Dark Matter searches at LHC

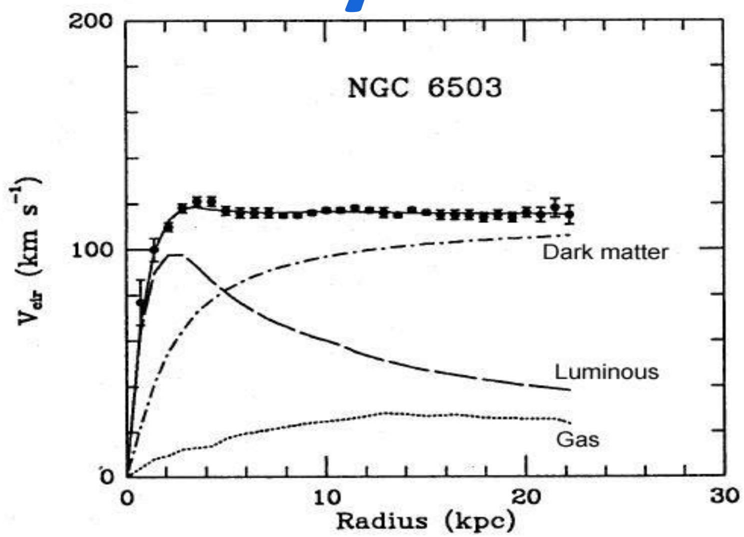
Bellan R. (Univ. Torino & INFN)

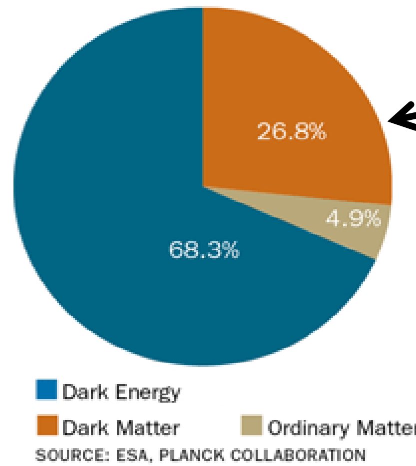
De Sanctis U. (Univ. Udine & INFN)

Outline

- DM evidence in a nutshell
- DM direct/indirect detection and its production at LHC;
- Theoretical framework (effective theory);
- DM searches in ATLAS &CMS experiments;
- Results
- Perspectives

Why do we need Dark Matter?





Dark Matter presence in the Universe

If a relic particle exists, its abundance will be:

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \frac{3\times 10^{-27}\, cm^3 s^{-1}}{\langle \sigma_A v\rangle}$$

For a new particle with a weak-scale interaction, we have:

$$\langle \sigma_A v\rangle \propto \frac{\alpha^2}{m_\chi^2} \approx \frac{\alpha^2}{(100 GeV)^2} \approx 10^{-25}\, cm^3 s^{-1}$$

$$\alpha \approx 10^{-2}$$

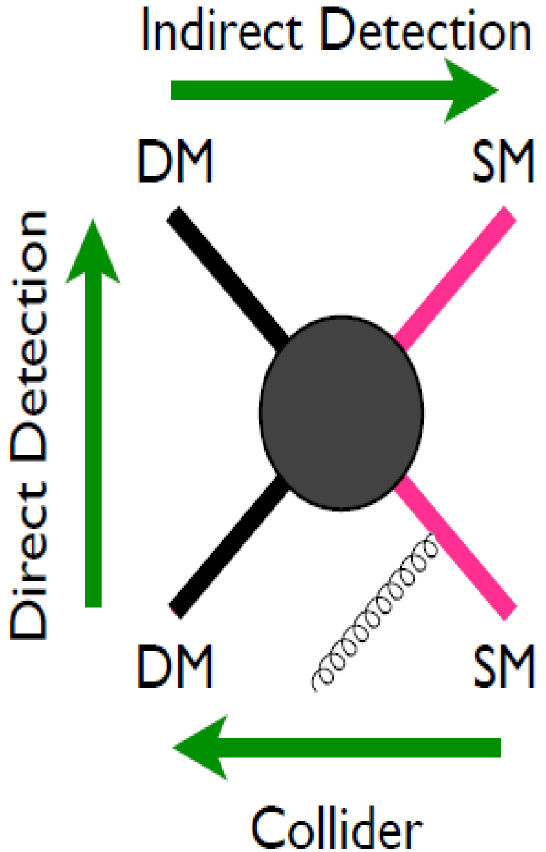
Close to the value required for the dark matter in the Universe!

- New elementary particles, produced in the early Universe either long lived or stable
  - Axions → pseudo-scalar m ~ 10^{-5} eV
  - WIMPs (Weakly Interacting Massive Particles): m ~ 10 GeV to few TeV
    - Candidates: from supersymmetry (neutralinos); from theories with universal extra dimensions (UED) (lightest Kaluza-Klein particle), and from many other BSM theories

Dark Matter detection

Dark matter

1109.4398
1008.1783



1. Direct Detection Experiments
- Dark Matter-nucleus scattering.
- Low mass DM particles not probed yet.
- Less sensitive to spin-dependent coupling.
- XENON-100, CDMS, CoGeNT

2. Indirect Detection Experiments
- Observe annihilation products.
- Low mass DM particles not accessible.
- Depends on DM density and annihilation model.
- Super-Kamiokande, IceCube, Fermi-LAT, AMS2

3. Collider Experiments
- Laboratory production of DM particles.
- Sensitive to wide mass range.
- Both spin-dependent and spin-independent couplings.
- Tevatron, LHC

Effective field theory approach

arXiv: 1008.1783; arXiv: 1109.4398

$$\mathcal{L} = \underbrace{\mathcal{L}_{SM}}_{\text{SM Lagrangian}} + \underbrace{i\bar{X}\gamma^\mu\partial_\mu X - M_X\bar{X}X}_{\text{kinetic terms for DM}} + \underbrace{\sum_q \sum_{i,j} \frac{G_{qij}}{\sqrt{2}} [\bar{X}\Gamma_i^X X][\bar{q}\Gamma_q^j q]}_{\text{set of 4-Fermion interactions between DM and SM quarks}},$$

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

- Operator **Γ** describes scalar, pseudoscalar vector, axial-vector and tensor operators.
- Masses for the DM candidate range from 1 GeV to 1 TeV

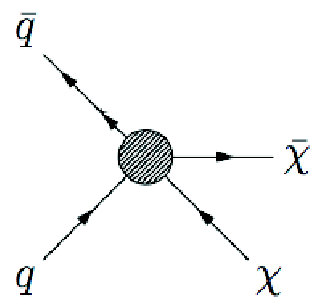
$$M_* = M/\sqrt{g_{q/g}g_\chi}$$

- Effective theory based on different interaction operators, assuming χ is a Dirac-fermion.
- Detection based on ISR gluon/photon/gauge boson
- Comparison with dedicated experiments for direct/indirect detection;

The experimental challenge

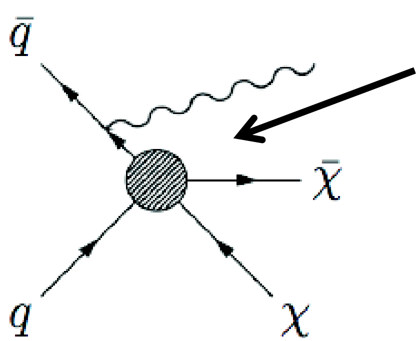
- Neutral and weakly interacting so difficult to observe
- No signal in LHC detectors ➔ missing transverse energy
- Direct production has small cross section and no signal in detector

➔ difficult searches

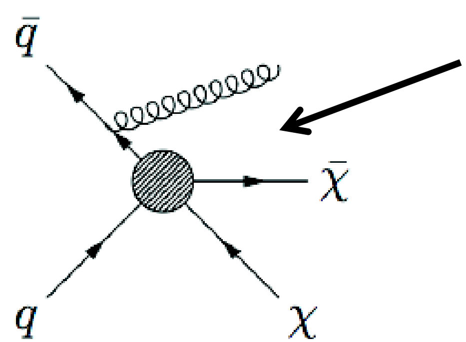


- Production in association with Standard Model particles easier:

option for detection → Design searches based on MET



MONO
GAUGE BOSON
PRODUCTION

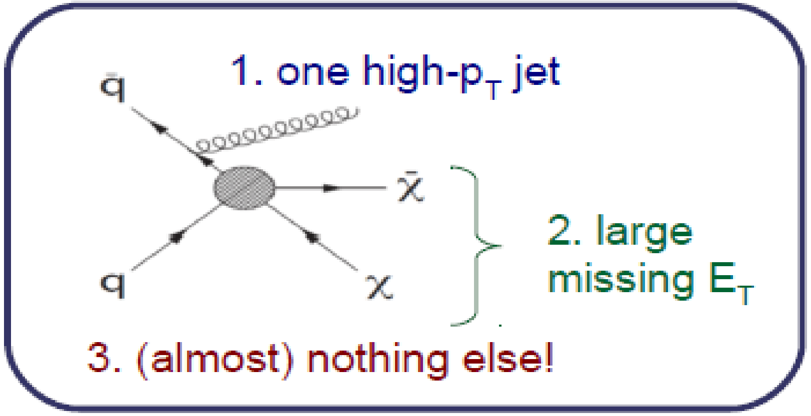


MONOJET
PRODUCTION

Monojet searches: Event selection

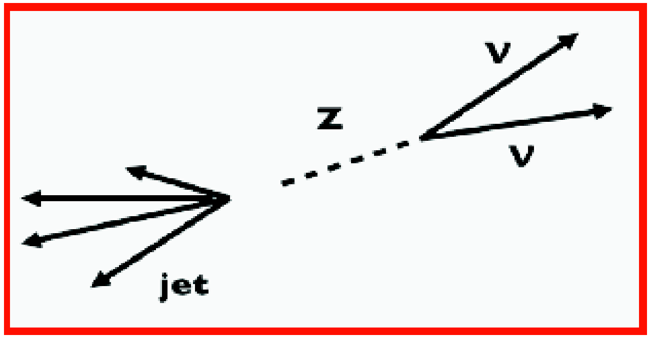
ATL-CONF-2012-147
CMS-PAS-EXO-12-048

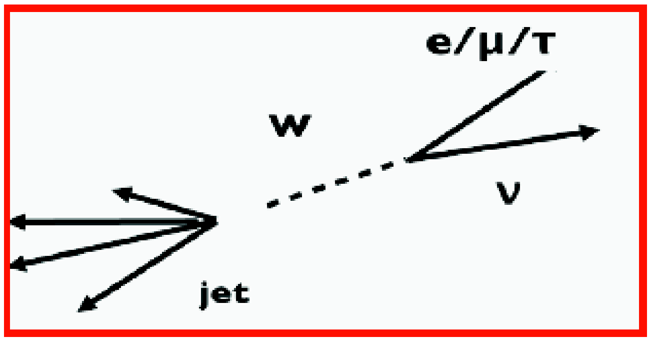
- Final state: one high-P_T jet from ISR radiation and high E^T_{MISS}.
- 19.5 (CMS)/10.5 (ATLAS)fb^{-1} @ 8 TeV

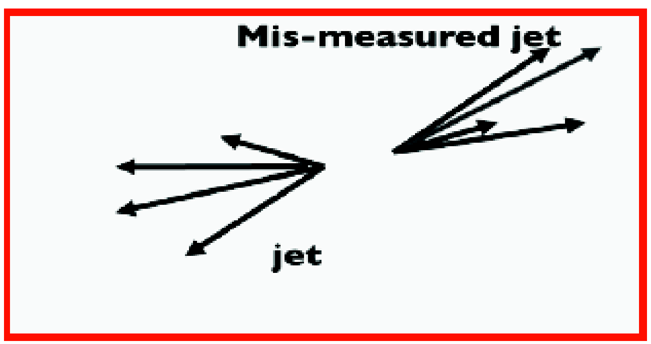


- **Event selection CMS (ATLAS):**
  - CMS has 2 triggers: E^T_{MISS} > 120 GeV + E^T_{MISS} > 120 GeV & Jet P_T > 80 GeV (in the central region); ATLAS has a single E^T_{MISS} trigger at 80 GeV
  - Leading jet P_T > 110 (120) GeV, $|\eta|$ < 2.4 (2.0) reconstructed with an anti-kT algorithm R=0.5 (0.4)
  - E^T_{MISS} > 250 (120)GeV;
  - Jet veto: < 3 jets with P_T > 30 GeV, $|\eta|$<4.5
  - CMS: $|\Delta\varphi(jet_1, jet_2)|$ < 2.5; ATLAS: $|\Delta\varphi(jet_2, E^T_{MISS})|$>0.5
  - No electrons with P_T>10 (20) GeV
  - No muons with P_T > 10 (7) GeV
  - No taus with P_T > 20 GeV, and $|\eta|$ < 2.3. ATLAS has no tau veto.

