Quest for Dark Matter

Satoshi Shirai (DESY)

1. WIMP Dark Matter

WIMP miracle
WIMP search

2. Coannihilation at LHC

Ex.) Mini-split SUSY

3. Summary

WIMP Dark Matter

What's Dark Matter?

- Stable
- Weakly Interacting
- Cold
- Correct Production Mechanism

Candidates

- Axion
- (Primordial) Black hole
- WIMP
- Others…

WIMP Dark Matter

Weakly Interacting Massive Particle

WIMP Dark Matter

Weakly Interacting Massive Particle

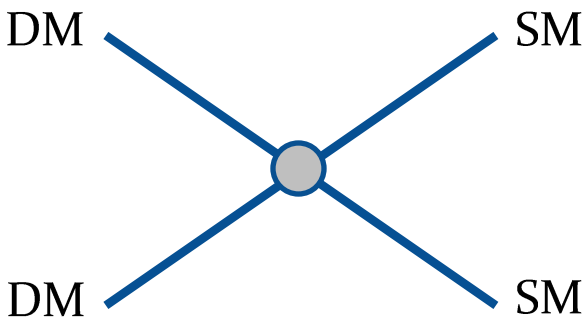
~Electroweak

~100 GeV – 10 TeV

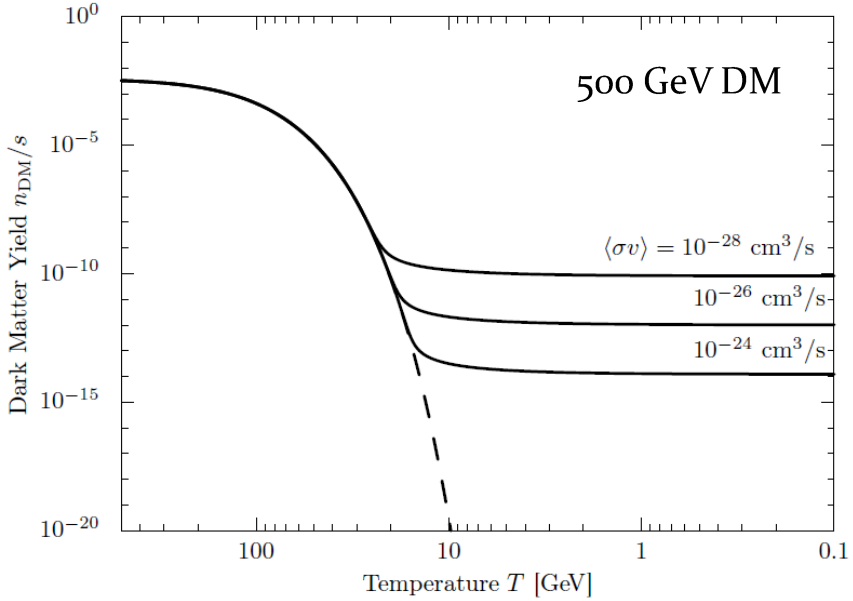
Abundance (conventional case)

DM annihilation rate in early Universe

Abundance



DM abundance



Time

WIMP Miracle

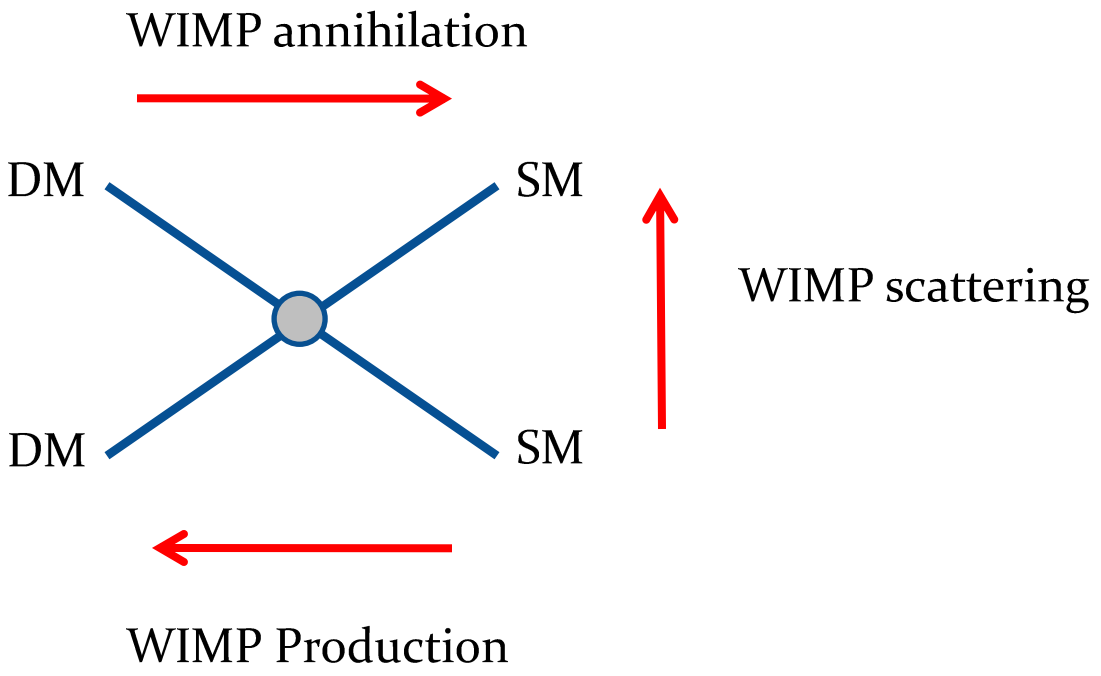
$$\Omega h^2 \simeq 0.1 \left(\frac{\langle \sigma v \rangle}{10^{-26}\ \mathrm{cm}^3/\mathrm{s}} \right)^{-1}$$

$$10^{-26}\ \mathrm{cm}^3/\mathrm{s} \simeq 10^{-9}\ \mathrm{GeV}^{-2} \sim \frac{g_2^2}{4\pi} \frac{1}{m_{\mathrm{DM}}^2}$$

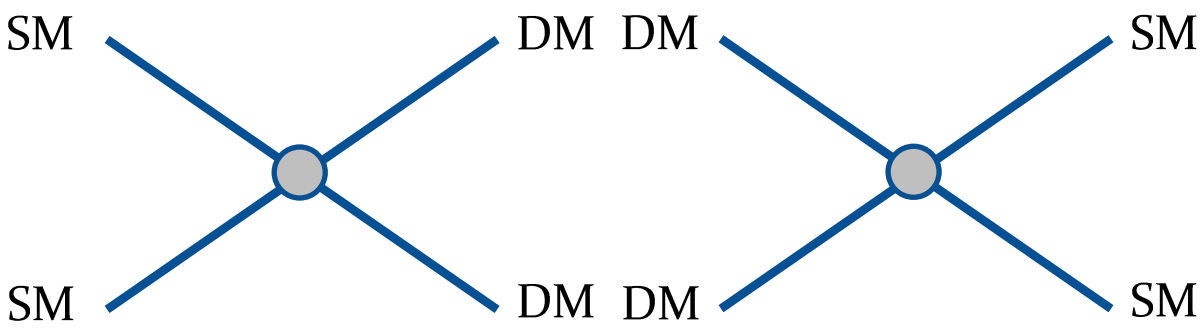
$m_{\mathrm{DM}} = O(1)\ \mathrm{TeV}$ leads to correct DM abundance

Good Target of LHC

WIMP Detection



More on WIMP Detection



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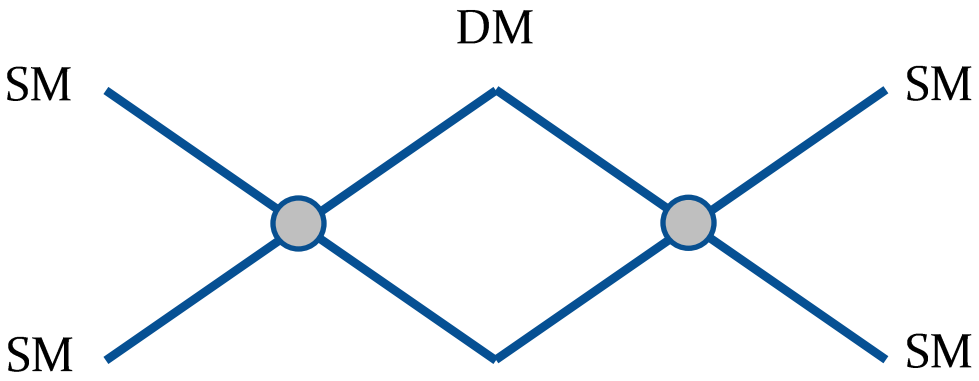
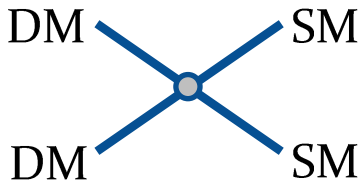


(Virtual) DM affects the SM process

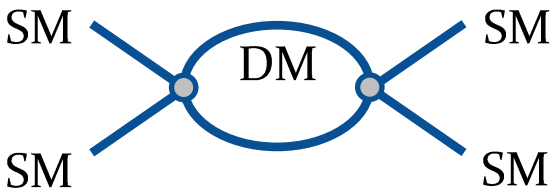
Precision measurement

EW, Flavor, CP…

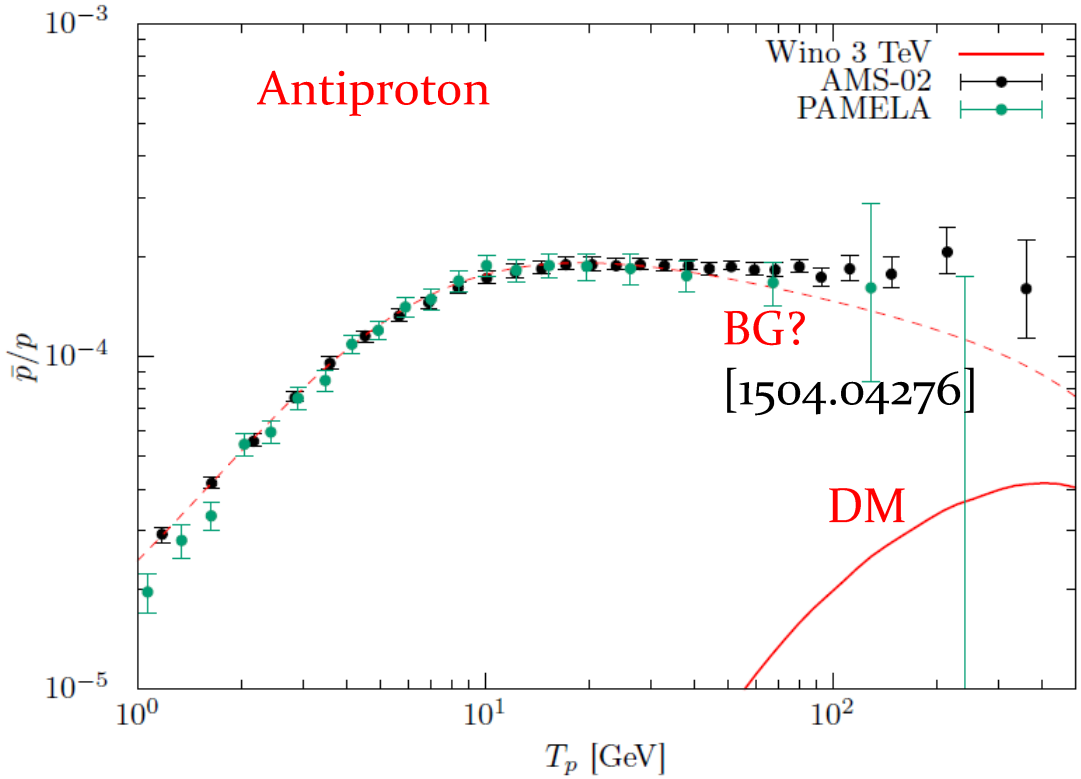
WIMP Search Strategy



- Cosmic ray
  - anti-matter : PAMELA, AMS-02…
  - gamma: Fermi, CTA…
- Scattering
  - XENON, LUX…
- Production
  - LHC, ILC, FCC
- Precision
  - EW process: ILC
  - CP violation: Electric dipole moment (EDM)



Annihilation: Cosmic Ray

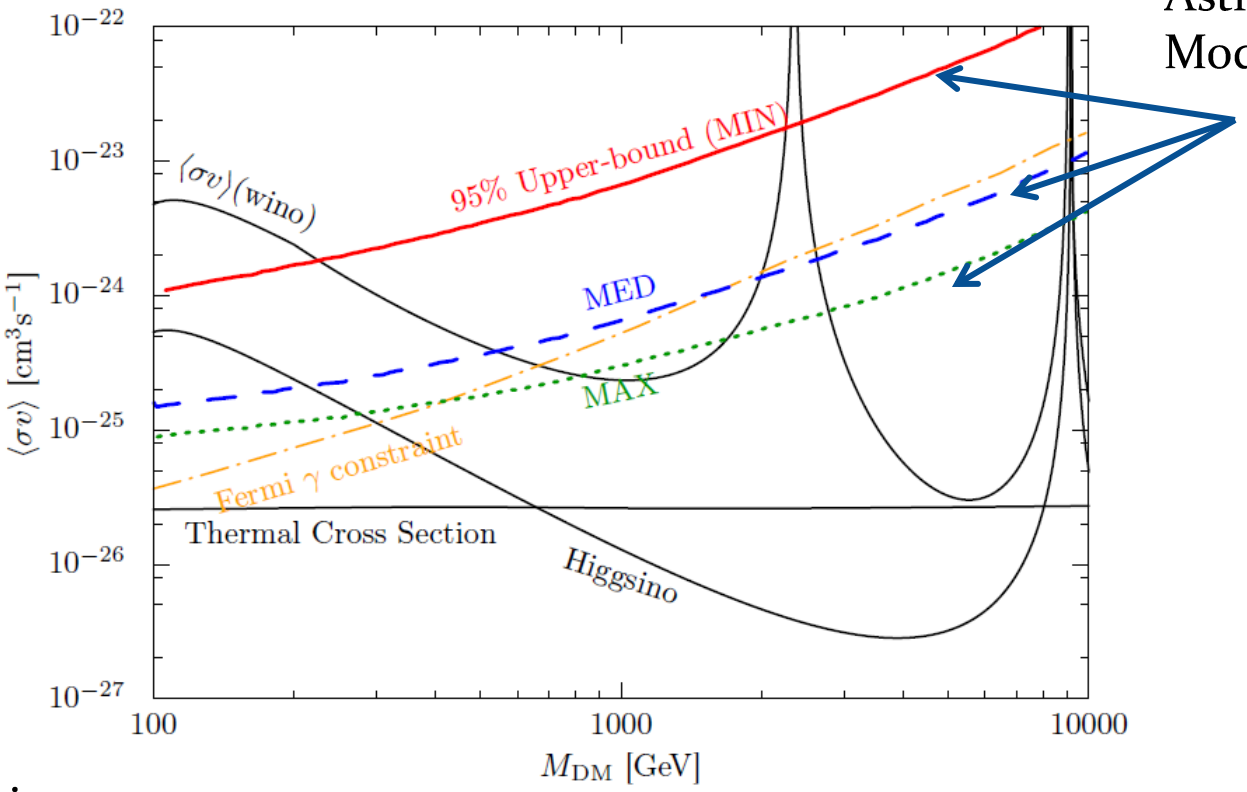


Antiproton: Conservative

Ibe, Matsumoto, SS, Yanagida '15

Free form of BG assumed

Astrophysical Model dep.

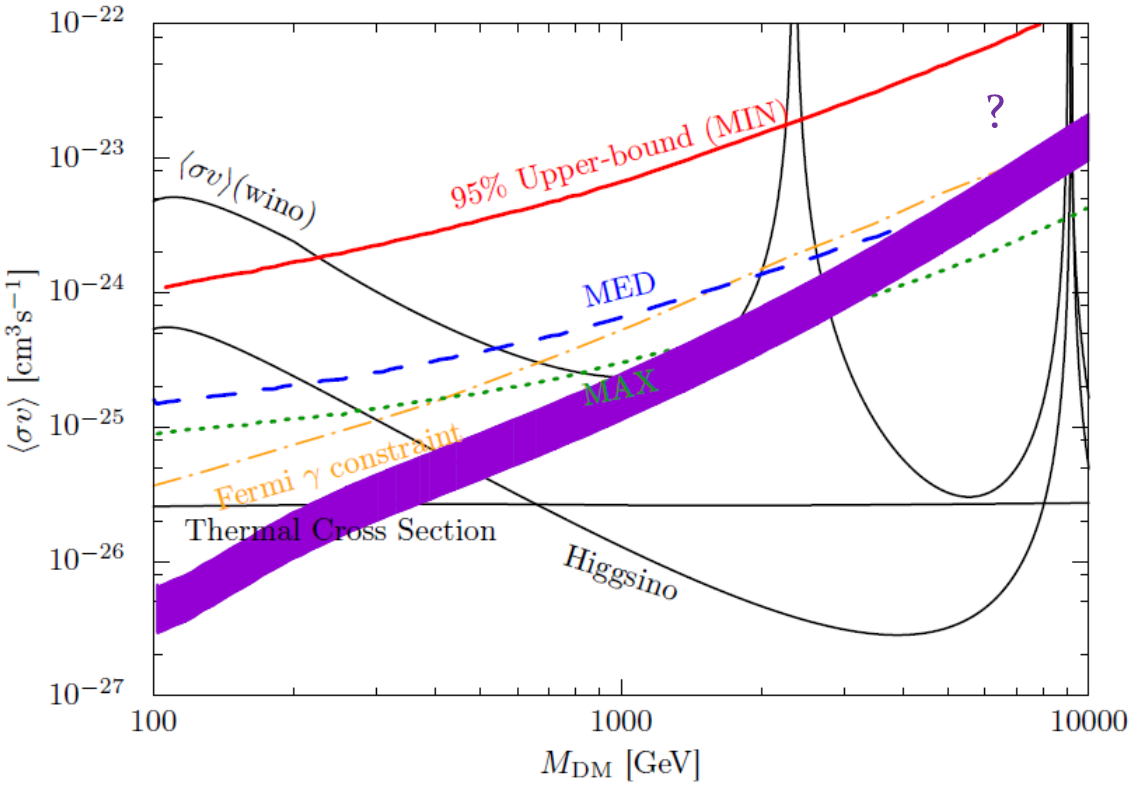


Fermi constraints:

Hayashi, Ichikawa, Matsumoto, Ibe, Ishigaki, Sugai, '16

Antiproton: Conservative

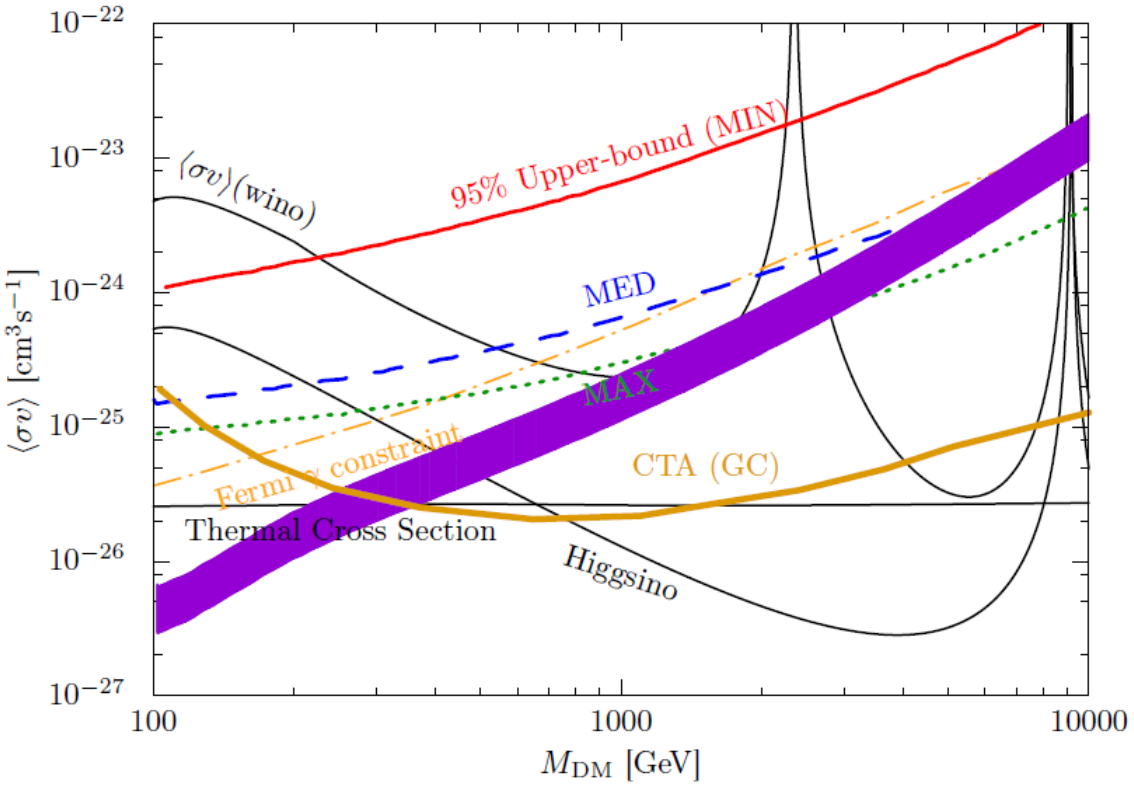
Hall, Nomura, SS, '12



BG modeling+
prop. model fix

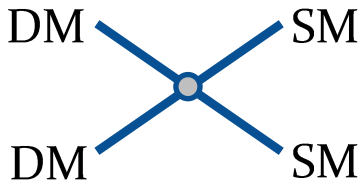
Simultaneous fit
B/C, ^{10}Be/^{9}Be...

Antiproton: Conservative



CTA col. [1208.5356]

WIMP Search Strategy



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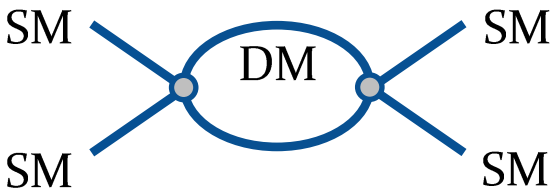
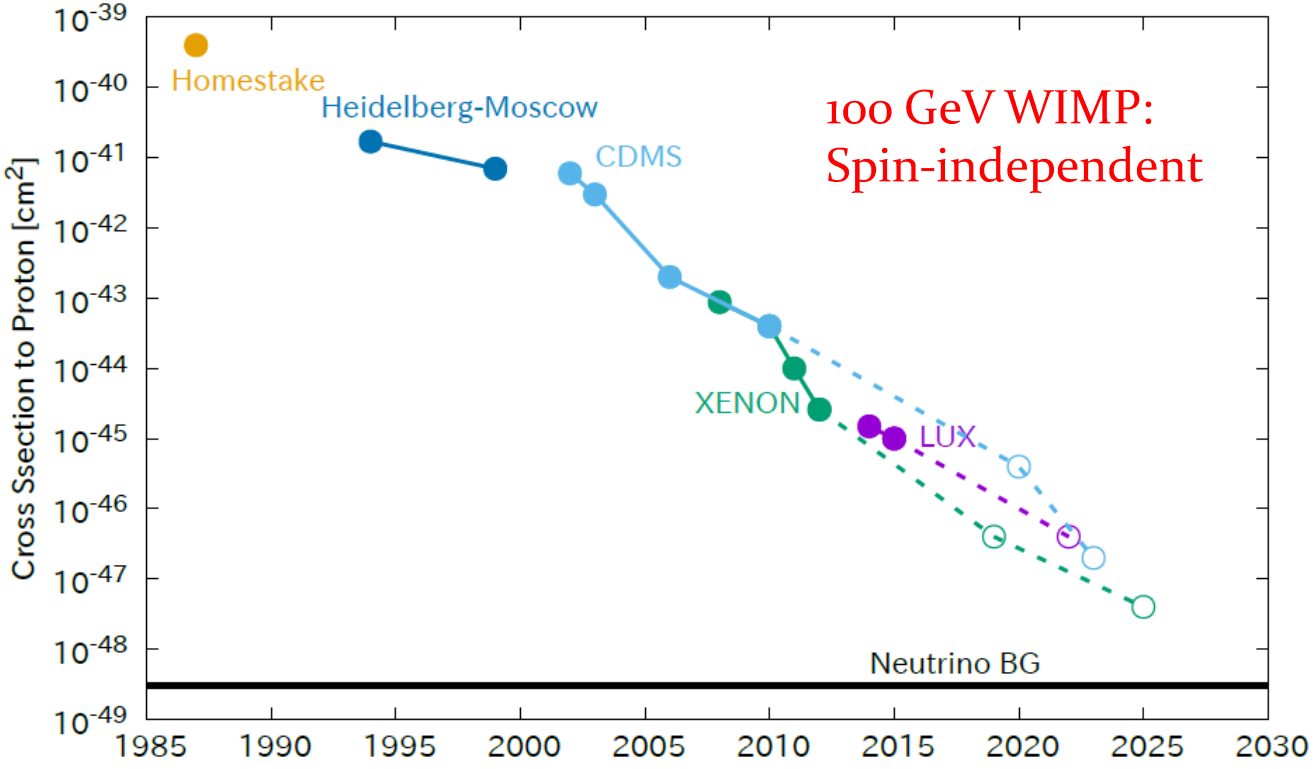
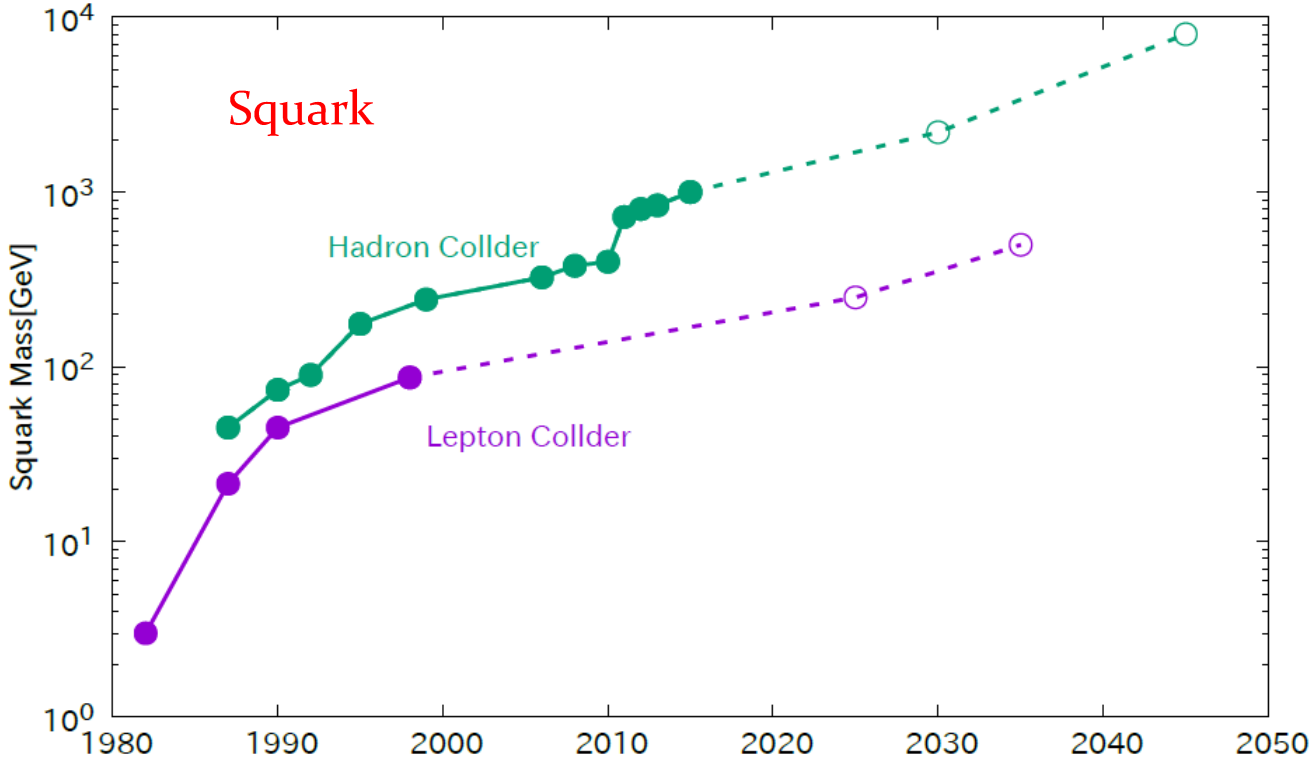


