Dark Side of the Universe 2016

Dark Matter Searches in ATLAS

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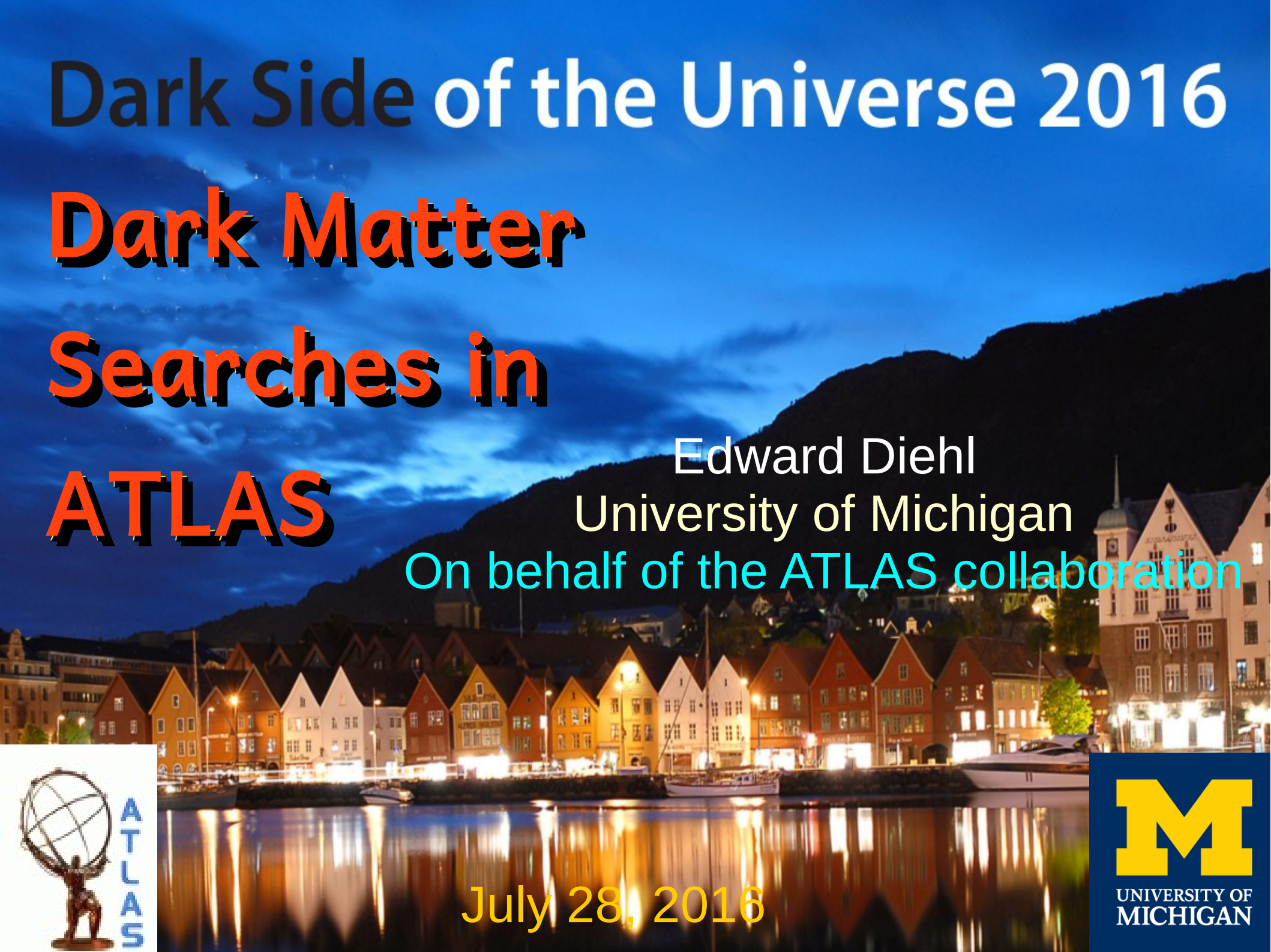
On behalf of the ATLAS collaboration

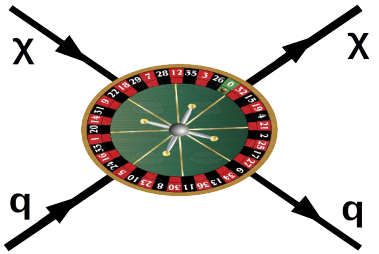


July 28, 2016

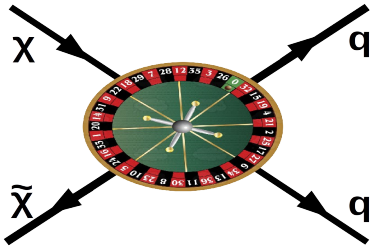
Dark Matter Detection

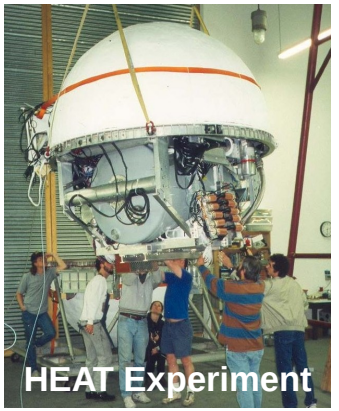
"It takes gray matter to find dark matter"

- Direct detection
  - Nuclear recoil from DM particle interactions.
  - Exclusion limits by: PICO-2L, Xenon100, LUX, SuperCDMS, PICASSO...

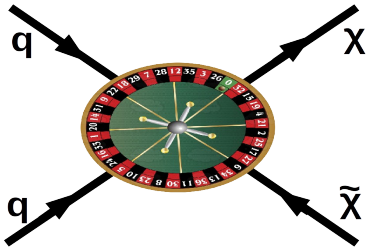


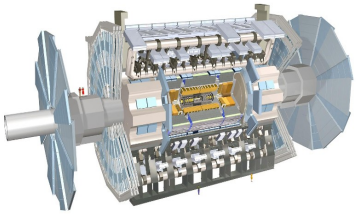
- Indirect astrophysical detection
  - eg, positron excess HEAT, PAMELA, AMS
  - as WIMP-WIMP annihilation ?
  - see "Secondary Production as the origin of the CR Positron Excess" arXiv 1410.7239





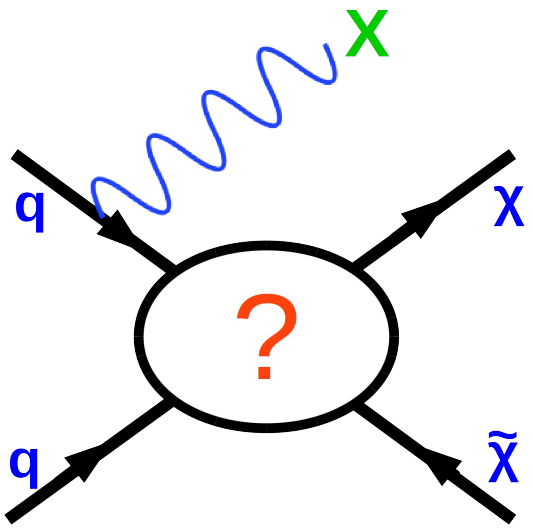
- Production in colliders:
  - if DM particles weakly interact with SM
  - Search for generic decay signatures





ATLAS at LHC

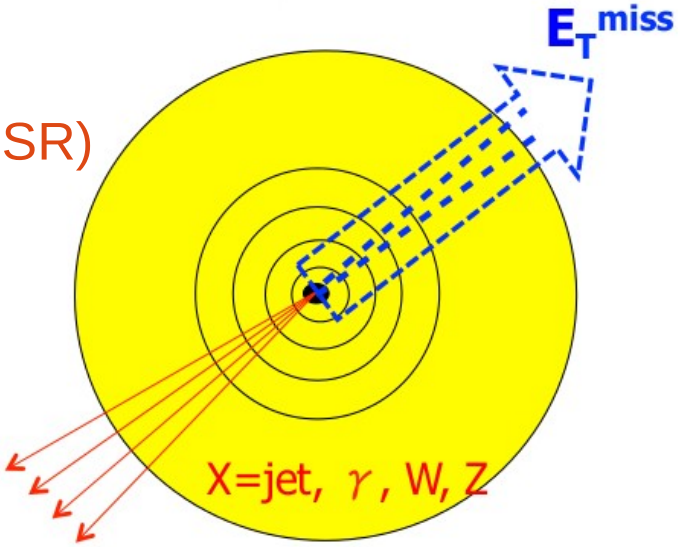
Collider "Monotonic" Searches: Mono-X



χχ escape undetected
⇒ Missing Transverse Energy (MET)

Event Signature: qq ⇒ stuff + nothing

- χχ cannot be directly seen
- Require χχ recoil against triggerable object X = W/Z, h, jet, γ, t,b
- χχ WIMP pairs production described by:
  - Simplified Models with initial state radiation (ISR)
  - Simplified Models with Higgs
  - Lightest stable SUSY particles
  - Effective Field Theory (EFT)



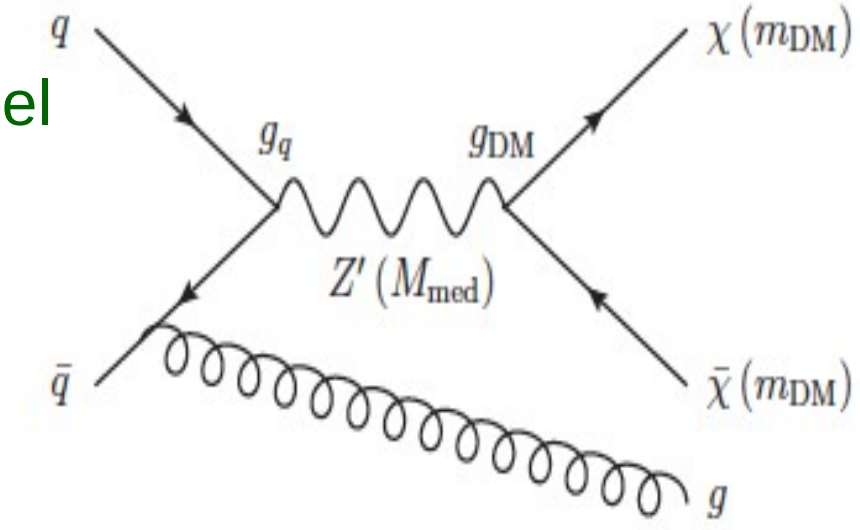
Simplified Models

EFT not valid at large $Q^2 \Rightarrow$

Switch to Simplified Models when Effective Field Theory becomes ineffective

Z/A mediator: generic weak interaction
axial-vector, vector, scalar, pseudoscalar

Benchmark: "Leptophobic Z'-like" model



Free parameters:

- $M_{Z'}$ = mediator mass
- m_χ = WIMP mass
- g_q = mediator-SM coupling
- g_χ = mediator-WIMP coupling

Γ_{min} = minimal width assumed (decays only to DM particles)

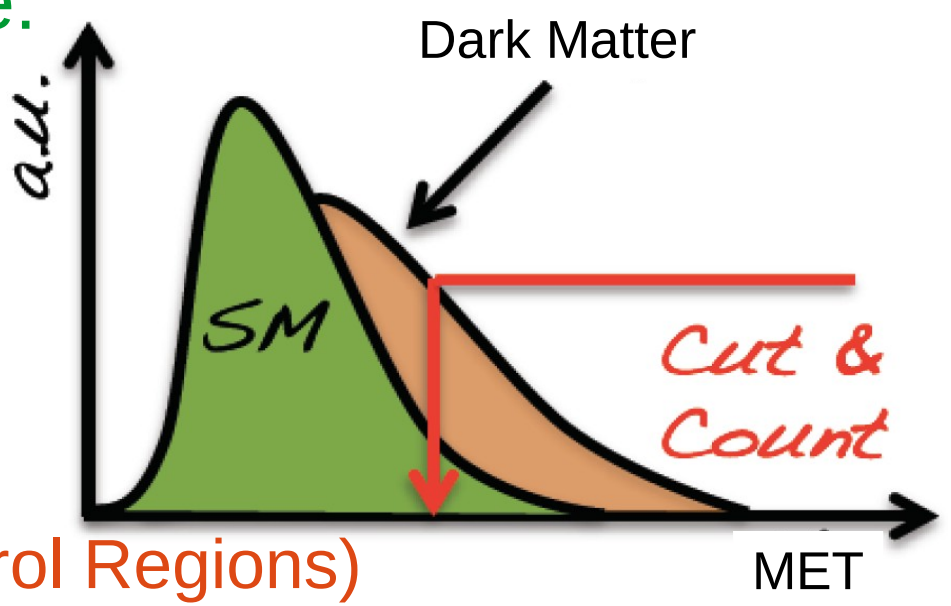
Axial vector case:

$$\Gamma_{\mathrm{min}} = \frac{g_\chi^2 m_A}{12\pi}\beta_\chi^3\theta(m_A - 2m_\chi) + \sum_q \frac{3g_q^2 m_A}{12\pi}\beta_q^3\theta(m_A - 2m_q)$$

Dark Matter Benchmark Models for Early LHC Run-2 Searches:
Report of the ATLAS/CMS Dark Matter Forum arXiv:1507.00966

