Search for Dark Matter with leptonically-decaying Z Bosons and Missing Transverse Energy in the ATLAS Detector at the LHC

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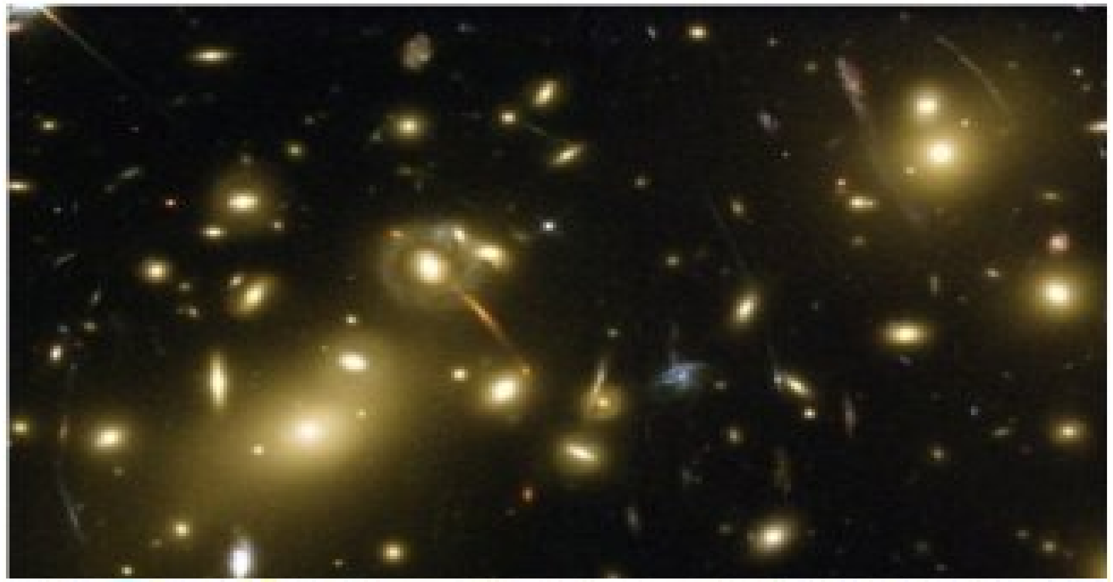
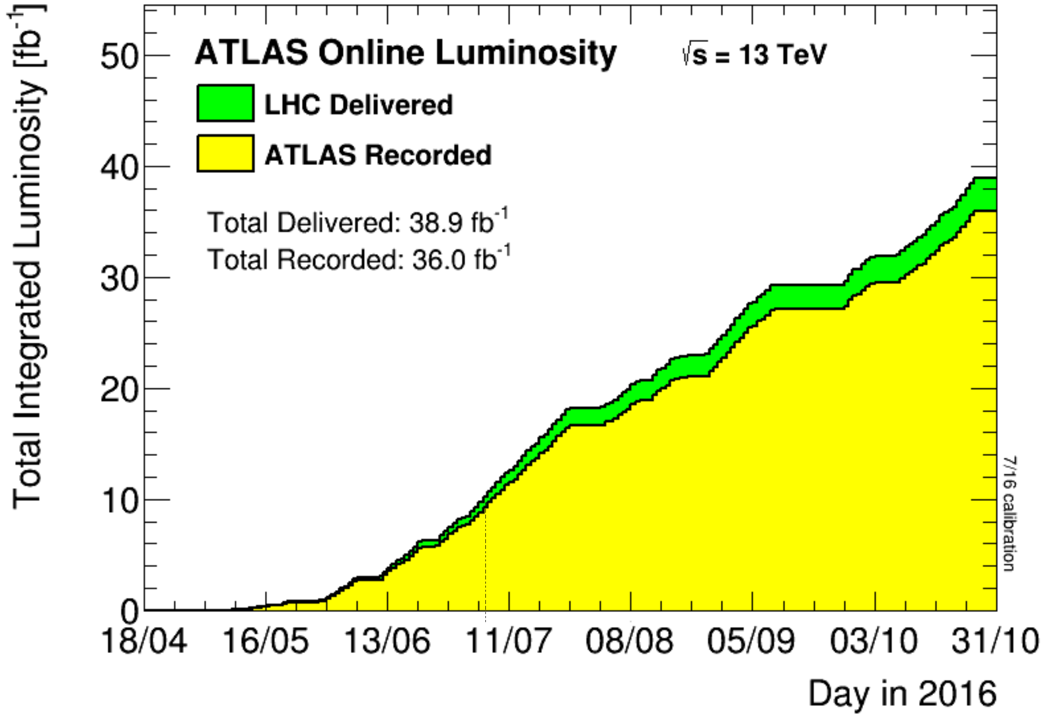
Big picture motivation

