Searches for single object and missing transverse energy with the ATLAS detector

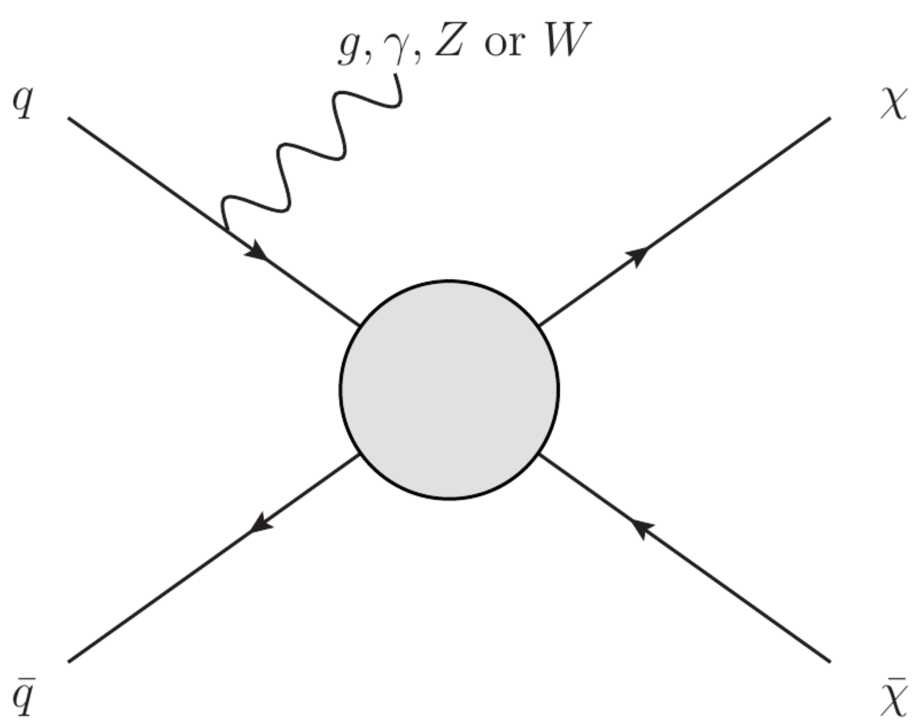
Marie-Hélène Genest

On behalf of the ATLAS Collaboration

The mono-X signature

Various models of new physics predict the production of a single high-p_T object (jet, photon, W, Z) associated with large missing transverse momentum, such as :

- Dark matter produced in association with initial state radiation



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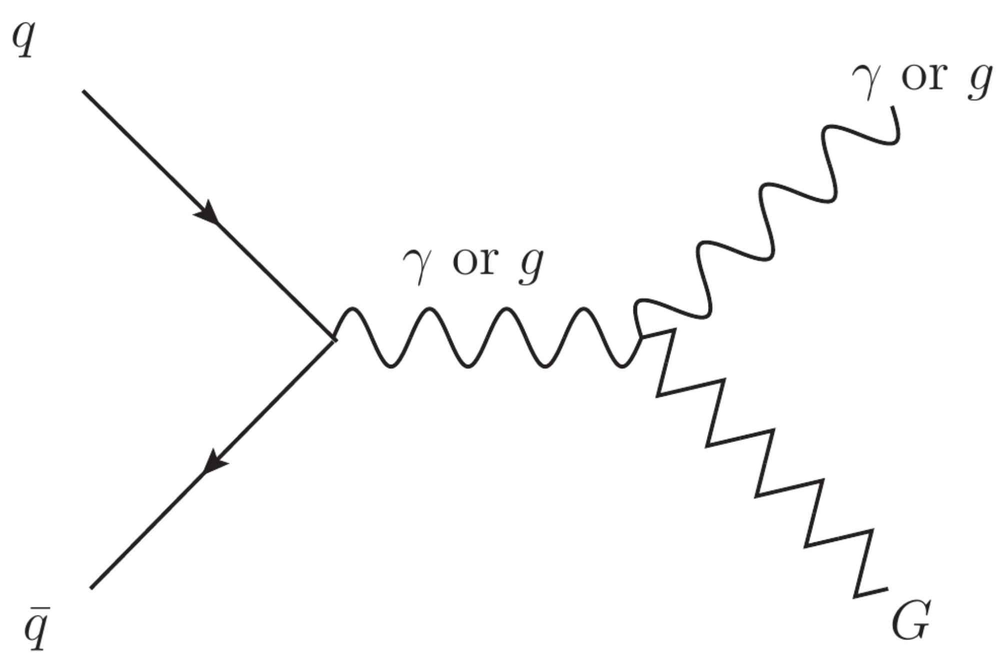

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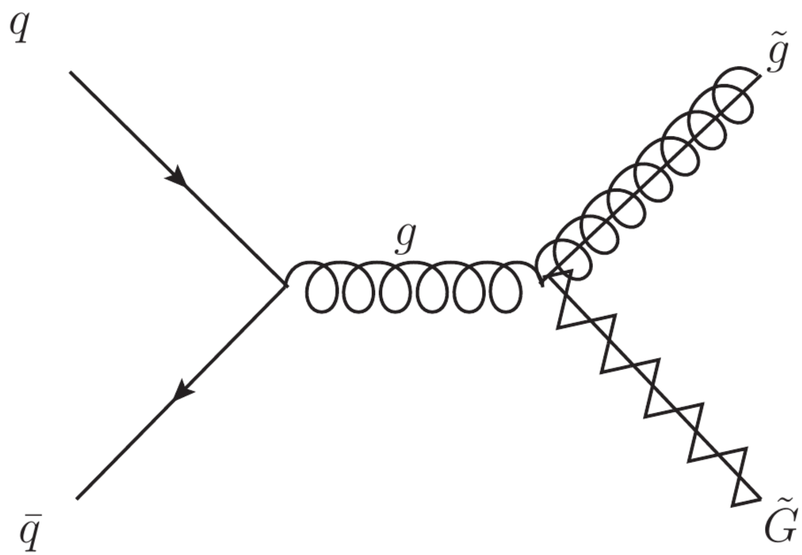

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- Dark matter produced in association with initial state radiation
- Gravitons propagating in extra space-time dimensions
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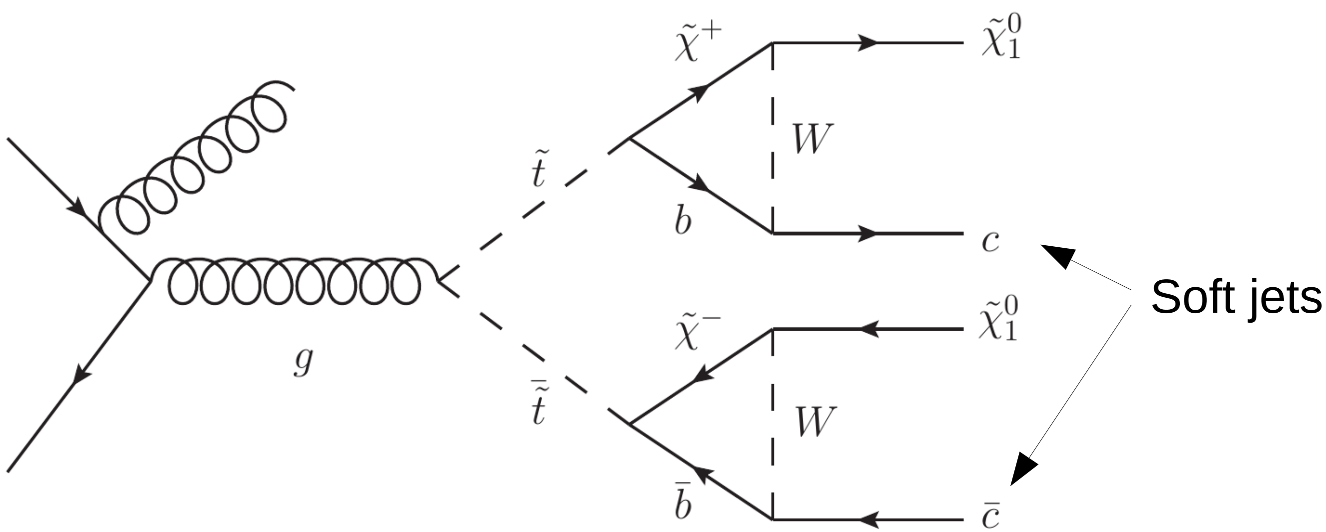
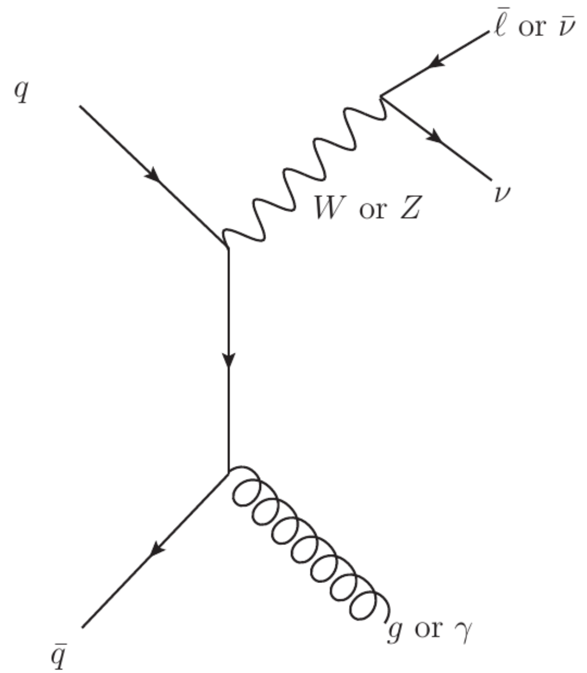
- Top squark decay with very small $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$



The mono-X signature

- Various models of new physics predict the production of a single high-p_T object (jet, photon, W, Z) associated with large missing transverse momentum
- Simple final state with well-known backgrounds from electroweak processes



The mono-X analyses

- Select events with a high-p_T object (jet, photon, hadronically decaying W/Z) and large missing transverse momentum
- Veto on events in which :
  - A lepton is identified : *remove electroweak background*
  - There is more than one extra jet : *remove top or multijet*
  - MET is pointing in the direction of the extra jet : *remove fake MET coming from jet mis-measurement*
- The backgrounds to the search are estimated :
  - $Z(\rightarrow \nu\bar{\nu}) + X$ (irreducible)
  - $W(\rightarrow \ell\nu) + X$, $Z(\rightarrow \ell\bar{\ell}) + X$ where ℓ is missed
  - multi-jet, γ+jets, with fake MET
  - *Non-collision events*

  } Using data-driven methods

  - top, diboson and $\gamma\gamma$

  } From simulation

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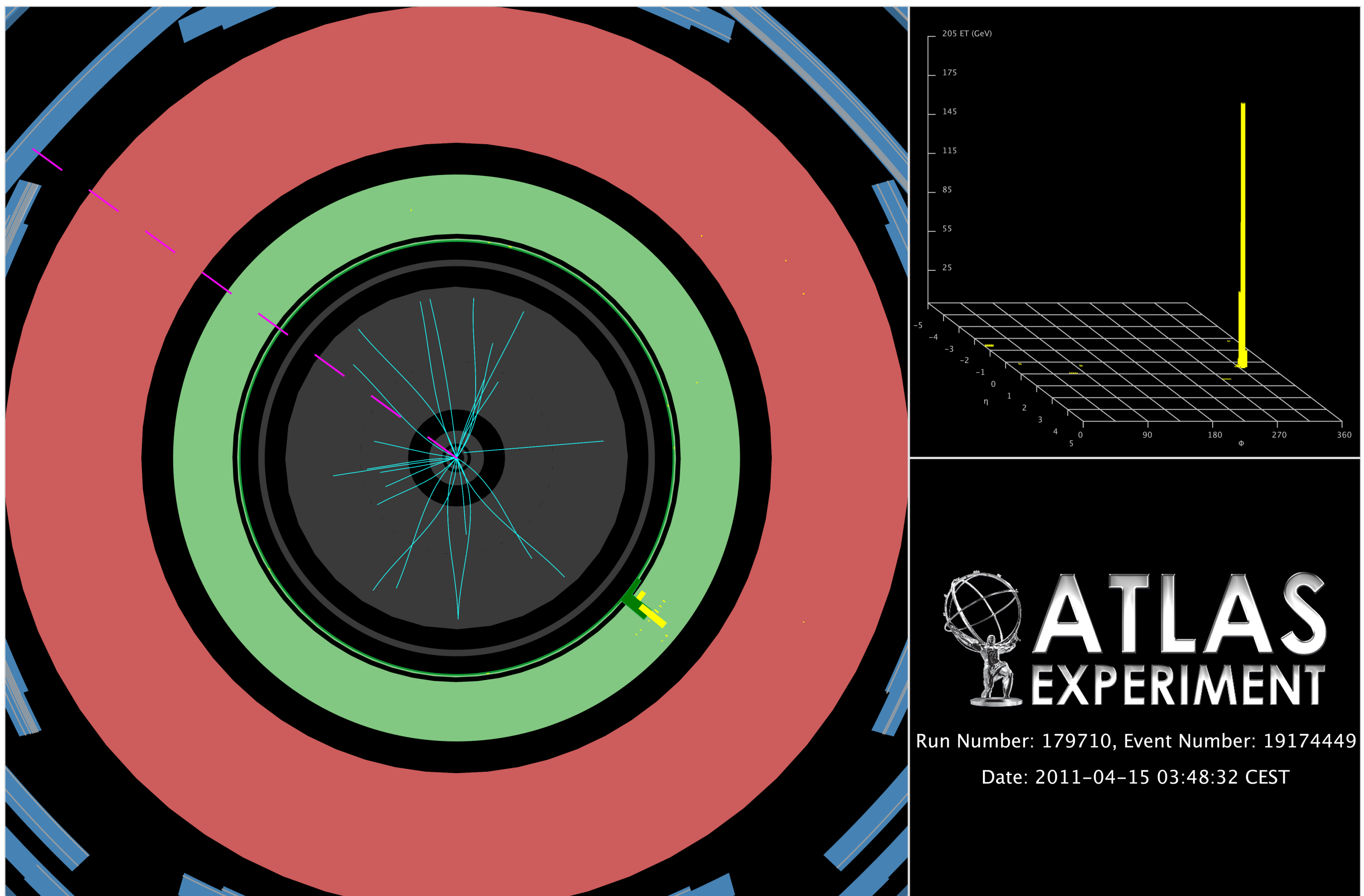
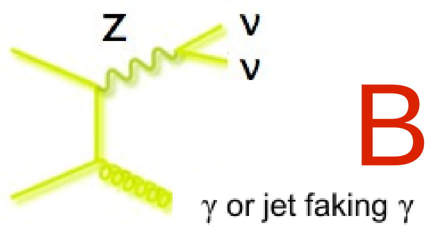
The monophoton analysis

