12 Nov. 2019
Dark Matter searches in the 2020s
U. of Tokyo, Kashiwa

SUSY Dark Matter Searches at LHC and Future Colliders

K. Terashi
ICEPP, University of Tokyo

Outline of the talk

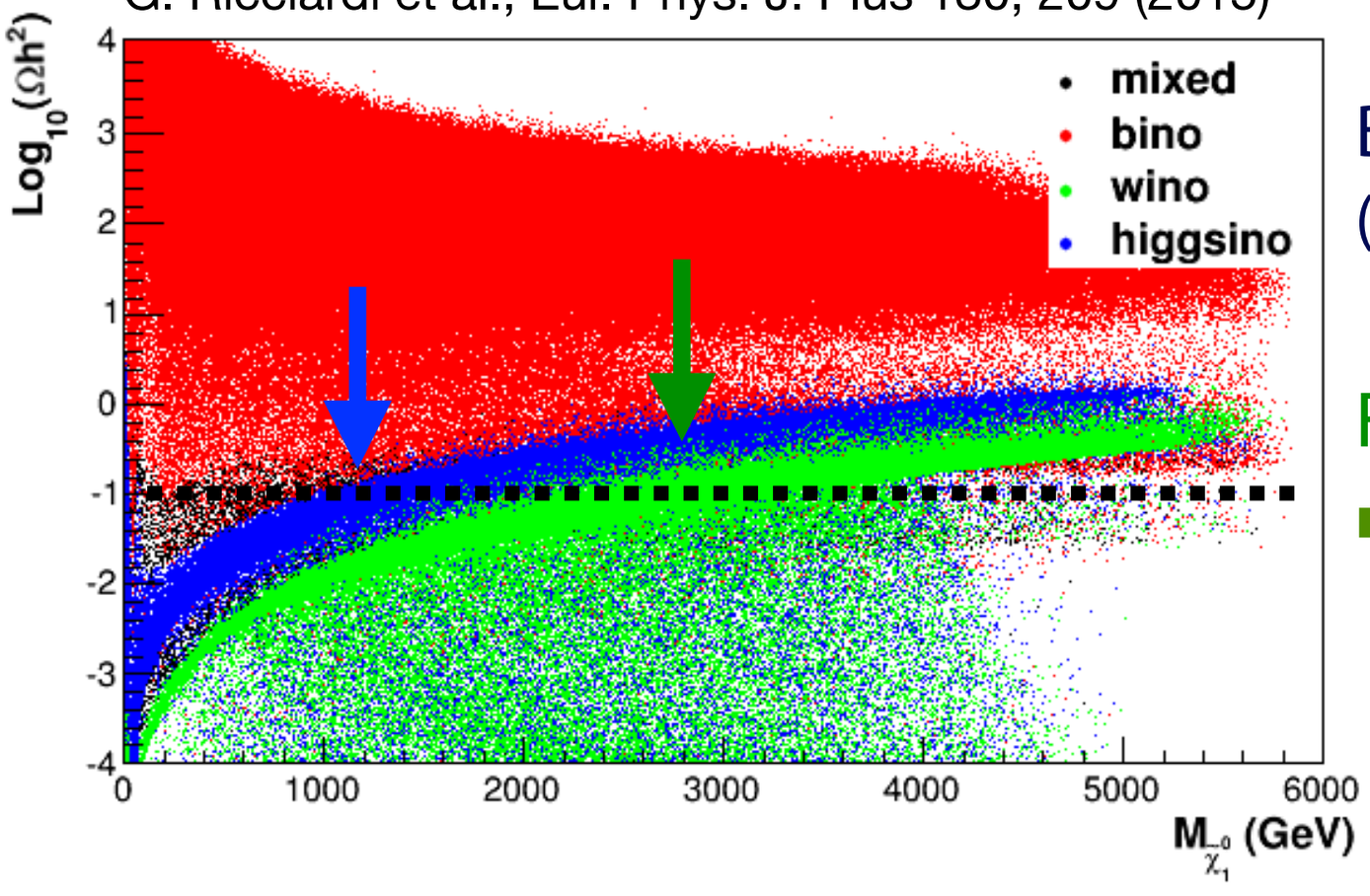
- Neutralino dark matter in SUSY
- Collider search strategy for Neutralino dark matter
- Signatures for direct electroweakino production
- Compressed dark matter searches
- Current and future bounds on compressed scenario

SUSY Dark Matter

Lightest neutralino in MSSM most extensively studied as DM candidate

- Bino DM over-produced due to too low cross section
- If thermally produced, the pure Wino(Higgsino) DM mass below ~3(1) TeV

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



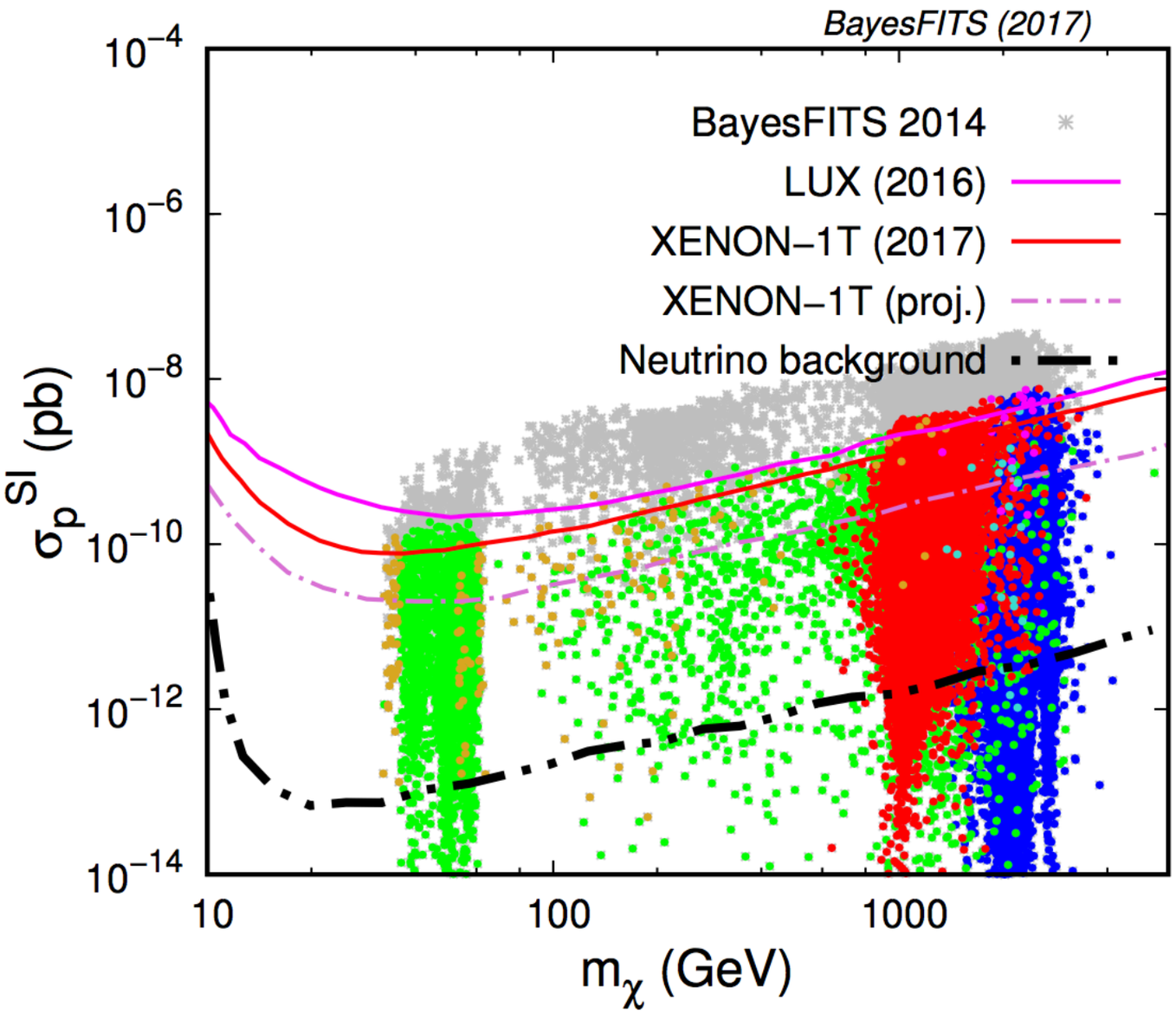
Bino DM significantly constrained (except e.g, stau-coannihilation region)

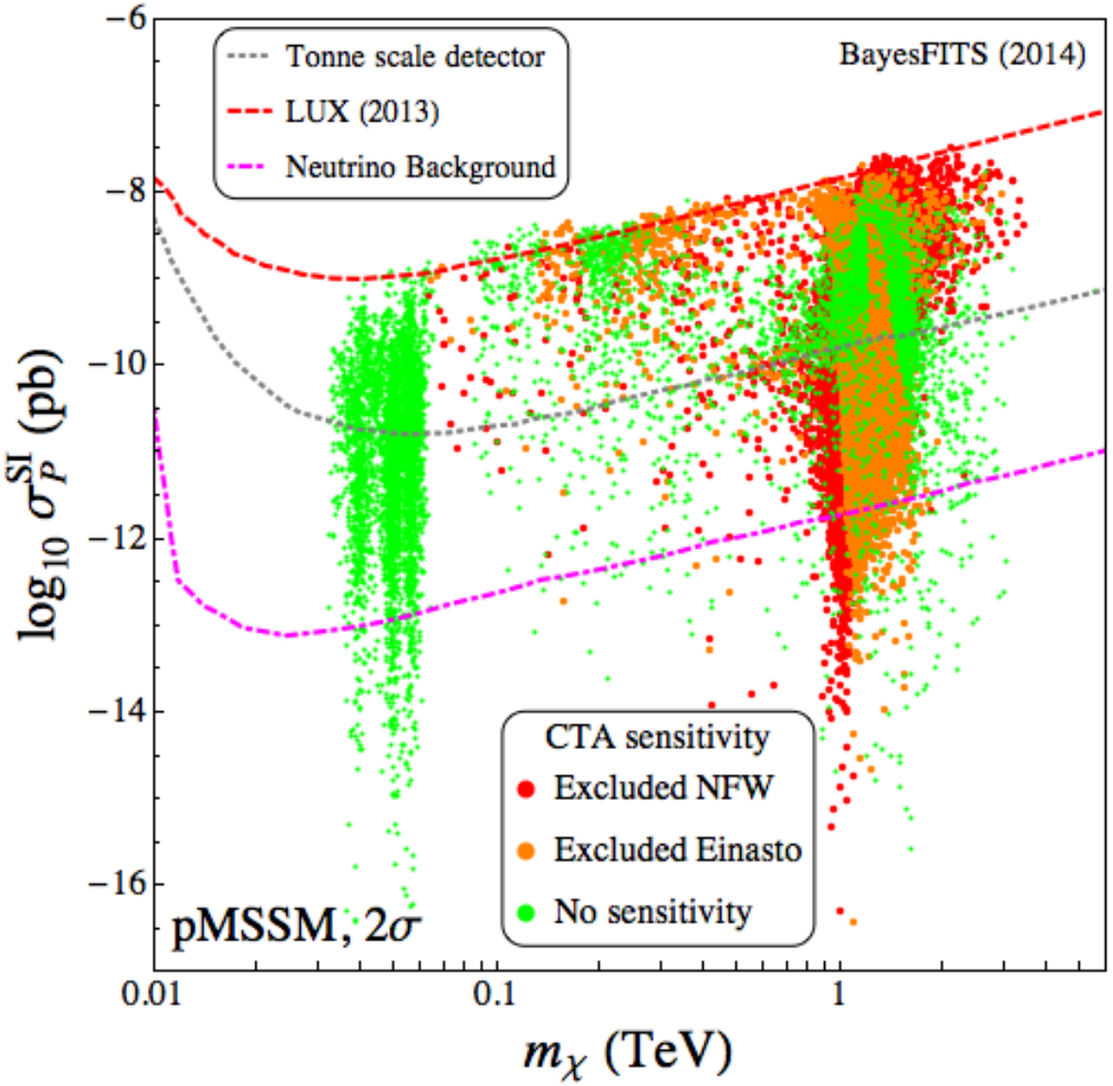
Focus on Wino and Higgsino DM

➡ *Compressed particle spectra expected naturally due to SU(2) gauge multiplet structure*

