Constraints on dark matter models using a fast simulation of the ATLAS detector

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ATLAS EXPERIMENT

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Introduction

Motivation

- Astronomical observations reveal the existence of *dark matter*
- The nature of dark matter is not explained by our current knowledge of physics

Detection methods

- Astronomical observations, ie: galaxy rotational curves, velocity dispersion, gravitational lensing
- Direct detection, ie: dark matter – nuclei scattering
- Indirect detection, ie: products of dark matter decay/annihilation
- Production of dark matter, ie: dark matter as a product from particle collisions

Interested in *production* of dark matter at the LHC

LHC and ATLAS

LHC

- *pp* beam collisions
- Most recent results from Run II (2015-2018) at 13 TeV
- Collection of 140 fb^{-1} of data so far
- Run III to operate from 2021-2024 at 13-14 TeV

ATLAS

- Cylindrical detector with nearly 4π coverage
- Searching for dark matter particle, no evidence yet
- Use data collected to *exclude dark matter models*
- *Missing transverse momentum* is usually the main discriminant variable

Two Higgs doublet model + pseudoscalar

Mono-Z signature: large E_T^{miss} **and Z boson**

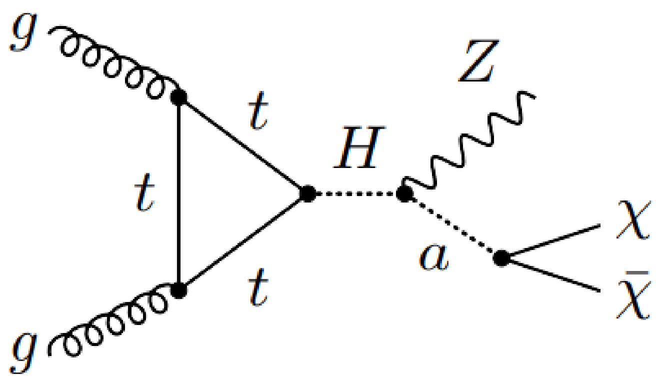
$p + p \rightarrow Z(\rightarrow l^+ l^-) + \chi\bar{\chi}$

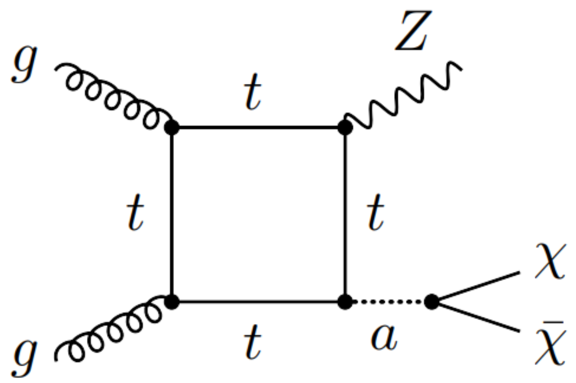
Z decays to two same-flavour leptons (e^+e^- *or* $\mu^+\mu^-$)

Discriminant variable is $m_T(ZZ)$

$$m_{T_{ZZ}}^2 = \left(\sqrt{m_Z^2 + |\vec{p}_T^{\,\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{E\!\!/}_T|^2}\right)^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E\!\!/}_T\right|^2$$

gg and bb-induced production, here showing two gg-induced leading order diagrams





5 free parameters:

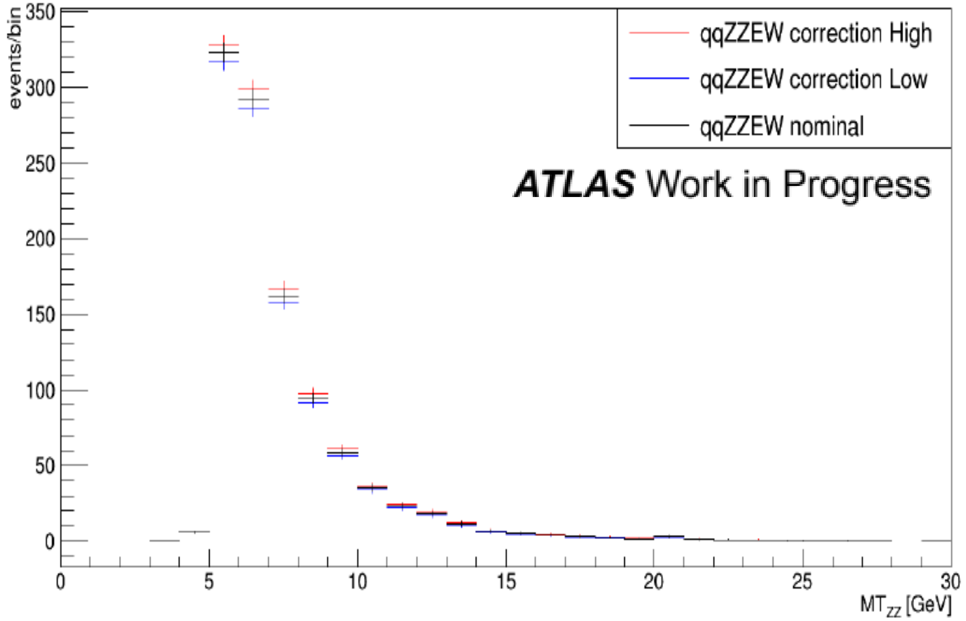
- $m_A = m_H = m_{H\pm}$ → Mass of $A, H, H^{\pm}$
- m_a → Mass of pseudoscalar *a*
- sinθ → Mixing angle between *A, a*
- tanβ → Ratio of VEVs of Higgs doublets
- m_χ → Dark matter mass

Background distributions and systematics

SM background processes

- Most dominant include *ZZ*, *WZ*, *Z*+jets, Non-resonant (ex: WW, Wt, $t\bar{t}$)
- Selection cuts are made to reduce background as much as possible while maximizing signal
- Distributions obtained from full ATLAS analysis

