Prospect of New Physics Searches using HL-LHC

On behalf of the ATLAS and CMS Collaborations

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DESY
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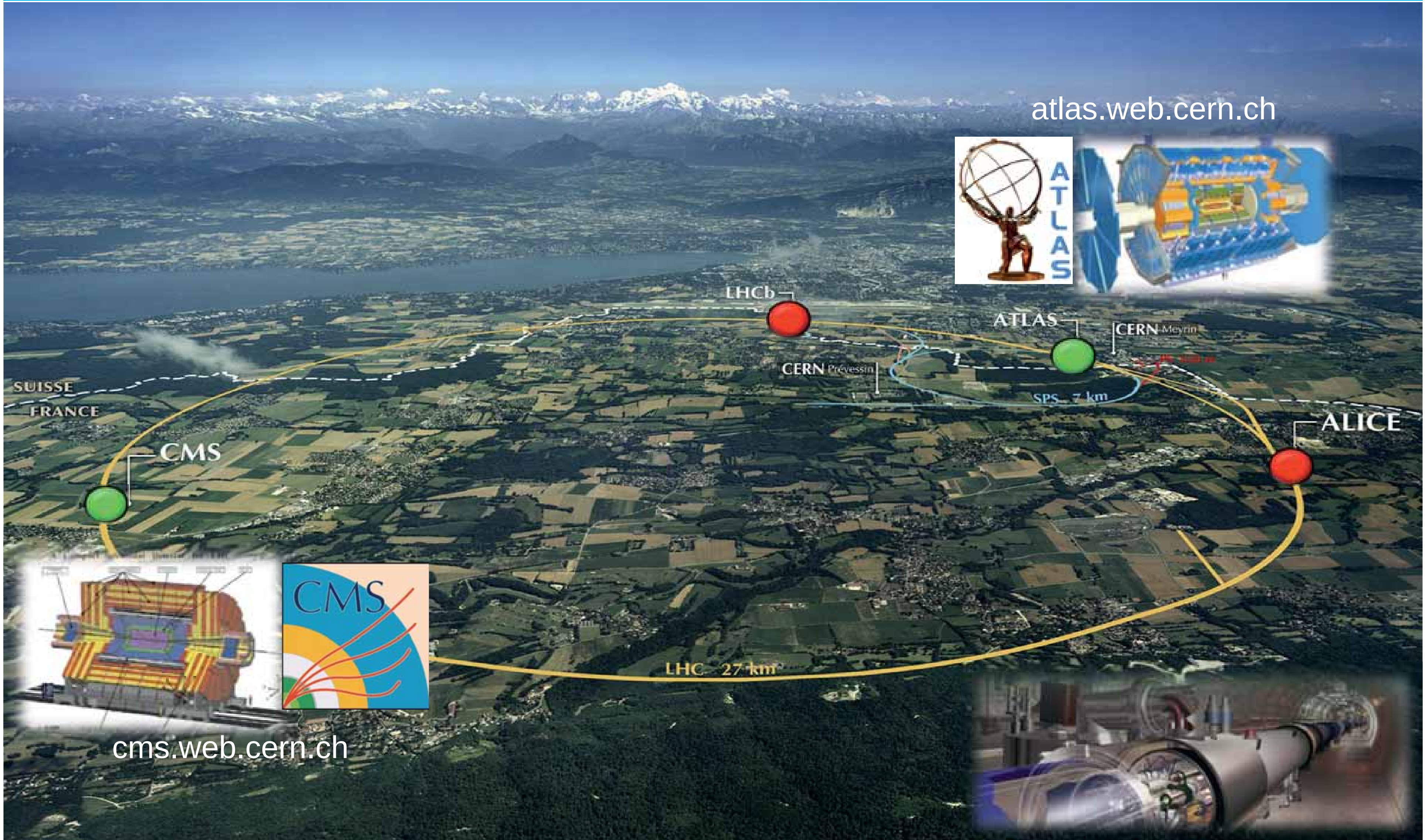
HELMHOLTZ | ASSOCIATION

Also presented at Next Steps in the Energy Frontier – Hadron Colliders Workshop at Fermilab, USA

ATLAS CMS DESY

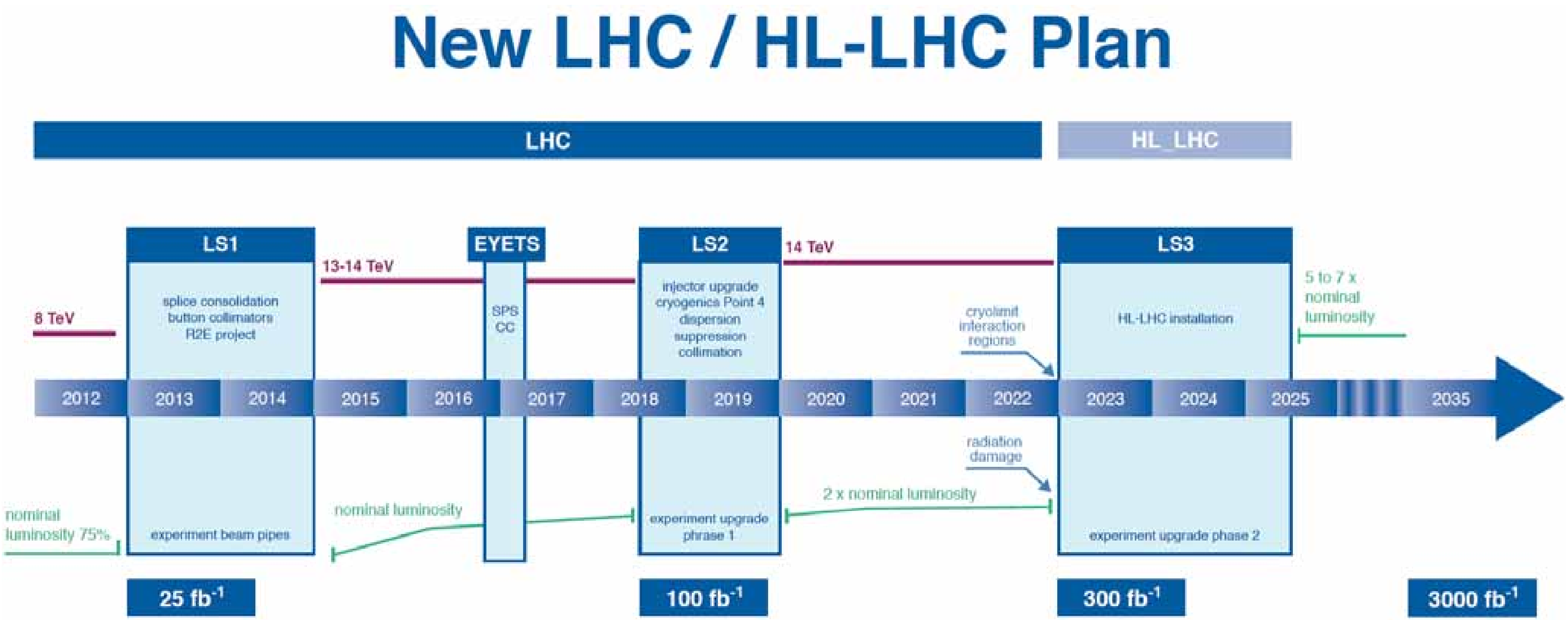
Large Hadron Collider (LHC)



The High-Lumi LHC Project

High Luminosity LHC

To extend its discovery potential, the LHC will need a major upgrade around 2020 to increase its luminosity (rate of collisions) by a factor of 10 beyond its design value.

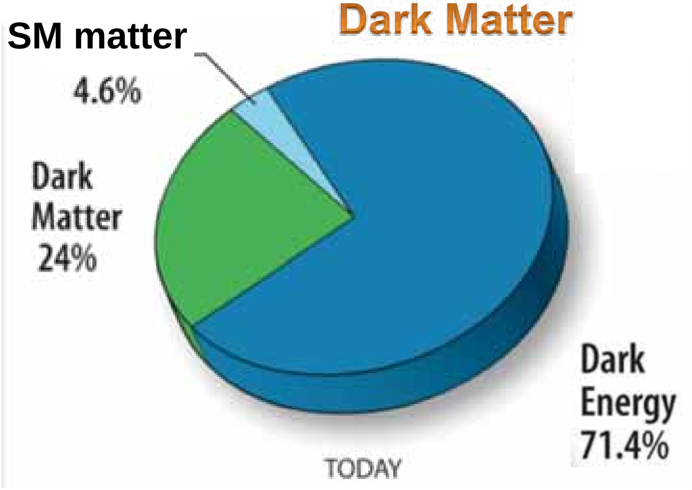


✓ provide more accurate measurements of new particles and enable observation of rare processes that occur below the current sensitivity level.

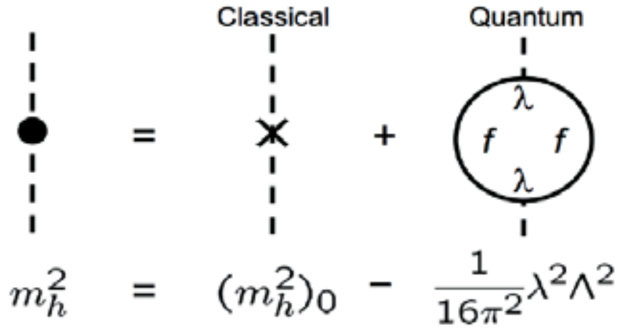
cern.ch/hilumilhc/

The Standard Model is incomplete: big questions

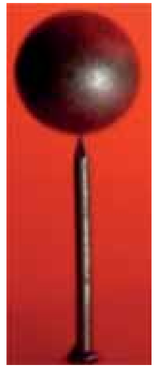
Dark Matter



Naturalness and fine tuning

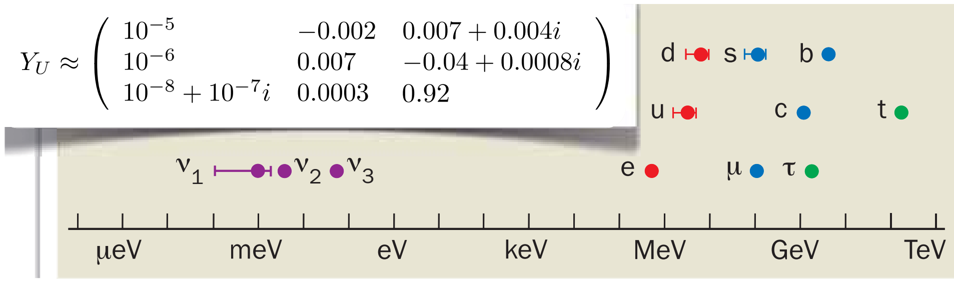


$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2$$



Origin of SM matter and flavor? Are particles elementary or composite?

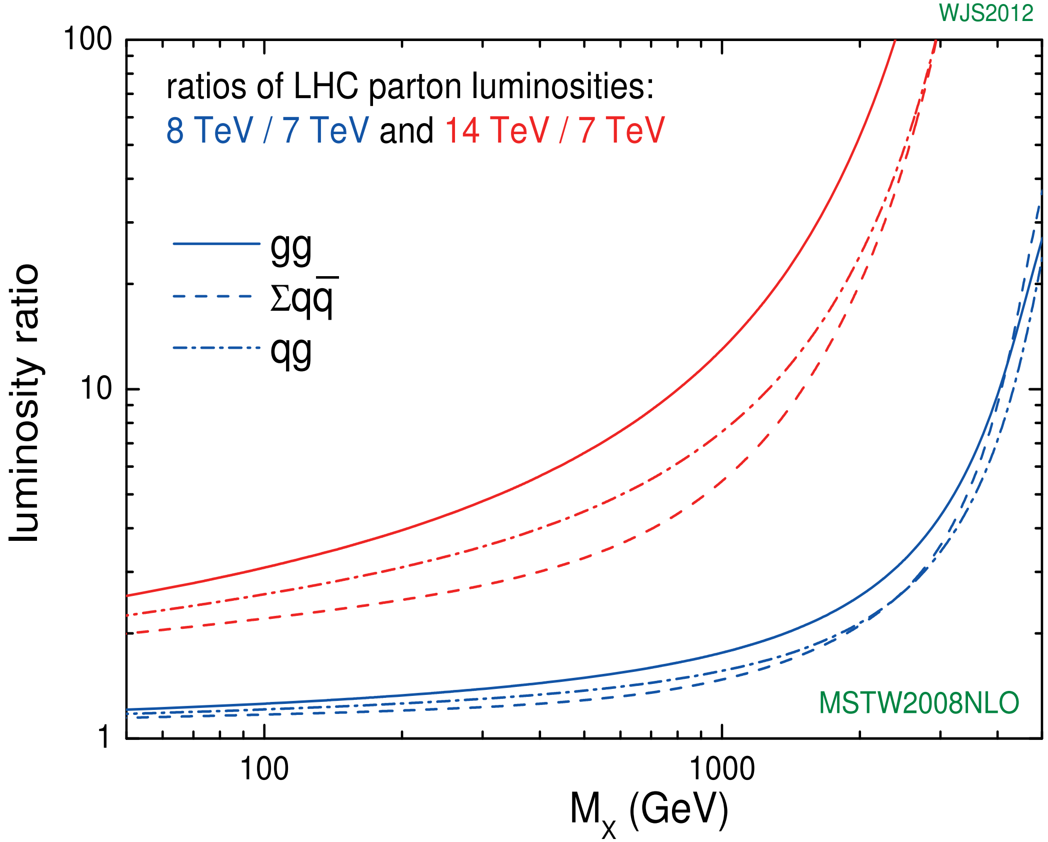
$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007+0.004i \\ 10^{-6} & 0.007 & -0.04+0.0008i \\ 10^{-8}+10^{-7}i & 0.0003 & 0.92 \end{pmatrix}$$



Unity of forces? New forces?

Most interesting theories offer solutions to open problems of the SM?

Why do we need HL-LHC?



- The **discovery of new physics** is one of the highest priorities for the current and future LHC
- The **multi-TeV energy** range will not be accessible at any other current facility.
- Strategy: **take existing searches and figure out reach at 14 TeV, for different luminosities!**

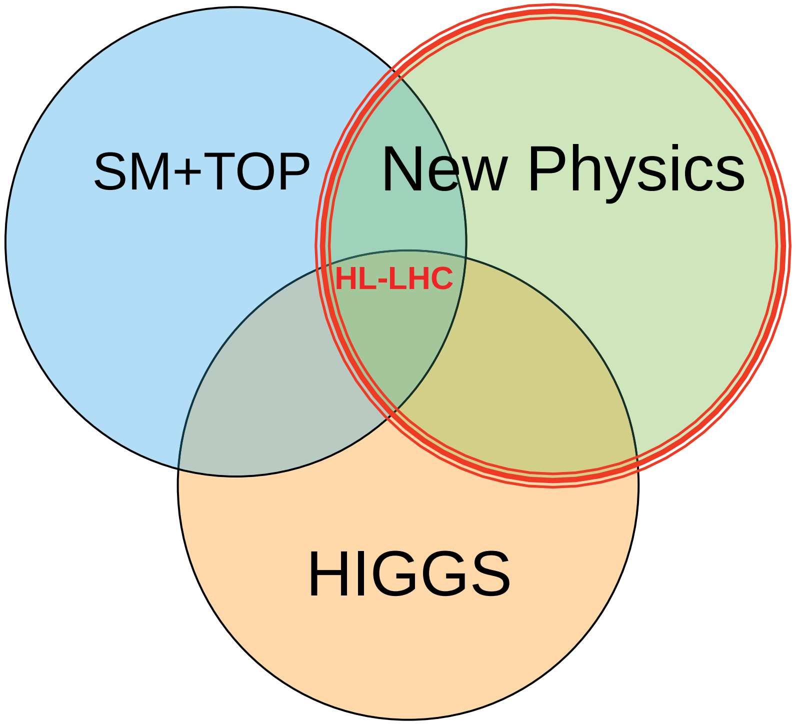
☑ **significant impact on the physics reach of CMS and ATLAS** beyond that gained by accumulating **10 or 100** times more data.

- Discuss expected sensitivity to broad range of Beyond the SM benchmark models for new physics searches at the CMS and ATLAS collaborations.

Outline: HL-LHC Analyses

- **Supersymmetry Searches**
  - Strongly produced SUSY: gluino and squarks searches
  - Third generation SUSY: direct stop and direct sbottom searches
  - Electroweak production of SUSY particles
  - Vector Boson Fusion in SUSY
- **Vector boson scattering and Triboson production**
- **Vector-like charge 2/3 quark search**
- *Search for ttbar and dilepton resonances*
- *Search for W` and Dark Matter*

HL-LHC will be the key!



ATLAS COLLABORATION:	CMS COLLABORATION:
ATLAS-PHYS-PUB-2013-003,	CMS-NOTE-13-002,
ATLAS-PHYS-PUB-2013-007,	CMS-FTR-13-006,
ATLAS-PHYS-PUB-2013-011,	CMS-FTR-13-014,
ATLAS-PHYS-PUB-2014-010 NEW	CMS-FTR-13-026

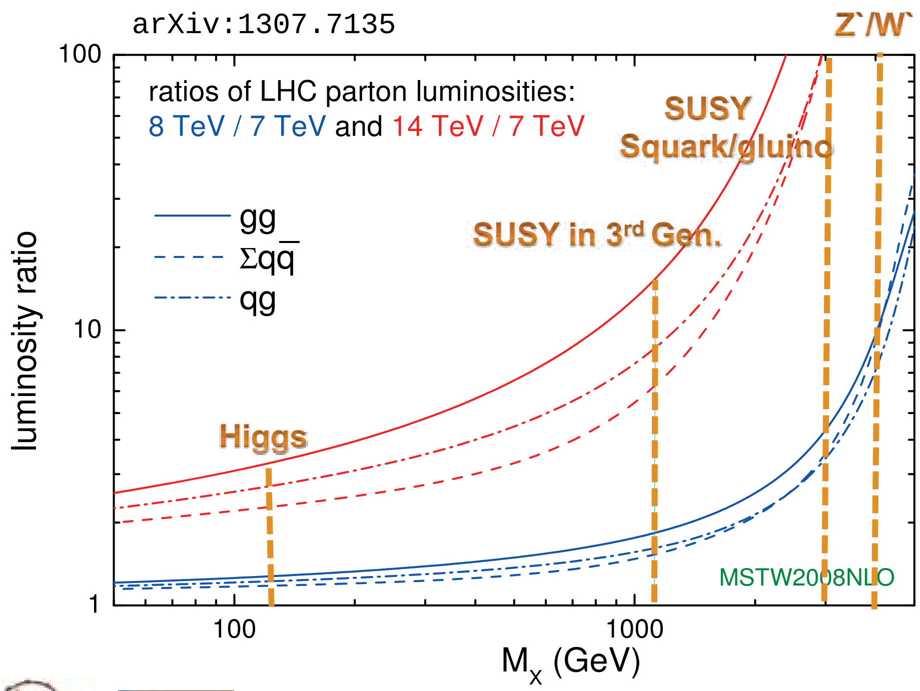
ATLAS Collaboration → https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
CMS Collaboration → https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

Studies of Future Physics Prospects

Both CMS and ATLAS studies have been performed for 5σ discovery reach with 300(0) fb^{-1} @ 14 TeV based on 20 fb^{-1} @ 8 TeV

① Conservative: all yields and uncertainties scaled by lumi and cross-section

② Optimistic: relative background uncertainty is assumed to be same

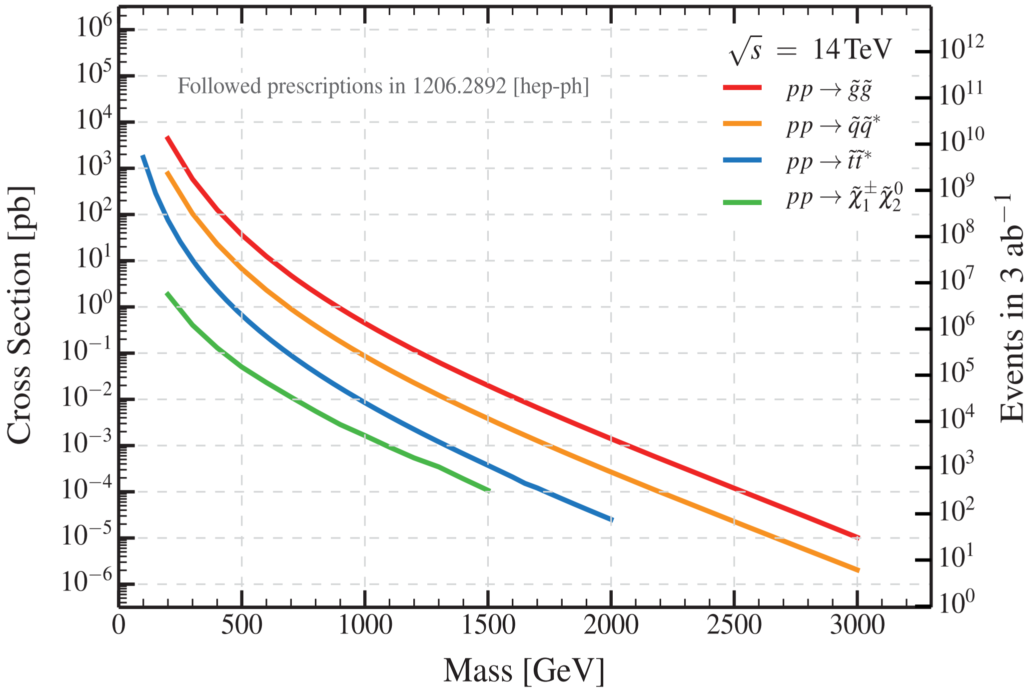


Strategies

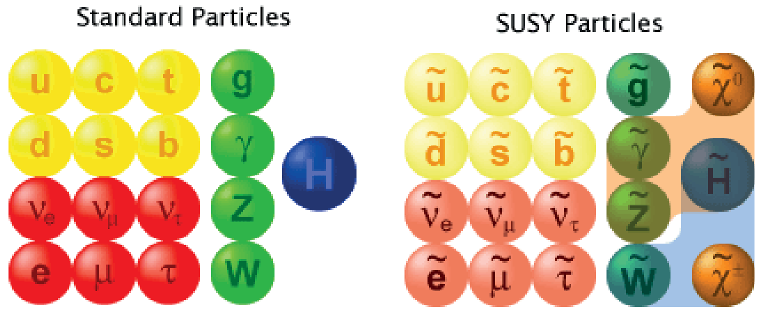
- Only slight analysis re-optimization
- No potential degradation studies
- All analyses have individual approach for projections:

taken into account relevant parameters

Searches for Supersymmetry at HL-LHC



- The strongest motivation for Supersymmetry (SUSY) comes from the need to stabilize the mass of the Higgs boson.
- The mass of the Higgs boson receives quadratic radiative corrections from particles at higher energy scales.



SM fermions ⇔ SUSY bosons
SM bosons ⇔ SUSY fermions

quarks leptons gauge bosons squarks sleptons gauginos

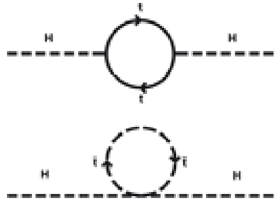
In order to be "natural" (i.e. to avoid fine tuning), it is required that the mass of the top squark is relatively small.

