

Long Lived Particles in Viable SUSY Dark Matter Models

Satoshi Shirai (Kavli IPMU)

Based on

H. Fukuda, N. Nagata, H. Otono, and SS,
“Probing bino–gluino coannihilation at the LHC,” [Phys.Lett. B748 \(2015\) 24](#),
“Probing bino–wino coannihilation at the LHC,” [JHEP 1510 \(2015\) 086](#),
“Cornering Compressed Gluino at the LHC,” [JHEP 1703 \(2017\) 025](#),
“Higgsino Dark Matter or Not,” [Phys.Lett. B781 \(2018\) 306](#)

1. SUSY after LHC

Higgs Mass

Mini-split SUSY

Dark Matter

2. Dark Matter Signatures in Mini-Split

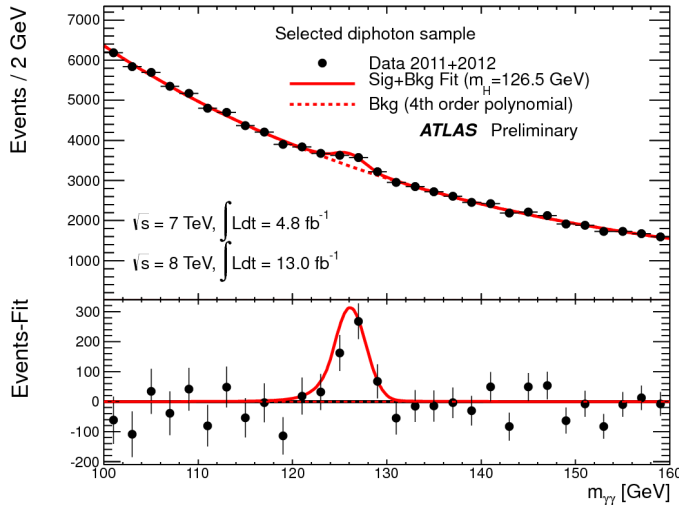
Wino

Gaugino coannihilation

Long lived particle signatures

3. Summary

Higgs and SUSY at LHC



ATLAS SUSY Searches* - 95% CL Lower Limits
December 2017

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

Model	$\epsilon, \mu, \tau, \gamma$	Jets	E_T^{miss}	$\int L dt [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference
Inclusive Searches	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	0-2 jets	Yes	36.1	1.57 TeV	$m(\tilde{g}) > 200$ GeV, $m(\tilde{t}^{\text{gen.}}) > m(2^{\text{nd}} \text{ gen. } \tilde{t})$	1712.0232	
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	710 GeV	$m(\tilde{g}) > 200$ GeV, $m(\tilde{t}^{\text{gen.}}) > 5$ GeV	1711.0301
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	0	2-6 jets	Yes	36.1	2.02 TeV	$m(\tilde{g}) > 200$ GeV	1712.0232
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	0	2-6 jets	Yes	36.1	2.01 TeV	$m(\tilde{g}) > 200$ GeV, $m(\tilde{t}^{\text{gen.}}) > 0.5(m(\tilde{t}^{\text{gen.}}) + m(\tilde{g}))$	1712.0232
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	ν_e, μ, τ	2 jets	Yes	14.7	1.7 TeV	$m(\tilde{g}) > 300$ GeV	1611.05791
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	3 e, μ	4 jets	Yes	36.1	1.87 TeV	$m(\tilde{g}) > 0$ GeV	1706.03731
	$\tilde{g}\tilde{g} \rightarrow \gamma\gamma^0$	0	7-11 jets	Yes	36.1	1.8 TeV	$m(\tilde{g}) > 400$ GeV	1706.02794
	GMSB (β NLSP)	1-2 $e, \mu + 0-1$	0-2 jets	Yes	3.2	2.0 TeV	$m(\tilde{g}) > 170$ GeV, $m(\text{NLSP}) > 0.1 \text{ mm}, \tau > 0.1 \text{ ns}$	1607.05979
	GGM (bino NLSP)	2 γ	2 jets	Yes	36.1	2.15 TeV	$m(\tilde{g}) > 170$ GeV, $m(\text{NLSP}) > 0.1 \text{ mm}, \tau > 0.1 \text{ ns}$	ATLAS-CONF-2017-080
	GGM (Higgsino NLSP)	2 γ	2 jets	Yes	36.1	2.05 TeV	$m(\tilde{g}) > 1.8 \times 10^{-1} \text{ eV}, m(\tilde{g}) > m(\tilde{g}) - 1.5 \text{ TeV}$	ATLAS-CONF-2017-080
	Gravitino LSP	0	mono-jet	Yes	20.3	865 GeV		1502.01518
1st gen. $\tilde{t}\tilde{t}$	$\tilde{t}\tilde{t} \rightarrow \text{hadrons}$	0	3 b	Yes	36.1	1.82 TeV	$m(\tilde{t}) > 600$ GeV	1711.01901
	$\tilde{t}\tilde{t} \rightarrow \text{hadrons}$	0-1 e, μ	3 b	Yes	36.1	1.87 TeV	$m(\tilde{t}) > 200$ GeV	1711.01901
3rd gen. squarks	$\tilde{b}_1\tilde{b}_1 \rightarrow \text{hadrons}$	0	2 b	Yes	36.1	950 GeV	$m(\tilde{b}_1) > 400$ GeV	1706.02926
	$\tilde{b}_1\tilde{b}_1 \rightarrow \text{hadrons}$	2 e, μ (SS)	1 b	Yes	36.1	275-700 GeV	$m(\tilde{b}_1) > 200$ GeV, $m(\tilde{t}^{\text{gen.}}) > m(\tilde{t}^{\text{gen.}}) + 100$ GeV	1706.03731
	$\tilde{f}_1\tilde{f}_1 \rightarrow \text{hadrons}$	0-2 e, μ	1-2 b	Yes	4.71/3.3	200-720 GeV	$m(\tilde{f}_1) > 200$ GeV, $m(\tilde{t}^{\text{gen.}}) > 40$ GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{f}_1\tilde{f}_1 \rightarrow \text{hadrons}$	0-2 e, μ	0-2 jets 1-2 b	Yes	20.3/36.1	90-198 GeV	$m(\tilde{f}_1) > 1$ GeV	1506.0816, 1709.04183, 1711.11520
3rd gen. squarks	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	0	mono-jet	Yes	36.1	90-430 GeV	$m(\tilde{t}_1) > 150$ GeV	1711.0301
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	0	mono-jet	Yes	36.1	150-600 GeV	$m(\tilde{t}_1) > 150$ GeV	1403.5222
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons} + Z$	3 e, μ (Z)	1 b	Yes	36.1	290-790 GeV	$m(\tilde{t}_1) > 0$ GeV	1706.03986
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons} + h$	1-2 e, μ	3 b	Yes	36.1	320-880 GeV	$m(\tilde{t}_1) > 0$ GeV	1706.03986
EW direct	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	2 e, μ	0	Yes	36.1	90-500 GeV	$m(\tilde{t}_1) > 0$	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	2 e, μ (SS)	1 b	Yes	36.1	750 GeV	$m(\tilde{t}_1) > 0, m(\tilde{t}^{\text{gen.}}) > 0.5(m(\tilde{t}^{\text{gen.}}) + m(\tilde{t}_1))$	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	2 γ	-	Yes	36.1	750 GeV	$m(\tilde{t}_1) > 0, m(\tilde{t}^{\text{gen.}}) > 0.5(m(\tilde{t}^{\text{gen.}}) + m(\tilde{t}_1))$	1706.07875
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	3 e, μ	0	Yes	36.1	1.13 TeV	$m(\tilde{t}_1) > m(\tilde{t}_1), m(\tilde{t}^{\text{gen.}}) > 0, m(\tilde{t}^{\text{gen.}}) > 0.5(m(\tilde{t}^{\text{gen.}}) + m(\tilde{t}_1))$	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	2-3 e, μ	0-2 jets	Yes	36.1	580 GeV	$m(\tilde{t}_1) > m(\tilde{t}_1), m(\tilde{t}^{\text{gen.}}) > 0, \tilde{t}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	e, μ, τ, γ	0-2 b	Yes	20.3	270 GeV	$m(\tilde{t}_1) > m(\tilde{t}_1), m(\tilde{t}^{\text{gen.}}) > 0, \tilde{t}$ decoupled	1501.07110
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	4 e, μ	0	Yes	20.3	635 GeV	$m(\tilde{t}_1) > m(\tilde{t}_1), m(\tilde{t}^{\text{gen.}}) > 0, \tilde{t}$ decoupled	1405.5066
	GGM (wino NLSP) weak prod., $\tilde{t}_1^{\text{gen.}} \rightarrow \tilde{t}_1 + \gamma$	1-2 $e, \mu + \gamma$	2 γ	Yes	20.3	115-370 GeV	$m(\tilde{t}_1) > m(\tilde{t}_1), m(\tilde{t}^{\text{gen.}}) > 0, \tilde{t}$ decoupled	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{t}_1^{\text{gen.}} \rightarrow \tilde{t}_1 + G$	2 γ	-	Yes	36.1	1.06 TeV	$m(\tilde{t}_1) > m(\tilde{t}_1), m(\tilde{t}^{\text{gen.}}) > 0, \tilde{t}$ decoupled	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde{t}_1\tilde{t}_1$ prod., long-lived $\tilde{t}_1^{\text{gen.}}$	Disapp. trk	1 jet	Yes	36.1	450 GeV	$m(\tilde{t}_1) > m(\tilde{t}_1) - 180 \text{ MeV}, m(\tilde{t}_1) > 0.2 \text{ ns}$	1712.02118
	Direct $\tilde{t}_1\tilde{t}_1$ prod., long-lived $\tilde{t}_1^{\text{gen.}}$	disapp. trk	-	Yes	18.4	455 GeV	$m(\tilde{t}_1) > m(\tilde{t}_1) - 180 \text{ MeV}, m(\tilde{t}_1) > 0.2 \text{ ns}$	1606.03392
	Stable, stopped \tilde{t}_1 R-hadron	0	1-5 jets	Yes	27.9	850 GeV	$m(\tilde{t}_1) > 100$ GeV, $10 \mu\text{s} < \tau < 1000 \text{ s}$	1310.6584
	Stable \tilde{t}_1 R-hadron	trk	-	3.2	-	1.58 TeV	$m(\tilde{t}_1) > 100$ GeV, $\tau > 10 \text{ ns}$	1606.05129
	Metastable \tilde{t}_1 R-hadron	disapp. trk	-	3.2	-	1.57 TeV	$m(\tilde{t}_1) > 100$ GeV, $10 \mu\text{s} < \tau < 1000 \text{ s}$	1604.04580
	Metastable \tilde{t}_1 R-hadron, $\tilde{t}_1 \rightarrow \gamma\gamma^0$	disapp. trk	-	32.8	-	2.37 TeV	$m(\tilde{t}_1) > 0.17 \text{ ns}, m(\tilde{t}_1) > 100$ GeV	1710.04901
	GMSB, stable $\tilde{t}_1, \tilde{t}_1^{\text{gen.}} \rightarrow \tilde{t}_1 + \text{hadrons}$	1-2 μ	-	19.1	-	537 GeV	$10\text{-camp} < 0$	1411.6795
	GMSB, $\tilde{t}_1^{\text{gen.}} \rightarrow G$, long-lived $\tilde{t}_1^{\text{gen.}}$	2 γ	-	20.3	-	440 GeV	$1\text{-camp} < 0$ ns, SPSS model	1409.3542
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons} + \mu\mu$	disapp. $e, \mu, \mu\mu$	-	20.3	-	1.0 TeV	$2\text{-camp} < 0.740 \text{ ns}, m(\tilde{t}_1) > 1.3 \text{ TeV}$	1504.05162
RPV	LFV $\tilde{g}\tilde{g} \rightarrow \tau, \tau, X, X \rightarrow \mu\mu/\tau\tau/\mu\tau$	$e, \mu, \tau, \mu\mu$	-	3.2	-	1.5 TeV	$A_{11} < 0.11, A_{21} < 0.007$	1607.08079
	Linear RPV GMSB	2 e, μ (SS)	0-3 b	Yes	20.3	1.45 TeV	$m(\tilde{g}) > 100$ GeV, $\tau_{\tilde{g}} < 1 \text{ ns}$	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1^{\text{gen.}} \rightarrow \text{hadrons}$	4 e, μ	-	Yes	13.3	1.14 TeV	$m(\tilde{t}_1) > 400$ GeV, $A_{12} > 0$ ($k = 1, 2$)	ATLAS-CONF-2016-075
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1^{\text{gen.}} \rightarrow \text{hadrons}$	3 $e, \mu + \tau$	-	Yes	20.3	450 GeV	$m(\tilde{t}_1) > 0, m(\tilde{t}^{\text{gen.}}) > 0, A_{12} > 0$	1405.5066
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	0	4-5 large-R jets	Yes	36.1	1.875 TeV	$m(\tilde{t}_1) > 100$ GeV	SUSY2016.22
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	1 e, μ	8-10 jets 0-4 b	Yes	36.1	2.1 TeV	$m(\tilde{t}_1) > 1 \text{ TeV}, m(\tilde{t}_1) > 0$	1704.08493
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	1 e, μ	8-10 jets 0-4 b	Yes	36.1	1.65 TeV	$m(\tilde{t}_1) > 1 \text{ TeV}, m(\tilde{t}_1) > 0$	1704.08493
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	0	2 jets + 2 b	Yes	36.7	100-470 GeV / 480-10 GeV	BR($\tilde{t}_1 \rightarrow \text{hadrons}$) > 20%	1710.07171
	$\tilde{t}_1\tilde{t}_1 \rightarrow \text{hadrons}$	2 e, μ	2 b	Yes	36.1	510 GeV	$m(\tilde{t}_1) > 200$ GeV	1501.01325
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{c}^0$	0	2 c	Yes	20.3	510 GeV	$m(\tilde{c}) > 200$ GeV	1501.01325

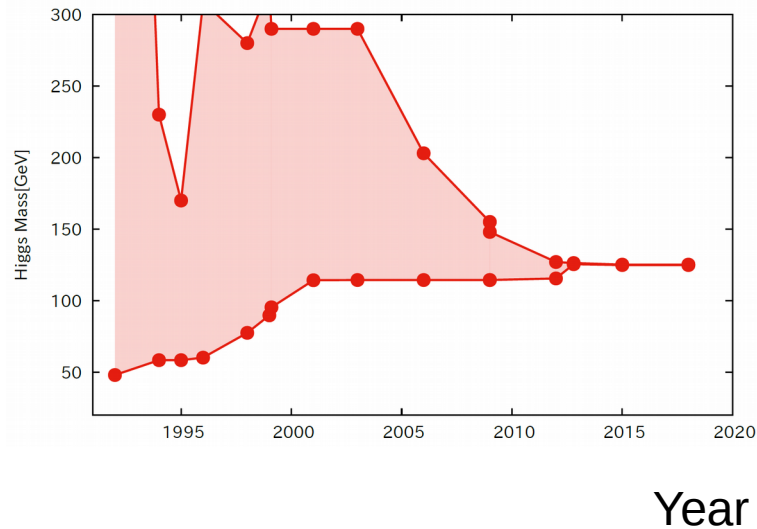
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Higgs Discovered!

