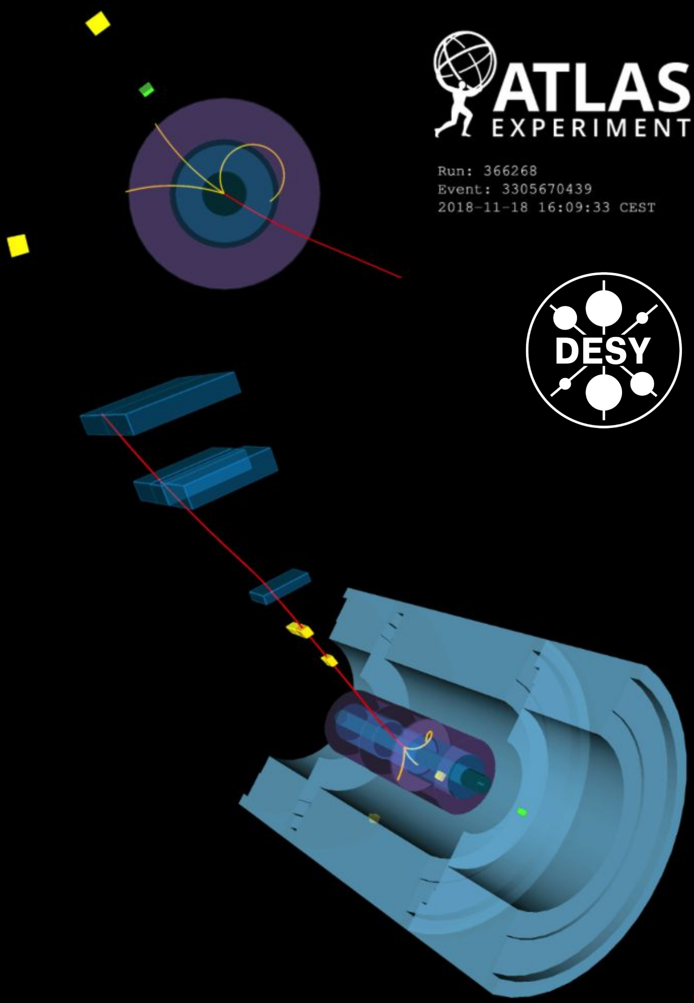
Measurement of differential $\gamma\gamma \rightarrow \tau\tau$ cross sections and constraints on τ-lepton electromagnetic moments

DPG Spring Meeting, Göttingen 2025



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Outline

- Motivation and analysis strategy
- Background modelling
- Detector-level distributions
- Unfolding procedure
- Differential cross sections
- Extraction of tau anomalous magnetic moment

Motivation

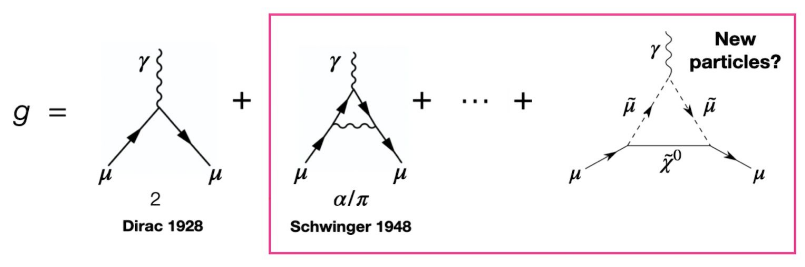
Electromagnetic moments of τ-lepton

Anomalous magnetic moment

- Defines how fermions interacts with magnetic field
- intrinsic magnetic moment:

$$\vec{\mu} = g \frac{q}{2m} \vec{s}$$

where:

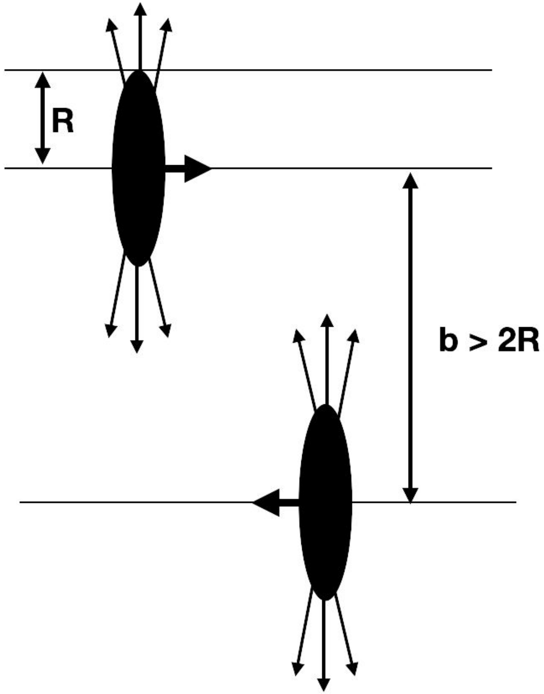


- Anomalous magnetic moment: a = ½ (g -2)
- a_e, a_μ are precisely measured observables, a_τ is much less constrained
- SM predicts atau close to 0: significantly smaller than the currently available experimental bounds
- Measuring atau with improved precision can be sensitive to BSM

Analysis strategy
Overview of the idea

Ultraperipheral heavy-ion collisions (UPC):

- UPC occurs when the impact parameter is larger than twice the radius of the ions (b>2R)
- photon-photon interactions can be observed opening completely new research opportunities.

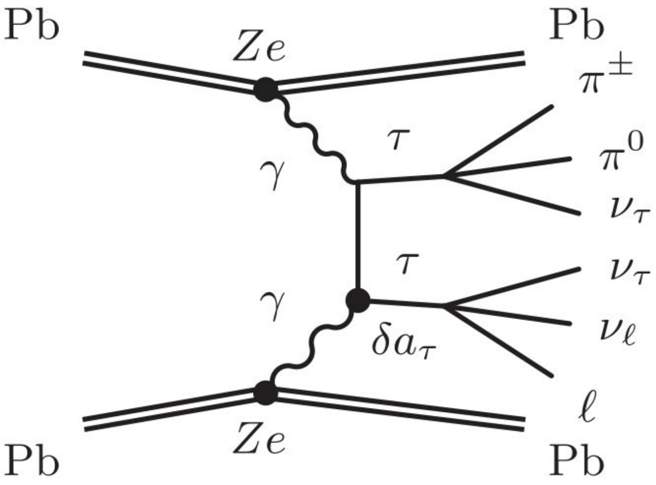


Analysis strategy
Overview of the idea

Advantages of UPC Pb+Pb over pp collisions

- huge photon fluxes → Z^4 cross-section enhancement (with Z = 82 for Pb)
- ~ no hadronic pile-up → exclusivity selections
- low p_T thresholds in trigger and offline reconstruction (access low mass region)

