Prospects for SUSY and BSM Physics at the High Luminosity LHC

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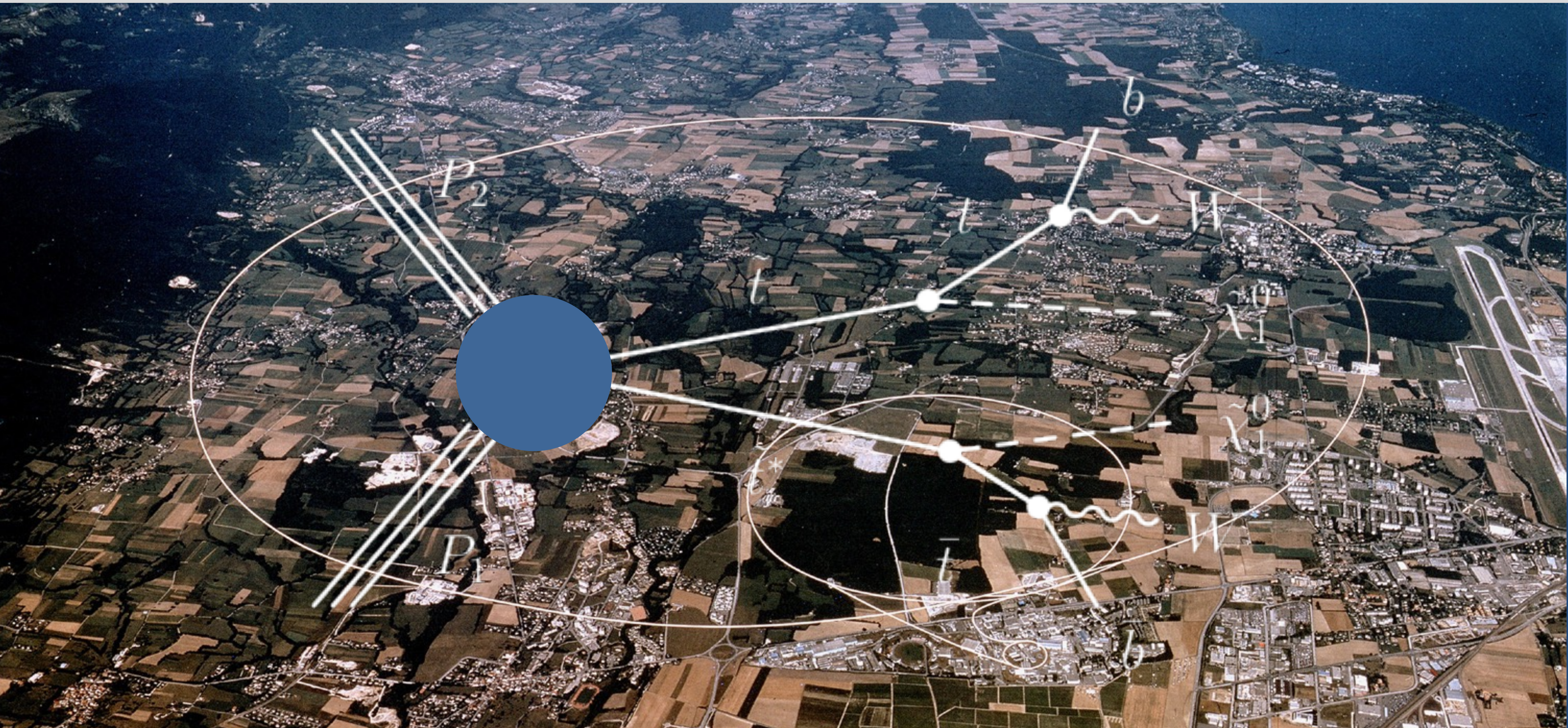
representing the ATLAS and CMS Collaborations



3rd Conference on Large Hadron Collider Physics (LHCP)
St. Petersburg, Russia, September 3, 2015

Outline

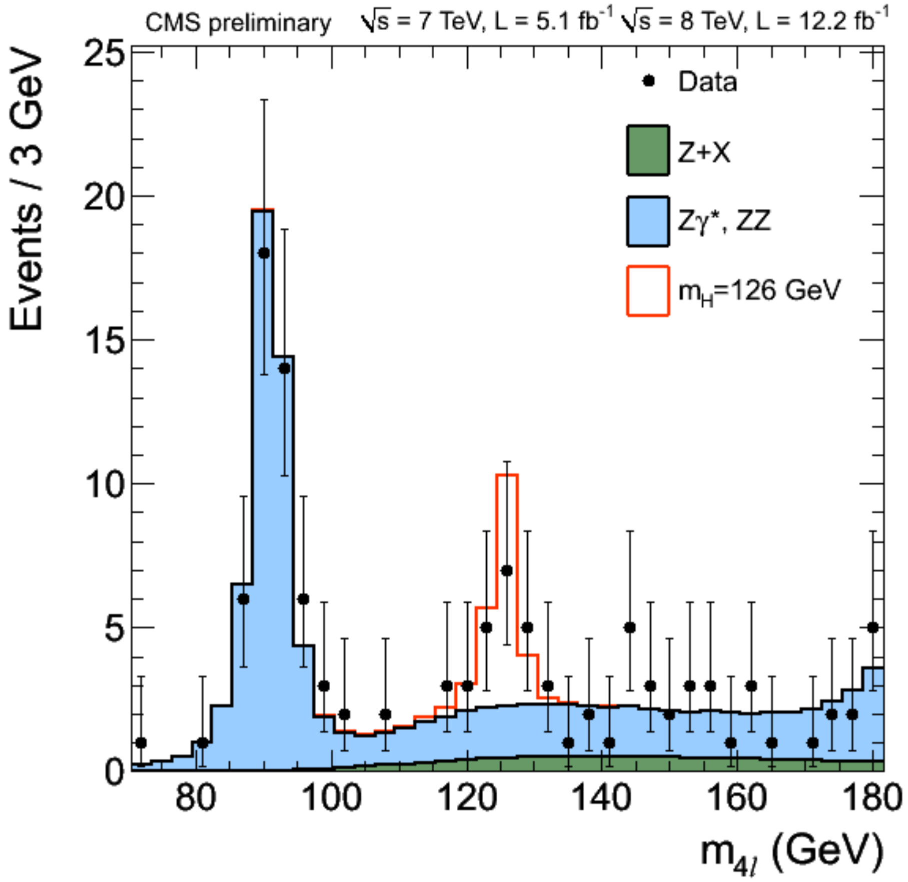
- Perspective on physics at the electroweak scale
- Supersymmetry
  - Sensitivities for key simplified models
  - Elucidating discoveries with signature patterns
- Searches for “Exotic” physics (focus on dilepton channel)
- Conclusions

Drawing courtesy Sergio Cittolin, CMS

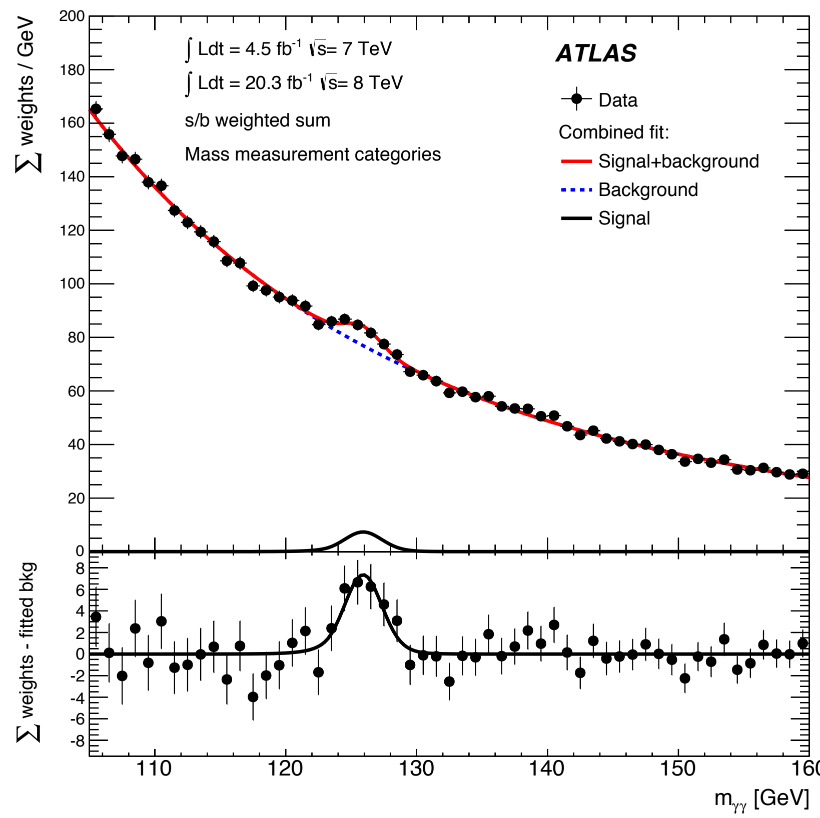
Disclaimer: there are many HL-LHC studies not shown here! Please see the references for more information.

Perspective from Run 1

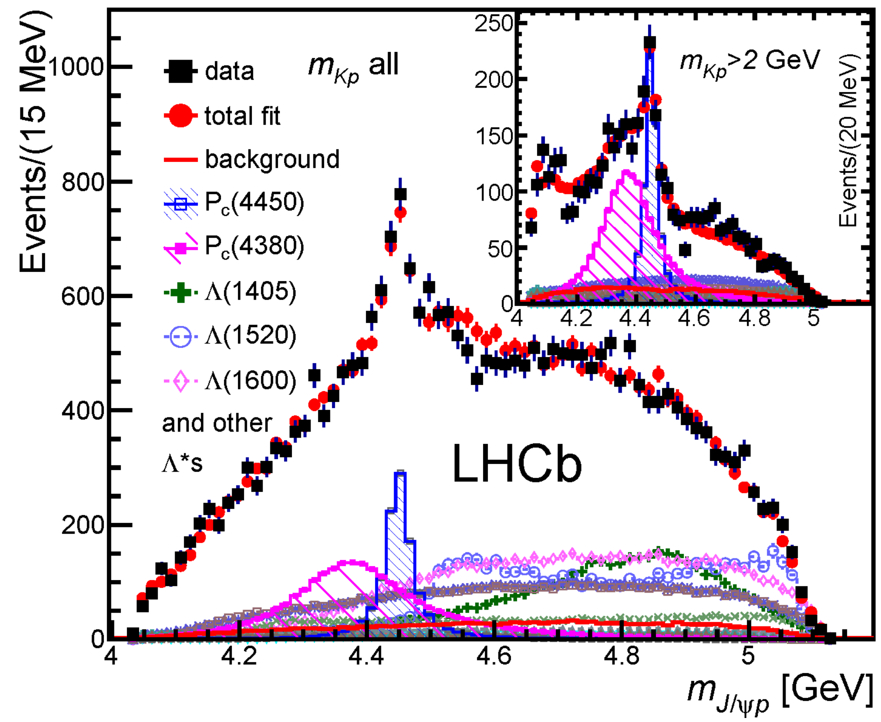
$H \rightarrow ZZ^*$



$H \rightarrow \gamma\gamma$



$\Lambda_b^0 \rightarrow K^- P_c^+(\bar{c}cuud);\ P_c^+ \rightarrow J/\psi p$



Phys. Rev. Lett. 115 (2015) 072001

Rapid interpretation of these discoveries!

- Higgs discovery: strong evidence for our overall picture of EW symmetry breaking. ***But the question of how the EW mass scale is stabilized against short-distance quantum corrections is now even more urgent.***
- LHC-b: 2 charmonium-pentaquark states → ***Still a lot to learn about the hadronic (~1 GeV) mass scale, 80 years after the discovery of the pion.***
- ***A guess: it will take at least as long to understand the physics of the EW scale. Long term HL-LHC program is an essential part of this exploration.***

Profound questions at the TeV scale

Hierarchy problem

~10^{18} GeV

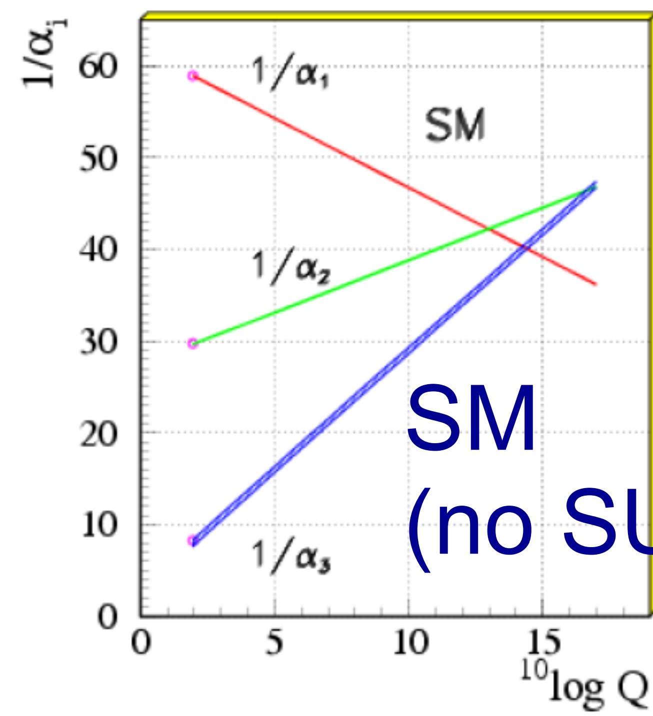
Planck scale
(quantum gravity)

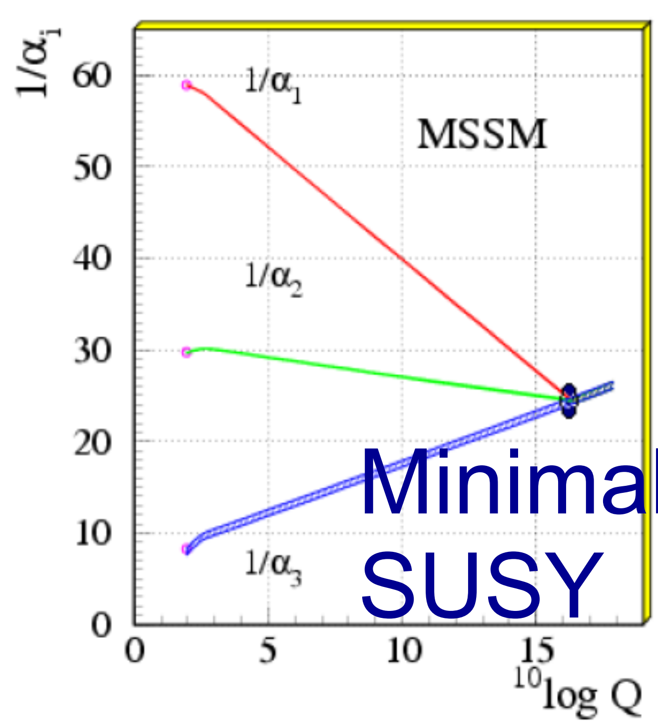
Separation of scales can be stabilized by SUSY, extra dim's,…

~10^2 -10^3 GeV

Electroweak scale
(unstable in SM)

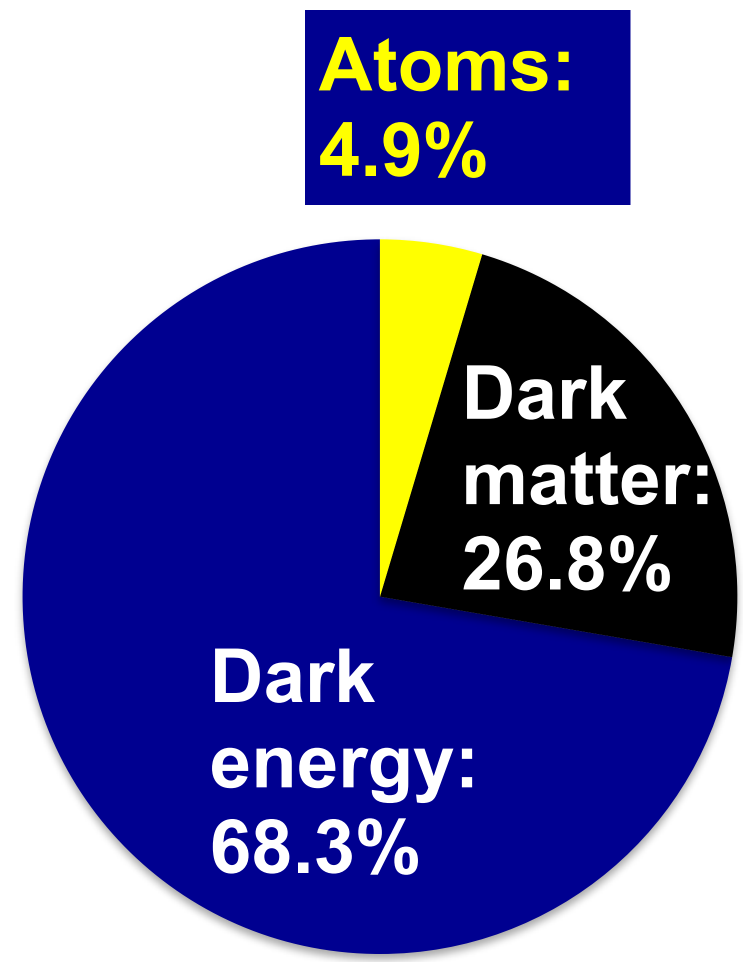
Unification of couplings





S. Raby, Particle Data Book.

Dark matter



WIMP Miracle → TeV scale

SUSY provides dark matter candidate particle (Lightest Supersymmetric Particle); in MSSM this is neutralino.

“Natural SUSY endures”: still the current fashion

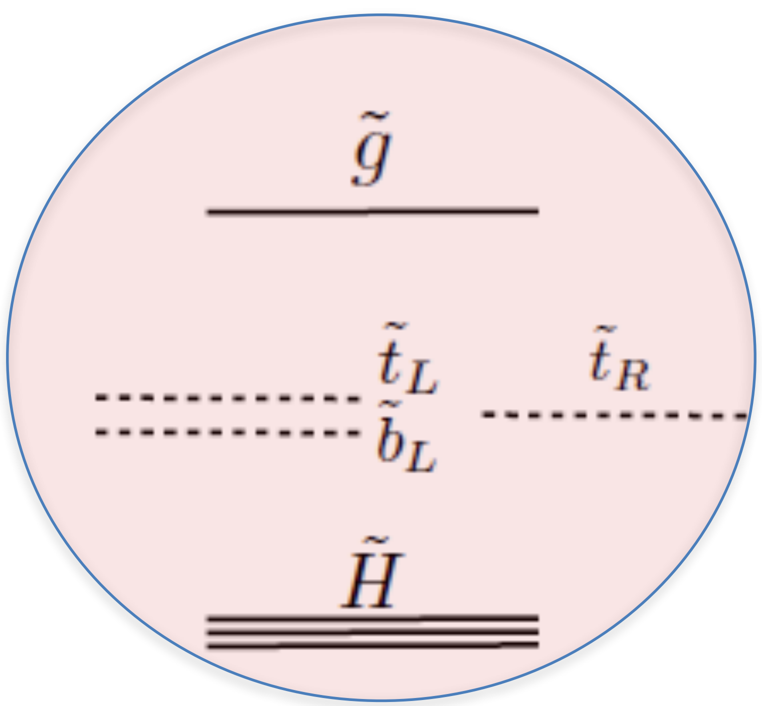
M. Papucci, J.T. Ruderman, and A. Weiler http://arxiv.org/abs/1110.6926

…but is under considerable stress from Run 1 constraints

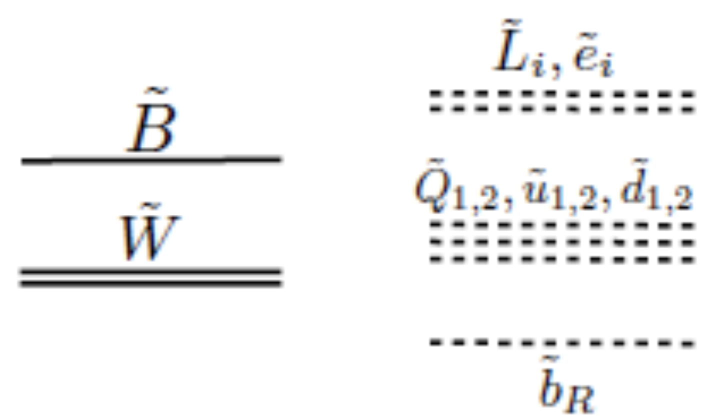
Stabilizing the EW scale in a “natural” way (without excessive fine tuning) involves only a subset of the SUSY spectrum. Which SUSY partners are constrained?

Focus of SUSY searches

TeV scale



natural SUSY



decoupled SUSY

See also: J. Feng, Naturalness and the Status of Supersymmetry, arXiv:1302.6587; N. Craig, The State of Supersymmetry after Run I of the LHC, arXiv:1309.0528; R. Barbieri and G.F. Giudice, Nucl. Phys. B 306, 63 (1988).

"Natural SUSY endures": still the current fashion

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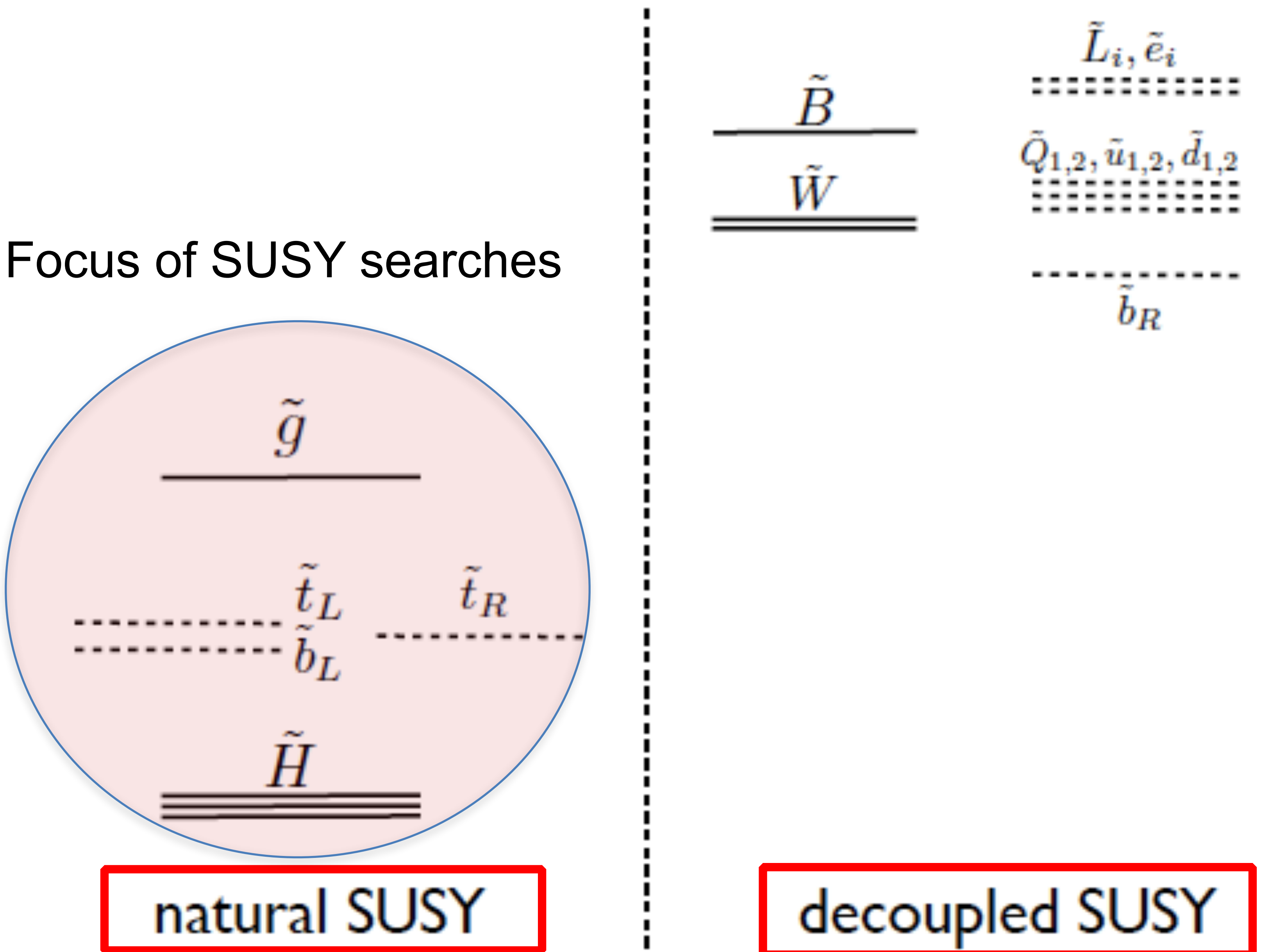
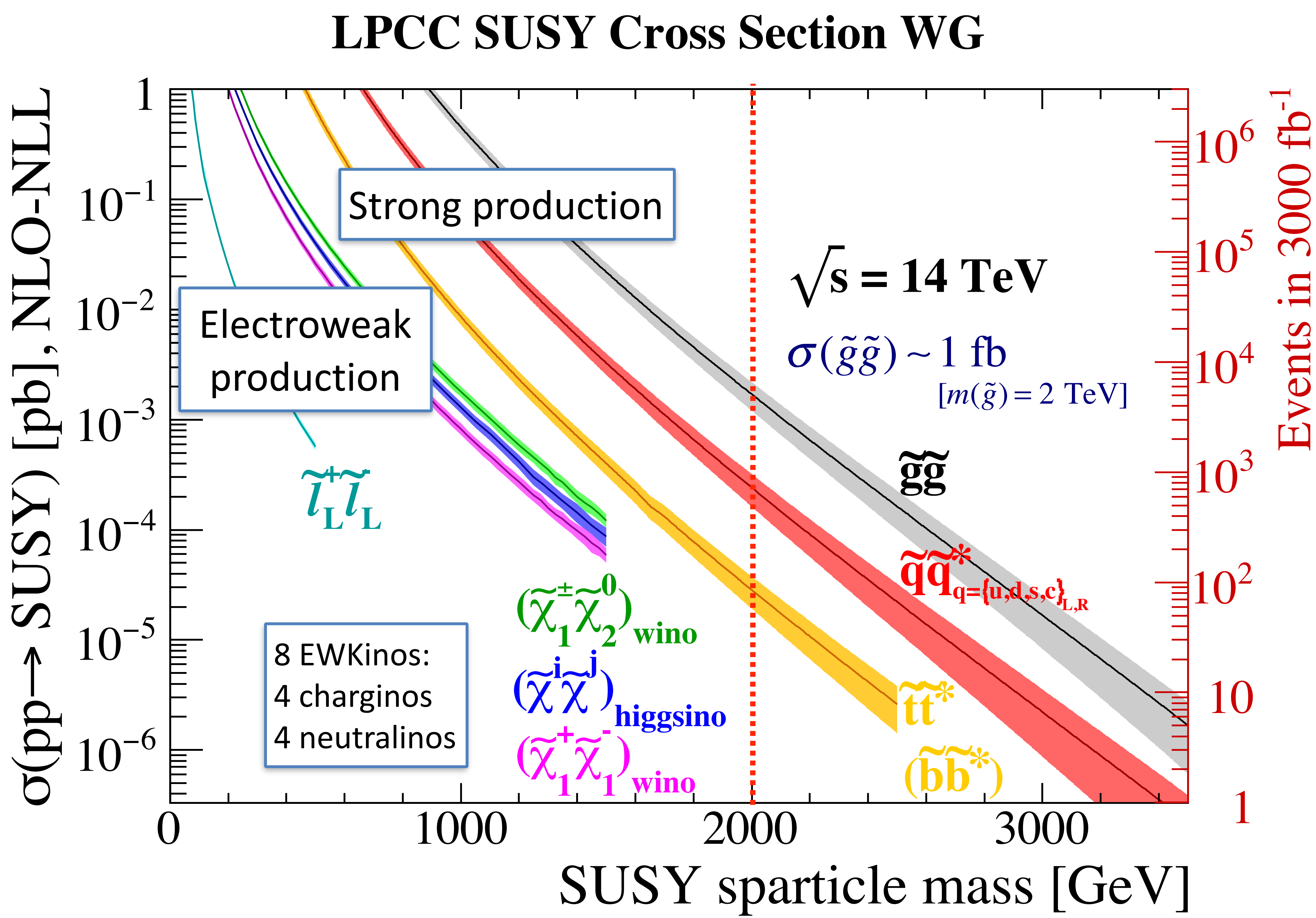


The natural SUSY spectrum is well-suited to a treatment in the simplified-model framework.

