SEARCH FOR NEW PHENOMENA IN MONOJET PLUS MISSING TRANSVERSE MOMENTUM FINAL STATES WITH ATLAS

Philippe Calfayan
(Ludwig-Maximilians Universität, München)

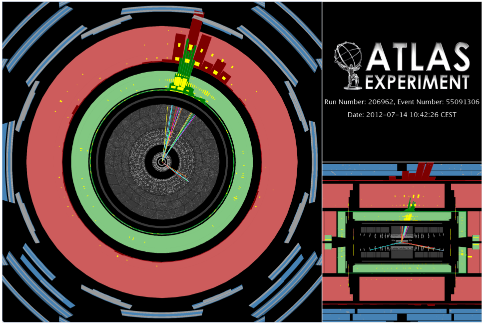
GDR Terascale
May 15, 2013

Mono-jet events

- An event with a single jet is balanced by “missing energy” in the transverse plan of the detector (referred to by $\not{E}_T$)

- The mono-jet topology allows to search for extensions of the Standard Model involving new particles that are undetected.

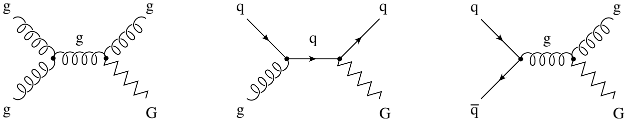
- Models investigated with the mono-jet final state can also be studied with events consisting of a mono-photon, mono-W, mono-Z, ... (not covered in this presentation)



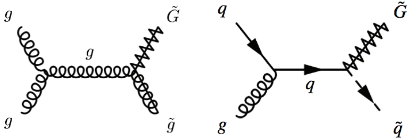
($\not{E}_T = 863\,\mathrm{GeV}$, leading jet $p_T = 852\,\mathrm{GeV}$)

Theoretical motivation

- $\boxed{pp \to \mathrm{X} + \mathrm{jet}}$ with X being:
  - Massive Graviton tower in Arkani-Hamed, Dimopoulos, Dvali (ADD) model of Large Extra Dimensions (LED) [see backup]

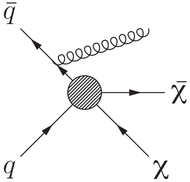


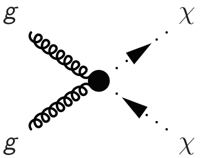
  - Unparticle (same production mode as ADD Graviton)
  - Supersymmetry: Gravitino + squark/gluino [see backup]



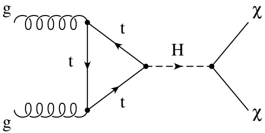
Theoretical motivation

- $\boxed{pp \to \mathrm{XX} + \mathrm{ISR\ jet}}$ with X being:
  - WIMP/Dark Matter (DM) candidate produced via contact interaction





  - WIMP/DM candidate produced via Higgs boson

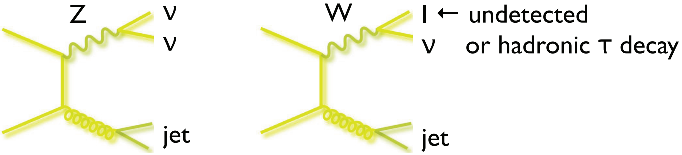


can investigate invisible Higgs decay

  - Compressed mass spectrum of supersymmetric particles

Contribution from the Standard Model

- Electroweak (EW) background [semi data-driven determination]
  - $Z(\to \nu\nu)$+jets: $\sim$ 50% of total background (*irreducible)*
  - $W(\to \ell\nu)$+jets and $Z(\to \ell\ell)$+jets $(\ell = e, \mu, \tau)$



- QCD multi-jets [data-driven determination]
- Non-collision [data-driven determination]
  - detector noise
  - cosmic ray showers
  - beam-induced background leading to fake jets
- Di-bosons, top [Monte-Carlo simulation]
  - $\sim$ 1% of the total background

