Winos from natural SUSY at the high luminosity LHC

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Overview

- Theoretical mystery about the SM: *Hierarchy problem*.
- Naturalness, fine-tuning and their implication on SUSY search in LHC
- Electroweakino pair production search ($\chi_2^\pm \chi_4^0$ and $\chi_2^\pm \chi_2^\mp$) in (HL)LHC under natural SUSY assumption
  - $\chi_2^\pm / \chi_4^0 \rightarrow W, Z, h + higgsino$
  - How they differ from the usual EWino pair search of most current search in ATLAS/CMS.

Old guidances led to the formulation of the SM

- Two principles that lead to the Standard Model:
  - *Symmetry*: both global and gauge symmetry
    - *Symmetry* limits the form of terms in Lagrangian can appear.
  - *Renormalizability*:
    - *Renormalizability* says given the possible forms of the terms required by the symmetry, there can not be infinite number of terms one can write down.
- These guidances led to the formulation of the SM as we know today, which is a self-consistent, but elegantly simple, fully renormalizable Quantum field theory that so far classifies all know fundamental particles and interactions (except for neutrinos).

Hierarchy problem in the SM

- However, being renormalizable also implies low-energy measurements are totally insensitive to whatever UV completion the SM can have since low-energy effect is determined by the symmetries the system has.
  - Contrasted with the situation before the SM.
    - Weak theory with massive vector boson is non-renormalizable. $\sigma(W_L Z_L \to W_L Z_L)$ unbounded as E_{CM} increases, and furthermore, violates the unitarity bound unless there is a Higgs boson (or entities playing the similar role like top condensate). Then, the contributions from Higgs exchange and gauge boson self-interaction diagram cancel out the unbounded part.
    - Unitarity bound limits the mass of Higgs (or entities playing the same role): $m_h \leq 1 TeV$. (Lee-Quigg-Thacker bound [Lee et al., 1977])
    - One of the reasons people believe Higgs (or similar entities) had to be found in LHC long before its construction.
  - Non-renormalizable theory tells where itself breaks down.
  - In principle, the SM could be valid up to $M_{planck} \sim 10^{19}$ TeV without self-inconsistency.

Hierarchy problem in the SM

- Mass terms in a Lagrangian is always super-renormalizable. For a scalar boson, quantum corrections to its mass terms is quadratic sensitive to the theory UV cutoff Λ in 4d QFT. For the SM Higgs,
- $$m_h^2 = m_0^2 + \frac{3\Lambda^2}{8\pi^2 v_{SM}^2}\left[c_h\left(\frac{m_h^2}{v_{SM}^2}\right)m_h^2 + 2c_W g^2 m_W^2 + c_Z\frac{g^2}{\cos^2\theta_W}m_Z^2 - c_t y_t^2 m_t^2 + \cdots\right] + \cdots$$
- The SM, if viewed as a low energy EFT, whose UV completion lives at Planck scale $M_{planck} \sim 10^{19}TeV$ leads to uncomfortable implication.
  - On the LHS: $m_h^2 \sim (100GeV)^2$
  - On the RHS: m_0 is the bare mass, which is a finite parameter predicted by the UV completion theory.
  - If the cutoff is at Planck scale, terms on the RHS $\sim (10^{19}GeV)^2$. Need to be tuned to $\frac{\Lambda_{SM}^2}{\Lambda_{Planck}^2} \sim 10^{-34}$ precision to miraculously cancel each other to get such a small value on LHS.

Hierarchy problem in the SM

- Why masses of fermions or gauge bosons are not problematic?
  - Protected by *custodial symmetry*:
    - Fermions by *chiral symmetry*.
    - Gauge bosons by *gauge symmetry*.
  - Protected even if the custodial symmetry is broken by the mass term, as is the case of fermion mass, since every symmetry violating loop diagram needs to be proportional to the violating term, which is the fermion mass itself.
  - Either case, UV scale decouples.

New guidance to search for theory — *Naturalness*

- Just the *symmetry principle* and *renormalizability* are not enough now for BSM physics.
- New tool: *Naturalness*— no fine tuning!
  - Hints the SM needs an extension.
- Look back the radiative correction to the Higgs boson mass

$$m_h^2 = m_0^2 + \frac{3\Lambda^2}{8\pi^2 v_{SM}^2}\left[c_h\left(\frac{m_h^2}{v_{SM}^2}\right)m_h^2 + 2c_W g^2 m_W^2 + c_Z \frac{g^2}{\cos^2\theta_W} m_Z^2 - c_t y_t^2 m_t^2 + \cdots\right] + \cdots$$

The corrections due to fermion loop and that of bosons loop are always opposite in signs.

- A new custodial symmetry connects fermion with boson to protect Higgs mass from radiative correction? — SUSY!
  - But needs to be broken softly since no superpartners have been discovered yet.
  - M_{SUSY} not far away from weak scale.

Minimal Supersymmetric Standard Model (MSSM)

- Minimal possible extension of the SM:
  - Each SM gauge boson together with their fermion superpartner — gaugino.
  - Each SM fermion together with their scalar superpartner — sfermion.
  - *Two* Higgs doublets H_u and H_d together with their fermion superpartner — higgsino. Two are required because a lone higgsino leaves the gauge anomaly uncanceled.
- Theoretical indications:
  - Simplest possible.
  - Gauge couplings unification.
  - Higgs boson we observed $m_h = 125GeV$. Unitarity bound only says $m_h < 1TeV$, but MSSM says $m_h < 135GeV$.

Physical states of MSSM after EWSB

States with the same gauge charge mixed together.

- SM gauge bosons, quarks, and leptons.
- Higgs: $h, H, A, H^{\pm}$
- gluino: $\tilde{g}$
- bino, neutral wino, neutral higgsinos mixed together (neutralinos): $\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$
- charged wino, charged higgsino mixed together (charginos): $\chi_1^{\pm}, \chi_2^{\pm}$
- squarks & sleptons

A Whisper from Naturalness

Not just hints extension for SM but also guides on MSSM and SUSY breaking search

- Naively, MSSM has 124 parameters in Lagrangian.
  - Just a reflection of our ignorance to the SUSY breaking mechanism.
  - In principle, most are derivable from the SUSY breaking mechanism, but we don't have the complete theory yet.
- Common to assume some soft SUSY breaking parameters are unified at GUT scale for phenomenological reasons (SUSY flavor problems, CP problems…).
  - For example, in mSUGRA*
    - Gauge unification, gaugino mass unification, scalar mass unification, trilinear scalar self-interactions coupling unification, etc…
    - Fixed by 5 parameters: $m_{1/2}, m_0, A_0, \tan\beta, sign(\mu)$
- Even these soft terms should not be expected to be independent but depends on the exact SUSY breaking mechanism and details of hidden sectors, which only a more fundamental theory could tell.
  - For example, in dilaton-dominated SUSY breaking: $m_0^2 = m_{3/2}^2, m_{1/2} = -A_0 = \sqrt{3}m_{3/2}$.
  - Reason the old naturalness measures ($\Delta_{HS}, \Delta_{BG}, \ldots$) has greatly overestimated the fine-tuning level of MSSM by a factor of 1000.

[Baer et al, 2023]

*Minimal Supersymmetric model with Universality, Gauge coupling unification, and RAdiative electroweak symmetry breaking

A Whisper from Naturalness

Not just hints extension for SM but also guides on MSSM and SUSY breaking search

- One should only estimate naturalness from low scale parameters, which can then guarantee to be model-independent, correlation-insensitive, conservative, and falsifiable from current or upcoming experiments.
- We use m_Z as representative of weak scale. With the well known relation in the MSSM:

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \sim -m_{H_u}^2 - \Sigma_u^u - \mu^2 \quad (1)$$

- *Practical naturalness*:
  - an observable $\mathcal{O}$ is natural if all *independent* contributions to $\mathcal{O}$ are comparable to or less than $\mathcal{O}$. [Baer et al, 2012]
- We use the naturalness measure Δ_{EW} defined as

$$\Delta_{EW} \equiv |\text{maximal term on the right} - \text{hand} - \text{side of Eq. (1)}|/(m_Z^2/2)$$

- $|\mu| \sim m_Z$, $m_{H_u}^2 \sim -m_Z^2$ for EWSB, radiative corrections $\Sigma \sim m_Z$.
- μ, typically arise from very different physics than SUSY breaking, is an *independent* contribution from others. The smallness of μ depends on which solution one approaches with the "μ problem".
- $\Delta_{EW} < 30$ and $\mu < 350$ GeV, observed $m_h \sim 125$ GeV $\implies 3 - 10\,\%$ fine-tuning level as what we define as "natural SUSY".

[Baer, Barger, and Savoy, 2016]

Naturalness says?

bounds from naturalness (3%)	BG/DG	Delta_EW	
mu	350 GeV	350 GeV	
gluino	400-600 GeV	6 TeV	
t1	450 GeV	3 TeV	
sq/sl	550-700 GeV	10-30 TeV	

$$\Delta_{BG} \equiv max_i \left| \frac{p_i}{m_Z^2} \frac{\partial m_Z^2}{\partial p_i} \right|,$$

where p_i represent high scale soft SUSY breaking terms. (Model-dependent!)

Experiment says:

$m(\tilde{t}_1) > 1.2$ TeV

$m(\tilde{g}) > 2.4$ TeV

Δ_{EW} is perfectly well safe from current experimental search bound! Not plagued by neither the fine-tuning nor experimental bounds.

