Two-pixel-hit searches for wino and higgsino

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Dark Side of the Universe 2017
Jul. 13, 2017
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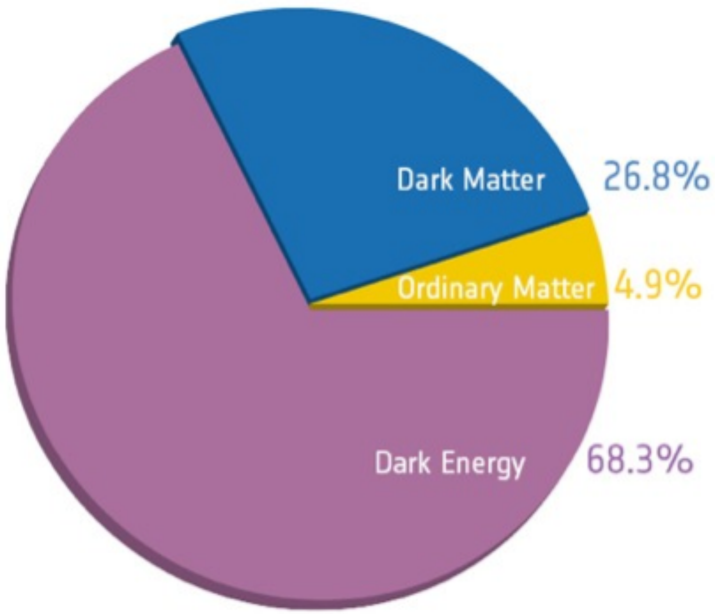
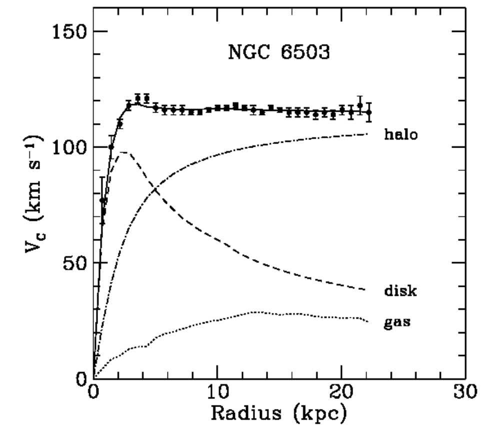
Based on H. Fukuda, N. Nagata, H. Otono, and S. Shirai, arXiv: 1703.09675.

Dark Matter (DM)

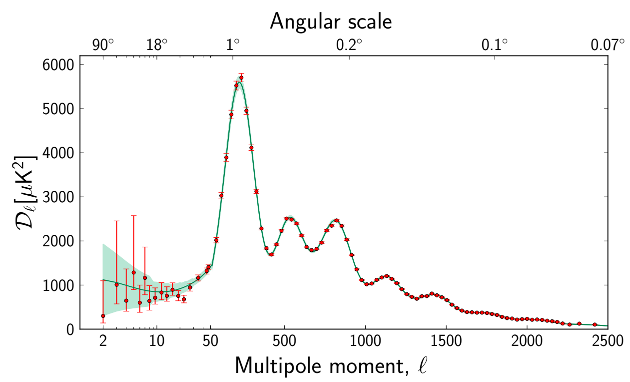
Evidence for DM



Planck (2013)



Begeman et. al. (1991)



Clowe et. al. (2006)

Weakly-Interacting Massive Particles (WIMPs)

- Neutral and stable particles with EW-scale masses.
- Weakly-interacting with ordinary matters.

Thermal relic abundance agrees with the observed DM density.

$$\Omega_{\rm DM} h^2 \simeq \frac{3 \times 10^{-27} {\rm cm}^3 {\rm s}^{-1}}{\langle \sigma_{\rm ann} v_{\rm rel} \rangle}$$

Supersymmetry (SUSY)

SUSY is the most promising candidate for physics beyond the SM.

Current constraints on SUSY

- Null results for SUSY searches
- 125 GeV Higgs mass

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

Is there any good WIMP dark matter candidate even in a high-scale SUSY model?

Focus-point, coannihilation region, electroweakino, …

Can we probe such a dark matter particle??

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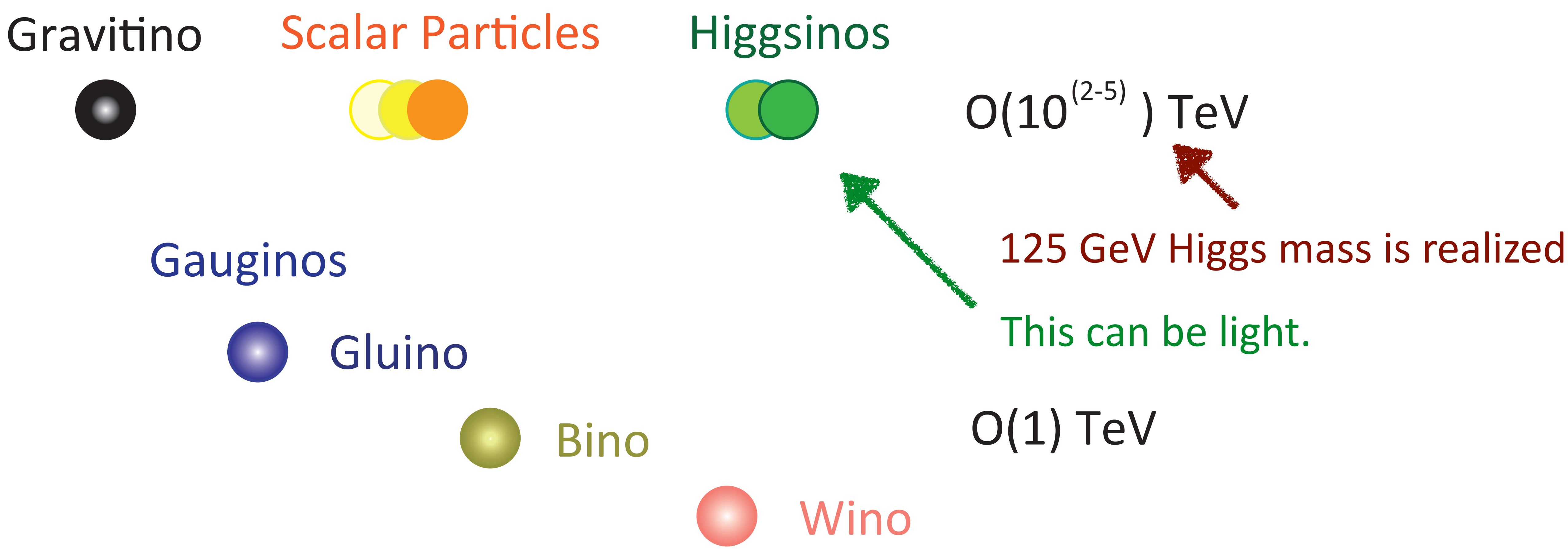
See talks by Jason L. Evans, Junichiro Kawamura, Seng Pei Liew, …

Can we probe such a dark matter particle??

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 by anomaly mediation.

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

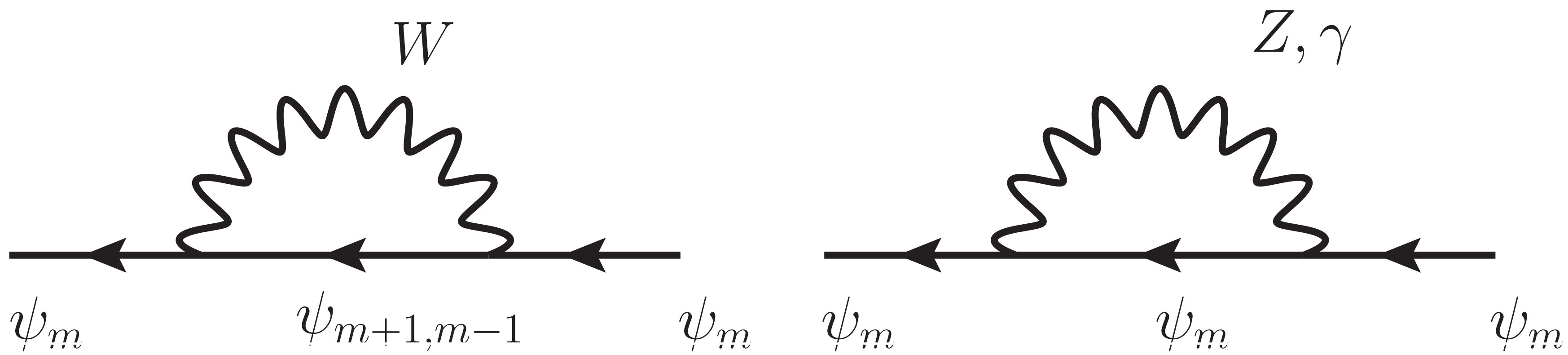
DM candidates:

- Wino (3 TeV)
- Higgsino (1 TeV)

Can we probe them at the LHC??

Mass splitting

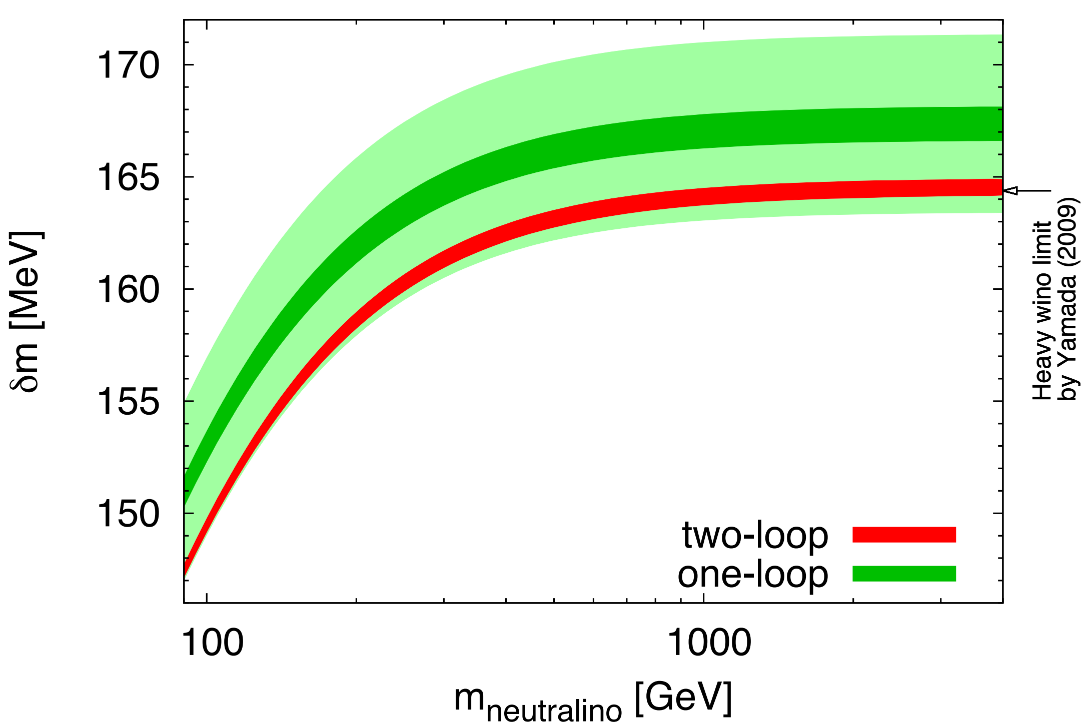
Charged-neutral mass splitting is generated via IR radiative corrections by EW gauge boson loops.



$$\Delta M \simeq \alpha_2 m_W \sin^2\frac{\theta_W}{2} + \alpha_2 Y m_W \left(\frac{1}{\cos\theta_W} - 1\right)$$

O(100) MeV.

Non-decoupling effect



Two-loop calculation (wino, Y = 0)

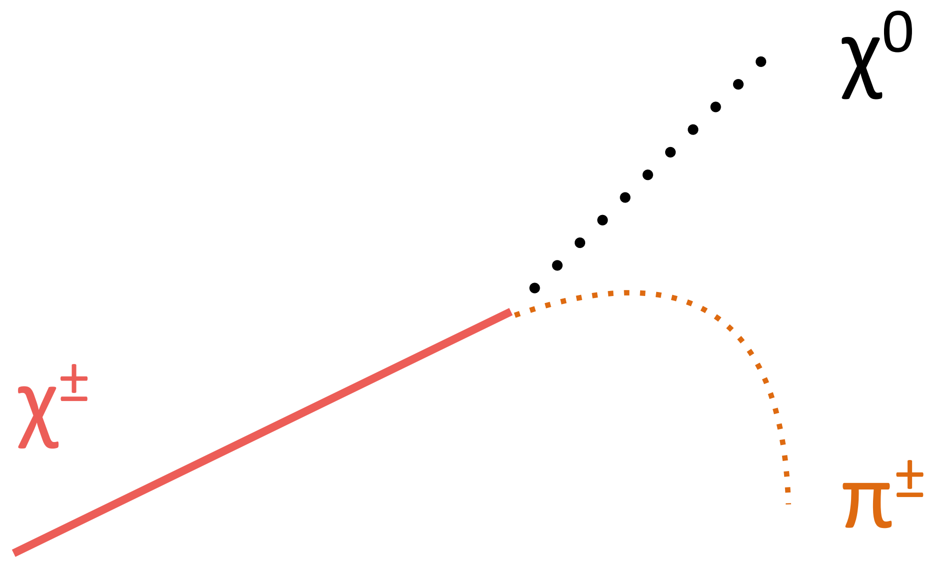
$$\Delta M \simeq 165 \text{ MeV}$$

M. Ibe, S. Matsumoto, R. Sato (2012).

LHC search

The production cross sections of these particles tend to be much smaller than those of colored particles.

Moreover, since the mass differences among the components are fairly small, momenta of decay products are very soft.



Hard to probe them at the LHC??

See also talk by Shoaib Munir.