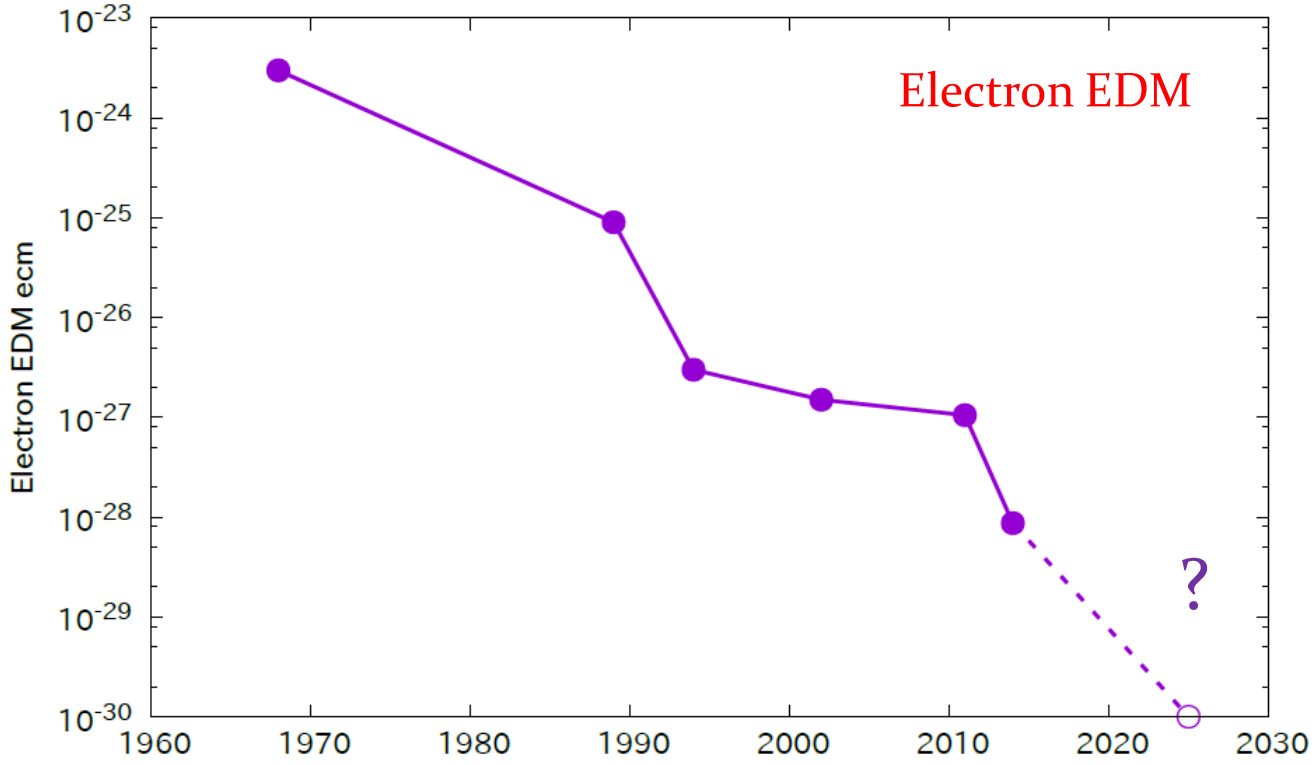
Scattering: Past and Future



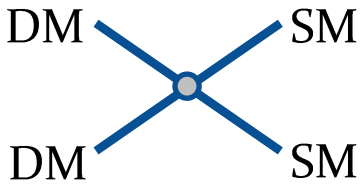
Production: Past and Future



EDM: Past and Future



Signal Interplay



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Cosmic Ray and EDM

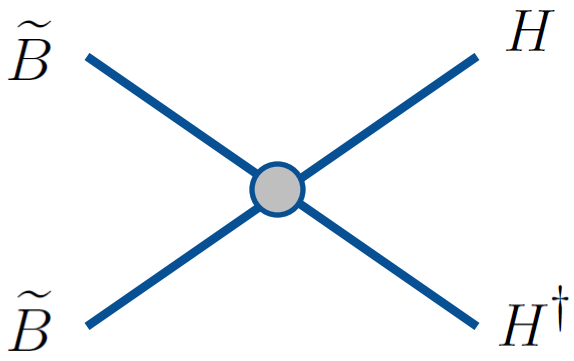
Bae, Macaluso, Nagata, Ruderman, Shih, SS, to appeaer

Ex: Singlet-doublet model, c.f. bino-higgsino in SUSY DM

$\widetilde{B}$ DM, majorana fermion $\widetilde{H}_u\widetilde{H}_d$ SU(2) doublet fermion

$$\mathcal{L}_{\rm int} = -\frac{1}{\sqrt{2}}\widetilde{g}'_u H^\dagger \widetilde{H}_u \widetilde{B} - \frac{1}{\sqrt{2}}\widetilde{g}'_d H \widetilde{H}_d \widetilde{B}$$

DM annihilation in halo



Cosmic Ray and EDM

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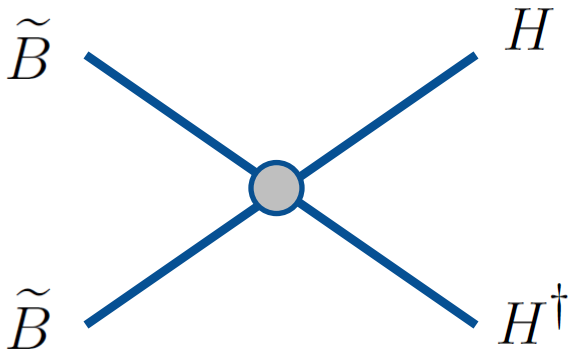


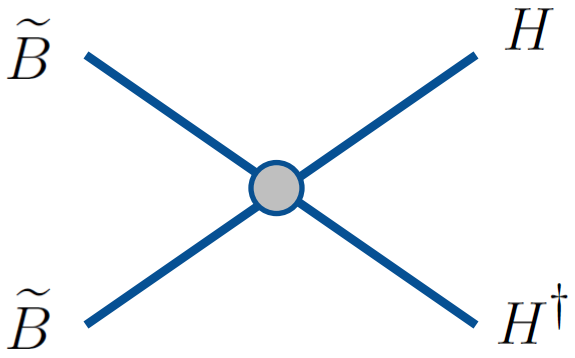
$$\sigma v = a v^0 + b(v/c)^2 + \cdots$$

S-wave P-wave

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

Cosmic Ray and EDM

DM annihilation in halo



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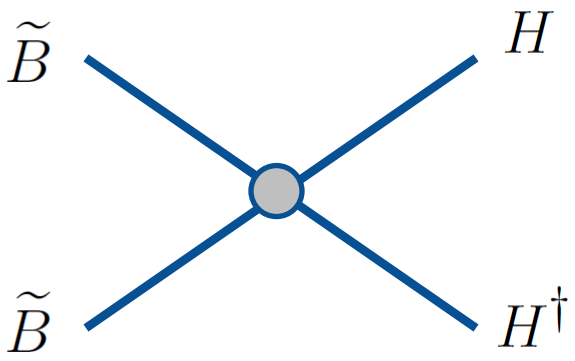

CP odd

CP even

$$(\bar{\widetilde{B}}\gamma^5\widetilde{B})(H^\dagger H)$$

Cosmic Ray and EDM

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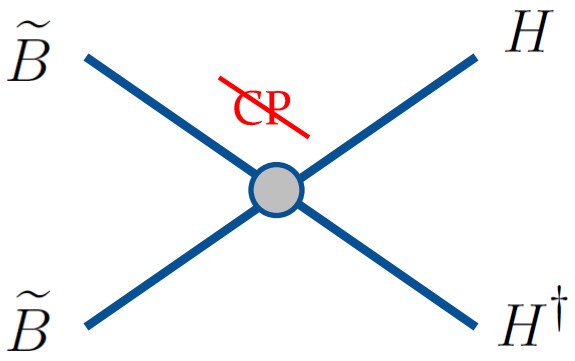

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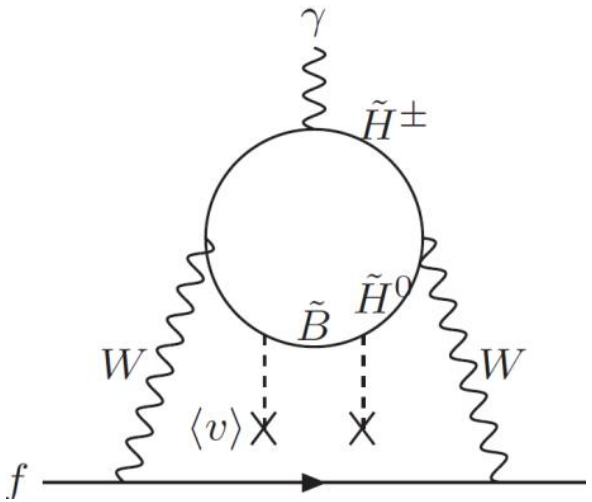
Cosmic Ray and EDM

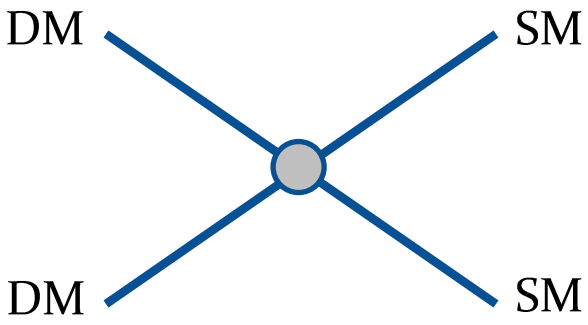
S-wave = CP violation = EDM



$$(\sigma v) \simeq 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \left(\frac{m_{\mathrm{DM}}}{100\ \mathrm{GeV}}\right) \left(\frac{d_e}{10^{-28}\ e\mathrm{cm}}\right)$$

EDM-cosmic ray relation as Smoking gun

WIMP Detection Summary



$$\Omega h^2 \simeq 0.1 \left(\frac{\langle \sigma v \rangle}{10^{-26}\ \mathrm{cm}^3/\mathrm{s}} \right)$$

DM abundance "guarantees" strength of SM-DM interaction

Various approaches to DM

Three exceptions

[Griest ,Seckel, 1991]

- Coannihilation
- Forbidden Channel
- Resonant Annihilation

Three exceptions

[Griest ,Seckel, 1991]

- Coannihilation
- Forbidden Channel
- Resonant Annihilation

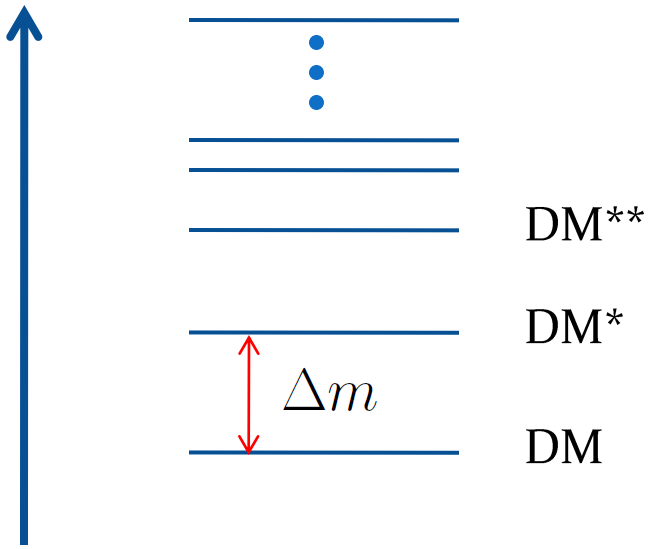
Coannihilation at LHC

based on works with N. Nagata and H. Otono

Mass Spectrum

BSM models may provide several particles in addition to DM.

BSM sector



Examples:

SUSY

Neutralino, Chargino, Gluino....

Extra Dimension

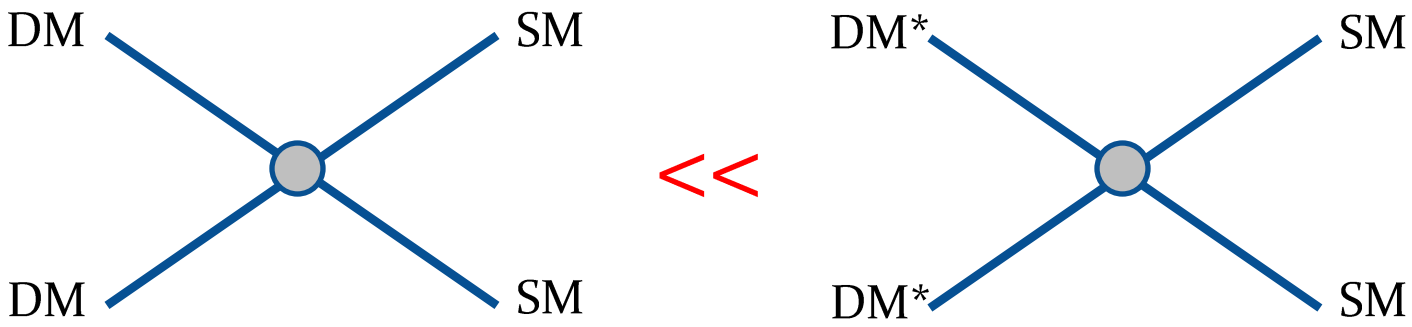
KK photon, KK gluon....

$\Delta m \ll m_{\mathrm{DM}}$ ⇒ Coannihilation

Coannihilation 1

Assumption (for simplicity)

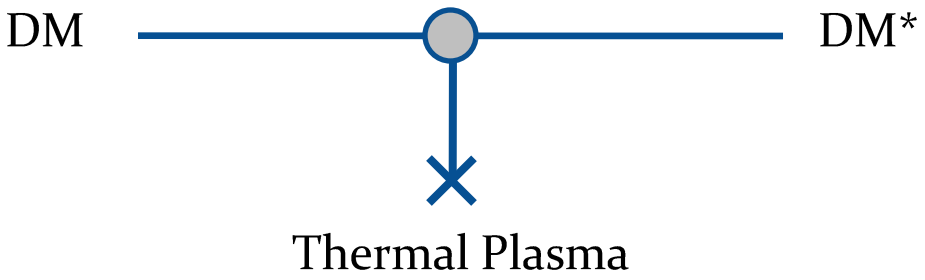
$$\sigma_{\mathrm{DM}} \ll \sigma_{\mathrm{DM}^*}$$



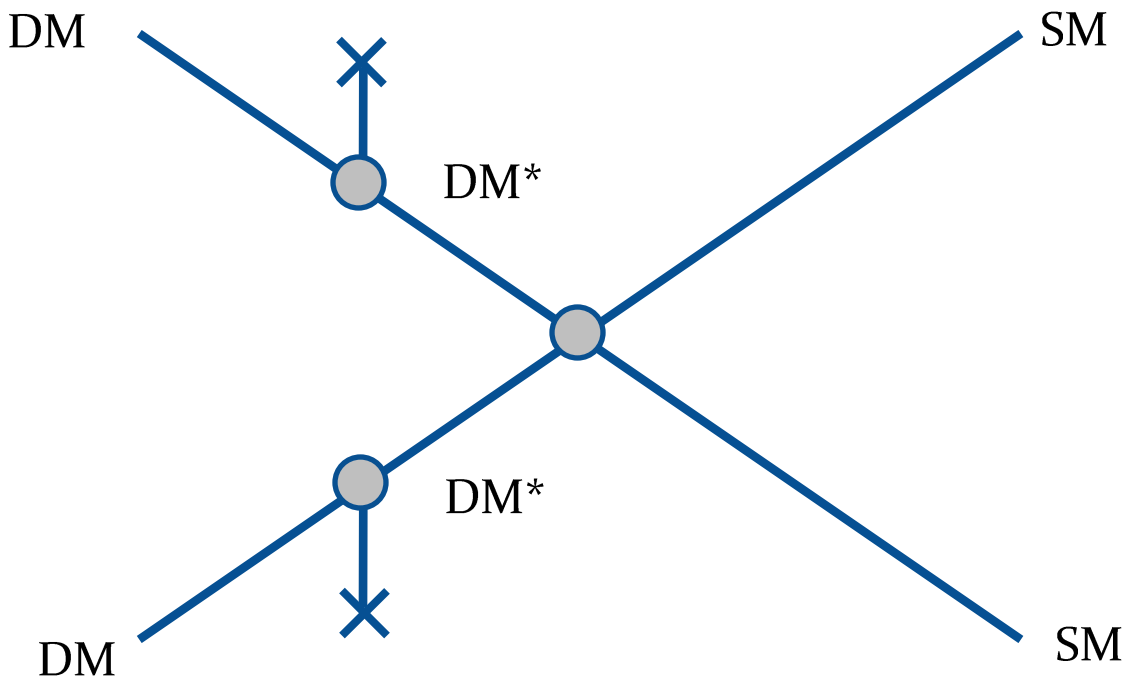
Coannihilation 2

In early universe,

transition DM <-> DM* is rapid



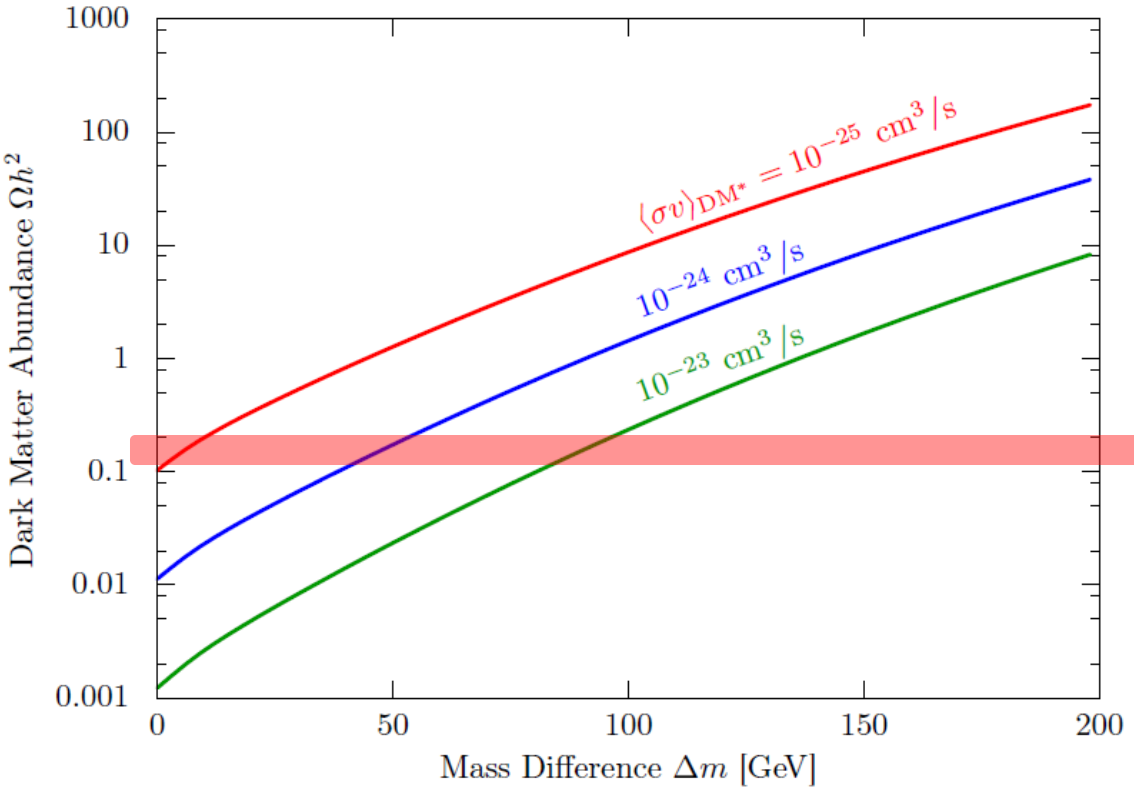
Coannihilation 3



In thermal plasma, DM annihilation rate effectively enhanced

Coannihilation 4

DM abundance v.s. mass difference



DM: 1TeV

observed

Coannihilation 5

Requirements for successful coannihilation

- Small mass difference
- Large annihilation of DM*
- (“Rapid” DM*<-> DM conversion)

LHC Signal

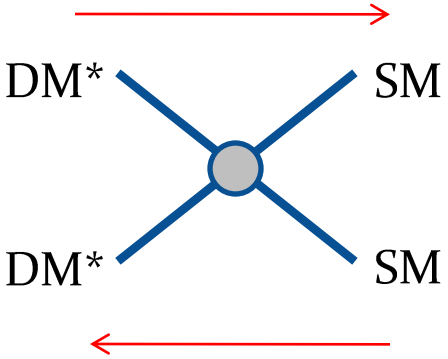
- Small mass difference

  DM* may be long-lived

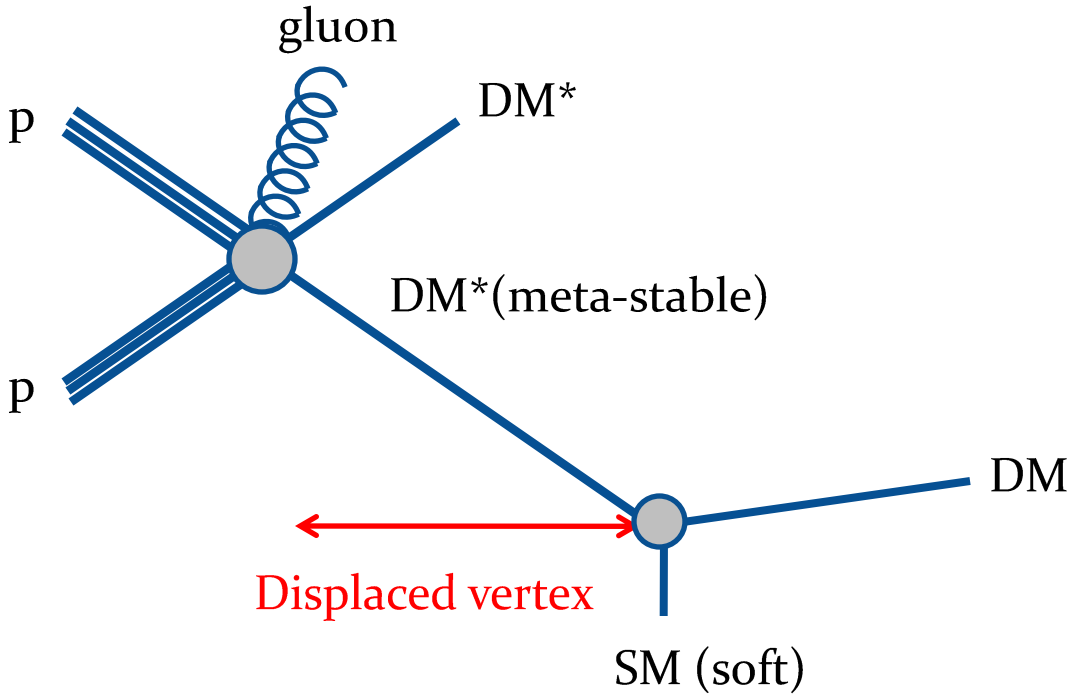
$$\Gamma(\mathrm{DM}^* \to \mathrm{DM}) \propto \Delta m^p$$

