Electroweakly Coupled New Physics: Experimental Prospects

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Why search for electroweak SUSY production?

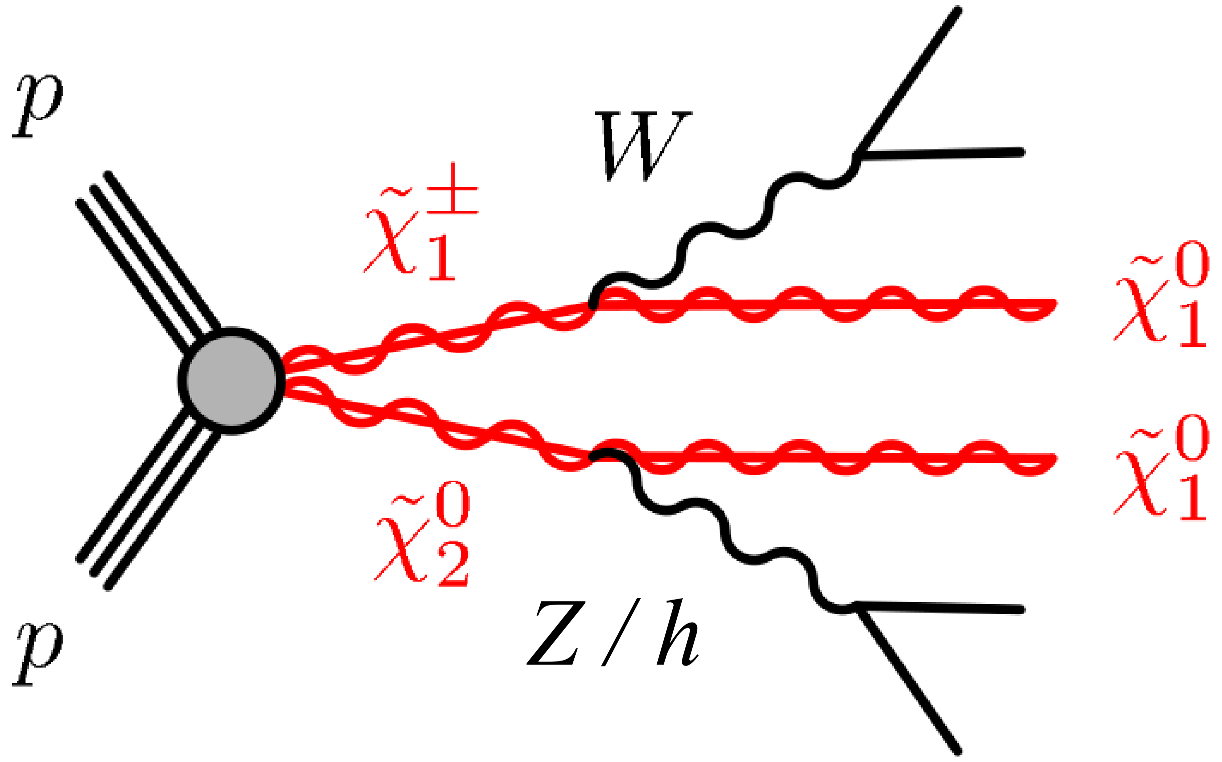
- Electroweak production may dominate if all strongly-coupled SUSY partners are too heavy to be produced
  - No evidence so far of strong SUSY production at the LHC

- Weakly Interacting Massive Particles (WIMPs) are a popular hypothesis for Dark Matter
  - In R-parity conserving SUSY, the lightest neutralino is a potential candidate if it is the Lightest Supersymmetric Particle (LSP)
  - Mass near electroweak scale → potentially see at LHC

- From Naturalness, expect higgsinos (SUSY partners of Higgs bosons) with masses of less than a few hundred GeV

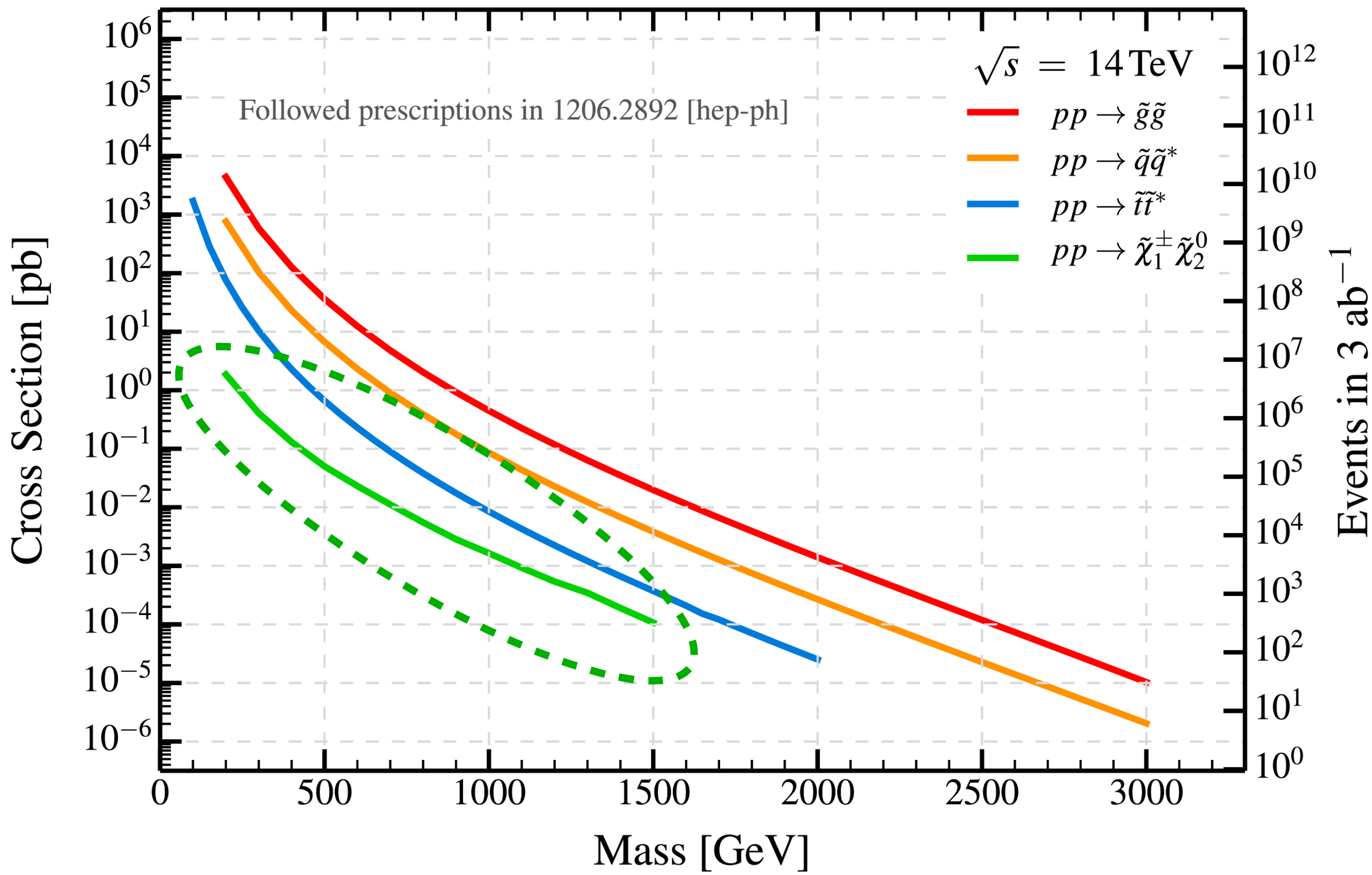
This talk: focus on $\chi^{\pm}\chi^{0}$ production, with largest electroweak cross section

- Direct decays to W and Z/h + LSP, if sleptons are heavy

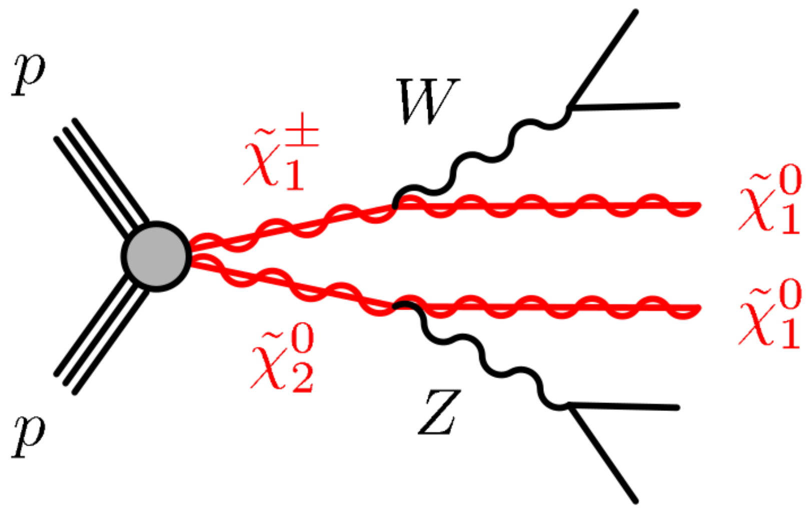


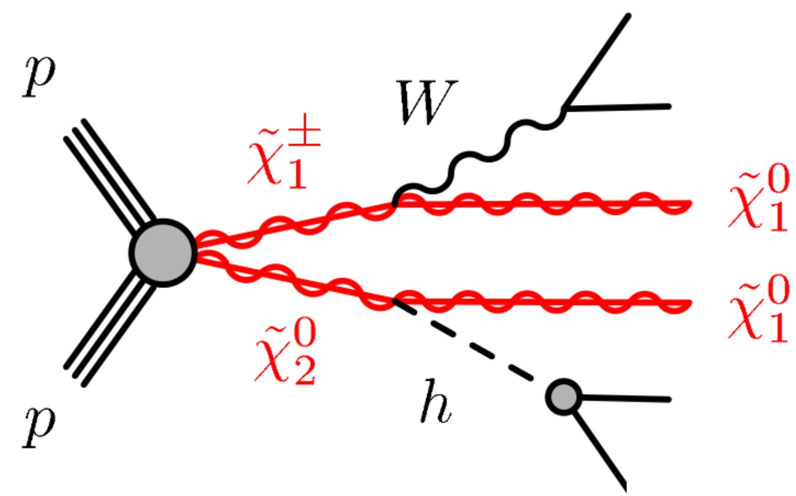
Electroweak searches benefit from large integrated luminosity

- Cross section for $\chi^{\pm}\chi^{0}$ production ranges from 1pb to 1fb, going from masses of 300 to 1100 GeV
- The full HL-LHC dataset is needed for high mass sensitivity



