Low-Mass Drell-Yan at $\sqrt{s} = 13\text{TeV}$ with the ATLAS Detector

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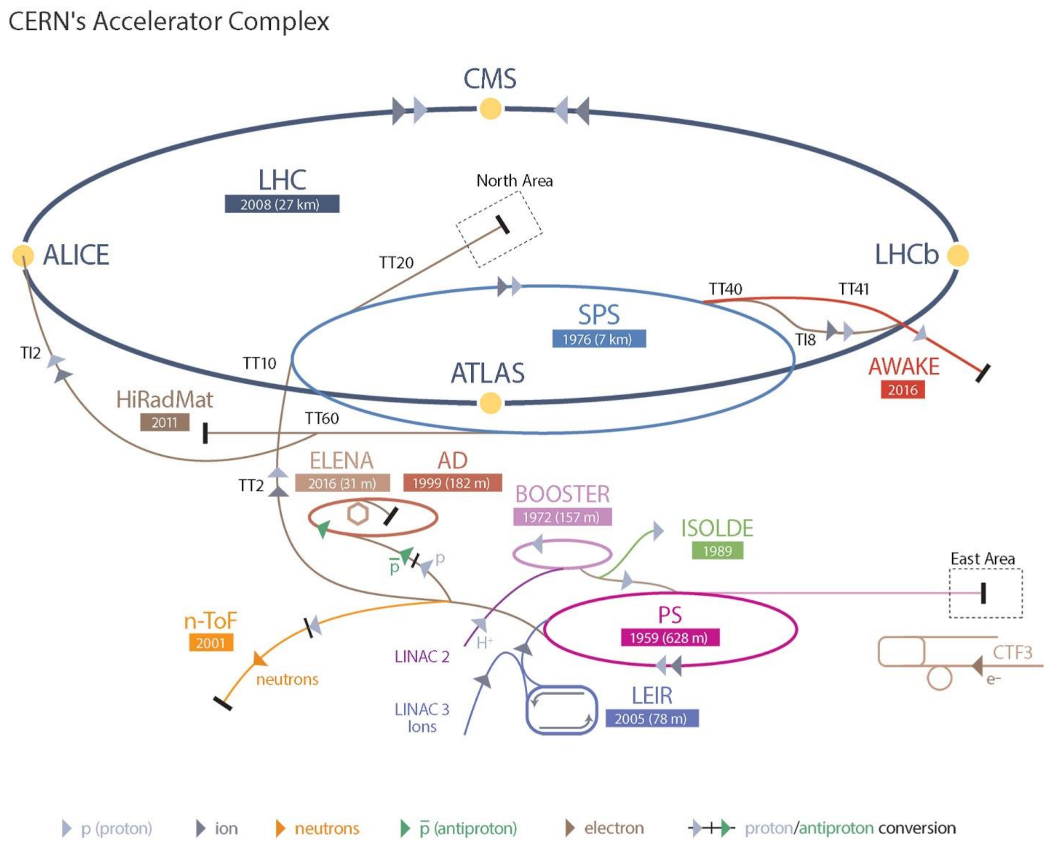
21.04.21

The Large Hadron Collider

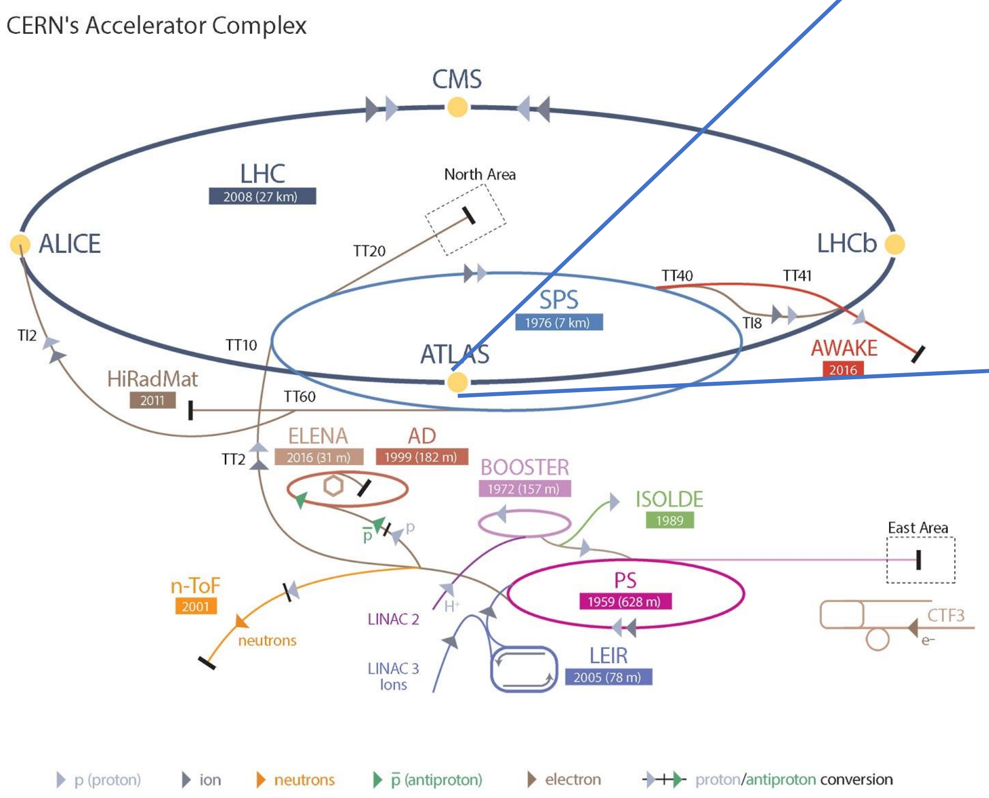


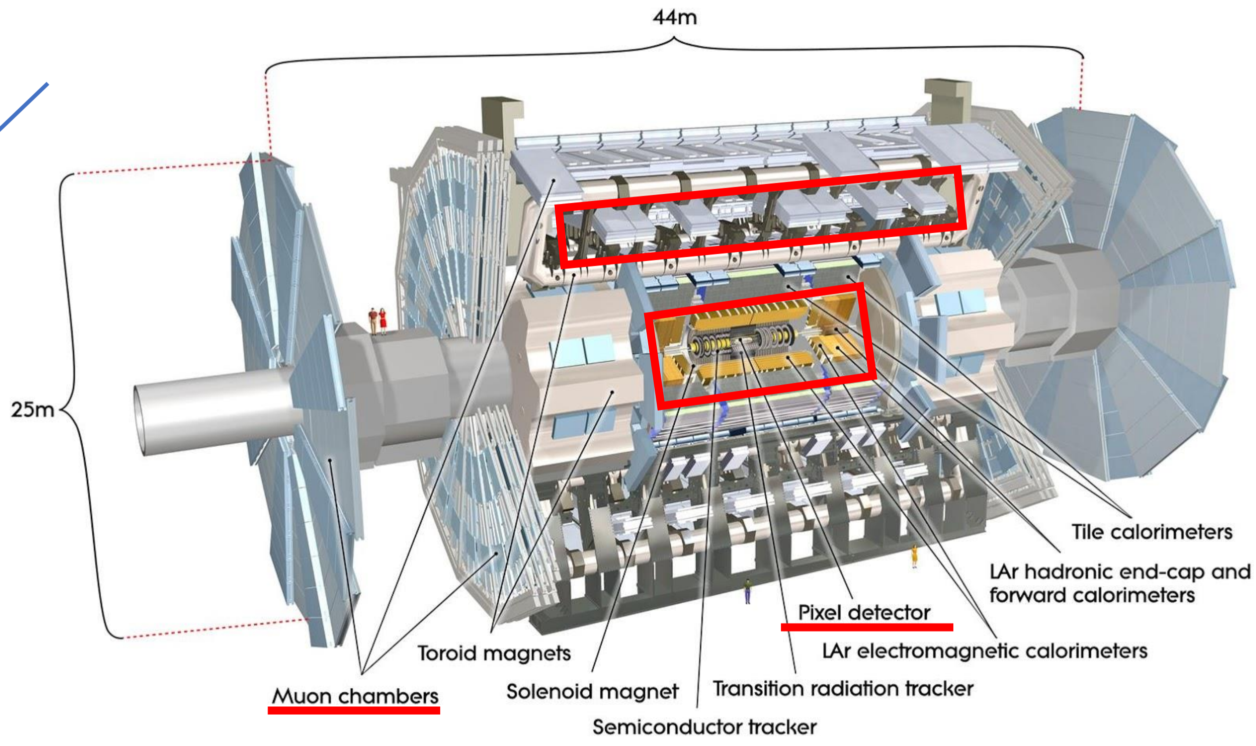
The LHC

- 27 km ring of accelerating structures and superconducting magnets
- 2 Proton beams are accelerated up to an energy of 6.5 TeV
- The protons beams are made collide in various interaction points by the various experiment

- LHC is now in the long shutdown phase
- Analysis of the data taken during the run2 (2015-2018) are ongoing

The ATLAS Detector





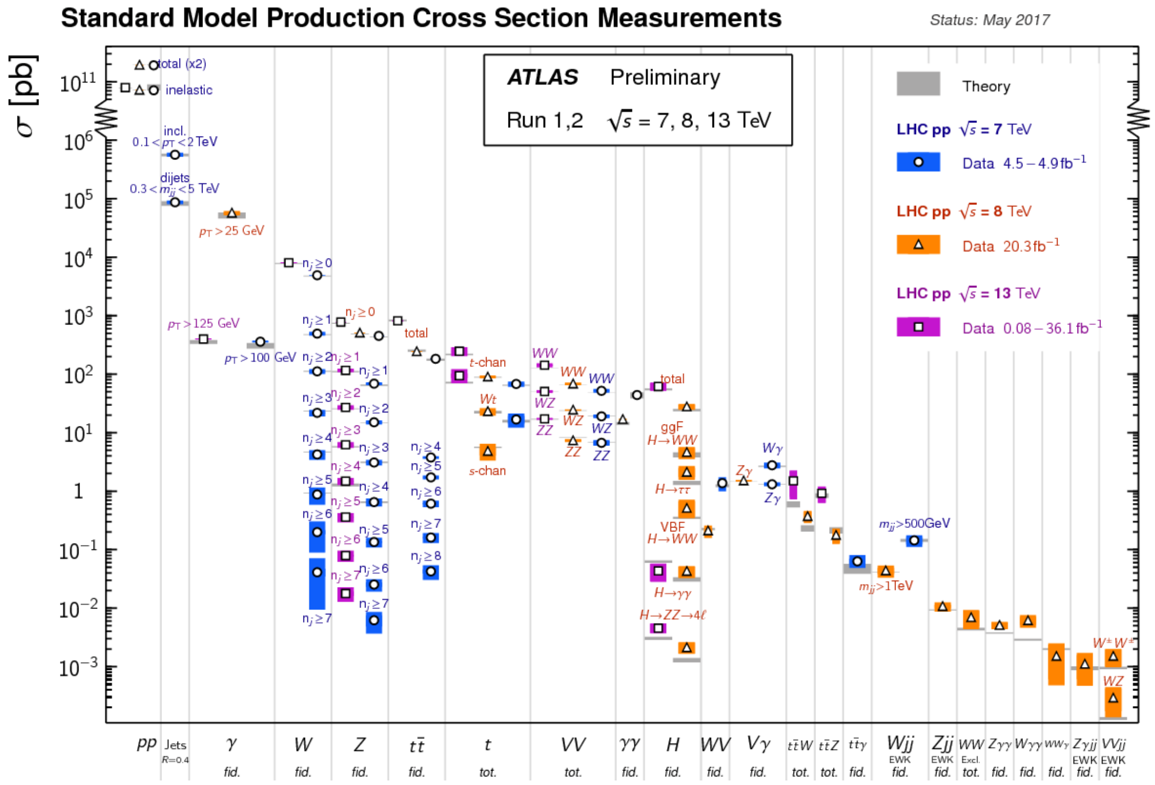
The ATLAS detector:

- Multipurpose detector
- Detect the particles coming from proton-proton interactions
- Reconstruct the tracks and the energies of the particles
- Cylindrical shape with a layered structures