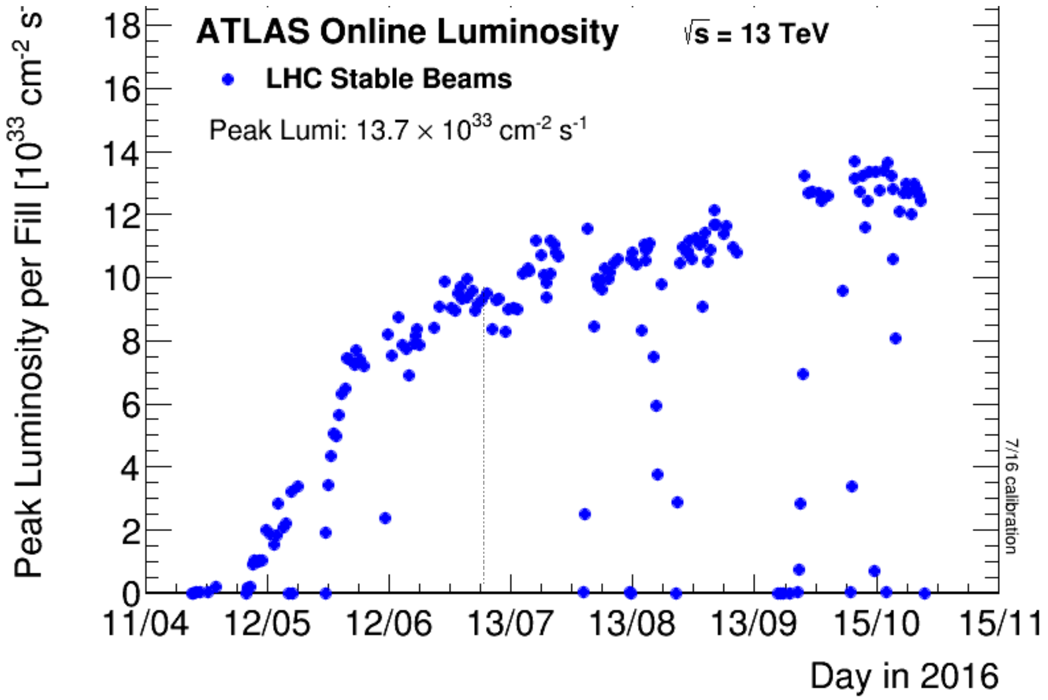
- Dark Matter: Unsolved problem
  - No Standard Model theory can explain it
  - Something beyond this theory clearly exists
- Astrophysical indicators
  - Cosmic Microwave Background
  - Gravitational lensing
  - Galaxy clusters
  - Galactic star motion
- How do we detect it?
  - Emission from galactic sources
  - Direct nuclear recoil underground
  - **Particle production in colliders**



ATLAS and the LHC in Run-2

- First time operating the LHC and collecting data at a centre-of-mass energy of 13 TeV
- A milestone peak luminosity of 1.37×10^{34} cm^{-2} s^{-1} reached
- Dataset from 2015: 3.21 fb^{-1} gathered and analyzed
- Dataset from 2016: 10.1 fb^{-1} gathered and analyzed (up to and including July 10th), > 36 fb^{-1} gathered in total!
- The ATLAS detector operated at better than 90% efficiency, and the LHC operation exceeded expectations!

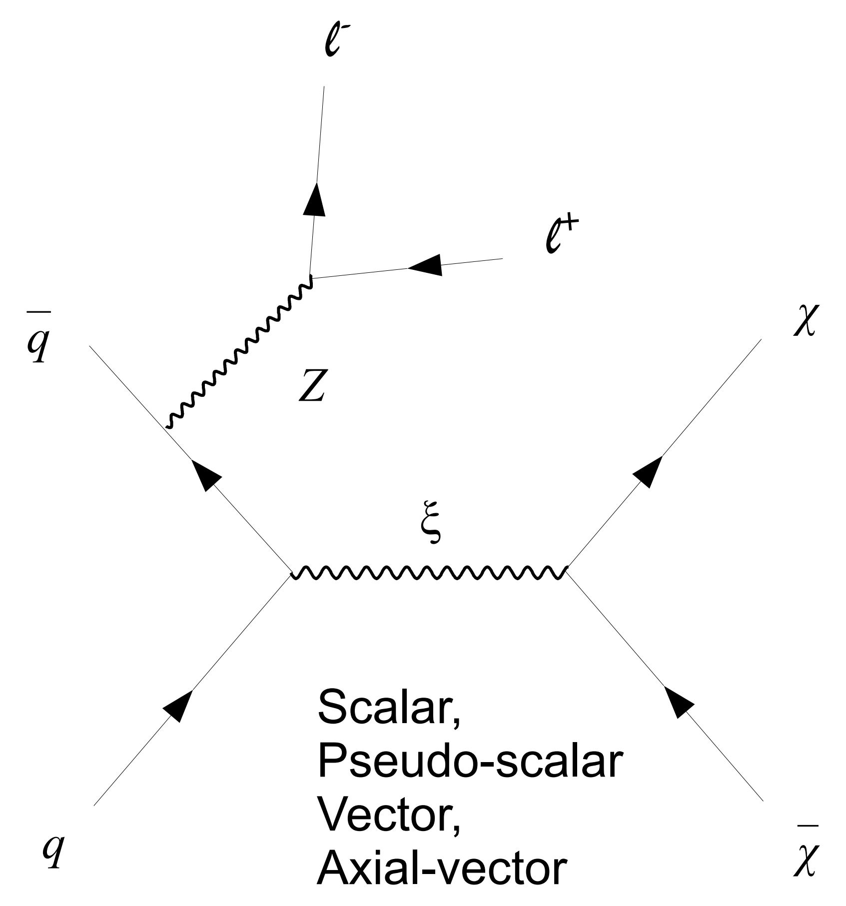




Searches for Mono-Z signature of dark matter

Z → ll, Dark Matter → invisible

- Dark matter particles produced along with a Z boson decaying to charged leptons
- Final states have other interpretations that include a higgs boson
- Models known as 'simplified models' are being considered to account for a possible mediator (ξ) whose mass may be near or above the momentum transfer.
- Dark matter models chosen by an expert team of experimentalists and theorists called the Dark Matter Forum are used to generate and reconstruct events with ATLAS simulation software.

