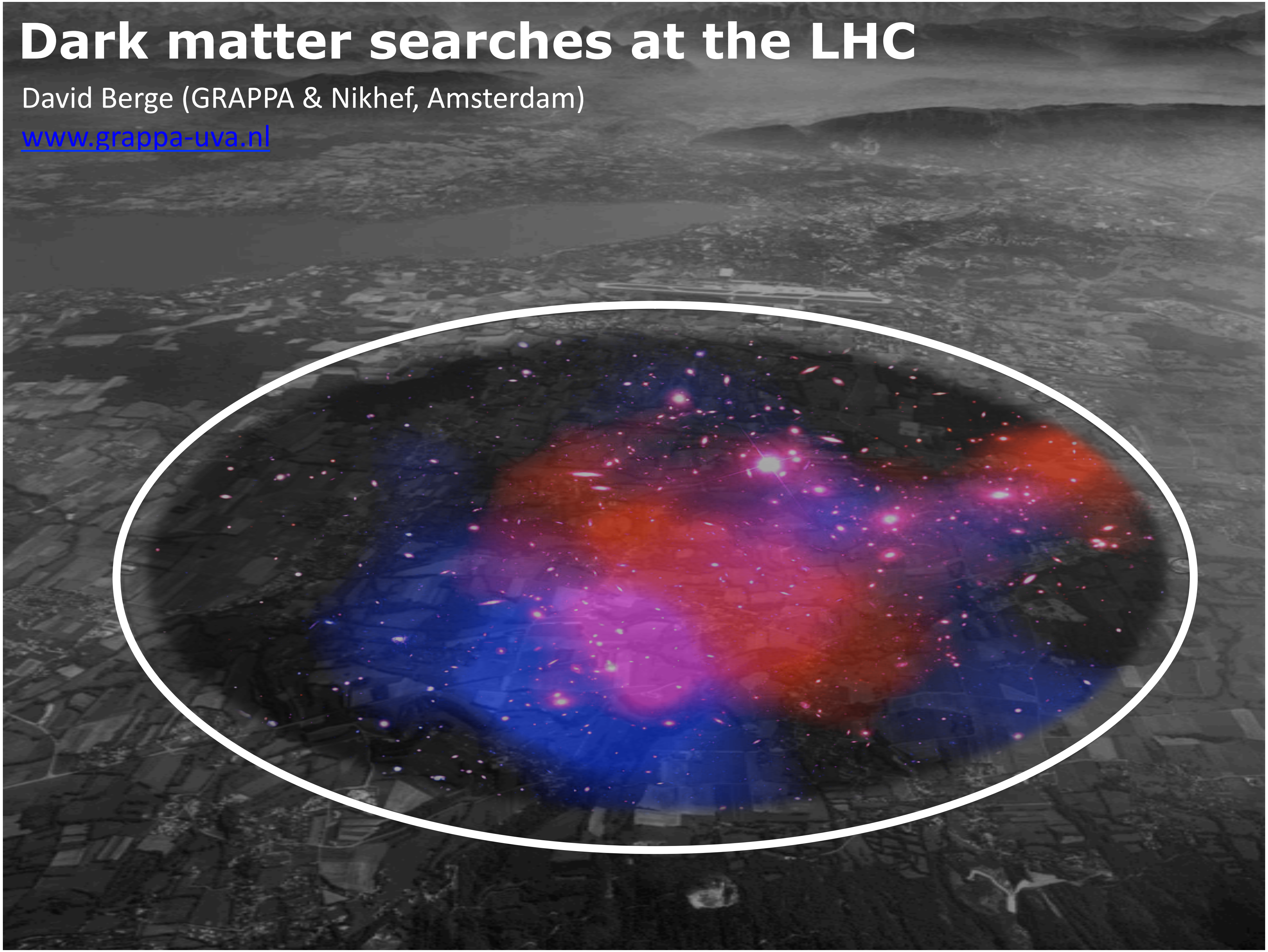
Dark matter searches at the LHC

David Berge (GRAPPA & Nikhef, Amsterdam)

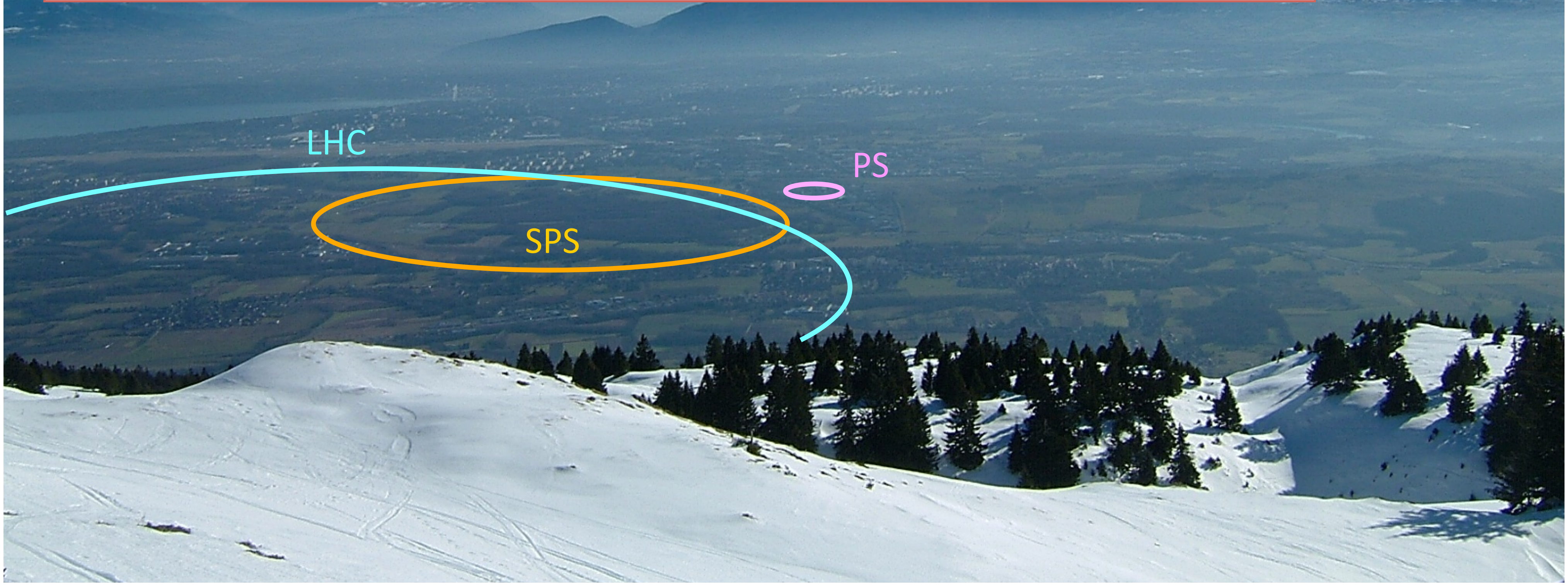
www.grappa-uva.nl



Two general-purpose experiments: ATLAS & CMS

The Large Hadron Collider

	2012 performance	2015 likely performance
Colliding bunches	1331	2520
Energy	4 TeV x 4 TeV	6.5 TeV x 6.5 TeV
Bunch spacing	50 ns	25 ns
Luminosity	7.7 x 10^{33} cm^{-2} s^{-1}	1.5 x 10^{34} cm^{-2} s^{-1}
Pile-up interactions	~35	~40



LHC schedule beyond LS1

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

🟩 Physics
🟥 Shutdown
🟨 Beam commissioning
🟦 Technical stop

(Extended) Year End Technical Stop: (E)YETS

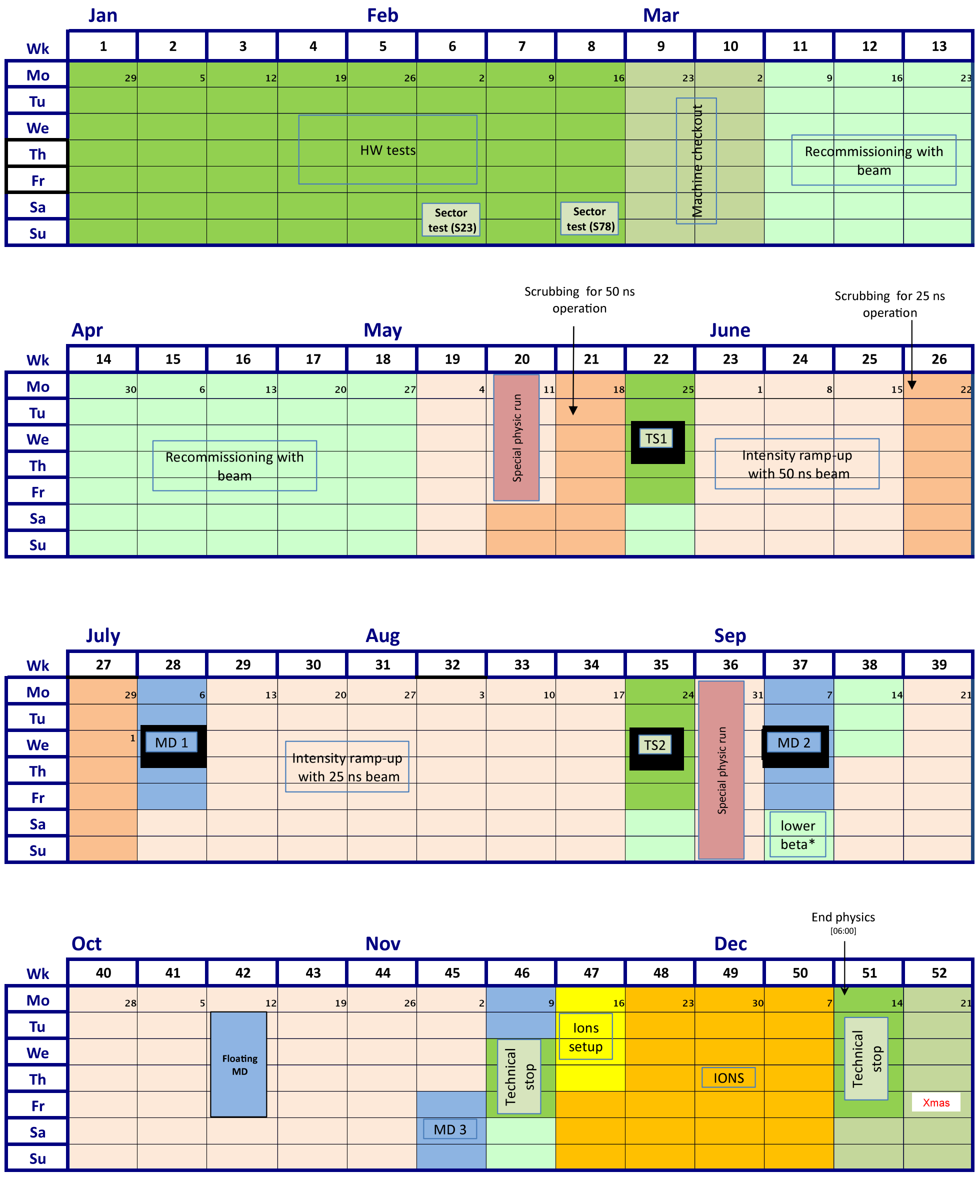
$3'000\ fb^{-1}$

R.Heuer, APP'14 Amsterdam

ML

September 4, 2014
V0.4

LHC Schedule - 2015
Draft for approval



	Jan				Feb				Mar				
Wk	1	2	3	4	5	6	7	8	9	10	11	12	13
Mo	29	5	12	19	26	2	9	16	23	2	9	16	23

	Apr				May					June			
Wk	14	15	16	17	18	19	20	21	22	23	24	25	26
Mo	30	6	13	20	27	4	11	18	25	1	8	15	22

	July				Aug					Sep			
Wk	27	28	29	30	31	32	33	34	35	36	37	38	39
Mo	29	6	13	20	27	3	10	17	24	31	7	14	21

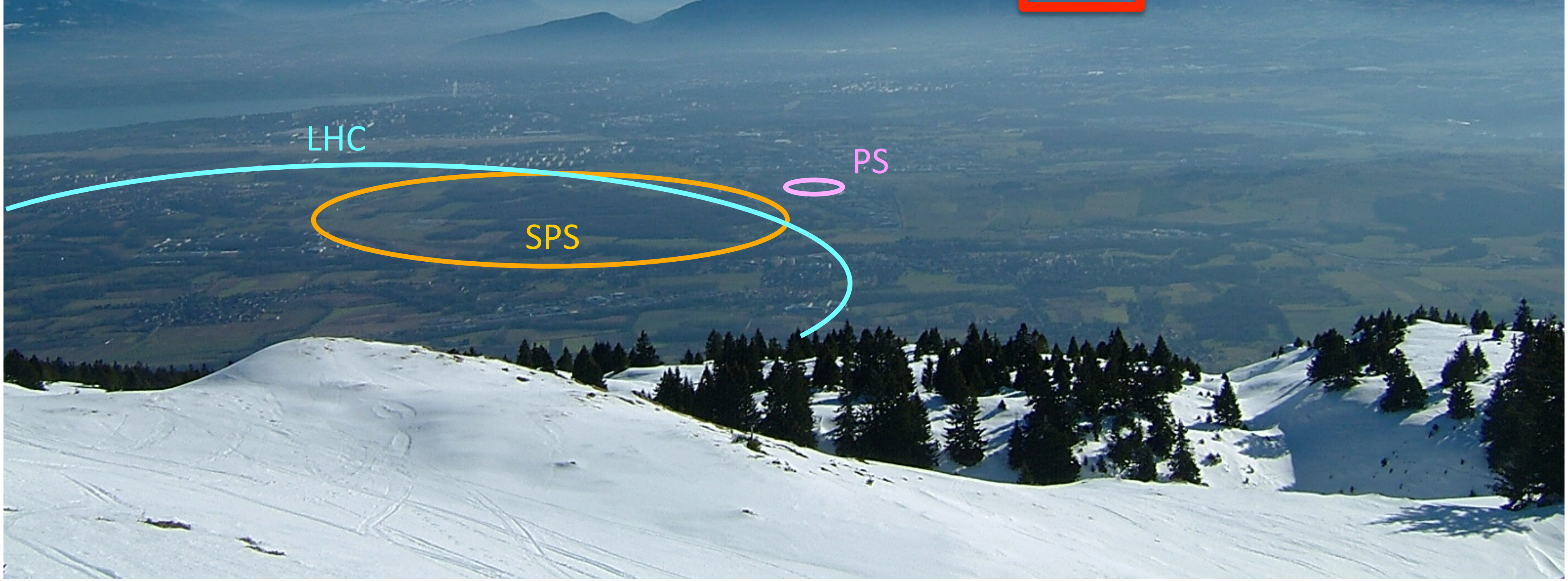
	Oct				Nov					Dec			
Wk	40	41	42	43	44	45	46	47	48	49	50	51	52
Mo	28	5	12	19	26	2	9	16	23	30	7	14	21