Background	Percent contribution	Estimation procedure
ZZ	59%	Simulation
WZ	25%	Simulation and data
Z + jets	8%	Data
Non-resonant	8%	Simulation and data
$ttV(V)$, VVV	<1%	Simulation



Systematics classified as either **theoretical** or **experimental**

- Affect yields and shape of discriminant variable distributions
- Theoretical – ie: QCD scale, PDF, parton showering
- Experimental – ie: detector reconstruction uncertainties
- Over 100 systematics considered in full analysis

Signal event generation

Want to reproduce parameter limit scans of DM models using
fast simulation software of ATLAS detector response and *simplified systematics*

Signal events with a $\boldsymbol{Z(\ell^+\ell^-) + \chi\bar{\chi}}$ **final state**, with fixed parameters
$m_H = m_A = 600$ GeV, $m_a = 200$ GeV, tan$\beta = 0.1, m_\chi = 10$ GeV

- **MadGraph** - hard scattering events
- **Pythia** - hadronization and parton showering
- **Delphes** - fast simulation of ATLAS detector response

$\sin\theta$	σ (fb)
0.1	1.0002 ± 0.0006
0.2	3.7410 ± 0.0060
0.3	7.5824 ± 0.0044
0.4	11.881 ± 0.021
0.5	16.062 ± 0.021
0.6	19.883 ± 0.019
0.7	23.159 ± 0.025
0.9	28.142 ± 0.024

Delphes default parameter card used with few changes:

- $\boldsymbol{E_T^{miss}}$ **calculation altered to be object-based**
- Other kinematic differences:
  - Min Jet p_T changed from 20 GeV to 30 GeV
  - Jet size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ changed from 0.6 to 0.4
    - where $\Delta\phi$ is the azimuthal separation, and $\Delta\eta$ is the pseudorapidity separation

Resulting events used as input for analysis step

- Apply object and event selection
- Compare kinematic distributions with those obtained using full detector simulation

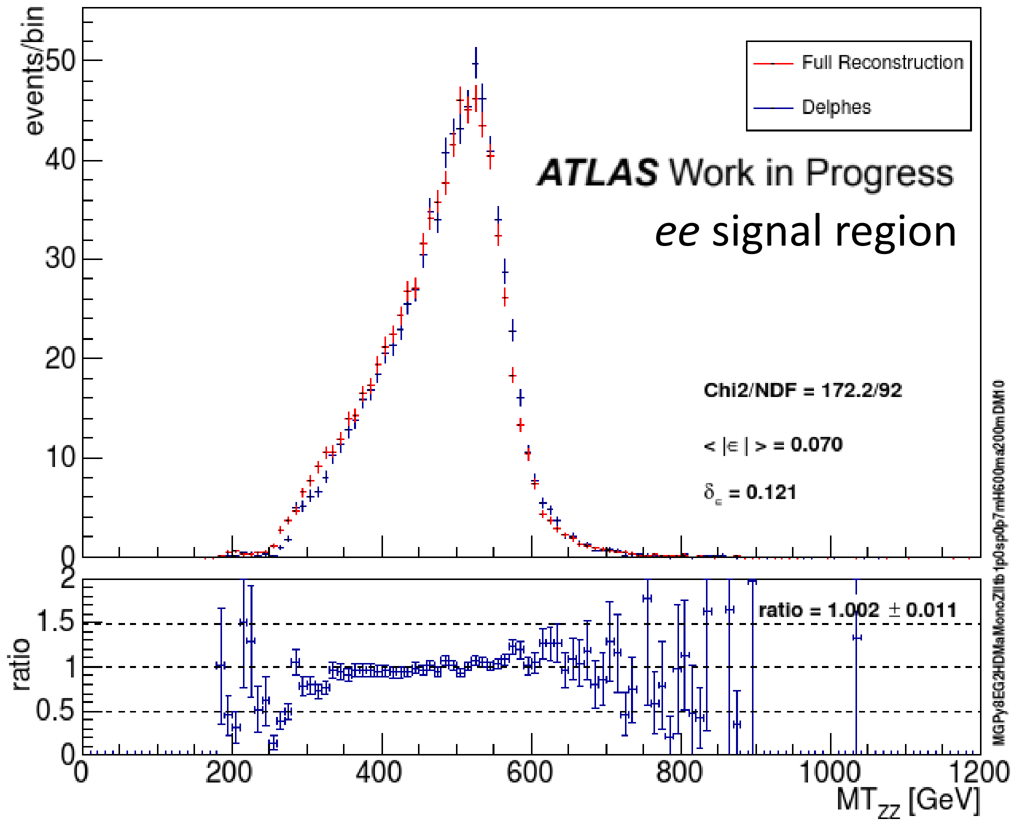
Signal event selection

Selection criteria	Background Reduced
Opposite-sign leptons, leading (subleading) $p_T > 30$ (20) GeV	–
Third lepton veto	WZ
$\lvert\eta_e\rvert < 2.47$, $\lvert\eta_\mu\rvert < 2.50$	–
$76 < m_{ll} < 106$ GeV	Non-resonant
$E_T^{\text{miss}} > 90$ GeV	Z+jets
$\Delta R_{ll} < 1.8$	Z+jets, Non-resonant
$\not{E}_T/\sqrt{H_T} > c$	Z+jets

E_T^{miss} Significance substitution

- Delphes 3 does not have object-based E_T^{miss} significance defined
  - $E_T^{miss}/\sqrt{H_T}$ used as a substitute
- Cut value *c* obtained for each sample

Delphes distribution agreement with ATLAS



$m_T(ZZ)$ overlay

Example signal kinematic distribution using Delphes compared to full reconstruction

Delphes distributions agree well with ATLAS distributions in **shape**

Delphes distributions normalization

- Muon acceptance agrees well with ATLAS
- Electron acceptance does not – **much lower**
- Rescaling using ATLAS normalization required