Monojet searches: CMS background estimation







Z→νν + jets (irred.); W→ℓν + jets

Normalised to data in W(μν) or Z(μμ) enriched CR orthogonal to SR (i.e. defined removing the lepton veto). Correction for acceptance and efficiencies for W and rescaling for Z→νν/Z→μμ ratio are applied.

Multijets

From MC normalised to dijet measured cross-section.

tt, single top and diboson production from MC

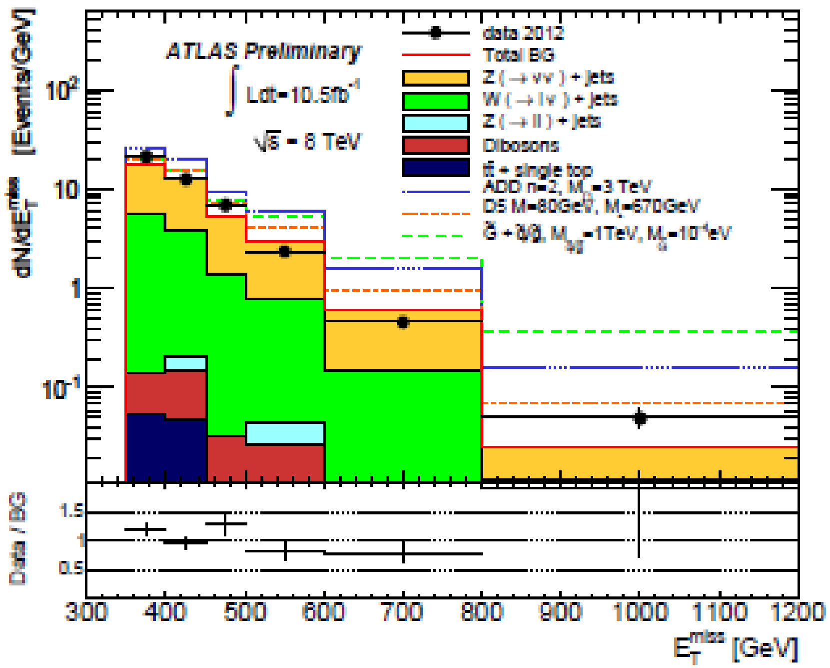
Monojet searches: ATLAS background estimation

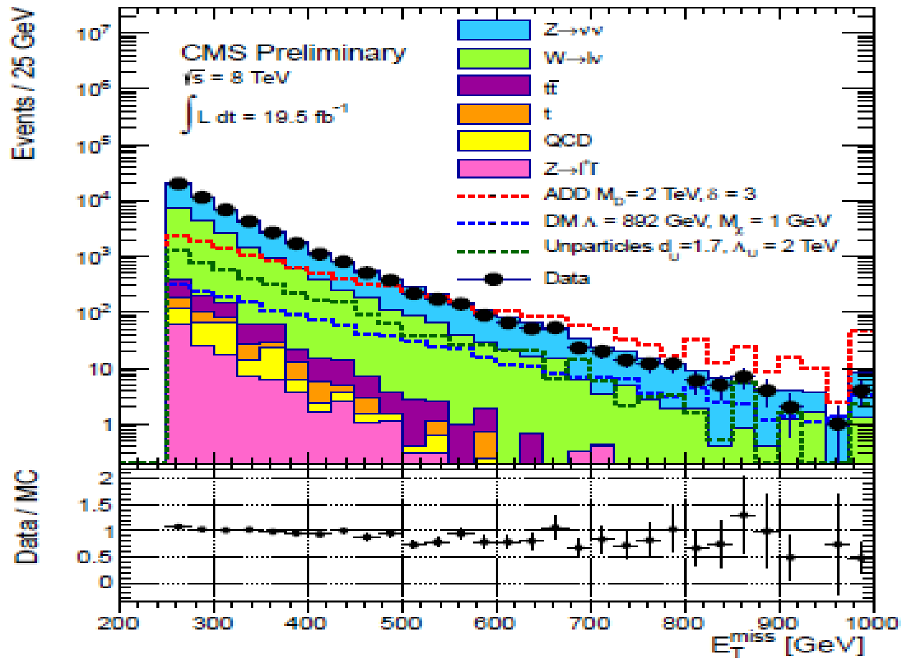
- $Z \rightarrow \nu\nu$ + jets (irreducible); $W \rightarrow \ell\nu$ + jets; $Z \rightarrow \ell\ell$ + jets. Normalised to data in W/Z enriched CR orthogonal to SR (i.e. defined inverting some selection cut) and then extrapolated bin-by-bin to the leading jet P_T and E^T_{MISS} distributions.
- Multijets: data driven from mis-reconstructed jets. CR dominated by events with 2 or 3 jets and $|\Delta\varphi(jet_{2/3}, E^T_{MISS})| < 0.5$.
- Non-collision background estimated from data
- tt and diboson production estimated from MC

Monojet searches: CMS/ ATLAS results

CMS: 7 SR: E^T_{MISS} (250, 300, 350, 400, 450, 500, 550 GeV)

ATLAS: 4 SR: Leading jet P_T & E^T_{MISS} (120, 220, 350, 500 GeV)





No New Physics signal seen →

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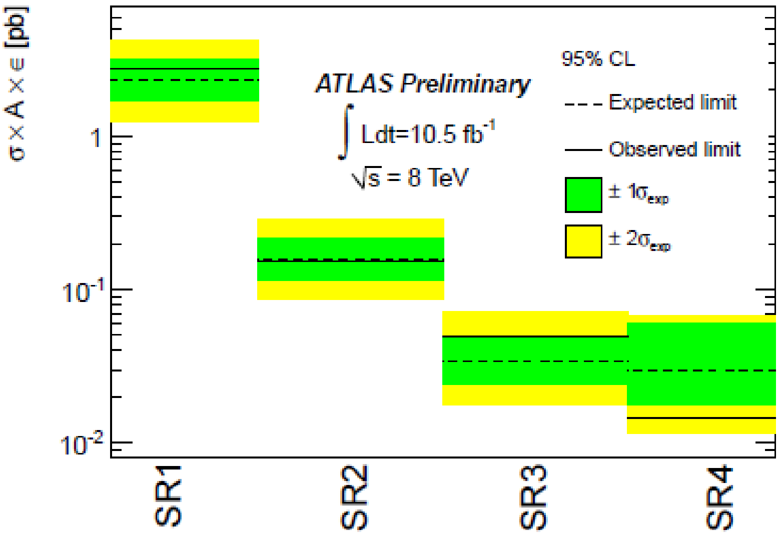
CMS-PAS-EXO-12-048

1) Set model-independent limits on σ·A·ε (ATLAS)

2) Use these limits to constrain specific models;

