Probing gaugino coannihilation with displaced vertex searches

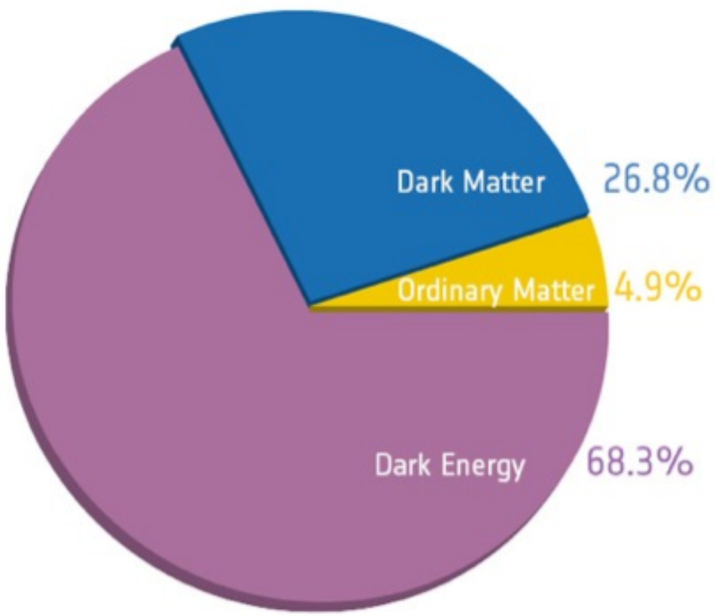
Natsumi Nagata
Univ. of Minnesota

Dark Side of the Universe 2015
Dec. 17, 2015
YITP, Kyoto University

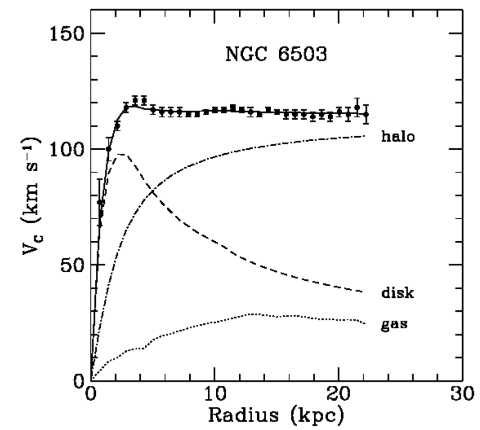
Based on N. Nagata, H. Otono, and S. Shirai JHEP **1510**, 086 (2015) [arXiv:1506.08206];
Phys. Lett. **B748**, 24 (2015) [arXiv:1504.00504].

Dark Matter (DM)

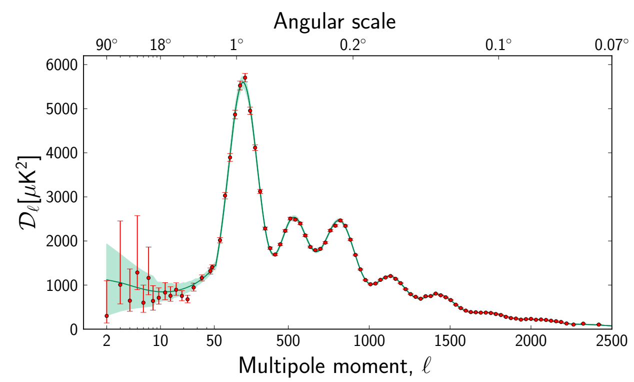
Evidences for DM



Planck (2013)



Begeman et. al. (1991)



Clowe et. al. (2006)

Weakly-Interacting Massive Particles (WIMPs)

- have masses roughly between 10 GeV and a few TeV.
- interact only through weak and gravitational interactions.
- explain the observed DM density with their thermal relic.
- appear in models beyond the Standard Model.

Supersymmetry (SUSY)

SUSY offers a WIMP DM candidate.

(with R-parity conservation)

➡ Neutralino

Mixed state of bino, wino and Higgsino.

Current constraints on SUSY

- Null results for SUSY searches
- 125 GeV Higgs mass

➡ SUSY scale may be much higher than the EW scale.

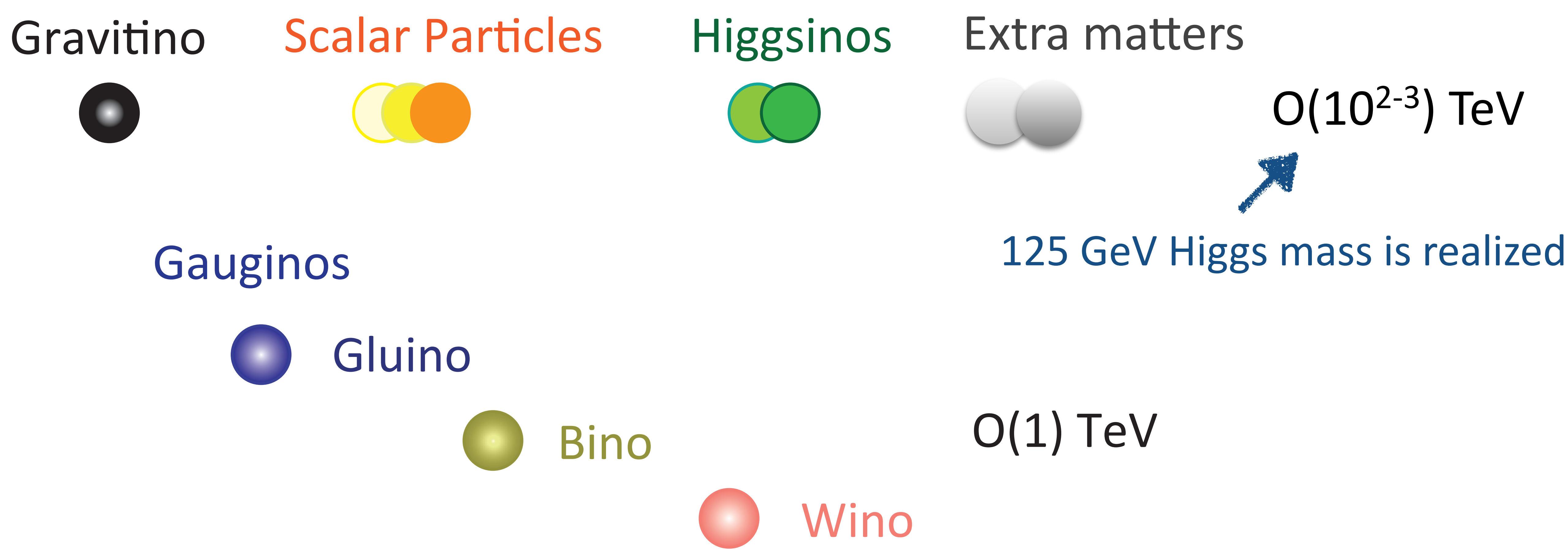
Neutralino DM is still promising?

Can we probe the neutralino DM??

High-scale SUSY

L. J. Hall, Y. Nomura, S. Shirai (2012)
M. Ibe, S. Matsumoto, T. T. Yanagida (2012)
A. Arvanitaki, N. Craig, S. Dimopoulos, G. Villadoro (2012)
N. Arkani-Hamed, A. Gupta, D. E. Kaplan, N. Weiner, and T. Zorawski (2012)

If the Kahler potential has a generic form and there is no singlet field in the SUSY breaking sector;



Gaugino masses are induced at loop level.

- Anomaly mediation

L. Randall and R. Sundrum (1998)
G. F. Giudice, M. A. Luty, H. Murayama, and R. Rattazzi (1998)

- Threshold corrections (Higgsinos, extra matters, ...)

DM in High-scale SUSY

This scenario accommodates neutralino DM.

- Wino DM
  - Thermal relic of 3 TeV wino accounts for the DM density.

J. Hisano, S. Matsumoto, M. Nagai, O. Saito, M. Senami (2006)

- Bino DM

In general, its thermal relic abundance is too large.

➡ Coannihilation!

In our setup, there are two possibilities:

- Bino-gluino coannihilation

S. Profumo, C. Yaguna (2004), D. Feldman, Z. Liu, P. Nath (2009), A. De Simone, G. F. Giudice, A. Strumia, K. Harigaya, K. Kaneta, S. Matsumoto (2014), J. Ellis, F. Luo, K. A. Olive (2015)

- Bino-wino coannihilation

H. Baer, T. Krupovnickas, A. Mustafayev, E. K. Park, S. Profumo et. al. (2005), M. Ibe, A. Kamada, S. Matsumoto (2013), K. Harigaya, K. Kaneta, S. Matsumoto (2014)

Today's topic

These scenarios require the lightest and the next-to-lightest particles to be degenerate in mass.

- Hard to probe with traditional LHC searches.

  (Decay products are too soft.)

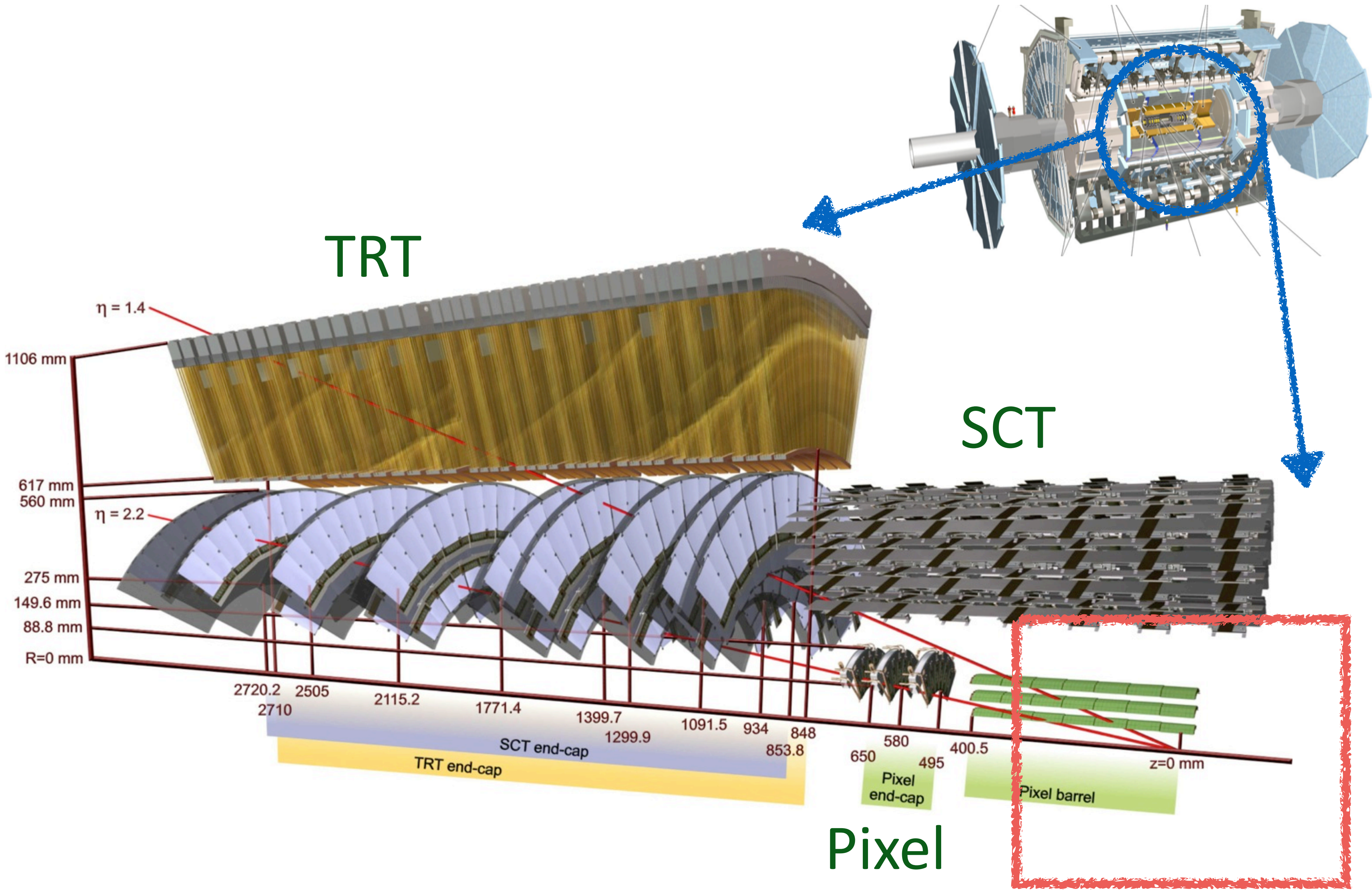
- Hard to probe with other DM searches.