- Large annihilation of DM*

  Large DM* production at LHC



LHC Signal

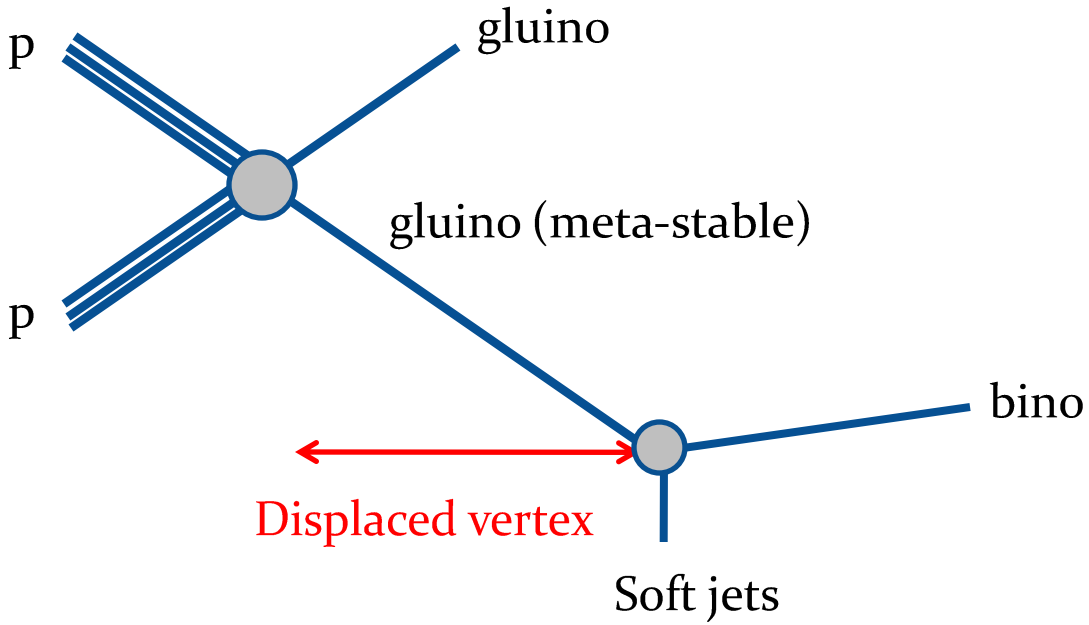


Characteristic DV + MET Signals

Concrete Model

Gaugino coannihilation

DM* = gluino or wino DM = bino

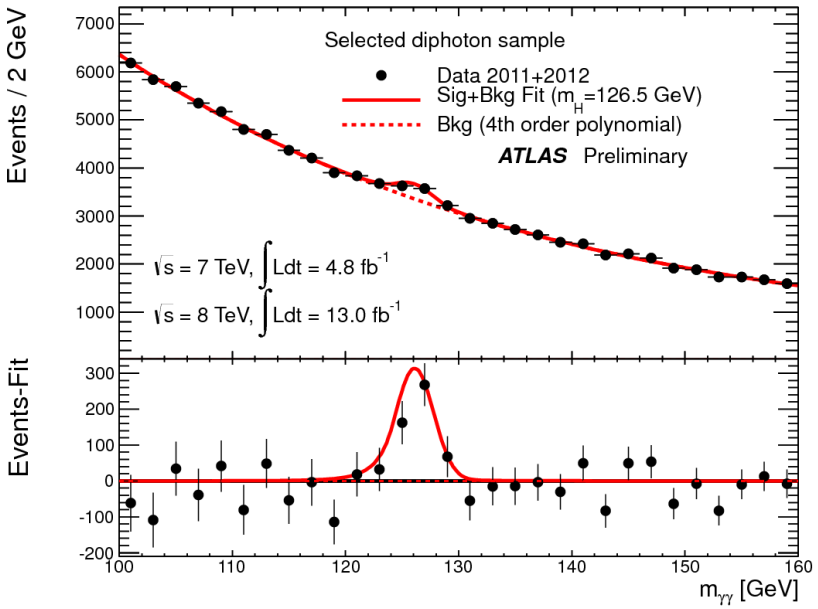


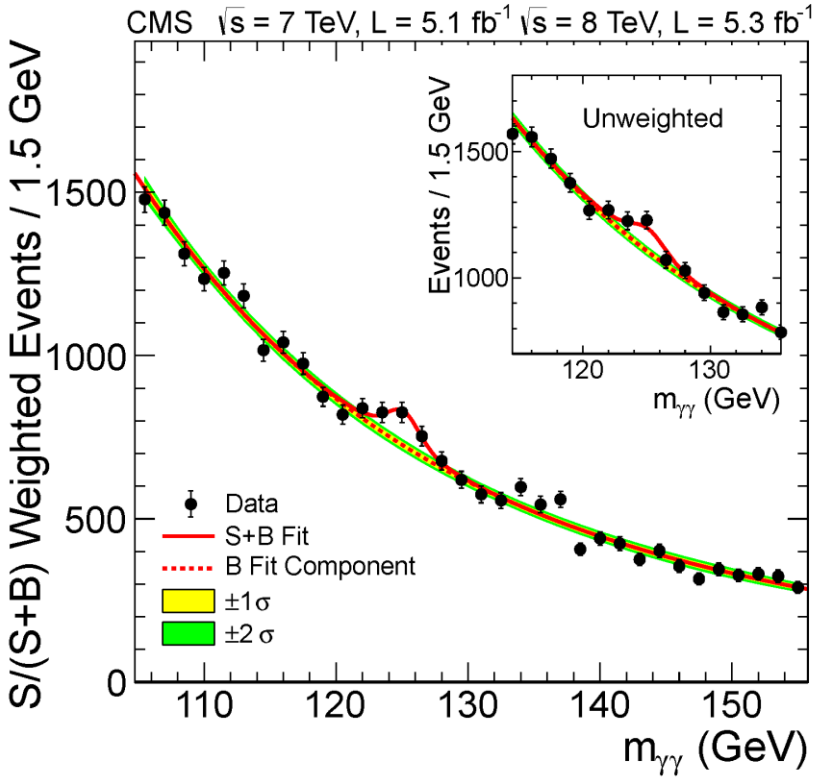
Example: Gaugino Coannihilation

Minimal SUSY Standard Model (MSSM)

Standard Model (SM)	SUSY Partner
Lepton	Scalar Lepton
Quark	Scalar Quark
Scalar Higgs	Higgsino
Gauge Boson	Gaugino
gluon	gluino
weak boson	wino
photon	bino

A “Higgs” Discovered!





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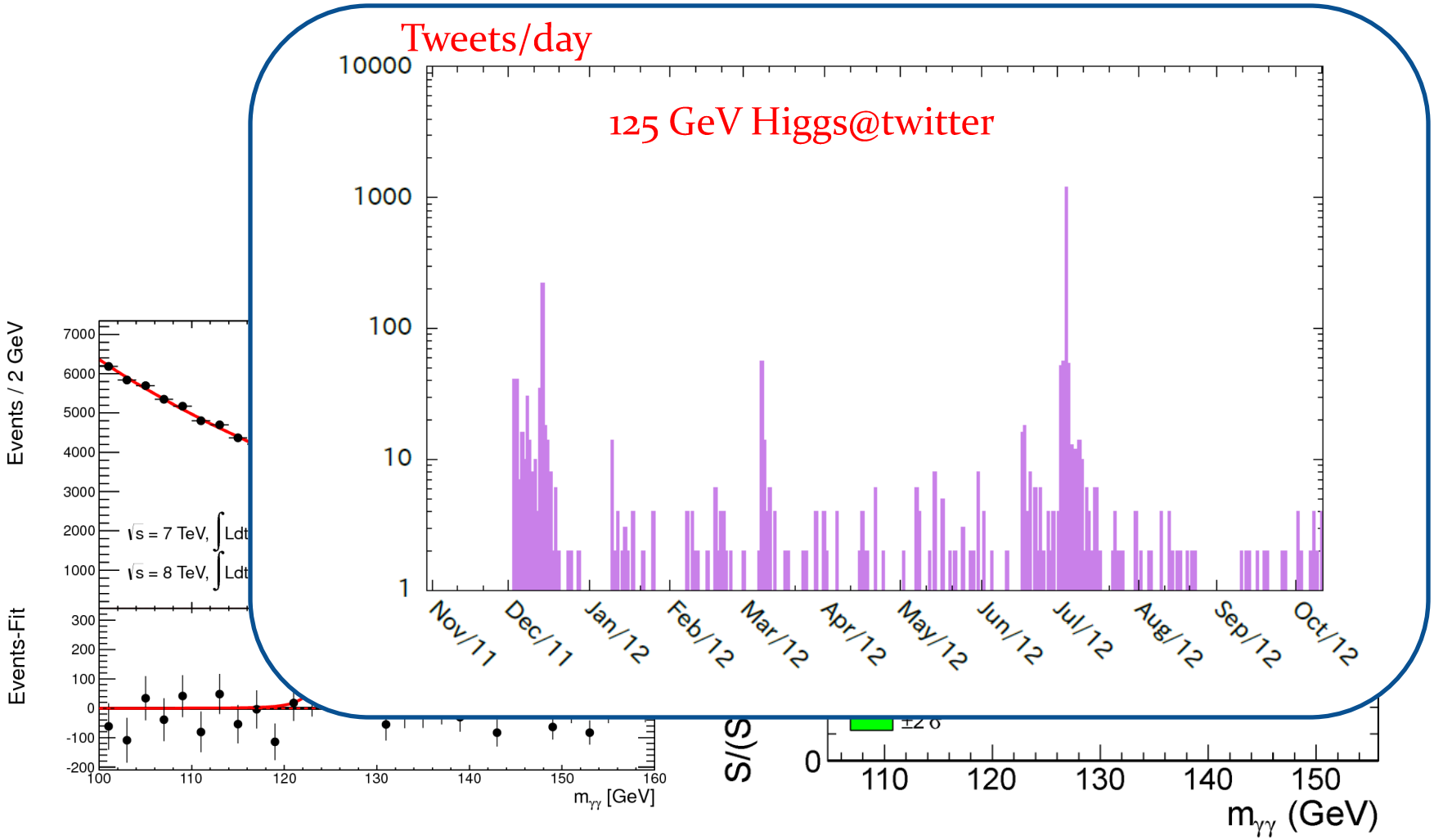

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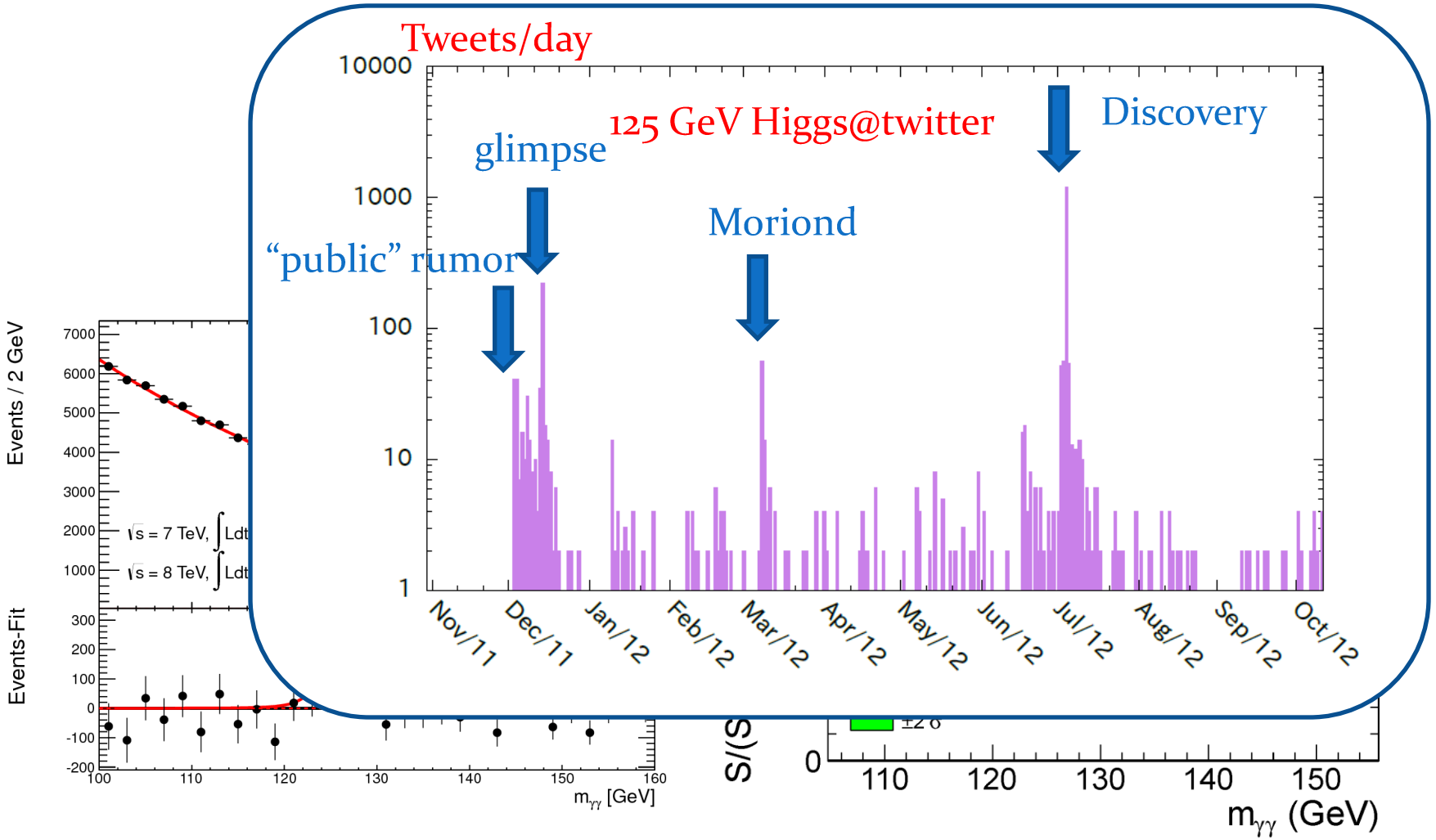


SUSY Higgs

Higgs potential

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

In MSSM

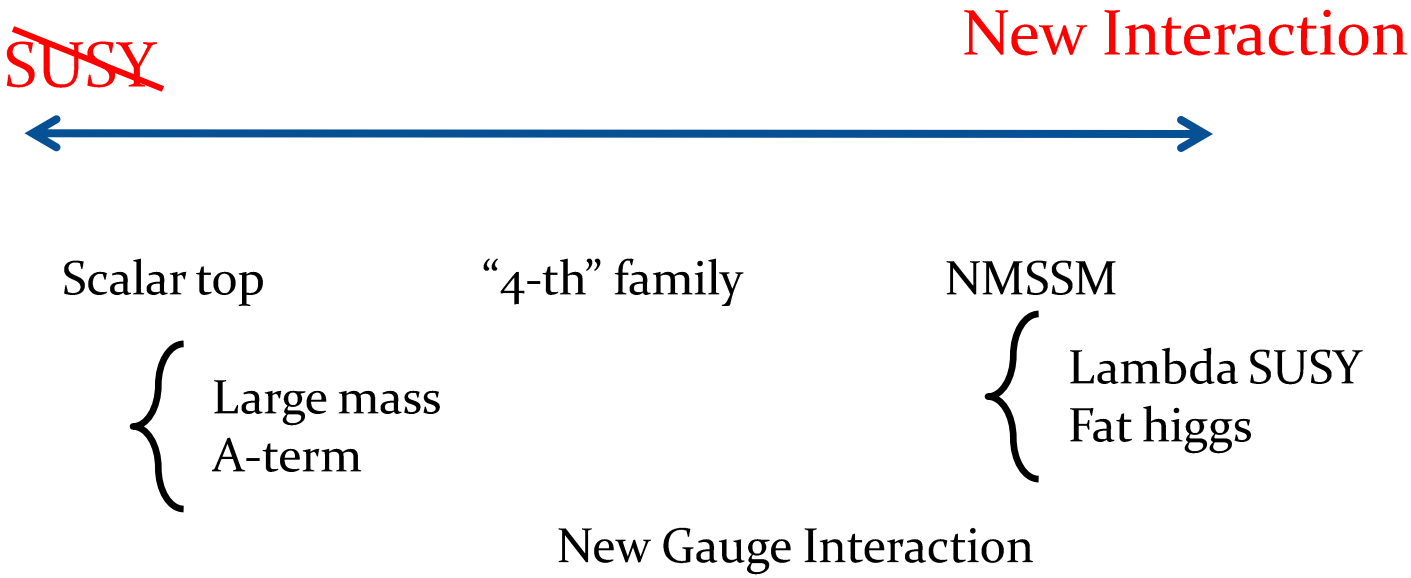
$$\lambda = \frac{1}{4}(g_2^2 + \frac{3}{5}g_1^2)\cos^2(2\beta)$$

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

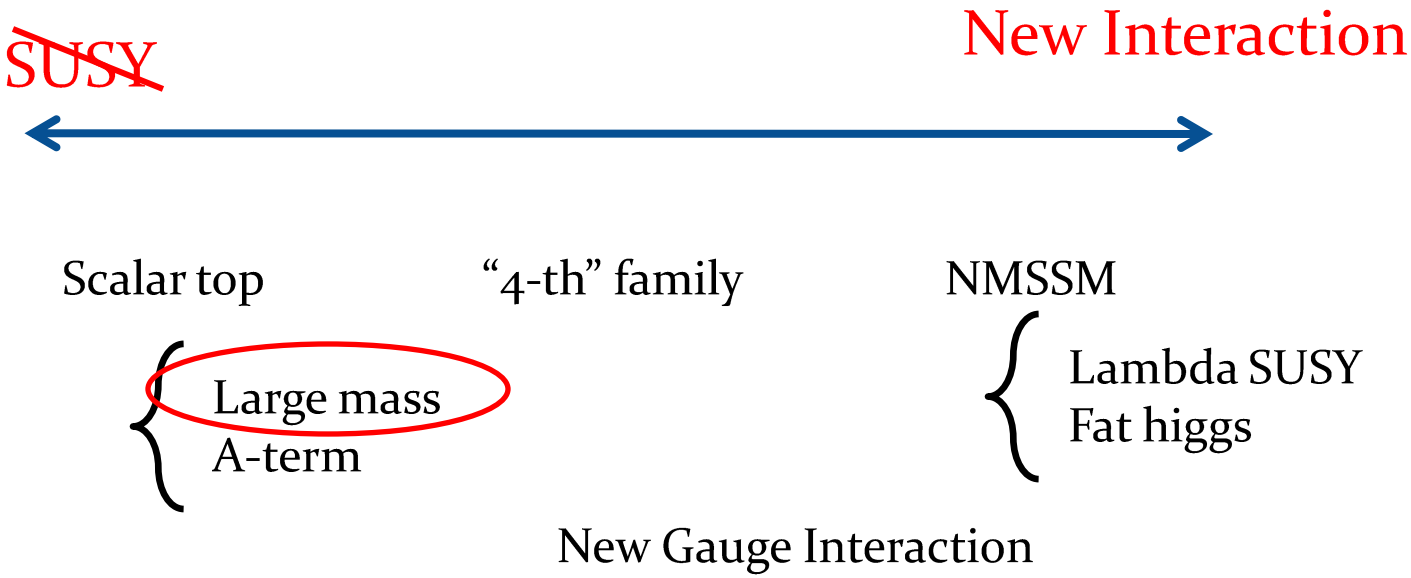
This is clearly less than observed 125 GeV Higgs!

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

SUSY after 125 GeV Higgs

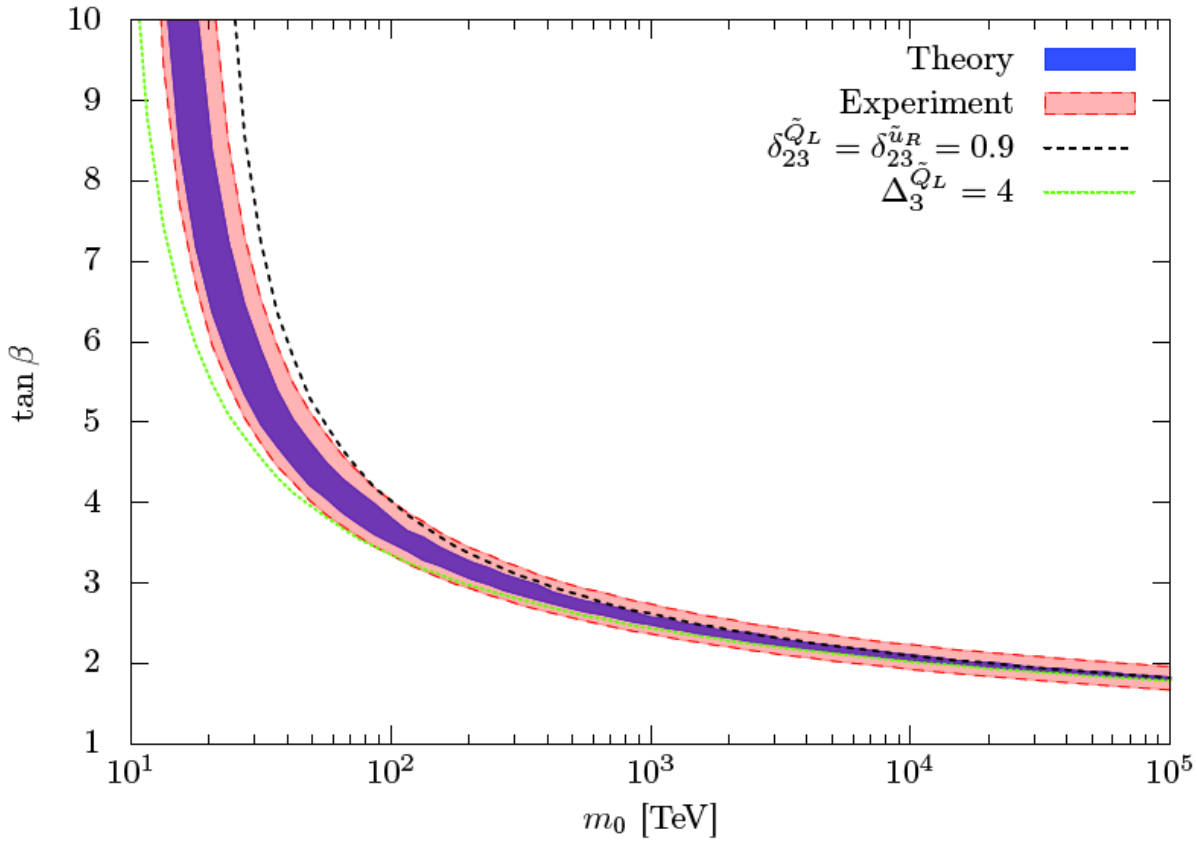


SUSY after 125 GeV Higgs



Higgs Mass from Stop

125 GeV Higgs OK regions



Mini-Split Mass Spectrum

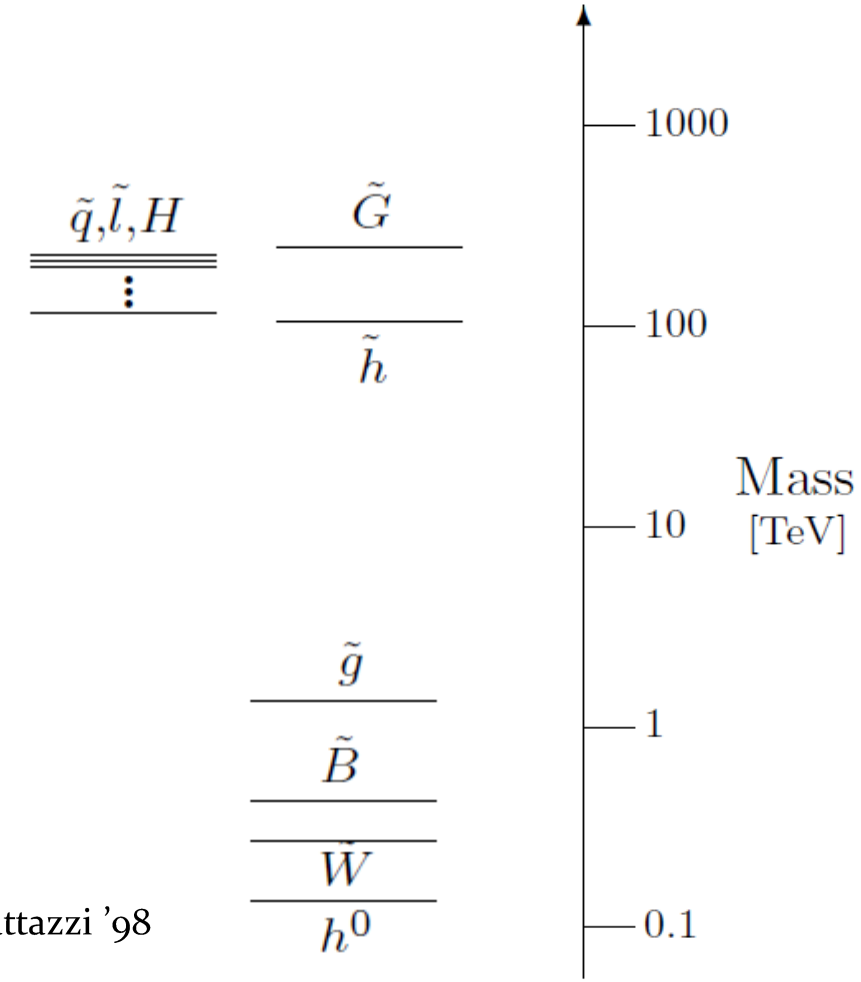
Gravity Mediation

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

Anomaly Mediation

$$M_i \sim \frac{\alpha_i}{4\pi} m_{3/2}$$

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

Benefit and demerit of SUSY

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

Possible demerit

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- ✓ • Model building

Mini-Split Mass Spectrum

Theory papers

Before Higgs Discovery

Wells, "PeV-Scale SUSY," 2004

Arkani-Hamed, et.al., “(Minimal) Split SUSY," 2005

After Higgs

Hall, Nomura, SS, "Spread SUSY” series

Ibe, Matsumoto,Yanagida,.., " Pure Gravity Mediation” series

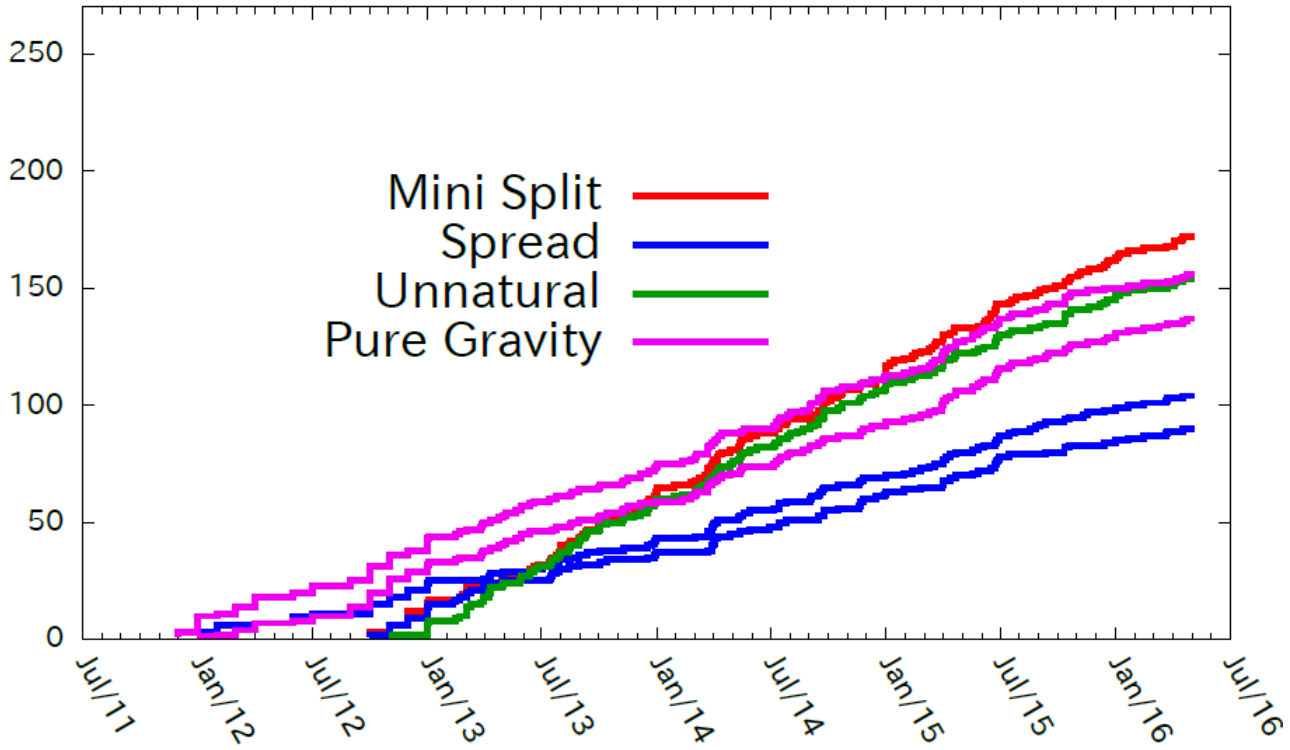
Arvanitaki, et.al., "Mini-Split"