Days: Mo, Tu, We, Th, Fr, Sa, Su

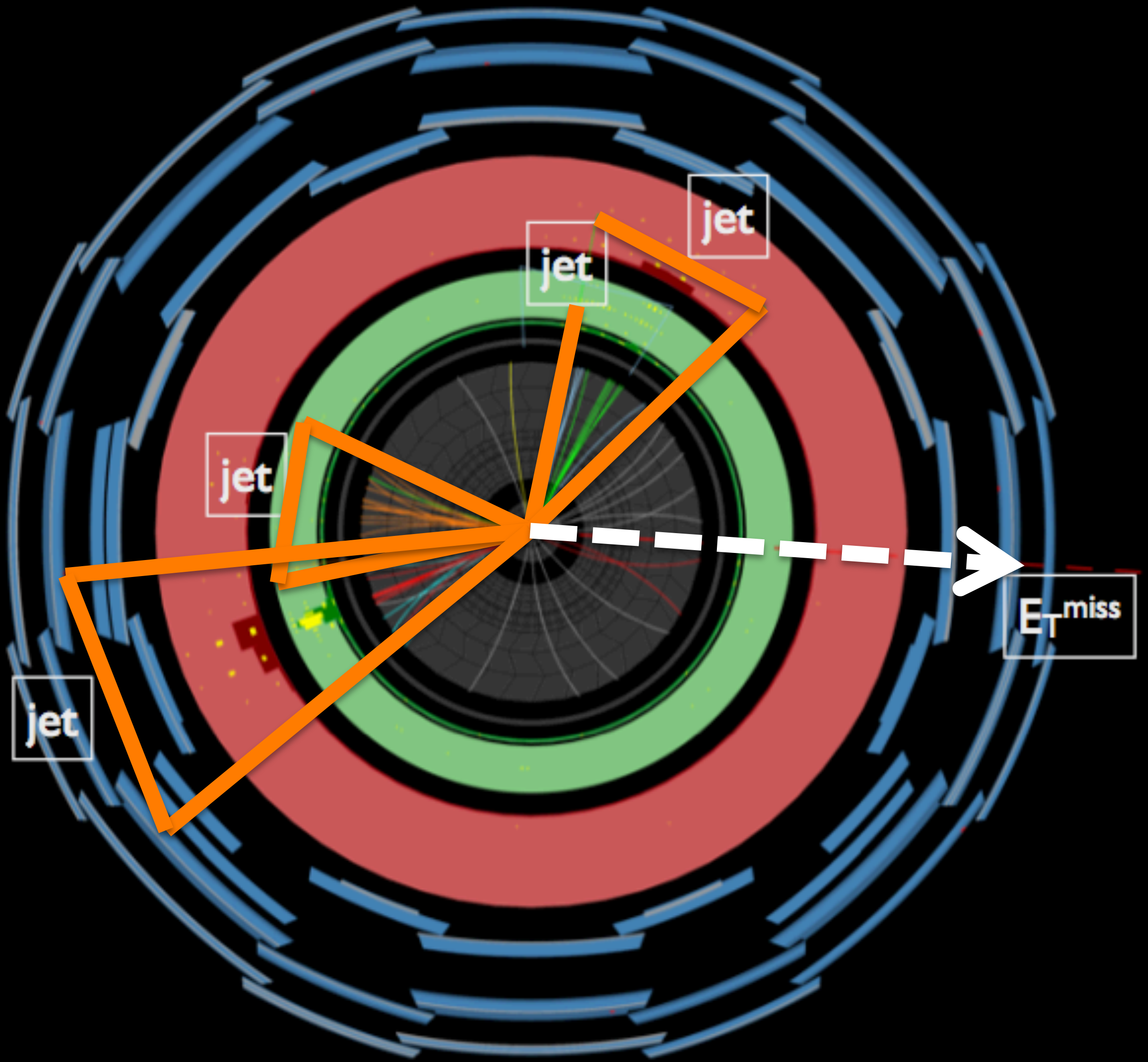
- 🟩 Technical Stop
- 🟦 Machine development
- 🟩 Recommissoning with beam
- 🟥 Special physics runs (indicative - schedule to be established)
- 🟧 Scrubbing (indicative - dates to be established)

The Large Hadron Collider

	2012 performance	2015 likely performance
Colliding bunches	1331	2520
Energy	4 TeV x 4 TeV	6.5 TeV x 6.5 TeV
Bunch spacing	50 ns	25 ns
Luminosity	7.7 x 10^{33} cm^{-2} s^{-1}	1.5 x 10^{34} cm^{-2} s^{-1}
Pile-up interactions	~35	~40