  (Interactions are too weak.)

- In both scenarios, the next-to-lightest particle becomes long-lived.

- Displaced vertex (DV) searches can probe the scenario.

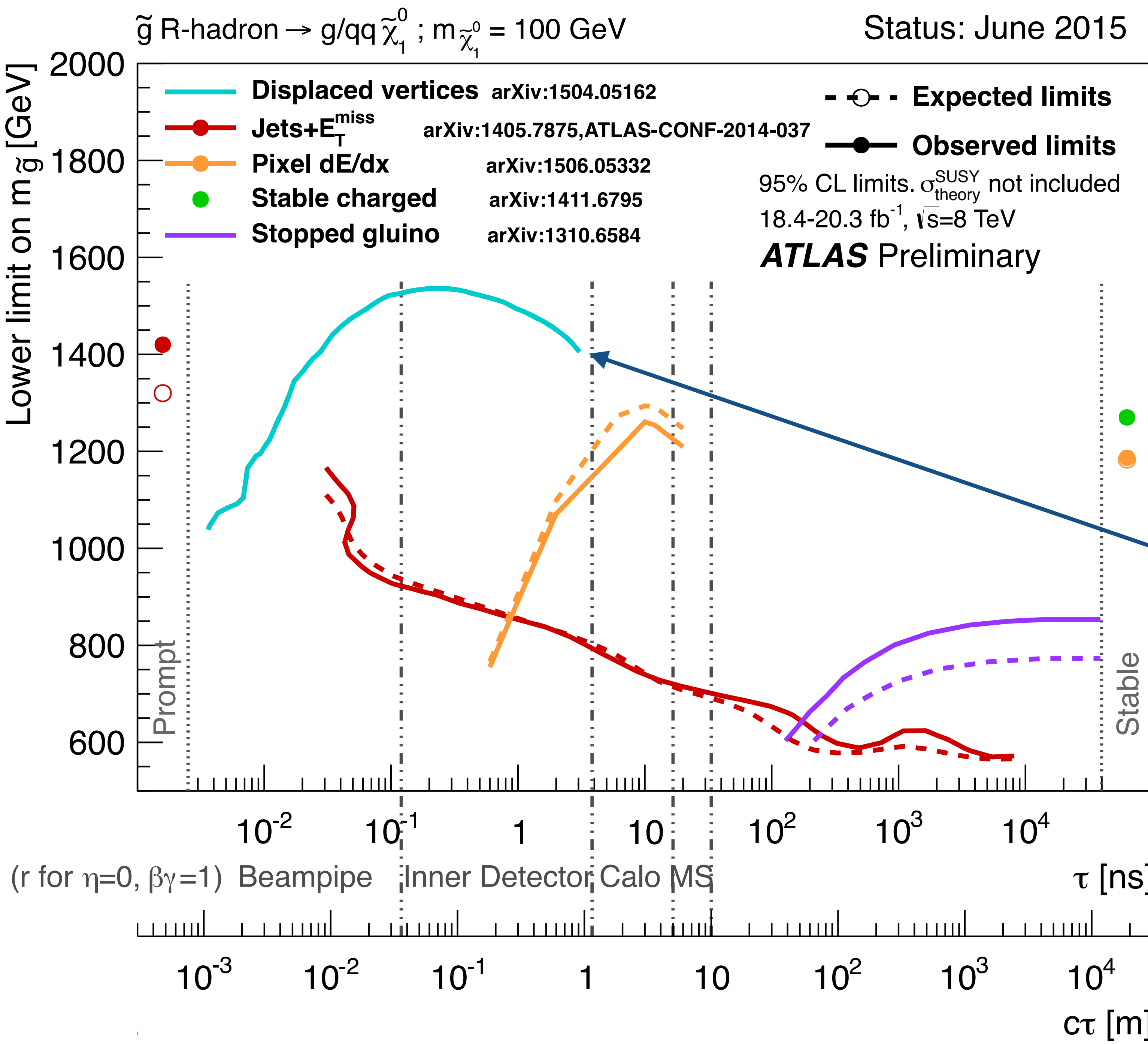
ATLAS Inner detector

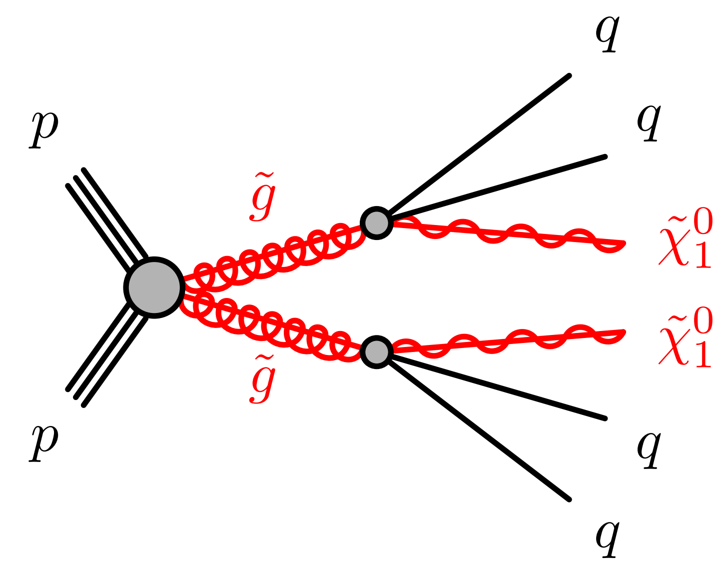


ATLAS has searched for DVs in the region of |z|<30 cm and r < 30 cm.

Sensitive to $1\ \mathrm{mm} \lesssim c\tau \lesssim 1\ \mathrm{m}$.

ATLAS DV + MET search





Strong limit from the DV search.

★ No SM background.

We will reinterpret this result, considering the small mass difference required by the coannihilation scenarios.

ATLAS, Phys. Rev. **D92**, 072004 (2015) [arXiv: 1504.05162]

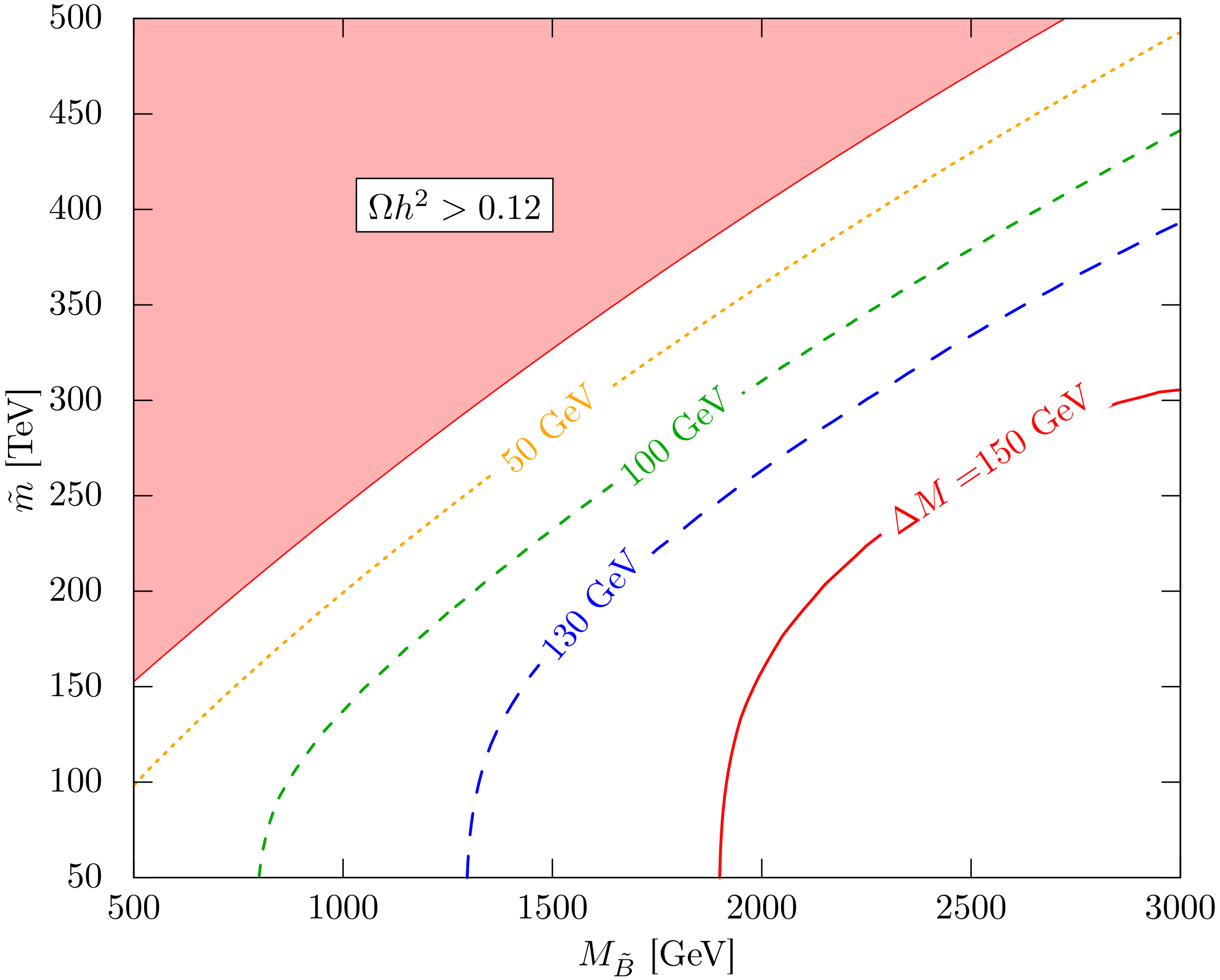
Our strategy

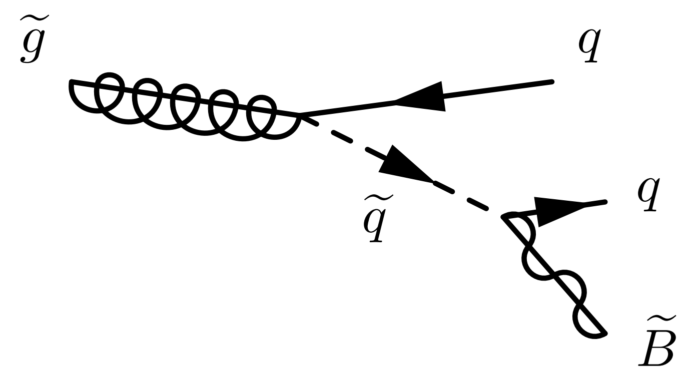
To take into account the small mass difference,

- Simulate the reduction of trigger efficiencies using public codes.
- Reconstruction efficiency of DVs is estimated from the plots in the ATLAS paper and our ignorance is shown as theoretical uncertainty.

Bino-gluino coannihilation

Contour for mass difference Δm which achieves $\Omega h^2 = 0.12$.