SUSY Constrained!

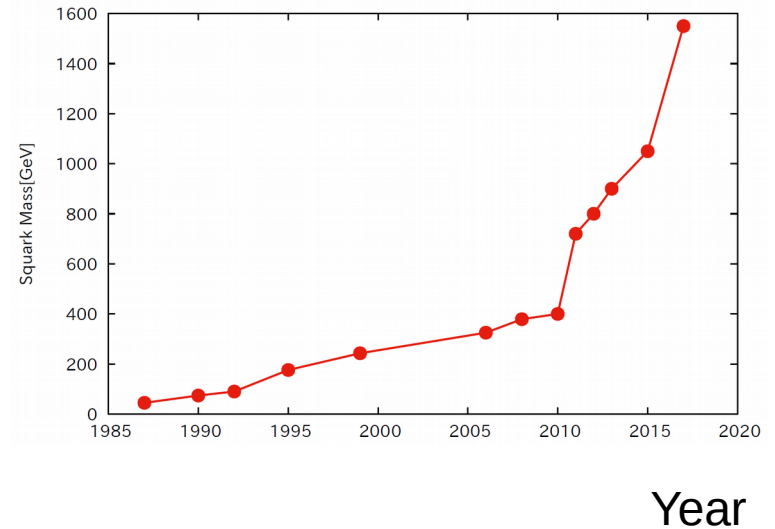
Cornering Higgs and SUSY

Higgs Mass Range



$$m_h = 125.18 \pm 0.16 \text{ GeV}$$

Squark Mass Limit



$$m_{\tilde{q}} > 1550 \text{ GeV}$$

SUSY Higgs

Higgs potential

$$V(H) = \frac{\lambda}{2} (HH^\dagger - v^2)^2$$

In MSSM

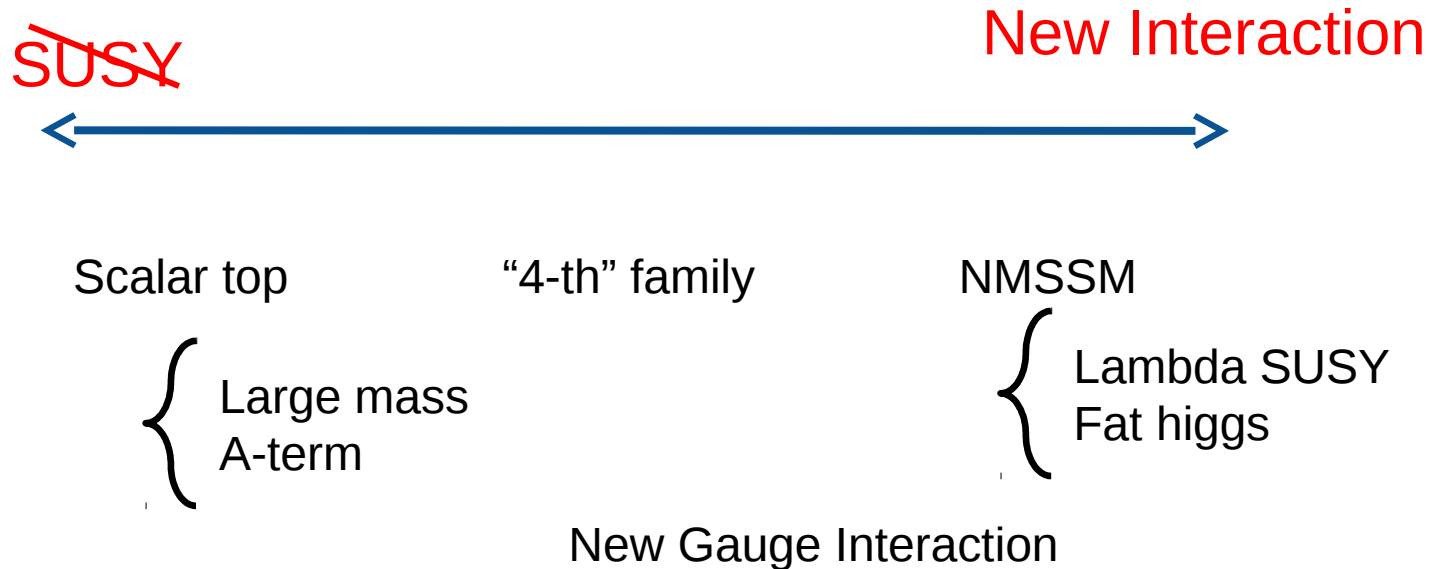
$$\lambda = \frac{1}{4} (g_1^2 + g_2^2) \cos(2\beta)$$

$$m_h = m_Z \cos(2\beta) \lesssim 91 \text{ GeV}$$

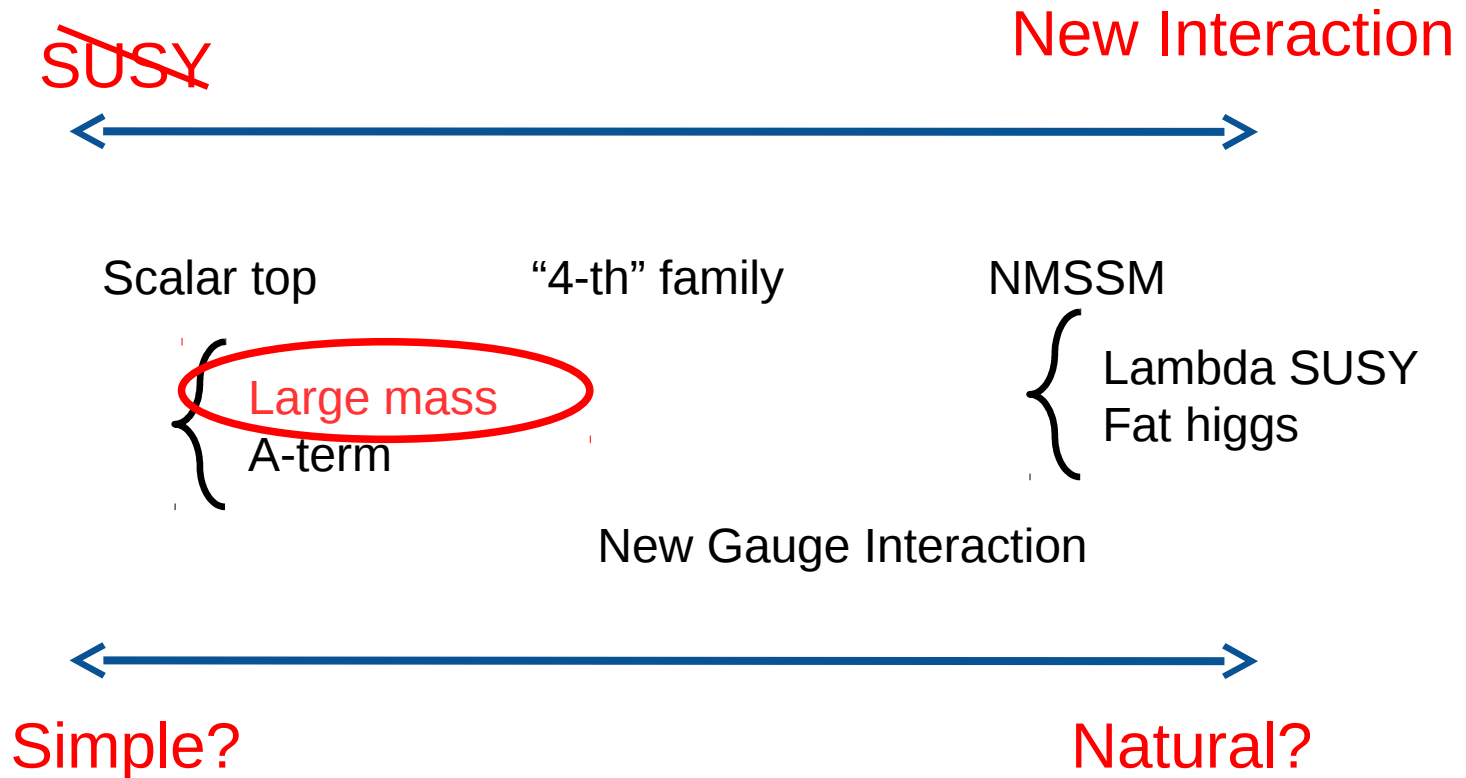
This is clearly less than observed 125 GeV Higgs!

$$\lambda = \lambda_{\text{MSSM}} + \lambda_{\text{SUSY breaking}} + \lambda_{\text{new interaction}}$$

