Going one up on Dark matter, STRONGLY

Implementing QCD corrections for Dark Matter computations

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Based on

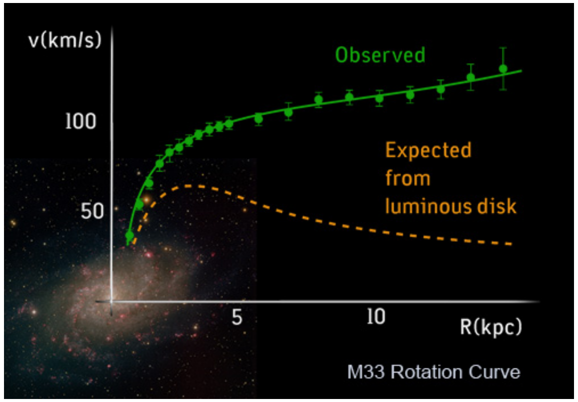
"Leading QCD corrections for indirect dark matter searches: A fresh look"

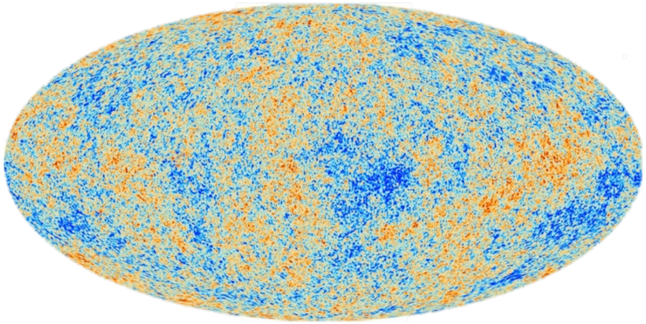
Phys. Rev. D 93, 043529

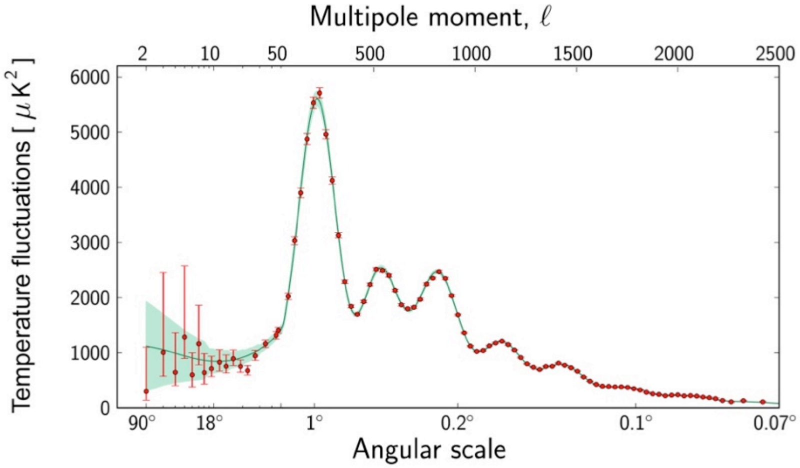
with **Torsten Bringmann and Ahmad Galea**

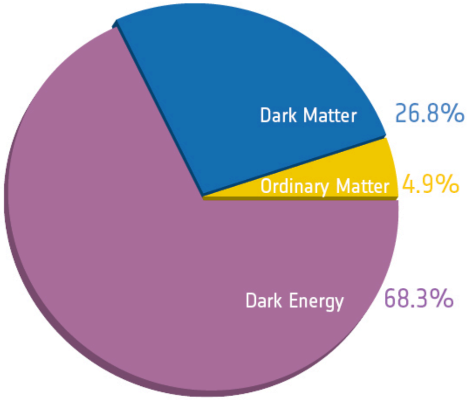
Dark Matter

What we know?







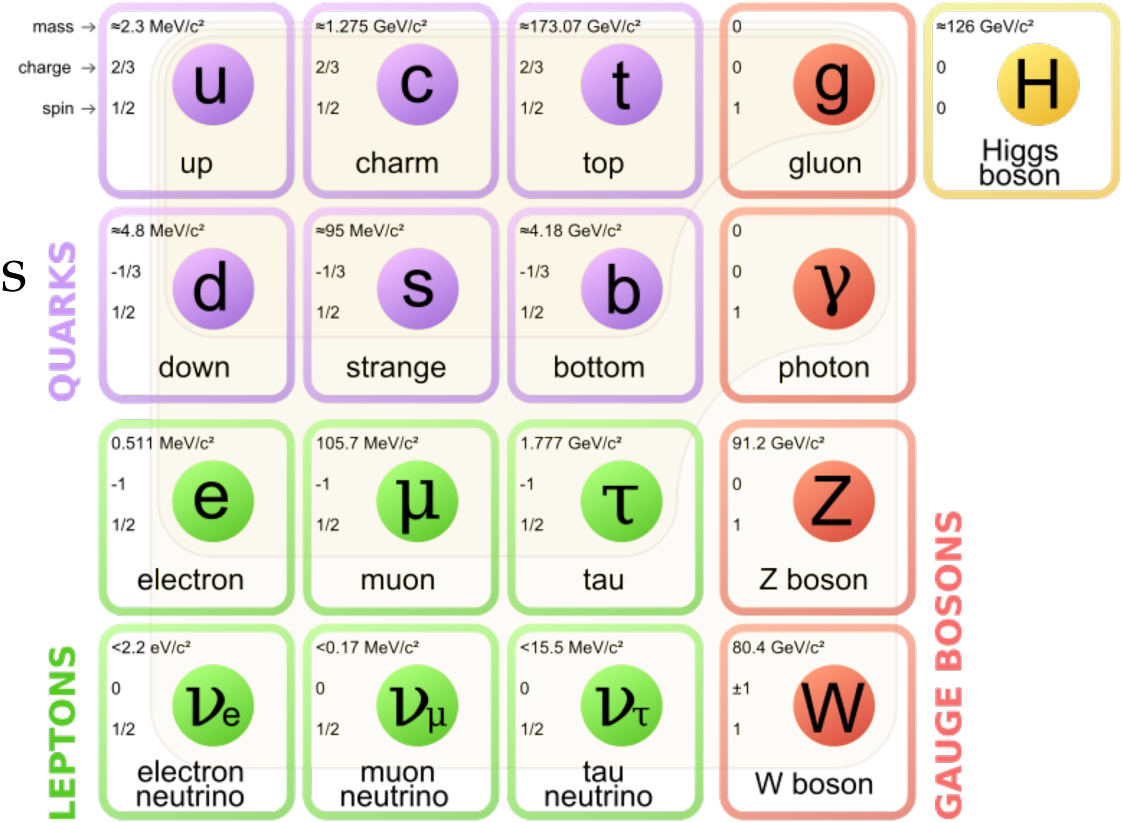


What?

Desired Properties

1. Electrically neutral
2. No strong interactions
3. Massive
4. Stable
5. Collisionless
6. Relic density
7. Structure Formation

$$\boxed{\Omega_\nu h^2 < 0.0062}$$



mass → charge → spin →	≈2.3 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈173.07 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c² 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c² -1 1/2 e electron	105.7 MeV/c² -1 1/2 μ muon	1.777 GeV/c² -1 1/2 τ tau	91.2 GeV/c² 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	80.4 GeV/c² ±1 1 W W boson	

Standard model particles cannot make the DM

New Particles?

Constituents

1. Primordial black holes
2. Axions
3. Sterile neutrinos
4. Weakly interacting Massive Particles (WIMPs)

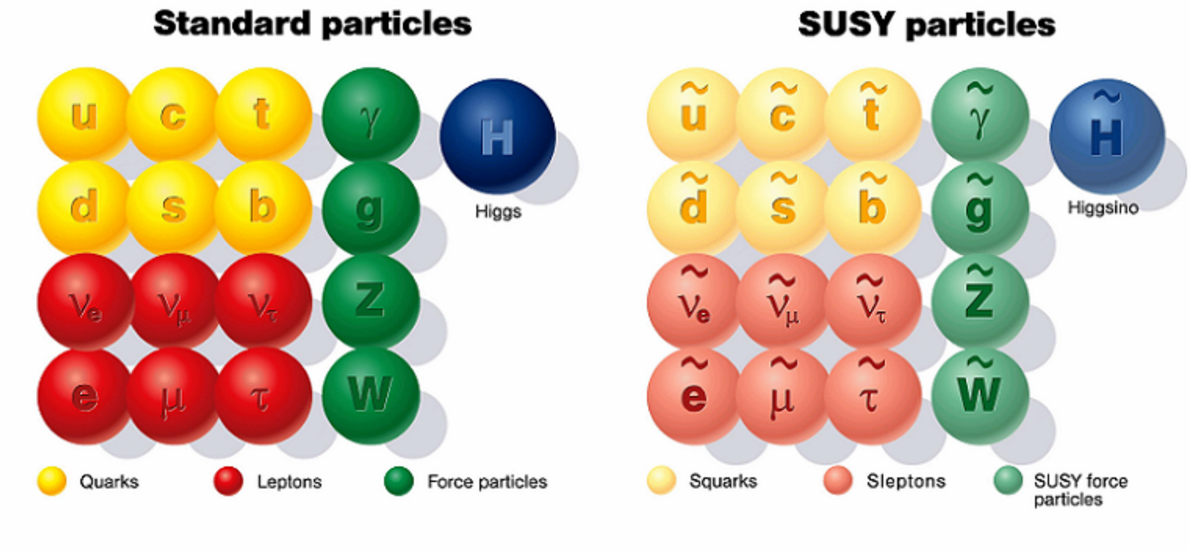
Theories

1. Supersymmetry
2. Extra Dimensions
3. Non-thermally produced, Axions, FIMPs

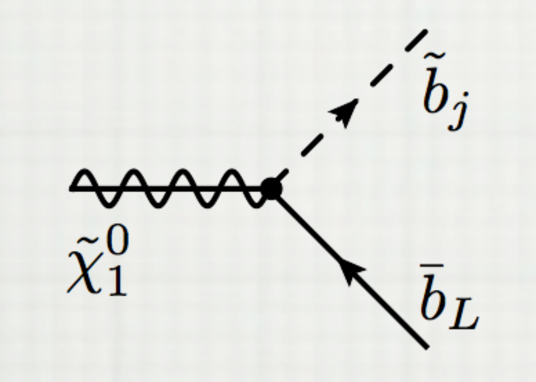
And many more!

For this talk we will consider WIMPs in MSSM framework

MSSM



R-Parity



Neutralinos

Higgs	$(H_u^+ \quad H_u^0)$	0	H_u
	$(H_d^0 \quad H_d^-)$	0	H_d
W bosons	$W^0, W^\pm$	1	
B boson	B^0	1	

Neutralinos

$$\chi_i^0 = N_{i1}\tilde{B} + N_{i2}\tilde{W}^3 + N_{i3}\tilde{H}_1^0 + N_{i4}\tilde{H}_2^0$$

$N_{01} \sim 1$, Bino Like
$N_{02} \sim 1$, Wino Like
$N_{03}(N_{04}) \sim 1$, Higgsino Like

For this talk, the lightest neutralino is DM

Higgs

In MSSM we have two complex doublets, meaning 8 d.o.f.