$\mu \sim m_h \sim 125$ GeV and:

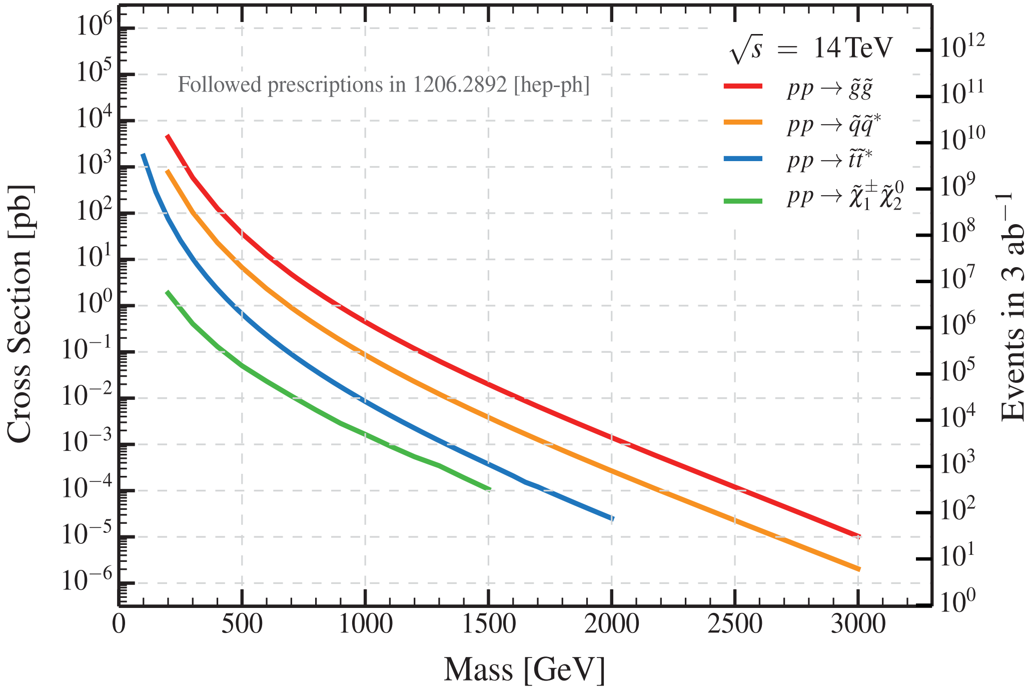
$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

EWK SUSY sector

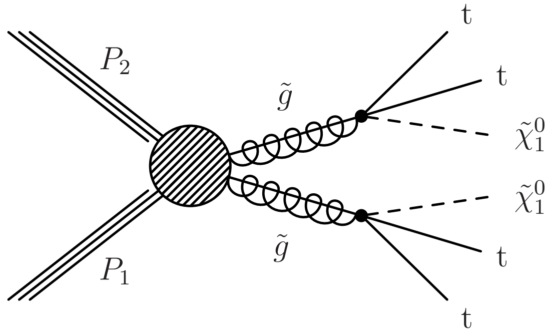
Stop and gluino contribution



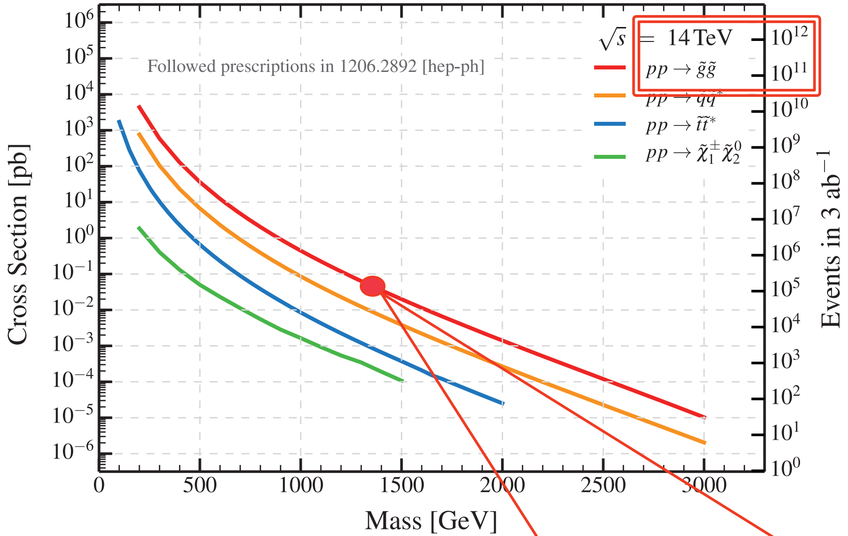
Strongly produced SUSY



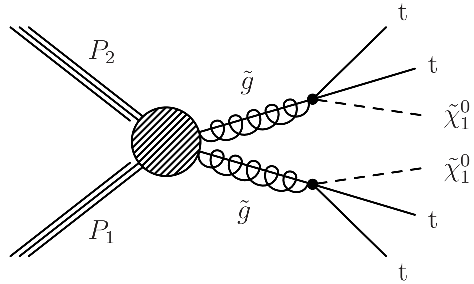
3rd generation squarks expected to be light compared to 1st and 2nd generation. Gluinos can decay with large branching fraction to 3rd generation squarks



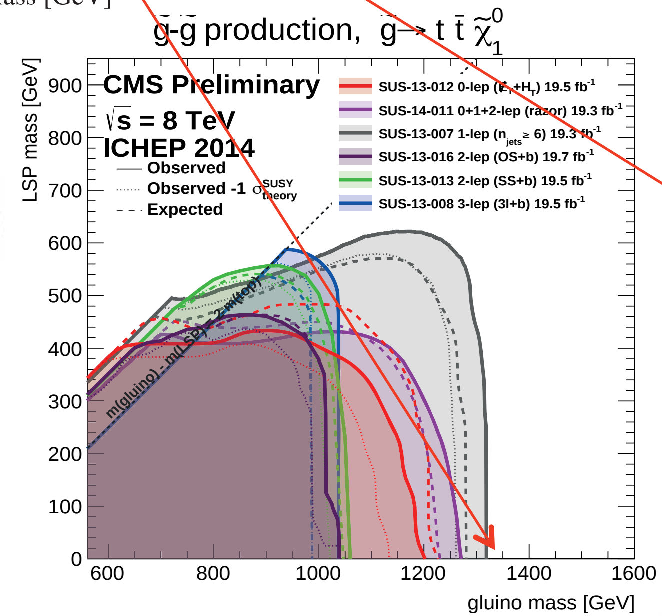
Strongly produced SUSY and Current Limits

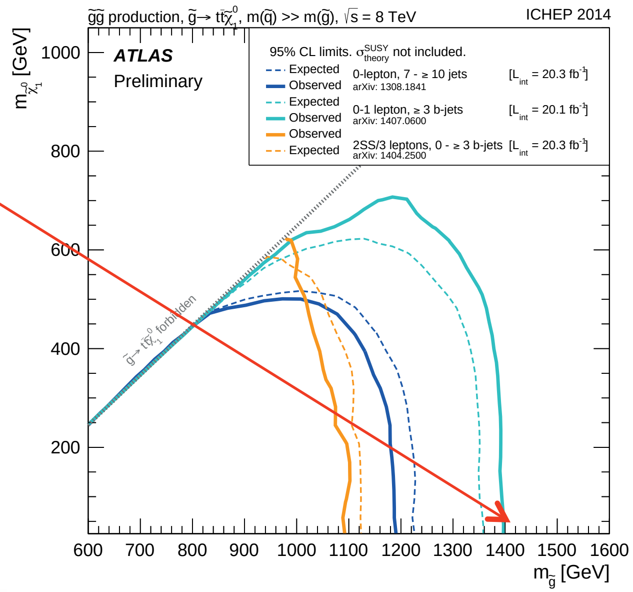


3rd generation squarks expected to be light compared to 1st and 2nd generation. Gluinos can decay with large branching fraction to 3rd generation squarks



Current limits from CMS and ATLAS collaborations @ ICHEP2014





Monte-Carlo Samples

Several Monte-Carlo (MC) generators are used to model the dominant SM processes and new physics signals relevant for the analyses.

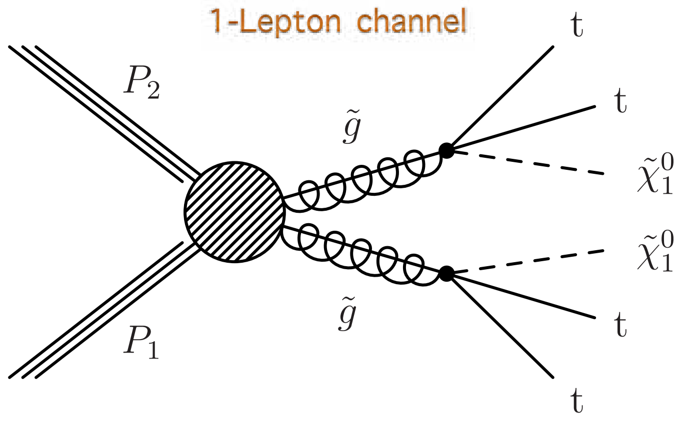
	ATLAS Collaboration	CMS Collaboration
SM Background	Top-pair, Diboson, W(*)+jets, Z(*)+jets: Sherpa W(*)+jets, Z(*)+jets: Alpgen ttV (V=W,Z), WWW,ZZZ, ZWW: Madgraph	Top-pair, Diboson, W(*)+jets, Z(*)+jets, ttV (V=W,Z), WWW,ZZZ, ZWW: Madgraph
Signal	Signal Samples, Prospino (xsec): Herwig++	Signal Samples, Prospino (xsec): Madgraph and Pythia6
PDF`s	cteq6l1 Madgraph and CT10 MC@NLO and Sherpa	Cteq6l1 and CT10
Detector	ATLAS fast simulation, based on parametrization of the trigger and detector response to generator level objects	Delphes fast simulation with CMS tuning, a few SM processes produced with full-simulation to validate Delphes simulation.

Strongly produced SUSY: Gluino Searches

CMS-PAS-FTR-13-014 (ECFA 2013)

Signal topology of such events:

- Many jets and Leptons
- Among them several b-jets
- Large missing energy (E_T^{Miss})



Pre-selection of events based on:

- An isolated electron (muon) p_T>20 GeV and $|\eta|$<2.5 (2.1)
- Leptons veto p_T>15 GeV, $|\eta|$<2.5
- nJets>6 p_T>40 GeV, $|\eta|$<2.4
- At least one b-tagged jet
- HT> 500 GeV and S_{Tlep} >250 GeV
- $\Delta\phi$ (W, Lepton)

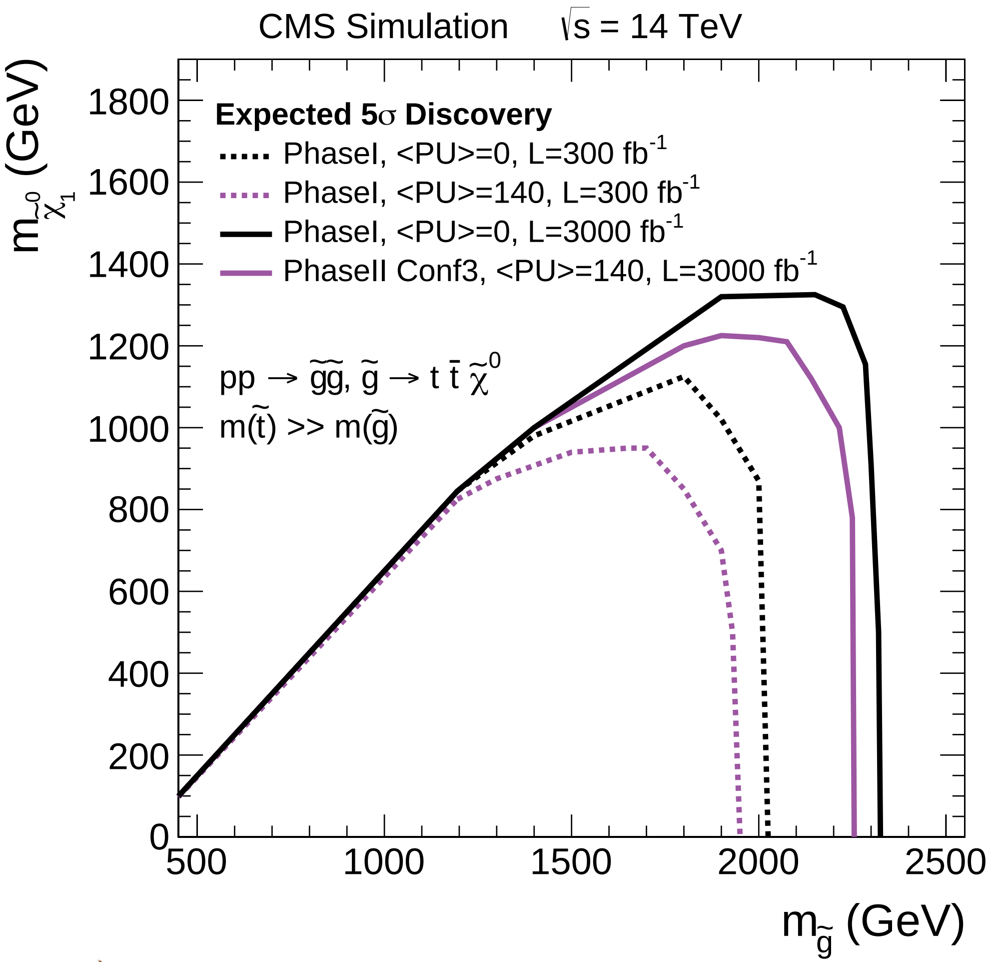
$$\underbrace{N^{\text{pred}}_{\text{SM}}(\Delta\phi(W,\ell) > 1)}_{\text{Signal region}} = R_{\text{CS}} \cdot \underbrace{N_{\text{data}}(\Delta\phi(W,\ell) < 1)}_{\text{Control region}}$$

Search regions: different S_T^{Lep} (MET + Σ_i $LepPt_i$) bins with different b-tagged jets

$$R_{\text{CS}} = \frac{N_{\text{signal}}}{N_{\text{control}}} = \frac{\text{Number of events with } \Delta\phi(W,\ell) > 1}{\text{Number of events with } \Delta\phi(W,\ell) < 1}$$

Single Lepton + b-tagged jets final state

Strongly produced SUSY: Gluino Searches



Search regions:

S_T^{lep}: [450, 550), [550, 650), [650, 750), and ≥ 750 GeV

N_b: =3, ≥ 4

- The uncertainty on the total SM background assumed to be 30 %

- The mass reach is reduced due to pileup by about ~ 100 GeV

- The discovery range of gluinos can be enhanced 300 GeV for 300 fb^{-1} to 3000 fb^{-1} up to 2.2 TeV, for χ_1^0 with mass of up to 1.2 TeV

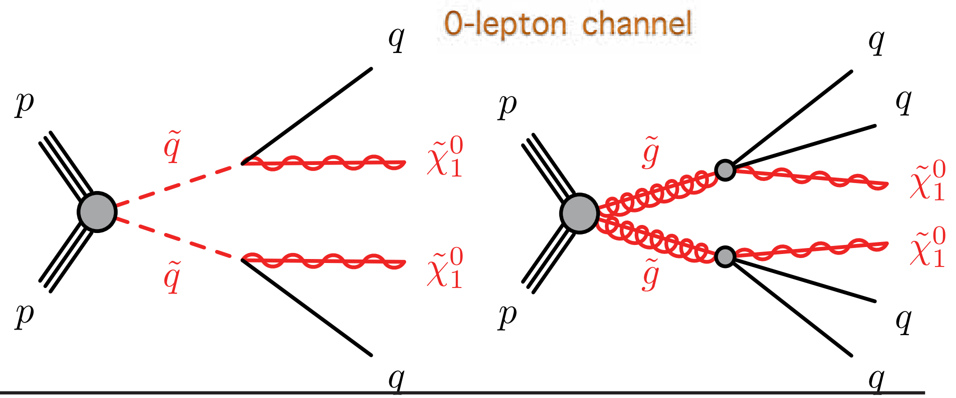
Strongly produced SUSY: Squark and gluino Searches

ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

Signal topology of such events:

- Many jets, no leptons
- Large missing energy (E_T^{Miss})
- Use of M_{eff} and $E_T^{Miss}/\sqrt{HT}$

The selection of events based on:



Selection	Channel									
	2jl	2jm	3j	4jl	4jm	4jt	5j	6jl	6jm	6jt
$p_T(j_1)$ [GeV] >	160									
$N_{jets}(p_T > 60$ [GeV]$) \geq$	2		3	4			5	6		
E_T^{miss} [GeV] >	160									
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$ [rad] >	0.4 (j_1, j_2, j_3), 0.2 (all $p_T > 40$ GeV jets)									
	$\langle\mu\rangle = 140$, 3000 fb^{-1} scenario									
E_T^{miss}/m_{eff} >	–	–	0.3	0.35	0.25	–	0.25	0.25	0.35	0.15
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] >	8	15	–	–	–	10	–	–	–	–
m_{eff} [GeV] >	4500, 5000	4500, 4900	4000	4000, 3800	4000	4500	4000	3400	3500	5000

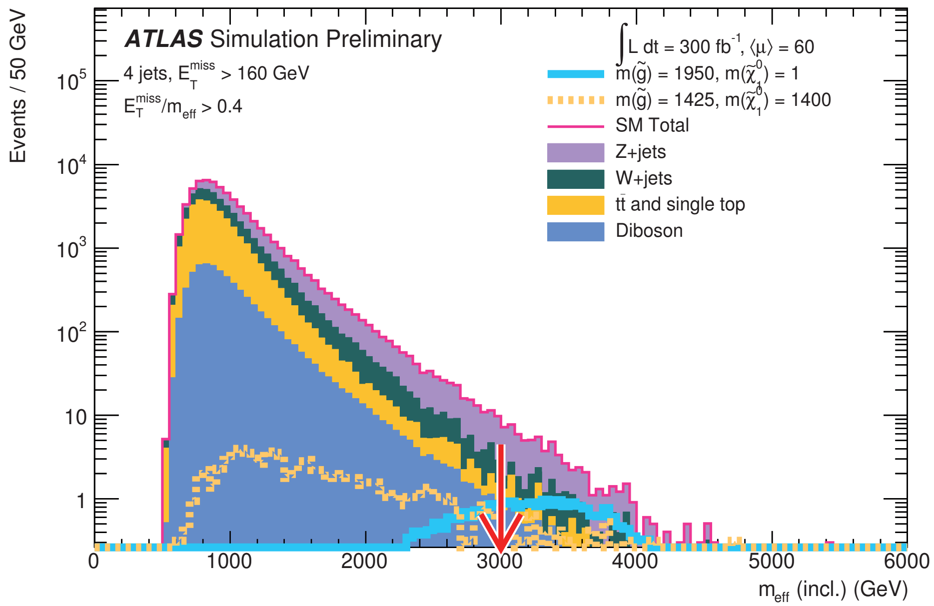
The uncertainty on the total SM background is assumed to be 10%.

Strongly produced SUSY: Squark and gluino Searches

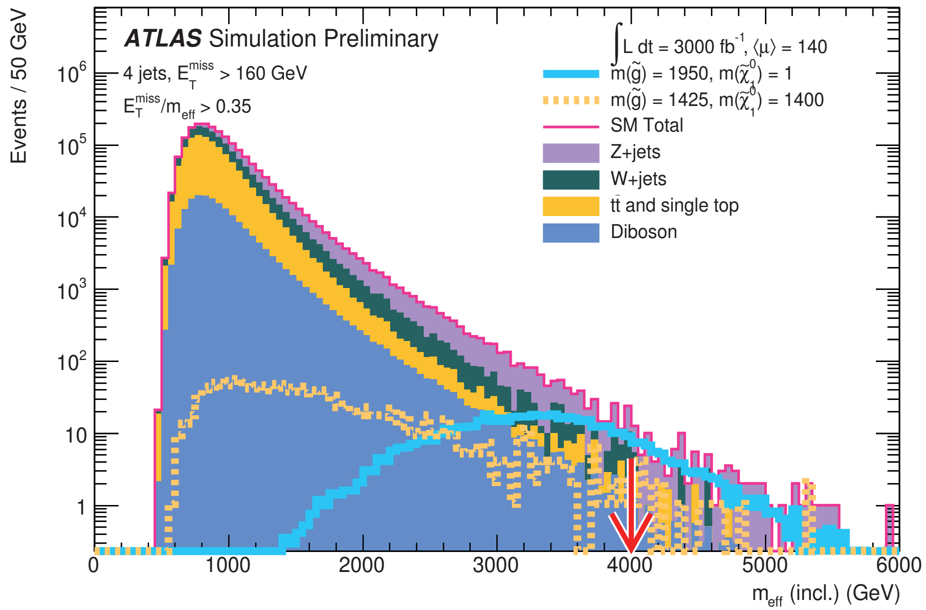
ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

Multiple signal regions have been optimized with requirements on the effective mass, E_T^{miss} and HT

$$m_{\text{eff}} = E_T^{\text{miss}} + \sum |p_T^{\text{jet}}| \quad , \quad E_T^{\text{miss}}/m_{\text{eff}} \quad , \quad E_T^{\text{miss}}/\sqrt{H_T}$$



(a) 4jl, 300 fb^{-1}



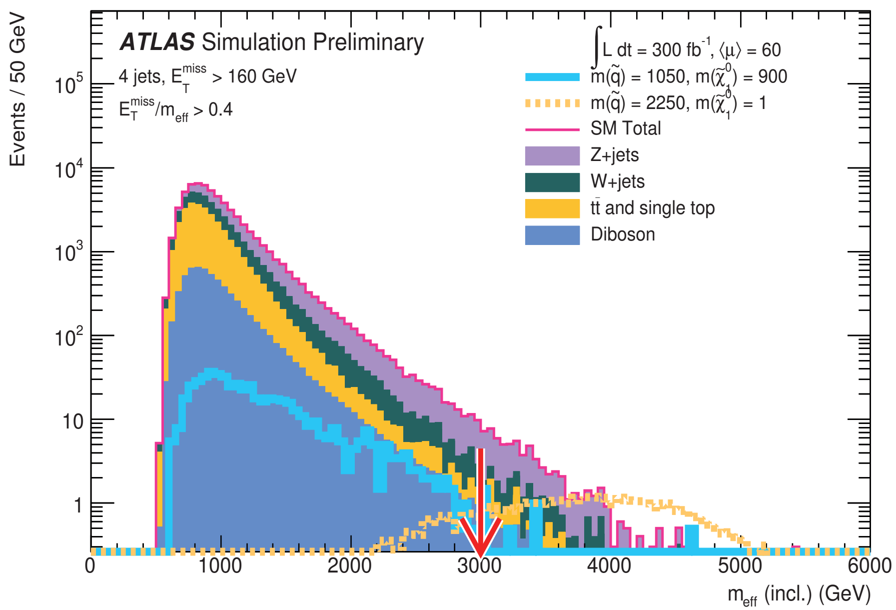
(b) 4jl, 3000 fb^{-1}

Gluino signals

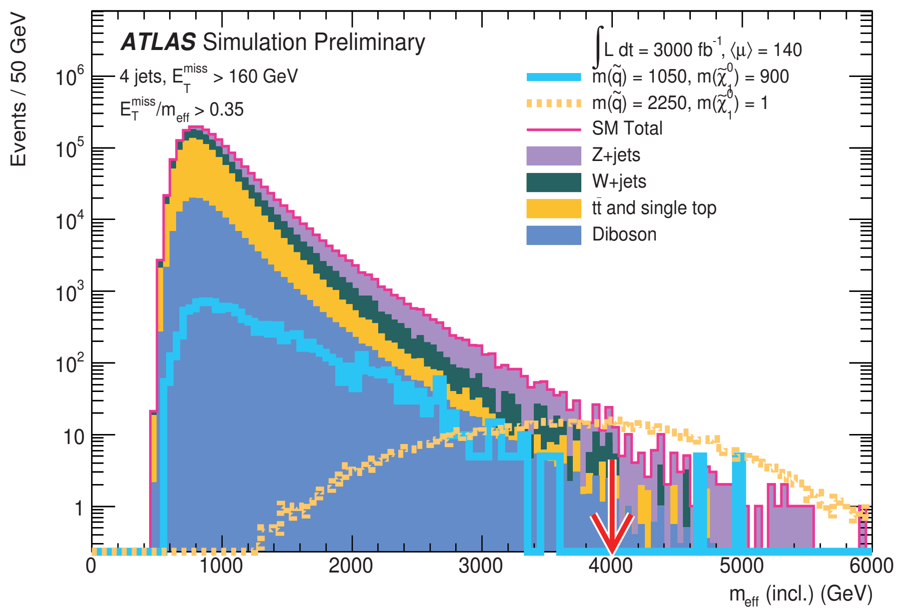
Strongly produced SUSY: Squark and gluino Searches

ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

- For squark-pair production two scenarios have been taken into account in this analysis:
  - The squarks are completely decoupled from gluino
  - The gluino mass is set to 4.5 TeV, which is above the expected HL-LHC
- The difference in selection efficiencies for these scenarios is found to be <30 %.