Arkani-Hamed, et.al, "Simply Unnatural SUSY"

and various literatures…

Mini-Split Mass Spectrum

Citation history



Mini-Split Mass Spectrum

Citation history

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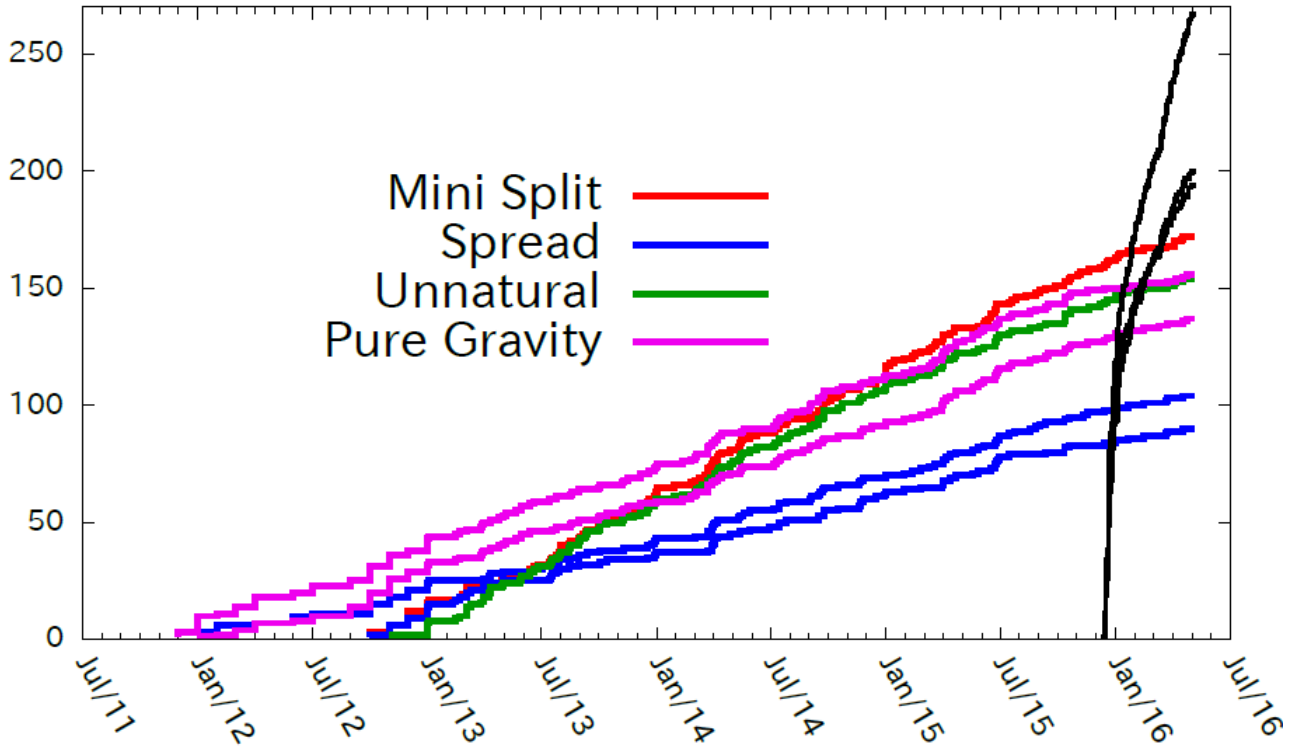

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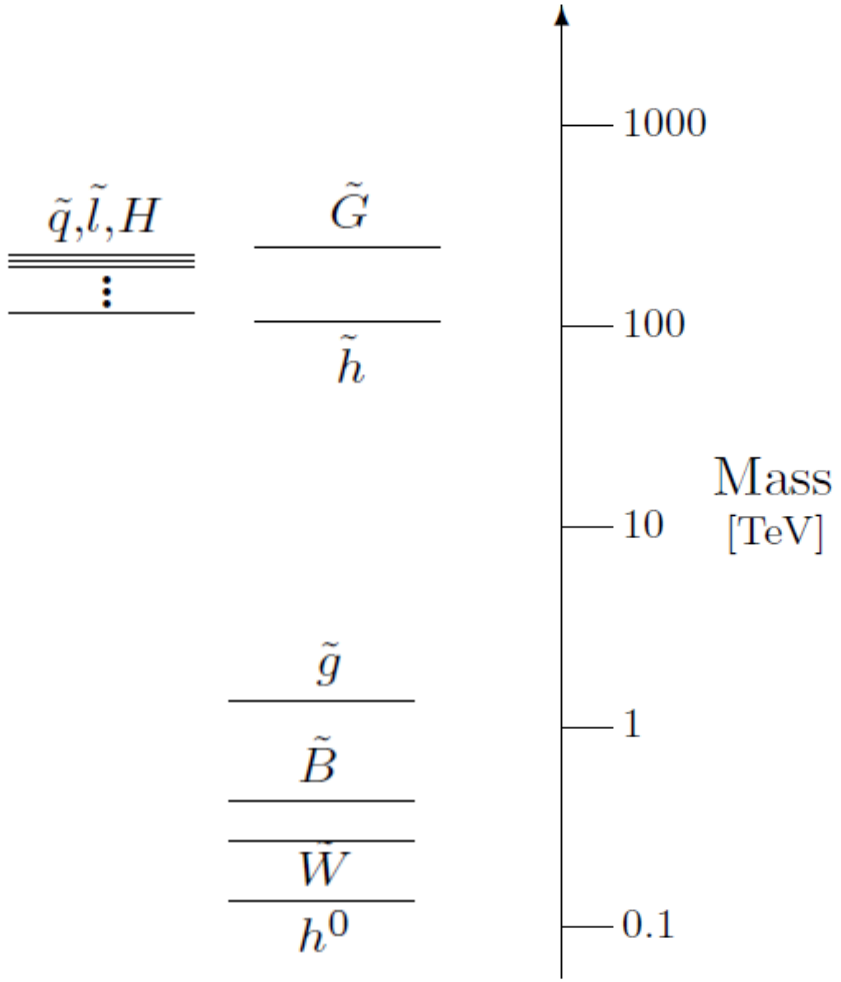
Gravity Mediation

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

Anomaly Mediation

$$M_i \sim \frac{\alpha_i}{4\pi} m_{3/2}$$



Gaugino Mass

$$
\begin{aligned}
M_1 &= \frac{3}{5}\frac{\alpha_1}{4\pi}(11 m_{3/2} + L), \\
M_2 &= \frac{\alpha_2}{4\pi}(m_{3/2} + L), \\
M_3 &= \frac{\alpha_3}{4\pi}(-3 m_{3/2})(1 + c_{\tilde{g}}).
\end{aligned}
$$

Gaugino Mass

AMSB

$$M_1 = \frac{3}{5}\frac{\alpha_1}{4\pi}(11 m_{3/2} + L),$$

Higgsino correction

$$M_2 = \frac{\alpha_2}{4\pi}(m_{3/2} + L),$$

$$M_3 = \frac{\alpha_3}{4\pi}(-3 m_{3/2})(1 + c_{\tilde{g}}).$$

Squark correction

+ High energy sector, such as Axion, also affects

Gaugino Mass

AMSB

$$M_1 = \frac{3}{5}\frac{\alpha_1}{4\pi}(11 m_{3/2} + L),$$

Higgsino correction

$$M_2 = \frac{\alpha_2}{4\pi}(m_{3/2} + L),$$

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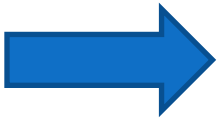
Squark correction

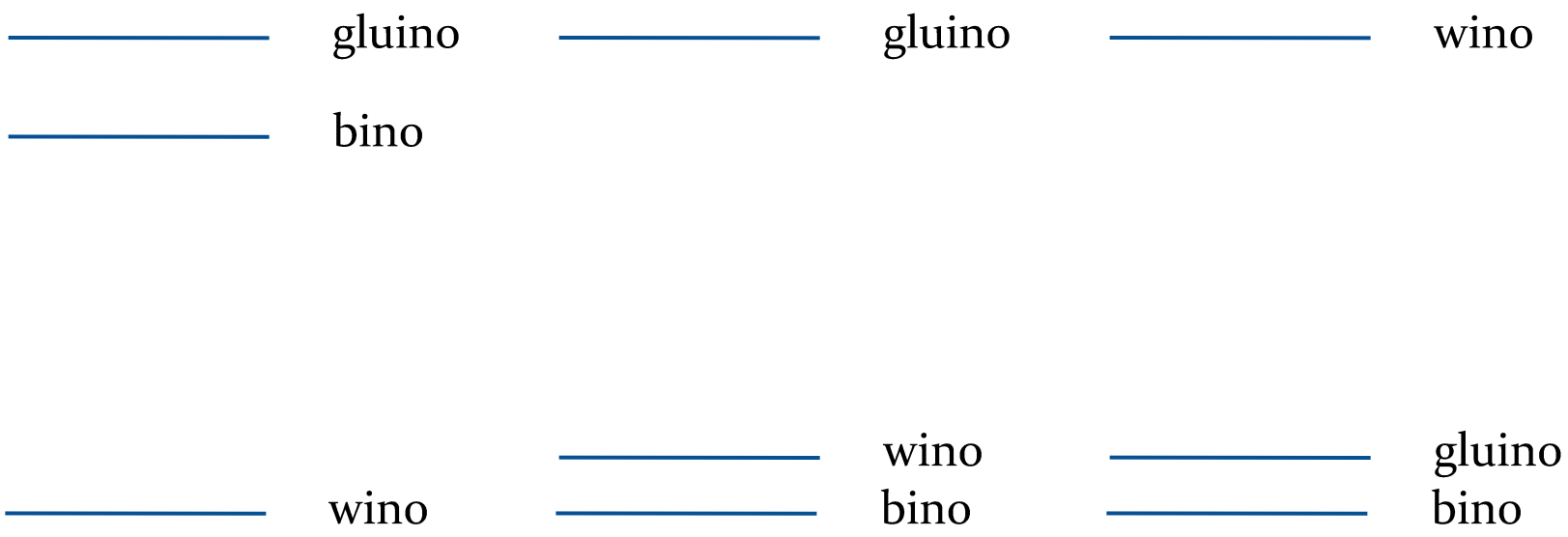
+ High energy sector, such as Axion, also affects



Free gaugino mass relation

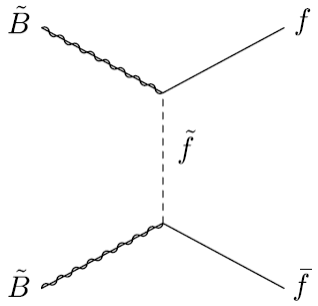
DM in Mini-split SUSY

Three Possibilities

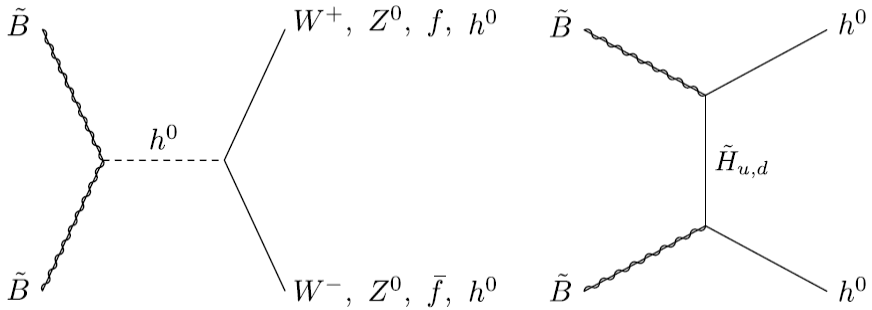


Bino DM 1

Bino interactions are tiny;
suppression by heavy higgsinos and sfermions



$$\Omega_{\tilde{B}}^{\text{sfermion}} h^2 \sim \mathcal{O}(10) \times \left(\frac{100\ \text{GeV}}{M_{\tilde{B}}}\right)^2 \left(\frac{M_s}{1\ \text{TeV}}\right)^4$$



$$\Omega_{\tilde{B}}^{\text{Higgsino}} h^2 \sim \mathcal{O}(100) \times \left(\frac{\tan\beta}{10}\right)^2 \left(\frac{\mu}{1\ \text{TeV}}\right)^2$$

Bino DM 2

Bino interactions are tiny;
suppression by heavy higgsinos and sfermions

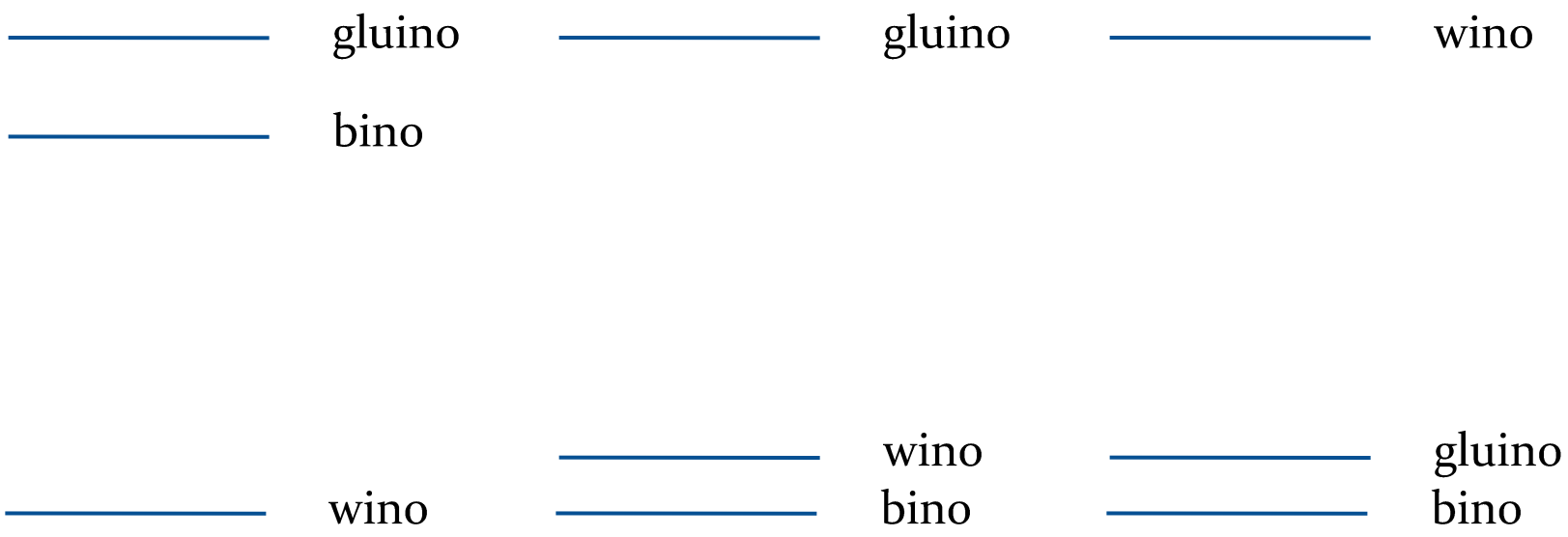
⇒ Too much abundance without coannihilation

Tiny constraints from CRs and direct detection.

⇒ Astrophysical probe is hard

LHC search is most important!

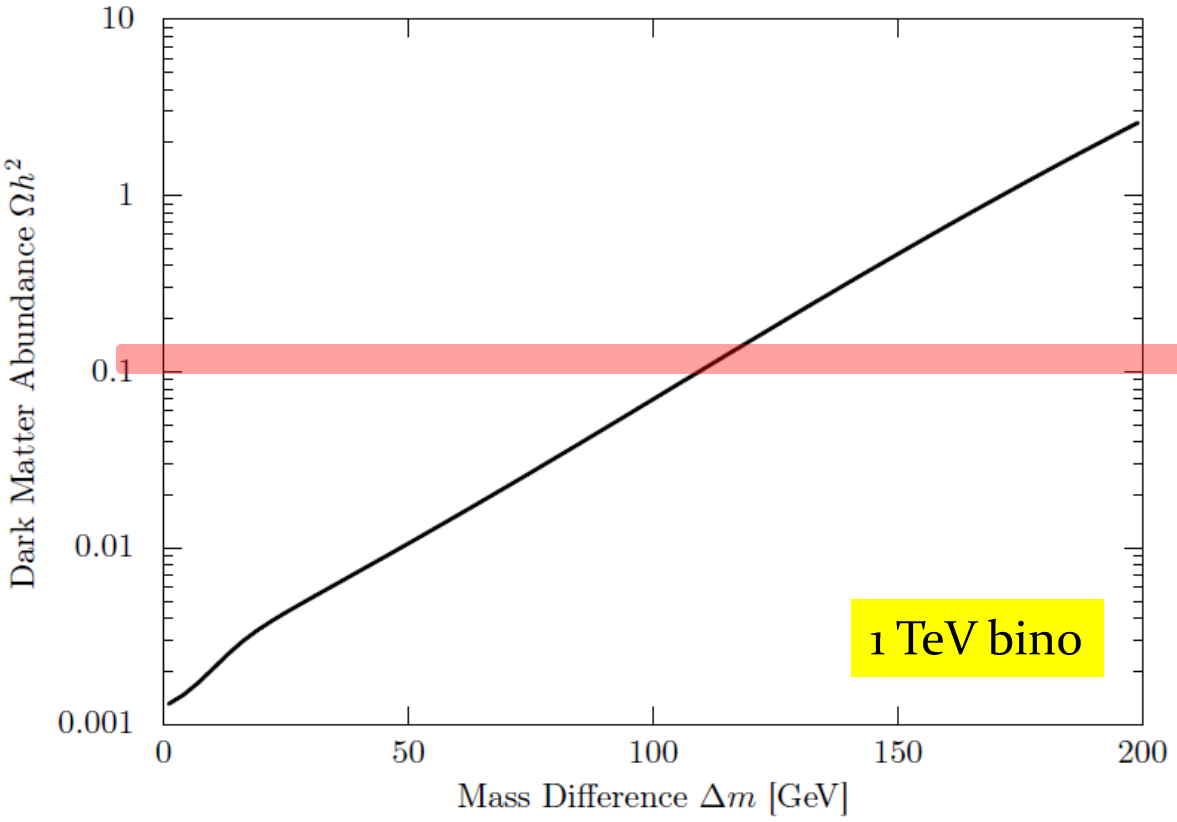
Three Possibilities



Bino-Gluino Coannihilation

Bino-Gluino Coannihilation 1

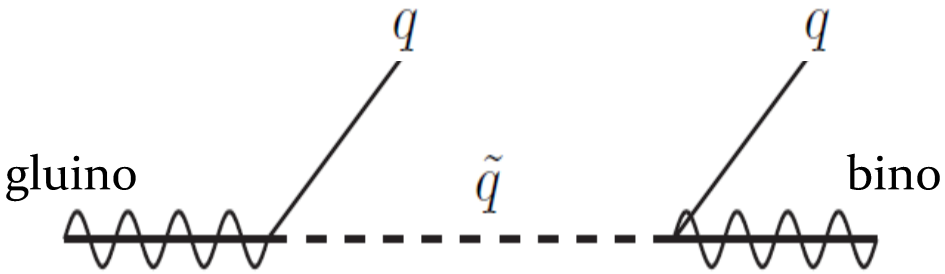
Dark matter abundance



Observed DM

Gluino-bino mass difference

Bino-Gluino Interaction



Bino-gluino interaction is suppressed by sfermion mass

Long-lived gluino

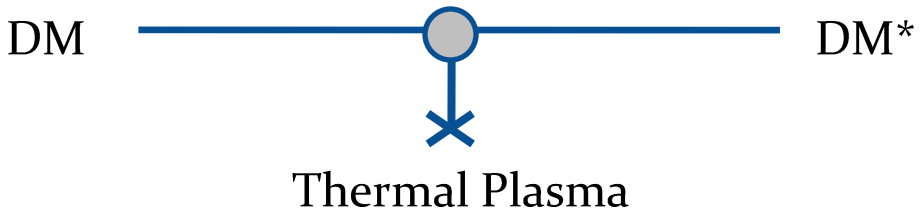
$$c\tau_{\tilde{g}} = O(1)\left(\frac{\Delta m}{100\ \mathrm{GeV}}\right)^{-5}\left(\frac{M_s}{100\ \mathrm{TeV}}\right)^{4}\ \mathrm{cm}$$