Neutralino DM - Status & Prospects -

L. Roszkowski et al., Rep. Prog. Phys. 81, 066201 (2018)

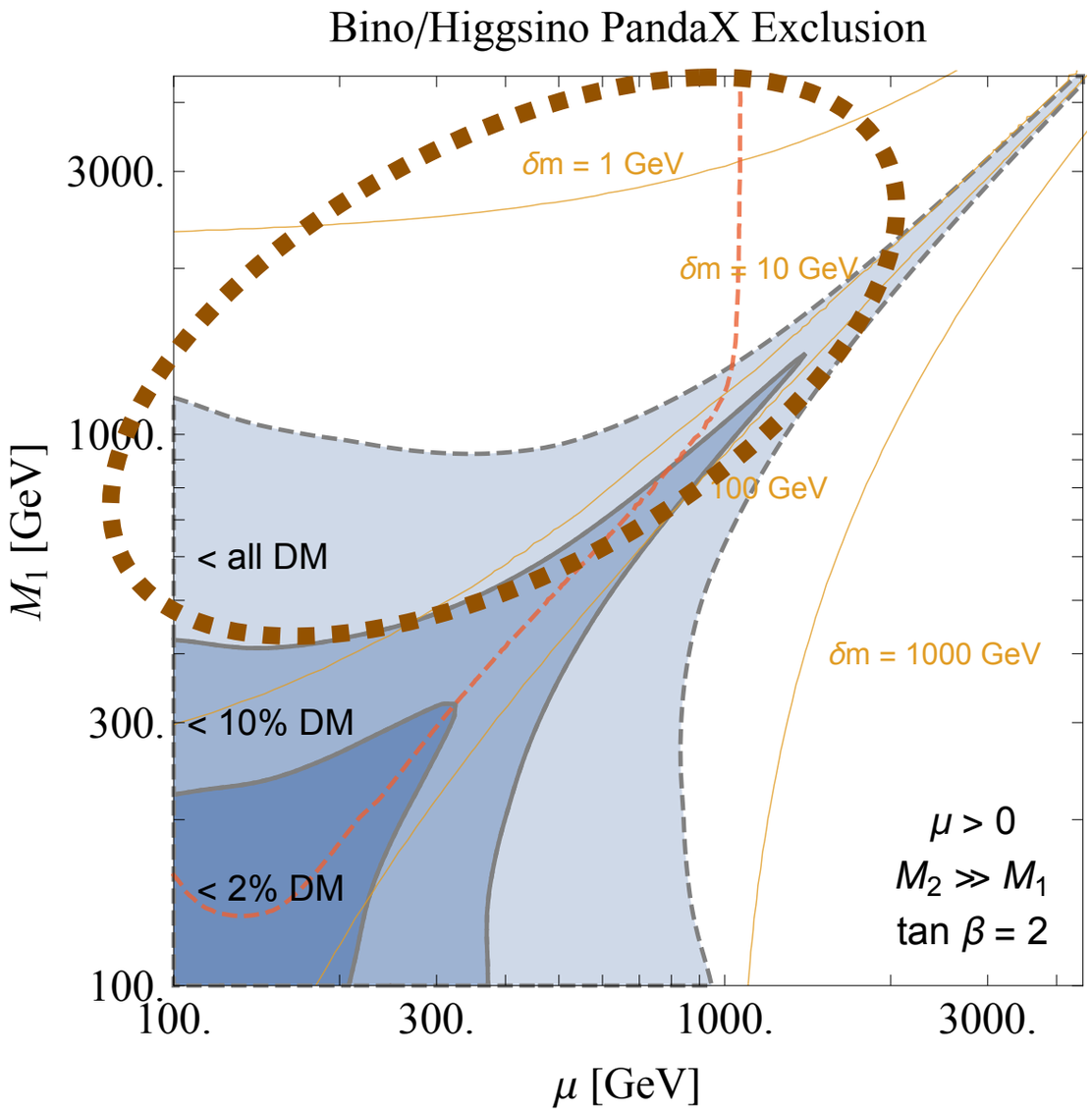


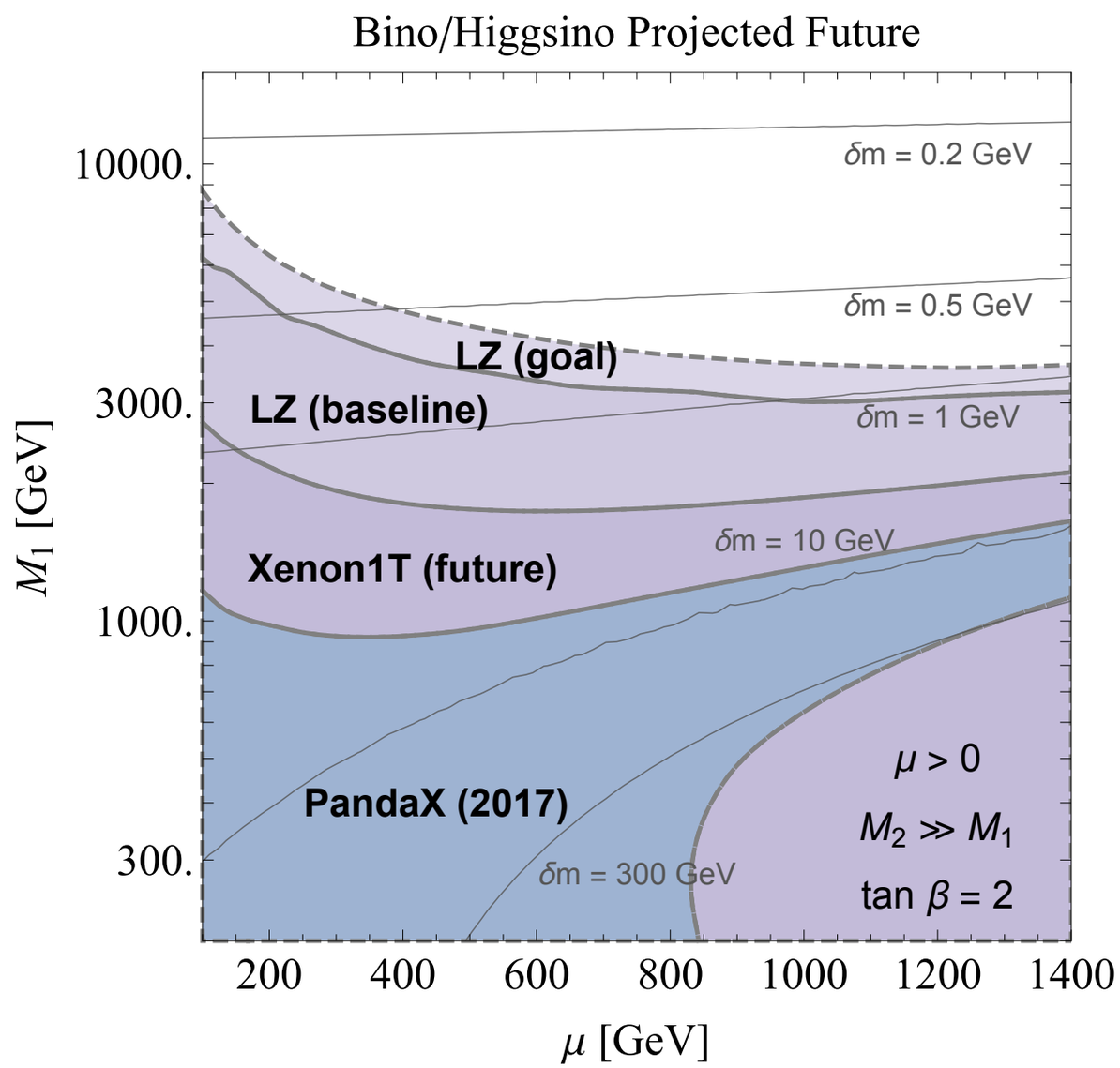


- Pure Wino DM constrained by indirect detection (with astrophysical uncertainty)
- Strong constraint from direct detection on nearly pure Higgsino DM
- Direct detection/future lepton colliders more sensitive to *Z*/Higgs-pole regions

Neutralino DM - Status & Prospects -

R. Krall, M. Reece, Chin. Phys. C 42, 043105 (2018)





- Mixed Bino/Higgsino states also constrained by direct detection while sensitivity depends on the mass splitting $\delta m = m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$

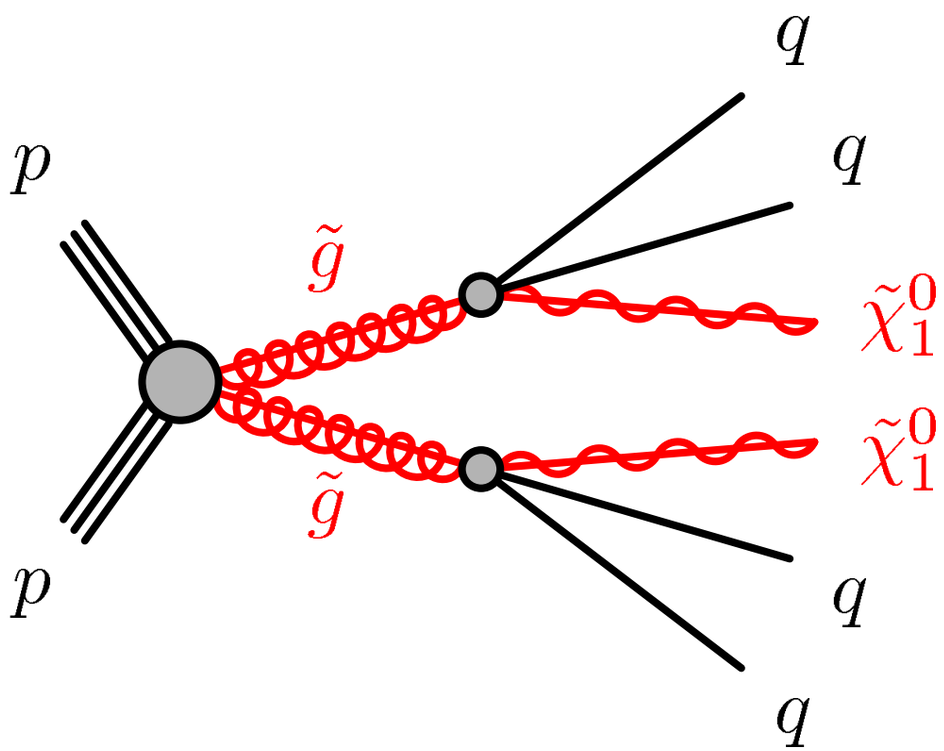
➡ What can collider do for mixed states (e.g, Bino-Wino, Bino-Higgsino) at $\delta m \sim \mathcal{O}(0.1\text{-}10)$ GeV?

Neutralino DM at Colliders

General search strategy for neutralino DM at LHC

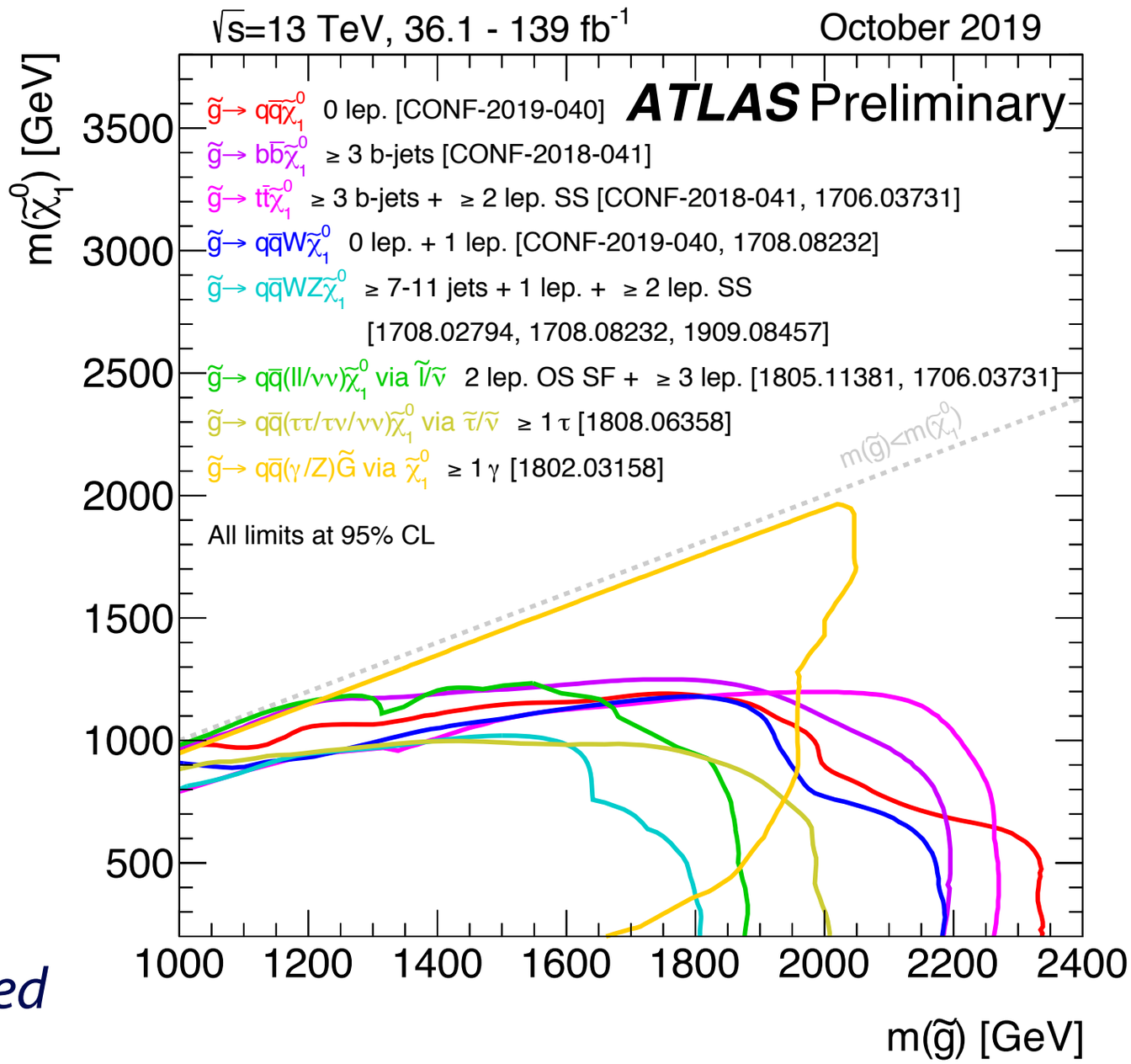
Consider accompanying particles when looking for DM in SUSY

- **Production in gluino/squark decays** (if they are not too heavy)