(c) 4jl, 300 fb^{-1}

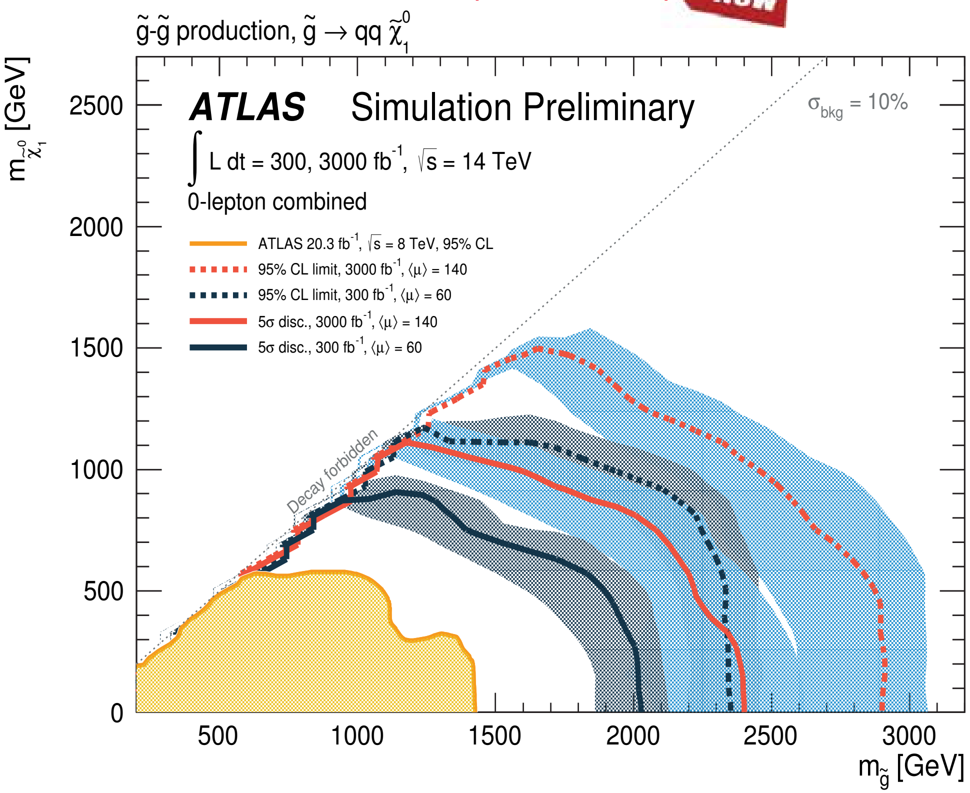


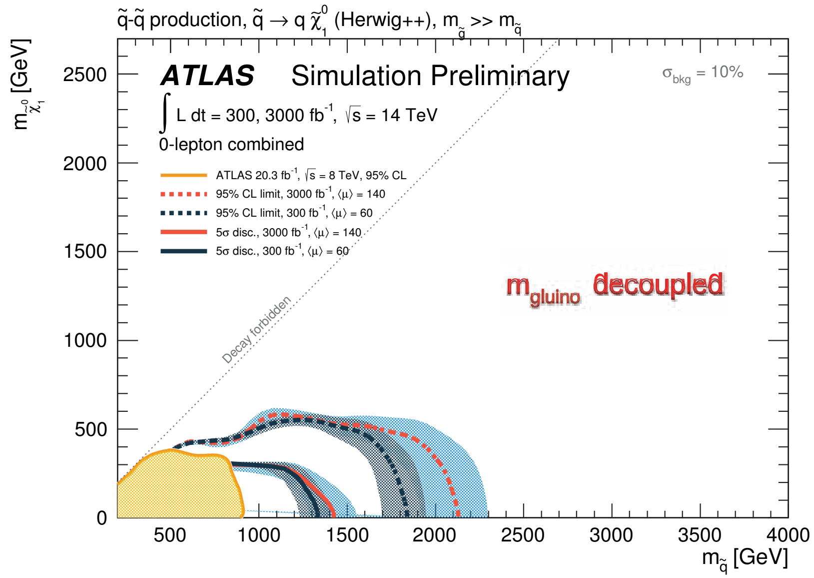
(d) 4jl, 3000 fb^{-1}

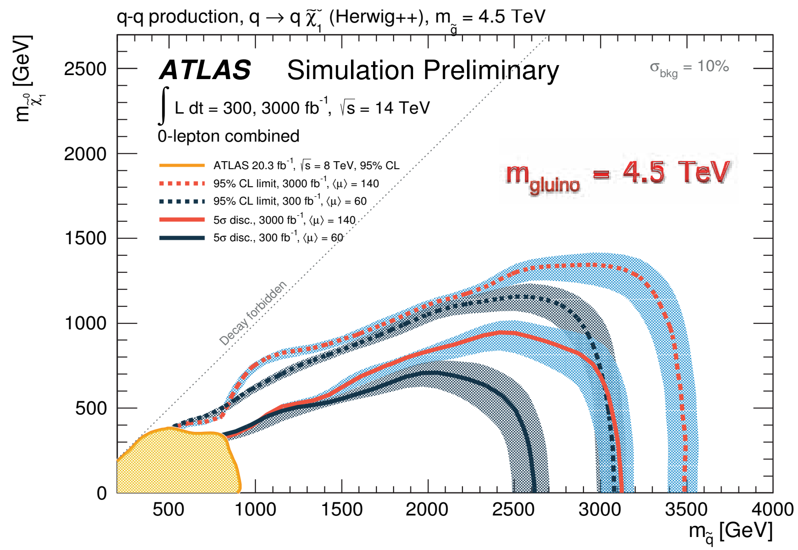
Squark signals

Strongly produced SUSY: Squark and gluino Searches

ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New



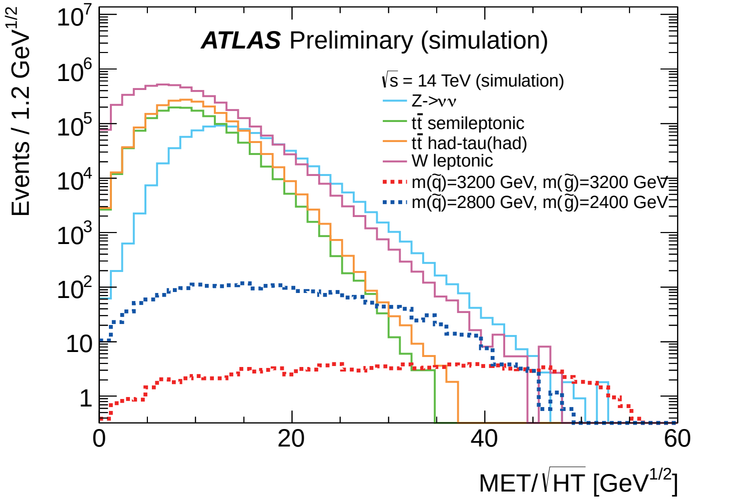


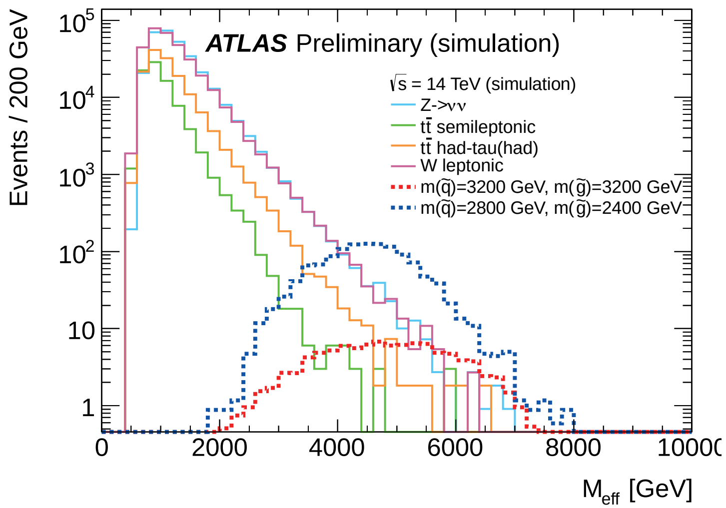


- **Gluinos** mass reach increases from 2 TeV to **2.4** TeV, and χ_1^0 from 800 GeV to **1.1** TeV

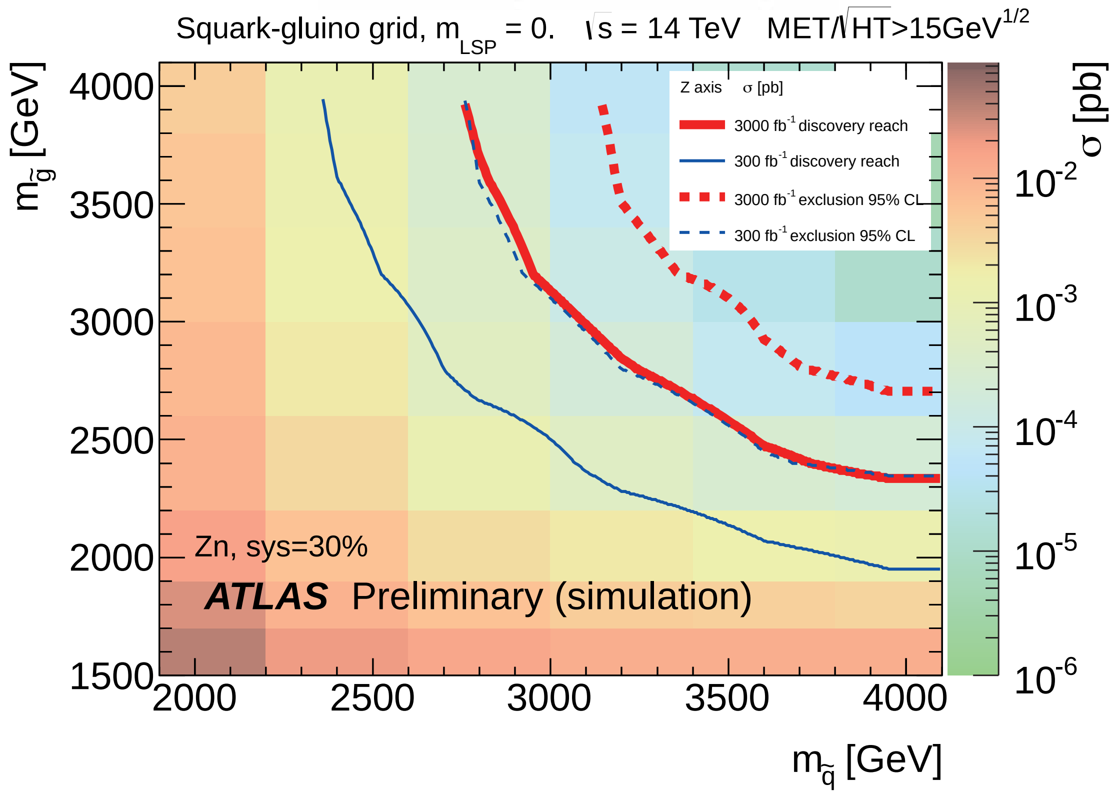
Strongly produced SUSY: Squark and gluino Searches

ATLAS-PHYS-PUB-2013-007 (Snowmass 2013)





Similar analysis from last year



Gain of ~400 GeV in gluino and squark mass

discovery reach (for $m_{LSP} = 0$) when going from $300\ fb^{-1}$ to $3000\ fb^{-1}$

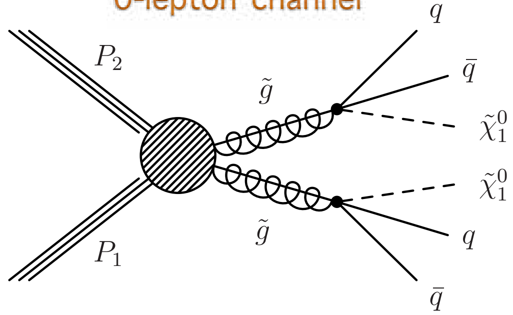
Strongly produced SUSY: Gluino Searches

CMS-PAS-FTR-13-014 (ECFA 2013)

Signal topology of such events:

- Many jets, no leptons
- Use of $H_T = \sum_{\text{jets}} p_T$ and $\not{H}_T = |-\sum_{\text{jets}} \vec{p}_T|$

0-lepton channel



Pre-selection of events based on:

- nJets>3 p_T > 50 GeV, |η| < 2.5
- Leptons veto p_T>10 GeV, |η| < 2.4(2.5)
- HT> 500 GeV and M_{HT} > 200 GeV
- HT> 500 GeV and S_{Tlep} >250 GeV
- |Δϕ (Jets$_{1,2}$, MHT)| > 0.5,
  |Δϕ (Jets$_3$, MHT)| > 0.3

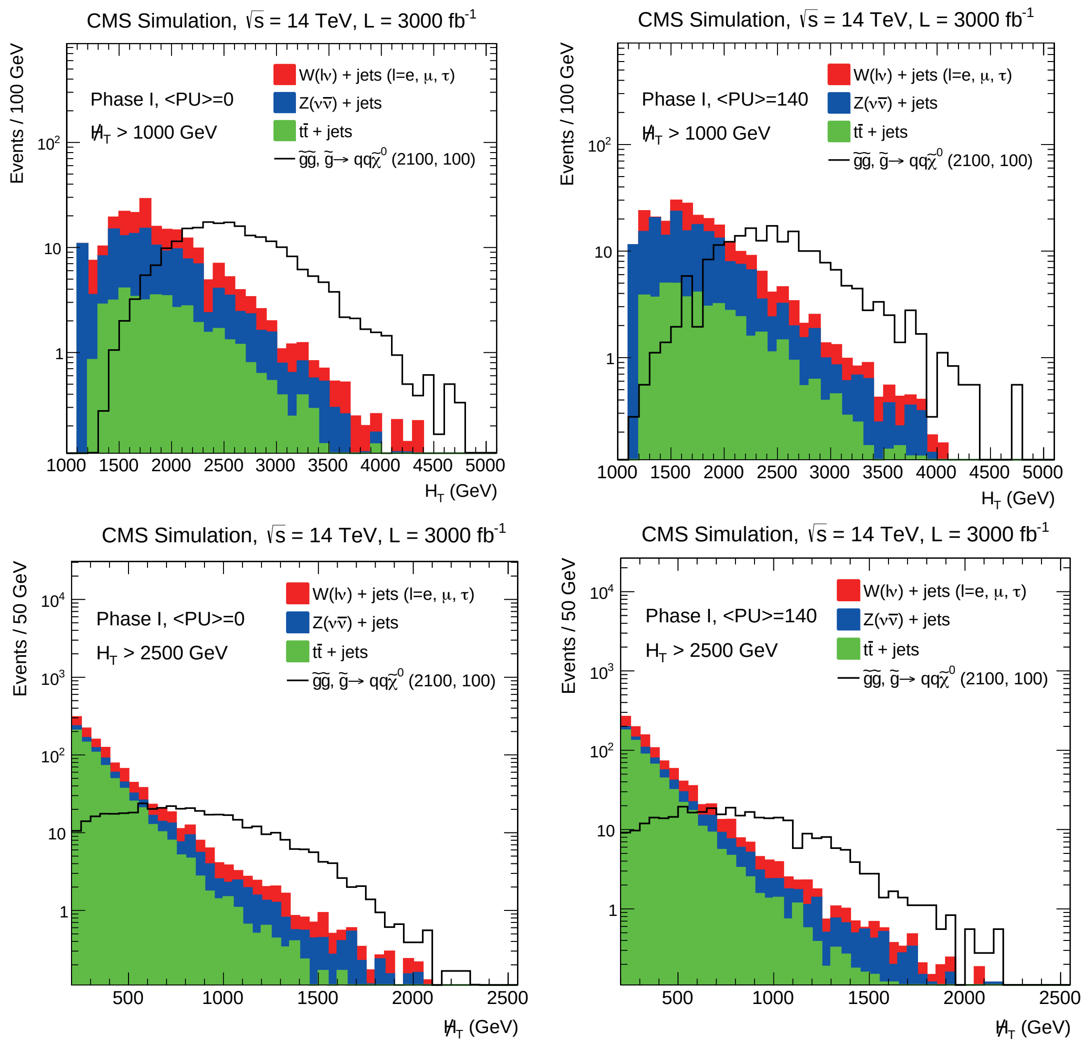
Search regions at 3000/fb

nJets > 6 HT > 2500 GeV MHT > 1000 GeV High gluino mass SR1	nJets > 6 HT > 1600 GeV MHT > 700 GeV High LSP mass SR2
nJets > 6 HT > 2000 GeV MHT > 1000 GeV Medium gluino and LSP masses SR3	nJets > 6 HT > 800 GeV MHT > 400 GeV Low gluino and LSP masses SR4

Strategy: Several exclusive search regions defined according to nJets, HT and M_{HT}

Strongly produced SUSY: Gluino Searches

CMS-PAS-FTR-13-014 (ECFA 2013)



- The uncertainty on the total SM background is assumed to be 30% based on typical CMS analysis at 8 TeV.
- All plots are done with Phase I detector with (140 PU) and without pile-up interactions
- Benchmark signal:

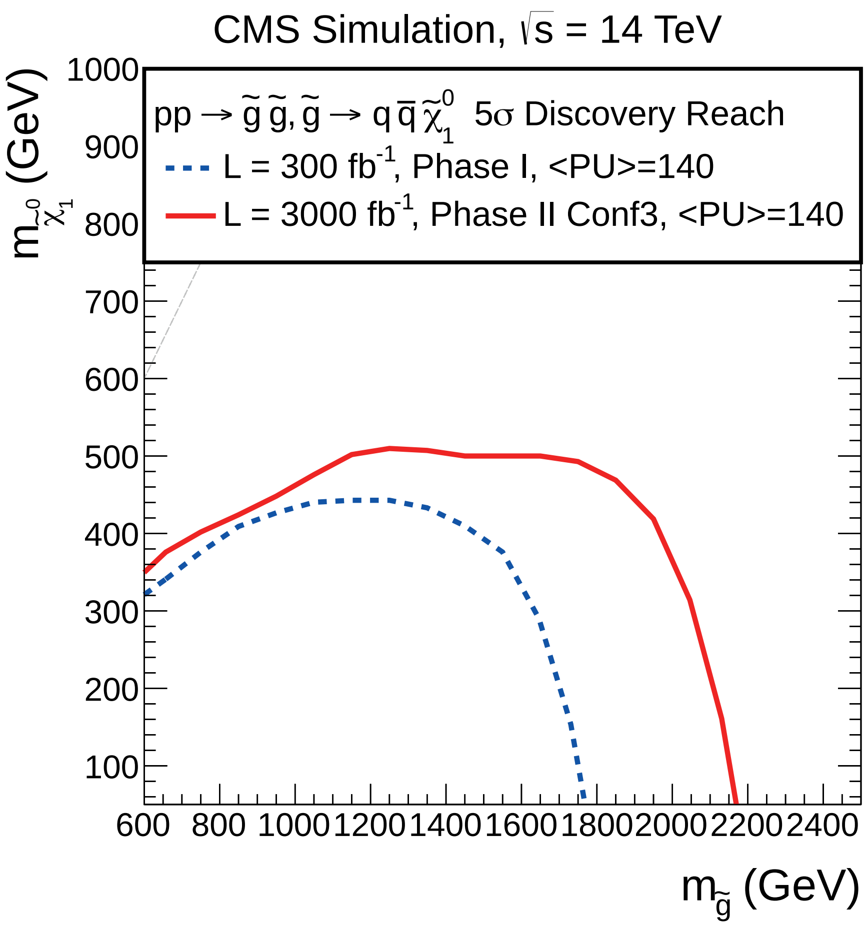
  $\tilde{g} \rightarrow qq\tilde{\chi}^0$ (2100, 100)

- Pile-up interactions do not have a major impact in the search regions.

Strongly produced SUSY: Gluino Searches

CMS-PAS-FTR-13-014 (ECFA 2013)

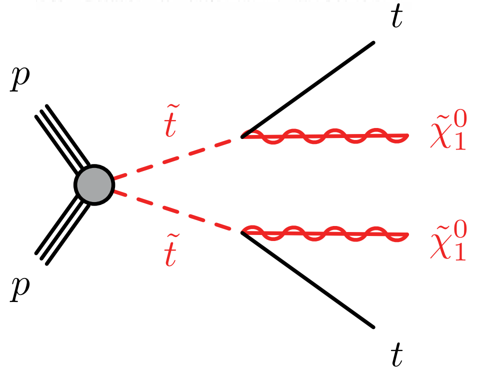
- Gluino masses up to ~ **2.2 (1.8)** TeV and LSP masses up to ~ **500 (400)** GeV can be discovered at √s = 14 with an integrated luminosity of 3000 (300) fb^{-1}.



Third generation SUSY: direct stop searches

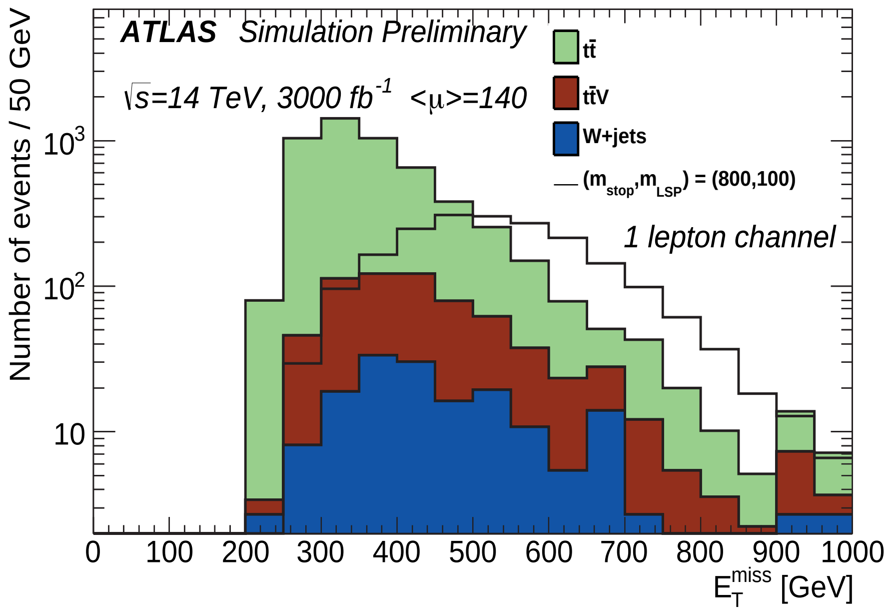
ATLAS-PHYS-PUB-2013-011 (ECFA 2013)

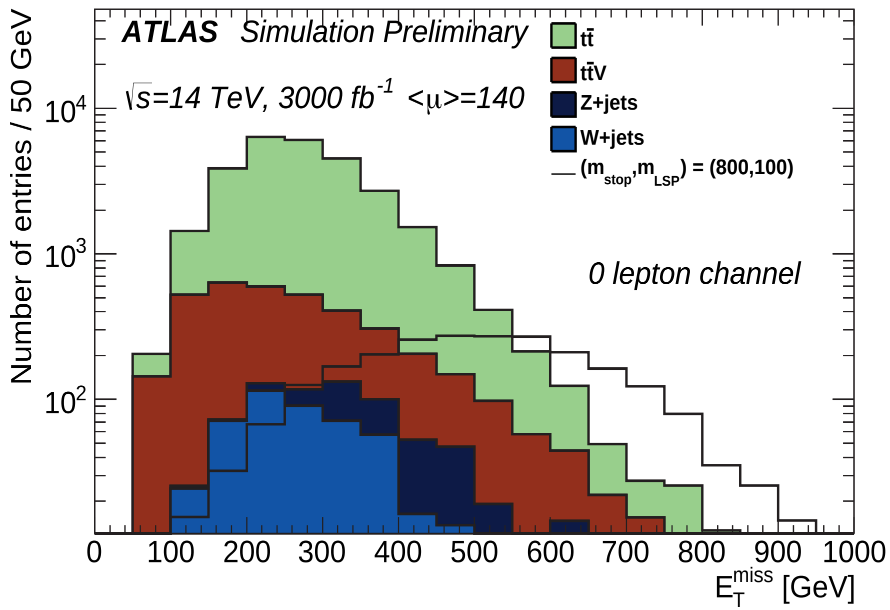
0- and 1-lepton channel



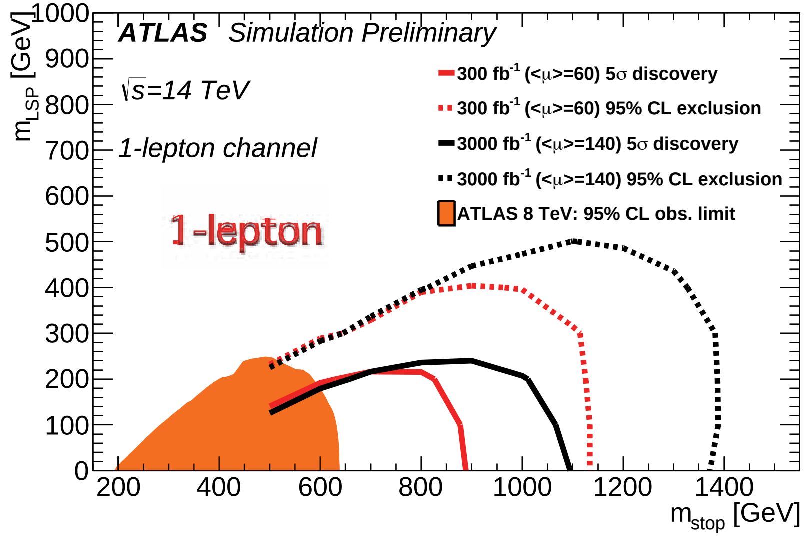
Signal topology of such events:

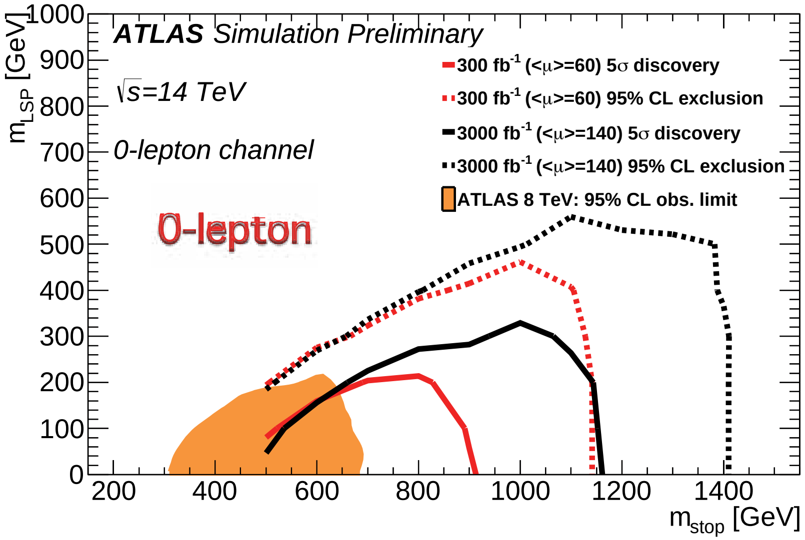
- A one lepton (e, mu) based selection
- An all-hadronic selection, vetoing on the presence of leptons (e, mu)
- HT, E_T^{Miss}, M_T, $\Delta\phi$ (lep, ETmiss), $E_T^{miss}/\sqrt{H_T}$

