Dark matter searches in ATLAS

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On behalf of ATLAS collaboration

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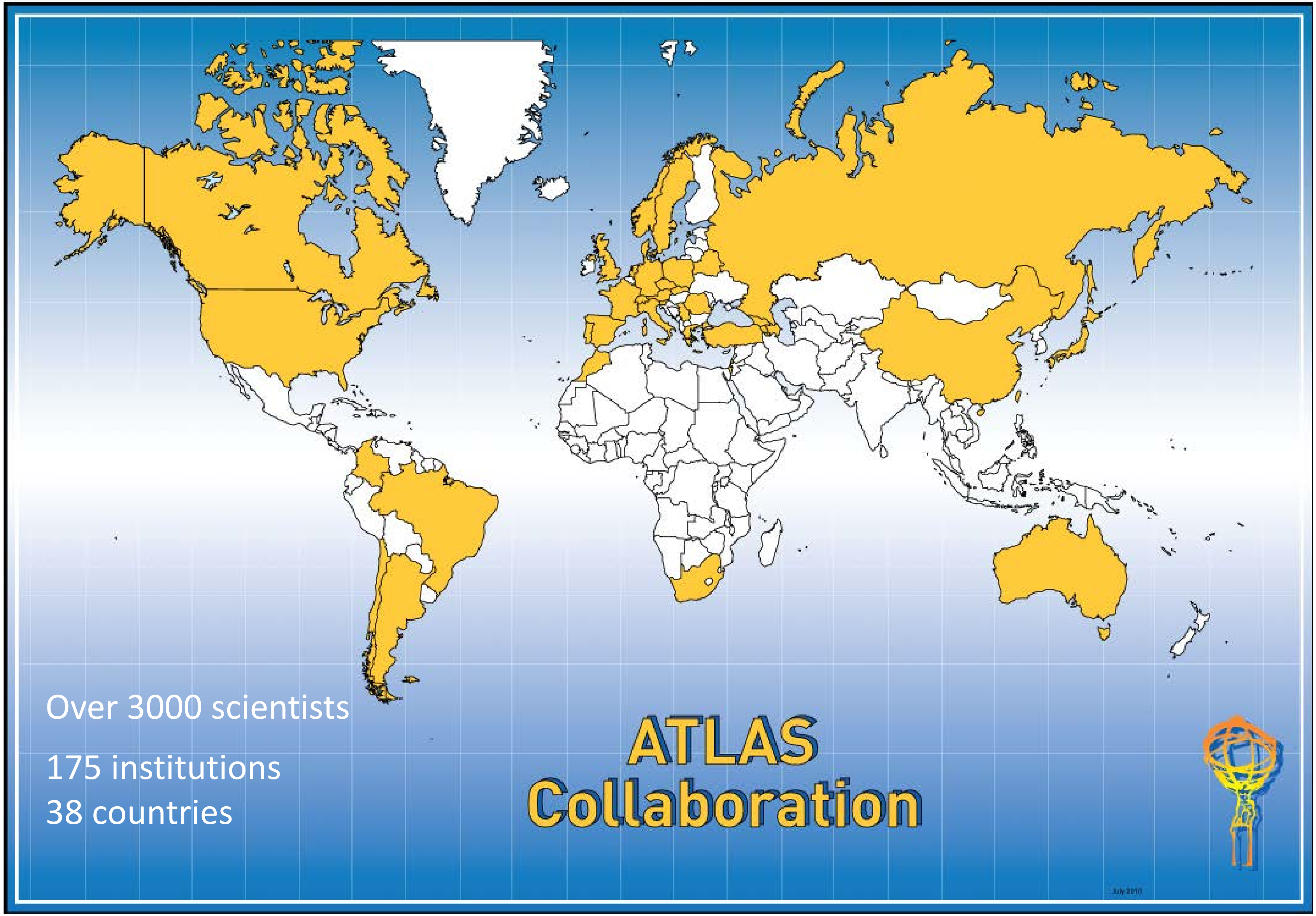
Outline

- ATLA Detector and collaboration
- Motivation, strategy and models
- Search channels:
  - Mono-jet
  - Mono-γ
  - Mono-Z (leptonic)
  - Mono-W/Z (hadronic)
  - Mono-W (leptonic)
  - Higgs invisible decays
- Summary

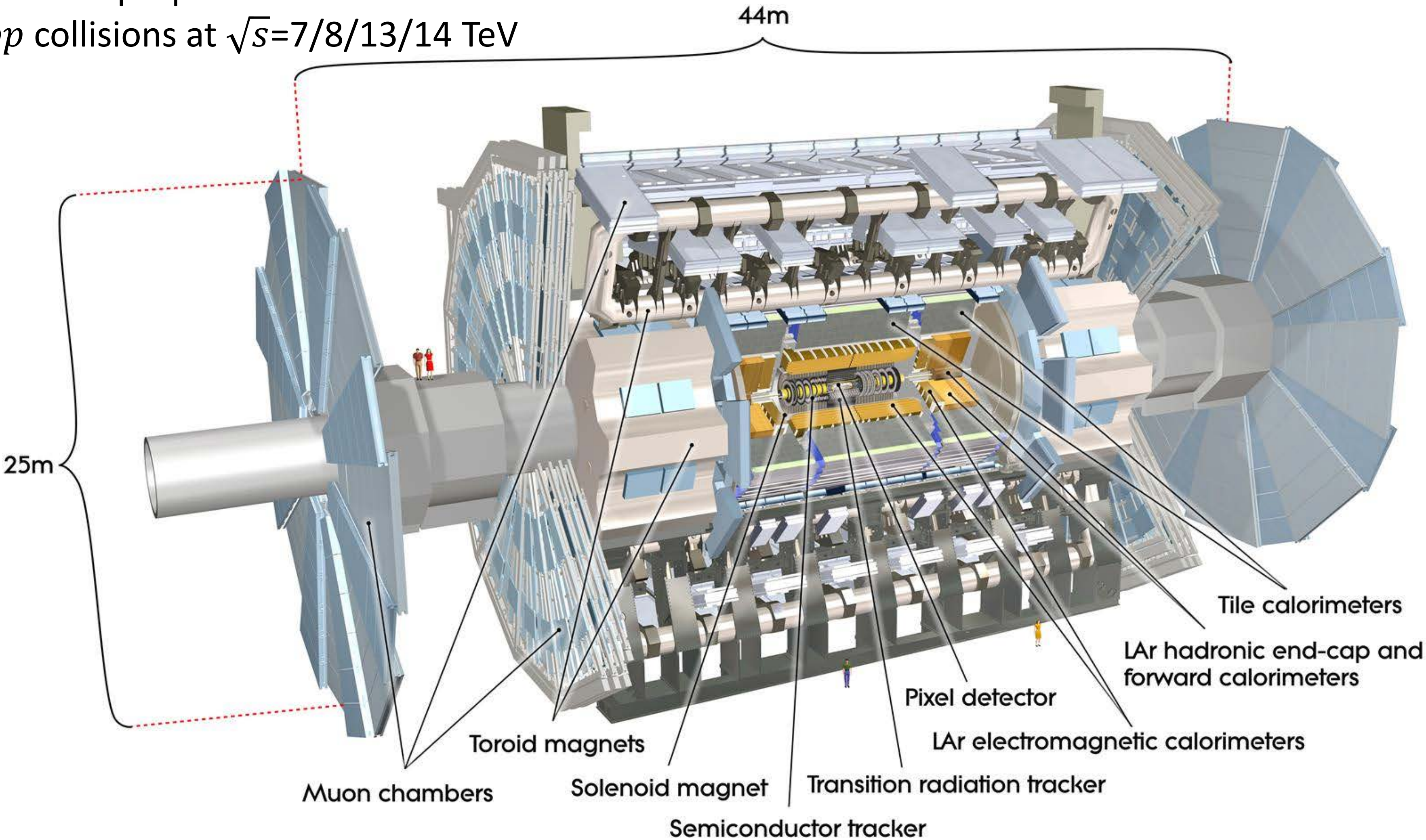
ATLAS collaboration



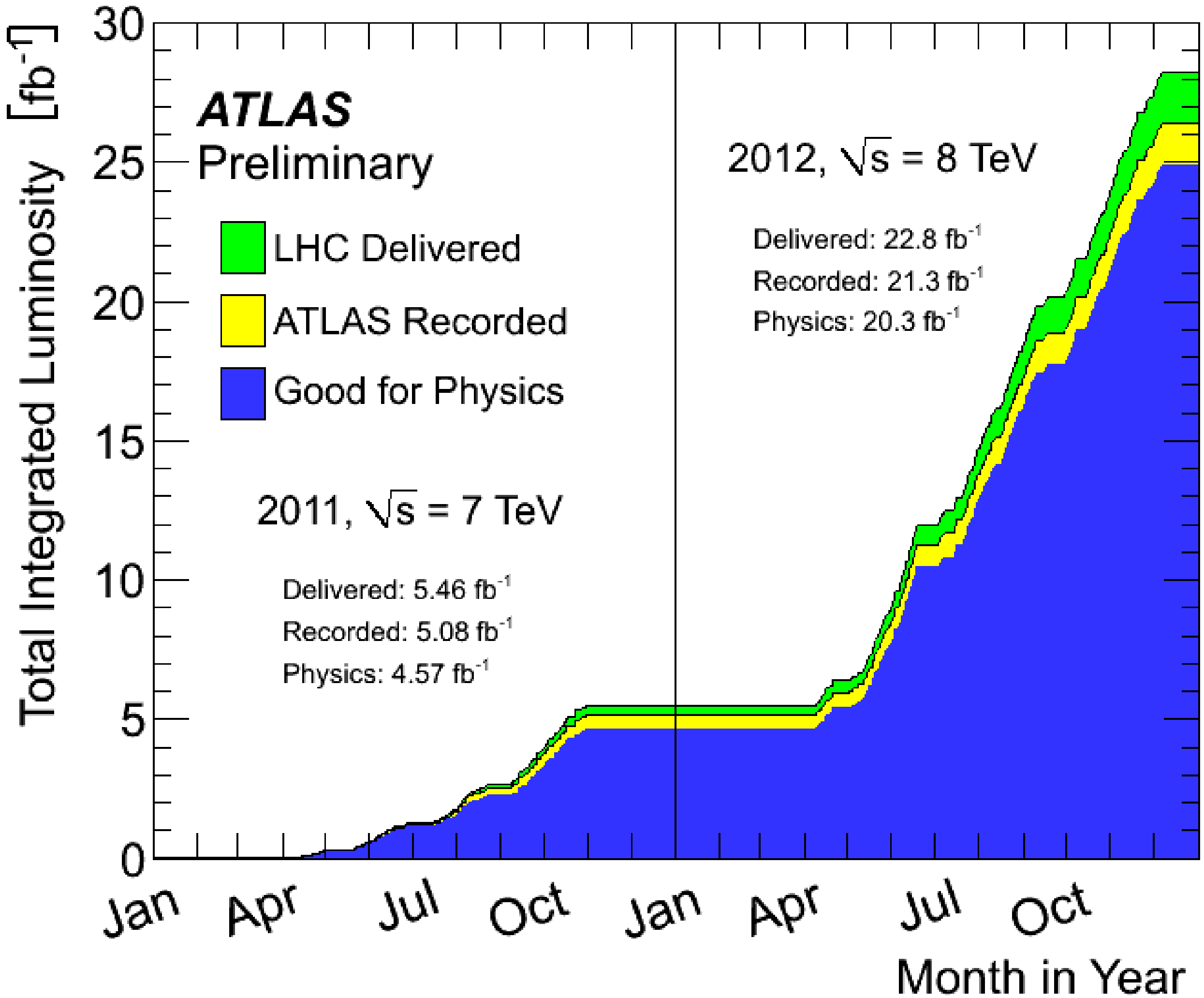
ATLAS detector

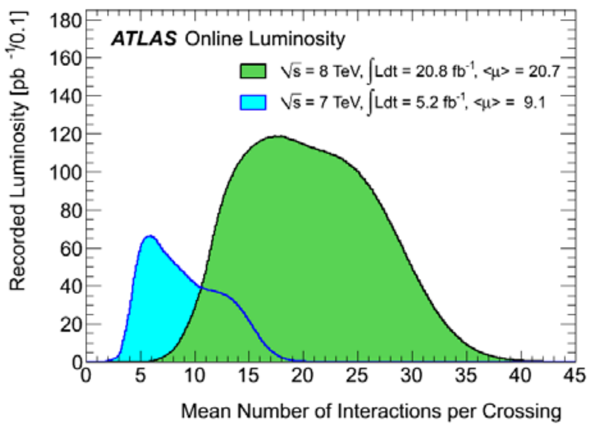
Operating at LHC point 1
General-purpose detector
pp collisions at $\sqrt{s}$=7/8/13/14 TeV

3 level trigger system



ATLAS Run-I dataset

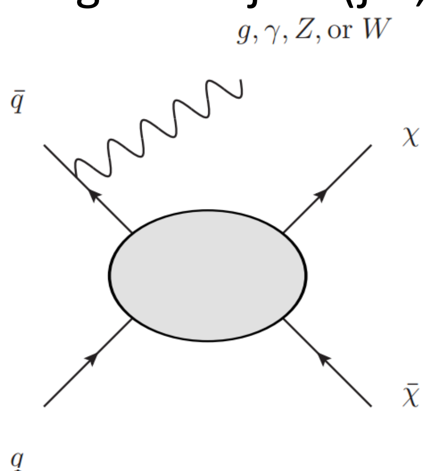


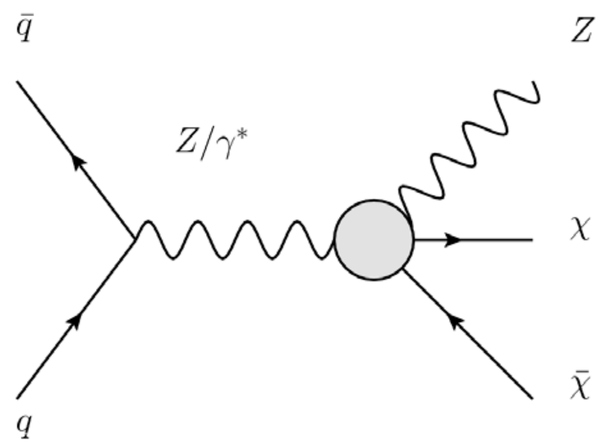


~ 25 fb^{-1} data good for physics recorded by ATLAS detector.

Introduction

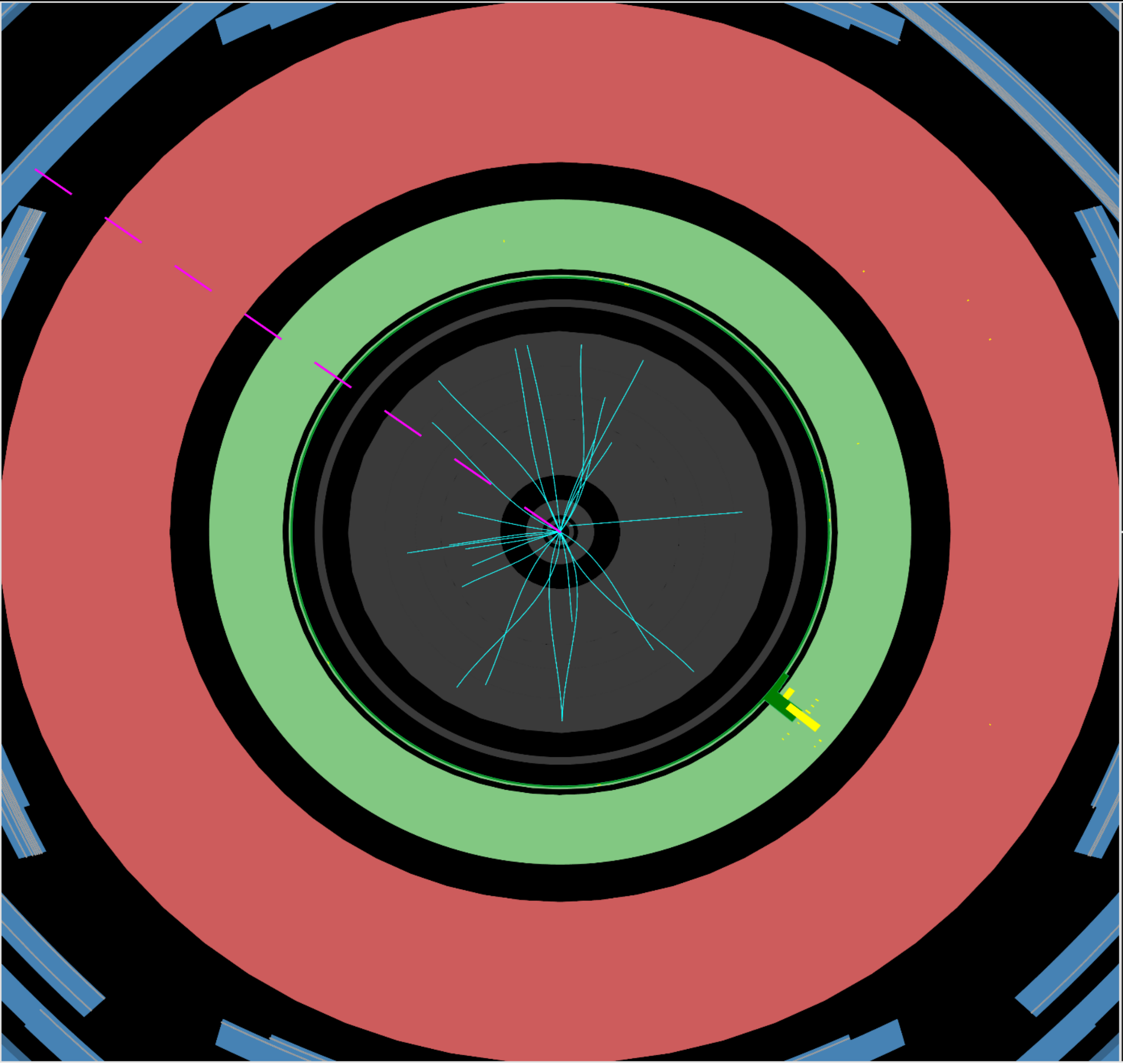
- Dark matter (DM) search at colliders has a better sensitivity compared to direct-detection experiments
  - at low mass with very large production rate.
  - in spin-dependent operators.
- The pair of weakly interacting massive particles (WIMPs) are studied as DM candidates in ATLAS with the signature of
  - Large missing transverse momentum ($\vec{p}_T^{\,\text{miss}}$) and energy ($E_T^{\text{miss}}$)
  - An energetic object (jet, W/Z boson or γ)

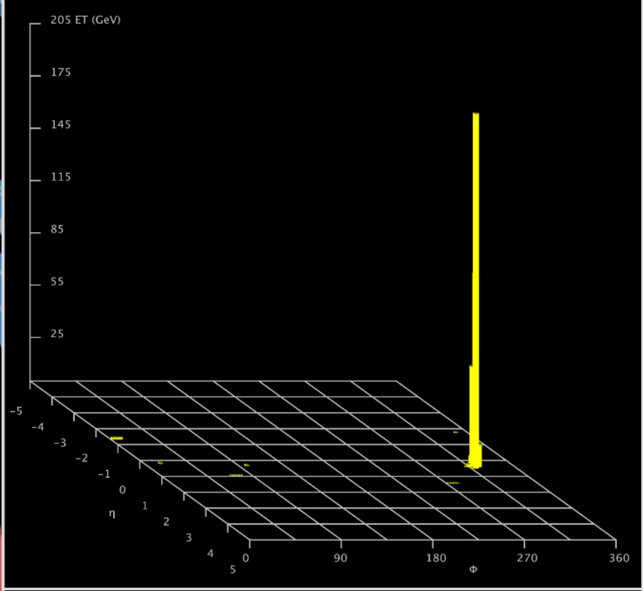




- Higgs boson invisible decays provide a portal for DM production at colliders.