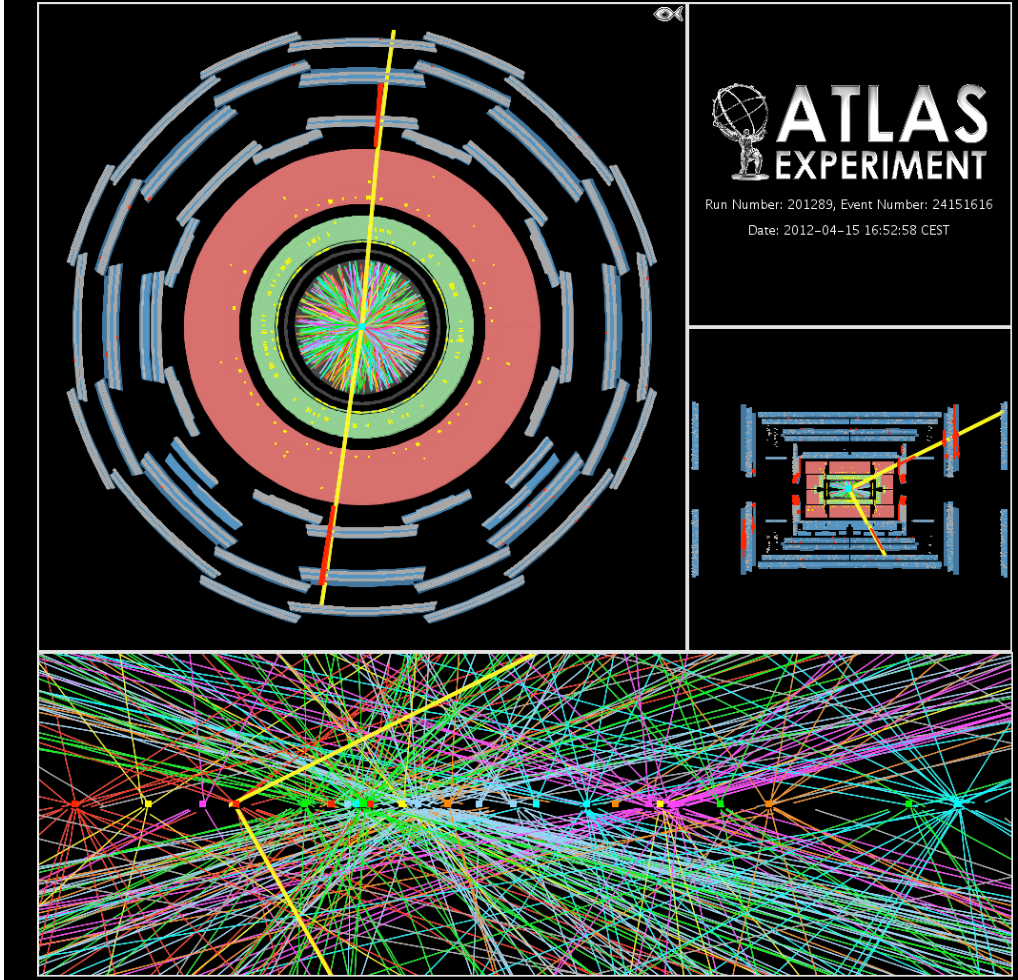


Task: measure transverse energy

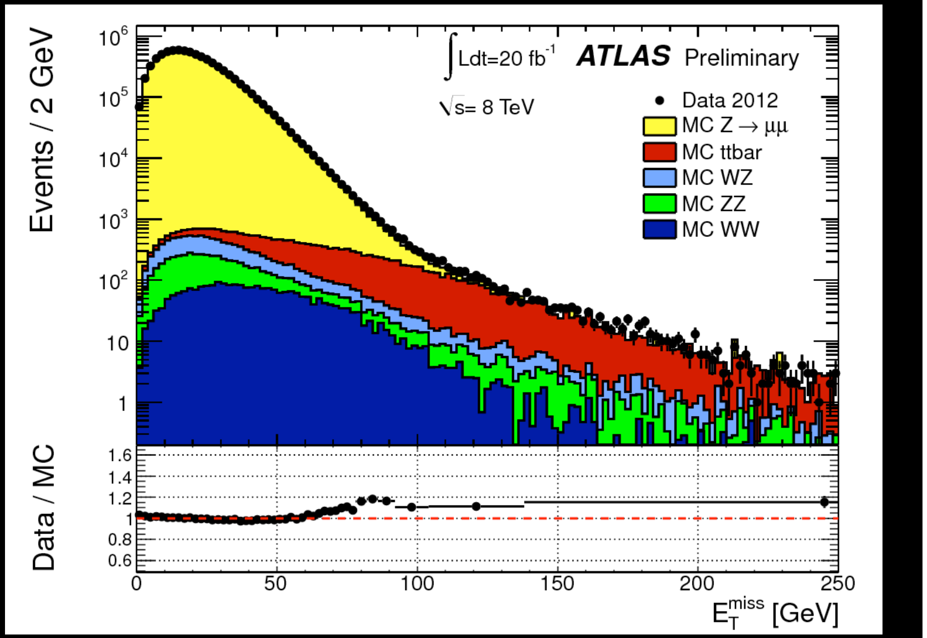


Difficulty: event pile-up

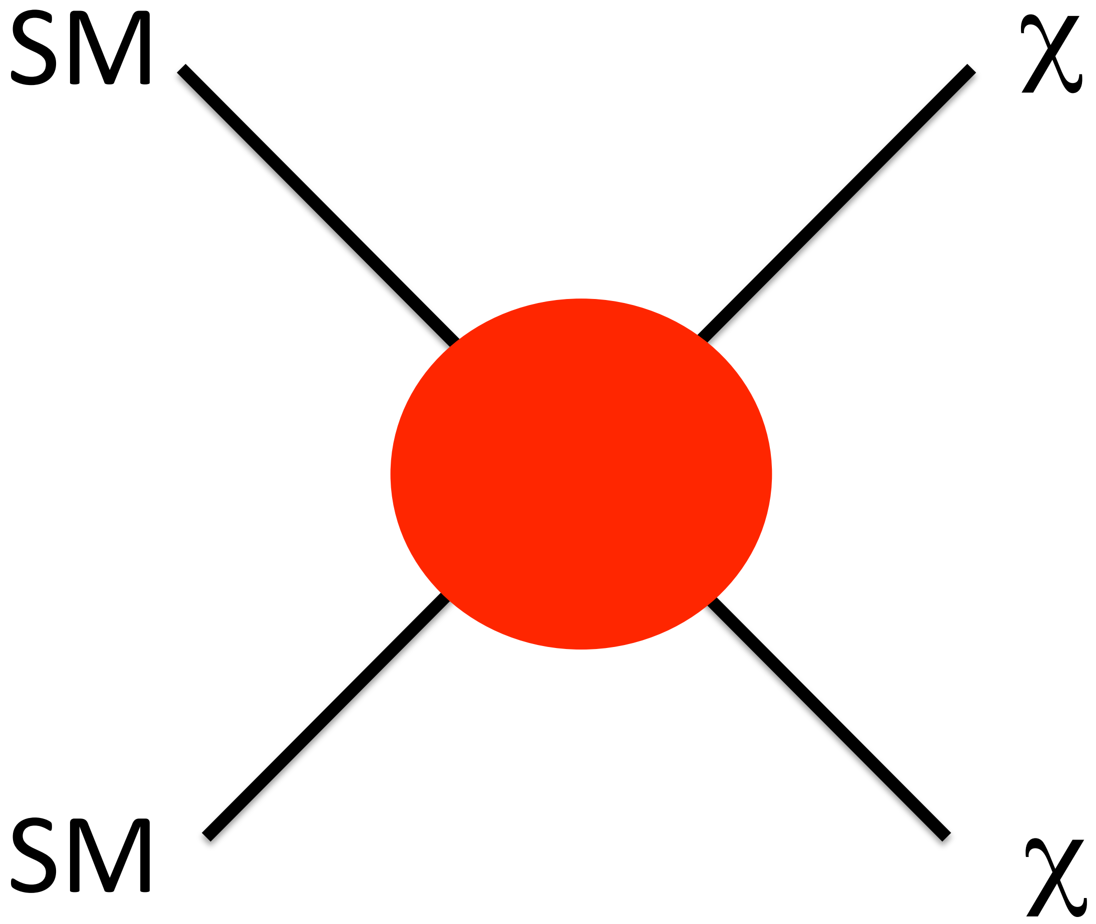
ATLAS-CONF-2013-082



$Z \rightarrow \mu\mu$ event in ATLAS with 25 reconstructed vertices

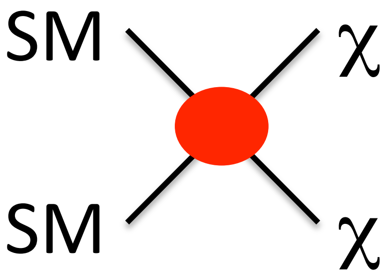


Dark matter production



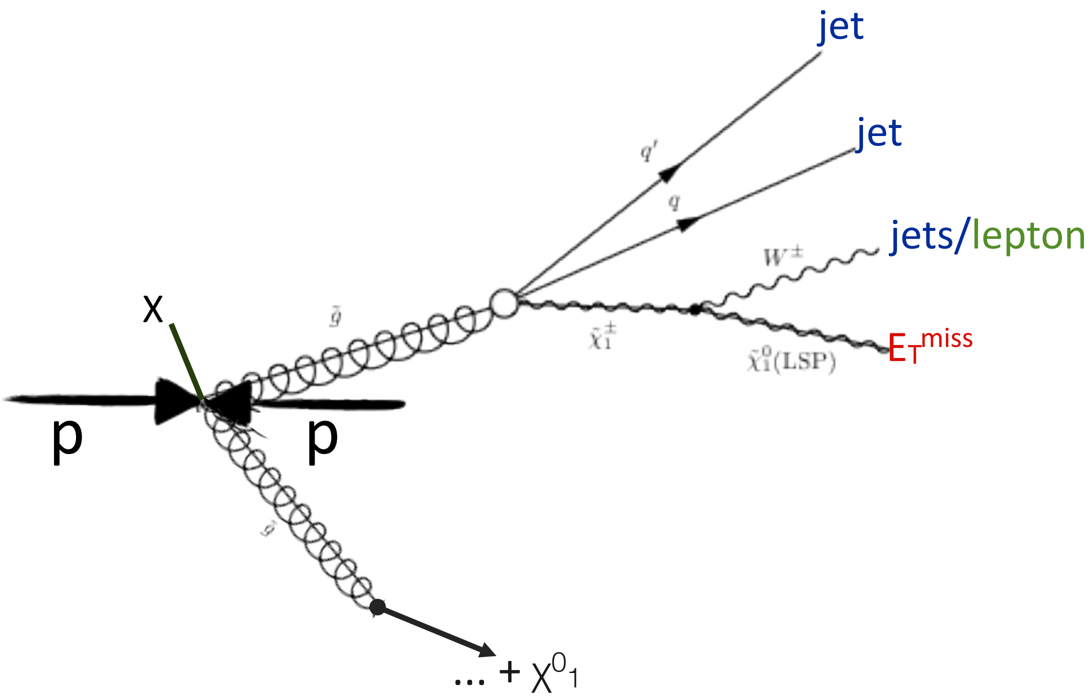
1. SUSY cascades
2. Lonely pairs

1: “Standard” Dark Matter Searches at Colliders



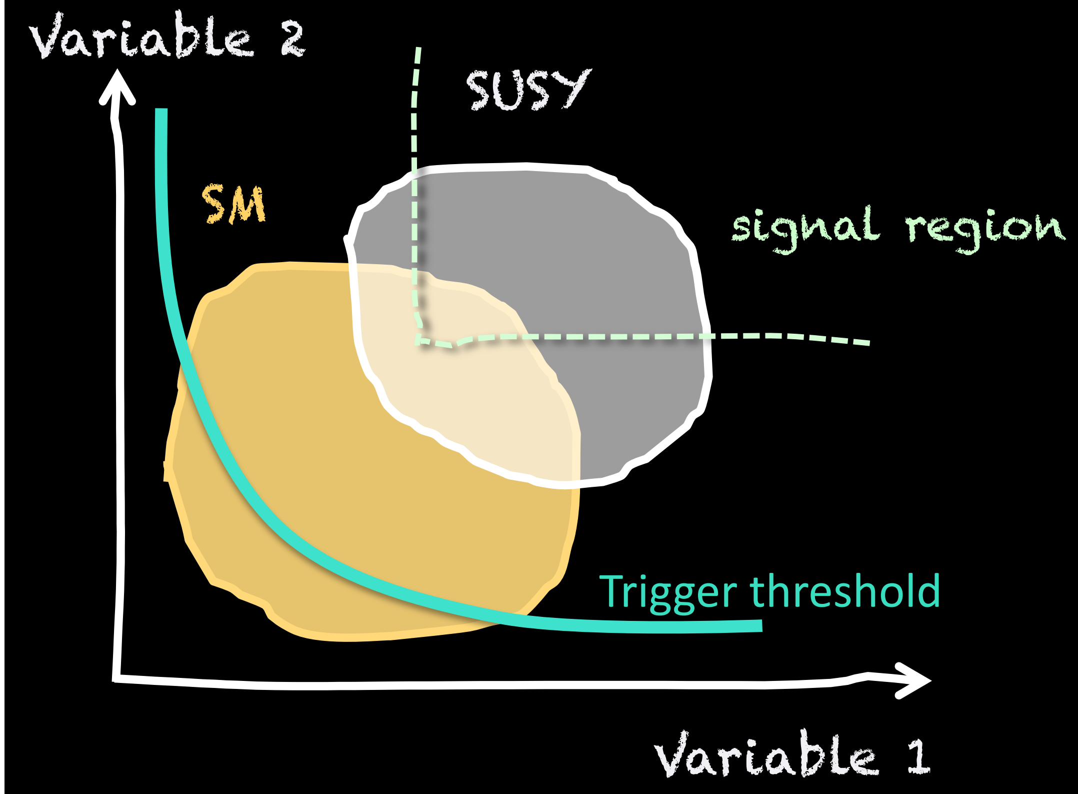
SUSY:

- High-p_T jets from squark & gluino decays
- Leptons from gaugino & slepton decays
- **Missing transverse energy from LSPs**



How do we search for SUSY ?

A brief primer ...



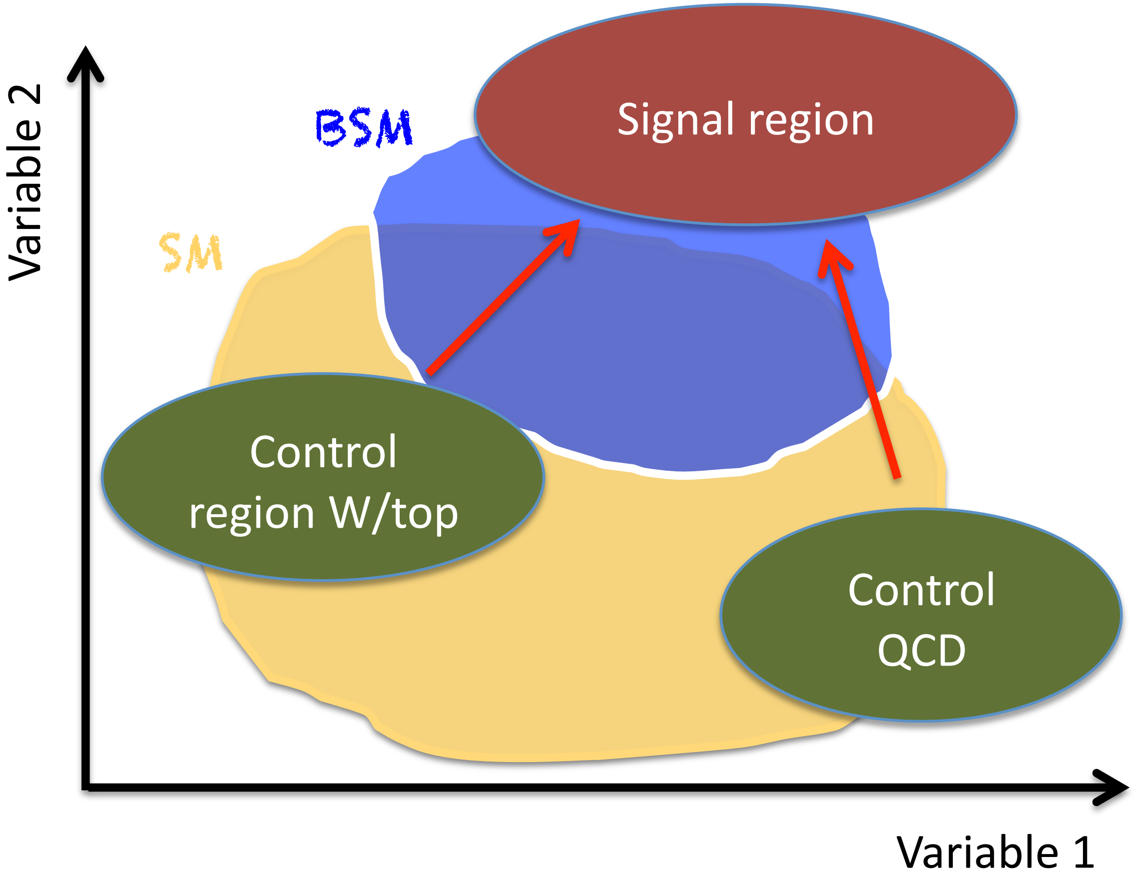
SUSY search analyses look for tails in distributions of observables sensitive to new heavy particles.

Can only exploit tails if detector response and SM backgrounds in signal region are understood.

How do we search for SUSY ?

A brief primer …

CR → SR transfer factors taken from MC simulation (many systematic effects cancel).

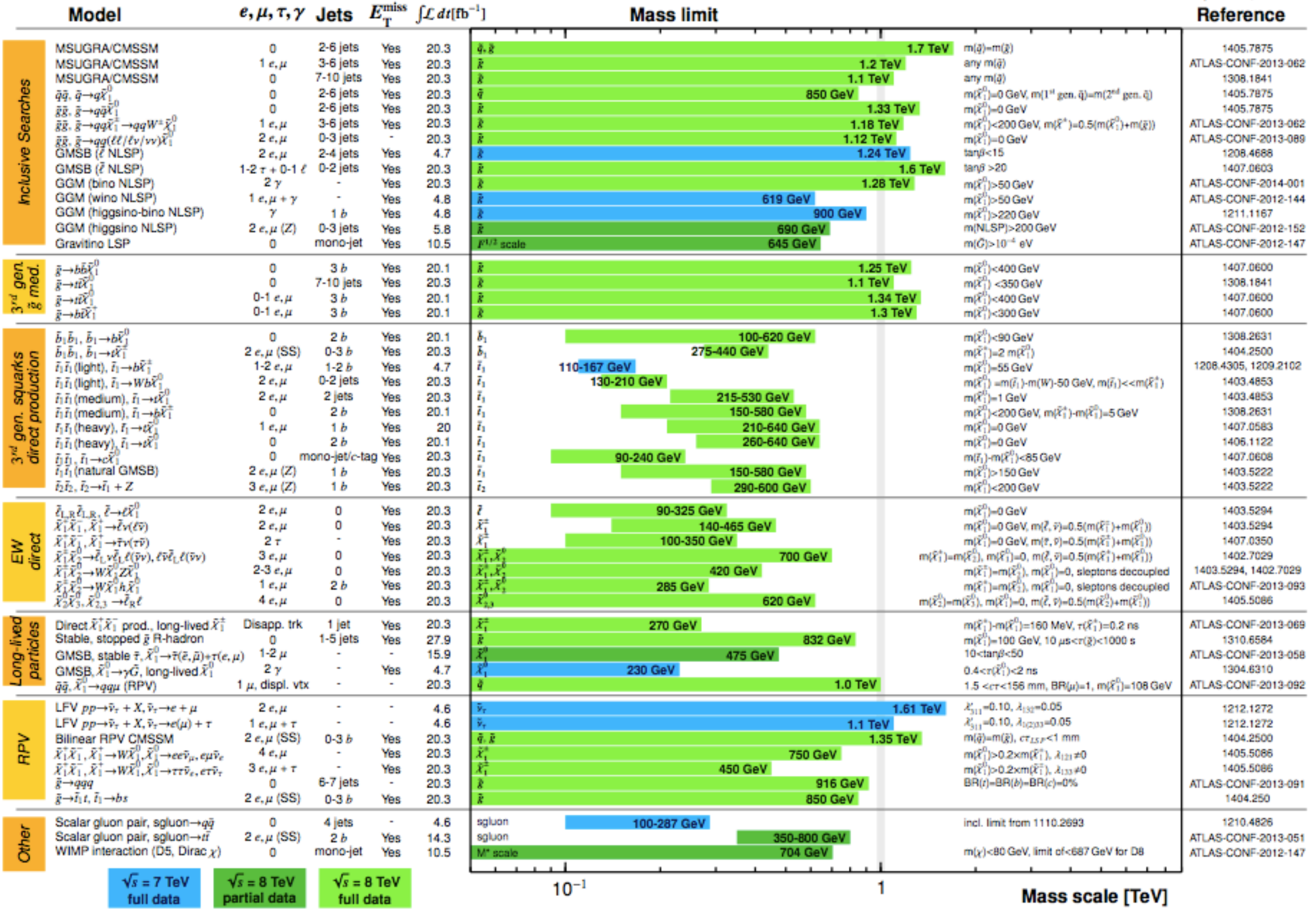


ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV



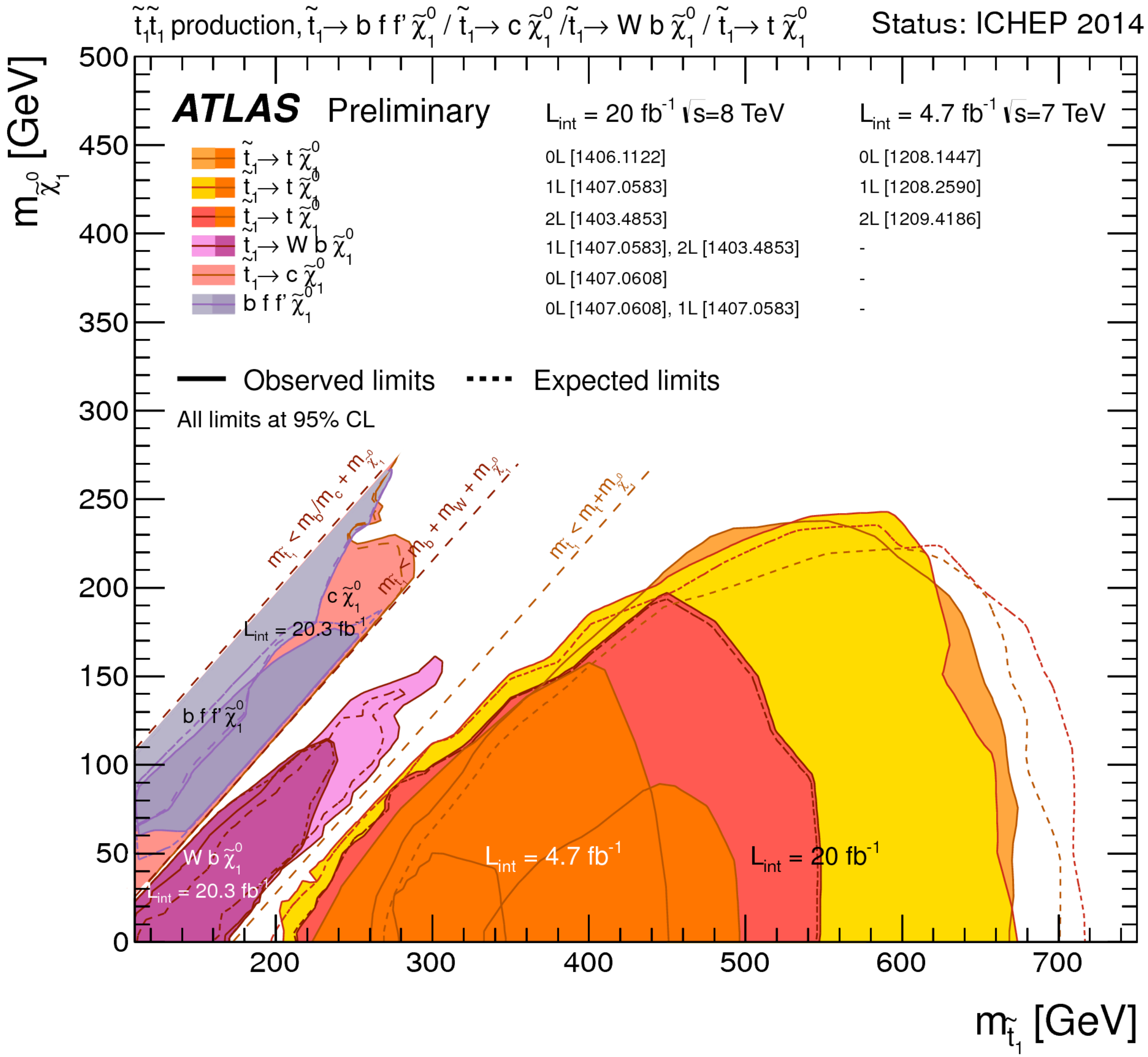
	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(1^{st}$ gen. $\tilde{q})=m(2^{nd}$ gen. $\tilde{q})$	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{G})>10^{-4}$ eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	$m(\tilde{\chi}_1^0)$ $=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	1403.4853
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M^* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Natural SUSY searches

Search for 3rd generation squarks, leptons, c/b-jets, jets, missing Et

Probe SUSY as solution to the hierarchy problem



Exclusion:

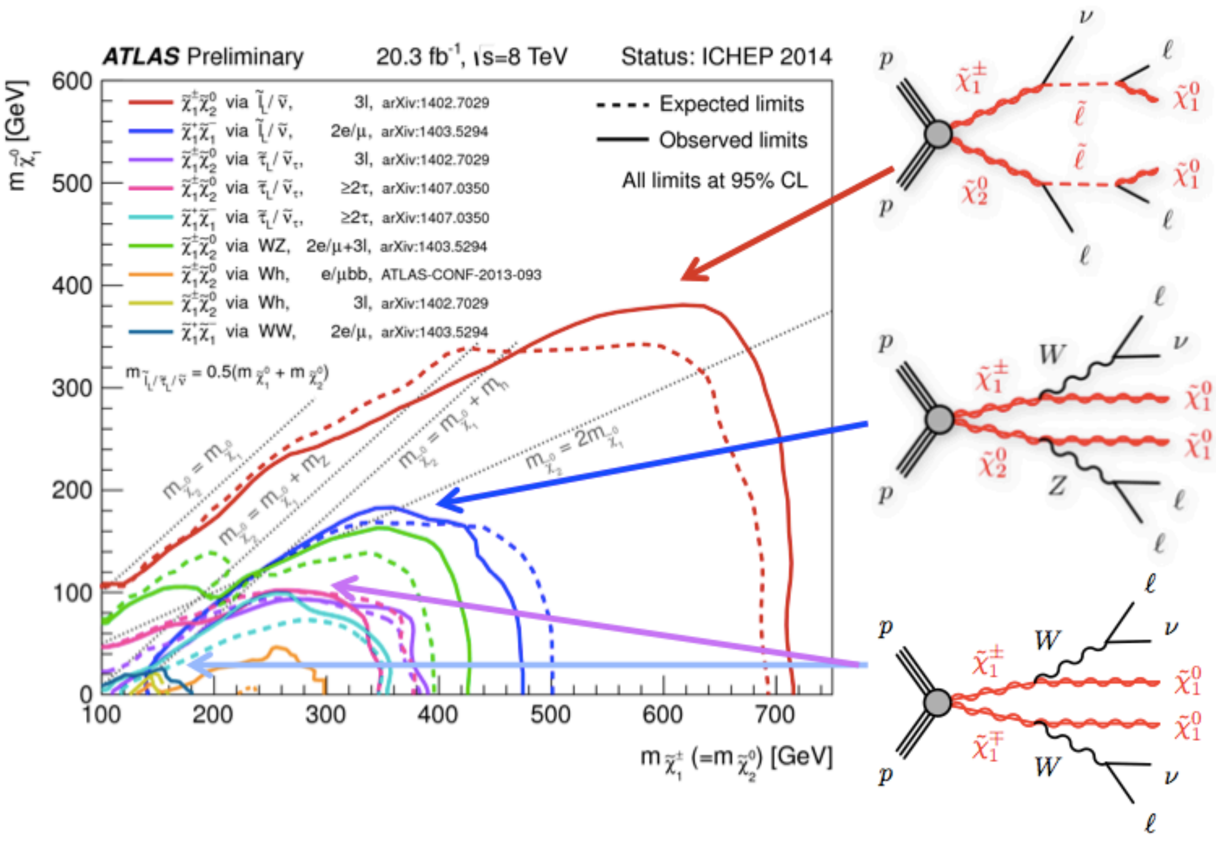
m_{stop} < 645 GeV for

m_{LSP} < 230 GeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/index.html#ATLAS_SUSY_StopAll

Weak production

Searches for chargino / neutralino pair production
Clean final states involving multi-leptons



Large cross-section.
3 lepton final states if light sleptons:
exclusion up to m_{LSP}<~380 GeV.

If heavy slepton, smaller cross-section to lepton WZ/h with 3/2 leptons:
up to m_{LSP}<~180 GeV

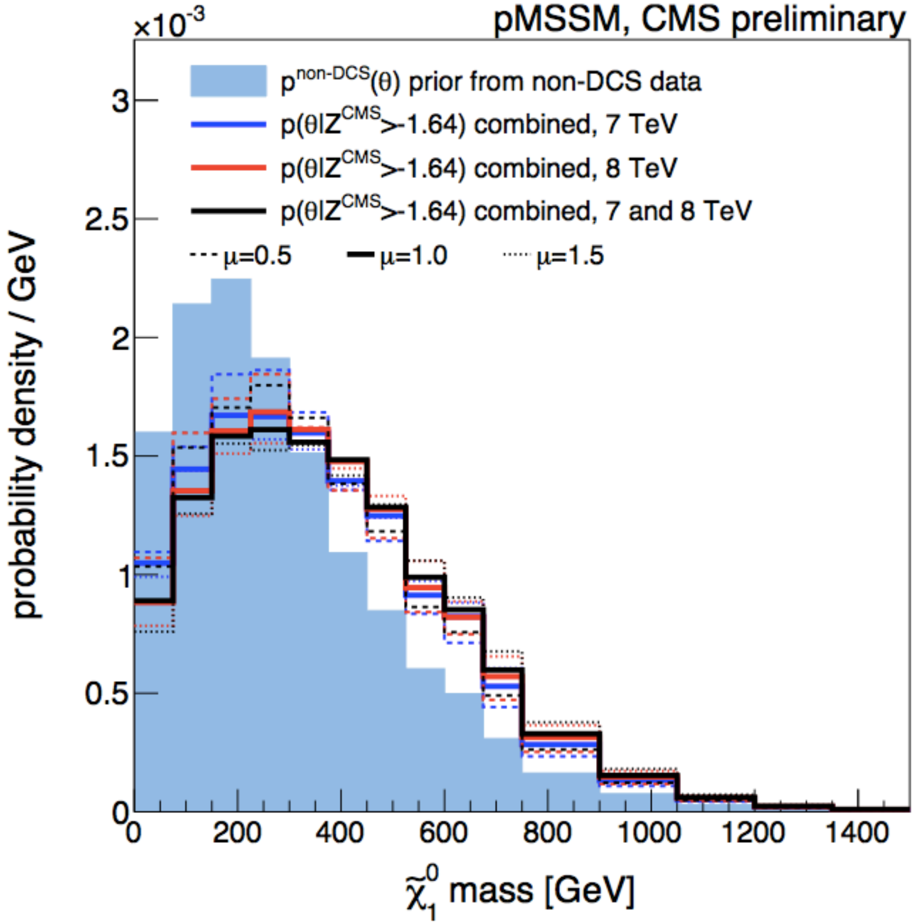
Tiny cross-section of chargino pair production via WW with 2 leptons.
Sensitivity increased if light stau.

JHEP 05 (2014) 071

pMSSM reinterpretation

CMS-SUSY-13-020

Reinterpretation, LEP constraints, flavor physics, neutralino LSP, $m_{sparticle}$<3 TeV



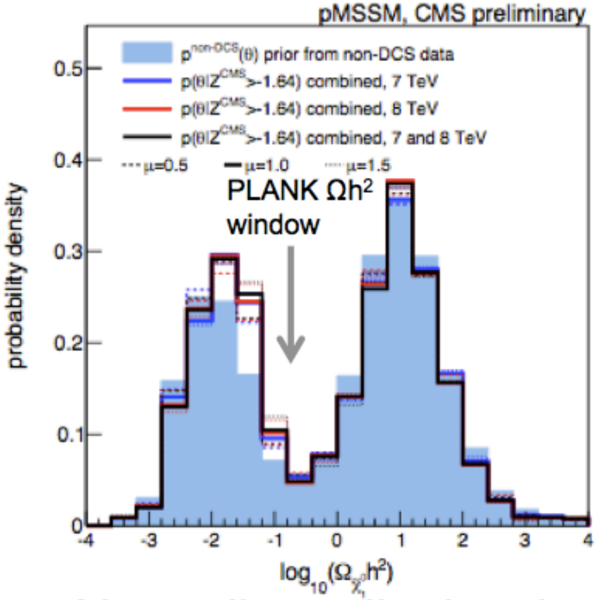
Blue area: w/o CMS data

Lines: w/ CMS data

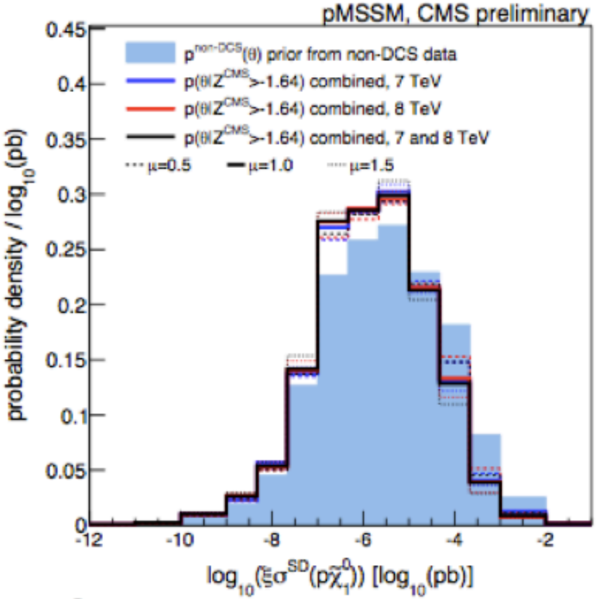
pMSSM reinterpretation

CMS-SUSY-13-020

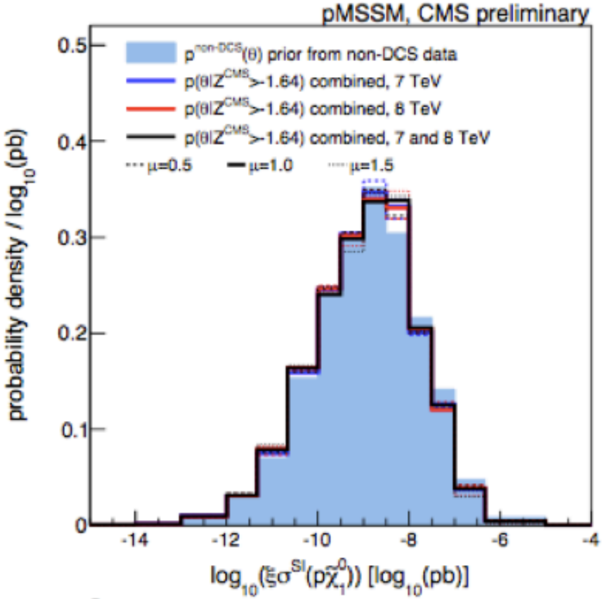
Reinterpretation, LEP constraints, flavor physics, neutralino LSP, $m_{sparticle}$<3 TeV