Use dedicated searches to target different decay modes





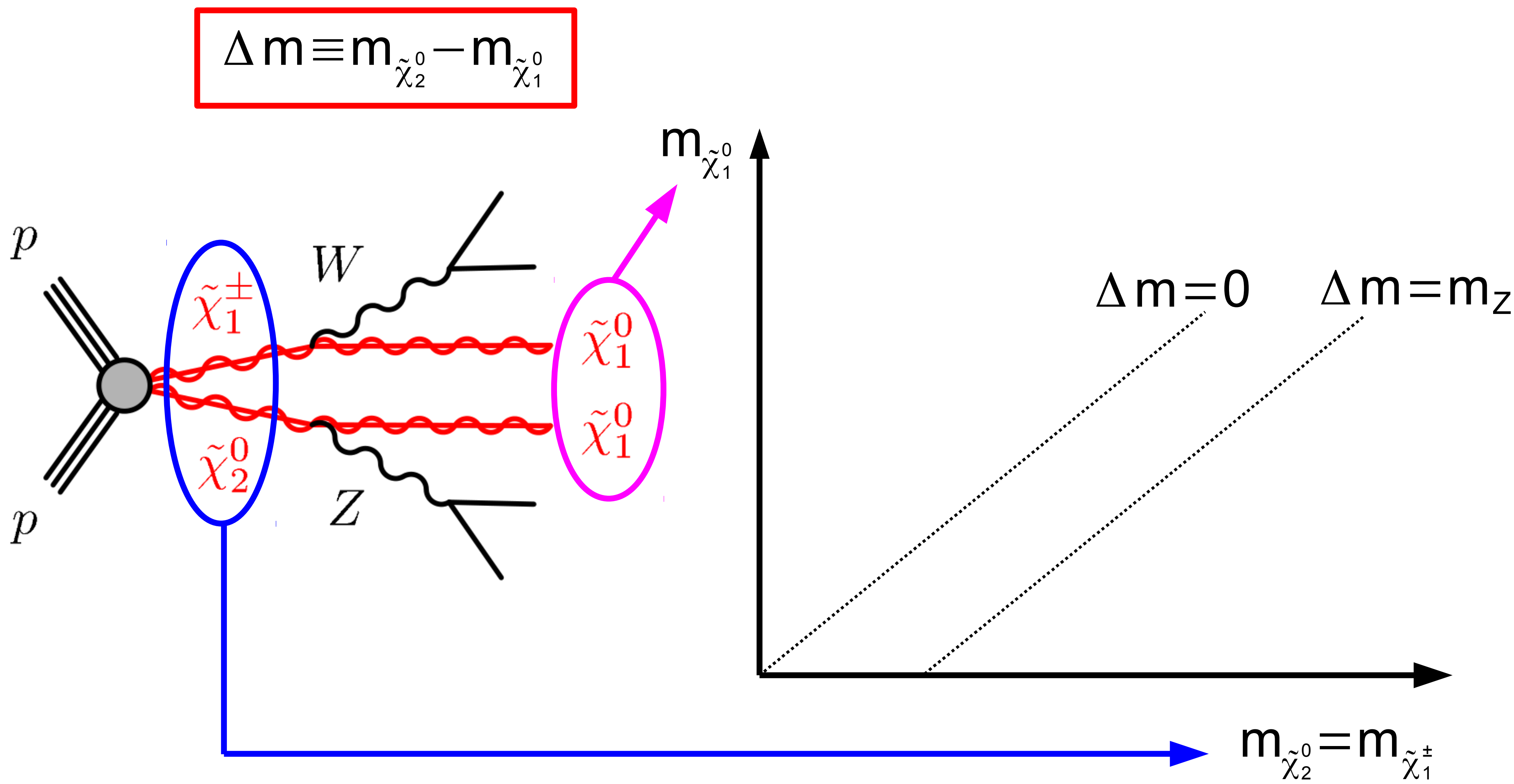
ATLAS & CMS
3ℓ: W(ℓν)Z(ℓℓ)

ATLAS
3ℓ: W(ℓν)h(WW,ττ)

CMS
1ℓ2b: W(ℓν)h(bb)

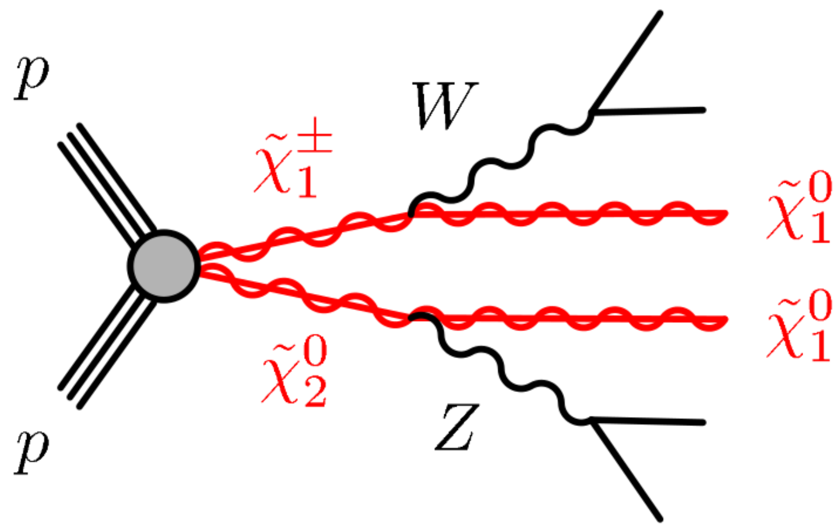
All results are taken from:
ATLAS: ATL-PHYS-PUB-2014-010
CMS: CMS-PAS-SUS-14-012

