Search for EWK SUSY with CMS at HL/HE

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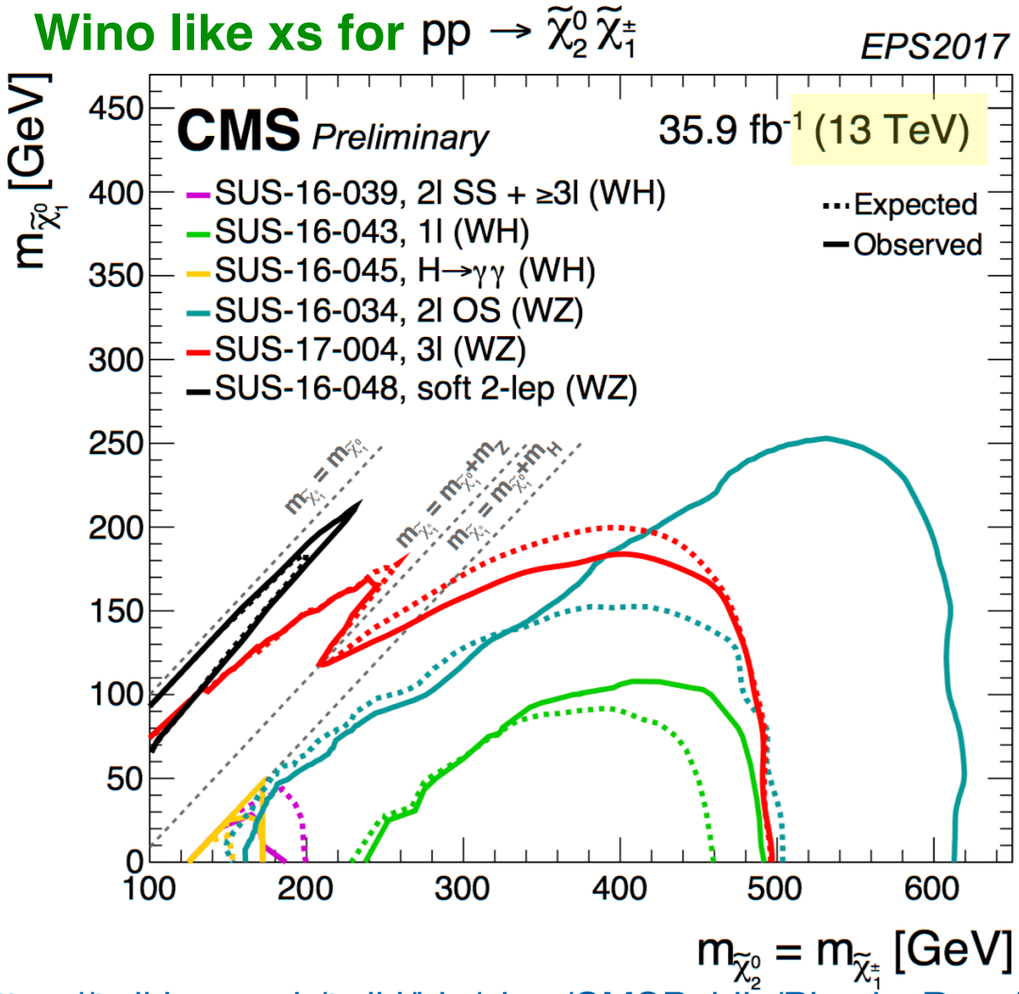
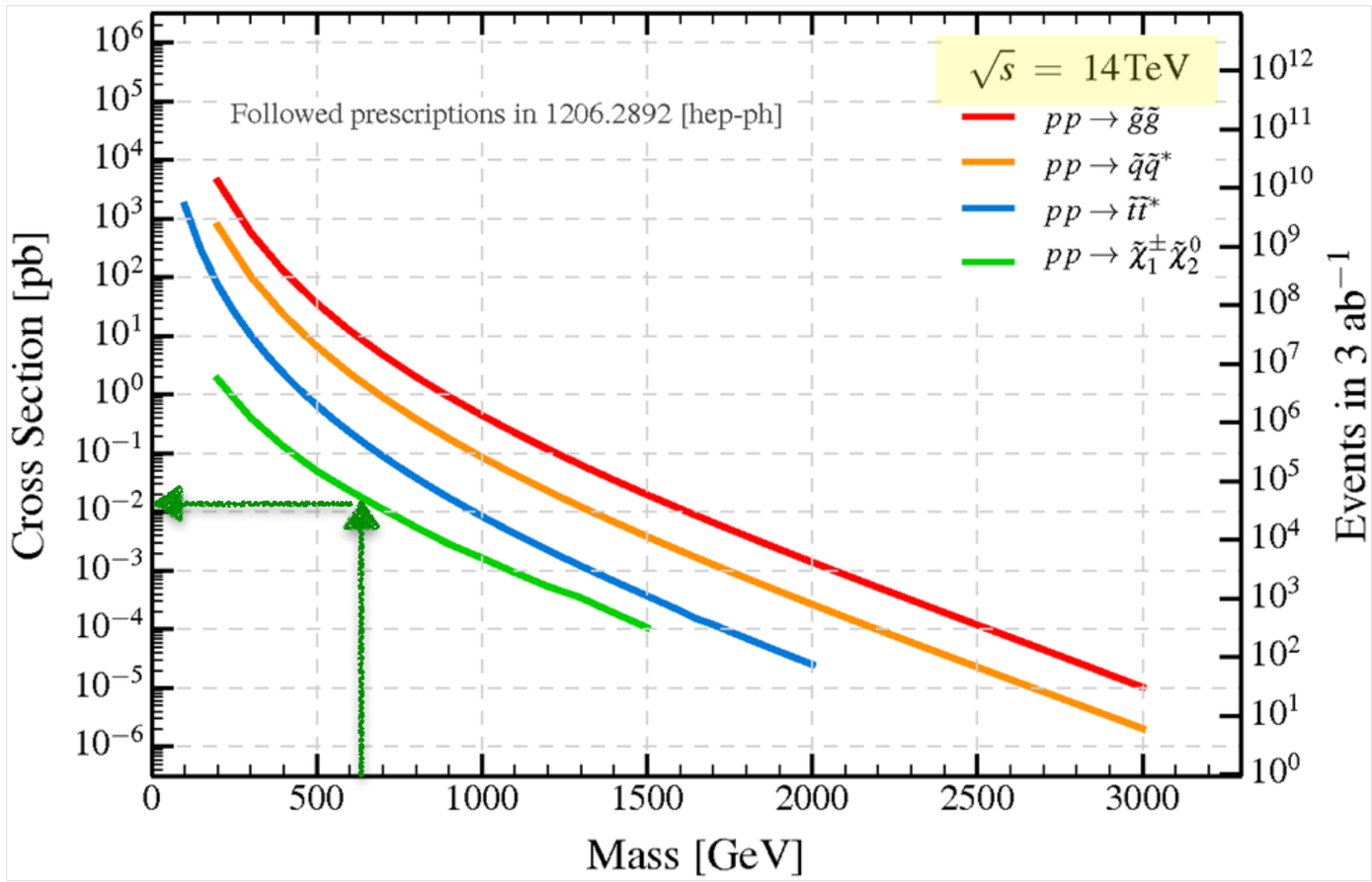
HL/HE LHC Meeting

April 4-6th, 2018

State of the art of CMS searches for EWK-inos in Run2 (I)

- EWK-inos are expected to be in the few hundreds GeV mass range based on naturalness and unification arguments ⇒ extracting the signal from the background is challenging
- EWK-inos are produced via EWK production ⇒ sensitivity up to ~10 fb (compared to ~1 fb for gluinos) in simplified models

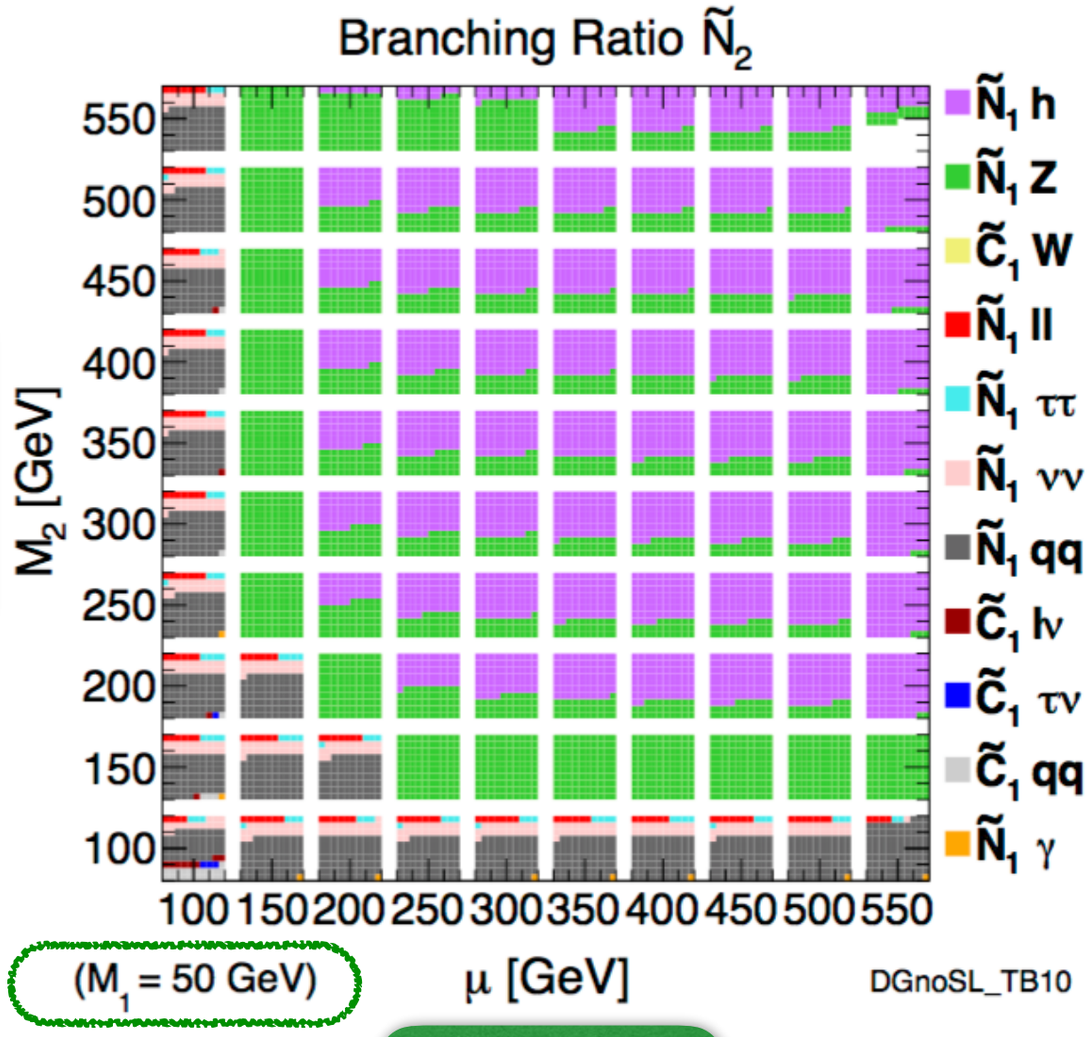




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

State of the art of CMS searches for EWK-inos in Run2 (II)

- Sensitivity strongly depends on EWK-inos composition, affects cross-sections and BRs
  - Wino into Bino mode via Wh (when kinematically allowed) and not WZ
  - If focus on WZ decay, sensitivity suppressed by reduced higgsinos xs



Winos

Higgsinos

Courtesy of Borge Gjelsten

C1, N2 mass (GeV)	Wino C1N2 σ (fb)	Higgsino C1N2 σ (fb)
100	22670	3277
200	1807	244
300	387	51
400	121	16
500	46	6
600	20	3

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections#Cross_sections_for_various_S_AN2

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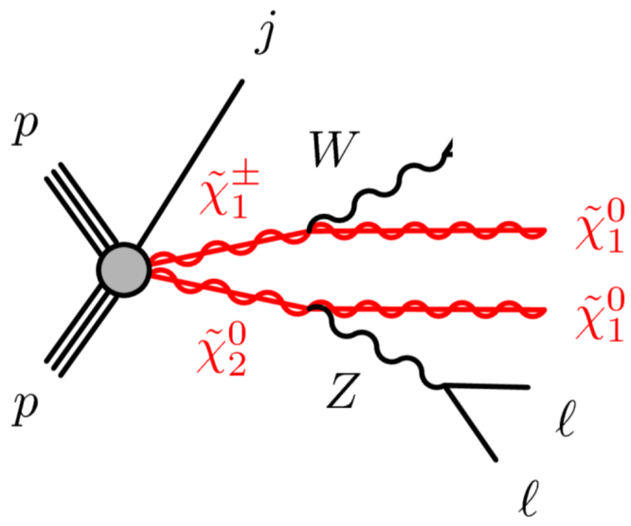
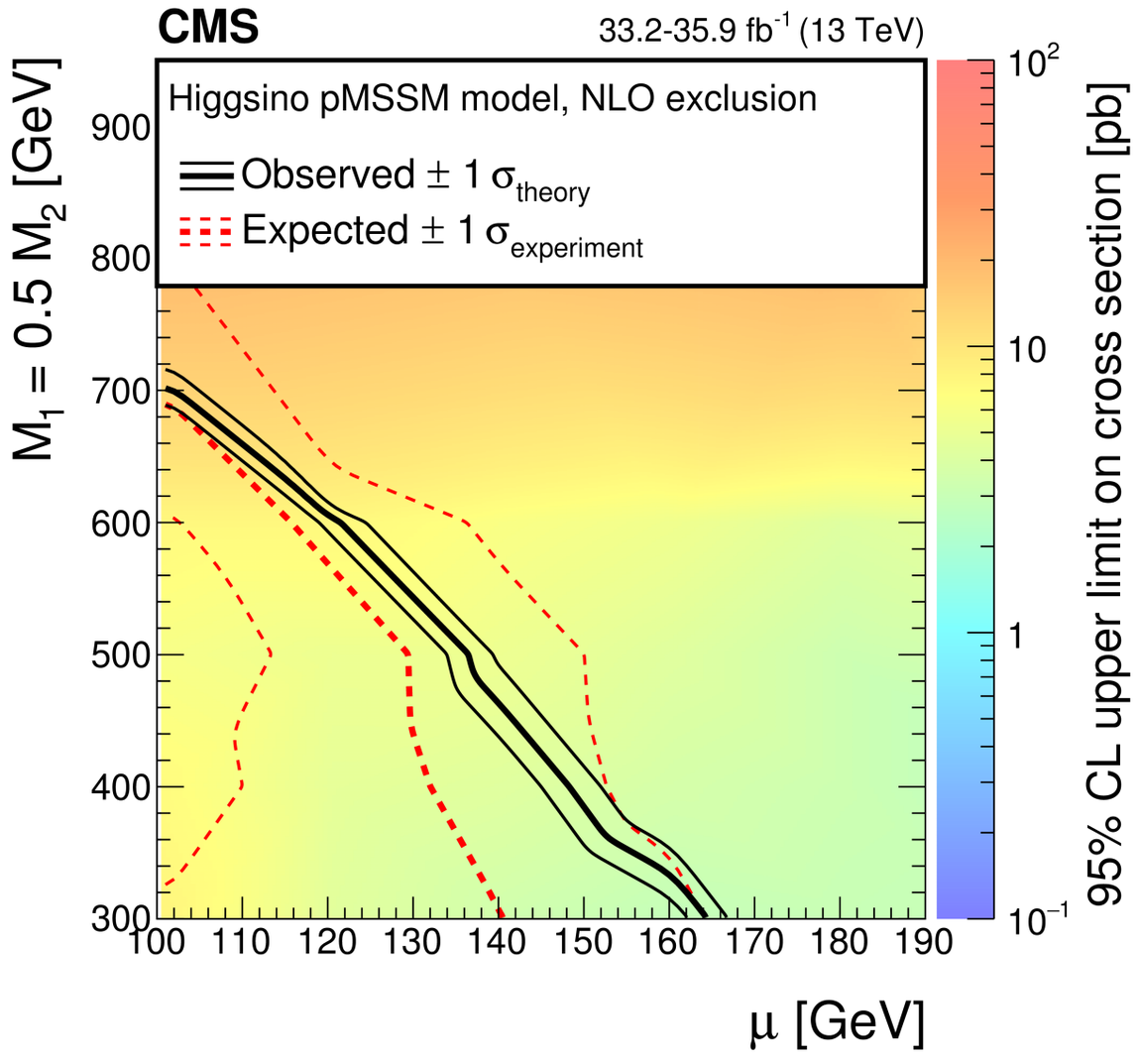
State of the art of CMS searches for EWK-inos in Run2 (III)

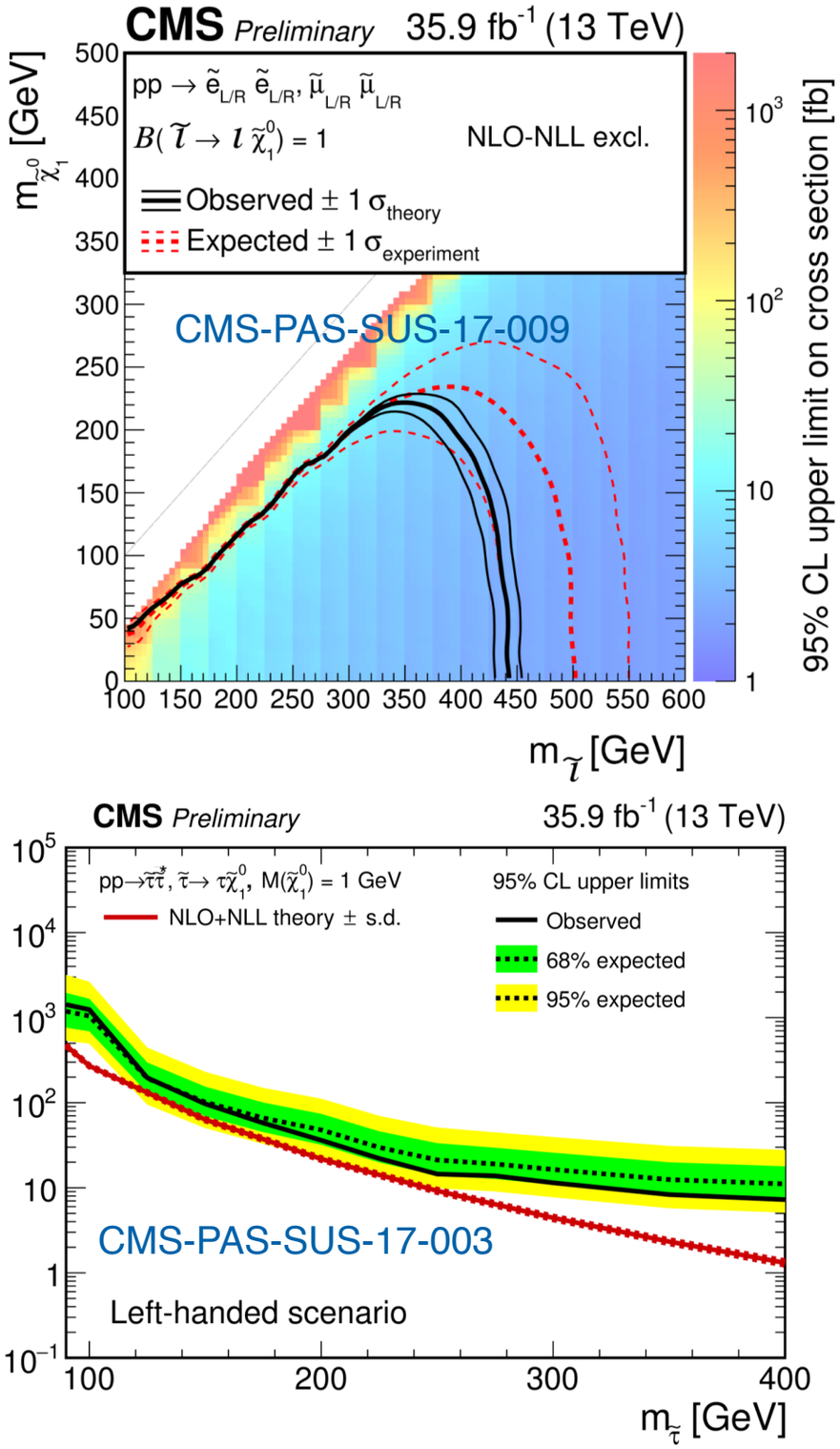
- Interpretation of analyses in (more) realistic scenarios is essential to assess actual sensitivity of LHC
  - higgsino expected to be at low mass
  - for decoupled winos, no exclusion beyond LEP
  - for low mass winos, sensitivity to higgsinos only up to 160 GeV



