

X + MET versus model-specific signatures: pros and cons.

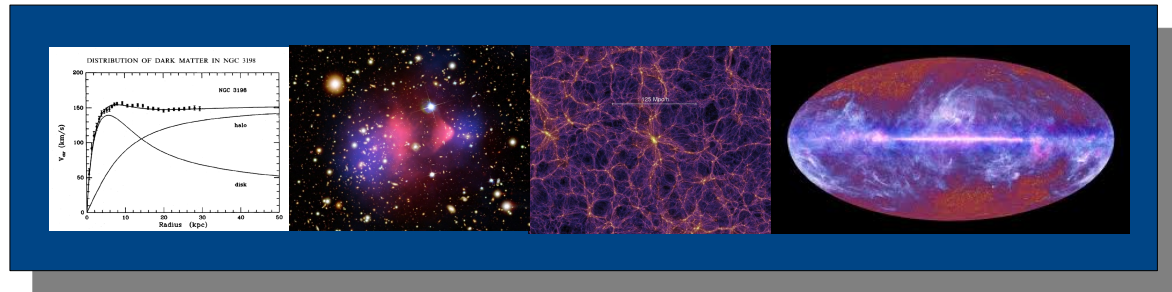
Kai Schmidt-Hoberg

Mandate:

“The contribution should highlight the complementarity between “simple” X + MET signatures that will have been discussed in the preceding session and “complex” model-specific signatures, as in e.g., supersymmetric models with dark matter candidates...”

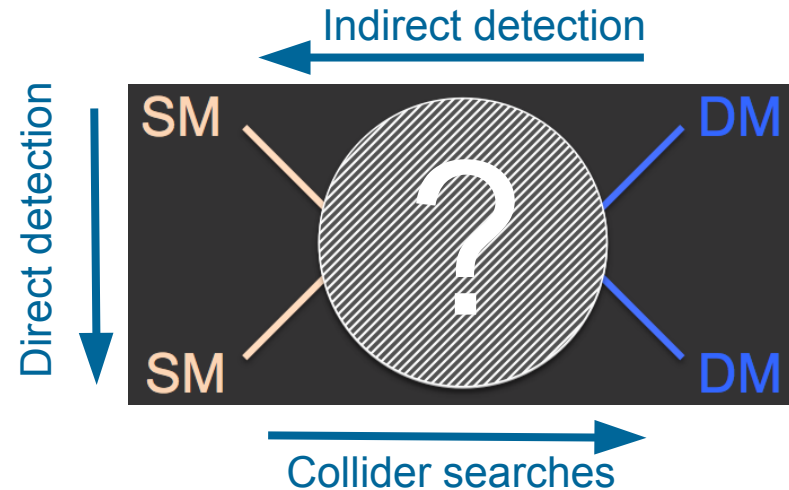
Dark matter – how will it reveal itself?

Dark matter exists!



...but we know next to nothing about its particle physics properties

Q: So how does it show up at colliders (if at all)?
A: ???
Q: How likely will it be in MET + X?
A: ???



Theory for dark matter

Need models for dark matter to shape expectations (and experimental search strategies)

UV

- Tackle fundamental problems such as e.g. hierarchy problem and look for implications
 - WIMPs
 - ...
- **Well-motivated** dark matter candidates, but also **strong theoretical bias**

IR

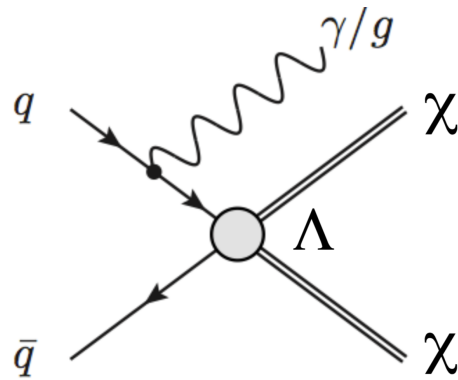
- Naturalness arguments suggest new physics at the LHC
- Nothing yet → motivates broader thinking.
- **As model independent as possible**
- **EFTs or simplified models**

DM production

> Expected signatures?

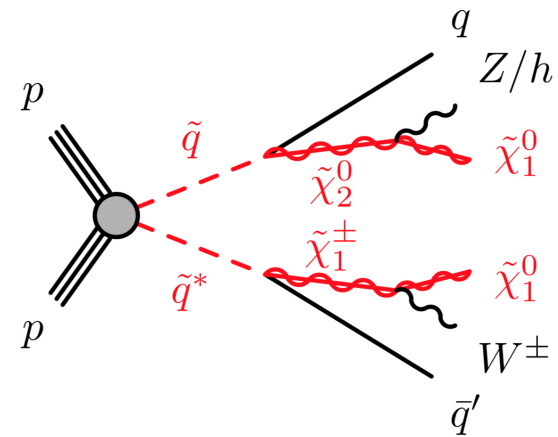
IR

Directly \rightarrow Mono-X



UV

via decay chains
 \rightarrow lots of stuff

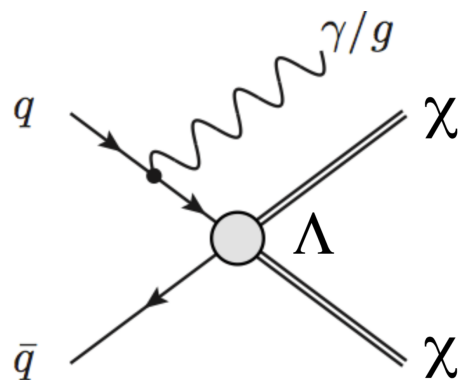


DM signatures

Plan: IR \rightarrow UV (simplified model \rightarrow SUSY scenarios \rightarrow other signatures)

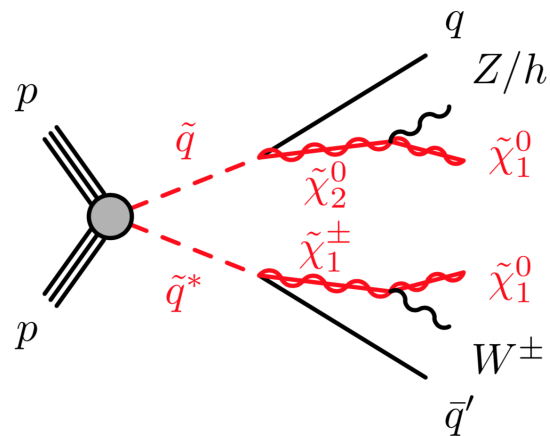
IR

Directly \rightarrow Mono-X



UV

via decay chains
 \rightarrow lots of stuff

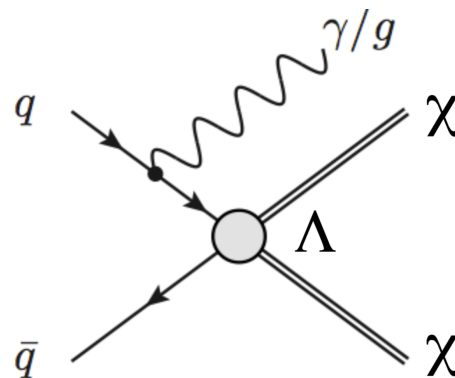


EFTs or Mono-X only

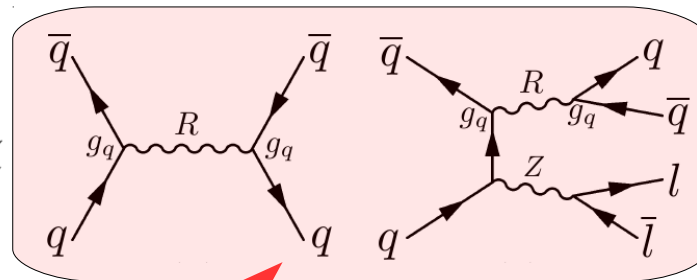
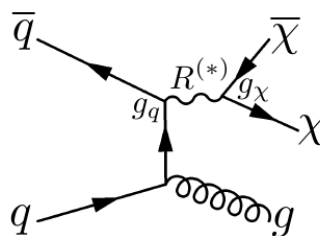
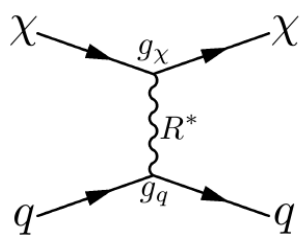
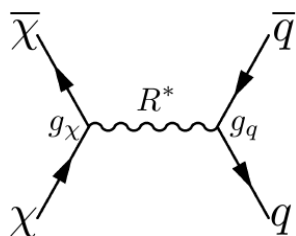
> **EFTs:** If mediating particles are sufficiently **heavy**, valid to use **effective operators**

> **Mono-X the only signature!**

> If the mediator is accessible at the LHC, additional signatures are possible



$$\frac{(\bar{\chi}\gamma_{\mu}\chi)(\bar{q}\gamma^{\mu}q)}{\Lambda^2}$$



> Complementarity of all searches:

- Where do we expect to see DM first?

