Search for signatures of BSM physics at the HL-LHC with the ATLAS and CMS detectors

ECFA High Luminosity LHC Experiments Workshop

Physics and technology challenges

1st – 3rd October

Aix-les-Bains

France

https://indico.cern.ch/conferenceDisplay.py?confId=252045

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Why do we need HL-LHC?

We are searching for answers for big questions in particle physics and cosmology!

- Dark matter?
- Origin of EWSB?
- Naturalness?
- Unification?
- New Forces?
- Origin of flavor?
- Are particles elementary or composite?

BSM theories/models provide answers!

- Supersymmetry
- Extra Dimensions
- Top partners
- Additional gauge bosons (W’,Z’)
- …

Outline

- Vector boson scattering (ATLAS Snowmass/ATLAS-PHYS-PUB-2013-003 and CMS-FTR-13-006)

- SUSY searches (CMS-FTR-13-014 and ATLAS-Conf-13-011):
  - Direct chargino-neutralino production with decay to WZ and neutralinos
  - Chargino-chargino production
  - Direct stop production with 0 and 1 lepton search
  - Direct sbottom production
  - VBF dark matter search
  - Gluino (l+b) production
  - Jet+MET

- Search for heavy vector-like quark (CMS-FTR-13-026)
- Search for Extra Dimensions and Z' with ttbar resonances (ATLAS Snowmass/ATLAS-PHYS-PUB-2013-003)
- Search for Z' with di-lepton resonances (ATLAS Snowmass/ATLAS-PHYS-PUB-2013-003)

Disclaimer

All presented analyses are based on (public) 8 TeV analyses:

- Baseline selection in most cases “borrowed” from 8 TeV analysis
- Tuning of few selected key variables and tightening of signal regions done for simple optimization

Vector Boson Scattering – Theory

First Standard Model measurement, then BSM search!

Any EFT, also the SM, has higher-dimensional operators (Weinberg, 1979):

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{a_i}{\Lambda} \mathcal{O}_i^{(5)} + \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \frac{e_i}{\Lambda^4} \mathcal{O}_i^{(8)} \cdots \right]$$

Observation of **anomalous quartic gauge coupling** would indicate **new physics in the electroweak symmetry breaking sector!**

Vector Boson Scattering – Motivation

Vector boson scattering can happen through:

- Double triple gauge coupling (TGC)
- Quartic gauge coupling (QGC)
- s-channel & t-channel Higgs scattering

Cross section for these processes rises quickly with energy

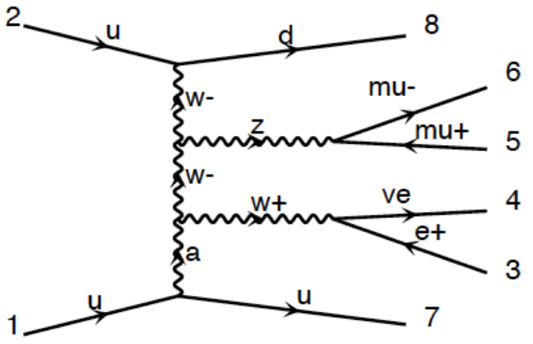
→ Individually these processes would violate unitarity

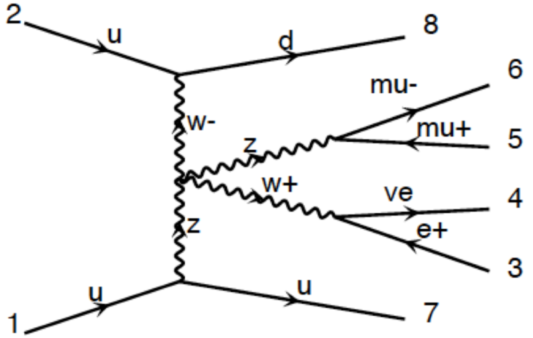
→ BUT: strong interference between these processes leads to finite cross section at all energies

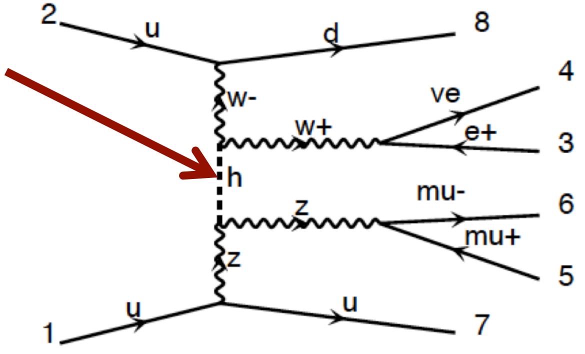
Observation of the SM scattering process would be:

- First observation of processes involving the quartic coupling of two massive vector bosons
- First observation of scattering via a Higgs particle

Cross section sensitive to new physics (additional Higgs bosons, other scalar particles, additional gauge bosons)





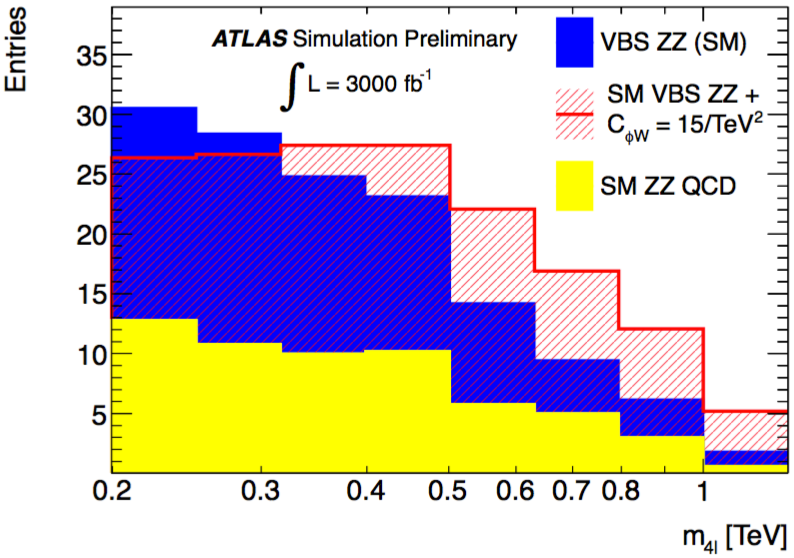


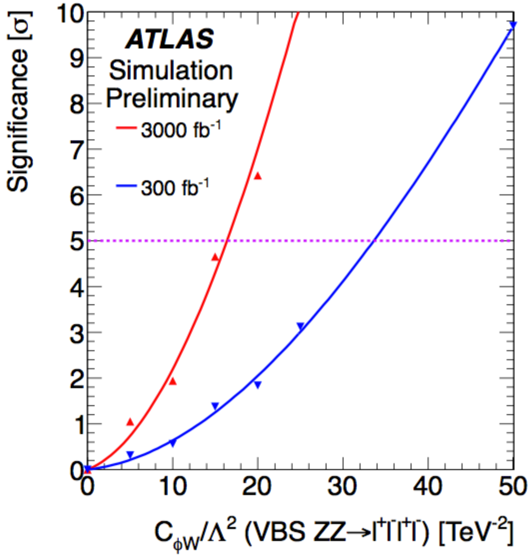
Vector Boson Scattering – Result for ZZ Channel

ZZ channel is sensitive to dimension-6 operator:

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

- Small cross section, but provides a clean, fully reconstructible ZZ resonance peak
- Forward jet-jet mass requirement of 1 TeV reduces the contribution from jets accompanying non-VBS di-boson production





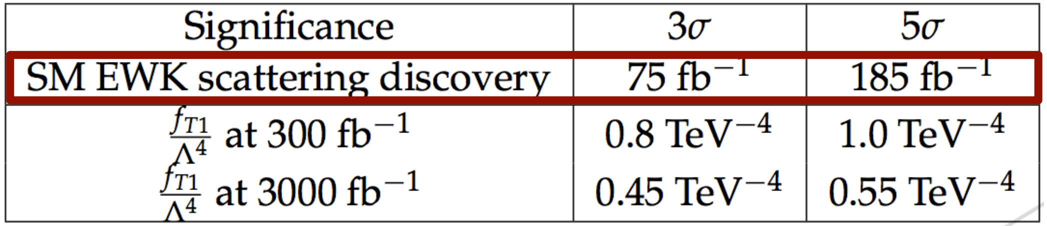
3000 fb^{-1} improves discovery range significantly