One mono-γ example event





ATLAS EXPERIMENT

Run Number: 179710, Event Number: 19174449

Date: 2011-04-15 03:48:32 CEST

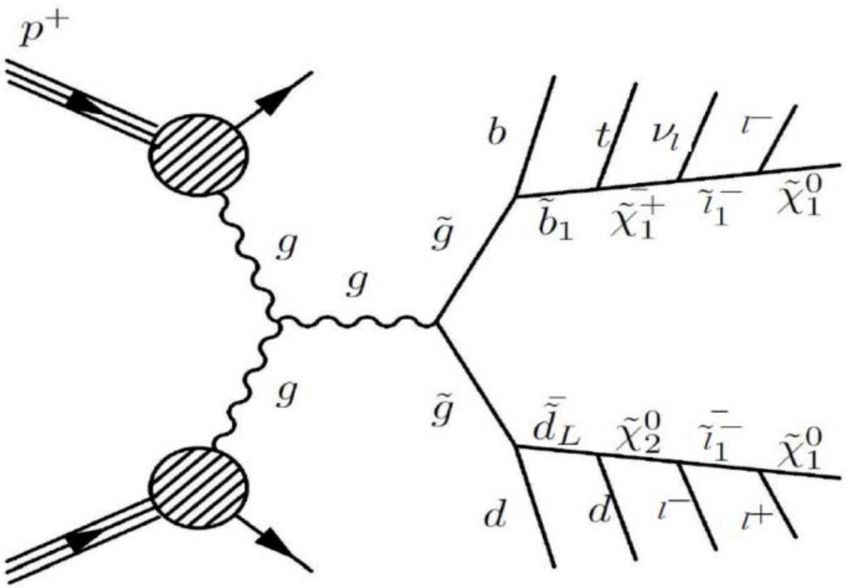
General analysis strategies

ATLAS EXPERIMENT

- The standard model (SM) processes are treated as background and compared with the number of data events.
- The signal region (SR) is usually defined with
  - Large E_T^{miss}, an energetic object, veto on additional objects
- The control regions (CRs) are defined to evaluate the background expectation in SR with similar kinematics but
  - Additional object(s)
  - Different E_T^{miss} selection in some cases
  - Orthogonal to SR
- One example:
  - $Z \to \nu\nu + \gamma$ background (calorimeter-based E_T^{miss}, lepton veto)
  - CR: 2 additional muons, dominated by $Z \to \mu\mu + \gamma$ process
  - Transfer factor (TF) from CR: $N_{\text{data}}/N_{\text{MC}}$
  - Apply TF to $Z \to \nu\nu + \gamma$ MC in signal region

SUSY WIMP search

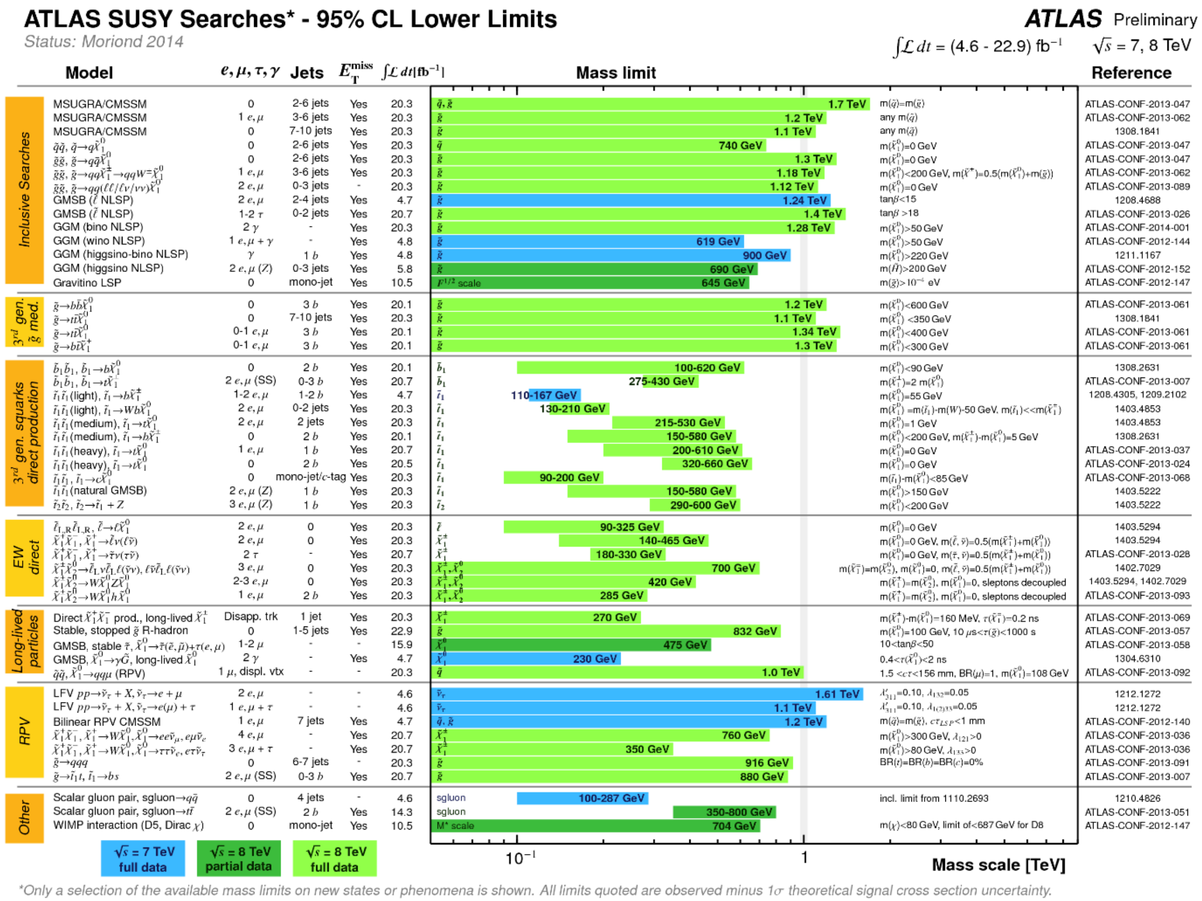
- Good: Supersymmetry (SUSY) provides 2 excellent possible WIMPs: the neutralino and the gravitino assuming R-parity conservation.
- Bad: SUSY introduces 128 new parameters. Assumptions and constraints can reduce parameters.
- Ugly: SUSY DM produced via long decay chains through heavier SUSY (strongly/EM interacting) intermediaries which are the first to search for. Limits SUSY DM highly model-dependent.



Example of production of SUSY particles and long decay chain producing neutralinos (assumed stable due to R-parity conservation), jets, leptons, and MET

SUSY limits

- Many SUSY searches undertaken, mainly for gluinos, squarks with indirect limits on WIMPs. Wide range of SUSY variants and final states covered. Limits on SUSY WIMPs indirectly and highly model-dependent. Not covered in this talk



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

Effective field theory (EFT)

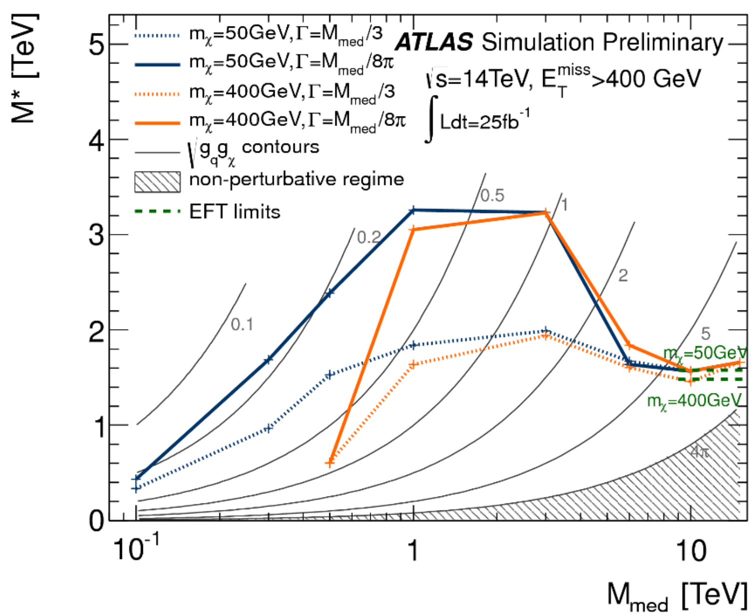
ATLAS EXPERIMENT

- EFT considers possible contact interactions of g, q producing WIMP pairs ($\chi\bar{\chi}$) suppressed by a mass scale M_* (i.e. mediator too massive to be created directly)
  - It is valid if the momentum transfer $Q_{\rm tr}<M_{\rm med}$
- Limit is set on the suppression scale $M_*=M_{\rm med}/\sqrt{g_{\rm SM}g_{\rm DM}}$
  - $Q_{\rm tr}<M_*\sqrt{g_{\rm SM}g_{\rm DM}}$ is required
  - EFT is more suitable for WIMP searches if
    - Less momentum transfer: lower center-of-mass energy, lower WIMP mass
    - Higher limit on M_*: more integrated luminosity
- The following EFT operators are interpreted in ATLAS:

Name	D1	D5	D11	D8	D9
Operator	$\bar{\chi}\chi\bar{q}q$ scalar	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$ vector	$\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$ scalar	$\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{q}\gamma_{\mu}\gamma^{5}q$ axial-vector	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ tensor
Coefficient	m_q/M_*^3	$1/M_*^2$	$\alpha_s/4M_*^3$	$1/M_*^2$	$1/M_*^2$
Spin	Independent			Dependent	

Simplified models

- Due to the validity issue of EFT, simplified models assume the mediator is not integrated out.
  - Validity question at high $Q_{\rm tr}$ is addressed
- Three domains based on $M_{\rm med}$
  - Low: high $Q_{\rm tr}$ results in off-shell production
  - Medium: resonant production, large cross section and strong limits
  - High: out of energy reach of the colliders, described by contact theory



ATL-PHYS-PUB-2014-007

Mono-jet

Dataset and event selection

- $\sqrt{s}$=7 TeV, 4.7 fb^{-1} data: *JHEP 04 (2013) 075*
- $\sqrt{s}$=8 TeV, 10.5 fb^{-1} data: *ATLAS-CONF-2012-147*
- The signal events are selected by requiring:
  - E_T^{miss} trigger at 70 GeV
  - A primary vertex with at least two associated tracks.
  - Suppression on detector noise, cosmic rays or beam-background muons.
  - no more than one additional jet has p_T>30 GeV.

Signal regions	SR1	SR2	SR3	SR4
Common requirements	Data quality + trigger + vertex + jet quality + $\lvert\eta^{\mathrm{jet1}}\rvert < 2.0$ + $\lvert\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathbf{p}_{\mathrm{T}}^{\mathrm{jet2}})\rvert > 0.5$ + $N_{\mathrm{jets}} \leq 2$ + lepton veto			
$E_{\mathrm{T}}^{\mathrm{miss}}$, $p_{\mathrm{T}}^{\mathrm{jet1}}$ >	120 GeV	220 GeV	350 GeV	500 GeV

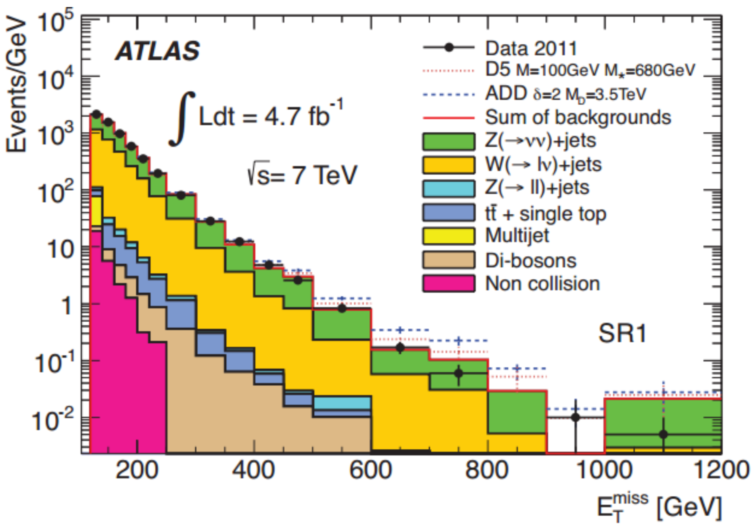
7 TeV results

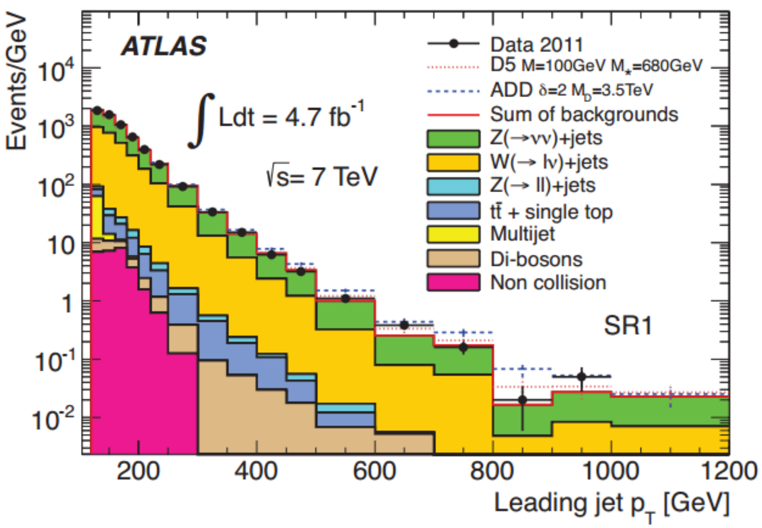
- No excess is observed above SM backgrounds.