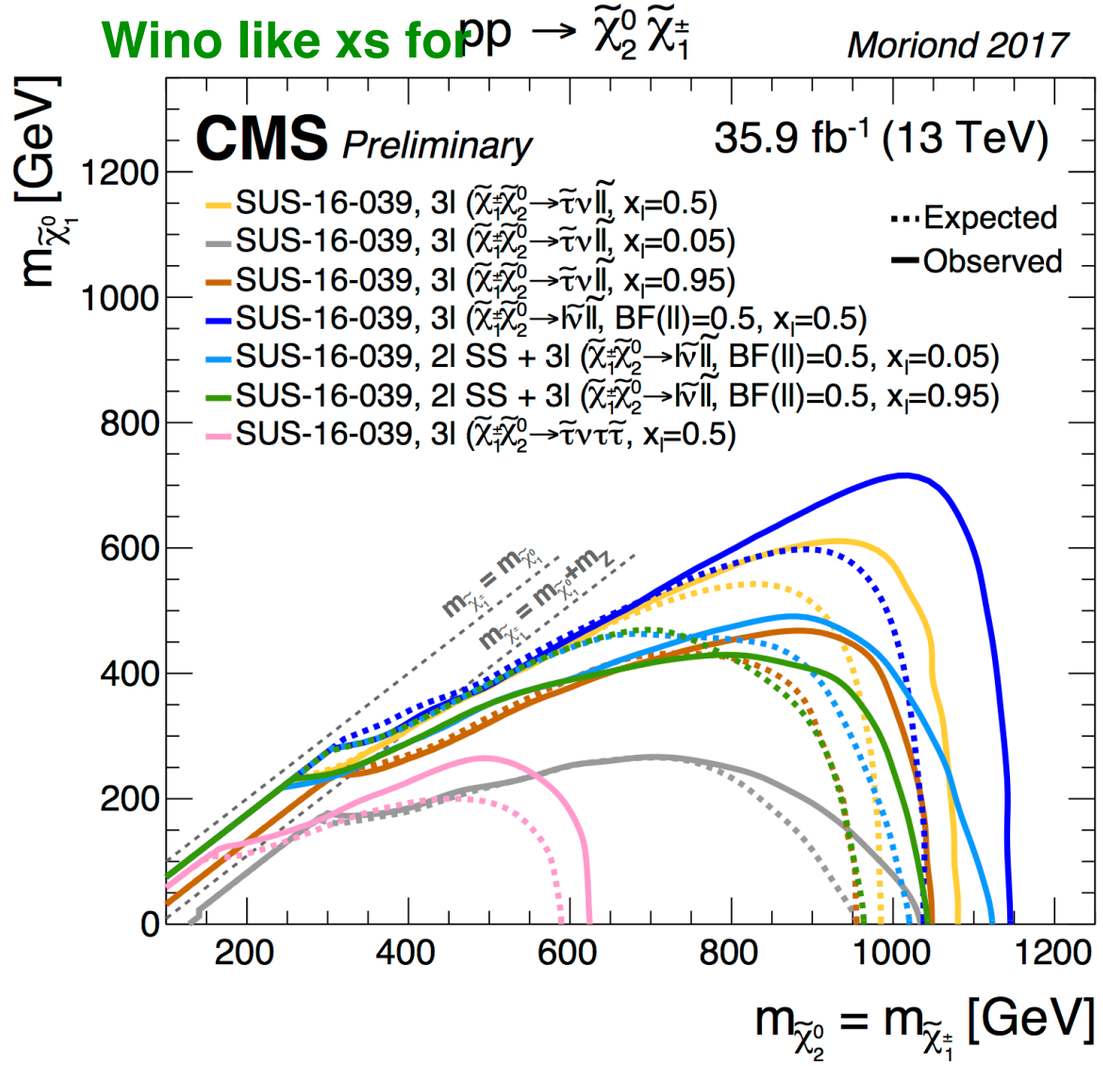
Search in events with 2 soft opposite sign same flavor leptons (or "SOS")
SUS-16-048



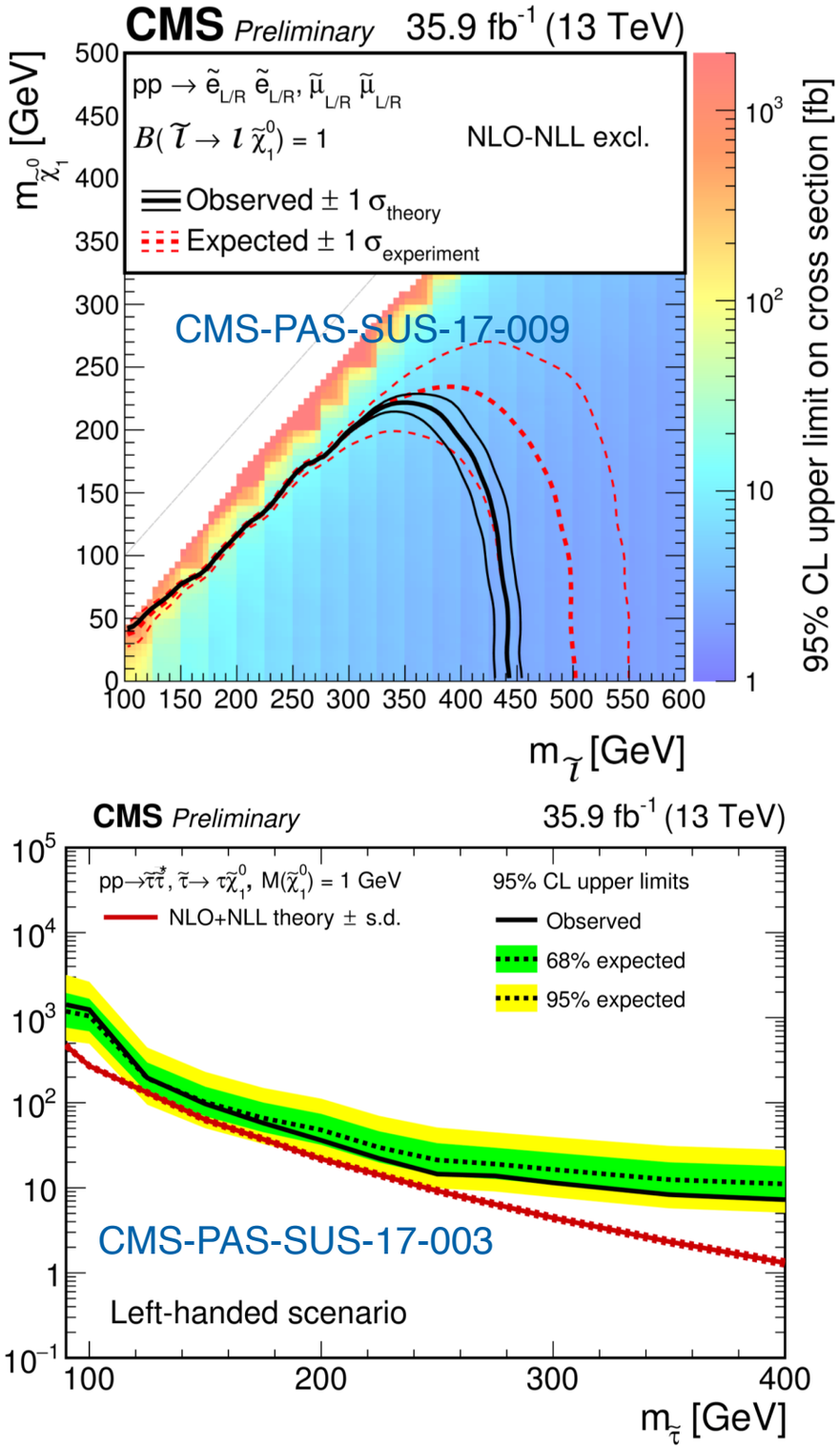
Spectra with low mass sleptons and EWK-inos (I)



- Sleptons are excluded up to ~450 GeV
  - no sensitivity to stau yet
- EWK-inos decaying via sleptons are excluded up to ~1.1 TeV



Spectra with low mass sleptons and EWK-inos (II)



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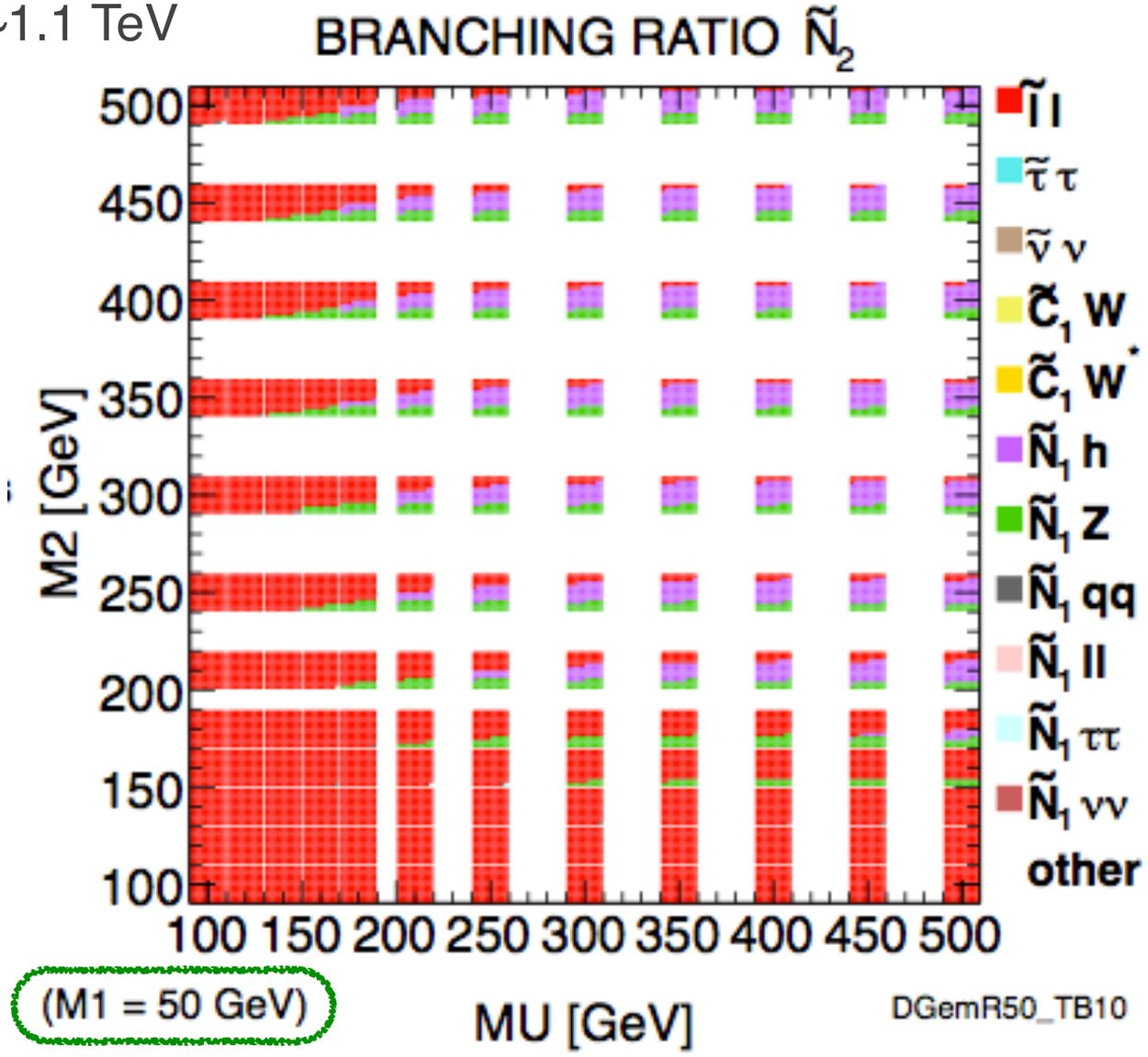

Courtesy of Borge Gjelsten

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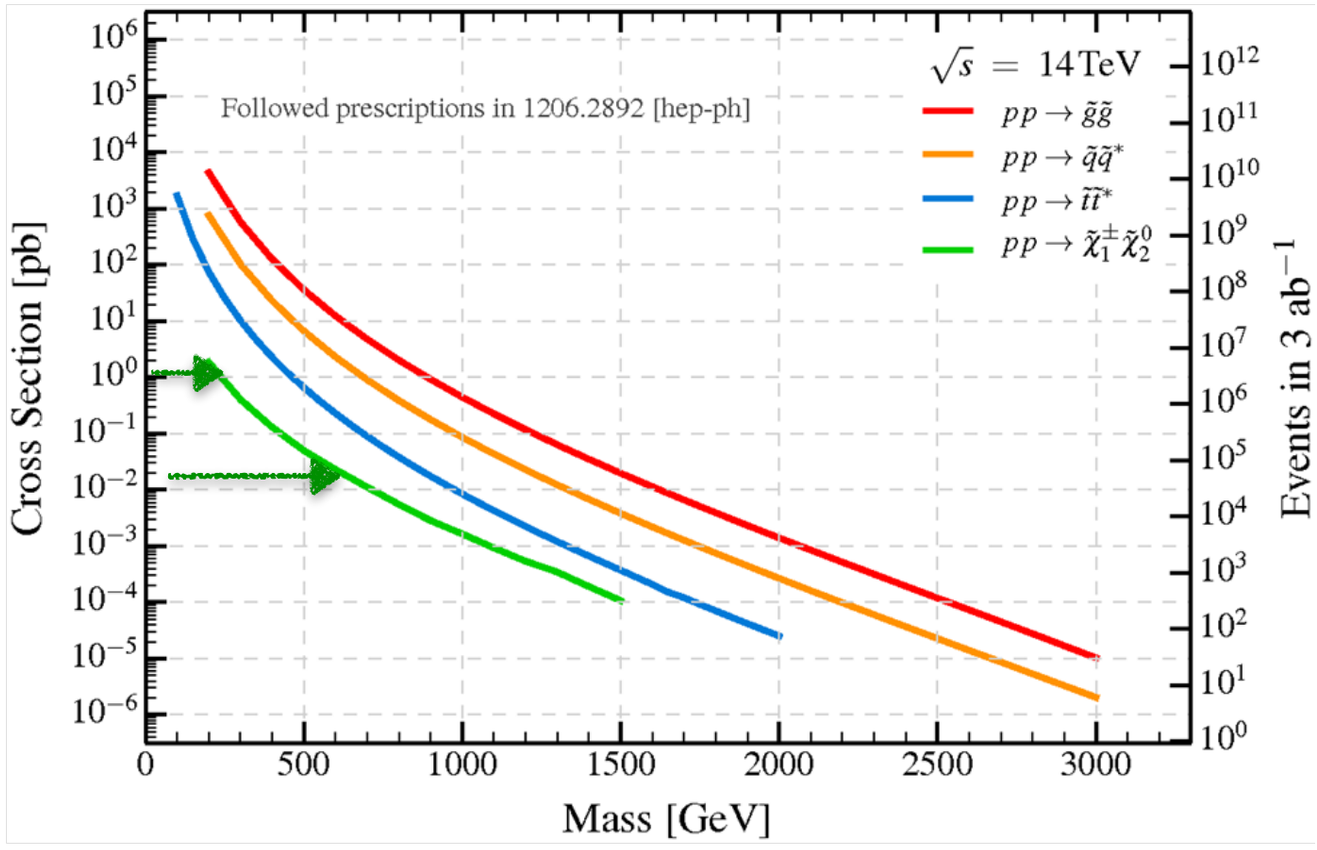
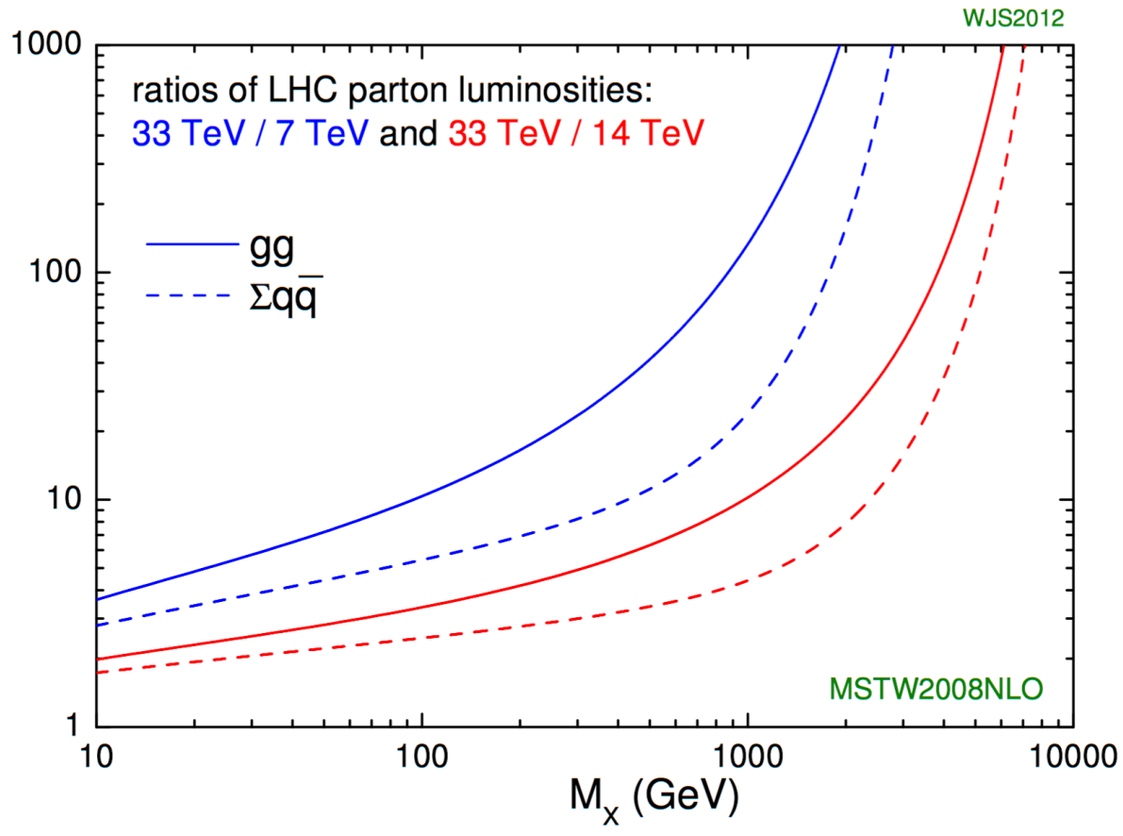
EWK SUSY at HL-LHC and HE-LHC?