Results are interpreted using Simplified Models

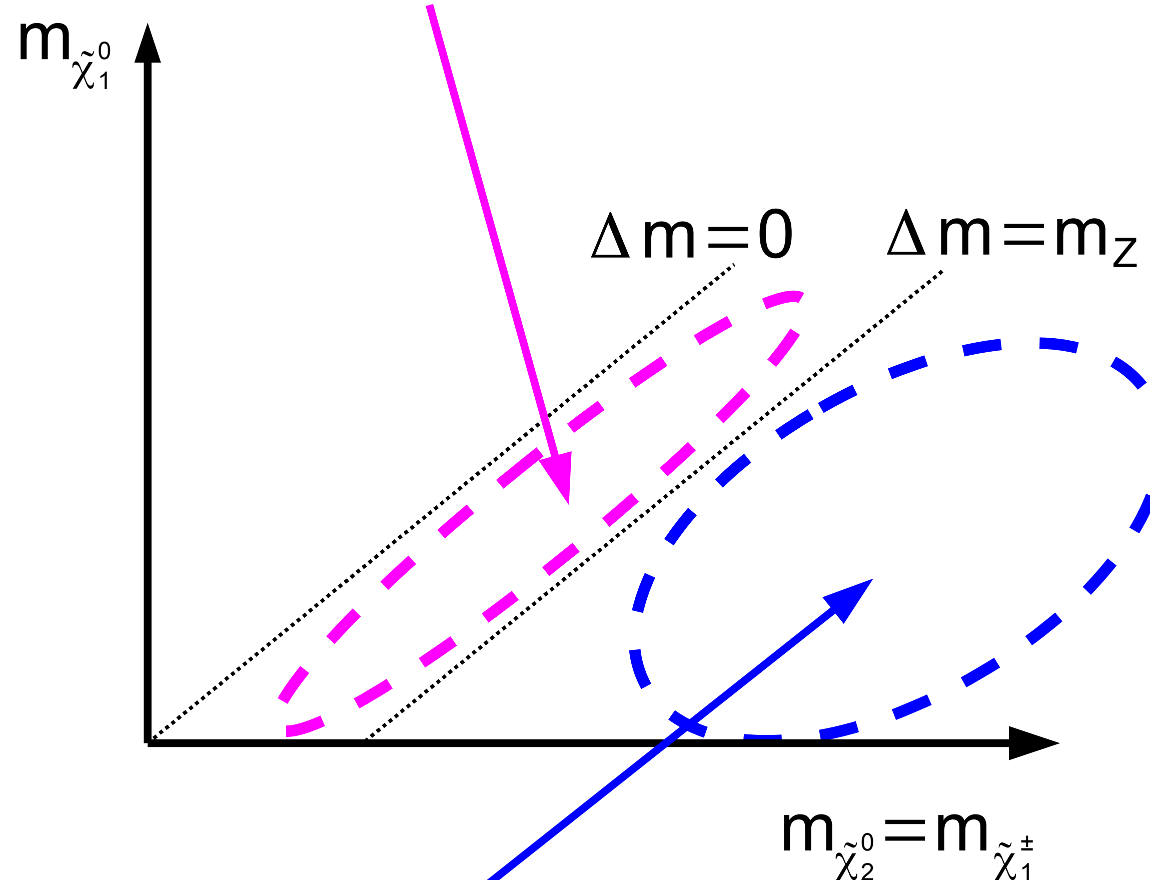


Future projections focus on region where Z/h are on-shell

$$\Delta m \equiv m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$

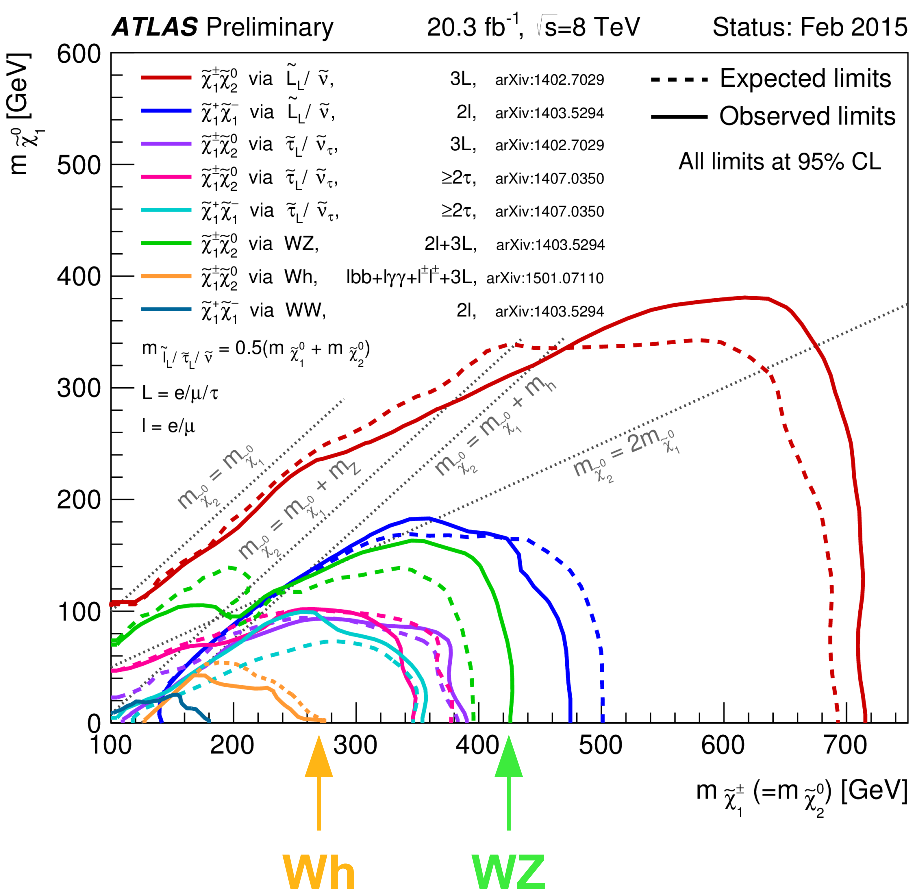


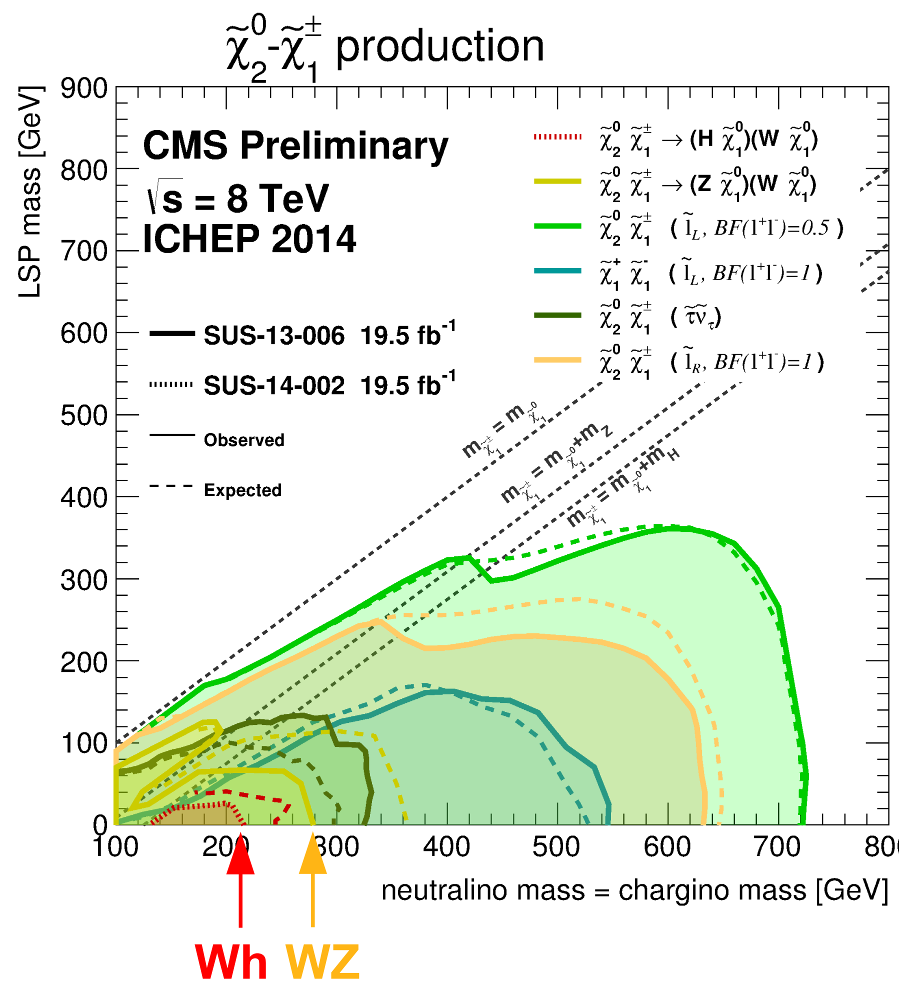
Off-shell region: have some limits in WZ topology from 8 TeV



On-shell region: bulk of phase space, concentrate here for future projections

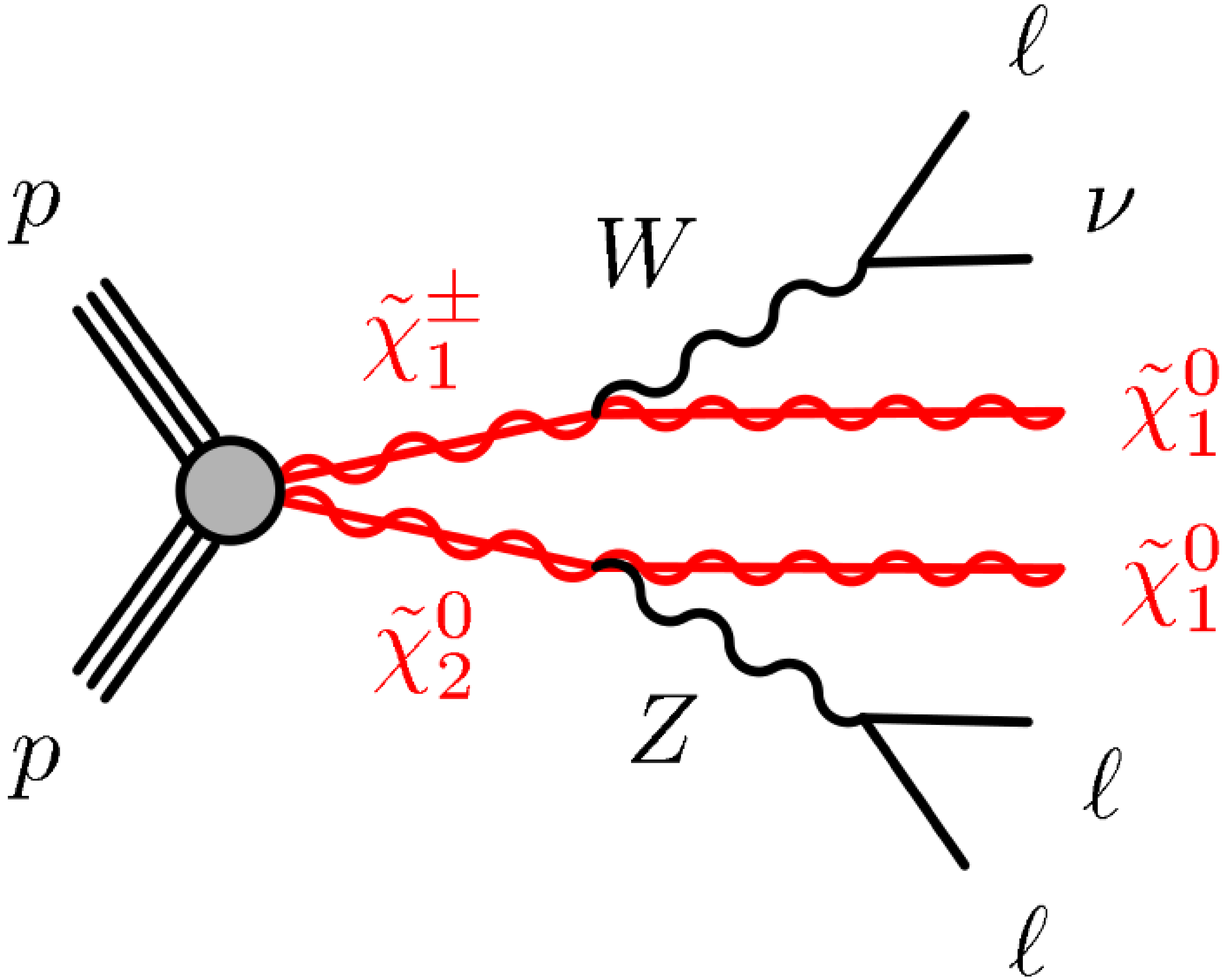
With 8 TeV results, probe $\chi^{\pm}\chi^{0}$ production up to 270-420 GeV in $M(\chi^{\pm})$





https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

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



p
p
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_2^0$
W
Z
ℓ
ν
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
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ℓ

The main background to WZ+MET is SM production of WZ

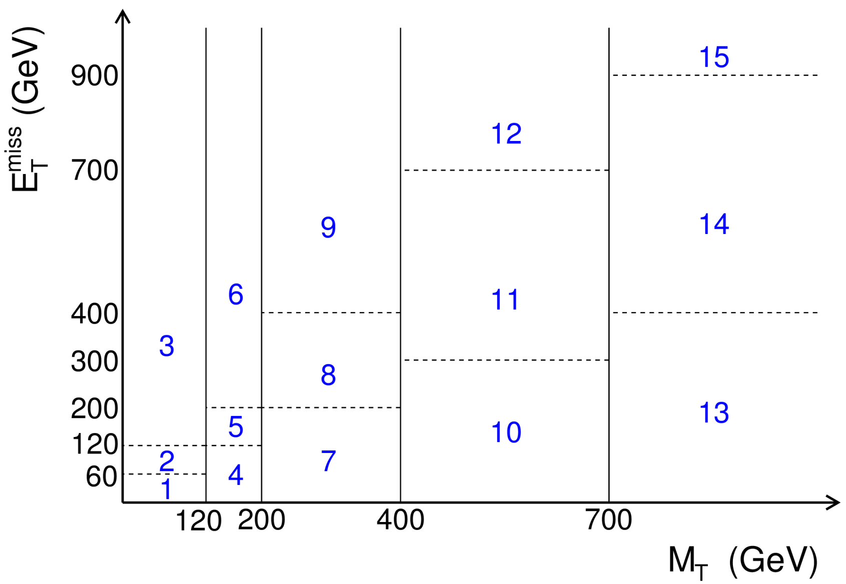
- Use extra MET from signal to suppress the WZ background
  - Requirements on MET, M_T of lepton from W

- Triboson production and ttV also contribute at high MET → irreducible

- Reducible background from ttbar when lepton from a b-quark is misidentified as prompt
  - Require lepton isolation, b-jet veto to suppress ttbar

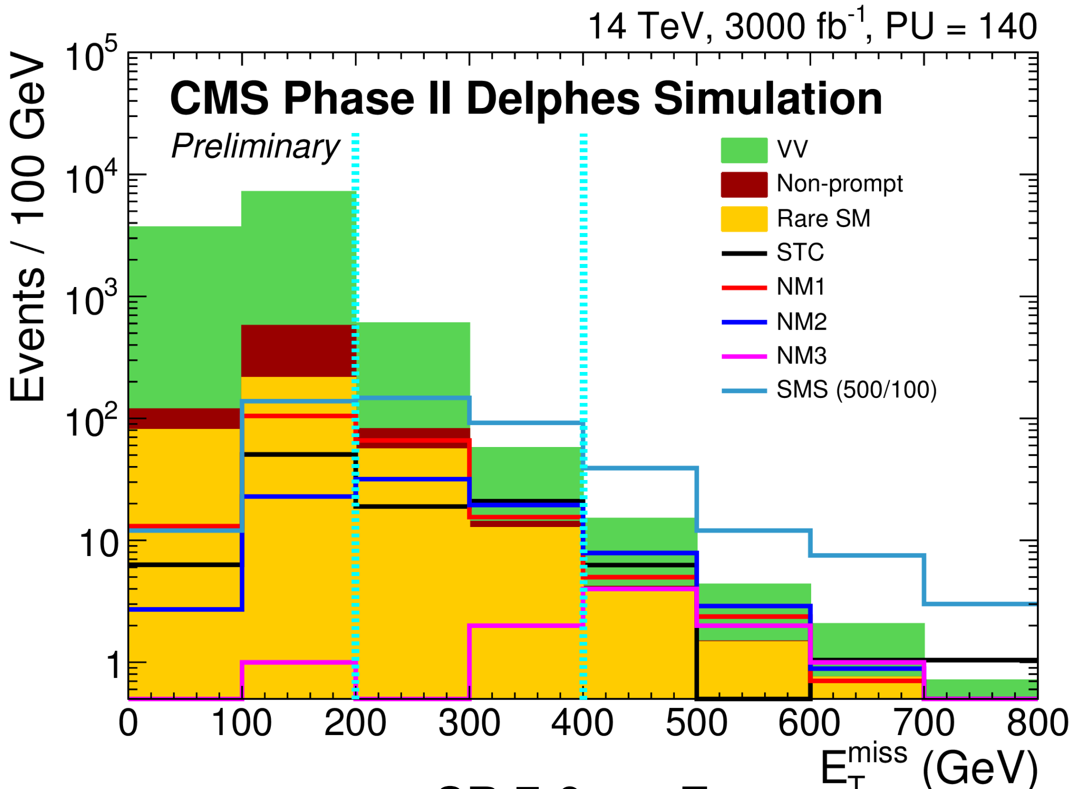
CMS selects 3 lepton events and bins them in MET and M_T