Too heavy sfermion prevents coannihilation

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

Bino-Glui

In early universe,
transition DM <-> DM* is rapid



gluino

Bino-gluino interaction is suppressed by sfermion mass

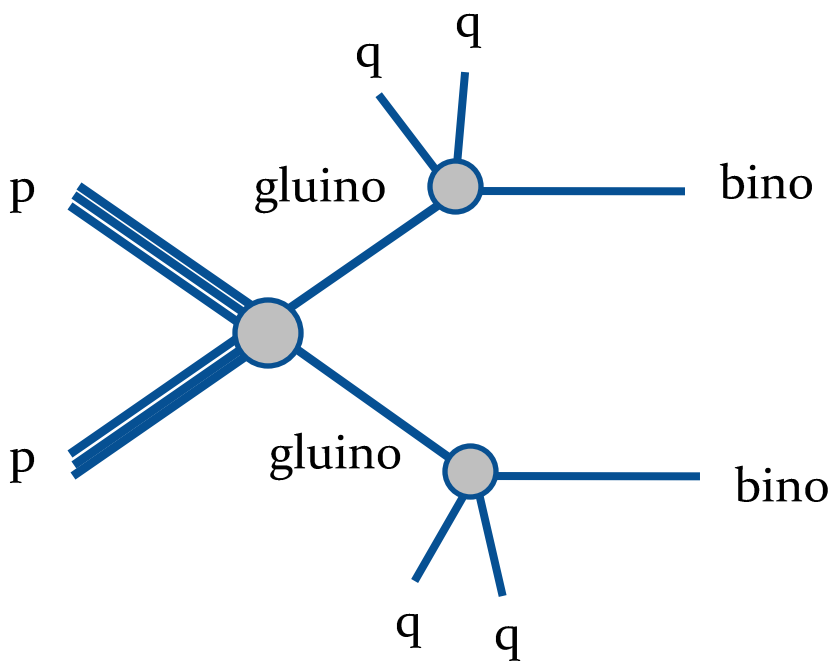
➡ Long-lived gluino

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

➡ Too heavy sfermion prevents coannihilation

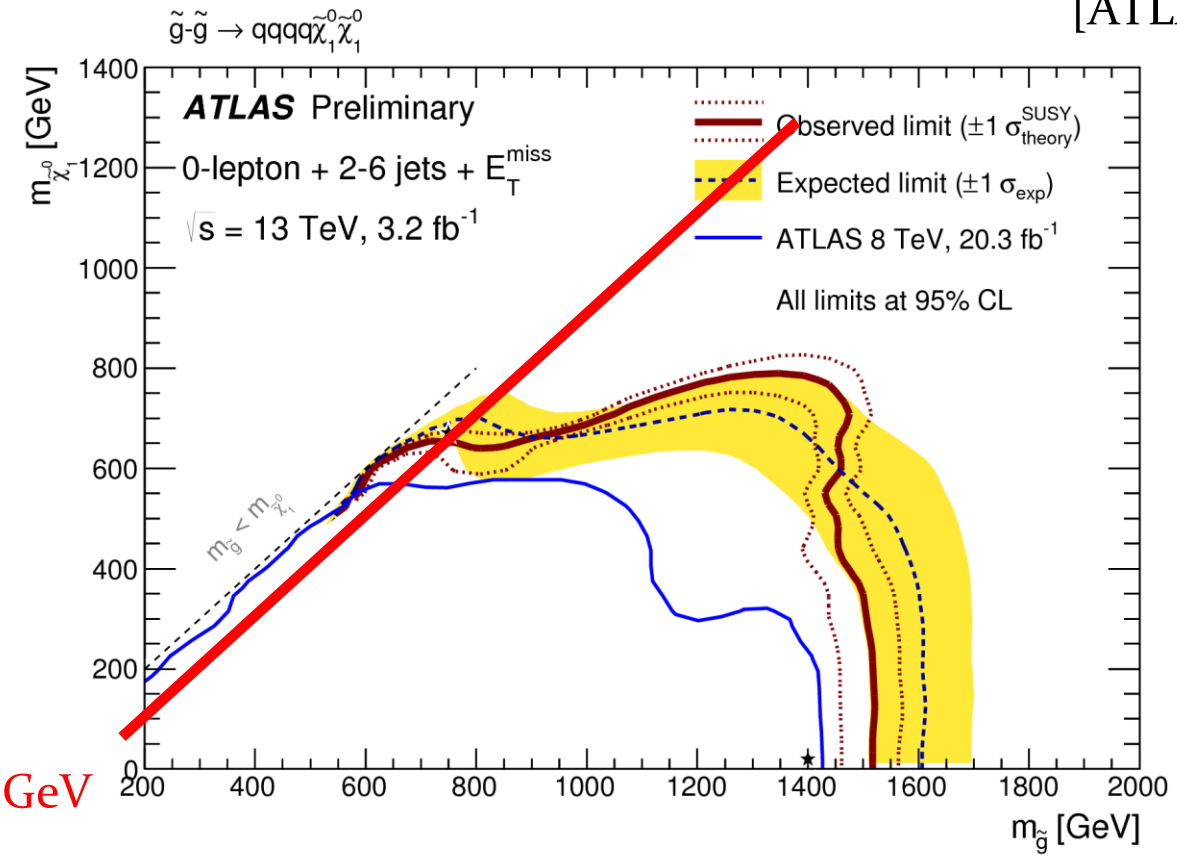
$$M_s \lesssim 250\left(\frac{M_{\mathrm{bino}}}{1\ \mathrm{TeV}}\right)^{3/4}\ \mathrm{TeV}$$

LHC Signals



Prompt Decay Case

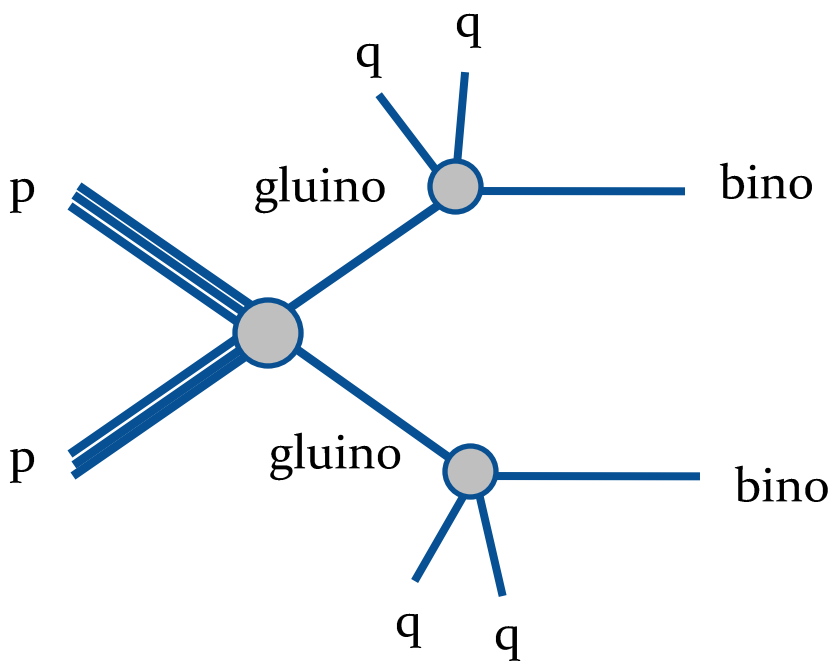
[ATLAS Col.]



Mass diff. = 100 GeV

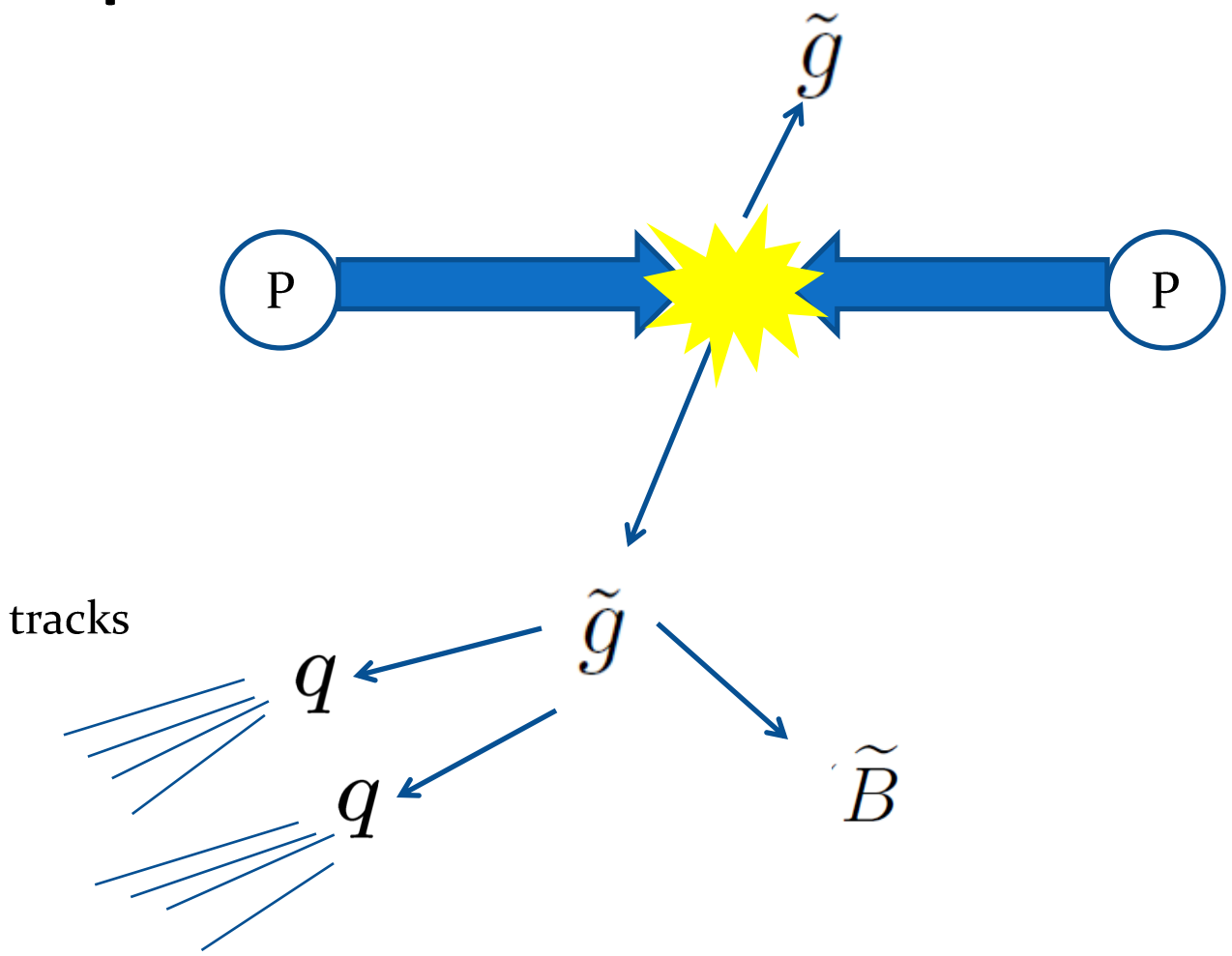
Very weak constraints

LHC Signals

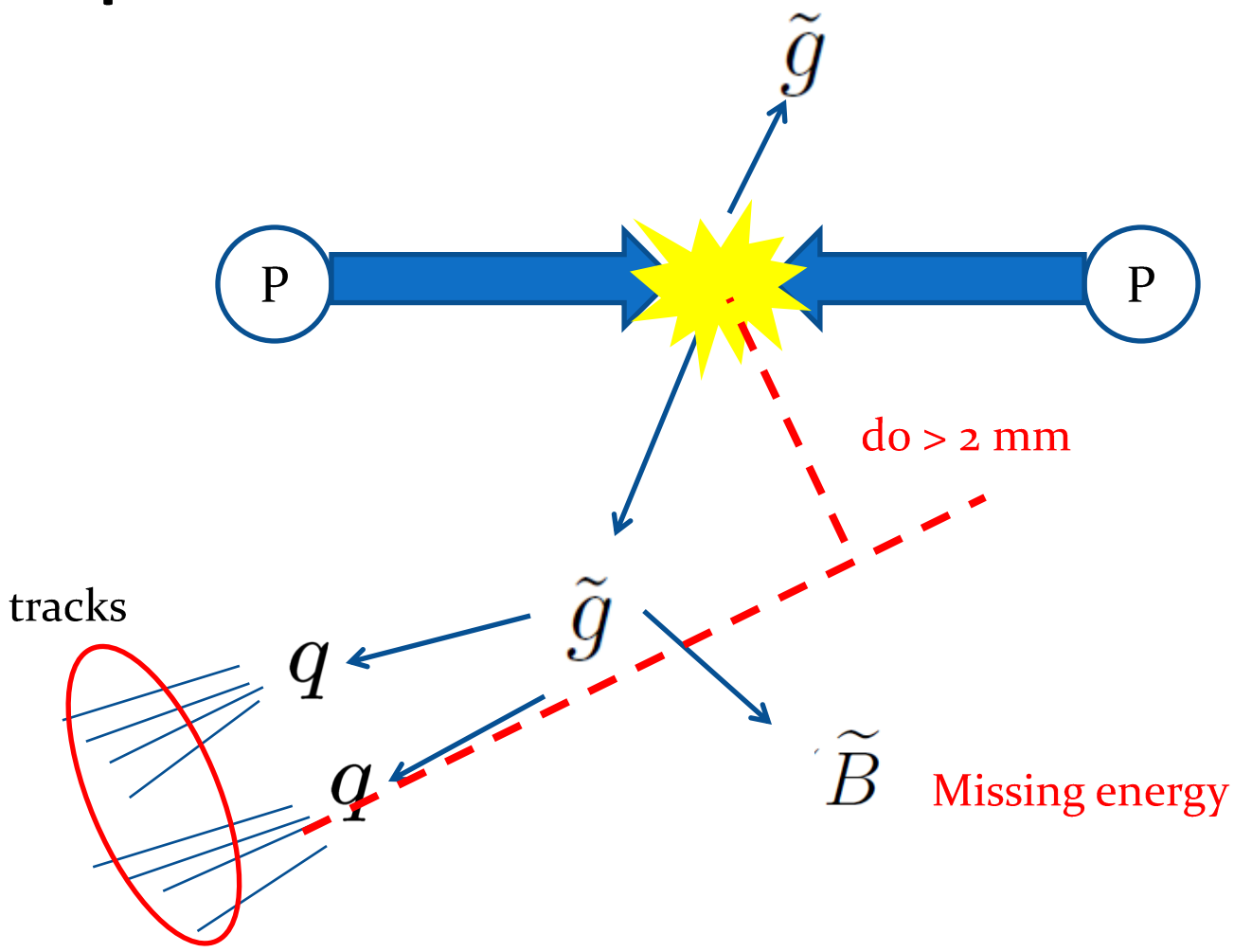


Low mass ~ 100 GeV DV
+
MET

Displaced Vertex



Displaced Vertex



ATLAS DV Search

[ATLAS, PRD 92 072004]

8 TeV 20.3 fb-1

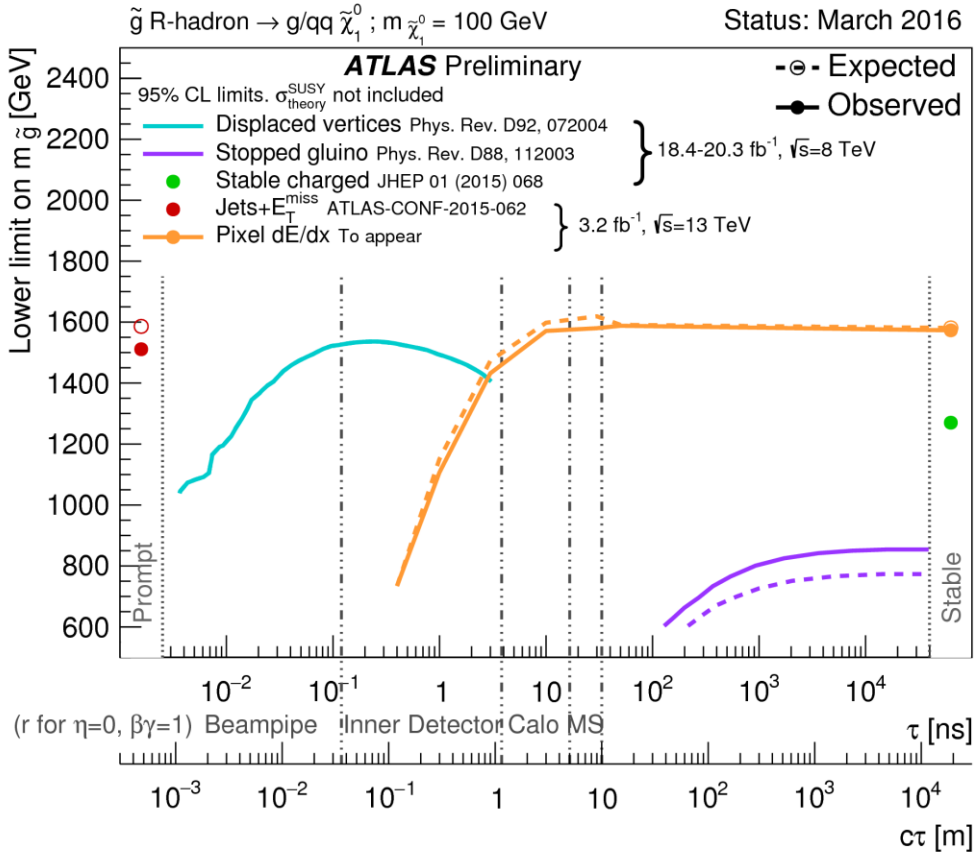
- MET trigger + event filer > 180 GeV
- DV with impact parameter > 2 mm
- Mass of DV > 10 GeV
- # of tracks >4

without DV BG O(10^5)

Channel	No. of background vertices ($\times 10^{-3}$)
DV+jet	$410 \pm 7 \pm 60$
DV+$E_{\mathrm{T}}^{\mathrm{miss}}$	$10.9 \pm 0.2 \pm 1.5$
DV+muon	$1.5 \pm 0.1 \pm 0.2$
DV+electron	$207 \pm 9 \pm 29$

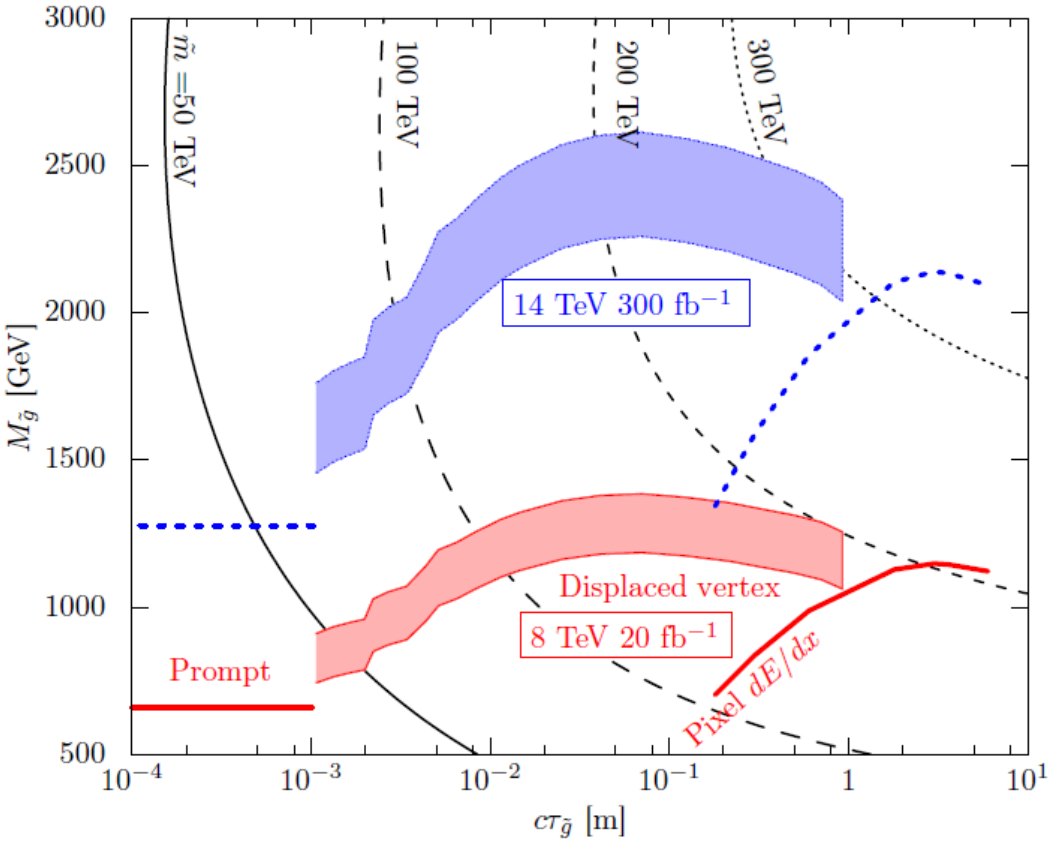
DV Search

[ATLAS web site]



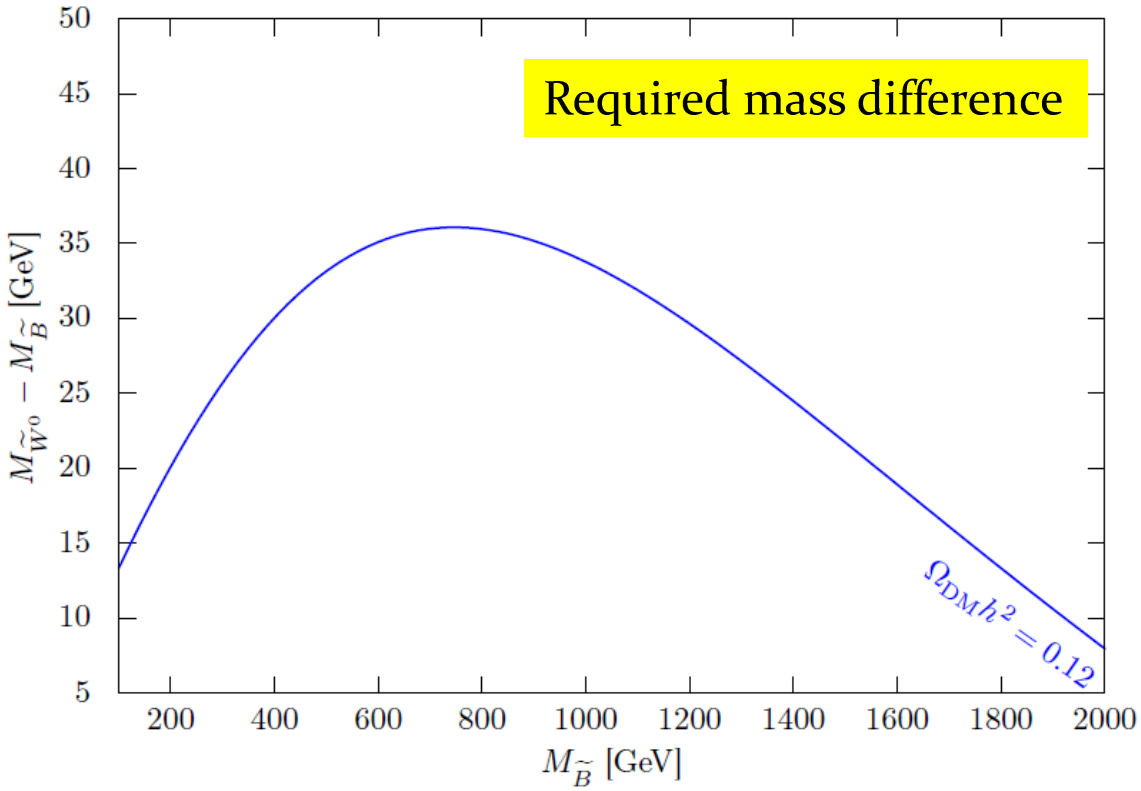
Prospects

Extrapolation from ATLAS result [arXiv:1504.05162]



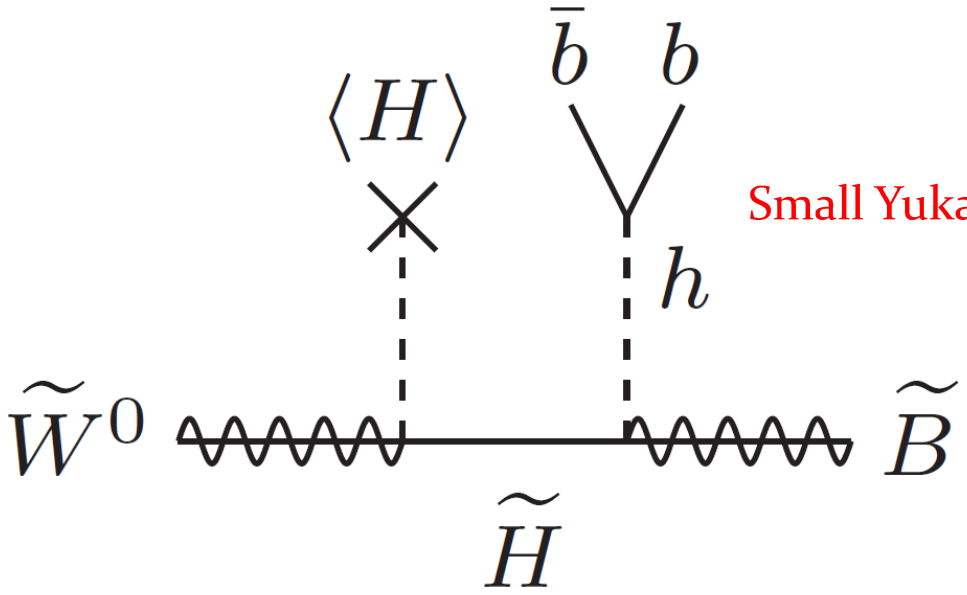
Bino-Wino Coannihilation

Bino-Wino Coannihilation



A few tens of GeV mass diff.