In natural model scenarios, typically assume that some or all these particles are very heavy.

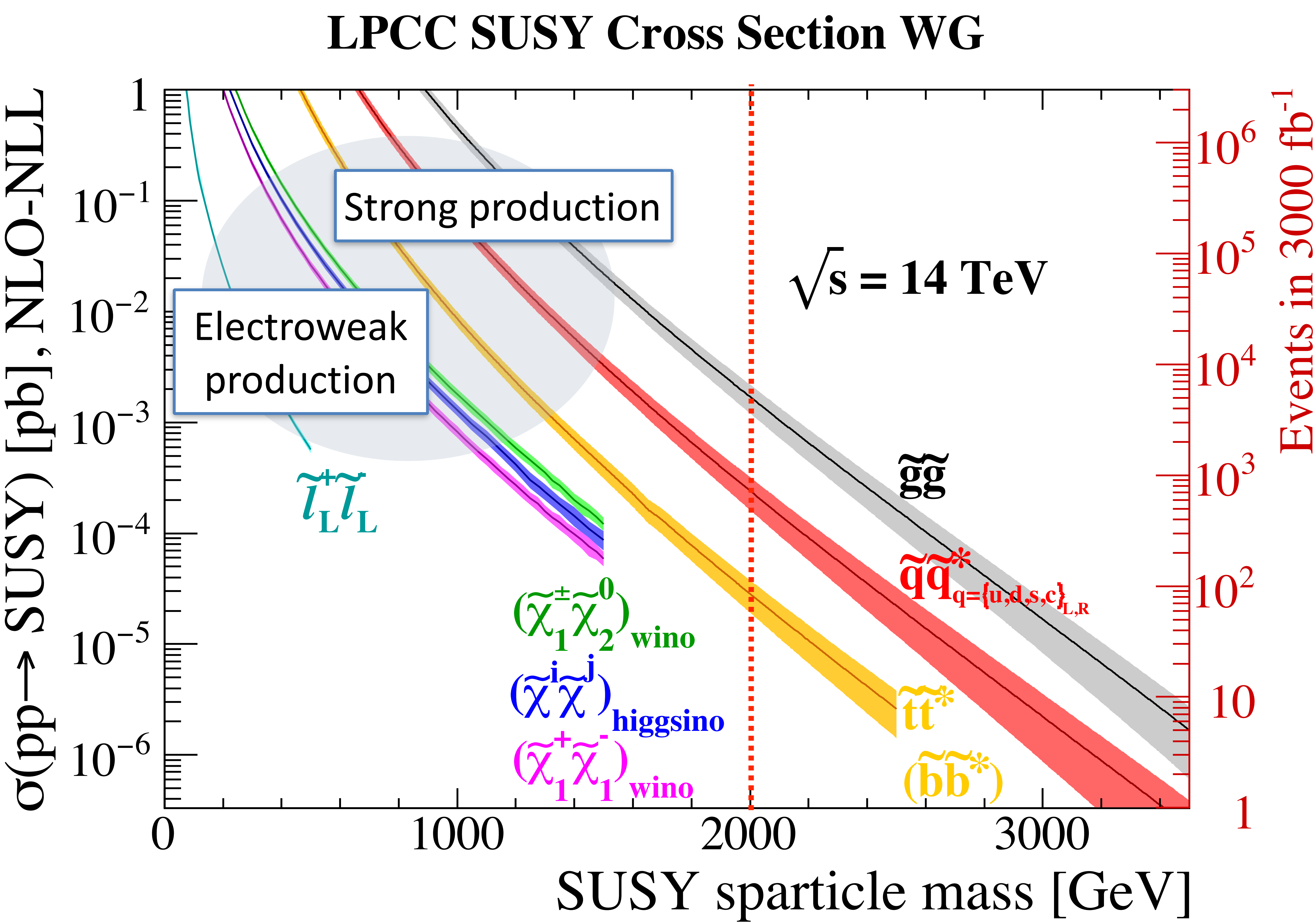
While natural SUSY models are a key focus, we do not restrict ourselves to them.

SUSY Production Cross Sections



https://twiki.cern.ch/twiki/bin/view/LHCPhysics arXiv:1407.5066

SUSY Production Cross Sections



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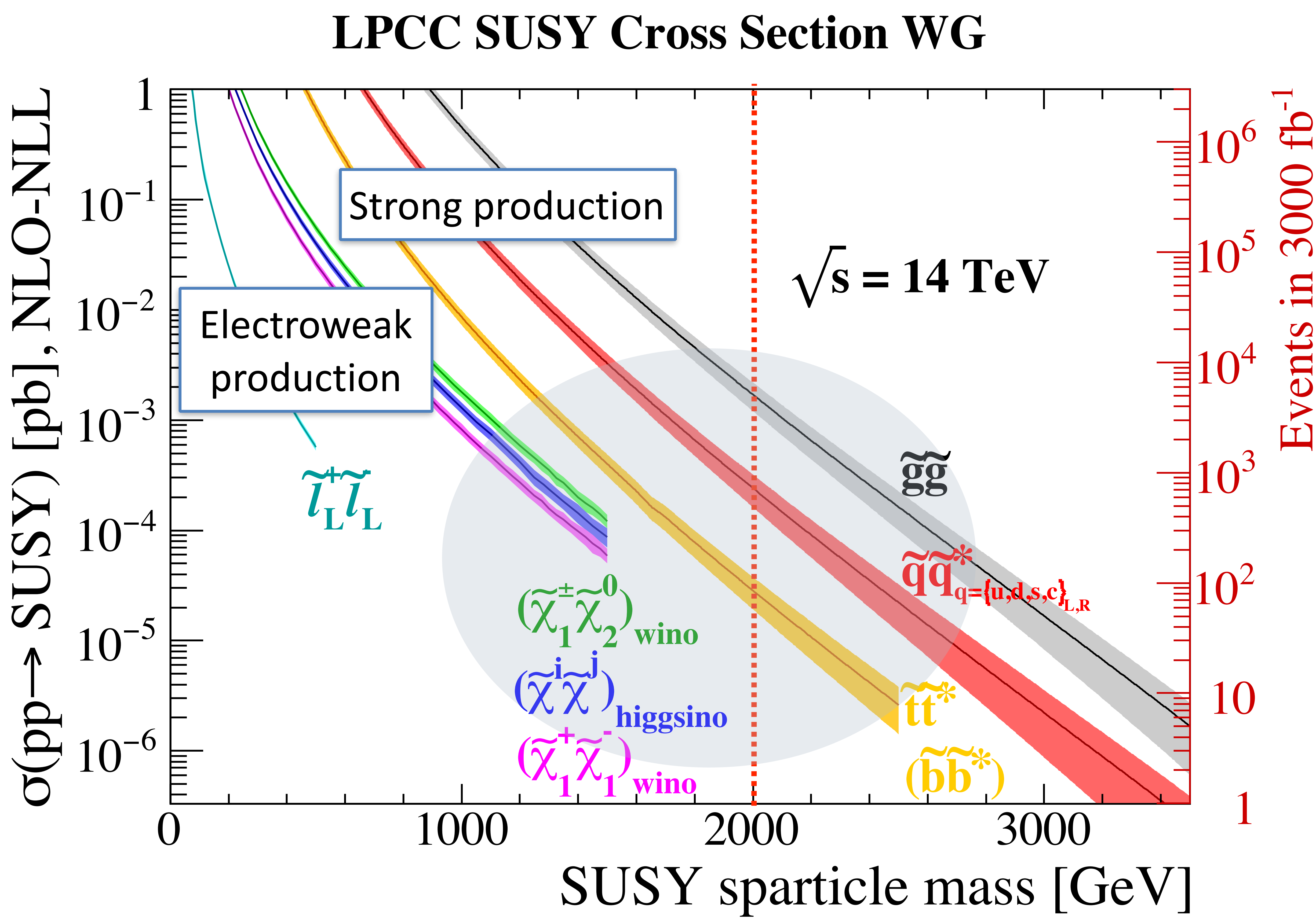
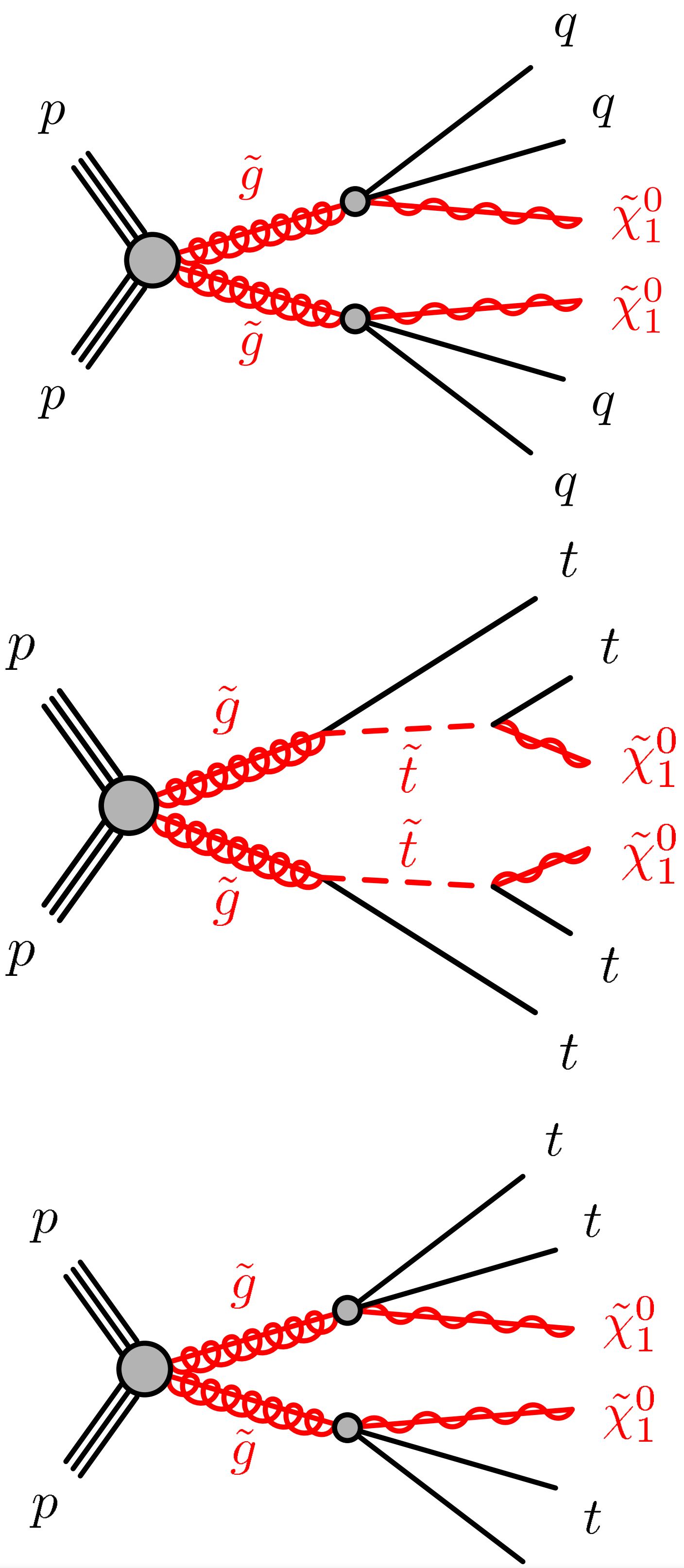
SUSY Production Cross Sections

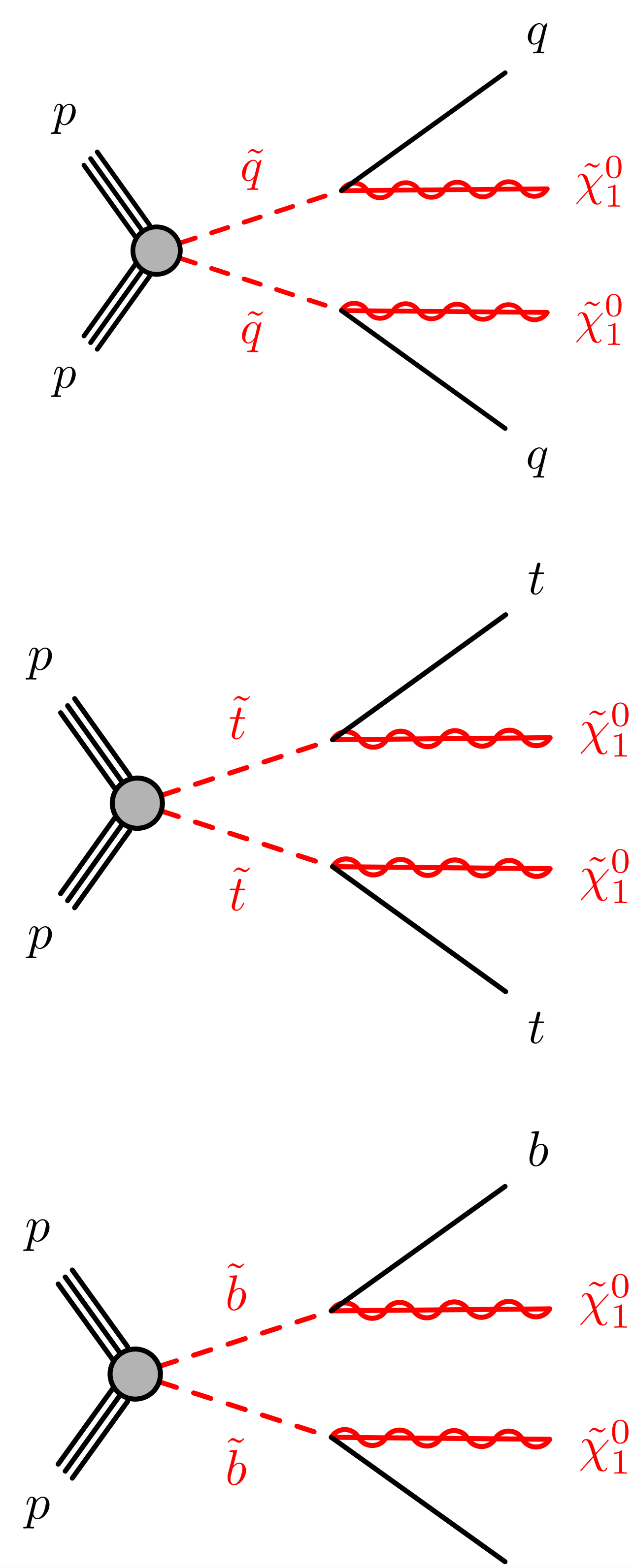


Simplified models for interpretation of search results

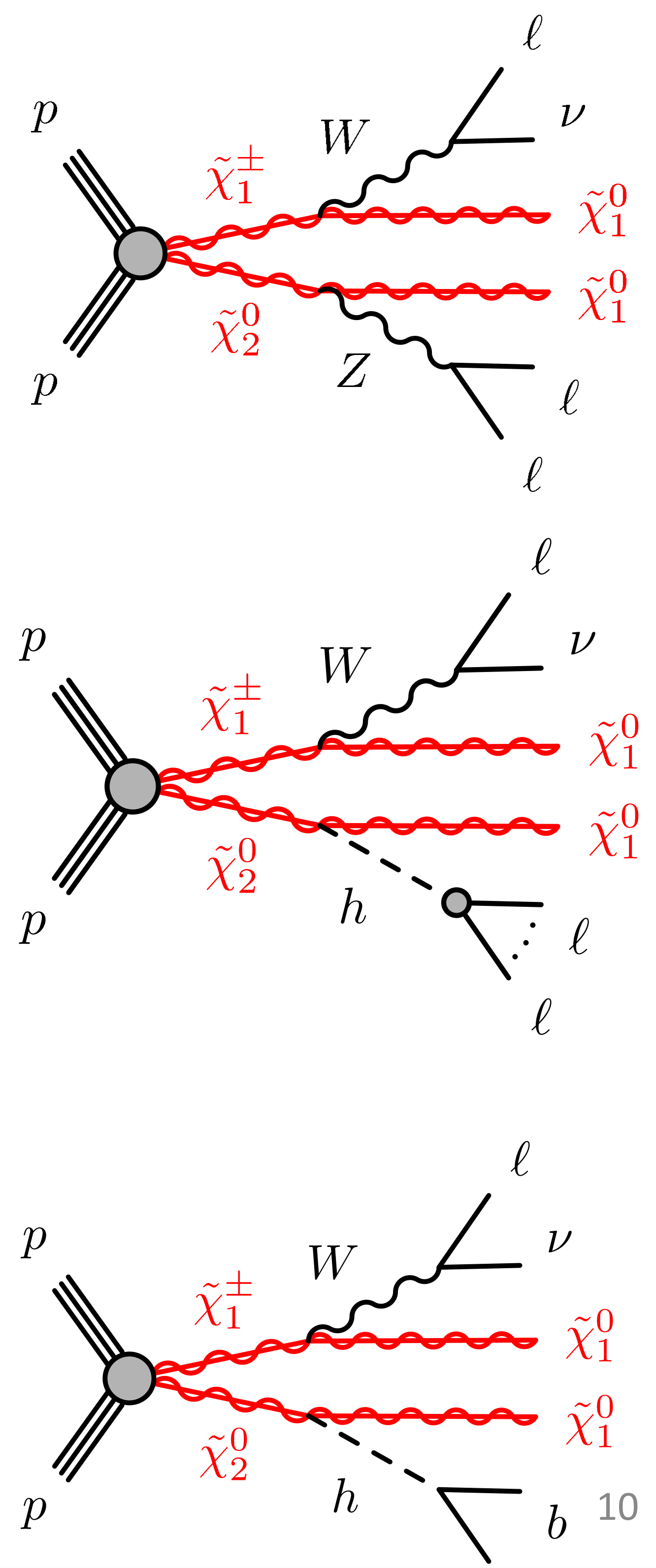
Strong production of gluinos



Strong production of squarks



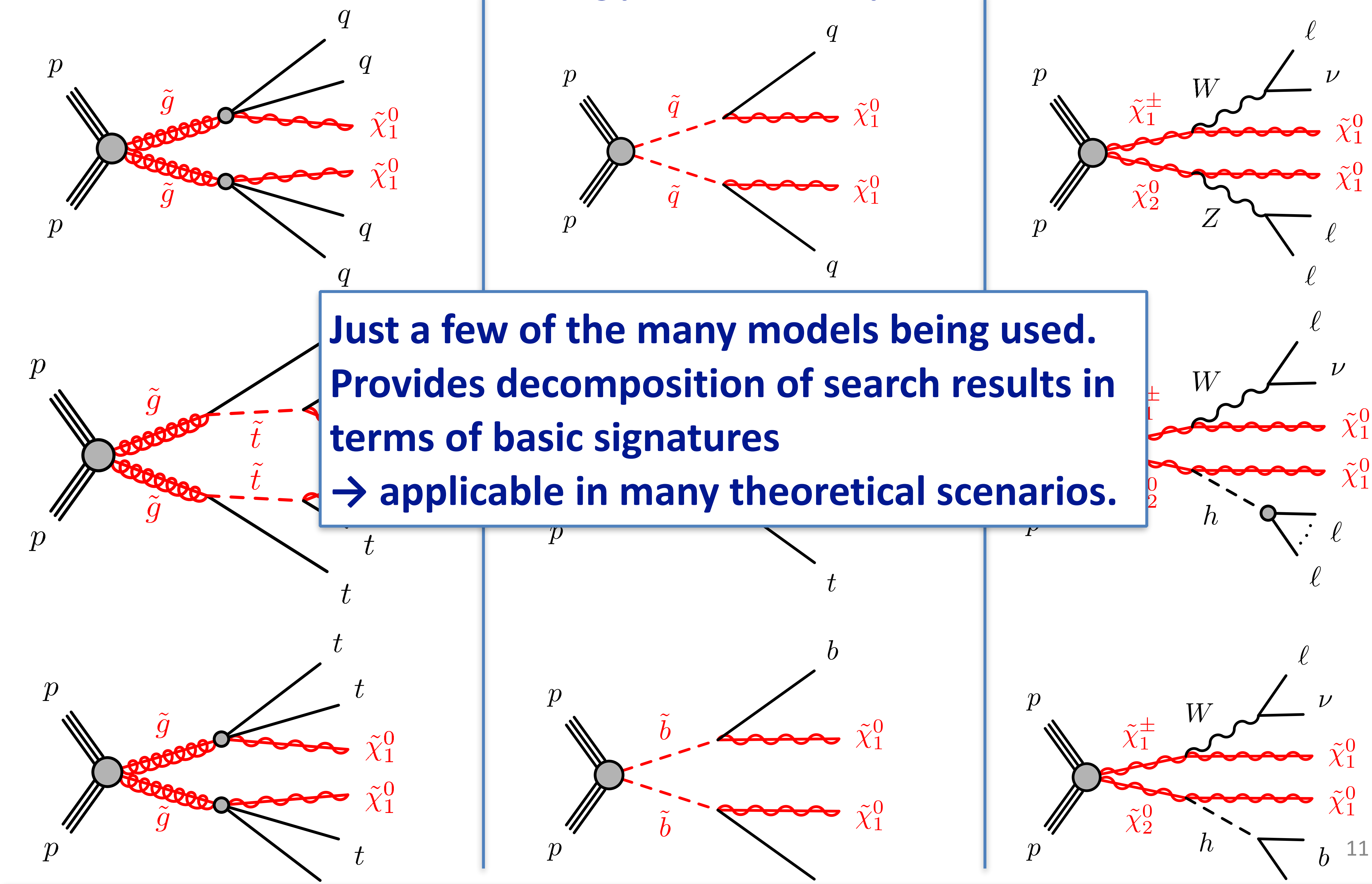
Electroweak Production



Avoids the SUSY *"curse of many parameters"*: in each case, the number of mass parameters is just 2-3.

Simplified models for interpretation of search results

Strong production of gluinos | **Strong production of squarks** | **Electroweak Production**



Just a few of the many models being used.
Provides decomposition of search results in terms of basic signatures
→ applicable in many theoretical scenarios.

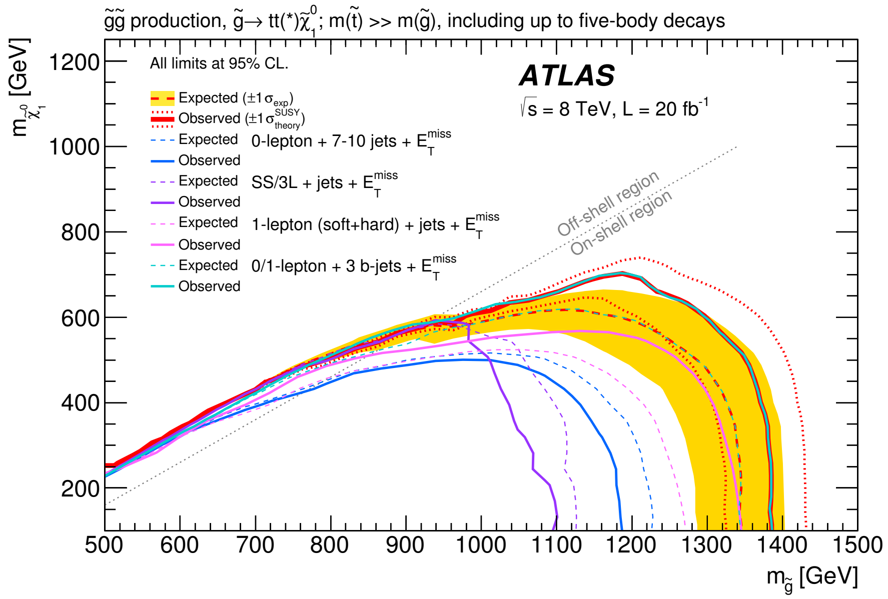
Avoids the "curse of many parameters": in each case, the number of mass parameters is just 2-3.

