Searching for Dark Matter at ATLAS

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April 1, 2015

Outline

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2. The ATLAS Detector
   - Jets
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3. The mono-jet+$\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ analysis
   - Core analysis
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   - Future prospects
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4. Summary

Dark Matter in astrophysics

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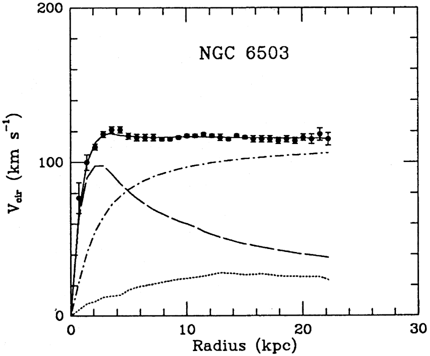
- Astrophysical measurements point to existence of invisible matter
  - Galactic rotation curves, as shown below
  - Large-scale galactic structure, Bullet Cluster
  - Precision cosmology, including the Cosmic Microwave Background
- From Newtonian gravity:
  - $v(r) = \sqrt{\frac{G_N M(r)}{r}}$
  - $M(r) = 4\pi \int^{r} \rho(r) r^2 \mathrm{d}r$
- Speed should fall off beyond region with visible matter
- This is not observed
  - Dotted lines: gas
  - Dashed lines: visible matter
  - Dash-dotted: inferred DM



Probing the nature of Dark Matter

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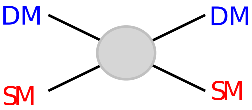
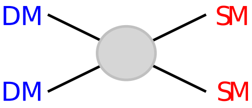
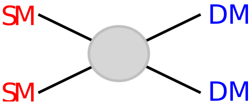
- Dark Matter (DM) has no known interactions beyond gravity
  - Electromagnetic and strong forces have already been ruled out
- What if it couples to Standard Model (SM) particles very weakly?
  - Weakly Interacting Massive Particle (WIMP) interpretation
  - Three paradigms for investigating DM under this assumption
  - Could be produced in pairs at colliders (DM is stable)



Direct detection
(WIMP-nucleon scattering)



Indirect detection
(WIMP annihilation)



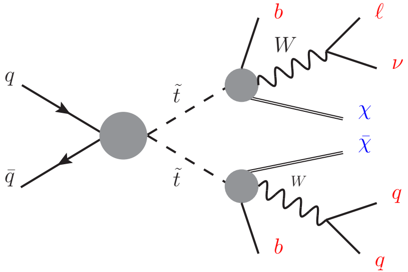
Collider searches
(WIMP pair production)

Collider searches for Dark Matter

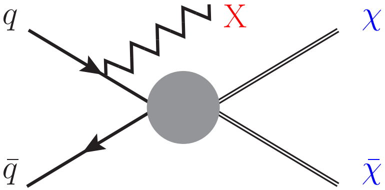
Two main strategies for DM searches at the LHC:

1. SUSY-style production of DM through decay chains
   - More model-dependent, but very sensitive to the given model
2. Direct pair-production of DM in simple final states
   - More generic approach with minimal model dependence

SUSY-style decay chain



Direct production, with a particle X



Mono-X searches for Dark Matter

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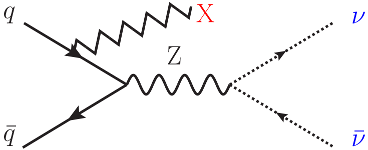
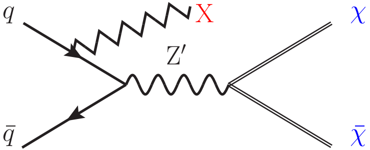
- A final state with only two DM particles is not detectable
  - Need something to balance the invisible particles
  - Exploit momentum conservation: missing transverse momentum, $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$
- Add a particle X, usually via Initial State Radiation (ISR)
  - X can be jets, photons, W/Z bosons, ...
  - Typically one ISR particle, creating mono-X $+$ $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ topologies
- Irreducible SM background: $\mathrm{Z} \rightarrow \nu\nu + \mathrm{X}$ (vs a signal $\mathrm{Z}' \rightarrow \chi\chi + \mathrm{X}$)





- The mono-jet$+\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ channel has the largest cross-section at the LHC
  - Provides an excellent means of probing DM pair-production

ATLAS and the mono-jet+E_T^{miss} analysis

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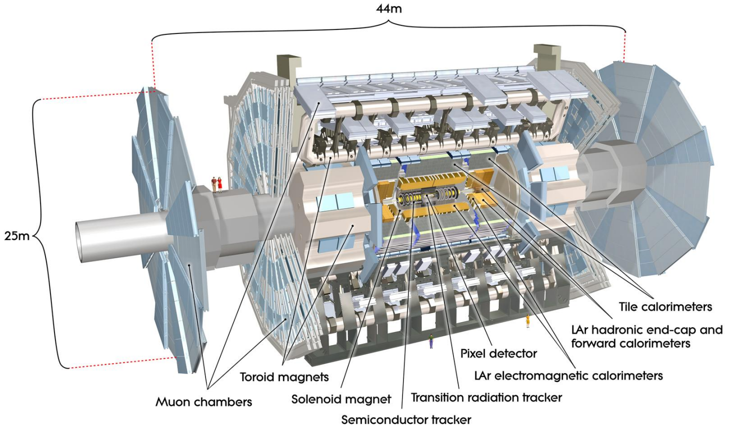
- The mono-jet+E_T^{miss} analysis depends heavily on jets and E_T^{miss}
- There are also secondary dependencies on electrons and muons
- Important to understand ATLAS measurements (reconstruction)



Particle identification in ATLAS

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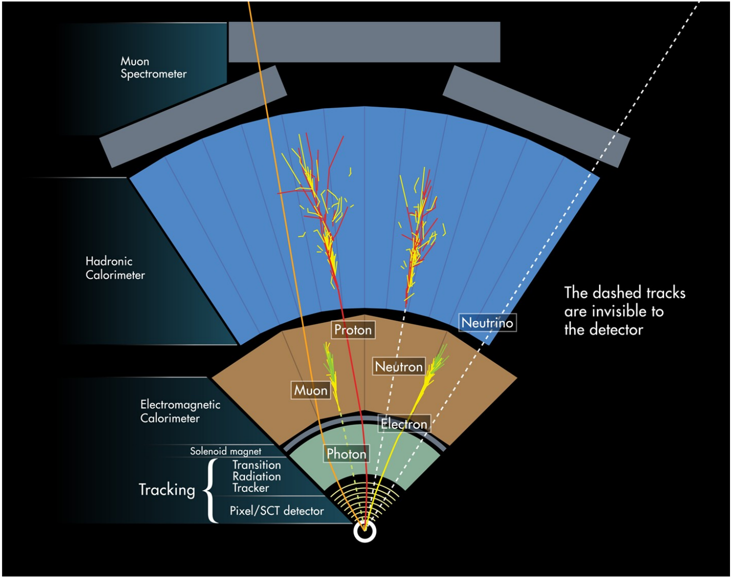

Jets in ATLAS

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- Unlike electrons and muons, jets are not a physical particle
- Jets are a useful tool to represent collimated sets of particles
  - Most commonly used to represent hadronic showers
    - Protons and neutrons both produce jets of particles in the calorimeters
    - Quarks and gluons also result in jets through hadronization
- Jets are only defined by the algorithm used to build them
- Our jet definition consists of three main pieces:
  - Inputs: clusters of energy in the calorimeters
  - Jet algorithm: Anti-k_t, start with the most energetic clusters
  - Distance parameter: allowed input separation, $\mathrm{R} = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$
- Large fraction of hadronic energy goes into *invisible* processes
  - Can be accounted for with compensating calorimeters
  - ATLAS is not compensating, must derive detailed calibrations

Jet calibration: pile-up correction

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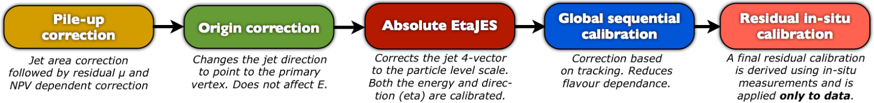
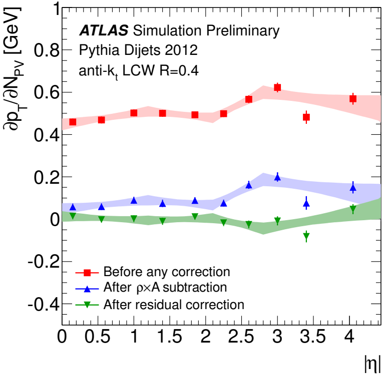


