LFU study in ttbar decays in pp collisions at the CMS detector with $\sqrt{s} = 13\ TeV$

UNIVERSITY OF LATVIA

RIGA TECHNICAL UNIVERSITY

Normunds Ralfs Strautnieks[1], Markus Seidel[2], Karlis Dreimanis[2], Elina Pajuste[1]

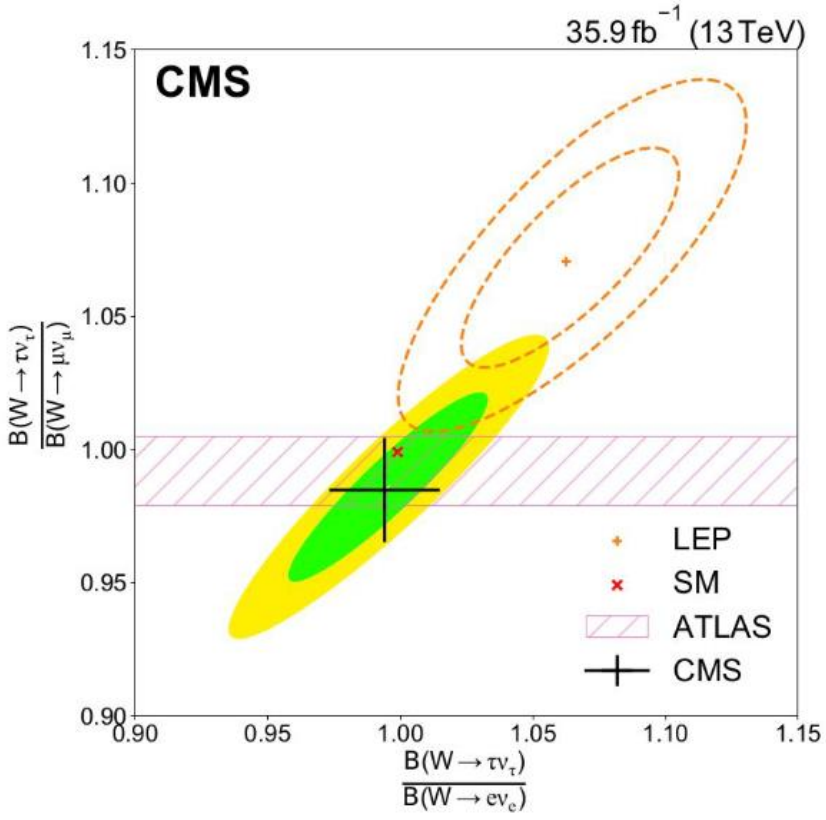
University of Latvia[1], Riga Technical University[2]

normunds.ralfs.strautnieks@cern.ch

16.10.2024.

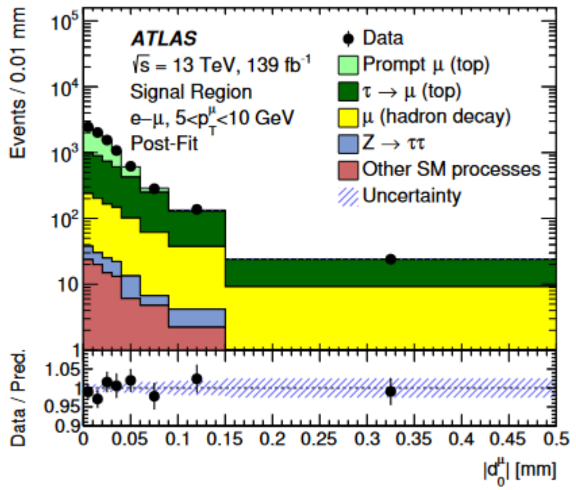
Analysis motivation

- LFU measurements provide a simple way of testing one of the fundemental axioms of the SM.
- Earlier LEP measurments showed slight tension with the SM predictions [1].
- Later CMS and ATLAS measurements moved the results much closer to and in agreement with the the SM prediction [2][3].
- Measuring the LFU with increasing precision helps us to test the SM prediction with higher and higher confidence.

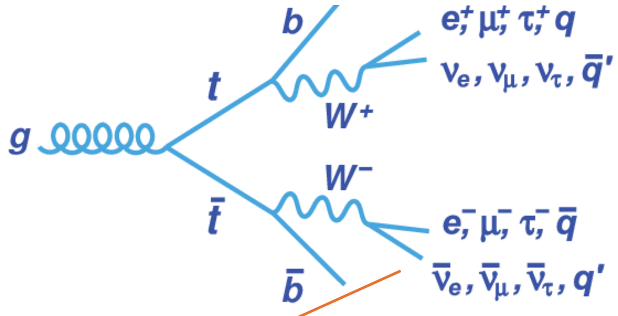


Analysis approach

- Measuring the LFU R(**τ/μ**) and R(**τ/e**) in the di-leptonic ttbar decays.
- Measurement is done in the leptonic decay channels of the **τ** lepton.
- Estimate the R(**τ/μ**) and R(**τ/e**) using 2-D likelihood fit in lepton d_{xy} and p_T distrbibutions to disintangle the prompt leptons (from W) and non-prompt leptons (from **τ** decay).
- Analysis is highly sensitive to lepton d_{xy}, so it needs correct treatment.
- Background contribution estimates are important for a correct prediction of the R(**τ/μ**) and R(**τ/e**).
- Result in R(*τ→e|μ* /**e**) and R(*τ→e|μ* /**μ**) *triggered* either by single electron or muon from the other W boson deay. So 4 resulting channels – *e*e,*μ*μ,*e*μ and *μ*e.

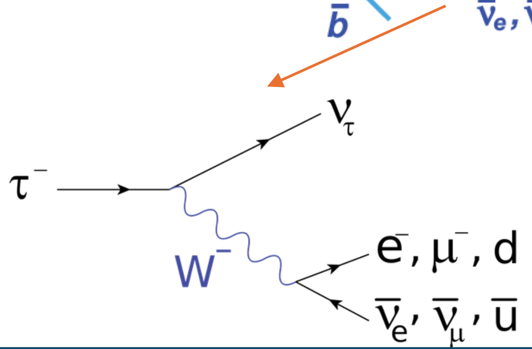


Result from a similar analysis done in ATLAS [link]. Goal is to get such result both for R(τ/μ) and R(τ/e).



Trigger events on **μ** or **e** from 1st **W** decay

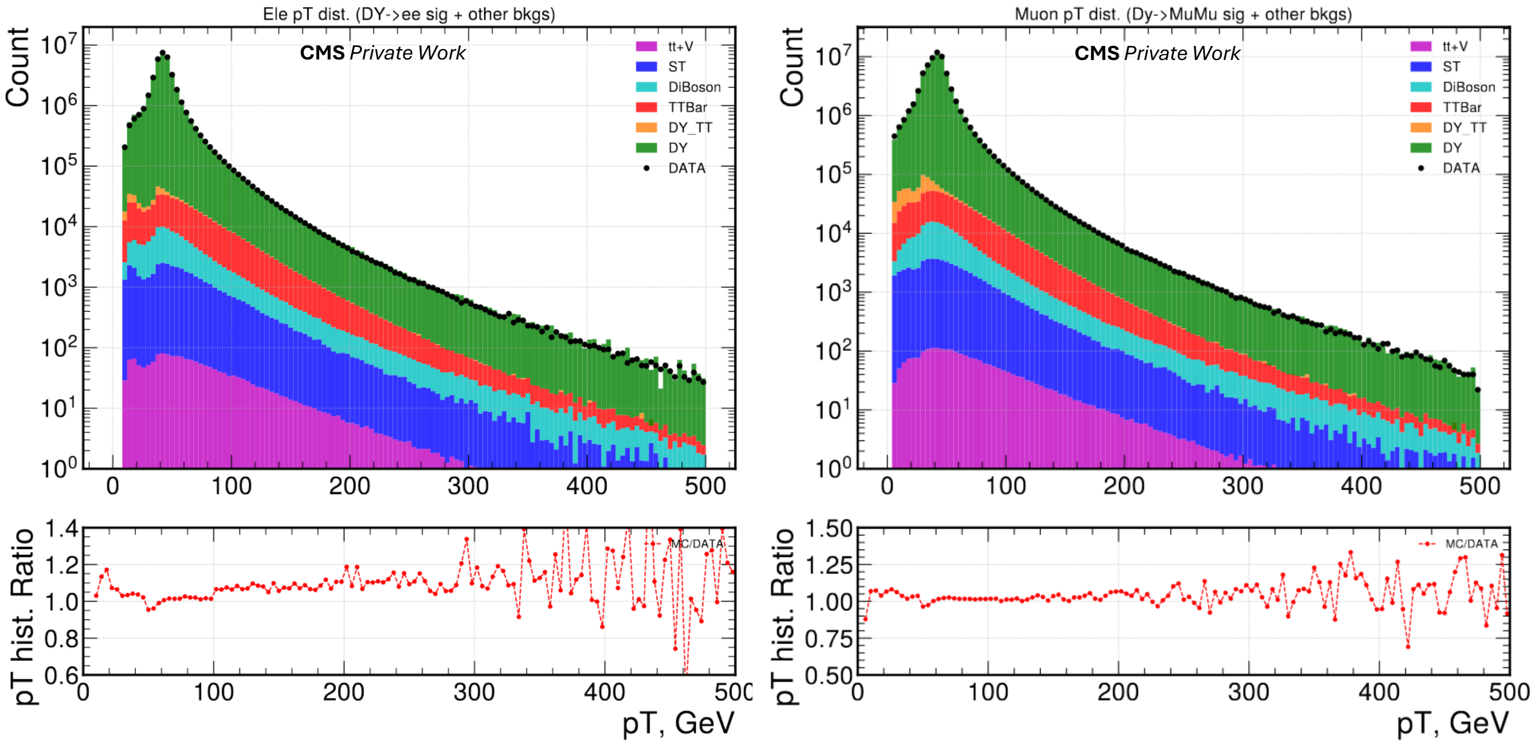
Measure the ratio of 2nd **W** decays to **τ/μ/e**