Yield	SR1	SR2	SR3	SR4
Total Bkg	124000±4000	8800±400	750±60	83±14
Data	124703	8631	785	77

- Exclusion limits are set on $\sigma_{\text{vis}} = \sigma \times A \times \epsilon$

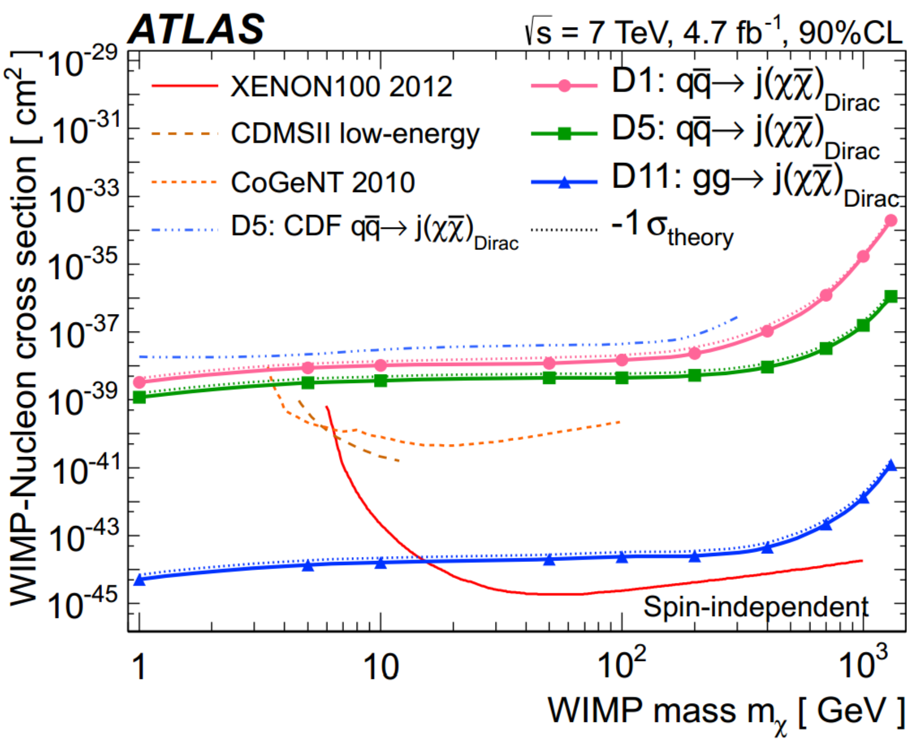
CL limit	SR1	SR2	SR3	SR4
$\sigma_{\text{vis}}^{\text{obs}}$ at 90% [fb]	1.63	0.13	0.026	0.0055
$\sigma_{\text{vis}}^{\text{obs}}$ at 95% [fb]	1.92	0.17	0.030	0.0079

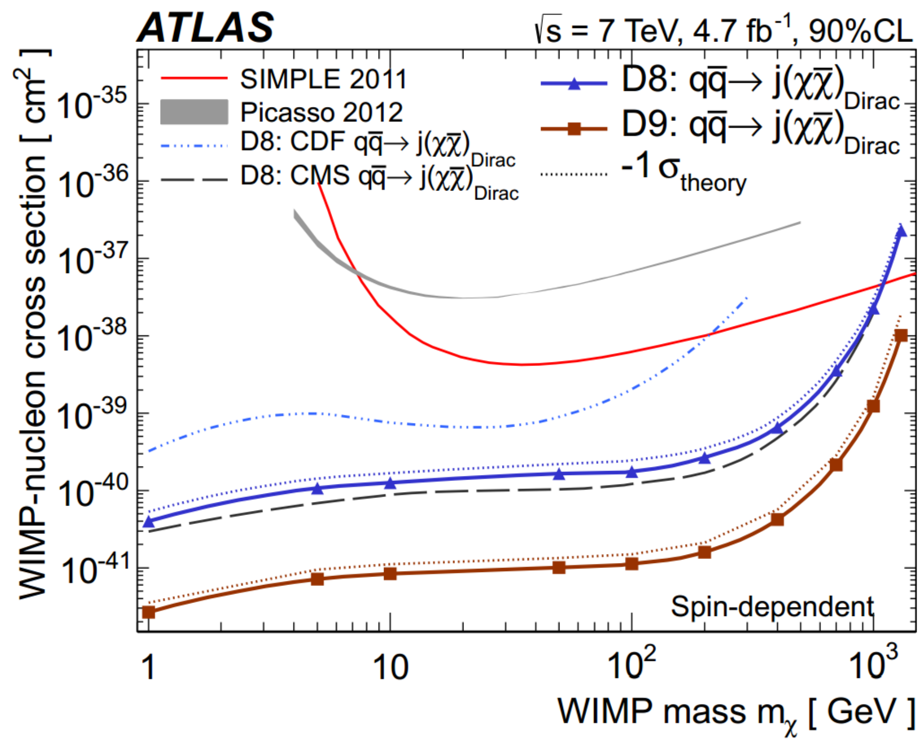




7 TeV results

- EFT interpretation
  - Translated to 90% CL limit on the WIMP-nucleon cross section



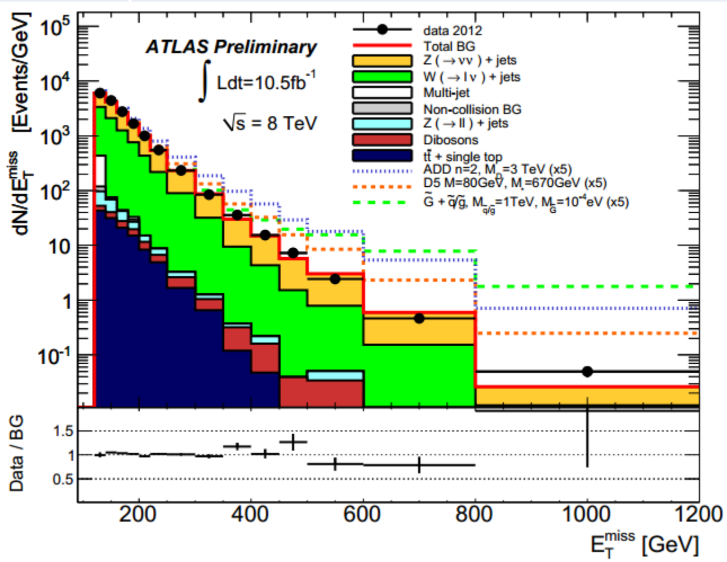


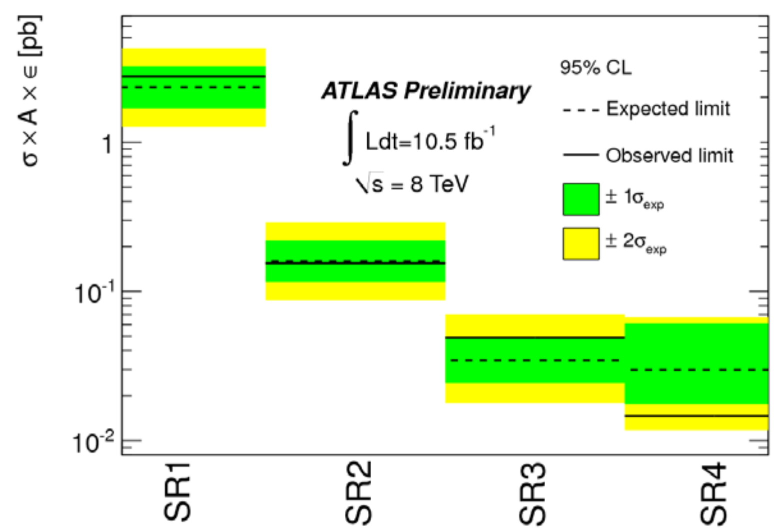
8TeV results

ATLAS EXPERIMENT

- No excess is observed above SM backgrounds.

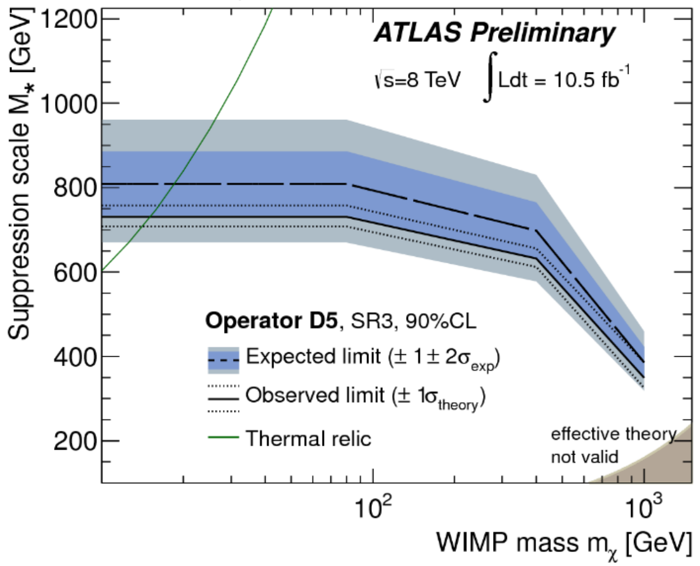
	Yield (±stat. data ± stat. MC ± syst.)	
Region	SR1	SR2
Total bkg	344400±900±2200±12600	25600±240±500±900
Data	350932	25515
Yield	**SR3**	**SR4**
Total bkg	2180±70±120±100	380±30±60±30
Data	2353	268

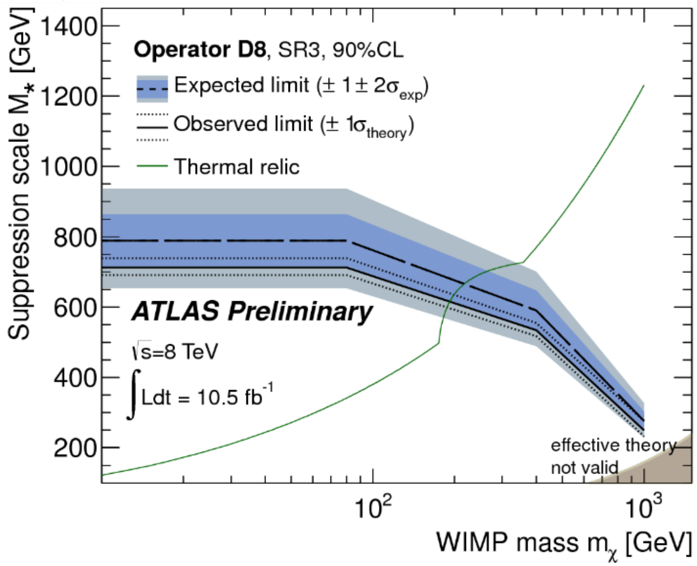


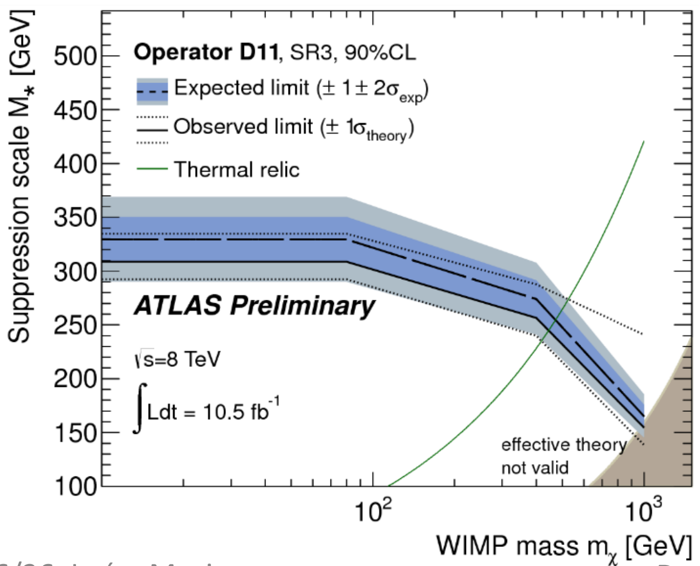


8 TeV results

- EFT interpretation (D5, D8, D11 operators)



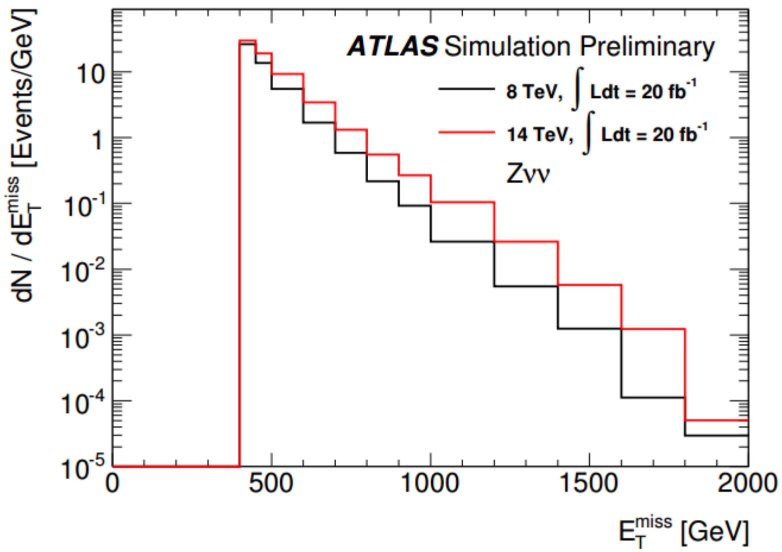


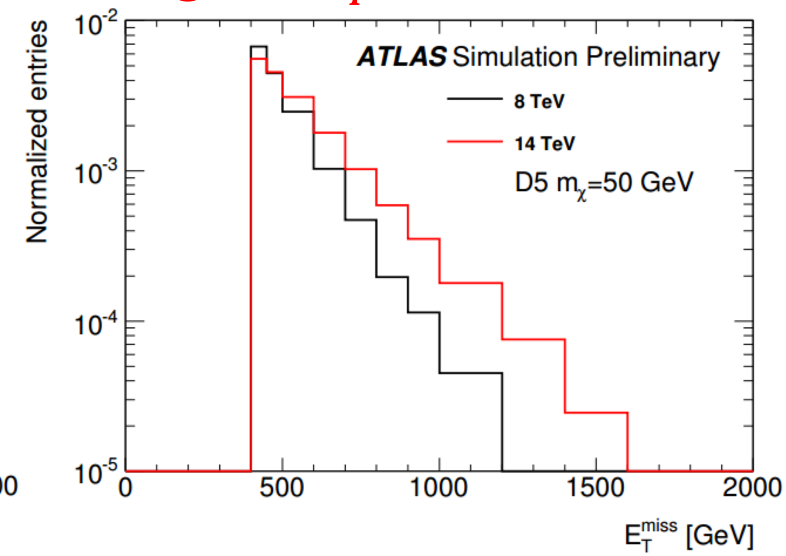


14 TeV prospect

ATL-PHYS-PUB-2014-007

- The LHC will run at $\sqrt{s}$=13/14 TeV in 2015.
  - More momentum transfer leads to higher E_T^{miss} tail.



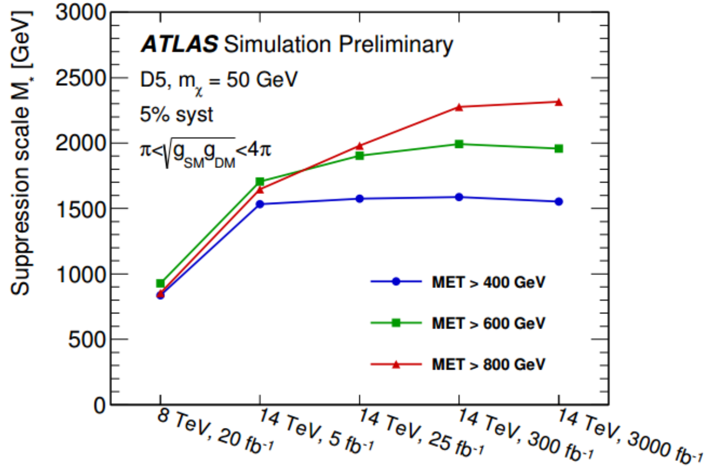


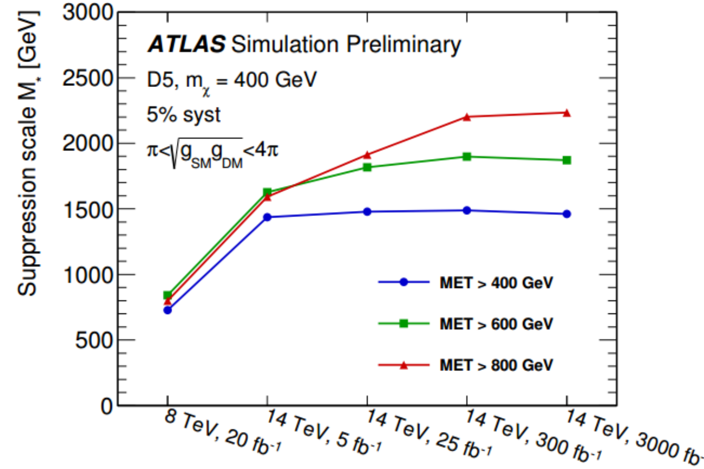
- The prospect is studied with truth level MC and emulated detector response at high pile-up conditions.
  - First a few month data-taking will give better sensitivity compared to Run I dataset.

	$\sqrt{s}$ [TeV]	μ	L [fb^{-1}]
	8	20	20
Phase 0 upgrade (2014-2015)	14	60	25
Phase 1 upgrade (2018)	14	60	300
Phase 2 upgrade (2022)	14	140	3000

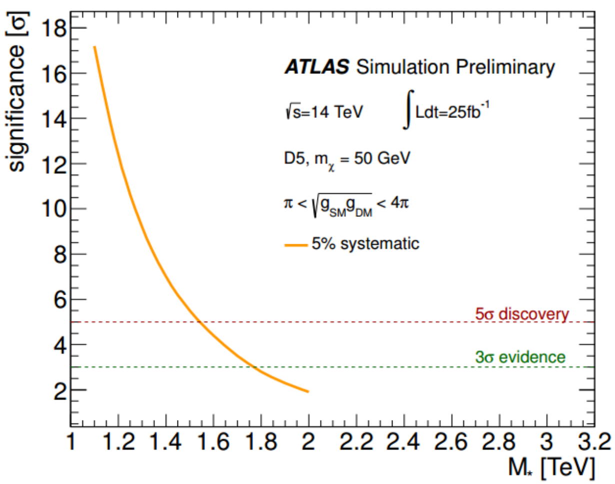
14 TeV prospect

- EFT (D5) interpretation as 95% CL limit on M_*.