- Presence of other interactions increases jet energy due to overlapping objects (pile-up)
  - Number of vertices: $\mathrm{N_{PV}}$
  - Av. num. interactions: $\langle\mu\rangle$
- Pile-up suppression mostly removes this dependency
- $p_{\mathrm{T}}^{\mathrm{corr}} = p_{\mathrm{T}} - \rho A_{\mathrm{T}} + \alpha[\mathrm{N_{PV}} - 1] + \beta\langle\mu\rangle$
  - Jet area A_{T}
  - Event average energy density ρ
  - Average residual factors α, β



Jet calibration: origin correction

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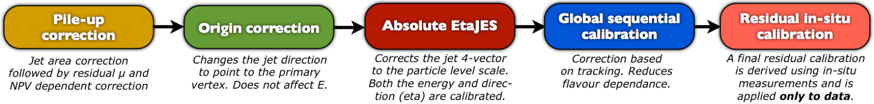

- Jets start out pointing at the nominal interaction vertex, (0,0,0)
- Correction adjusts the jet energy-weighted central axis (centroid)
  - Corrected centroid points to actual interaction vertex
- Unfortunately, no public plots are available yet

Jet calibration: MC absolute correction

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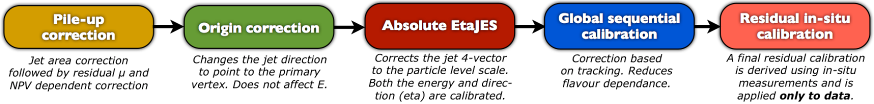
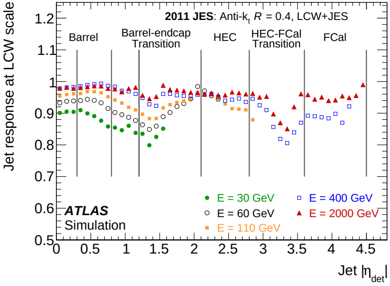


- Single largest calibration step
- Correct jets back to the *truth*
  - Derive response $\mathcal{R} = \frac{X_{\text{reco}}}{X_{\text{true}}}$
  - In this case, $X = E_{\text{jet}}$
  - Depends on E_{jet} and $|\eta_{\text{jet}}|$
- Derived in MC (requires truth)
  - Applied to data and MC
  - Assumes that MC is a good representation of data
  - Assumption validity is quantified in later steps



Jet calibration: global sequential calibration

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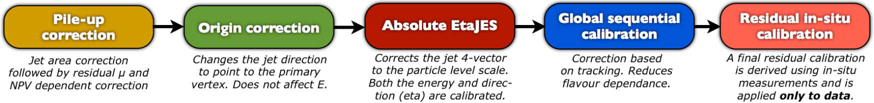
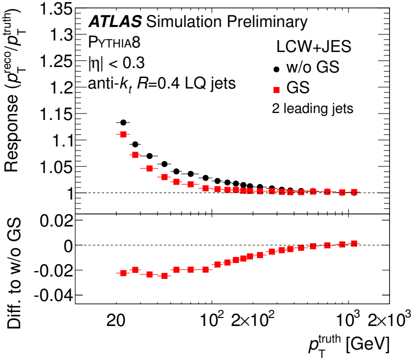


- Once again, use jet response:
  - Track variables reduce p_{T} dependence on initial parton
  - Calorimeter variables reduce jet resolution effects
  - Jets escaping calorimeters fixed with muon system info
- Largest impact at low p_{T}
- Correction for uncontained jets will become more important



Jet calibration: in-situ correction

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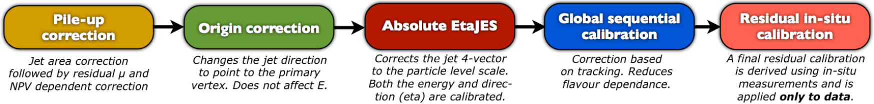
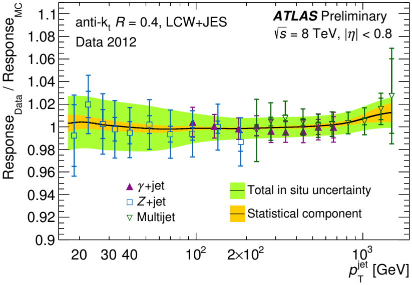


- In-situ techniques quantify agreement between data & MC
  - Remaining diff: uncertainty
- Probes p_T and η dependence
- Four techniques used:
  1. Dijet η-intercalibration [η]
  2. Z+jet balance [p_T]
  3. γ+jet balance [p_T]
  4. Multi-jet balance [p_T]
- Last three results combined



Jet uncertainties

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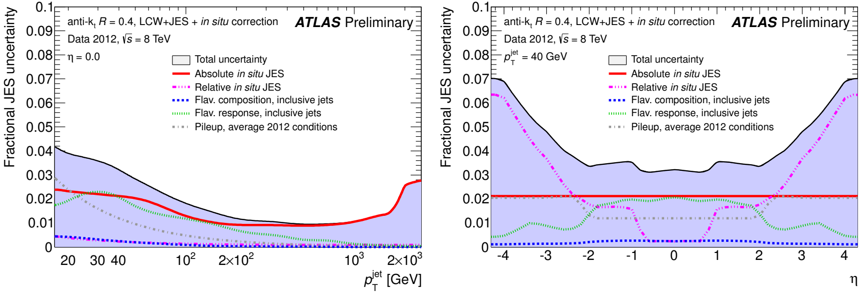
- Resulting jet uncertainties are combination of in-situ measurements
  - Depend primarily on $p_{\mathrm{T}}^{\mathrm{jet}}$ and $|\eta_{\mathrm{jet}}|$
- Results in $\mathcal{O}(70)$ independent uncertainty sources
  - This is too many for most uses, $\mathcal{O}(20)$ set is derived
  - Very little information is lost in this procedure
- Many other scenarios with varied assumptions are provided



Missing transverse momentum, E_T^{miss}

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- Particles such as neutrinos and DM escape the detector unobserved
  - Unlike other particles, they cannot be directly measured
  - Instead, they must be inferred using the conservation of momentum
- At a hadron collider, total momentum is not an observable
  - The fraction of the proton energy carried by the collision is unknown
- However, transverse momentum p_T is zero before the collision
  - Momentum in the xy plane (for a beam along the z axis)
  - After the collision, the sum of all particle p_T must also be zero
- A simple E_T^{miss} observable can thus be defined: $E_T^{miss} = -\sum p_T^{visible}$
  - Quantifies the balance of the visible sector of the event
  - Large values of E_T^{miss} is a strong indication of invisible particles

mono-jet+E_T^{miss} event display (p_T^{jet}=852 GeV)

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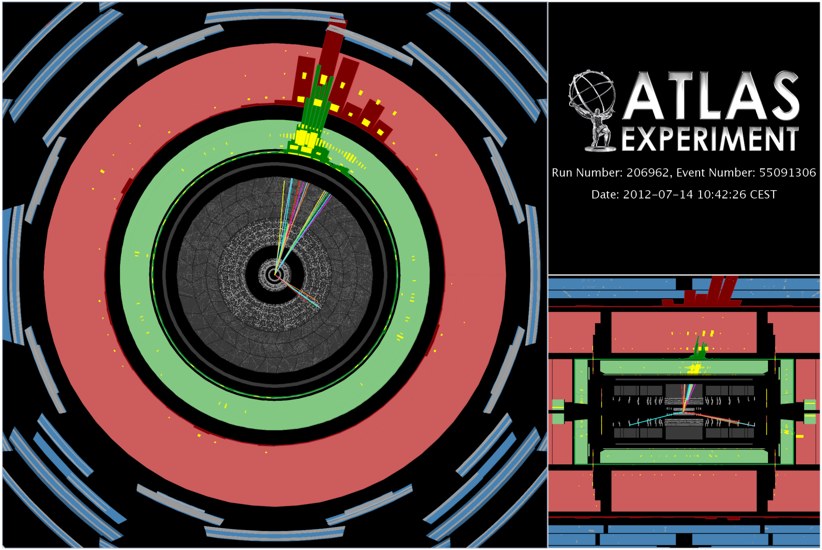