Analysis Strategy

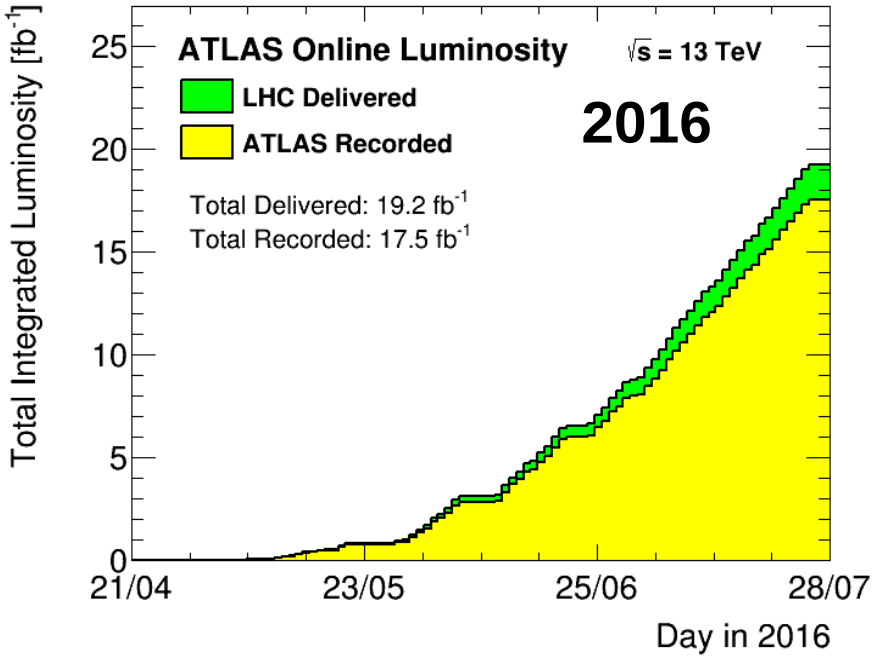
- Look for a clean signature:
  - high momentum object
  - with large ET miss
- backgrounds:
  - data driven
  - MC (normalized with Control Regions)

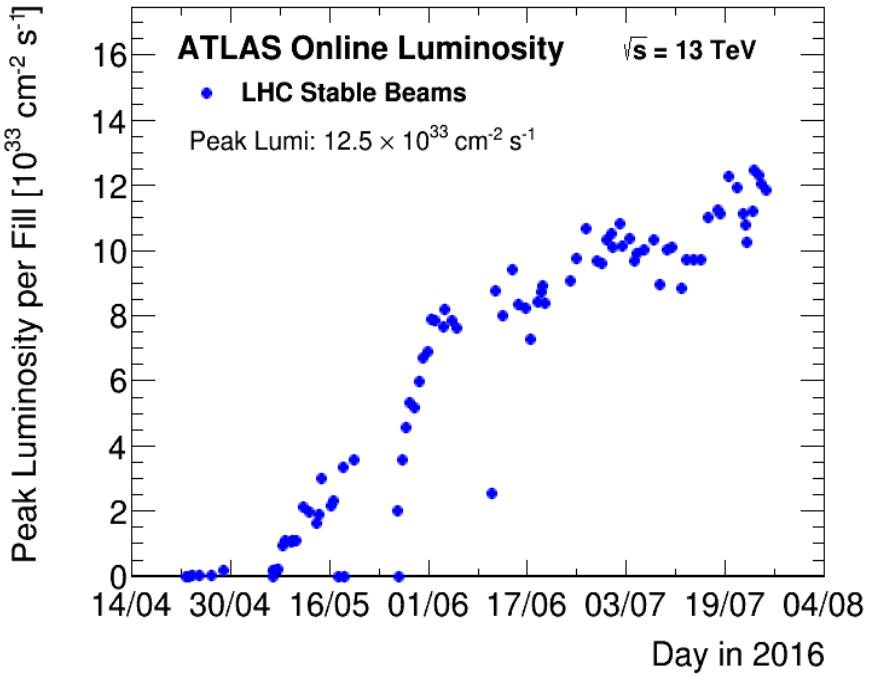


- kinematic cuts define Signal Regions
- count number of events in Signal Regions
- look for excess over SM background

LHC Operations

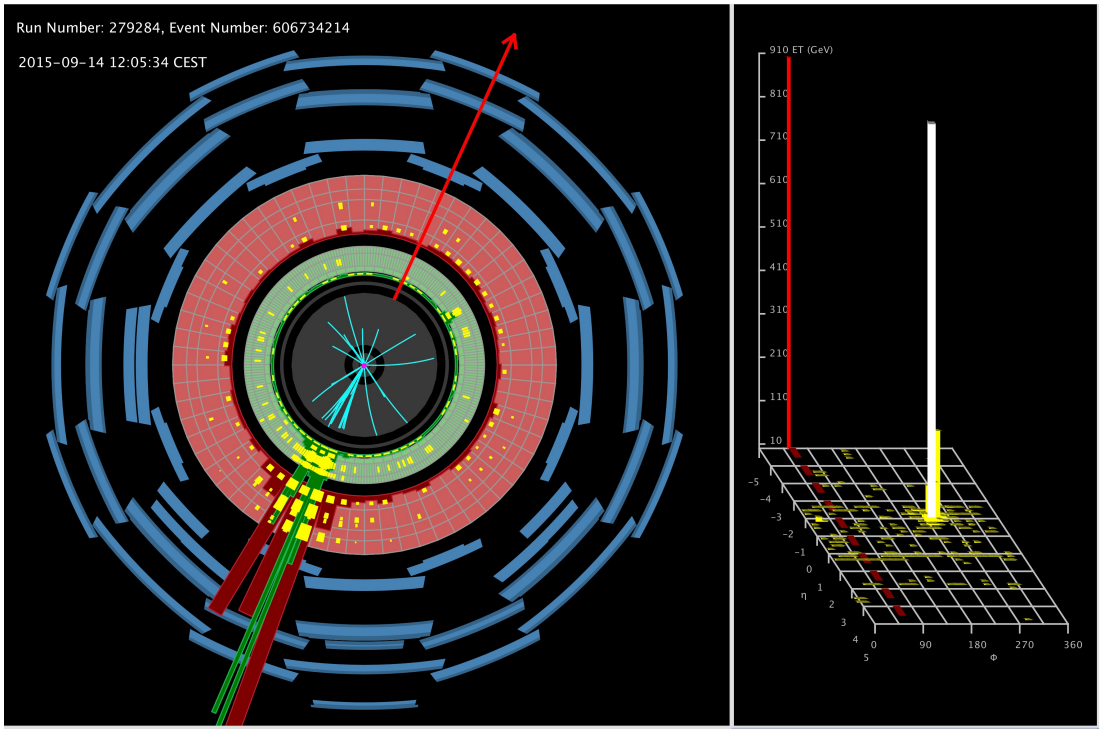
- The LHC has worked spectacularly for the last 6 years.
- Run1: 2011-12 ~25 fb^{-1} of pp data @ 7 & 8 TeV
- Run2: 2015-16 ~19 fb^{-1} of pp data @ 13 TeV so far
- LHC luminosity at 1.2 x 10^{34} cm^{-2} s^{-1}, 20% over design goal!
- This talk: results from 3.2 fb^{-1} 13 TeV data from 2015.





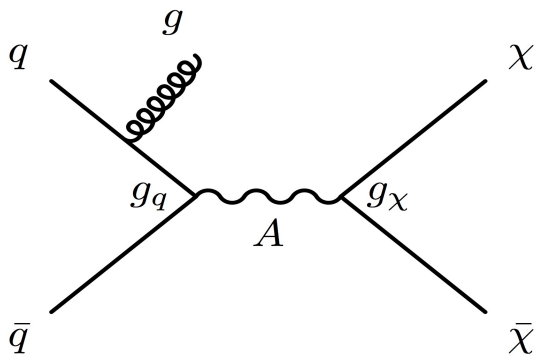
Monojets – Most sensitive search channel

13TeV Monojet Event



WIMP signals – Simplified Model

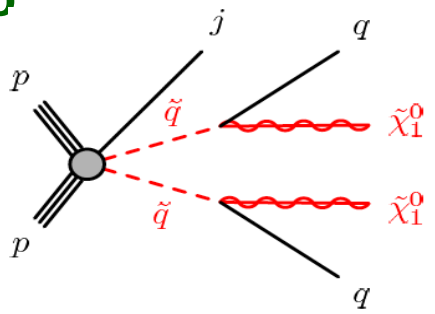
"Leptophobic Z'" (only couples to quarks)
S-channel, spin-1 mediator @ NLO
B-W propagator, g_X=1, g_q=0.25



Compressed SUSY scenario

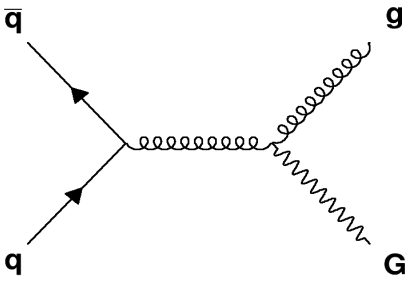
5 GeV < Δm = m_q – m_X < 25 GeV
(Madgraph-5_aMC@NLO)

stop, sbottom, squark pairs:
250 GeV < M_{squark} < 700 GeV



LED ADD: Large Extra Dimensions

Arkani-Hamed, Dimopoulos, Dvali
Unifies Planck and EW scales via
MD = Fundamental Planck scale
N = Number of extra dimensions



Jet + Graviton Emission

Monojet Analysis

Signal Selection

- E_T^{miss} trigger
- Jets recons with anti-kt R=0.4
- Primary vertex in beam spot
- E_T^{miss} > 250 GeV

7 signal regions to 700 GeV

- P_T ($jet_{leading}$) > 250 GeV $|\eta| < 2.4$
- $\Delta\varphi(P_T^{jet}, P_T^{miss}) > 0.4$ for all jets
- veto leptons (e/μ) > 20/10 GeV
- veto: > 4 jets (P_T > 30 GeV)

Backgrounds (MC+ 3 Control Regions)

Process	Fraction E_T^{miss} > 250, 700 GeV
Z → νν + jets	58% , 65%
W → νl + jets	35% , 23%
Z/γ → ll + jets	
multijet, t, tt	7% , 12%
diboson	
non-collision	

Example Control Region : Z → νν + jets bkg:
Select W (→ μν) + jets using 30 < M_T <100 GeV

$$m_T = \sqrt{2p_T^{\ell}p_T^{\nu}[1 - cos(\phi^{\ell} - \phi^{\nu})]}$$

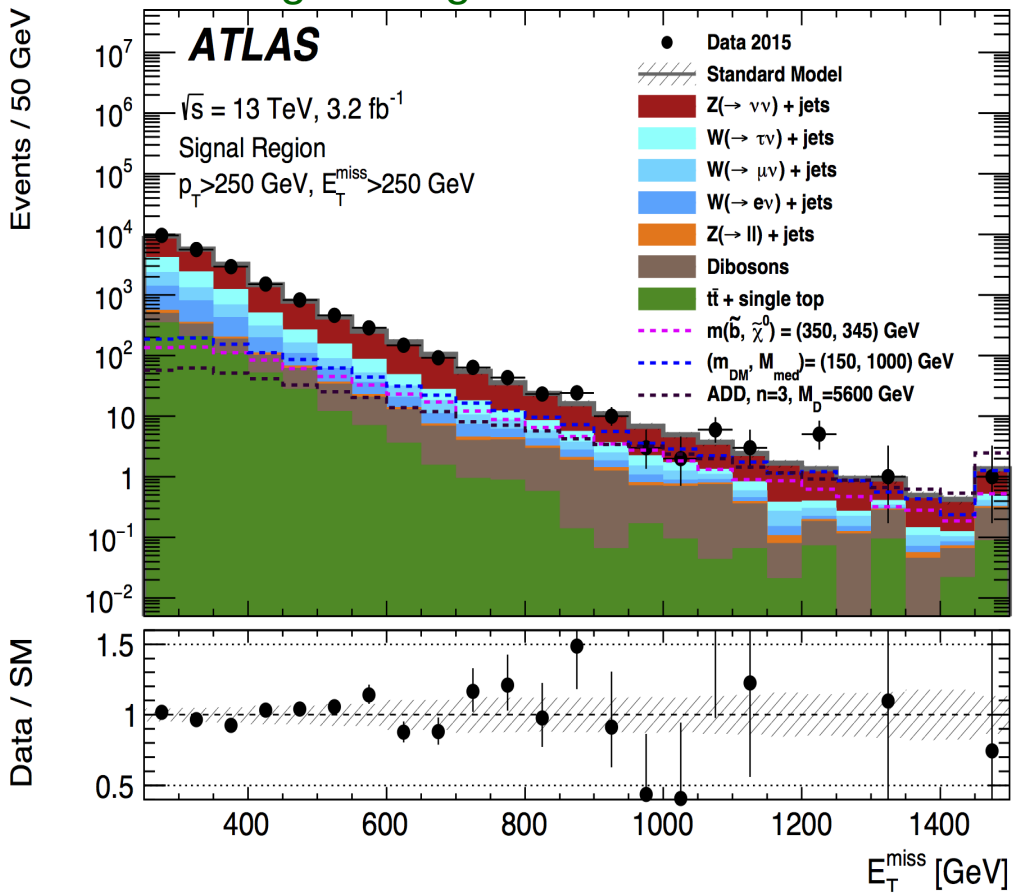
$$N_{signal}^{Z(\to\nu\bar{\nu})} = (N_{W(\to\mu\nu),control}^{data} - N_{W(\to\mu\nu),control}^{non-W}) \times \frac{N_{signal}^{MC(Z(\to\nu\bar{\nu}))}}{N_{W(\to\mu\nu),control}^{MC}}$$