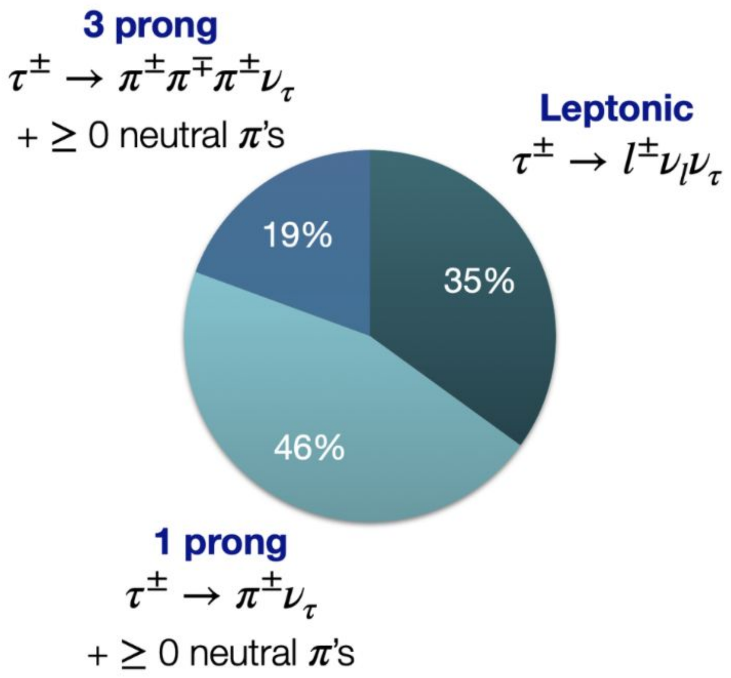
The presence of the $\gamma\gamma\tau$ vertex provides sensitivity to the electromagnetic couplings of the τ-lepton

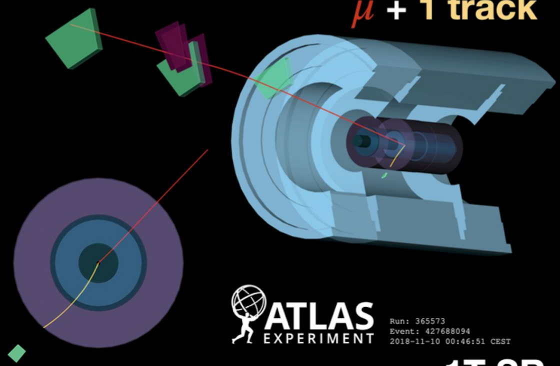


Analysis strategy

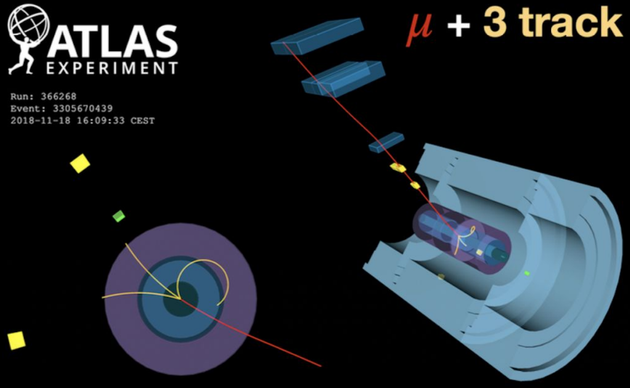
Overview of the idea

- **Full LHC Run2 PbPb data (1.93 nb^{-1} of data) recorded by ATLAS**
- Single muon based triggers
- Signal candidates are selected using **muonic tau decays** and categorised using electrons or low-pT tracks:
    - **1M1T**: 1 muon + 1 track
    - **1M3T**: 1 muon + 3 tracks
    - **1M1E**: 1 muon + 1 electron
- Measurement of differential cross sections: unfolding:
    - correct for detector effects →enables theorists to reinterpret our results for other models
- Detector-level & truth-level extractions of tau electromagnetic moments