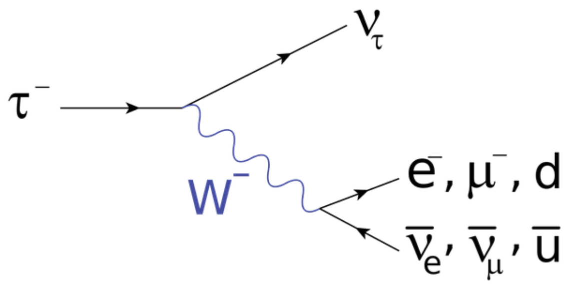
τ are found by searching for a displaced lower p_T **μ/e**

Analysis activities

- Important aspect of this analysis is the fact that the identification of τ lepton is done by searching for more displaced lower-p_T lepton.
- This is a challenging aspect since in τ leptonic decays two additional neutrinos are created.
- This puts a special interest of pushing the non-triggered lepton's p_T cut as low as possible to acquire more signal statistics.
- Usually, this means going below the object group's officially provided SFs p_T lower bounds and makes a need for manual SF calculation present.



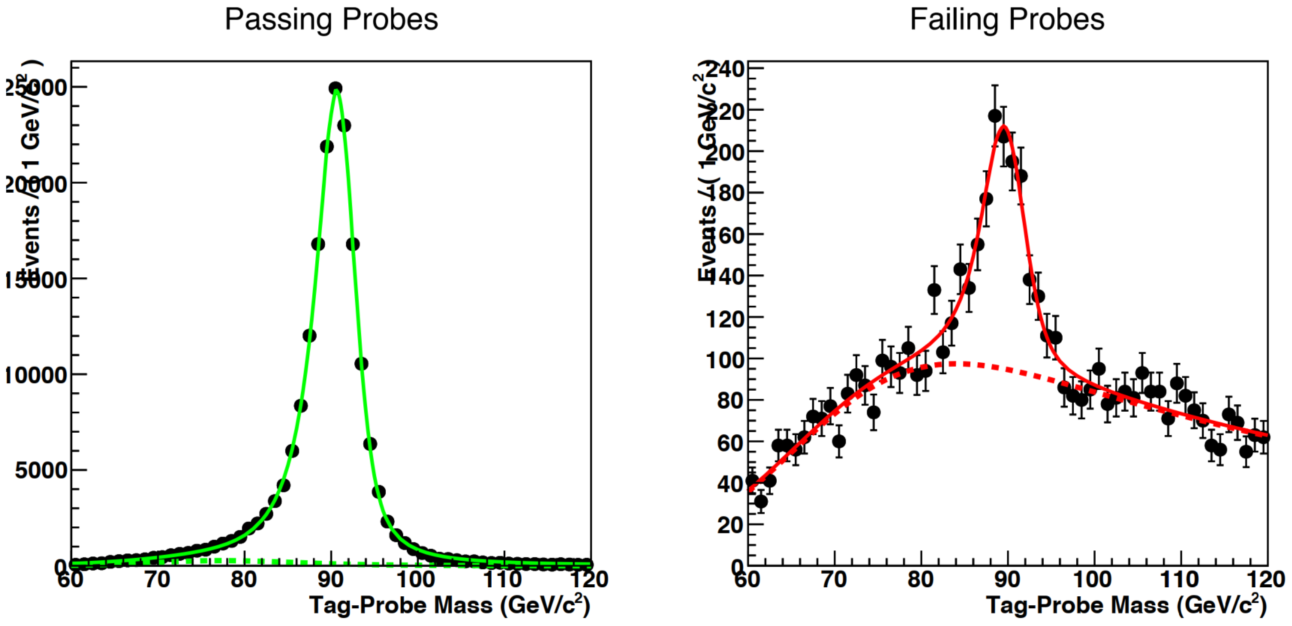
p_T distributions of electrons (*left*) and muons (*right*) in di-leptonic decays triggered by a single lepton trigger. Leptons from τ decay (*orange*) are at the low-p_T part of the distribution.



τ leptonic decay Feynman diagram

Analysis activities – Scale Factors (SFs), Tag&Probe (TnP) measurement

- Lepton SF measurements are done using Tag&Probe method.
- In this method a well know resonance is used (Z,J/ψ) and its leptonic decays are exploited.
- The pair of leptons is selected by requiring tight cuts on tag lepton and afterwards an efficiency is measured using probe lepton for a specific selection criteria. This is done both in DATA and MC.
- The efficiency is measured by counting how many probe leptons passed the selection criteria.
- Usually, the passing and failing probe count is acquired using fits, to get rid of any background contributions.
- In the end, the SF is calculated by dividing the acquired DATA and MC efficiencies.

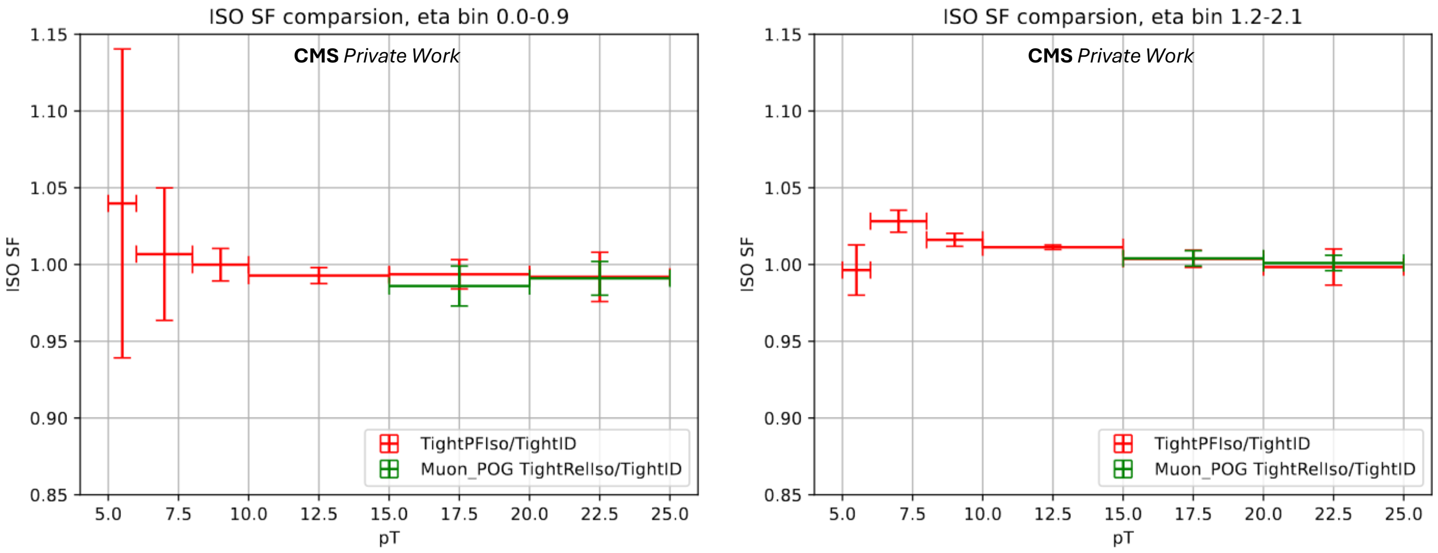


Example for passing and failing probe fits in Tag&Probe method.

$$\epsilon_{DATA\ or\ MC} = \frac{N_{pass}}{N_{pass} + N_{fail}} \qquad Scale\ Factor = \frac{\epsilon_{DATA}}{\epsilon_{MC}}$$

Analysis activities – SFs, low-p_T results

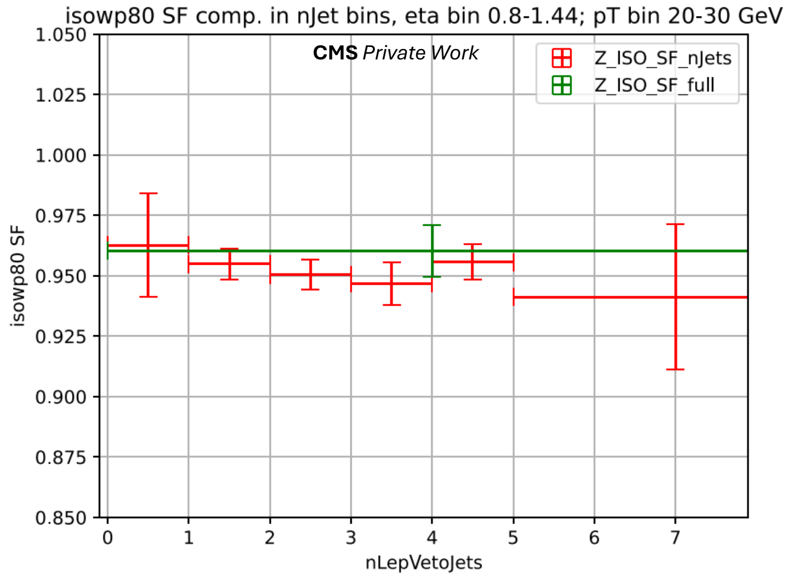
- Official muon reconstruction (RECO) and identification (ID) SFs, are provided without any systematical uncertainties below p_T of 15 GeV.
- A calculation was done to recalculate the SFs with full uncertainties included.
- There are no isolation (ISO) SFs provided below p_T of 15 GeV.
- A calculation was done on Z->μμ events with full uncertainties. (Needs Extra discussion with Muon Object group's convenors)
- Additional investigations using J/ψ resonance for low-p_T SF calculation was done. Particularly, using the Bparking dataset.