Muon scaling factor found to be 1.026

Electron scaling factor found to be 1.697

Statistical treatment

Upper limit on signal strength μ can be calculated using *frequentist profile likelihood method* based on CLs statistic:

$$\mathrm{CL}_s = \frac{\mathrm{CL}_{s+b}}{\mathrm{CL}_b} = \frac{p_{s+b}}{1 - p_b}$$

where p_{s+b} is the p-value for the signal+background hypothesis, and p_b is that for the background-only hypothesis

Upper limit μ_{up} is the value of μ that gives CL_s value of CL_s = 0.05, which corresponds to **95% CL**

μ_{up} is calculated for each value of sinθ

- these upper limits are collectively used to make limit scans to *exclude regions of parameter space*

Reducing systematics

Want to create *sinθ limit scan* for sinθ = 0.1 – 0.9

Systematic uncertainties are included as nuisance parameters in the fit

Want to assess the use of Delphes along with reduced systematics

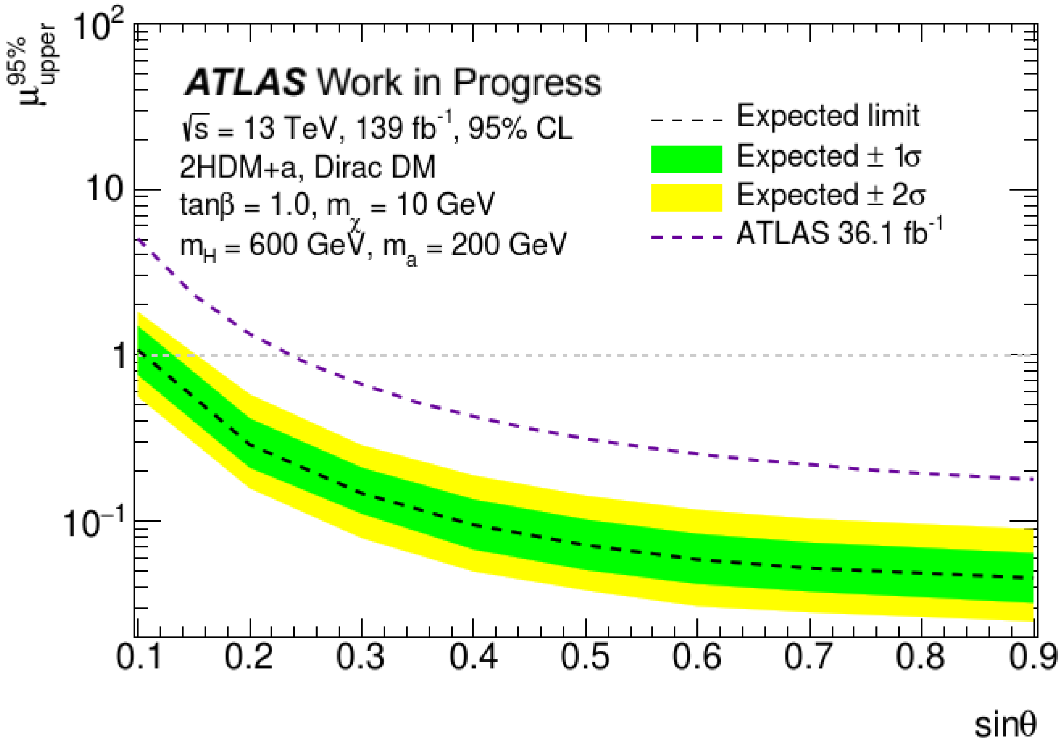
- **Over 100** systematics in full analysis – only want to consider the most important
- 10% signal systematic included from uncertainties on acceptance

Consider two cases of reduced systematics

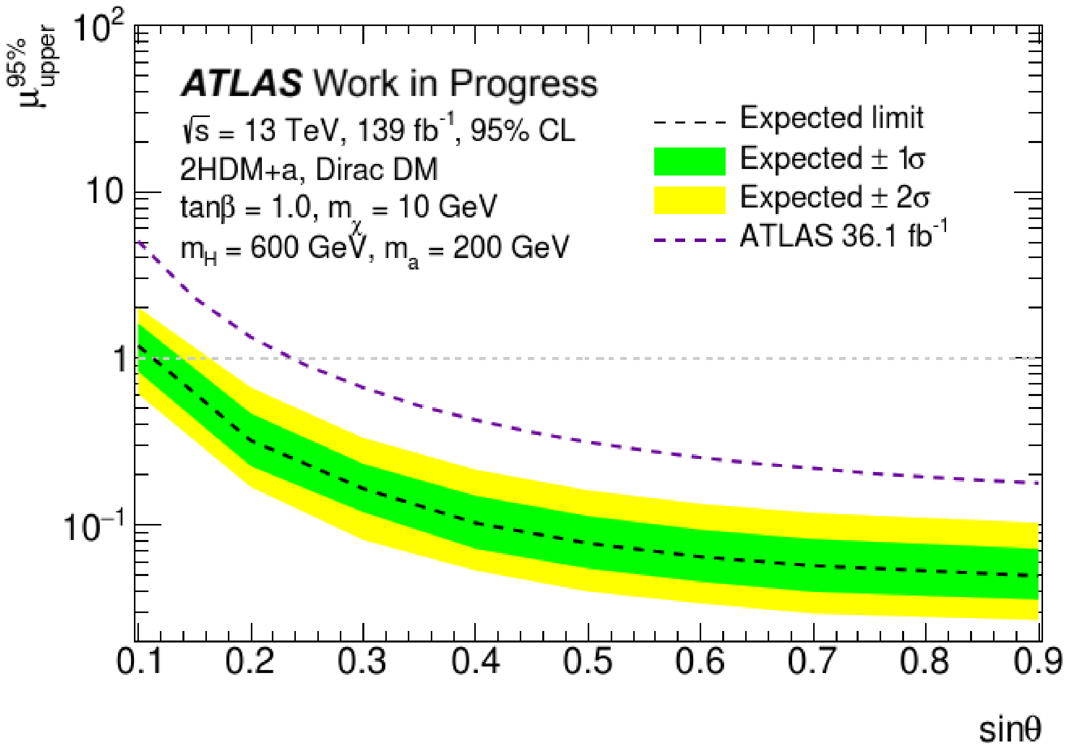
- First case – **top 14** systematics along with uncertainty in luminosity
- Second case – **top 8** systematics along with uncertainty in luminosity