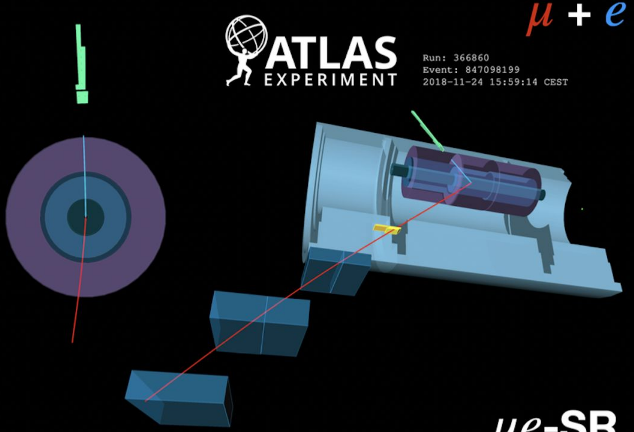




μ1T-SR



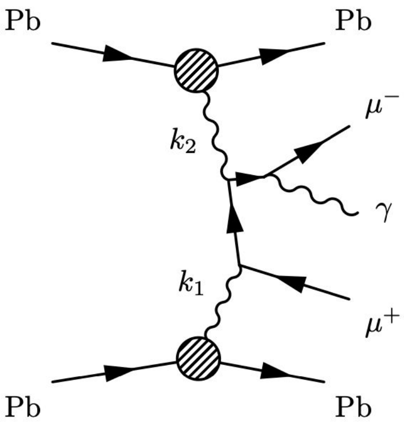
μ3T-SR



μe-SR

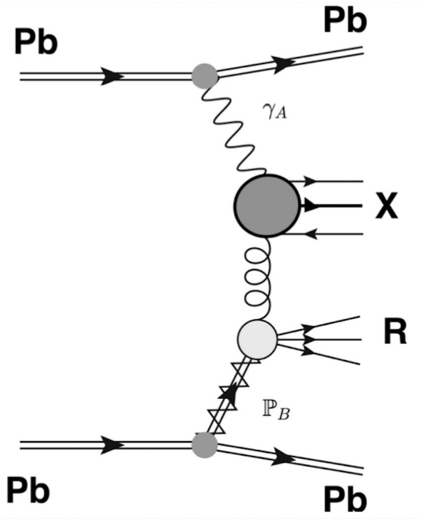
Background modelling

Exclusive dimuon production
γγ→μμ



Estimated using MC

Diffractive photonuclear particle production

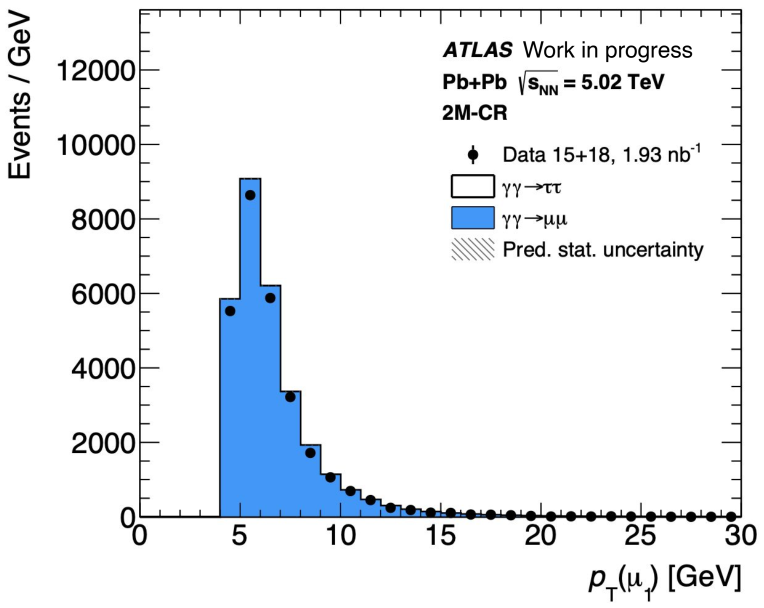


Estimated using fully data-driven method

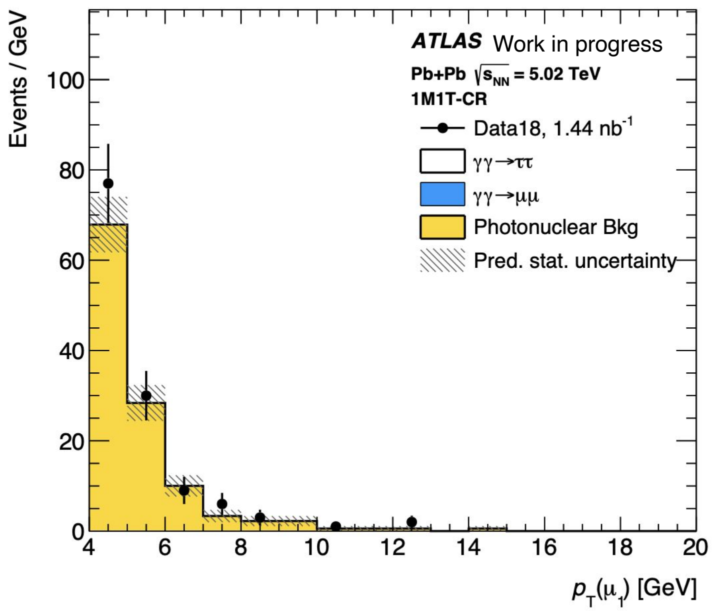
Background modelling

Detector-level distributions in dedicated control regions

Dimuon background



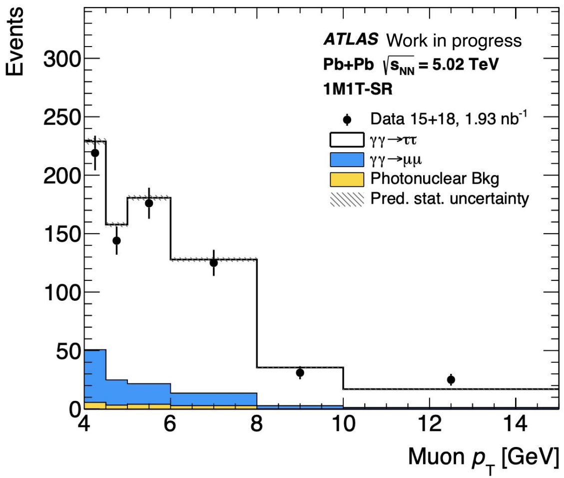
Photonuclear background



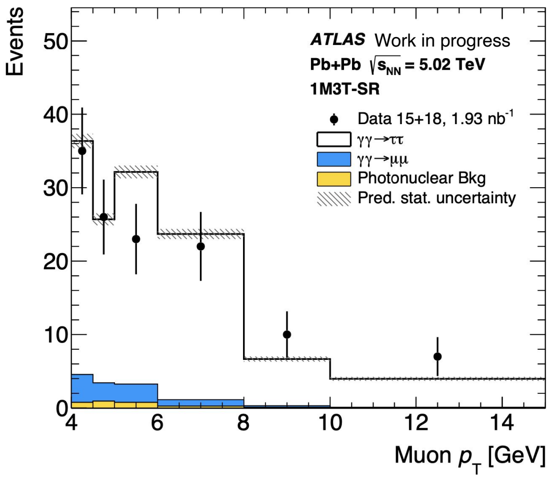
- good modelling for each of these backgrounds

Detector-level distributions

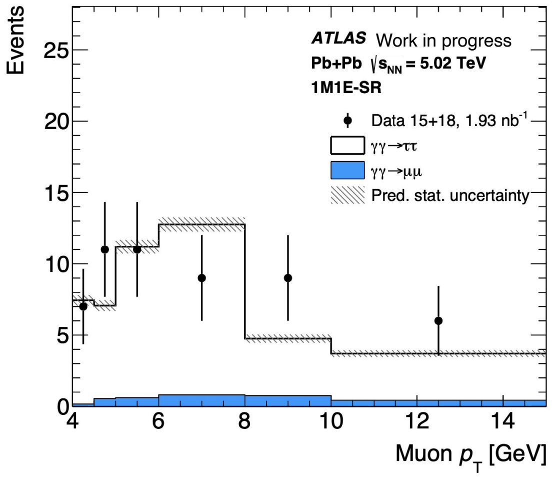
1M1T



1M3T



1M1E



- clear signal with very small background contribution
- good agreement between data and prediction

Unfolding procedure

Truth objects and fiducial regions definition

Property	Signal
Truth Muons	
Kinematic	$p_{\mathrm{T}} > 4$ GeV, $\lvert\eta\rvert < 2.5$
Truth Electrons	
Kinematic	$p_{\mathrm{T}} > 4$ GeV, $\lvert\eta\rvert < 2.5$
Truth hadrons and truth charged leptons with $p_{\mathrm{T}}^{\ell} < 4$ GeV	
Kinematic	$p_{\mathrm{T}} > 100$ MeV, $\lvert\eta\rvert < 2.5$

Observable	Preselection		
$E_{\mathrm{ZDC}}^{A,C}$	< 1 TeV		
Region	1M1T FR	1M3T FR	1M1E FR
N_{μ}^{sig}	$= 1$	$= 1$	$= 1$
N_{e}^{sig}	$= 0$	$= 0$	$= 1$
$N_{\mathrm{trk}} \Delta R > 0.1$ from μ^{sig}	$= 1$	$= 3$	—
$N_{\mathrm{trk}} \Delta R > 0.1$ from ℓ^{sig}	—	—	$= 0$
$\sum$ charge	$= 0$	$= 0$	$= 0$
$p_{\mathrm{T}}^{(\mu,\mathrm{trk})}$	> 1 GeV	—	—
m_{trks}	—	< 1.7 GeV	—
$A_{\phi}^{\mu,\mathrm{trk(s)}}$	< 0.4	< 0.2	—

- definition of "tracks" is chosen to stay as close as possible to the SR definitions
- **unfold seven variables in each region**

Unfolding procedure

We use Iterative Bayesian Unfolding (IBU).