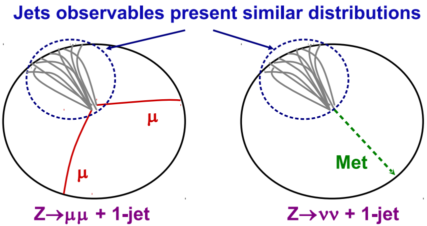
Event selection and signal regions (SR)

- Events selected with trigger based on calorimeter $\not{E}_T$ with online threshold up to 80 GeV for 8 TeV data.
- Standard quality cuts are required (data quality, jet cleaning)
- Leading jet required to be central ($|\eta| < 2$)
- At most 2 jets with $p_T > 30$ GeV to allow radiation from leading jet
- To suppress QCD multi-jet events: $\Delta\phi(\not{E}_T, jet_2) > 0.5$ (no mis-reconstructed jet)
- Veto on events containing electrons ($p_T > 20$ GeV) or muons ($p_T > 7$ GeV)
- Lower cuts on main observables to define 4 inclusive SR
  $\rightarrow$ Both leading jet p_T and $\not{E}_T > 120, 220, 350$ and 500 GeV (SR 1-4)
- Summary:

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

Electroweak background determination

- Electroweak W/Z background in SR is determined using control regions (CR) from data. These consists in W/Z processes with unvetoed leptonic decays.
- For instance: $\mathrm{Z} \to \nu\nu$ can be derived from $\mathrm{Z} \to \mu\mu$ data candidates



- Transfer from CR to SR achieved via a ratio of expected events in SR and CR, which implies reduced systematics. Such transfer factor accounts for phase space, cross section and Br differences.

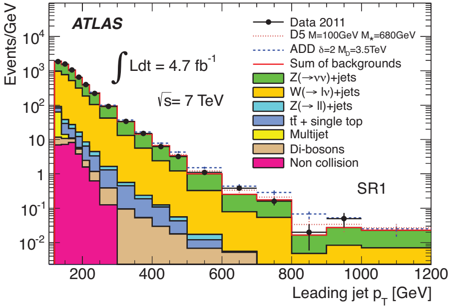
e.g.: $$N_{SR}^{predicted}(Z\nu\nu) = (N_{Data}^{CR}(Z\mu\mu) - N_{Background}^{CR}) \times N_{MC}^{SR}(Z\nu\nu)/N_{MC}^{CR}(Z\mu\mu)$$

Data vs background in SR (hep-ex/1210.4491)

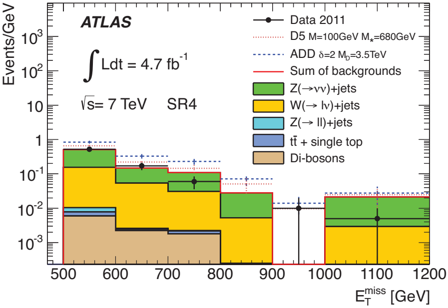
- $Z \to \nu\nu$ can be determined from 4 CR based on $Z \to \ell\ell$ or $W \to \ell\nu$ $(\ell \neq \tau)$
  $\Rightarrow$ 4 independent measurements are combined

- All corrections to CR are applied bin-by-bin as function of the variable of interest
  $\Rightarrow$ shapes of observables in SR can be modelled

Signal region 1:

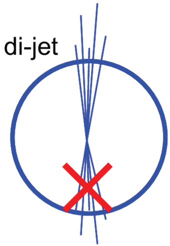


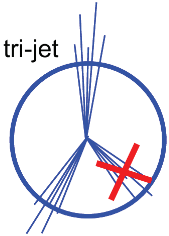
Signal region 4:

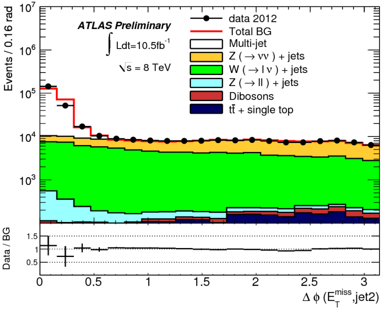


Determination of the QCD multi-jet background (hep-ex/1210.4491)

- Multi-jet events with misreconstructed jets can pass the selection ($p_T > 30\,\mathrm{GeV}$)
- Dominant contribution: 2-jets and 3-jets events in which one jet is lost
- Misreconstructed jets are pointing in the direction of the $\not{E}_T$
  $\Rightarrow$ multi-jet CR: $\Delta\Phi(\not{E}_T, jet_i) < 0.5$ with $i \leq 3$
- Method: calculate integral of extrapolated p_T of jet_i below $30\,\mathrm{GeV}$ in CR
- The jet p_T extrapolatation suffers from large uncertainties from the choice of the fit range, the fit function, and the EW background subtraction







Systematics uncertainties (hep-ex/1210.4491)

- Summary of all uncertainties in the 4 SR:

Source	SR1	SR2	SR3	SR4
JES/JER/$E_{\mathrm{T}}^{\mathrm{miss}}$	1.0	2.6	4.9	5.8
MC Z/W modelling	2.9	2.9	2.9	3.0
MC stat. uncert.	0.5	1.4	3.4	8.9
$1 - f_{\mathrm{EW}}$	1.0	1.0	0.7	0.7
Muon scale and resolution	0.03	0.02	0.08	0.61
Lepton scale factors	0.4	0.5	0.6	0.7
Multijet BG in electron CR	0.1	0.1	0.3	0.6
Di-boson, top, multijet, non-collisions	0.8	0.7	1.1	0.3
Total systematic uncertainty	3.4	4.4	6.8	11.1
Total statistical uncertainty	0.5	1.7	4.3	11.8

→ JES/JER/$\not\!\!E_T$: Jet and $\not\!\!E_T$ energy scale and resolution

→ MC Z/W modelling: parton shower and hadronisation

→ (1-f_{EW}): background to CR

- Semi data-driven determination of EW background is limited by uncertainties on MC in high-energy kinematic regions.

Mono-jet analysis results (hep-ex/1210.4491)

	SR1	SR2	SR3	SR4
$Z \to \nu\bar{\nu}$+jets	63000 ± 2100	5300 ± 280	500 ± 40	58 ± 9
$W \to \tau\nu$+jets	31400 ± 1000	1853 ± 81	133 ± 13	13 ± 3
$W \to e\nu$+jets	14600 ± 500	679 ± 43	40 ± 8	5 ± 2
$W \to \mu\nu$+jets	11100 ± 600	704 ± 60	55 ± 6	6 ± 1
$t\bar{t}$ + single t	1240 ± 250	57 ± 12	4 ± 1	-
Multijets	1100 ± 900	64 ± 64	8^{+9}_{-8}	-
Non-coll. Background	575 ± 83	25 ± 13	-	-
$Z/\gamma^* \to \tau\tau$+jets	421 ± 25	15 ± 2	2 ± 1	-
Di-bosons	302 ± 61	29 ± 5	5 ± 1	1 ± 1
$Z/\gamma^* \to \mu\mu$+jets	204 ± 19	8 ± 4	-	-
Total Background	124000 ± 4000	8800 ± 400	750 ± 60	83 ± 14
Events in Data (4.7 fb^{-1})	124703	8631	785	77
$\sigma_{\text{vis}}^{\text{obs}}$ at 90% [pb]	1.63	0.13	0.026	0.006
$\sigma_{\text{vis}}^{\text{exp}}$ at 90% [pb]	1.54	0.15	0.020	0.006
$\sigma_{\text{vis}}^{\text{obs}}$ at 95% [pb]	1.92	0.16	0.030	0.007
$\sigma_{\text{vis}}^{\text{exp}}$ at 95% [pb]	1.82	0.17	0.024	0.008

- The observed data is consistent with the prediction from the SM within uncertainties (statistics+systematics)

$\rightarrow$ 90% and 95% confidence level (CL) upper bounds on visible cross section ($\sigma \times A \times \epsilon$) are set

Mono-jet analysis results (ATLAS-CONF-2012-147)

- Update with $10\,\mathrm{fb}^{-1}$ of data at $8\,\mathrm{TeV}$
- Similar results as $7\,\mathrm{TeV}$, yet limited by available MC statistics.