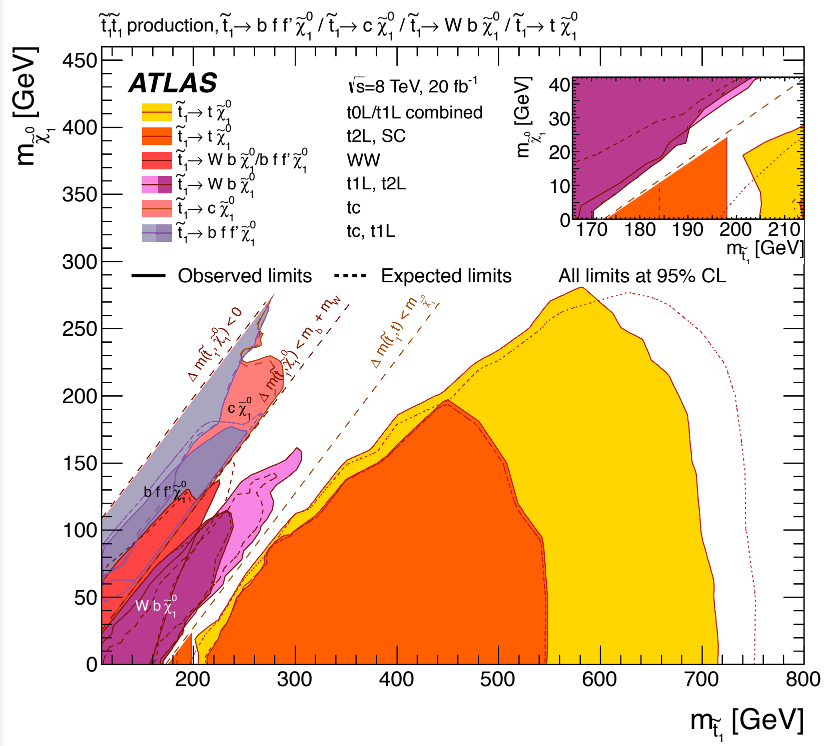
SUSY searches: where are we now?

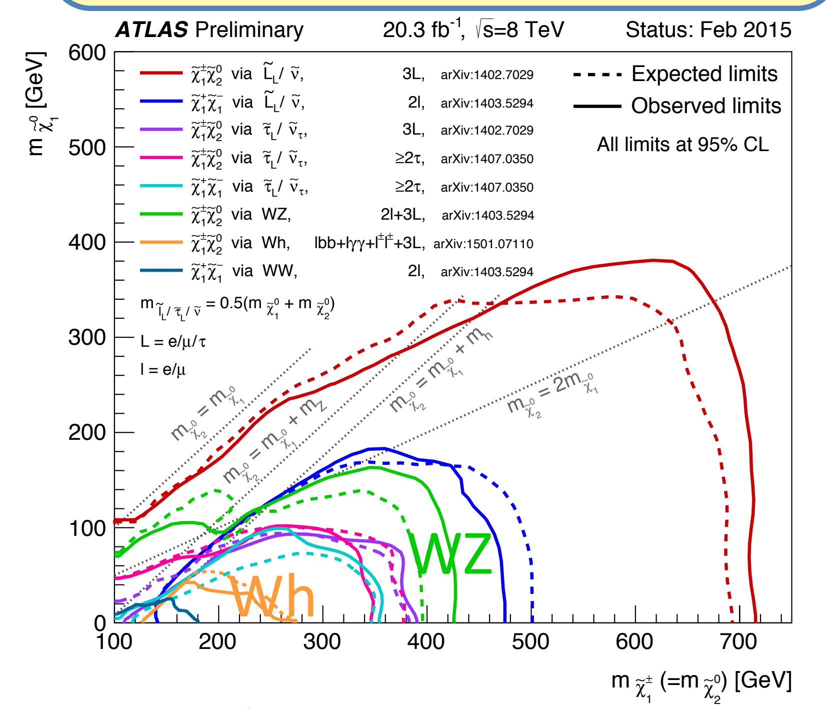
$$M(\tilde{g}) > 1.35\ \mathrm{TeV}$$
$$\text{for } \tilde{g} \rightarrow \tilde{t}\bar{t};\ B(\tilde{t} \rightarrow t\tilde{\chi}_1^0) = 1$$
$$\text{and small } M(\tilde{\chi}_1^0)$$

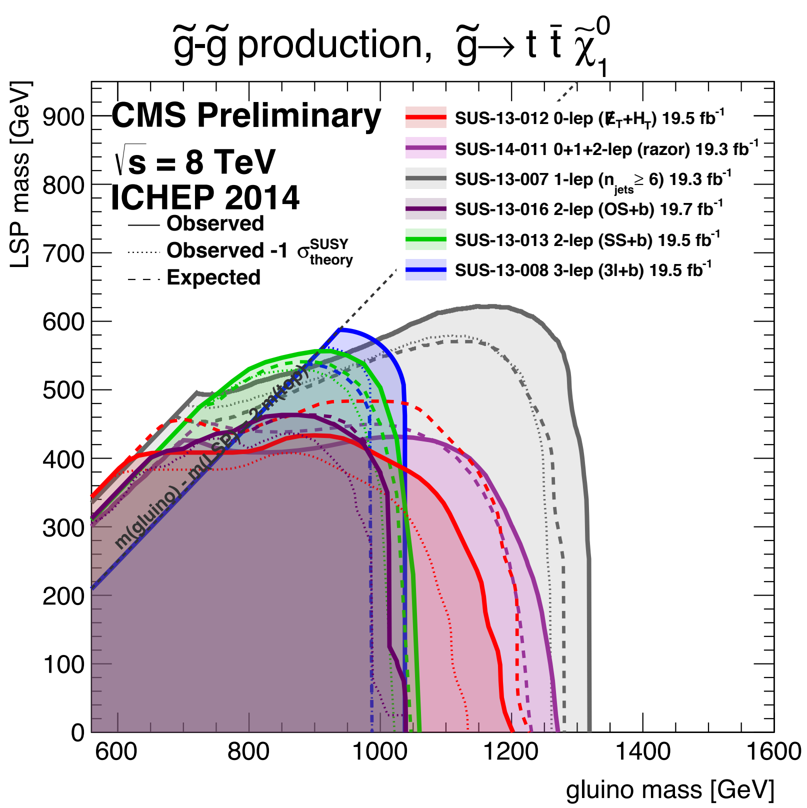
$$M(\tilde{t}) > 750\ \mathrm{GeV}$$
$$\text{for } B(\tilde{t} \rightarrow t\tilde{\chi}_1^0) = 1$$
$$\text{and small } M(\tilde{\chi}_1^0)$$

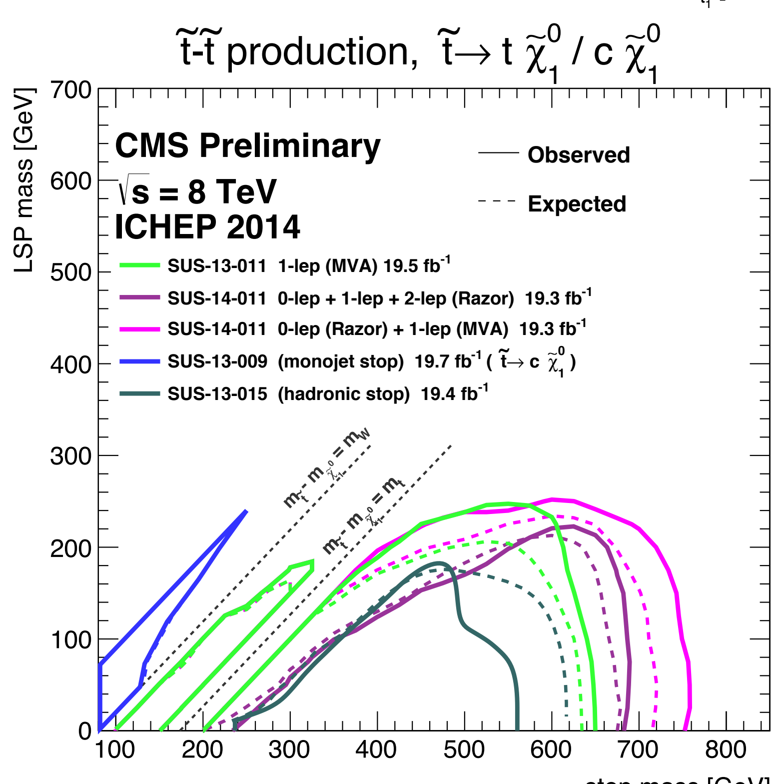
$$M(\tilde{\chi}_1^\pm) = M(\tilde{\chi}_2^0) > 420\ \mathrm{GeV}$$
$$\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow W^\pm\tilde{\chi}_1^0$$
$$M(\tilde{\chi}_1^\pm) = M(\tilde{\chi}_2^0) > 250\ \mathrm{GeV}$$
$$\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow W^\pm\tilde{\chi}_1^0$$

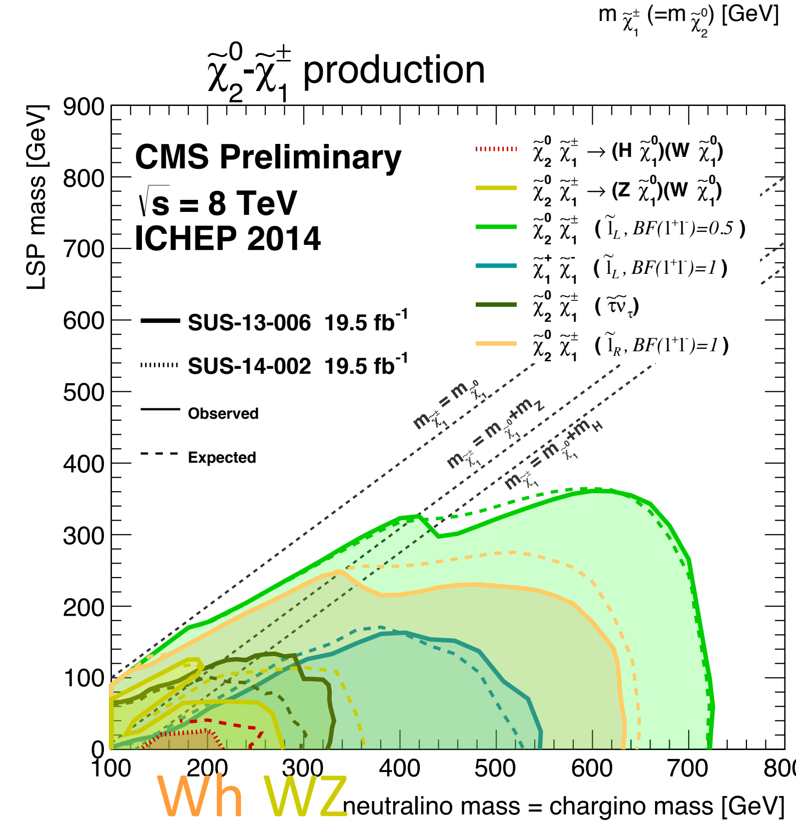




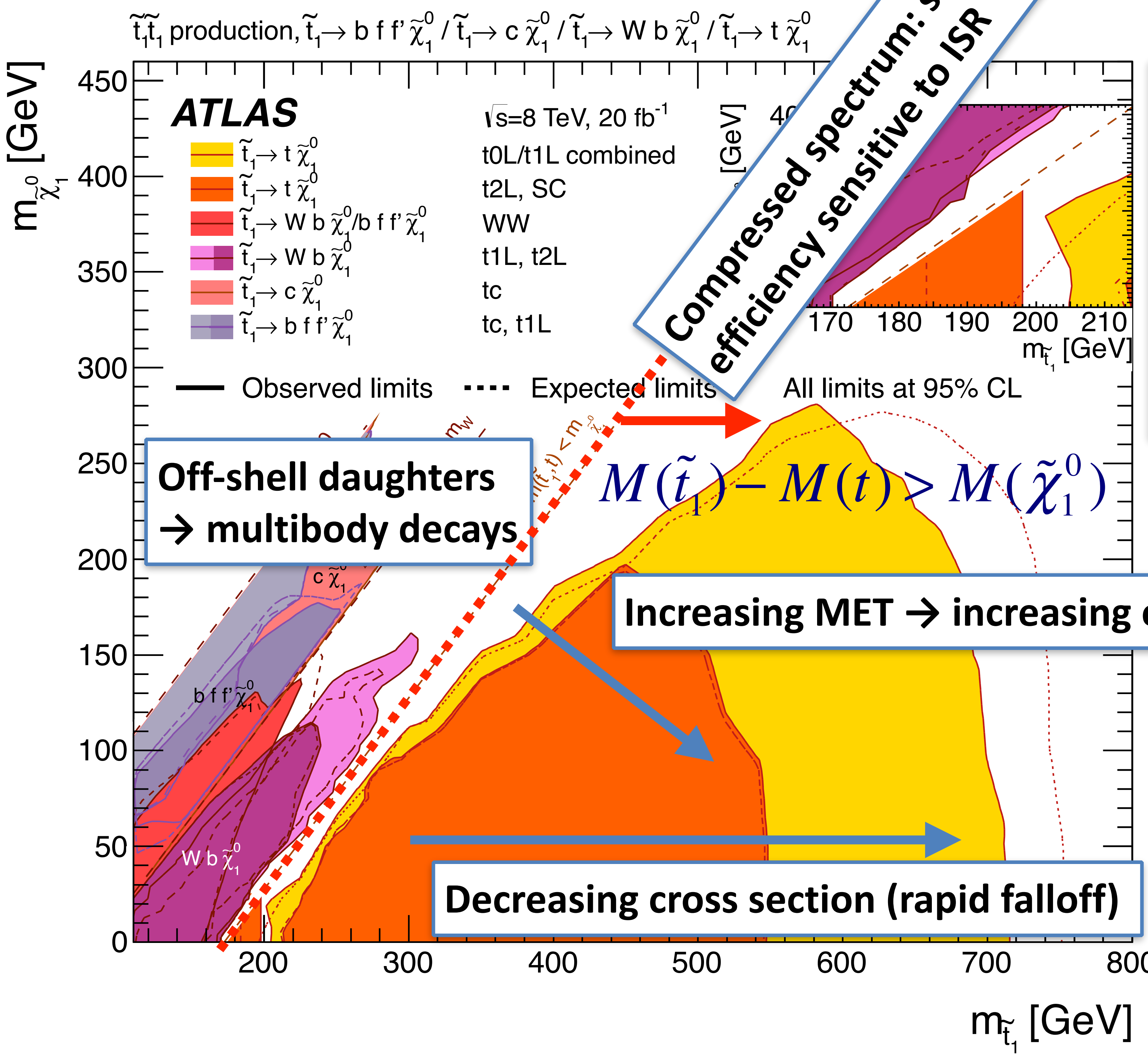








How to read a simplified model exclusion plot



Compressed spectrum: signal efficiency sensitive to ISR

Limit extends to m($\tilde{t}_1$)≈750 GeV for low m($\tilde{\chi}_1^0$).

No limit on m($\tilde{t}_1$) for m($\tilde{\chi}_1^0$)≳275 GeV.

Off-shell daughters → multibody decays

$$M(\tilde{t}_1) - M(t) > M(\tilde{\chi}_1^0)$$

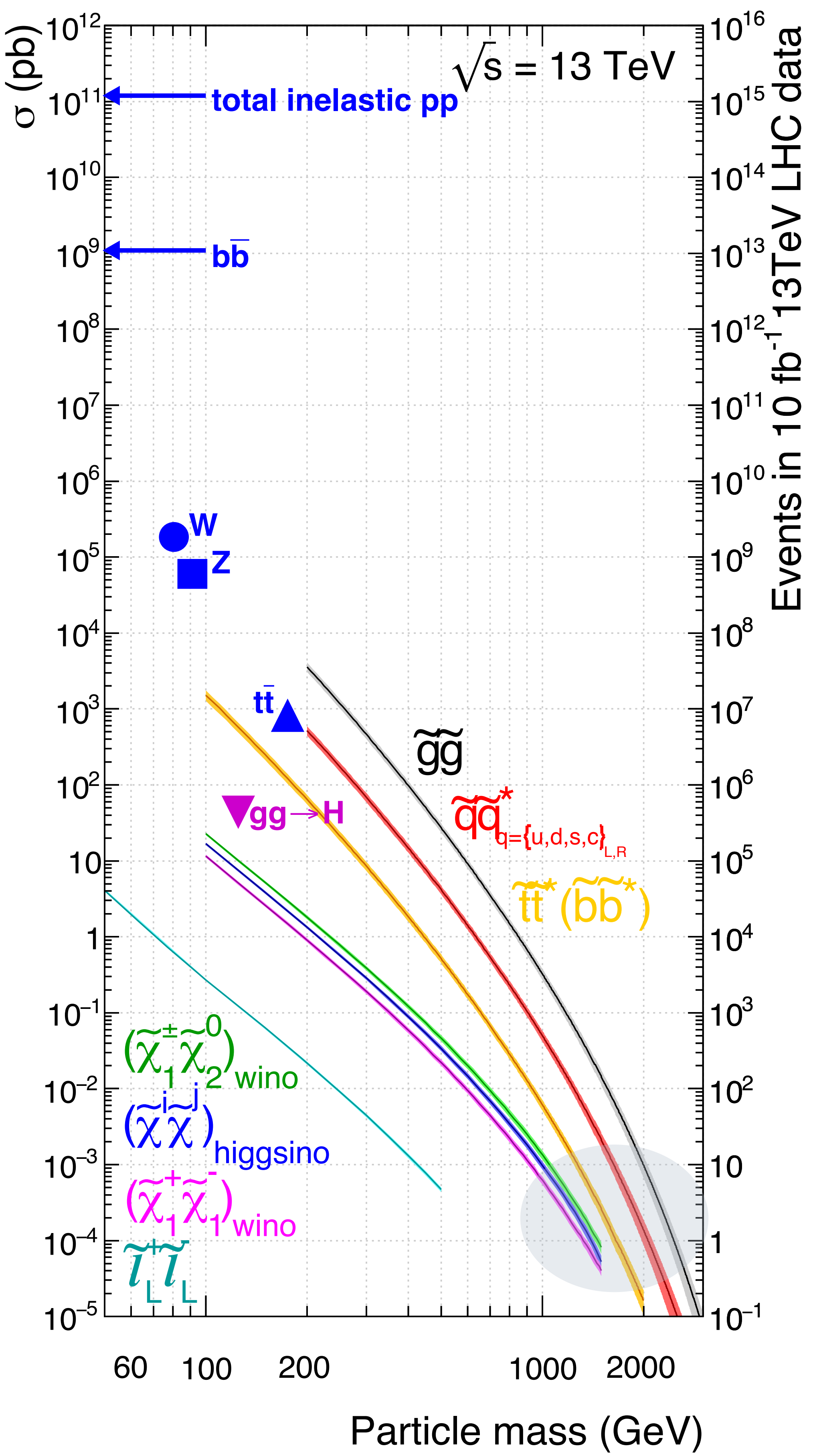
Increasing MET → increasing efficiency

Decreasing cross section (rapid falloff)

Mass of LSP (neutralino) → mass splitting → MET → sig. efficiency

Mass of produced particle - determines cross section

Remarks on backgrounds and methods



- Have entered the territory where SUSY cross sections are much less than those of the dominant SM backgrounds.
- Very tight kinematic cuts; operate on extreme tails of SM distributions such as E_T^{miss}. "Weak" signatures (no peaks).
- Most HL-LHC simulations use parametrized MC with background uncertainties either guessed (based on actual measurements with 8 TeV data), or simply assumed.
- Studies generally use simple methods; best to regard the results as *indicative*.
- Compare reach for 300 fb^{-1} & 3000 fb^{-1}.

ATLAS: strong production sensitivity at 3000 fb^{-1}

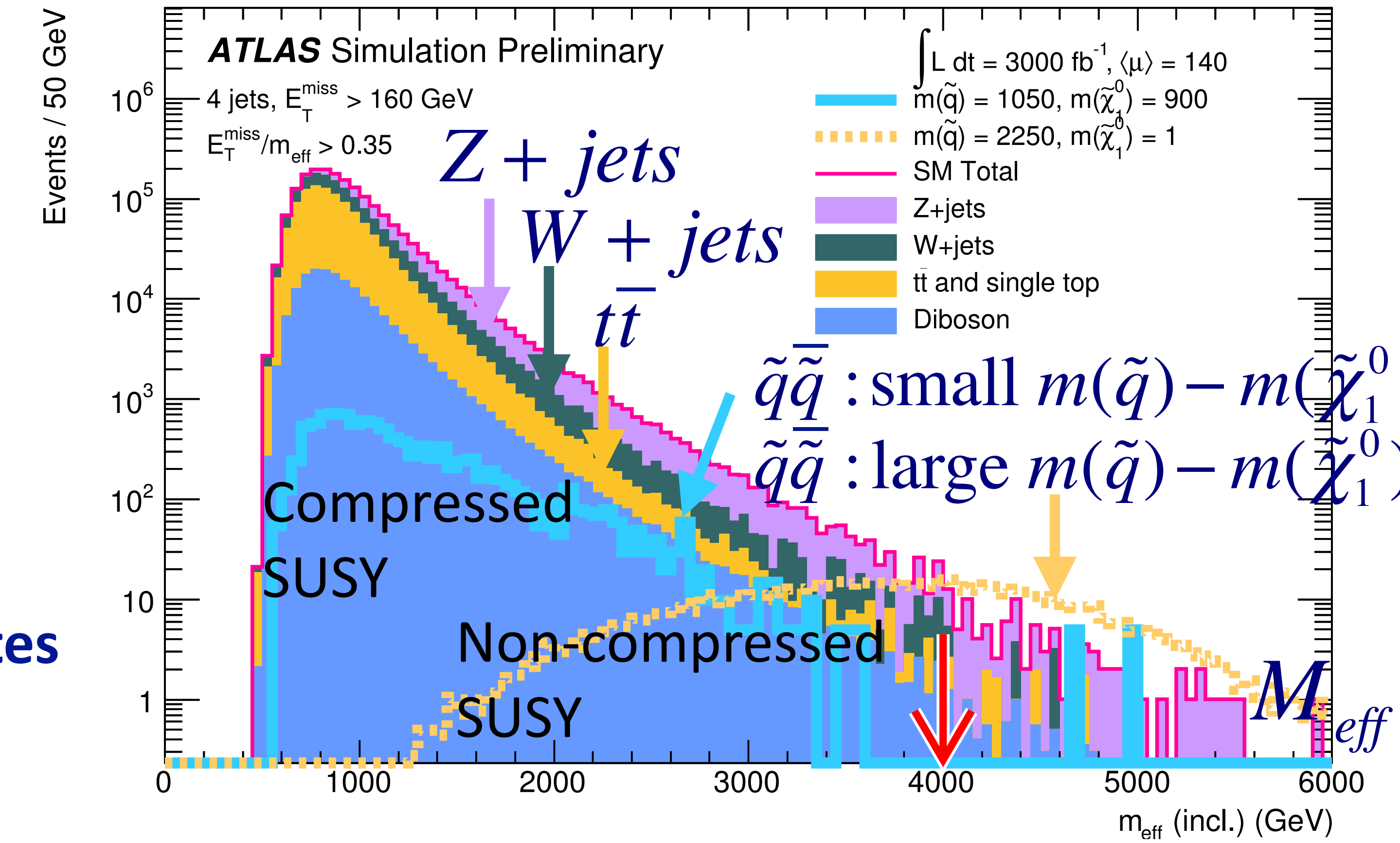
Inclusive all-hadronic analysis
Njets ≥ 2-6, no leptons, m_{eff}, E_T^{miss}
ATL-PHYS-PUB-2014-010

$$M_{eff} = E_T^{miss} + \sum_{jets} |\vec{p}_T|$$

Sensitive to both

$\tilde{q}\bar{\tilde{q}}$, $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ **1st+2nd gen ⇒ 8 states**

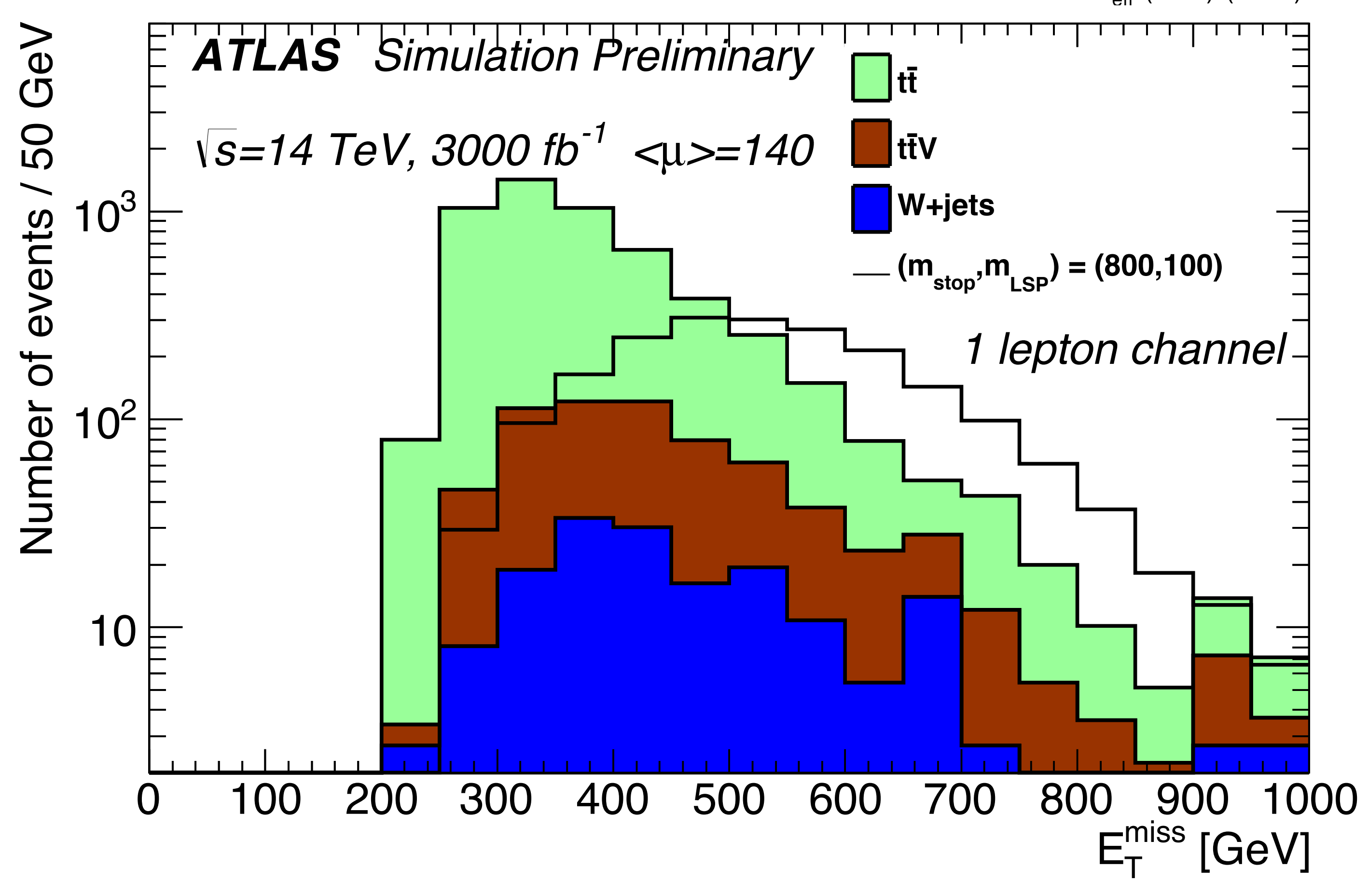
$\tilde{g}\tilde{g}$, $\tilde{g} \rightarrow \tilde{q}\bar{q} \rightarrow q\bar{q}\tilde{\chi}_1^0$



0 lepton + ≥6 jets + ≥ 2 b-tag + E_T^{miss}
1 lepton + ≥4 jets + ≥ 1 b-tag + E_T^{miss}
ATL-PHYS-PUB-2013-011

$\tilde{t}\bar{\tilde{t}}$, $\tilde{t} \rightarrow t\tilde{\chi}_1^0$

- Naturalness: expect $m(\tilde{t}) \lesssim$1 TeV.
- $t\bar{t}$ is dominant background; b-tagging suppresses Z+jets, W+jets.