The mono-jet+E_T^{miss} analysis

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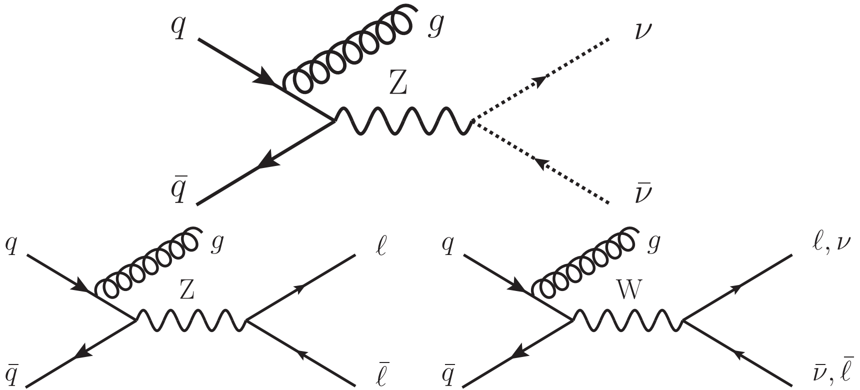
- The name suggests that a single jet is balanced by E_T^{miss}
  - This was the original motivation, but has since been expanded
  - Most recent version simply requires the leading jet to be dominant
- Simplified analysis selection:
  - E_T^{miss} trigger used to select events
  - $E_T^{miss} > 150\,\text{GeV}$
    - 200, 250, 300, 350, 400, 500, 600, 700 GeV thresholds also considered
  - $p_T^{jet1} > 120\,\text{GeV}$
  - $p_T^{jet1}/E_T^{miss} > 0.5$
  - Leading jet is central and of good quality
  - E_T^{miss} is not aligned with any jet
  - Veto events with electrons and/or muons

The $Z \to \nu\nu + \text{jets}$ background

- Dominant Standard Model (SM) background is $Z \to \nu\nu + \text{jets}$
    - Number of events must be estimated from similar final states
    - $Z \to \ell\ell + \text{jets}$ and $W \to \ell\nu + \text{jets}$ for $\ell = e, \mu$ are good choices



Data-driven $Z \to \nu\nu + \text{jets}$ estimation

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- Want to estimate number of $Z \to \nu\nu + \text{jets}$ in the *signal region* (SR)
  - Want to do this in a data-driven way to reduce uncertainties
- First select good $Z \to \ell\ell + \text{jets}$ and $W \to \ell\nu + \text{jets}$ events
  - These are *control regions* (CRs), which must be orthogonal to SR
  - Require zero leptons in SR, 1 or 2 leptons as applicable in CR
- Then consider the W/Z boson p_T for each final state:
  - $Z \to \nu\nu + \text{jets}$: $p_T^Z = p_T^{\nu_1} + p_T^{\nu_2} = E_T^{miss}$
  - $Z \to \ell\ell + \text{jets}$: $p_T^Z = p_T^{\ell_1} + p_T^{\ell_2}$
  - $W \to \ell\nu + \text{jets}$: $p_T^W = p_T^{\ell} + p_T^{\nu}$
- Use boson p_T as link between CRs and SR, estimate $Z \to \nu\nu$ in SR
  - $A = Z \to \nu\nu + \text{jets}$, $B = W \to \ell\nu + \text{jets}$ or $Z \to \ell\ell + \text{jets}$

$$N_A^{SR,DD} = \left(N_{all}^{CR,data} - N_{B,\text{not } W/Z}^{CR,MC}\right) \cdot \frac{N_A^{SR,MC}}{N_B^{CR,MC}} \cdot \frac{SF_\ell^{SR}}{SF_\ell^{CR}} \cdot \mathcal{R}_{trig}$$

Control region plots

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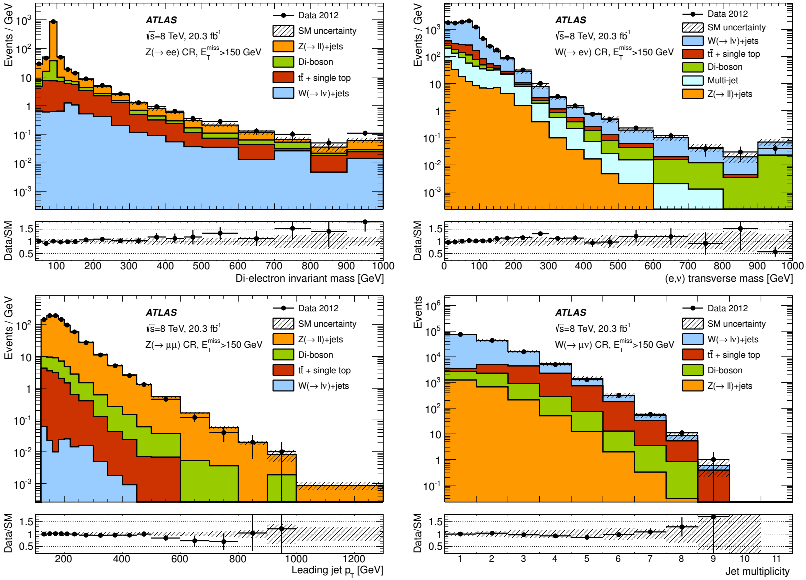

Other SM backgrounds

- $Z \to \nu\nu + \text{jets}$ is the largest SR background, but it's not alone
- $W \to \ell\nu + \text{jets}$: lepton is missed or tau decays hadronically
  - Data-driven estimation from the $W \to \ell\nu + \text{jets}$ CRs
- QCD (multijet): missed or mis-reconstructed jets give fake E_T^{miss}
  - Data-driven estimation in QCD CR, negligible at high E_T^{miss}
- Non-Collision Background (NCB): beam through the calorimeter
  - NCB tagger validated in NCB CR, negligible at high E_T^{miss}
- Top: small outside of CRs, semi-leptonic $t\bar{t}$ in $W \to \ell\nu + \text{jets}$ CRs
  - Normalization uncertainty fixed by additional $t\bar{t}$ CRs
- Diboson: small outside of CRs, naturally passes CR selections
  - Directly from MC, scale variations for uncertainties
- $Z \to \ell\ell + \text{jets}$: missed both leptons or two hadronic tau decays
  - Directly from MC, assume large conservative uncertainty

Uncertainties and results

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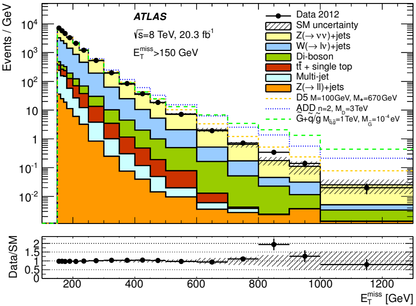
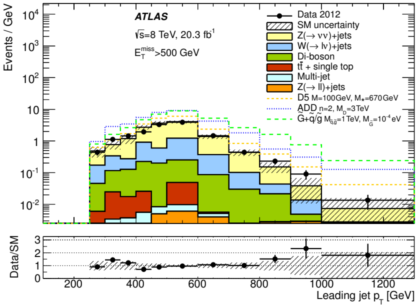
- Many E_T^{miss} cuts studied: 150,200,250,300,350,400,500,600,700 GeV
- Low E_T^{miss}: diboson and top normalization uncertainties dominate
- High E_T^{miss}: data statistics is the limitation
  - Second is the diboson and top normalization uncertainties
  - Third is theoretical uncertainties, fourth is the jet energy scale
- Demonstrates the strength of the data-driven estimation
  - Primary limitations are statistics, MC-only backgrounds, and theory





Mono-jet DM interpretation

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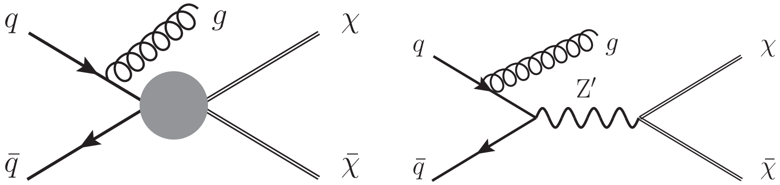
- Good agreement between data and SM expectation: set limits
  - Numbers taken from the SR (E_T^{miss} cut) providing best expected limits
- Consider Effective Field Theories (EFTs) and simplified models of DM
  - EFT: the mediator between SM and DM is beyond LHC energy scale
  - Simplified model: a specific mediator structure is considered