Neutralino relic density

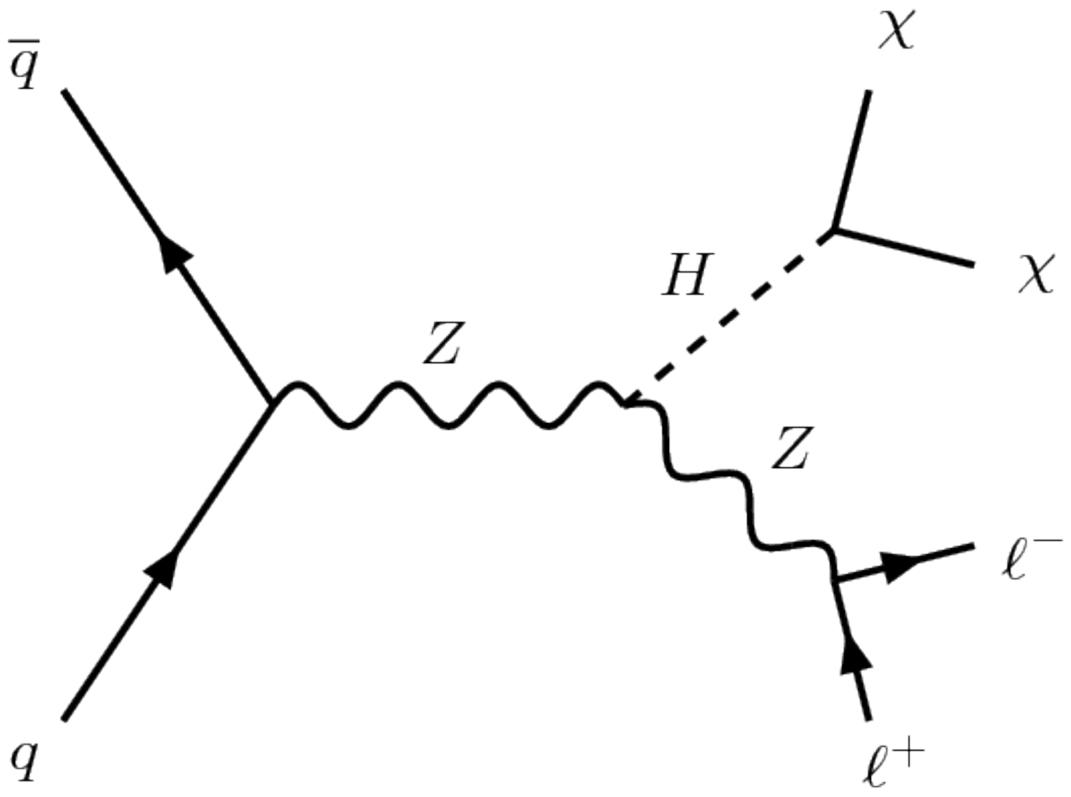


Spin-dependent direct DM detection cross-section

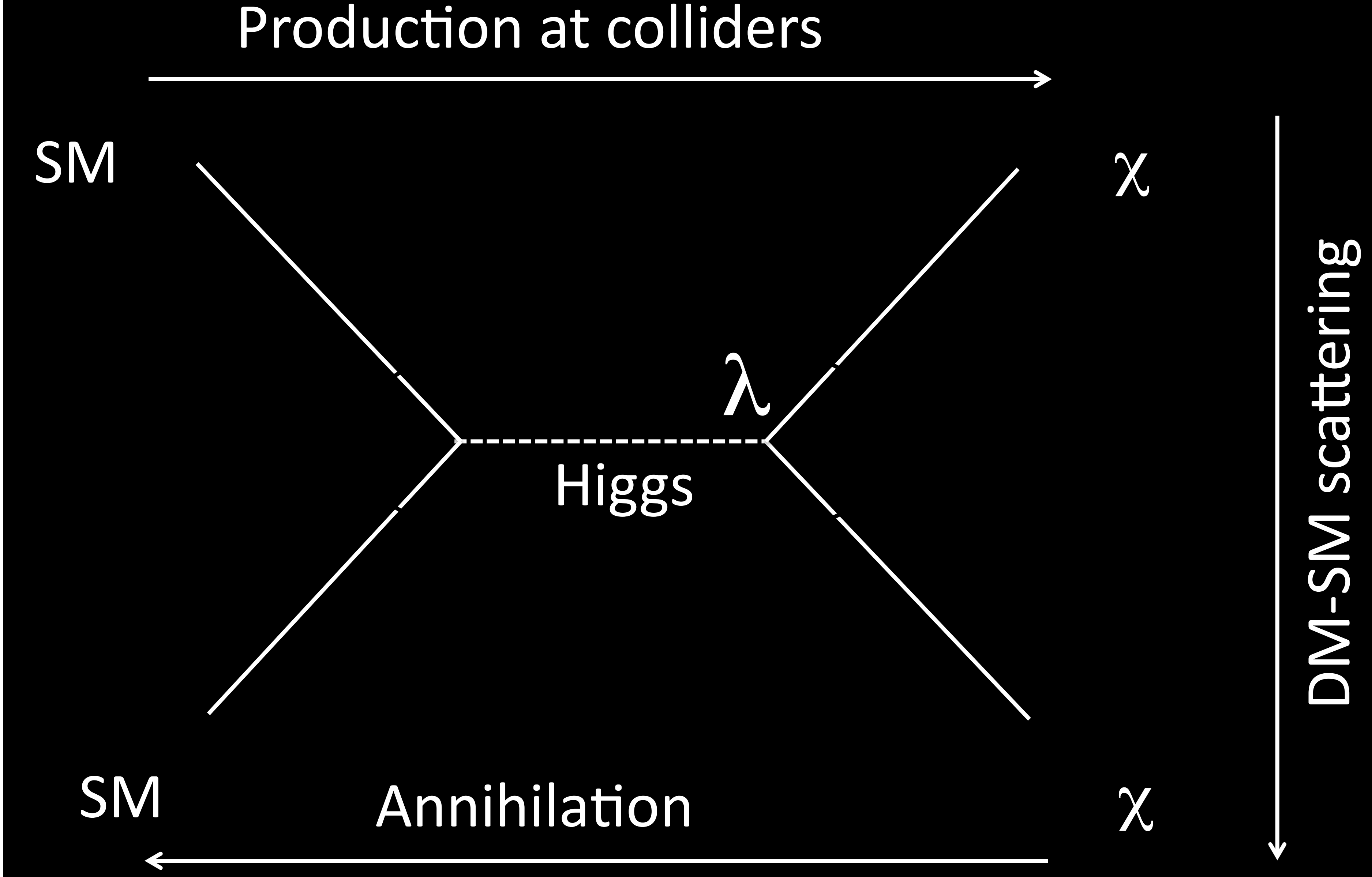


Spin-dependent direct DM cross-section

2. Dark Matter Pair Production



Higgs portal to dark sector



Production at colliders

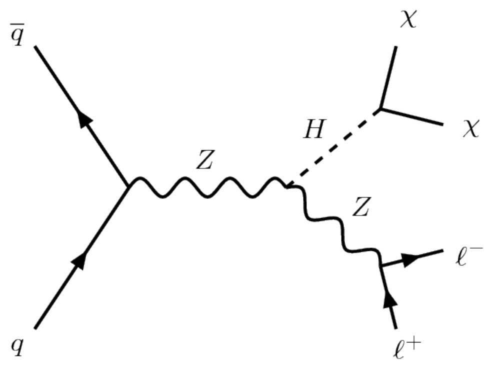
DM-SM scattering

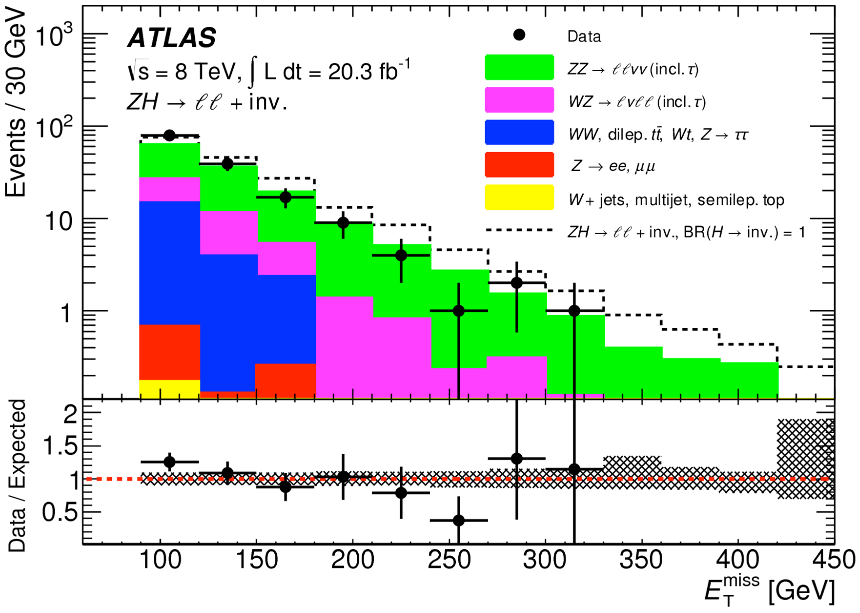
Annihilation

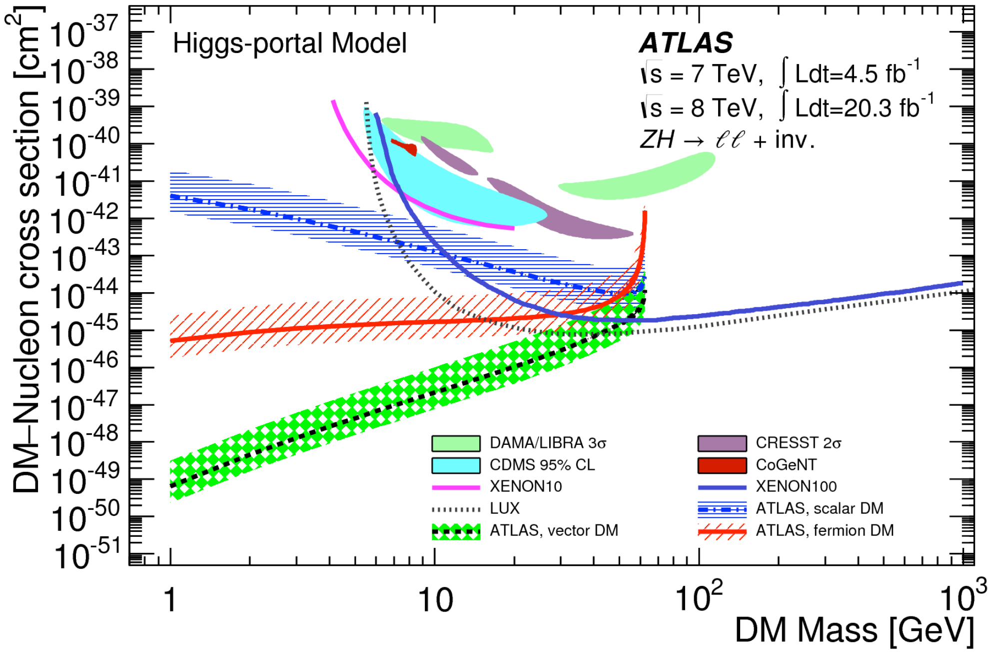
Higgs portal to dark sector

Direct search for invisible Higgs decays (PRL 112 (2014) 201802)
Constrain invisible Higgs width to <75% of the full SM width

CMS limit: <60% of SM width (EPJC 74 (2014) 2980)





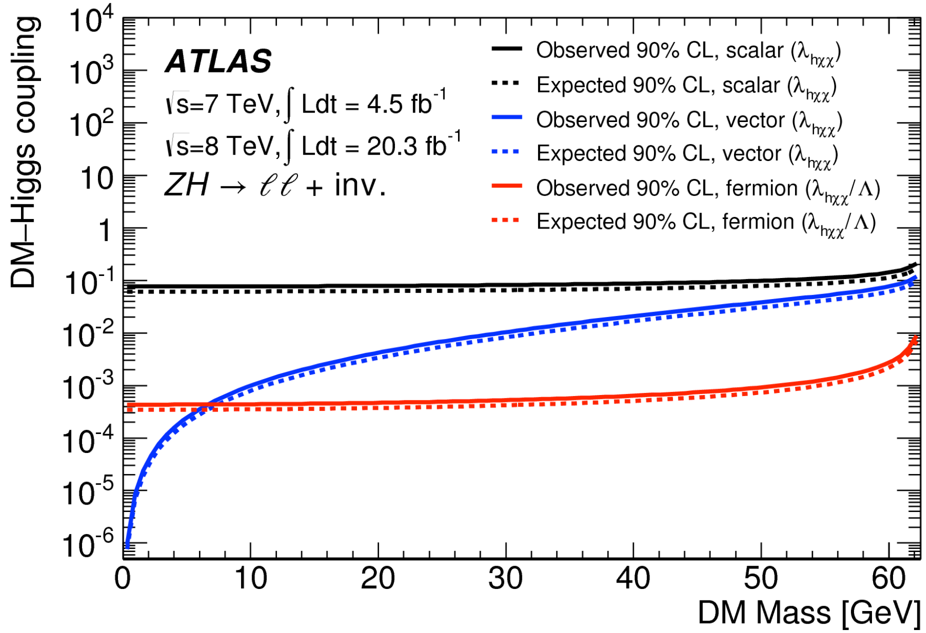


'Light' mediator, simplest connection of SM and dark sector.

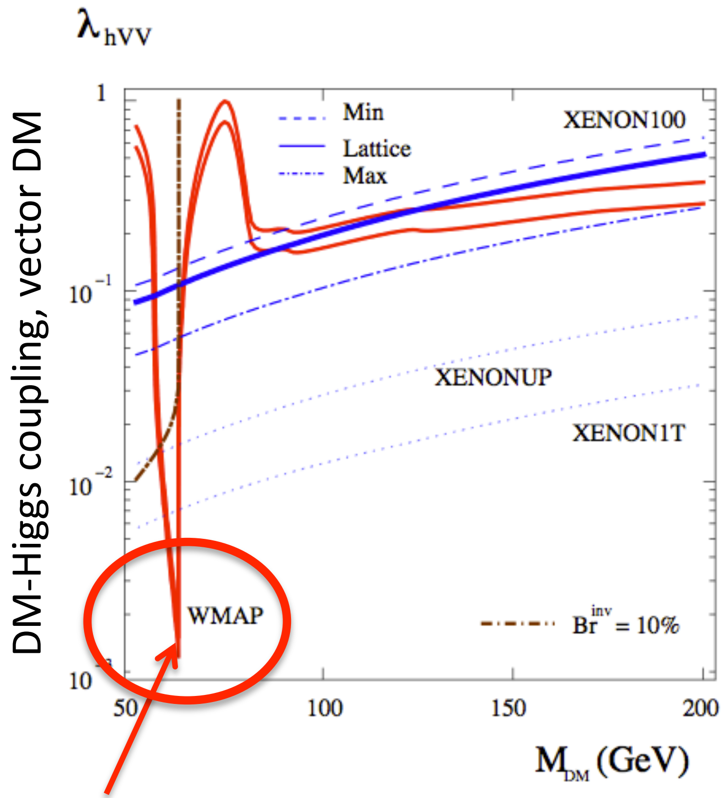
Higgs portal to dark sector

Direct search for invisible Higgs decays (PRL 112 (2014) 201802)
Constrain invisible Higgs width to <75% of the full SM width

CMS limit: <60% of SM width (EPJC 74 (2014) 2980)



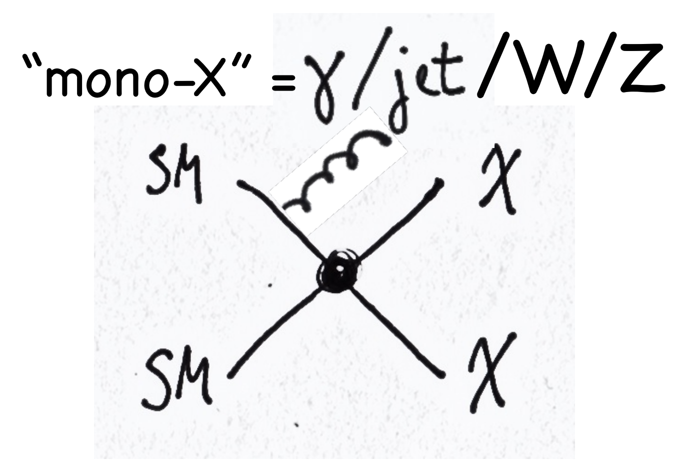
A. Djouadi *et al.*, Phys. Lett. B 709, 65 (2012), arXiv:1112.3299



Higgs pole

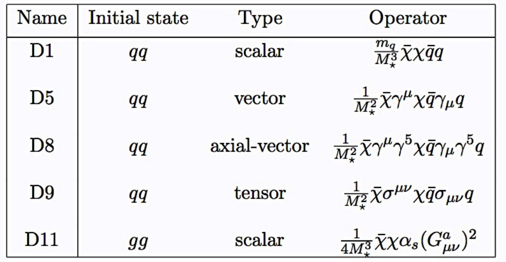
This, together with the relic density, basically rules out the simplest Higgs portals for DM up to half the Higgs mass, except right at the Higgs pole!

2: Dark Matter Pair Production



Assume contact interaction with mass suppression scale M*.

Dark matter mass m_χ, plus higher-dimensional operators (e.g. D1-D11), fix cross sections.



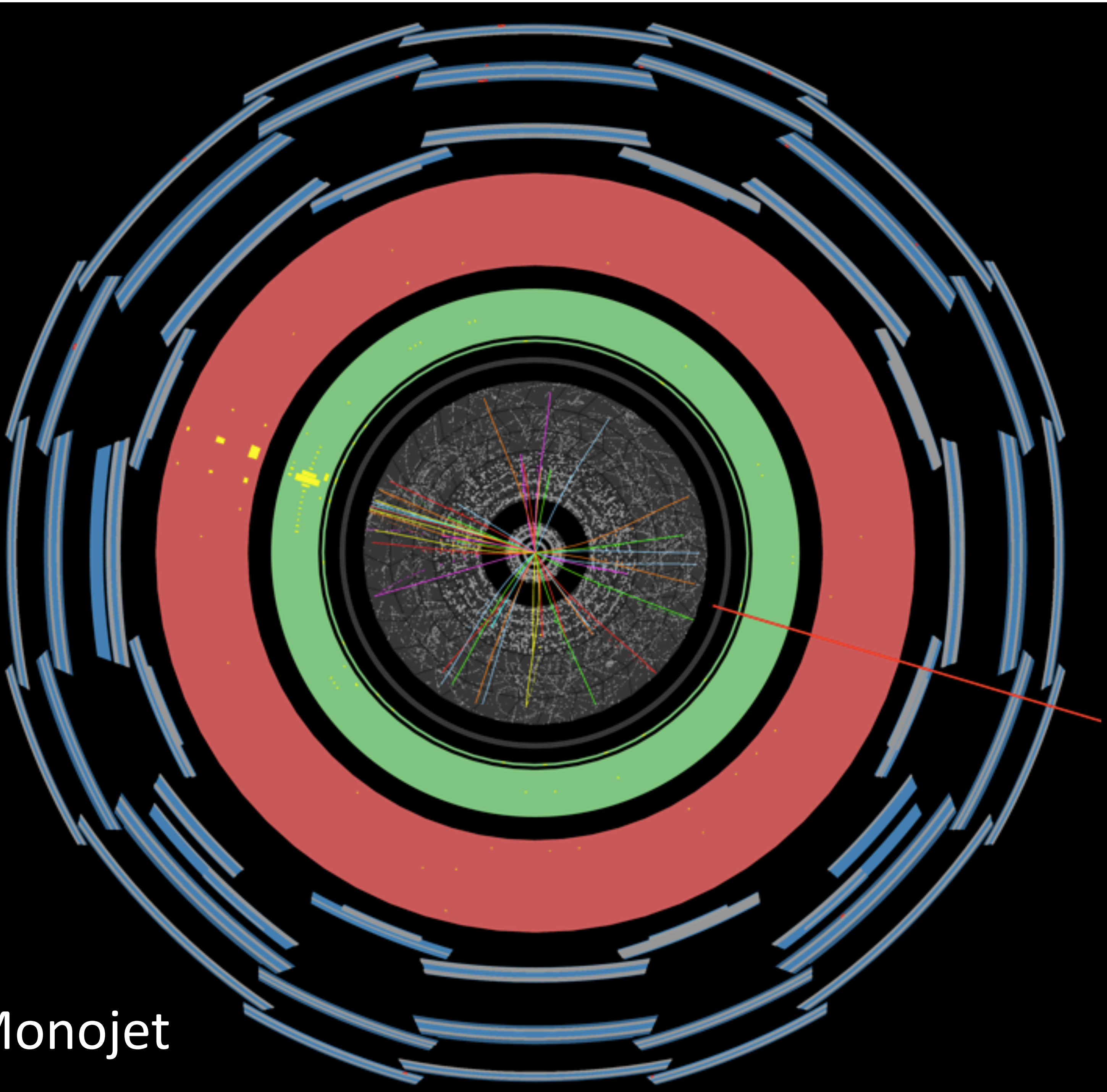
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$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