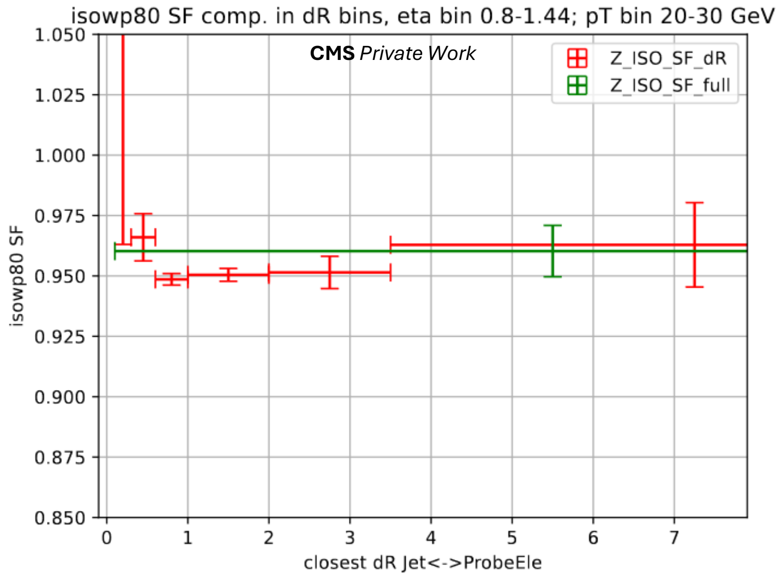


Example of muon low-p_T ISO SFs in one barrel and one endcap |η| bin.

Analysis activities – ISO SFs, extra uncertainty

- All centrally provided SFs are calculated from Drell-Yan process resonances, which is a rather clean event topology.
- A general recommendation exists to add extra uncertainty to lepton ISO SFs when they are applied to ttbar processes.
- This additional systematic uncertainty would limit the precision of the analysis.
- Additional studies of SFs dependance on nJets and dR to the closest jet were done to see if there is any clear dependance.
- Goal of these studies is to forgo the application of this extra uncertainty.
- Electron object group have agreed to drop this, now in discussion with the muon object group.

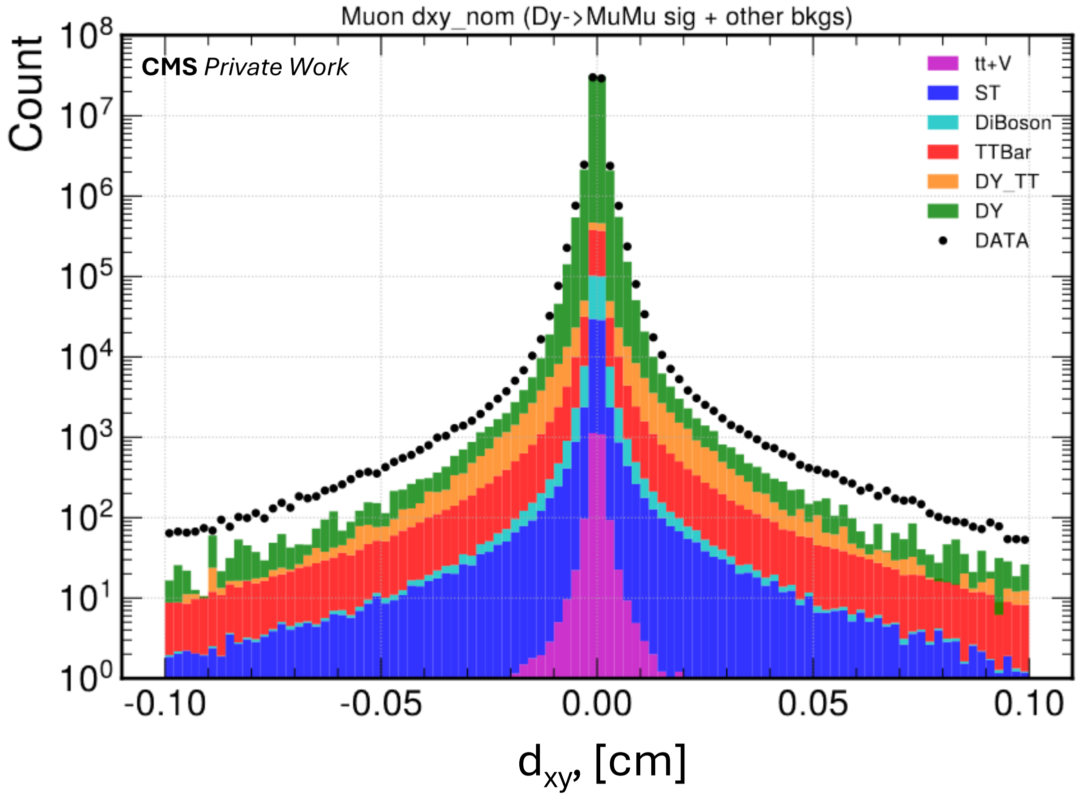




Example of electron ID+ISO SF trend in nJet (*left*) and dR (*right*) bins (in a particular p_T and $|\eta|$ bin).

Analysis activities – lepton d_{xy} corrections, general problem

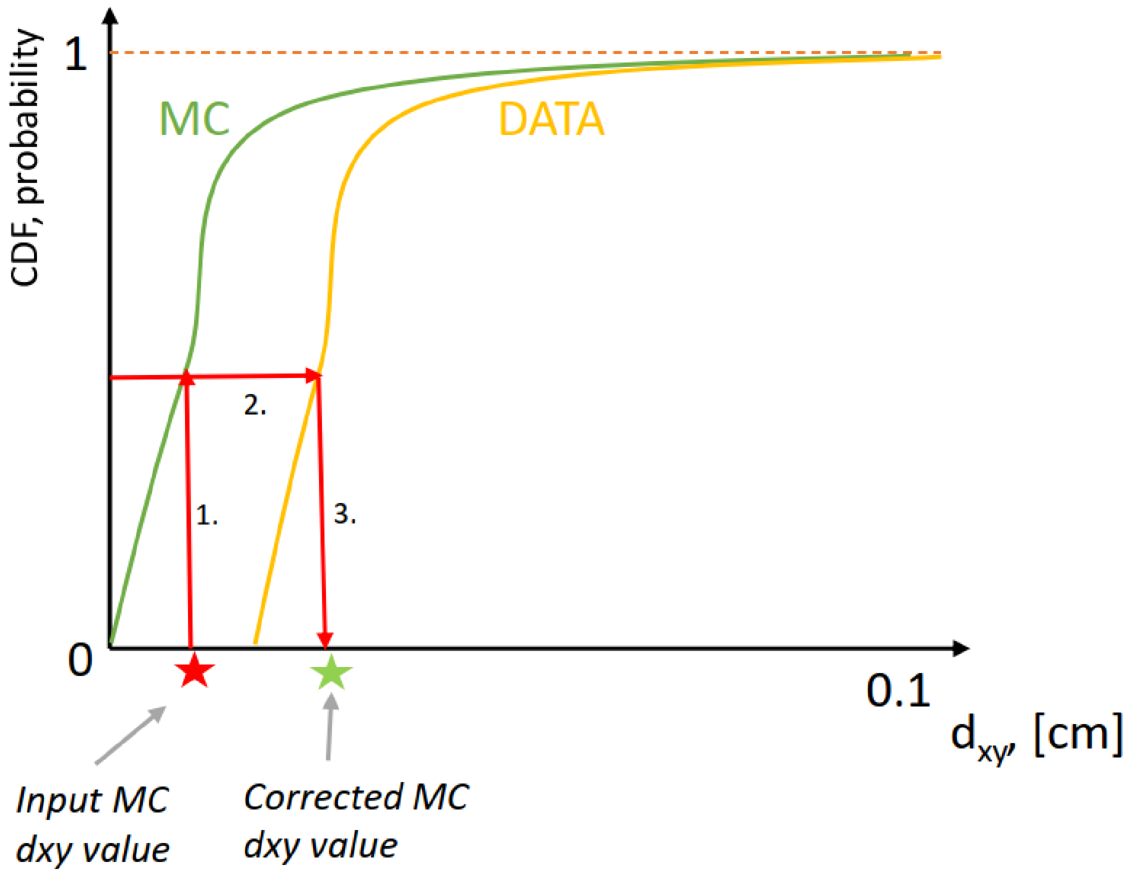
- d_{xy} parameter is of paramount importance in this analysis.
- A quick look at the nominal d_{xy} distributions in DATA and MC, shows a clear discrepancy between the two distributions.
- This is due to some extrapolations used in MC and usage of a limited precision magnetic field map in the reconstruction process.
- Before any measurement can be done, the MC d_{xy} distributions must be corrected so that it would match the distribution observed in DATA.