7 TeV dataset (4.6 fb^{-1})

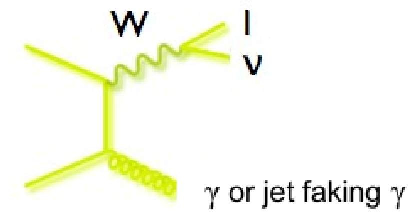


The monophoton analysis

- Event selection :
  - Isolated high-p_T photon with p_T > 150 GeV
  - MET > 150 GeV
  - Veto on electrons and muons ($p_{T,el(\mu)}$ >20(10) GeV)
  - No more than 1 jet with p_T>30 GeV
  - Objects are well separated by $\Delta\varphi$ > 0.4 between :
    - MET and γ
    - MET and jet, γ and jet (if a jet is present)



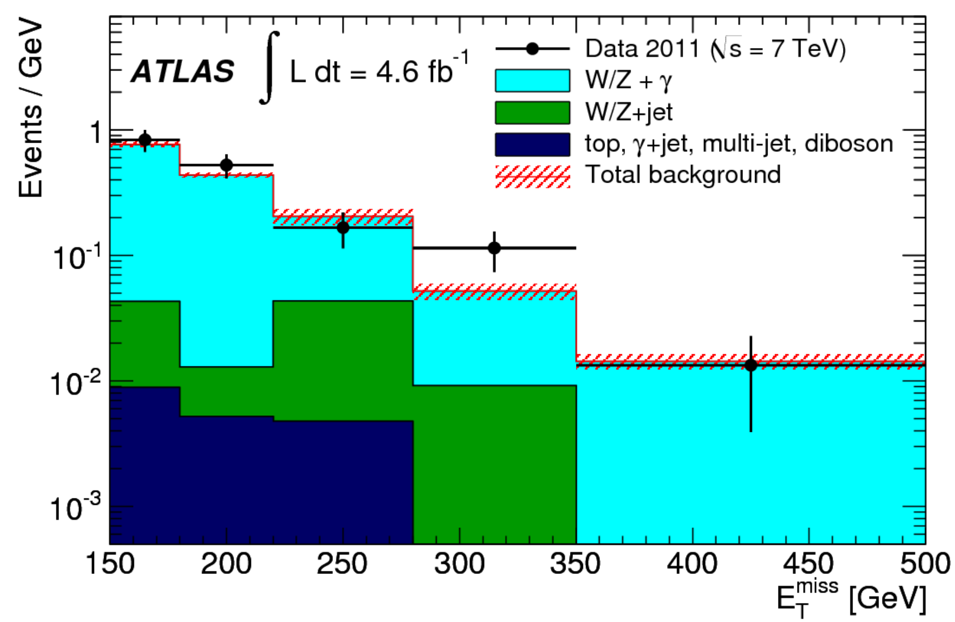
Background estimation

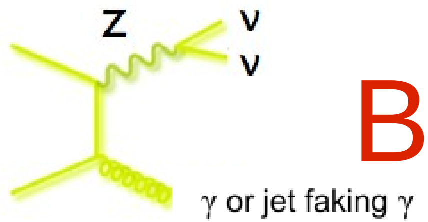


Estimate the dominant W/Z + γ background in the signal region (SR) from data using the number of events found in an orthogonal but kinematically close MET+γ+μ control region (CR) :

$$N_{BG}^{SR} = N_{MC,BG}^{SR} \times \boxed{\frac{N_{measured}^{CR}}{N_{MC,BG}^{CR}}}$$

Correction factor





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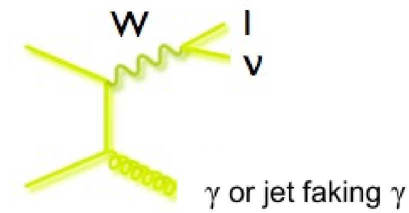


- W/Z+jet :
  - e ➝ γ fake rate derived from a Z sample and applied to a MET + e CR
  - Jet ➝ γ component from a MET+γ CR in which the photon is non-isolated and/or it is identified only in a looser version of the nominal identification requirements :

Identification	non-isolated	isolated
nominal	CR A	SR
loose	CR B	CR C

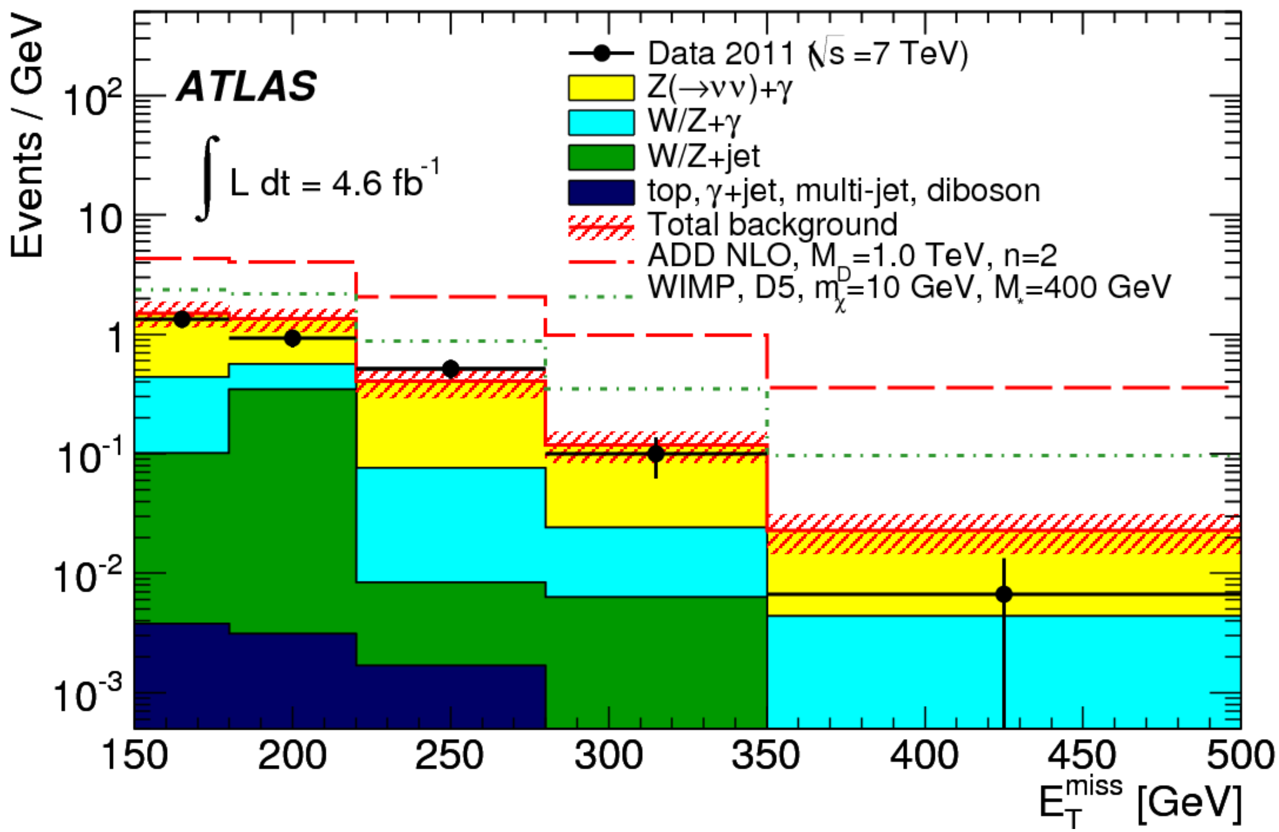
$$N_{\mathrm{SR}} = N_{\mathrm{CR\ C}} \times \frac{N_{\mathrm{CR\ A}}}{N_{\mathrm{CR\ B}}}$$

- γ+jet and multijet from a MET+γ+jet CR with Δφ(j,MET)<0.4

Results

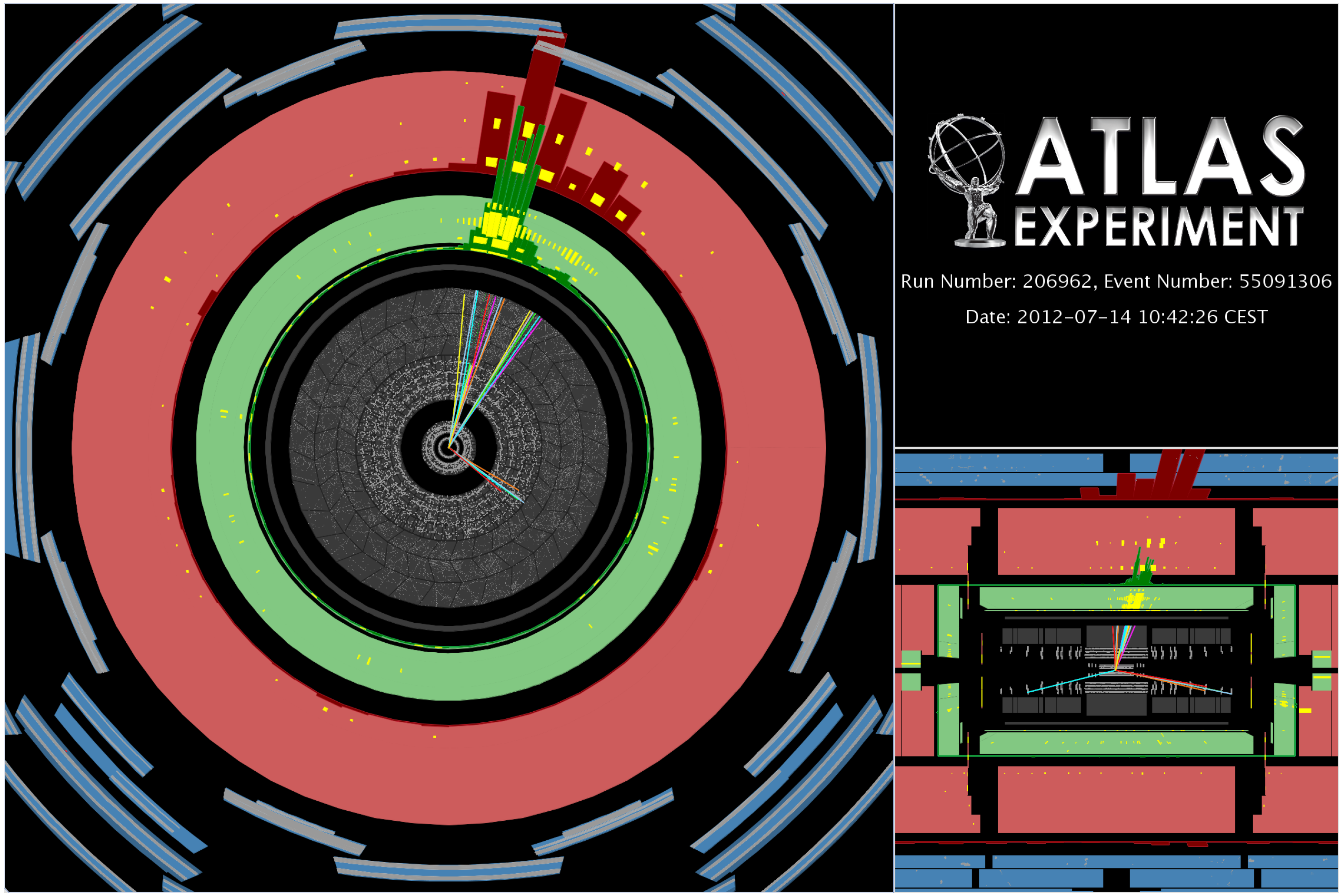
Background source	$N_{expected} \pm (stat.) \pm (syst.)$
$W/Z + \gamma$	$117 \pm 17 \pm 8$
$W/Z +$ jets	$18 \pm - \pm 6$
$\gamma +$ jets and multi-jet	$1.0 \pm - \pm 0.5$
Others ($t\bar{t}$, single top, diboson)	$0.4 \pm 0.1 \pm 0.1$
Total background	$137 \pm 18 \pm 9$
Events in data (4.6 fb^{-1})	116

Exclude σ x A x ε above 5.6 (6.8) fb at 90 % (95 %) CL



The monojet analysis

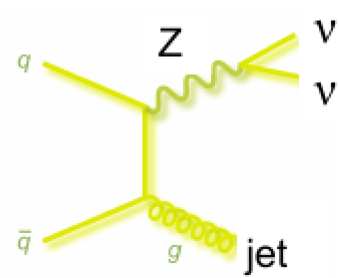
Part of the 8 TeV dataset (10.5 fb^{-1})