Wino Decay (tree)

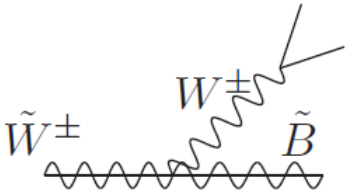


Small Yukawa

Suppressed by Higgsino mass

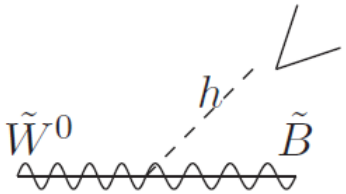
Long-lived neutral wino

Wino Decay

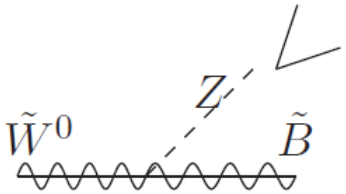


$\propto \mu^{-1}$

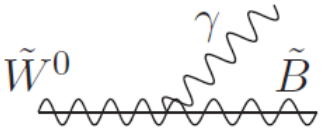
Prompt charged Wino decay



$\propto \mu^{-1}$



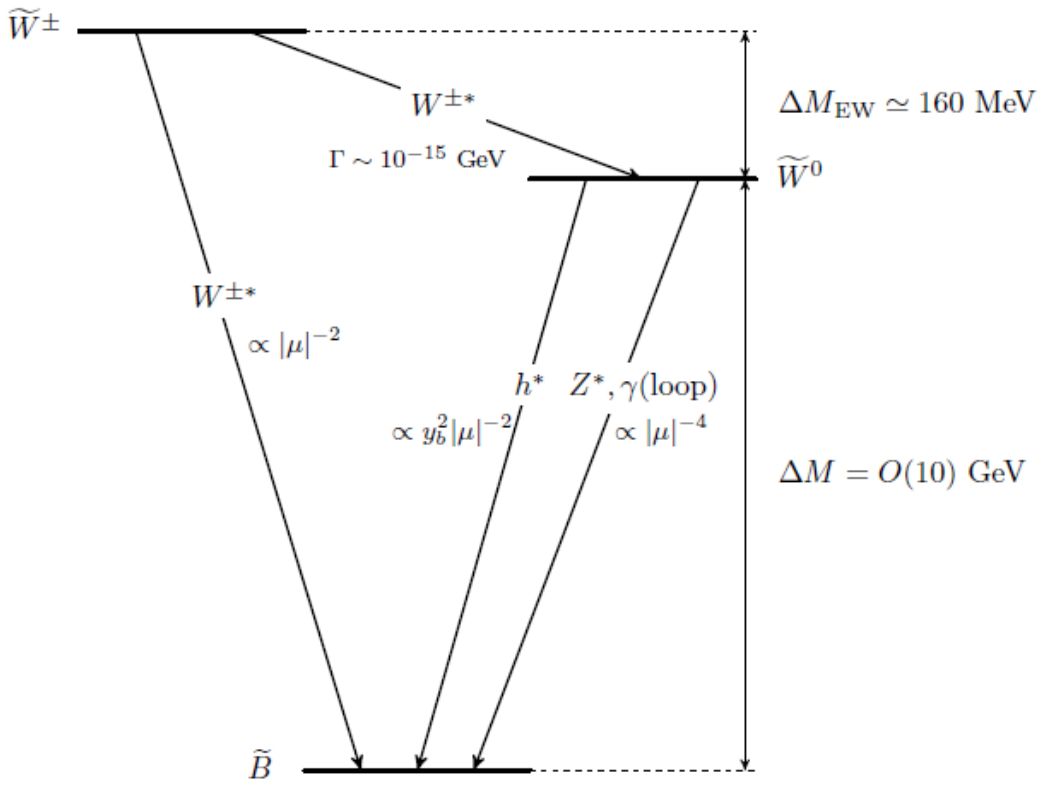
$\propto \mu^{-2}$



$\propto \frac{\alpha}{4\pi}\mu^{-2}, \left(\frac{\alpha}{4\pi}\right)^{2}\mu^{-1}$

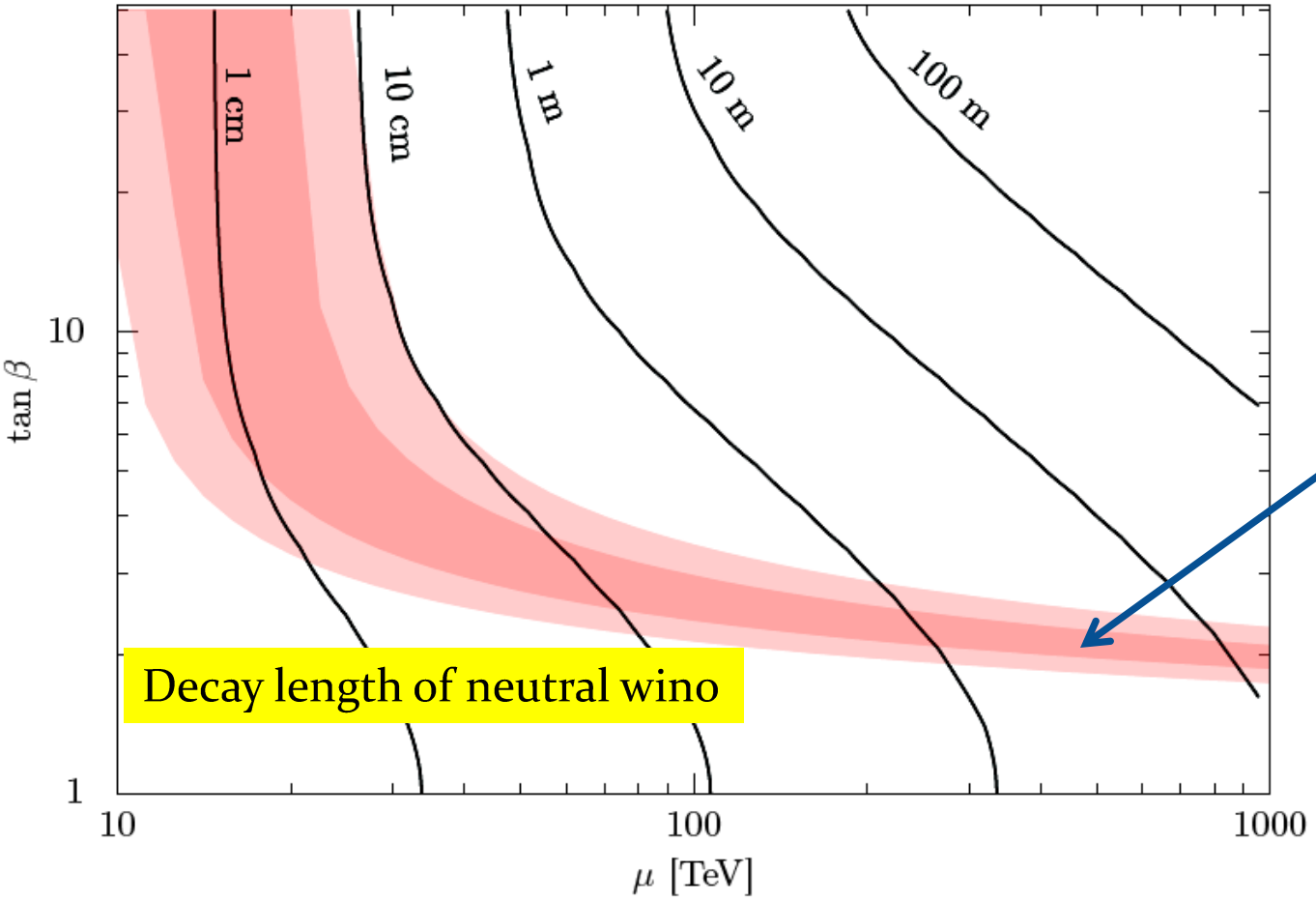
Displaced neutral Wino decay

Mass Spectrum



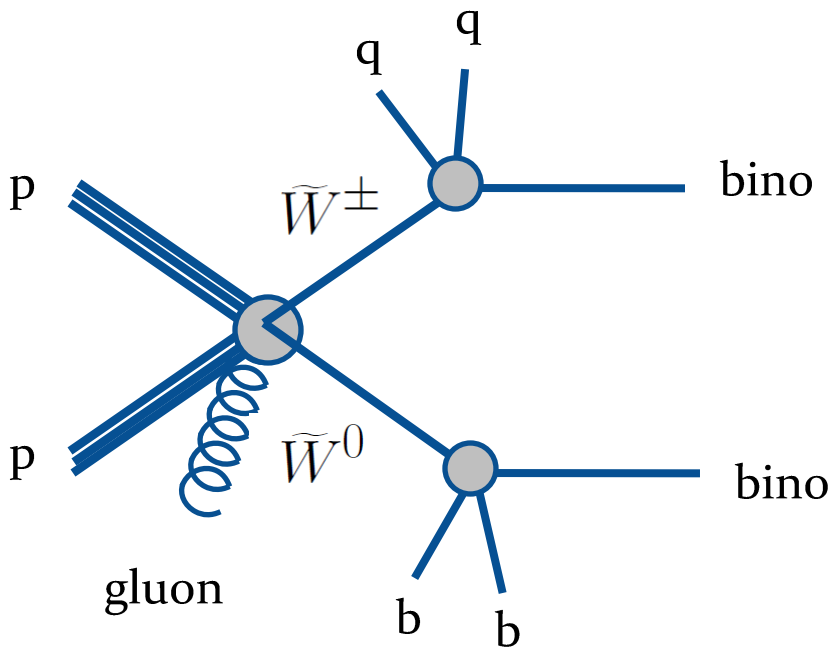
Wino Decay

Bino = 400 GeV
Wino = 430 GeV

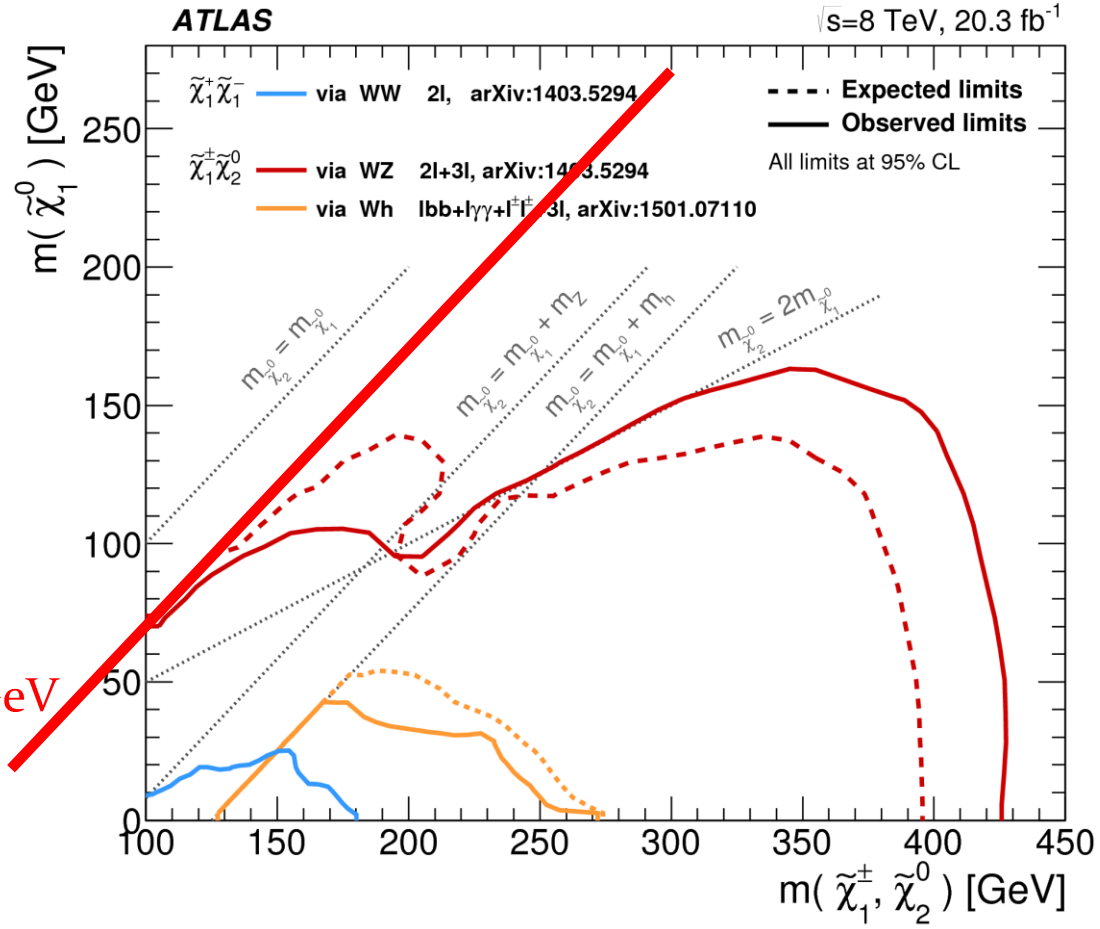


Higgs mass OK

LHC Signals

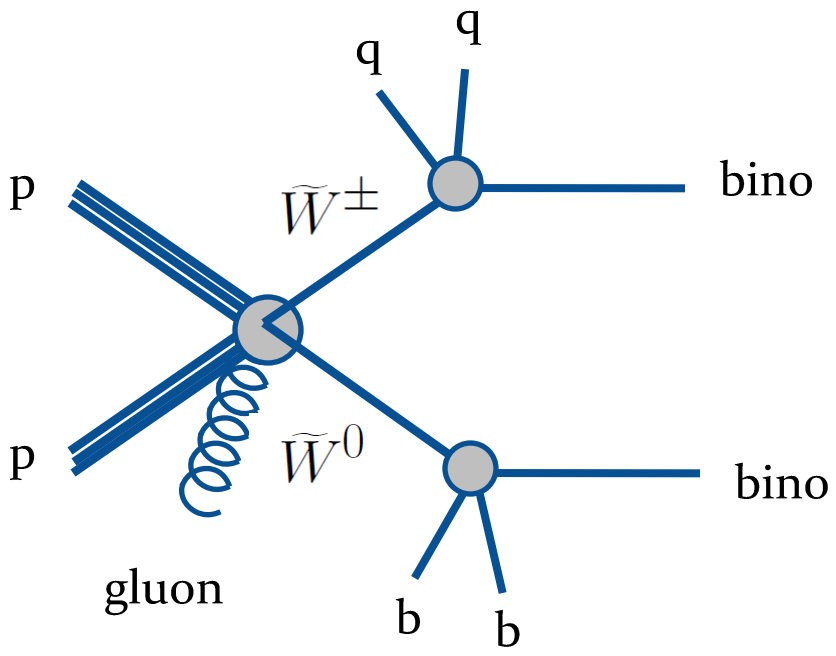


LHC Signals



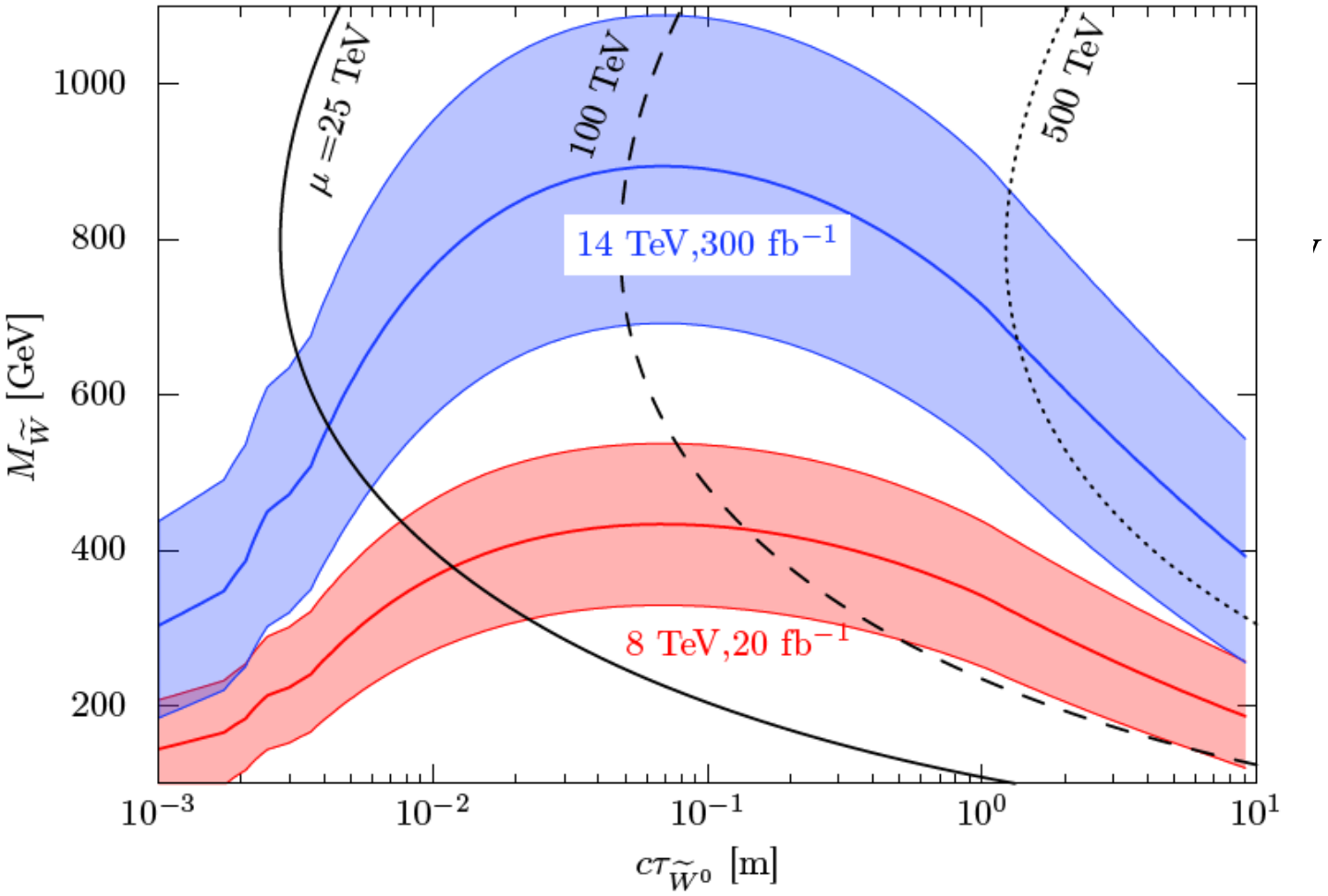
Mass diff. 30 GeV

LHC Signals



Low mass ~ 10 GeV DV
+
MET

LHC Signals


μ =25 TeV
100 TeV
500 TeV
14 TeV,300 fb^{-1}
8 TeV,20 fb^{-1}
$M_{\widetilde{W}}$ [GeV]
$c\tau_{\widetilde{W}^0}$ [m]
1000
800
600
400
200
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

Coannihilation Summary

- DV + MET search is powerful probe of DM coannihilation.

- In gaugino coanihilation in mini-split,
  - Both wino and gluino coannihilation lead to DV.

  - 1 TeV wino and 2.5 TeV gluino can be probed.

- Low mass DV will be experimentally quite challenging.
  - ATLAS started to study this scenario.

- Other examples and generalization..
  - e.g., Bound state model for 750 GeV Digamma

Conclusion

- Present and future experiments are so powerful
- Further study to fully utilize the experiments
  - Improve discovery/exclusion
  - DM characterization
- Enjoy golden age for new physics search!

Backup

Extrapolation

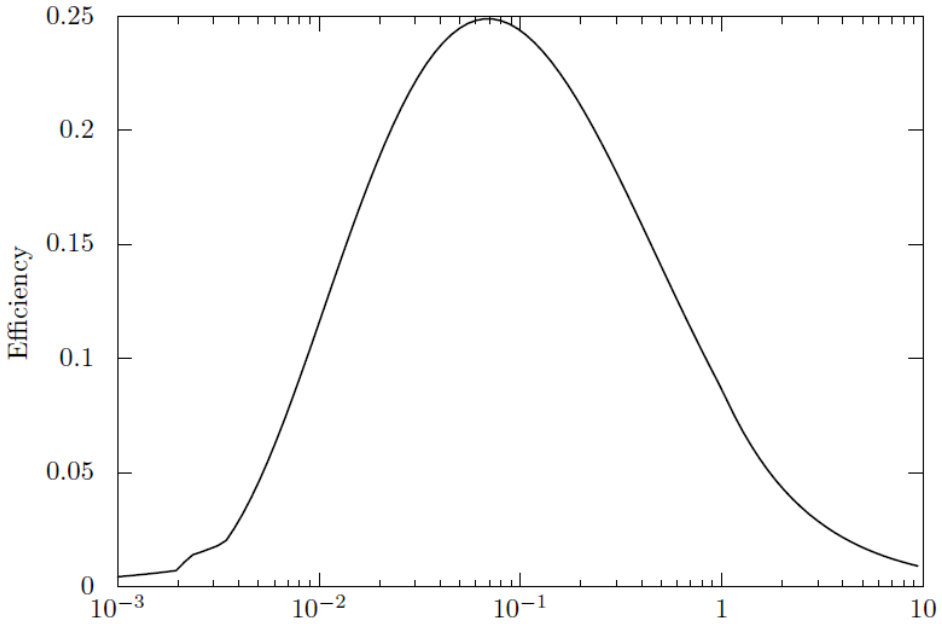
- Trigger:
  MET > 100 GeV for 8 TeV -> acceptance ~40%
  MET > 200 GeV for 14 TeV -> acceptance ~15%

- DV quality
  mDV > 10 GeV and n_track > 4.
  Efficiency is estimated from the ATLAS gluino

$$\epsilon_{\text{gluino}} = \frac{\sigma_{\text{obs}}(= 0.15 \text{ fb})}{\sigma(\text{gluino}) \times A_{\text{MET}>180 \text{ GeV\&good DV}}}$$

- Trigger + DV quality + Efficiency

Extrapolation



SUSY Parameters

- Scalar mass
- Gaugino mass
- Mu term
- Gravitino mass

SUSY Parameters

- Scalar mass

Scalar >O(100) TeV

Flavor/CP problem

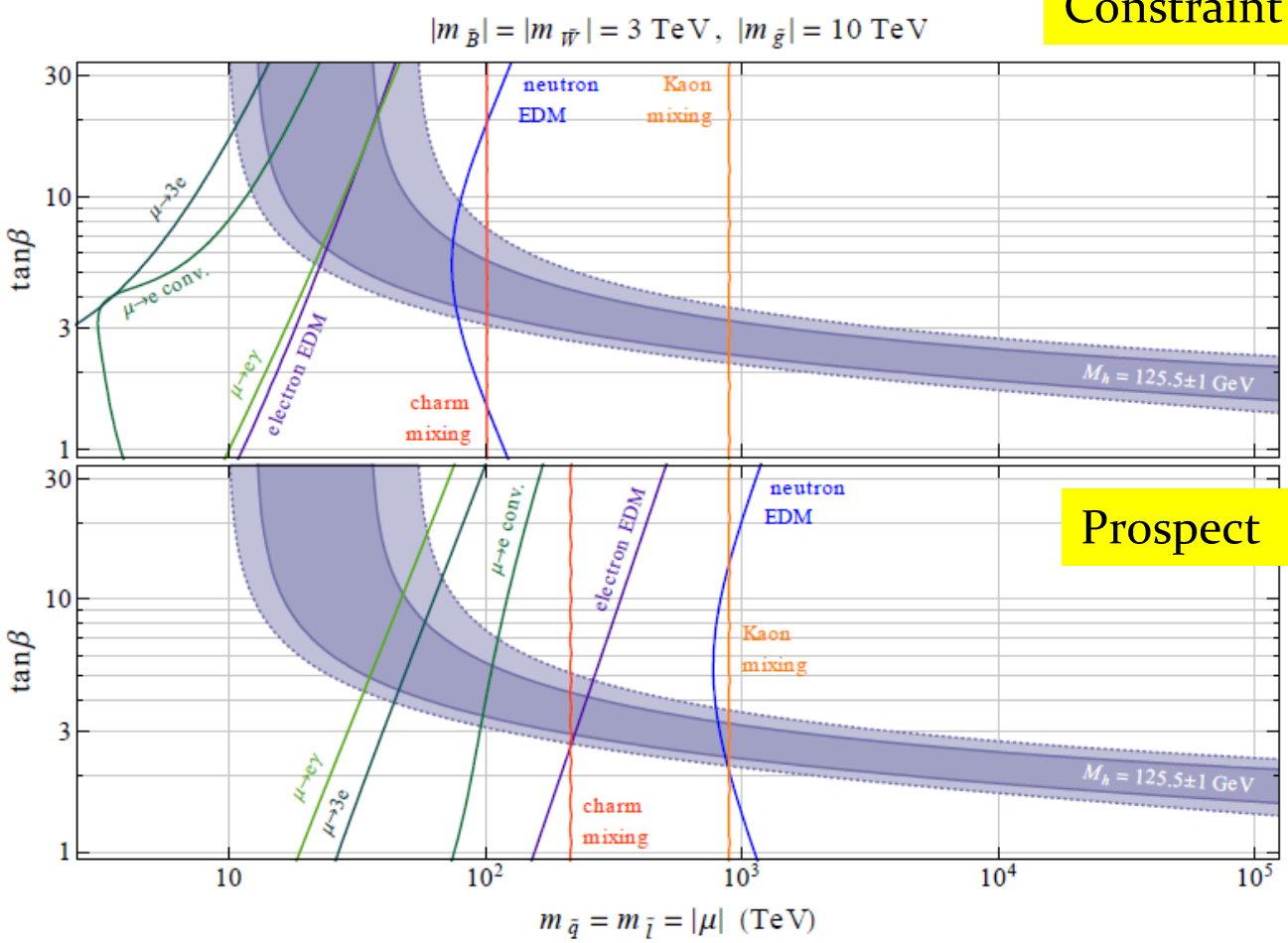
- Gaugino mass
- Mu term
- Gravitino mass

SUSY Parameters

[Altmannshofer,Harnik,Zupan,1308.3653]