Transfer factor from Control Region to Signal Region

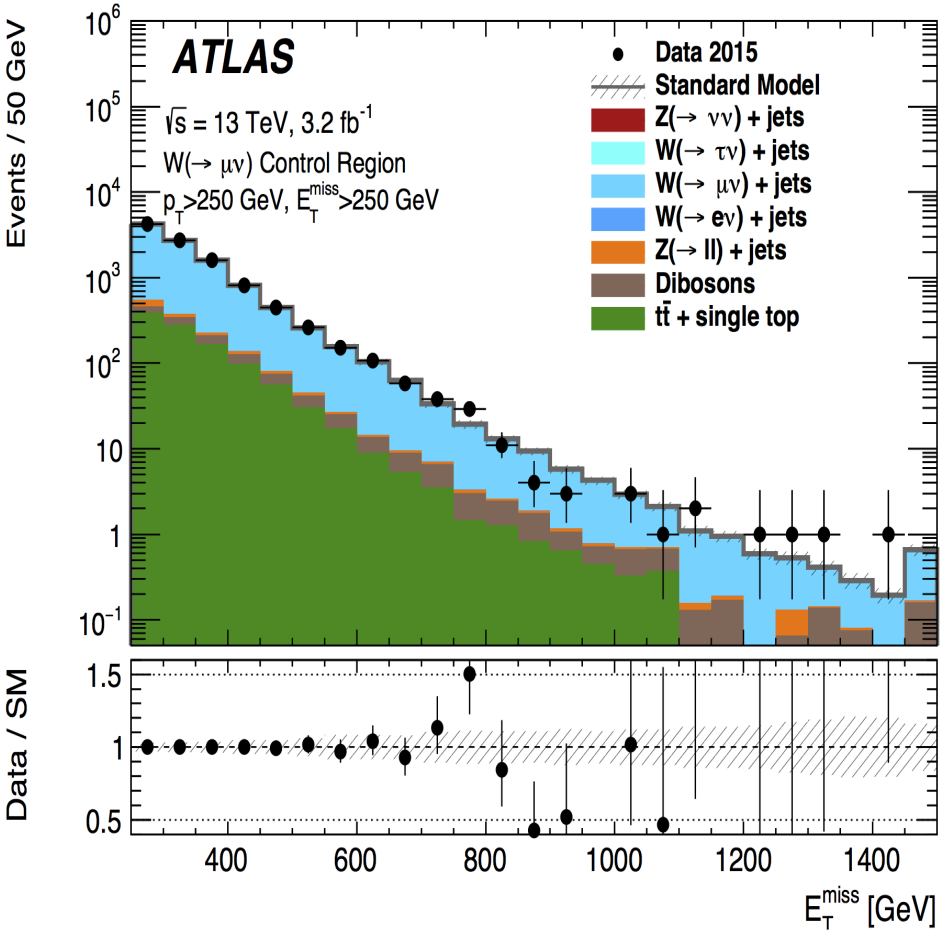
Do simultaneous global fit of 7 exclusive SR+CR

Monojet Control & Signal Regions

Signal Region > 250 GeV



W→μν +jets control region
(No lepton veto)



Systematics:

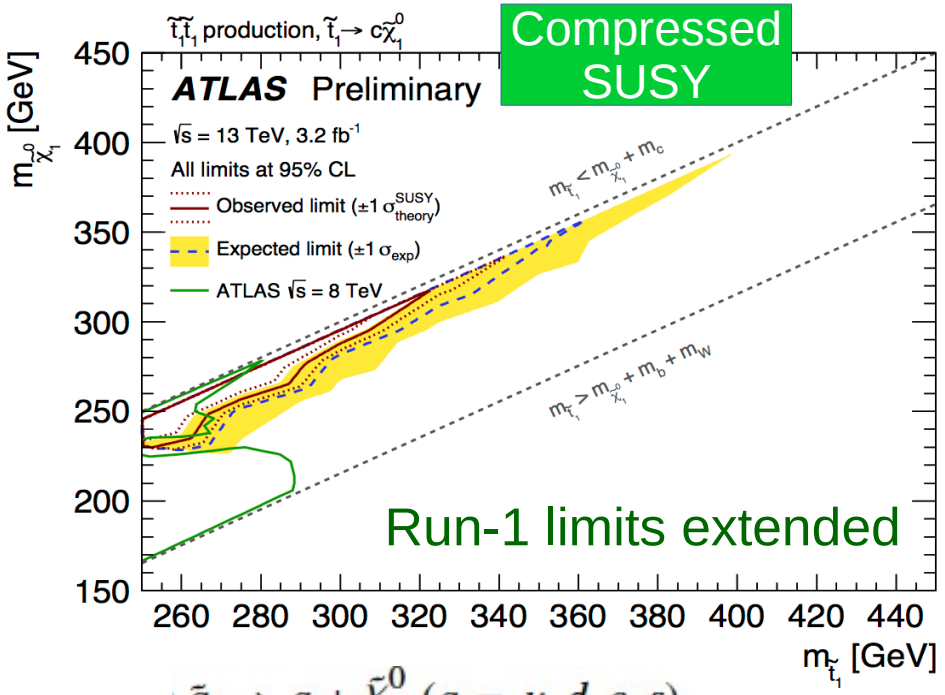
jet , E_T^{miss} energy scale 1.6%

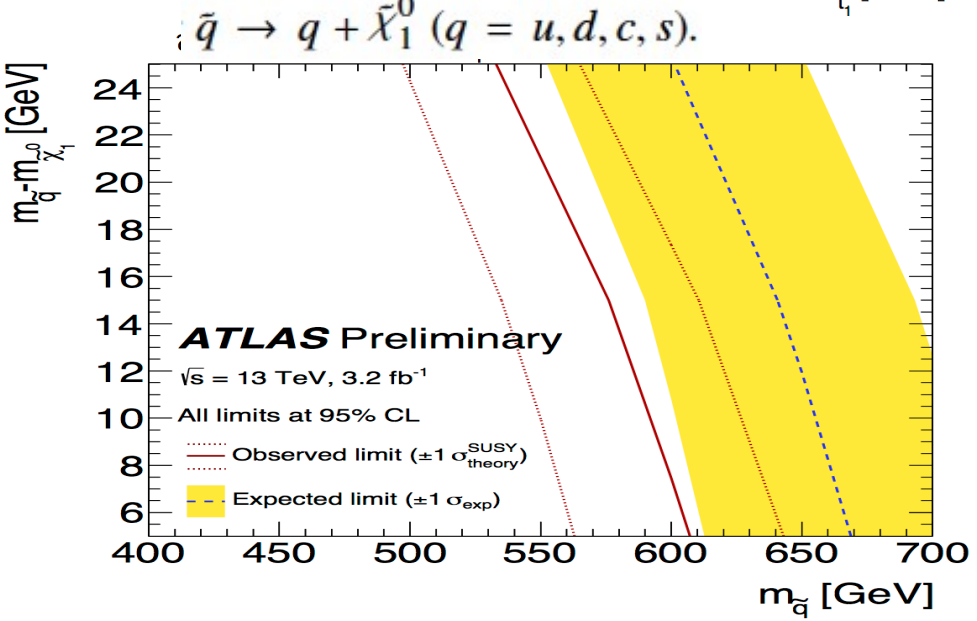
lepton ID < 2.6%

W/Z+jets modeling 2%-4%

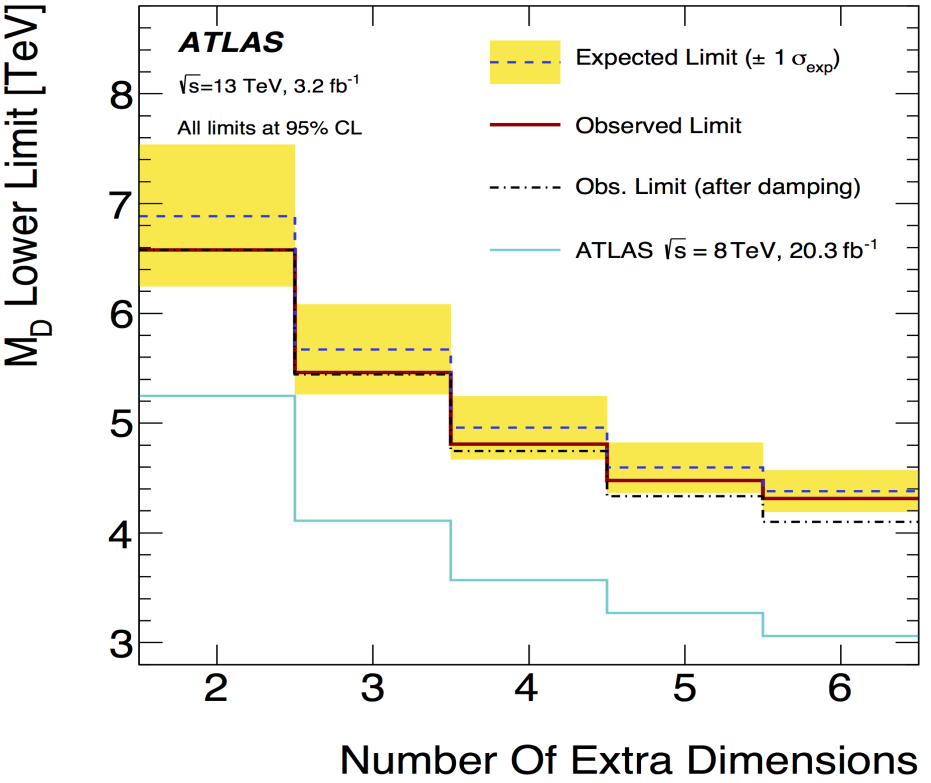
Monojet SUSY & ADD Limits

Compressed SUSY

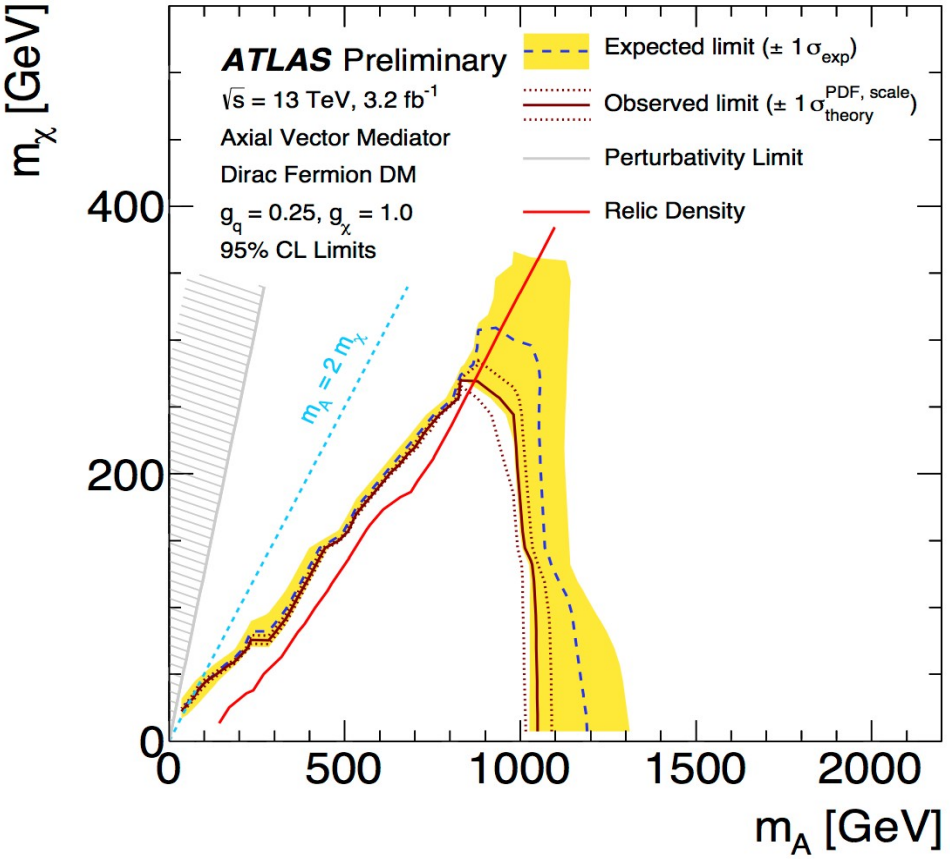


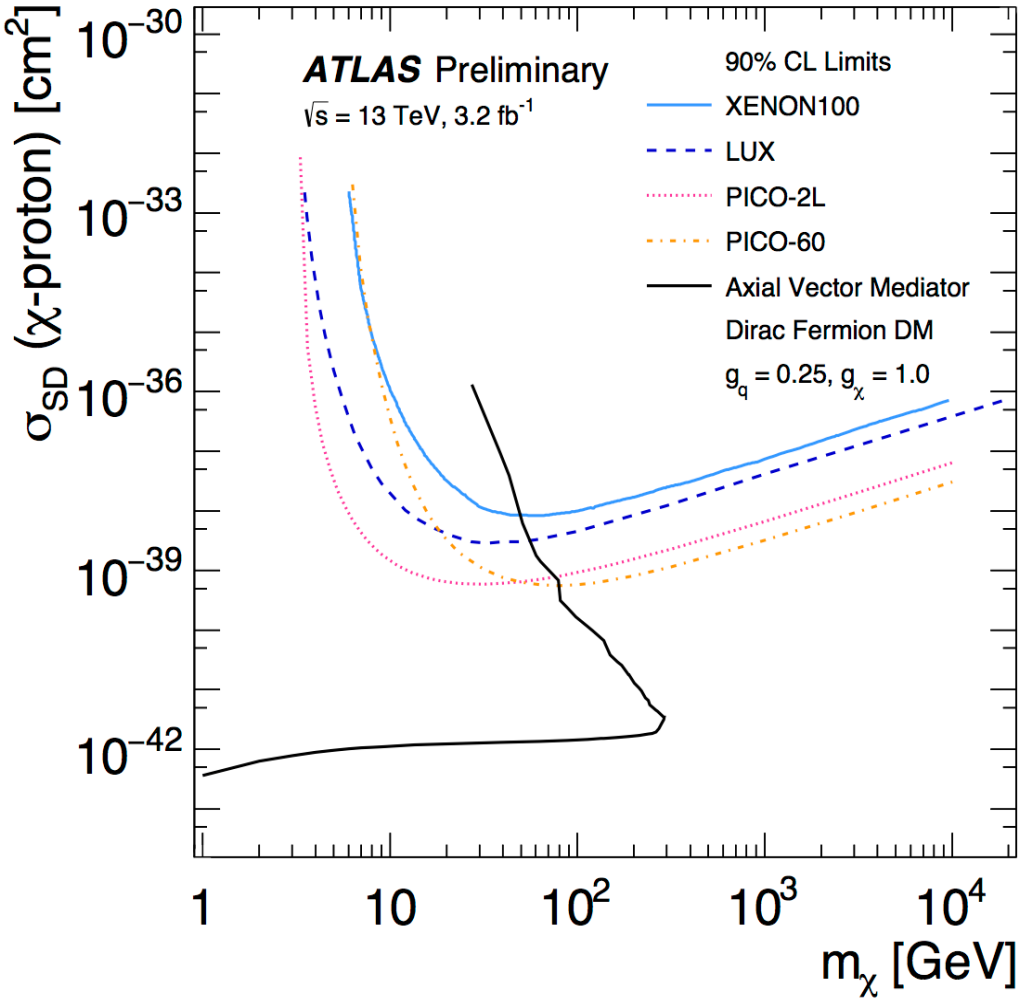


LED ADD



Monojet WIMP Limits





Simplified Model limits
- Exclude up to 1 TeV in mediator mass
- Relic abundance based on WMAP, Planck assumes only the specified interaction
- below relic abundance curve: DM over production
- above relic abundance curve: DM under production

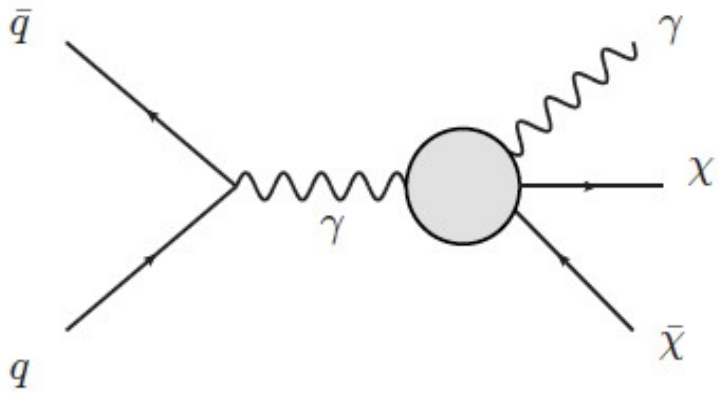
Simplified Model cross section limits expressed as Direct Detection limits

NOTE: Only valid for "Leptonphobic Z'" Simplified model

Mono γ – Next best search channel

Signals
dimension-7 EFT operator
(same as Mono-Z with $k_1=k_2=1$)
arXiv 1212.3352

$$L = \frac{1}{\Lambda_7^3}\,\bar{\chi}\chi \sum_i k_i F_i^{\mu\nu} F^i_{\mu\nu}$$

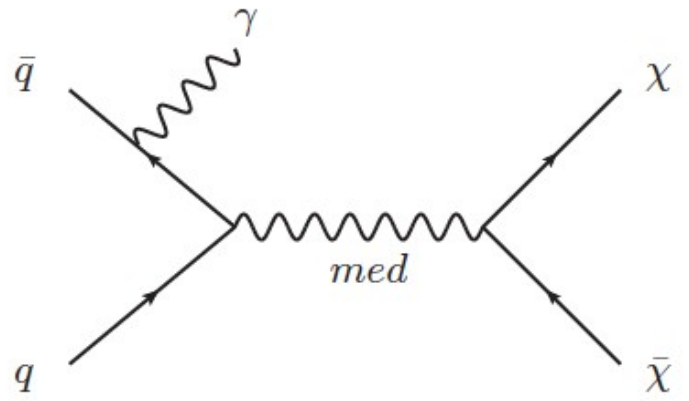


Signal acceptance 0.43-0.55

Event Selection

γ trigger 70 GeV (99.7% eff)
primary vertex, > 2 tracks at 0.4 GeV
Photon P_T > 150 GeV
E_T^{miss} > 150GeV leading γ $|\eta|$ < 2.37
$\Delta\phi(\gamma, P_T) > 0.4$
0 or 1 jet P_T > 30 GeV $|\eta|$ < 4.5
Lepton veto

Simplified model - Leptophobic Z'
with $g_\chi=1$ $g_q=0.25$



Mono γ Results

	SR
Observed events	264
Fitted background	295 ± 34
$Z(\rightarrow \nu\nu) + \gamma$	171 ± 29
$W(\rightarrow \ell\nu) + \gamma$	58 ± 9
$Z(\rightarrow \ell\ell) + \gamma$	3.3 ± 0.6
γ + jets	15 ± 4
Fake photons from electrons	22 ± 18
Fake photons from jets	26 ± 12
Pre-fit background	249 ± 29