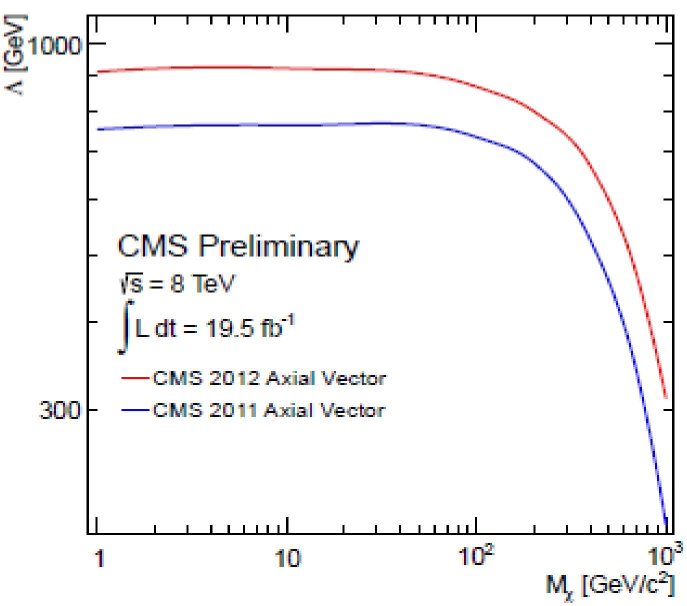
Monojet searches: Limits

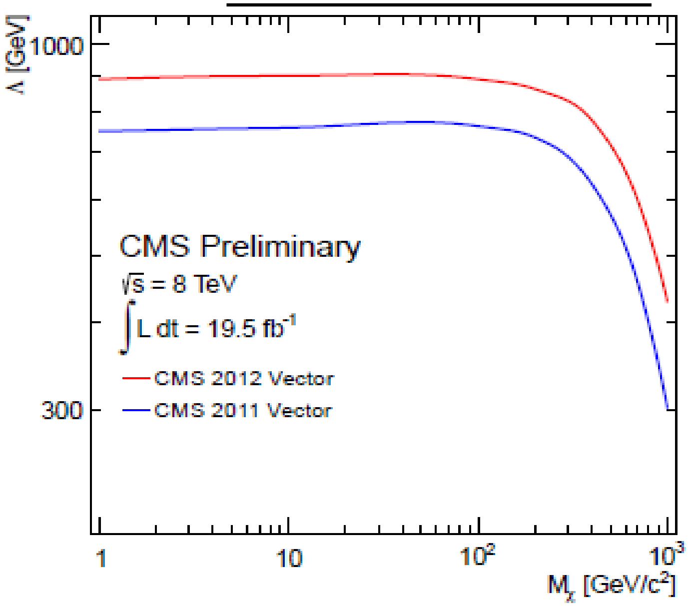


Model independent limit on σ·A·ε for the 4 SR

ATL-CONF-2012-147

CMS-PAS-EXO-12-048

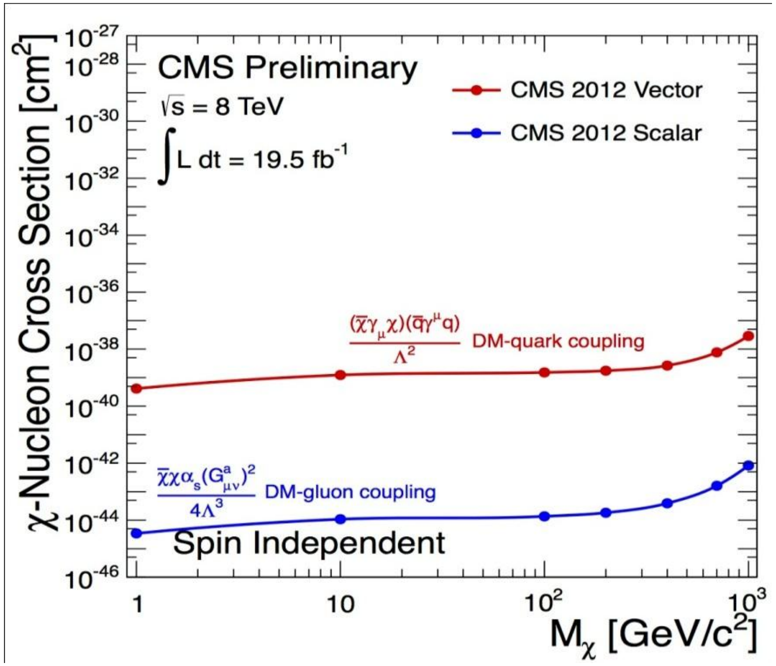


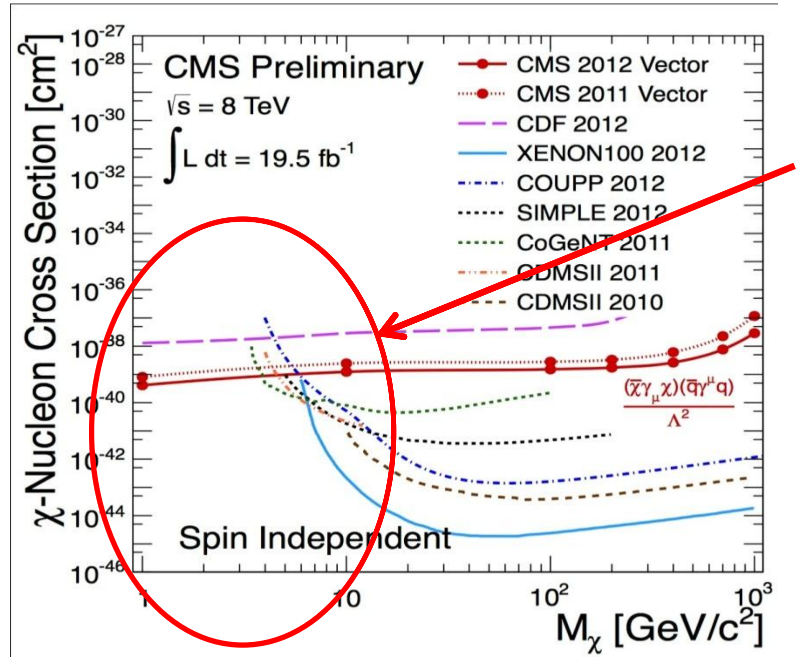


Evolution of the limits on the Vector D5 and Axial-Vector D8 operators

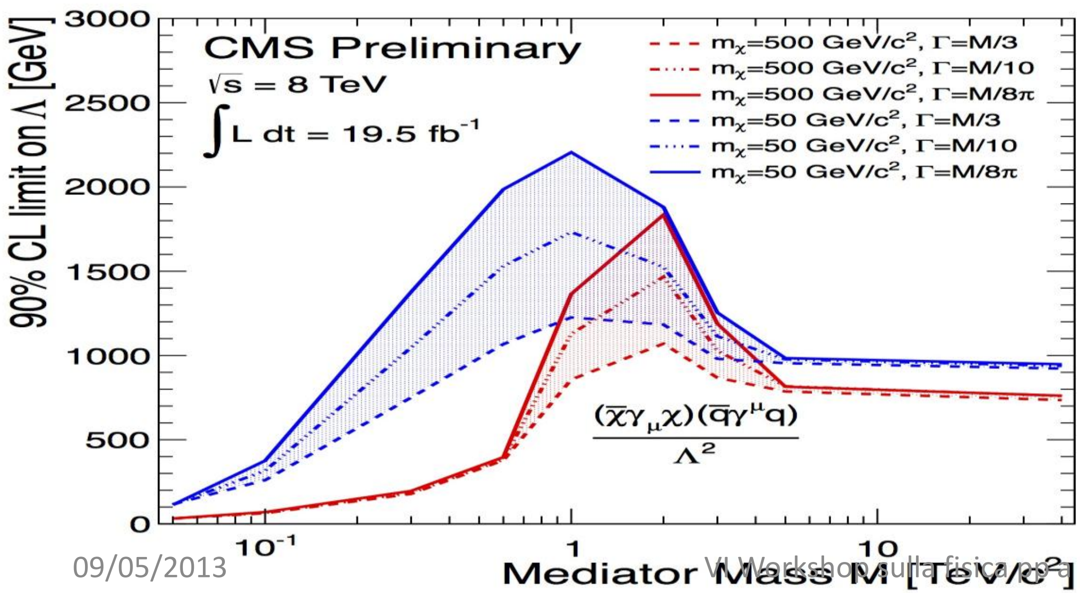
$$\Lambda = M_* = M/\sqrt{g_q g_\chi}$$

Monojet searches in CMS: Limits





Collider results drive the searches.

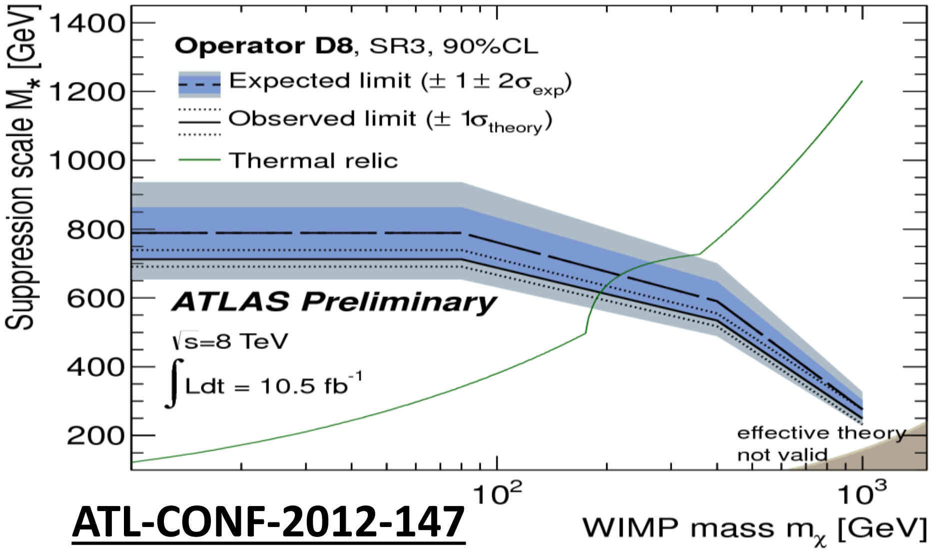


CMS-PAS-EXO-12-048

Observed limits on Λ as a function of the mass of the mediator (M), assuming vector interactions and a dark matter mass of 50 GeV (blue) and 500 GeV (red). The width of the mediator was varied between M/3, M/10 and M/8π.

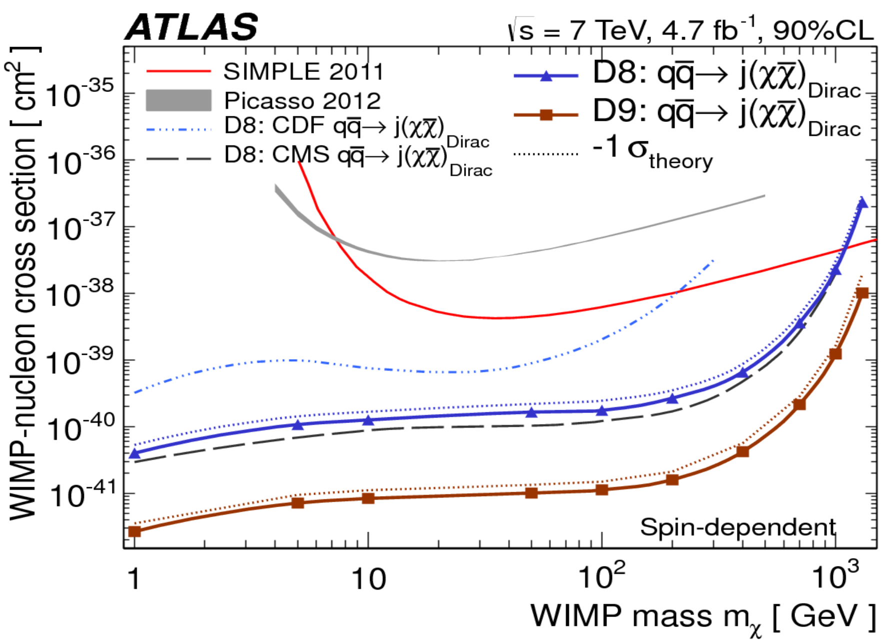
Limits on D-operators

$M_* = M/\sqrt{g_{q/g}g_\chi}$



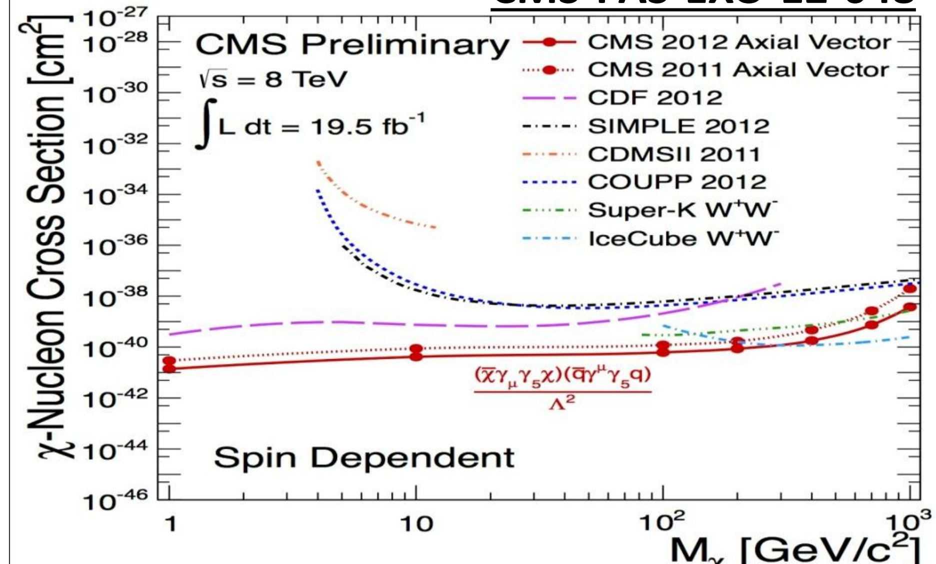
ATL-CONF-2012-147

	Vector	Axial-vector	Vector from gg
m_χ	D5	D8	D11
≤ 80	731 (704)	713 (687)	309 (301)
400	632 (608)	535 (515)	257 (250)
1000	349 (336)	250 (240)	155 (151)

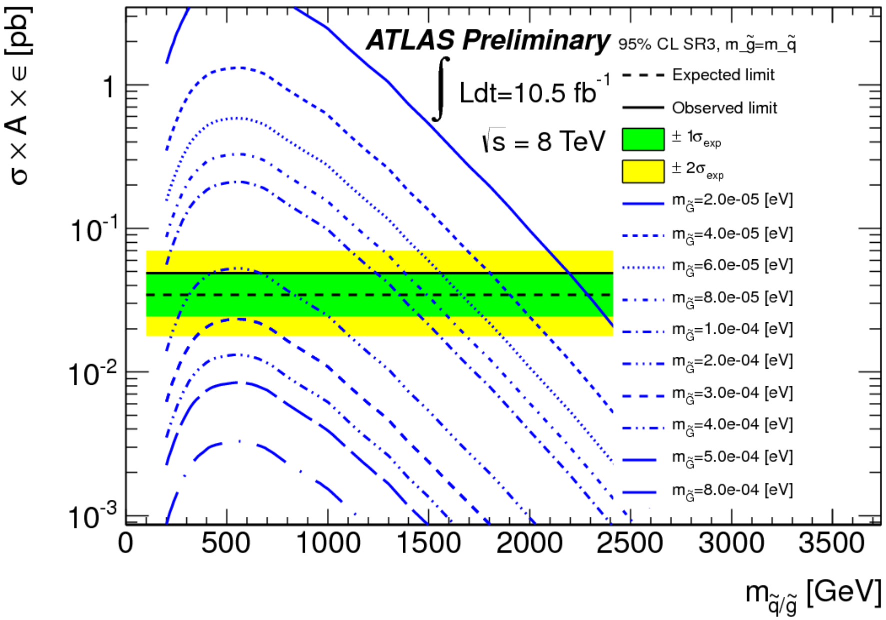


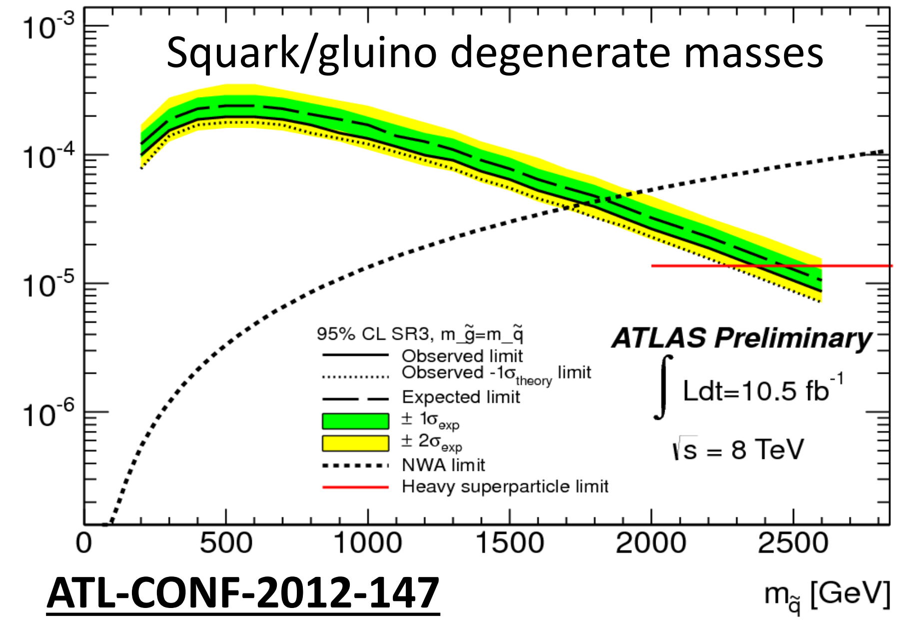
Similar sensitivity for equal luminosity

CMS-PAS-EXO-12-048



Limits on gravitino $\tilde{G}$ mass: ATLAS





ATL-CONF-2012-147

- 95% C.L. limits on σ·A·ε for the associated production of a gluino/squark in the simplified model with a decay chain $\tilde{g}/\tilde{q}$→g/q$\tilde{G}$.
- Limits set using the SR3 with the leading jet P_T & E^T_{MISS} >350 GeV
- Squarks/gluino masses considered up to 2.6 TeV
- Several benchmarks used in terms of $\tilde{g}/\tilde{q}$ masses ratio: degenerate, 2, 4, 1/2, ¼
- Degenerate case: m($\tilde{G}$)<10^{-4}($4\cdot10^{-5}$) eV excluded for 500(1700)GeV $\tilde{g}/\tilde{q}$ mass. For high $\tilde{g}/\tilde{q}$ masses, the NWA used fails (widht/mass ratio larger than 25%)
- For non-degenerate cases, limit ranges between $3\cdot10^{-4}$ eV and $3\cdot10^{-5}$ eV.