$m(\tilde{\chi}_1^0)$ excluded up to ~1 TeV
for $m(\tilde{g})$ ~2 TeV

Under simplified model where only colored particles and DM are considered

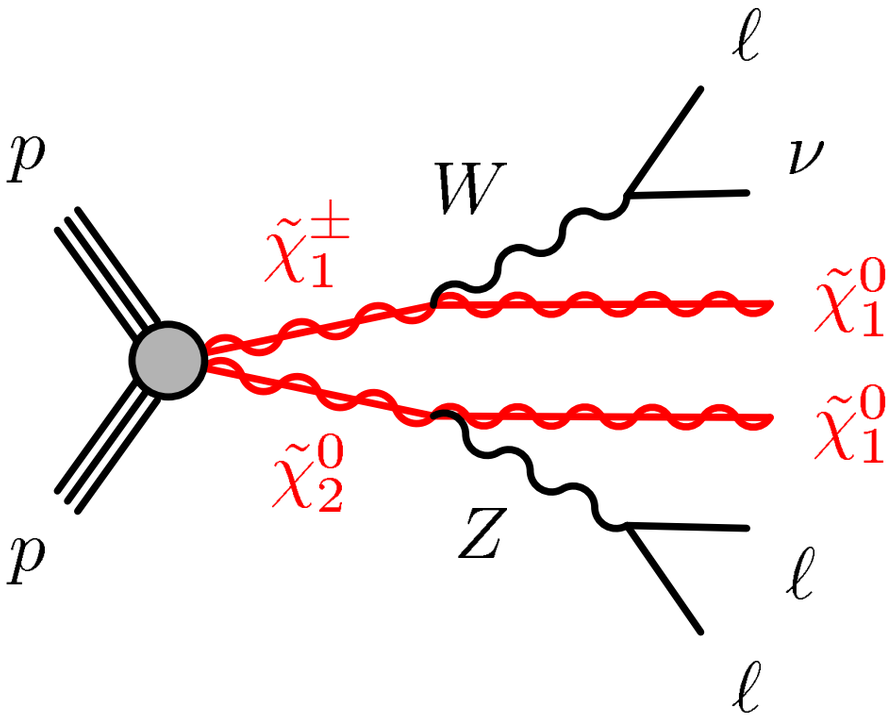


Neutralino DM at Colliders

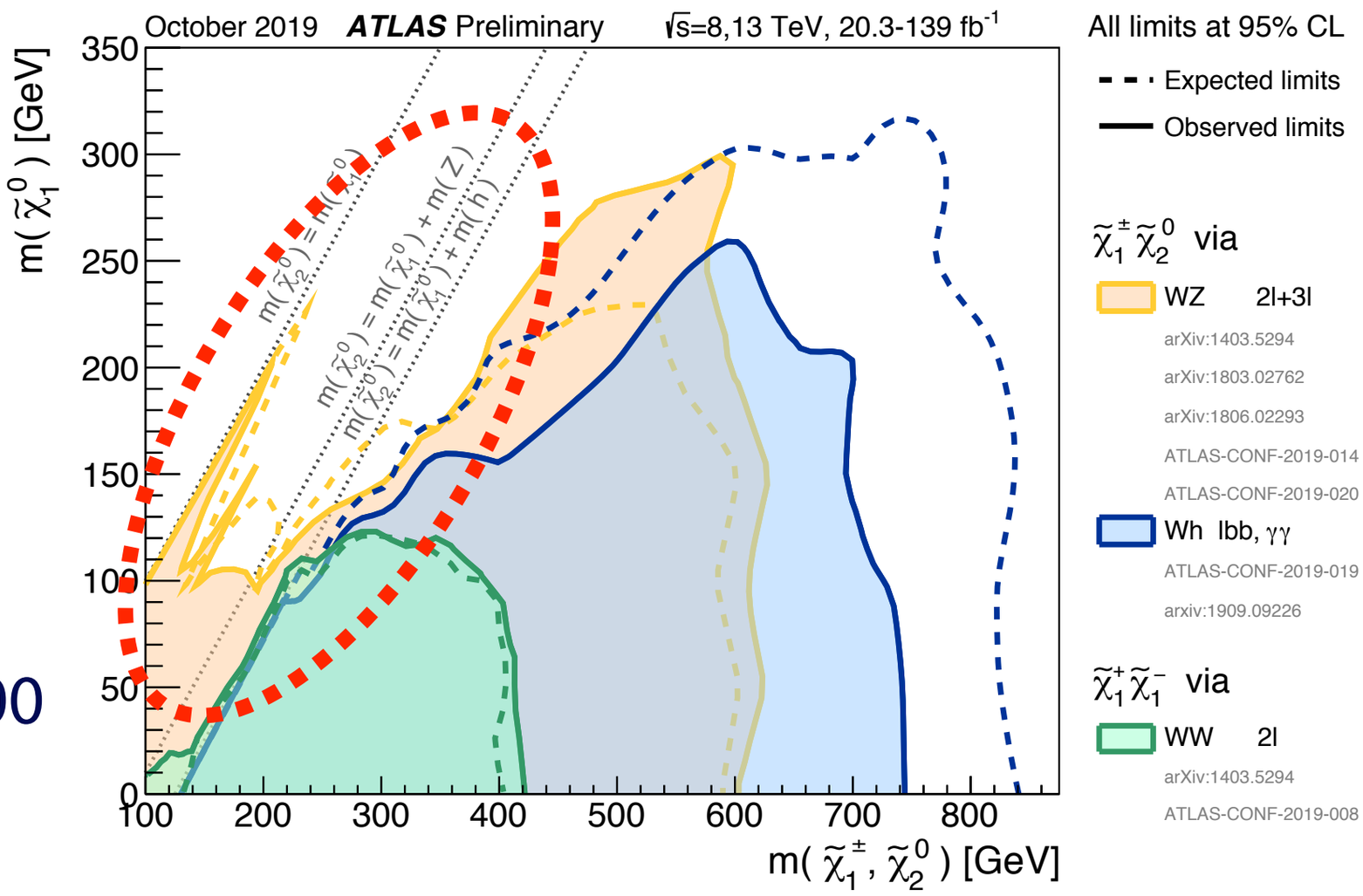
General search strategy for neutralino DM at LHC

Consider accompanying particles when looking for DM in SUSY

- **Production in gluino/squark decays** (if they are not too heavy)
- **Direct production with weak iso-spin partners**



$m(\tilde{\chi}_1^0)$ excluded up to ~300 GeV, but much weaker for "compressed" region

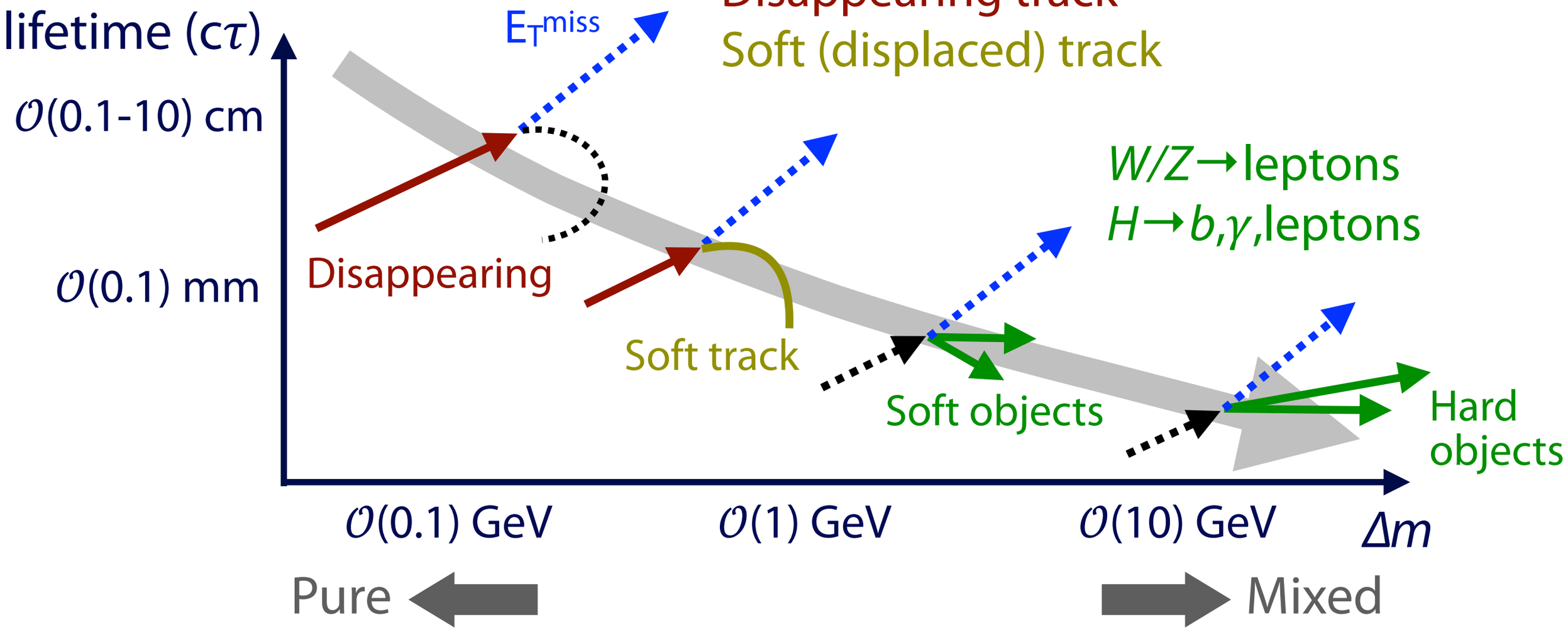


Neutralino DM at Colliders

Search strategy for direct production with weak iso-spin partners

Signature depends on compositions/masses of electroweakino states

- Decay mode : $\tilde{\chi}_1^{\pm} \to W^{\pm}/\pi^{\pm} + \tilde{\chi}_1^0 \quad \tilde{\chi}_2^0 \to Z/H + \tilde{\chi}_1^0$
- Mass splitting : $\Delta m_{\pm} = m(\tilde{\chi}_1^{\pm}) - m(\tilde{\chi}_1^0) \quad \Delta m_0 = m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$

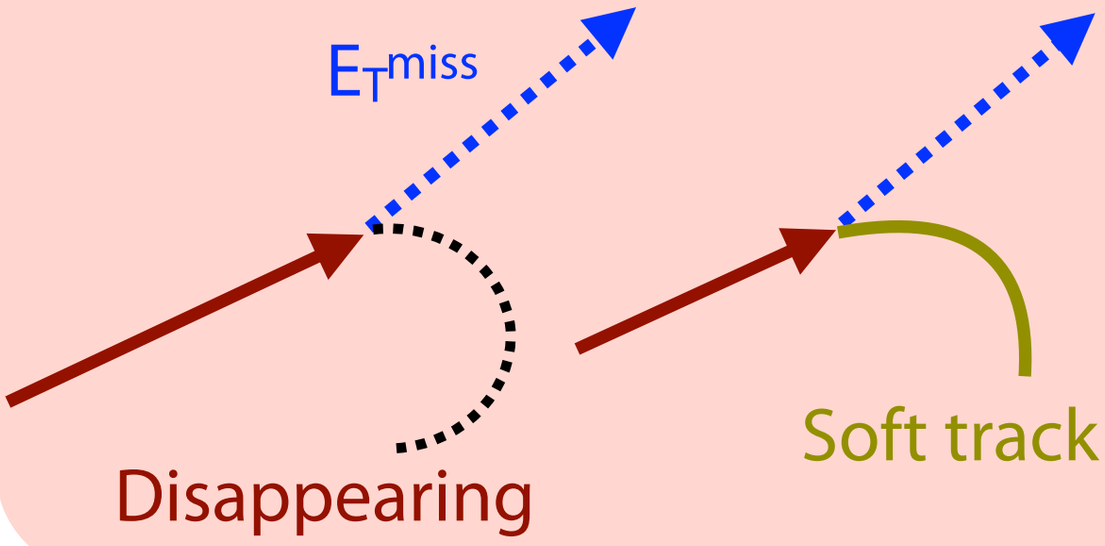


Search for Direct Production

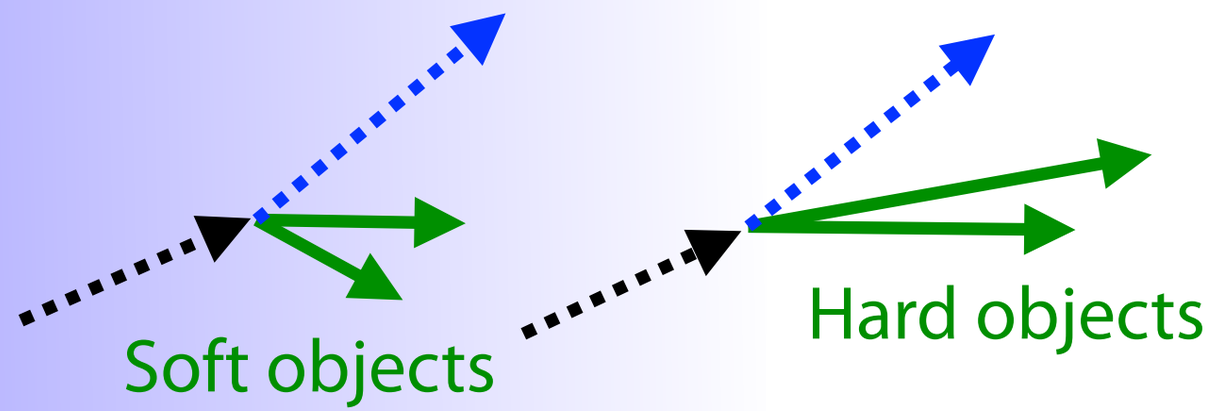
Target in this talk : mixed states with $\Delta m \sim \mathcal{O}$(1-10) GeV

- ➡ high(low)-p_T leptons from on(off)-shell W/Z decay
- ➡ ISR jet or VBF jets to boost DM system (trigger, reconstruction)
- ➡ large E_T^{miss} (trigger)

R. Sawada's talk



My talk



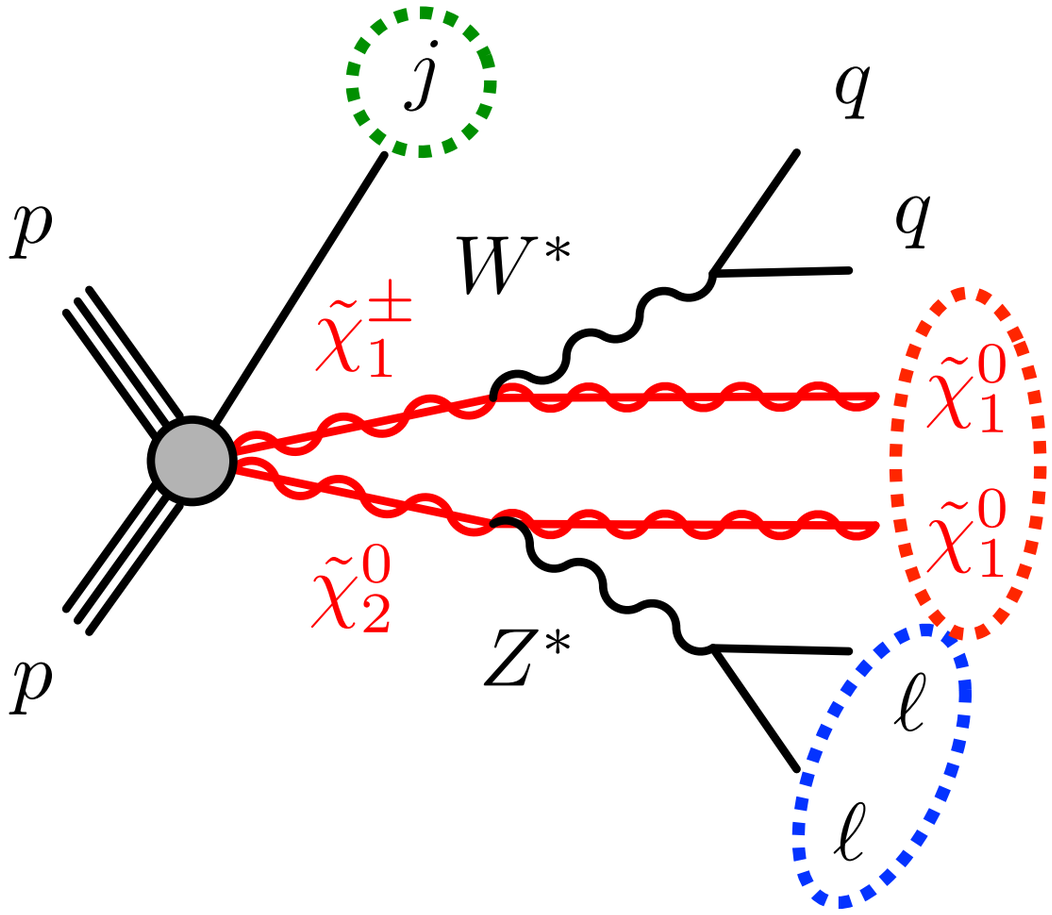
Focus on compressed signature searches (not exhaustive) in this talk