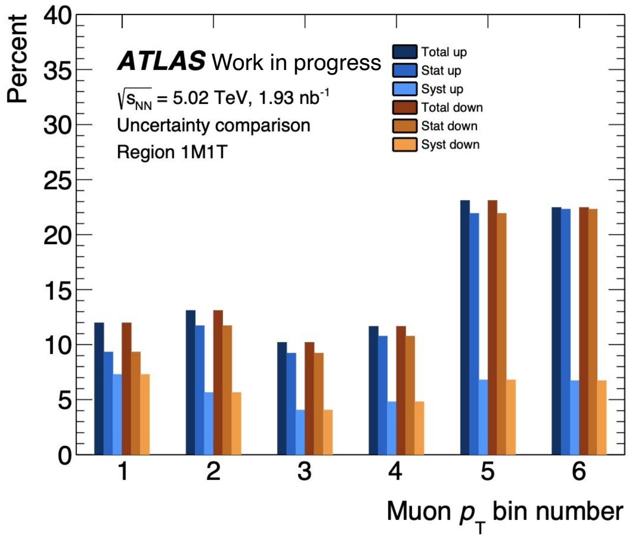
Statistical uncertainties and correlations

- analysis limited by data statistics
- determine the statistical uncertainty on the unfolded cross sections using bootstrapping

Systematic uncertainties

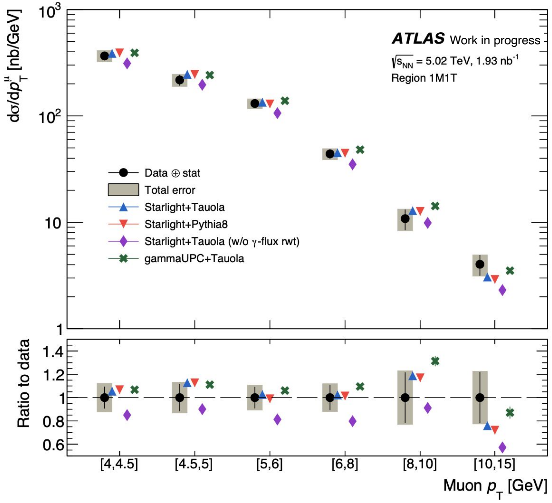
- systematic uncertainties can affect one/some/all of: background, signal at reconstruction-level or truth-level
- depending on which of these is affected, appropriately varied inputs are used in the unfolding

- Impact of the uncertainties: statistical uncertainties for every bin are larger that systematic ones

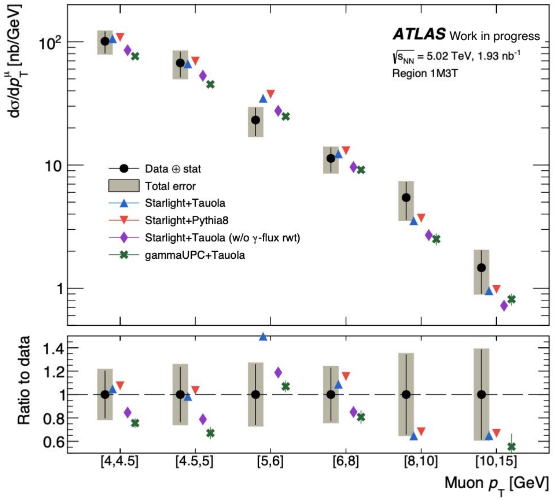


Cross section at truth level

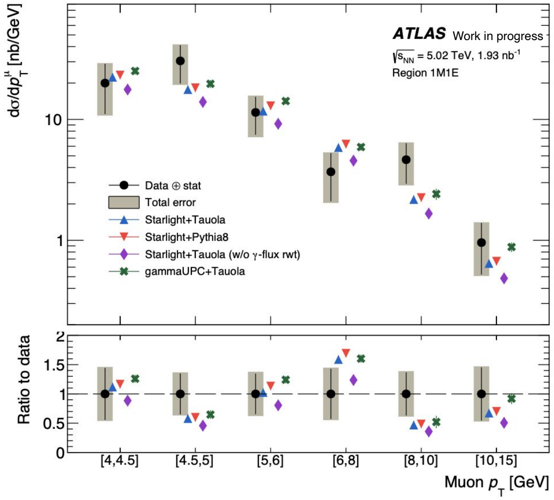
1M1T



1M3T



1M1E



- 2015 and 2018 inputs are combined before unfolding
- The cross section per-bin is estimated by dividing the number of events at truth level, by the bin width times the central value of the 2015+2018 luminosity
- good agreement between the truth and the unfolded distribution (given the uncertainties)

BSM signal prediction

a_τ and d_τ signal parametrization

- same parametrization of $\gamma\gamma\tau$ vertex as in the previous ATLAS analysis
- photon-lepton vertex function depends on the momentum transfer q:

$$i\Gamma_\mu^{(\gamma\tau\tau)}(q) = -ie\left[\gamma_\mu F_1(q^2) + \frac{i}{2m_\tau}\sigma_{\mu\nu}q^\nu F_2(q^2) + \frac{1}{2m_\tau}\gamma^5\sigma_{\mu\nu}q^\nu F_3(q^2)\right]$$

- $F_1(q^2)$ and $F_2(q^2)$ are the Dirac and Pauli form factors, $F_3(q^2)$ is the electric dipole form factor

  At $q^2 \to 0$ (fulfilled in Pb+Pb collisions):

$$F_1(0) = 1 \qquad F_2(0) = a_\tau \qquad F_3(0) = d_\tau \frac{2m_\tau}{e}$$

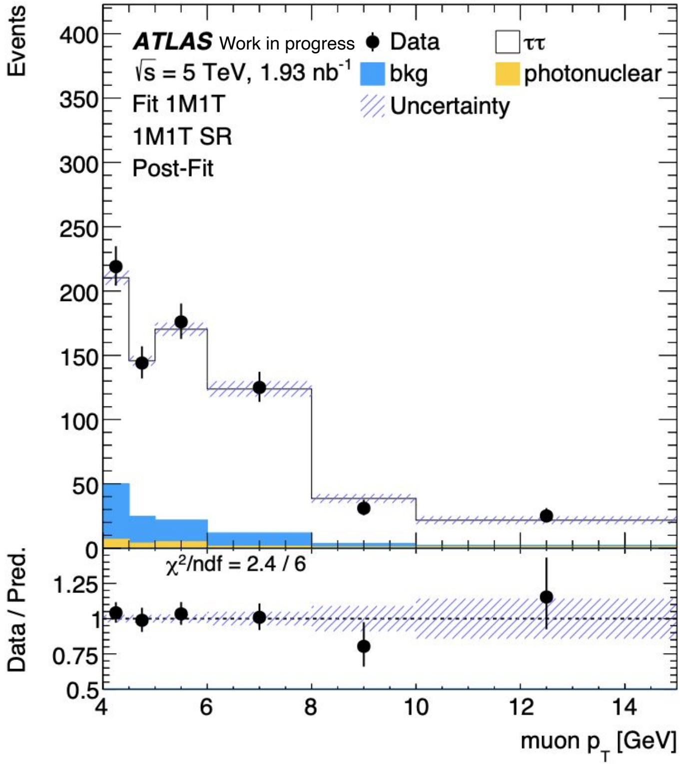
- BSM predictions obtained through reweighting procedure from SM samples