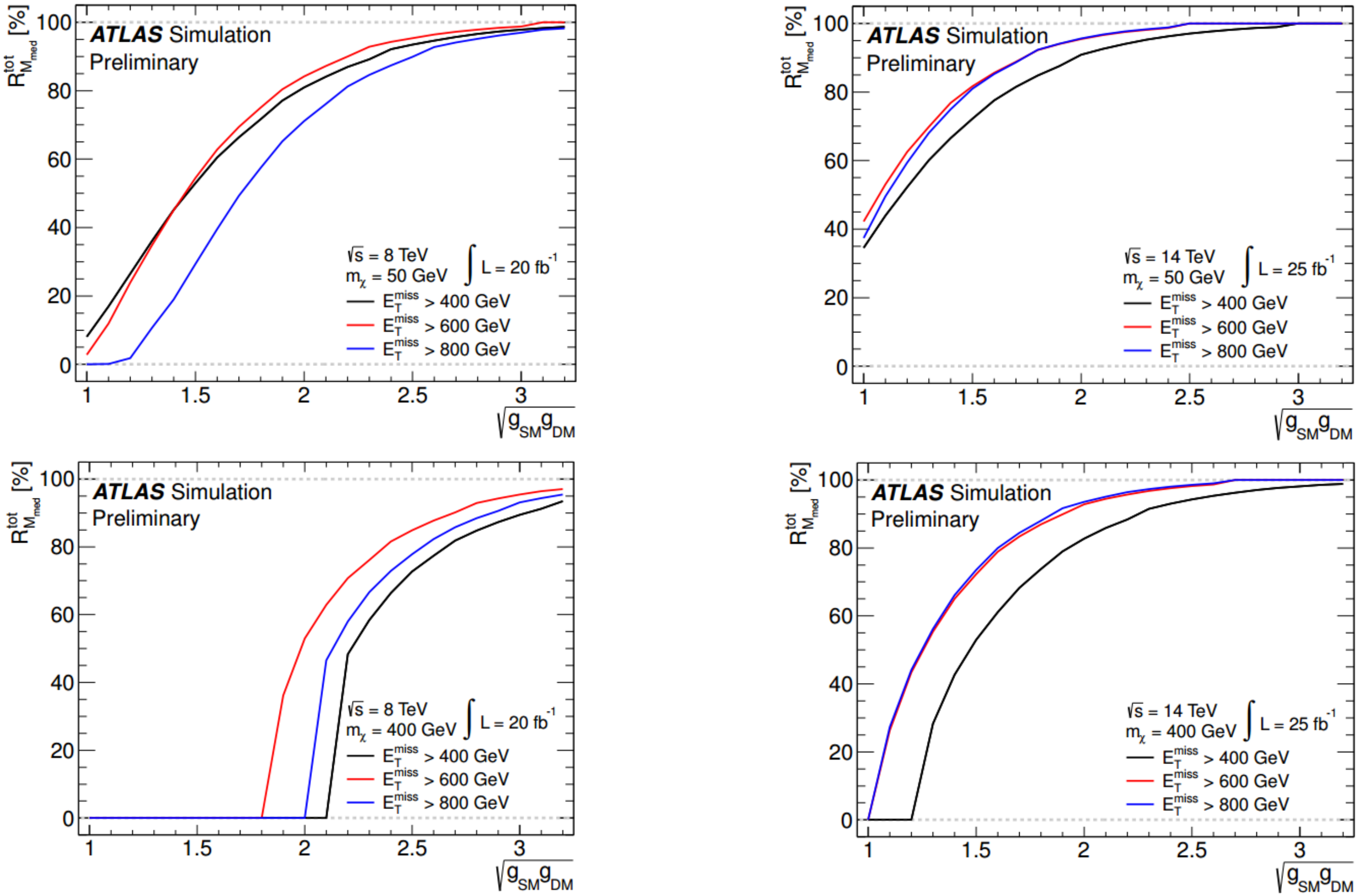
- Potential to discovery.



Integrated lumi [fb^{-1}]	Higher M_* boundary for discovery	
	1% systematic	5% systematic
25	-	1.6 TeV
300	2.2 TeV	1.8 TeV
3000	2.6 TeV	1.8 TeV

EFT validity at 14 TeV

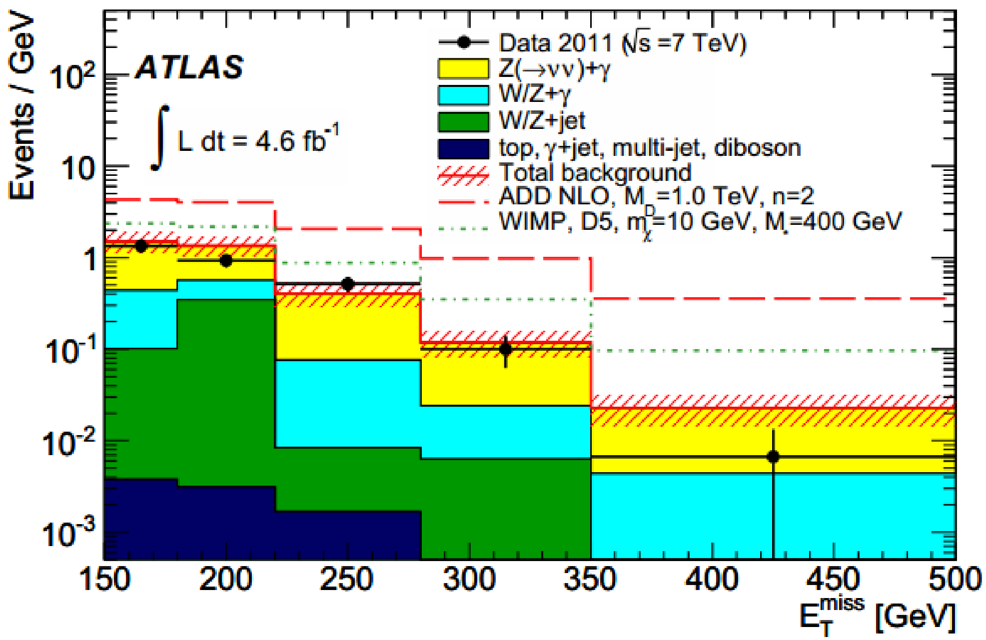
- $R^{\mathrm{tot}}_{M_{\mathrm{med}}}$: faction of valid events with $Q_{\mathrm{tr}} < M_{*}\sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}}$
- Stringent limits at 14 TeV lead to larger valid ranges for EFT



Mono-γ

Dataset and event selection

- $\sqrt{s}$=7 TeV, 4.6 fb^{-1}: *PRL 110, 011802 (2013)*
- The signal events are selected by requiring:
  - E_T^{miss} trigger at 70 GeV
  - A isolated γ, p_T>150 GeV, passing tight identification (ID) criteria
  - E_T^{miss}>150 GeV and $\Delta\phi(E_T^{\text{miss}},\gamma)$>0.4
  - $\leq$ 1 jet. $\Delta R(\gamma$,jet)>0.4 and $\Delta\phi(E_T^{\text{miss}}$,jet)>0.4
  - No electrons or muons.



Results

- No excess is observed compared to background expectation.

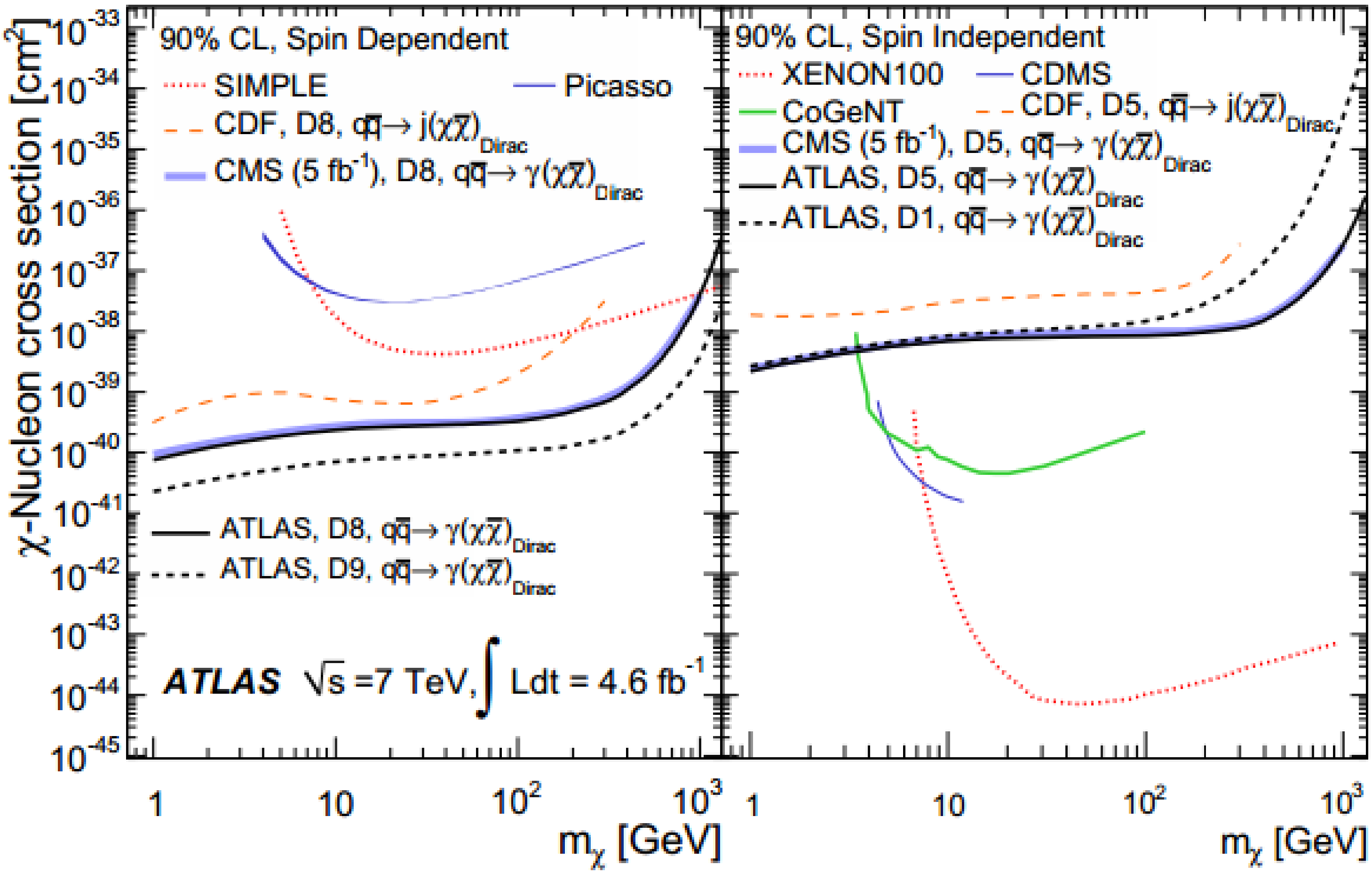
Background source	Prediction	± (stat.)	± (syst.)
$Z(\rightarrow \nu\bar{\nu}) + \gamma$	93	± 16	± 8
$Z/\gamma^{*}(\rightarrow \ell^{+}\ell^{-}) + \gamma$	0.4	± 0.2	± 0.1
$W(\rightarrow \ell\nu) + \gamma$	24	± 5	± 2
W/Z + jets	18	–	± 6
Top	0.07	± 0.07	± 0.01
$WW, WZ, ZZ, \gamma\gamma$	0.3	± 0.1	± 0.1
γ+jets and multi-jet	1.0	–	± 0.5
Total background	137	± 18	± 9
Events in data (4.6 fb^{-1})	116		

- The 90% (95%) CL limit on the $\sigma \times A \times \epsilon$ is 5.6 (6.8) fb.

EFT interpretation

ATLAS EXPERIMENT

- The comparison is only valid within EFT framework.



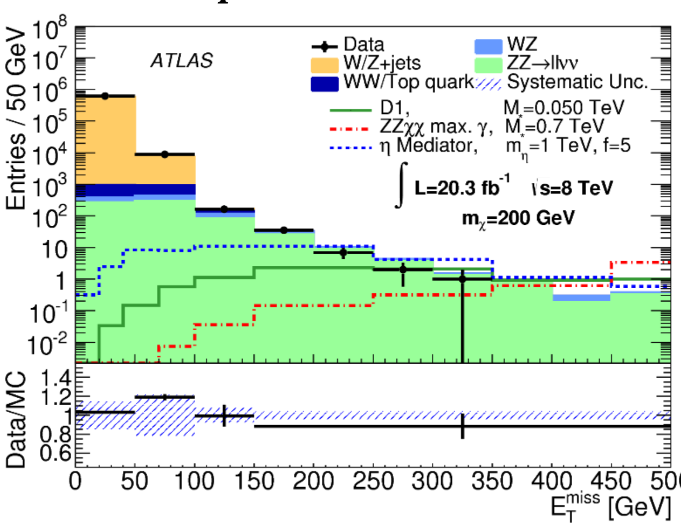
Mono-Z (leptonic)

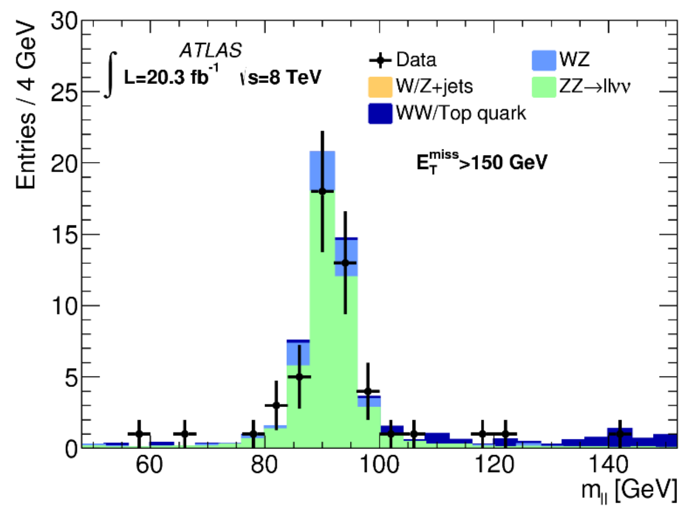
Dataset and event selection

ATLAS EXPERIMENT

- $\sqrt{s}$=8 TeV, 20.3 fb^{-1}: *arXiv 1404.0051*, accepted by *PRD*
- The signal events are selected by requiring:
  - Single lepton or di-lepton triggers
  - A primary vertex with at least three associated tracks
  - Two opposite-sign, same-flavor leptons balancing E_T^{miss}
    - $\Delta\phi(E_T^{\text{miss}}, p_T^{ll})$>2.5, $|\eta^{ll}|$<2.5, $|p_T^{ll} - E_T^{\text{miss}}|/p_T^{ll}$<0.5
  - 76<m_{ll}<106 GeV and no additional looser leptons or jets
- 4 SRs, with E_T^{miss} > 150, 250, 350 and 450 GeV

new



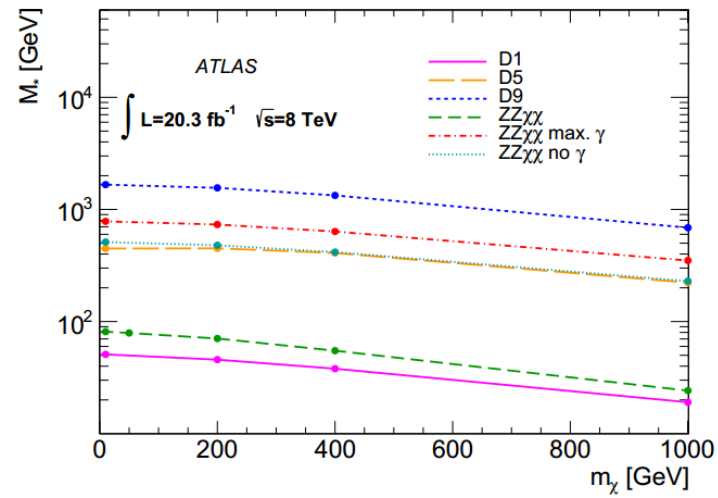


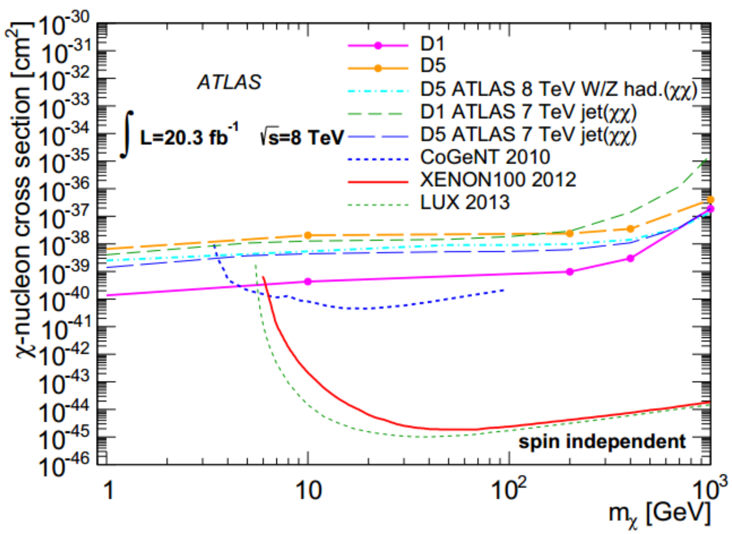
Results

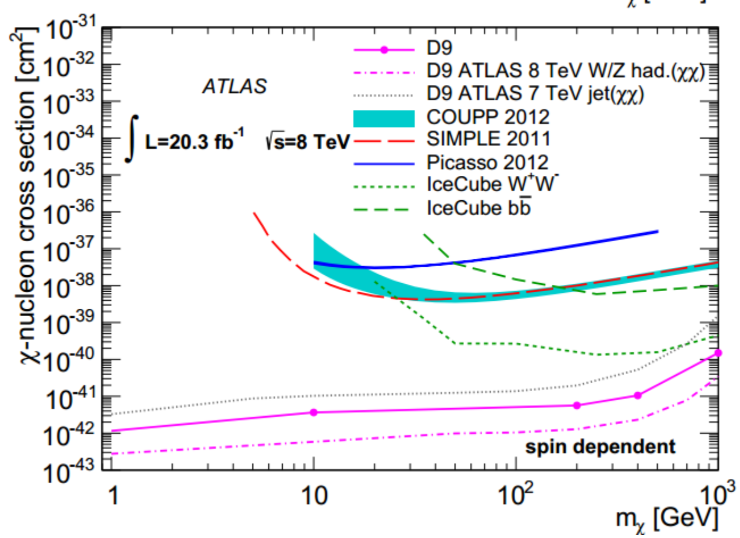
ATLAS EXPERIMENT

- No excess is observed above SM expectation.
- EFT (heavy mediator)