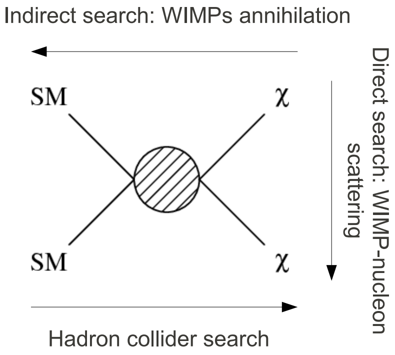
	Background Predictions ± (stat.data)± (stat.MC) ± (syst.)			
	SR1	SR2	SR3	SR4
$Z(\rightarrow \nu\bar{\nu})$+jets	173600 ± 500 ± 1300 ± 5500	15600 ± 200 ± 300 ± 500	1520 ± 50 ± 90 ± 60	270 ± 30 ± 40 ± 20
$W \rightarrow \tau\nu$+jets	87400 ± 300 ± 800 ± 3700	5580 ± 60 ± 190 ± 300	370 ± 10 ± 40 ± 30	39 ± 4 ± 11 ± 2
$W \rightarrow e\nu$+jets	36700 ± 200 ± 500 ± 1500	1880 ± 30 ± 100 ± 100	112 ± 5 ± 18 ± 9	16 ± 2 ± 6 ± 2
$W \rightarrow \mu\nu$+jets	34200 ± 100 ± 400 ± 1600	2050 ± 20 ± 100 ± 130	158 ± 5 ± 21 ± 14	42 ± 4 ± 13 ± 8
$Z \rightarrow \tau\tau$+jets	1263 ± 7 ± 44 ± 92	54 ± 1 ± 9 ± 5	1.3 ± 0.1 ± 1.3 ± 0.2	1.4 ± 0.2 ± 1.5 ± 0.2
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$+jets	783 ± 2 ± 35 ± 53	26 ± 0 ± 6 ± 1	2.7 ± 0.1 ± 1.9 ± 0.3	–
$Z/\gamma^*(\rightarrow e^+e^-)$+jets	–	–	–	–
Multijet	6400 ± 90 ± 5500	200 ± 20 ± 200	–	–
$t\bar{t}$ + single t	2660 ± 60 ± 530	120 ± 10 ± 20	7 ± 3 ± 1	1.2 ± 1.2 ± 0.2
Dibosons	815 ± 9 ± 163	83 ± 3 ± 17	14 ± 1 ± 3	3 ± 1 ± 1
Non-collision background	640 ± 40 ± 60	22 ± 7 ± 2	–	–
Total background	344400 ± 900 ± 2200 ± 12600	25600 ± 240 ± 500 ± 900	2180 ± 70 ± 120 ± 100	380 ± 30 ± 60 ± 30
Data	350932	25515	2353	268

WIMP/DM interpretation

Dark matter candidate and detection

- We assume there is an interaction between SM and dark sector, not necessarily the weak one. In the following, we equally refer to "WIMP" or "Dark Matter" (DM) particle to describe a DM candidate.

