Search for Dark Matter Produced in Association with a Dark Higgs Boson with the ATLAS Detector

WNPPC Conference

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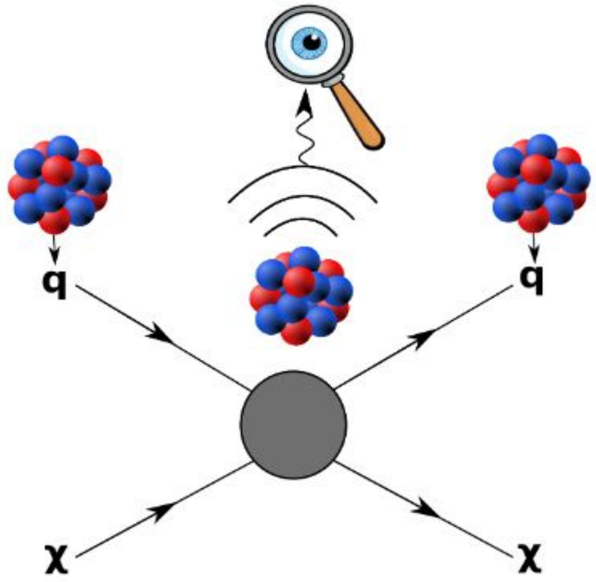
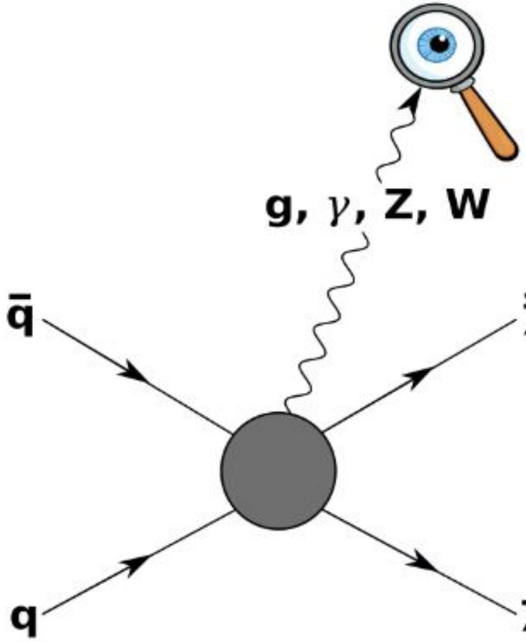
ATLAS EXPERIMENT
CERN

Dark Matter Detection





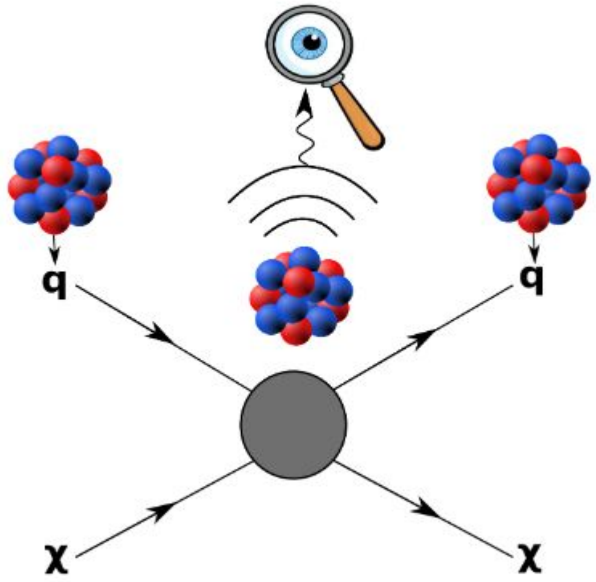
Direct detection searches:

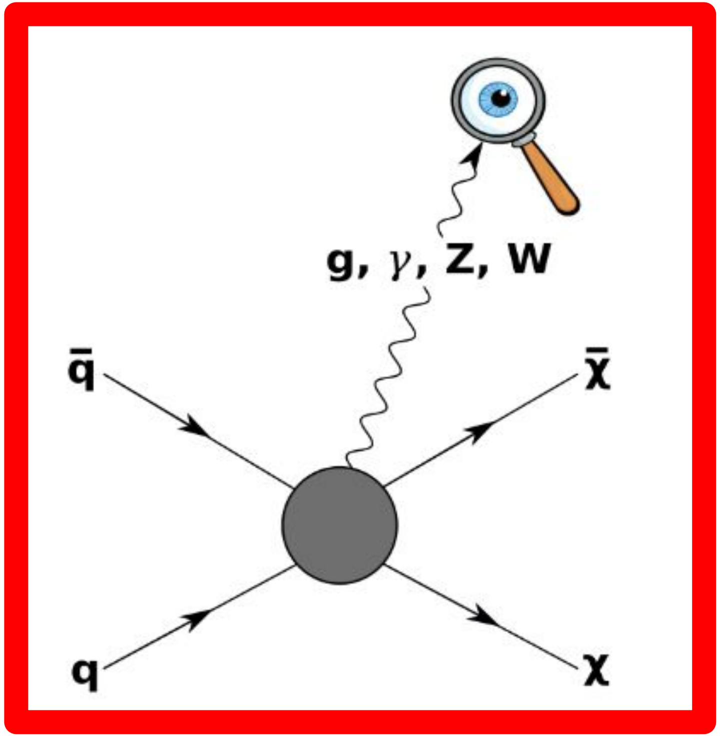
- Dark matter scatters off particle (nucleon, photon, etc.) in detector material
  - Measure recoil energy
- Search target: galactic dark matter

Collider searches:

- Dark matter produced in high-energy collision along with detectable particle(s)
- Search target: dark matter produced by collision

Dark Matter Detection





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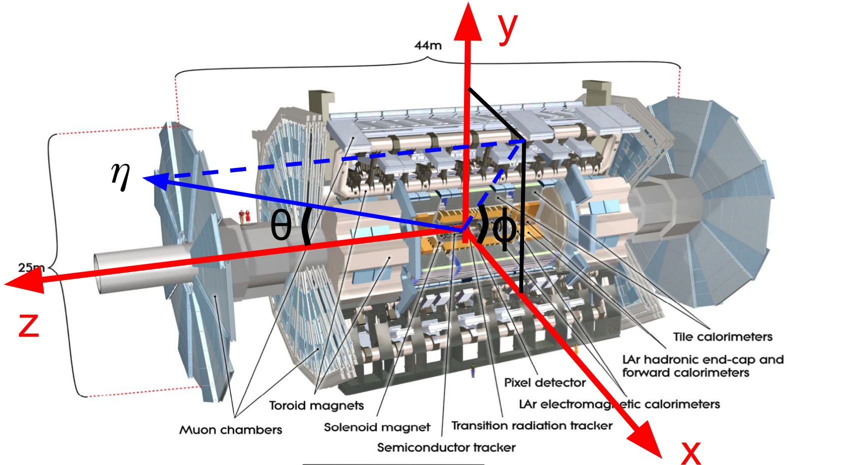
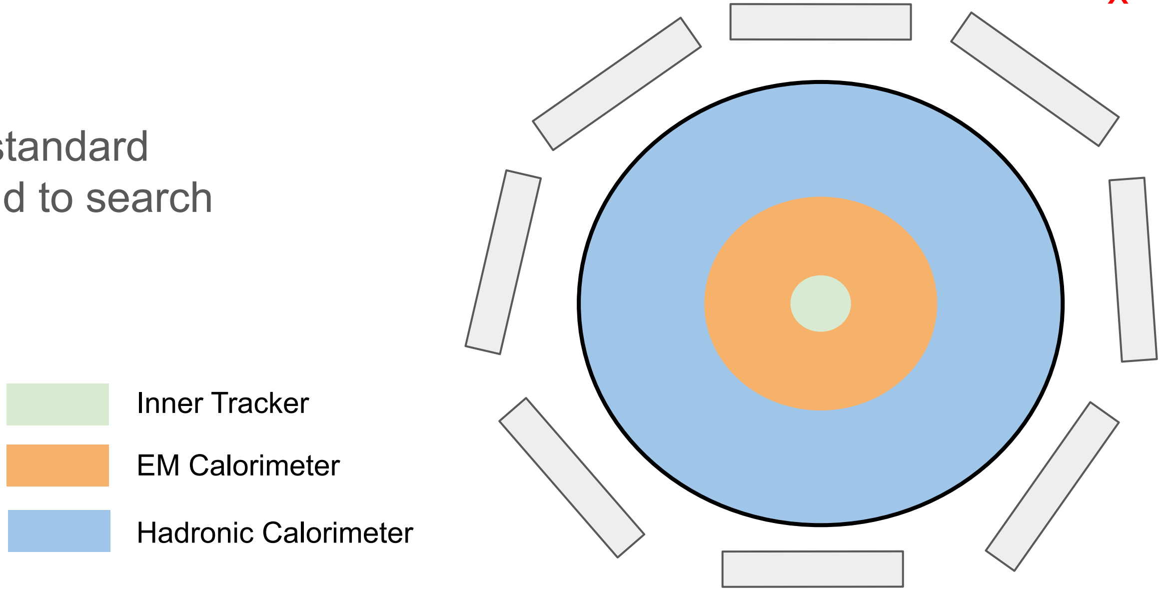
The ATLAS Detector

- General-purpose detector for studying particles produced by high-energy beam collisions at the LHC
- Used both for precision standard model measurements and to search for new physics



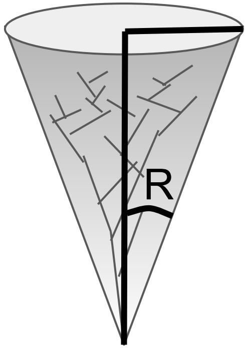


The ATLAS Detector

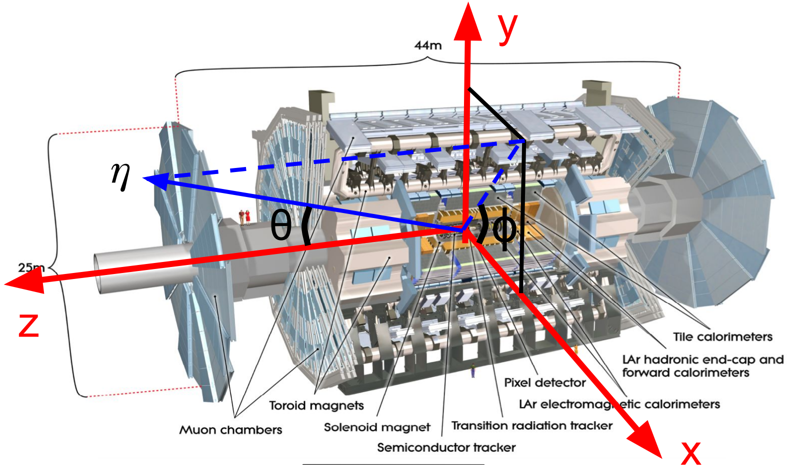
- Showers initiated by quarks and gluons referred to as “jets”