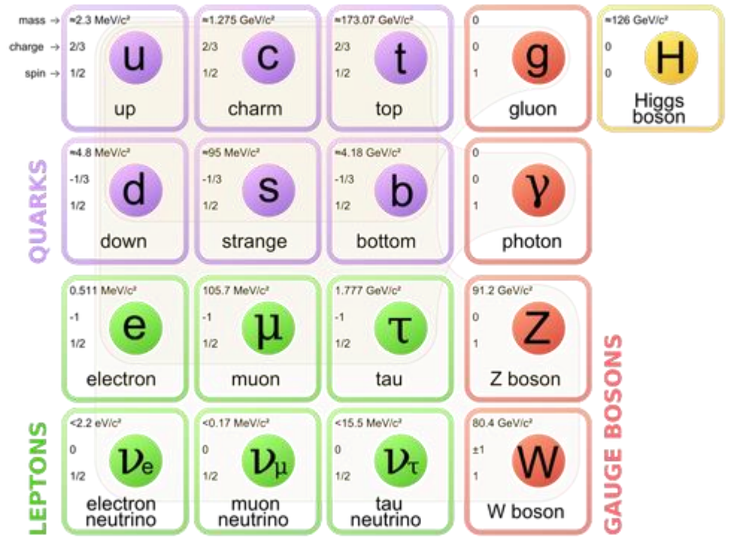
ATLAS and the Standard Model

The discovery of the Higgs boson in 2012 by ATLAS and CMS completed the Standard Model (SM) Picture

- SM successfully describe all the measurement performed in ATLAS so far



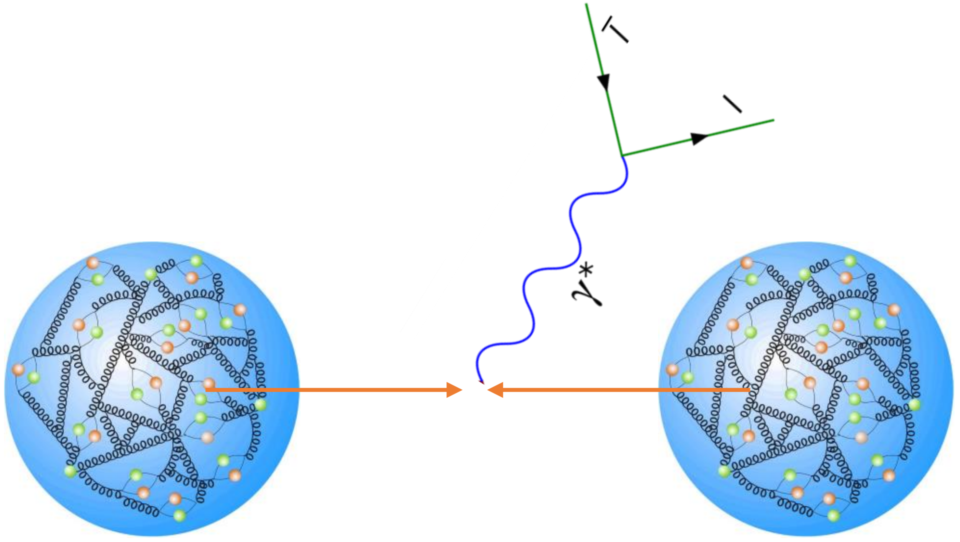
Elementary Particles of the Standard Model



ATLAS has a wide physics program to test the Standard Model

- Probe new theory beyond the Standard Model
- Precision measurement of the SM processes
  - Stress the theory predictions exploring extreme region of the phase space ← Low Mass Drell-Yan

Proton-Proton Collision at LHC



At the LHC proton are colliding
- At high energy their structure is broken
- We observe the product of their constituent interaction

An **input for the calculation** of all the process at the LHC
- Information encoded in the **Parton Distribution Functions**
  - Intrinsically non perturbative quantities
- Most of the PDF input come from **electron-proton scattering** data from the HERA experiment
- Represent the probability that a parton carries a fraction *x* of the proton momentum
- LHC PDF program complementary to HERA

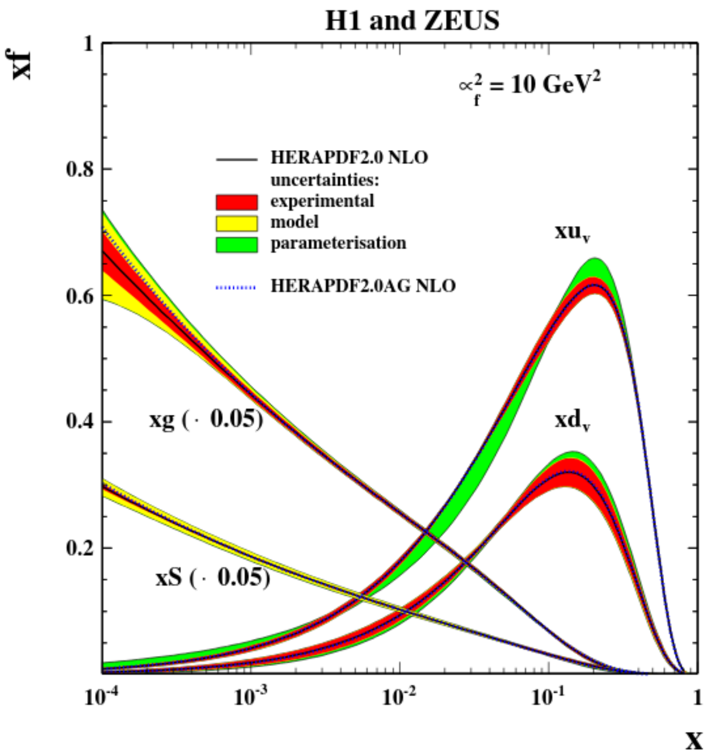
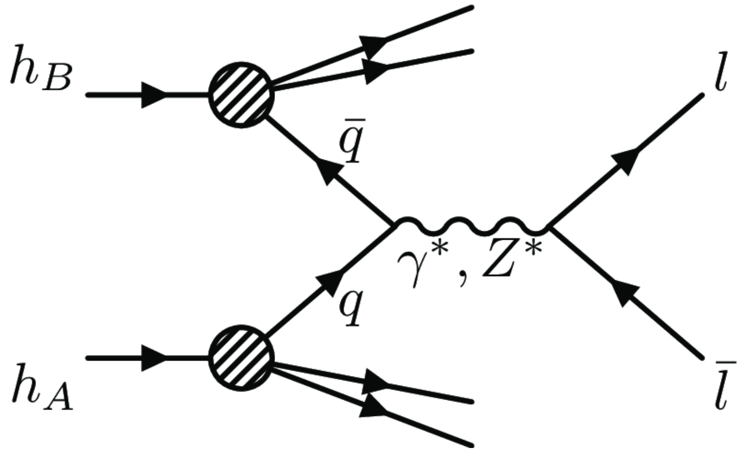


Image from 0911.0884

The Drell-Yan Process



Vector Boson creation in high energy hadron collision

- A quark and an antiquark annihilate into a vector boson
- The boson then decay leptonically
- simplest pp $2 \rightarrow 2$ process for a QCD calculation since it's EW couplings plus PDFs only

Main Production mode for Z boson ($m_Z = 91.2$ GeV) at the LHC

Interesting for:

- Precision measurement and test of the Standard Model
  - QCD and EW measurement
  - Input for Parton Distribution Function (PDF) evaluation

The Low Mass Drell-Yan

Measurement of the inclusive **Drell-Yan process in the dimuon channel**

- In proton-proton collision at $\sqrt{s} = 13$ TeV
- At **low invariant mass**, $m_{\mu\mu} = 7 - 60$ GeV

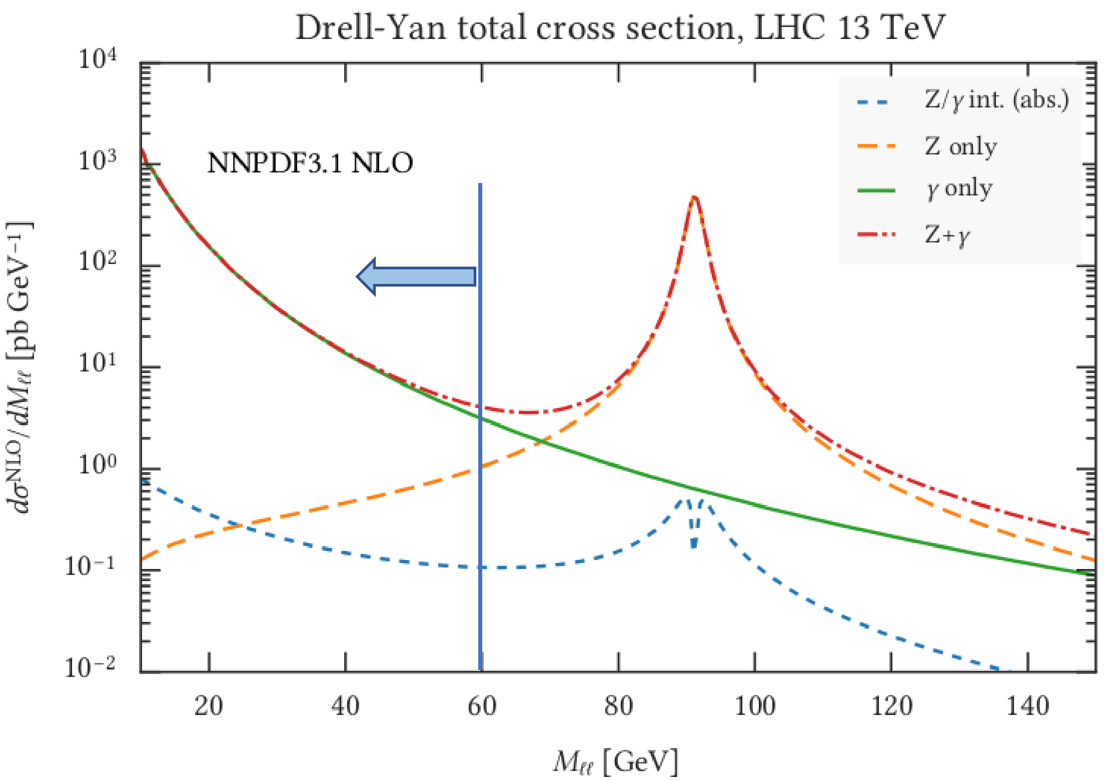
Measure Single and Double **differential cross section** in dimuon pair quantities

- $\frac{d\sigma}{dm_{\mu\mu}}$
- $\frac{d\sigma}{dm_{\mu\mu}\, dp_T^{\mu\mu}}$
- $\frac{d\sigma}{dm_{\mu\mu}\, d|y_{\mu\mu}|}$

$$y = \frac{1}{2}\ln\left(\frac{E + p_z c}{E - p_z c}\right)$$

Rapidity Definition

Previous ATLAS measurement at 7 TeV (only differential in mass)