SUSY after 125 GeV Higgs

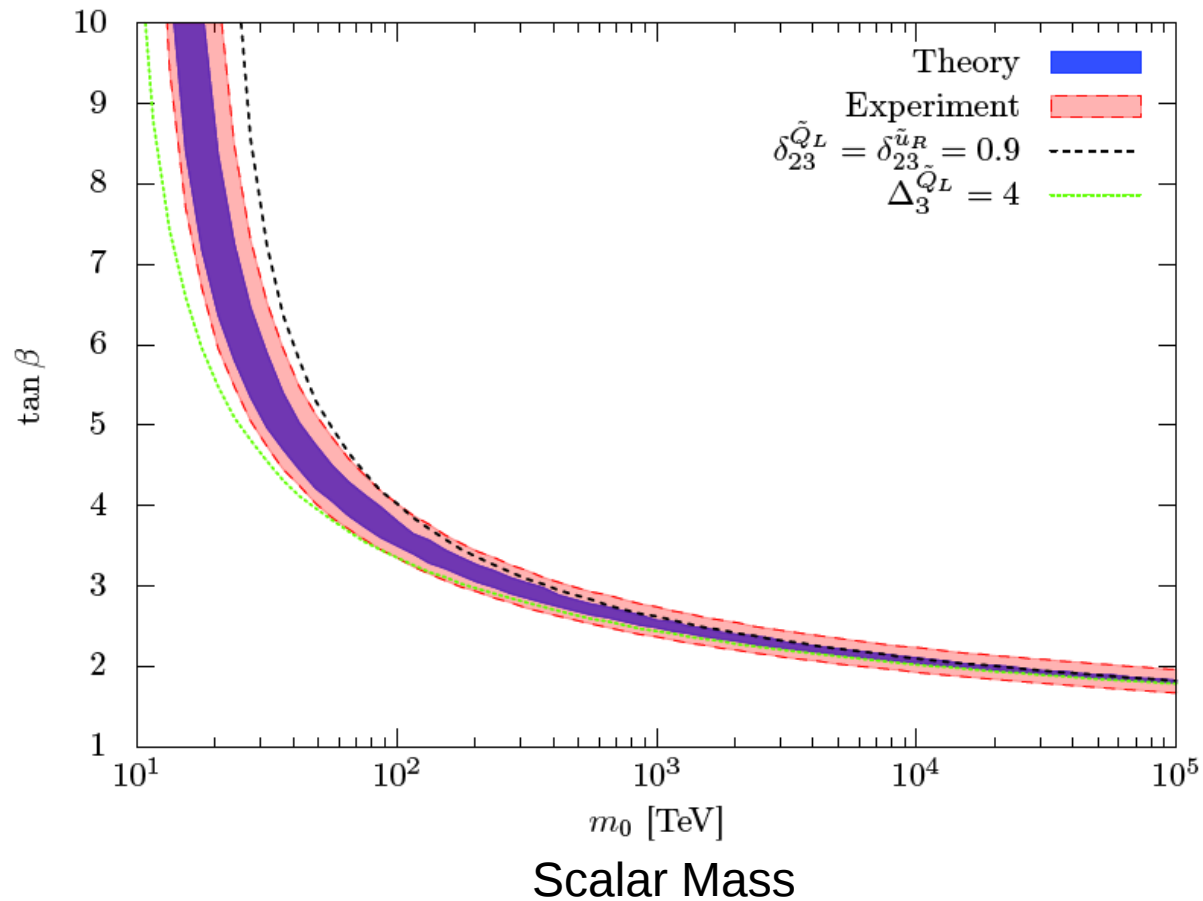


SUSY after 125 GeV Higgs



Higgs Mass from Stop

125 GeV Higgs OK regions



Benefit and demerit of SUSY

Benefit

- Hierarchy Problem
- GUT unification
- DM

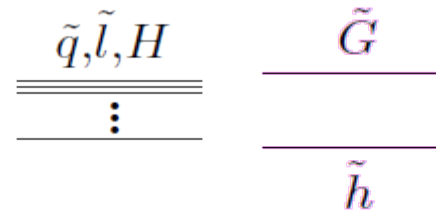
Possible demerit

- Flavor/CP Problem
- Cosmological Gravitino Problem
- Model building

Mini-Split Mass Spectrum

Tree level Gravity Mediation

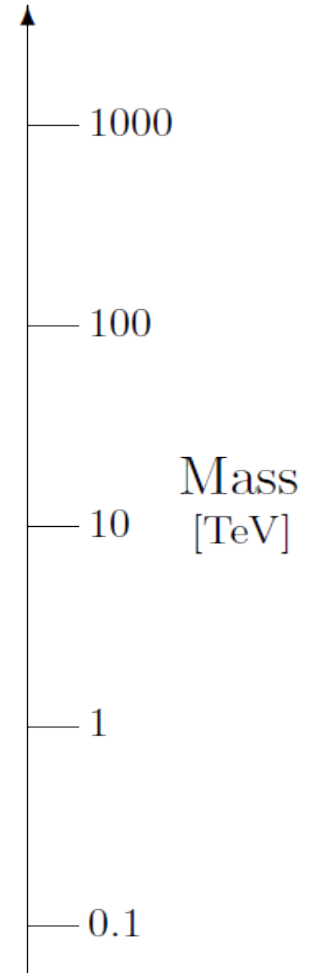
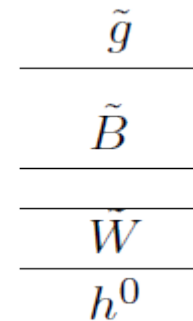
$$|m_0| \sim |\mu| \sim m_{3/2}$$



Loop suppressed: e.g., Anomaly Mediation

$$M_a \sim \frac{\alpha_a}{4\pi} m_{3/2}$$

Randall, Sundrum '98
Giudice, Luty, Murayama, Rattazzi '98



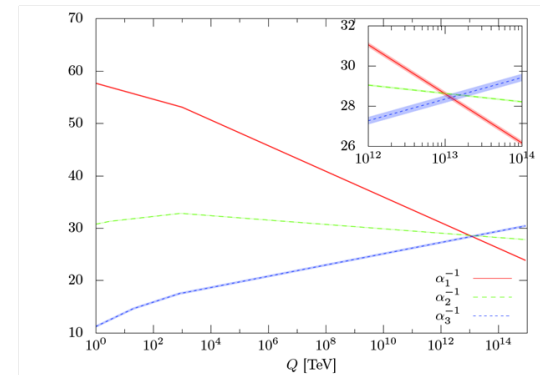
Benefit and demerit of SUSY

Benefit

- ? • Hierarchy Problem
- ✓ • GUT unification
- ✓ • DM

Possible demerit

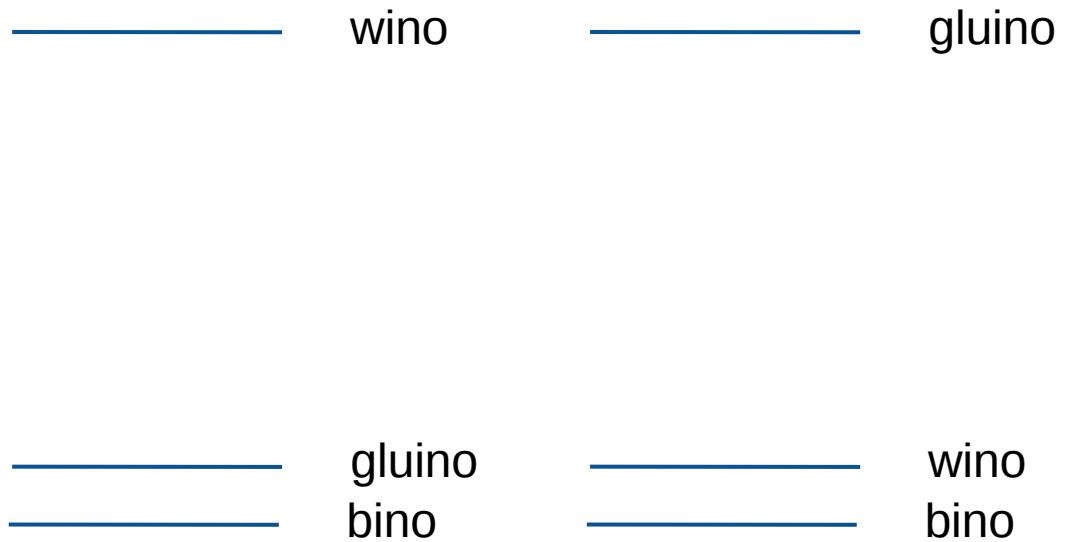
- ✓ • Flavor/CP Problem
- ✓ • Cosmological Gravitino Problem
- ✓ • Model building



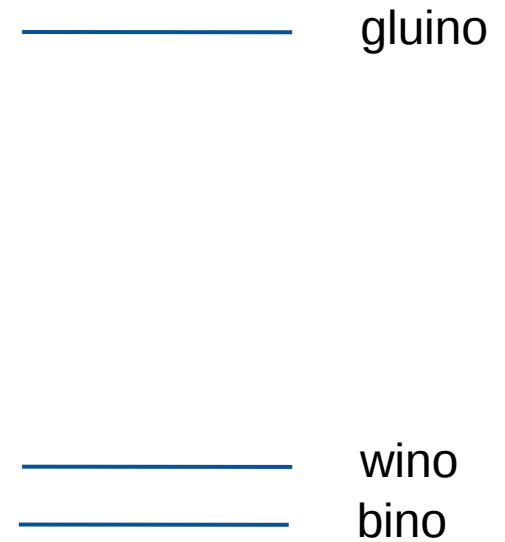
Three Possibilities for DM



Wino DM



Bino-gluino
coannihilation

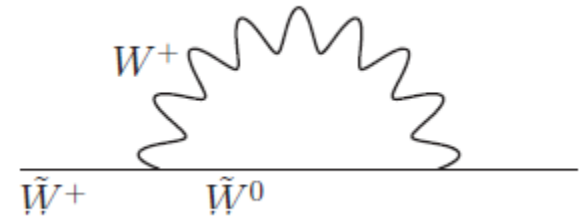


Bino-wino
coannihilation

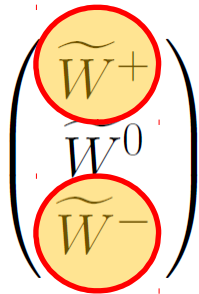


Wino DM case

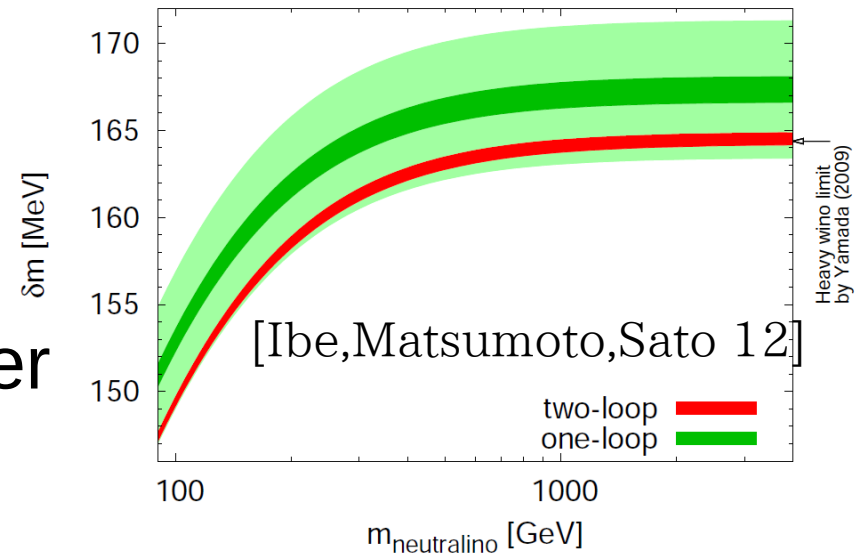
Wino Spectrum



Radiative correction

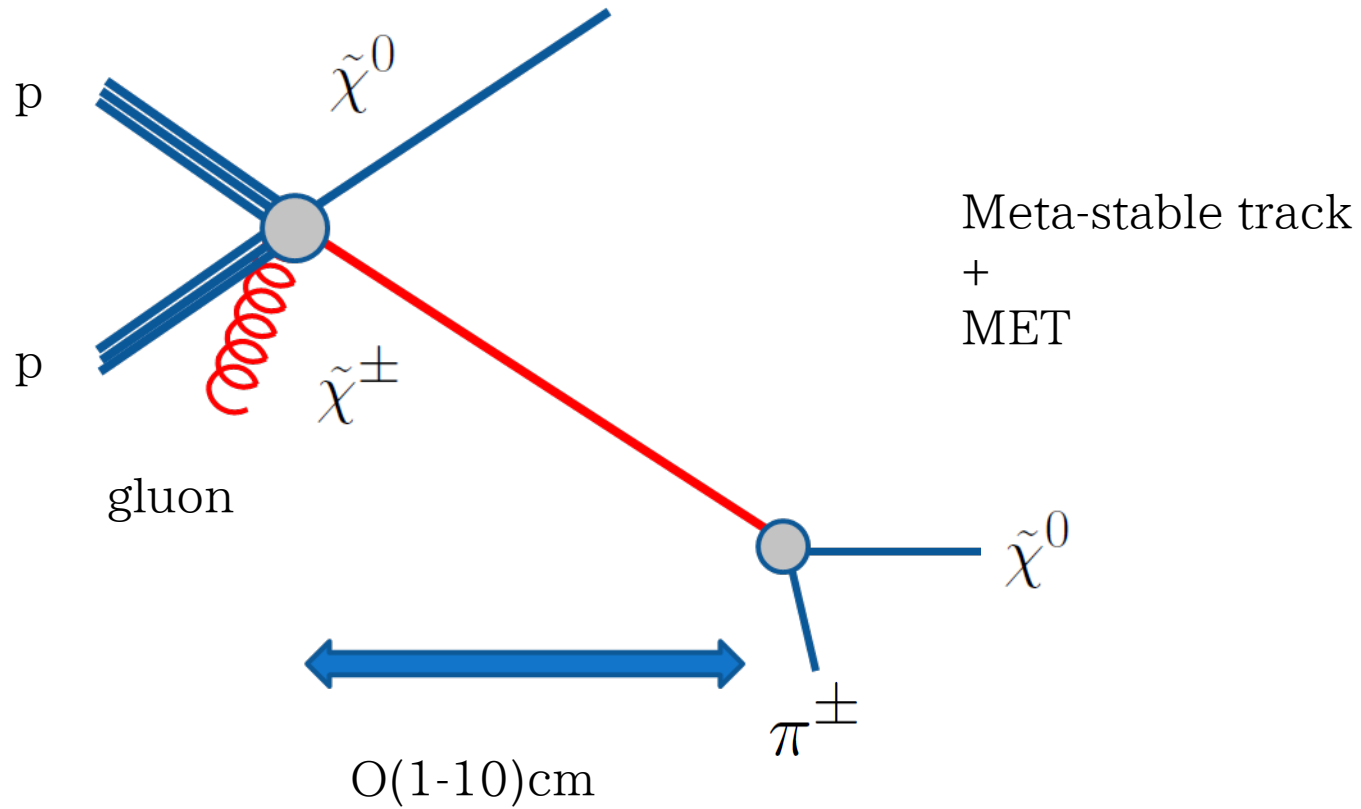


Charged slightly heavier

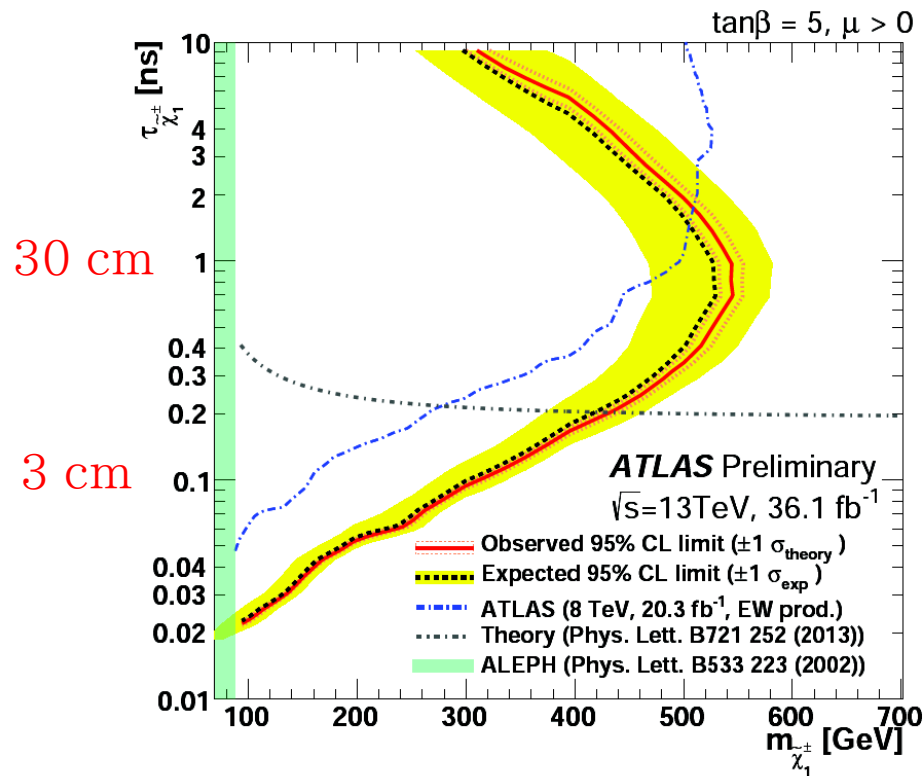


$$c\tau(\tilde{W}^\pm \rightarrow \tilde{W}^0 \pi^\pm) \simeq 7 \text{ cm} \left(\frac{\Delta m}{165 \text{ MeV}} \right)^{-3}$$

