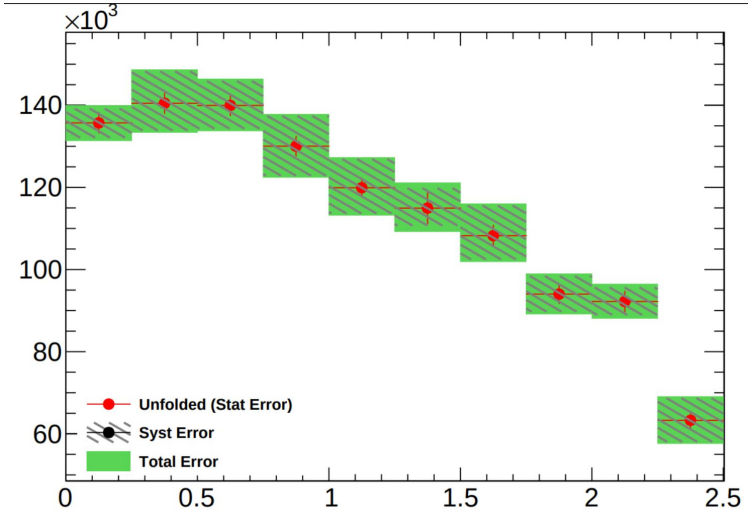
W+ + W- above

W+ left

W- right





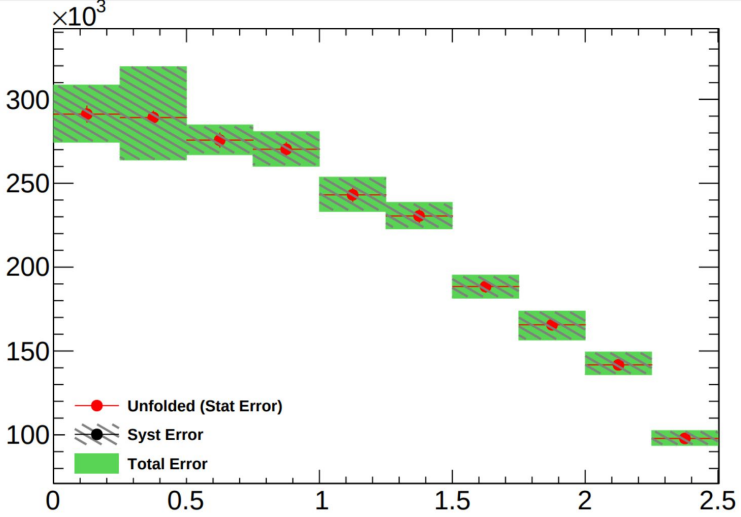


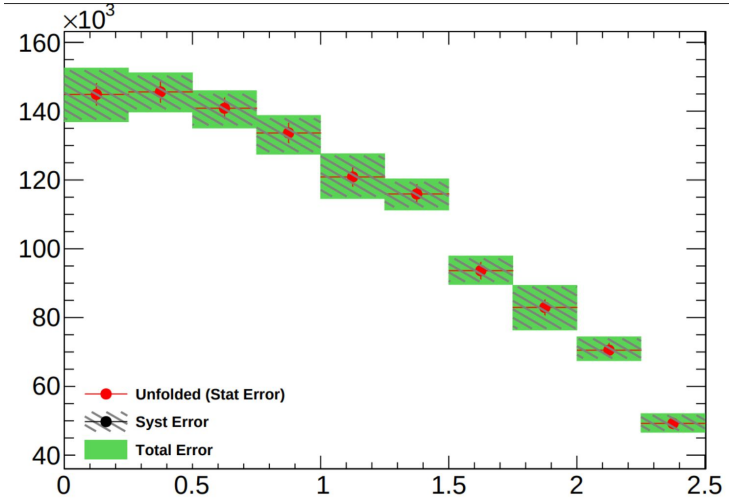
ELE - JY

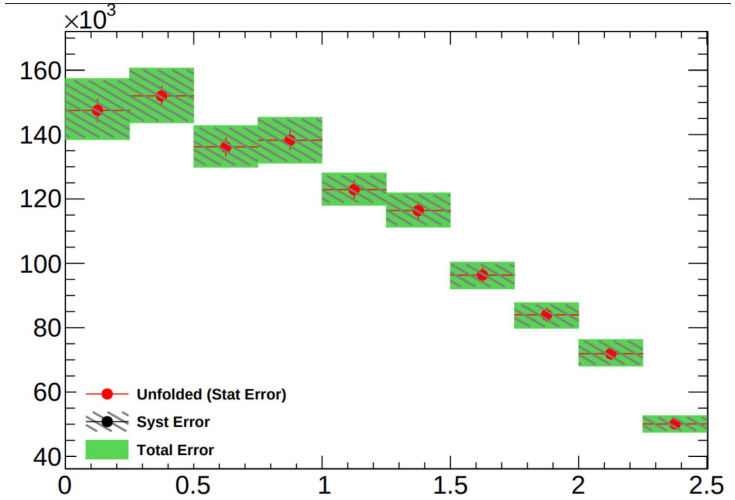
W+ + W- above

W+ left

W- right





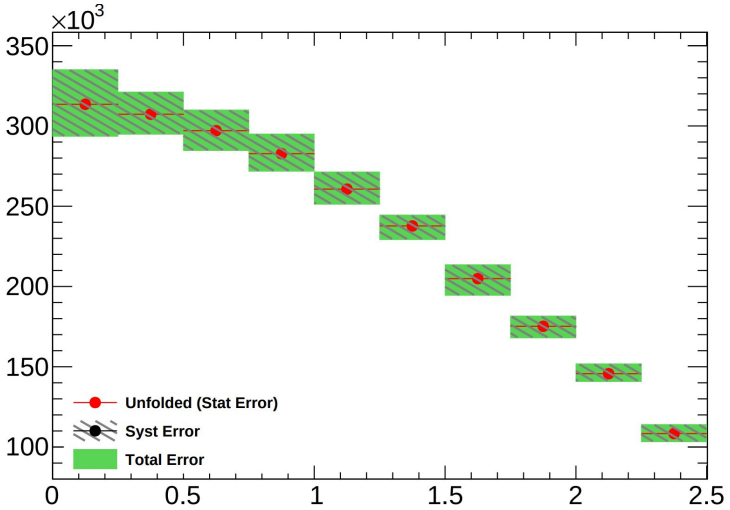