Higgs	$(H_u^+ \quad H_u^0)$	0	H_u
	$(H_d^0 \quad H_d^-)$	0	H_d

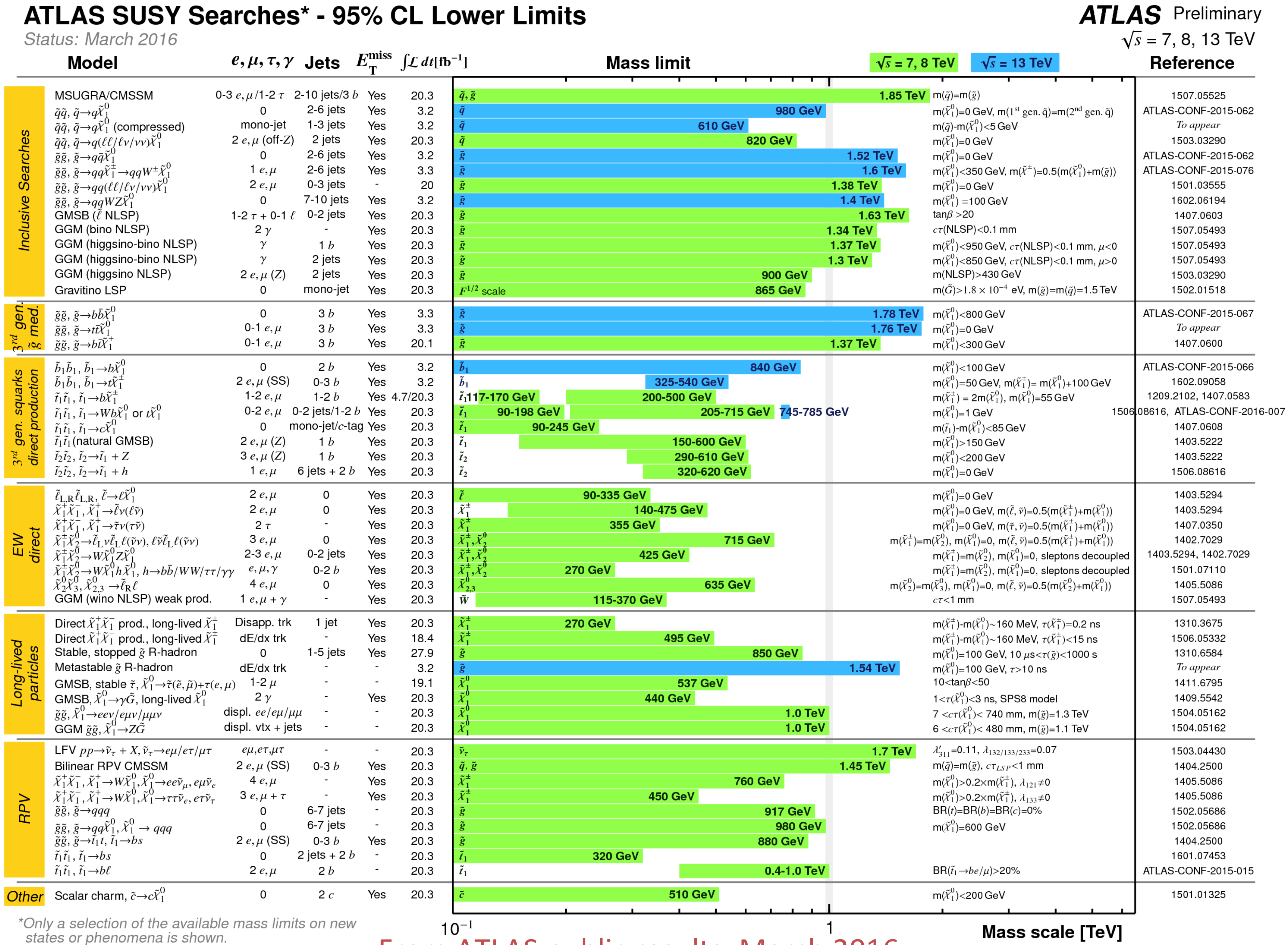
After EWSB

Pseudoscalar Higgs, A

Two neutral scalar Higgs, h, H

Two charged higgs, $H^{\pm}$

Now we know that, $m_h \sim 125 \text{ GeV}$



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

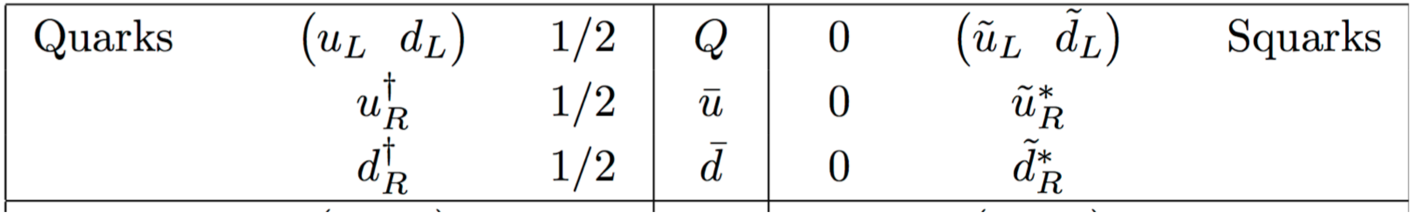
🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	🟩 $\tilde{q},\tilde{g}$ 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	3.2	🟦 $\tilde{q}$ 980 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2015-062
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde{q}$ 610 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	*To appear*
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	🟩 $\tilde{q}$ 820 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	3.2	🟦 $\tilde{g}$ 1.52 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2015-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	2-6 jets	Yes	3.3	🟦 $\tilde{g}$ 1.6 TeV	m($\tilde{\chi}_1^0$)<350 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2015-076
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	🟩 $\tilde{g}$ 1.38 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-10 jets	Yes	3.2	🟦 $\tilde{g}$ 1.4 TeV	m($\tilde{\chi}_1^0$) =100 GeV	1602.06194
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	🟩 $\tilde{g}$ 1.63 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	🟩 $\tilde{g}$ 1.34 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	🟩 $\tilde{g}$ 1.37 TeV	m($\tilde{\chi}_1^0$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	🟩 $\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	🟩 $\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	3.3	🟦 $\tilde{g}$ 1.78 TeV	m($\tilde{\chi}_1^0$)<800 GeV	ATLAS-CONF-2015-067
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	3.3	🟦 $\tilde{g}$ 1.76 TeV	m($\tilde{\chi}_1^0$)=0 GeV	*To appear*
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	🟩 $\tilde{g}$ 1.37 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	🟦 $\tilde{b}_1$ 840 GeV	m($\tilde{\chi}_1^0$)<100 GeV	ATLAS-CONF-2015-066
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	3.2	🟦 $\tilde{b}_1$ 325-540 GeV	m($\tilde{\chi}_1^0$)=50 GeV, m($\tilde{\chi}_1^{\pm}$)= m($\tilde{\chi}_1^0$)+100 GeV	1602.09058
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7/20.3	🟩 $\tilde{t}_1$ 117-170 GeV 🟩 200-500 GeV	m($\tilde{\chi}_1^{\pm}$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	🟩 $\tilde{t}_1$ 90-198 GeV 🟩 205-715 GeV 🟦 745-785 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, ATLAS-CONF-2016-007
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	🟩 $\tilde{t}_1$ 90-245 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	🟩 $\tilde{t}_1$ 150-600 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	🟩 $\tilde{t}_2$ 290-610 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	🟩 $\tilde{t}_2$ 320-620 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1506.08616
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	🟩 $\tilde{\ell}$ 90-335 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	🟩 $\tilde{\chi}_1^{\pm}$ 140-475 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	🟩 $\tilde{\chi}_1^{\pm}$ 355 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	🟩 $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 715 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	0-2 jets	Yes	20.3	🟩 $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 425 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 270 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}_{2,3}^0$ 635 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
	GGM (wino NLSP) weak prod.	1 $e,\mu+\gamma$	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
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, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}_1^{\pm}$ 495 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$ 850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$ 1.54 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	*To appear*
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}_1^0$ 440 GeV	1<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	🟩 $\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau$($\tilde{\chi}_1^0$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	20.3	🟩 $\tilde{\nu}_\tau$ 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q},\tilde{g}$ 1.45 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	🟩 $\tilde{\chi}_1^{\pm}$ 760 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
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	6-7 jets	-	20.3	🟩 $\tilde{g}$ 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	🟩 $\tilde{g}$ 980 GeV	m($\tilde{\chi}_1^0$)=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{g}$ 880 GeV		1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	🟩 $\tilde{t}_1$ 320 GeV		1601.07453
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	🟩 $\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	🟩 $\tilde{c}$ 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

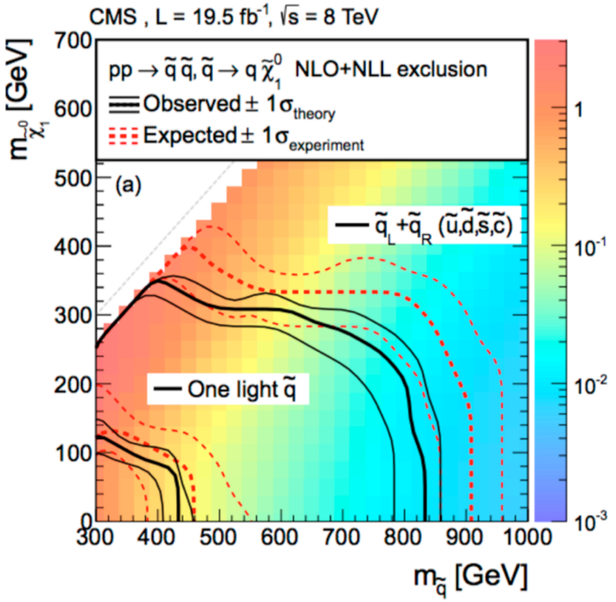
*Only a selection of the available mass limits on new states or phenomena is shown.

From ATLAS public results, March 2016

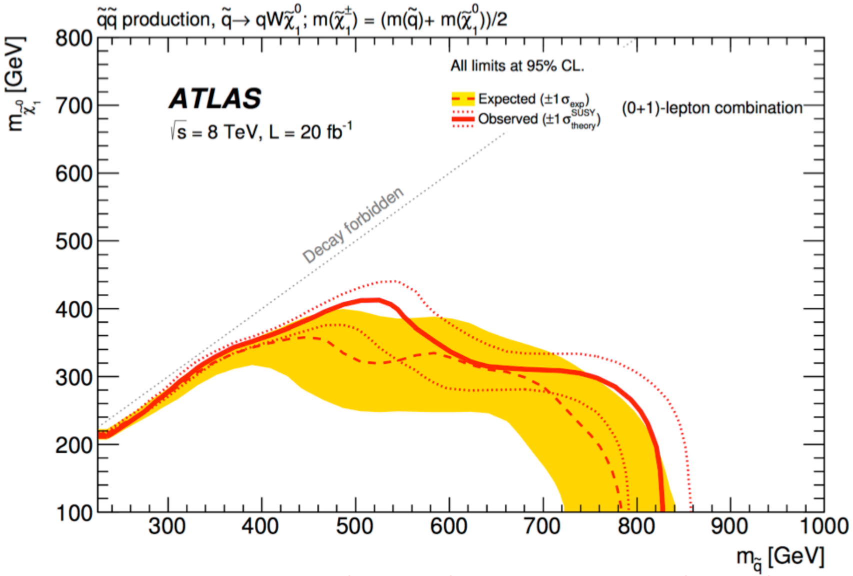
Squarks



Quarks	$(u_L \quad d_L)$	$1/2$	Q	0	$(\tilde{u}_L \quad \tilde{d}_L)$	Squarks
	$u_R^\dagger$	$1/2$	$\bar{u}$	0	$\tilde{u}_R^*$	
	$d_R^\dagger$	$1/2$	$\bar{d}$	0	$\tilde{d}_R^*$	



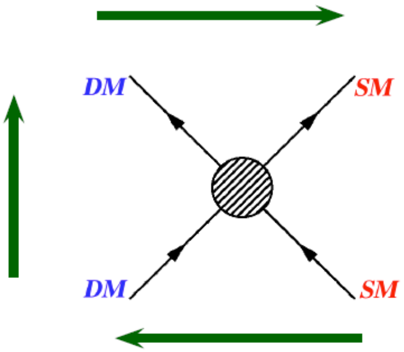
S. Chatrchyan et al. (CMS), JHEP 06, 055 (2014)

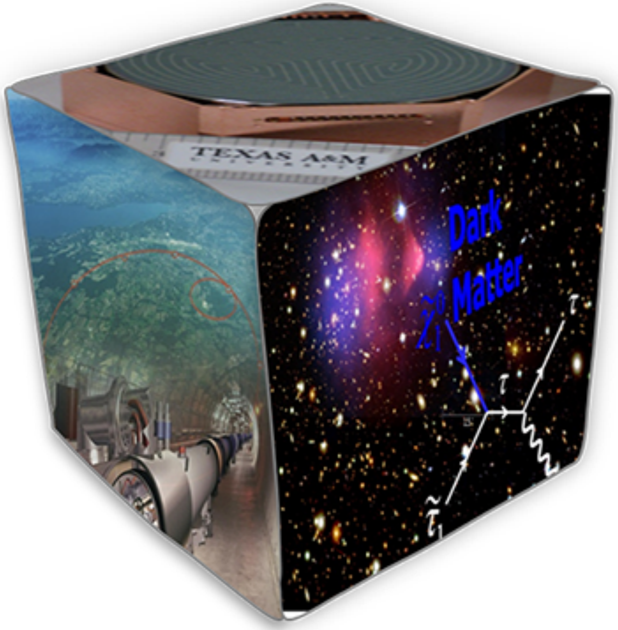


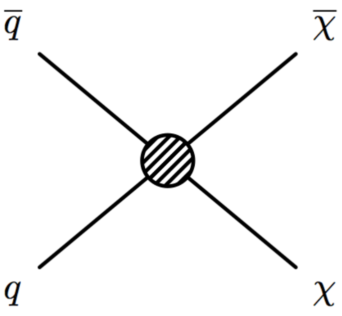
G. Aad et al. (ATLAS), JHEP 10, 054 (2015)

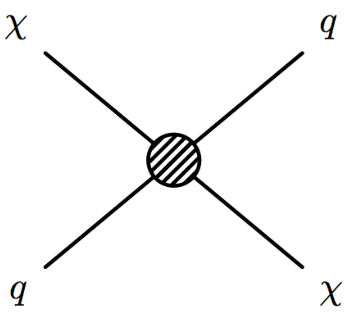
Doesn't constrain highly degenerate squark scenario!