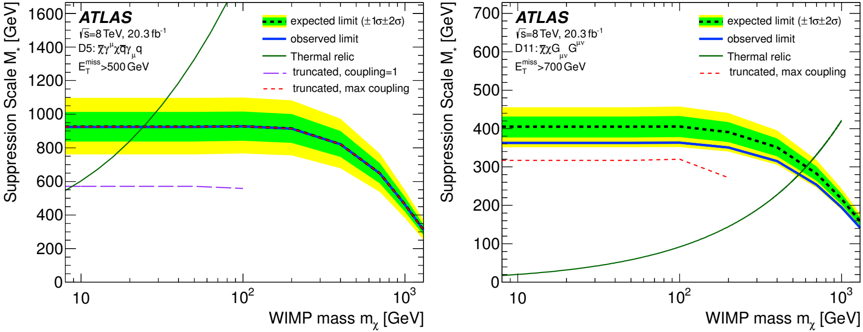
- Covered 20 EFTs and one pure vector Z'-like simplified model
  - EFTs cover many possible couplings to both fermionic and scalar DM
  - The 20 EFTs can be categorized into 5 kinematically distinct sets

EFT validity constraints

- EFTs are useful for their minimal model dependence
- However, the validity of the EFT approach is in question at the LHC
  - The mediator between the SM and dark sector may be accessible
  - Even if EFT limits are usually conservative, resulting constraints are not robust and may lead to non-perturbative couplings
- For EFT to be valid, $Q_{tr} \ll M_{med}$ (momentum transfer $\ll$ mediator mass)
  - Cannot quantify *much less than*, use minimal constraint: $Q_{tr} < M_{med}$
- However, M_{med} has been integrated out when forming the EFT
  - Only have access to the suppression scale M_*
  - Can derive $M_{med}(M_*, g_q, g_\chi)$, where g_q, g_χ are unknown couplings
    - Must be derived under the assumption of a specific UV completion
  - Scan over the permissible coupling range to probe validity
- Validity particularly important when comparing to other experiments
  - Very different energy scales: LHC $\mathcal{O}(\mathrm{TeV})$, direct detection $\mathcal{O}(\mathrm{keV})$

EFT collider results

- EFT limits are set on the suppression scale M_* for each operator
  - Two validity scenarios also shown: couplings of 1 and the perturb. limit
  - Truncated limits accounting for validity are overlaid where possible
- Two of the EFT operators considered are shown
  - Left: quark annihilation producing fermionic DM via a vector coupling
  - Right: gluon fusion producing fermionic DM via a scalar coupling



EFT comparisons to other experiments

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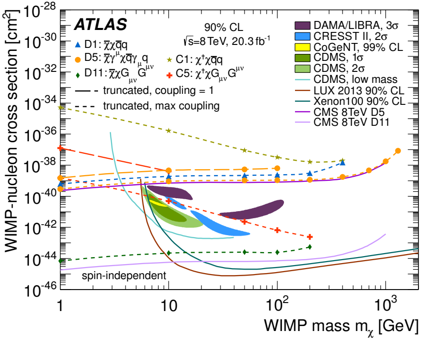
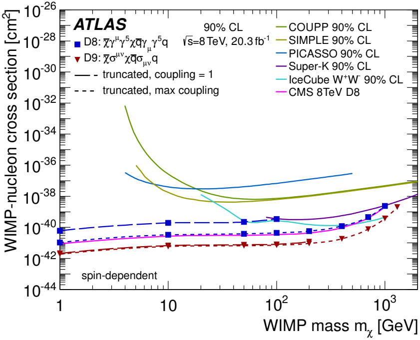
- M_* then translated into limits on $\sigma^{\mathrm{scattering}}_{\mathrm{WIMP-nucleon}}$ and $\sigma^{\mathrm{annihilation}}_{\mathrm{WIMP-WIMP}}$
- In this case, validity is enforced due to different energy scales
  - All ATLAS lines shown include validity constraints





Simplified model results

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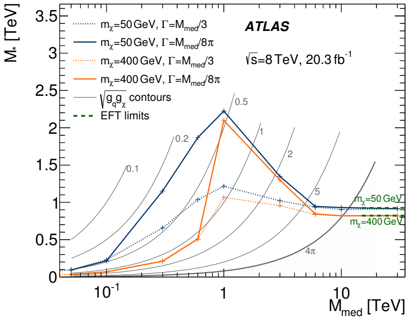
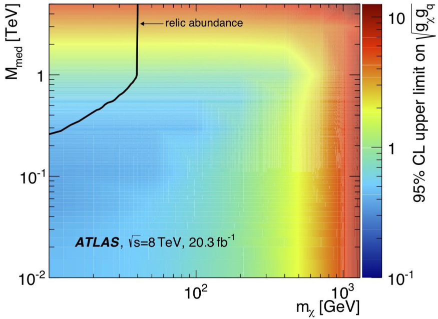
- Simplified model limits are set on geometric average coupling $\sqrt{g_q g_\chi}$
- Comparison to relevant EFT limit shows importance of the resonance
- Full scan over mediator and DM mass also performed
- Note: relic abundance line only provides general idea of expectations
  - Multiple particle dark sector: larger coupling values allowed
  - Multiple connections to dark sector: smaller coupling values allowed





Mono-jet expectations at an upgraded LHC

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Event selection:

	8 TeV	14 TeV
N_{jets}	1 or 2	
p_T^{jet}	30 GeV	50 GeV
p_T^{jet1}	120 GeV	300 GeV
$\Delta\phi$	$\Delta\phi(\text{jet}, E_T^{\text{miss}}) > 0.5$	
ℓ veto	Veto on e, μ	
E_T^{miss}	400, 600, 800 GeV	

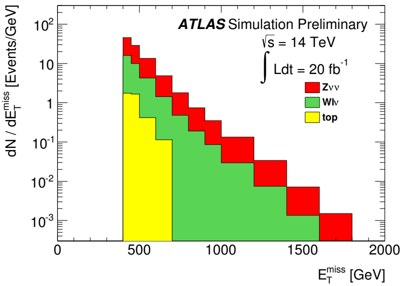
Main backgrounds:

- Pure MC, both 8 and 14 TeV
- $Z \to \nu\nu + \text{jets}$: irreducible
- $W \to \ell\nu + \text{jets}$: missed ℓ, τ_{had}
- Top included, not diboson

Uncertainties considered:

- Two flat systematics studied:
  - 5%, reasonable early Run-II
  - 1%, ultimate HL-LHC goal
- Statistics varies with lumi
  - 5, 20/25, 300, 3000 fb^{-1}

14 TeV signal region



Sensitivity projections

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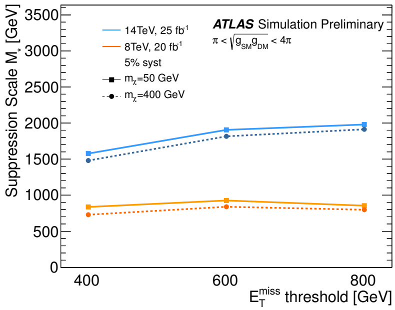
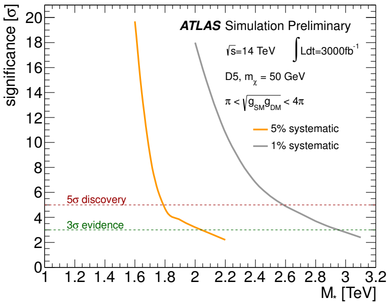
- Limits improve by factor of 2 with first ~year of 14 TeV data
- Reducing systematics doesn't help too much yet - need lumi
- E_T^{miss} threshold limited by lumi

- 5σ discovery potential out to $M_* \approx 2.5\,\mathrm{TeV}$ with HL-LHC
  - Aggressive 1% systematic
- Systematics dominated:
  - Limited impact of additional data, need higher E_T^{miss} cuts

$25\,\mathrm{fb}^{-1}$ limit strength



$3000\,\mathrm{fb}^{-1}$ discovery potential



Summary

- Astrophysics provides compelling evidence for the existence of DM
- If DM is a Weakly Interacting Massive Particle (WIMP) and isn't too heavy, the LHC can produce pairs of DM particles
- The mono-jet topology is an excellent WIMP DM search channel
- The 8 TeV mono-jet analysis is now complete
  - No significant deviations with respect to the SM were observed
  - Limits are set on both DM EFTs and a Z' simplified model
  - EFT validity constraints are considered/required as appropriate
- First sensitivity studies of the mono-jet analysis at 14 TeV conducted
  - Factor of 2 improvement with first expected year of data
  - Further improvements less dramatic, depends more on $\sqrt{s}$ than $\int\mathcal{L}\,\mathrm{d}t$