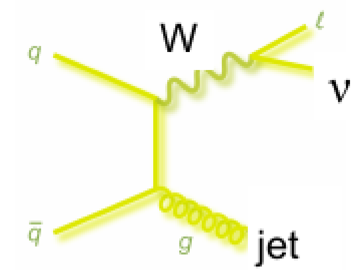
The monojet analysis

- Event selection :
  - Veto on electrons and muons
  - At least one jet with p_T>120 GeV and $|\eta|$<2.0
  - No more than 2 jet with p_T>30 GeV in $|\eta|$<4.5
  - $\Delta\varphi$(jet2,MET) > 0.5
- Four signal regions :

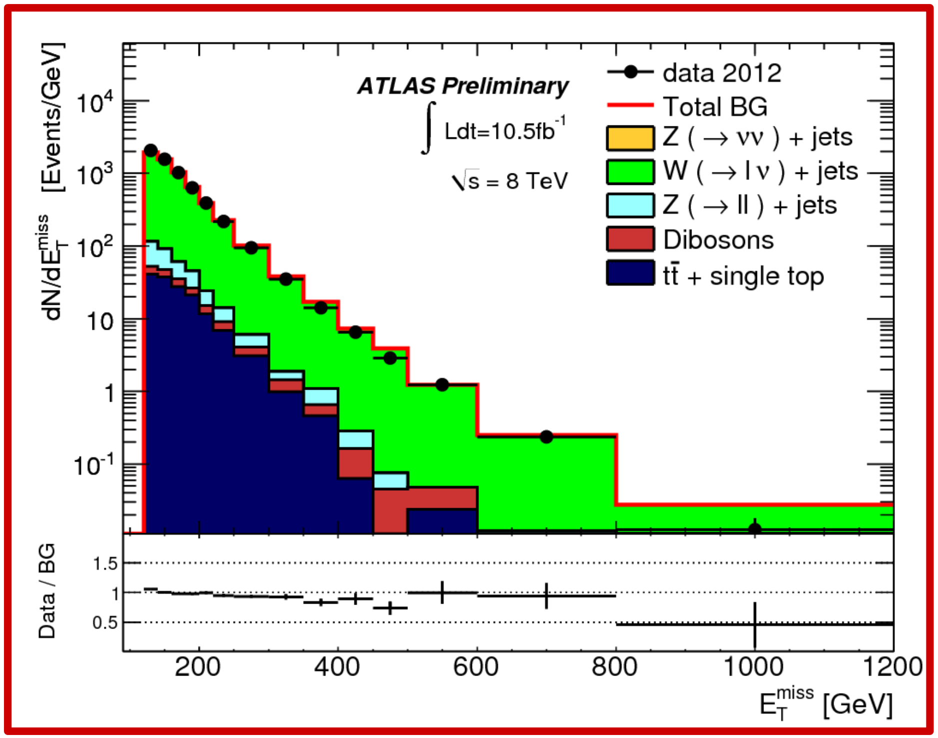
Signal region	SR1	SR2	SR3	SR4
minimum leading jet p_T (GeV)	120	220	350	500
minimum MET (GeV)	120	220	350	500

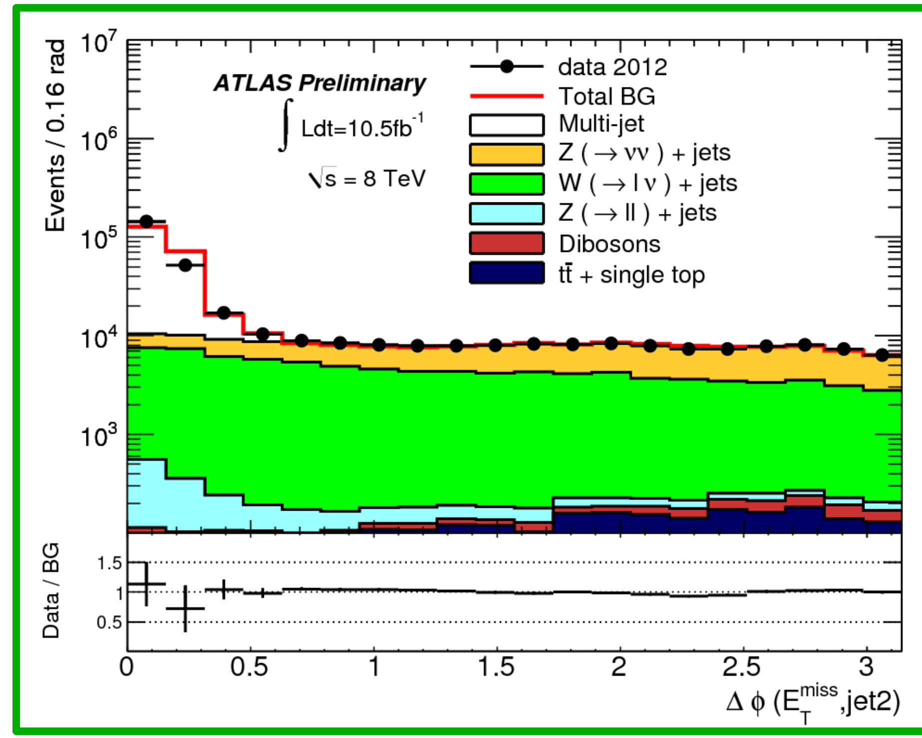


Background estimation



- $Z \rightarrow \nu\bar{\nu}(\mu\bar{\mu}, e\bar{e}, \tau\bar{\tau}) + \text{jets}$ and $W \rightarrow e\nu(\mu\nu, \tau\nu) + \text{jets}$ are estimated using CR with leptons enriched in $W \rightarrow \mu\nu + \text{jets}$ and $W \rightarrow e\nu + \text{jets}$ (also cross checked with a $Z \rightarrow \mu\bar{\mu} + \text{jets}$ CR)



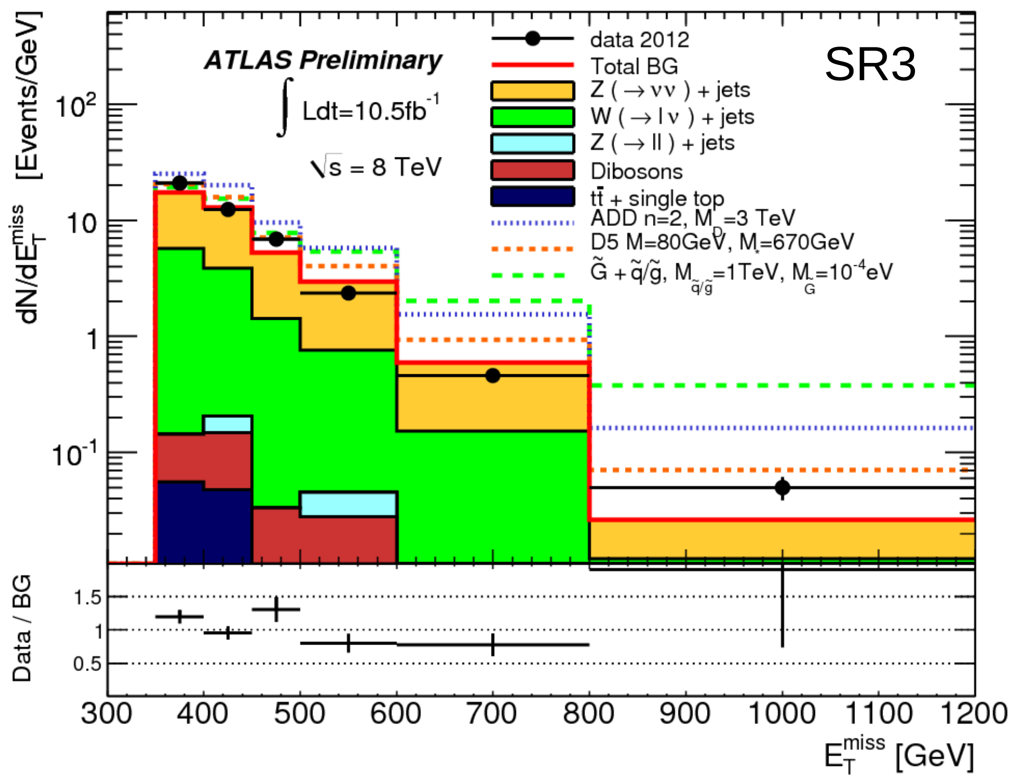


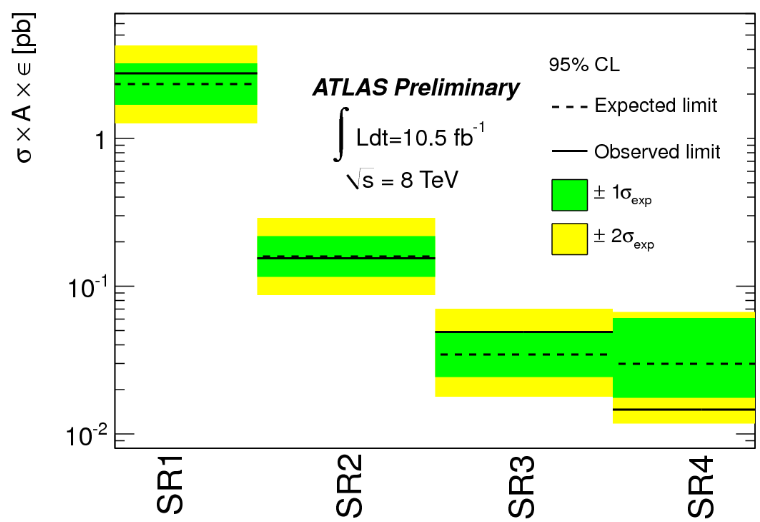
- Multijet background estimated using a MET+ 2(3) jets CR where Δφ(MET,jet2(3))<0.5

Results

Total background prediction $\pm$ (stat. data) $\pm$ (stat. MC) $\pm$ (syst.) compared to data

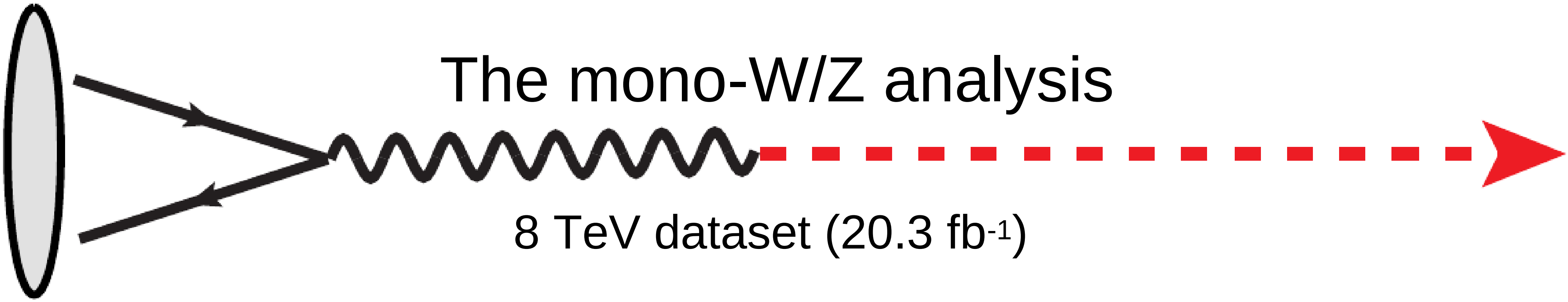
SR1	SR2	SR3	SR4
344400 $\pm 900 \pm 2200 \pm 12600$	25600 $\pm 240 \pm 500 \pm 900$	2180 $\pm 70 \pm 120 \pm 100$	380 $\pm 30 \pm 60 \pm 30$
350932	25515	2353	268





The preliminary 8 TeV limits are equivalent to the 7 TeV analysis ones due to limited MC statistics (but note that the 8 TeV analysis adds new interpretations and that it will be updated soon)

The mono-W/Z analysis



8 TeV dataset (20.3 fb^{-1})

Focuses on W/Z hadronic decays using jet substructure techniques :*
for highly boosted objects, decay products have narrow ΔR *distribution*

- *Single large-radius Cambridge/Aachen jet encompassing all decay products*
- *Revert last step of clustering and look for two low-mass, symmetric sub-jets*

**Details on jet substructure performance can be found in arXiv:1306.4945*

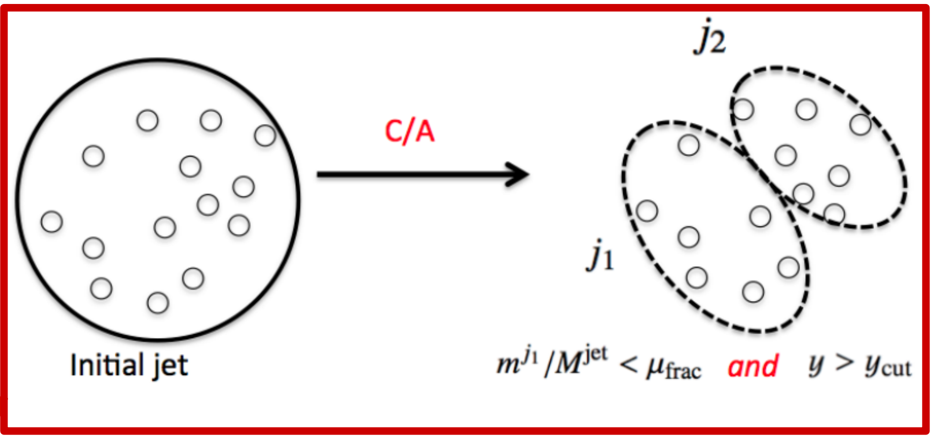
Reminder : $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