Nominal muon dxy distribution for DATA and MC. A clear mismatch can be seen.

Analysis activities – lepton d_{xy} corrections, quantile corrections

- To correct the MC d_{xy} distributions a '*quantile correction*' method is used.
- Method can be explained in a few steps:
  - Acquire the **c**umulative **d**istribution **f**unction (CDF) of the DATA and MC distributions.
  - Calculate the amount of shift needed for MC d_{xy} values, so that the CDF of MC d_{xy} distribution would match the one from DATA.
  - The calculated shift of d_{xy} values for MC is the correction that needs to be applied to all the MC points.
- Such corrections are calculated in various p_T/η bins to account for detector geometry and kinematical effects.



Schematic view of the quantile corrections method (Differences between MC and DATA CDFs are exagarated for illustrative purpose)

Analysis activities – lepton d_{xy} corrections, quantile corrections

How to calculate the CDF of the d_{xy} distribution?

- **Binned approach:**
  - *CDF calculation:*
    - Calculate the CDF from the histogram bins of the d_{xy} distribution.
  - *Limitations/problems:*
    - Needs a fine binning
    - Limited events in the tail region can make the CDF ‘jumpy’ (multiple d_{xy} value bins can have the same CDF value).
  - *Uncertainties:*
    - Use the Poissonian uncertainty for histogram bins as a statstical uncertainty and different bin count as a systematical uncertainty.

Analysis activities – lepton d_{xy} corrections, quantile corrections

How to calculate the CDF of the d_{xy} distribution?

- **Binned approach:**
  - *CDF calculation:*
    - Calculate the CDF from the histogram bins of the d_{xy} distribution.
  - *Limitations/problems:*
    - Needs a fine binning
    - Limited events in the tail region can make the CDF 'jumpy' (multiple d_{xy} value bins can have the same CDF value).
  - *Uncertainties:*
    - Use the Poissonian uncertainty for histogram bins as a statstical uncertainty and different bin count as a systematical uncertainty.

- **Full fit approach:**
  - *CDF calculation:*
    - Fit the whole d_{xy} distribution and calculate the CDF for the fitted function.
    - Improves the ''smoothness'' in the tail region.
  - *Limitations/problems:*
    - Problematic to fit the peak and tails perfectly at the same time.
  - *Uncertainties:*
    - The fit parameter uncertainties for a statistical uncertainty and different fit function for a systematical uncertainty.

Analysis activities – lepton d_{xy} corrections, quantile corrections

How to calculate the CDF of the d_{xy} distribution?

- **Binned approach:**
  - *CDF calculation:*
    - Calculate the CDF from the histogram bins of the d_{xy} distribution.
  - *Limitations/problems:*
    - Needs a fine binning
    - Limited events in the tail region can make the CDF 'jumpy' (multiple d_{xy} value bins can have the same CDF value).
  - *Uncertainties:*
    - Use the Poissonian uncertainty for histogram bins as a statstical uncertainty and different bin count as a systematical uncertainty.

- **Full fit approach:**
  - *CDF calculation:*
    - Fit the whole d_{xy} distribution and calculate the CDF for the fitted function.
    - Improves the ''smoothness'' in the tail region.
  - *Limitations/problems:*
    - Problematic to fit the peak and tails perfectly at the same time.
  - *Uncertainties:*
    - The fit parameter uncertainties for a statistical uncertainty and different fit function for a systematical uncertainty

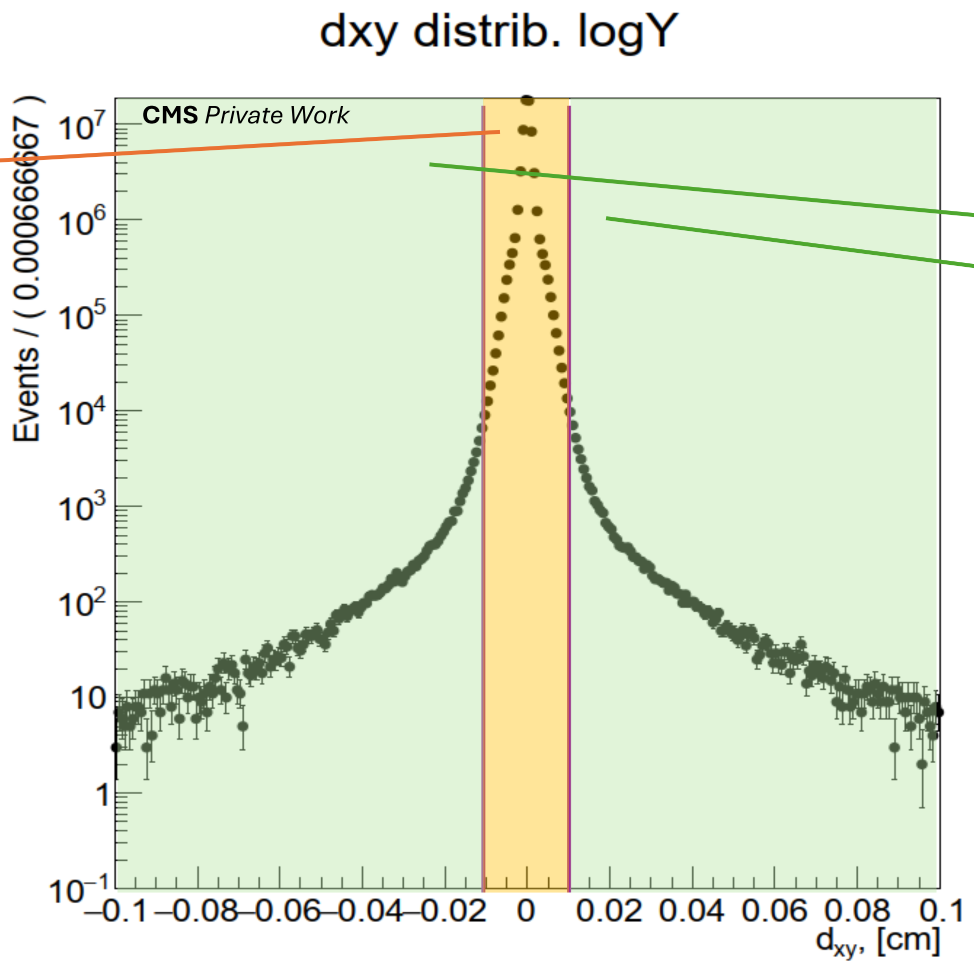
- <u>**Modified approach: (chosen way)**</u>
  - *CDF calculation:*
    - Use the binned approach at the center of the distribution.
    - Use fits in the tail part of the distribution.
    - Combine the results to from the CDF of the d_{xy} distribution.
    - Takes the best parts of each method.
  - *Limitations/problems:*
    - Combination of the two methods.
  - *Uncertainties:*
    - Combination of binned and pure fit method uncertainty estimation.

d_{xy} correction methodology – calculating correction

- Applying the modified method for CDF calculation to the lepton d_{xy} distribution

- In the central part of the distribution the binned approach is used for the CDF calculation.
- **abs(d_{xy}) [0.0-0.01] cm**

- Just count the event count in the histogram bins.
- For CDF calculations the absolute values and distributions of dxy are used.