Backup Material

Mono-jet selection

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Pre-selection

Selection type	SR	$Z \to \mu\mu$ CR	$W \to \mu\nu$ CR	$Z \to ee$ CR	$W \to e\nu$ [Z] CR	$W \to e\nu$ [W] CR
Trigger	EF_xe80_tclcw			EF_e24vhi_medium1 || EF_e60_medium1		EF_xe80_tclcw
Event cleaning	As recommended by the DQ group					
Leading jet	$p_{\mathrm{T}} > 120\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.0$, $f_{\mathrm{ch}}/f_{\mathrm{max}} > 0.1$					
Jet cleaning	No *looser* bad jets					
Tile cleaning	Jet 1 and 2 not pointing to masked modules, others pass cleaning cuts					
Leptons	$\varnothing$	$2\mu, 0e$	$1\mu, 0e$	$0\mu, 2e$	$0\mu, 1e$	$0\mu, 1e$
Track veto	Veto on any track not identified as a lepton					
Observable > 150 GeV	$\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{Z}} \equiv \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{W}} \equiv \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{Z}} \equiv \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}} - \sum p_{\mathrm{T}}^{e}$	$p_{\mathrm{T}}^{\mathrm{W}} \equiv \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{e}$	$\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$

Region-specific selection

Selection type	SR	$Z \to \mu\mu$ CR	$W \to \mu\nu$ CR	$Z \to ee$ CR	$W \to e\nu$ [Z] CR	$W \to e\nu$ [W] CR
Trigger	EF_xe80_tclcw			EF_e24vhi_medium1 || EF_e60_medium1		EF_xe80_tclcw
Observable	$\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{Z}} \equiv \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{W}} \equiv \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{Z}} \equiv \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}} - \sum p_{\mathrm{T}}^{e}$	$p_{\mathrm{T}}^{\mathrm{W}} \equiv \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{e}$	$\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$
Region threshold	Observable > {150, 200, 250, 300, 350, 400, 500, 600, 700} GeV, region numbers 1 to 9					
QCD/top rejection	$\Delta\phi$ (observable, jets) > 1.0 for all jets, (leading jet p_{T}) / (observable) > 0.5					
Lepton selection	$0\mu, 0e$	$2\mu, 0e$	$1\mu, 0e$	$0\mu, 2e$	$0\mu, 1e$	$0\mu, 1e$
Boson cuts [GeV]	$\varnothing$	$66 < \mathrm{m}_{\mu\mu} < 116$	$40 < \mathrm{m}_{\mathrm{T}}^{\mu} < 100$	$66 < \mathrm{m}_{ee} < 116$	$40 < \mathrm{m}_{\mathrm{T}}^{e} < 100$	$\varnothing$
Additional cuts	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$	$\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}} > 25\,\mathrm{GeV}$	$\varnothing$

Mono-jet event yields

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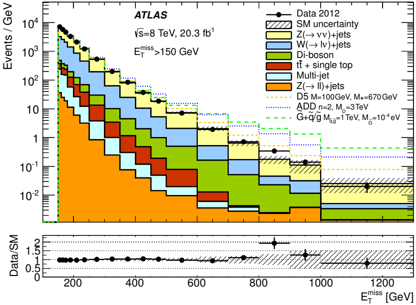
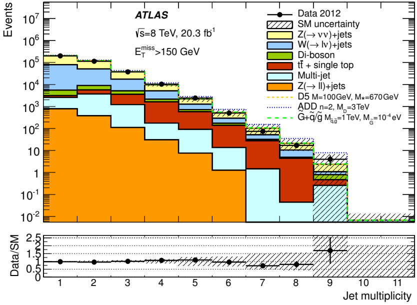
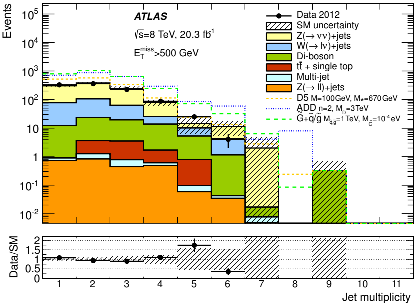
Process	Estimation method	Signal region E_T^{miss} threshold [GeV] 150	200	250	300	350	400	500	600	700
$Z \to \nu\nu$ + jets	$W \to \mu\nu$ CR	216900 ± 6862	77831 ± 3096	28889 ± 1346	11999 ± 660	5451 ± 414	2649 ± 219	757 ± 90	228 ± 39	75 ± 16
$Z \to \nu\nu$ + jets	$W \to e\nu$ [Z] CR	219023 ± 9833	77953 ± 3883	29407 ± 1675	12399 ± 831	5484 ± 489	2673 ± 260	738 ± 101	247 ± 40	84 ± 19
$Z \to \nu\nu$ + jets	$Z \to \mu\mu$ CR	217770 ± 4178	80402 ± 1864	30142 ± 871	12614 ± 494	5959 ± 317	2907 ± 201	778 ± 102	195 ± 50	38 ± 24
$Z \to \nu\nu$ + jets	$Z \to ee$ CR	217919 ± 6124	80346 ± 2348	30904 ± 1070	13313 ± 568	6082 ± 333	3091 ± 212	699 ± 91	313 ± 59	115 ± 36
$Z \to \nu\nu$ + jets	BLUE	217768 ± 3907	80143 ± 1674	30244 ± 762	12771 ± 406	5943 ± 244	2906 ± 147	741 ± 64	235 ± 29	71 ± 13
$W \to \tau\nu$ + jets	$W \to e\nu$ [W] CR	79344 ± 3303	23830 ± 1204	7717 ± 468	2761 ± 205	1166 ± 107	542 ± 57	133 ± 19	34 ± 8	11 ± 3
$W \to e\nu$ + jets	$W \to e\nu$ [W] CR	23547 ± 1729	7129 ± 559	2374 ± 198	875 ± 83	367 ± 39	168 ± 21	43 ± 7	9 ± 3	3 ± 1
$W \to \mu\nu$ + jets	$W \to \mu\nu$ CR	28340 ± 1558	8211 ± 532	2517 ± 193	852 ± 79	332 ± 38	141 ± 20	35 ± 6	10 ± 2	2 ± 1
$Z \to \tau\tau$ + jets	MC	783 ± 323	184 ± 76	45 ± 19	14 ± 6	5 ± 2	2 ± 1	0 ± 0	0 ± 0	0 ± 0
$Z \to ee$ + jets	MC	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
$Z \to \mu\mu$ + jets	MC	527 ± 224	97 ± 42	19 ± 8	7 ± 3	4 ± 2	3 ± 1	2 ± 1	1 ± 1	1 ± 0
Top	MC	6901 ± 1407	2320 ± 491	681 ± 163	198 ± 66	75 ± 41	32 ± 20	7 ± 7	1 ± 1	0 ± 0
Diboson	MC	7983 ± 1737	3491 ± 838	1507 ± 402	685 ± 204	351 ± 117	183 ± 70	65 ± 35	23 ± 16	8 ± 7
Multi-jet	Data-driven	6453 ± 6453	785 ± 785	177 ± 177	44 ± 44	15 ± 15	6 ± 6	1 ± 1	0 ± 0	0 ± 0
Non-collision	Data-driven	449 ± 449	47 ± 47	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Total expected	$Z \to \nu\nu$ from $W \to \mu\nu$	371226 ± 11986	123925 ± 4254	43926 ± 1679	17435 ± 780	7765 ± 465	3725 ± 237	1044 ± 89	307 ± 39	101 ± 16
Total expected	$Z \to \nu\nu$ from $Z \to \mu\mu$	372097 ± 9733	126496 ± 2787	45178 ± 1113	18050 ± 565	8274 ± 348	3983 ± 210	1065 ± 101	273 ± 49	64 ± 24
Total expected	$Z \to \nu\nu$ from $W \to e\nu$ [Z]	373349 ± 14557	124047 ± 5099	44444 ± 2049	17835 ± 973	7798 ± 554	3749 ± 289	1025 ± 107	325 ± 45	110 ± 22
Total expected	$Z \to \nu\nu$ from $Z \to ee$	372245 ± 11599	126440 ± 3474	45941 ± 1392	18750 ± 668	8397 ± 368	4168 ± 226	986 ± 90	391 ± 57	141 ± 35
Total expected	$Z \to \nu\nu$ from BLUE	372094 ± 9941	126237 ± 2864	45281 ± 1094	18207 ± 514	8257 ± 286	3982 ± 164	1028 ± 64	313 ± 30	97 ± 14
Data		364378	123228	44715	18020	7988	3813	1028	318	126