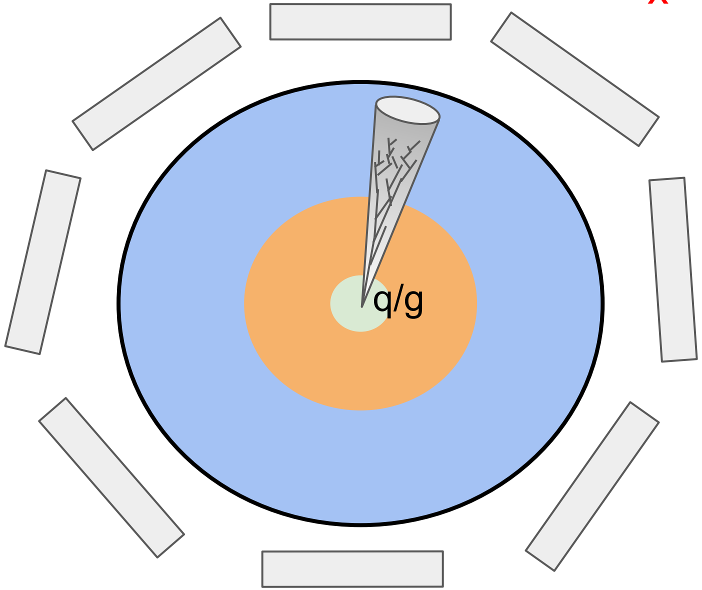
- Jets reconstructed in cone of angular radius R

- “small-radius” jet: R=0.2→0.4
- “large-radius” jet: R=0.8→1.0



$$R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$



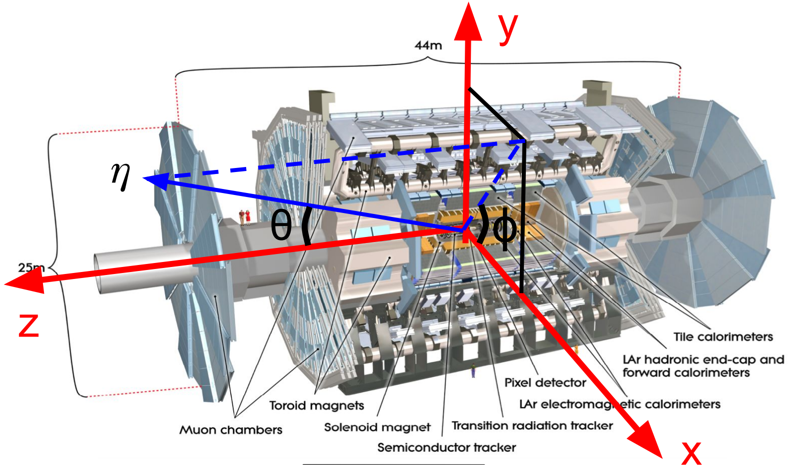


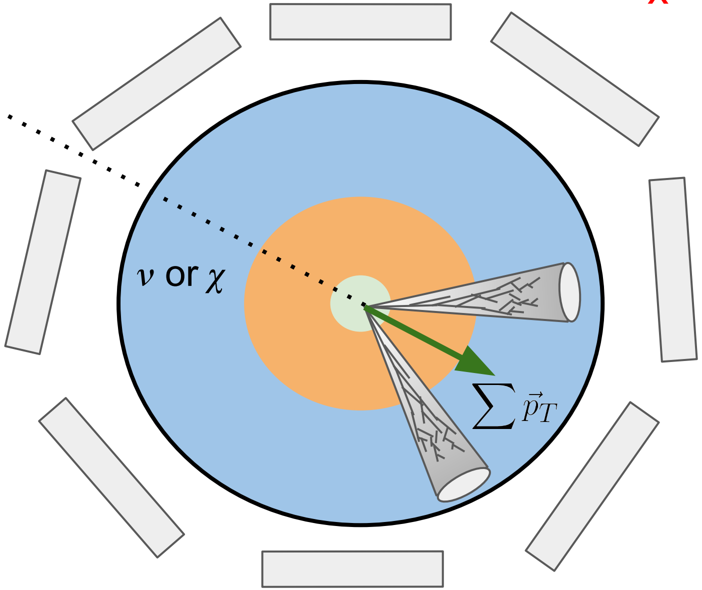
The ATLAS Detector

- Neutrinos (ν) and dark matter particles (χ) pass through undetected

  → Presence inferred from imbalance of momentum transverse to the beam line, a.k.a. E_T^{miss}

$$E_T^{\text{miss}} = -\left|\sum \vec{p}_T\right|$$

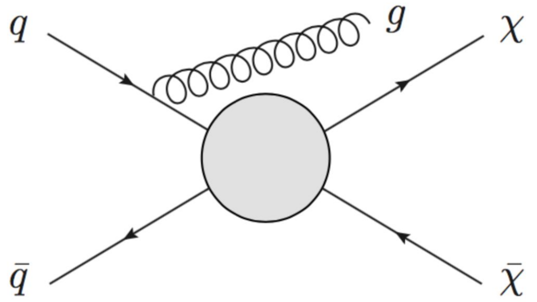




Dark Matter Production Models for Collider Searches

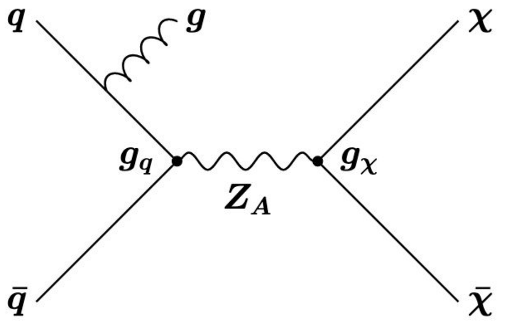
Effective Field Theories (EFT)

- Dark matter production mechanism unspecified



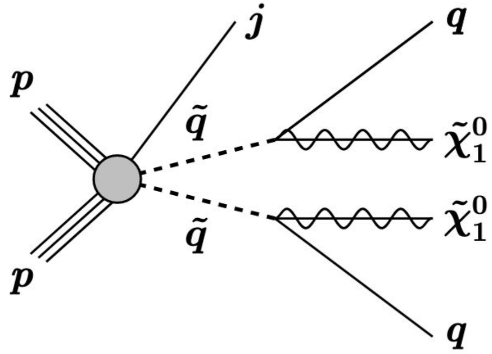
Simplified Models

- First-order description of new physics
- Bridge gap between EFT and complete models



Complete Models

- Dark matter predicted as part of a complete unified theory
- Eg. Supersymmetry



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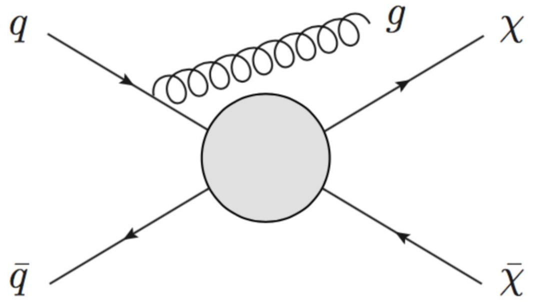

Simplified Models

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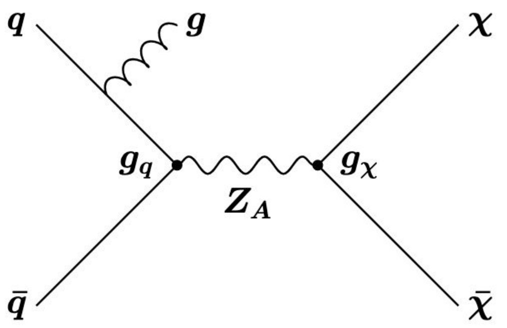
- Bridge gap between EFT and complete models

v



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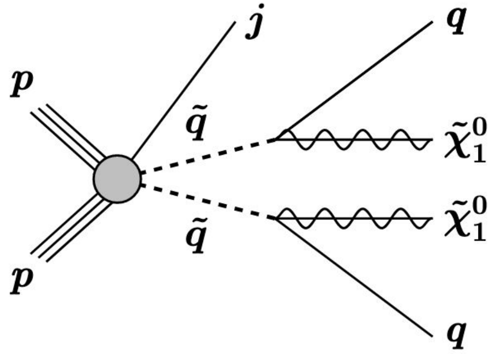
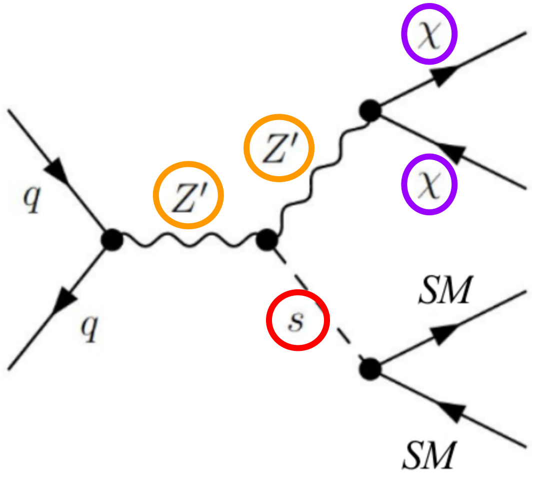


“Dark Higgs” Signal Model



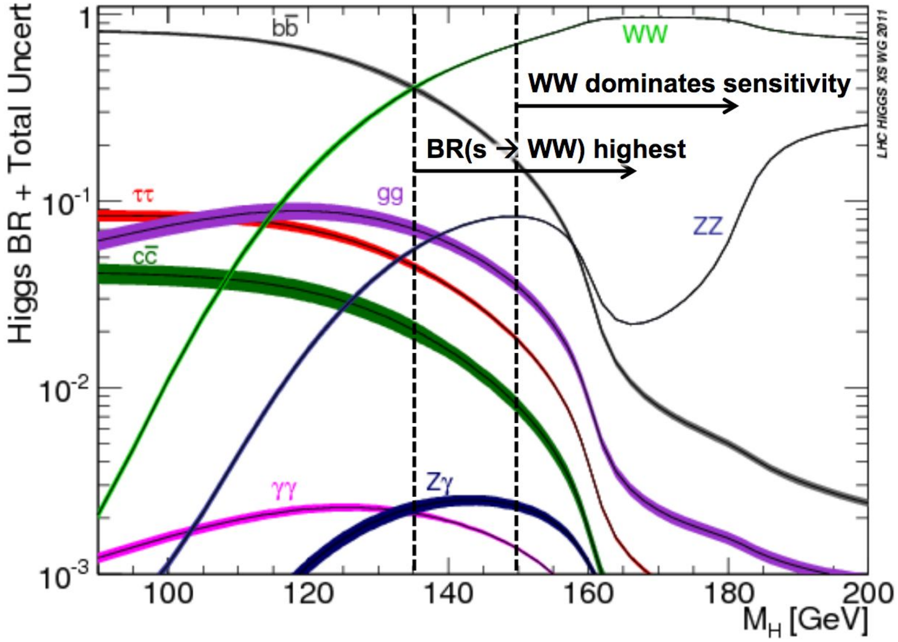
10.1007/JHEP04(2017)143

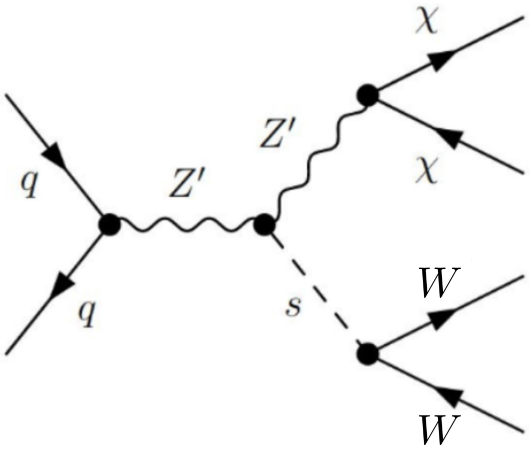
- χ: Dark Matter
  - Mass fixed to 200 GeV for consistency with other LHC searches