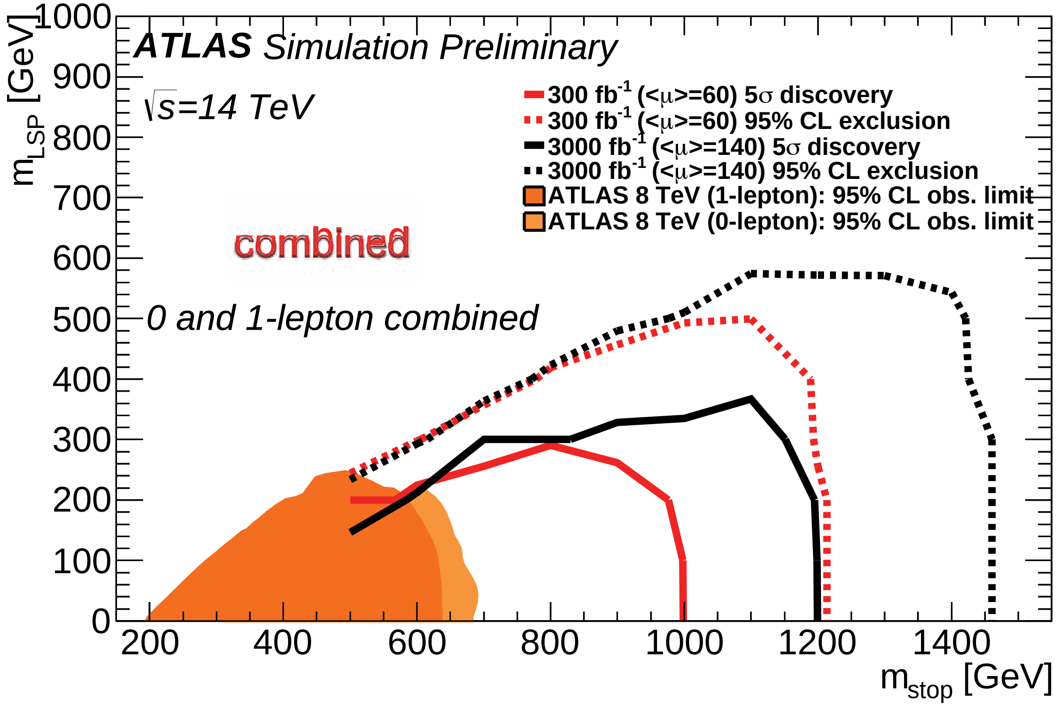




Third generation SUSY: direct stop searches





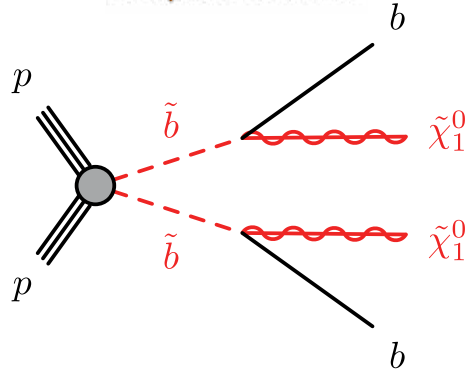


- Discovery and exclusion potential for the 1-lepton and 0-lepton analyses. For LSP masses below ~ **300** GeV a stop discovery at 5σ would be possible with 3000 fb^{-1} for stop masses up to ~ **1.2** TeV

Third generation SUSY: direct sbottom searches

ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

0-lepton channel



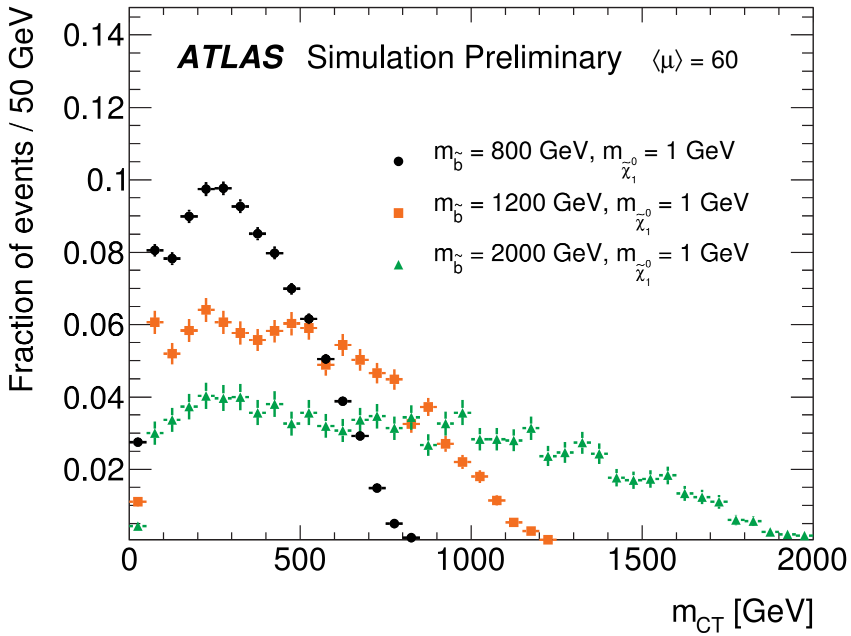
Signal topology of such events:

- An all-hadronic selection with b-tagged jets, vetoing on the presence of leptons (e, mu)
- E_T^{Miss}, M_{CT}, $\Delta\phi$ (lep, E_T^{Miss}), m_{bb}

➢ The main variable used to discriminate the bottom squark pair signal from background is the boost corrected cotransverse mass:

$$m_{CT}^{max} = \frac{m^2(\tilde{b}) - m^2(\tilde{\chi}_1^0)}{m(\tilde{b})}.$$

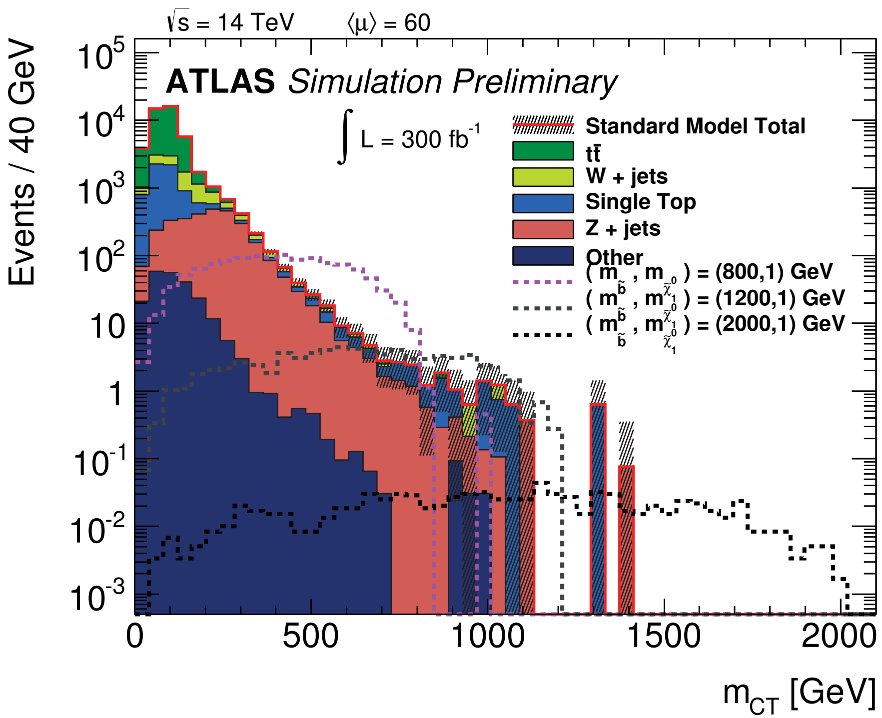
➢ m_{CT} is bounded by an analytical combination of particle masses.



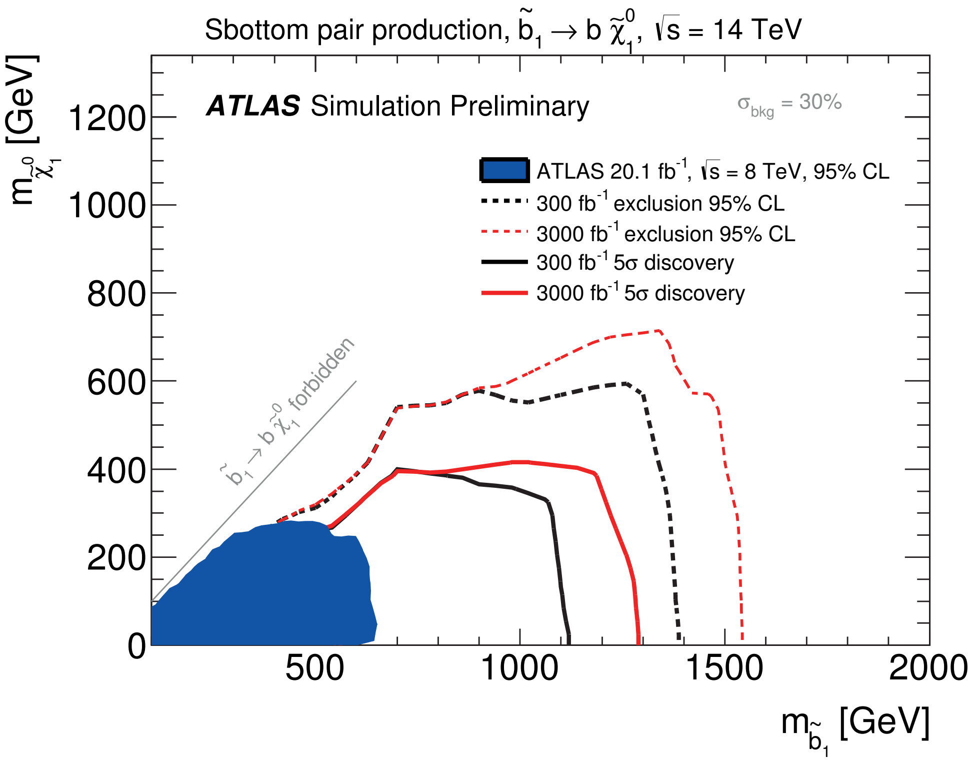
Third generation SUSY: direct sbottom searches

ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

- Different m_{CT} values have been studied for different signal regions. The systematic uncertainty for the signal regions have been assumed to be 30%

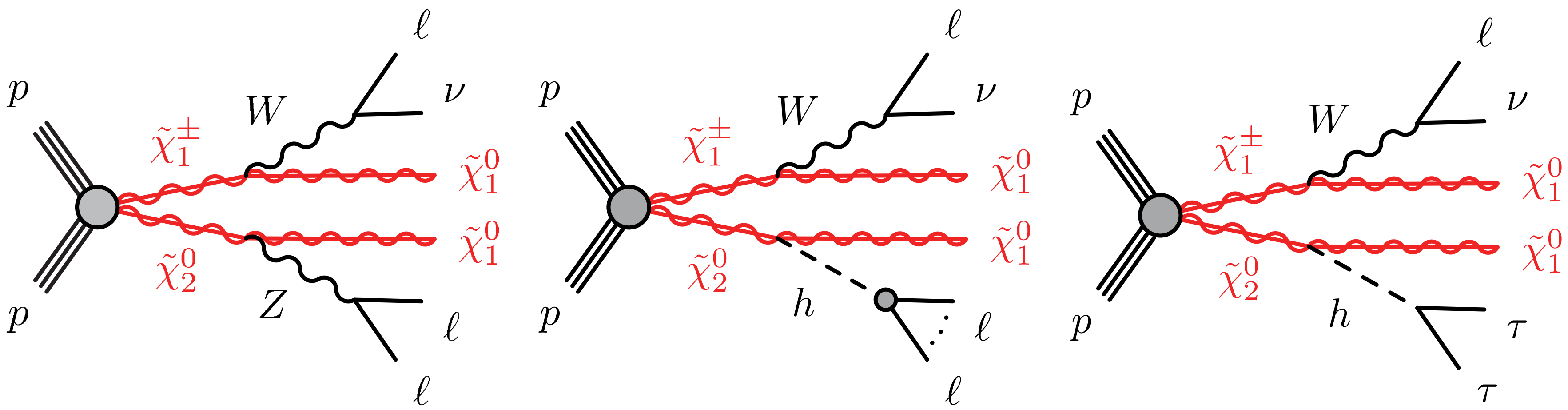


- Bottom squarks with masses of ~ **1100 (1300)** GeV can be discovered with 5σ significance with 300(3000) fb^{-1}.



Electroweak production of SUSY particles

- Searches for direct electroweak production of SUSY particles are challenging at the LHC due to its low production cross-section and low hadronic activities in the event



WZ-mediated | Wh-mediated (h→ ll) | Wh-mediated (h→ ττ)

- Analyses strategies: In order to reduce the background as efficiently as possible, it is concentrated on the decays where all bosons (W, Z and h) decay leptonically, leading to a final state with three leptons.

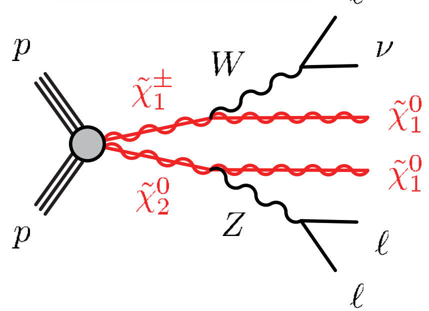
Electroweak production of SUSY particles

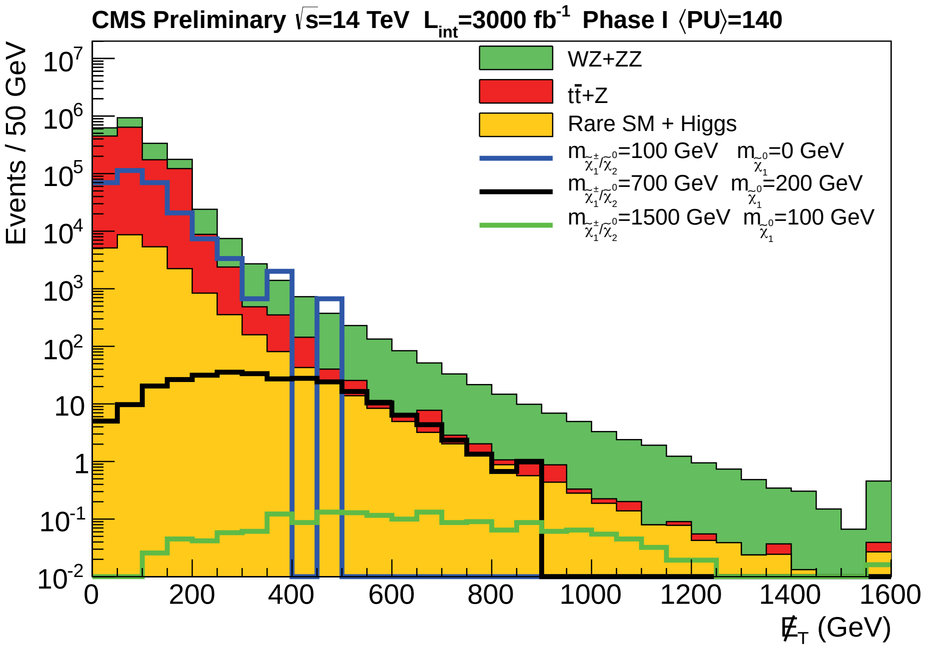
CMS-PAS-FTR-13-014 (ECFA 2013)

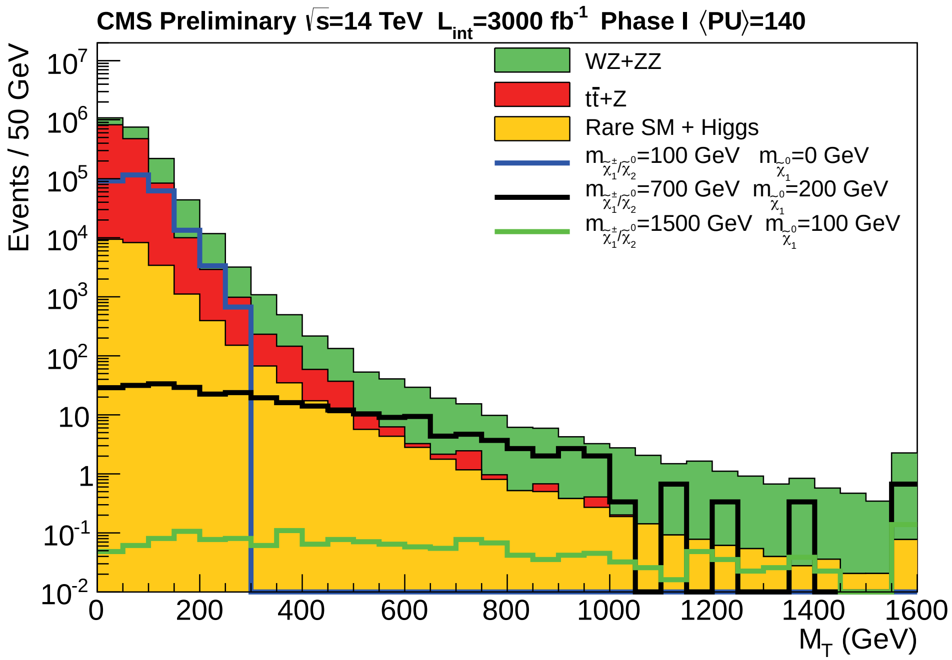
Signal topology of such events:

- Multi-leptons
- The presence of a pair of leptons with same flavor and opposite charge (OSSF)
- Select the pair closest to the Z-boson and the remaining lepton is assigned to the W decay

3-lepton channel







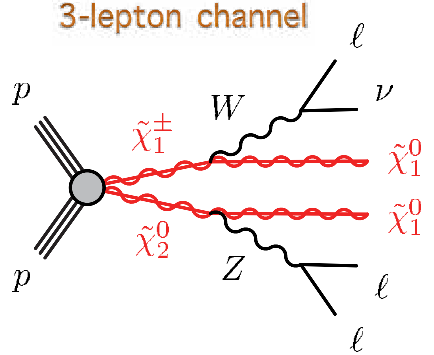
Electroweak production of SUSY particles

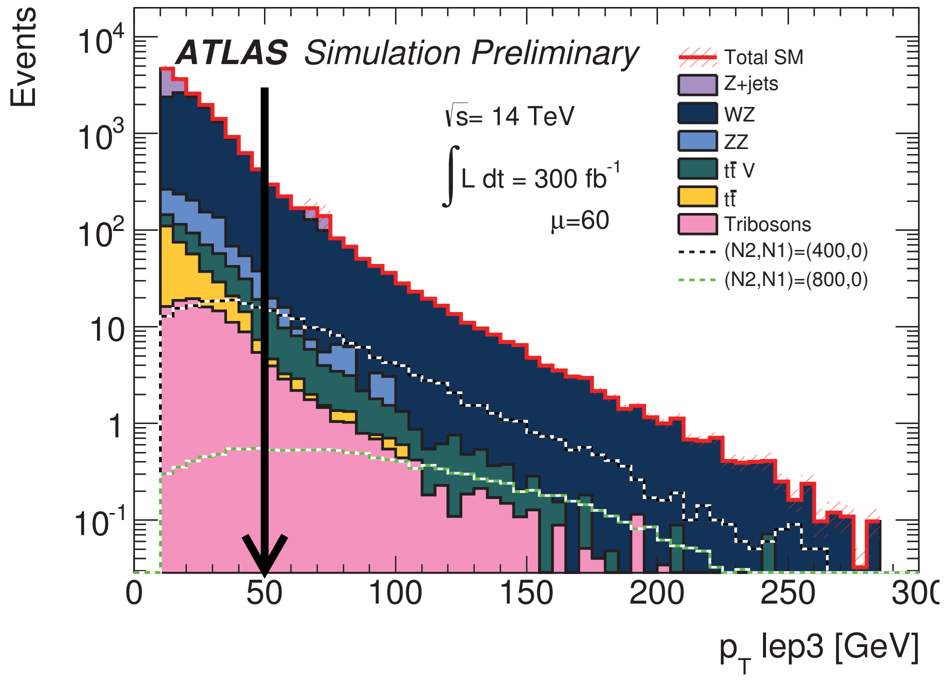
ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

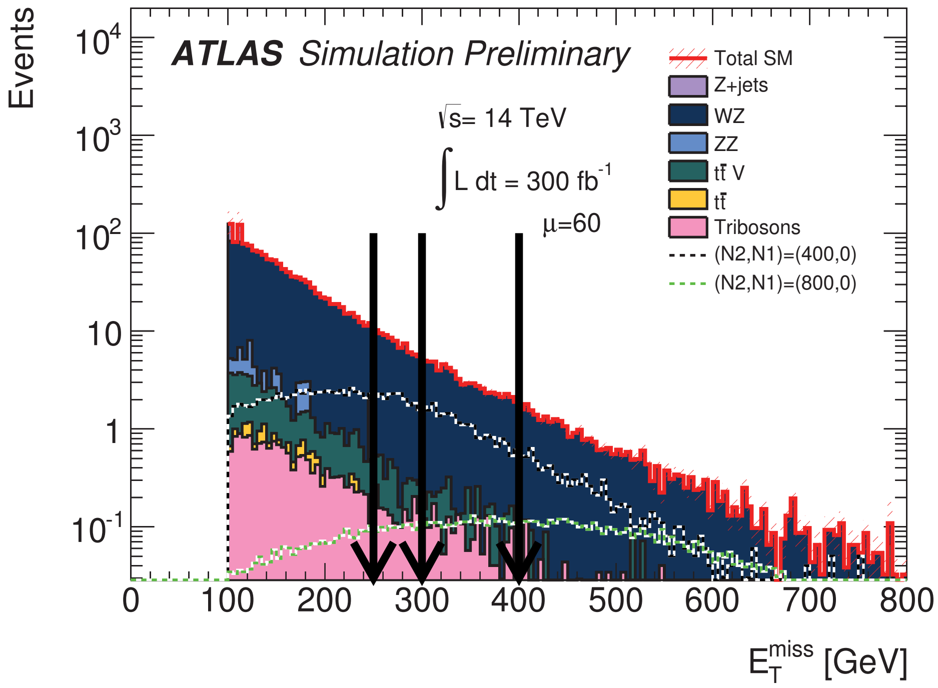
ATLAS analysis in the same production channel:

- Similar strategy based on OSSF pair in the event
- Events with b-tagged jets are vetoed
- M_T reconstructed from the third lepton (from W)

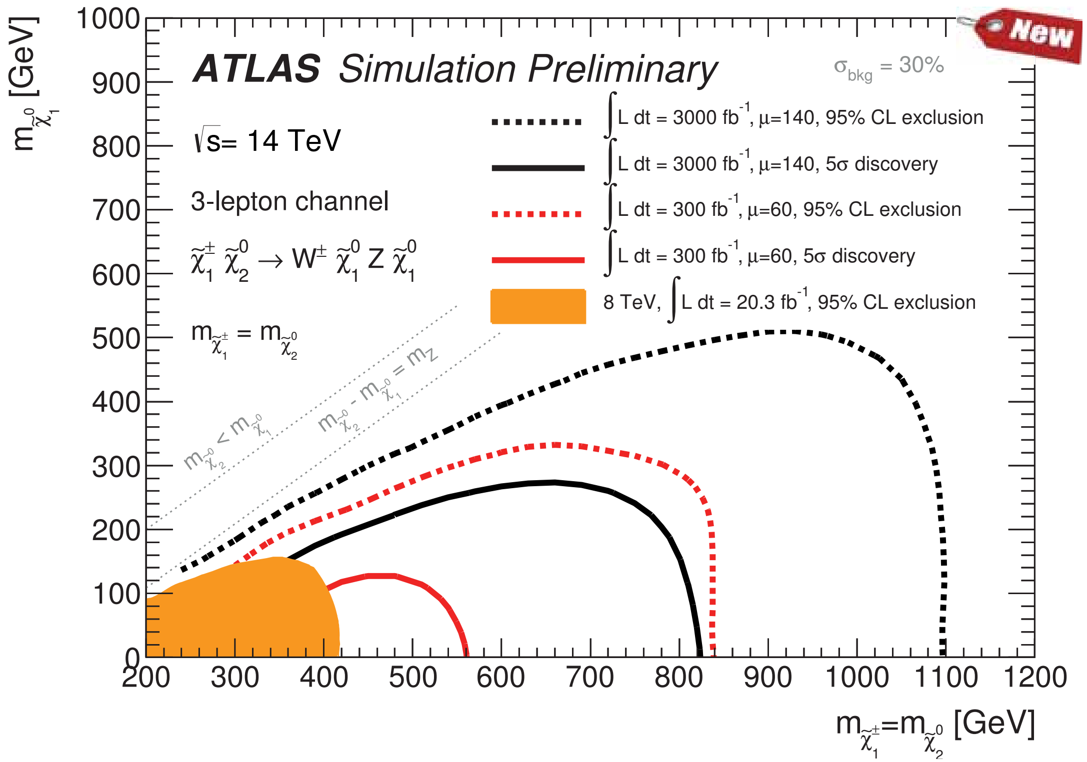
3-lepton channel

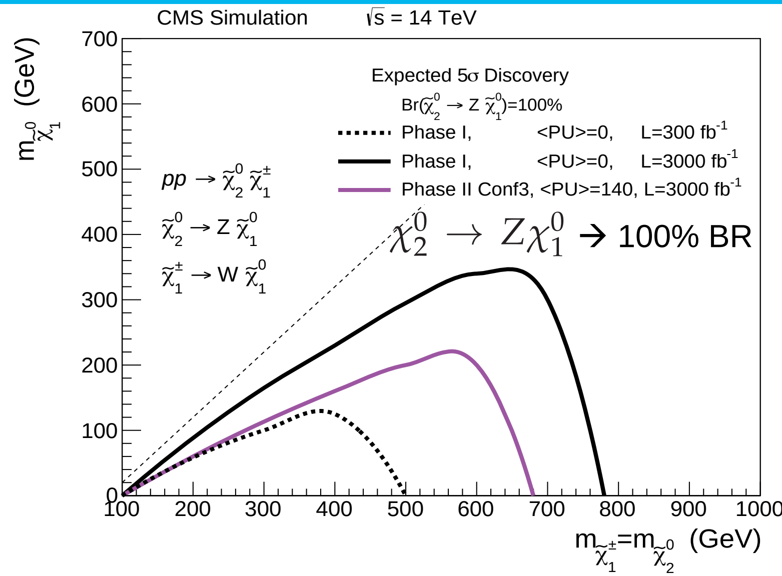


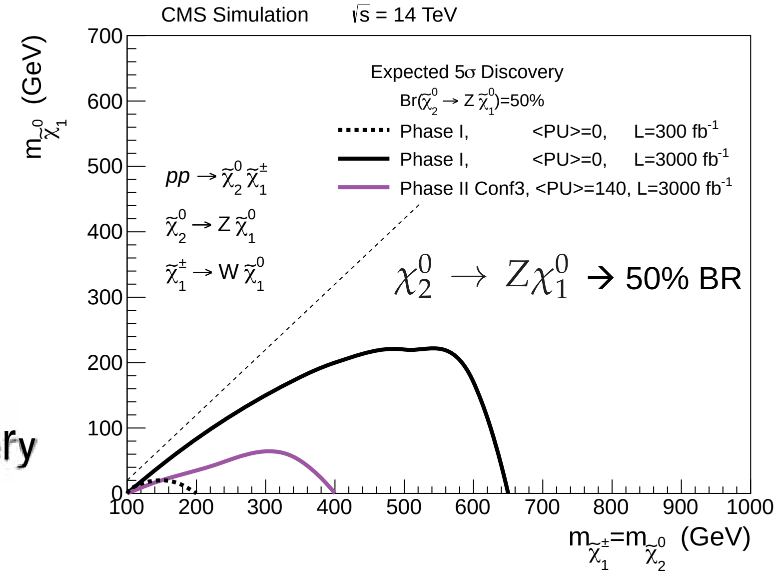




Electroweak production of SUSY particles







5σ discovery reach for the direct production of charginos and neutralinos, that decay to 100% (and 50%) via W and Z boson.