- DM candidate must fulfill the following requirements:
  - Massive
  - Neutral
  - Interact weakly with Standard Model (SM) particles
  - Stable (detector time scale)

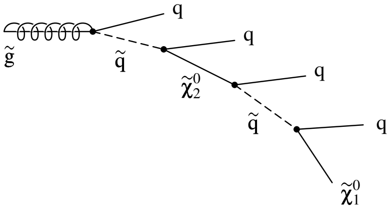


WIMP/DM interpretation

Search for Dark Matter at Hadron Collider

- Case where new SM/DM mediators heavier than DM can be produced directly

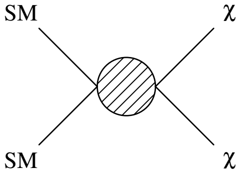
  e.g.: cascade decays of supersymmetric (SUSY) particles down to a stable neutralino (LSP)



- Case where all new particles mediating the interaction between DM candidate and SM particles are too heavy to be produced directly at LHC

⇒ DM production via contact interactions [Maverick Dark Matter, hep-ph/1002.4137]

SM/DM coupling proportional to a suppression scale $M_\star$



WIMP/DM interpretation

Assumptions on DM candidate pair production via contact interaction

- All new particles mediating the interaction between DM candidate and SM particles are too heavy to be produced directly
- Interaction between DM and SM not explicitly via weak interactions
- DM particles are assumed to be Dirac fermions (Majorana fermions would lead to higher production cross section)
- Out of 14 operators for Dirac fermions, 4 categories are distinguished according to $\not{E}_T$ shapes: D1, D5, D9, D11 (D8 in same category as D5)
- DM particle couple to SM light quarks or gluons universally and with one given operator exclusively

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	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

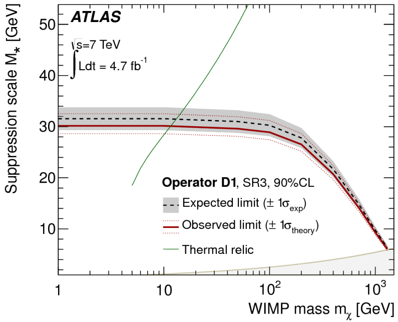
- The effective theory must be valid for given the parameters $M_\star$ and m_χ (DM particle mass)

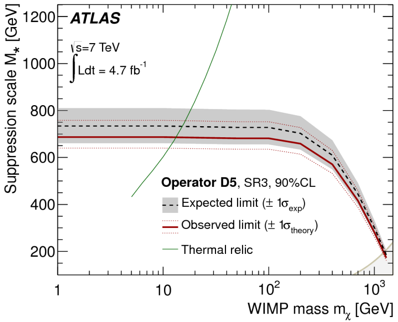
WIMP/DM interpretation (hep-ex/1210.4491)

Limits on the suppresion scale $M_\star$

- Generator: MADGRAPH + PYTHIA
- Lower limits at 90% CL on $M_\star$ are computed as function of the DM particle mass m_χ, for different DM/SM couplings
- SR3 is used for operators D1 and D5, while SR4 is utilized for D9 and D11 (based on sensitivity)

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	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$





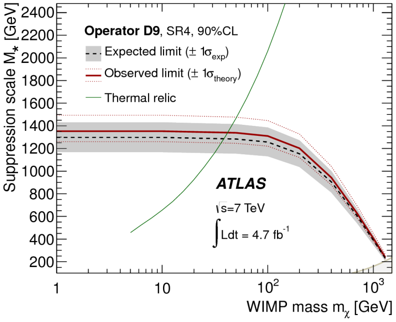
WIMP/DM interpretation (hep-ex/1210.4491)

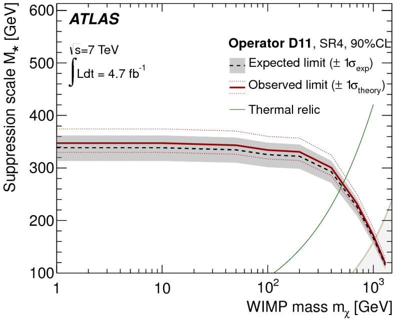
Limits on the suppresion scale $M_\star$

$$\boxed{\Omega_\chi \propto \frac{1}{<\sigma\nu>} \sim \frac{m_\chi^2}{g_\chi^4}} \text{ with } \begin{cases} \Omega_\chi: & \text{observed thermal relic density} \sim 0.24 \\ \langle\sigma\nu\rangle: & \text{thermally-averaged annihilation cross section} \\ m_\chi: & \text{DM particle mass} \\ g_\chi: & \text{coupling between DM and SM particles} \end{cases}$$