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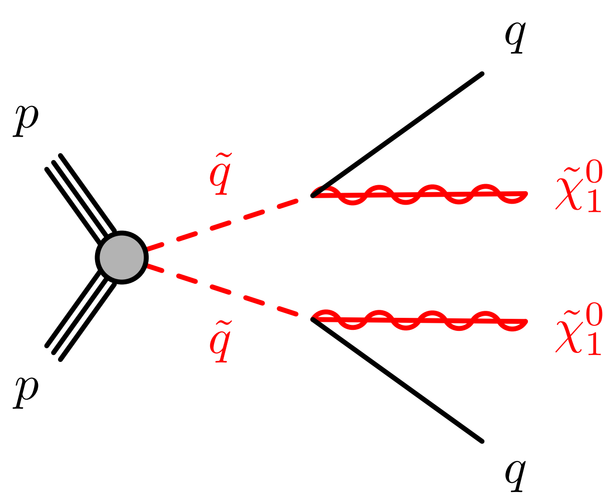
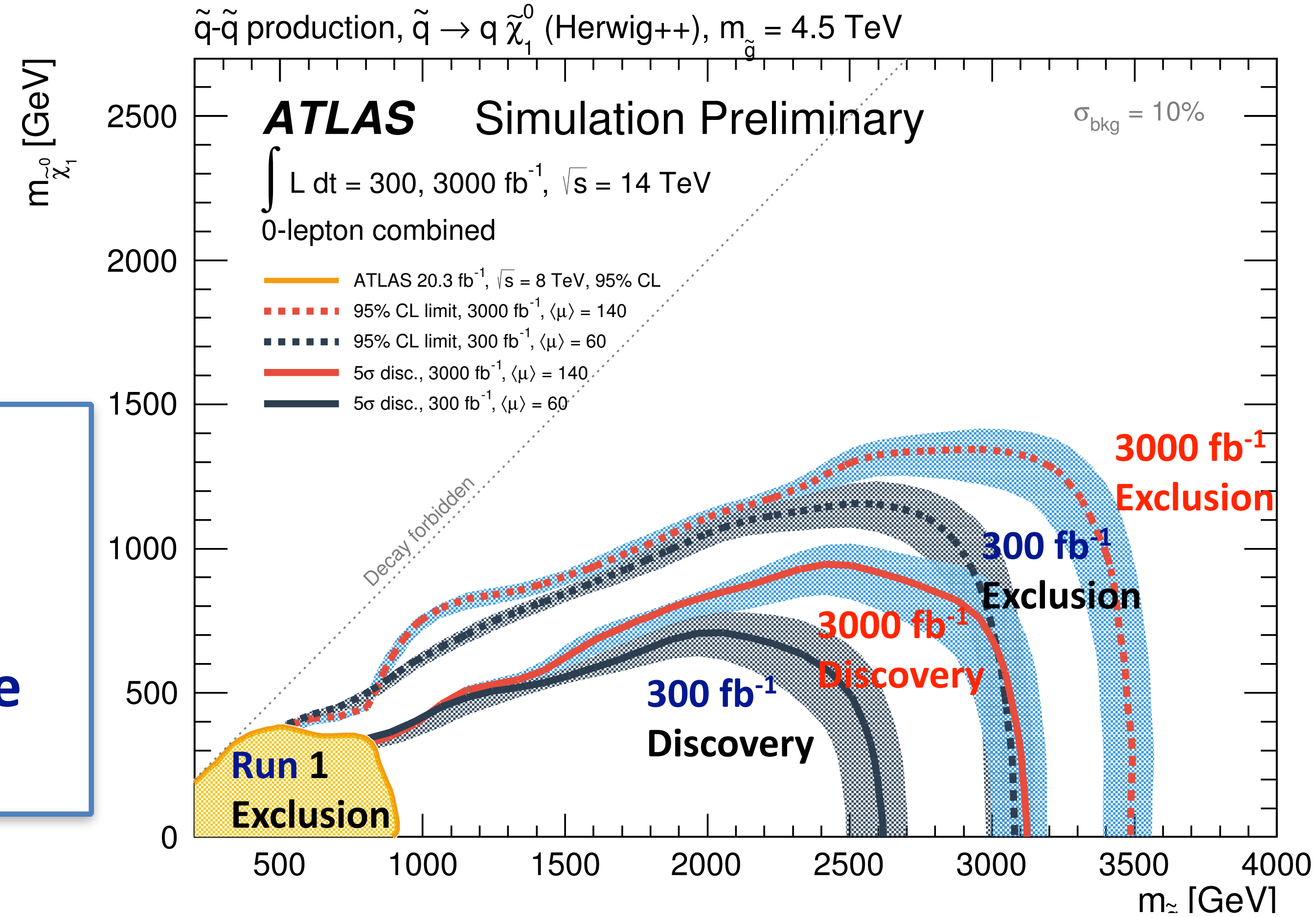
ATL-PHYS-PUB-2014-010



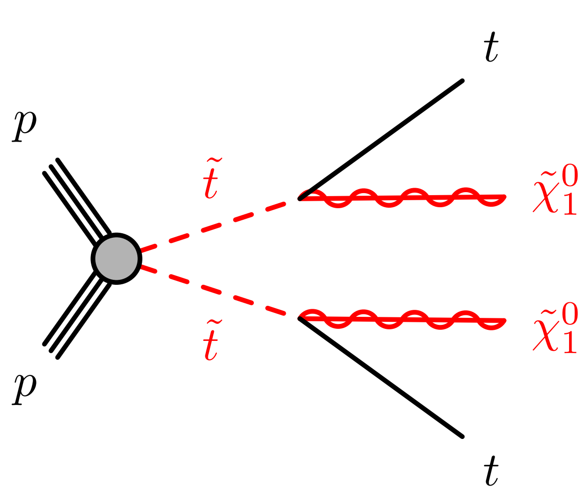
Discovery sensitivity: up to ~3.1 TeV.
Excl.: up to 3.5 TeV
Also pushing up range for LSP!



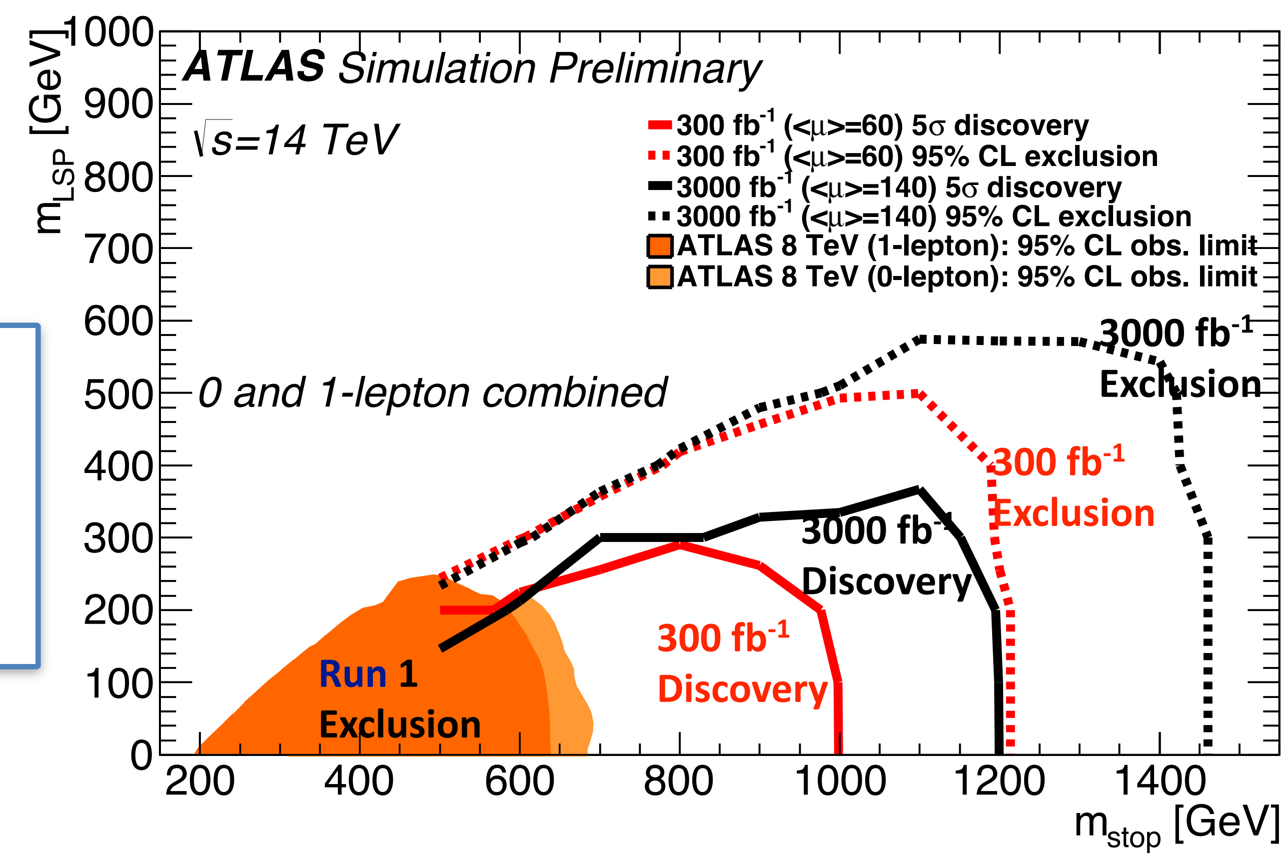
0 lepton + ≥6 jets + ≥ 2 b-tag + E_T^{miss}

1 lepton + ≥4 jets + ≥ 1 b-tag + E_T^{miss}

ATL-PHYS-PUB-2013-011



Discovery sensitivity (combined 0, 1 lepton): up to ~1.2 TeV.
Excl. : up to ~1.45 TeV



ATLAS: $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$ with $\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^{0}$, $\tilde{\chi}_2^{0} \rightarrow (h,Z)\tilde{\chi}_1^{0}$

Search for WZ + E_T^{miss}

3 leptons + m(Z) + E_T^{miss}+ b-jet veto + mT cut

Dominant SM background: WZ production

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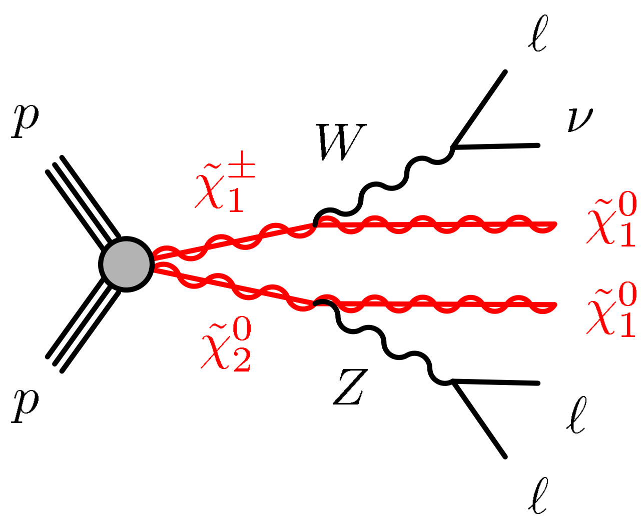
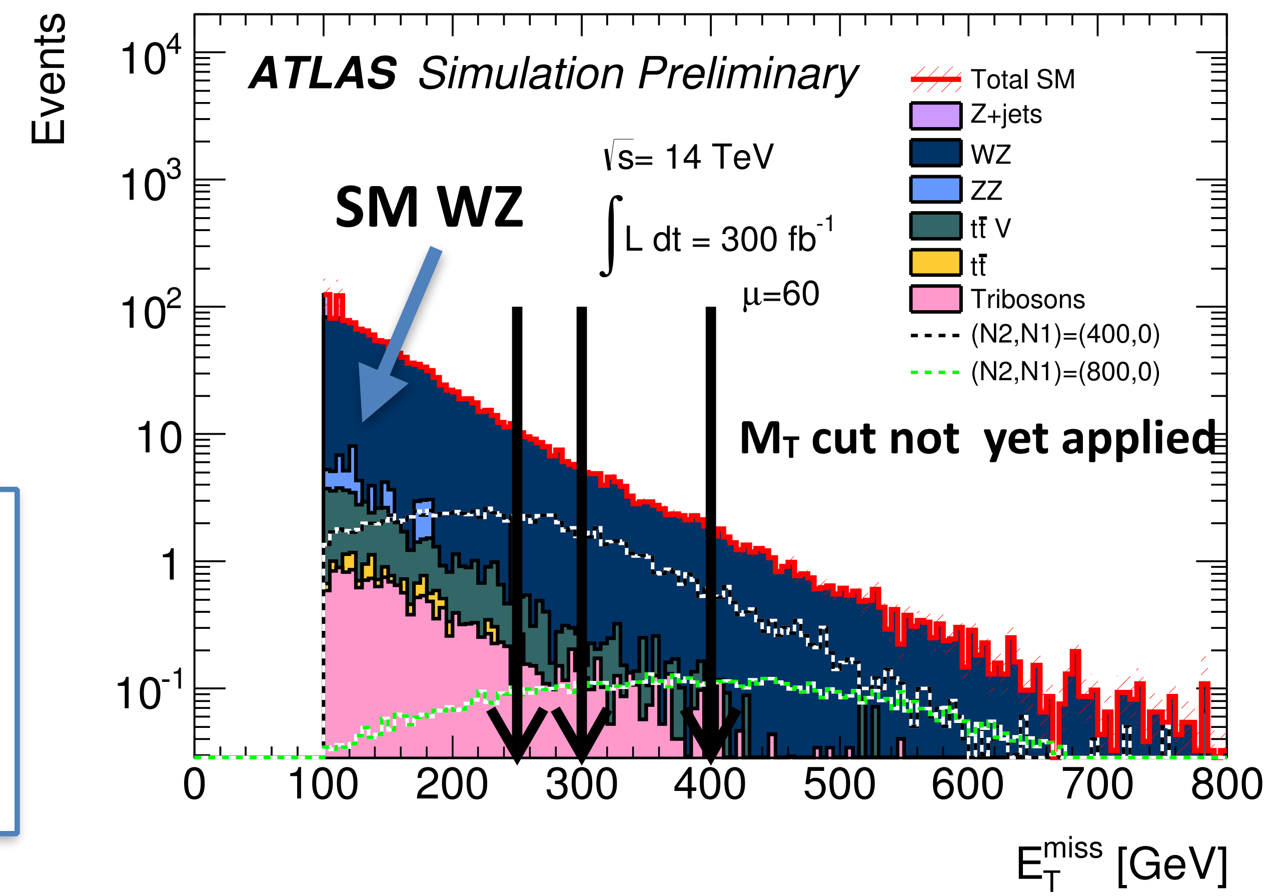


Small cross section but powerful, low-background signature.



Search for Wh(bb) + E_T^{miss}

1 lepton + m(bb) + E_T^{miss} + mT cut + mCT

Dominant SM background: ttbar production

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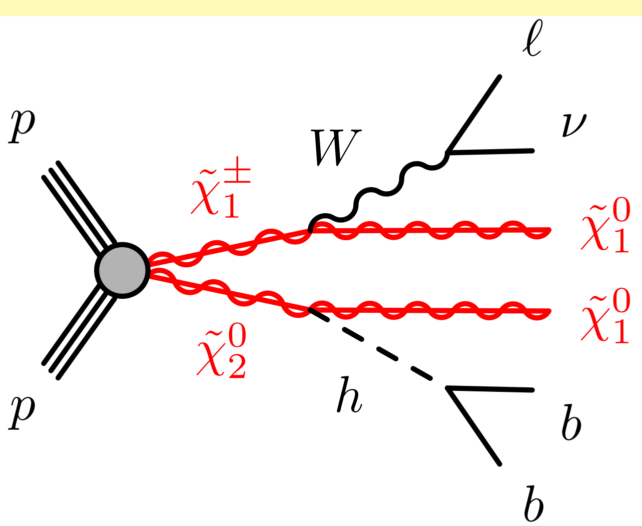
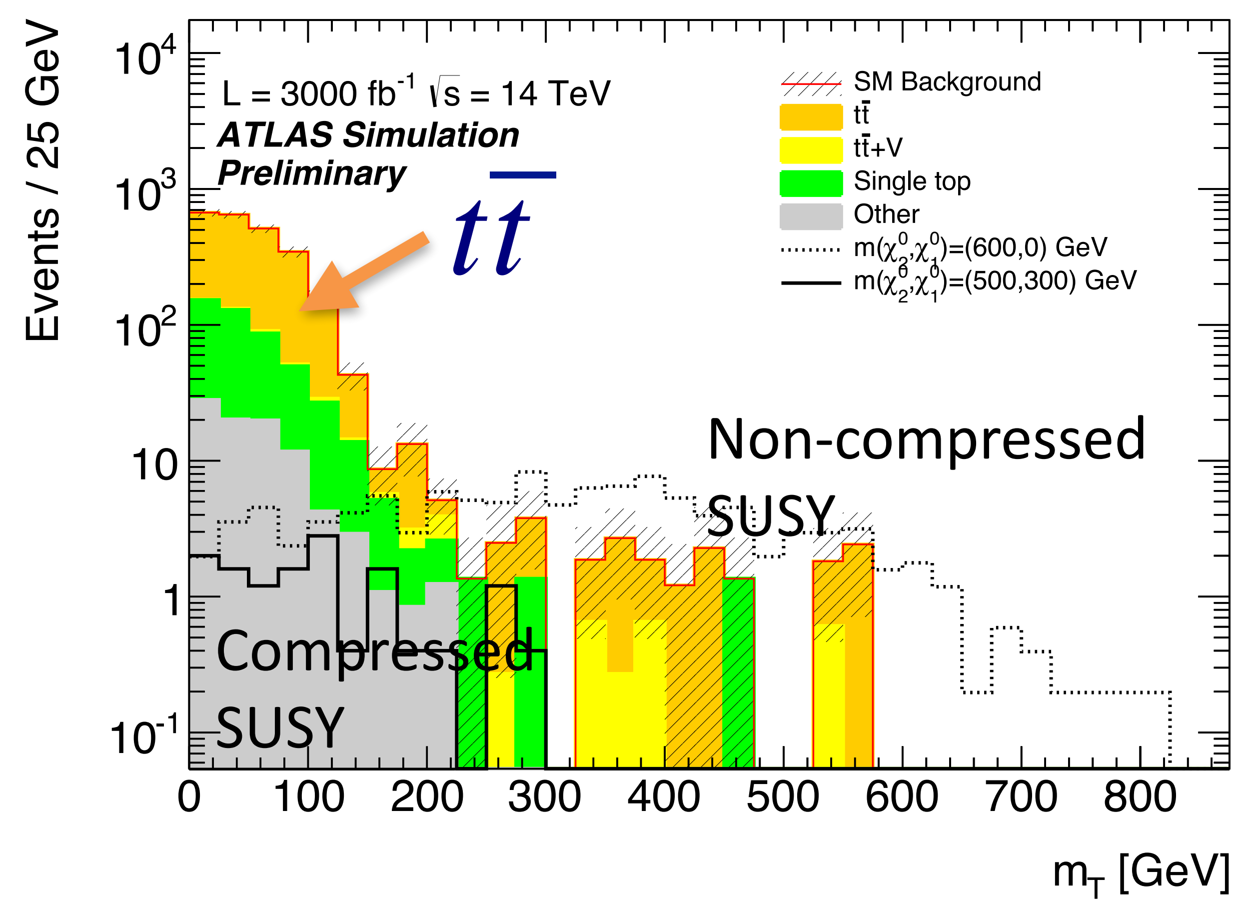


Higgs boson in the signature!



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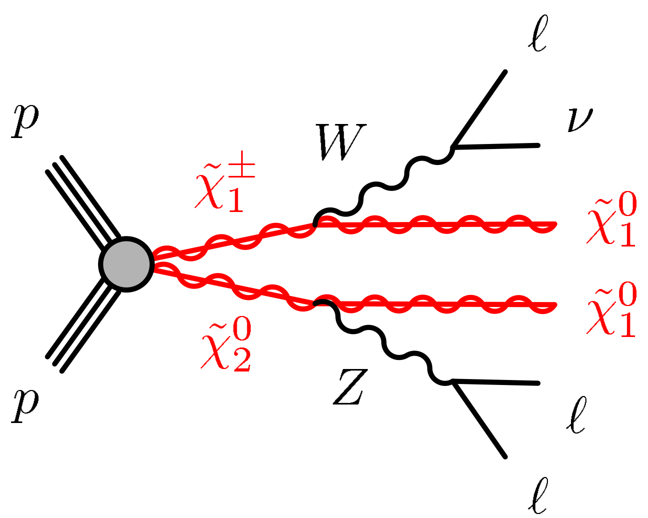
Search for WZ + E_T^{miss}

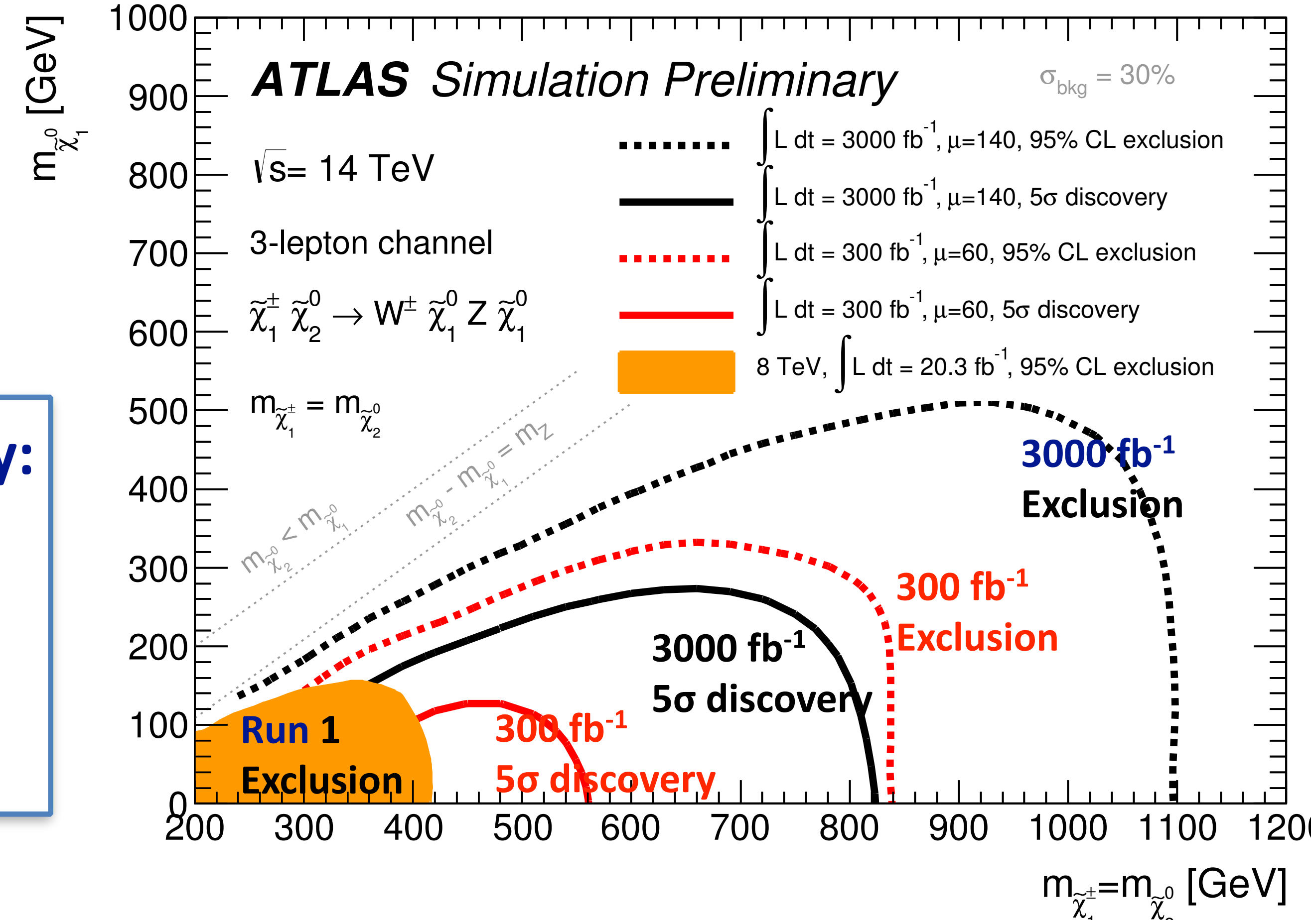
3 leptons + m(Z) + E_T^{miss}+ b-jet veto + mT cut