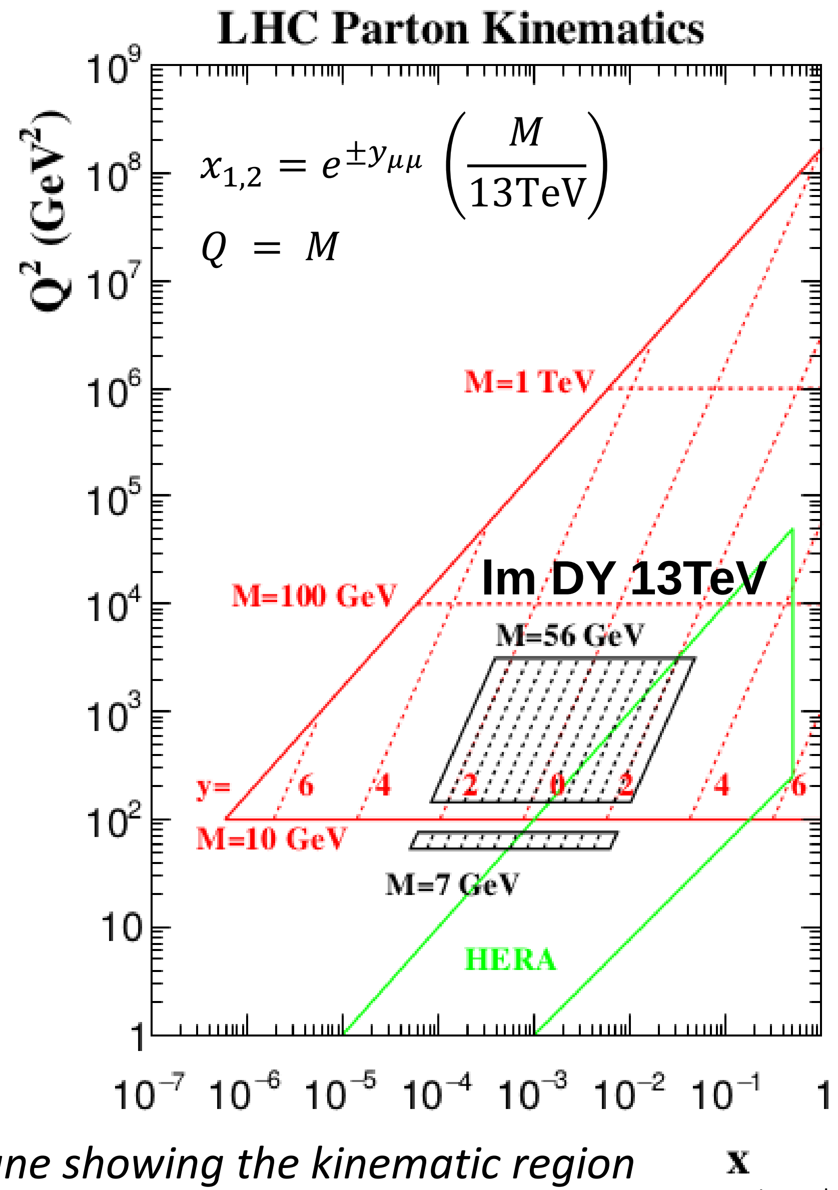


Simulation of the Drell-Yan cross-section in wide mass range

Interest of the Analysis

The analysis explores **extreme region of the phase**

- With $m_{\mu\mu}$~8 GeV → $x \sim 4 \cdot 10^{-5}$
    - **Low-x** resumed result gave interesting results with HERA data comparison
    - Interest for a comparison with this measurement
- Binning in rapidity we are more sensitive to low-x
    - $\frac{d\sigma}{dm_{\mu\mu}\, d|y_{\mu\mu}|}$
- Input for a Parton Distribution Function Fit



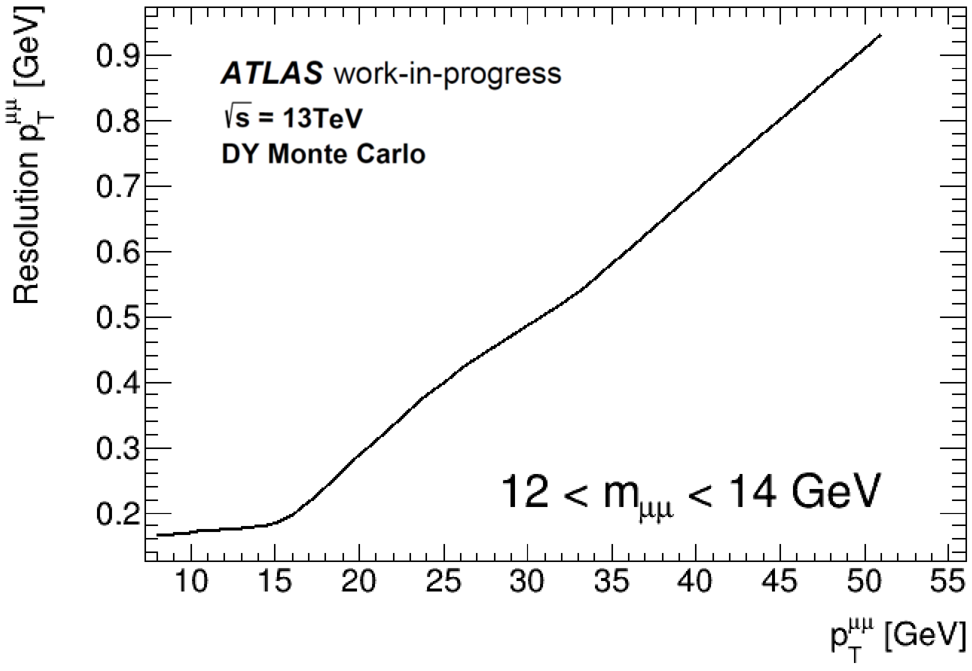
x-Q² plane showing the kinematic region accessed by the analysis, complementary region to one accessed by HERA

Image based on http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html

Interest of the Analysis

Measurement of dimuon pair p_T spectrum at low invariant mass

- $\frac{d\sigma}{dm_{\mu\mu}\, dp_T^{\mu\mu}}$
- Exploit the **good μ momentum resolution** of the ATLAS detector at low mass
- Difficult distribution to be predicted
- **Tuning of non perturbative parameters** in the theoretical prediction in kinematics region never explored before
  - Useful to confirm W boson p_T extrapolation from the $Z \to \mu\mu$ spectrum
  - W p_T extrapolation is a key input for W mass measurement



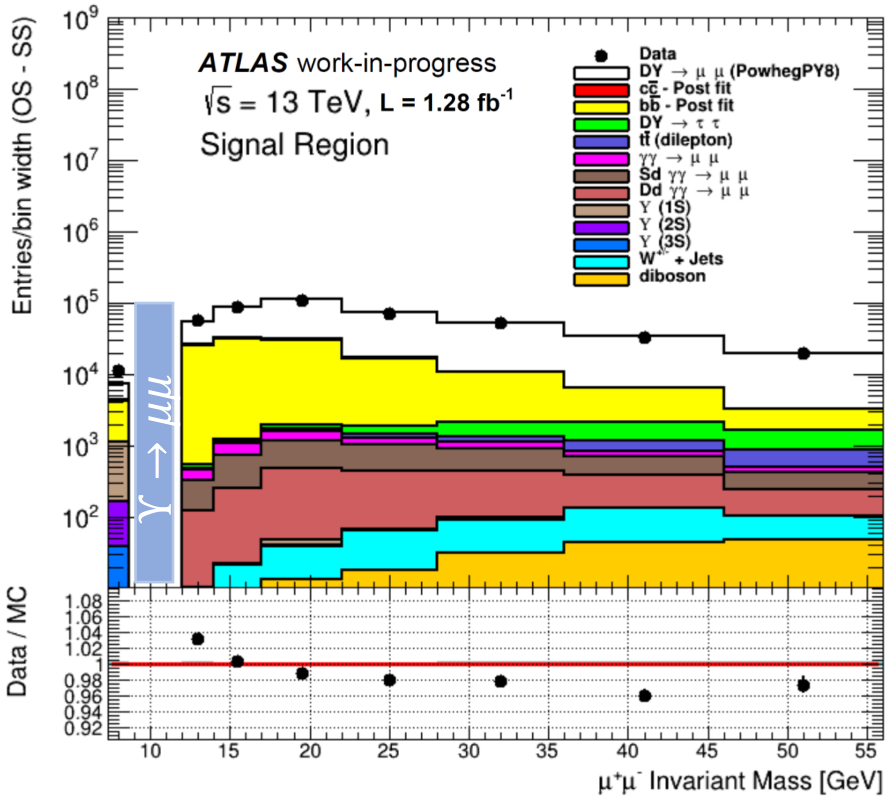
***Di-muon Momentum Resolution** at low mass,*
reconstruction as function of $p_T^{\mu\mu}$ at low mass

The Low Mass Drell-Yan Event Selection

Drell-Yan process measurement in the dimuon channel in proton proton collision at $\sqrt{s} = 13$ TeV

Event Selection

- ATLAS 2015 dataset
  - 1.28 fb^{-1}
  - Need to use special low mass di-muon triggers (next slide)
- **2 muons**
- **Low invariant mass** selection
  - $m_{\mu\mu}$ = (7.3, 8.7)+(12, 56) GeV
- **Low Pt** requirement
  - $p_T^{\mu} > 4.5$ GeV
  - Typical p_T^{μ} cut for Z analysis, $p_T^{\mu} > 20$ GeV
- **Isolation** Requirement
- NO charge requirement
  - Distribution are plotted as OppositeSign – SameSign Subtraction



Mass Spectrum of the selected signal region

Trigger Selection

Explore low invariant mass and low p_T^μ event selection

- Use of **special di-muon trigger**
  - Z and High Mass Drell-Yan typically use single muon trigger
  - Can’t trigger at low mass on single muon event, too may events
- To keep the ATLAS trigger rate at $\sim 1\mathrm{kHz}$ **low mass trigger are prescaled** (rejection rate)
- Different pre-scale between the different trigger in the trigger chain that needed to be taken into account in MC

Trigger	Prescale	Luminosity
HLT $p_T^\mu > 4, GeV\ m_{\mu\mu} \in (7,\ 9)GeV$	4	$319.68\ \mathrm{pb}^{-1}$
HLT $p_T^\mu > 4, GeV\ m_{\mu\mu} \in (12, 60)GeV$	4	$319.68\ \mathrm{pb}^{-1}$
HLT $p_T^\mu > 6, GeV\ m_{\mu\mu} \in (12,\ 24)GeV$	1	$1280.28\ \mathrm{pb}^{-1}$
HLT $p_T^\mu > 6, GeV\ m_{\mu\mu} \in (24,\ 60)GeV$	1	$1280.28\ \mathrm{pb}^{-1}$

Background

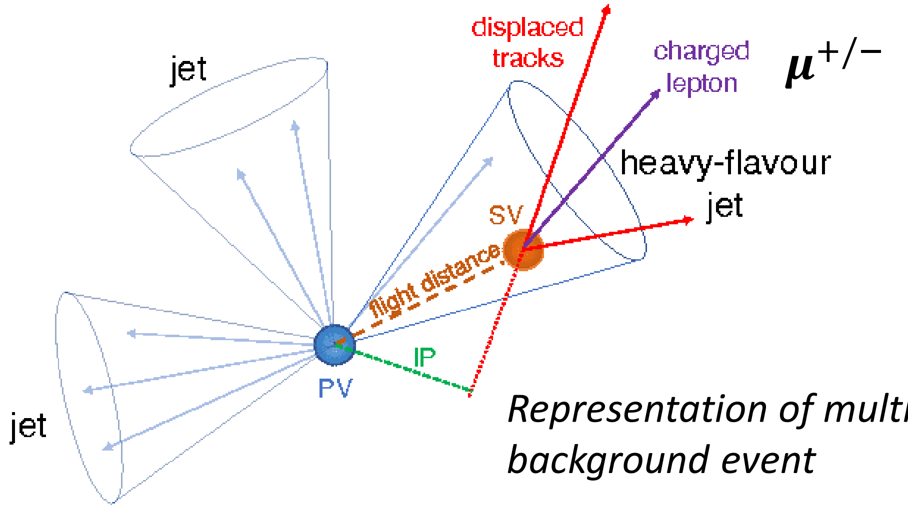
Perform the measurement – subtract the background