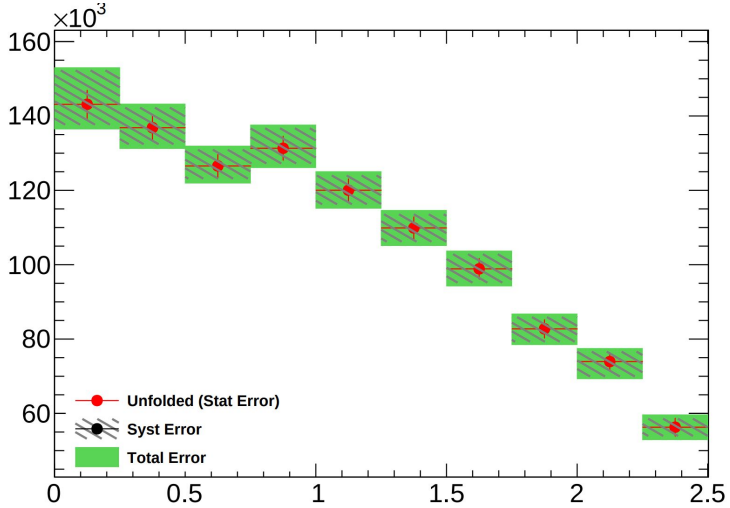
ELE - SMY

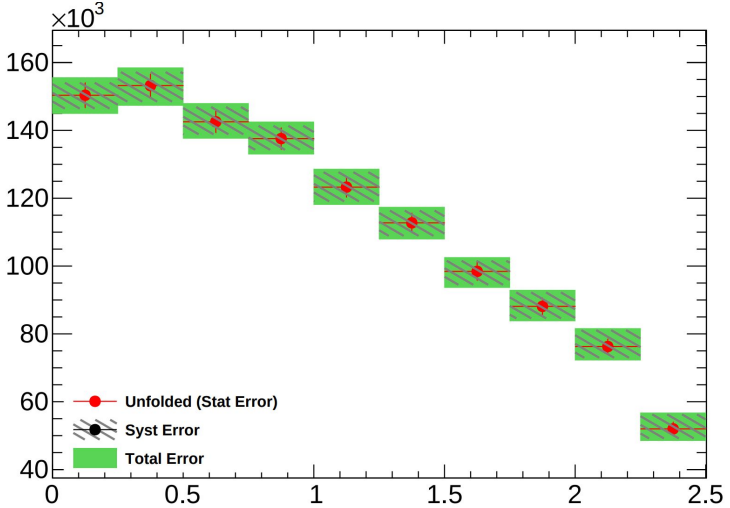
W+ + W- above

W+ left

W- right





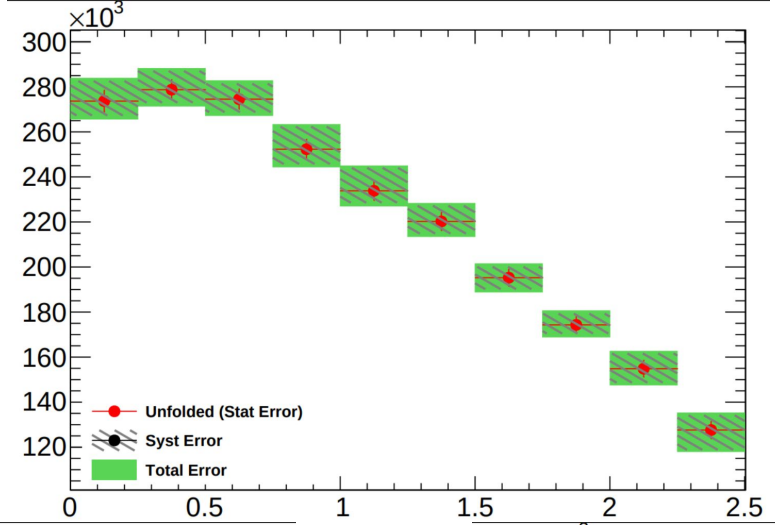


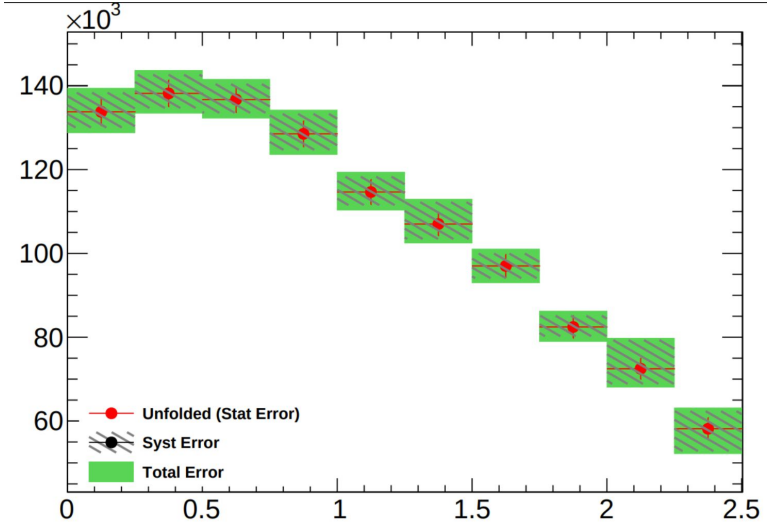
MUO - LY

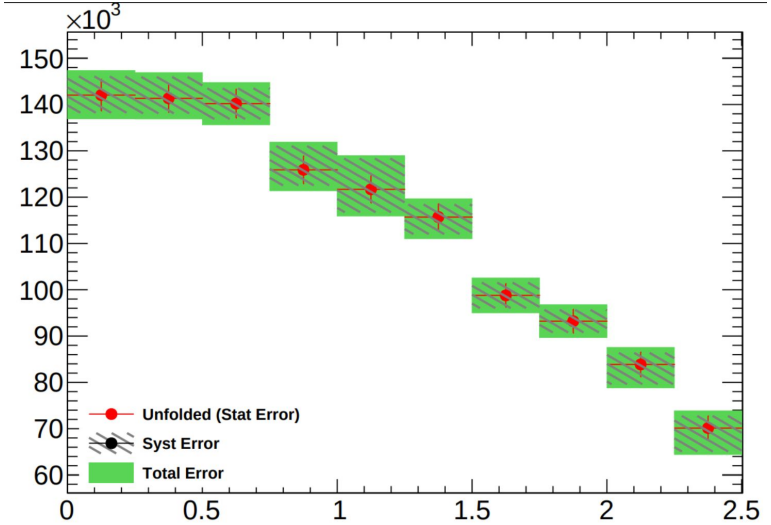