Dominant SM background: WZ production

ATL-PHYS-PUB-2014-010



Discovery sensitivity: up to ~820 GeV. Assumes Wino production and $m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0)$

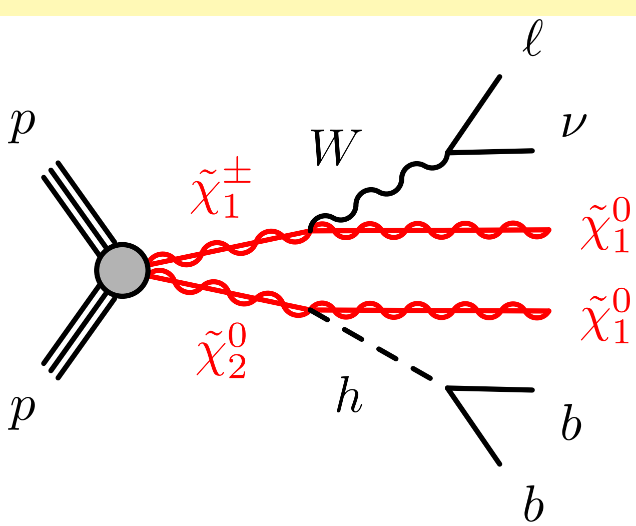


Search for Wh(bb) + E_T^{miss}

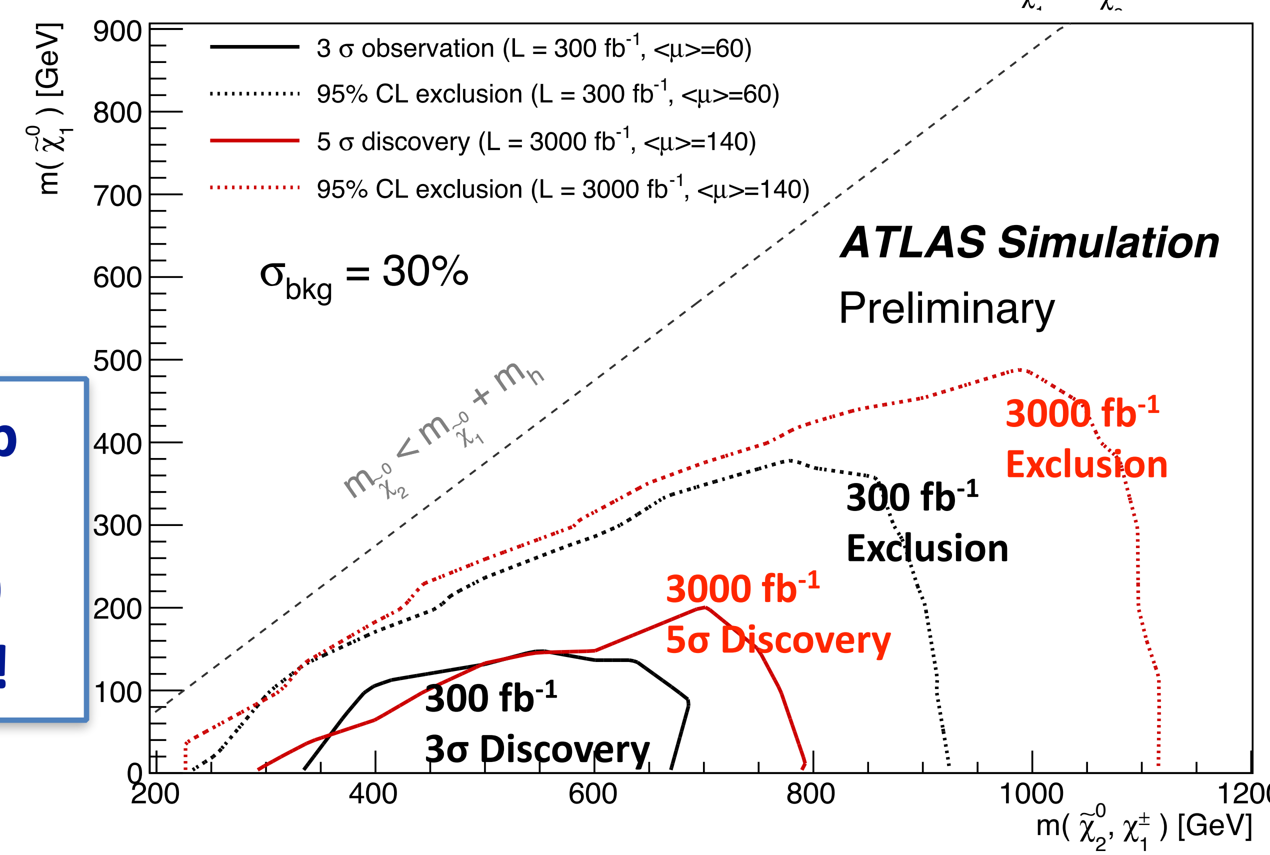
1 lepton + m(bb) + E_T^{miss} + mT cut + mCT

Dominant SM background: ttbar production

ATL-PHYS-PUB-2015-032



Discovery sensitivity: up to 800 GeV with Cut & Count. Increase to ~950 GeV with MVA analysis!



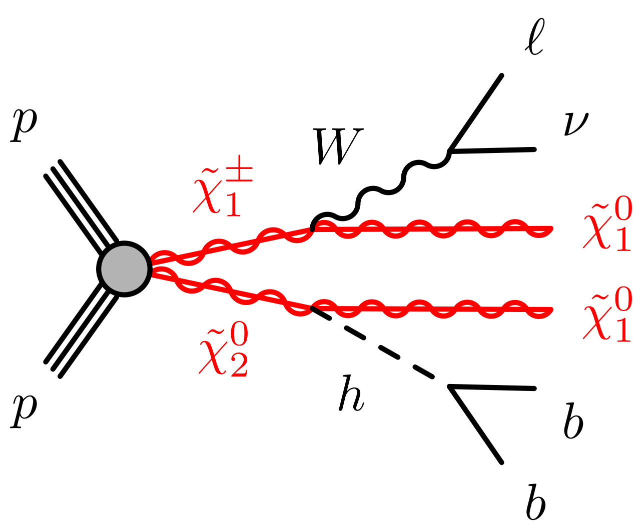
CMS: $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ with $\tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$

Search for Wh(bb) + E_T^{miss}

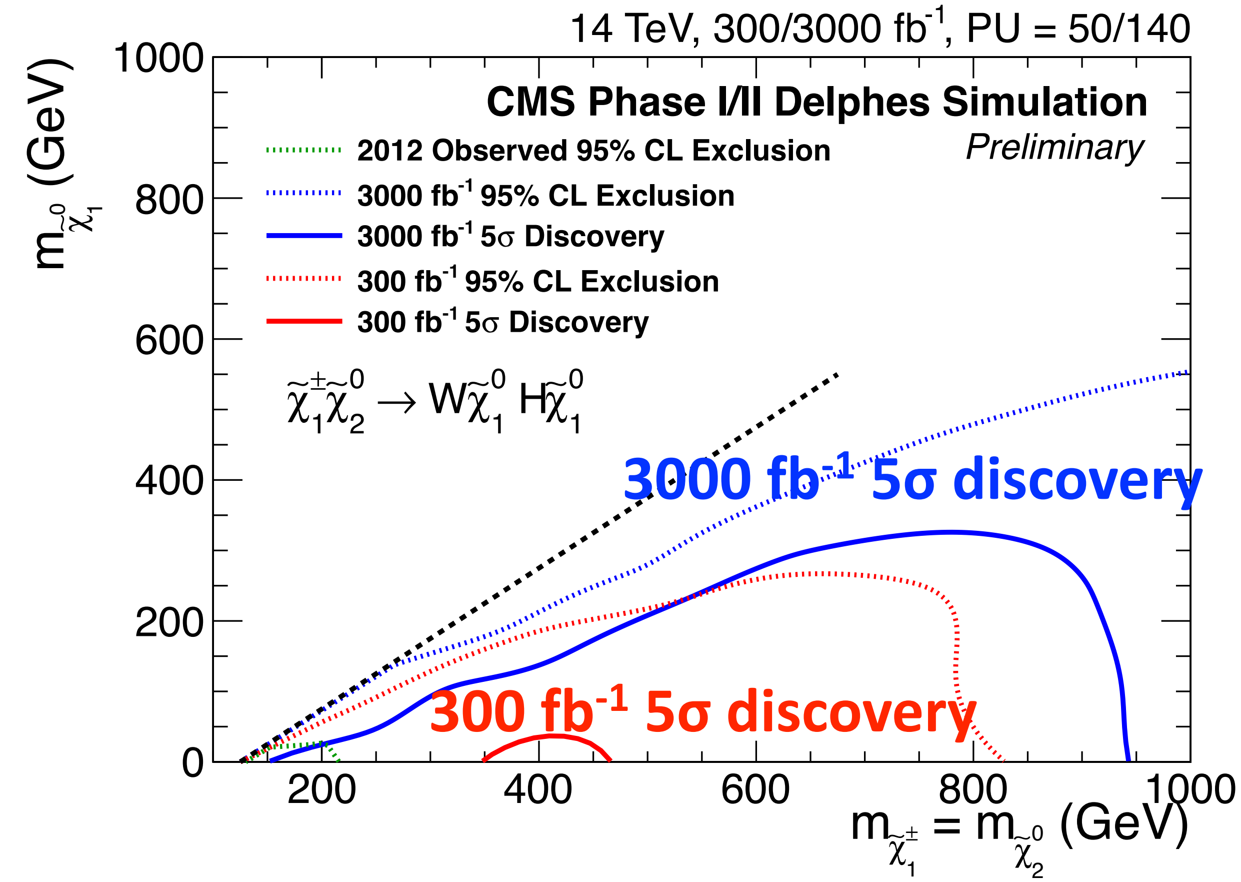
1 lepton + m(bb) + E_T^{miss} + mT cut + mCT

Dominant SM background: ttbar production

CMS-PAS-SUS-14-012



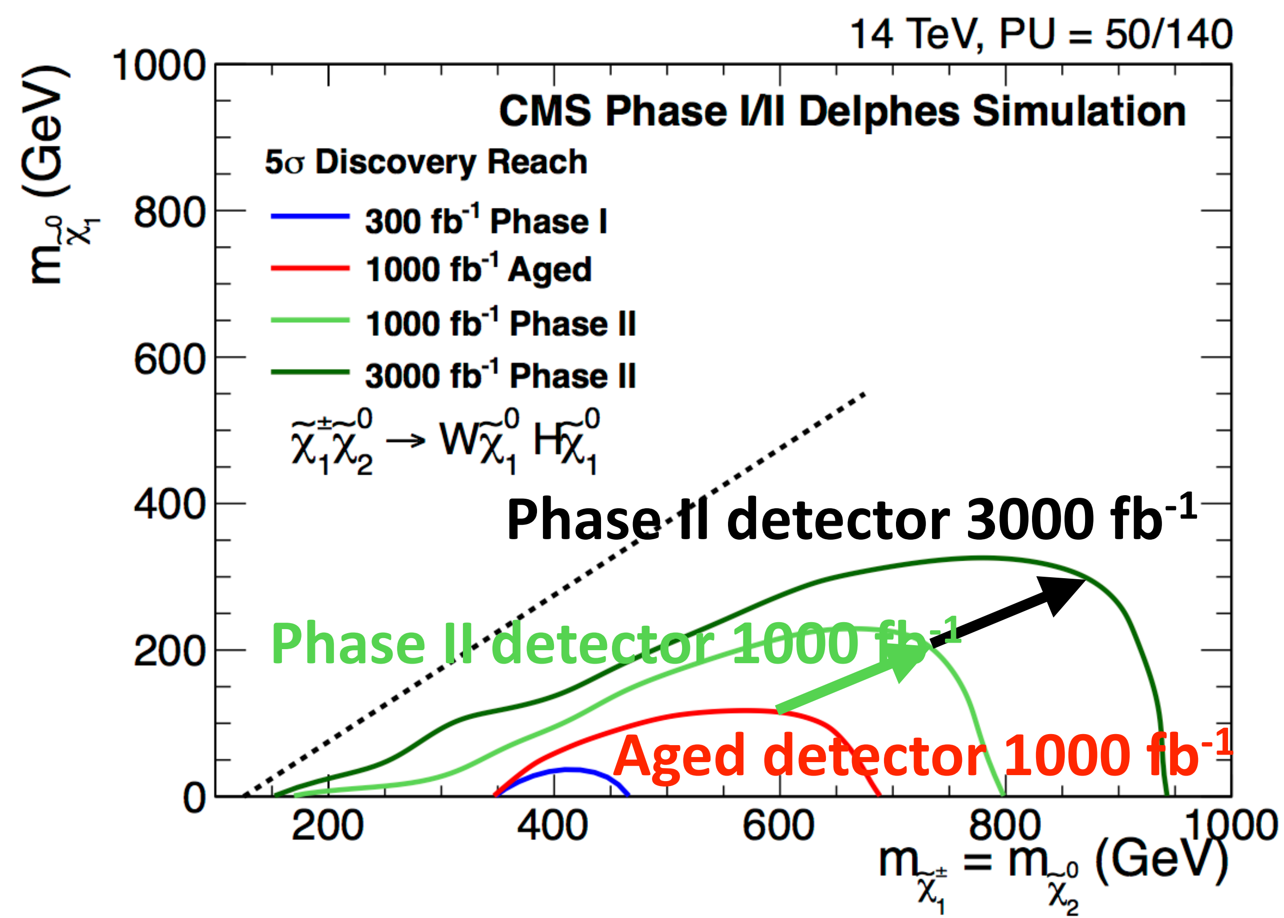
Discovery sensitivity: up to ~950 GeV.



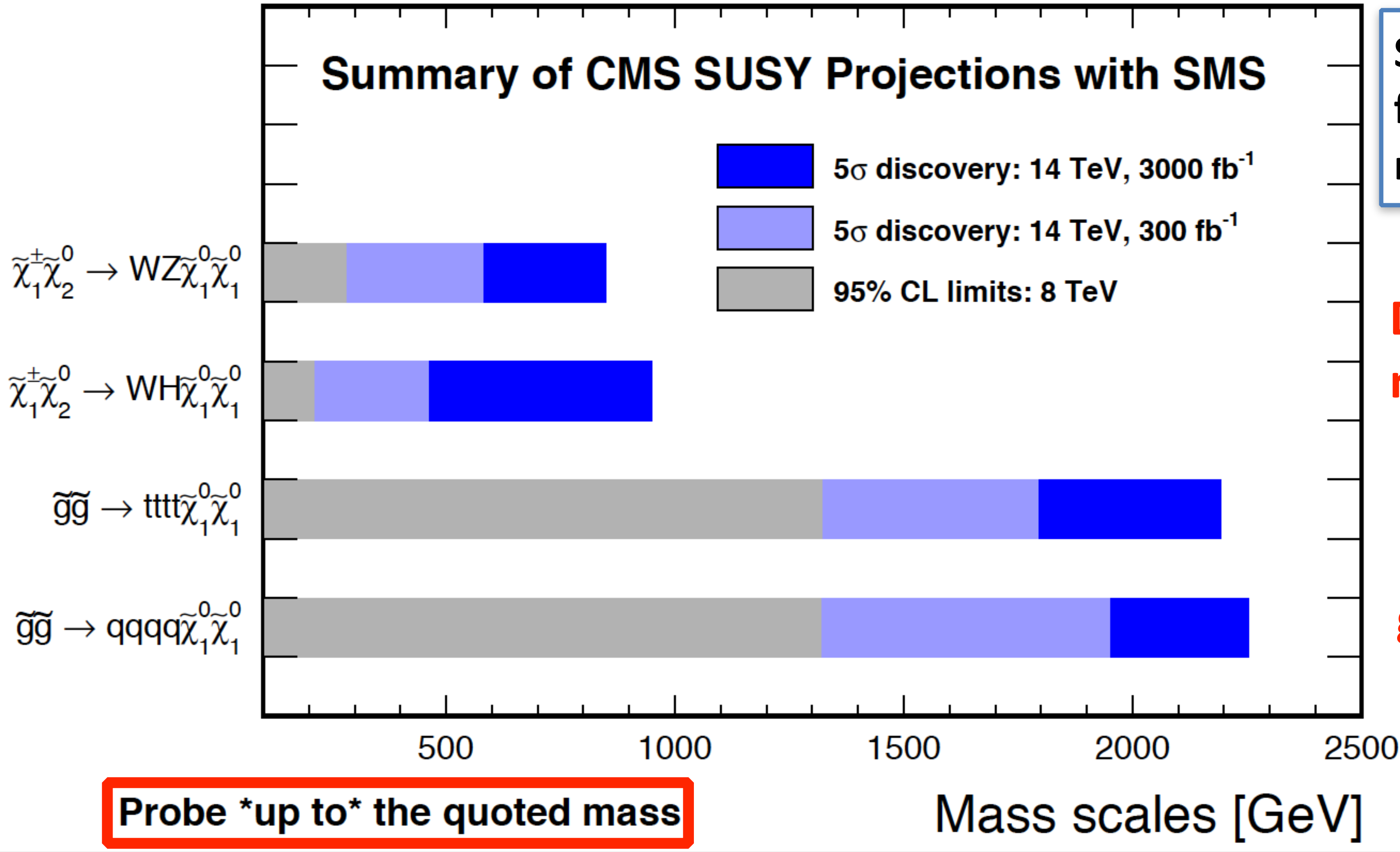
Effect of aged Run 1 detector performance on search for Wh(bb) + E_T^{miss}

Study based on full simulation.

- Emulated aged detector with worse E_T^{miss} resolution (→impact MT), b-tagging efficiency, e/μ efficiency.
- Discovery sensitivity substantially reduced with aged detector.



CMS: discovery reach at 300 fb^{-1} & 3000 fb^{-1}



Probe *up to* the quoted mass

Simplified model framework: single decay mode dominates.

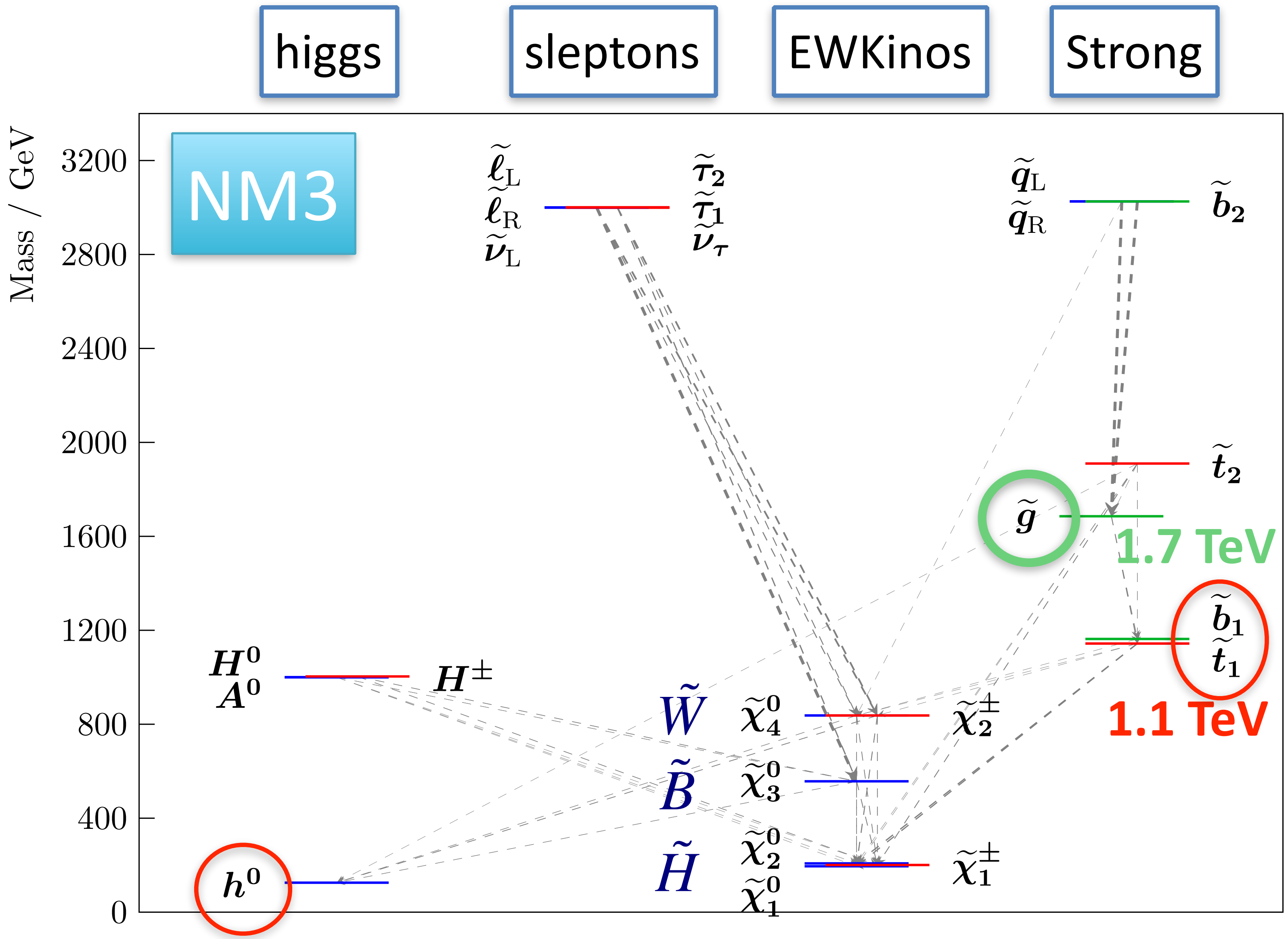
Discovery sensitivity: neutralinos up to ~1 TeV

Discovery sensitivity: gluinos up to ~2.2 TeV

- **Largest increase in discovery sensitivity with HL-LHC is for direct production of electroweak SUSY partners (EWKinos). Small cross section!**
- Up to 500 GeV increase in discovery reach with HL-LHC for chargino-neutralino pair production (Wh mode).
- **If strongly interacting SUSY partners are too heavy to be produced, EWKinos may be our best window to SUSY at the HL-LHC. Searches for ~degenerate Higgsinos are extremely difficult but highly motivated by naturalness.**

Discovery scenarios with full-spectrum models

CMS PAS SUS-14-012



The nature of the EWKino sector has a large influence on the decays of the top squark.