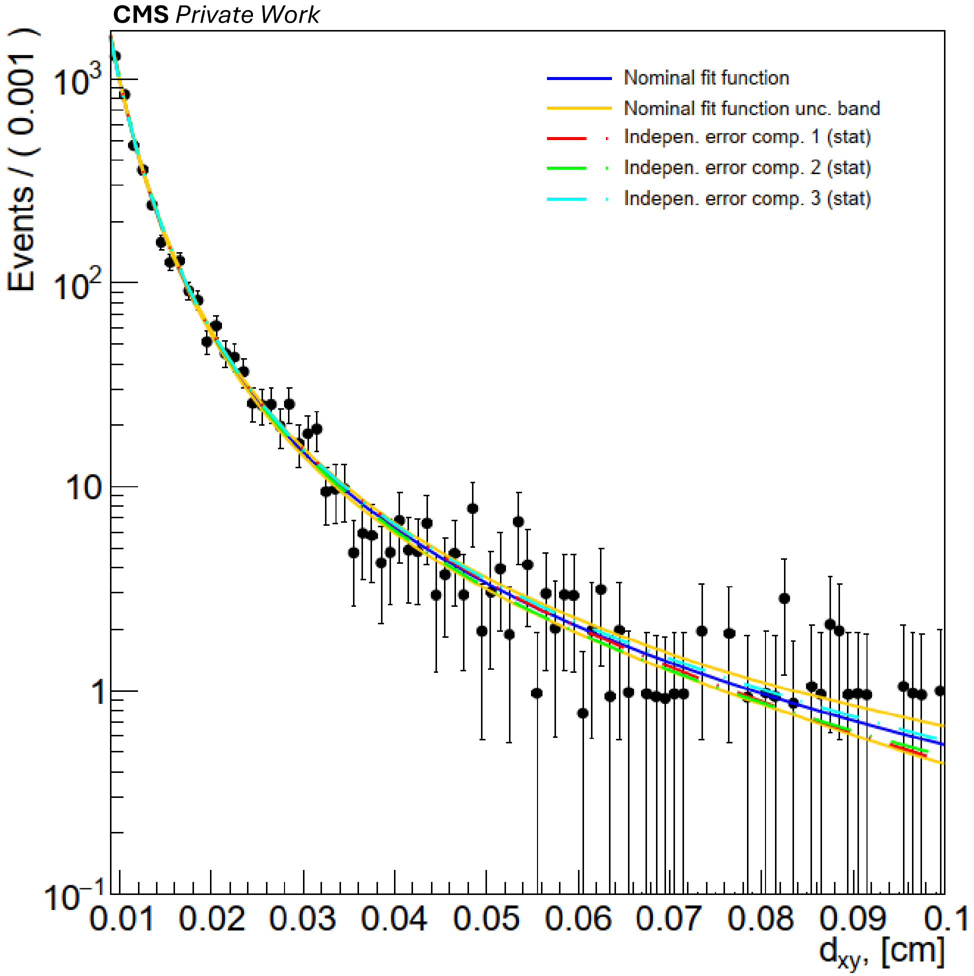


- In the tail part of the distribution the fit approach is used for the CDF calculation.
- **abs(d_{xy}) [0.01-0.1] cm**

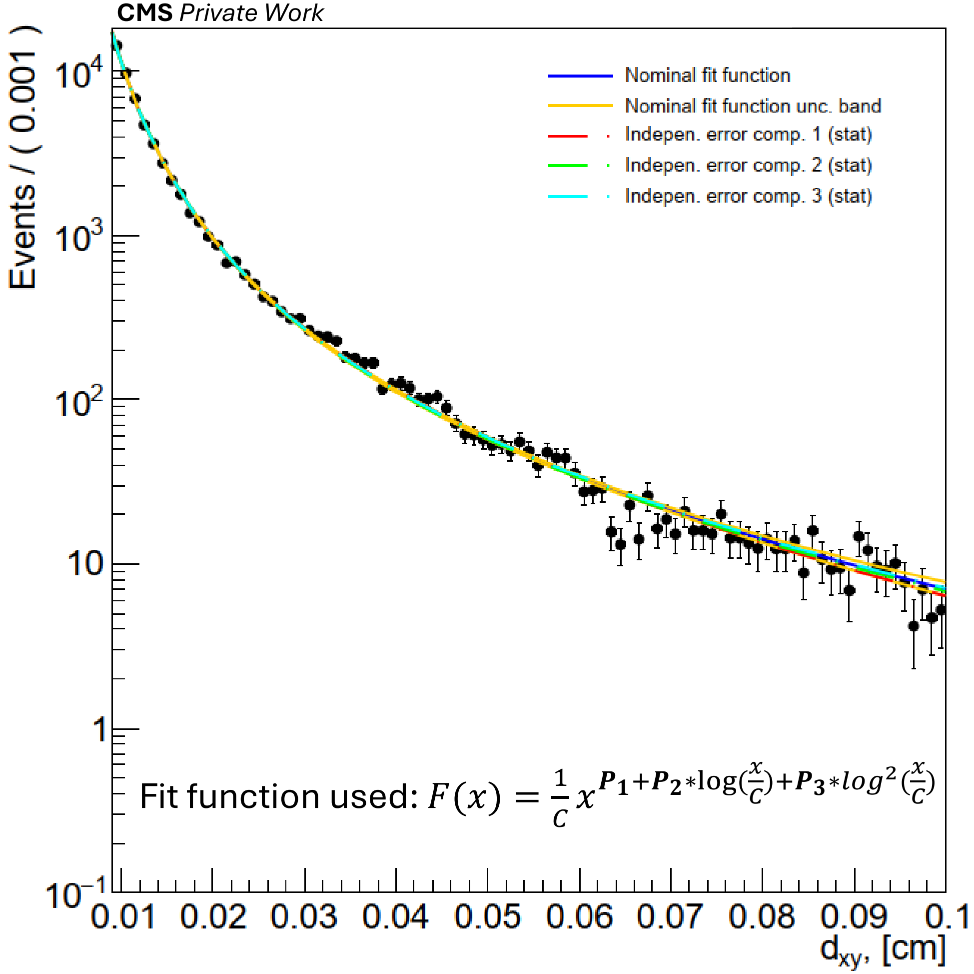
- The event count is estimated from the fitted function.
- For CDF calculations the absolute values and distributions of dxy are used.

Analysis activities – lepton d_{xy} corrections, MC fit example

- Example MC d_{xy} distribution tail fit for Muons:



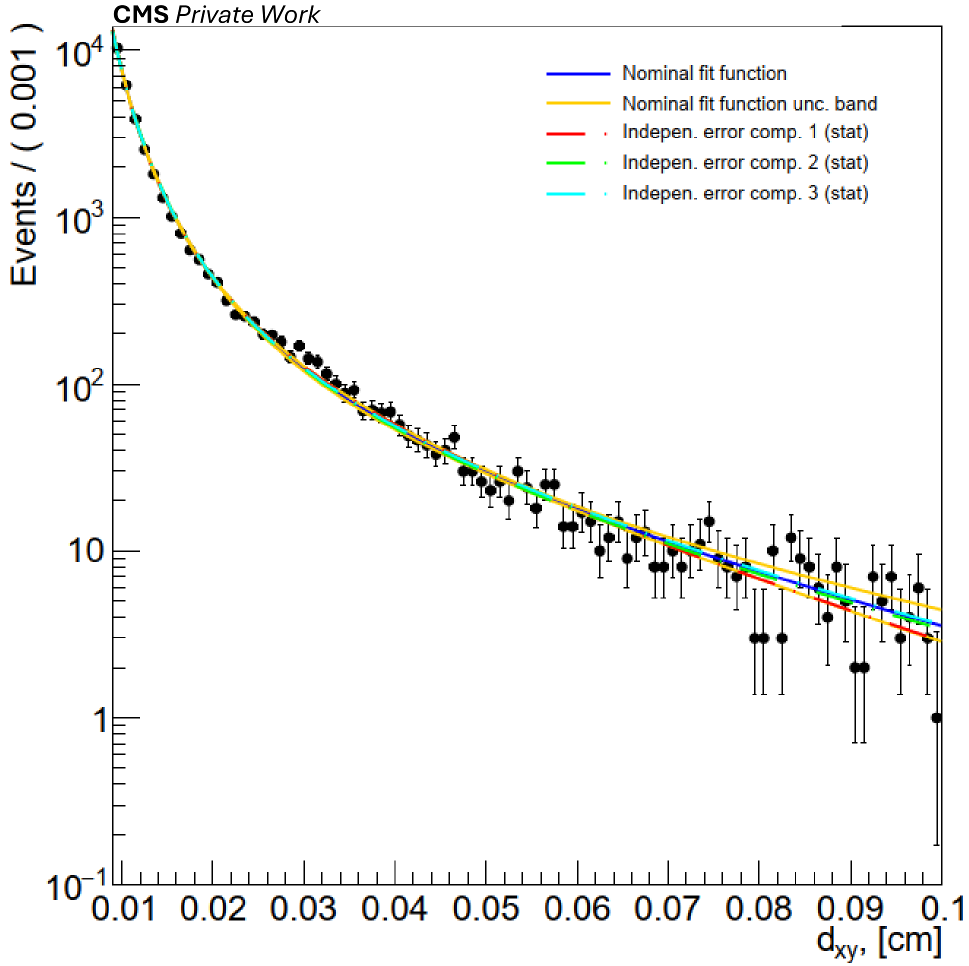
- Example MC d_{xy} distribution tail fit for Electrons:



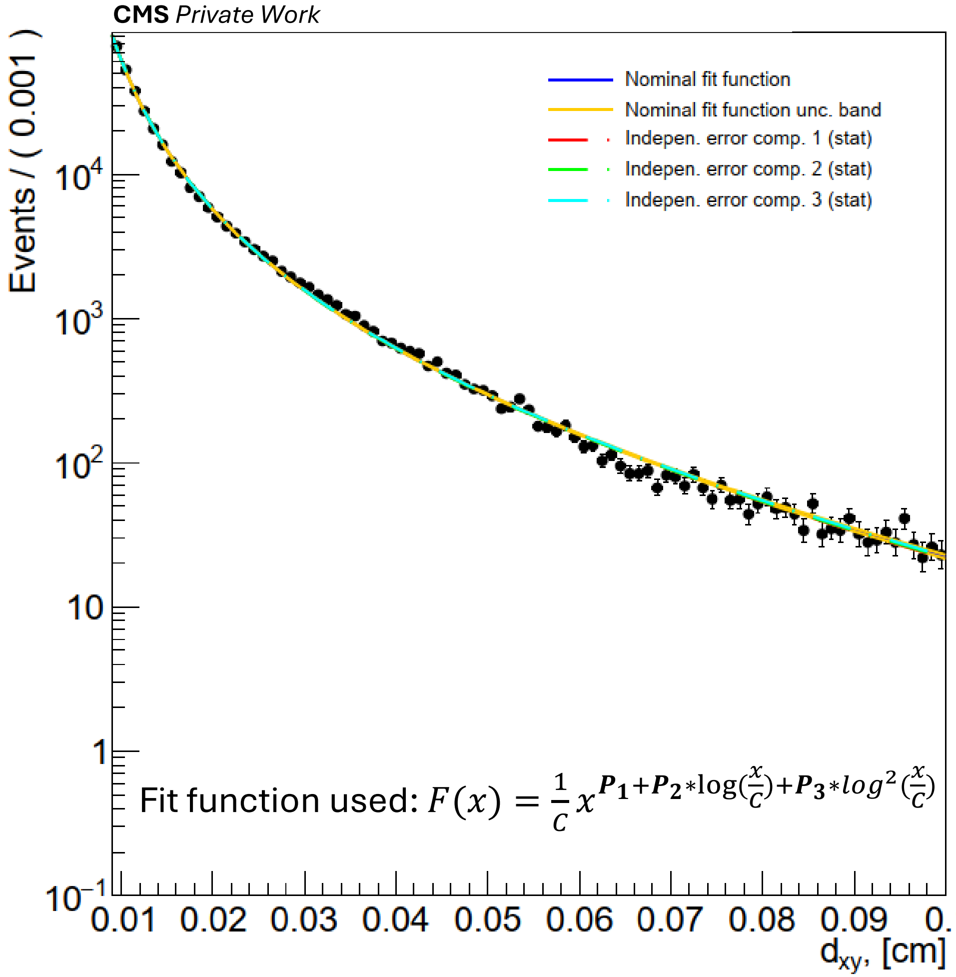
Fits in p_T [20 ; 50] GeV bin and [0.0 ; 0.9] abs(η) bin

Analysis activities – lepton d_{xy} corrections, DATA fit example

- Example DATA d_{xy} distribution tail fit for Muons:



- Example DATA d_{xy} distribution tail fit for Electrons:



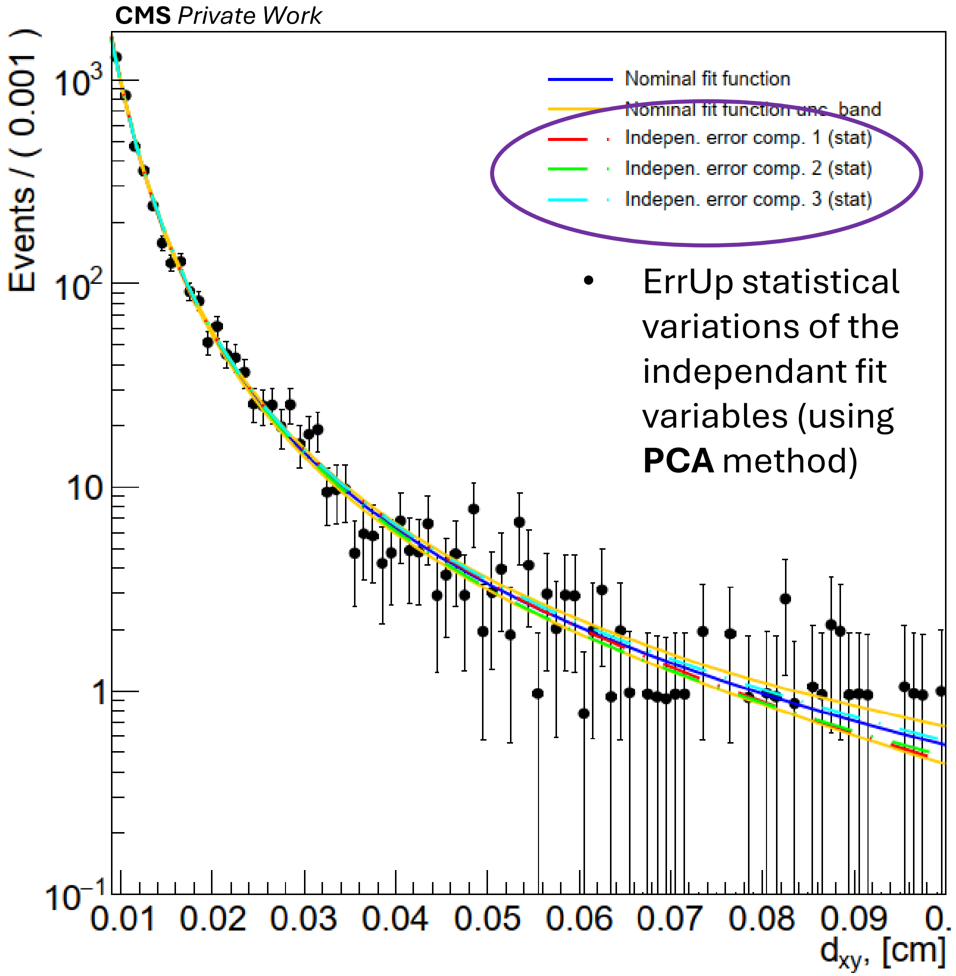
Fits in p_T [20 ; 50] GeV bin and [0.0 ; 0.9] abs(η) bin

d_{xy} correction methodology – estimating the correction's uncertainty

Uncertainty estimation for the d_{xy} correction:

- Statistical uncertainty:
  - Histogram/binned method part:
    - Recalculate the CDF using binned values with errorUp/Dn added from Poissonian uncertainty.
    - The difference in the resulting correction from the recalculated CDF is the statistical uncertainty.
  - Fit part:
    - Using '**P**rincipal **C**omponent **A**nalysis' approach, find the independent variables as a linear combination of the fit variables used.
    - Recalcualte the CDF for fit part using fit parameters+ErrUp/Dn from the independent variable uncertainties.
    - The difference in the resulting correction from the recalculated CDF is the statistical uncertainty.
    - Uncertainty gets calculate for each independant component and the resulting contributions get summed in quadrature. (As they are independent from each other)

$|d_{xy}|$ histogram fit in log scale



- ErrUp statistical variations of the independant fit variables (using **PCA** method)

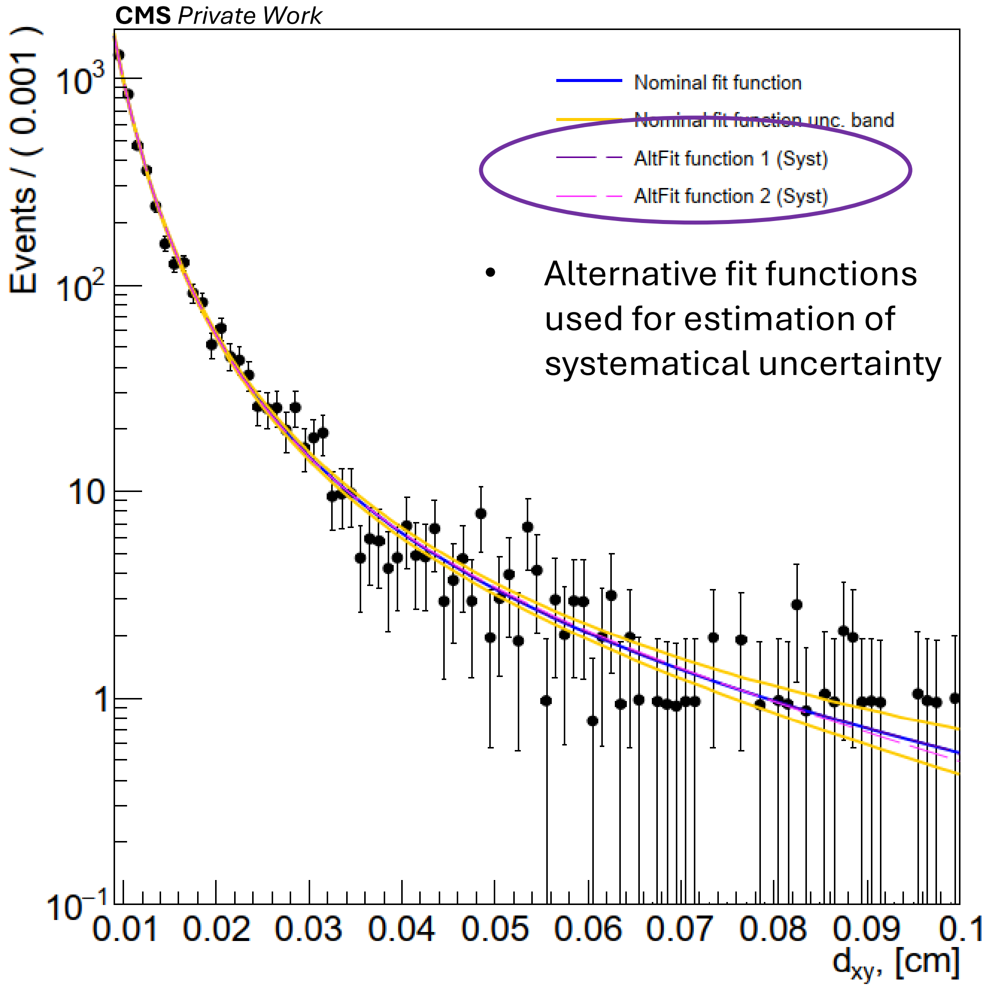
MC muon d_{xy} fit in p_T [20 ; 50] GeV bin and [0.0 ; 0.9] abs(η) bin

d_{xy} correction methodology – estimating the correction's uncertainty

Uncertainty estimation for the d_{xy} correction:

- Systematical uncertainty:
  - Histogram/binned method part:
    - Potential check - Recalculate the CDF using different histogram bin count.
    - The difference in the resulting correction from the recalculated CDF is the systematical uncertainty.
  - Fit part:
    - Use a different fit function and recalculate the CDF.
    - The difference in the resulting correction from the recalculated CDF is the systematical uncertainty.
    - Potential check – change the bin count used in the histogram that gets fitted. Estimate additional systematical uncertainty form this change of binning.
- Total uncertainty:
  - Combine the statistical and systematical contributions in quadrature.