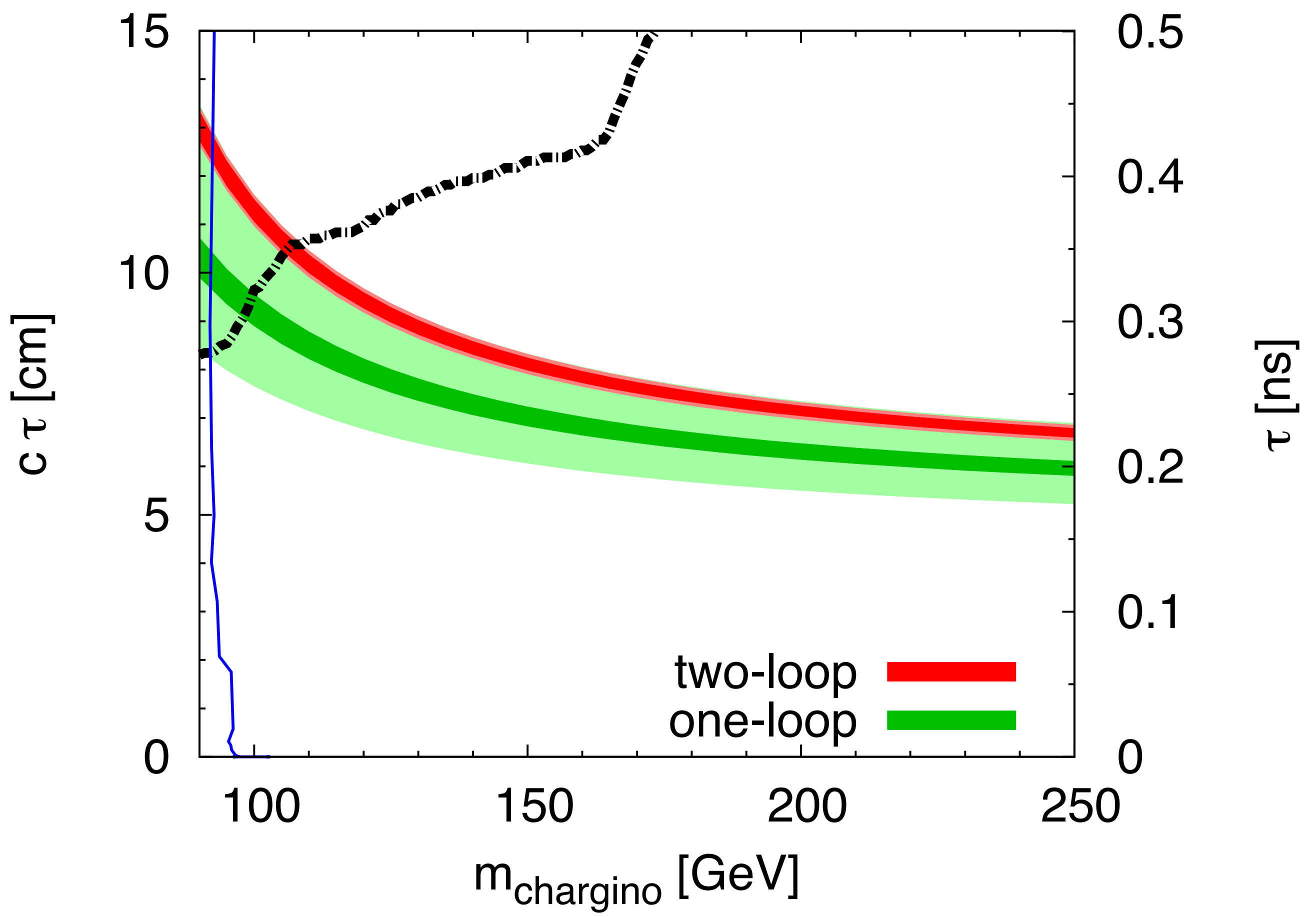
Wino lifetime

Due to the small mass splitting, wino becomes rather long-lived.

Main decay channel: $\chi^{\pm} \to \chi^{0} + \pi^{\pm}$

Branching fraction for the leptonic decay modes (three-body decay) is a few %.

$$\Gamma(\chi^{\pm} \to \chi^{0} + \pi^{\pm}) = \frac{4G_F^2 V_{ud}^2 f_\pi^2}{\pi} \Delta M^3 \left(1 - \frac{m_\pi^2}{\Delta M^2}\right)^{\frac{1}{2}}$$



M. Ibe, S. Matsumoto, R. Sato (2012).

$\tau \simeq 0.2$ ns

$c\tau \simeq 6$ cm

Decay within a detector!

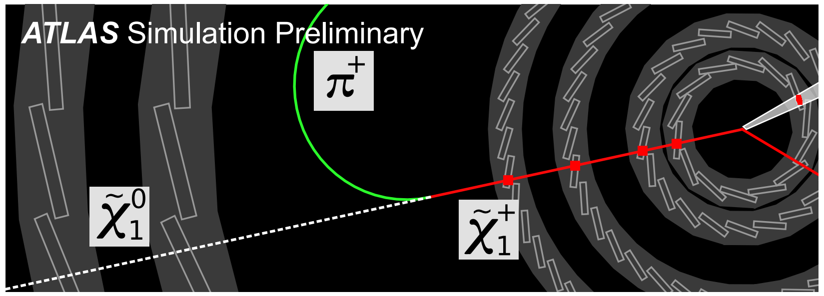
Disappearing track searches

A charged wino with a decay length of O(1) cm leaves a disappearing track in detectors.

J. L. Feng, T. Moroi, L. Randall, M. Strassler, S. F. Su (1999);
M. Ibe, T. Moroi, T. T. Yanagida (2006), etc...

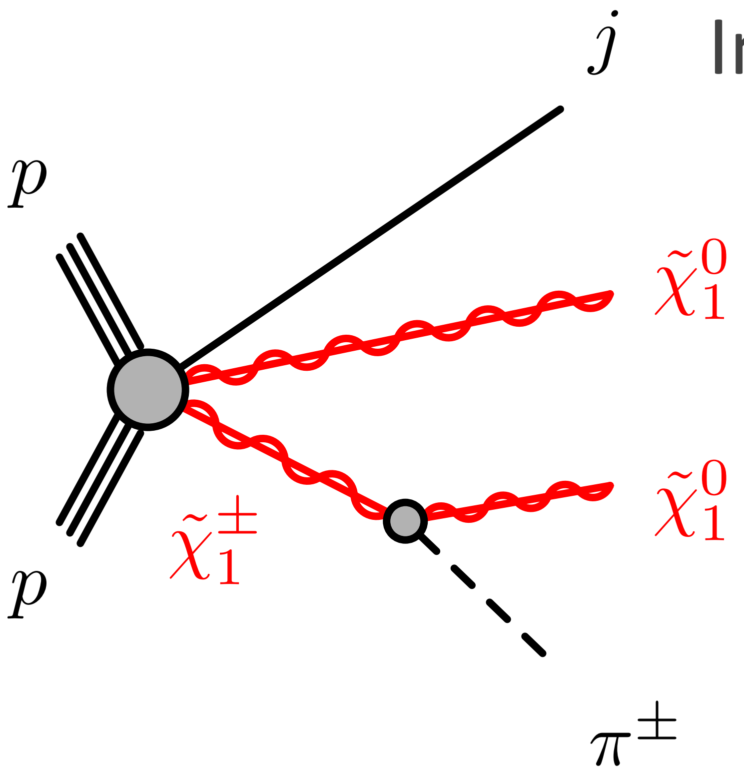
Charged track $\chi^{\pm} \to \chi^{0} + \pi^{\pm}$

E_T^{miss} Too soft to be detected



Requiring this signature, we can reduce SM BG significantly.

Signal topology



Initial State Radiation (ISR)

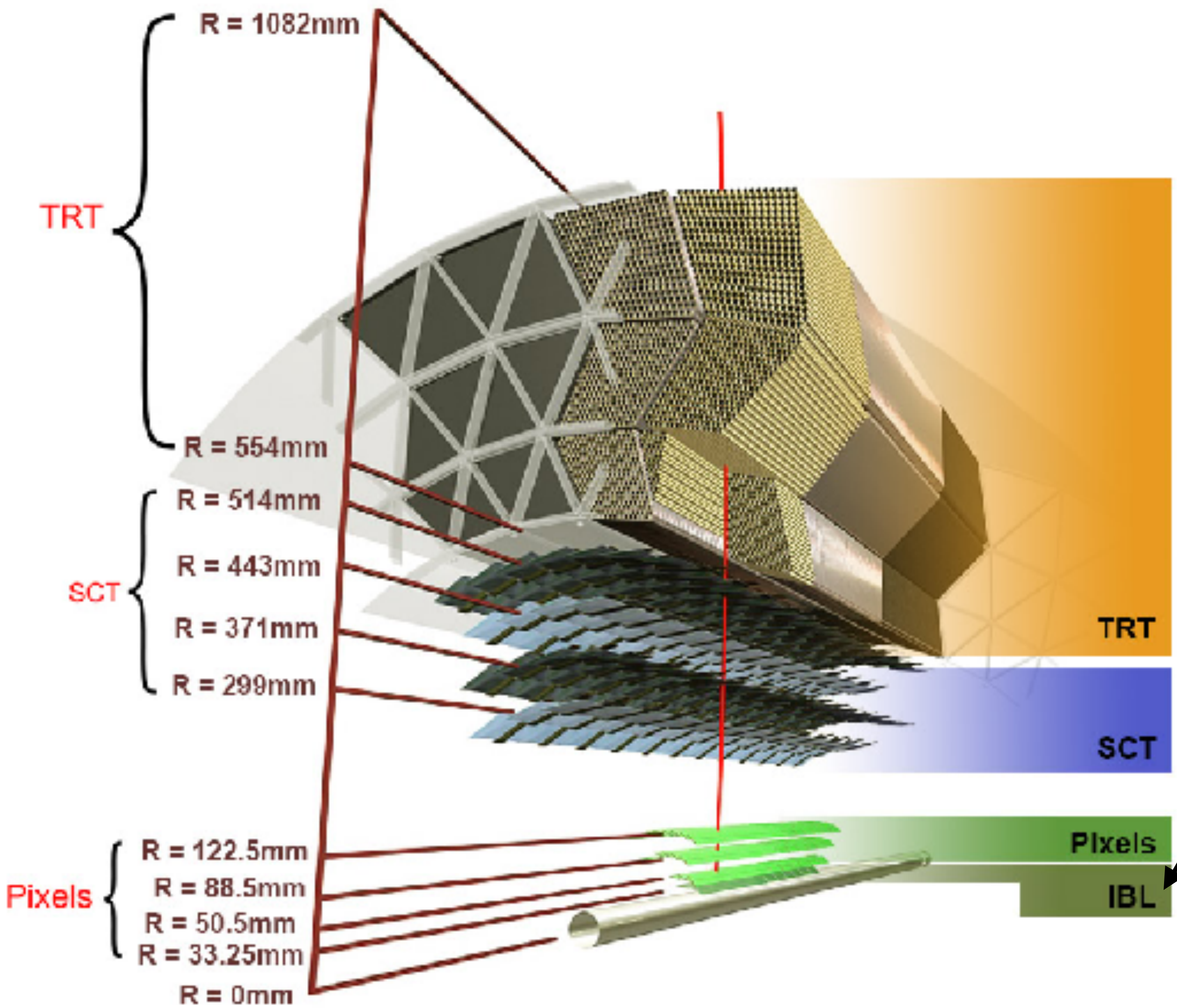
Large E_T^{miss}
Single jet
Disappearing track

Role of ISR

- Trigger
- Boost the system

Improvement from Run-1 @ ATLAS

ATLAS inner detector



New!!

Insertable B-layer (IBL)

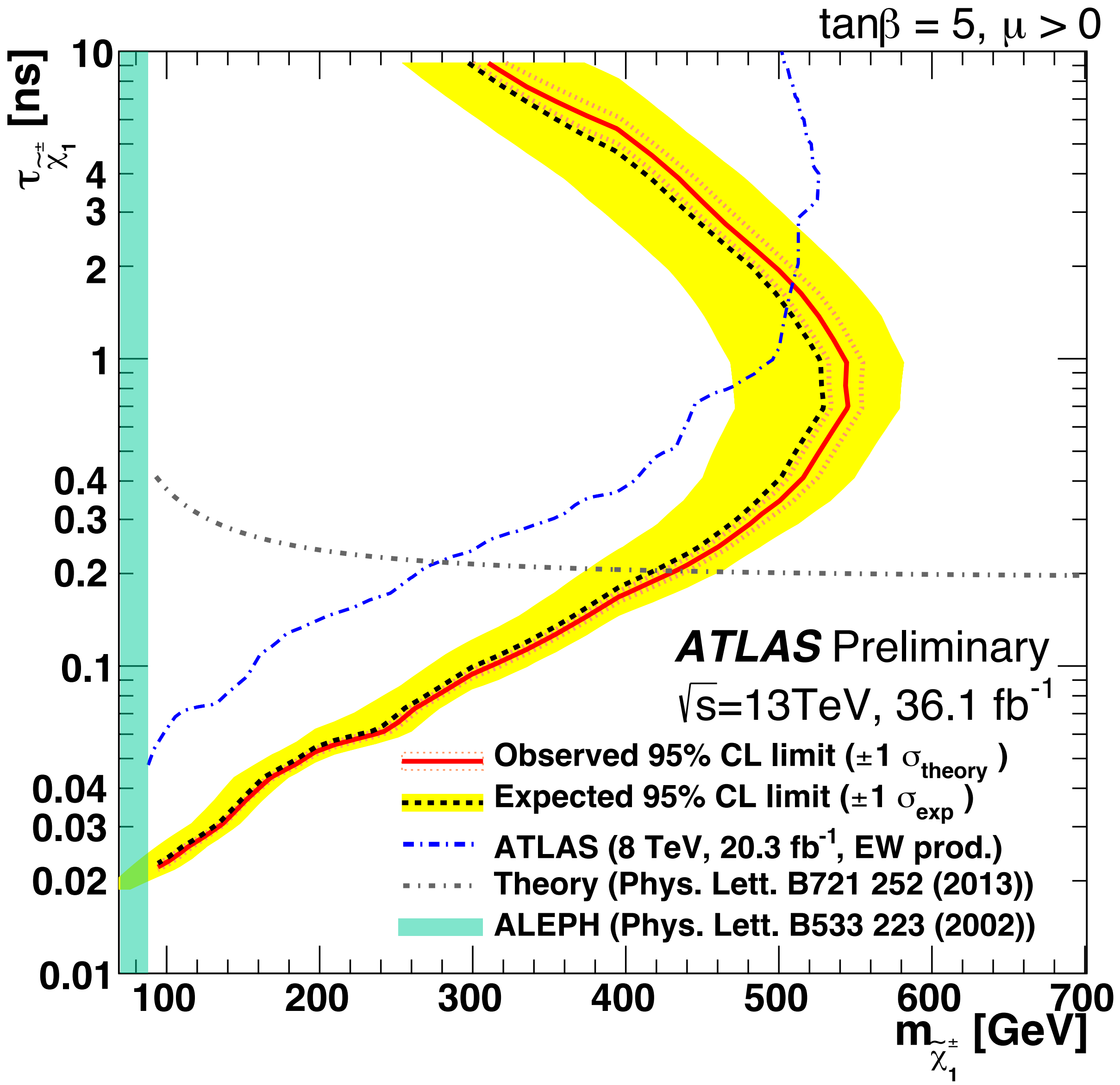
Requirement for disappearing tracks

Run-1: 3 pixel + 1 SCT hits

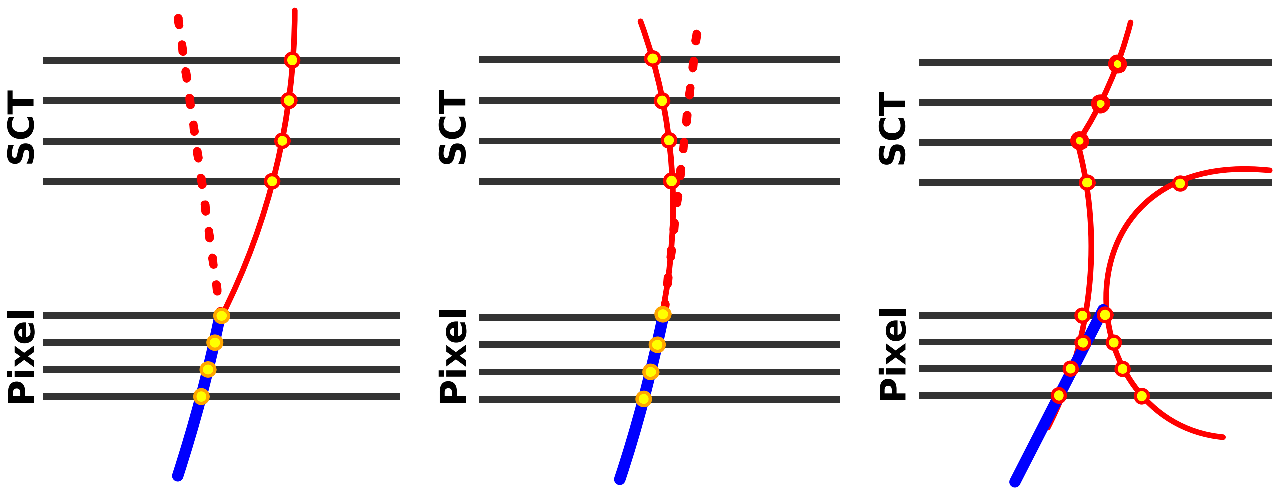
Run-2: 4 pixel hits

30 cm → 12 cm

Results



BG: ttbar, W+ jets



Hadronic scattering　Bremsstrahlung　Two nearby tracks (fake)

Wino with a mass up to 430 GeV has been excluded!