Fake Muons: $\pi^{\pm}, K$ misidentified as muons

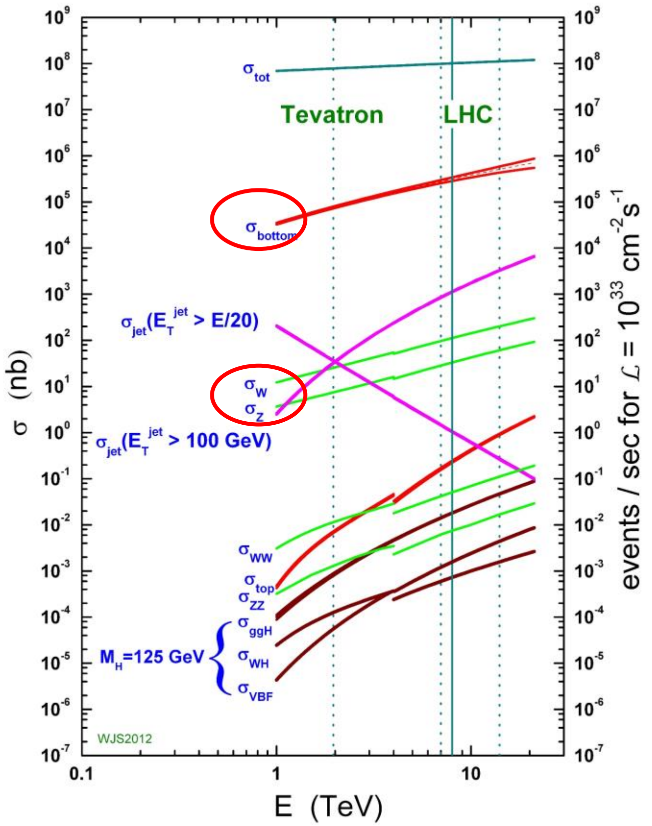
- Require high quality muons
- Assumed to be symmetric in charge
- $N_{fake}^{+,-} + N_{fake}^{-,+} = N_{fake}^{+,+} + N_{fake}^{-,-}$
    - Reduced by plotting the distribution as opposite sign minus same sign subtraction

Biggest background components is given by muon generated in
Multijets + $b\bar{b}$ / $c\bar{c}$ jets events

- Non prompt decay muons are misidentified as DY muons
- Excess in opposite sign muons
- Track isolation requirement greatly reduce this component…
    - …but still a large number of these events enter in the selection
- Poorly described in MC
    - Difficult to describe the rate of these events in the selection
    - Data-driven estimation approach



Representation of multijet background event



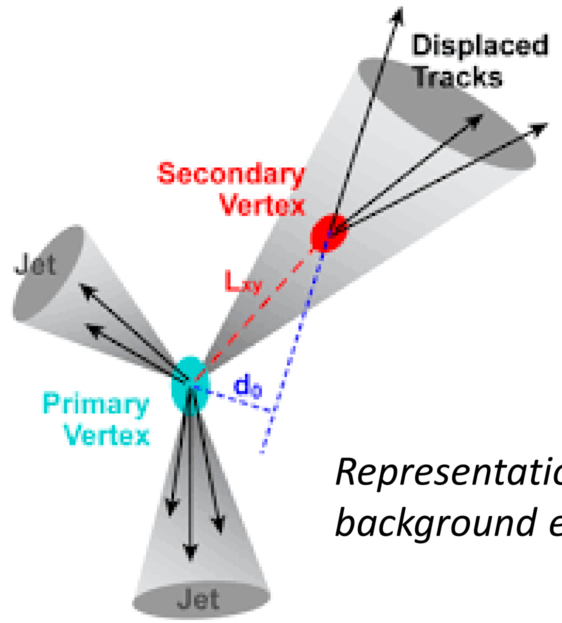
Analysis Strategy

Data-driven estimation of the Multijets + $b\bar{b}$ / $c\bar{c}$ jets background components

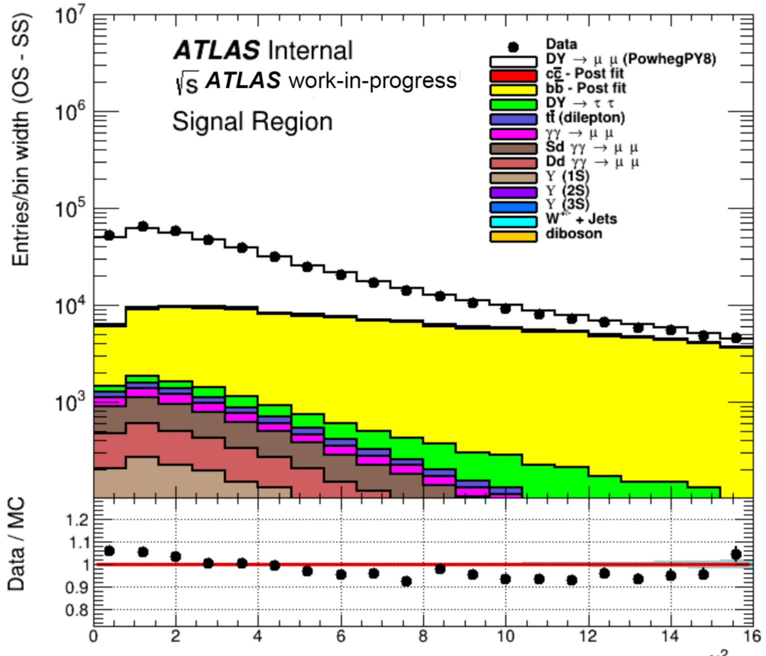
- This component is extracted by a **data-driven approach**
- **Use the impact parameters quantities to discriminate** between signal events and background events
    - Fit the quantity given by the squared sum of the d_0 and Δz_0 significance

$$\chi^2_{QCD} = \left(\frac{d_0(\mu_1)}{\sigma_{d0}(\mu_1)}\right)^2 + \left(\frac{d_0(\mu_2)}{\sigma_{d0}(\mu_2)}\right)^2 + \left(\frac{\Delta z_0(\mu_1,\mu_2)}{\sqrt{\sigma^2_{z_0}(\mu_1) + \sigma^2_{z_0}(\mu_2)}}\right)^2$$

- $\Delta z_0(\mu_1,\mu_2) = z_0(\mu_1) - z_0(\mu_2)$



Representation of multijet background event

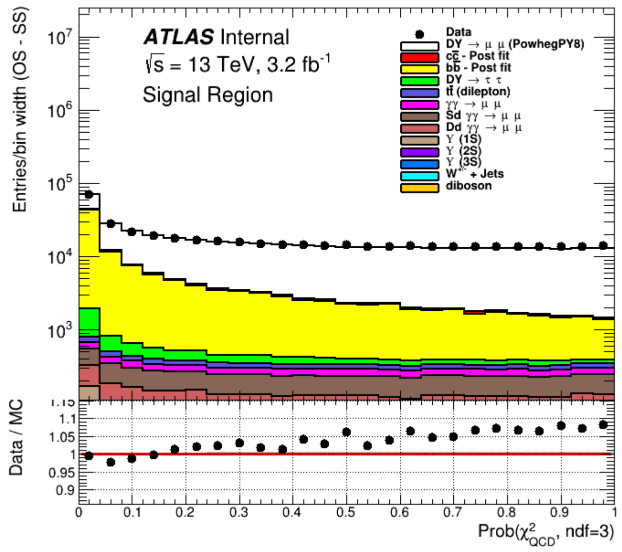


χ^2_{QCD} distribution in Data and MC

Analysis Strategy

The probability

$$Prob(\chi^2_{QCD}, ndf = 3)$$



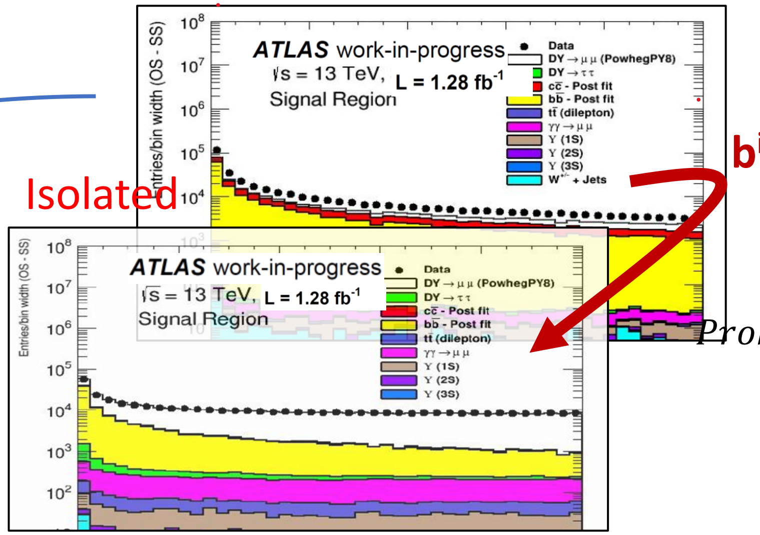
Represents the probability that the 2 muons are coming from the same vertex

- Use **Control Region given by not isolated muons**
    - Gives template for Background from data
- Fit this quantity to the real data

$$Prob^{not-isolated}(\chi^2_{QCD}, ndf = 3) \sim BG_i$$

$$Prob^{isolated}(\chi^2_{QCD}, ndf = 3) \sim k \cdot DY^{iso-iso} + b^{iso-iso} BG_i$$

Not Isolated



$Prob(\chi^2_{QCD})$

$Prob(\chi^2_{QCD})$

Blue component – from Monte Carlo

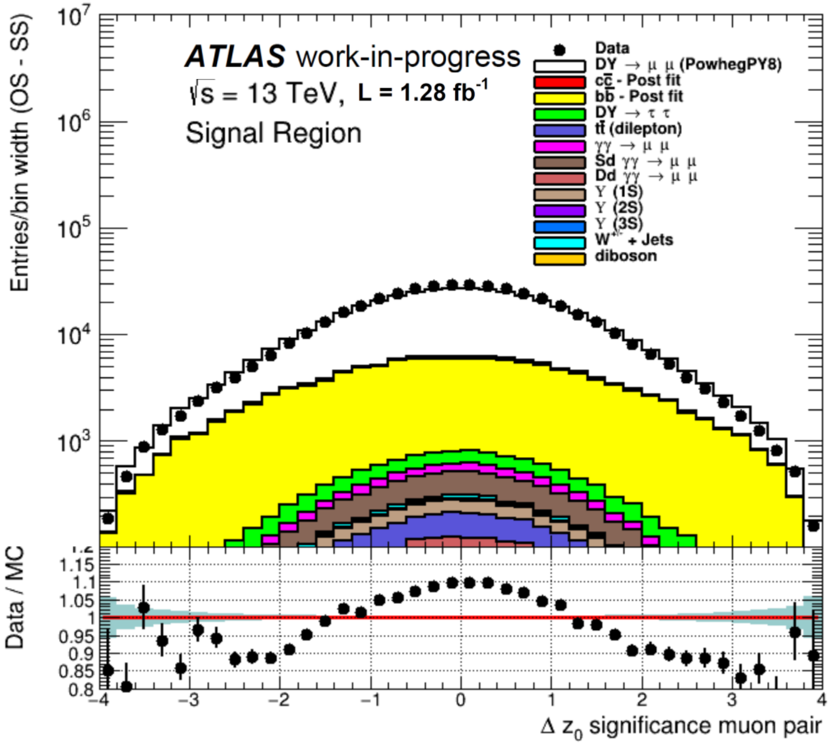
Red component – fitted to the data

$Prob(\chi^2_{QCD}, ndf = 3)$ distribution for isolated and not-isolated selection

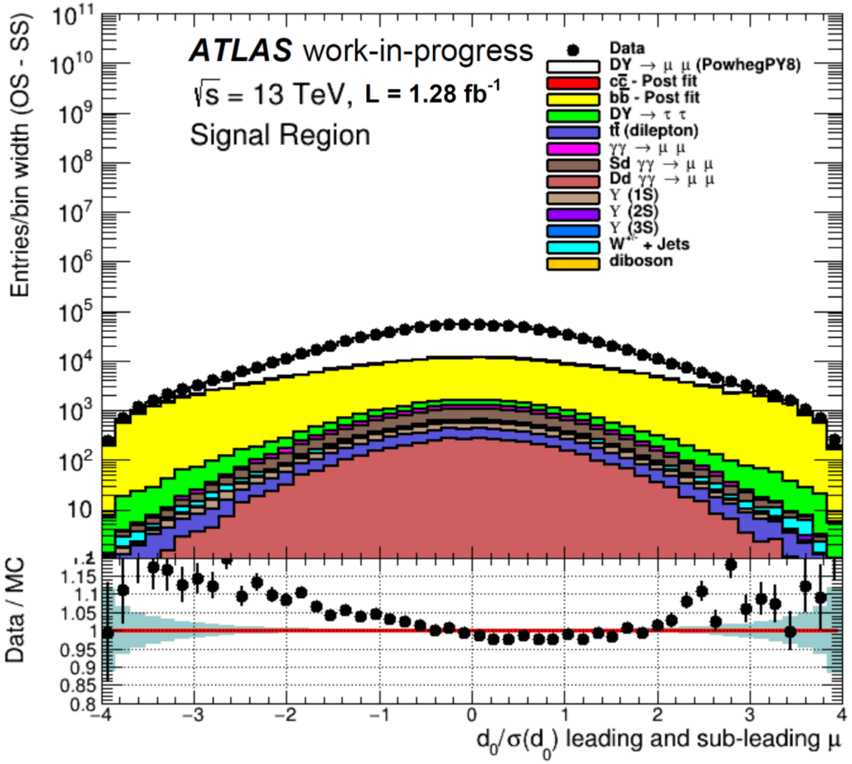
Modelling of the Impact Parameters

Check that the impact parameters are well described in Monte Carlo

- Distance of the track from the beam spot
- These quantities enter in the Background estimation