Gain of ~300 GeV in chargino/neutralino mass discovery reach when going from 300 fb^{-1} to 3000 fb^{-1}.

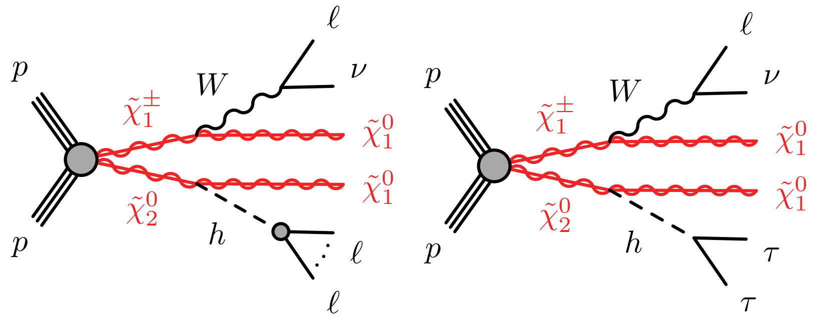
Electroweak production of SUSY particles

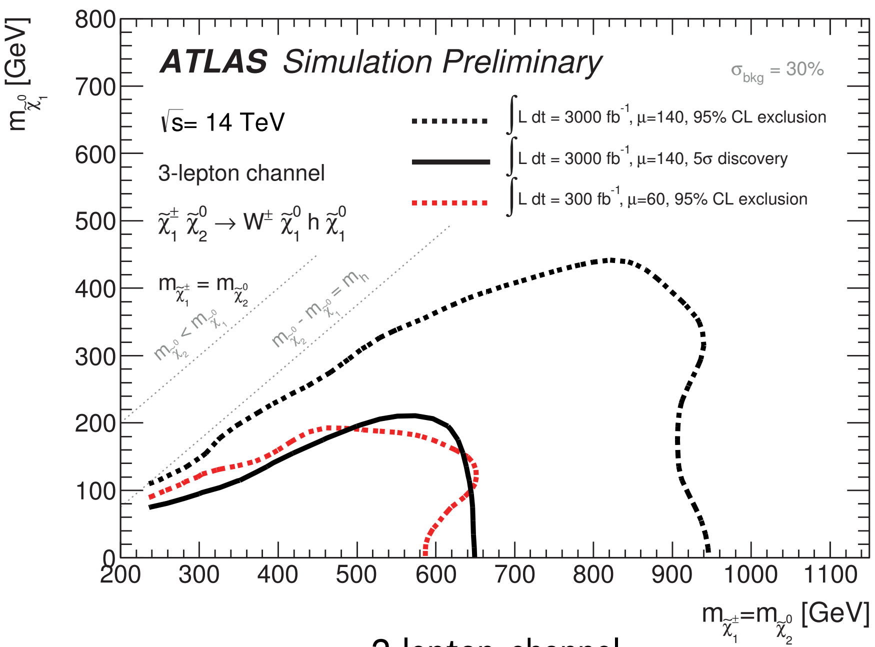
ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

Signal topology of Wh-mediated channel:

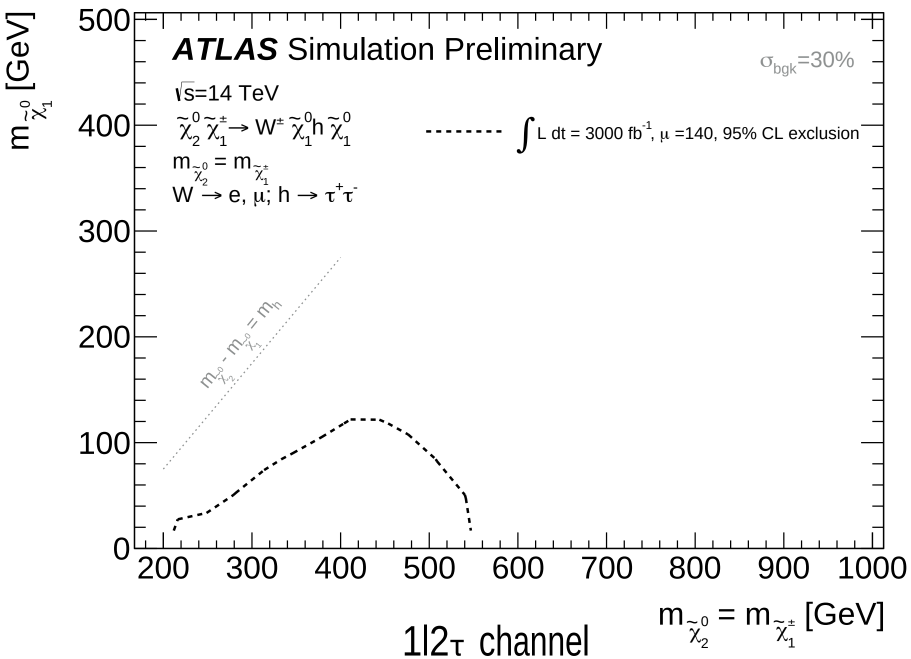
- Multi-leptons: 3-leptons with and without taus
- The presence of a pair of OSSF leptons and veto them for WZ contribution
- Veto b-tagged jets for ttH avd ttV contributions

3-lepton channel





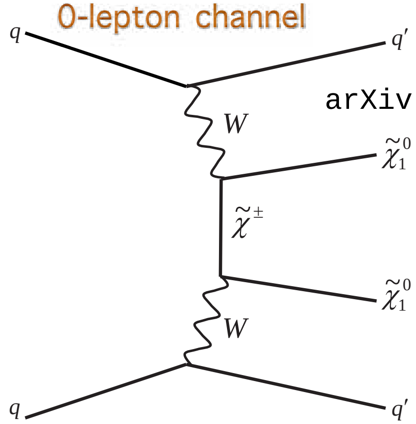
3-lepton channel



$1l2\tau$ channel

Vector Boson Fusion in SUSY

CMS-PAS-FTR-13-014 (ECFA 2013)



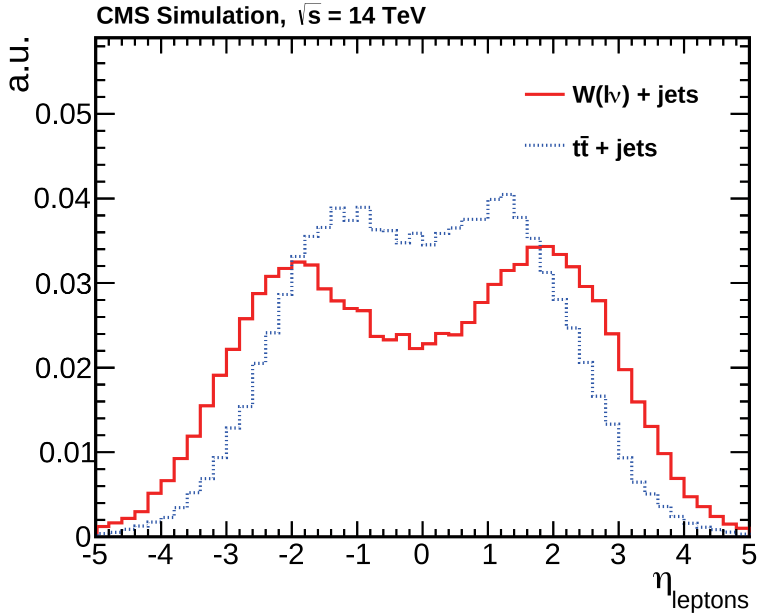
arXiv:1304.7779

Signal topology of such events:

- Two jets with large di-jet invariant mass in the forward region in opposite hemispheres
- Large E_T^{Miss}, and no leptons
- small cross-section → challenging at HL-LHC

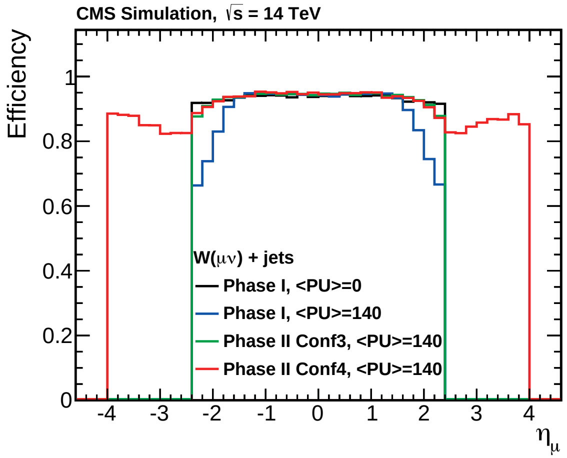
Selection of events based on:

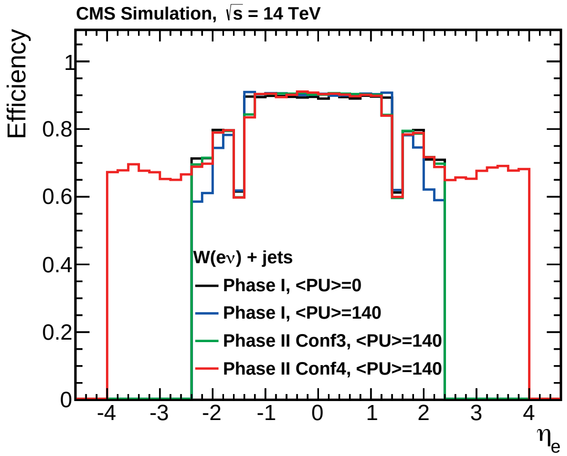
- nJets=2 p_T>30 GeV, $|\eta|$ < 5
- $\eta_1 - \eta_2 > 4.2$ $\eta_1 * \eta_2 < 0$
- p_{Tjet1} > 200 GeV, p_{TJet2} > 100 GeV
- M_{jj} > 1500 GeV
- Veto 3rd jet within jet1 and jet2
- Veto of b-tagged jet
- Veto of leptons, it is very crucial for the success of the analysis
- E_T^{Miss} > 200 GeV



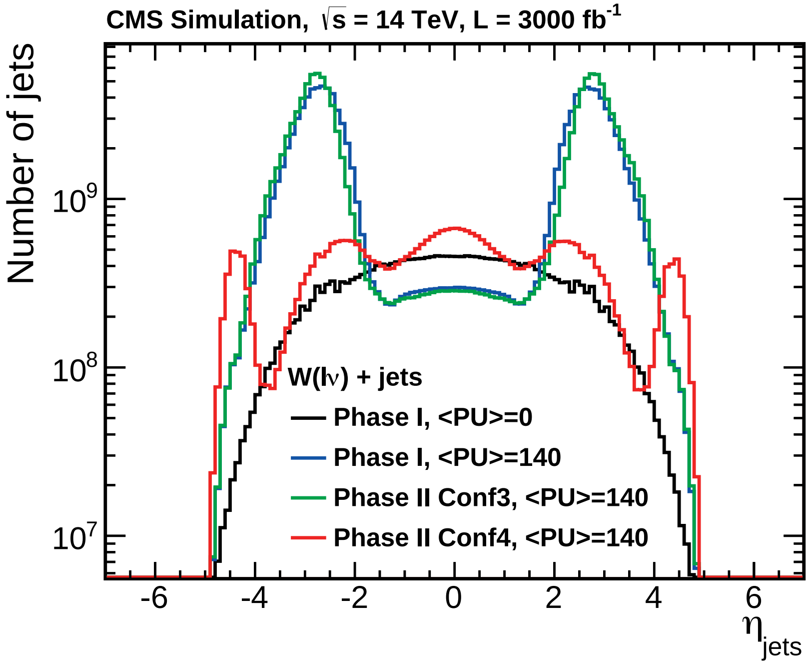
➢ A significant amount of leptons fall outside the current geometrical acceptance of $|\eta|$ < 2.5

Vector Boson Fusion in SUSY





- The lepton selection efficiency is crucial in order to achieve high efficiency for lepton vetoes to reduce W and tt backgrounds.

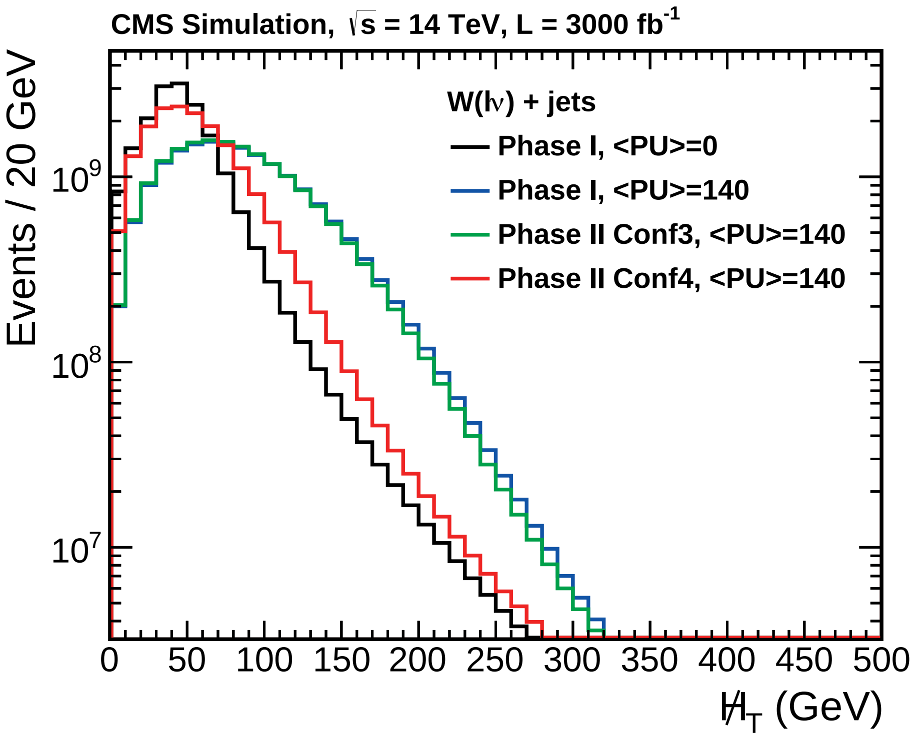


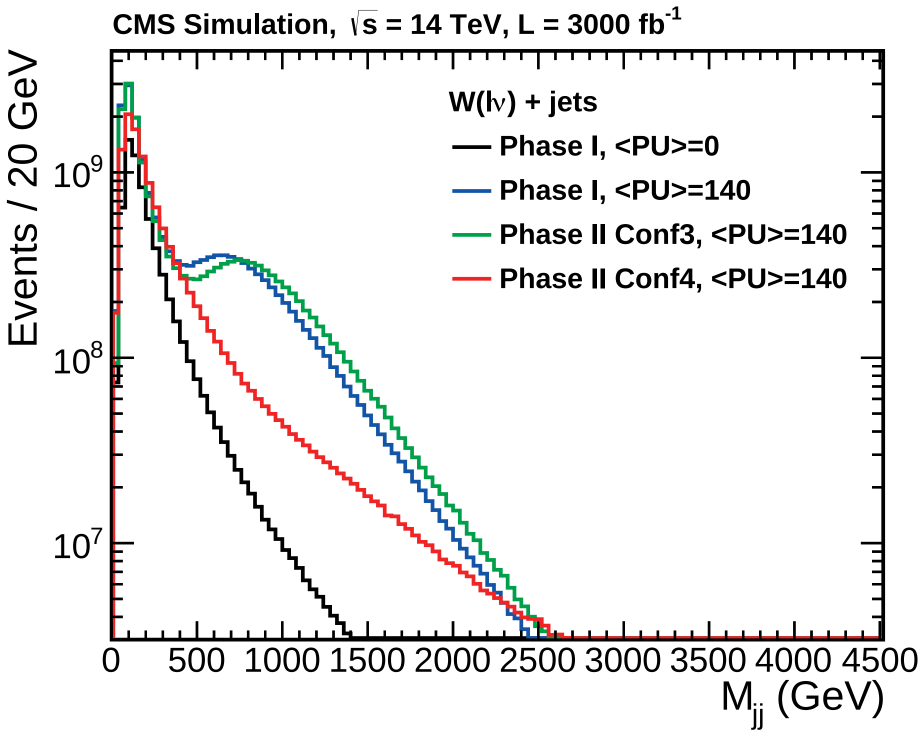
- The pileup jets outside the tracking coverage (CMS) are visible in **the forward region outside the tracking coverage** for 140 pileup scenarios.
- HL-LHC → the extended tracker coverage can reduce pileup jets substantially up to $|\eta| \sim 4$

Vector Boson Fusion in SUSY: Detector configuration

- Number of jets rises dramatically in forward region without tracking
  → MHT and Mjj strongly affected
- Analyses depending on measurement of forward jets profit most from <u>tracking up to $|\eta| < 4$</u>

➢ Background reduction by factor 3-10 expected

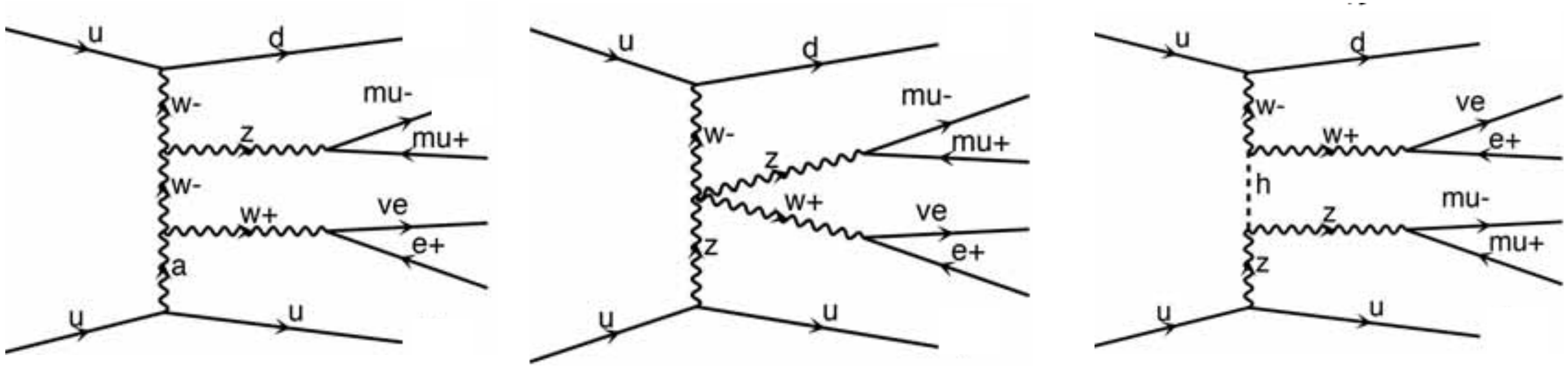




Vector Boson Scattering And Triboson Production

ATLAS-PHYS-PUB-2013-006 (ECFA 2013)

- Sensitivity to new physics can be achieved through heavy vector boson scattering via EWK processes.



A striking experimental feature of vector boson scattering is the presence of two high-*pT* jets in the forward regions, similar to those found in Higgs production via vector boson fusion.

- Vector boson scattering happen through
  - Double triple gauge coupling (TGC)
  - Quartic gauge coupling (QGC)
  - s-channel and t-channel Higgs scattering
- Observation
  - Cross-section rises quickly with the energy
  - Exploring gauge-Higgs sector in detail

Vector Boson Scattering: Results for ZZ channel

ATLAS-PHYS-PUB-2013-006 (ECFA 2013)

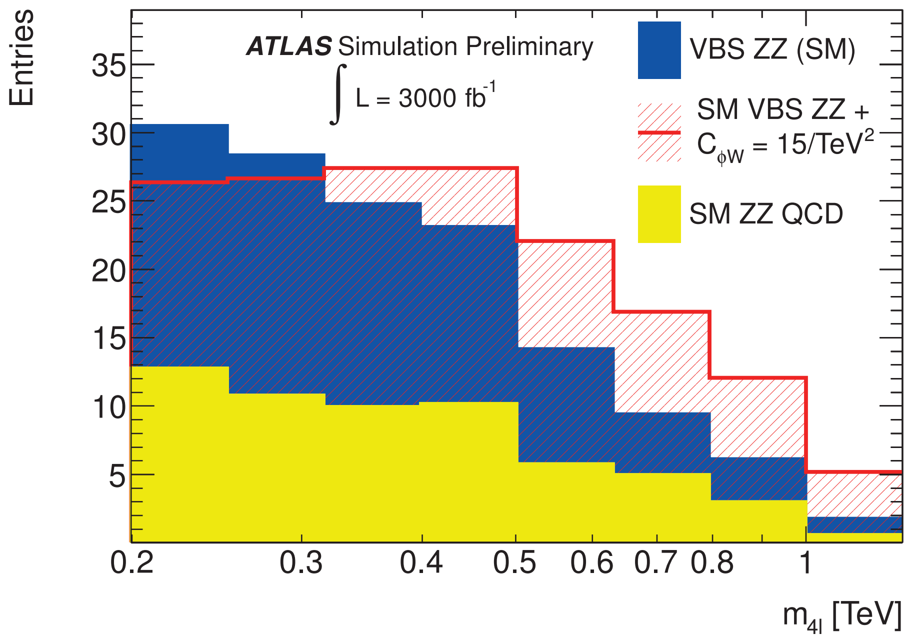
Signal topology of such events:

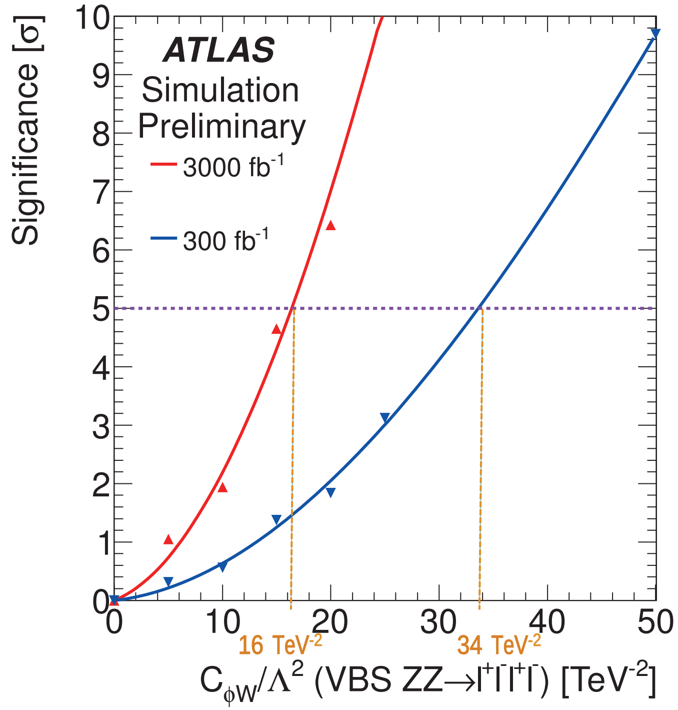
- Multi-leptons with two forward jets
- M_{jj} > 1 TeV for non-VBS diboson production
- small cross section but provides clean, reconstructible final state.