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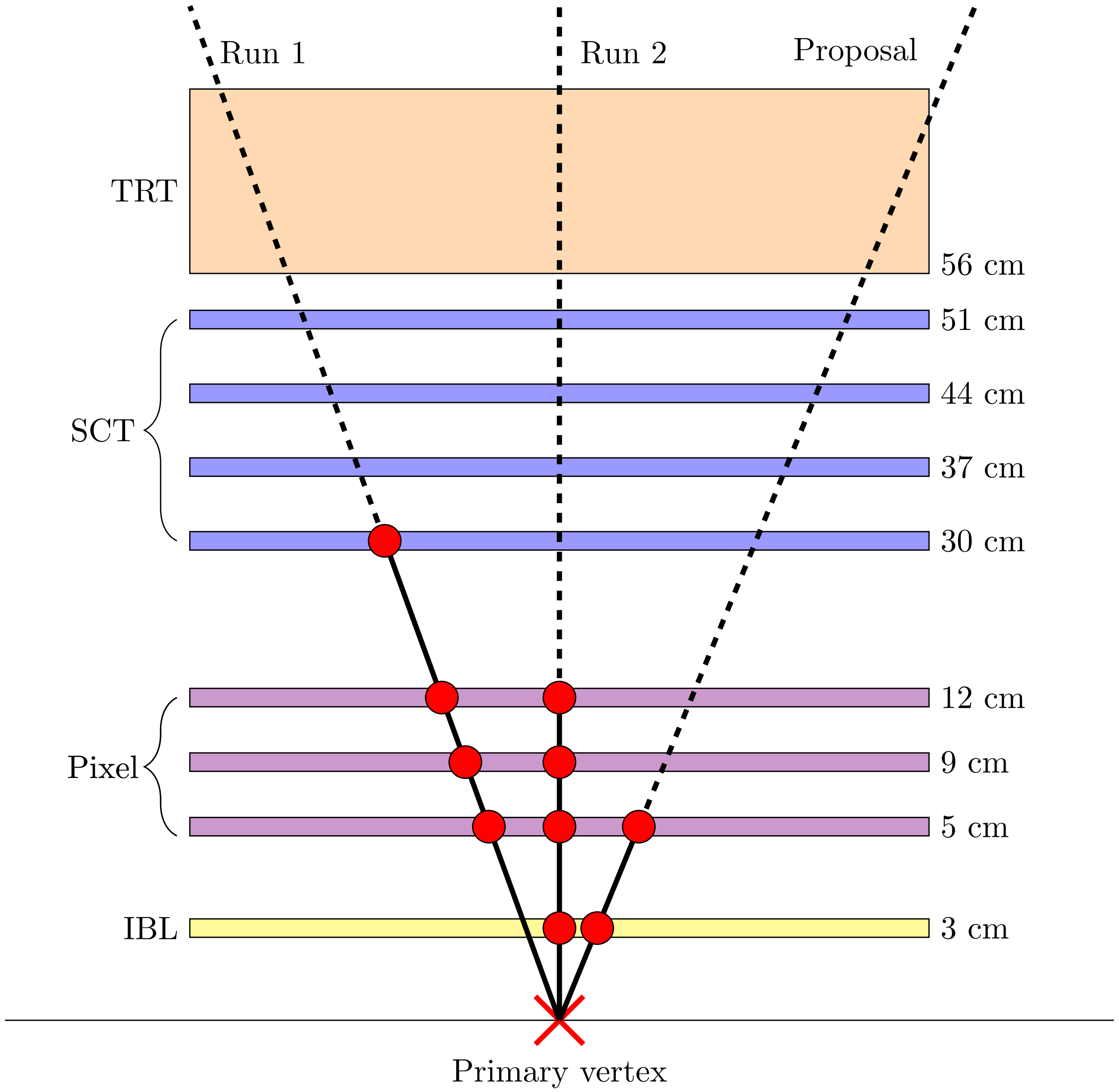
Shorter disappearing tracks

If required number of hits is reduced, then the signal events are much enhanced.



We may use the primary vertex together with two pixel layers!

But momentum resolution becomes very poor….

Need to consider further strategies to reduce BG events.

Background reduction

- Use displaced vertices

BG events tend to be associated with tracks with a large impact parameter.

➡ DV reconstruction technique may be used to eliminate them.

- Use anomalously large energy deposit

Being developed by ATLAS people

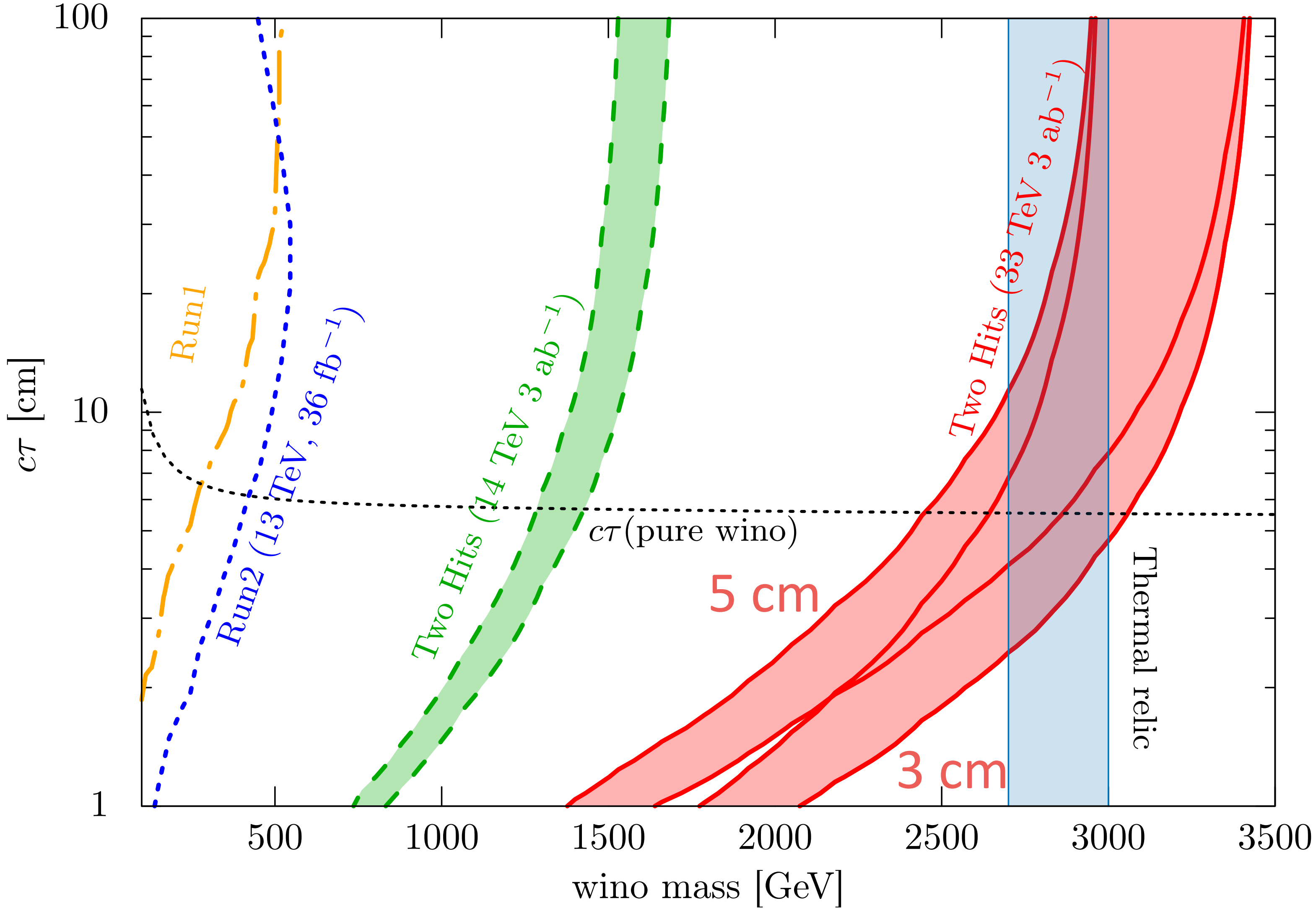
- Smaller size pixel trackers??

Considered seriously [1511.02080].

Two-hit strategy

Let us be optimistic. Suppose we can reduce BG sufficiently.

Expected limits



# of BG events: 0—10

E_T^{miss}, P_T^{lead} > 400 GeV for 14 TeV.

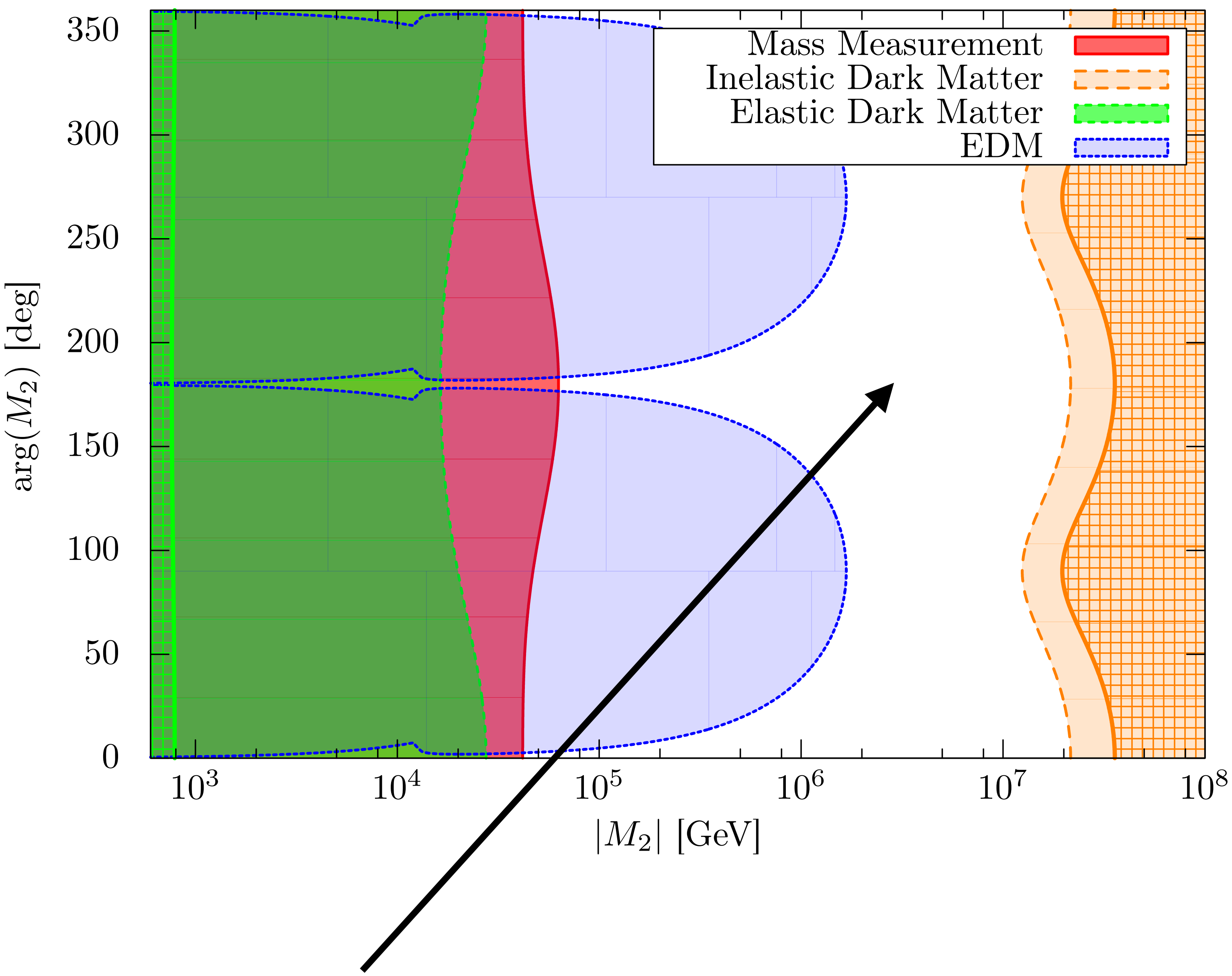
E_T^{miss}, P_T^{lead} > 600 GeV for 33 TeV.

1 TeV wino is within the reach of the LHC.

We may probe whole region with a 33 TeV collider!

Based on H. Fukuda, N. Nagata, H. Otono, and S. Shirai [arXiv:1703.09675].