- The **HL-LHC dataset** has the potential to increase the sensitivity to EWK SUSY by 3000/36 ~ 80x
  - *assuming no deterioration in the performance of the detector*
- The **HE-LHC at 27 TeV** can lead to a ~2x increase of signal xs for sub-TeV EKW-inos

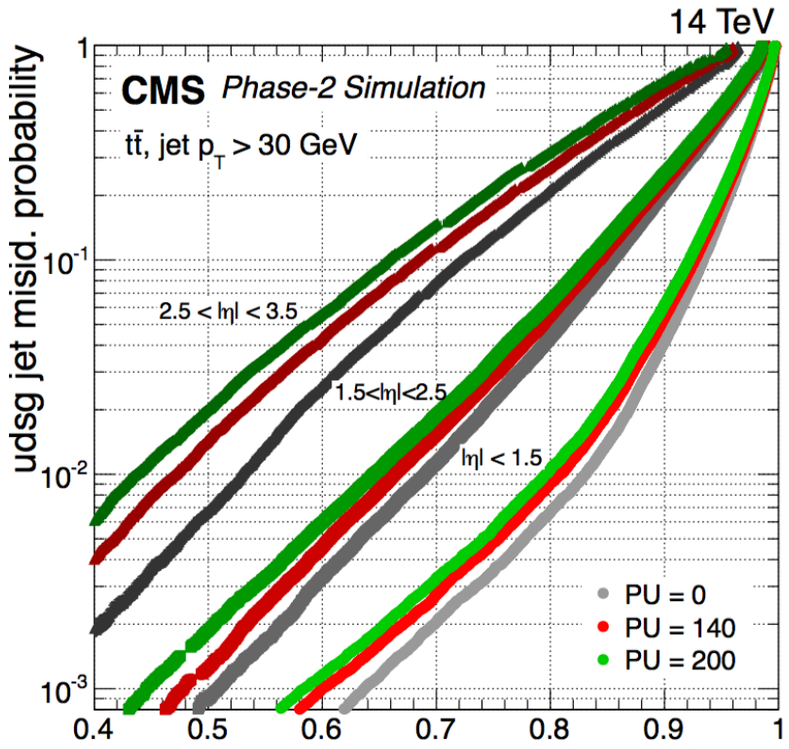


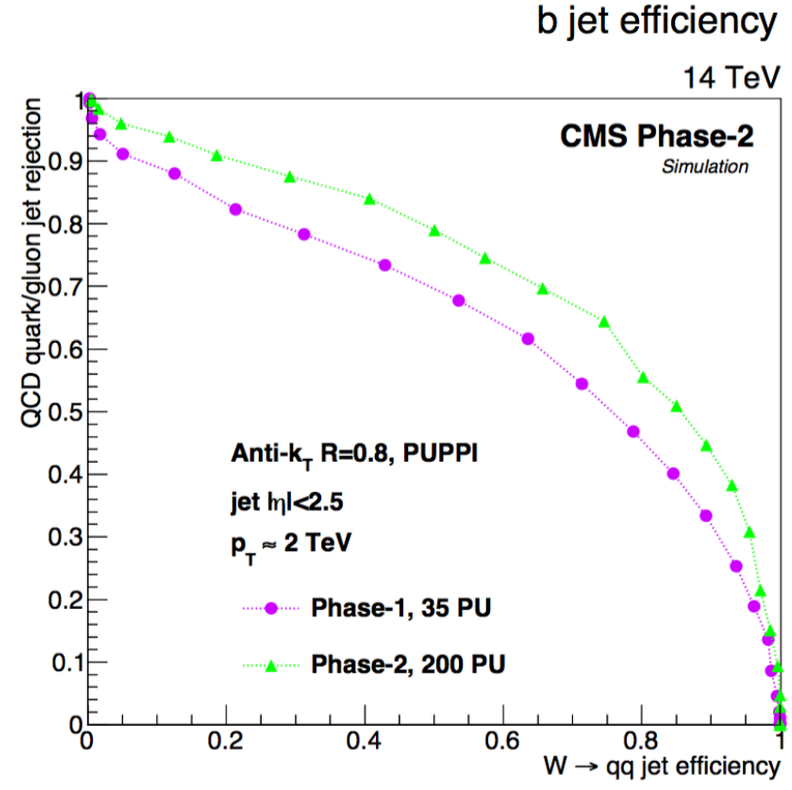


http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html

Key ingredients for EWK searches at HL-LHC

- Discovery potential of the HL-LHC critically depends upon the performance of the upgraded CMS detector
- Essential to the success of the EWK searches at HL-LHC:
  - **Excellent MET resolution**
  - **Triggers with low and sharp turn-ons**
    - *e.g.* Run2 SOS analysis based on MET > 90-120 GeV trigger and MET & soft muons trigger
  - **Excellent performance of lepton reconstruction** over a broad pT range
    - to also probe (highly motivated) compressed scenarios
- **Efficient and pure b-tagging**
- **Efficient reconstruction of boosted bosons**
  - to maximize sensitivity at high mass EWK-inos in non-compressed scenarios



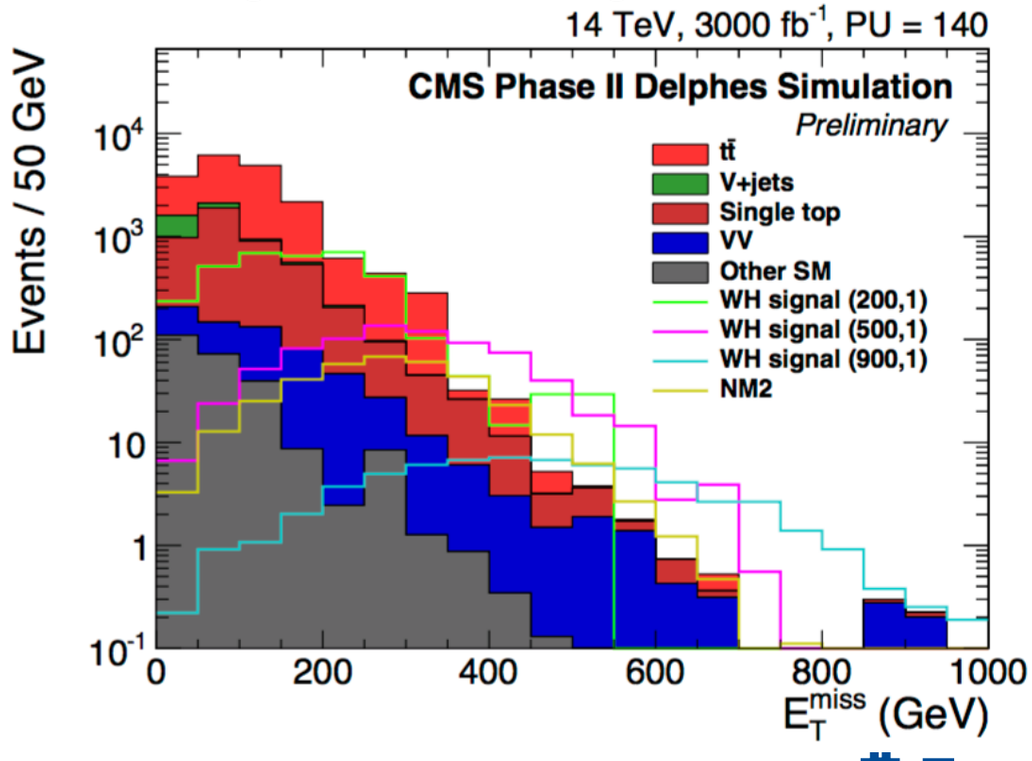


Search for Wino-like C1N2 decaying into Wh 1Lbb (I)

- Signal and background shapes are determined using **Delphes** 3.0.10
  - objects efficiencies and resolutions corrected using a preliminary Full Simulation of the Phase 2 detector
  - PYTHIA 6.4 used for generation of pile up events (<mu>=140)
  - signal and background events generated with MADGRAPH5, including up to 4 extra parsons from ISR and FSR, matched to PYTHIA 6.4
  - NLO xs used for both the signal and the background
  - systematic uncertainties assumed to be 1/2 w.r.t to that measured in 8 TeV analyses
- MET and MCT are the essential observables to discriminate signal from background

One electron/muon pT > 40 GeV & letal < 2.4
no other leptons with pT > 10 GeV
2 b tagged jets with pT > 30 GeV & letal < 2.4
mbb in 90-150 GeV
no other jets pT > 30 GeV & letal < 2.4
mT > 100 GeV & mCT > 160 GeV

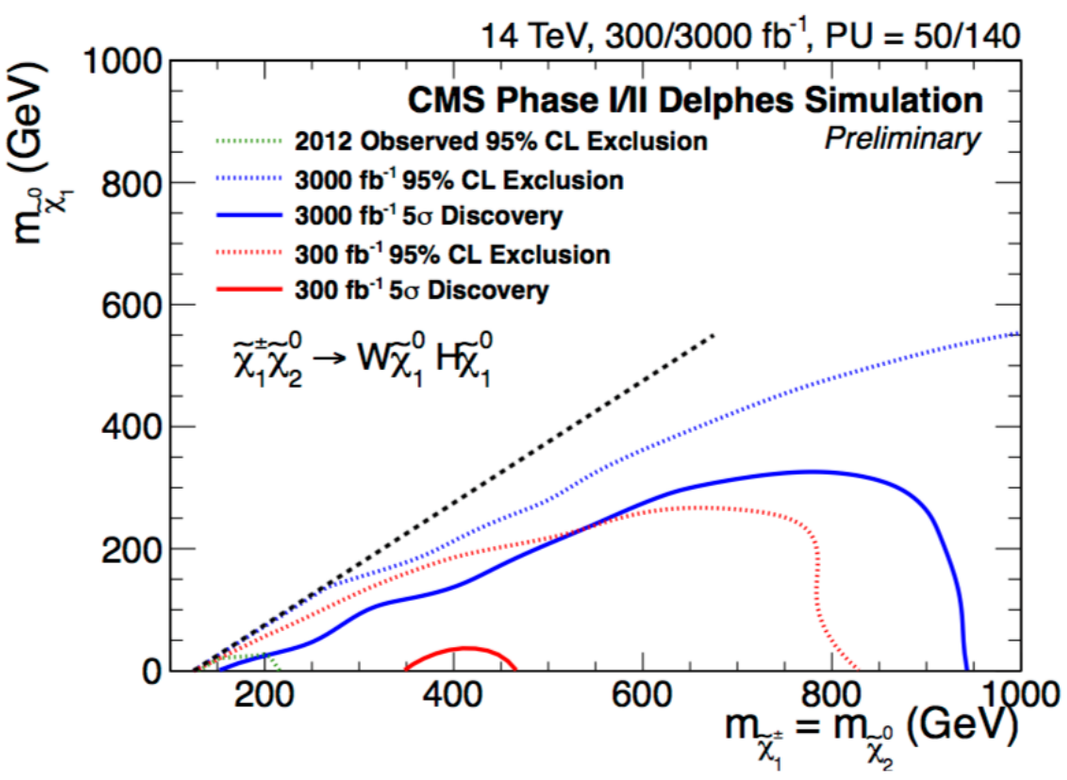
$$M_{\mathrm{CT}}^2(j_1,j_2) = [E_{\mathrm{T}}(j_1)+E_{\mathrm{T}}(j_2)]^2 - [\vec{p}_{\mathrm{T}}(j_1)-\vec{p}_{\mathrm{T}}(j_2)]^2$$
$$= 2p_{\mathrm{T}}(j_1)p_{\mathrm{T}}(j_2)(1+\cos\Delta\phi(j_1,j_2))$$



Search for Wino-like C1N2 decaying into Wh 1Lbb (II)

Sample	$E_T^{miss} > 200$ GeV	$E_T^{miss} > 300$ GeV	$E_T^{miss} > 400$ GeV	$E_T^{miss} > 500$ GeV
	25% Background Uncertainty			
WH signal (200,1)	2.8	1.9	4.3	5.5
WH signal (500,1)	1.4	3.0	7.6	6.9
WH signal (900,1)	-	0.4	2.5	4.7
Natural Model 2	0.6	1.3	2.9	2.4
	12.5% Background Uncertainty			
WH signal (200,1)	5.8	3.8	6.7	6.8
WH signal (500,1)	2.9	5.9	12	8.6
WH signal (900,1)	-	0.9	3.9	5.8
Natural Model 2	1.4	2.7	4.7	3.0

- Sensitivity to low mass scale is achieved even with 25% uncertainty on the background
  - but significant impact of systematics especially for signal in the low MET regions



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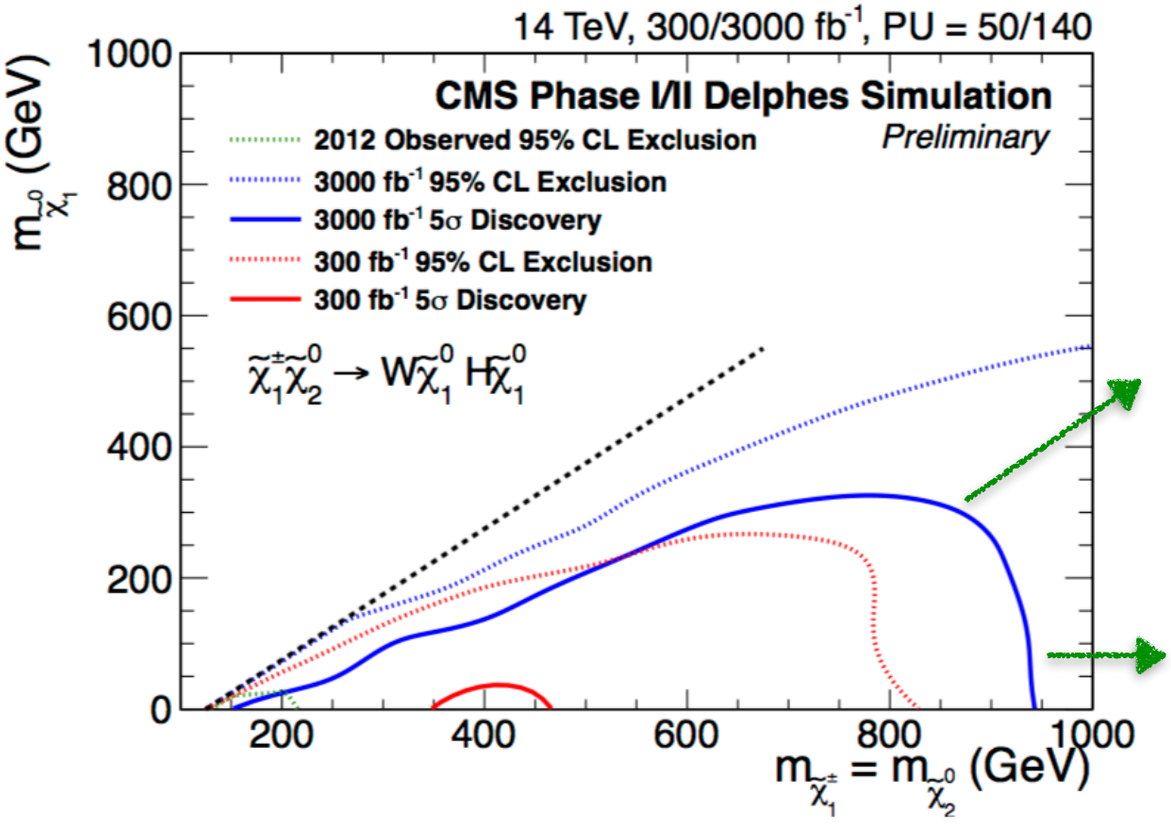
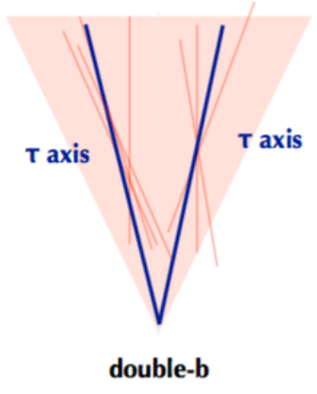
Potential Improvements to the Wh(1Lbb) search

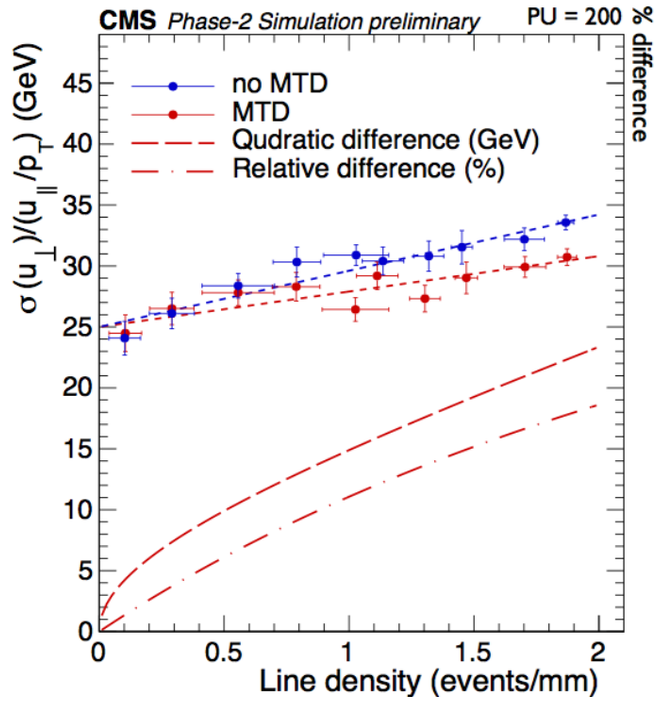
Improved MET resolution

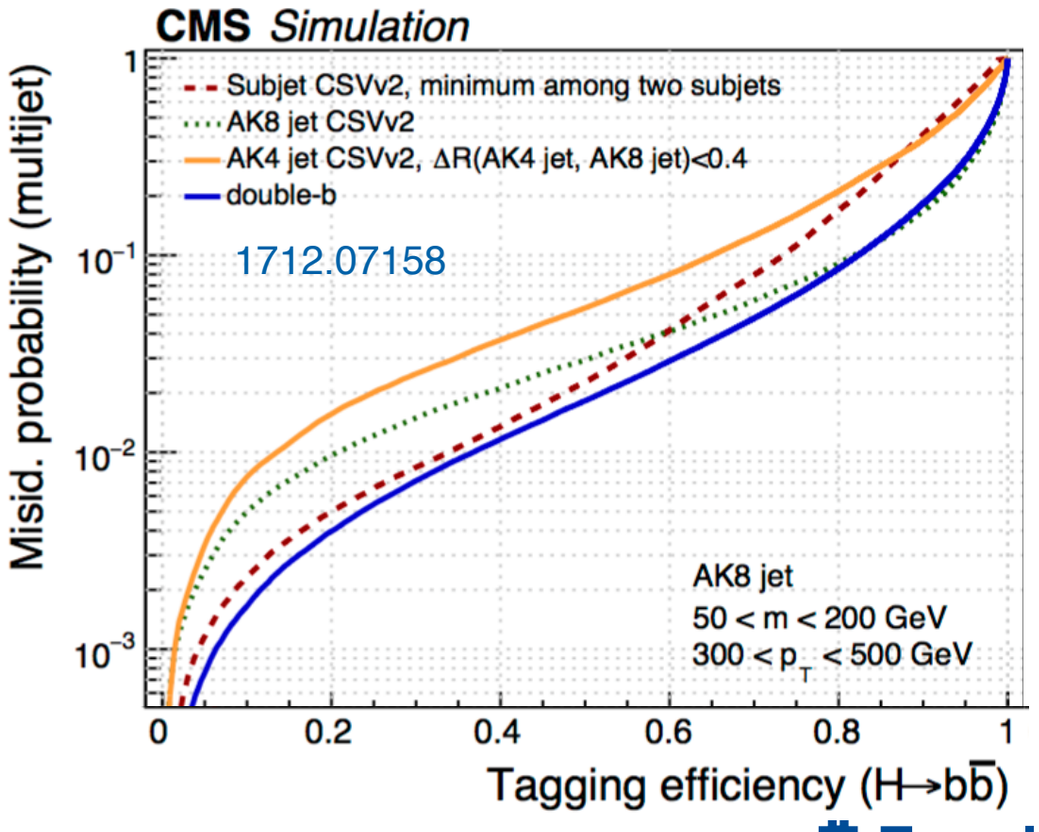
with timing information





Improve acceptance to boosted Higgs bosons through double-b tagger?