mass

Everything else

Δm very large

Dark matter

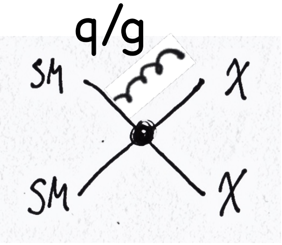


ATLAS Monojet

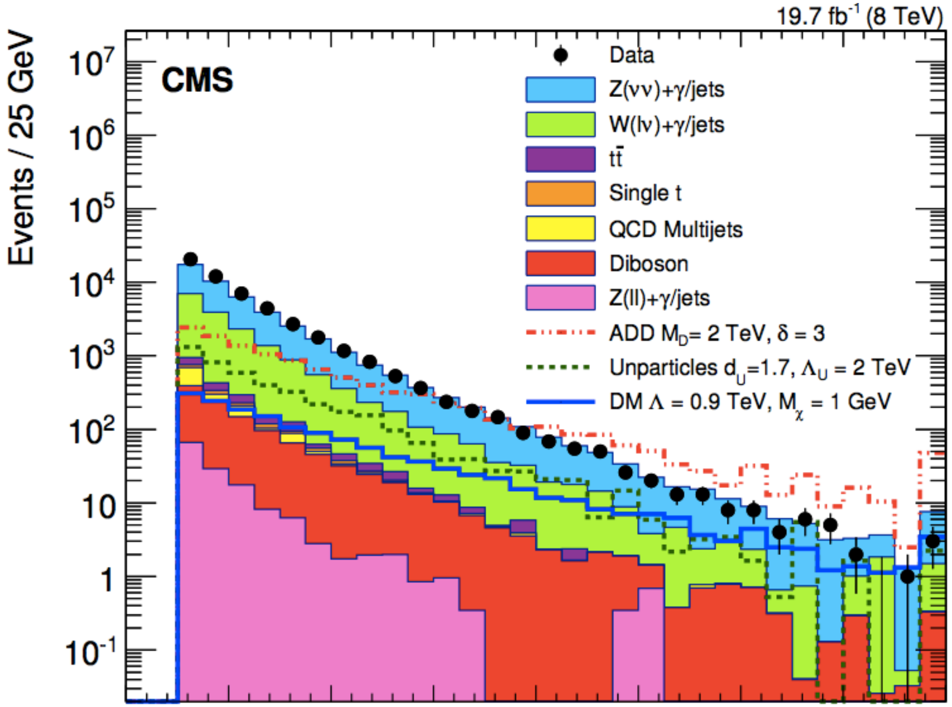
jet p_T 551 GeV
missing E_T 542 GeV

CMS Mono-jet

Monojets

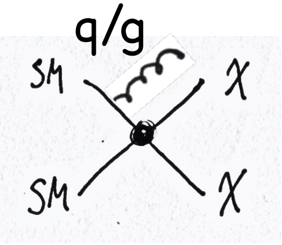


- 8 TeV, 20 fb^{-1}, arxiv:1408.3583
- Central leading jet, balanced by missing E_T
- Veto on leptons
- Main background $Z \rightarrow \nu\nu$, estimated with $W/Z \rightarrow \mu$ control region

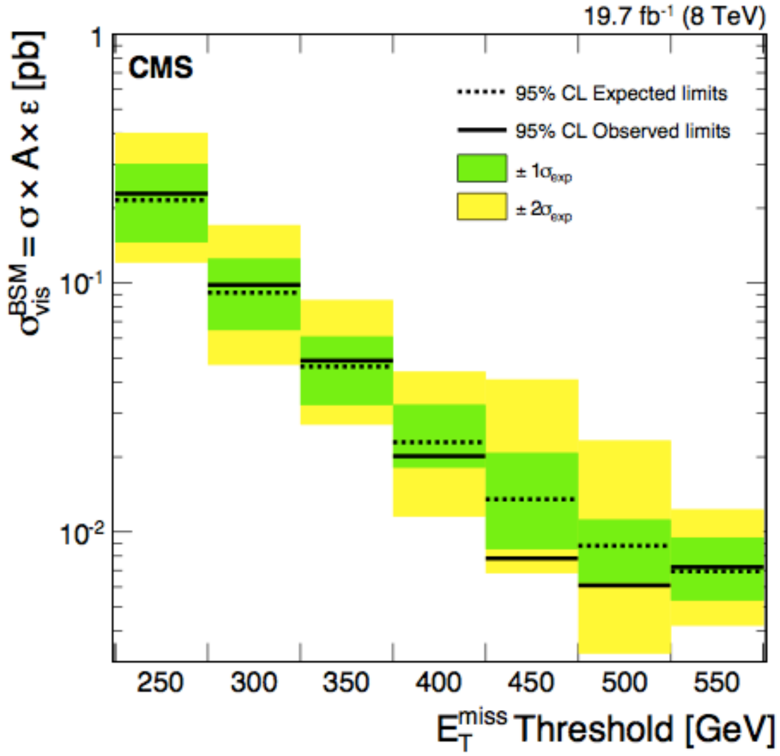


CMS Mono-jet

Monojets

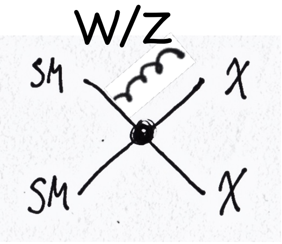


- 8 TeV, 20 fb^{-1}, arxiv:1408.3583
- Central leading jet, balanced by missing E_T
- Veto on leptons
- Main background Z→ νν, estimated with W/Z → μ control region

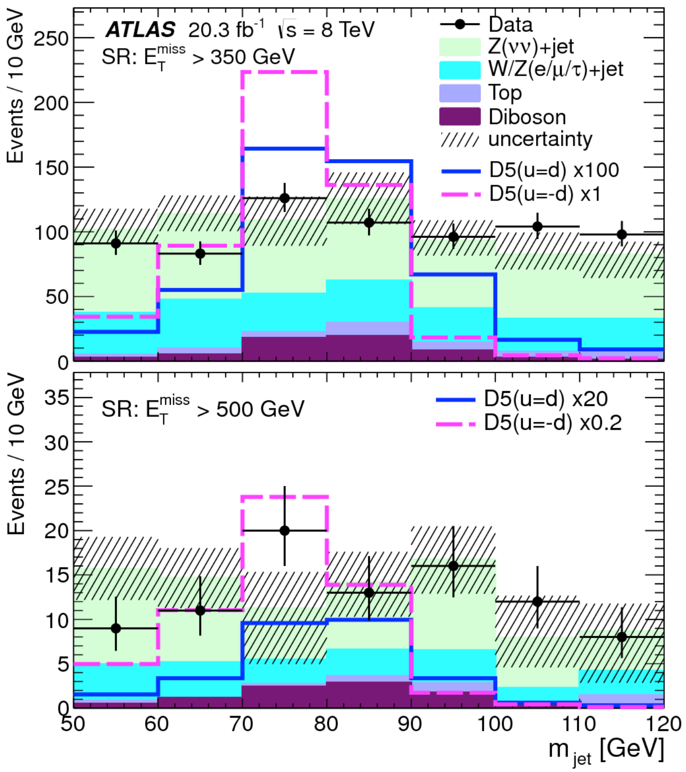


ATLAS Mono-W/Z

Mono-W/Z→qq

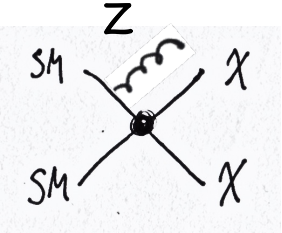


- 8 TeV, 20 fb^{-1}, PRL 112, 041802 (2014)
- Central massive fat jet, 50 GeV < m_{jet} < 120 GeV, validated in top control region, balanced by missing E_T
- Veto on leptons and photons
- Main background Z→ νν & W→ lν, estimated with W/Z → μ control region

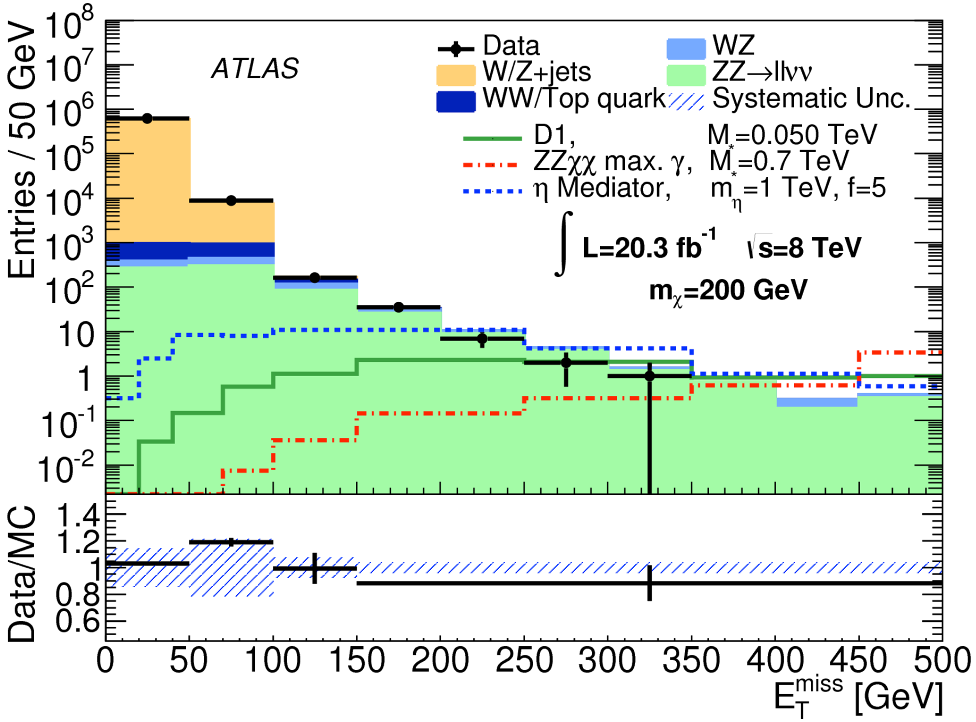


ATLAS Mono-Z

Mono-Z→ll

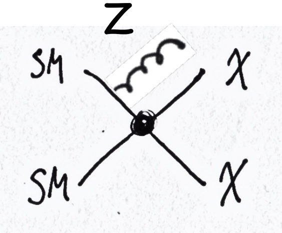


- 8 TeV, 20 fb^{-1}, PRD (submitted), arXiv: 1404.0051
- Two leptons, Z invariant mass cut, balanced by missing ET
- Veto on >2 leptons and jets
- Main background SM ZZ/WZ (from NLO MC)

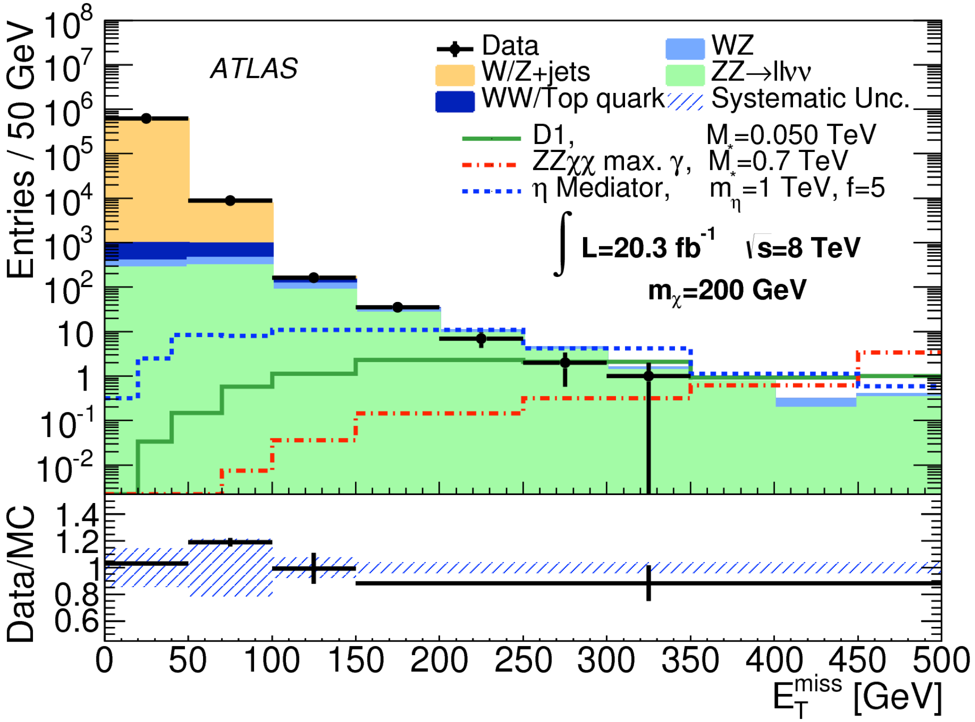


ATLAS Mono-Z

Mono-Z→ll

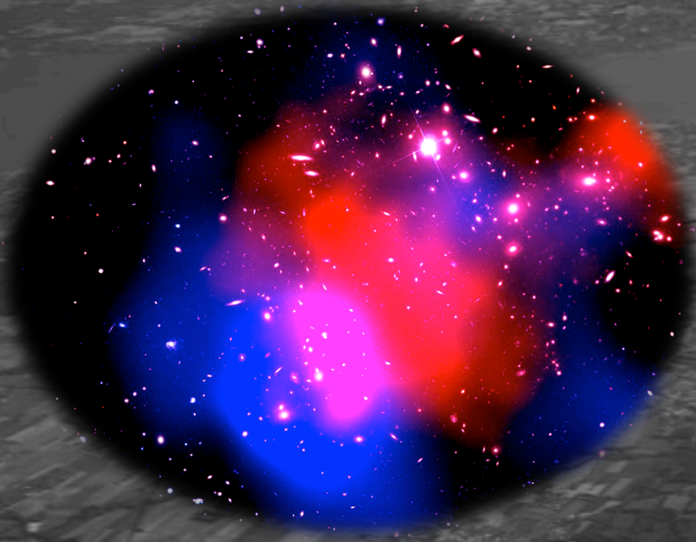


- 8 TeV, 20 fb^{-1}, PRD (submitted), arXiv: 1404.0051
- Two leptons, Z invariant mass cut, balanced by missing ET
- Veto on >2 leptons and jets
- Main background SM ZZ/WZ (from NLO MC)



Plus a lot more from both ATLAS and CMS: mono-lepton, mono-b, mono-top, mono-photon

Dark matter contact interactions



Galaxy cluster Abell 2744

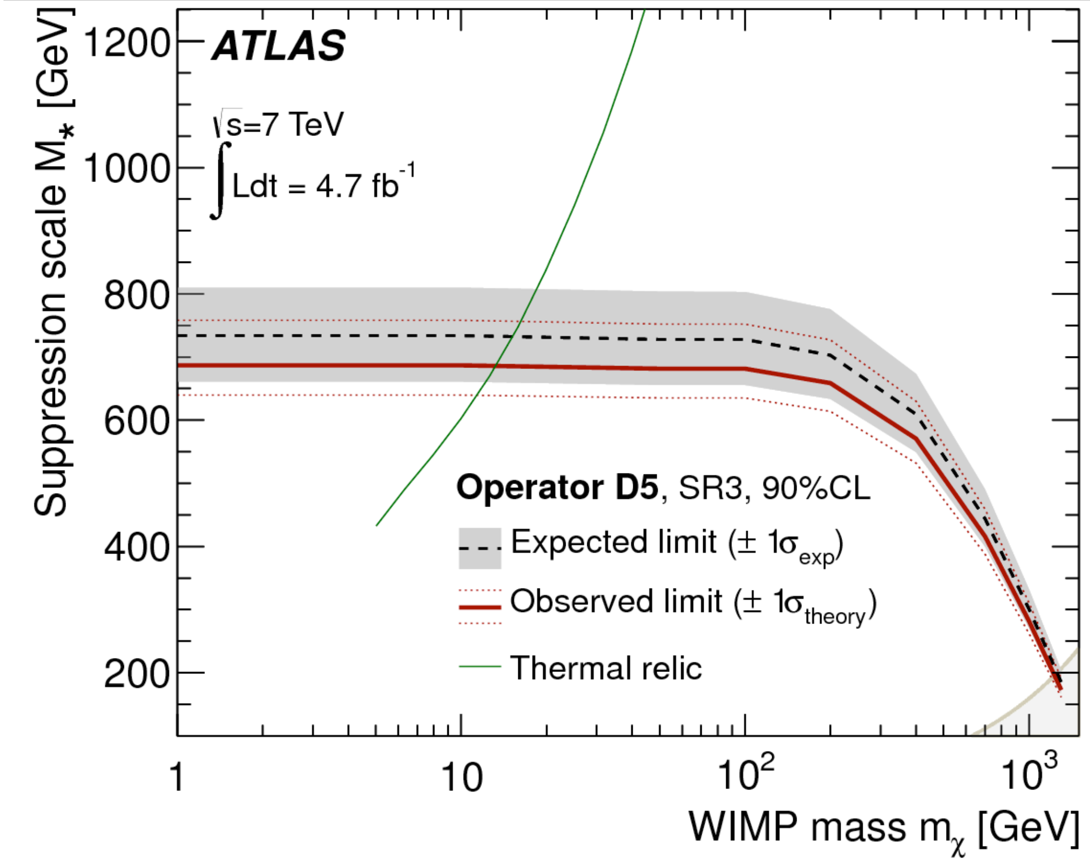
M_* and m_χ fix dark-matter nucleon scattering and annihilation cross sections (for given interaction type)!