Differences between Delphes and ATLAS distributions are included as uncertainty

sinθ limit scan for 2HDMa



Delphes signal, reduced systematics case 1



Full ATLAS simulation

Conclusion

Looking for dark matter at the LHC

- Dark matter particle not found yet
- Set limits on 2HDMa dark matter model parameters

Explore effects of analysis simplifications

- Simplified detector simulation – **MadGraph + Pythia + Delphes**
- Simplified systematic treatment – only top systematics considered
- Find very similar result as full analysis

Thank you!

Backup

$E_T^{miss} / \sqrt{H_T}$ cut values

$\sin\theta$	$\not{E}_T/\sqrt{H_T}$ Cut	Eff % (D, ee)	Eff % (D, $\mu\mu$)	Eff % (A, ee)	Eff % (A, $\mu\mu$)
0.35*	9.15	0.838 ± 0.009	0.833 ± 0.007	0.835 ± 0.003	0.833 ± 0.003
0.7**	9.10	0.842 ± 0.008	0.826 ± 0.007	0.836 ± 0.002	0.831 ± 0.002
0.1	9.35	0.833 ± 0.009	0.823 ± 0.007	0.839 ± 0.003	0.832 ± 0.003
0.2	9.00	0.831 ± 0.009	0.839 ± 0.007	0.838 ± 0.003	0.832 ± 0.003
0.3	9.02	0.842 ± 0.009	0.830 ± 0.007	0.838 ± 0.003	0.832 ± 0.003
0.4	9.27	0.832 ± 0.009	0.838 ± 0.007	0.838 ± 0.002	0.832 ± 0.002
0.5	9.20	0.839 ± 0.008	0.831 ± 0.007	0.837 ± 0.002	0.831 ± 0.002
0.6	9.20	0.836 ± 0.009	0.833 ± 0.007	0.837 ± 0.002	0.831 ± 0.002
0.9	9.20	0.844 ± 0.009	0.821 ± 0.007	0.835 ± 0.003	0.831 ± 0.003

Acceptances

$\sin\theta$	ϵ	a (A, ee)	a (A, $\mu\mu$)	a (D, ee)	a (D, $\mu\mu$)	r_{ee}	$r_{\mu\mu}$
0.35*	0.9900	0.2503 ± 0.0052	0.2532 ± 0.0053	0.1454 ± 0.0023	0.2582 ± 0.0029	1.737 ± 0.045	0.9828 ± 0.0233
0.7**	0.9897	0.2509 ± 0.0072	0.2529 ± 0.0073	0.1496 ± 0.0011	0.2463 ± 0.0014	1.677 ± 0.050	1.027 ± 0.029
0.1	-	0.2534 ± 0.0025	0.2544 ± 0.0025	0.1503 ± 0.0030	0.2362 ± 0.0036	1.685 ± 0.038	1.077 ± 0.020
0.2	-	0.2534 ± 0.0025	0.2544 ± 0.0025	0.1503 ± 0.0011	0.2512 ± 0.0014	1.685 ± 0.021	1.012 ± 0.011
0.3	-	0.2534 ± 0.0025	0.2544 ± 0.0025	0.1528 ± 0.0017	0.2490 ± 0.0021	1.659 ± 0.025	1.022 ± 0.013
0.4	-	0.2534 ± 0.0025	0.2544 ± 0.0025	0.1493 ± 0.0011	0.2461 ± 0.0014	1.692 ± 0.021	1.031 ± 0.012
0.5	-	0.2534 ± 0.0025	0.2544 ± 0.0025	0.1477 ± 0.0021	0.2462 ± 0.0014	1.707 ± 0.030	1.030 ± 0.012
0.6	-	0.2534 ± 0.0025	0.2544 ± 0.0025	0.1468 ± 0.0022	0.2445 ± 0.0014	1.712 ± 0.031	1.035 ± 0.012
0.7	-	0.2534 ± 0.0025	0.2544 ± 0.0025	0.1496 ± 0.0011	0.2463 ± 0.0014	1.694 ± 0.021	1.033 ± 0.012
0.9	-	0.2534 ± 0.0025	0.2544 ± 0.0025	0.1451 ± 0.0020	0.2492 ± 0.0025	1.725 ± 0.029	1.013 ± 0.014

Validation

For two independent histograms, one with bin content a_j and error σ_{aj} and the other with bin content b_j and error σ_{bj} for bin j, the average of the relative difference between the two is

$$\langle\epsilon\rangle = \frac{\sum_j \frac{\epsilon_j}{\sigma_{\epsilon j}^2}}{\sum_j \frac{1}{\sigma_{\epsilon j}^2}},$$