Δz0 significance distribution



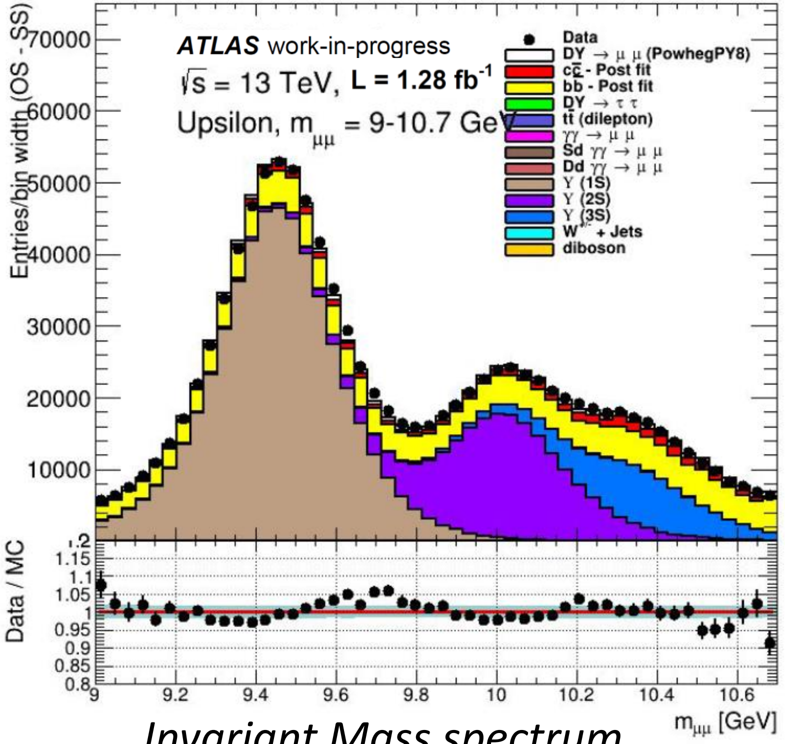
d0 significance distribution

Evaluate a data driven correction to improve the Data/MC agreement

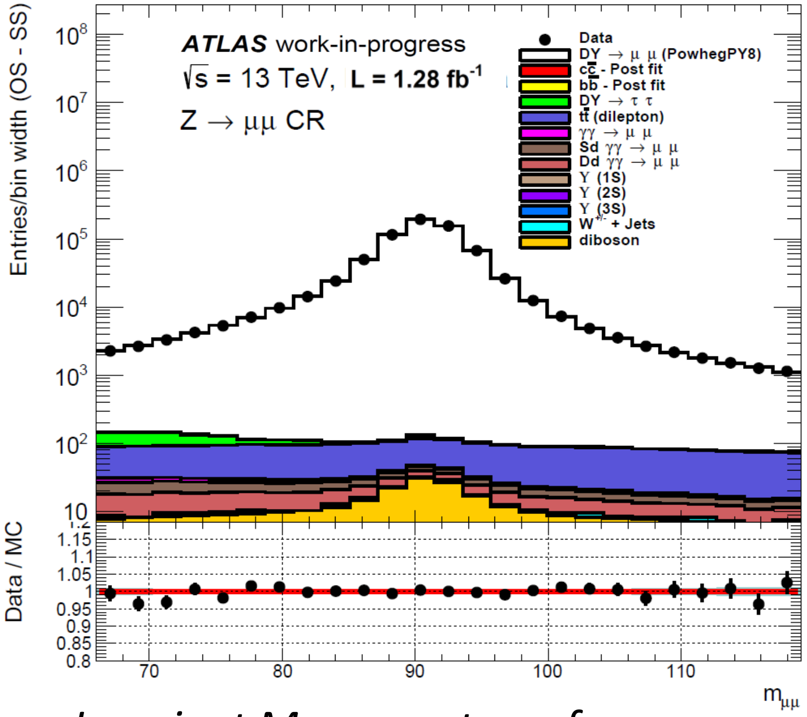
Modelling of the Impact Parameters

Extrapolate a data driven correction for the Impact Parameters distribution outside the Signal Region

- Look at region excluded by the invariant mass selection
  - Υ → μμ Region ($m_{\Upsilon_{1S}} = 9.46$ GeV)
  - Z → μμ peak region ($m_Z = 91.2$ GeV)

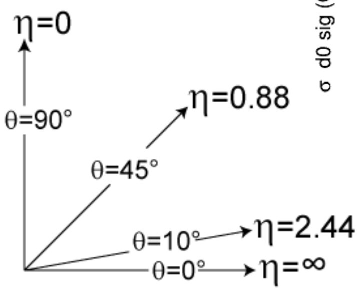


Invariant Mass spectrum for the Υ → μμ Region

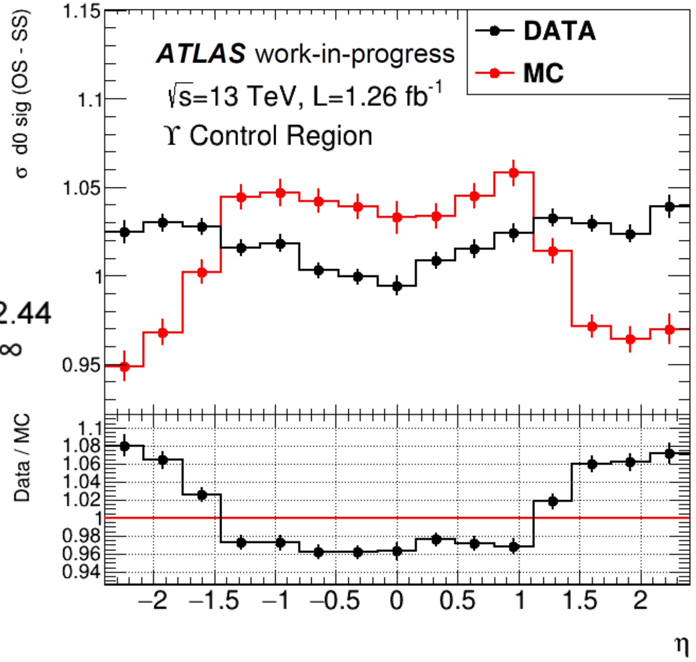


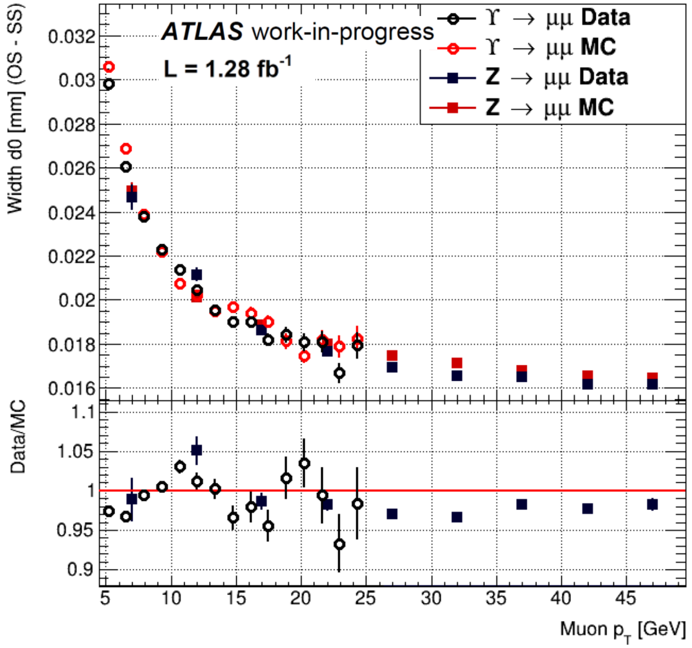
Invariant Mass spectrum for the Z → μμ peak region

Modelling of the Impact Parameter



Pseudorapidity



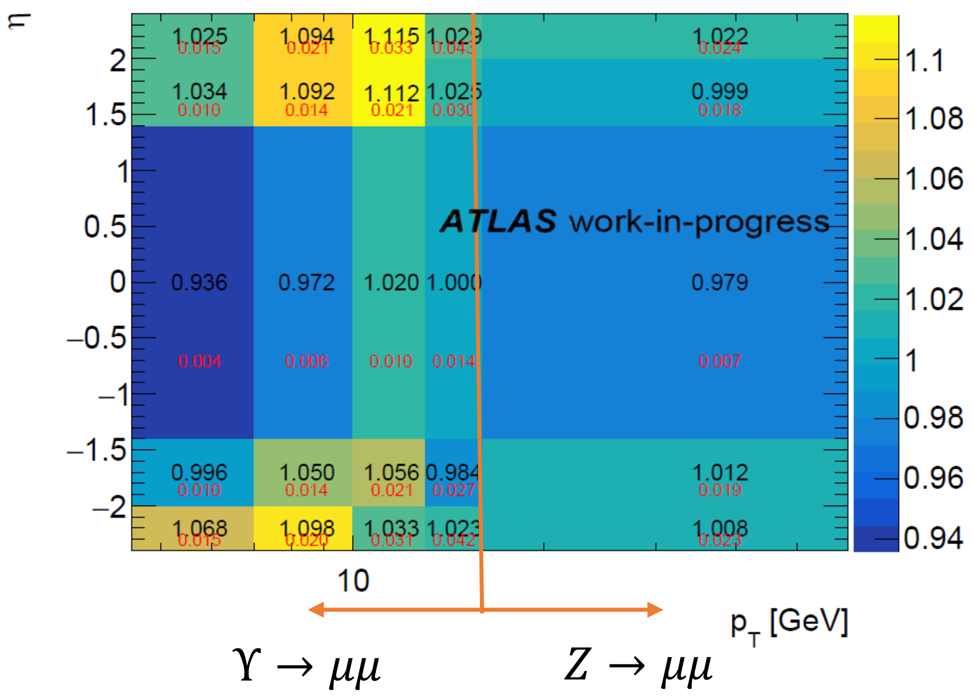


The data/MC agreement has been checked as a function of the detector coordinate and the energy (p_T^μ) of the muon (multiple scattering effect)

IP resolution study as function of p_T^μ, shows good agreement between the $Z \rightarrow \mu\mu$ events (high p_T^μ) and the $\Upsilon \rightarrow \mu\mu$ (low p_T^μ)