Process	$E_{\mathrm{T}}^{\mathrm{miss}}$ threshold [GeV]			
	150	250	350	450
ZZ	41 ± 15	6.4 ± 2.4	1.3 ± 0.5	0.3 ± 0.1
WZ	8.0 ± 3.1	0.8 ± 0.4	0.2 ± 0.1	0.1 ± 0.1
WW, $t\bar{t}$, $Z \to \tau^+\tau^-$	1.9 ± 1.4	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$	$0^{+0.7}_{-0.0}$
Z+jets	0.1 ± 0.1	–	–	–
W+jets	0.5 ± 0.3	–	–	–
Total	52 ± 18	7.2 ± 2.8	1.4 ± 0.9	$0.4^{+0.7}_{-0.4}$
Data	45	3	0	0

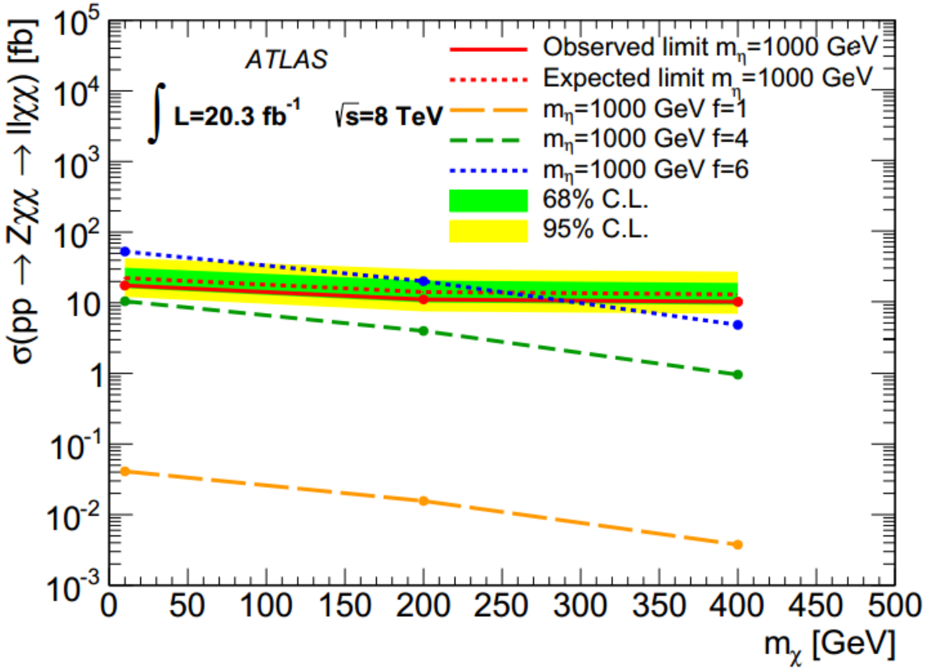


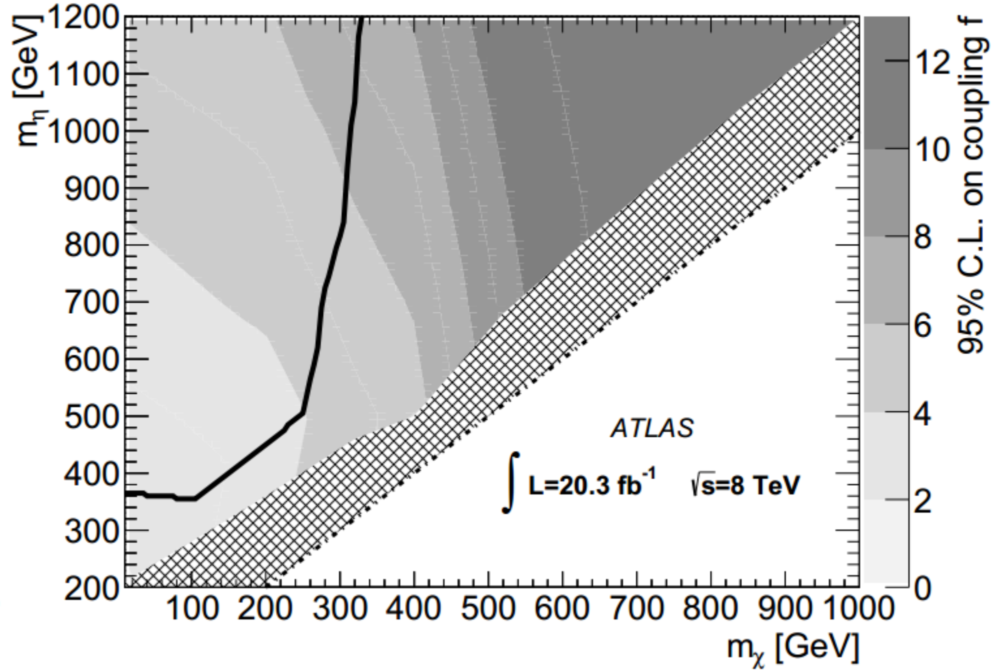




Results

- Simplified model (light mediator)



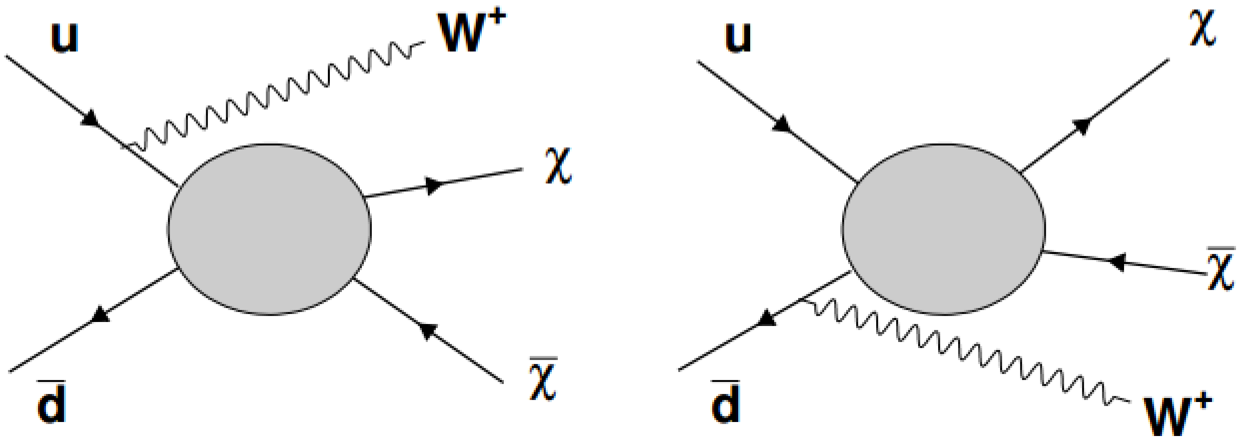


Mono-W/Z (hadronic)

Mono-W/Z (hadronic)

Motivation

- Mono-jet and mono-γ searches assume the same DM coupling for up and down quarks [$C(u) = C(d)$].
- If the couplings have the opposite sign as $C(u) = -C(d)$, the mono-W production will be dominant.



- $\sqrt{s}$=8 TeV, 20.3 fb^{-1}: *PRL 112, 041802 (2014)*.

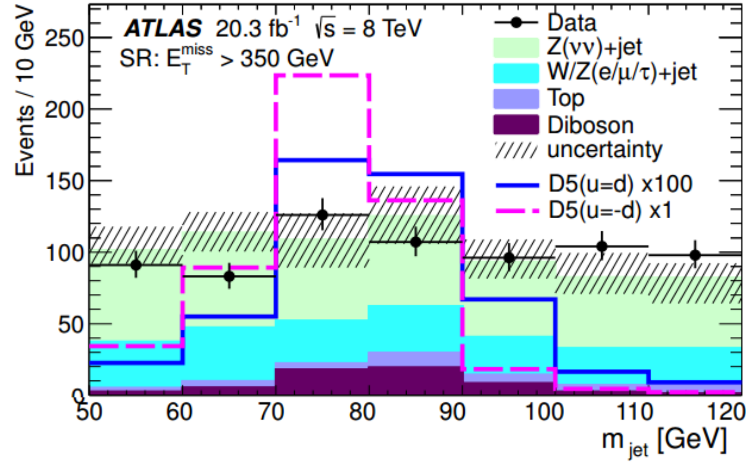
Event selection

- Jet definition:
  - Large radius jet (large-R jet): Cambridge-Aachen algorithm with distance parameter of 1.2
  - Narrow jet (j): anti-k_t algorithm with distance parameter of 0.4
- The signal events are selected by requiring:
  - E_T^{miss} trigger
  - $\geq$ 1 large-R jet, with p_T>250 GeV, $|\eta|$<1.2, 50<m_{jet}<120 GeV and $\min(p_{T1}, p_{T2})\,\Delta R/m_{\mathrm{jet}}$>0.4.
  - $\leq$1 j not overlapping with the leading large-R jet(ΔR>0.9).
  - Veto events with narrow jet $\Delta\phi(E_T^{\mathrm{miss}}$, j)<0.4.
  - Veto events with any reconstructed electrons, muons or photons.
- Two SRs, with $E_T^{\mathrm{miss}} > 350$ or 500 GeV.

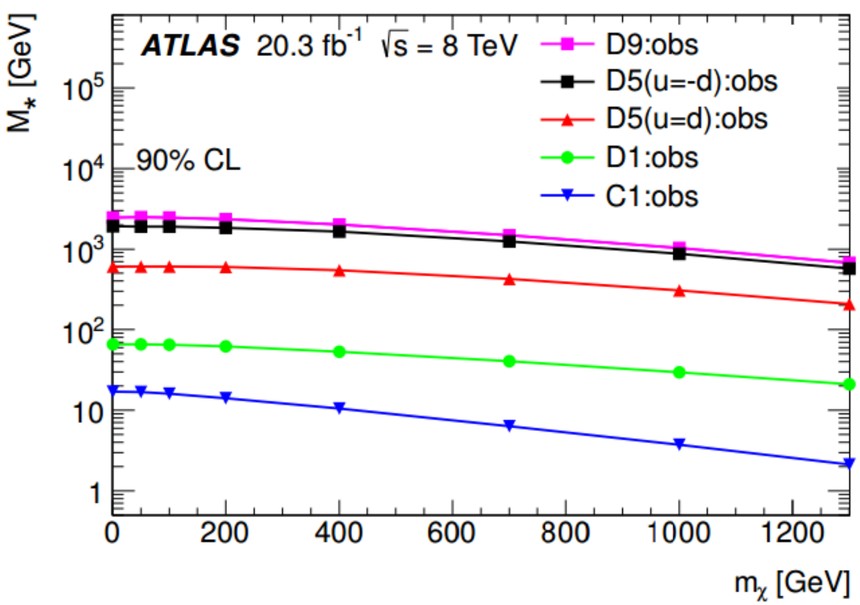
Results

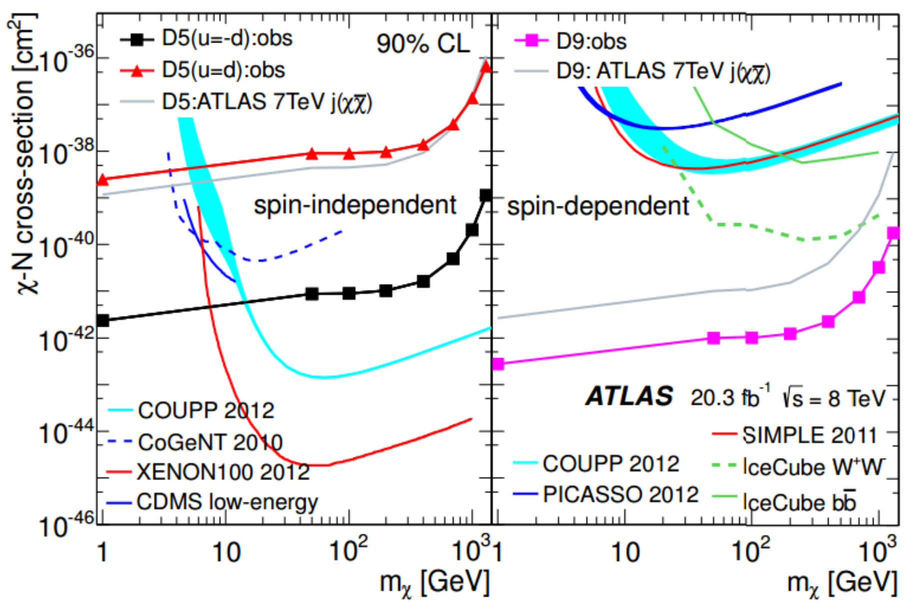
- No excess observed above the SM background expectation.

Process	$E_T^{miss} > 350$ GeV	$E_T^{miss} > 500$ GeV
$Z \to \nu\bar{\nu}$	402^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^{\pm}\nu$, $Z \to \ell^{\pm}\ell^{\mp}$	210^{+20}_{-18}	22^{+4}_{-5}
WW, WZ, ZZ	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.3}$
Total	707^{+48}_{-38}	89^{+9}_{-12}
Data	705	89



- EFT interpretations.





Mono-W (leptonic)

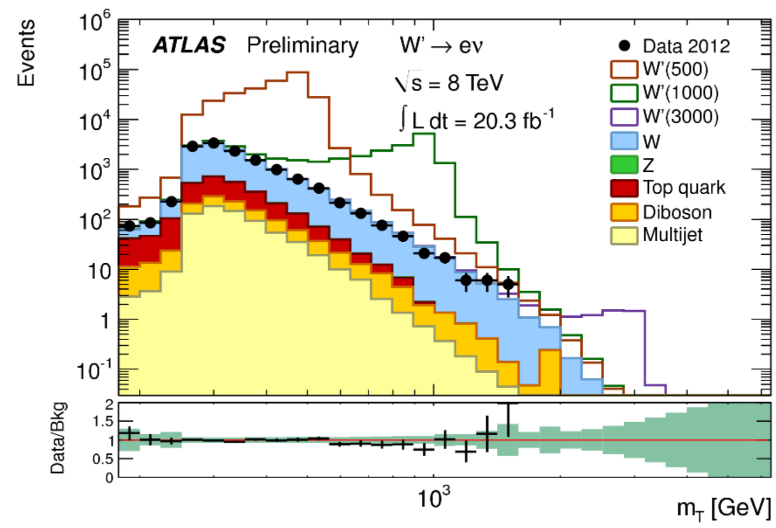
Mono-W (leptonic)

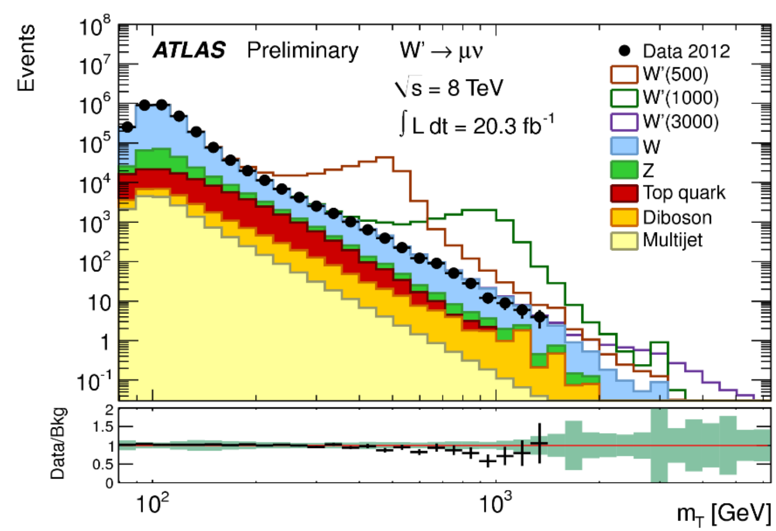
Event selection

- $\sqrt{s}$=8 TeV, 20.3 fb^{-1}: *ATLAS-CONF-2014-017*

new

- Event selection:
  - At least one primary vertex with three associated tracks
  - Electron channel:
    - Trigger on single electron with p_T>120 GeV
    - One isolated electron with p_T>125 GeV, E_T^{miss}>125 GeV
  - Muon channel:
    - Trigger on single muon with p_T>36 GeV
    - One isolated muon with p_T>45 GeV, E_T^{miss}>45 GeV
  - Cut on $m_T(l, E_T^{\text{miss}})$ to suppress non-W background