Vector Boson Scattering – Result for WZ Channel

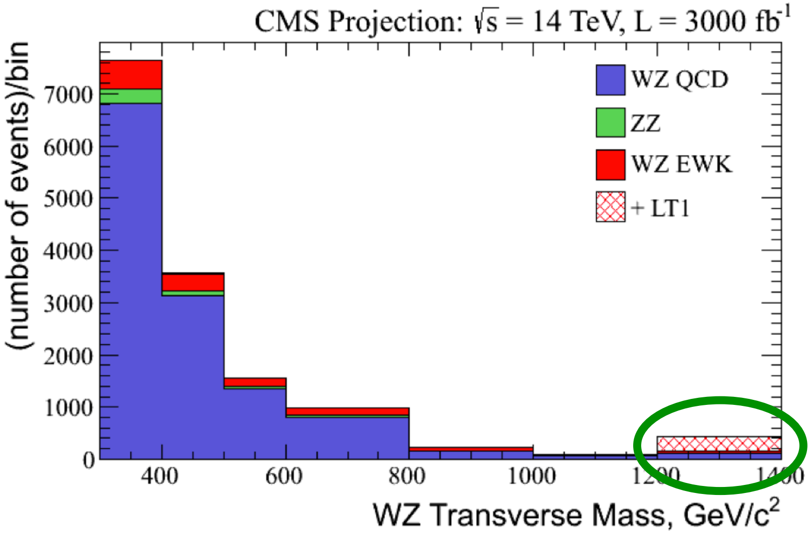
WZ channel is sensitive to dimension-8 operator:

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

- Larger cross section than ZZ, and one Z still fully reconstructible



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}



SM discovery expected with 185 fb^{-1}

BSM contribution at TeV Scale possible at 300 fb^{-1}

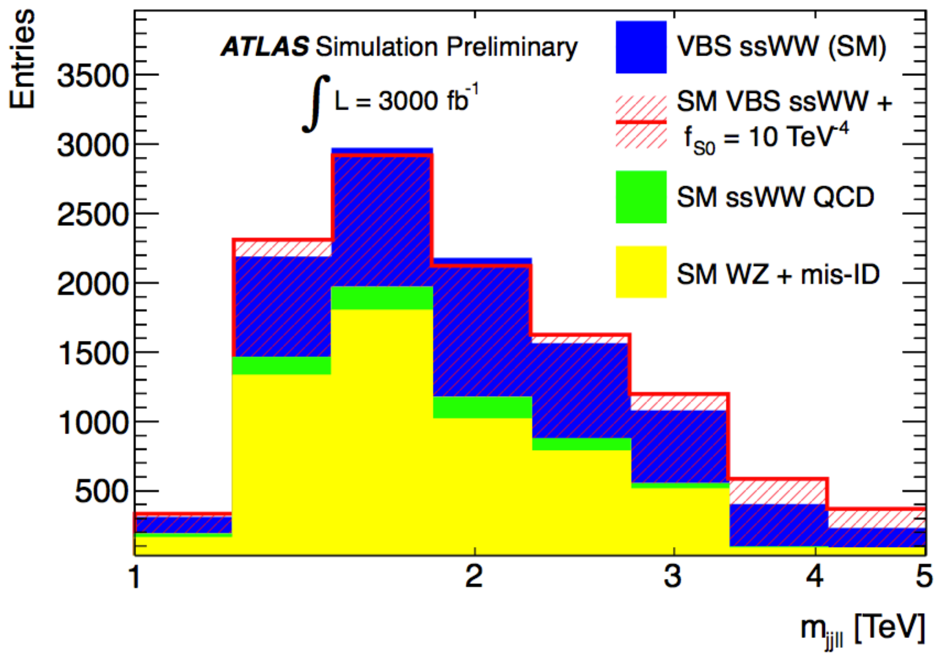
3000 fb^{-1} probes much larger range of quartic coupling!

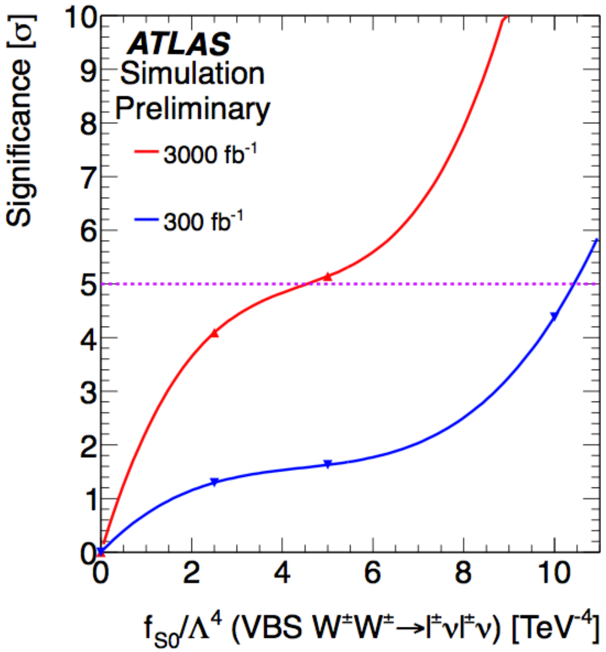
Vector Boson Scattering – Result for WW Channel

Result also obtained in WW (same-sign) channel, sensitive to dimension-8 operator:

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

- Two same-sign leptons + 2 forward jets with m_{jj} >1 TeV





3000 fb^{-1} improves discovery range significantly

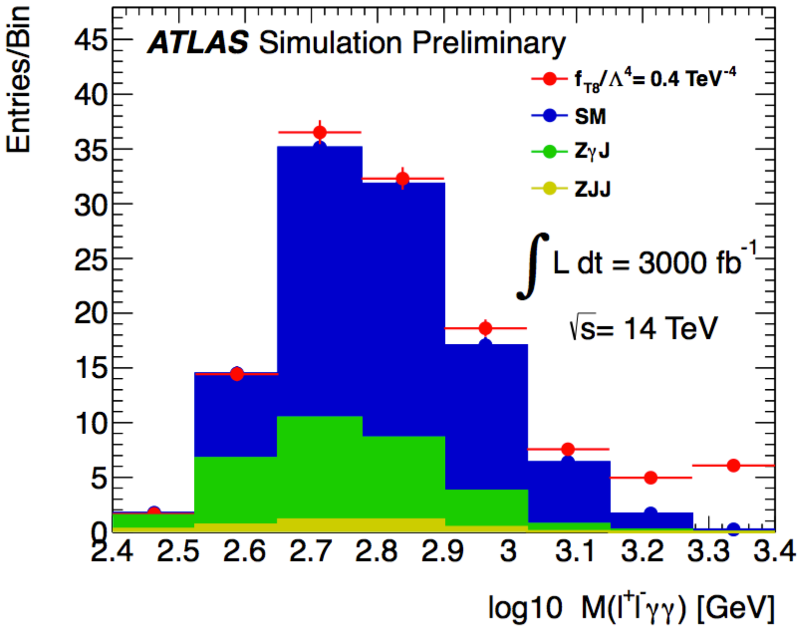
Vector Boson Scattering – Triboson Scattering

