Probing metastable gluinos at the LHC

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Olivefest
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University of Minnesota

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1. Introduction

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.

Are there good SUSY models which are consistent with these observations?

Can we probe such models??

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;

Gravitino

Scalar Particles

Higgsinos

Extra matters

O($10^{2\text{-}3}$) TeV

125 GeV Higgs mass is realized.

Gauginos

Gluino

Bino

Wino

O(1) TeV

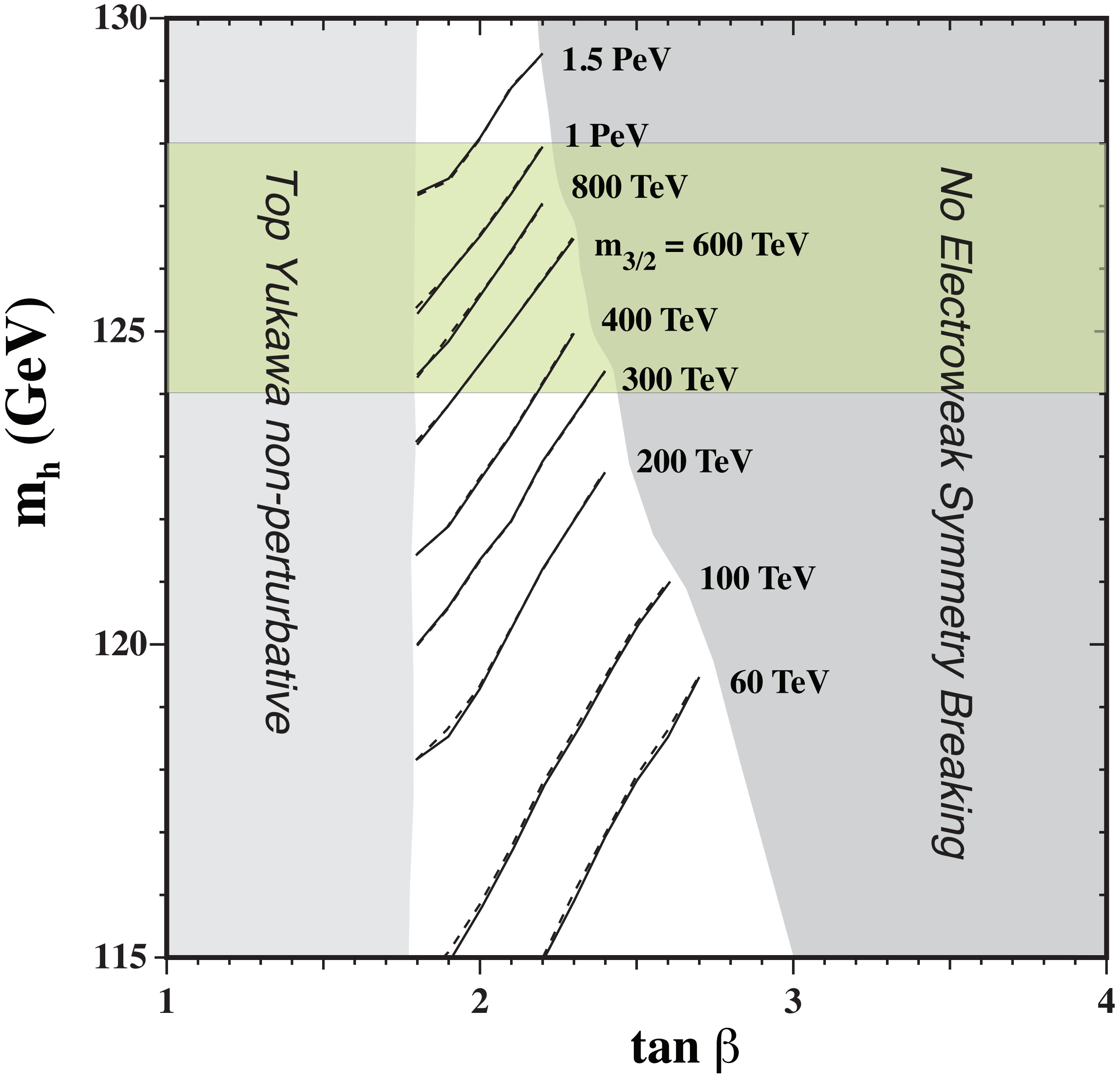
Gaugino masses are induced at loop level.

- Anomaly mediation
- Threshold corrections (Higgsinos, extra matters, …)

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

Pure Gravity Mediation

Even the simplest setup is still promising.



J. L. Evans, M. Ibe, K. A. Olive, T. T. Yanagida (2013).

- Universal scalar mass: $m_0 = m_{3/2}$
- Gaugino masses: anomaly mediation
- A_0: negligibly small
- Giudice-Masiero term

G. F. Giudice and A. Masiero (1988).

Phenomenology is completely determined by

$$m_{3/2}, \quad \tan\beta, \quad \mathrm{sgn}(\mu)$$

Other extensions also work well.

J. L. Evans, M. Ibe, K. A. Olive, T. T. Yanagida (2013, 2014); J. L. Evans and K. A. Olive (2014).

Virtues of High-scale SUSY

- Evades SUSY flavor&CP problems.

  FCNC, EDMs are suppressed by heavy sfermion masses.

- Consistent with minimal SUSY GUT

  Gauge coupling unification is achieved. Dim-5 proton decay limit is relaxed.

  [*e.g.*, J. L. Evans, N. Nagata, K. A. Olive (2015)]

- Accommodates DM candidates

  Wino, bino-gaugino coannihilation, higgsino, ….

- 125 GeV Higgs boson mass

- Avoid cosmological problems Gravitino problem, etc…

High-scale SUSY models are phenomenologically viable and interesting.

Today's topic

Can we probe this class of models at the LHC??

Gauginos are relatively light.

➡ Nice target @ the LHC!

As we will see, long-lived gauginos often appear in these theories.

Talk plan

1. Introduction
2. Metastable gluino searches
3. Metastable wino searches
4. Conclusion

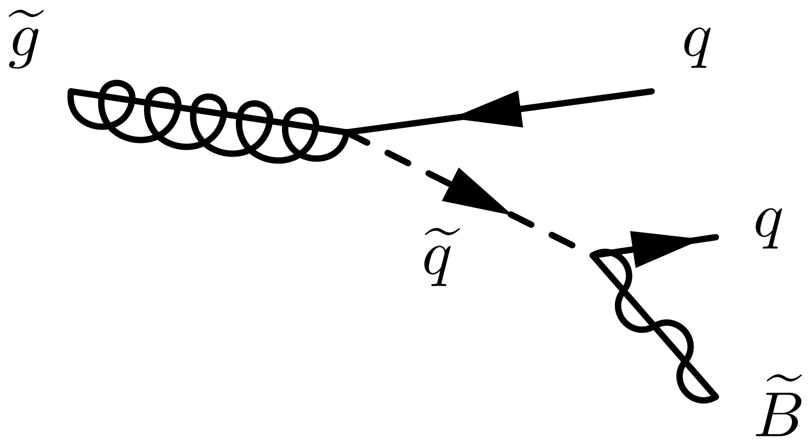
2. Metastable gluinos

Sub-millimeter displaced vertices

Based on H. Ito, O. Jinnouchi, T. Moroi, N. Nagata, and H. Otono [`arXiv:1702.08613`].

Gluinos in high-scale SUSY

When sfermion masses are heavy, gluinos tend to be long-lived.



$$c\tau_{\tilde{g}} \simeq 200\ \mu\mathrm{m} \times \left(\frac{m_{\tilde{q}}}{10^3\ \mathrm{TeV}}\right)^4 \left(\frac{2\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^5$$

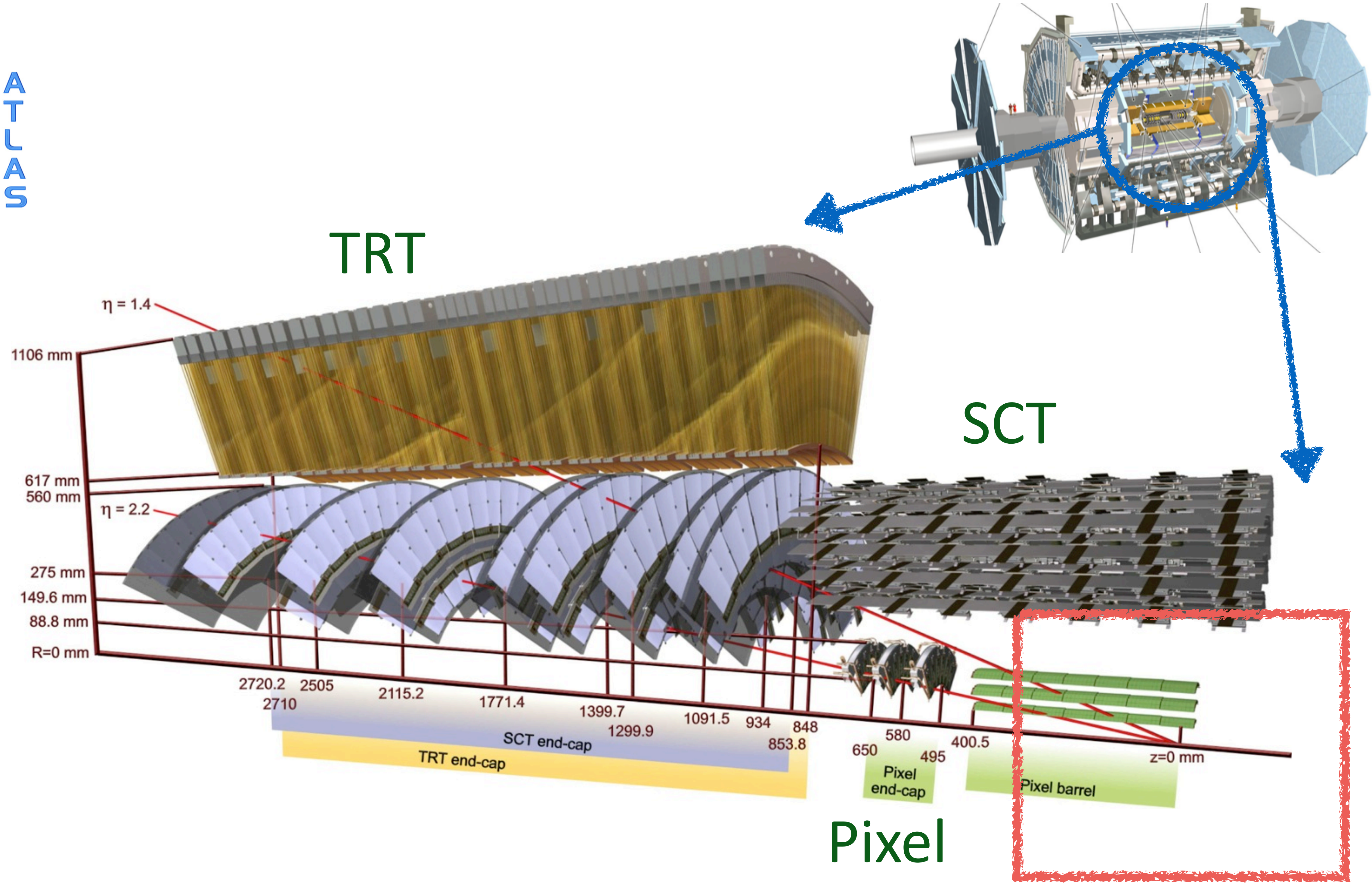
→ Displaced Vertex (DV)

In the minimal setup, squark masses are related to the gravitino mass (and thus the gluino mass).

→ This relation can be relaxed if squark masses are induced by generic Kahler potential terms with M* lower than the Planck scale.

$$\frac{1}{M_*^2}\int d^4\theta\, |Z|^2|Q|^2 \quad \Rightarrow \quad m_{\tilde{q}}^2 \simeq \frac{|F_Z|^2}{M_*^2} \gg m_{3/2}^2 \quad \text{for } M_* \ll M_P$$

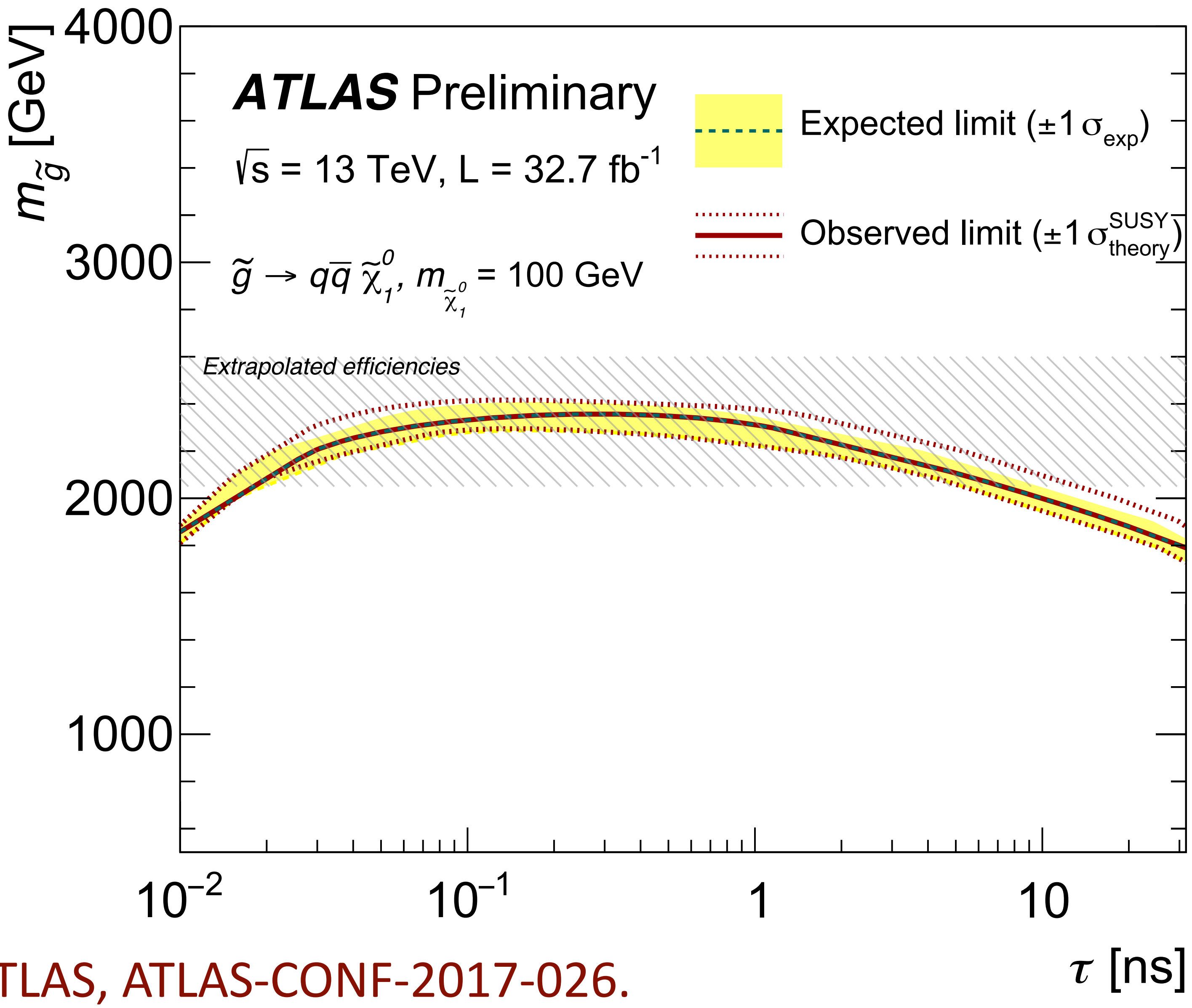
ATLAS Inner detector



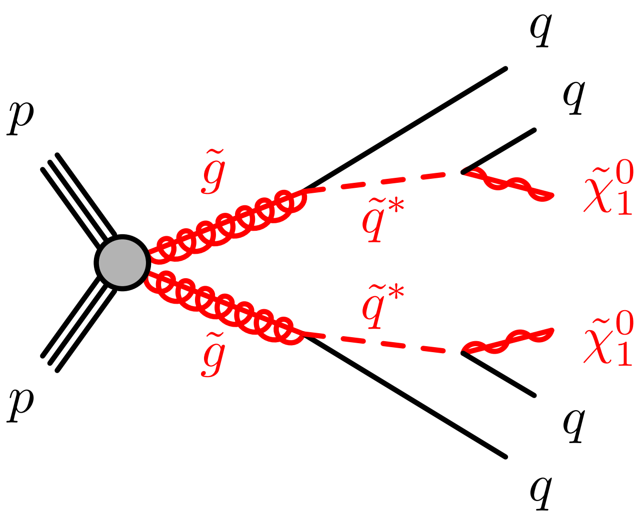
ATLAS has searched for DVs in the region of $|z|<30$ cm and $r < 30$ cm.

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

ATLAS DV + MET search



ATLAS, ATLAS-CONF-2017-026.



★ No SM background.

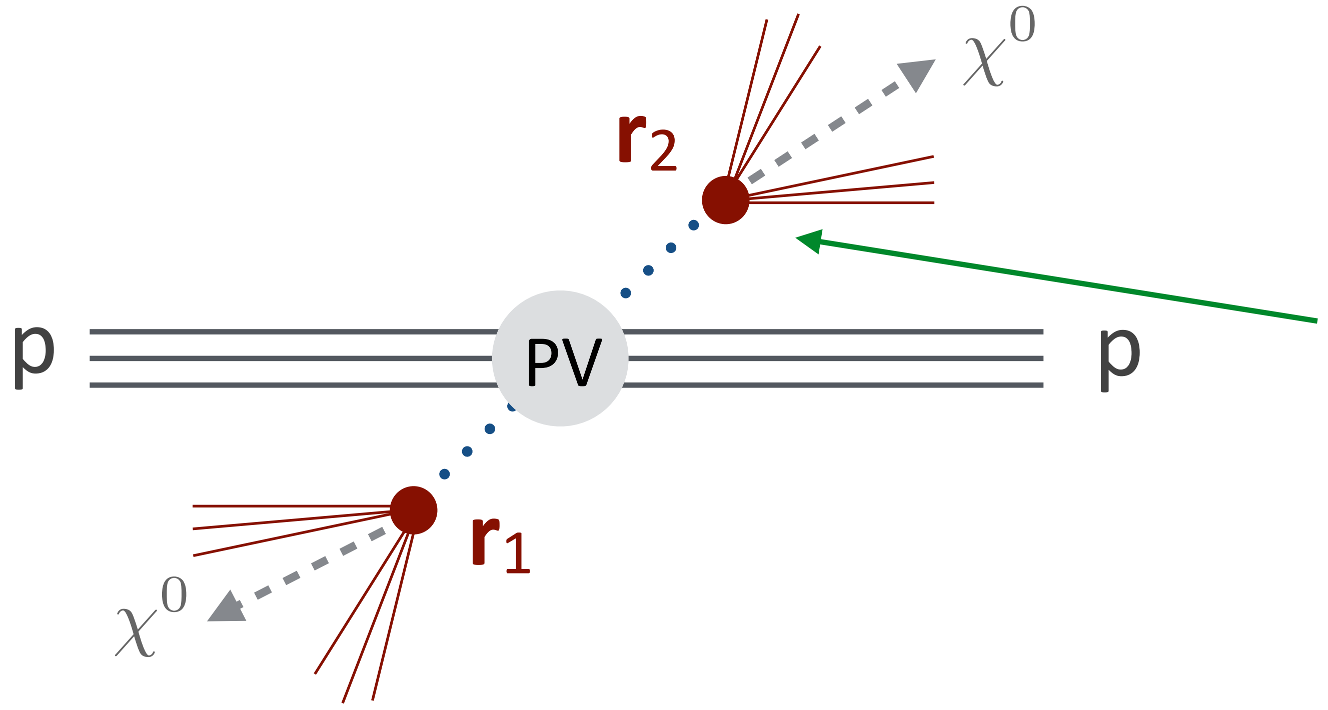
Strong limit from the DV search.

★ Stronger than the prompt search (~2 TeV).

However, the sub-millimeter region has not been probed in this search.

Our strategy

To probe the sub-millimeter DVs, we reconstruct them in a similar manner that is used for the primary vertex reconstruction.



Reconstructed in a similar way as the PV.

[O(10) μm accuracy]

Then, we impose a cut based on $|\mathbf{r}_1 - \mathbf{r}_2|$ in addition to the standard kinematical cuts for gluino searches.

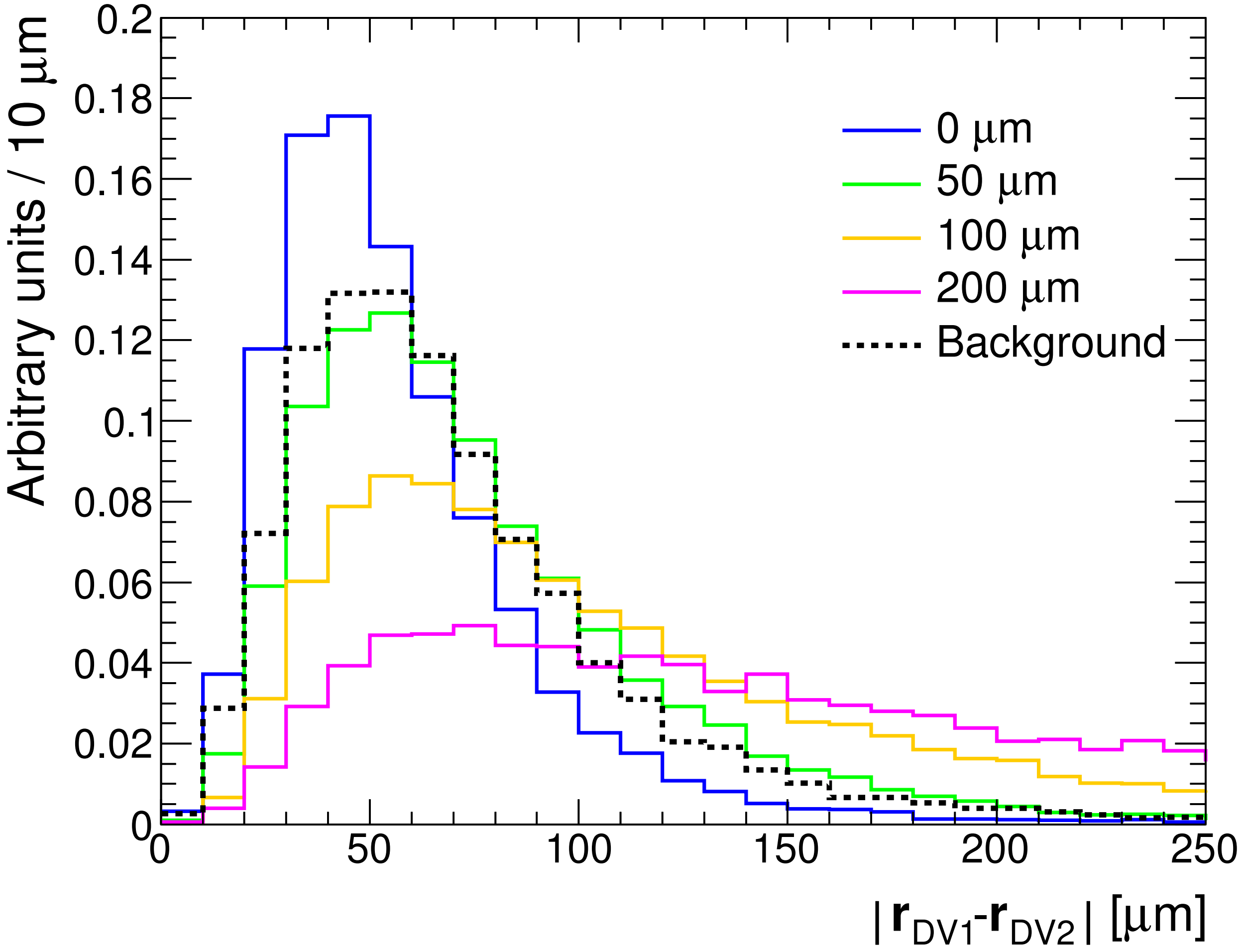
↑

Most of the BG events are eliminated with kinematical cuts.

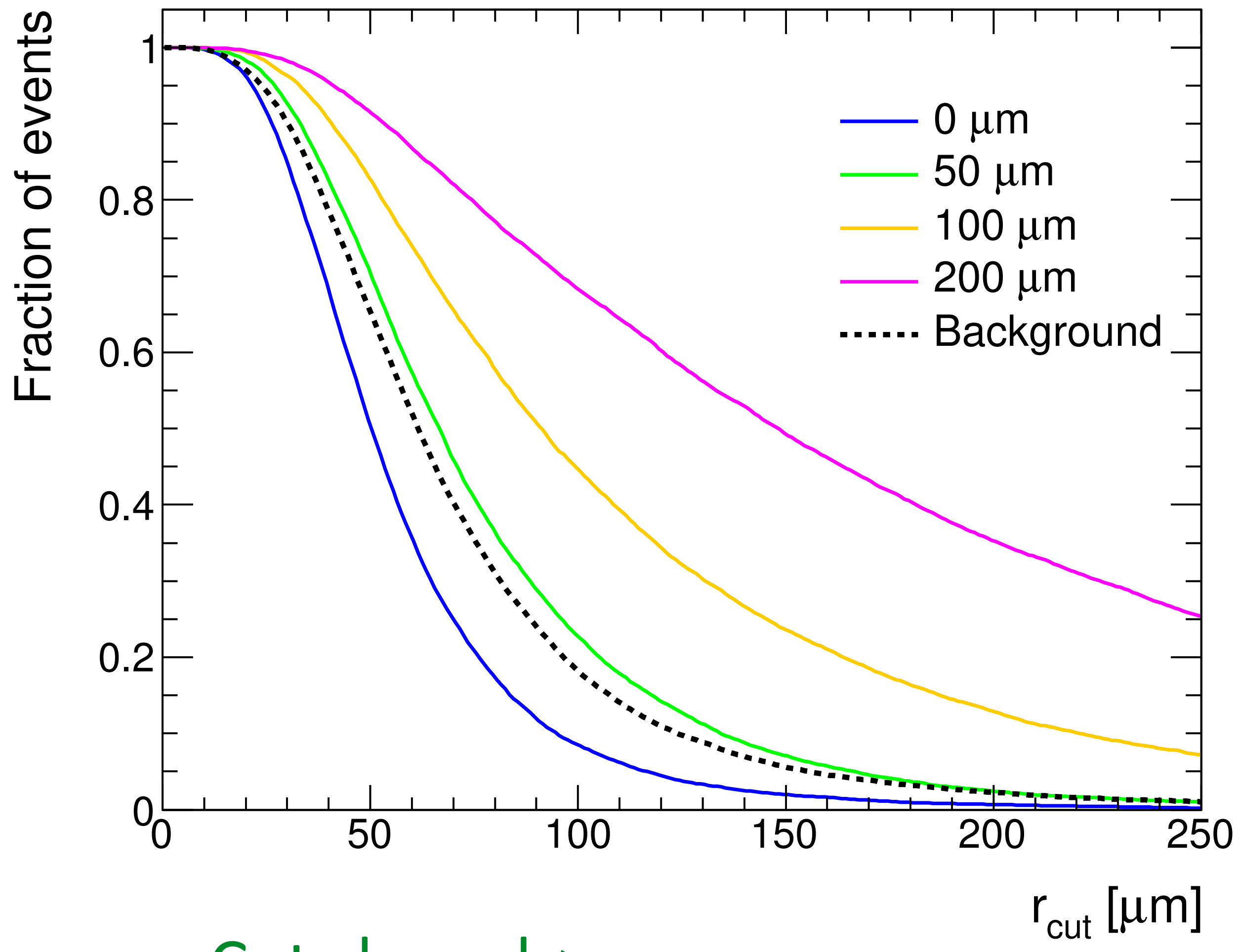
DV cuts

`MadGraph5_aMC@NLO v2`
`PYTHIA v8.2`
`DELPHES v3`

Distributions



Efficiency



Cut: |$\mathbf{r}_1$-$\mathbf{r}_2$| > r_{cut}

- Kinematic selection cut: **`Meff-4j-2600`**
- Gluino mass: 2.2 GeV
- LSP mass: 100 GeV.

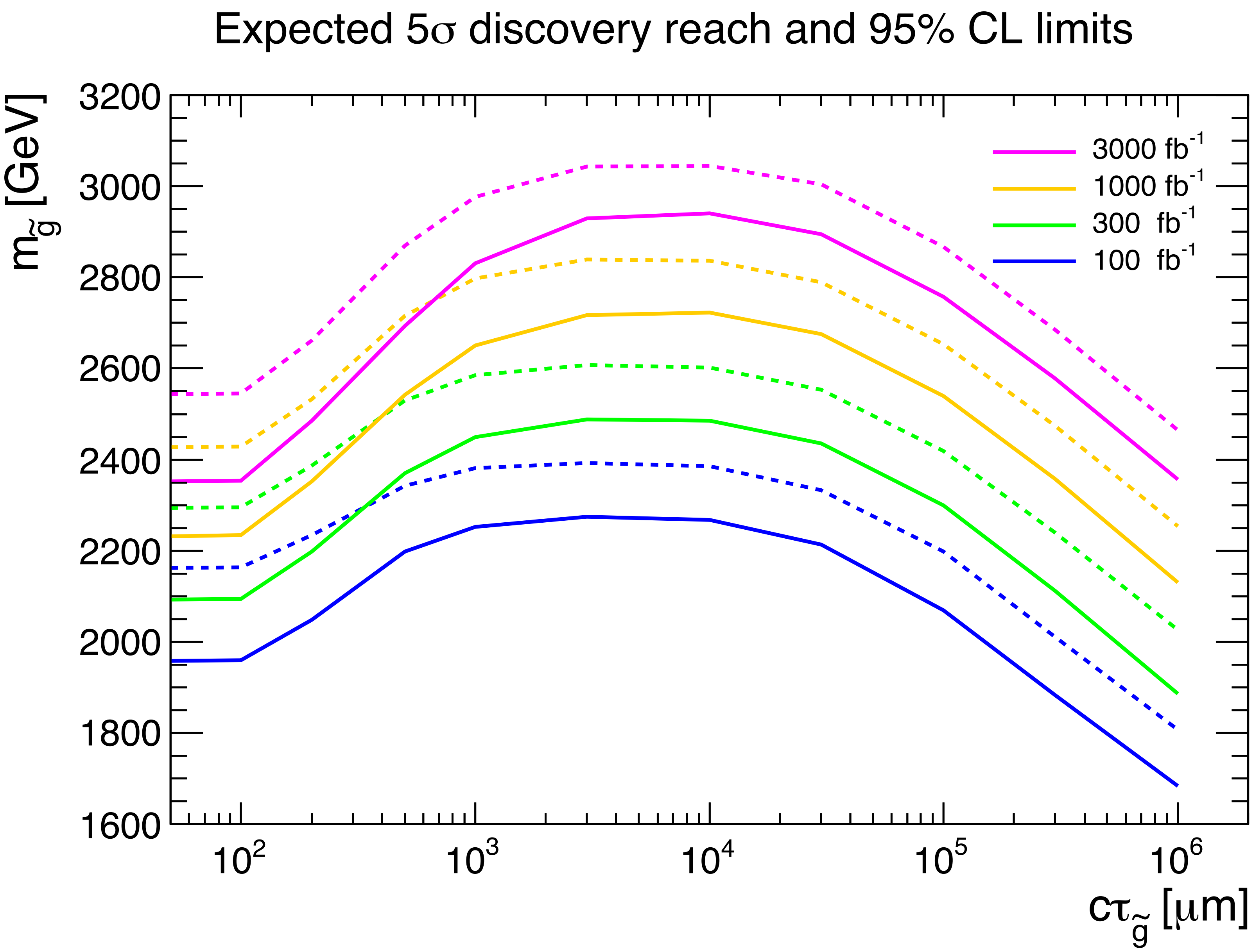
ATLAS-CONF-2016-078.

Gluinos are assumed to decay into the first generation quarks.

O(100) μm DVs can be discriminated from the PV.

H. Ito, O. Jinnouchi, T. Moroi, N. Nagata, and H. Otono [`arXiv:1702.08613`].

Prospects



13 TeV LHC

LSP mass: 100 GeV

`Meff-4j-2600` ATLAS-CONF-2016-078.

cτ = 0 corresponds to the reach of the prompt decaying gluino search.

$r_{\text{cut}} \sim 200\ \mu\text{m}$ for $\mathcal{L} = 100\ \text{fb}^{-1}$

$|d_0| < 10\ \text{mm} \quad |z_0| < 320\ \text{mm}$

The LHC reach can be significantly extended for gluinos with cτ > 100 μm.

Further optimization may improve this reach. (*e.g.*, Relax kinematical cuts.)

H. Ito, O. Jinnouchi, T. Moroi, N. Nagata, and H. Otono [`arXiv:1702.08613`].

2. Metastable gluinos

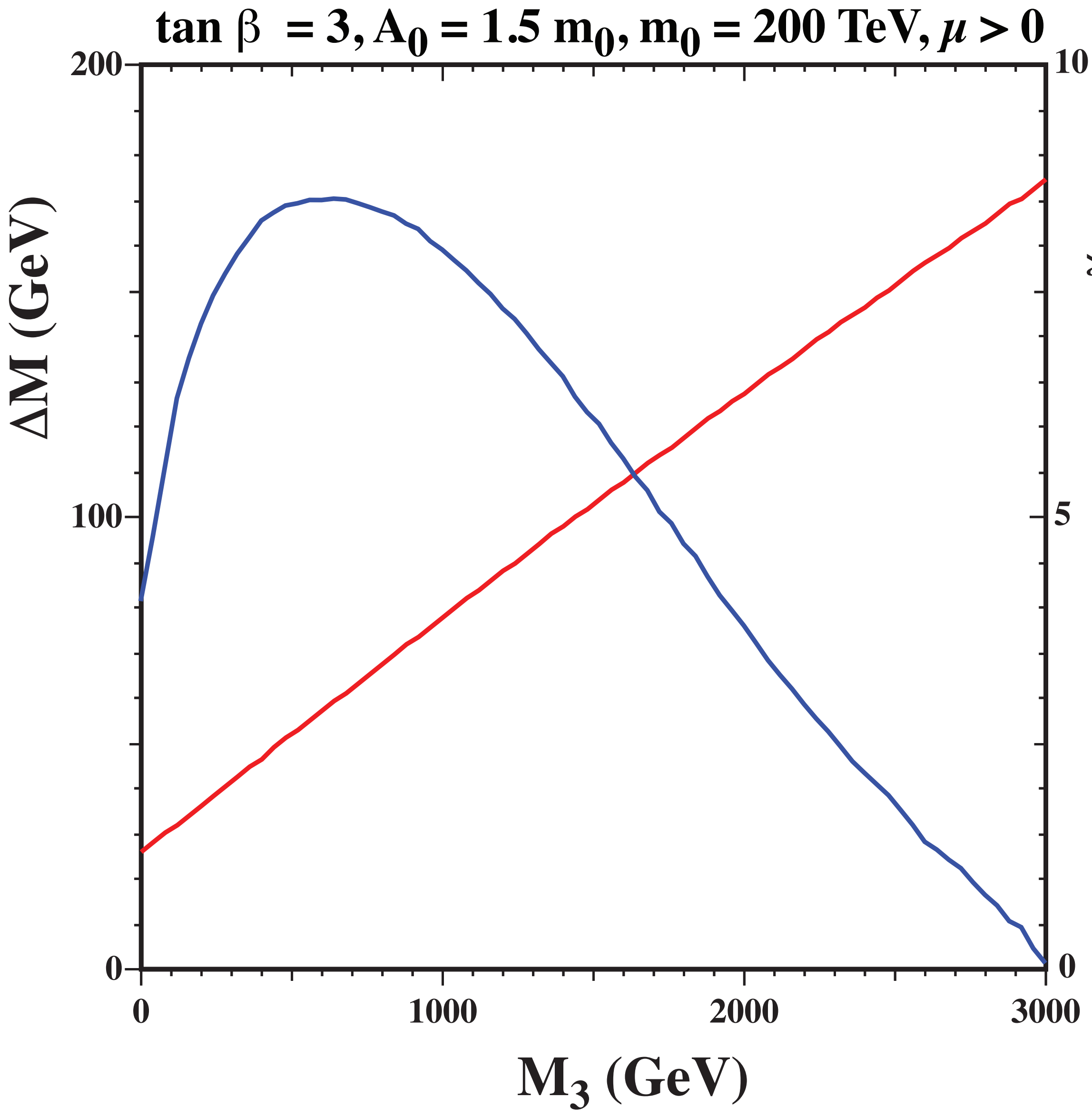
Bino-gluino coannihilation

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

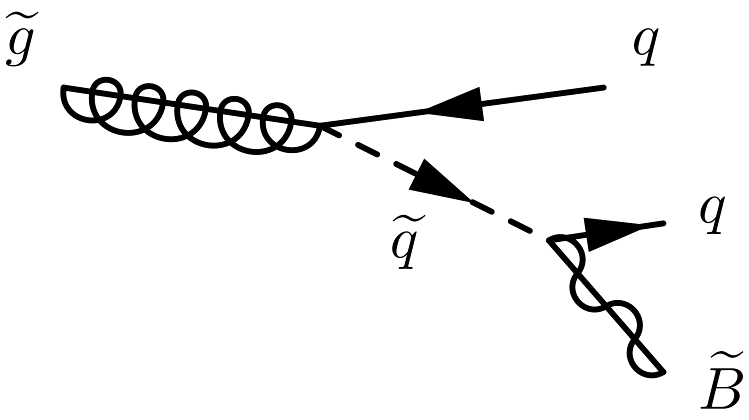
Bino-gluino coannihilation

Bino DM can explain the observed DM density if the bino is degenerate with gluino in mass (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)



J. Ellis, J. L. Evans, F. Luo, and K. A. Olive (2015).



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

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

Within the conventional DV search region.

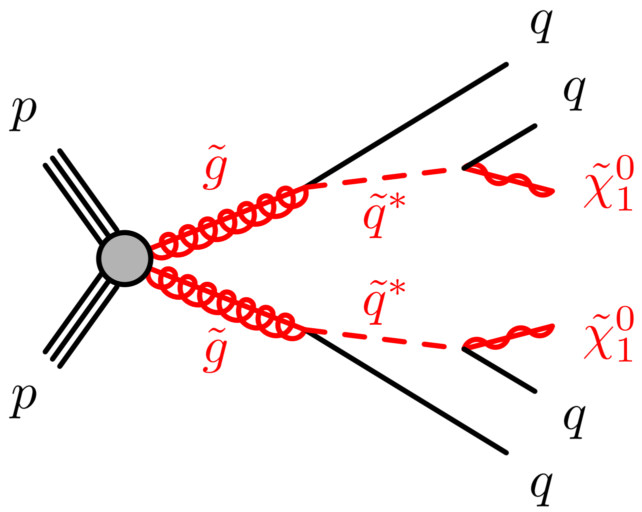
Our strategy

We cannot use the ATLAS DV search result as it is since they fixed the LSP mass to be 100 GeV.

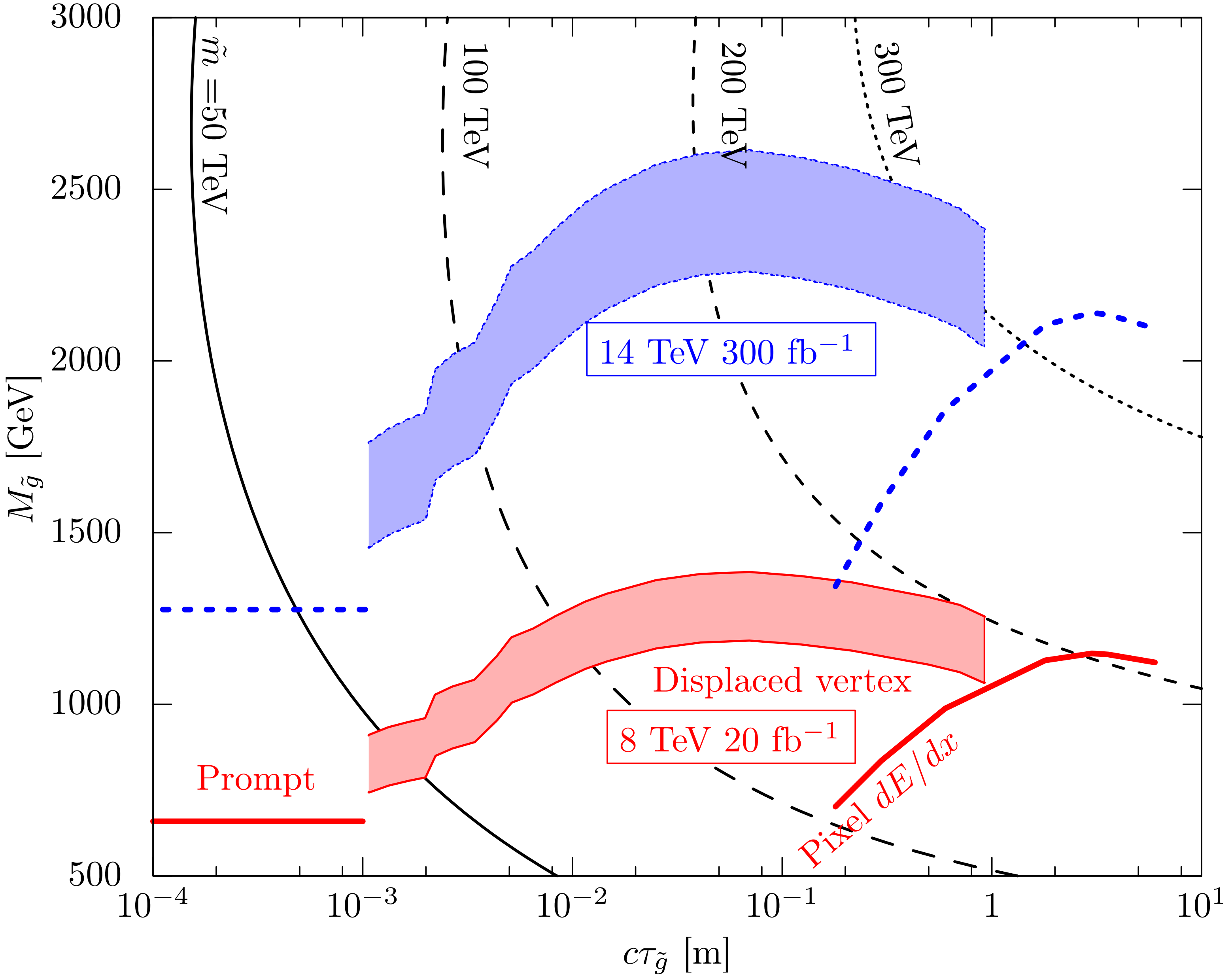
Small mass difference ➡ Inefficiency in trigger

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.



Prospects for the long-lived gluino search



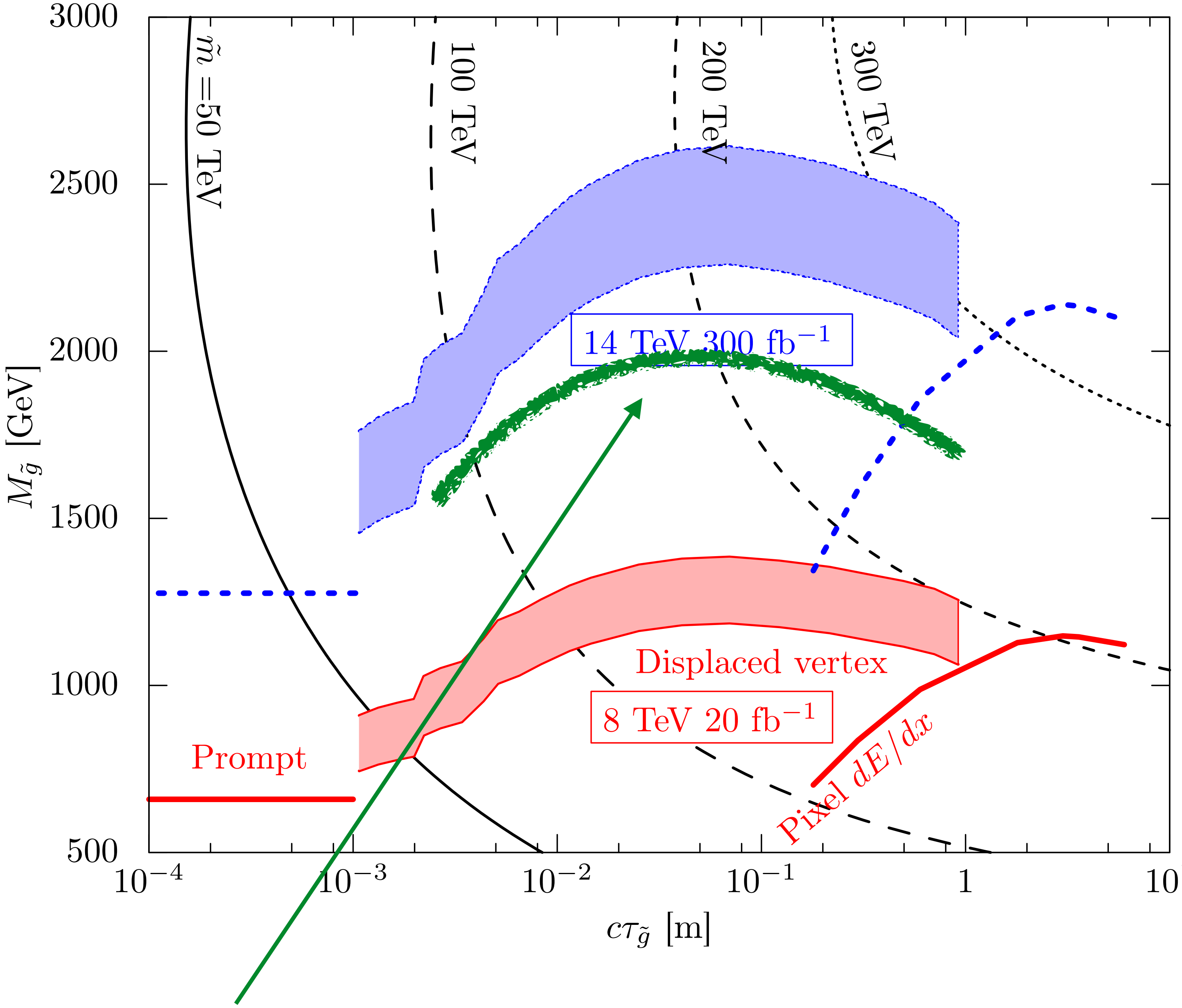
Δm = 100 GeV.

Reconstruction efficiency for DVs is varied between 20–100% compared to the previous ATLAS result.

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]

Prospects for the long-lived gluino search



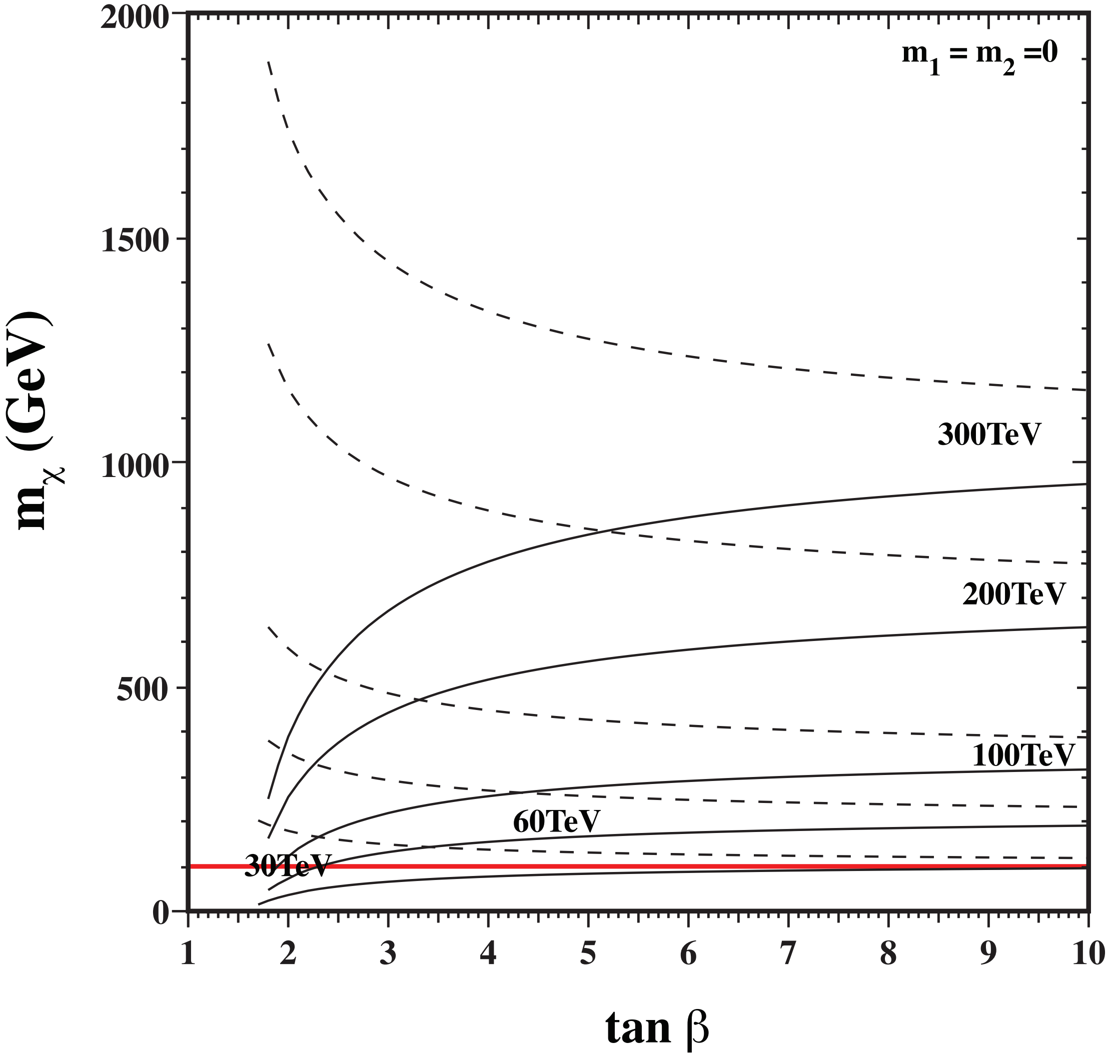
The ATLAS collaboration is now analyzing the small mass difference case (Δm = 100 GeV) for the 13 TeV 33 fb^{-1} data.

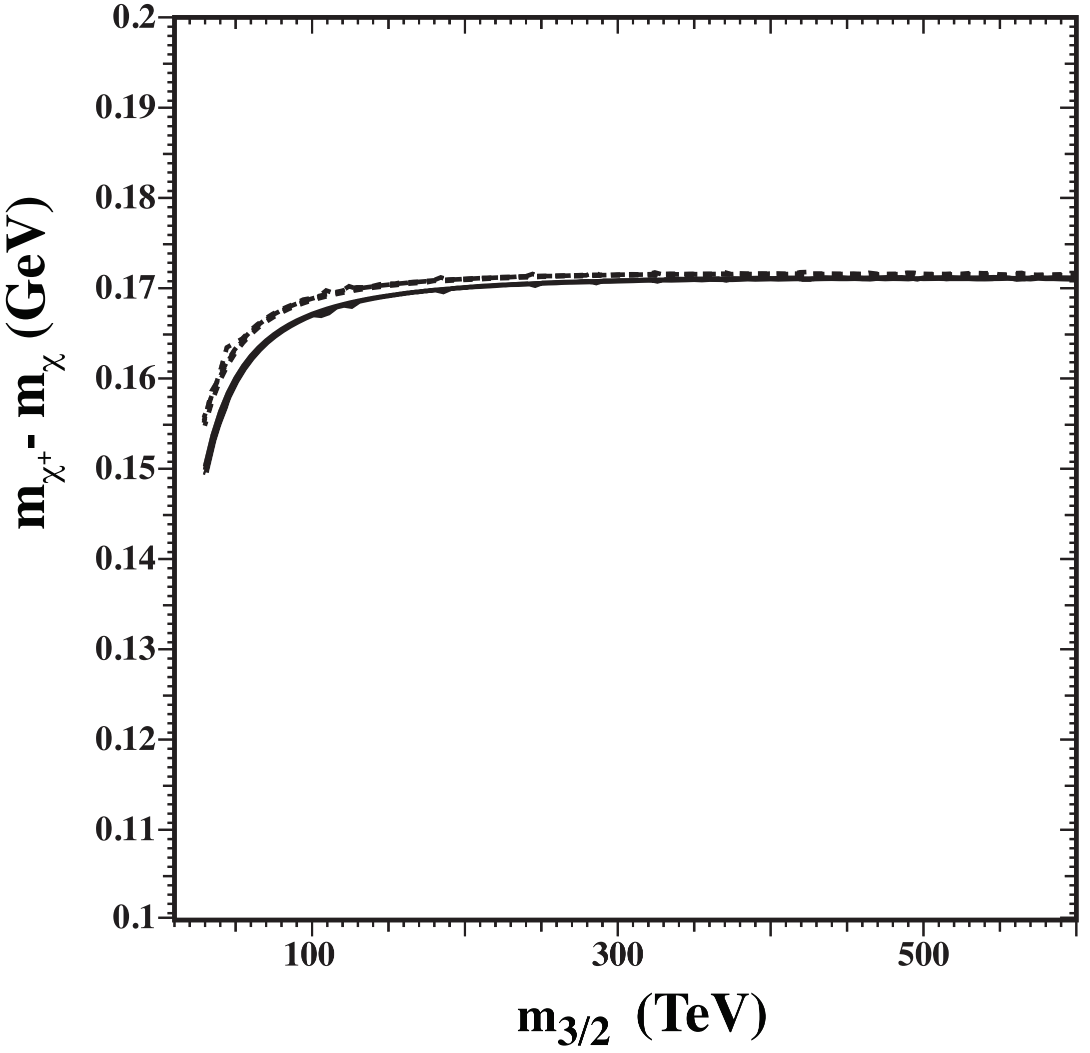
Coming soon!!

3. Metastable winos

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

Wino in the high-scale SUSY





J. L. Evans, M. Ibe, K. A. Olive, T. T. Yanagida (2013).

Wino mass is predicted to be O(100) GeV—a few TeV.

Charged wino is highly degenerate with neutral wino in mass.

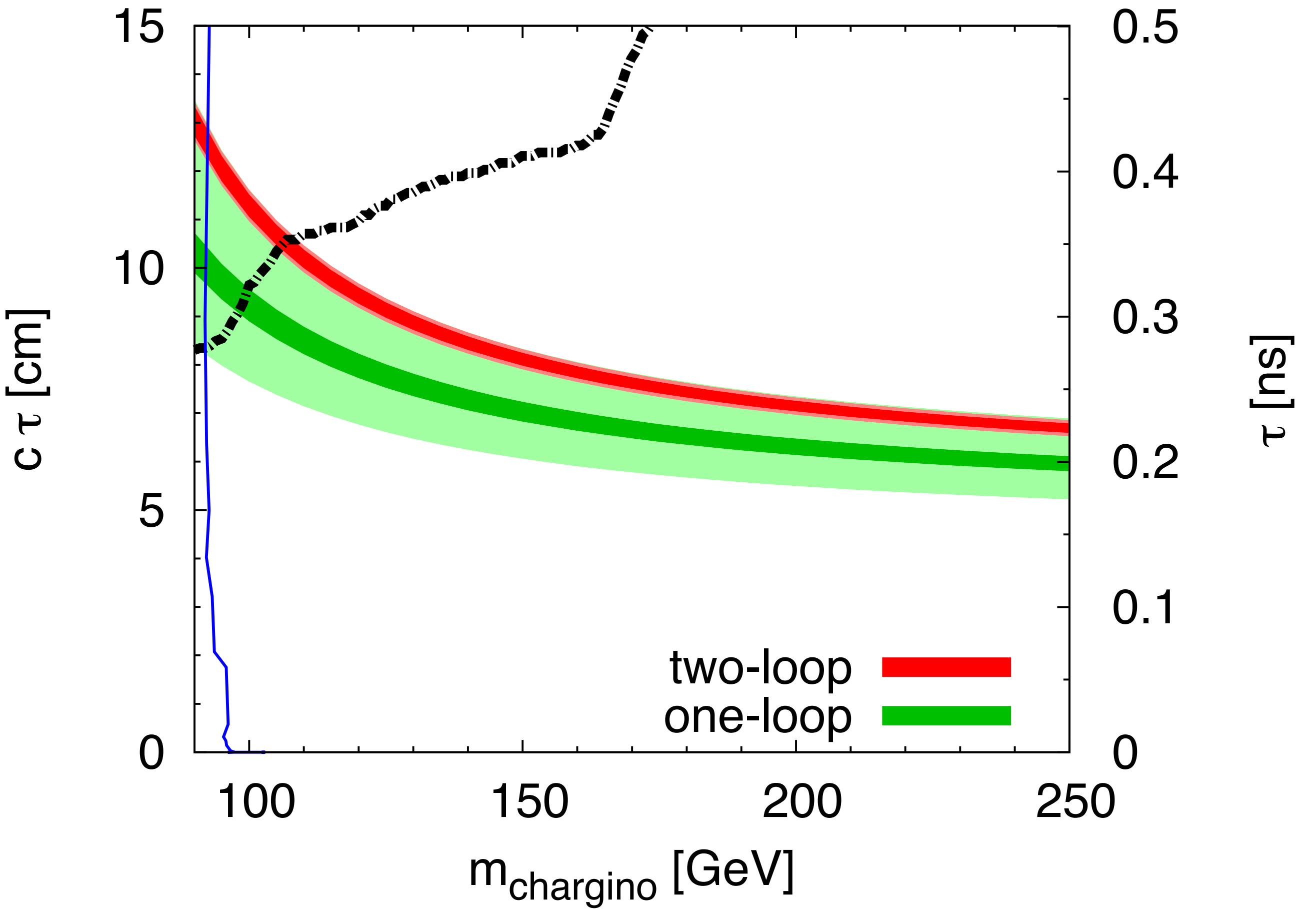
Wino lifetime

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).

$$\tau \simeq 0.2 \text{ ns}$$

$$c\tau \simeq 6 \text{ cm}$$

Decay within a detector!

Disappearing track searches

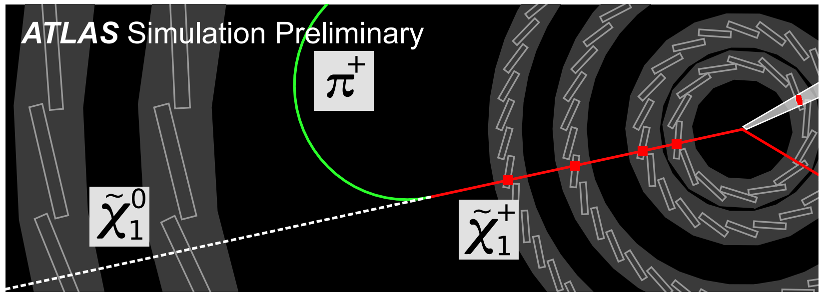
A charged wino with a decay length of O(1) cm leaves a disappearing track in detectors.

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

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

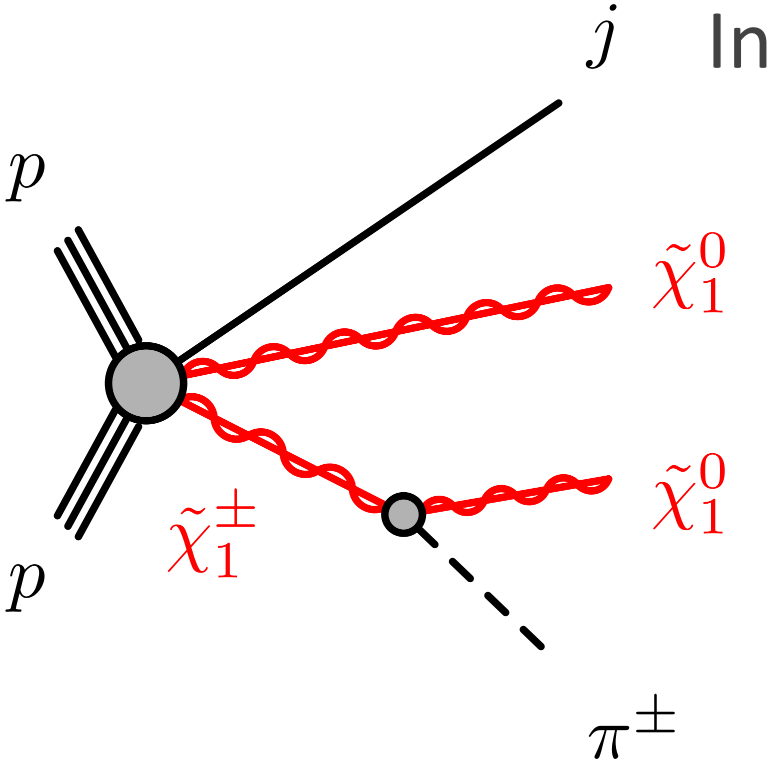
E_T^{miss}

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

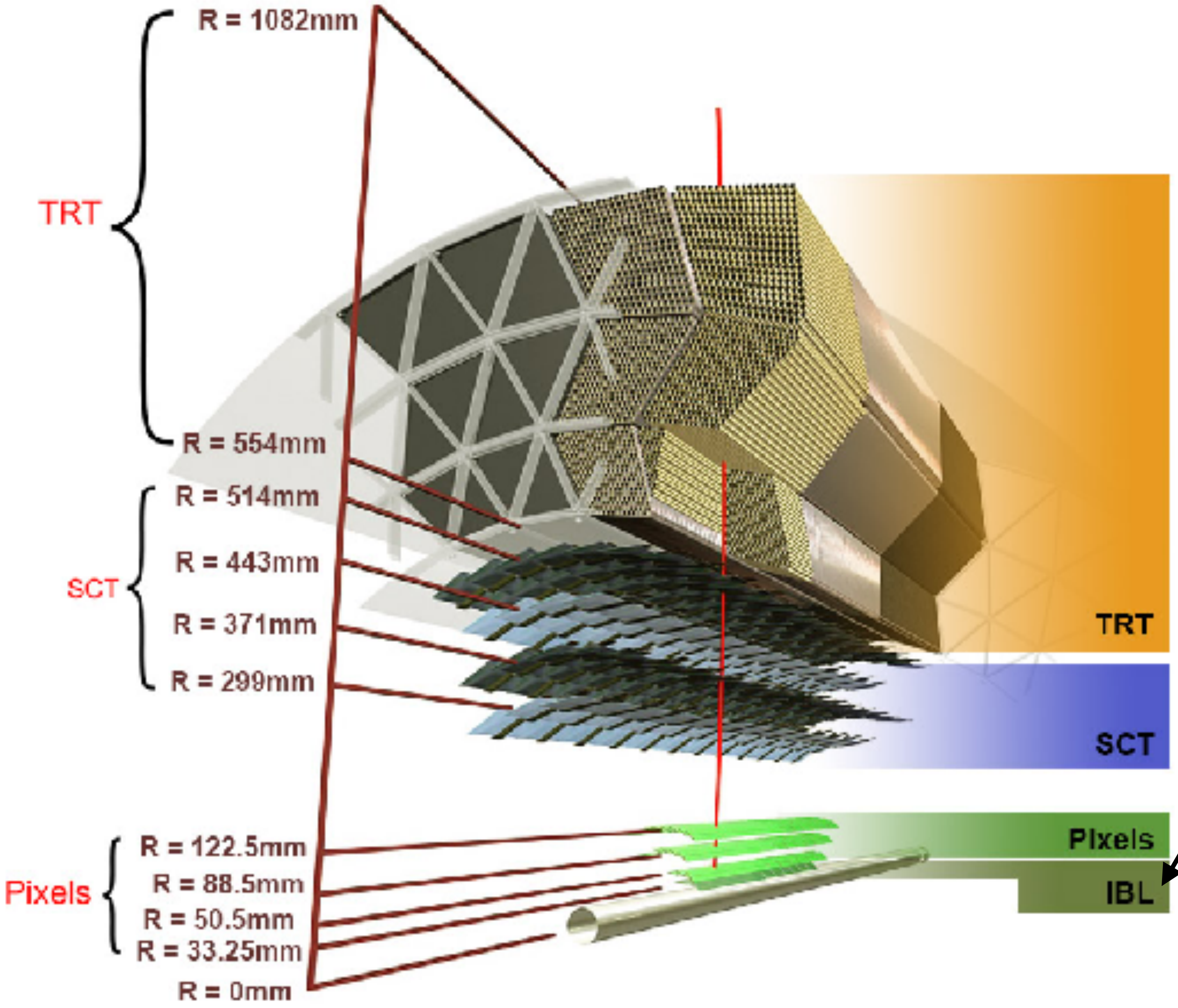
Disappearing track

Role of ISR

- Trigger
- Boost the system

Improvement from Run-1 @ ATLAS

ATLAS inner detector



New!!

Insertable B-layer (IBL)

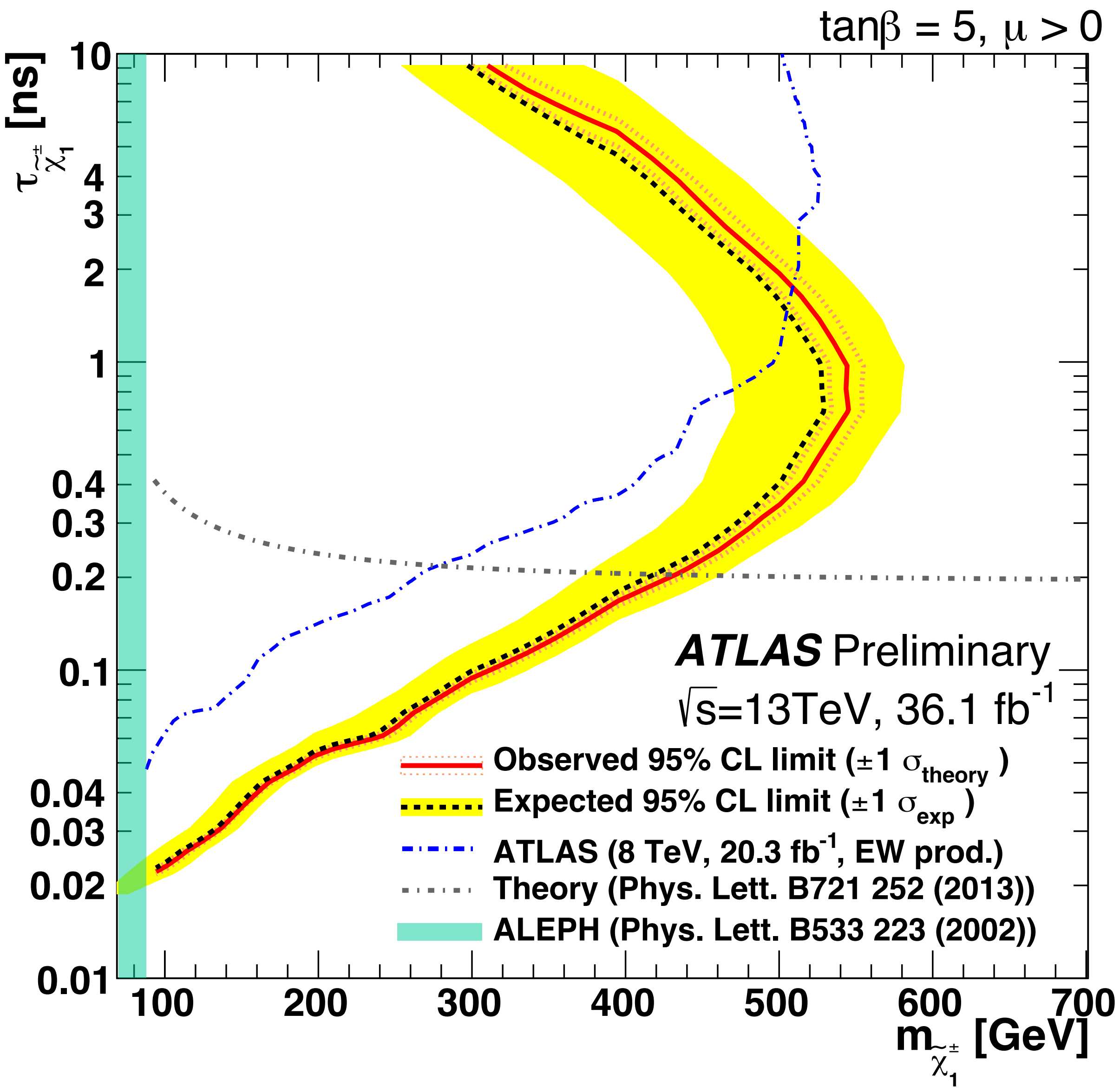
Requirement for disappearing tracks

Run-1: 3 pixel + 1 SCT hits

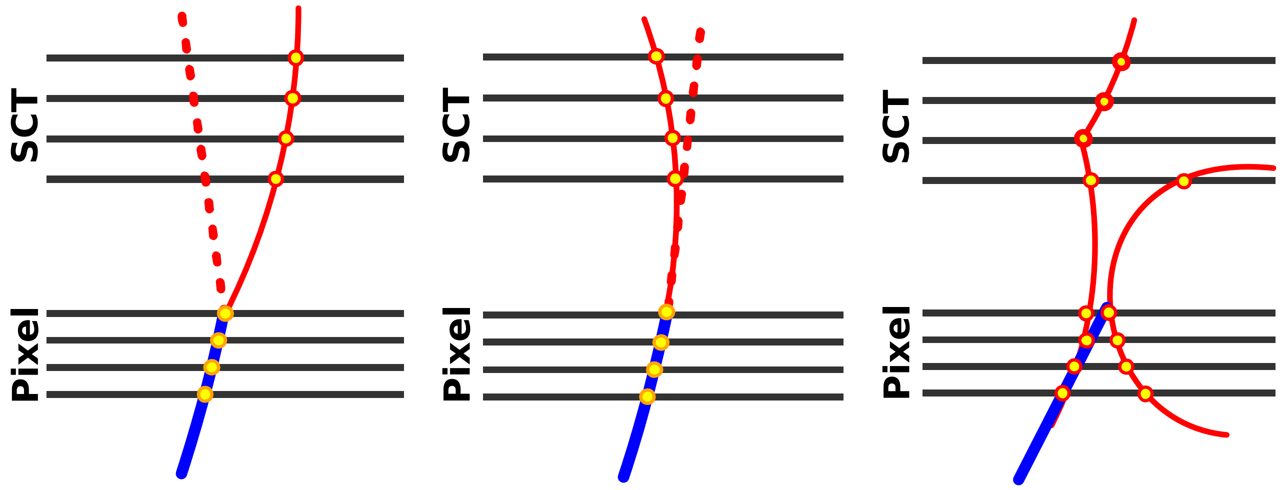
Run-2: 4 pixel hits

30 cm → 12 cm

Results



BG: ttbar, W+ jets



Hadronic scattering

Bremsstrahlung

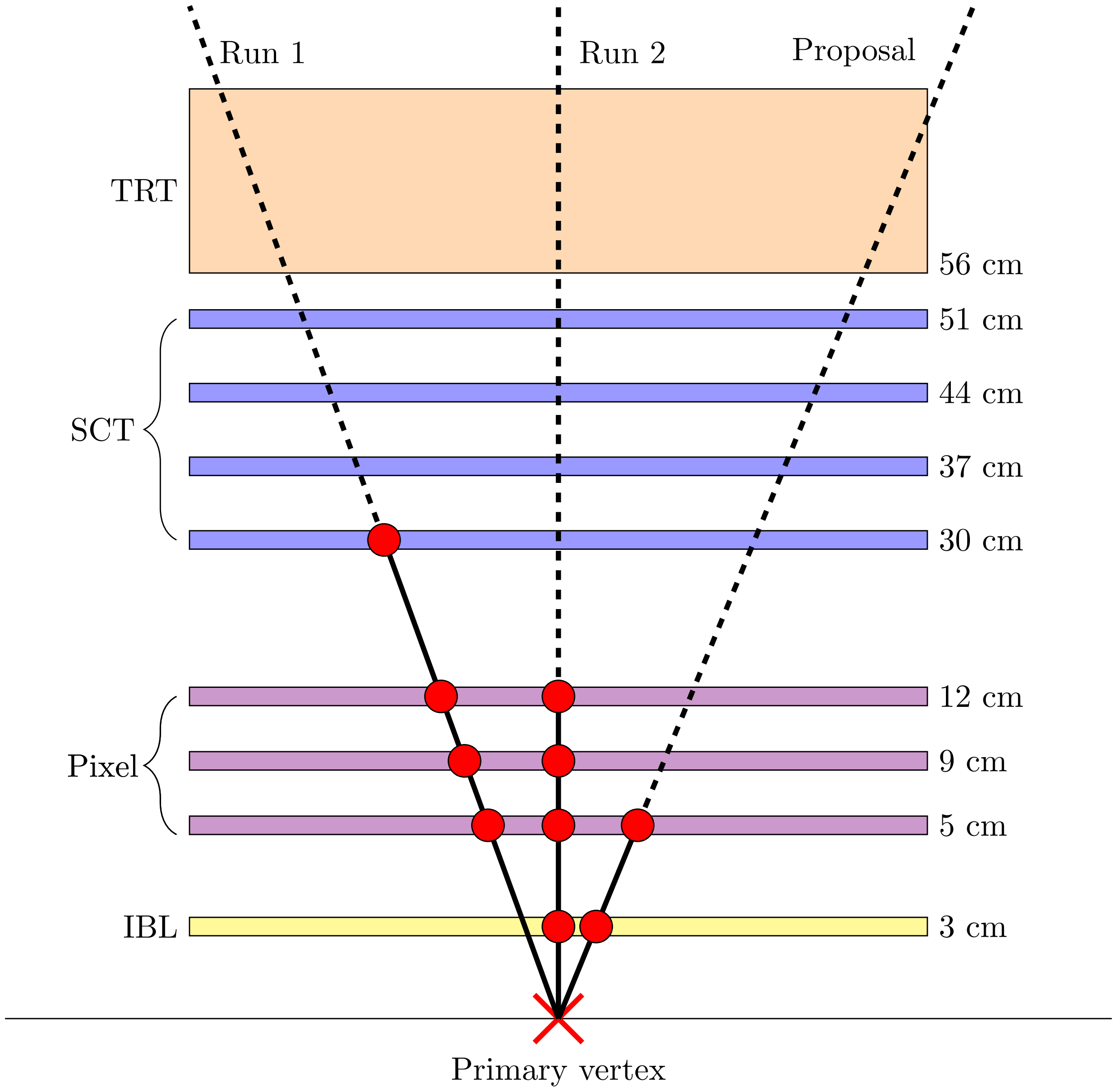
Two nearby tracks (fake)

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

ATLAS-CONF-2017-017

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….

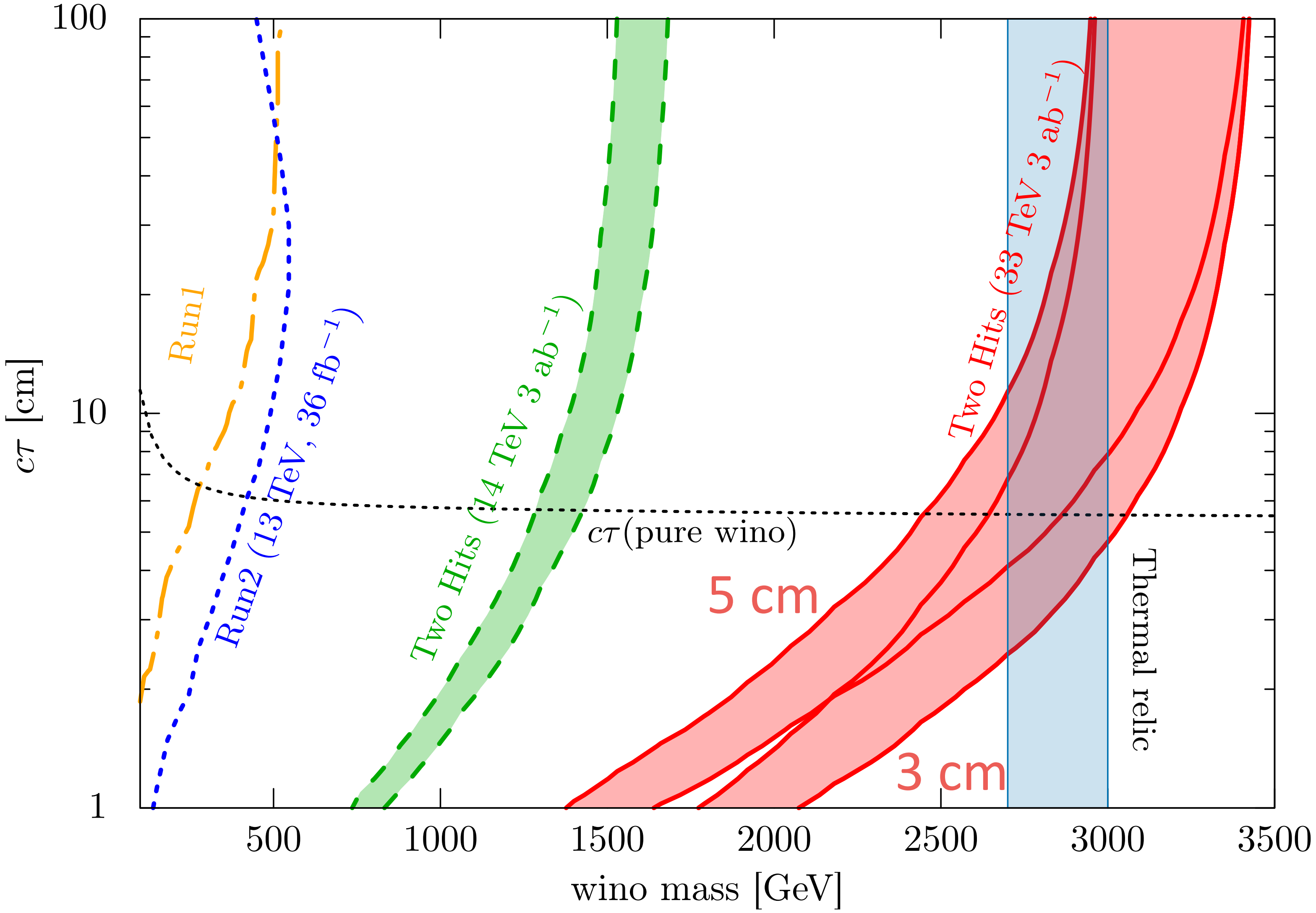
Need to consider further strategies to reduce BG events.

- Use dE/dx
- Use displaced vertices
- Smaller size pixel trackers

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`].

4. Conclusion

Conclusion

- We have discussed the prospects of gaugino searches at the LHC in the high-scale SUSY scenario.
- Metastable gluinos due to heavy sfermions can be probed using the DV cut.
- Long-lived gluinos motivated by the bino-gluino coannihilation scenario can be probed with DV searches.
- Winos can be probed in the disappearing track searches with a few layers of pixel detectors.

Backup

Monte Carlo (MC) simulation

To take into account the performance of the track reconstruction, we shift each track obtained from the MC-truth information in parallel by impact parameters.

Resolution of impact parameters

$$\sigma_X(p_T) = \sigma_X(\infty)(1 \oplus p_X/p_{\mathrm{T}}) \qquad X = d_0, z_0 \sin\theta$$

- Resolutions regarding track directions are sufficiently small.
- η-dependence is sufficiently small for p_T > a few GeV.

ATLAS [arXiv: 0901.0512]

We determine the parameters in the above equation by fitting this onto the p_T dependence of the track impact parameter resolutions obtained by ATLAS.

ATLAS-PHYS-PUB-2015-018.

- For p_T > 400 MeV

$$\sigma_{d_0}(\infty) = 30\ \mu\mathrm{m} \qquad \sigma_{z_0 \sin\theta}(\infty) = 90\ \mu\mathrm{m} \qquad p_{d_0} = 2.1\ \mathrm{GeV} \qquad p_{z_0 \sin\theta} = 1.0\ \mathrm{GeV}$$

- For p_T > 1 GeV

$$\sigma_{d_0}(\infty) = 23\ \mu\mathrm{m} \qquad \sigma_{z_0 \sin\theta}(\infty) = 78\ \mu\mathrm{m} \qquad p_{d_0} = 3.1\ \mathrm{GeV} \qquad p_{z_0 \sin\theta} = 1.6\ \mathrm{GeV}$$

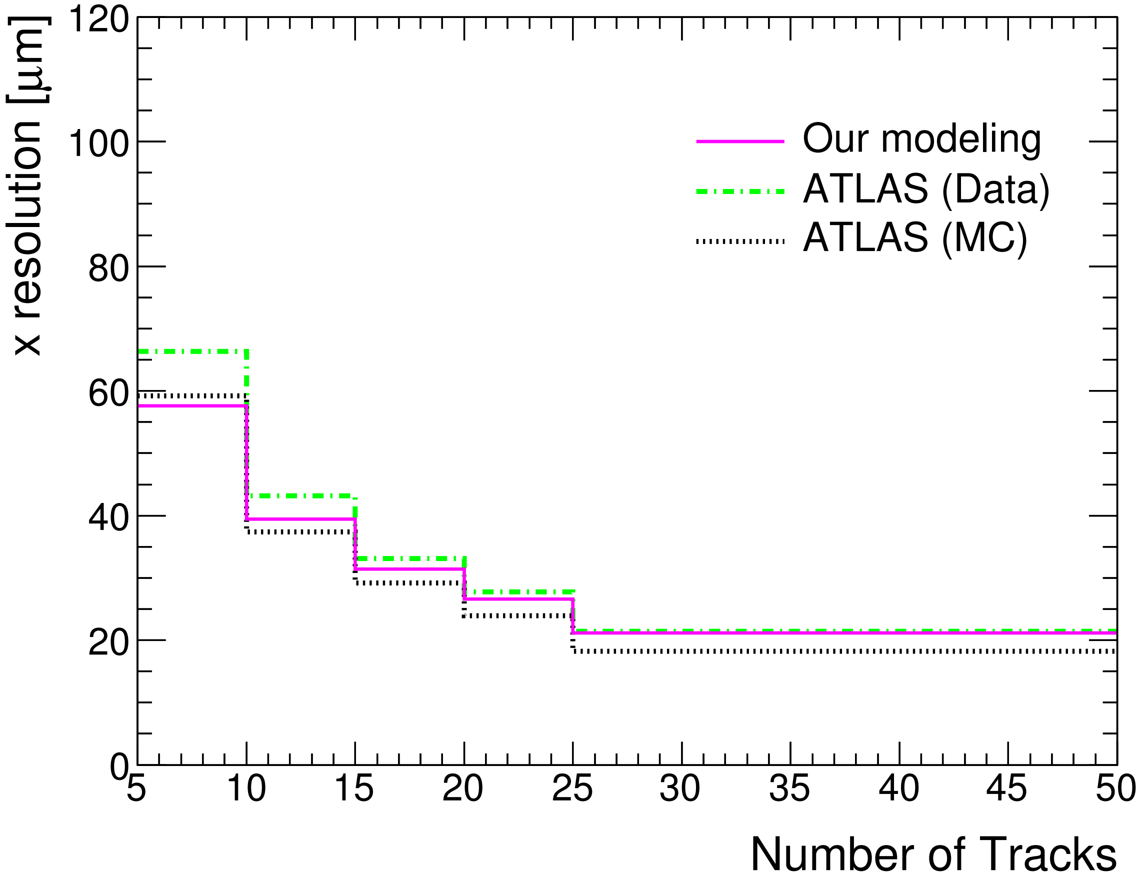
Vertex reconstruction

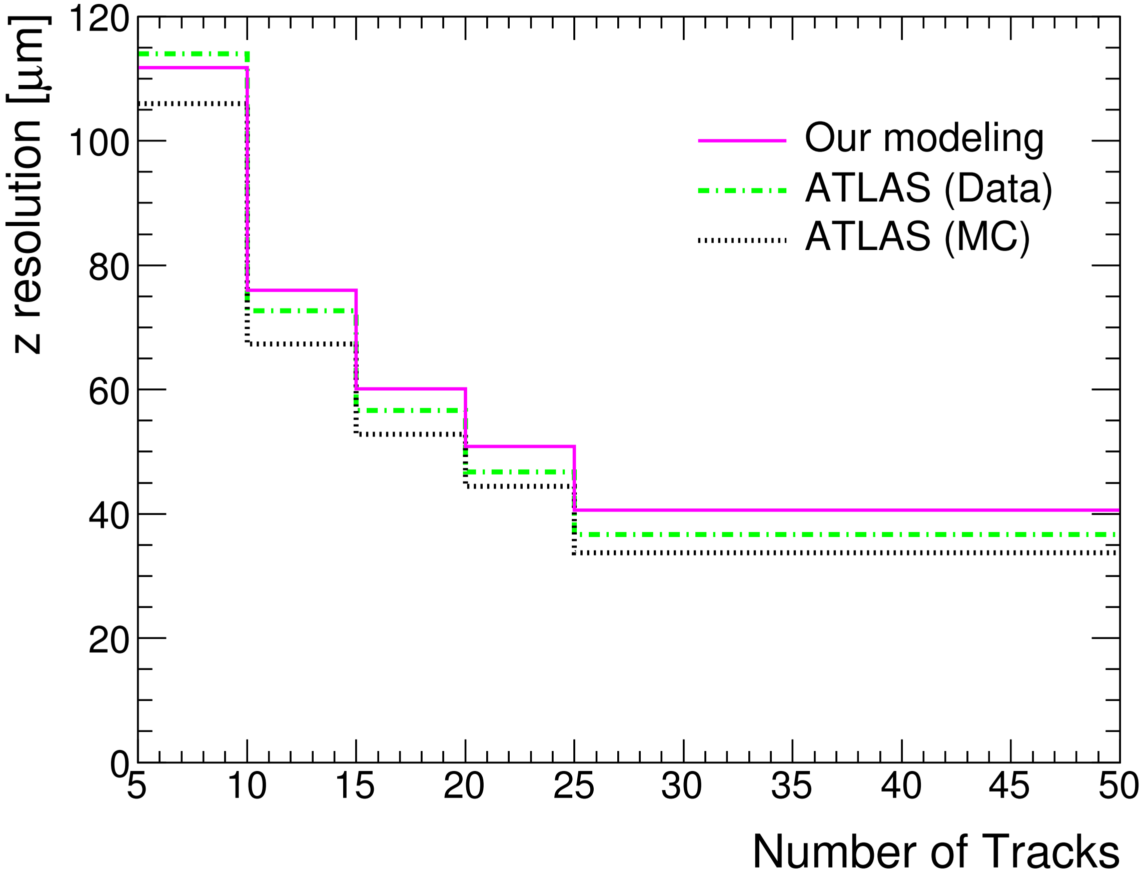
We follow the prescription given in [ATLAS, arxiv: 1611.10235], where the adaptive vertex fitting algorithm is used to determine the vertex position.

R. Fruhwirth, W. Waltenberger, and P. Vanlaer, J. Phys. G34, N343 (2007).

Using this method, we reconstruct the position of primary vertices in minimum-bias events and evaluate their resolution.

`PYTHIA v8.2`

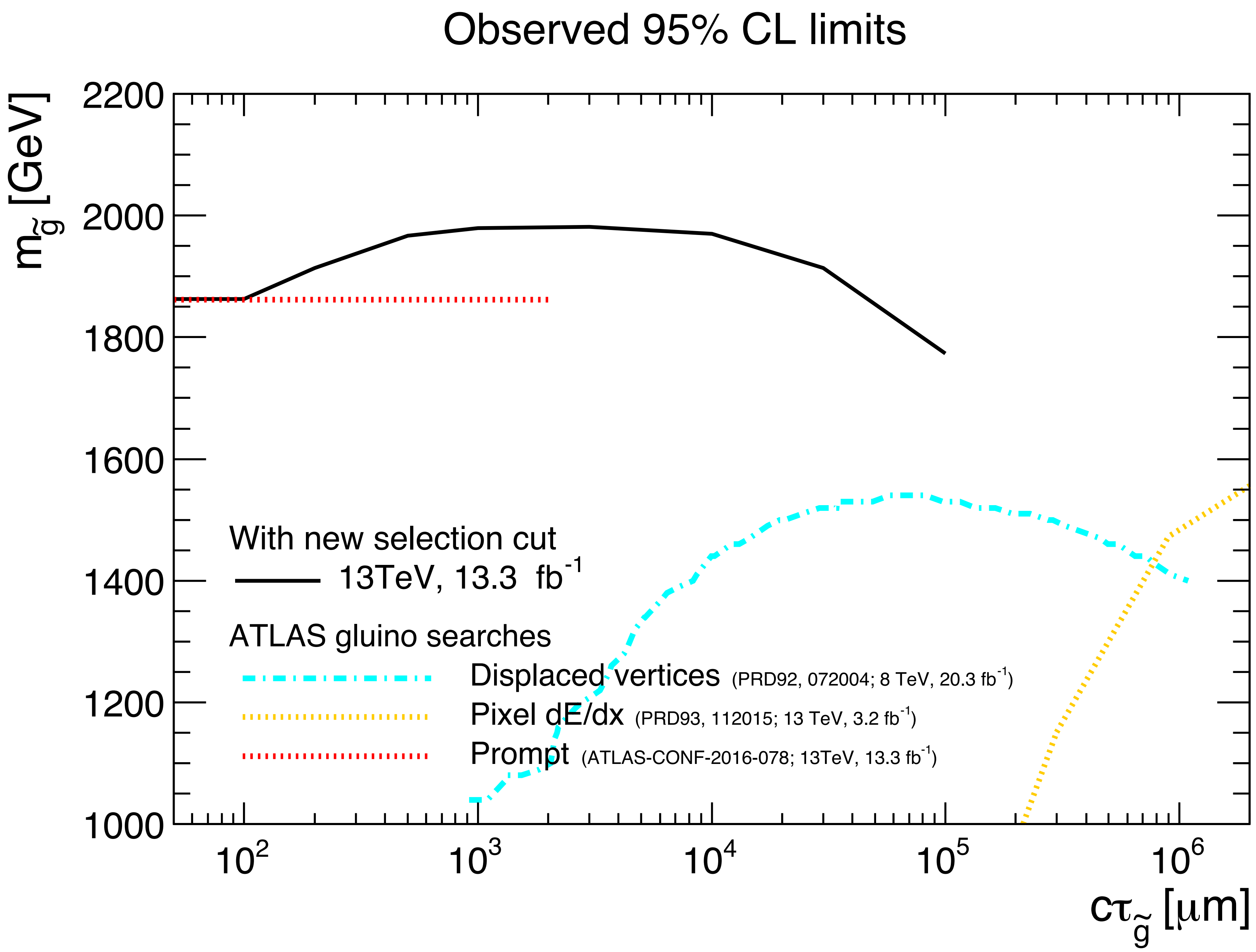




Good agreement!

H. Ito, O. Jinnouchi, T. Moroi, N. Nagata, and H. Otono [`arXiv:1702.08613`].

Comparison



13 TeV LHC

LSP mass: 100 GeV

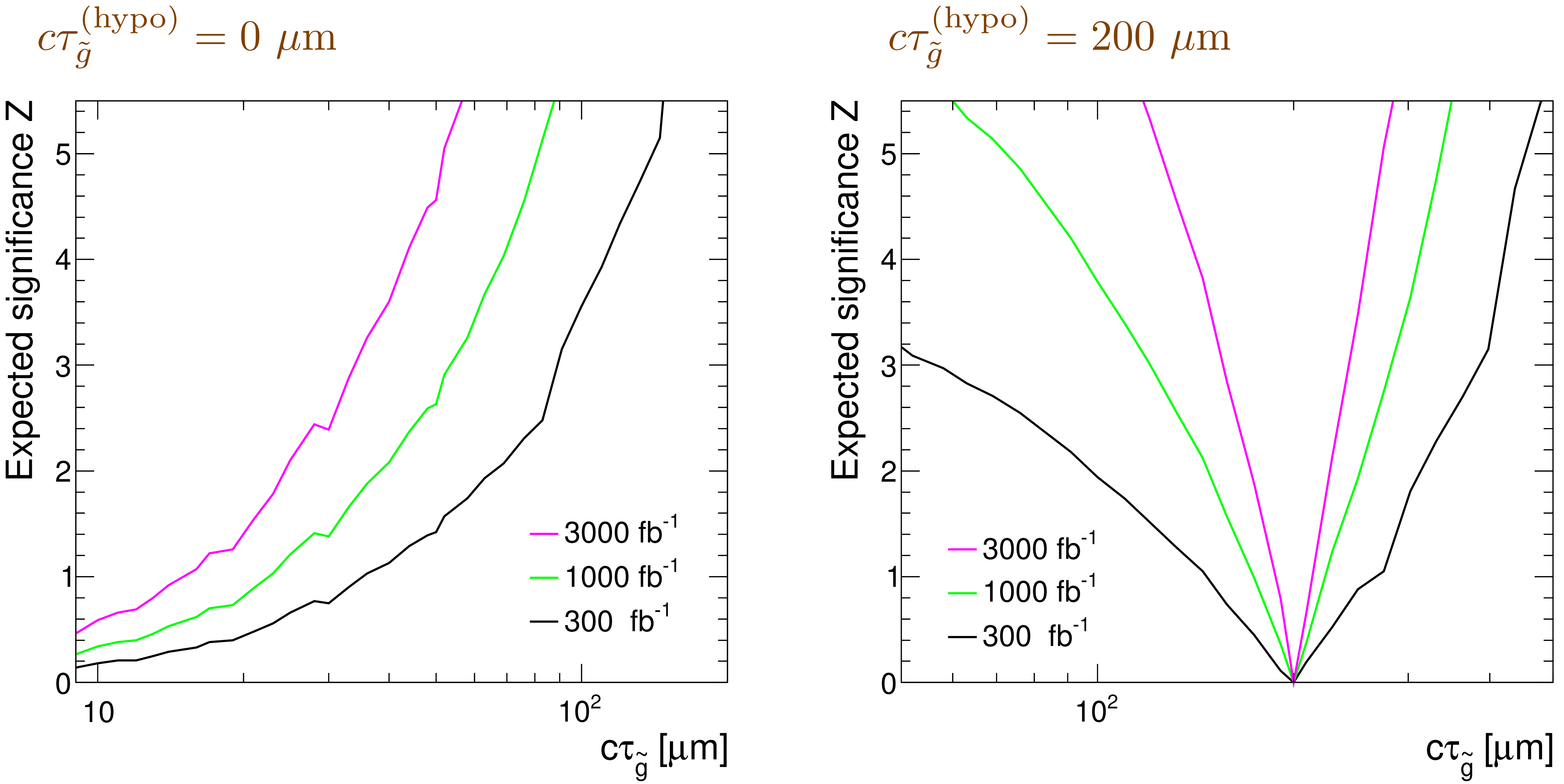
`Meff-4j-2600`

ATLAS-CONF-2016-078.

The new search strategy plays a complementary role in probing metastable gluinos.

H. Ito, O. Jinnouchi, T. Moroi, N. Nagata, and H. Otono [`arXiv:1702.08613`].

Lifetime measurement



$c\tau_{\tilde{g}}^{(\mathrm{hypo})} = 0\ \mu\mathrm{m}$

$c\tau_{\tilde{g}}^{(\mathrm{hypo})} = 200\ \mu\mathrm{m}$

13 TeV LHC

Gluino mass: 2.2 TeV

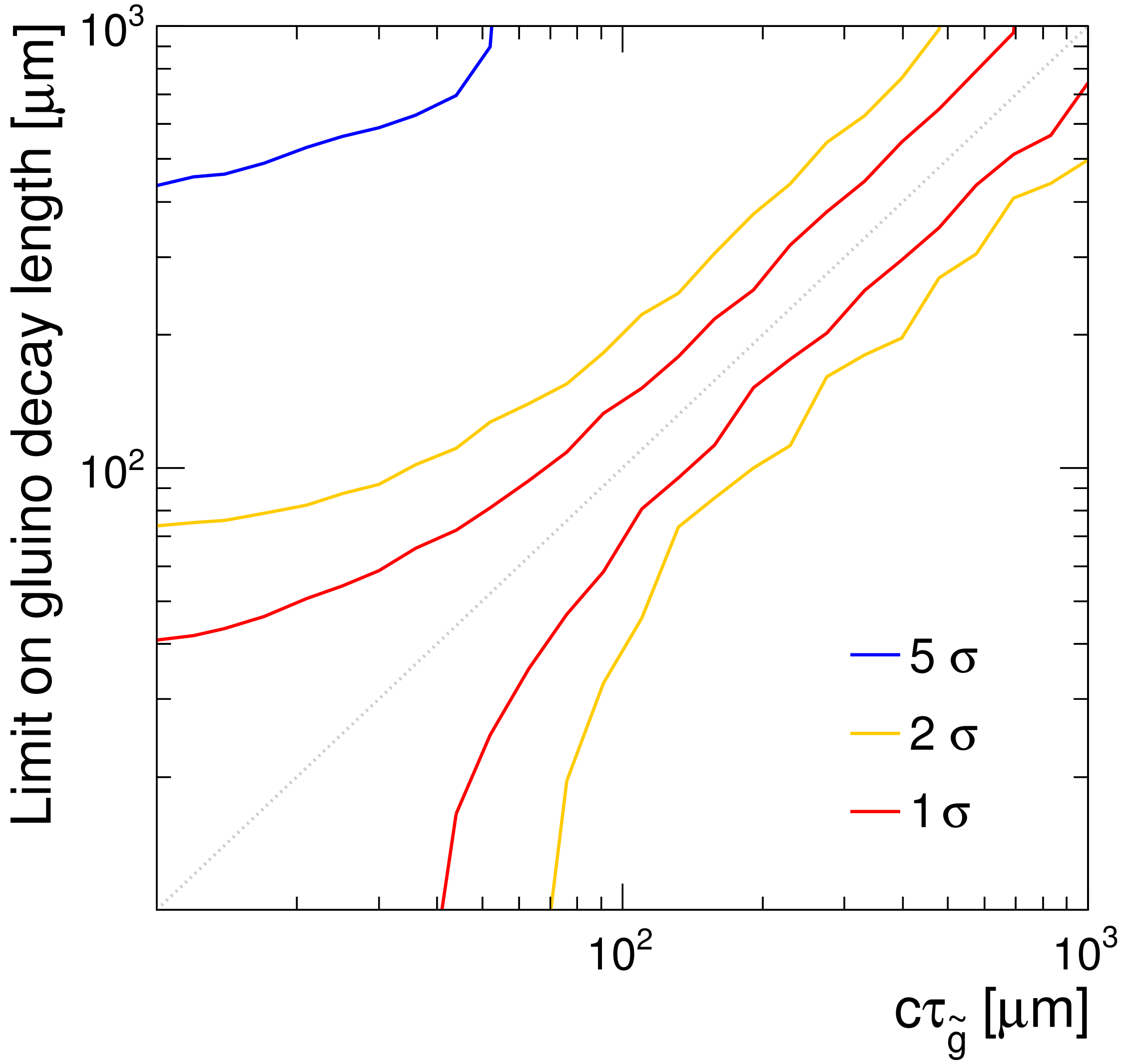
LSP mass: 100 GeV

`Meff-4j-2600` ATLAS-CONF-2016-078.

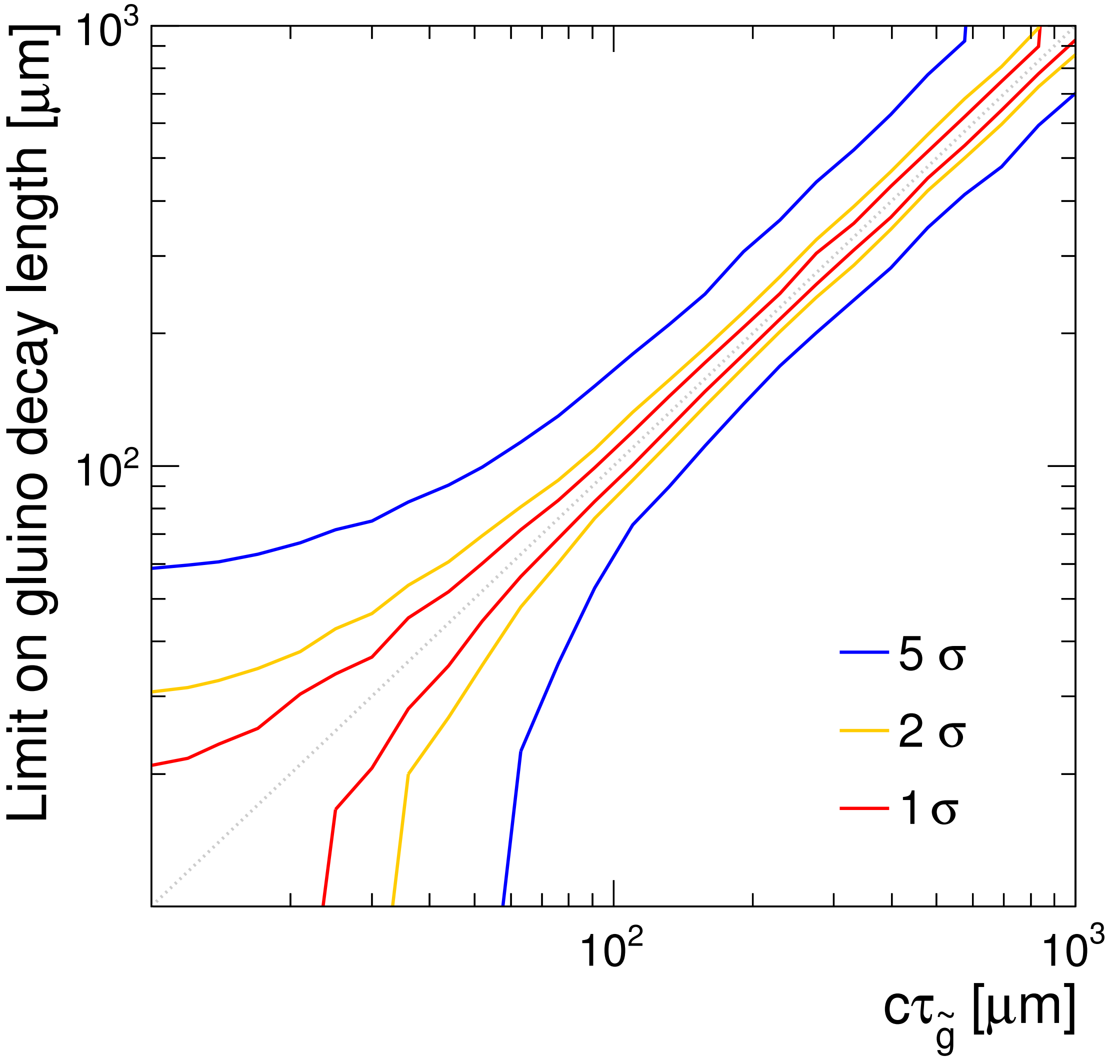
H. Ito, O. Jinnouchi, T. Moroi, N. Nagata, and H. Otono [`arXiv:1702.08613`].

Lifetime measurement

$\mathcal{L} = 300\ \text{fb}^{-1}$



$\mathcal{L} = 3000\ \text{fb}^{-1}$



13 TeV LHC

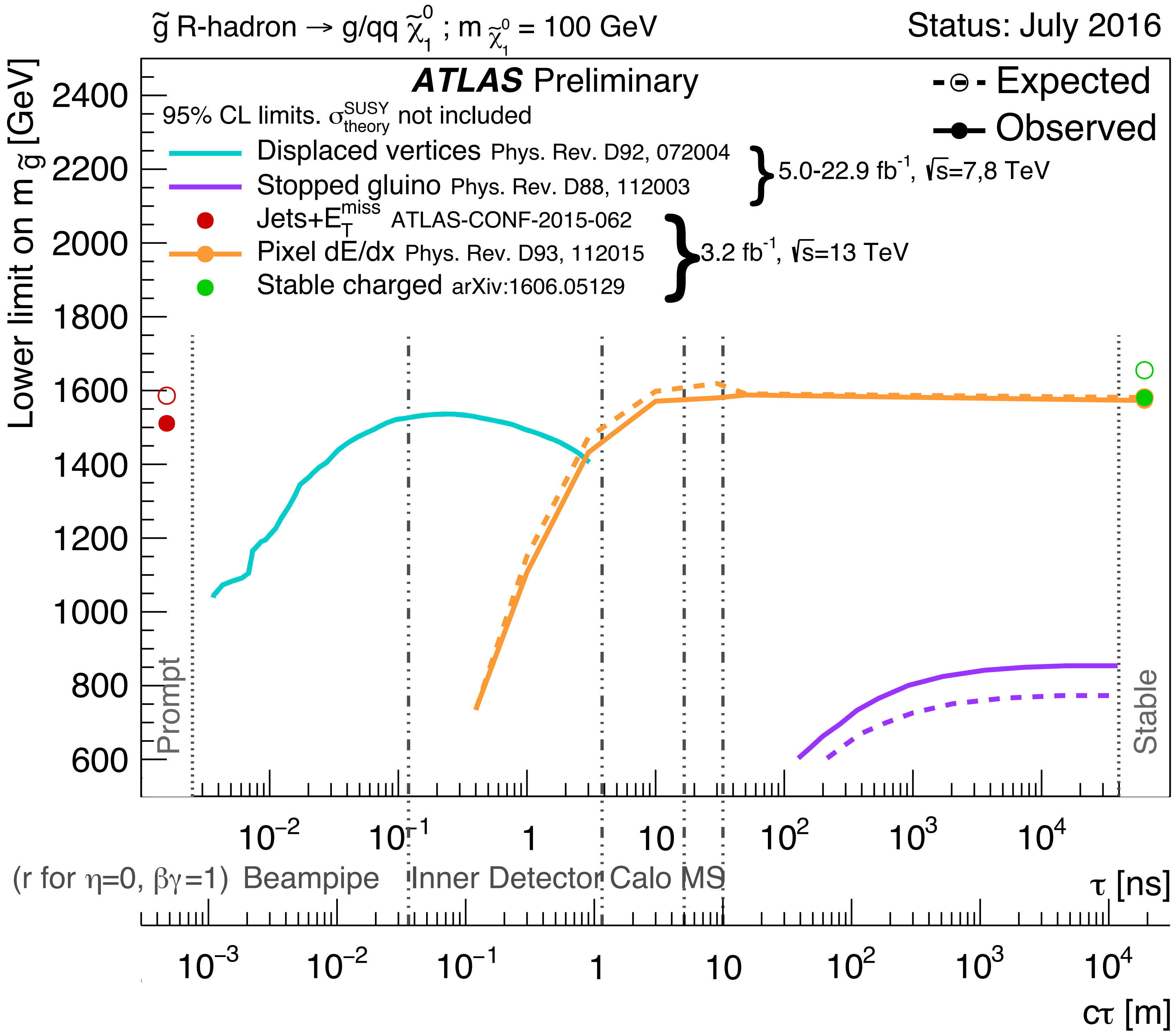
Gluino mass: 2.2 TeV

LSP mass: 100 GeV

`Meff-4j-2600` ATLAS-CONF-2016-078.

H. Ito, O. Jinnouchi, T. Moroi, N. Nagata, and H. Otono [`arXiv:1702.08613`].

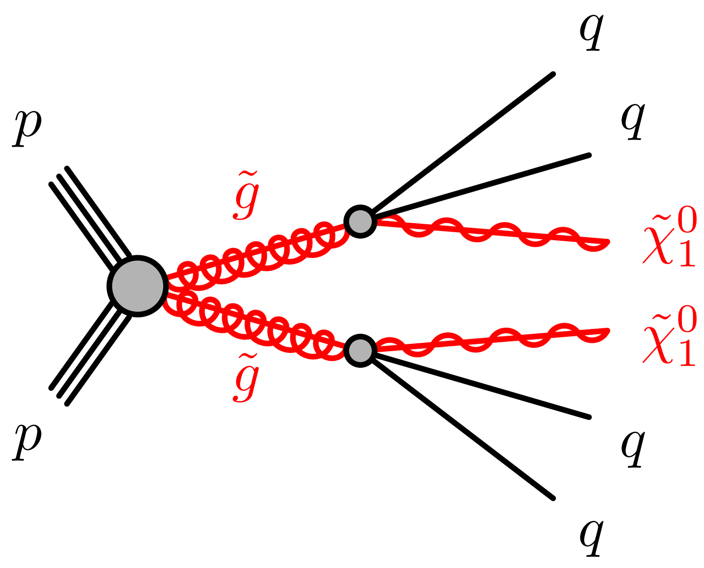
ATLAS long-lived gluino searches



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
  - $E_T^{\text{miss}} > 180 \text{ GeV}$



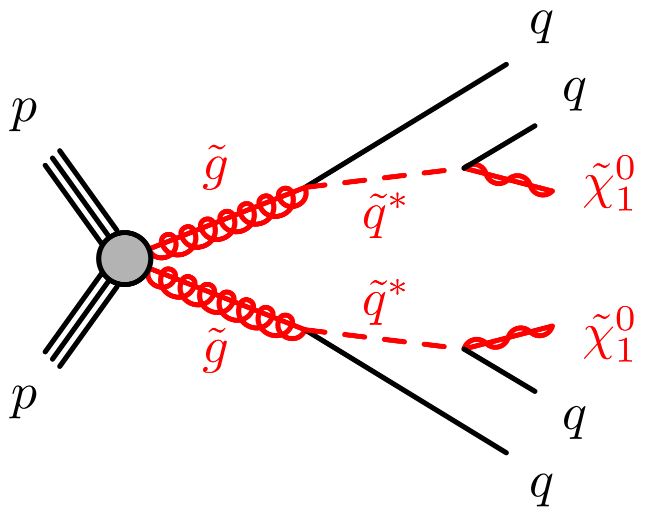
ATLAS [arXiv: 1504.05162]

Re-interpretation of the ATLAS result

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

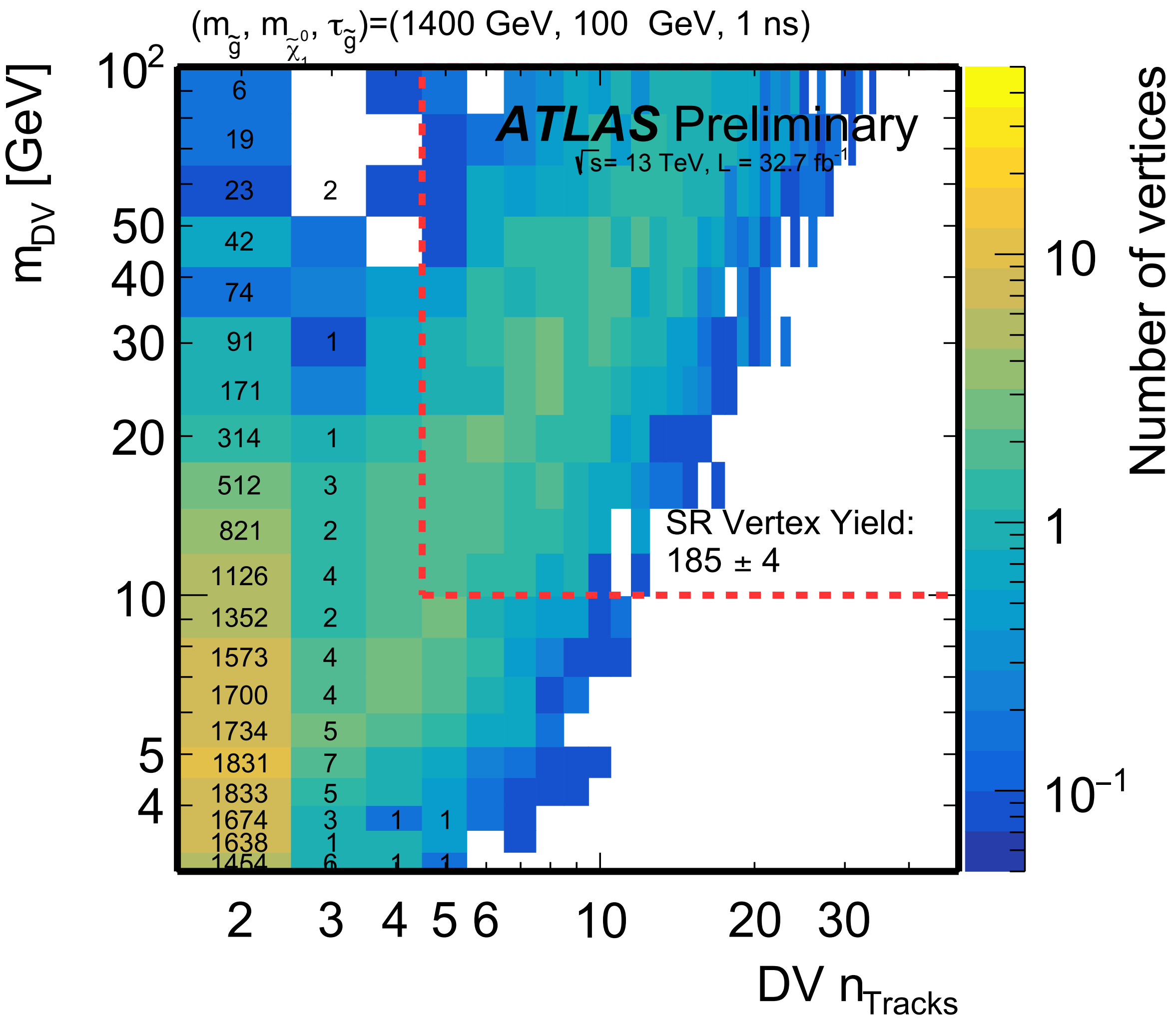
- 8 TeV LHC with 20 fb^{-1}
  - $E_T^{\text{miss}} > 100 \text{ GeV}$
  - Trigger efficiency is simulated to be 40%.
- 14 TeV LHC with 300 fb^{-1}
  - $E_T^{\text{miss}} > 200 \text{ GeV}$
  - Trigger efficiency is simulated to be 15%.

HERWIG 6
ACERDET



ATLAS long-lived gluino search

DV + missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$

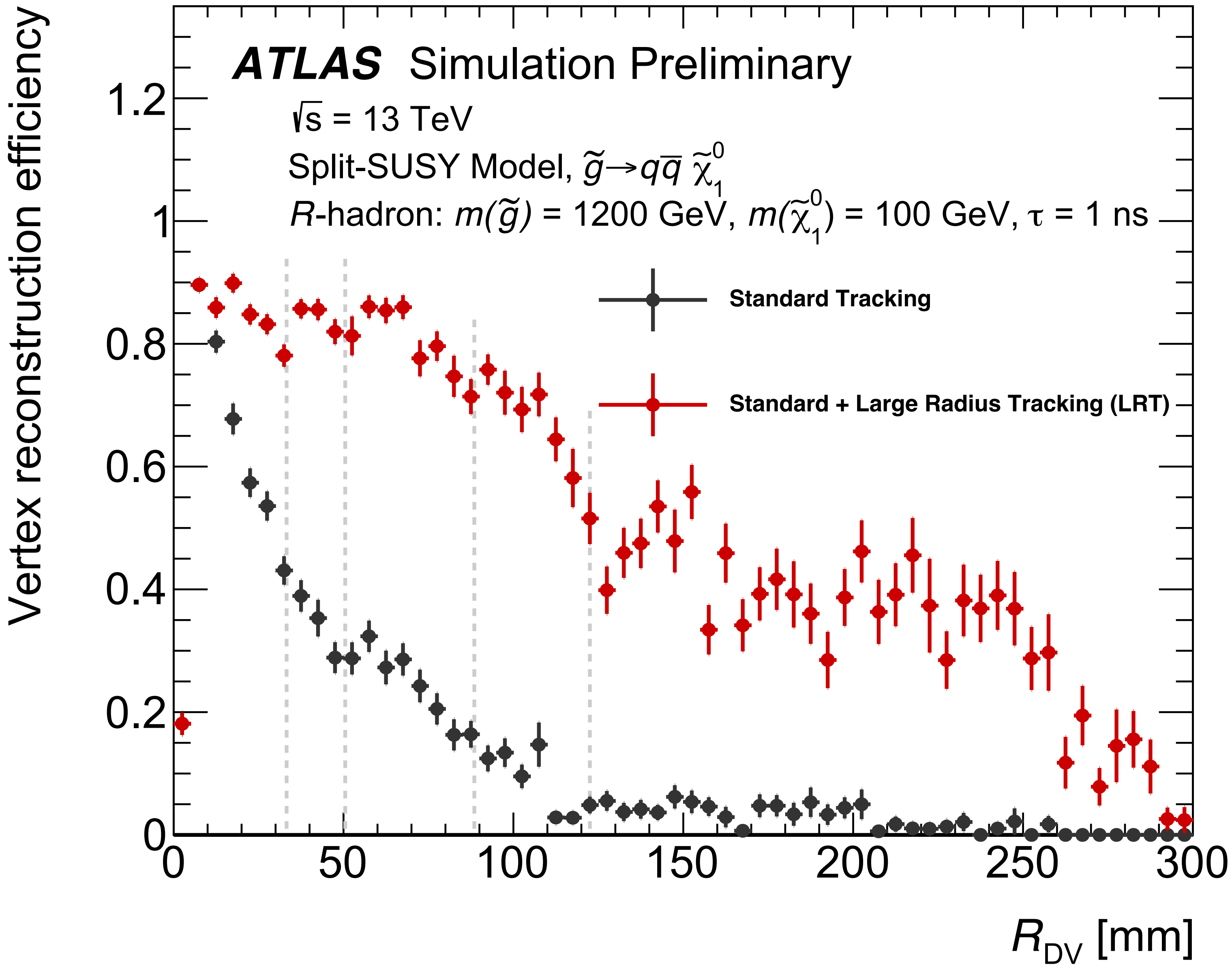


Selection	Sub-Region	Estimated	Observed
Event pre-selection $n_{\mathrm{trk}} = 3,\ m_{\mathrm{DV}} > 10$ GeV			3093
Event pre-selection $n_{\mathrm{trk}} = 4,\ m_{\mathrm{DV}} > 10$ GeV	VRLM	9 ± 2	9
	VRM	150 ± 60	177
Event pre-selection $n_{\mathrm{trk}} \geq 5,\ m_{\mathrm{DV}} > 10$ GeV	5-tracks	2.2 ± 2.8	1
	6-tracks	0.6 ± 0.6	1
	≥7-tracks	1 ± 3	3
	Total	4.2 ± 4.1	5
Full SR selection	**Total**	0.02 ± 0.02	0

ATLAS, ATLAS-CONF-2017-026.

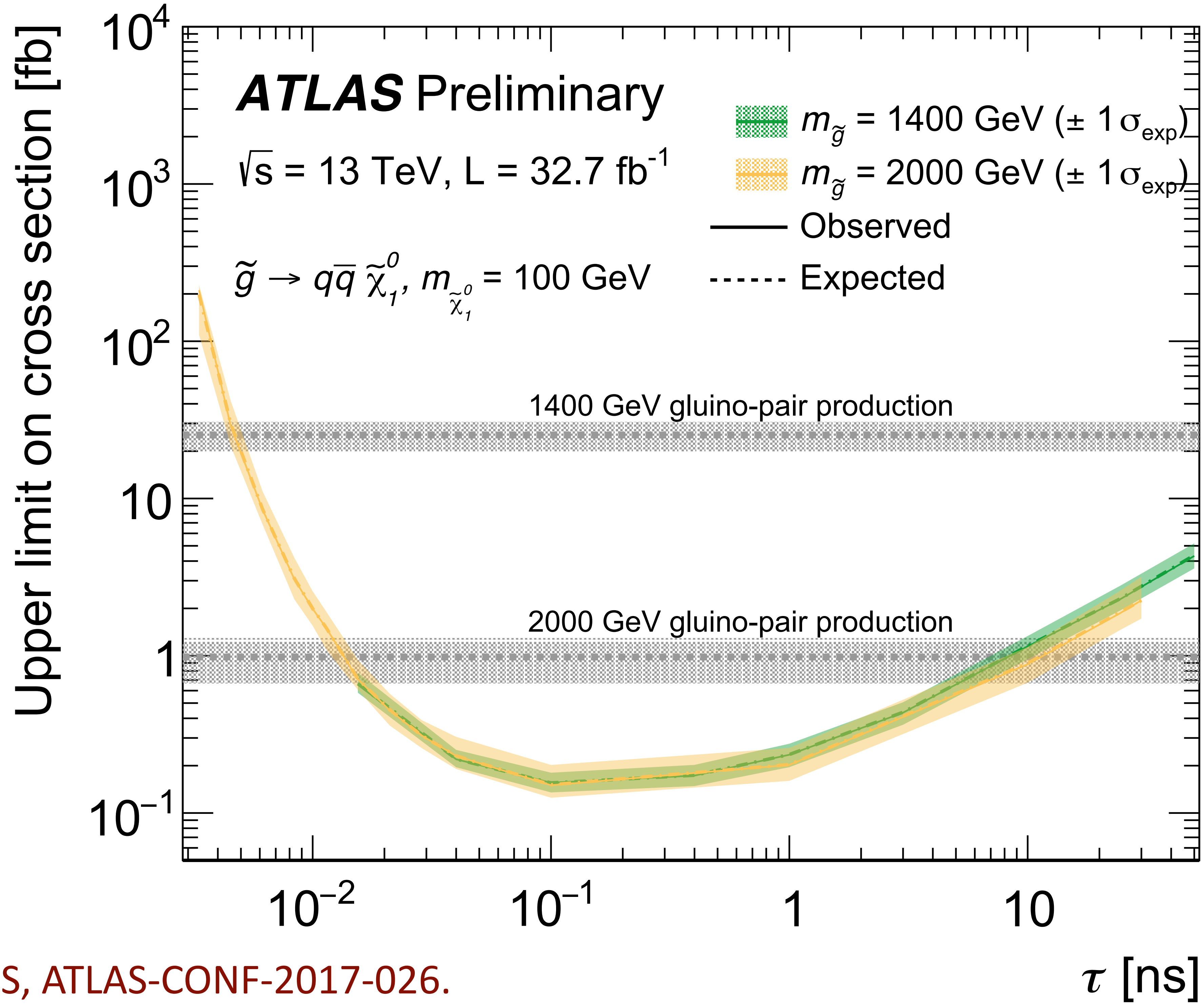
No signal has been observed!

Vertex reconstruction efficiency



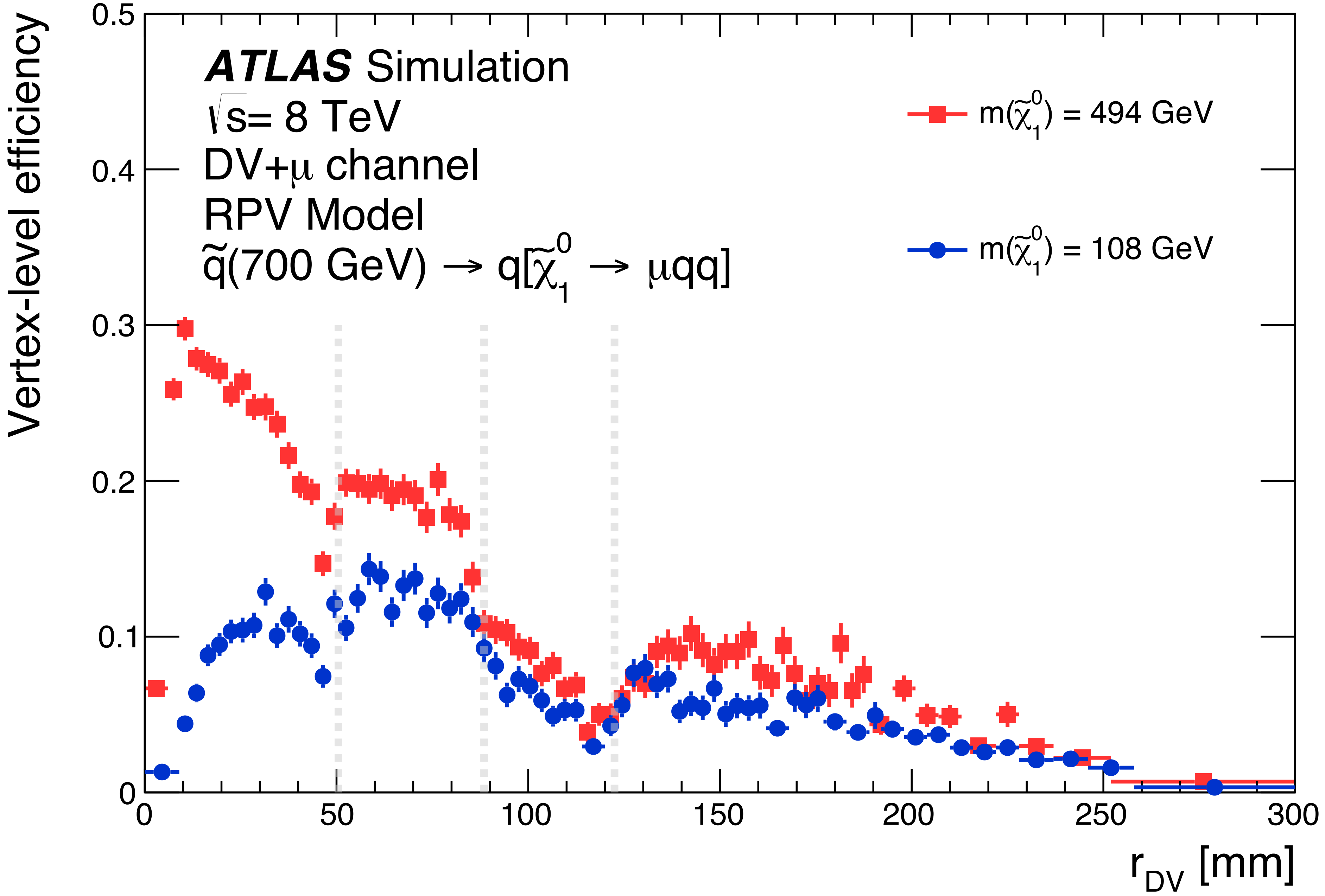
ATLAS, ATLAS-CONF-2017-026.

ATLAS long-lived gluino search



ATLAS, ATLAS-CONF-2017-026.

Vertex-level efficiency



ATLAS [arXiv: 1504.05162]

Bino-gluino coannihilation

- Bino self-annihilation
- Bino-gluino annihilation

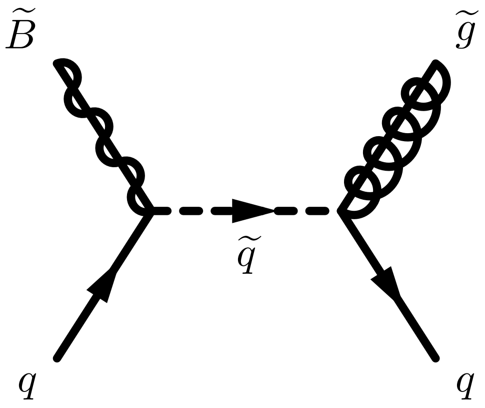
Very small cross section

- Gluino self-annihilation

Large cross section

(due to strong coupling)

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



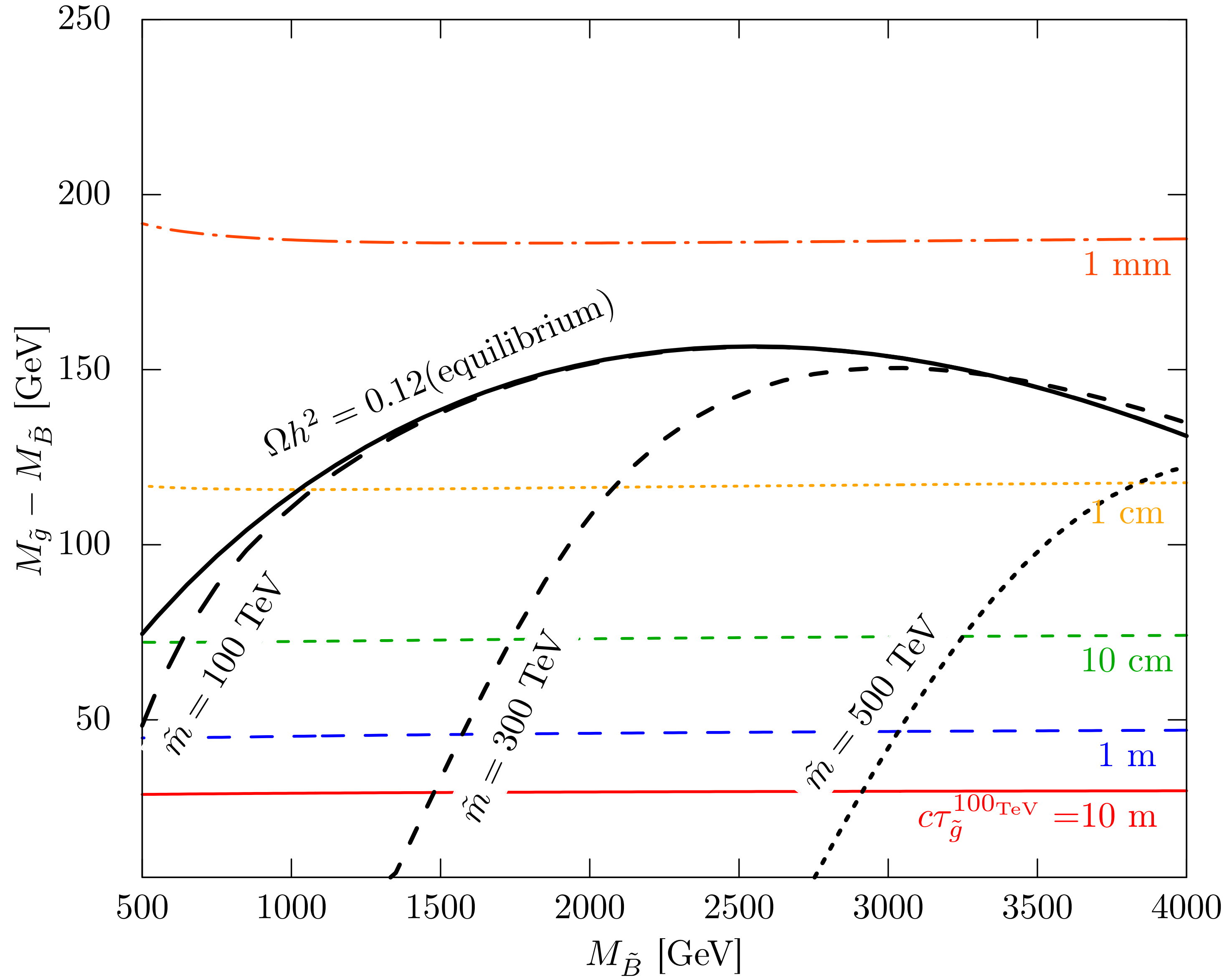
The transition rate between them should be much larger than the Hubble rate.

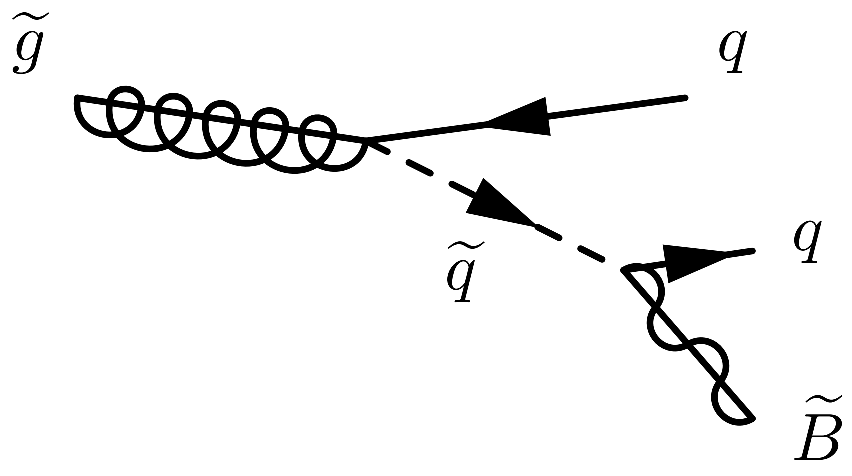
$$\Gamma(\widetilde{B}q \to \widetilde{g}q) \sim T^3 \cdot \frac{T^2}{\widetilde{m}^4} \gg H \sim \frac{T^2}{M_{\mathrm{Pl}}}$$

for $T \gtrsim M_{\widetilde{B}}/20$

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

Gluino decay length

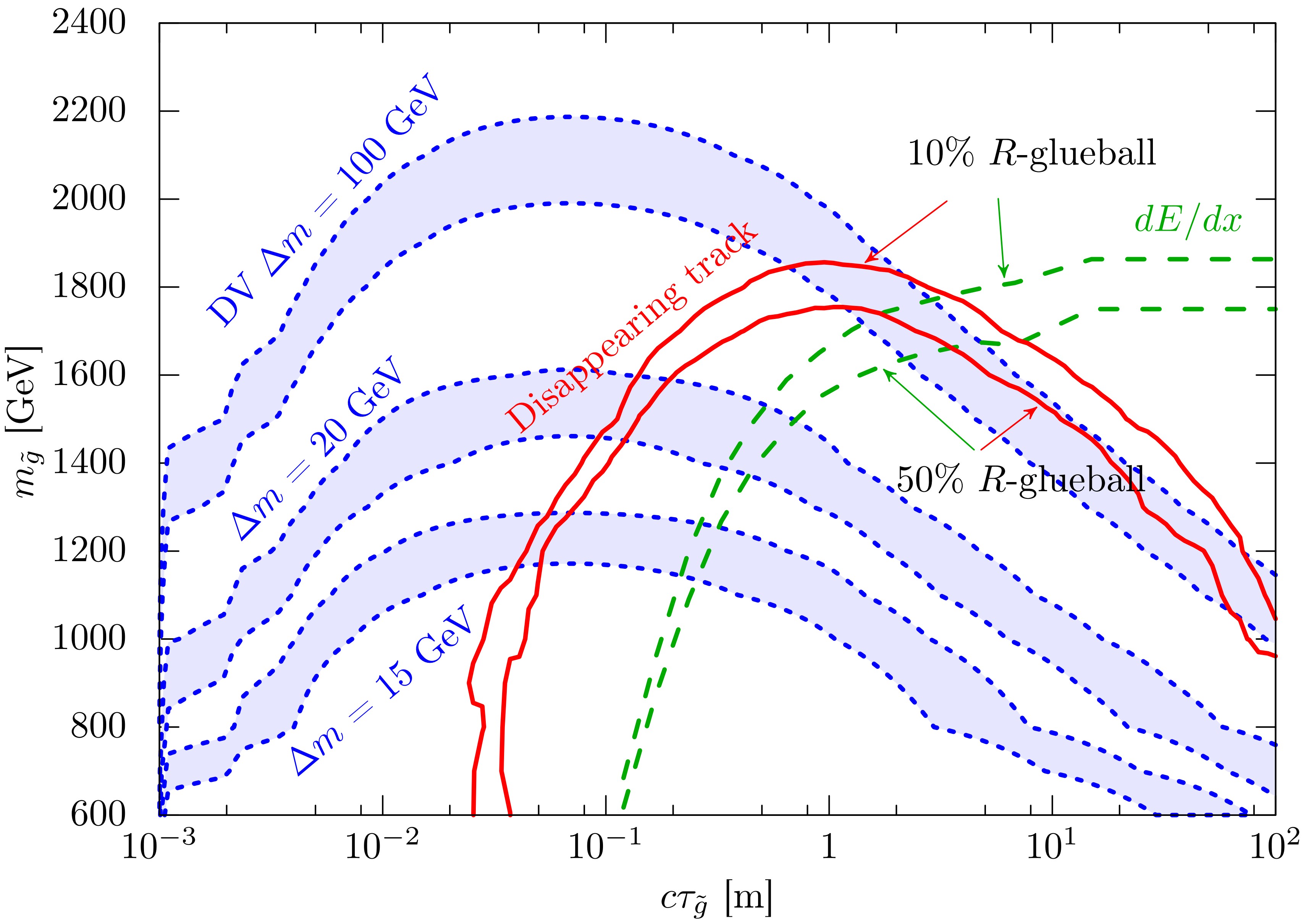




$$c\tau_{\tilde{g}} \simeq \left(\frac{\Delta M}{100\ \mathrm{GeV}}\right)^{-5} \left(\frac{\tilde{m}}{100\ \mathrm{TeV}}\right)^{4}\ \mathrm{cm}$$

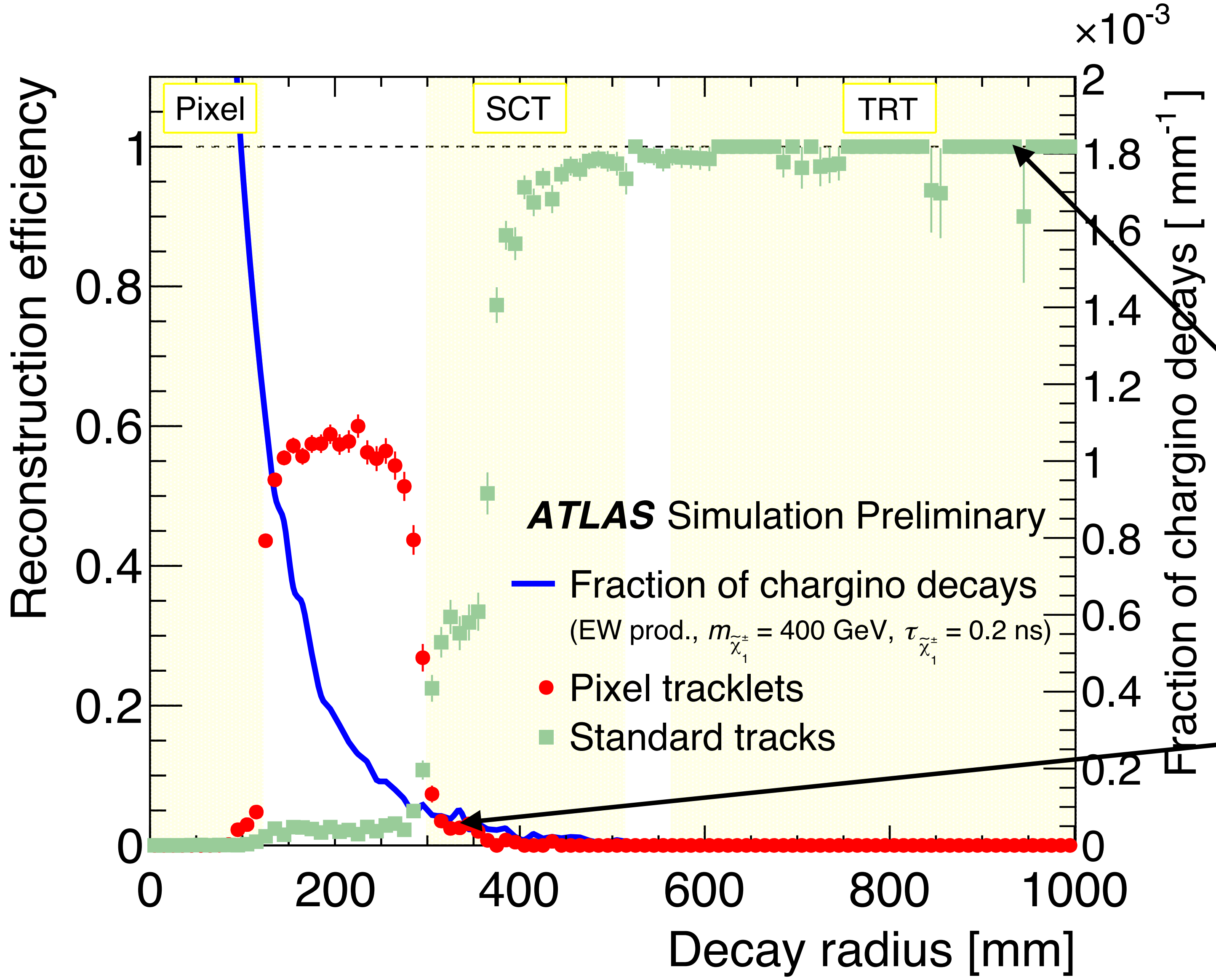
We expect $c\tau_{\tilde{g}} > \mathcal{O}(1)$ mm

Long-lived gluino searches



N. Nagata, H. Otono, S. Shirai, JHEP **1703**, 025 (2017) [arXiv: 1701.07664]

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%.

ATLAS-CONF-2017-017

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.

ATLAS-CONF-2017-017

Event selection criteria

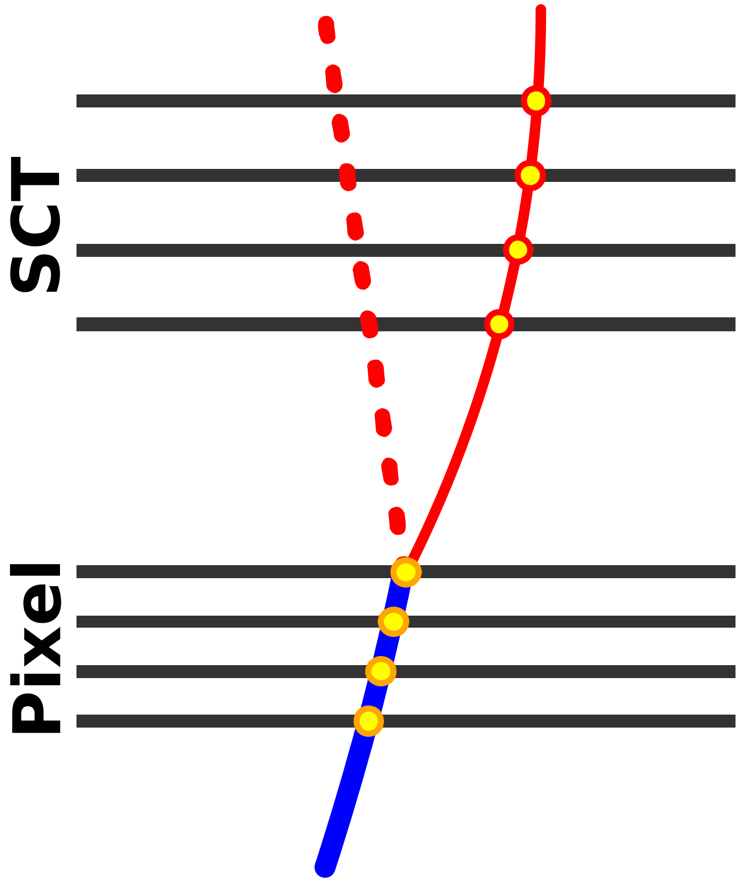
Kinematical selection 40% (400 GeV wino with a lifetime of 0.2 ns)

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

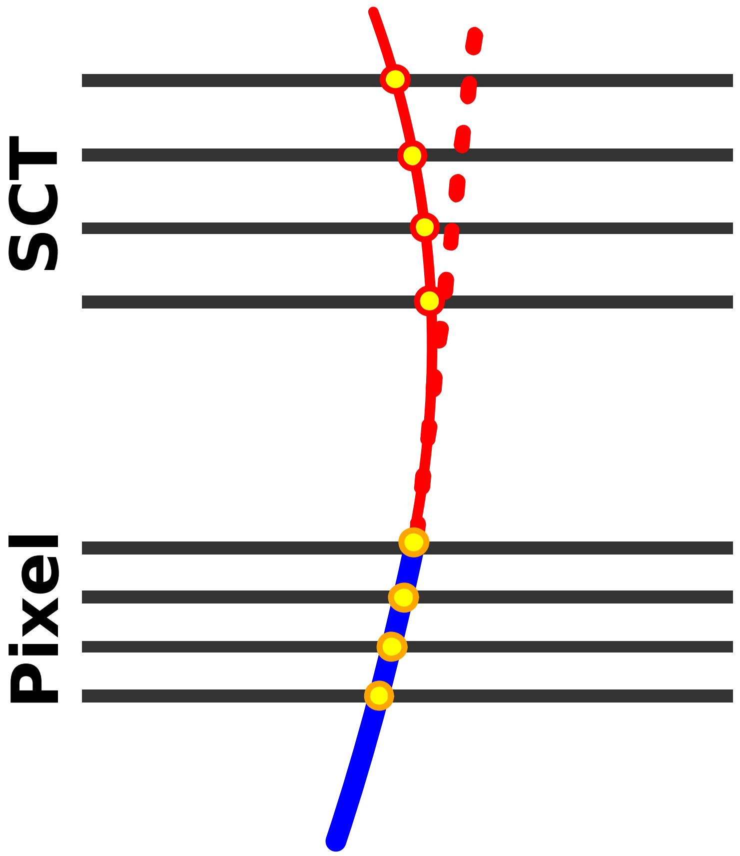
ATLAS-CONF-2017-017

Background

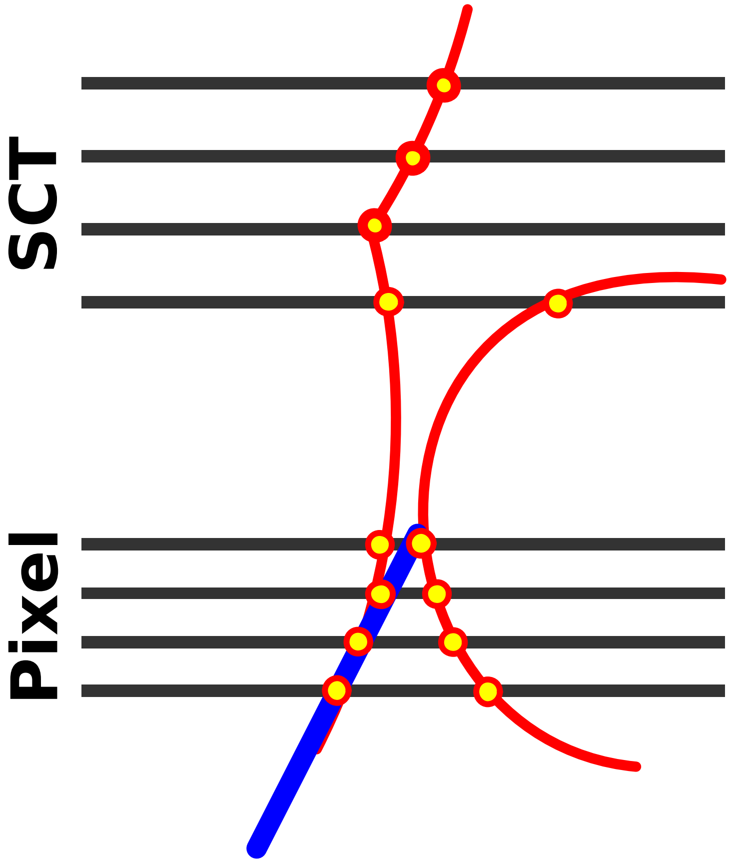
BG events mainly come from ttbar, W + jets (W → eν, τν)



Hadronic scattering



Bremsstrahlung (leptons)



Two nearby tracks (fake)

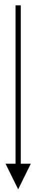
Fit data with p_T shapes of BG + signal components with an unbinned likelihood function.

Need p_T distributions of each component.

Background estimation

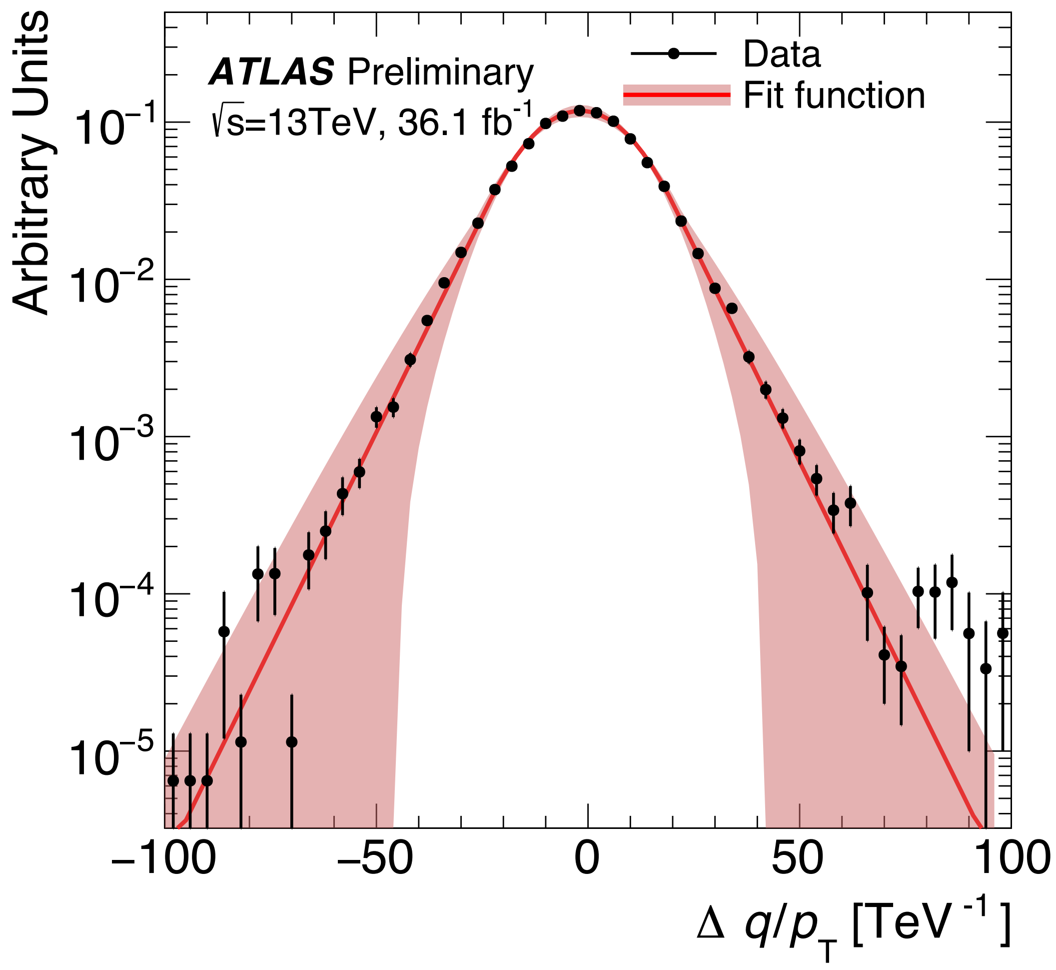
To estimate BG, we need to obtain p_T distribution of pixel-only tracks.

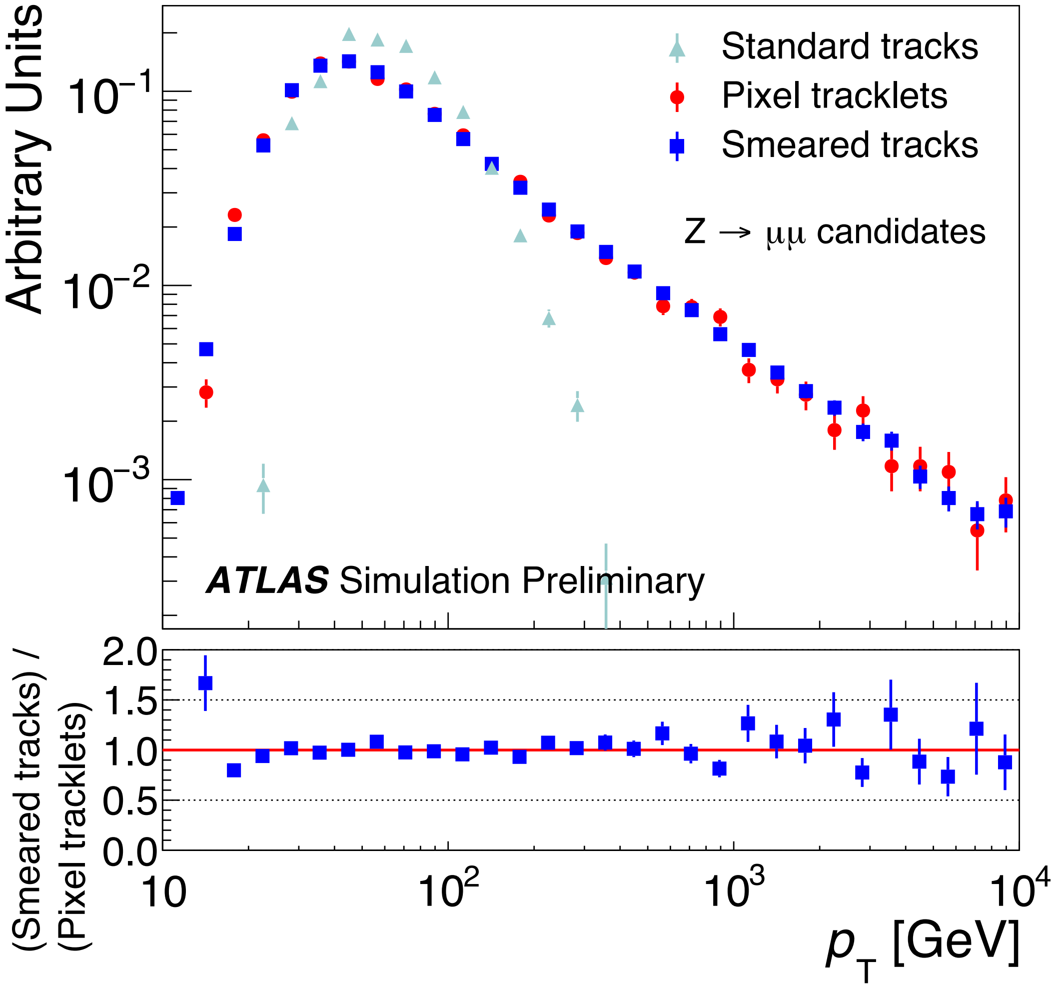
p_T distribution of standard tracks



Smearing (obtained from Z → μμ)

p_T distribution of pixel-only tracks





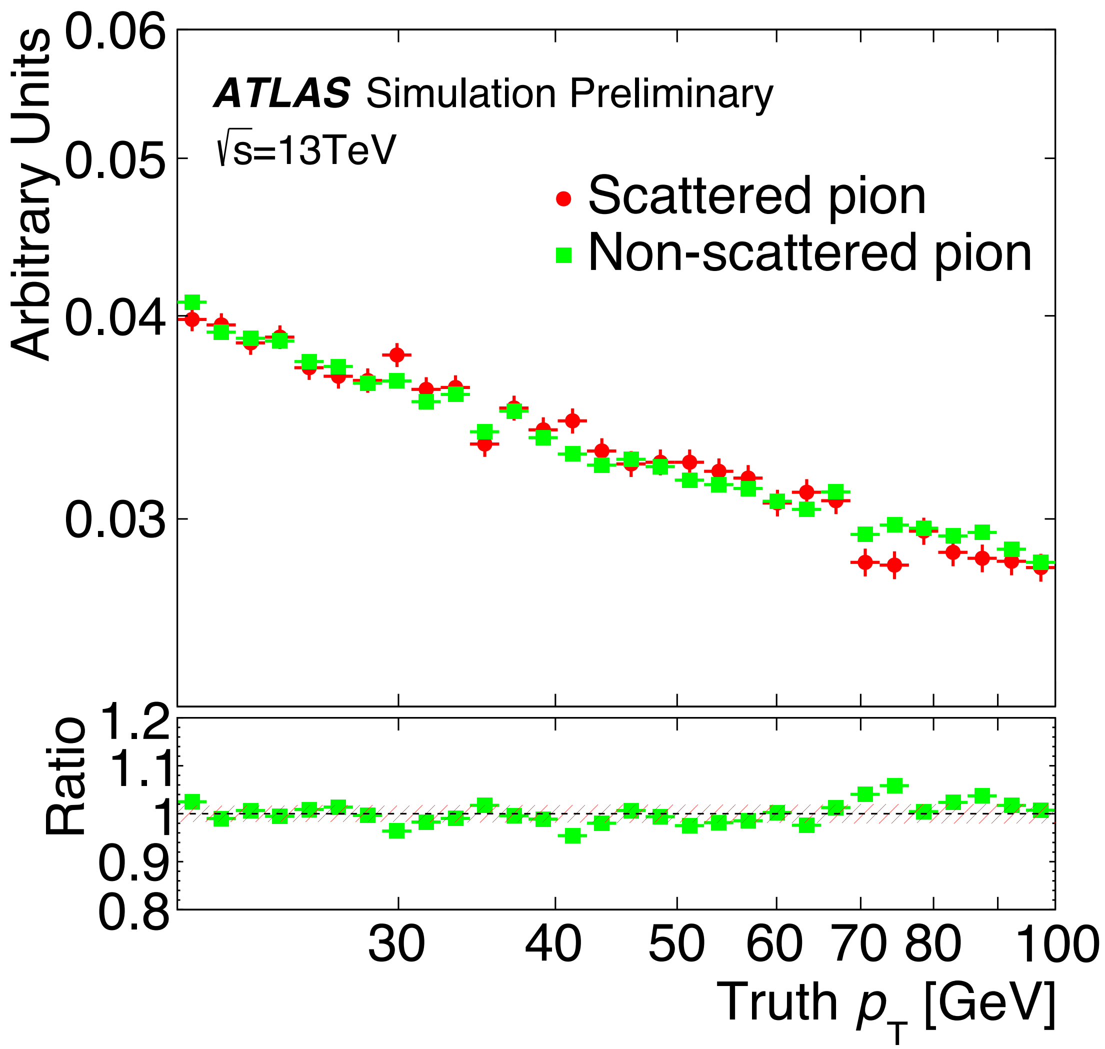
Look into difference between standard and pixel-only tracks.

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.

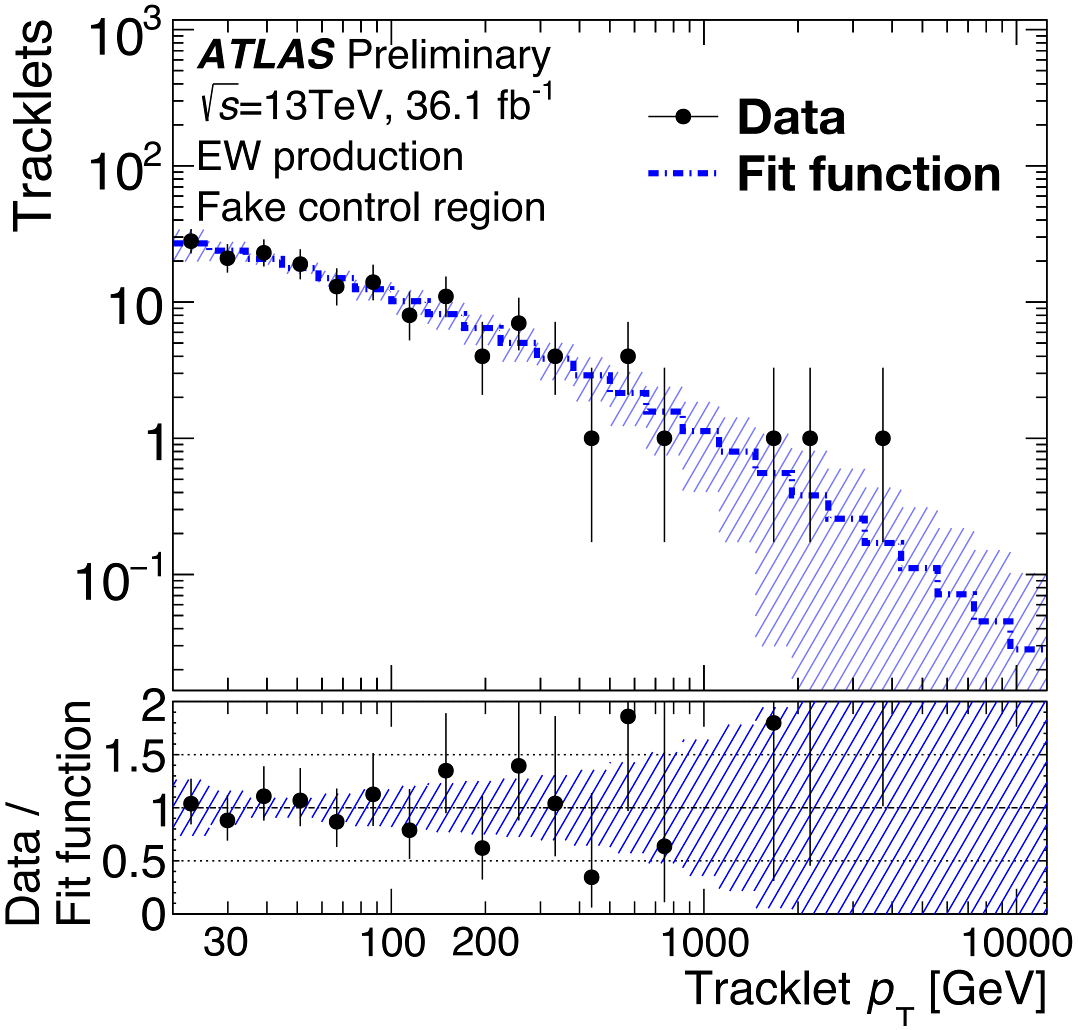
Background estimation

Fake tracks

These tracks tend to have a large impact parameter.

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

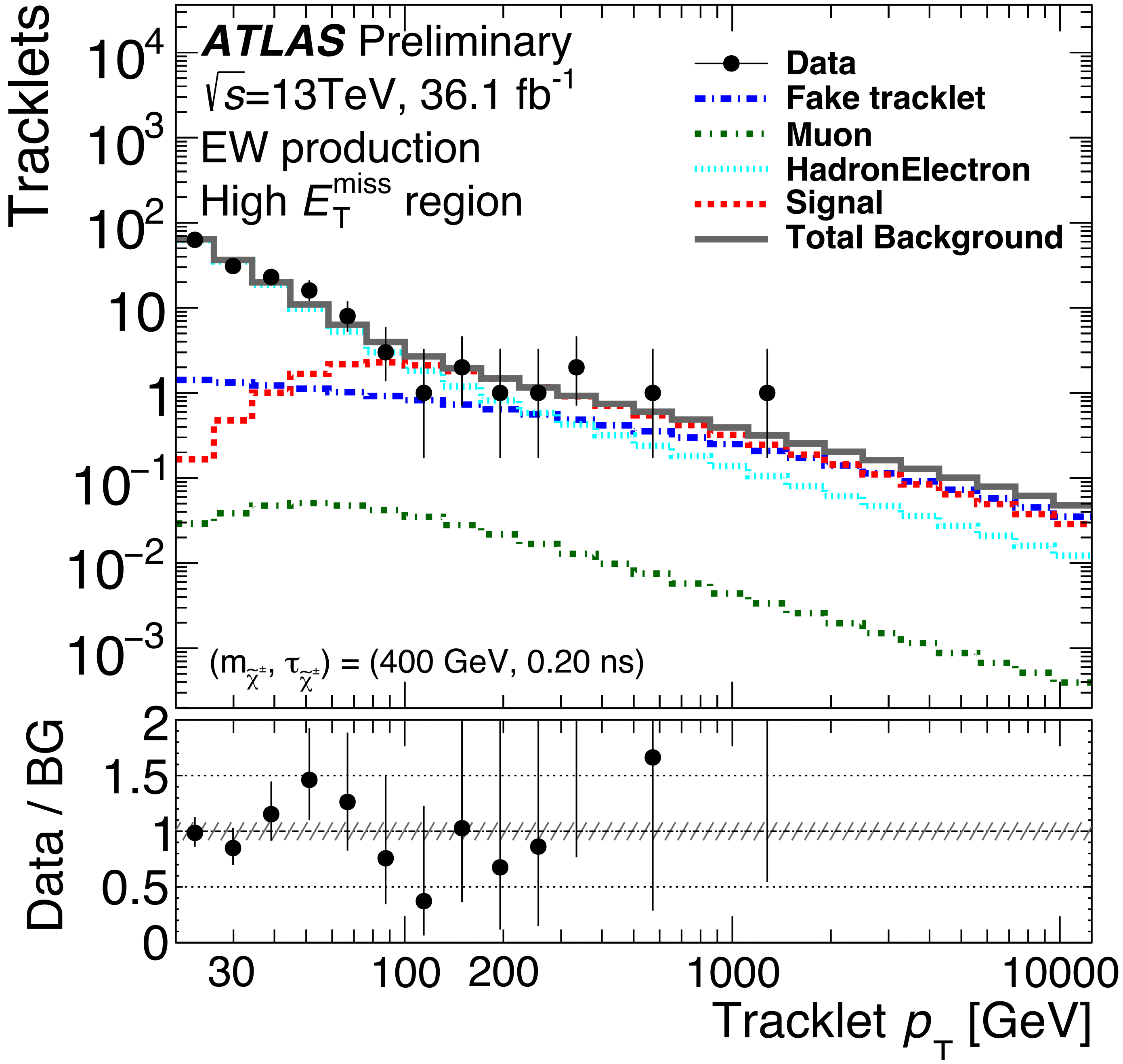
Fit the following empirical function: $f(p_T) = \exp\left(-p_0 \log(p_T) - p_1 (\log(p_T))^2\right)$



No E_T^{miss} dependence was found.

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

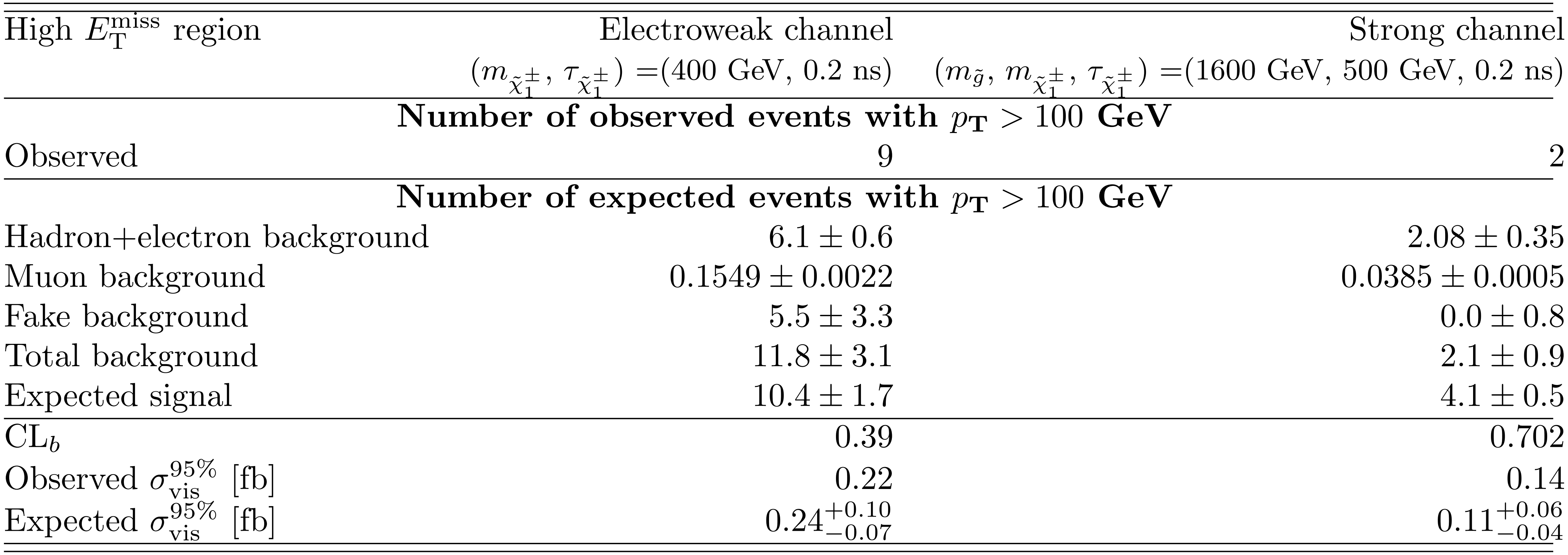
Results



No excess has been observed!

ATLAS-CONF-2017-017

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 $p_{\mathrm{T}} > 100$ GeV		
Observed	9	2
Number of expected events with $p_{\mathrm{T}} > 100$ 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!

ATLAS-CONF-2017-017

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].