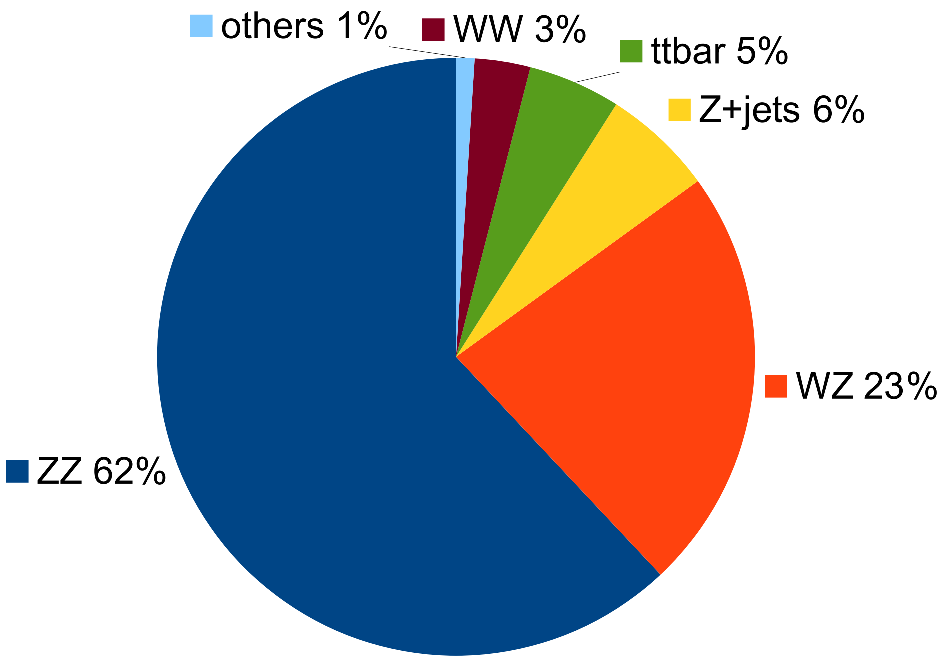


Strategy: search "missing energy" (MET) distributions for an excess; otherwise set limits on dark matter models defined by parameters m_ξ and m_χ

Experimental Considerations

Measuring leptons and MET

- Passing detector requirements
- Inside detector's central rapidity region, and minimum transverse momentum of 20 GeV
- Well reconstructed (object quality)
- Separated and isolated from other reconstructed quantities



Backgrounds

Distribution shape and yields are simulated with Monte Carlo techniques, and where possible, actual yields are determined experimentally

- Largest background is the indistinguishable but well-known and measured Standard Model process:

ZZ: $Z \rightarrow ll$, $Z \rightarrow$ invisible

- Next largest background is a process that is estimated through an independent control region (3 lepton)

WZ: $Z \rightarrow ll$, $W \rightarrow l$ + invisible

- The Z+jets, ttbar, and WW backgrounds are estimated through control regions (ABCD and eμ)

Z+jets: $Z \rightarrow ll$, jets mismeasured
ttbar: $tt \rightarrow l\,l$ + jets + invisible
WW: $WW \rightarrow l\,l$ + invisible

- Others are estimated with Monte Carlo simulations

Event selection – finding a 'Mono-Z' event

- Leptons' momentum (p_T) > 30(20) GeV
- Two same-flavour leptons (makes 2 analyses)
- Veto events with 3rd lepton
- Two leptons have opposite charge
- Within +/- 15 GeV of the Z mass (91 GeV)
- Veto events with *b*-jets of $p_T \geq 25$ GeV

Selections are physically motivated to reduce backgrounds and have high quality leptons and minimize background

Mono-Z Specific Cuts

- Missing energy (MET) > 90 GeV
- Angle between the leptons < 1.8 rad
- Angle between leptons' p_T and MET > 2.7 rad
- Fraction between leptons' p_T & MET+jets < 20%
- Angle between jets and MET > 0.7 rad
- Balance between leptons' p_T and m_T < 0.9 rad

Selections are motivated by high signal efficiency and purity, with large background rejection

(optimized for signal significance)

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Mathematical tools to measure success

ATLAS EXPERIMENT

- Significance (S) of a signal is often approximated as the number of signal events (s) over the root of the number of background events (b):

$$S = \frac{s}{\sqrt{b}}$$

  This is an approximation for when b >> s. The full formula for significance[‡] is used in this investigation:

$$S = \sqrt{2\left(\left(s+b\right)\ln\left(1+\frac{s}{b}\right)-s\right)}$$

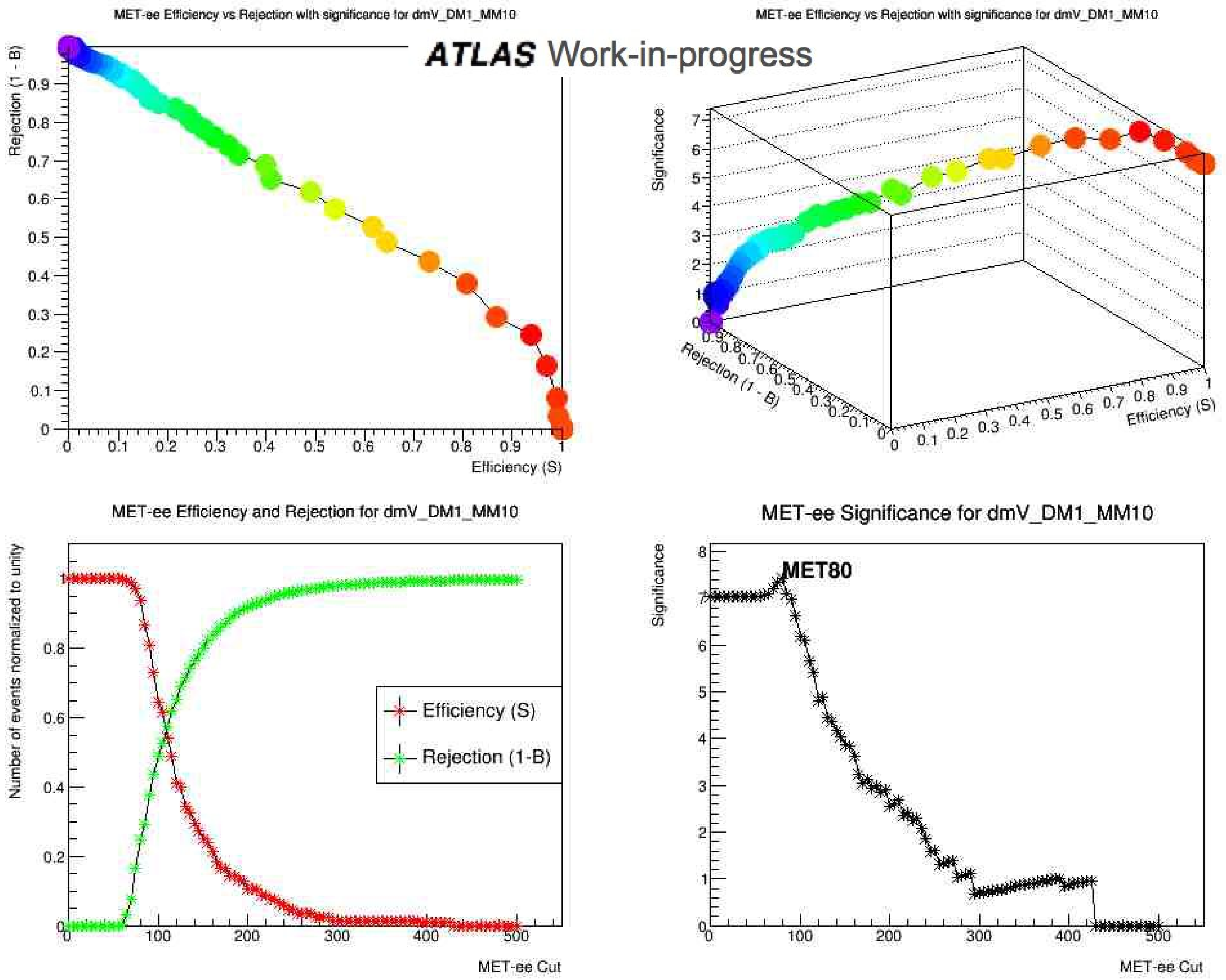
- Purity is the fraction of signal events out of the total number of events.
- Efficiency is the number of signal events left (measured after selection) relative to the number of total signal events before selection.