- Z’: Vector boson in dark sector
  - Mass not fixed in model
  - Search region explores $m_{Z'} > 2m_{\chi}$, thus allowing for Z’ $\rightarrow \chi\chi$ decay

- s: Higgs boson in dark sector (a.k.a. “dark Higgs”)
  - Mass not fixed in model
  - Search region explores $m_s < 2m_{\chi}$, thus forbidding s $\rightarrow \chi\chi$ decay

Search with Dark Higgs Decay to WW



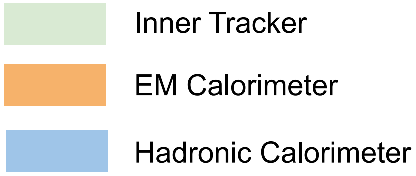


- Search for dark Higgs model in s → bb channel was completed in 2019 (ATL-PHYS-PUB-2019-032)

- s → bb decay has highest cross section for $m_s \lesssim 135$ GeV
- s → WW dominates for high-mass dark higgs

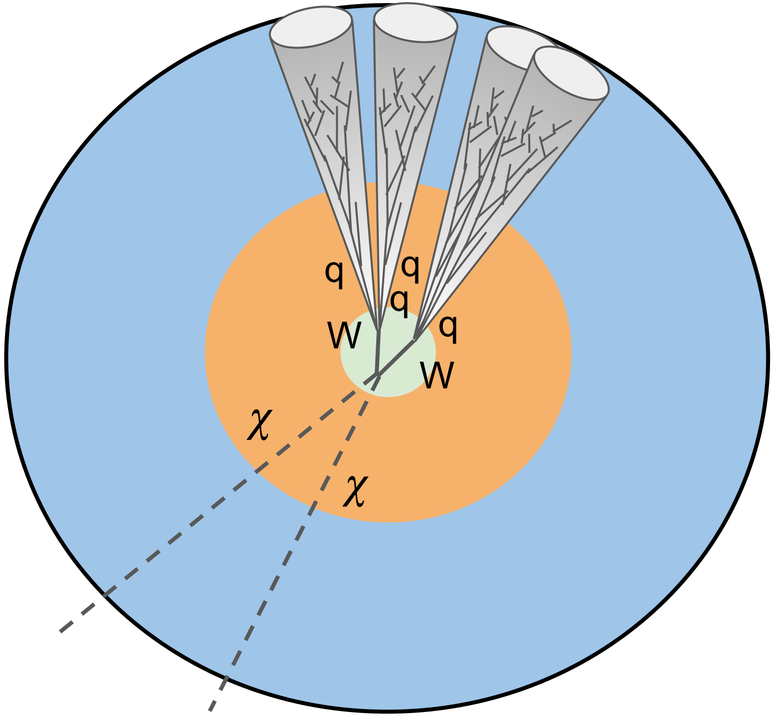
⇒ Motivates dedicated dark matter search in s → WW channel

Search in Hadronic Channel (WW $\rightarrow$ qqqq)



Completed in late 2020

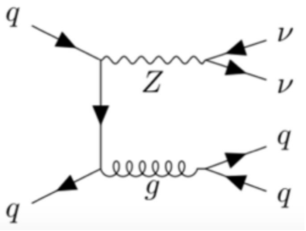
- https://arxiv.org/pdf/2010.06548.pdf
- Used full ATLAS Run 2 data



Signature in ATLAS detector:

- Hadronic jets in calorimeter recoiling against missing transverse momentum from $\chi\chi$
- WW pair boosted due to high-mass Z' mediator

Dominant standard model background: Z+jets (where Z $\rightarrow \nu\nu$)



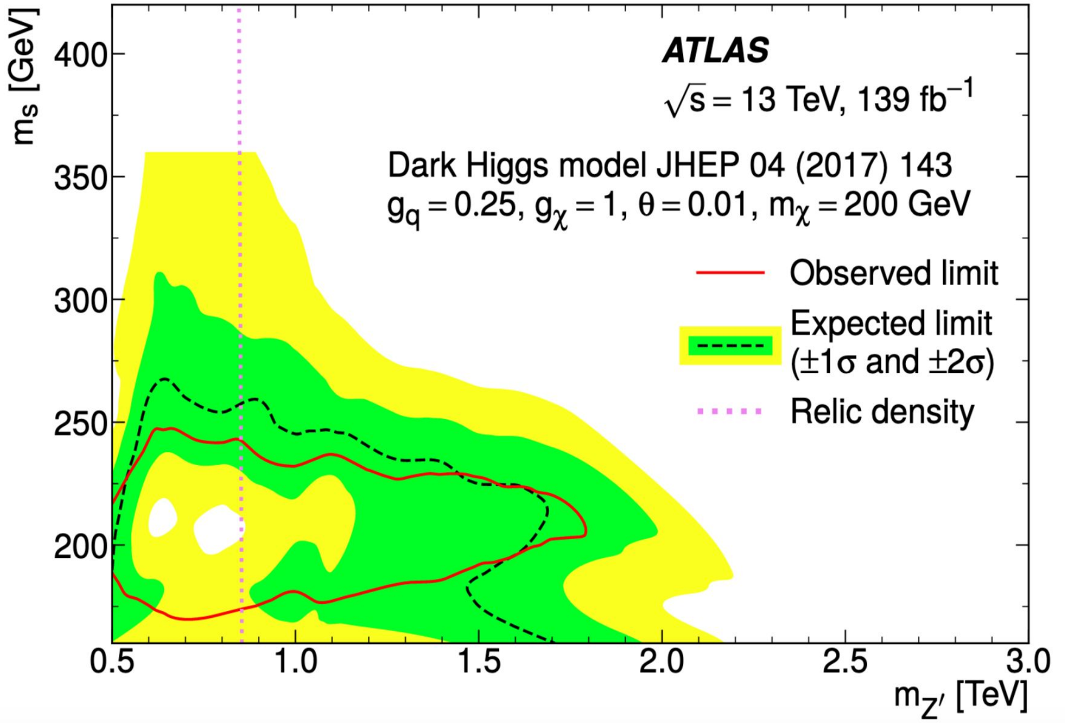
Search in Hadronic Channel ($WW \rightarrow qqqq$)

https://arxiv.org/pdf/2010.06548.pdf

- Constrained dark Higgs model parameters m_s and $m_{Z'}$ in the appx. range:

  160 GeV < m_s < 240 GeV

  (s → bb coverage: 50 GeV < m_s < 150 GeV)

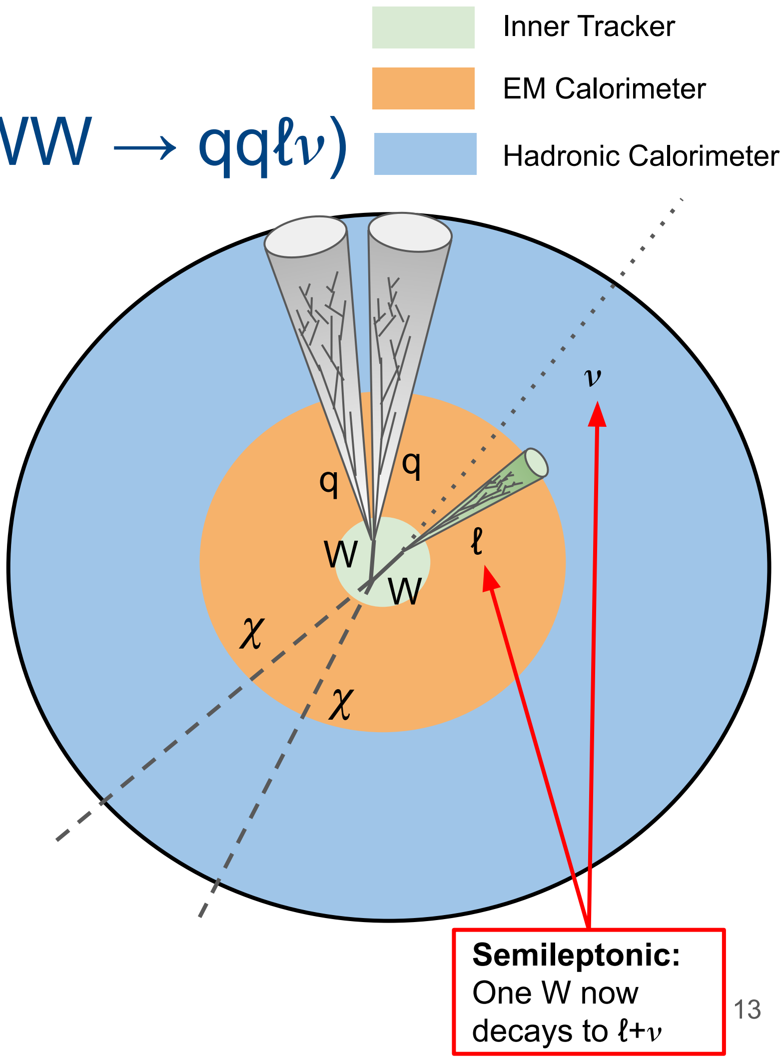


Search in Semileptonic Channel (WW → qqℓν)

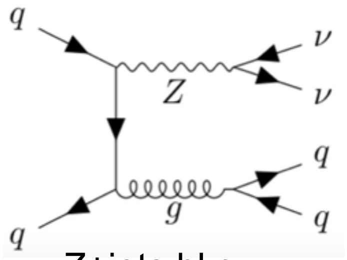
Ongoing → search began last February
- Using full ATLAS Run 2 data

Signature in ATLAS detector:
- Hadronic jets + lepton in calorimeter recoiling against E_T^{miss} from $\chi\chi$

- E_T^{miss} includes contributions from $\chi\chi$ and ν



Semileptonic vs. Hadronic Channel



Z+jets bkg

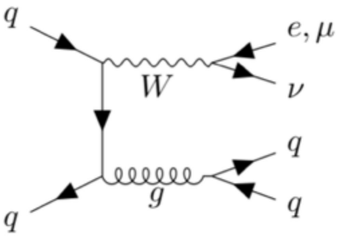
Pros

- 1-lepton requirement reduces some backgrounds compared with hadronic channel (eg. Z+jets)
- Ability to reconstruct hadronically-decaying W boson → can select for mass window near on-shell W mass (80.4 GeV)

Cons

- ν in final state:
  - adds additional (non-dark-matter) source of E_T^{miss}
  - prevents direct reconstruction of dark higgs candidate
    - Developed a minimization strategy for approximate dark higgs mass reco (see backup)