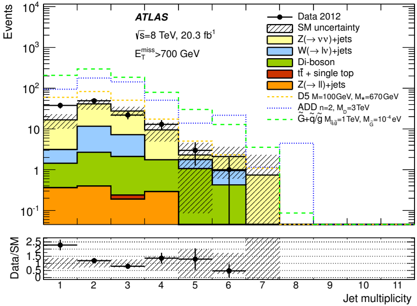
Mono-jet results, SR1





Mono-jet results, SR7 and SR9, Njets





Mono-jet results, SR7 and SR9, jet p_T

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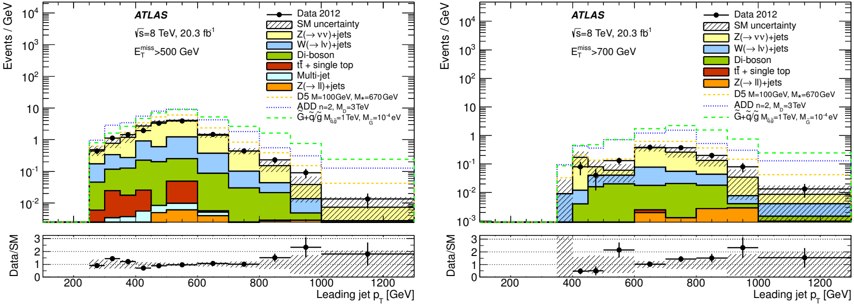

Mono-jet results, SR7 and SR9, $p_T^{\mathrm{jet1}}/E_T^{\mathrm{miss}}$

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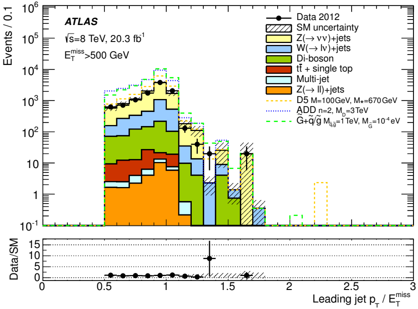

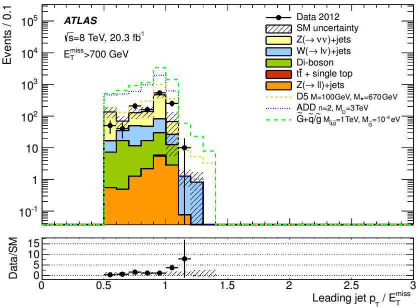

DM: EFT operators

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Name	Operator	Name	Operator
D1	$\frac{m_q}{(\mathrm{M}_*)^3}\bar{\chi}\chi\bar{q}q$	D2	$\frac{im_q}{(\mathrm{M}_*)^3}\bar{\chi}\gamma^5\chi\bar{q}q$
D3	$\frac{im_q}{(\mathrm{M}_*)^3}\bar{\chi}\chi\bar{q}\gamma^5 q$	D4	$\frac{m_q}{(\mathrm{M}_*)^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$
D5	$\frac{1}{(\mathrm{M}_*)^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	D6	$\frac{1}{(\mathrm{M}_*)^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$
D7	$\frac{1}{(\mathrm{M}_*)^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	D8	$\frac{1}{(\mathrm{M}_*)^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	$\frac{1}{(\mathrm{M}_*)^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	D10	$\frac{i}{(\mathrm{M}_*)^2}\epsilon_{\mu\nu}{}^{\alpha\beta}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\alpha\beta} q$
D11	$\frac{\alpha_s}{4(\mathrm{M}_*)^3}\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	D12	$\frac{i\alpha_s}{4(\mathrm{M}_*)^3}\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$
D13	$\frac{i\alpha_s}{4(\mathrm{M}_*)^3}\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	D14	$\frac{\alpha_s}{4(\mathrm{M}_*)^3}\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$

Name	Operator	Name	Operator
C1	$\frac{m_q}{(\mathrm{M}_*)^2}\chi^\dagger\chi\bar{q}q$	C2	$\frac{im_q}{(\mathrm{M}_*)^2}\chi^\dagger\chi\bar{q}\gamma^5 q$
C3	$\frac{1}{(\mathrm{M}_*)^2}\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	C4	$\frac{i}{(\mathrm{M}_*)^2}\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$
C5	$\frac{\alpha_s}{4(\mathrm{M}_*)^2}\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	C6	$\frac{i\alpha_s}{4(\mathrm{M}_*)^2}\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$

DM: EFT representative operator plots

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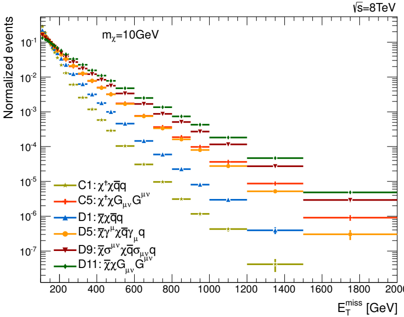
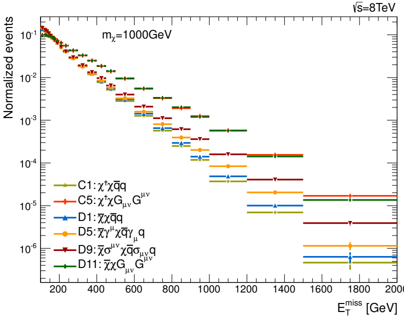
Name	Coupling	Parton type	DM type	Operator
D1	Scalar coupling	Quarks	Fermion	$\frac{m_q}{(\mathrm{M}_*)^3}\bar{\chi}\chi\bar{q}q$
C1	Scalar coupling	Quarks	Scalar	$\frac{m_q}{(\mathrm{M}_*)^2}\chi^\dagger\chi\bar{q}q$
D5, C3	Vector coupling	Quarks	Fermion, Scalar	$\frac{1}{(\mathrm{M}_*)^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$, $\frac{1}{(\mathrm{M}_*)^2}\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$
D9	Tensor coupling	Quarks	Fermion	$\frac{1}{(\mathrm{M}_*)^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	Scalar coupling	Gluons	Fermion	$\frac{\alpha_s}{4(\mathrm{M}_*)^3}\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$
C5	Scalar coupling	Gluons	Scalar	$\frac{\alpha_s}{4(\mathrm{M}_*)^2}\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$





DM: EFT validity procedure, summary

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Operator(s)	Relation between $\mathrm{M_{med}}$ and $\mathrm{M_*}$	Coupling term range
D1	$\mathrm{M_{med}} = \sqrt{y_\mathrm{q} g_\chi}\ \sqrt{\mathrm{M_*^3/m}_q}$	$\sqrt{y_\mathrm{q} g_\chi} \in (0, 4\pi)$
C1	$\mathrm{M_{med}} = y_\mathrm{q} \lambda_\chi \zeta_\lambda\ \mathrm{M_*^2/m}_q$	$y_\mathrm{q} \lambda_\chi \zeta_\lambda \in \left(0, [4\pi]^2 \cdot \zeta_\lambda\right)$
D5, D8, D9	$\mathrm{M_{med}} = \sqrt{g_\mathrm{q} g_\chi}\ \mathrm{M_*}$	$\sqrt{g_\mathrm{q} g_\chi} \in (0, 4\pi)$
C3	$\mathrm{M_{med}} = \sqrt{g_\mathrm{q} \lambda_\chi}\ \mathrm{M_*}$	$\sqrt{g_\mathrm{q} \lambda_\chi} \in (0, 4\pi)$
D11	$\mathrm{M_{med}} = \sqrt[3]{a g_\chi}\ \mathrm{M_*}$	$\sqrt[3]{a g_\chi} \in \left(0, \sqrt[3]{16\pi}\right)$
C5	$\mathrm{M_{med}} = \sqrt{a \lambda_\chi \zeta_\lambda}\ \mathrm{M_*}$	$\sqrt{a \lambda_\chi \zeta_\lambda} \in \left(0, 4\sqrt{\pi \zeta_\lambda}\right)$

Note: assumed that $\zeta_\lambda = 1$

DM: EFT validity procedure, cross-section

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1. Construct the $\mathrm{Q_{tr}}$ distribution for a given MC sample
2. Scan over $\mathrm{M_*}$ and compare to the $\mathrm{Q_{tr}}$ distribution, determining $R^{\mathrm{tot}}_{\mathrm{M_{med}}}$ for each value of $\mathrm{M_*}$
3. Rescale the nominal expected/observed limit on the cross-section of each signal sample, $\sigma_{\mathrm{exp}}(\mathrm{M_*})$, so that it corresponds to only the valid events: $\sigma_{\mathrm{valid}}(\mathrm{M_*}) = \sigma_{\mathrm{exp}}(\mathrm{M_*}) \cdot R^{\mathrm{tot}}_{\mathrm{M_{med}}}(\mathrm{M_*})$.
4. Determine the point where σ_{valid} and the experimental limit on the visible cross-section σ_{vis} meet, and take the corresponding $\mathrm{M_*}$ value as the truncated limit on the suppression scale $\mathrm{M_*^{valid}}$.