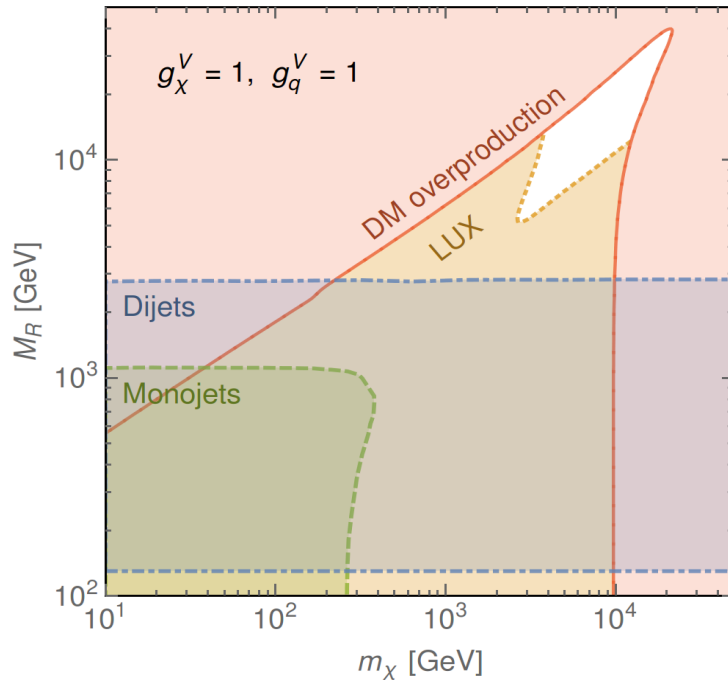
Interactions not present in the EFT

→ Sarah Malik's talk

Where do we expect to see DM first?

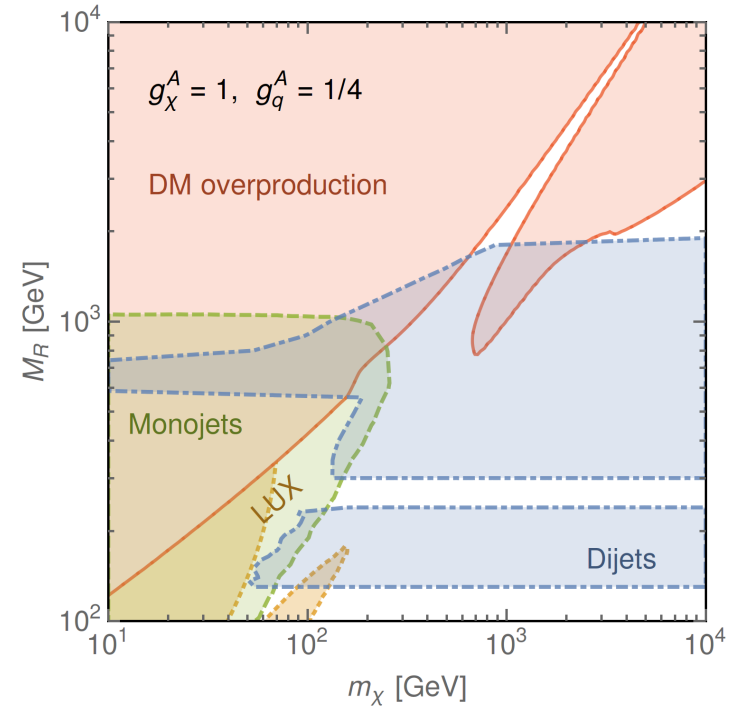
Vector couplings

Chala et al, 1503.05916



- Direct detection experiments are the obvious discovery channel for vector couplings

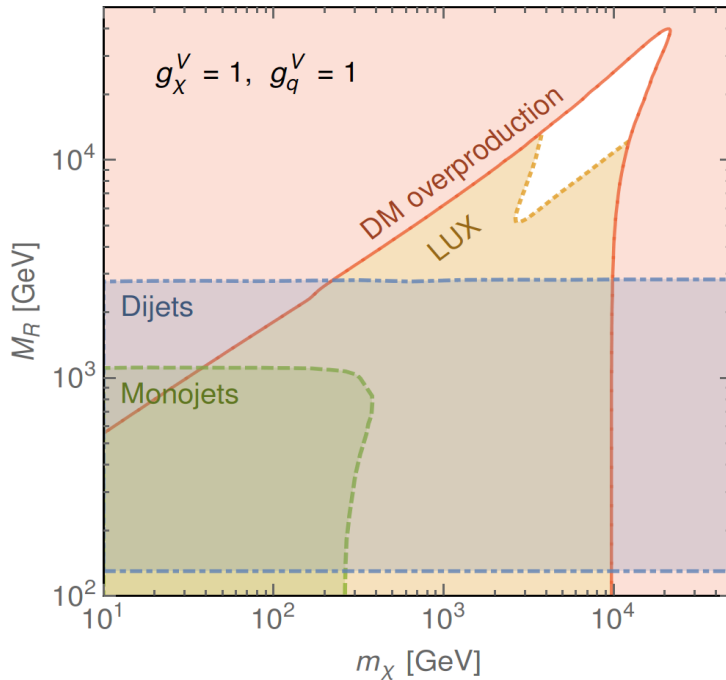
Axial couplings



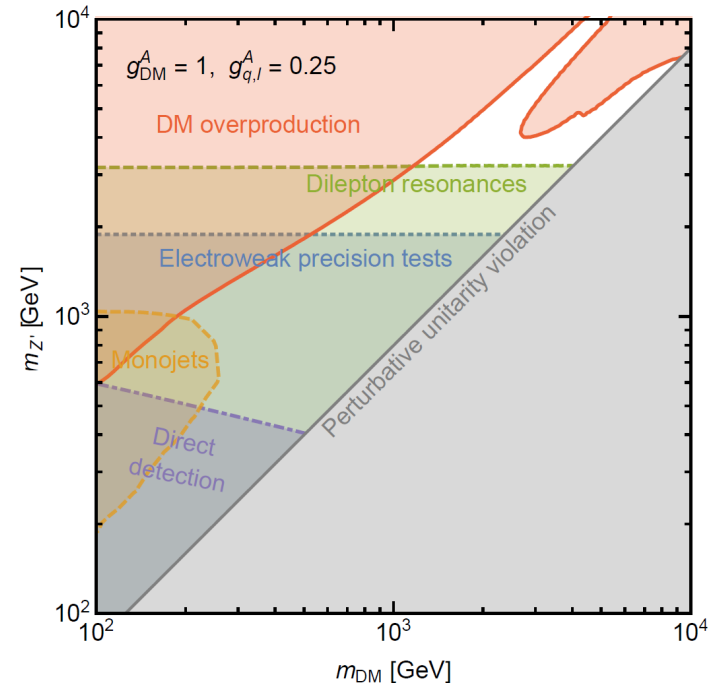
- Almost no constraints from direct detection
- Strong complementarity between monojet and dijet searches

Where do we expect to see DM first?

Vector couplings



Axial couplings

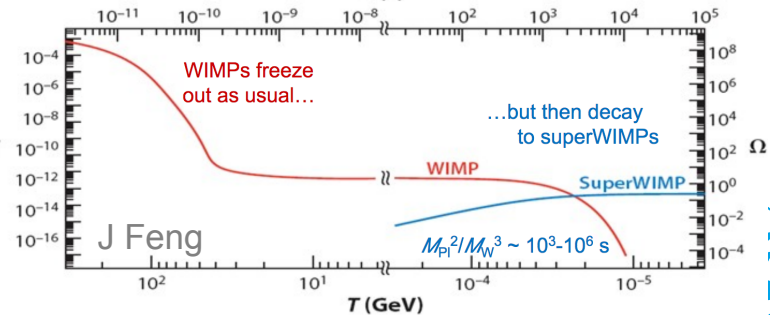
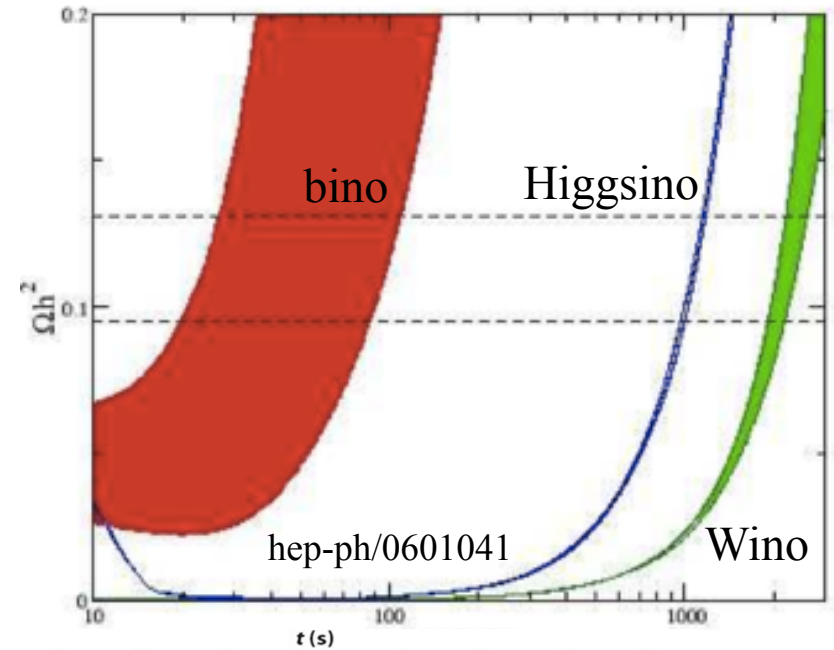


➤ Direct detection experiments are the obvious discovery channel for vector couplings

- But: issues with unitarity and gauge invariance → Felix' talk!
- Picture different again – monojets typically not competitive
- Need dark Higgs
→ Talk by Michael Duerr!