Semileptonic Channel: Transverse Mass



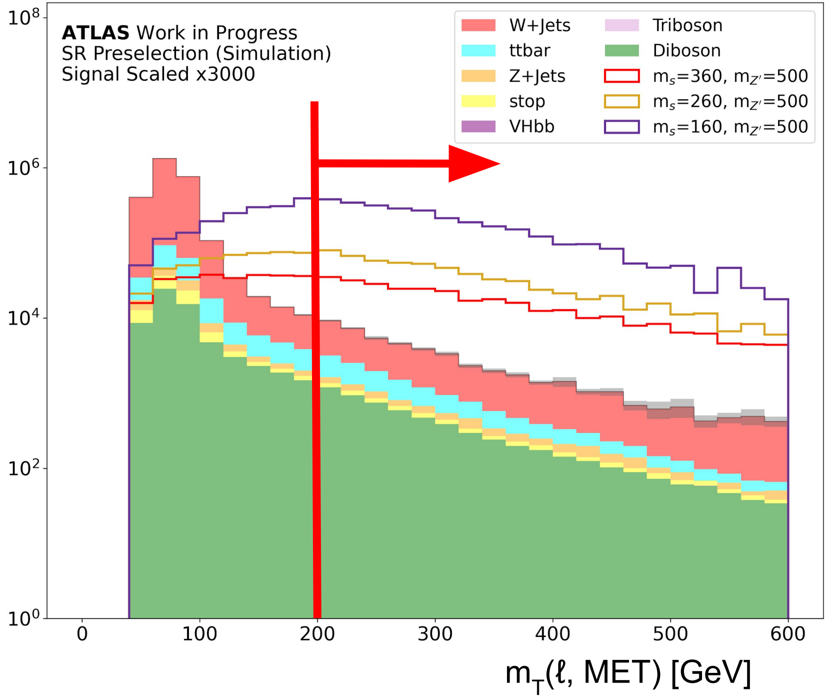
W+jets bkg

$$m_T(\ell, E_T^{miss}) = \sqrt{2 p_{T,\ell} E_T^{miss} (1 - \cos\theta_{\ell, E_T^{miss}})}$$

- Expectation for standard model background (for on-shell W):

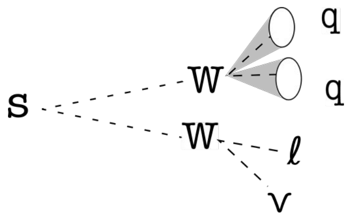
  $m_T(\ell, E_T^{miss}) \leq m_W$

- Dark matter in signal model adds E_T^{miss} with different $\cos\theta_{\ell,\, ETmiss}$ distribution
- Selecting $m_T(\ell, E_T^{miss}) > 200$ GeV substantially reduces standard model backgrounds, especially W+jets
- **Interesting feature:** Remaining W+jets background is mainly events with very off-shell W mass (>> 80.4 GeV)

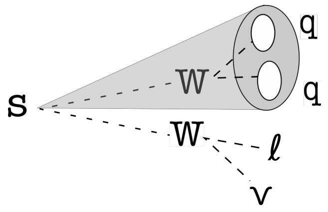


Semileptonic Channel: Analysis Regions

Resolved Category
- Less-boosted
- Hadronized quarks reconstructed as two resolved small-radius jets

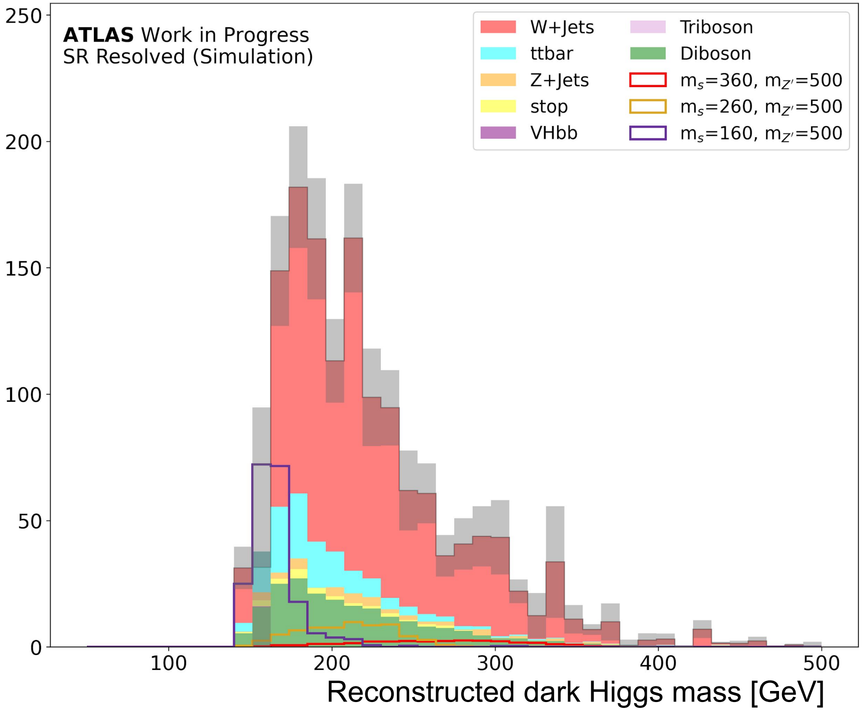


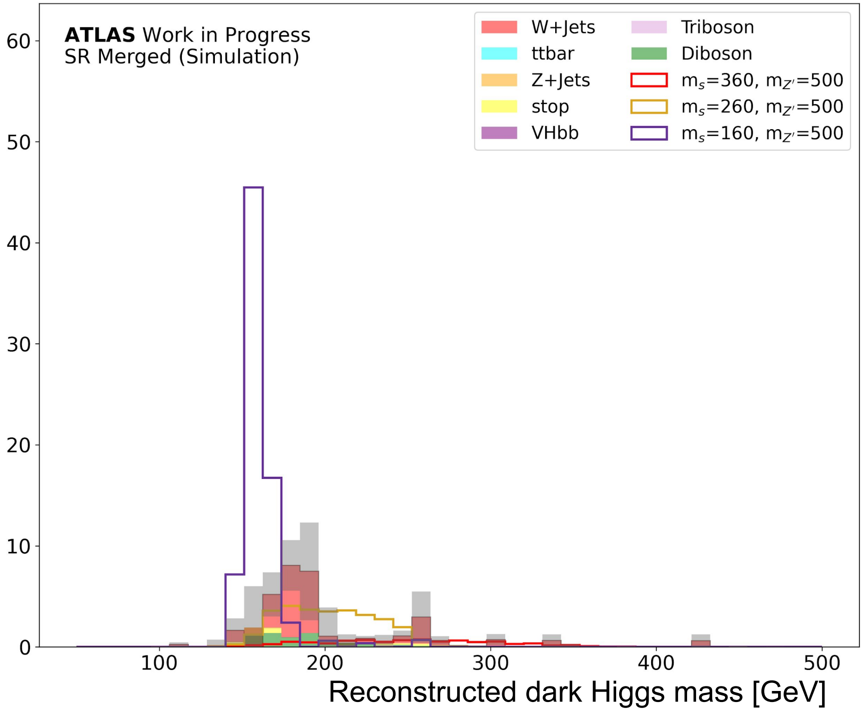
Merged Category
- More-boosted
- Hadronized quarks reconstructed as large-radius jet



No signal scaling

Semileptonic Channel: Analysis Regions



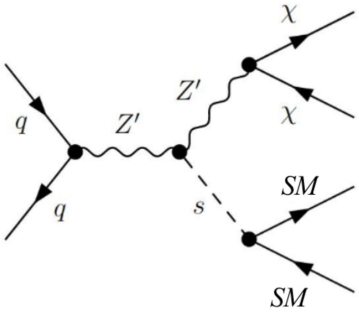


Resolved category: Higher stats, lower signal/background

Merged category: Lower stats, higher signal/background

Summary

- Ongoing search for dark matter production with WW+E_T^{miss} in final state
- Motivated and optimized with “dark Higgs” simplified model
- Exclusion limits have been set in WW → qqqq final state
- Search in WW → $qq\ell\nu$ final state ongoing



Backup Slides

Definitions

Transverse Mass

- Reconstructed mass of two final-state objects in the plane transverse to the LHC beam line
- Transverse mass between lepton and E_T^{miss} is defined assuming lepton and E_T^{miss}-producing object(s) are appx. massless:

$$m_T(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) = \sqrt{2p_{T,\ell}E_{\mathrm{T}}^{\mathrm{miss}}(1 - \cos\theta_{\ell,E_{\mathrm{T}}^{\mathrm{miss}}})}$$

Missing Transverse Energy (E_T^{miss})

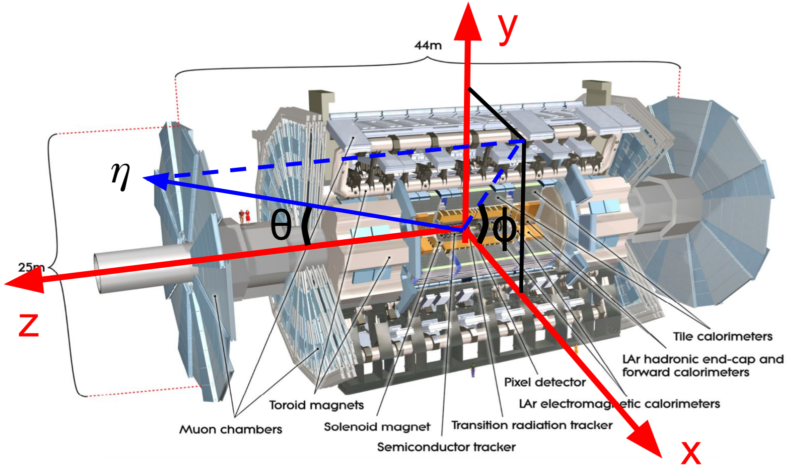
- Total momentum of undetected final-state objects in the plane transverse to the beam line
- Two-dimensional vectorial sum over all visible final-state objects in the transverse

$$\vec{E}_{\mathrm{T}}^{\mathrm{miss}} = -\sum_i \vec{p}_{x,i} + \vec{p}_{y,i}$$

LHC Run 2

- Data collected at the LHC from 2015-2018 at a proton-proton collision energy of 13 TeV

Definitions, cont.