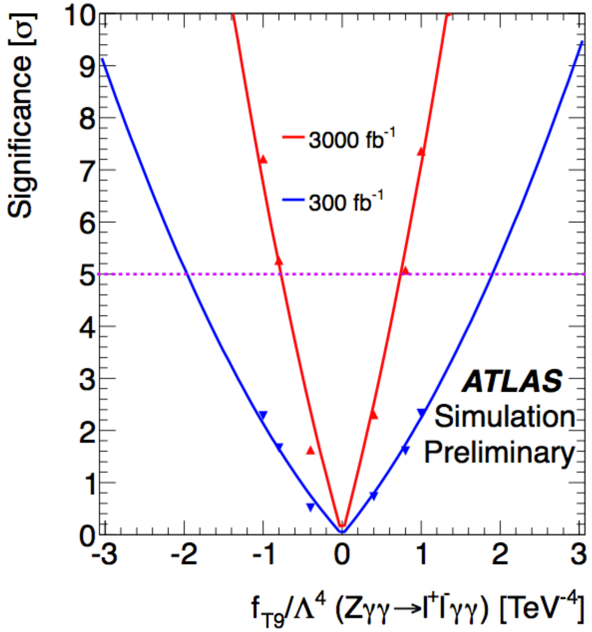
Zγγ mass spectrum at high mass:

- → sensitive to **BSM triboson** contributions through quartic gauge couplings
- → Lepton-photon channel allows full reconstruction of the final state and the Zγγ invariant mass
- → Sensitive to BSM operators:

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

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





Vector Boson Scattering – Summary

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

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}

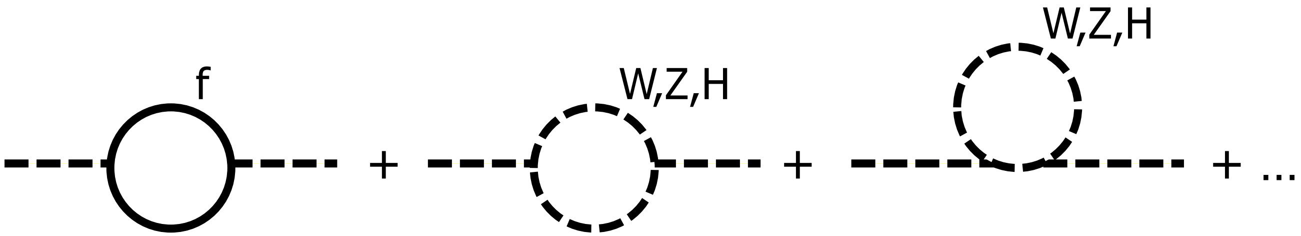
SM discovery expected with 185 fb^{-1}

BSM contribution at TeV Scale might be observed at 300 fb^{-1}!

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

Big question: Naturalness

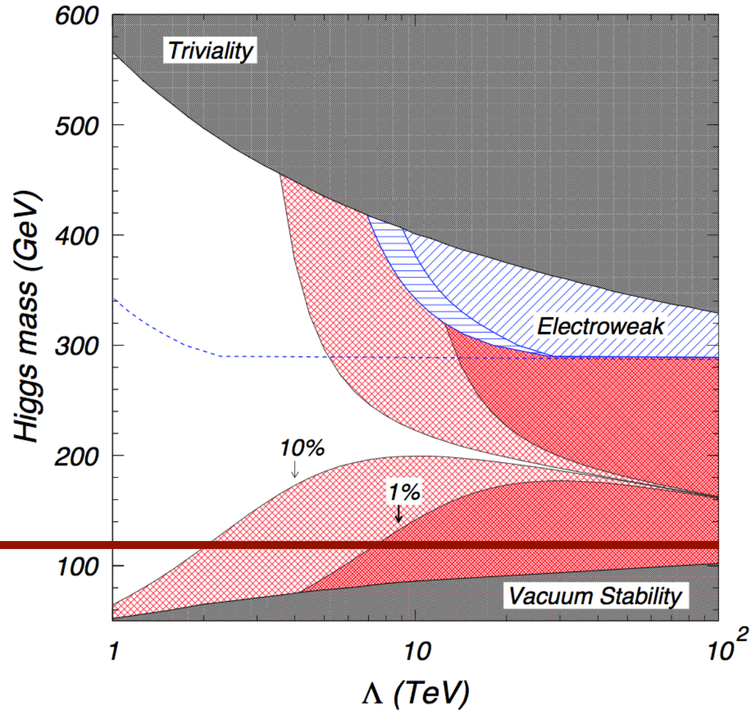
Higgs is found – what about its mass corrections?



C. Kolda,
H.Murayama,
hep-ph/0003170

Corrections at loop level:
$\delta m_H^2 \sim \Lambda^2(4m_t^2 - 2m_W^2 – 2m_Z^2 - 2m_H^2)$

→ If no new physics at scale Λ, we need a cancellation with large fine tuning!



amount of fine tuning

How much finetuning is still natural?

Natural Supersymmetry

Natural 

R. Barbieri and G. F. Giudice,
Nucl. Phys. B 306 (1988) 63;
M. Papucci, J.T.Ruderman,
A.Weiler, JHEP 09 (2012) 035

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

EWK SUSY sector

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

Stop and gluino contribution

→ Especially superpartners with close ties to Higgs must not be too far above the weak scale – especially higgsinos (mass controlled by μ)

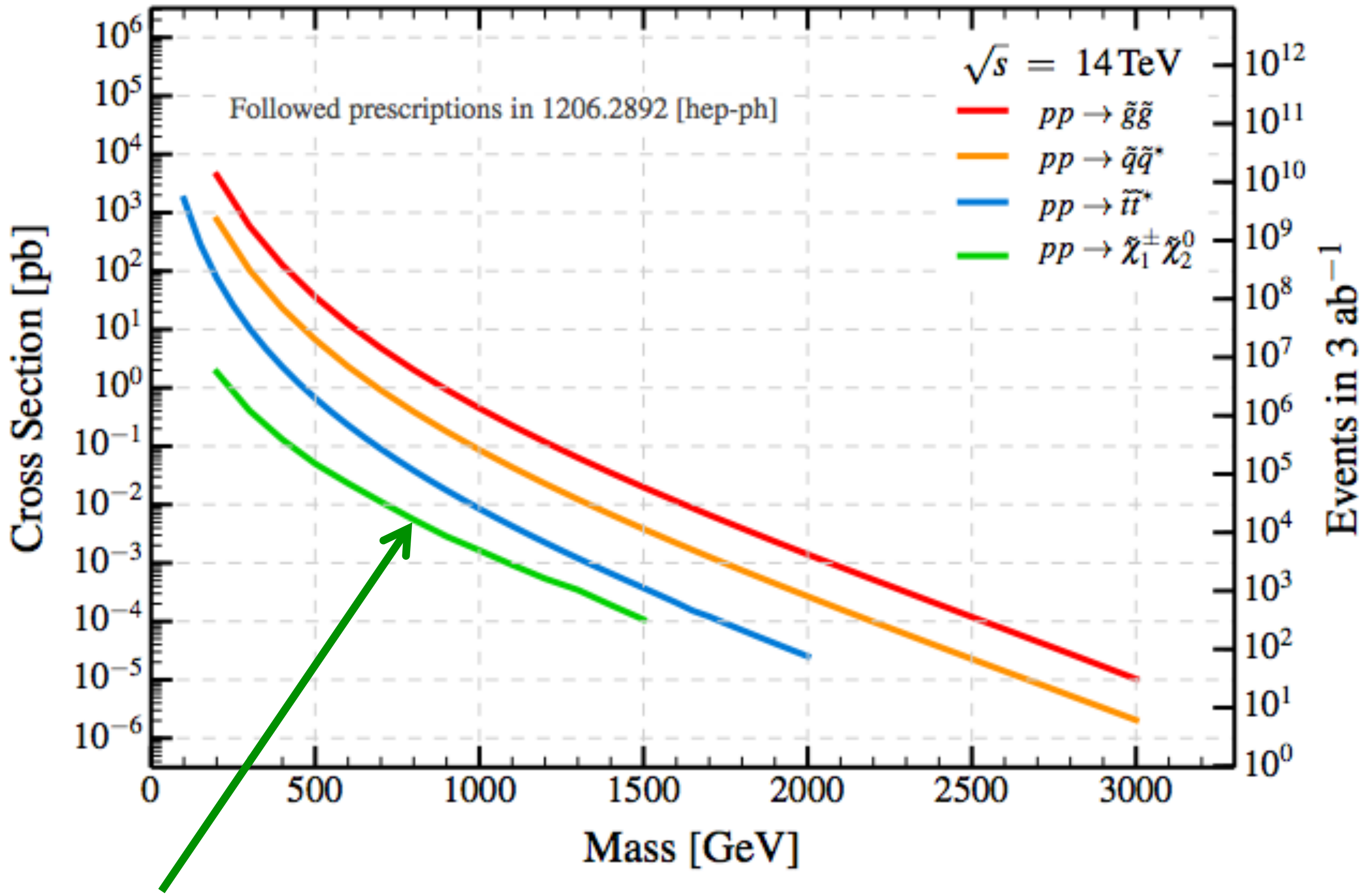
→ If superpartners are too heavy, contributions on right must be fine tuned against each other to achieve electroweak symmetry breaking