Constraint

Prospect



SUSY Parameters

- Scalar mass

Scalar >O(100) TeV

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SUSY Parameters

- Scalar mass
- Gaugino mass
- Mu term
- Gravitino mass

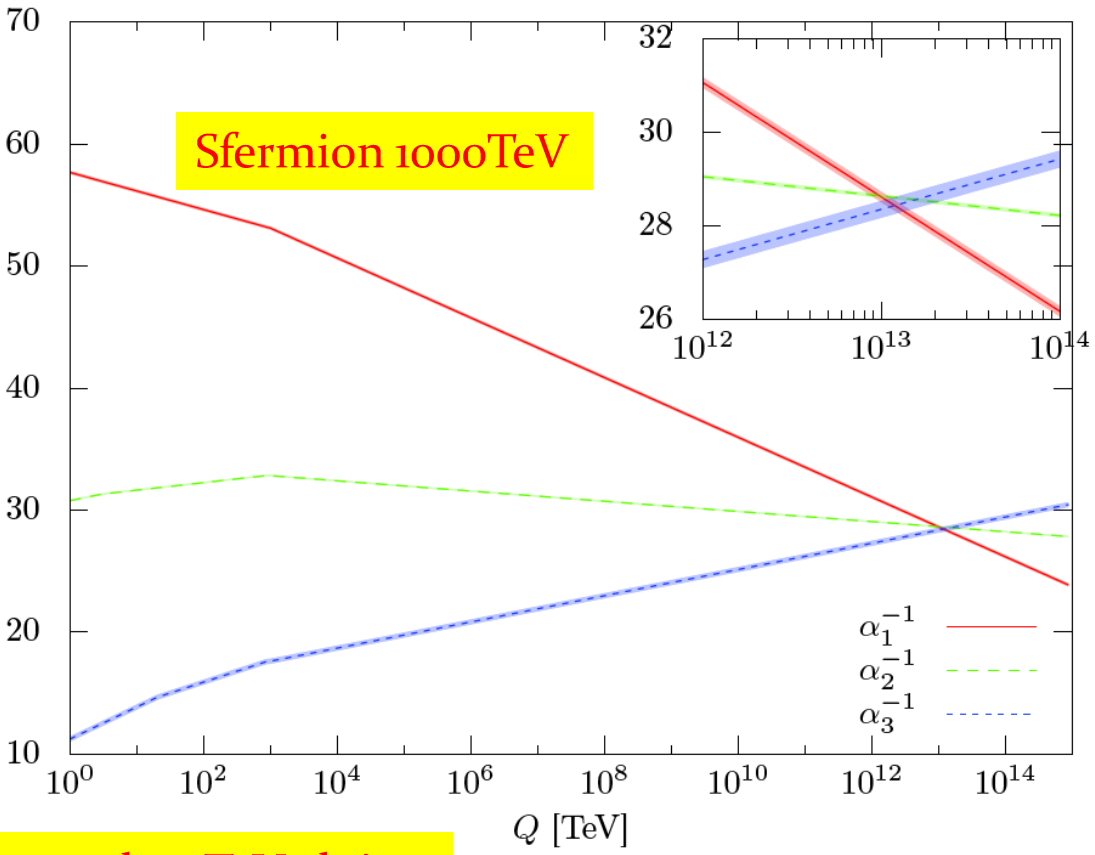
Scalar >O(100) TeV

Flavor/CP problem

Light fermion

GUT unification

SUSY Parameters



3 TeV Wino and 30 TeV gluino

SUSY Parameters

- Scalar mass
- Gaugino mass
- Mu term
- Gravitino mass

Scalar >O(100) TeV

Flavor/CP problem

Light fermion

GUT unification

SUSY Parameters

- Scalar mass
- Gaugino mass
- Mu term
- Gravitino mass

Scalar >O(100) TeV

Flavor/CP problem

Light fermion

GUT unification

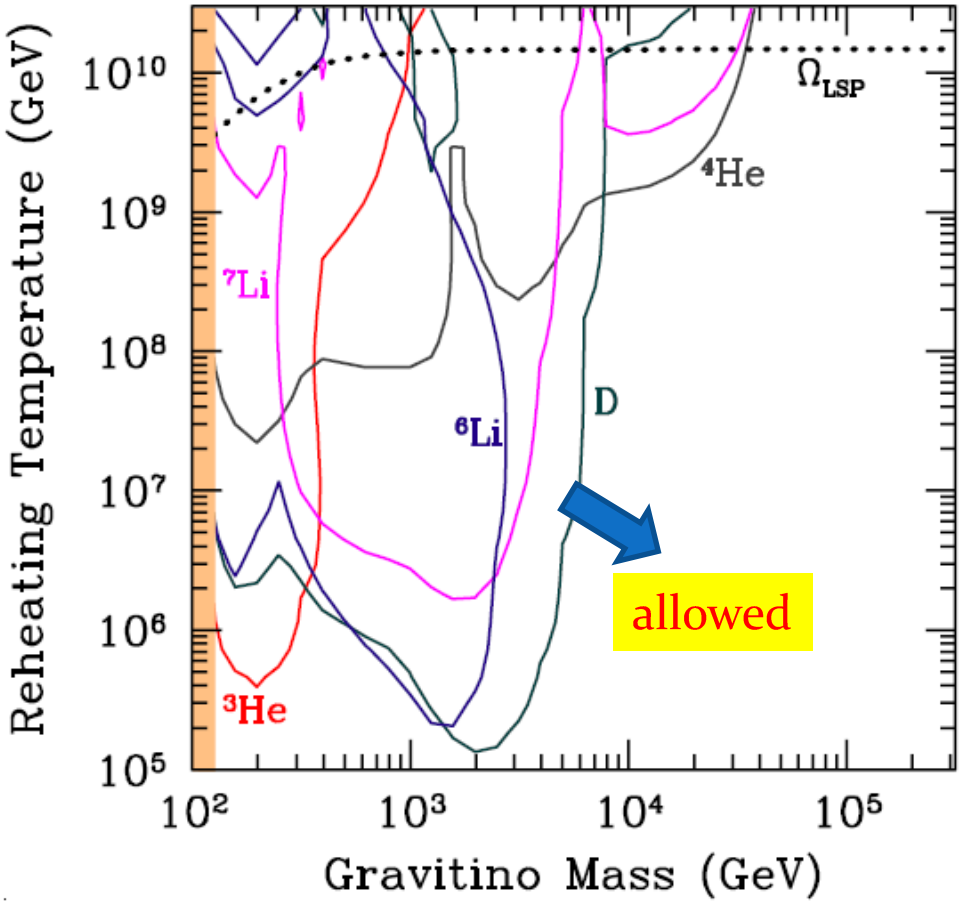
Gravitino > 10 TeV

Gravitino problem

SUSY Parameters

[Kawasaki et.al, arXiv:0804.3745]

Cosmological constraints



$$\tau_{\widetilde{G}} \simeq 10 \left(\frac{m_{3/2}}{10\ \mathrm{TeV}} \right)^{-3} \ \mathrm{sec}$$

Decay before BBN era (~1 sec)

SUSY Parameters

- Scalar mass
- Gaugino mass
- Mu term
- Gravitino mass

Scalar >O(100) TeV

Flavor/CP problem

Light fermion

GUT unification

Gravitino > 10 TeV

Gravitino problem

SUSY Parameters

- Scalar mass
- Gaugino mass
- Mu term
- Gravitino mass

Scalar >O(100) TeV

Flavor/CP problem

Light fermion

GUT unification

Gravitino > 10 TeV

Gravitino problem

LSP abundance

Gaugino or higgsino < O(1) TeV

How Rapid Transition Rate Needed?

Transition rate should be larger than Hubble rate

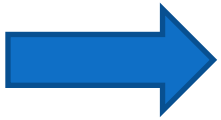
$$\Gamma(\widetilde{B}q \to \widetilde{g}q) \gg H$$

$$\Gamma(\widetilde{B}q \to \widetilde{g}q) \sim \frac{T^5}{\widetilde{m}^4} \qquad H \simeq \frac{T^2}{M_{\rm Pl}}$$

$$M_{\rm Pl} = 2 \times 10^{18}\ {\rm GeV}$$

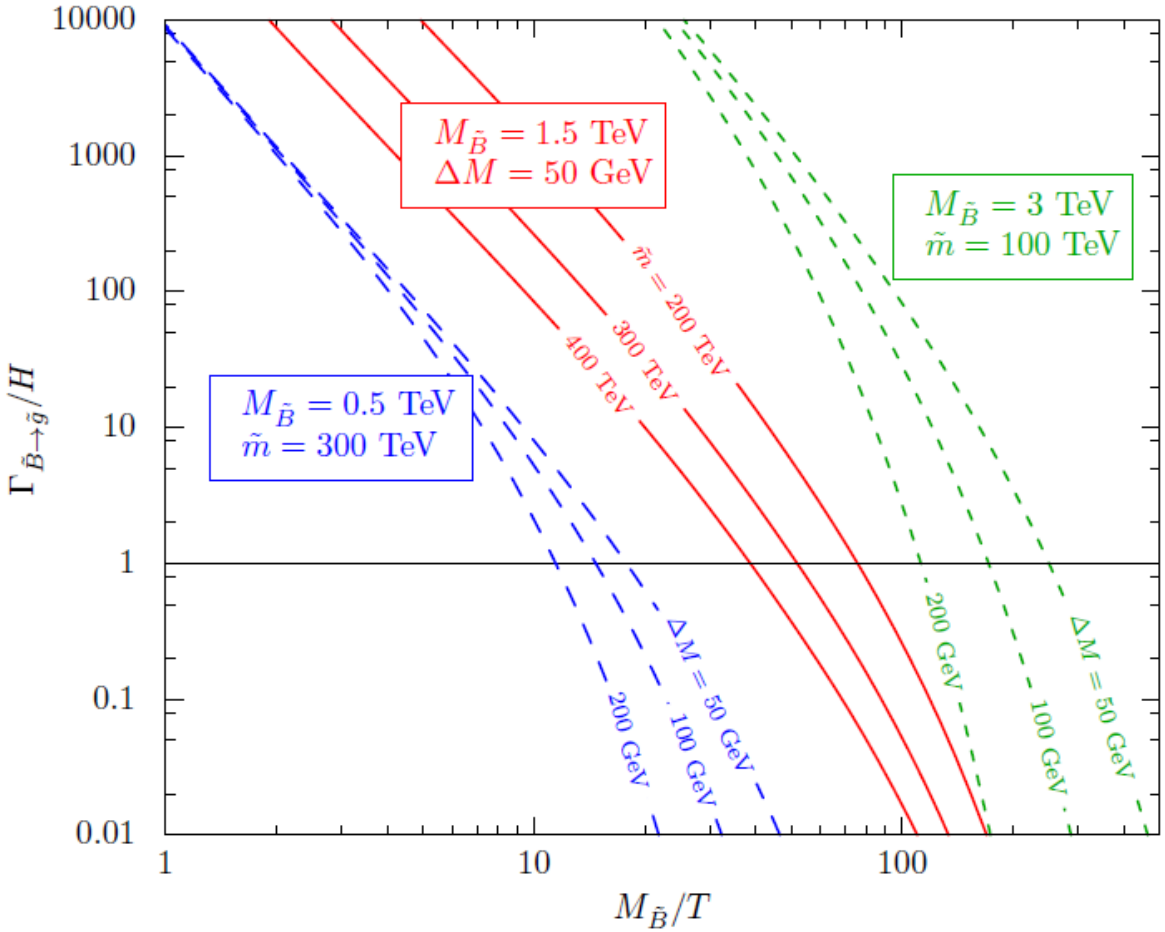
This relation should be kept until freeze-out temperature

$$T_f \sim \frac{M_{\tilde{B}}}{20}$$



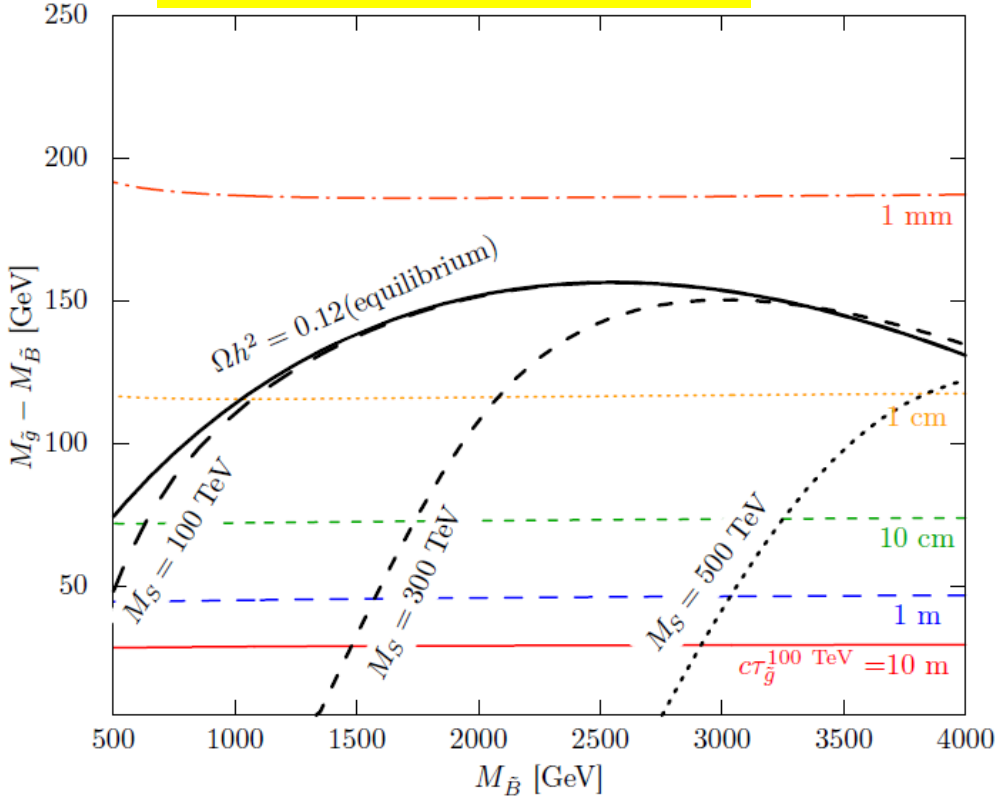
$$\widetilde{m} \lesssim 250 \times \left(\frac{M_{\tilde{B}}}{1\ {\rm TeV}}\right)^{\frac{3}{4}}\ {\rm TeV}$$

Transition rate / Hubble rate



Bino-Gluino Coannihilation 2

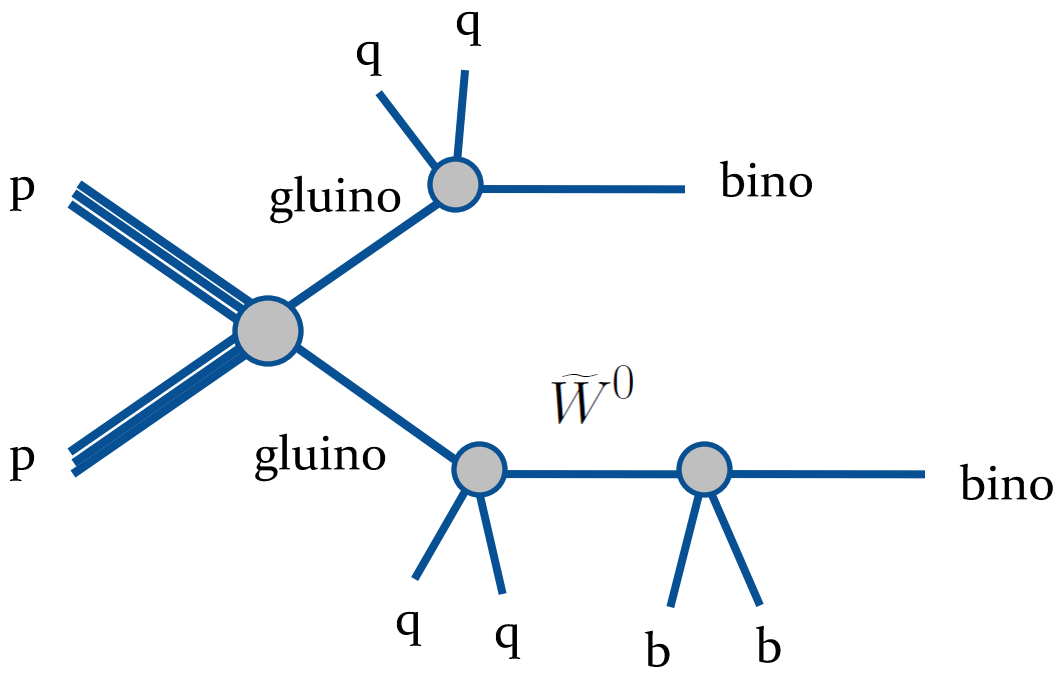
Required mass difference



E.g.,
For 100 TeV sfermion,

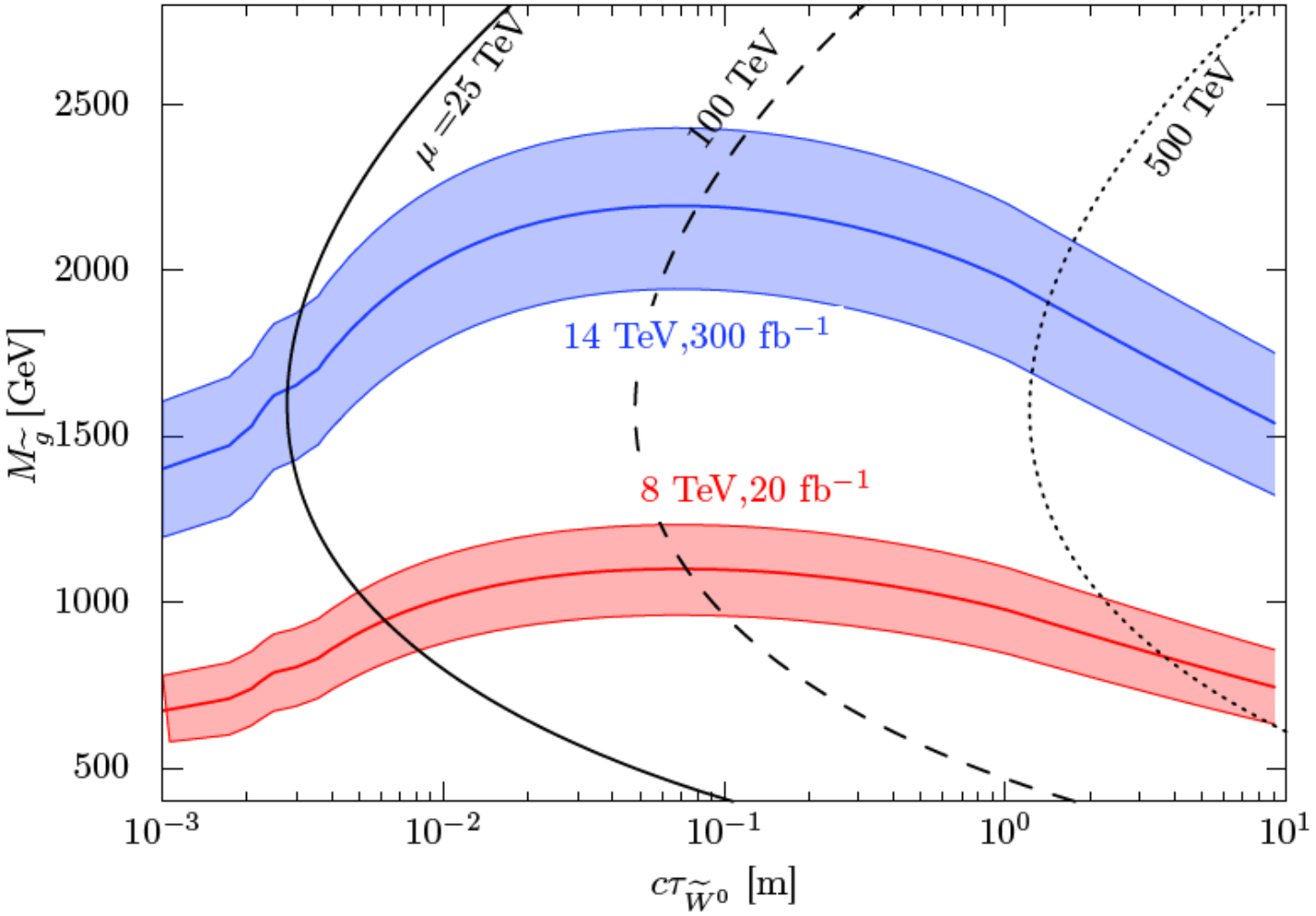
Mass diff. ~ 100 GeV
Decay length ~ cm

LHC Signals: gluino production



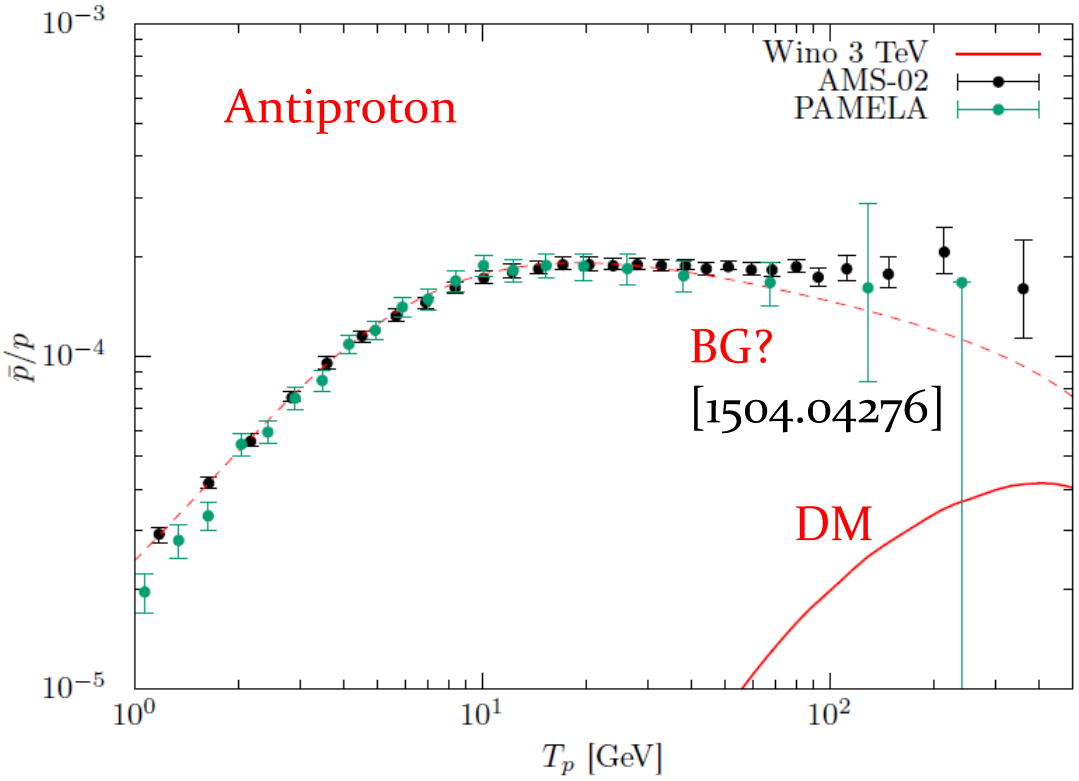
Low mass ~ 10 GeV DV
+
MET

LHC Signals



' DV

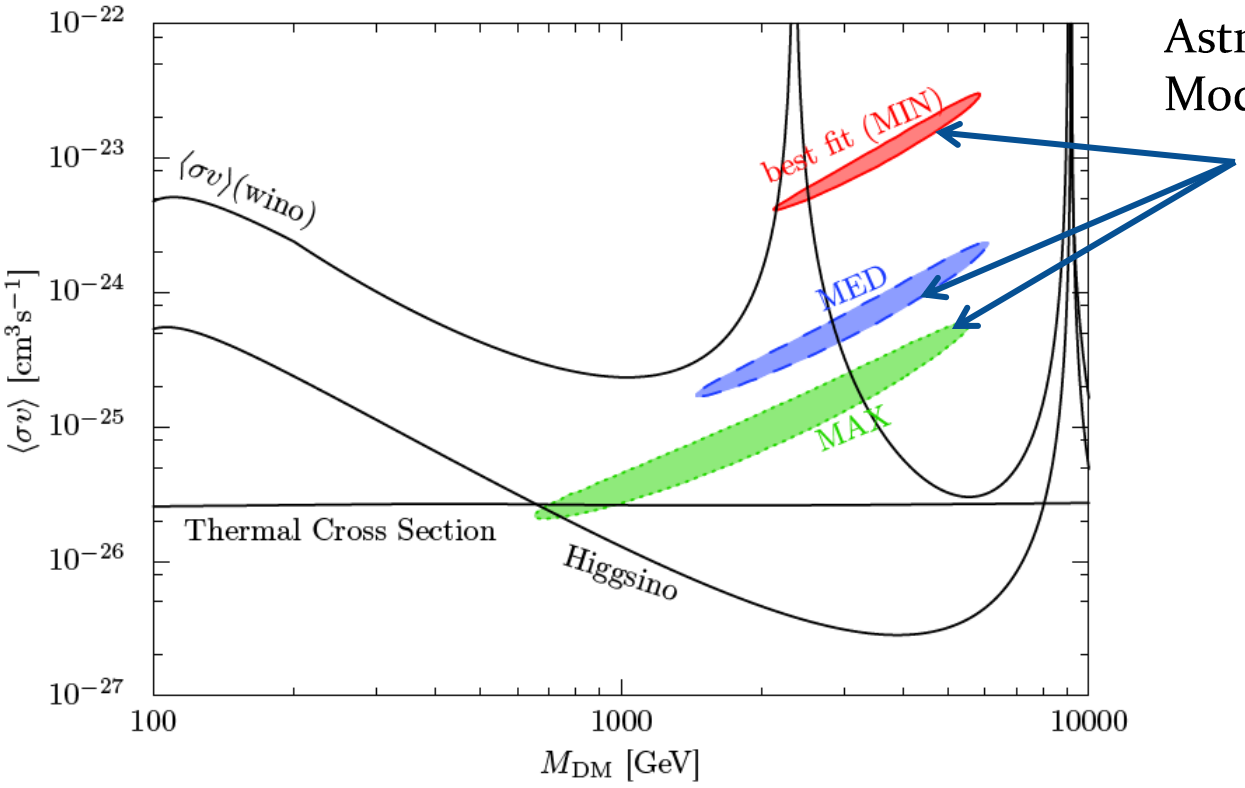
Annihilation: Cosmic Ray



Deviation?
DM?

Antiproton: Fitting with DM

Ibe, Matsumoto, SS, Yanagida '15 and work in progress



Astrophysical Model dep.