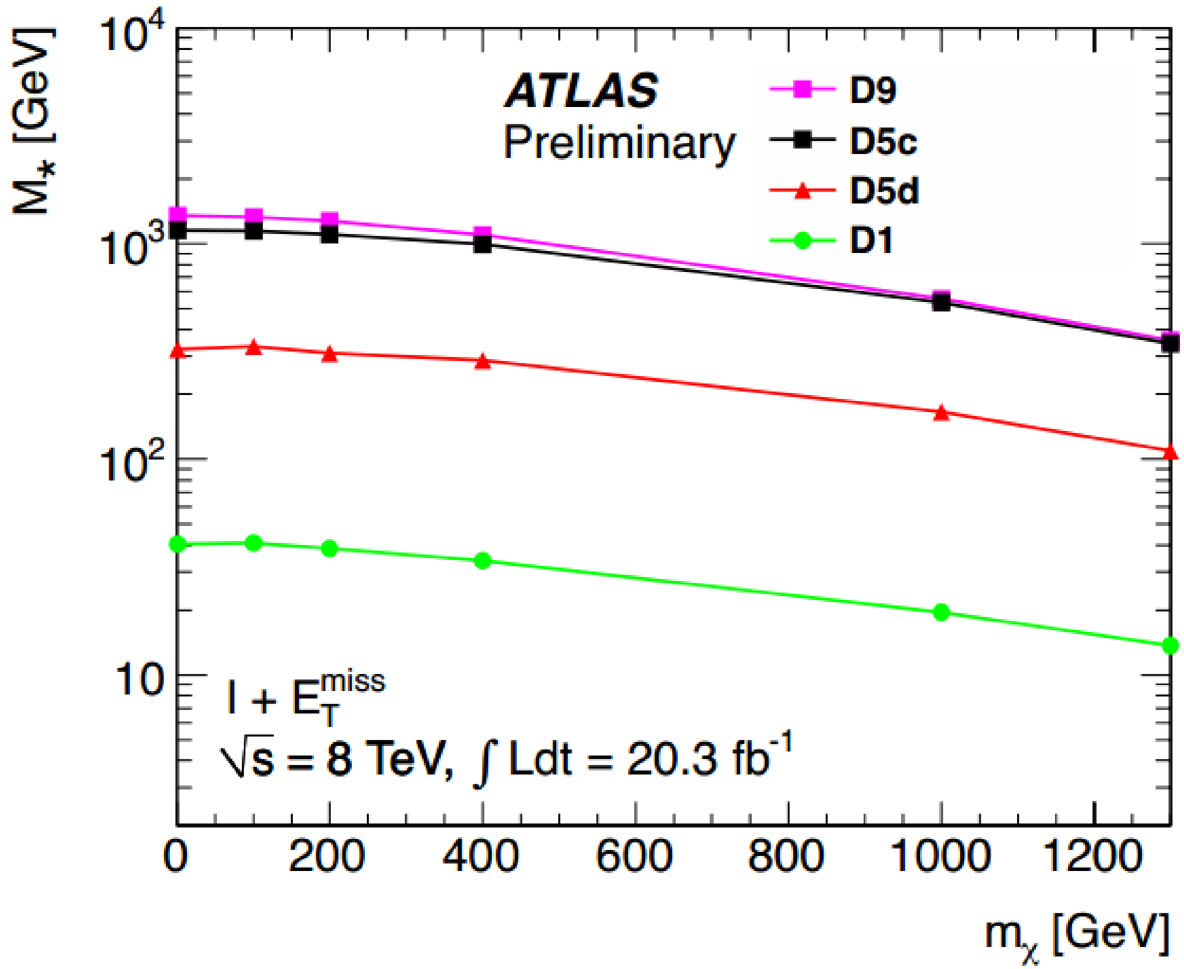




Results

ATLAS EXPERIMENT

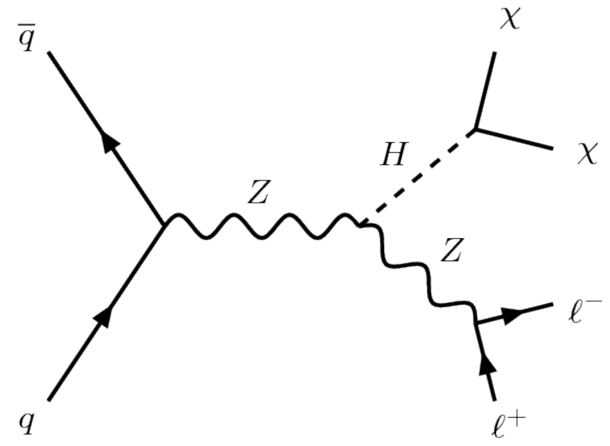
- No significant excess is observed.
- 95% CL limit on M^* in EFT framework.



Higgs invisible decay

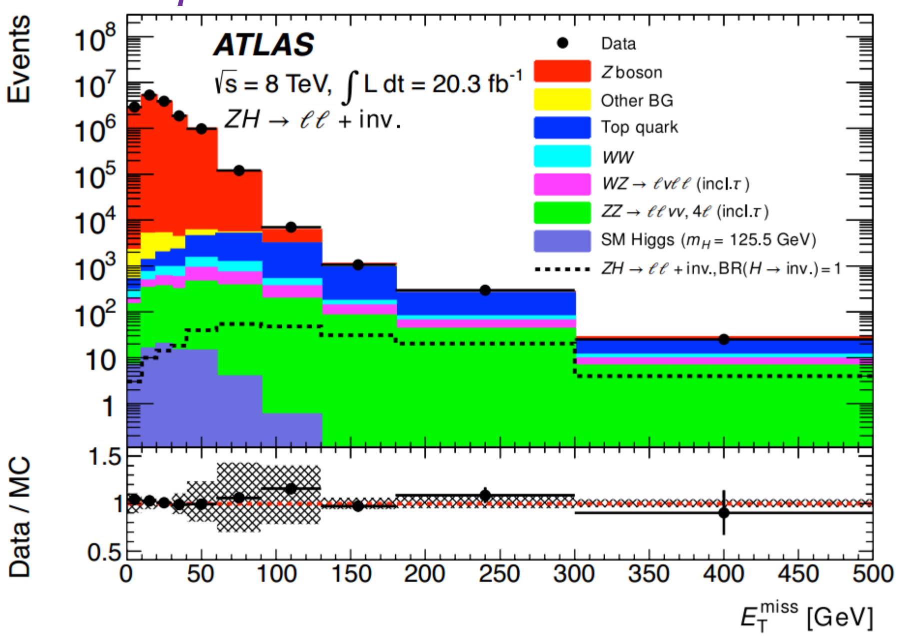
Motivation

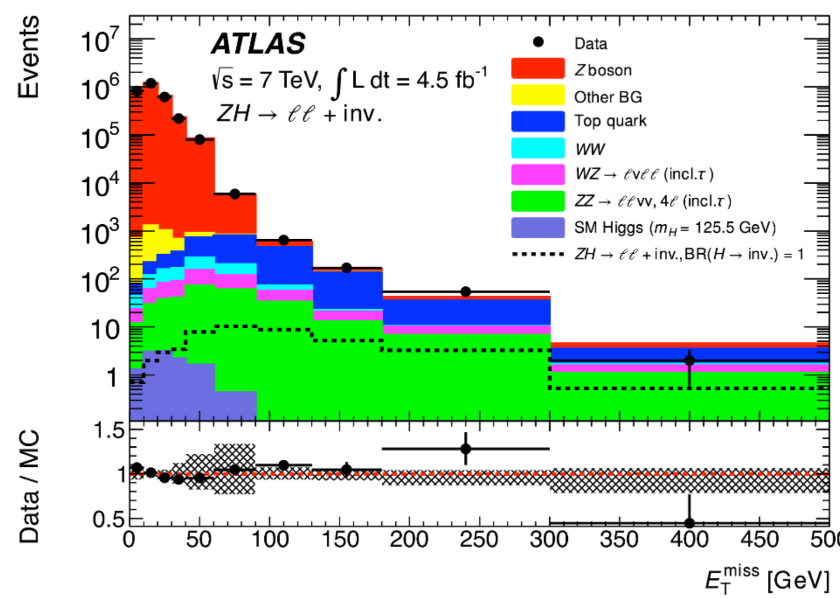
- The Higgs boson is discovered by the ATLAS/CMS.
  - Best-fit mass in ATLAS is at m_H=125.4 GeV. [*arXiv:1406.3827*]
- In some extensions of SM, the Higgs boson can decay to stable or long-lived particles invisible in the detector, which can be dark matter candidates.
  - This decay is allowed only if $m_\chi < m_H/2$
- The only invisible SM decay of Higgs boson is $H \to ZZ^* \to 4\nu$, which this search is not sensitive to.
- ZH production mode with leptons and large E_T^{miss} is studied.



Dataset and event selection

- $\sqrt{s}$=7 (8) TeV, 4.5 (20.3) fb^{-1}
  - *Phys. Rev. Lett. 112, 201802 (2014)*
- The selection is very similar to Mono-Z (leptonic) search with some optimization based on a Higgs boson as the mediator:
  - E_T^{miss}>90 GeV and $\Delta\phi(E_T^{\text{miss}}, \vec{p}_T^{\text{miss}})$<0.2
  - $\Delta\phi(E_T^{\text{miss}}, p_T^{ll})$>2.6, $\Delta\phi(l,l)$<1.7, $|p_T^{ll} - E_T^{\text{miss}}|/p_T^{ll}$<0.2
- The E_T^{miss} distribution is fitted to extract the exclusion limit.

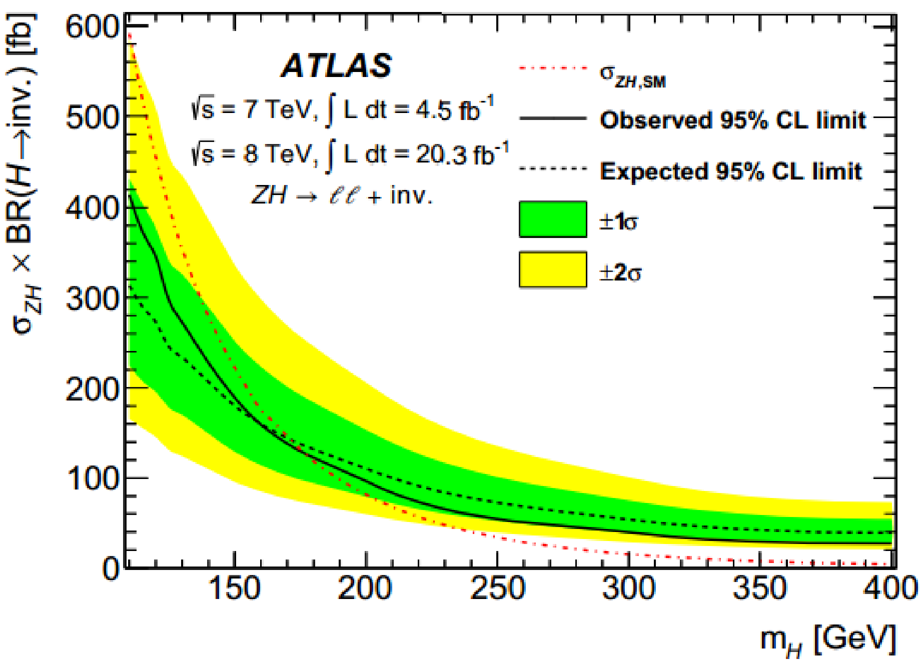


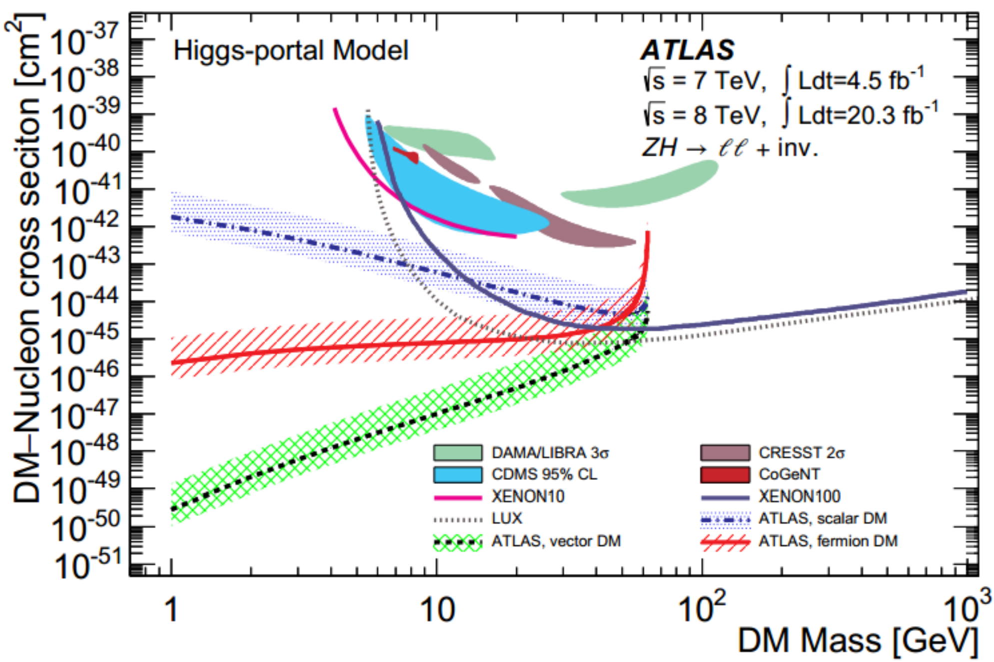


Results

- **No significant excess** is observed above SM backgrounds.

Data Period	2011 (7 TeV)	2012 (8 TeV)
$ZZ \to \ell\ell\nu\nu$	$20.0 \pm 0.7 \pm 1.6$	$91 \pm 1 \pm 7$
$WZ \to \ell\nu\ell\ell$	$4.8 \pm 0.3 \pm 0.5$	$26 \pm 1 \pm 3$
Dileptonic $t\bar{t}$, Wt, WW, $Z \to \tau\tau$	$0.5 \pm 0.4 \pm 0.1$	$20 \pm 3 \pm 5$
$Z \to ee$, $Z \to \mu\mu$	$0.13 \pm 0.12 \pm 0.07$	$0.9 \pm 0.3 \pm 0.5$
W + jets, multijet, semileptonic top	$0.020 \pm 0.005 \pm 0.008$	$0.29 \pm 0.02 \pm 0.06$
Total background	$25.4 \pm 0.8 \pm 1.7$	$138 \pm 4 \pm 9$
Signal ($m_H = 125.5$ GeV, $\sigma_{SM}(ZH)$, BR($H \to$ inv.) = 1)	$8.9 \pm 0.1 \pm 0.5$	$44 \pm 1 \pm 3$
Observed	28	152

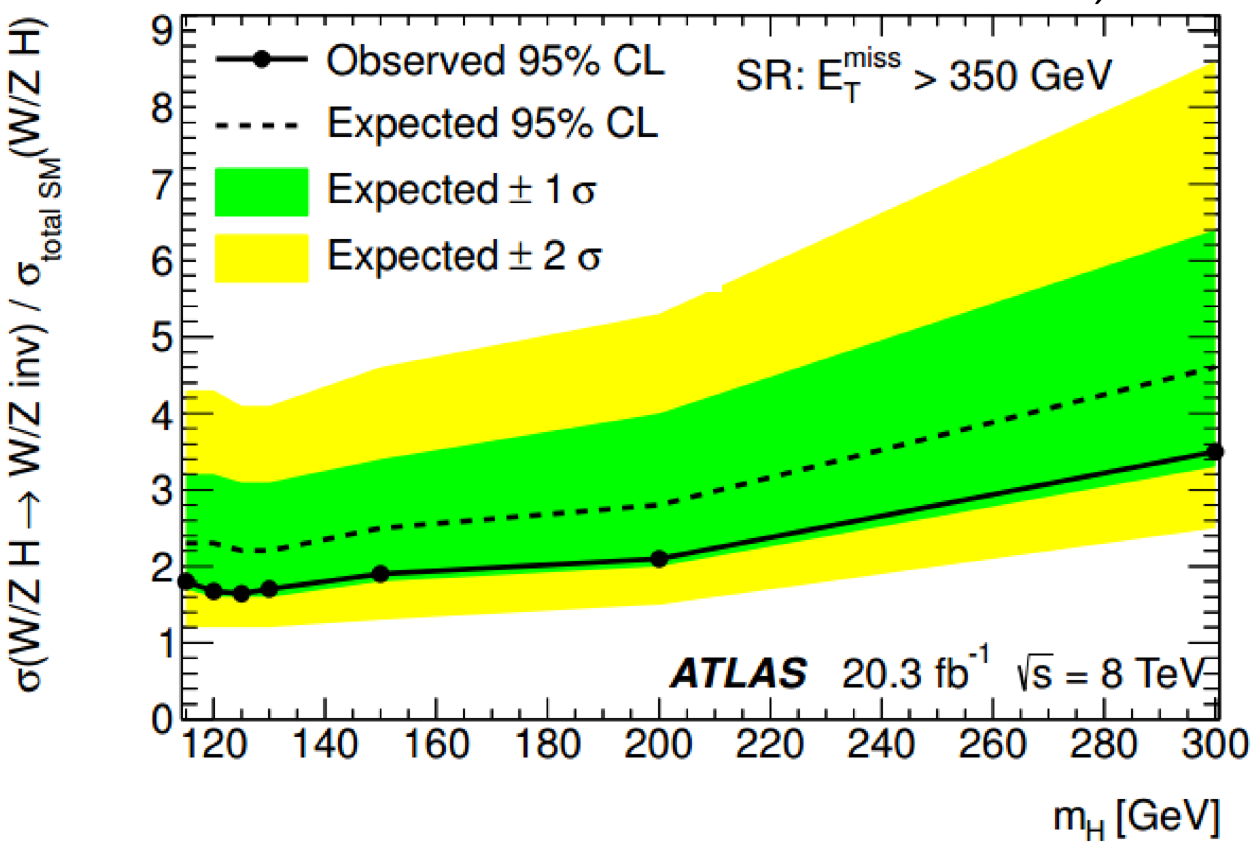




Mono-*W*/*Z* (hadronic)

- The limit is set on $\sigma \times \mathrm{BR}$ Higgs invisible decay in association with a W or Z boson.