- Require 3 leptons (e,μ): p_T > 120, 90, 40 GeV
- Veto on 4th lepton: p_T > 10 GeV, $|\eta| < 2.4$
- Form OSSF pair with $M(\ell\ell)$ closest to M_Z, require $75 < M(\ell\ell) < 105$ GeV
- Veto event if b-jet p_T > 30 GeV, $|\eta| < 2.4$
  - Or any jet with p_T > 100 GeV
- Compute M_T with lepton not used for Z
  - Bin in MET and M_T



Potential to see signal in the tails of MET and M_T

- Orthogonal regions are combined statistically to determine discovery sensitivity



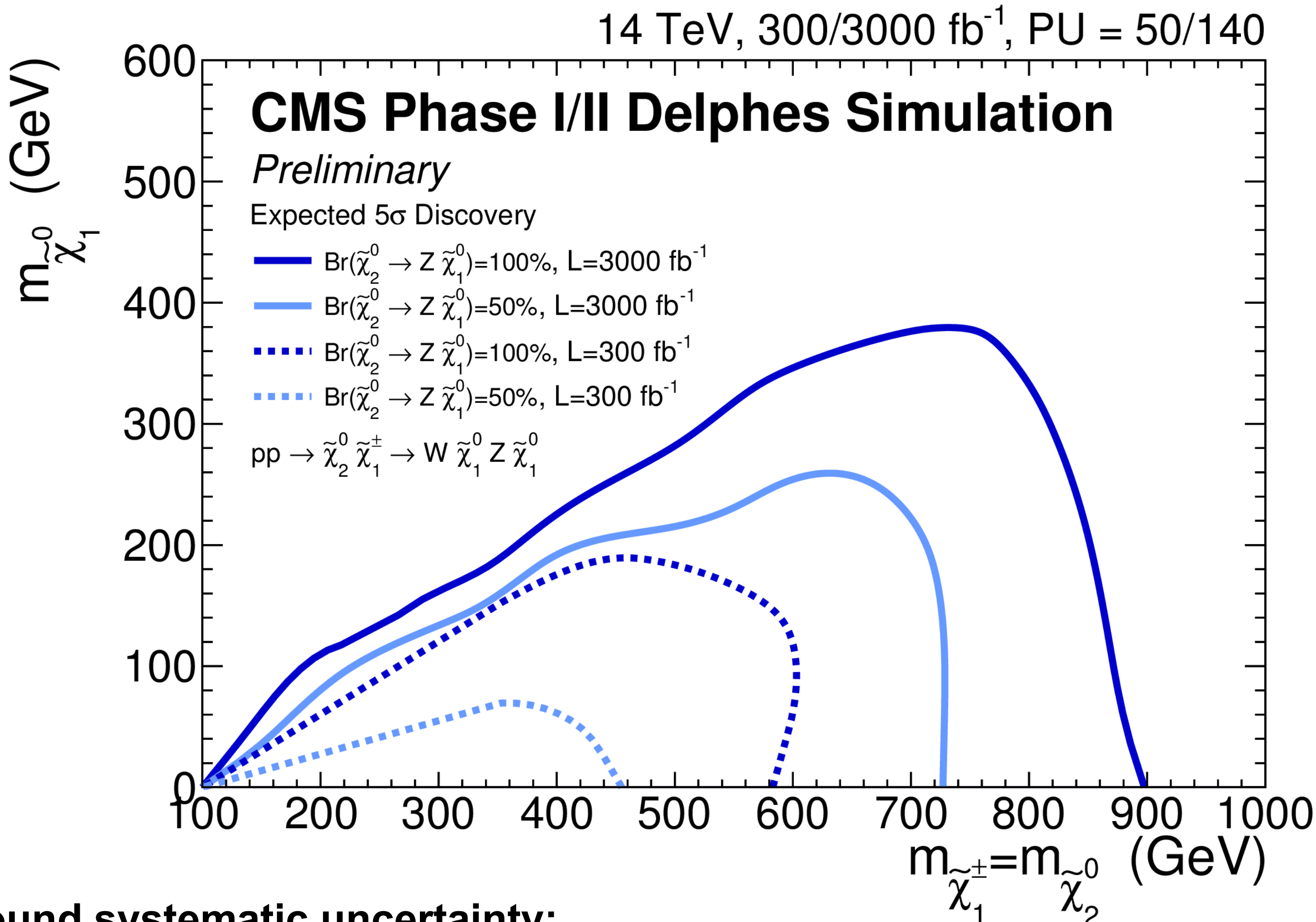
SR 7-9, on-Z
200 < M_T < 400 GeV
looser lepton p_T cuts, no jet veto

$m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0} = 500, 100$ GeV

SR		Total SM	SMS
on-Z	1	1010000 ± 190000	21
	2	810000 ± 150000	73
	3	167000 ± 26000	300
	4	99400 ± 8900	41
	5	41300 ± 9100	66
	6	2700 ± 1300	140
	7	10900 ± 1600	150
	8	660 ± 230	240
	9	22.9 ± 6.3	63
	10	282 ± 82	50
	11	72 ± 16	120
	12	0.8 ± 0.3	0
	13	21.3 ± 2.0	6.0
	14	32.9 ± 4.9	21
	15	1.5 ± 0.4	0

looser lepton p_T cuts, no jet veto

Discovery reach extends to 900 GeV with 3000/fb



Background systematic uncertainty:

3% per lepton, 1% for trigger, scale MET by ± 5%
amounts to 10 – 25% depending on signal region

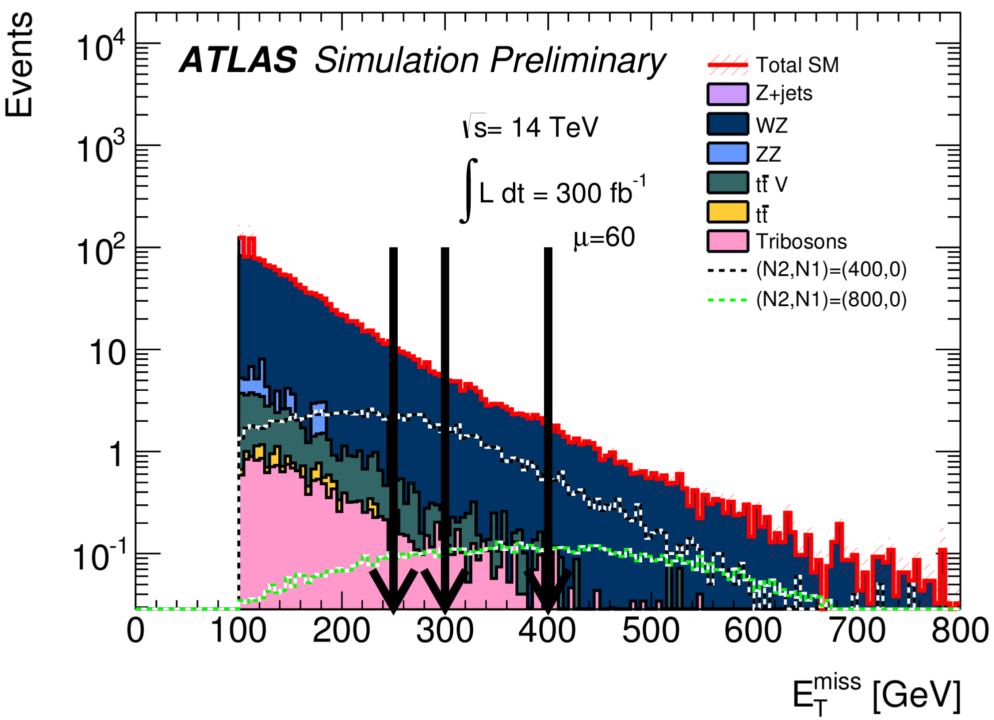
ATLAS optimizes signal regions for discovery and exclusion

- Require 3 leptons with p_T > 50 GeV, |η| < 2.47 (2.4) for e (μ)
  - Veto on 4th lepton with p_T > 10 GeV
- Veto on b-tagged jet with p_T > 20 GeV, |eta| < 2.5
- Z candidate from OSSF pair, compute M_T using non-Z lepton
- SRA optimized for discovery, looser cuts
- SRB,C,D optimized for limit setting, tighter cuts

Selection	SRA	SRB	SRC	SRD
m_{SFOS}[GeV]	81.2-101.2			
# b-tagged jets	0			
lepton p_T (1,2,3)[GeV]	> 50			
$E_{\text{T}}^{\text{miss}}$[GeV]	> 250	> 300	> 400	> 500
m_{T} [GeV]	> 150	> 200	> 200	> 200
$\langle\mu\rangle = 60$, 300 fb^{-1} scenario	yes	yes	yes	–
$\langle\mu\rangle = 140$, 3000 fb^{-1} scenario	yes	yes	yes	yes