[‡]Cowan,G. et al.: Eur.Phys.J.C71:1554,2011

Optimization example

Efficiency vs rejection

Efficiency-rejection-significance



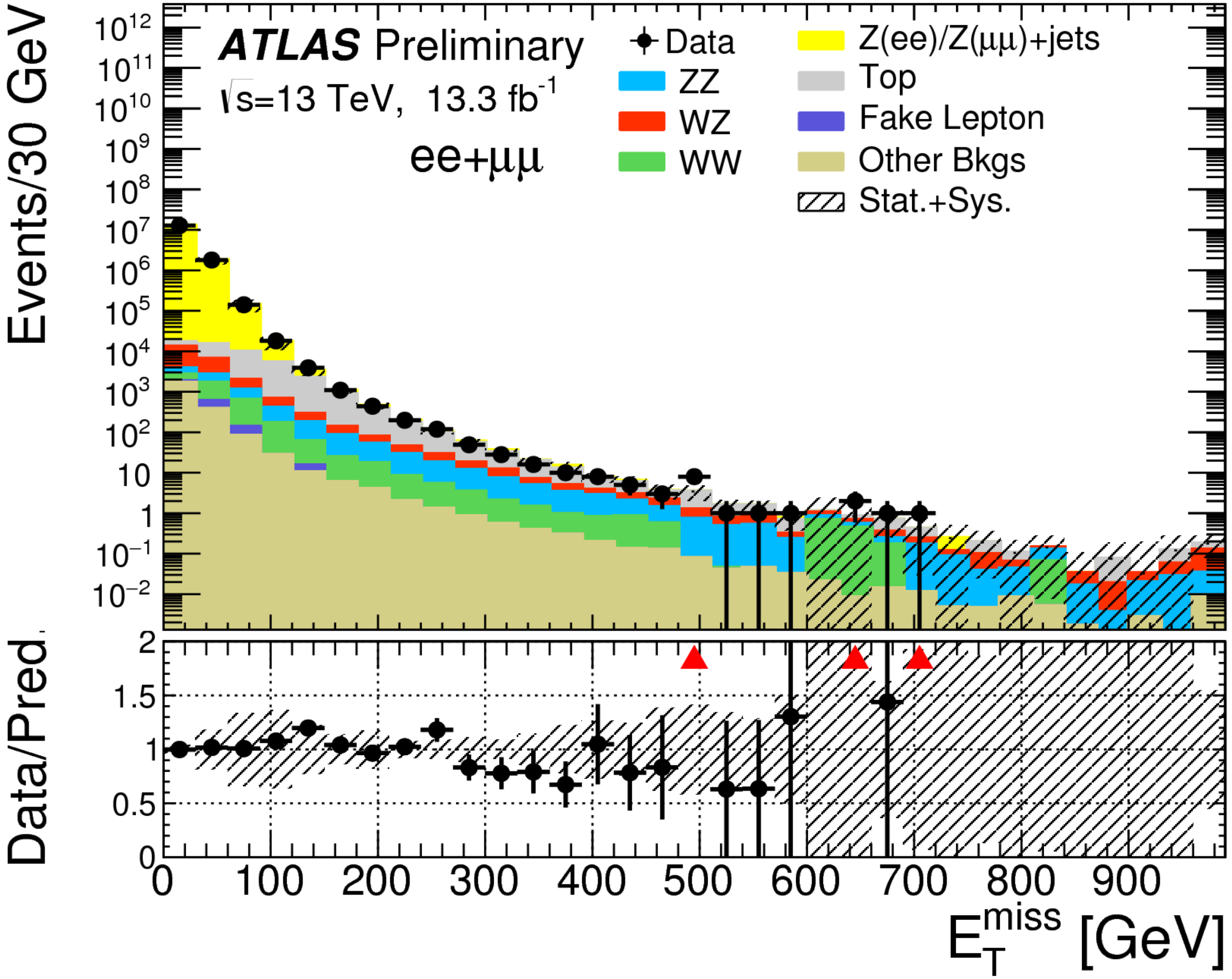
Efficiency and rejection vs MET

Significance vs MET value

Optimization strategy for the selection

- Optimization of the analysis is done by making cuts on the Mono-Z specific variables in order to maximize the significance for the signal samples.
    - Optimization was done individually on each sample for the specific cuts that were chosen (50 samples x 4 cuts x 2 final-state particle types = 400 different selections!!).
    - After optimization is done on the signals, the most significant samples were grouped together and found to have similar enough cuts to do one analysis.
- With the selections chosen, the set of simulated samples was analyzed against the background expectation from MC or data-driven techniques.