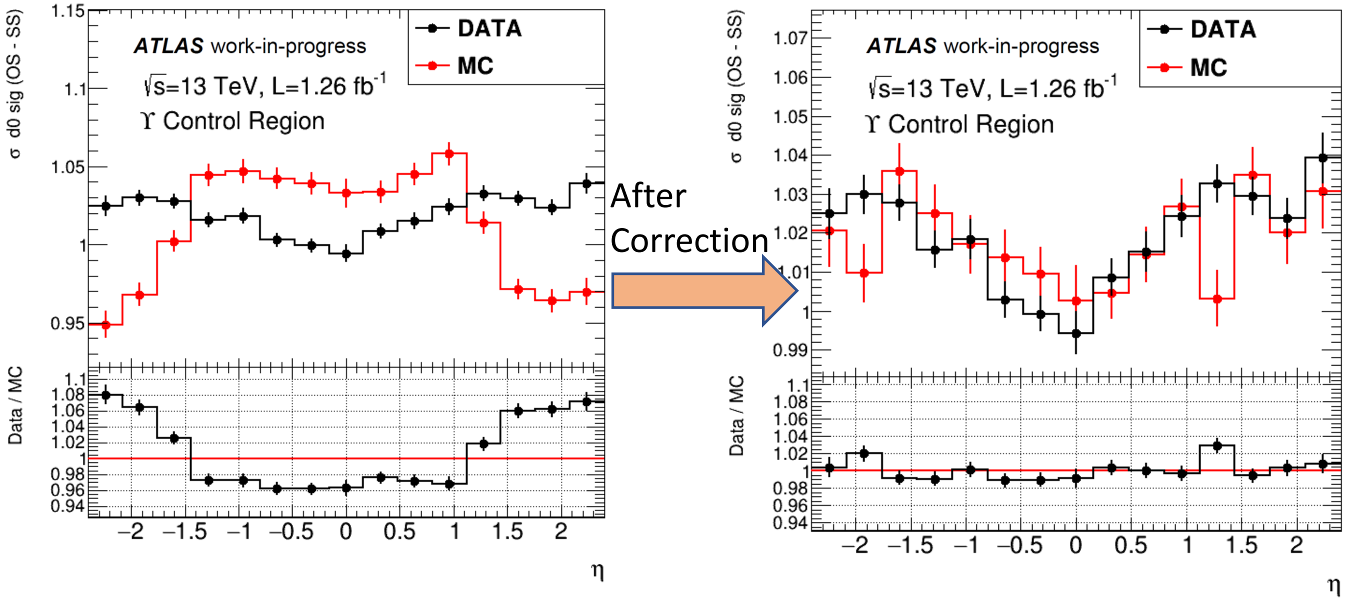
IP resolution study as function of p_T^μ, shows good agreement between the $Z \rightarrow \mu\mu$ events (high p_T^μ) and the $\Upsilon \rightarrow \mu\mu$ (low p_T^μ)

Impact Parameter Corrections



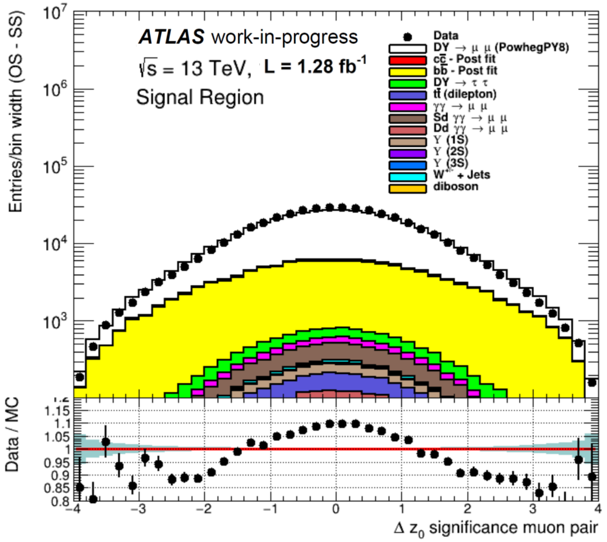
Evaluate a correction

- span a wide p_T^{μ}
- p_T^{μ} and η^{μ} dependent correction
- Rescale the Monte Carlo IP resolution to the Data one

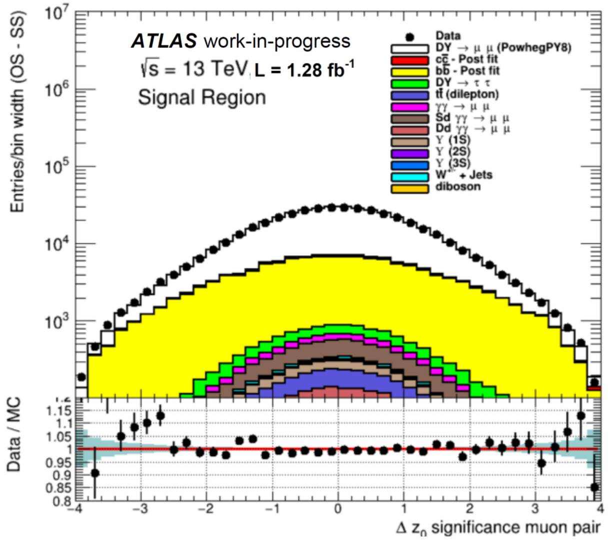


The agreement is restored as function of η and p_T^{μ}

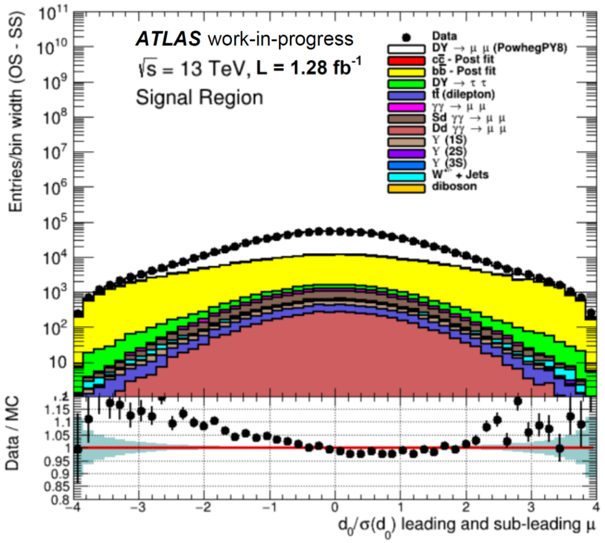
Impact Parameter Correction



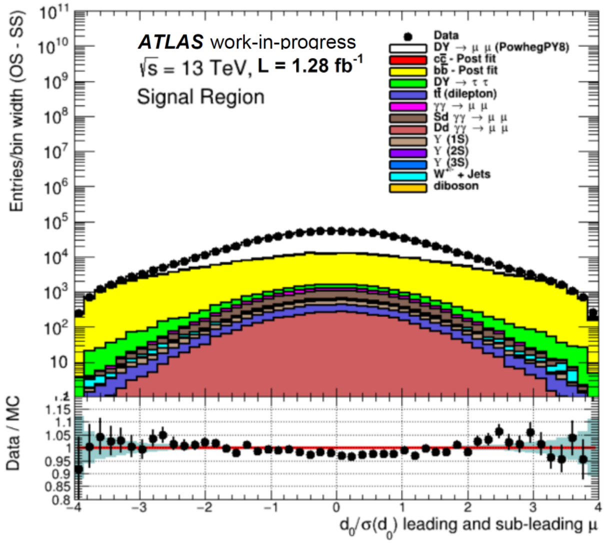
After Correction



After the data-driven correction there's a great improvement in the Data/MC comparison



After Correction

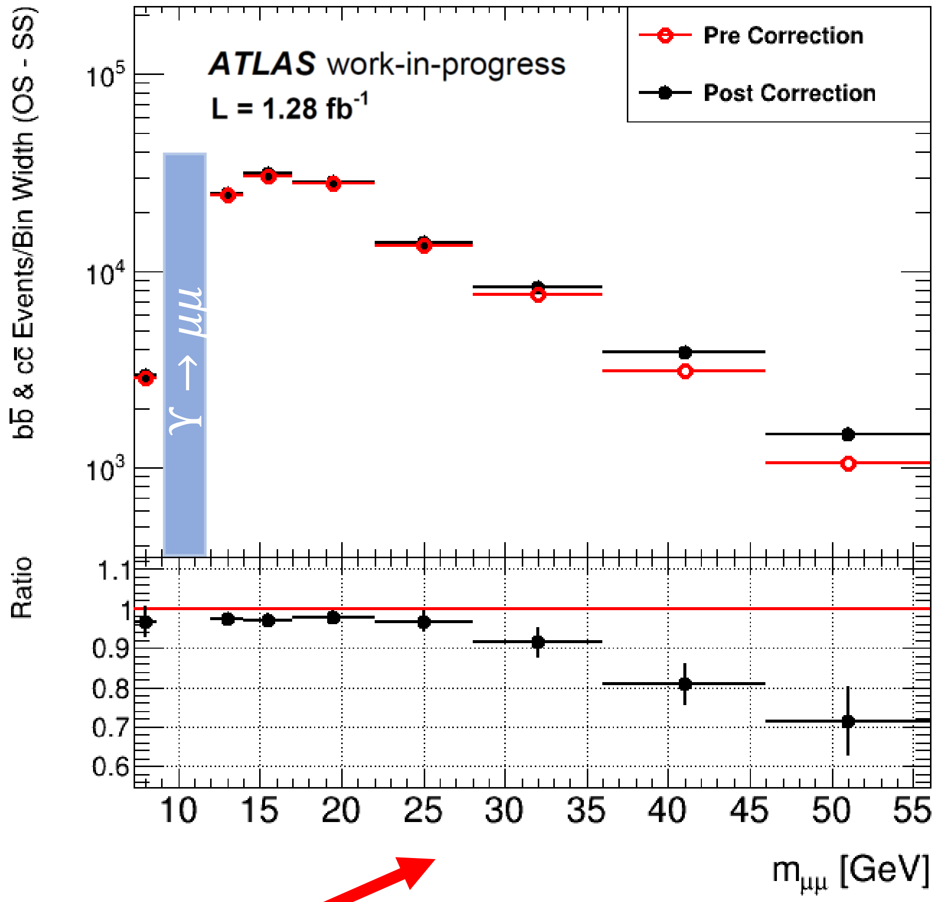


Δz0 and d0 significance inclusive distribution before and after applying the impact parameters correction

Impact Parameter Correction

The d_0 and z_0 quantities are used to extract a data driven estimation of the QCD multijet background

- The Impact Parameter correction have an effect on the on the result of fit method
- Plot the estimated background component before and after the IP correction
  - The number of estimated $b\bar{b}$ / $c\bar{c}$ increases after the correction



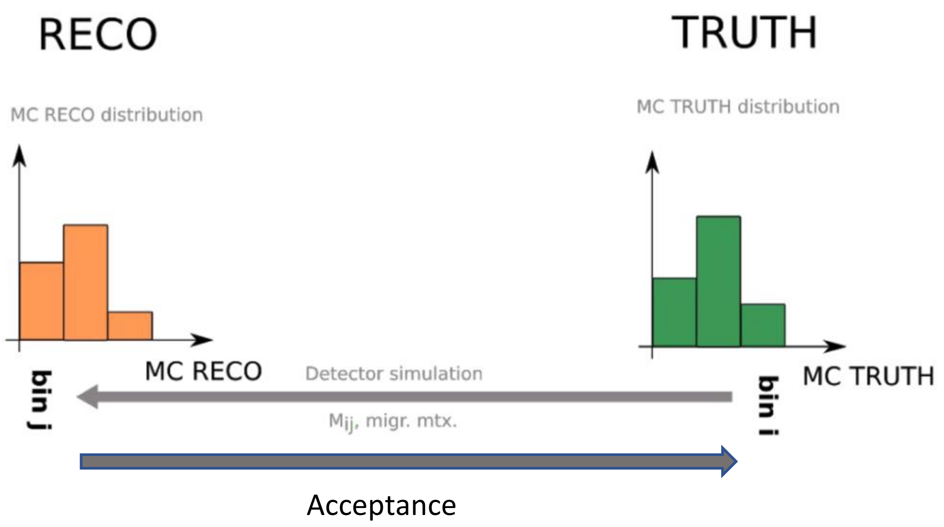
$$Prob^{not-isolated}\left(\chi^2_{QCD}, ndf = 3\right) \sim B_i$$

$$Prob^{isolated}\left(\chi^2_{QCD}, ndf = 3\right) \sim k \cdot DY^{notiso-notiso} + b^{iso-iso} B_i$$