Backgrounds

Z + ISR → νν + γ CR

W +ISR→ νll+ γ CR

Z → ll + γ CR

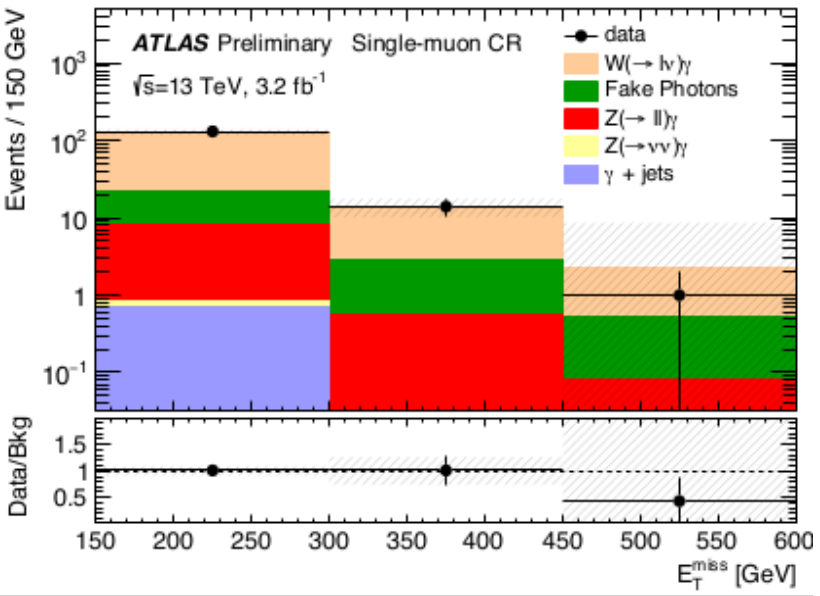
Z/W+jets

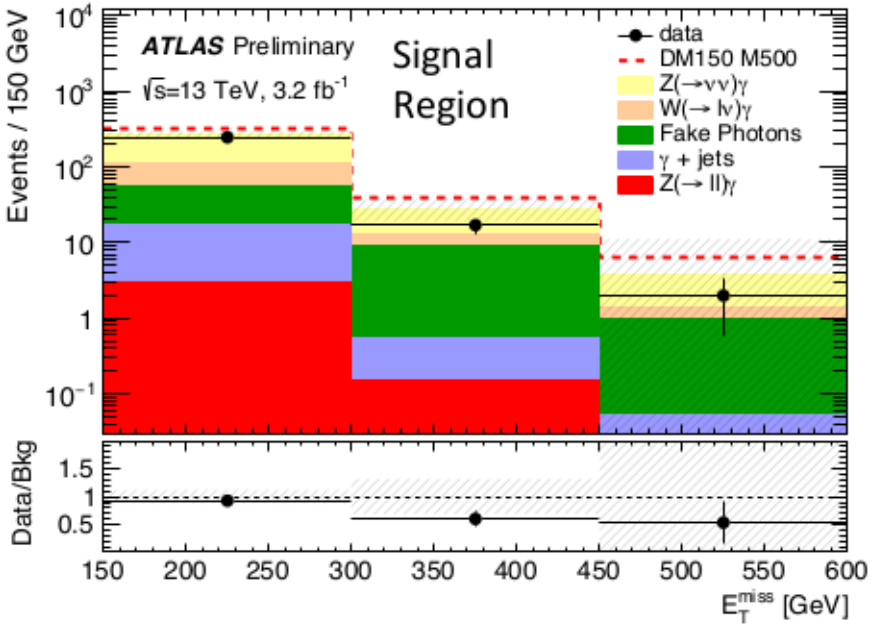
tt,γ+jets,multijets: data driven

3 Control Region: Invert 1 or 2 vetos

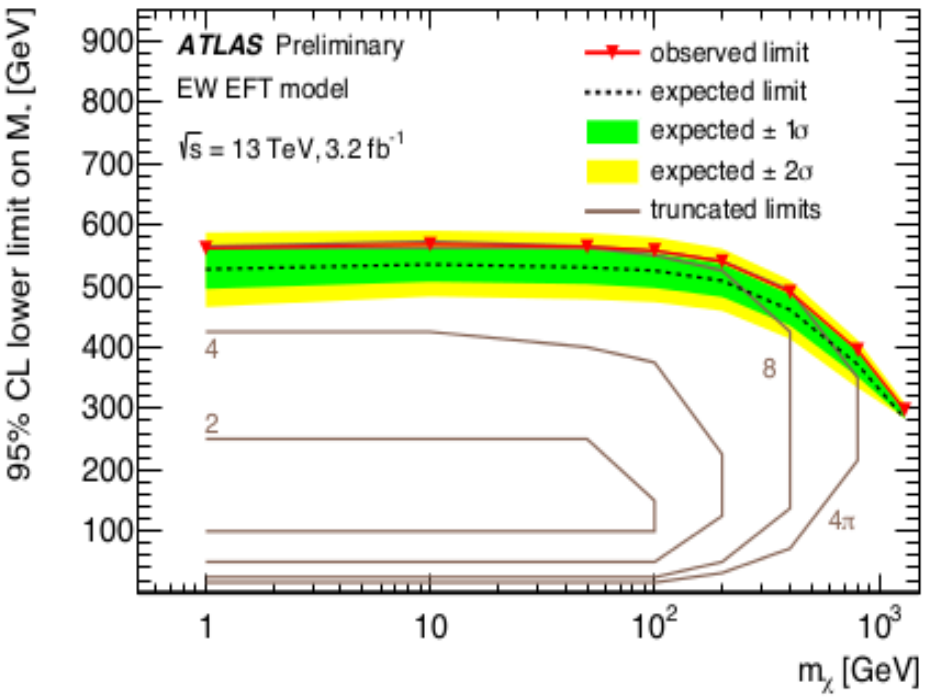
⇒ use to normalize the W+γ & Z+γ MC

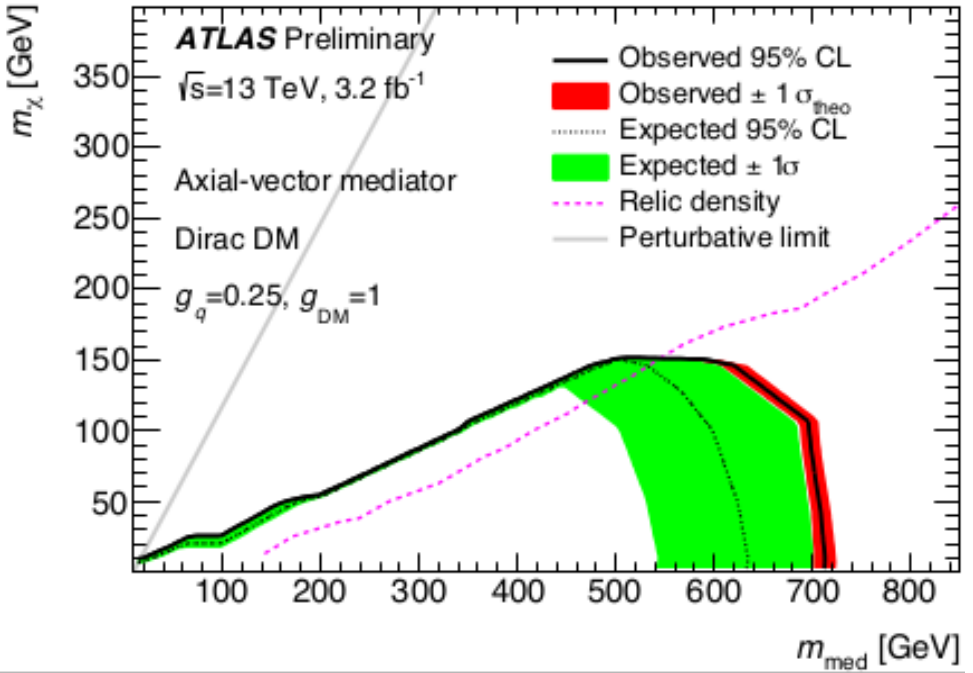
Single muon W→ lν Control Region





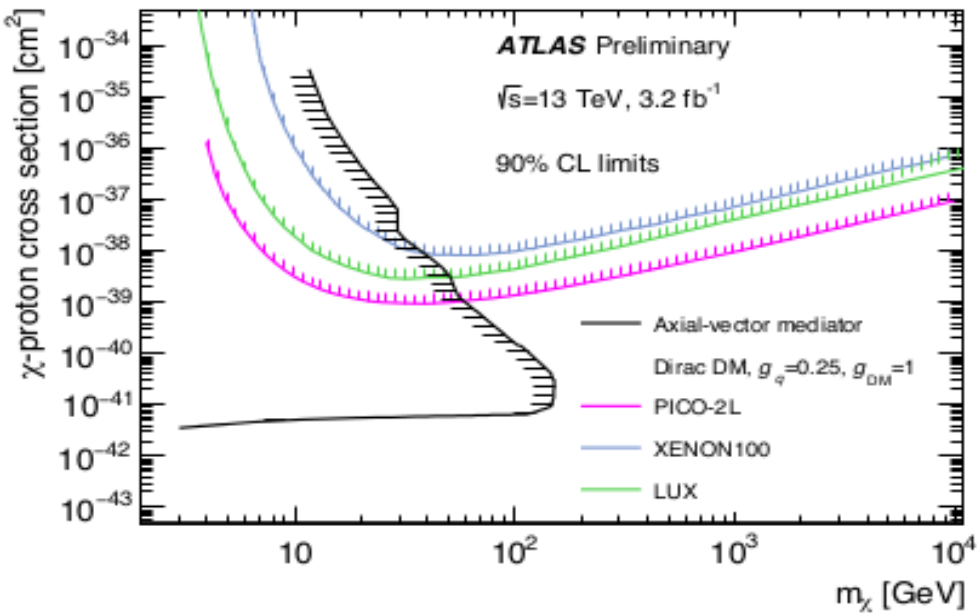
Mono γ Results





Truncated limits on suppression scale M* requires $E_{CM} < g^*M^*$
Truncation due to limits of EFT validity

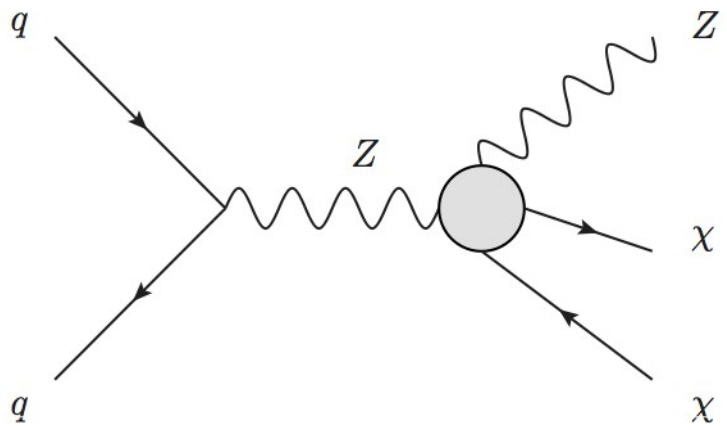
σ(χ +P) limits for
A-V simplified model ⇒



Mono Z/W (hadronic)

Two DM production models considered:

EFT Dimension 7 operator

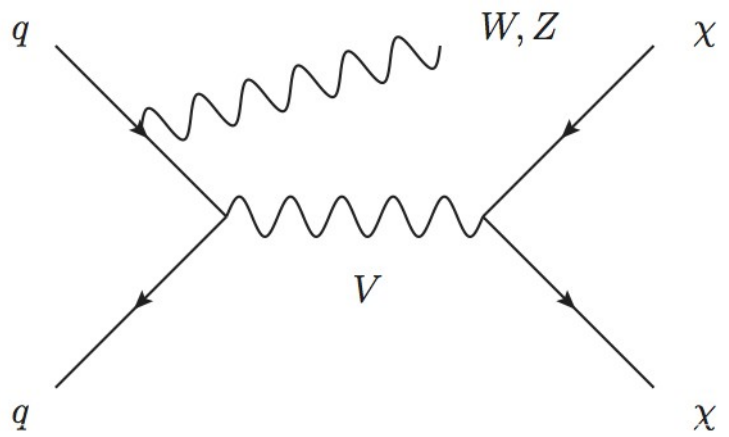


ArXiv 1212:3352

$$L = \frac{1}{\Lambda_7^3}\,\bar{\chi}\chi \sum_i k_i F_i^{\mu\nu} F^i_{\mu\nu}$$

F_i = field strengths for SM U(1), SU(2), SU(3) gauge groups.

Axial Vector mediated model



$M_{Z'}$ = 0-1 TeV
M_X = 0 -0.5 TeV
g_q, = 0.25
g_X = 1

} DM Forum Benchmarks

Mono Z/W ⇒ high Et miss + boosted W/Z (fatjet)

Event Selection

E_T^{miss} trigger > 80 GeV

E_T^{miss} > 200 GeV

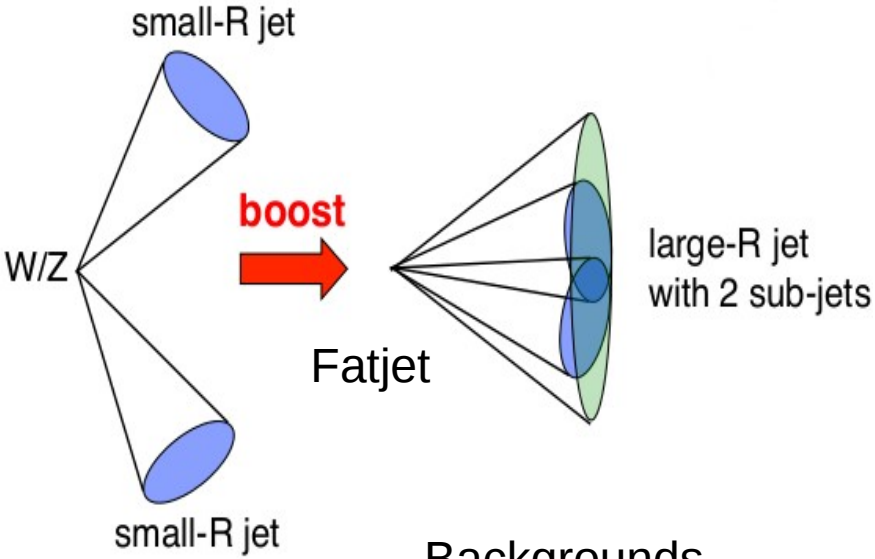
at least 1 large (anti-kt R = 1.0) jet: P_T > 250 GeV

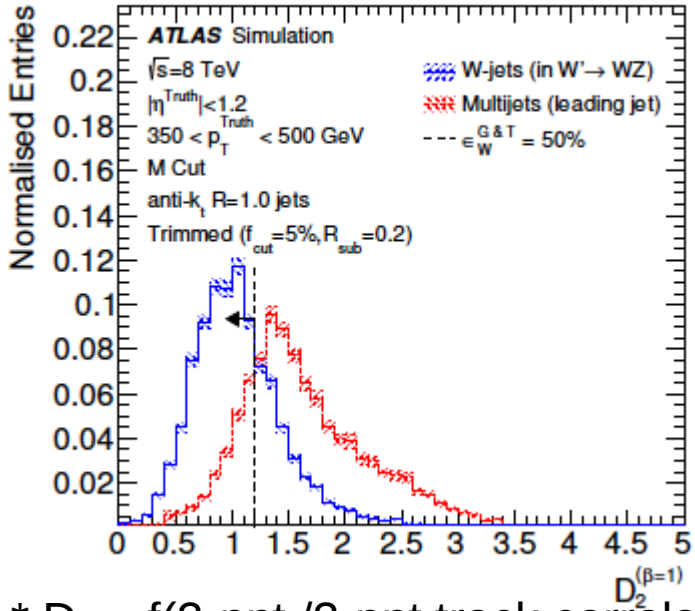
$M_{jet} = M_Z / M_W \pm 15$ GeV

no loose leptons ⇒ e,μ P_T > 7 GeV $|\eta| < 2.47, 2.7$

substructure variable $D_2(P_T)$ ⇒

discriminate W/Z from QCD





* D_2 = f(2-pnt /3-pnt track correlation)

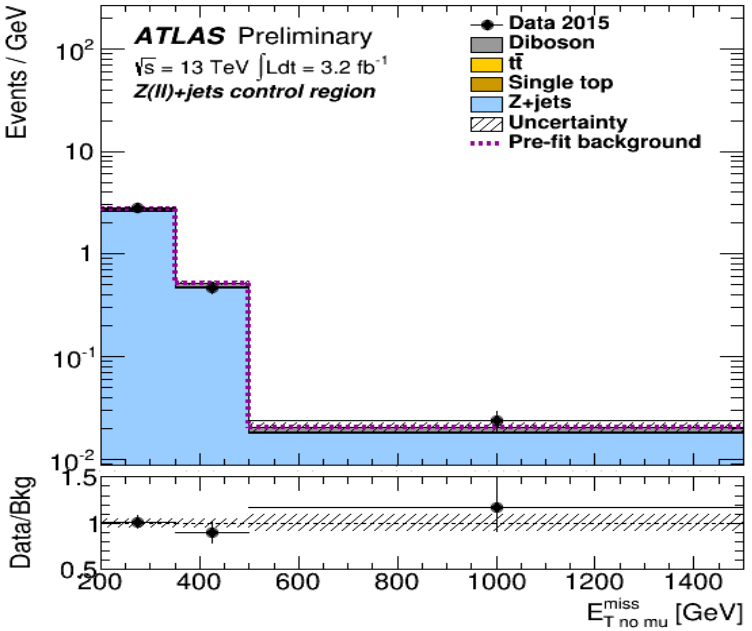
arXiv 1409.6298

Backgrounds

Process	events
Z+jets	519 ± 31
W+jets	326 ± 22
$t\bar{t}$ and single-top	217 ± 18
Diboson	88 ± 12
Total Background	1150 ± 30
Data	1143

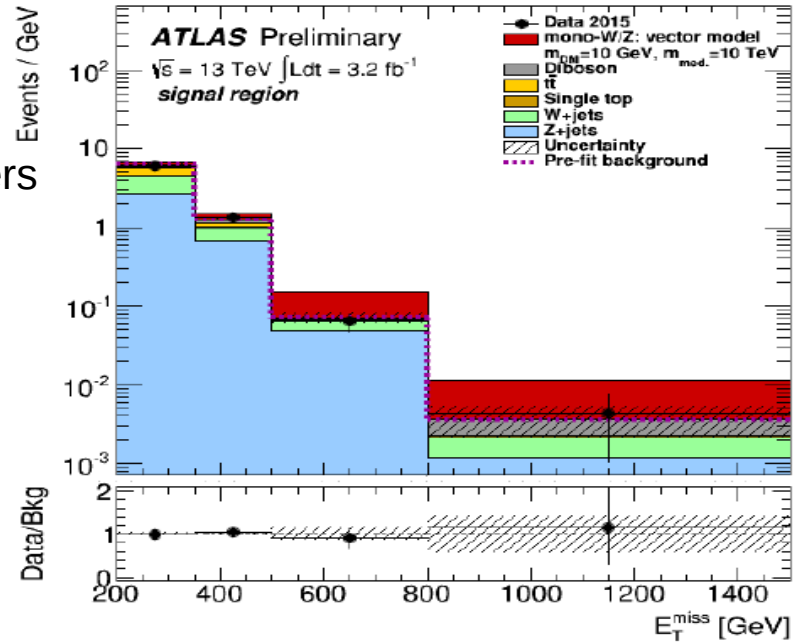
Simultaneous profile likelihood fit of 3 Control Regions constrains MC