Full-blown models – here: SUSY

- Neutralinos (mixture of bino, Wino and Higgsino) and gravitino good dark matter candidates
- Neutralino relic abundance? → freeze out
- Bino: Typically need to finely tune via coannihilations or resonances :-)
- Wino: $m \sim 3\text{TeV}$, challenged by ID
Lisanti et al 1307.4082
- Higgsino: $m \sim 1\text{TeV}$, looking good :-)
- Pure states → very small DD cross sections
- Gravitino: 'UV freeze in' or superWIMP



Overview SUSY channels

ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

ATLAS Preliminary

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

Model	e, μ, τ, γ	Jets	$E_{\text{miss}}^{\text{T}}$	$\mathcal{L} dt [\text{fb}^{-1}]$	Mass limit		Reference		
					$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$			
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{q}	1.57 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q}) = m(2^{\text{nd}} \text{ gen. } \tilde{q})$	1712.02332
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	\tilde{q}	710 GeV	$m(\tilde{q}) - m(\tilde{\chi}_1^0) < 5 \text{ GeV}$	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.02 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	2.01 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}^{\pm}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{g}))$	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	e, μ	2 jets	Yes	14.7	\tilde{g}	1.7 TeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$	1611.05791
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	\tilde{g}	1.87 TeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	\tilde{g}	1.8 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	1708.02794
	GMSB ($\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	3.2	\tilde{g}	2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	36.1	\tilde{g}	2.15 TeV	$c\tau(\text{NLSP}) < 0.1 \text{ mm}$	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	\tilde{g}	2.05 TeV	$m(\tilde{\chi}_1^0) = 1700 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu > 0$	ATLAS-CONF-2017-080
	Gravitino LSP	0	mono-jet	Yes	20.3	$R^{1/2} \text{ scale}$	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g}) = m(\tilde{q}) = 1.5 \text{ TeV}$	1502.01518
3 rd gen. \tilde{g} med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	\tilde{g}	1.92 TeV	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	1711.01901
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	\tilde{g}	1.97 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1711.01901
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	\tilde{b}_1	950 GeV	$m(\tilde{\chi}_1^0) < 420 \text{ GeV}$	1708.09266
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^0$	2 e, μ (SS)	1 b	Yes	36.1	\tilde{b}_1	275-700 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0) + 100 \text{ GeV}$	1706.03731
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	0-2 e, μ	1-2 b	Yes 4.	13.3	\tilde{t}_1	117-170 GeV	$m(\tilde{\chi}_1^0) = 2m(\tilde{\chi}_1^{\pm}), m(\tilde{\chi}_1^{\pm}) = 55 \text{ GeV}$	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{b}\tilde{\chi}_1^0$ or $\tilde{t}_1\tilde{t}_1$	0-2 e, μ	0-2 jets/1-2 b	Yes 20	36.1	\tilde{t}_1	90-198 GeV	$m(\tilde{\chi}_1^0) = 1 \text{ GeV}$	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	\tilde{t}_1	90-430 GeV	$m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1711.03301
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	150-600 GeV	$m(\tilde{\chi}_1^0) > 150 \text{ GeV}$	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	\tilde{t}_2	290-790 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	\tilde{t}_2	320-880 GeV	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	1706.03986
EW direct	$\tilde{\chi}_{1,2}^0\tilde{\chi}_{1,2}^0, \tilde{\chi}_1^0 \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^0$	90-500 GeV	$m(\tilde{\chi}_1^0) = 0$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \ell\tilde{\nu}(\ell\nu)$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^0$	750 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tilde{\nu}(\tau\nu), \tilde{\chi}_2^0 \rightarrow \tau\tilde{\nu}(\tau\nu)$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^0$	760 GeV	$m(\tilde{\chi}_1^0) = 0, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0))$	1708.07875
	$\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\nu}_\ell(\ell\nu), \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \tau\tilde{\nu}(\tau\nu)$	3 e, μ	0	Yes	36.1	$\tilde{\chi}_1^0, \tilde{\chi}_2^0$	1.13 TeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^0, \tilde{\chi}_2^0$	580 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0h\tilde{\chi}_1^0, h \rightarrow b\tilde{b}/W\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^0, \tilde{\chi}_2^0$	270 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, \tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_2^0$	635 GeV	$m(\tilde{\chi}_2^0) = m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_2^0) + m(\tilde{\chi}_3^0))$	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	\tilde{W}	115-370 GeV	$c\tau < 1 \text{ mm}$	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$	2 γ	-	Yes	20.3	\tilde{W}	1.06 TeV	$c\tau < 1 \text{ mm}$	ATLAS-CONF-2017-080
	Long-lived particles	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^0$	460 GeV	$m(\tilde{\chi}_1^0) - m(\tilde{\chi}_2^0) = 160 \text{ MeV}, \tau(\tilde{\chi}_1^0) = 0.2 \text{ ns}$
Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$		dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^0$	495 GeV	$m(\tilde{\chi}_1^0) - m(\tilde{\chi}_2^0) = 160 \text{ MeV}, \tau(\tilde{\chi}_1^0) < 15 \text{ ns}$	1506.05332
Stable, stopped \tilde{g} R-hadron		0	1-5 jets	Yes	27.9	\tilde{g}	850 GeV	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}, 10 \mu\text{s} < c\tau(\tilde{g}) < 1000 \text{ s}$	1310.6584
Stable \tilde{g} R-hadron		trk	-	-	3.2	\tilde{g}	1.58 TeV		1606.05129
Metastable \tilde{g} R-hadron		dE/dx trk	-	-	3.2	\tilde{g}	1.57 TeV	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}, \tau > 10 \text{ ns}$	1604.04520
Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$		displ. vtx	-	Yes	32.8	\tilde{g}	2.37 TeV	$\tau(\tilde{g}) = 0.17 \text{ ns}, m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	1710.04901
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tau(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$		1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$10 < \tan\beta < 50$	1411.6795
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$		2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	$1 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{SPS8 model}$	1409.5542
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ee/\mu\mu/\mu\mu$		displ. $ee/\mu\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7 < c\tau(\tilde{\chi}_1^0) < 740 \text{ mm}, m(\tilde{g}) = 1.3 \text{ TeV}$	1504.05162
RPV		LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu/\mu\tau$	$e, \mu, \tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	$\lambda_{311} = 0.11, \lambda_{132}/\lambda_{233}/\lambda_{333} = 0.07$
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{q}, \tilde{g}	1.45 TeV	$m(\tilde{q}) = m(\tilde{g}), c\tau_{\text{LSP}} < 1 \text{ mm}$	1404.2500
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow ee\nu, \mu\nu, \mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^0$	1.14 TeV	$m(\tilde{\chi}_1^0) > 400 \text{ GeV}, \lambda_{12k} \neq 0 (k = 1, 2)$	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tau\nu_e, \tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^0$	450 GeV	$m(\tilde{\chi}_1^0) > 0.2 \times m(\tilde{\chi}_2^0), \lambda_{133} \neq 0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}$	0	4-5 large-R jets	-	36.1	\tilde{g}	1.875 TeV	$m(\tilde{\chi}_1^0) = 1075 \text{ GeV}$	SUSY-2016-22
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	2.1 TeV	$m(\tilde{\chi}_1^0) = 1 \text{ TeV}, \lambda_{112} \neq 0$	1704.08493
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}, \tilde{\chi}_1^0 \rightarrow b\tilde{s}$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g}	1.65 TeV	$m(\tilde{t}_1) = 1 \text{ TeV}, \lambda_{323} \neq 0$	1704.08493
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	0	2 jets + 2 b	-	36.1	\tilde{t}_1	100-470 GeV		1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\ell}$	2 e, μ	2 b	-	36.1	\tilde{t}_1	480-610 GeV	$BR(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$	1710.05544	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{c}	510 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1501.01325

*Only a selection of the available mass limits on new states and phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