Input parameters and spectrum for natural SUSY search

parameter	m_h^{125}(nat)
m_0	5 TeV
$m_{1/2}$	1.2 TeV
A_0	-8 TeV
$\tan\beta$	10
μ	250 GeV
m_A	2 TeV
$m_{\tilde{g}}$	2830 GeV
$m_{\tilde{u}_L}$	5440 GeV
$m_{\tilde{u}_R}$	5561 GeV
$m_{\tilde{e}_R}$	4822 GeV
$m_{\tilde{t}_1}$	1714 GeV
$m_{\tilde{t}_2}$	3915 GeV
$m_{\tilde{b}_1}$	3949 GeV
$m_{\tilde{b}_2}$	5287 GeV
$m_{\tilde{\tau}_1}$	4746 GeV
$m_{\tilde{\tau}_2}$	5110 GeV
$m_{\tilde{\nu}_\tau}$	5107 GeV
$m_{\tilde{\chi}_1^\pm}$	261.7 GeV
$m_{\tilde{\chi}_2^\pm}$	1020.6 GeV
$m_{\tilde{\chi}_1^0}$	248.1 GeV
$m_{\tilde{\chi}_2^0}$	259.2 GeV
$m_{\tilde{\chi}_3^0}$	541.0 GeV
$m_{\tilde{\chi}_4^0}$	1033.9 GeV
m_h	124.7 GeV
$\Omega_{\tilde{z}_1}^{std}h^2$	0.016
$BF(b \to s\gamma) \times 10^4$	3.1
$BF(B_s \to \mu^+\mu^-) \times 10^9$	3.8
$\sigma^{SI}(\tilde{\chi}_1^0, p)$ (pb)	2.2×10^{-9}
$\sigma^{SD}(\tilde{\chi}_1^0, p)$ (pb)	2.9×10^{-5}
$\langle\sigma v\rangle\|_{v\to 0}$ (cm^3/sec)	1.3×10^{-25}
$\Delta_{\rm EW}$	22

Inputs for NUHM2 model with $m_t = 173.2$ GeV using Isajet 7.88

Due to $\mu < m_{1/2}$ in natural SUSY, $\tilde{\chi}_2^\pm/\tilde{\chi}_4^0$ are wino-like, $\tilde{\chi}_3^0$ is bino-like, $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0$ are higgsino-like. More importantly, the higgsinos has compressed spectrum $m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} < 12$ GeV.

For phenomenological SUSY study, NUHM2 is very convenient: essentially mSUGRA but allows m_{H_u} and m_{H_d} to be non-universal, which are then traded for m_A and μ for weak scale study. Thus, the input parameters are:

$m_0, m_{1/2}, A_0, \tan\beta, \mu, m_A$

For electroweakino search,

- $m_0 = 5$ TeV
- $A_0 = 8$ TeV
- $\tan\beta = 10$
- $\mu = 250$ GeV
- $m_A = 2$ TeV
- $m_{1/2}$: 1 - 2 TeV
    - $\Longrightarrow$ $m_{\tilde{\chi}_2^\pm} \sim m_{\tilde{\chi}_4^0}$: 0.8 - 1.7 TeV

Respect all current experimental limit while maintaining $\Delta_{EW} < 30$.

Collider phenomenology of wino pair production

In natural SUSY, the heaviest charginos/neutralinos $\chi_2^{\pm}\chi_4^0$ and $\chi_2^{\pm}\chi_2^{\mp}$ are wino-like and are which considered for the search study as they are relatively large cross sections and cleaner signatures from the backgrounds

**Based on Baer, Barger, Tata, and Zhang (2023)*

Unique pattern in natural SUSY: $BF(\tilde{\chi}_2^\pm/\tilde{\chi}_4^0 \to W^\pm + higgsinos) : BF(\tilde{\chi}_2^\pm/\tilde{\chi}_4^0 \to Z + higgsinos) : BF(\tilde{\chi}_2^\pm/\tilde{\chi}_4^0 \to h + higgsinos) = 2 : 1 : 1.$

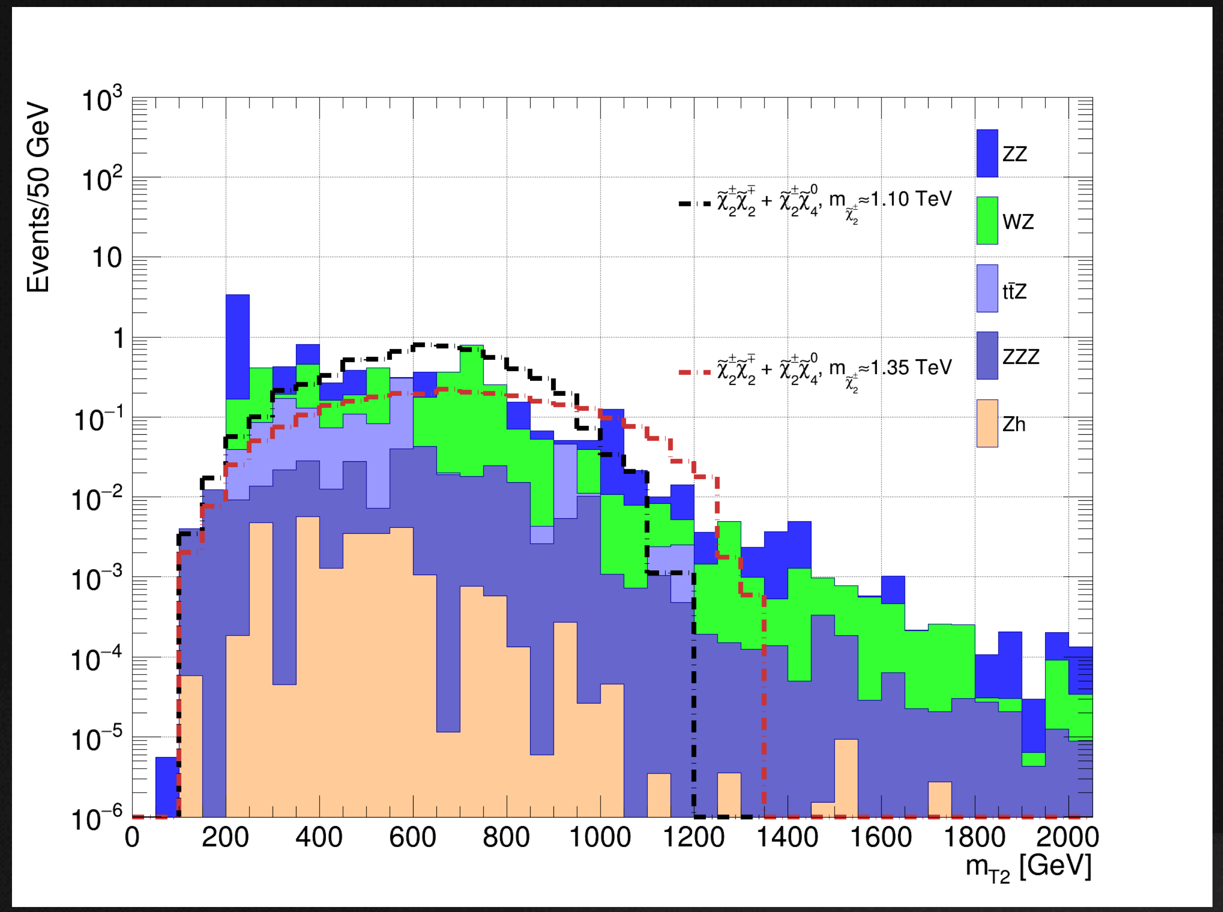
In particular, contrasted with most current LHC searches, which usually assume $m_{higgsino(\tilde{\chi}_2^\pm/\tilde{\chi}_3^0/\tilde{\chi}_4^0)} > m_{wino(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0)} > m_{bino(\tilde{\chi}_1^0)}$ and search for wino decays. The wino->bino+Z is then very suppressed due to little higgsino components mixing in light neutralinos.