Mono-γ searches

- Final state: one high-P_T photon from ISR radiation and high E^T_{MISS}. **ATLAS** **arXiv: 1209.4625** Phys. Rev. Lett 110, 011802 (2013)
- 4.7 fb^{-1} @ 7 TeV **CMS** **arXiv:1204.0821** Phys. Rev. Lett. 108 (2012) 261803
- **Event selection ATLAS (CMS):**
  - E^T_{MISS} trigger with 70 GeV threshold (98% efficiency for E^T_{MISS} > 150 GeV); CMS uses high- P_T photon trigger;
  - 1 high-P_T isolated photon (P_T>120(145)GeV, |η|<2.37 (1.44))
  - At most 1 jet with P_T > 30 (40) GeV , |η| < 4.5;

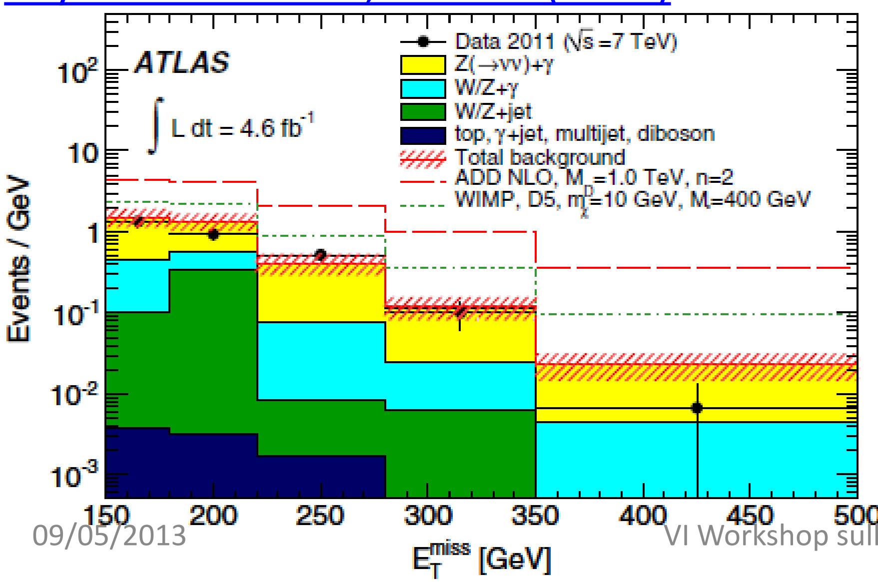
  CMS adds ΔR > 0.5 from the photon direction
  - E^T_{MISS} > 150 (130)GeV, |Δφ(jet$_2$, E^T_{MISS})|>0.4 (suppress dijet events)
  - No *medium* electrons with P_T >20 GeV, |η| < 2.47
  - No *combined* muons with P_T > 7GeV, |η|< 2.5

Mono-γ searches: ATLAS Results

- Dominated by statistical uncertainties (13%) in the CR ;
- Systematic uncertainties (energy scale, photon ID, parton shower, etc..) 7%
- Data compatible with SM predictions

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

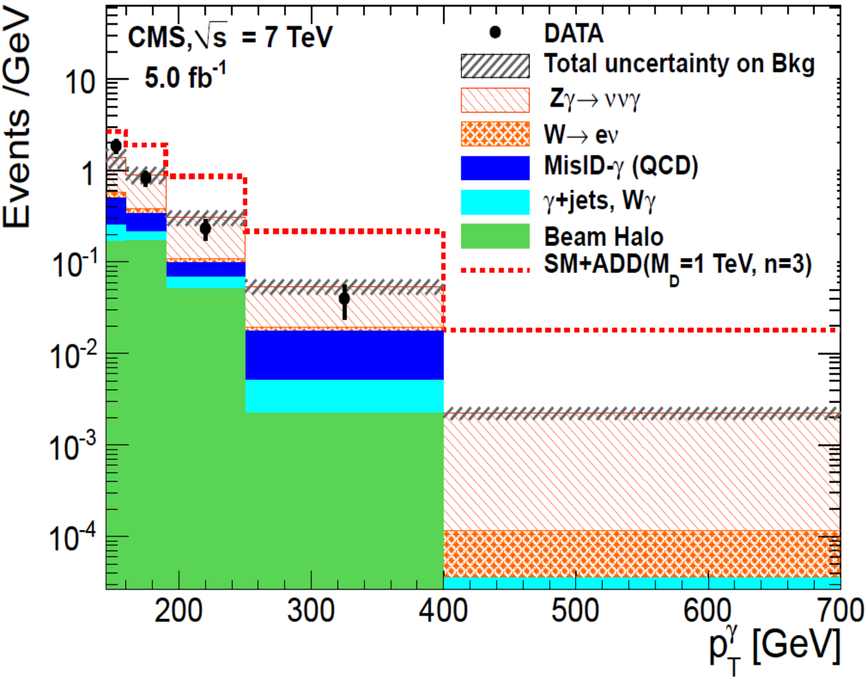
Phys. Rev. Lett 110, 011802 (2013)



- Model-independent limits on σ·A·ε: above **5.6 (6.8) fb** excluded at **90 (95)% C.L.**
- Use these limits to constrain specific models;

Mono-γ searches: CMS Results

Phys. Rev. Lett. 108 (2012) 261803

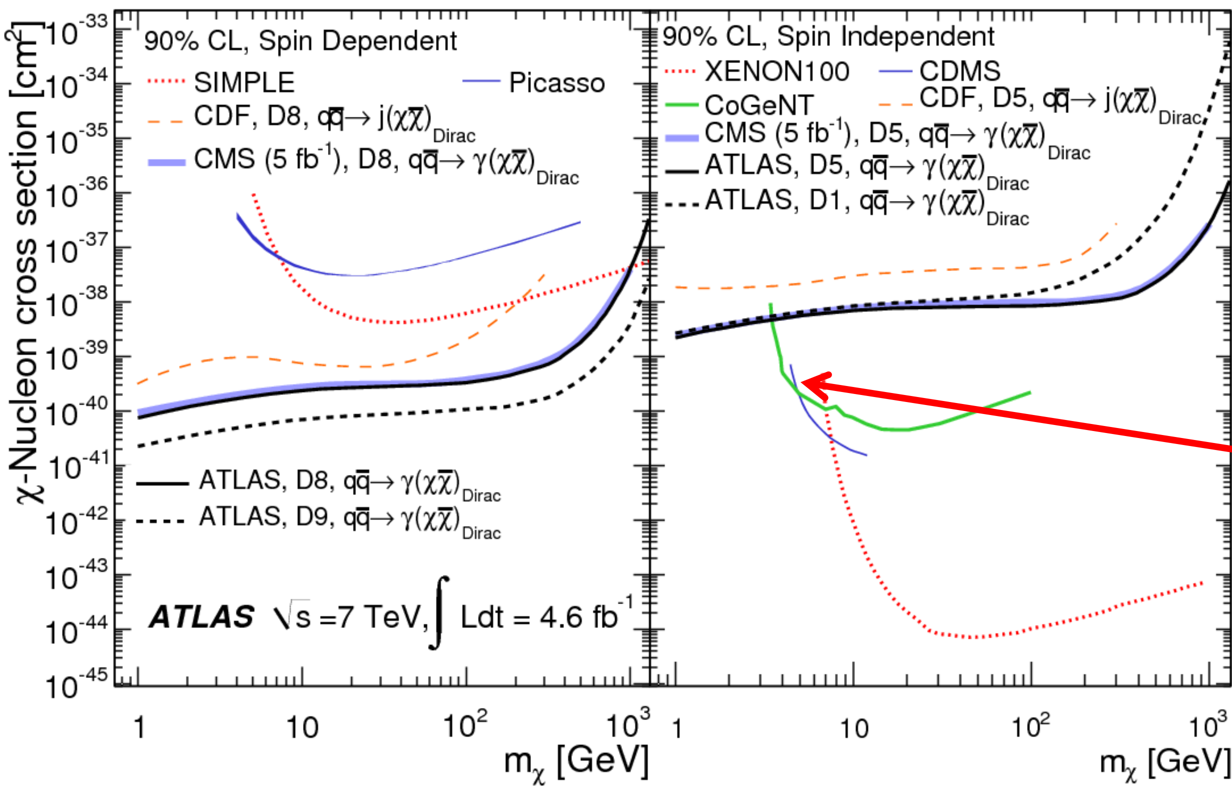


- Non collision background: 11.1 ± 5.6
- E → gamma misid: 3.5 ± 1.5
- Jet → gamma misid: 11.2 ± 2.8
- EWK bosons:
  - Zgamma: 45.3 ± 6.9
  - Wgamma,gamma+jet: 4.1 ± 1.0
- Total exp. background: 75.1 ± 9.5
- Total observed data: 73

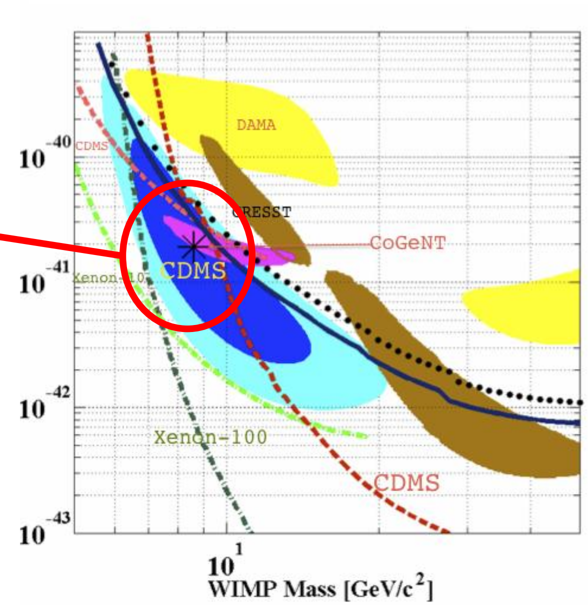
Mono-γ searches: ATLAS/CMS limits

- Limits on pair-production WIMP x-sec for D-operators
- Limits on σ·A·ε translated also in nucleon-WIMP x-sec limits to allow comparison with direct-detection experiments

ATLAS: [Phys. Rev. Lett. 110 ,011802 (2013)] **CMS:** [Phys. Rev. Lett. 108 (2012) 261803]