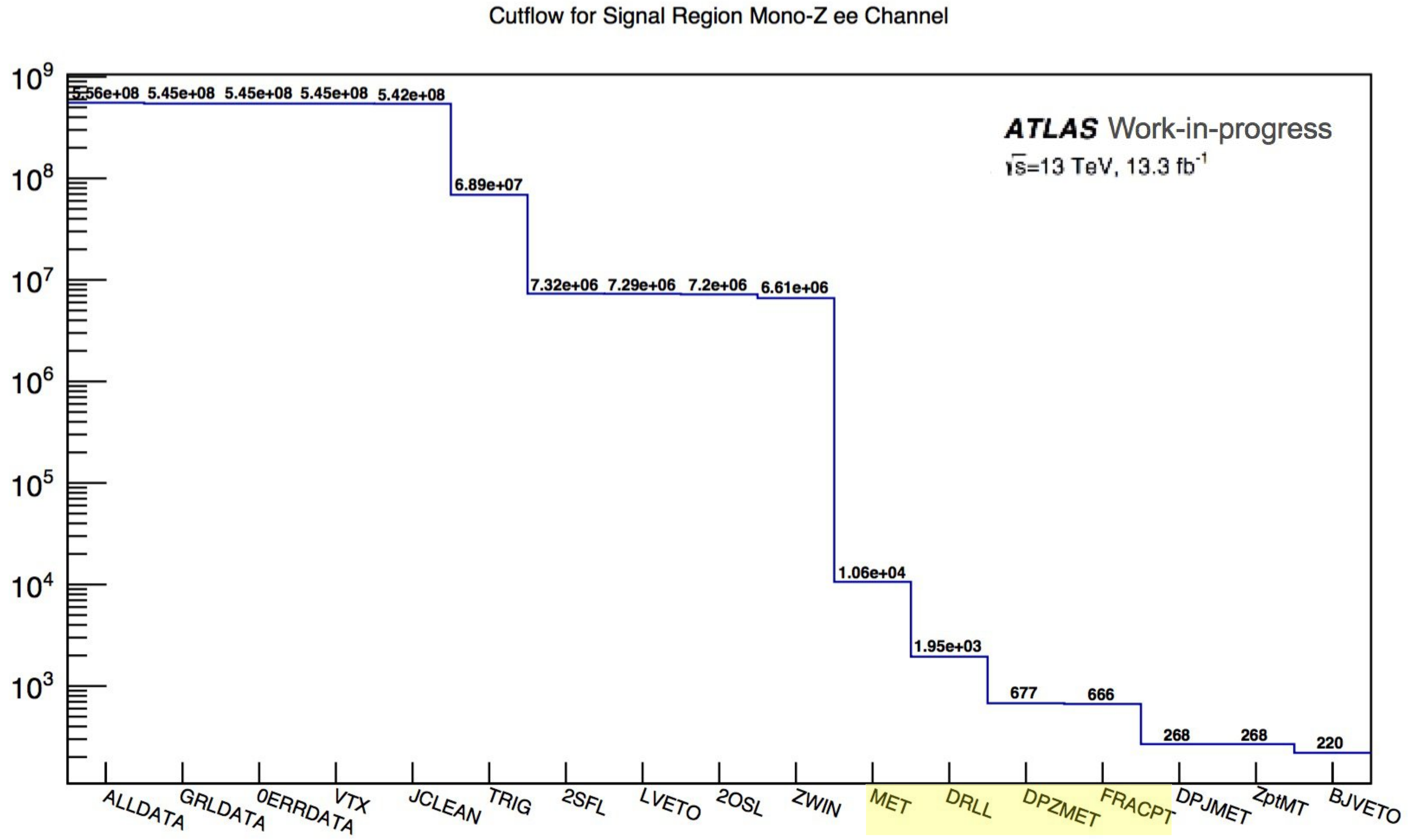
Before most cuts are applied



The ATLAS Collaboration, ATLAS-CONF-2016-056, 2016

Reduction of events: *ee* channel

**Highlighted cuts were the focus of optimization



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After all cuts applied: Mono-Z signal region