Mono Z/W Results

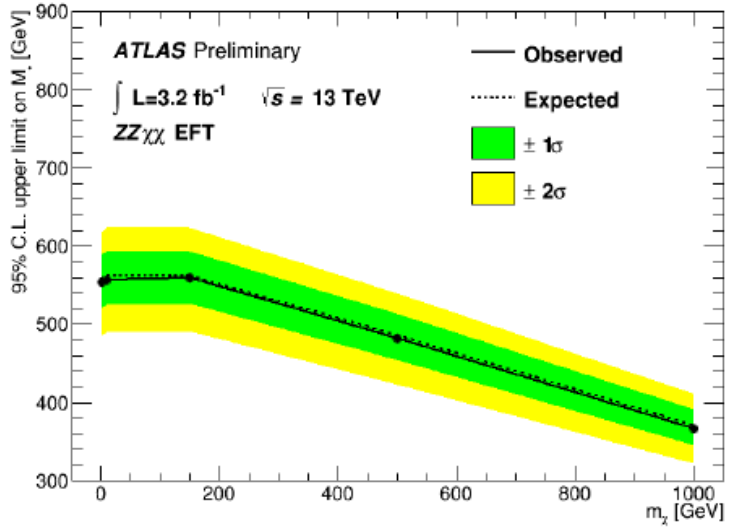


systematics dominated
By large R jet parameters

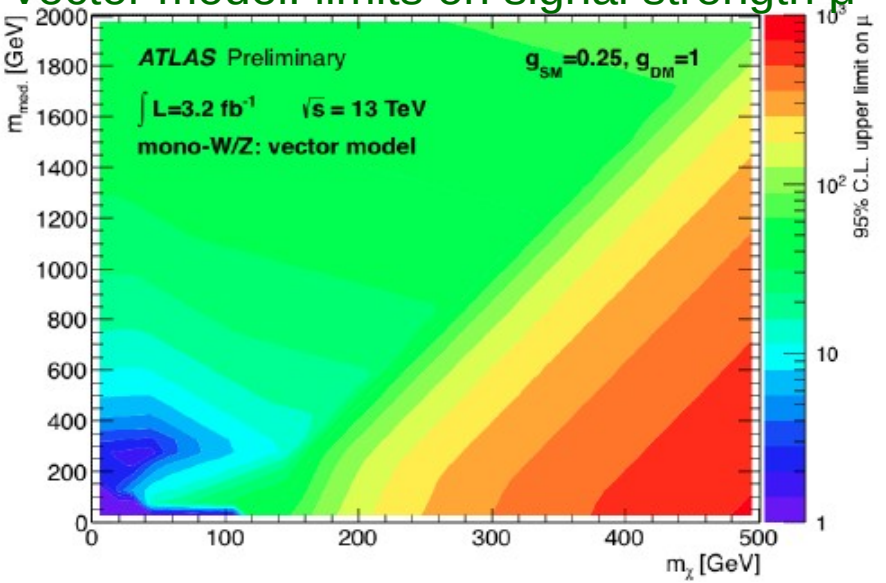
mass resolution: 10%
D_2 scale: 5-10 %



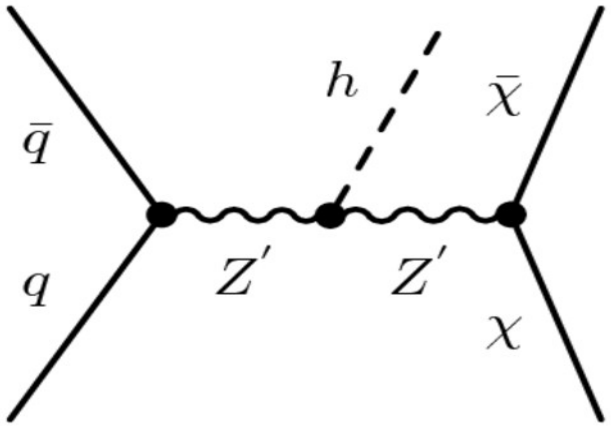
Limit on EFT suppression scale M* vs Mχ



Vector model: limits on signal strength μ



Mono Higgs (h→bb,h→γγ,h→4l)



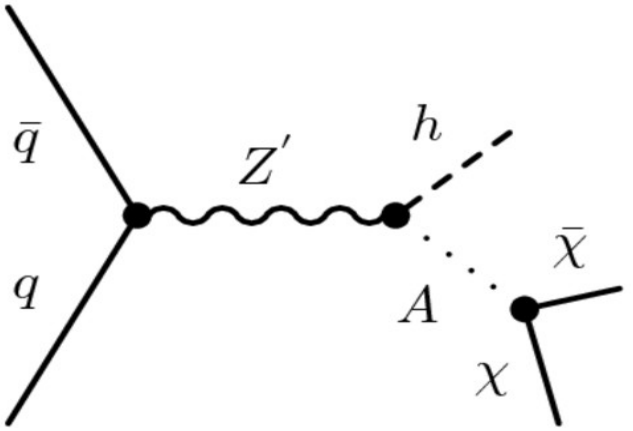
Final states:

$h \rightarrow bb + E_T^{miss}$

two b-jets + E_t^{miss}

$h \rightarrow \gamma\gamma + E_t^{miss}$

$h \rightarrow 4l + E_T^{miss}$



ISR of Higgs is Yukawa suppressed (i.e. coupling to light quarks is small)

Model 1: Simplified... massive vector mediator w/ baryon number radiates Higgs, decays to WIMPS (also with baryon number)

specified by: g_q , g_X , $g_{Z'}$, $M_{Z'}$,M_X , mixing angle sin ϑ : SM h to baryonic H

Model 2 (2HDM): vector mediator (Z') + two-Higgs-doublet (five Higgses)

Z' → A^0 + regular Higgs h, $A^0 \rightarrow \chi\chi$ (BR ~ 1)

specified by: g_q , g_X , $M_{Z'}$,M_A, M_X

h – H mixing angle α & tan β

assumes alignment limit → cos(α-β)=0

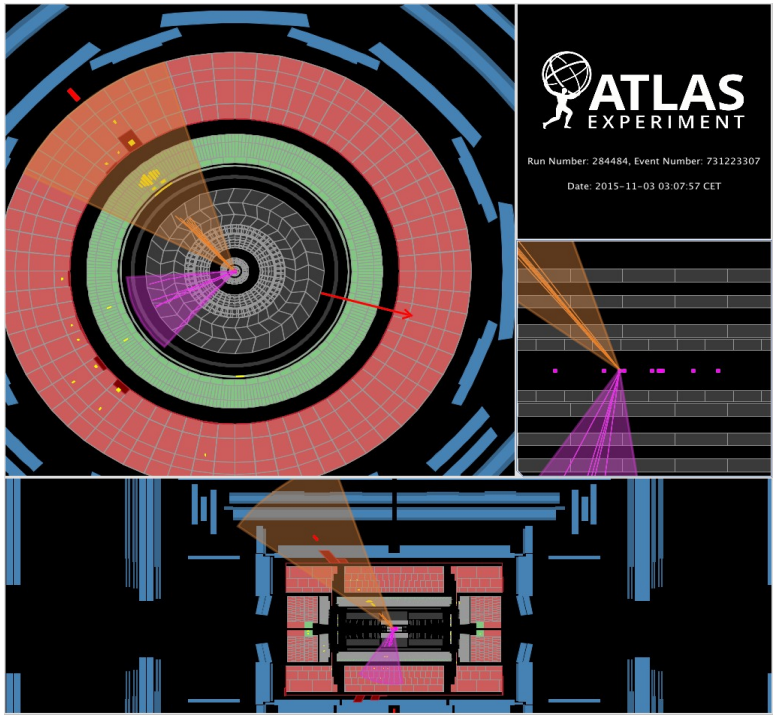
Mono Higgs (h→bb)

Event Selection

- E_T^{miss} trigger > 80 GeV
- E_T^{miss} > 150 GeV , P_T^{miss} > 30 GeV central region, lepton veto
- resolved region: E_T^{miss} < 500 GeV ⇒ two central jets, R = 0.4, 2 b-tag)
- merged region: E_T^{miss} > 500 GeV ⇒ one large R jet (w/ btag+ 2 track jets)
- Δφ (E_T^{miss} , P_T^{miss}) < π/2 ⇒ suppress fake E_{Tt}^{miss}
- Δφ (E_T^{miss}, h) > 120°
- Δφ (jet1, jet2) < 140° } suppress QCD di-jets
- B-tag eff=70%, mis-ID=12%

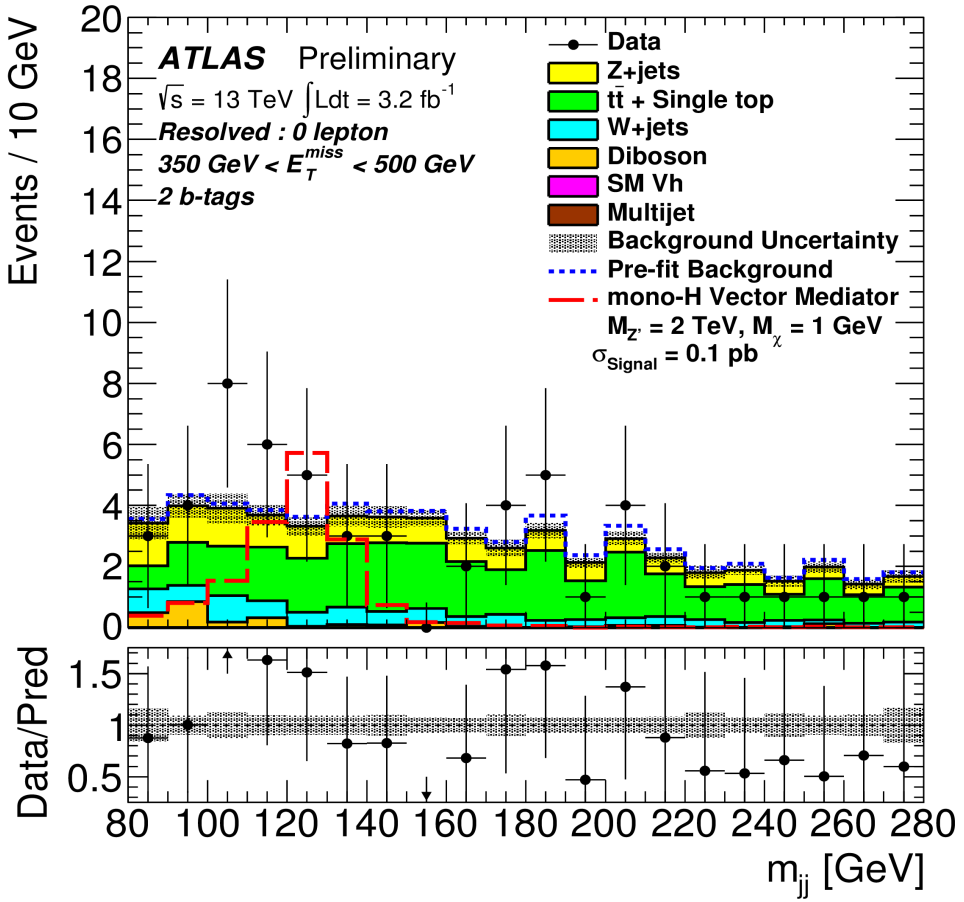
E_T^{miss} (GeV)	150–200	Merged >500
$Z + jets$	259 ± 27	3.80 ± 0.44
$W + jets$	95 ± 28	2.48 ± 0.71
$t\bar{t}$ & Single top	1444 ± 44	4.83 ± 0.88
Multijet	21 ± 10	–
Diboson	17.8 ± 1.6	1.20 ± 0.12
$SMVh$	2.8 ± 1.3	0.15 ± 0.08
Tot. Bkg.	1840 ± 33	12.5 ± 1.3
Data	1830	20
Exp. Signal	80 ± 8	149 ± 34

do profile fit to M_{inv} in Higgs window for all CR, SR

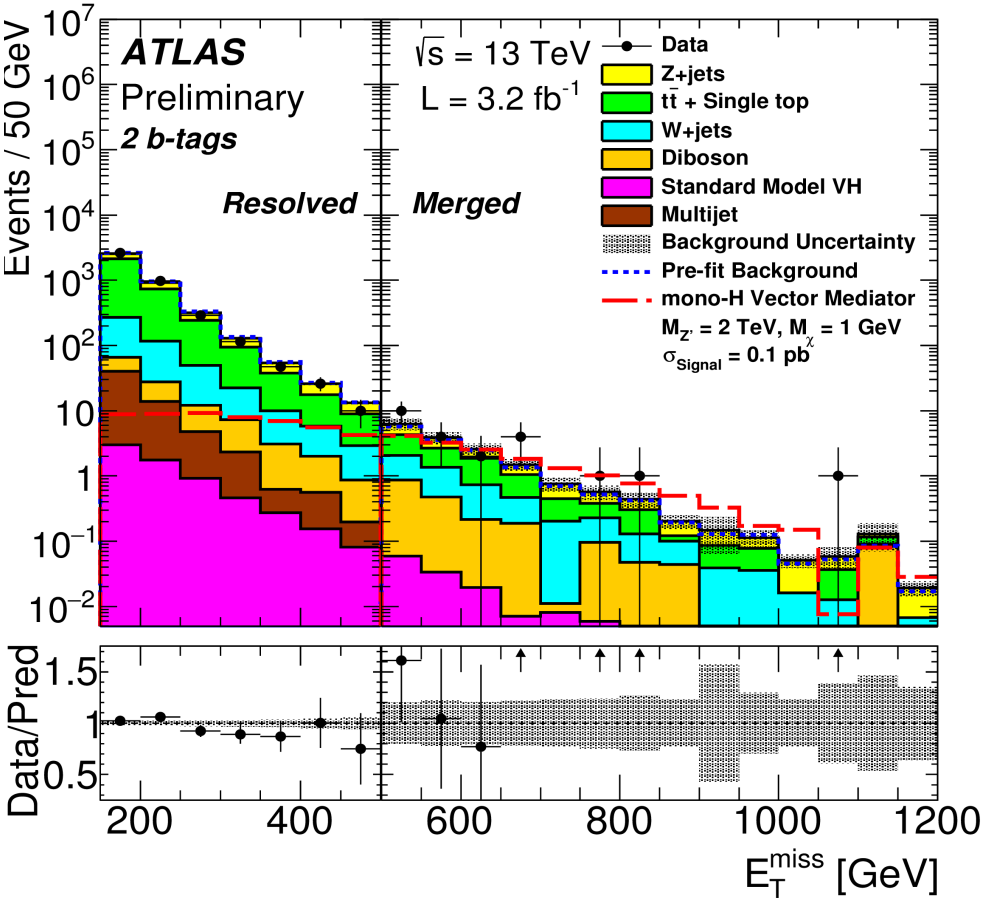


Signal Event
E_T^{miss} = 213 GeV
M_{jj} =120 GeV

Mono Higgs (h→bb)