VBS $ZZ \rightarrow \ell\ell\ell\ell$

Direct interaction of the gauge boson fields via a field strength tensor

$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} \mathrm{Tr}(W^{\mu\nu} W_{\mu\nu}) \phi^\dagger \phi$$





Vector Boson Scattering: Results for WW channel

ATLAS-PHYS-PUB-2013-006 (ECFA 2013)

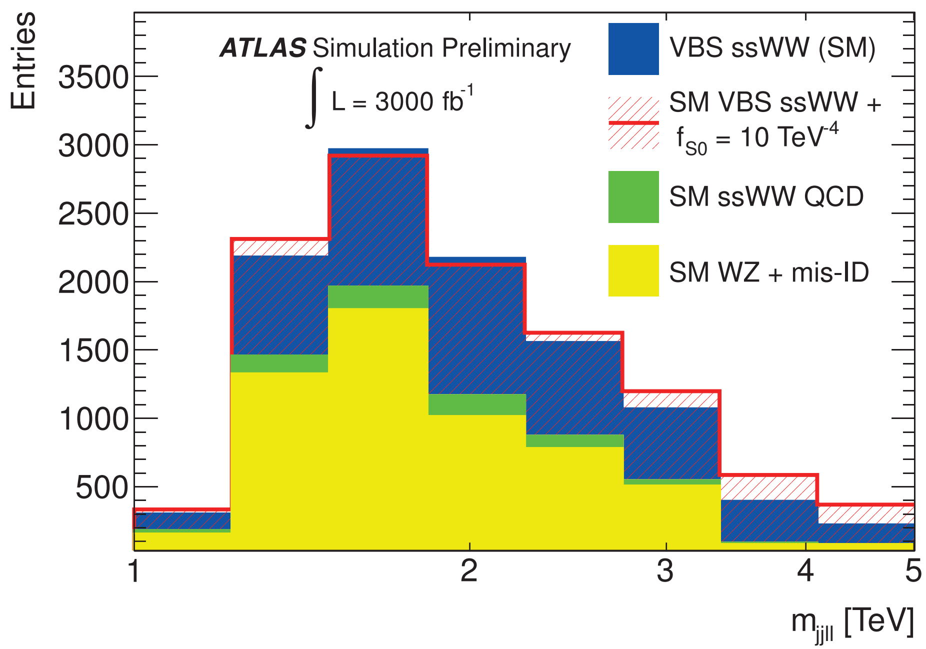
Signal topology of such events:

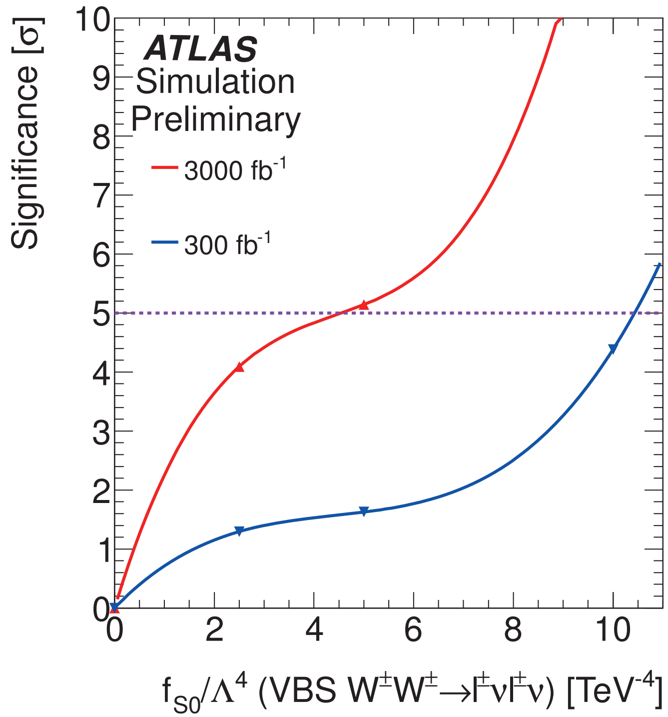
- Two same-sign leptons with two forward jets
- M_{jj} > 1 TeV for non-VBS diboson production
- Major backgrounds: WZjj, Wγ, WZ and WW-QCD

VBS $W^{\pm}W^{\pm} \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu$

$$\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4}[(D_{\mu}\phi)^{\dagger}D_{\nu}\phi)] \times [(D^{\mu}\phi)^{\dagger}D^{\nu}\phi)]$$

3000/fb improved the analysis significantly





Vector Boson Scattering: Triboson Scattering

ATLAS-PHYS-PUB-2013-006 (ECFA 2013)

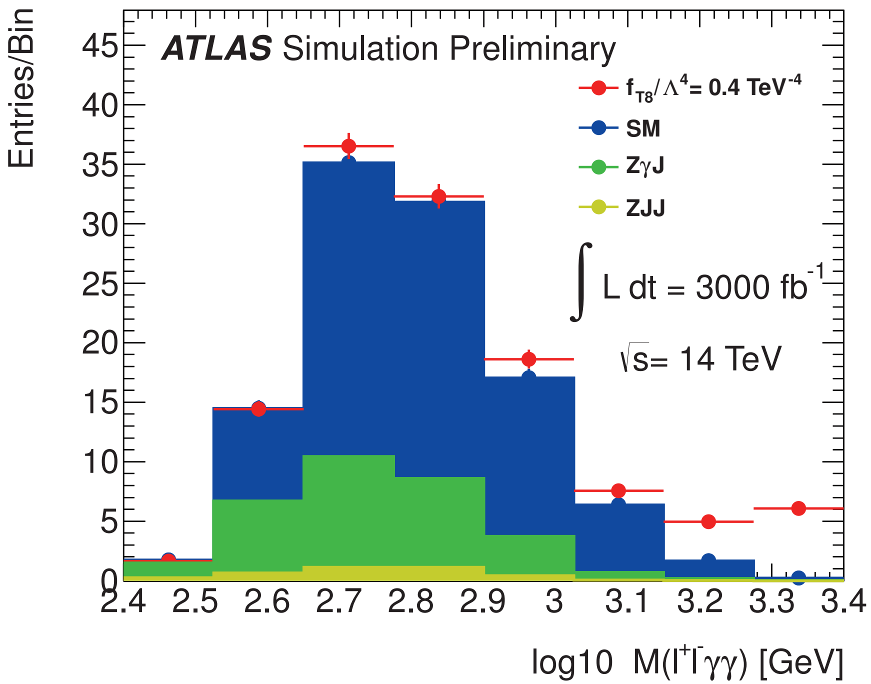
Signal topology of such events:

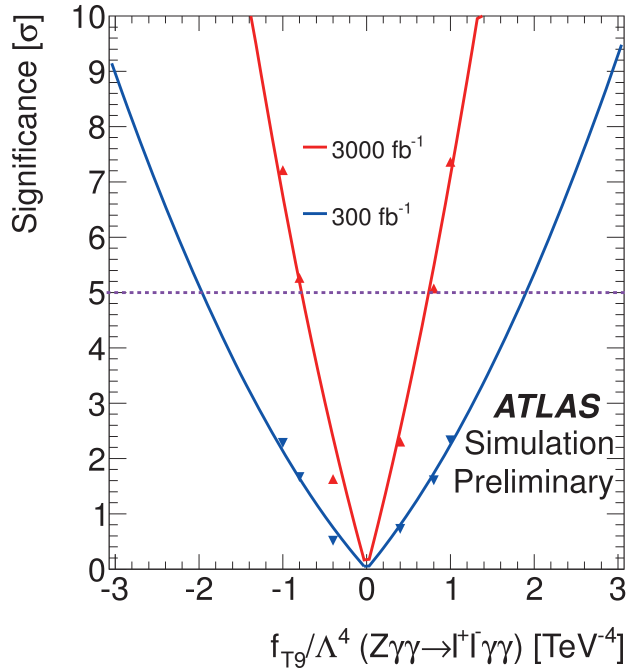
- Final state with di-lepton and di-photon
- Allows full reconstruction and calculate Zγγ invariant mass

$Z\gamma\gamma$

$$\mathcal{L}_{T,8} = \frac{f_{T8}}{\Lambda^4} B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$





Vector Boson Scattering: Summary

- HL-LHC enhances discovery range for new higher-dimension electroweak operators by more than a factor of two.

If Beyond the SM discovered in 300 fb^{-1} dataset, then the coefficients on the new operators could be measured to 5% precision with 3000 fb^{-1}

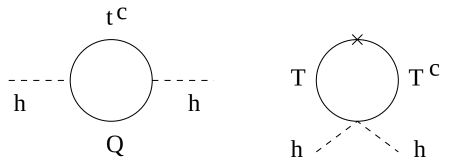
Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Λ_{UV}: unitarity violation bound corresponding to the sensitivity with 3000 fb^{-1}

Vector Like Charge 2/3 Quark Search

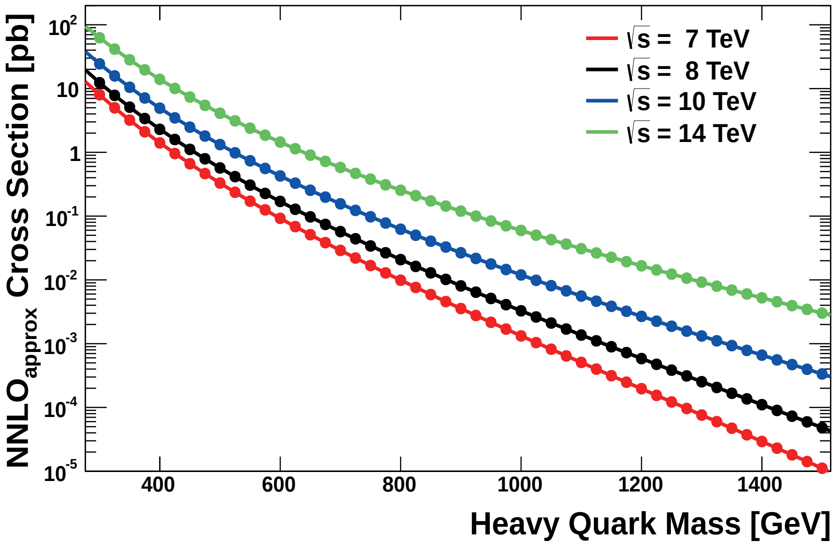
CMS-PAS-FTR-13-026 (ECFA 2013)

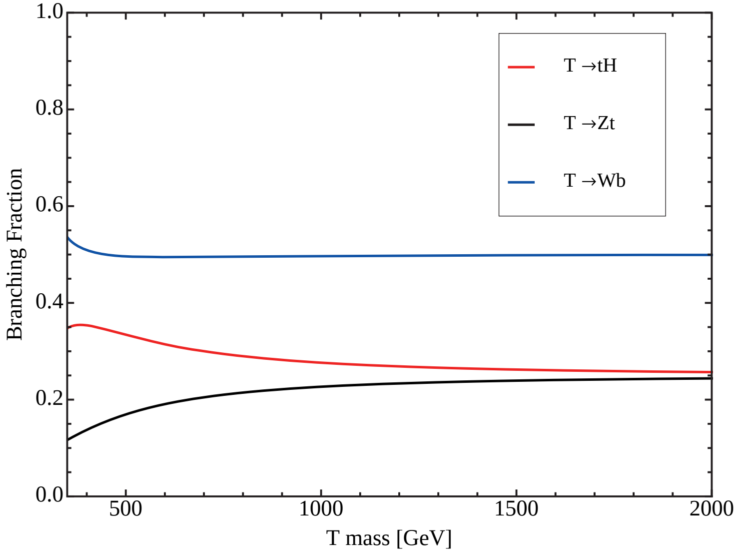
- Vector like quarks differ from SM quark since they have only vector-couplings to the W boson
  - Vector-like mass term does not violate gauge invariance without the need for a Yukawa coupling to the Higgs boson
  - Vector-like quarks are e.g. predicted by little Higgs models
  - **Another natural solution to cancel the diverging contributions of top quark loops to the Higgs boson mass!**



Analysis based on arXiv:0105239 and performed in
- Single Lepton
- Multi-Lepton

Hathor-MC used for signal production



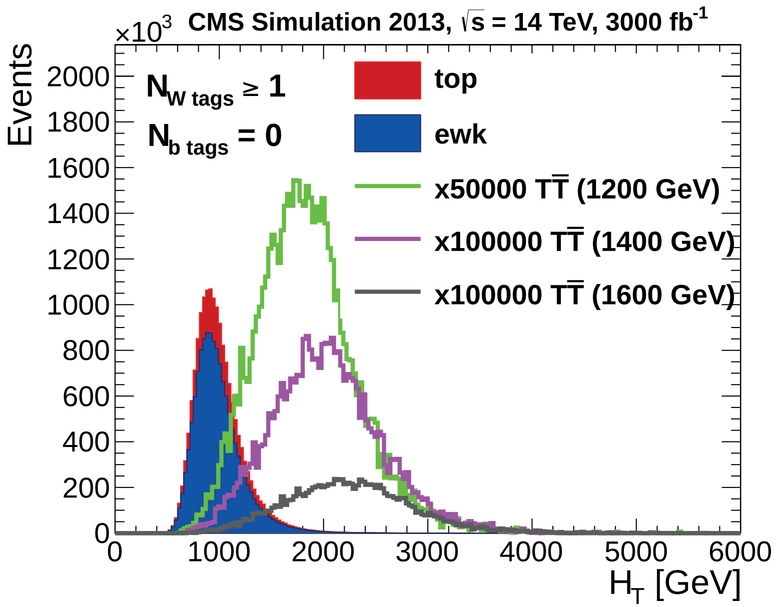


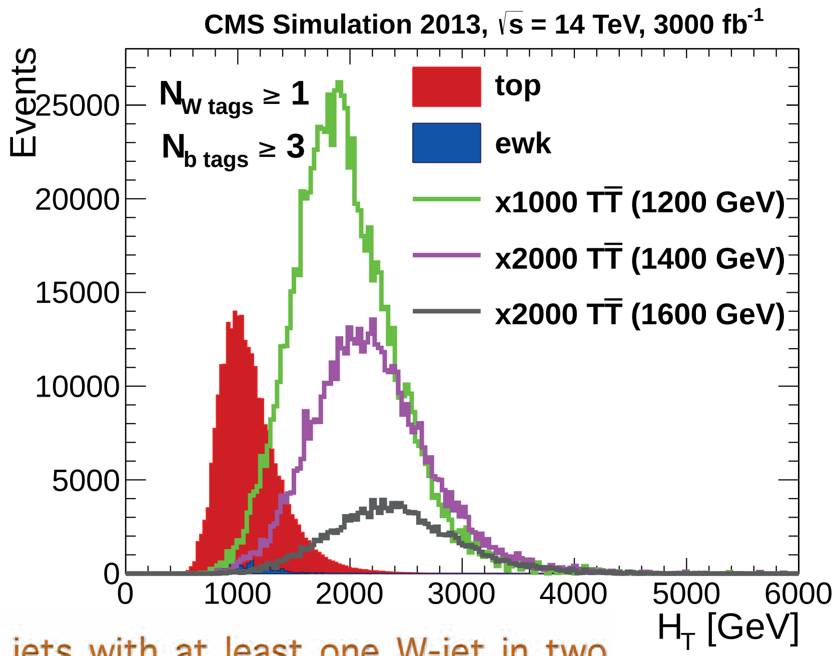
Vector Like Charge 2/3 Quark Search

CMS-PAS-FTR-13-026 (ECFA 2013)

Signal topology of such events:

- Massive T quarks characterized by two to four vector bosons and at least two b-quarks.
- Single lepton → one W boson decays leptonically and all the other bosons decay to hadrons (categories based on jet multiplicity and b-tagged jets)
- Multi Lepton → at least one Z boson or at least two W bosons decay leptonically (categories based on multiplicity and charged of leptons)

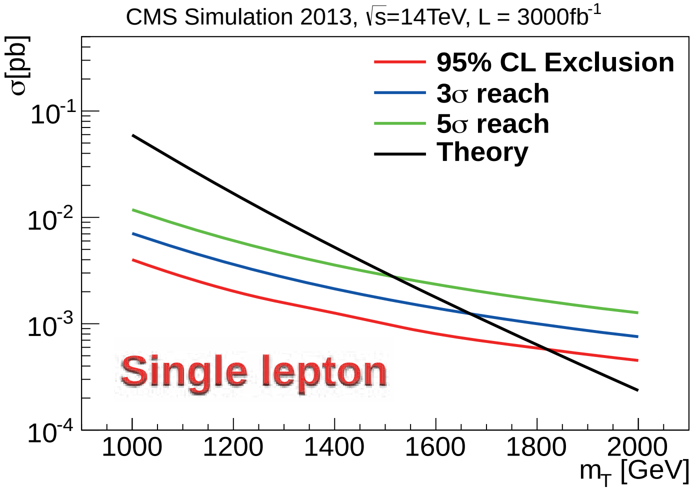


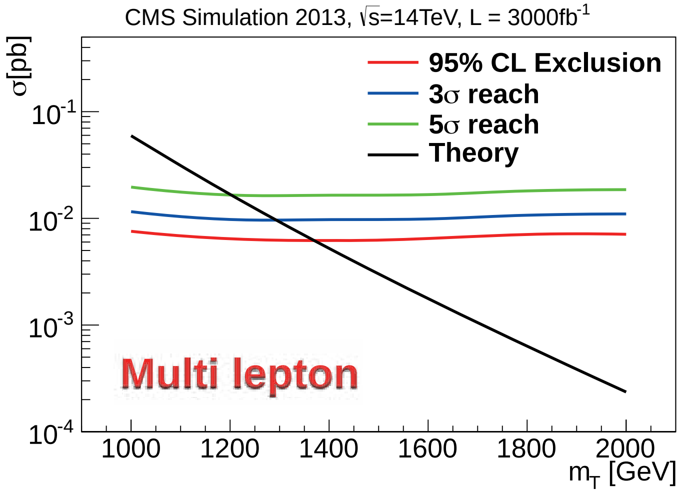


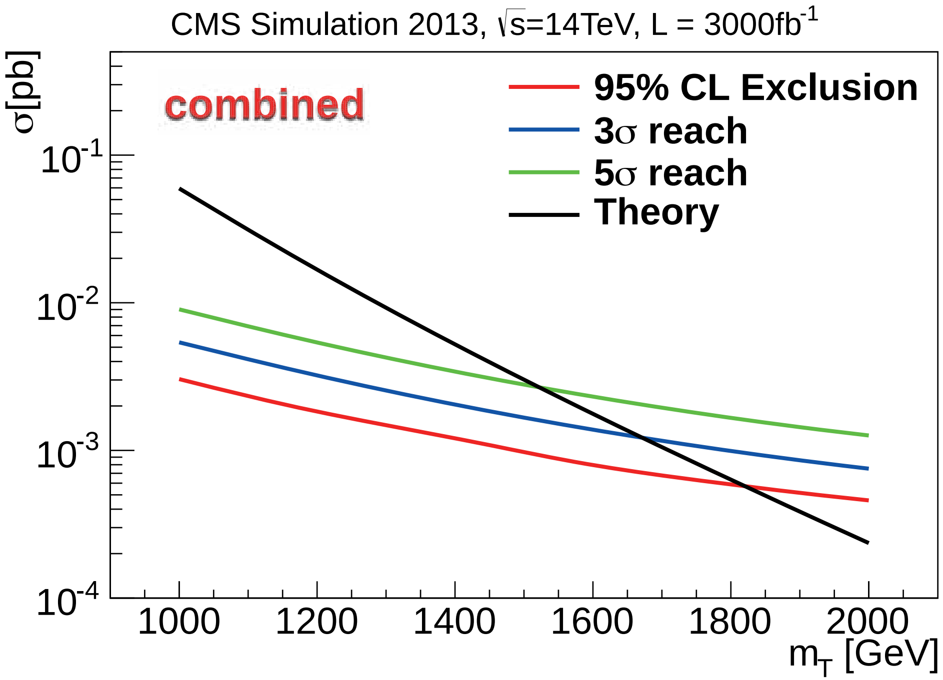
Single lepton with nJets>= 3 jets with at least one W-jet in two different b-tagged jet categories

Vector Like Charge 2/3 Quark Search

CMS-PAS-FTR-13-026 (ECFA 2013)







- The mass reach for the discovery of a heavy T quark at 3σ and 5σ level is expected to be **1.65** TeV and **1.48** TeV, respectively.

- A light Higgs at 126 GeV on composite Higgs model → light top partners with masses around few TeV are essential for a moderate level of tuning

Summary I

- **Supersymmetry and naturalness:**
  - **Gluinos** mass reach enhanced by 400 GeV up to **2.4** TeV, for χ_1^0 with mass of up to **1.1** TeV.
  - **Squarks mass reach** shows strong dependency based on gluino mass assumptions
  - For **LSP** masses below ~ **300** GeV a **stop discovery** would be possible up to ~ **1.2** TeV
  - For **LSP** masses below ~ **300** GeV a **sbottom discovery** would be possible up to~ **1.3** TeV
  - Gain of **~300 GeV** in **chargino/neutralino** mass discovery reach when going from 300 fb^{-1} to 3000 fb^{-1}
- **VBF searches, dark matter and forward tracking**
  - depend crucially on **forward tracking for pileup mitigation**
- **Vector Boson scattering**
  - **HL-LHC** enhances discovery range for **new higher-dimension electroweak operators** by more than a **factor of two**.
- **Vector Like charge 2/3 quark:** search can probe masses up to **1.5** TeV
- **Search for ttbar and dilepton resonances**
  - gain up to **50%** in mass reach for KK gluons or **dilepton** to several TeV
- **Search for W` and heavy stable charged particles:** signal efficiency and TOF importance are very critical for discovery

Summary II

- Key questions?
  - Is the mass scale beyond the LHC reach?
  - Is the mass scale within LHC`s reach, but final states are elusive?

- We must carefully analyze the implications of these two items in formulating detector concepts, and planning running conditions.
  - optimized to address sub-TeV and multi-TeV physics, respectively

Conclusion and Outlook

The results from ATLAS and CMS will continue to set the agenda across **the energy frontier for the foreseeable future**

- ✓ Run-I demonstrated the excellent performance and sensitivity over wide range of signatures but
  - in fact just started to test various BSM physics
- ✓ HL-LHC era improves significantly the current boundaries and open an important window to new physics prospects

Benefits of HL-LHC

- Reduced statistical and systematic uncertainties in searches
  - Improvement of detector modeling and understanding of background processes
- Increased sensitivity of low cross section processes
- Probe a significant part of the interesting range of phase space for new physics prospects


BACKUP

Vector Boson Scattering: Results for WZ channel

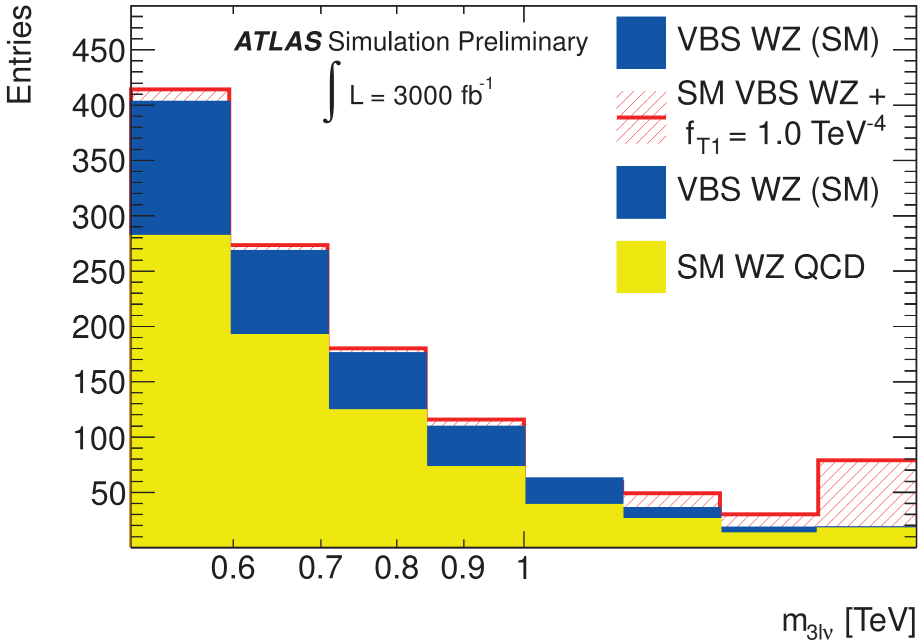
ATLAS-PHYS-PUB-2013-006 (ECFA 2013)

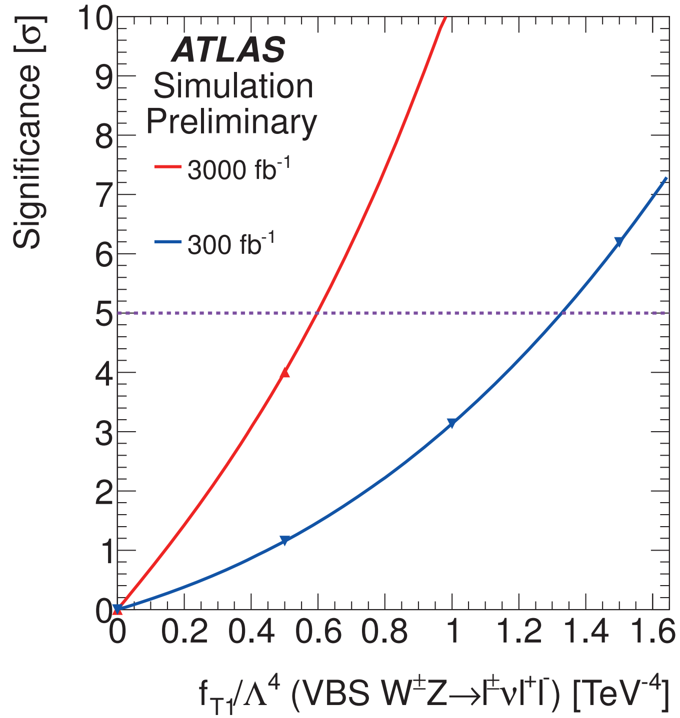
Signal topology of such events:

- Multi-leptons with two forward jets
- Lepton from W should be identified
- Larger cross section but there is an unidentified lepton in the event.

VBS $WZ \rightarrow \ell\nu\ell\ell$

$$\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$$





Vector Boson Scattering: Results for WZ channel

CMS-FTR-13-006(ECFA 2013)

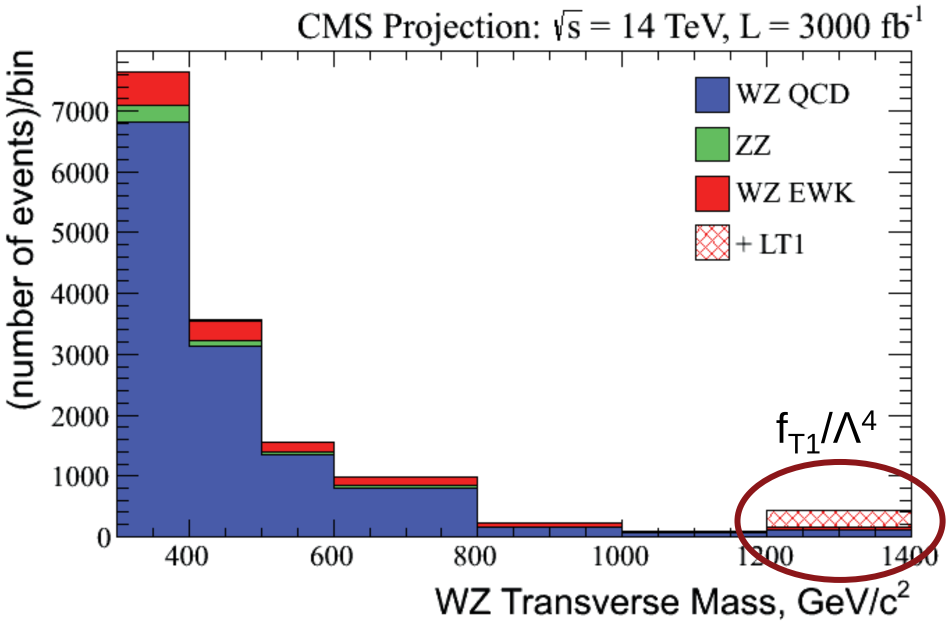
Signal topology of such events:

- Multi-leptons with two forward jets
- Lepton from W should be identified
- Larger cross section but there is an unidentified lepton in the event.

$$\textbf{VBS } WZ \rightarrow \ell\nu\ell\ell$$

$$\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$$

Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
$\frac{f_{T1}}{\Lambda^4}$ at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
$\frac{f_{T1}}{\Lambda^4}$ at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}



Observation of anomalous couplings of this type may indicate new physics in the electroweak symmetry breaking sector.