Higgs-portal DM

Effective DM model

$$-\frac{1}{2}M_B\widetilde{B}\widetilde{B}+\frac{1}{\Lambda}HH^\dagger\widetilde{B}\widetilde{B}$$

UV model	EDM/Cosmic -ray
scalar-mediation	~o
singlet-doublet model	so-so
SUSY	much
…	…

EDM-cosmic ray relation as Smoking gun

P-wave

$$\langle \sigma v \rangle = a + b\langle v^2 \rangle \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

$$\langle v^2 \rangle \sim 0.3$$

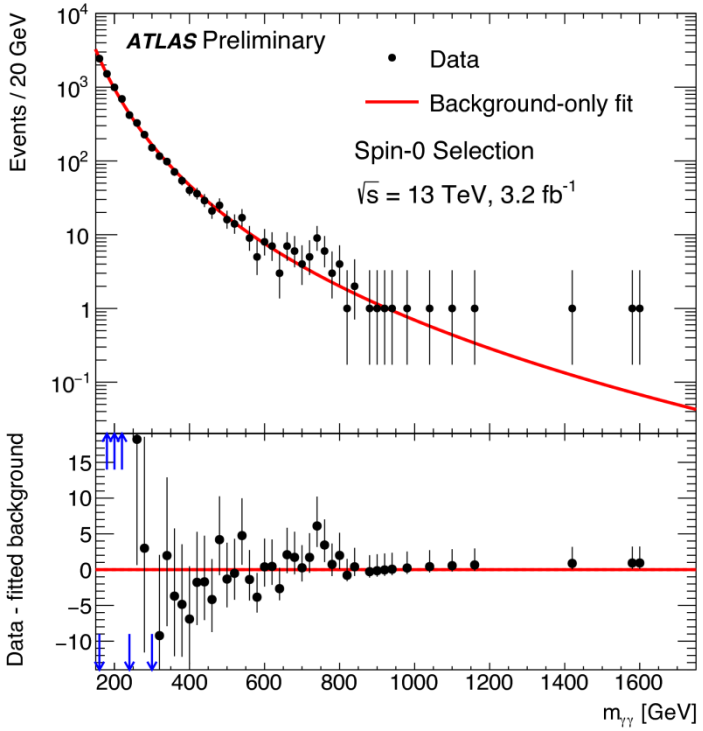
Larger b is required and maybe strong coupling

$$-\frac{1}{2} M_B \widetilde{B}\widetilde{B} + \frac{1}{\Lambda} H H^\dagger \widetilde{B}\widetilde{B}$$

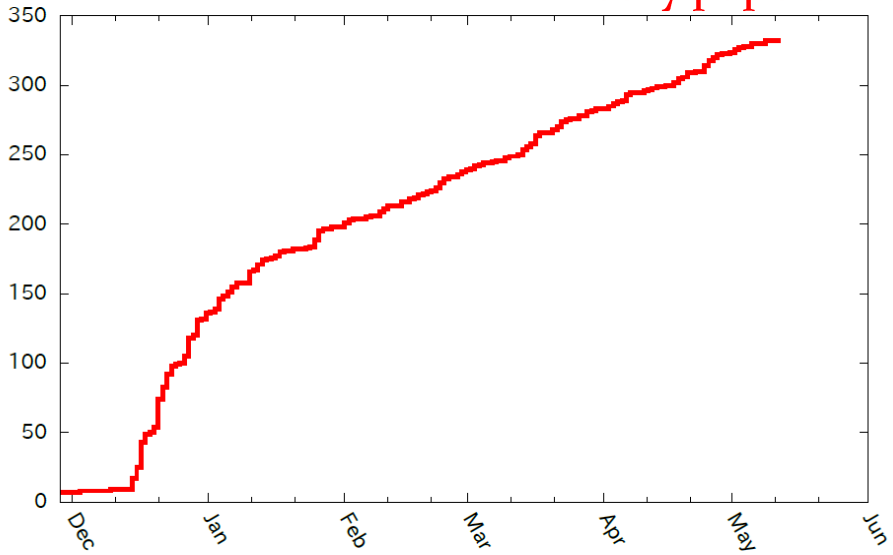
pure p-wave $\quad \Omega h^2 \sim 0.1 \left(\frac{\Lambda}{1\ \mathrm{TeV}} \right)^2 \quad \sigma_{\mathrm{SI}} \sim 4 \times 10^{-44}\ \mathrm{cm}^2 \left(\frac{\Lambda}{1\ \mathrm{TeV}} \right)^{-2}$

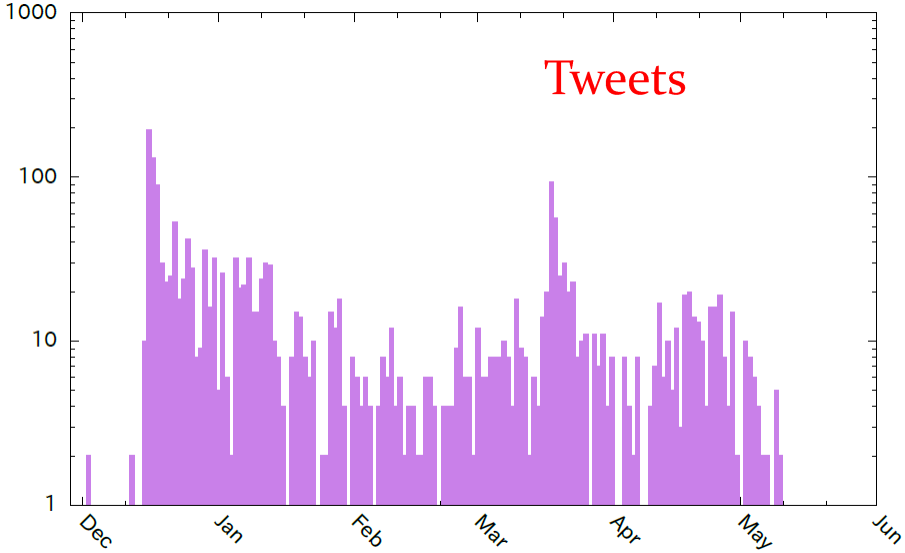
Example: Bound state model for $F(750)$

Digamma (750) fever



Theory papers



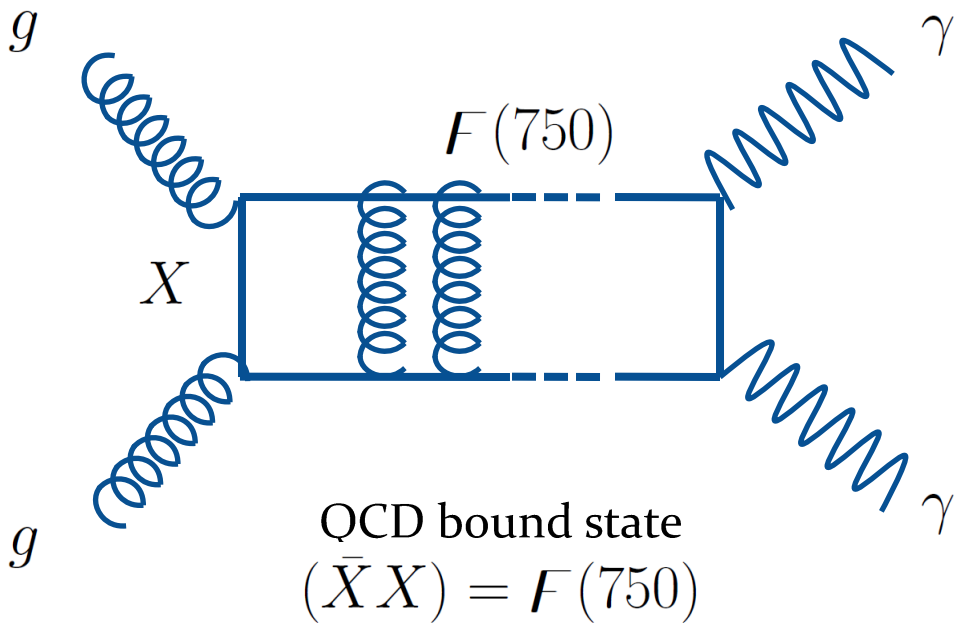


Diphoton Model with DM

Han, Ichikawa, Matsumoto, Nojiri, Takeuchi

X Colored, Y=4/3, 375 GeV

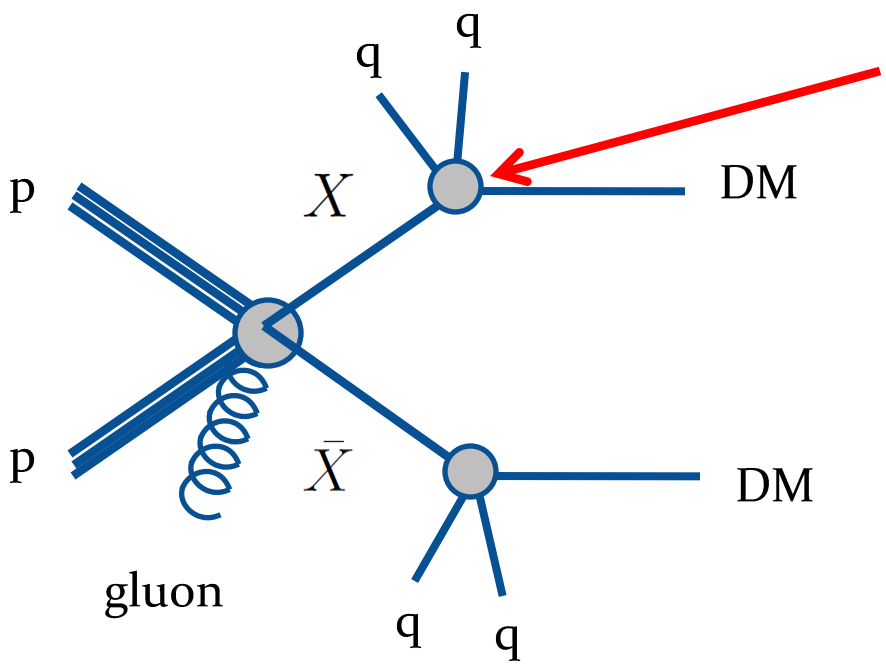
$\phi_{\rm DM}$ Singlet scalar or $\psi_{\rm DM}$ Singlet fermion



QCD bound state

$(\bar{X}X) = F(750)$

LHC Signals



$$\frac{1}{\Lambda^3}\phi_{\rm DM}(Xd)(du)$$

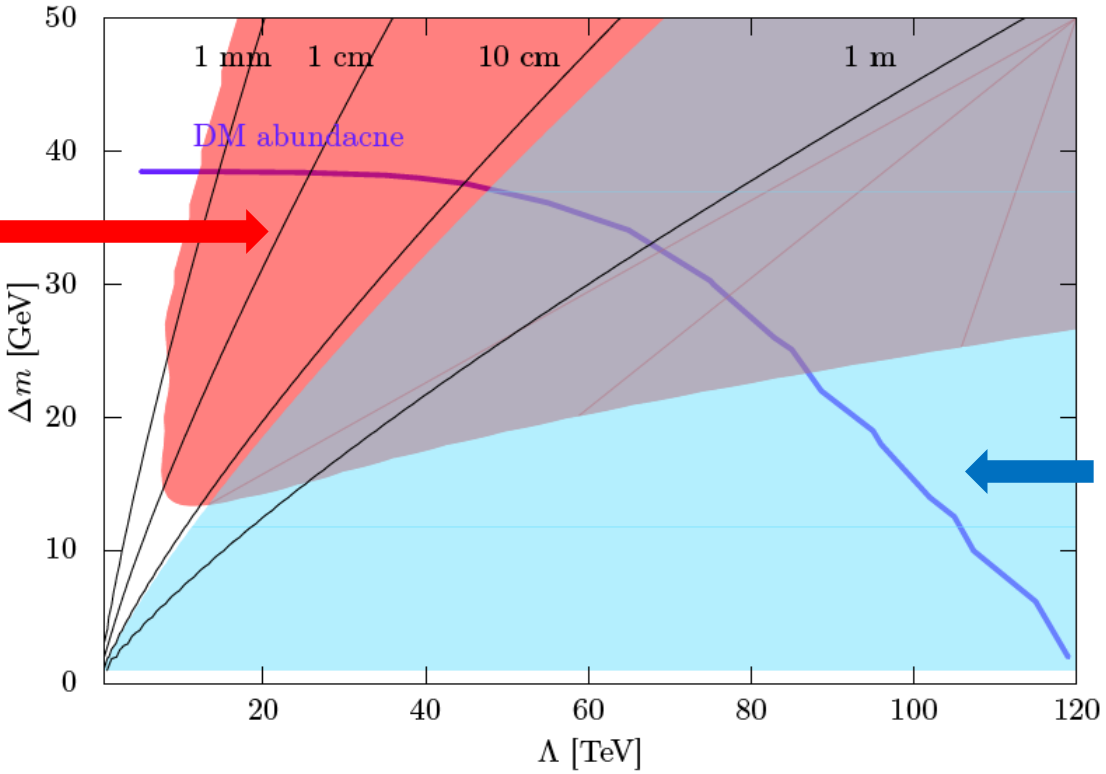
$$\frac{1}{\Lambda^2}(X\psi_{\rm DM})(uu)$$

Assumption: DM abundance solely comes from coannihilation with X

Fermion DM

$$\frac{1}{\Lambda^2}(X\psi_{\rm DM})(uu) \quad c\tau \sim 1\ \mathrm{m}\left(\frac{\Delta m}{50\ \mathrm{GeV}}\right)^{-5}\left(\frac{\Lambda}{100\ \mathrm{TeV}}\right)^{4}$$

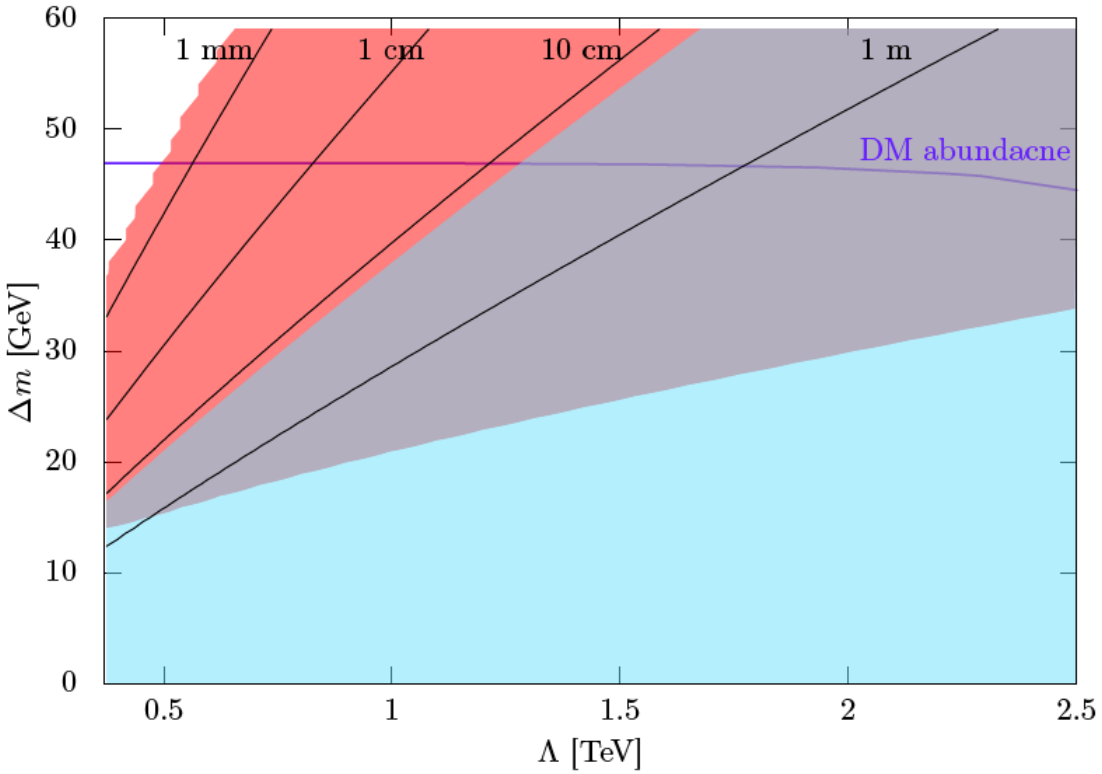
DV search



Charged track

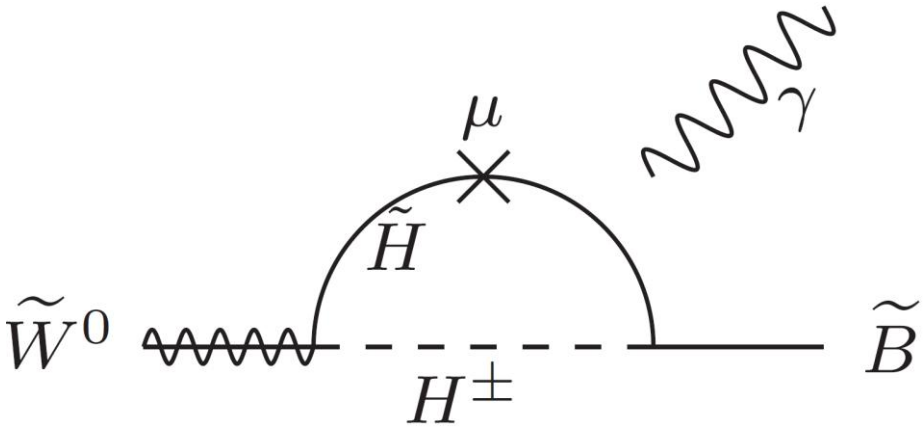
Scalar DM

$$\frac{1}{\Lambda^3}\phi_{\rm DM}(Xd)(du) \quad c\tau \sim 1\ {\rm cm}\left(\frac{\Delta m}{50\ {\rm GeV}}\right)^{-7}\left(\frac{\Lambda}{1\ {\rm TeV}}\right)^{6}$$

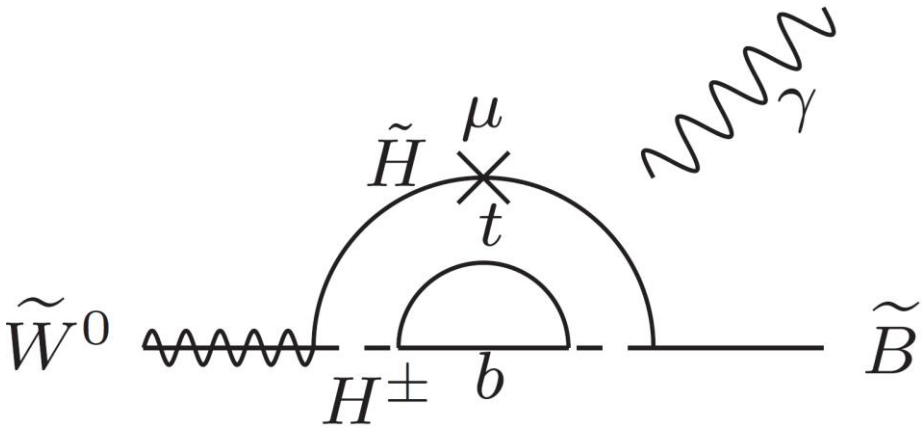


Radiative Wino Decay

Small contribution

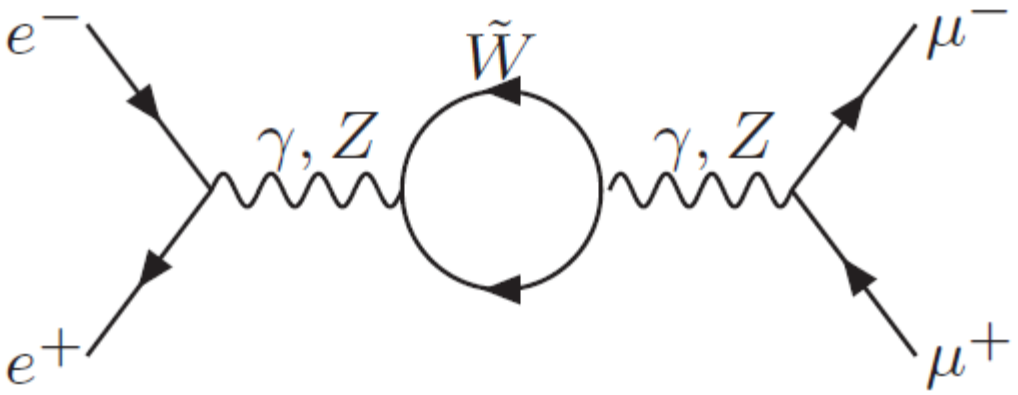


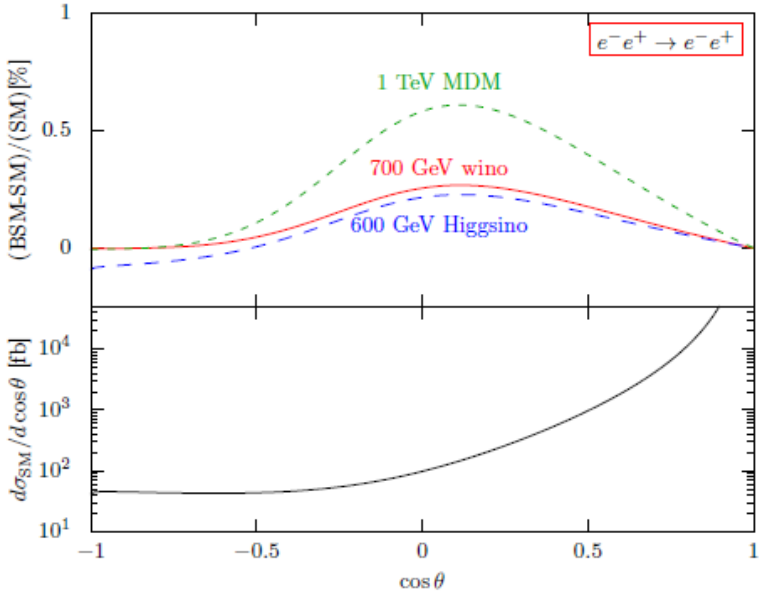
~~$\frac{\alpha}{4\pi}\mu^{-1}$~~ $\frac{\alpha}{4\pi}\mu^{-2}$



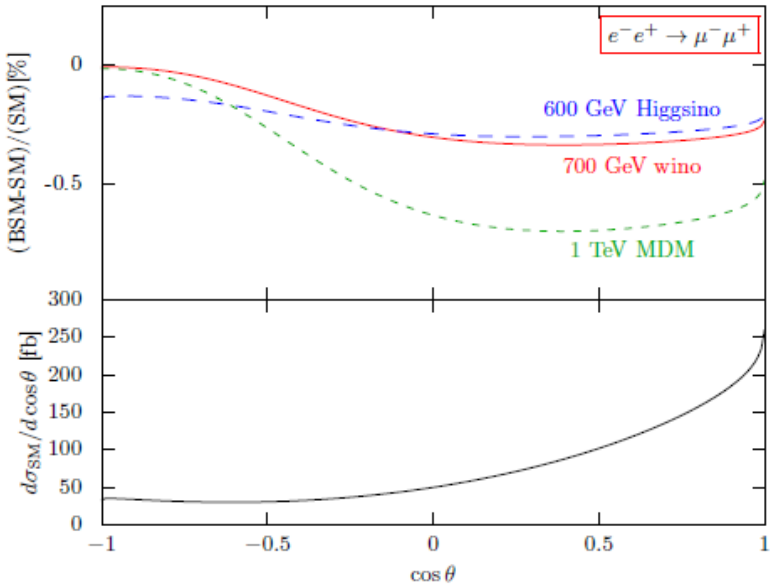
$\left(\frac{\alpha}{4\pi}\right)^2\mu^{-1}$

ILC





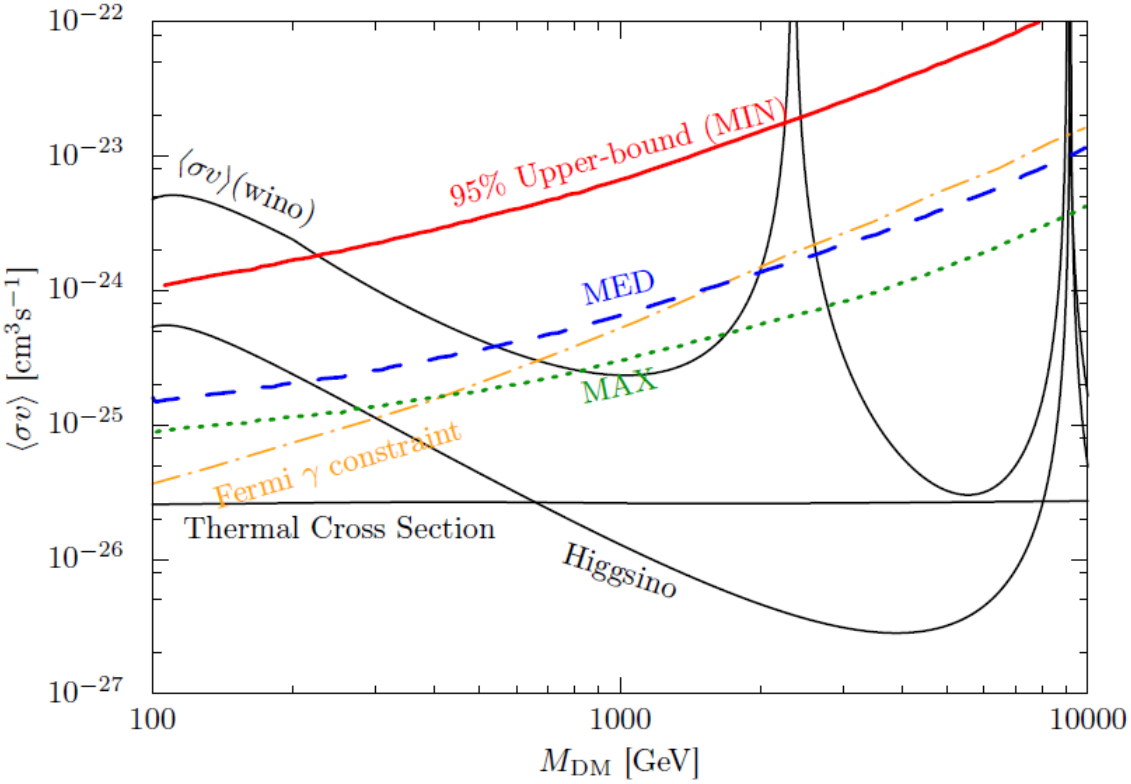
(a) $e^-e^+ \to e^-e^+$



(b) $e^-e^+ \to \mu^-\mu^+$

Wino DM: Cosmic Ray Signals

Gamma-ray and antiproton constraints



M <700 GeV is constrained