Compressed Signatures (I)

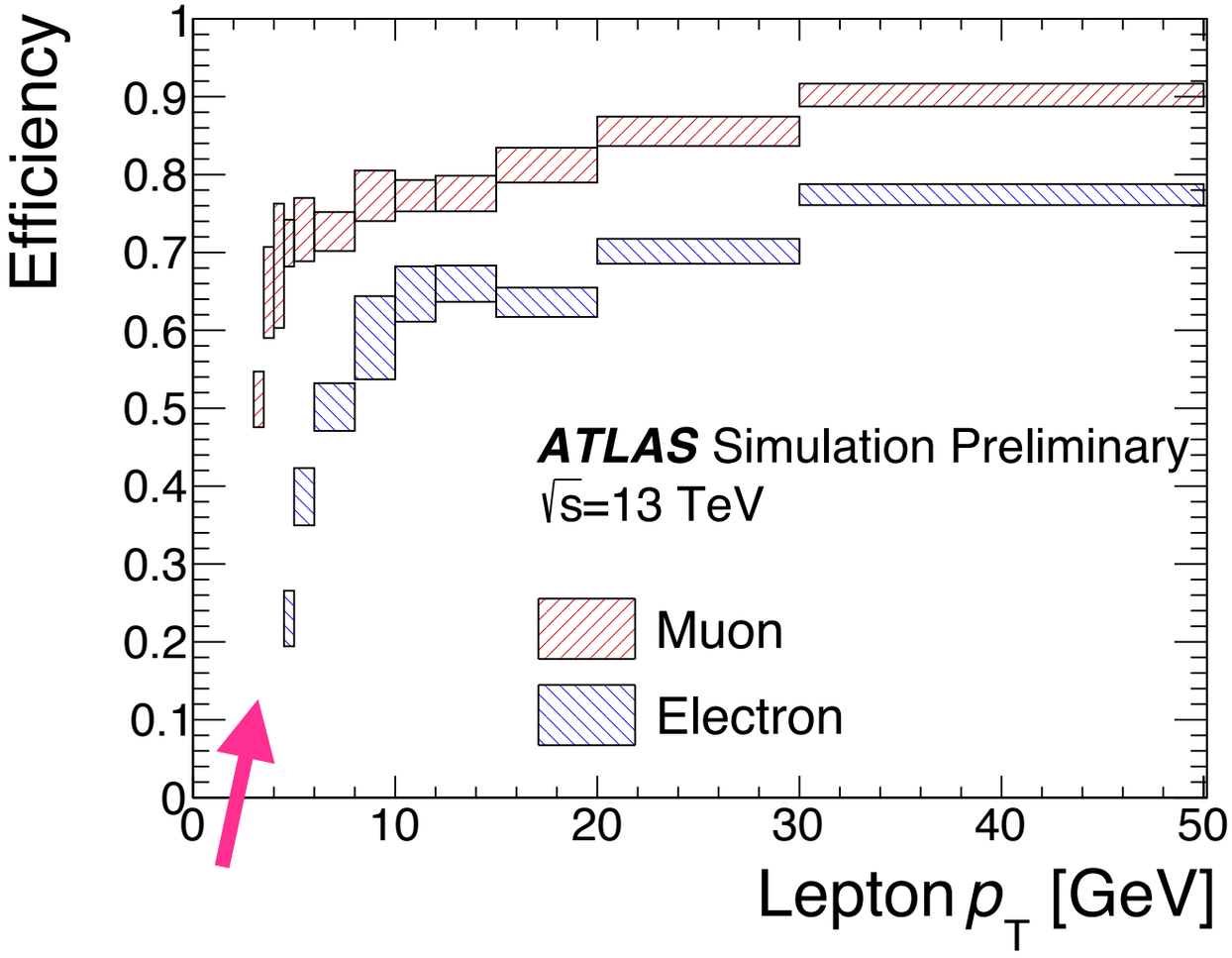
Multi-leptons + ISR jet + E_T^{miss} for DY production

ATLAS-CONF-2019-014

- ➡ low-p_T leptons from off-shell *W/Z*
- ➡ large E_T^{miss} (trigger) + ISR jet to boost DM system



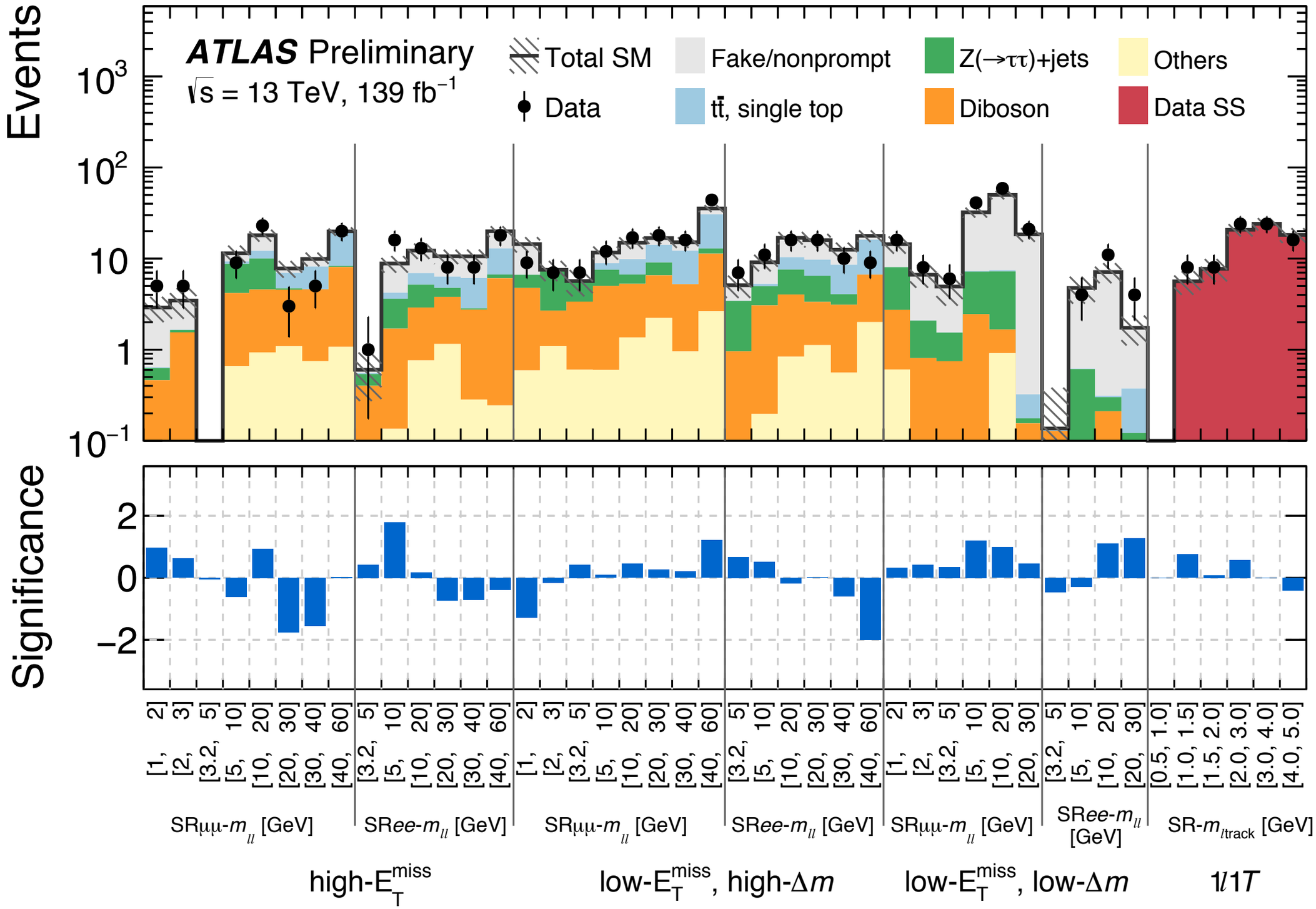
Low-p_T efficiency is a key!!



2-leptons and 1-lepton+1-track (to recover lepton inefficiency at low p_T)

Multiple signal regions to target signal with different E_T^{miss} and Δm values

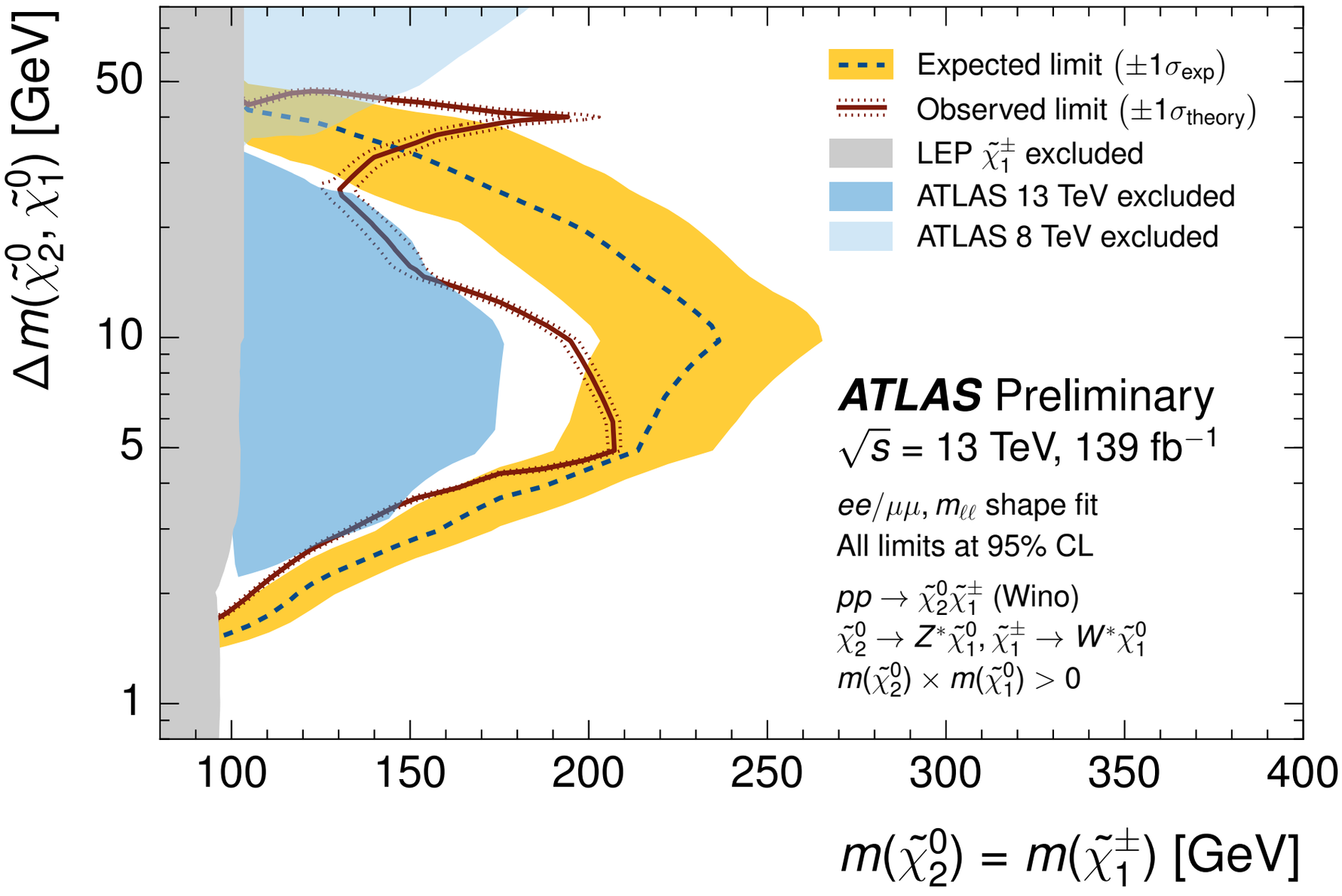
Multi-Lepton Searches



No significant deviations from background predictions

Multi-Lepton Searches

Bino-Wino



- Obs. limits worse or better than Exp. limits due to fluctuations in data
- 1-lepton+1-track contributes to small Δm region, but only marginal