	NM1	NM2	NM3
$B(\tilde{t} \to t\tilde{\chi}_1^0)$	0.6%	1.5%	39%

- **Studied 5 full-spectrum SUSY models.**
- **9 analyses performed in parallel.**
- m_H = 125 GeV
- **NM 1,2,3** =“Natural” Model 1, 2, 3

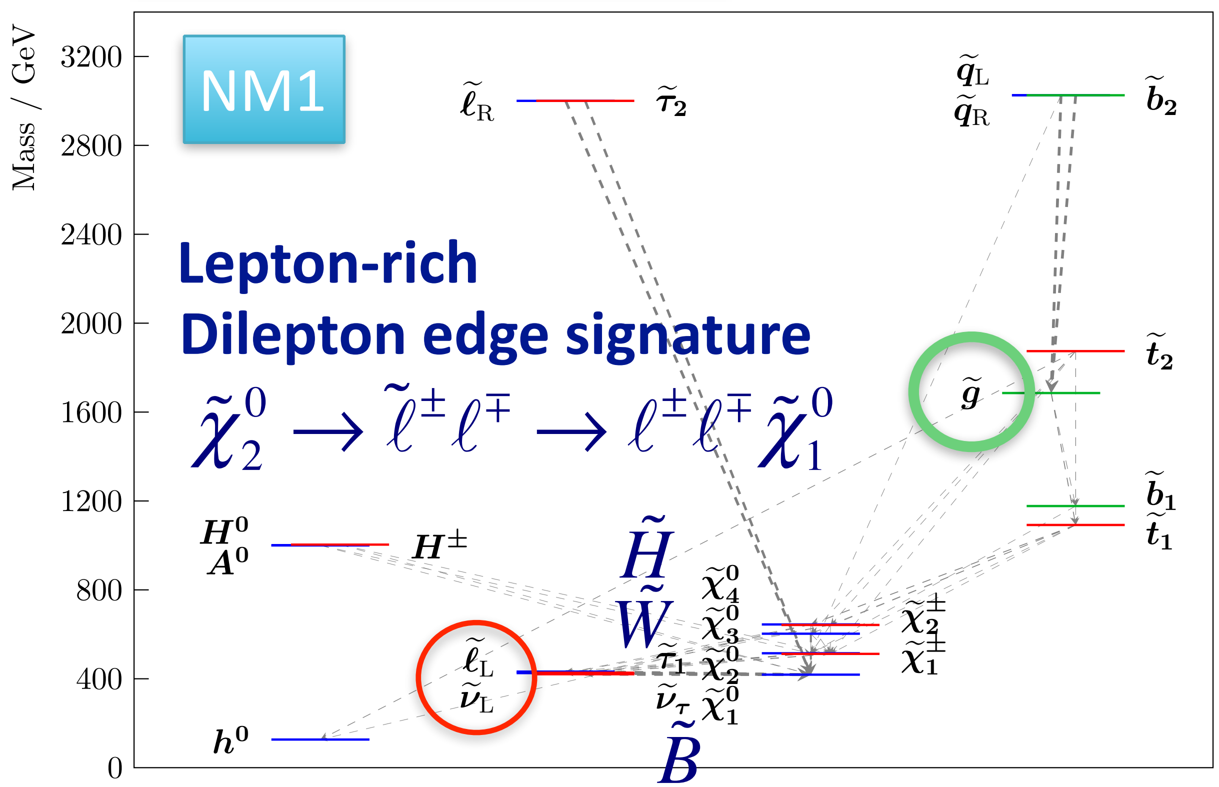
  $m(\tilde{g})$=1.7 TeV, $m(\tilde{t})$=1.1 TeV
- **STC** -Stau co-annihilation

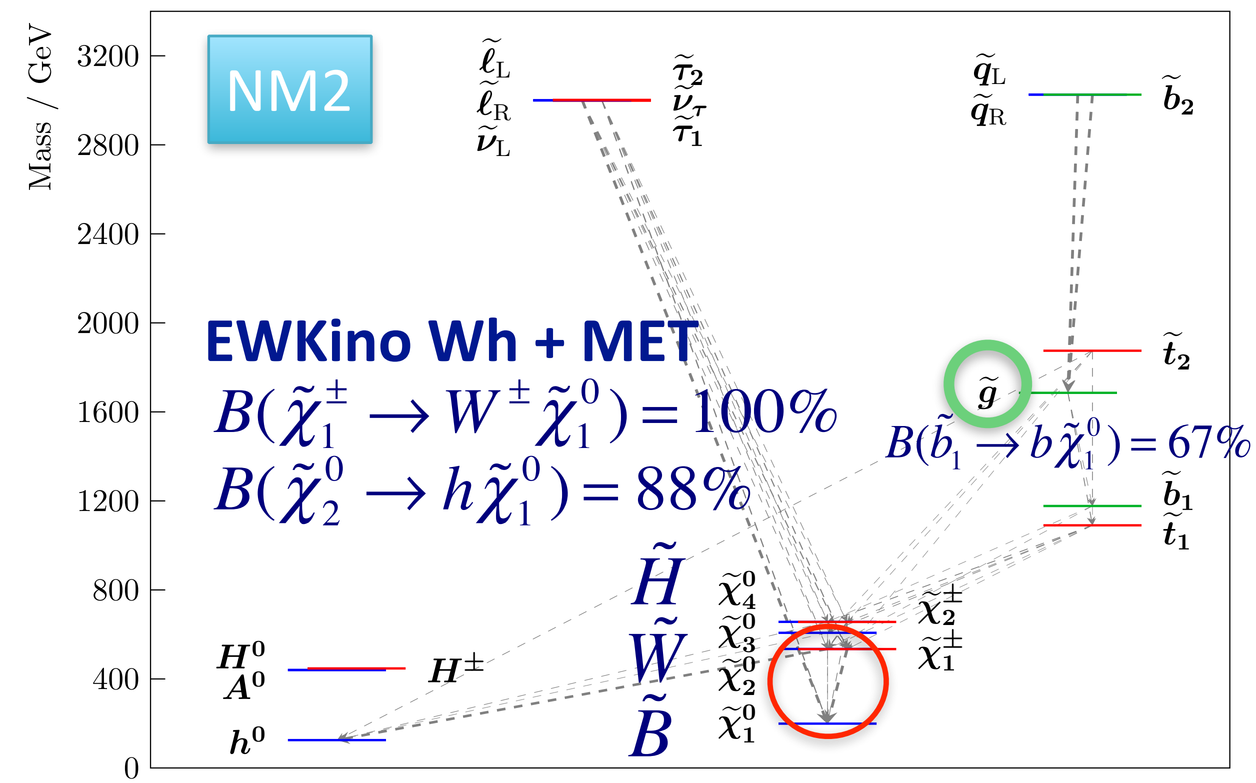
  $m(\tilde{\tau}_1) \approx m(\tilde{\chi}_1^0) \approx 190$ GeV
- **STOC**-Stop co-annihilation

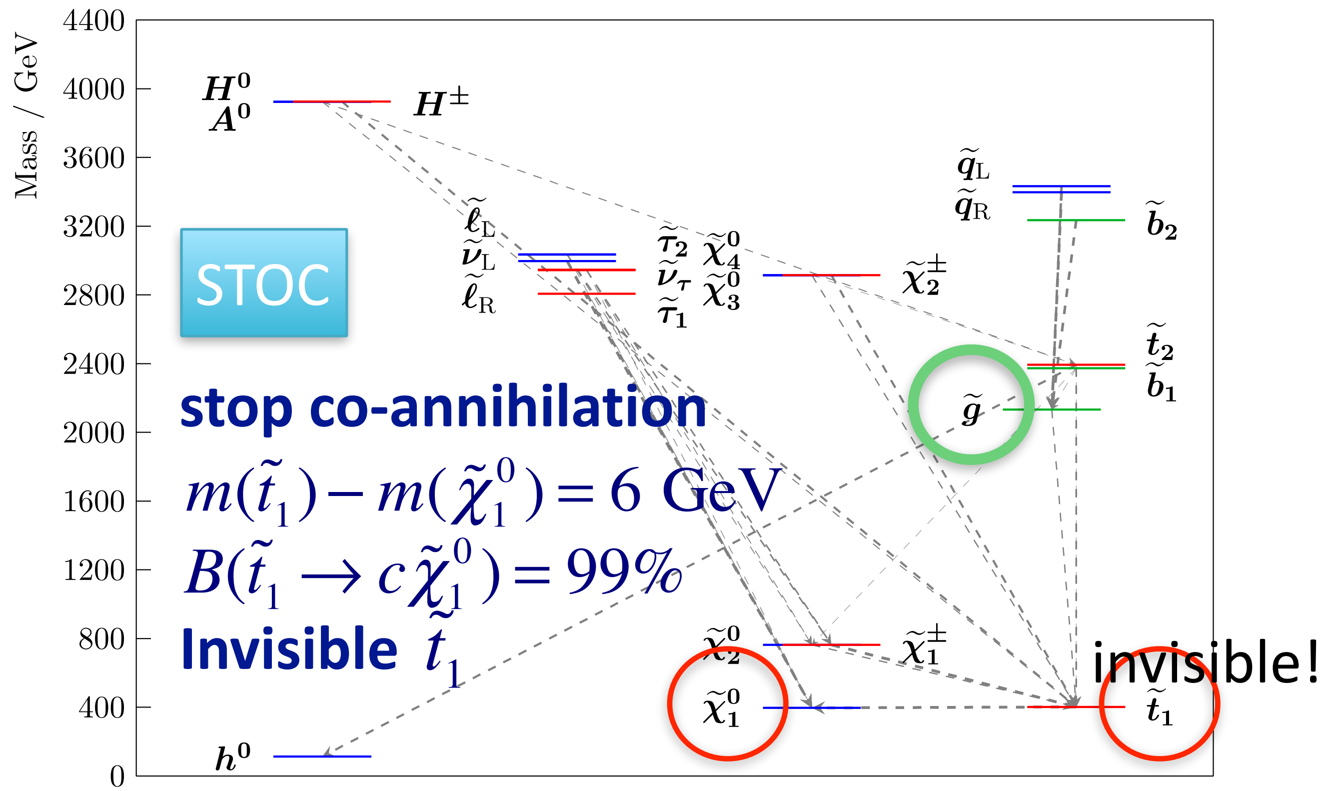
  $m(\tilde{t}_1) \approx m(\tilde{\chi}_1^0) \approx 400$ GeV

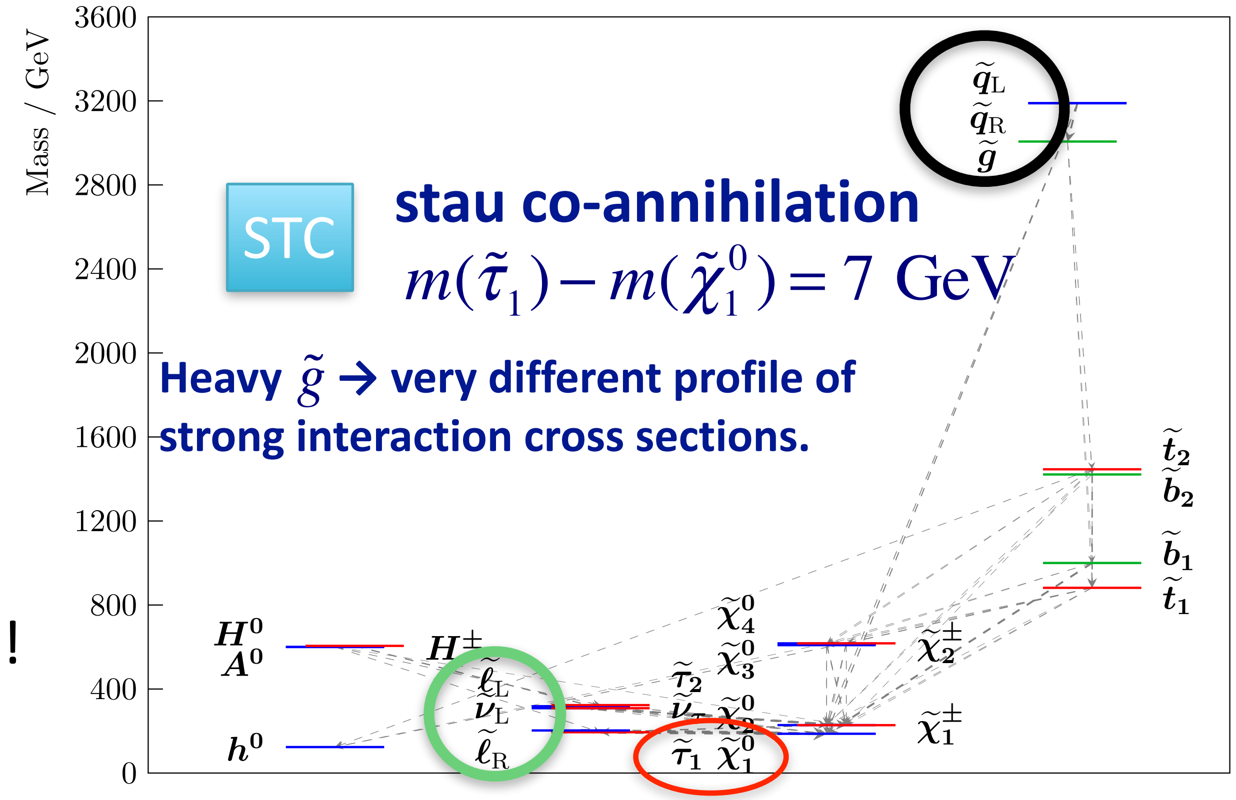
Discovery scenarios with full-spectrum models

CMS PAS SUS-14-012



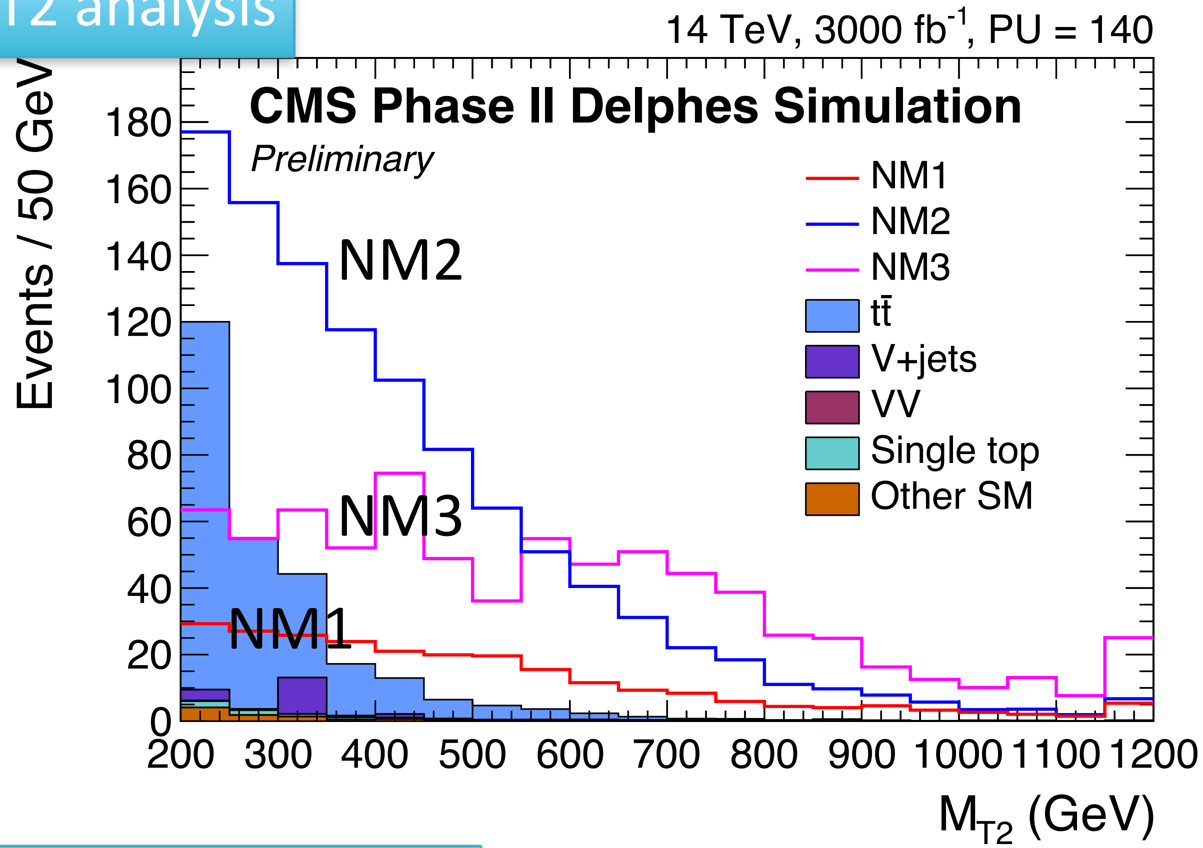






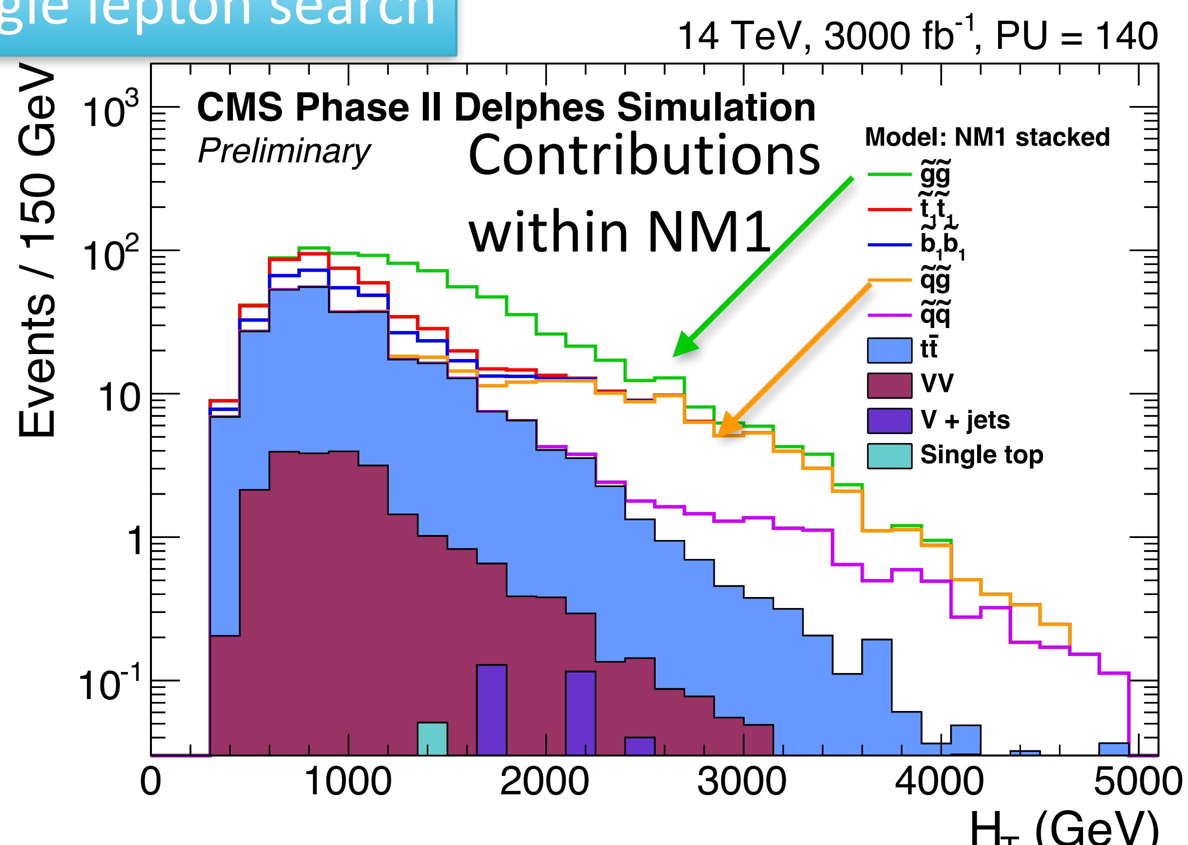
CMS: lessons from full-spectrum SUSY studies

MT2 analysis



- Search for all-hadronic jets + MET.
- MT2 can provide valuable information on the kinematics/ mass splittings of the signal processes
- NM1: more leptons → few events in hadronic channel.

Single lepton search



- Designed as 1-lepton search for top-squark pair production.
- Show stacked contributions from NM1 model. Target process does not dominate the observed yield!
- **"Discovery" does not mean you found what you were looking for!**

SUSY models & multi-signature fingerprints

SUSY Model

Experimental signature

Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-$H_\mathrm{T}^\mathrm{miss}$) search	300					
	3000					
all-hadronic (M_T2) search	300					
	3000					
all-hadronic $\tilde{\mathrm{b}}_1$ search	300					
	3000					
1-lepton $\tilde{\mathrm{t}}_1$ search	300					
	3000					
monojet $\tilde{\mathrm{t}}_1$ 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					

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

No mass peaks! Interpretation will be very complex. Is it even SUSY?
Different signatures can require very different amounts of data to detect!

SUSY models & multi-signature fingerprints

SUSY Model

Experimental signature

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					

- **Powerful approach, but in reality, there are an infinite number of possible theories (not 5), so the challenge is very significant.**
- **Multi-signature fingerprint will require large data samples to acquire.**
- **Different search channels can produce significant signals at very different times.**
- **Interpretation of a significant excess is likely to be much slower than for the Higgs discovery.**
- **“Discovery” could take place with multiple 3-4 σ excesses, rather than a single 5σ excess.**

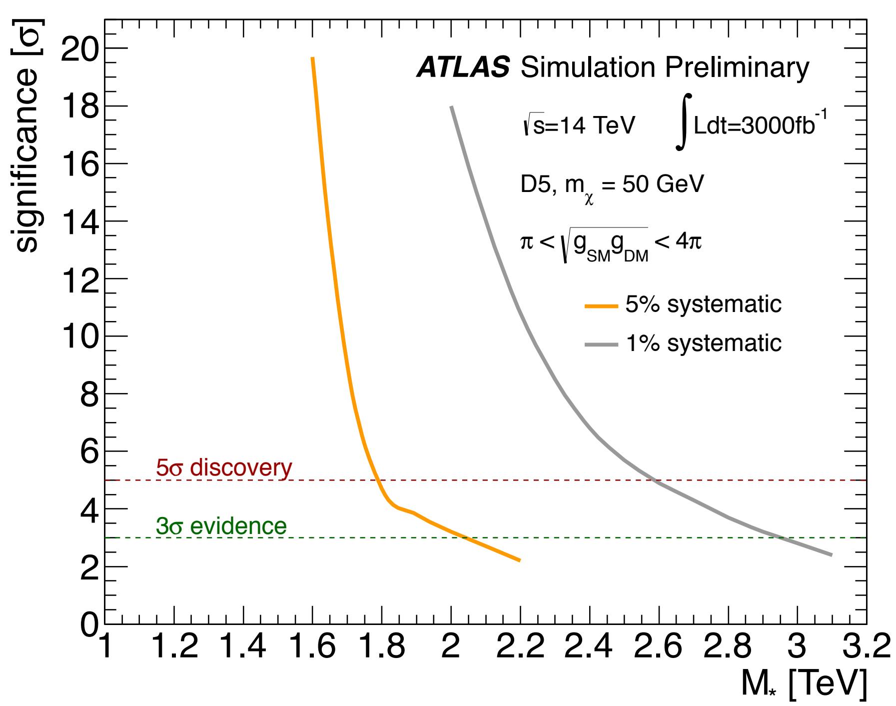
$< 3\sigma$	$3 - 5\sigma$	$> 5\sigma$

Exotic particle searches from ATLAS & CMS

- Assess discovery reach and impact of detector performance on broad range of exotica searches.
- Dilepton and di-top resonances (Z'), dark matter, R-parity violating and stealth SUSY, degenerate Higgsinos, Heavy Stable Charged Particles (HSCP), long-lived particles with displaced vertices,… (see references).
- Will focus on dilepton searches (Z', G_{RS},…).

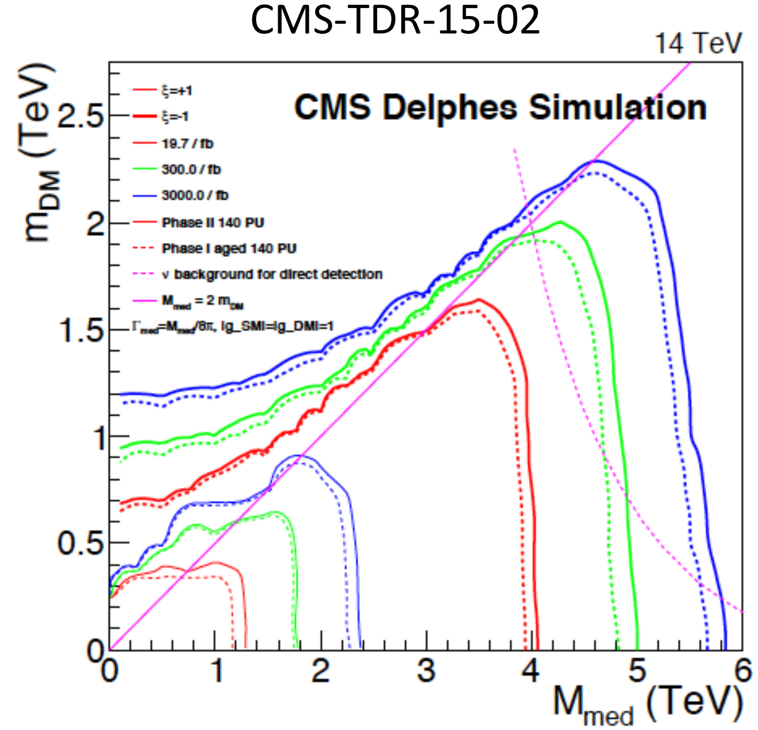
ATLAS: Dark matter searches

ATL-PHYS-PUB-2014-007



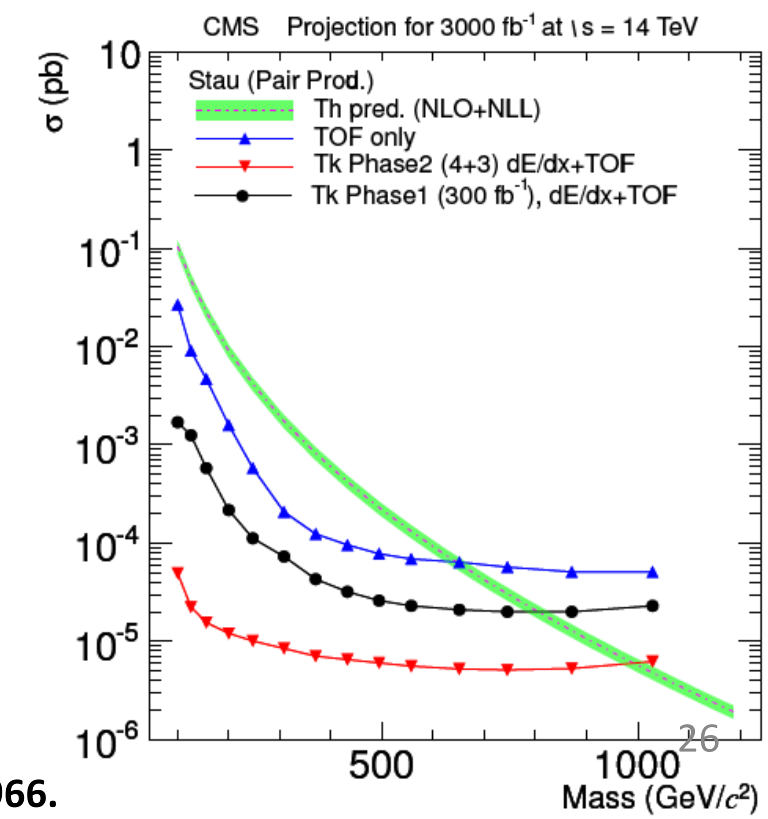
CMS: Dark matter search in mono-lepton + MET

CMS-TDR-15-02



CMS HSCP search and dE/dx

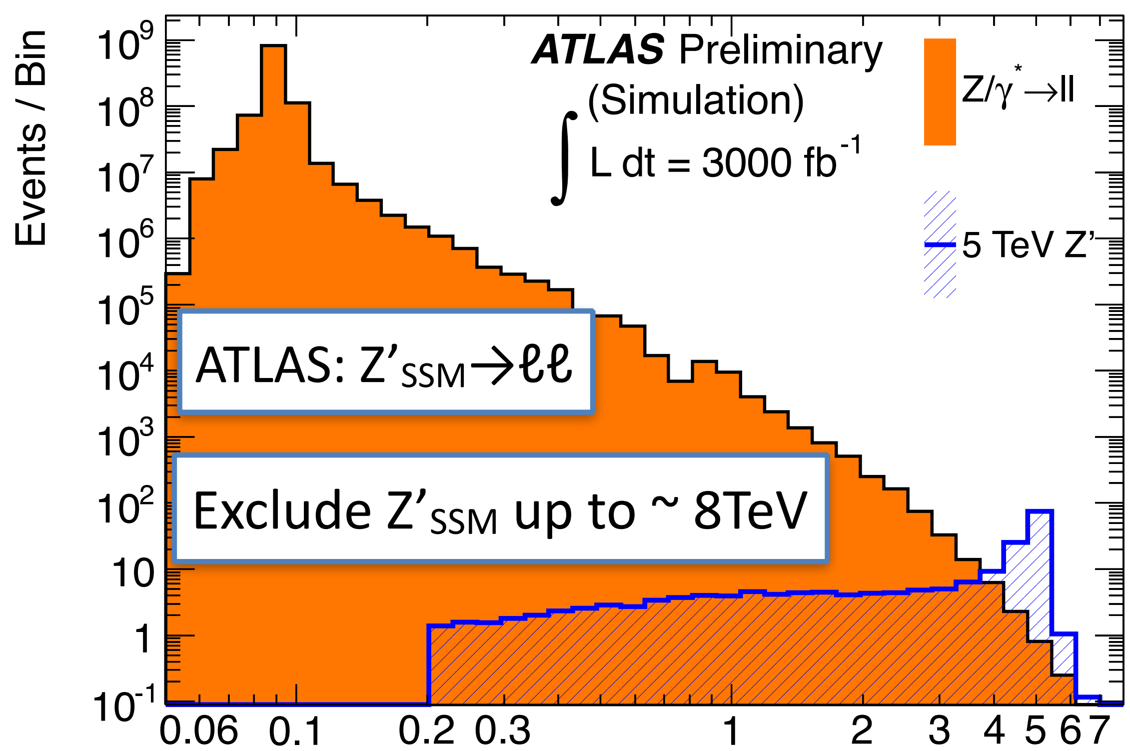
CMS-TDR-15-02



DM searches starting to be re-expressed using simplified models - see references, e.g., arXiv:1507.00966.