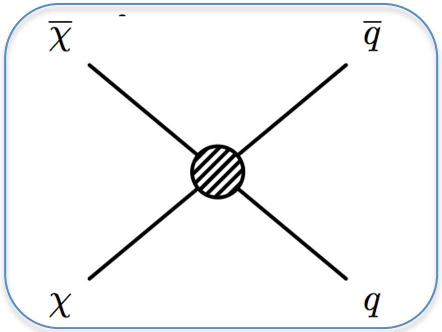
DM Interactions





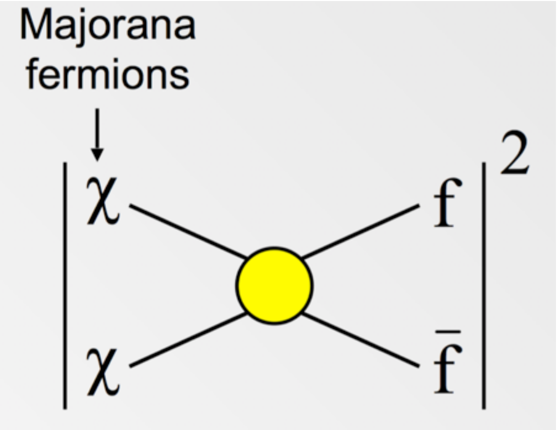






Neutralino annihilation to fermions

$$\langle \sigma v \rangle \simeq a_0 + a_1 \langle v^2 \rangle + \ldots = a_0 + \frac{3a_1}{2}\frac{T}{m_\chi} + \ldots$$



S-wave

Helicity Suppression

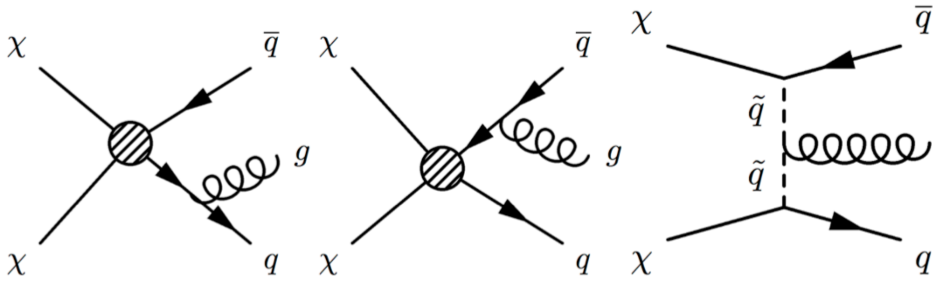
$$a_0 \propto \frac{m_f^2}{m_\chi^2}$$

P-wave

Velocity suppression

$$v \sim 10^{-3} c$$

Gauge boson bremsstrahlung



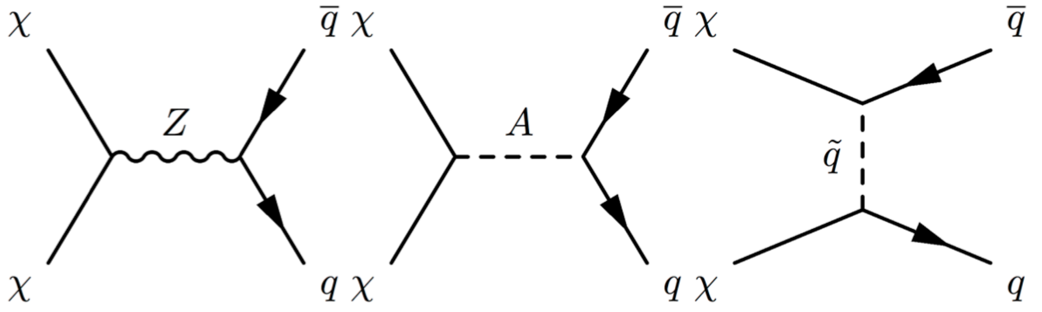
$$\langle \sigma v \rangle \simeq a_0 + a_1 \langle v^2 \rangle + \ldots = a_0 + \frac{3a_1}{2}\frac{T}{m_\chi} + \ldots$$

S-wave

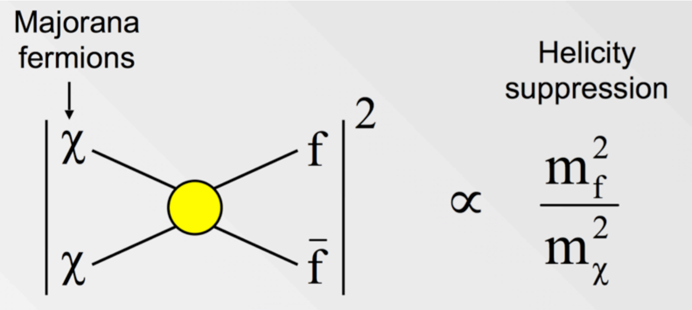
$$a_0 \propto \alpha$$

L. Bergström, Phys. Lett. B 232, 377 (1989)

Neutralino annihilation to quarks

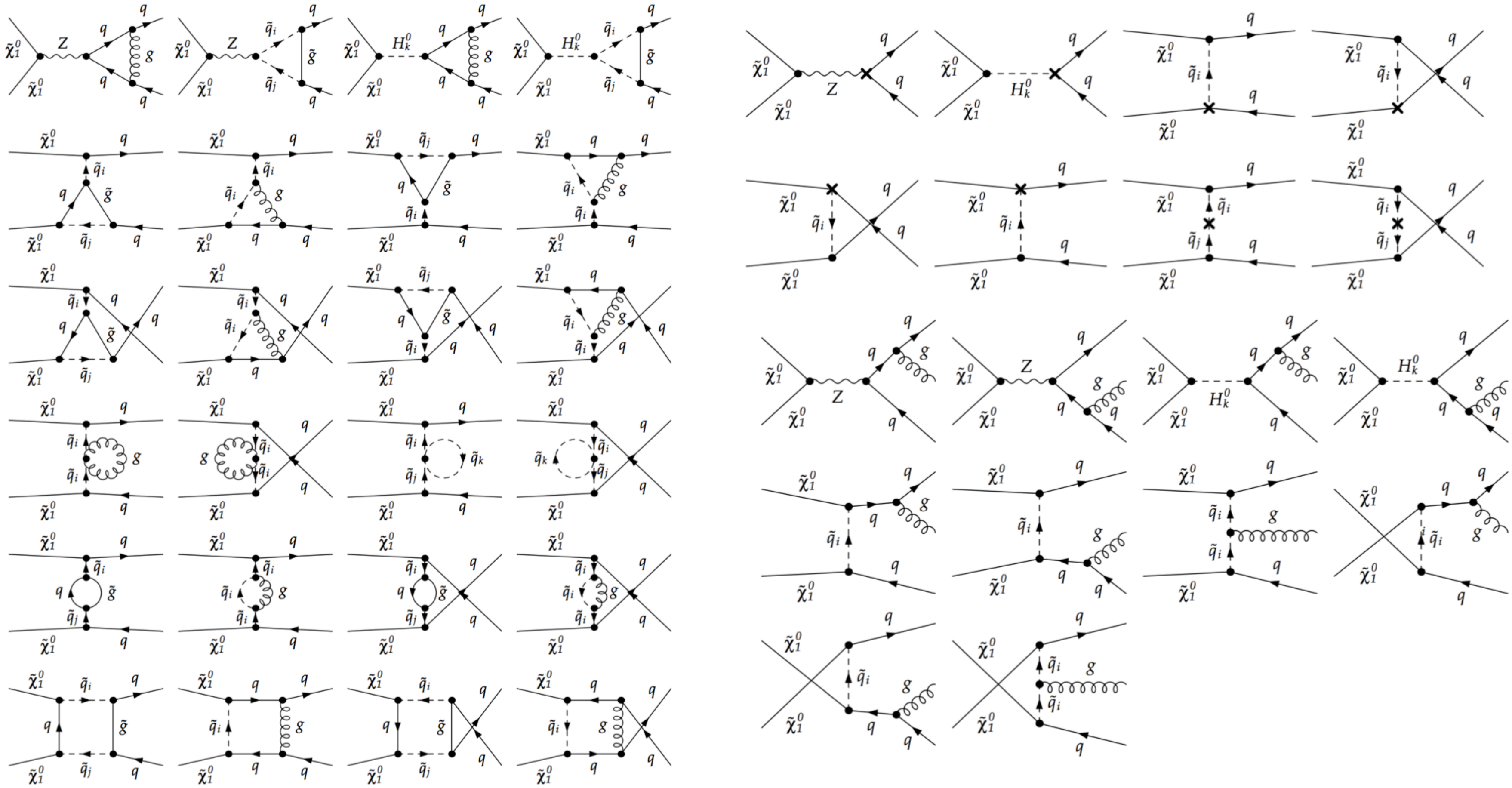


Tree level diagrams in non-relativistic limit



$$\left| \cdots \right|^2 \propto \frac{m_f^2}{m_\chi^2}$$

Neutralino annihilation to quarks



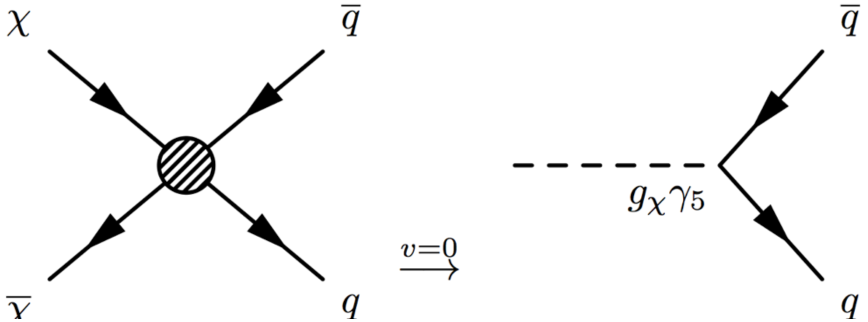
Figures from B. Herrmann et al., 2009

Non-Relativistic limit

For Majorana pair

L	**S**	$\mathbf{P = (-)^{L+1}}$	$\mathbf{C = (-)^{L+S}}$	$\mathbf{^{2S+1}L_J}$	$\mathbf{J^{PC}}$	**Name**	**Dirac Op**	$\mathbf{v^{2L}}$
C-even states								
0	0	$-$	$+$	$^1S_0$	0^{-+}	pseudo-scalar	$i\gamma_5$	v^0
1	1	$+$	$+$	$^3P_0$	0^{++}	scalar	1	v^2
1	1	$+$	$+$	$^3P_1$	1^{++}	axial-vector	$\gamma_5\gamma^k$	v^2
0	0	$-$	$+$	$^1S_0$	0^{-+}		$\gamma_5\gamma^0$	v^0