where $\epsilon_j = \frac{b_j - a_j}{s_j}$, and

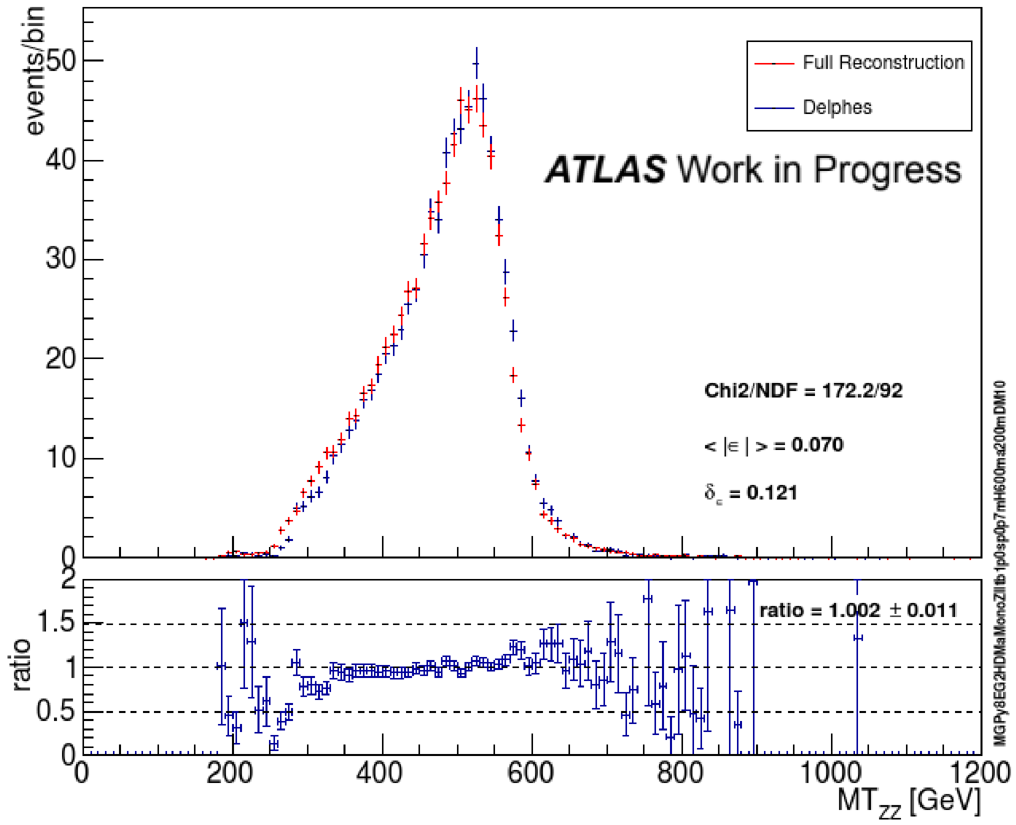
$$s_j = \frac{\frac{a_j}{\sigma_{aj}^2} + \frac{b_j}{\sigma_{bj}^2}}{\frac{1}{\sigma_{aj}^2} + \frac{1}{\sigma_{bj}^2}}$$

is the MLE of the true bin content. The average of the absolute of the relative difference and the square of the rms of the relative difference are then given by

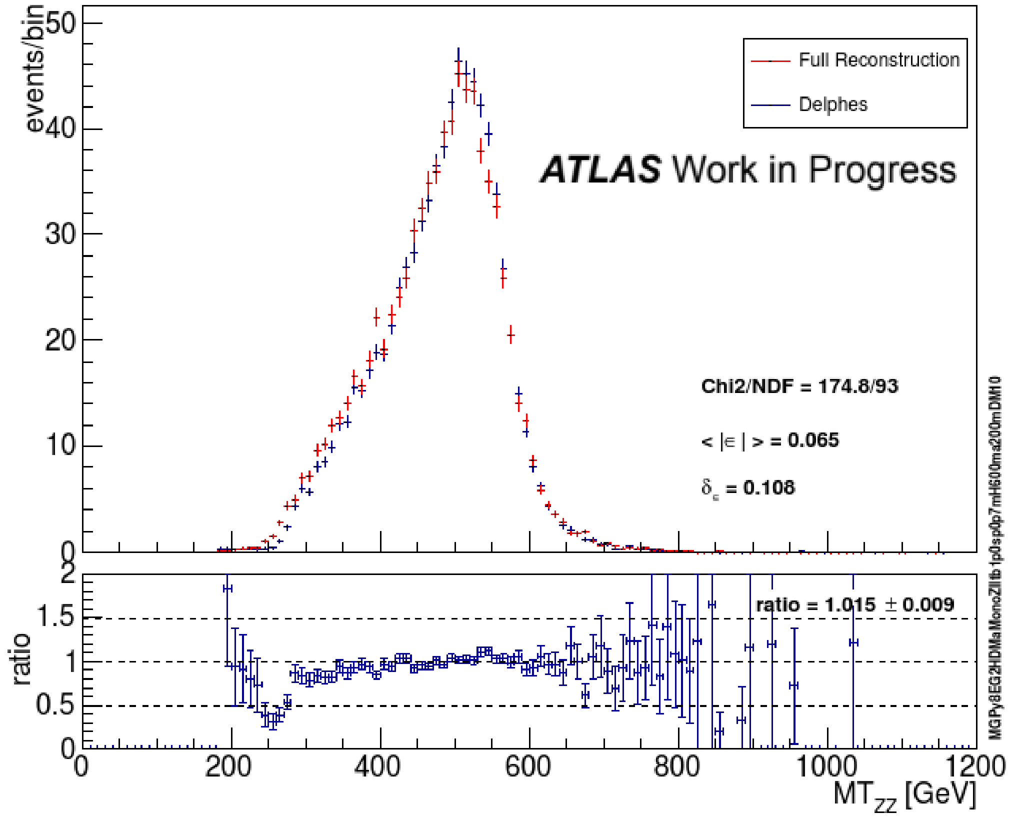
$$\langle|\epsilon|\rangle = \frac{\sum_j \frac{|\epsilon_j|}{\sigma_{\epsilon j}^2}}{\sum_j \frac{1}{\sigma_{\epsilon j}^2}}$$

$$\delta_\epsilon^2 = \langle\epsilon^2\rangle = \frac{\sum_j \frac{\epsilon j^2}{\sigma_{\epsilon j}^2}}{\sum_j \frac{1}{\sigma_{\epsilon j}^2}}$$