→ Stop corrects m_{Hu}^2 at one loop:
with $\mu \sim 150\text{-}200$ GeV → $m_{stop} = 1\text{-}1.5$ TeV

→ Gluinos corrects M_{Hu}^2 at two loops: should be lighter than several TeV

- 1st and 2nd generation sfermions: O(10)TeV without problem for naturalness, yielding a decoupling solution to the SUSY flavor and CP problem

Supersymmetry – Cross sections @ 14 TeV

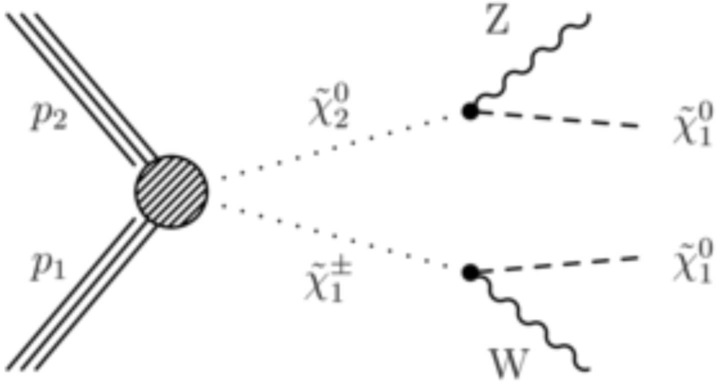


Neutralino/chargino cross sections (here assuming Wino states) are very small

→ need high luminosity!!!

Search for direct $\chi^{\pm}\chi^0$ Production – Motivation

Naturalness predicts light electroweak sparticles



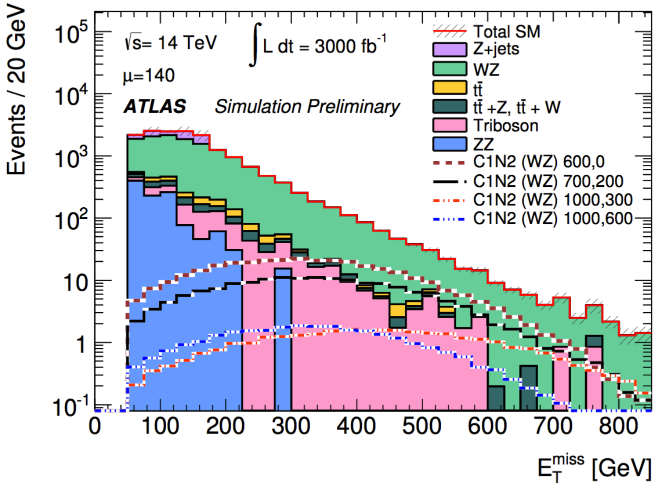
- → Concentrate here on final state with W and Z
- → Exact branching ratio is strongly model dependent, here SMS with BR=100%
- → Dedicated analysis: 3 leptons + MET
  - → very clean final state
  - → good lepton resolution
  - → small background

Analyses based on CMS PAS-SUS-13-006 and on ATLAS-2013-035

Search for direct $\chi^{\pm}\chi^{0}$ Production – Analysis Overview

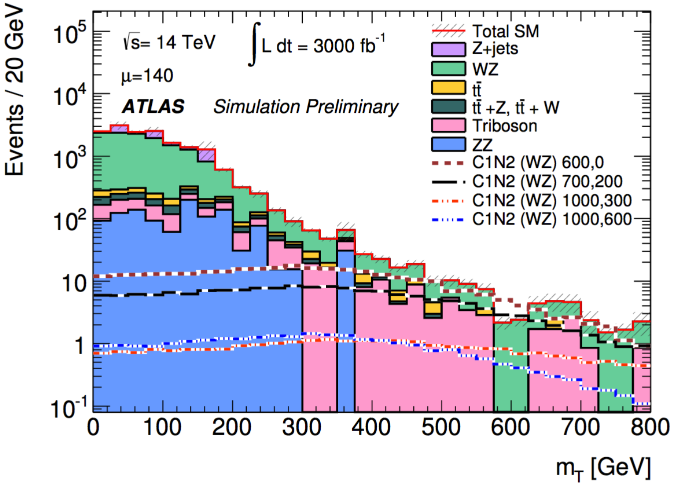
Event selection:

- b-jet veto
- 3 l (e, μ)
- 1 OSSF pair with inv. mass close to Z
- M_T calculated with 3rd lepton and MET
- Search regions defined by M_T and MET



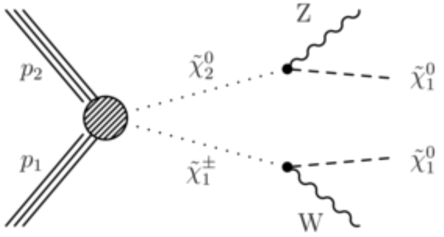
Backgrounds:

- WZ (3 leptons + MET from neutrino)
  → suppressed by MT cut
- ttbar (2 prompt l + 1 non-prompt l)
  → suppressed by b-jet veto
- Rare backgrounds
  → negligible due to low cross section
- Single boson background (no intrinsic MET)
  → suppressed by MET and MT cut



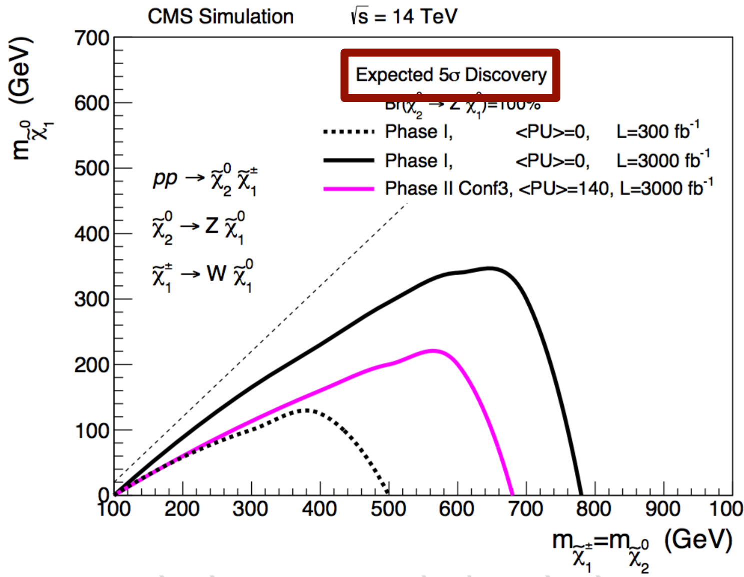
Search region binned in MET and MT

Search for direct $\chi^{\pm}\chi^{0}$ Production – Interpretation



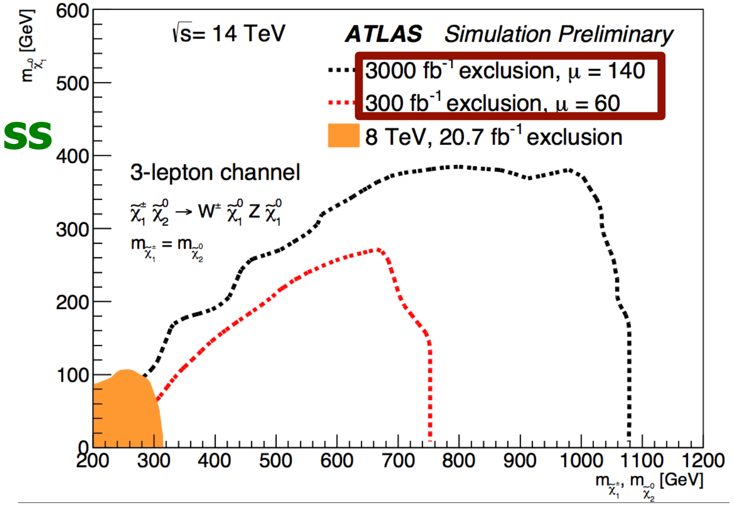
Sensitive to 5σ discovery of chargino and neutralino masses up to 700 GeV (exclusion possible up to 1100 GeV) and LSP masses up to 200 GeV