Almost Pure Higgsino



Parameters

$\mu = 500$ GeV

$\widetilde{m} = M_1 = M_2 = M_3$

A-terms: 0

Higgs mass → tanβ

Future prospects

$|d_e| < 10^{-31}\ e \cdot \mathrm{cm}$

$\sigma_{\mathrm{SI}} < 10^{-48}\ \mathrm{cm}^2$

$\Delta m < 300$ keV

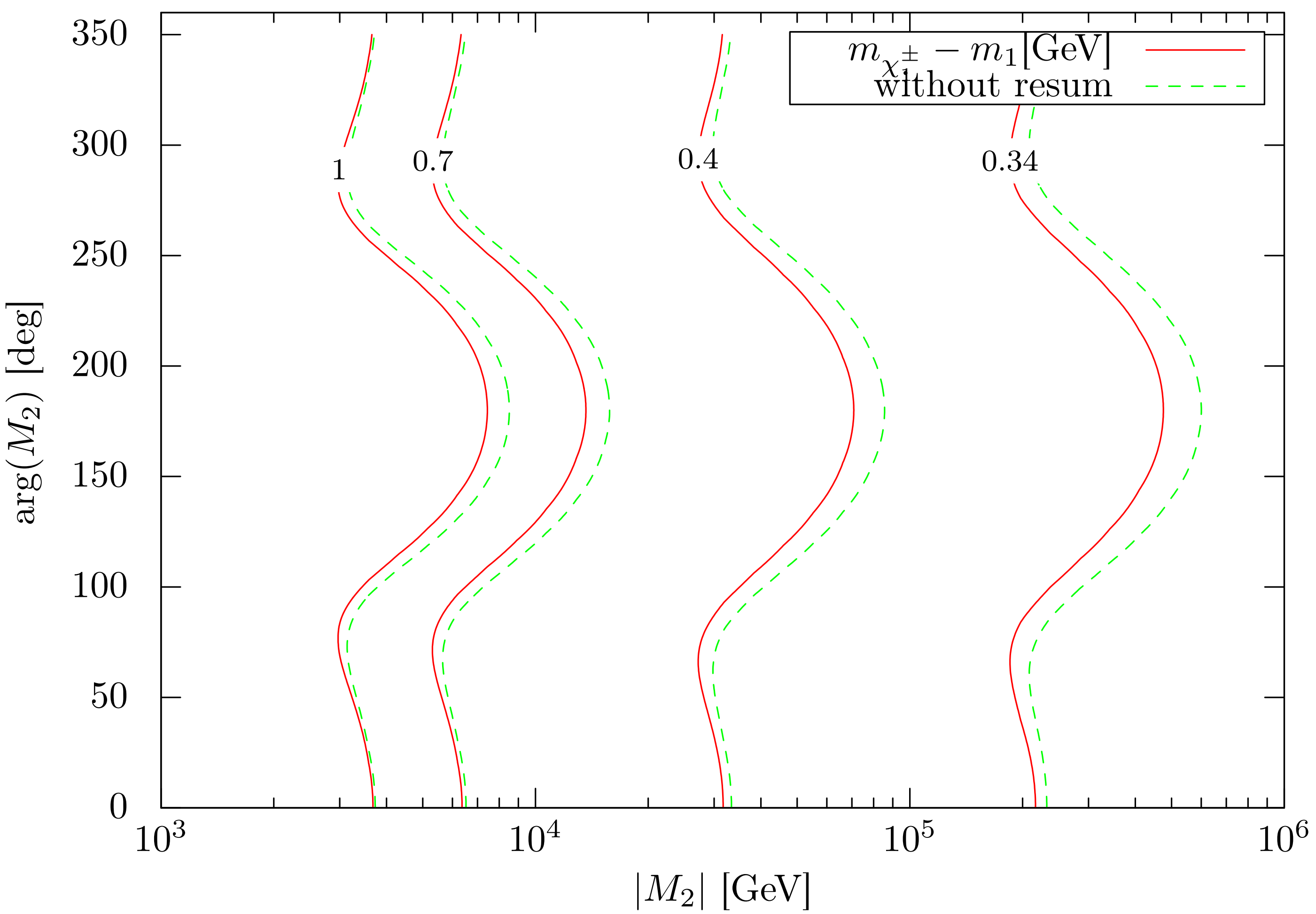
$\Delta m_+|_{\mathrm{tree}} > 0.2 \Delta m_+|_{\mathrm{rad}}$

This "almost pure Higgsino" DM region is hard to probe.

N. Nagata and S. Shirai, JHEP **1501**, 029 (2015).

Pure Higgsino

Charged-neutral mass difference



$\tan\beta = 2,\ \mu = 500\ \text{GeV},\ M_1 = M_2$

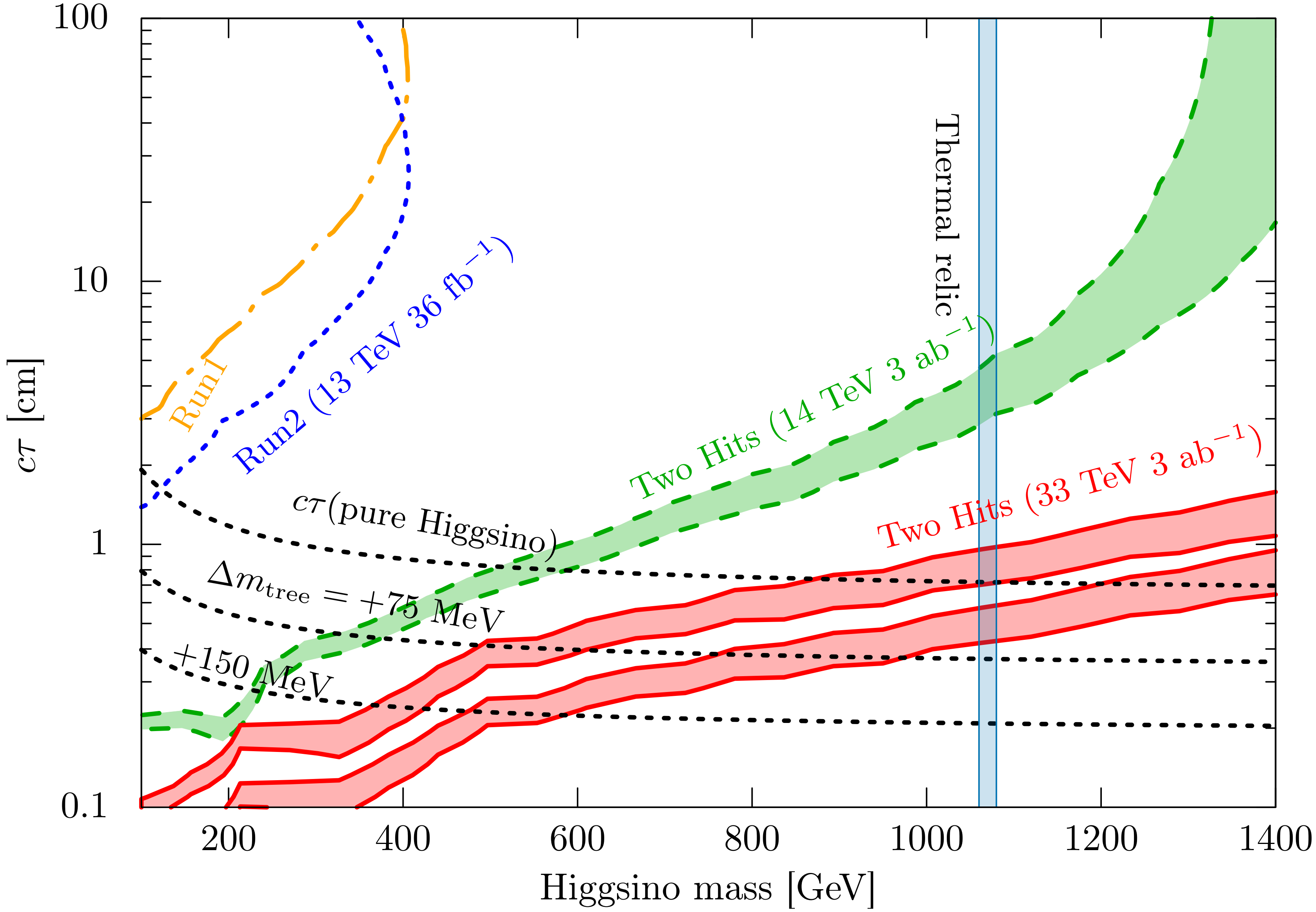
Contrary to the wino case, it is difficult to search for a pure Higgsino with conventional disappearing track searches.

$\Delta m \sim 350\ \text{MeV}$ → $c\tau \sim 1\ \text{cm}$

Too short to be probed so far…

Two-hit strategy for Higgsino

With the two-hit strategy, even pure Higgsino may be probed.



# of BG events: 0—10

E_T^{miss}, P_T^{lead} > 400 GeV for 14 TeV.

E_T^{miss}, P_T^{lead} > 600 GeV for 33 TeV.

Again, whole region can be covered with a 33 TeV collider!

H. Fukuda, N. Nagata, H. Otono, and S. Shirai, arXiv: 1703.09675.

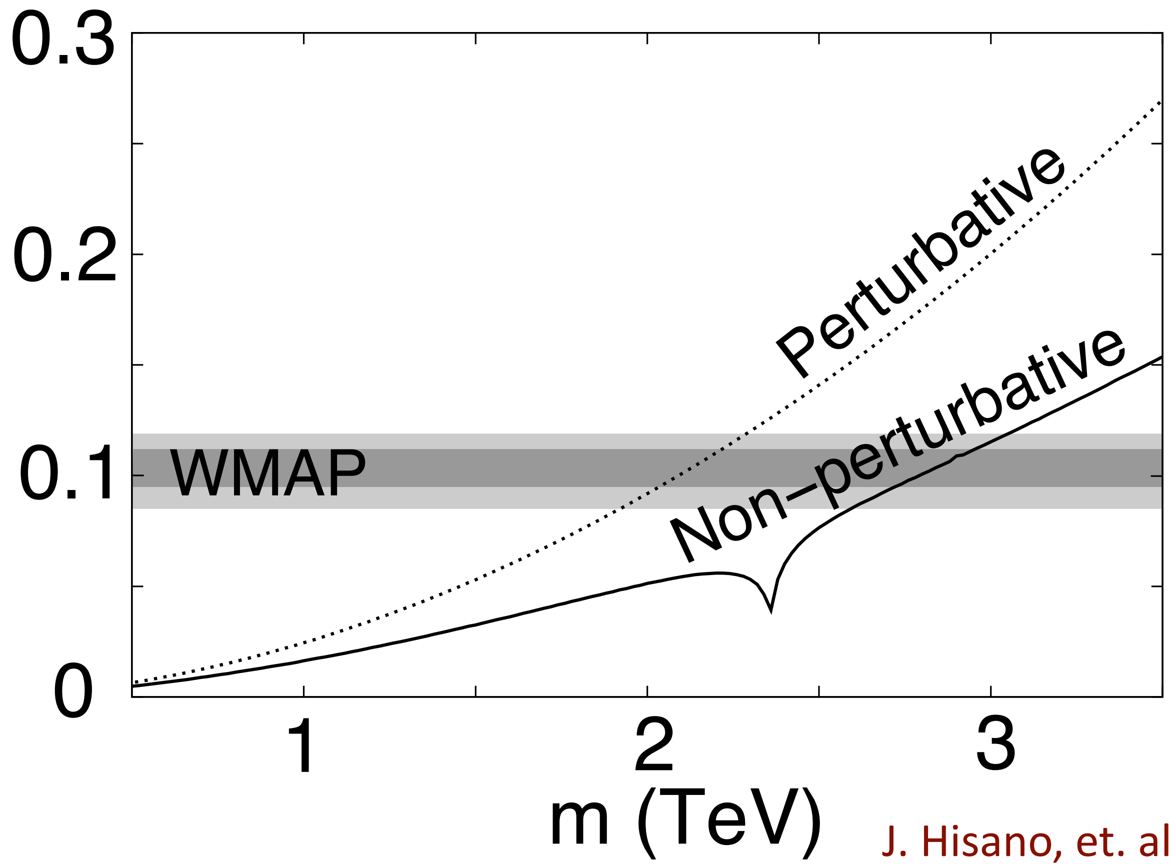
Conclusion

- In high-scale SUSY scenarios, wino or higgsino is a good DM candidate.
- The charged-neutral mass splitting of these particles is induced at loop level.
- Because of the small mass difference, these particles have a decay length of O(1) cm, which allows us to probe them with disappearing track searches.
- Disappearing track searches with two pixel hits are very promising.
- Wino (higgsino) with a mass of 1.2 TeV (500 GeV) can be probed at the LHC.