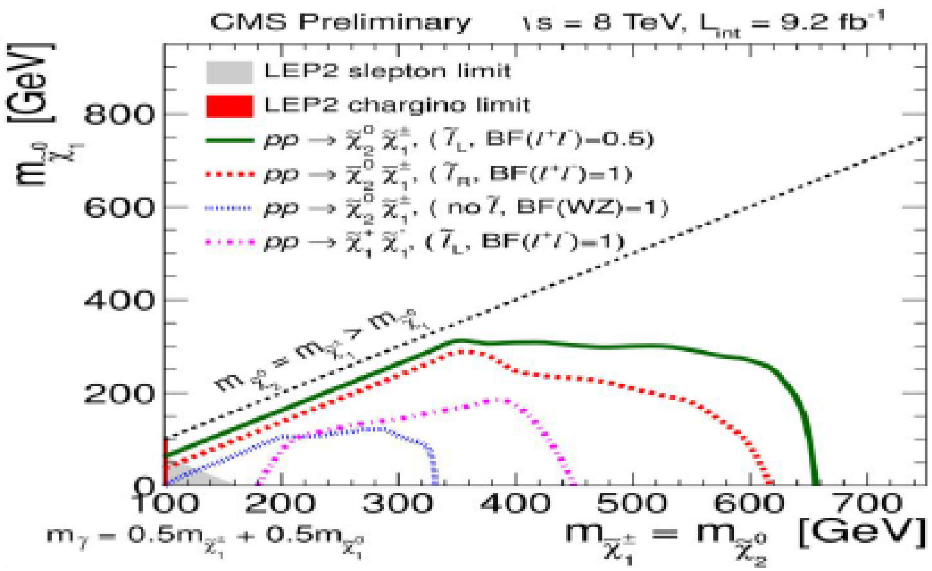


No enough sensitivity to confirm the CDMSII/DAMA/COGENT excess at ~10 GeV

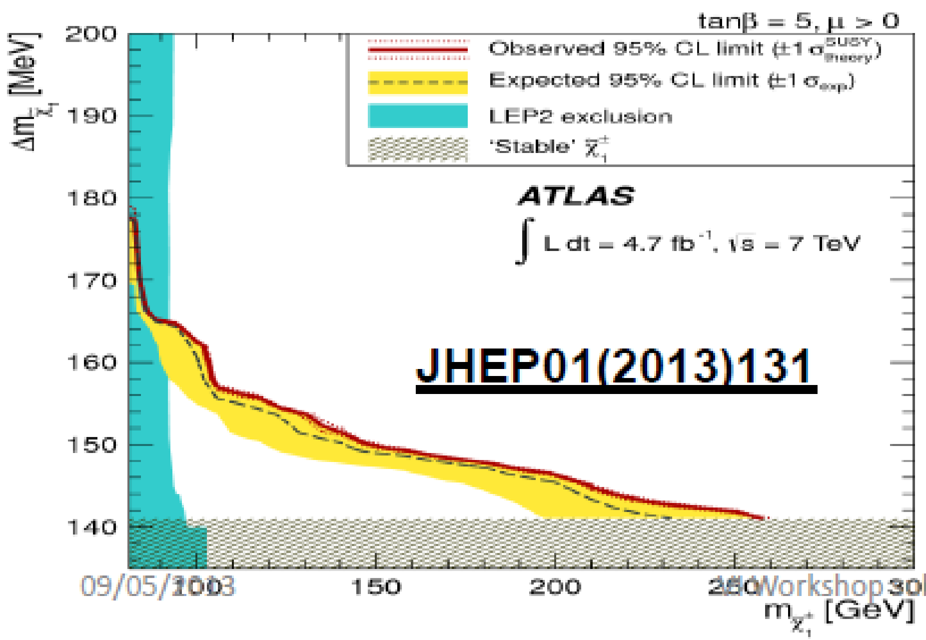


…and don't forget what SUSY can tell us

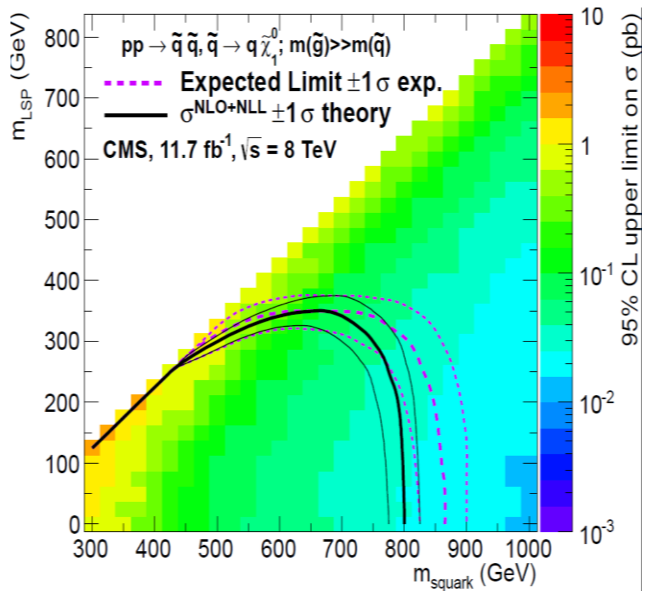
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

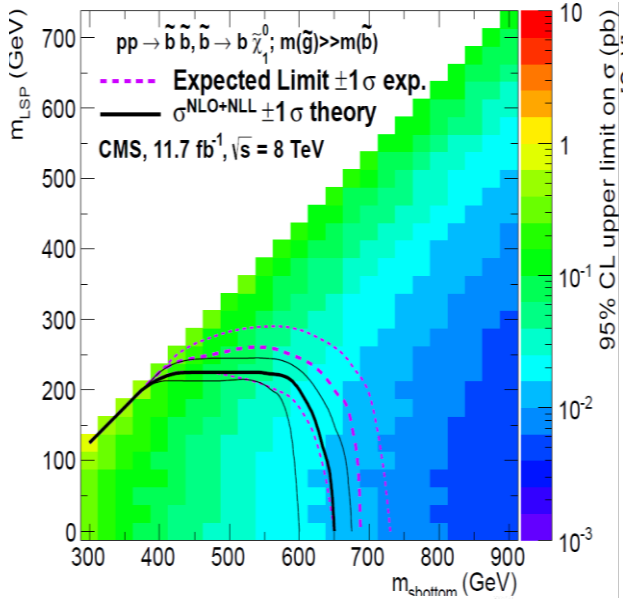


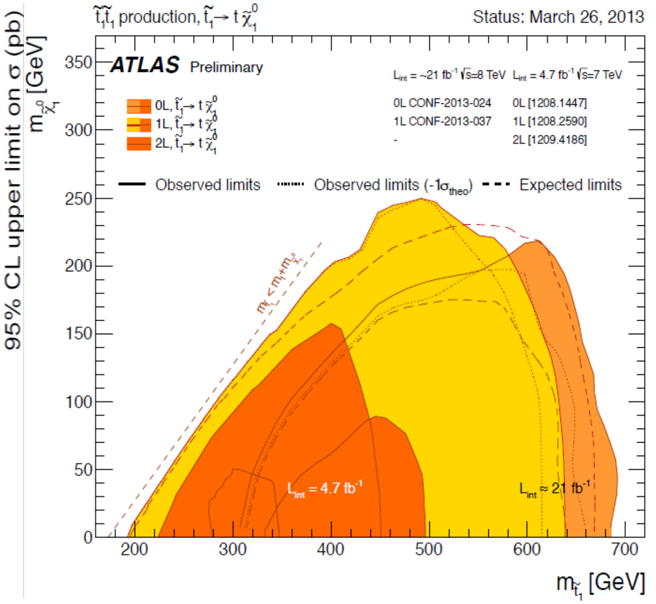
- Direct production of EWK-inos decaying to LSP via slepton, W, Z
- Final state with 3 leptons + E^{T}_{MISS}
- Limit in the $\chi^{\pm}{}_{1} = \chi^{0}{}_{2}$ case

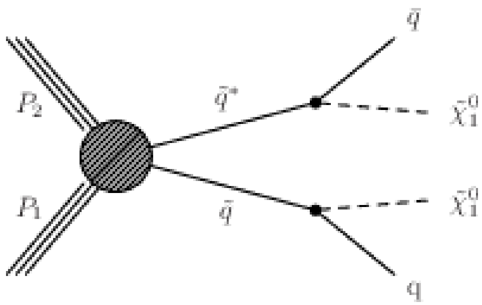


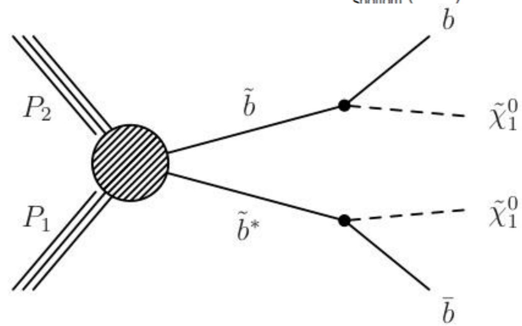
- **AMSB model**. $\Delta m = m(\chi^{\pm}) - m(\chi^{0})$~150-200 MeV→ Production of $\chi^{\pm}$, decay in χ_0 $\pi^{\pm}$ after few cm in the tracking system
- Final state: high P_T jet + E^{T}_{MISS} + high-P_T disappearing track.
- Exclusion of the most probable values of $m(\chi^{\pm})$ and Δm, but still interesting signature (it explains FERMI/PAMELA excesses)

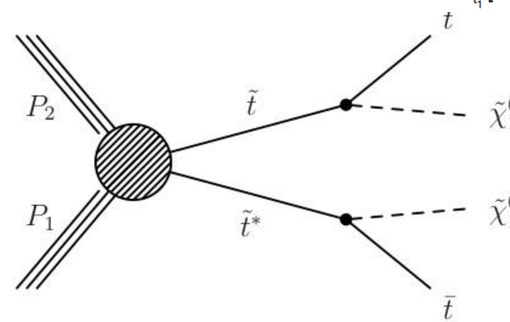










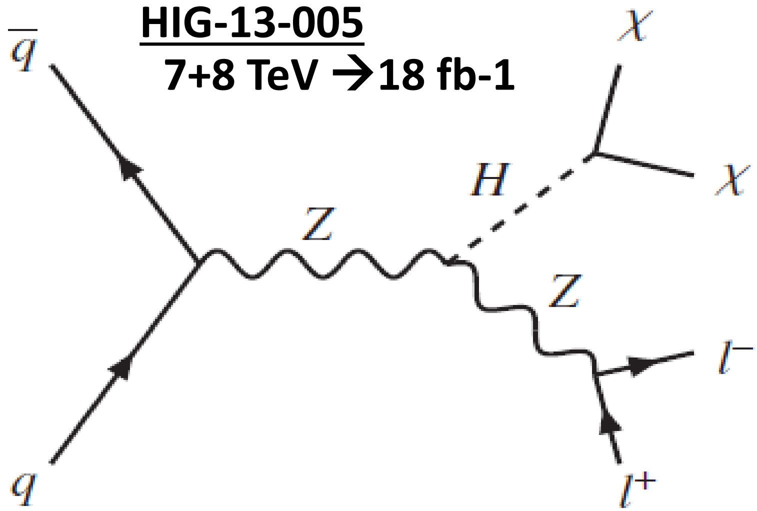


CMS-PAS-SUS-12-028
arXiv:1303.2985

arxiv:1208.1447 (0-lepton 7 TeV); arxiv:1208.2590 (1-lepton 7 TeV)
arxiv:1209.4186 (2-lepton 7 TeV); ATLAS-CONF-2013-037 (1-lepton 8 TeV, 21 fb^{-1});
ATLAS-CONF-2013-024 (0-lepton 8 TeV, 21 fb^{-1})

- Exclusion of DM candidate can be seen in terms of its production in association with specific (top, bottom, light quarks) SM particle
- Limits on the x-sec, for given LSP and NLSP masses, useful to test various models with the same signature.

The newcomer: H→invisible



ATL-CONF-2013-011
HIG-13-005
7+8 TeV →18 fb-1

- GOAL: find enhancements to the invisible Higgs decays due to BSM physics (DM for example…)
- Associated production with a Z→leptons assuming ZH SM coupling.
- H→ZZ→4ν contribution negligible, but used to simulate the signature with BR=100%.

Experimental signature: large E^T_{MISS}+2 high-P_T leptons (e,μ) in the final state

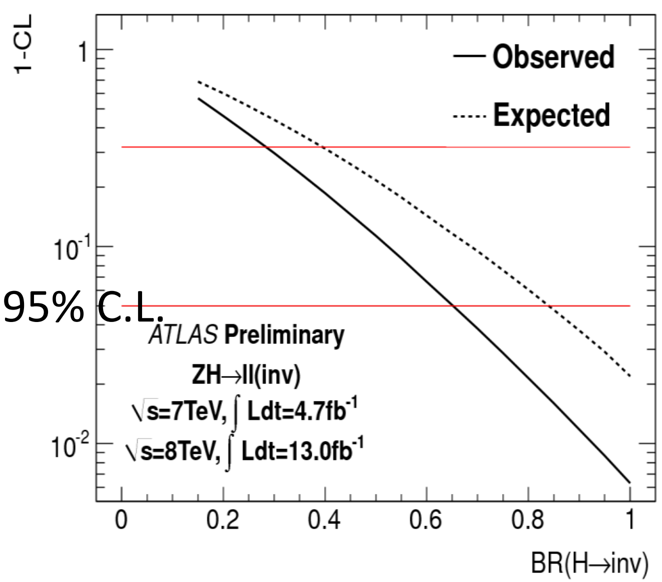
- Trigger: combination of single and dilepton triggers;
- P_T (e,μ) > 20 GeV; Isolation in ΔR=0.2 cone at 0.1*E(P_T)
- 2 OS leptons with $|m(\ell\ell)-m(Z)| < 15$ GeV; Veto 3rd lepton $P_T > 7$ GeV;
- No jets with $P_T > 20$ GeV, $|\eta|<2.5$;
- $E^T_{MISS} > 90$ GeV; $\Delta\phi(E^T_{MISS}, \vec{P}^T_{MISS}) < 0.2$ suppress fake E^T_{MISS}
- $\Delta\phi(E^T_{MISS}, Z) > 2.6$ since the Higgs is supposed to recoil against the Z
- $\Delta\phi(\ell\ell)<1.7$ (boosted Z) and $|E^T_{MISS} - P_T(\ell\ell)|/P_T(\ell\ell) < 0.2$ (H/Z P_T balance)

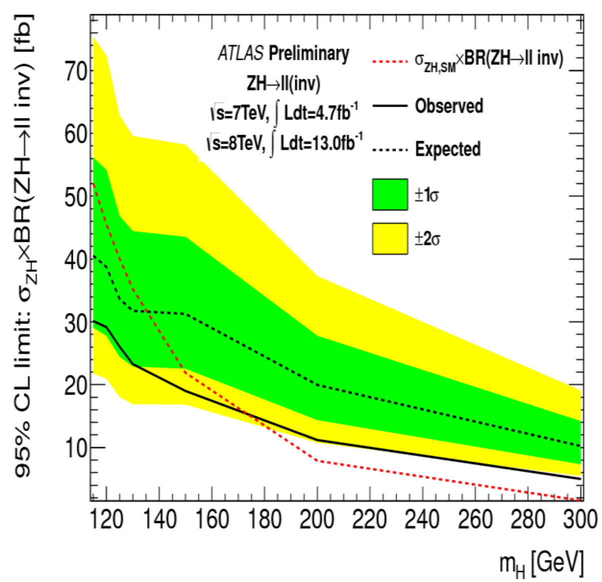
The newcomer: H→invisible

ATL-CONF-2013-011
HIG-13-005

Main backgrounds:

- ZZ→$\ell\ell\nu\nu$ (irreducible, 70%); WZ→ $\ell\nu\ell\ell$ (1 lepton lost, 20%) are normalised to NLO x-sec, estimated in MC, validated in CR;
- WW→ $\ell\nu\ell\nu$ (5%), tt (2%), Wt, Z→ττ estimated in eμ CR (w/o E^T_{MISS} cut) and then extrapolated to ee, μμ SR considering different e/μ efficiencies;
- Z→$\ell\ell$ incl.: ABCD method between ($\Delta\phi(E^T_{MISS}, \vec{P}^T_{MISS})$ and $|E^T_{MISS}-P_T(ll)|/P_T(ll)$;
- W+jets/mulitjets: Matrix Method generalised to the dilepton case





- Assuming m(H)=125 GeV and ZH SM coupling a **BR larger than 65%** H→ inv. is excluded at 95% C.L. (left)
- Limits on σ(ZH)xBR(inv.) for m(H) up to 300 GeV.
- CMS sets a 95% C.L. limit on BR of 65% using all the BRs of the Higgs in the other decay channels.