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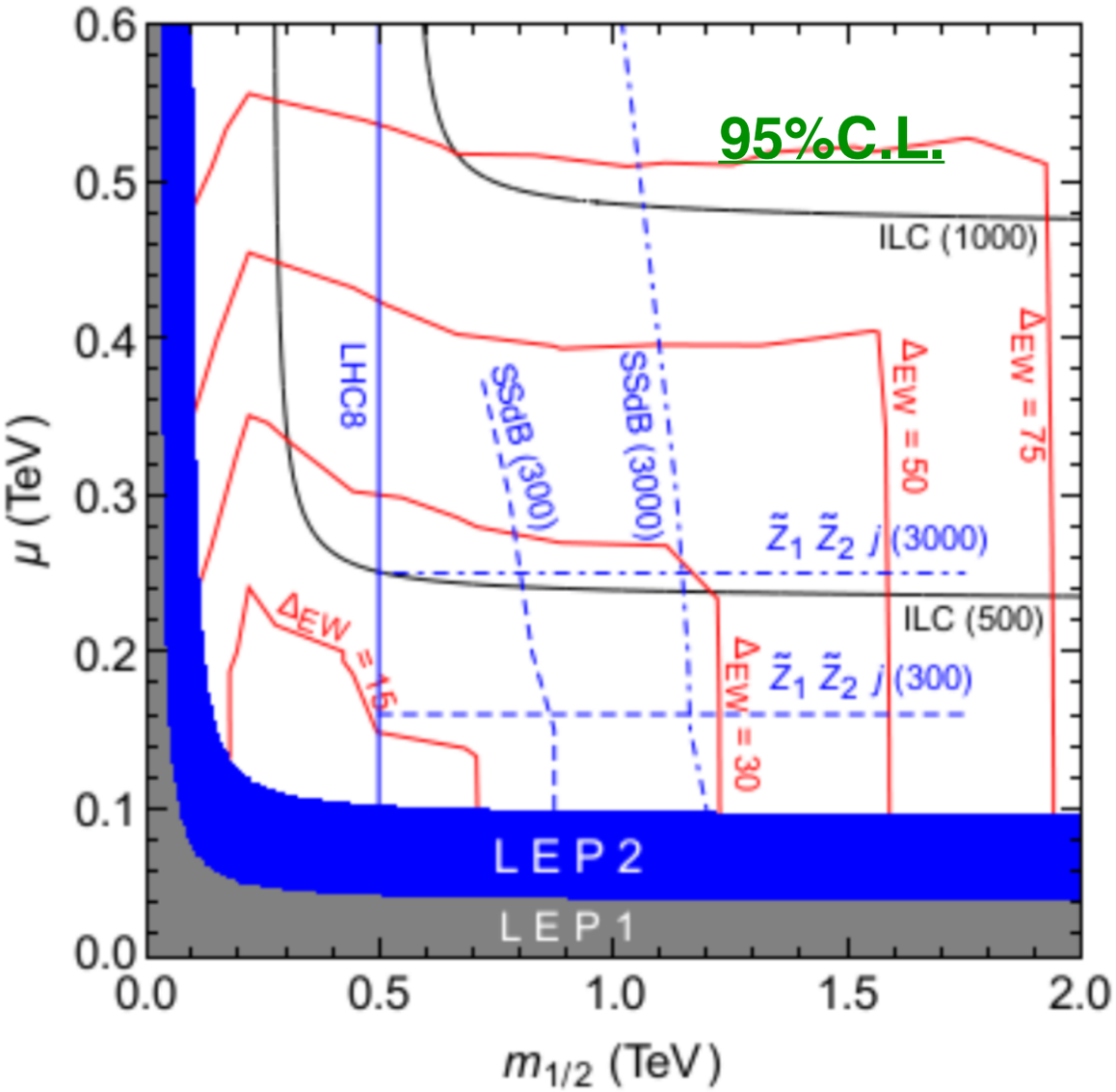
Plan for SUSY studies at HL-LHC - Yellow Report

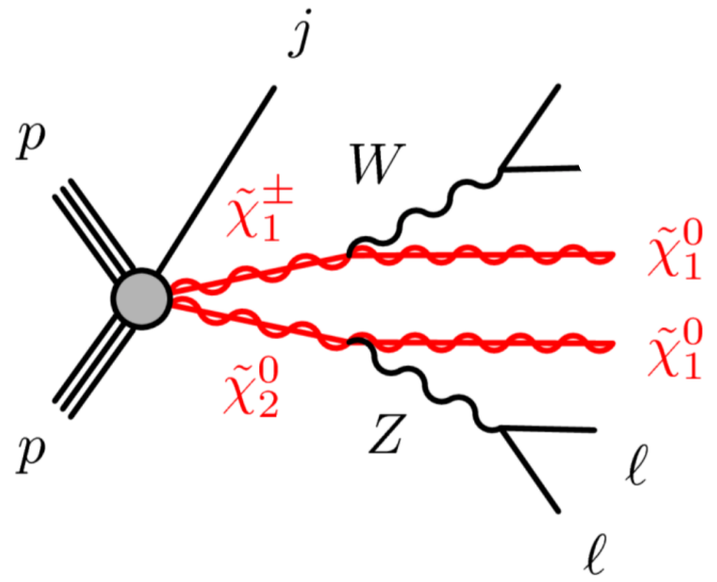
- **Core program including searches for natural SUSY scenarios and spectra with low mass sleptons**
- Results interpreted in **simplified models** and within **realistic models**

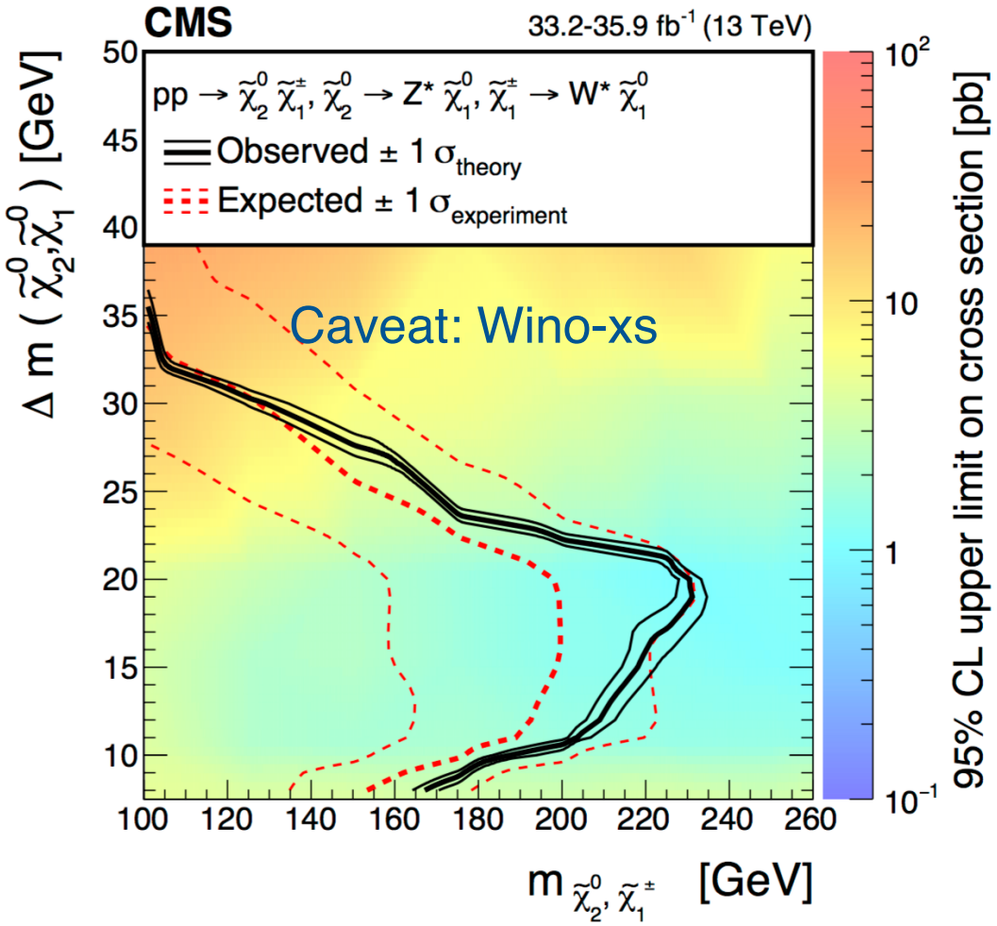


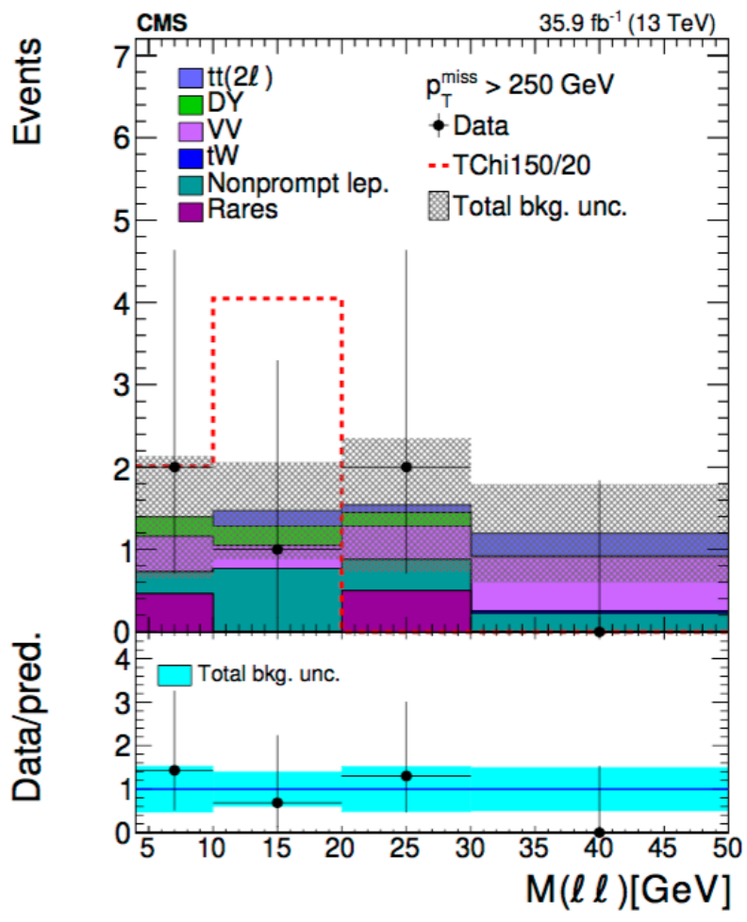
- Radiative Natural SUSY (*H. Baer et al. 1604.07438; 1710.09103.pdf*) reconciling the Z and higgs mass close to ~100 GeV with gluinos and squarks beyond the TeV scale
- No large cancellations are required

Search for Higgsinos (I)

- Search for events with Higgsinos produced in association with an ISR jet
  - boosted system leading to relatively high momentum leptons
  - search inspired by Run2 search https://arxiv.org/abs/1801.01846
  - SRs based on low pT leptons (up to 5GeV in Run2), MET and dilepton invariant mass







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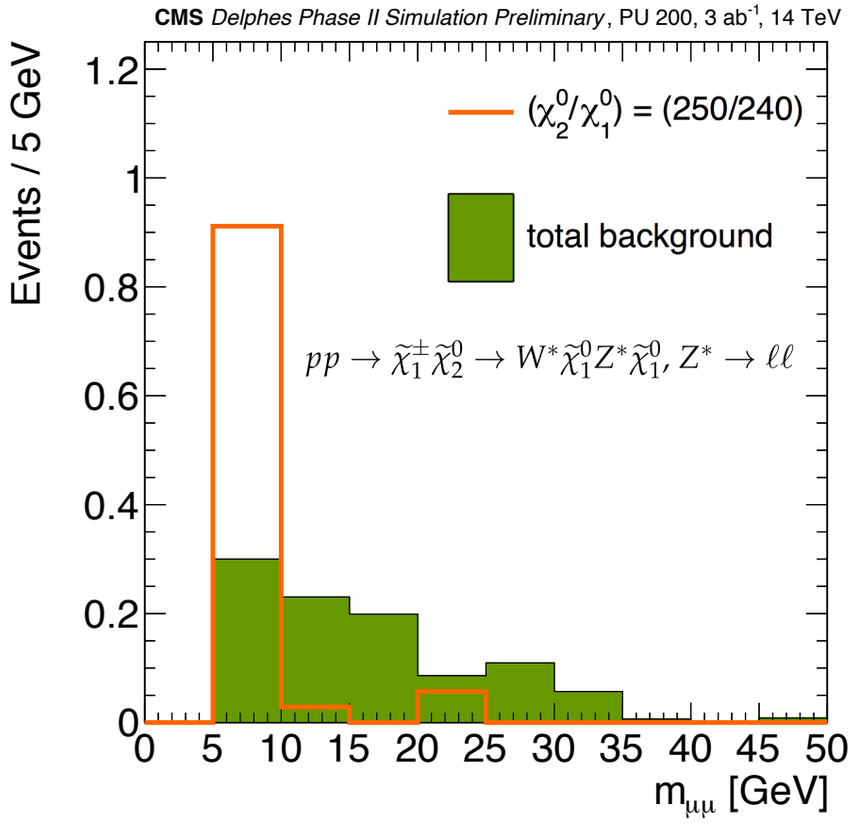
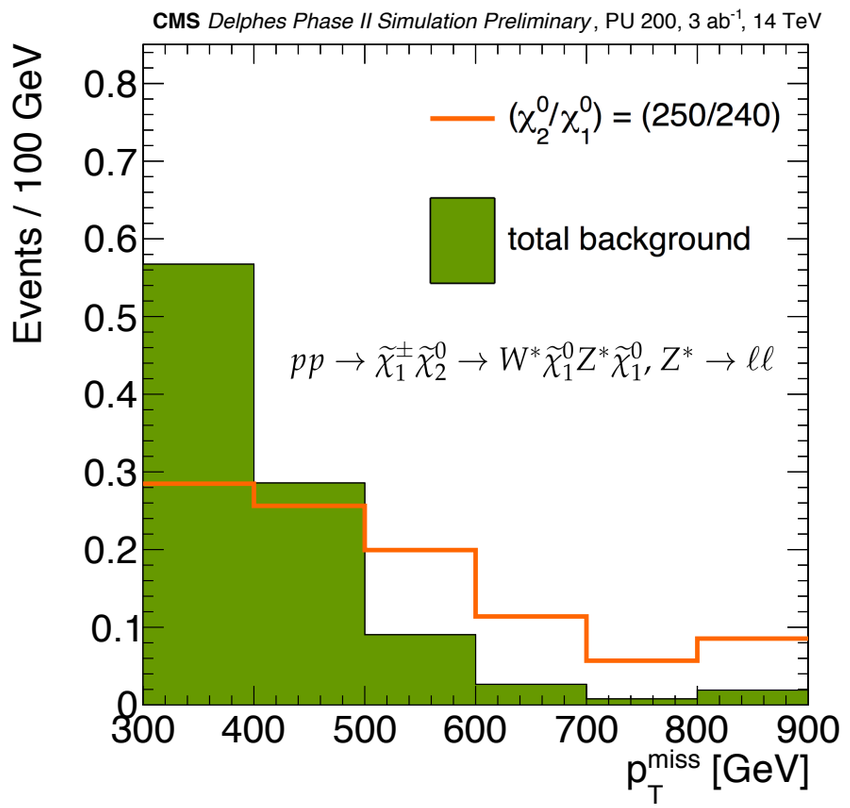
Search for Higgsinos (II)

- **Delphes** simulation based on latest Full Simulation of Phase2 detector
  - Tracker, Barrel Calorimeter, Muon Chambers, EC Calorimeter
  - *no timing information incorporated yet*
- Baseline SRs requiring
  - two muons with pT 5 < pT < 30 GeV and letal < 2.4
  - di-muon invariant mass in the range 5 to 50 GeV
  - no pT > 30 GeV b-jets
  - HT(pT > 25 GeV) > 400 GeV
  - one jet with pT > 250 GeV
  - MET > 300 GeV
- Di-lepton invariant mass and MET confirmed to be most sensitive observables
- *Expect sensitivity up to 200-300 GeV for small mass gap*
  - *potential improvement from adding 3L final states and VBF production*





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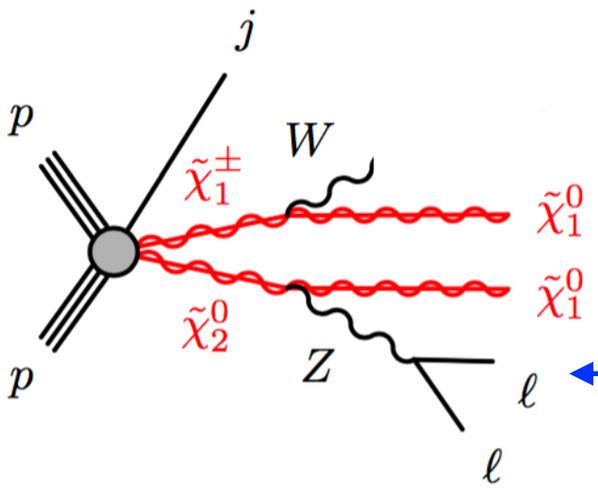
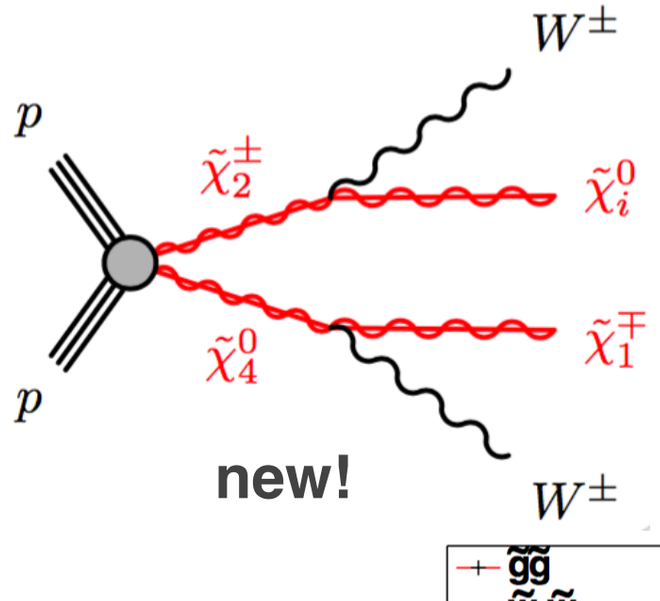
Additional search for Natural SUSY