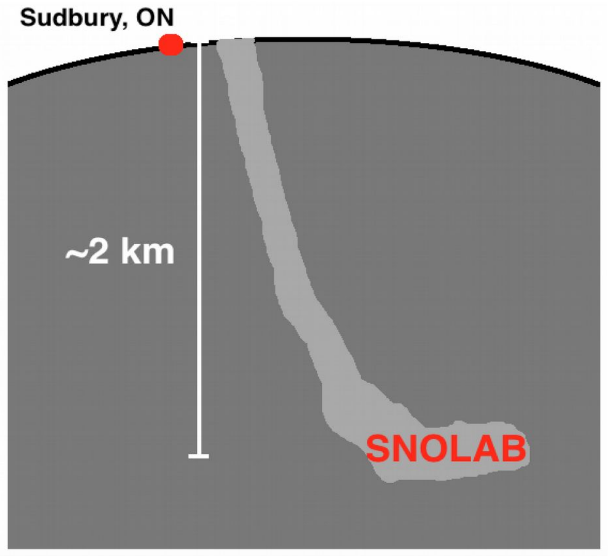
Pseudorapidity

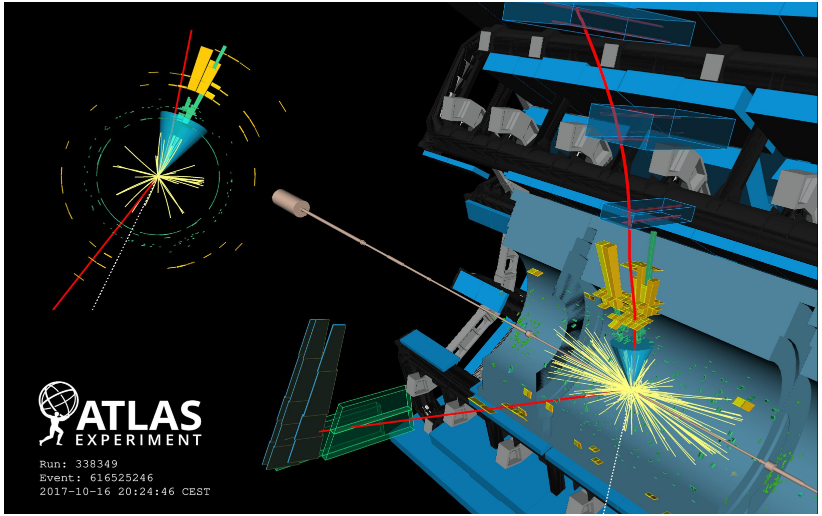
- Describes angle of particle relative to beam axis (z-axis)
- Changes $\Delta\eta$ in pseudorapidity are Lorentz invariant under boosts along the longitudinal axis

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

- $\Delta N/\Delta\eta$ is approximately constant for $|\eta| \lesssim 5$
  - N: number of charged tracks in pileup events

Dark Matter Detection





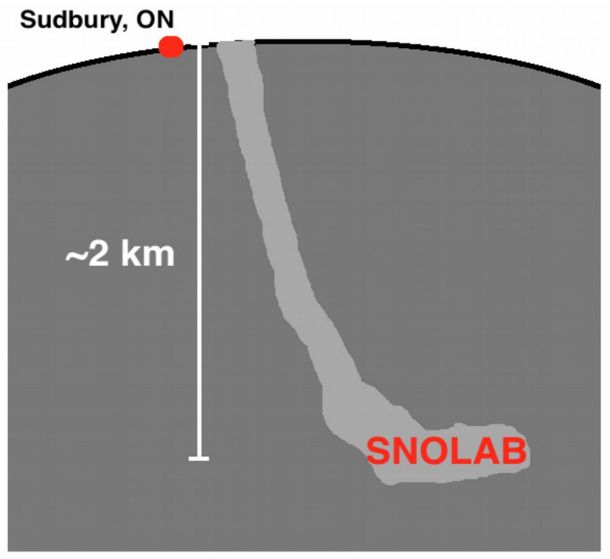
Direct detection searches:

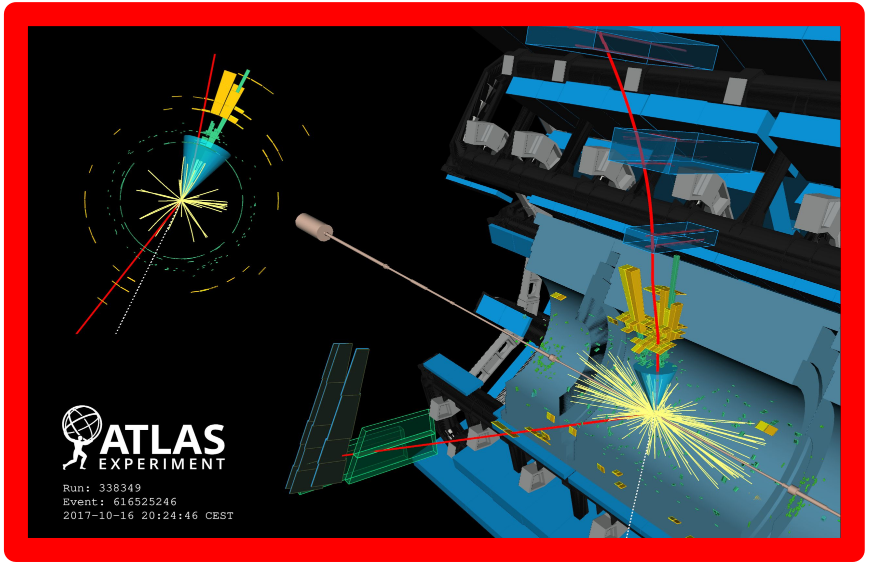
- Low energy (~keV)
- Low background

Collider searches:

- High energy (~TeV)
- High background

Dark Matter Detection





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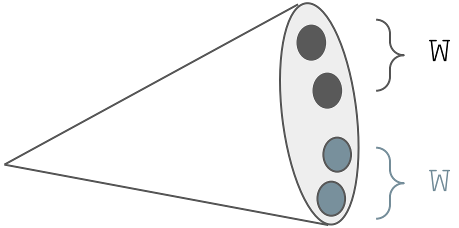
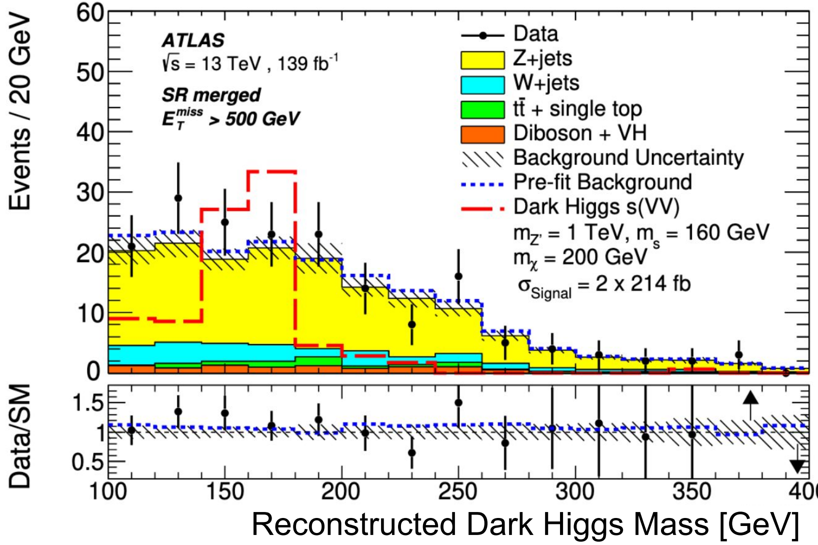
Search in Hadronic Channel (WW → qqqq)

- Most sensitive in the “merged” regime
- None of the jets can be resolved into individual small-radius jets → all reconstructed within a single large-radius jet





https://arxiv.org/pdf/2010.06548.pdf

Search in Hadronic Channel (WW → qqqq)

Merged Category

- Most boosted regime
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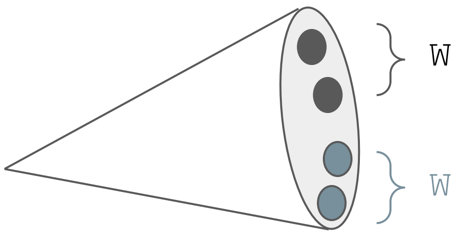
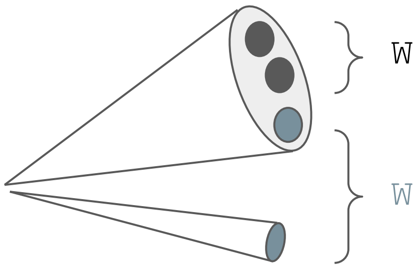


Intermediate Category

- Less-boosted regime
- Some of the jets can be resolved into individual small-radius jets



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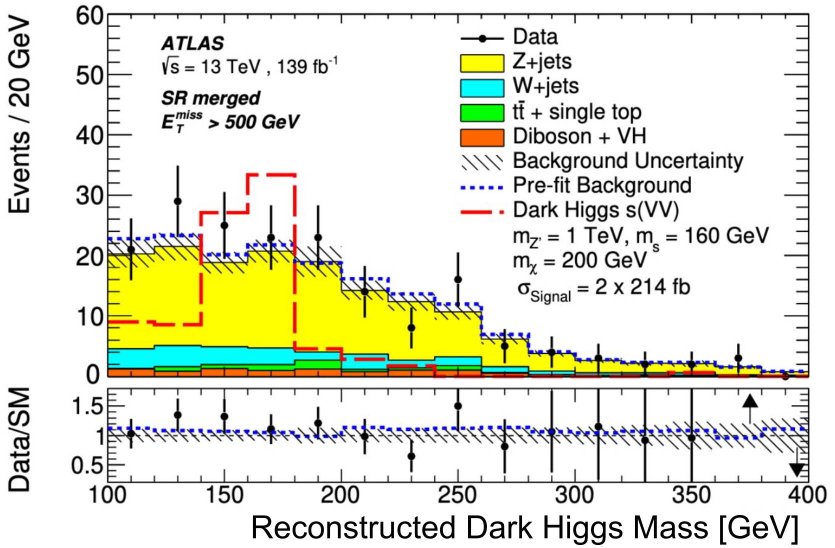

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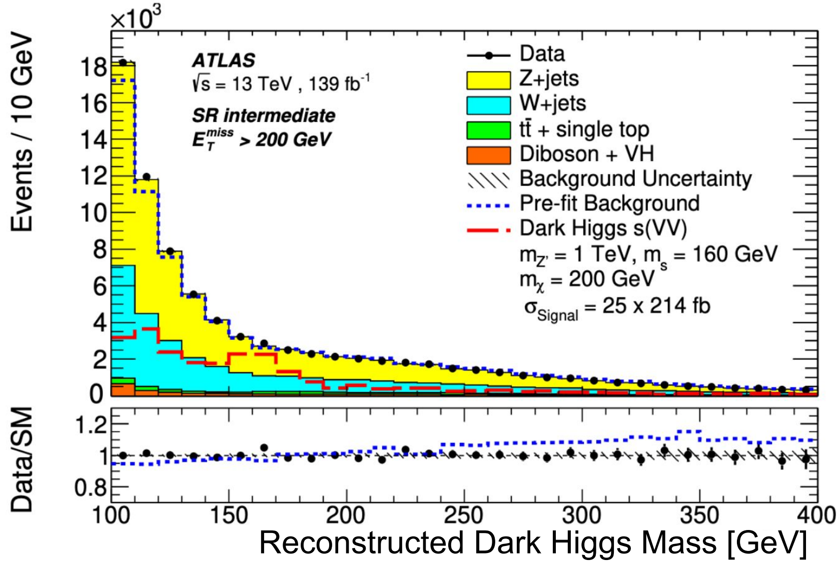