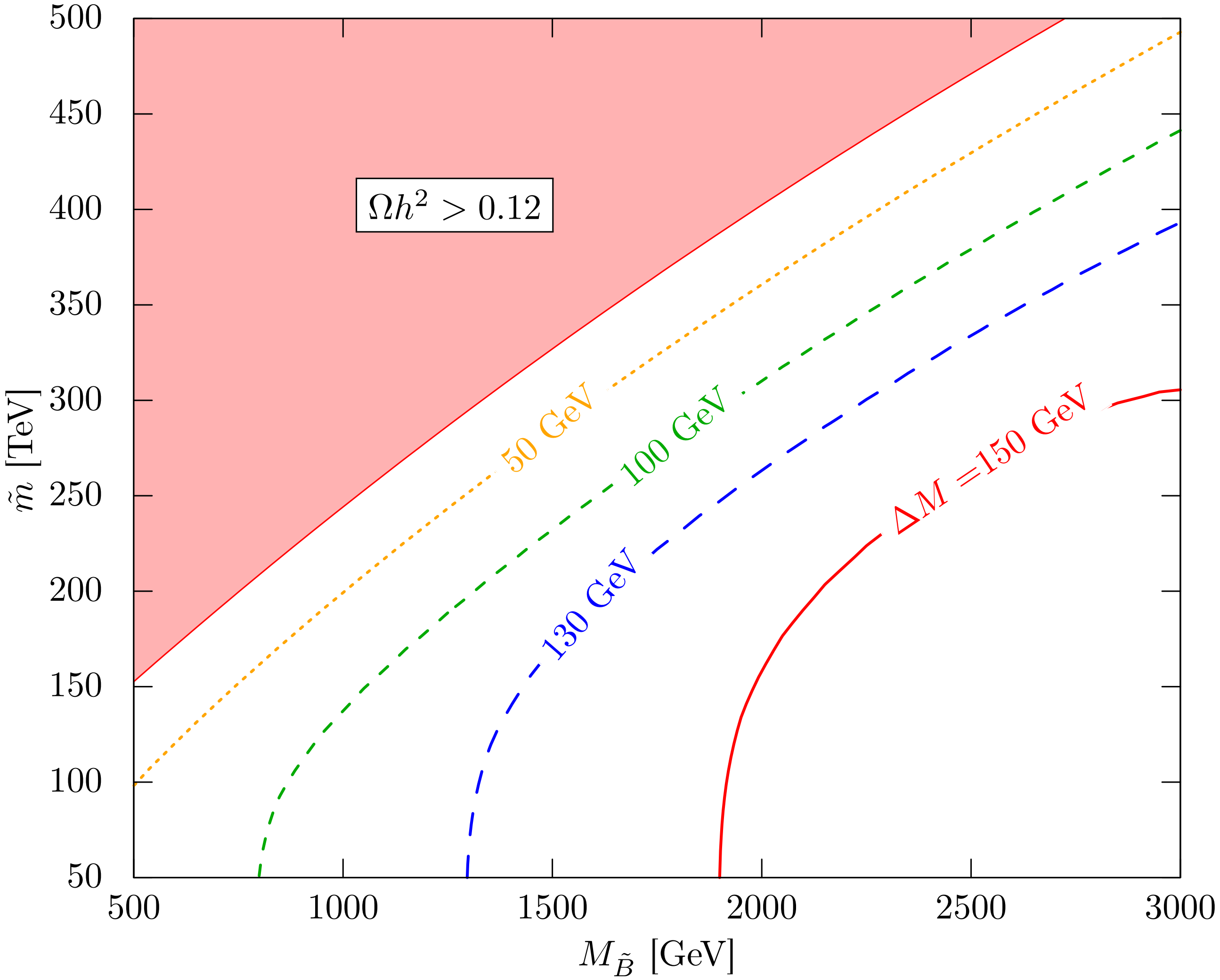
$$c\tau_{\tilde{g}} \simeq \left(\frac{\Delta M}{100\ \mathrm{GeV}}\right)^{-5} \left(\frac{\tilde{m}}{100\ \mathrm{TeV}}\right)^{4} \ \mathrm{cm}$$

Δm ~ 100 GeV yields the correct DM abundance.

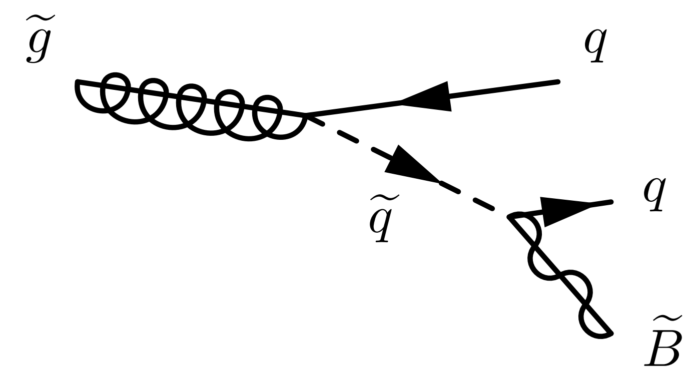
➡ We expect $c\tau_{\tilde{g}} > \mathcal{O}(1)\ \mathrm{mm}$

Bino-gluino coannihilation

Contour for mass difference Δm which achieves $\Omega h^2 = 0.12$.



★ Feng Luo's talk!

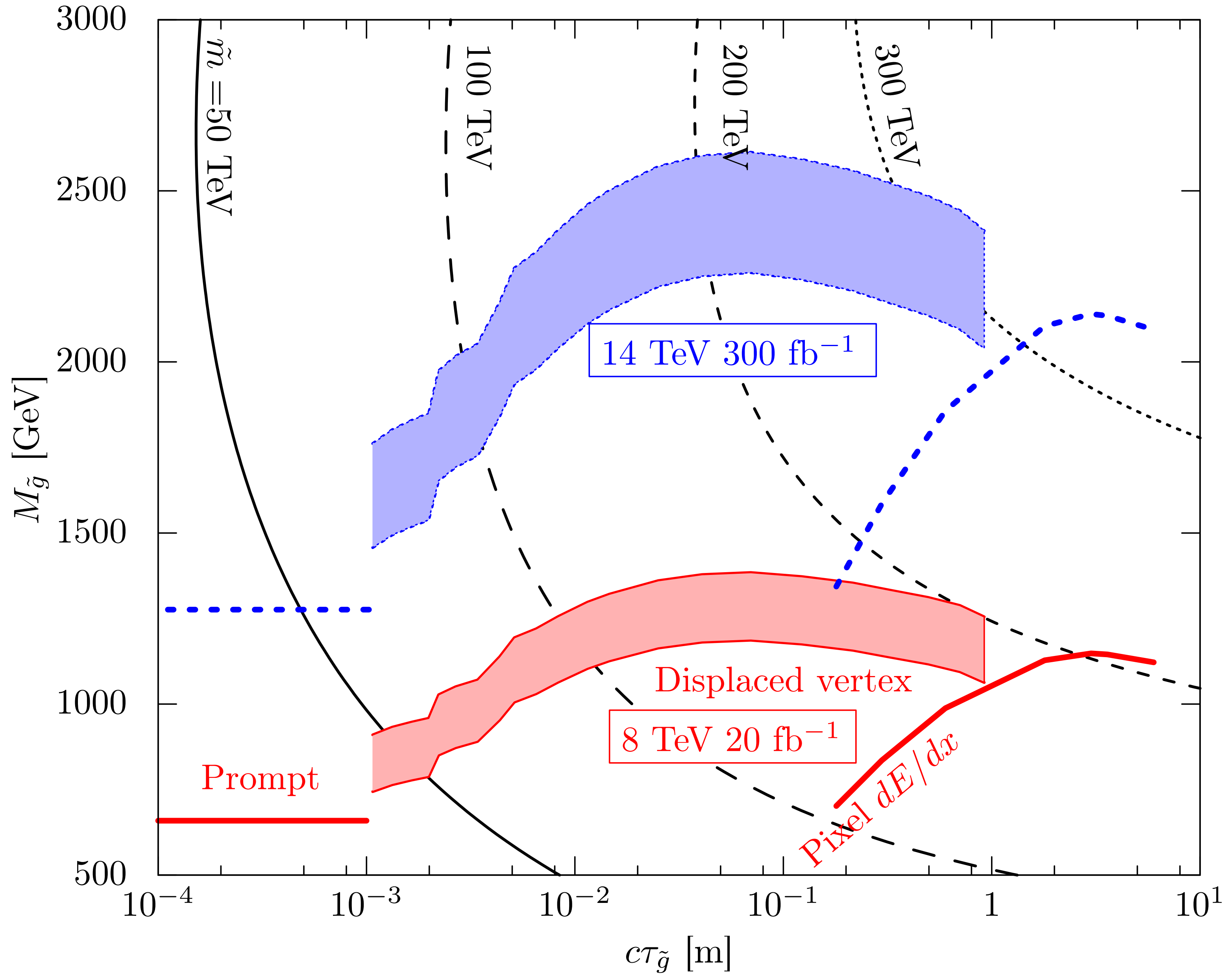


$$c\tau_{\tilde{g}} \simeq \left(\frac{\Delta M}{100\ \mathrm{GeV}}\right)^{-5} \left(\frac{\tilde{m}}{100\ \mathrm{TeV}}\right)^{4}\ \mathrm{cm}$$

Δm ~ 100 GeV yields the correct DM abundance.

➡ We expect $c\tau_{\tilde{g}} > \mathcal{O}(1)\ \mathrm{mm}$

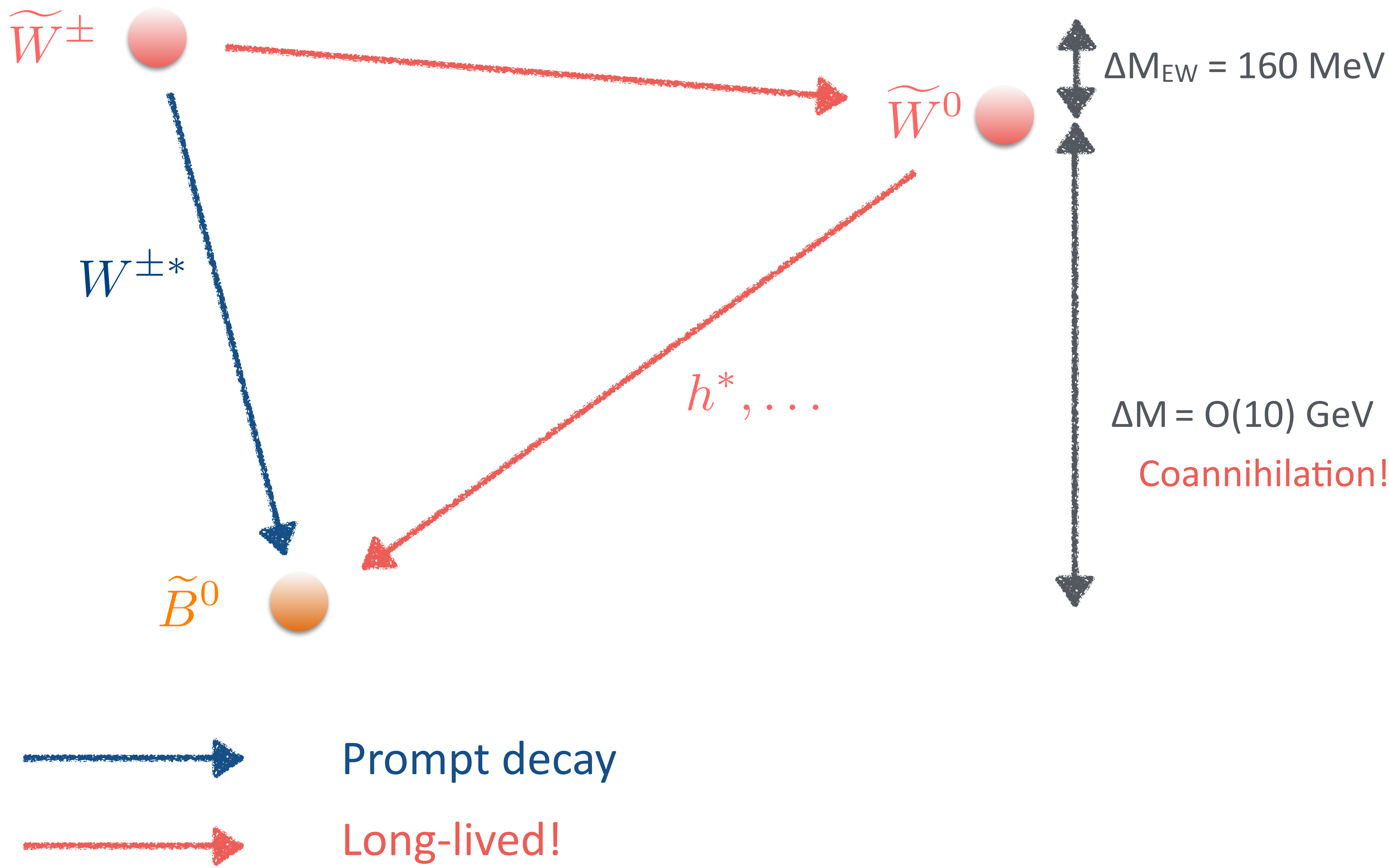
Prospects for the long-lived gluino search



The sensitivity is better than the existing searches based on jets plus missing energy.