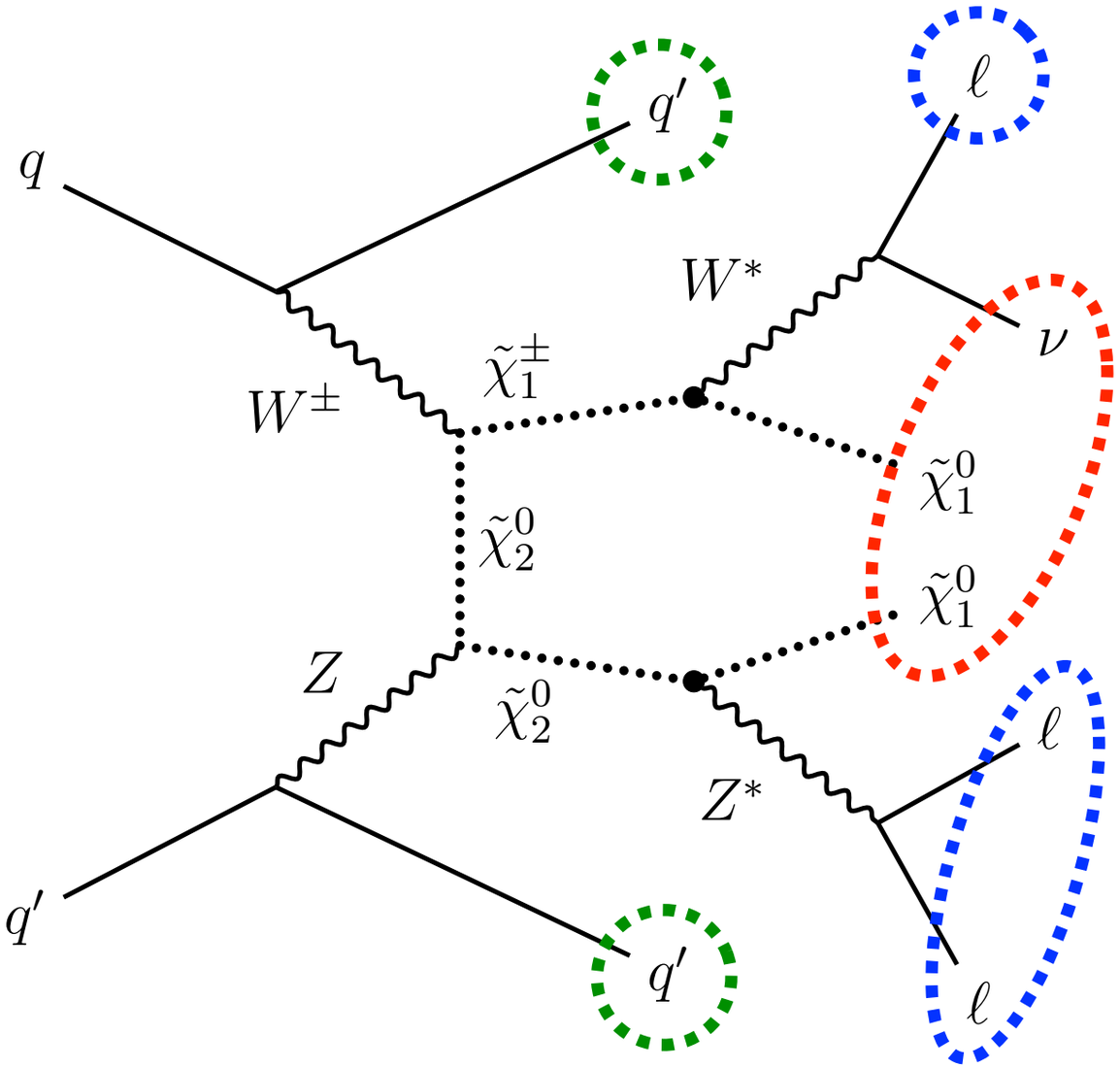
➡ Important to improve (very) low-p_T lepton tagging to go smaller Δm

Compressed Signatures (II)

JHEP 08 (2019) 150

Leptons + forward jets + E_T^{miss} for VBF production

- ➡ low-p_T lepton from off-shell *W/Z*
- ➡ large E_T^{miss} and H_T^{miss} (trigger) + VBF jets to boost DM system



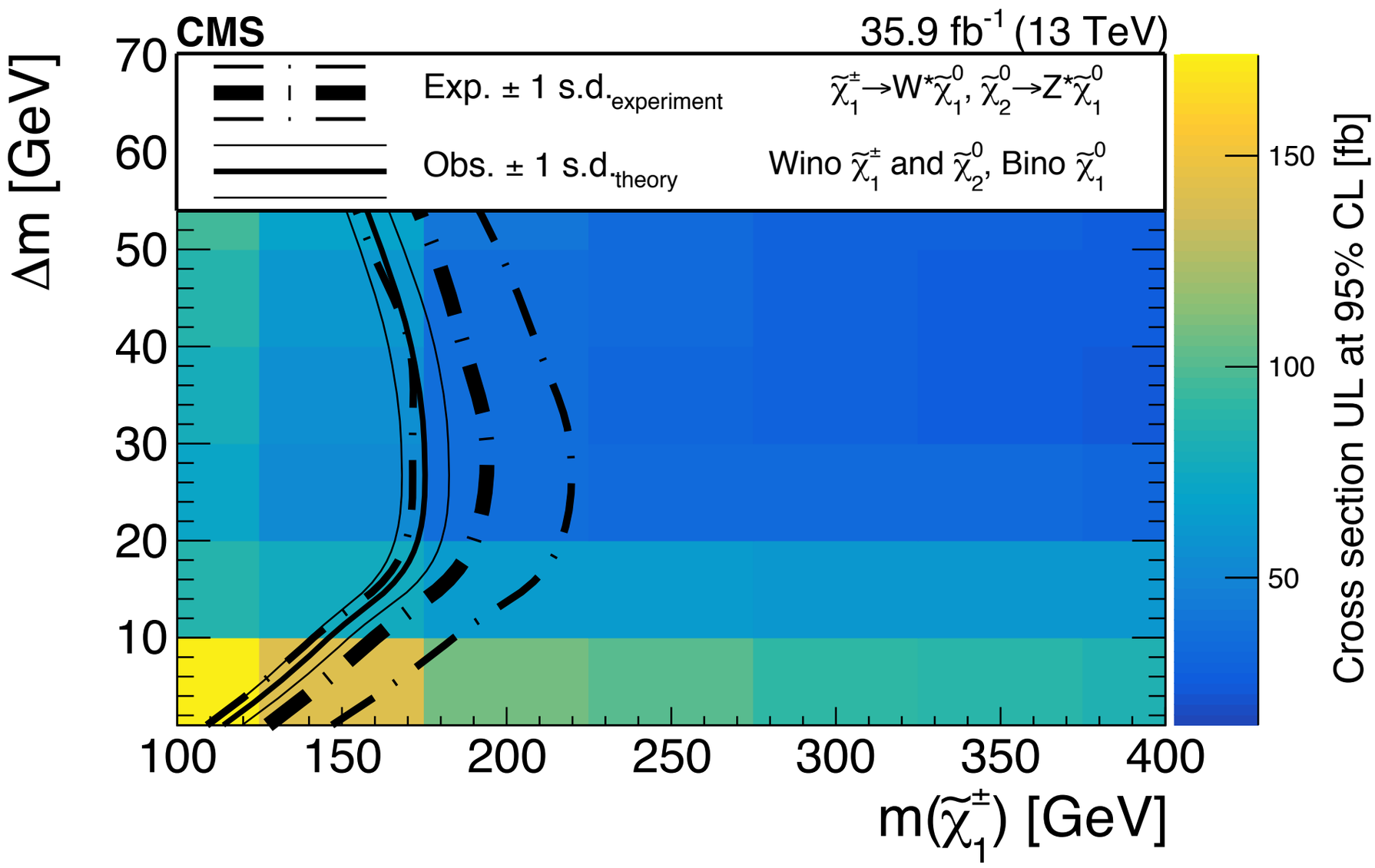
Accessible to small *Δm* by boosting the DM system while suppressing BG using forward jets

0-lepton and 1-lepton (μ, e, τ_{had}) channels

(leptons often too soft to be reconstructed)

VBF Topology Searches

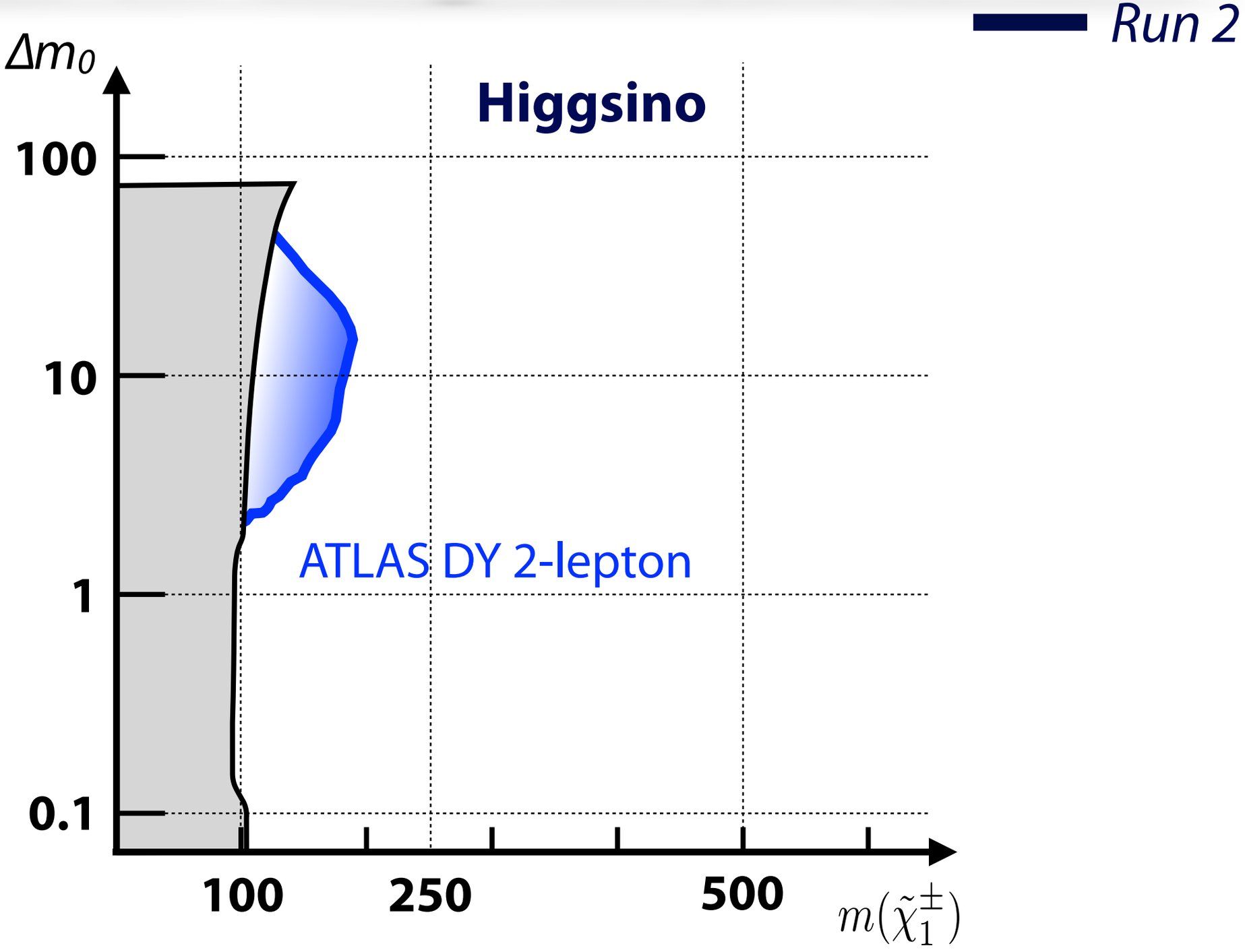
Bino-Wino



- Sensitivity to $\tilde{\chi}_1^{\pm}$ with 100-150 GeV in the range $1<\Delta m_0<10$ GeV
- 0-lepton channel dominates sensitivity at small Δm_0 ~1 GeV