Backup

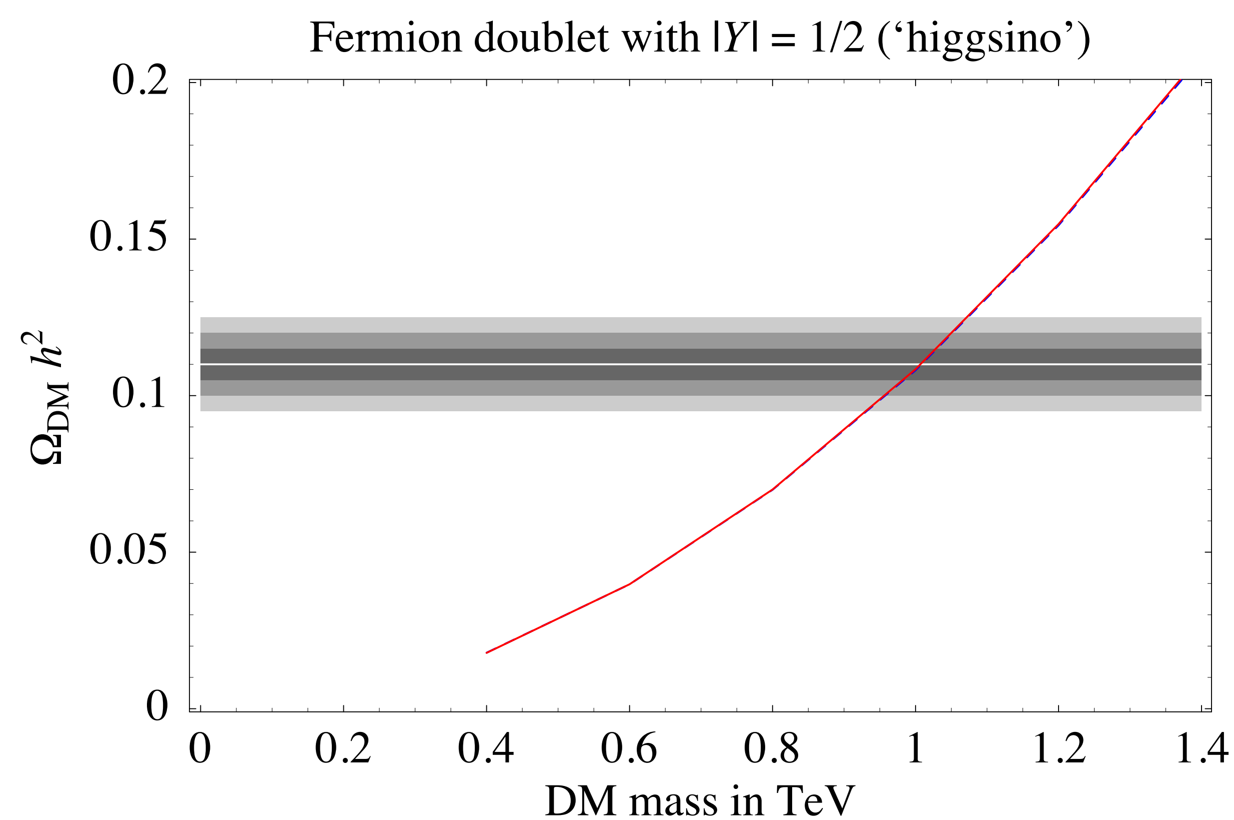
Sommerfeld effects

Wino



J. Hisano, et. al., (2006).

Higgsino



M. Cirelli, et. al., (2007).

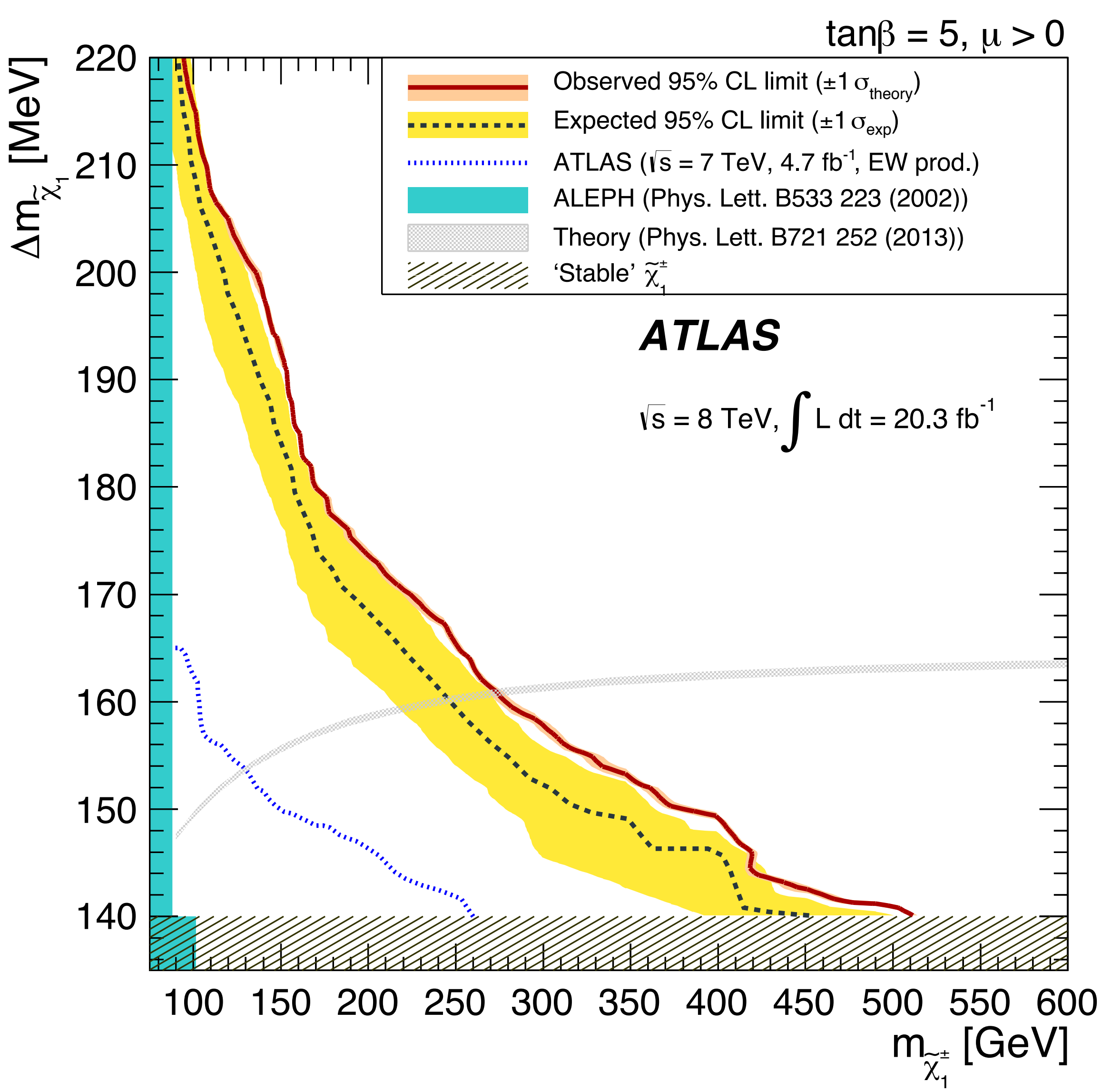
Sommerfeld effect significantly enhances annihilation cross sections.

➡ A heavier mass is favored in terms of thermal relic.

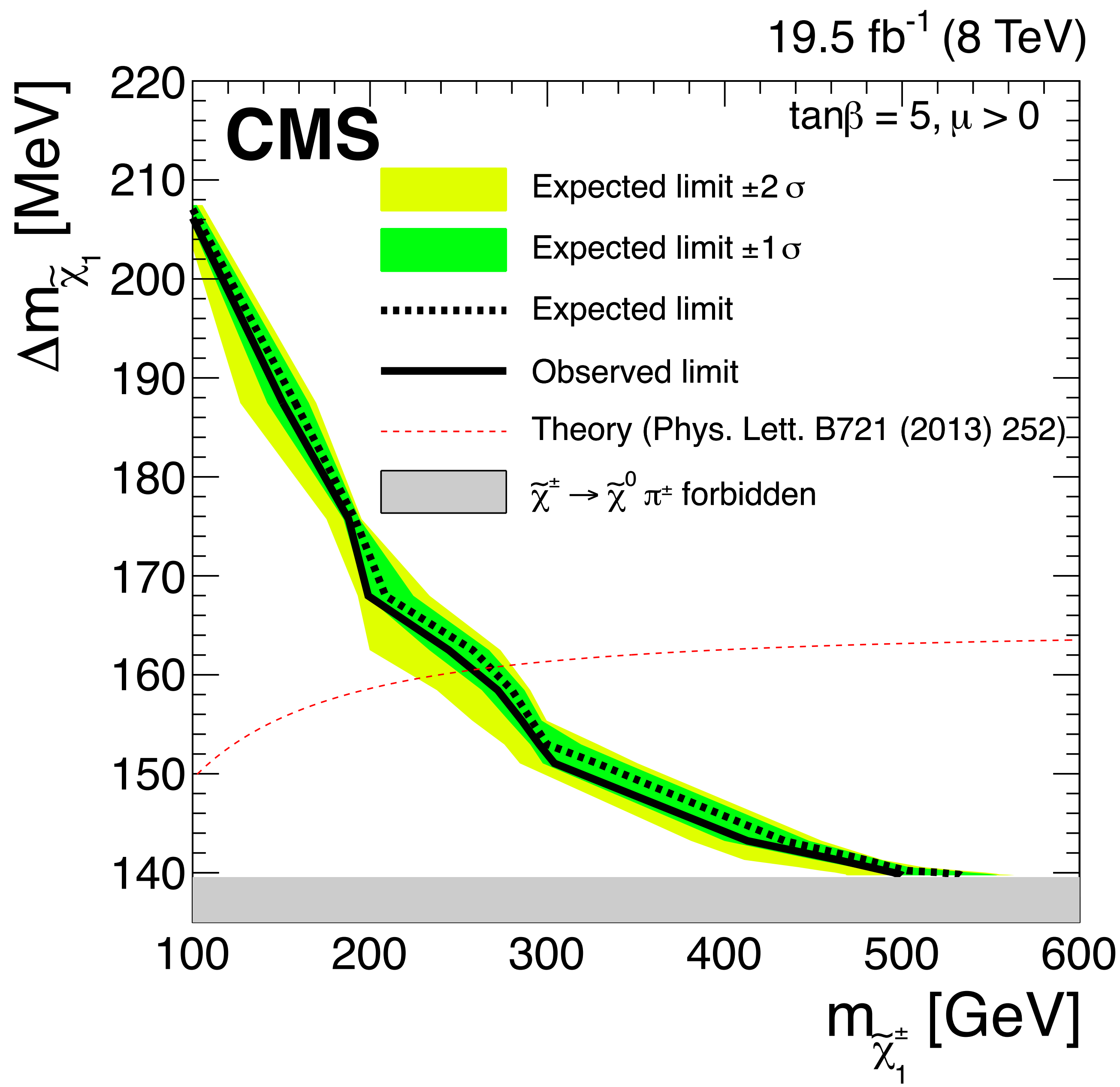
In order to make a precise prediction for the DM mass, we need to take this effect into account.

8 TeV results

ATLAS

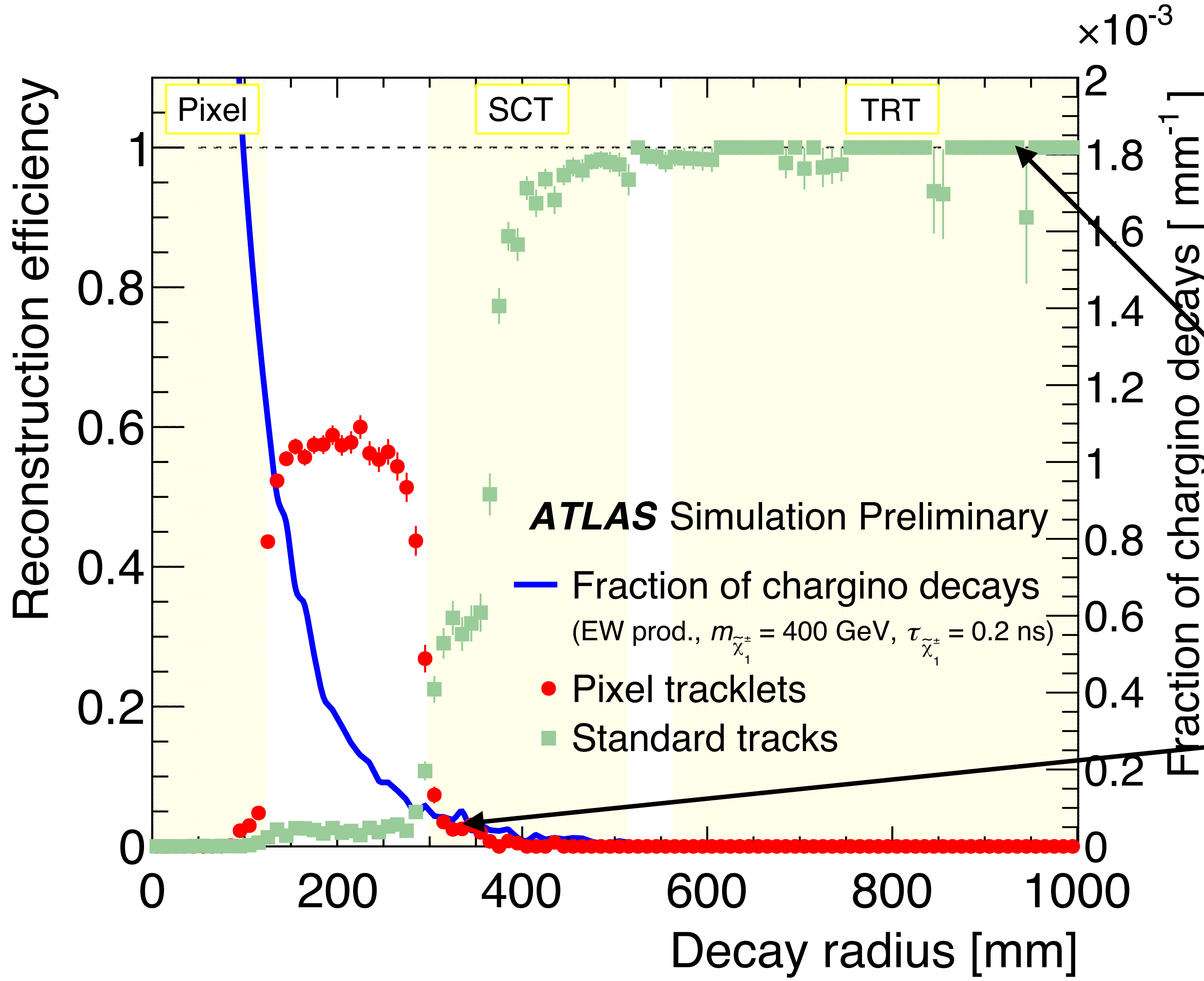


CMS



A wino with a mass of < 270 (260) GeV was excluded by the ATLAS (CMS) 8 TeV result.

Reconstruction efficiency



Require 7 hits in the silicon detector

No hit in SCT is required.

Reconstruction efficiency before applying the fake-rejection criteria

For charginos with a lifetime of 0.2 ns, the reconstruction efficiency using pixel tracklets is 5—10%.

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Event selection criteria

Selection for disappearing tracks

Isolation and p_T 90% ← Signal efficiency for a wino with a lifetime of 0.2 ns

- $p_T > 20$ GeV
- $\Delta R > 0.4$ for any jets ($p_T > 50$ GeV)
- $\Delta R > 0.4$ for muon spectrometer track ($p_T > 10$ GeV)
- $p_T^{cone40}/p_T < 0.04$

Quality 65—70%

- 4 hits in the pixel detector
- $|d_0|/\sigma(d_0) < 2.0$
- $|z_0 \sin\theta| < 0.5$ mm
- χ^2-probability of track fit > 10%

← Reduce fake tracks

Geometrical acceptance 85—90%

- $0.1 < |\eta| < 1.9$

Disappearing condition 75—85%

- No hit in the SCT

After all the selection cuts, the signal efficiency is 4% for a 400 GeV wino with a lifetime of 2ns.

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Event selection criteria

Kinematical selection 40% (400 GeV wino with a lifetime of 0.2 ns)

- Lepton veto
- $E_T^{miss} > 140$ GeV
- $\Delta\phi$ ($Jet_{1,2,3,4,}$) > 1.0

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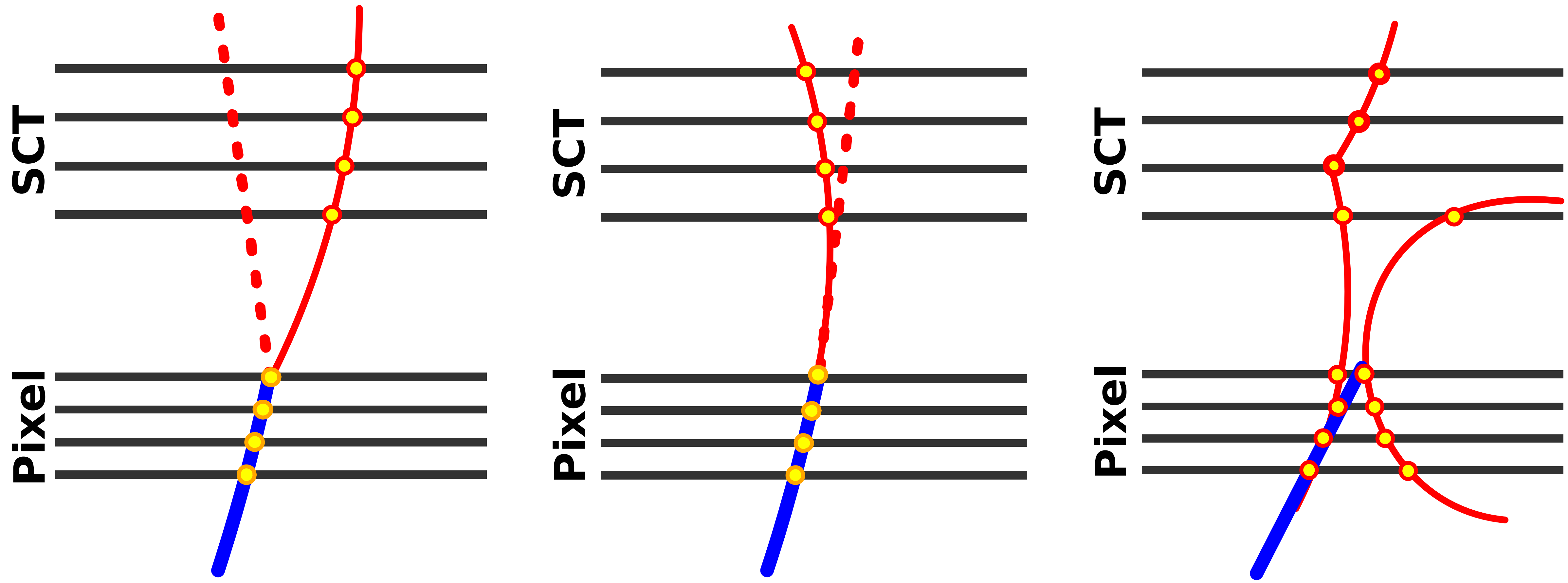
Background

BG events mainly come from ttbar, W + jets (W → eν, τν)



Hadronic scattering | Bremsstrahlung (leptons) | Two nearby tracks (fake)

Fit data with p_T shapes of BG + signal components with an unbinned likelihood function.

➡ Need p_T distributions of each component.

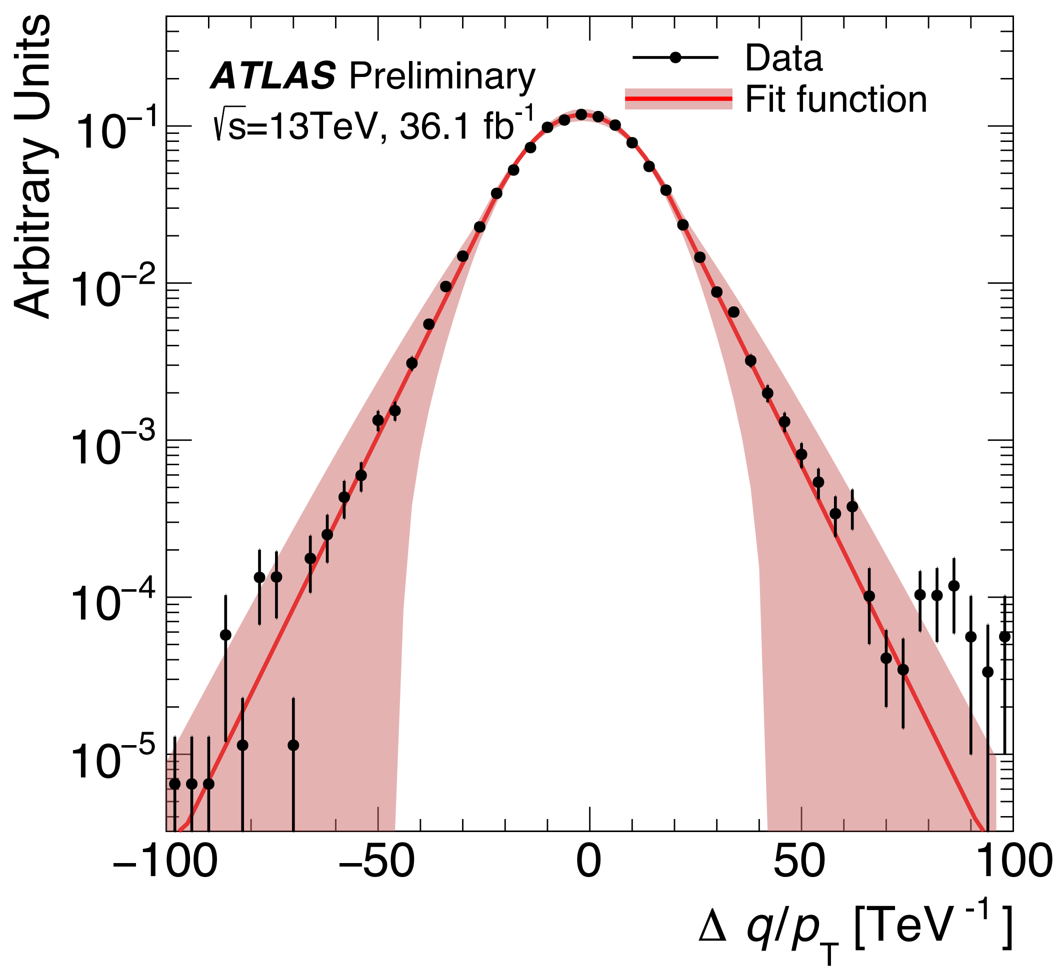
Background estimation

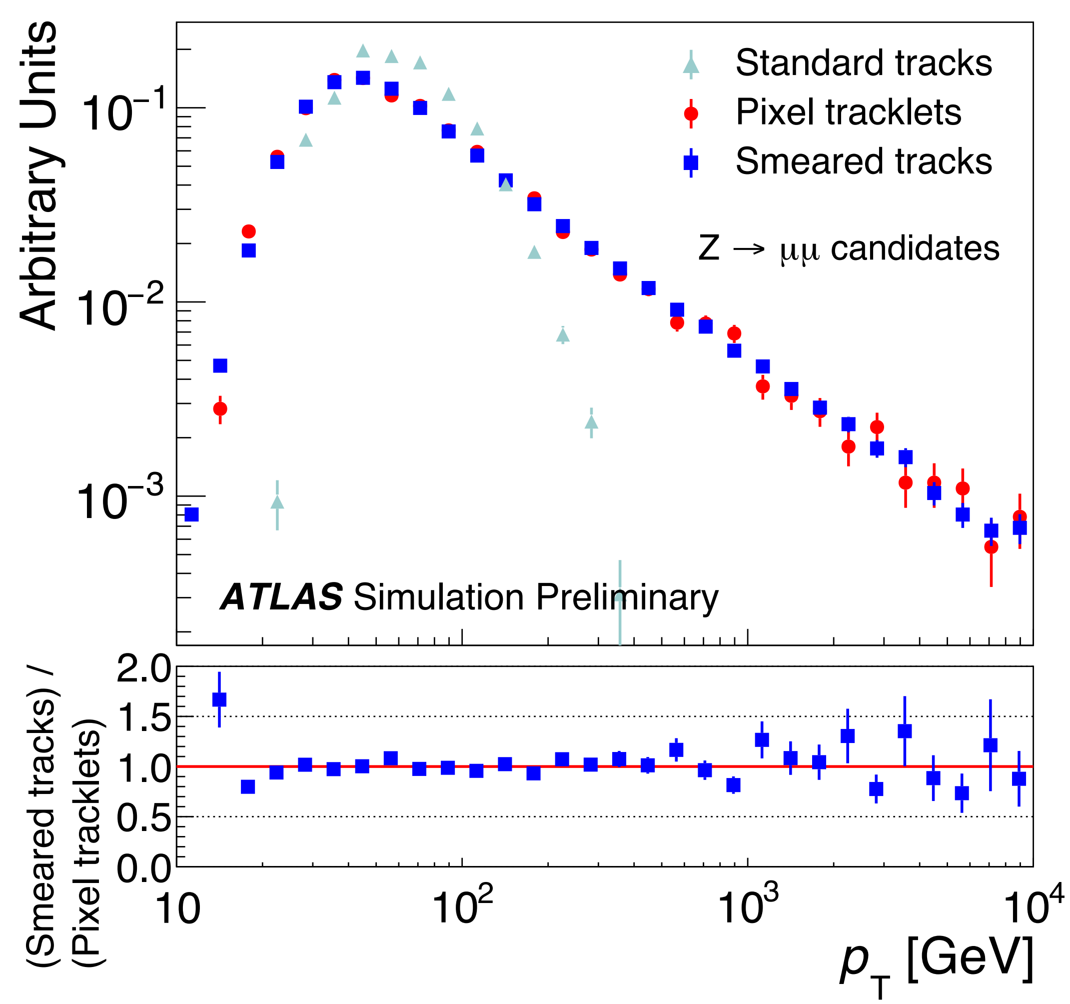
To estimate BG, we need to obtain p_T distribution of pixel-only tracks.

p_T distribution of standard tracks

↓ Smearing (obtained from $Z \rightarrow \mu\mu$)

p_T distribution of pixel-only tracks





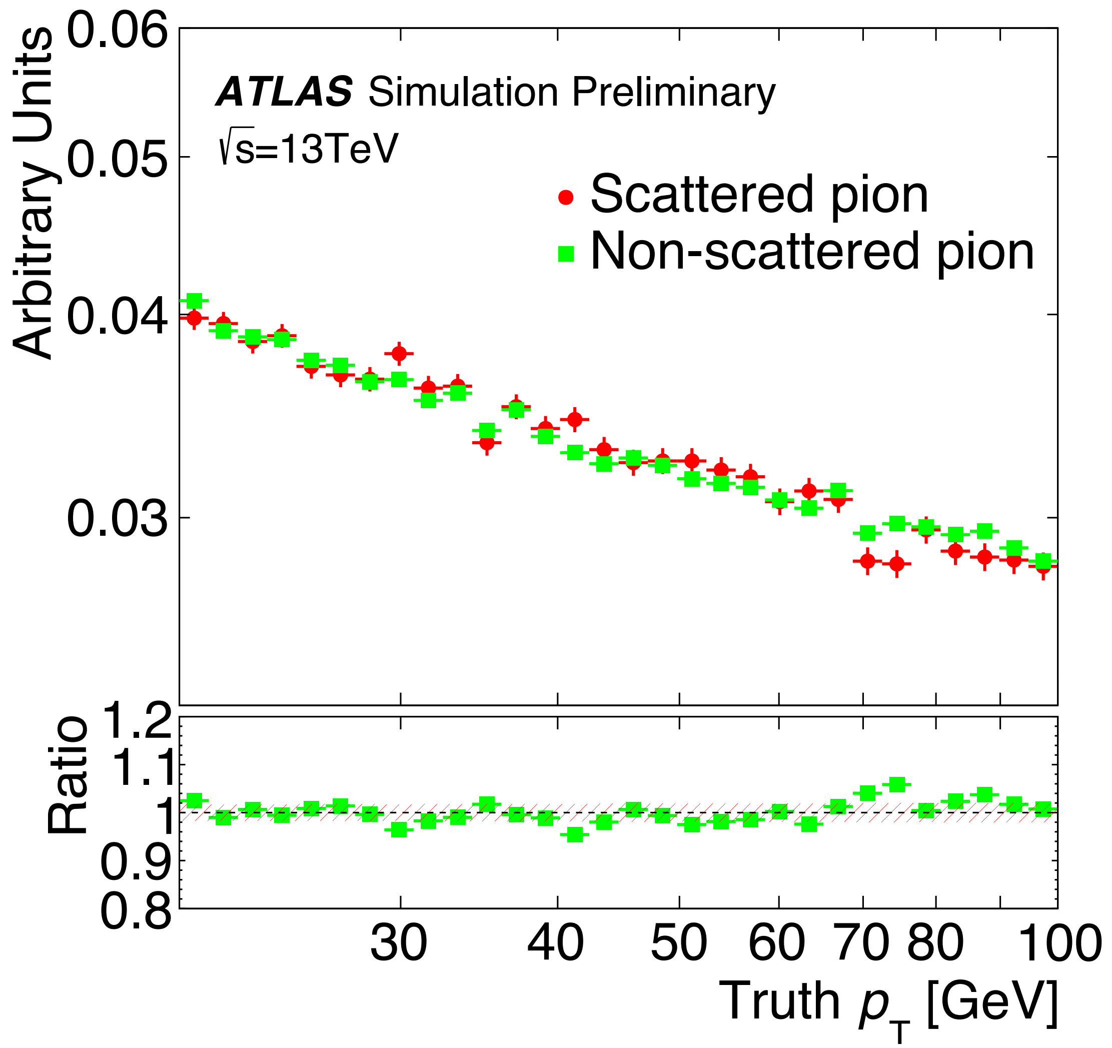
Look into difference between standard and pixel-only tracks.

Background estimation

Hadron background

Determine the p_T distribution shape in the control region, and smear it to obtain that in the signal region.

The p_T distribution of scattered hadrons is the same as that of non-scattered hadrons (simulations).



Background estimation

Lepton background

Use one-lepton events.

p_T distribution of the lepton control sample

↓ Transfer factor R (probability for a lepton to pass the disappearing track selection)

Smear p_T spectrum by using a smear function

Transfer factor

Tag-and-probe method using $Z \rightarrow \mu\mu$

Tag: well-identified electron

Probe: energy cluster in the calorimeter with an associated track satisfying the quality, isolation, p_T criteria.

$$R = \frac{\text{\# of probes yielding a disappearing track}}{\text{\# of total probes}}$$

Similar procedure for muons.

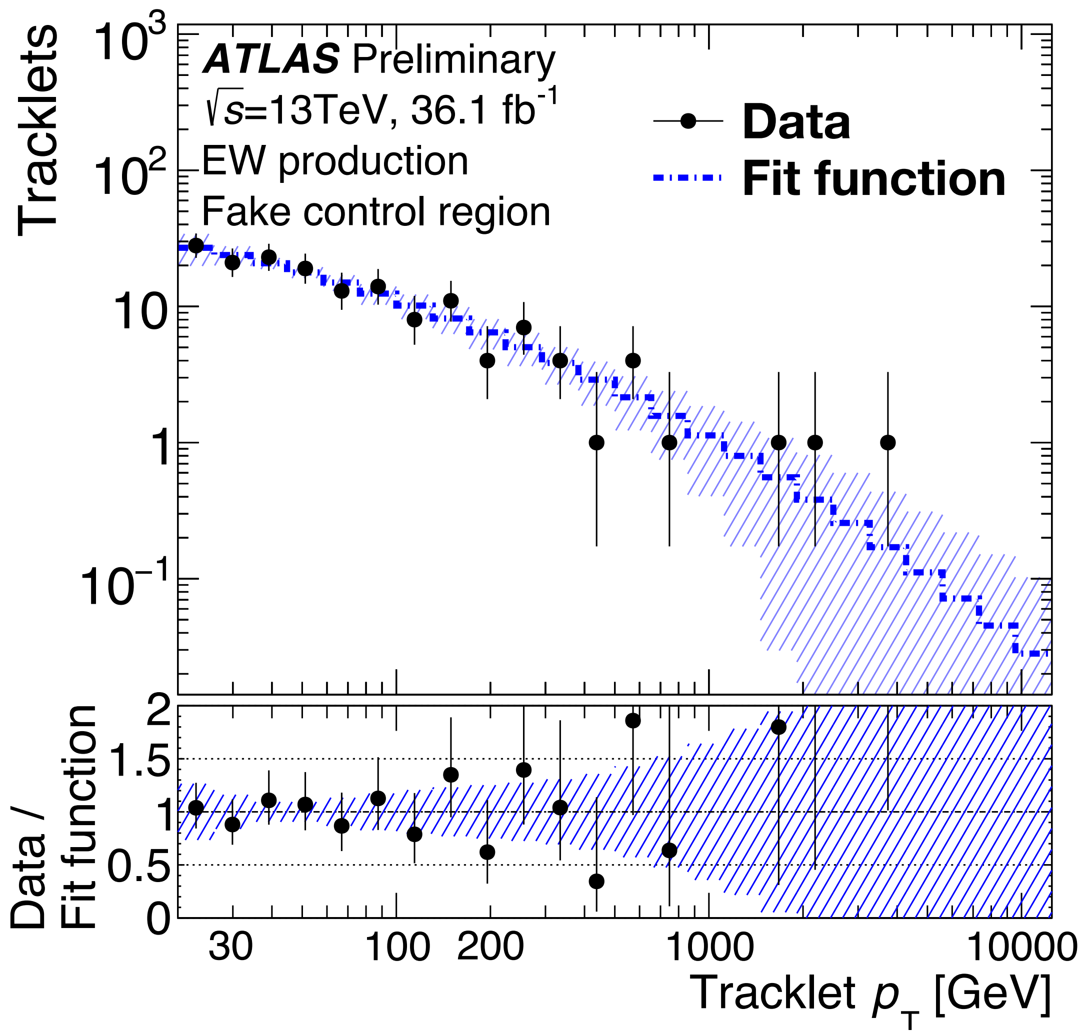
Background estimation

Fake tracks

These tracks tend to have a large impact parameter.

- $|d_0|/\sigma(d_0) > 10$
- Without E_T^{miss} requirement

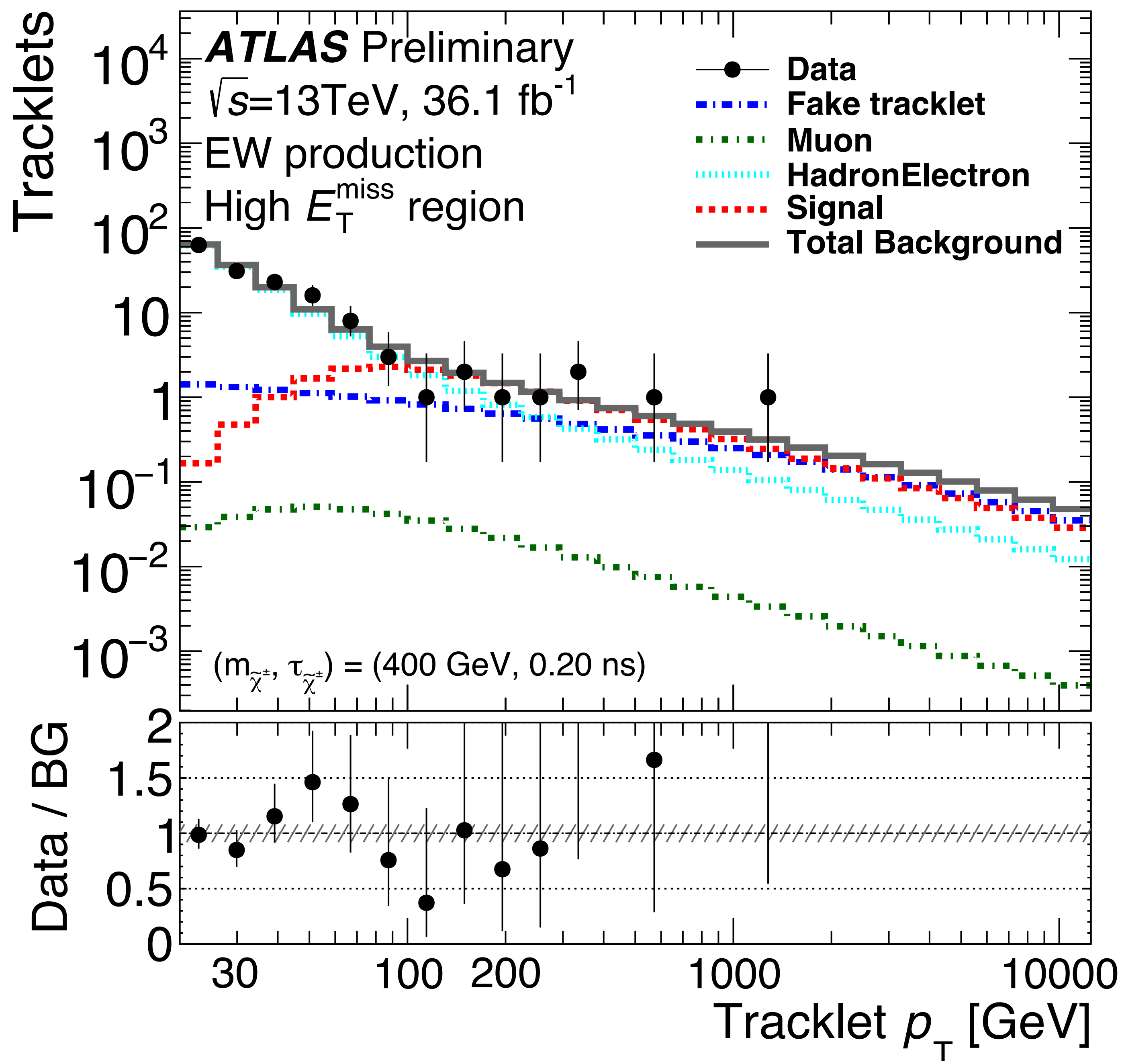
Fit the following empirical function: $f(p_T) = \exp\left(-p_0 \log(p_T) - p_1 (\log(p_T))^2\right)$



No E_T^{miss} dependence was found.

Small $|d_0|/\sigma(d_0)$ dependence is taken into account as uncertainty.

Results



No excess has been observed!

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Results

High $E_{\mathrm{T}}^{\mathrm{miss}}$ region	Electroweak channel $(m_{\tilde{\chi}_1^{\pm}}, \tau_{\tilde{\chi}_1^{\pm}})$ =(400 GeV, 0.2 ns)	Strong channel $(m_{\tilde{g}}, m_{\tilde{\chi}_1^{\pm}}, \tau_{\tilde{\chi}_1^{\pm}})$ =(1600 GeV, 500 GeV, 0.2 ns)
Number of observed events with $p_{\mathbf{T}} > 100$ GeV		
Observed	9	2
Number of expected events with $p_{\mathbf{T}} > 100$ GeV		
Hadron+electron background	6.1 ± 0.6	2.08 ± 0.35
Muon background	0.1549 ± 0.0022	0.0385 ± 0.0005
Fake background	5.5 ± 3.3	0.0 ± 0.8
Total background	11.8 ± 3.1	2.1 ± 0.9
Expected signal	10.4 ± 1.7	4.1 ± 0.5
CL_b	0.39	0.702
Observed $\sigma_{\mathrm{vis}}^{95\%}$ [fb]	0.22	0.14
Expected $\sigma_{\mathrm{vis}}^{95\%}$ [fb]	$0.24^{+0.10}_{-0.07}$	$0.11^{+0.06}_{-0.04}$

No excess has been observed!

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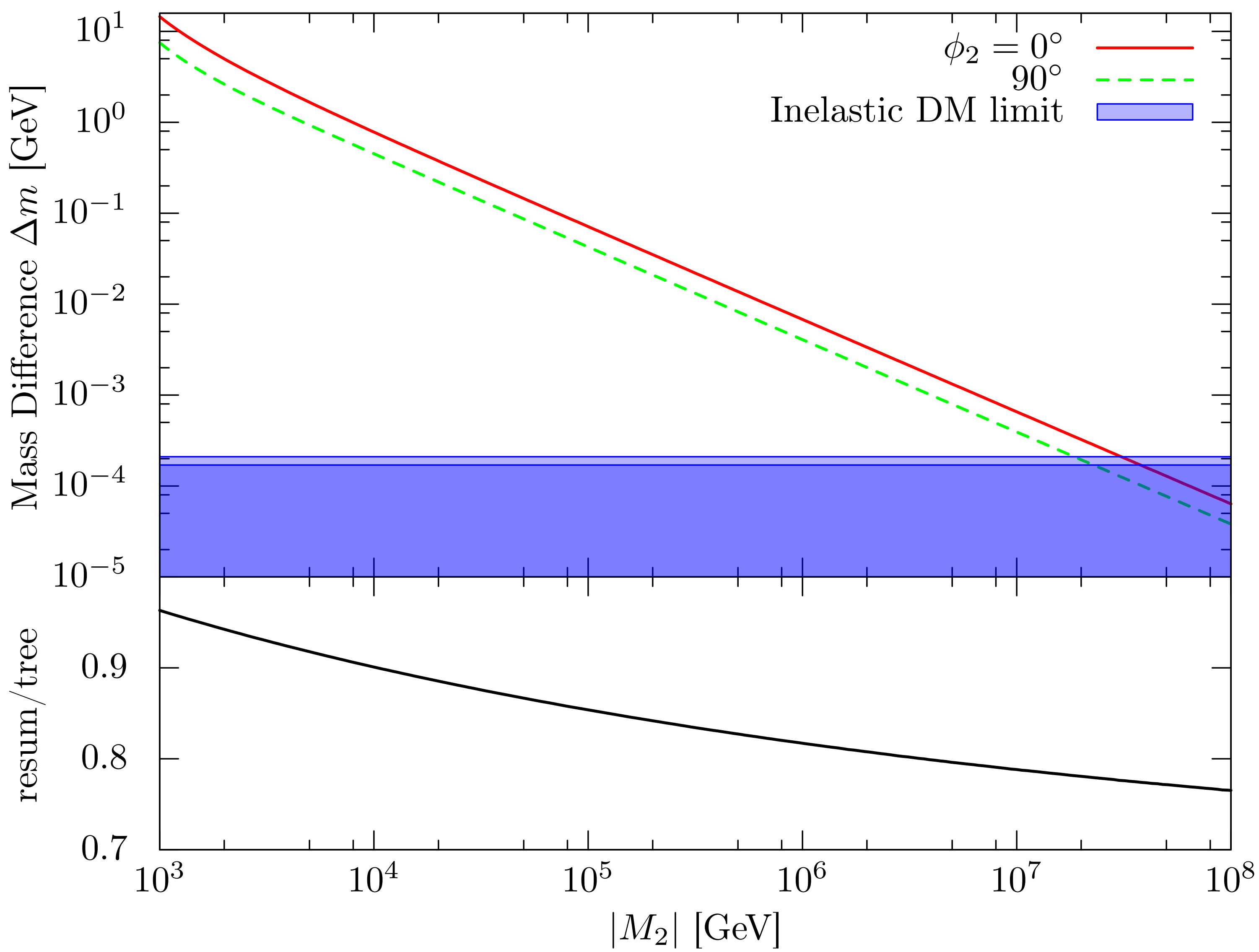
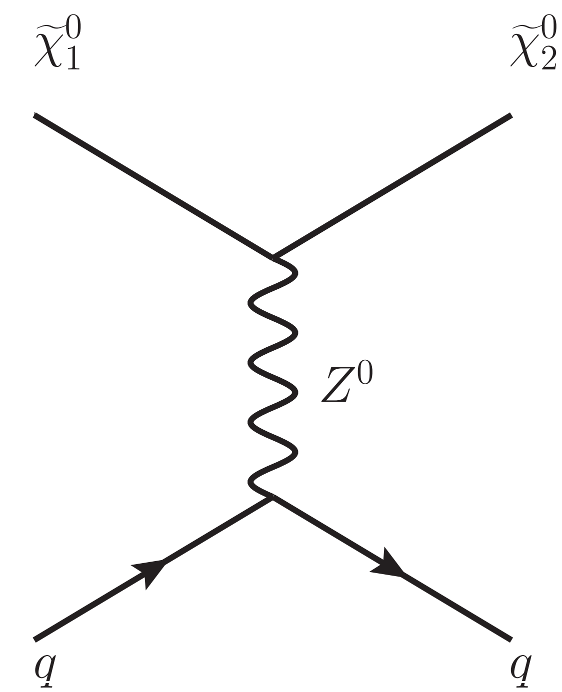
Inelastic scattering bound

There is an upper bound on the gaugino masses from the inelastic scattering bound.





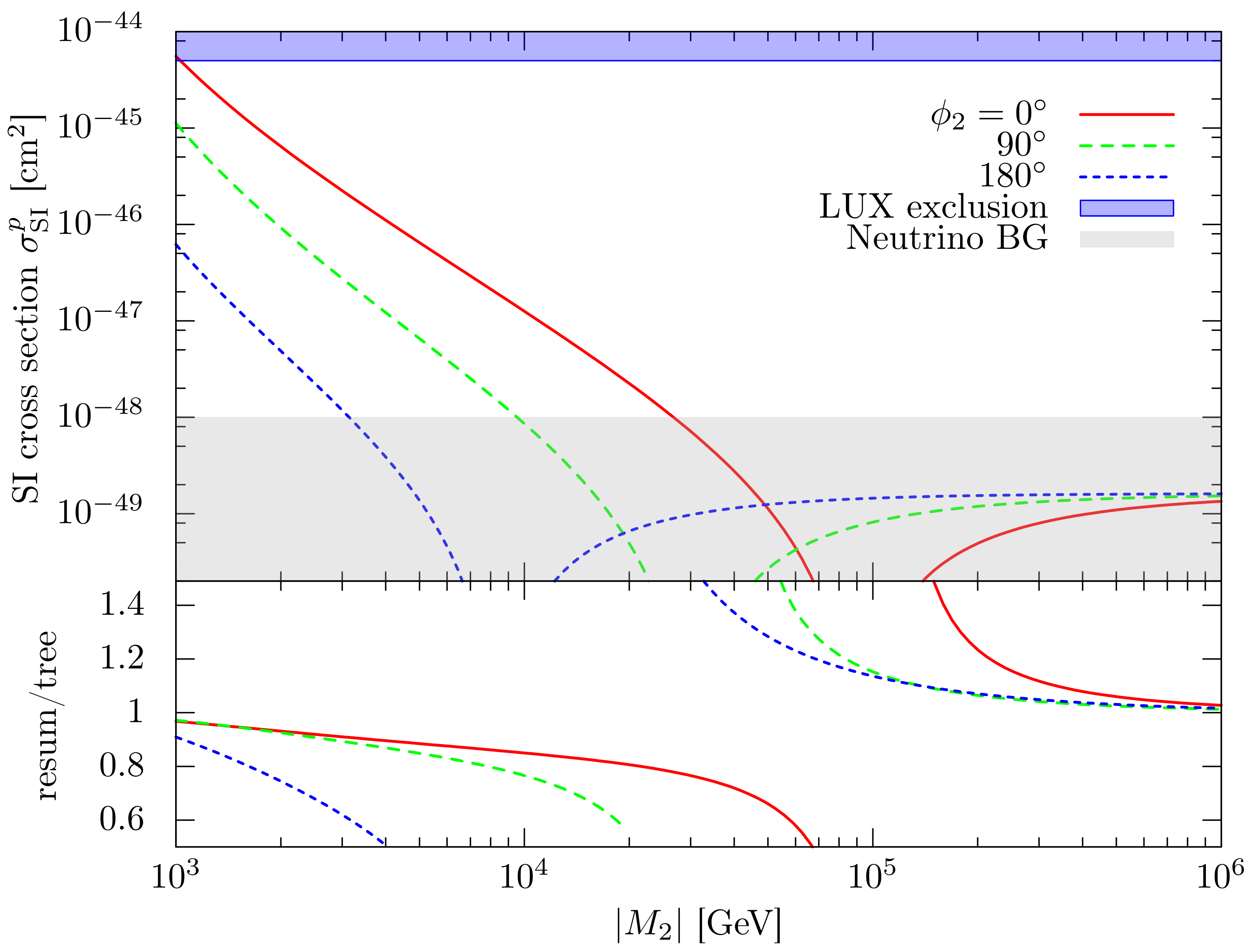
$$\phi_2 = \arg(M_2\mu)$$

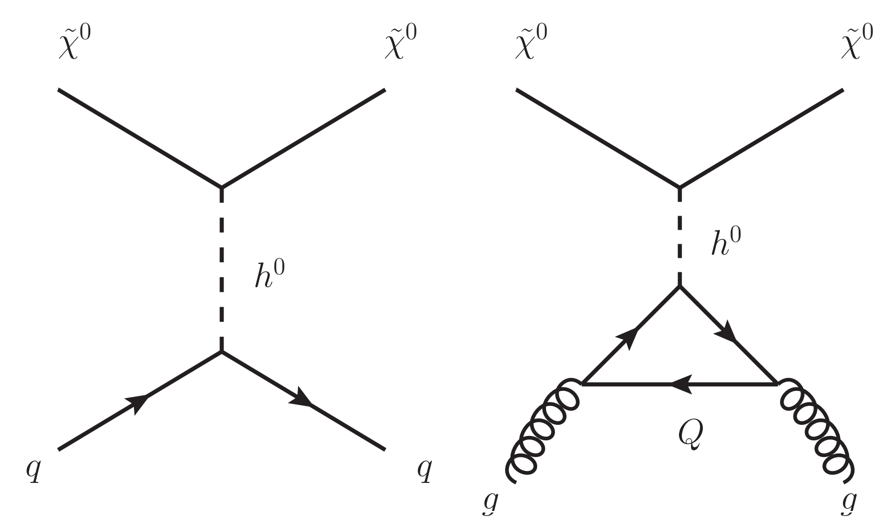
$$\tan\beta = 2,\ \mu = 500\ \mathrm{GeV},\ M_1 = M_2$$

Gaugino masses should be smaller than $\sim 10^4$ TeV.