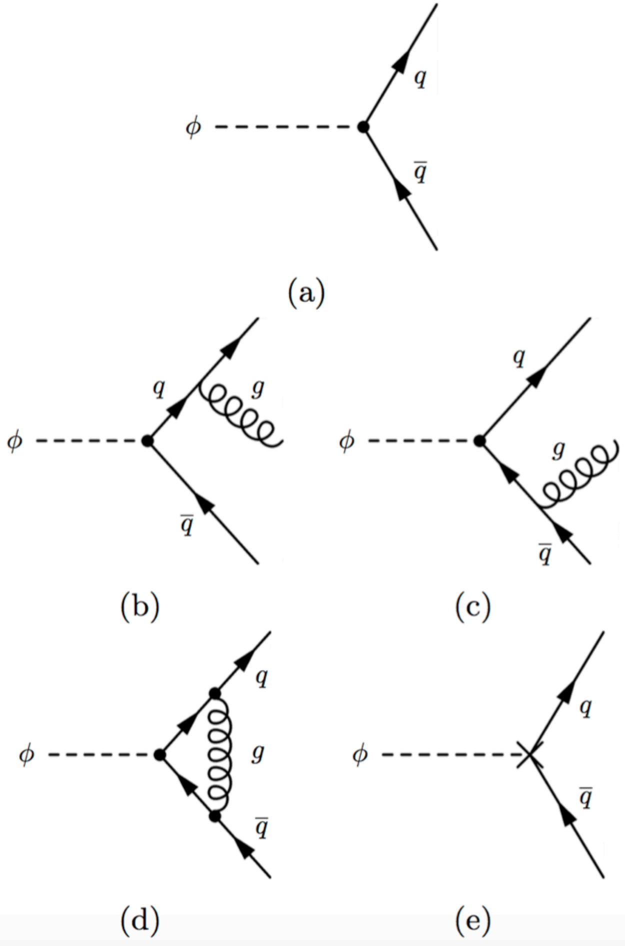
Table from T. Weiler, AIP Conf. Proc. 1534, 165 (2013)



Pseudoscalar approximation

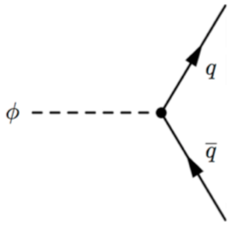
$$\mathcal{L}_{\text{int}}^{\text{simp}} = -g_p \phi \bar{q} i \gamma^5 q - \frac{1}{\Lambda_a} \partial_\mu \phi \bar{q} \gamma^\mu \gamma^5 q$$

with $m_\phi = 2 m_\chi$

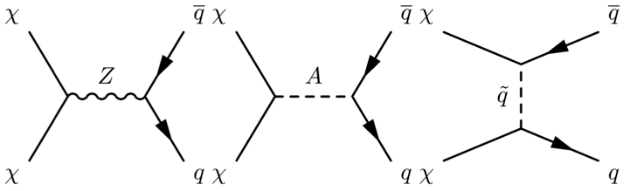


Pseudoscalar approximation

$\Gamma_0^{\text{simp}} =$



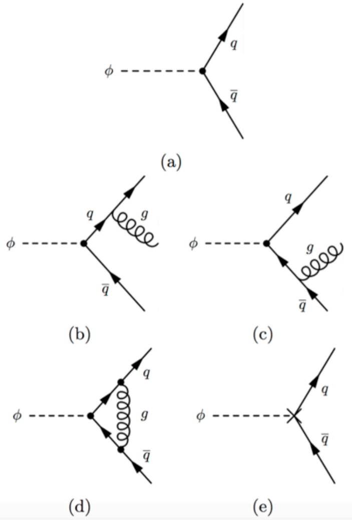
$\sigma_0^{\text{full}} =$



$$\Gamma_0^{\text{simp}} = A^2 m_\chi \sigma_0^{\text{full}} v$$

NLO result

$$\sigma_{\text{tot}}^{\text{simp}} \simeq \sigma_0^{\text{simp}} \left[1 + \frac{3\alpha_s C_F}{4\pi}\left(3 + 2\log\frac{\mu_q}{4}\right)\right]$$



(a)

(b) (c)

(d) (e)

Where we have defined $\sigma_X^{\text{simp}} v \equiv \dfrac{\Gamma_X^{\text{simp}}}{A^2 m_\chi}$

$$\mu_q \equiv m_q^2/m_\chi^2, \text{ and } C_F = 4/3$$

Pseudoscalar approximation

NLO result

$$\sigma_{\rm tot}^{\rm simp} \simeq \sigma_0^{\rm simp}\left[1+\frac{3\alpha_s C_F}{4\pi}\left(3+2\log\frac{\mu_q}{4}\right)\right]$$

Resumming the leading logarithms

$$\frac{6\alpha_s C_F}{\pi}\log\frac{\mu_q}{4} \to \left(\frac{\ln(4m_q^2/\Lambda_{QCD}^2)}{\ln(s/\Lambda_{QCD}^2)}\right)^{\frac{24}{33-2N_f}}$$

$$\frac{\overline{m}(\mu)}{\overline{m}(\mu_0)} = \left[\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right]^{\frac{2}{\pi b}} = \left[\frac{\ln(\mu_0/\Lambda_{QCD})}{\ln(\mu/\Lambda_{QCD})}\right]^{\frac{2}{\pi b}}$$

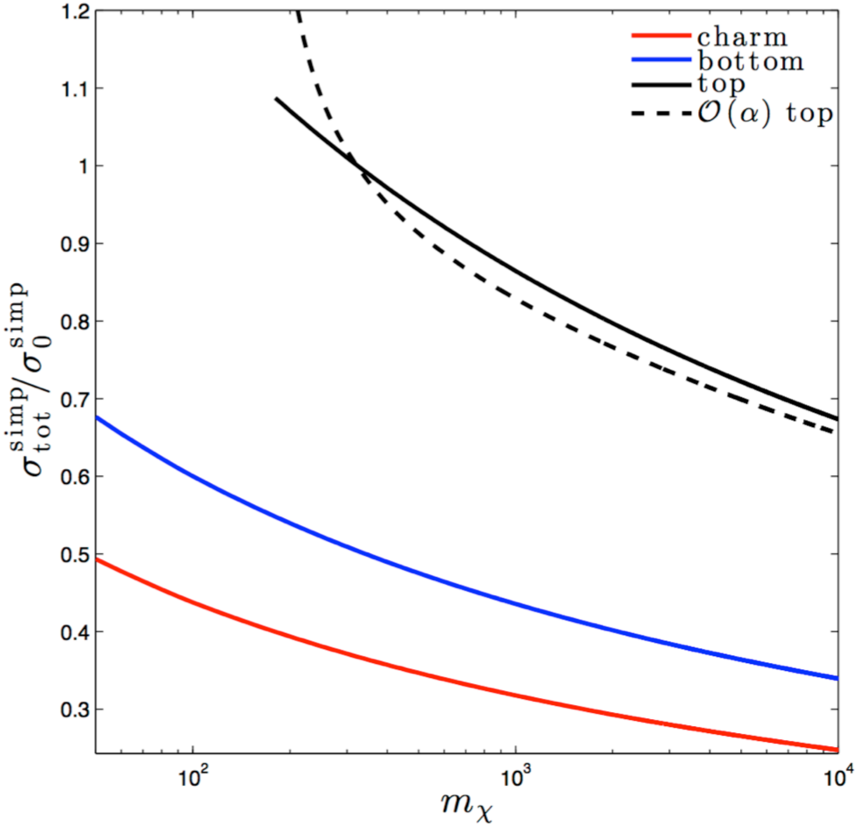
Resummed result

$$\boxed{\frac{\sigma_{\rm tot}^{\rm simp}}{\sigma_0^{\rm simp}} \simeq \frac{\overline{m}^2(\sqrt{s})}{\overline{m}^2(2m_q)}\left[1+\frac{9\alpha_s C_F}{4\pi}\right]}$$

First derived in E. Braaten and J. Leveille, Phys.Rev. D22, 715 (1980).
M. Drees and K. Hikasa, Phys.Lett. B240, 455 (1990).

Pseudoscalar approximation

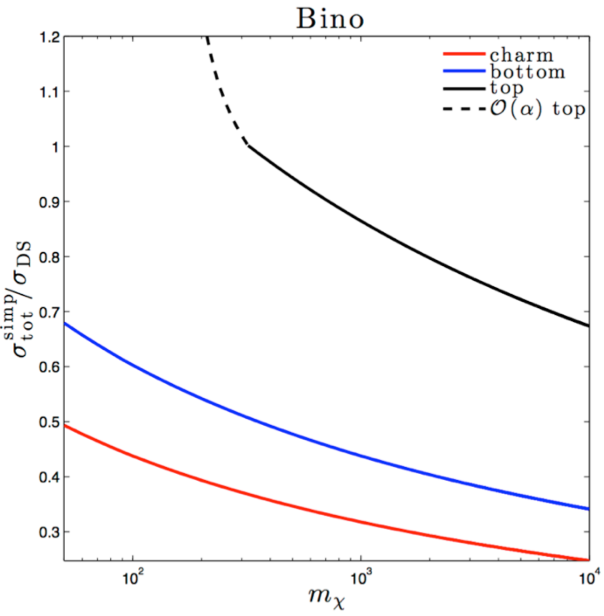
$$\frac{\sigma_{\rm tot}^{\rm simp}}{\sigma_0^{\rm simp}} \simeq \frac{\overline{m}^2(\sqrt{s})}{\overline{m}^2(2m_q)}\left[1+\frac{9\alpha_s C_F}{4\pi}\right]$$

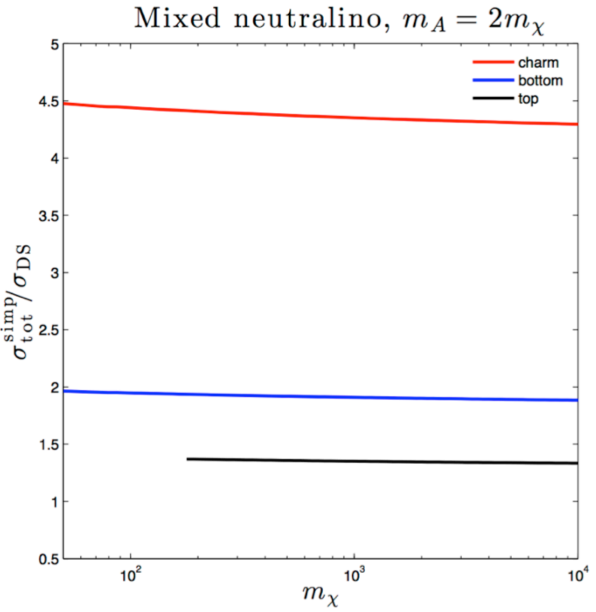


What scale to use?

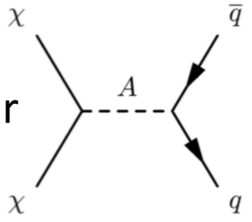
$$\boxed{\frac{\sigma^{\rm simp}_{\rm tot}}{\sigma^{\rm simp}_0} \simeq \frac{\overline{m}^2(\sqrt{s})}{\overline{m}^2(2m_q)}\left[1+\frac{9\alpha_s C_F}{4\pi}\right]}$$

$$\frac{\overline{m}(\mu)}{\overline{m}(\mu_0)} = \left[\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right]^{\frac{2}{\pi b}} = \left[\frac{\ln(\mu_0/\Lambda_{QCD})}{\ln(\mu/\Lambda_{QCD})}\right]^{\frac{2}{\pi b}}$$