BFs of gauginos in natural SUSY

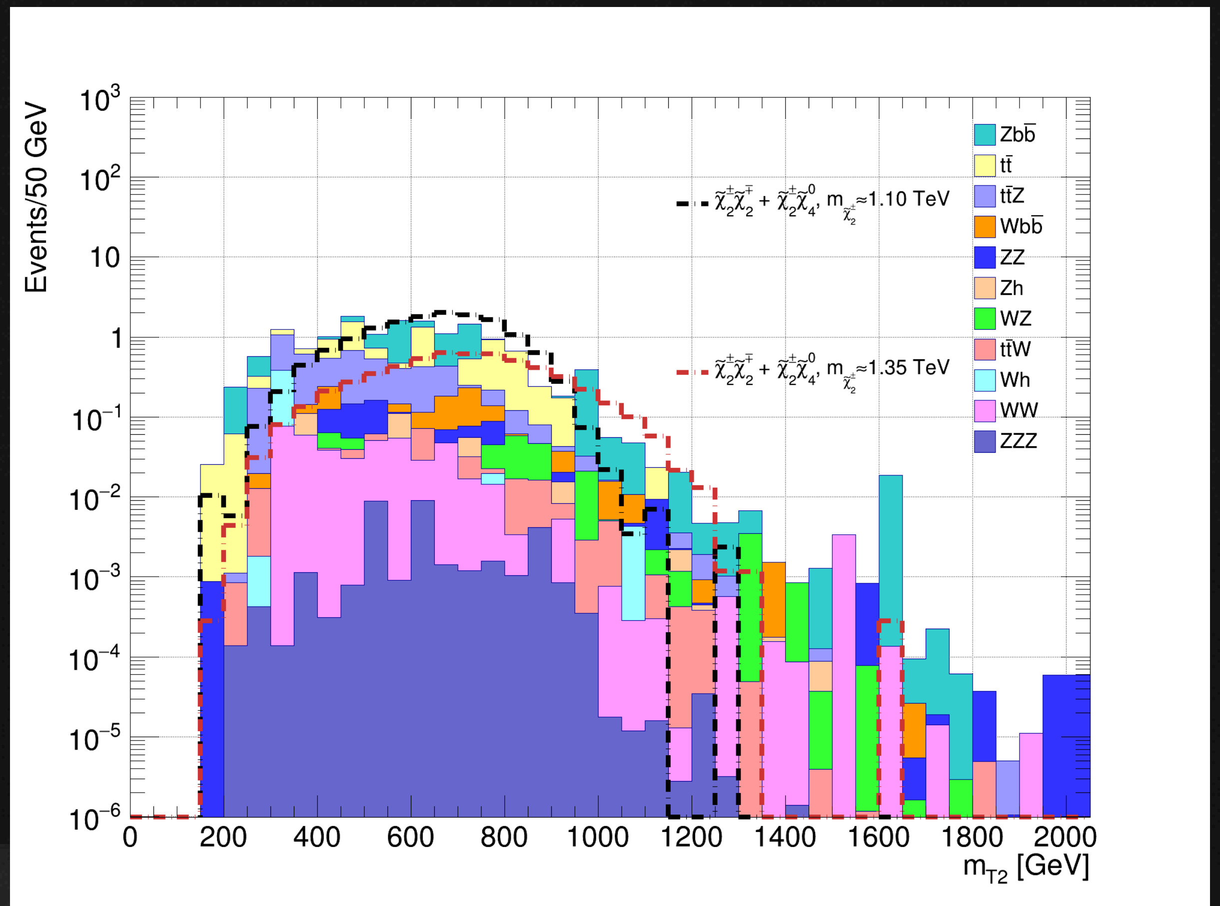
Gaugino pair production search

$\chi_2^{\pm}\chi_4^0$ and $\chi_2^{\pm}\chi_2^{\mp}$, $\quad \chi_2^{\pm}/\chi_4^0 \rightarrow W, Z, h + higgsinos$

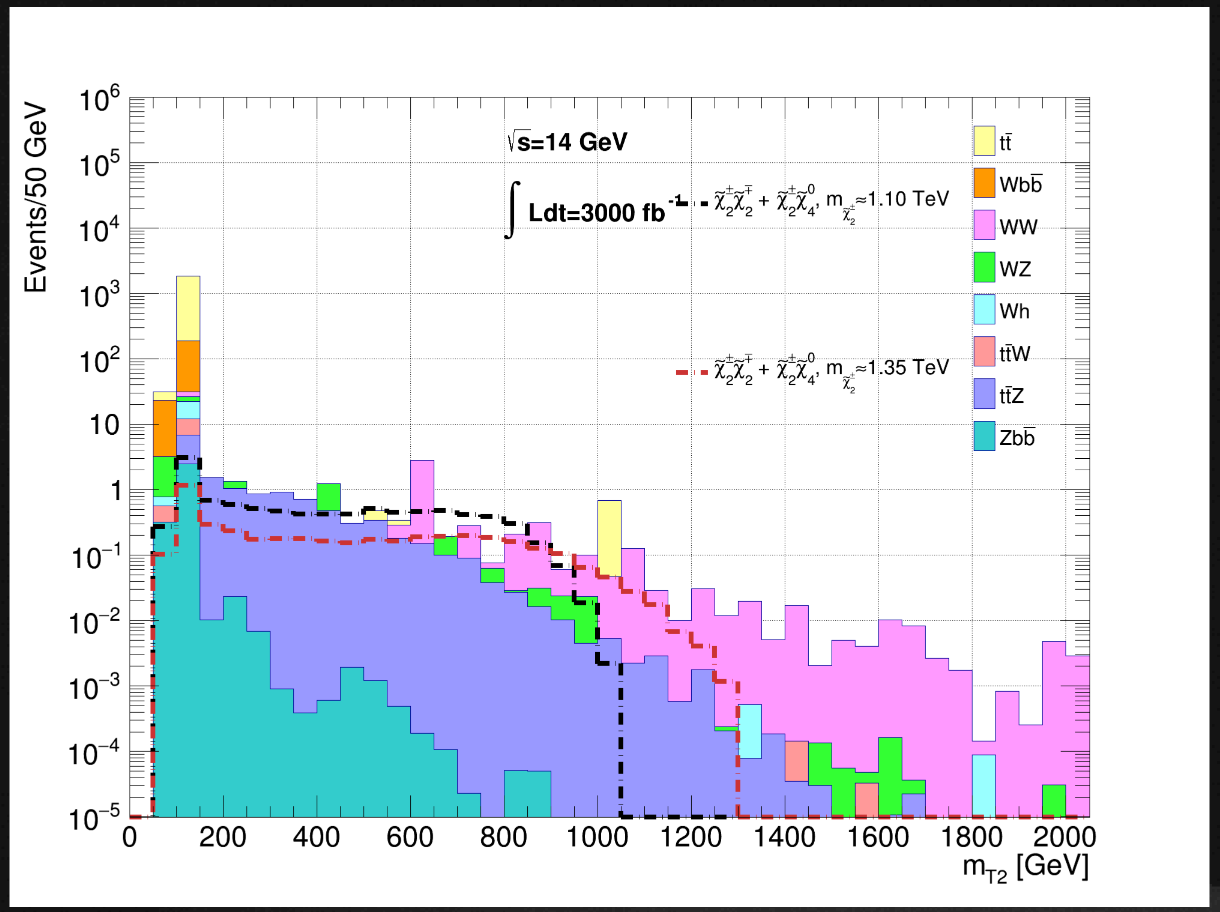
- Decay channels are featured by presence of a pair of SM bosons + large MET.
- Final products can be categorized based on the intermediate SM bosons decayed leptonically (also purely invisible) or hadronically, we considered
  - One decays leptonically, the other hadronically: m_{T2} is reconstructed
    - $Z(\rightarrow ll)B + MET$, where B stands for hadronically decayed "Boson", can either be W, Z, or h.
    - $h/Z(\rightarrow ll)B + MET$,
    - $W(\rightarrow l)B_{W/Z} + MET$,
    - $W(\rightarrow l)h + MET$,
  - Both decay hadronically: m_{T2} is reconstructed
    - $BB + MET$
  - One decays invisibly to neutrinos ($Z \rightarrow \nu\nu$): m_T is reconstructed
    - $h/Z(\rightarrow bb) + MET$
    - $Z(\rightarrow l^+l^-) + MET$
  - One special channel!: L_T is reconstructed
    - $W^{\pm}W^{\pm}(\rightarrow l^{\pm}l^{\pm})$ + MET
- Kinematics cuts such as MET, angular separations, pT cuts, etc… are then implemented to improve sensitivity.