N. Nagata, H. Otono, S. Shirai, Phys. Lett. **B748**, 24 (2015) [arXiv: 1504.00504]

Mass spectrum and decay chains

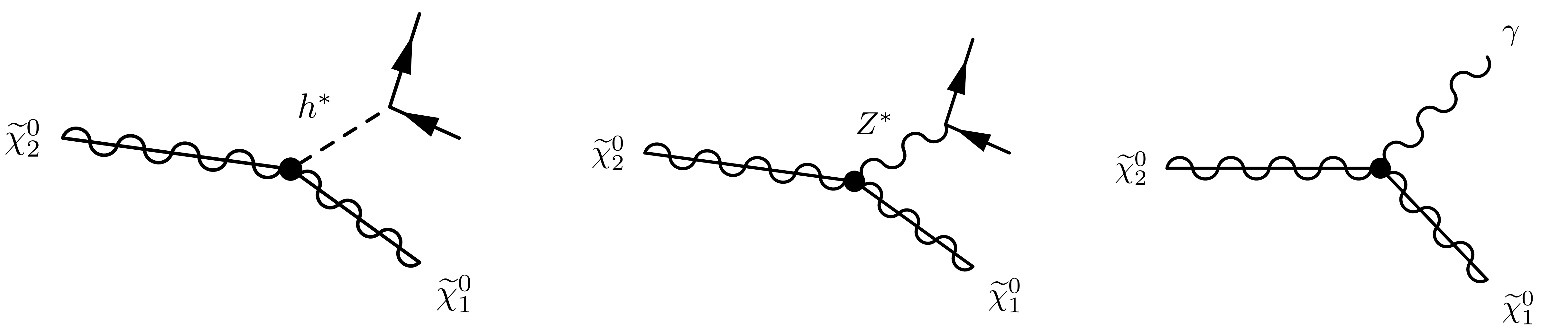


Neutral wino decay

A neutral wino can decay into the bino LSP via Higgsino mixing.

➡ The decay rate is suppressed for a large Higgsino mass.

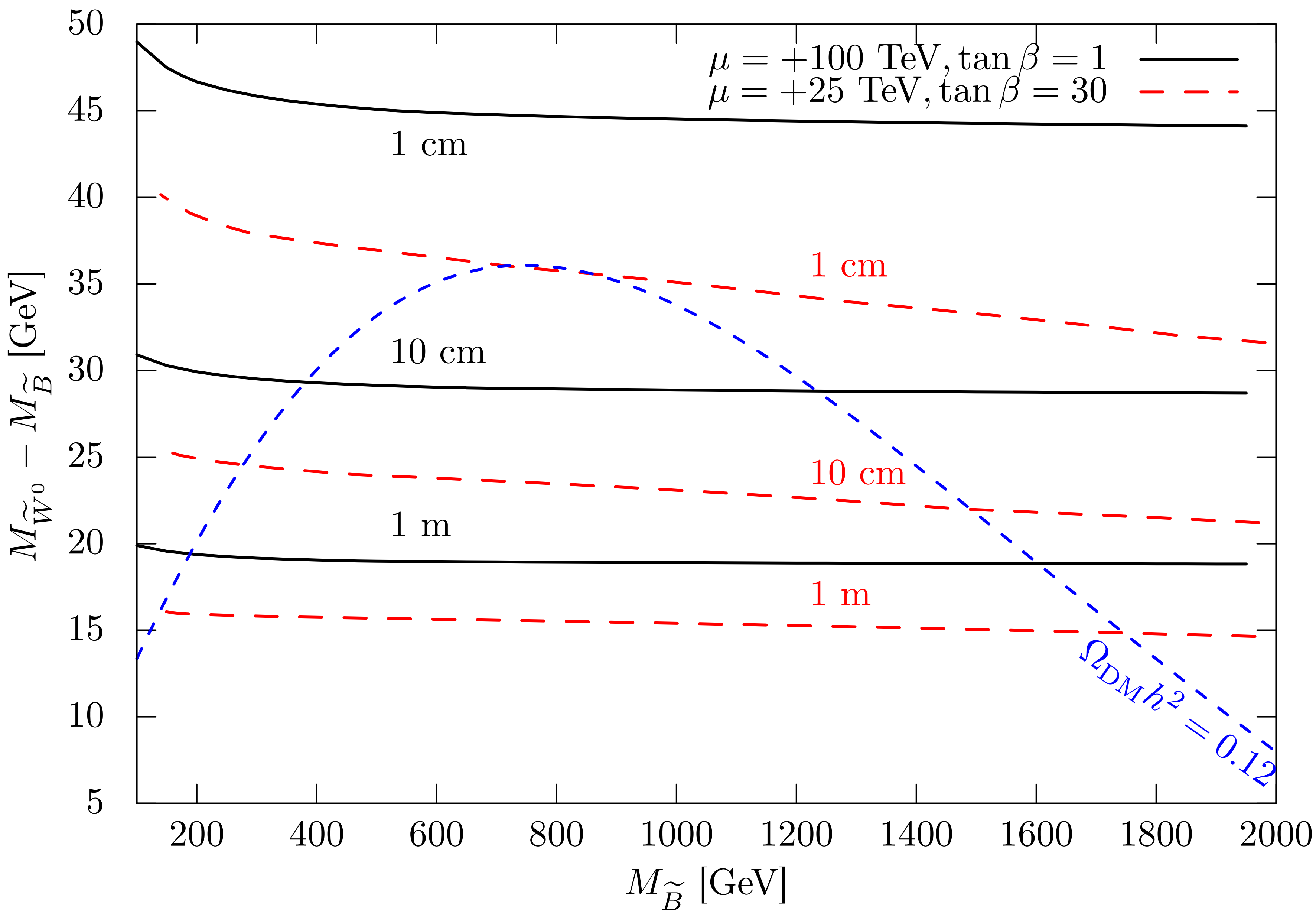
Dominant diagram | Sub-dominant diagrams



$$\propto y_f \sin(2\beta)\frac{m_W}{\mu} \qquad \propto \cos(2\beta)\frac{m_Z^2}{|\mu|^2} \qquad \propto \cos(2\beta)\frac{M_{\widetilde{\chi}^0}}{16\pi^2|\mu|^2}$$

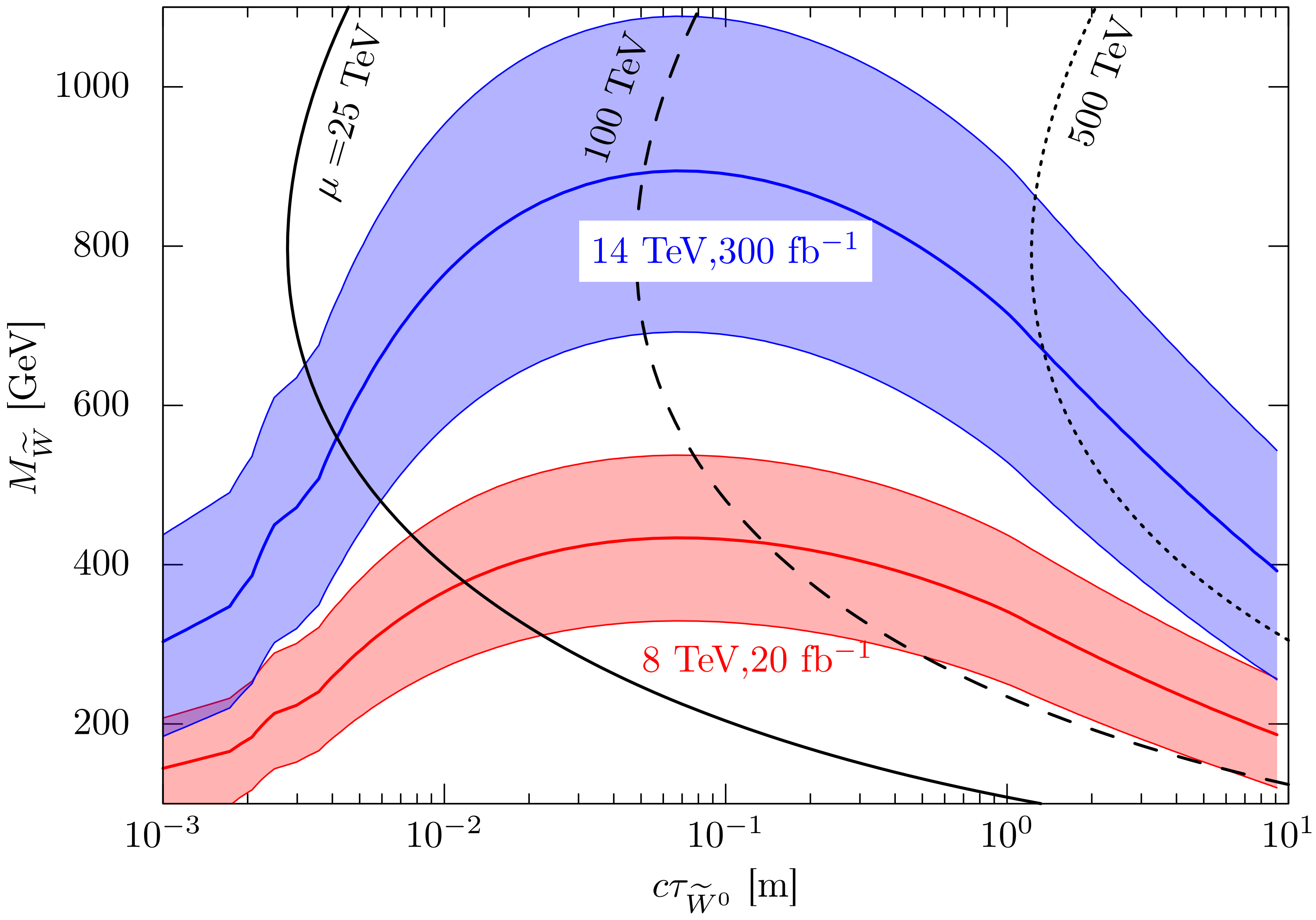
When Higgsino mass is quite large, the neutral wino $\widetilde{W}^0$ becomes long-lived.

Decay length of neutral wino



Neutral wino has a decay length of > 1 cm over parameter region motivated by coannihilation.

Prospects for the long-lived wino search



ΔM = 30 GeV

tanβ = 2

400 GeV (800 GeV) wino can be probed at 8 (14) TeV LHC.

N. Nagata, H. Otono, S. Shirai, JHEP **1510**, 086 (2015) [arXiv: 1506.08206]

Conclusion

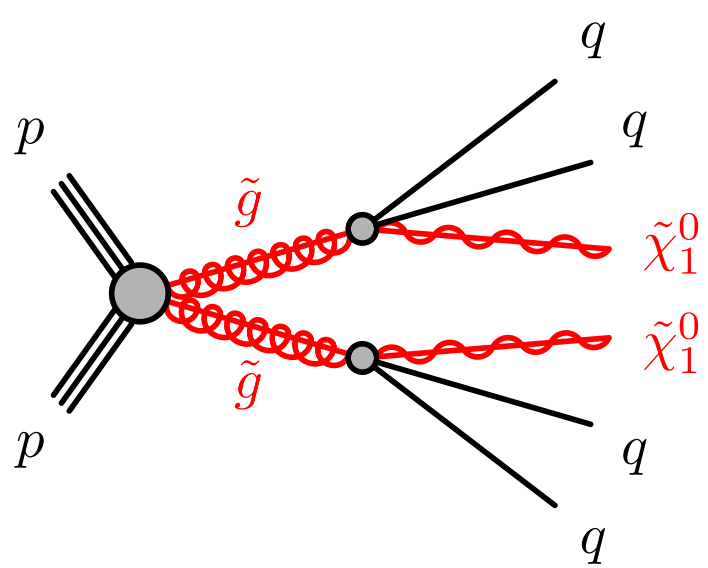
- We discuss bino DM in the high-scale SUSY scenario.
- The observed DM density is accounted for by the bino DM if gluino/wino is degenerate with the DM in mass.
- The displaced vertex searches at the LHC are quite promising for probing these scenarios.
- For the bino-gluino coannihilation, the 14 TeV LHC can reach a gluino mass of ~ 2 TeV.
- In the case of the bino-wino coannihilation, the expected reach for the wino mass is ~ 800 GeV.