Fit setup

atau fit

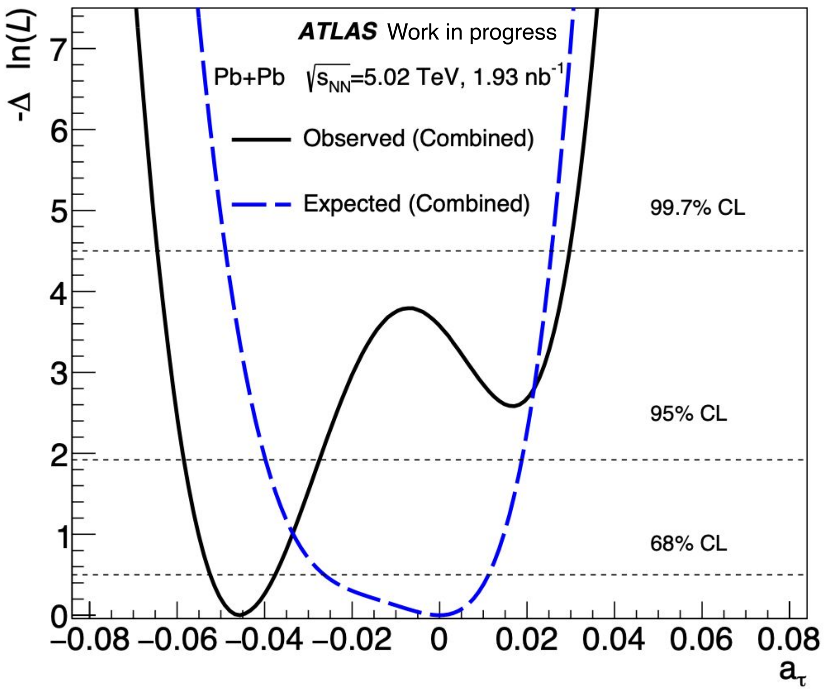
Detector-level fit

- use detector-level distribution of muon pT
- TRExFitter with Poisson likelihood model
- Negative Log Likelihood minimisation finds best fit and 68%CL limits



Fitting results
Asimov atau fit

- negative log-likelihood curves as a function of atau
- two local minima where the one at negative atau is stronger and thus determines best-fit value



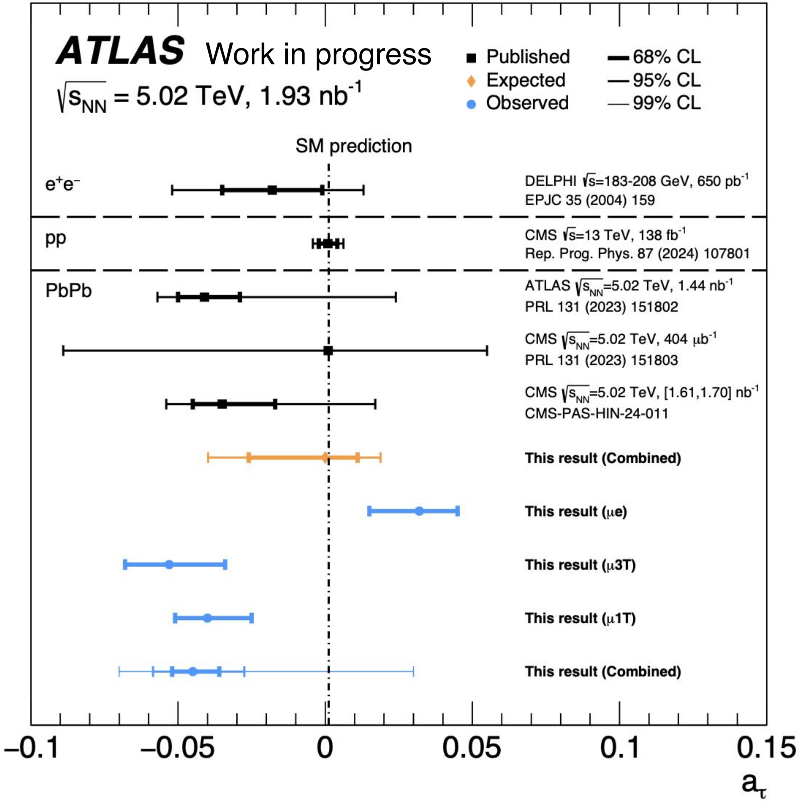
Comparison with other measurements

[ATLAS Pb+Pb](2023):
68% [−0.050,−0.029]
95% [-0.057,0.024]

[CMS p+p](2024):
95% ~ [−0.0042,0.0062]

[CMS Pb+Pb](PAS, 2024):
68% ~ [−0.045,−0.015]
95% ~ [−0.055,+0.018]

This measurement:
68% ~ [-0.058, -0.026]
95% ~ [-0.052, -0.037]



Summary

Full LHC Run2 Pb+Pb data analysis aiming for first differential cross section measurement of $\gamma\gamma\rightarrow\tau\tau$ and extraction of electromagnetic moments of the tau-lepton:

- 3 signal regions + dimuon control region
- Background modelling completed
- Unfolding procedure to obtain differential cross sections fully in place
- 7 unfolded observables in each signal region
- Statistical uncertainties in the data propagated through bootstrapping -> Provides full statistical correlations also between observables
- Extraction of atau from muon pT: most stringent constraints to date in Pb+Pb collisions
- **We plan to perform global fits to the unfolded cross-sections and additionally extract dtau.**

Thank you!