Conclusions

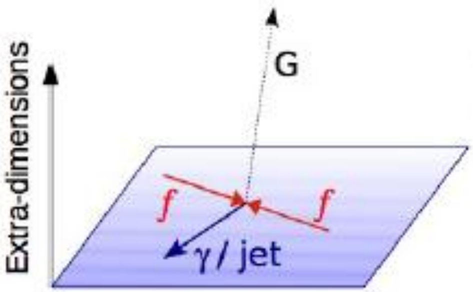
- Dark Matter searches at LHC have been presented for both CMS & ATLAS experiments
- Analysis strategies are similar and results comparable
- Main channels: monojet/monophoton + MET
- First results on Higgs to invisible from ATLAS, but also CMS has the analysis in the pipeline
- Other searches: mono-W/Z ongoing for both experiments
- No evidence of DM production, only limits on cross-section and/or WIMP mass
- Collider searches competitive with direct/indirect DM searches in the 1-10 GeV WIMP mass range for the spin-independent case while are globally more sensitive for spin-dependent case

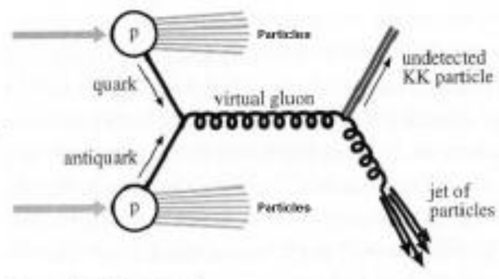
BACKUP

Motivations

Large extra dimensions

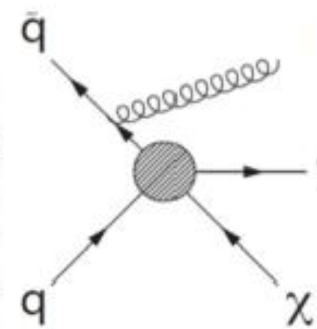
Graviton propagates into extra dimensions





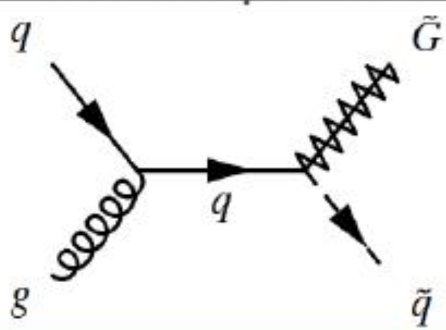
Arkani-Hamed, Dimopoulos, Dvali (ADD)

Dark Matter production

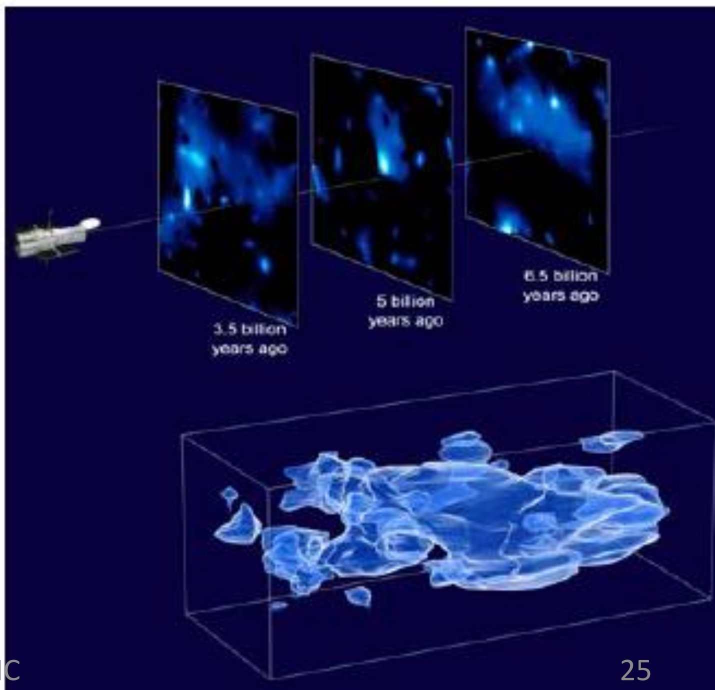


Production of undetected new particles and ISR

Light Gravitino production



- Sensitivity to a large number of models
- Well understood background from electro-weak processes Z/W+jet/photon



Backgrounds estimation: ATLAS

- W/Z + γ (85%): Normalisation derived for both simultaneously in a CR obtained inverting the muon veto cut.
- W/Z + e/jet faking a γ (13%): measured in data for Z→ee events where an electron is reconstructed as a photon. Fake prob. used also for W→eν + jets in SR
- Multijets and γ+jets(1%): data driven from mis-reconstructed jets. CR defined asking at least 1 jet with $P_T > 30$ GeV and $|\Delta\varphi(\text{jet}, E^T_{MISS})| < 0.4$. Then extrapolated linearly to the $P_T < 30$ GeV region.
- Non-collision backgrounds negligible
- tt, single top, WW, WZ, ZZ estimated from MC

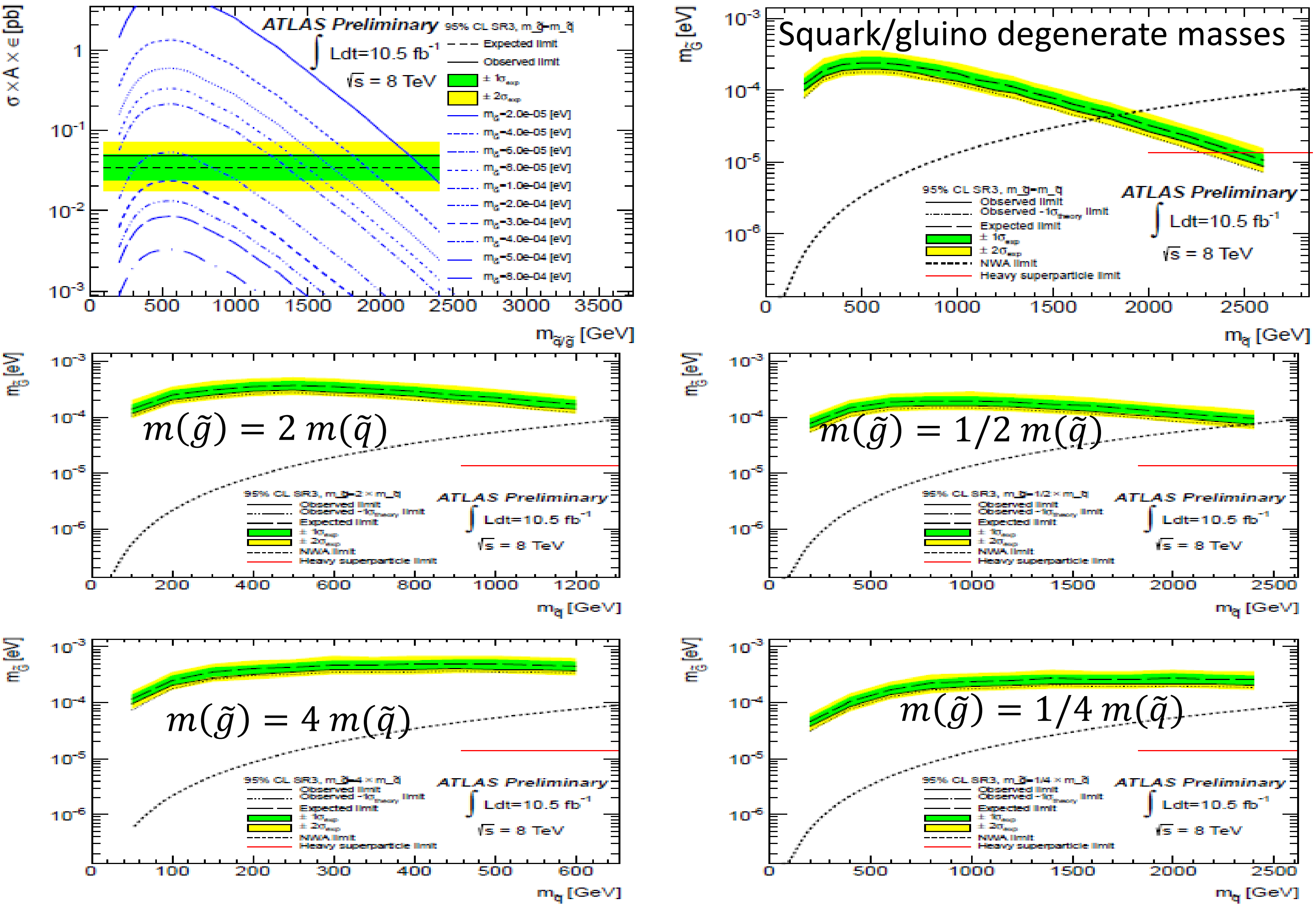
Backgrounds estimation: CMS

- Jet faking a photon background (15%) measured using fake rate method, estimating, from an EM-enriched QCD sample, the probability for an event that passes looser photon ID criteria to pass also the signal ones. Contribution from single photon events is estimated in an independent QCD sample and then subtracted.
- Electron faking a photon background (5%) estimated using $W \rightarrow e\nu$ (correcting for pixel-matching efficiency).
- Out-of-time, cosmic-ray μ and beam halo backgrounds (15%) estimated from data. μ from beam halo dominant contribution.
- Other backgrounds (67%): $Z \rightarrow \nu\nu+\gamma$, $W\gamma \rightarrow l\nu\gamma$, γ+jet and diphoton events simulated from MC.