- Thermal relic density observed by WMAP (green curve) is compatible with DM having couplings and mass comparable to weak scale masses and weak force

→ If $M_\star$ above relic line, other annihilation processes required for consistency to WMAP



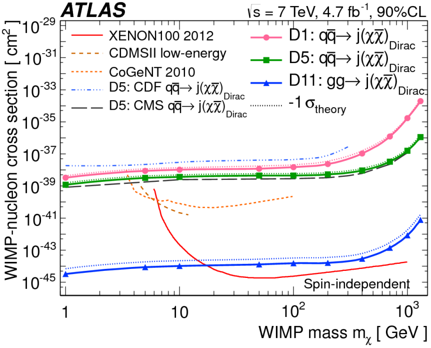


WIMP/DM interpretation (hep-ex/1210.4491)

Limits on WIMP-nucleon scattering cross section

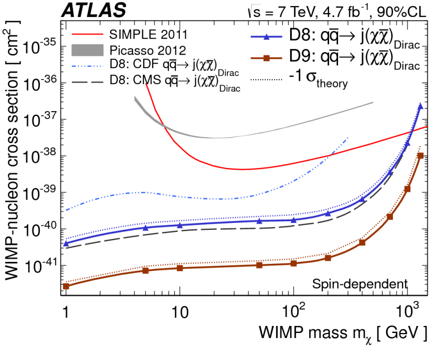
- Bounds on $M_\star$ can be converted to bounds on WIMP-nucleon scattering in the effective operator approach $\rightarrow$ comparison with direct DM detection experiments

- Spin-independent interaction:



$\Rightarrow$ LHC more sensitive for D1 & D5 at low m_χ region, and for D11 at $\sim$ any m_χ

- Spin-dependent interaction:



$\Rightarrow$ LHC limits stronger for D8 & D9

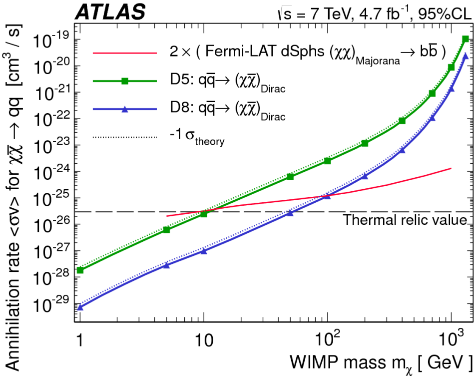
WIMP/DM interpretation (hep-ex/1210.4491)

Limits on Dark Matter annihilation cross section

- Bounds on vector and axial-vector interactions can be translated into cross section upper limits on WIMP annihilations to 4 light *q* (flavor universal interaction)
- The results are compared to the annihilations to *bb* from Galactic high energy gamma ray observations by Fermi LAT

- Results are comparable and complementary
- Below 10 GeV for D5 and 70 GeV for D8, ATLAS limits below relic value

  → abundance not consistent with WMAP



Conclusion

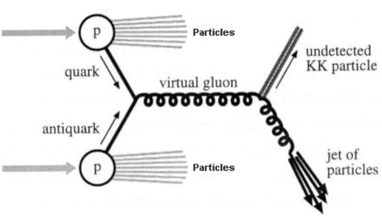
- The mono-jet final state involves a large scope of theoretical interpretations including Supersymmetry, Dark Matter, and large extra dimensions.
- No evidence of new physics has been observed but limits have been set on the model parameters of the theoretical scenarios involved.
- Accurate "data-driven" techniques have been used for the determination of the main backgrounds.
- Dark Matter interpretation is complementary to results of direct and indirect astroparticle experiments. Very good sensitivity for low-mass Dark Matter.
- Recent ATLAS mono-jet analyses:
    - 7 TeV, 4.7 fb^{-1}: hep-ex/1210.4491 (accepted by JHEP)
    - 8 TeV, 10.5 fb^{-1}: ATLAS-CONF-2012-147
- Update with full 2012 8 TeV dataset (20 fb^{-1}) ongoing.