Cross-section Extrapolation

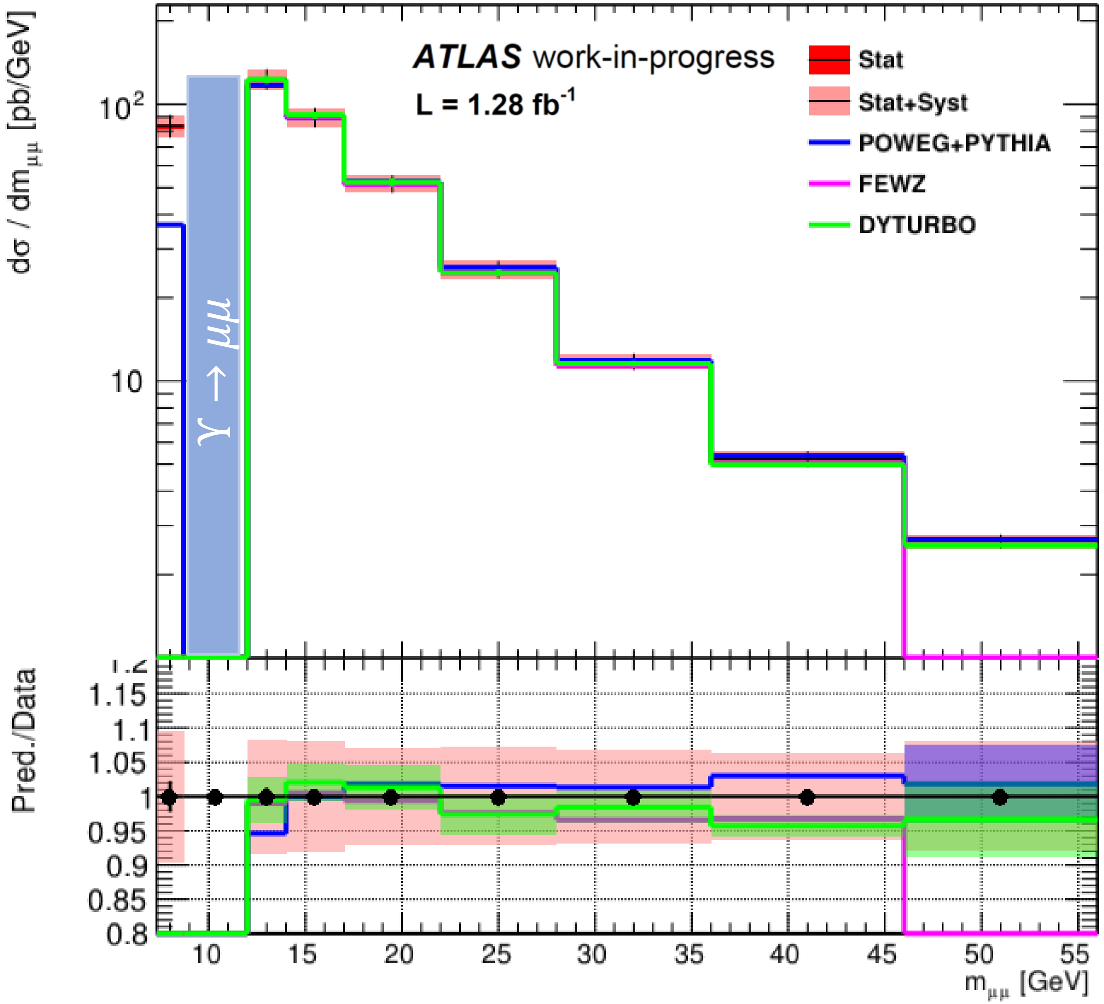
In the Next Slides studies on the systematic uncertainties affecting the analysis are presented
The studies show the effect of the uncertainties on the cross-section results

- The cross-section extrapolated with bin-by-bin unfolding
- $\left(\frac{d\sigma}{dm_{\mu\mu}}\right) = \frac{N_i^{DATA} - N_i^{BG}}{L \cdot C_{DY,i} \cdot \Gamma_i}$
  - C_{DY} = Acceptance
  - Γ_i = Bin size



Future Plan: more sophisticated unfolding method

Results – Single Differential Result



Data plotted with (first determination) of systematic and statistical uncertainty

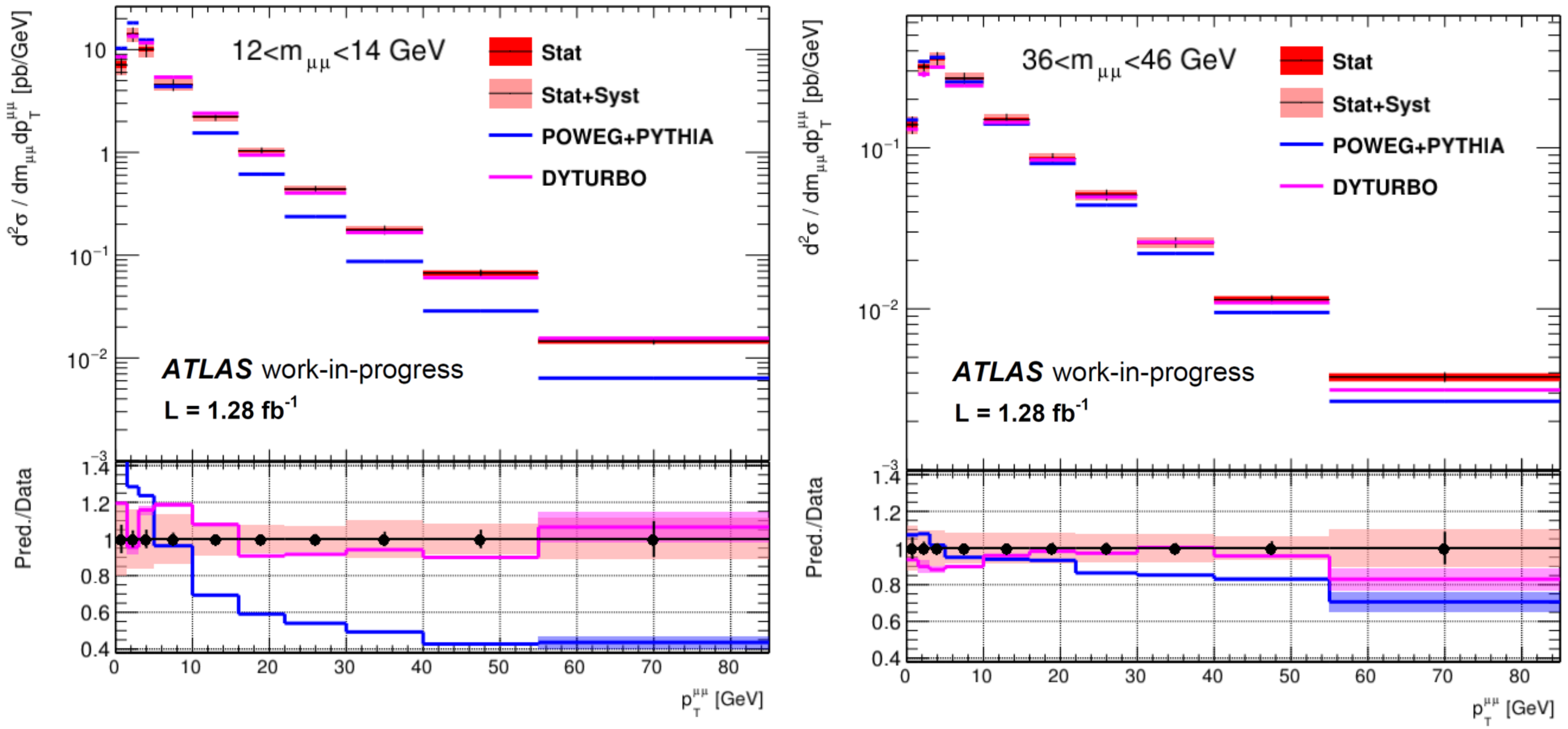
- Poweg+Pythia: NLO (+ LL Parton Shower)
  - NNLO QCD k_F
  - MC generator used in the analysis
- FEWZ → NNLO + NLO EW Correction
  - In the **first and last bin** FEWZ is set to Zero: the prediction are not ready yet
- DYTURBO → NNLO + NNLL + NLO EW Correction

Uncertainty studies not finalised

Systematic Uncertainty

- Isolation efficiency systematic
- Trigger efficiency systematic

Results – Double Differential Result

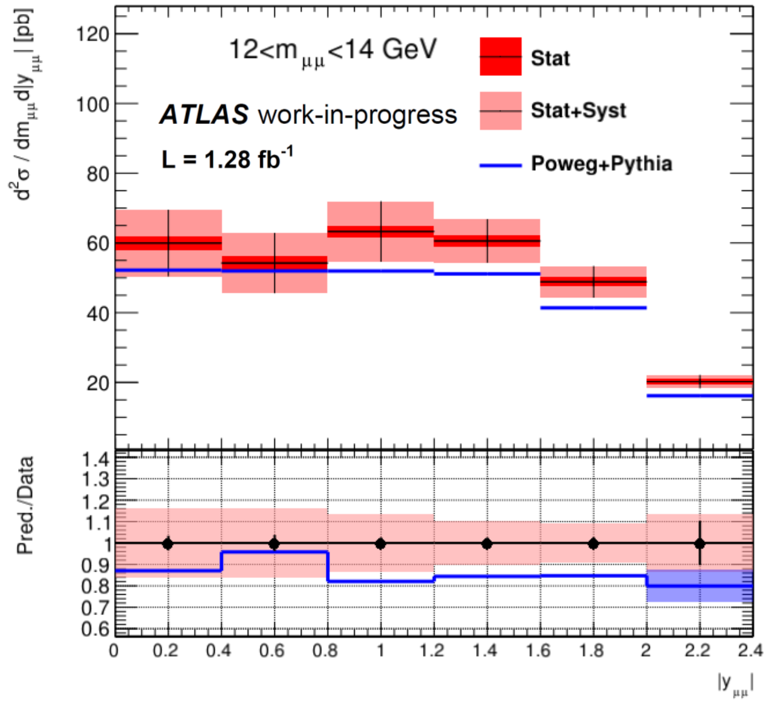


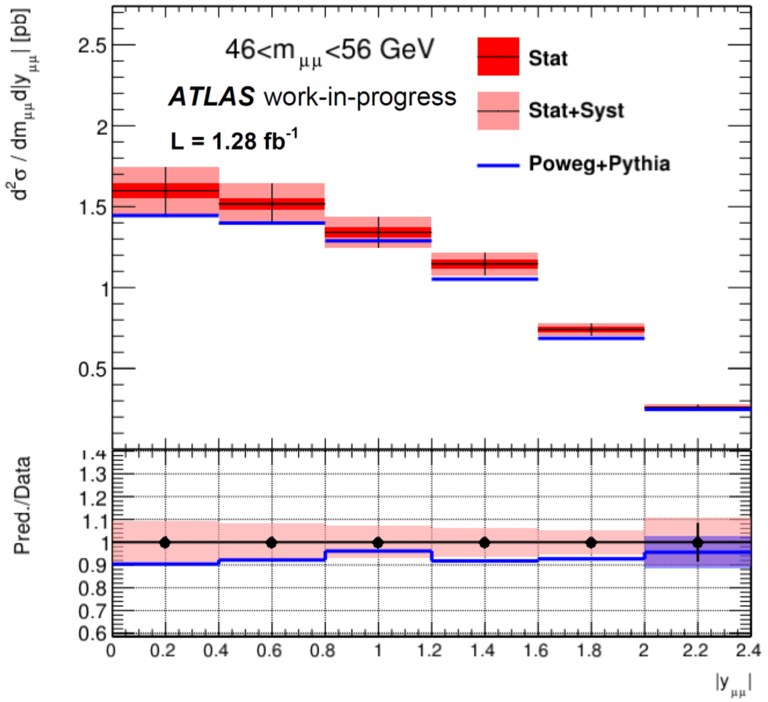
Cross-section results unfolded in $m_{\mu\mu}$ and $p_T^{\mu\mu}$

- Poweg+Pythia
  - NLO (+LL from Parton Shower)
- DYTURBO
  - (N3LO+N3LL) + NNLO

Double differential cross-section result at low mass and high mass

Results – Double Differential Result





Cross-section results unfolded in $m_{\mu\mu}$ and $|y_{\mu\mu}|$

- Poweg+Pythia
  - ➢ NLO (+LL from Parton Shower)

Dominating Uncertainty

Systematic Uncertainty

- Isolation efficiency systematic
- Trigger efficiency systematic

Double differential cross-section result at low mass and high mass

Summary and Outlook

Low Mass Drell-Yan Analysis

- **Probe extreme region of the phase space**
- Test Low-x region
- Test low-$p_T^{\mu\mu}$ prediction in new phase space region