Backup

Motivation

Electromagnetic moments of τ-lepton

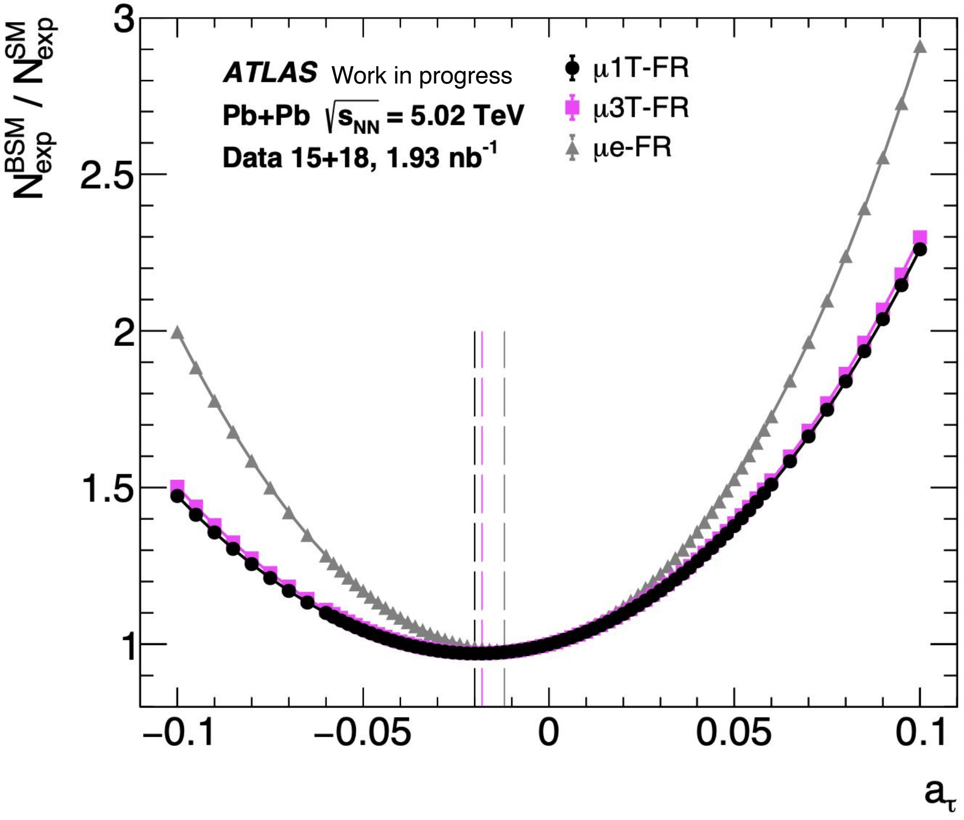
Electric dipole moment

- Defines how fermions interacts with electric field
- The EDM (dtau) of a particle is defined through the interaction of its spin **S** with an external electric field **E**:

$$H_{\mathrm{EDM}} = -d_\tau \mathbf{S} \cdot \mathbf{E}$$

- SM predicts dtau **< ~ 10^{-37}**: currently available experimental bounds are at the level of **10^{-17}**
- Measuring dtau is interesting because it provides a direct test of **CP violation** in the lepton sector: EDM is aligned with the spin, while under time reversal, **spin reverses direction** but the EDM remains unchanged.

Number of events vs atau



Data and MC samples

2015 data

Data sample: data15_hi.periodAllYear.physics_UPC.PhysCont.DAOD_HION4.grp15_v01_p4952

GRL: data15_hi.periodAllYear_DetStatus-v105-pro22-13_Unknown_PHYS_HeavyIonP_All_Good_tolerable_L1CALmisconfigSatBCID

Trigger: HLT_mb_sptrk_vetombts2in_L1MU0_VTE50

Luminosity: 0.49 nb-1

2018 data

Data sample: data18_hi.periodAllYear.physics_UPC.PhysCont.DAOD_HION4.grp18_v01_p4952

GRL: data18_hi.periodAllYear_DetStatus-v106-pro22-14_Unknown_PHYS_HeavyIonP_All_Good

Trigger: HLT_mu4_hi_upc_FgapAC3_L1MU4_VTE50

Luminosity: 1.44 nb-1

Total luminosity of 1.93 nb-1

MC samples

Signal samples:

- nominal: STARlight + Tauola
- alternative: STARlight + Pythia8

Background samples (γγ→μμ):

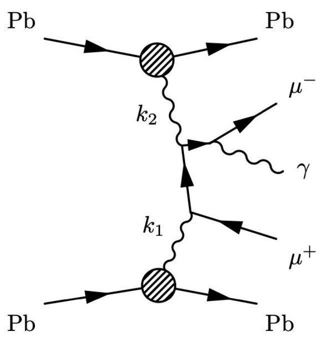
- STARlight + Pythia8
- Madgraph + Pythia8

Additionally:

- truth-level $\gamma\gamma \rightarrow \tau\tau$ sample simulated with gammaUPC generator (for theory predictions - work in progress)

Background modelling

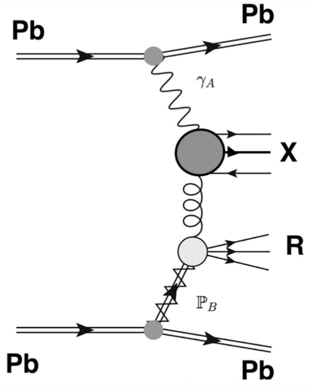
Exclusive dimuon production
$\gamma\gamma \rightarrow \mu\mu$



Estimated using MC:

- STARlight+Pythia 8 and MG5+Pythia 8 event generators
- photon flux reweighted to match the flux from SuperChic

Diffractive photonuclear particle production



Estimated using fully data-driven method

- Template distributions built from events having extra 'soft' track with low pT < 0.5 GeV