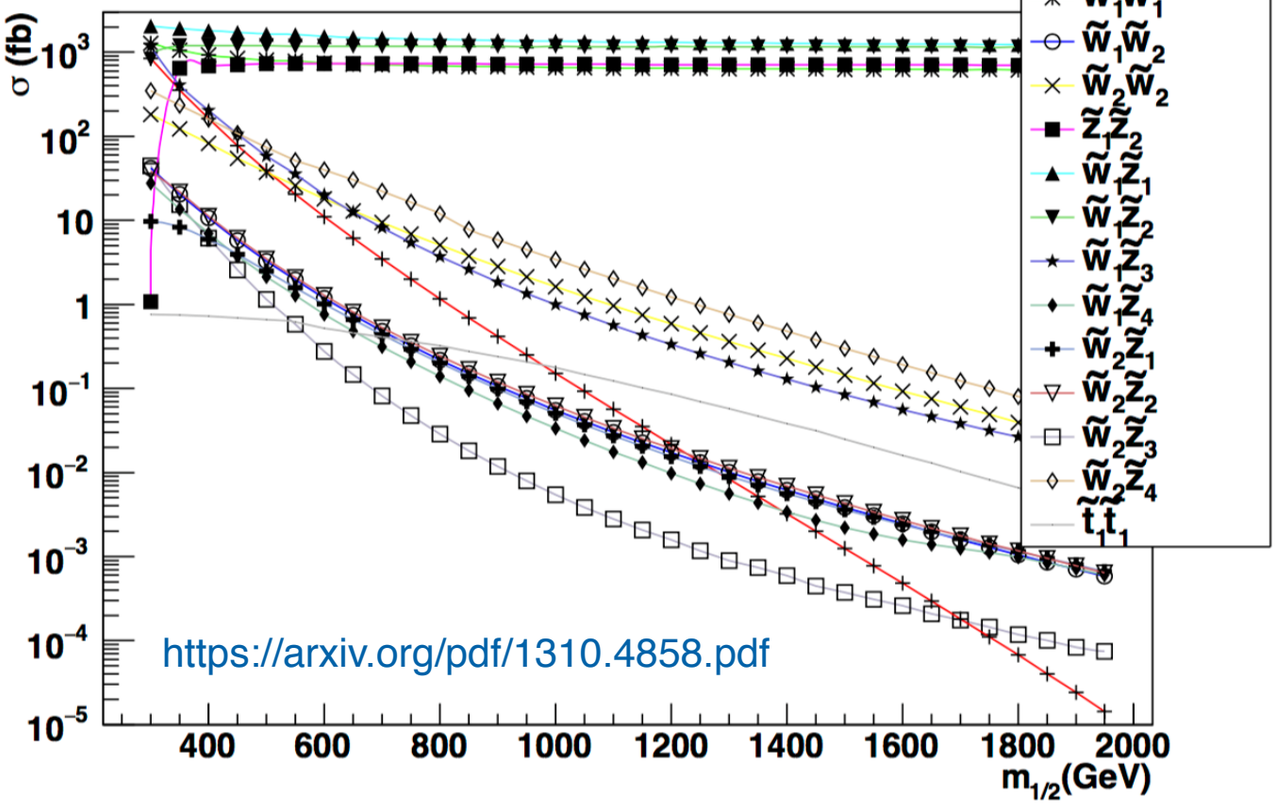
M2 — C2, N4

M1 — N3

mu — C1, N1, N2



- In RNS C2N4 largest visible cross-section
  - 25% BR into SS Ws
- Powerful probe complementing direct searches for higgsinos and enhancing sensitivity to natural scenarios



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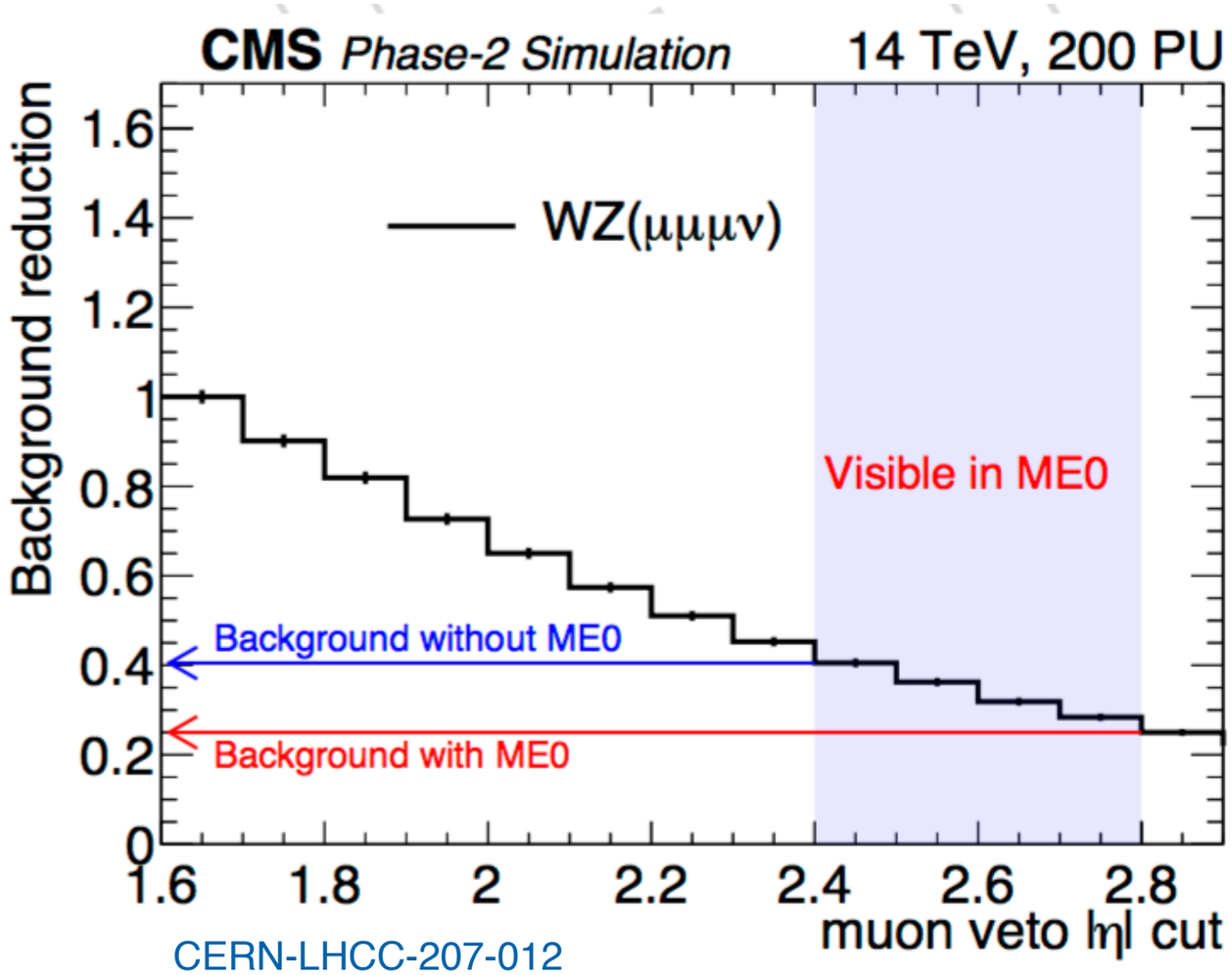
Search for Wino-like C2N4 decaying into same sign Ws (I)

- Signal and background shapes determined using Delphes updated to the latest Phase 2 Full Simulation
  - using very tight requirement on lepton identification (derived from Run2 search in SS final states)
  - Delphes yields of V+HF scaled by 25% to include contribution from LF and conversions
- Systematic uncertainties assumed to be the same as in the Run2 search
  - 20% (50%, 20%) on prompt (fake, signal) yields

Two electron/muon pT > 20 GeV & letal < 1.6
No other leptons with pT > 5 GeV & letal < 4.0
no b-jets pT > 30 GeV & letal < 2.4
no jets pT > 25 GeV & letal < 2.4



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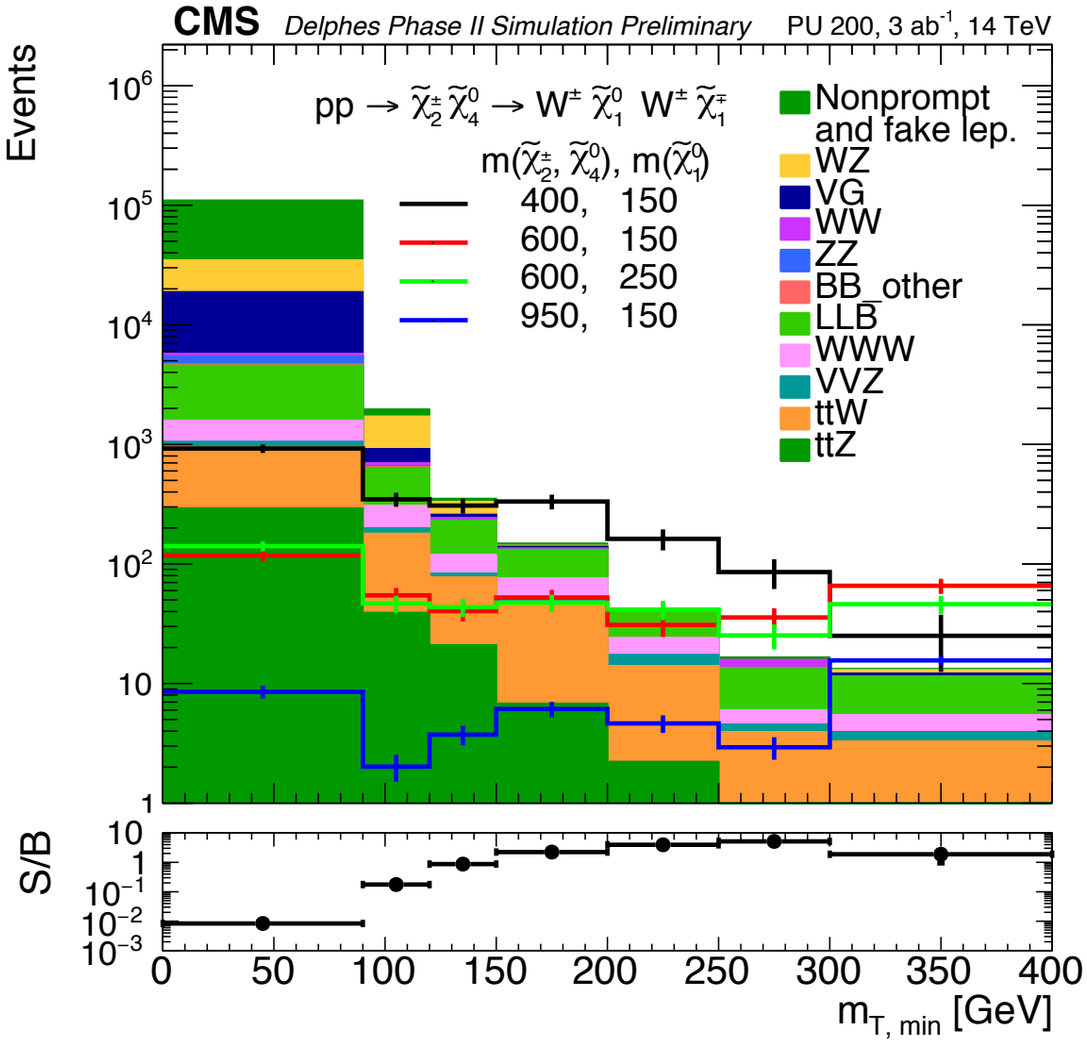
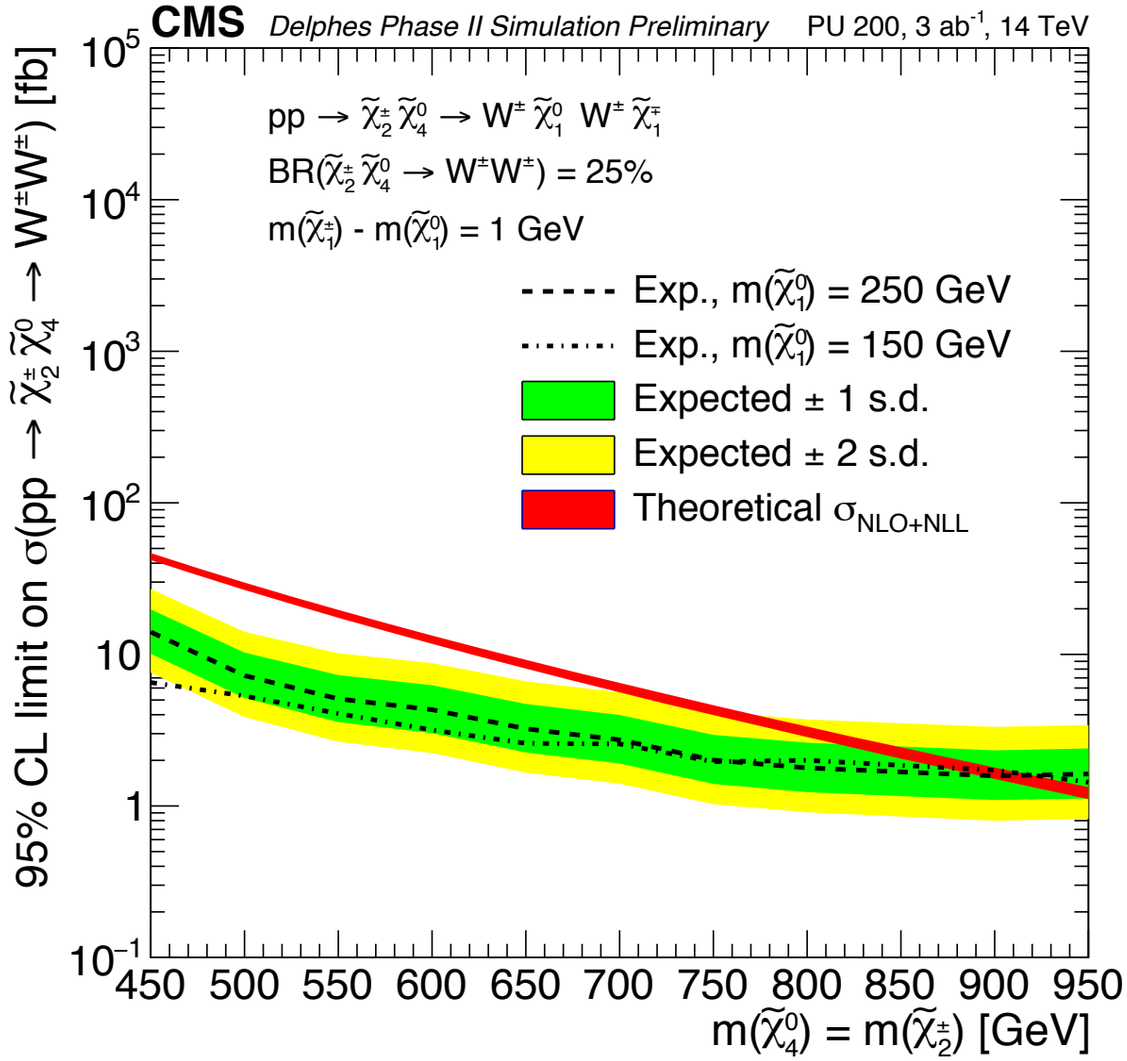
Search for Wino-like C2N4 decaying into same sign Ws (II)

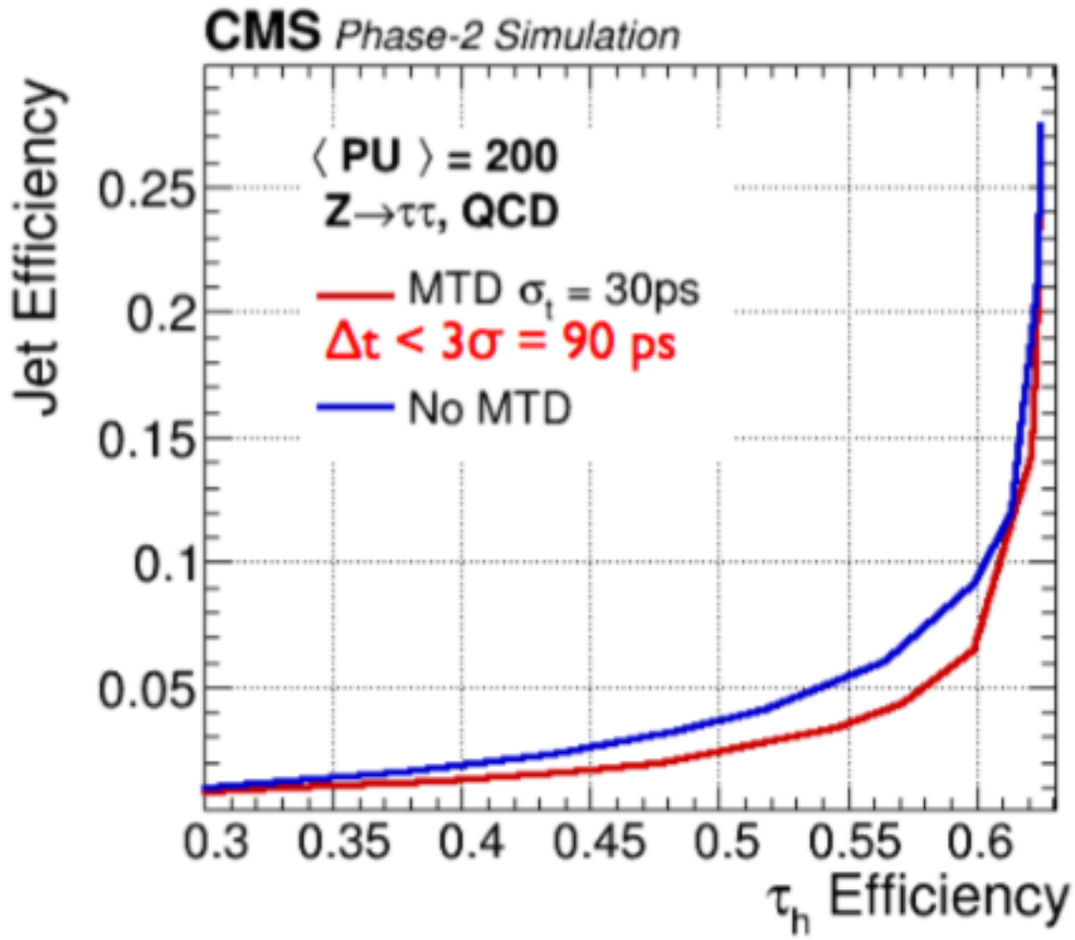
- Baseline SR binned into 7 MTmin based regions
  - [0, 90), [90, 120), [120, 150), [150; 200), [200; 250), [250; 300), and [300; inf) GeV
- Search sensitive up to ~900 GeV scale for both assumptions on N1 (150, 250 GeV)