W+ + W- above

W+ left

W- right





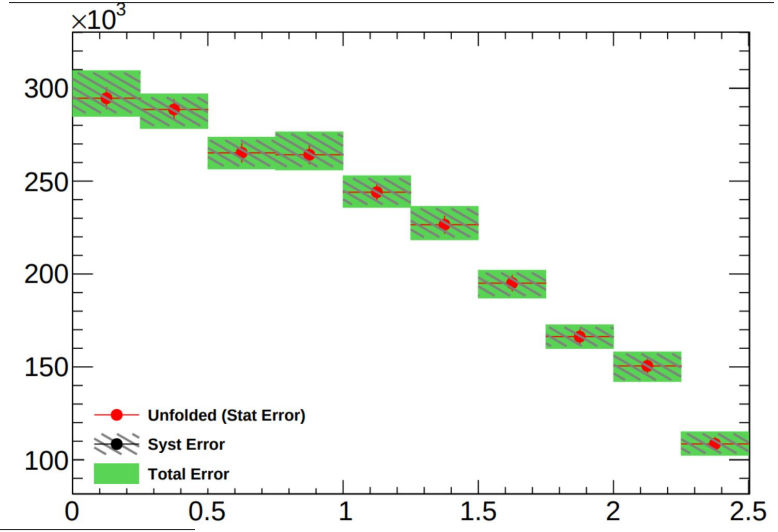


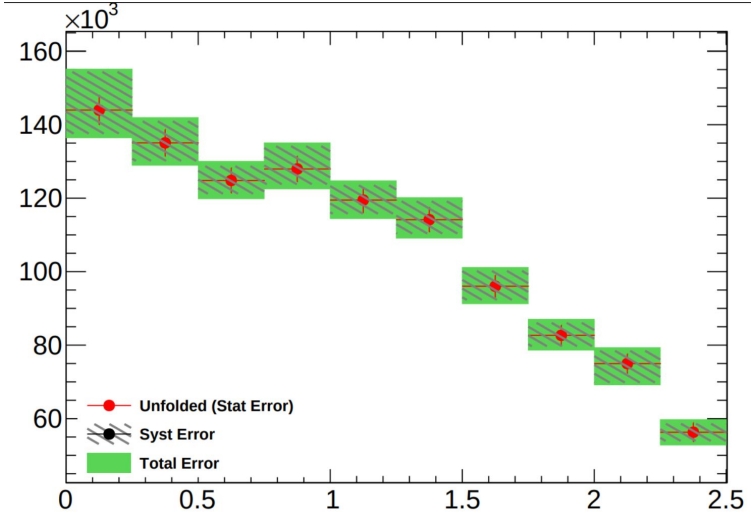
MUO - JY

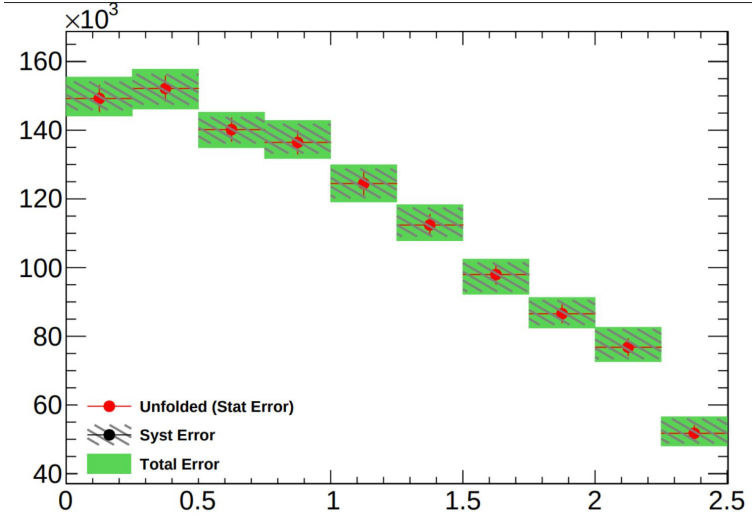
W+ + W- above

W+ left

W- right





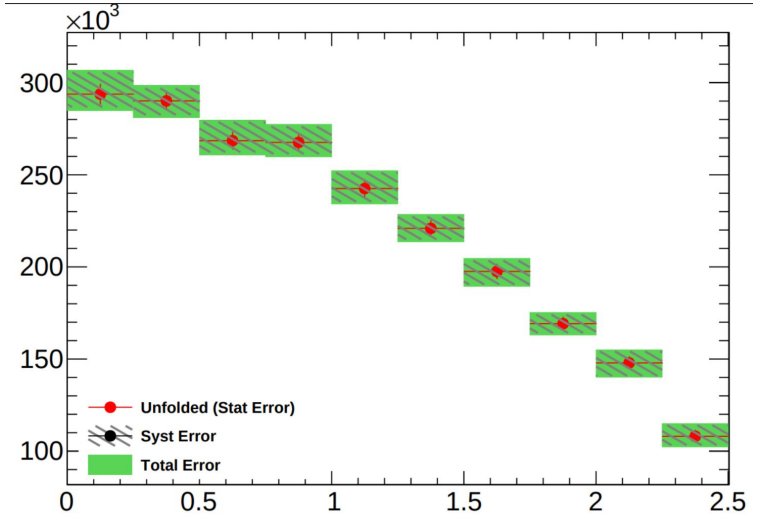


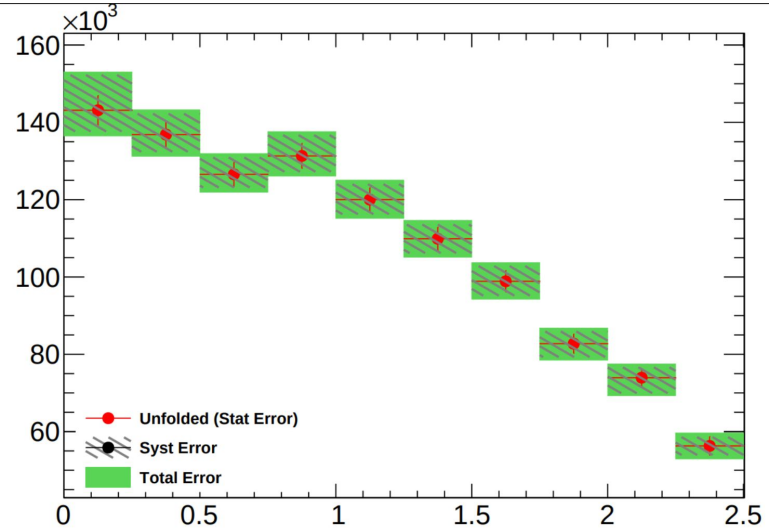