Overview SUSY channels

Model		e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt$	ATLAS Preliminary $\sqrt{s} = 7, 8, 13 \text{ TeV}$ Reference		
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	1712.02332 1711.03301 1712.02332 1712.02332		
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	1611.05791 1706.03731 1708.02794		
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	1607.05979 ATLAS-CONF-2017-080		
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^\pm \rightarrow qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	ATLAS-CONF-2017-080 1502.01518		
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7	1711.01901 1711.01901		
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	1708.09266 1706.03731		
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	1209.2102, ATLAS-CONF-2016-077 506.08616, 1709.04183, 1711.11520		
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	1711.03301 1403.5222 1706.03986 1706.03986		
	GGM (bino NLSP)	2 γ	-	Yes	36.1	ATLAS-CONF-2017-039 ATLAS-CONF-2017-039		
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	ATLAS-CONF-2017-039 ATLAS-CONF-2017-039		
Gravitino LSP	0	mono-jet	Yes	20.3	1501.07110 1405.5086 1507.05493 ATLAS-CONF-2017-080			
Long-lived Gluinos	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 460 GeV	$m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) \sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm) = 0.2 \text{ ns}$	1712.02118
	Direct $\tilde{\chi}_1^0\tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$ 495 GeV	$m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) \sim 160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm) < 15 \text{ ns}$	1506.05332
	Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	\tilde{g} 850 GeV	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	1310.6584
	Stable \tilde{g} R-hadron	trk	-	-	3.2	\tilde{g} 1.58 TeV		1606.05129
Long-lived Staus	GMSB, $\tilde{\chi}_1^0 \rightarrow \tilde{\nu}\nu$, long-lived $\tilde{\chi}_1^\pm$	$e\gamma$	Yes	20.3	$\tilde{\chi}_1^\pm$ 440 GeV	$1 < \tau(\tilde{\chi}_1^\pm) < 3 \text{ ns}$, SPSB model	1409.3342	
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow ee\nu/\mu\nu$	displ. $ee/\mu\mu$	-	20.3	$\tilde{\chi}_1^\pm$ 1.0 TeV	$7 < c\tau(\tilde{\chi}_1^\pm) < 740 \text{ mm}, m(\tilde{g}) = 1.3 \text{ TeV}$	1504.05162	
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau/\mu$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9 TeV	$\lambda'_{311} = 0.11, A_{132/133/233} = 0.07$	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{q}, \tilde{g} 1.45 TeV	$m(\tilde{q}) = m(\tilde{g}), c\tau_{\tilde{LSP}} < 1 \text{ mm}$	1404.2500
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\nu, \mu\nu, \mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^\pm$ 1.14 TeV	$m(\tilde{\chi}_1^\pm) > 400 \text{ GeV}, A_{12k} \neq 0 (k = 1, 2)$	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\nu_e, \sigma\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^\pm) > 0.2 \times m(\tilde{\chi}_1^0), A_{1333} \neq 0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	0	4-5 large-R jets	-	36.1	\tilde{g} 1.875 TeV	$m(\tilde{\chi}_1^0) = 1075 \text{ GeV}$	SUSY-2016-22
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g} 2.1 TeV	$m(\tilde{\chi}_1^0) = 1 \text{ TeV}, A_{112} \neq 0$	1704.08493
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	\tilde{g} 1.65 TeV	$m(\tilde{t}_1) = 1 \text{ TeV}, A_{323} \neq 0$	1704.08493
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	0	2 jets + 2 b	-	36.7	\tilde{t}_1 100-470 GeV, 480-610 GeV		1710.07171	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$	2 e, μ	2 b	-	36.1	\tilde{t}_1 0.4-1.45 TeV	$BR(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$	1710.05544	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{c} 510 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	1501.01325

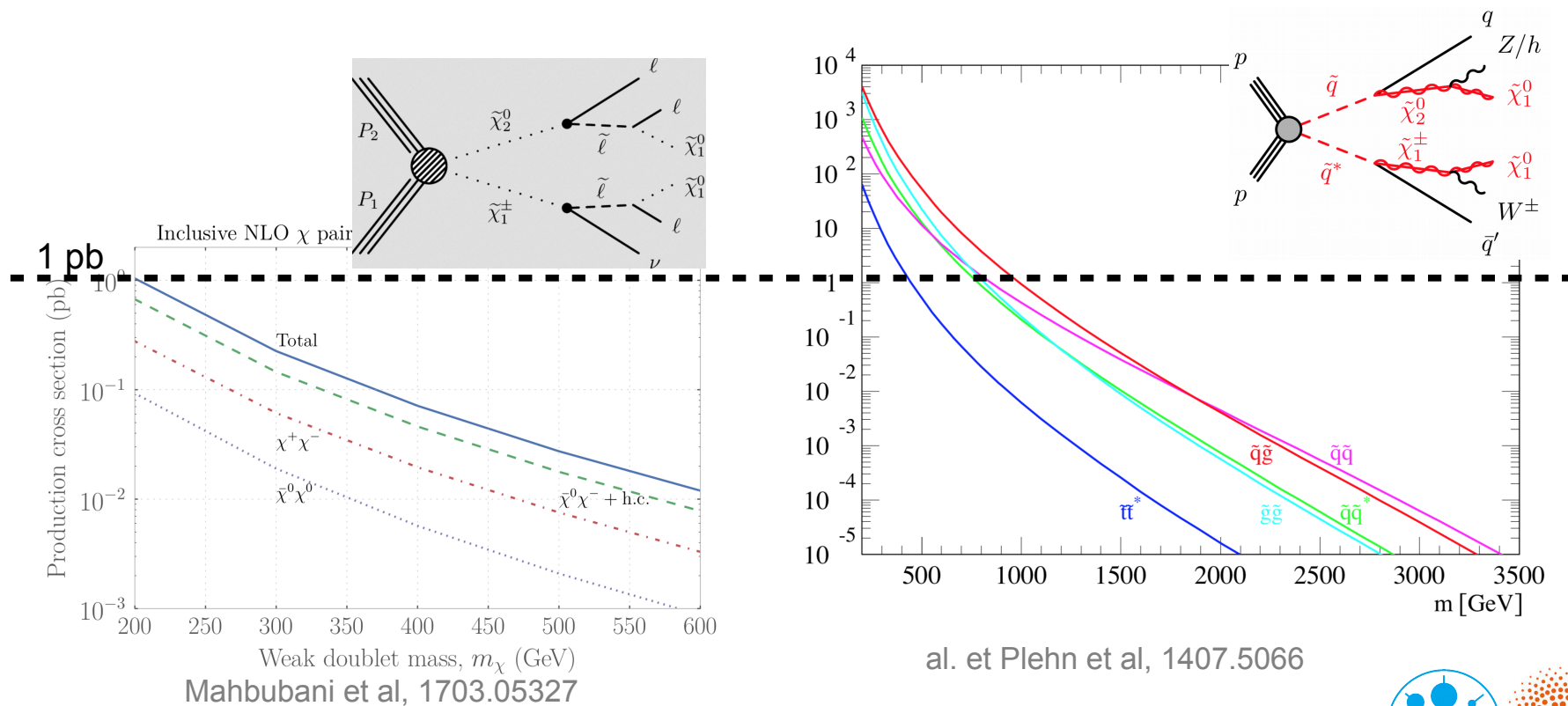
➤ Most searches are X+MET (although typically X is more than a monojet)

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



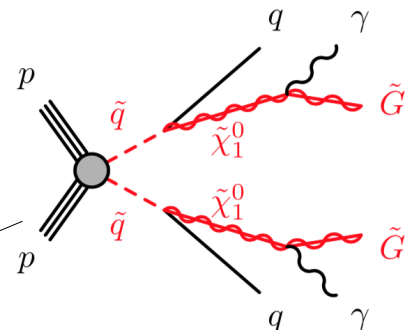
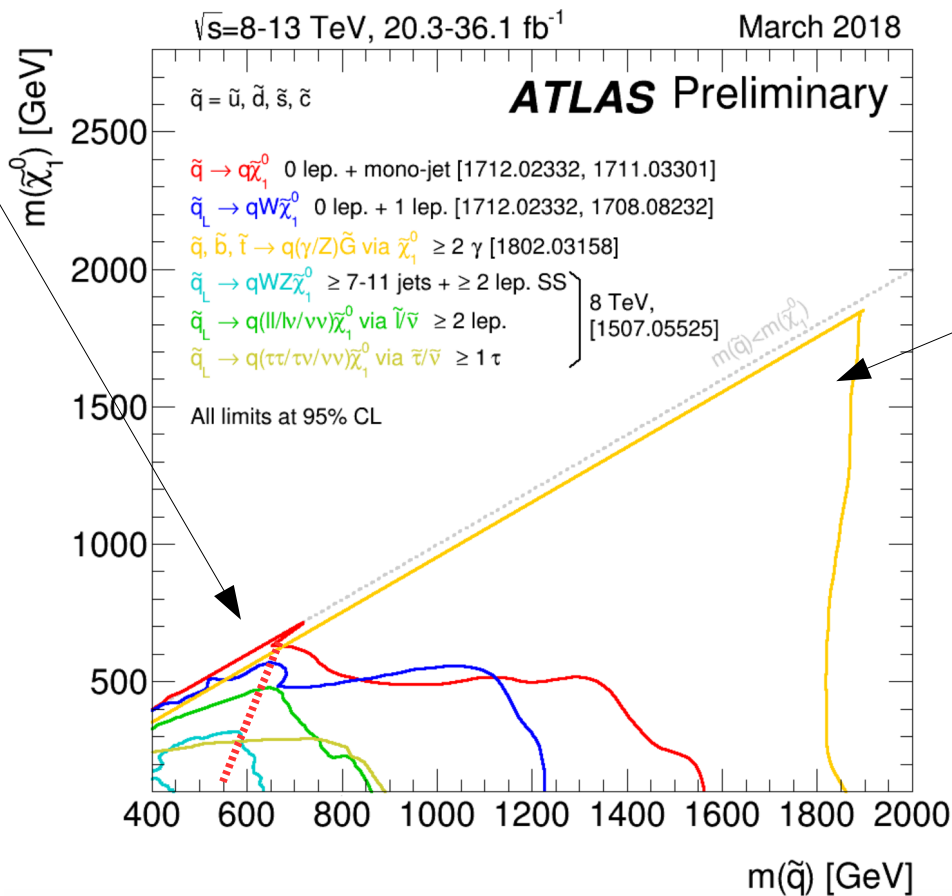
Strong vs EW production

- Monojets for SUSY?
- Direct DM (or electroweakino) production: cross sections too small
- Relevant constraints via strong production (if other particles too soft).



Monojets for the MSSM

- Monojets can give the leading constraints for very compressed spectra.