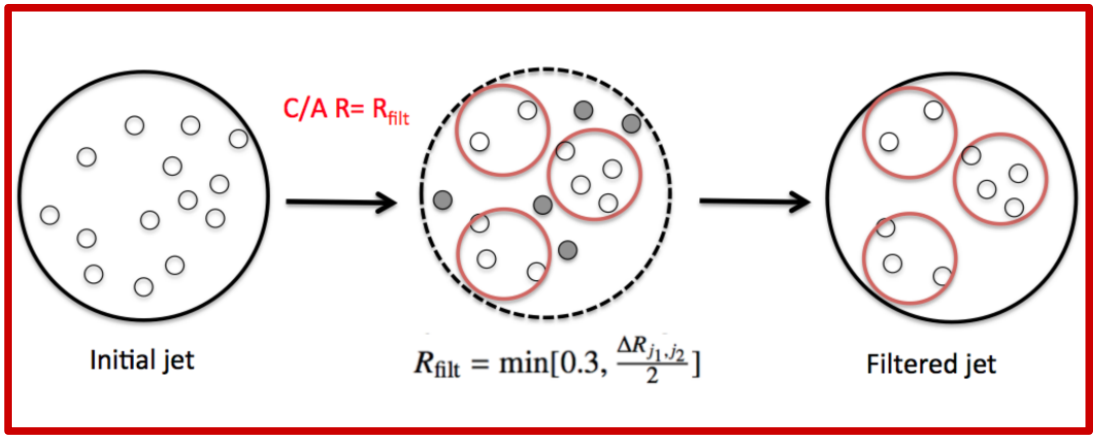
The mono-W/Z analysis

Event Selection:

- ≥1 Cambridge-Aachen large-radius (R=1.2) filtered jet with p_T>250 GeV, |η| < 1.2 and 50 GeV<M_{jet}<120 GeV : *capture the hadronic products of both quarks coming from the W/Z decay*
- $\sqrt{y} > 0.4$ where $\sqrt{y} = \min(p_{T,1}, p_{T,2})\Delta R/M_{\rm jet}$ *: probe the internal structure of this jet in terms of momentum balance of the two leading subjets*

Mass-drop filtering in two steps :



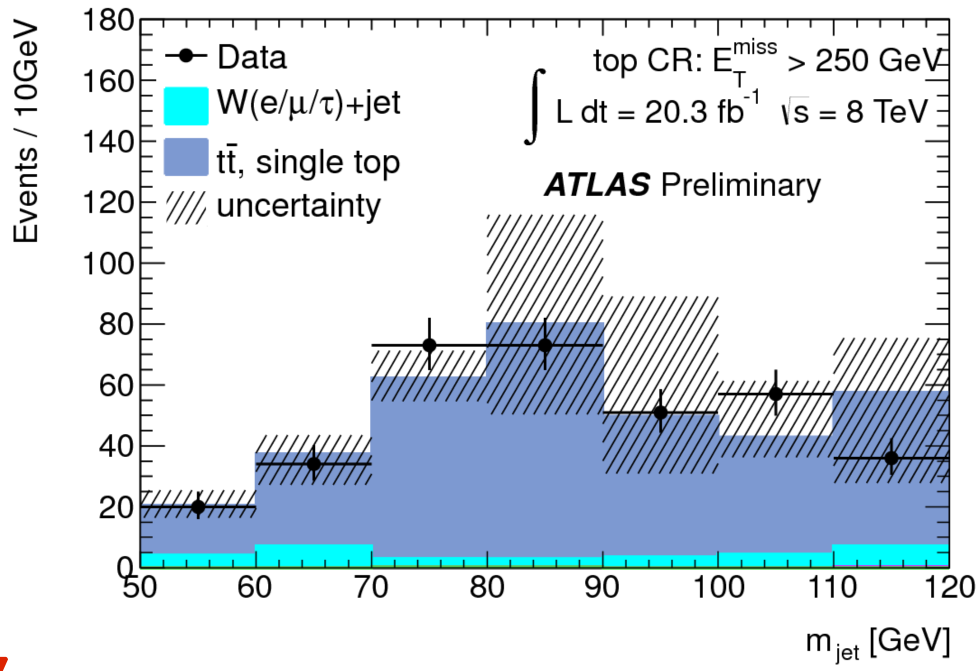


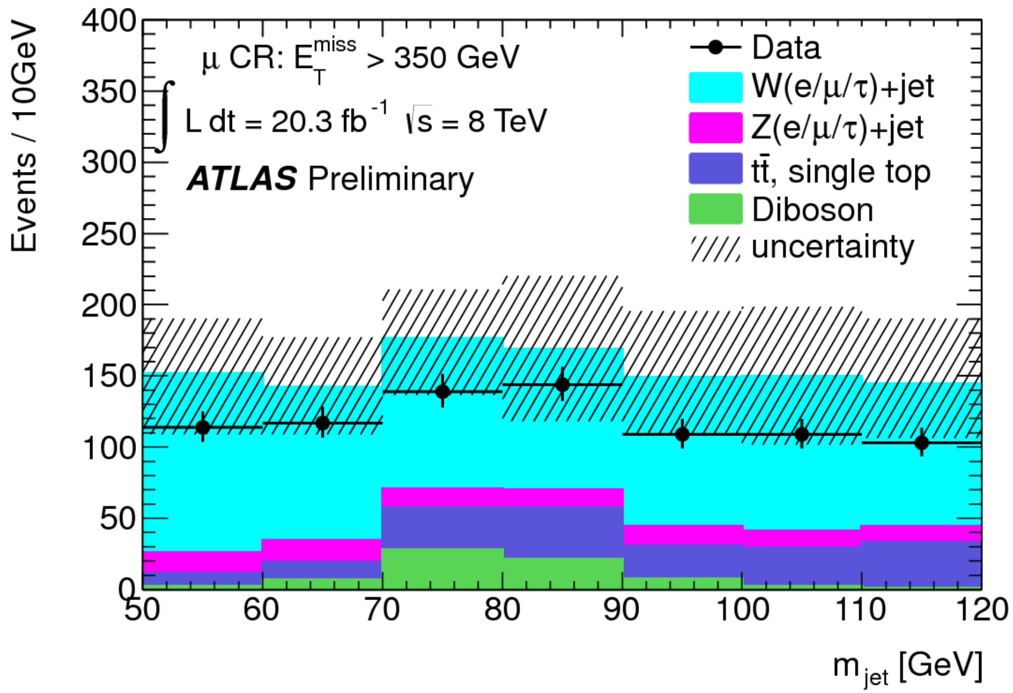
The mono-W/Z analysis

- Event Selection:
  - At least one Cambridge-Aachen large-radius (R=1.2) jet with $p_T >$ 250 GeV, $|\eta| < 1.2$ and 50 GeV$<M_{jet}<$120 GeV : *capture the hadronic products of both quarks coming from the W/Z decay*
  - $\sqrt{y} > 0.4$ where $\sqrt{y} = \min(p_{T,1}, p_{T,2})\Delta R/M_{\mathrm{jet}}$ *: probe the internal structure of this jet in terms of momentum balance of the two leading subjets*
  - No more than 1 additional narrow (anti-k_T R=0.4) jet ($p_T >$ 40 GeV, $|\eta| < 4.5$ and $\Delta R(j^{narrow}, j^{large}) > 0.9$)
  - $\Delta\varphi(j^{narrow}, \mathrm{MET}) > 0.4$
  - Lepton and photon veto
- Two signal regions :
  - MET > 350 GeV (SR1) or MET > 500 GeV (SR2)

Background estimation

- The reconstruction of the hadronic W decay with large-radius jets is validated in a top dominated μ + MET + b-jet CR
- Estimate the dominant W/Z+jets background from a MET+jet+μ control region (cross checked in a MET+jet+μμ CR and a low MET+jet CR)

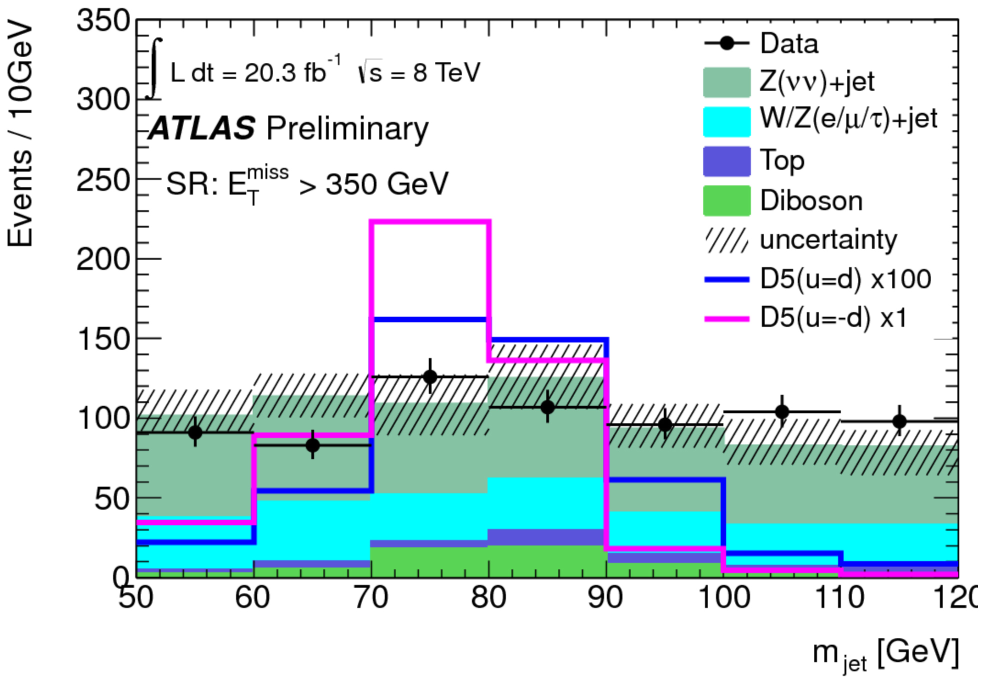


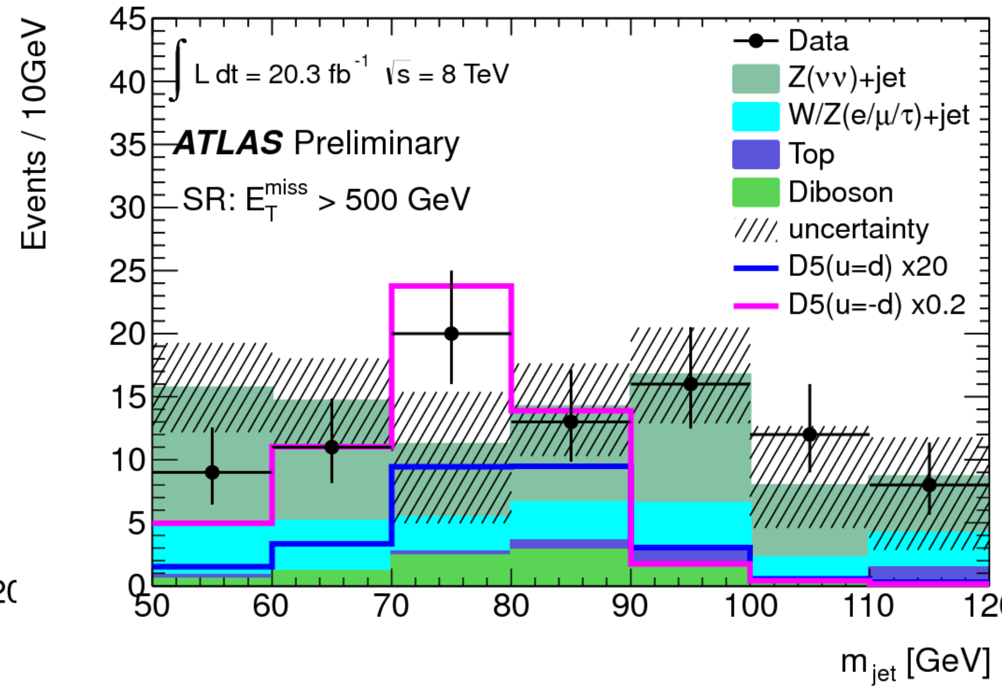


Results

Process	$E_T^{miss} > 350$ GeV	$E_T^{miss} > 500$ GeV
$Z \to \nu\bar{\nu}$	400^{+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	710^{+48}_{-38}	89^{+9}_{-12}
Data	705	89

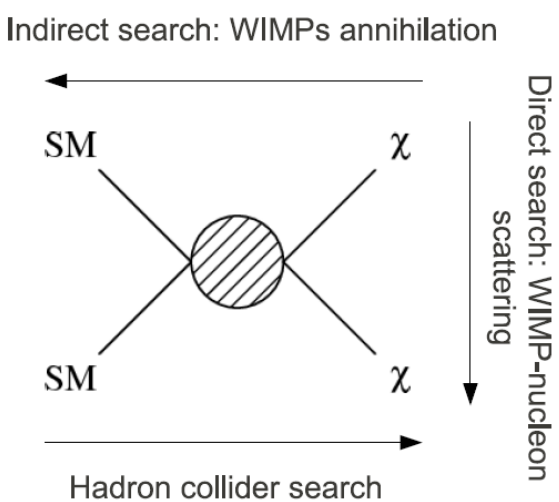
Exclude σ x A x ε in SR1 (SR2) above 3 (1.5) fb at 95 % CL





Interpretation : Dark Matter

- Direct production of Dark Matter at the LHC is complementary to direct and indirect detection methods