Backup

ATLAS long-lived gluino search

DV + missing transverse energy E_T^{miss}

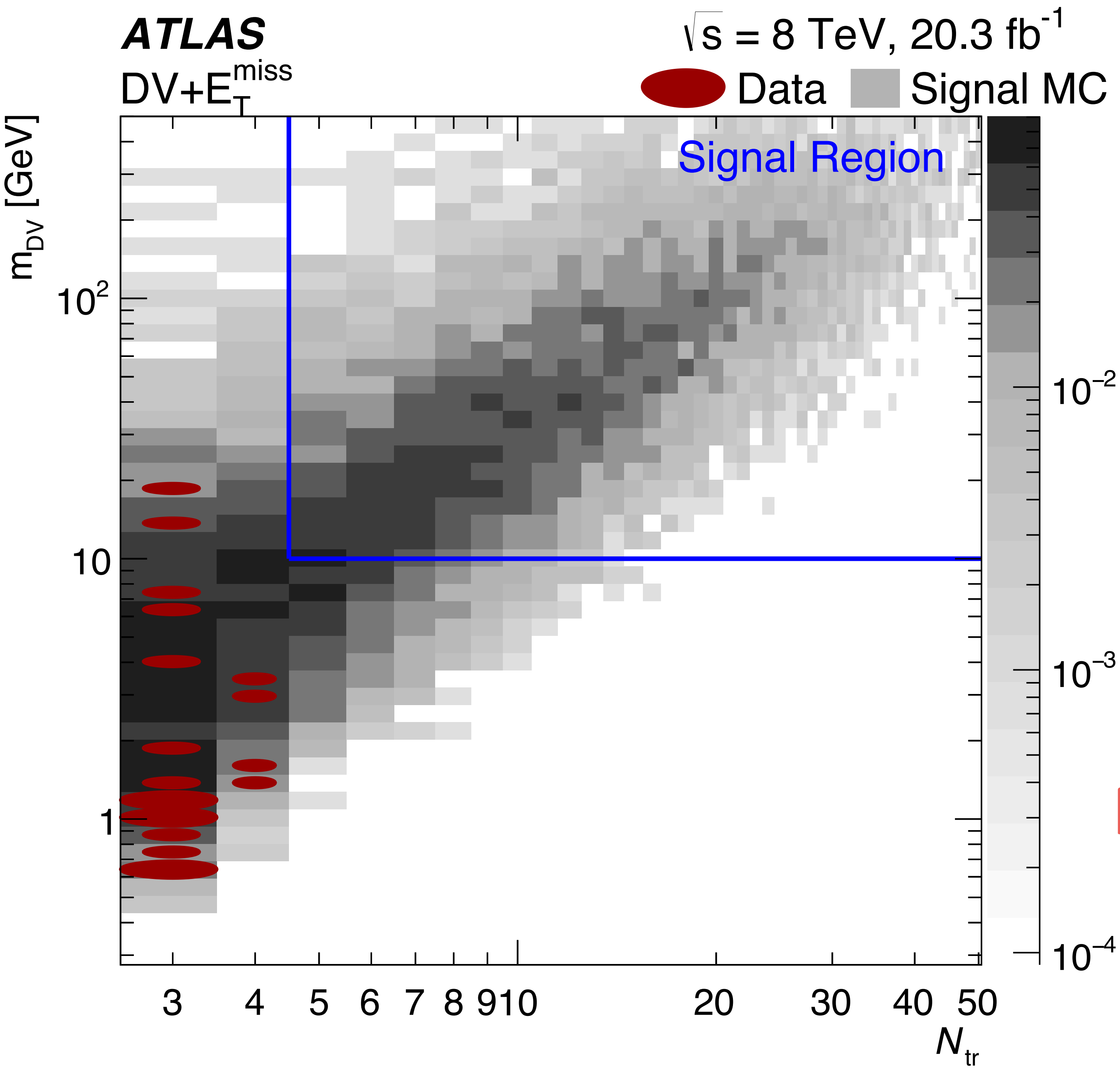
- Displaced vertex
  - should be accompanied with more than four tracks
  - invariant mass should be more than 10 GeV
  - Two jets with $p_T > 50$ GeV.
- Missing transverse energy
  - $E_T^{miss} > 180$ GeV



ATLAS [arXiv: 1504.05162]

ATLAS long-lived gluino search

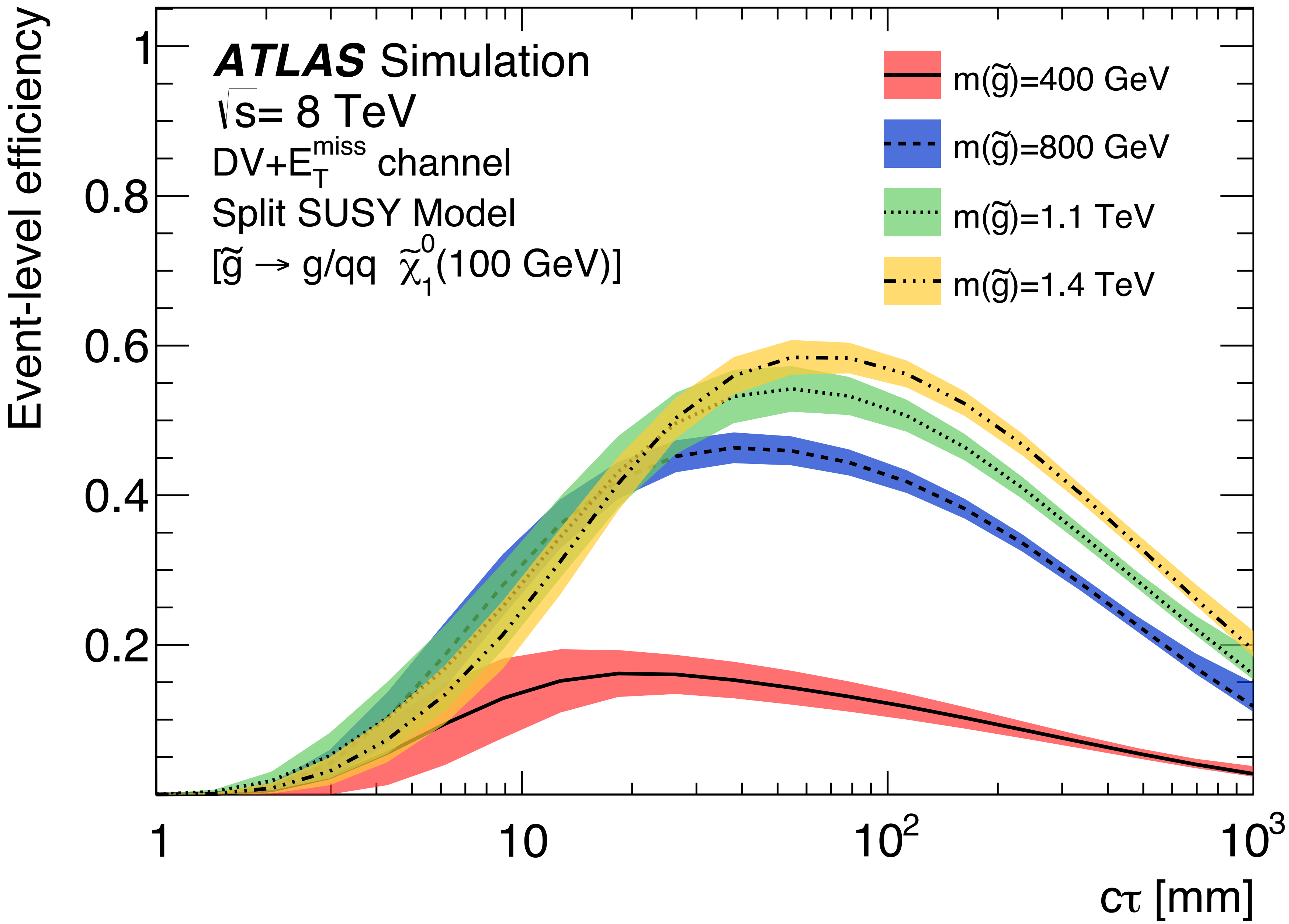
DV + missing transverse energy E_T^{miss}

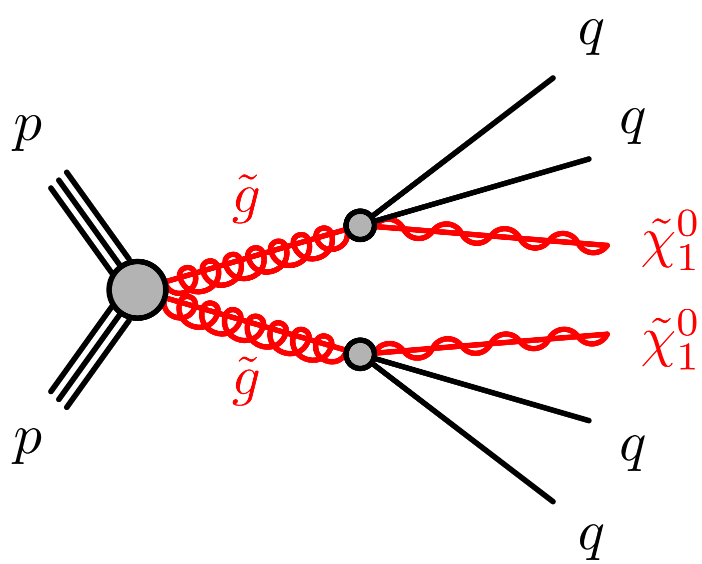


No signal has been observed!

ATLAS [arXiv: 1504.05162]

Event-level efficiency for DV + MET





ATLAS [arXiv: 1504.05162]

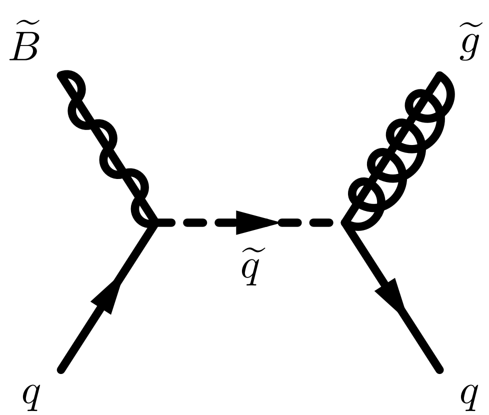
Bino-gluino coannihilation

- Bino self-annihilation
- Bino-gluino annihilation
- Gluino self-annihilation

→ Very small cross section

→ Large cross section (due to strong coupling)

For bino-gluino coannihilation to work effectively, chemical equilibrium between bino and gluino is required.