As with CMS, discovery potential in tails of MET and M_T

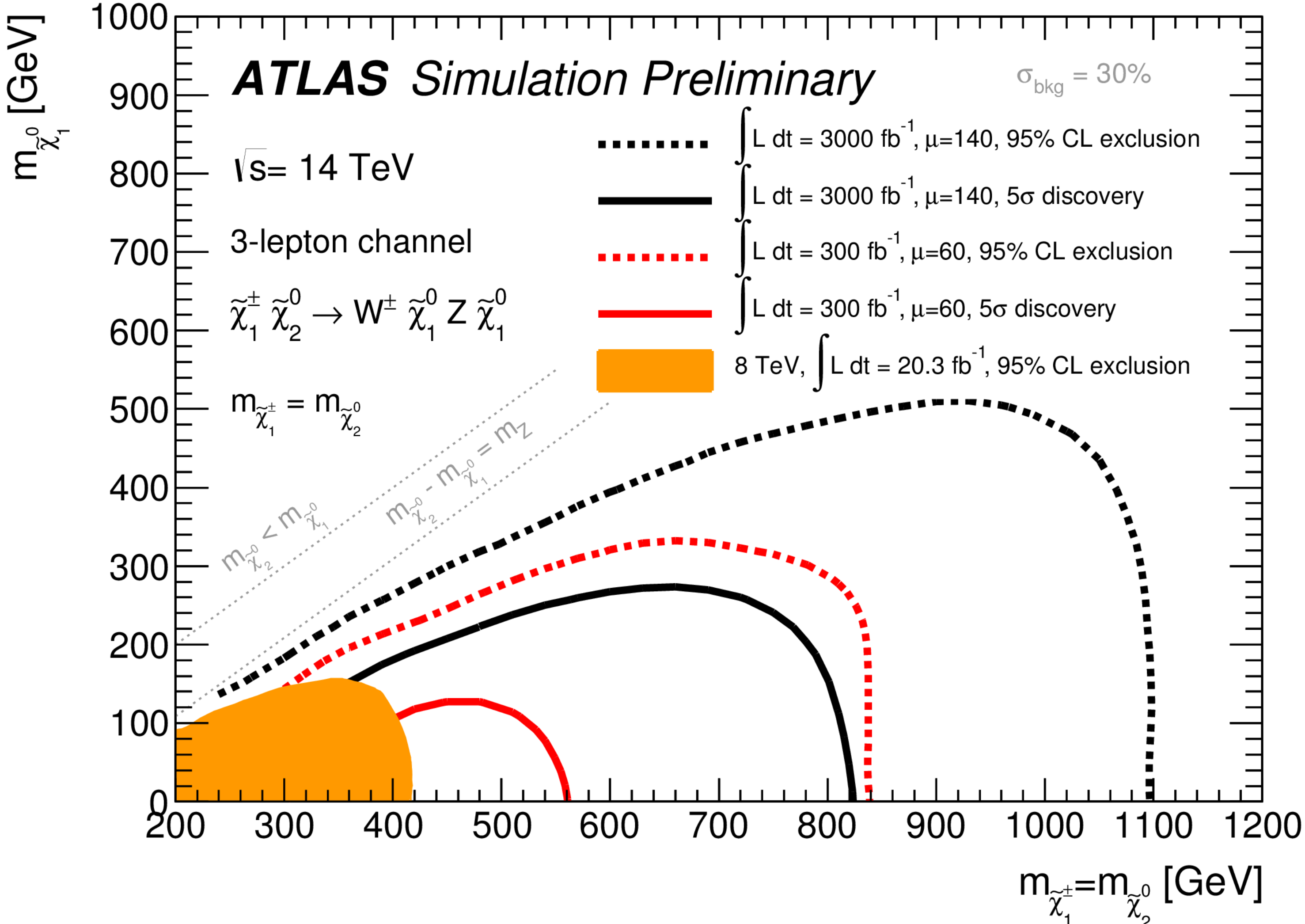
- To evaluate sensitivity, regions are made orthogonal and significances combined



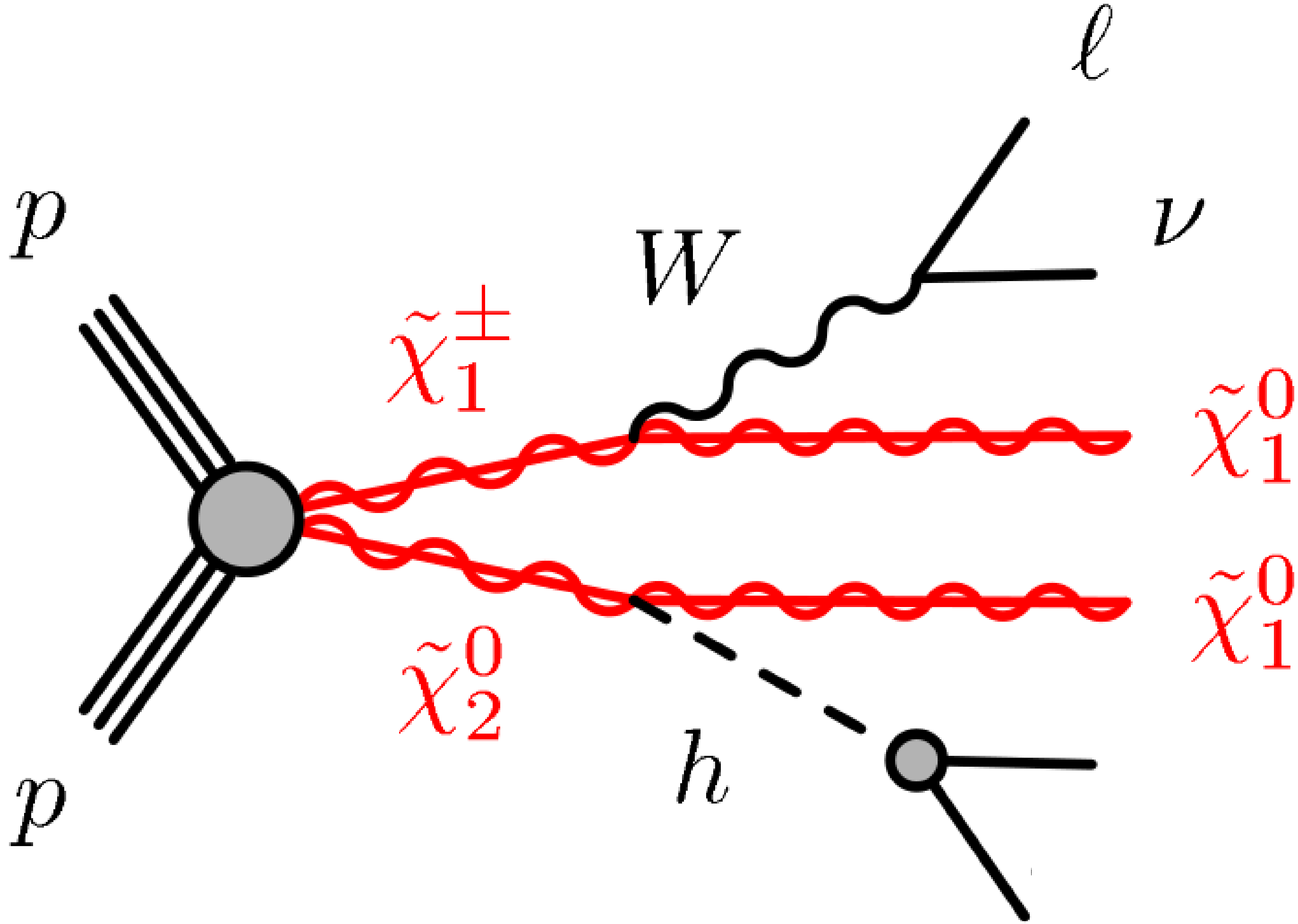
after all cuts except M_T

Sample Scenario	SRA	SRB	SRC	SRD
	3000 fb^{-1}, μ=140			
WZ	200±5	59.4±2.5	22.0±1.5	8.3±1.0
ZZ	0	0	0	0
VVV	24.3±1.9	12.1±1.4	5.4±0.8	2.0±0.5
Wh	0	0	0	0
$t\bar{t}V$	14.4±2.8	4.2±1.6	0.31±0.31	0
$t\bar{t}$	0	0	0	0
Σ MC	239±6	75.6±3.3	27.7±1.8	10.3±1.1
WZ-mediated				
$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(400,0) GeV	407±6	224±5	67.9±2.6	19.7±1.4
$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(600,0) GeV	194.8±2.0	148.9±1.7	81.6±1.3	33.5±0.8
$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(800,0) GeV	69.6±0.6	59.1±0.6	42.4±0.5	25.2±0.4
$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(1000,0) GeV	22.94±0.19	20.42±0.18	16.36±0.16	11.55±0.14

With 3000/fb, discovery reach extends to 820 GeV, exclusion to 1100 GeV



Background systematic uncertainty: 30%


p
p
$\tilde{\chi}_1^{\pm}$
$\tilde{\chi}_2^0$
W
ℓ
ν
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
h

ATLAS selects 3 lepton events focusing on $W(\ell\nu)h(WW)$

- Same object selection as WZ+MET search
- Events with exactly 3 leptons and an OSSF pair are vetoed to reduce the WZ background
- A cut on the invariant mass of the OS pair closest in ΔR reduces the ttbar and WWW backgrounds
- Require large M_T for each lepton

Selection	SRE	SRF	SRG	SRH
SFOS pair		veto		
# b-tagged jets		0		
E_T^{miss} [GeV]		> 100		
$m_{OS}^{min\Delta R}$ [GeV]		< 75		
$m_T(\ell_1)$ [GeV]	> 200	> 200	> 300	> 400
$m_T(\ell_2)$ [GeV]	> 100	> 150	> 150	> 150
$m_T(\ell_3)$ [GeV]	> 100	> 100	> 100	> 100
$\langle\mu\rangle = 60$, $300\,fb^{-1}$ scenario	yes	yes	yes	—
$\langle\mu\rangle = 140$, $3000\,fb^{-1}$ scenario	yes	yes	yes	yes

ATLAS also searches for W($\ell\nu$)h($\tau\tau$) by selecting 1 lepton and 2 τ_h

- Object selections same as ATLAS 3ℓ analysis
- Select τ_h with p_T > 20 GeV, require OS pair
- Require M($\tau\tau$) consistent with Higgs mass
- Also require large MET, M_T, sum of τ_h p_T values
- Largest background is ttbar, then WZ and WW

Selection	SR1ℓ2τ
# e, μ	1
# τ	2 (OS)
# b-tagged jets	0
E_T^{miss} [GeV]	$>$ 250
$m_{\tau\tau}$ [GeV]	80-130
$\lvert p_T(\tau_1)\rvert + \lvert p_T(\tau_2)\rvert$ [GeV]	$>$ 190
$m_T(\ell)$ [GeV]	$>$ 130

The 3ℓ search has good sensitivity in tighter signal regions

- The $1\ell 2\tau$ search has more difficult backgrounds
  - Sees S/B ~ 1 or less

Sample Scenario	SRE	SRF	SRG	SRH
	$3000\,\text{fb}^{-1}$, μ=140			
WZ	6.2±0.8	2.9±0.6	0.76±0.29	0.43±0.22
ZZ	0	0	0	0
VVV	34±4	17.5±3.1	1.3±0.8	0.8±0.6
Wh	10.1±2.9	2.5±1.5	0.8±0.8	0
$t\bar{t}V$	9.6±1.8	4.1±1.3	1.1±0.6	0.4±0.4
$t\bar{t}$	121±10	36±5	3.9±1.8	0
Σ MC	181±11	63±6	7.9±2.2	1.6±0.7
Wh-mediated				
$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(200,0) GeV	181±31	99±23	27±12	0
$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(300,0) GeV	166±16	121±13	46±8	13±4
$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(500,0) GeV	57±4	46.1±3.4	31.9±2.8	20.5±2.2
$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(700,0) GeV	18.1±1.1	15.9±1.0	12.8±0.9	9.1±0.8