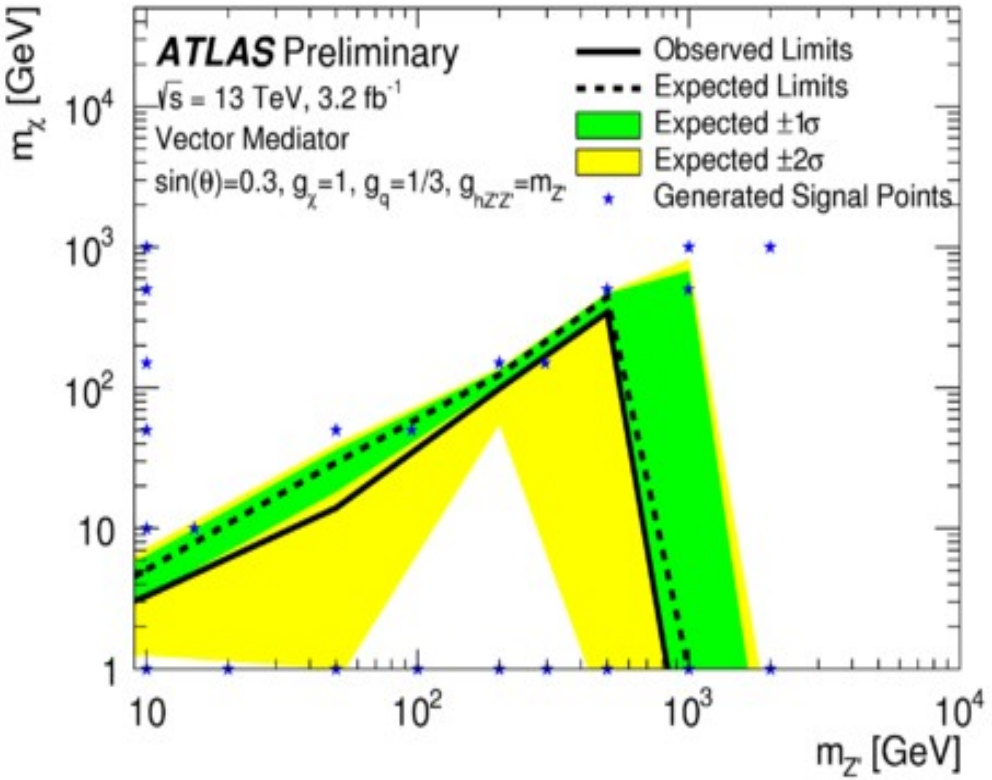


dijet invariant mass (2 b-tag)
350 <E_T^{miss} < 500 GeV
Showing signal template



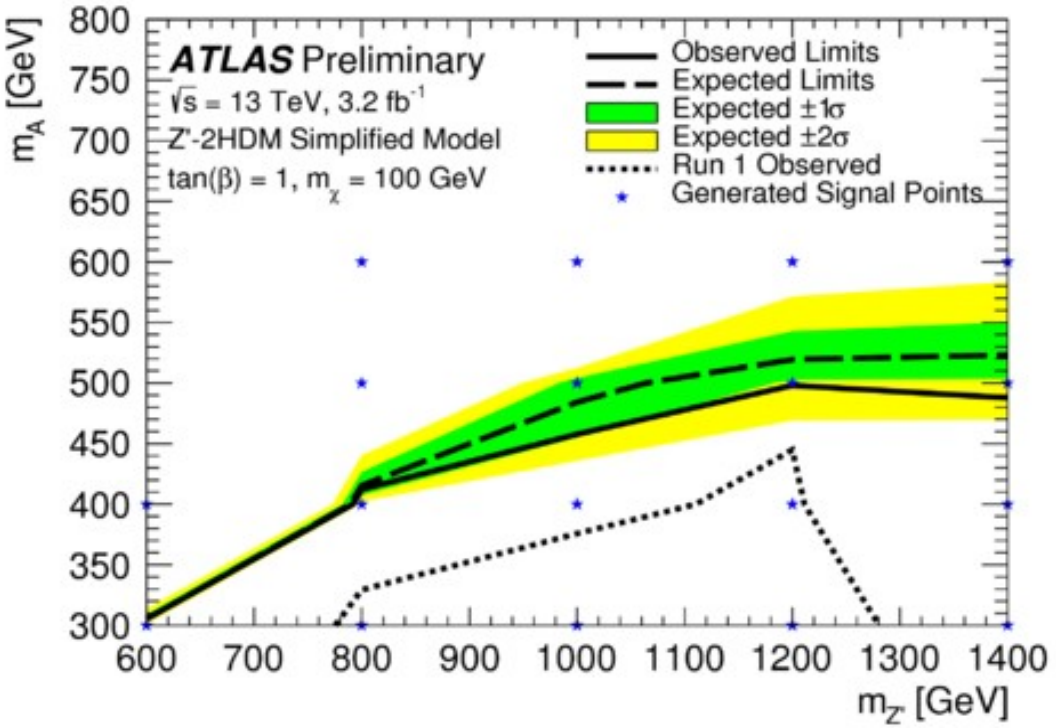
E_T^{miss} all signal regions

Mono Higgs Results (h→bb)



Limits on WIMP Mass –
for Vector Mediator model

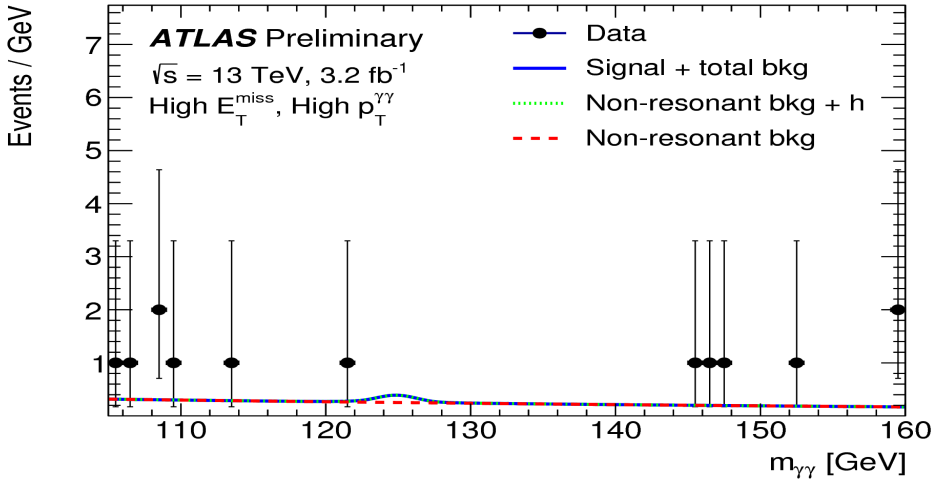
specified by: g_q =1/3 g_χ =1 , $g_{Z'}$ =$M_{Z'}$
sin ϑ=0.3

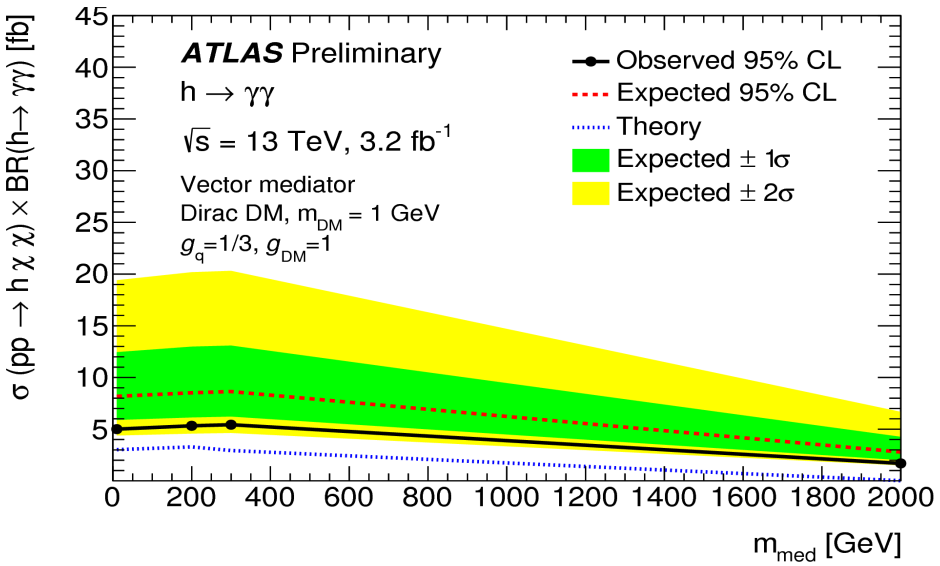


Limits on Z'+2DHM Model
pseudo-scalar A Heavy Higgs mass
vs Vector Mediator mass
limits to 500 GeV on A

Mono Higgs Results (h→γγ,h→4l)

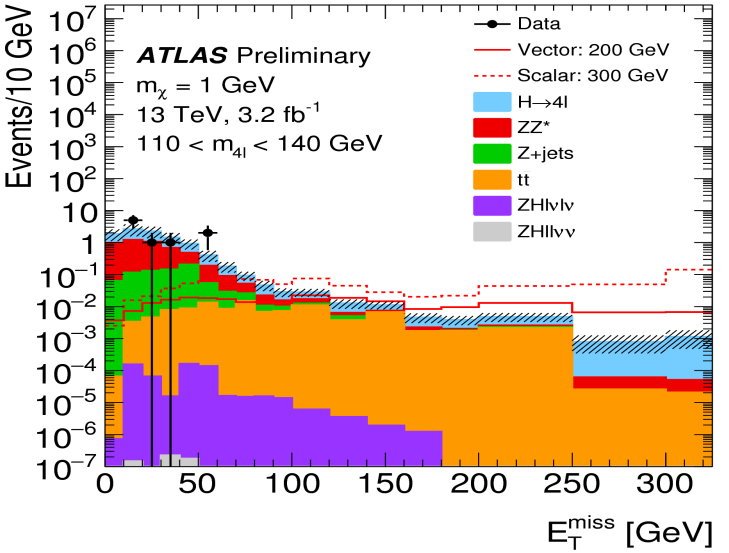
- h→γγ small BR (0.002), but clean signal
- Search for peak at $m_{\gamma\gamma} \sim m_h$
- No excess ⇒ set limits on σ(pp ⇒ hχχ)

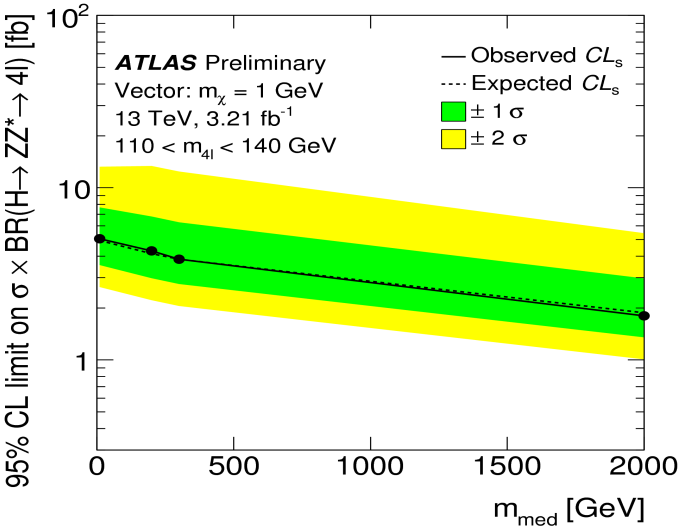




h→4l Very clean but low BR

- Search for excess high MET events
- No excess ⇒ set limits on σ(pp ⇒ hχχ)





ATLAS Mono-X Results

"X"	Run1	Run2
>= jet	EPJC 75 (2015) 299 (hep-ex 1502.01518)	Submitted to PRD (hep-ex 1604.07773)
Photon	PRD 91(2015)012008 (hep-ex 1411.1559)	JHEP06(2016)059 (hep-ex 1604.01306)
W→lν	JHEP 09 (2014) 037 (hep-ex 1407.7494)	
Z→ll	PRD 90 (2014) 012004 (hep-ex 1404.0051)	
W or Z (qq)	PRL112 (2014) 041802 (hep-ex 1309.4017)	ATLAS-CONF-2015-080
t/b jet	EPJC75 (2015) 92 (hep-ex 1410.4031)	
H→bb	ATLAS PRD 93 072007 (2016) (hep-ex 1510.06218)	ATLAS-CONF-2016-019
H→γγ	PRL 115 (2015) 131801 (hep-ex 1506.01081)	ATLAS-CONF-2016-011
H→4l		ATLAS-CONF-2015-059

2016 will provide much more data to extend these analyses...