N. Nagata and S. Shirai, JHEP **1501**, 029 (2015).

Direct detection





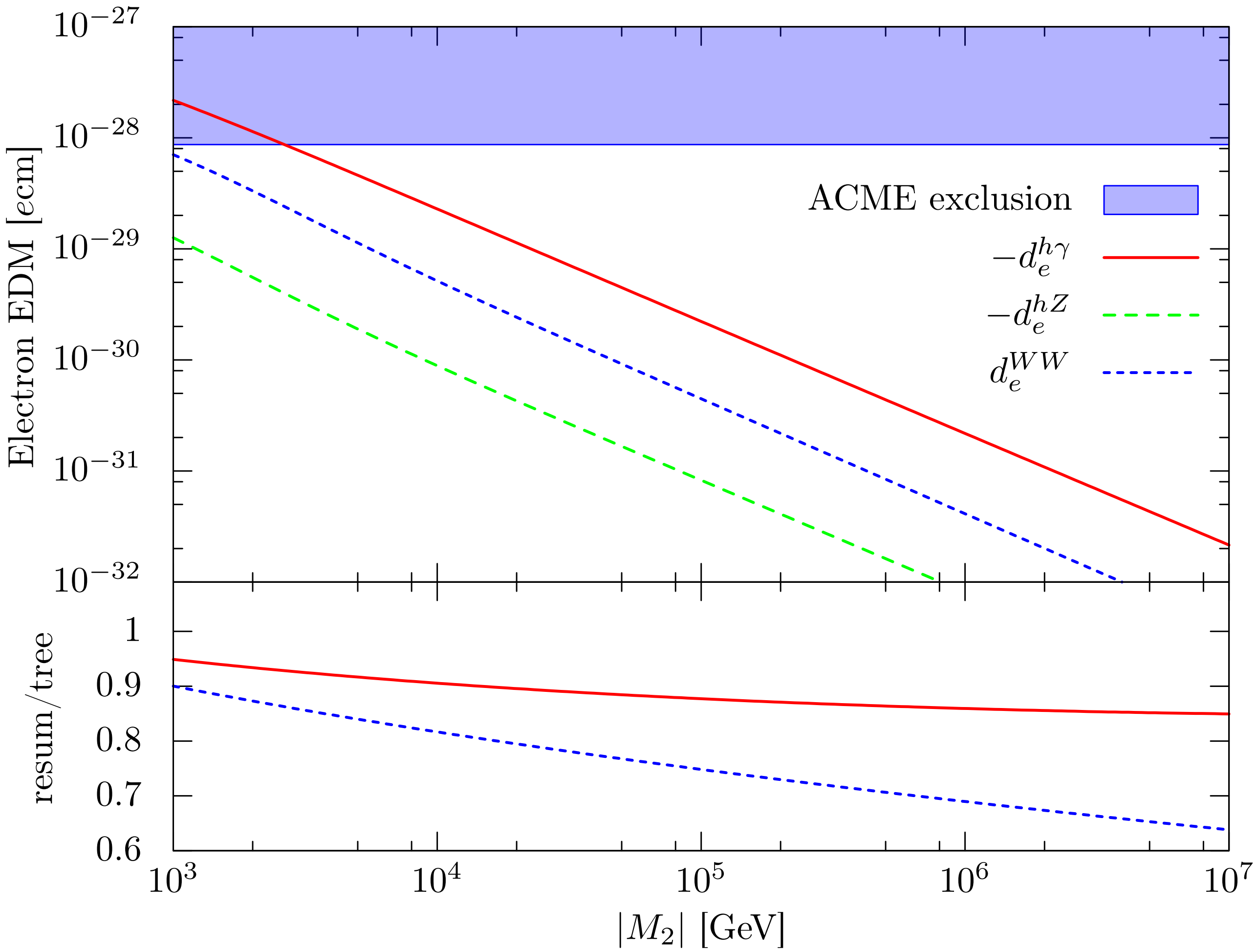
$$\phi_2 = \arg(M_2\mu)$$

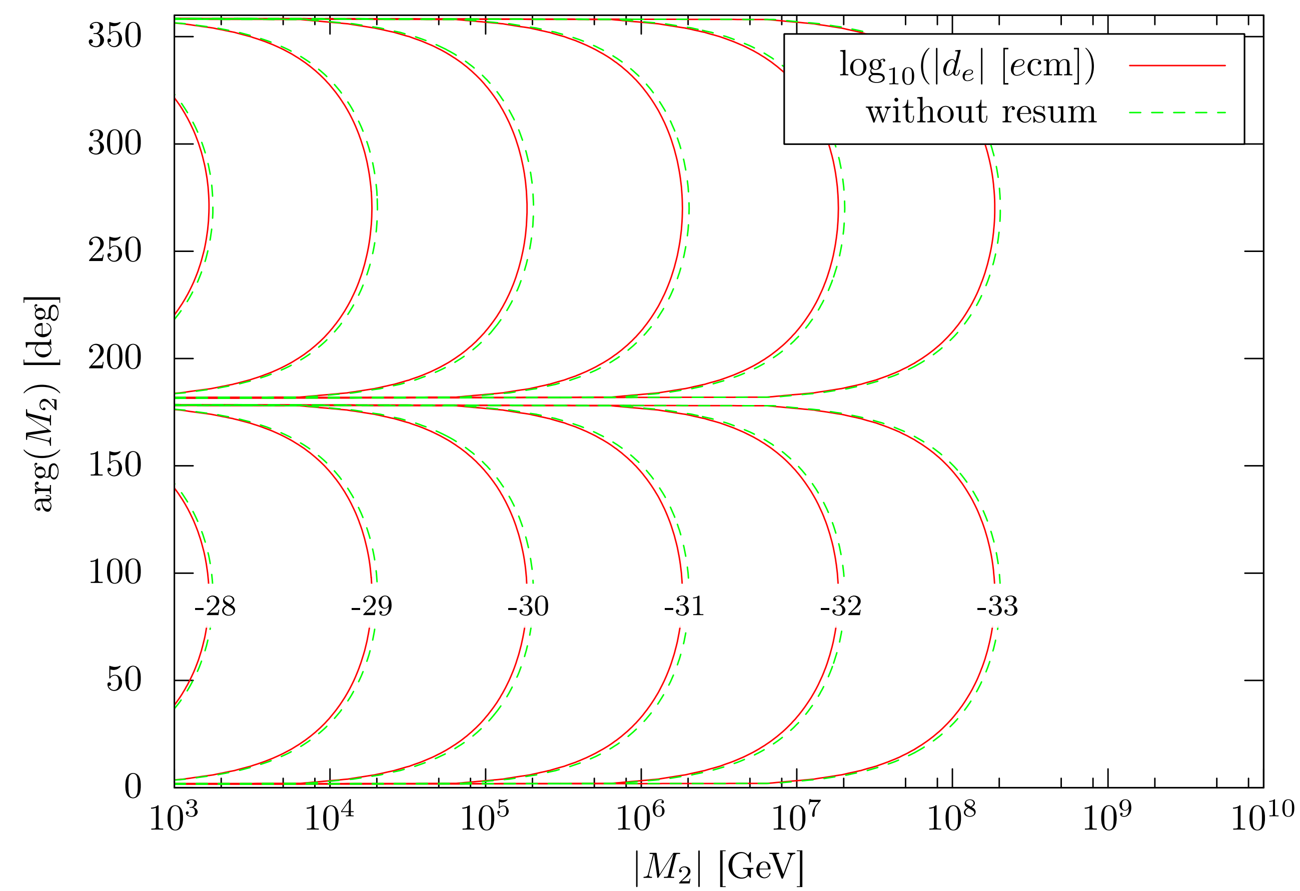
$$\tan\beta = 2,\ \mu = 500\ \text{GeV},\ M_1 = M_2$$

- SI cross section significantly depends on the CP phase.
- Direct detection experiments now start probing this scenario.

N. Nagata and S. Shirai, JHEP **1501**, 029 (2015).

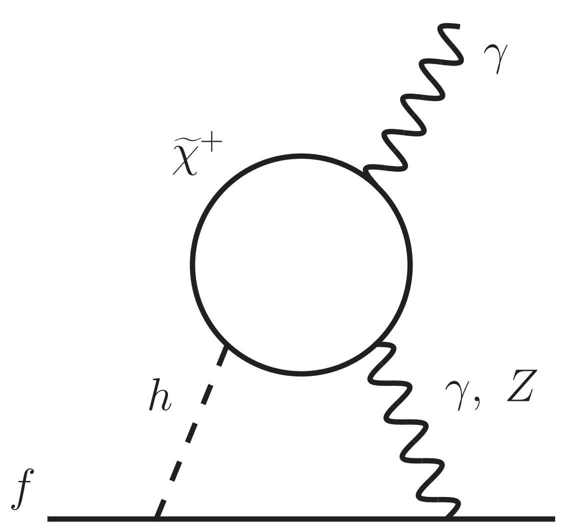
EDMs

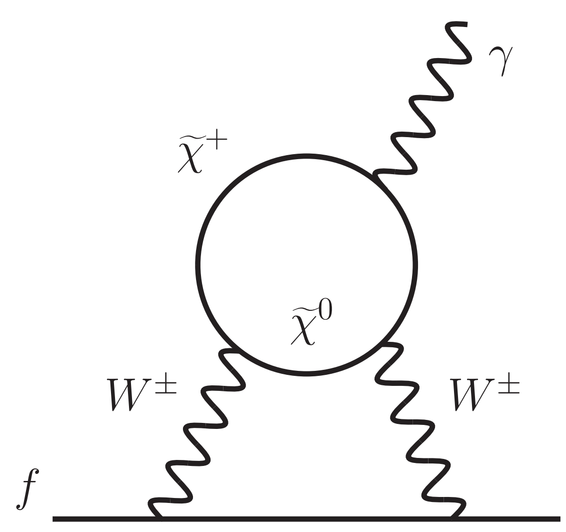




$$\tan\beta = 2,\ \mu = 500\ \text{GeV},\ M_1 = M_2$$

$$\arg(\mu) = 0,\quad \arg(M_2) = \pi/2$$

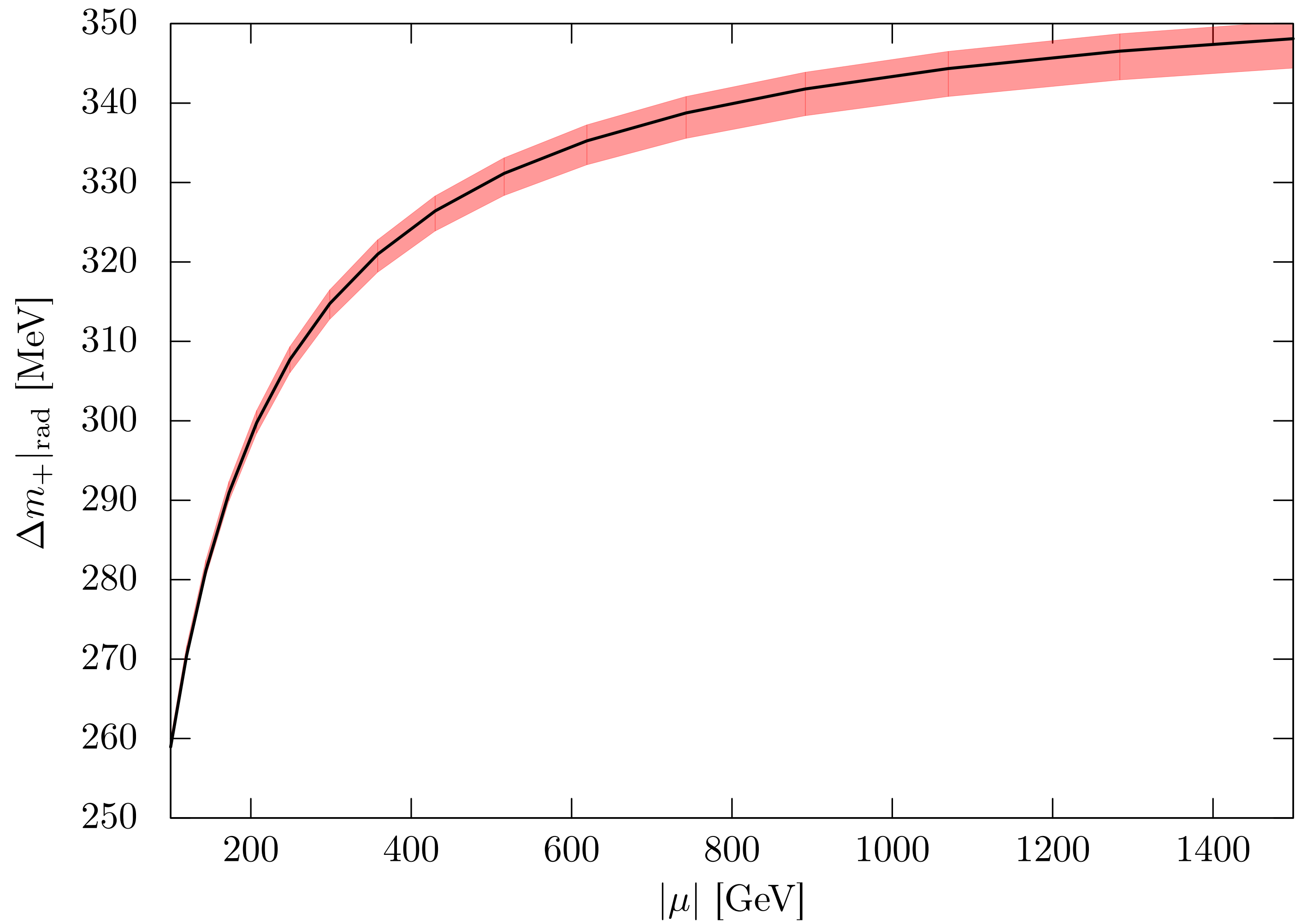




EDM bound has already restricted parameter space.

N. Nagata and S. Shirai, JHEP **1501**, 029 (2015).

Radiatively induced mass splitting



Lifetime

$$c\tau \simeq 0.7\ \text{cm} \times \left[\left(\frac{\Delta m}{340\ \text{MeV}} \right)^3 \sqrt{1 - \frac{m_\pi^2}{\delta m^2}} \right]^{-1}$$