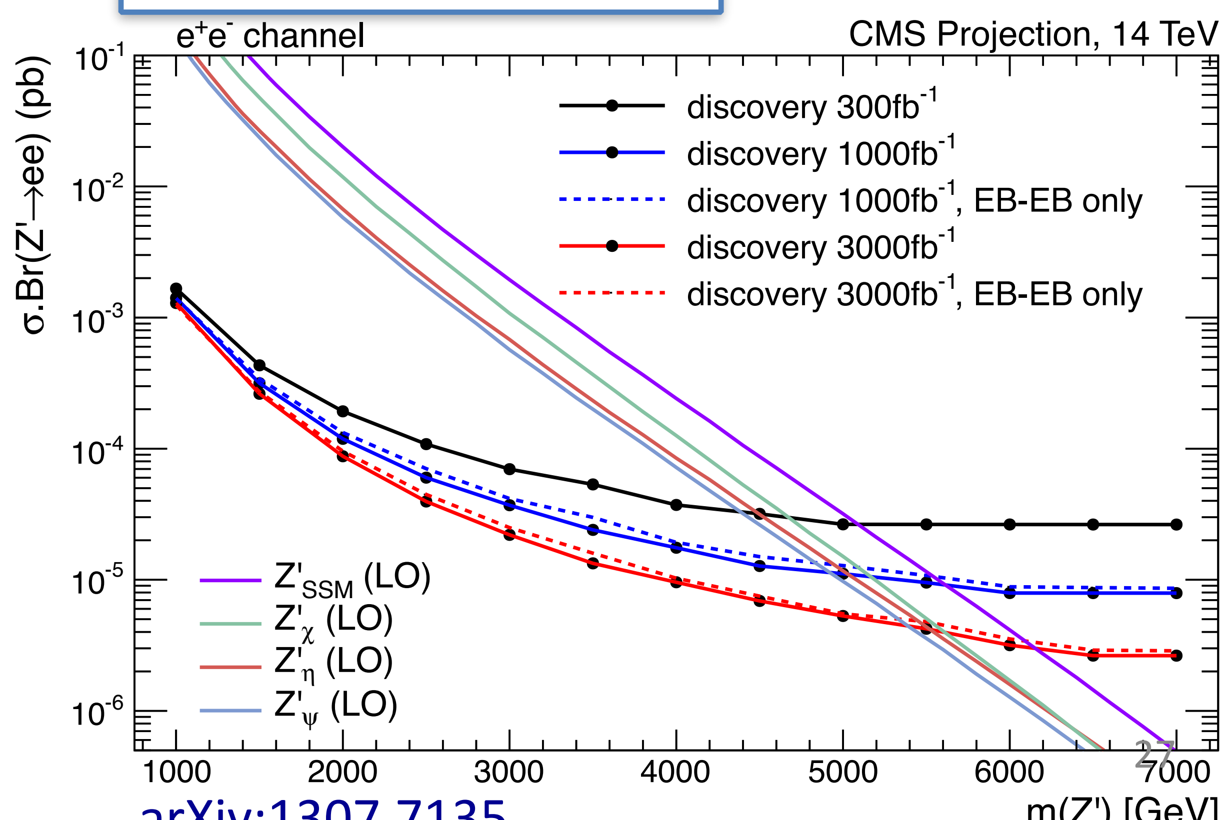
High-mass resonances in the dilepton channel

- Many BSM theories predict modifications to the dilepton mass spectra (resonances, extra non-res rate, A_{FB}).
  - E_6 GUTs - SM gauge group can arise from breaking of larger group to G_{SM} + U(1)' groups → Z' (J=1) resonances.
  - Large extra dimensions (ADD) - continuum of graviton states → general excess & possible A_{FB} shift in high-mass dilepton spectrum.
  - Randall-Sundrum warped extra dimensions → RS-graviton resonances (J=2) at TeV scale.



ATL-PHYS-PUB-2013-003

CMS: Z'(SSM, E6)→ee



arXiv:1307.7135

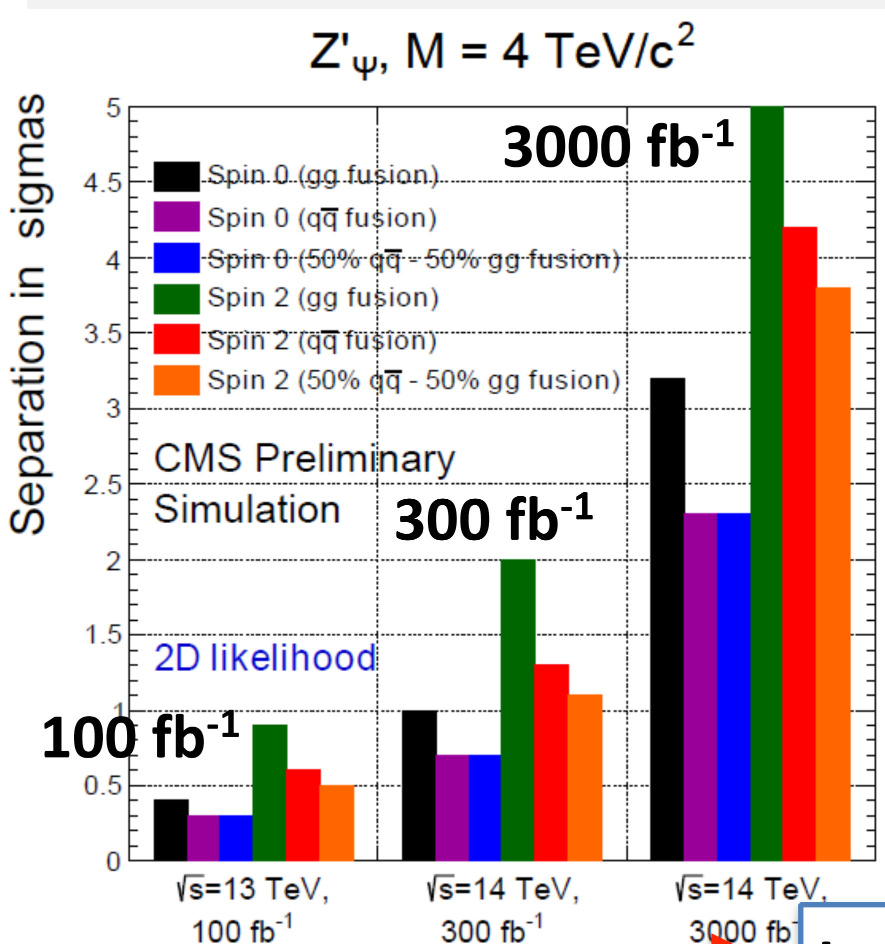
Spin measurements for dilepton resonances

- After observation of a dilepton resonance, will be critical to understand spin (J = 0, 1, 2) & production.

4 TeV

100 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
~few evts	10-40 evts	100-400 evts

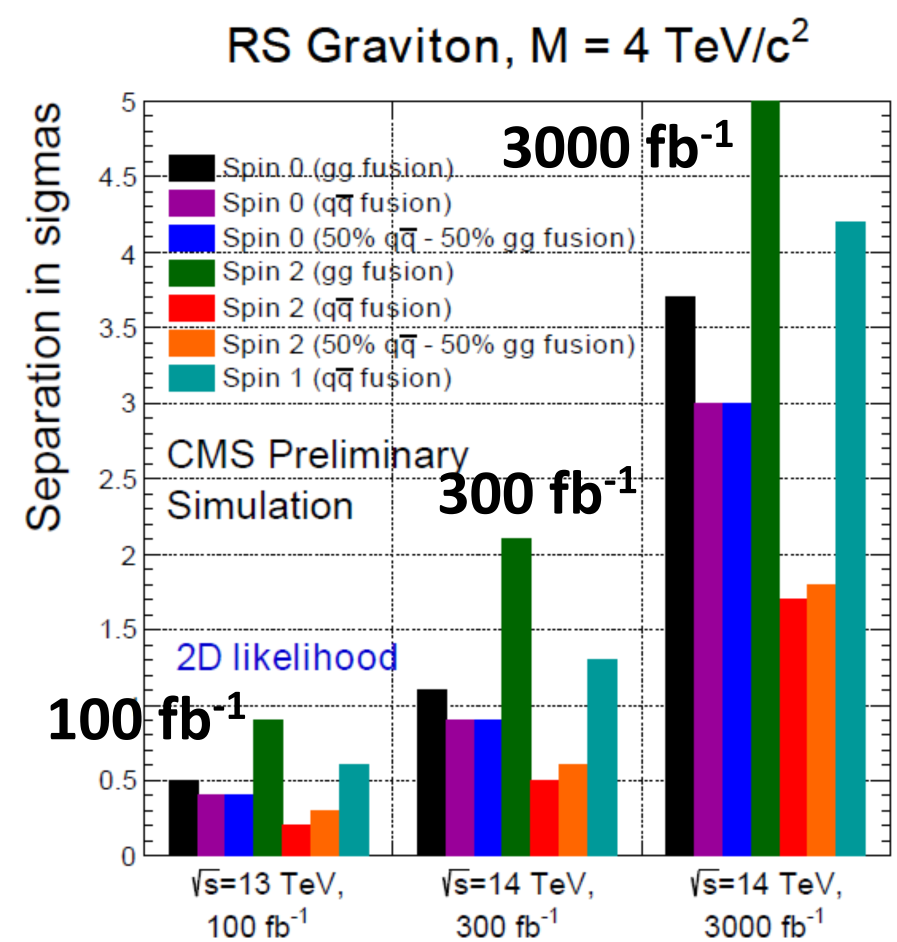
- Lepton decay angular distribution is determined by J but also helicity amplitudes, which are partly controlled by production mechanisms, e.g., gg, $q\bar{q}$. ($q\bar{q} \rightarrow J = 1$)
- Separate spin/production hypotheses using $\cos\theta_{CS}$ and $y(\ell^+\ell^-)$; A_{FB}.



Luminosity

(Left) Assume observed state is J=1: separation with respect to alternative hypotheses. (Constant signal yield.)

(Right) Assume observed state RS graviton (J=2): separation with respect to alternative hypotheses.



Summary/Observations

- Exploration of the TeV scale requires a broad, multi-decade physics program analogous to the study of the GeV scale.
- Evidence or discovery of an excess event yield over the SM with ~300 fb^{-1} will open the door to an intensive HL-LHC program to illuminate the nature of the excess.
- A compelling discovery scenario may arise with several 3-4 σ effects, rather than a single 5σ effect. Life could be quite complicated (e.g., look-elsewhere effects).
- Multi-signature fingerprints could play a key role.
- Even "easy" signatures (e.g., $\ell^+\ell^-$) require detailed studies (J, A_{FB})
- If no significant excess is observed with ~300 fb^{-1}, the strongest discovery possibilities may be associated with electroweak production and light higgsinos, where the limitation is cross section (couplings) rather than masses (kinematics).

History and a prediction

New York Times, January 5, 1993

January 5, 1993

315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE

Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

Ouch…

New York Times, January 5, 2022

I hope….

8,345 Physicists Report Discovery of Something But Aren't Exactly Sure What It Is

Eight thousand, three hundred and forty five physicists worked on two gigantic experiments, ATLAS and CMS.

Their apparatus included the Large Hadron Collider, the world's most powerful particle accelerator, as well as…

History and a prediction

New York Times, January 5, 1993

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Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But there is precedent!

(and this is a problem we want to have)

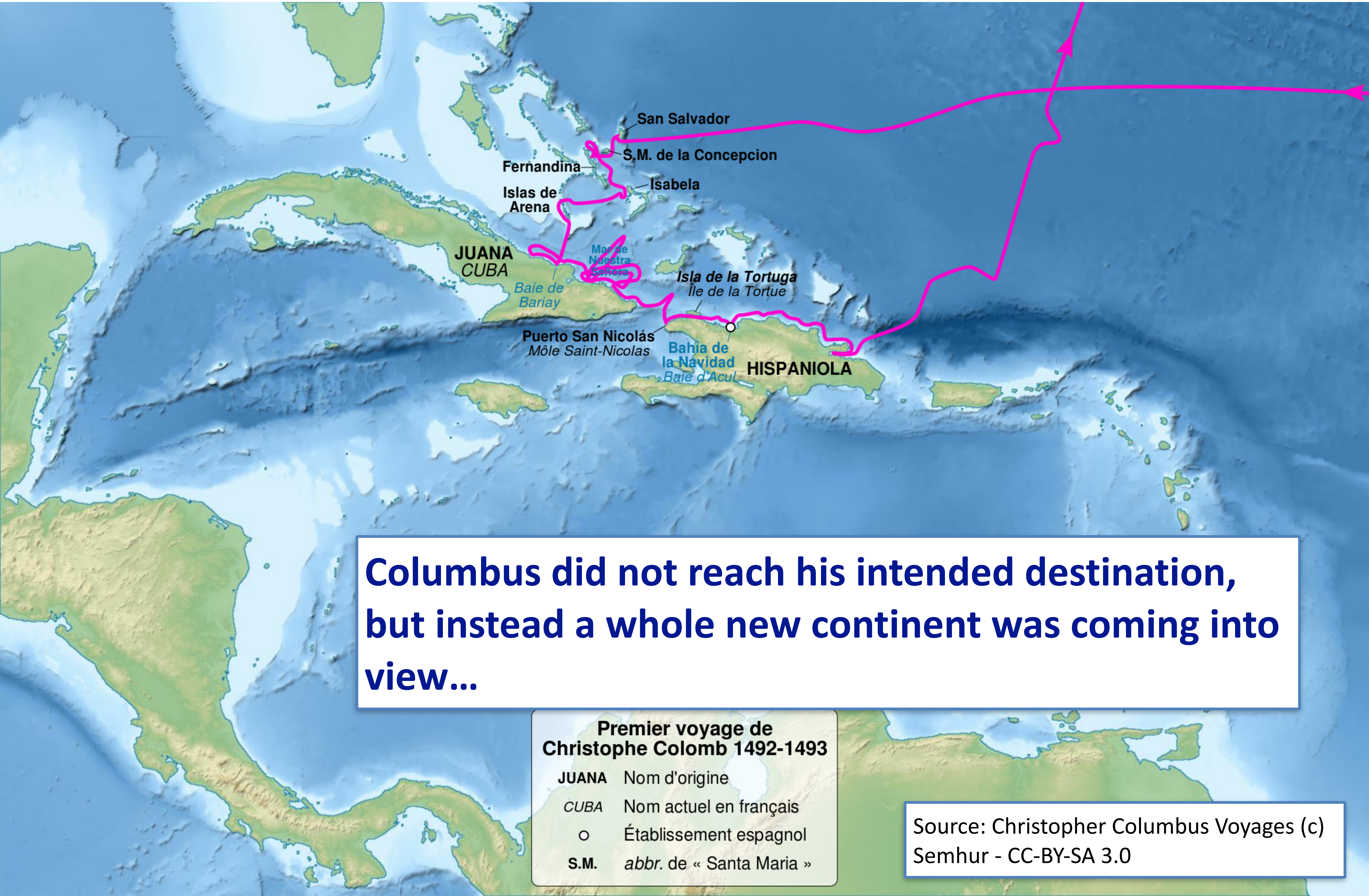
New York Times, January 5, 2022

8,345 Physicists Report Discovery of Something But Aren't Exactly Sure What It Is

Eight thousand, three hundred and forty five physicists worked on two gigantic experiments, ATLAS and CMS.

Their apparatus included the Large Hadron Collider, the world's most powerful particle accelerator, as well as…

You can discover something and not know what it is



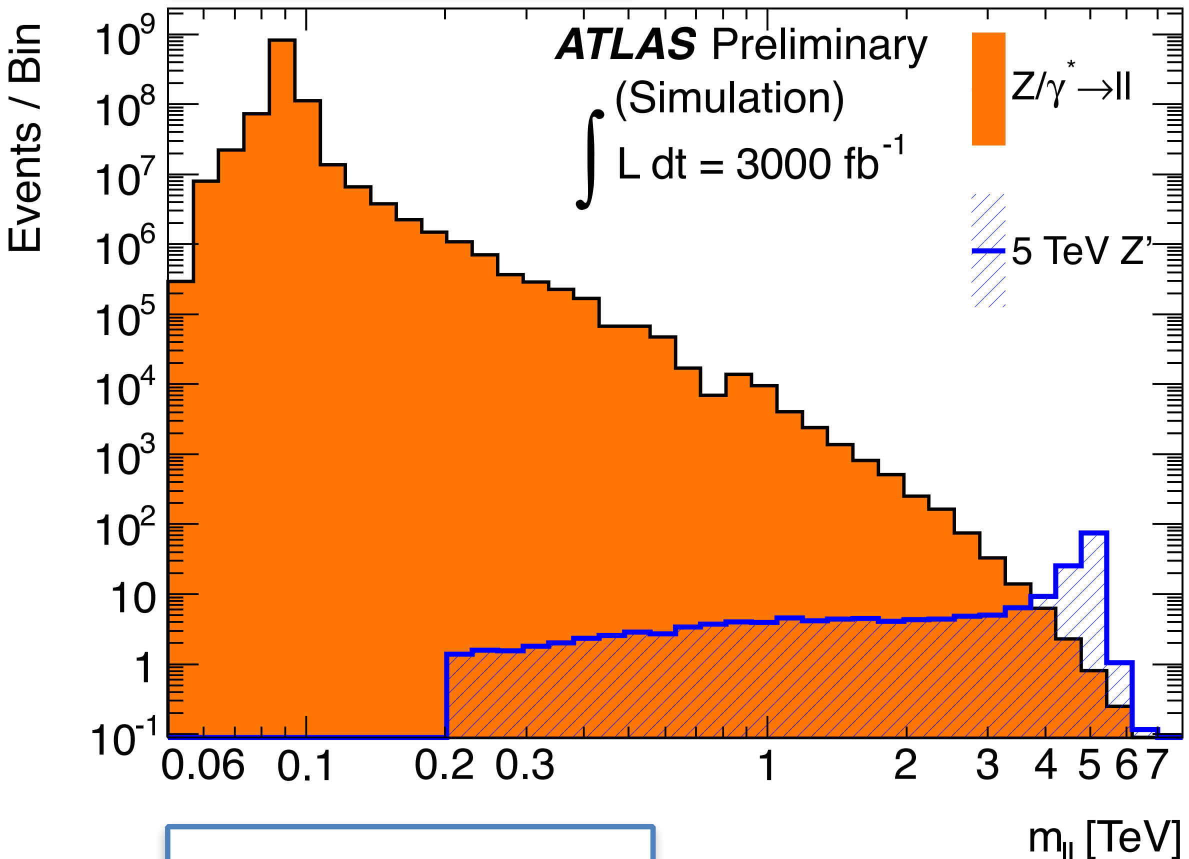
Columbus did not reach his intended destination, but instead a whole new continent was coming into view…

BACKUP SLIDES

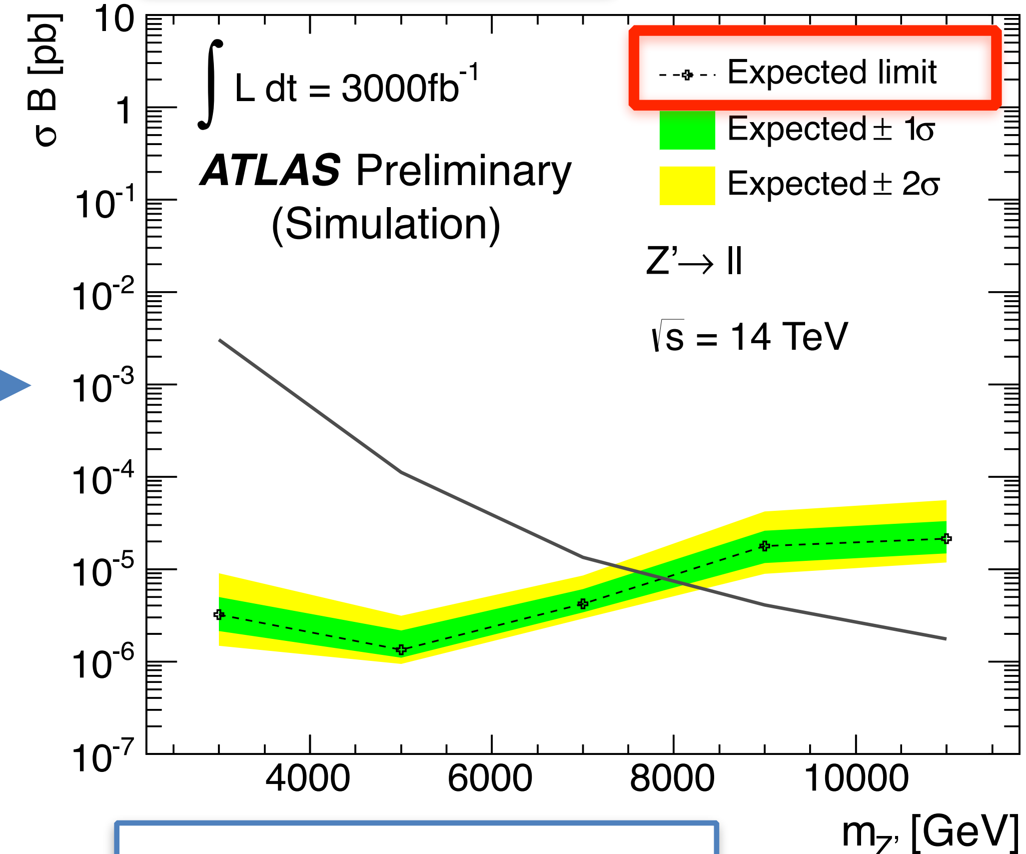
Sensitivity for dilepton and ttbar resonances

ATLAS: Z'$_{SSM}$→ℓℓ

ATL-PHYS-PUB-2013-003

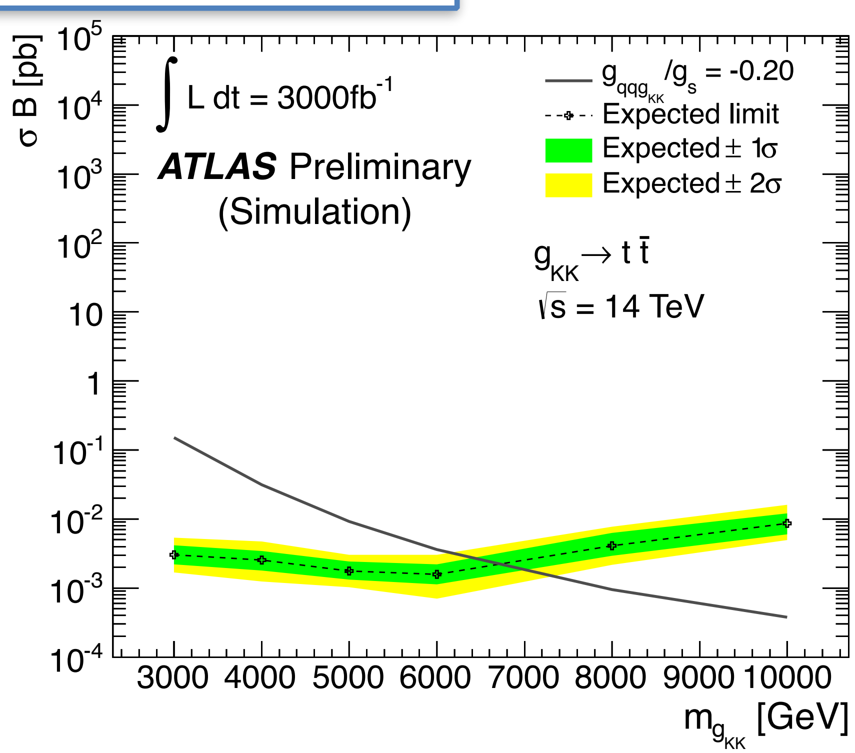


ATLAS: Z'$_{SSM}$→ℓℓ



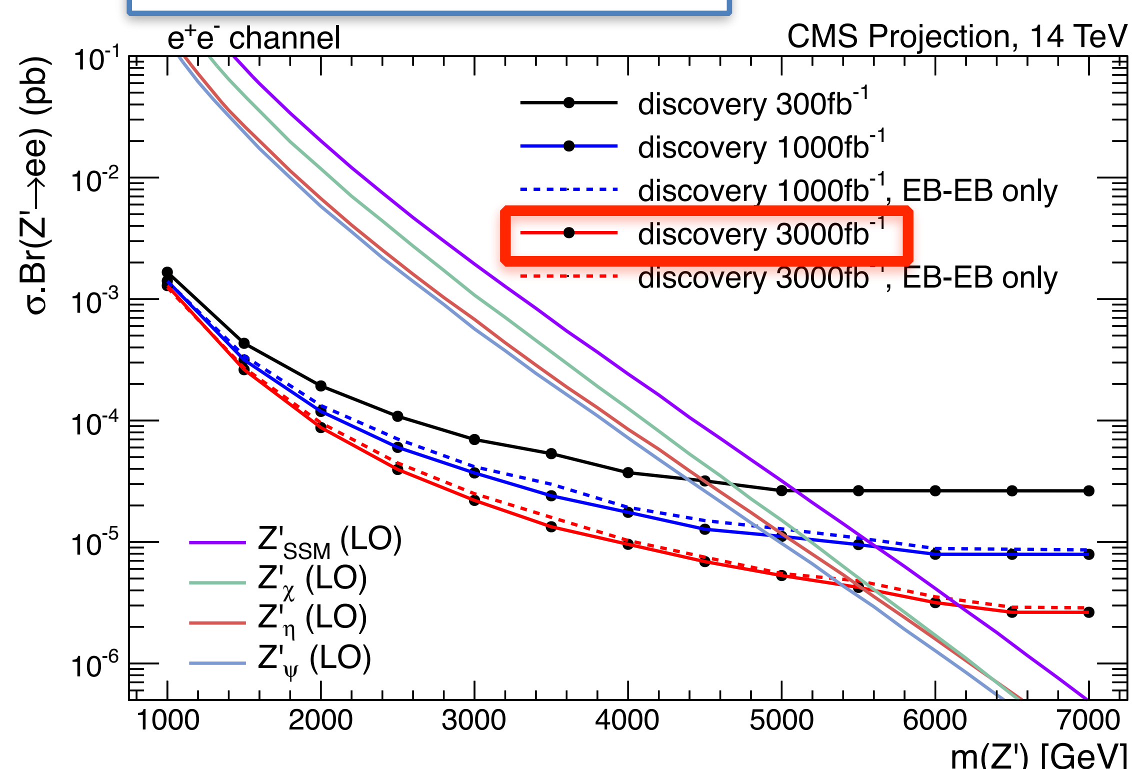
ATLAS: g$_{KK}$→ttbar

ATL-PHYS-PUB-2013-003



CMS: Z'(SSM, E6)→ee

arXiv:1307.7135



Documents and References

Continued in the backup slides.