PRL 112, 041802 (2014).

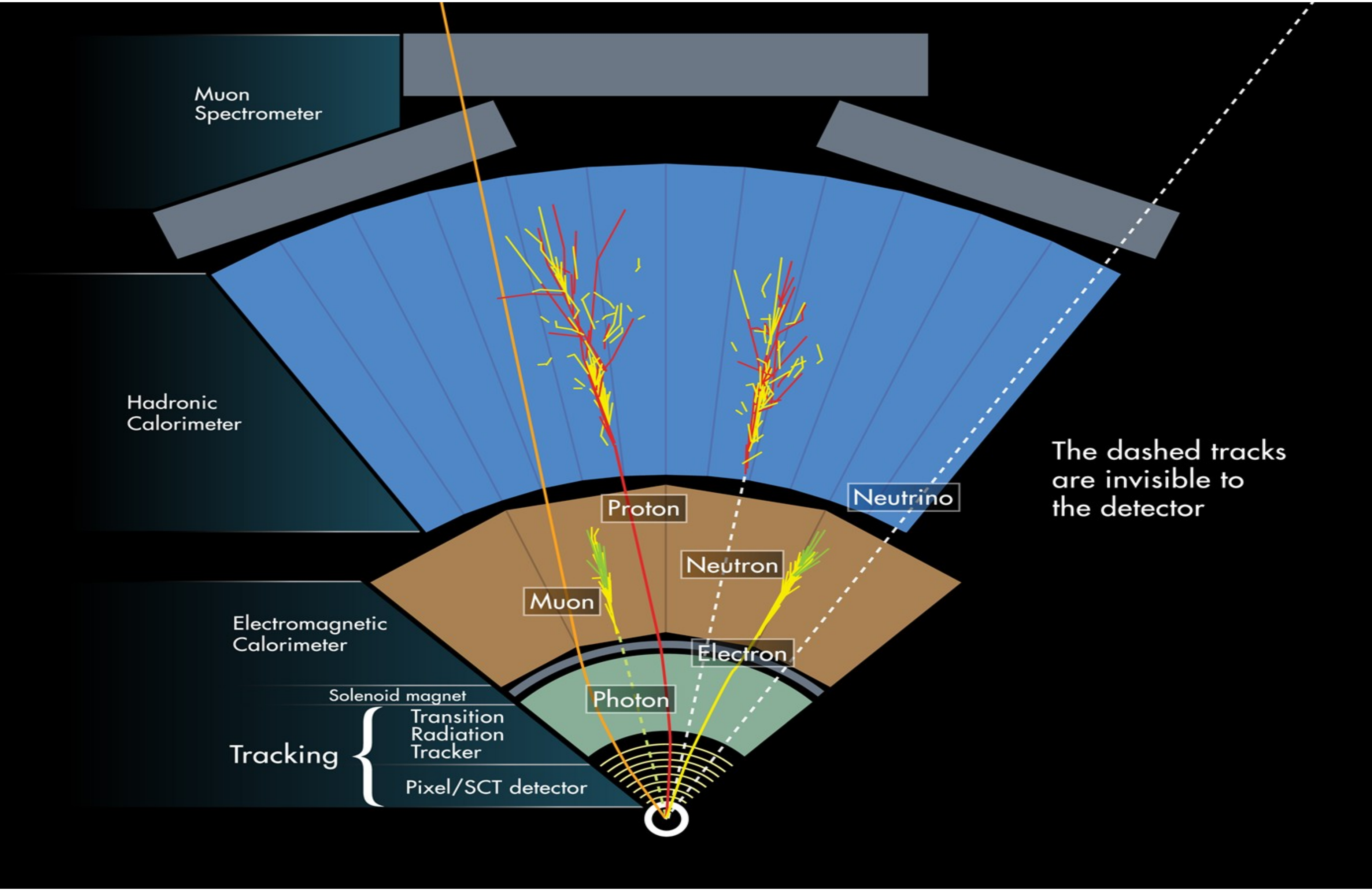


Summary

- The dark matter searches are being performed in ATLAS with the Run-I dataset into various mono-object final states
  - No significant excess beyond SM is observed in any channel.
- The limits are interpreted for EFT and simplified models.
- The Higgs boson as a light mediator is studied in association with W or Z bosons
  - It gives stringent limit on the low mass DM-nucleon cross section.
- At the coming 13/14 TeV runs, the dark matter search in ATLAS will have a better sensitivity. Please stay tuned!
- Theoretical inputs are welcome!

Backup

ATLAS detector slice



Mono-jet: Background CRs

- Minor contributions from multi-jets, $t\bar{t}$, single-top, non-collision background and di-bosons
  - <1% in SRs
- The major backgrounds are W/Z+jets processes.
  - $Z \to \nu\nu, W \to l\nu$ with misidentified leptons or hadronic decaying τ
  - Define various CRs to study TF $N_{\mathrm{SR}}^{\mathrm{MC}}/N_{\mathrm{jet}/E_T^{\mathrm{miss}}}^{\mathrm{MC}}$
    - $N_{\mathrm{jet}/E_T^{\mathrm{miss}}}^{\mathrm{MC}}$: yield with only jet and E_T^{miss} kinematics cut
  - SR expectation $N_{\mathrm{SR}}^{\mathrm{predicted}} = \left(N_{\mathrm{CR}}^{\mathrm{data}} - N_{\mathrm{CR}}^{\mathrm{bkg:other}}\right) \times$TF
- Object definitions are modified in CRs:
  - Electrons: tighter quality cut on shower shapes and higher p_T cut
  - Muons: require muon spectrometer track and higher p_T cut
  - In SR E_T^{miss} is calorimeter-based. In CRs, define:
    - $E_T^{\mathrm{miss,no}\ e}=|\vec{p}_T^{\mathrm{miss}} + \vec{p}_T^{\mathrm{electrons}}|$
    - $E_T^{\mathrm{miss},\mu}=|\vec{p}_T^{\mathrm{miss}} - \vec{p}_T^{\mathrm{muons}}|$

Mono-jet: Background CRs

- W/Z leptonically decaying processes are used as CRs:
  - One or two opposite-sign same-flavor leptons
  - $W \rightarrow e\nu$+jets: E_T^{miss}>25 GeV, 40<m_T<110 GeV, $E_T^{\text{miss,no }e}$ is used
  - $W \rightarrow \mu\nu$+jets: $E_T^{\text{miss},\mu}$>25 GeV, m_T>40 GeV
  - $Z \rightarrow ee$+jets: 66<m_{ee}<116 GeV, $E_T^{\text{miss,no }e}$ is used
    - 7 TeV analysis only
  - $Z \rightarrow \mu\mu$+jets: 66<$m_{\mu\mu}$<116 GeV
- The multi-jet backgrounds are normalized in the CR requiring $\Delta\phi(E_T^{\text{miss}}$,jet)<0.4 and extrapolated to SR.
- CRs are defined according to p_T^{jet} and E_T^{miss} cuts in SR
  - 17 (13) CRs for 7 (8) TeV analyses

SR process	$Z \rightarrow \nu\bar{\nu}$+jets	$W \rightarrow \tau\nu$+jets $W \rightarrow \mu\nu$+jets	$W \rightarrow e\nu$+jets	$Z \rightarrow \tau^+\tau^-$+jets $Z \rightarrow \mu^+\mu^-$+jets
CR process	$W \rightarrow e\nu$+jets $W \rightarrow \mu\nu$+jets $Z \rightarrow e^+e^-$+jets $Z \rightarrow \mu^+\mu^-$+jets	$W \rightarrow \mu\nu$+jets	$W \rightarrow e\nu$+jets	$Z \rightarrow \mu^+\mu^-$+jets

Mono-γ: background yield

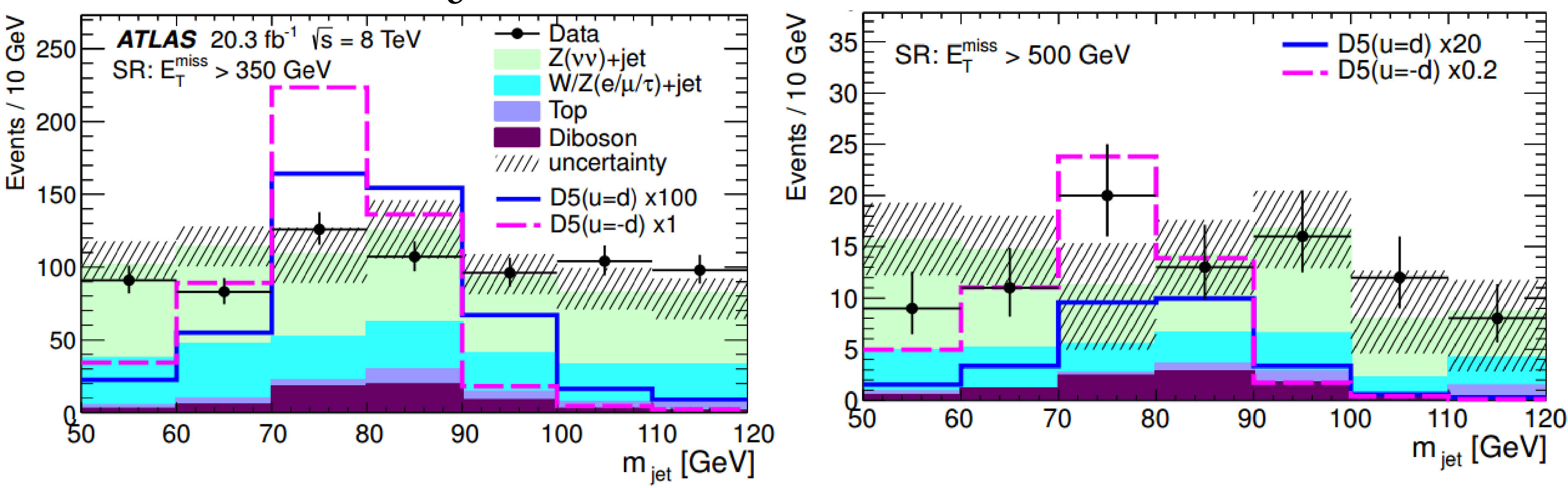
- 1- and 2-muon CRs
  - $W+\gamma$ and $Z+\gamma$ enriched CRs
  - Evaluate the data/MC ratios $\kappa = N^{\mathrm{data}}/N^{\mathrm{MC}}$
  - Apply κ's to $W+\gamma$ and $Z+\gamma$ MC expectation in SR
- W/Z +jets background is estimated according to fake factors:
  - Rate of e-faking-γ is studied in a data sample of Z candidates as a function of p_T and $|\eta|$
  - Rate of Jet-faking-γ is studied in a CR of non-isolated γ candidates, or the γ's passing loose ID but failing tight ID
- The γ+jets or multi-jet backgrounds are normalized in the CR requiring $\Delta\phi(E_T^{\mathrm{miss}}$,jet)<0.4 and extrapolated to SR.

Mono-Z: background yield

- The dominant background process is SM $ZZ \to ll\nu\nu$
  - Estimated from NLO MC.
  - A 35% theoretical systematical uncertainty is assigned.
- Minor background processes include
  - $WZ \to \bar{q}q'll$ and $ZZ \to llq\bar{q}$: estimated from NLO MC
  - $t\bar{t} \to l\nu bl\bar{\nu}\bar{b}, Wt$ and $Z \to \tau\tau$
    - Obtained from $e\mu$ CR which is otherwise defined the same as SR
    - Expect contributions ee: $\mu\mu$: $e\mu$ = 1:1:2
    - $WW \to l\nu l\nu$ process is estimated in the same way
  - $Z \to ll$+jets
    - Consistent results using ABCD method based on E_T^{miss} and η^{ll}, and using extrapolation from fitted distributions of E_T^{miss} and $\Delta\phi(E_T^{\text{miss}}, p_T^{ll})$ at small values.

Mono-W/Z: Background CRs

- Minor background contributions are estimated with MC.
- Define W/Z+jets enriched CRs with similar selection as SR except that the muon veto is inverted.
  - Other background contribution is subtracted using MC expectation.
  - Derive two extrapolation factors for $Z \rightarrow \nu\nu$+jets and W/Z+jets as functions of $m_{\mathfrak{J}}$.