➡ Good complementarity by the 0-, 1- and 2-lepton channels

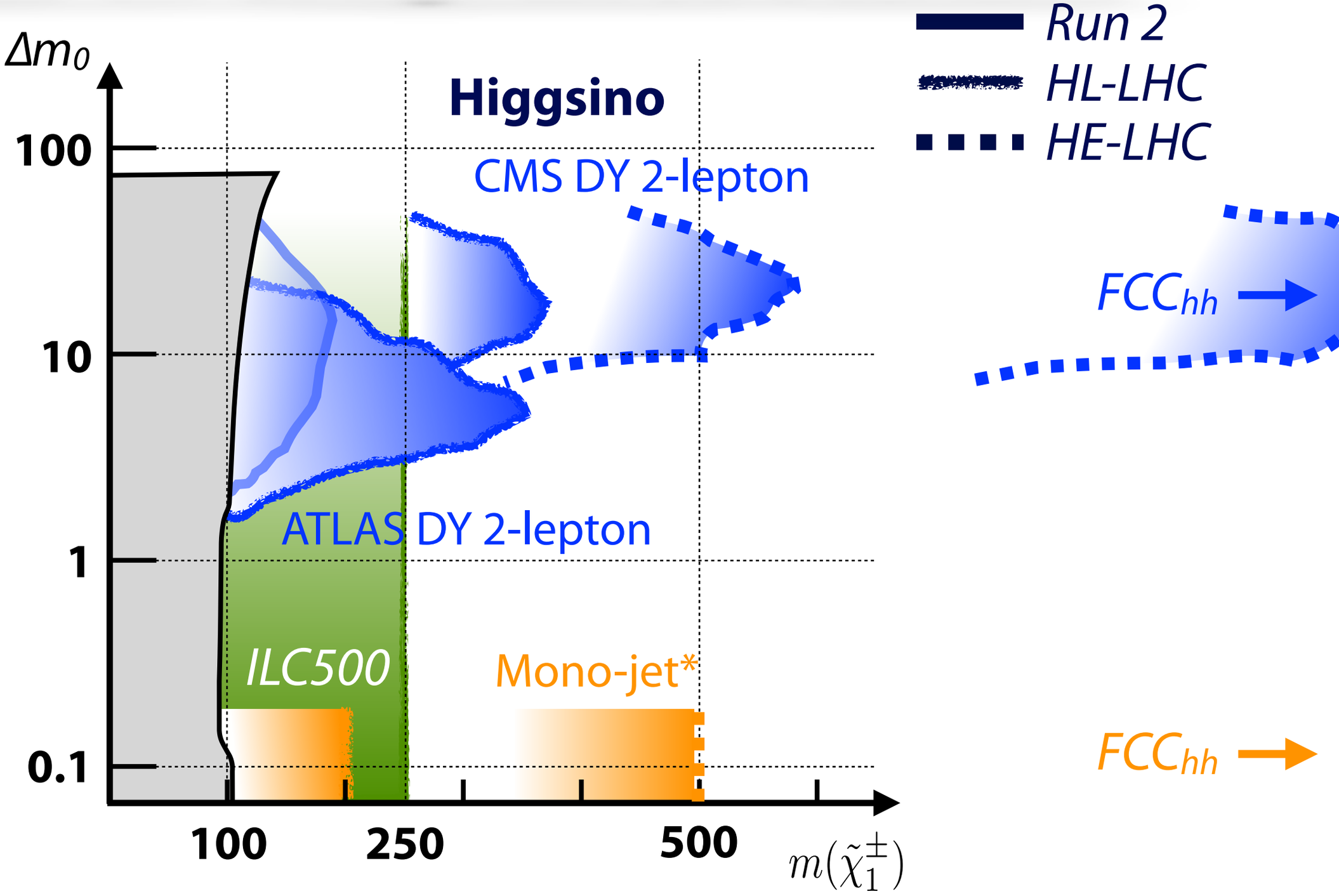
Bounds on Compressed Scenario



No Higgsino interpretation for the VBF result…

Bounds from disappearing track not shown here

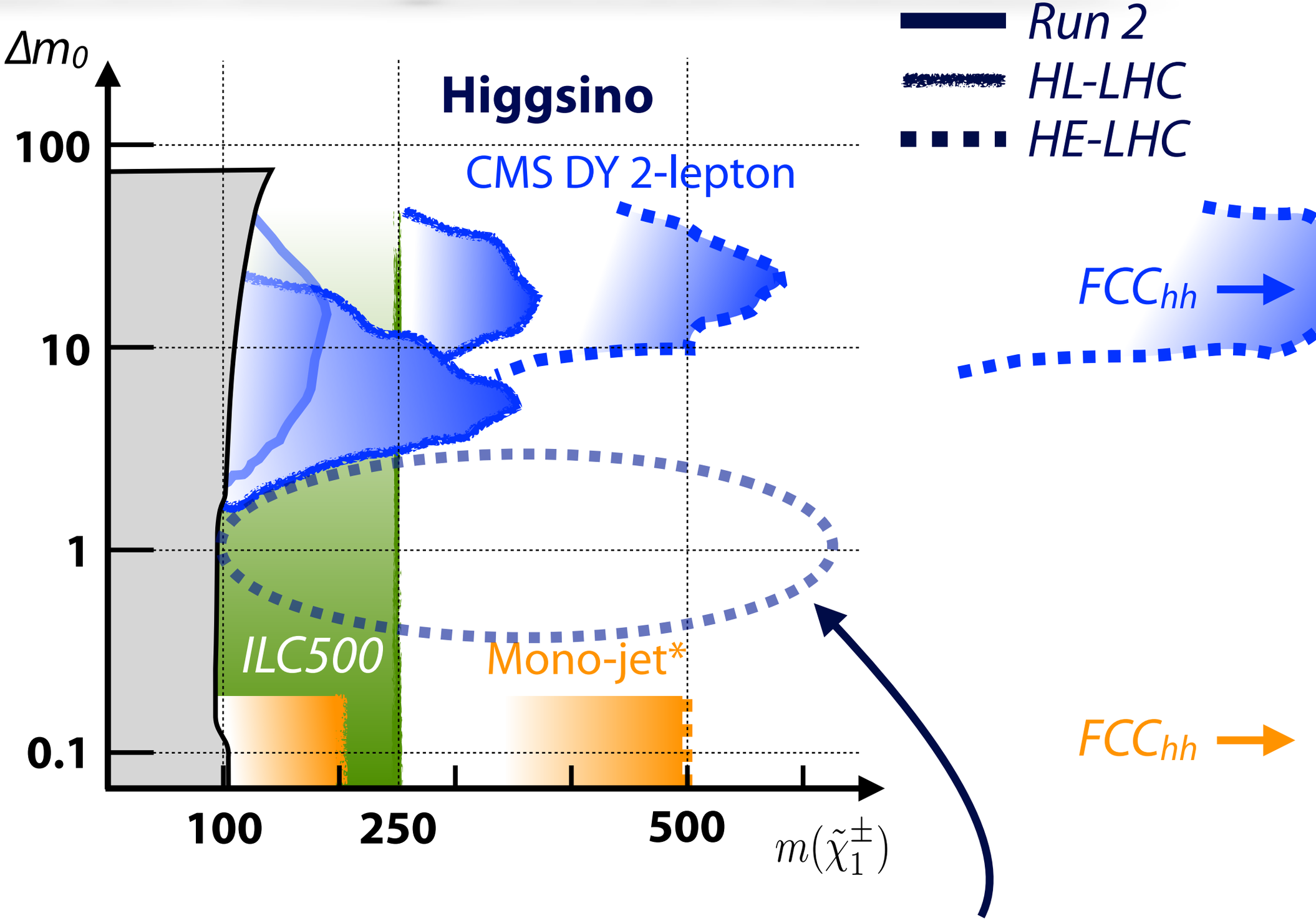
Bounds on Compressed Scenario



Projections for future colliders (Lepton collider sensitive up to √s/2)

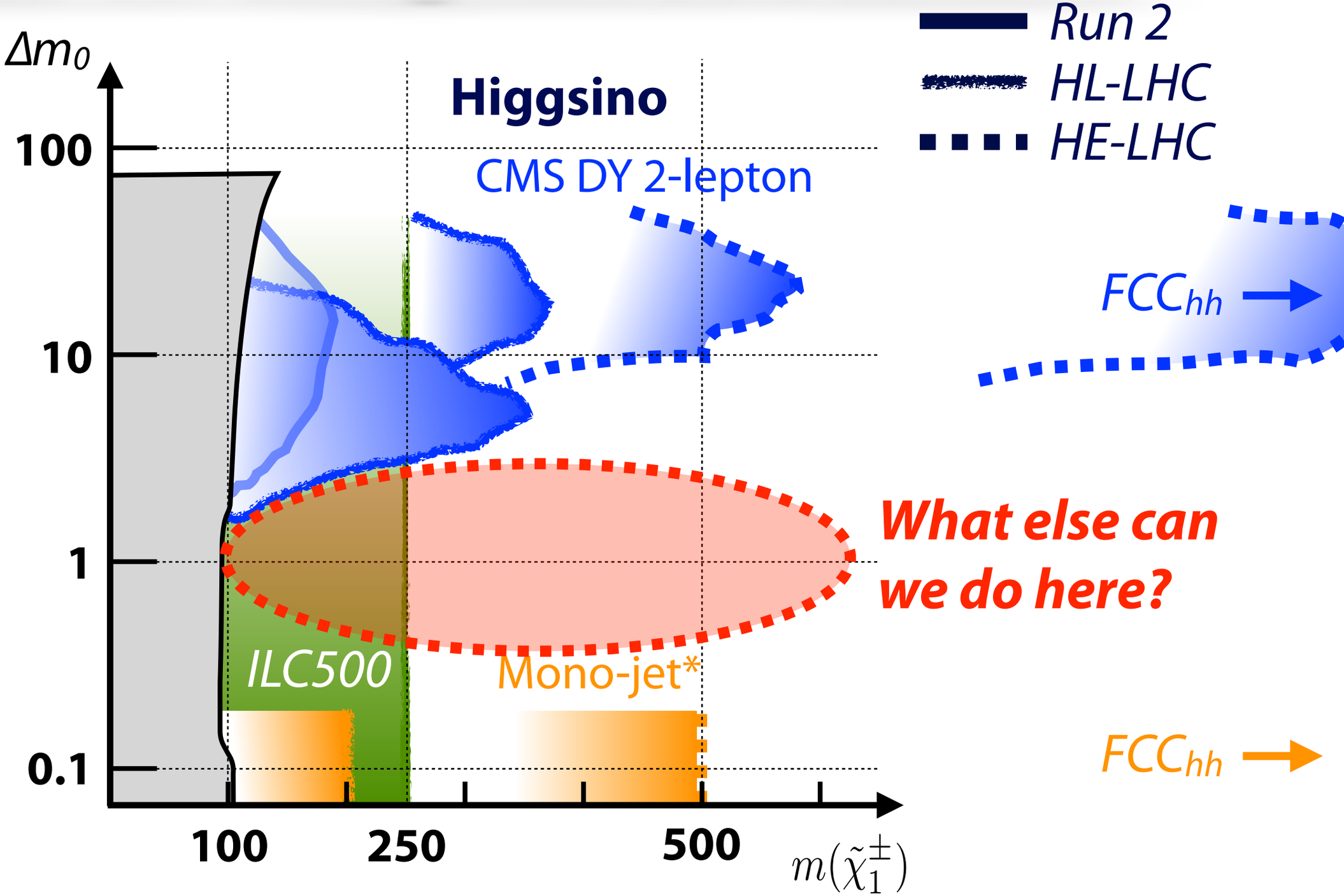
HL/HE-LHC Yellow Report
Physics Briefing Book (2020 ESU)

Bounds on Compressed Scenario



Interesting to explore this phase space with VBF analysis

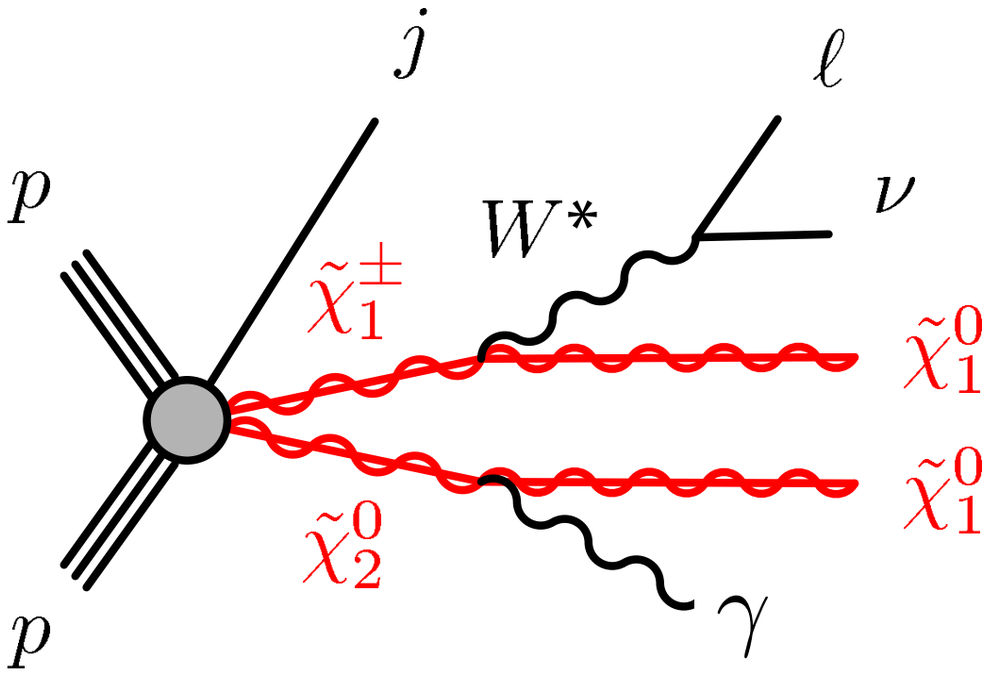
Bounds on Compressed Scenario



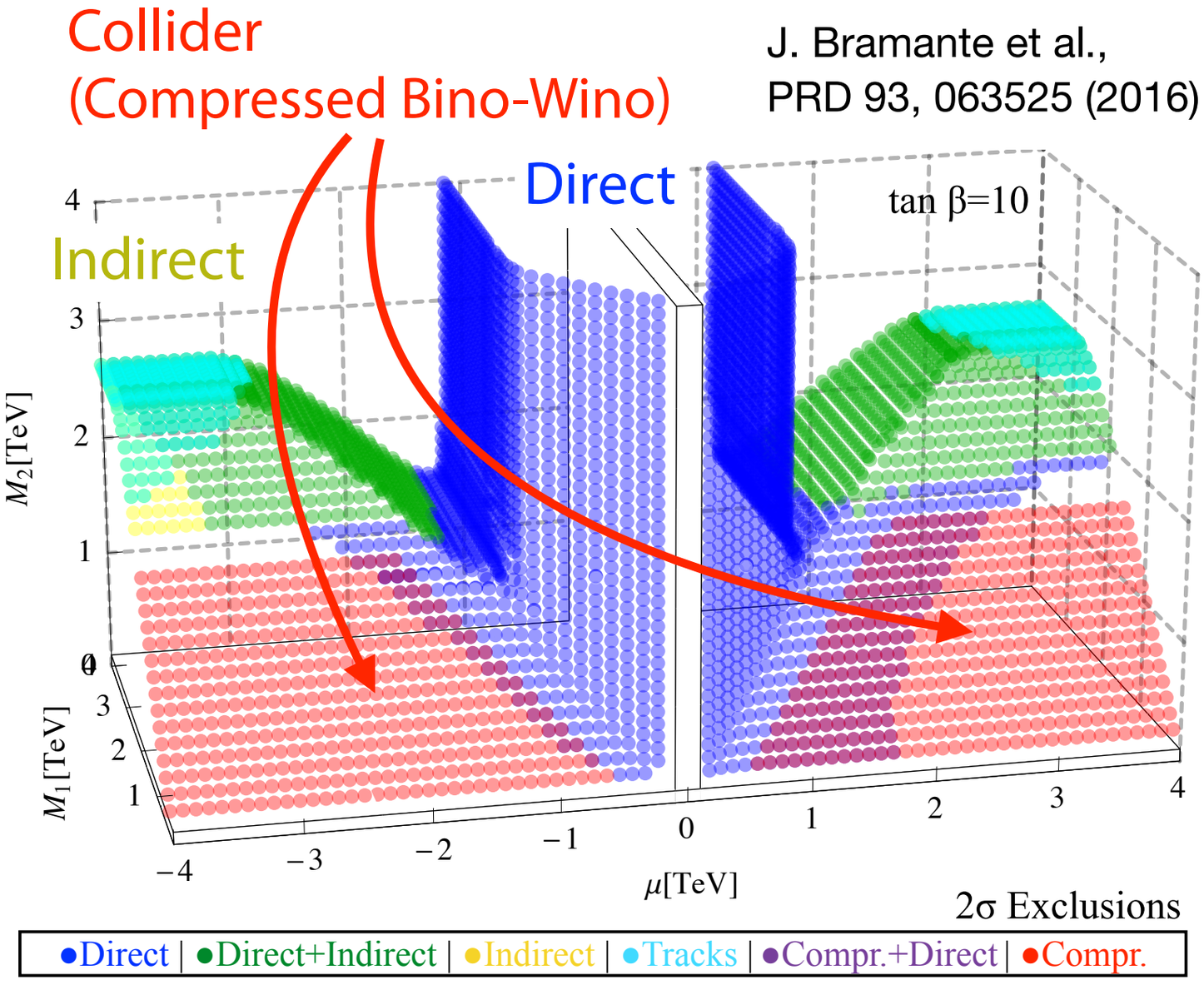
Δm~1 GeV region to be filled with new techniques