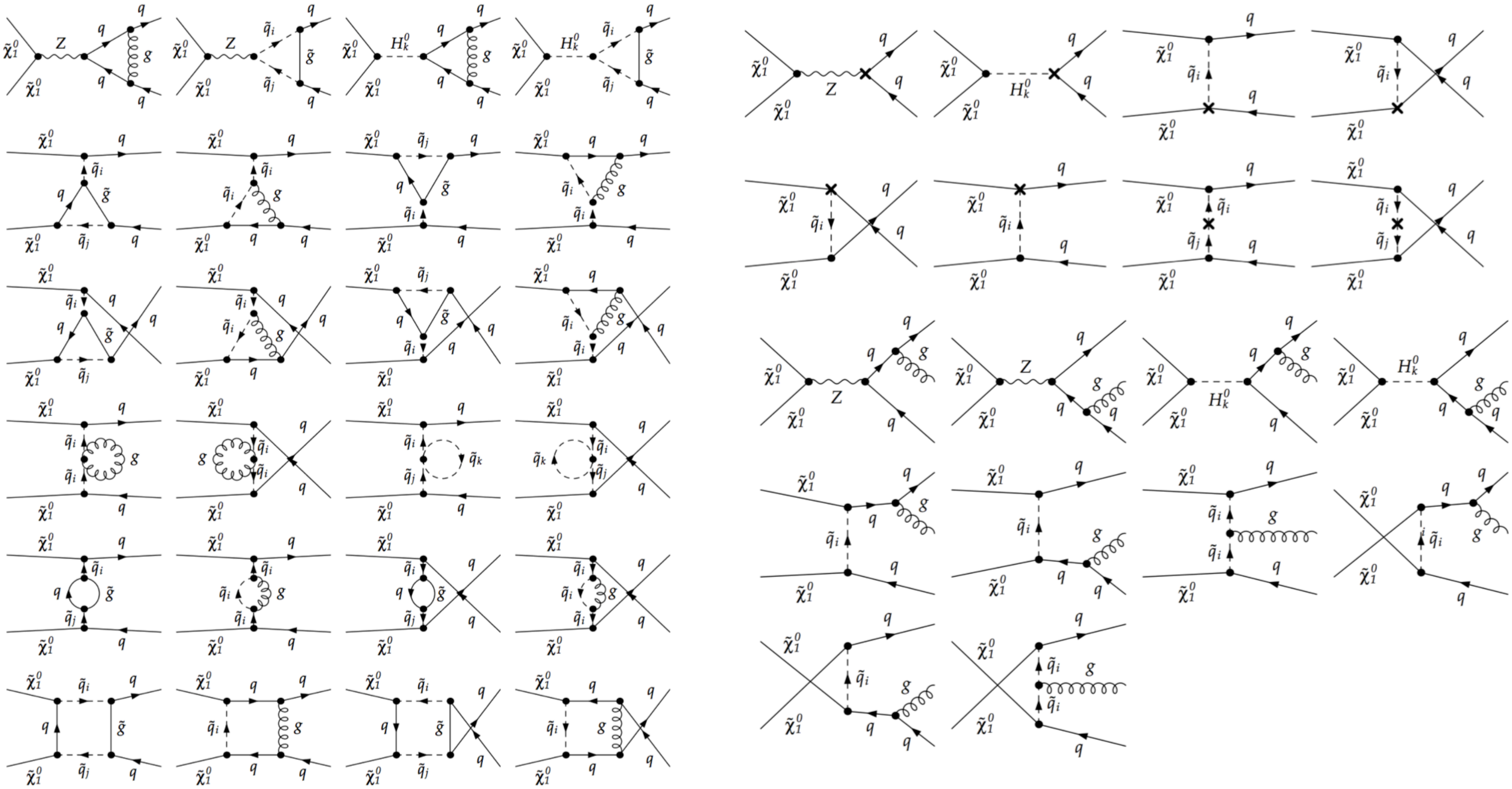


For



MicrOMEGAs and DarkSUSY are using $\frac{\overline{m}^2(\sqrt{s})}{m_q^2}$

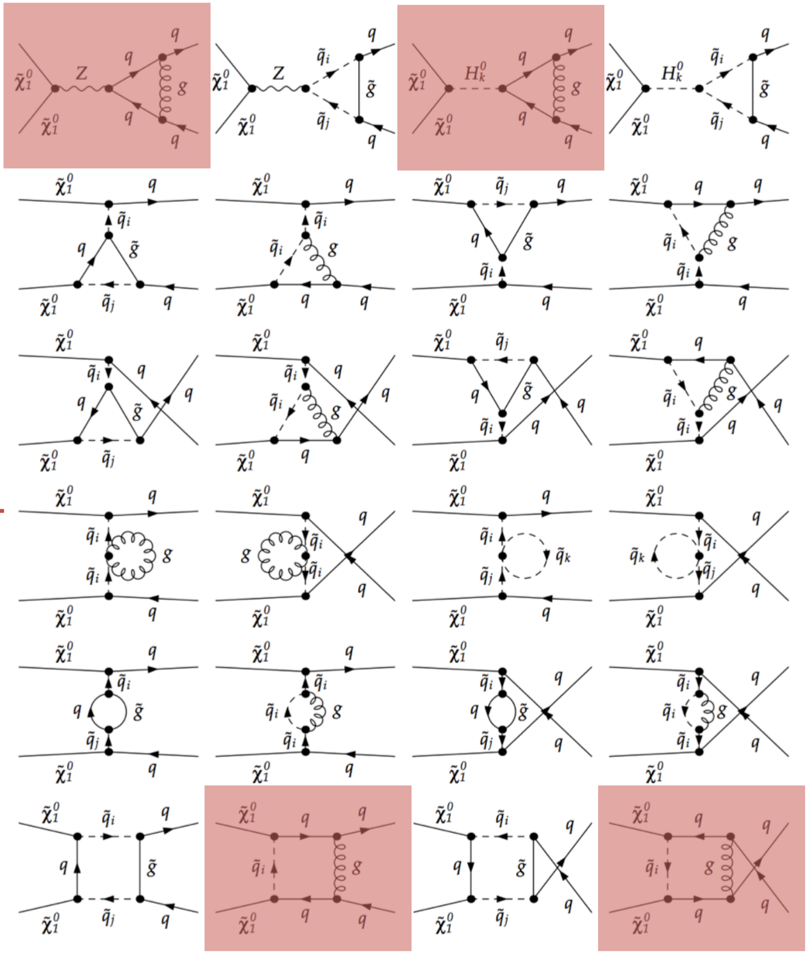
Neutralino annihilation to quarks



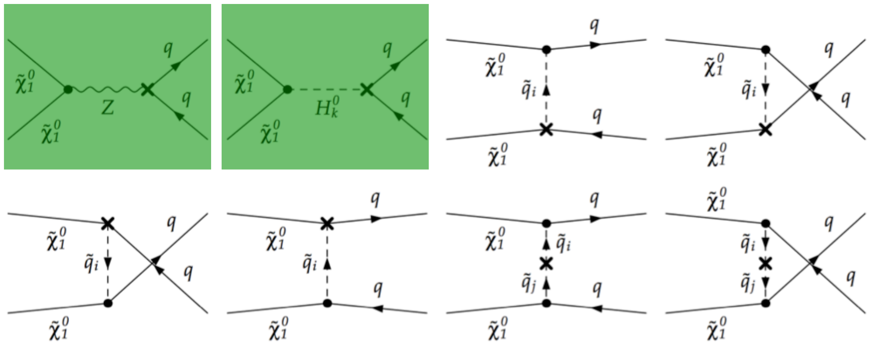
Figures from B. Herrmann et al., 2009

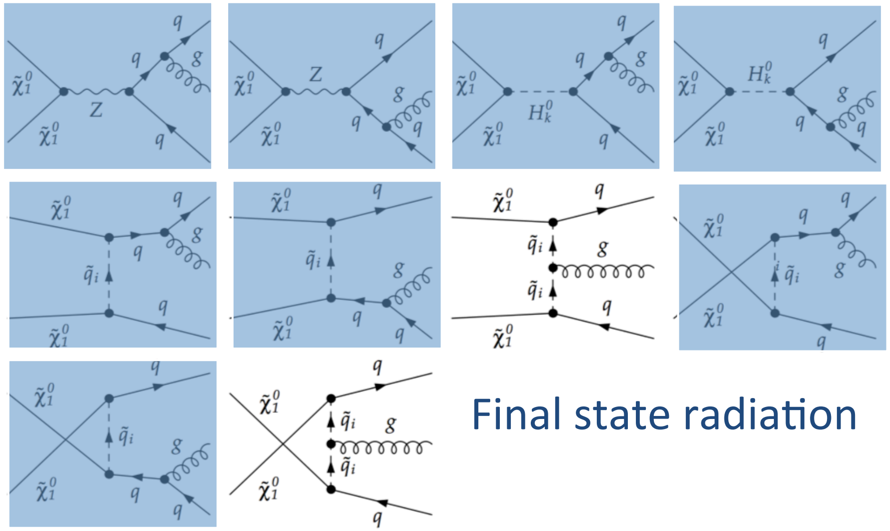
Neutralino annihilation to quarks

Gluon Loop Corrections



Counter terms

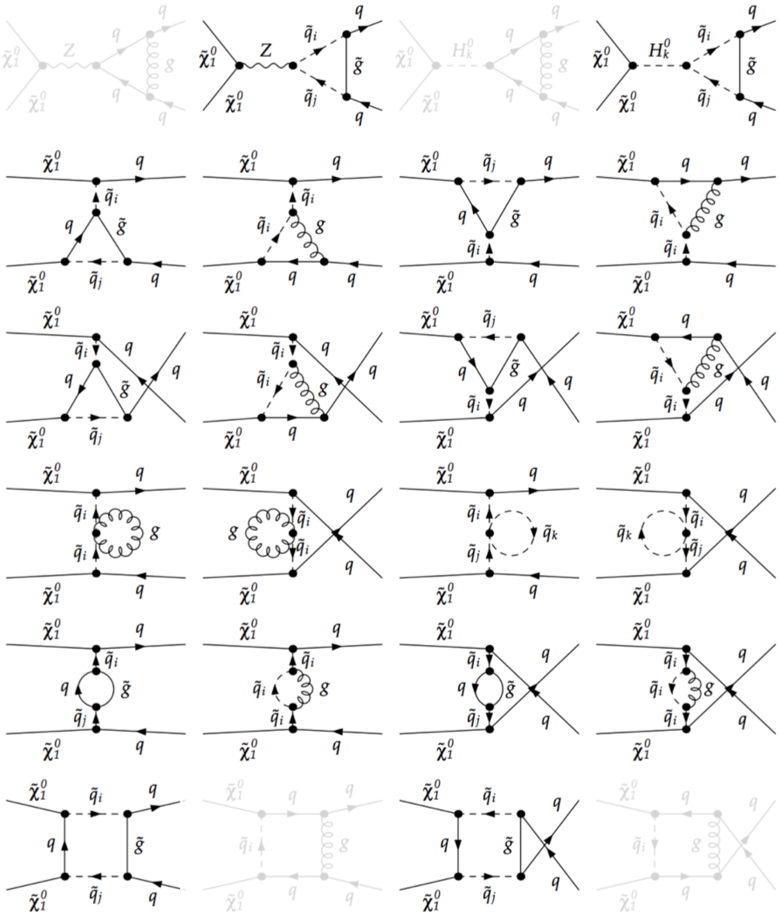


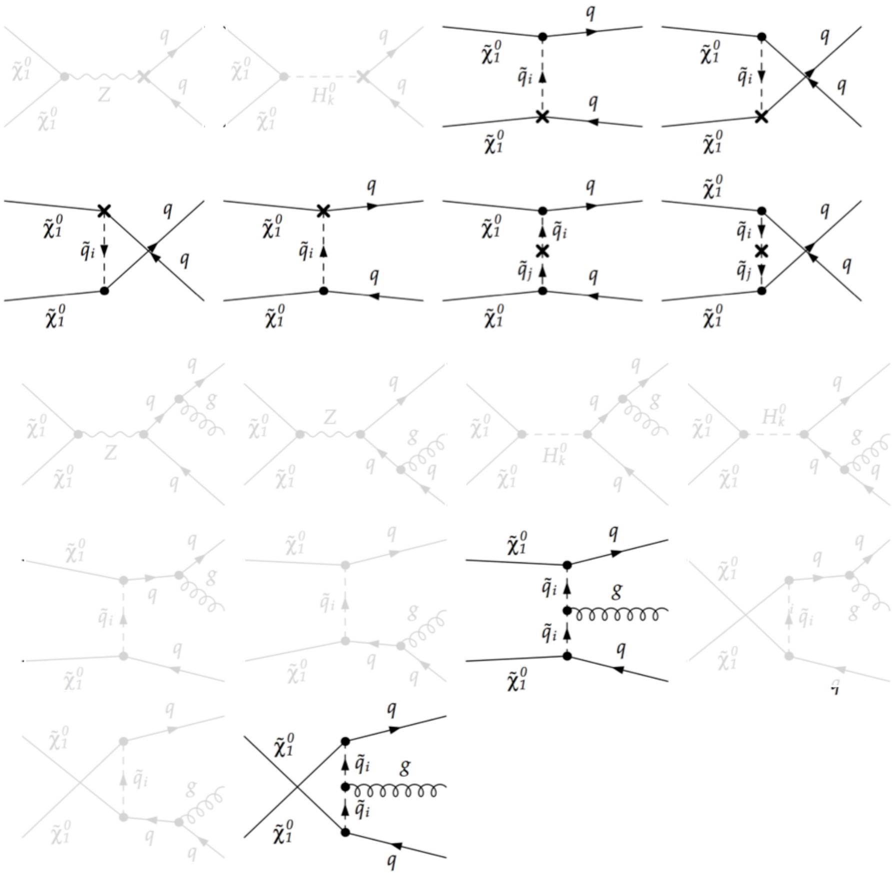


Final state radiation

Figures from B. Herrmann et al., 2009

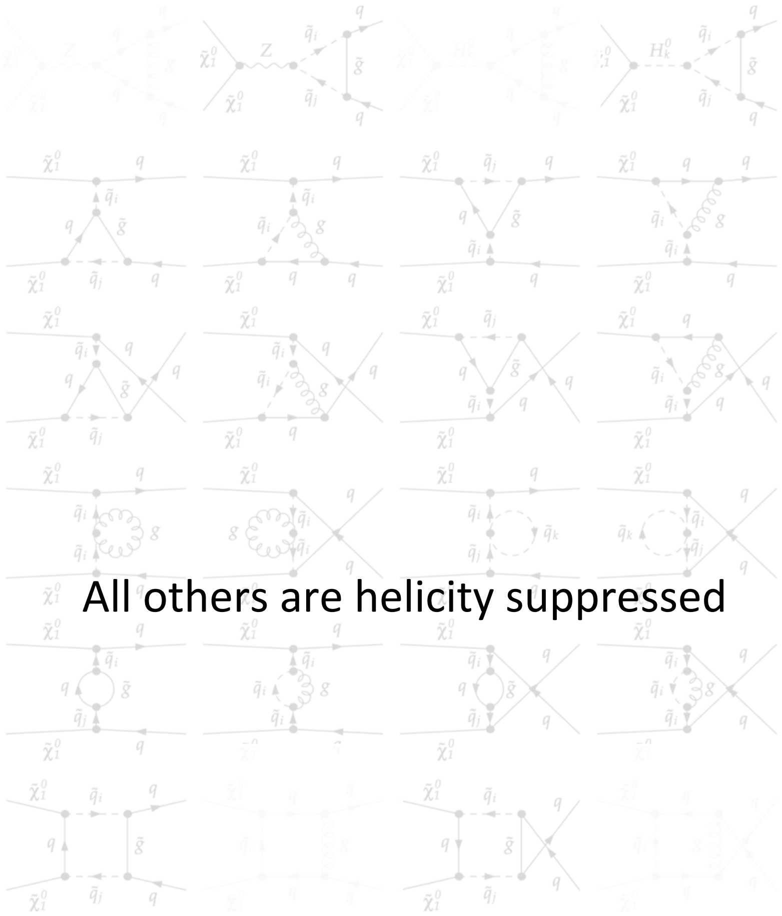
Neutralino annihilation to quarks



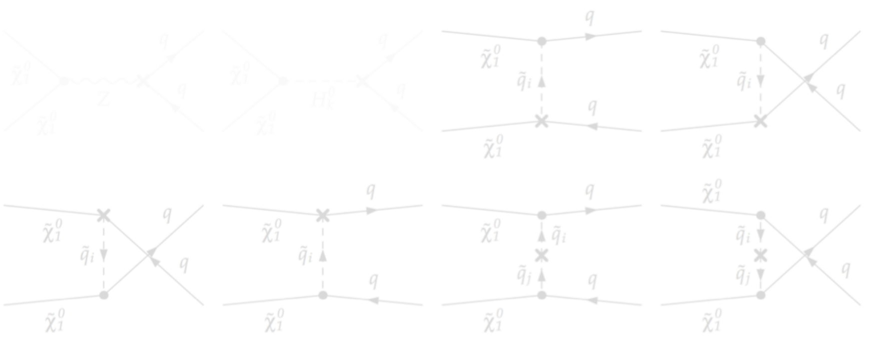


Figures from B. Herrmann et al., 2009

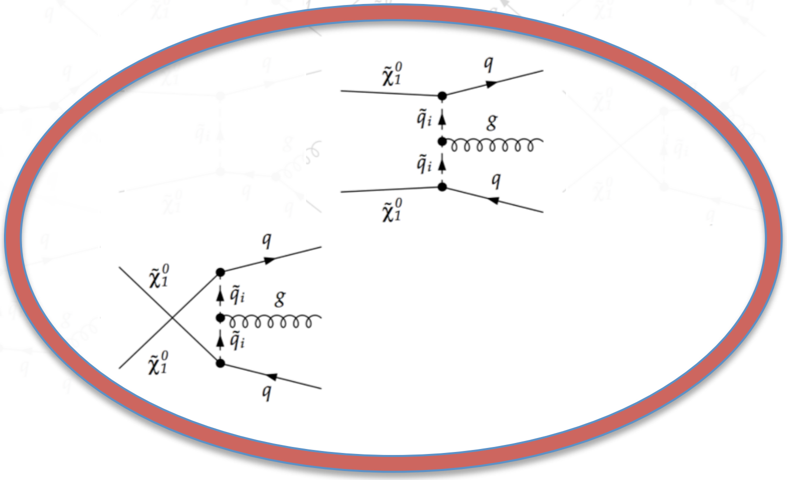
Neutralino annihilation to quarks



All others are helicity suppressed

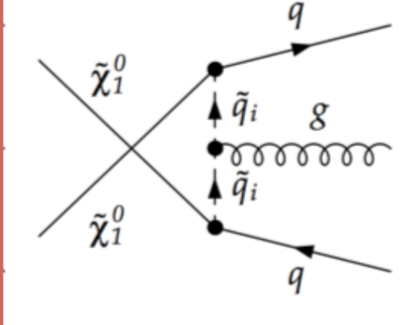


Virtual **I**nternal **B**remsstrahlung



Figures from B. Herrmann et al., 2009

VIB



VIB dominates the total cross sections for the case when

1. $m_\chi \gg m_q / \sqrt{\alpha_s / \pi}$
2. Squarks and neutralino are highly degenerate.

For totally degenerate case

$$\sigma_{3\text{body}} / \sigma_{2\text{body}} \sim (\alpha_{\text{em}}/\pi)\, m_\chi^2 / m_q^2$$

Decreases by a factor of 2(3) for mass differences of 10% (20%)

Error estimation

Models from B. Herrmann et al., 2009

	$m_0[GeV]$	$M_2[GeV]$	$A_0[GeV]$	$\tan\beta$	sign(μ)	$m_{H_u}[GeV]$	$m_{H_d}[GeV]$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{t}}$	Δ_{full} [112]([55])	Δ_{simp} [this work]	Diff. [%]