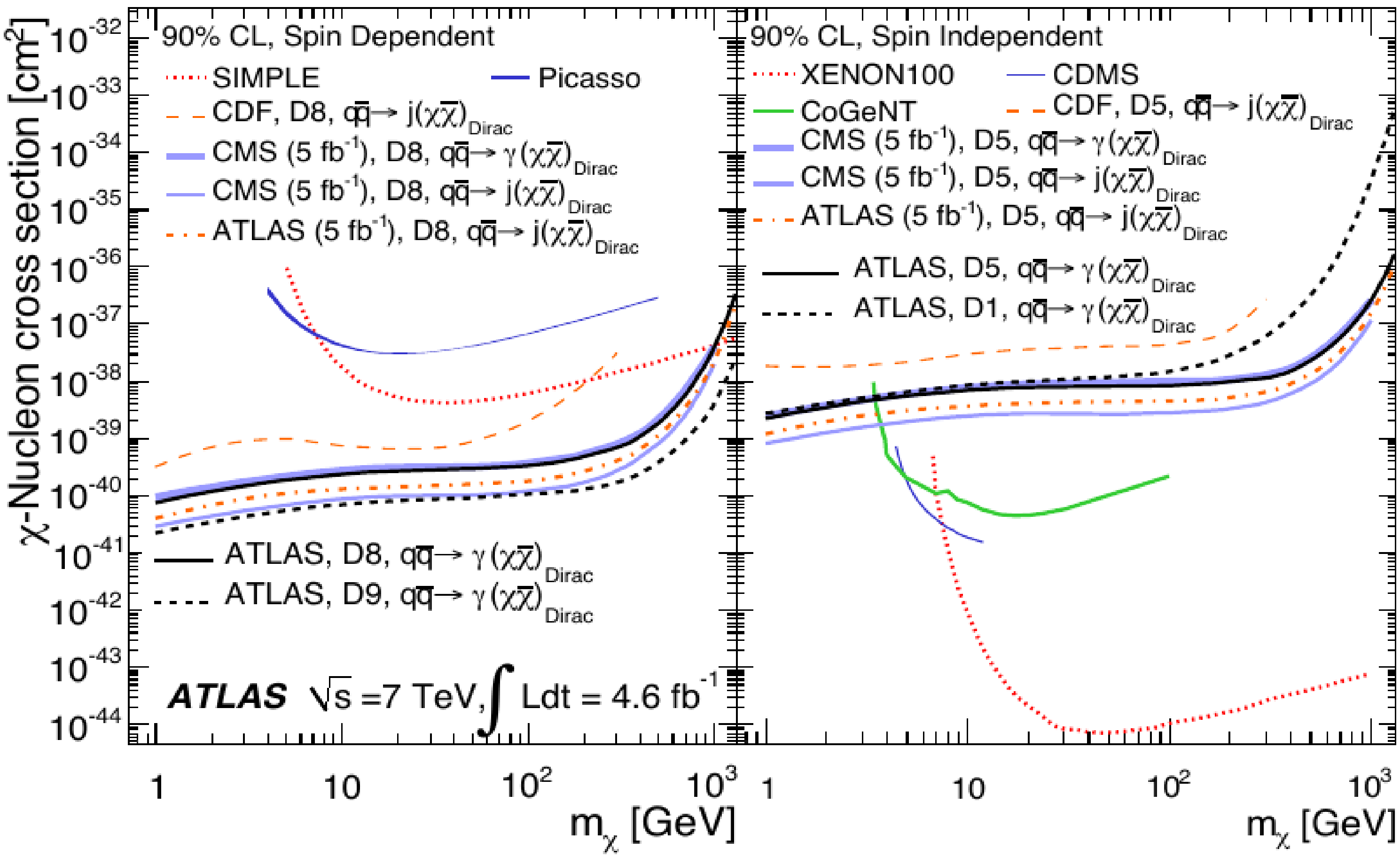
- Limits derived in the context of an effective field theory with contact interaction
  - Valid if the scale of interaction is less than the mediator mass M
  - Different operators considered in turn, assuming χ is a Dirac fermion

Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Limits on dark matter

Within EFT framework, low mass and spin-dependent limits are stronger than direct detection limits

Monophoton + Monojet 5 fb^{-1} limits



Limits on dark matter

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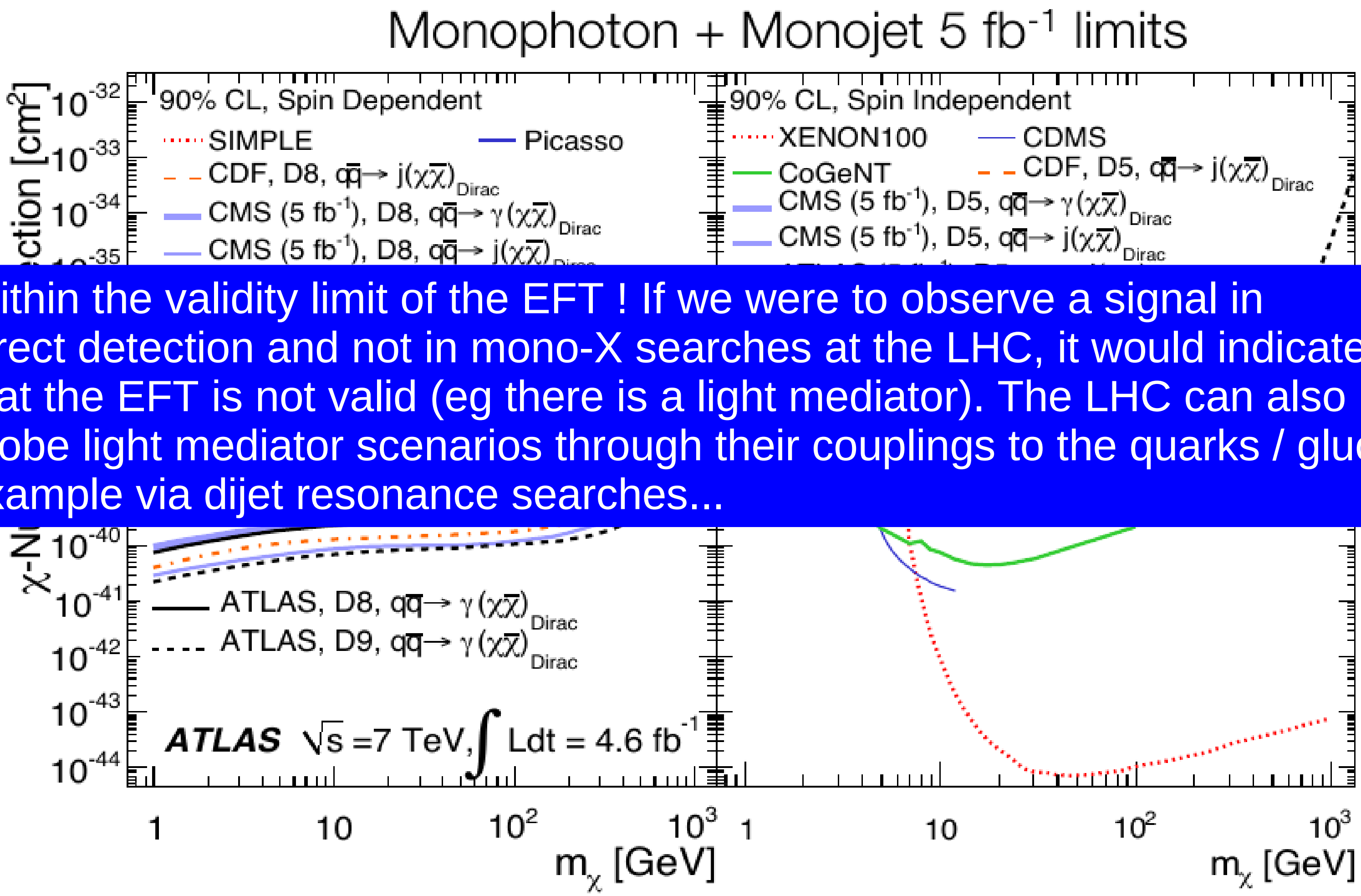
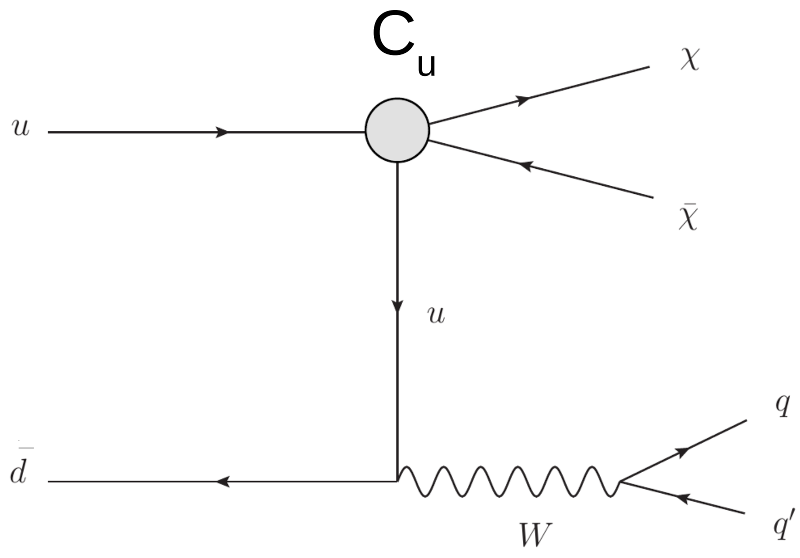
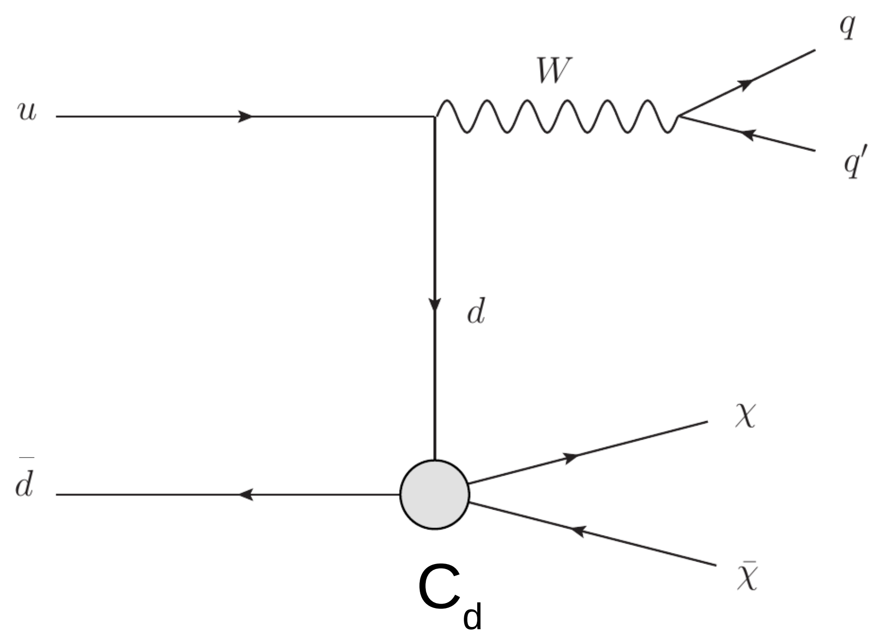


Within the validity limit of the EFT ! If we were to observe a signal in direct detection and not in mono-X searches at the LHC, it would indicate that the EFT is not valid (eg there is a light mediator). The LHC can also probe light mediator scenarios through their couplings to the quarks / gluons, for example via dijet resonance searches...

Limits on dark matter

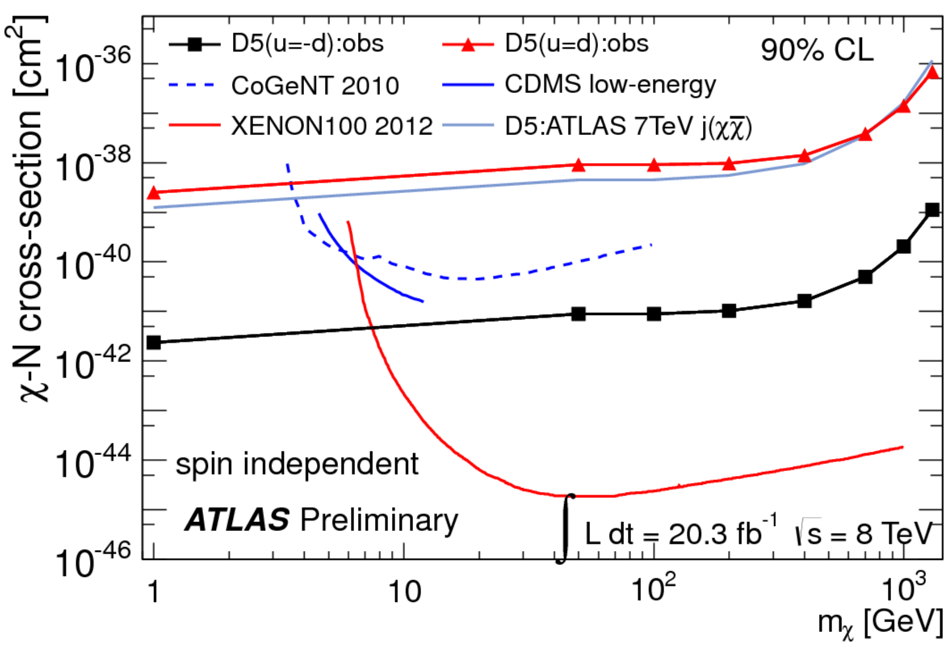
- Mono-Z/W analysis:
  - As the mono-W production diagrams can have some interference, this analysis can probe the relative coupling of DM particles to up and down quarks