(in case of reduced BR of $\chi_2^0 \rightarrow Z+\chi_1^0$
mass reach is significantly reduced,
e.g. by ~150GeV for 0 pileup and 50% BR)



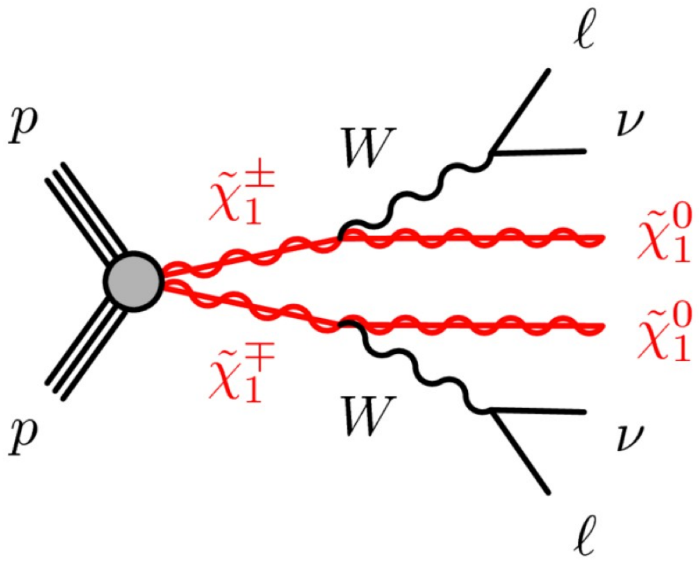
Gain of ~200 GeV in chargino/neutralino mass discovery reach when going from 300 fb^{-1} to 3000 fb^{-1}

→ **most interesting mass range could be covered!**



Search for direct $\chi^{\pm}\chi^{\pm}$ Production

EWKino predicted to be light even if colored sector is heavy



Final state:

- 2 leptons
- MET
- No hadronic activity

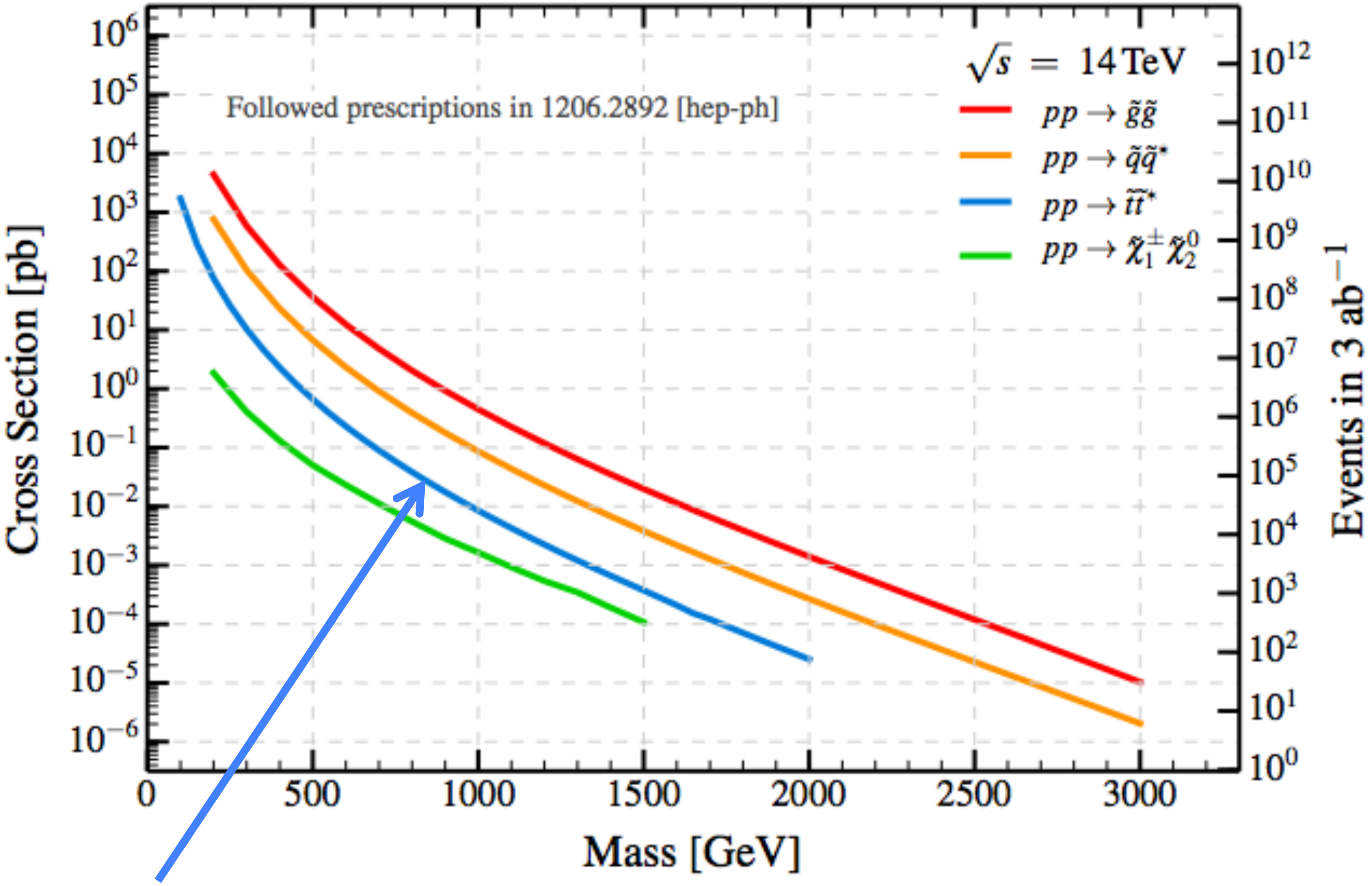
Extrapolation of existing 8 TeV analysis (ATLAS-CONF-2013-049):

- Background scaled
- Different pileup conditions not taken into account
- Event selection tightened

Result:

Gain of ~150 GeV in chargino mass up to 400 GeV
discovery reach when going from 300 fb^{-1} to 3000 fb^{-1}

Supersymmetry – Cross sections @ 14 TeV

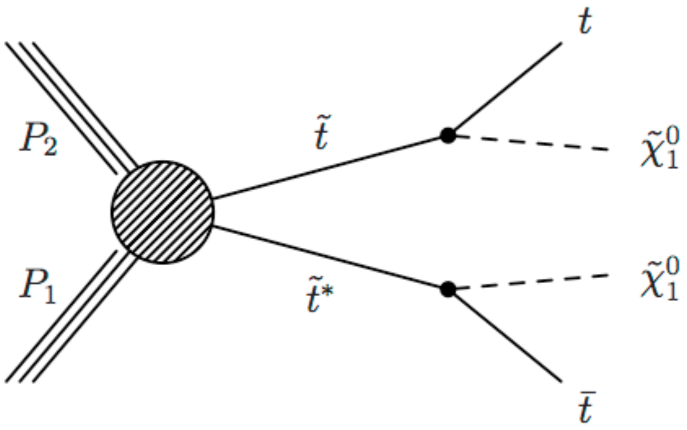


Also stop cross sections quite small → need high luminosity!!!