$m_T(ZZ)$

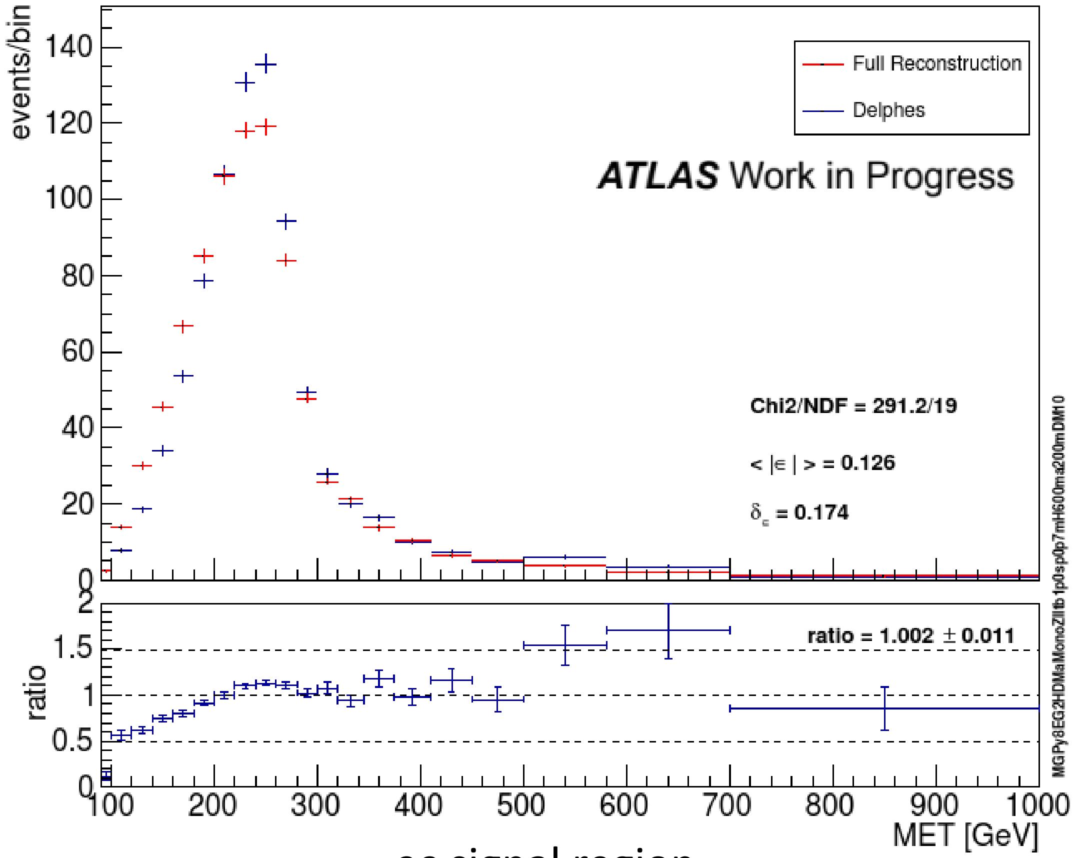


ee signal region

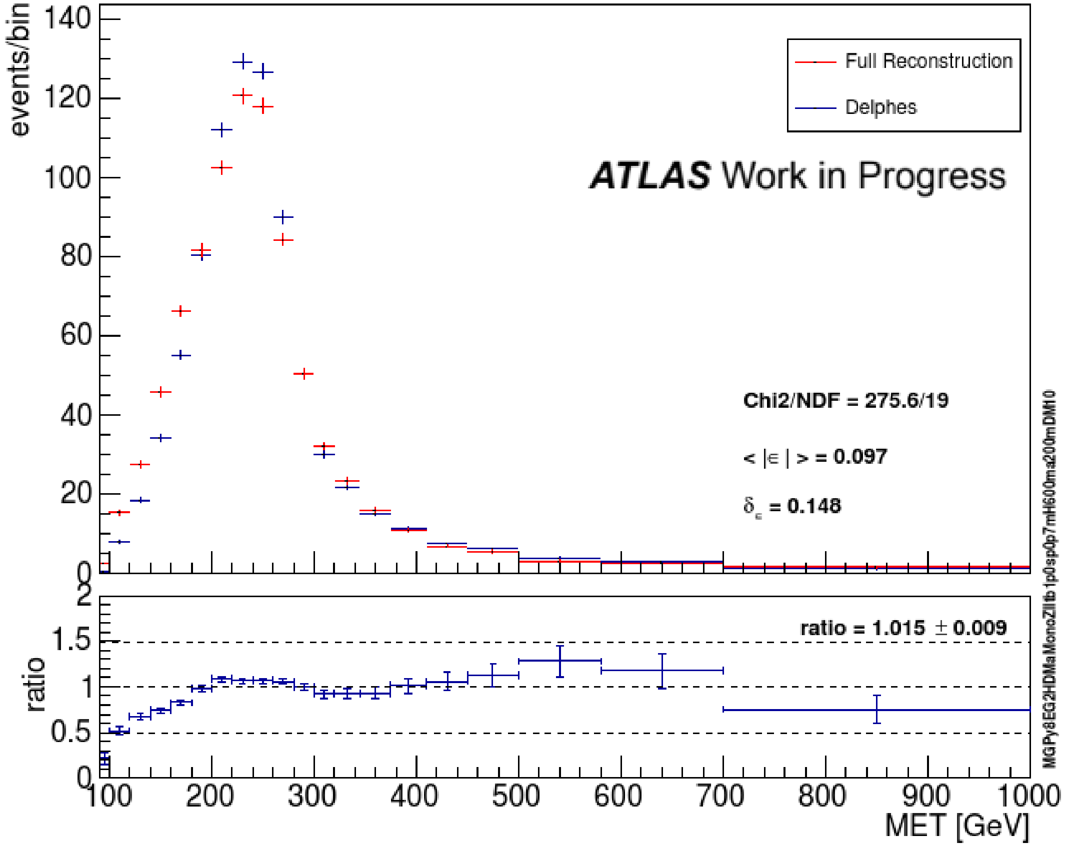


$\mu\mu$ signal region

E_T^{miss}

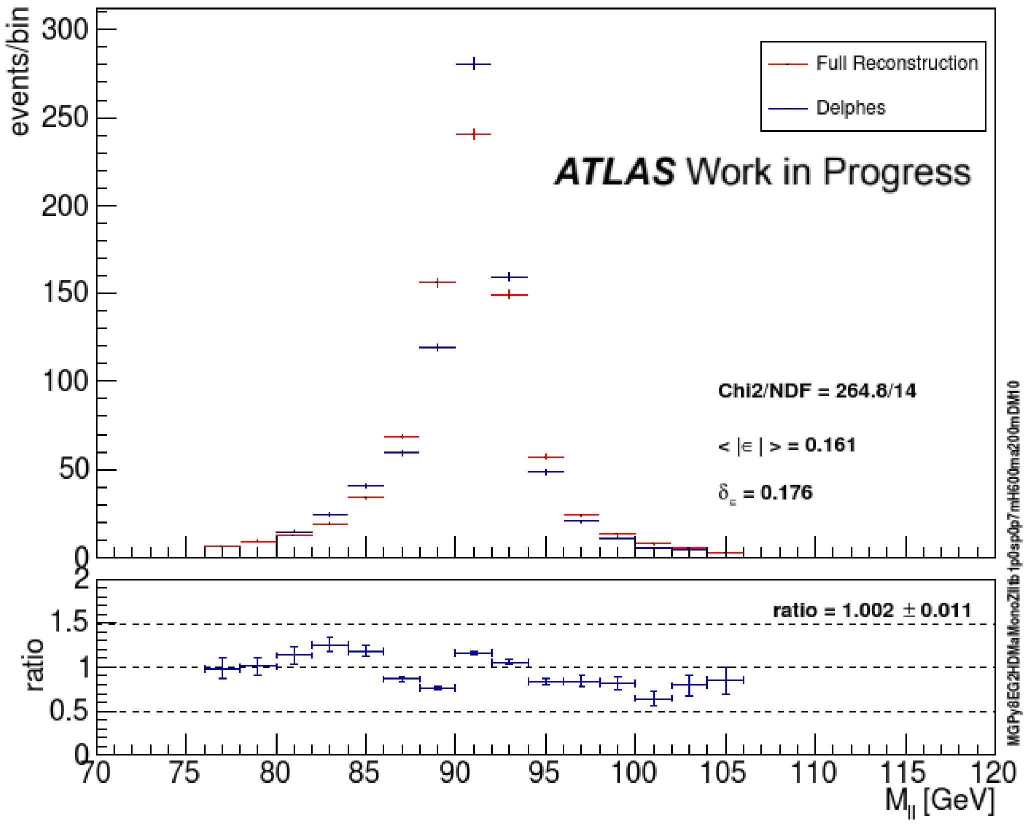


ee signal region

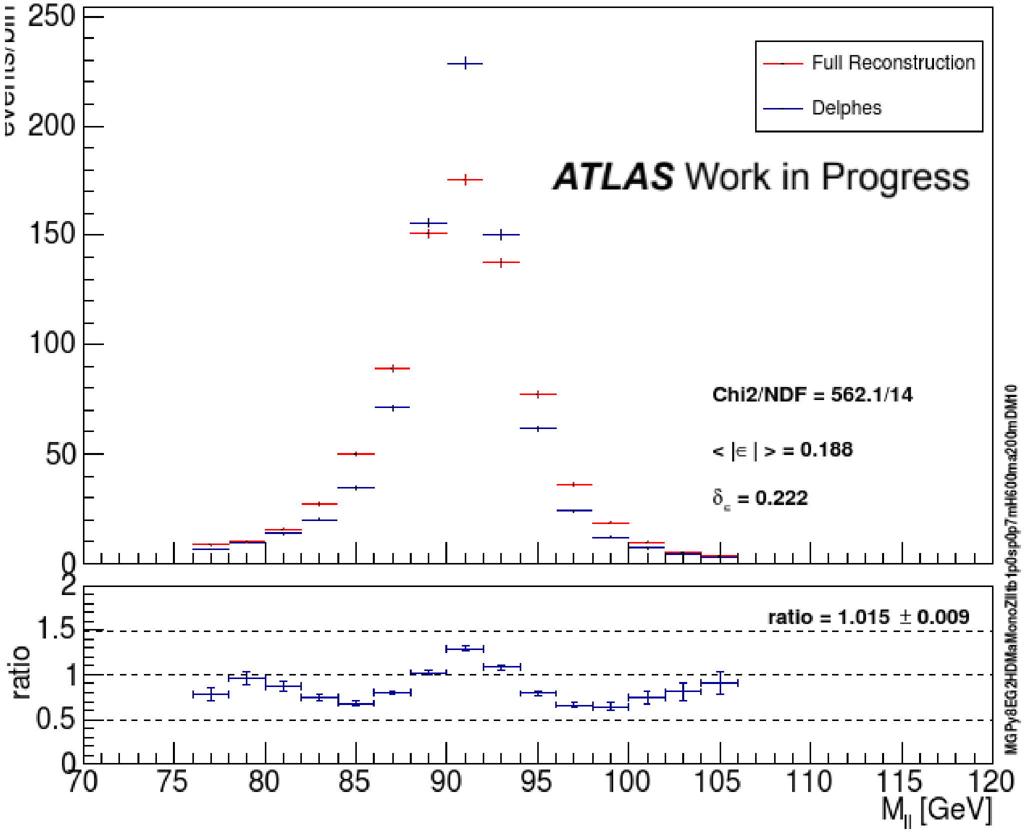


$\mu\mu$ signal region

$M_{\ell\ell}$



ee signal region



$\mu\mu$ signal region

Statistical treatment for limit setting

Frequentist profile likelihood test – based around profile likelihood ratio

- Consider expected number of events given by $\nu_j = \mu s_j + b_j$, then the likelihood is given by

$$L(\mu, \boldsymbol{\theta}) = \prod_{j}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \times \prod_{k}^{M} G(\theta_{j,k})$$