Object reconstruction

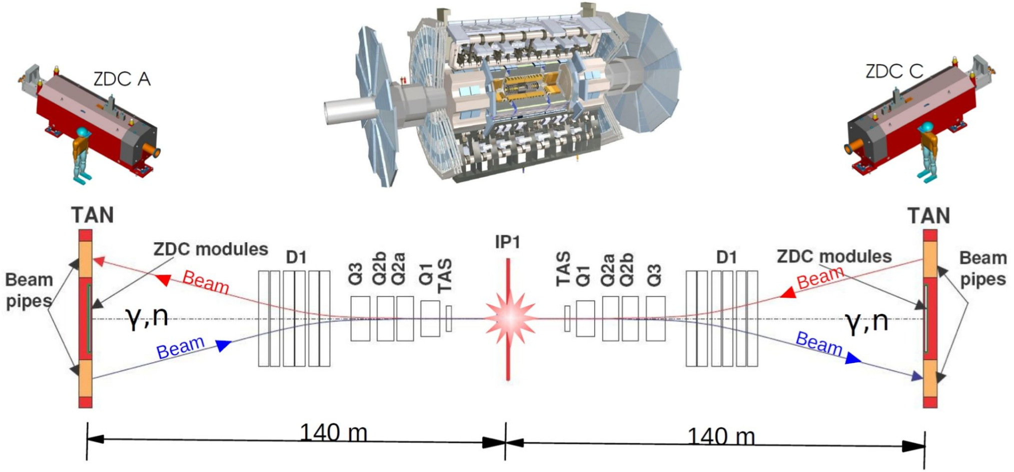
Property	Signal	Baseline
Muons		
Kinematic	$p_T > 4$ GeV, $\|\eta\| < 2.4$	$p_T > 2$ GeV, $\|\eta\| < 2.5$
Identification	LowPt	—
Impact parameter	$\|d_0\| < 0.3$ mm	—
Electrons		
Kinematic	$p_T > 4$ GeV, $\|\eta\| < 2.47$ (excluding $1.37 < \|\eta\| < 1.52$)	—
Identification	LHLoose	—
Object Quality (OQ)	Good	—
Impact parameter	$\|d_0\| < 0.5$ mm	—
Tracks		
Kinematic	$p_T > 100$ MeV, $\|\eta\| < 2.5$	—
Reconstruction	Loose Primary	—
Impact parameter	$\|d_0\| < 1.5$ mm	—
Photons		
Kinematic	$p_T > 1.5$ GeV, $\|\eta\| < 2.37$ (excluding $1.37 < \|\eta\| < 1.52$)	—
Identification	Author, NN_PID	—
Object Quality (OQ) and Cleaning	Good	—
Cleaning	pass OQ quality	—
TopoClusters		
Kinematic	$p_T > 1$ GeV for $\|\eta\| < 2.5$ $p_T > 0.1$ GeV for $2.5 < \|\eta\| < 4.9$	—
Quality	pass TopoSigCut pass HotspotCleaning	—

Event selection

Observable	Preselection			
GRL	Pass			
$E_{\mathrm{ZDC}}^{A,C}$	< 1 TeV			
Trigger	HLT_mb_sptrk_vetombts2in_L1MU0_VTE50 for 2015 data or HLT_mu4_hi_upc_FgapAC3_L1MU4_VTE50 for 2018 data			
Region	**1M1T SR**	**1M3T SR**	**1M1E SR**	**2M CR**
$N_{\mu}^{\mathrm{baseline}}$	$= 1$	$= 1$	—	—
N_{μ}^{sig}	$= 1$	$= 1$	$= 1$	$= 2$
N_{e}^{sig}	$= 0$	$= 0$	$= 1$	—
N_{trk} ($\Delta R > 0.1$ from μ^{sig})	$= 1$	$= 3$	—	—
N_{trk} ($\Delta R > 0.1$ from ℓ^{sig})	—	—	$= 0$	$= 0$
$N_{\mathrm{clust}}^{\mathrm{unmatched}}$	$= 0$	$= 0$	—	—
$\sum_i q_i$	$= 0$	$= 0$	$= 0$	—
$p_{\mathrm{T}}^{(\mu,\mathrm{trk})}$	> 1 GeV	—	—	—
$p_{\mathrm{T}}^{(\mu,\mathrm{trk},\gamma)}$	> 1 GeV	—	—	—
$p_{\mathrm{T}}^{(\mu,\mathrm{trk},\mathrm{cluster})}$	> 1 GeV	—	—	—
m_{trks}	—	< 1.7 GeV	—	—
$A_{\phi}^{\mu,\mathrm{trk(s)}}$	< 0.4	< 0.2	—	—
$m_{\mu\mu}$	—	—	—	> 11 GeV

0n0n topology weights

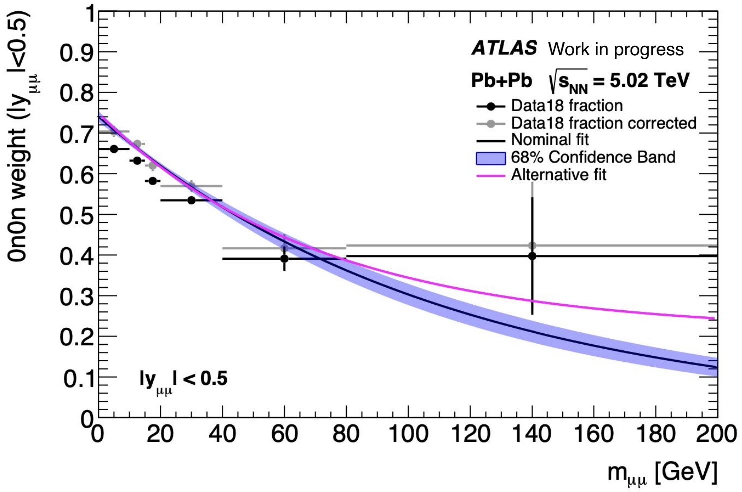
- 0n0n topology = no neutrons detected on the both sides of the Zero-Degree Calorimeter (ZDC)

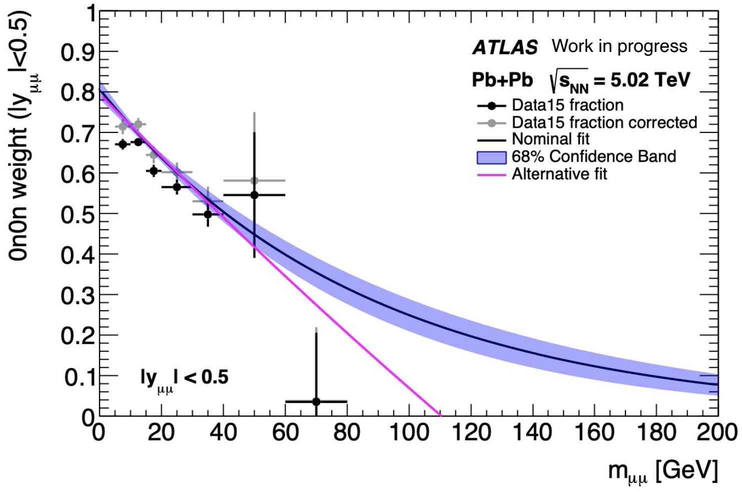


- Large suppression of photonuclear background
- MC includes 0n0n, 0nXn, XnXn topologies → need extra reweighting to restrict to 0n0n topology
- Data-driven extraction of 0n0n probability using dimuon events:

0n0n probability = ratio 0n0n/„inclusive ZDC" events as function of dimuon mass in bins of dimuon rapidity

0n0n topology weights





- nominal weight - exponential fit
- 68% CL band to estimate statistical uncertainty
- systematic uncertainty - alternative fit (exponent with additional constant parameter)
- weights are additionally corrected for EM pileup

Unfolding procedure

List of variables to unfold

1M1T Signal (Fiducial) Region:

- muon pT
- track pT
- (muon+track) invariant mass
- (muon+track) pT
- (muon+track) acoplanarity
- (muon-track) dη
- (muon+track) η

1M3T Signal (Fiducial) Region:

- muon pT
- 3-tracks pT
- (muon+3tracks) invariant mass
- (muon+3tracks) pT
- (muon+3tracks) acoplanarity
- (muon-3tracks) dη
- (muon+3tracks) η