Search for Direct Stop Production – Motivation

Naturalness predicts a light third generation

→ investigate direct stop production



Two signatures:

- hadronic top decays → 0 leptons + b-tagged jets + MET
- semi-leptonic top decays → 1 lepton + b-tagged jets + MET

Both analyses are exclusive and are combined for the result

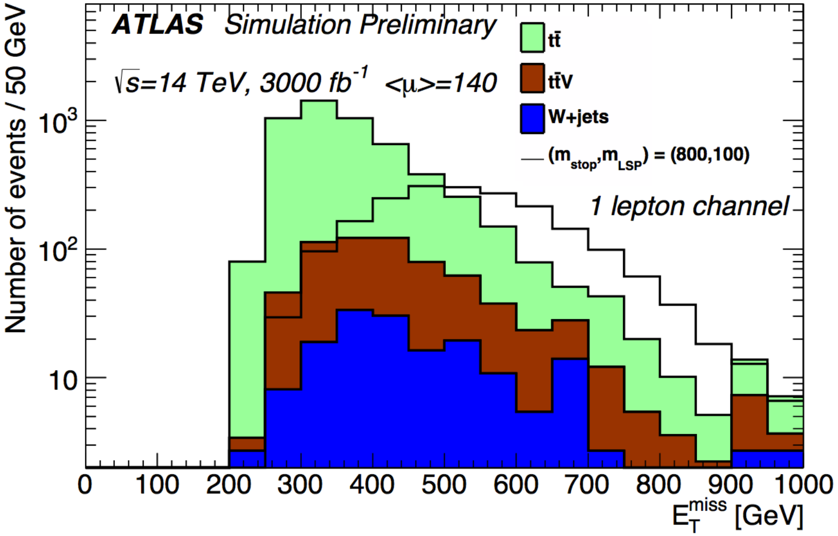
Search for Direct Stop Production – Analysis Strategy

Baseline selection 1-lepton channel (based on Phys.Rev.Lett. 109 (2012) 211803):

- 1 e (μ) with p_T>25 (20) GeV, $|\eta|<2.5$ (2.4)
- veto 2nd loose lepton
- $N_{jet} \geq 4$ with p_T> 80,60,40,25 GeV, $|\eta|<2.5$
- $N_{b\text{-}jet} \geq 1$
- $\Delta\Phi(\text{jet}_{1,2}, \text{MET}) > 0.8$
- Reconstruction of hadronic top with 3-jet mass: 130 GeV < m_{jjj} < 205 GeV

Signal regions depending on probed stop masses, with differing requirements on:
MET, MT, MET/$\sqrt{H_T}$
(with H_T calculated from first 4 jets)

	(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

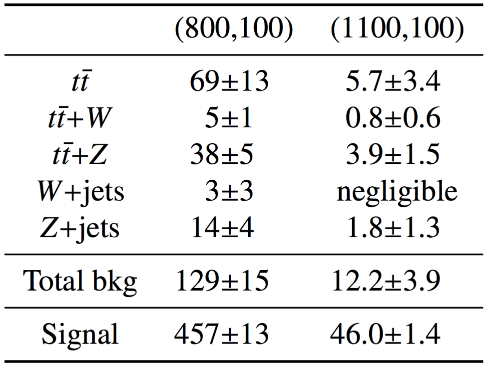


Search for Direct Stop Production – Analysis Strategy

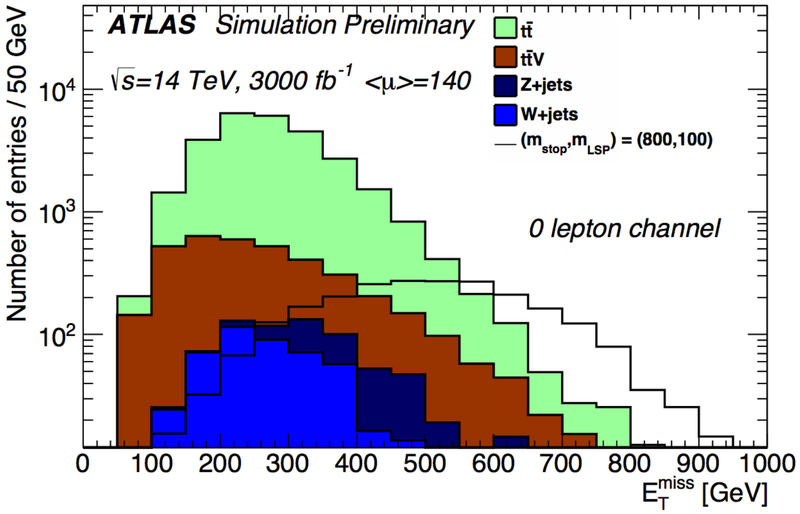
Baseline selection 0-lepton channel (based on Phys.Rev.Lett. 109 (2012) 211803):

- veto events containing e (μ) with p_T>20 (10) GeV, $|\eta|$<2.5 (2.4)
- $N_{jet} \geq 6$ with p_T> 80,80,35,35,35,35 GeV, $|\eta|$<2.5
- $N_{b\text{-}jet} \geq 2$
- $\Delta\Phi(jet_{1,2,3}, MET) > 0.2\pi$
- Reconstruction of 2 hadronic tops with 3-jet mass: 80 GeV < m_{jjj} < 270 GeV

Signal regions depending on probed stop masses, with differing requirements on: MET, M_T^b (invariant mass of b-jet and MET)

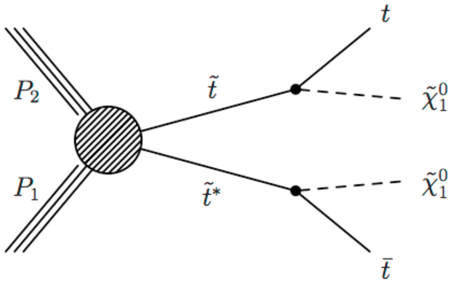


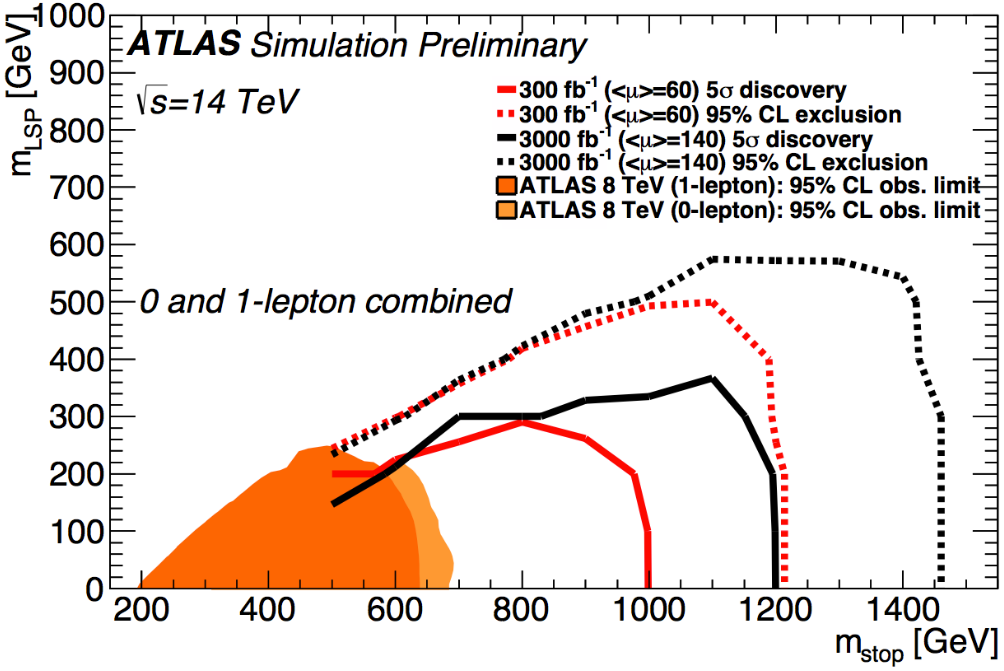
	(800,100)	(1100,100)
$t\bar{t}$	69±13	5.7±3.4
$t\bar{t}$+W	5±1	0.8±0.6
$t\bar{t}$+Z	38±5	3.9±1.5
W+jets	3±3	negligible
Z+jets	14±4	1.8±1.3
Total bkg	129±15	12.2±3.9
Signal	457±13	46.0±1.4