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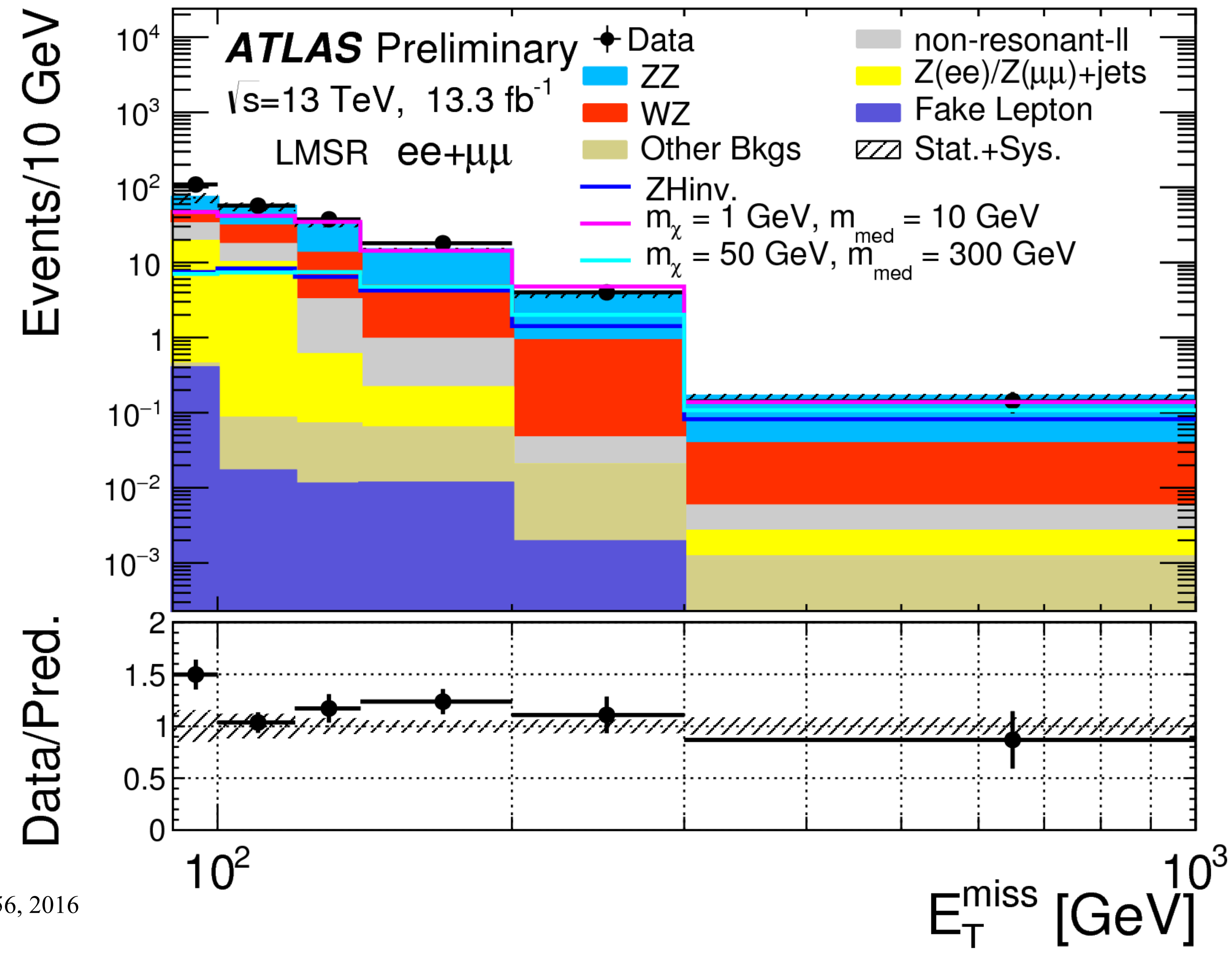
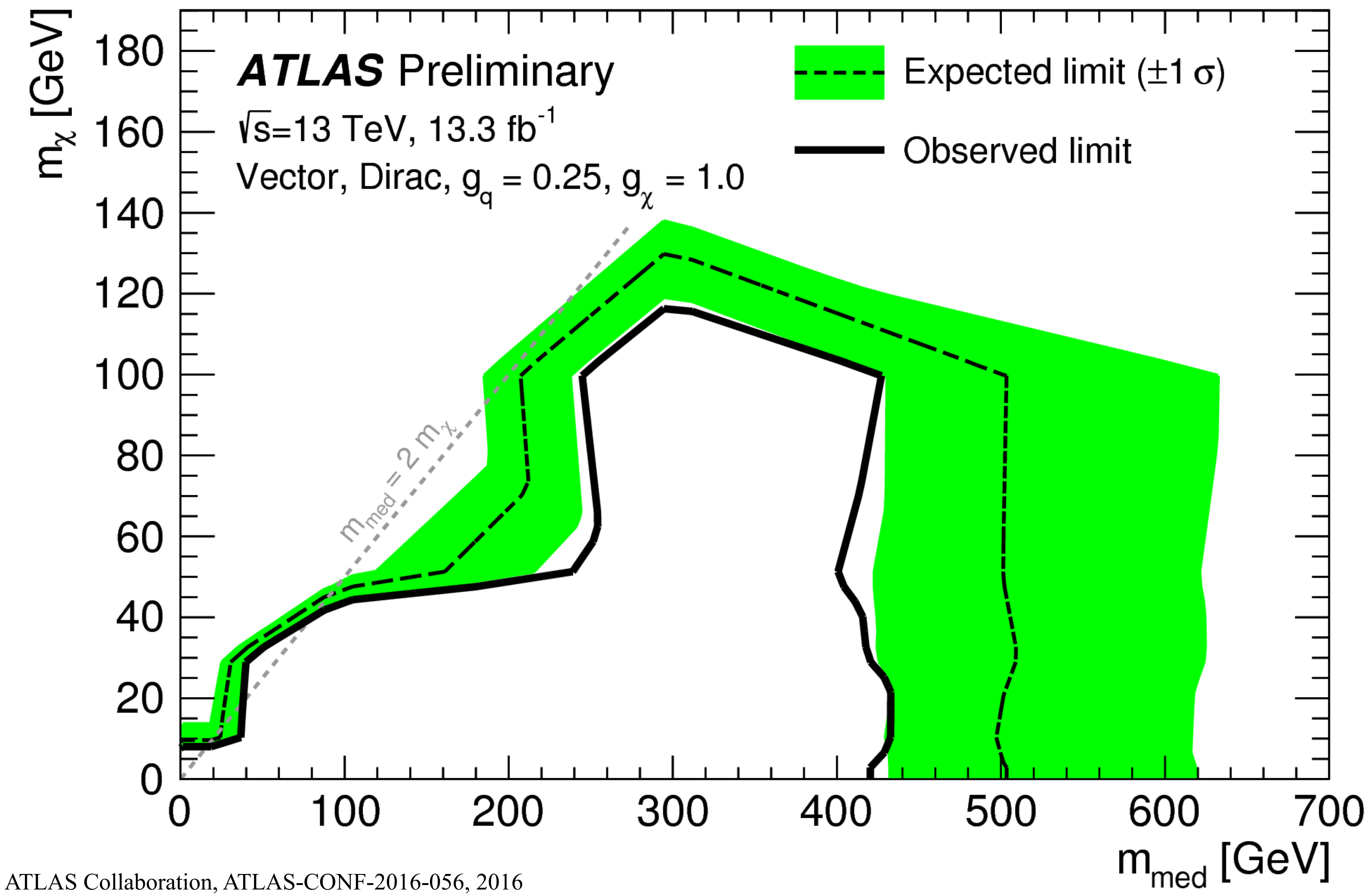


The ATLAS Collaboration, ATLAS-CONF-2016-056, 2016

Since all the known physics contributions (solid colours) add up to the data (points on the plot), there is no evidence for additional physics, examples of which are given as the solid lines in plots.