Search for ttbar resonances

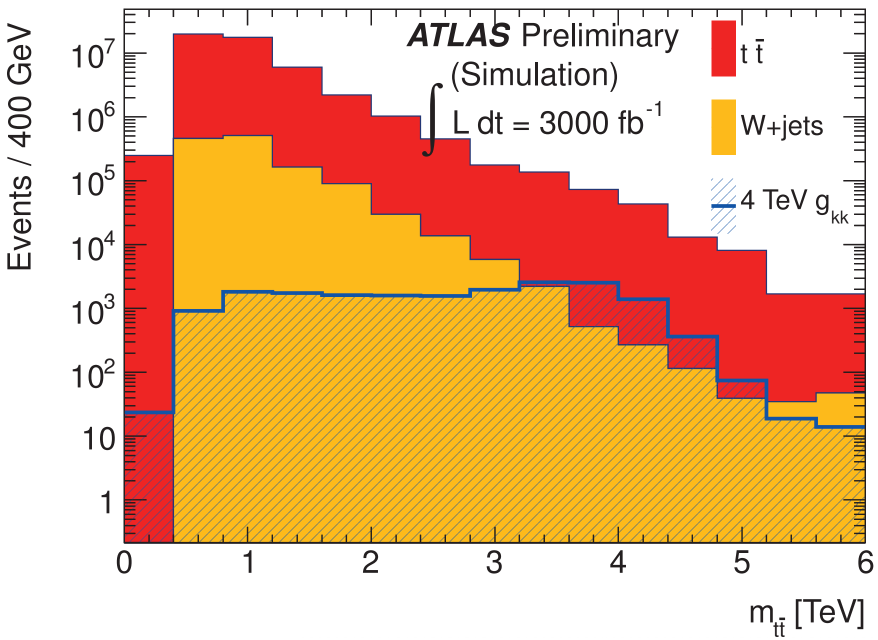
ATLAS-PHYS-PUB-2013-006 (ECFA 2013)

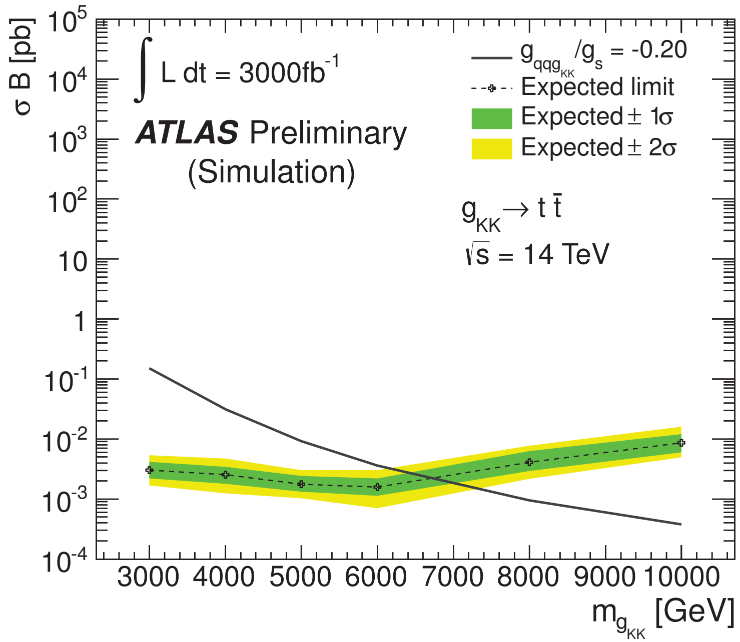
Signal topology of ttbar resonances:

- Final state with di-lepton and single lepton
  - Leptonic ttbar: clean final state but more difficult reconstruction of ttbar invariant mass
  - Semi-leptonic ttbar: more complete reconstruction, but higher background

$g_{KK} \rightarrow t\bar{t}$ and $Z'_{\text{topcolor}} \rightarrow t\bar{t}$

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
Z'_{topcolor}	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)





di-leptonic selection (similar results for single-lepton selection)

Search for di-lepton resonances

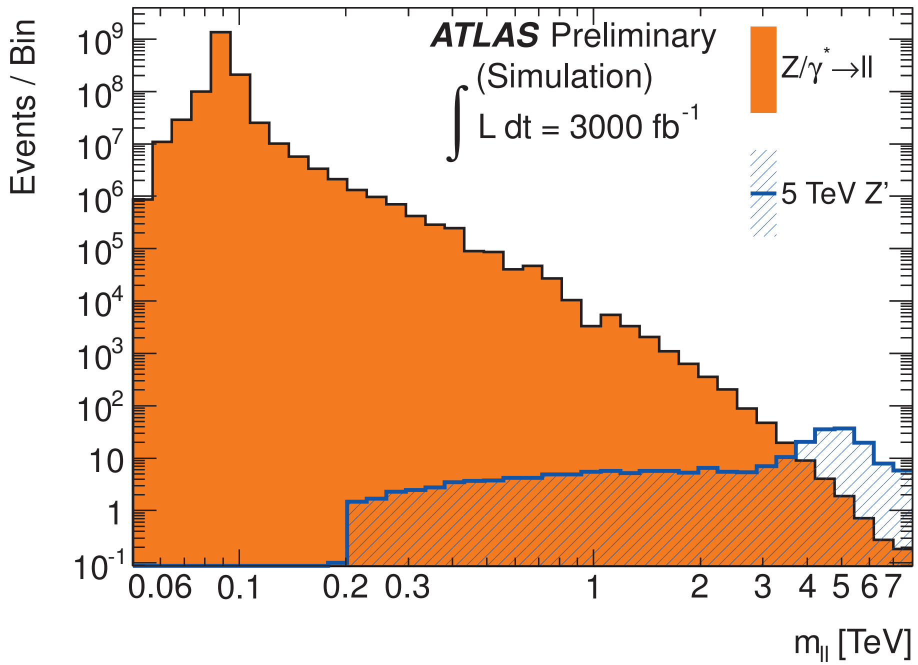
ATLAS-PHYS-PUB-2013-006 (ECFA 2013)

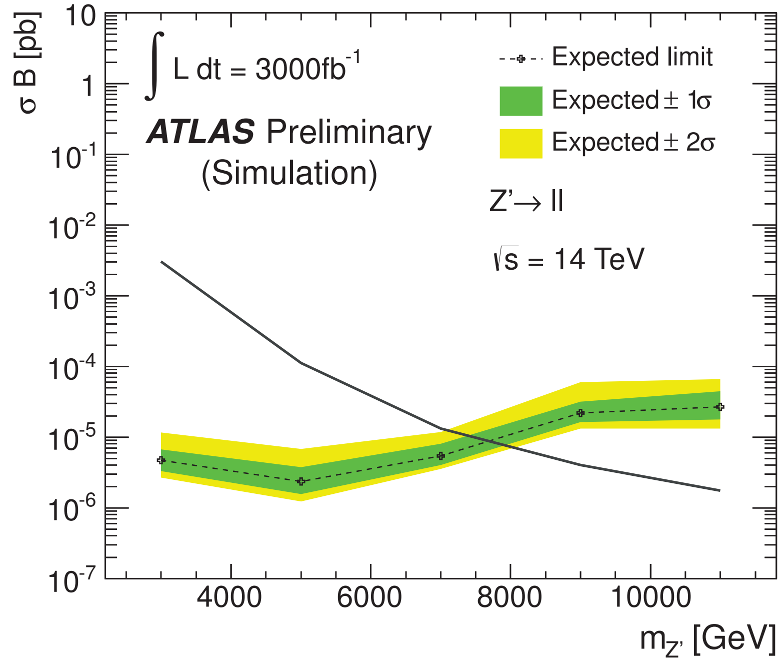
Signal topology of ttbar resonances:

- Exactly two selected same flavor leptons
- Z`→mumu candidate events must have two opposite-sign muons

Mass reach for Z' dileptons can be enhanced by 20% with 3000 fb^{-1}

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
$Z'_{SSM} \to ee$	6.5	7.2	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6





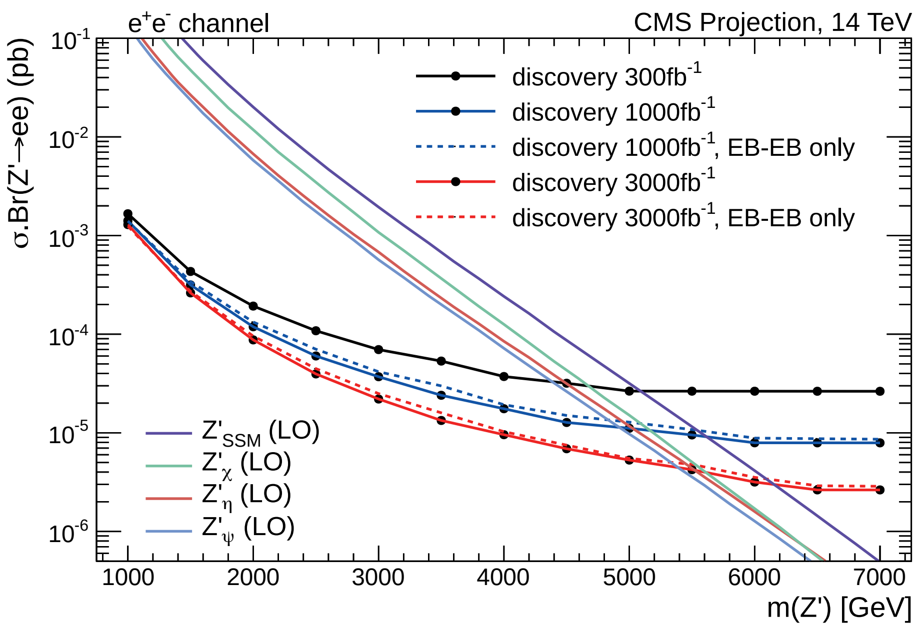
The reconstructed di-muon mass spectrum (similar results for di-electron)

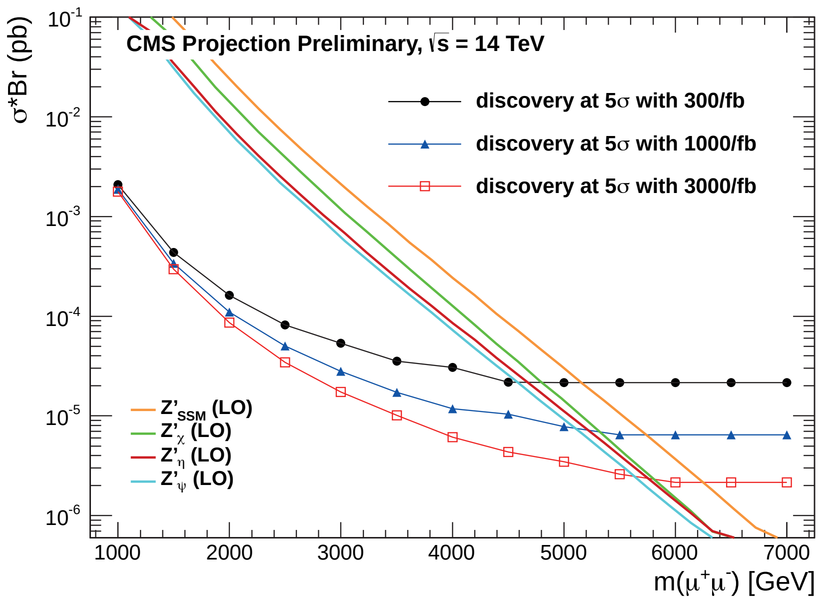
Search for Heavy Gauge bosons via di-leptons

CMS-NOTE-13-002 (Snowmass 2013)

Signal topology of Z` searches:

- Di-lepton pairs - electron (muon) p_T > 35 (45) GeV and |η| < 2.5 (2.4)
- Electron (muon) identification efficiency 88 (85)% taken from 8 TeV analysis
- Use ECAL barrel and endcap regions
- One electron must be found in barrel region
- Also studied is a case reduced acceptance due to degradation of the ECAL endcaps at HL-LHC



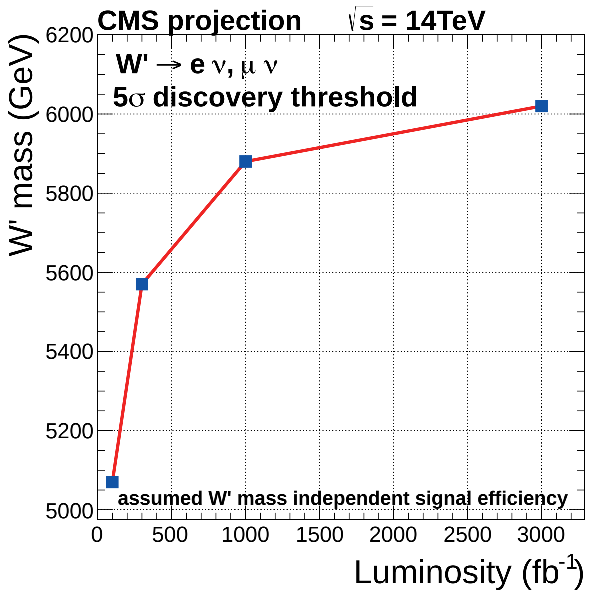


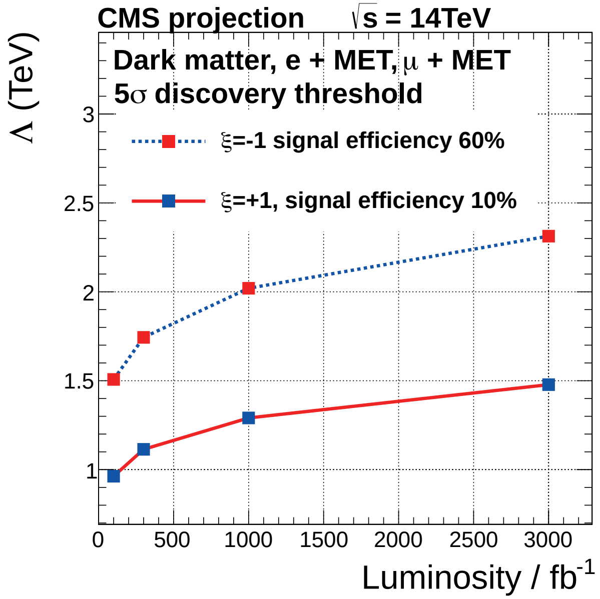
Search for W` and Dark Matter

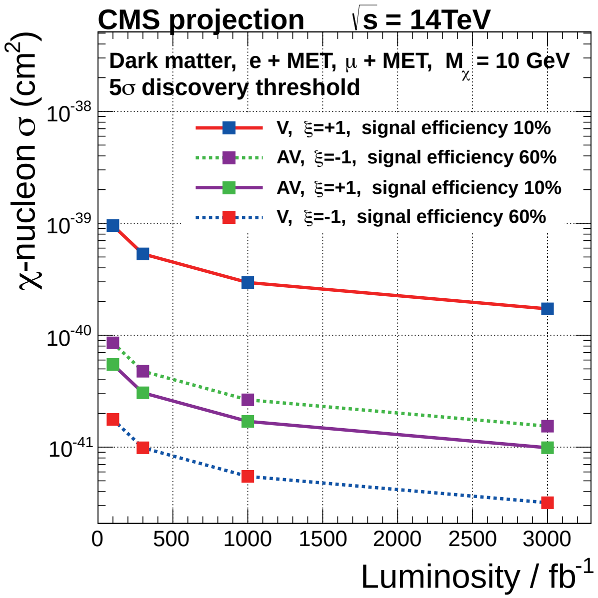
CMS-NOTE-13-002 (Snowmass 2013)

Signal topology of W` searches (SSM W` and dark matter effective theory):

- High p_T lepton and missing energy
- W` considered to be heavy analog of W boson
- Dark matter model → a pair of dark matter particles are produced in association with a lepton and a neutrino deriving from an intermediate SM W
- The signal efficiency 60 (10) % in the case of constructive (destructive) interference (8 TeV)





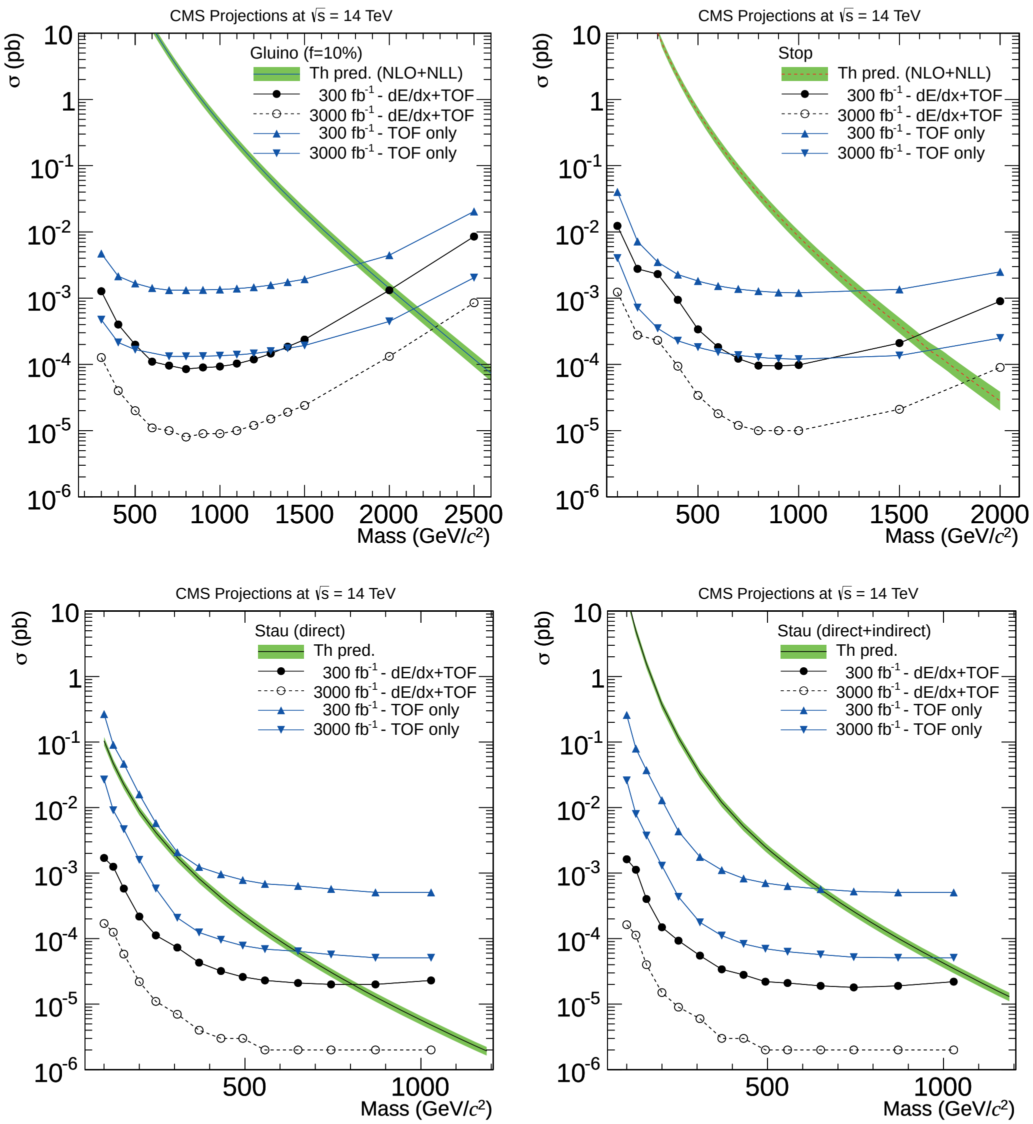


Search for Heavy Stable Charged Particles

CMS-NOTE-13-002 (Snowmass 2013)

Signal topology of the search

- **Long lived gluinos, stops and staus**
- various combinations of signatures in the inner tracker only, inner tracker and muon detector only
- long time-of-flight (TOF) to the outer muon system and anomalously large energy deposition in the inner tracker
- Background → instrumental effects
- dE/dx unchanged with the combination of long time-of-flight and highly ionizing signatures for HL-LHC



➢ the exclusion results rely entirely on theoretical cross section predictions made in the context of a given model (Split SUSY, GMSB and UED)

Strongly produced SUSY: Gluino Searches

S_T^{lep} region	sample	N_{signal}	$N_{control}$	R_{CS}
$450 \leq S_T^{lep} < 550\,\text{GeV}$	$t\bar{t}$	16.7±4.5	227.4±19.1	0.073095
	$t\bar{t}V$	0.8±0.2	18.1±4.4	0.047
	single top	0.0±0.0	1.2±0.5	0.038
	V + jets	0.0±0.0	0.0±0.0	0.000
	SM all	17.5±4.5	246.7±19.6	0.071
	signal(2000,300)	6.3±1.0	3.3±0.7	1.909
$550 \leq S_T^{lep} < 650\,\text{GeV}$	$t\bar{t}$	4.4±1.4	76.8±9.8	0.057
	$t\bar{t}V$	0.4±0.1	3.7±0.6	0.109
	single top	0.0±0.0	0.2±0.1	0.211
	V + jets	0.0±0.0	1.6±1.6	0.000
	SM all	4.8±1.4	82.3±9.9	0.059
	signal(2000,300)	5.1±0.9	3.8±0.8	1.360
$650 \leq S_T^{lep} < 750\,\text{GeV}$	$t\bar{t}$	0.8±0.2	29.1±5.1	0.027
	$t\bar{t}V$	0.1±0.0	1.6±0.4	0.055
	single top	0.0±0.0	0.3±0.1	0.000
	V + jets	0.0±0.0	0.0±0.0	0.000
	SM all	0.9±0.2	31.1±5.1	0.028
	signal(2000,300)	7.3±1.1	3.9±0.8	1.885
$S_T^{lep} \geq 750\,\text{GeV}$	$t\bar{t}$	1.5±0.4	15.5±2.8	0.095
	$t\bar{t}V$	0.2±0.1	1.0±0.3	0.162
	single top	0.0±0.0	0.1±0.0	0.050
	V + jets	0.0±0.0	2.5±1.6	0.000
	SM all	1.6±0.4	19.1±3.3	0.086
	signal(2000,300)	31.6±2.2	17.6±1.6	1.803

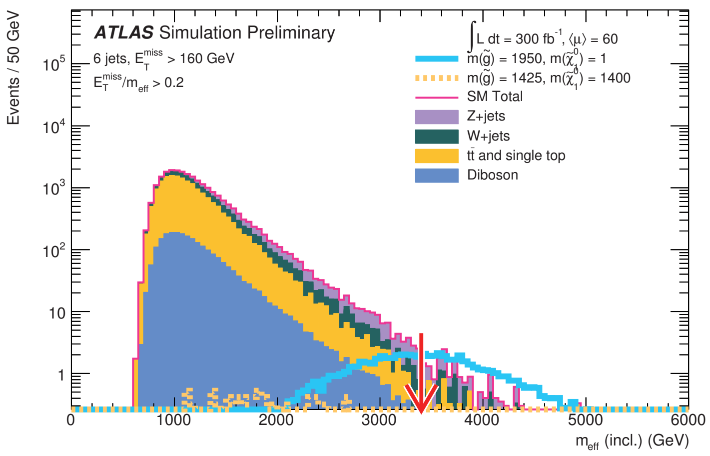
- The discovery range of gluinos can be enhanced 300 GeV for 300 fb^{-1} to 3000 fb^{-1} up to 2.2 TeV, for χ_1^0 with mass of up to 1.2 TeV

Strongly produced SUSY: Squark and gluino Searches

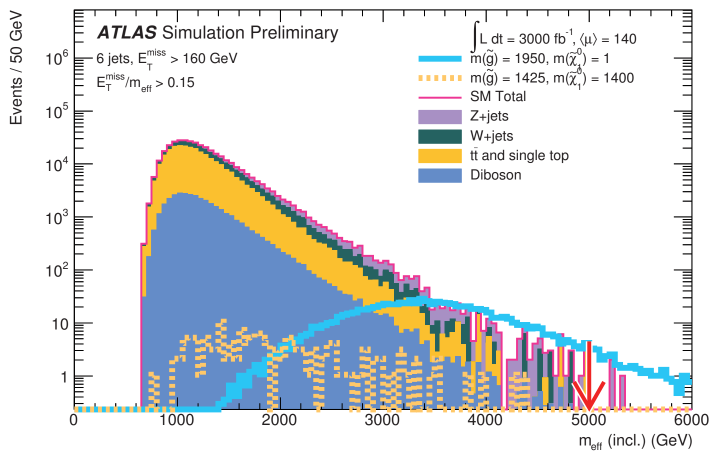
ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

Table 8: Yields for the main backgrounds and selected signal points simulated with $\langle\mu\rangle = 60$, normalised to $\mathcal{L} = 300$ fb^{-1}. The signal samples samples are normalized for the scenario with a gluino mass of 4.5 TeV.