Search for Direct Stop Production – Result

Combined 5σ discovery and 95% exclusion





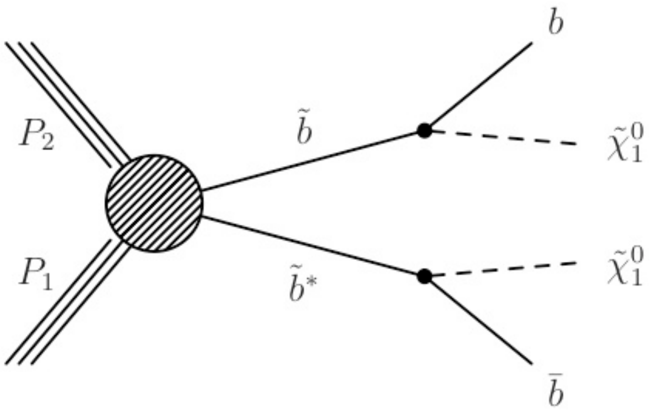
Limit on stop mass can be extended by 200 GeV

when going from 300 fb^{-1} to 3000 fb^{-1}

→ **most interesting mass range will be covered!**

Search for Direct Sbottom Production

Naturalness predicts a light third generation
→ investigate direct sbottom production



Extrapolation of existing 8 TeV analysis (arXiv:1308.2631)

- Background scaled (including PDF reweighting)
- Different pileup conditions not taken into account
- Event selection tightened

Result:

Gain of ~200 GeV in sbottom mass up to 1250 GeV
discovery reach when going from 300 fb^{-1} to 3000 fb^{-1}
→ **most interesting mass range will be covered!**

VBF Dark Matter Search – Motivation

Vector boson fusion processes at the LHC provide a unique opportunity to search for new physics with electroweak couplings, here:
Supersymmetric dark matter produced directly at HL-LHC in VBF processes

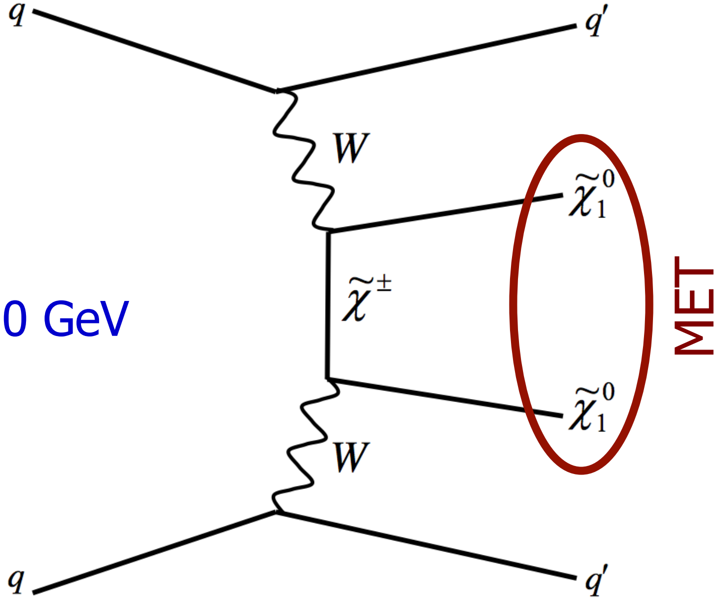
Signature:

- 2 high-energetic forward jets
- Missing transverse energy

Event selection:

- "Standard" VBF selection
  - $N_{jet} = 2$ with $p_T > 30$ GeV, $|\eta| < 5$
  - $\eta_1 - \eta_2 > 4.2$, $\eta_1 * \eta_2 < 0$
- 140 PU: p_T(jet1) > 200 GeV, p_T(jet2) > 100 GeV
- $M_{jj} > 1500$ GeV
- Veto of 3rd jet within jet1 and jet2
- Veto of b-tagged jet
- Lepton veto (e, μ, τ)
- MET > 200 GeV