Other searches

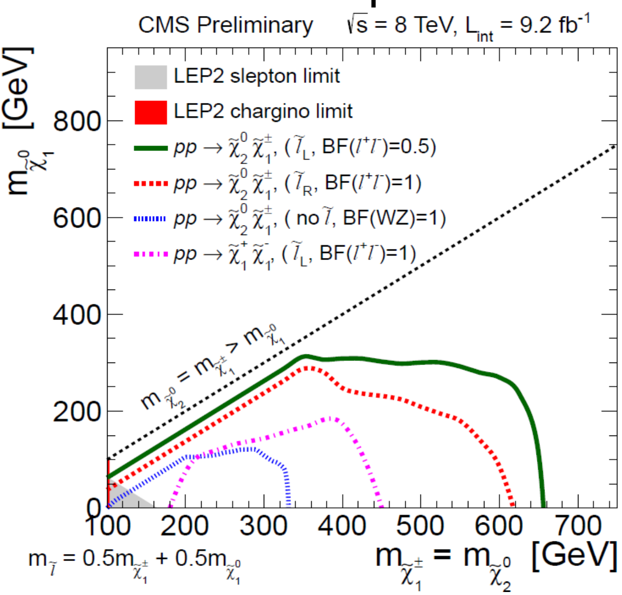
- Mono-W/Z efforts just started. Nothing public yet
- Higgs to invisible. Ongoing efforts in two directions:
  - Monojet results can constraint the H→inv. BR;
  - Connection with the so-called «Higgs-portal» model, where Higgs couples to DM candidates http://arxiv.org/pdf/1205.3169v2.pdf
  - W/ZH associated production with H→inv. and its relationship with direct detection experiments

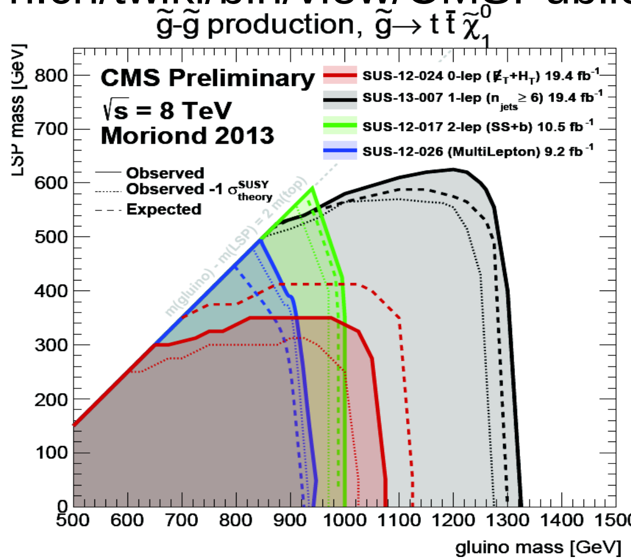
Limits on gravitino mass: ATLAS

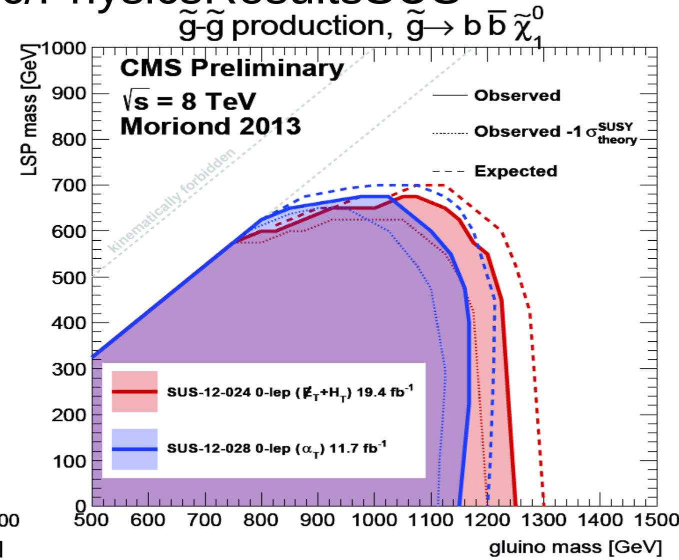


....and don’t forget SUSY searches

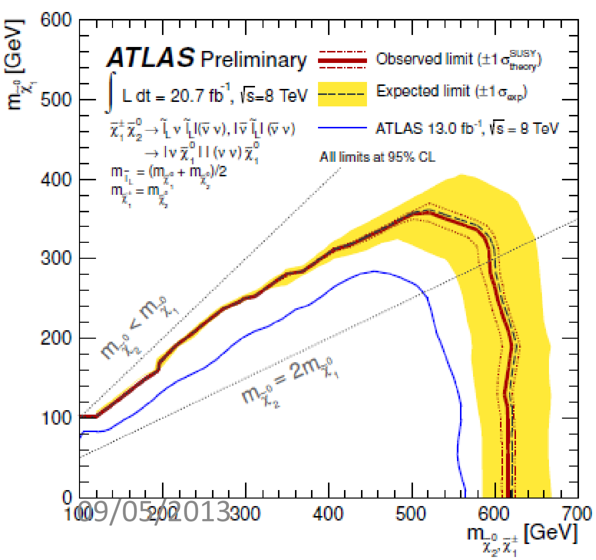
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

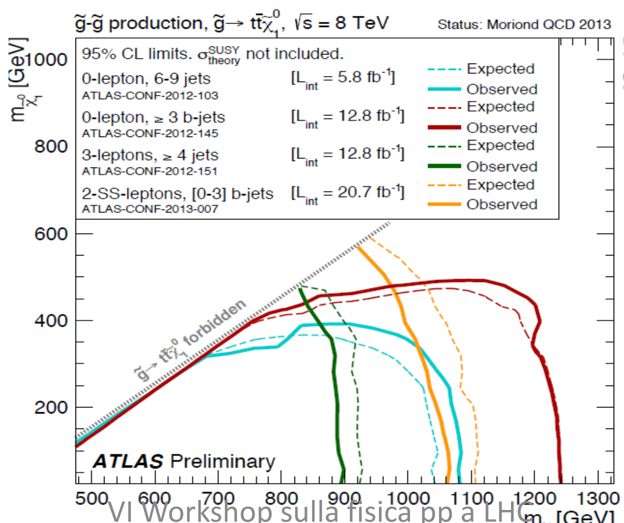


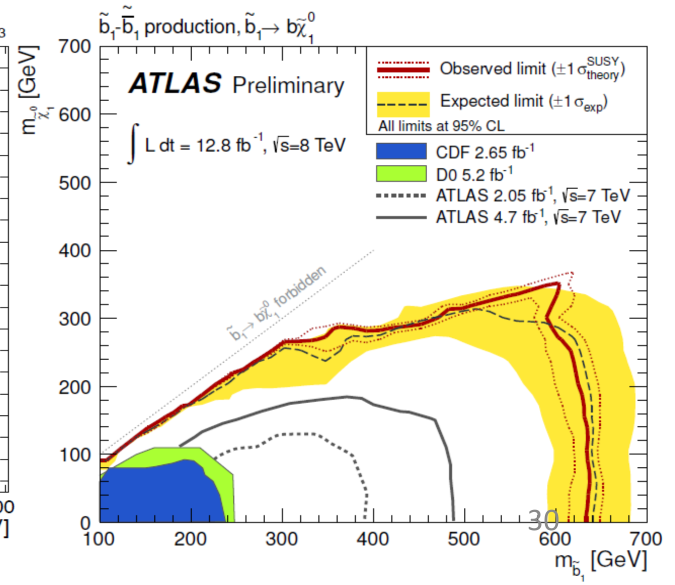




ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

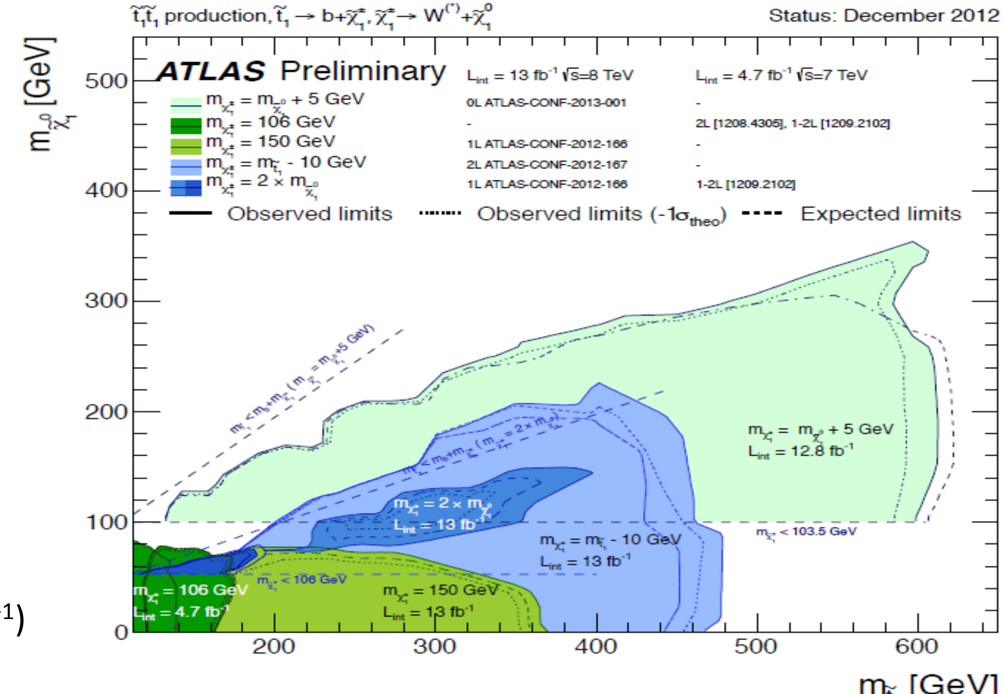


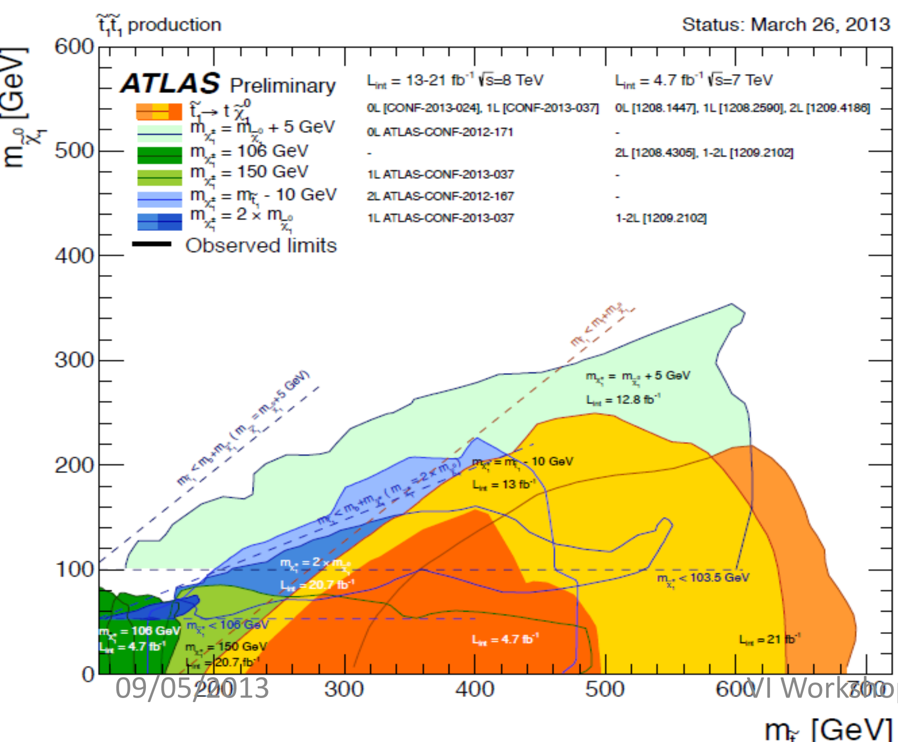


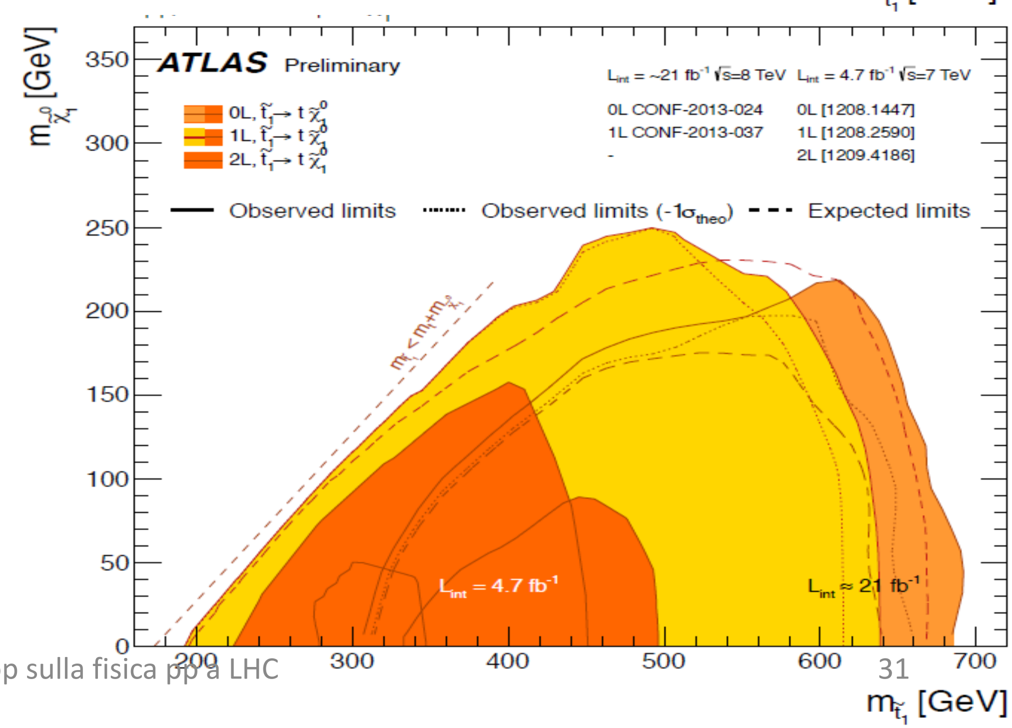


ATLAS LIMITS ON THE $\tilde{t} - \tilde{\chi}$ PLANE

[1] arxiv:1208.1447 (0-lepton 7 TeV)
[2] arxiv:1208.2590 (1-lepton 7 TeV)
[3] arxiv:1209.4186 (2-lepton 7 TeV)
[4] ATLAS-CONF-2013-037 (1-lepton 8 TeV, 21 fb^{-1})
[5] ATLAS-CONF-2013-024 (0-lepton 8 TeV, 21 fb^{-1})
[6] arxiv:1208.4305 (very light stop: 2-lepton 7 TeV)
[7] arxiv:1209.2102 (light stop: 1/2-lepton, bjets 7 TeV)
[8] ATLAS-CONF-2012-167 (2-lepton 8 TeV, 13 fb^{-1})
[9] ATLAS-CONF-2013-001 (0-lepton, bb+MET 8 TeV, 13 fb^{-1})