Region	SR2jl	SR2jm	SR3j	SR4jl	SR4jm	SR4jt	SR5j	SR6jl	SR6jm	SR6jt
W+jets	45.0 ± 3.5	2.7 ± 0.9	11.2 ± 1.8	11.8 ± 1.8	25.7 ± 2.7	113 ± 6	30.4 ± 2.9	8.5 ± 1.5	6.3 ± 1.3	3.6 ± 1.0
Z+jets	104.4 ± 3.1	16.9 ± 1.2	43.0 ± 2.0	48.5 ± 2.1	75.9 ± 2.6	111.1 ± 3.2	74.4 ± 2.6	20.7 ± 1.4	13.0 ± 1.1	10.0 ± 1.0
$t\bar{t}$	15.7 ± 1.8	1.6 ± 0.5	4.2 ± 0.8	5.1 ± 1.1	10.6 ± 1.5	45.9 ± 3.4	19.3 ± 2.2	5.2 ± 1.1	6.0 ± 1.2	3.4 ± 0.9
Diboson	18.4 ± 1.7	2.4 ± 0.5	6.5 ± 0.9	7.3 ± 1.0	12.5 ± 1.3	30.0 ± 2.4	13.8 ± 1.5	3.8 ± 0.8	2.8 ± 0.7	1.9 ± 0.5
Total background	183 ± 5	23.6 ± 1.7	64.9 ± 2.9	72.6 ± 3.1	125 ± 4	300 ± 8	138 ± 5	38.3 ± 2.5	28.1 ± 2.2	18.8 ± 1.7
$m_{\tilde{g}}$ = 1950 GeV, $m_{\tilde{\chi}_1^0}$ = 1 GeV	68.8 ± 0.6	12.48 ± 0.27	35.4 ± 0.5	18.41 ± 0.33	70.6 ± 0.7	102.4 ± 0.8	83.4 ± 0.7	25.6 ± 0.4	44.6 ± 0.5	35.4 ± 0.5
$m_{\tilde{g}}$ = 1425 GeV, $m_{\tilde{\chi}_1^0}$ = 1400 GeV	12.6 ± 1.2	3.7 ± 0.6	8.5 ± 1.0	7.5 ± 0.9	8.1 ± 0.9	6.2 ± 0.8	4.7 ± 0.7	1.6 ± 0.4	1.05 ± 0.33	1.05 ± 0.33
$m_{\tilde{q}}$ = 1050 GeV, $m_{\tilde{\chi}_1^0}$ = 900 GeV	2.5 ± 1.1	1.5 ± 0.9	2.0 ± 1.0	3.5 ± 1.3	6.4 ± 1.8	4.0 ± 1.4	7.4 ± 1.9	3.5 ± 1.3	1.5 ± 0.9	1.5 ± 0.9
$m_{\tilde{q}}$ = 2250 GeV, $m_{\tilde{\chi}_1^0}$ = 1 GeV	141.7 ± 0.9	60.1 ± 0.6	82.1 ± 0.7	39.2 ± 0.5	59.3 ± 0.6	58.9 ± 0.6	28.4 ± 0.4	7.84 ± 0.21	8.00 ± 0.21	7.57 ± 0.20



(c) 6jt, 300 fb^{-1}



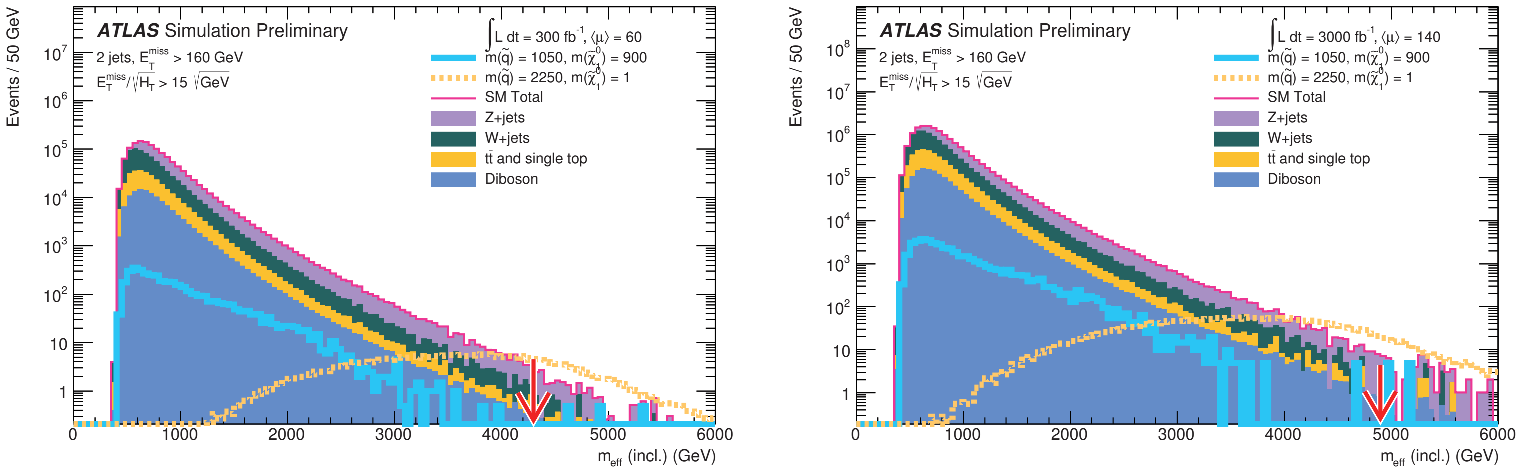
(d) 6jt, 3000 fb^{-1}

Strongly produced SUSY: Squark and gluino Searches

ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

Table 9: Yields for the main backgrounds and selected signal points simulated with $\langle\mu\rangle = 140$, normalised to $\mathcal{L} = 3000\ \mathrm{fb}^{-1}$. The signal samples samples are normalized for the scenario with a gluino mass of 4.5 TeV.

Region	SR2jl	SR2jm	SR3j	SR4jl	SR4jm	SR4jt	SR5j	SR6jl	SR6jm	SR6jt
W+jets	8 ± 5	5 ± 4	38 ± 10	8 ± 5	14 ± 6	101 ± 17	14 ± 6	25 ± 8	11 ± 5	0.00 ± 0.00
Z+jets	51 ± 7	51 ± 7	185 ± 13	78 ± 8	127 ± 11	125 ± 11	65 ± 8	85 ± 9	29 ± 5	3.6 ± 1.8
$t\bar{t}$	9 ± 4	9 ± 4	20 ± 5	7.0 ± 3.1	18 ± 6	37 ± 9	11 ± 4	17 ± 5	3.5 ± 2.1	1.4 ± 1.4
Diboson	7.6 ± 3.1	7.2 ± 2.9	10.4 ± 3.4	18 ± 5	29 ± 7	9.9 ± 3.5	14 ± 4	4.8 ± 2.6	0.6 ± 0.8	
Total background	76 ± 10	72 ± 9	269 ± 18	104 ± 11	176 ± 14	292 ± 23	99 ± 11	141 ± 14	48 ± 8	5.6 ± 2.4
$m_{\tilde{g}}$ = 1950 GeV, $m_{\tilde{\chi}_1^0}$ = 1 GeV	55.8 ± 1.8	43.4 ± 1.6	163.9 ± 3.1	75.2 ± 2.1	191.0 ± 3.4	159.1 ± 3.1	152.7 ± 3.0	257 ± 4	73.4 ± 2.1	36.0 ± 1.5
$m_{\tilde{g}}$ = 1425 GeV, $m_{\tilde{\chi}_1^0}$ = 1400 GeV	10.5 ± 3.3	15 ± 4	48 ± 7	19 ± 4	23 ± 5	8.4 ± 3.0	14 ± 4	7.4 ± 2.8	5.3 ± 2.4	0.00 ± 0.00
$m_{\tilde{q}}$ = 1050 GeV, $m_{\tilde{\chi}_1^0}$ = 900 GeV	5 ± 5	10 ± 7	15 ± 9	10 ± 7	15 ± 9	15 ± 9	10 ± 7	25 ± 11	5 ± 5	5 ± 5
$m_{\tilde{q}}$ = 2250 GeV, $m_{\tilde{\chi}_1^0}$ = 1 GeV	186 ± 3	208.2 ± 3.4	558 ± 6	254 ± 4	320 ± 4	182.6 ± 3.2	136.4 ± 2.7	75.2 ± 2.0	50.9 ± 1.7	13.6 ± 0.9



(a) 2jm, 300 fb^{-1}

(b) 2jm, 3000 fb^{-1}

Third generation SUSY: direct stop searches

ATLAS-PHYS-PUB-2013-011 (ECFA 2013)

	(800,100)	(1100,100)
$t\bar{t}$	257±25	6.6±3.8
$t\bar{t}+W$	15±2	0.9±0.5
$t\bar{t}+Z$	71±7	8.5±2.3
W+jets	41±11	5.4±3.8
Total bkg	385±28	21.4±5.9
Signal	880±18	55.7±1.5

1-lepton channel

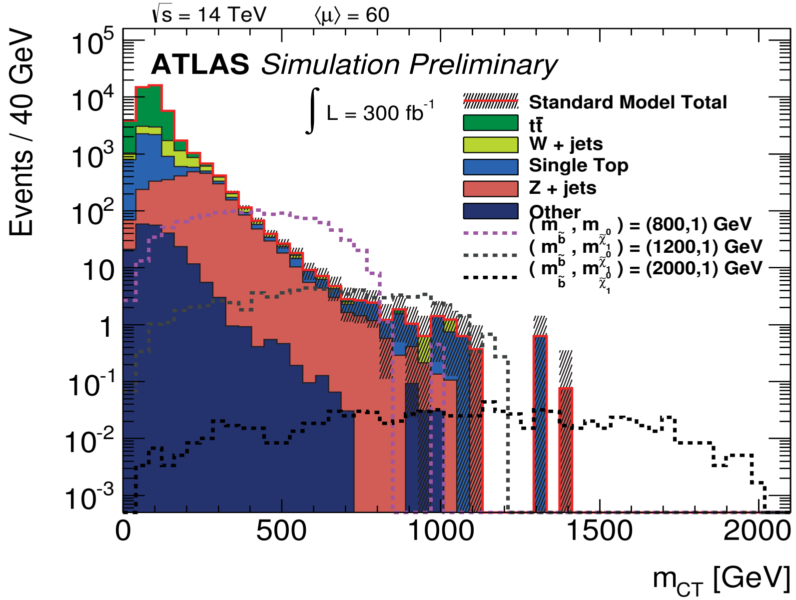
	(800,100)	(1100,100)
$t\bar{t}$	69±13	5.7±3.4
$t\bar{t}+W$	5±1	0.8±0.6
$t\bar{t}+Z$	38±5	3.9±1.5
W+jets	3±3	negligible
Z+jets	14±4	1.8±1.3
Total bkg	129±15	12.2±3.9
Signal	457±13	46.0±1.4

0-lepton channel

Third generation SUSY: direct sbottom searches

ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

Selection	SRx
Lepton veto	No e/μ with $p_T > 7(6)$ GeV for $e(\mu)$
E_T^{miss}	> 150 GeV
Leading jet $p_T(j_1)$	> 130 GeV
Third jet $p_T(j_3)$	veto if > 50 GeV
b-tagging	leading 2 jets ($p_T > 50$ GeV, $\lvert\eta\rvert < 2.5$)
$\Delta\phi_{min}$	> 0.4
$E_T^{miss}/m_{eff}(2)$	$E_T^{miss}/m_{eff}(2) > 0.25$
m_{CT}	$> x$ GeV
m_{bb}	> 200 GeV



	SRA300	SRA350	SRA450	SRA550	SRA650	SRA750
$(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0}) = (1000, 1)$	216 ± 4	200 ± 4	161 ± 4	118.5 ± 3.2	78.6 ± 2.6	44.0 ± 1.9
$(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0}) = (1400, 1)$	19.3 ± 0.9	18.4 ± 0.9	16.8 ± 0.8	14.9 ± 0.8	12.8 ± 0.7	10.2 ± 0.6
$(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0}) = (1600, 1)$	6.04 ± 0.28	5.84 ± 0.28	5.55 ± 0.27	5.19 ± 0.26	4.57 ± 0.25	3.78 ± 0.22
$t\bar{t}$	32.6 ± 3.0	14.8 ± 2.0	4.3 ± 1.1	1.5 ± 0.7	0.6 ± 0.4	0.29 ± 0.29
single top	146 ± 12	83 ± 8	41 ± 6	25 ± 5	12.7 ± 3.2	8.9 ± 2.5
Z+jets	508 ± 8	249 ± 5	70.5 ± 2.7	23.1 ± 1.5	9.1 ± 1.0	4.1 ± 0.7
W+jets	92 ± 5	44 ± 4	9.3 ± 1.7	2.9 ± 0.9	1.6 ± 0.8	0.9 ± 0.6
Other	5.4 ± 0.5	3.3 ± 0.4	1.59 ± 0.28	0.50 ± 0.16	0.18 ± 0.09	0.15 ± 0.08

Electroweak production of SUSY particles

CMS-PAS-FTR-13-014 (ECFA 2013)

Table 2: Standard model background predictions for the different scenarios at 3000 fb^{-1}.

Selection in GeV		Phase I $\langle PU \rangle$=0 yield $\pm$ uncert.	Phase I $\langle PU \rangle$=140 yield $\pm$ uncert.	Phase II Conf3 $\langle PU \rangle$=140 yield $\pm$ uncert.
$0 < M_T < 120$	$0 < \not{E}_T < 60$	$(7.3 \pm 0.7) \times 10^5$	$(8.0 \pm 1.2) \times 10^5$	$(9.3 \pm 1.2) \times 10^5$
$0 < M_T < 120$	$60 < \not{E}_T < 120$	$(1.8 \pm 0.2) \times 10^5$	$(8.4 \pm 1.2) \times 10^5$	$(9.3 \pm 1.1) \times 10^5$
$0 < M_T < 120$	$120 < \not{E}_T < \infty$	$(5.6 \pm 0.8) \times 10^4$	$(3.3 \pm 0.7) \times 10^5$	$(3.3 \pm 0.7) \times 10^5$
$120 < M_T < 200$	$0 < \not{E}_T < 120$	$(7.9 \pm 0.8) \times 10^3$	$(7.7 \pm 0.7) \times 10^4$	$(8.2 \pm 0.7) \times 10^4$
$120 < M_T < 200$	$120 < \not{E}_T < 200$	$(1.2 \pm 0.2) \times 10^3$	$(4.0 \pm 0.7) \times 10^4$	$(4.3 \pm 0.7) \times 10^4$
$120 < M_T < 200$	$200 < \not{E}_T < \infty$	359 ± 84	$(5.7 \pm 2.3) \times 10^3$	$(4.8 \pm 2.1) \times 10^3$
$200 < M_T < 400$	$0 < \not{E}_T < 200$	$(2.3 \pm 0.2) \times 10^3$	$(1.5 \pm 0.2) \times 10^4$	$(1.5 \pm 0.2) \times 10^4$
$200 < M_T < 400$	$200 < \not{E}_T < 400$	303 ± 52	$(1.6 \pm 0.5) \times 10^3$	$(1.4 \pm 0.5) \times 10^3$
$200 < M_T < 400$	$400 < \not{E}_T < \infty$	24 ± 4	69 ± 35	39 ± 12
$400 < M_T < 700$	$0 < \not{E}_T < 300$	249 ± 24	395 ± 58	390 ± 42
$400 < M_T < 700$	$300 < \not{E}_T < 700$	67 ± 13	95 ± 19	100 ± 24
$400 < M_T < 700$	$700 < \not{E}_T < \infty$	1.1 ± 0.4	1.3 ± 0.5	1.4 ± 0.4
$700 < M_T < \infty$	$0 < \not{E}_T < 400$	30 ± 3	27 ± 3	27 ± 3
$700 < M_T < \infty$	$400 < \not{E}_T < 900$	32 ± 5	31 ± 5	30 ± 5
$700 < M_T < \infty$	$900 < \not{E}_T < \infty$	1.4 ± 0.4	1.5 ± 0.5	1.2 ± 0.4

Electroweak production of SUSY particles

ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

Selection	SRA	SRB	SRC	SRD
m_{SFOS}[GeV]	81.2-101.2			
# b-tagged jets	0			
lepton p_T (1,2,3)[GeV]	> 50			
$E_{\mathrm{T}}^{\mathrm{miss}}$[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

Table 2: Expected numbers of events for SM background and four SUSY scenarios for the WZ-mediated signal regions. Uncertainties are statistical only.

Sample / Scenario	SRA (300 fb^{-1}, μ=60)	SRB (300 fb^{-1}, μ=60)	SRC (300 fb^{-1}, μ=60)	SRA (3000 fb^{-1}, μ=140)	SRB (3000 fb^{-1}, μ=140)	SRC (3000 fb^{-1}, μ=140)	SRD (3000 fb^{-1}, μ=140)
WZ	9.60±0.32	4.59±0.22	1.91±0.14	200±5	59.4±2.5	22.0±1.5	8.3±1.0
ZZ	0	0	0	0	0	0	0
VVV	2.11±0.18	1.07±0.13	0.44±0.08	24.3±1.9	12.1±1.4	5.4±0.8	2.0±0.5
Wh	0	0	0	0	0	0	0
$t\bar{t}V$	0.67±0.19	0.23±0.12	0	14.4±2.8	4.2±1.6	0.31±0.31	0
$t\bar{t}$	0	0	0	0	0	0	0
Σ MC	12.4±0.4	5.89±0.28	2.35±0.16	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	38.5±0.6	20.1±0.5	5.47±0.23	407±6	224±5	67.9±2.6	19.7±1.4
$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(600,0) GeV	19.40±0.20	14.69±0.17	7.76±0.12	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	6.97±0.06	5.90±0.06	4.21±0.05	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	2.31±0.02	2.05±0.02	1.64±0.02	22.94±0.19	20.42±0.18	16.36±0.16	11.55±0.14

Electroweak production of SUSY particles

ATLAS-PHYS-PUB-2014-010 (ICHEP 2014) New

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

Table 5: Expected numbers of events for SM background and four SUSY scenarios for the Wh-mediated 3ℓ signal regions. Uncertainties are statistical only.

Sample / Scenario	SRE (300 fb^{-1}, μ=60)	SRF (300 fb^{-1}, μ=60)	SRG (300 fb^{-1}, μ=60)	SRE (3000 fb^{-1}, μ=140)	SRF (3000 fb^{-1}, μ=140)	SRG (3000 fb^{-1}, μ=140)	SRH (3000 fb^{-1}, μ=140)
WZ	0.28±0.06	0.14±0.04	0.05±0.02	6.2±0.8	2.9±0.6	0.76±0.29	0.43±0.22
ZZ	0	0	0	0	0	0	0
VVV	2.05±0.33	1.04±0.24	0.11±0.08	34±4	17.5±3.1	1.3±0.8	0.8±0.6
Wh	0.25±0.15	0.08±0.08	0	10.1±2.9	2.5±1.5	0.8±0.8	0
$t\bar{t}V$	0.68±0.15	0.21±0.08	0.07±0.05	9.6±1.8	4.1±1.3	1.1±0.6	0.4±0.4
$t\bar{t}$	3.7±0.5	0.95±0.27	0	121±10	36±5	3.9±1.8	0
Σ MC	7.0±0.7	2.4±0.4	0.23±0.10	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	13.2±2.7	7.7±2.1	2.2±1.1	181±31	99±23	27±12	0
$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(300,0) GeV	15.1±1.5	10.4±1.2	3.4±0.7	166±16	121±13	46±8	13±4
$m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=(500,0) GeV	5.4±0.4	4.58±0.33	3.19±0.28	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	1.75±0.10	1.55±0.10	1.27±0.09	18.1±1.1	15.9±1.0	12.8±0.9	9.1±0.8

Vector Like Charge 2/3 Quark Search

CMS-PAS-FTR-13-026 (ECFA 2013)

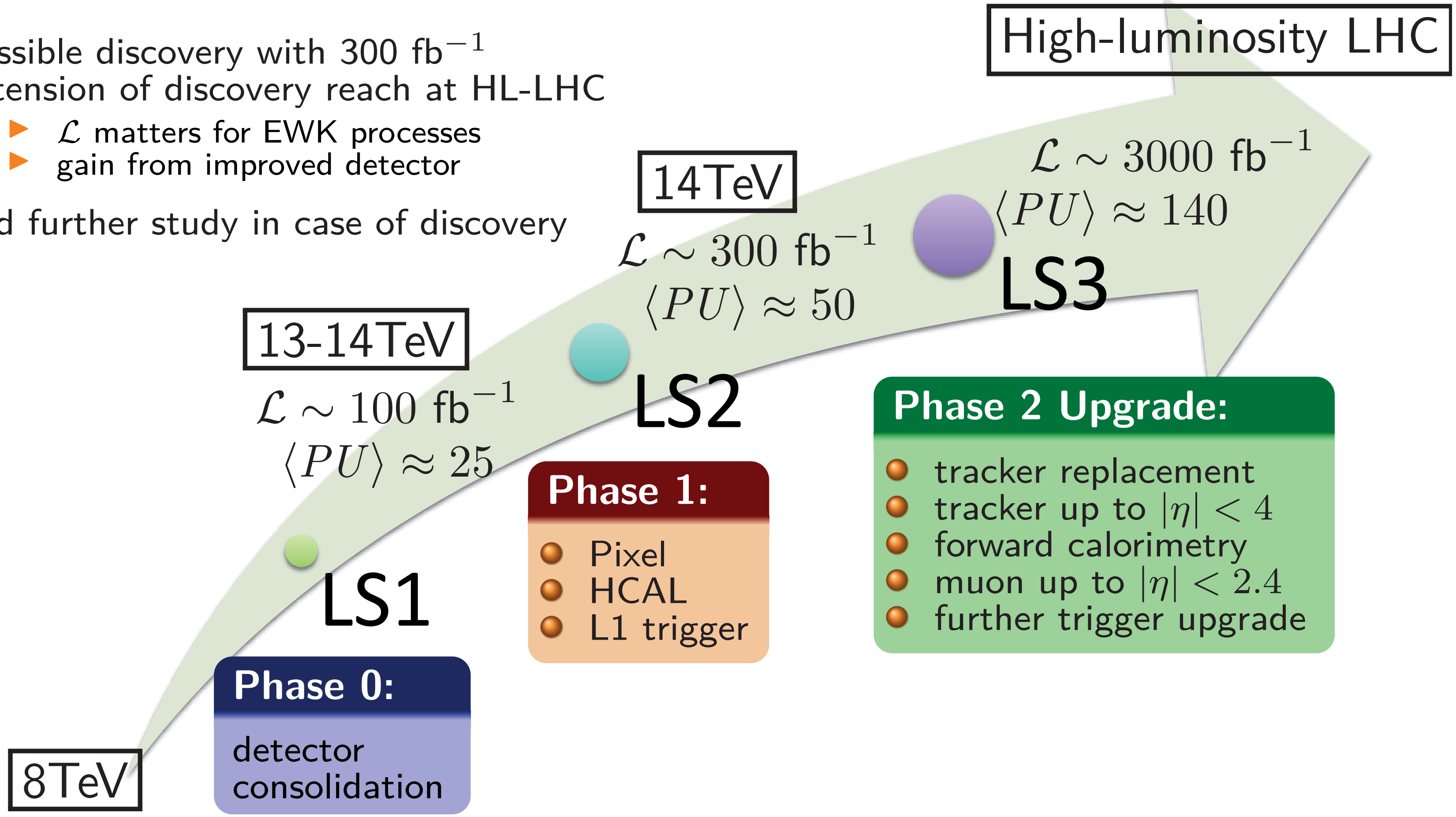
Mass (GeV)	$e3+\mu3$ 0b	1b	2b	≥3b	$e4+\mu4$ 0b	1b	2b	≥3b
Signal Event Yields								
1000	3988	8767	8358	3079	1850	4236	4291	1383
1200	1110	2578	2414	865	523	1313	1288	408
1400	336	808	751	258	179	458	449	136
1600	109	267	241	80	67	177	168	52
1800	36	91	81	27	26	71	66	19
2000	12	32	28	9	10	29	27	8
Background Event Yields $\times10^5$								
$t\bar{t}$	31.3±6.2	24.2±4.8	17.3±3.4	2.5±0.5	37.4±7.4	21.3±4.2	15.6±3.1	2.1±0.4
Electroweak	135.9±27.1	8.7±1.7	1.2±0.2	0.08±0.01	331.5±66.3	16.7±3.3	1.9±0.4	0.10±0.02
Total Background	167.3±33.4	33.0±6.6	18.4±3.7	2.6±0.5	368.9±73.8	38.0±7.6	17.5±3.5	2.2±0.4

Mass (GeV)	OS23	OS5+	SS	$\geq 3\ell$
Signal Event Yields				
1000	505	1050	467	431
1200	195	303	134	134
1400	69	93	38	40
1600	26	29	11	12
1800	10	10	4	4
2000	4	3	1	1
Background Event Yields				
$t\bar{t}$+non-prompt	1757±352	17922±3585	2428±486	170±34
Electroweak	532 ± 106	2908±581	2428±486	397±79
Total Background	2289 ± 458	20830 ± 4166	4857 ± 971	568 ± 113

CMS Detector Upgrade

At 13–14 TeV:

- possible discovery with 300 fb^{-1}
- extension of discovery reach at HL-LHC
  - $\mathcal{L}$ matters for EWK processes
  - gain from improved detector
- and further study in case of discovery



Courtesy L. Schutzka