I	500	500	0	10	+	1500	1000	207.2	606.4	– (1.22)	1.22	<1
II	620	580	0	10	+	1020	1020	223.7	923.8	1.32 (1.59)	1.15	-13
III	500	500	-1200	10	+	1250	2290	200.7	259.3	1.26 (1.22)	1.25	1

	$m_0[GeV]$	$M_2[GeV]$	$A_0[GeV]$	$\tan\beta$	sign(μ)	$\frac{M_1}{M_2}$	$\frac{M_3}{M_2}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{t}}$	Δ_{full} [112]([55])	Δ_{simp} [this work]	Difference [%]
IV	300	700	-350	10	+	2/3	1/3	183.4	281.9	1.43 (1.25)	1.49	4
V	1500	600	0	10	+	1	4/9	235.6	939.0	1.34 (1.55)	1.12	-16

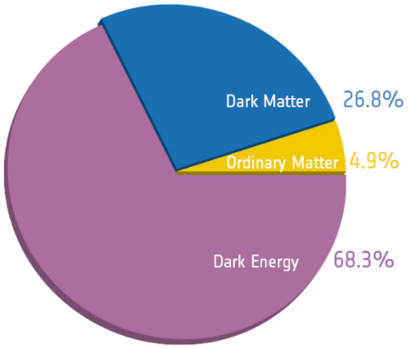
$$\Delta_{\text{full}} \equiv \sigma_{\text{tot}}^{\text{full}}/\sigma_0 \qquad \Delta_{\text{simp}} \equiv \sigma_{\text{tot}}^{\text{simp}}/\sigma_0$$

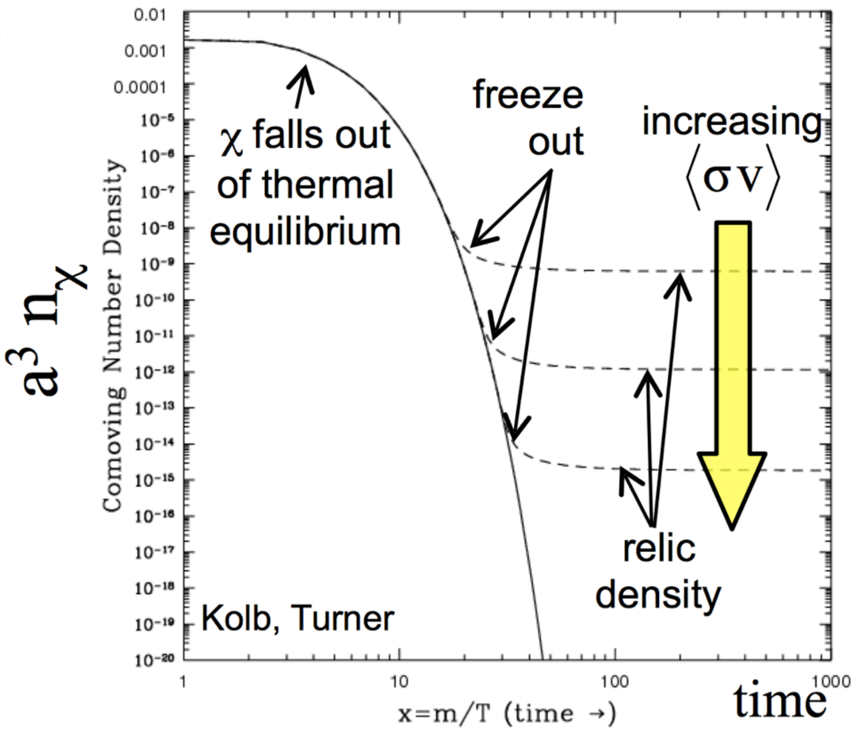
NOTE: DM@NLO unable to handle zero velocity limit

Model I : A exchange
Model II & V: Z exchange
Model III & IV: squark exchange

Relic Density

Relic Density





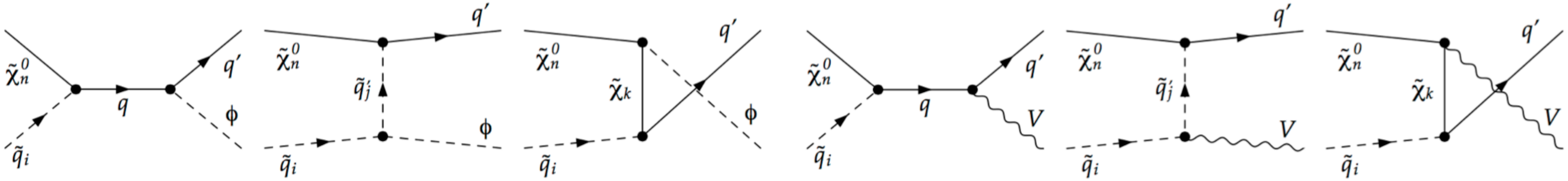
$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{\rm eq}^2)$$

$$\Omega_\chi h^2 \approx \frac{3\times 10^{-27} cm^3/s}{\langle\sigma v\rangle} \sim 0.1$$

$$\langle\sigma v\rangle \simeq 3\times 10^{-26} cm^3/s$$

$$\langle\sigma v\rangle \simeq a_0 + a_1\langle v^2\rangle + \ldots = a_0 + \frac{3a_1}{2}\frac{T}{m_\chi} + \ldots$$

Co-annihilations



$$\frac{\mathrm{d}n}{\mathrm{d}t} = -3Hn - \langle \sigma_{\mathrm{ann}} v \rangle \left(n^2 - n_{\mathrm{eq}}^2 \right)$$

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} cm^3/s}{\langle \sigma v \rangle} \sim 0.1$$