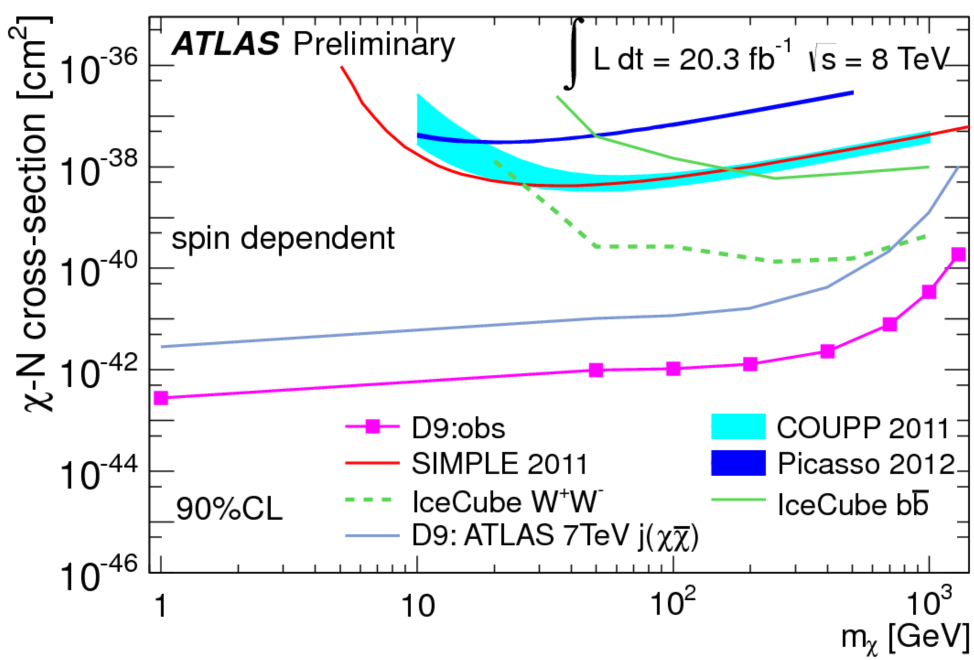




Limits on dark matter

- Mono-Z/W :
  - Same-sign couplings : mono-W/Z limit weaker than the monojet one





  - Strongest limits if u and d have opposite sign couplings

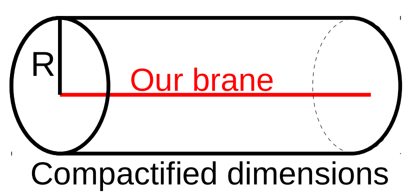
Interpretation : extra dimensions

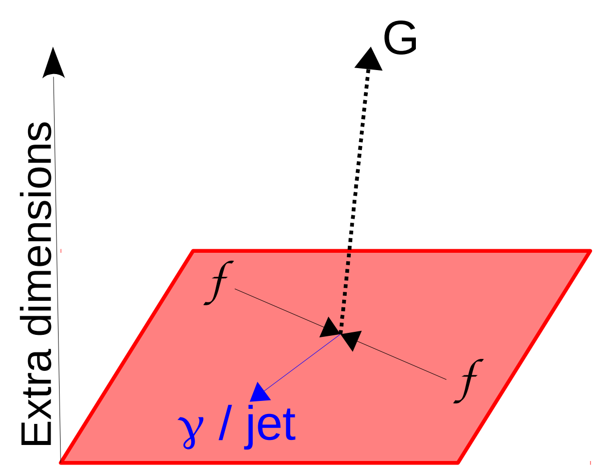
Arkani-Hamed, Dimopoulos, Dvali (ADD)

- Proposed solution the hierarchy problem
  - The gravity can propagate in the extra dimensions
  - New fundamental Planck scale M_D for n extra dimensions:

$$M_{Pl}^2 = M_D^{2+n} R^n$$

  - The extra dimensions are compactified resulting in Kaluza-Klein towers of massive graviton modes

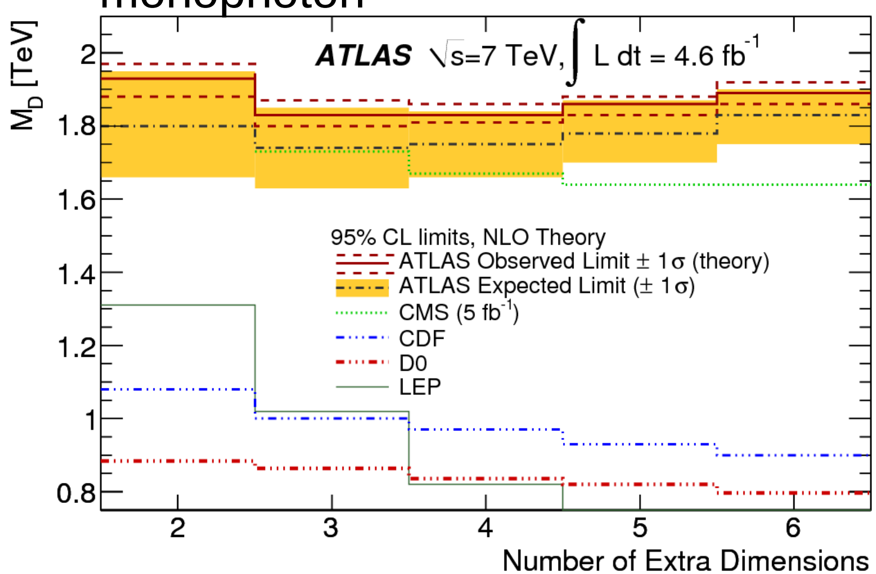




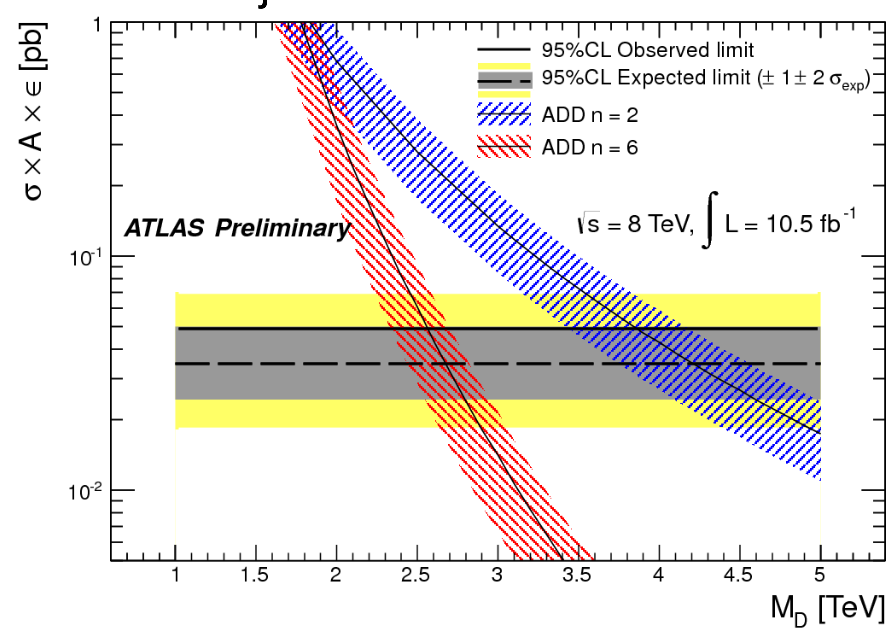
Limits on extra dimensions

- Limits on M_D depending on the number of extra dimensions n
  - Monophoton 7 TeV limits (4.6 fb^{-1}): 1.8-1.9 TeV
  - Monojet 8 TeV limits (10.5 fb^{-1}): 2.6-3.9 TeV

monophoton



monojet

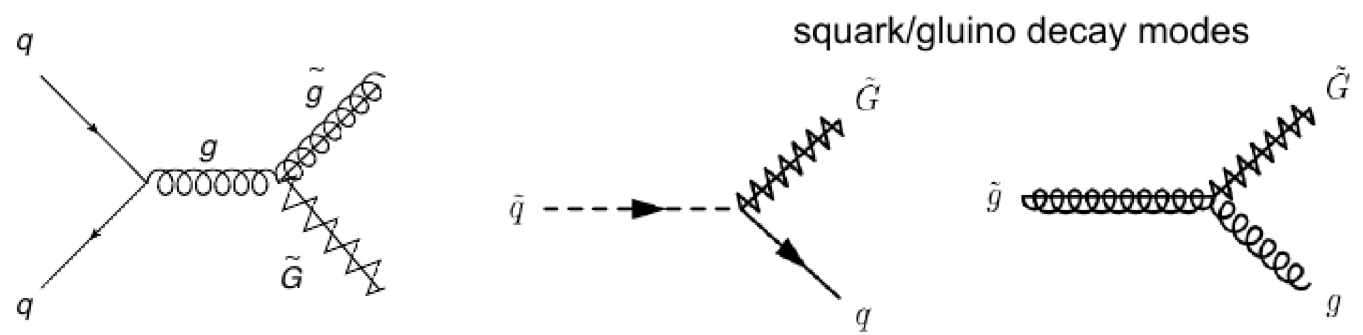


Interpretation : gravitinos

- In gauge-mediated SUSY breaking scenario, the gravitino is often the lightest supersymmetric particle
- The gravitino mass is related to the SUSY breaking scale :

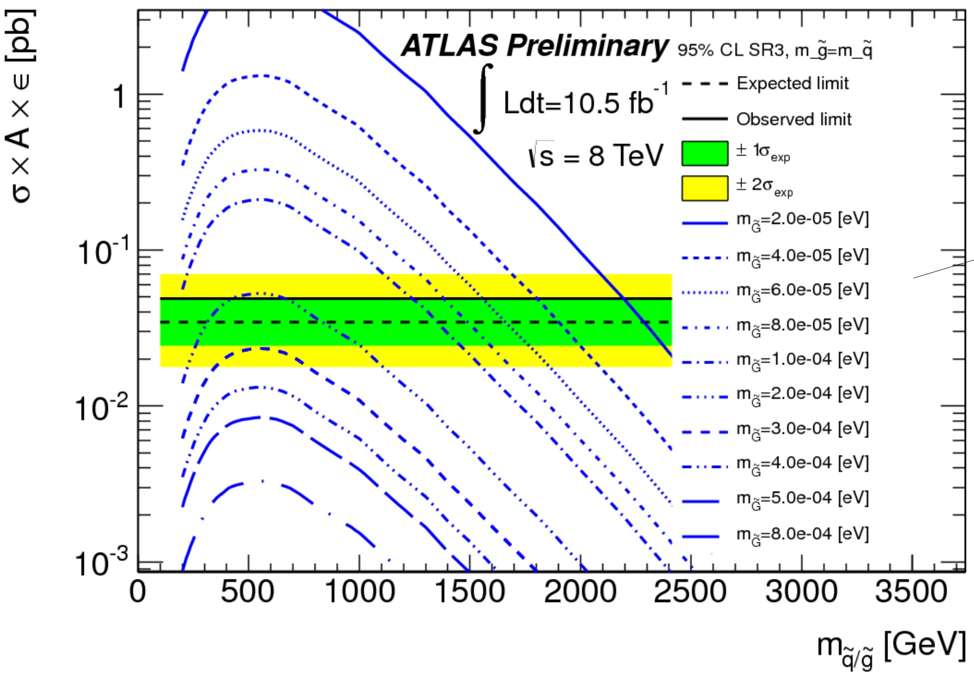
$$m_{\tilde{G}} \propto F/M_{Pl}$$

- Can represent a significant fraction of the DM
- Considered here : associated production of a gravitino with a gluino/squark, followed by the decay of the gluino/squark into a gravitino and a gluon/quark

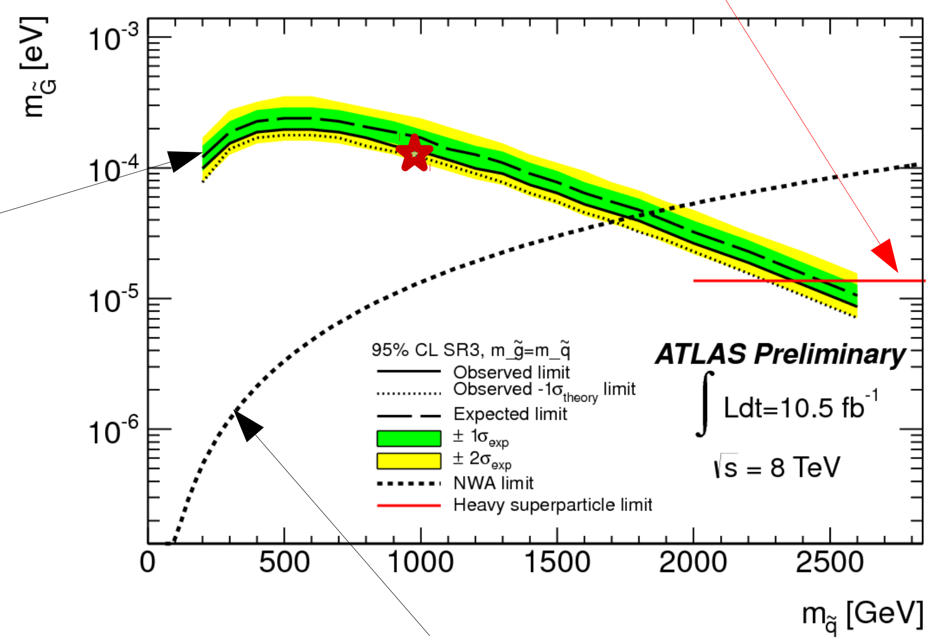


Limits on gravitino

- Set by the monojet analysis (10.5 fb^{-1})



Heavy sparticle limit coming from LEP/Tevatron: $m_{Gravitino}$> 1.37 x 10^{-5} eV