Results

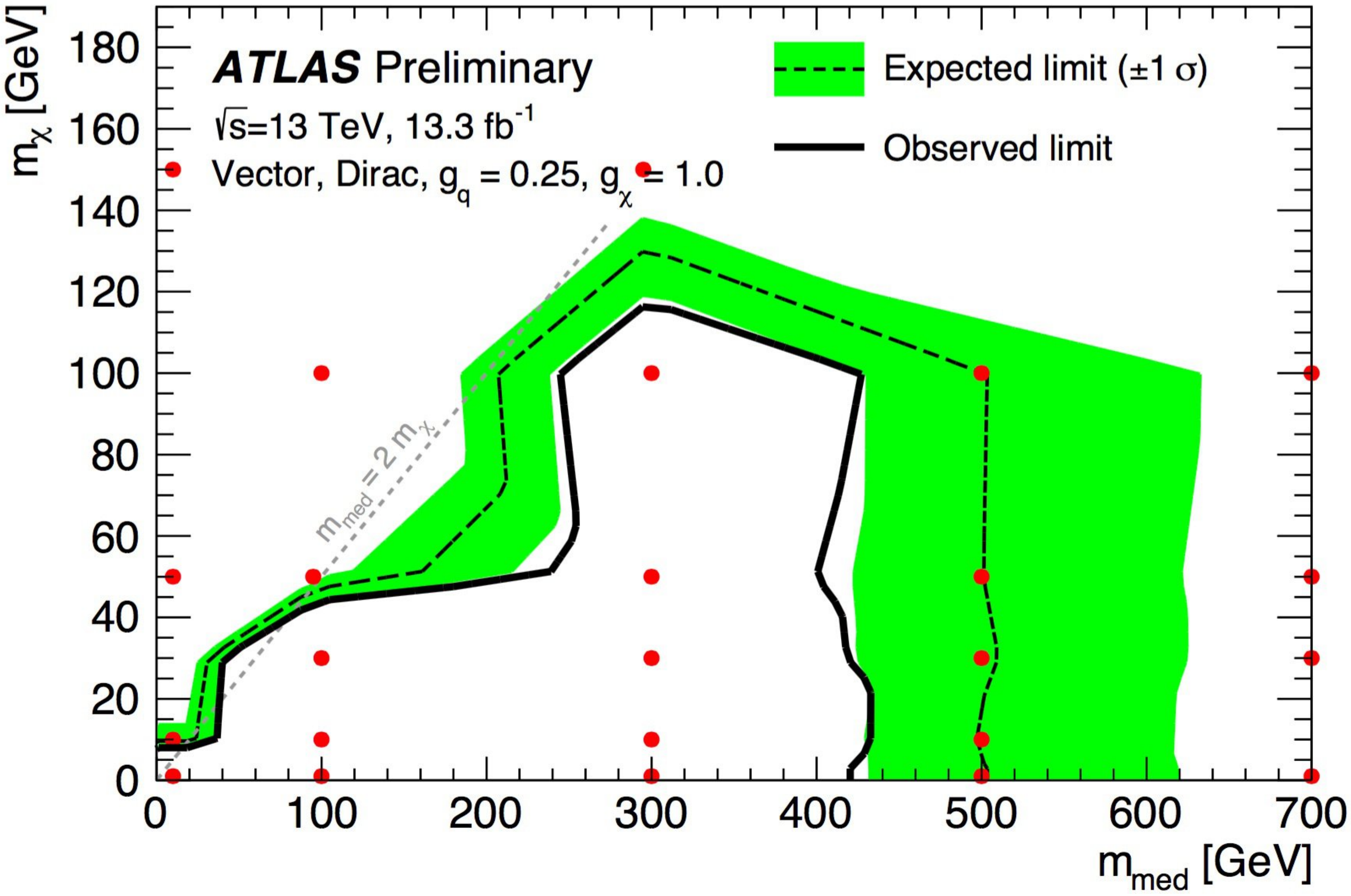
Nothing statistically significant beyond the Standard Model was found
→ Limits are set on set of vector mediated dark matter models



Note:
med ≡ ξ

Improvements

Improvements on the shape of the contour are possible with simulation of more dark matter models (red points) to allow for a more even interpolation