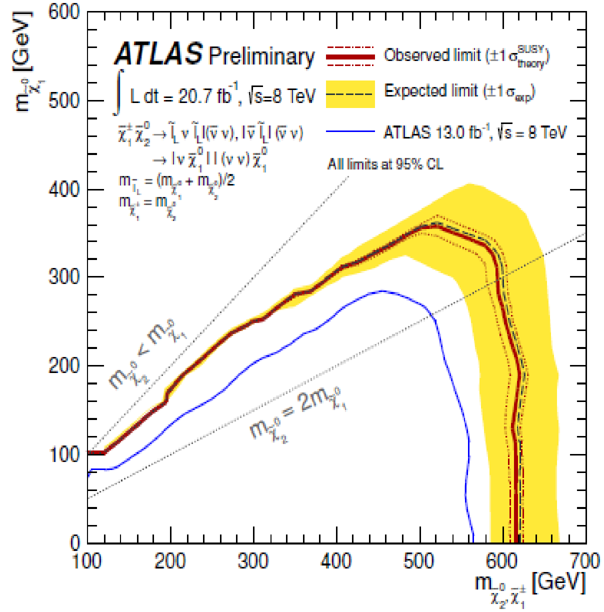




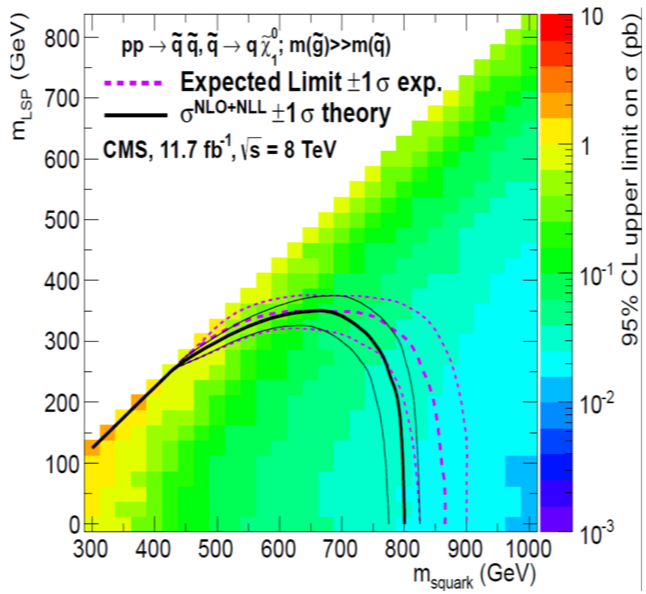
….and don't forget SUSY searches

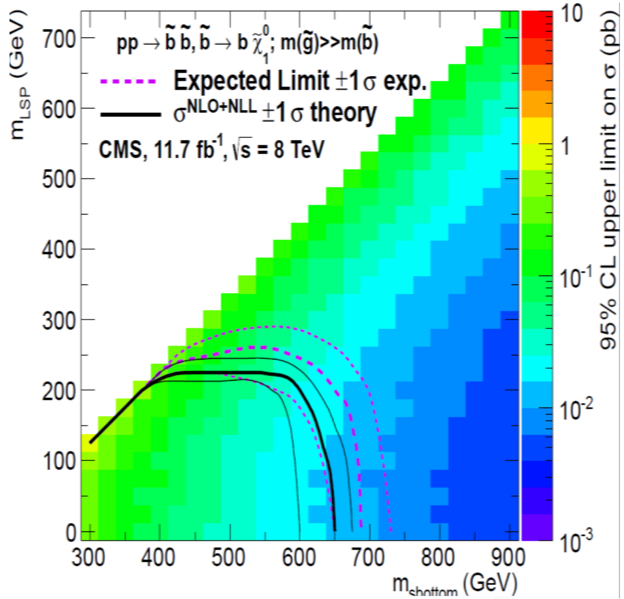
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

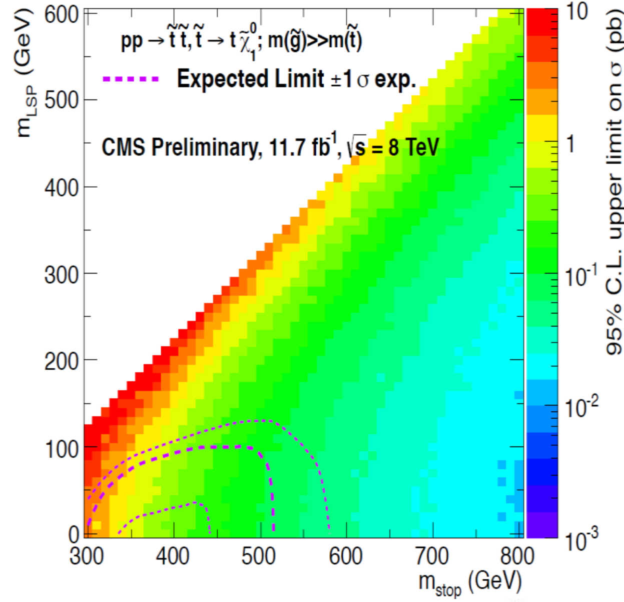
ATLAS-CONF-2013-035

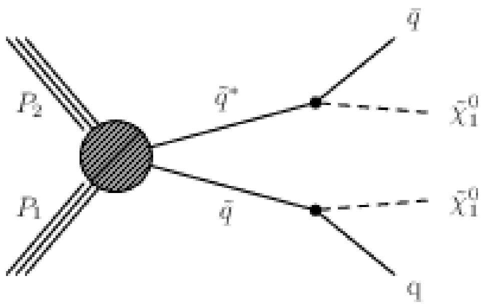


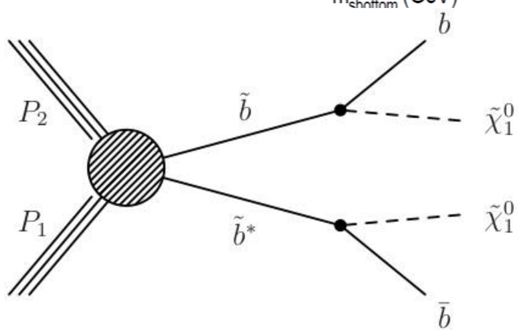
- Direct production of EWK-inos decaying to LSP via slepton, W, Z
- Final state with 3 leptons + E^{T}_{MISS}
- Possible interplay with DM models that foresee EWK doublet(s) to explain DM (even if the mass gap between EWK-inos and LSP is big)

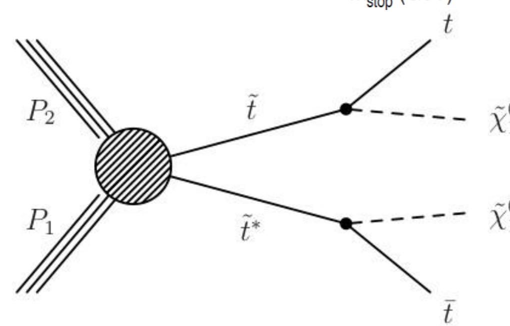










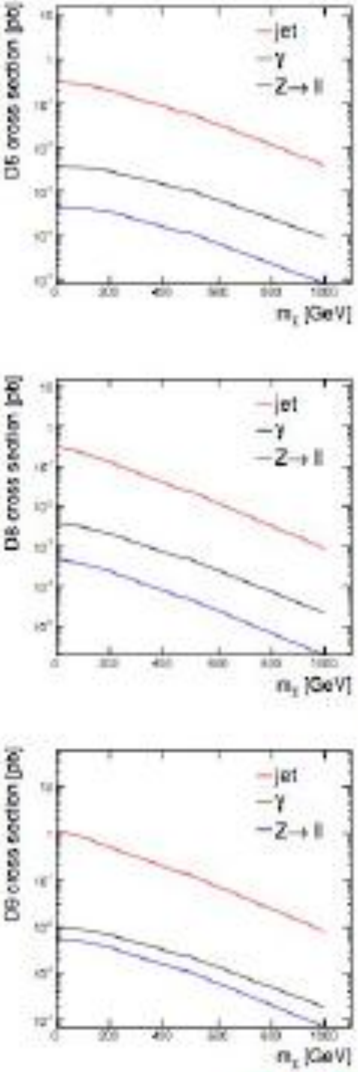


CMS-PAS-SUS-12-028
arXiv:1303.2985

- As an example, fully hadronic final state searches (here in the gluino-decoupled scenario).
- Exclusion of DM candidate can be seen in terms of its production in association with specific SM particle

ATLAS/CMS combination

arXiv:1302.3619v1

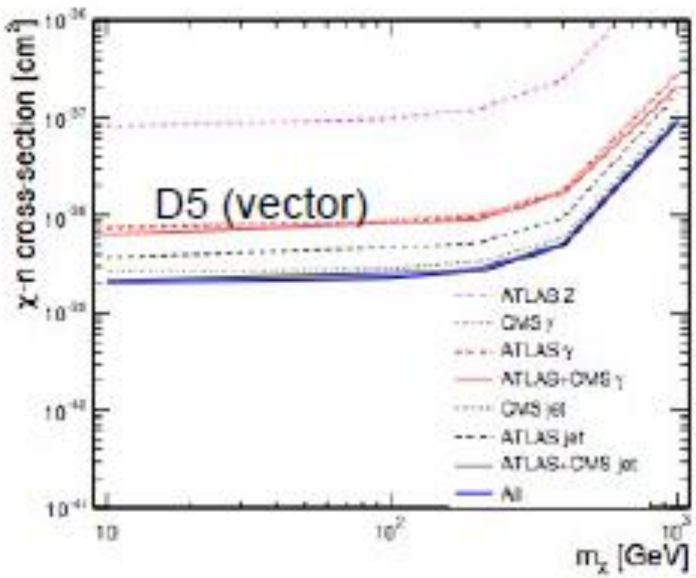


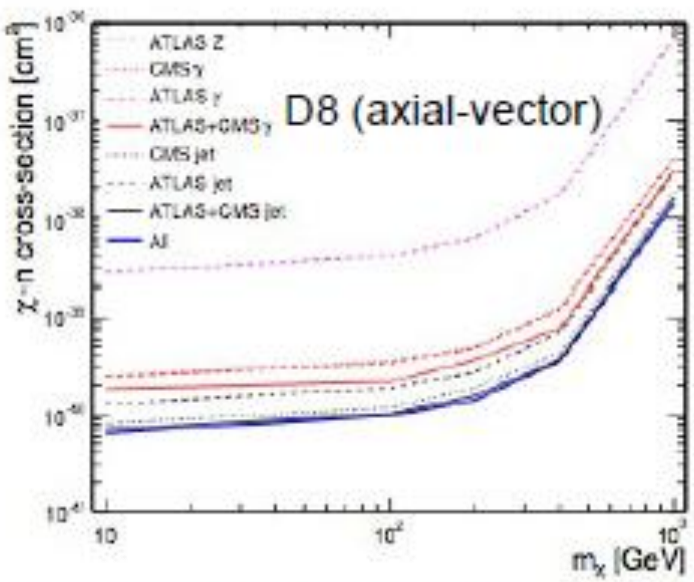
Mono-everything: combined limits on dark matter production at colliders from multiple final states

Ning Zhou,[1] David Berge,[2] and Daniel Whiteson[1]

[1] Department of Physics and Astronomy, University of California, Irvine, CA 92697
[2] GRAPPA Institute, University of Amsterdam, Netherlands

Searches for dark matter production at particle colliders are complementary to direct-detection and indirect-detection experiments, and especially powerful for small masses, $m_\chi < 100$ GeV. An important collider dark matter signature is due to the production of a pair of these invisible particles with the initial-state radiation of a standard model particle. Currently, collider searches use individual and nearly orthogonal final states to search for initial-state jets, photons or massive gauge bosons. We combine these results across final states and across experiments to give the strongest current collider-based limits in the context of effective field theories, and map these to limits on dark matter interactions with nuclei and to dark matter self-annihilation.





The combination is dominated by the mono-jet channel

16

The newcomer: H→invisible

- CMS limit on H→ inv. Assuming SM width and combining the measurements in all the channels, a limit on BR to invisible at 95% C.L. is derived.
- Similar performance as ATLAS, but uses the full 2012 statistics.

HIG-13-005