$Z(\to ll)B + MET$

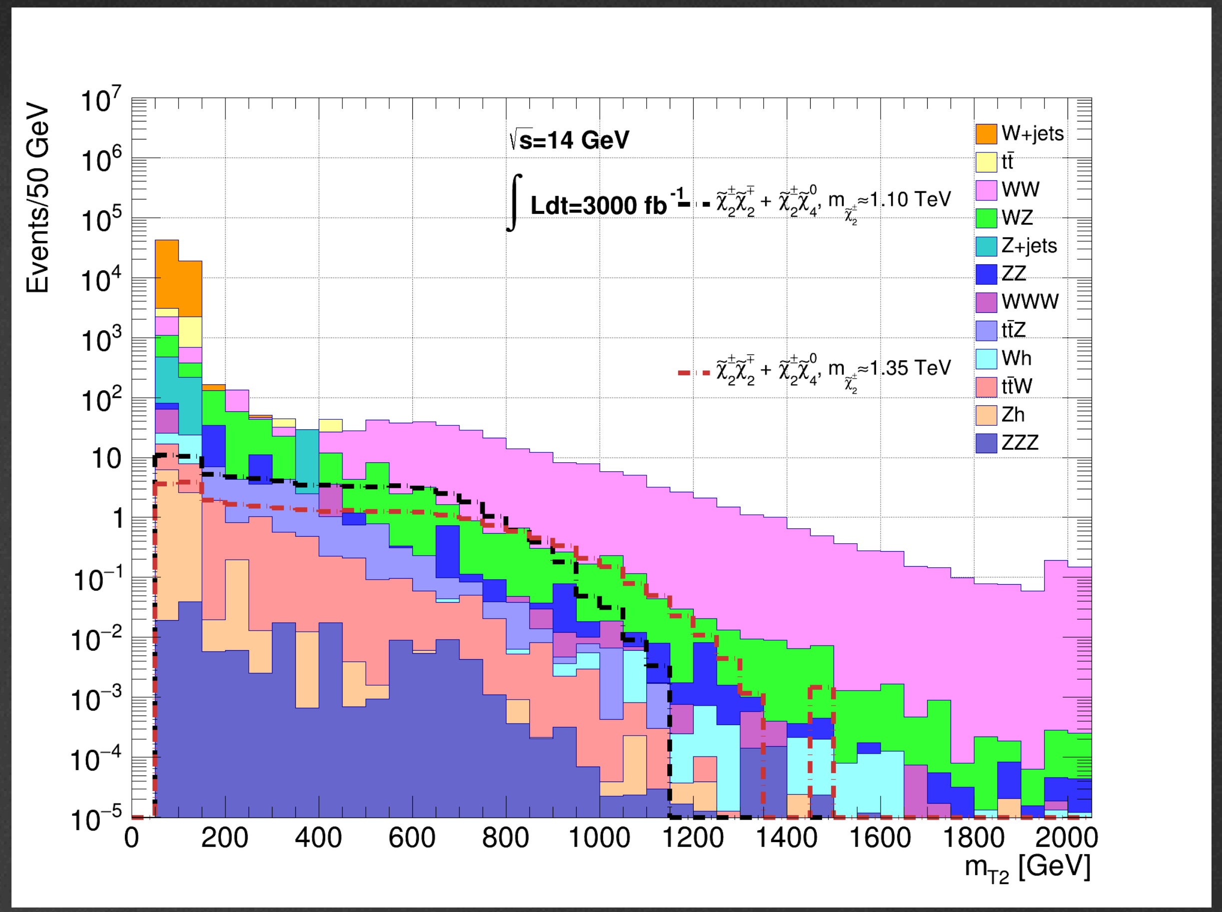


$h/Z(\to bb)B + MET$

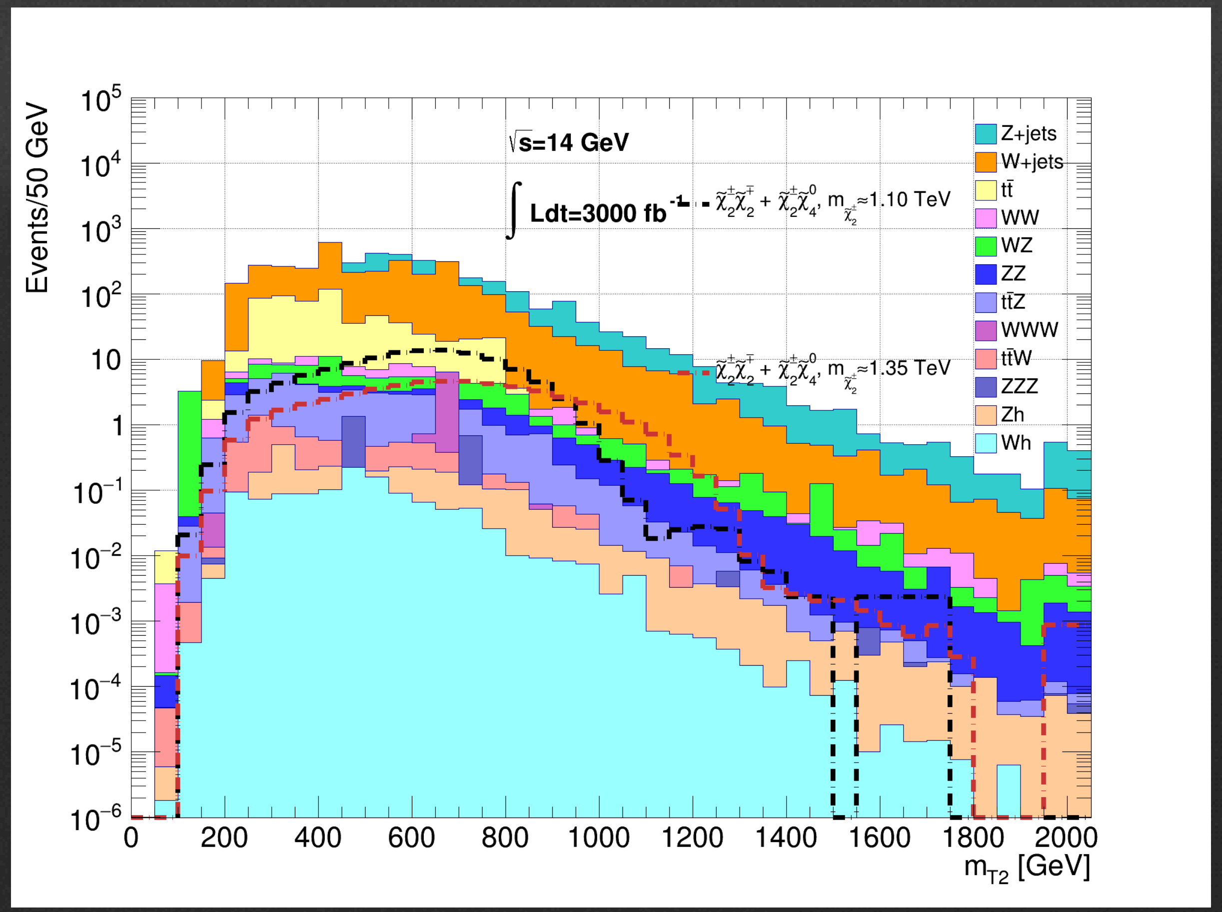


$l^{\pm}h + MET$

2 distinct bosons channels

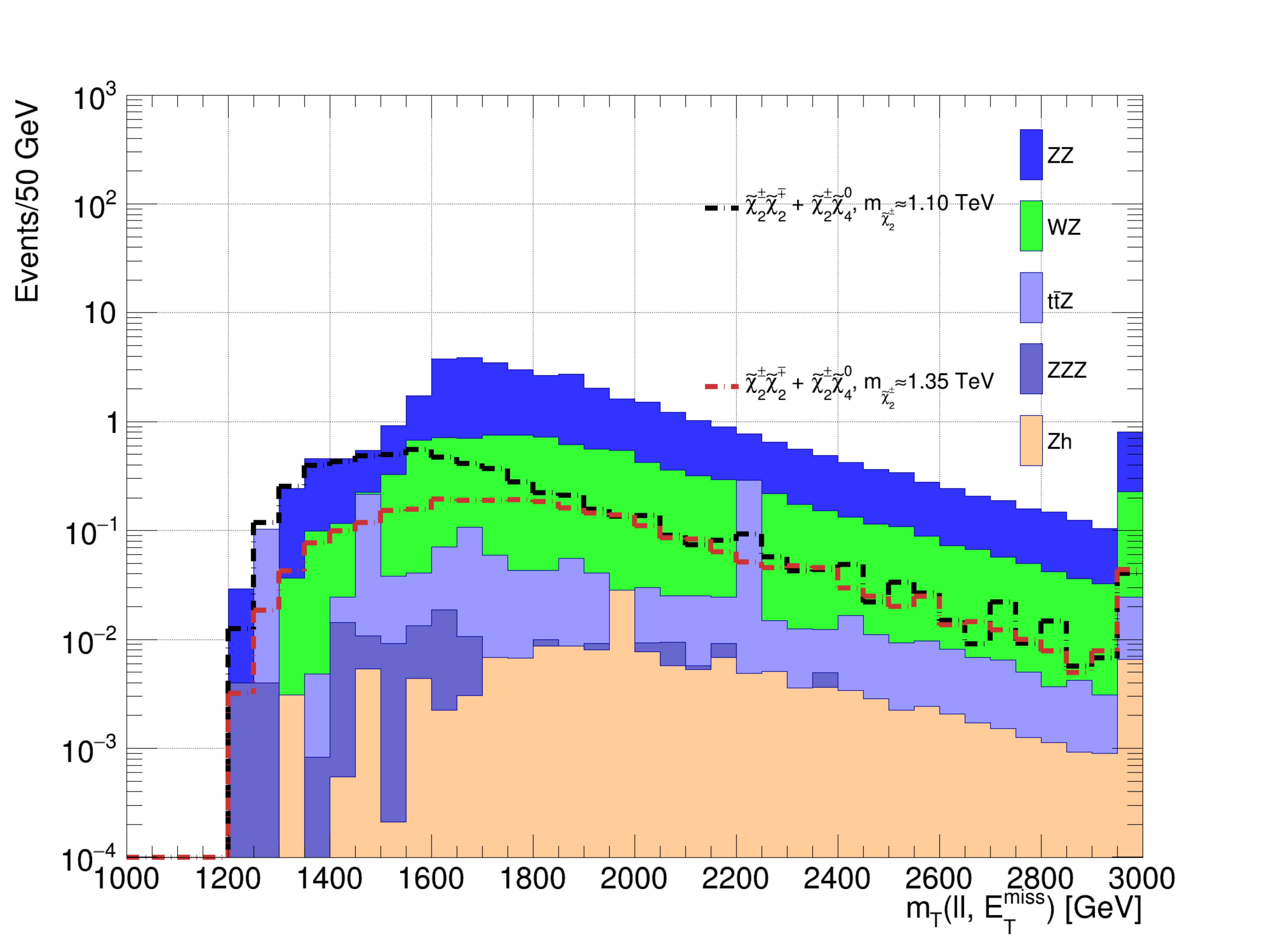


$l^{\pm}B_{W/Z} + MET$