DM: EFT validity procedure, rescaling

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1. Start with the nominal expected/observed limit on M_* assuming 100% validity, named $\mathrm{M}_*^{\mathrm{exp}}$.
2. For each step i, obtain the relative fraction of valid events $R^{\mathrm{i}}_{\mathrm{M}_{\mathrm{med}}}$ satisfying $\mathrm{Q}_{\mathrm{tr}} < \mathrm{M}^{\mathrm{in}}_{\mathrm{med}}$ with respect to all events passing the previous iteration. $\mathrm{M}^{\mathrm{in}}_{\mathrm{med}}$ is the mediator mass limit obtained in the previous step, which depends on $\mathrm{M}_*^{\mathrm{in}}$. For the first step, $\mathrm{M}_*^{\mathrm{in}} = \mathrm{M}_*^{\mathrm{exp}}$.
3. Rescale M_*: $\mathrm{M}_*^{\mathrm{out}} = \left[R^{i}_{\mathrm{M}_{\mathrm{med}}}\right]^{1/2(d-4)} \mathrm{M}_*^{\mathrm{in}}$, noting that D1 and D11 are dimension $d = 7$ operators, while D5, D9, C1, and C5 are dimension $d = 6$.
4. Go to step 2, using the current $\mathrm{M}_*^{\mathrm{out}}$ as the new $\mathrm{M}_*^{\mathrm{in}}$, repeating until the fraction of valid events at a given step $R^{\mathrm{i}}_{\mathrm{M}_{\mathrm{med}}}$ reaches 0 or 1.
5. Calculate the total validity fraction $R^{\mathrm{tot}}_{\mathrm{M}_{\mathrm{med}}} = \prod_i R^{\mathrm{i}}_{\mathrm{M}_{\mathrm{med}}}$ and the final rescaled limit on the suppression scale $\mathrm{M}_*^{\mathrm{valid}} = \left[R^{\mathrm{tot}}_{\mathrm{M}_{\mathrm{med}}}\right]^{1/2(d-4)} \mathrm{M}_*^{\mathrm{exp}}$.

DM: EFT validity, D1 and C1

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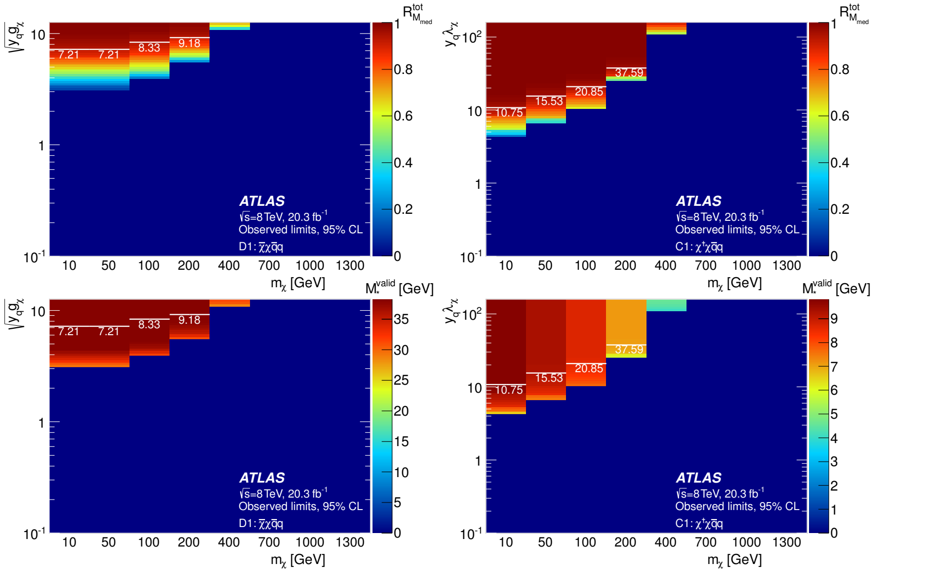

DM: EFT validity, D5 and D8

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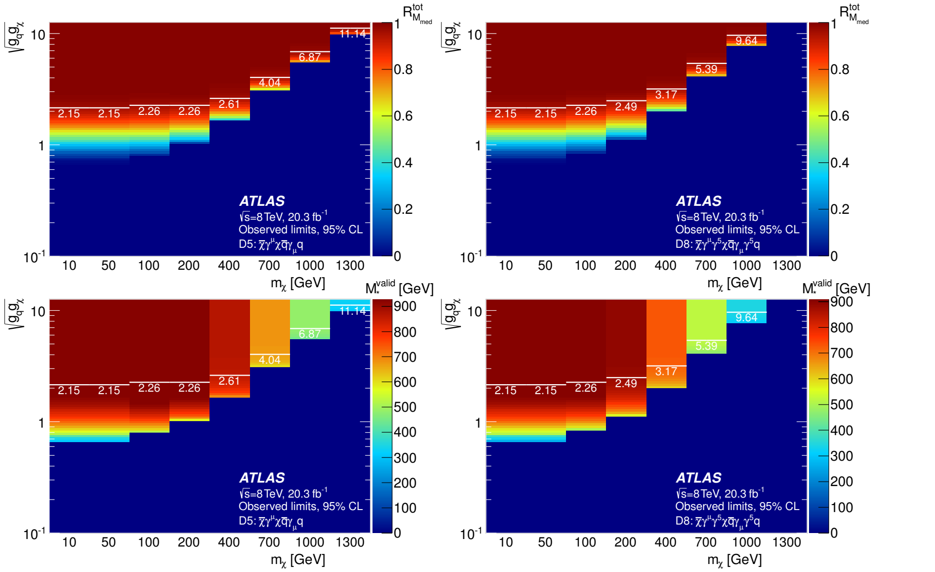
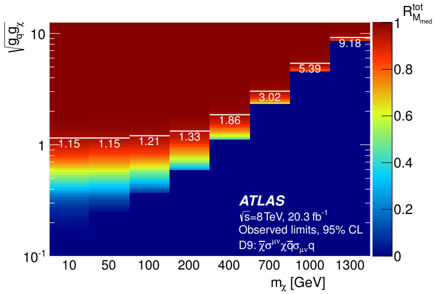
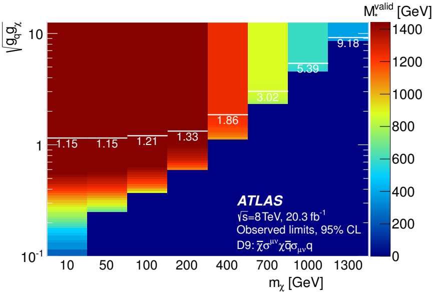


DM: EFT validity, D9





DM: EFT validity, D11 and C5

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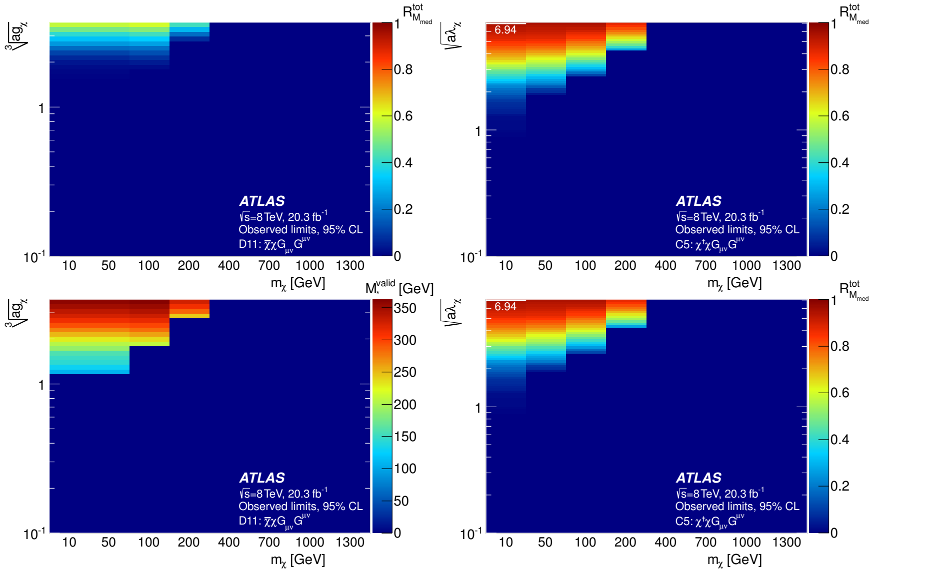