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} cm^3/s$$

$$\langle \sigma_{\mathrm{ann}} v \rangle = \sum_{i,j} \sigma_{ij} v_{ij} \frac{n_i^{\mathrm{eq}}}{n_\chi^{\mathrm{eq}}} \frac{n_j^{\mathrm{eq}}}{n_\chi^{\mathrm{eq}}}$$

$$\frac{n_i^{\mathrm{eq}}}{n_\chi^{\mathrm{eq}}} \sim \exp\left\{ -\frac{m_i - m_\chi}{T} \right\}$$

Relic Density

$$\langle \sigma v \rangle \simeq a_0 + a_1 \langle v^2 \rangle + \ldots = a_0 + \frac{3a_1}{2}\frac{T}{m_\chi} + \ldots$$

Typical decoupling Temperatures $T \sim m_\chi/25$

Including VIB can make the first term comparable to the second

The suppression is α_s/π rather than m_q^2/m_χ^2

Relic Density

$$\langle \sigma v \rangle \simeq a_0 + a_1 \langle v^2 \rangle + \ldots = a_0 + \frac{3a_1}{2}\frac{T}{m_\chi} + \ldots$$

The obstacles-

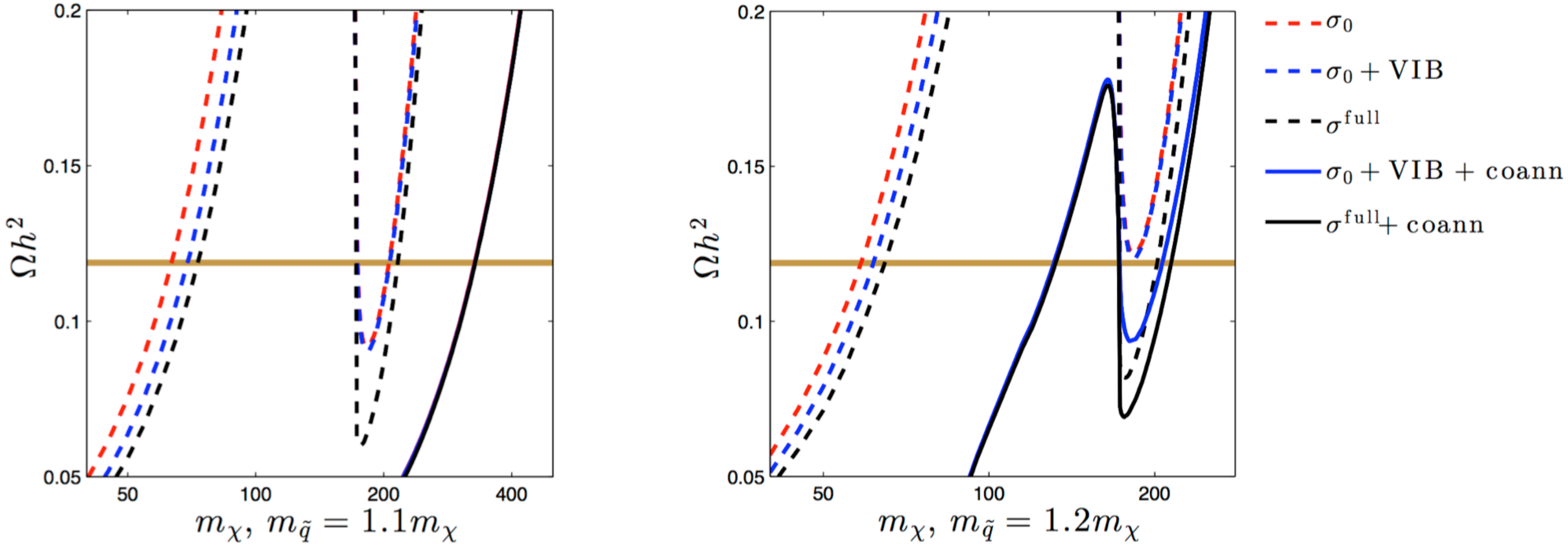
1. For significant VIB contribution $m_\chi \gg m_q / \sqrt{\alpha_s / \pi}$

Top and Electroweak boson final states possible, which are "unsuppressed"

2. Small mass splitting between neutralino and squark masses required

Co-annihilations dominate in this parameter region

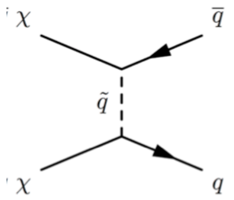
Relic Density



Variation of Ωh^2 vs m_χ for a pure Bino model.

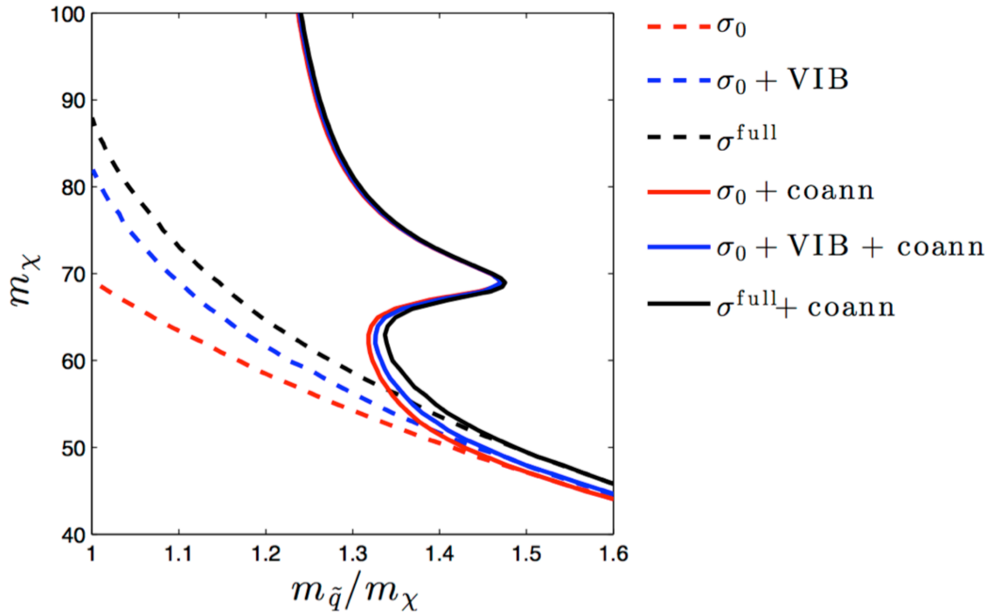
Note: σ^{full} also contains gluon pair contribution, which is unsuppressed.
All the sparticle masses other than squarks and neutralino have been set very high.

For Bino-like neutralino only one diagram contributes at tree level



Now implemented in DarkSUSY

Relic Density

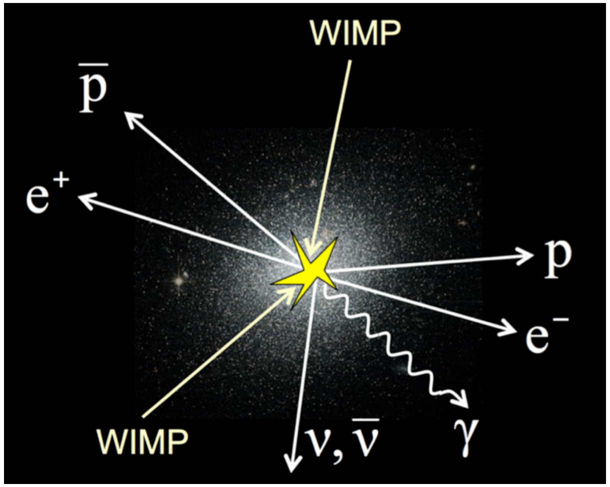


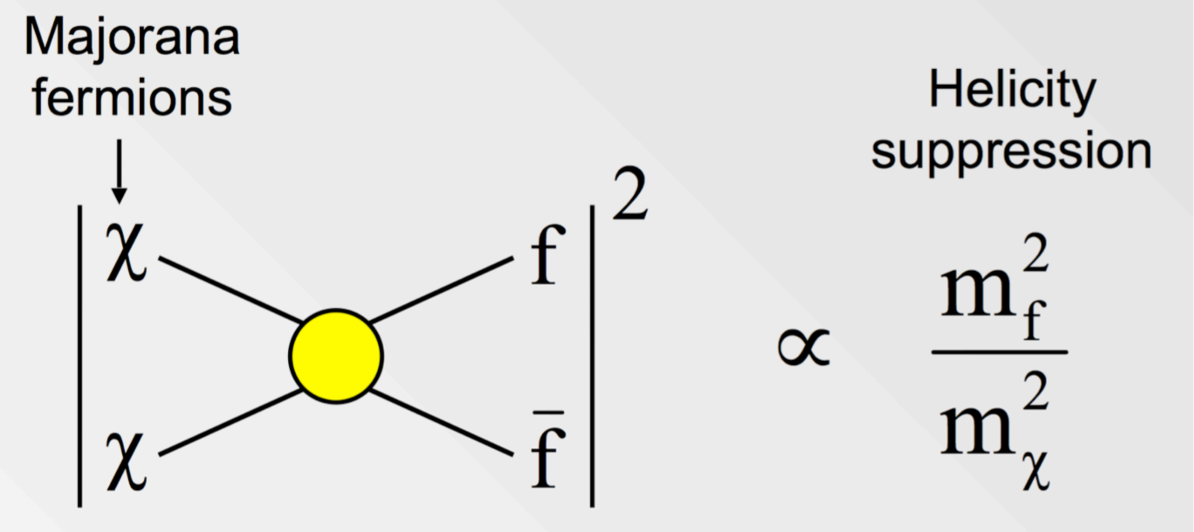
The plot shows the values of neutralino and squark masses to achieve the correct relic density