(→ See R. Sawada's talk for track-based approaches)

Compressed Searches - Option 1 -



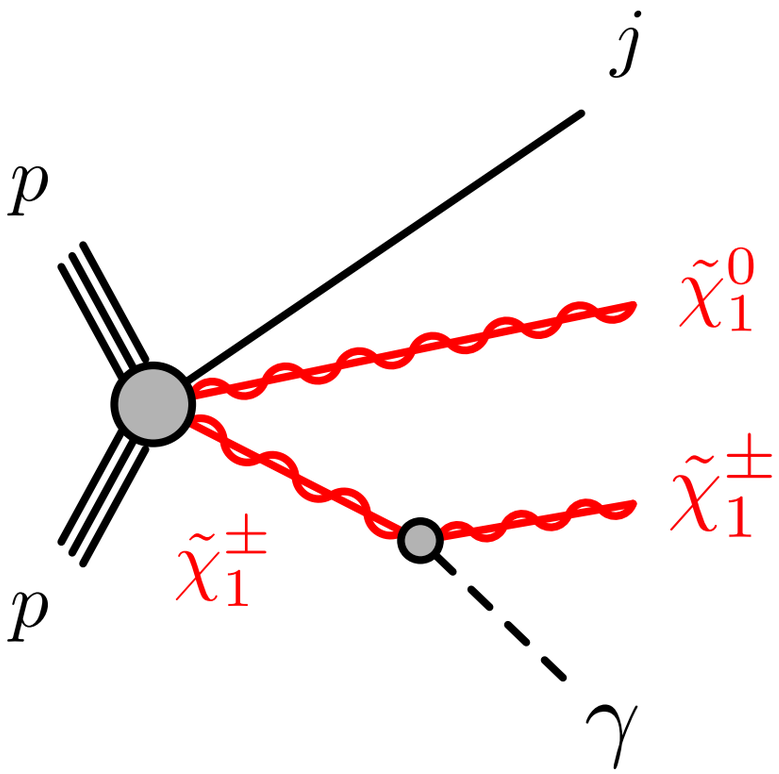
Exploit soft photon from $\tilde{\chi}_2^0 \to \gamma + \tilde{\chi}_1^0$ to access intermediate Δm_0 range



- Bino-Wino (Δm_0~10-40GeV) probed up to ~1.6 TeV at 100 TeV, 10 ab^{-1}
- Very little sensitivity from direct or indirect searches

➡ Unique advantage of future 100 TeV collider for compressed Bino-Wino scenario

Compressed Searches - Option 2 -

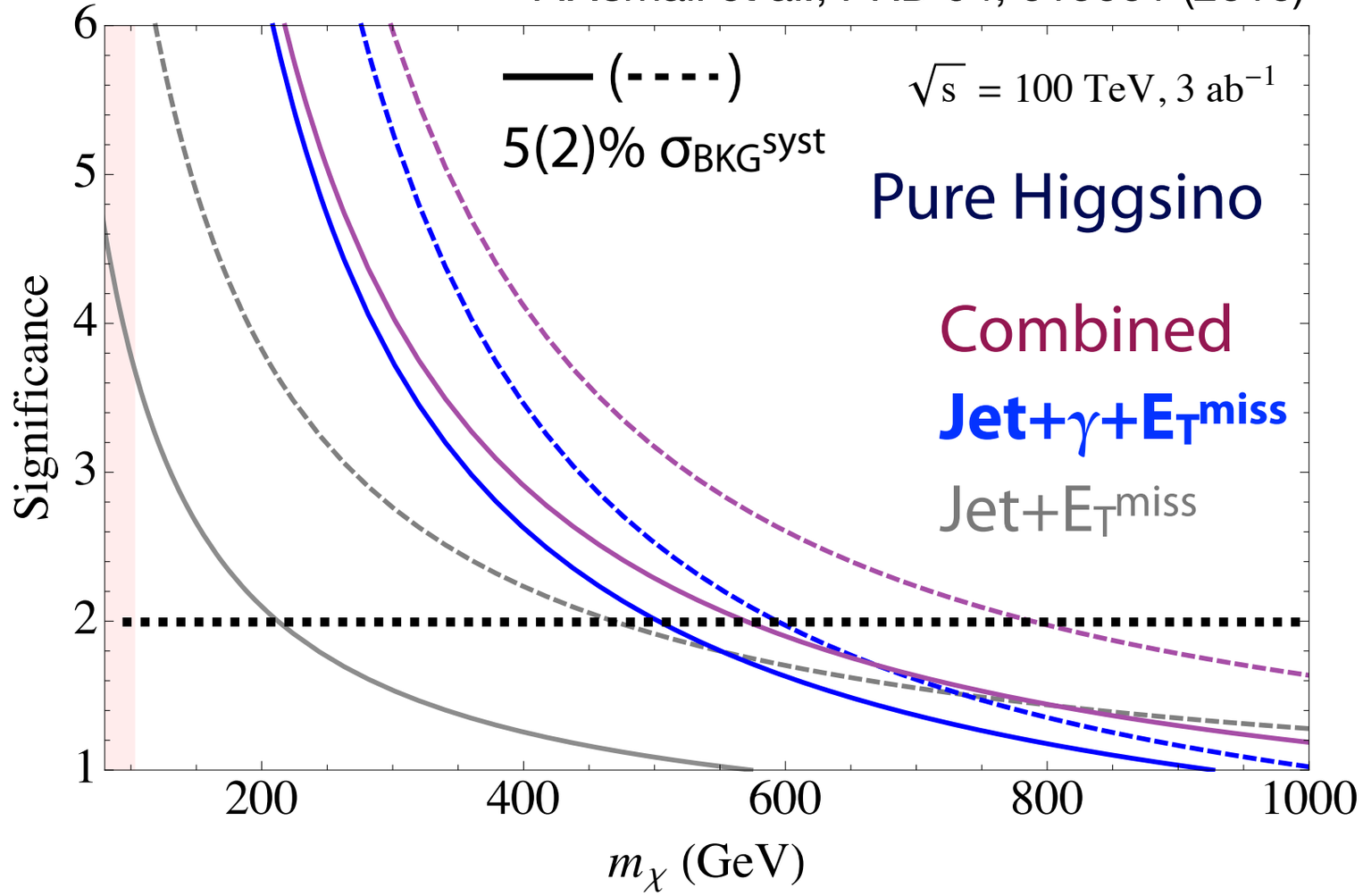


Exploit FSR photon from $\tilde{\chi}_1^\pm$
(no look at $\tilde{\chi}_1^\pm$ decay)

➔ Insensitive to $\Delta m_\pm$!!

Expected significance at 100 TeV collider

A. Ismail et al., PRD 94, 015001 (2016)



- Pure Higgsino ($\Delta m_\pm$~350MeV) probed up to ~(130)500 GeV at 14(100) TeV

➡ Potentially no "blind spot" in this analysis?
Good to demonstrate the performance with (HL-)LHC data!

Summary

- Neutralinos composed of Wino, Higgsino or mixed states are promising DM candidates
- Compressed spectra posing experimental challenge at hadron collider
- Several new ideas emerging to further constrain compressed states at hadron collider (→ *More in R. Sawada's talk*)

Summary

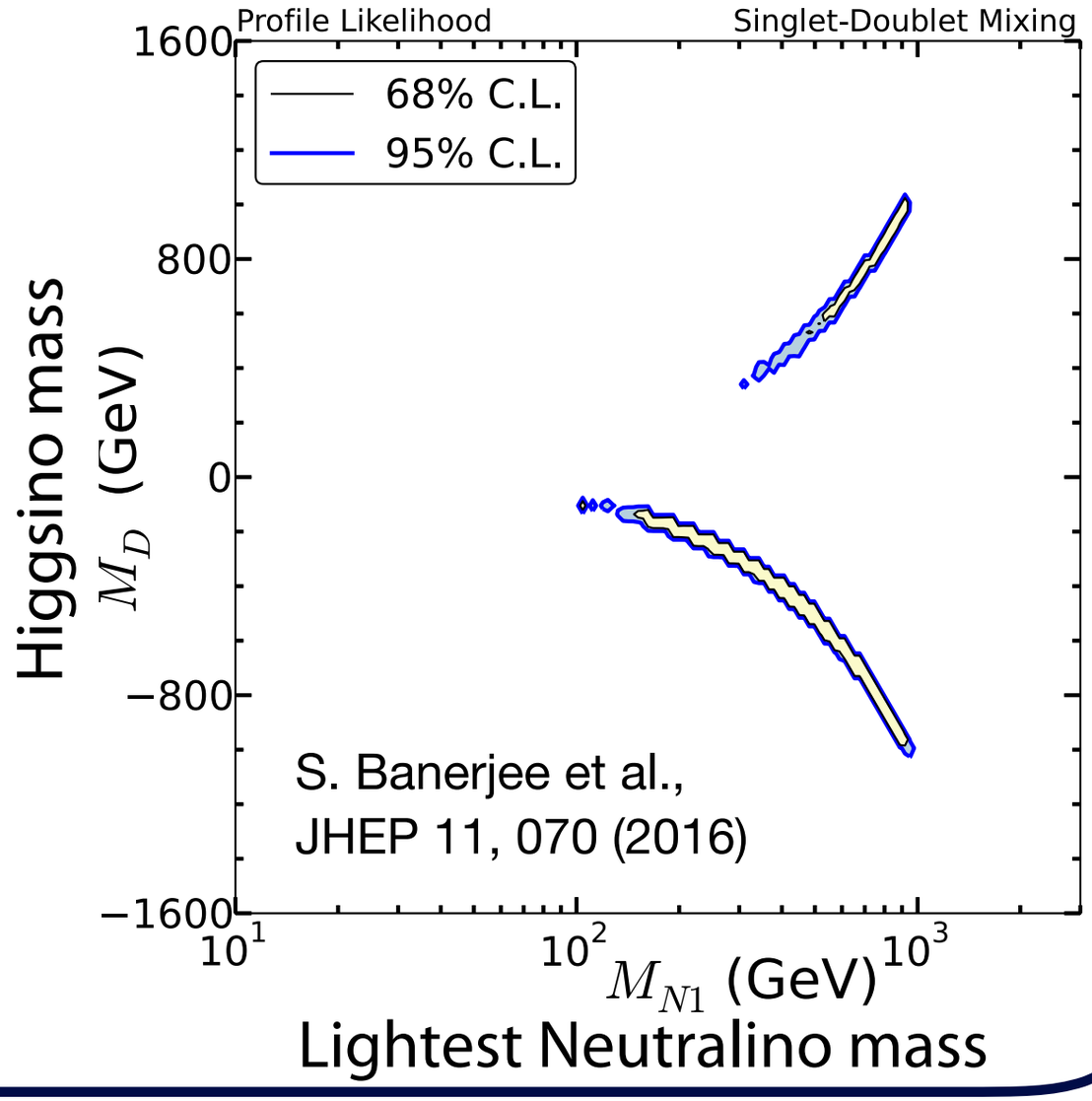
- Neutralinos composed of Wino, Higgsino or mixed states are promising DM candidates
- Compressed spectra posing experimental challenge at hadron collider
- Several new ideas emerging to further constrain compressed states at hadron collider (→ *More in R. Sawada's talk*)

Future prospects for Singlet-Doublet WIMP dark matter

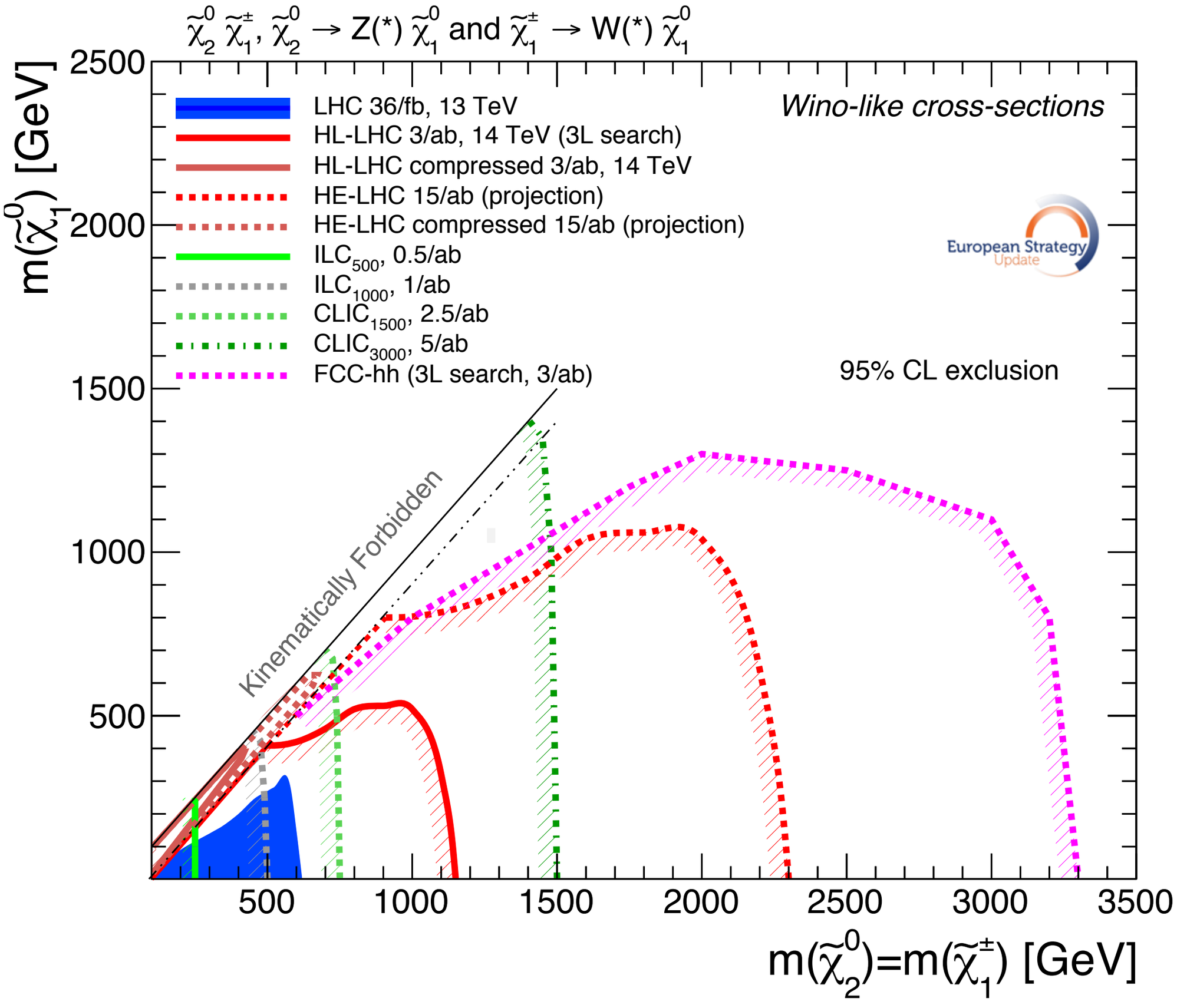
- Strong constraints from direct & indirect detections
- HL-LHC sensitivity quite limited…