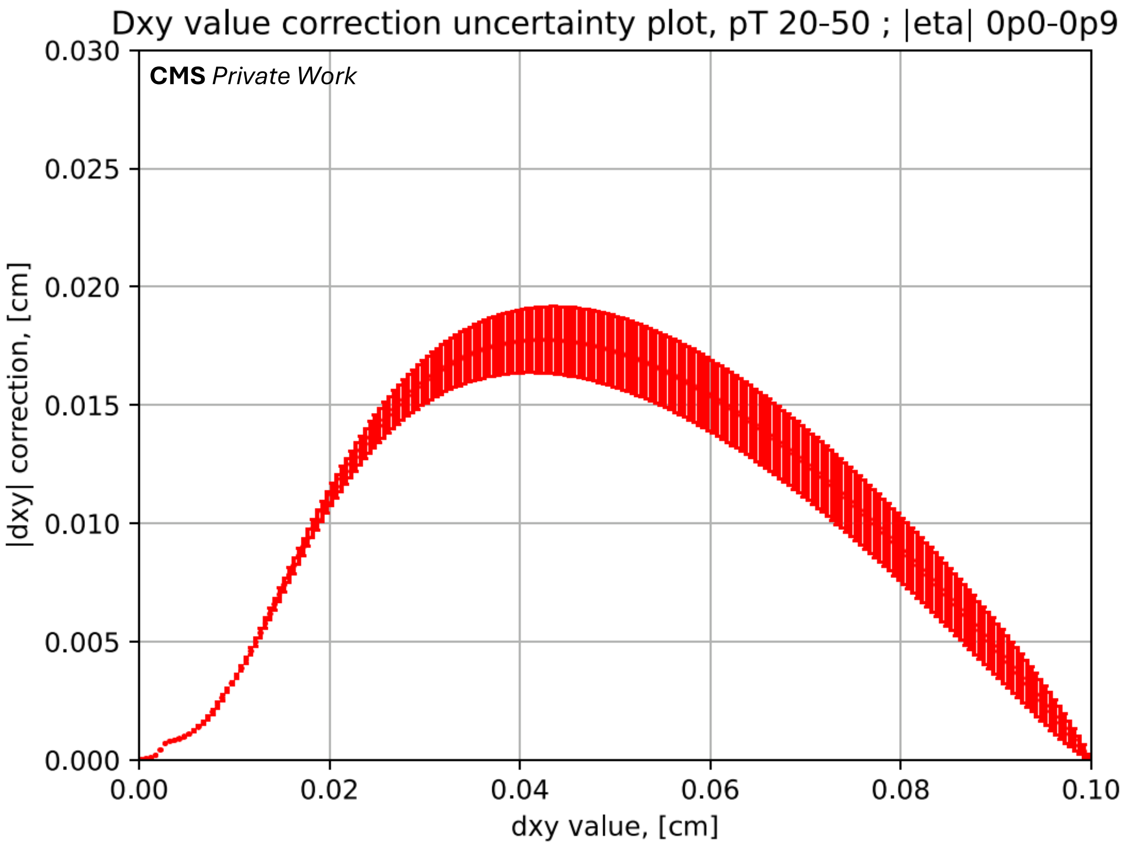
$|d_{xy}|$ histogram fit in log scale



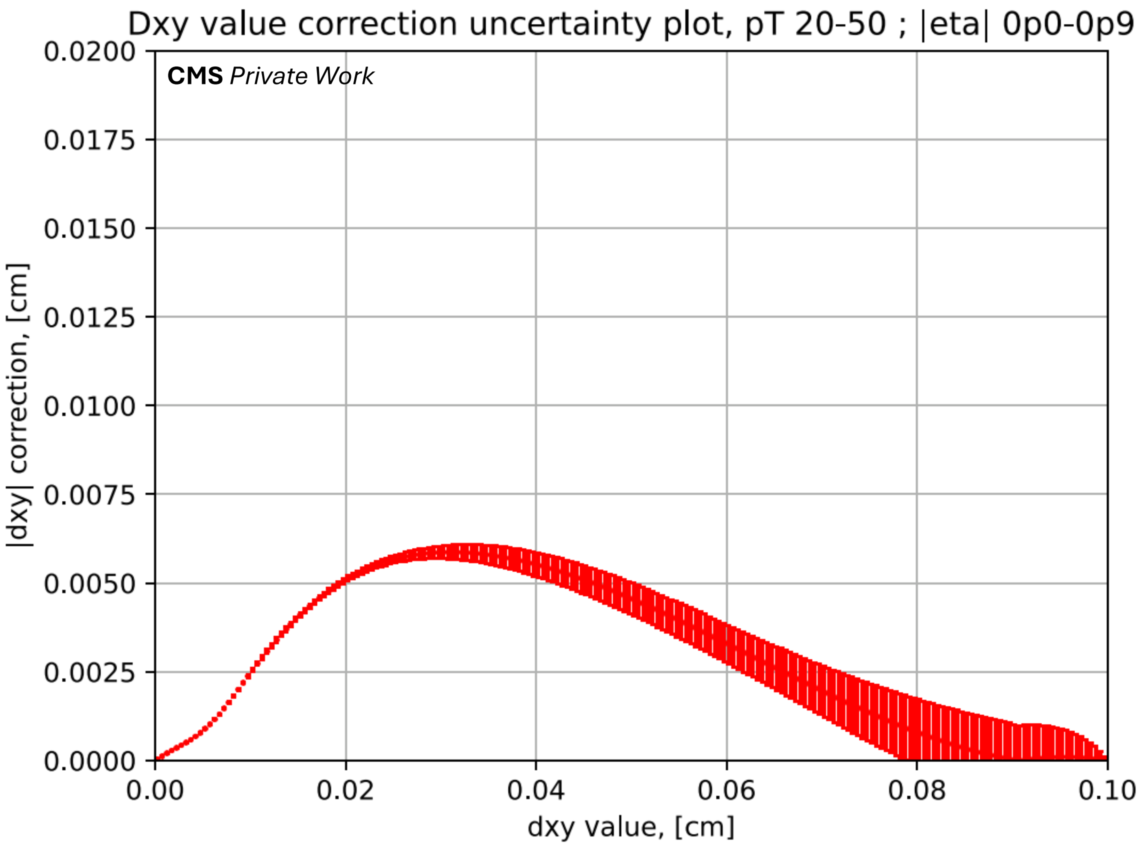
MC muon d_{xy} fit in p_T [20 ; 50] GeV bin and [0.0 ; 0.9] abs(η) bin