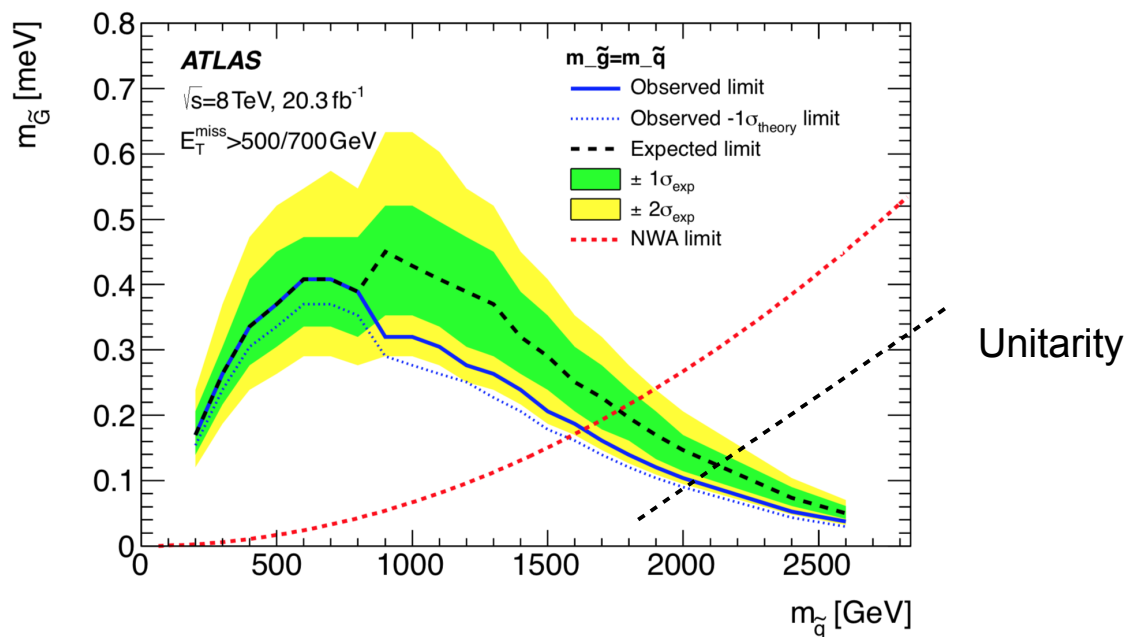
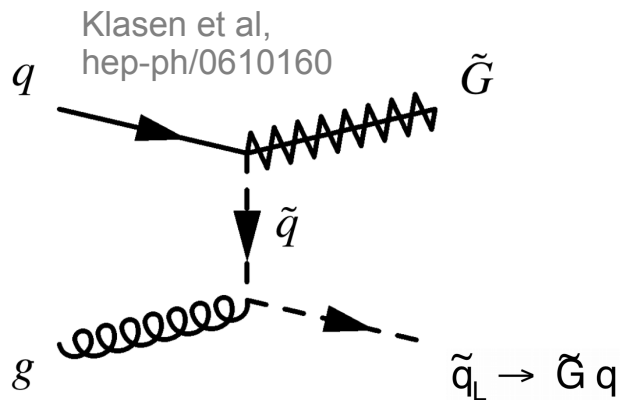
- **Not the same models (so no 1-1 comparison)!**

Monojets for the MSSM

- Monojets also relevant for a very light gravitino LSP (without ISR)

$$\sigma \sim 1/m_{\tilde{G}}^2$$

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



Weak scale gravitino

- Dark matter production may also happen completely **without large MET**
- Consider a heavier gravitino → very weakly coupled
- NLSP can be charged (e.g. stau) and have very long lifetime
- Collider signature: **'stable', charged, massive particles (no MET)**

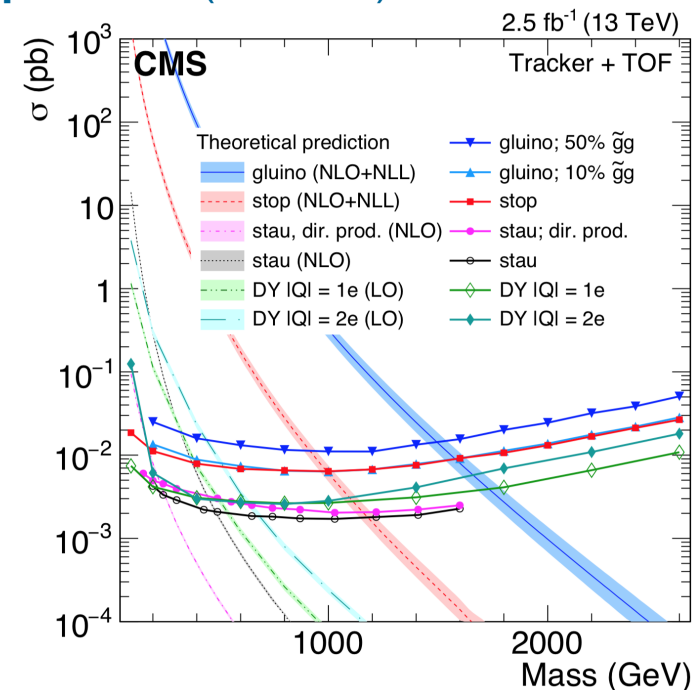
$$M_{\text{P}}^2(\text{supergravity}) = \frac{1}{48\pi} \frac{1}{\Gamma_{\tilde{\tau}}} \frac{m_{\tilde{\tau}}^5}{m_{\tilde{G}}^2} \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

measurable (using energy momentum) "measurable"
 $m_{\tilde{G}}^2 = m_{\tilde{\tau}}^2 - 2m_{\tilde{\tau}}E_{\tilde{\tau}} - m_{\tilde{\tau}}^2$

$\tau \leftarrow \bullet \text{---} \rightarrow \tilde{G}$

$$M_{\text{P}}^2(\text{gravity}) = (8\pi G_{\text{N}})^{-1} = (2.44 \times 10^{18} \text{ GeV})^2$$

Newton const.

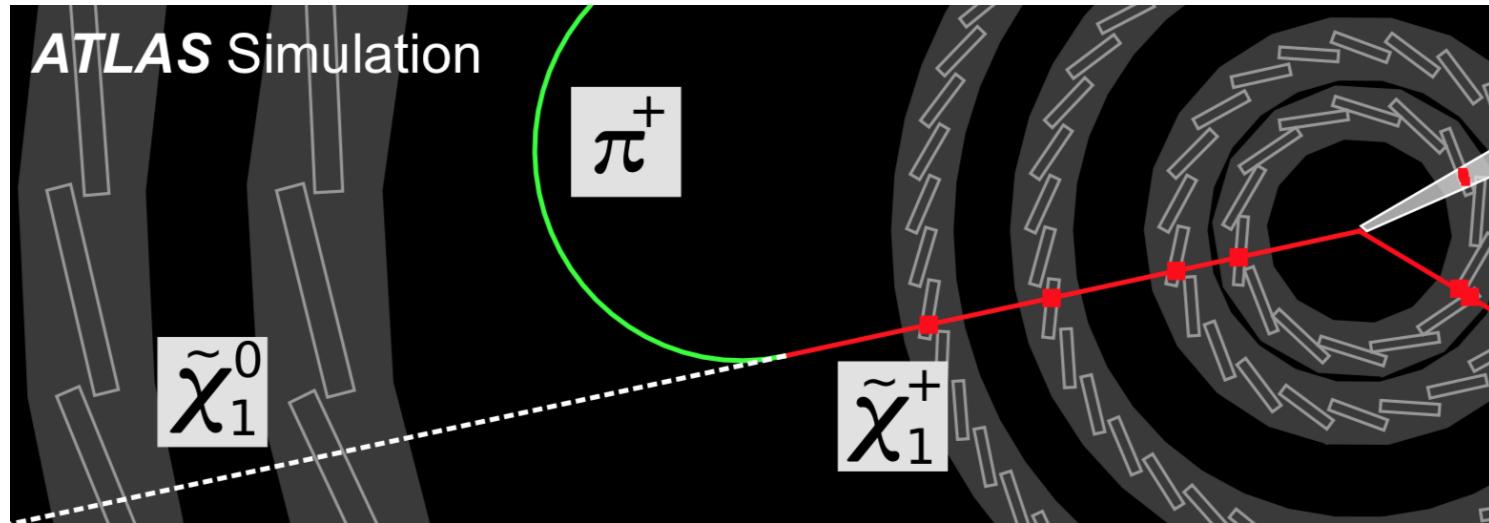
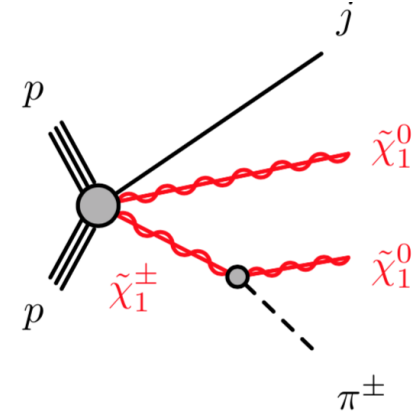


From K Hamaguchi

Newton const.