Particle Dark Matter Searches based on:

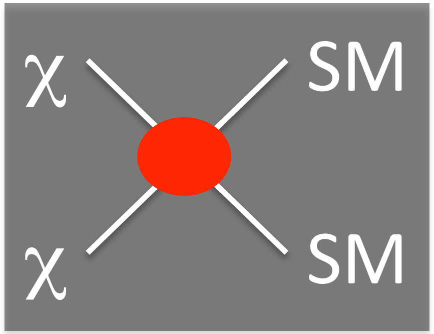
Monojets 7 TeV

Suppression scale M$_*$ **lower** limits

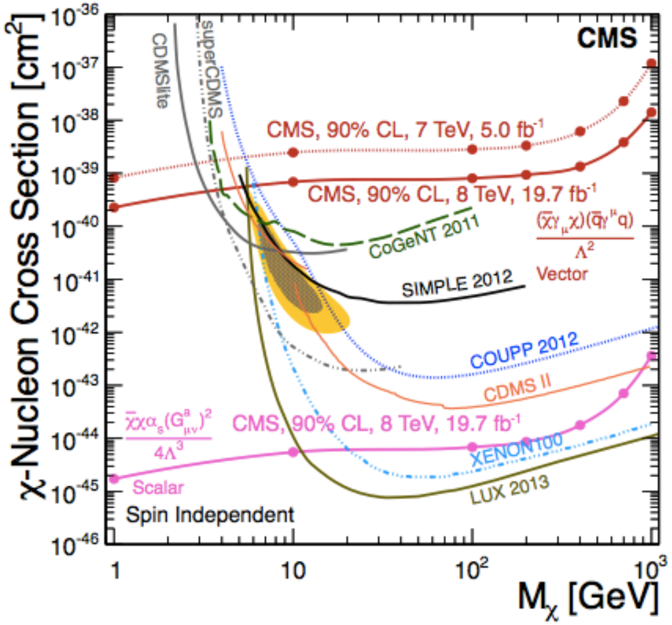
arXiv:1210.4491



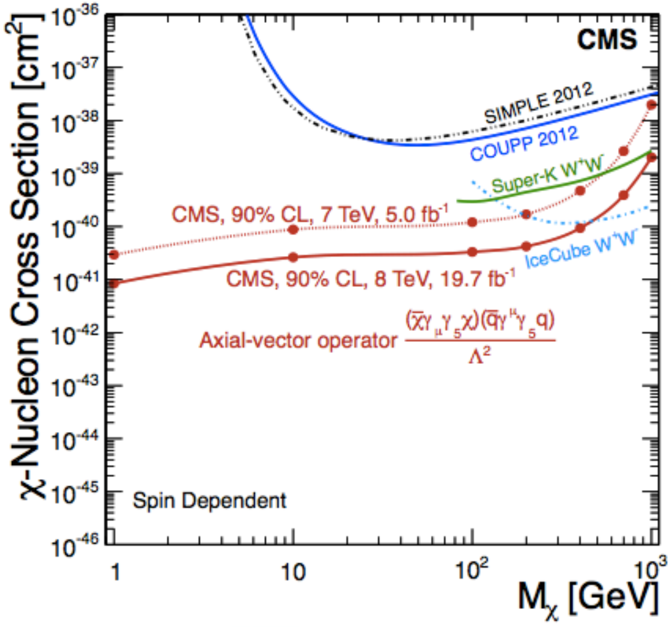
- M$_*$ fixes coupling SM-χ
- Coupling fixes annihilation cross section χ to SM
- Relic density (WMAP) corresponds to cross section
- Probe thermal relic dark matter particle at LHC!
- Red above green line: conflict!
  - Exclusion for this operator, or
  - Additional annihilation channels (leptons!), or
  - Wrong assumptions



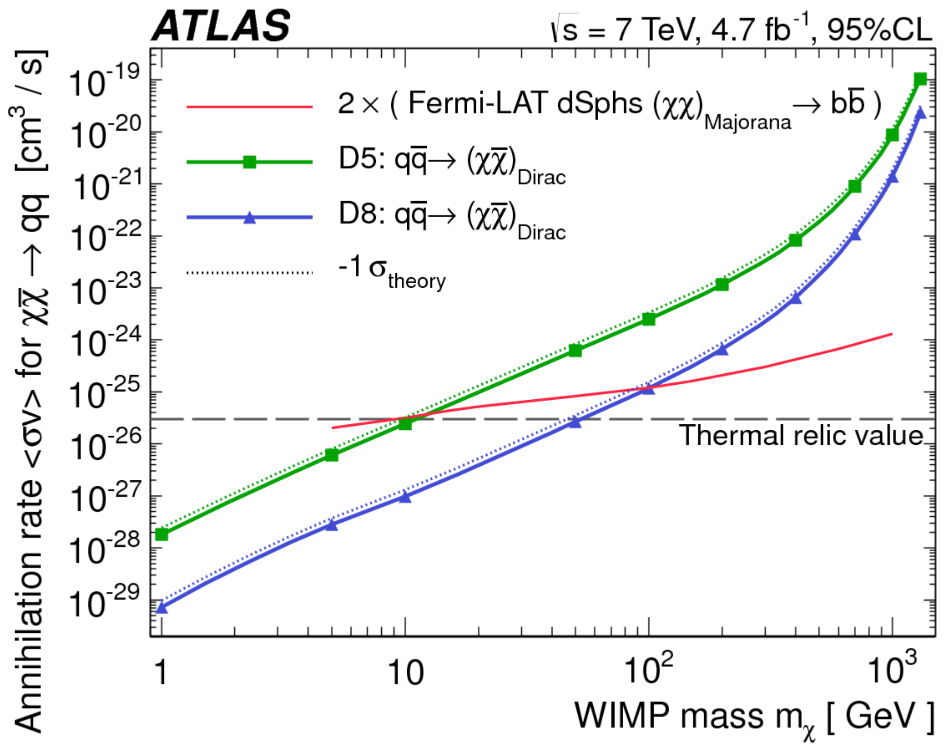
More examples



[arXiv:1408.3583](https://arxiv.org/abs/1408.3583)

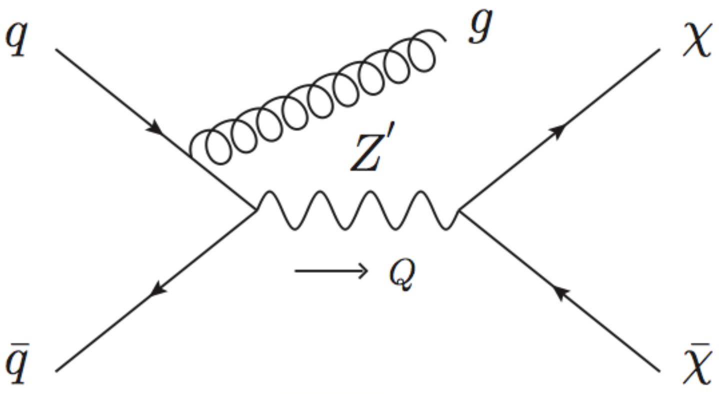


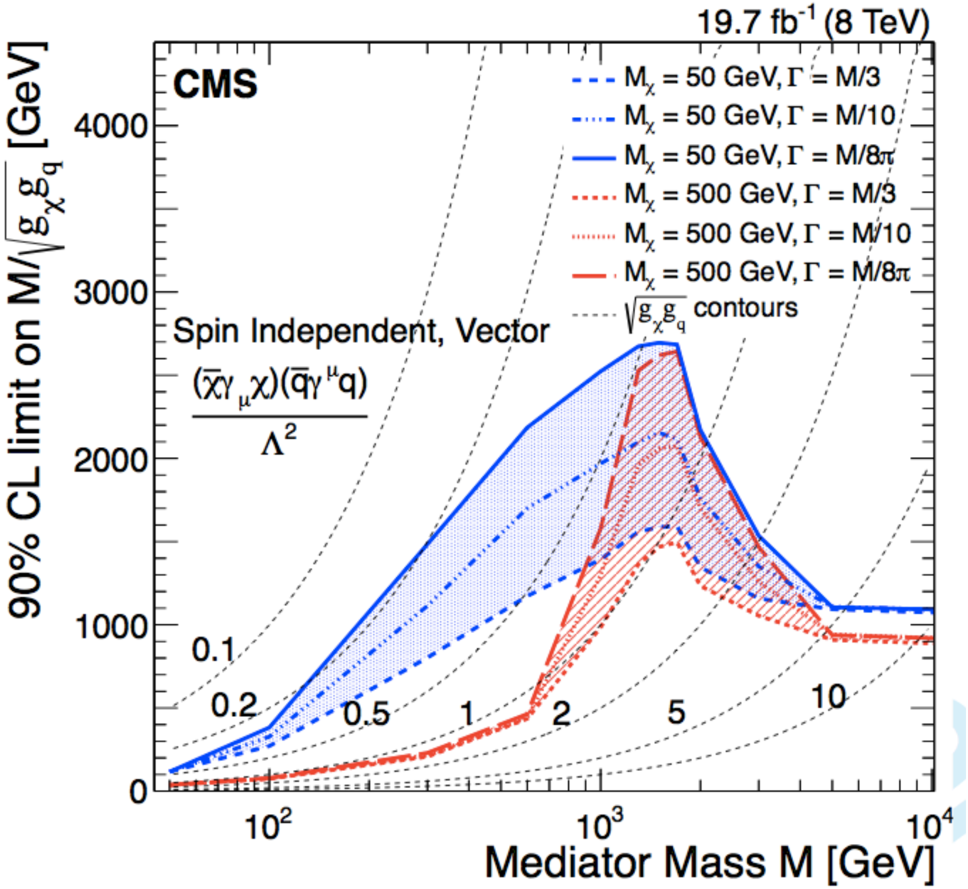
[arXiv:1210.4491](https://arxiv.org/abs/1210.4491)



EFT Validity – CMS monojets

Address with simplified models

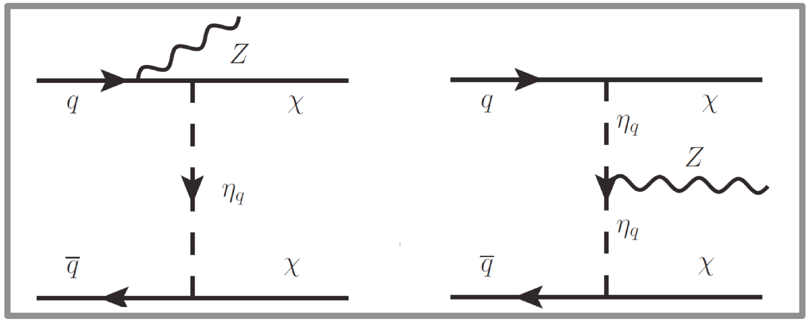


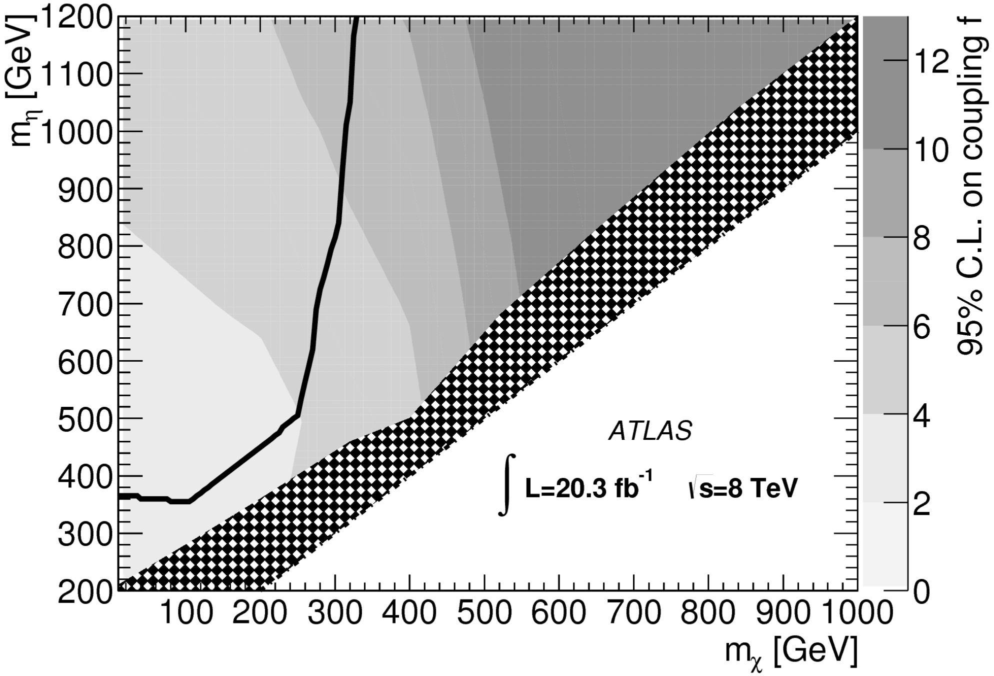


arXiv:1408.3583

EFT validity – ATLAS mono-Z(ll)

arXiv:1404.0051





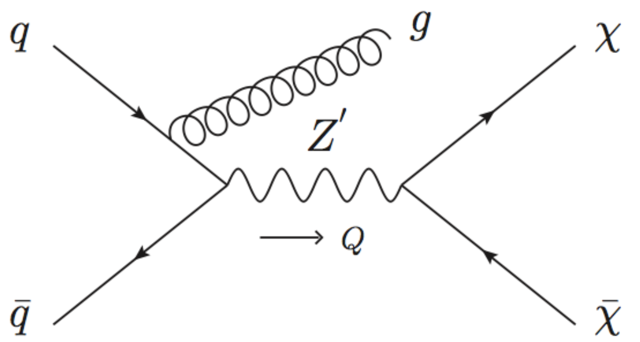
t-channel diagram, scalar colored mediator η