Searches for Staus

- Staus expected at low mass scale in selected SUSY models (*e.g.* co-annihilation scenarios)
- Very challenging search due to low xs for producing stau pair (~few pb @ 100GeV), and low acceptance
- HL-LHC is critical to probe for this process
- **Both searches currently based on Full Simulation of the Phase 2 detector**
  - *expect significant improvement from timing information, not included yet*
- Developing two searches based on the Run2 experience
  - CMS-PAS-SUS-17-003, CMS-PAS-SUS-17-002
- MET and MTsum exploited to discriminate signal from background in both final states



Information from timing detector expected to significantly impact tau ID performance (not included yet)

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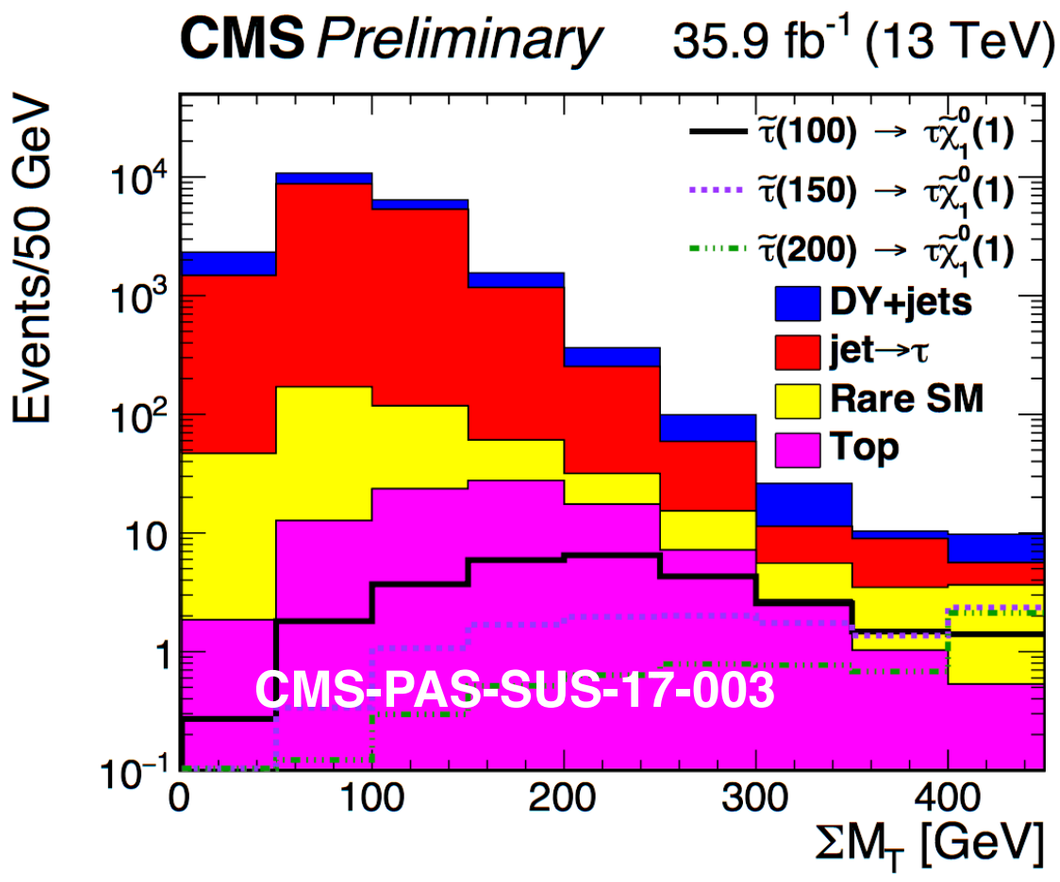


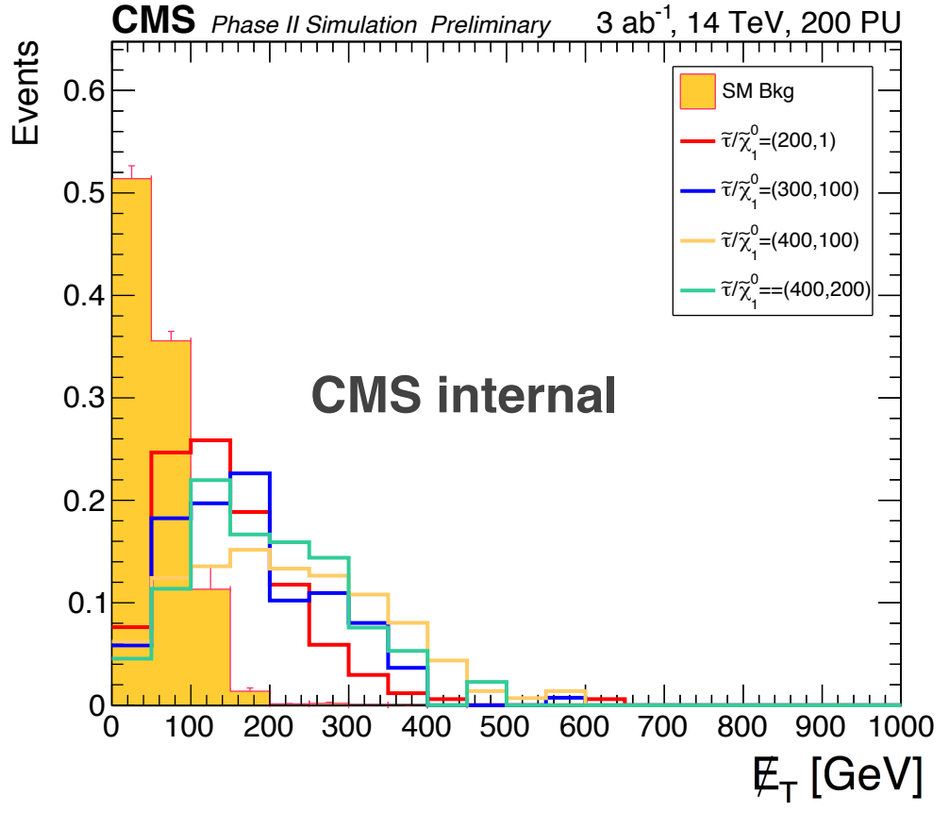
$$M_{\mathrm{T}}(\ell_i) = \sqrt{2 p_{\mathrm{T}}(\ell_i) p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\Phi(\ell_i, p_{\mathrm{T}}^{\mathrm{miss}}))}$$

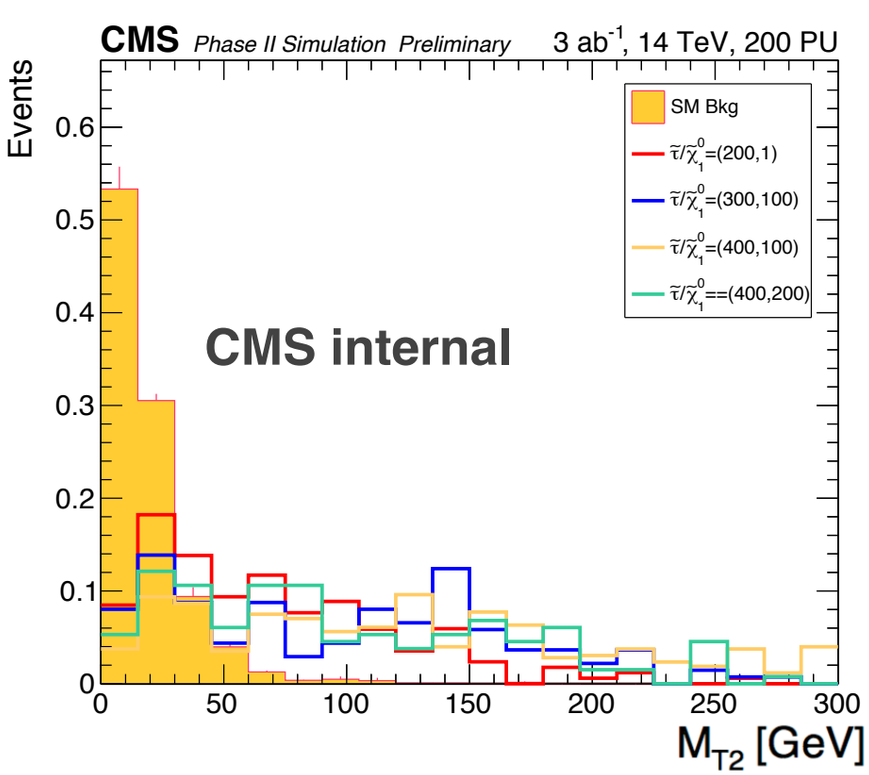
$$M_{\mathrm{Tsum}} = M_{\mathrm{T}}(\ell_1) + M_{\mathrm{T}}(\ell_2).$$

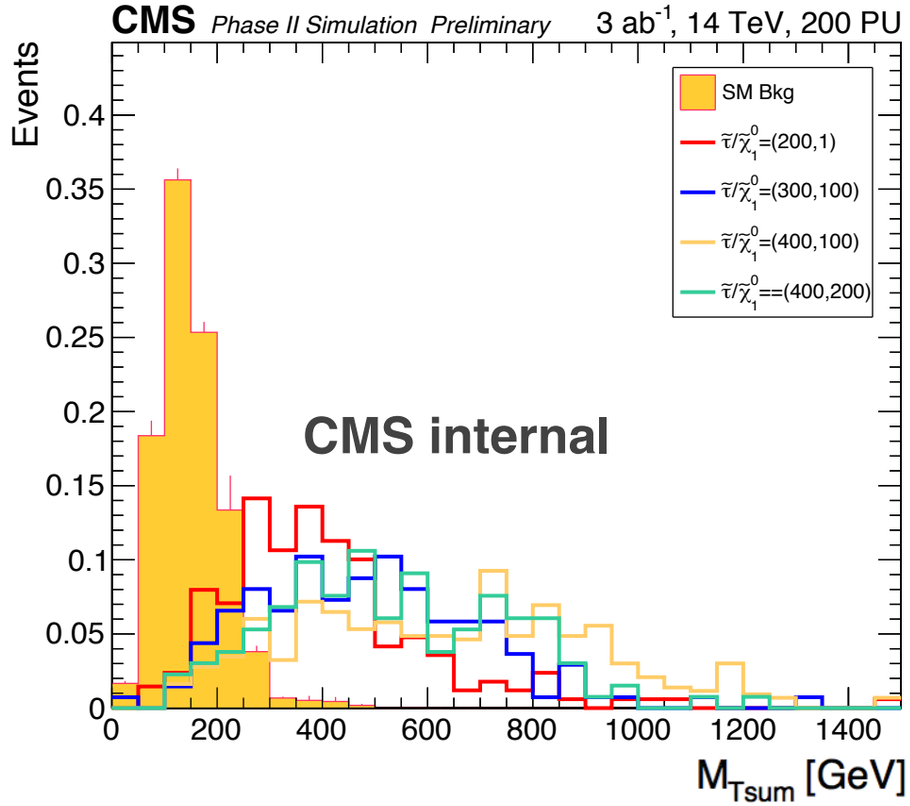
Searches for Staus in ττ final state

- Dominant decay mode but highest background contamination final state
- Events selected if they contain two tight tau with pT > 50 GeV, no additional leptons, no additional b-jets
- Selection based on MT2 providing additional background suppression w.r.t to MET and MTsum

$$M_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\,\mathrm{X}(1)} + \vec{p}_{\mathrm{T}}^{\,\mathrm{X}(2)} = \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left[\max\left(M_{\mathrm{T}}^{(1)}, M_{\mathrm{T}}^{(2)} \right) \right]$$







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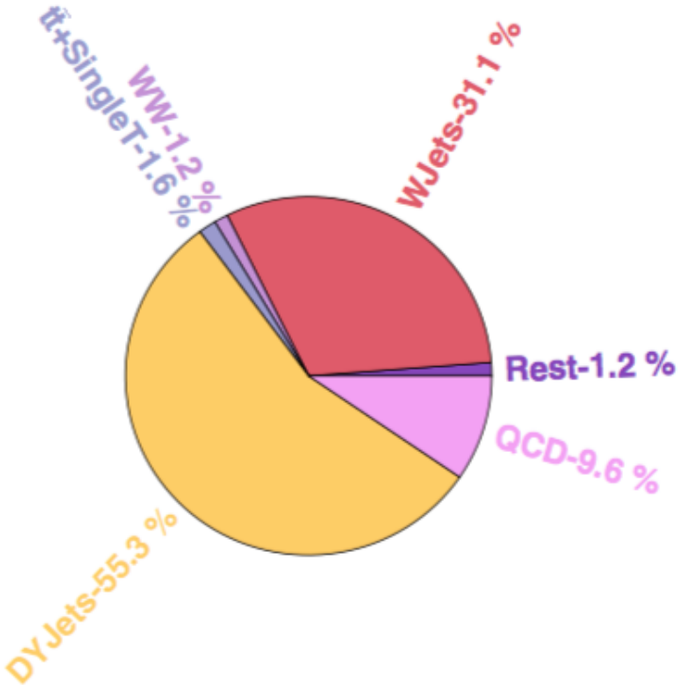
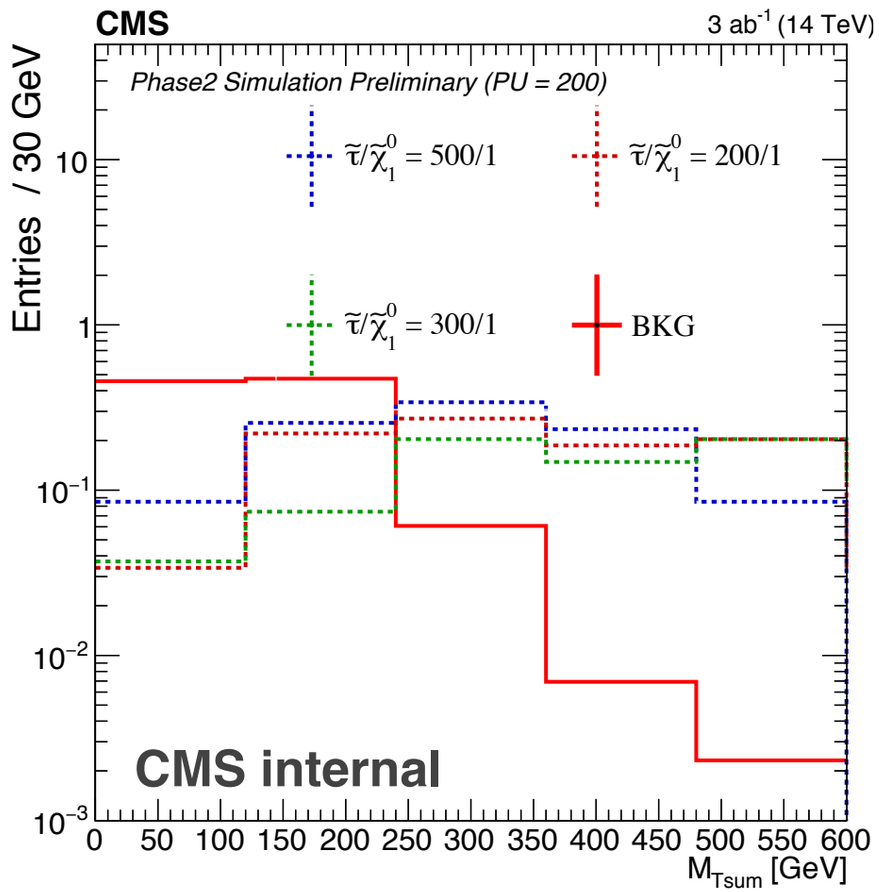
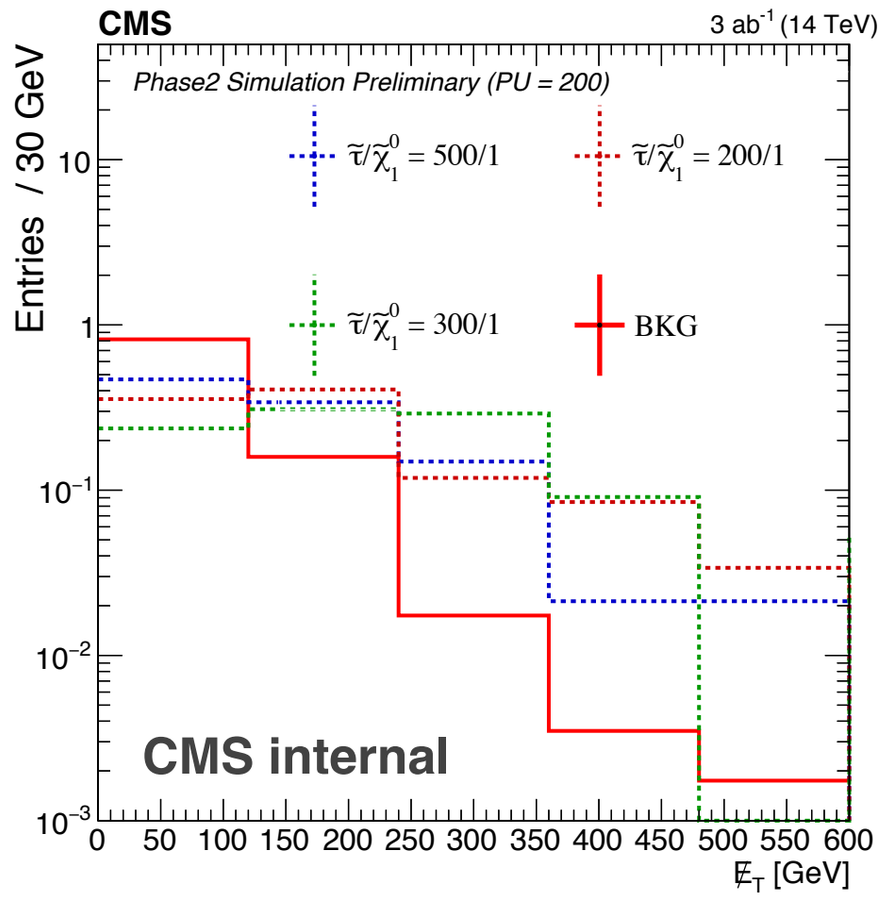
Searches for Staus in the μτ final state

- Additional sensitivity provided by search in the lepton-τ final states
- Events selected if they contain one tight tau with pT > 40 GeV, one tight muon with pT > 25 GeV, no additional leptons, no additional b-jets
- *Expect sensitivity up to 500-600 GeV for current assumption on Phase2 detector*



Relative composition of background μτ (Run2)