LHC Signals

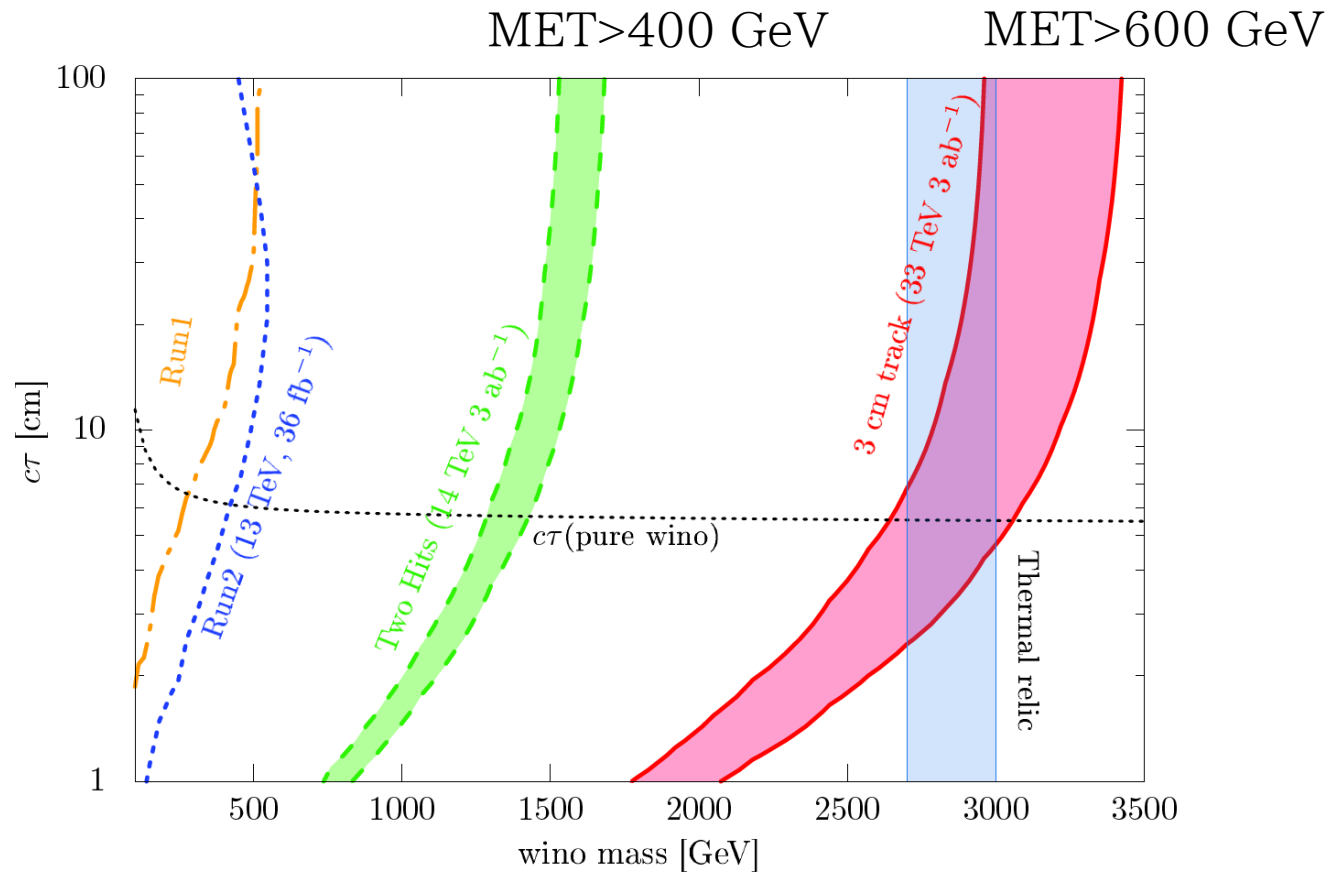


Current Constraint(wino)



