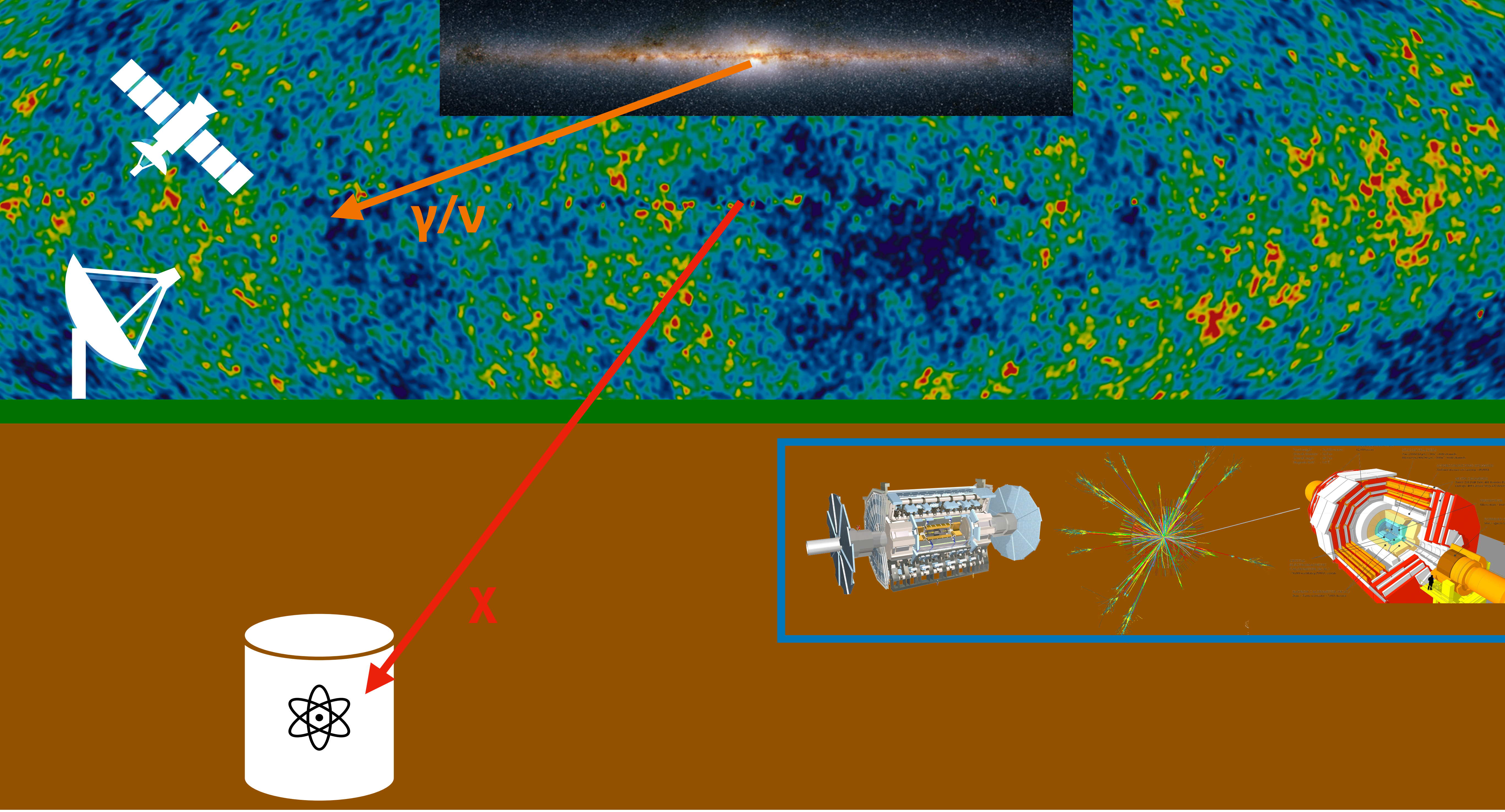


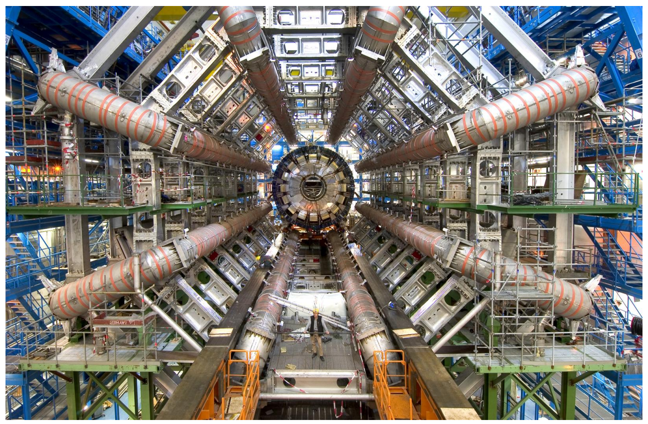

# SUSY dark matter searches at the LHC

Shion Chen (Kyoto University)

CTA Japan workshop 7-8 Jan 2025

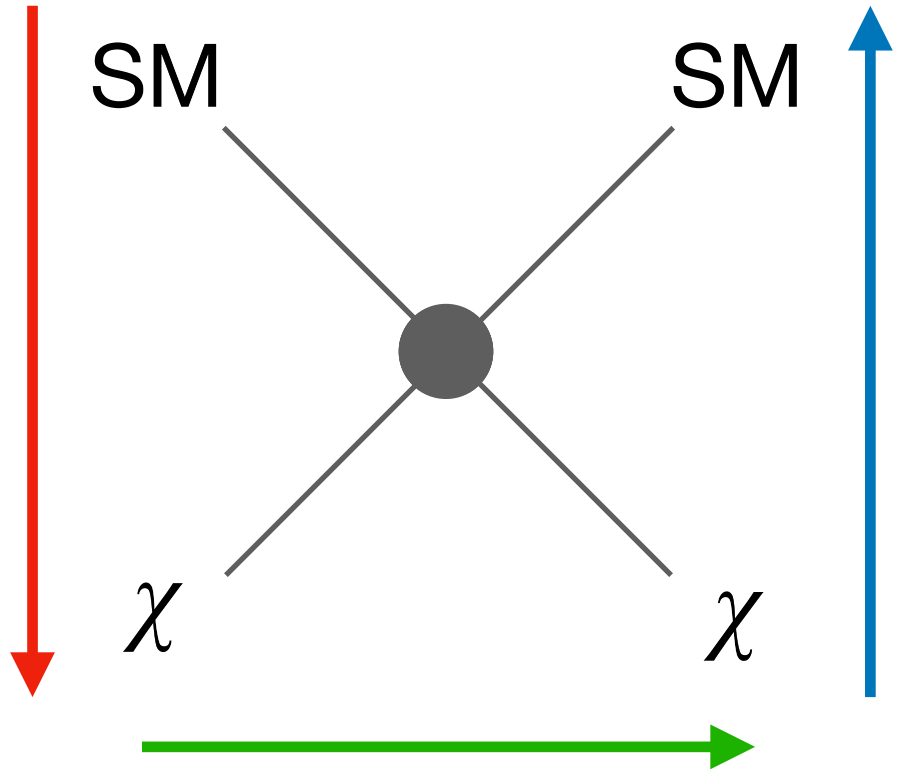
# The DM search trifecta

**Production:** collider

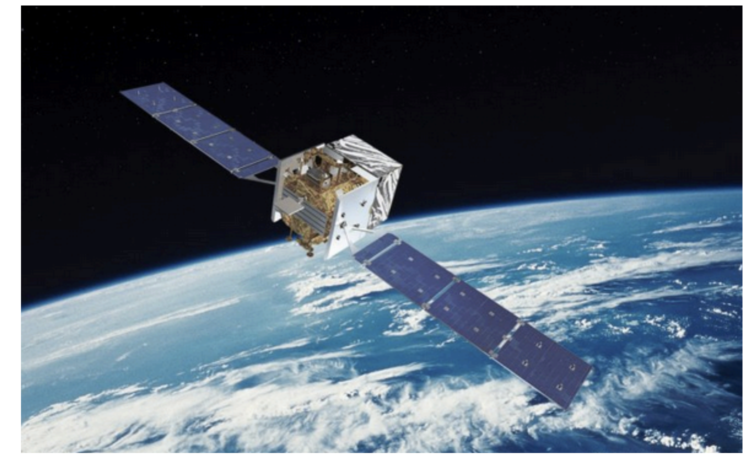


😃 Small uncertainty
on the production rate

😞 Low mass reach
at this point (100-700GeV)



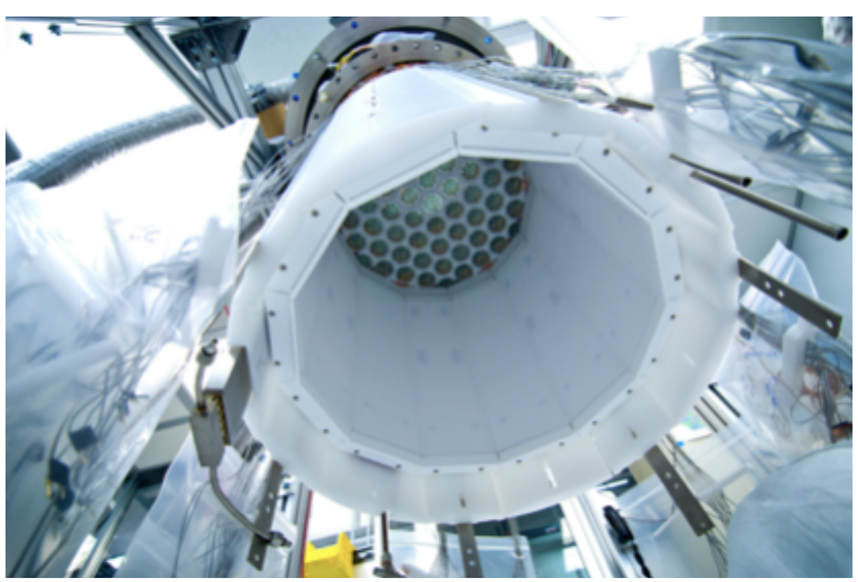

**Annihilation:** indirect detection



😞 Large uncertainty on the galaxy center DM profile
e.g. "core-cusp" problem

😃 Excellent high mass sensitivity (~ a few TeV)

**Scattering:** direct detection

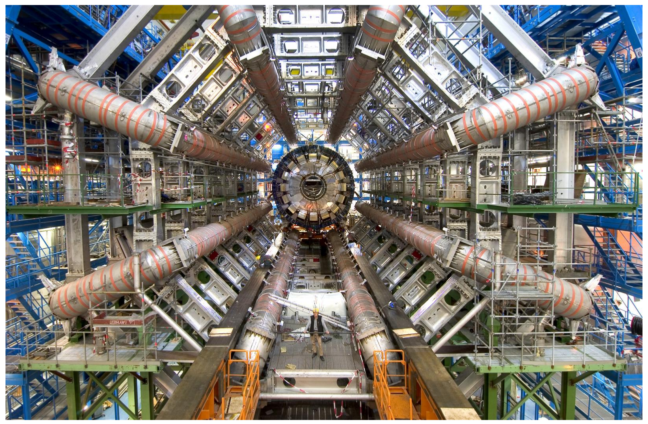


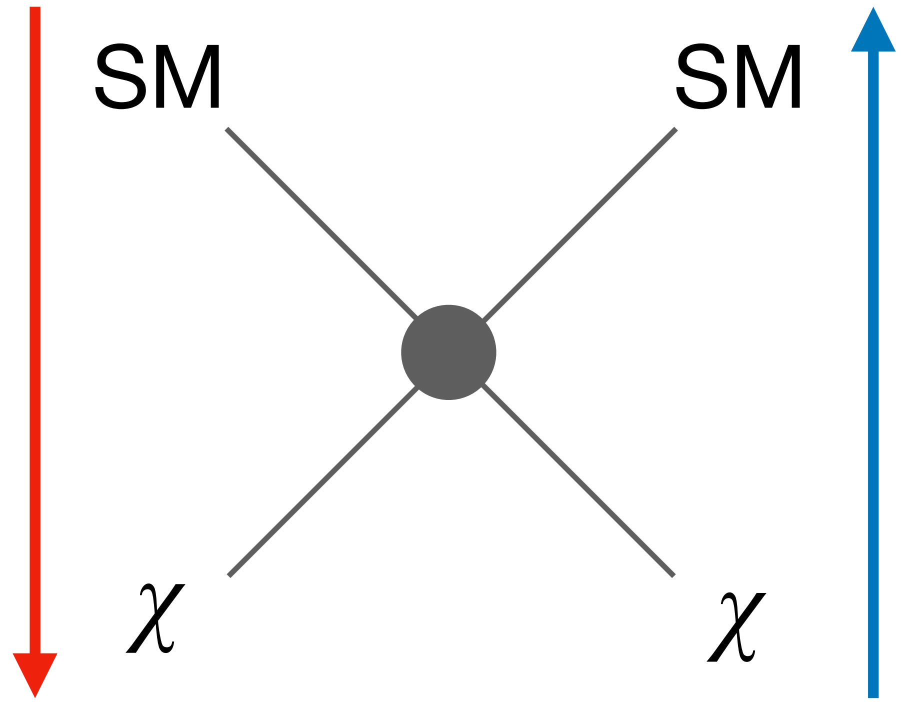
😞 Need to assume the local DM density
Nightmare scenario: no DM around the earth

😃 Excellent high mass sensitivity (~1TeV)

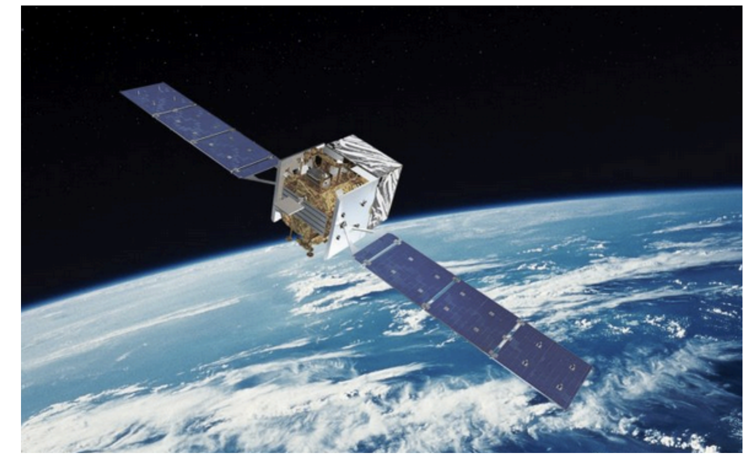
# Objective of this talk

**Production:** collider





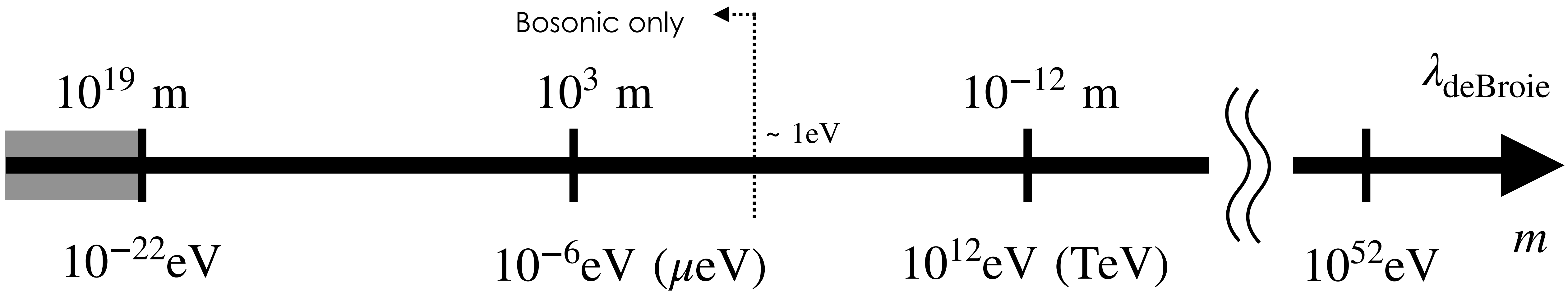

**Annihilation:** indirect detection



**My personal goal in the workshop:**

- ○ Understand the model coverage
- ○ Figure out the commonality/complementarity of sensitivity

# Dark matter we're looking for in LHC




Primordial blackholes

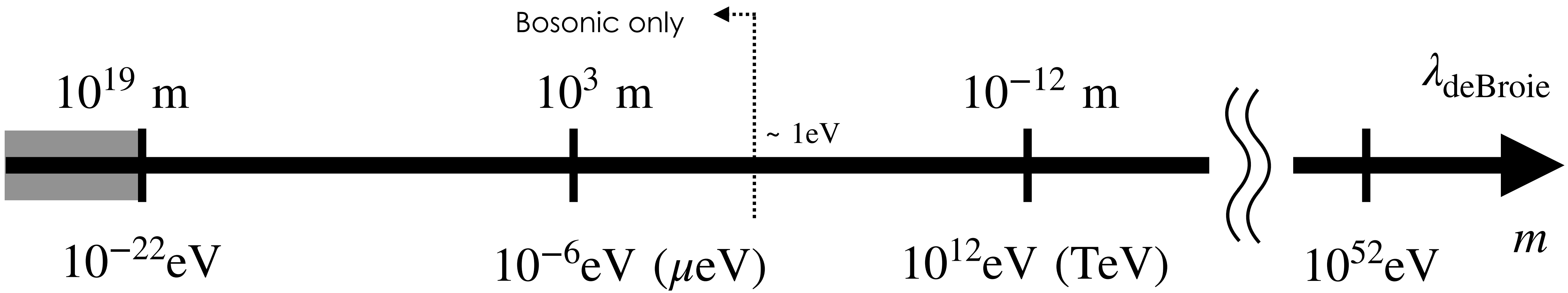
**Light scalars**

- ○ Dark photon
- ○ Axion-Like Particle (ALP)

**WIMP**

- ○ UV complete model benchmark: SUSY
- ○ Model independent approaches

# Dark matter we're looking for in LHC




Primordial blackholes

**Light scalars**

- Dark photon
- Axion-Like Particle (ALP)

**WIMP**

- **UV complete model benchmark: SUSY**
- Model independent approaches

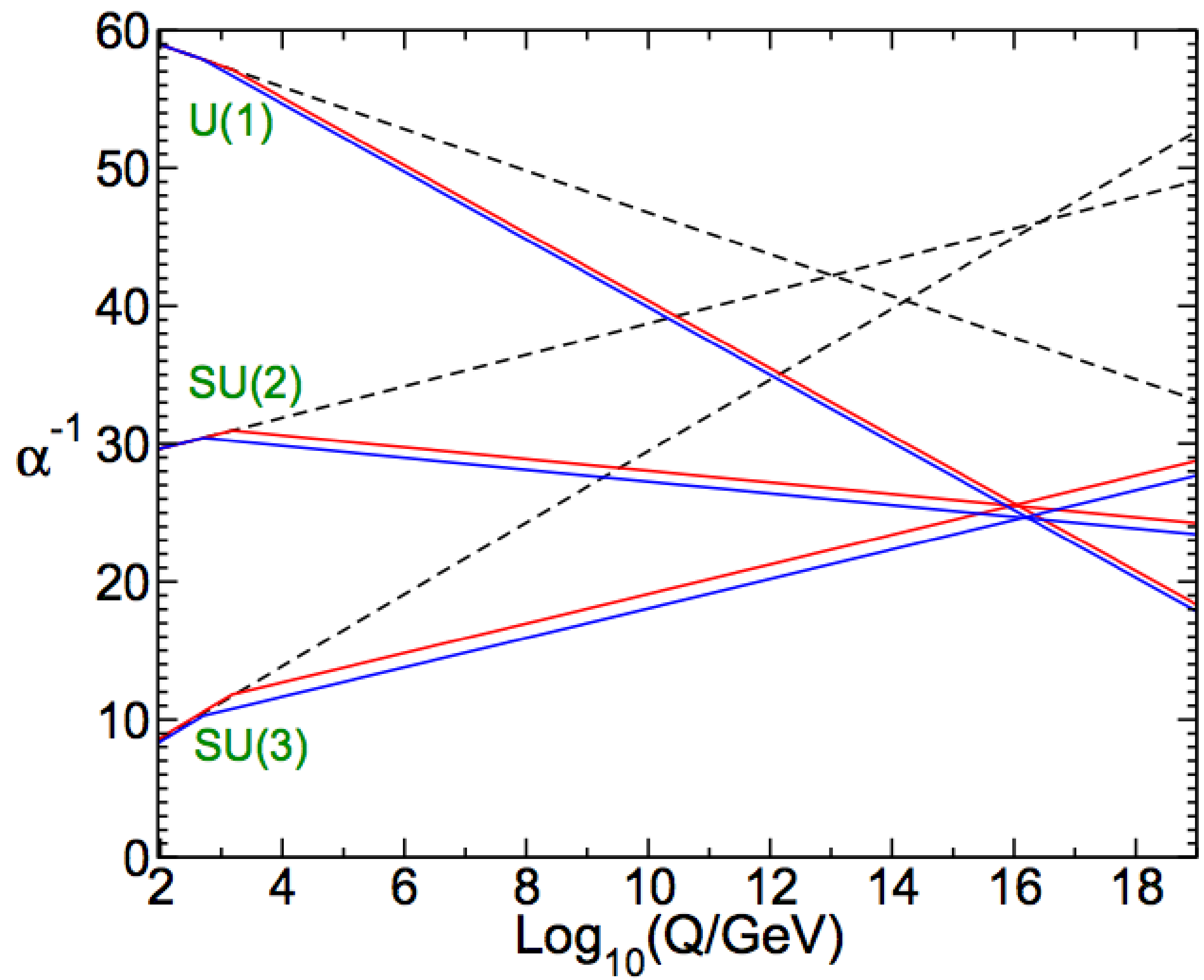
Others → Coffee

# Why SUSY? → GUT

The extra particle content in SUSY will bend the running couplings.

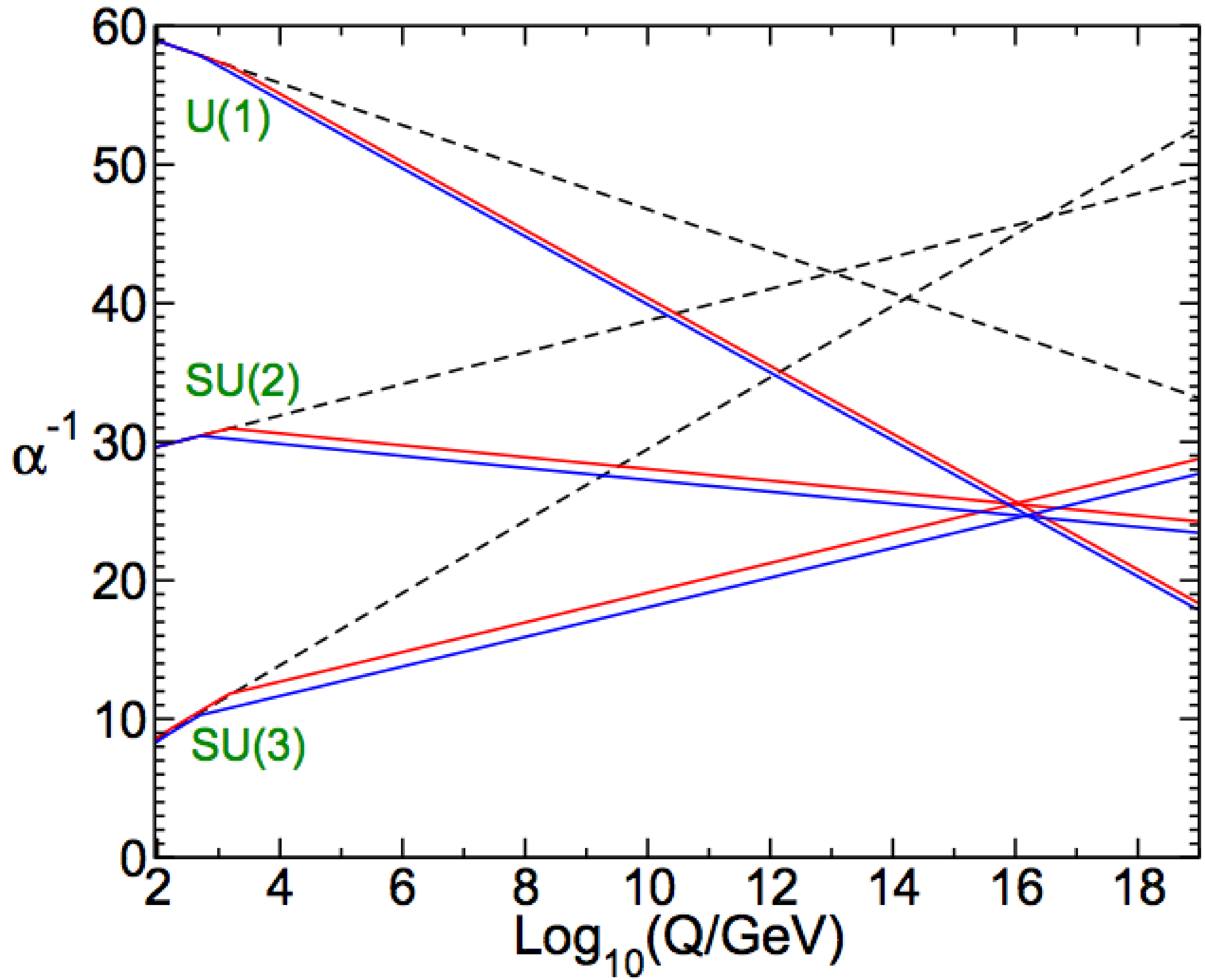
**Too good unification as an accident!**


SM MSSM




Unblinded >500 times and found nothing
U(1)
SU(2)
SU(3)
$\alpha^{-1}$
0 10 20 30 40 50 60
2 4 6 8 10 12 14 16 18
$\mathrm{Log}_{10}(Q/\mathrm{GeV})$

# **But!** GUT doesn't necessarily need TeV SUSY




mSUSY=1TeV

mSUSY=10TeV

# But! GUT doesn't necessarily need TeV SUSY

Needs a separate motivation if one wants to search SUSY in experiment where realistic reach is a few-O(10) TeV

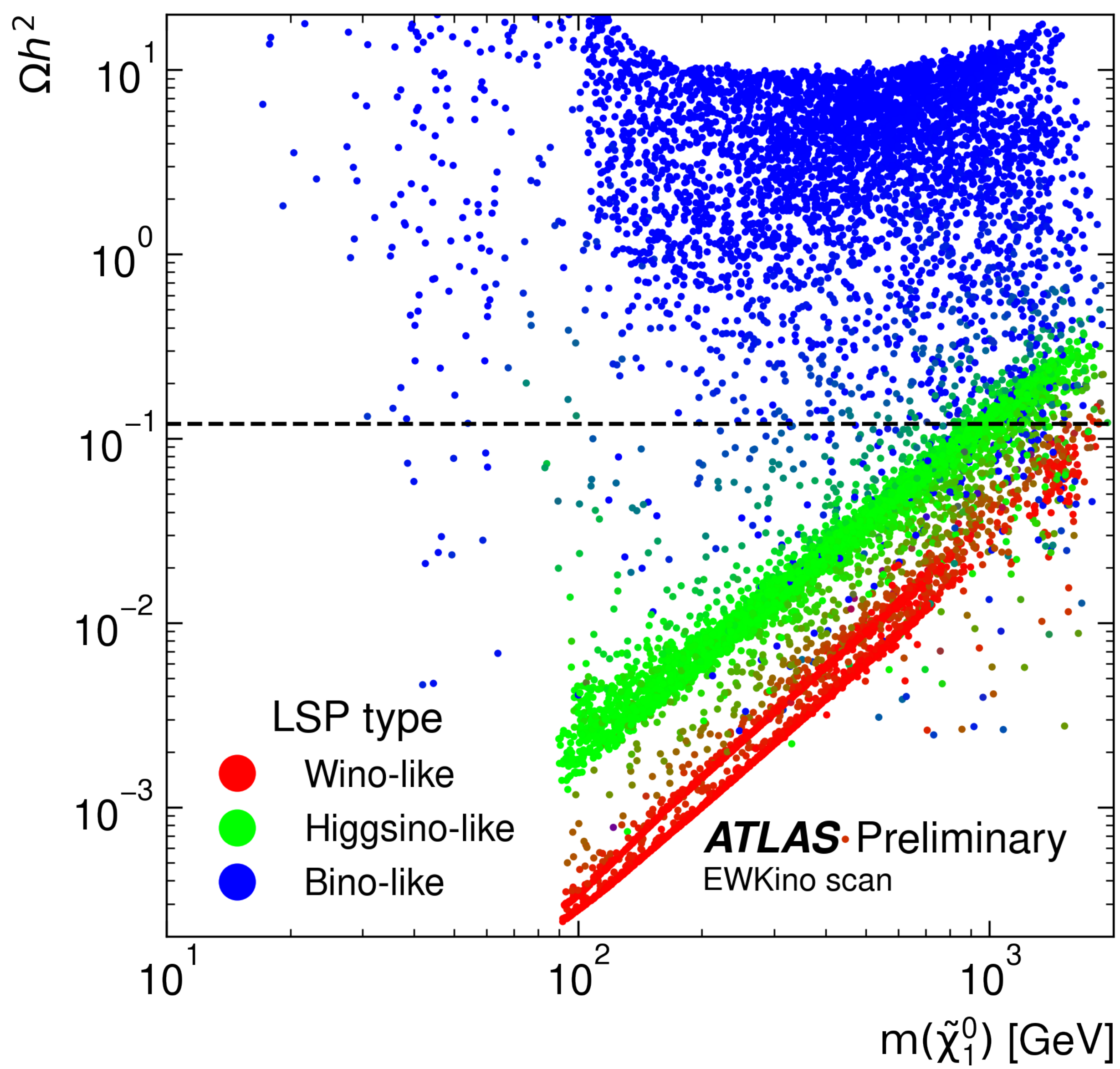
**e.g. Dark matter**

**<3TeV from relic abundance**

※ Others can be:

- ○ Naturalness
- ○ Muon g-2 etc.

[ATLAS-CONF-2023-055 ]



# Dark matter candidates in SUSY

R-parity conservation (~SUSY number conservation)

→ **Lightest SUSY particle (LSP) becomes DM if neutral**

**Neutralino DM** Most common candidate👑

Weak Eigenstates

Bino ($M_1$): $\tilde{B}$

Winos ($M_2$): $\tilde{W}^0, \tilde{W}^\pm$

Higgsinos (μ): $\tilde{H}_u^0, \tilde{H}_d^0, \tilde{H}_u^+, \tilde{H}_d^-$


Mass Eigenstates

Neutralinos: $\tilde{\chi}^0_{1,2,3,4}$

Charginos: $\tilde{\chi}^\pm_{1,2}$

Thermal relic density constraint

**Wino LSP: < 3 TeV**

**Higgsino LSP: < 1 TeV**

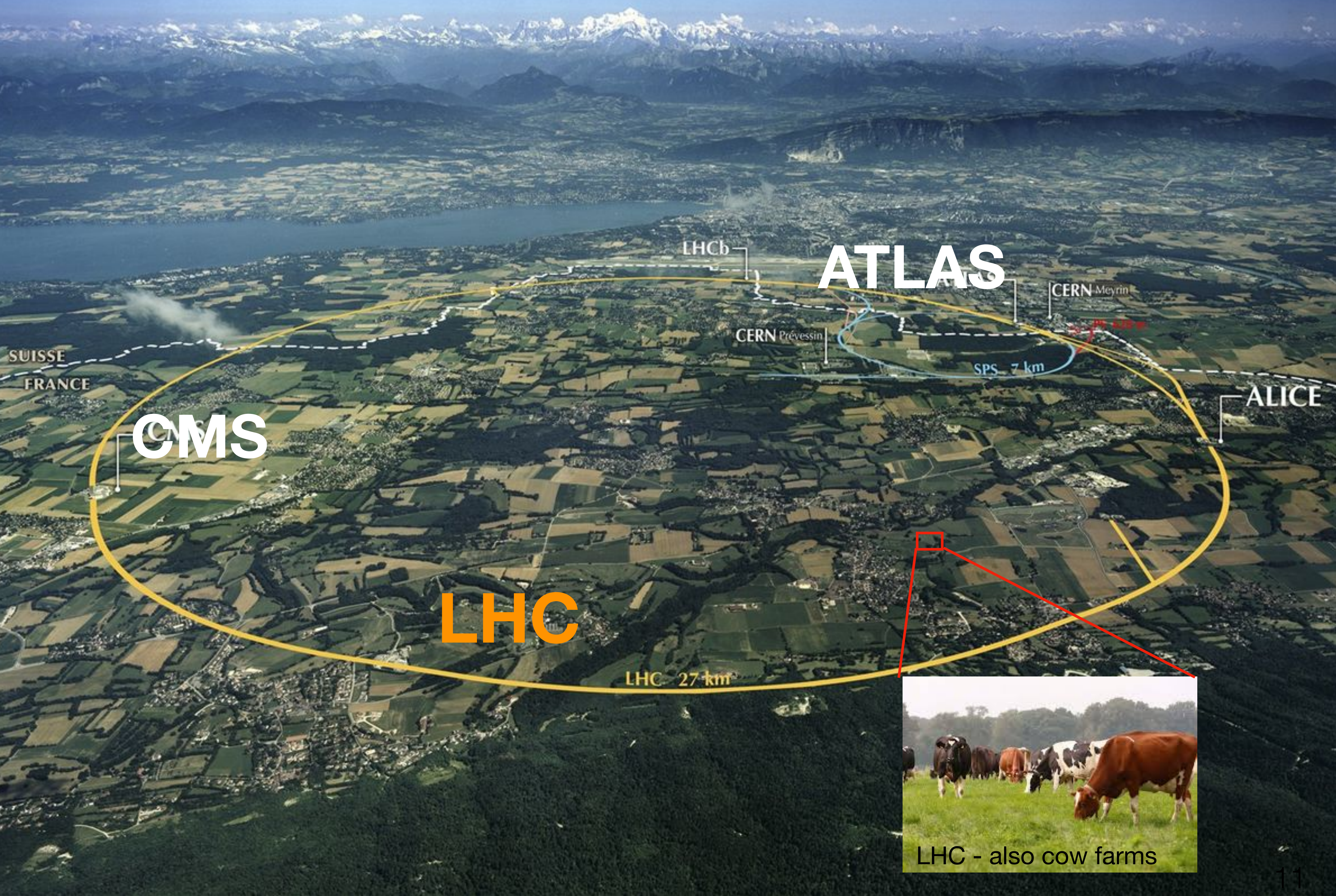
**Bino LSP: 100 GeV ~ a few TeV**

Sneutrino DM — Strongly constrained by direct search

Gravitino DM — Nearly massless → Hot DM. Also "Gravitino problem".

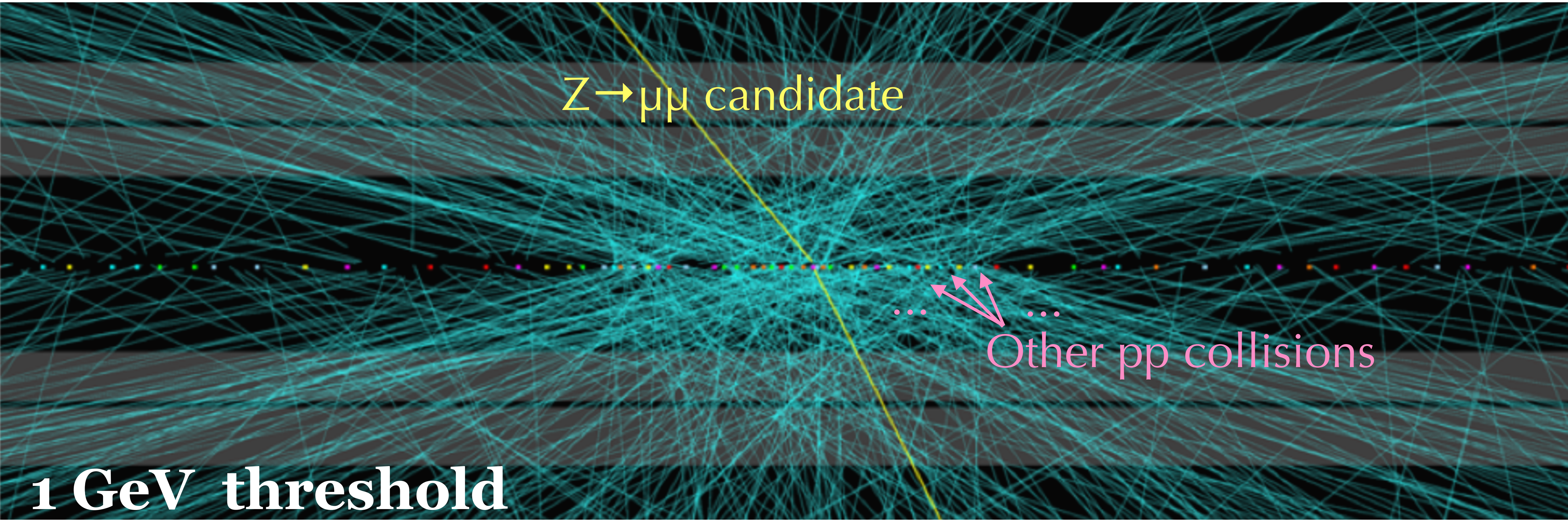
Beyond the MSSM — NMSSM Singlino, Axino ... etc. less constrained but exotic

# LHC - the SUSY farm



# LHC basics

Example of a "bunch crossing"

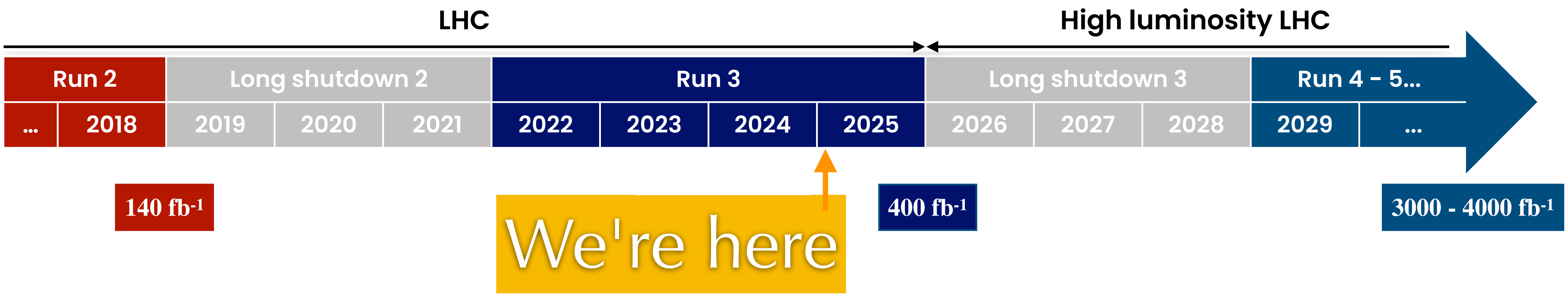



- Center of mass energy: 13.6TeV (Run3)
- Colliding a pair of bunches of $10^{10}$ protons every 25ns (40MHz).
- Pile up: ~60 per bunch crossing

  σ(soft QCD) >>> σ(interesting) → Just look at the hardest collision

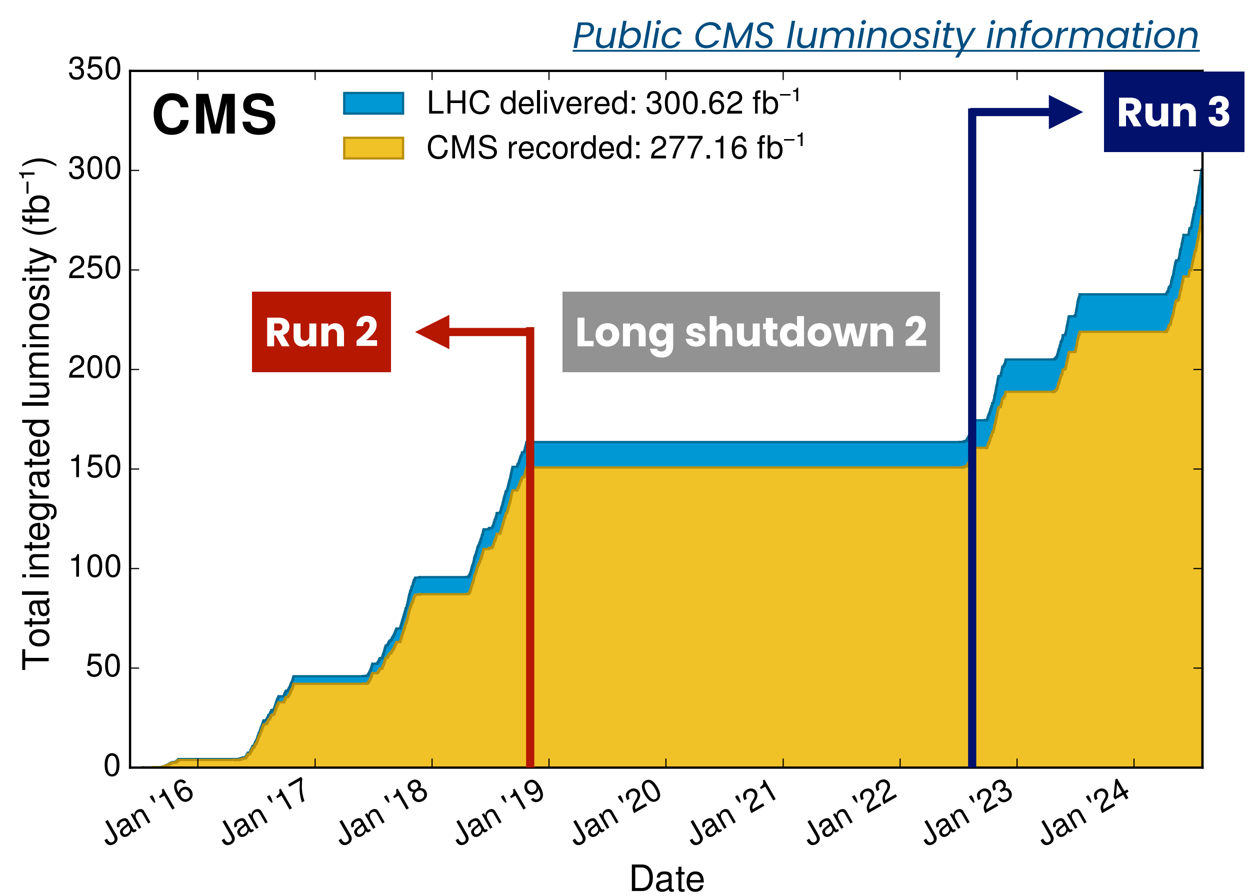
  **"Primary vertex"**

# Time-scale vs Available data statistics



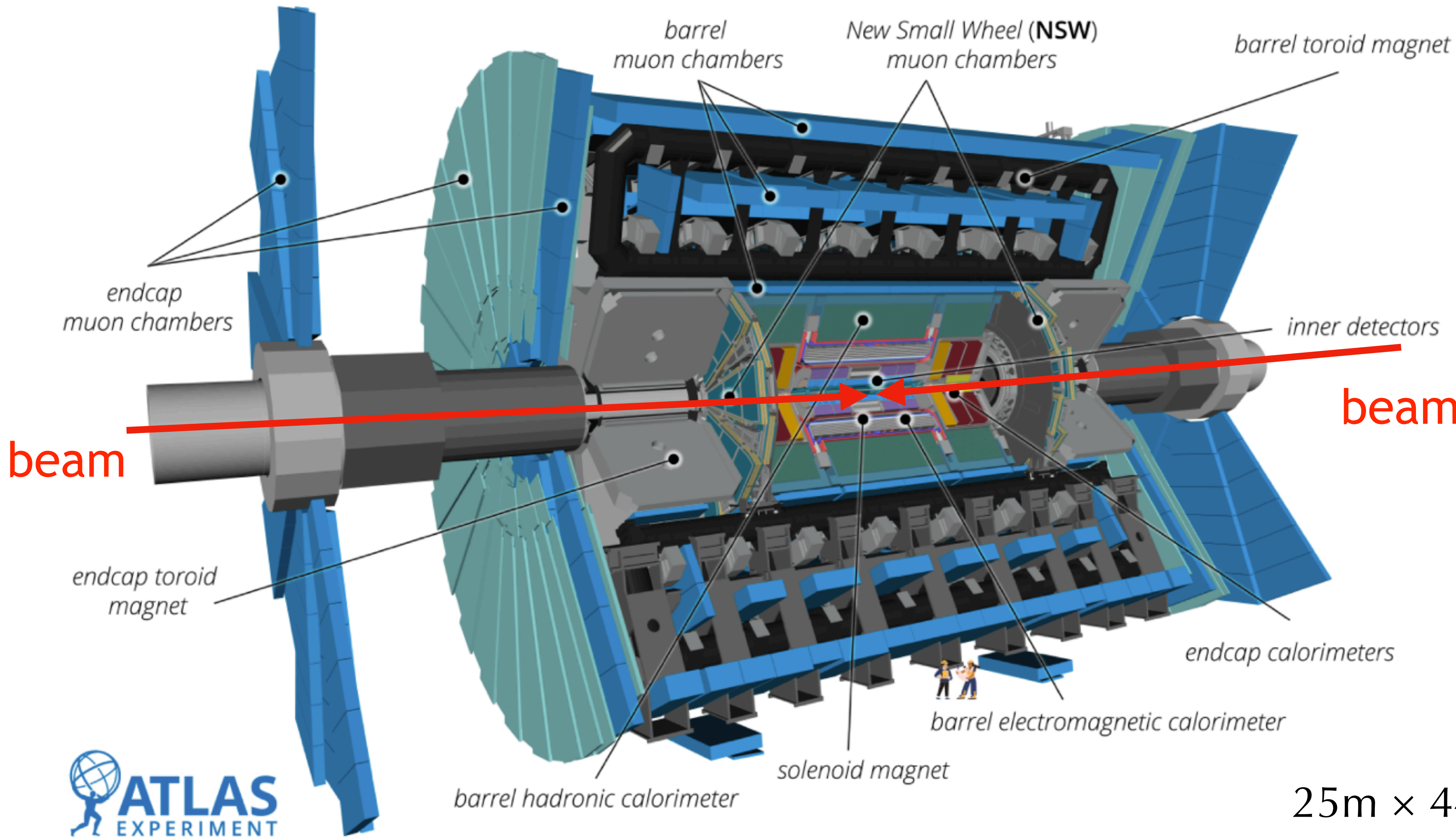

- Run2 (13TeV) +Run3 (13.6TeV):

  ~140+200 $fb^{-1}$ available now
- ×10 by the end of HL-LHC



# Detector e.g. ATLAS

arXiv: 2305.16623

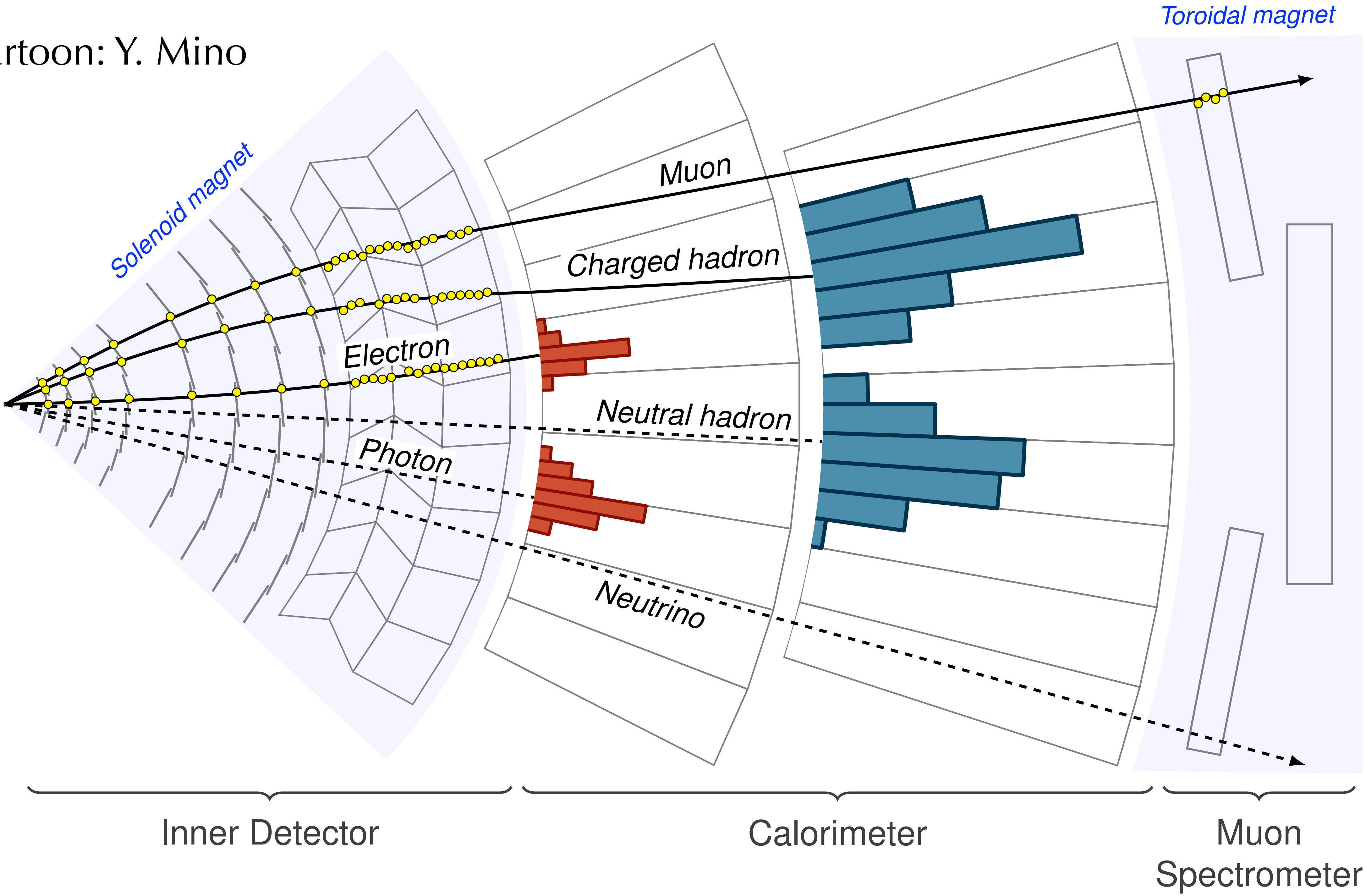



25m × 44m

- Inner tracker (innermost) → Calorimeter → Muon spectrometer (outermost)
- Tight trigger requirement: ×1/40000 reduction in rate

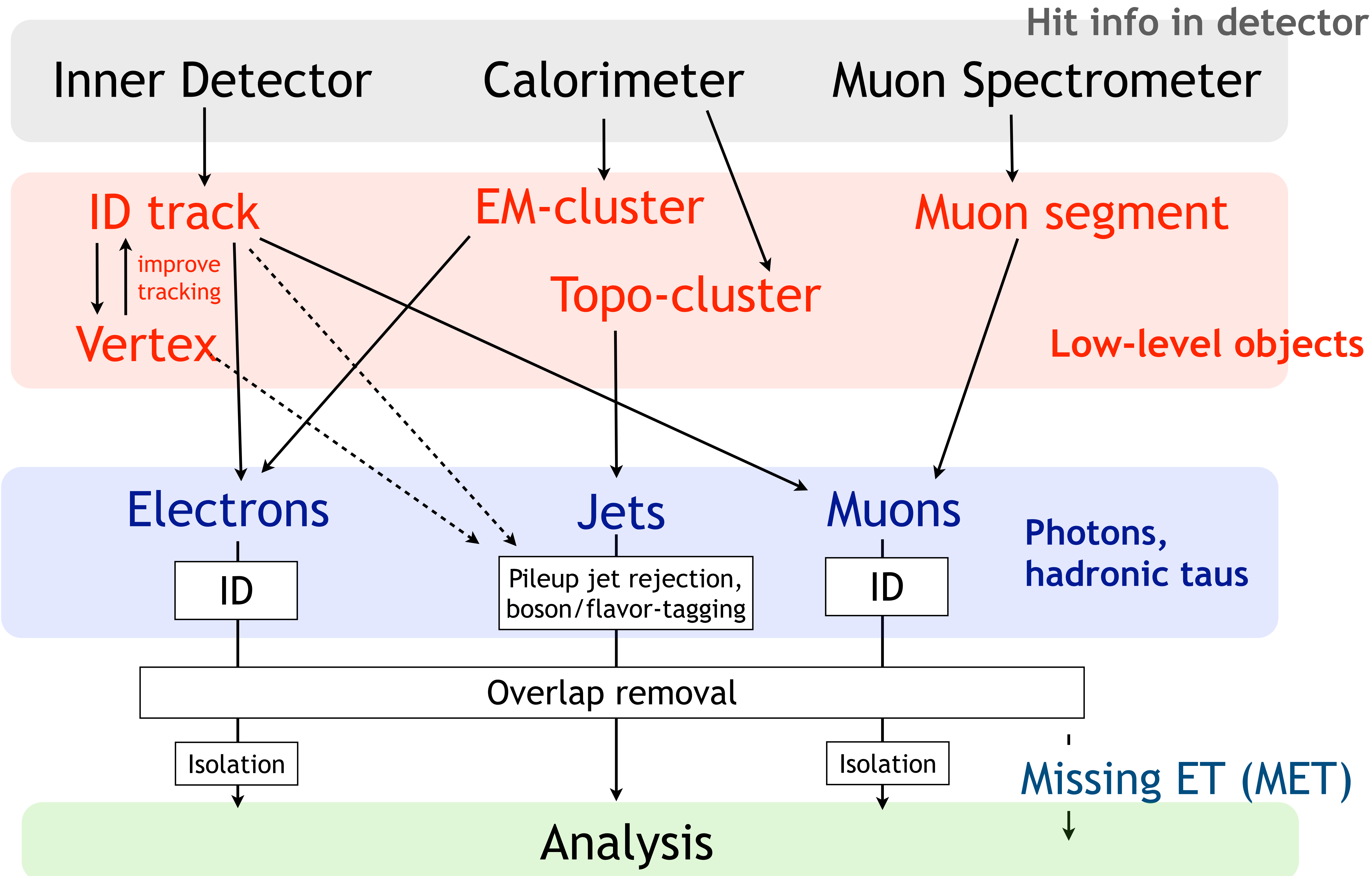
# Particle reconstruction

Cartoon: Y. Mino

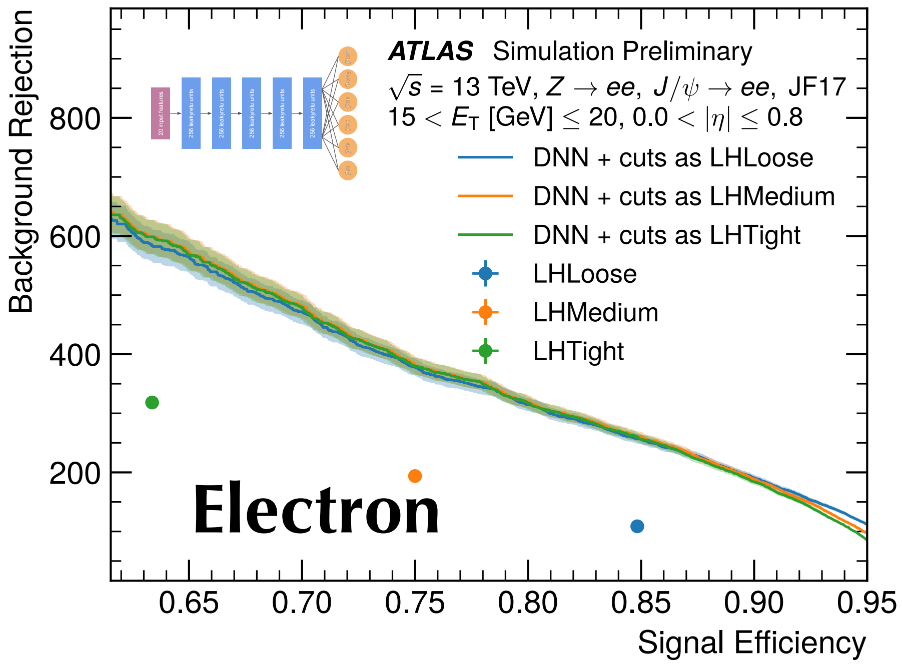


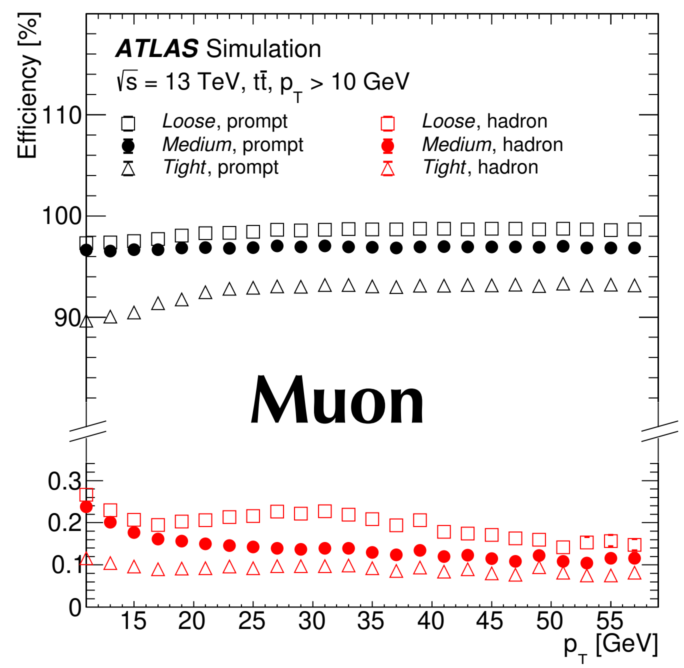

ID track Cluster Muon segment

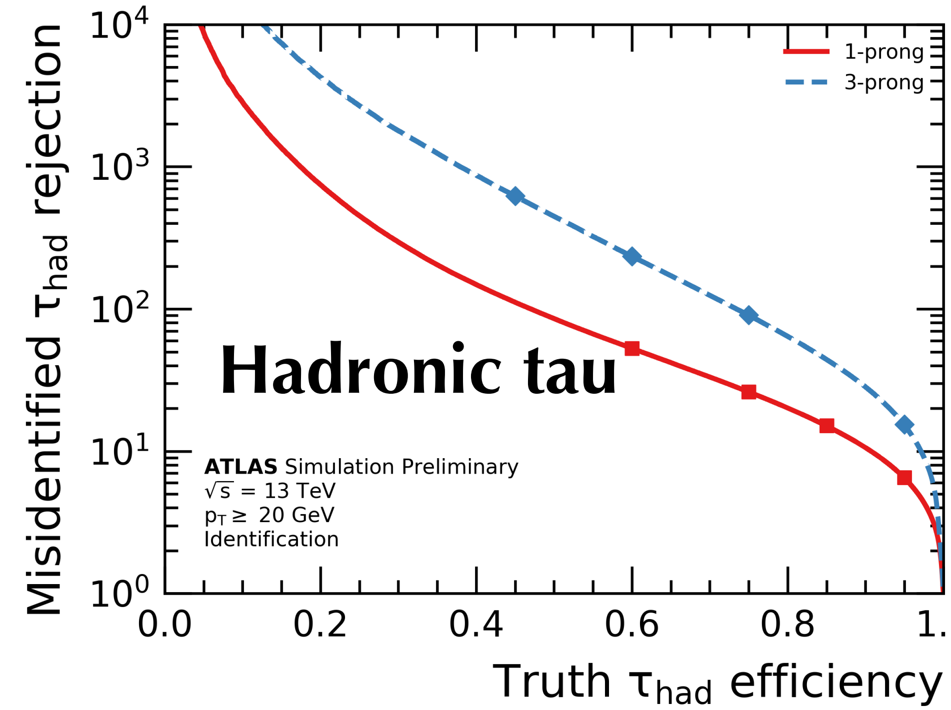
# Particle reconstruction

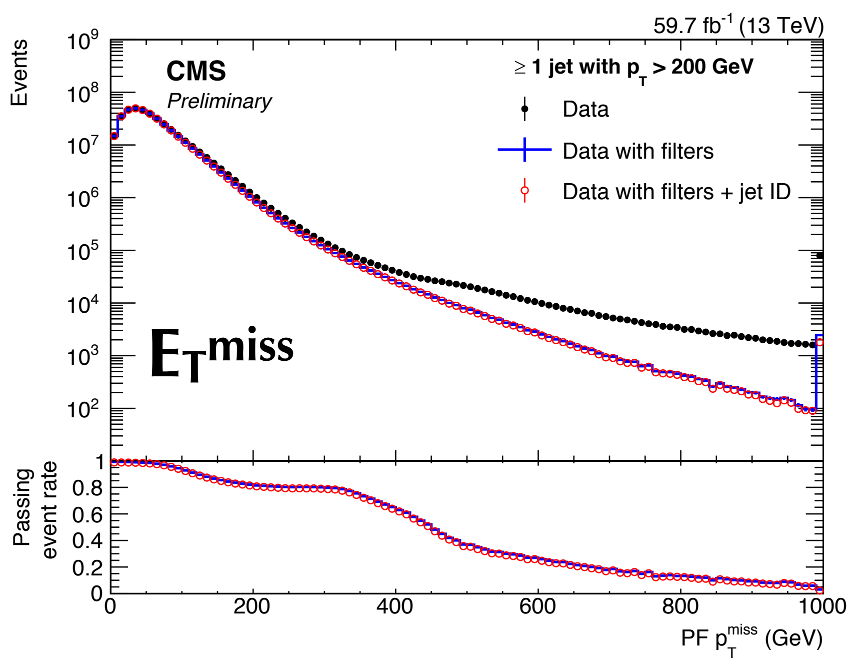


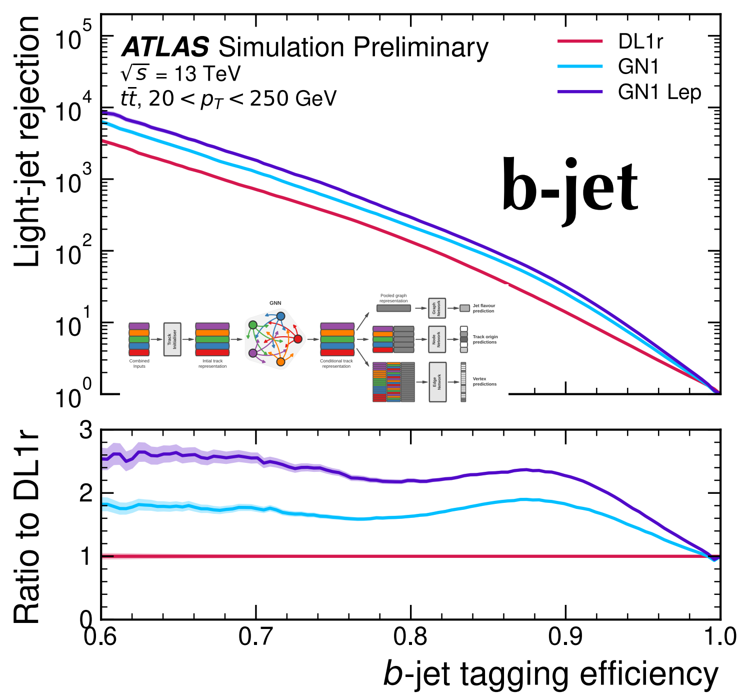
# Particle reconstruction

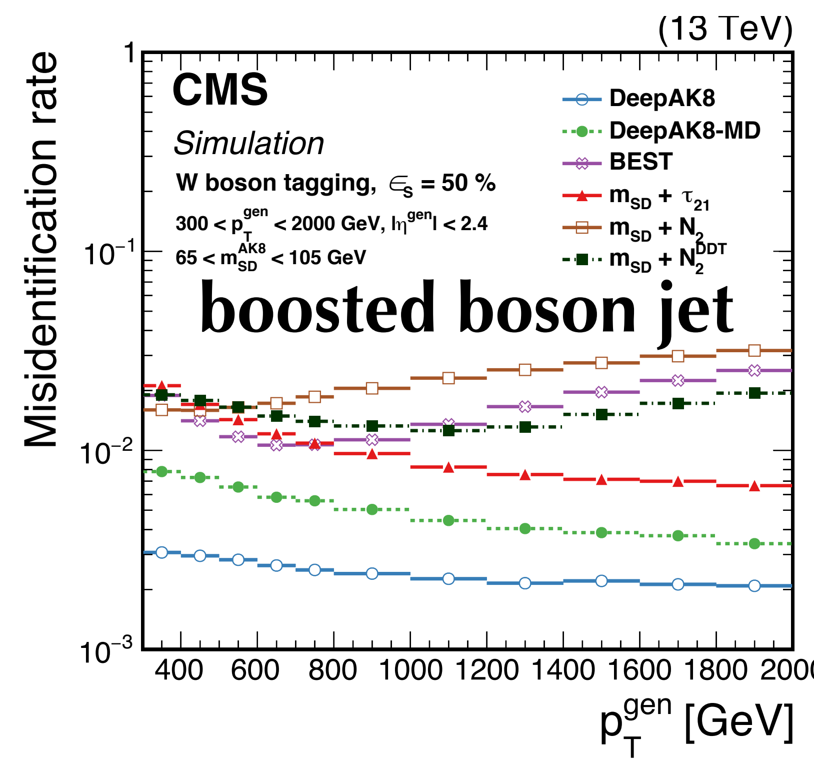


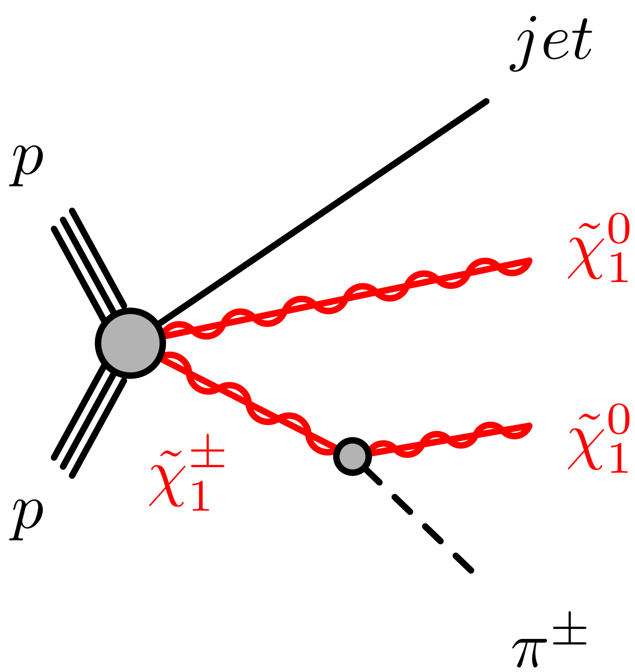



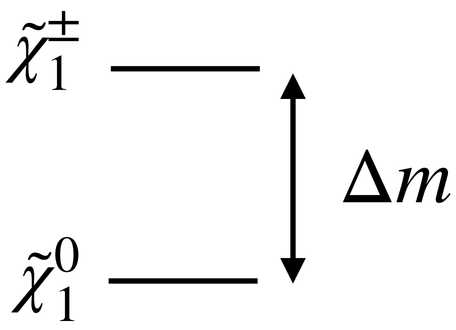



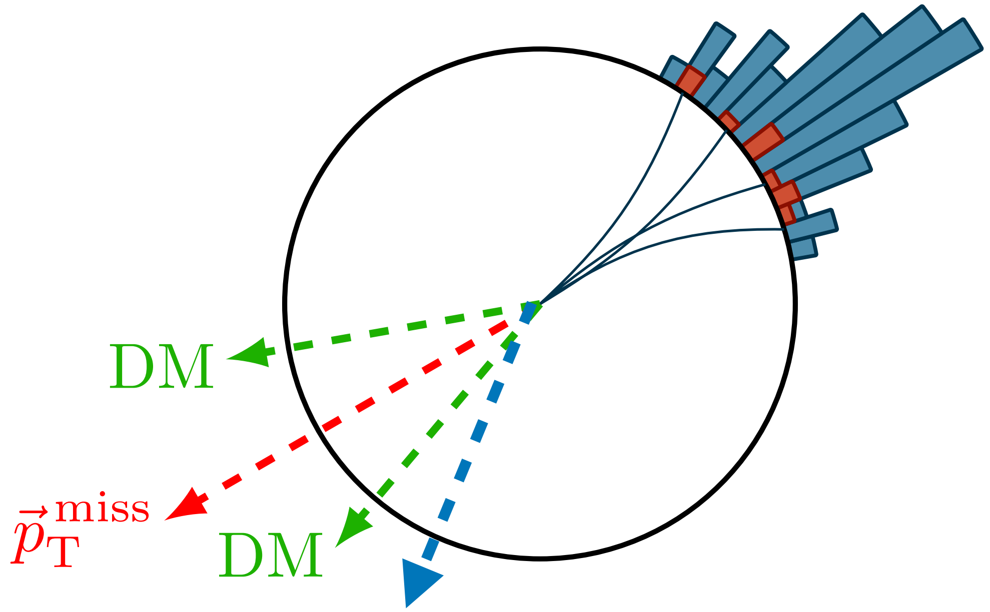




Electron, muon, hadron jet, b-jet, hadronic tau, photon, boosted boson/top jet, ETmiss, pileup rejection etc. ML is being the standard now.

# Typical SUSY DM signature

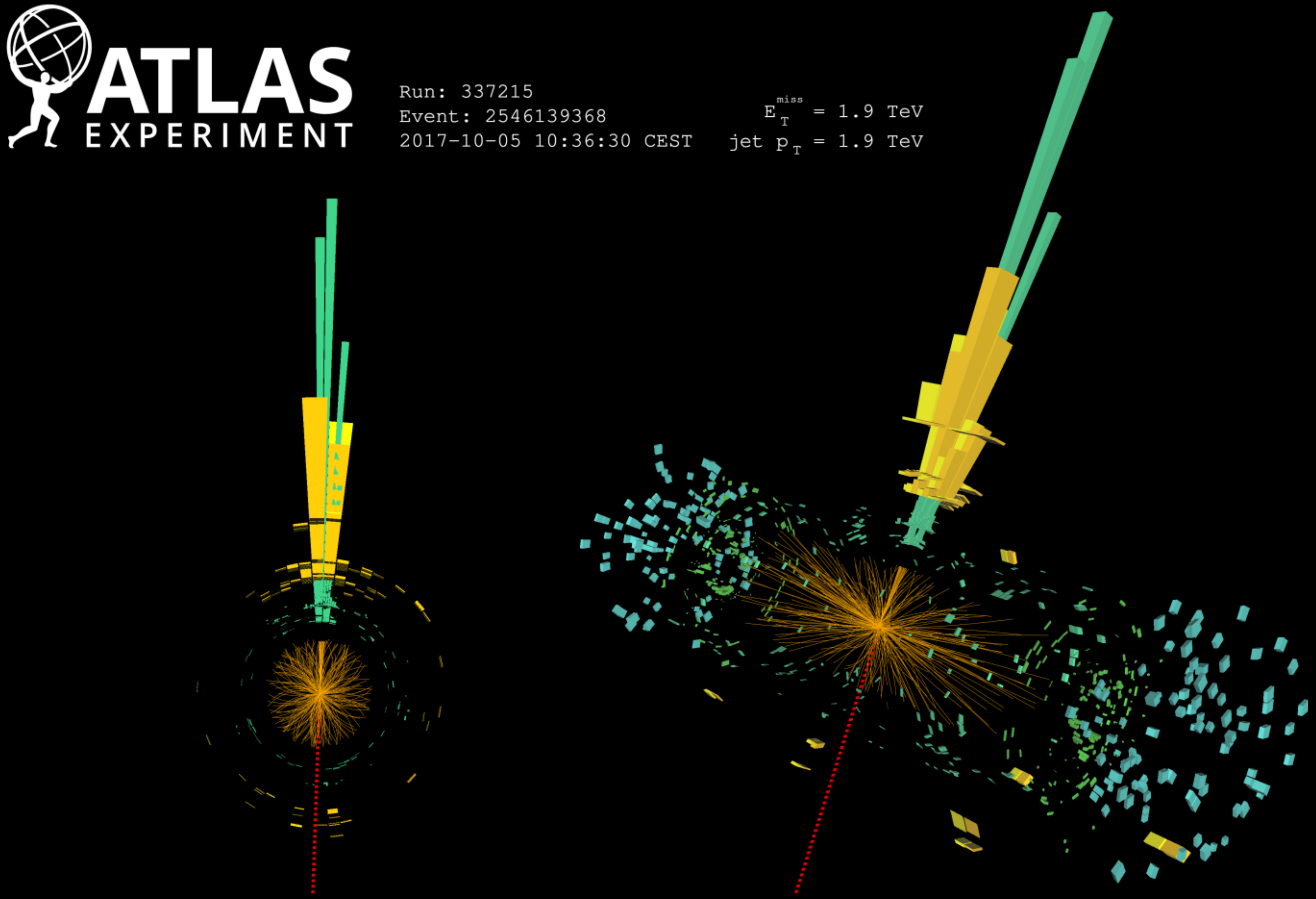



- **Pair production**
- **Generate heavier state → look for the products when decaying into LSP**
  - Δm: Proxy of "hardness" of the observables
  - "Missing momentum" ($p_T^{miss}$) due to the LSPs escaping the detector
- **Δm is typically small.** Only soft particles in final state.

  → Require a hard ISR jet to trigger the event.


ATLAS EXPERIMENT
Run: 337215
Event: 2546139368
2017-10-05 10:36:30 CEST
$E_T^{miss}$ = 1.9 TeV
jet $p_T$ = 1.9 TeV

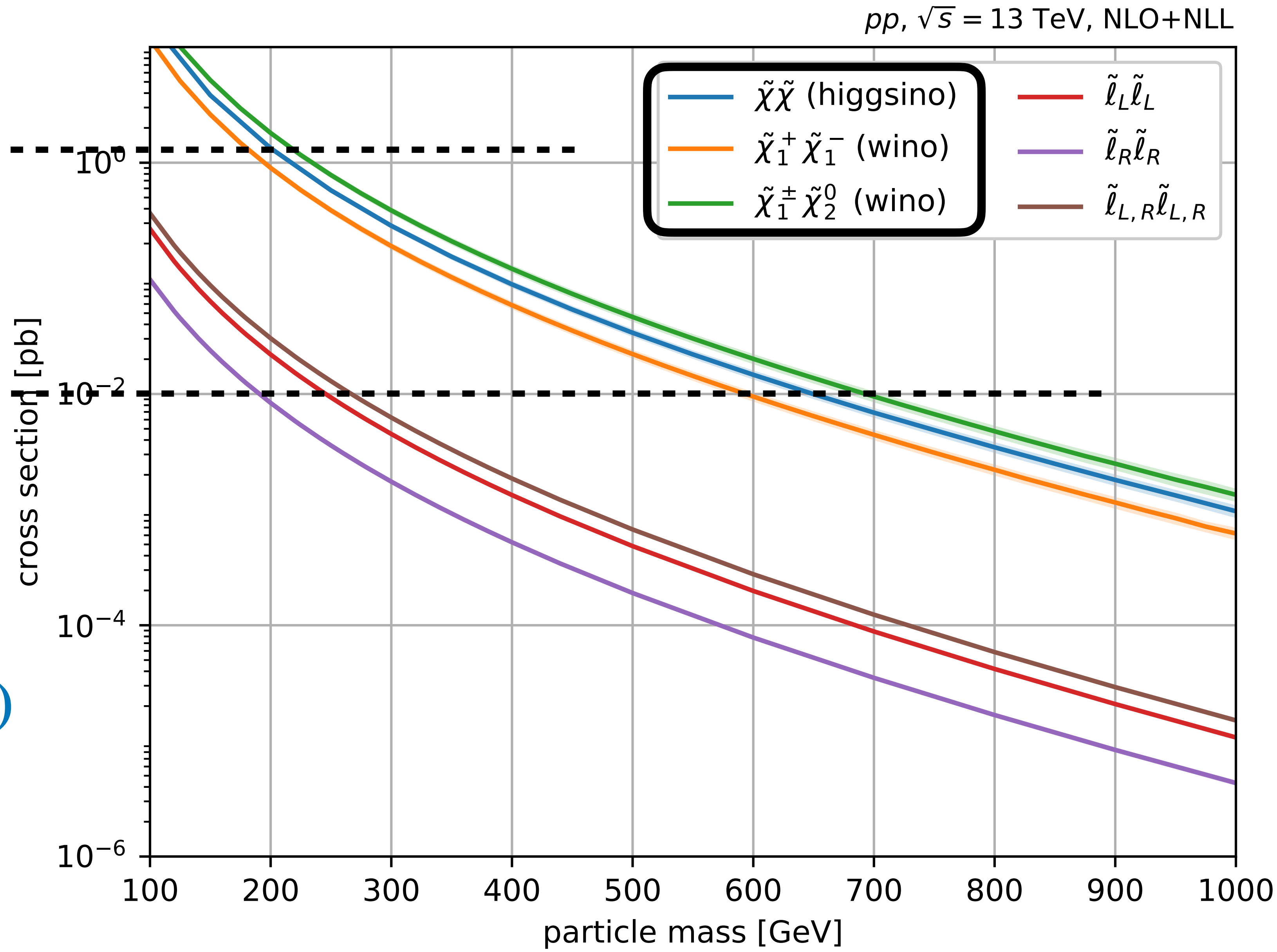
# How many events generated already?

**1.5 M events w/ 140fb$^{-1}$**

Higgsinos limit ~ 200GeV

**1400 events w/ 140fb$^{-1}$**

Wino limit ~ 700GeV

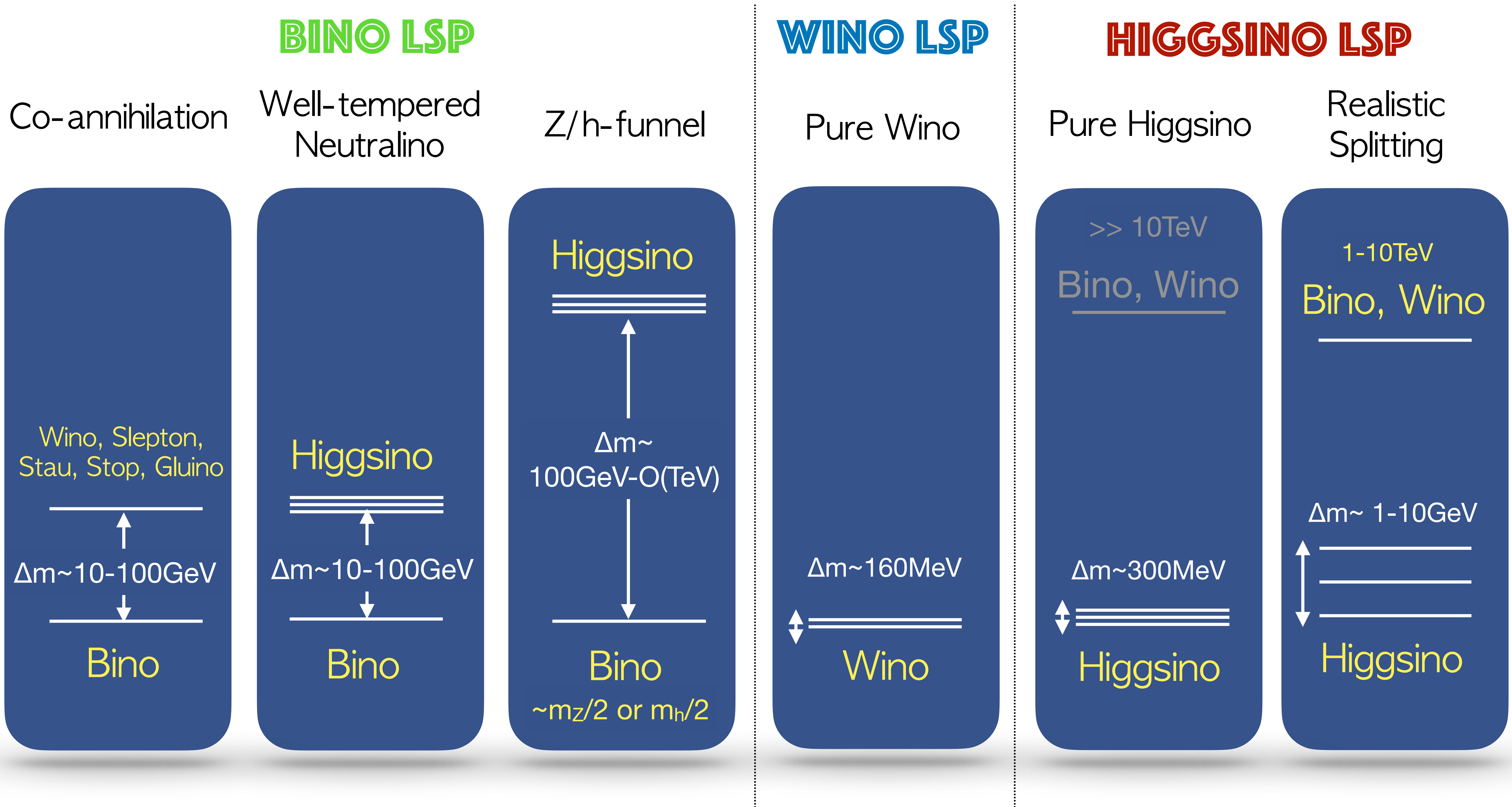



**+ An ISR jet ($p_T$>200GeV)**

**→ σ~×1/50**

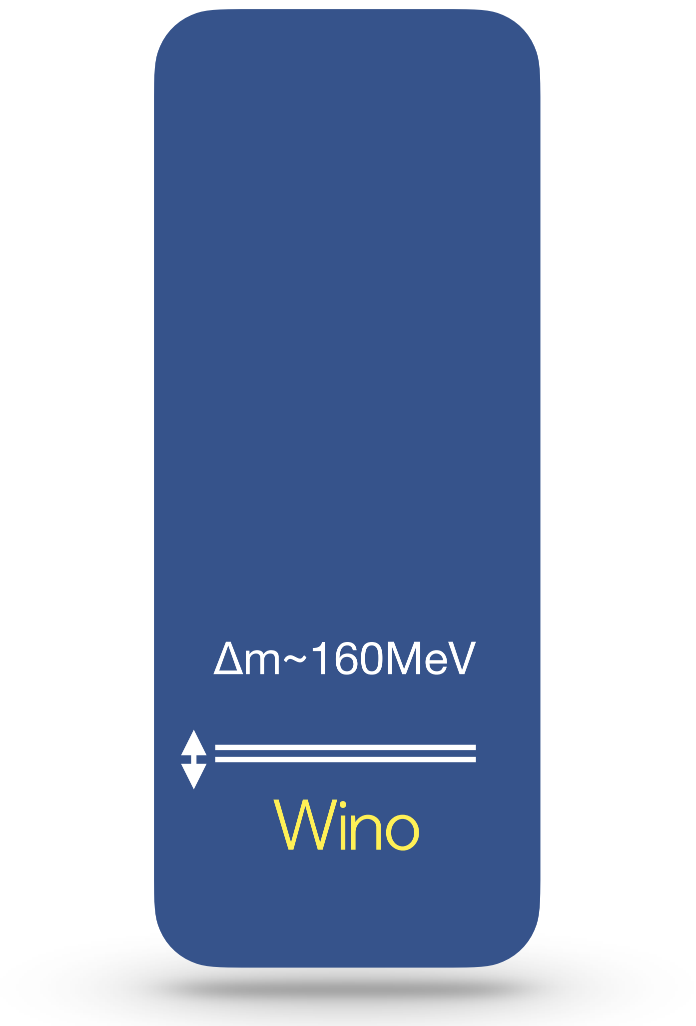
○ Most of the results so far are with the Run2 only dataset (140 fb$^{-1}$)

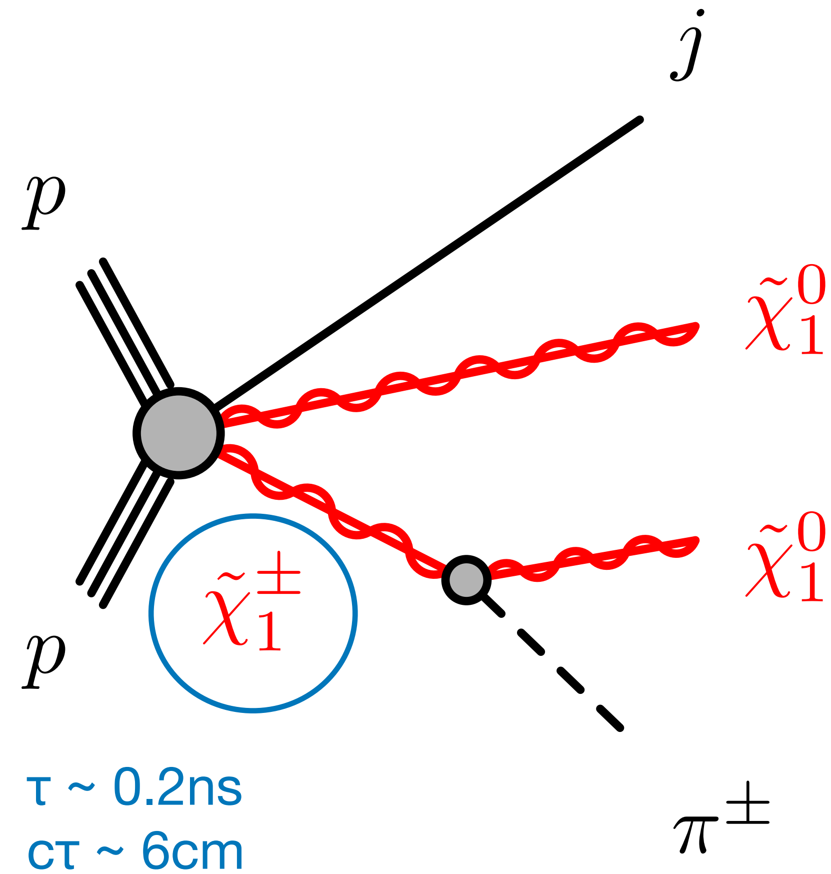
# Neutralino DM scenarios @MSSM




LSP := Lightest SUSY Particle

# Wino LSP

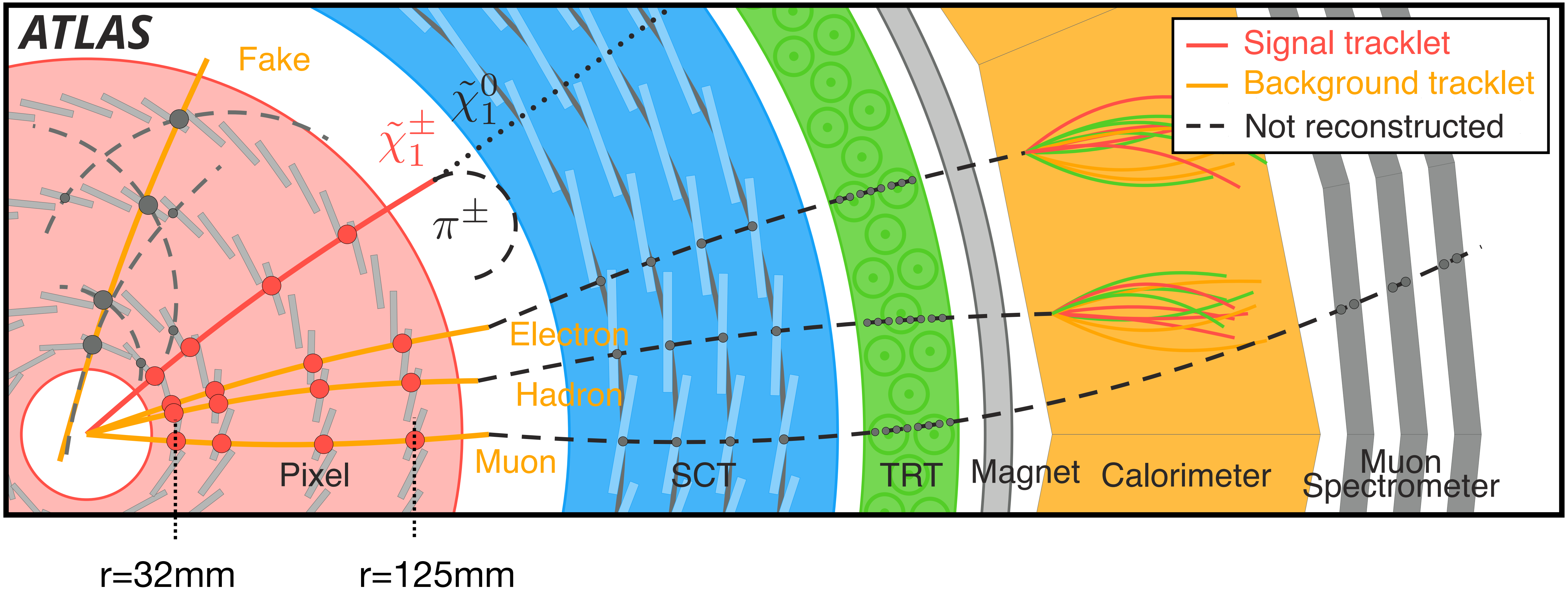



- One charged wino + neutral wino in mass degenerate (~160MeV)
- Very low-pT ("soft") pion from the decay → invisible
- Charged wino has macroscopic lifetime before decaying into the wino LSP

# Wino LSP Search: Disappearing track

ATLAS: 2201.02472
CMS: 2004.05153

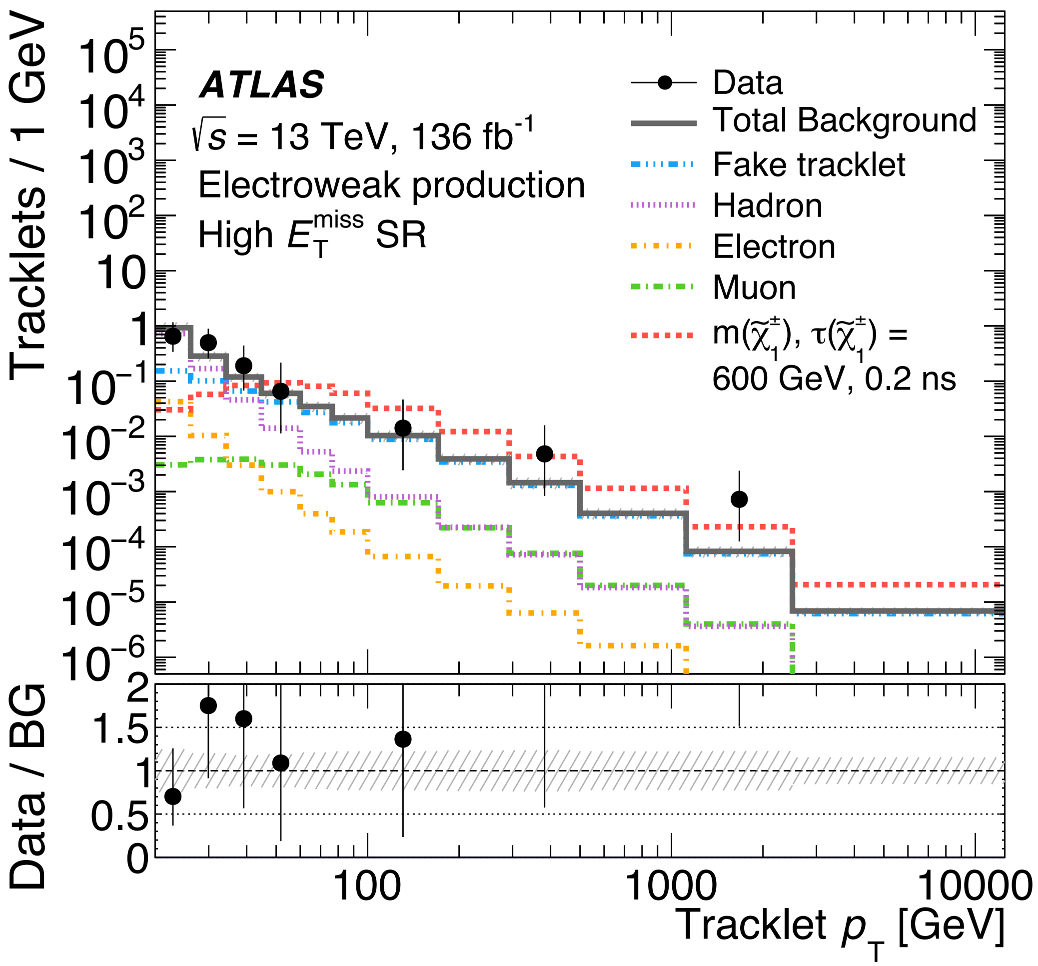


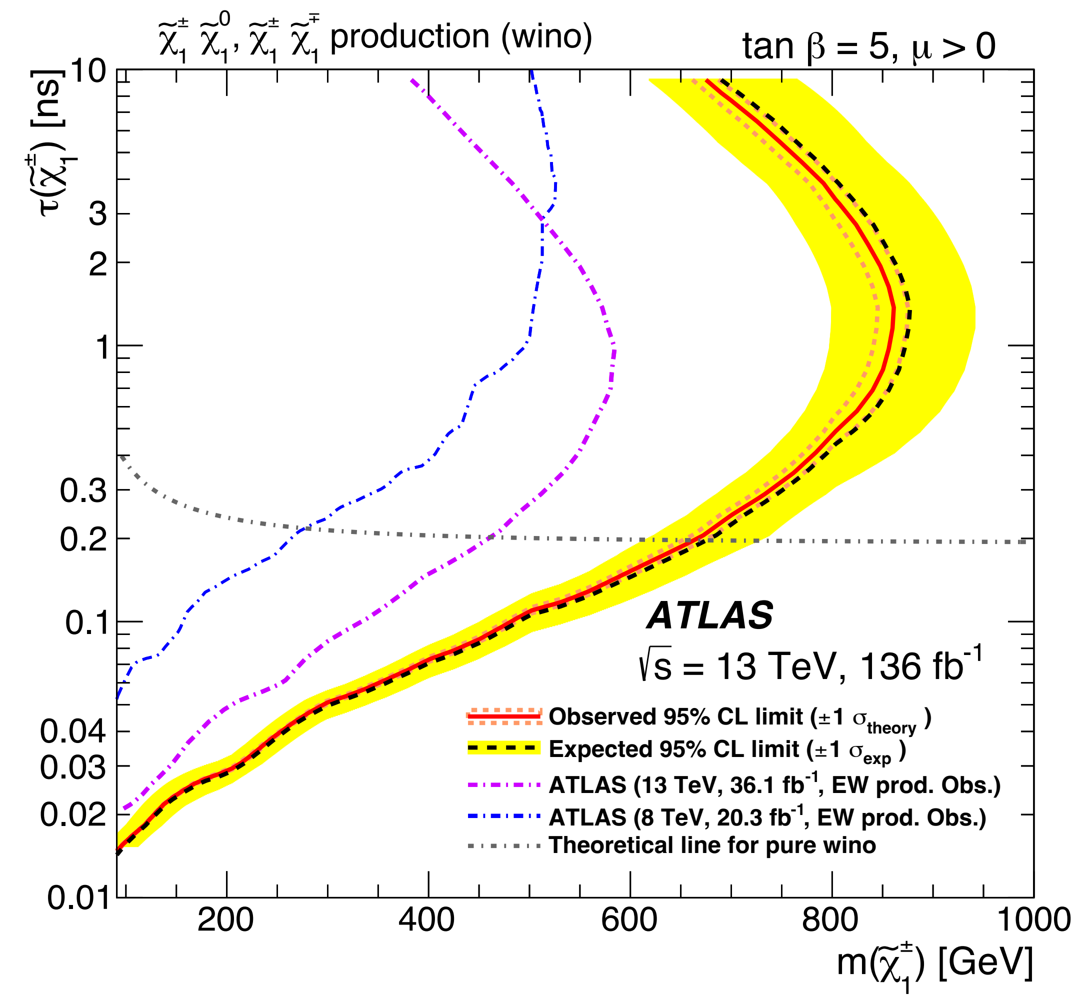

- A charged wino directly interacts with the detector material → **a track**
- Decays in the middle leaving a LSP & an non-reconstructable soft pion → **disappearing**
  - SM particles never leave such weird track → clean
  - BG events are from instrumental effects e.g. random crossing ("fake track")

# Wino LSP Search: Disappearing track

ATLAS: 2201.02472
CMS: 2004.05153

e.g. ATLAS

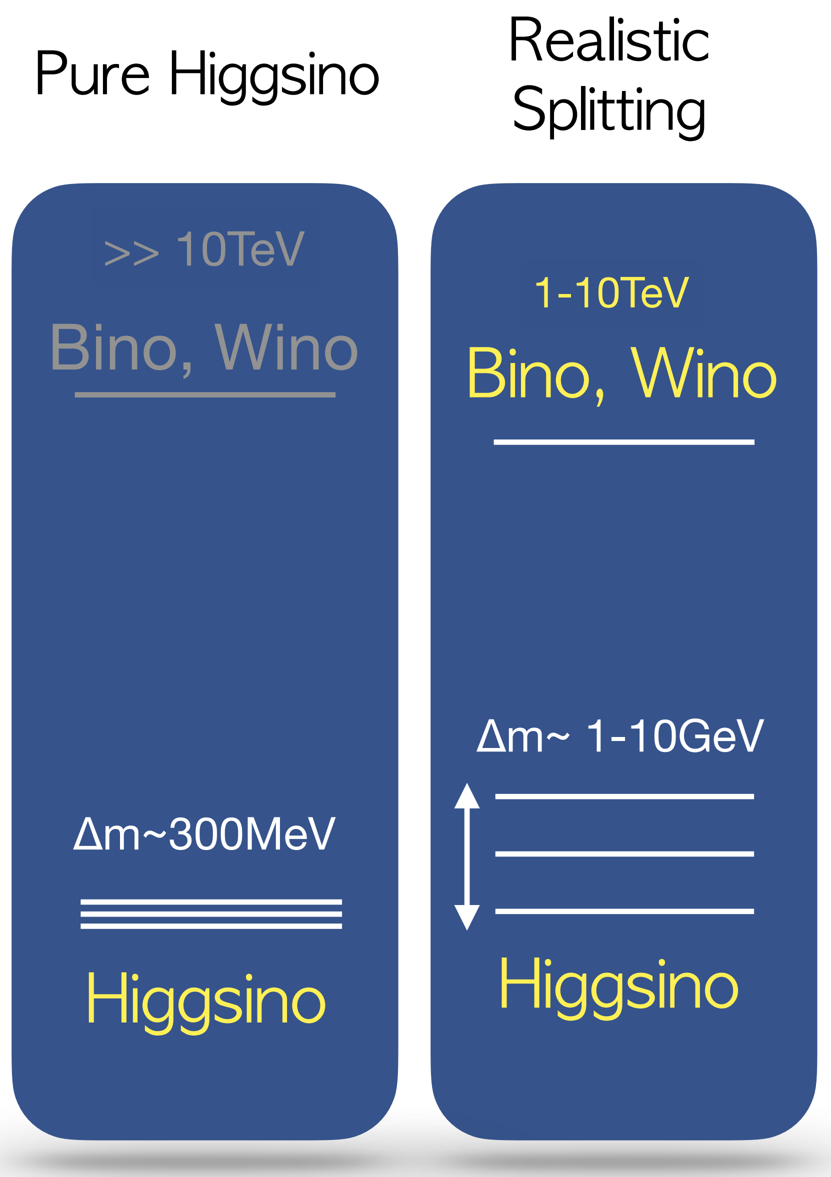


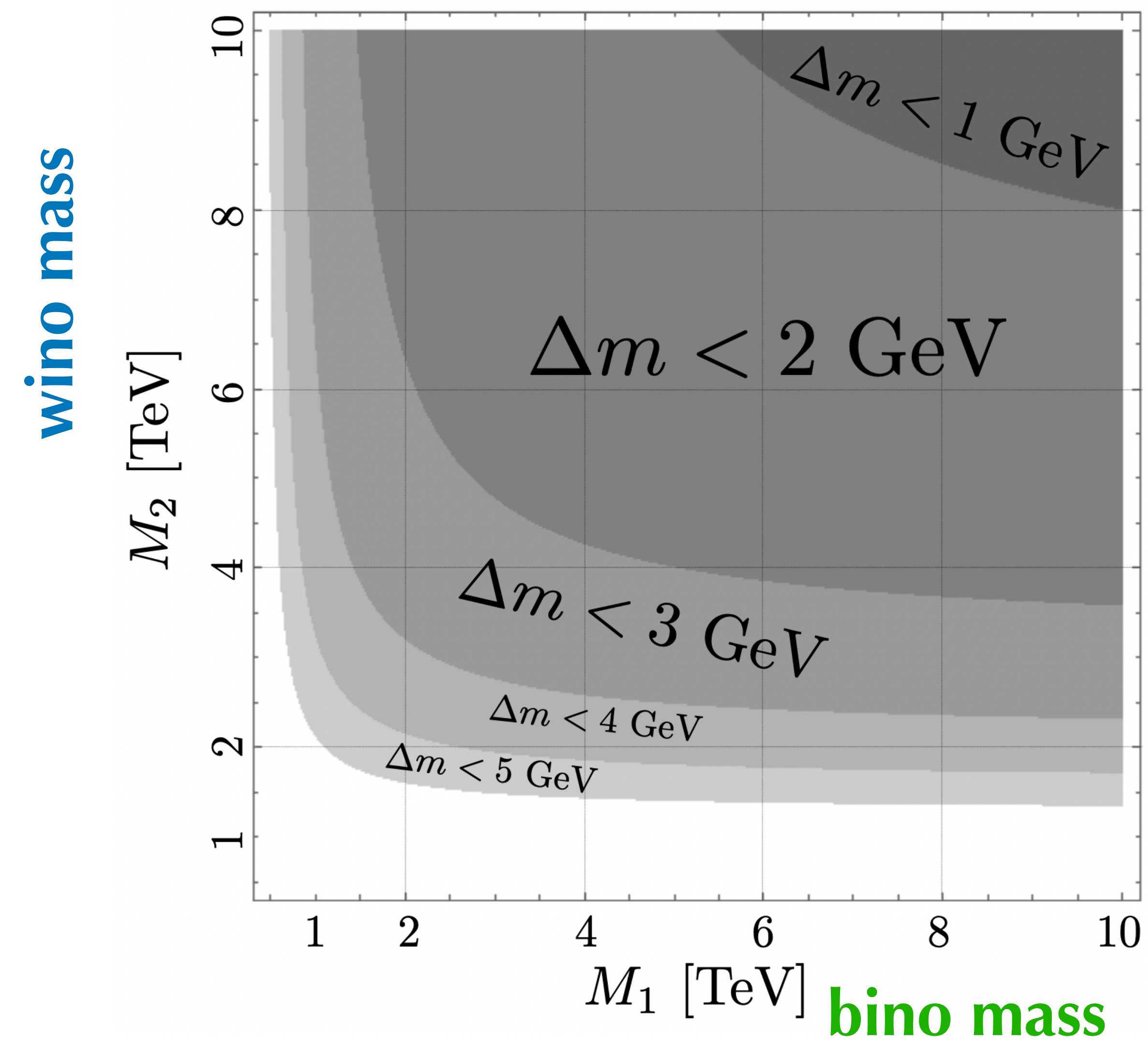




- Fake tracks are estimated by the fully-data driven estimation
  - Dedicated control region to enrich the fake → $p_T$ template measurement
  - Simultaneously fit to the data in the signal region with the signal template
- No significant deviation from the BG is seen.
- **Pure wino: ~700 GeV excluded with small model uncertainty.**

# Higgsino LSP

$$\Delta m \approx \frac{m_W^2}{\min(M_1, M_2)}$$



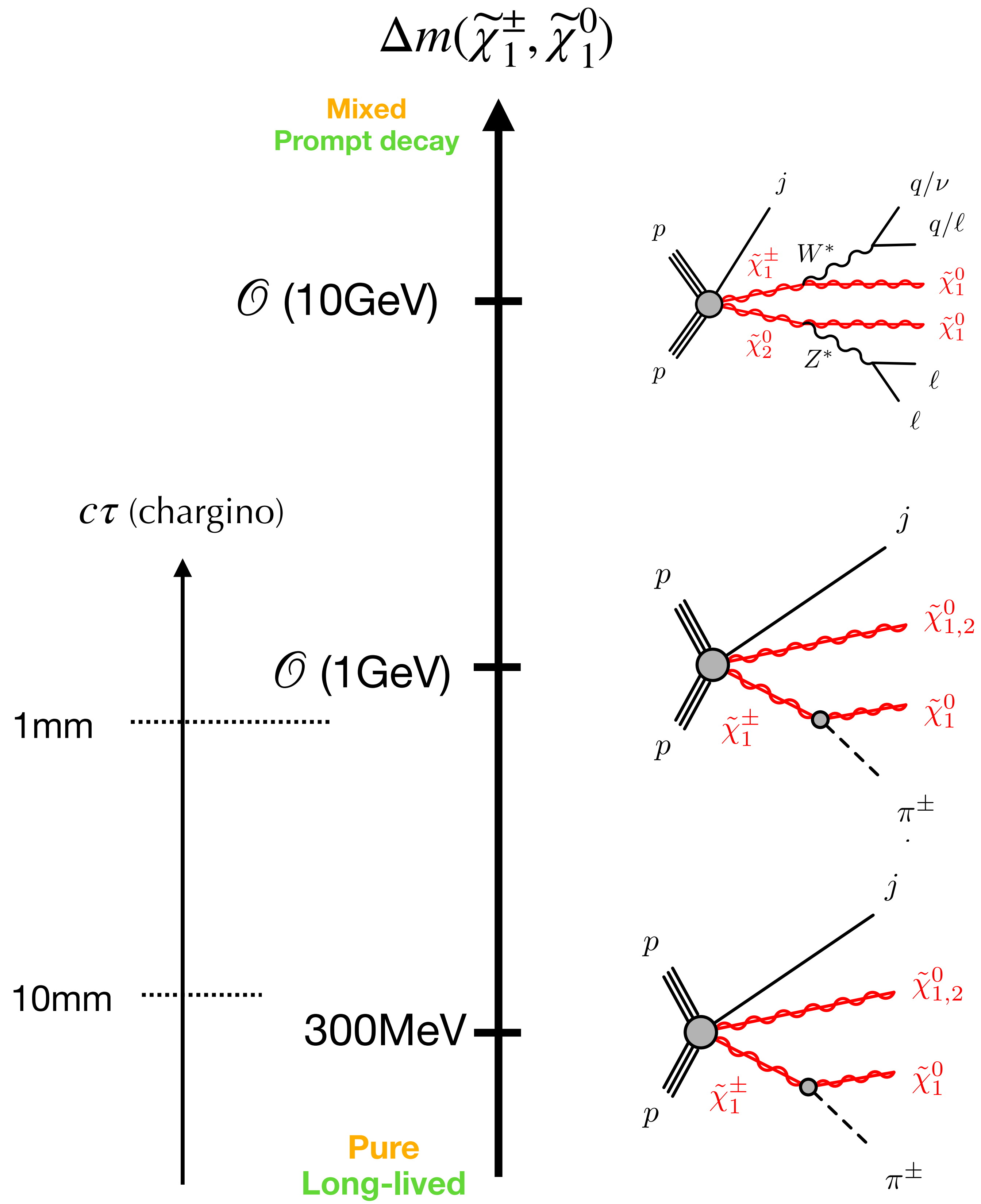




○ One charged + two neutral (the lighter one is LSP) in mass degenerate

○ The degeneracy is very sensitive to the small mixing with the bino/wino

**~300MeV (pure limit)** — **10GeV (when bino/wino is ~500GeV)**

# Higgsino LSP search




**Off-shell boson decays**

→ ISR jet + **soft leptons** + $E_T^{miss}$

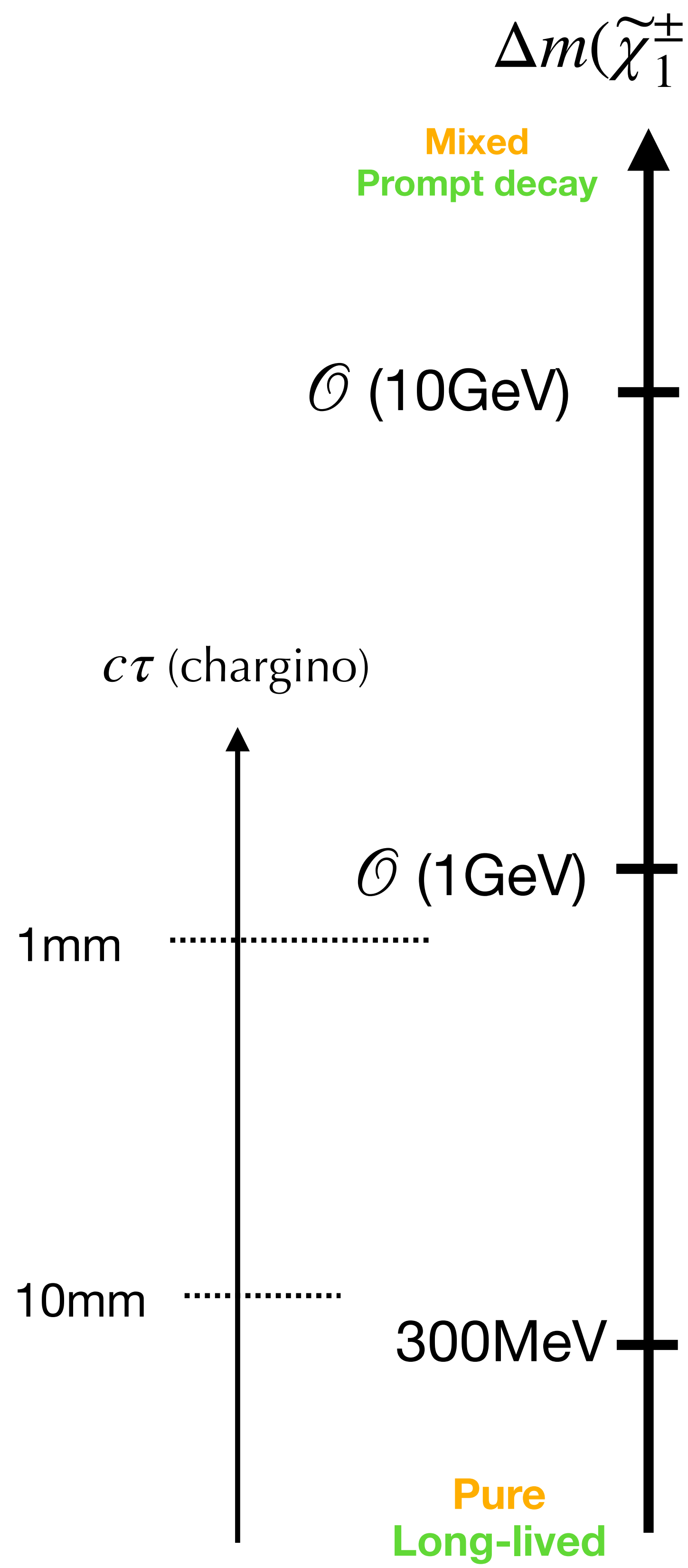
**Slightly long-lived chargino**

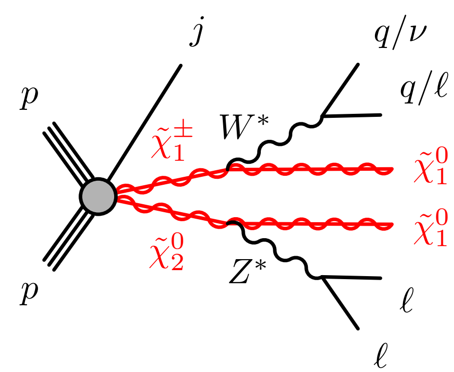
→ ISR jet + **soft *displaced* pion** + $E_T^{miss}$

**Long-lived chargino**

→ ISR jet + **disappearing track** + $E_T^{miss}$

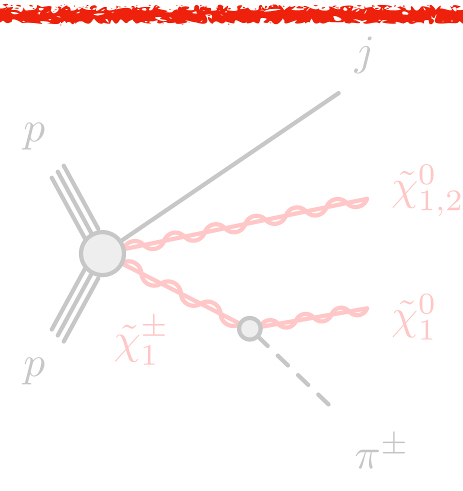
# Higgsino LSP search



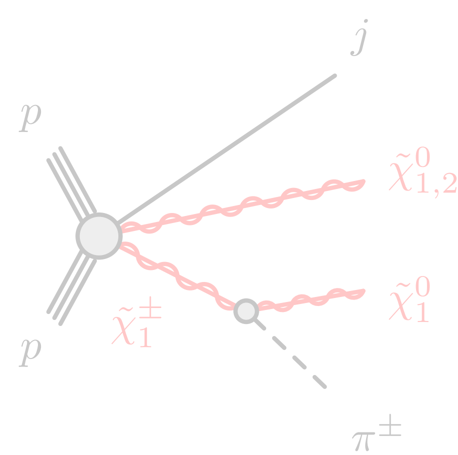

**Off-shell boson decays**

→ ISR jet + **soft leptons** + $E_T{}^{miss}$




**Slightly long-lived chargino**

→ ISR jet + **soft *displaced* pion** + $E_T{}^{miss}$




**Long-lived chargino**

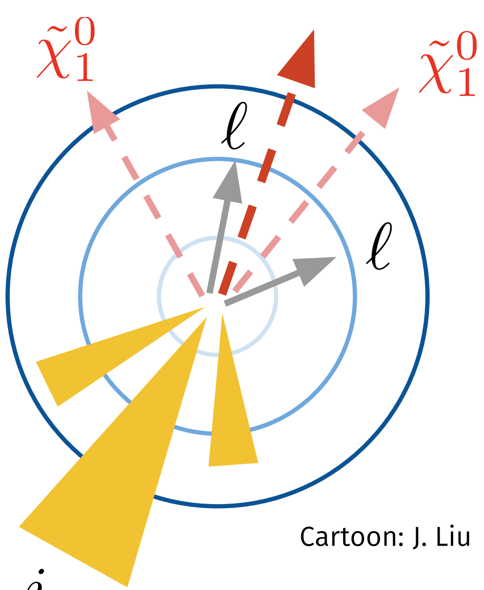
→ ISR jet + **disappearing track** + $E_T{}^{miss}$

# Higgsino LSP search (1): Soft leptons

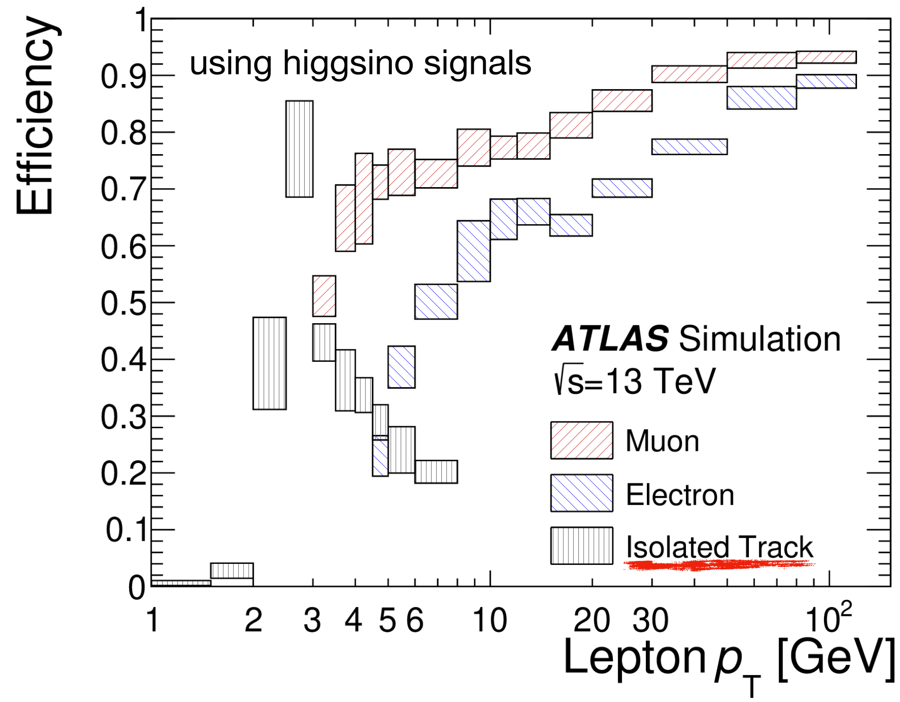
ATLAS soft 2L: 1911.12606
ATLAS 3L: 2106.01676
CMS soft leptons: 2111.06296
CMS multi-lepton: 2106.14246

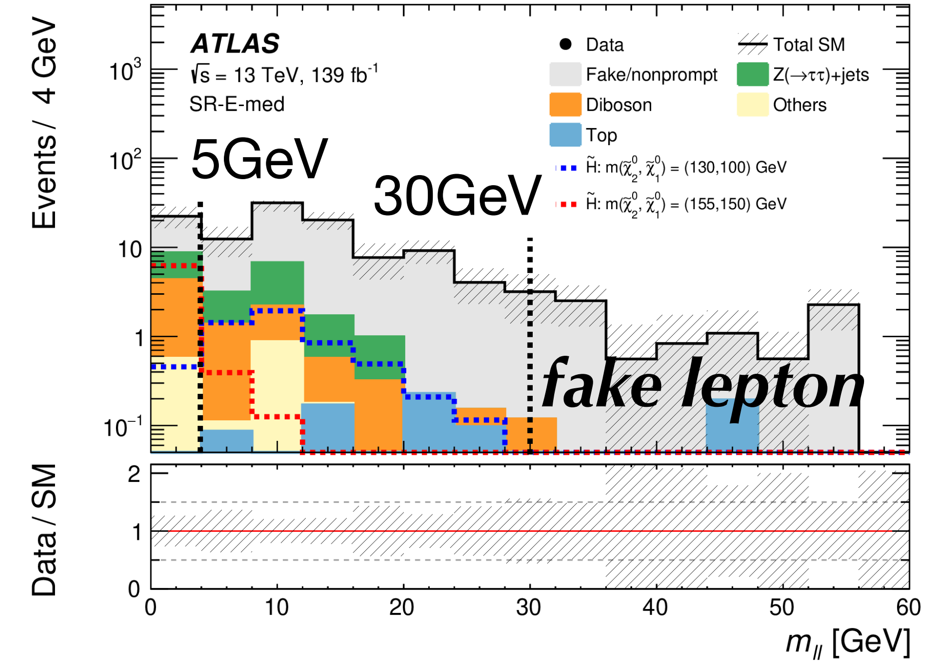
e.g. ATLAS search

**Signatures: 2 soft leptons + MET + ISR**




Cartoon: J. Liu



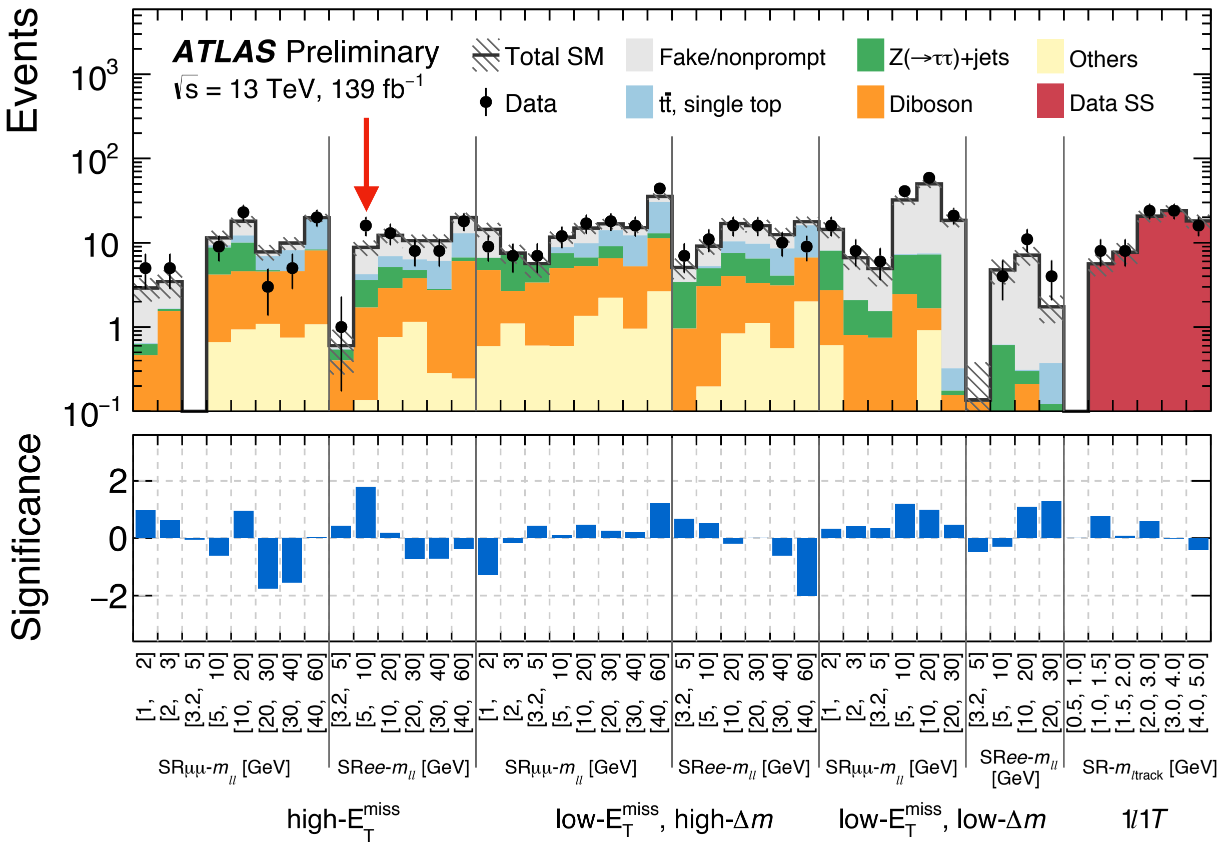

- **Electron: $p_T$ > 4.5 GeV / 5 GeV @ATLAS/CMS**
- **Muon: $p_T$ > 3 GeV / 3.5 GeV @ATLAS/CMS**
- **Enormous challenge in rejecting & estimating the *fake lepton* contribution**

  ML-based isolation, data-driven estimation etc.
- Exploiting the kinematic end-point in the di-lepton invariant mass: $m_{\ell\ell}$ < signal $\Delta m$

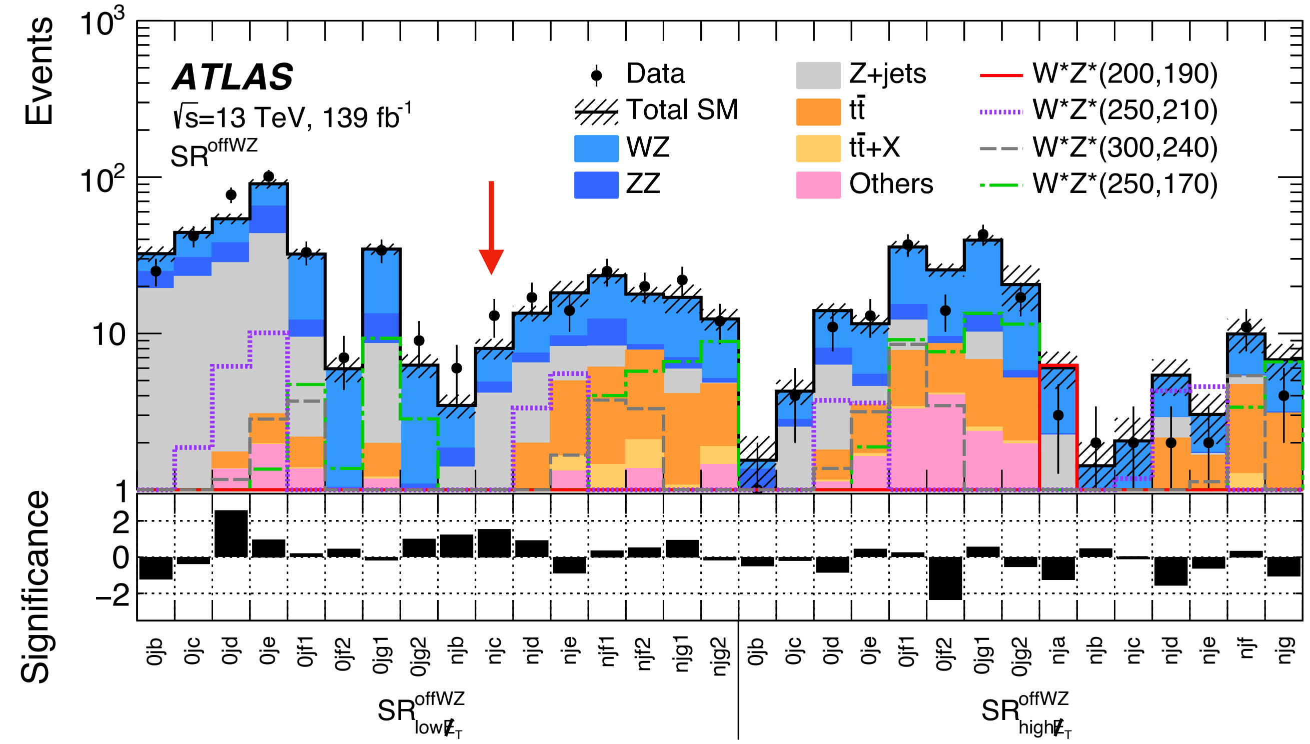
# Higgsino LSP search (1): Soft leptons

ATLAS soft 2L: 1911.12606
ATLAS 3L: 2106.01676
CMS soft leptons: 2111.06296
CMS multi-lepton: 2106.14246

## ATLAS 2-lepton signal regions

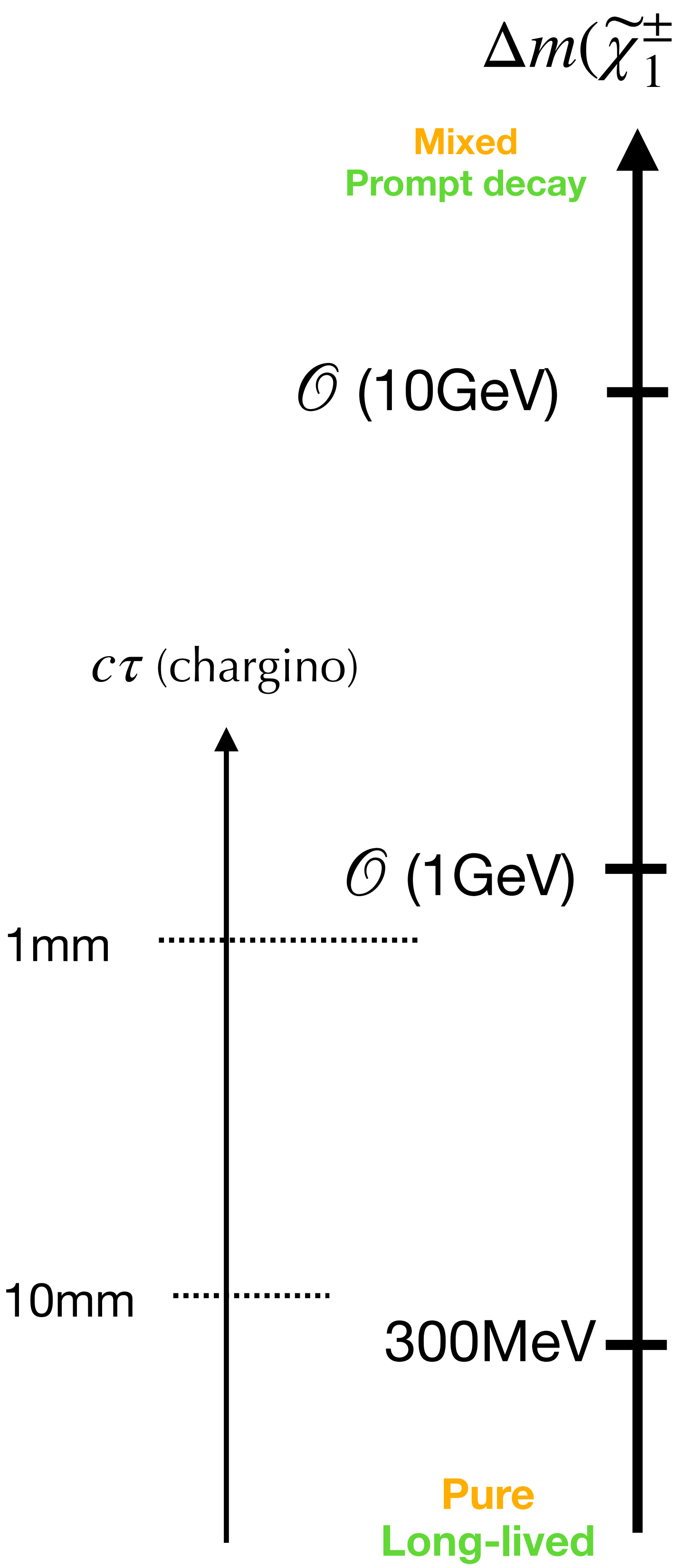


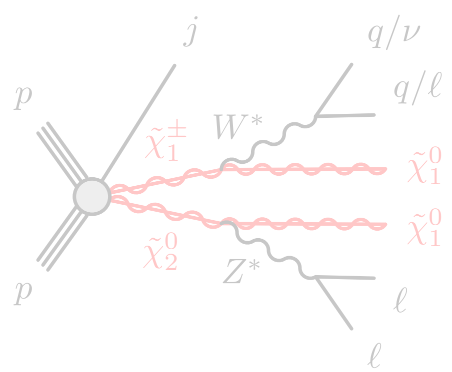

## ATLAS 3-lepton signal regions




- **Mild but coherent excess (~2σ) seen in both 2L & 3L channels + both ATLAS & CMS**
  - Explained by the same signal hypothesis (Δm=10-20GeV) arXiv: 2404.12423
  - Follow-up using the Run3 data ongoing
- **Search sensitivity achieved down to Δm~2GeV**

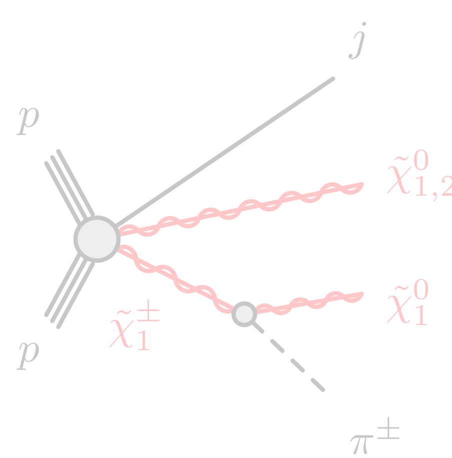
# Higgsino LSP search



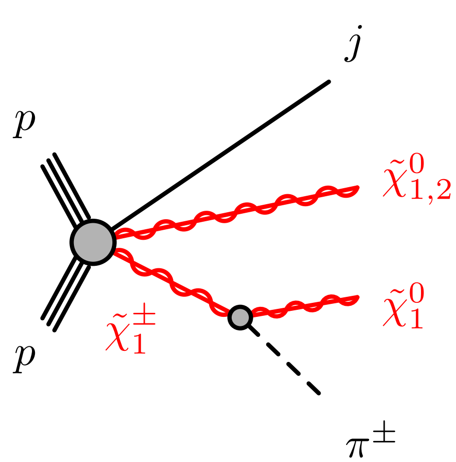

**Off-shell boson decays**

→ ISR jet + **soft leptons** + $E_T^{miss}$




**Slightly long-lived chargino**

→ ISR jet + **soft *displaced* pion** + $E_T^{miss}$

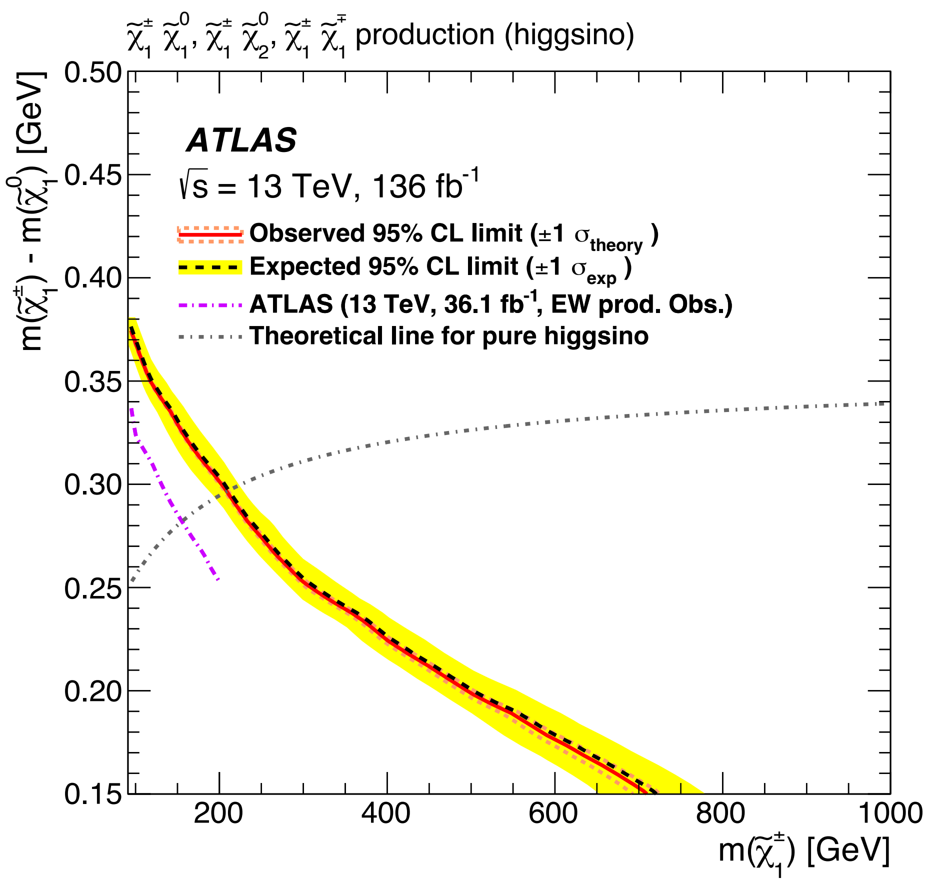


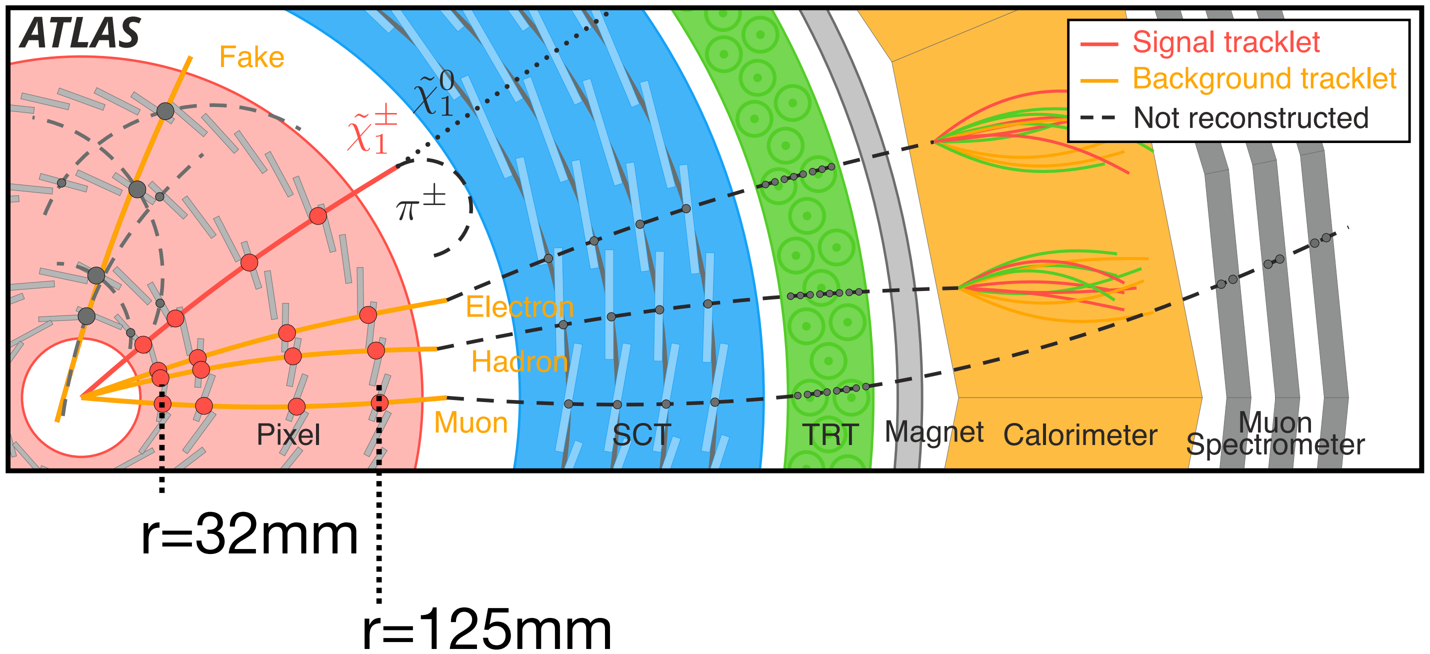

**Long-lived chargino**

→ ISR jet + **disappearing track** + $E_T^{miss}$

# Higgsino LSP search (2): Disappearing track

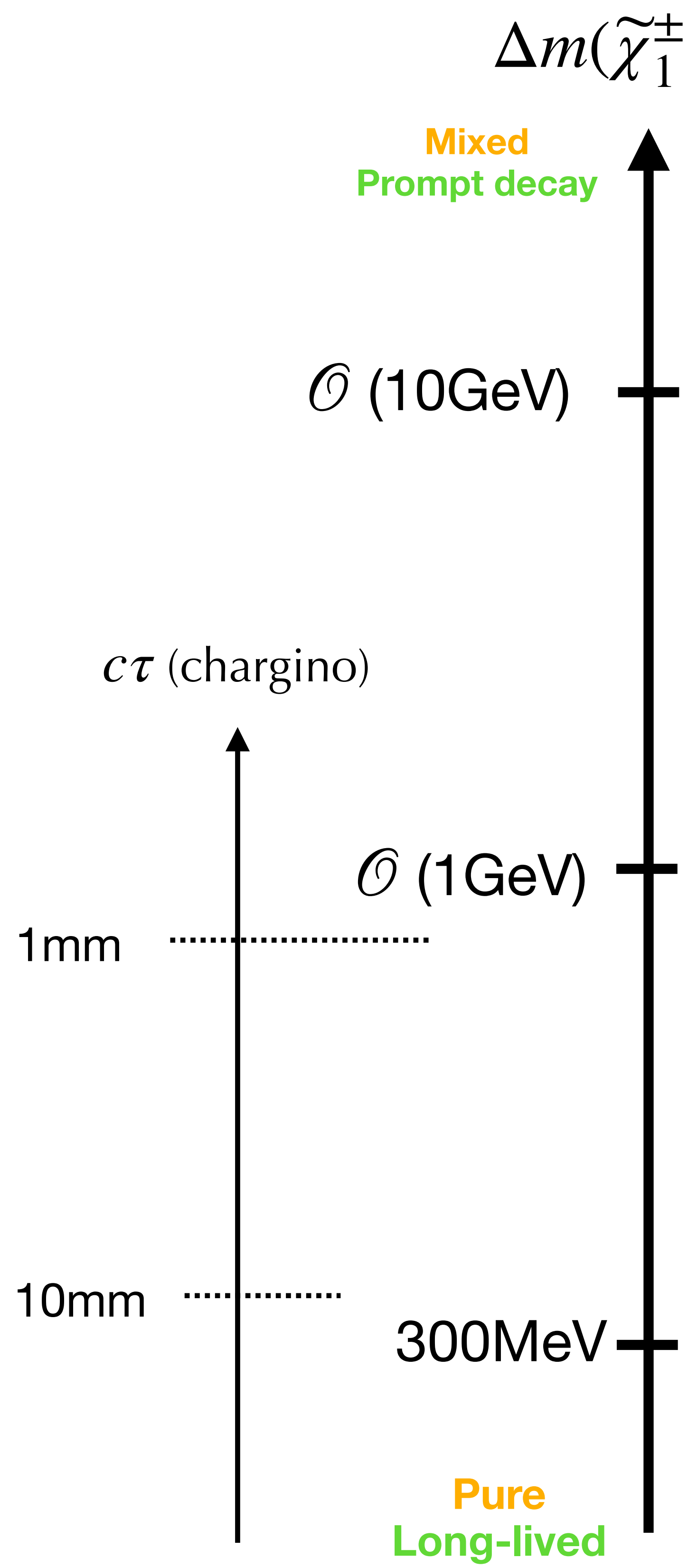
ATLAS: 2201.02472
CMS: 2004.05153

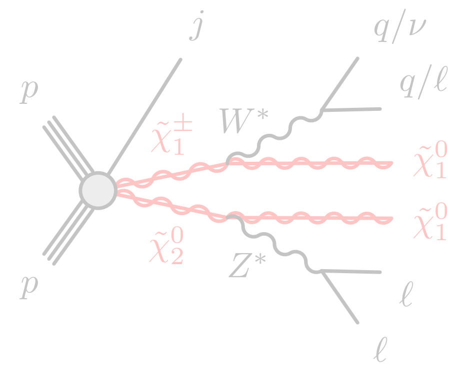



- Same analysis as the wino search
- ~210GeV excluded (both in ATLAS and CMS)
- Tracklet requires >=4 hits in the inner detector (r>=125mm)
  - **Higgsinos average decay length ~ 11mm → challenging selection efficiency**
  - Possibility of shorter tracklet reconstruction is being sought

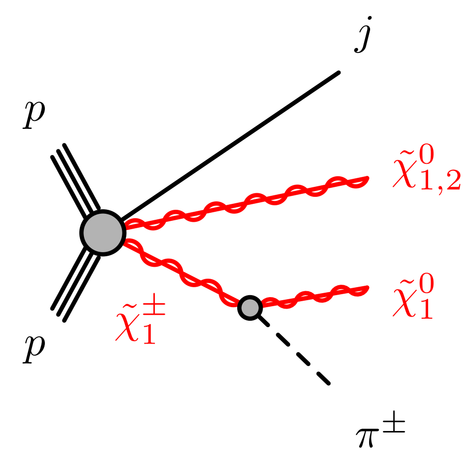
# Higgsino LSP search



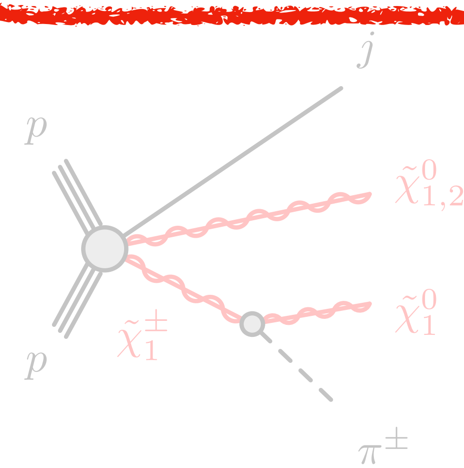

**Off-shell boson decays**

→ ISR jet + **soft leptons** + $E_T{}^{miss}$




**Slightly long-lived chargino**

→ ISR jet + ***soft displaced* pion** + $E_T{}^{miss}$

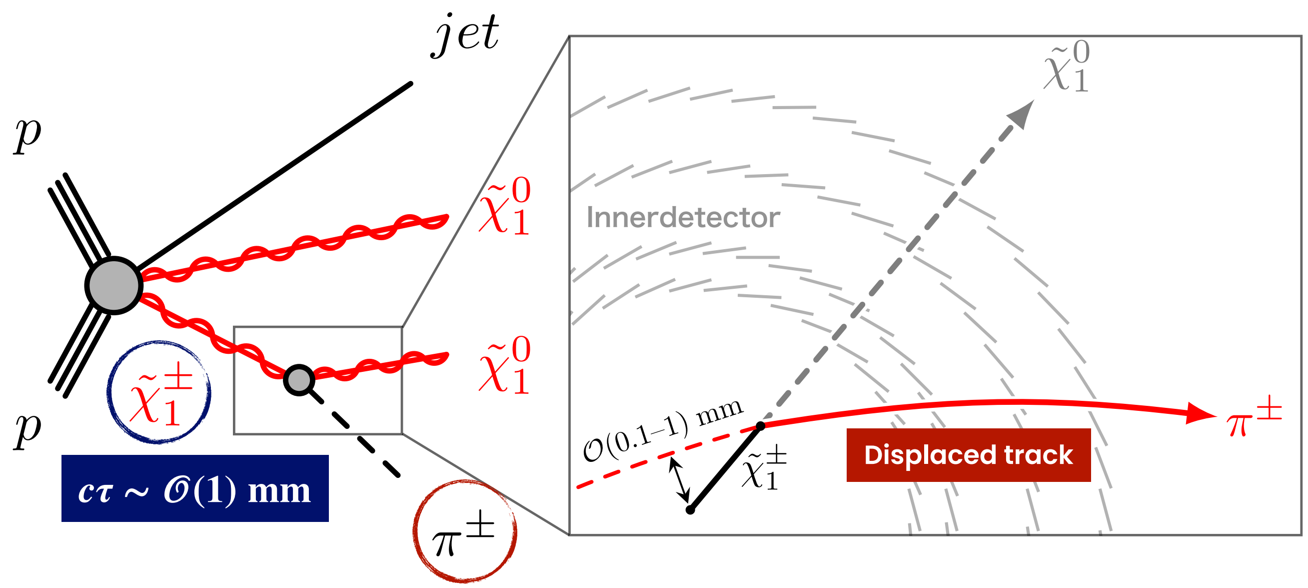


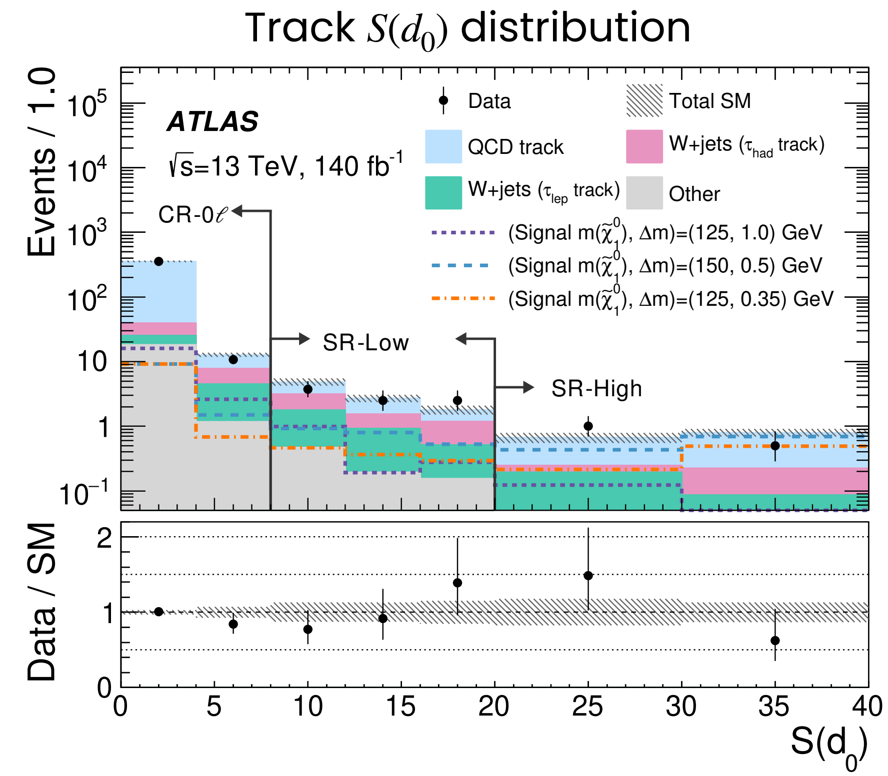

**Long-lived chargino**

→ ISR jet + **disappearing track** + $E_T{}^{miss}$

# Higgsino LSP search (3): Soft *displaced* track

ATLAS: 2401.14046




**Slightly larger Δm = 0.5-1GeV**

- Shorter higgsino lifetime: cτ=0.1-1mm
- But higher pion $p_T$ ~ 2-5GeV → pion is now visible

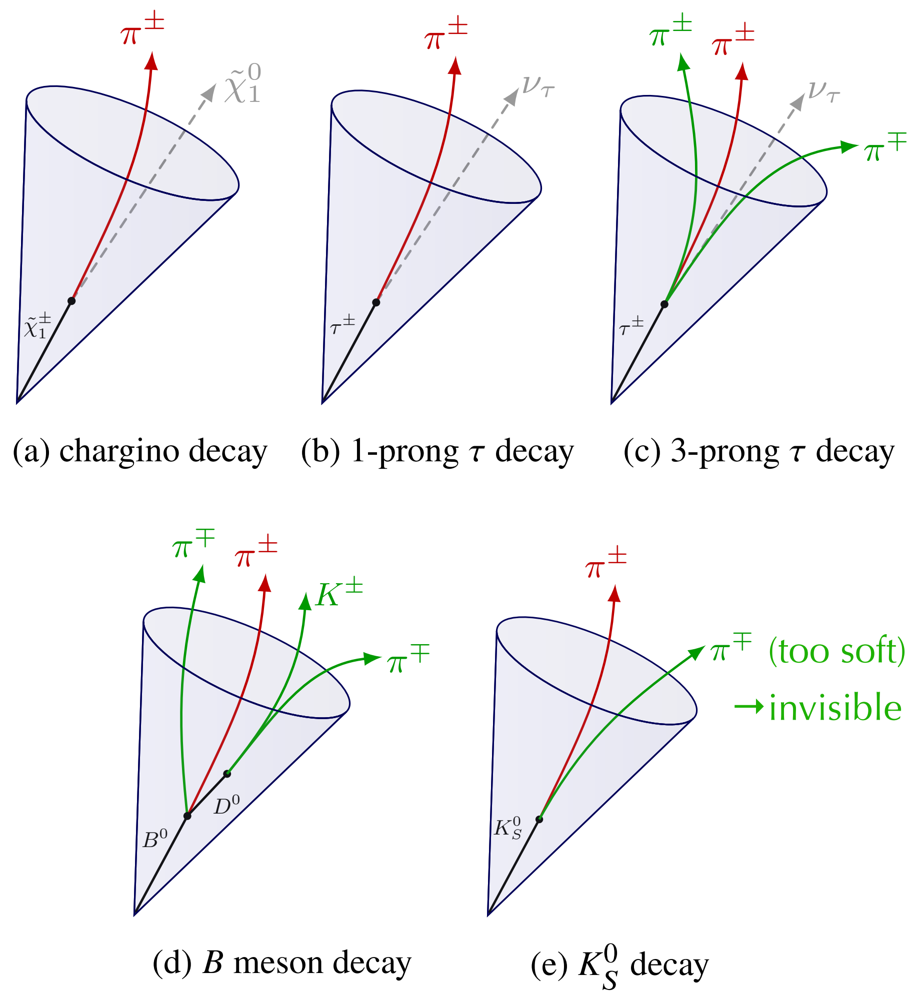
**Slight displacement from the primary vertex reflecting the Higgsinos lifetime**

- Impact parameter resolution @ATLAS: 0.01-0.1mm → distinct signature

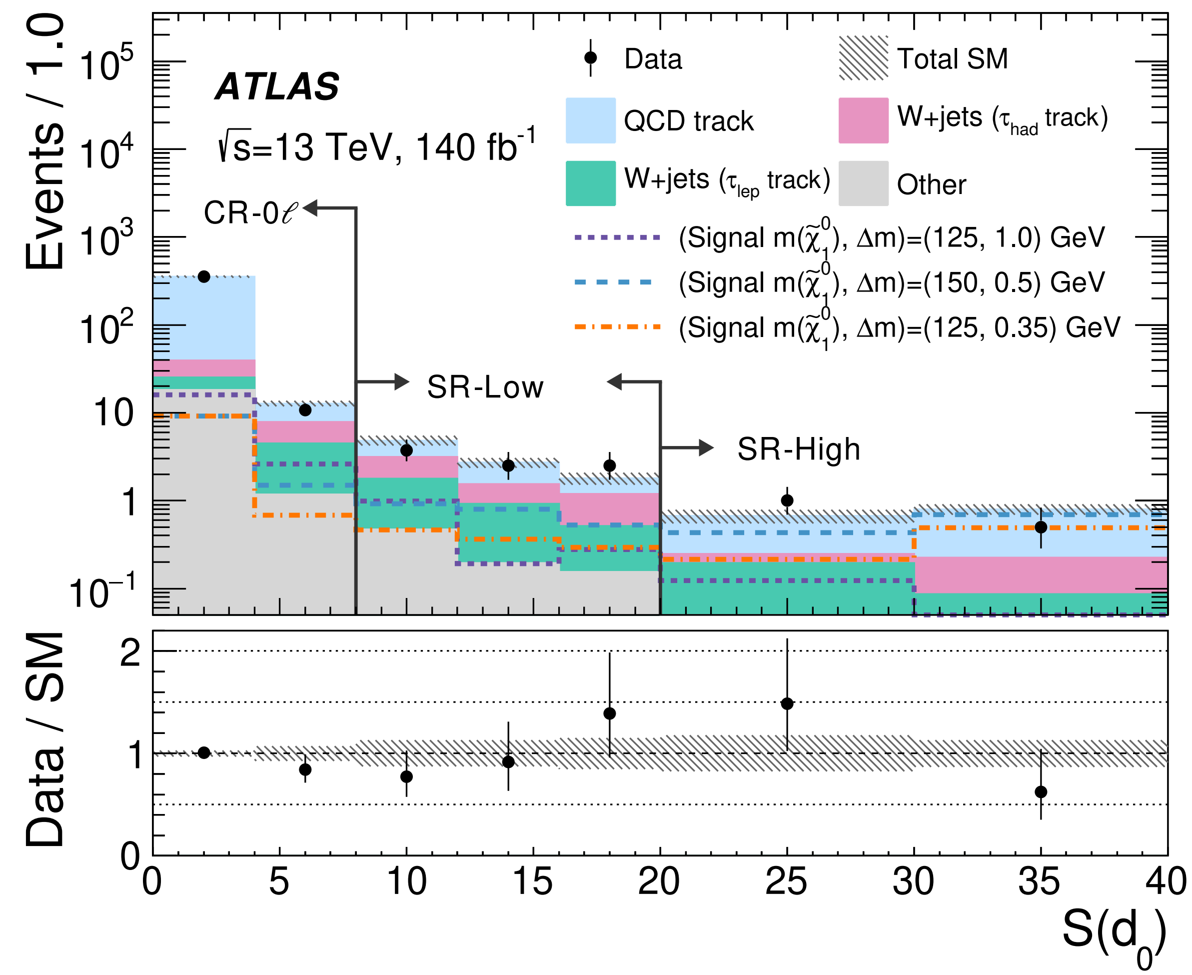
**Event selection**

- ISR, large $E_T^{miss}$ (>600GeV), $\Delta\phi(E_T^{miss}$, soft track$)<0.4$  etc.

# Higgsino LSP search (3): Soft *displaced* track




Track $S(d_0)$ distribution



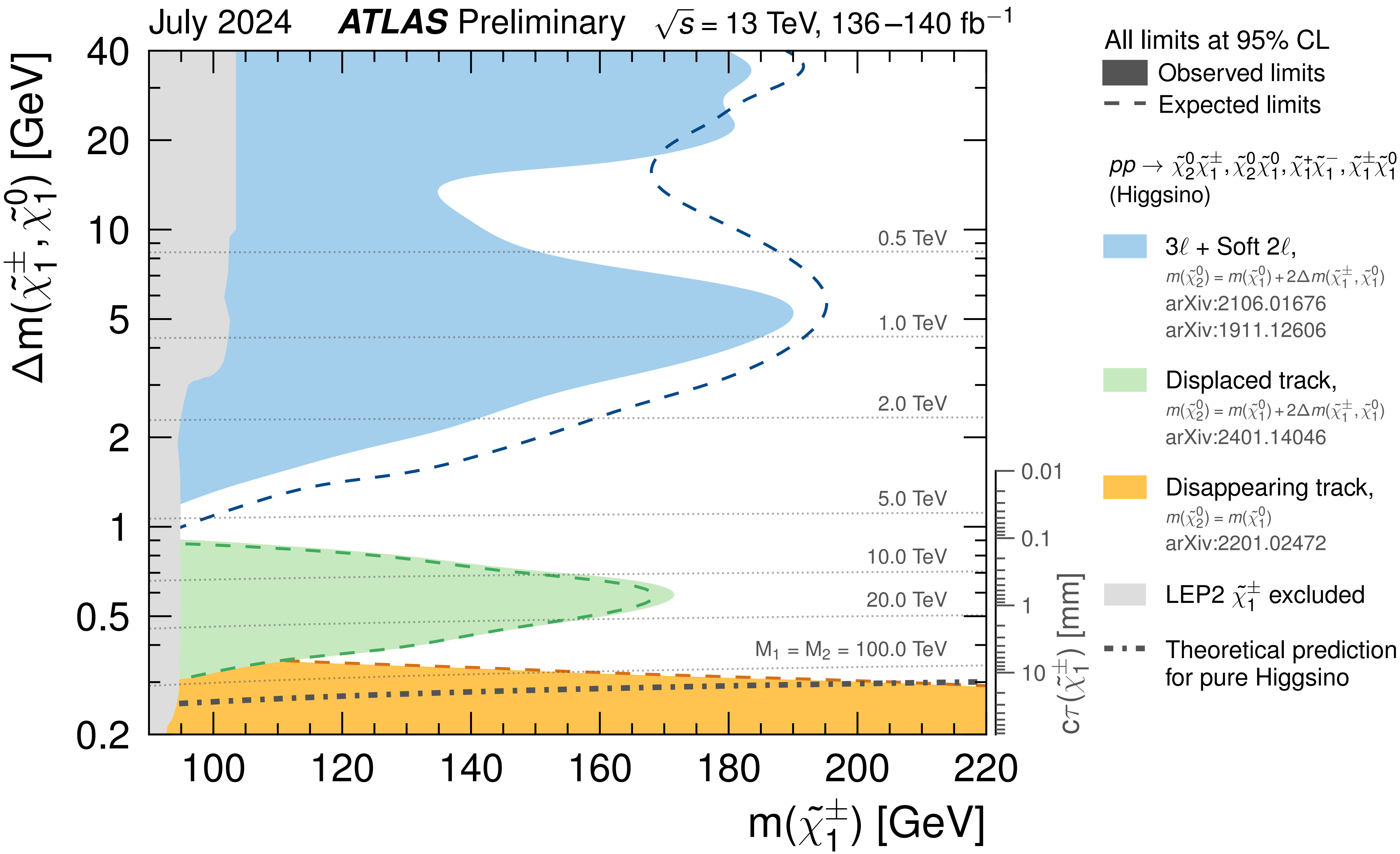

## Main BG

- Tau decays
- Long-lived hadrons from pileup jets, fractured protons

## No significant excess found in the signal region

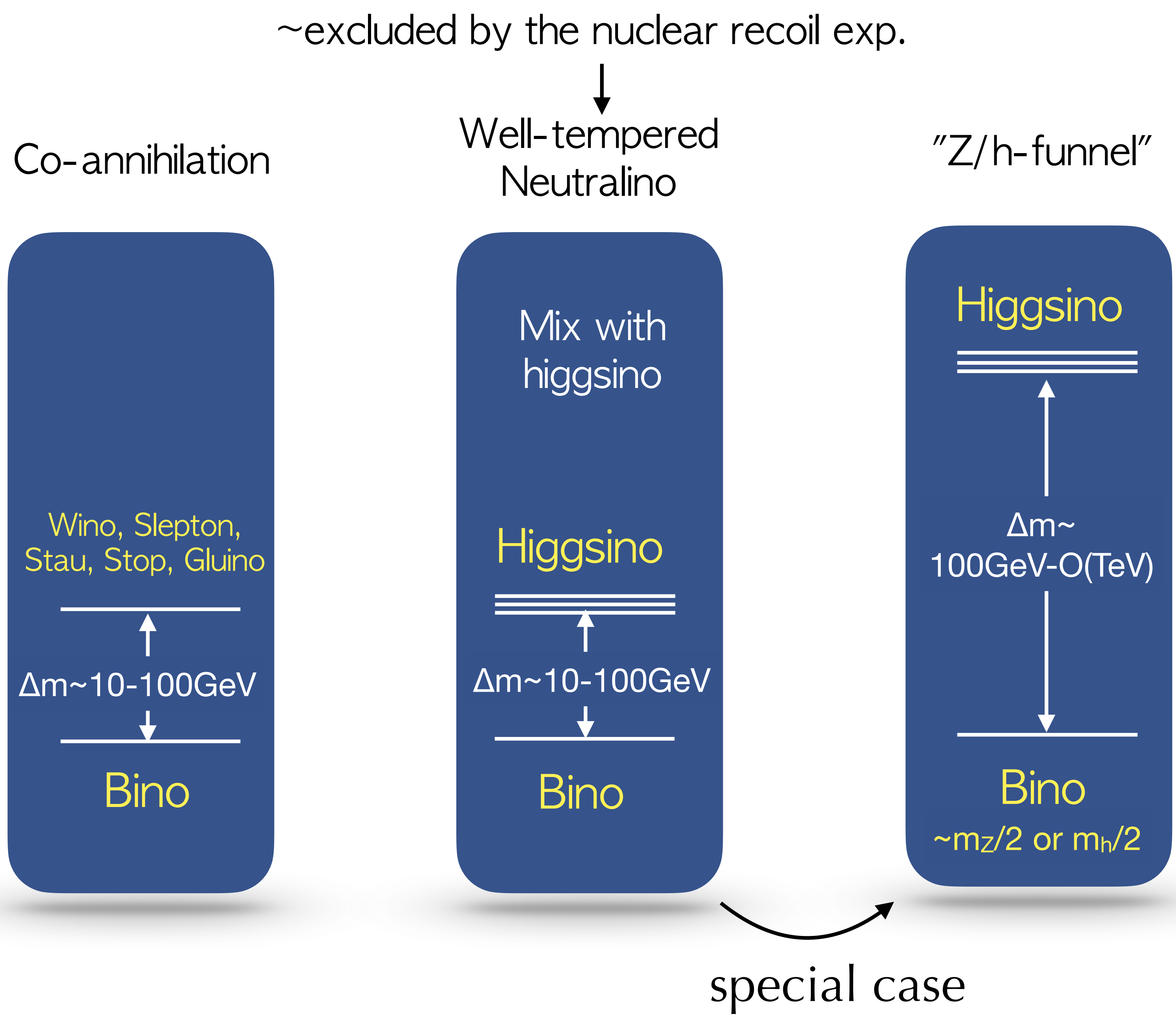
- But first ever possible to set the limit in this Δm region since LEP

# Higgsino LSP search: Status @Collider



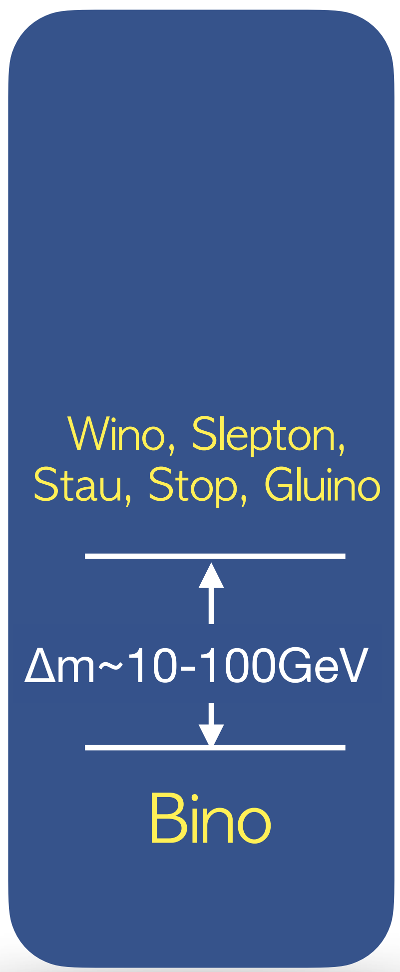

- Now that all Δm ranges are finally covered ✔
- Will try push the reach towards heavier side

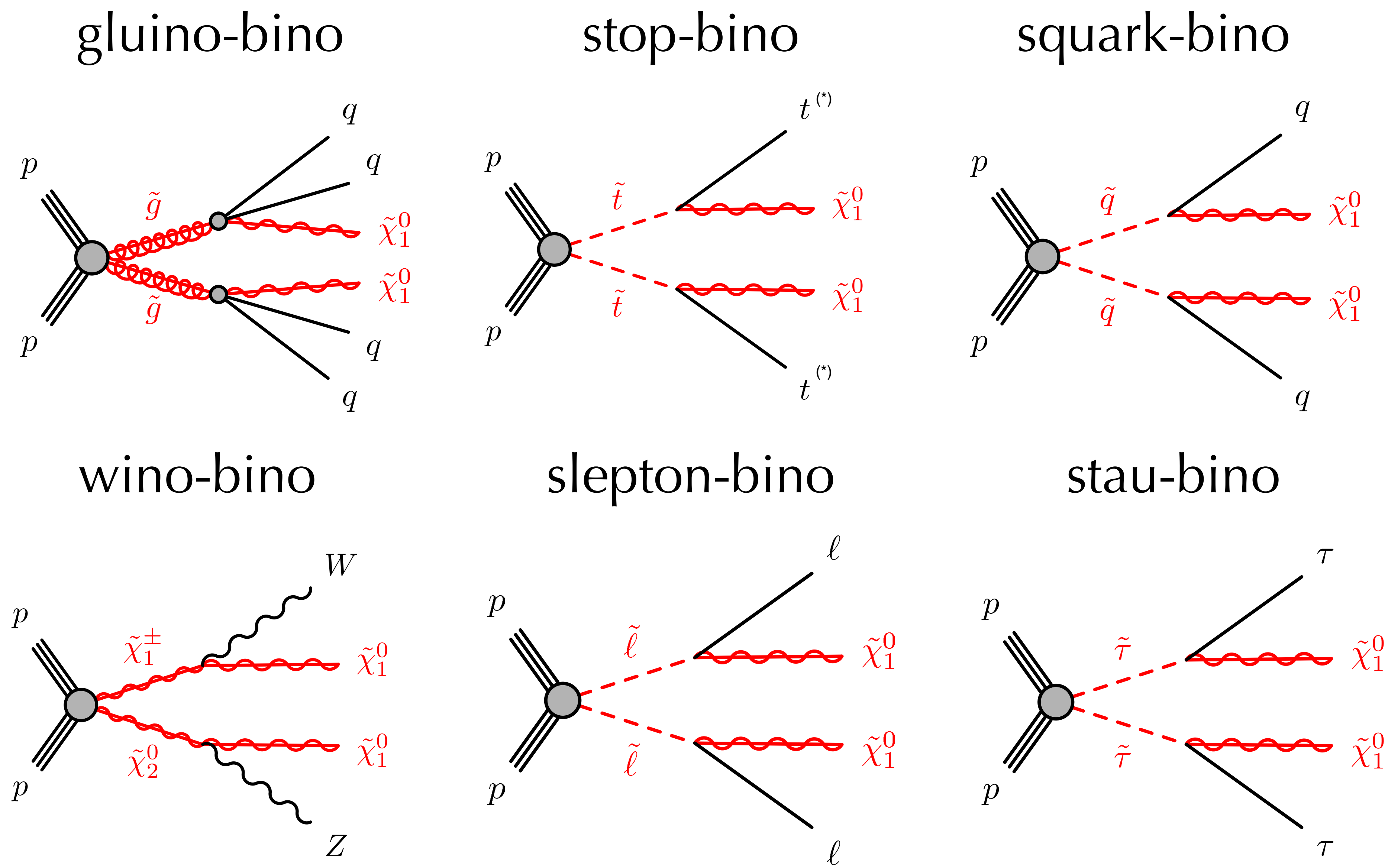
# Bino LSP




- **Bino does not have bino-SM-SM vertices** (only bino-SUSY-SM vertices).
- Need some mechanisms to get non-zero annihilation cross-section.

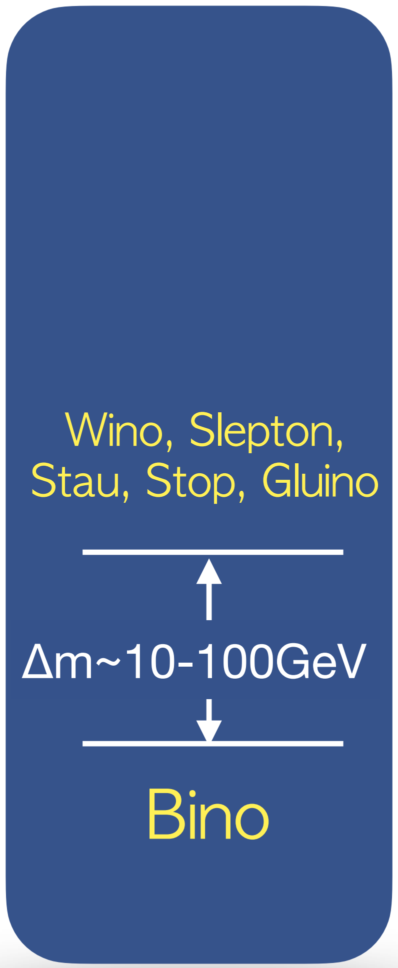
# Bino LSP - "Co-annihilation"



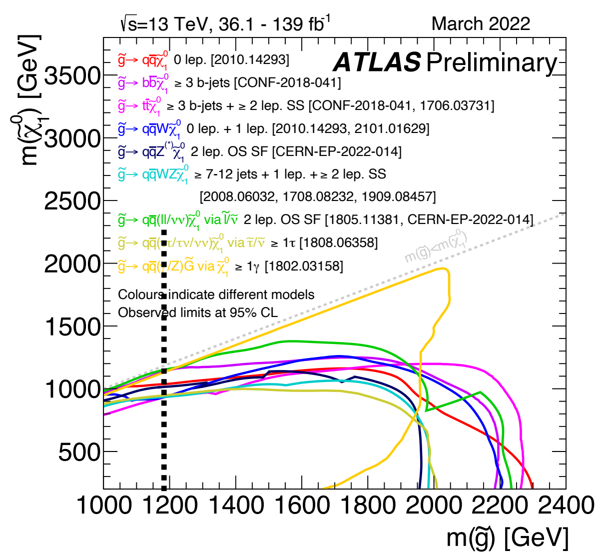




- **Moderately low-pT final state particle (leptons, jets, taus, $E_T^{miss}$)**
- Challenging BG rejection since Δm~100GeV signals have similar kinematics as SM processes ($p_T$ ~ EW scale).

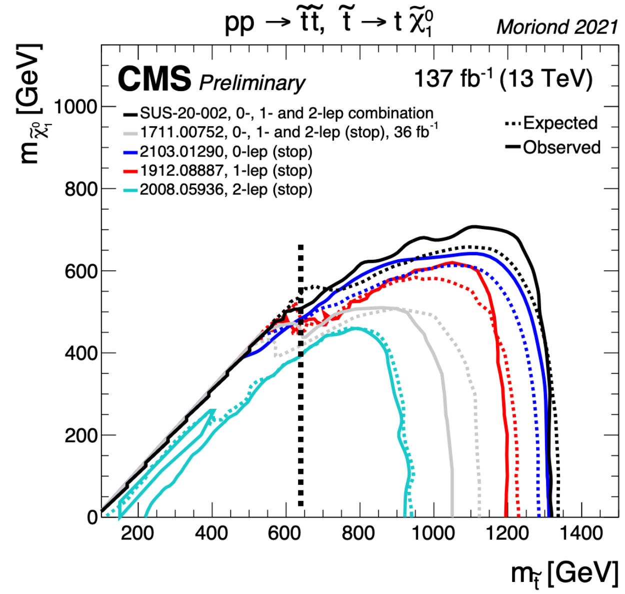
# Bino LSP - "Co-annihilation"



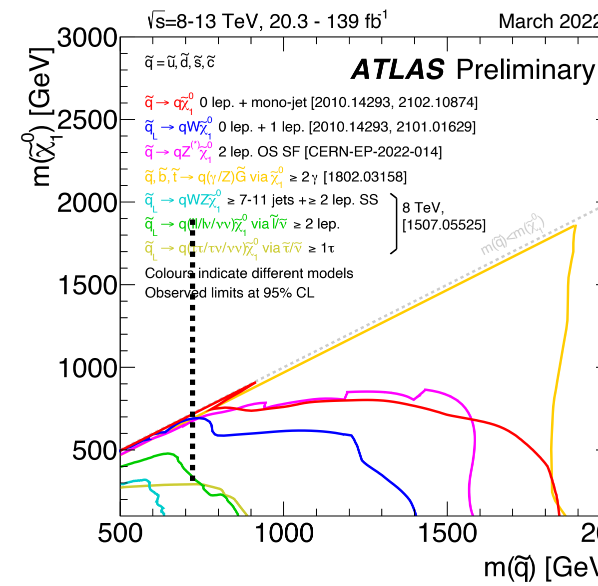

gluino-bino



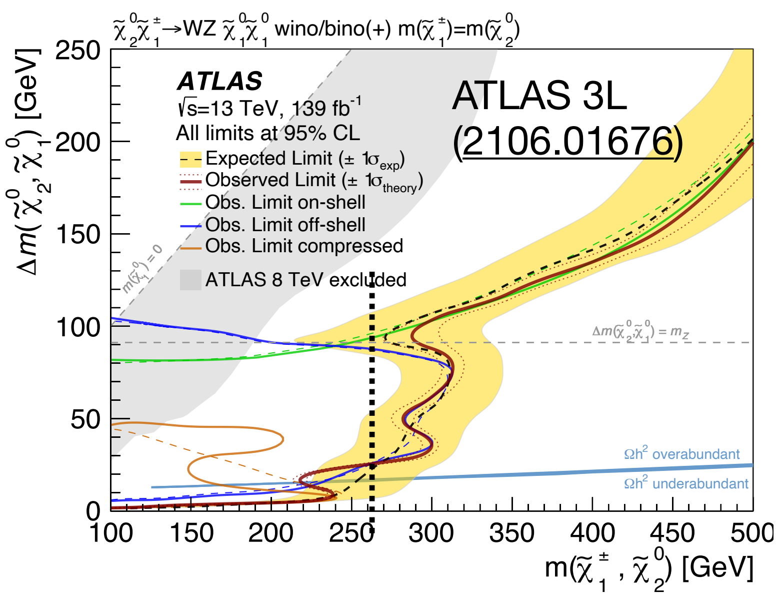

stop-bino



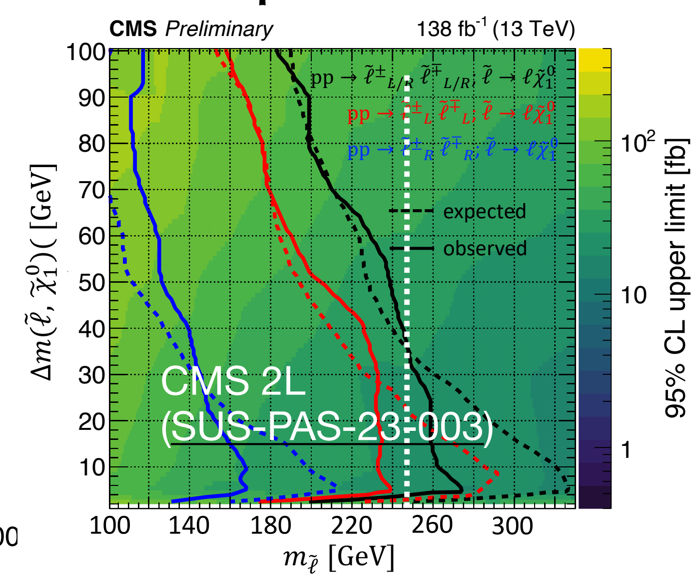

squark-bino



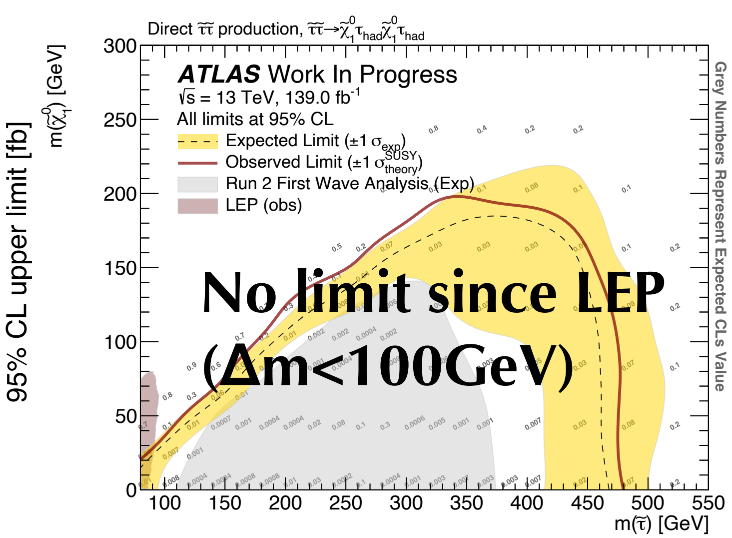

wino-bino




slepton-bino

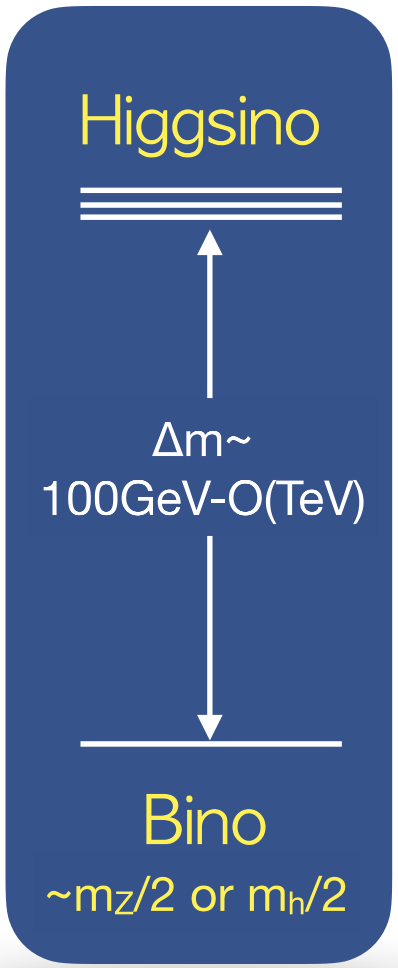


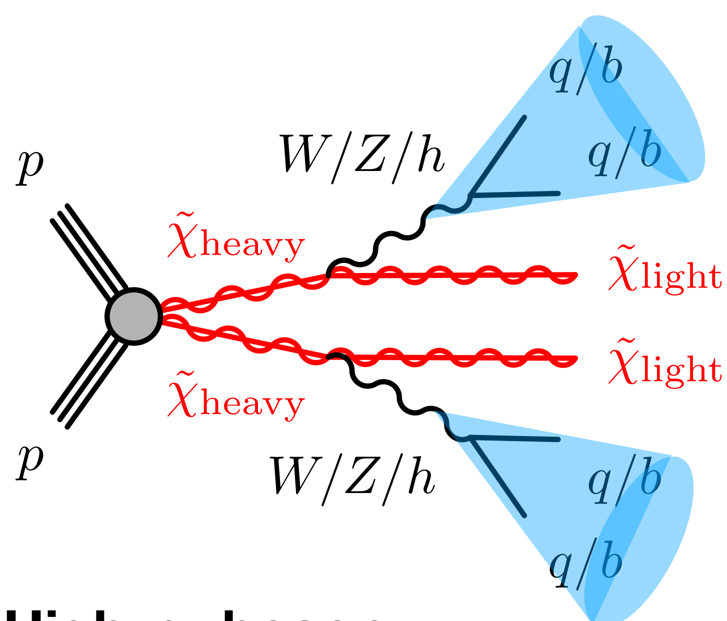

stau-bino




- **Gluino, stop, squark: relatively well-covered** Exclusion 600GeV-1TeV
- **Wino, slepton, stau: very limited constraints yet** Exclusion 90-300 GeV

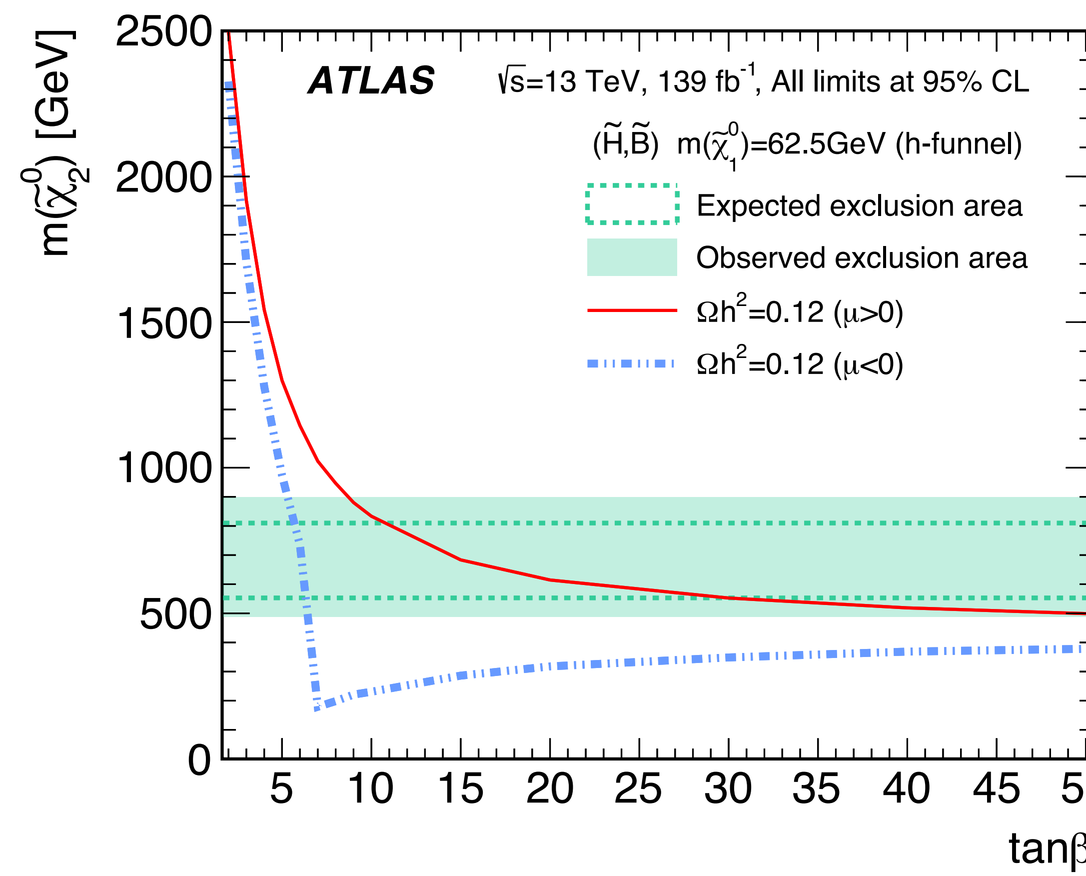
# Bino LSP - "Z/h-funnel"




**High-$p_T$ boson**
→ collimated two jets
→ seen as a single "fat jet"

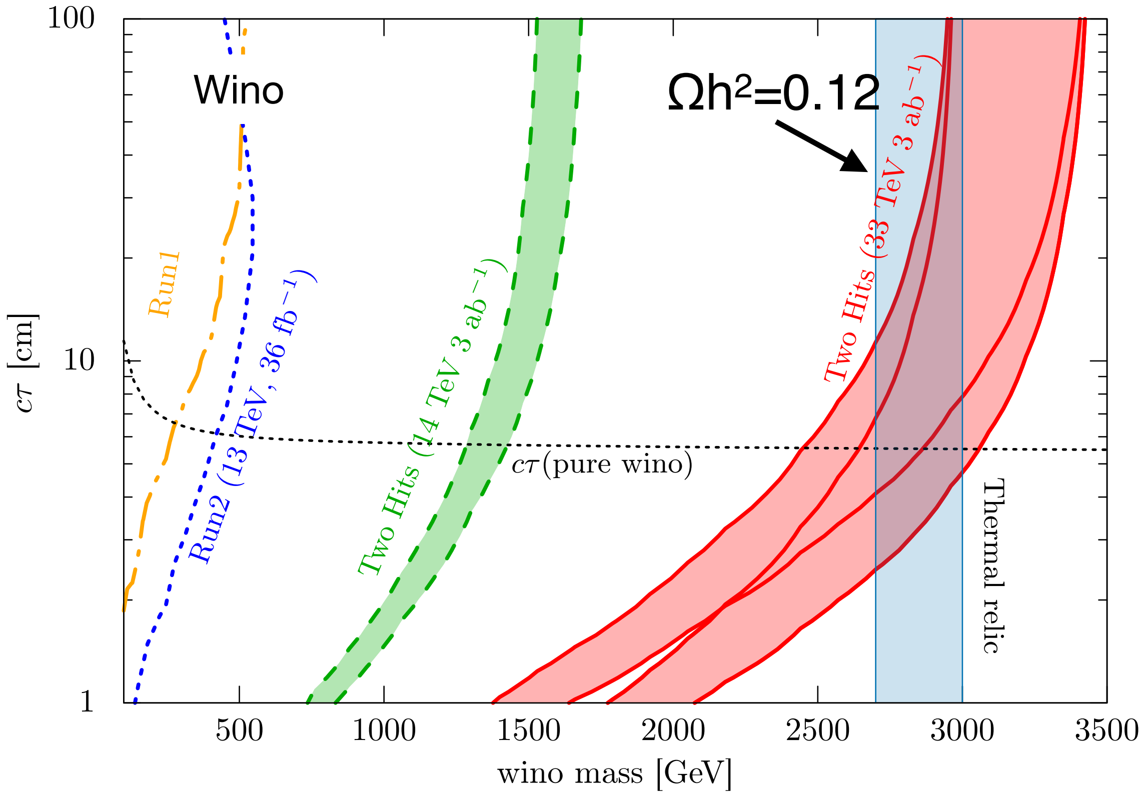
ATLAS all-had arXiv: 2108.07586



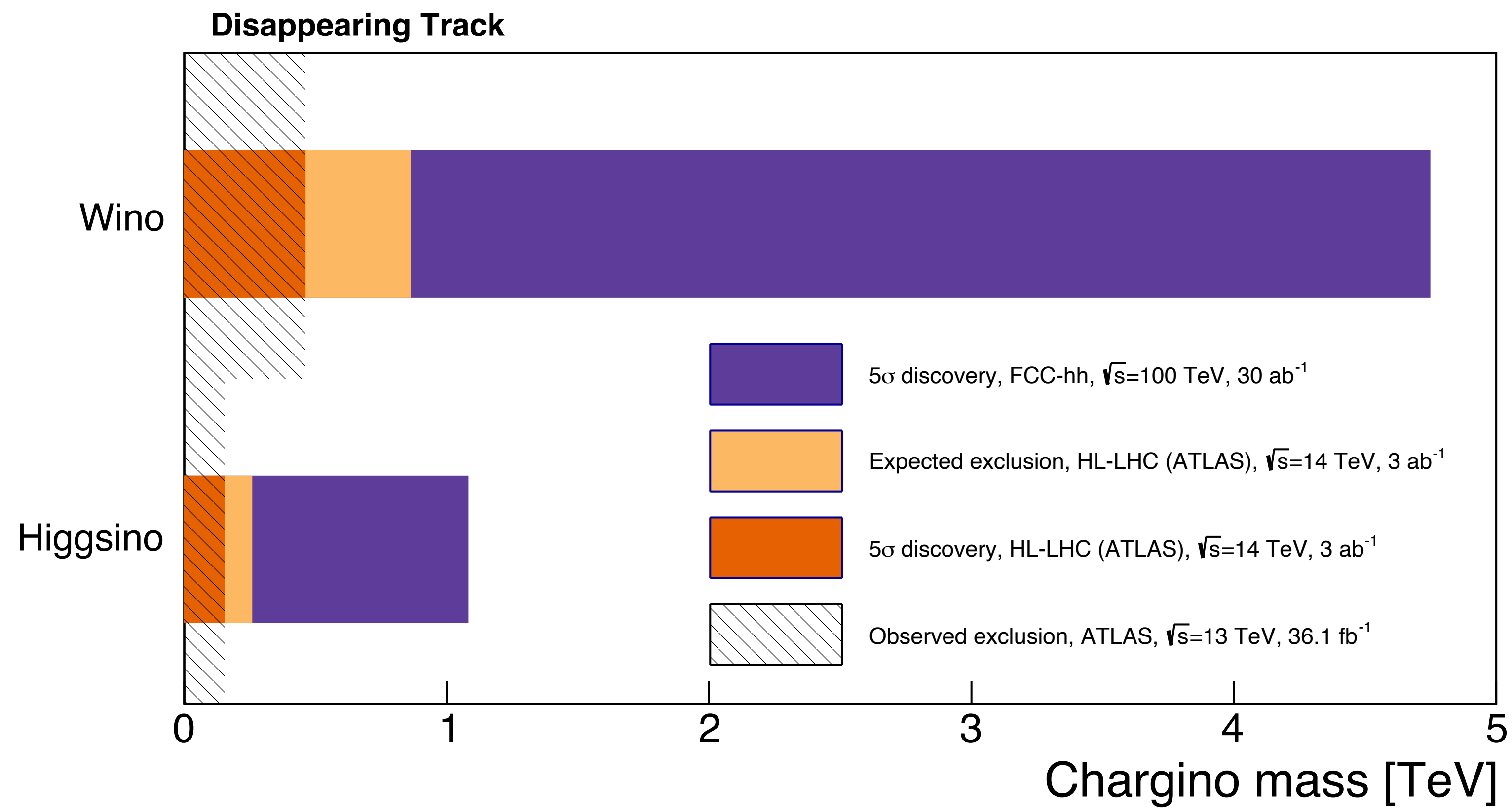

- Bino LSP acquires some Higgsino component to annihilate when they are close in mass
- Large Δm is exceptionally allowed when $m_{Bino} \sim m_Z/2$ or $m_{higgs}/2$ (resonant annihilation)
  Only need very tiny higgsino admixture to achieve the correct annihilation xsec.
- Hadronic analysis with high-$p_T$ boson jets addresses the best sensitivity
- **tanβ>7 has been excluded where typically the nuclear recoil exp. struggles.**

# Long future projection: Wino LSP

**HE-LHC projections** Fukuda et al. (1703.09675)




**FCC-hh projections** Saito et al. (1901.02987)

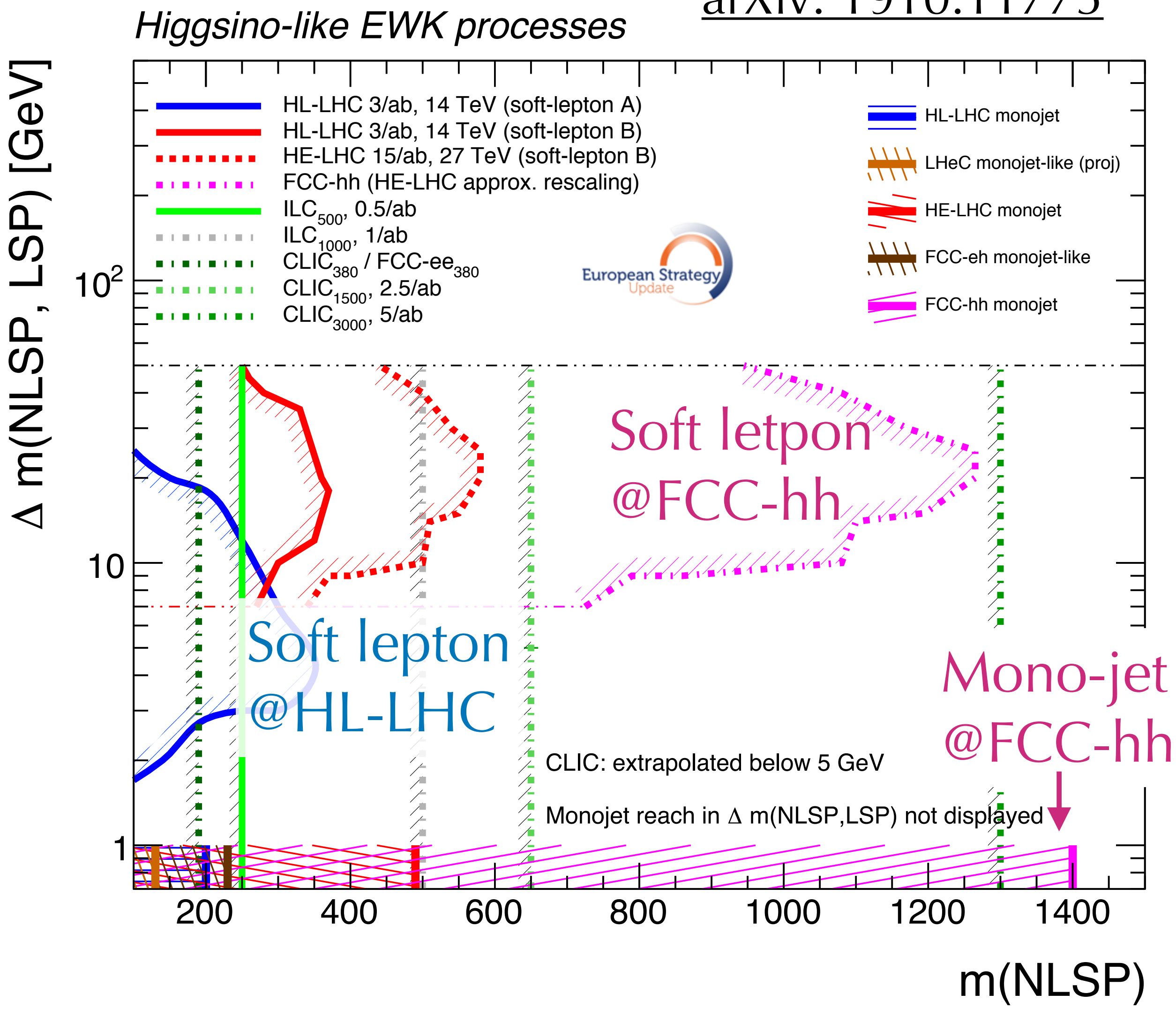



- Can possibly reach the 3TeV wino with HE-LHC / FCC-hh but generally on the verge
- Sensitivity strongly depends on the inner detector geometry, track reconstruction and pileup

# Long future projection: Higgsino LSP

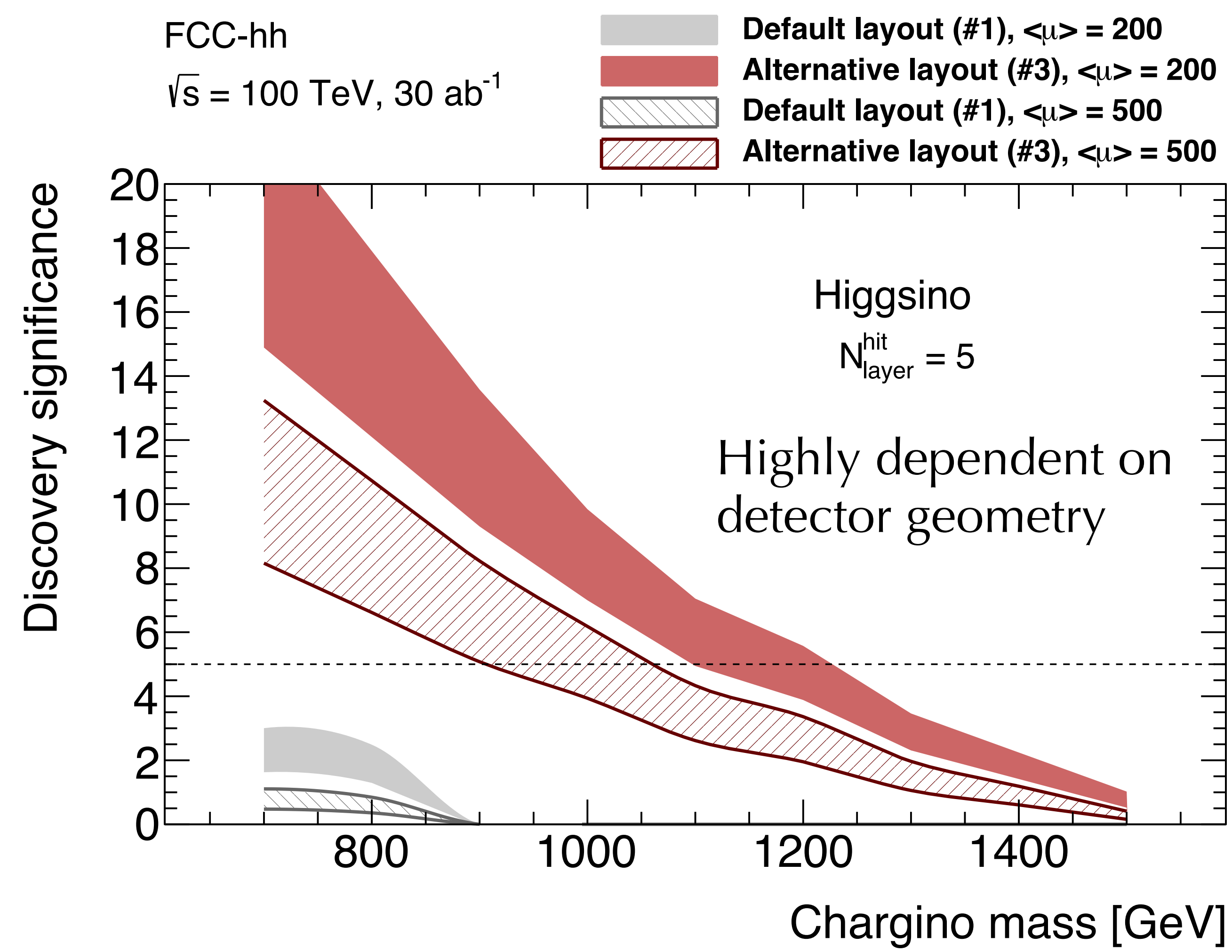
## Soft lepton / mono-jet

European Strategy
arXiv: 1910.11775




## Disappearing track @FCC-hh

arXiv: 1901.02987

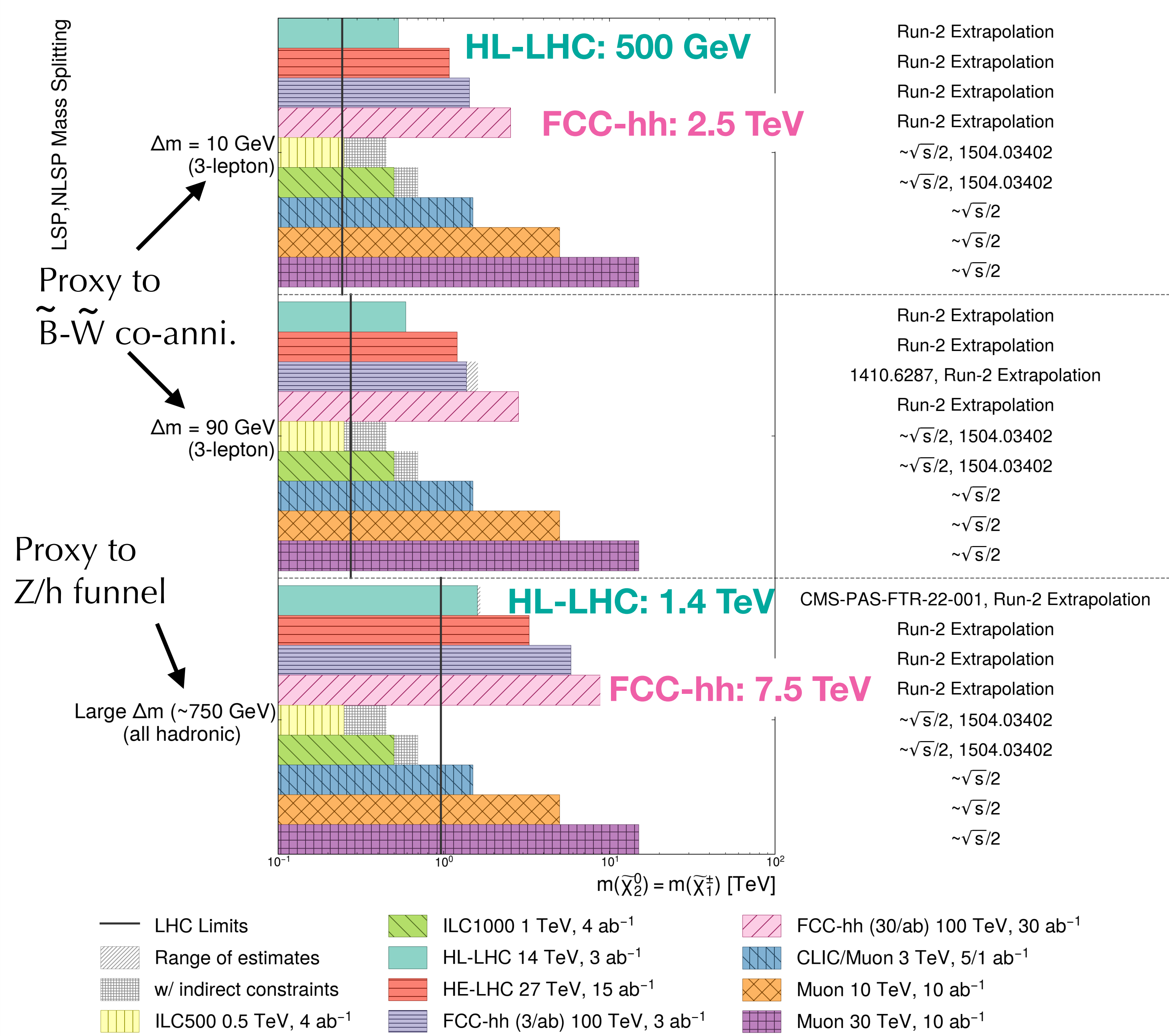



- Challenging to reach 1.1TeV thermal limit @HL-LHC & Some possibility suggested in FCC-hh.
- **Note: simple extrapolation from the current analysis!**
- Disappearing track search will be outdated for Higgsinos from HL-LHC
  Due to the detector upgrade that push the 1st layer even farther from the beam axis
- No projection available for displaced track yet

# Long future projection: Bino LSP

Snowmass 2021 energy frontier WG summary report: 2209.13128

Projection on wino prod. decaying into bino LSP



# Summary / Thoughts

**LHC has a comprehensive search program on Wino/Higgsino/Bino LSP**

- Current limit: wino < 700GeV, higgsino < 200GeV, bino < 100GeV-1TeV
- "Lowest-$p_T$" is the frontier to tackle the SUSY DM

**Projection based on the current analysis:**

- HL-LHC: Wino ~ 1.2TeV, Higgsino ~ 350GeV,
  Bino ~ 0.8-1.5TeV (gluino/squark-bino coann.) 100GeV (stau-bino coann.)
- May touch the thermal relic density limit with the FCC-hh for wino/higgsino

**Bino LSP DM by the indirect search?**

- Similar annihilation signals as wino/higgsino in principle

Full list of results

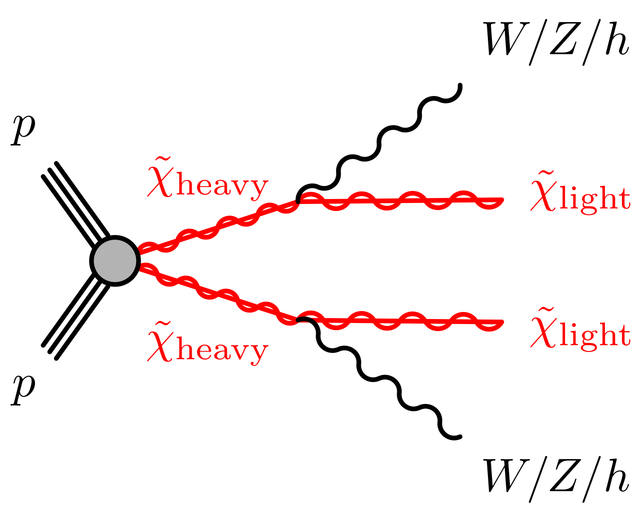
ATLAS: Publication / Preliminary / Summary

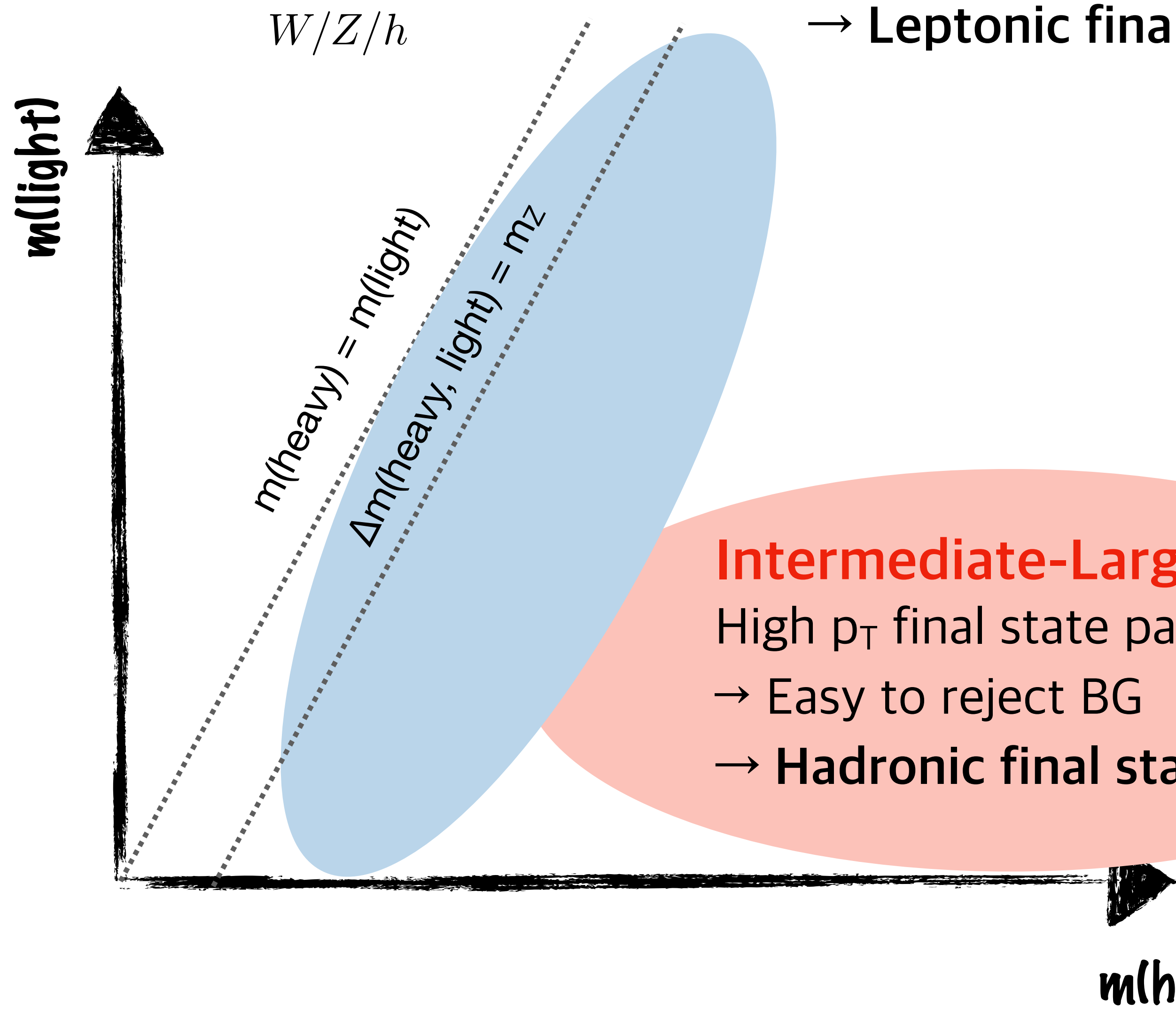
CMS: Publication / Preliminary / Summary

# Backup


Sandbox Studio, Chicago with Steve Shanabruch

# Diboson+MET Search: Overview




**Small Δm**

Low $p_T$ final state particles

→ Hard to reject BG

→ **Leptonic final state**

**Intermediate-Large Δm**

High $p_T$ final state particles

→ Easy to reject BG

→ **Hadronic final state**

e.g. WZ final state: small Δm

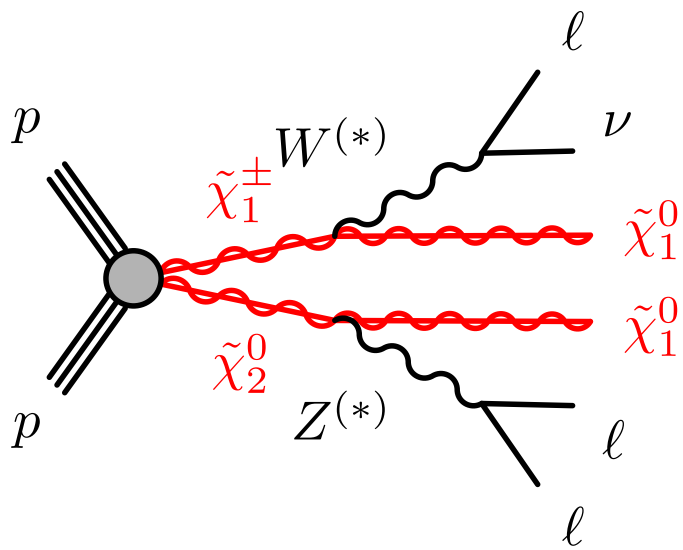
| | |
|---|---|
| ATLAS soft 2L: | 1911.12606 |
| ATLAS 3L: | 2106.01676 |
| CMS soft leptons: | 2111.06296 |
| CMS multi-lepton: | 2106.14246 |

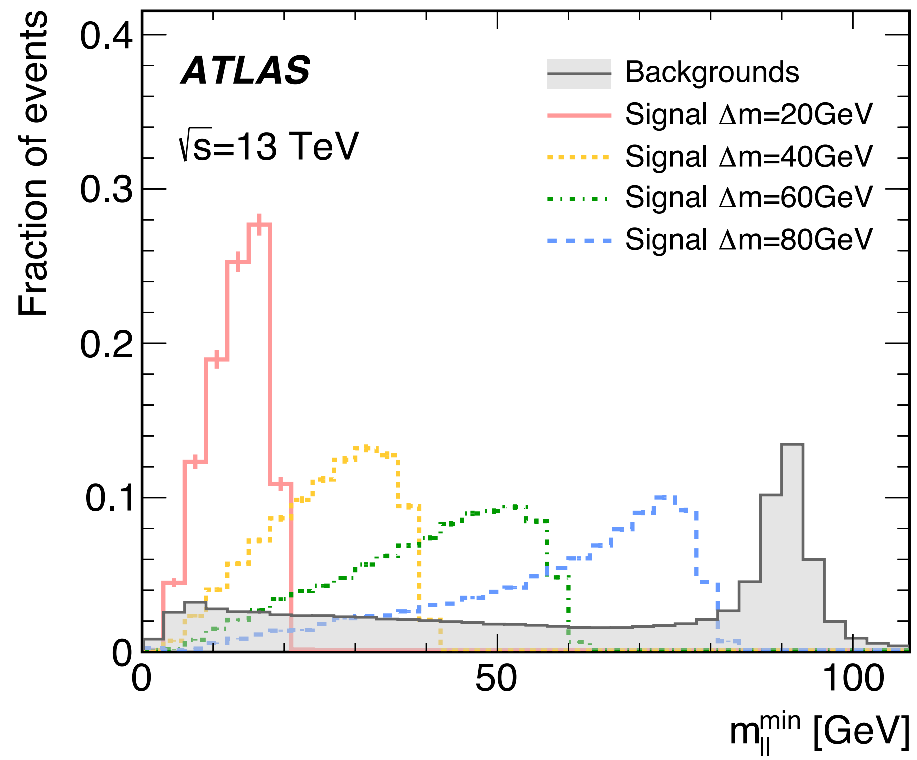
e.g. WZ final state: large Δm

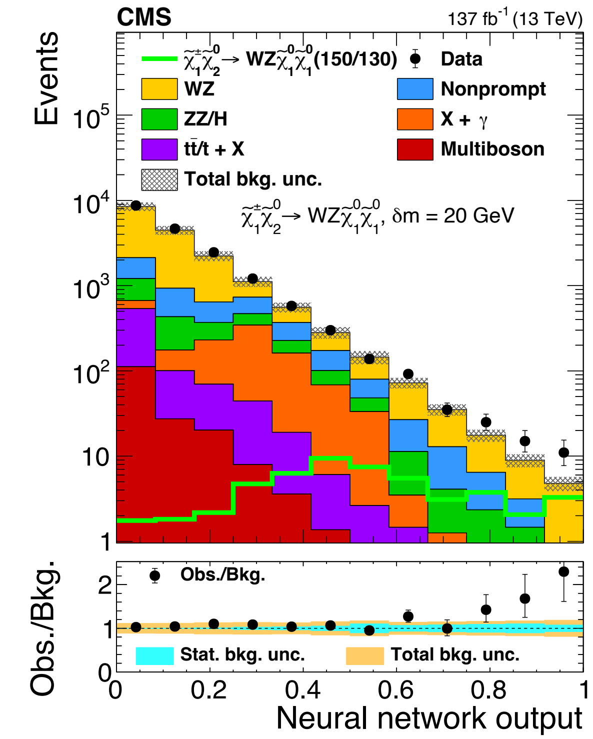
| | |
|---|---|
| ATLAS all-hadronic: | 2108.07586 |
| ATLAS 2L+2J: | 2204.13072 |
| CMS all-hadronic: | 2205.09597 |
| CMS 2LOS: | 2012.08600 |

# Small-Δm: Multi-lepton

ATLAS 3-lepton: 2106.01676
CMS multi-lepton: 2106.14246




- Main BG: SM WZ
- **For Δm < 80 GeV signals: on-shell Z-veto to reject WZ**

  ATLAS: 3L, exploit kinematic end-point variables ($m_{\ell\ell}^{min}$, $m_{T2}$), BDT-based low-$p_T$ e/μ isolation, ISR+MET category.

  CMS: Parametric NN for accommodating varying Δm, 3L and same-sign 2L category (one soft missing lepton).

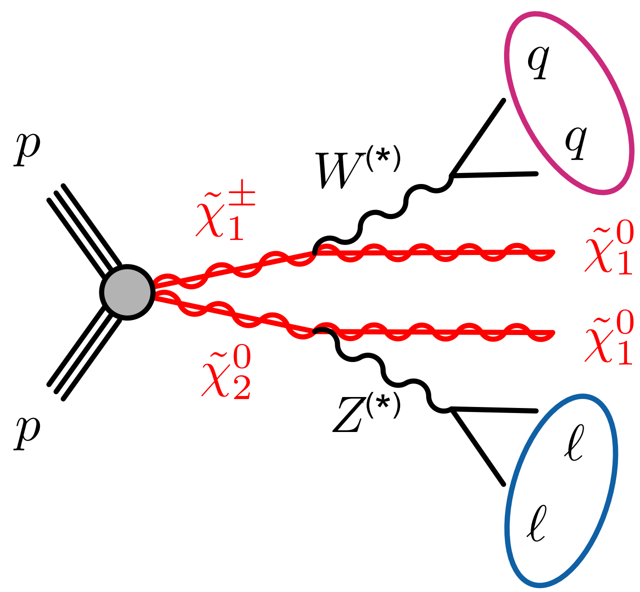
- **For Δm>80GeV signals: on-shell Z-tagging, requires high-$m_T$ to reject WZ**

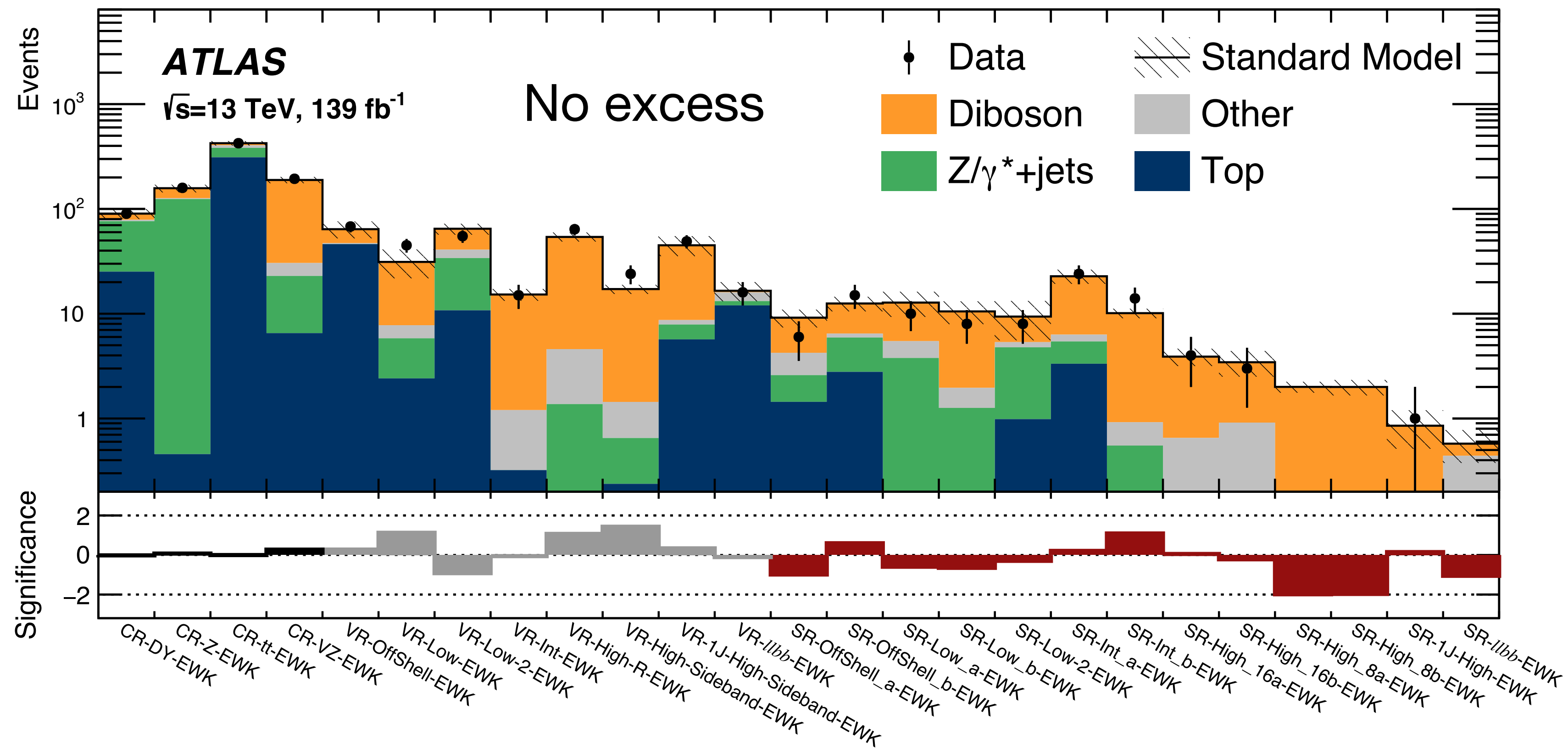
  ATLAS: Multi-bin fit in MET/$m_T$/$H_T$ CMS: Parametric NN

# Intermediate-Δm: 2-lepton + 2 jets

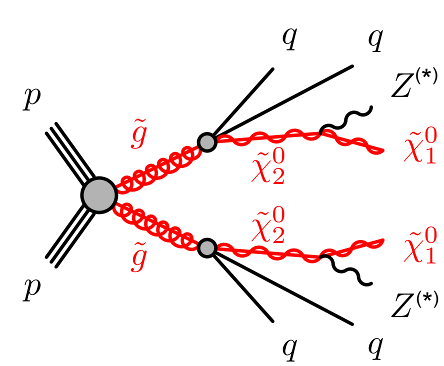
ATLAS 2L+2J: 2204.13072
CMS 2LOS: 2012.08600

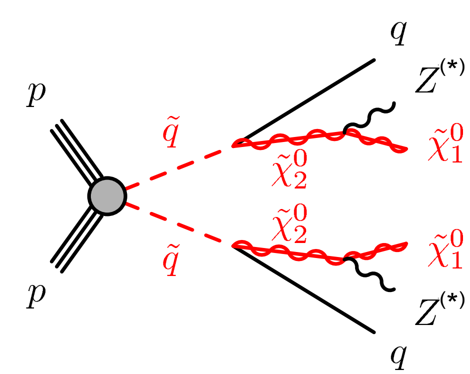
**New result from ATLAS**



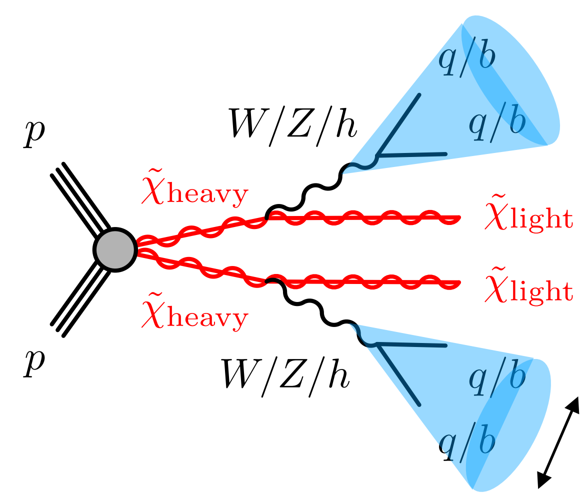

- **Di-lepton + Di-jet resonance + $E_T^{miss}$:** clean at this point already
- Main BG: WW/ZZ(→ℓℓνν)+jets ($m_{jj}$ accidentally consistent with $m_W$)
  Estimated using the MC normalized in the dedicated CRs.
- The search also targets strong production
  (gluino/squark decaying with Z) altogether.



# Large-Δm: Hadronic

ATLAS all-hadronic: 2108.07586
CMS all-hadronic: 2205.09597

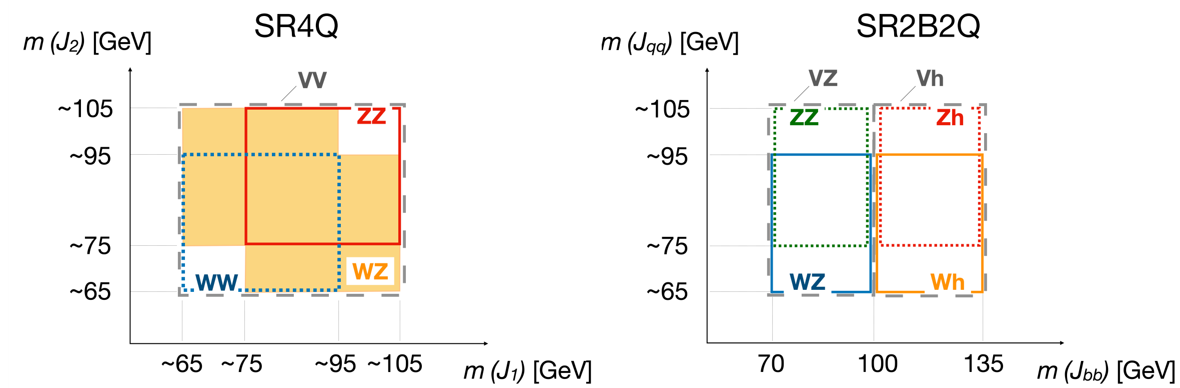



**High-$p_T$ boson**
→ collimated two jets
→ seen as a single "fat jet"

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

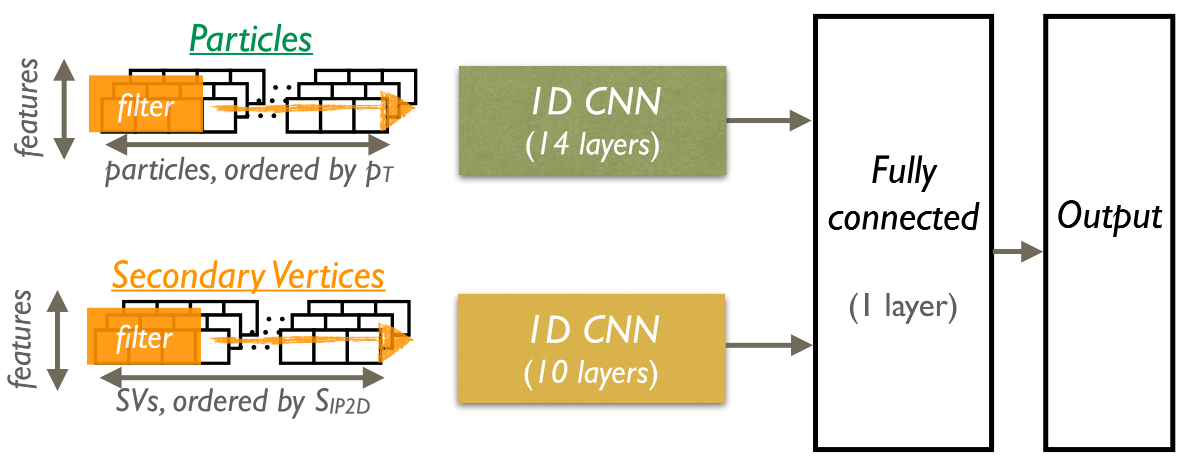
c.f. normal jets: R=0.4

**Can target W/Z/h simultaneously** e.g. ATLAS

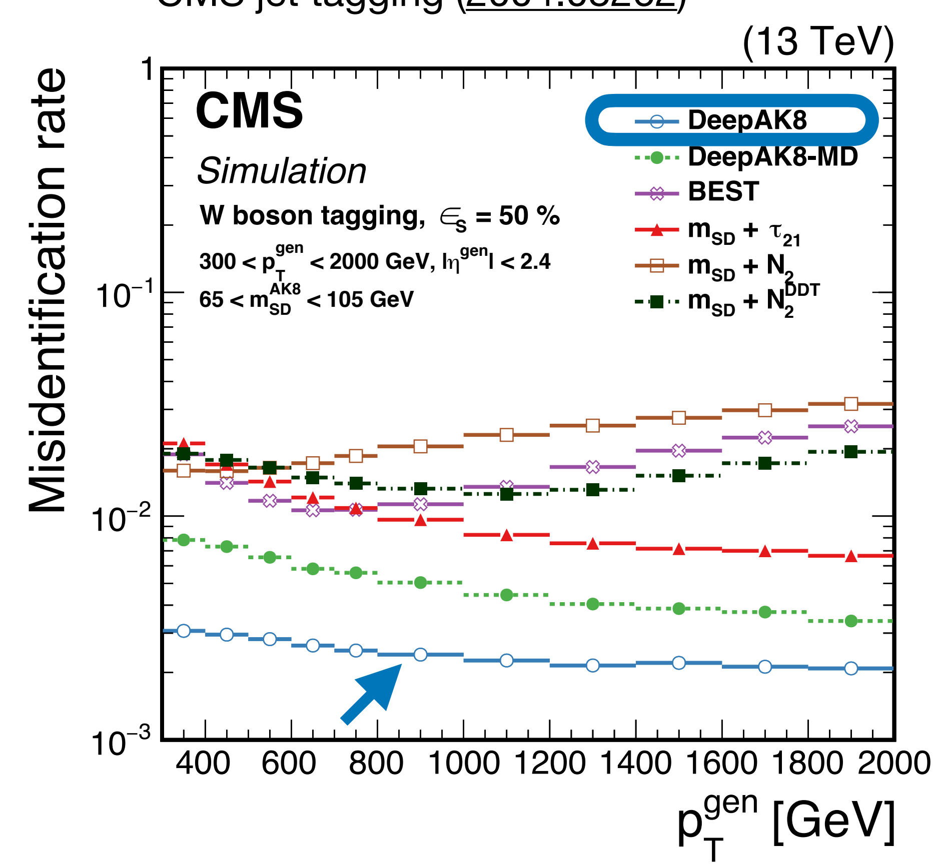



## Jet tagging: boosted boson jet ID

e.g. CMS: Anti-kt R=0.8 + DNN *"DeepAK8"*




CMS jet tagging (2004.08262)



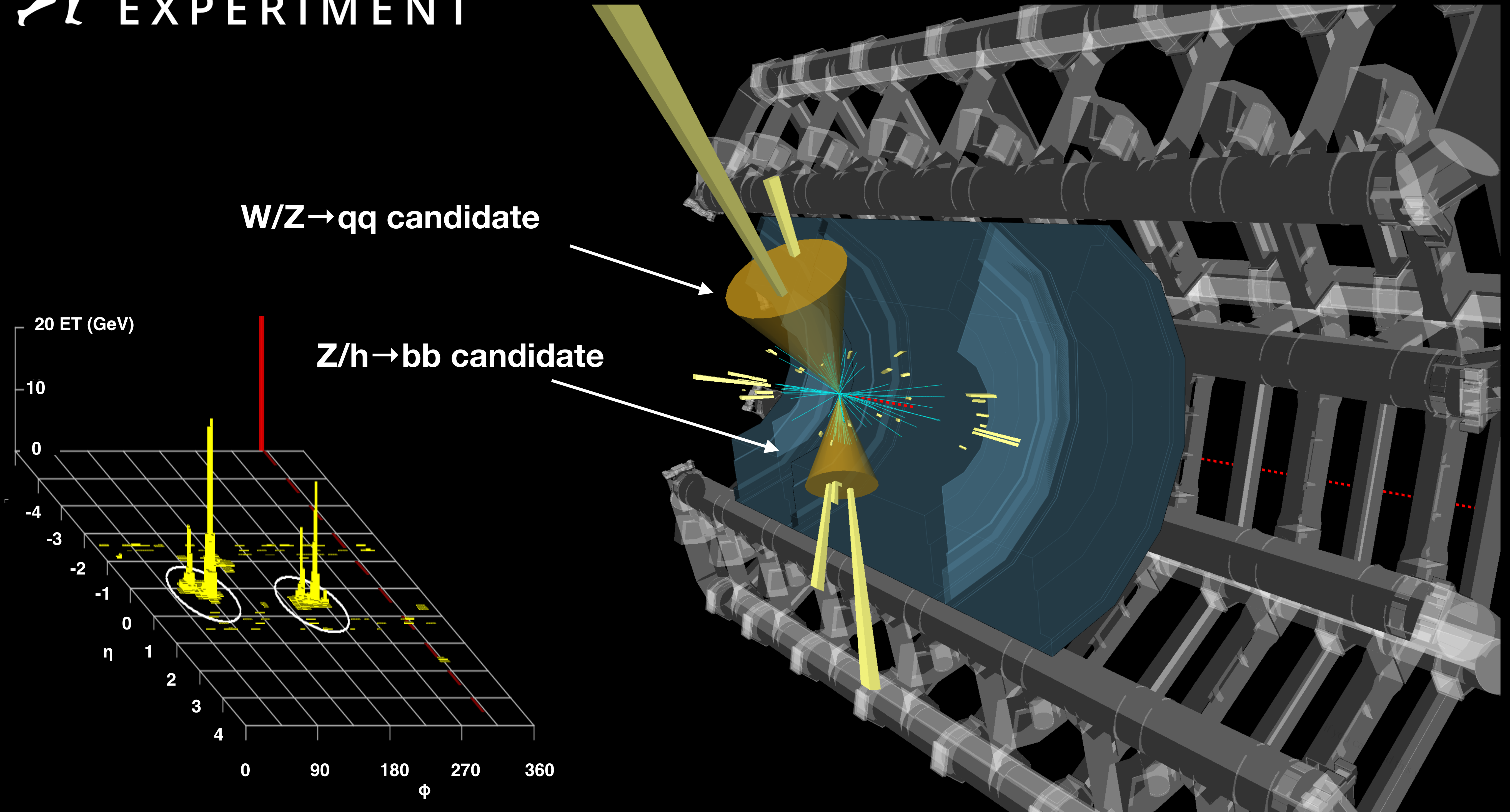

**Typical efficiency**

Signal: 40~50% BG: 0.1%-1% per jet

**→ O($10^3$-$10^5$) improvement in S/N with 2 jets tagged**

ATLAS EXPERIMENT

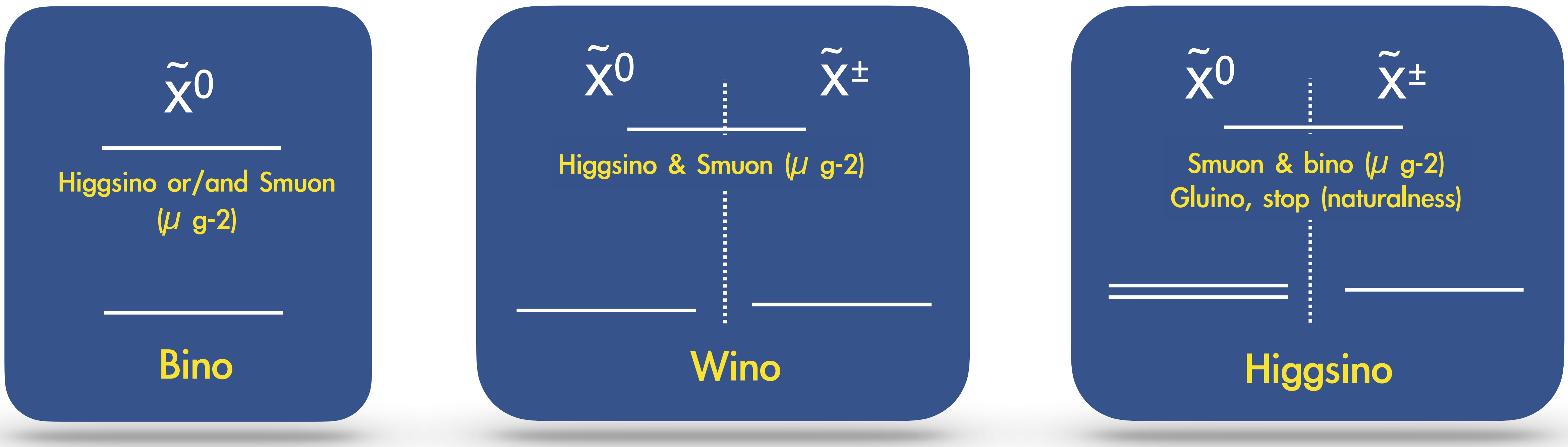
Run: 284484
Event: 993033541
2015-11-03 12:20:12 CEST




An event in the ATLAS search signal region

## More pheno arguments → More light SUSYs → Less-standalone DM searches

**Bino LSP** | **Wino LSP** | **Higgsino LSP**




**e.g. Muon g-2 explaining scenario**

>=3 of (wino, higgsino, bino, left-handed smuon, right-handed smuon) need to be <O(1TeV).

**e.g. Naturalness oriented spectra**

Light higgsino, stop, gluino

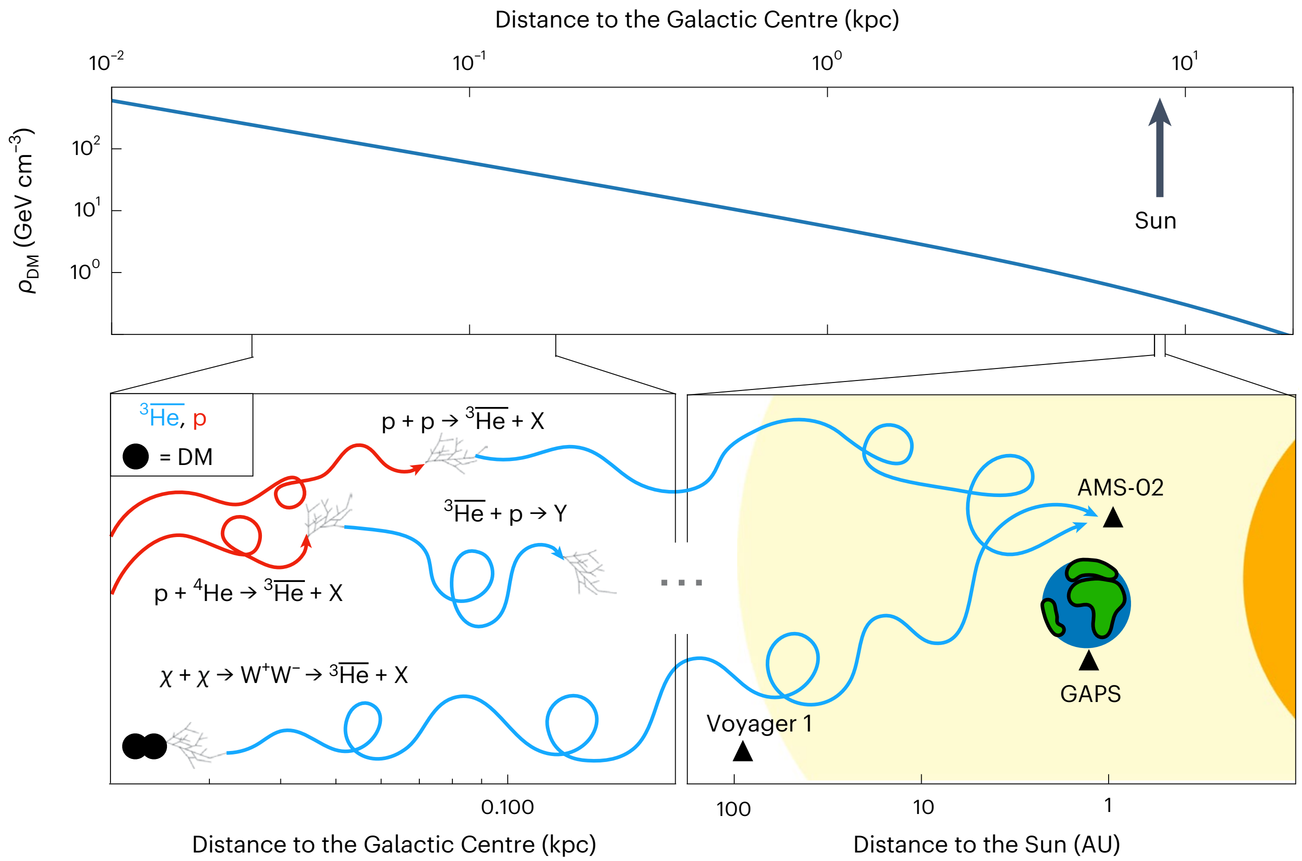
**More light SUSY particles → More handles in the search**

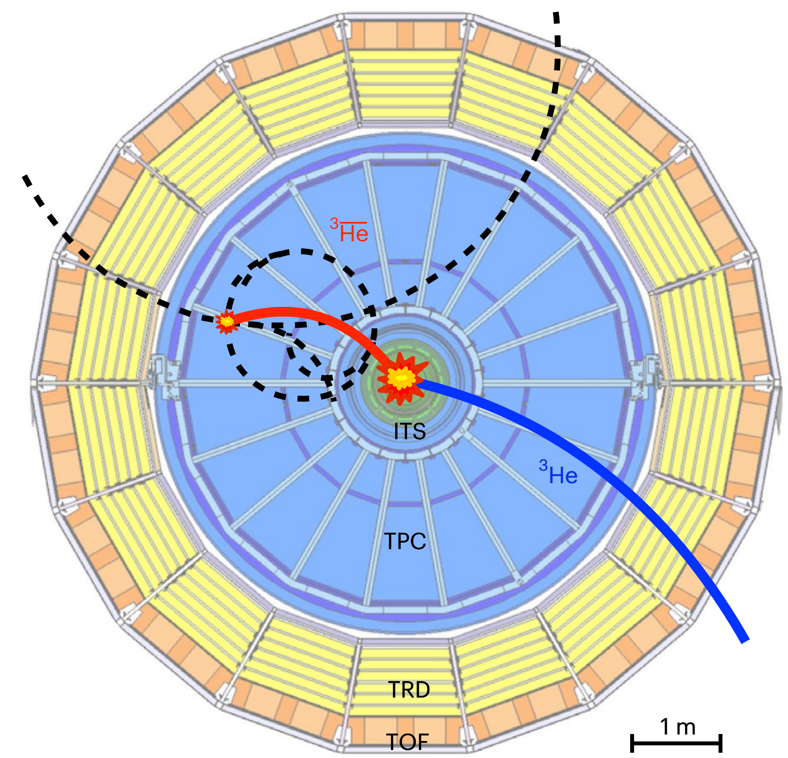
- Larger Δm, more prod. channels, longer cascade decays → more final state objects, etc.
- Can do much better than the minimal DM-oriented SUSY search.

# オマケ: W→qq→反ヘリウム原子核

ALICE Nature 19 61-71 (2023)

Doubly-charged particleとして見える



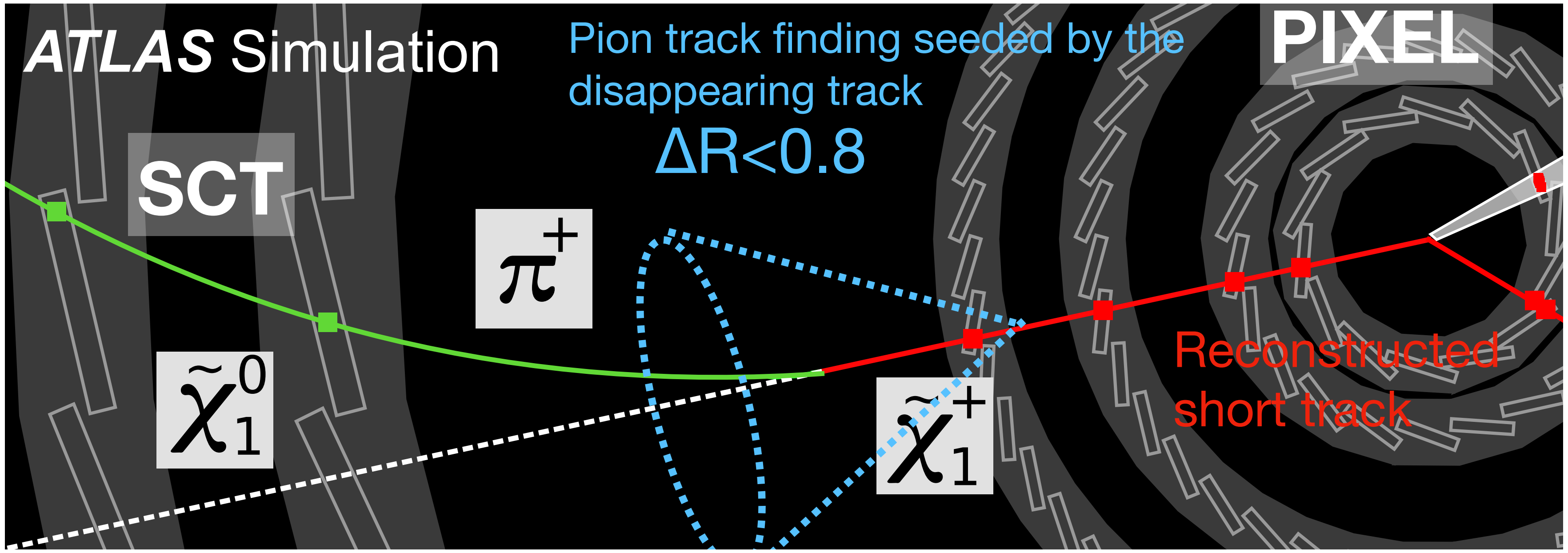

- **最近流行りの気球実験:** DM対消滅 → WW → qqqq → 反原子核。1発見えれば発見。
- **本当にそんなprocess起こんのか？**
  - LHCで反原子核の生成は確認。モデルの予想とも概ね合っている。が、W由来ではない (僕の理解)。
  - ALICEが反He3原子核と物質の対消滅断面積を測定。宇宙空間での減衰も大丈夫そうなのを確認。
- **やっぱWからの反原子核見たくないか？**

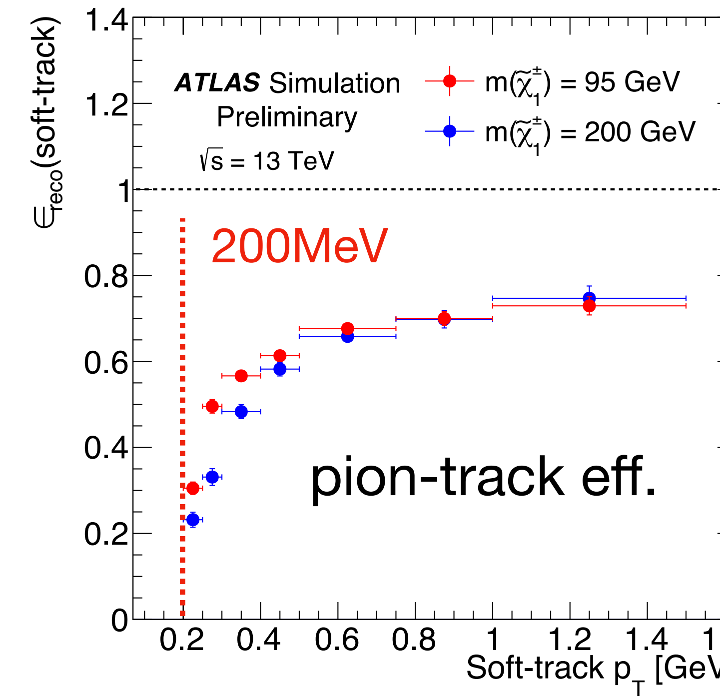
高統計・pureなhadronicサンプルが必要 → **ATLASのsemi-leptonic ttbar使う？**

2b+1Lでほぼsemi-lep ttbarだけになるので, そこにdoubly-chargedな物体がいるかを見ればok

# Prospects: Wino LSP/Pure-higgsino LSP (Disappearing track search)

Soft pion reconstruction @ATLAS (ATL-PHYS-PUB-2019-011)



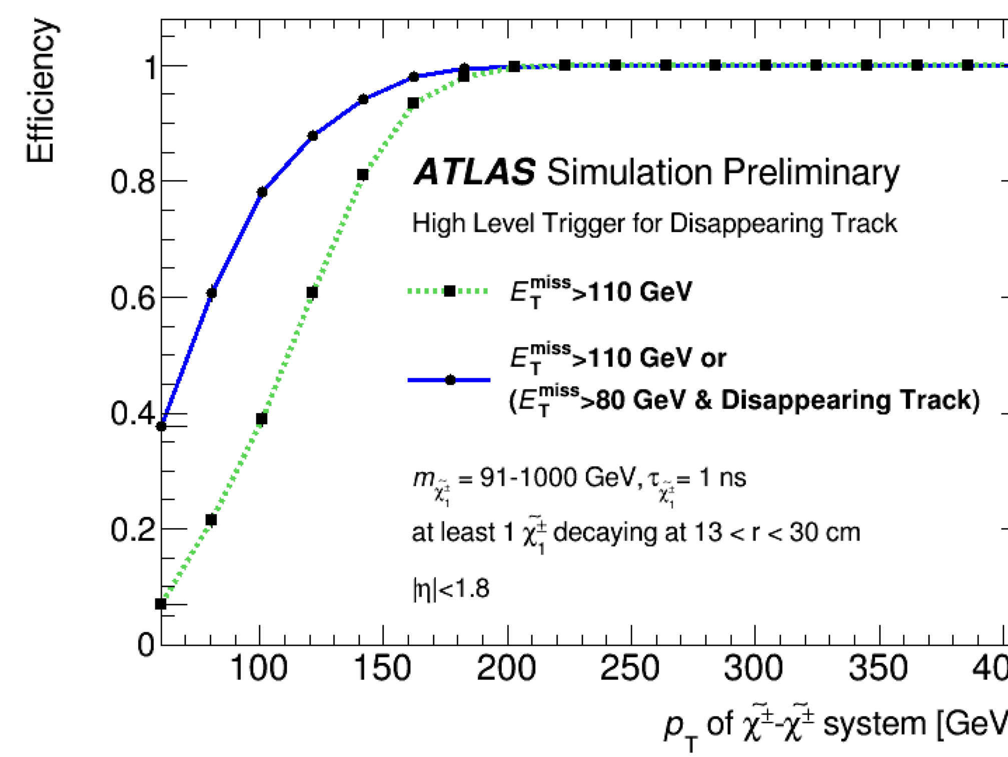

**Areas for further improvement @LHC**

- ○ Disappearing track trigger

  Ultimately no need to ask for a hard ISR.
- ○ Soft-pion reconstruction & vertex association.
- ○ Exploration of per-hit dE/dx

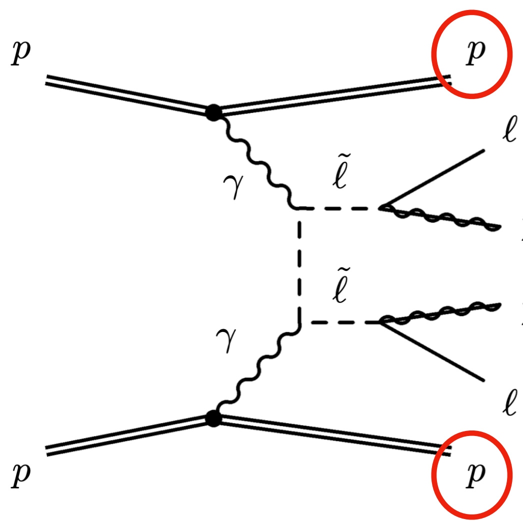
  Now that the target chargino becomes heavier

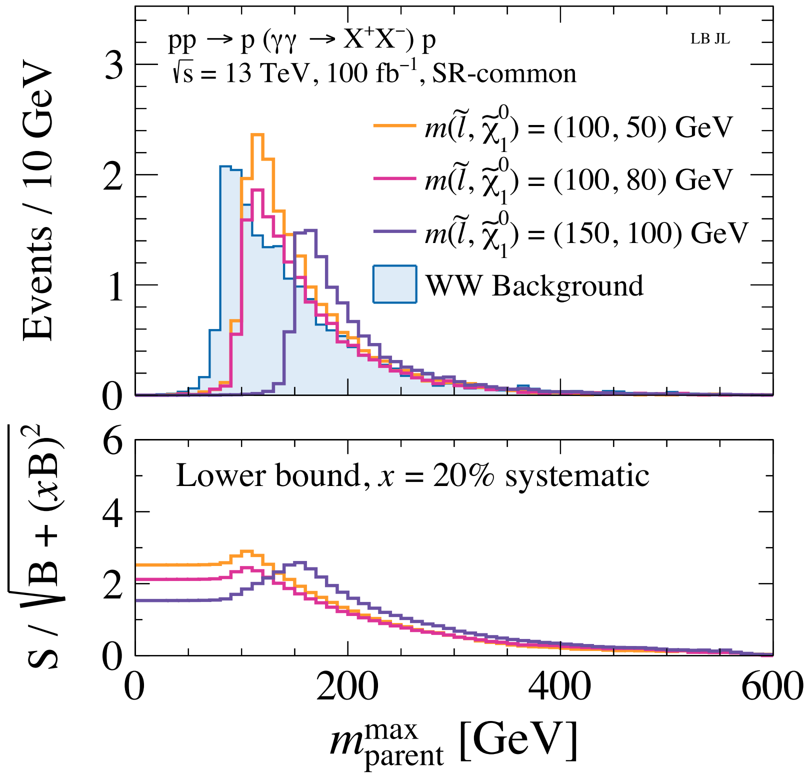
Disappearing track+MET trigger @ATLAS Run3 (link)

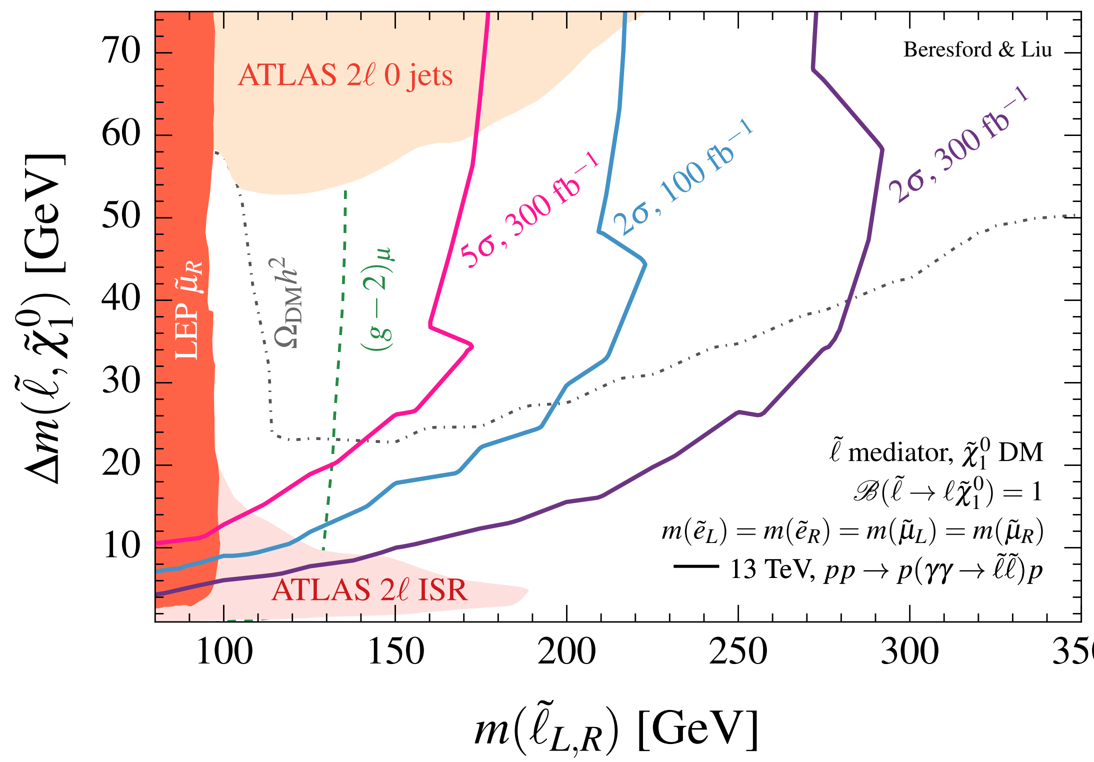


# Proton Tagging Opportunities @ATLAS/CMS

Beresford & Liu (1811.06465)




**LHC is also a photon collider**

- Fusion of two almost-on-shell photons spilled from the beam protons.
- Substantial effective γγ luminosity: ~$10^{29\ (27)}$ $cm^{-2}s^{-1}GeV^{-1}$ @$\sqrt{\hat{s}}$=100 GeV (1 TeV).

**Diffracted beam protons stay intact → Tag/measure using the forward detectors**

- Exclusive selection of γγ fusion events → Much cleaner than the pp version of the search.
- Full knowledge of center-of-mass 4-vector thanks to the forward proton tagging

  **→ Direct access to $\sqrt{\hat{s}}$ instead Δm. No more pain from small-Δm.**

**Anticipated target: Slepton/Stau with Δm=10-50 GeV.**

- Can already potentially close the "bino+slepton gap" with the Run3 statistics.

# A few words on the Sneutrlino LSP

**Sneutrinos are always right under left-handed slepton/stau**

$\tilde{\mu}_L, \tilde{\nu}$  $\tilde{\ell}_L^{\pm} \to \tilde{\nu}\, W^*$

$$m_{\tilde{l}} - m_{\tilde{\nu}} \approx \frac{m_W^2(-\cos 2\beta)}{m_{\tilde{l}} + m_{\tilde{\nu}}}$$

Typically Δm < 10 GeV

**Not only because it's "dead" but its standalone search is genuinely hard in hadron colliers.**

- Small prod. cross-section: σ(slepton pair) ~ σ(higgsino chargino-neutralino)/20
- Only the soft W*s will be visible.

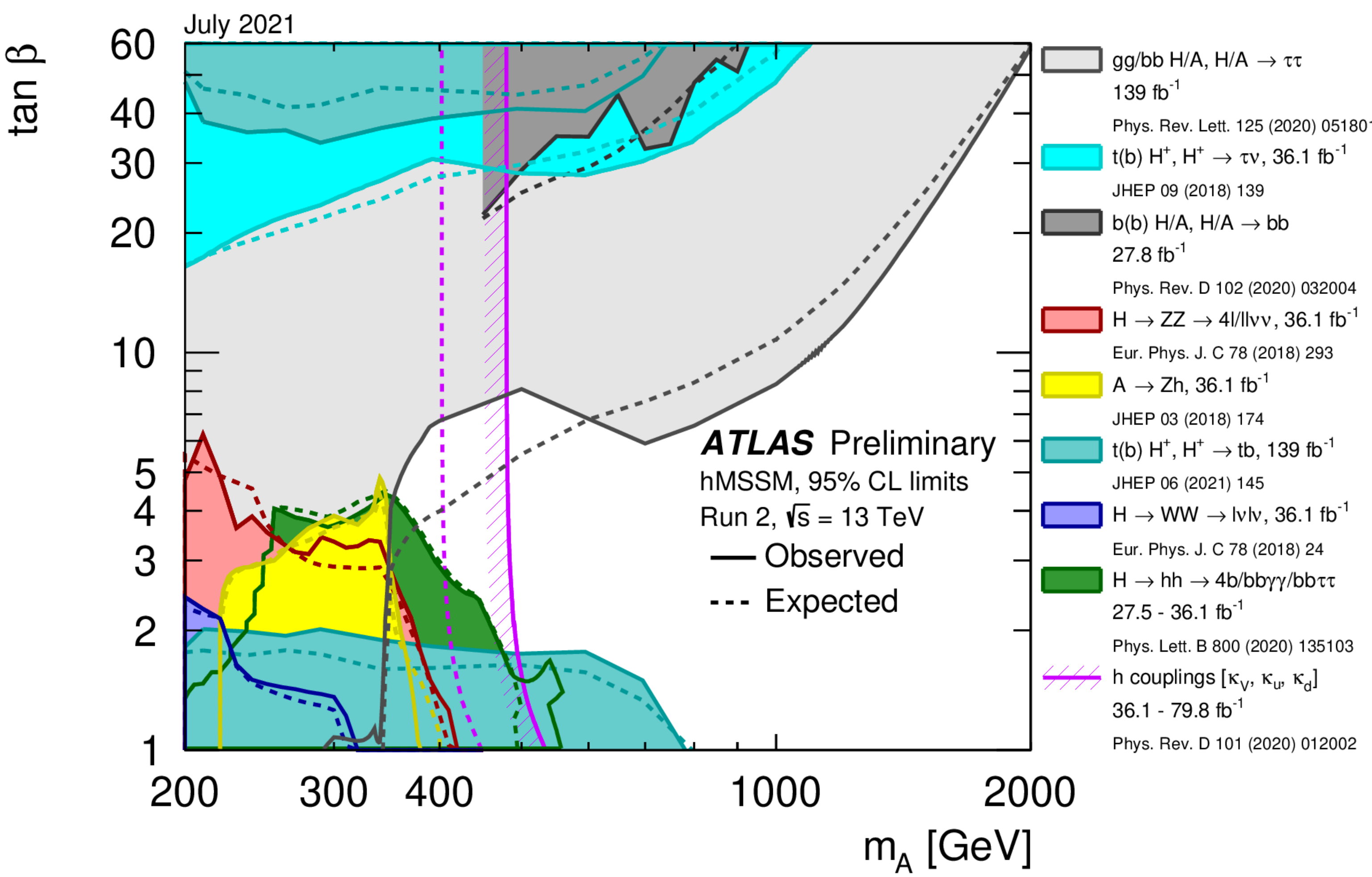
  Di-leptonic BR ~ 4%, $p_T(\ell)$ ~ Δm(slep, sneu)/4

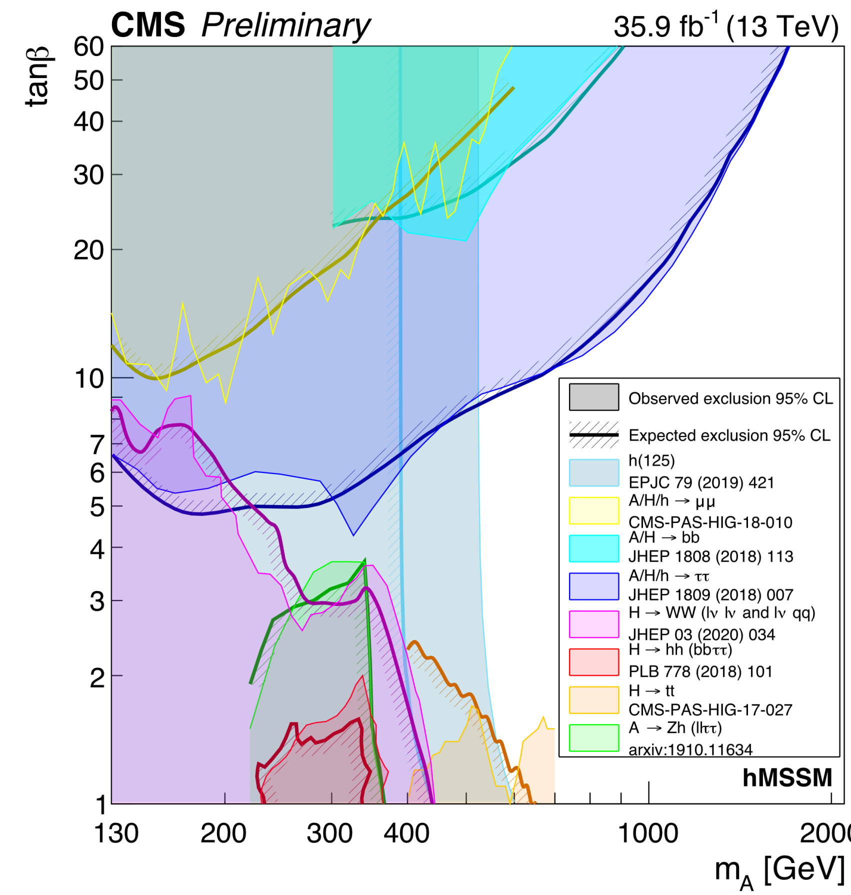
  Assuming the same acceptance as the higgsino search, no exclusion yet for >100GeV sleptons.
- Much higher potential in lepton/photon colliders

**Next minimal mass spectra scenarios are likely covered by the existing multi-lepton searches:**

- Signatures: Other SUSYs → slepton pair+X → 2L+sneutrino LSP pair+X

# $m_{Bino} = m_H/2, m_A/2$ → Resonant bino annihilation via H/A




**General H/A→SM particle resonance search would be the most sensitive channels.**

Decays into down-type fermions become significant in the large tanβ regime ($\sigma \propto \tan^4\beta$)

**No much motivation to start dedicate H/A→RPC SUSY searches for now.**

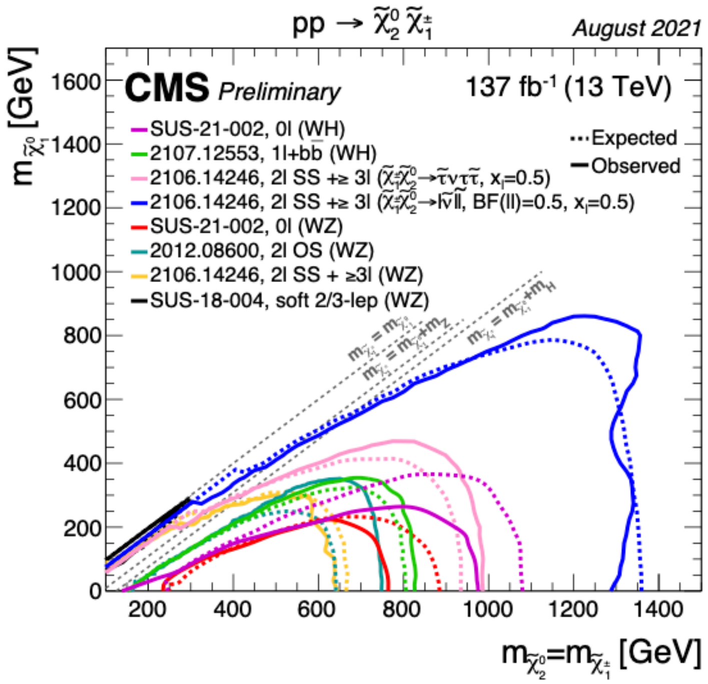
Will be important to determine SUSY's nature when they are found in the direct searches in the future.

# Diboson+MET @ATLAS/CMS

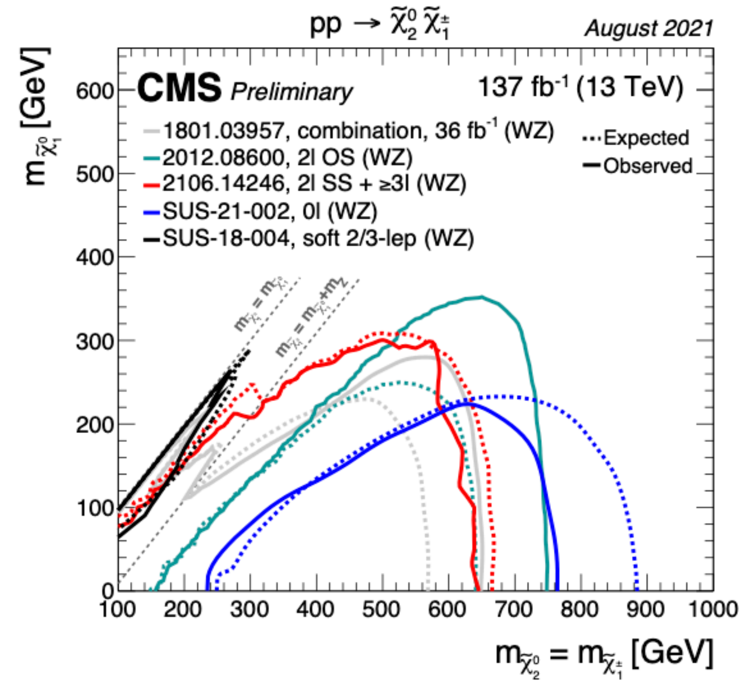
Wino NLSP/Bino LSP simplified model

Top: ATLAS / Bottom: CMS

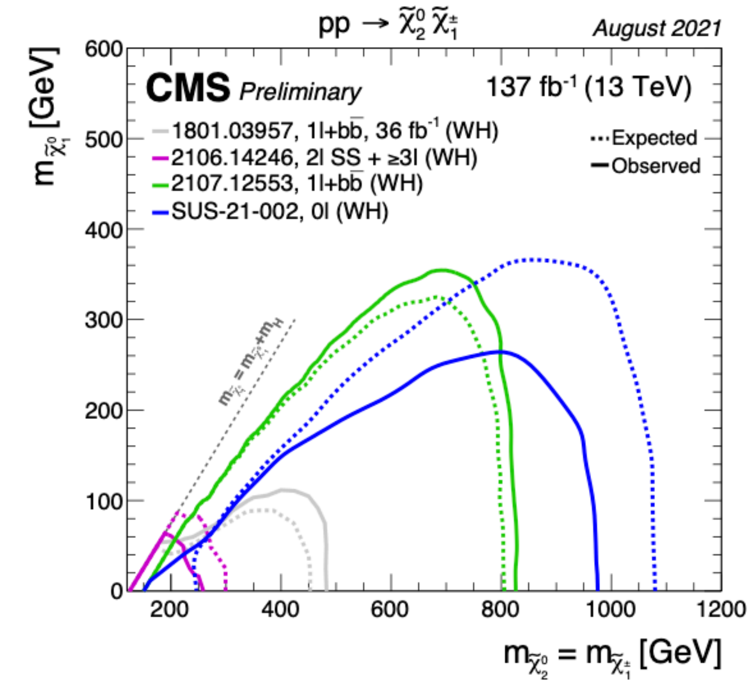
## Summary

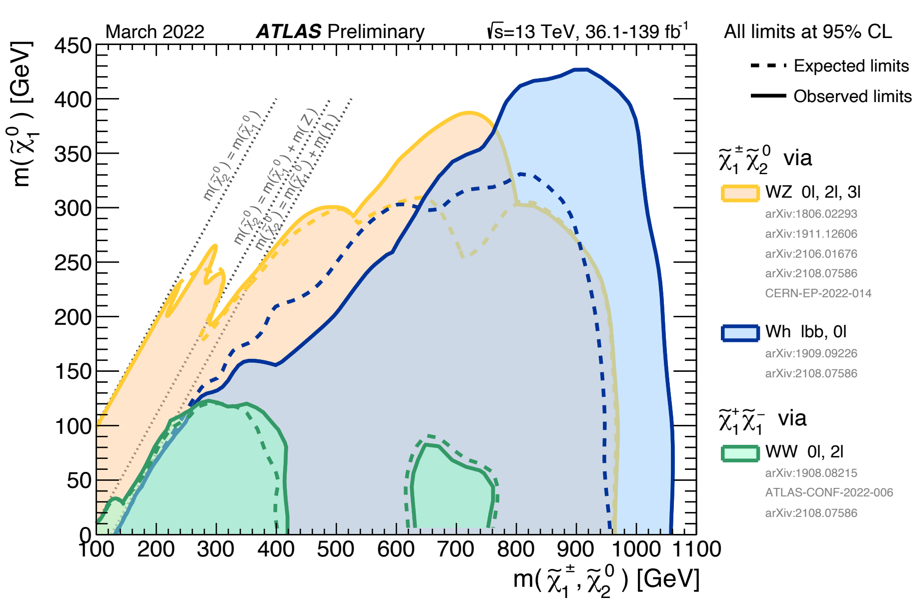


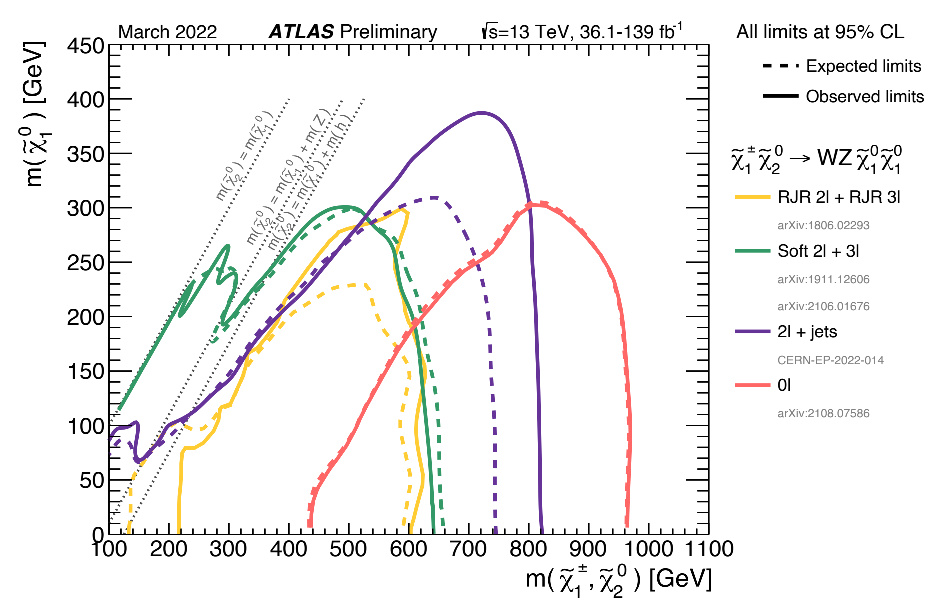

## C1N2→WZ

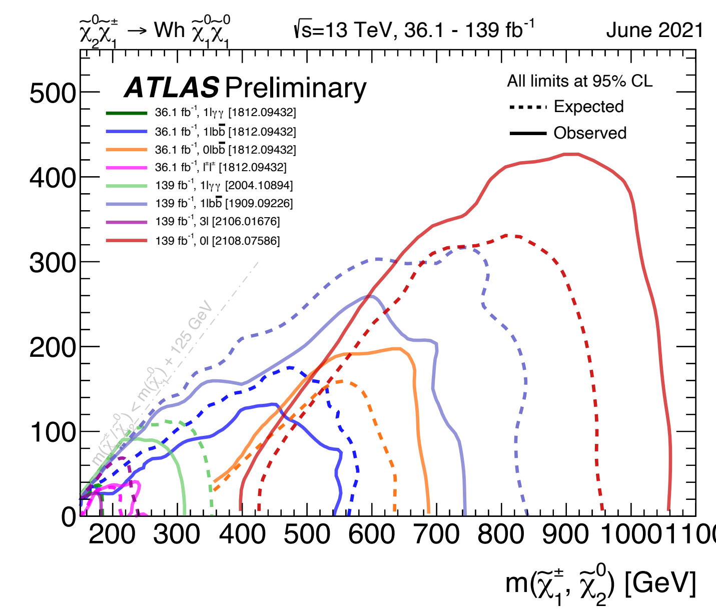



## C1N2→Wh



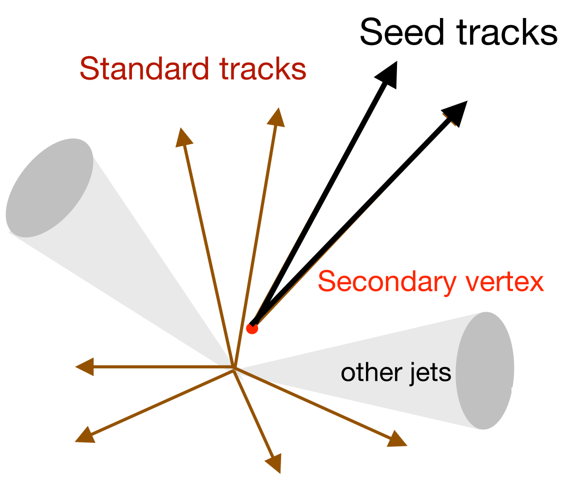



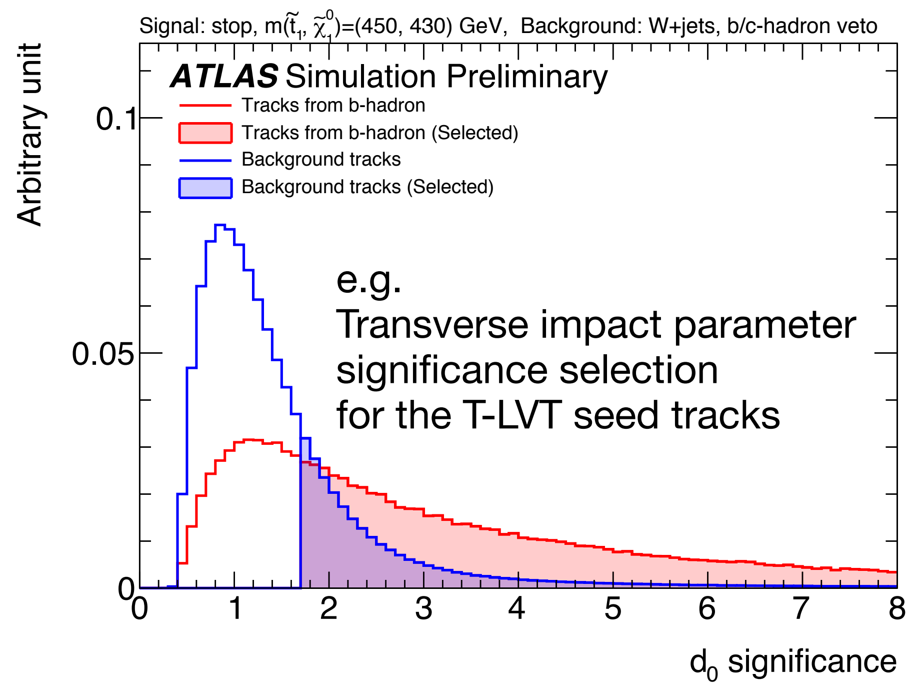



# Soft b-tagging

Δm小さいとb-jetがヒョロヒョロになる

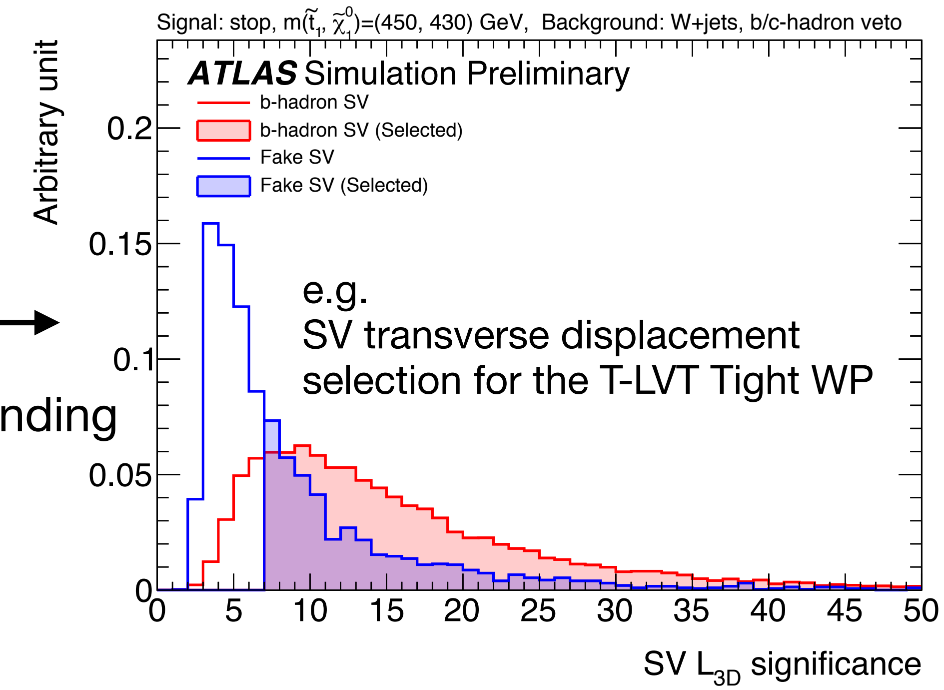



**Seed track selection**




SV finding

**Cuts on SV properties**

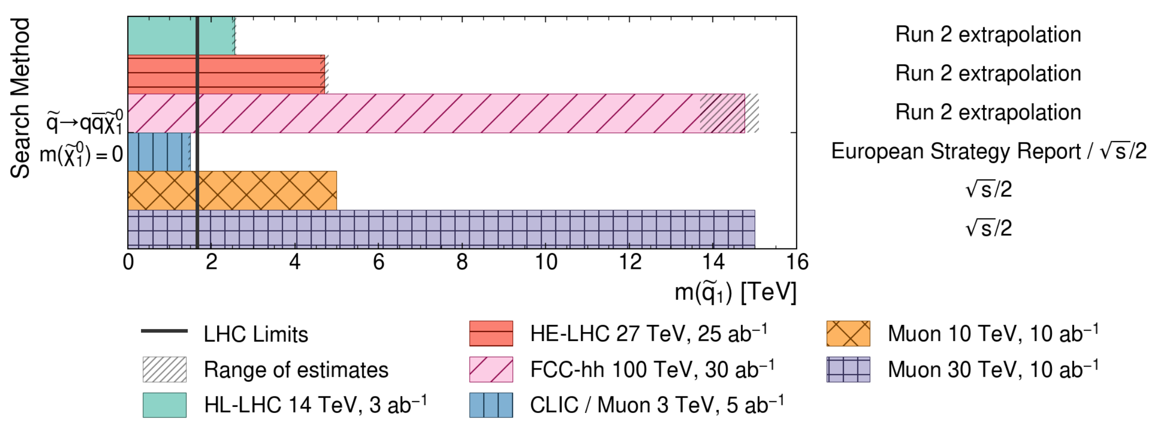



- **Bottleneck of low-$p_T$ b-tagging: It doesn't form a 'jet' anymore**
  - e.g. 5GeV initial b-quark → ΔR(final-state particles)~1.0, while standard jet clustering is with R=0.4.
  - Also fewer final-state particles due to the soft initial quark.
- **New dedicated algorithm based only on secondary vertex (SV) finding** seeded by:
  - mildly displaced tracks isolated from jets (T-LVT), or
  - a system of collimated low-$p_T$ tracks (TC-LVT).
- **Optimized selection after the SV formation** (e.g. mass, transverse displacement of SV)

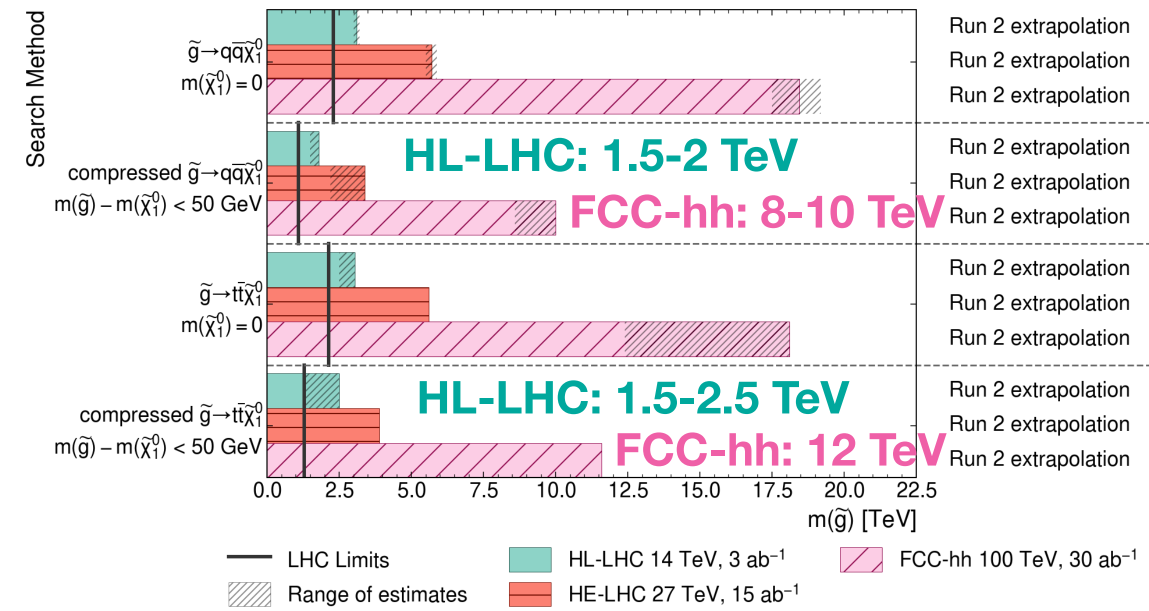
# Prospects: Bino LSP (other co-annihilation motivating ones)

Snowmass 2021 high-energy frontier working group summary report: 2209.13128

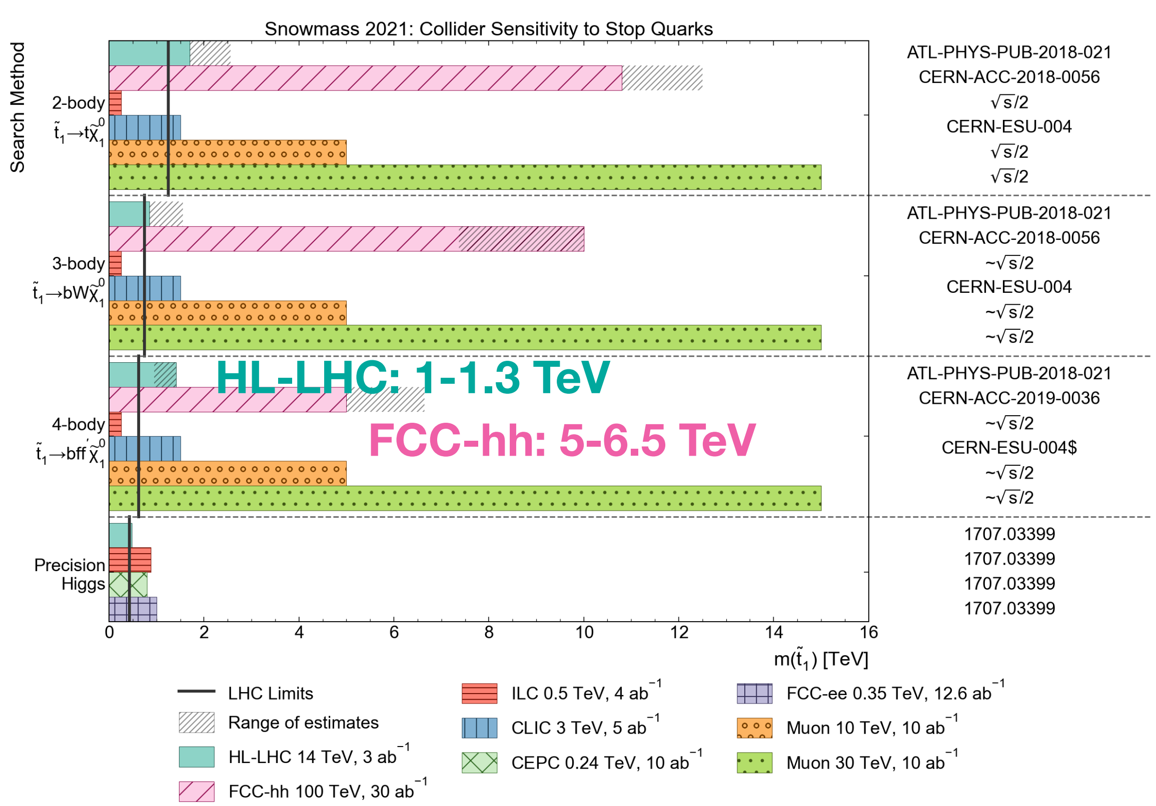
## Light-flavor squark → bino



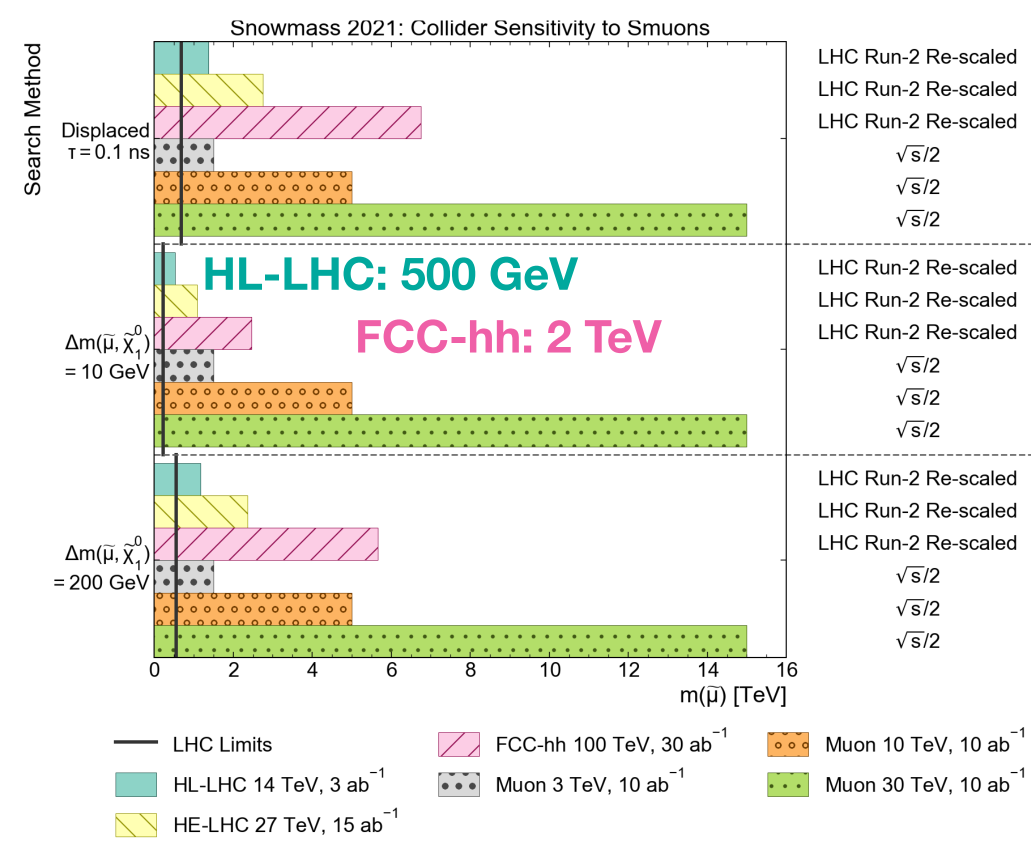

## Gluino → bino




## Stop → bino




## Left-handed smuon → bino



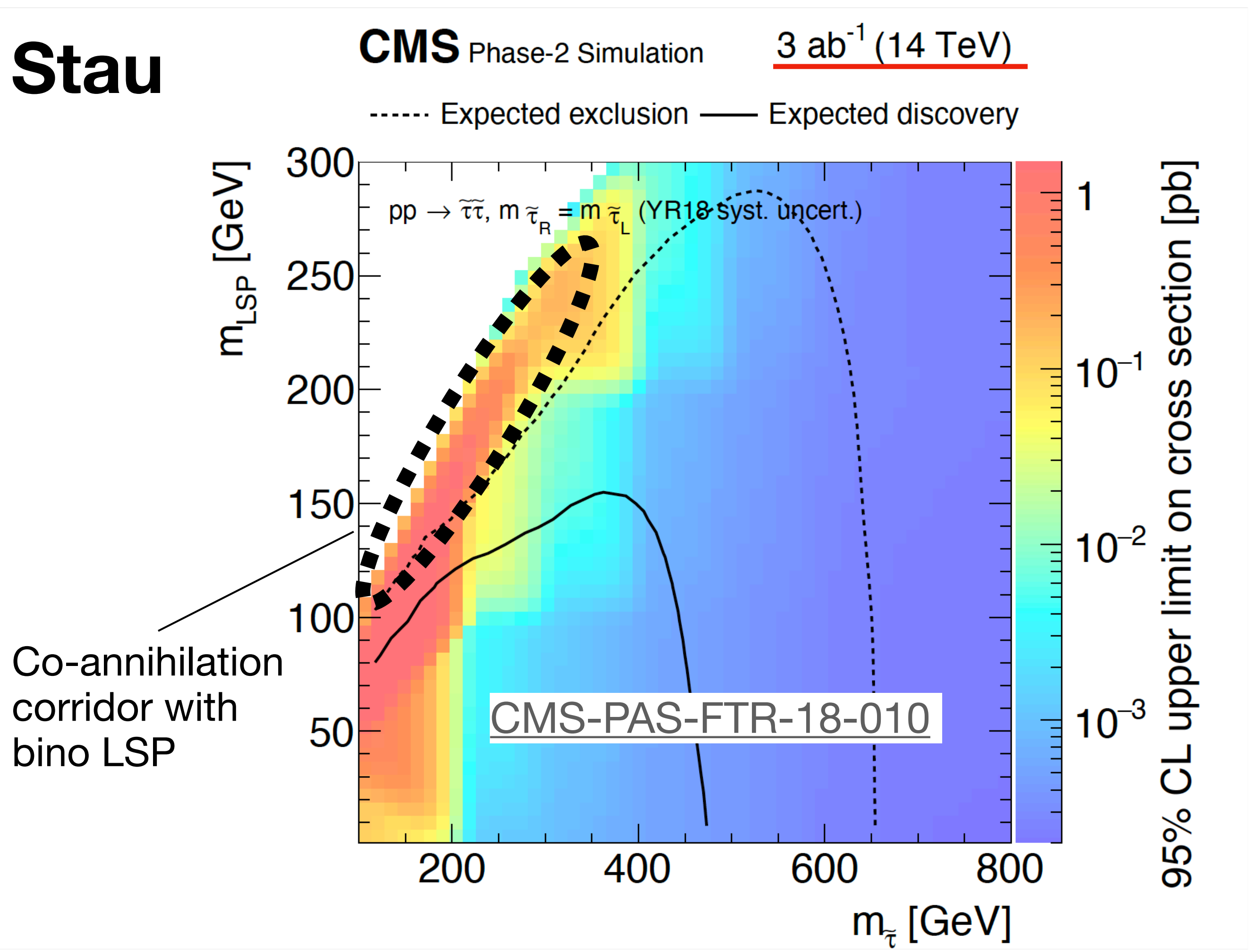
# 150 GeV SUSY is viable!

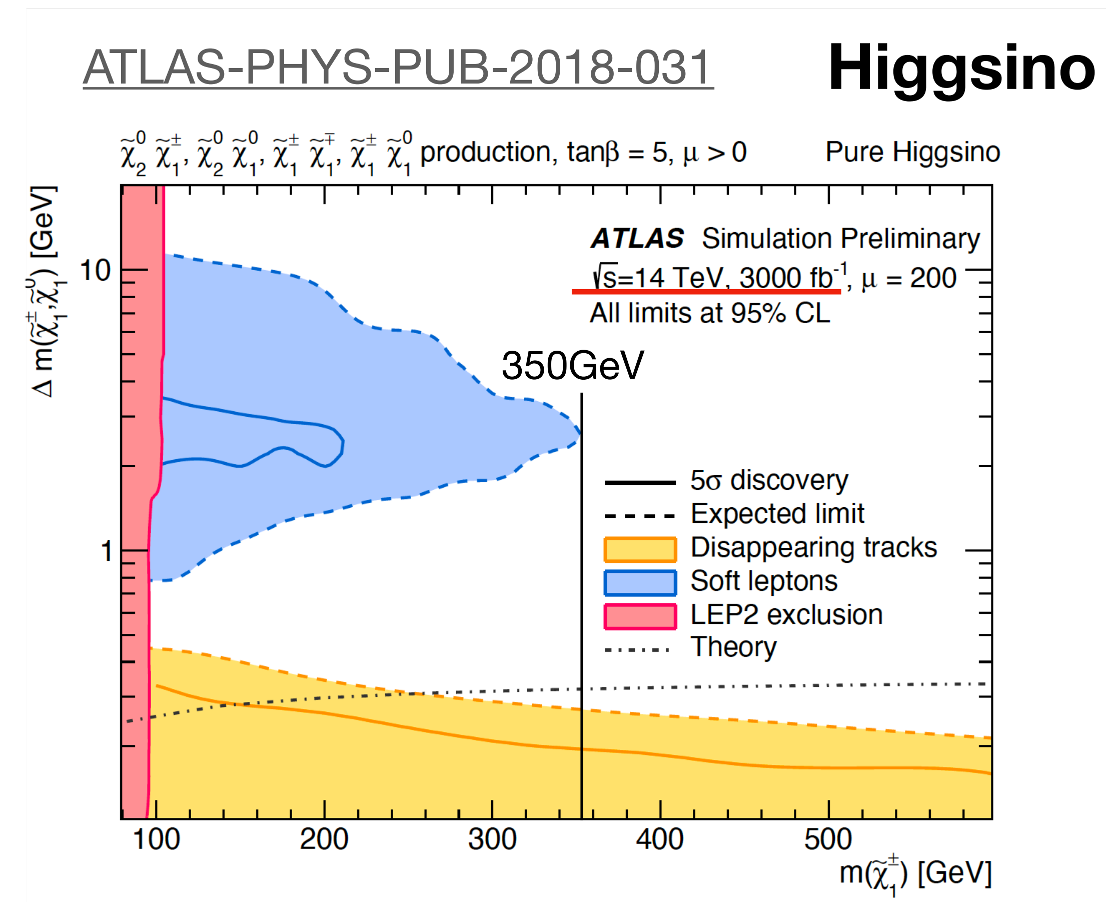
**Not even in a contrived way e.g.**

- (Pseudo-) pure higgsino LSP
- Compressed slepton-/stau-bino (muon g-2, bino DM co-annihilation)

Upcoming LHC-Run3 is exciting but just adding more data won't help much.

**New schemes wanted!** e.g. **γγ-collision**, **semi-long-lived signatures**, loop?, bound-state?




c.f. Need 1TeV to achieve correct DM relic density