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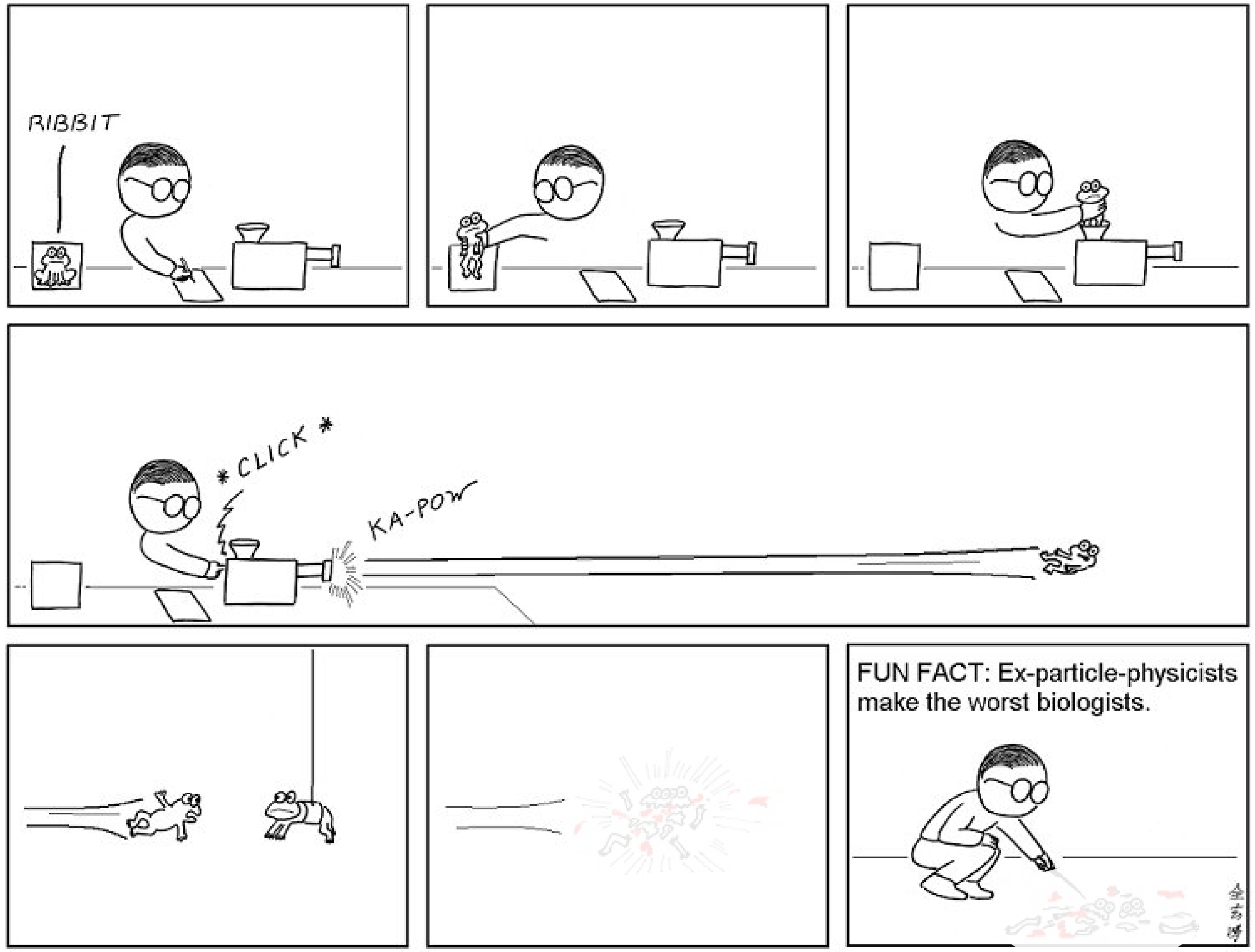
Conclusion

- There is strong motivation for dark matter from astrophysical sources
- Many different final states to be searched in colliders
- Exciting times happening with more data at higher energies!



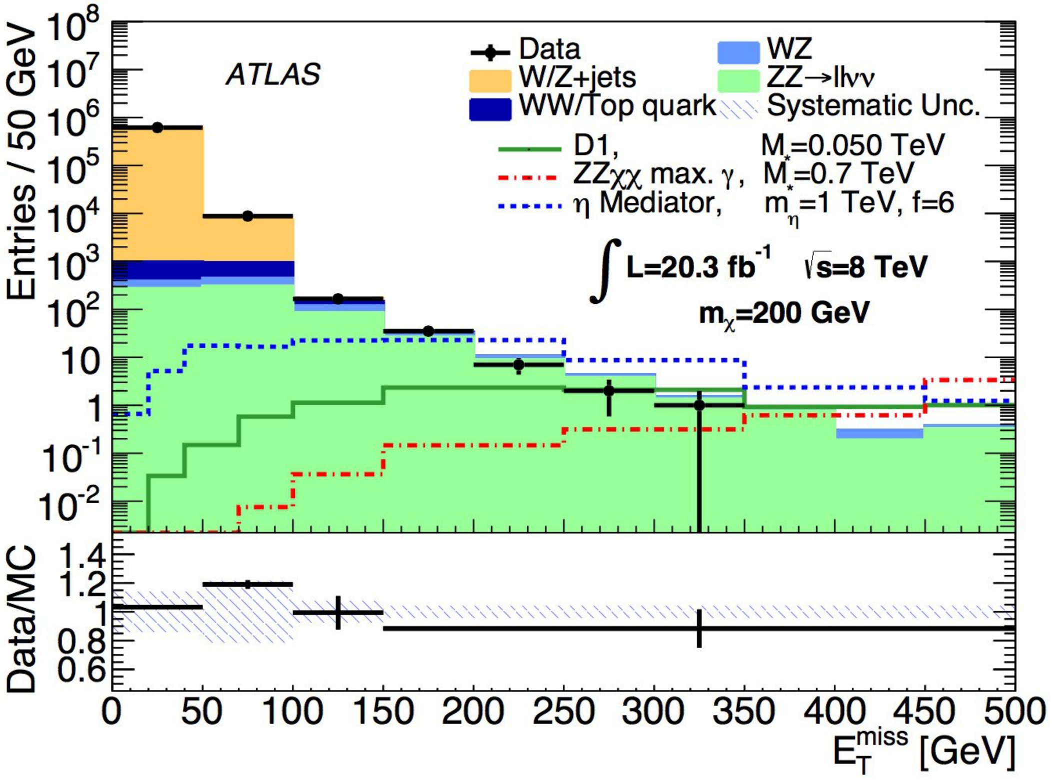
http://abstrusegoose.com/156

Backup

Previous results at 8 TeV

The Mono-Z channel takes advantage of a clean signature in the detector, and is able to provide a complementary cross-check if dark matter is seen in another channel (mono-jet, mono-photon...).

- Dark matter searches tagged with a *Z* boson were done at ATLAS using 20.3 fb^{-1} of data taken at 8 TeV centre of mass energy.



ATLAS Collaboration: Phys. Rev. D. 90, 012004 (2014)