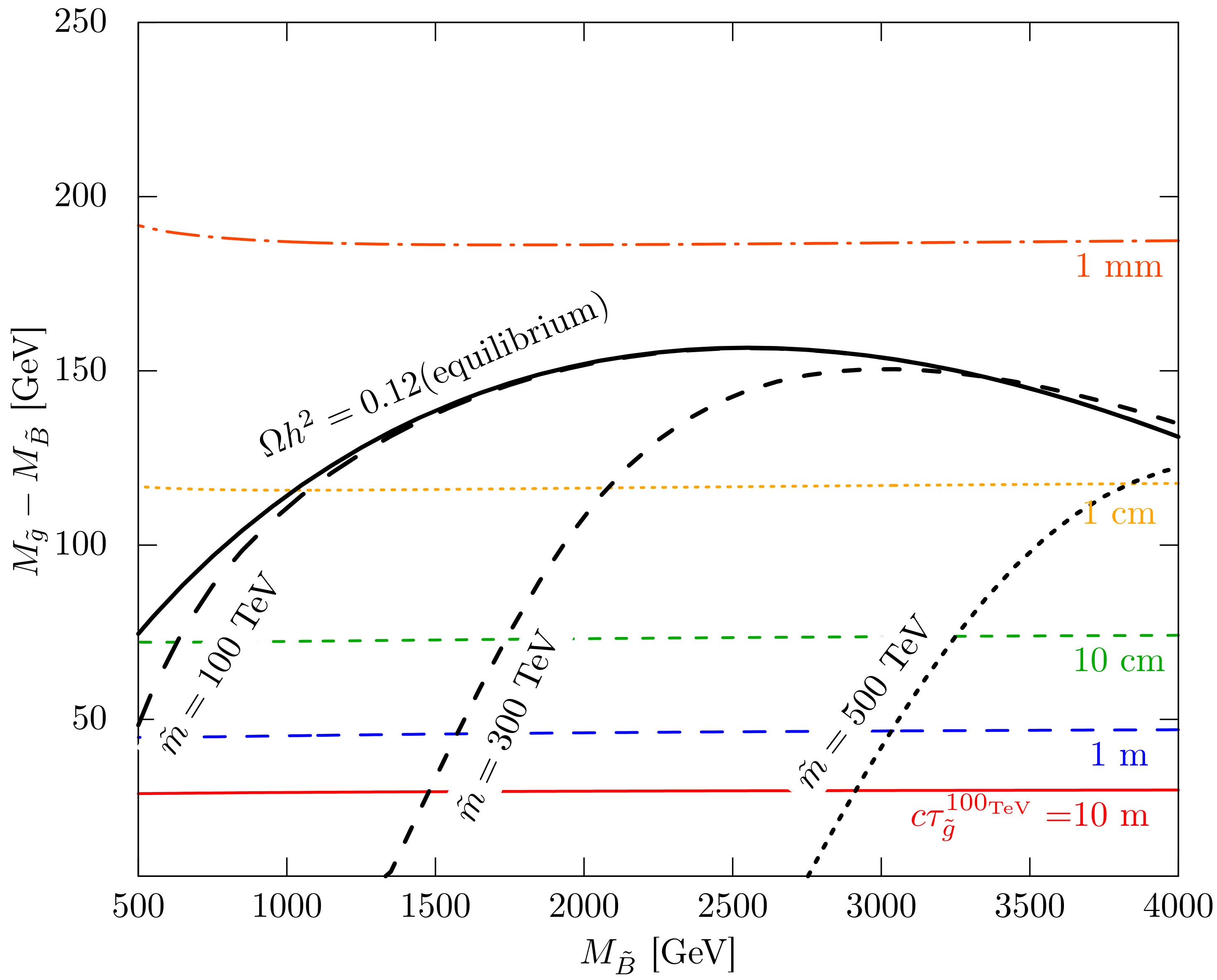


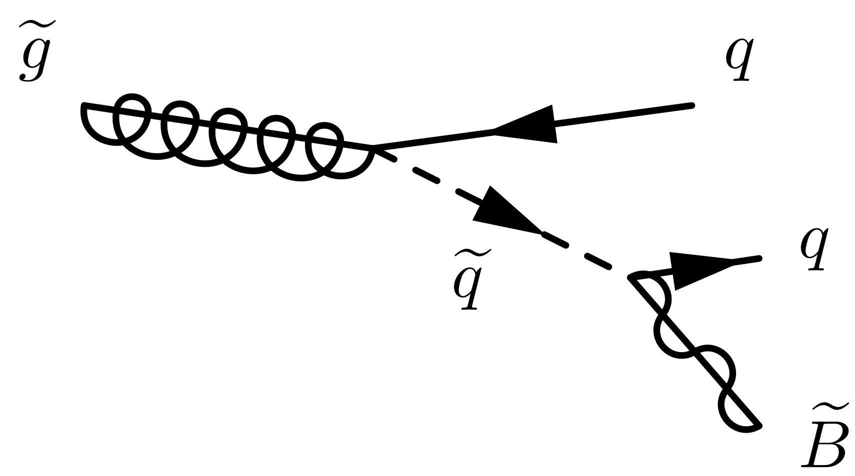
→ The transition rate between them should be much larger than the Hubble rate.

$$\Gamma(\widetilde{B}q \to \widetilde{g}q) \sim T^3 \cdot \frac{T^2}{\widetilde{m}^4} \gg H \sim \frac{T^2}{M_{\rm Pl}} \qquad \text{for} \quad T \gtrsim M_{\widetilde{B}}/20$$

This condition gives an upper bound on the sfermion mass scale $\widetilde{m}$

Gluino decay length





$$c\tau_{\widetilde{g}} \simeq \left(\frac{\Delta M}{100\ \text{GeV}}\right)^{-5}\left(\frac{\widetilde{m}}{100\ \text{TeV}}\right)^{4}\ \text{cm}$$

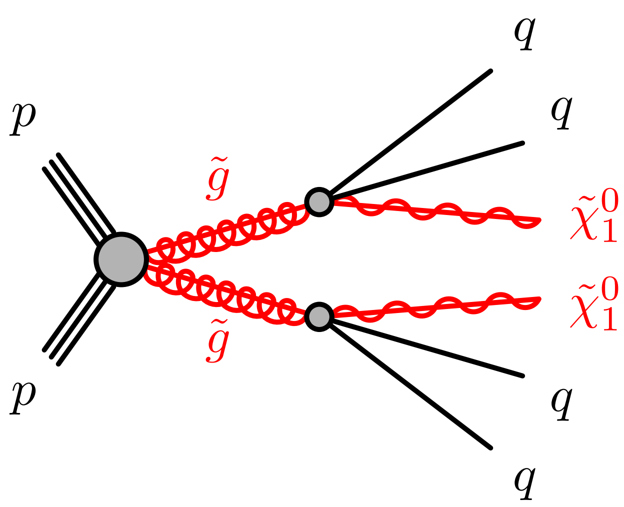
We expect $c\tau_{\widetilde{g}} > \mathcal{O}(1)$ mm

Re-interpretation of the ATLAS result

We reinterpret the ATLAS DV + MET search result considering the small bino-gluino mass difference in our scenario.

- 8 TeV LHC with 20 fb^{-1}
  - $E_{\rm T}^{\rm miss} > 100\ {\rm GeV}$
  - Trigger efficiency is simulated to be 40%.
- 14 TeV LHC with 300 fb^{-1}
  - $E_{\rm T}^{\rm miss} > 200\ {\rm GeV}$
  - Trigger efficiency is simulated to be 15%.

HERWIG 6
ACERDET



Re-interpretation of the ATLAS result

We reinterpret the ATLAS DV + MET search result to optimize it for the bino-wino coannihilation scenario.

- 8 TeV LHC with 20 fb^{-1}
  - $E_T^{\rm miss} > 100~{\rm GeV}$
  - Acceptance rate is simulated to be 3%.
- 14 TeV LHC with 300 fb^{-1}
  - $E_T^{\rm miss} > 200~{\rm GeV}$
  - Acceptance rate is simulated to be 1%.

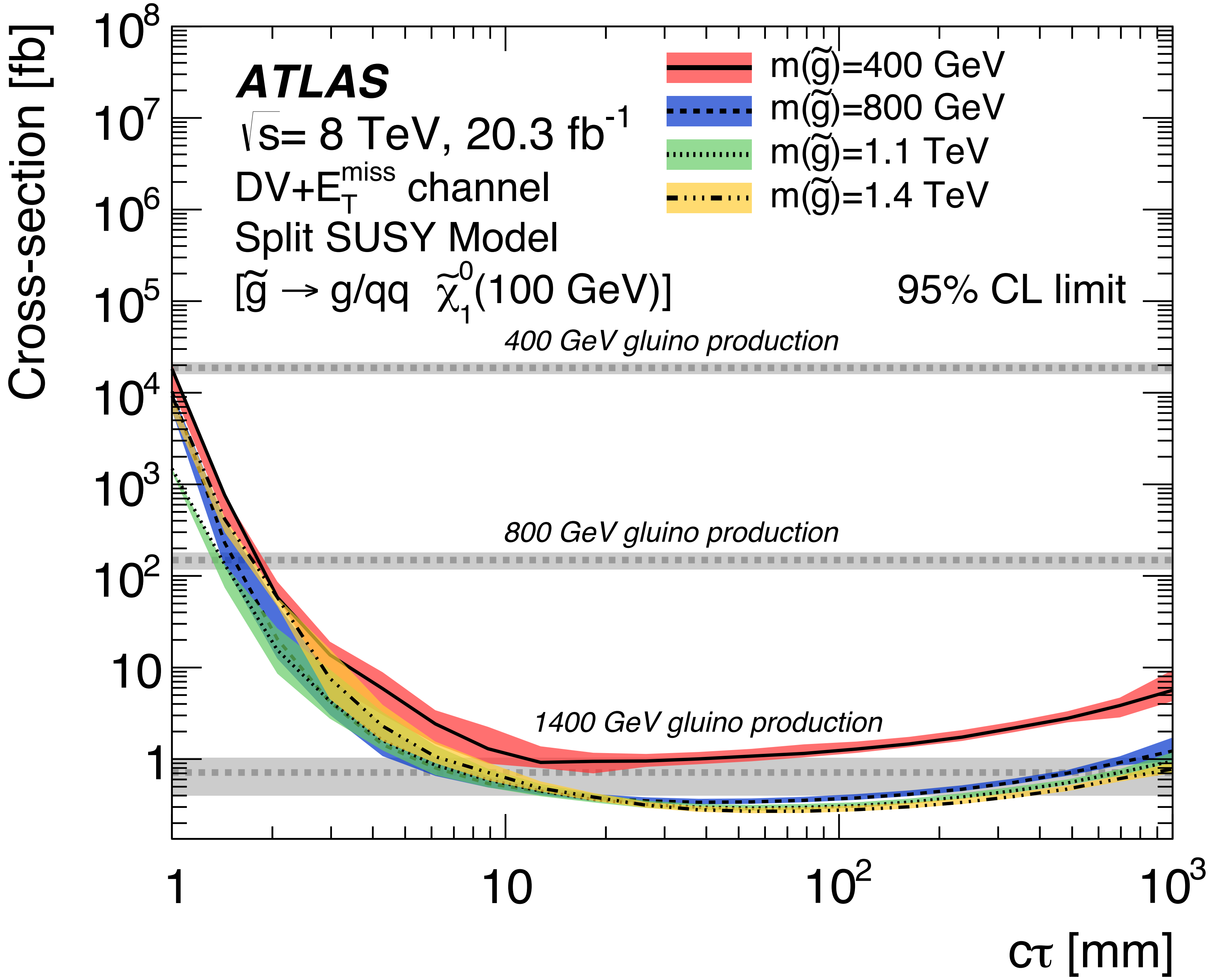
MADGRAPH5
PYTHIA6
DELPHES3
PROSPINO2

$$M_{\widetilde{W}} = 400~{\rm GeV}$$
$$M_{\widetilde{B}} = 370~{\rm GeV}$$

★ We have dropped the P_T condition for DVs.

★ MET comes from the back reaction of ISR.

ATLAS long-lived gluino search



ATLAS [arXiv: 1504.05162]

Full theory

Gaugino-Higgsino-Higgs interactions

$$\mathcal{L}_{\rm int} = -\frac{1}{\sqrt{2}}\{g_{1u} H^\dagger \widetilde{H}_u + g_{1d}\epsilon^{\alpha\beta}(H)_\alpha(\widetilde{H}_d)_\beta\}\widetilde{B}$$
$$-\sqrt{2}\{g_{2u} H^\dagger T^A \widetilde{H}_u - g_{2d}\epsilon^{\alpha\beta}(H)_\alpha(T^A\widetilde{H}_d)_\beta\}\widetilde{W}^A + {\rm h.c.}\ ,$$

with

$$g_{1u} = g'\sin\beta, \qquad g_{1d} = g'\cos\beta\ ,$$
$$g_{2u} = g\sin\beta, \qquad g_{2d} = g\cos\beta\ ,$$

Mass terms

$$\mathcal{L}_{\rm mass} = -\frac{M_1}{2}\widetilde{B}\widetilde{B} - \frac{M_2}{2}\widetilde{W}^A\widetilde{W}^A - \mu\ \epsilon^{\alpha\beta}(\widetilde{H}_u)_\alpha(\widetilde{H}_d)_\beta + {\rm h.c.}\ ,$$

Effective theory

Effective interactions

$$\Delta\mathcal{L}_{\rm int} = \sum_{i=1,2} C_i^{(5)}\mathcal{O}_i^{(5)} + \sum_{i=1,2} \widetilde{C}_i\mathcal{Q}_i + C^{(6)}\mathcal{O}^{(6)} + \text{h.c.}$$

