Disappearing track searches at LHC and future colliders

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ICEPP, the University of Tokyo

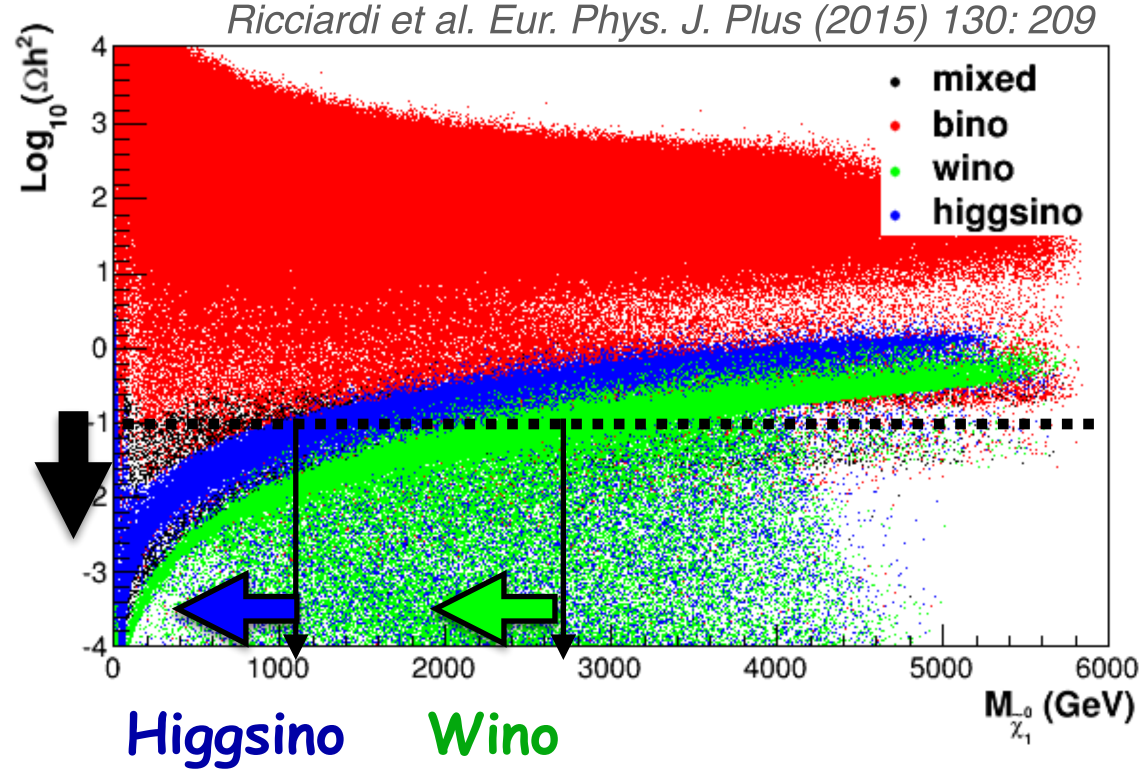
Dark Matter searches in the 2020s
At the crossroads of the WIMP
11—13 Nov, 2019, U-Tokyo, Kashiwa Campus

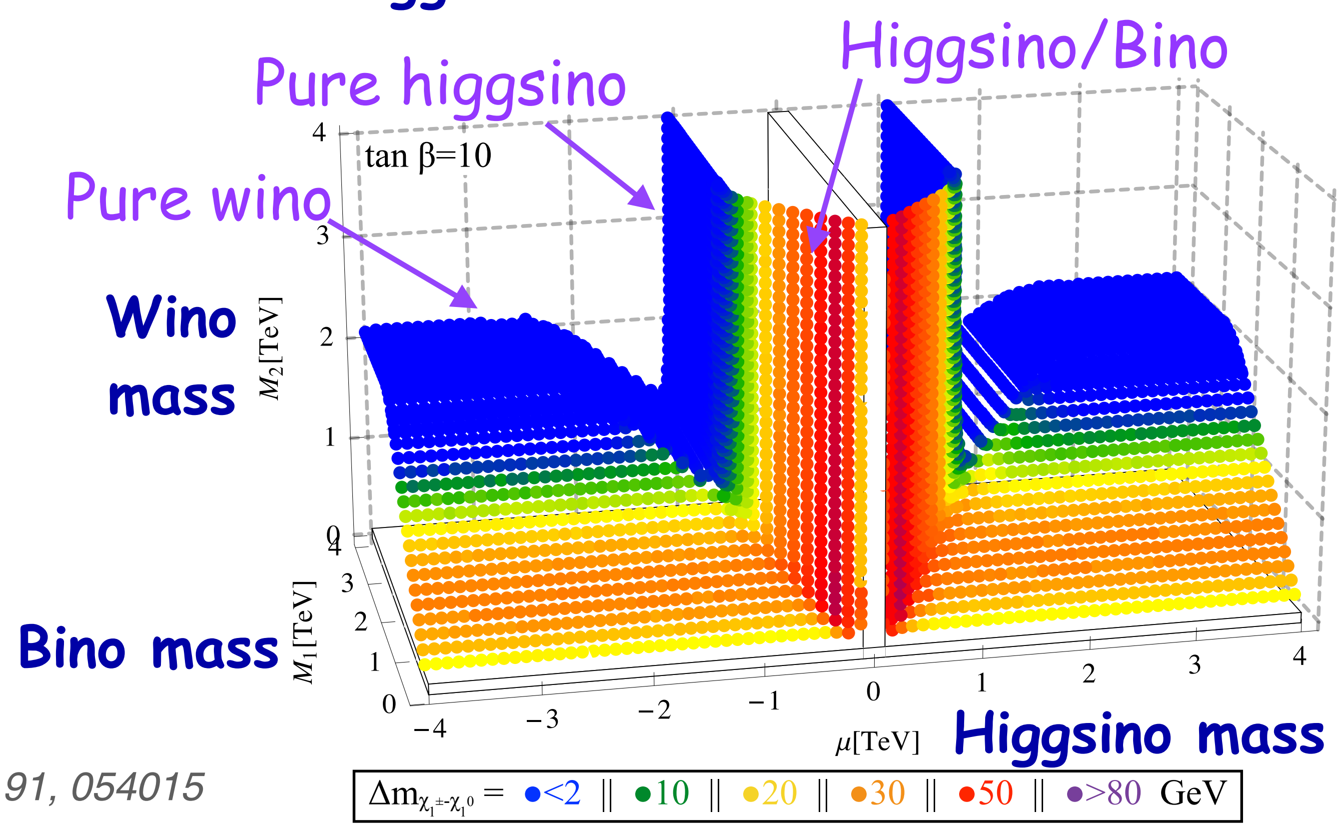
ICEPP
The University of Tokyo

Neutralino dark matter

- The lightest neutralino is a good candidate of dark matter.
- Bino DM would be overproduced, while **Wino** and **Higgsino** could have the right relic density.
- If thermally produced, the dark matter mass should be < ~**1 TeV for Higgsino** and < ~**3 TeV for Wino**.
- **Small mass difference** between the lightest **chargino** and **neutralino(= DM)** is favoured.

Ricciardi et al. Eur. Phys. J. Plus (2015) 130: 209





Phys. Rev. D 91, 054015

Viable parameter space

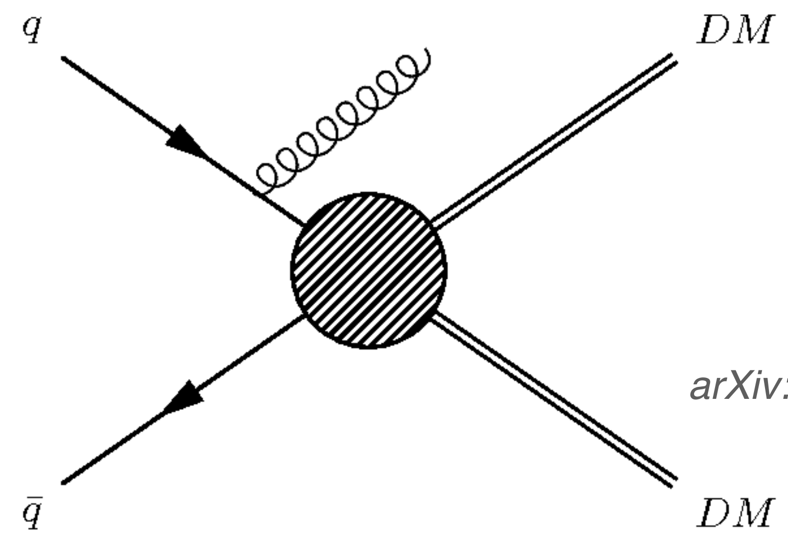
- **Wino DM**
  - The lightest SUSY particle in AMSB and PGM models
  - **It is not excluded** (except for narrow region around ~2.4 TeV) **by indirect DM searches** when the DM-halo densities in galaxies have flat central profiles ("cores").
  - **It is not excluded by direct searches** due to the extremely small direct-detection cross-section.

- **Higgsino DM**
  - **Very pure higgsino DM is excluded** due to too high Z-boson-mediated nucleon scattering cross section. **Gaugino mass should be < O(10) PeV**.
  - The electron EDM limit and direct DM searches require **gaugino masses to be > O(TeV)**.

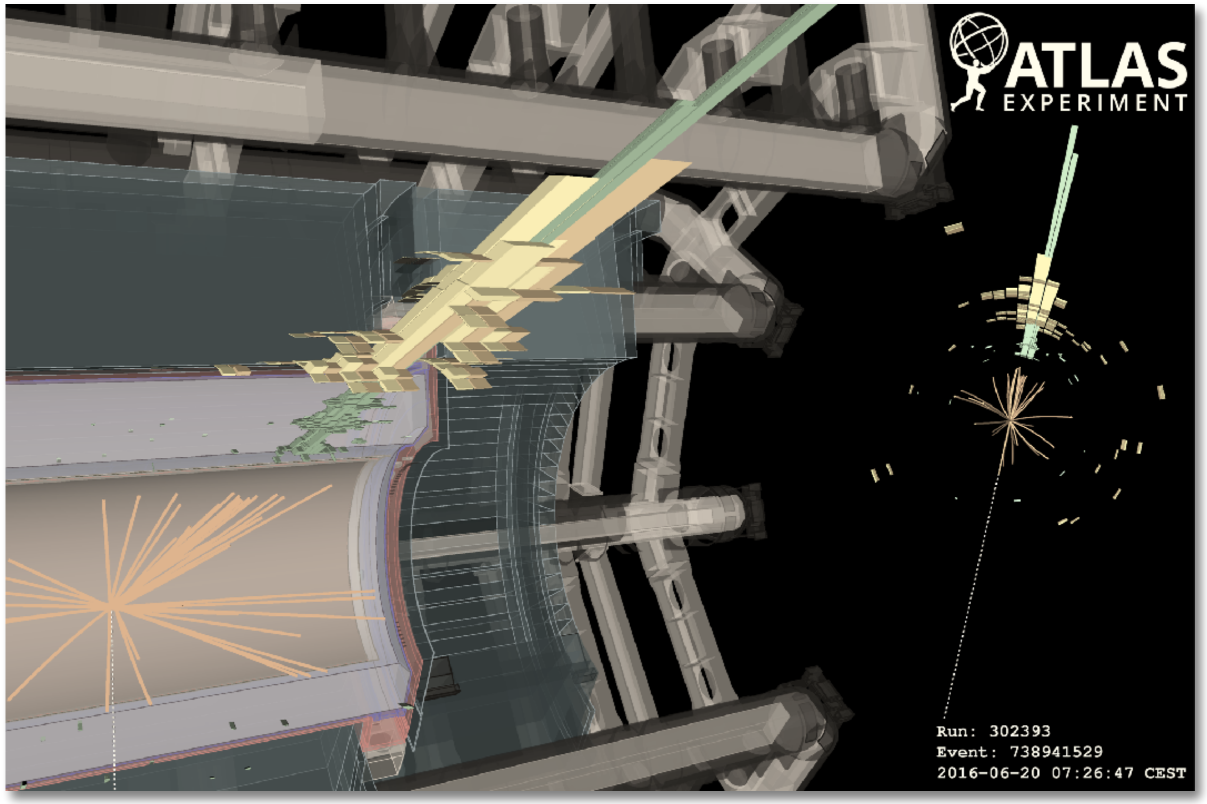
Can wino/higgsino DM be discovered at the LHC ?

- In general DM searches, mono-X (X = jet, higgs, Z…) signatures are used *.
- **Low sensitivity by mono-jet** for wino and higgsino DM due to the small production cross section.
- For suppression BG, we need **additional object**.

Mono jet signature



arXiv:1408.3583



* Also di-X (X= jet etc.) signature from mediator-decay is also used.

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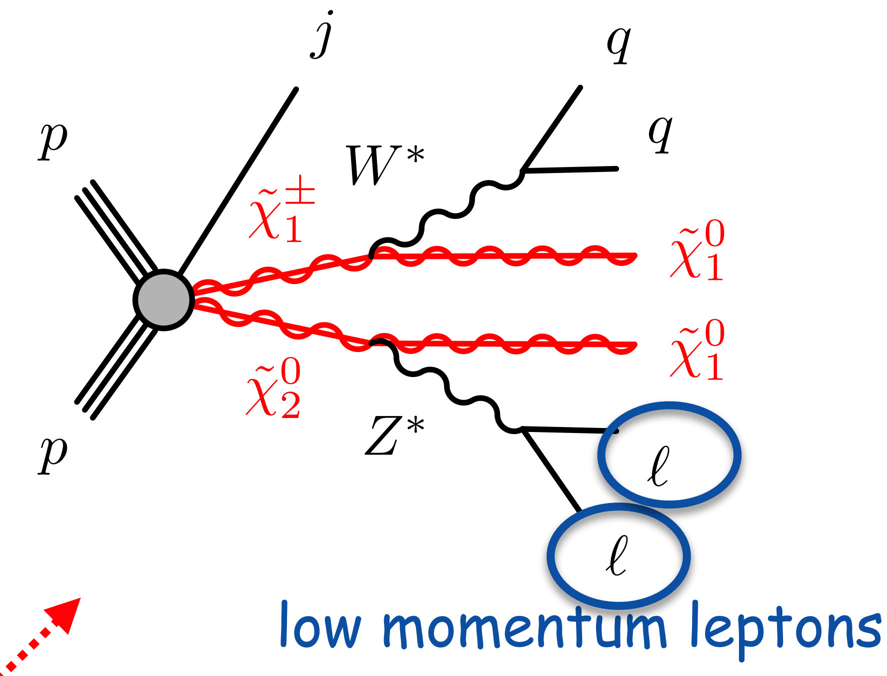
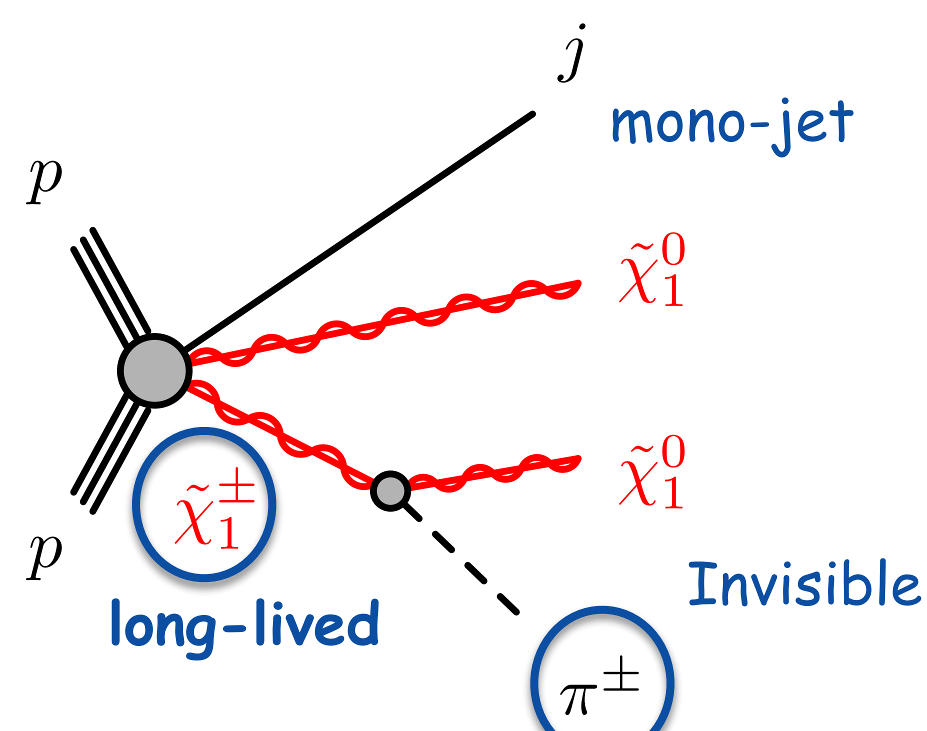
- **Low sensitivity by mono-jet** for wino and higgsino DM due to the small production cross section.
- For suppression BG, we need **additional object**.
  - If Δm (chargino-neutralino splitting) is not too small

    → **Low momentum leptons** from off-shell W and Z
  - If Δm is tiny, **chargino's lifetime is long**

    → **Disappearing track**





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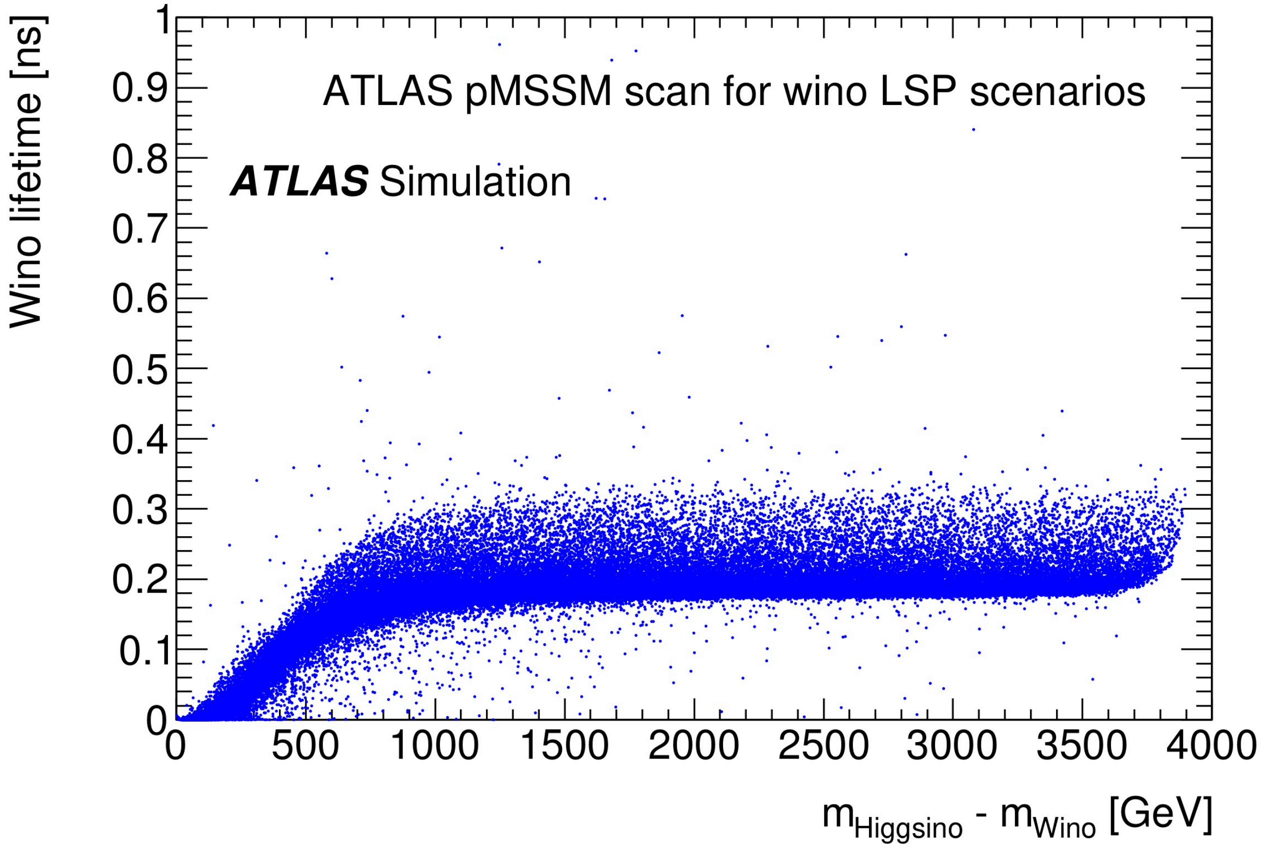
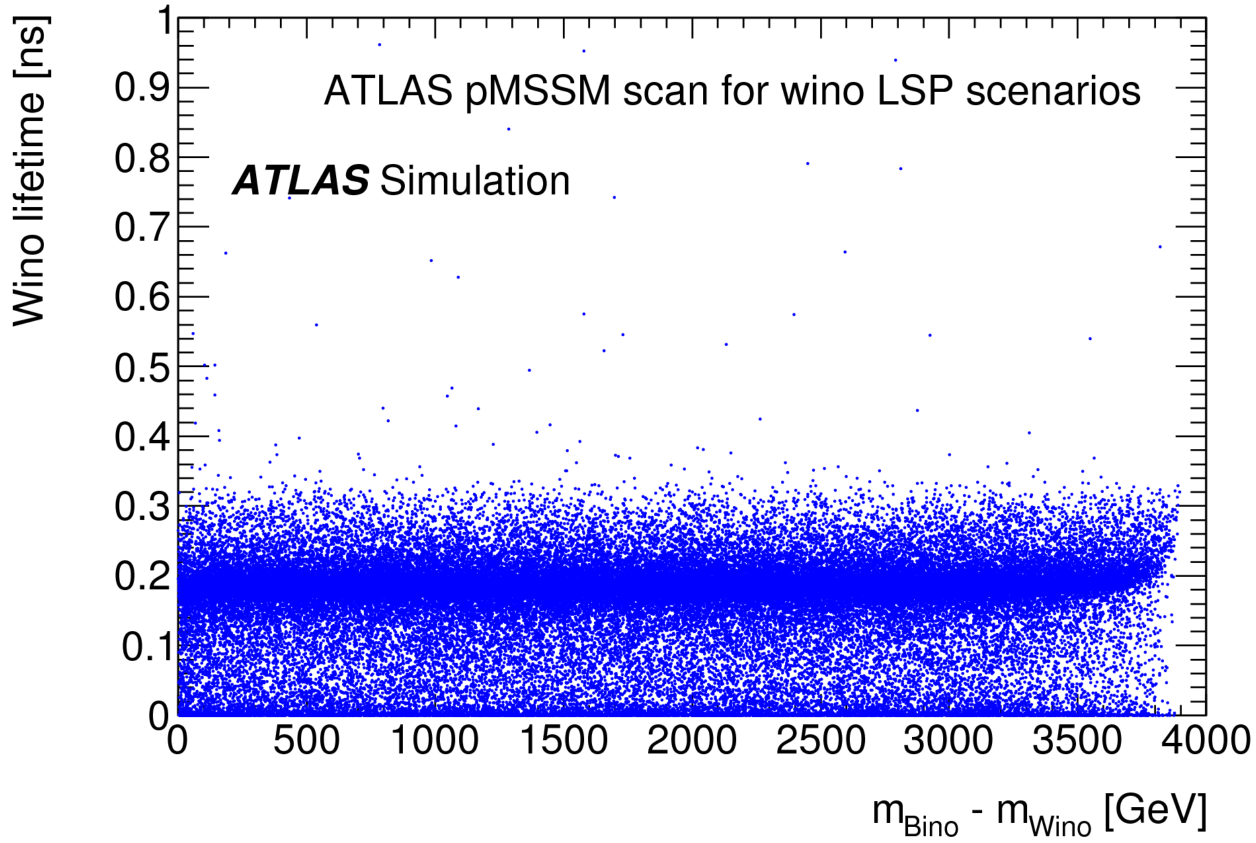
Charged wino lifetime

JHEP 06 (2018) 022, auxiliary material

Higgsino mass dependence



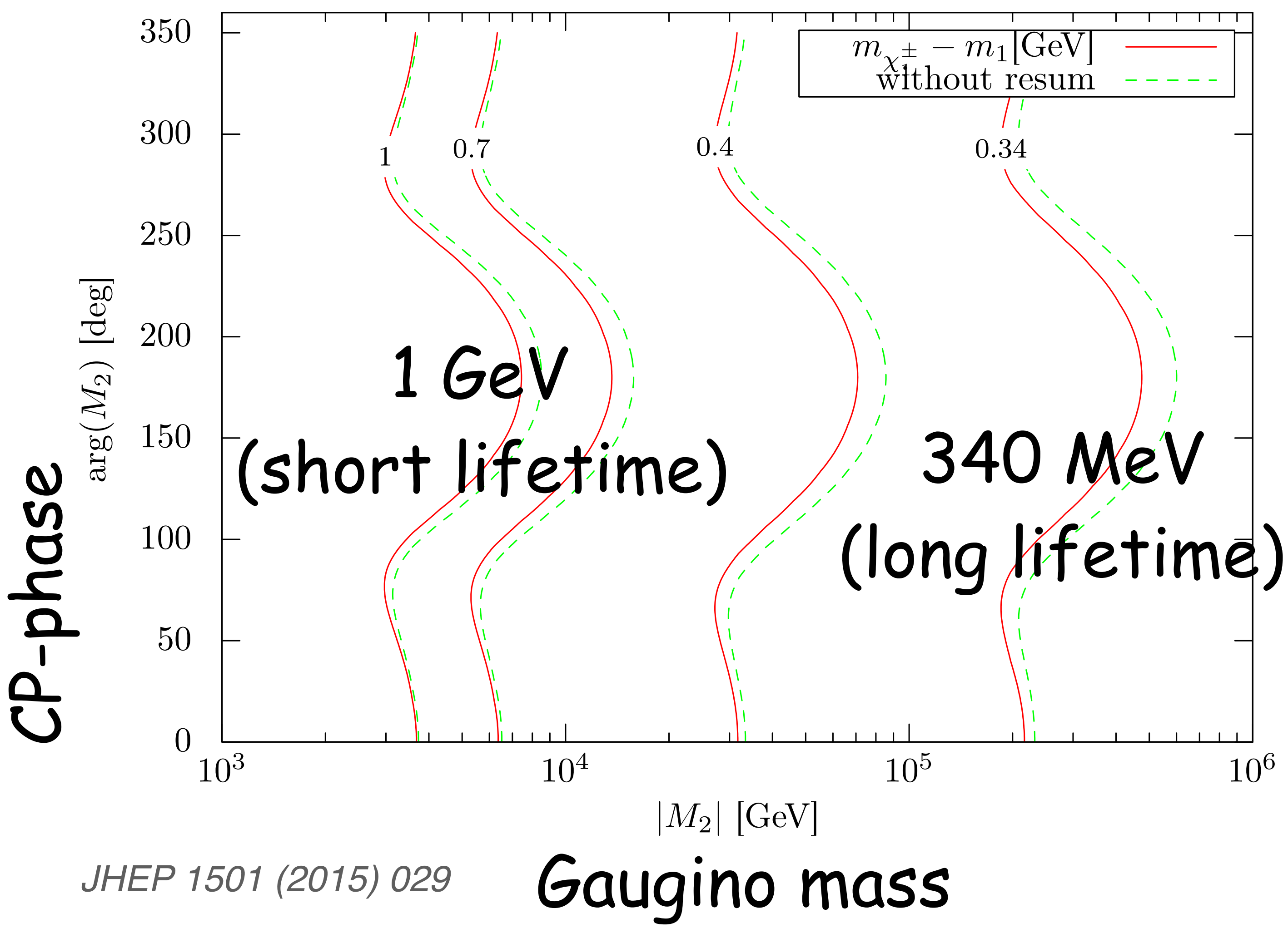
Bino mass dependence



- When wino is the lightest SUSY particle, the lightest neutralino is "pure" wino in a wide parameter region (i.e. higgsino is heavier than wino by ~ 1 TeV)
  - **Δm ~ 160 MeV**
  - **Chargino $c\tau_0$ ~ 6 cm**

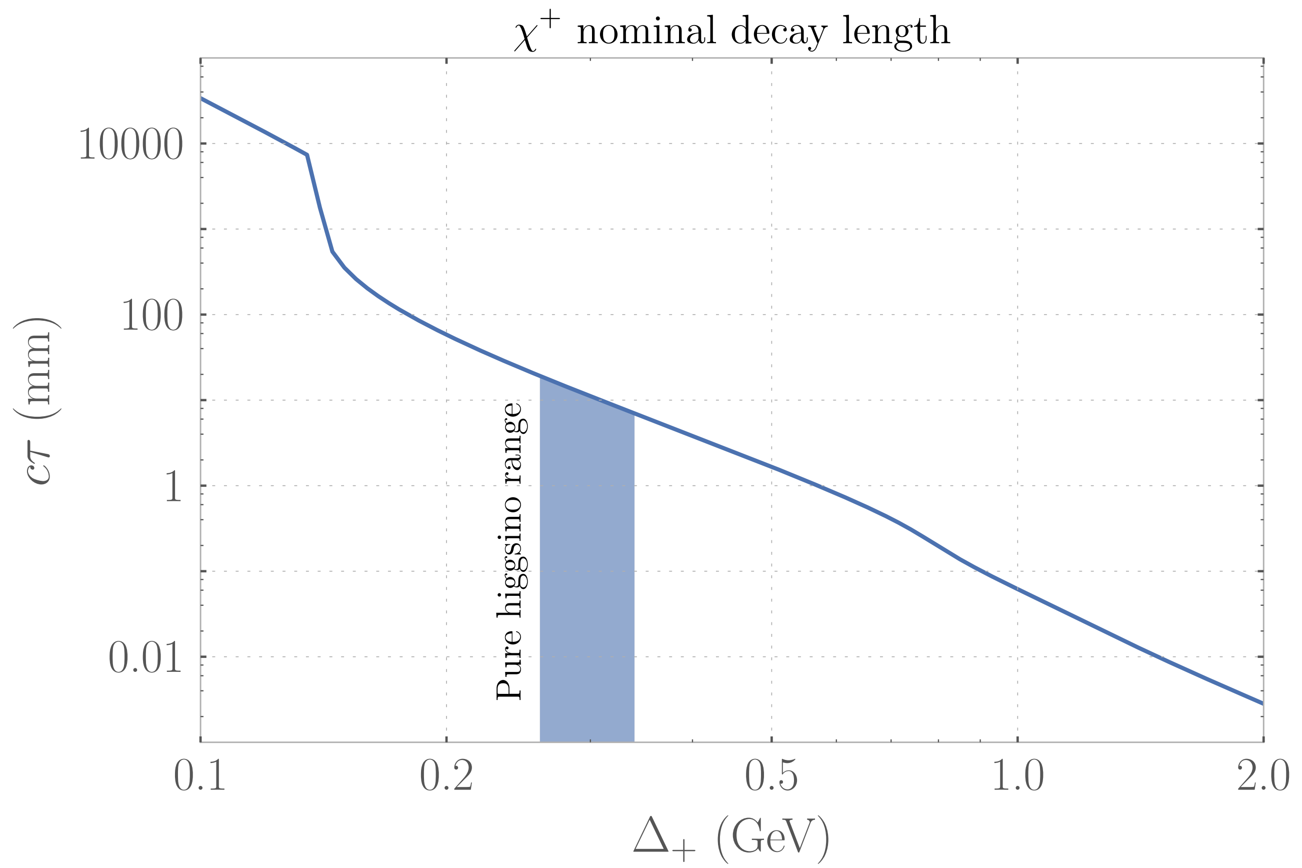
Charged higgsino lifetime

- Lifetime of charged higgsino depends on gaugino masses (due to mixing).
- EDM and direct-DM searches favour smaller mixing, so smaller Δm.
  - **Δm < O(1GeV)**
  - **Higgsino : $c\tau_0$ < ~2 cm**



JHEP 1501 (2015) 029

JHEP06(2017)119



Long-lived chargino : history

1997: **C.-H. Chen, M. Drees, and J. F. Gunion** mention ideas for the search *.

"We will also find that the $\tilde{\chi}_1^{\pm}$'s lifetime is not likely to be sufficiently long that it will appear as a stable particle track in the detector— short tracks in a vertex detector are, however, a distinct possibility. "

Phys. Rev. D 55, 330 (1997)

2008: **S. Asai, T. Moroi, T. T. Yanagida** proposed a method to measure wino properties using ATLAS detector and the disappearing tracks.

- mass measurement using the velocity (ToF) and momentum
- lifetime measurement from decay radius distribution.

Phys. Lett. B 664, 185 (2008)

2011: The first ATLAS result

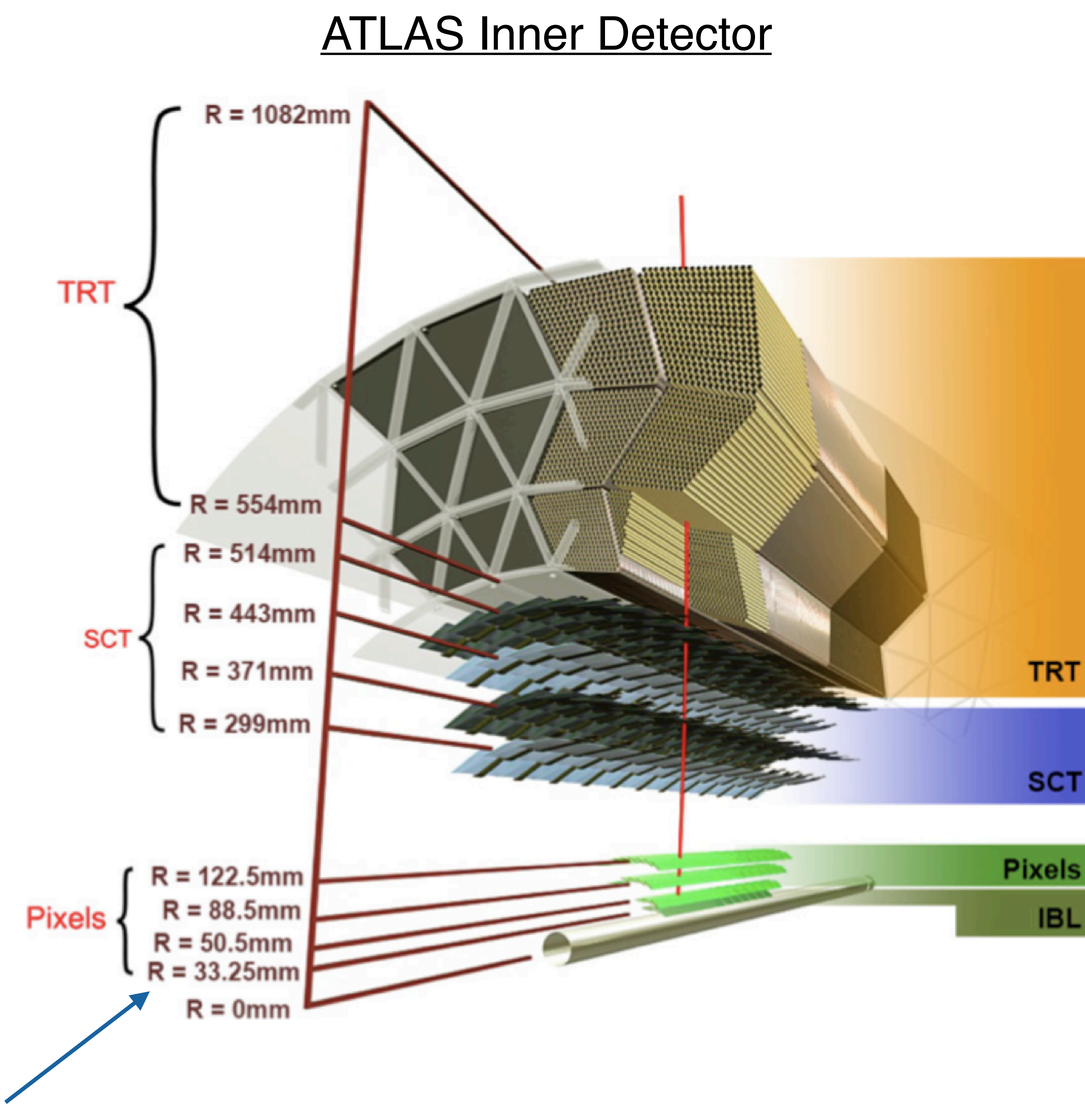
2015: The first CMS result

* This paper mention also about heavily-ionizing particles and soft tracks from the chargino decay

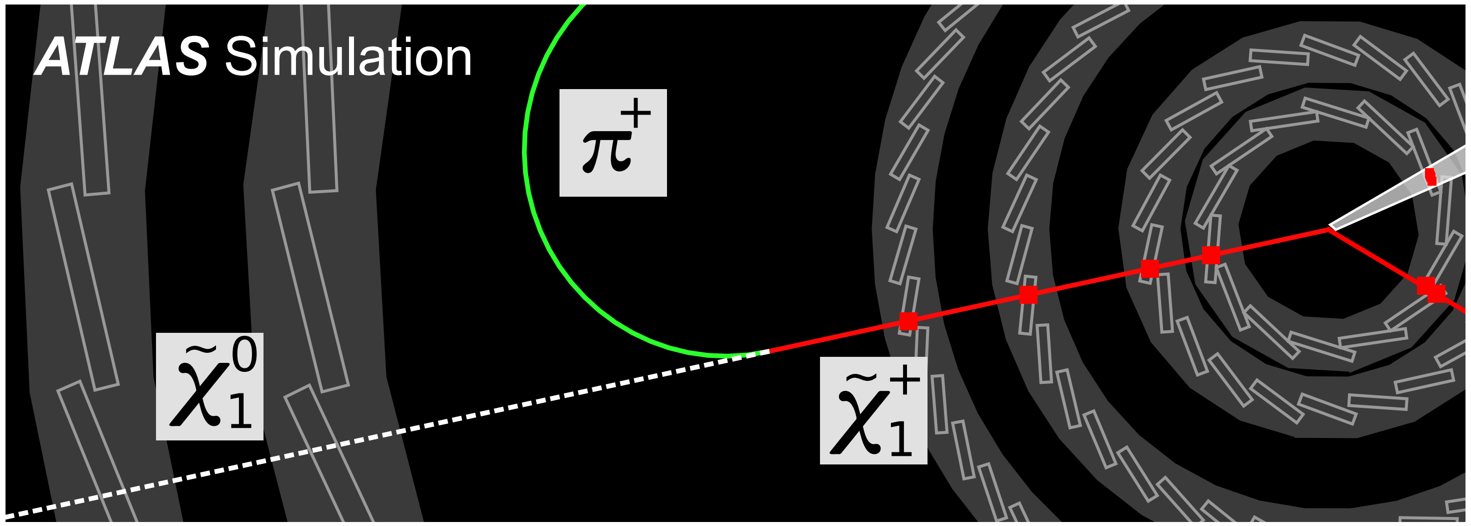
Inner tracking detector

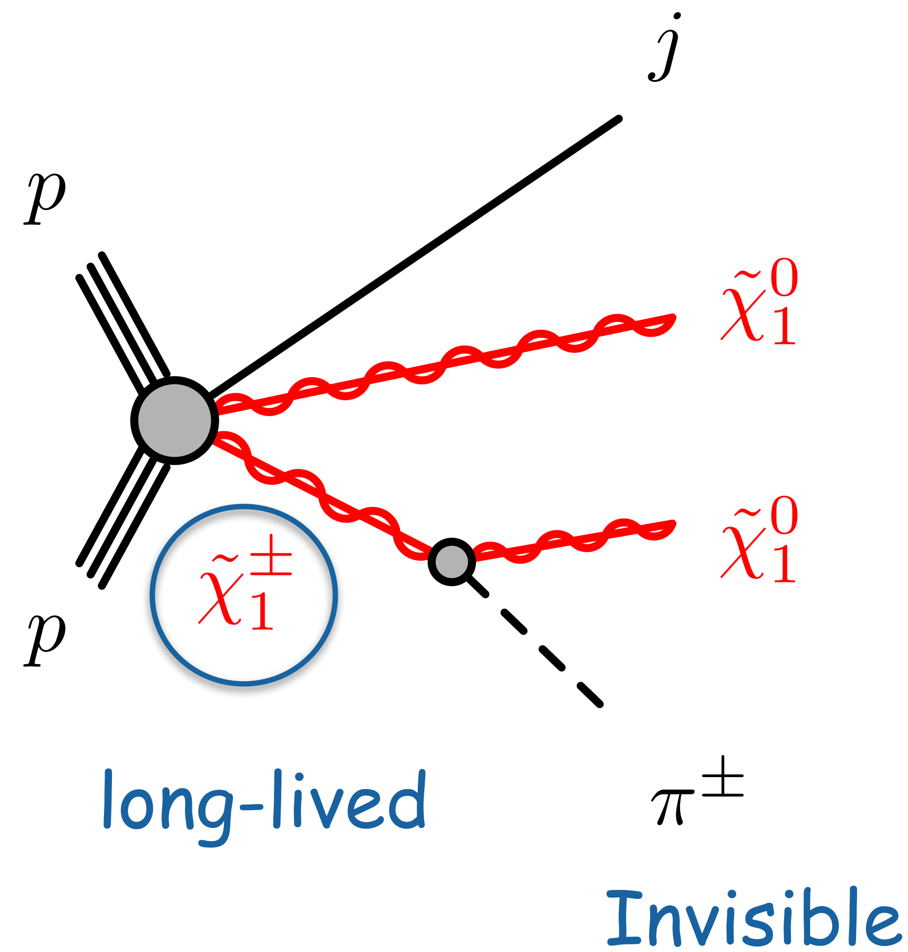
- ATLAS Barrel
  - Four layers of **pixel**
  - Four layers of **silicon strip** (SCT)
  - **Transition radiation tracker**
  - 2 T solenoid field

- CMS Barrel
  - Four **pixel** layers since 2017
  - 10 **silicon strip** layers
  - 4 T solenoid field



Disappearing track search @ LHC





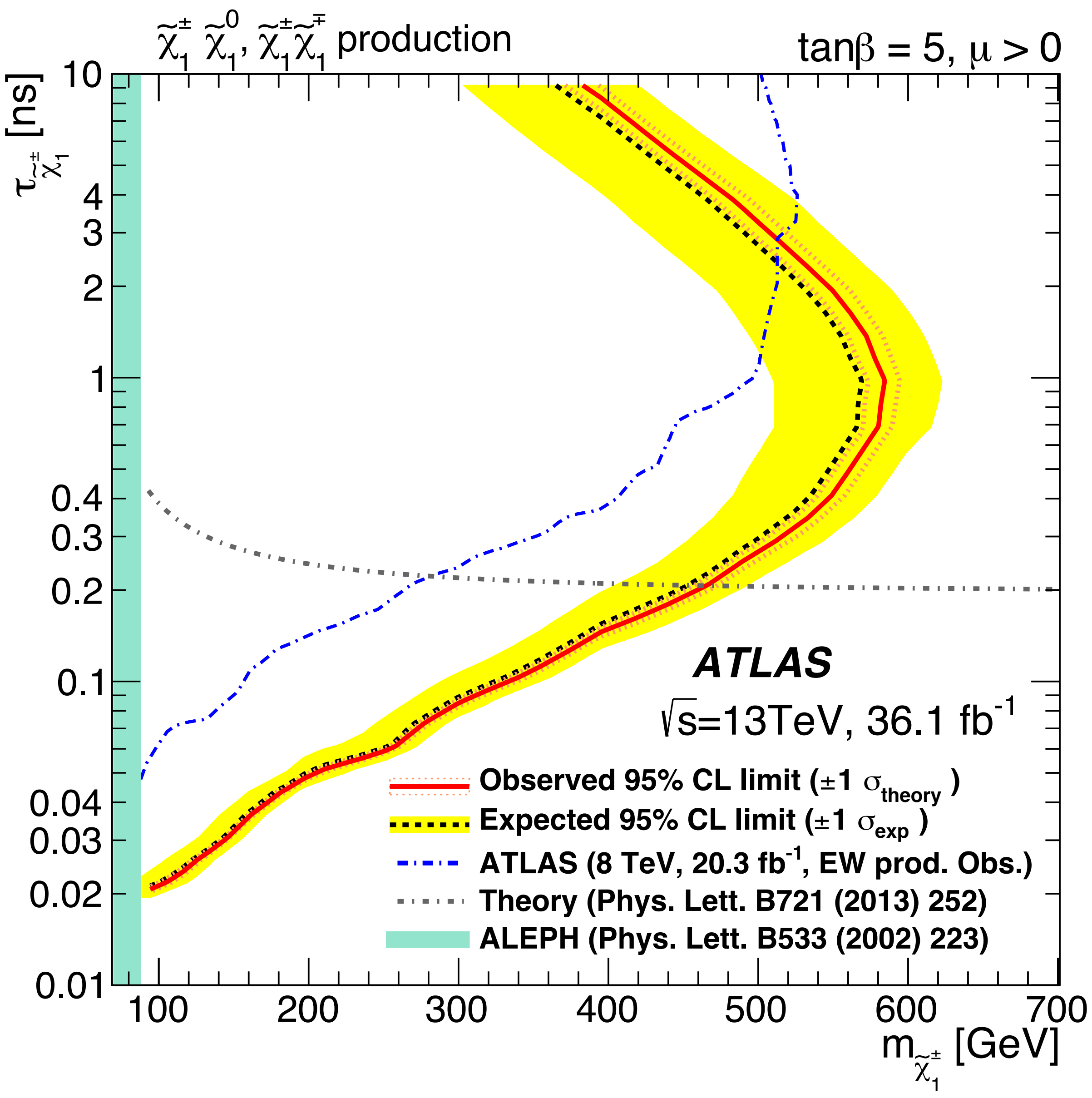
- Long lived chargino searches using **disappearing track**
  - Short tracks which do not have associated hits in the outer part of the tracker and calorimeters.
- Pions, with the transverse momentum about the mass difference (i.e. **~200 MeV from wino, ~300 MeV from higgsino**), are not reconstructed in standard tracking algorithms. (e.g. **Track threshold in ATLAS is ~500 MeV**)

Wino search by ATLAS/CMS

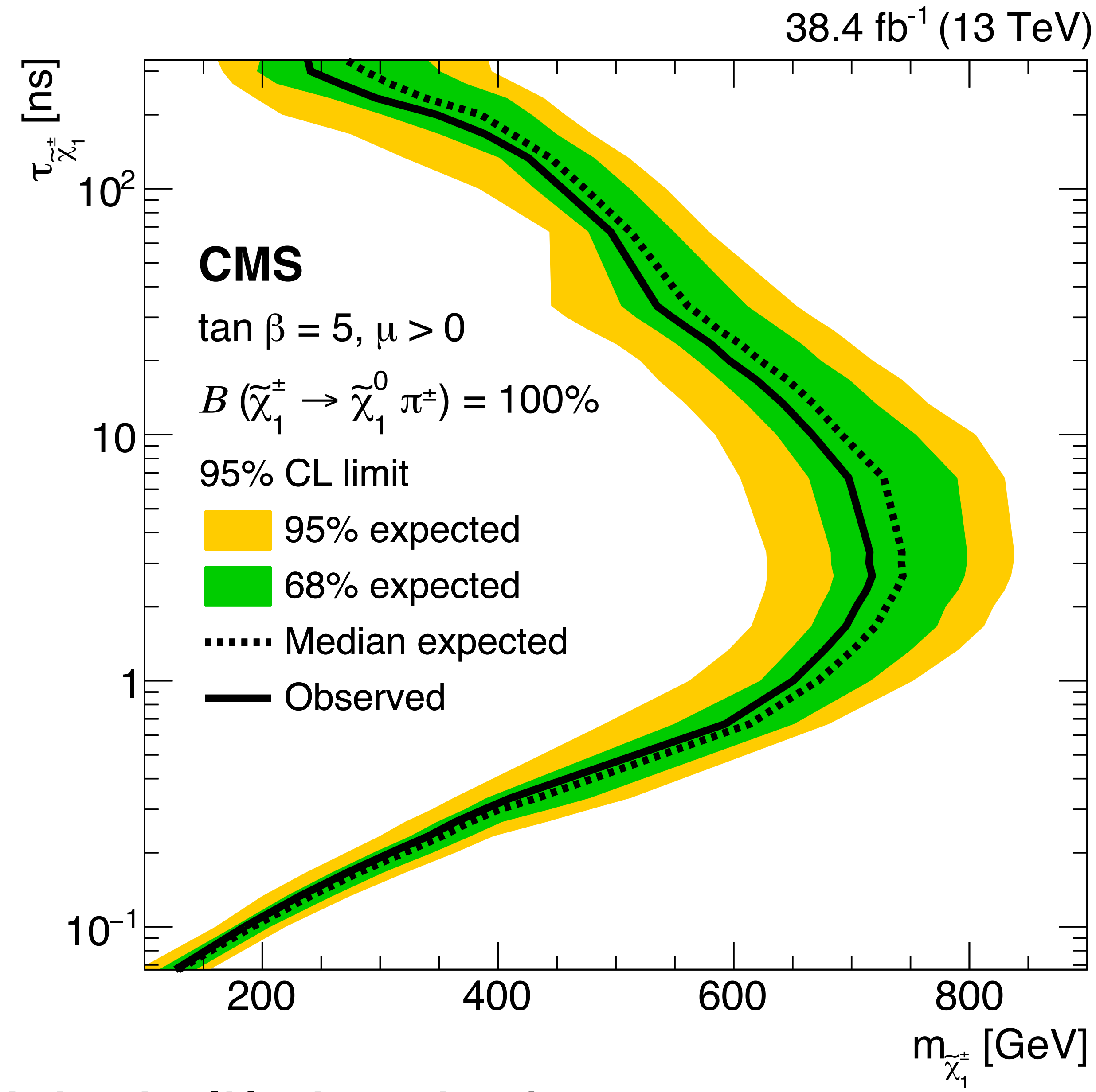
2015—2016 data

<u>ATLAS (36 fb-1)</u>

Pure Wino excluded below **460 GeV**



<u>CMS (38 fb-1)</u>



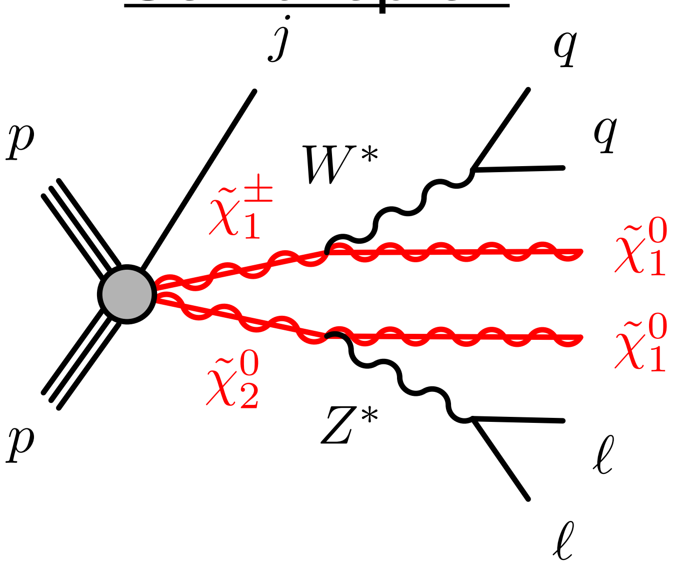
JHEP 06 (2018) 022

The difference in peak sensitivity in lifetime is due to that in the track length (shorter in ATLAS).

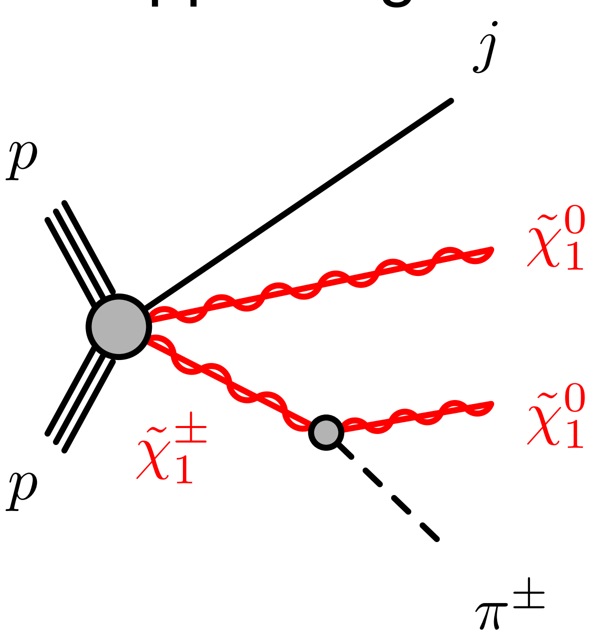
JHEP 08 (2018) 016

Higgsino direct production

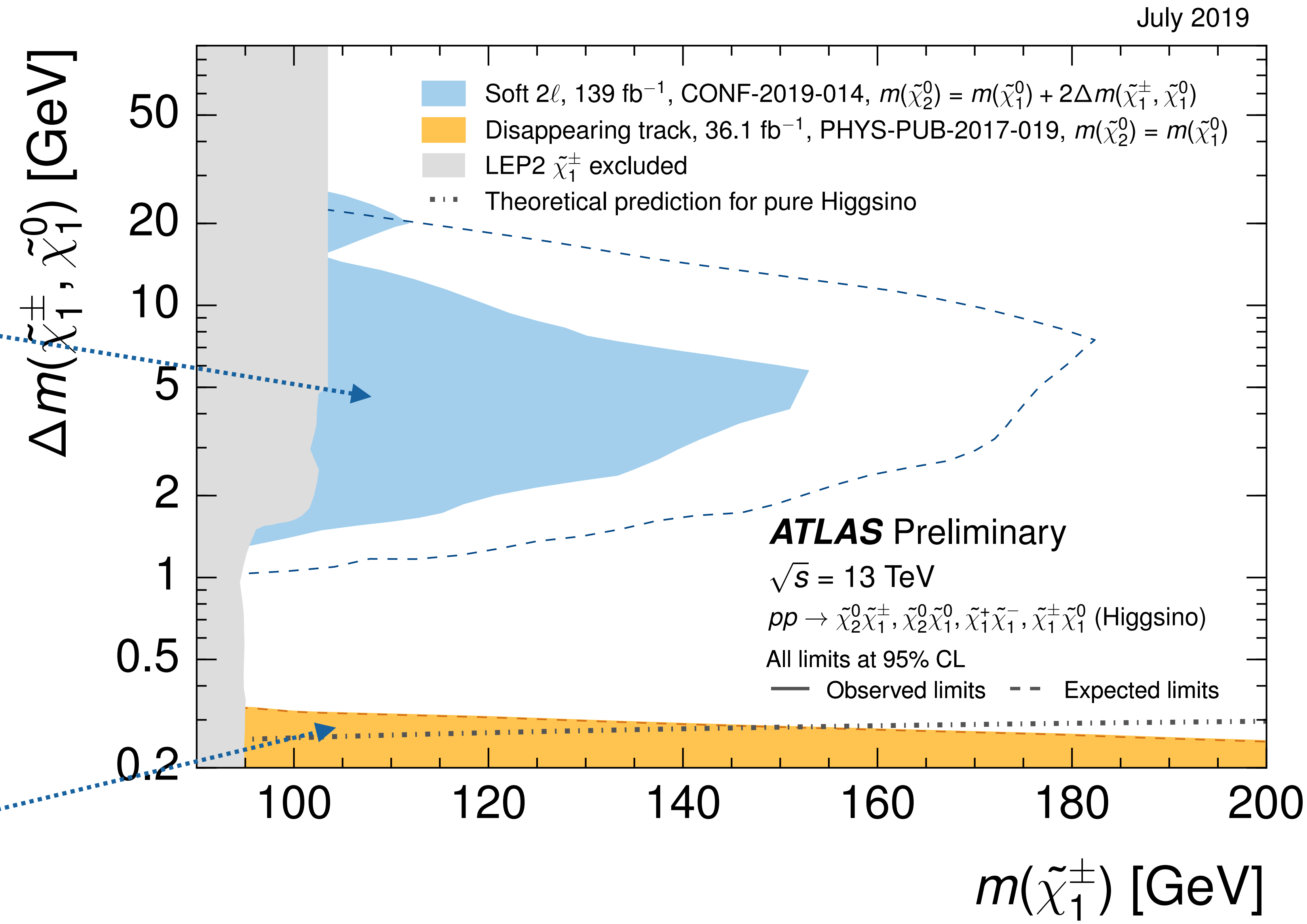
Soft dilepton



Disappearing track



Pure Higgsino excluded below **152 GeV**



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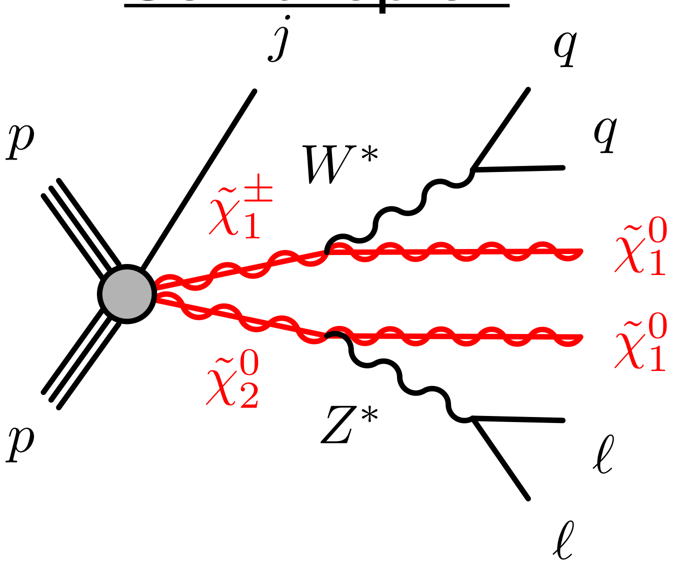
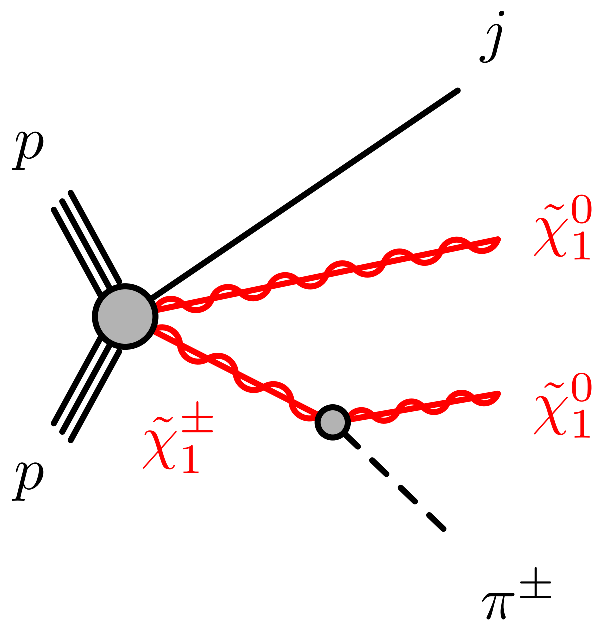


Disappearing track



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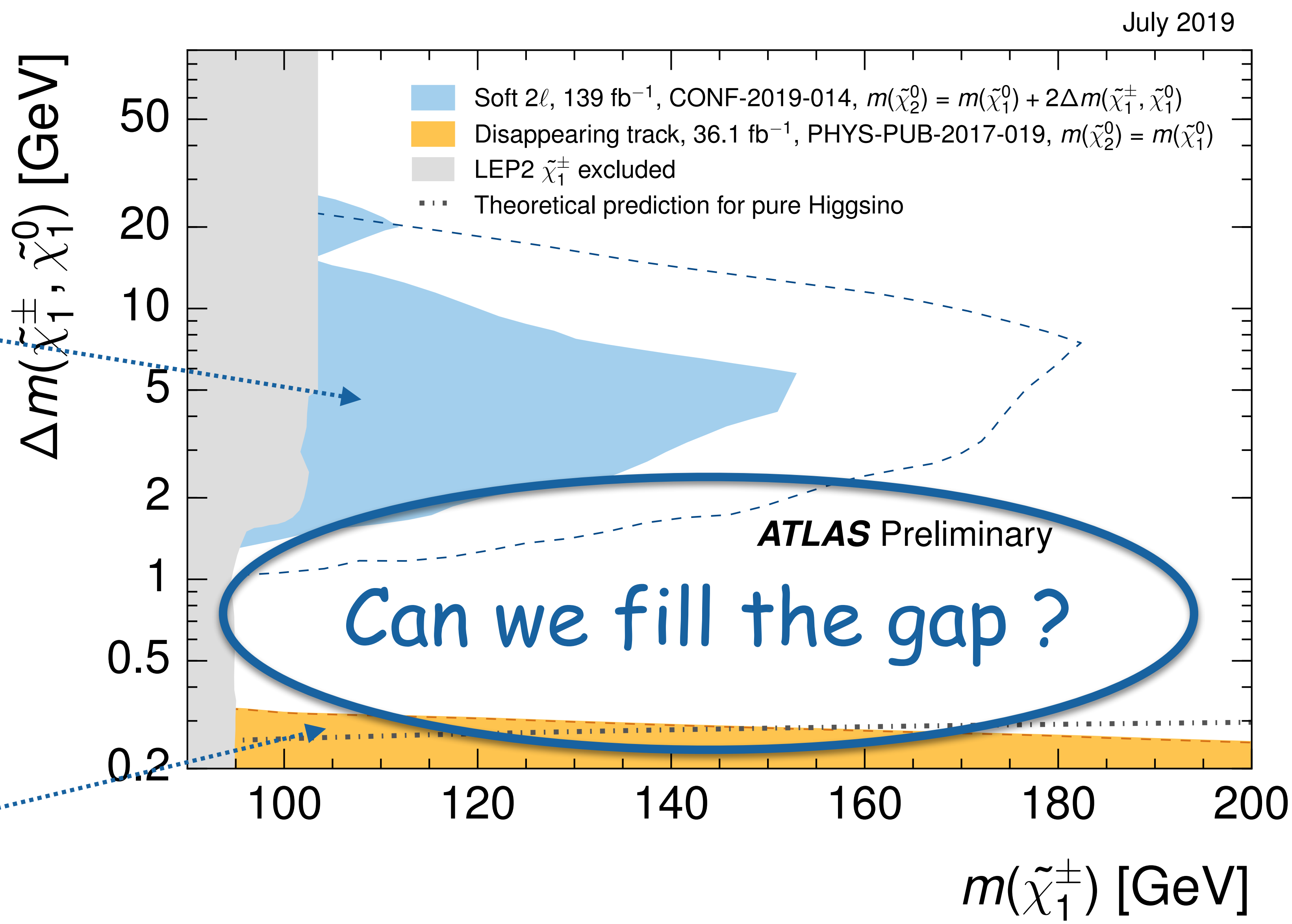
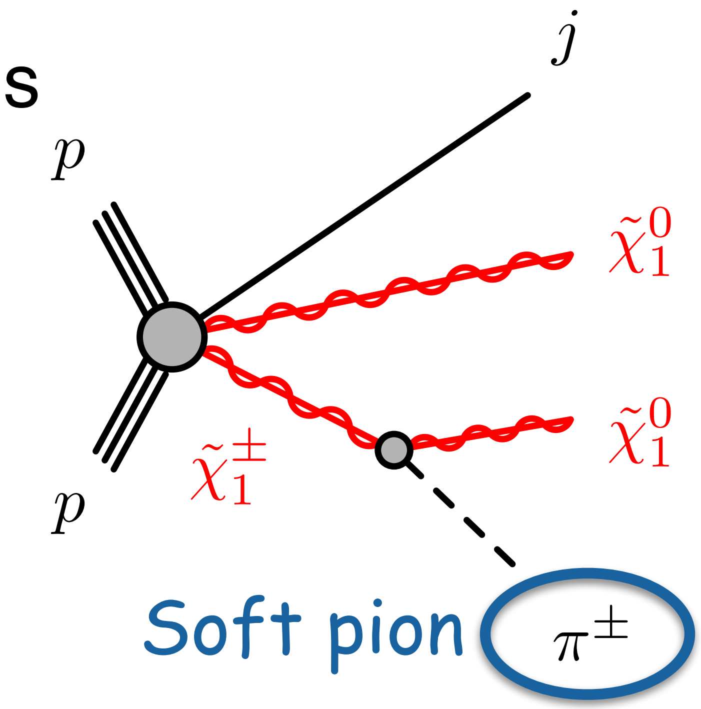


Two long-lived-search ideas on following pages.
Please see also Koji's slides.

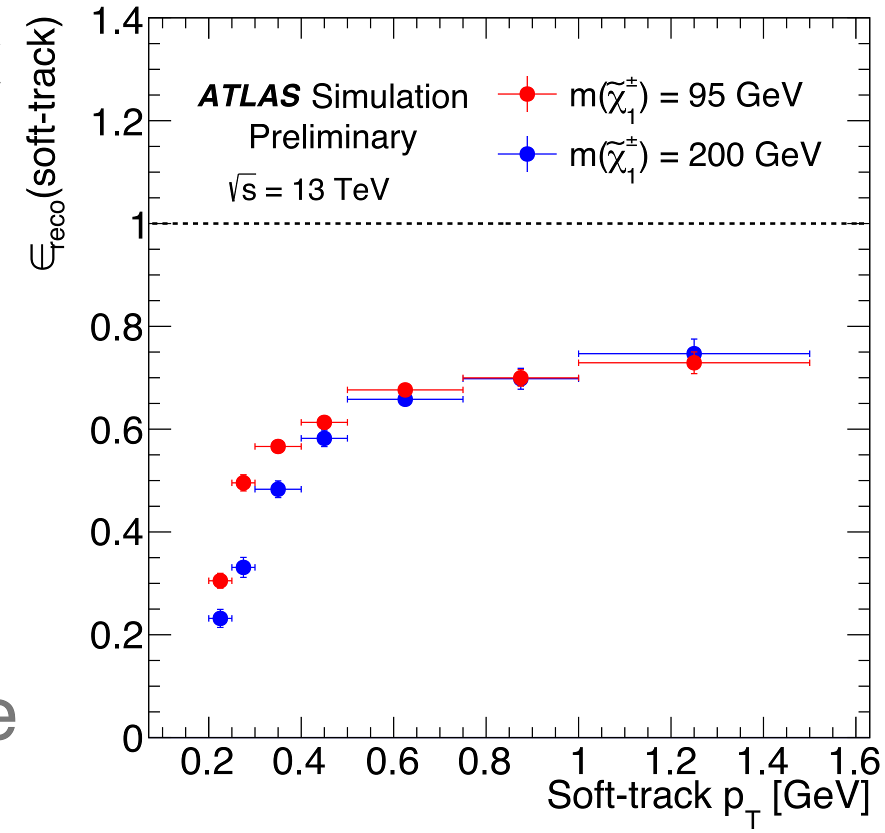
Higgsino: Filling the gap 1

ATL-PHYS-PUB-2019-011

Improving the disappearing track search for shorter lifetimes



- Currently, **4-layer pixel tracks** (R~12 cm) are used in ATLAS
- We could use **3-layer pixel tracks** (R~8cm) for better sensitivity, but it is technically challenging.
  - **Poor momentum resolution**
    - Could be mitigated by using the collision vertex as additional point in tracking (**vertex-constraint**).
  - **High combinatorial background rate**
    - Suppress BG by adding **low momentum-pion tracking** (pT > 300 MeV) to the signature.
    - For reducing CPU and disk, soft-pion tracks are seeded only around the disappearing track.

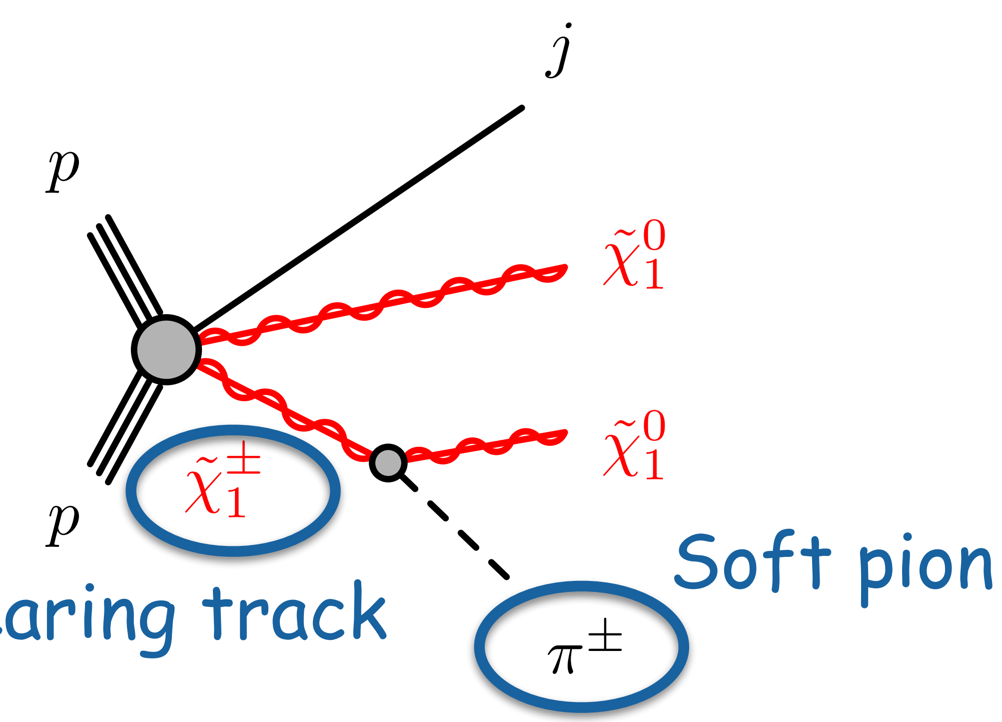


Higgsino: Filling the gap 2

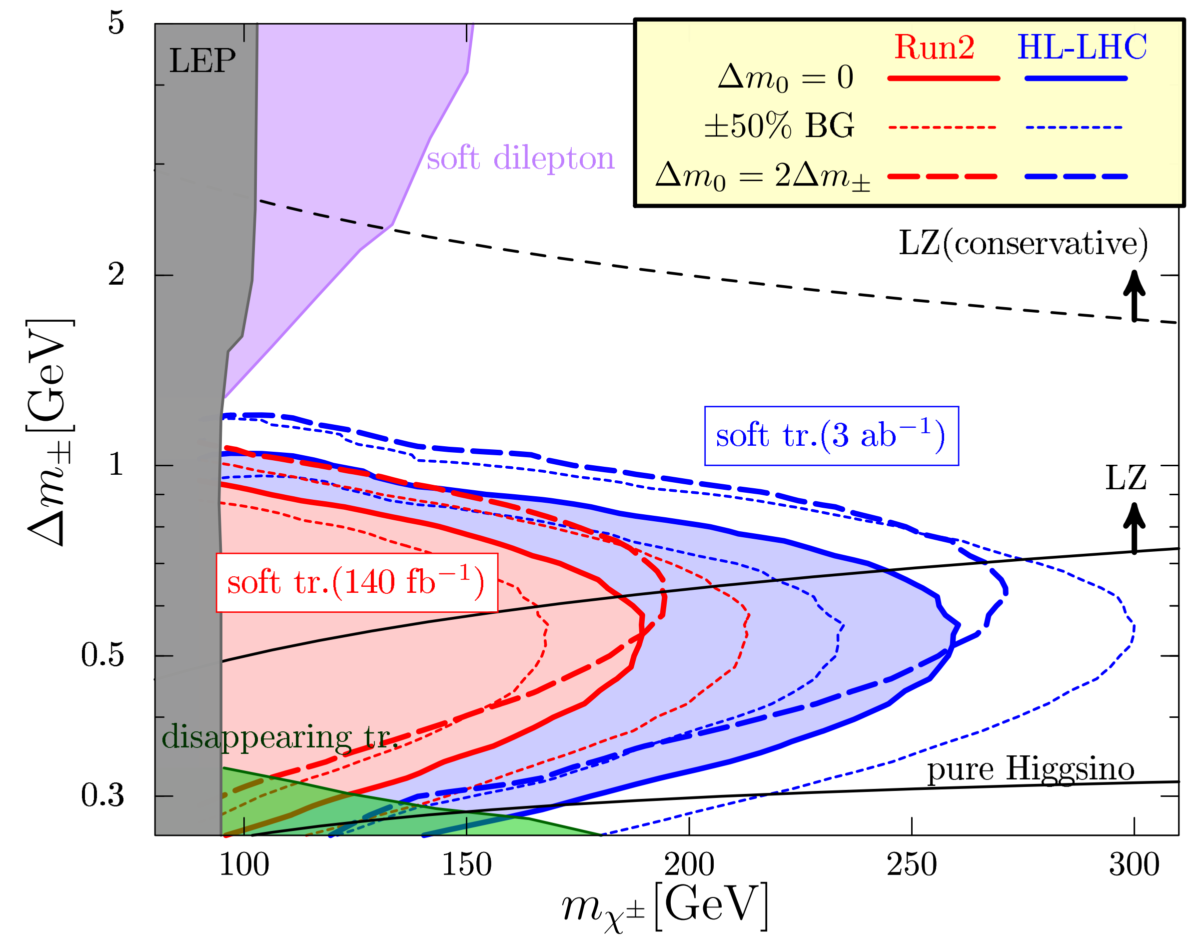
arXiv:1910.08065

Soft pion track analysis

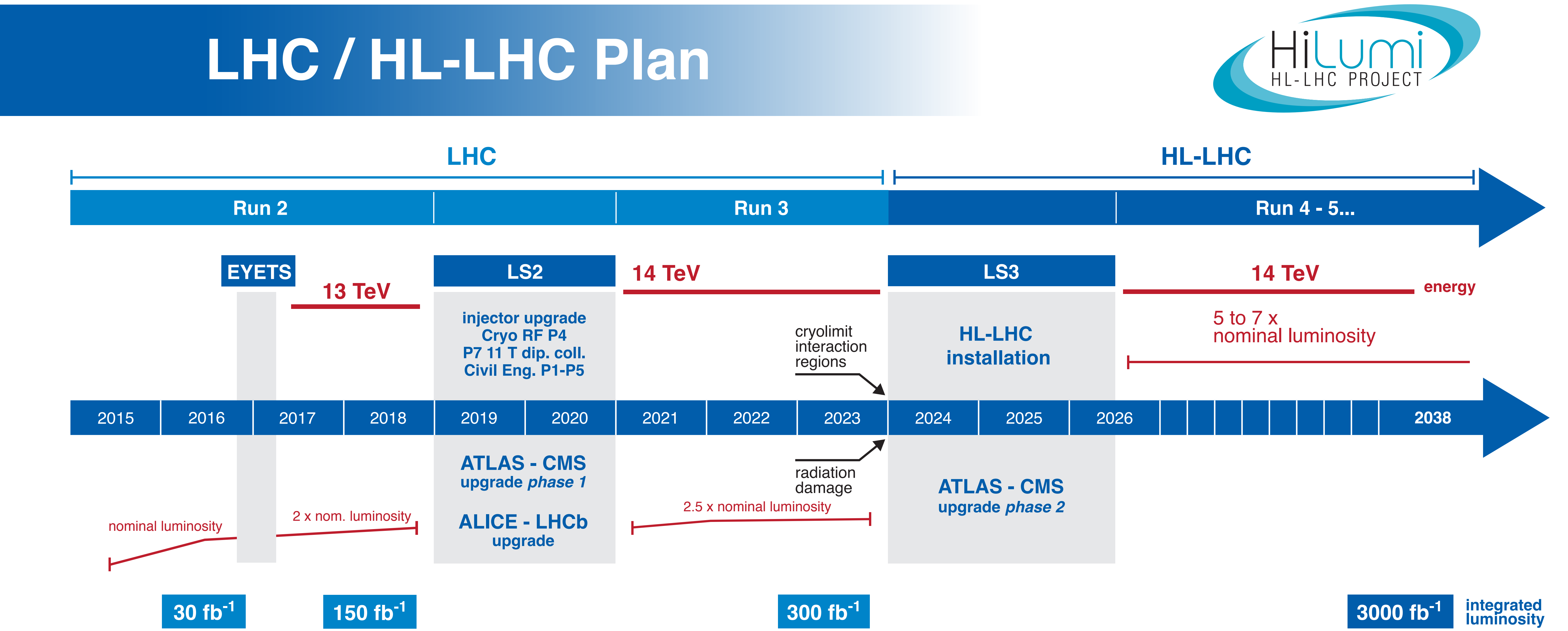
Nealy pure	Small gaugino mix
ΔM: ~350 MeV τ: ~ 1cm	ΔM: larger τ: shorter
Disappearing track (+ soft pion)	Only soft pion



- For small ΔM region, chargino lifetime is too short for disappearing track analysis.
- But the pion track momentum is higher.
  → Higher tracking efficiency
- Those analyses would explore the region unreachable by LZ.



LHC / HL-LHC plan



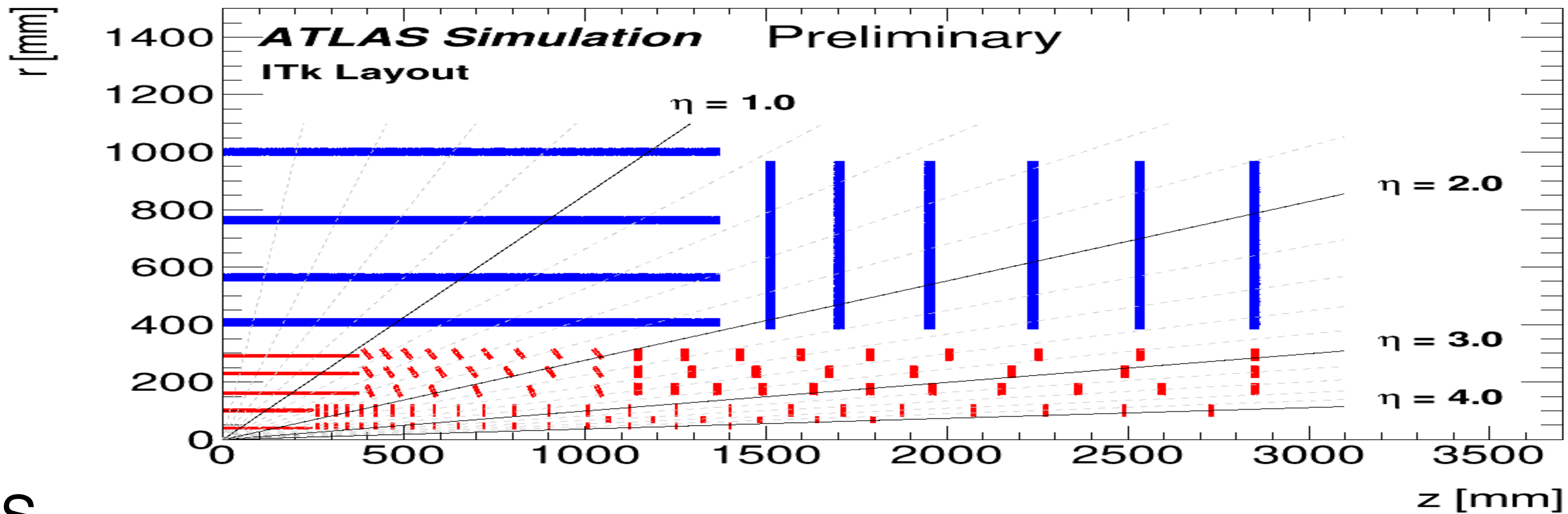
Comput. Softw. Big Sci. 3 (2019) 7

20 time more data will be collected at the HL-LHC

HL-LHC: Inner detector

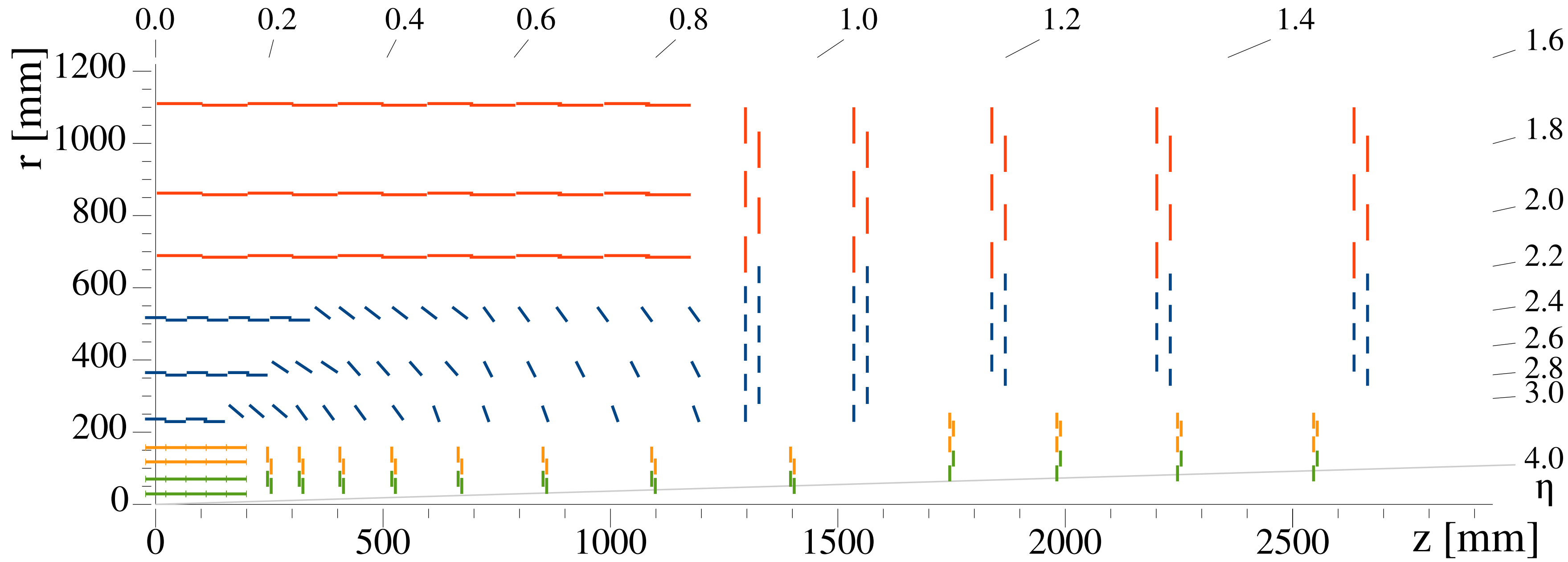
ATLAS (scaled)

ATL-PHYS-PUB-2019-014



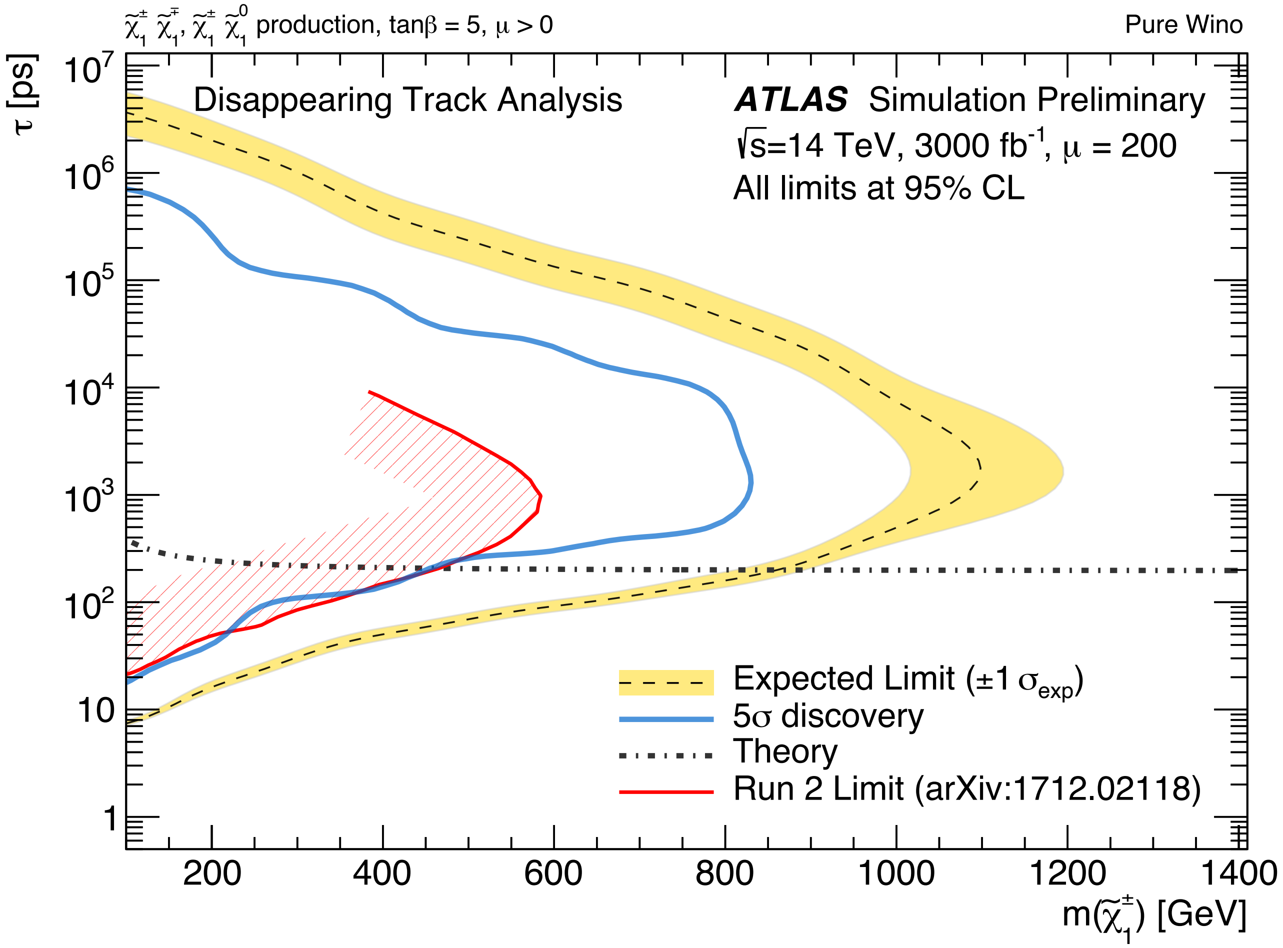
CMS

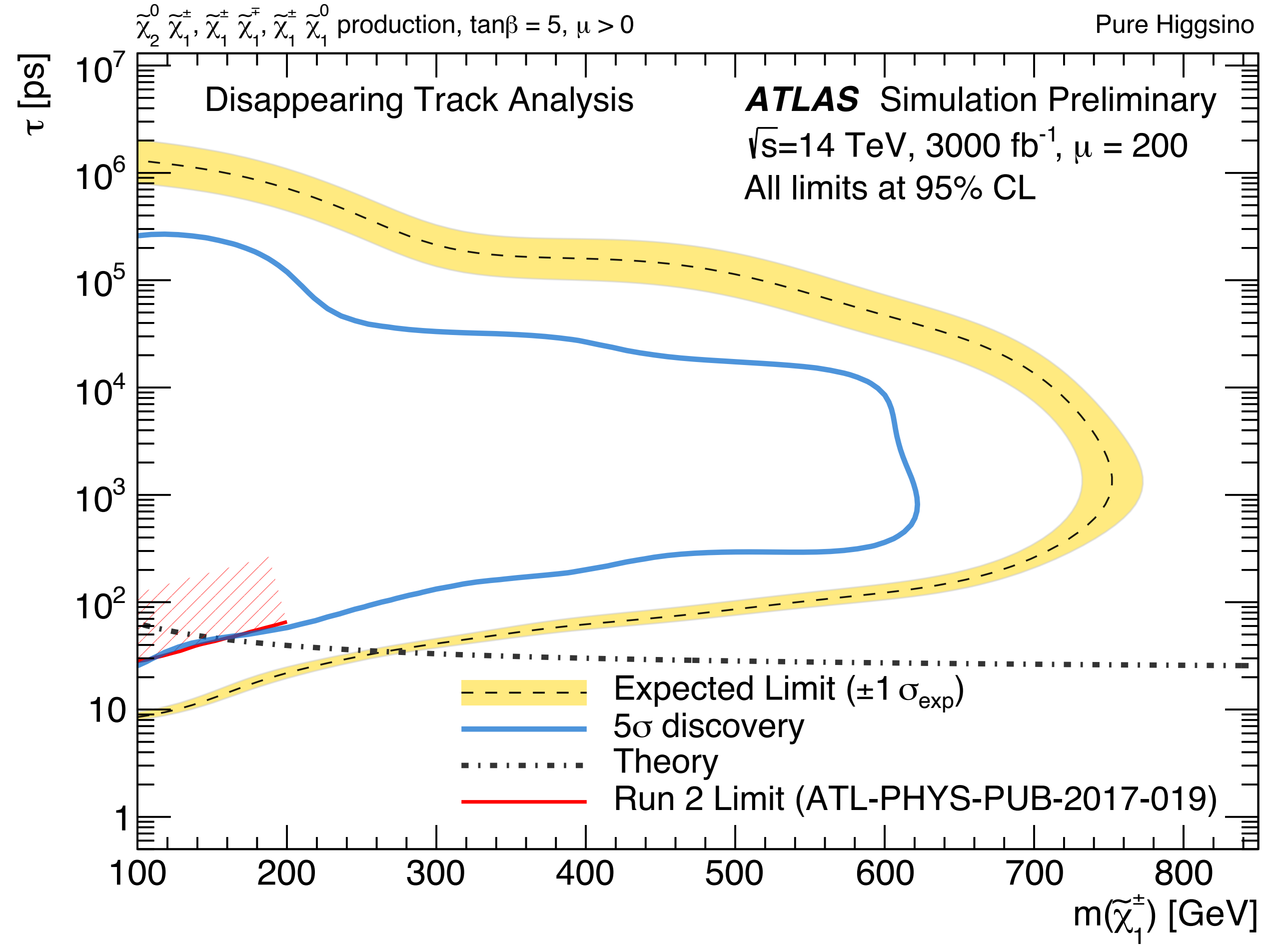
CMS-TDR-014



Wino/Higgsino at the HL-LHC

ATL-PHYS-PUB-2018-031



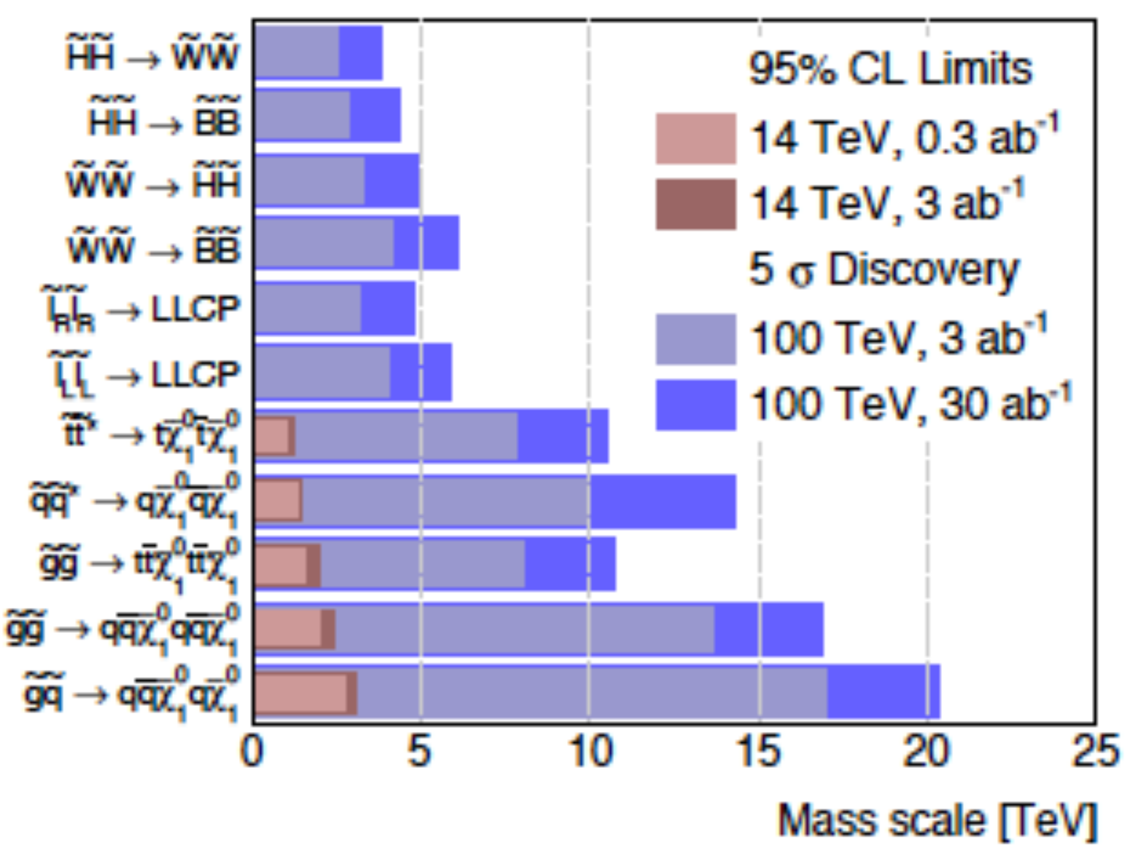


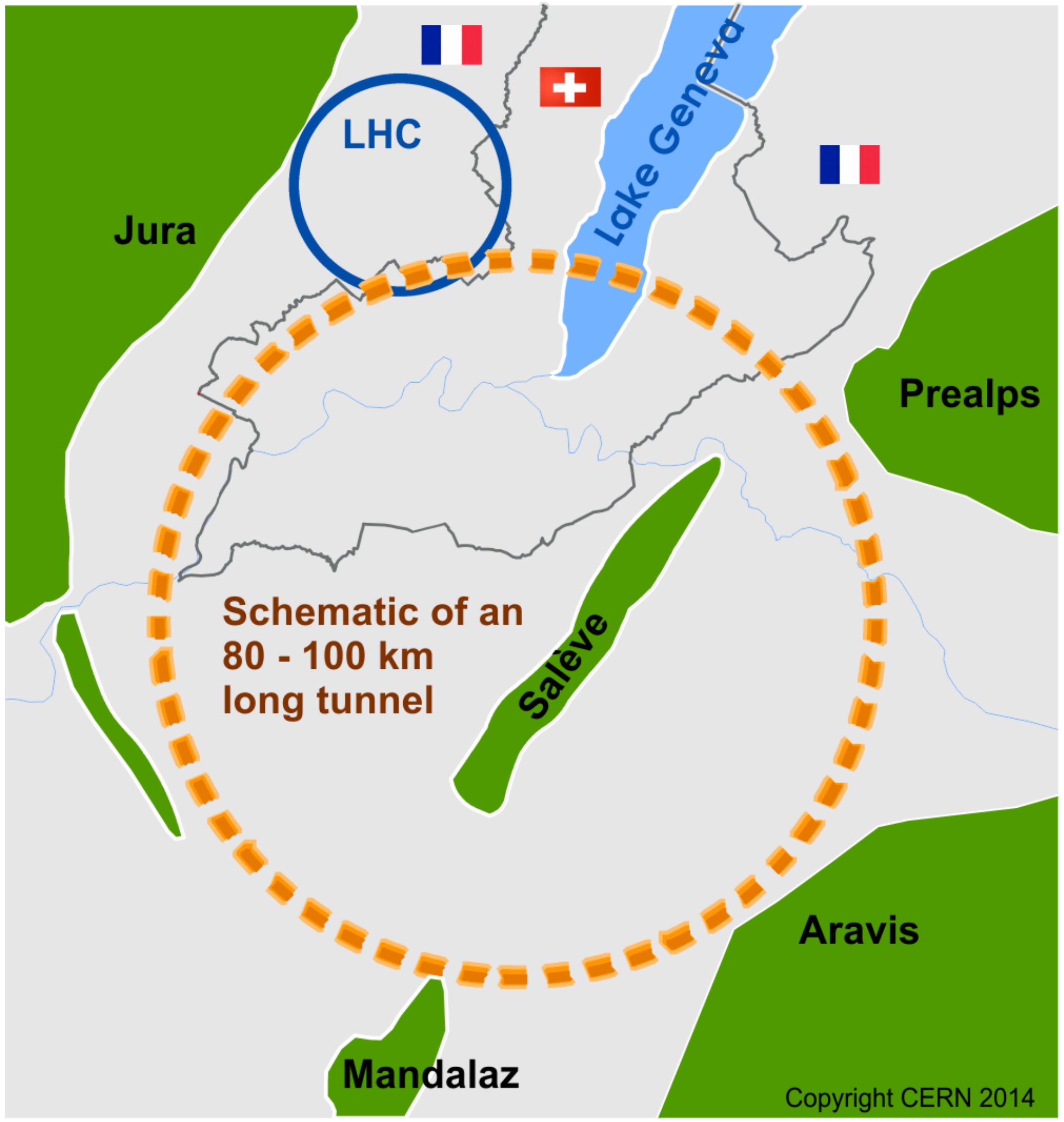
Sensitivity (95%CL exclusion): **wino: 850 GeV**, **higgsino: 250GeV**, assuming a similar analysis to the 36 fb^{-1} would be done.

The reach may be higher by improving the analysis technique.

Future Circular Collider (FCC-hh)

- 100 km tunnel in Geneva area
- *pp* collider with $\sqrt{s}$ = 100 TeV
- 200—1000 collisions per bunch crossing
- Total integrated lumi. ~ 20 ab^{-1}
- Much higher sensitivities to various new physics than LHC





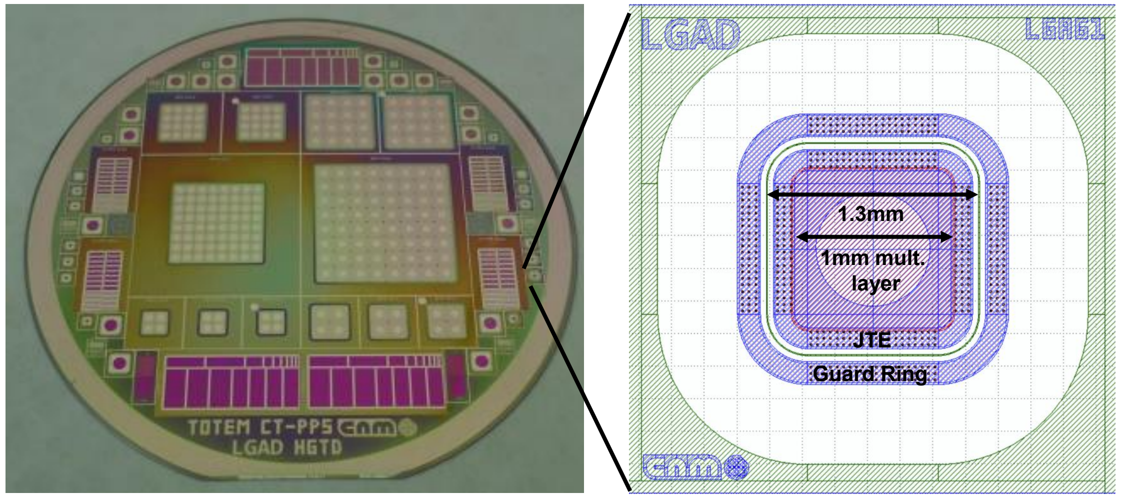
Details in Filip's talk

Future Circular Collider Study. Volume 3, CERN-ACC-2018-0058. Submitted to Eur. Phys. J. ST.

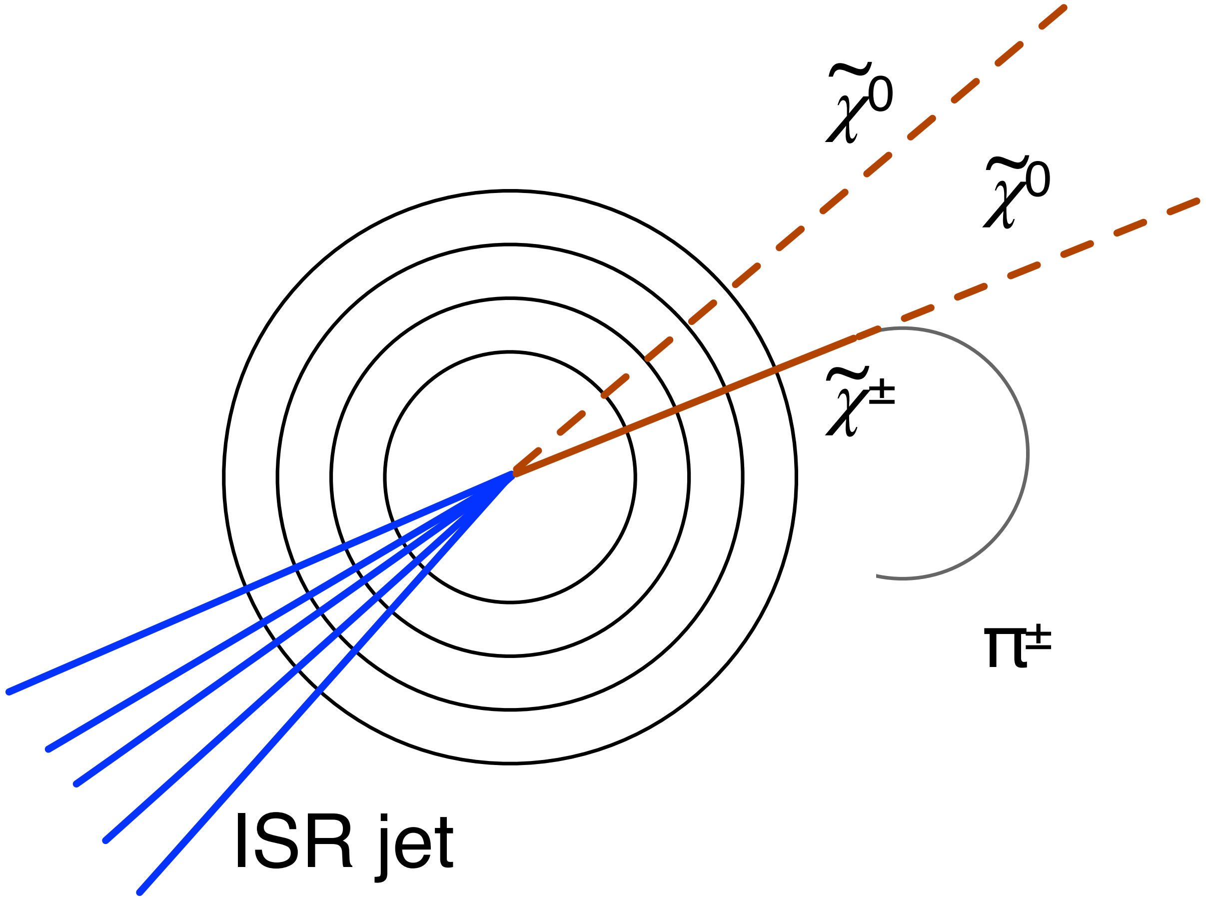
DT + Hit-time information

- **Low Gain Avalanche Detectors** (LGAD) have time resolution of **10—30 ps**
- **If** the detector can be used in FCC as the inner pixel-detector (not at an additional timing-layer), we can use the hit-time for two purpose

1. **BG fake tracks** (random-combination) decrease by requiring consistent time of pixel-hits on track.
2. Measure **the velocity of a particle**.
    - If hit-time resolution is 20 ps, velocity resolution for charginos could be ~6%.



2017 JINST 12 P05003

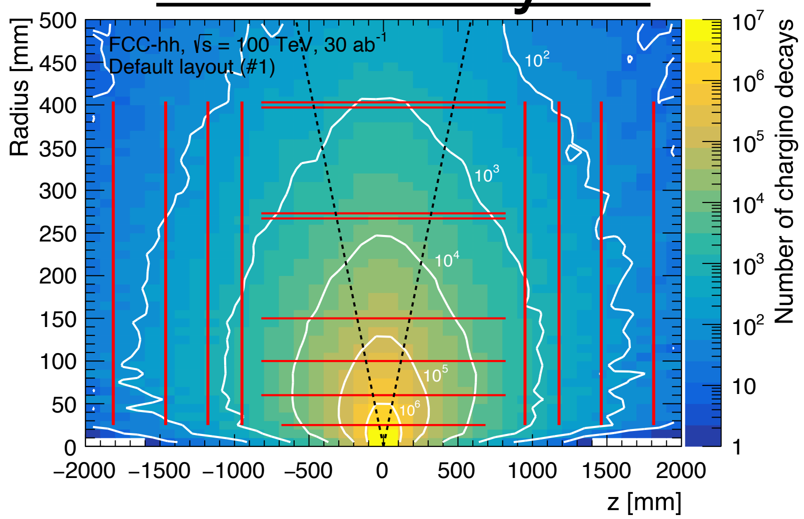


Expected reach at FCC

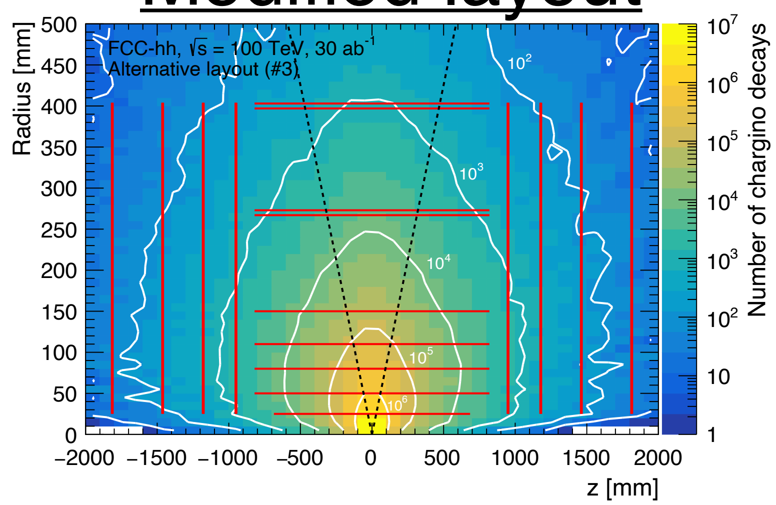
Eur. Phys. J. C 79 (2019) 469

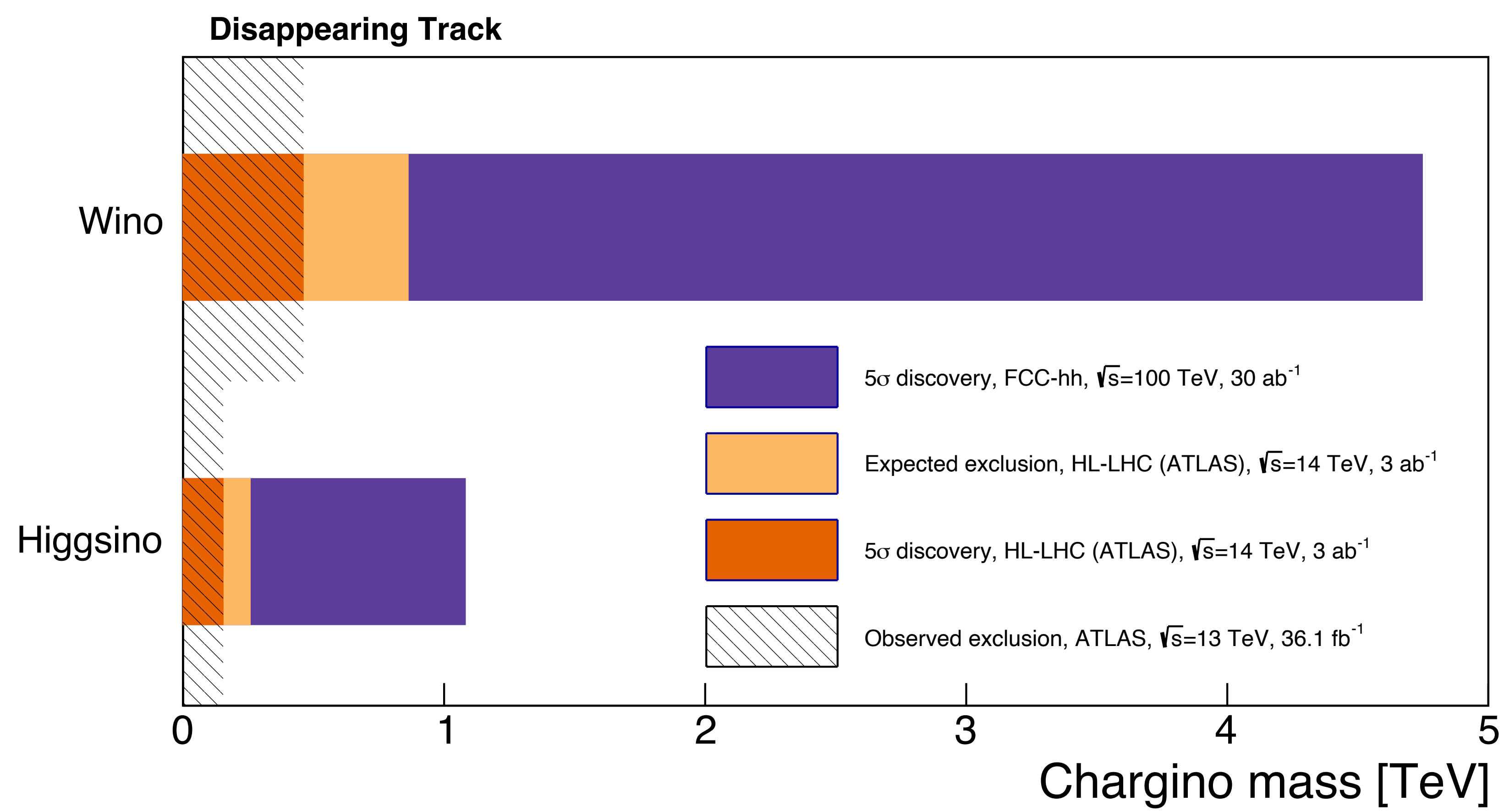
- Modified pixel-detector layout (5 layers within 15cm from the beamline)
- BG rejection using time information (χ^2/ndf in the fit)

Nominal layout



Modified layout



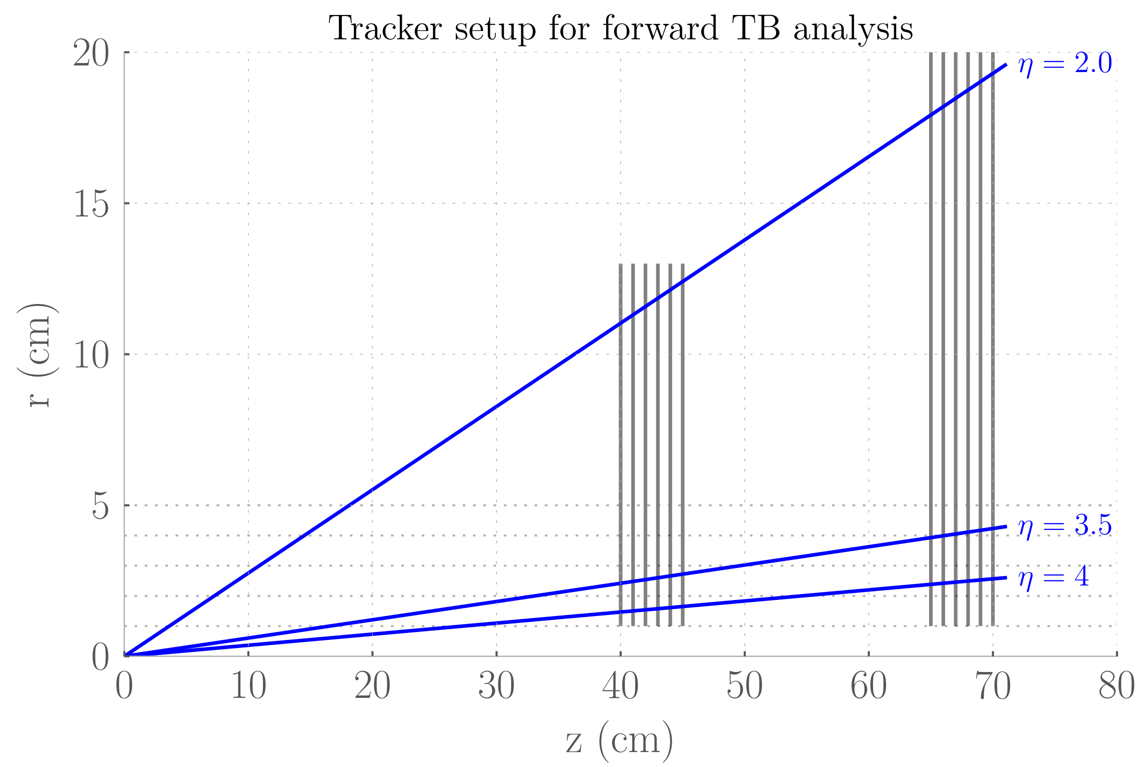


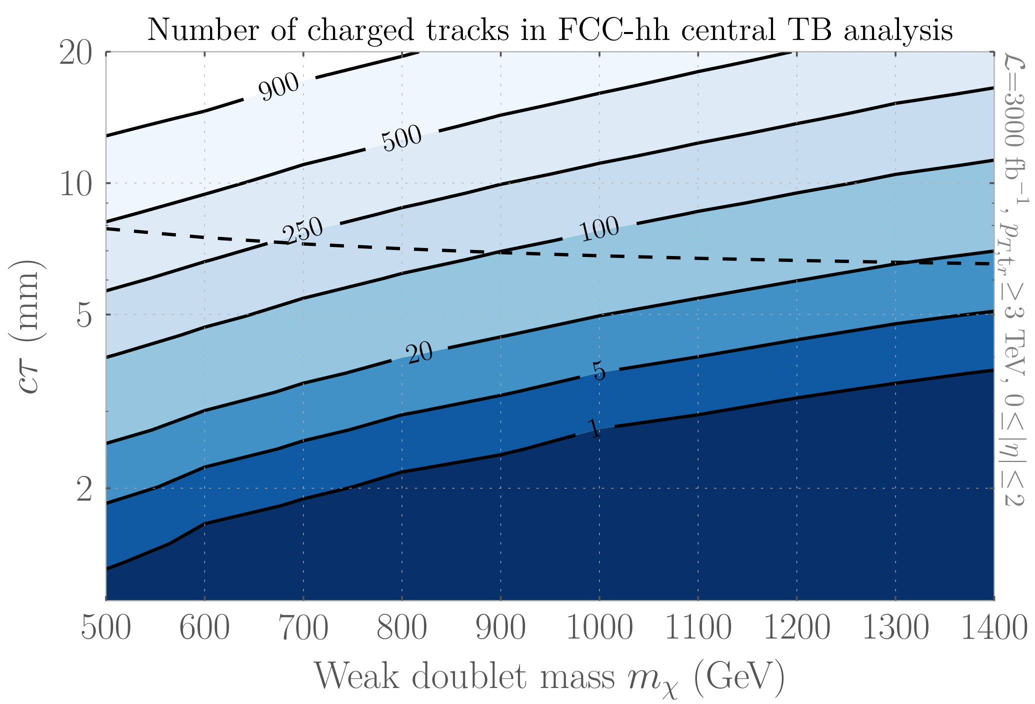
We can discover 3 TeV wino or 1 TeV higgsino

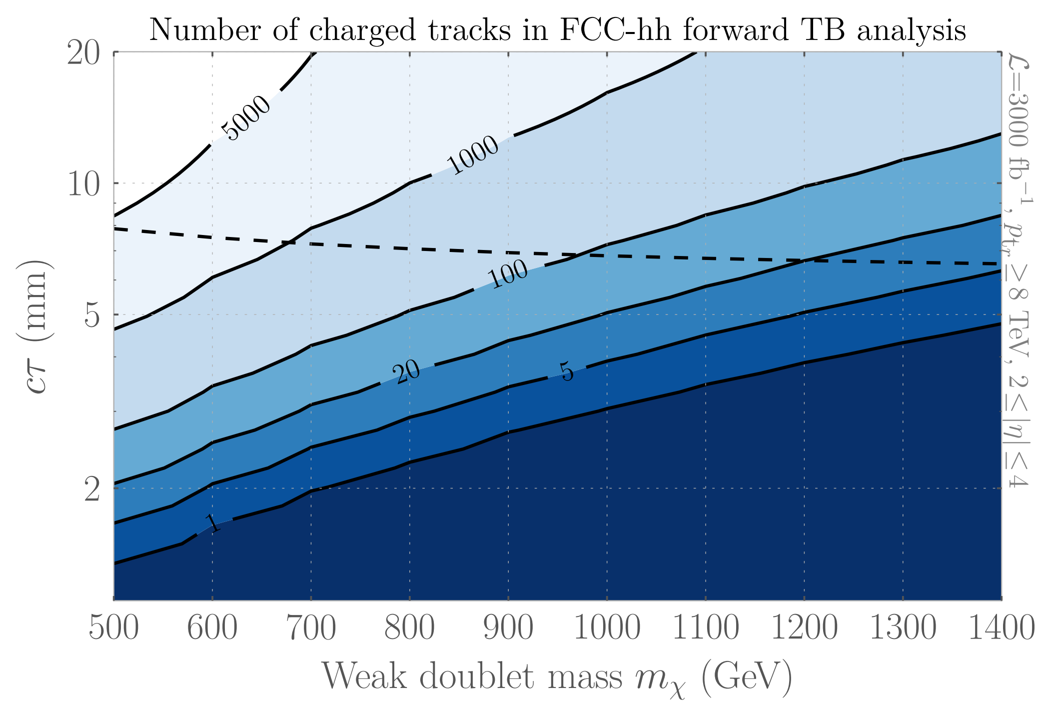
FCC-hh: forward region ?

JHEP06(2017)119

- Due to the very high beam energy, signal charginos are emitted also to the forward region.
- The lifetime in the lab-frame is longer due to the boost.
- We could have significant signal events in the forward region by putting the tracker close to the target (~40 cm)





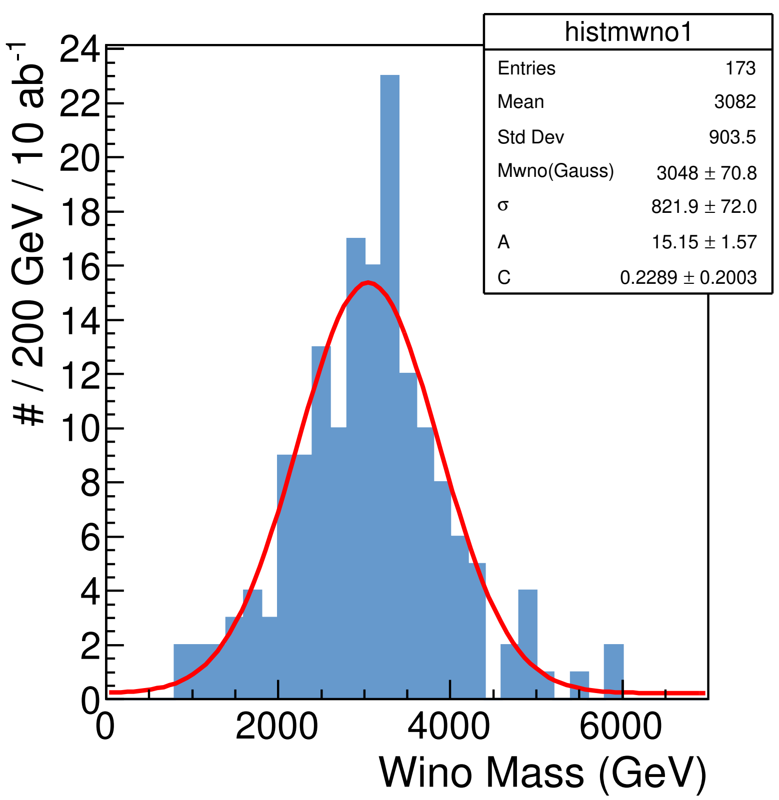


Gaugino mass measurement at the FCC-hh

JHEP 05 (2019) 179

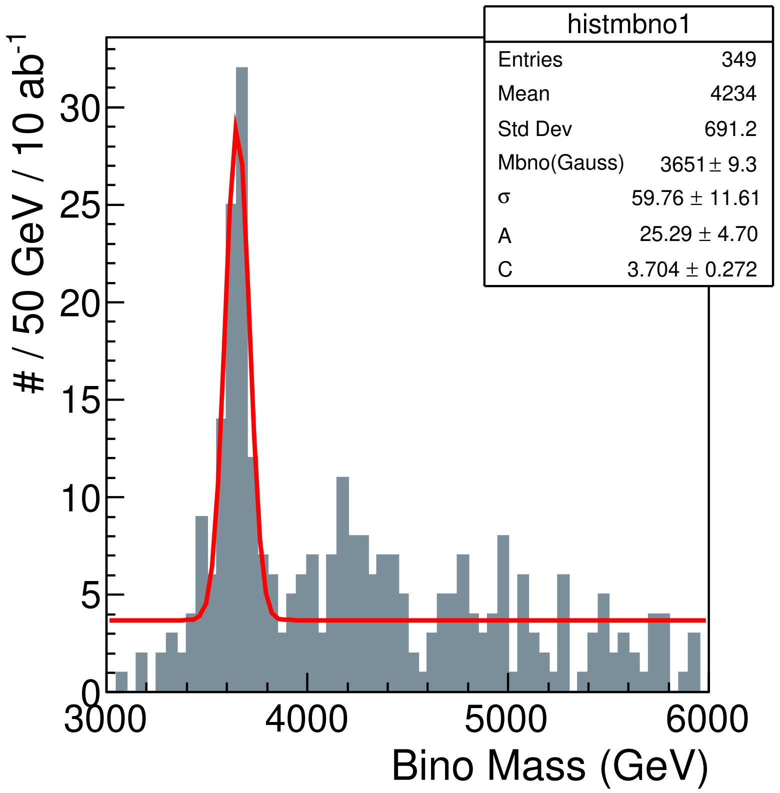
- If we can measure the velocity and momentum of **wino**, the mass can be measured.
- Other gaugino masses (i.e. **bino** and **gluino**) can be reconstructed by using the measured wino mass.
- The gaugino mass measurements would imply also the next particle-mass scale (**higgsino, Higgses and sfermions**)

Reconstructed **wino** mass



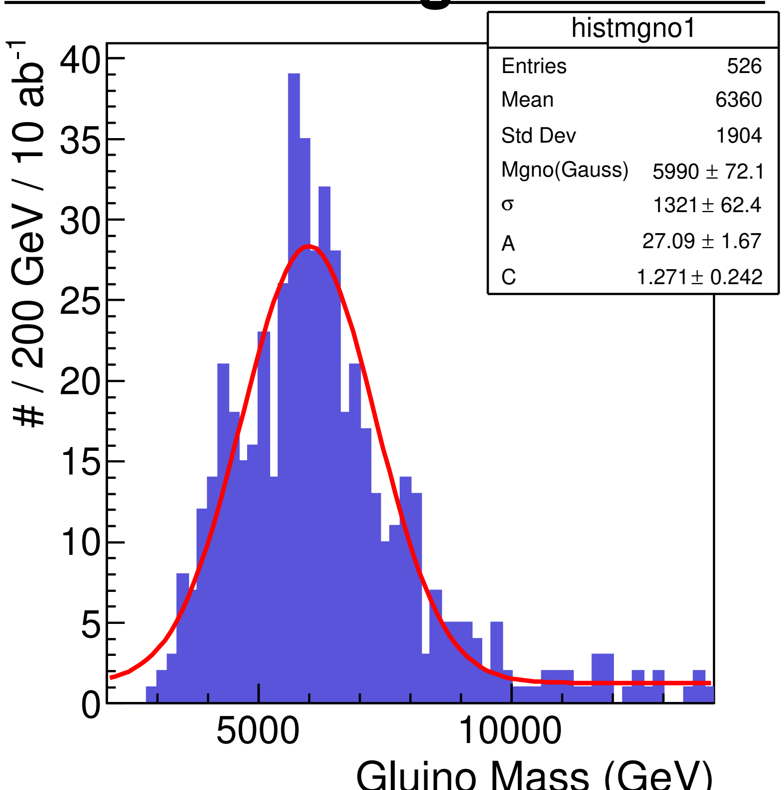
2% precision @ 2.9 TeV

Reconstructed **Bino** mass



<2% precision @ 3.7 TeV

Reconstructed **gluino** mass



<2% precision @ 6 TeV

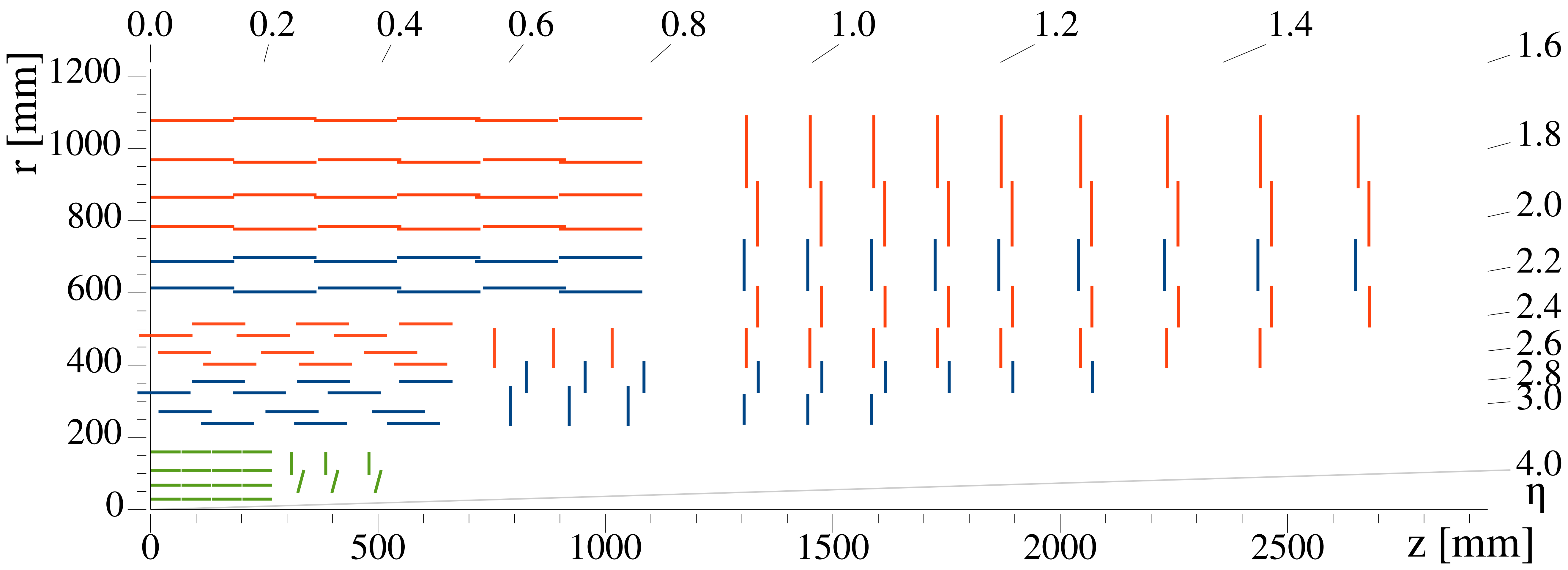
Conclusion

- **Disappearing track** is a unique tool to search for (nearly) pure wino and higgsino at the LHC.
- For nearly pure higgsino, there is **a gap between the prompt and disappearing track searches**. There are **several ideas to explore the gap region**.
- FCC-hh will **completely cover** the mass region having the correct DM relic abundance.

Back up

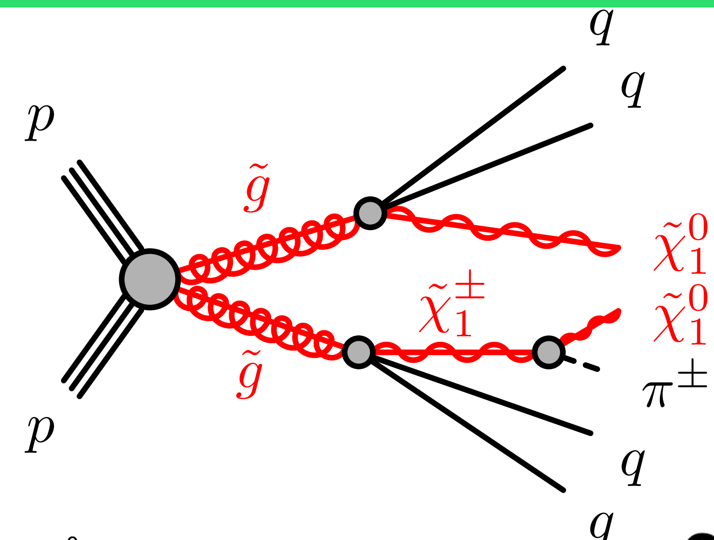
CMS inner tracker

CMS-TDR-014



Strong production ATLAS/CMS

From gluino decay

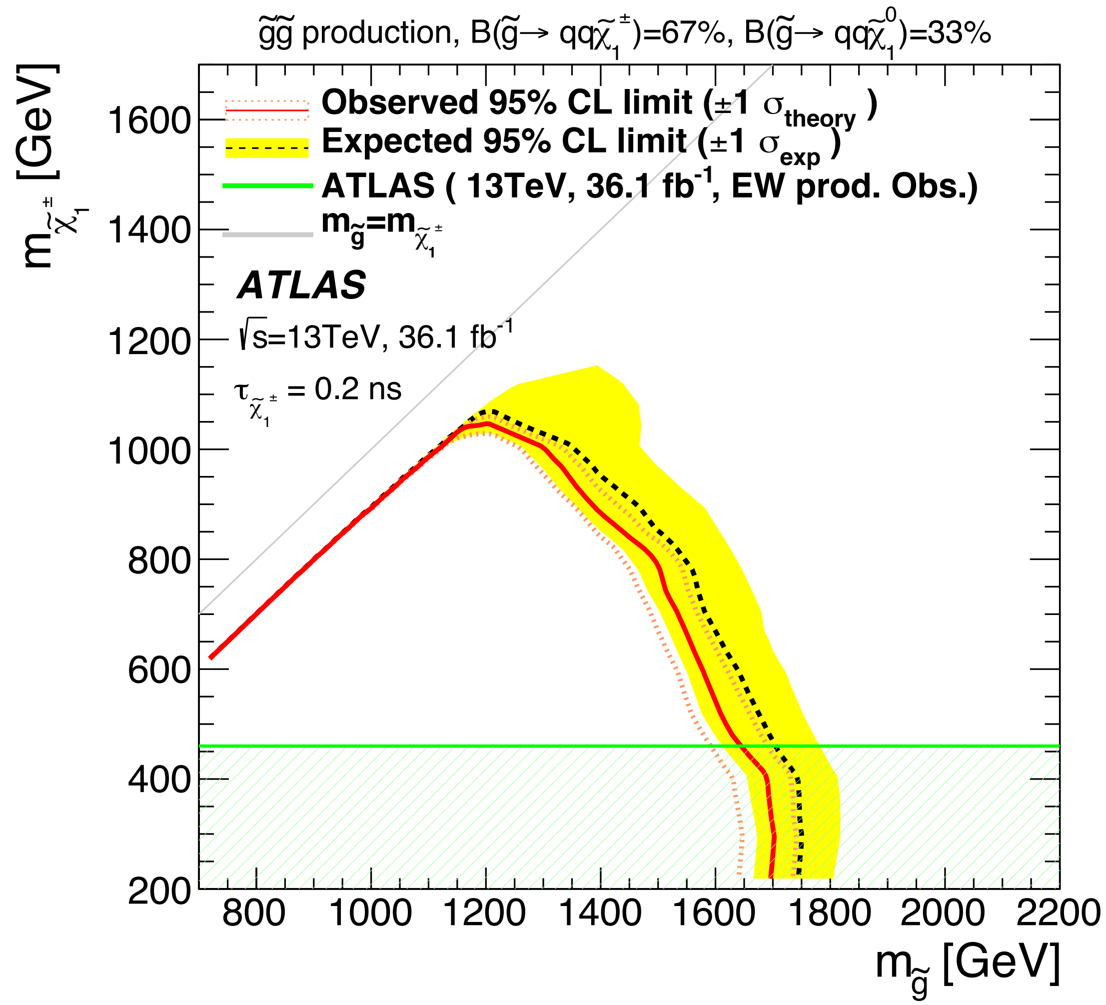


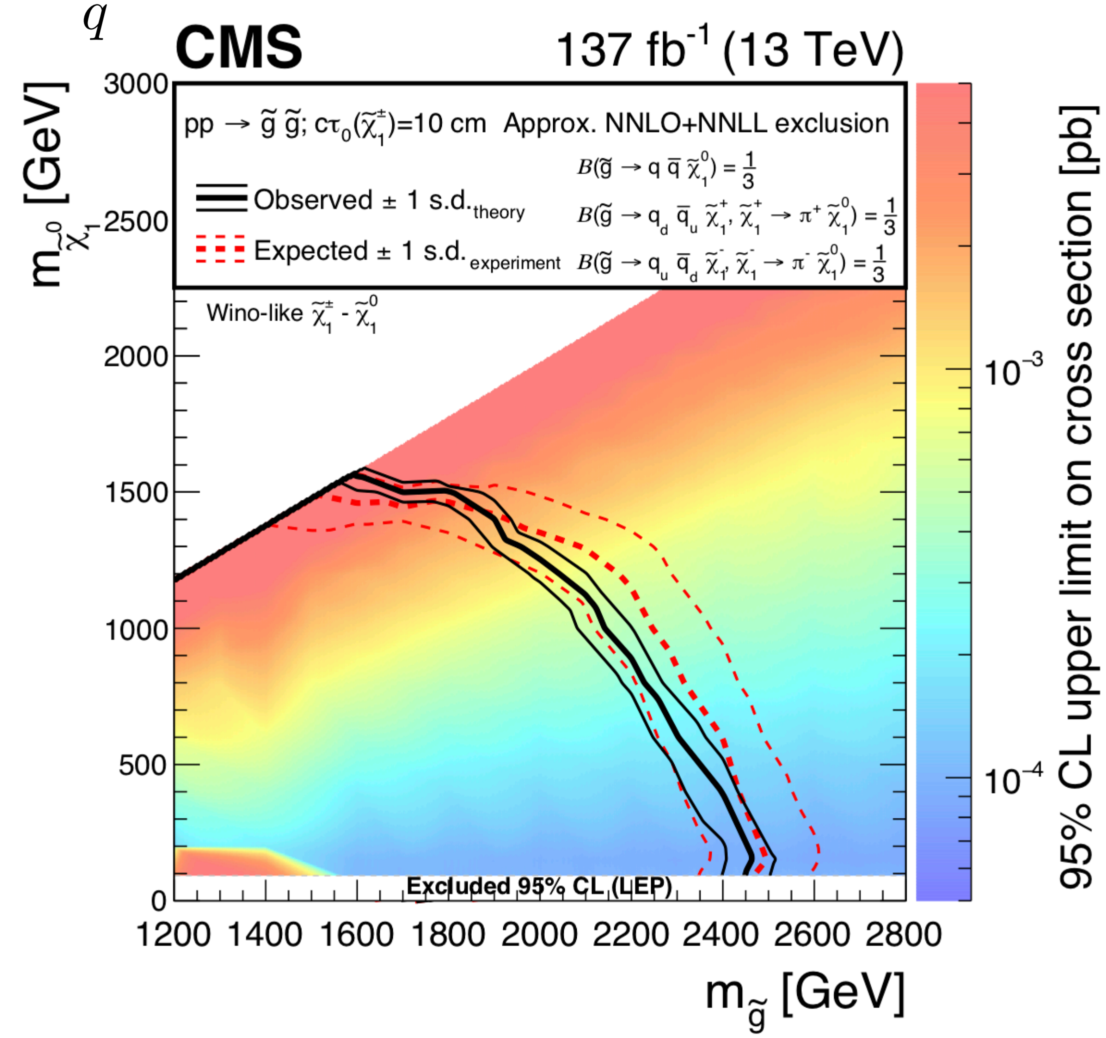
ATLAS (36 fb-1)

τ_0 = 0.2 ns

CMS (137 fb-1)

τ_0 = 0.33 ns





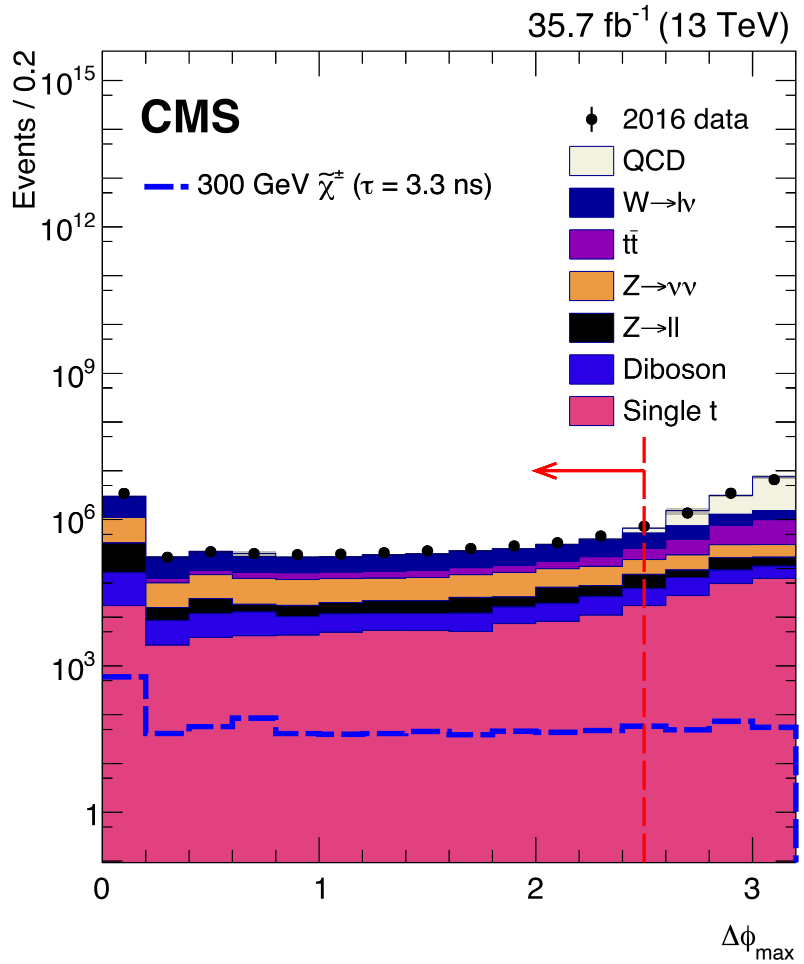
JHEP 06 (2018) 022

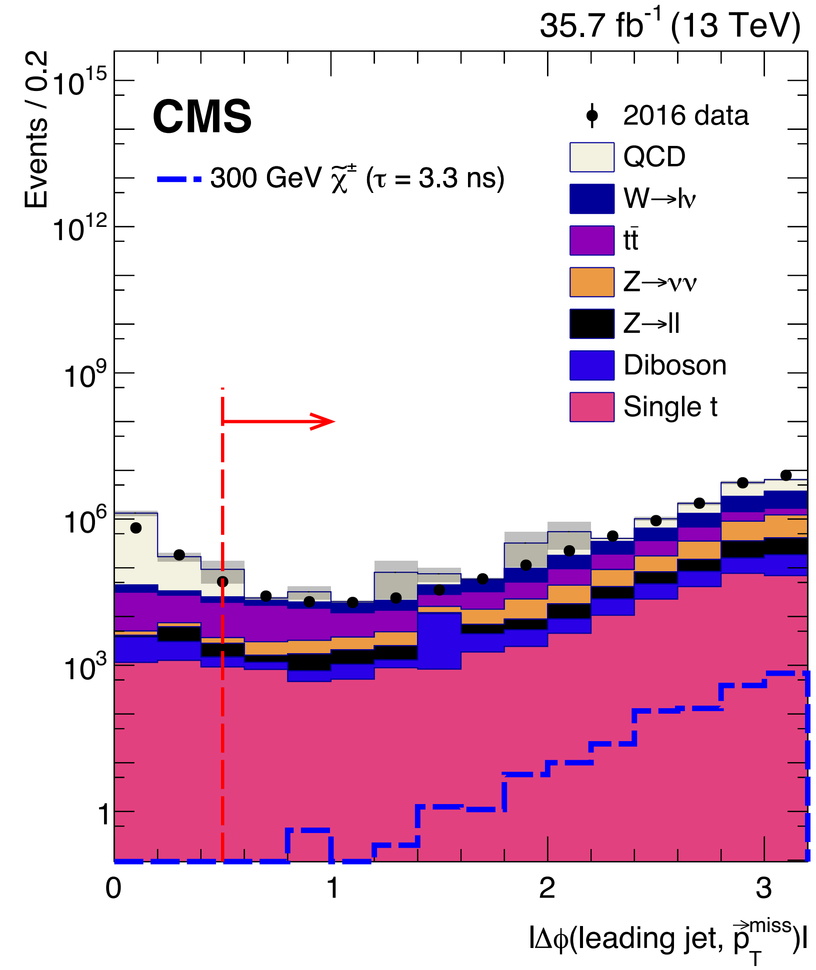
arXiv:1909.03460

CMS analysis

JHEP 08 (2018) 016

CMS (38 fb-1)





Run period	Estimated number of background events			Observed events
	Leptons	Spurious tracks	Total	
2015	0.1 ± 0.1	$0^{+0.1}_{-0}$	0.1 ± 0.1	1
2016A	$2.0 \pm 0.4 \pm 0.1$	$0.4 \pm 0.2 \pm 0.4$	$2.4 \pm 0.5 \pm 0.4$	2
2016B	$3.1 \pm 0.6 \pm 0.2$	$0.9 \pm 0.4 \pm 0.9$	$4.0 \pm 0.7 \pm 0.9$	4
Total	$5.2 \pm 0.8 \pm 0.3$	$1.3 \pm 0.4 \pm 1.0$	$6.5 \pm 0.9 \pm 1.0$	7

ATLAS analysis

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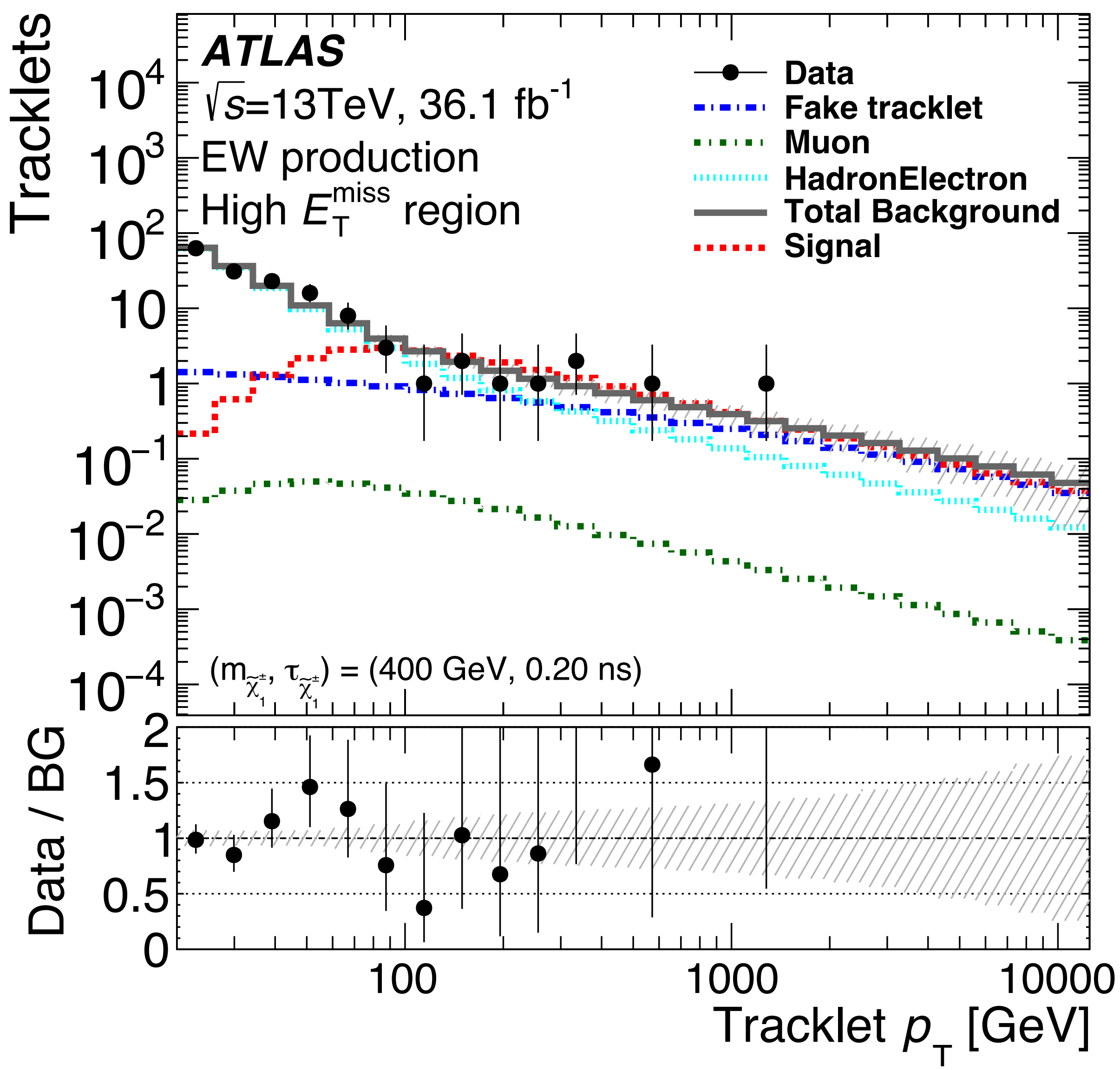
ATLAS (36 fb-1)



	Electroweak channel		Strong channel	
Number of observed events with $p_T > 100$ GeV in high-E_T^{miss} regions				
	9		2	
Number of expected events with $p_T > 100$ GeV in high-E_T^{miss} regions				
Hadron+electron background	6.1	± 0.6	1.78	± 0.32
Muon background	0.15	± 0.09	0.05	± 0.08
Fake background	5.5	± 3.3	0.1	± 0.4
Total background	11.8	± 3.1	1.9	± 0.4
p_0	0.5		0.47	
Observed $\sigma_{vis}^{95\%}$ [fb]	0.22		0.12	
Expected $\sigma_{vis}^{95\%}$ [fb]	$0.28^{+0.11}_{-0.08}$		$0.12^{+0.07}_{-0.04}$	
Number of expected signal events with $p_T > 100$ GeV in high-E_T^{miss} regions				
	13.5	± 2.1	5.6	± 0.8

Wino mass measurement

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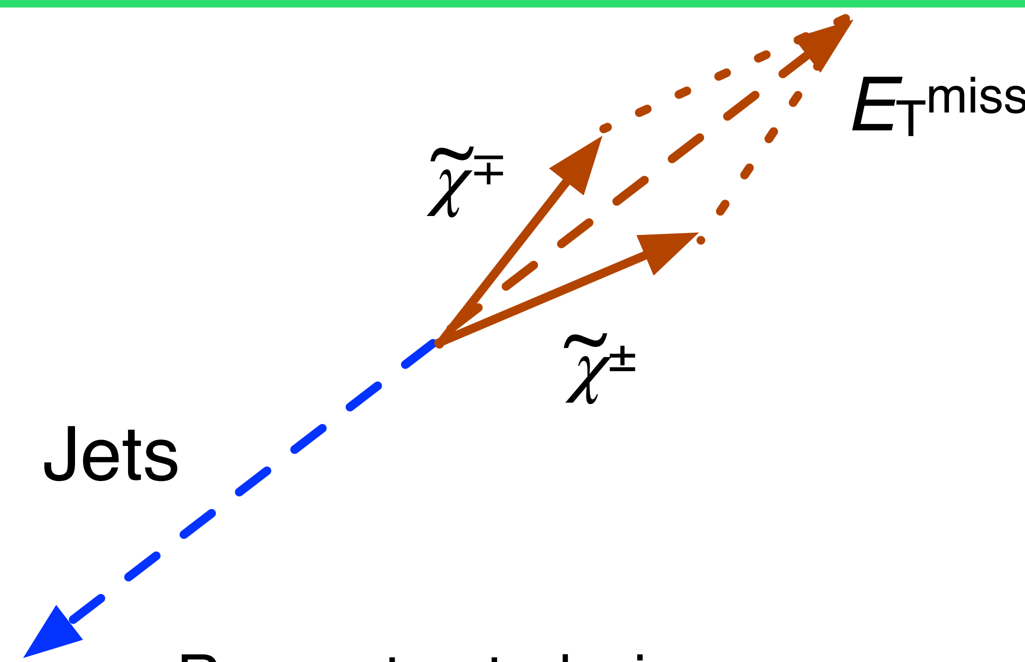
$$\text{mass} = \text{momentum}/\beta \cdot \sqrt{(1-\beta^2)}\ ,$$