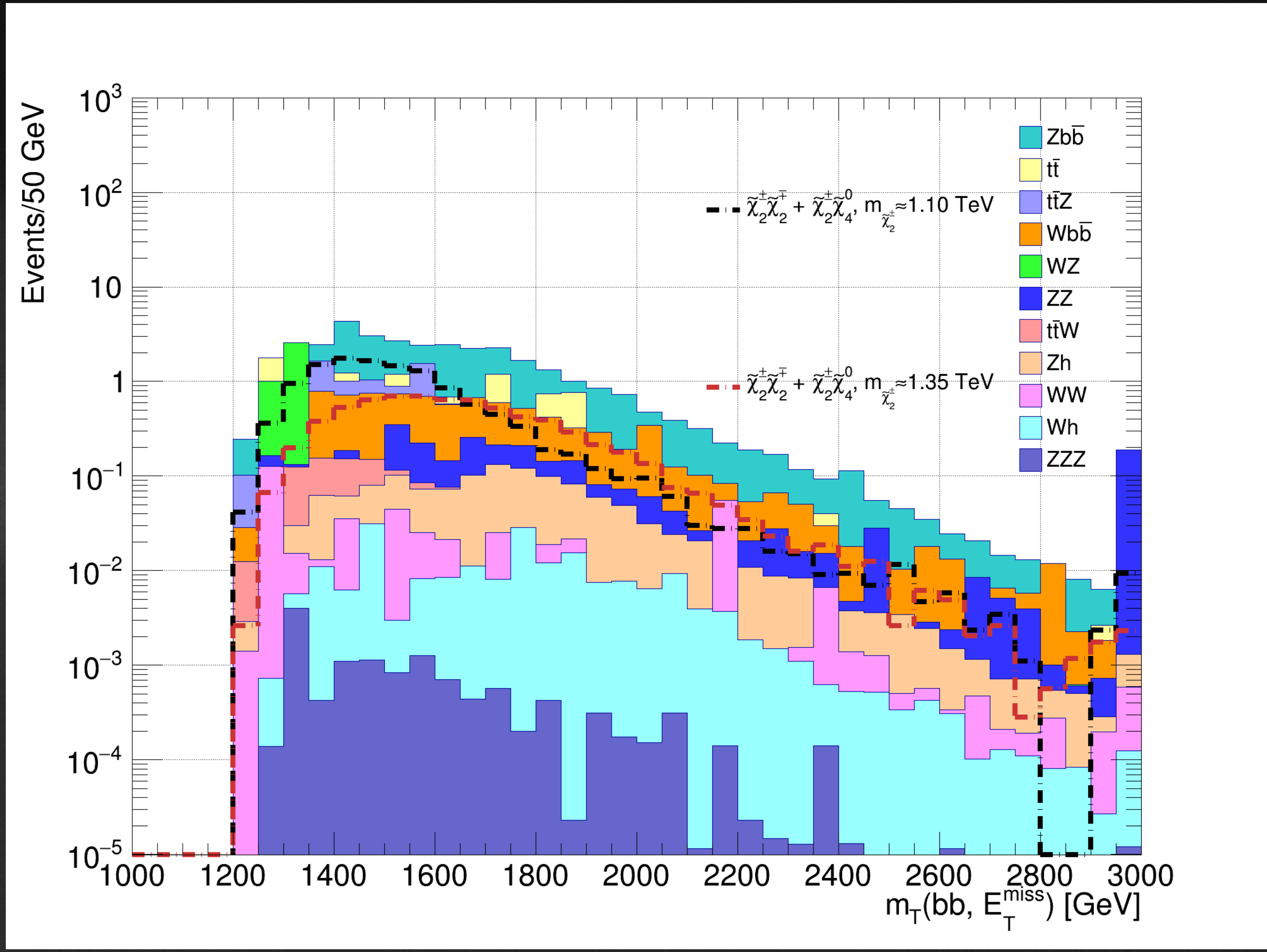


$BB + MET$

1 distinct bosons channels

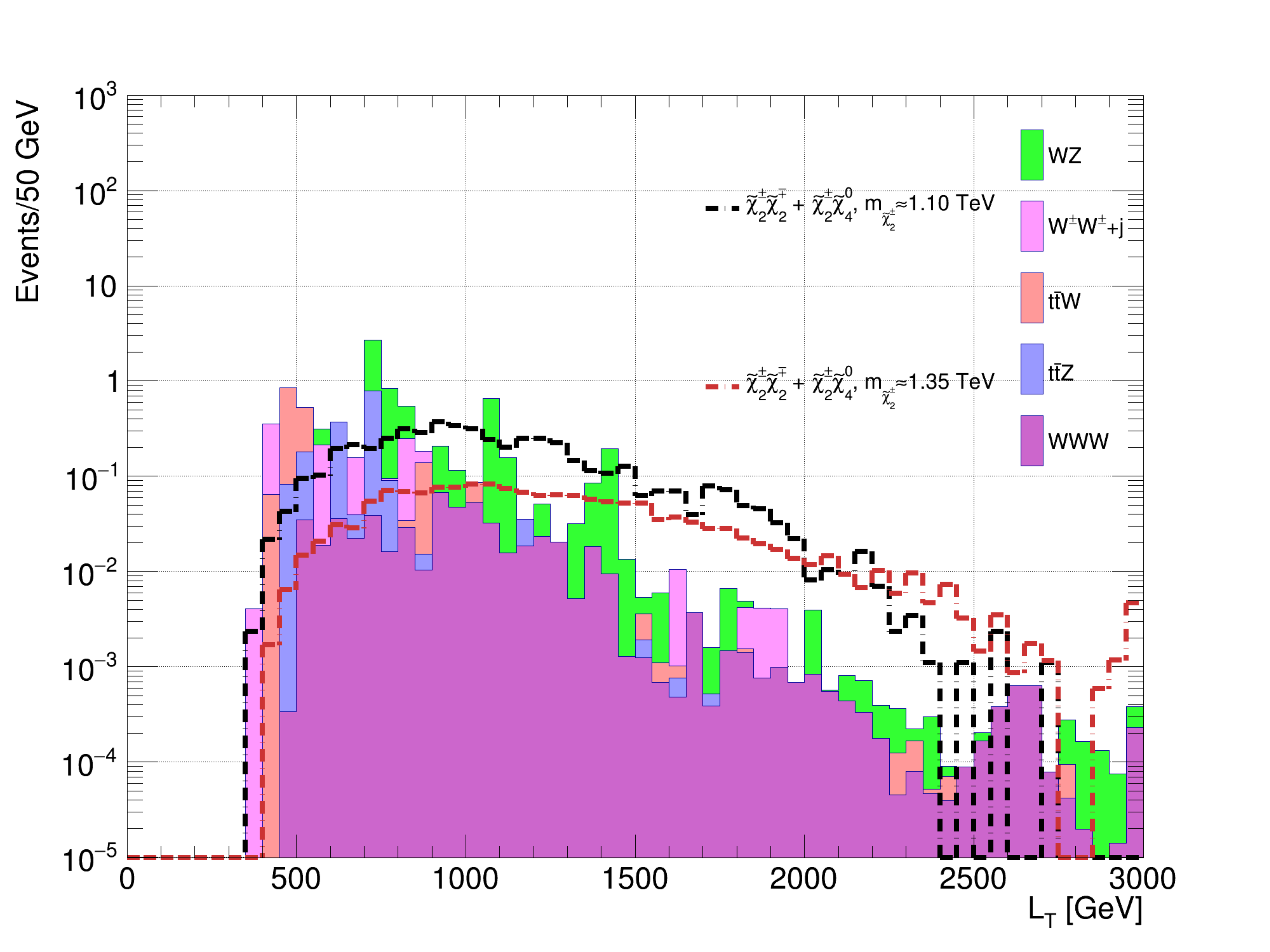


$Z(\to l^+l^-) + MET$



$h/Z(\to bb) + MET$

A very special channel: same-signed di-boson (ssdb)