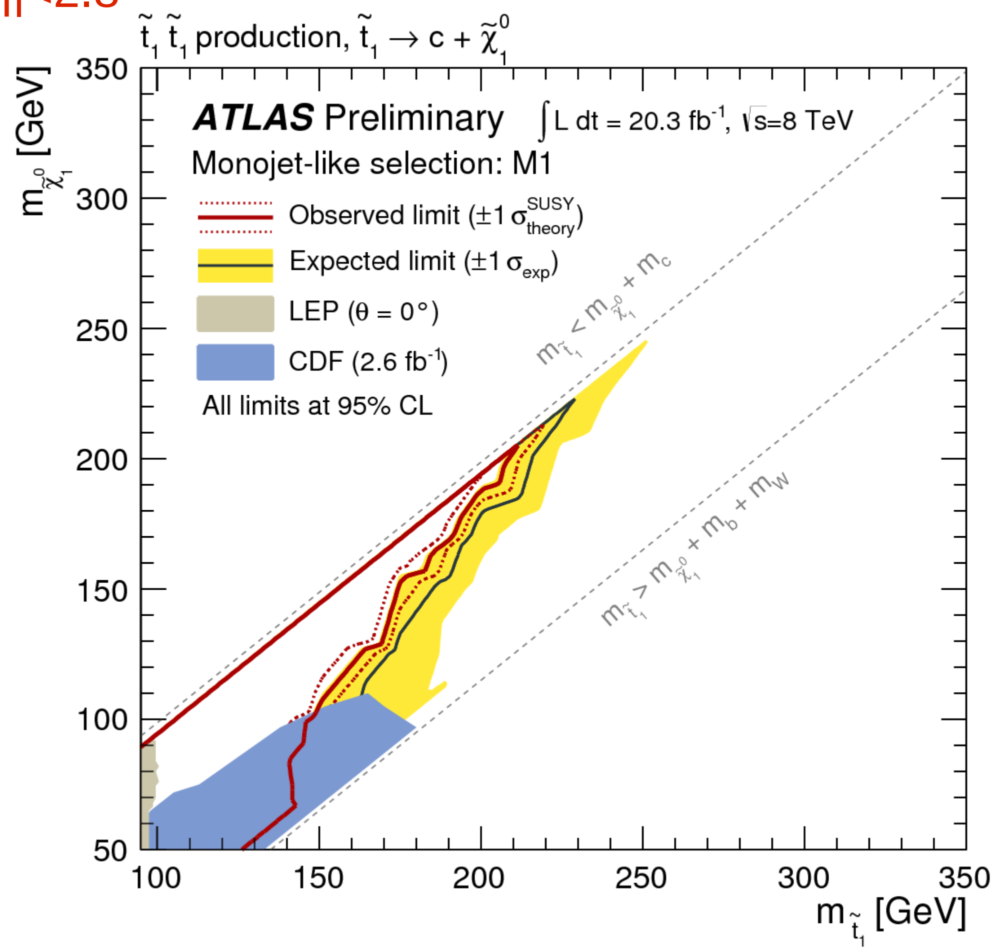
Narrow-width approximation for the gluino/squark decay no longer applies

$m_{Gravitino}$ > 1.0 x 10^{-4} eV for m_{squark} = m_{gluino} ≈ 1 TeV

Interpretation : top squarks

More details on this analysis in P. Jackson's talk (SUSY Phenomenology parallel session)

- Using a monojet-like analysis for very compressed spectra
- Differences with respect to the monojet selection :
  - No more than 3 jets with p_T>30 GeV in $|\eta|$<2.8
  - $\Delta\varphi$(jets,MET) > 0.4
  - P_T^{jet1} > 280 GeV and MET>220 GeV
- 29800 ± 900 events expected
- 30793 observed events
- Also combined to a charm-tagged analysis for moderate mass splitting (not show here)



Conclusions

- Analyses probing the production of invisible particles in association with a photon, a jet or a W/Z
- Now putting limits on various new physics models, for example :
  - Dark Matter production - complementary to direct/indirect searches, able to probe low-mass WIMPs
  - Large extra dimensions
  - Gravitino production
  - Top squark pair production for very compressed spectra
- All results can be found here:
  - http://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
- Stay tuned !
  - Monojet and monophoton analyses to be updated with the full 2012 dataset soon

Extra slides

Non-collision background in the monojet analysis

suppress coherent noise and electronic noise bursts in the calorimeter

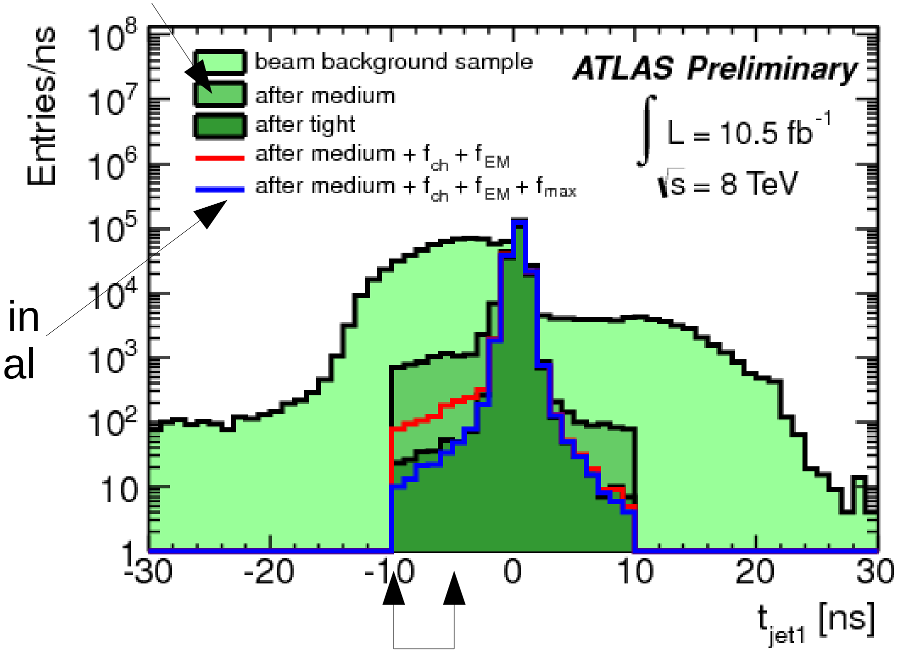
$$f_{\mathrm{ch}} > 0.2,\ f_{\mathrm{em}} > 0.1, \text{ and } f_{\max} < 0.8$$

$$f_{\mathrm{ch}} = \sum p_T^{\mathrm{track,jet}} / p_T^{\mathrm{jet}}$$

$f_{\max}$ denotes the maximum fraction of the jet energy collected by a single calorimeter layer.

f_{em} electromagnetic fraction in the calorimeter

Applied in the signal region

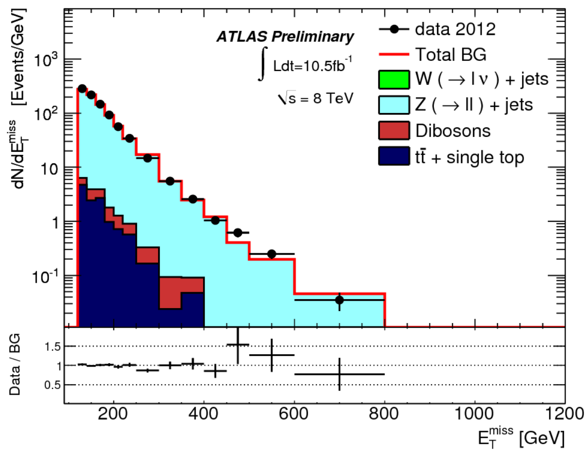


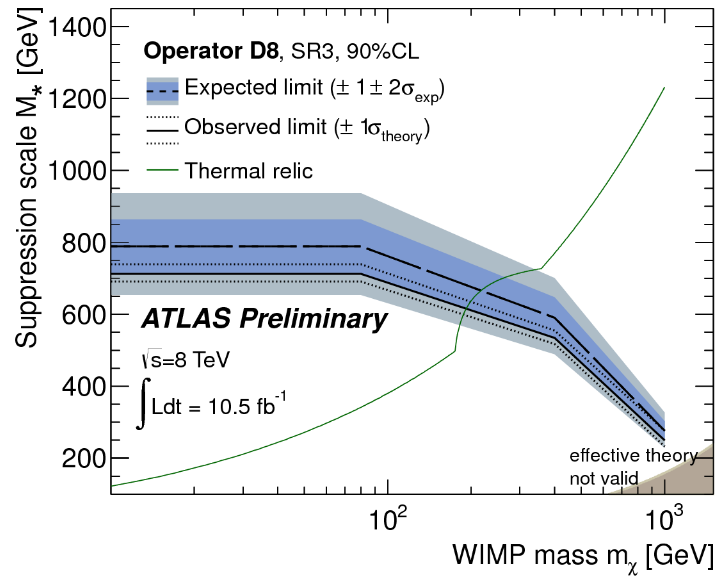
An upper limit on the remaining non-collision background events in the signal region is obtained from data using the measured timing distribution of the leading jet in the events with a leading jet in the region −10 ns < t < −5 ns. The shape of the timing distribution for non-collision background events is reconstructed from a control data sample with relaxed jet cleanup cuts. The contamination in SR1 is less than 0.2 %.

$$N_{\mathrm{NCB}}^{\mathrm{SR}} = N_{-10<t<-5}^{\mathrm{SR}} \times \frac{N^{\mathrm{NCB}}}{N_{-10<t<-5}^{\mathrm{NCB}}}$$

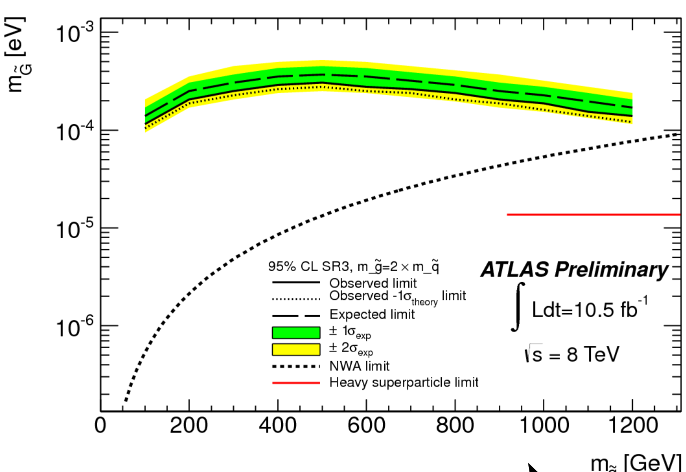
Further plots from monojet

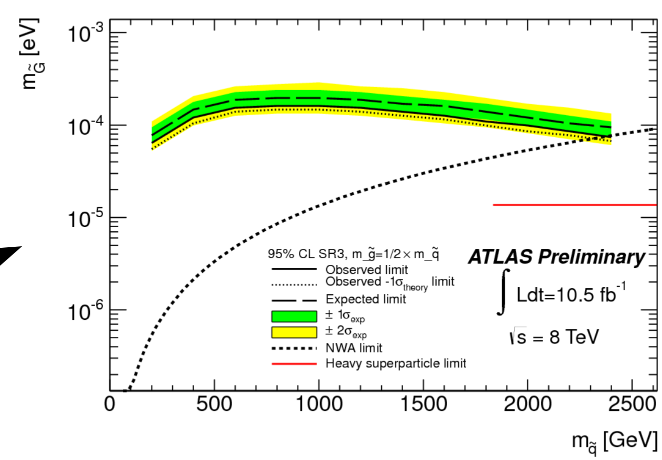
Cross check in the Z($\mu\mu$)+jets CR





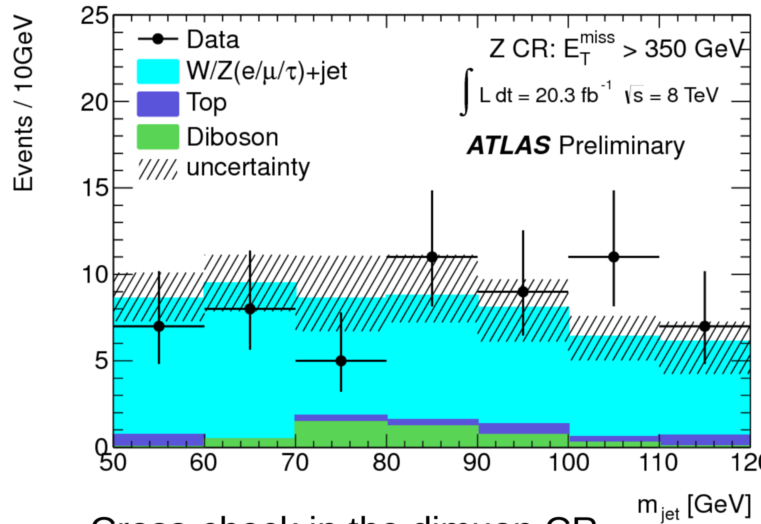
Limits on the effective theory mass scale M* compared to the relic density : if DM is entirely thermal relics, ATLAS limits exceeding the observed thermal relic density exclude a DM annihilating exclusively via the corresponding operator.