MET + disappearing track

Prospects for Wino



Three Possibilities for DM



Wino DM

Bino-gluino
coannihilation

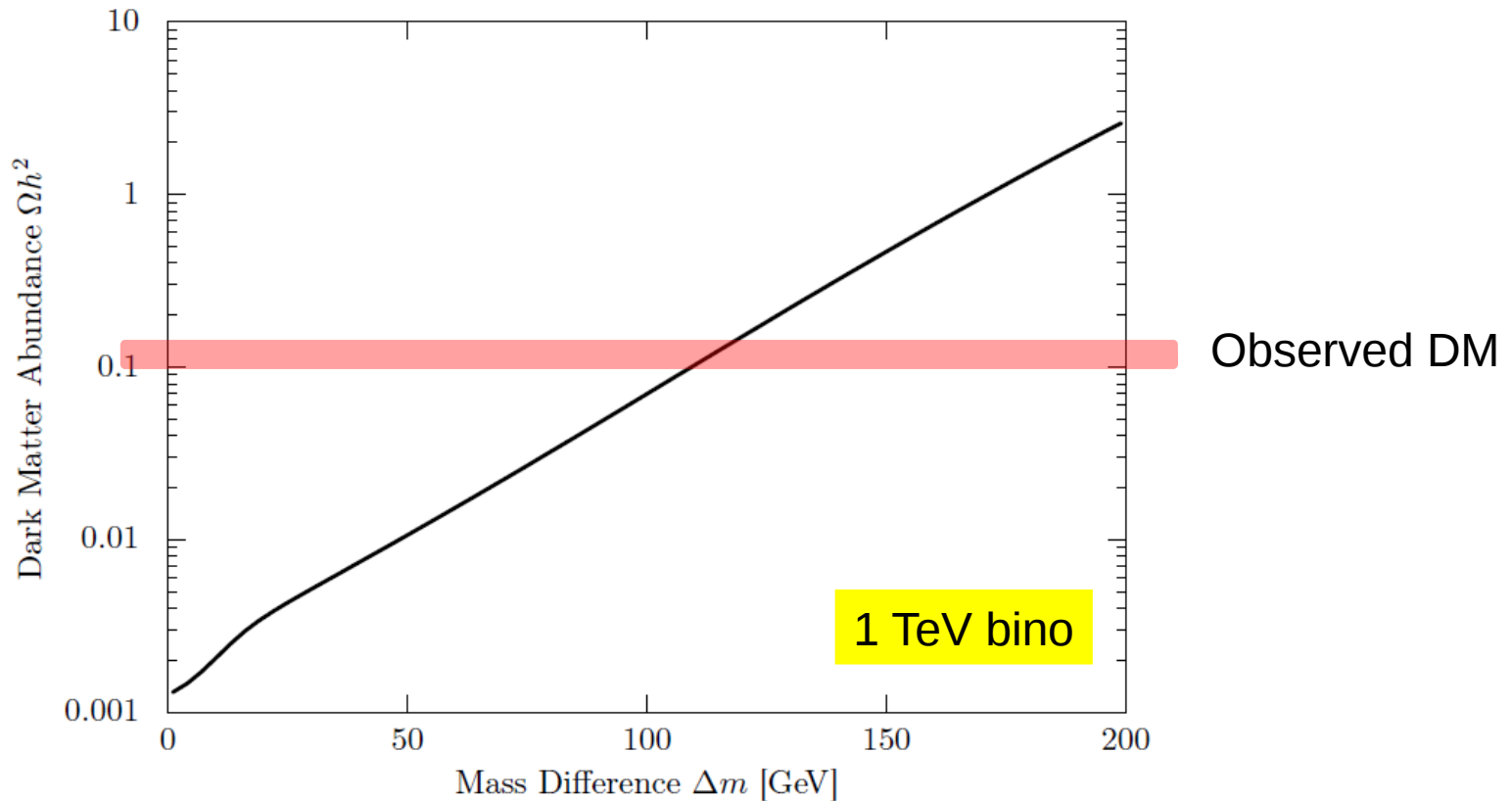
Bino-wino
coannihilation



Bino-Gluino Coannihilation

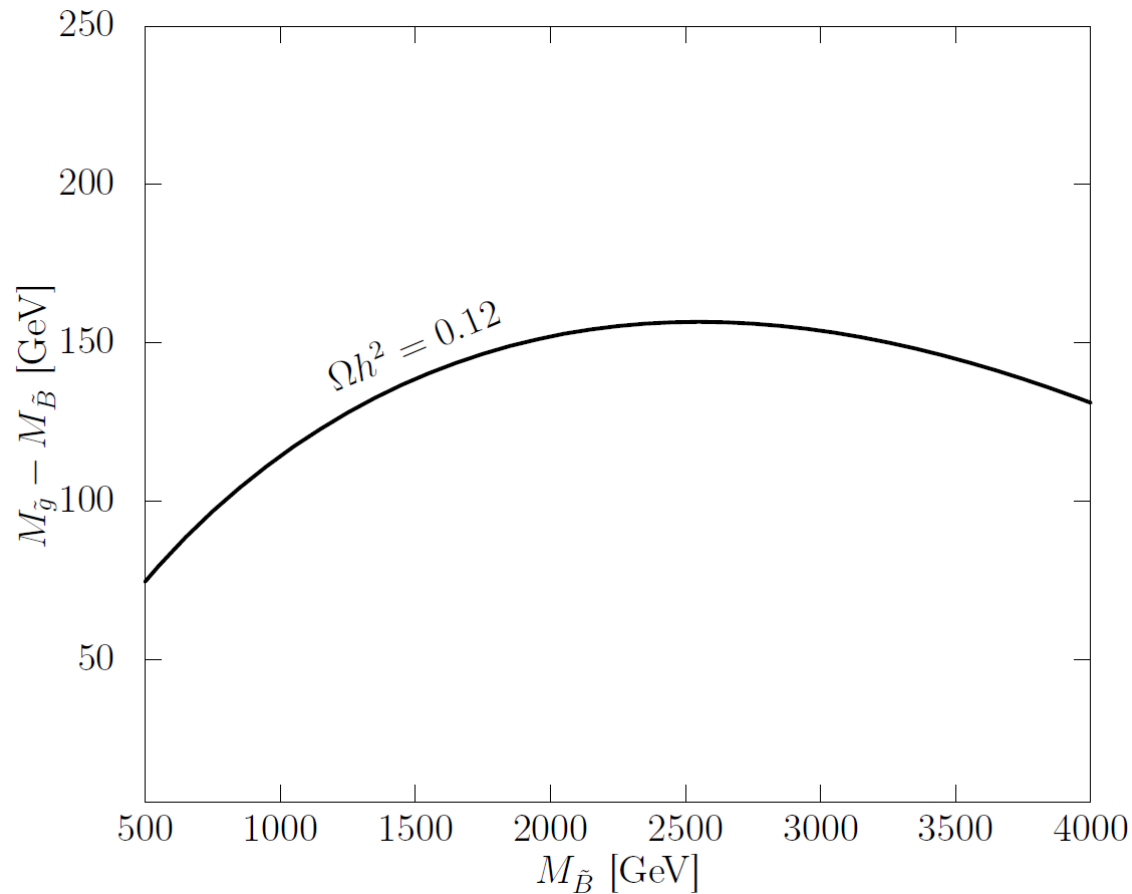
Bino-Gluino Coannihilation 1

Dark matter abundance

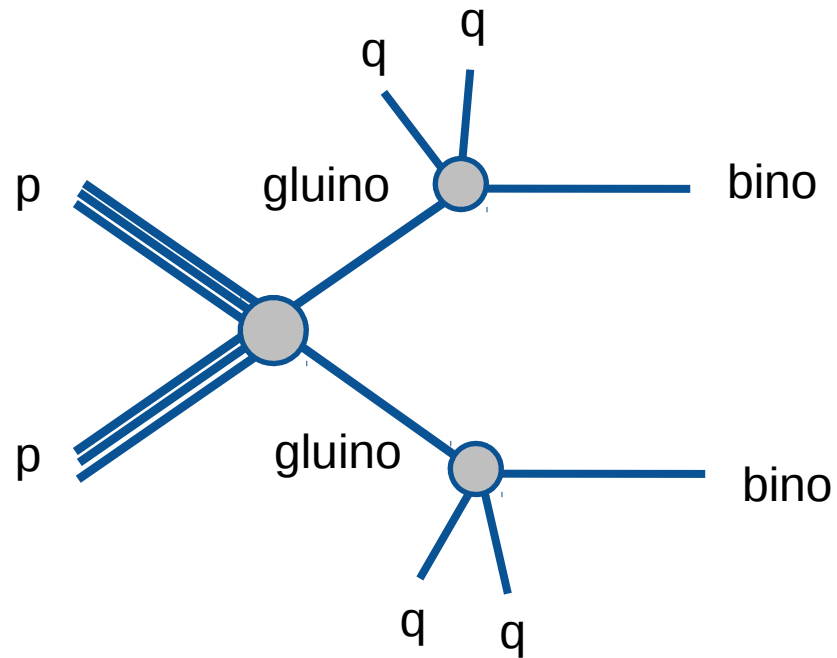


Gluino-bino mass difference

Gluino Coannihilation

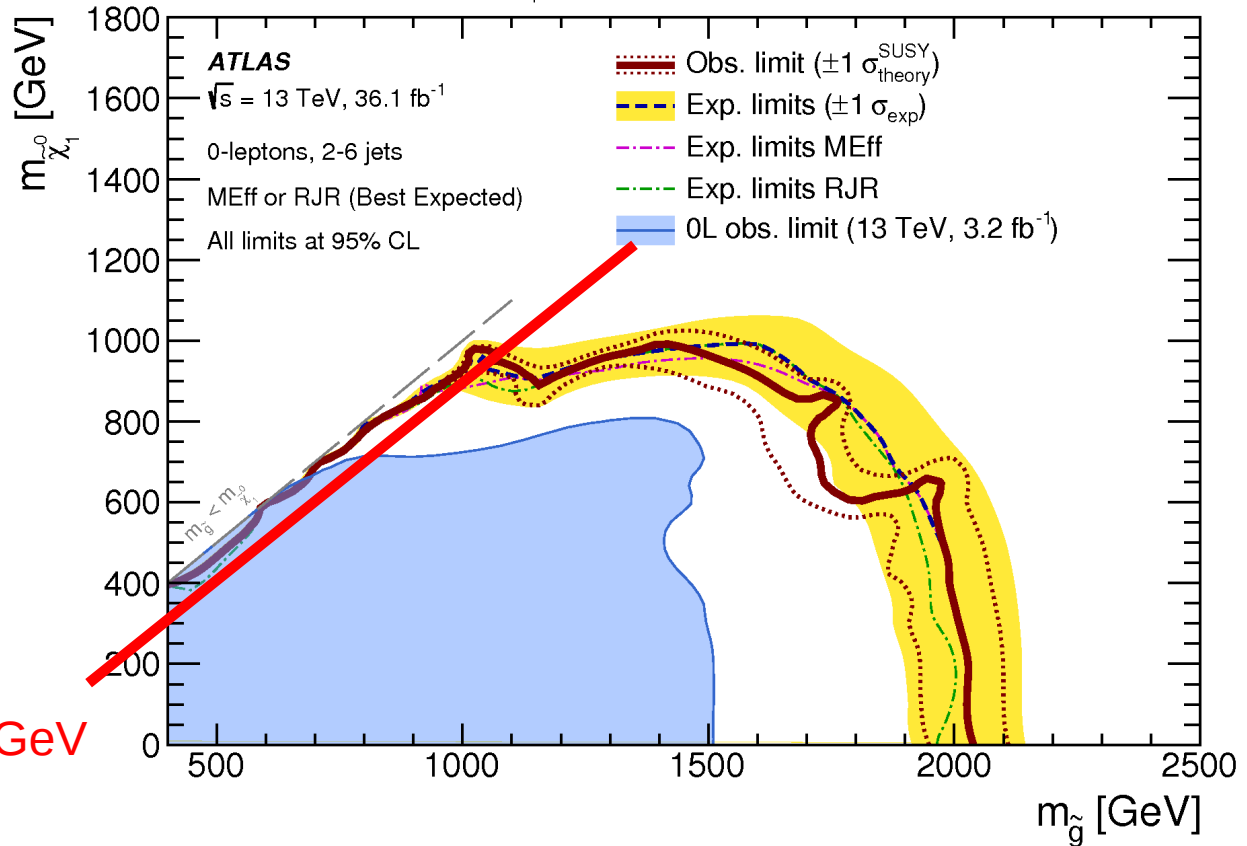


LHC Signals



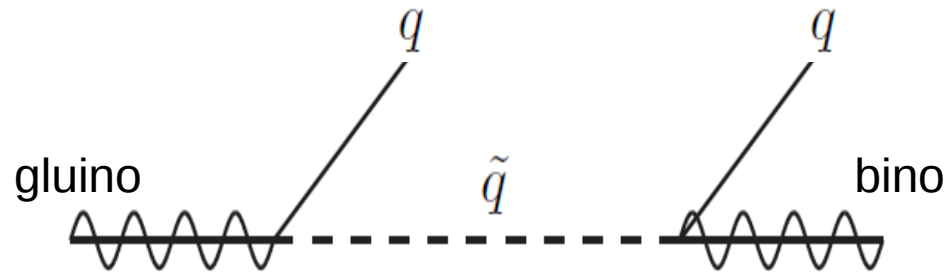
Prompt Decay Case

$\tilde{g}\tilde{g}$ production, $B(\tilde{g} \rightarrow qq \tilde{\chi}_1^0) = 100\%$

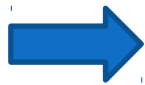


Mass diff. = 100 GeV

Bino-Gluino Interaction



Bino-gluino interaction is suppressed by sfermion mass



Long-lived gluino

$$c\tau_{\tilde{g}} = O(1) \left(\frac{\Delta m}{100 \text{ GeV}} \right)^{-5} \left(\frac{M_s}{100 \text{ TeV}} \right)^4 \text{ cm}$$

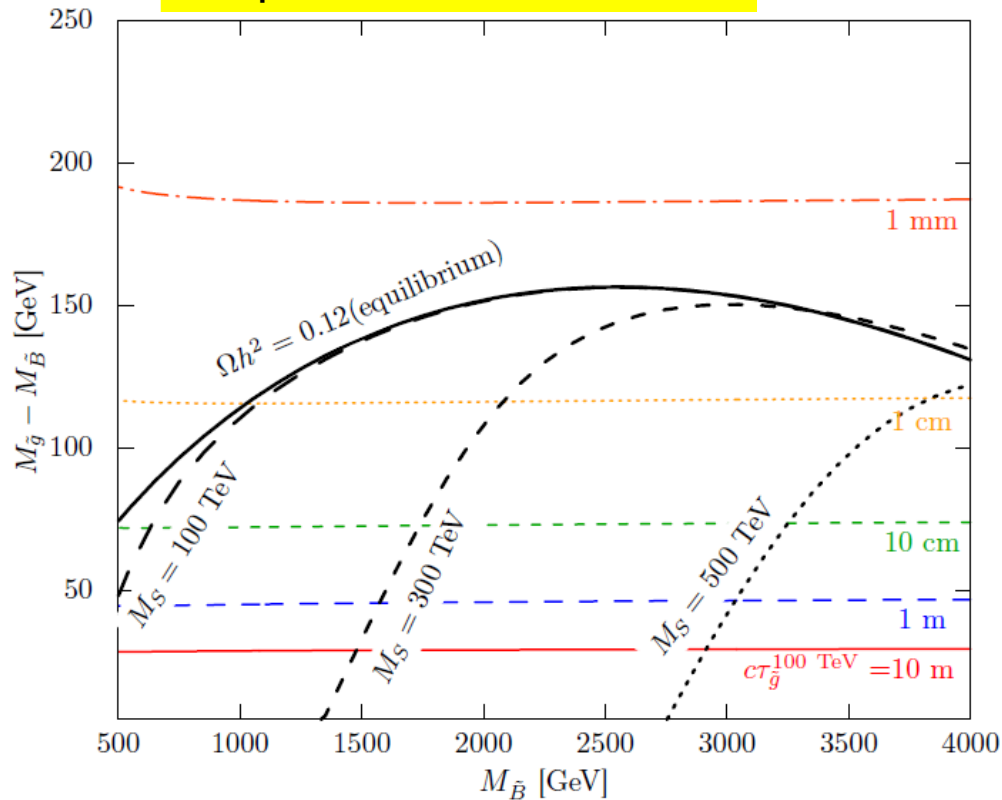


Too heavy sfermion prevents coannihilation

$$M_s \lesssim 250 \left(\frac{M_{\text{bino}}}{1 \text{ TeV}} \right)^{3/4} \text{ TeV}$$