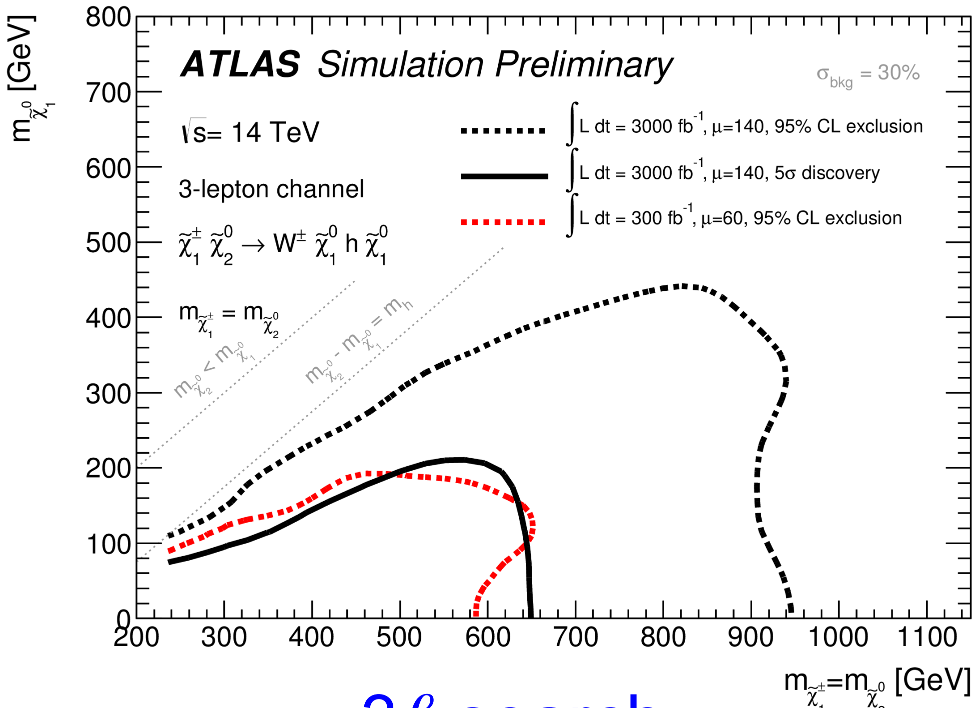
3ℓ search

SM background	yield	SUSY signal	yield
WZ	2.3	$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(200,0) GeV	20
VVV	0.21	$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(500,200) GeV	9
$t\bar{t}+V$	0.03	$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(700,0) GeV	7
$t\bar{t}$	8.1	$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(1200,600) GeV	0.5
WW	3.5		
W+ jets	1.4		
Total	15.5		

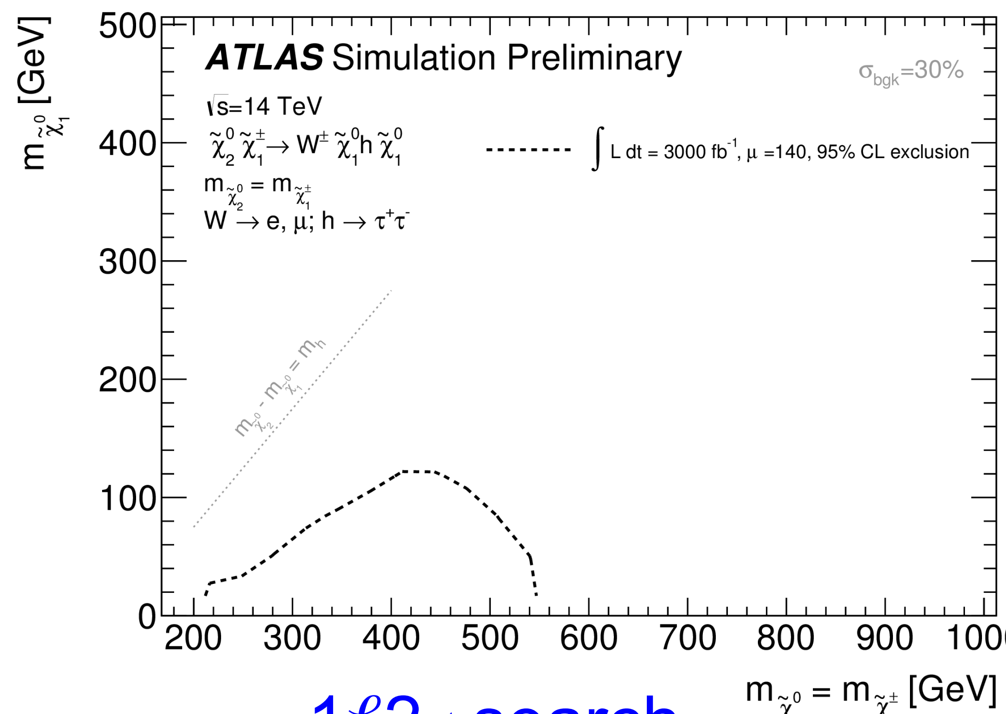
$1\ell 2\tau$ search

Discovery reach extends to 650 GeV using the 3ℓ channel, with 3000/fb

- The 3ℓ channel exclusion reaches 950 GeV
- The $1\ell 2\tau$ channel doesn't achieve discovery sensitivity by itself but can exclude up to 550 GeV



3ℓ search

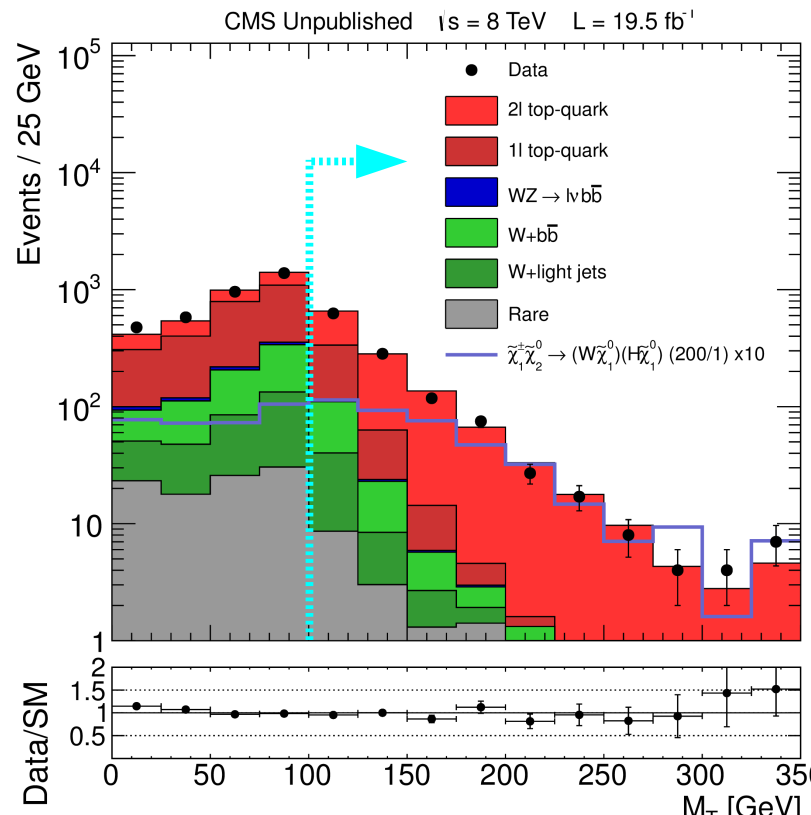


$1\ell 2\tau$ search

Background systematic uncertainty: 30%

CMS searches for W($\ell\nu$)h(bb)+MET, which has several backgrounds

- ttbar $\rightarrow$ 1ℓ, W+jets, WZ $\rightarrow$ $\ell\nu$bb
  - Suppress using M_T cut
  - MET resolution is key to having a sharp peak in M_T
- ttbar $\rightarrow$ 2ℓ
  - Suppress using 2nd lepton veto, kinematic variable with endpoint
- SM WH is small after analysis cuts



M_T in 8 TeV CMS analysis after preselection

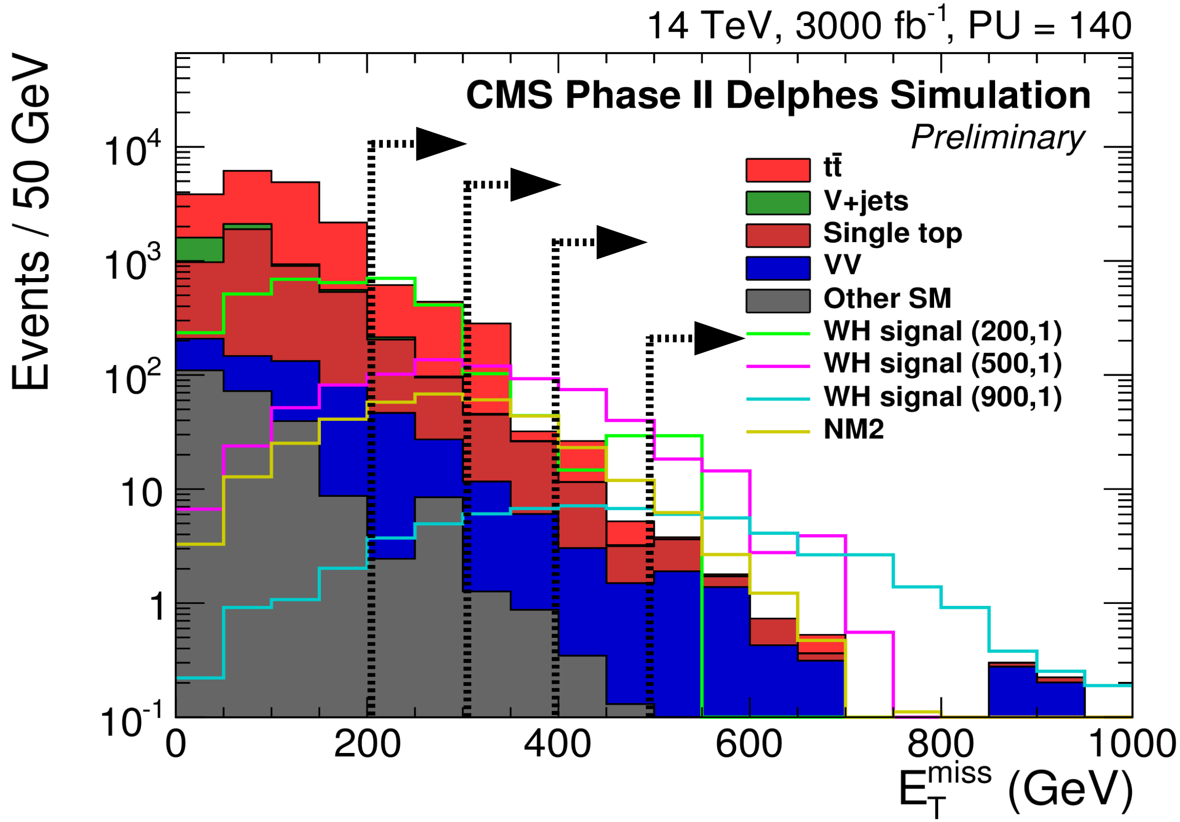
EPJC 74 (2014) 3036

CMS selects events with exactly 1 lepton and 2 b-jets

- Lepton: p_T > 40 GeV, $|\eta| < 2.4$
  - Veto additional leptons with p_T > 10 GeV
- Jets: p_T > 30, $|\eta| < 2.4$
  - Require exactly 2 jets to suppress ttbar $\rightarrow 1\ell$
- Cut on kinematic variable $M_{CT}(b_1,b_2)$: has endpoint for ttbar but not for signal
- Require M(bb) consistent with Higgs mass

Cut	Signal Requirement
N(leptons)	$= 1$
N(jets)	$= 2$
N(b-tags)	$= 2$
$M_{b\bar{b}}$	$\in$[90,150] GeV
M_T	$>$ 100 GeV
M_{CT}	$>$ 160 GeV
E_T^{miss}	$>$ 200,300,400(,500) GeV