Effective operators

$$\mathcal{O}_1^{(5)} = \widetilde{B}\widetilde{W}^A H^\dagger T^A H \ , \qquad \mathcal{O}^{(6)} = \widetilde{B}^\dagger\overline{\sigma}^\mu\widetilde{W}^A H^\dagger T^A i\overleftrightarrow{D}_\mu H \ ,$$

$$\mathcal{O}_2^{(5)} = \widetilde{B}\sigma^{\mu\nu}\widetilde{W}^A W^A_{\mu\nu} \ ,$$

$$\mathcal{Q}_1 = \frac{1}{2}\widetilde{B}\widetilde{B}|H|^2 \ ,$$

$$\mathcal{Q}_2 = \frac{1}{2}\widetilde{W}^A\widetilde{W}^A|H|^2 \ ,$$

Wilson coefficients

$$C_1^{(5)} = \frac{1}{\mu}(g_{1u}g_{2d} + g_{1d}g_{2u}) + \frac{1}{2|\mu|^2}[(g_{1u}^* g_{2u} + g_{1d}^* g_{2d})M_1 + (g_{1u}g_{2u}^* + g_{1d}g_{2d}^*)M_2] \ ,$$

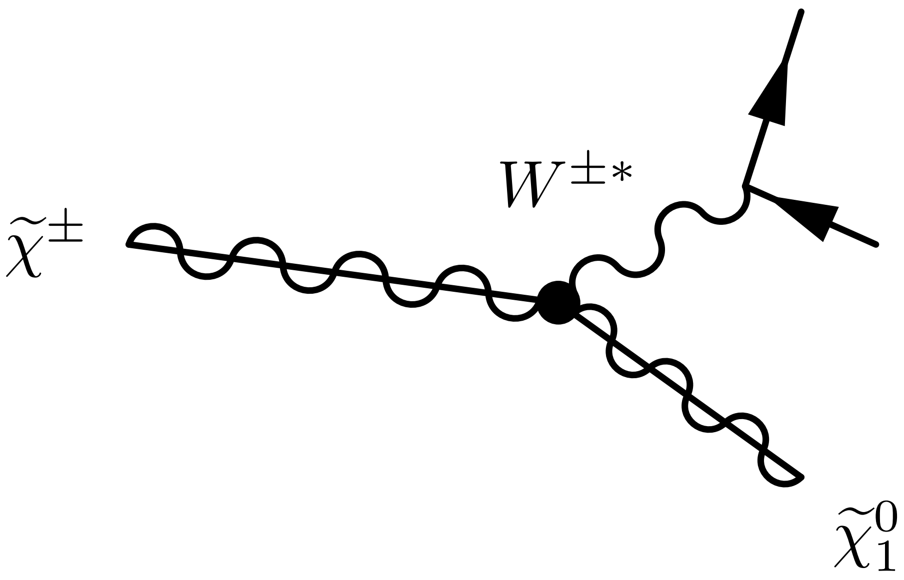
$$C^{(6)} = -\frac{1}{2|\mu|^2}(g_{1u}^* g_{2u} - g_{1d}^* g_{2d}) \ ,$$

$$\widetilde{C}_1 = \frac{g_{1u}g_{1d}}{\mu} + \frac{M_1}{2|\mu|^2}(|g_{1u}|^2 + |g_{1d}|^2) \ ,$$

$$\widetilde{C}_2 = \frac{g_{2u}g_{2d}}{\mu} + \frac{M_2}{2|\mu|^2}(|g_{2u}|^2 + |g_{2d}|^2) \ .$$

$$C_2^{(5)} = +\frac{g}{2(4\pi)^2\mu}(g_{1u}g_{2d} - g_{1d}g_{2u}) - \frac{g}{8(4\pi)^2}\left[(g_{1u}^* g_{2u} - g_{1d}^* g_{2d})\frac{M_1}{|\mu|^2} - (g_{1u}g_{2u}^* - g_{1d}g_{2d}^*)\frac{M_2}{|\mu|^2}\right] \ ,$$

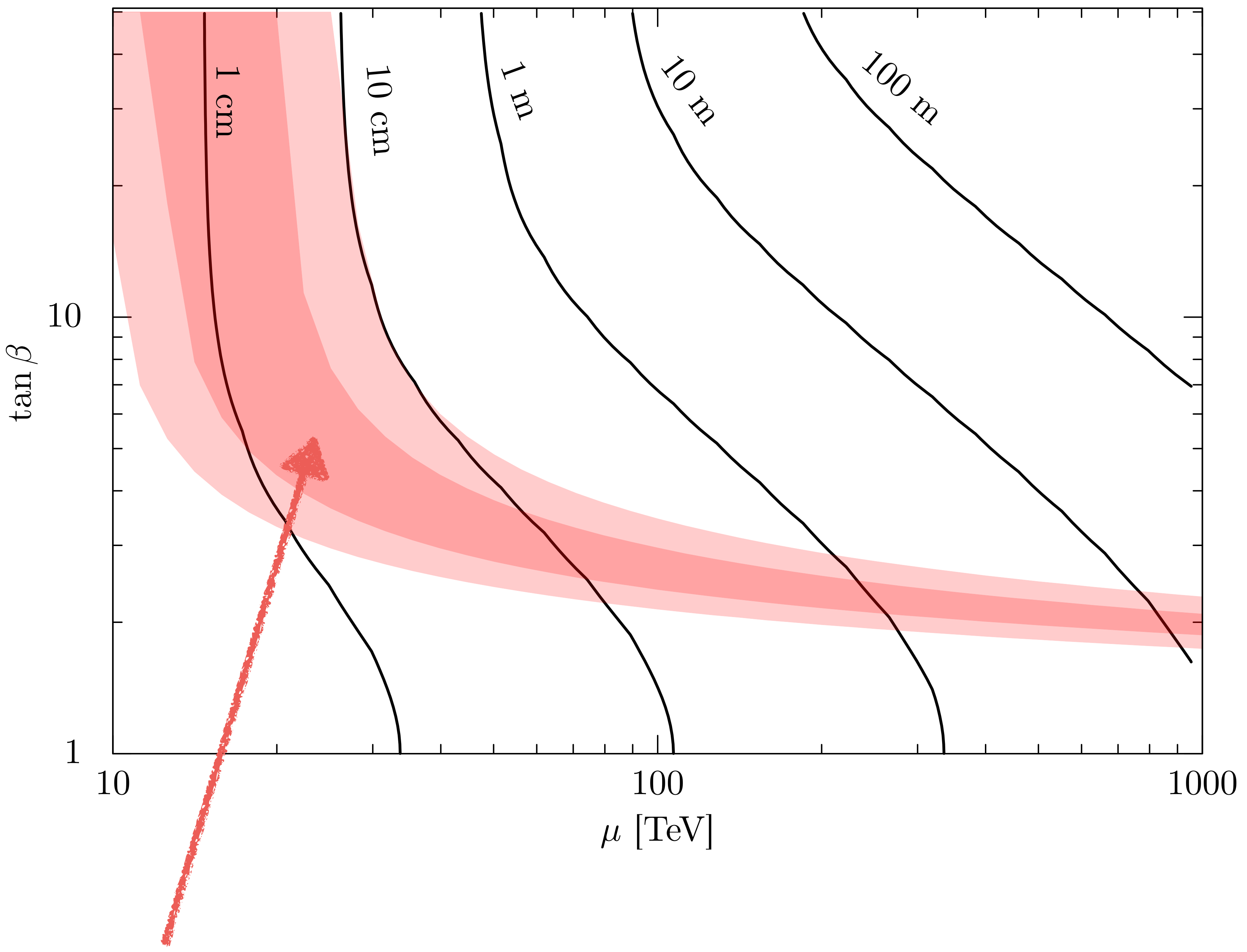
Charged wino decay



$$\propto \sin(2\beta)\frac{m_W^2}{\mu \Delta M}$$

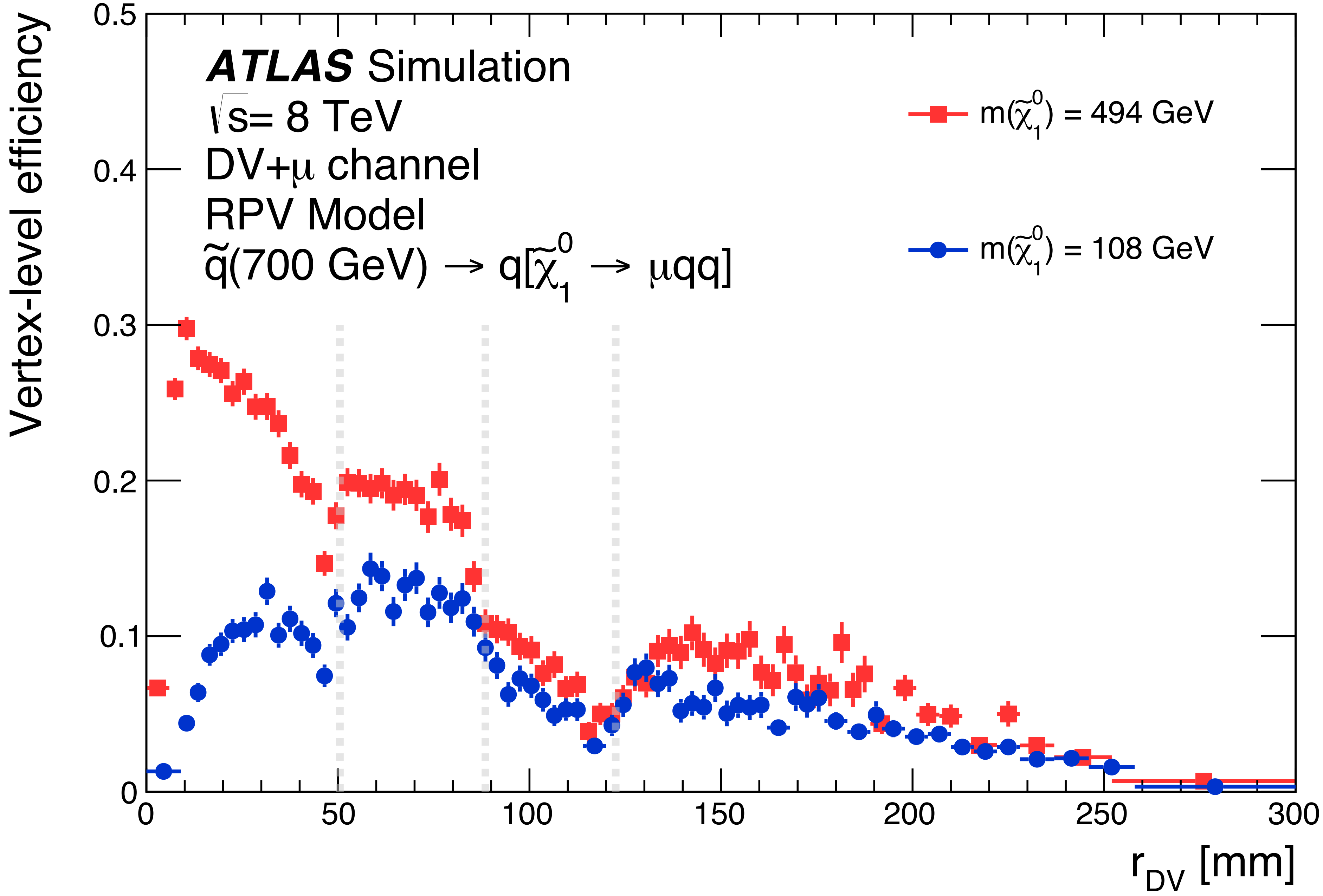
Charged wino decays promptly for $|\mu| < O(10^4)$ TeV.