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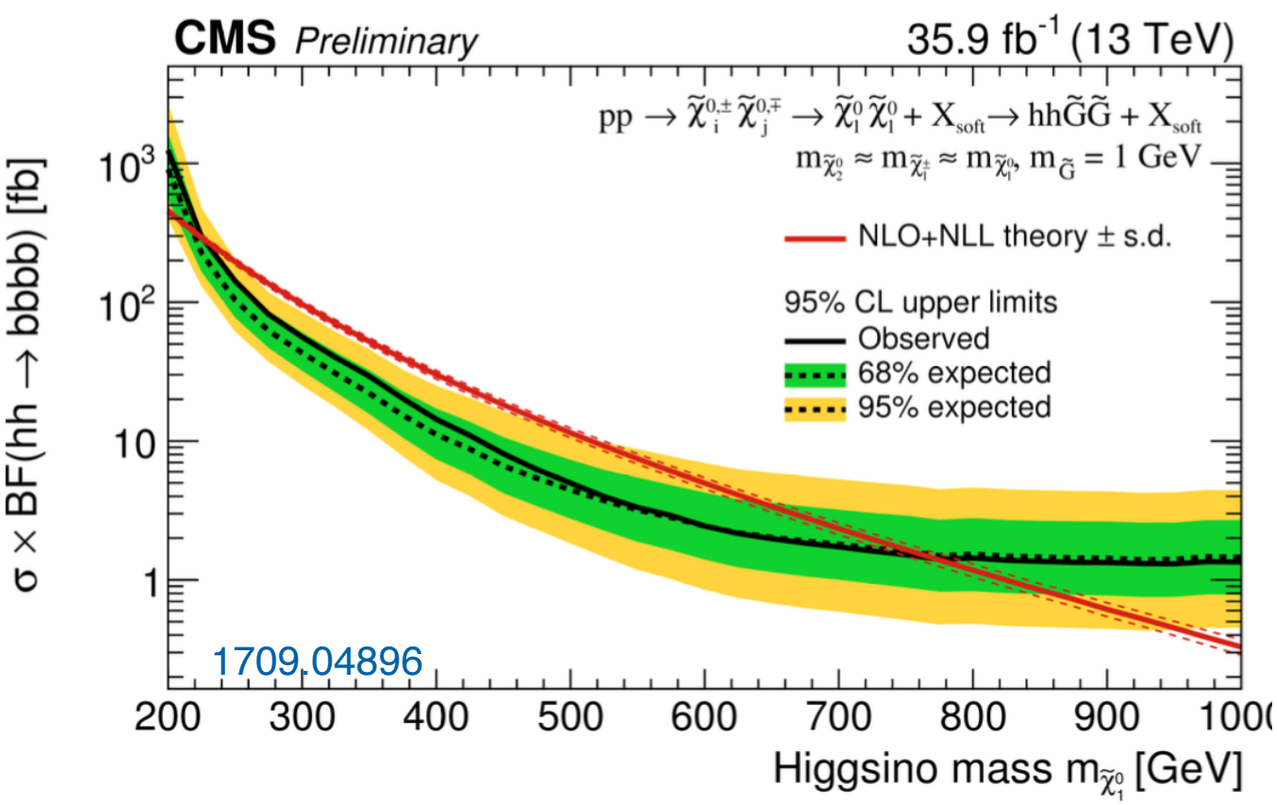
Plans for the Studies of SUSY at HL-HE with CMS (I)

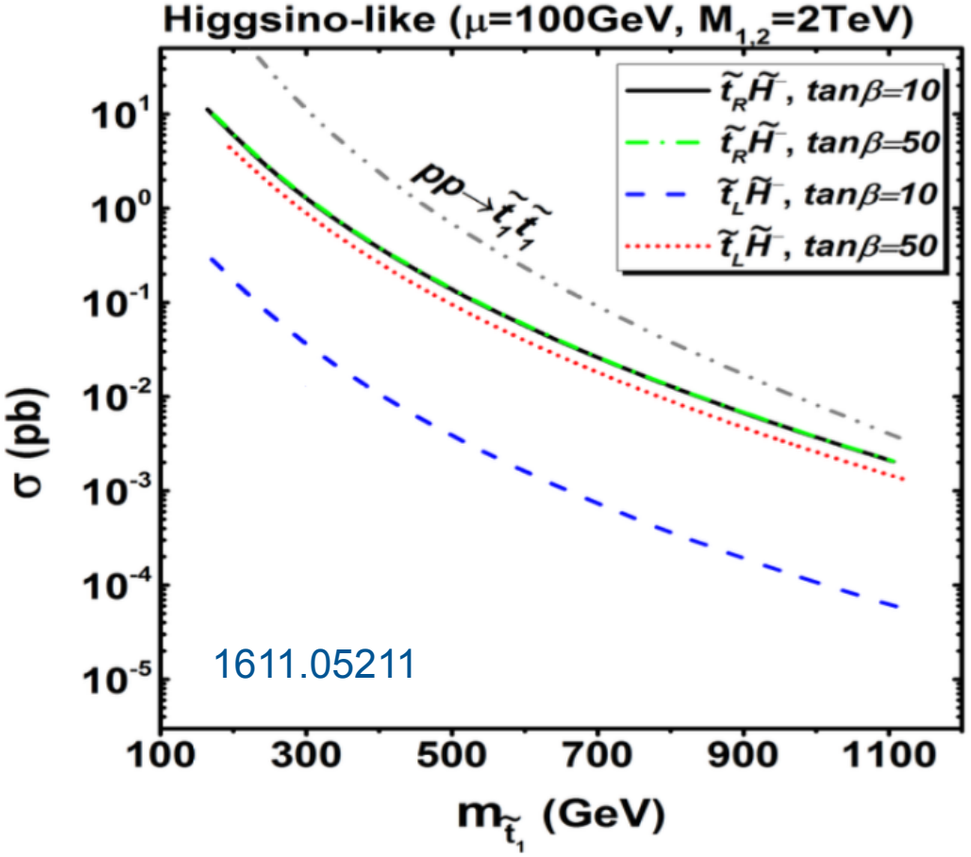
- The Run2 based searches for EWK SUSY set the foundations for searches at HL and HE-LHC
  - The current sensitivity to most promising models is at ~200 GeV scale
- Both HL-LHC and HE offer unprecedented opportunities to explore the EWK production of SUSY
  - electroweakinos (higgsinos, gauginos)
  - sleptons
- The **Technical Proposal** includes searches for wino like C1N2 in WZ / Wh decay modes
  - achieved sensitivity to the ~TeV scale at HL-LHC with preliminary detector simulation

- **The current plan for the Yellow Report is to develop targeted and complementary searches for Natural SUSY scenarios and for low mass staus**
  - search for Higgsinos-like C1N2 in the final states with one ISR jet and soft leptons
  - search for wino-like C2N4 in the final states with two SS leptons
  - searches for staus in both the lep-τ_h and $\tau_h\tau_h$ final states
  - *Results will be interpreted in both simplified models and realistic models (RNS)*

Plans for the Studies of SUSY at HL-HE with CMS (II)

- **Additional promising searches for SUSY**
  - higgsinos-like C1N2 in the VBF topology
  - wino-like C1N2 in the Wh(1Lbb) with timing information at object level reconstruction & final states with boosted Higgs bosons
  - N1N1 in the 4b final states (GMSB models)
  - single stop in the mono-top final states





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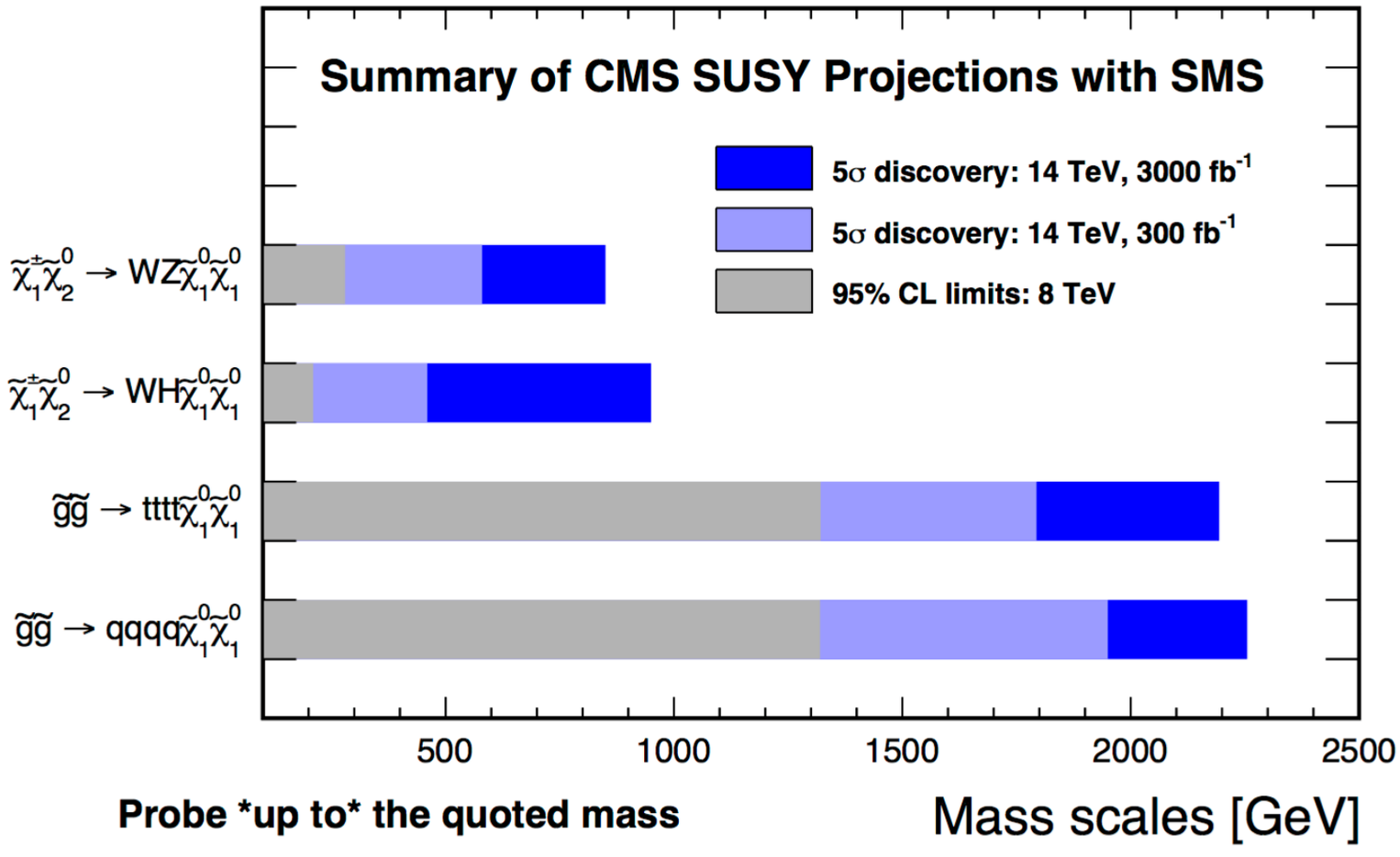
Additional Material

Searches for Wino like C1N2 decaying into WZ and Wh

- Projection of sensitivity based on selected 8 TeV CMS searches
  - results included in the Technical Proposal for the CMS Phase 2 detector upgrades
  - assuming no deterioration due to HL condition and detector aging
  - expected sensitivity *e.g.* for C1N2 in Wh up to 900 GeV



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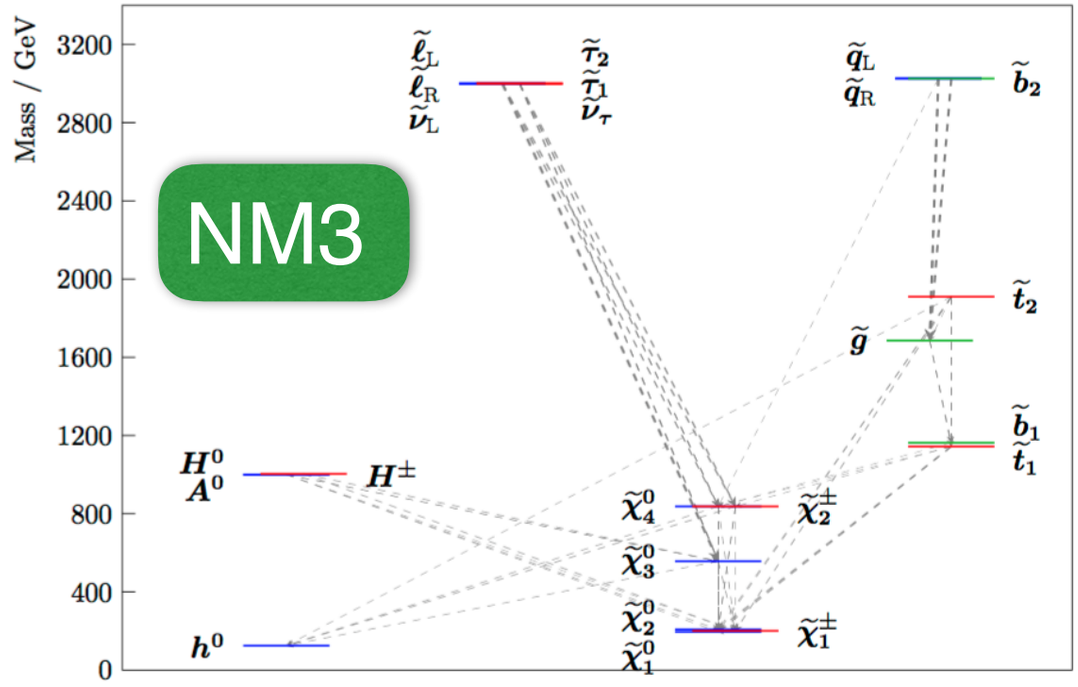
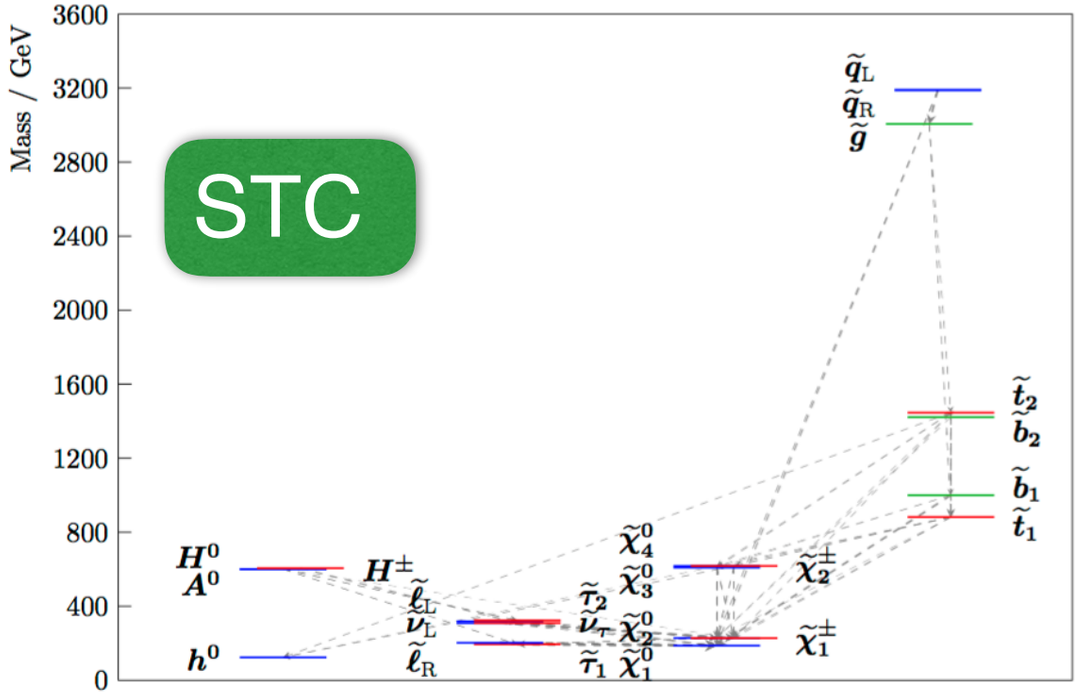
Results from SUSY Searches - Full spectrum Models (I)

- **Natural scenarios (NM1, NM2, NM3)**
  - strong interaction sector and decay BR of the gluinos similar in the three models
    - **NM1 (Bino like LSP)**
    - **NM2 (Wino like LSP)**
    - **NM3 (Higgsino like LSP)**
- **Stau co-annihilation model (STC)**
  - light stau1 almost mass degenerate with bino-like neutralino1
- **Stop co-annihilation model (STOC)**
  - light stop1 almost mass degenerate with bino-like neutralino1
  - stop decays into charm-neutralino1
  - gluino-gluino & gluino-squarks cross-sections are smaller but not negligible





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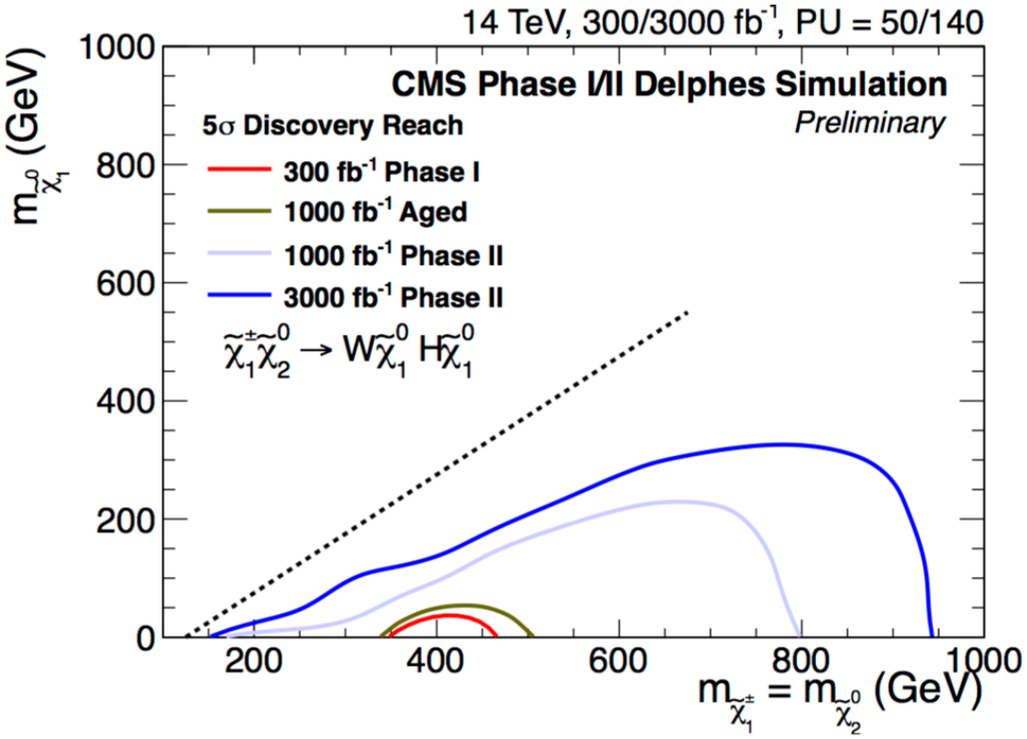
Results from SUSY Searches - Full spectrum Models (II)