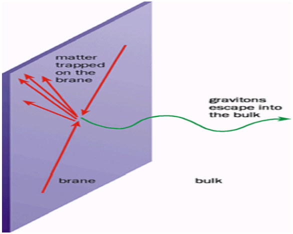
BACKUP

LED interpretation

- **Physics model:** Arkani-Hamed, Dimopoulos, Dvali (ADD) Kaluza-Klein LED:
  - Provide essential ingredient to a solution to the hierarchy problem
  - $M_{Pl}^2 \simeq M_D^{2+n} R^n$ with n and R the number and compactification radius of the extra dimensions
  - Gravity propagates in (4+n)-dimensional bulk space while SM fields are confined to 4 dimensions
  - Kaluza-Klein tower of massive graviton (G) modes

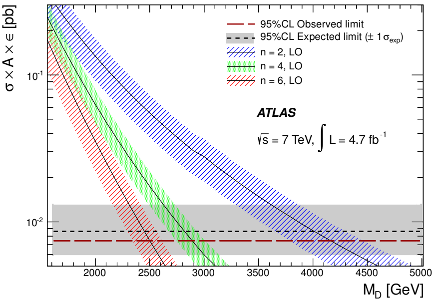
- **Production of G at LHC:** in a low-energy effective theory (of energy scale M_D):

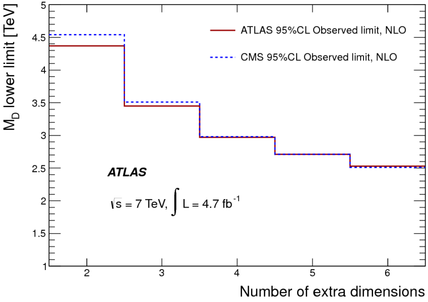




LED interpretation (hep-ex/1210.4491)

- Signal events have been generated with PYTHIA
- 95% CL model-independent upper limits on $\sigma \times A \times \epsilon$ compared to prediction
  $\Rightarrow$ 95% CL lower limits on M_D as function of n





LED interpretation (hep-ex/1210.4491)

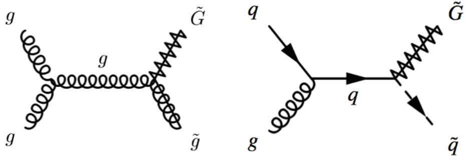
- Contribution to signal production cross section from region where $\hat{s} \gtrsim \mathrm{M}_D^2$ is not valid (unknown UV behavior of the theory)

  $\Rightarrow$ differences of signal production cross sections bewteen complete and truncated ($\hat{s} < \mathrm{M}_D^2$) samples are provided

n	M_D [TeV]		R [pm]		Cross section truncation	
	LO	NLO	LO	NLO	LO	NLO
2	4.17	4.37	2.8×10^7	2.5×10^7	0.02%	0.01%
3	3.32	3.45	4.8×10^2	4.5×10^2	1.9%	1.3%
4	2.89	2.97	2.0	1.9	11.8%	9.9%
5	2.66	2.71	7.1×10^{-2}	7.0×10^{-2}	29.5%	27.2%
6	2.51	2.53	0.8×10^{-2}	0.8×10^{-2}	49.1%	47.9%

Gravitino interpretation (ATLAS-CONF-2012-147)

- Generator: MADGRAPH + PYTHIA (decay)