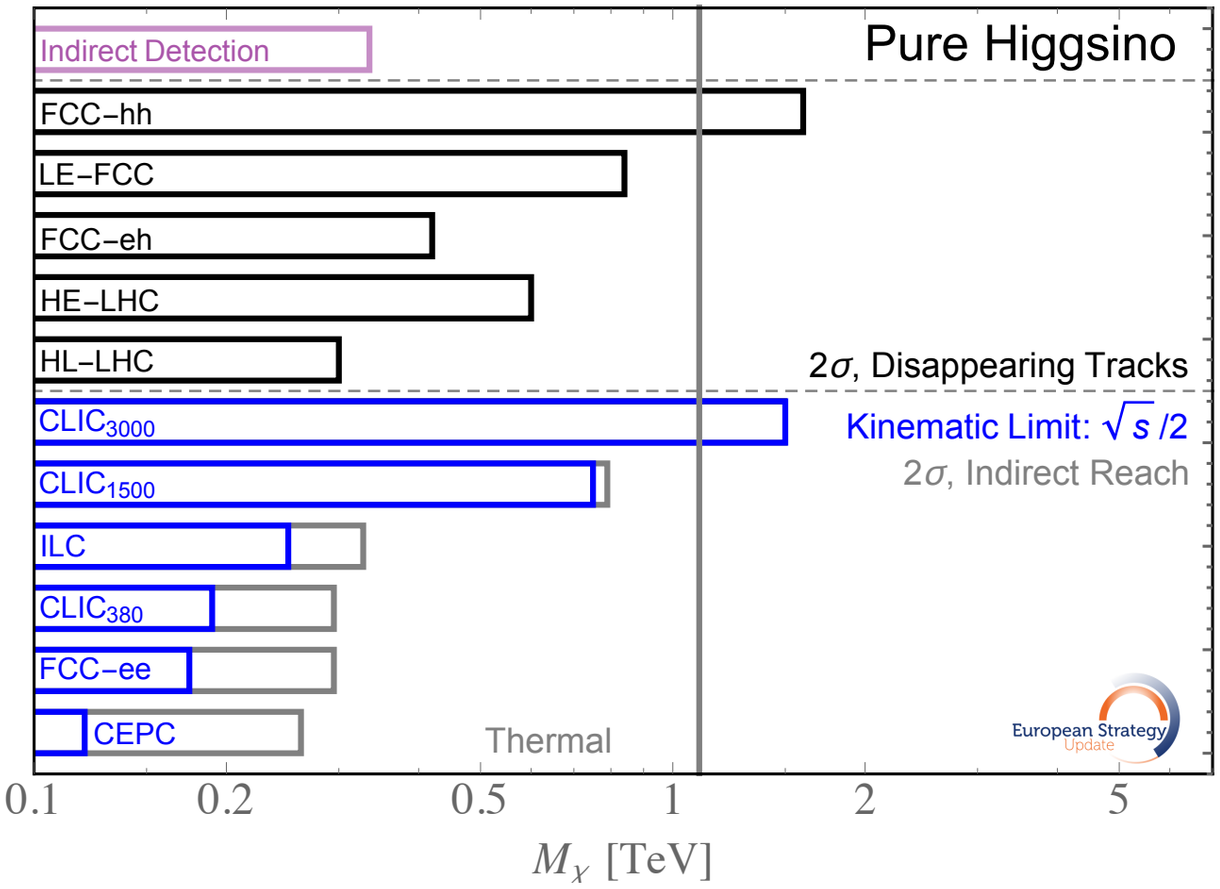
  Only on-shell W/Z analysis (p_T^{lepton}>50 GeV) available at that time

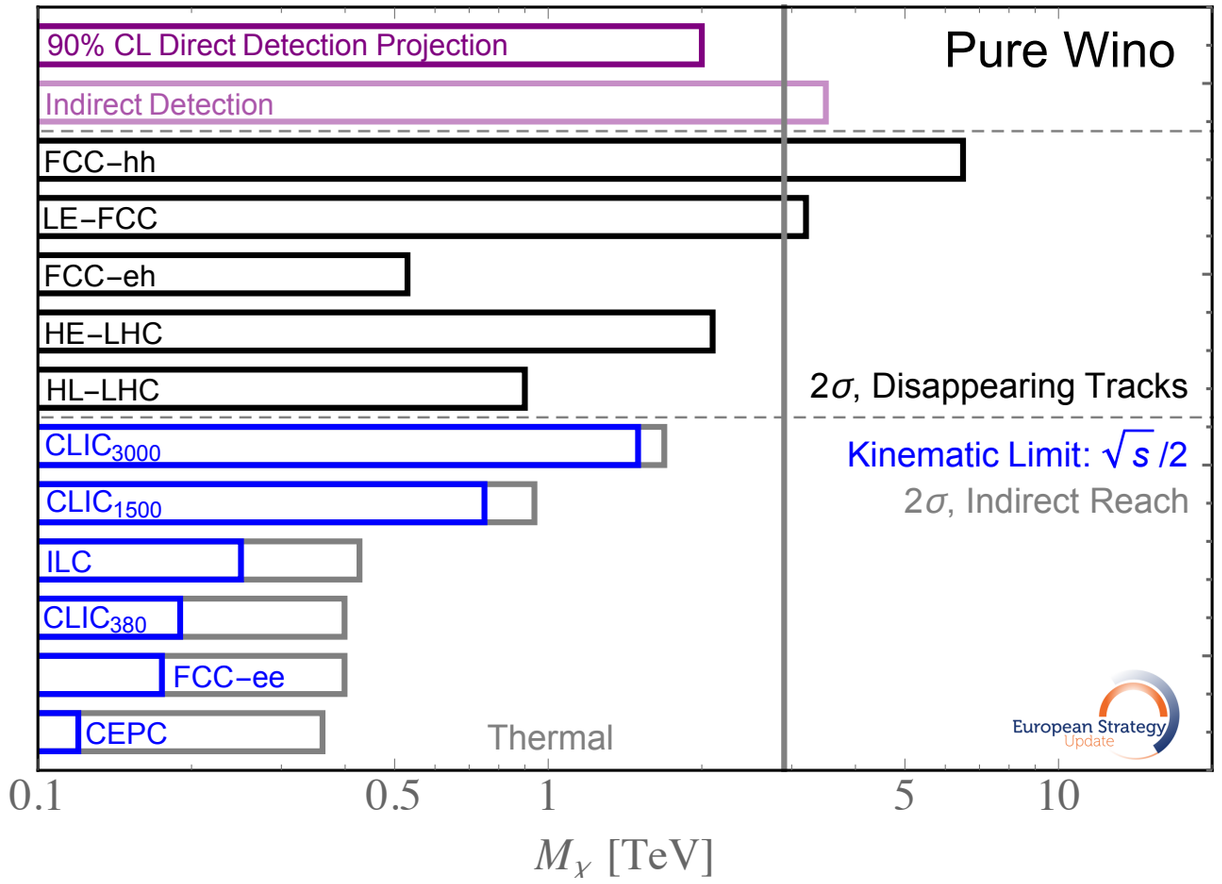
Could (near) future colliders enter into the game again?



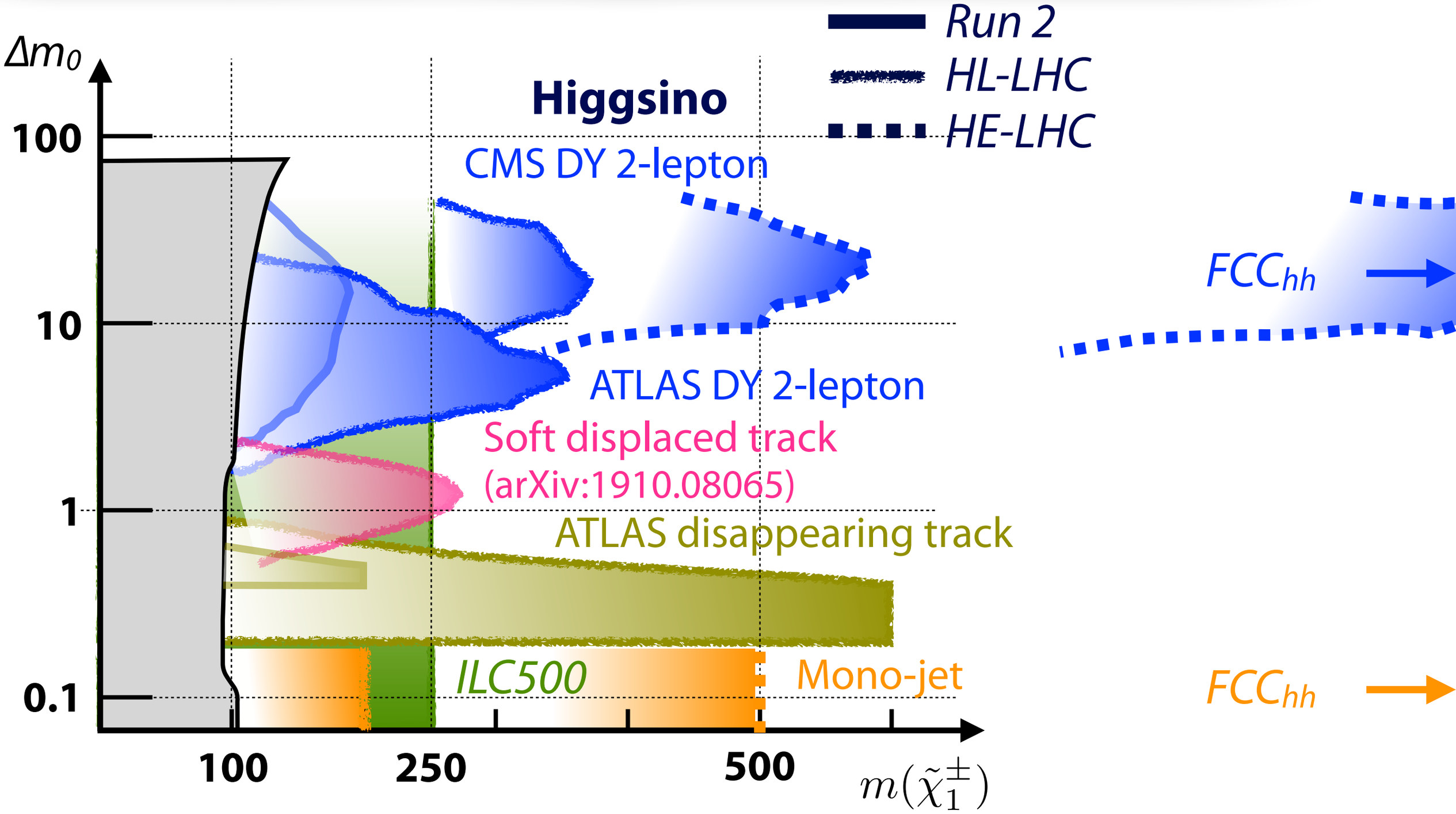
Backup


$\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0 \rightarrow Z(*)\,\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm \rightarrow W(*)\,\tilde{\chi}_1^0$
Wino-like cross-sections
LHC 36/fb, 13 TeV
HL-LHC 3/ab, 14 TeV (3L search)
HL-LHC compressed 3/ab, 14 TeV
HE-LHC 15/ab (projection)
HE-LHC compressed 15/ab (projection)
ILC_{500}, 0.5/ab
ILC_{1000}, 1/ab
$CLIC_{1500}$, 2.5/ab
$CLIC_{3000}$, 5/ab
FCC-hh (3L search, 3/ab)
95% CL exclusion
European Strategy Update
Kinematically Forbidden
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_1^\pm)$ [GeV]
500
1000
1500
2000
2500
3000
3500


Pure Higgsino
Indirect Detection
FCC−hh
LE−FCC
FCC−eh
HE−LHC
HL−LHC
2σ, Disappearing Tracks
CLIC3000
Kinematic Limit: √s /2
CLIC1500
2σ, Indirect Reach
ILC
CLIC380
FCC−ee
CEPC
Thermal
European Strategy Update
0.1
0.2
0.5
1
2
5
MX [TeV]


Pure Wino
90% CL Direct Detection Projection
Indirect Detection
FCC−hh
LE−FCC
FCC−eh
HE−LHC
HL−LHC
2σ, Disappearing Tracks
CLIC3000
Kinematic Limit: √s /2
CLIC1500
2σ, Indirect Reach
ILC
CLIC380
FCC−ee
CEPC
Thermal
European Strategy Update
0.1
0.5
1
5
10
MX [TeV]

Bounds on Compressed Scenario



Combination of hadron & lepton colliders could cover $m(\tilde{\chi}_1^{\pm})$ up to ~300 GeV at *any* Δm_0 < ~10 GeV