Conclusions

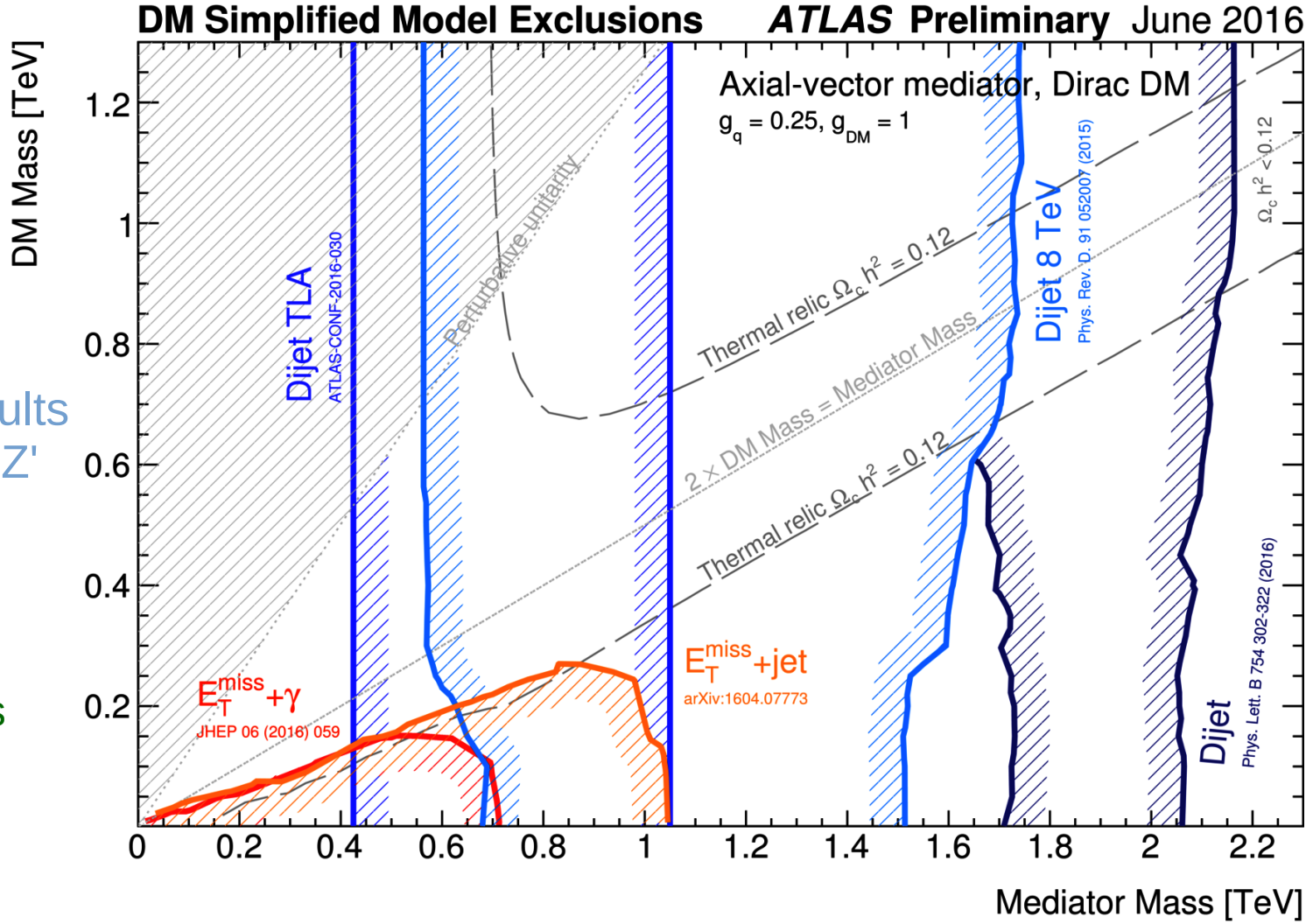
First ATLAS searches at 13 TeV 3.2 fb^{-1} for Dark Matter signatures with mono-jets, -photon, -higgs, -W/Z final states

No excesses in Signal Regions ⇒ compatible with Standard Model

Limits are set for Dark Matter Forum benchmark simplified models

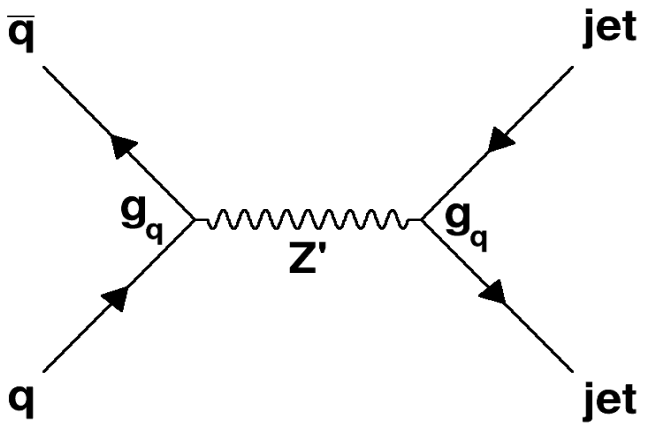
Compendium of all ATLAS results for Leptophobic Z' model.

Includes limits from dijet analysis not covered in this talk.



Dijet Resonance Searches

- Look for resonance in dijet spectrum
- More sensitive than mono-X searches over wider range of mediator masses.
- But an observed excess not necessarily related to DM

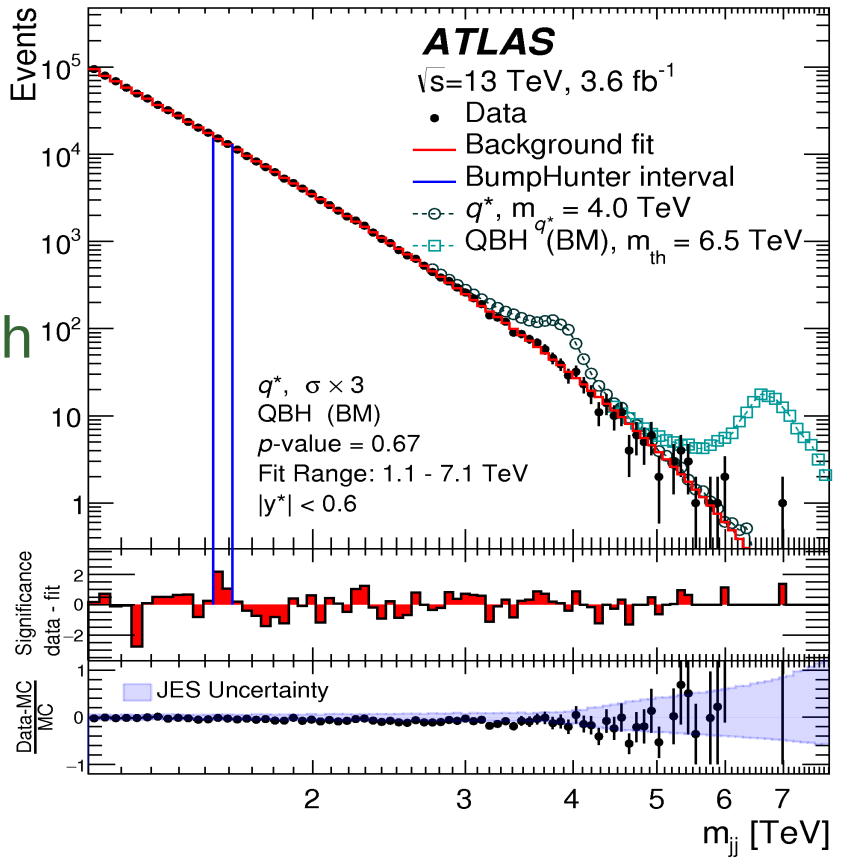


Three search strategies

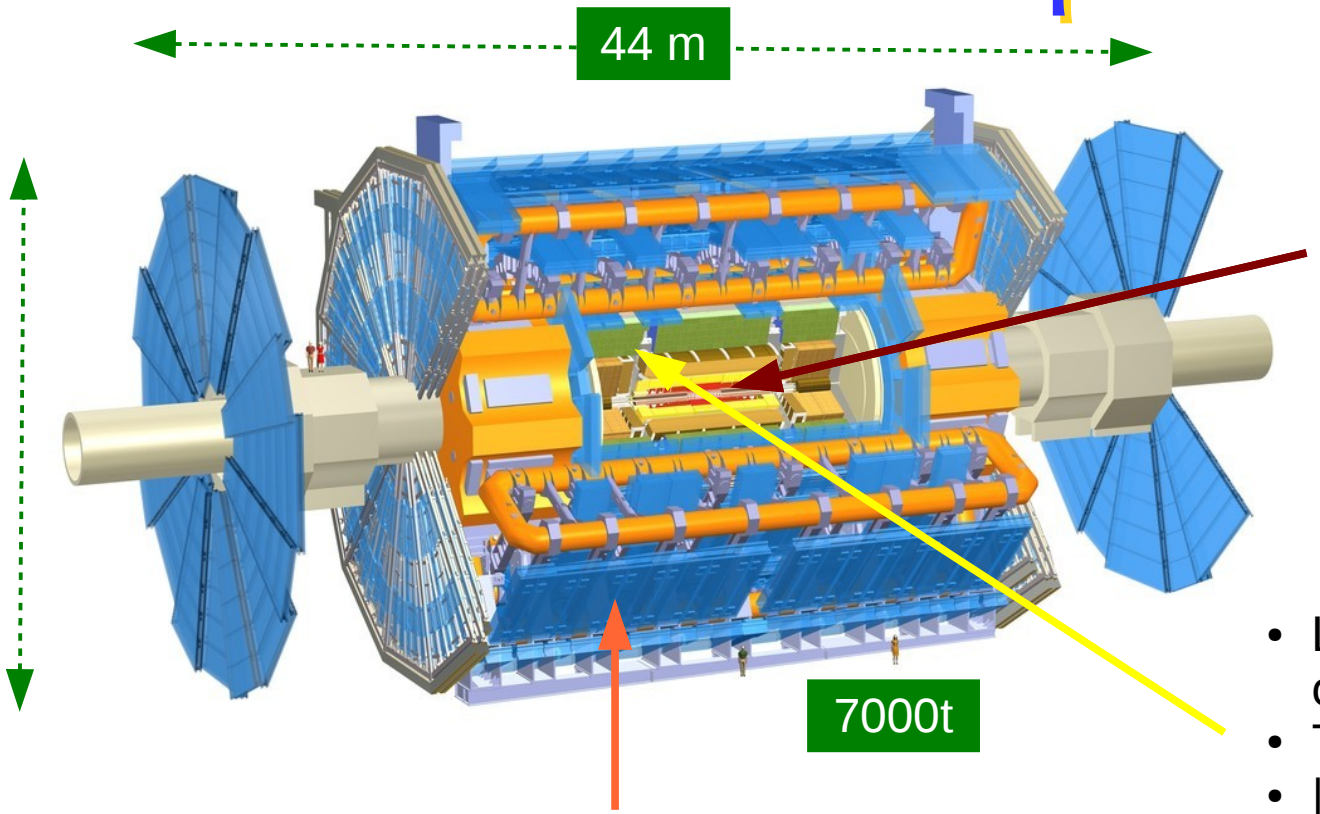
1) High mass dijet search
- High rate so high threshold required
- Probe mediator mass > 1.5 TeV
- PLB 754 (2016) 302

2) Low mass dijet search performed with trigger objects (“data scouting”)
- 450 GeV < mediator mass < 950 GeV
- ATLAS-CONF-2016-030

3) Trigger on ISR photon to avoid high jet trigger thresholds
- Probe mediator mass < 450 GeV
- ATLAS-CONF-2016-029



ATLAS Experiment



Inner Detector:

- 2T solenoid
- Silicon pixel & strip detectors
- Transition radiation tracker
- Interaction vertex
- $|\eta| < 2.5$
- Several hundred tracks per collision

Calorimeters:

- Liquid argon electromagnetic calorimeter
- Tile hadronic calorimeter
- $|\eta| < 4.9$
- 9.7 interaction lengths at $\eta=0$

Muon Spectrometer:

- 0.5-1T toroidal magnetic field
- Resistive Plate Chambers & Thin Gap Chambers for trigger
- Monitored Drift tubes & Cathode Strip Chambers measure sagitta
- $|\eta| < 2.5$

Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \lvert\eta\rvert < 4.9$	$3.1 < \lvert\eta\rvert < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at p_T = 1 TeV	± 2.7	± 2.4