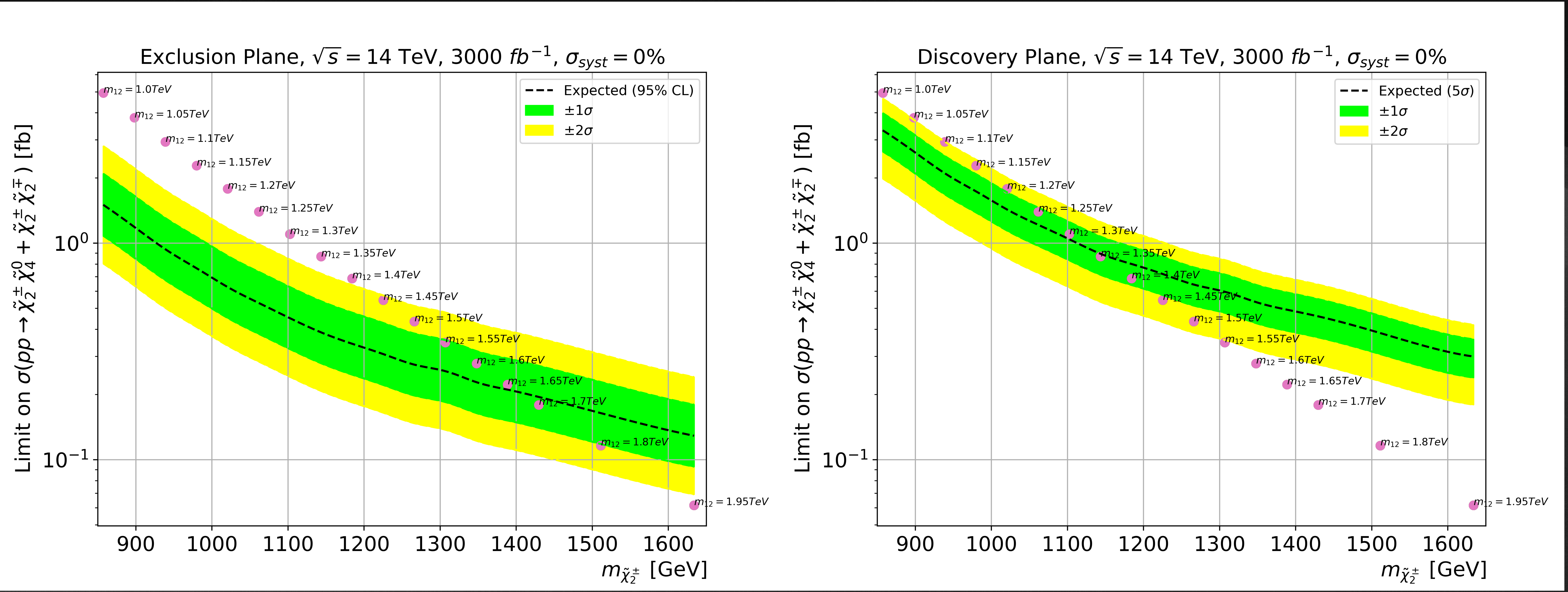


Unique prediction from natural SUSY!

$$W^\pm W^\pm(\to l^\pm l^\pm) + MET$$

An extra charged carried off by an almost invisible charged higgsino. Very clean from SM backgrounds. Resilient from the background systematic uncertainty. Such channel would not present in models where the higgsino states are heavy and decoupled.

Reach on $\sigma \times BF$ vs. $m_{\tilde{\chi}_2^{\pm}}$ plane combined all channels



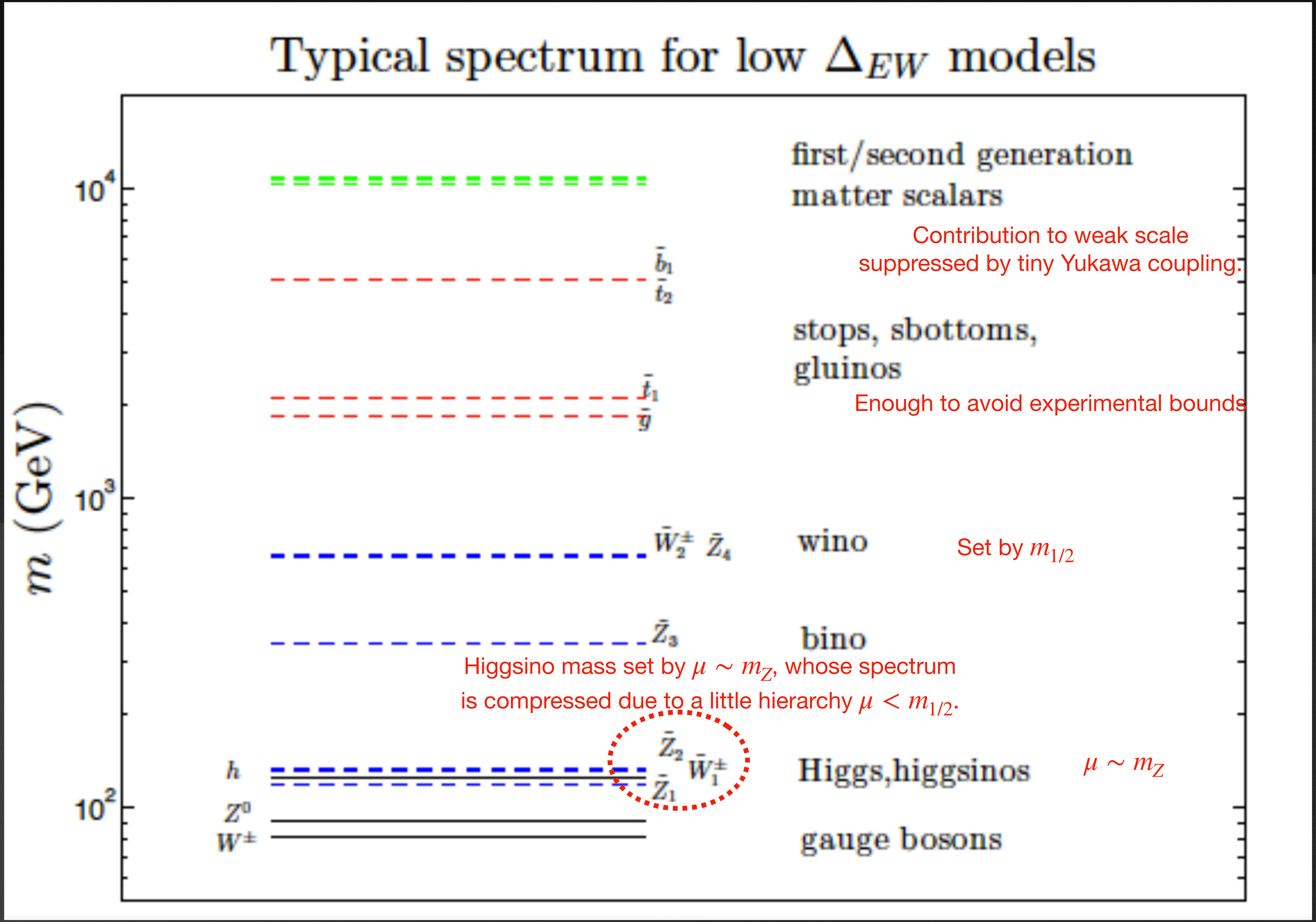
Natural SUSY could exclude(discover) reach up to $m_{\tilde{\chi}_2^{\pm}} \sim 1.4(1.15)$ TeV in HL-LHC.

Summary

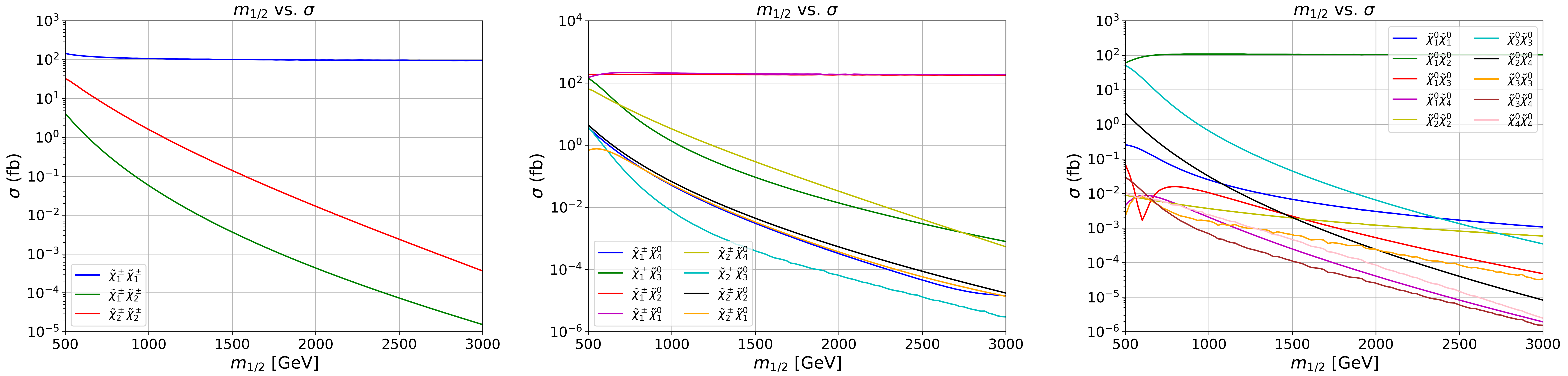
- Naturalness as a new guidance to hint and test for new theory.
- Necessary to give up the old measures of naturalness, which overestimates the fine-tuning and is very model-dependent.
- With the new naturalness measure Δ_{EW}, vast parameter space in natural SUSY. HL-LHC can start to probe some of the interesting regions.
- Many new and exotic phenomenology
  - New search channels (ssdB in EWino pair search, $H/A/H^{\pm} \rightarrow sparticles$, etc)
  - Specific BF pattern (In principle, can be tested and served as differentiating different SUSY models)
  - Most have been overlooked in the current or previous experimental studies.

Thank you!