- **Physics Studies for ATLAS Upgrades:** https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
- **Prospect for a search for direct pair production of a chargino and a neutralino decaying via a W boson and the lightest Higgs boson…with the ATLAS detector,** ATL-PHYS-PUB-2015-032.
- **Search for Supersymmetry at the high luminosity LHC with the ATLAS Detector**, ATL-PHYS-PUB-2014-010.
- **Prospects for benchmark Supersymmetry searches at the high luminosity LHC with the ATLAS Detector,** ATL-PHYS-PUB-2013-011.
- **Sensitivity to WIMP Dark Matter in the Monojet plus Missing Transverse Energy Final States with the ATLAS Detector at a High-Luminosity LHC**, ATL-PHYS-PUB-2014-007.
- **Studies of Sensitivity to New DIlepton and Ditop Resonances with an Upgraded ATLAS Detector at a High-Luminosity LHC**, ATL-PHYS-PUB-2013-003.

- **CMS Upgrade and physics documents Twiki**: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP
- **Technical Proposal for the Phase-II Upgrade of the Compact Muon Solenoid**, CMS-TDR-15-02, CERN-LHCC-2015-010.
- **Supersymmetry discovery potential in future LHC and HL-LHC running with the CMS detector,** CMS-PAS-SUS-14-012.
- **Projected Performance of an Upgraded CMS Detector at the LHC and HL-LHC: Contribution to the Snowmass Process**, CMS-NOTE-2013-002, arXiv:1307.7135.
- **Enhanced scope of a Phase 2 CMS detector for the study of exotic physics signatures at the HL-LHC,** CMS PAS EXO-14-007.

ATLAS PUBLIC RESULTS
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

CMS PUBLIC RESULTS
http://cms-results.web.cern.ch/cms-results/public-results/publications/

Additional Documents and References

- **Dijet Resonance Searches with the ATLAS Detector at 14 TeV LHC**, ATLAS Collab., ATL-PHYS-PUB-2015-004.
- **Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum,** arXiv:1507:00966.
- **New Particles Working Group Report of the Snowmass 2013 Community Summer Study**, Y. Gershtein et al., arXiv:1311.0299.
- **Natural SUSY Endures**, M. Papucci et al., arXiv:1110.6926.
- **Naturalness and the Status of Supersymmetry**, J.L. Feng, arXiv:1302.6587.
- **The State of Supersymmetry after Run I of the LHC**, N. Craig, arXiv:1309.0528.
- **Hunting Quasi-Degenerate Higgsinos**, Z.Han et al., arXiv 1401.1235.
- **Constraining Supersymmetry at the LHC with Simplified Models for Squark Production**. L. Edelhauser et al., arXiv:1410.0965.
- **The Physics of Heavy Z' Gauge Bosons**, P. Langacker, arXiv:0801.1345.

CMS full-spectrum SUSY models

Sparticle	Mass (GeV)				
	NM1	NM2	NM3	STC	STOC
$\tilde{g}$	1686	1686	1686	3007	2132
$\tilde{b}_1$	1177	1177	1163	1000	2374
$\tilde{t}_1$	1092	1090	1144	882	402
$\tilde{t}_2$	1874	1875	1910	1446	2393
$\tilde{q}$	3025	3025	3026	3189	3417
$\tilde{\ell}_L^{\pm}$	432	3000	3000	318	3037
$\tilde{\ell}_R^{\pm}$	3000	3000	3000	203	2997
$\tilde{\tau}_1$	427	2999	3000	194	2806
$\tilde{\chi}_1^0$	419	199	195	187	396
$\tilde{\chi}_2^0$	515	535	208	228	763
$\tilde{\chi}_3^0$	603	607	557	609	2913
$\tilde{\chi}_4^0$	644	656	837	617	2915
$\tilde{\chi}_1^{\pm}$	512	534	201	228	763
$\tilde{\chi}_2^{\pm}$	642	656	837	618	2915

Process	Cross section (fb)				
	NM1	NM2	NM3	STC	STOC
$\tilde{g}\tilde{g}$	5.4	5.4	5.4	0.007	0.53
$\tilde{q}\tilde{g}$	2.0	2.0	2.0	0.05	0.30
$\tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*$	0.14	0.14	0.14	0.07	0.03
$\tilde{b}_1\tilde{b}_1^*$	2.6	2.6	2.8	8.3	-
$\tilde{t}_1\tilde{t}_1^*$	4.4	4.4	3.1	19	2110
$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$	1.1	0.2	520	11	-
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$	29	22	460	1104	5.5
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	-	-	258	0.02	-
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	15	11	278	553	2.6
$\tilde{\ell}^+\tilde{\ell}^-$	3.3	-	-	34	-
$\tilde{\ell}^+\tilde{\nu}, \tilde{\ell}^-\tilde{\nu}^*$	12	-	-	32	-
$\tilde{\nu}\tilde{\nu}^*$	3.3	-	-	13	-

Decay	Branching fraction				
	NM1	NM2	NM3	STC	STOC
$\tilde{g} \to \tilde{t}_1\bar{t}, \tilde{t}_1^*t$	59%	60%	53%	28%	50%
$\tilde{g} \to \tilde{b}_1\bar{b}, \tilde{b}_1^*b$	41%	40%	47%	28%	50%
$\tilde{g} \to \tilde{t}_2\bar{t}, \tilde{t}_2^*t$	-	-	-	22%	-
$\tilde{g} \to \tilde{b}_2\bar{b}, \tilde{b}_2^*b$	-	-	-	21%	-
$\tilde{t}_1 \to t\tilde{\chi}_1^0$	0.6%	1.5%	39%	20%	-
$\tilde{t}_1 \to t\tilde{\chi}_2^0$	13%	13%	41%	5.4%	-
$\tilde{t}_1 \to t\tilde{\chi}_3^0$	22%	23%	1.3%	20%	-
$\tilde{t}_1 \to t\tilde{\chi}_4^0$	30%	30%	5.5%	9.2%	-
$\tilde{t}_1 \to b\tilde{\chi}_1^+$	16%	12%	2.1%	12%	-
$\tilde{t}_1 \to b\tilde{\chi}_2^+$	18%	21%	11%	34%	-
$\tilde{t}_1 \to c\tilde{\chi}_1^0$	-	-	-	-	99%
$\tilde{b}_1 \to b\tilde{\chi}_1^0$	1.5%	1.0%	1.3%	67%	-
$\tilde{b}_1 \to b\tilde{\chi}_2^0$	11%	10%	1.0%	2.2%	5.7%
$\tilde{b}_1 \to b\tilde{\chi}_3^0$	0.6%	0.6%	0.4%	8.2%	-
$\tilde{b}_1 \to b\tilde{\chi}_4^0$	4.5%	5.7%	5.7%	7.6%	-
$\tilde{b}_1 \to t\tilde{\chi}_1^-$	32%	34%	80%	3.4%	11%
$\tilde{b}_1 \to t\tilde{\chi}_2^-$	49%	48%	12%	12%	-
$\tilde{b}_1 \to W^-\tilde{t}_1$	0.4%	0.7%	-	$< 0.1\%$	65%
$\tilde{b}_1 \to b\tilde{g}$	-	-	-	-	18%
$\tilde{\chi}_1^+ \to \ell^+\tilde{\nu}$	56%	-	-	-	-
$\tilde{\chi}_1^+ \to \nu\tilde{\ell}^+$	43%	-	-	100% (only $\nu_\tau\tilde{\tau}_1^+$)	-
$\tilde{\chi}_1^+ \to W^+\tilde{\chi}_1^0$	1.8%	100%	-	-	-
$\tilde{\chi}_1^+ \to q\bar{q}'\tilde{\chi}_1^0$	-	-	70%	-	-
$\tilde{\chi}_1^+ \to \ell^+\nu\tilde{\chi}_1^0$	-	-	30%	-	-
$\tilde{\chi}_1^+ \to \tilde{t}_1\bar{b}$	-	-	-	-	100%
$\tilde{\chi}_2^0 \to \ell^+\tilde{\ell}^-, \ell^-\tilde{\ell}^+$	59%	-	-	100%	-
$\tilde{\chi}_2^0 \to \tilde{\nu}\bar{\nu}, \tilde{\nu}^*\nu$	41%	-	-	-	-
$\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$	$< 0.1\%$	12%	-	-	-
$\tilde{\chi}_2^0 \to H\tilde{\chi}_1^0$	-	88%	-	-	-
$\tilde{\chi}_2^0 \to q\bar{q}\tilde{\chi}_1^0$	-	-	56%	-	-
$\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$	-	-	10%	-	-
$\tilde{\chi}_2^0 \to \nu\bar{\nu}\tilde{\chi}_1^0$	-	-	21%	-	-
$\tilde{\chi}_2^0 \to q\bar{q}'\tilde{\chi}_1^{\pm}$	-	-	8.8%	-	-
$\tilde{\chi}_2^0 \to \ell^+\nu\tilde{\chi}_1^-, \ell^-\bar{\nu}\tilde{\chi}_1^+$	-	-	4.0%	-	-
$\tilde{\chi}_2^0 \to \tilde{t}_1\bar{t}, \tilde{t}_1^*t$	-	-	-	-	100%

PDG for CMS full-spectrum SUSY models

CMS PAS SUS-14-012

Process	Cross section (fb)				
	NM1	NM2	NM3	STC	STOC
$\tilde{g}\tilde{g}$	5.4	5.4	5.4	0.007	0.53
$\tilde{q}\tilde{g}$	2.0	2.0	2.0	0.05	0.30
$\tilde{q}\tilde{q}$, $\tilde{q}\tilde{q}^*$	0.14	0.14	0.14	0.07	0.03
$\tilde{b}_1\tilde{b}_1^*$	2.6	2.6	2.8	8.3	-
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Decay	Branching fraction				
	NM1	NM2	NM3	STC	STOC
$\tilde{g} \to \tilde{t}_1\bar{t}, \tilde{t}_1^* t$	59%	60%	53%	28%	50%
$\tilde{g} \to \tilde{b}_1\bar{b}, \tilde{b}_1^* b$	41%	40%	47%	28%	50%
$\tilde{g} \to \tilde{t}_2\bar{t}, \tilde{t}_2^* t$	-	-	-	22%	-
$\tilde{g} \to \tilde{b}_2\bar{b}, \tilde{b}_2^* b$	-	-	-	21%	-
$\tilde{t}_1 \to t\tilde{\chi}_1^0$	0.6%	1.5%	39%	20%	-
$\tilde{t}_1 \to t\tilde{\chi}_2^0$	13%	13%	41%	5.4%	-
$\tilde{t}_1 \to t\tilde{\chi}_3^0$	22%	23%	1.3%	20%	-
$\tilde{t}_1 \to t\tilde{\chi}_4^0$	30%	30%	5.5%	9.2%	-
$\tilde{t}_1 \to b\tilde{\chi}_1^+$	16%	12%	2.1%	12%	-
$\tilde{t}_1 \to b\tilde{\chi}_2^+$	18%	21%	11%	34%	-
$\tilde{t}_1 \to c\tilde{\chi}_1^0$	-	-	-	-	99%
$\tilde{b}_1 \to b\tilde{\chi}_1^0$	1.5%	1.0%	1.3%	67%	-
$\tilde{b}_1 \to b\tilde{\chi}_2^0$	11%	10%	1.0%	2.2%	5.7%
$\tilde{b}_1 \to b\tilde{\chi}_3^0$	0.6%	0.6%	0.4%	8.2%	-
$\tilde{b}_1 \to b\tilde{\chi}_4^0$	4.5%	5.7%	5.7%	7.6%	-
$\tilde{b}_1 \to t\tilde{\chi}_1^-$	32%	34%	80%	3.4%	11%
$\tilde{b}_1 \to t\tilde{\chi}_2^-$	49%	48%	12%	12%	-
$\tilde{b}_1 \to W^-\tilde{t}_1$	0.4%	0.7%	-	$< 0.1\%$	65%
$\tilde{b}_1 \to b\tilde{g}$	-	-	-	-	18%
$\tilde{\chi}_1^+ \to \ell^+\tilde{\nu}$	56%	-	-	-	-
$\tilde{\chi}_1^+ \to \nu\tilde{\ell}^+$	43%	-	-	100% (only $\nu_\tau\tilde{\tau}_1^+$)	-
$\tilde{\chi}_1^+ \to W^+\tilde{\chi}_1^0$	1.8%	100%	-	-	-
$\tilde{\chi}_1^+ \to q\bar{q}'\tilde{\chi}_1^0$	-	-	70%	-	-
$\tilde{\chi}_1^+ \to \ell^+\nu\tilde{\chi}_1^0$	-	-	30%	-	-
$\tilde{\chi}_1^+ \to \tilde{t}_1\bar{b}$	-	-	-	-	100%
$\tilde{\chi}_2^0 \to \ell^+\tilde{\ell}^-, \ell^-\tilde{\ell}^+$	59%	-	-	100%	-
$\tilde{\chi}_2^0 \to \tilde{\nu}\bar{\nu}, \tilde{\nu}^*\nu$	41%	-	-	-	-
$\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$	$< 0.1\%$	12%	-	-	-
$\tilde{\chi}_2^0 \to H\tilde{\chi}_1^0$	-	88%	-	-	-
$\tilde{\chi}_2^0 \to q\bar{q}\tilde{\chi}_1^0$	-	-	56%	-	-
$\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$	-	-	10%	-	-
$\tilde{\chi}_2^0 \to \nu\bar{\nu}\tilde{\chi}_1^0$	-	-	21%	-	-
$\tilde{\chi}_2^0 \to q\bar{q}'\tilde{\chi}_1^{\pm}$	-	-	8.8%	-	-
$\tilde{\chi}_2^0 \to \ell^+\nu\tilde{\chi}_1^-, \ell^-\bar{\nu}\tilde{\chi}_1^+$	-	-	4.0%	-	-
$\tilde{\chi}_2^0 \to \tilde{t}_1\bar{t}, \tilde{t}_1^* t$	-	-	-	-	100%

gluino: $\tilde{t}\tilde{t} + \tilde{b}\tilde{b}$

SUSY spectrum in gauge/higgs sector (MSSM)

Particle	J	Degrees of freedom
W^+	1	3
W^-	1	3
Z	1	3
γ	1	2
H	0	1
h	0	1
H^+	0	1
H^-	0	1
A	0	1
Total		16

Particle	J	Degrees of freedom
$\tilde{W}^+$	1/2	2
$\tilde{W}^-$	1/2	2
$\tilde{Z} \;\vert\; \tilde{W}^0$	1/2	2
$\tilde{\gamma} \;\vert\; \tilde{B}$	1/2	2
$\tilde{H}$	1/2	2
$\tilde{h}$	1/2	2
$\tilde{H}^+$	1/2	2
$\tilde{H}^-$	1/2	2
Total		16

Mixing

Particle	J	Degrees of freedom
$\tilde{\chi}_1^+$	1/2	2
$\tilde{\chi}_1^-$	1/2	2
$\tilde{\chi}_2^+$	1/2	2
$\tilde{\chi}_2^-$	1/2	2
$\tilde{\chi}_1^0$	1/2	2
$\tilde{\chi}_2^0$	1/2	2
$\tilde{\chi}_3^0$	1/2	2
$\tilde{\chi}_4^0$	1/2	2
Total		16

If lightest neutralino is LSP, then can be dark matter candidate.

Gauginos = SUSY partners of SM gauge bosons
Higgsinos = SUSY partners of higgs bosons
Neutralinos = mix of neutral gauginos and higgsinos
Charginos = mix of charged gauginos and higgsinos
EWKinos = term that denotes neutralinos or charginos

The gluino ($\tilde{g}$) is special: because of color, it cannot mix with any other particles.

Event yields for dilepton signal hypotheses

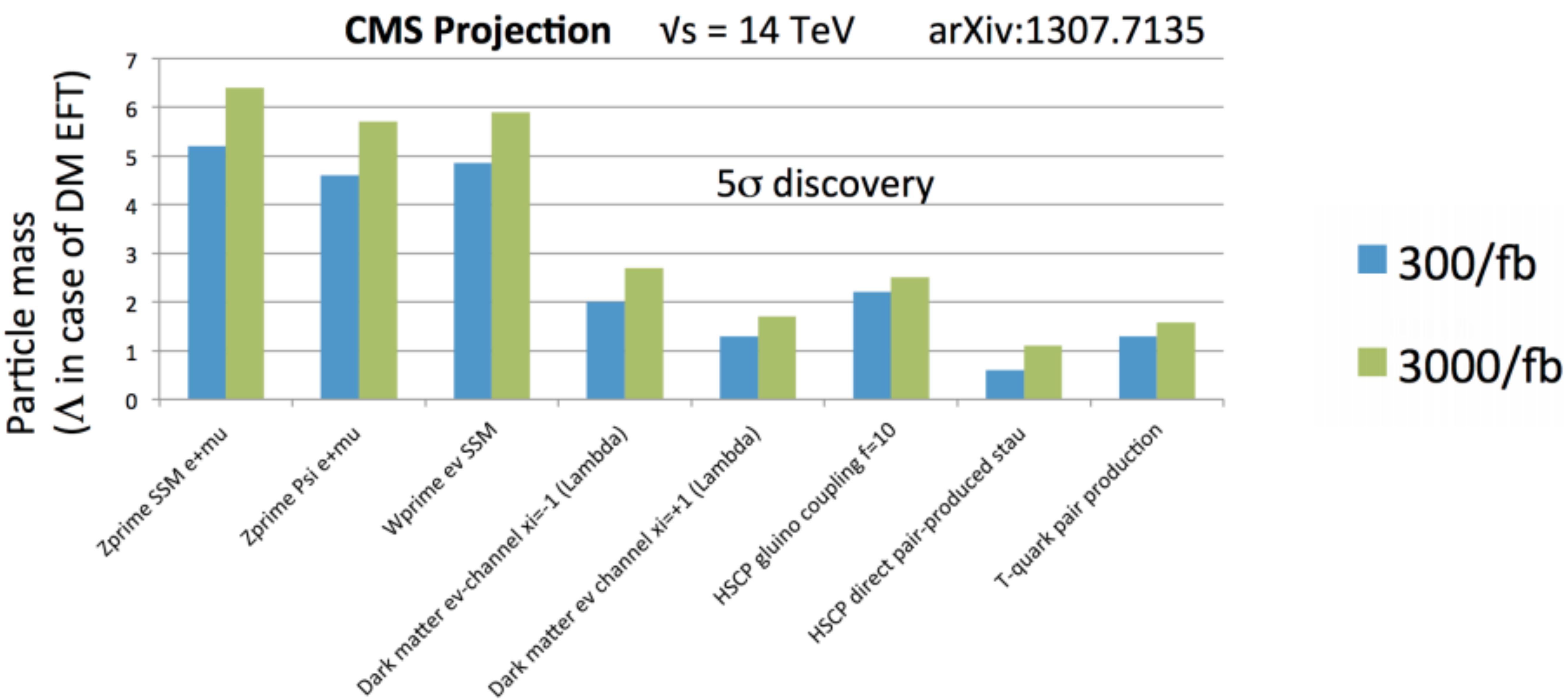
Model/process	$\sqrt{s}$=13 TeV, 100 fb^{-1}	$\sqrt{s}$=14 TeV, 300 fb^{-1}	$\sqrt{s}$=14 TeV, 3000 fb^{-1}	$\sqrt{s}$=14 TeV, 3000 fb^{-1} (Opp. charge)
G_{RS} (M=4 TeV, c=0.1)	3.5	17.8	177.7	164.2
Z'_{SSM} (M=4 TeV)	9.7	40.2	401.8	368.8
Z'_{Ψ} (M=4 TeV)	3.1	13.9	139.5	128.0
Z'_{I} (M=4 TeV)	3.3	16.4	164.2	150.8
Drell-Yan, $M_{ee} > 4$ TeV	0.0	0.4	3.8	3.5

Vector and Axial-Vector couplings for E_6 models

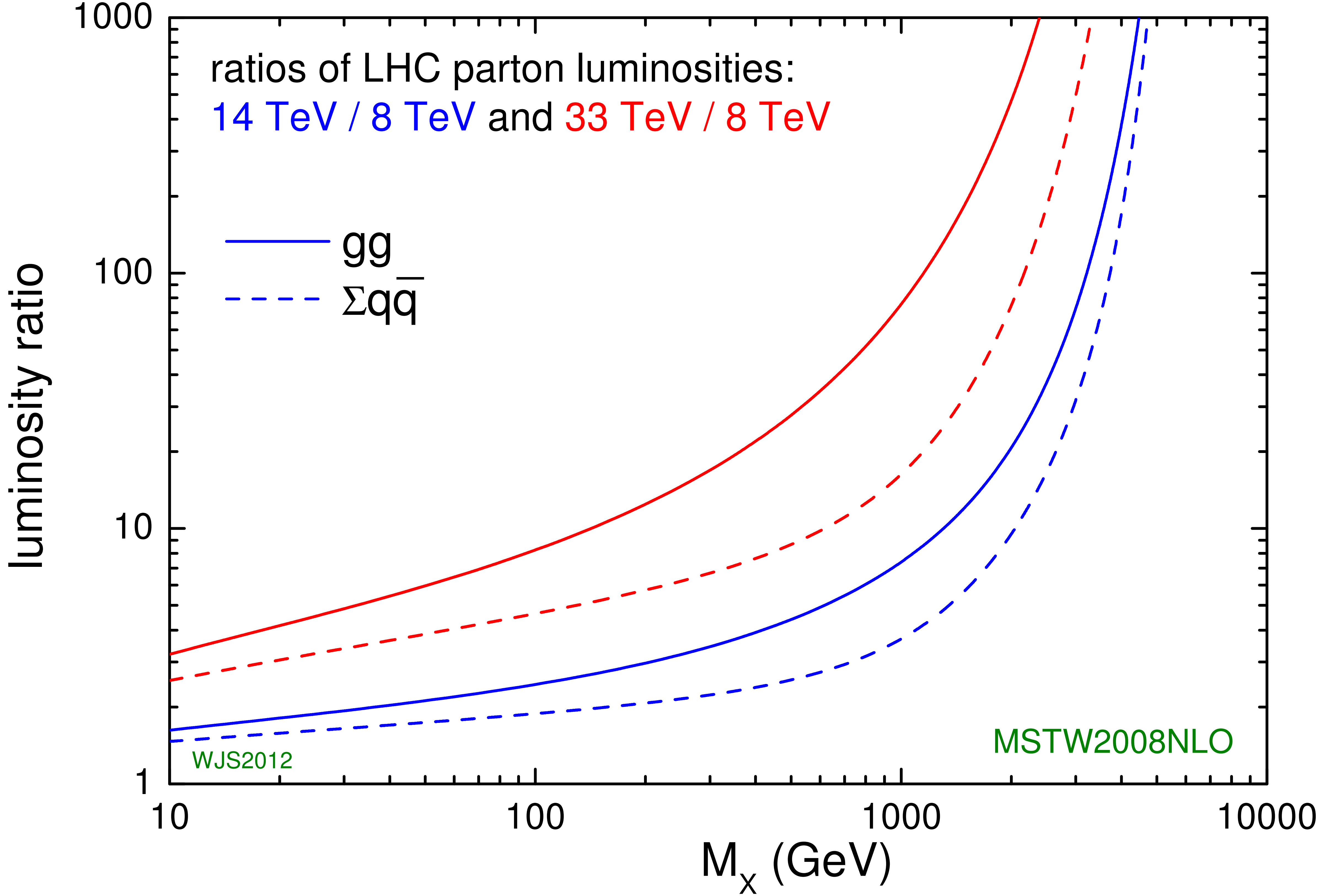
Model	c_V^u	c_A^u	c_V^d	c_A^d	c_V^l	c_A^l
Z'_ψ	0	0.300547	0	0.300547	0	0.300547
Z'_η	0	0.380165	-0.285124	0.095041	0.285124	0.095041
Z'_χ	0	0.073458	-0.416249	-0.342792	0.416249	-0.342792
Z'_I	0	0	0.620752	-0.620752	-0.620752	-0.620752
Z'_{SSM}	-0.227388	0.592979	0.410183	-0.592979	0.044592	-0.592979

Table 1.4: Vector (c_V) and axial-vector (c_A) couplings of the Z' boson to up quarks (u), down quarks (d) and the charged leptons (l) for various models corresponding to different values of θ_{E_6}. The values are calculated according to the convention adopted in [24]. For comparison, the Z'_{SSM} couplings, which are identical to the Z boson couplings are also given.

Overview of exotic particle sensitivity



CMS studies of discovery scenarios



CMS dilepton edge study in NM1