Bino-Gluino Coannihilation

Required mass difference

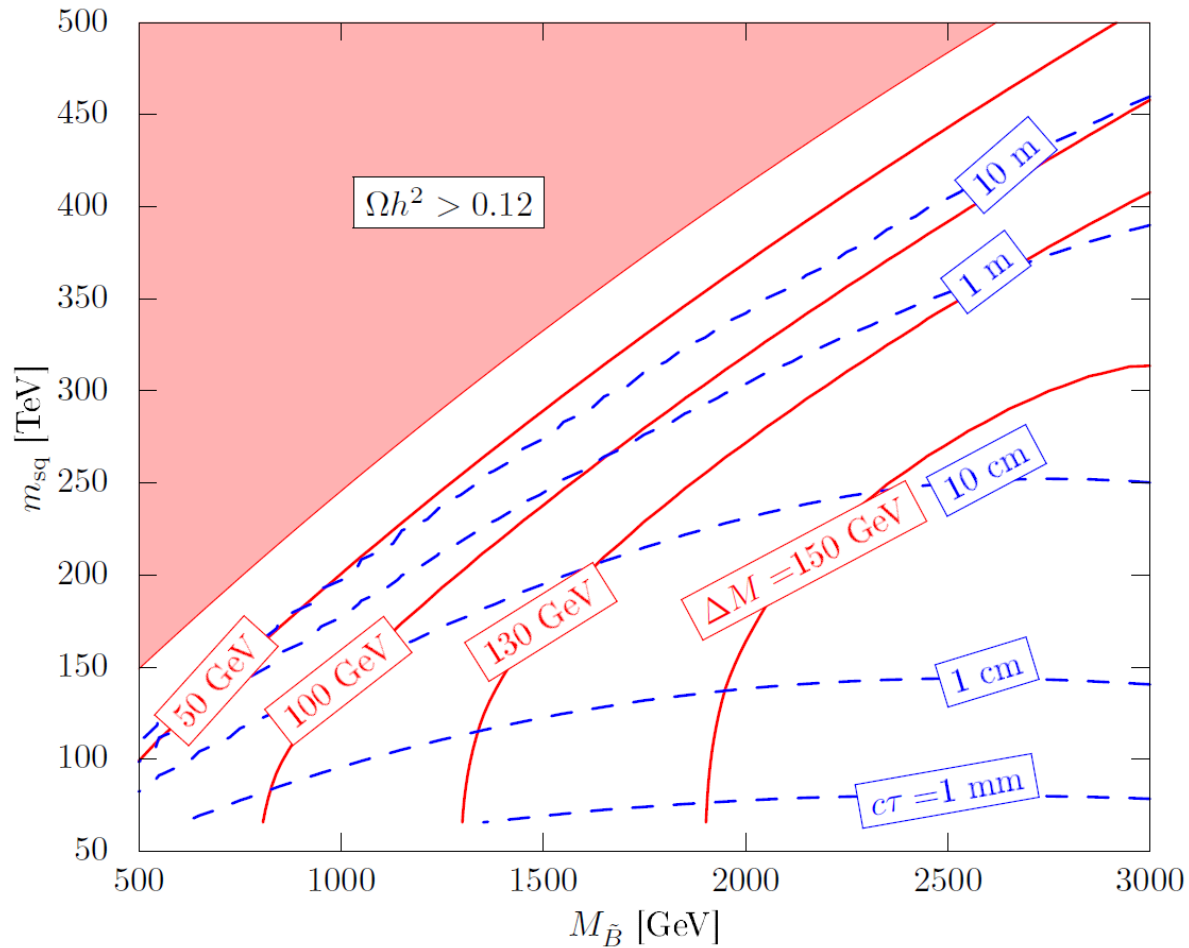


E.g.,
For 100 TeV
sfermion,

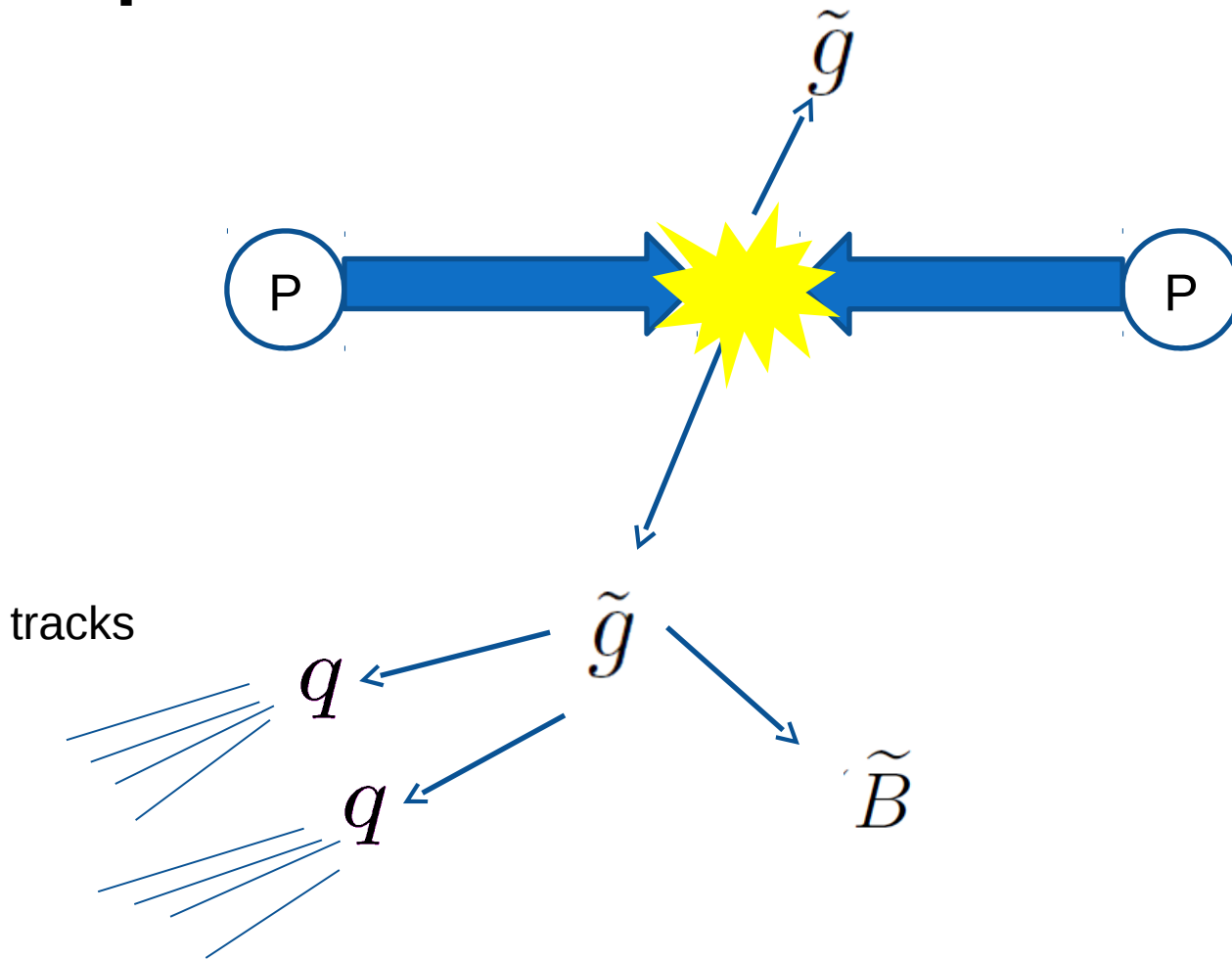
Mass diff. ~ 100
GeV

Decay length $\sim \text{cm}$

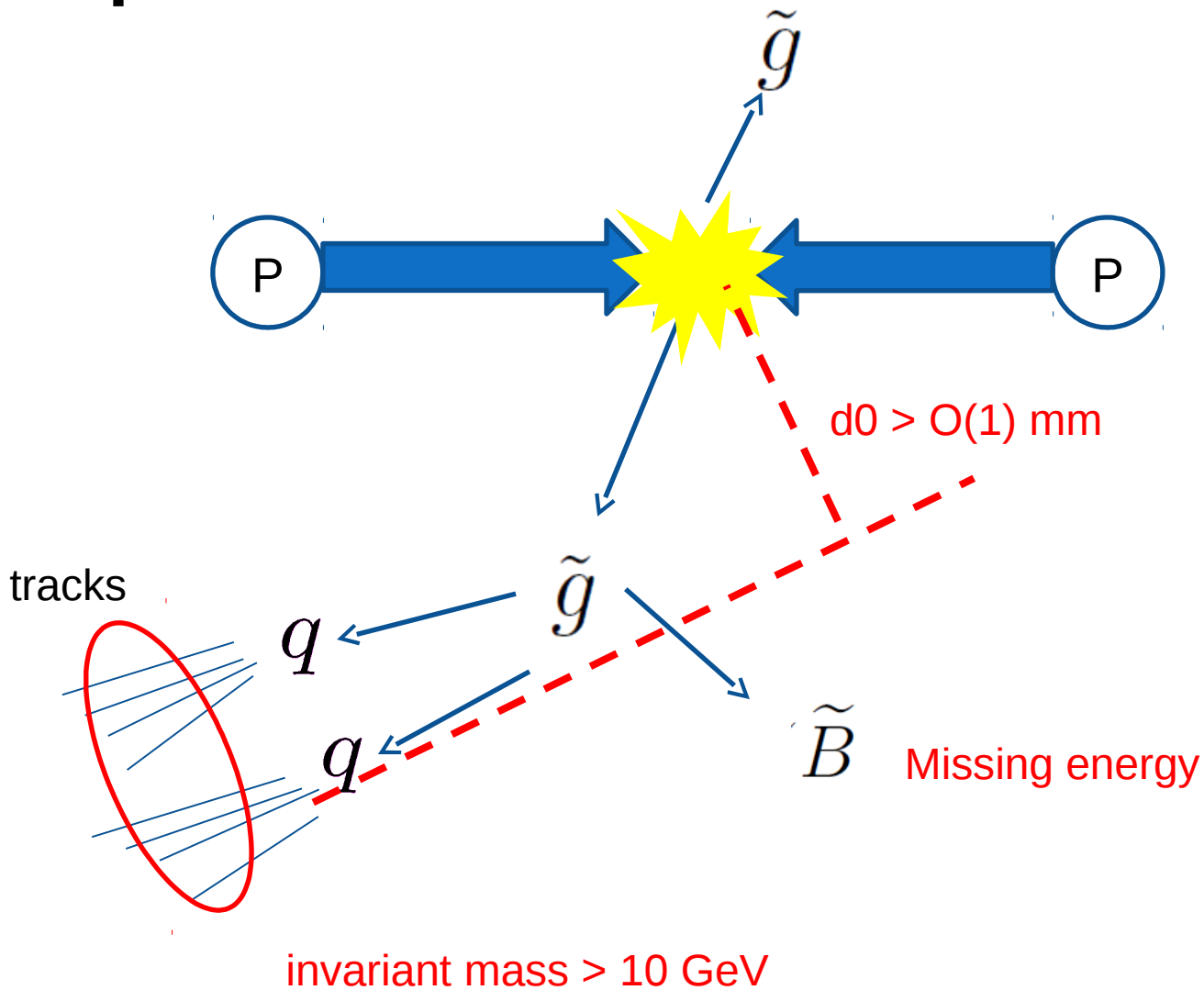
Bino-Gluino Coannihilation 2



Displaced Vertex



Displaced Vertex



ATLAS DV Search

[ATLAS, PRD 97 052012]

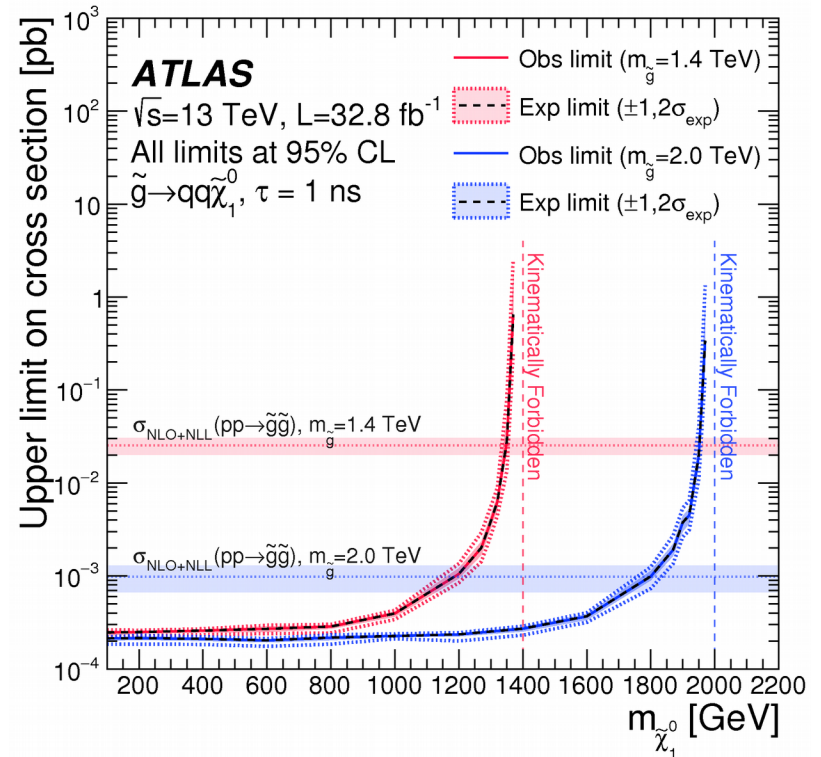
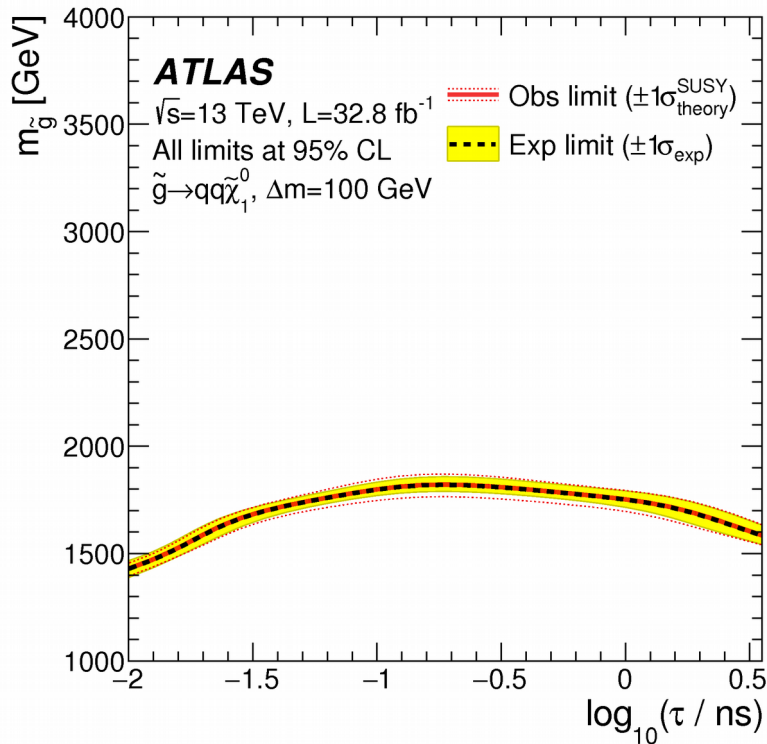
13 TeV 32.8 fb-1

- MET trigger + event filter > 250 GeV
- DV with impact parameter > 2 mm
- Mass of DV > 10 GeV
- # of tracks >4

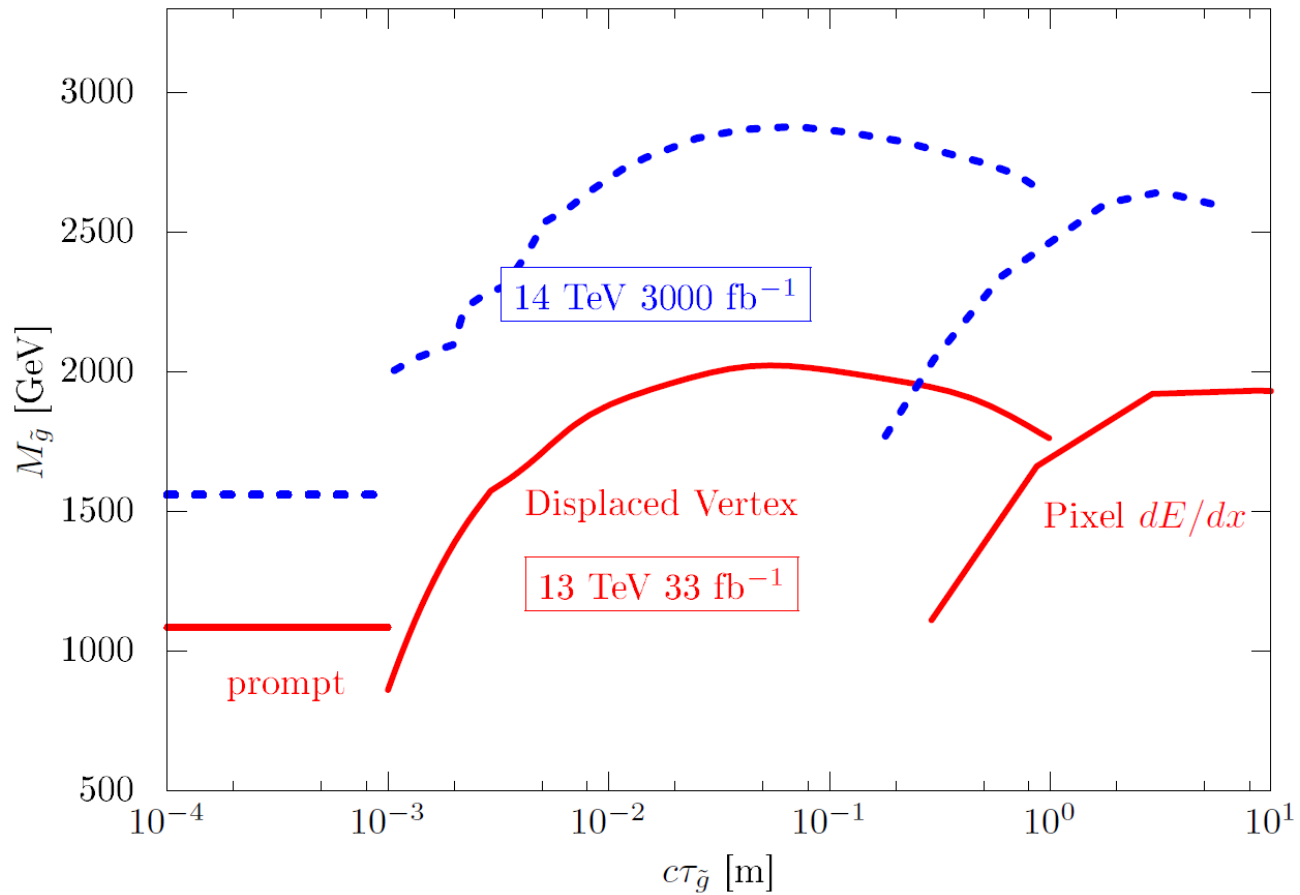
without DV BG $O(10^5)$

Selection	Subregion	Estimated	Observed
<i>Event preselection</i>			
$n_{\text{trk}} = 3, m_{\text{DV}} > 10 \text{ GeV}$			3093
<i>Event preselection</i>			
$n_{\text{trk}} = 4, m_{\text{DV}} > 10 \text{ GeV}$	VRLM	9 ± 2	9
	VRM	150^{+60}_{-30}	177
<i>Event preselection</i>			
$n_{\text{trk}} \geq 5, m_{\text{DV}} > 10 \text{ GeV}$	5-tracks	$2.2^{+2.8}_{-0.9}$	1
	6-tracks	$0.6^{+0.6}_{-0.2}$	1
	≥ 7 -tracks	1^{+3}_{-1}	3
	<i>Total</i>	$4.2^{+4.1}_{-1.4}$	5
<i>Full SR selection</i>			
	<i>Total</i>	$0.02^{+0.02}_{-0.01}$	0