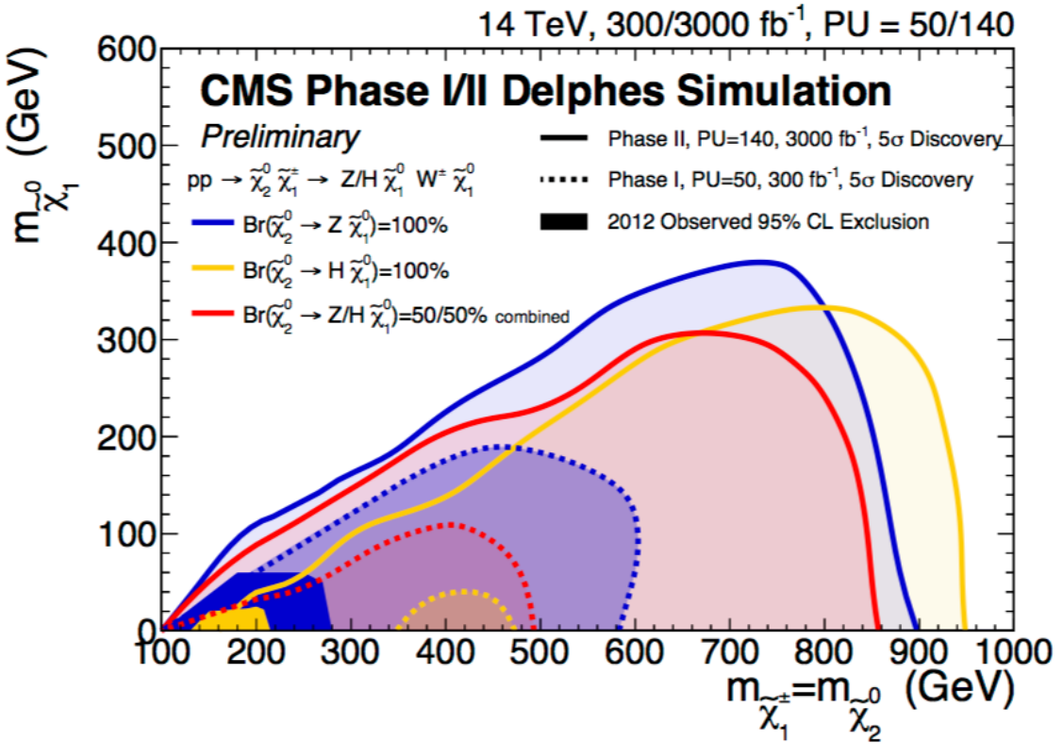
Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-H_T^{miss}) search	300					
	3000					
all-hadronic (M_{T2}) search	300					
	3000					
all-hadronic $\tilde{b}_1$ search	300					
	3000					
1-lepton $\tilde{t}_1$ search	300					
	3000					
monojet $\tilde{t}_1$ search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

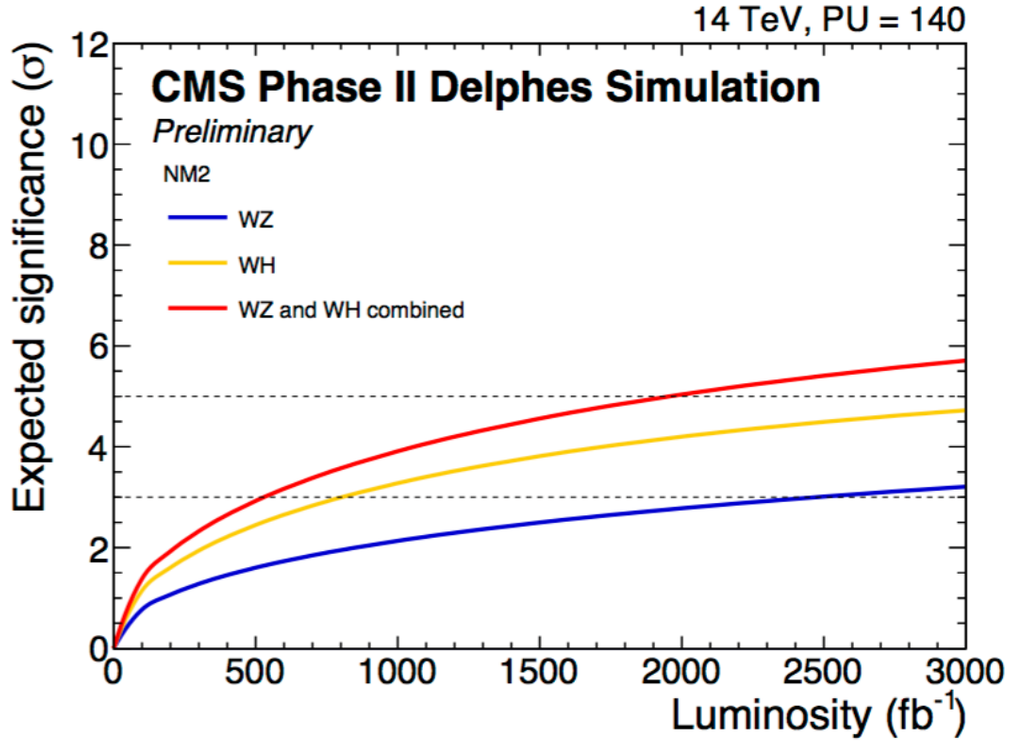
$< 3\sigma$	$3 - 5\sigma$	$> 5\sigma$

Search for Wino like C1N2 decaying into Wh 1Lbb



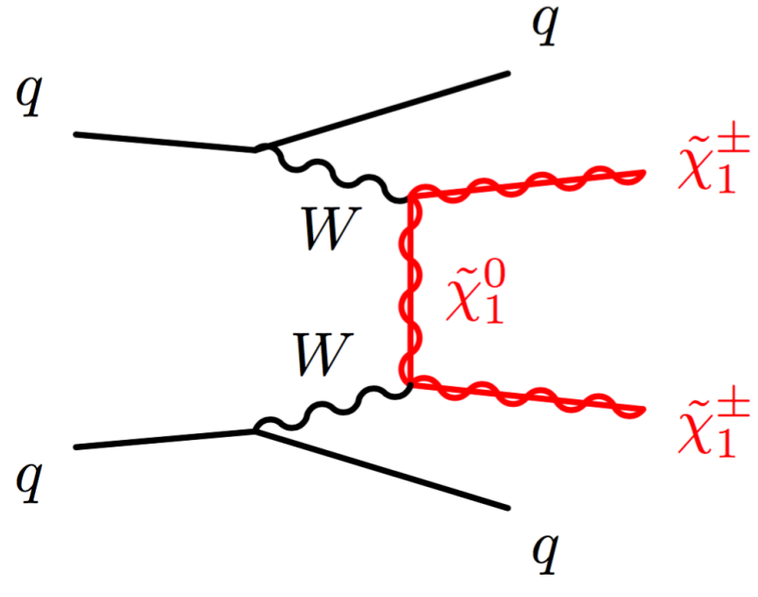
Sensitivity may improve significantly if timing information is used and channels with boosted higgs bosons are included





Extend the search to Higgsinos produced via VBF (I)

- The importance of vector boson fusion signatures has been long recognized and it has become a well established experimental technique
- **EWK-inos can be produced via VBF with a signature of forward jets and missing transverse momentum**
- Searches for VBF production of winos decaying via staus has been carried out in Run2 (SUS-14-019 - 0L, SUS-14-005 - 2L)
  - 2L: dominated by tt and DY/W+j
  - 0L: dominated by Znn, W+j

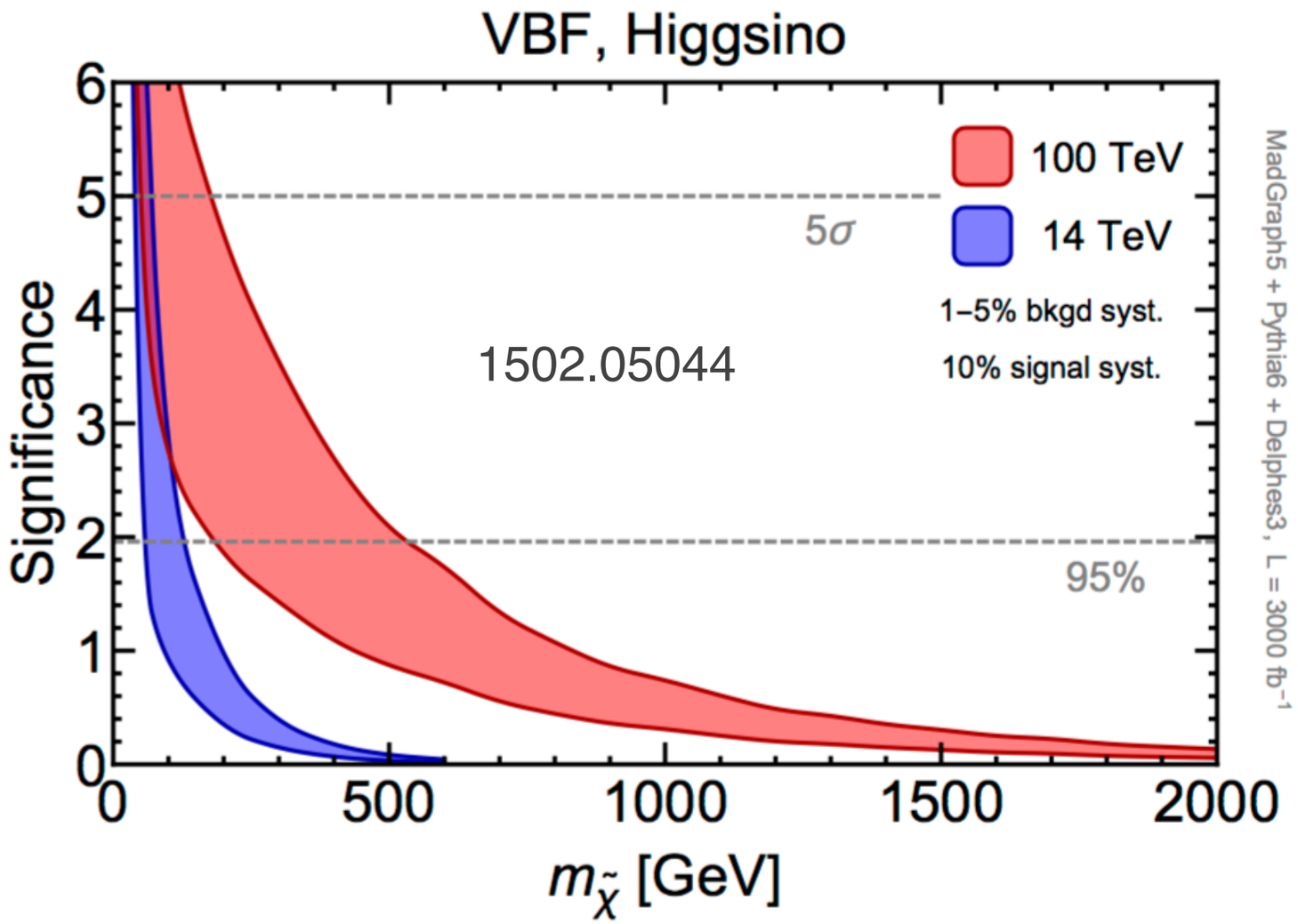


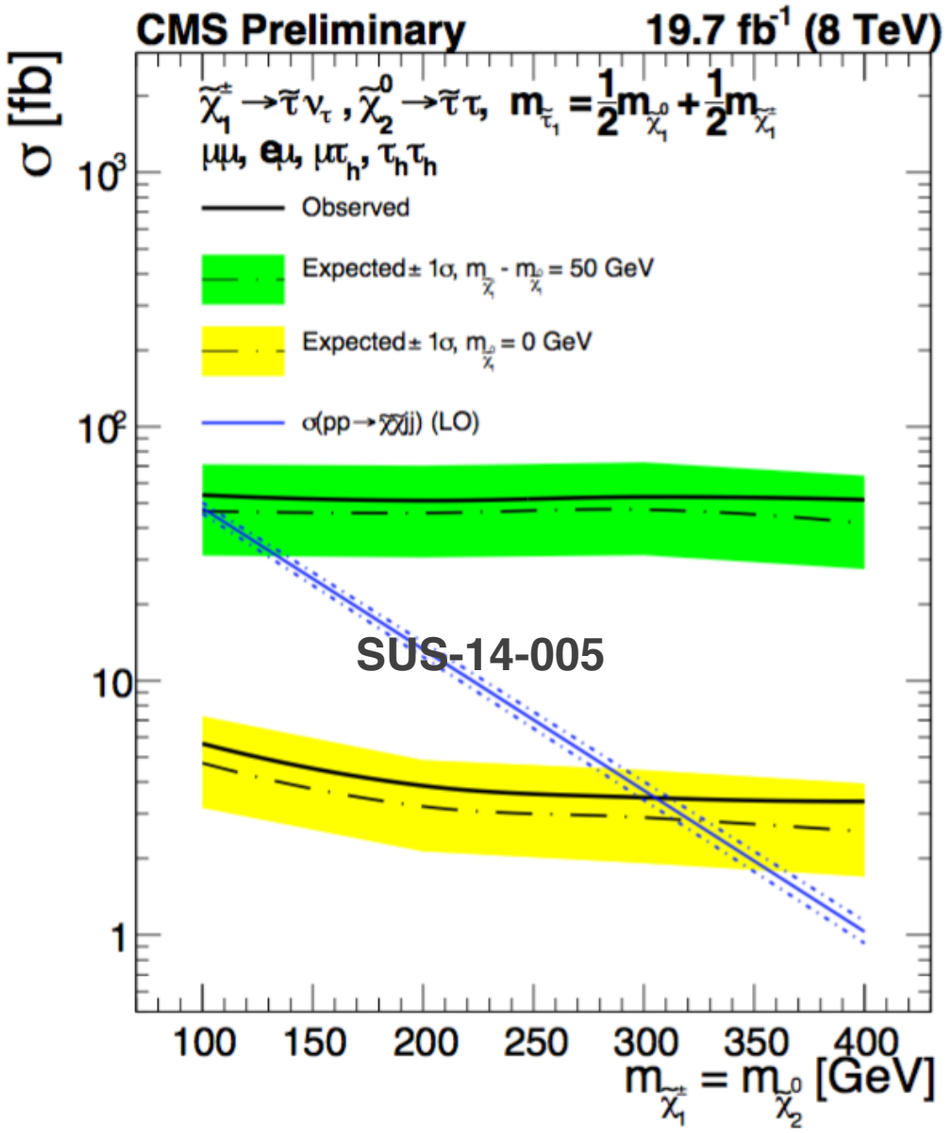
SUS-14-005

Selection	$\ell_{e/\mu}\mu jj$	$\mu\tau_h jj$	$\tau_h\tau_h jj$
$p_T(\mu)$[GeV]	≥30	≥30	—
$p_T(\ell_{e/\mu})$[GeV]	≥15(e), ≥10(μ)	—	—
$p_T(\tau_h)$[GeV]	—	≥20	≥45
$\lvert\eta(\ell_{\mu,e,\tau_h})\rvert$	<2.1	<2.1	<2.1
$N_{jets}^{b\text{-tag}}$	0	0	0
p_T^{miss}[GeV]	>75	>75	>30
p_T(jets)	≥30/50	≥50	≥30
$\lvert\eta$(jets)$\rvert$	≤5	≤5	≤5
$\lvert\Delta\eta$(jets)$\rvert$	>4.2	>4.2	>4.2
$\eta_1\eta_2$	<0	<0	<0

Extend the search to Higgsinos produced via VBF (II)

- Strong interest in theory community as well (1210.0964 - 2L, 1304.7779 - 0L, 1502.05044 - 0L)





Sensitivity may improve significantly if timing information is used to suppress PU induced background and channels with soft leptons are included

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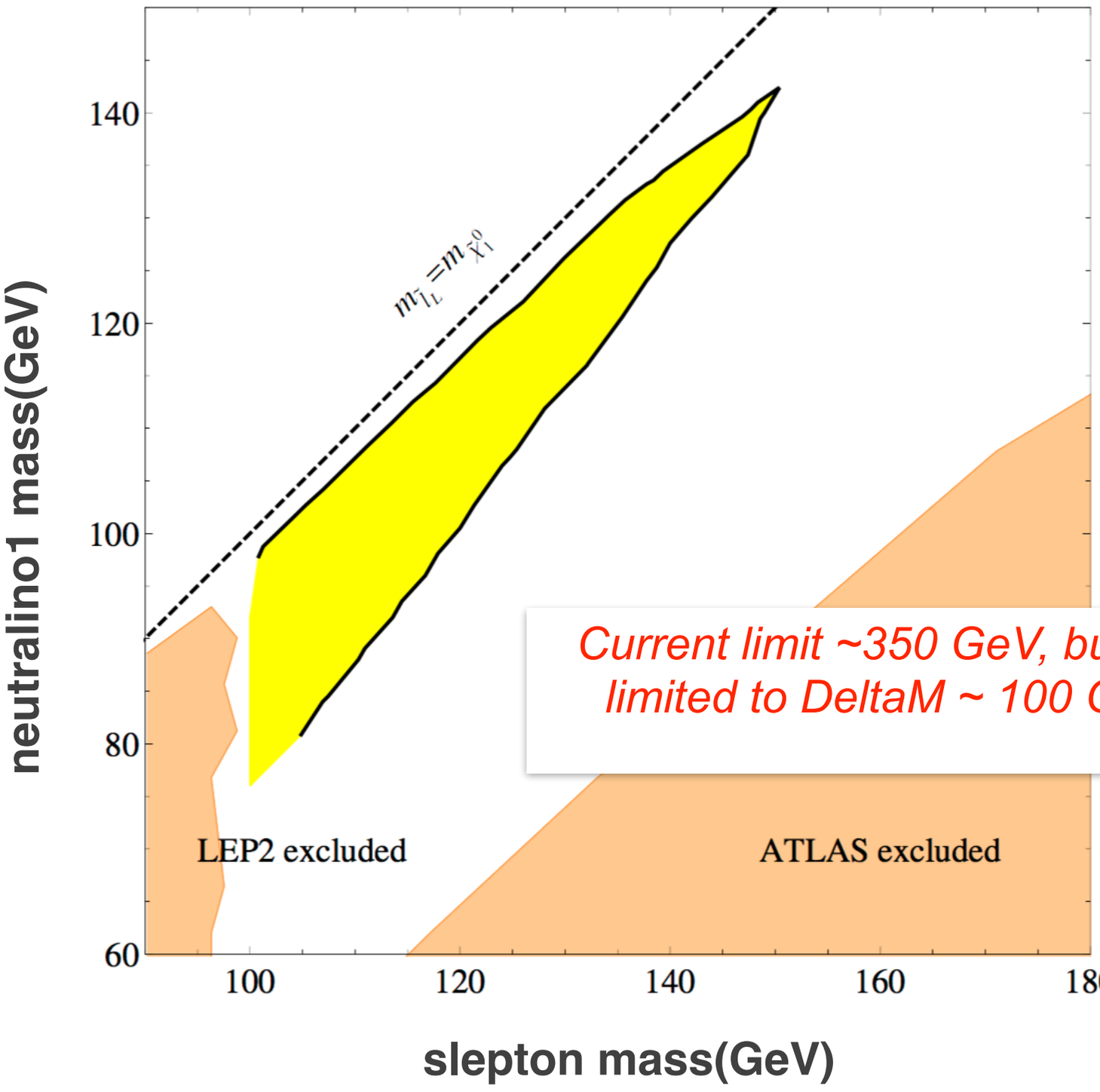
Searches for Sleptons



Sensitivity from re-interpretation of the search for higgsinos in the final state with one jet and soft opposite signs and same flavor leptons

Current limit ~350 GeV, but still limited to DeltaM ~ 100 GeV

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Long Term Plan

- **Extend the program to full EWK-inos spectrum**
  - *e.g.* pair production of N2N3 leading to final states with multiple bosons (hh, Zh, ZZ)
  - new signatures with b-jets (usage of double b-tag?)
- **Explore the 3rd generation section**
  - single-stop production to probe compressed stop-higgsinos scenarios
  - search for heavy states (e.g sbottom decaying into stop+W) when low mass ones are experimentally invisible