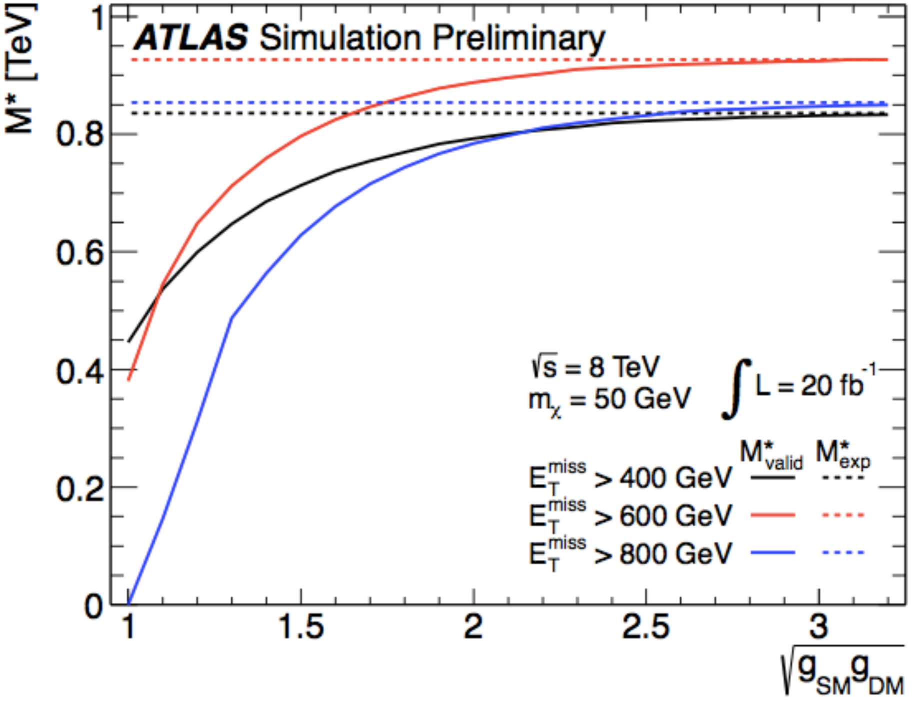
Limits on χ-η coupling constant f shown. Above black line, lower limit on f below f from relic abundance calculations.

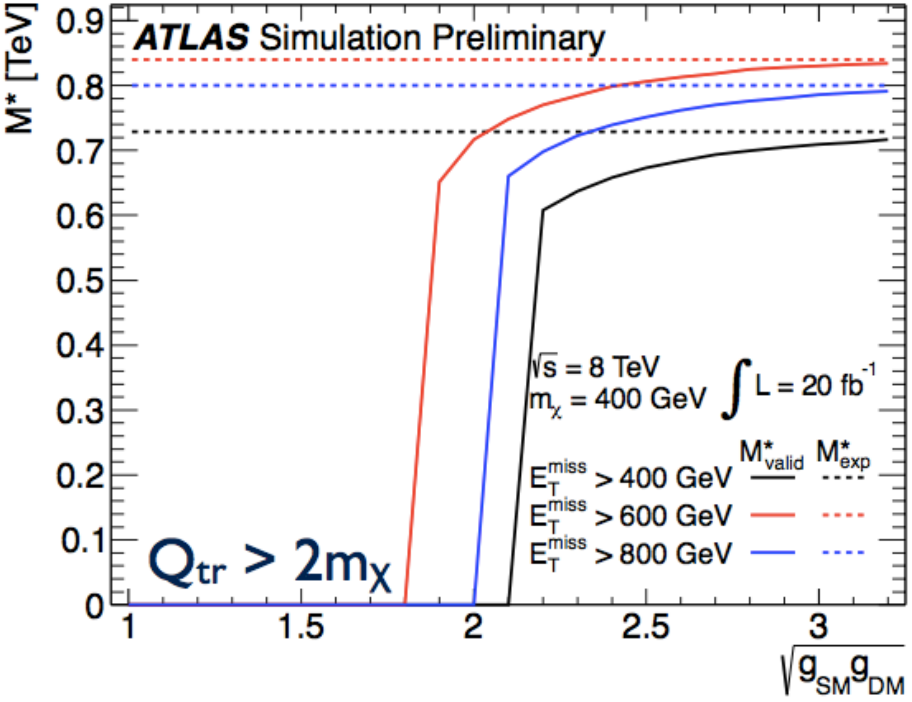
EFT validity

Check event kinematics

$$Q_{tr} < M_{med} = \sqrt{g_q g_\chi}\, M^*$$







ATLAS-PHYS-PUB-2014-007

Run-II prospects

ATL-PHYS-PUB-2014-007

Event selection

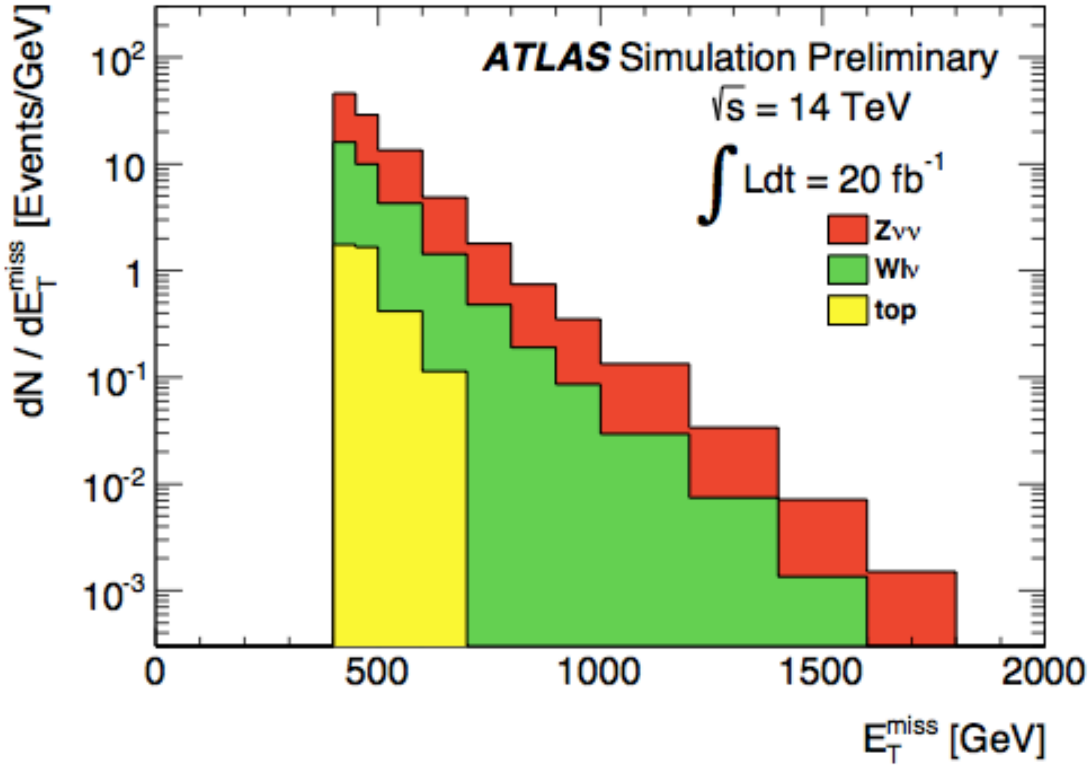
- leading jet pT > 300 GeV
- $\Delta\varphi$(jet, MET) > 0.5
- electron and muon veto
- at most two jets
    - pT > 30 GeV @ 8 TeV
    - pT > 50 GeV @ 14 TeV
- SR defined by MET > 400, 600, 800 GeV

Backgrounds

- pure MC study

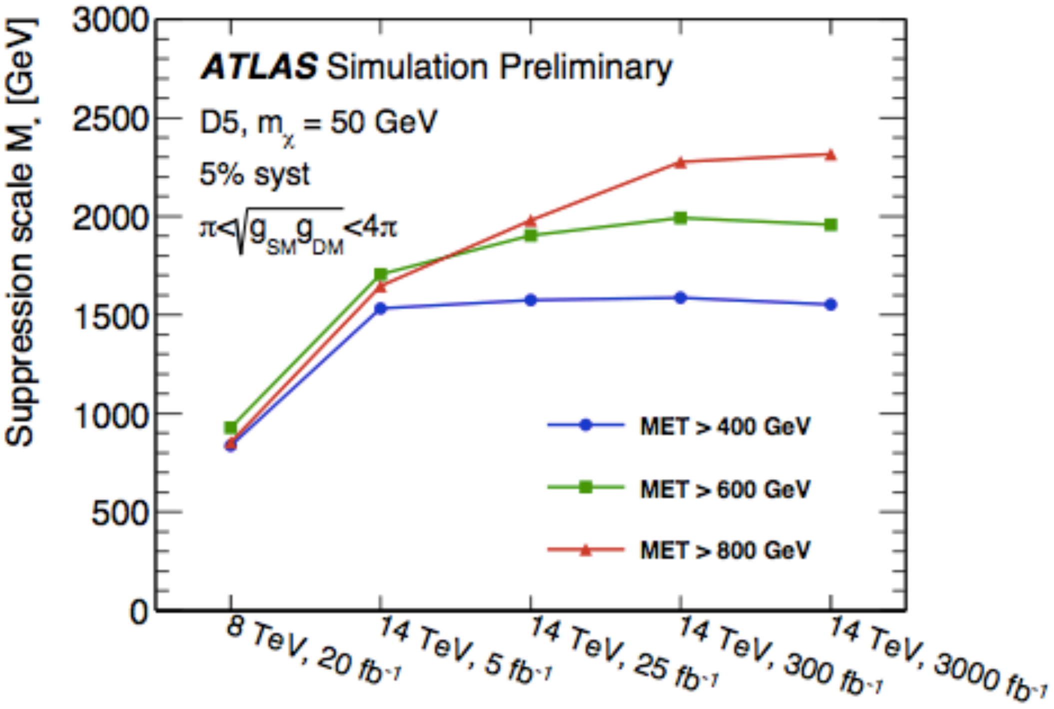
Systematic uncertainties

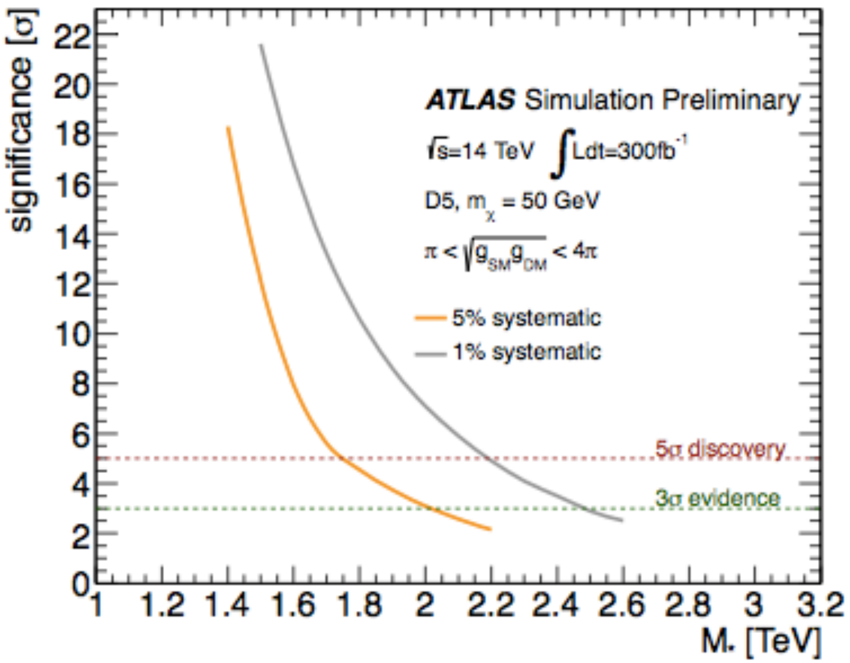
- 5% reasonable expectation for early Run-II
- 1% ultimate goal for HL-LHC



Run-II prospects

- Already first data from Run-II will bring improvements in sensitivity to DM.
  - Exclusion limits can be improved by factor of 2 with first few fb^{-1}.
  - 5σ discovery potential for M* ~ 1.7 TeV with 300 fb^{-1}.





Conclusions

- The one model independent result we have about dark matter: we have not discovered it yet at the LHC!

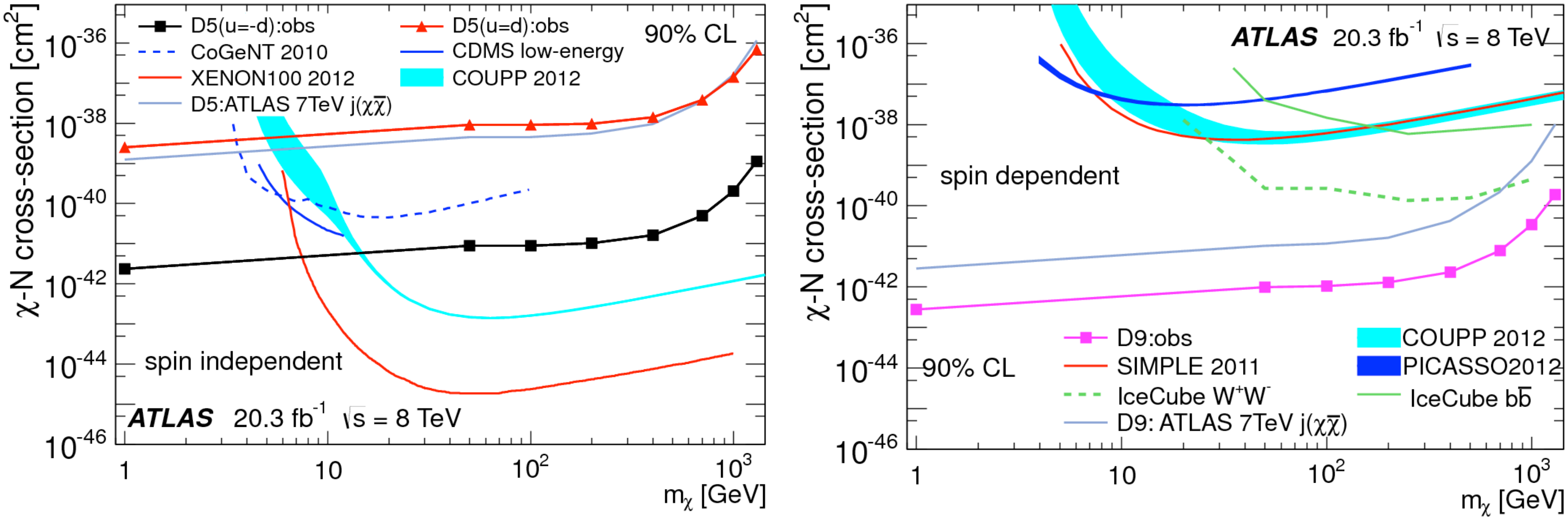
- Intense search program ongoing

- Full steam ahead to run-II at 13 TeV

David Berge / GRAPPA & Nikhef

Mono-W/Z→qq vs Monojets

arXiv:1309.4017



Constructive interference with potentially large effect!