Higgsino/Wino dark matter

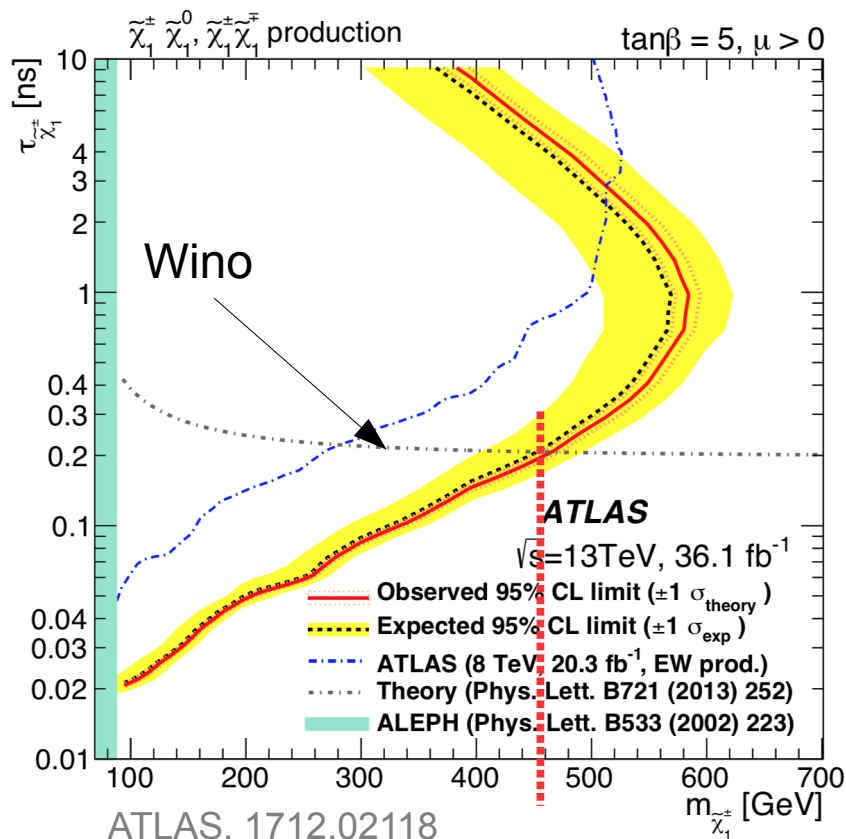
- Direct Electroweakino production?
- Dark matter state accompanied by nearly degenerate charged state (chargino)
- Long lifetime (few cm) due to small mass splitting! → disappearing charged tracks!



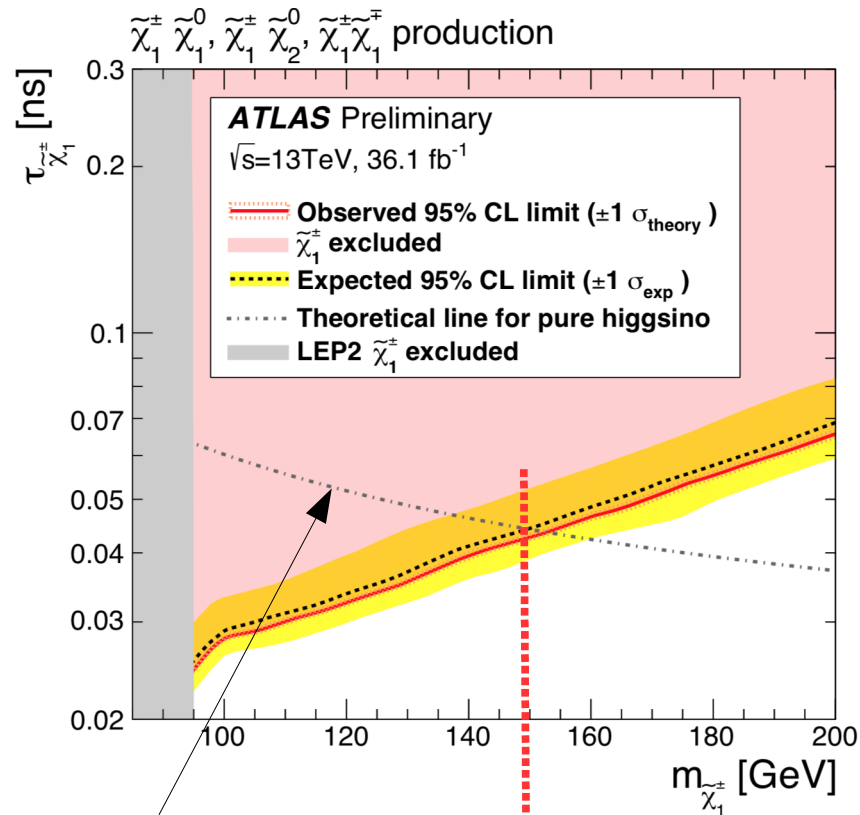
12cm

Higgsino/Wino dark matter

- Relevant constraints for Winos ($\Delta m \sim 160 \text{ MeV} \rightarrow 6 \text{ cm}$)
- Higgsinos have larger mass splitting ($\Delta m \sim 350 \text{ MeV} \rightarrow 0.7 \text{ cm}$)



~460 GeV



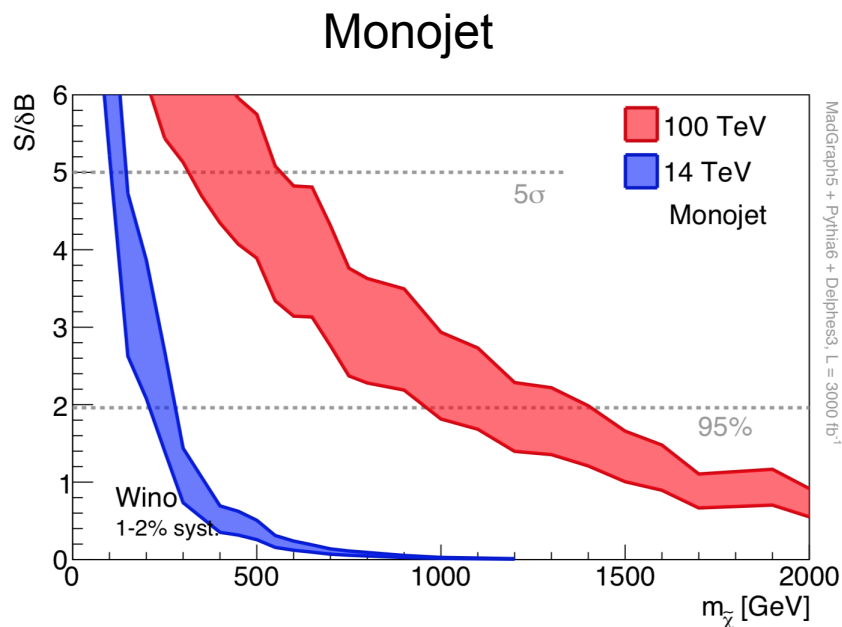
Higgsino

~150 GeV

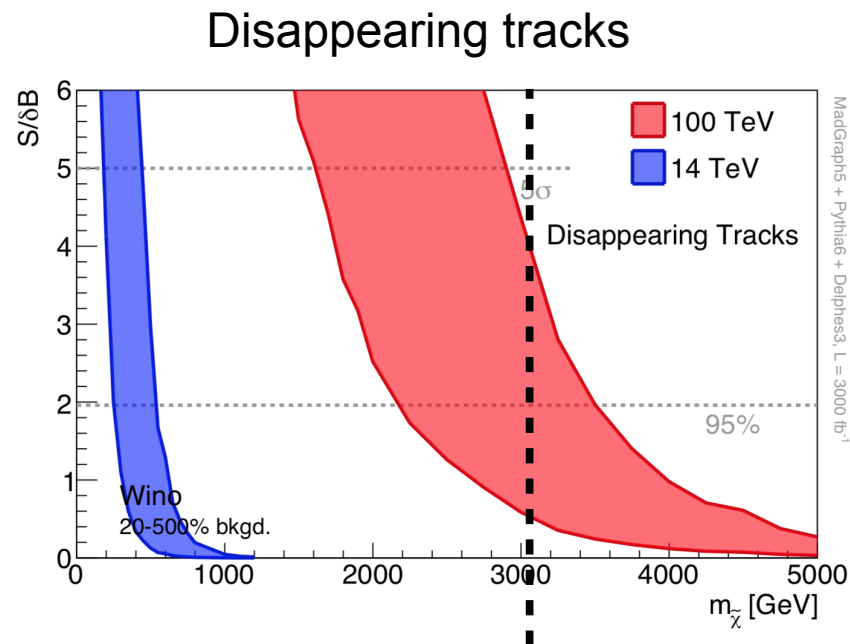
Higgsino/Wino dark matter – the future

- Good prospects for discovery at 100 TeV collider (higher boosts → longer tracks)