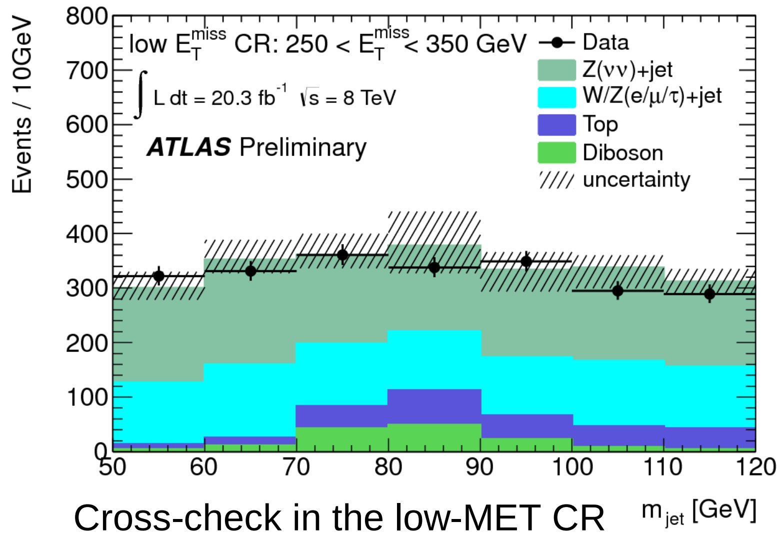


Gravitino limit with m_{gluino}=2 x m_{squark} or 0.5 x m_{squark}

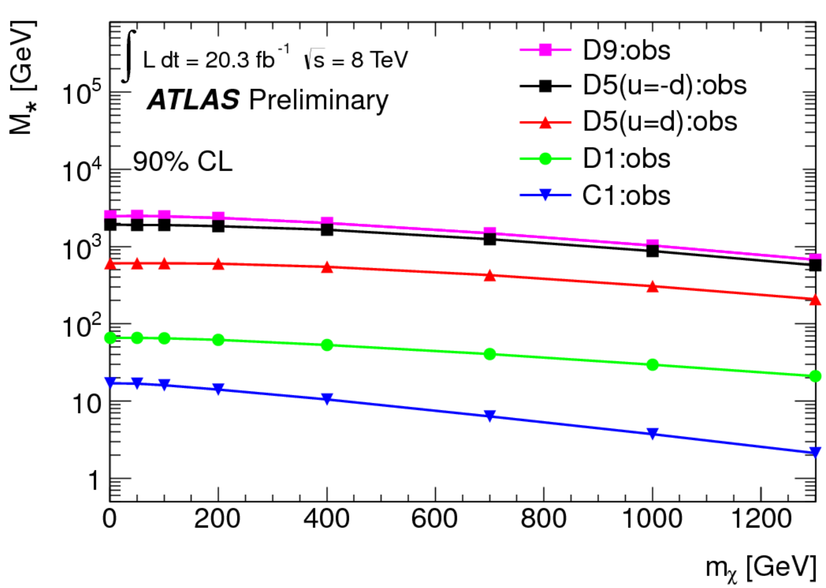
Further plots from mono-W/Z



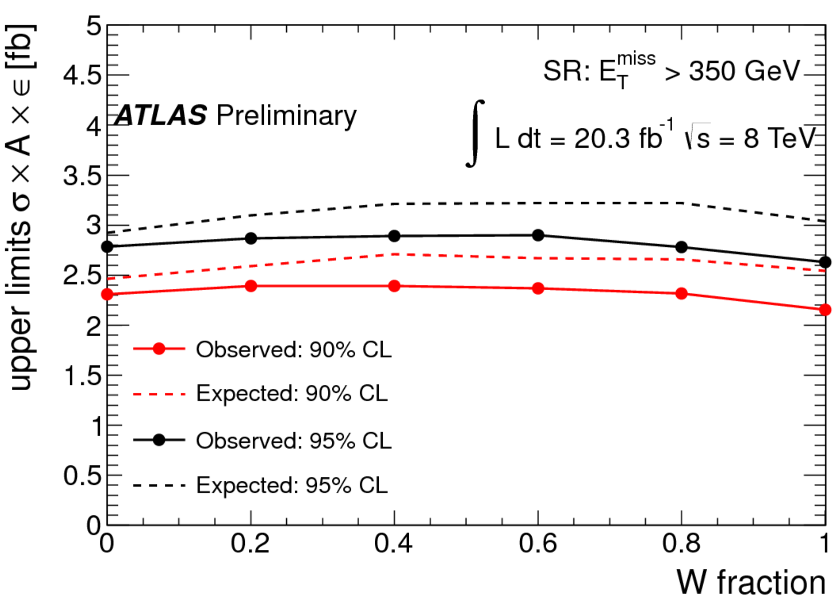
Cross-check in the dimuon CR



Cross-check in the low-MET CR



Limits on the effective theory mass scale M*

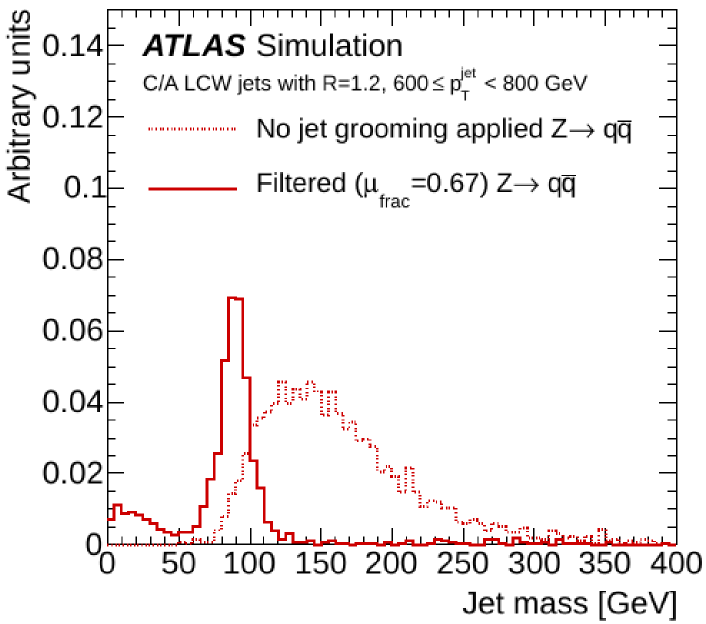


Limits on σ × A × ε as a function of W-boson fraction in combined single W/Z-boson signal samples. D5 destructive operator with m_χ = 1 GeV. Limits from SR1.

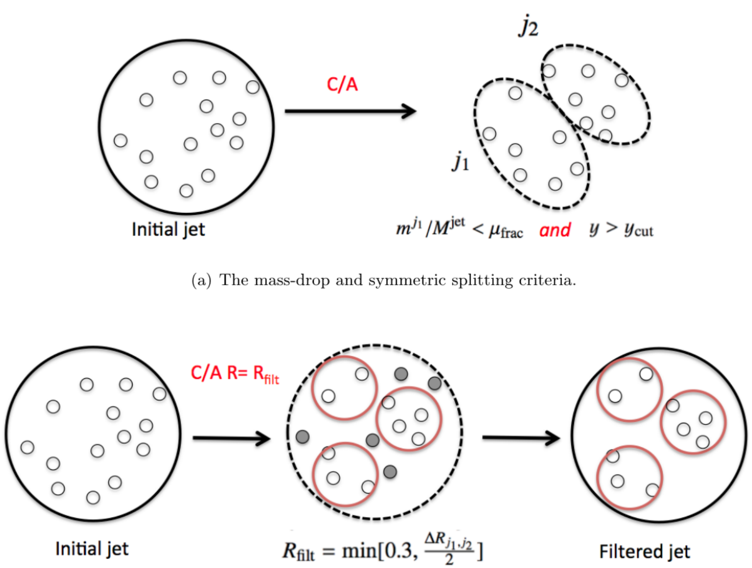
Large-jet substructure techniques

The jet reconstruction algorithms : $d_{ij} = min(p_{Ti}^{2p}, p_{Tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$

- p=1 : Kt algorithm. Priority to low Pt constituents
- p=0 : Cambridge-Aachen variant. Purely geometrical
- p=-1 : Anti-kt variant. Priority to high Pt constituents



Grooming algorithms (here : mass-drop filtering):
- retain the characteristic substructure
- reduce the impact of parton shower fluctuations and UE
=> improve the mass resolution and mitigate the influence of pile-up
=> powerful tool to discriminate between multijet BG and a heavy-particle decay



(a) The mass-drop and symmetric splitting criteria.

(b) Filtering.

More on the EFT

Fox, Harnik, Kopp and Tsai (2011)
10.1103/PhysRevD.85.056011

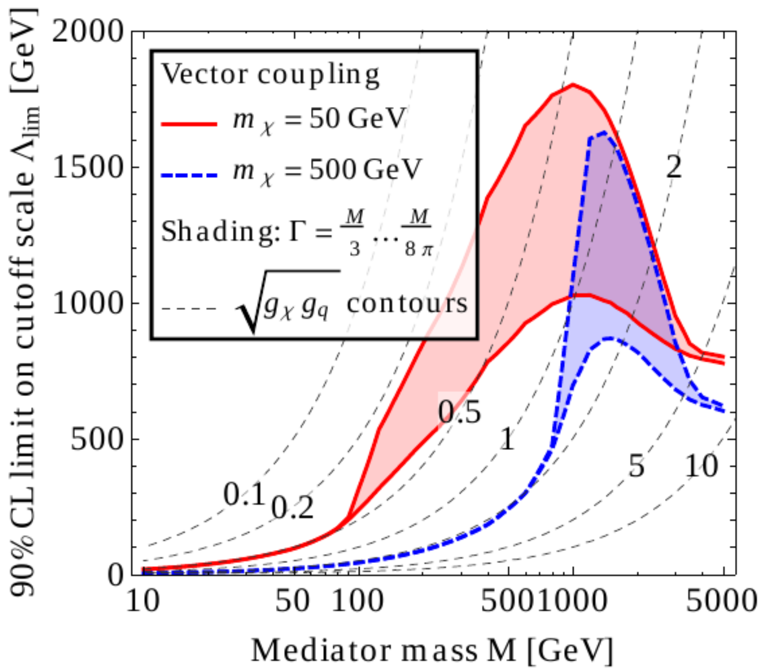
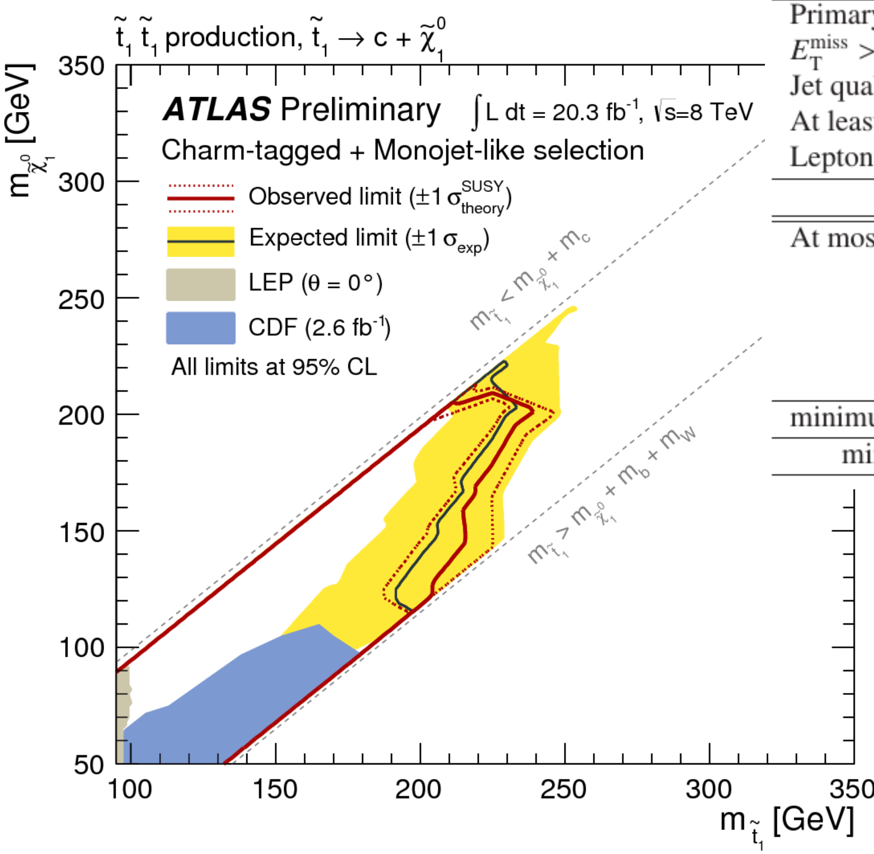


Figure 7: ATLAS limit on $\Lambda \equiv M/\sqrt{g_\chi g_q}$ as a function of the mass M of the particle mediating dark matter–quark interactions. We have assumed s-channel vector-type interactions, and we have considered the values $m_\chi = 50$ GeV (red) and $m_\chi = 500$ GeV (blue) for the dark matter mass. We have varied the width Γ of the mediator between the values $M/3$ (lower boundary of colored bands) and $M/8\pi$ (upper boundary of colored bands). Dashed dark gray lines show contours of constant $\sqrt{g_\chi g_q}$.

More on the top squark analysis



Selection criteria	
Preselection	
Primary vertex $E_T^{miss} > 120$ GeV Jet quality requirements At least one jet with $p_T > 120$ GeV and $\lvert\eta\rvert < 2.8$ Lepton vetoes: no isolated electrons (muons) with $p_T > 20$ GeV ($p_T > 10$ GeV)	
Monojet-like selection M1	Charm-tagged selection C1
At most three jets with $p_T > 30$ GeV and $\lvert\eta\rvert < 2.8$ $\Delta\phi(\text{jet}, \mathbf{p}_T^{miss}) > 0.4$	At least three jets with $p_T > 30$ GeVand $\lvert\eta\rvert < 2.5$ (in addition to the leading jet) *b*-veto for second and third jet *medium c*-tag for fourth jet $\Delta\phi(\text{jet}, \mathbf{p}_T^{miss}) > 0.4$
minimum leading jet p_T (GeV) 280	270
minimum E_T^{miss} (GeV) 220	410

Loose c-tagging :
- efficiency of ~95 %
- rejection of ~2 (b-jet)
- no significant rejection of light- or tau-jet

Medium c-tagging :
- efficiency of ~20 %
- rejection of ~5 (b-jet), ~10 (tau-jet), ~140 (light-jet)