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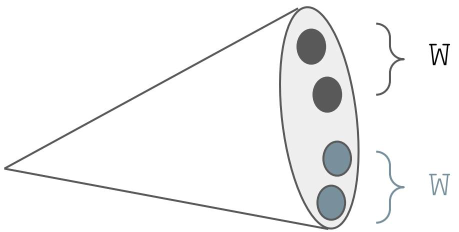

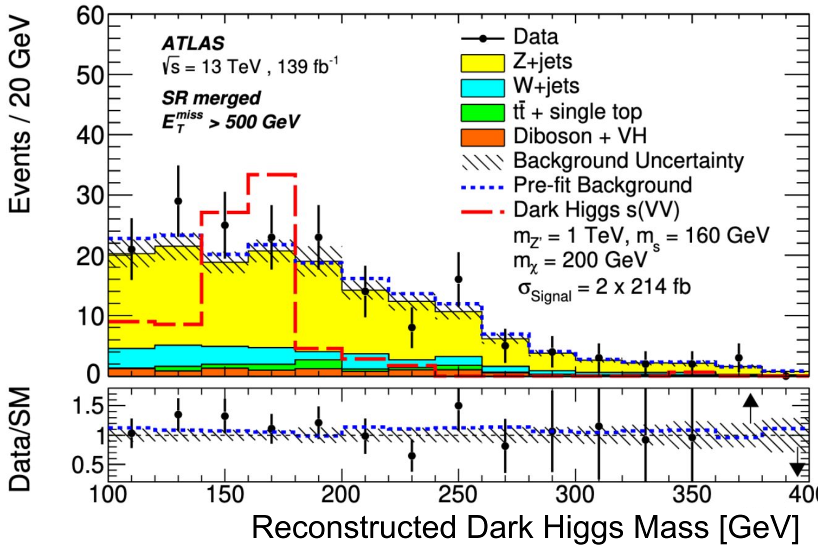

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Analytical Solution of m_S in $s \rightarrow WW \rightarrow qq\ell\nu$ System

- **Idea:** Find the minimum m_S consistent with observed W_H and ℓ momenta and W mass constraint m_W=80.4 GeV.

1. In frame where ℓ travels along the z axis and W_H is in the xz frame:

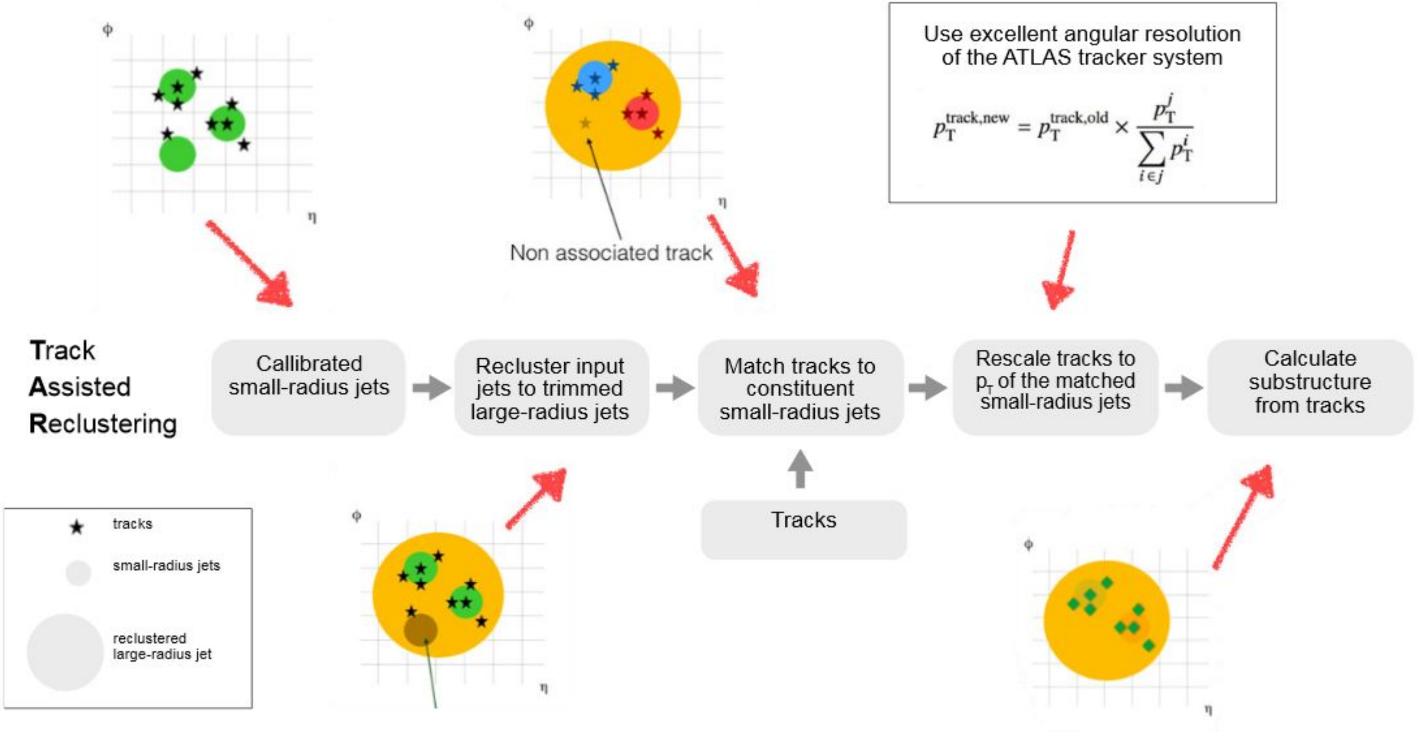
$$m_S^2 = \left(p_{W_H} + p_l + p_\nu\right)^2$$

$$m_S^2 = \left(E_{W_H} + E_l + E_\nu\right)^2 - \left(p_{W_{Hx}} + E_\nu \sin\theta_{l\nu} \cos\phi_\nu\right)^2$$

$$-(E_\nu \sin\theta_{l\nu} \sin\phi_\nu)^2 - \left(E_l + p_{W_{Hz}} + E_\nu \cos\theta_{l\nu}\right)^2$$

2. Determine ϕ_ν and $\theta_{\ell\nu}$ that minimize m_S.
   - ϕ_ν=0, and $\theta_{\ell\nu}$ can be solved for numerically.
3. Eliminate E_ν using W mass constraint for $W \rightarrow \ell\nu$ system, then rotate back to lab frame.

The TAR Algorithm



Asimov Signal Significance

Expected Asimov signal significance Z used in optimizing selection cuts. Defined as:

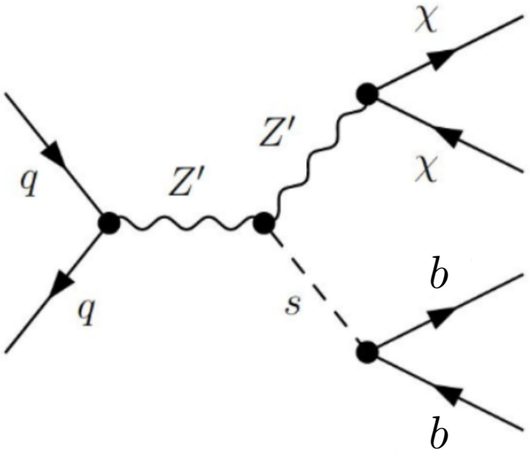
$$Z = \sqrt{2\left[\ln\left(\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\right) - \frac{b^2}{\sigma_b^2}\ln\left(1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\right)\right]}$$

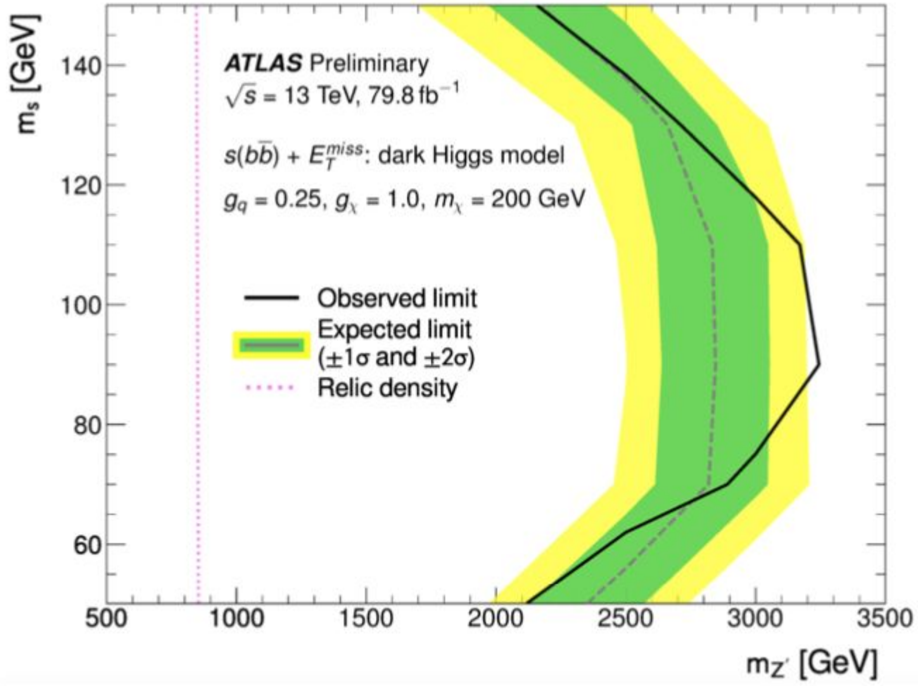
s: expected number of signal events (based on simulation)

b: expected number of background events (based on simulation)

σ_b: uncertainty associated with expected number of background events

Search with Dark Higgs Decay to bb

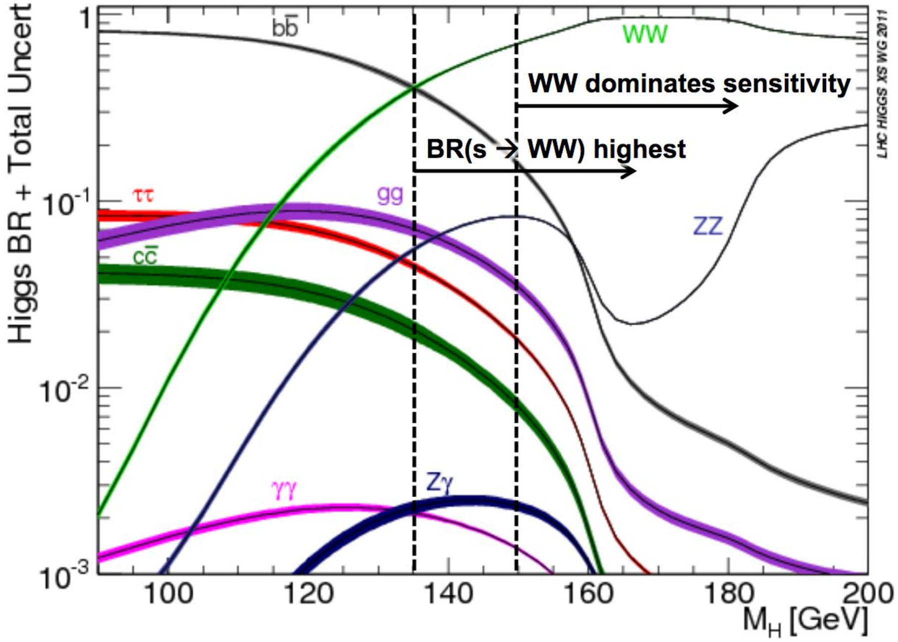


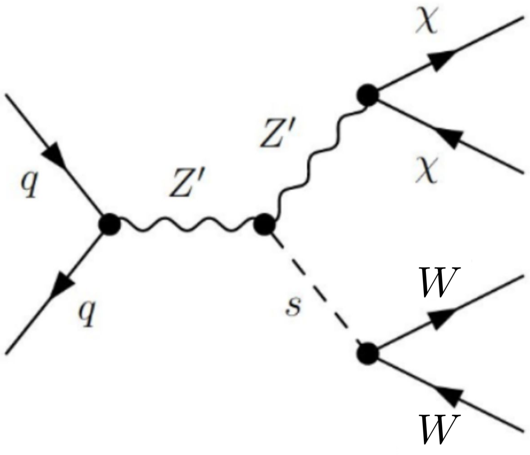


- Search completed in 2019
  - ATL-PHYS-PUB-2019-032
  - Used partial ATLAS Run 2 data