- The profile likelihood ratio is then given by

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

Discovery statistics

$$q_0 = \begin{cases} -2\ln\lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

$$p_0 = \int_{q_{0,\text{obs}}}^{\infty} f(q_0|0) dq_0$$

$$Z = \Phi^{-1}(1 - p)$$

Statistical treatment for limit setting

Statistics for limit setting

- If no excess signal is found, can set upper limit on signal strength using CLs method

$$\tilde{q}_\mu = \begin{cases} -2\ln\frac{L(\mu,\hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(0,\hat{\hat{\boldsymbol{\theta}}}(0)} & \hat{\mu} < 0 \\ -2\ln\frac{L(\mu,\hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu},\hat{\boldsymbol{\theta}})} & 0 \leq \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

$$p_\mu = \int_{\tilde{q}_{\mu,\mathrm{obs}}}^{\infty} f(\tilde{q}_\mu|\mu)\,d\tilde{q}_\mu$$

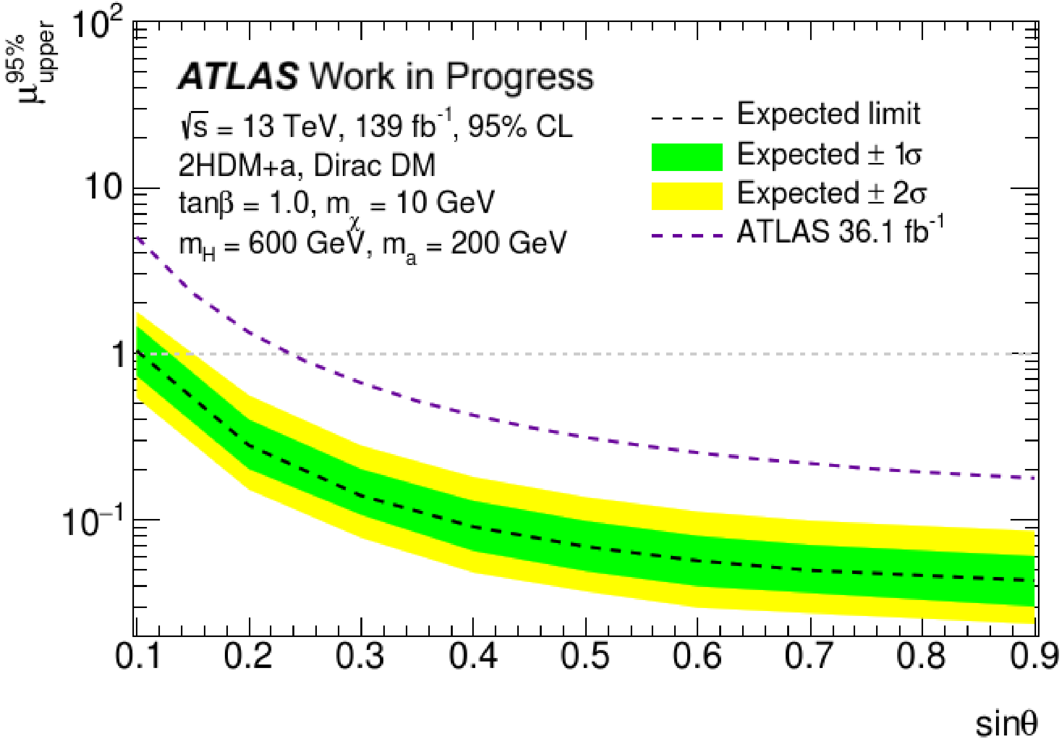
$$\mathrm{CL}_s = \frac{\mathrm{CL}_{s+b}}{\mathrm{CL}_b} = \frac{p_{s+b}}{1-p_b}$$

where

$$p_{s+b} = \int_{\tilde{q}_{\mu,\mathrm{obs}}}^{\infty} f(\tilde{q}_\mu|\mu=1)\,d\tilde{q}_\mu \qquad p_b = \int_{\tilde{q}_{\mu,\mathrm{obs}}}^{\infty} f(\tilde{q}_\mu|\mu=0)\,d\tilde{q}_\mu$$

Reduced systematics

		Background	Systematic
1	2		
x	x	SignalTh	10%
x	x	DelphesTh	Asymmetric
x	x	$qqZZ$	qqZZEWcorr
x		$qqZZ$	qqZZQCDscale
x		$qqZZ$	qqZZPSCKKW
x		$qqZZ$	lumi
x	x	$ggZZ$	ggZZQCDscale
x		$ggZZ$	lumi
x	x	Electroweak ZZ	EWKZZPDF
x		Electroweak ZZ	lumi
x	x	WZ	var_th_QCD
x		WZ	var_th_MUR1_MUF1_PDF
x		WZ	lumi
x	x	Z+jets	photonZjetsExpSys
x		Z+jets	photonZjetsMisModellingSys
x		Z+jets	photonZjetsStatSys
x		Z+jets	photonZjetsTheorySys
x		Z+jets	lumi
x	x	Non-resonant	ttbarQCD
x		Non-resonant	lumi
x	x	ttV	QCD
x		ttV	lumi
x	x	VVV	QCD
x		VVV	lumi



Delphes signal, reduced systematics case 2