Main challenges in the analysis

- **Large Background component**
    - Data driven template method
- **Modelling of the Impact Parameters** quantities
    - Data driven correction evaluated from control region

Next Steps

- **Refine the uncertainties evaluation**
    - Isolation efficiency, trigger efficiency uncertainties
- Use iterative method for the cross-section unfolding
- **PDF study (Fit)** with our measurement

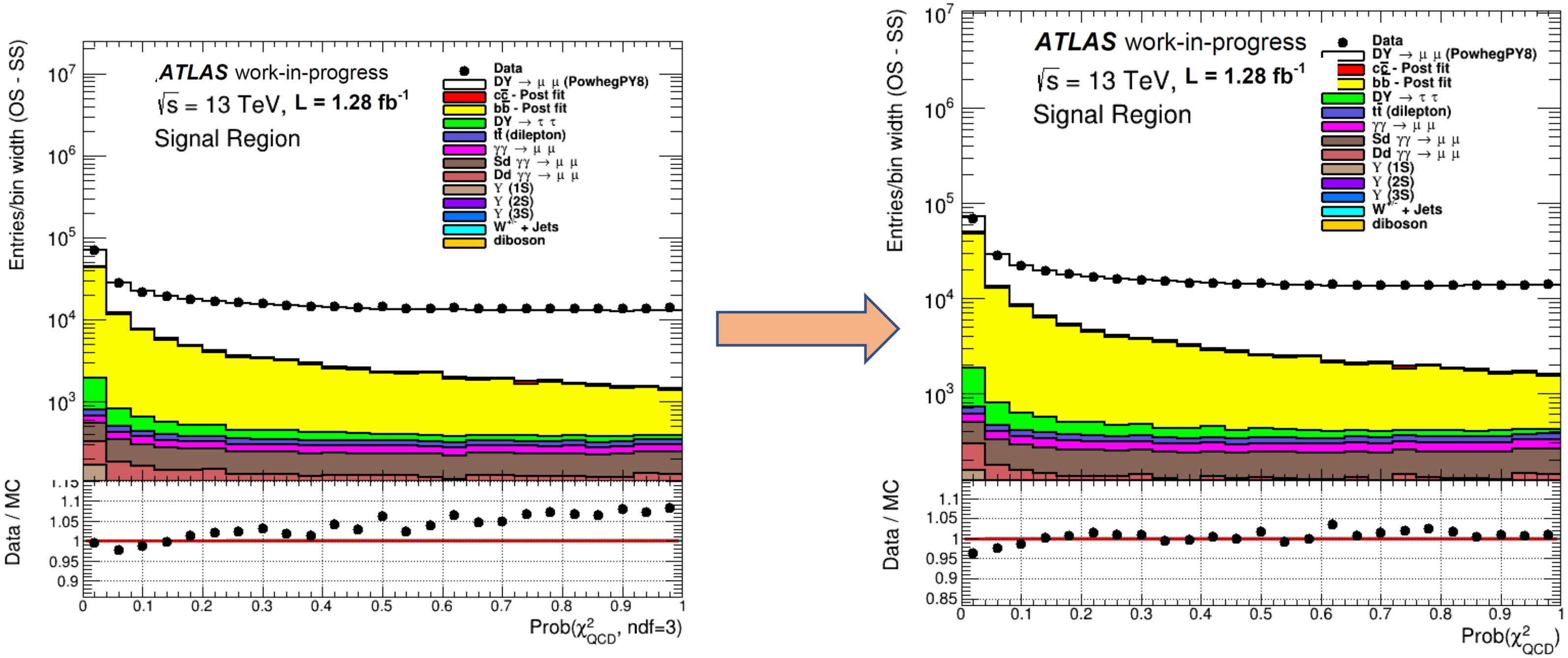
Thank You!

BACKUP

Impact Parameter Correction

Overall the correction leads to a lower DY normalization from the fit, compensated by an higher QCD background normalization

- The kinematic control plot are performed applying the QCD Background normalization

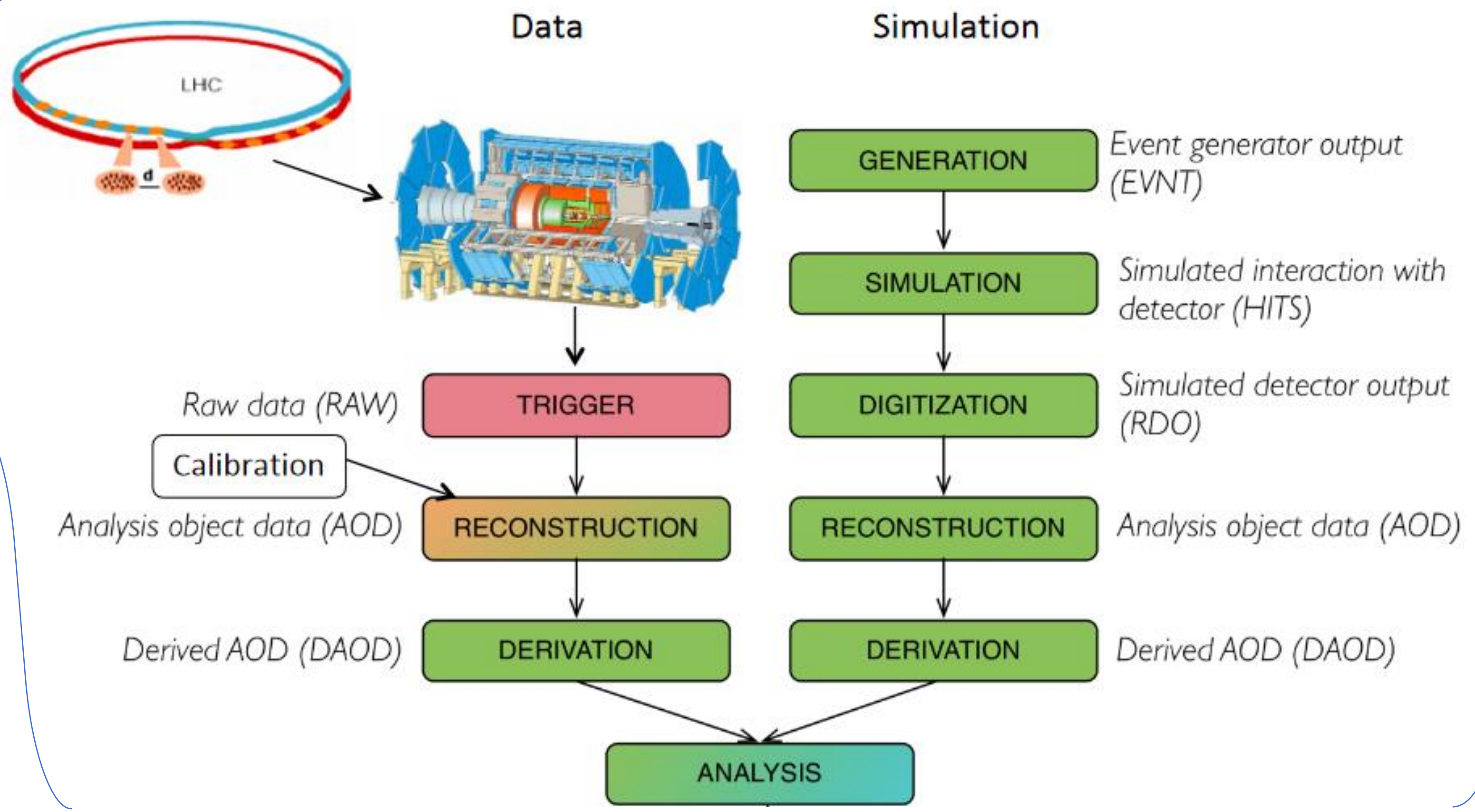


We check that the IP correction works well on the low massDY region

Prob (χ^2_{QCD} , ndf = 3) inclusive distribution (the quantity fitted in the background estimation method)

Physics Analysis

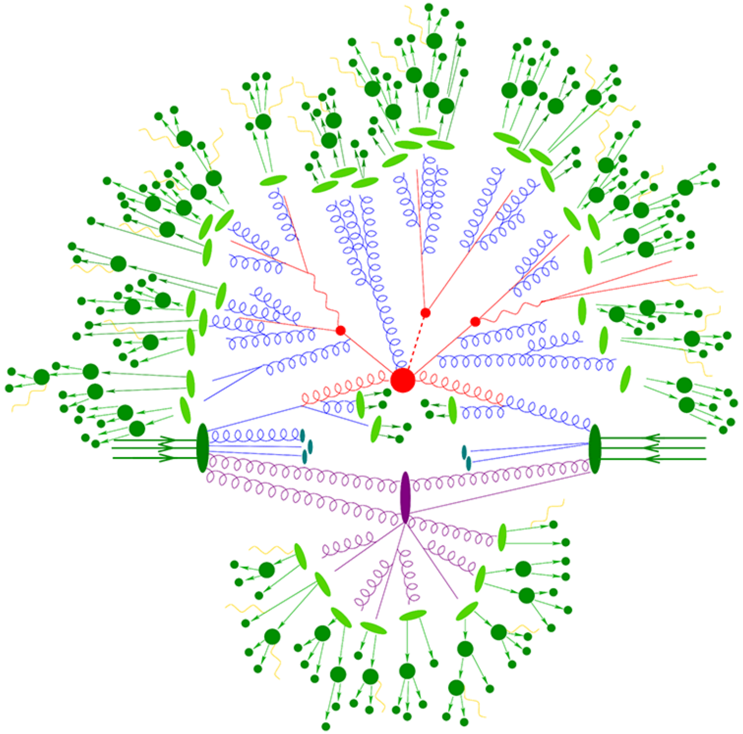
Data Selection and reconstruction workflow



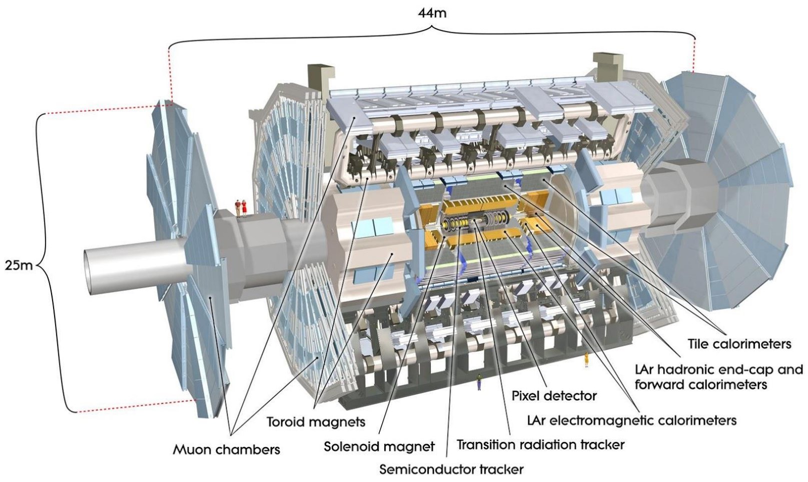
Monte Carlo simulation workflow

Event Selection, improvement of BG estimation, assessment of the uncertainty…

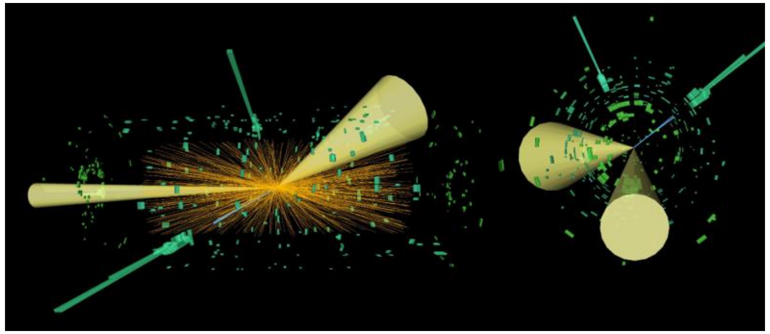
MC Generation and Detector Simulation



Event Generation



Detector Simulation and digitization



Reconstruction

Difference between real and simulated performance of the detector are studies

- Correction for MC events are evaluated