1M1E Signal (Fiducial) Region:

- muon pT
- electron pT
- (muon+electron) invariant mass
- (muon+electron) pT
- (muon+electron) acoplanarity
- (muon-electron) dη
- (muon+electron) η

Unfolding procedure

- remove detector effects (resolution, smearing etc.) from the observed data
- determination of particle-level differential cross sections

We use Iterative Bayesian Unfolding (IBU) as the unfolding method

- formulate migration matrix using cause (C) and effect (E):

$$\begin{matrix} S_i = \sum_j R_{ij} T_j \\ U_i = \sum_j \left(R^{-1}\right)_{ij} D_j \end{matrix} \rightarrow \begin{matrix} S_i = \sum_j P\left(E_i|C_j\right) T_j \\ U_i = \sum_j P\left(C_i|E_j\right) D_j \end{matrix}$$

i,j - bin indices, **S** - signal reco, **T** - signal truth, **D** - data, **U** - unfolded distributions, **R** - migration matrix

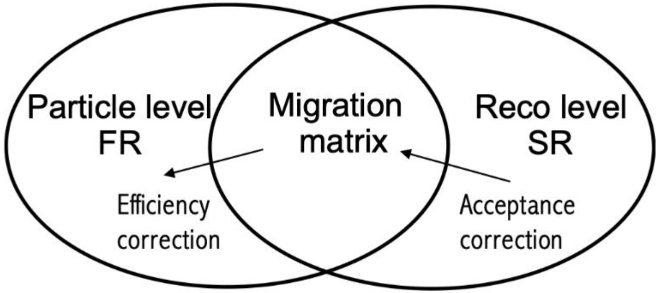
- **$P(C_i|E_j)$** - unknown, determined using Bayes theorem:

$$P\left(C_i|E_j\right) = \frac{P\left(E_j|C_i\right) \Pr\left(C_i\right)}{\sum_k P\left(E_j|C_k\right) \Pr\left(C_k\right)}$$

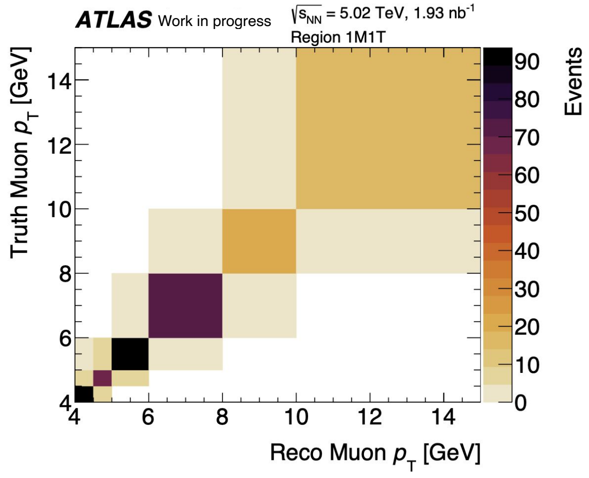
Pr() - prior, initial prior = MC truth distribution, iterated priors = unfolding result from previous unfolding iteration

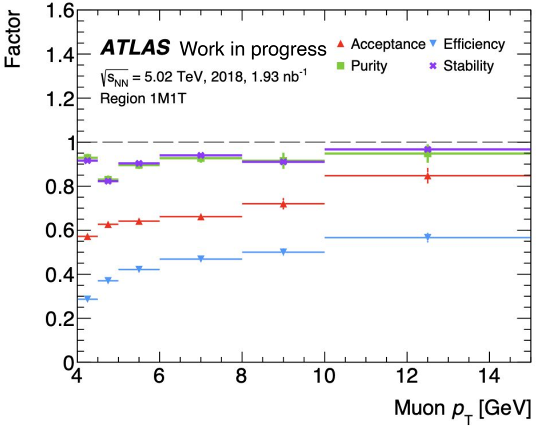
Unfolding procedure
Response Matrices

- Response matrices are defined in the intersection region of the signal region and fiducial region
- **efficiency** - fraction of truth-level events that satisfy the detector and reconstruction criteria and are successfully reconstructed
- **acceptance** - fraction of reconstructed events that originate from the targeted fiducial phase space



- **purity** - how cleanly a reconstructed bin corresponds to its associated truth-level bin
- **stability** - how stable the mapping is from a truth-level bin to its corresponding reconstructed bin





Truth level fits

Fit methodology: Poisson based likelihood model

- used statistical procedure is different from the “standard” methods in ATLAS

Standard ATLAS likelihood model

$$\mathcal{L}\left(\vec{\mu};\vec{b}\right) = \prod_{i=1}^{N_{\text{bins}}} \frac{f_i\left(\vec{\mu};\vec{b}\right)^{n_i} e^{-f_i\left(\vec{\mu};\vec{b}\right)}}{n_i!} \prod_{j=1}^{N_{\text{syst}}} e^{-\frac{b_j^2}{2}}$$

- where n_i - observed data, f_i(μ;b) - prediction depending on a set of parameters of interest (POI's) and nuisance parameters
- second product: penalty terms for each nuisance parameter (Gaussians with means of 0 and errors of 1)
- maximize this likelihood with respect to μ and b

- This model assumes that the measurements are statistically uncorrelated.
- However, in the case of the fiducial cross section measurements, **they are correlated**
- modelling the measurements with Poisson probabilities is not appropriate → **use Gaussian probabilities**

Truth level fits

Fit methodology: Gaussian based likelihood model

- inspired by ATLAS global PDF fit and HERA PDF fits

Alternative likelihood model

$$\mathcal{L}\left(\vec{\mu};\vec{b}\right) = \exp\left[-\frac{1}{2}\sum_{i,k=1}^{N_{\text{bins}}}\left(n_i - f_i\left(\vec{\mu};\vec{b}\right)\right)\left(V^{-1}\right)_{ik}\left(n_k - f_k\left(\vec{\mu};\vec{b}\right)\right)\right]\prod_{j=1}^{N_{\text{syst}}} e^{-\frac{b_j^2}{2}}$$

- V is the covariance matrix between the measured data points
- The diagonal entries of V correspond to the quadratic sums of statistical uncertainties in data, signal MC and backgrounds.
- **Systematic uncertainties are allowed to be correlated between bins (also among different observables) by assuming that they are proportional to the prediction:**

$$f_i\left(\vec{\mu};\vec{b}\right) \equiv f_i\left(\vec{\mu}\right)\left(1 - \sum_{j=1}^{N_{\text{syst}}}\gamma_{ij}b_j\right)$$

- f_i(μ;b) - nominal prediction, γ_{ij} - systematic uncertainty due a source j in ith bin.
- maximize this likelihood with respect to μ and b
- -2lnL now corresponds to a chi2 definition