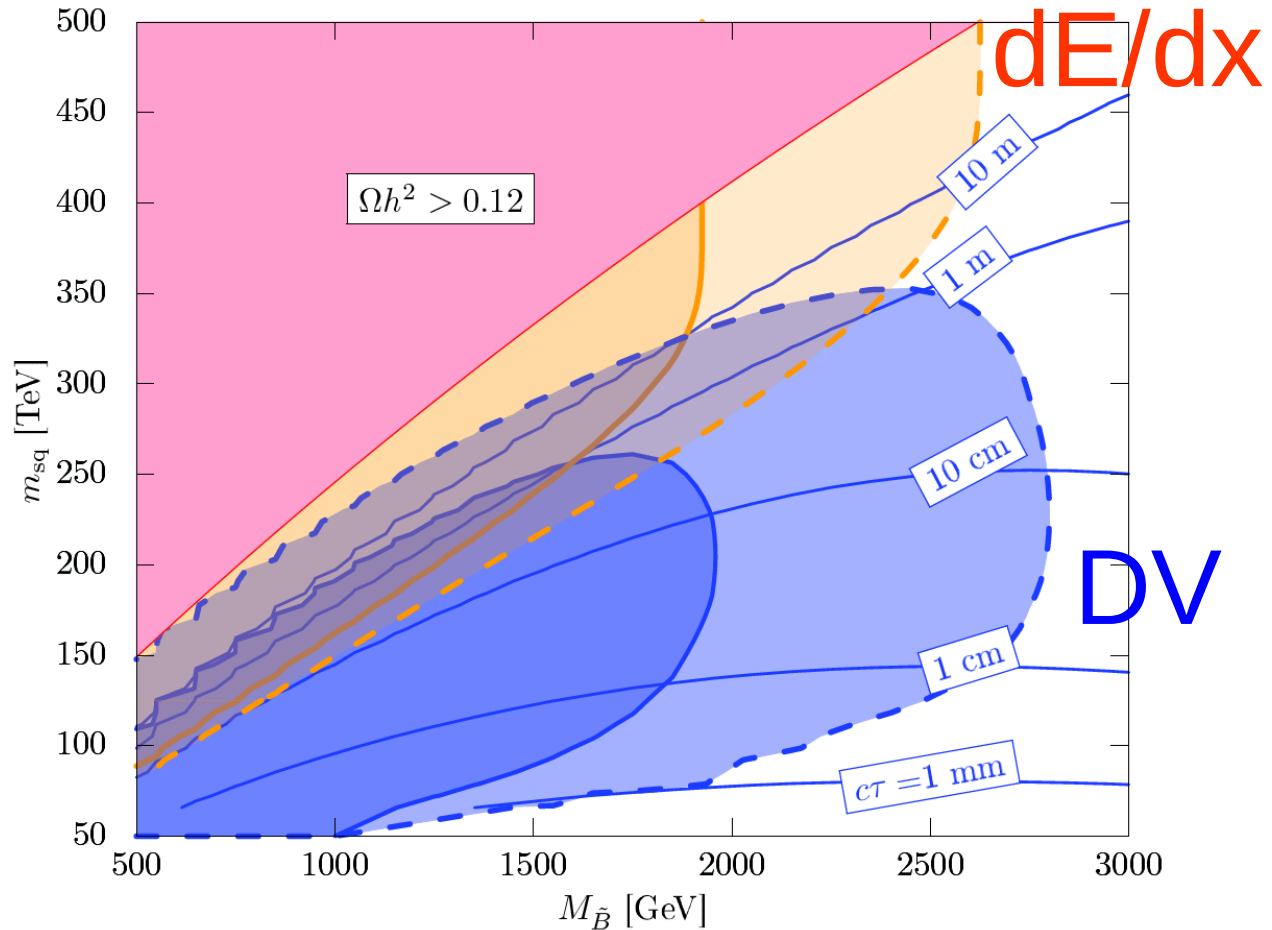
Bino-Gluino Interaction



Prospects



Bino-Gluino Prospects



Three Possibilities for DM



Wino DM

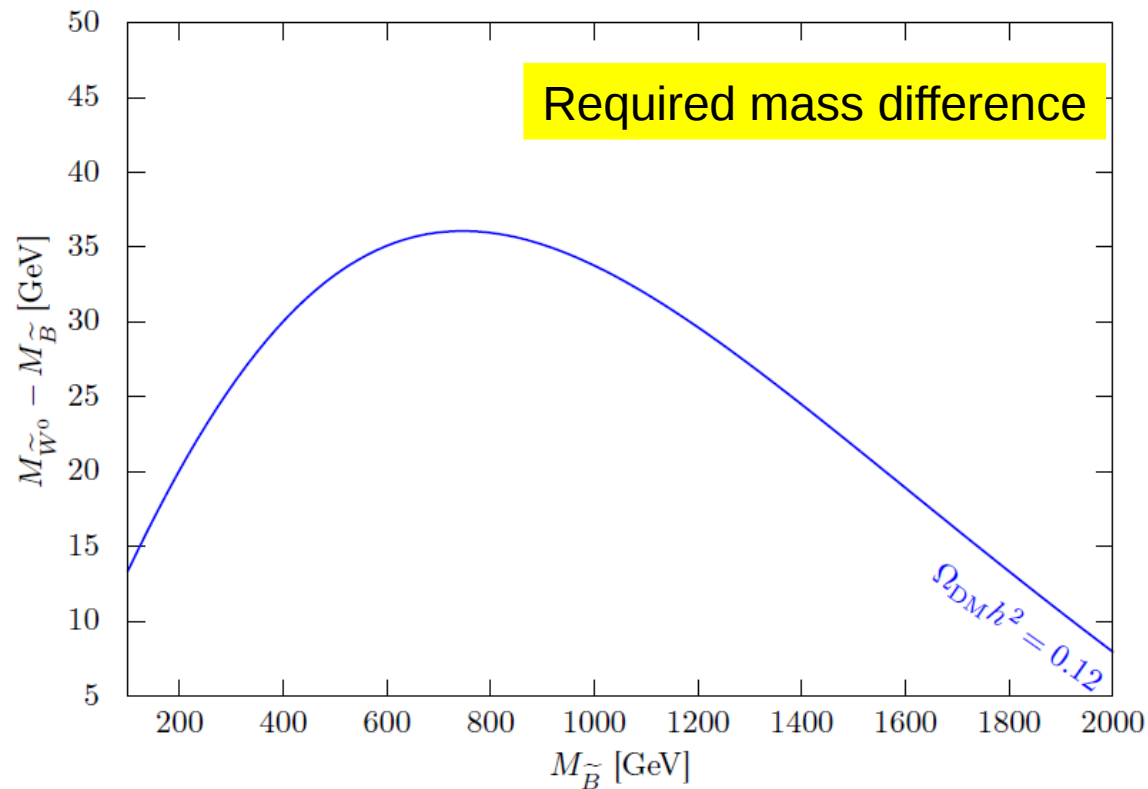
Bino-gluino
coannihilation

Bino-wino
coannihilation



Bino-Wino Coannihilation

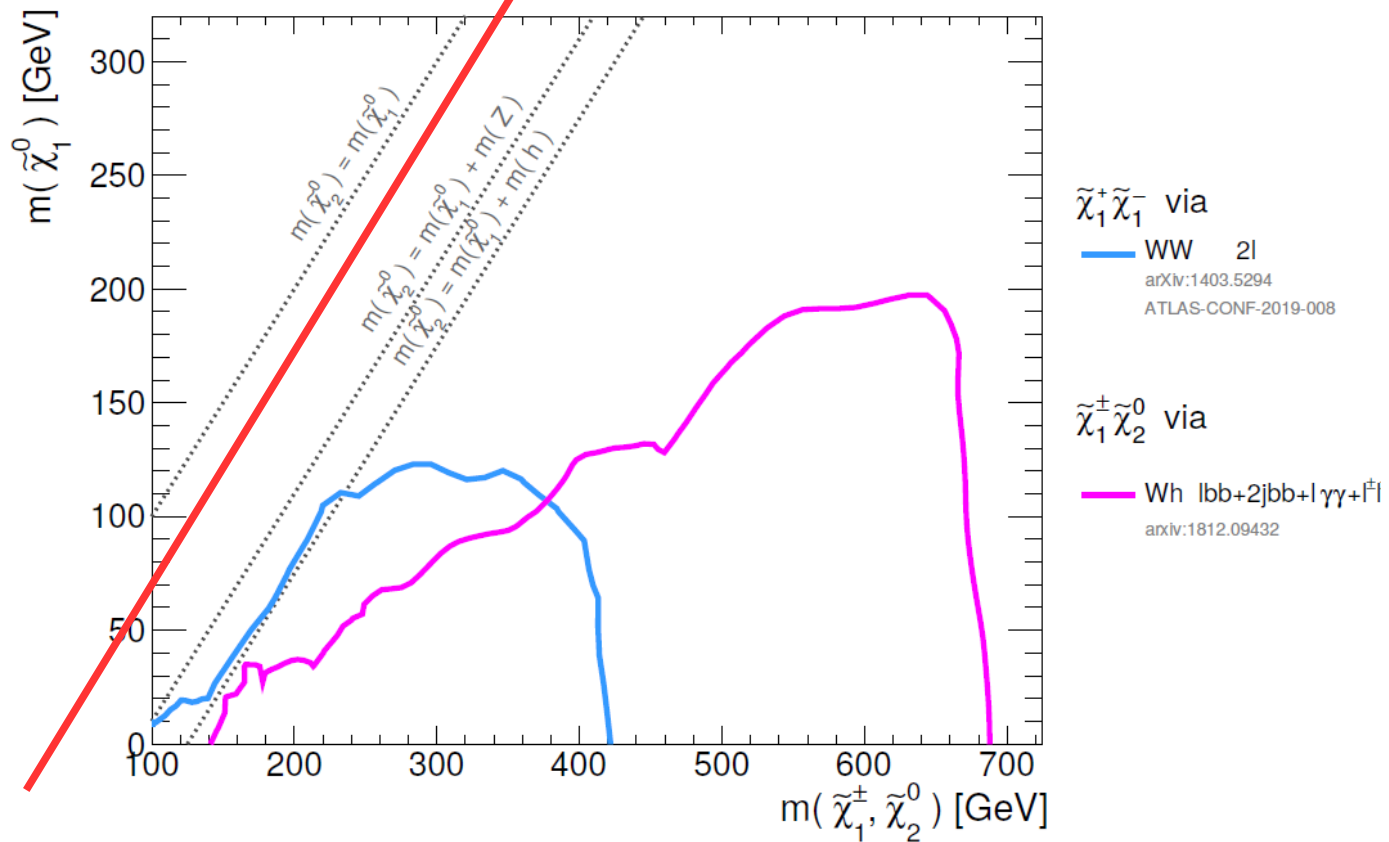
Bino-Wino Coannihilation



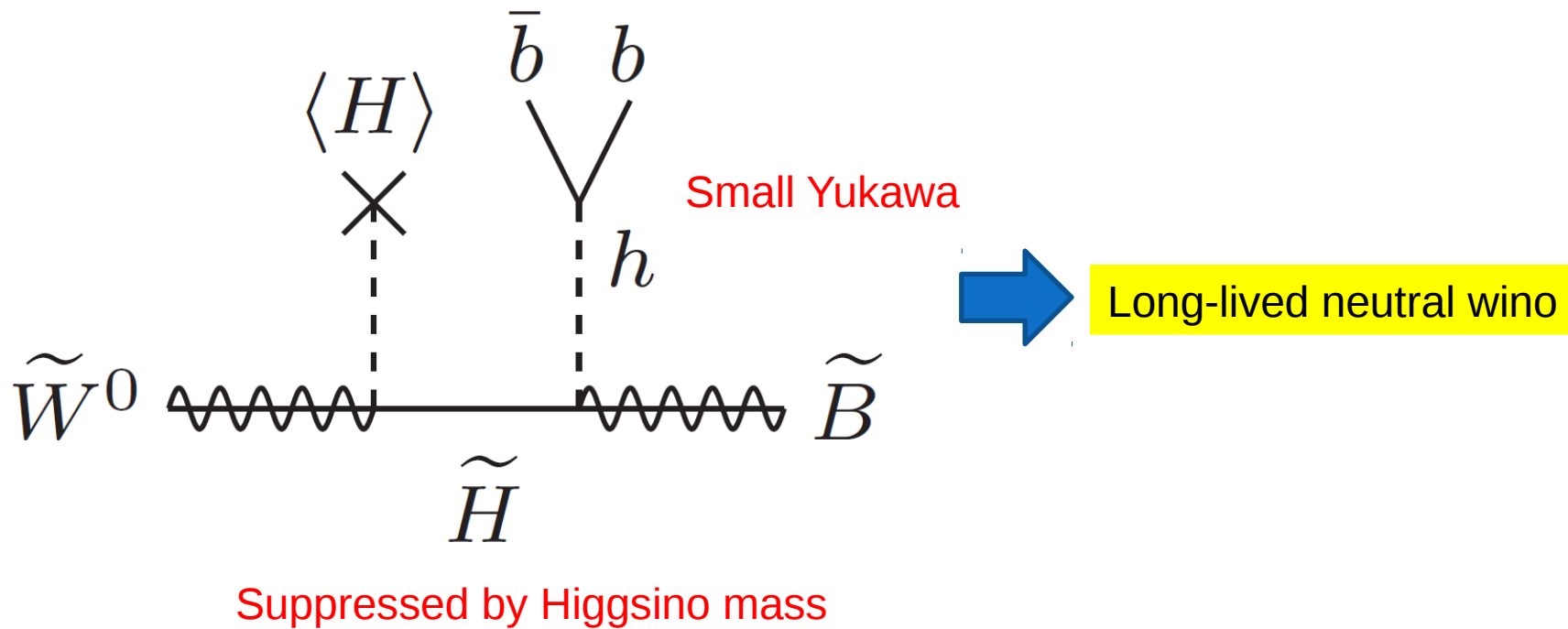
A few tens of GeV mass diff.