d_{xy} correction methodology – estimating the correction's uncertainty

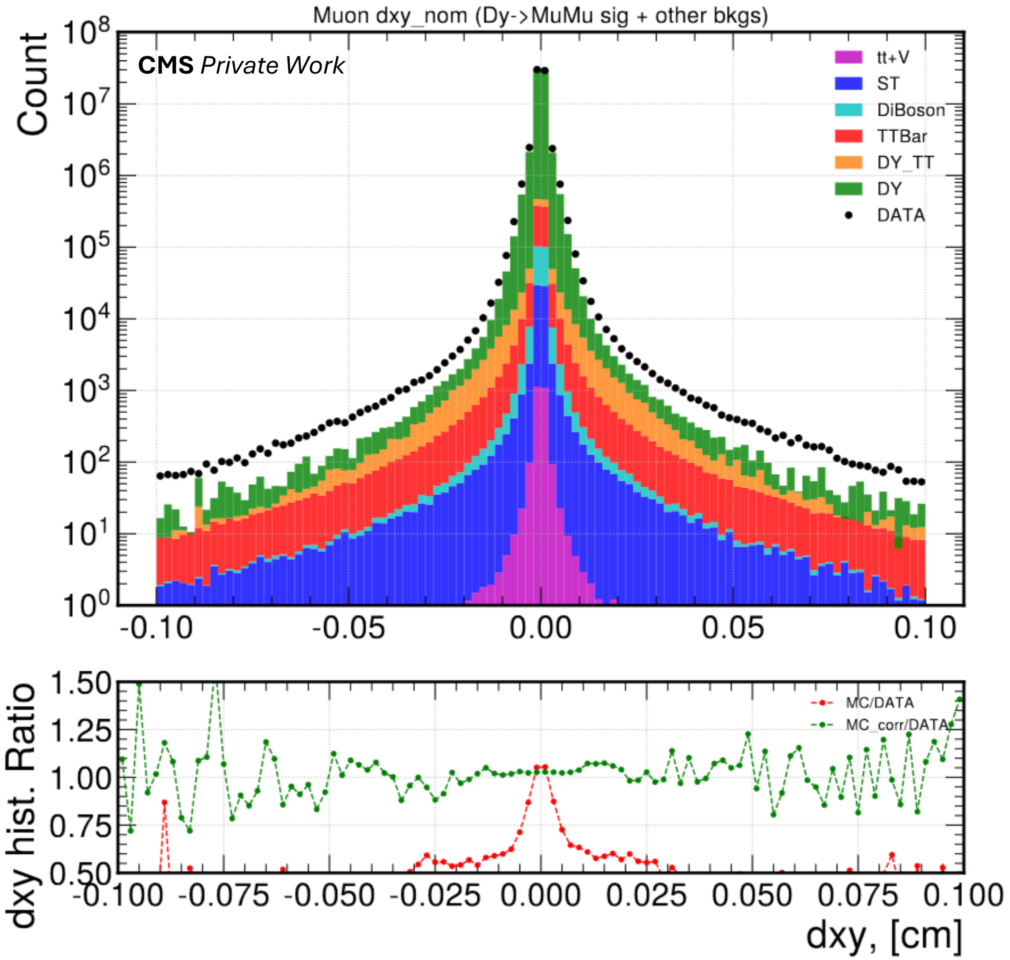
- Example d_{xy} correction uncertainties for Muons:

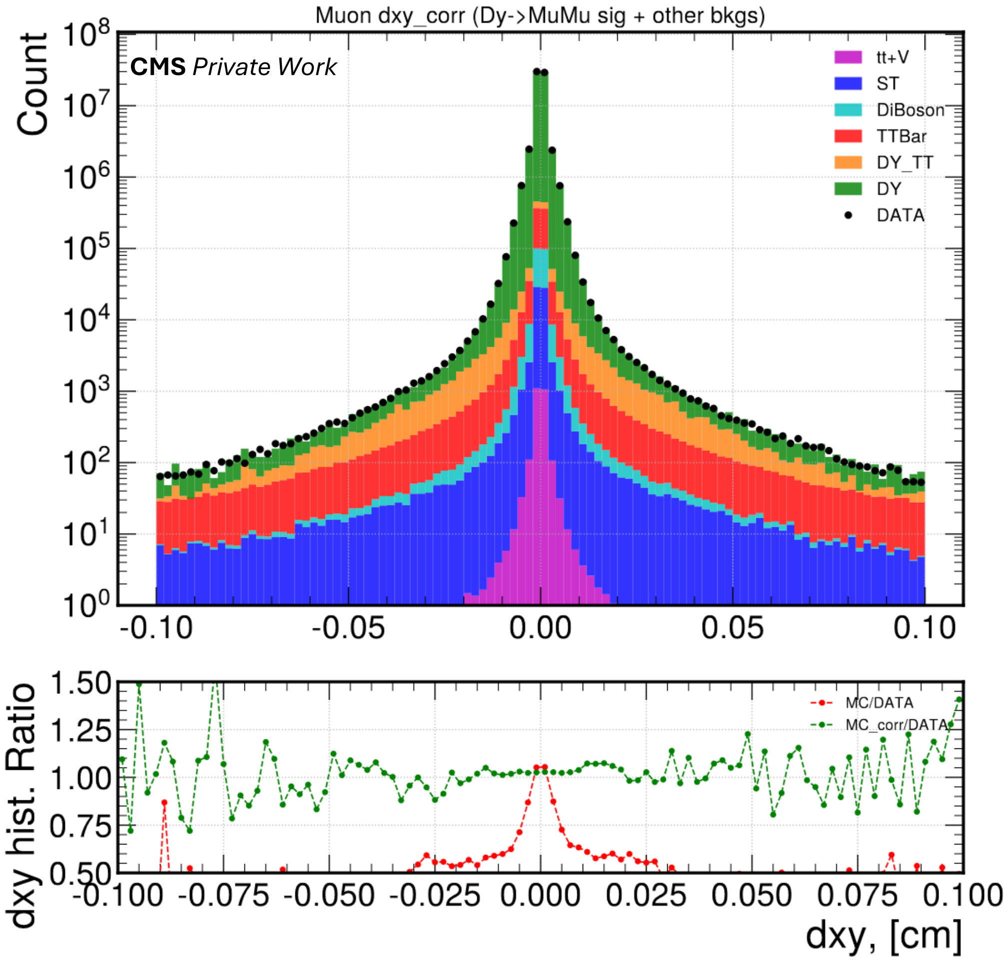


- Example d_{xy} correction uncertainties for Electrons:



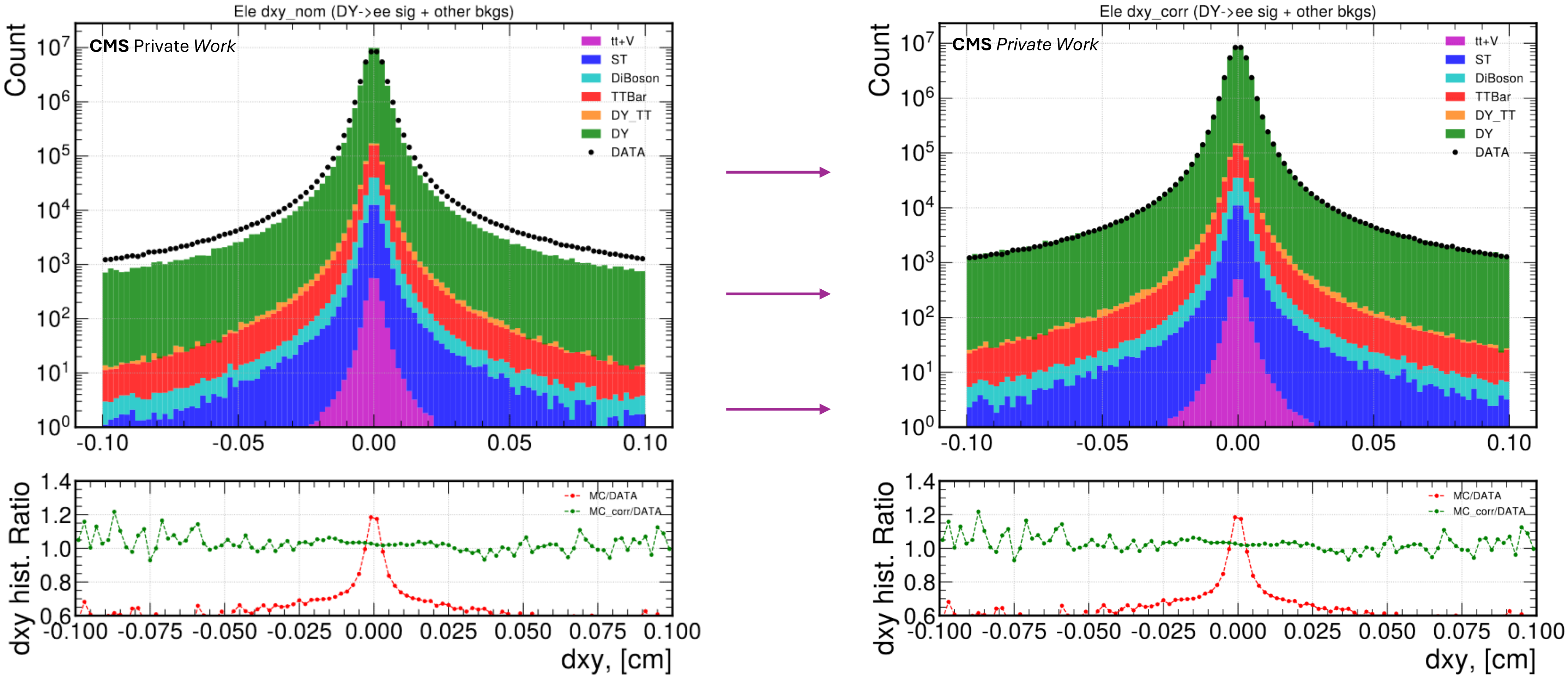
Analysis activities – lepton d_{xy} corrections, muon results





Muon dxy MC distribution before (left) and after (right) the application of the correction.

Analysis activities – lepton d_{xy} corrections, electron results



Electron dxy MC distribution before (left) and after (right) the application of the correction.

Outlook and future tasks

- Additional control region checks for the d_{xy} corrections.
- Add the missing corrections in the analysis:
  - Rochester corrections
  - Jet energy/resolution corrections
- Estimate the QCD background using data-driven methods (ABCD method).
- Setup the 'combine' tool for the final fit and ratio extraction from the d_{xy} and p_T distributions
  - Include all the uncertainty sources

Thank You for Your attention!

Questions, comments and suggestions are welcome!