DM: EFT limits, D1, C1, D5, D8

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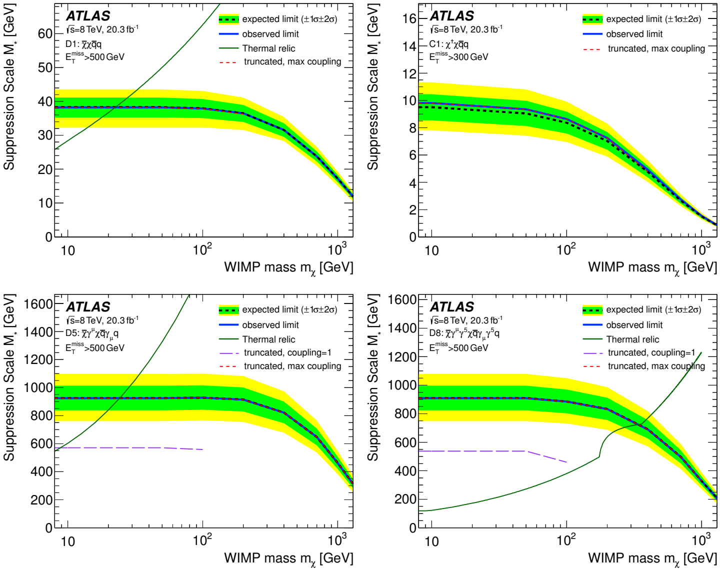

DM: EFT limits, D9, D11, C5

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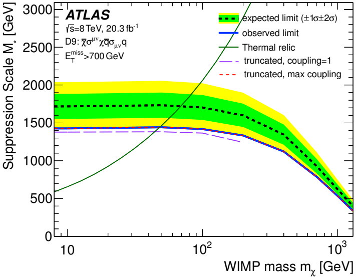

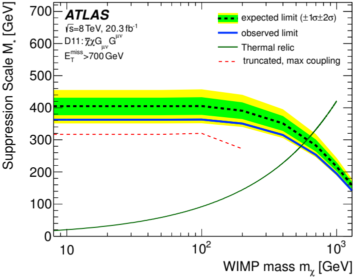

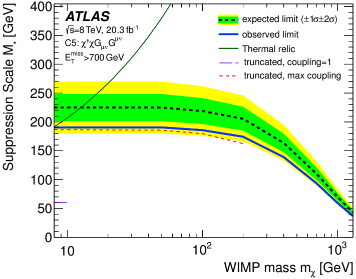

DM: EFT limits, WIMP-nucleon

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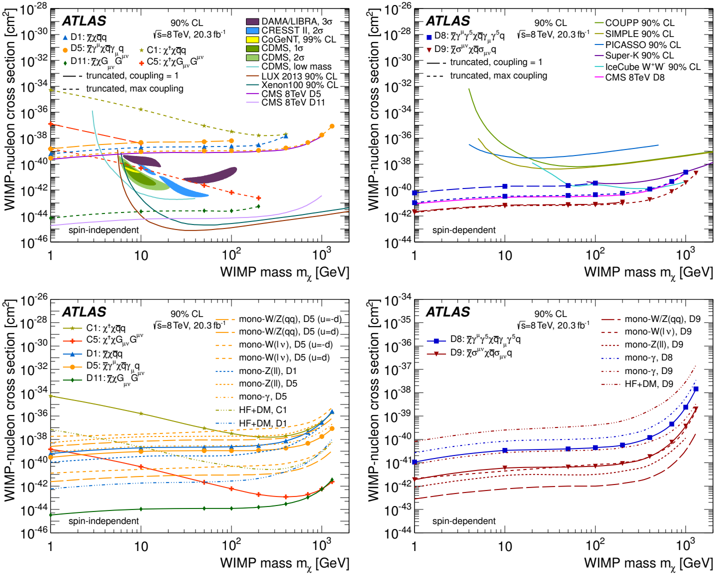

DM: EFT limits, other

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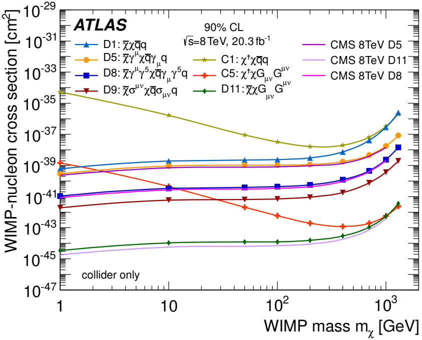

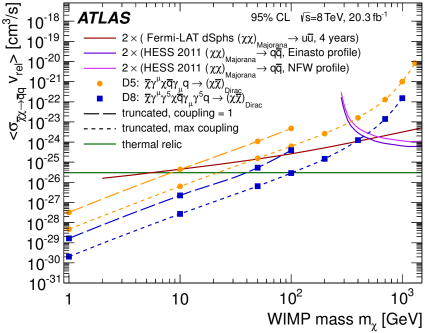

Prospects: EFT limits (5% syst top, 1% syst bot)

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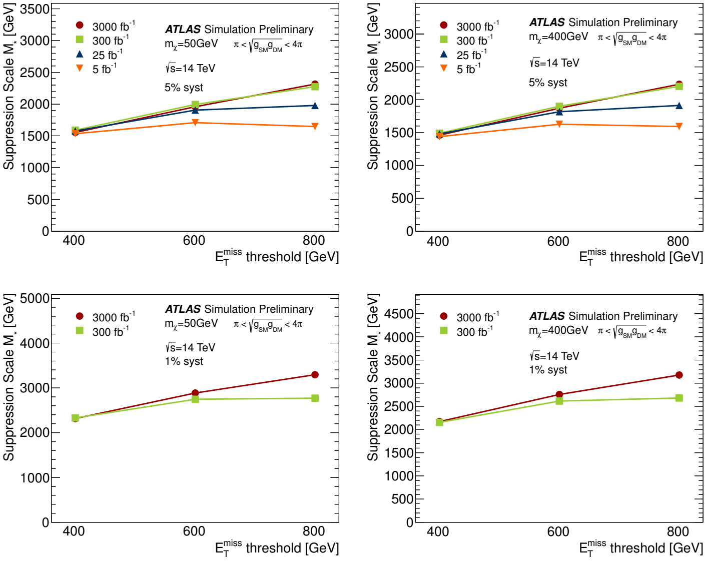
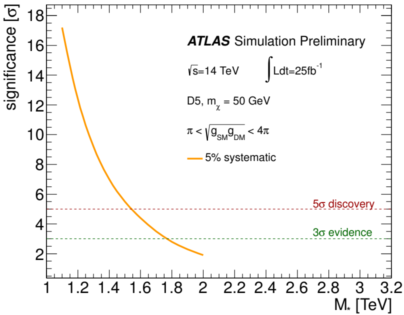
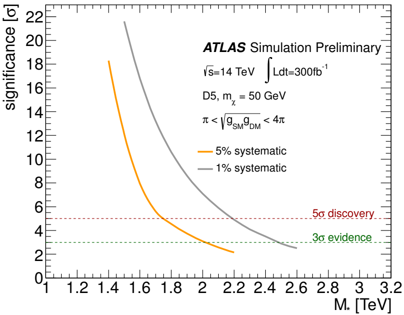


Prospects: Discovery potential





Prospects: EFT validity

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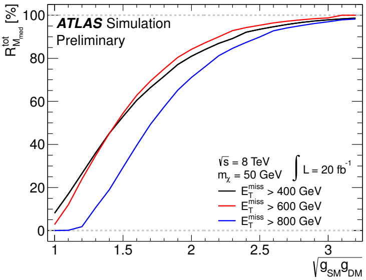

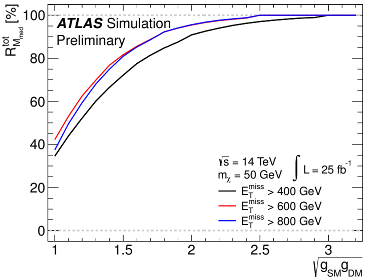

Prospects: Z' model limits

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