LHC Signals

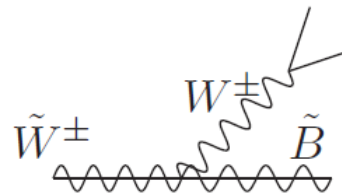
Mass diff. 30 GeV



Wino Decay (tree)



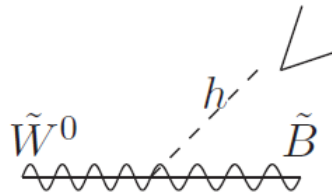
Wino Decay



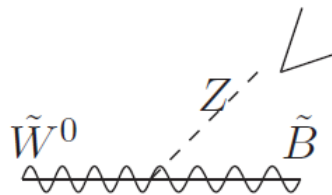
$$\tilde{W}^\pm \rightarrow W^\pm + \tilde{B} \quad \propto \mu^{-1}$$



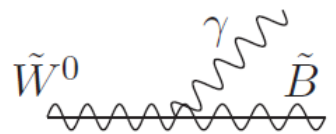
Prompt charged Wino decay



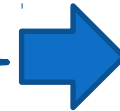
$$\tilde{W}^0 \rightarrow h + \tilde{B} \quad \propto \mu^{-1}$$



$$\tilde{W}^0 \rightarrow Z + \tilde{B} \quad \propto \mu^{-2}$$



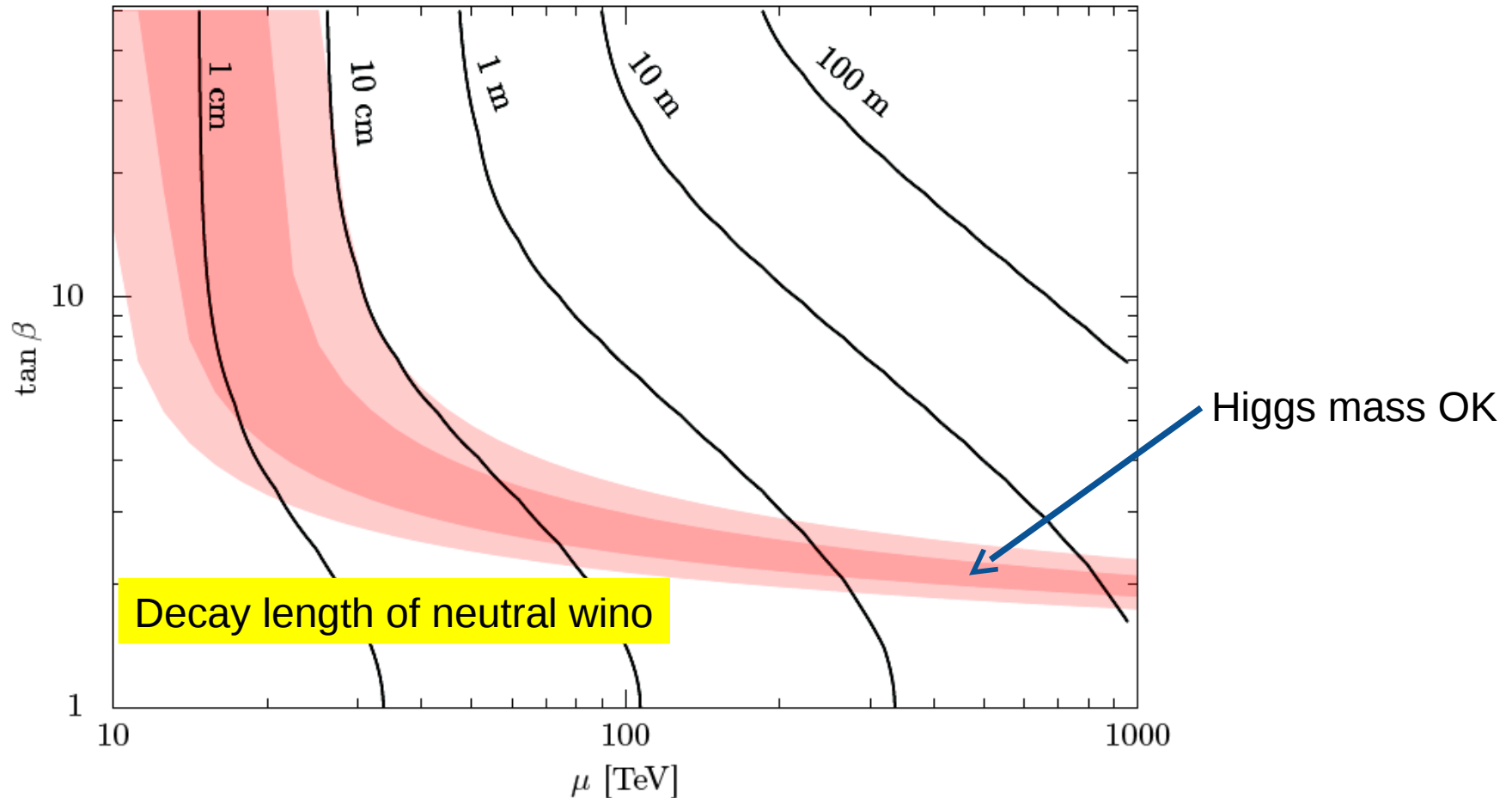
$$\tilde{W}^0 \rightarrow \gamma + \tilde{B} \quad \propto \frac{\alpha}{4\pi} \mu^{-2}, \left(\frac{\alpha}{4\pi}\right)^2 \mu^{-1}$$



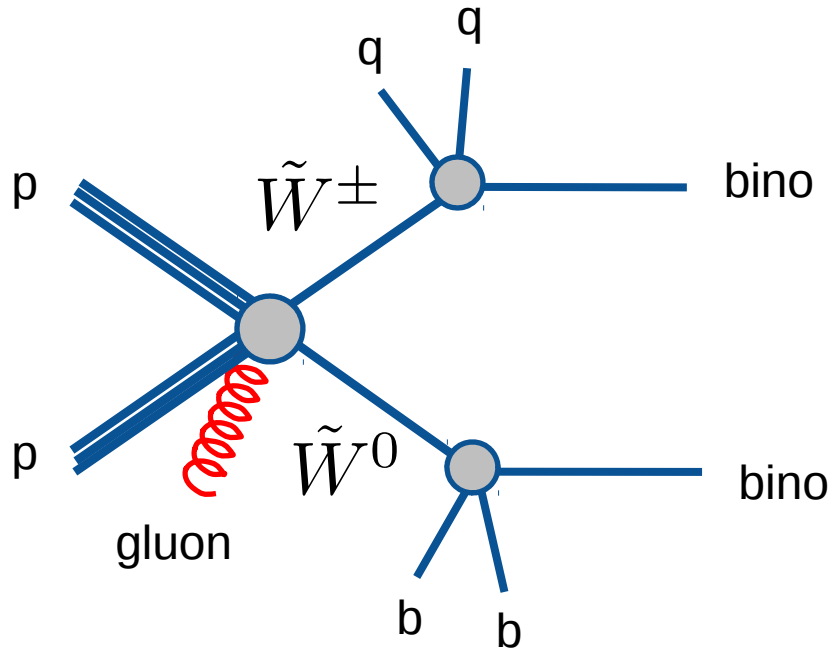
Displaced neutral Wino decay

Wino Decay

Bino = 400 GeV
Wino = 430 GeV

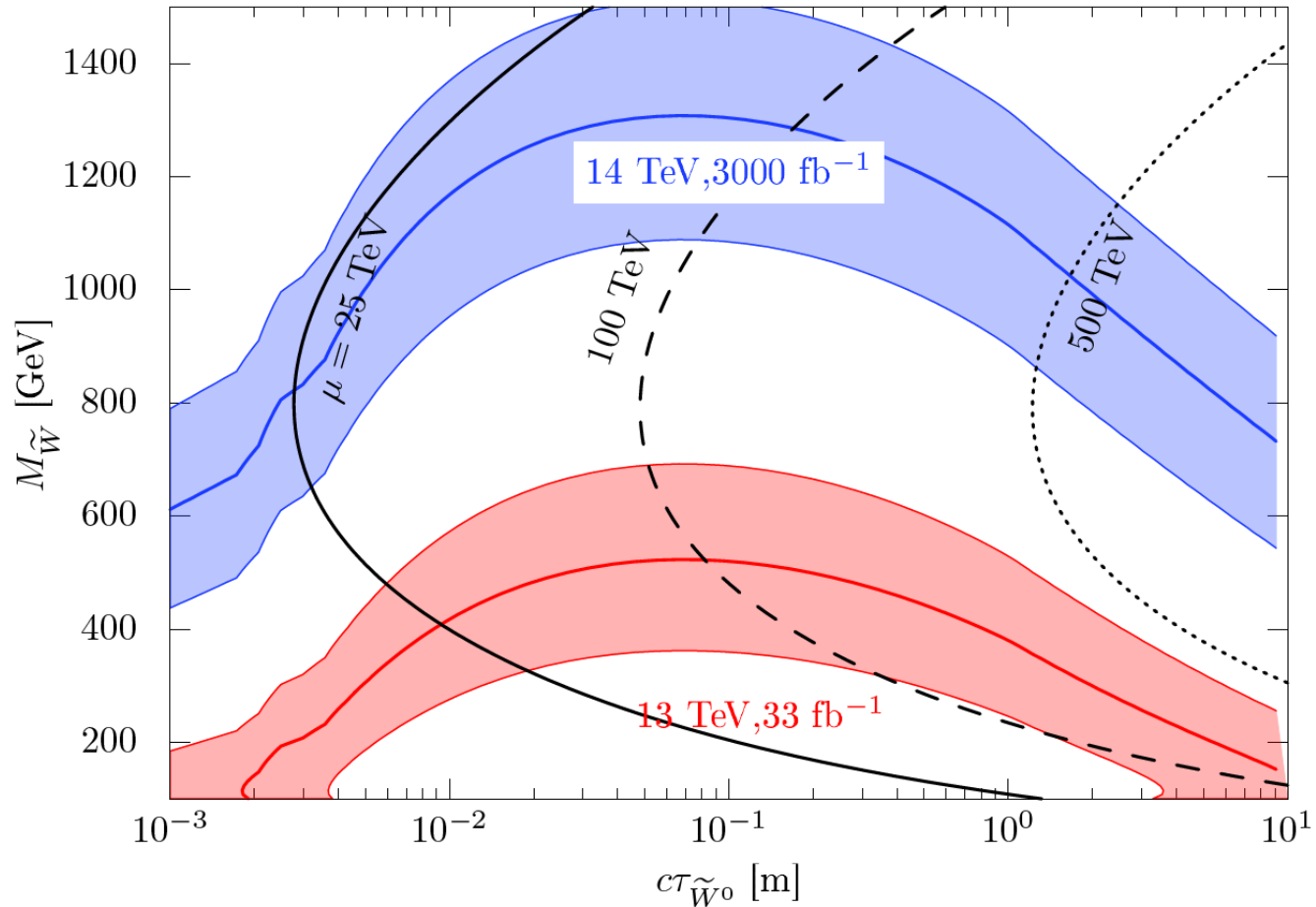


LHC Signals



Low mass ~ 10 GeV DV
+
MET

LHC Prospects



Summary

- Mini-split is simplest SUSY model with 125 GeV Higgs
- DM in mini-split likely provide **meta-stable** particles
 - **Wino DM**: disappearing track
 - **Gluino-bino DM**: long-lived R-hadron
 - **Wino-bino DM**: long-lived neutral wino
- Improvement of LLP detection