MUO - SMY

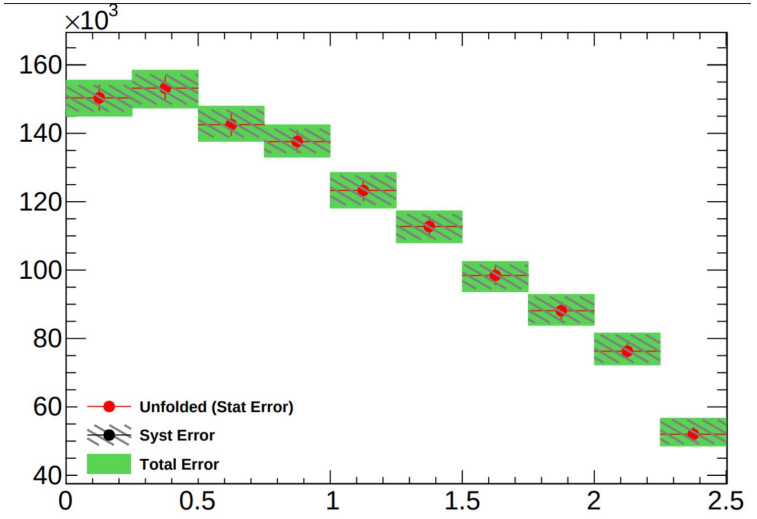
W+ + W- above

W+ left

W- right







Stat + Full(*) Systematics

ELE - ErrUp, Down %	Sum	W+	W-
LY	+2.7% -2.6%	+2.6% -2.5%	+4.2% -4.0%
JY	+3.6% -3.6%	+2.3% -2.3%	+3.6% -3.6%
SMY	+3.0% -3.1%	+2.4% -2.4%	+3.8% -3.7%

MUO - ErrUp, Down %	Sum	W+	W-
LY	+2.9 -2.0%	+2.8% -2.2%	+2.5% -2.6%
JY	+2.8% -2.1%	+3.1 -2.6%	+2.6% -2.4%
SMY	+2.8% -2.1%	+3.2% -2.4%	+2.4% -2.5%

(*) We are still resolving minor bugs regarding some systematics

CKM

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}$$