Conclusion: Co-annihilations would always dominate over VIB

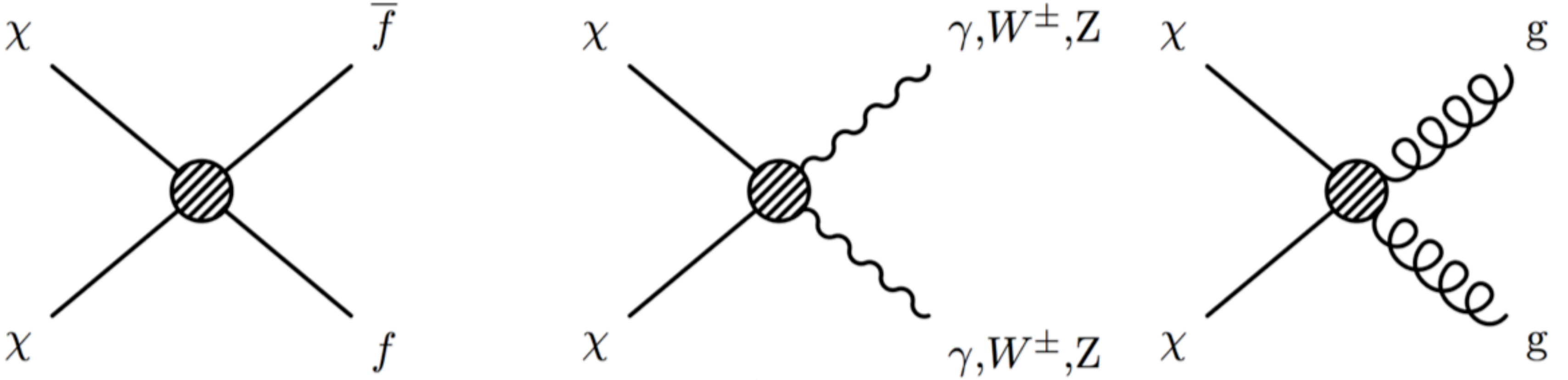
Indirect detection

Indirect searches

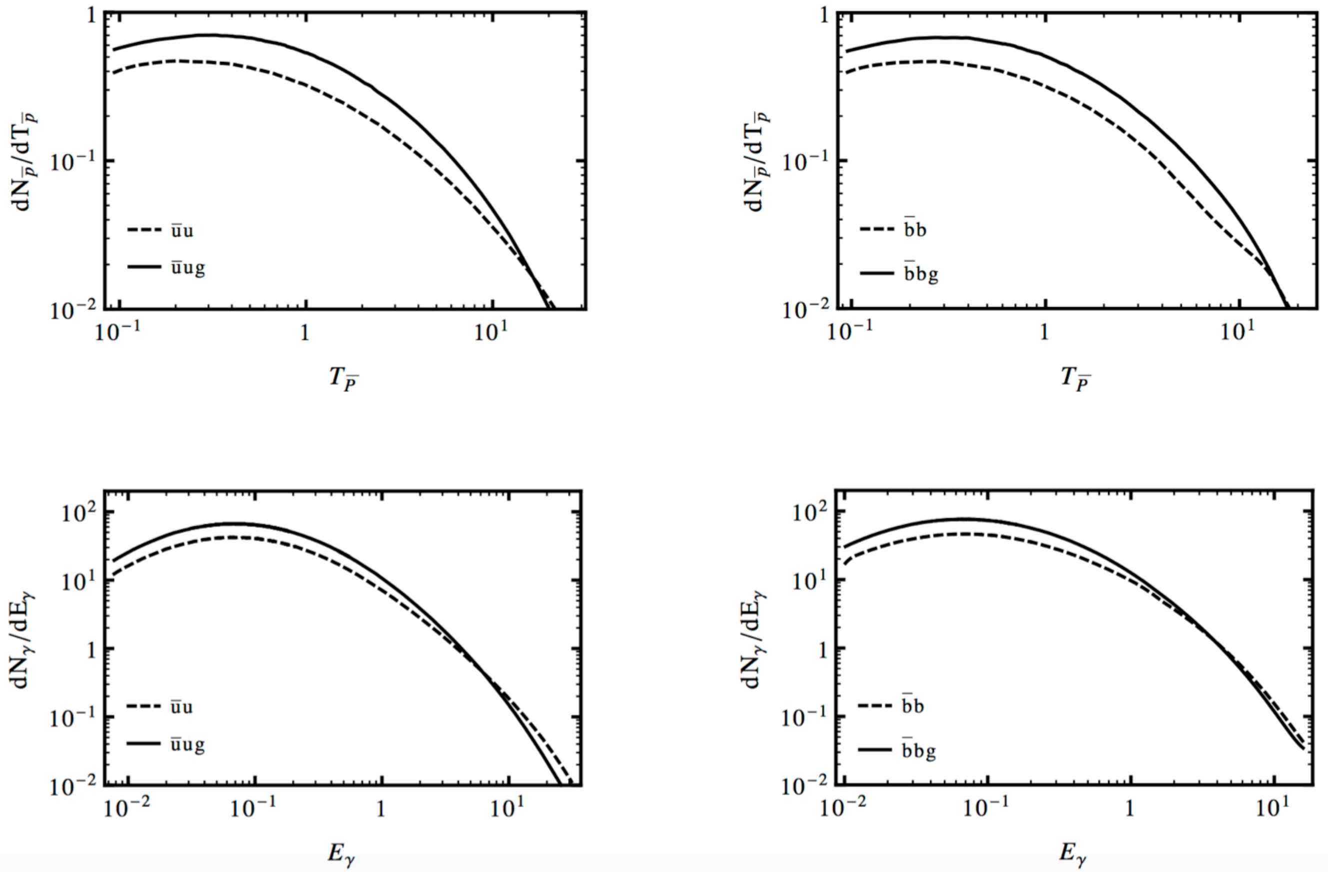




$$\left| \chi\chi \to f\bar{f} \right|^2 \propto \frac{m_f^2}{m_\chi^2}$$



Antiproton and photon spectrum



$m_{\chi} = 100\,\mathrm{GeV}$

Maximal VIB case

$m_{\chi} = m_{\tilde{b}}$

Using PYTHIA 8.2, 10^{7} runs

Indirect searches

$$\frac{d\tilde{N}_{\mathrm{\bar{q}qg}}}{dT_{\bar{p}}} \simeq y_{\bar{p}} \frac{d\tilde{N}^{\mathrm{VIB}}_{\bar{q}qg}}{dT_{\bar{p}}} + (1 - y_{\bar{p}}) \frac{d\tilde{N}^{m_{\tilde{q}} \to \infty}_{\bar{q}qg}}{dT_{\bar{p}}}$$

$$\frac{d\tilde{N}_{\mathrm{\bar{q}qg}}}{dE_{\gamma}} \simeq y_{\gamma} \frac{d\tilde{N}^{\mathrm{VIB}}_{\bar{q}qg}}{dE_{\gamma}} + (1 - y_{\gamma}) \frac{d\tilde{N}^{m_{\tilde{q}} \to \infty}_{\bar{q}qg}}{dE_{\gamma}}$$

$$r \equiv \frac{r'_{\mathrm{true}} - r'_{\tilde{m} \to \infty}}{r'_{\mathrm{VIB}} - r'_{\tilde{m} \to \infty}}$$

$$r'_{\mathrm{X}} = dN^{\mathrm{X}}_{\bar{q}qg}(x_{\mathrm{max}})/dx_g$$

$$\log_{10}(y) = \log_{10}(r) + \sum_i c_i r^{n_i}$$

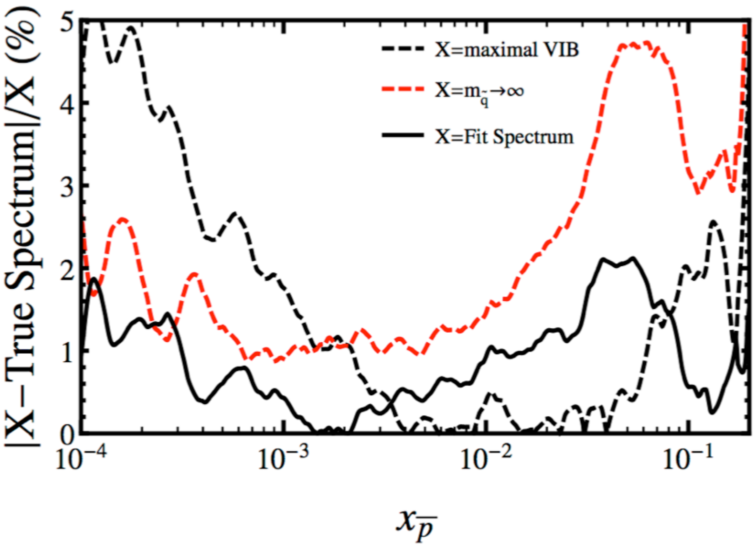
Antiproton spectrum

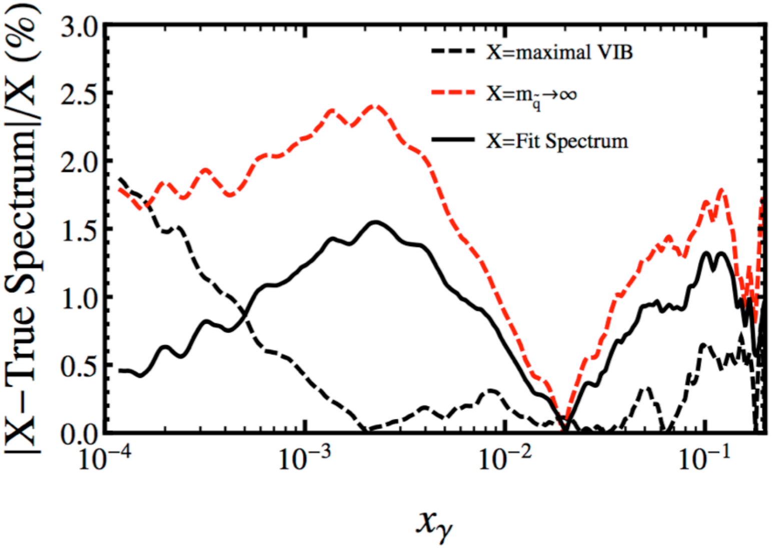
$\bar{q}q$	$g^{\mathrm{r}}_{\tilde{q}i}$	c_1	c_2	c_3	n_1	n_2	n_3
$\bar{c}c$	$\geq 10^{-4}$	-0.13	5.35	-5.22	0	9.8	9.15
$\bar{s}s$	$\geq 10^{-4}$	-0.4	-9.14	9.54	0	8.1	9.98
$\bar{t}t$	$\geq 10^{-4}$	-0.67	-2.41	3.08	0	0.43	0.27
$\bar{b}b$	$\geq 10^{-4}$	8.1	-8.32	0.22	0	0.02	9.53
$\bar{t}t$	$< 10^{-4}$	0.1	0.21	-0.31	0	8.73	5.53

Gamma-ray spectrum

$\bar{q}q$	$g^{\mathrm{r}}_{\tilde{q}i}$	c_1	c_2	c_3	n_1	n_2	n_3
$\bar{c}c$	$\geq 10^{-4}$	0.03	-7.97	7.94	0	8.08	9.83
$\bar{s}s$	$\geq 10^{-4}$	0.12	-8.24	8.12	0	7.05	9.63
$\bar{t}t$	$\geq 10^{-4}$	-4.8	6.44	-1.64	0	0.06	0.34
$\bar{b}b$	$\geq 10^{-4}$	0.26	3.89	-4.15	0	2.22	1.63
$\bar{t}t$	$< 10^{-4}$	0.08	1.05	-1.13	0	8.36	7.45

Indirect searches





$$10^{-3}m_\chi < T_{\bar p}/E_\gamma < 0.2m_\chi$$

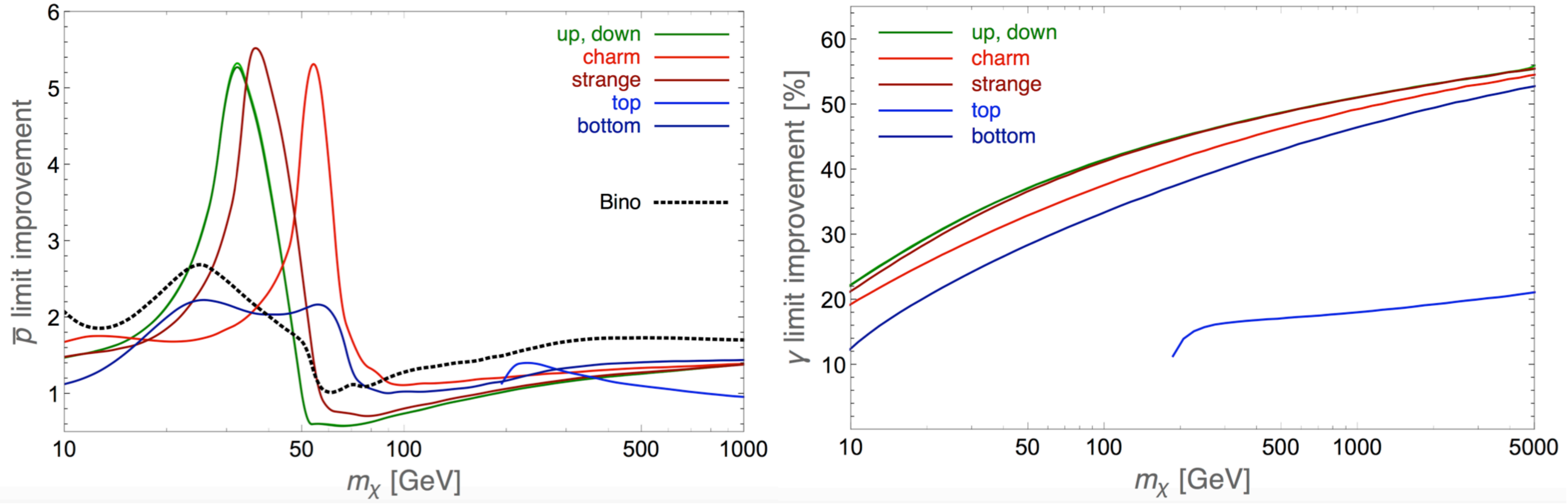
Inaccuracy <3%

$$T_{\bar p}/E_\gamma > 0.2m_\chi$$

Inaccuracy <10%

Now implemented in DarkSUSY

Limits



Bino masses upto 60 GeV are excluded

Summary

- Pseudoscalar approximation is a good approximation and saves computation time significantly.
- Relic density is always dominated by coannihilations for degenerate squark scenario, hence rendering VIB contribution insignificant.
- Cross sections from DM@NLO are not good in zero velocity limit.
- Indirect detection limits improved by a factor of 5 for antiprotons by including VIB contributions.

Takk!