Backup



Typical spectrum for low Δ_{EW} models
m (GeV)
10^4
10^3
10^2
first/second generation
matter scalars
Contribution to weak scale
suppressed by tiny Yukawa coupling.
$\tilde{b}_1$
$\tilde{t}_2$
stops, sbottoms,
gluinos
Enough to avoid experimental bounds
$\tilde{t}_1$
$\tilde{g}$
$\tilde{W}_2^\pm$ $\tilde{Z}_4$
wino
Set by $m_{1/2}$
$\tilde{Z}_3$
bino
Higgsino mass set by $\mu \sim m_Z$, whose spectrum
is compressed due to a little hierarchy $\mu < m_{1/2}$.
h
$\tilde{Z}_2$ $\tilde{W}_1^\pm$ $\tilde{Z}_1$
Higgs,higgsinos
$\mu \sim m_Z$
Z^0
$W^\pm$
gauge bosons



$\chi_2^\pm \chi_4^0$ and $\chi_2^\pm \chi_2^\mp$ are considered for the search study as they are relatively large cross sections and cleaner signatures from the backgrounds

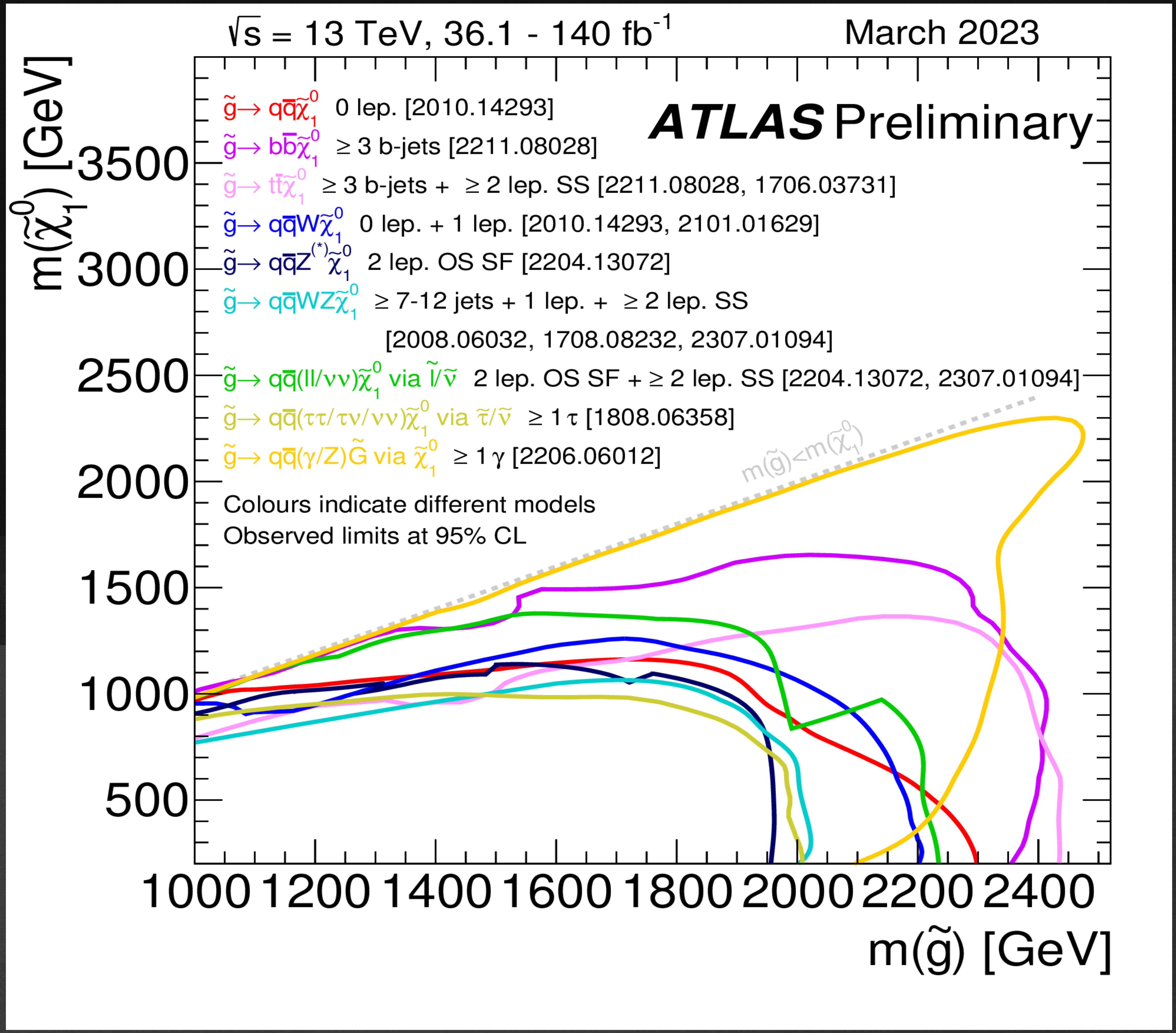
Cross sections of gauginos in natural SUSY

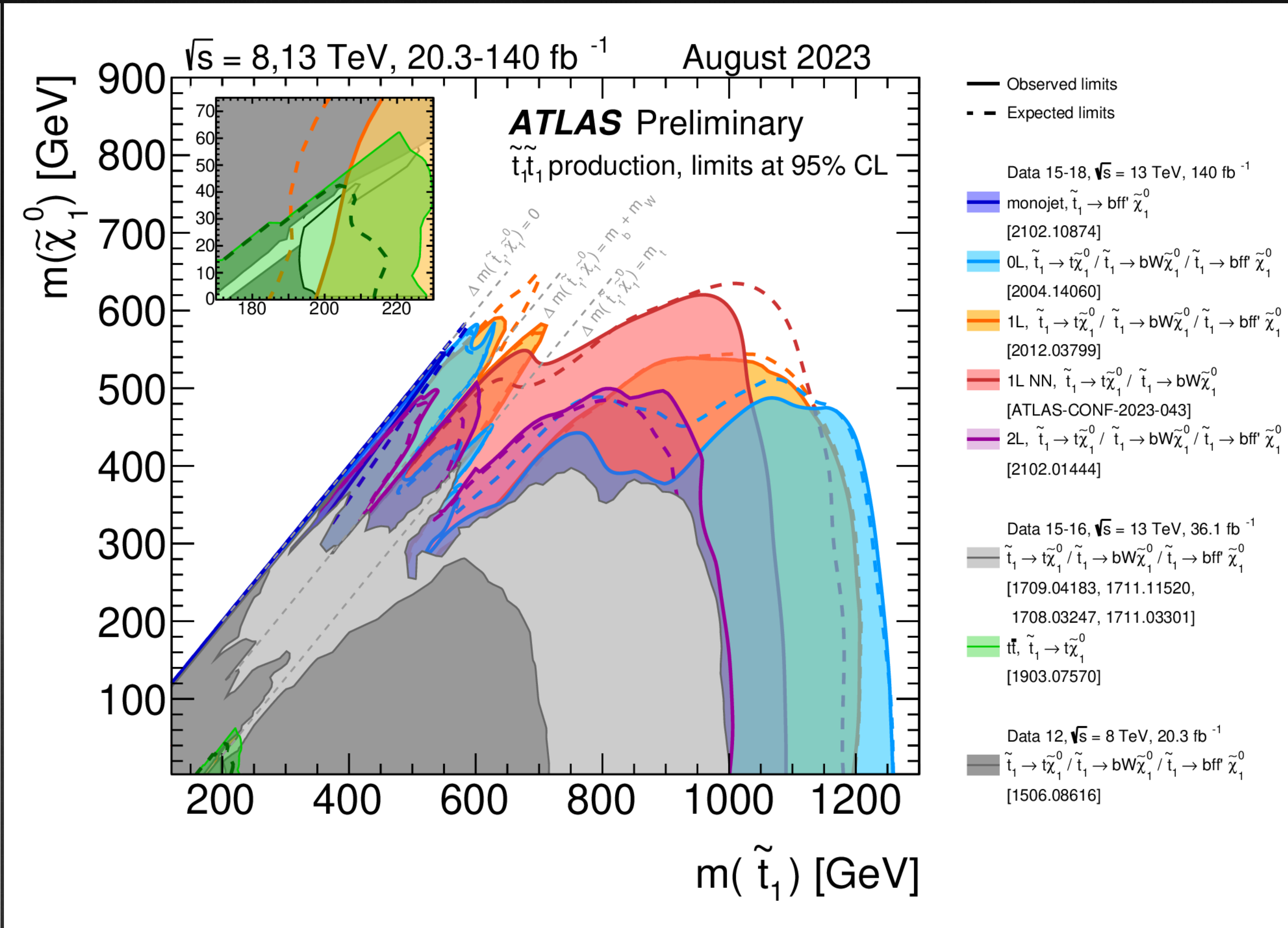
Unique pattern in natural SUSY: $BF(\tilde{\chi}_2^\pm/\tilde{\chi}_4^0 \to W^\pm + higgsinos) : BF(\tilde{\chi}_2^\pm/\tilde{\chi}_4^0 \to Z + higgsinos) : BF(\tilde{\chi}_2^\pm/\tilde{\chi}_4^0 \to h + higgsinos) = 2 : 1 : 1.$

The pattern is due to $\mu^2 \ll M_2^2, \gamma_L \ - \gamma_R \frac{\mu}{M_2} \implies \gamma_L \ll \gamma_R$ so coupling comes from gaugino-higgsino mixing and thus don't differentiate W/Z/h

BFs of gauginos in natural SUSY

Current LHC bounds

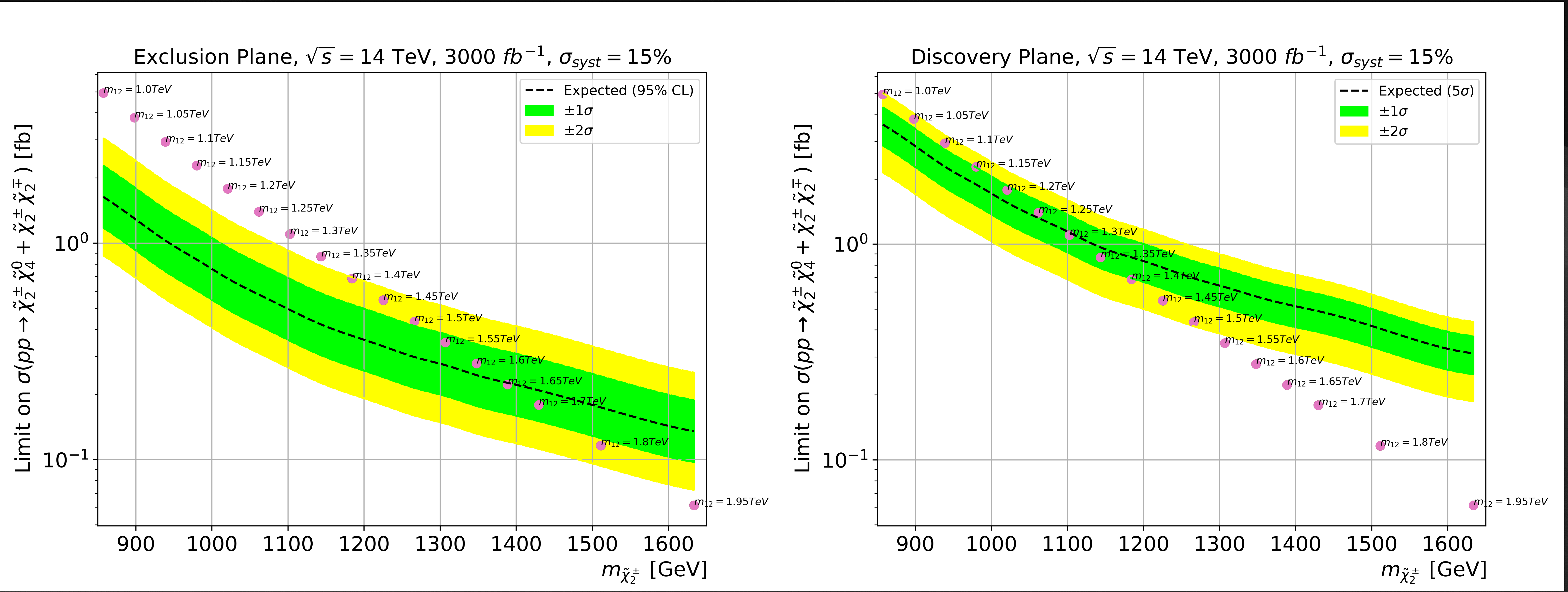




$m(\tilde{g}) > 2.4$ TeV

$m(\tilde{t}_1) > 1.2$ TeV

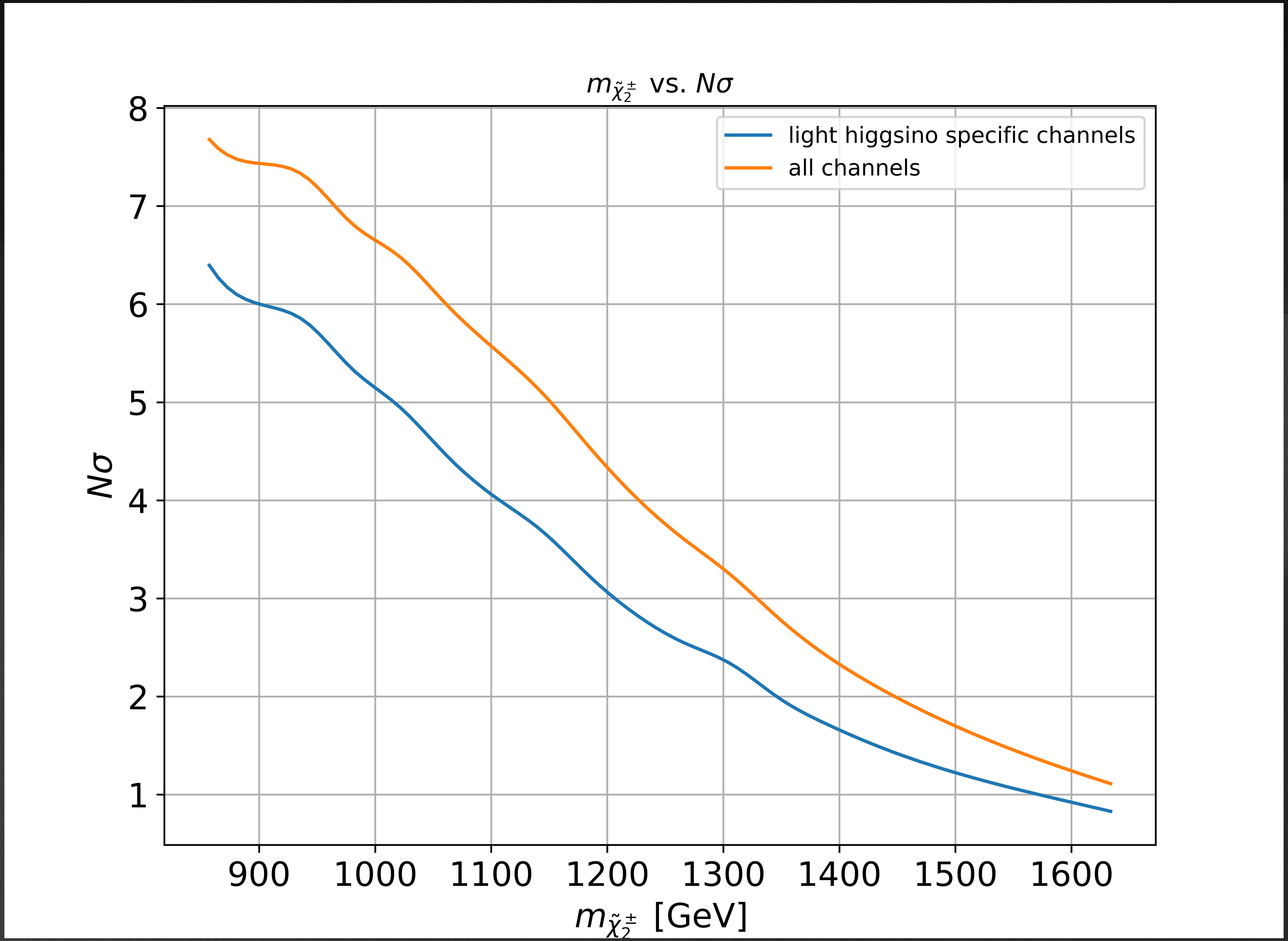
Reach on $\sigma \times BF$ vs. $m_{\tilde{\chi}_2^\pm}$ plane combined all channels (15% systematic)



Natural SUSY could exclude(discover) reach up to $m_{\tilde{\chi}_2^\pm} \sim 1.4(1.15)$ TeV in HL-LHC.

Statistical significance

- To construct the significance, likelihood method is used.
  - Likelihood function is built as the product of Poissonian terms for each bin in the kinematics distribution.
  - Ratio of likelihood for two competing hypothesis is used as the test statistics $\lambda(\mu)$. μ is signal strength in the null hypothesis. $\mu = 0$ for discovery sensitivity. $\mu = 1$ for exclusion sensitivity.
  - $$\lambda(0) = \prod_{i \in \text{bins, channels}} \frac{\frac{e^{-b_i}}{(s_i+b_i)!} b_i^{(s_i+b_i)}}{\frac{e^{-(s_i+b_i)}}{(s_i+b_i)!} (s_i+b_i)^{(s_i+b_i)}}, \quad \text{(Discovery)}$$
  - $$\lambda(1) = \prod_{i \in \text{bins, channels}} \frac{\frac{e^{-(s_i+b_i)}}{b_i!} (s_i+b_i)^{b_i}}{\frac{e^{-b_i}}{b_i!} b_i^{b_i}}. \quad \text{(Exclusion)}$$
- Statistics significance and confidence level are then extracted from these test statistics following Wilks' theorem with certain assumptions.
- Signal discovery is set to correspond to 5σ. Signal exclusion is set to 95% CLs


$m_{\tilde{\chi}_2^\pm}$ vs. $N\sigma$
light higgsino specific channels
all channels
$N\sigma$
$m_{\tilde{\chi}_2^\pm}$ [GeV]
8
7
6
5
4
3
2
1
900
1000
1100
1200
1300
1400
1500
1600

In DFSZ axion model, the PQ field and the Higgs field interact via a potential that has the same form as the mu term.

One can postulate that the PQ symmetry prevents a mu term in the Lagrangian and an effective mu term can only be generated after the PQ symmetry breaking.

Why might mu<<m(soft)?

SUSY mu problem: mu term is SUSY, not SUSY breaking: expect mu~M(Pl) but phenomenology requires mu~m(Z)

- NMSSM: mu~m(soft); but beware singlets!
- Giudice-Masiero: mu forbidden by some symmetry: generate via Higgs coupling to hidden sector: mu~m(soft)
- Kim-Nilles: invoke SUSY version of DFSZ axion solution to strong CP:

KN: PQ symmetry forbids mu term, but then it is generated via PQ breaking

$$\mu \sim \lambda_\mu f_a^2/m_P$$

$$m(soft) \sim m_{3/2} \sim m_{hidden}^2/m_P$$

Little Hierarchy due to mismatch between PQ breaking and SUSY breaking scales?

$$f_a < m_{hidden} \Rightarrow$$
$$\mu \ll m(soft)$$

Higgs mass m(h)~mu tells us where to look for axion!

$$m_a \sim 6.2\mu\text{eV}\left(\frac{10^{12}\ \text{GeV}}{f_a}\right)$$

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