Wino



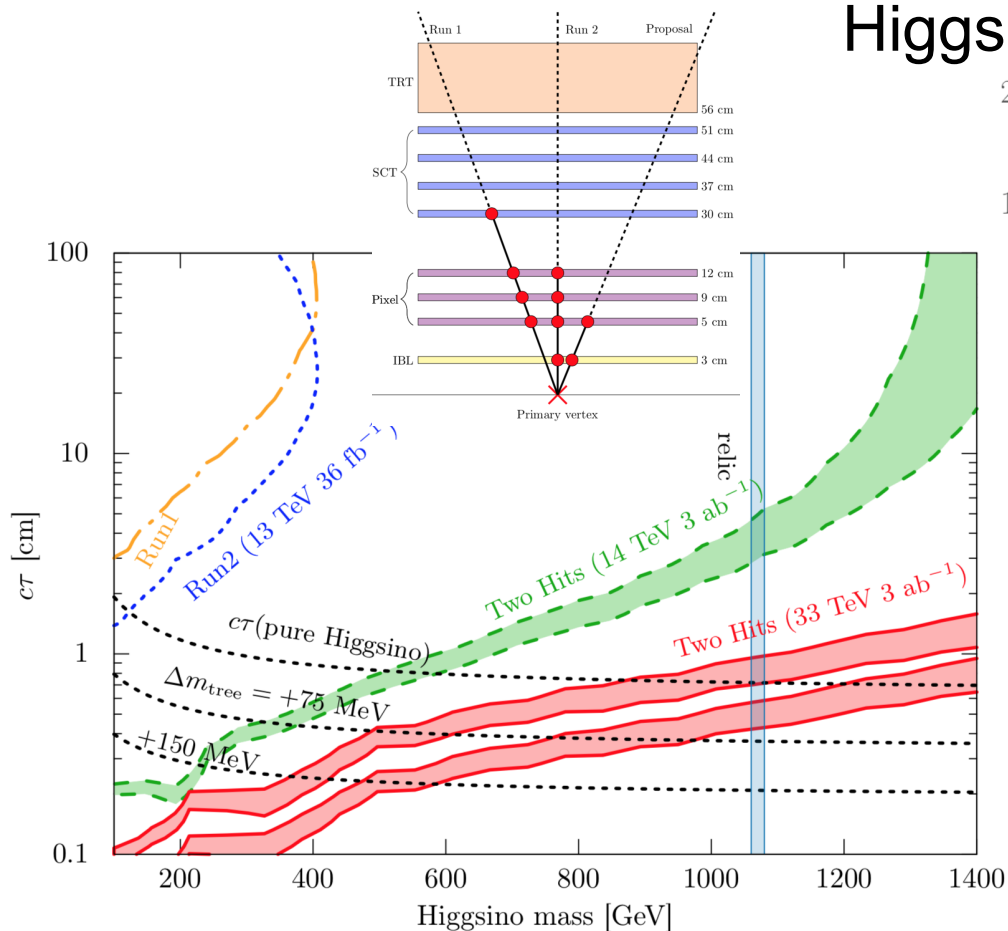
Low et al., 1404.0682



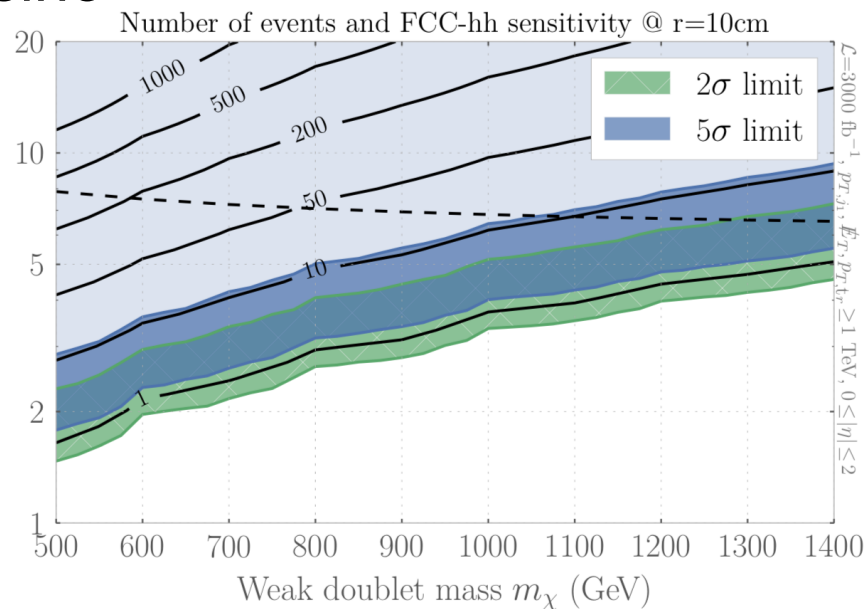
thermal relic

Higgsino/Wino dark matter – the future

- Good prospects for discovery at 100 TeV collider (higher boosts → longer tracks)