Decay length of neutral wino



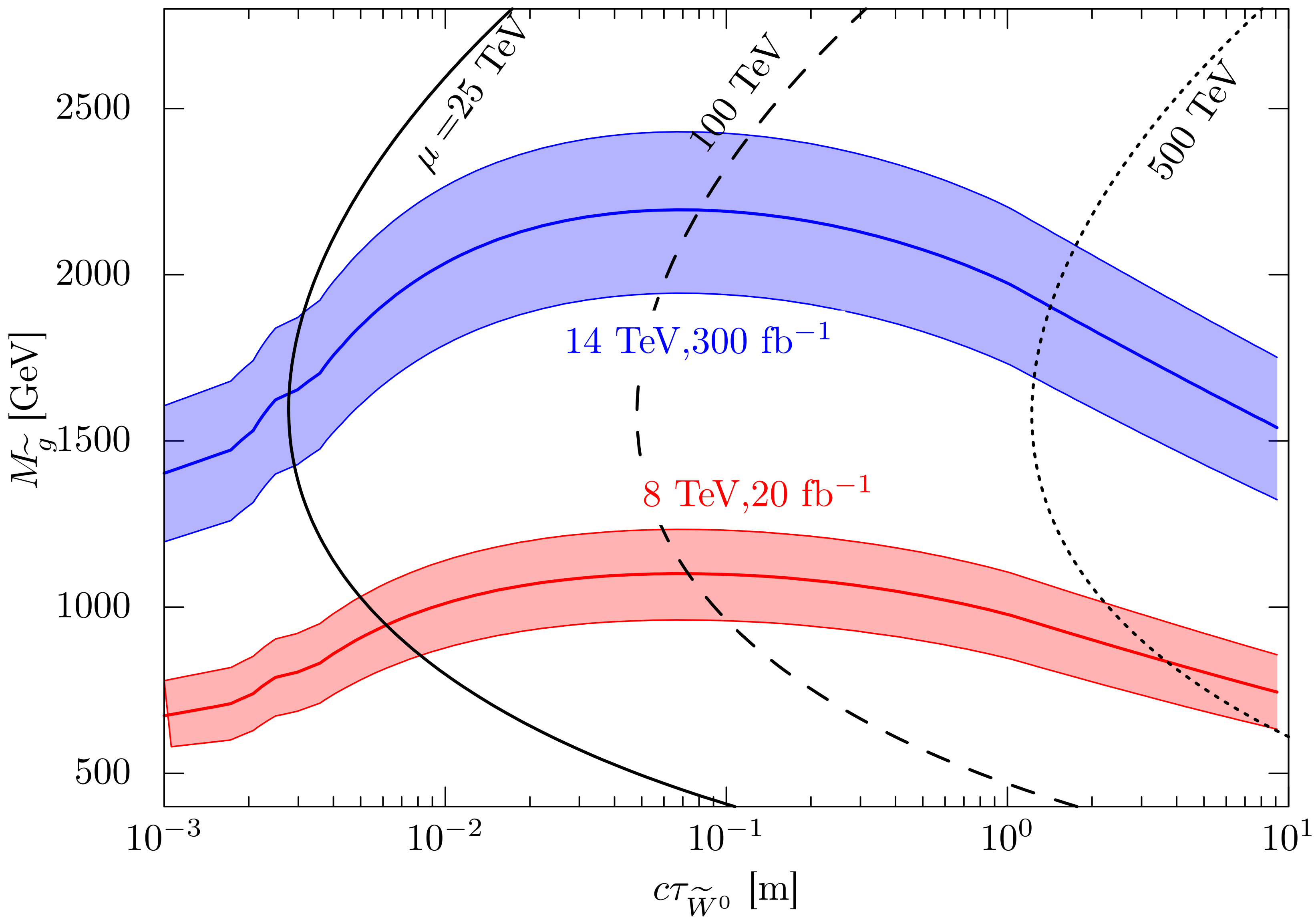
Realize 125 GeV Higgs mass when sfermion masses are equal to the Higgsino mass.

Vertex-level efficiency



ATLAS [arXiv: 1504.05162]

Winos from gluino decay

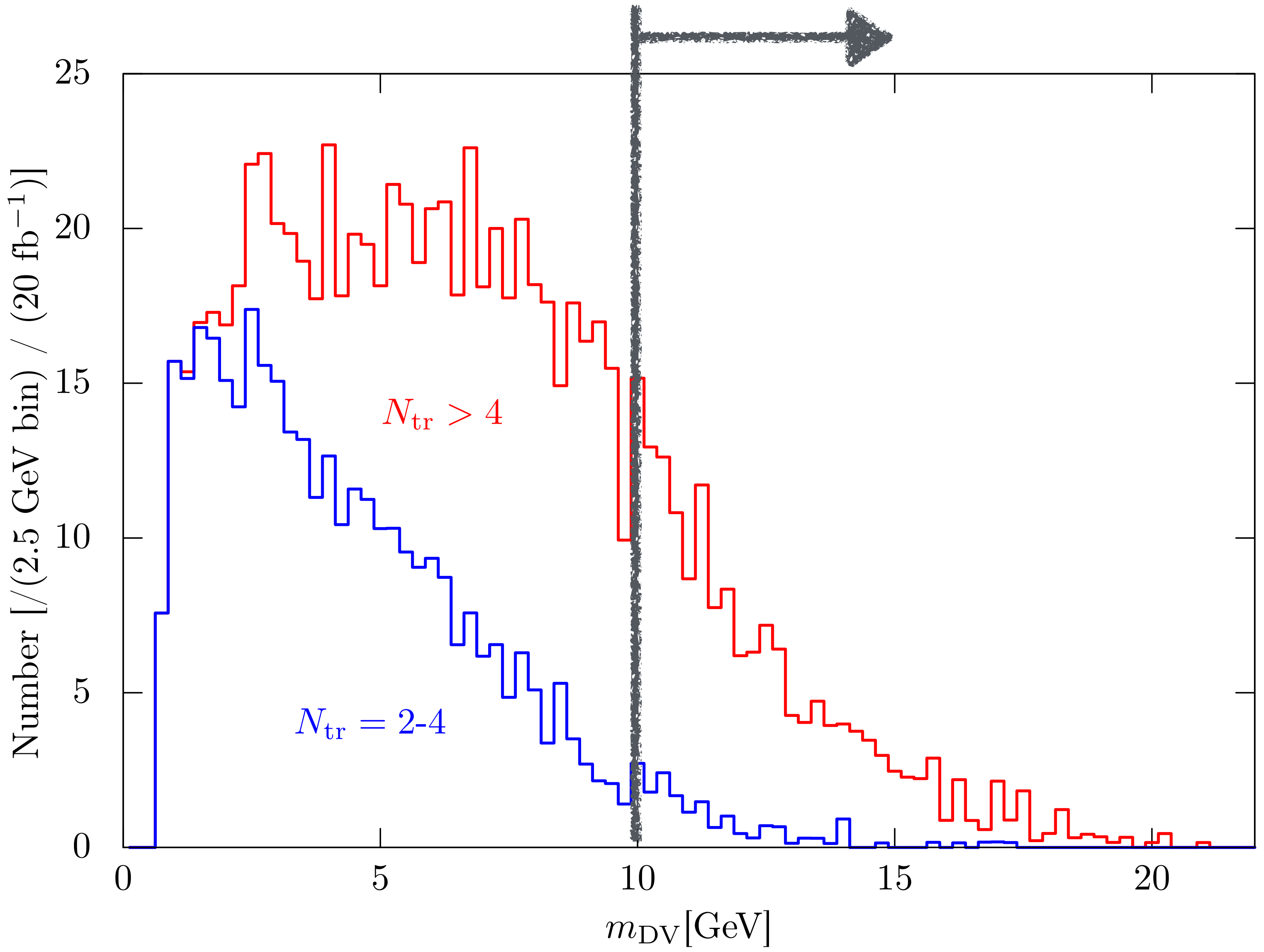


$$M_{\widetilde{g}} = 2M_{\widetilde{W}}$$

$\Delta M = 30$ GeV

$\tan\beta = 2$

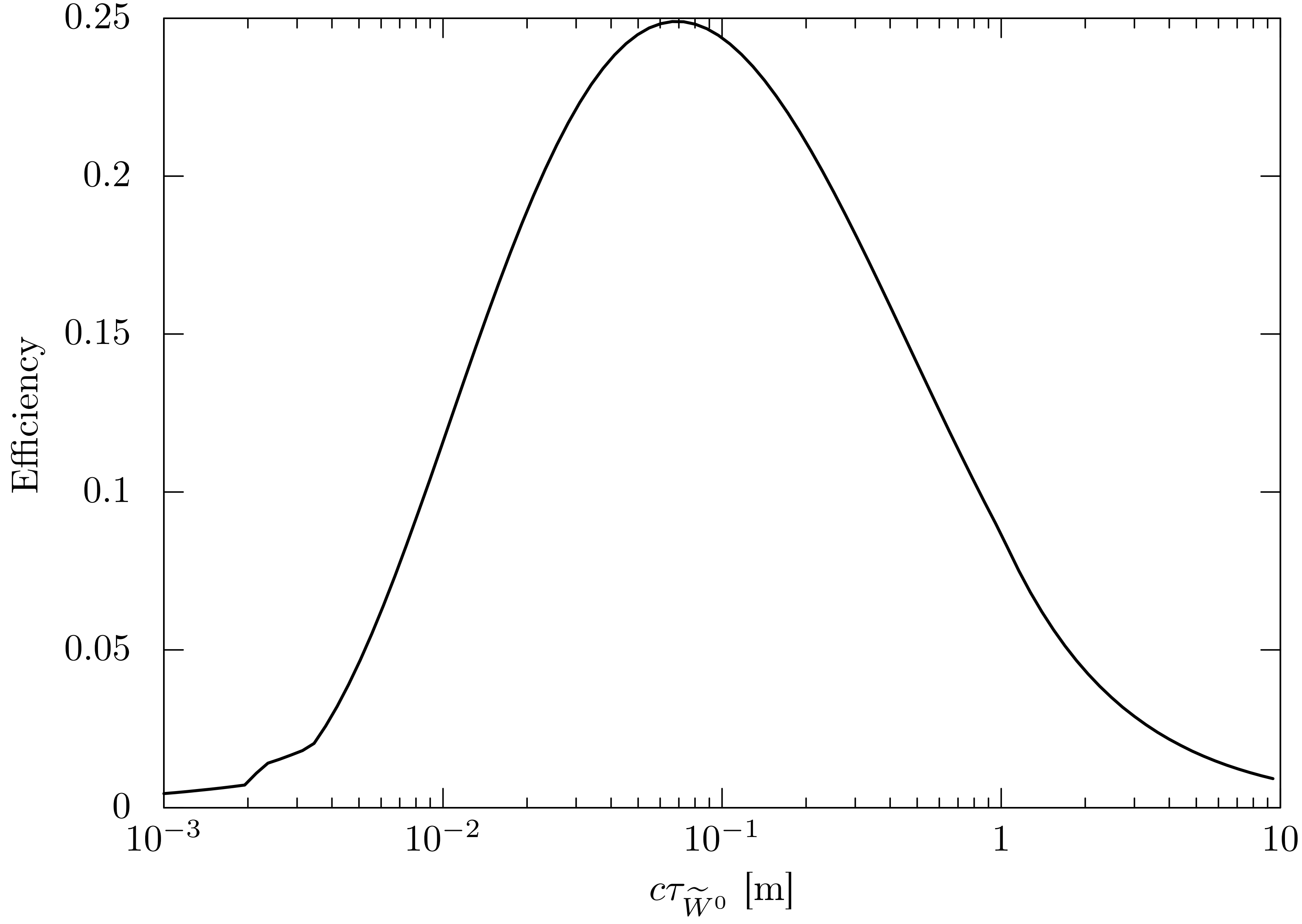
Distributions of m_{DV}



$$M_{\widetilde{W}} = 400\ \mathrm{GeV}$$

$$M_{\widetilde{B}} = 370\ \mathrm{GeV}$$

Vertex-level efficiency



$$M_{\widetilde{W}} = 400 \text{ GeV}$$

$$M_{\widetilde{B}} = 370 \text{ GeV}$$

Table 19: Cutflow table for DV+E_T^{miss} channel on the 2012 dataset.

Event selection cuts			
	Num events	Relative Efficiency (%)	Overall Efficiency (%)
All evts	26563830	100.	100.
GRL	24923461	93.8	93.8
EventCleaning	24737381	99.2	93.1
Trigger	8640339	34.9	32.5
PassesDESD	19279	0.22	0.07
PV_n	19261	99.9	0.07
PV_z	19221	99.7	0.07
PV_nTrk	19089	99.3	0.07
METCut	6485	33.9	0.02
Vertex selection cuts			
	Num events	Relative Efficiency (%)	Overall Efficiency (%)
hasDV	1647	25.3	0.00
DV_fid	1165	70.7	0.00
DV_PVdist	1140	97.8	0.00
DV_chisq	1106	97.0	0.00
DV_material	720	65.0	0.00
DV_nTrk	0	0.0	0.0
DV_mass	0	0.0	0.0