- Placed upper limits on $m_{Z'}$ in dark Higgs model for 50 GeV < m_s < 150 GeV

Search with Dark Higgs Decay to WW



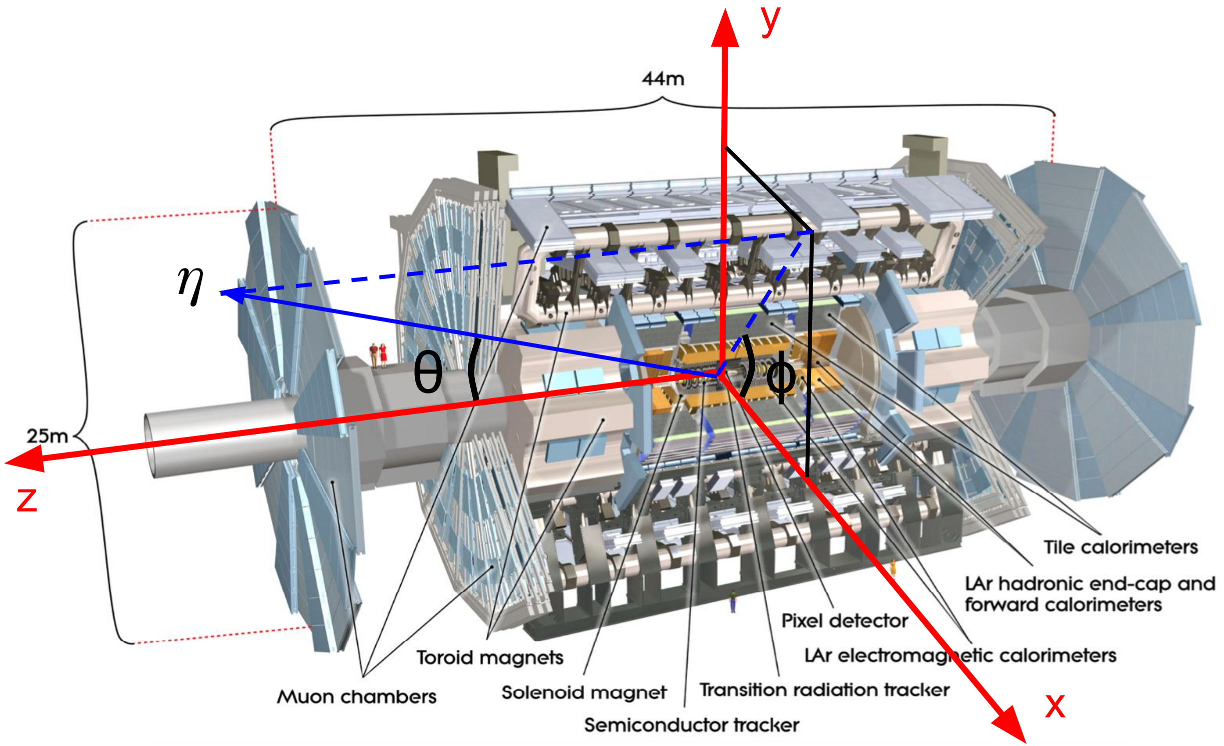


- s → bb decay has highest cross section for $m_s \lesssim 135$ GeV
- s → WW dominates for high-mass dark higgs

⇒ Motivates dedicated dark matter search in s → WW channel

The ATLAS Detector

- General-purpose detector for studying particles produced by high-energy beam collisions at the LHC
- Used both for precision standard model measurements and to search for new physics



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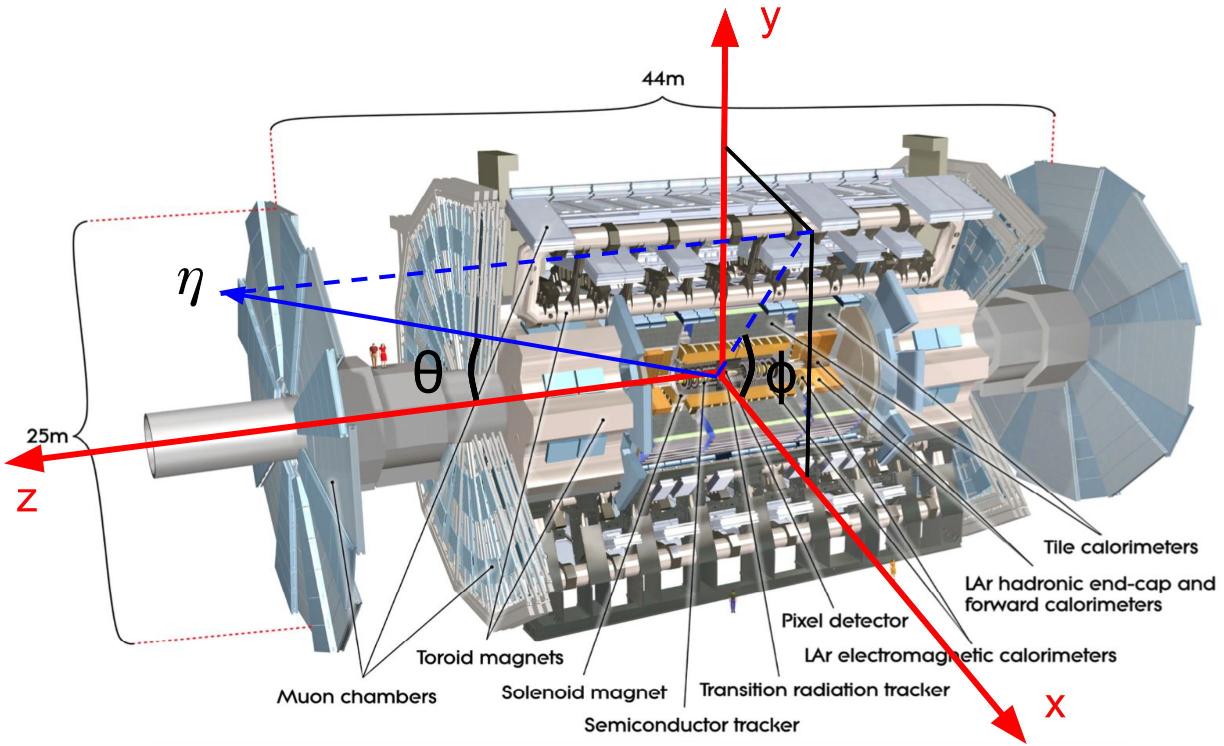

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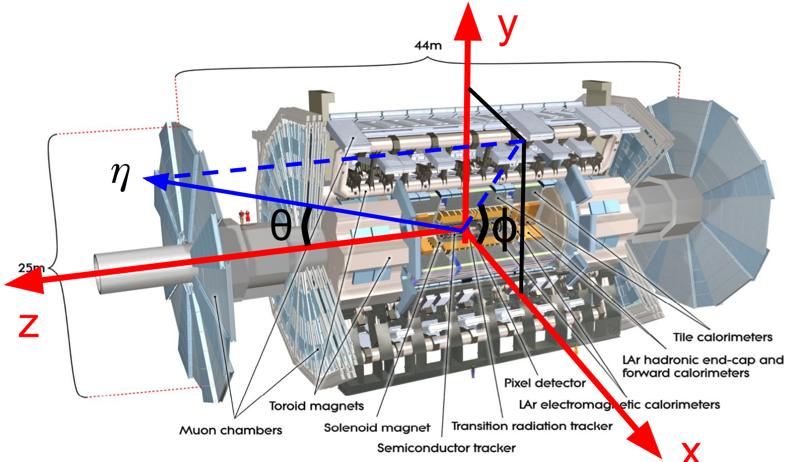
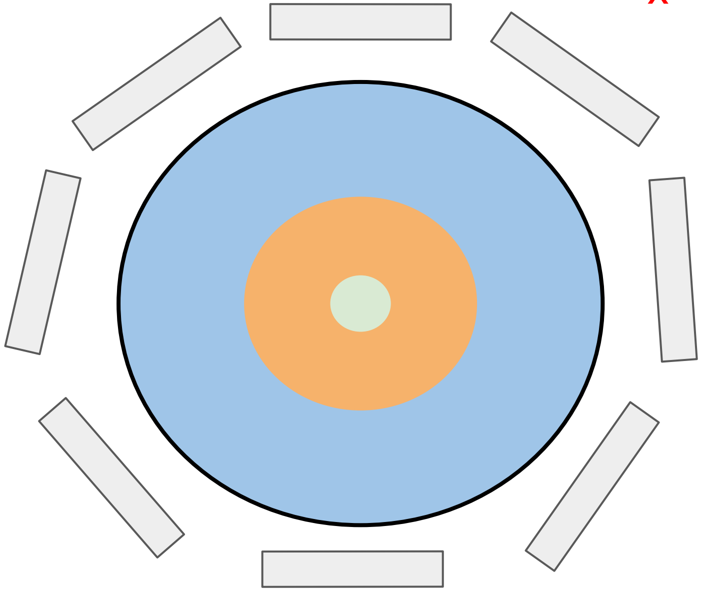
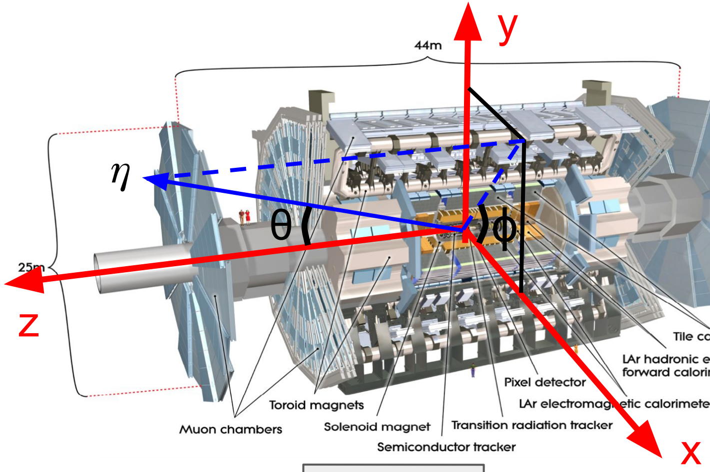
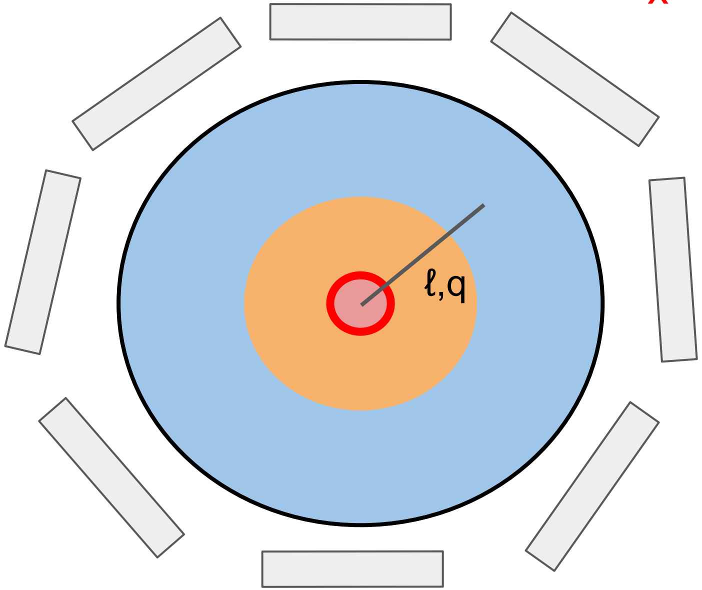