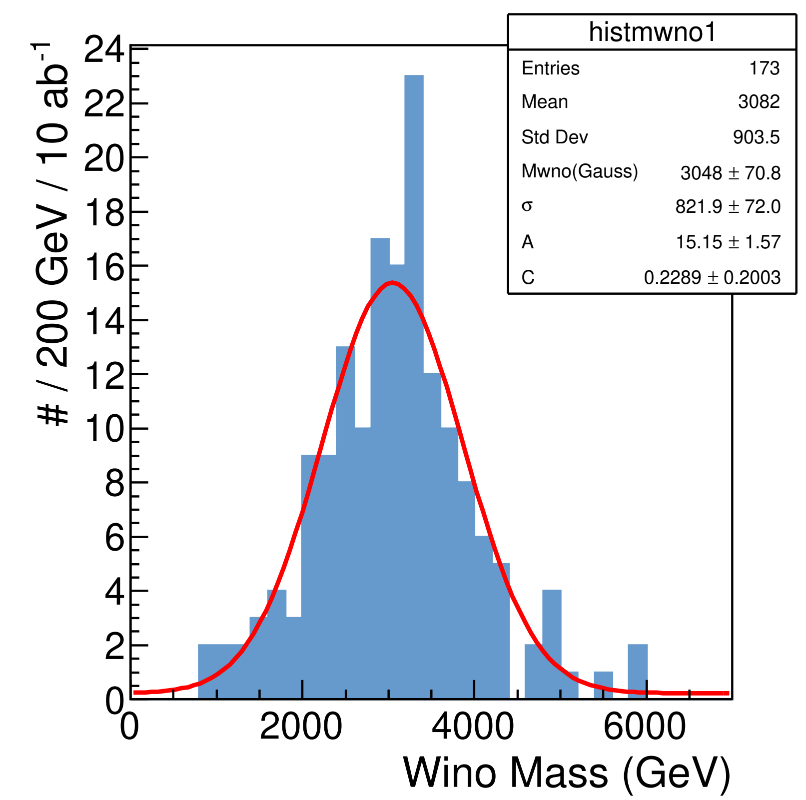
$$\beta = v/c$$



- **Velocity** is measured by the tracker using **time information**
- How to measure the **momentum** ?
  - We can not use the momentum of charged-wino tracks because of the **too poor resolution**; the track length is too short (< 10cm) !
  - Instead, we can reconstruct from ***E_T^{miss}* and direction of charged winos**, because pion carry little momentum (O(100 MeV))

Isolated lepton-veto is also applied

Reconstructed wino mass



2% precision @ 2.9 TeV

Bino mass measurement

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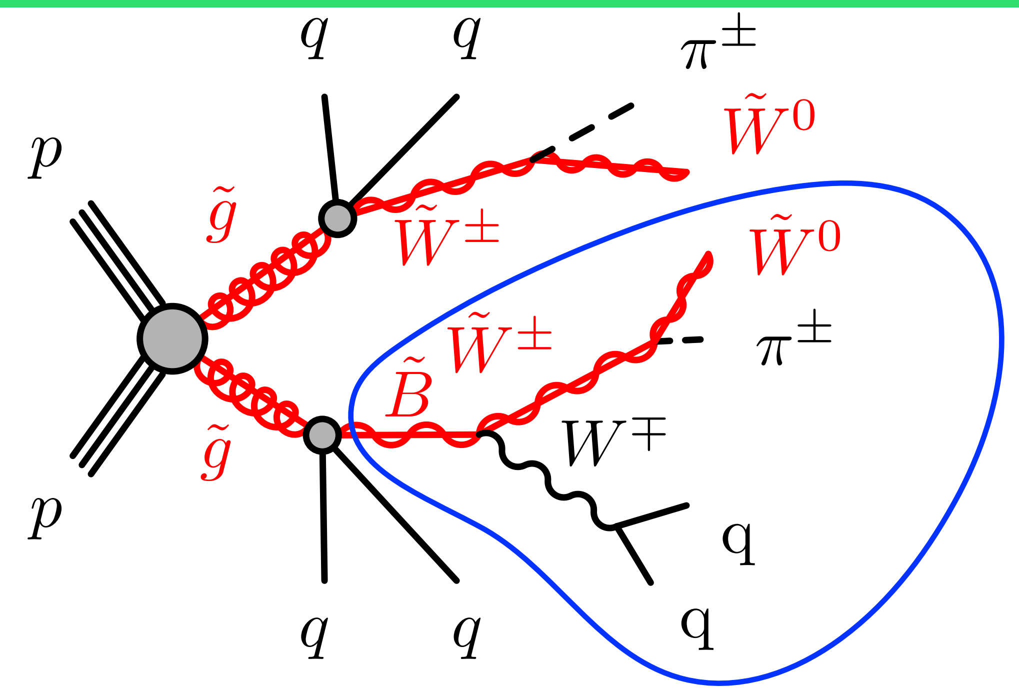
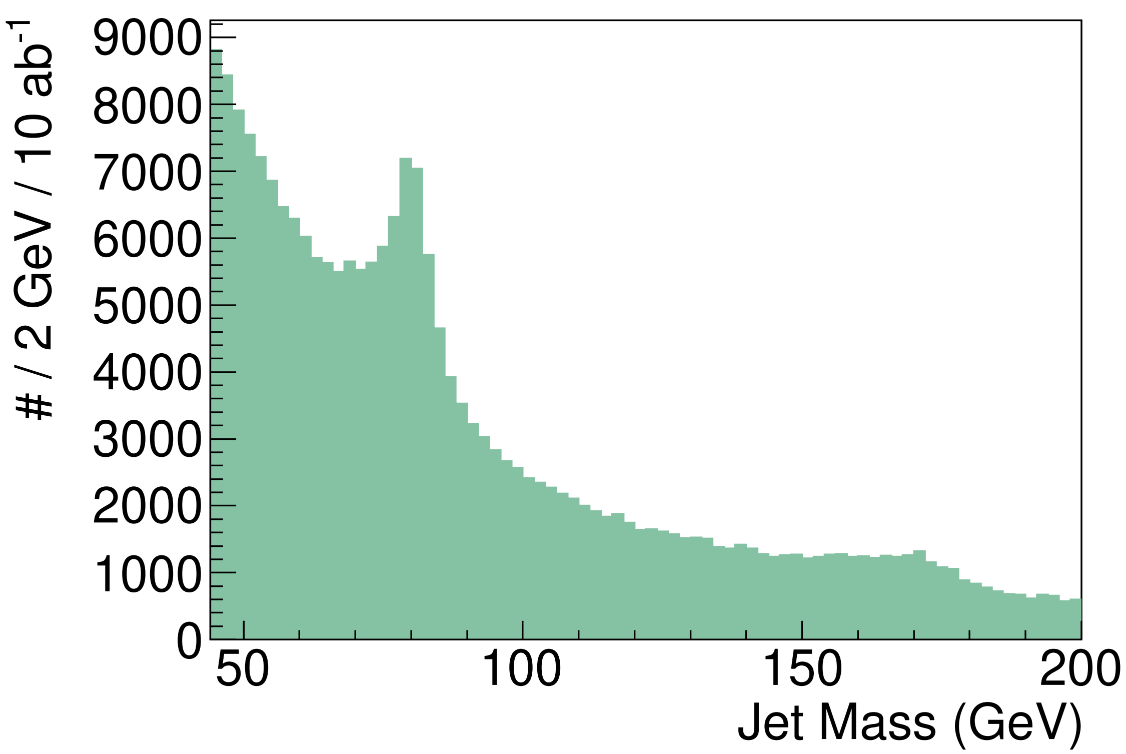
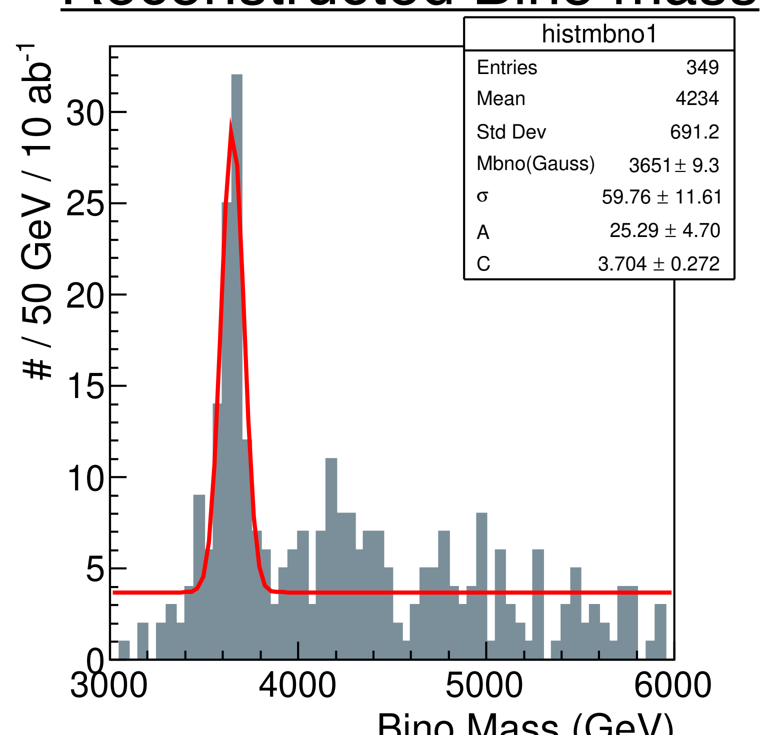
- Reconstruct **Bino mass** from **Wino and W momentum**
  - **Wino momentum** : reconstruct from the measured **velocity** and Wino **mass**.
  - **W momentum** : reconstruct using **fat jets**.



Fat jet mass



Reconstructed Bino mass



<2% precision @ 3.7 TeV

Gluino mass measurement

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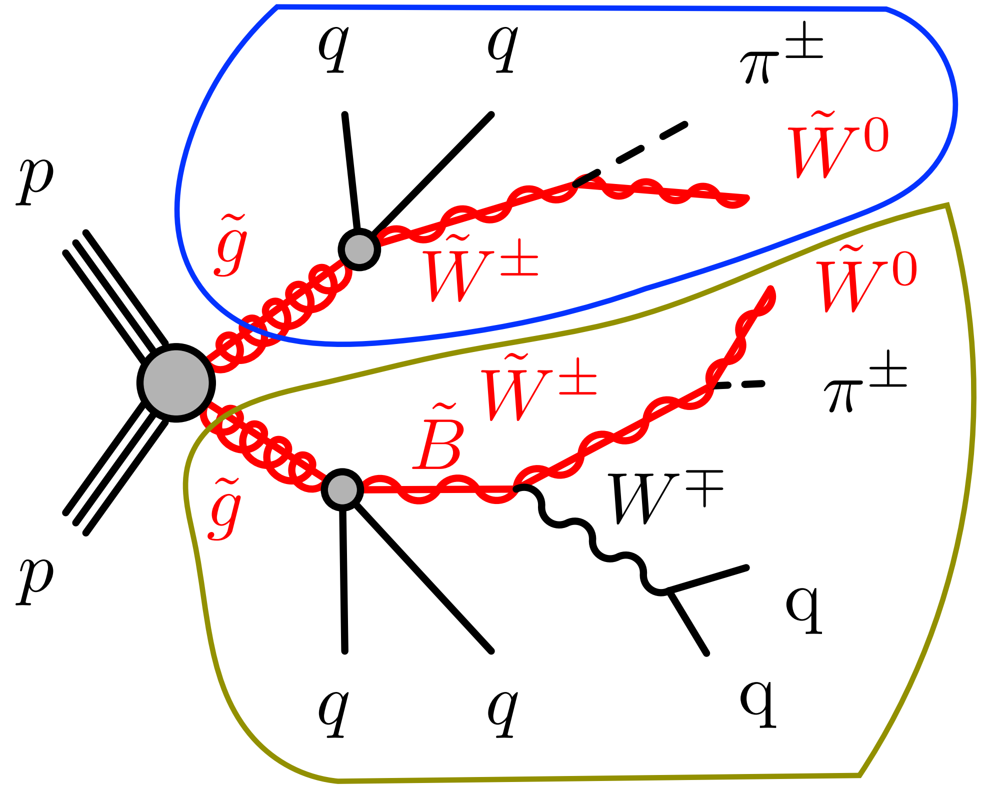
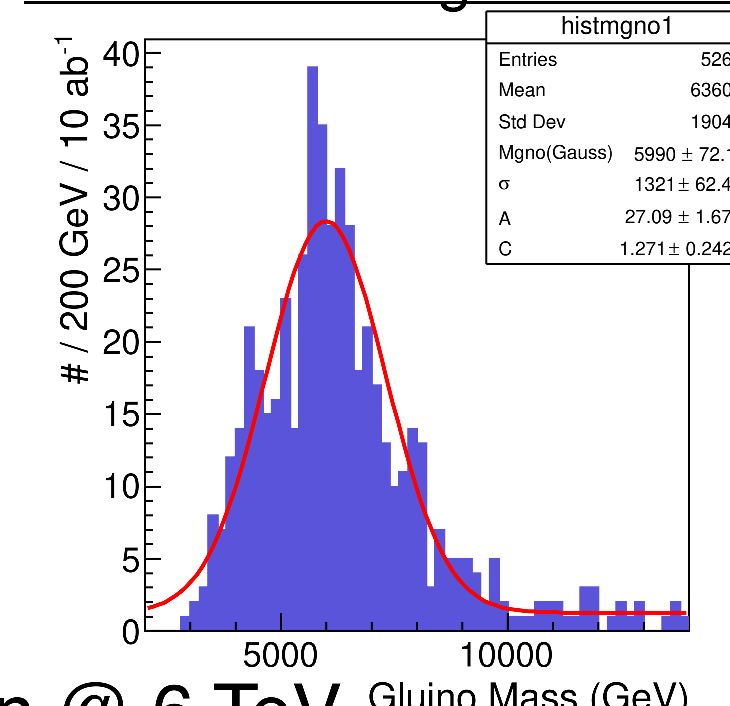
- **Gluino mass** is reconstructed by **"hemi-sphere" analysis**
  1. Define two hemi-spheres using two disappearing-track directions
  2. Iteratively assign jets to each hemi-sphere and update the directions
  3. Reconstruct the gluino mass from jets and Winos.



- Gluino mass can be estimated from the **cross-section**.
  - Comparing the two estimates would be **good test of SUSY hypothesis**.

Reconstructed gluino mass



Isolated lepton-veto is also applied

<2% precision @ 6 TeV

Implication

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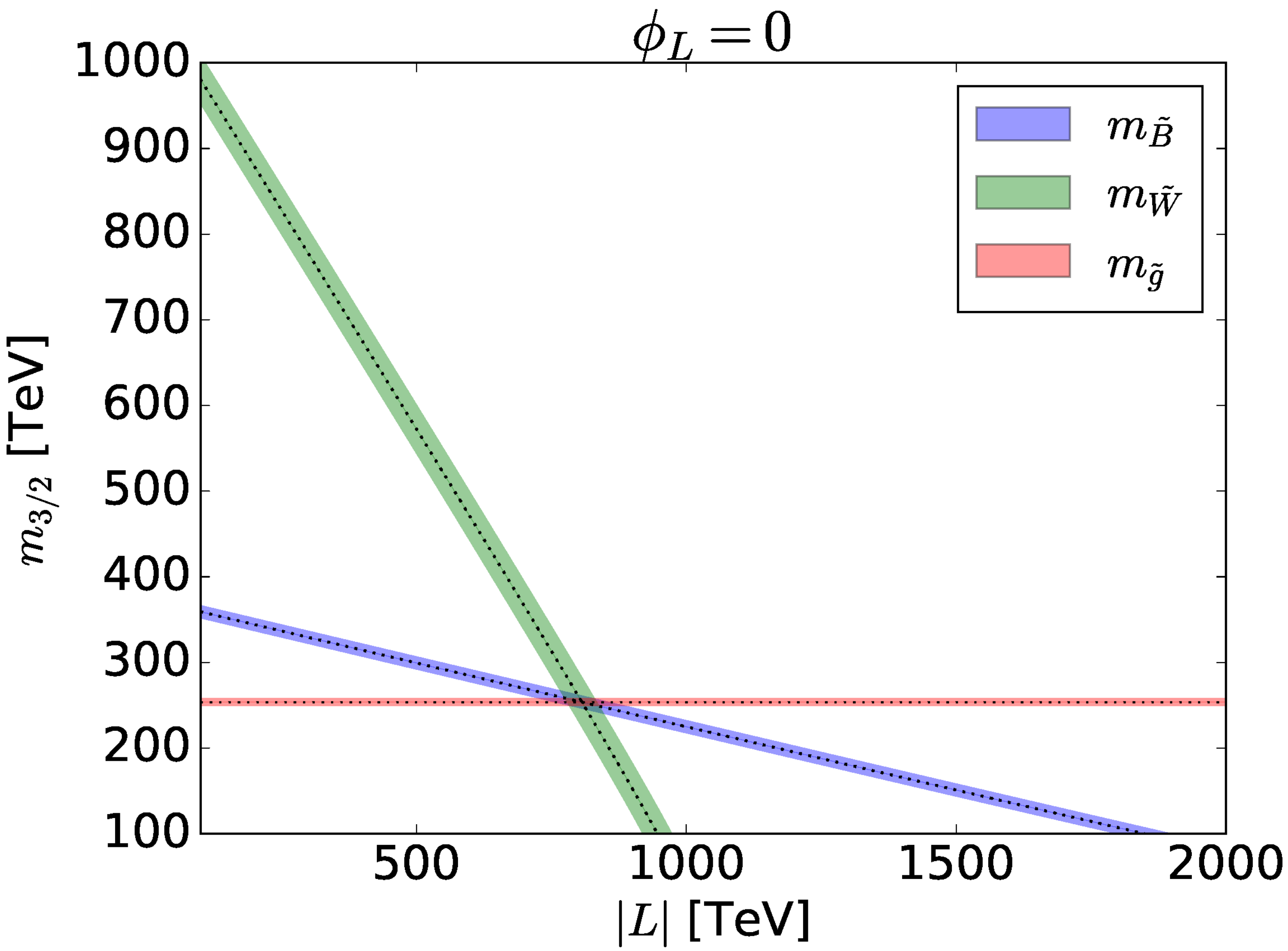

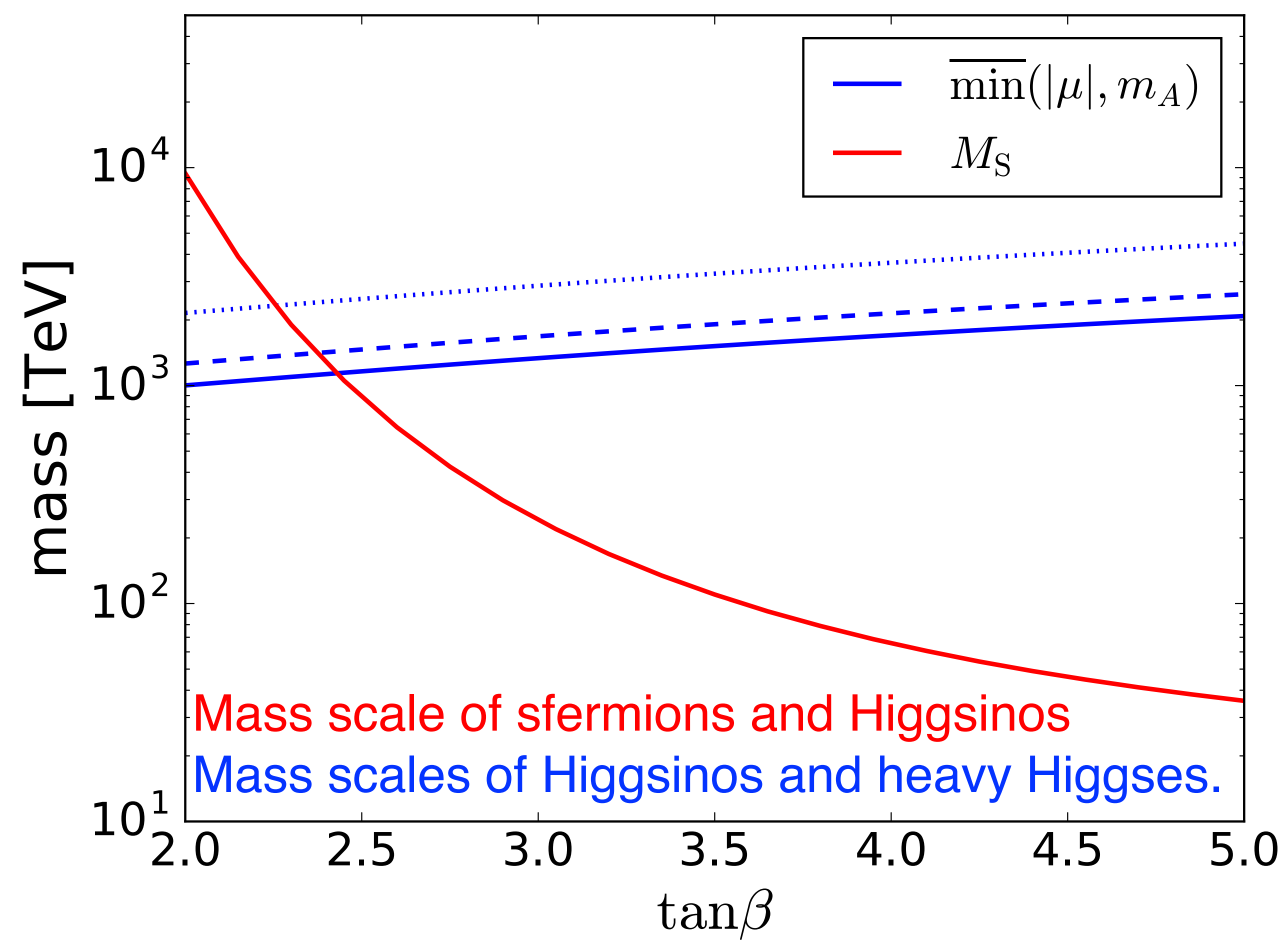

Three model parameters can be constrained by the gaugino mass measurements.

The gaugino mass measurements would imply also **the next particle-mass scale** (Higgsino, Higgses and sferimions)