Higgsino



Mahbubani et al, 1703.05327

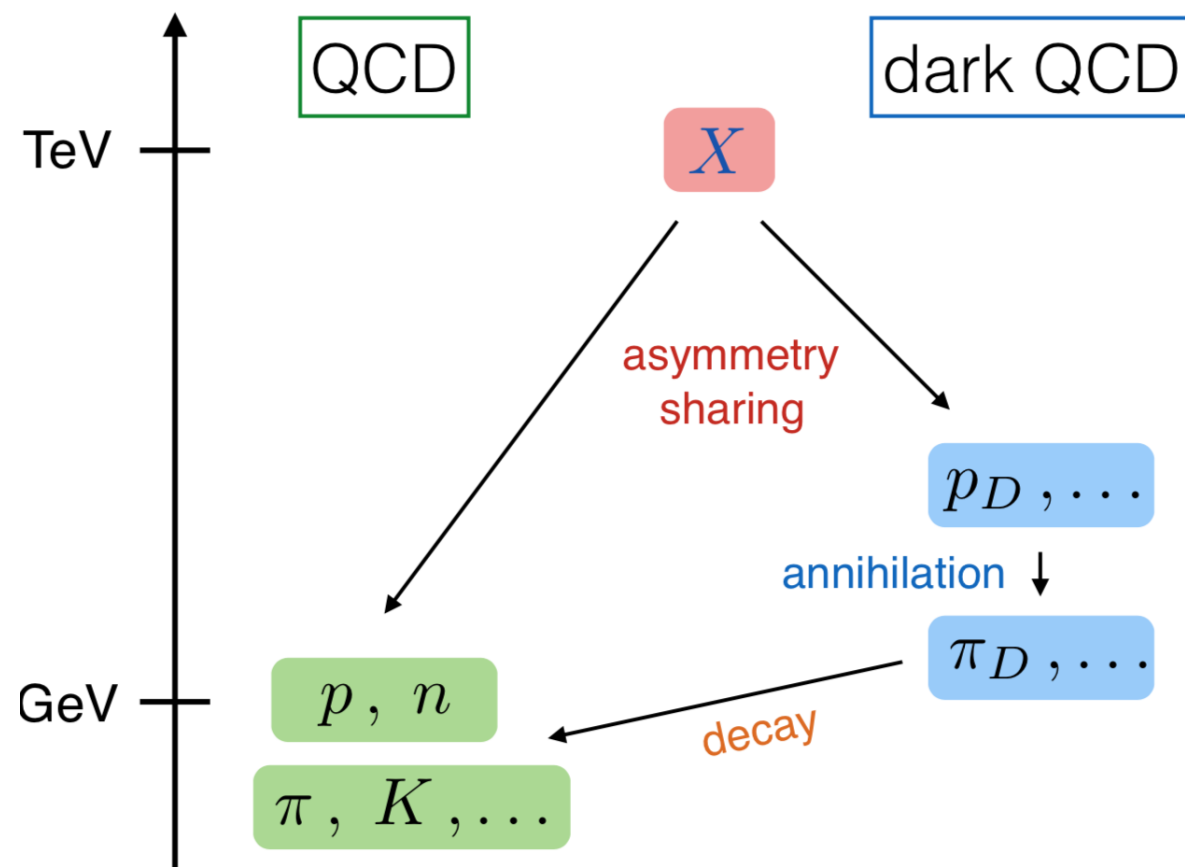
Fukuda at al, 1703.09675

Other signatures

Slide from P Schwaller
→ Kathryn Zurek's talk

Hidden valley idea by
Strassler & Zurek

Dark QCD

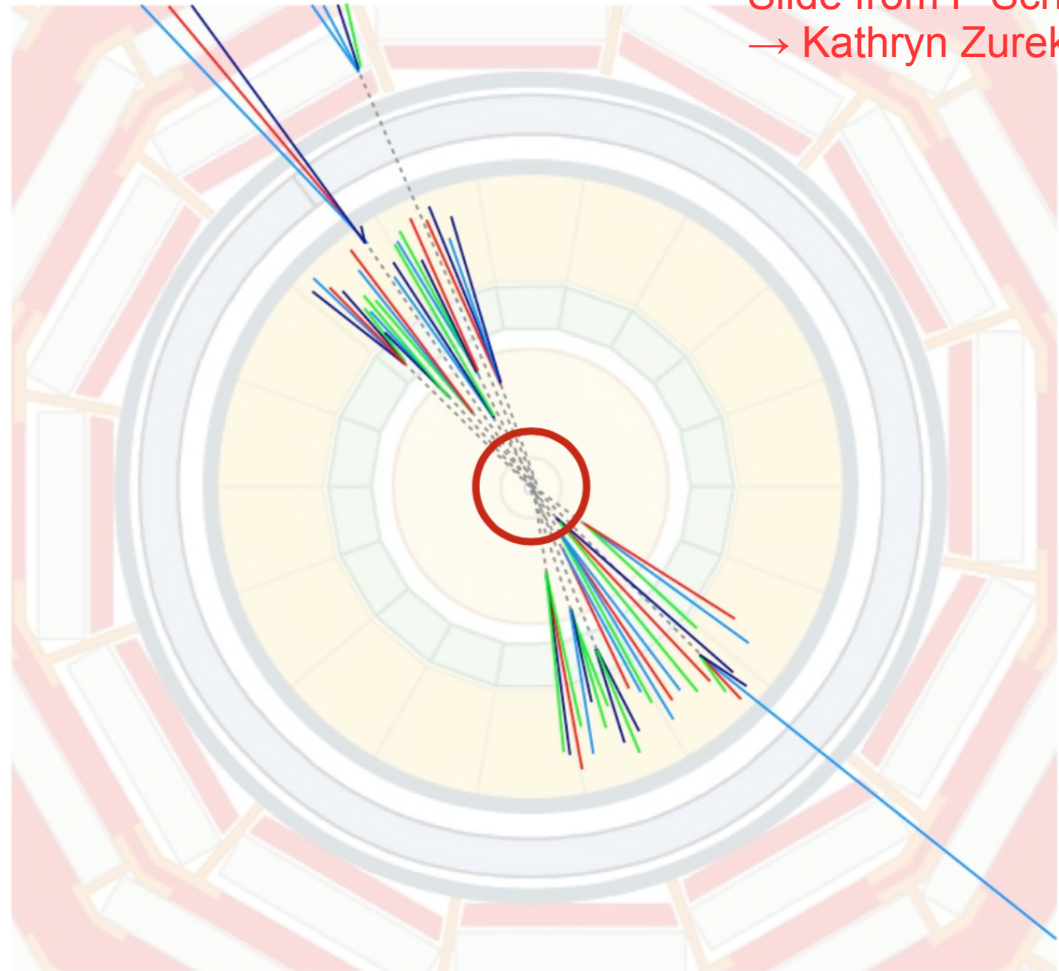


- SU(N) dark sector with neutral “dark quarks”
- Confinement scale Λ_{darkQCD}
- DM is composite “dark proton”
- “Dark pions” unstable, long lived

Emerging Jets at the LHC

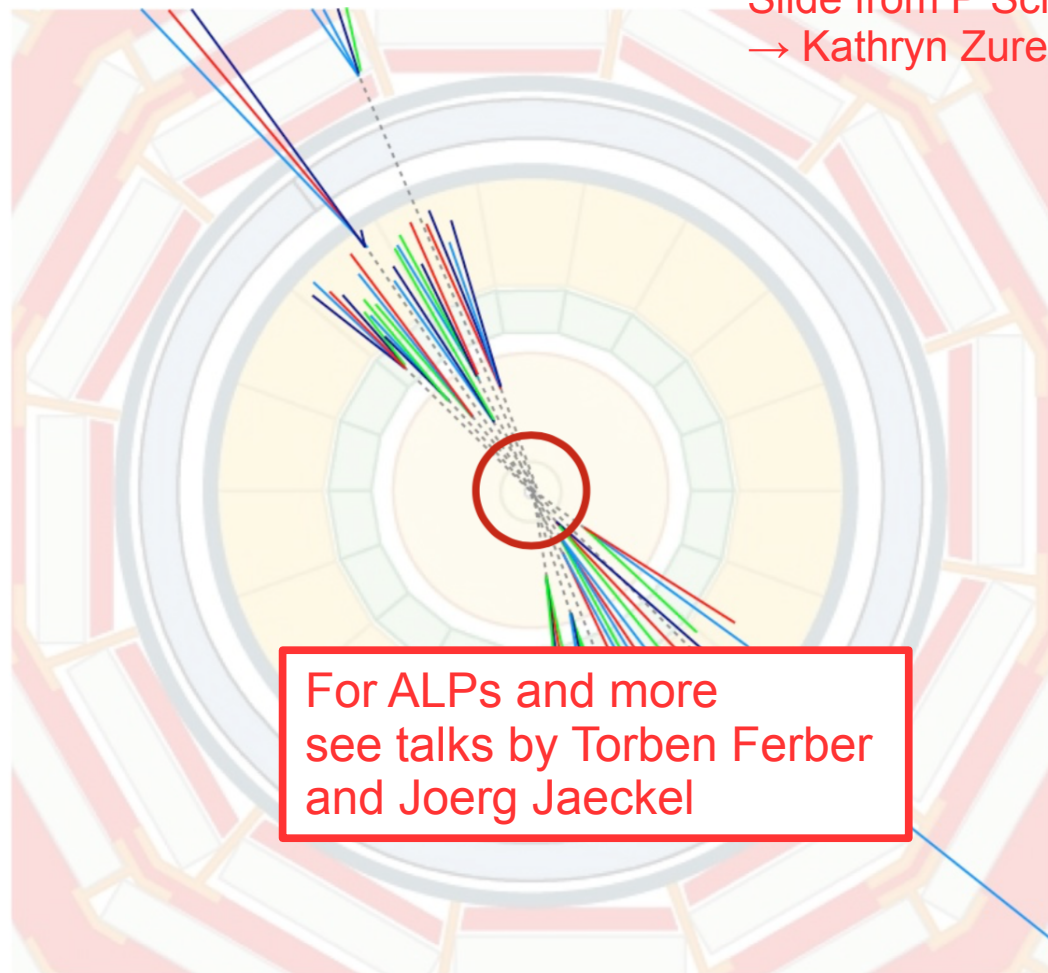
Slide from P Schwaller
→ Kathryn Zurek's talk

- Production of mediator, decay to dark quarks
- Characteristic:
 - few/no tracks in inner tracker
- New “emerging” jet signature
- Smoking gun of composite hidden sectors



Emerging Jets at the LHC

- Production of mediator, decay to dark quarks
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Slide from P Schwaller
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IR

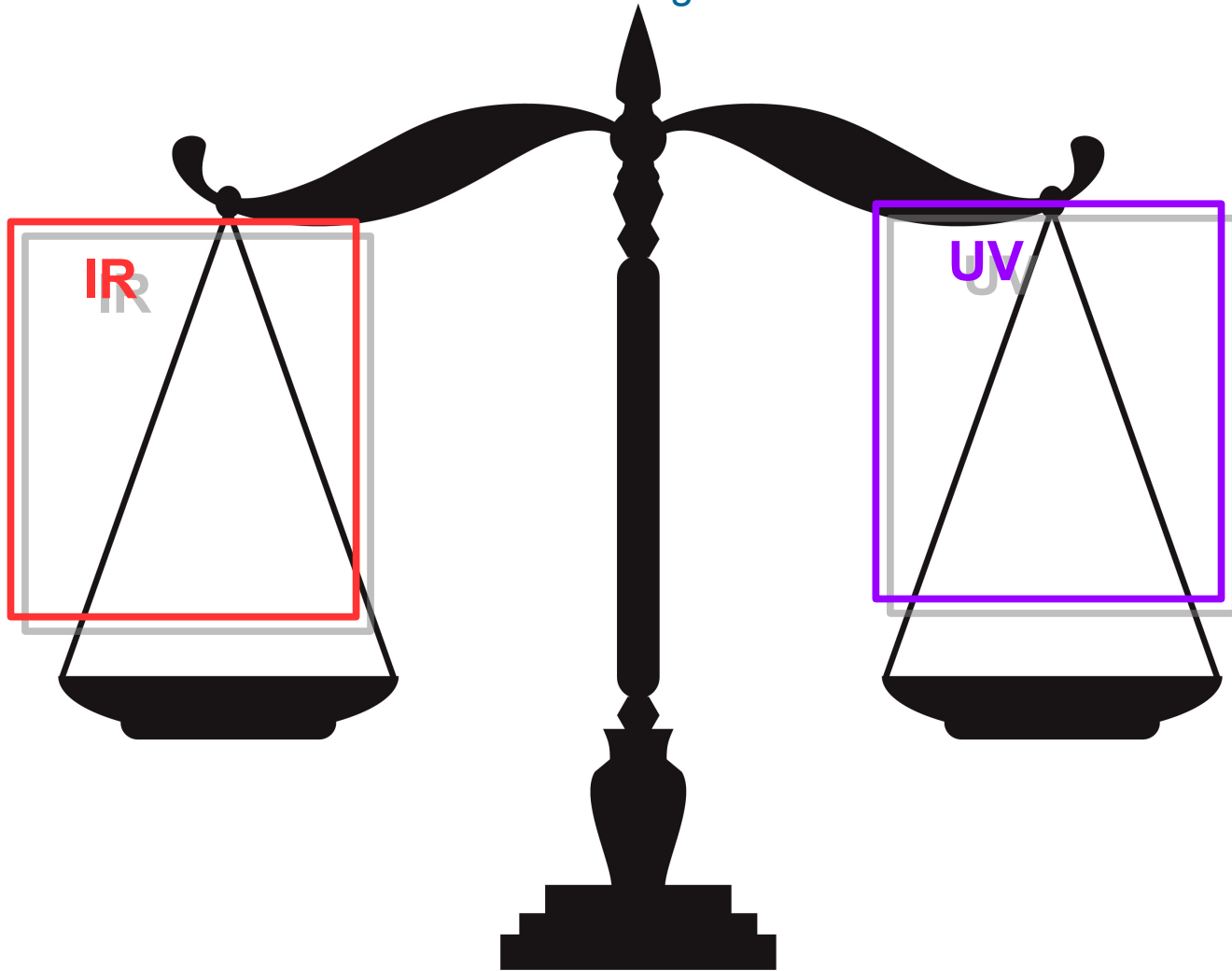
- ✓ Mono-X rather model independent signature
- ✗ May not give the leading constraint – i.e. DM may be discovered in a different channel (hopefully!!!)
- ✗ Some DM models don't feature Mono-X at all

UV

- ✓ Well-motivated signatures
- ✓ Study of consistent UV theories may reveal signature which hasn't been thought of
- ✗ Very model-dependent

Conclusion

Which then should we choose: the generic or the realistic?



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