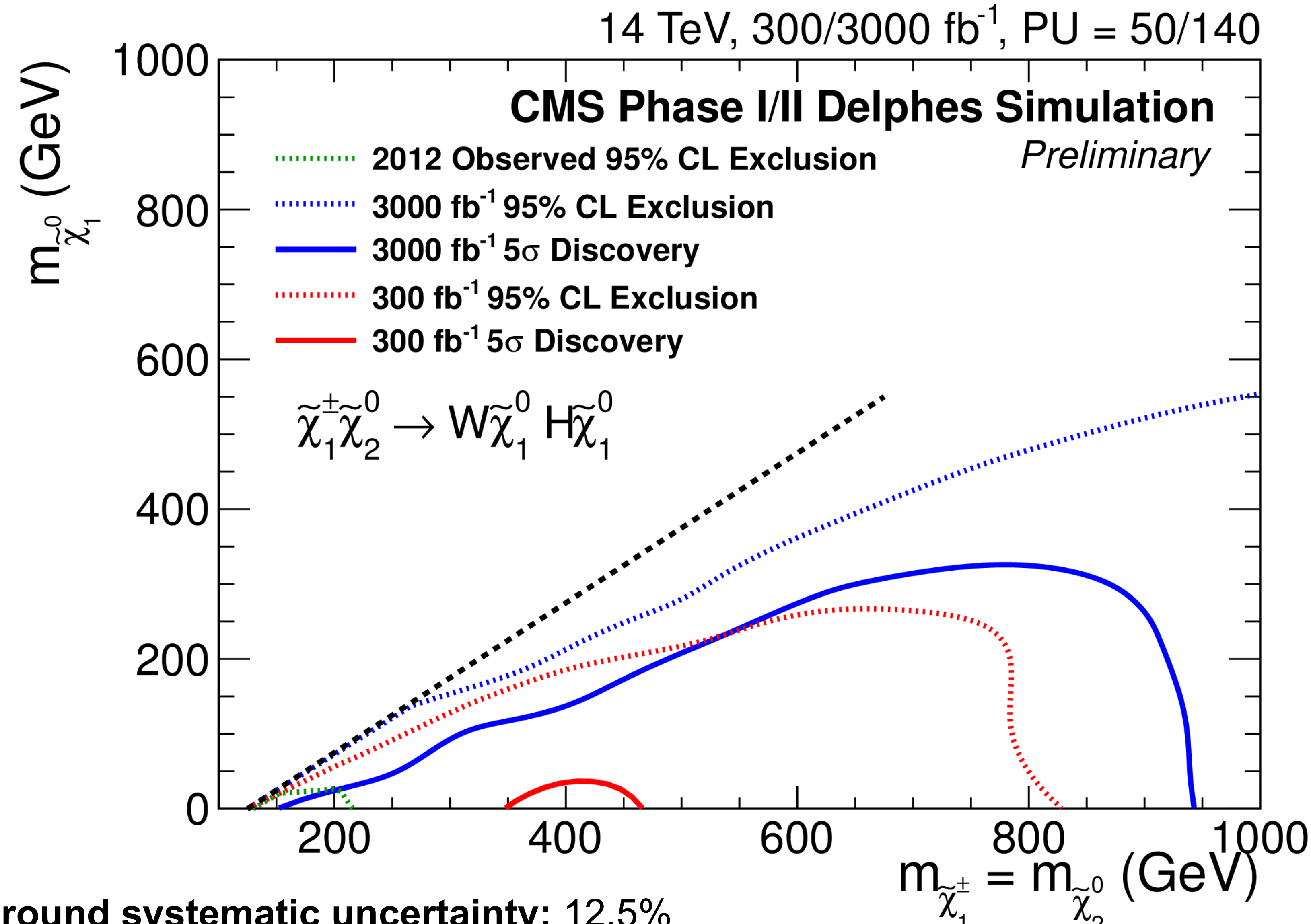
As in 3 lepton analyses, sensitivity comes in the tail of MET



After full selection except MET cut

Sample	$E_T^{miss} > 200$ GeV	$E_T^{miss} > 300$ GeV	$E_T^{miss} > 400$ GeV	$E_T^{miss} > 500$ GeV
$t\bar{t}$	1000 ± 260	261 ± 130	17 ± 13	0.5 ± 0.2
V + jets	14 ± 4	1.2 ± 0.3	0.1 ± 0.1	0.0 ± 0.0
single top	291 ± 38	66 ± 11	13 ± 4	2.5 ± 0.8
diboson	87 ± 16	24 ± 5	8.4 ± 2.0	4.4 ± 1.4
Other SM	14 ± 5	2.7 ± 0.6	0.6 ± 0.1	0.1 ± 0.0
Total SM	1410 ± 260	354 ± 130	39 ± 14	7.5 ± 1.6
WH signal (200,1)	1340 ± 140	220 ± 57	73 ± 33	29 ± 21
WH signal (500,1)	605 ± 18	367 ± 14	154 ± 9	40 ± 5
WH signal (900,1)	60 ± 1	51 ± 1	38 ± 1	24 ± 1
Natural Model 2	276 ± 4	150 ± 3	46 ± 2	11 ± 1

Discovery reach extends to 950 GeV with 3000/fb



<u>Background systematic uncertainty:</u> 12.5%
Discussion on later slide

Several theoretical and experimental assumptions enter these results

Theory:

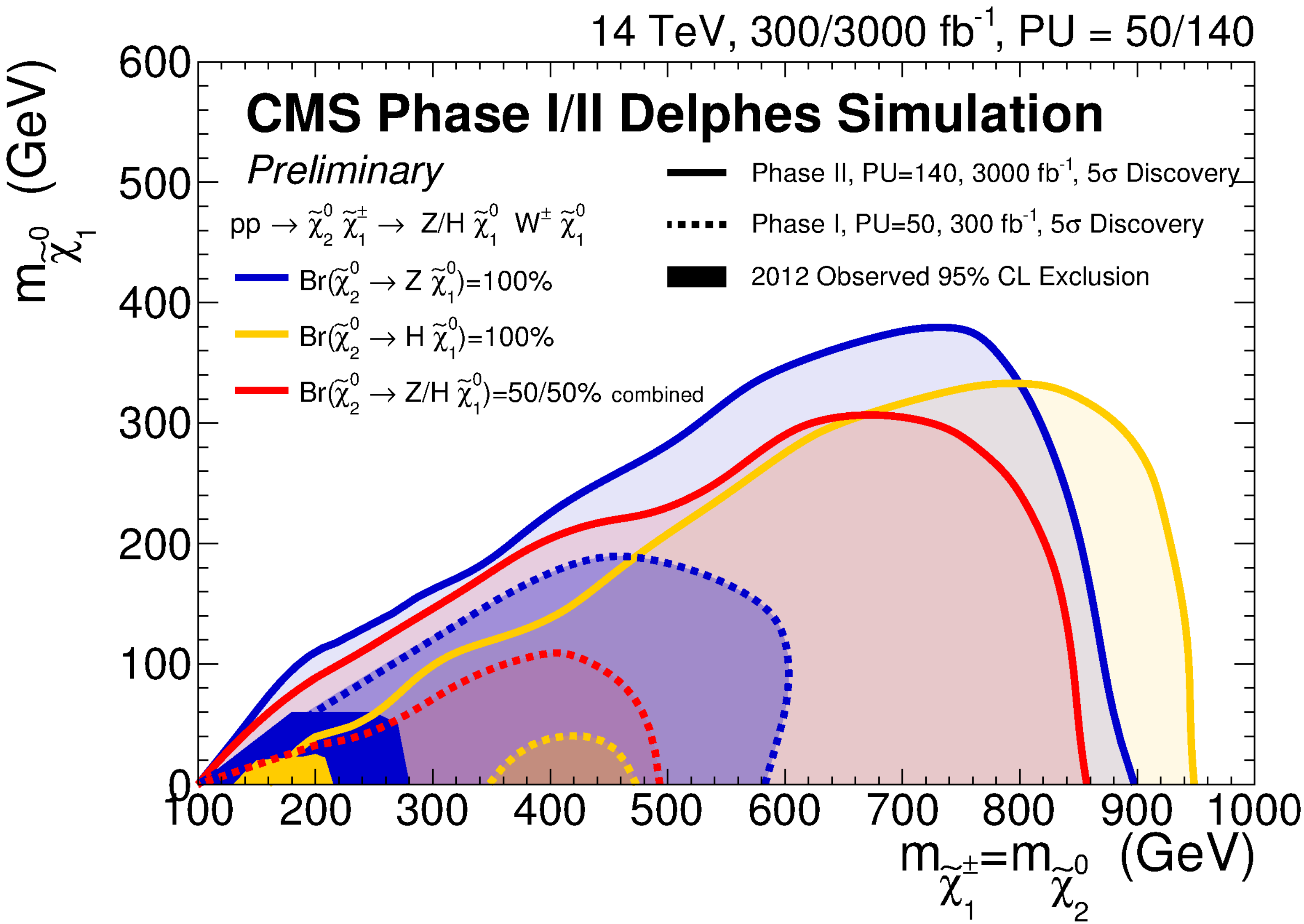
- Simplified Models assume 100% branching ratio to Z or h. What if both decays are present?

Experiment:

- How would these results look if the detectors are not upgraded for HL-LHC?
- Similarly, how would they look if the performance estimates are too optimistic?