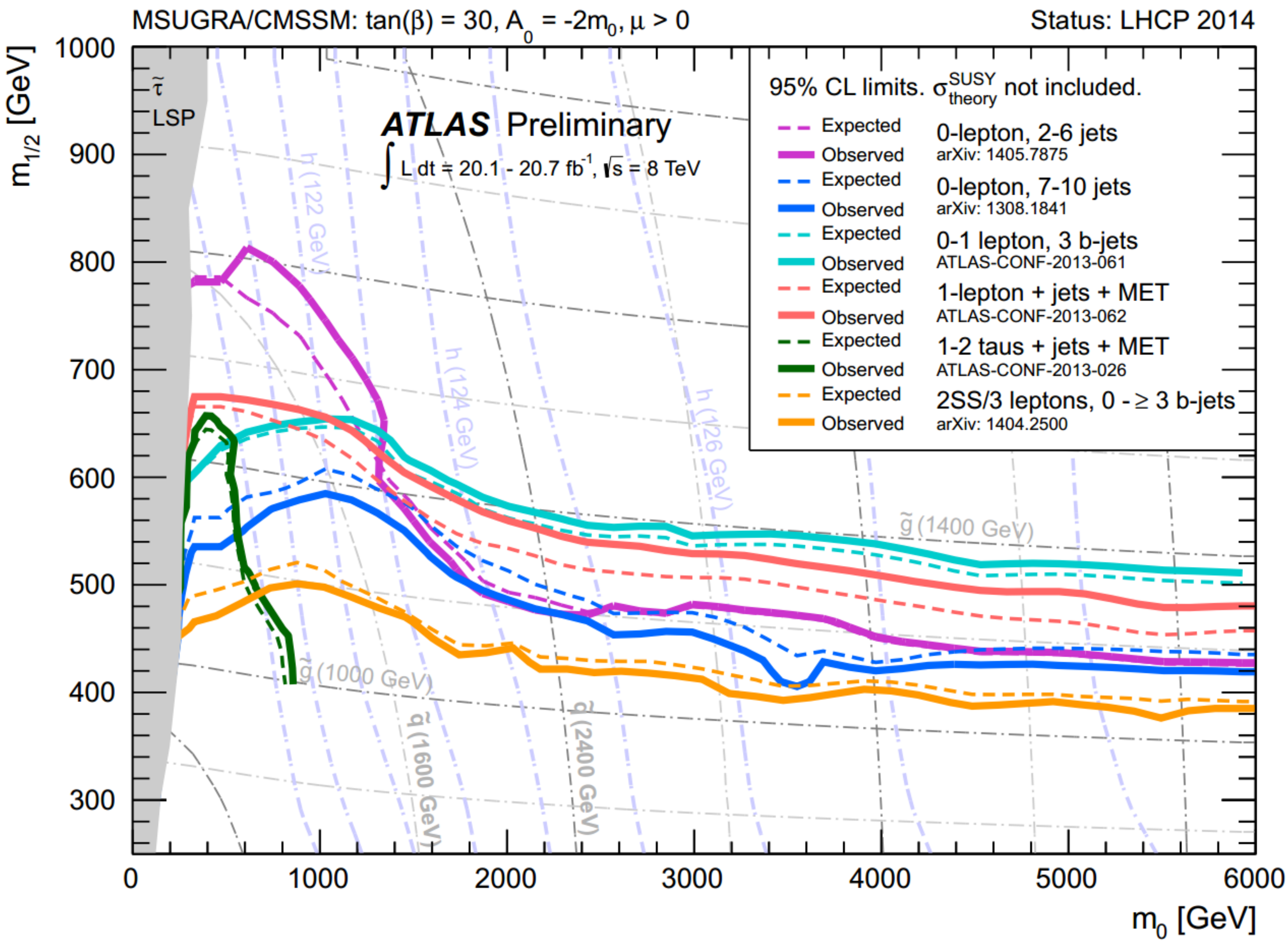


EFT operators

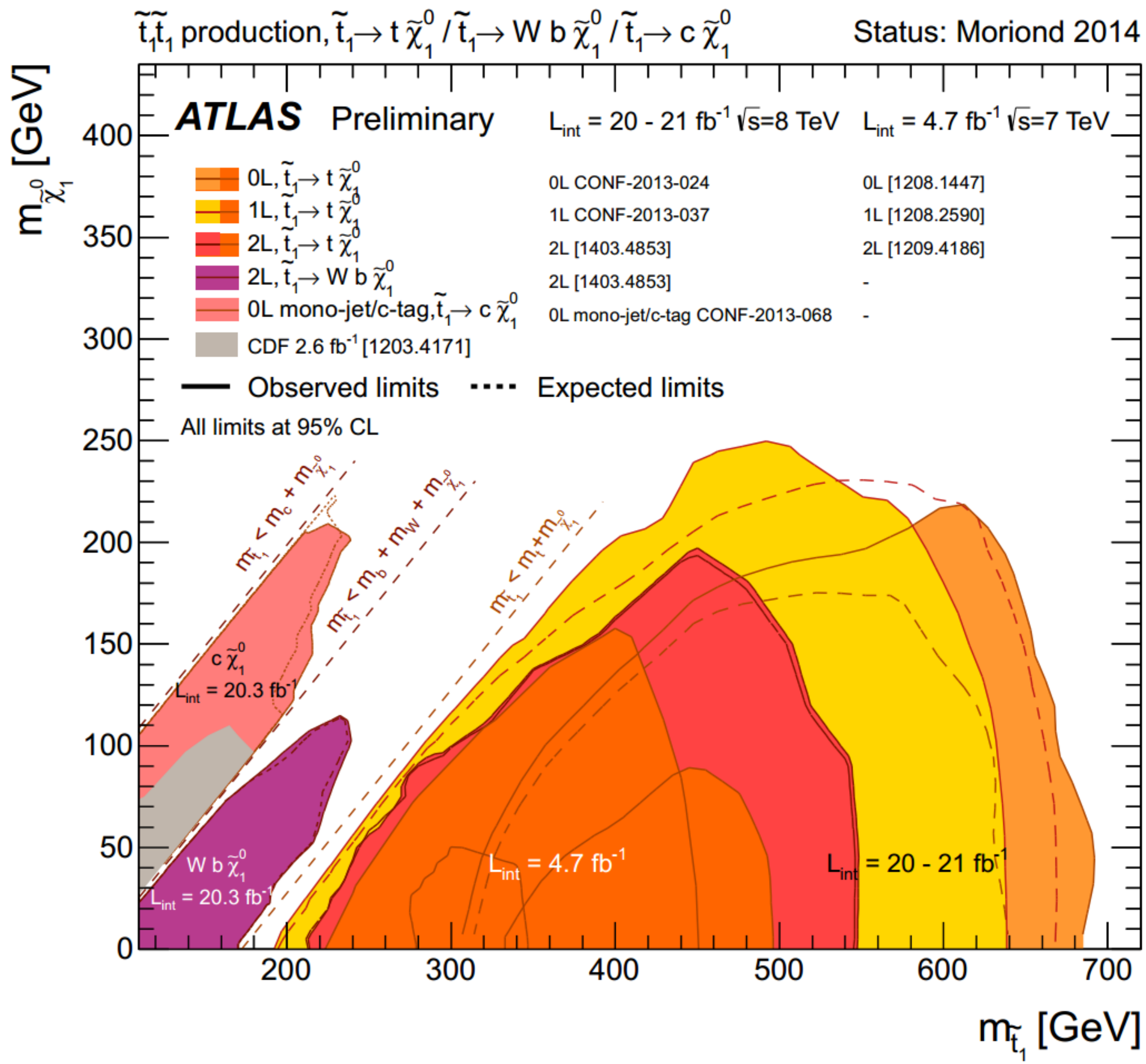
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu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

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

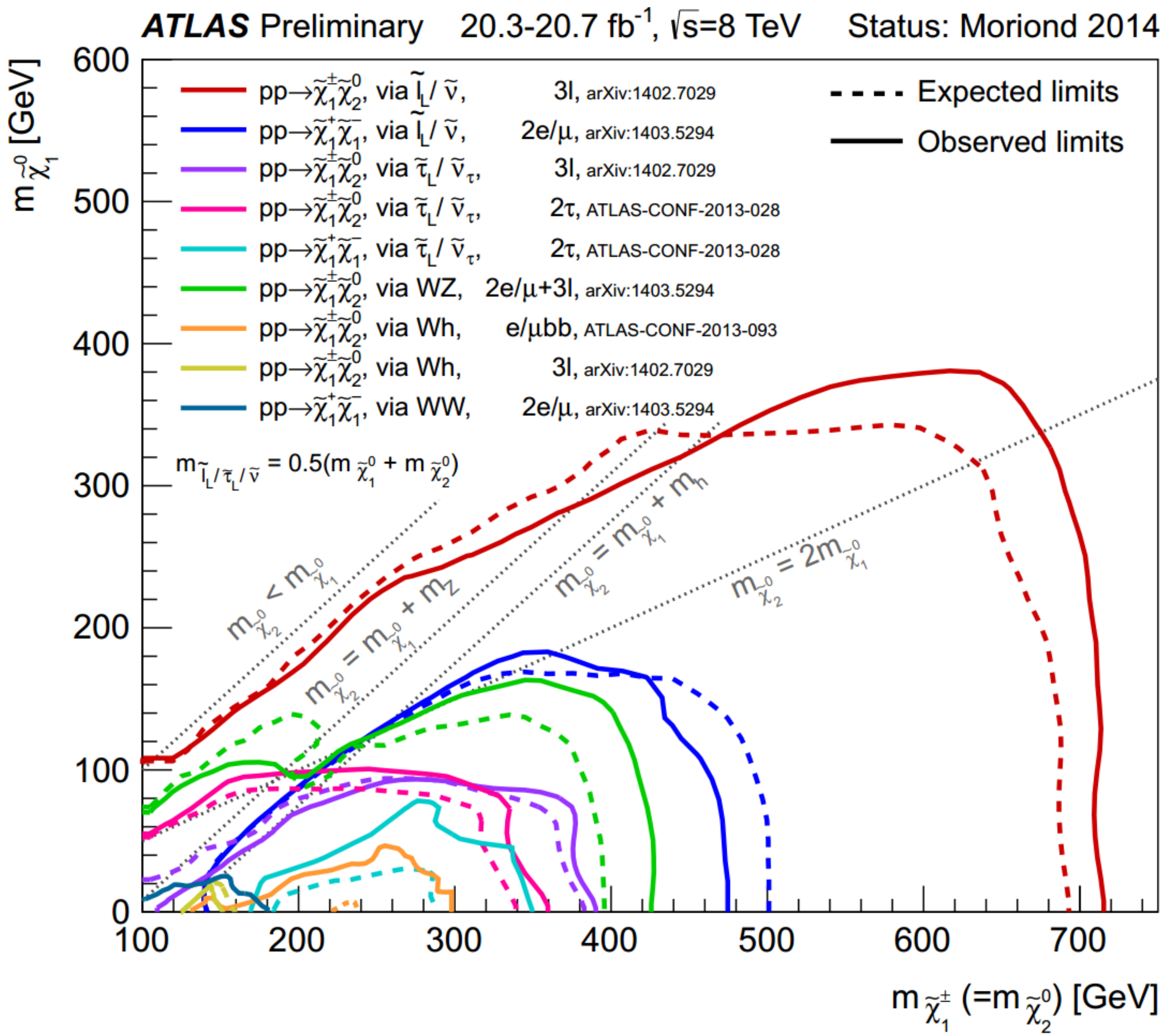
mSUGRA


MSUGRA/CMSSM: tan(β) = 30, A0 = -2m0, μ > 0
Status: LHCP 2014
ATLAS Preliminary
∫ L dt = 20.1 - 20.7 fb-1, √s = 8 TeV
95% CL limits. σ SUSY theory not included.
Expected
Observed
0-lepton, 2-6 jets
arXiv: 1405.7875
0-lepton, 7-10 jets
arXiv: 1308.1841
0-1 lepton, 3 b-jets
ATLAS-CONF-2013-061
1-lepton + jets + MET
ATLAS-CONF-2013-062
1-2 taus + jets + MET
ATLAS-CONF-2013-026
2SS/3 leptons, 0 - ≥ 3 b-jets
arXiv: 1404.2500
τ̃ LSP
h (122 GeV)
h (124 GeV)
h (126 GeV)
g̃ (1000 GeV)
g̃ (1400 GeV)
q̃ (1600 GeV)
q̃ (2400 GeV)
m1/2 [GeV]
m0 [GeV]
1000
900
800
700
600
500
400
300
0
1000
2000
3000
4000
5000
6000

Third generation squark

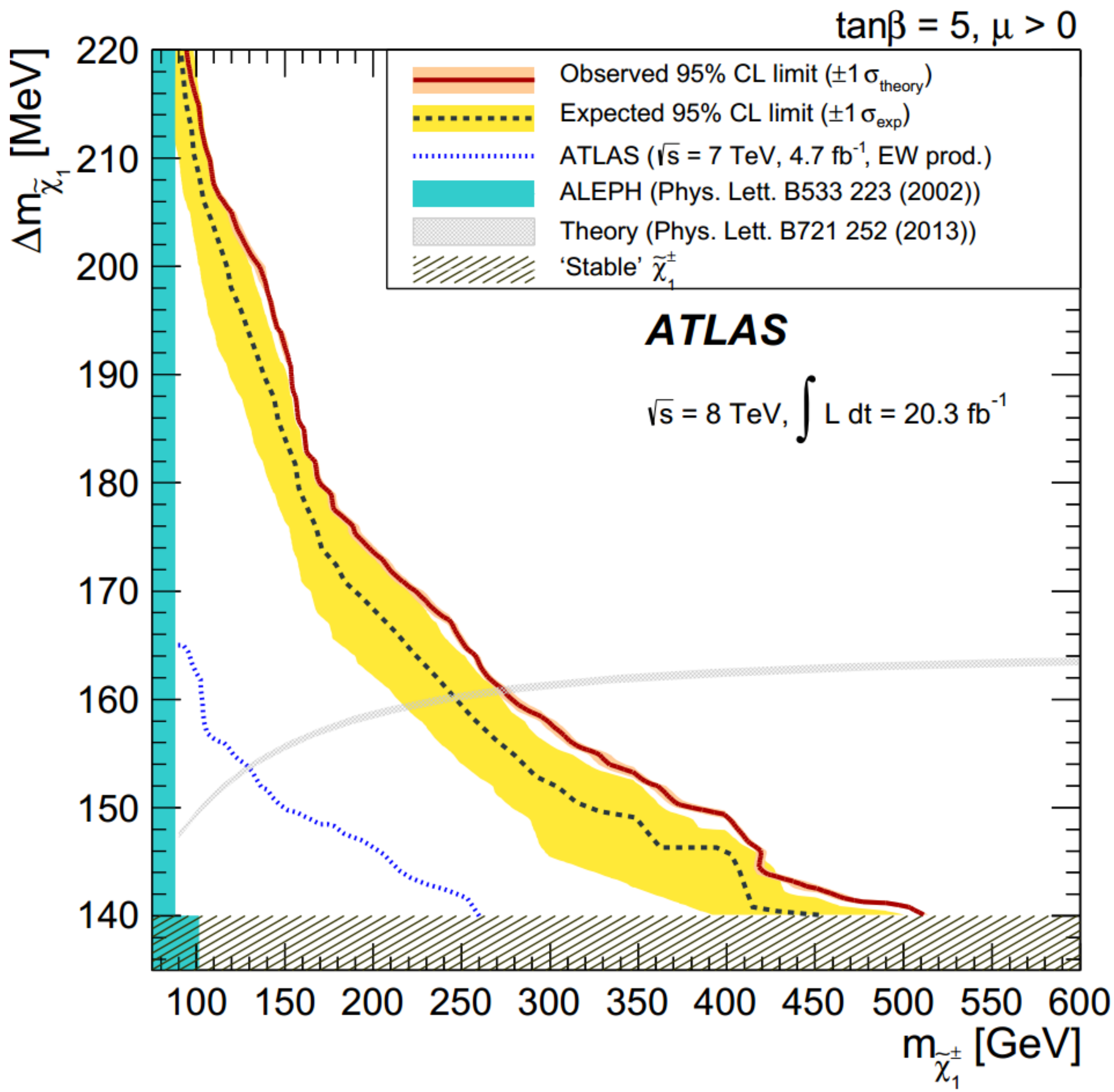


EW gaugino production



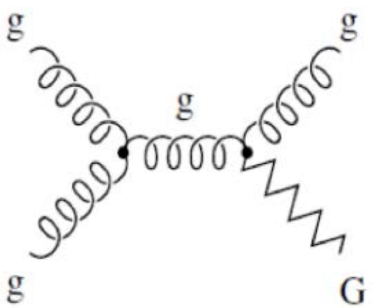
AMSB model

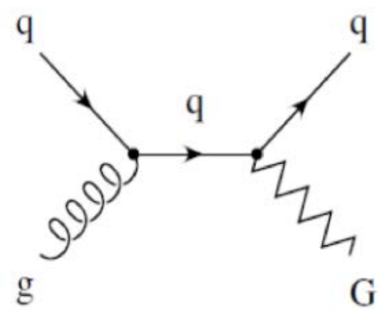
Phys. Rev. D 88, 112006 (2013)

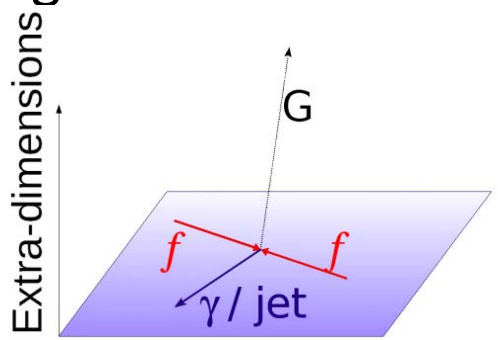


Large extra dimensions

- Models of large extra dimensions can provide solutions to so-called hierarchy problem of SM.
- Arkani-Hamed, Dimopoulos, Davil model (ADD)
  - Gravity propagates in 4+n dimension bulk space
  - SM fields confined to 4 dimensions. n extra dimensions (ED).
  - 4D Plank scale M_{Pl} linked to fundamental Plank scale in 4+n dims $M_{\mathrm{Pl}}^2 \sim M_{\mathrm{D}}^{2+n} R^n$
  - $M_{\mathrm{D}} \ll M_{\mathrm{Pl}}$ if R is of O(mm), R = size of extra dimensions
  - Conservation of KK-parity → lightest KK state is stable
    - Phenomenology similar to SUSY, but no DM candidate (graviton moves in EDs)
- At LHC, gravitons can be produced in association with jets or photons, leading to mono-jet or mono-photon detector signatures.



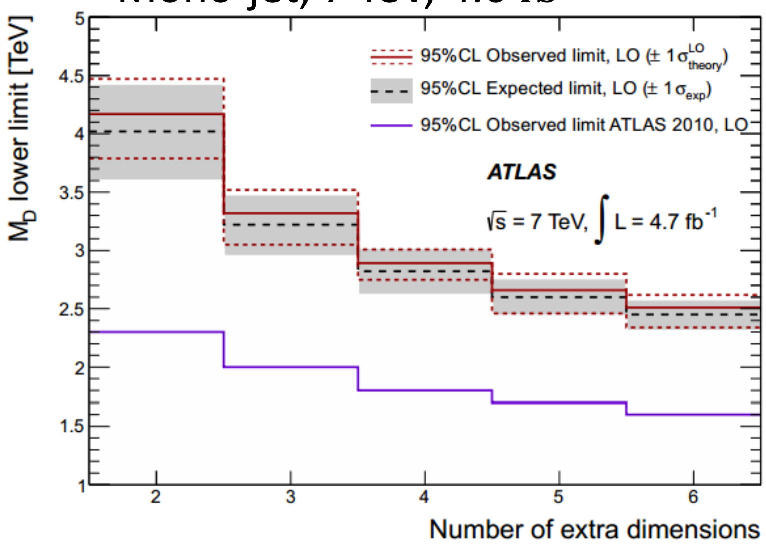




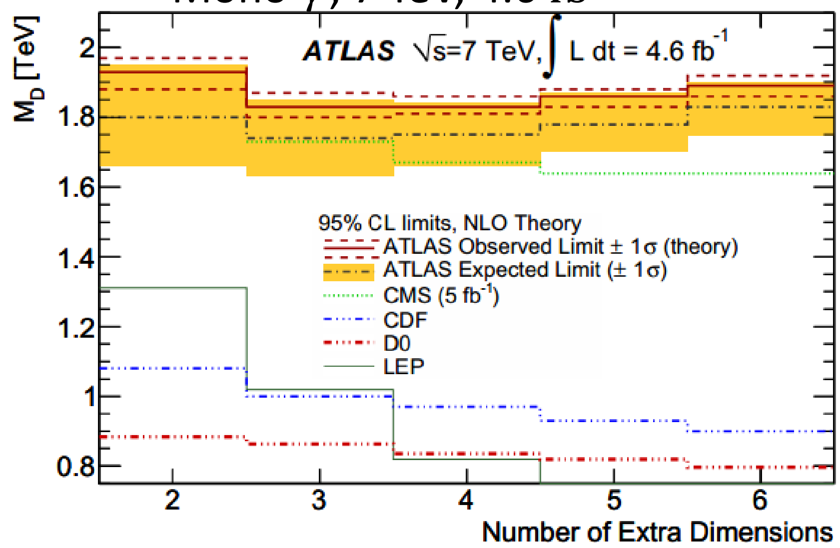
ADD interpretation

- Results of mono-γ and mono-jet searches can be interpreted in context of ADD model.
- 95% CL limits set on M_{D} as function of number of extra dimensions

Mono-jet, 7 TeV, 4.6 fb^{-1}



Mono-γ, 7 TeV, 4.6 fb^{-1}



Mono-jet, 8 TeV, 10.5 fb^{-1}

Extra-dimensions	2	3	4	5	6
95% CL observed lower limit on M_{DM} [TeV]	3.88	3.16	2.84	2.65	2.58