The ATLAS Detector

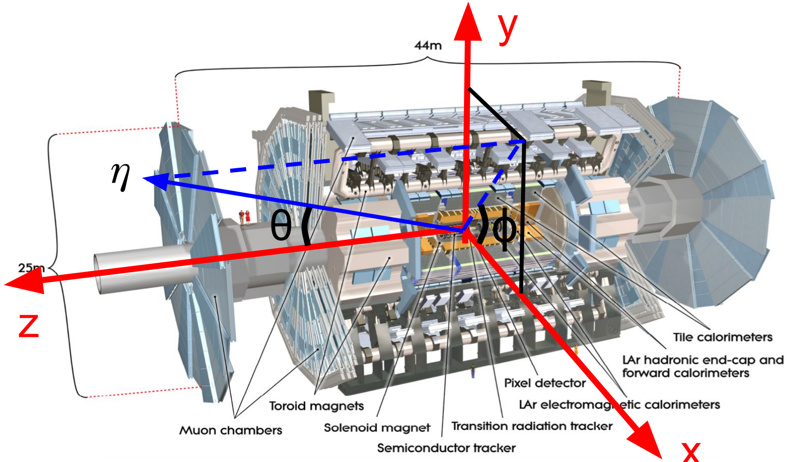
- Inner tracker detects charged particles (leptons and hadrons)

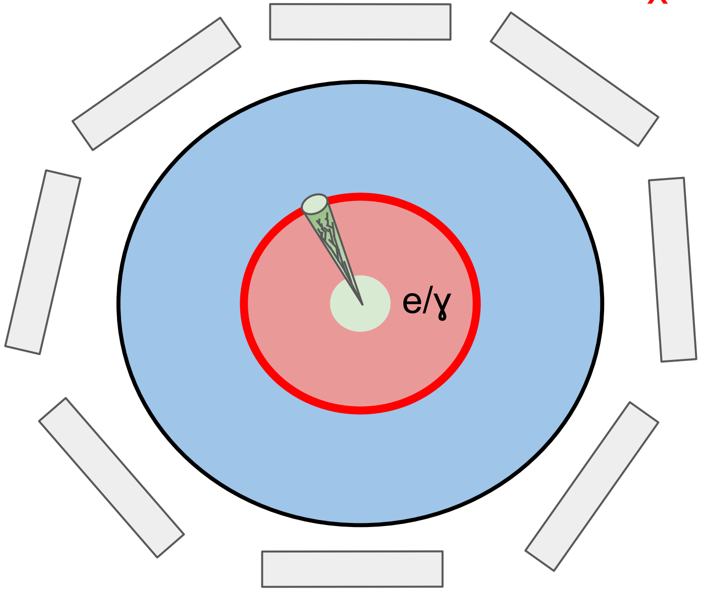




The ATLAS Detector

- Inner tracker detects charged particles (leptons and hadrons)
- Electromagnetic (EM) calorimeter detects electrons and photons (ɣ) via EM showers





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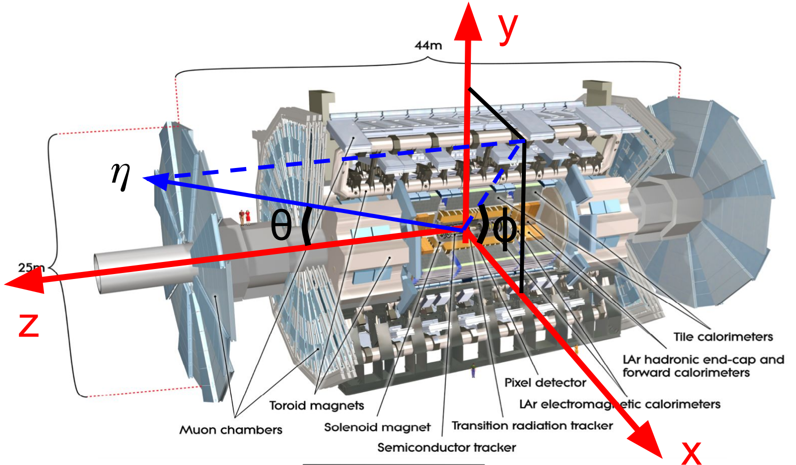
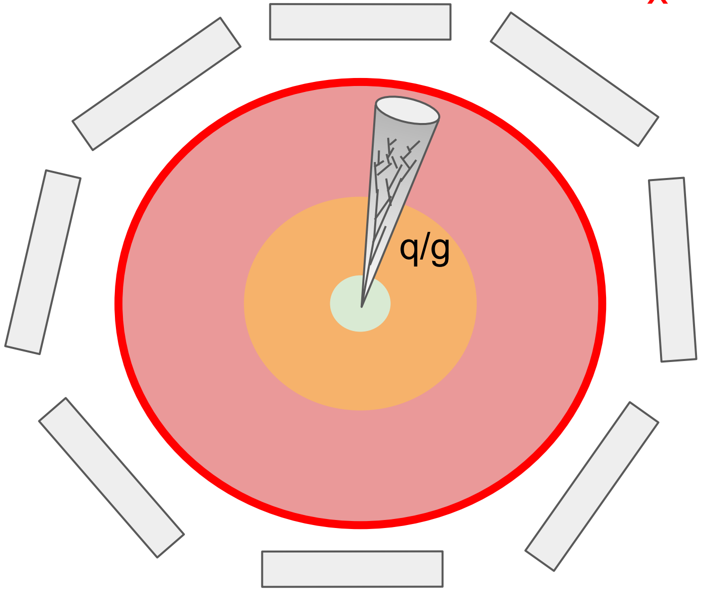
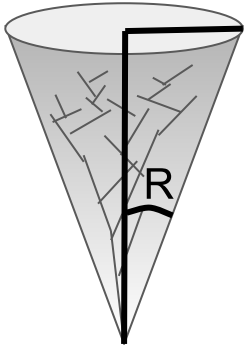


- Inner tracker detects charged particles (leptons and hadrons)
- Electromagnetic (EM) calorimeter detects electrons and photons (ɣ) via EM showers
- Hadronic calorimeter detects hadrons which pass through the EM calorimeter via hadronic showers
- Showers initiated by quarks and gluons are referred to as "jets"





Jets reconstructed in cone of angular radius R

$$R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

- "small-radius" jet: R=0.2→0.4
- "large-radius" jet: R=0.8→1.0

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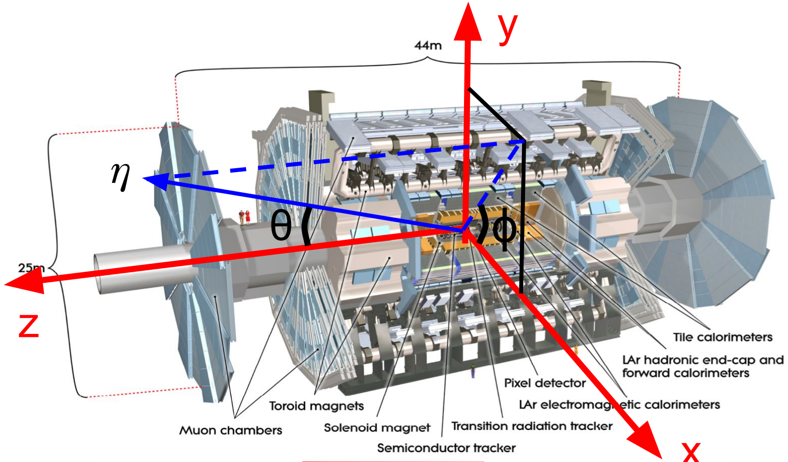

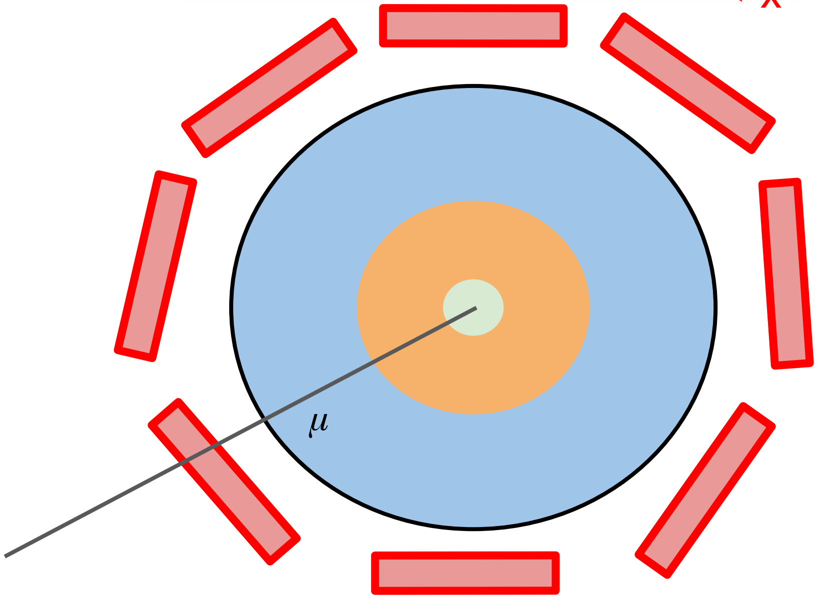

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- Inner tracker detects charged particles (leptons and hadrons)
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- Neutrinos (ν) and dark matter particles (χ) pass through undetected

  → Presence inferred from imbalance of momentum transverse to the beam line, a.k.a. E_T^{miss}