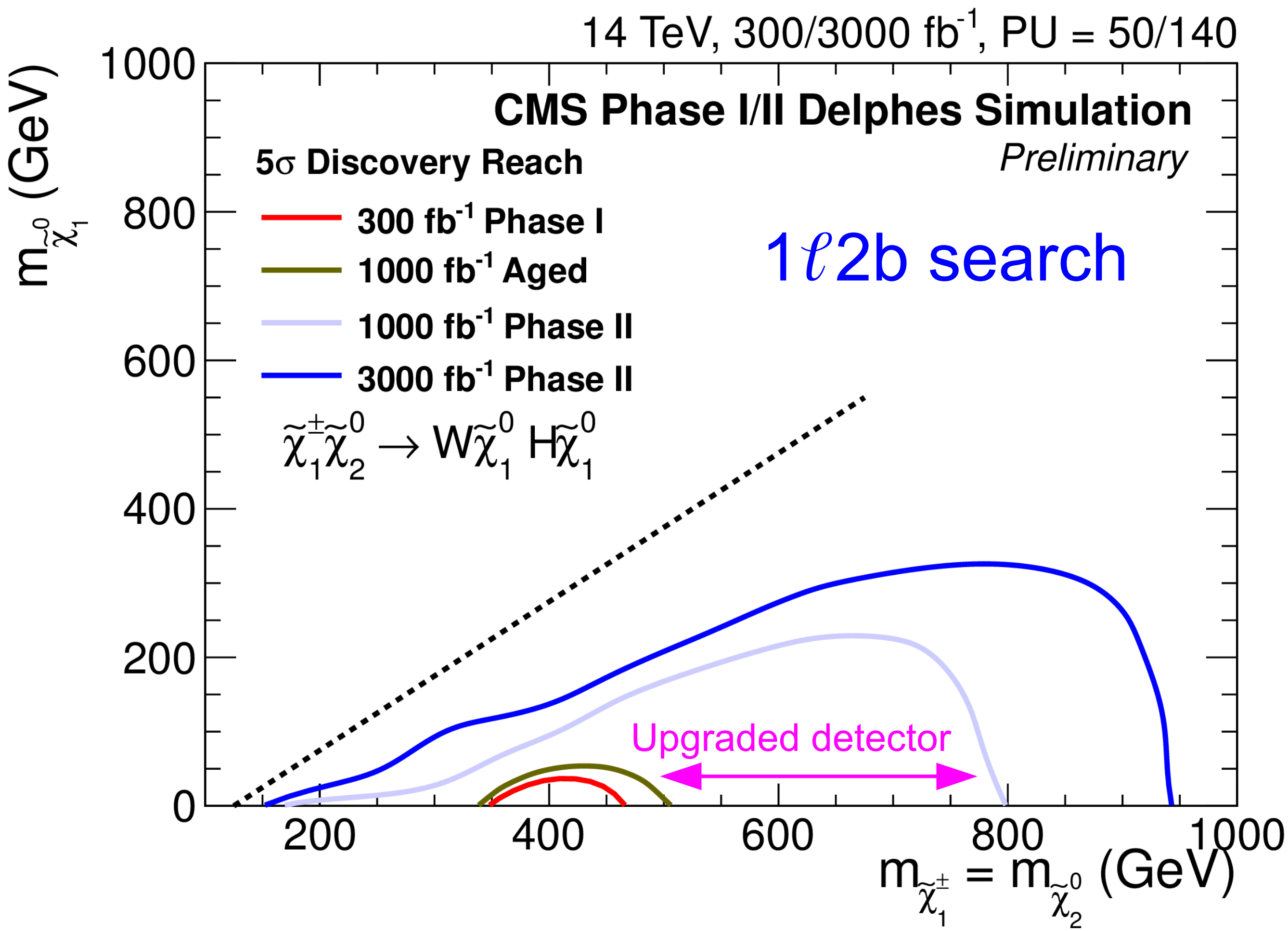
- Sometimes systematic uncertainties are assumed based on improving the 8 TeV analyses. What if these are optimistic?

With 50% branching to Z/h, combining searches gives good sensitivity



An aged (or reduced performance) detector degrades sensitivity

- Based on full simulation, emulated “aged” detector with:
  - 16% worse e/μ efficiency, 33% worse b-tagging efficiency
  - 40 GeV worse MET resolution → impacts M_T

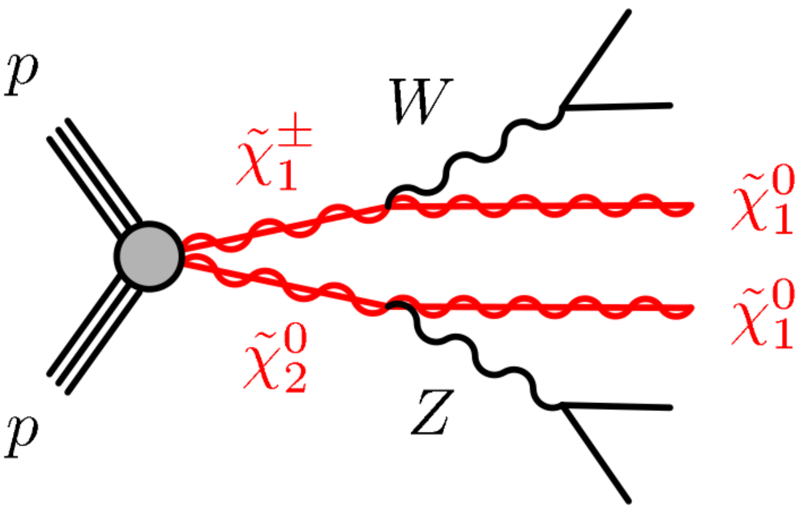


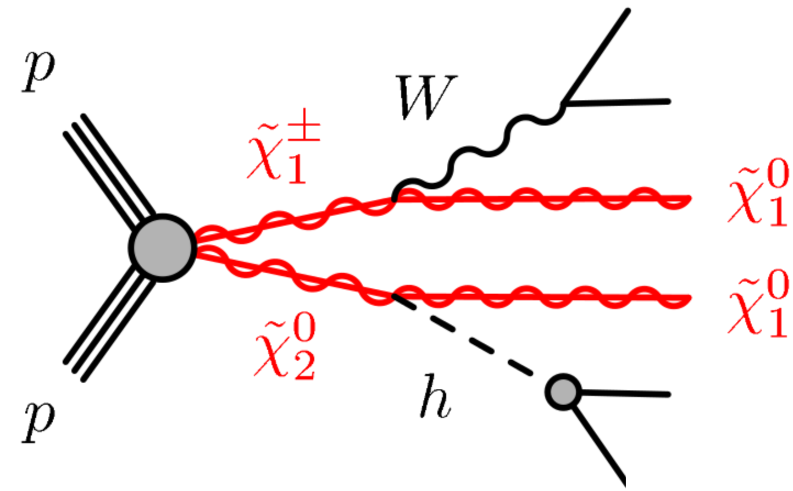
Larger systematic uncertainties reduce potential discovery reach

- CMS $1\ell 2b$ search: total background uncertainty of 25% at 8 TeV, dominated by control sample size
  - Assumed this can be reduced to 12.5% for results shown
- With 25% uncertainty, discovery reach decreases from 950 GeV to less than 900 GeV
- Exclusion limits not very sensitive to background uncertainty

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

Additional channels were used at 8 TeV to improve sensitivity





3ℓ: W(ℓν)Z(ℓℓ)
OS 2ℓ2j: W(jj)Z(ℓℓ)

1ℓ2b: W(ℓν)h(bb)
1ℓ2γ: W(ℓν)h(γγ)
SS 2ℓ: W($\ell^{\pm}$ν)h, h → W($\ell^{\pm}$ν)W(jj)
≥3ℓ: W(ℓν)h(WW,ττ,ZZ)

Channels in blue used for projection

Conclusions

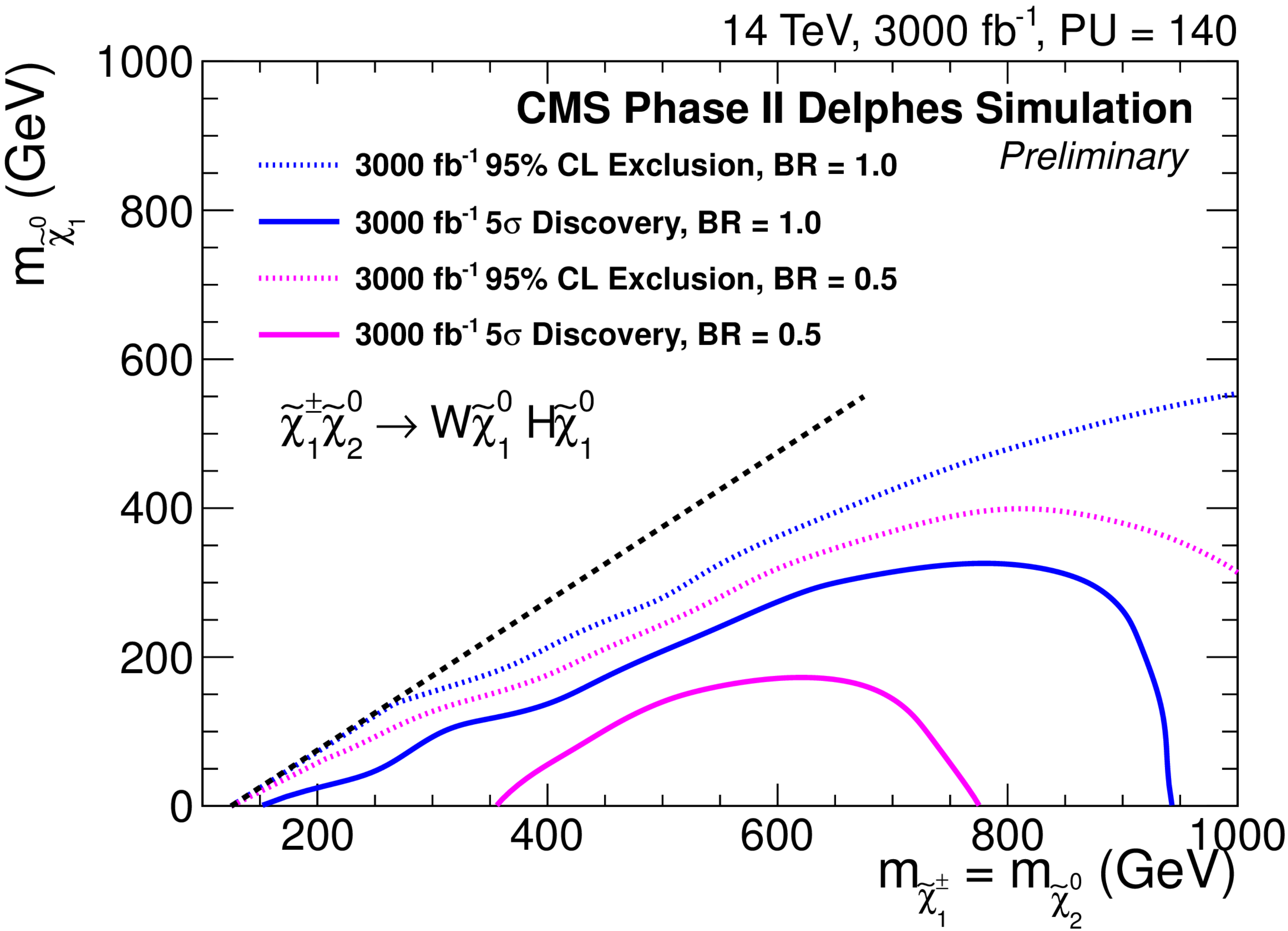
- 8 TeV searches have only begun to probe electroweak SUSY production, with limits extending to 270-420 GeV for $\chi^{\pm}\chi^{0}$
  - Limits for higher masses exist, but assuming light sleptons
- HL-LHC and 3000/fb extends discovery reach substantially beyond 300/fb
  - For WZ+MET, ~300 GeV further reach moving to 3000/fb
  - For Wh+MET, discovery potential up to 950 GeV with 3000/fb
    - Almost no discovery potential at 300/fb in these studies
- Many assumptions enter these projections
  - Excellent performance and control of systematic uncertainties will be needed to maximize the discovery potential at HL-LHC

Bonus Slides

Parameterized simulations are used for these studies

- Also 3000/fb is a lot of events to generate → strategy needed
  - At 14 TeV, ttbar xsec is ~1nb → 3 billion events
  - Focus on kinematic tails instead of bulk
- ATLAS:
  - Uses parameterized simulation tuned based on full simulation
  - Generates events with a gen-level MET cut, 50 or 120 GeV
- CMS:
  - Uses Delphes parameterized simulation with a tune based on full simulation
  - Generates events in bins of S_T (scalar sum of p_T for all stable particles)

Branching ratio impact for CMS WH+MET search



A natural model with W+h/Z+MET