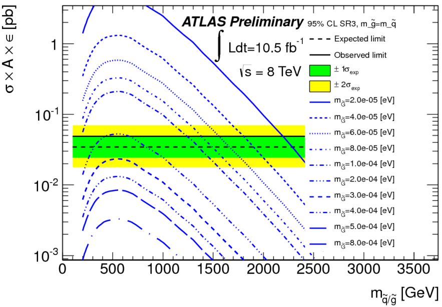
- In gauge-mediated SUSY breaking (GMSB) scenarios, the gravitino $\tilde{G}$ (spin-3/2 superpartner of the graviton) is often considered the lightest supersymmetric particle (LSP) and a potential candidate for DM
- Narrow-width approximation is assumed for $m_{\tilde{g}}$ and $m_{\tilde{q}}$ decays $\rightarrow$ valid when $\Gamma \ll m_{\tilde{g}}, m_{\tilde{q}}$
- Assumption: $\tilde{g}$ and $\tilde{q}$ decay such that $\begin{cases} \mathrm{BR}(\tilde{g} \rightarrow g + \tilde{G}) = 1 \\ \mathrm{BR}(\tilde{q} \rightarrow q + \tilde{G}) = 1 \end{cases}$

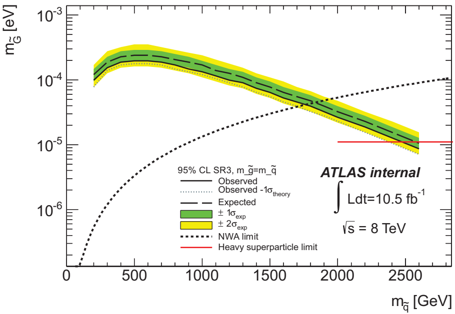
Gravitino interpretation (ATLAS-CONF-2012-147)

Limits in degenerated case: $m_{\tilde{g}} = m_{\tilde{q}}$

- 95% CL limits on $\sigma \times A \times \epsilon$ compared to prediction

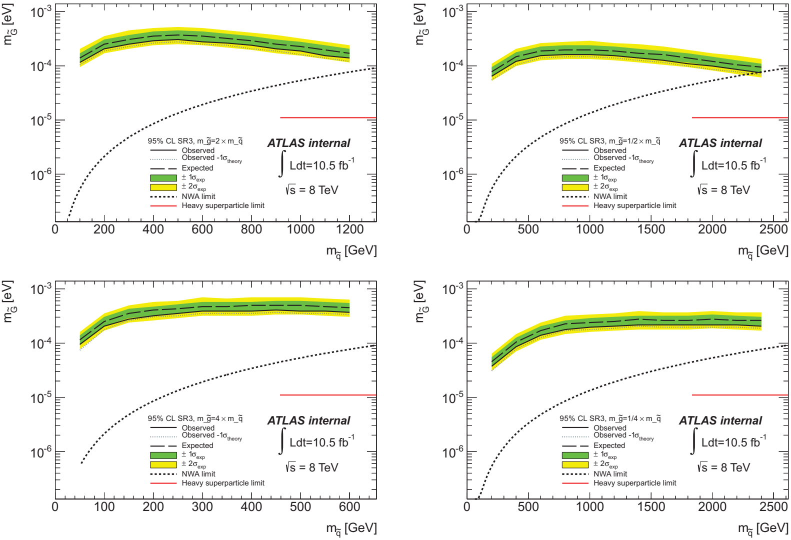
  $\Rightarrow$ lower limits on $m_{\tilde{G}}$ as function of $m_{\tilde{q}}$





Gravitino interpretation

Limits: non-degenerated case



CR of EW background estimate (hep-ex/1210.4491)

- Z and W CR are obtained with standard selections including cuts based on reconstructed Z and W masses.
- Shapes of variables involved in CR cuts required to be well modelled by simulation
- Below, leading muon p_T and $\not{E}_T$ and the $Z \to ee$ and $\mathrm{W} \to \mu\nu$ CR, respectively: