Searches for SUSY and other non-resonant signatures from CMS

Giovanni Zevi Della Porta,
on behalf of the CMS Collaboration

Workshop on the physics of HL-LHC,
and perspectives at HE-LHC

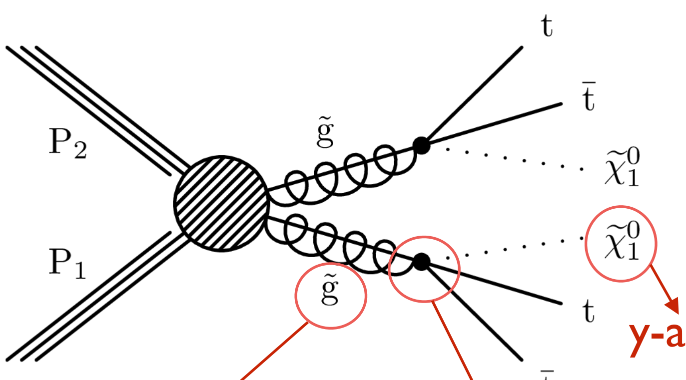
1 November 2016

https://indico.cern.ch/event/647676

Why SUSY?

(At least) two ways to see SUSY:

1. SUSY is an opportunity/framework to explore data in interesting topologies
    - Compare data to SM predictions in different regions of phase space
    - Use simplified models to estimate acceptance for hypothetical signal
    - Measure signal significance or cross-section limits across the mass spectrum

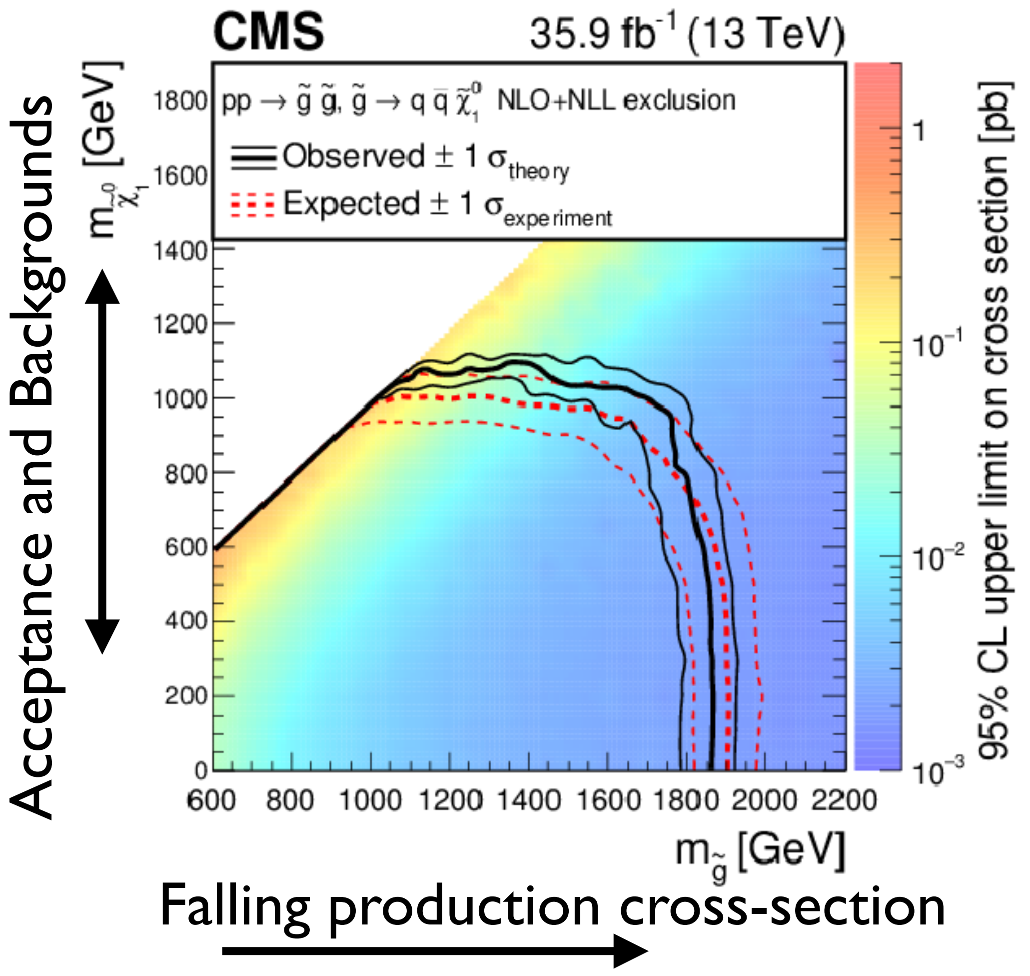


Color = limit on cross-section
Lines = limit on masses

y-axis: LSP mass

x-axis: produced particle mass

Simplified Model: 100% branching fraction



Acceptance and Backgrounds

Falling production cross-section

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2. SUSY is a well defined, falsifiable theory
   - The SUSY cross-sections are linked to the SM ones, so specific configurations can be excluded for good
   - Some regions of SUSY are more likely/interesting than others
     - especially where SUSY solves naturalness and/or dark matter

Here we use (2) to give us a well-defined goal, but CMS must also continue to pursue (1) at the HL-LHC

Current status: CMS SUSY searches at 36 fb^{-1}

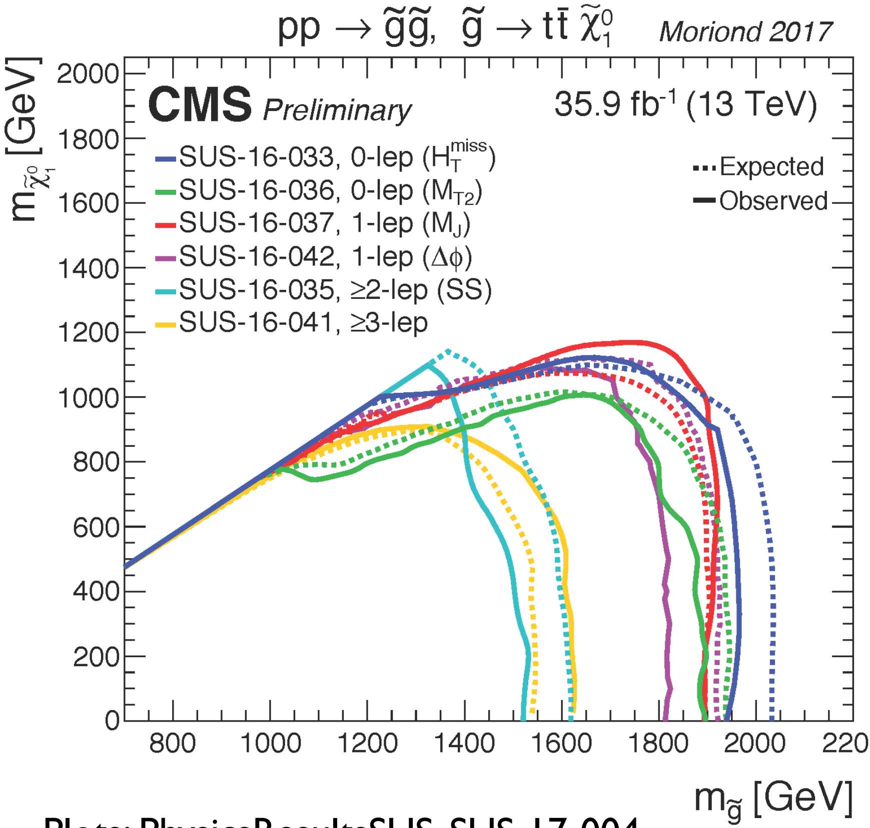
Latest limits are based on the full 2016 dataset: 36 fb^{-1} at 13 TeV

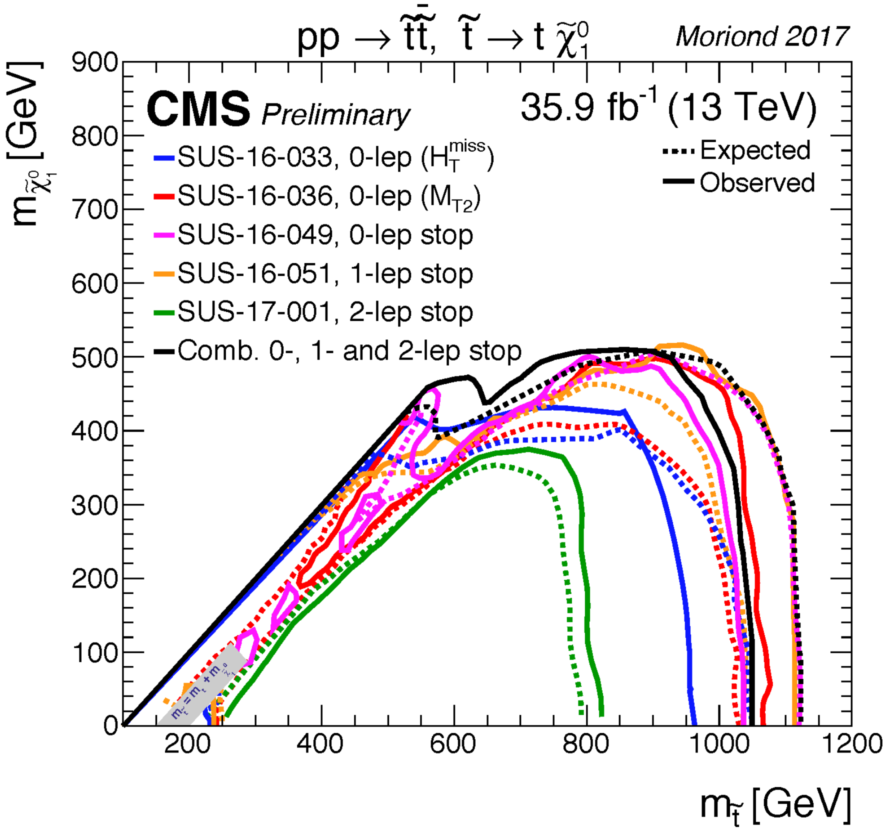
Gluinos: 1.4-1.9 TeV

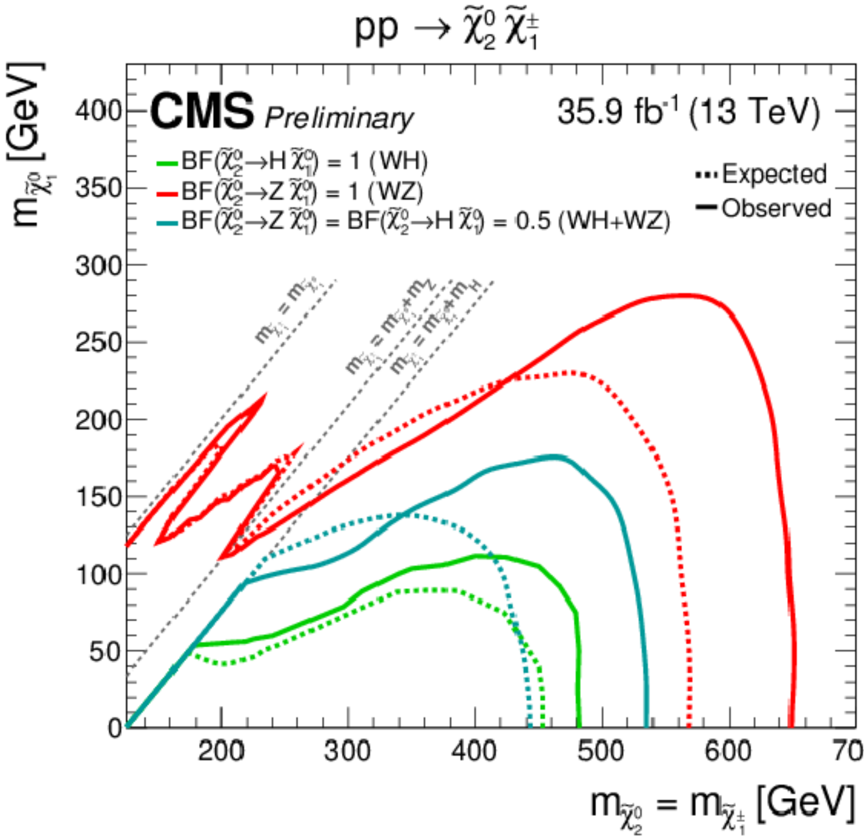
Squarks: 0.6-1.1 TeV

EWK-inos (Wino cross section):

- C1N2 —> $W^{(*)}Z^{(*)}$+MET: 150-650 GeV
- C1N2 —> WH+MET: 180-480 GeV







Plots: PhysicsResultsSUS, SUS-17-004

Simplified models: handle with care!

Wino pair production has significant interference from t-channel squark diagrams

With current ~q exclusion at 1 TeV, purple line is quite possible

Only a few % effect for higgsinos

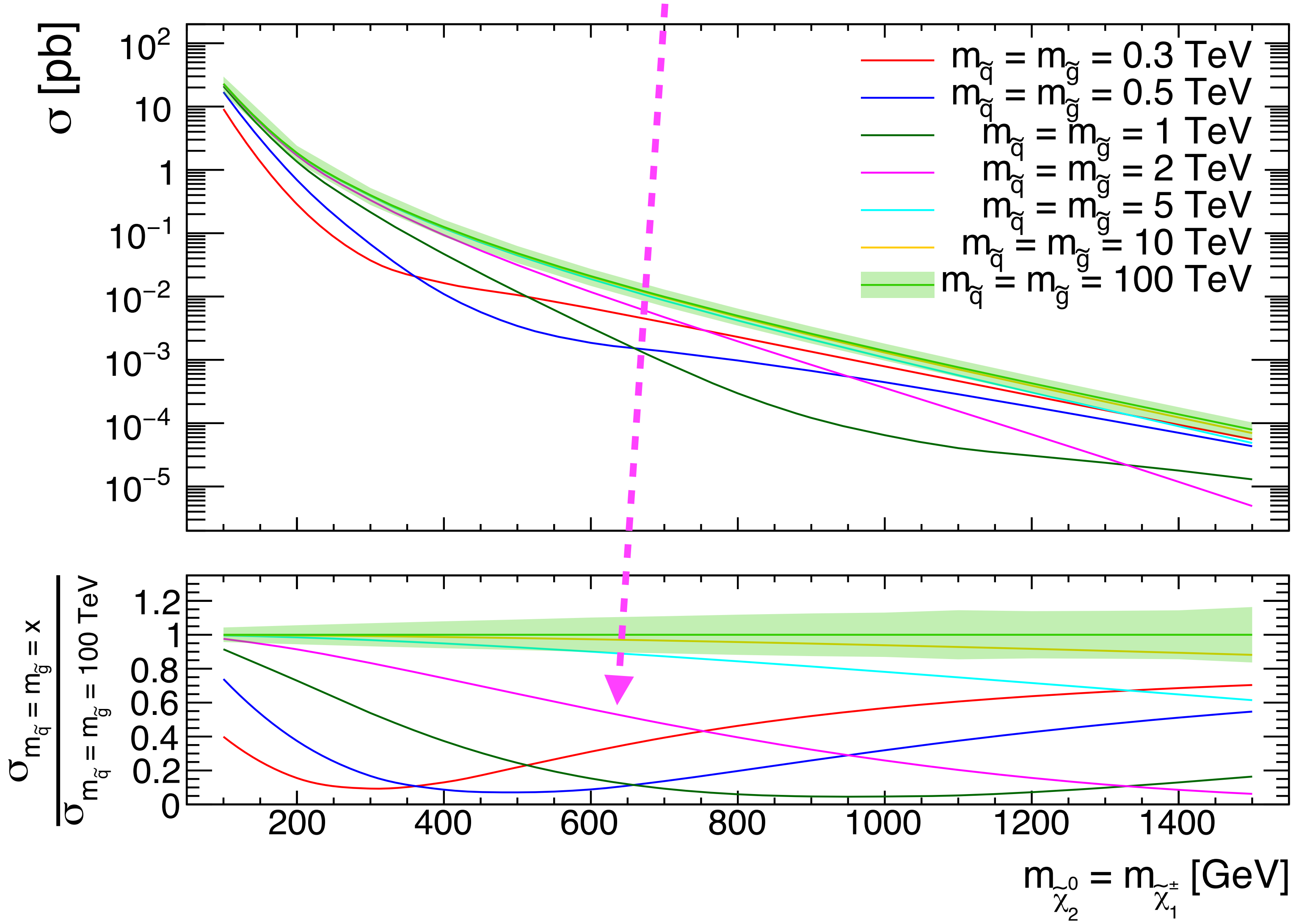


Figure 3: Cross section for $\widetilde{\chi}_1^{\mp}\widetilde{\chi}_2^{\upsilon}$ production at $\sqrt{s} = 13$ TeV versus the wino mass, assuming mass-degenerate wino $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_2^0$. The various curves show different assumptions on the masses of the squarks and gluinos, as described in the legend. The green band shows the theoretical uncertainty in the cross section calculation for the 100 TeV squark and gluino mass assumption.

SUS-17-004

How do we estimate future reach?

1. Back of the envelope: extrapolation for L and σ

Assumptions:

- 1. Comparable detector performance
- 2. Exclusion driven by signal regions with 0 background events
  —> Works well for high Δm

2. Parametrized simulations, <u>based on expected performance in full simulation</u>

Construct full analyses

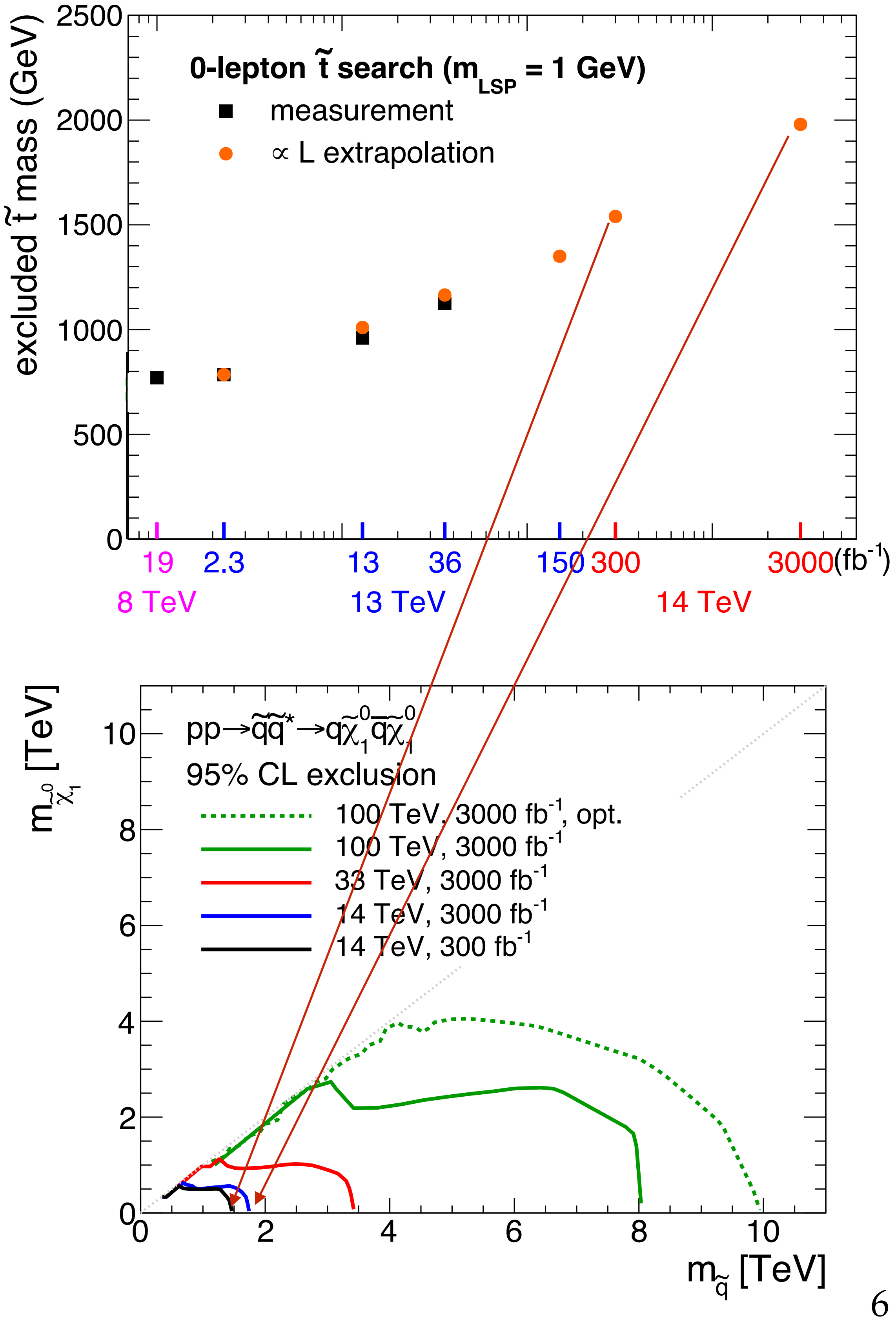
Understand backgrounds, acceptance, kinematics

—> Necessary for low Δm (“compressed”) regions

[3. Full simulations]

Cannot afford to generate 3 ab^{-1}

But generate enough to understand performance of <u>every</u> object (leptons, jets, MET, tagging)



Top: L. Shchutska (Moriond EWK 2017); Bottom: 100 TeV report (arXiv:1606.00947)

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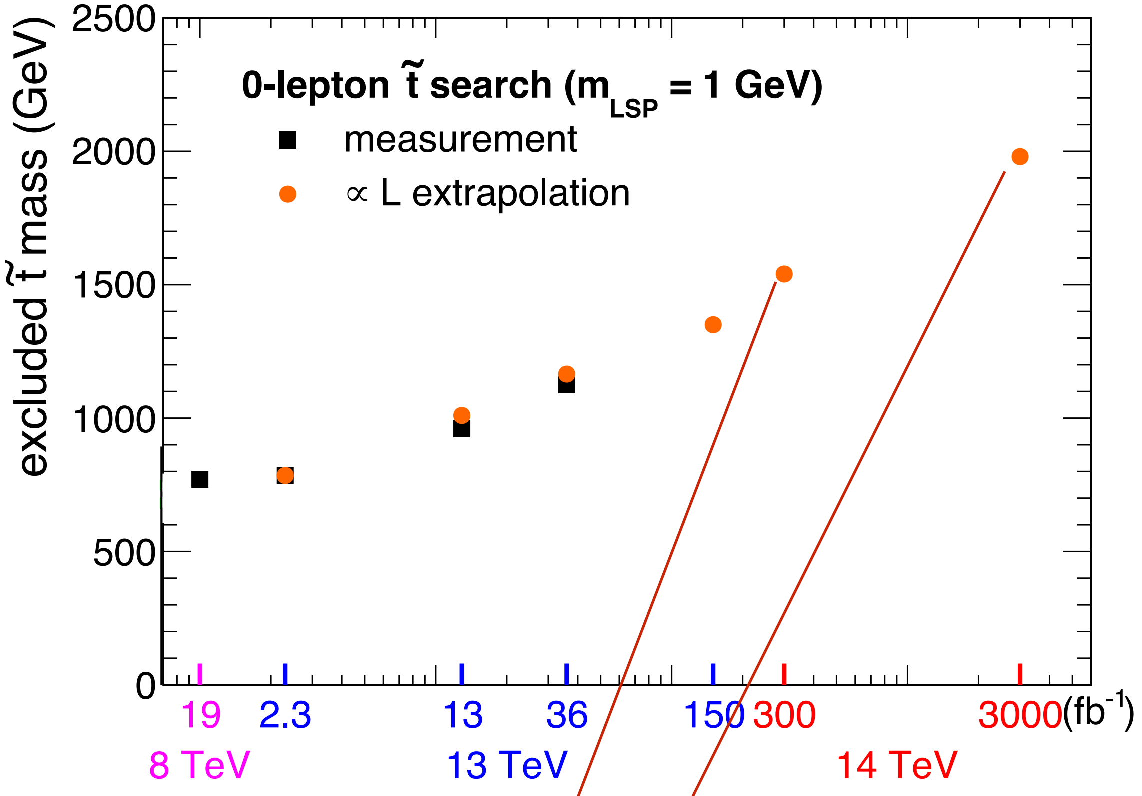
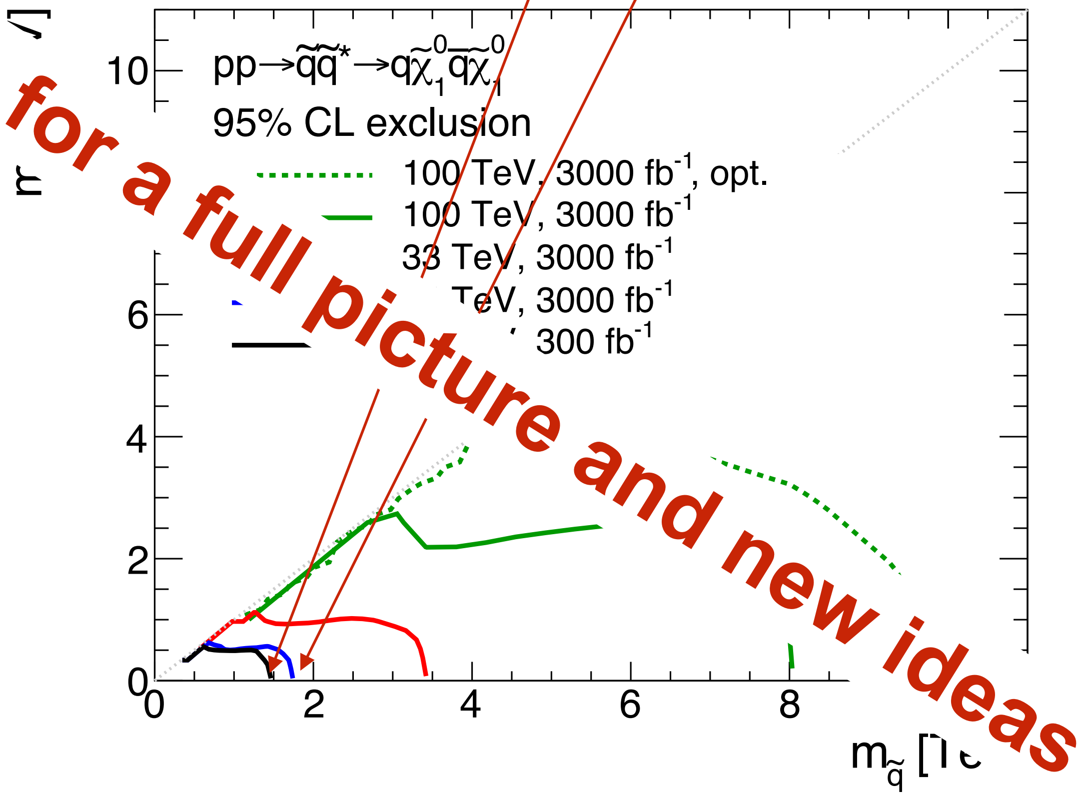




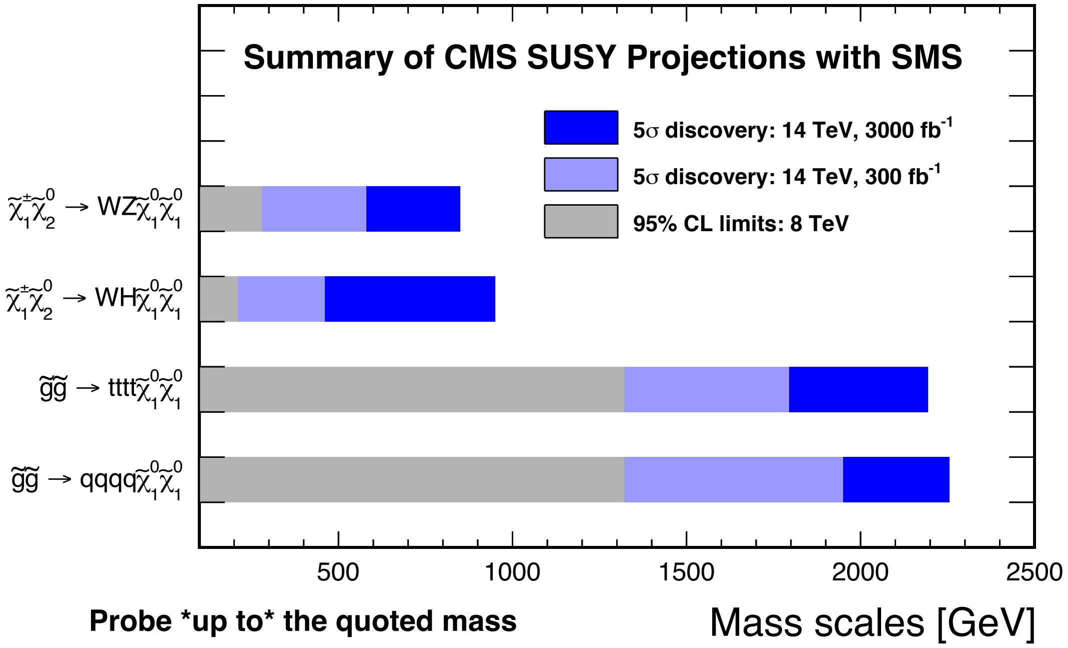
See talk by Keith Ulmer (BSM Session 1) for a full picture and new ideas

Top: L. Shchutska (Moriond EWK 2017); Bottom: 100 TeV report (arXiv:1606.00947)

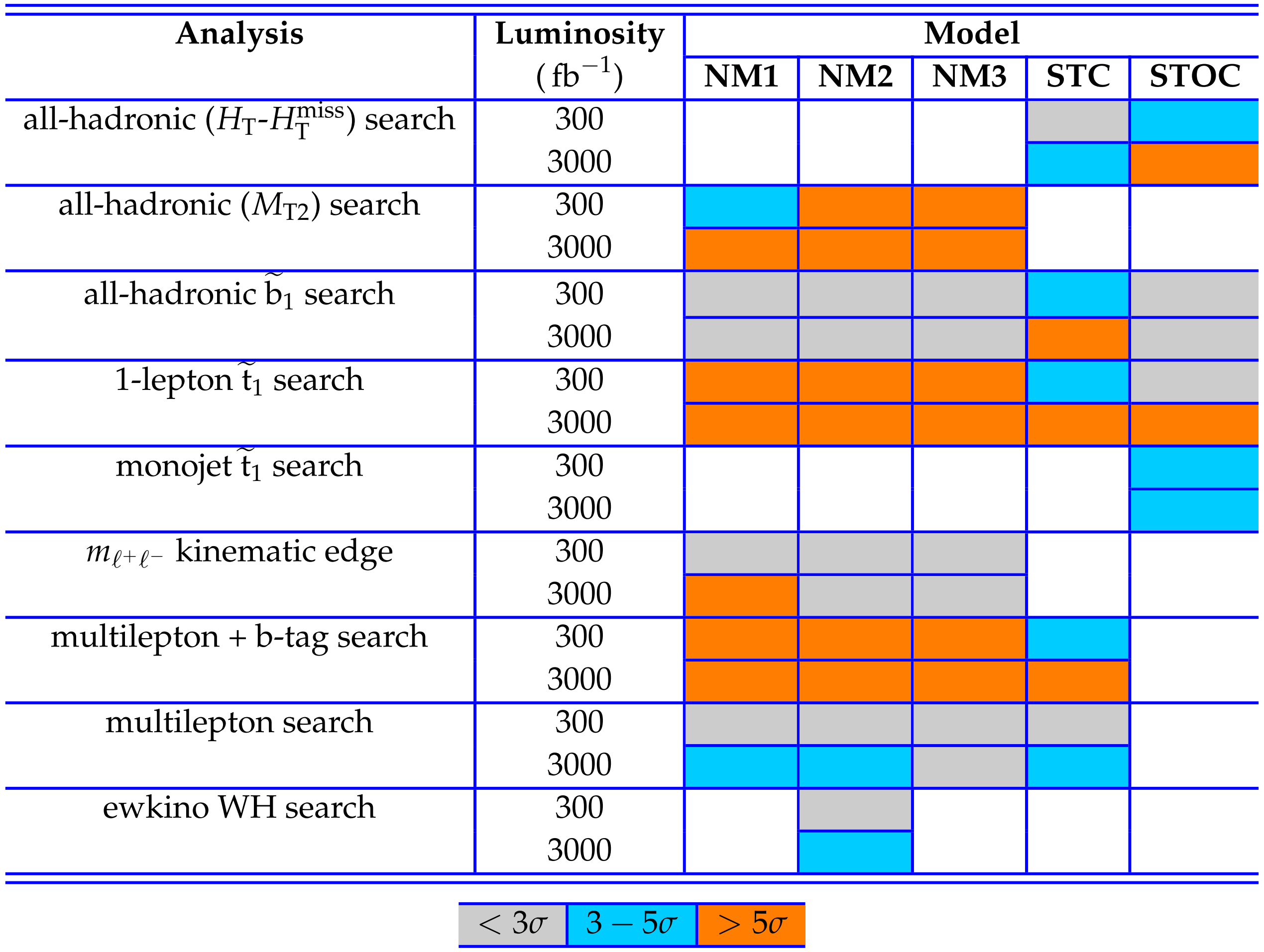
Starting point: 2015 Technical Proposal

Most complete SUSY@HL-LHC results are documented in the **<u>Phase 2 Technical Proposal</u>**

1) Projections of individual analyses for simplified models (FTR-13-014)
2) Interplay of several analyses for full models (SUS-14-012)
   - If there is SUSY, it will be seen across multiple signatures
   - Important to keep a broad program: 2-3σ evidence in several places can be as interesting as 5σ in a single analysis



Probe *up to* the quoted mass



Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-H_T^{miss}) search	300				▨	🟦
	3000				🟦	🟧
all-hadronic (M_{T2}) search	300	🟦	🟧	🟧		
	3000	🟧	🟧	🟧		
all-hadronic $\tilde{b}_1$ search	300	▨	▨	▨	🟦	▨
	3000	▨	▨	▨	🟧	▨
1-lepton $\tilde{t}_1$ search	300	🟧	🟧	🟧	🟦	▨
	3000	🟧	🟧	🟧	🟧	🟧
monojet $\tilde{t}_1$ search	300					🟦
	3000					🟦
$m_{\ell^+\ell^-}$ kinematic edge	300	▨	▨	▨		
	3000	🟧	▨	▨		
multilepton + b-tag search	300	🟧	🟧	🟧	🟦	
	3000	🟧	🟧	🟧	🟧	
multilepton search	300	▨	▨	▨	▨	
	3000	🟦	🟦	▨	🟦	
ewkino WH search	300		▨			
	3000		🟦			

▨ $< 3\sigma$ 🟦 $3-5\sigma$ 🟧 $> 5\sigma$

Future CMS Studies

Currently focus of CMS Future Studies group: Technical Design Reports for HL-LHC

Possible directions of improvements with respect to Technical Proposal

1. **Extend the "toolbox" of experimental techniques using strategies from Run 2**

New experimental techniques

Several object improvements in Run 2: these are now integral parts of our program, we need to make sure they are still feasible at the HL-LHC

Soft leptons: muons (electrons) down to 3.5 (5) GeV

- Developed for compressed EWK-ino search (next slide)
- Offline: typical efficiencies are 60-80% (μ), 30-50% (e)
- Online: dedicated MET+μμ tigger added in mid-2016
  - 80% efficiency for events with MET > 125 GeV, $p_T(\mu)$ > 5 GeV

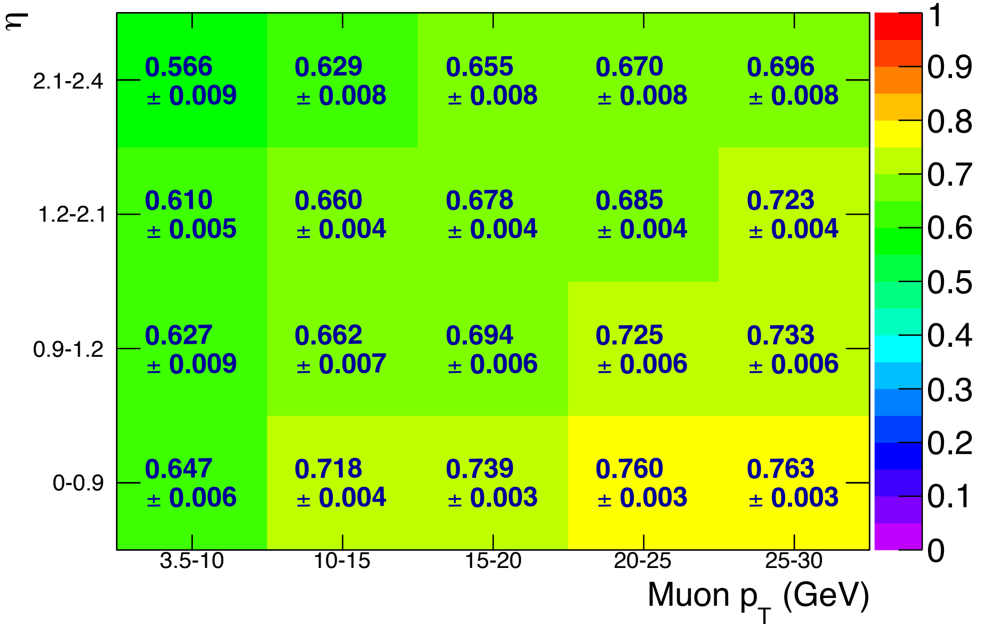
Soft b-tagging: b hadrons with 10 < p_T < 20 GeV

- Developed for all-hadronic stop search (arXiv: 1707.03316)
- Recovers acceptance in compressed region

Boosted double-b-tagging:

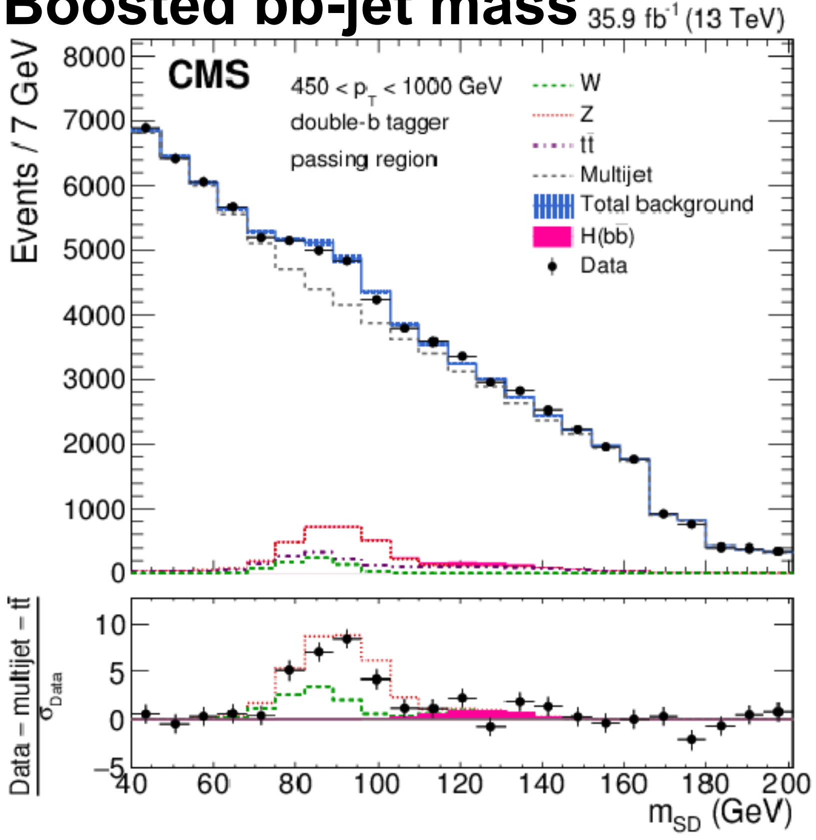
- Developed in BTV-15-002
- Hints of boosted boosted pp—>H—>bb (HIG-17-010)
- Applicable to Higgsino pair-production at high mass

Soft Muon Efficiency



η	3.5-10	10-15	15-20	20-25	25-30
2.1-2.4	0.566 ± 0.009	0.629 ± 0.008	0.655 ± 0.008	0.670 ± 0.008	0.696 ± 0.008
1.2-2.1	0.610 ± 0.005	0.660 ± 0.004	0.678 ± 0.004	0.685 ± 0.004	0.723 ± 0.004
0.9-1.2	0.627 ± 0.009	0.662 ± 0.007	0.694 ± 0.006	0.725 ± 0.006	0.733 ± 0.006
0-0.9	0.647 ± 0.006	0.718 ± 0.004	0.739 ± 0.003	0.760 ± 0.003	0.763 ± 0.003

Boosted bb-jet mass



Plots: SUSMoriond2017ObjectsEfficiency, HIG-17-010

New final state: ISR + soft leptons

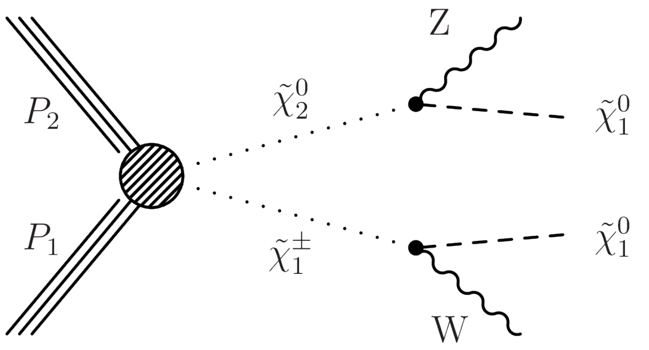
New strategy to address compressed EWK-inos

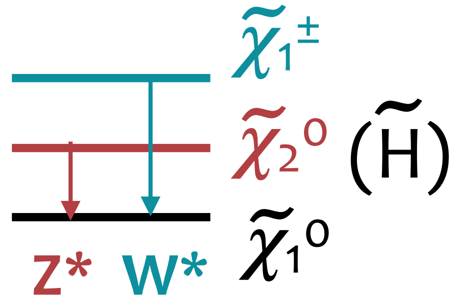
Suggested by arXiv:1401.1235 and arXiv:1409.7058

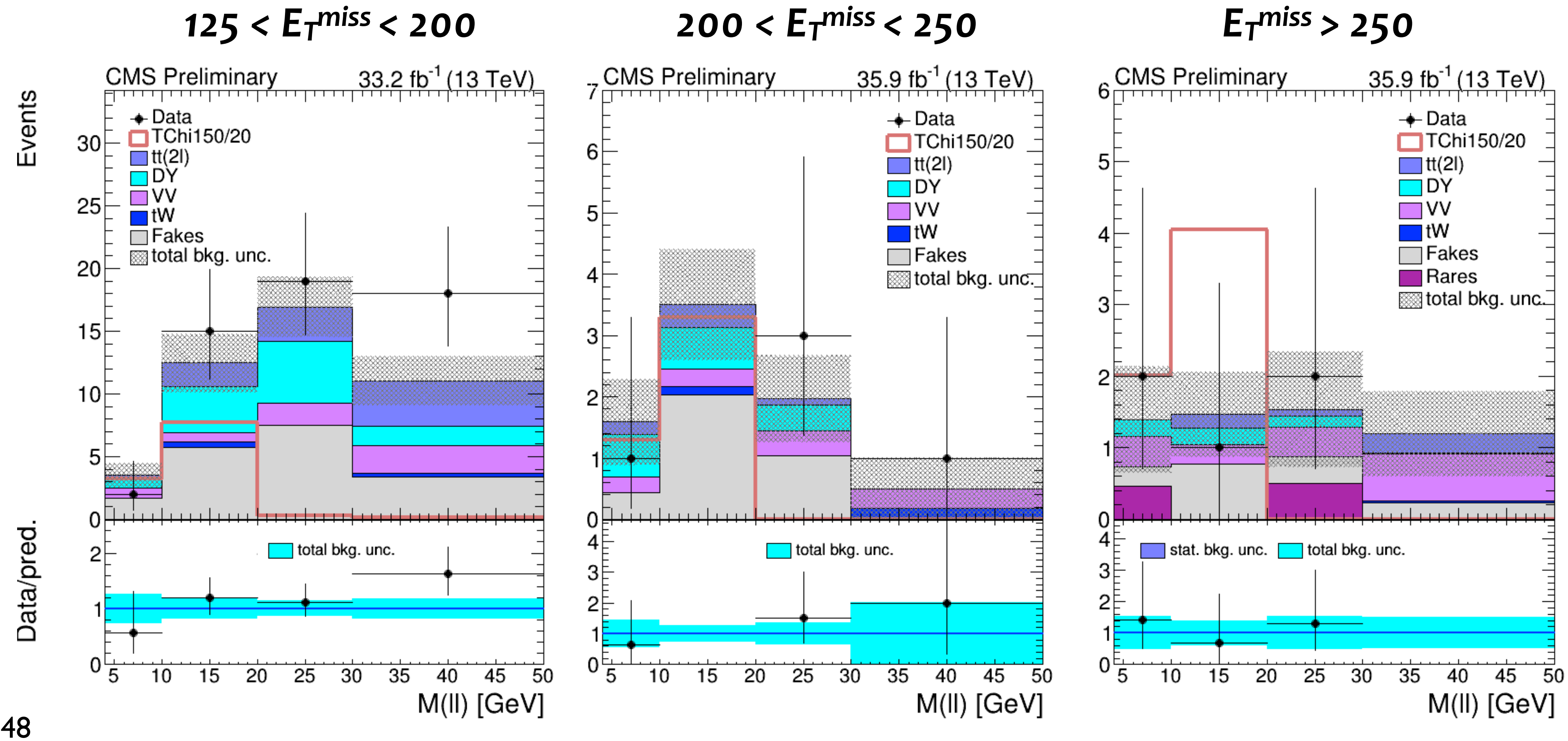
- Require ISR jet, and focus on soft lepton from off-shell Z decay
- Use event kinematics to reduce DY(ττ) and tt backgrounds
- m(l,l) ≤ Δm ⟶ Bin in MET and opposite-sign m(l,l)

Largest experimental challenge: nonprompt leptons

- Estimate: “fake rate” method (improved by CMS in Run 2)
- Validation region to constrain uncertainty: same-sign lepton






$125 < E_T^{miss} < 200$ $200 < E_T^{miss} < 250$ $E_T^{miss} > 250$

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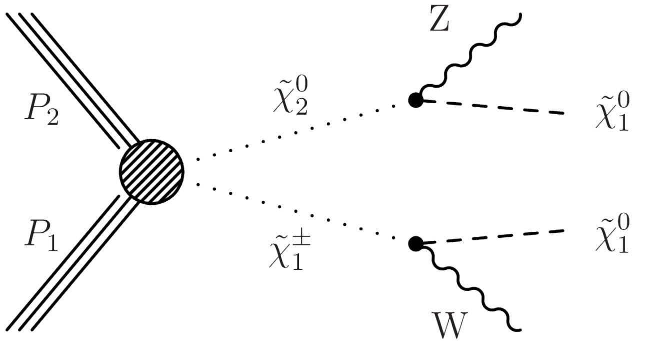
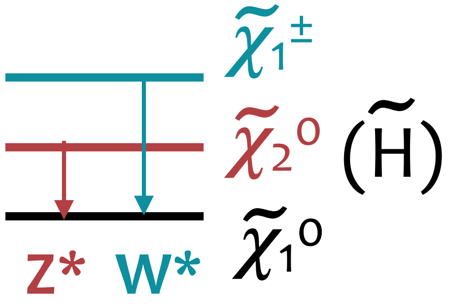
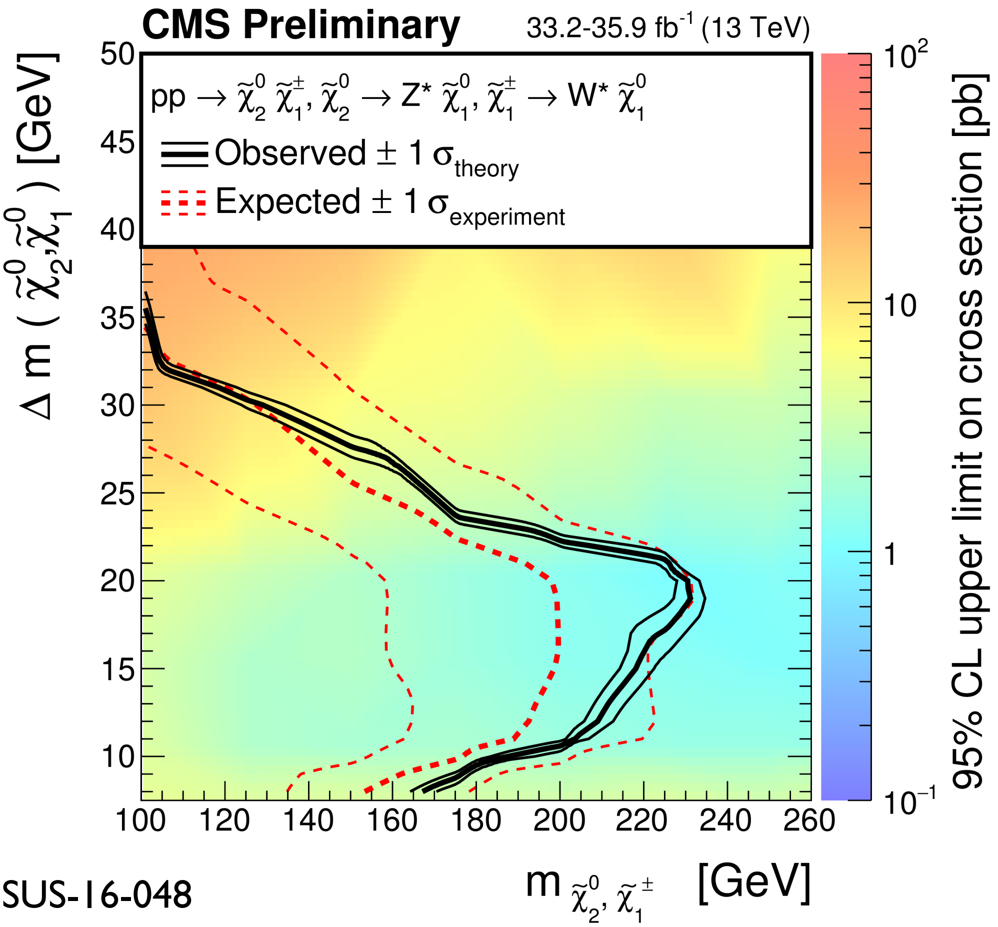
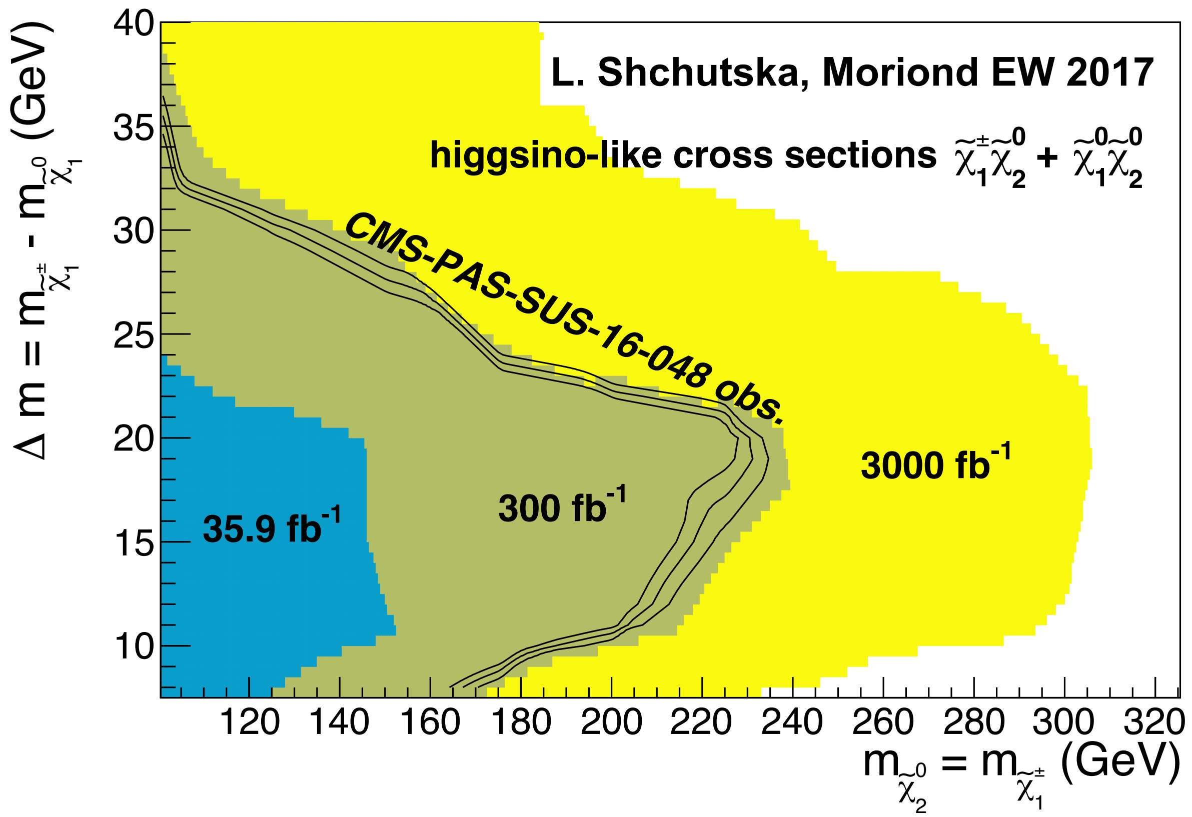




Wino cross section



Higgsino cross section (projection only)



CMS-PAS-SUS-16-048

New final states: bbbb, $\tau_h\tau_h$

Other recent searches, to be considered for HL-LHC extensions

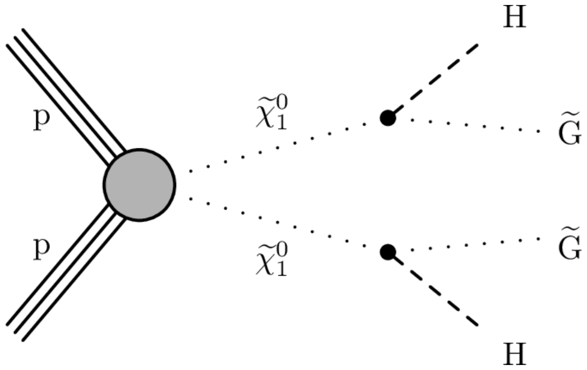
4 b-jets + MET: low Δm Higgsino pair production, Goldstino/Gravitino LSP

- Wide mass range excluded. High-mass regions are background-free
- Analysis uses resolved b-jets. Boosted techniques needed to extend to higher mass

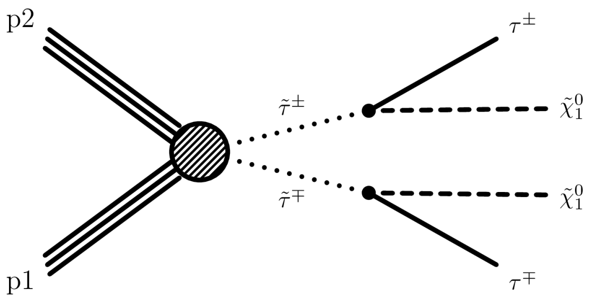
2 hadronic taus + MET: Stau pair production:

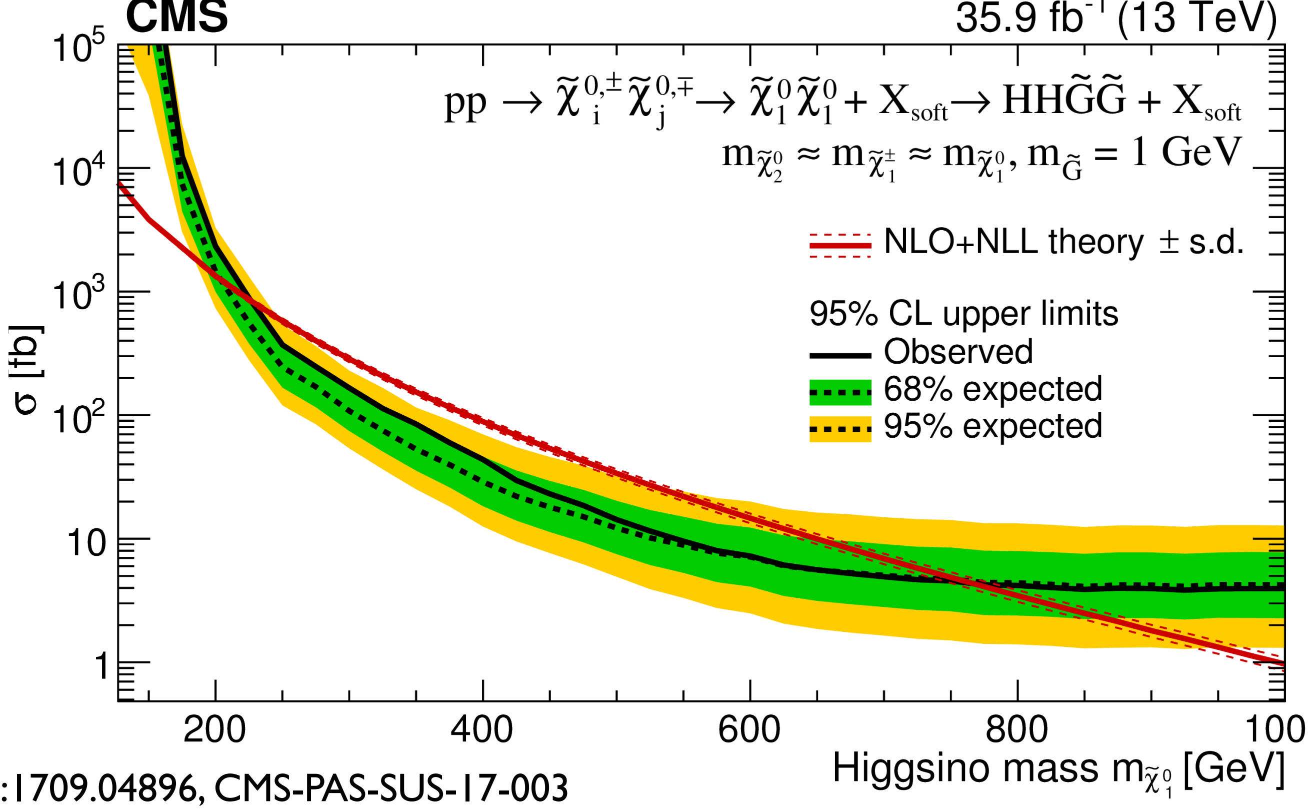
- Approaching sensitivity to direct staus in Run 2. Interesting to explore for HL-LHC

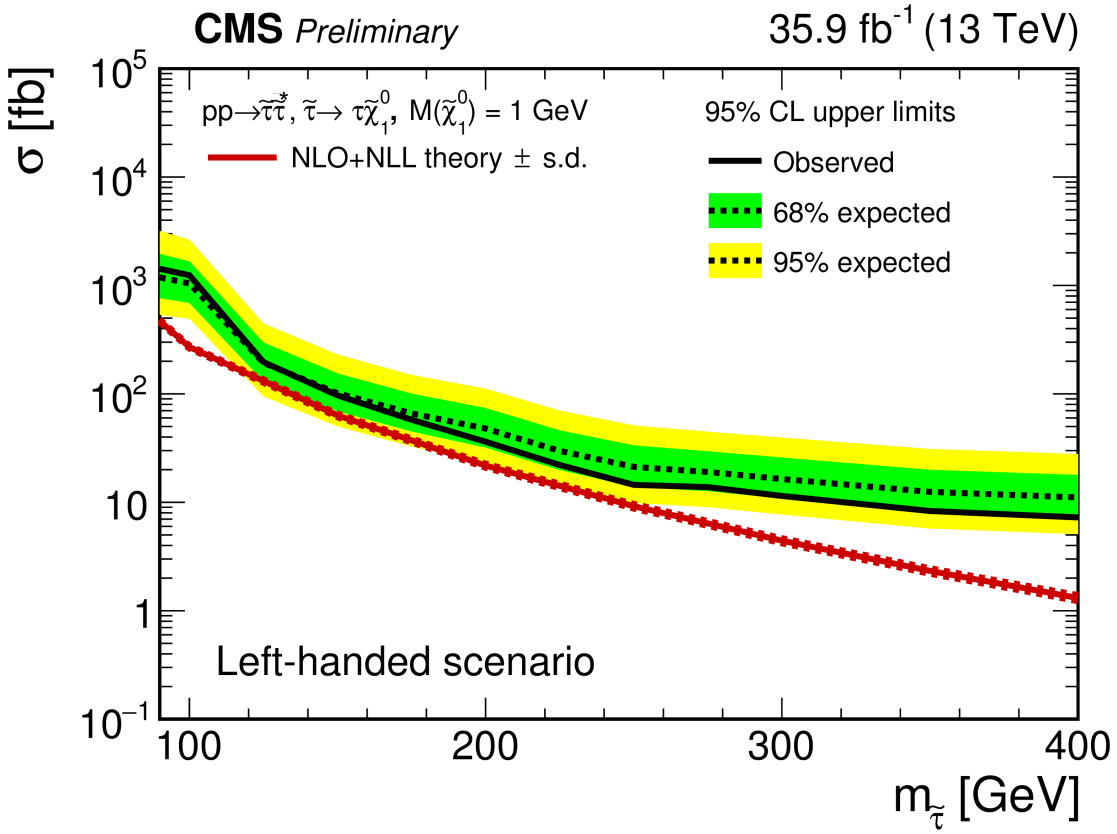
bbbb+MET



$\tau_h\tau_h$+MET







arXiv:1709.04896, CMS-PAS-SUS-17-003

Future CMS Studies

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Possible directions of improvements with respect to Technical Proposal

1. Extend the “toolbox” of experimental techniques using strategies from Run 2

2. **Showcase the new detector capabilities of the planned HL-LHC upgrades**

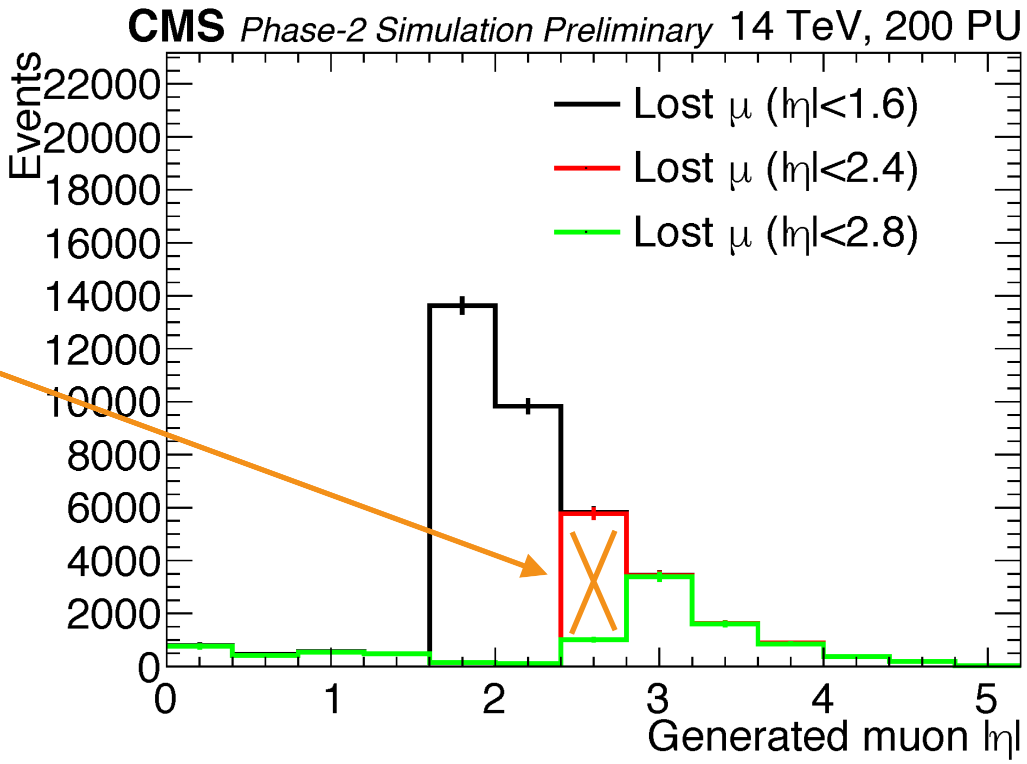
New detector capabilities

Focus on the effect of specific detector improvements on analyses

This is a key ingredient to motivate the CMS detector upgrade for HL-LHC

Extension of muon spectrometer coverage at high η:

- Lepton vetoes improve with extended coverage
- Ex: WZ(μμμ) background in same-sign dileptons
  - Bkg reduced by 35% extending η from 2.4 to 2.8

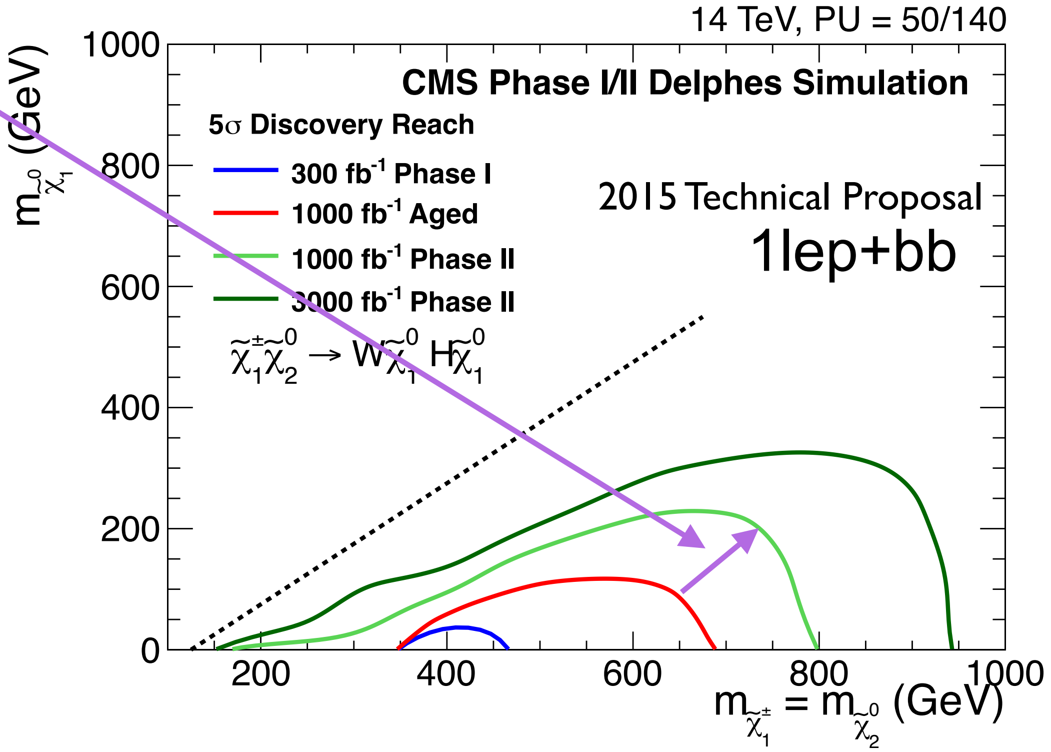


MET resolution impact of HGCAL and Timing Layer

- Many analyses rely on MET-related edges:
  - m_T(lep, MET), M_{T2}(lep1, lep2)
  - Studied during Technical Proposal, to be updated with latest detector and reconstruction plans

Impact of HL-LHC detectors on VBF topologies

- Studied in FTR-13-014 and FTR-16-002, but impact of new detectors not yet fully simulated



Plots: CMS-TDR-17-003, CMS-TDR-15-002

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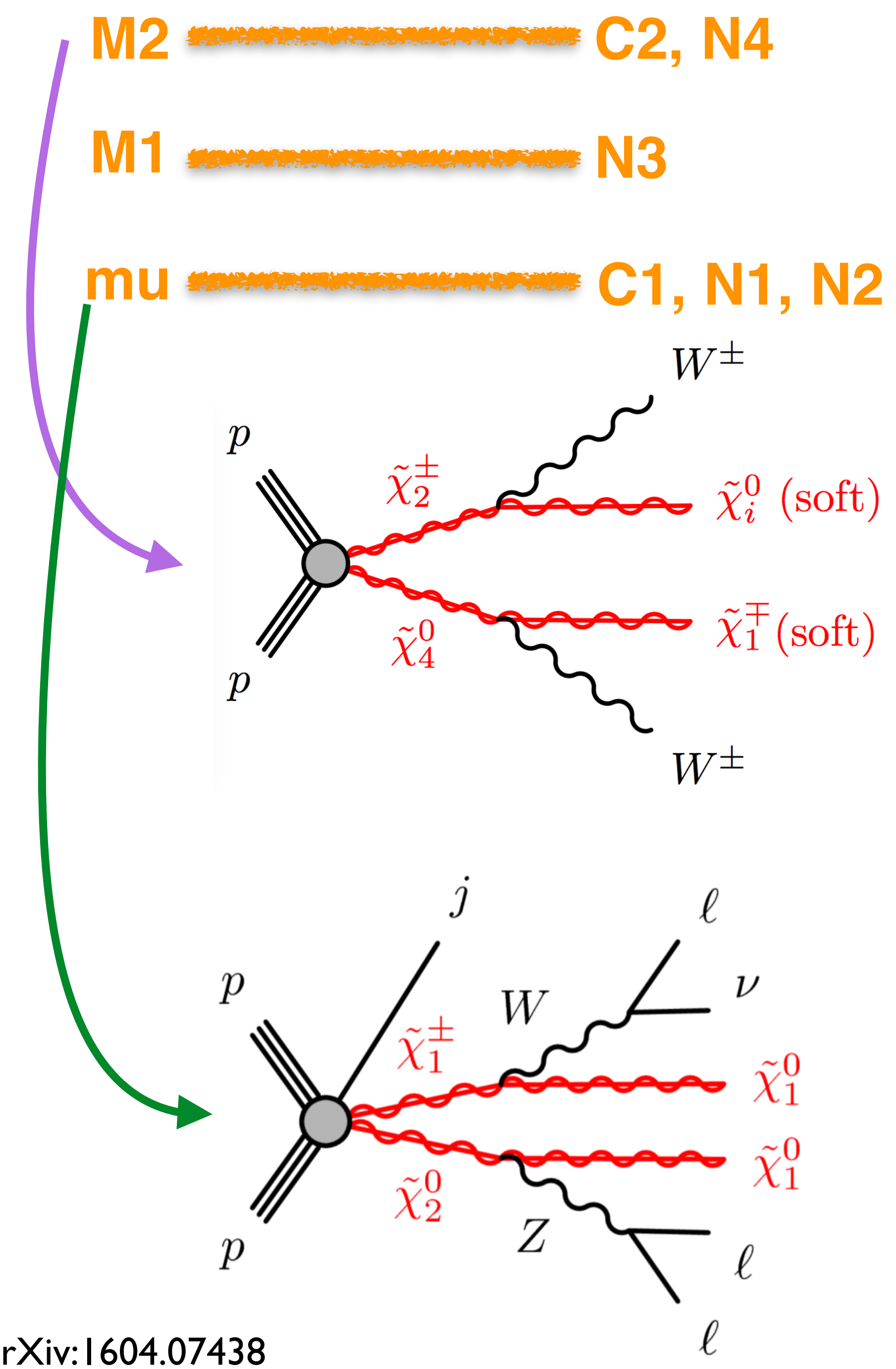
Possible directions of improvements with respect to Technical Proposal

1. Extend the “toolbox” of experimental techniques using strategies from Run 2
2. Showcase the new detector capabilities of the planned HL-LHC upgrades
3. **Explore ideas from the theory community, fill holes in the (natural) SUSY program**
   [Completely arbitrary selection]

Radiatively-driven Natural Susy

Reconcile m_Z and m_H close to 100 GeV with gluinos and squarks beyond the TeV scale, without large cancellation

Interplay between two existing final states used to reject “natural” region

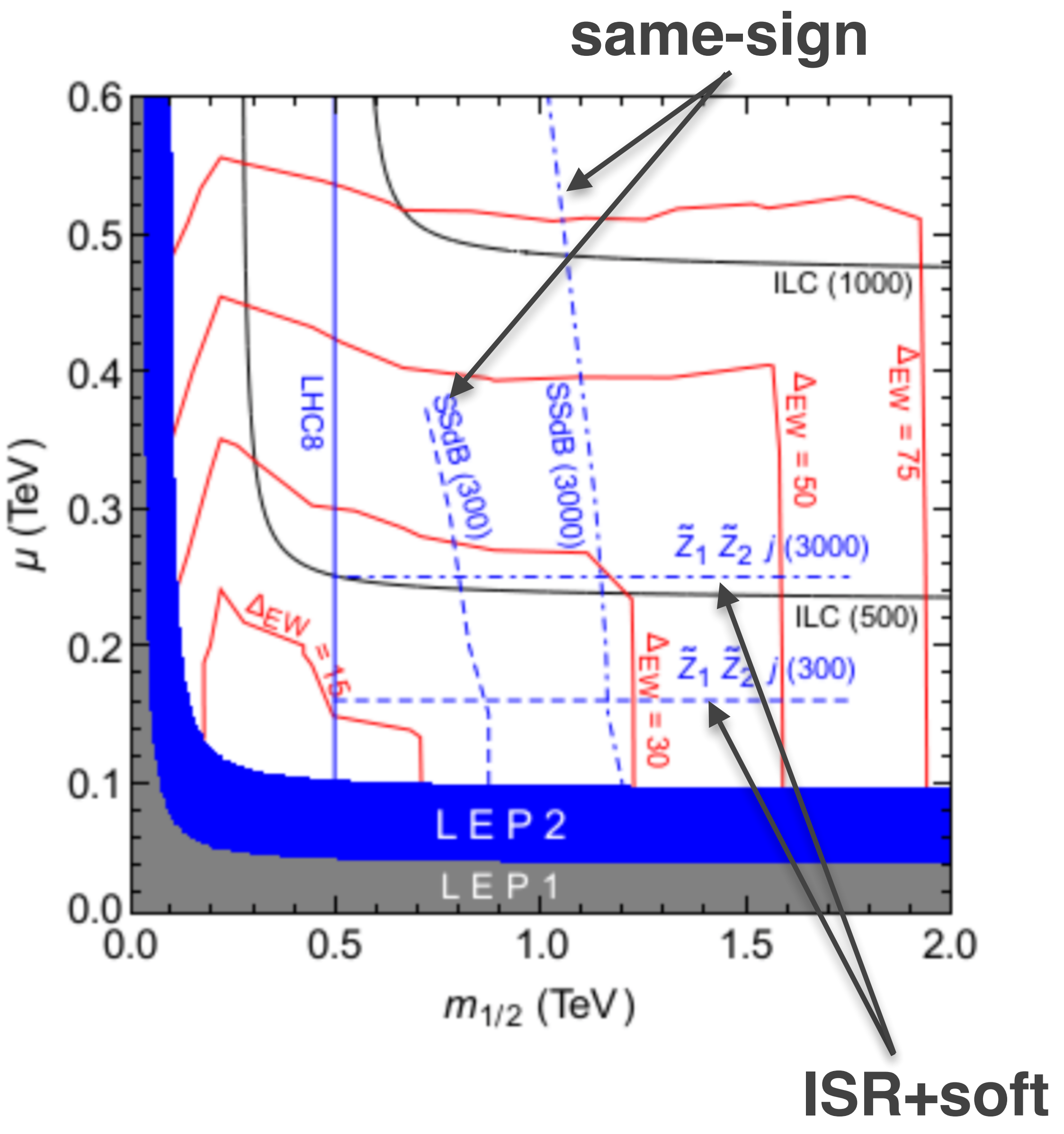


Winos:
< 1 TeV

Higgsinos:
100-300 GeV

same-sign
dileptons

ISR+soft leptons



same-sign

ISR+soft

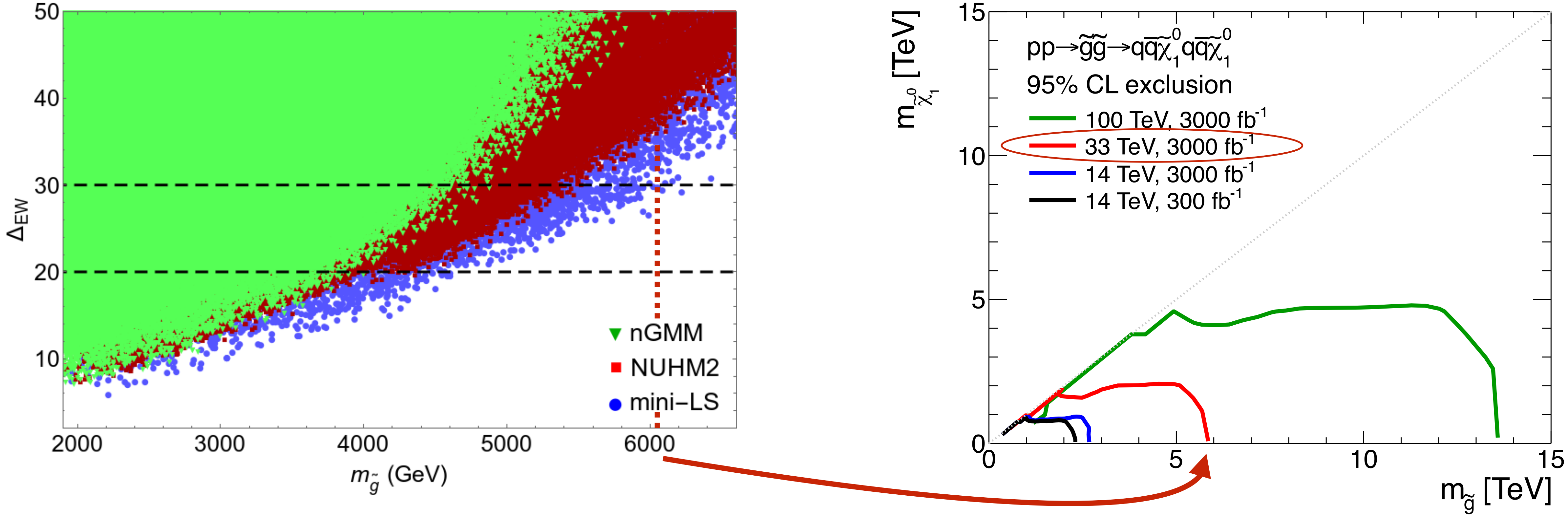
arXiv:1604.07438

What if the Winos are out of reach?

Other models with light Higgsinos, different from RNS, can still achieve naturalness without requiring Winos with mass < 1 TeV

In all cases they have gluinos with mass < 6 TeV

- Out of reach for HL-LHC (~2.5 TeV), but perfect for a 33 TeV HE-LHC



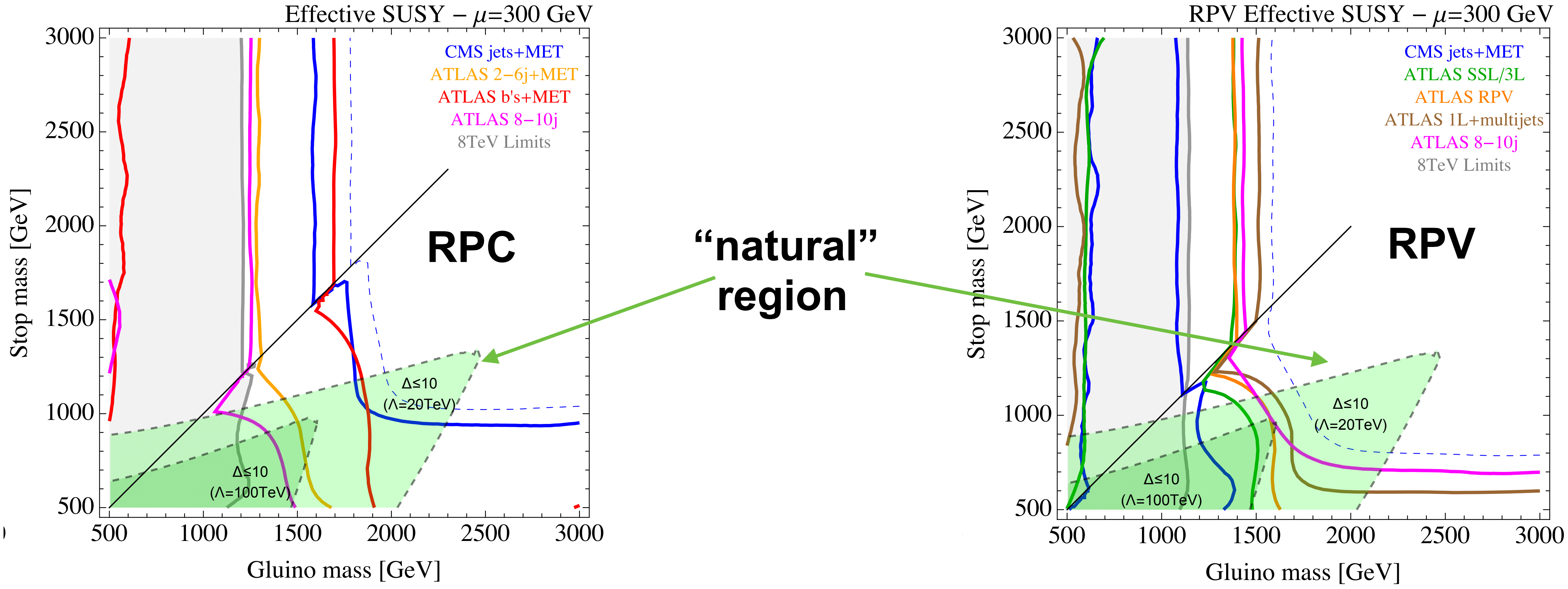
(1) arXiv:1702.06588, arXiv:1708.09054; (2) arXiv:1606.00947

RPV: another hiding place for naturalness?

Bounds on ~t and ~g are weaker in RPV than RPC models (arXiv:1610.08059)

[Here Δ is defined differently from previous slides, thus dependent on log(Λ)]

HL-LHC needed to completely cover “natural” region



“natural” region

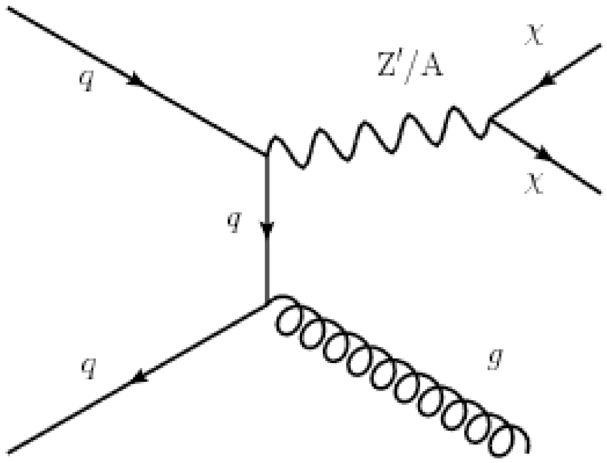
But <u>not all RPV bounds are necessarily weaker than RPC ones</u>:

See arXiv:1706.09418, focusing on <u>CMSSM</u> models.

See talk by M. Krauss (next BSM session)

arXiv:1610.08059

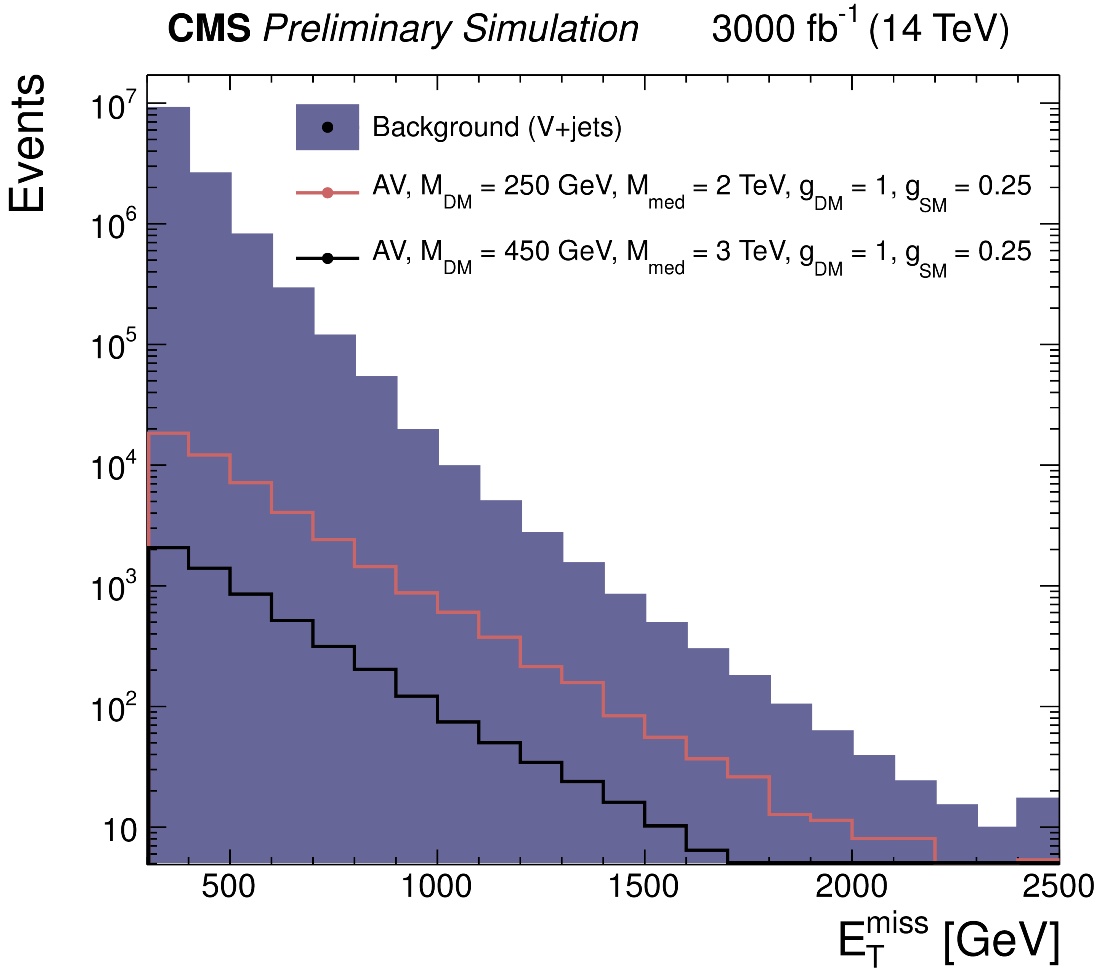
What about other non-resonant signatures?

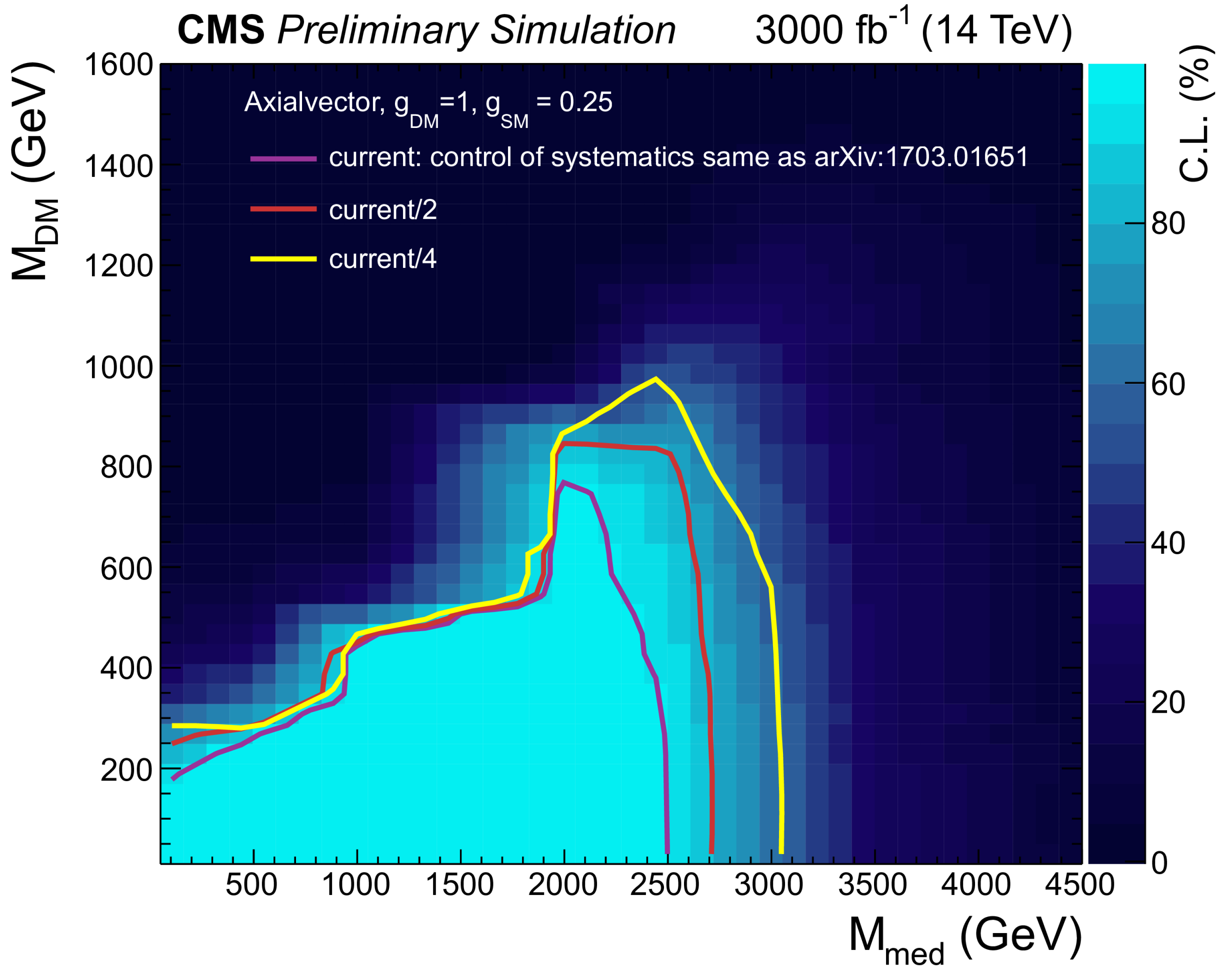


MonoX dark matter searches

Same signature as very compressed SUSY spectra

- Simplified models based on the production of a single SM-DM mediator particle
- Example: Jet+MET, 10% syst in highest MET bin (>2.4 TeV) based on Run 2 analysis





See dedicated talk by Anne-Marie Magnan in the Higgs+BSM Session

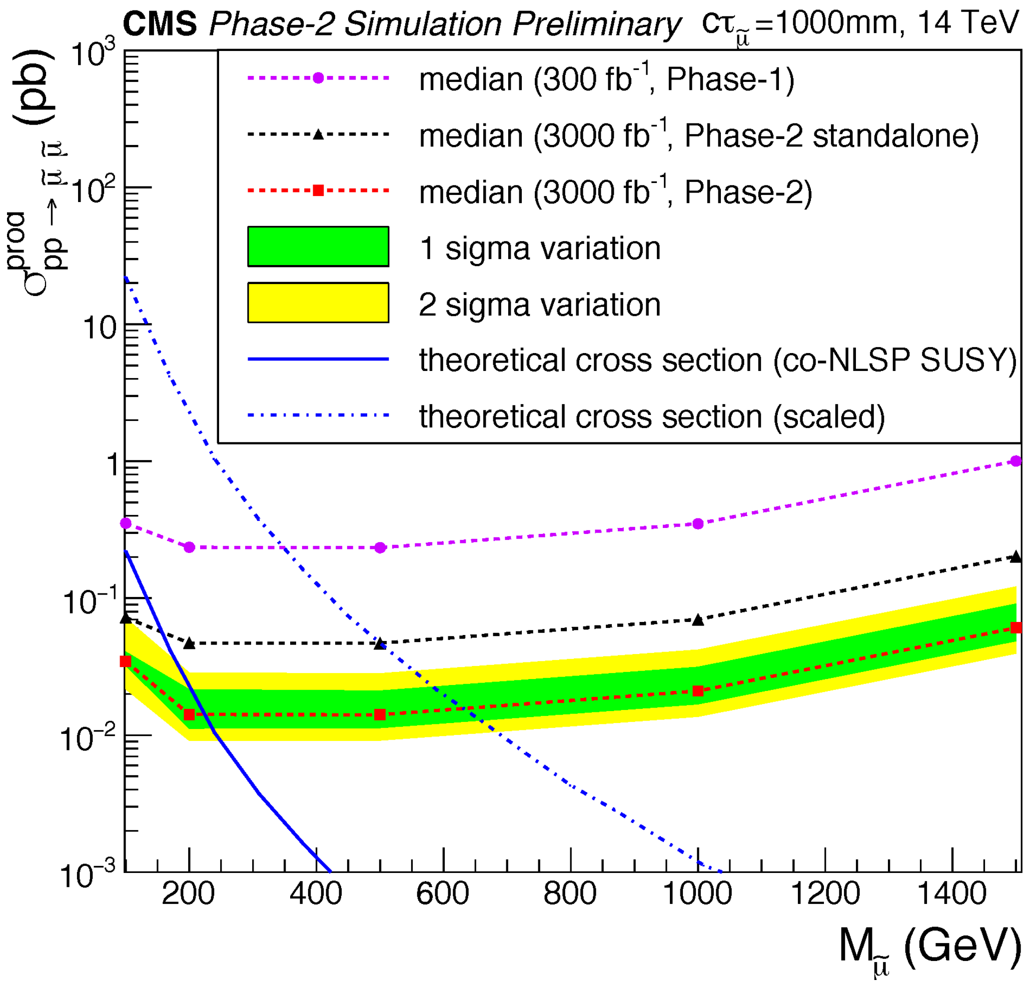
CMS-PAS-FTR-16-005

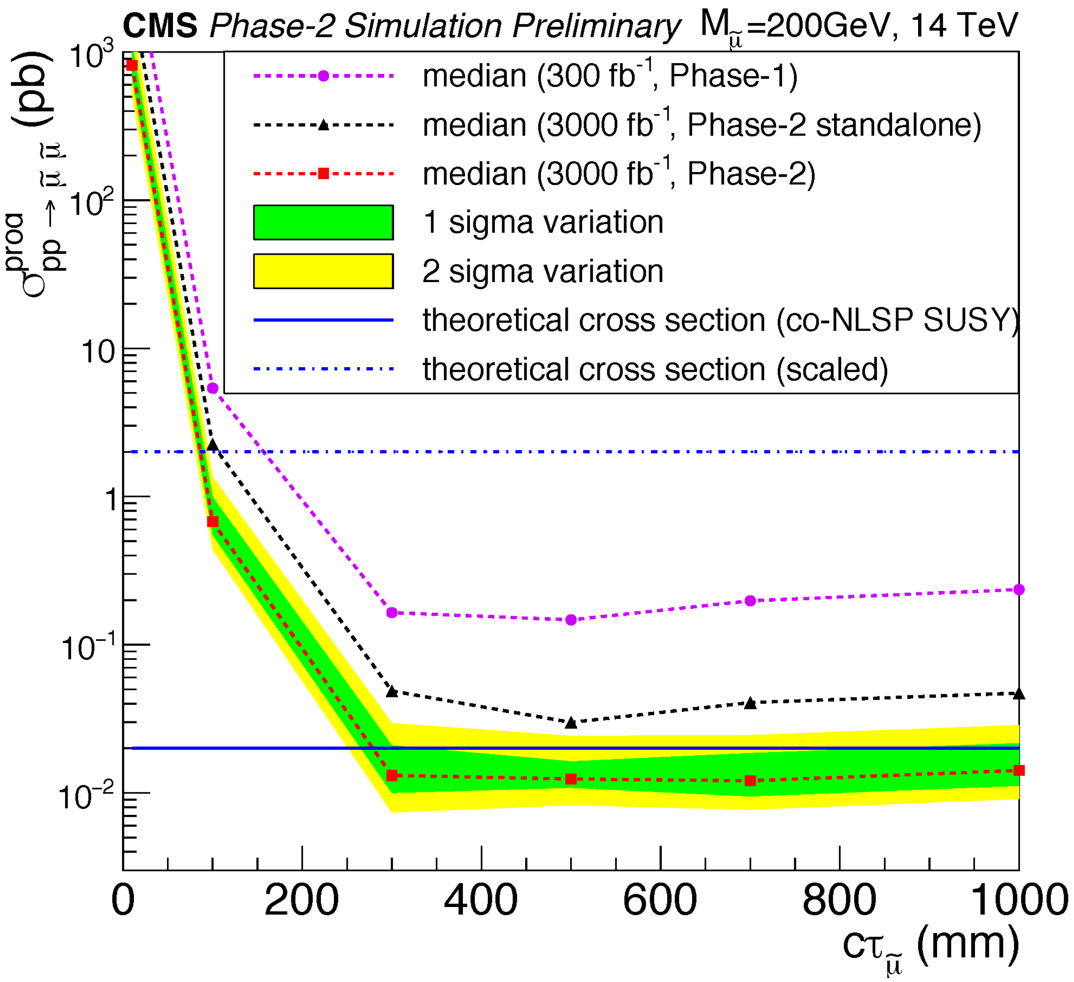
What about other non-resonant signatures?

Long-lived particle searches

For example: pair-production of long lived smuons

$$q\bar{q} \to \tilde{\mu}\bar{\tilde{\mu}}, \tilde{\mu} \to \mu\tilde{G}$$





Explored in depth for Tracker and Muon upgrade TDRs

See dedicated talk by Juliette Alimena in BSM Session 1

CMS-TDR-17-003

Summary

Since the Technical Proposal of 2015, CMS has a solid basis for understanding HL-LHC reach of classic SUSY searches

1. Individual searches exploring individual simplified models
2. Interplay between multiple searches exploring full SUSY models

Ongoing explorations are based on three general directions:

1. Explore the potential of recent (Run 2) advances and searches
2. Take advantage of HL-LHC detector capabilities
3. Test ideas and suggestions from the theory community

Reminder: as we explore the reach of HL-LHC, it is important not to lose track of the detectors which we are proposing to build

Anchoring all our objects to realistic detector simulations and reconstruction will be crucial to be confident in our expected results