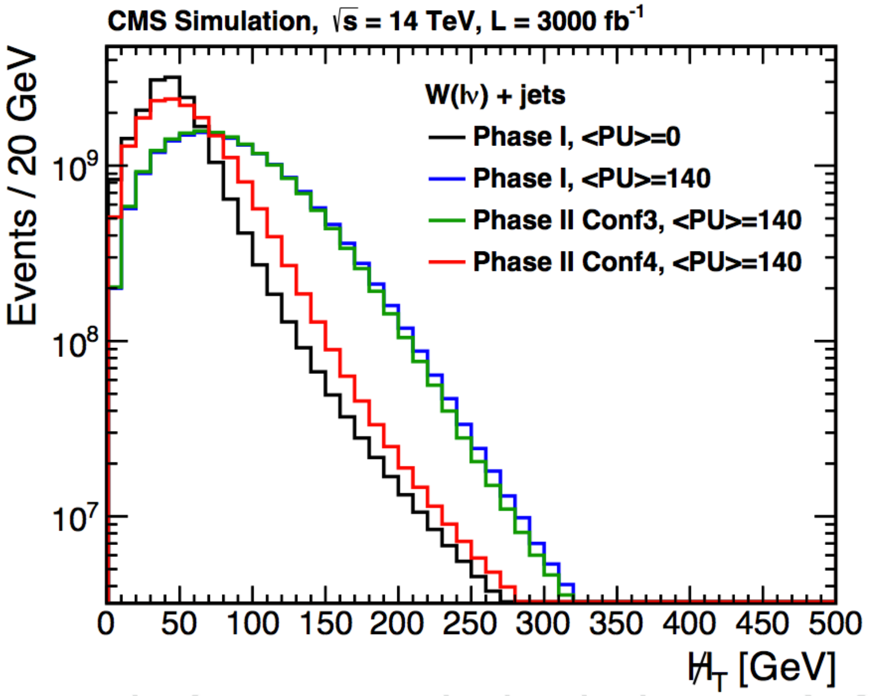
A.G.Delannoy et al.
arXiv:1304.7779

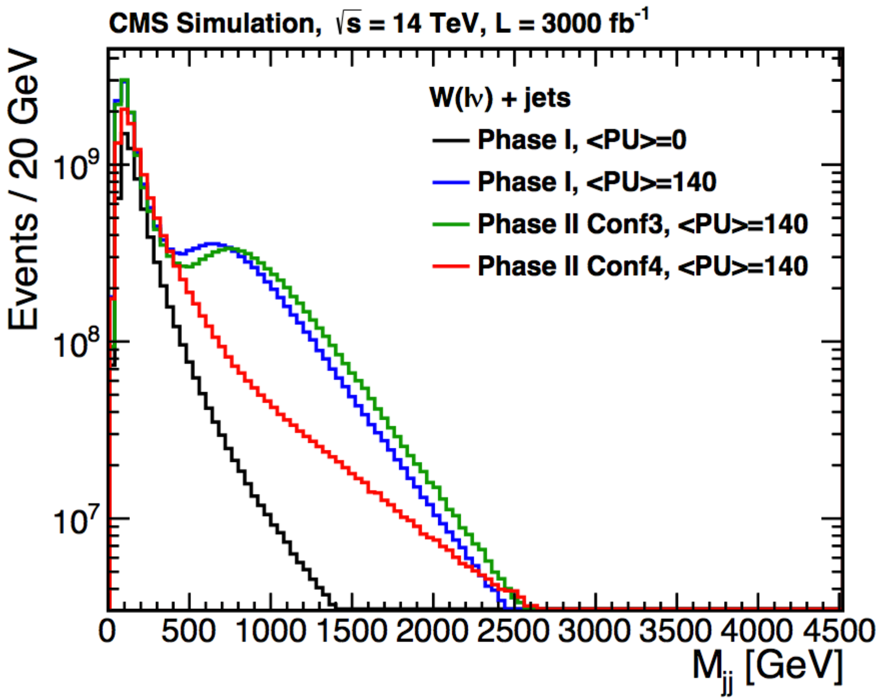


VBF Dark Matter Search – Necessity of the forward Tracker

Number of jets rises dramatically in forward region without tracking

→ MHT and M_{jj} strongly affected





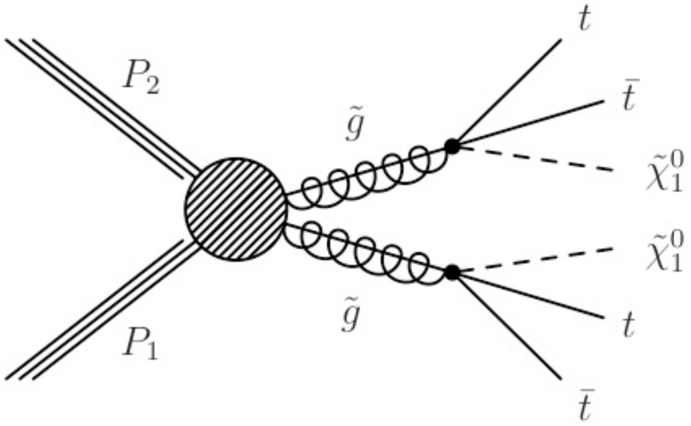
→ Analyses depending on good measurement of forward jets profit most from tracking up to $|\eta| < 4$ (see also presentation from B. Dahmes)

→ Background reduction by factor 3-10 expected!

Gluino (l+b) Search – Motivation

3rd generation squarks expected to be light compared to 1st and 2nd generation

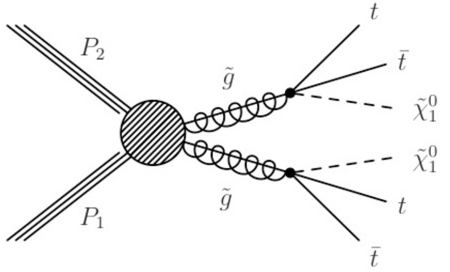
→ Gluinos (if heavier than 3rd generation) can decay with large branching fraction to 3rd generation squarks



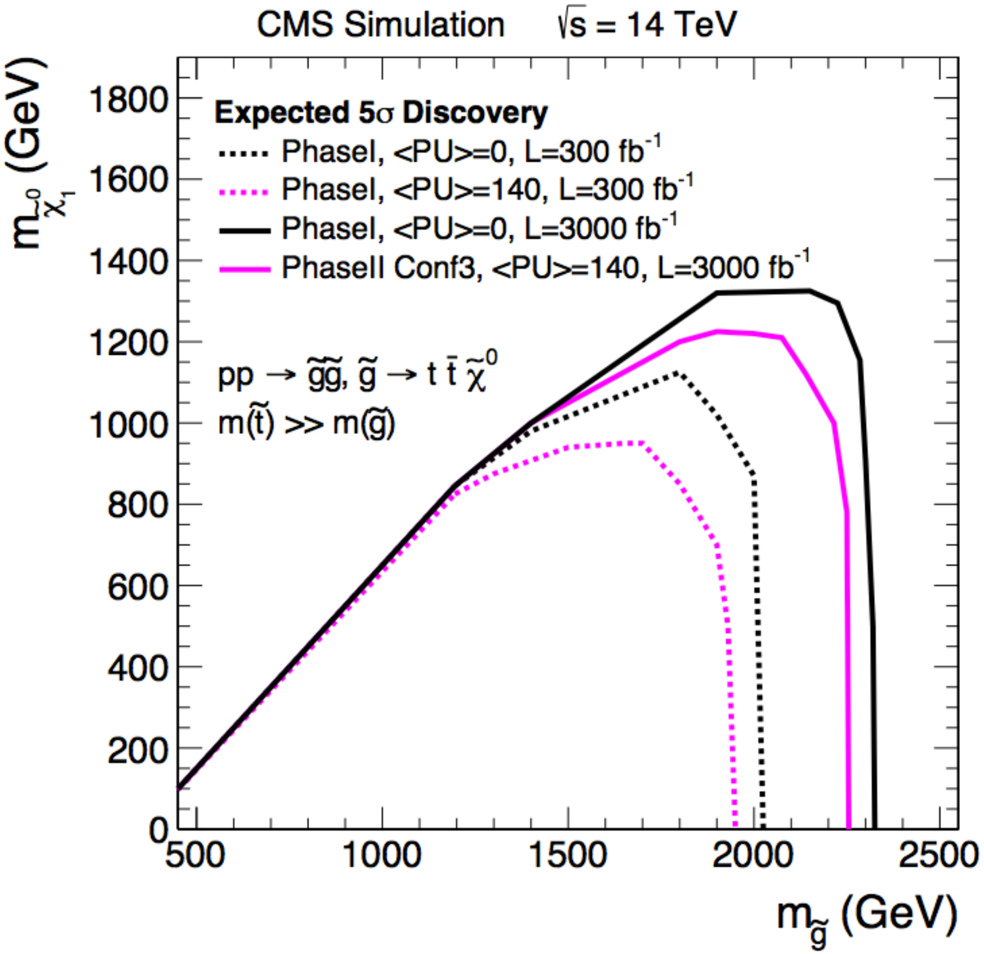
Typical signature of such events:

- Many jets
- Among them several b-jets
- Large MET
- Angle between lepton and W ($\Delta\Phi$) larger for signal than for typical background (semileptonic ttbar), where MET and lepton are correlated

Gluino (l+b) Search – Result



Sensitive to
gluino masses up to 2.2 TeV and
LSP masses up to 1.2 GeV



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

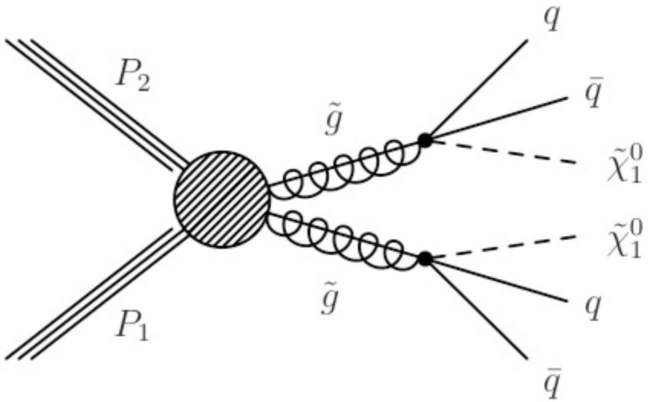
→ **about half of the interesting mass range will be covered!**

SUSY: Jets + MHT Search – Analysis Overview

Search for direct gluino production with multiple jets and large MET

based on 8 TeV analysis

CMS-PAS-SUS-13-012



Baseline selection from 8 TeV analysis (omitting possible trigger constrains):

- Electron and muon veto (p_T > 10 GeV and $|\eta|$ < 2.4 (μ) or 2.5 (e))
- n_{jets} > 3 (p_T > 50 GeV and $|\eta|$ < 2.5)
- MHT > 200 GeV (with MHT=$|-\Sigma(\vec{p}_T(\text{jets})|$ with p_T> 30 GeV))
- H_T > 500 GeV ($\Sigma(p_T(\text{jets})$ with p_T > 50 GeV and $|\eta|$ < 2.5))
- $\Delta\Phi$(MHT, Jet(1,2,3) > 0.5, 0.5, 0.3

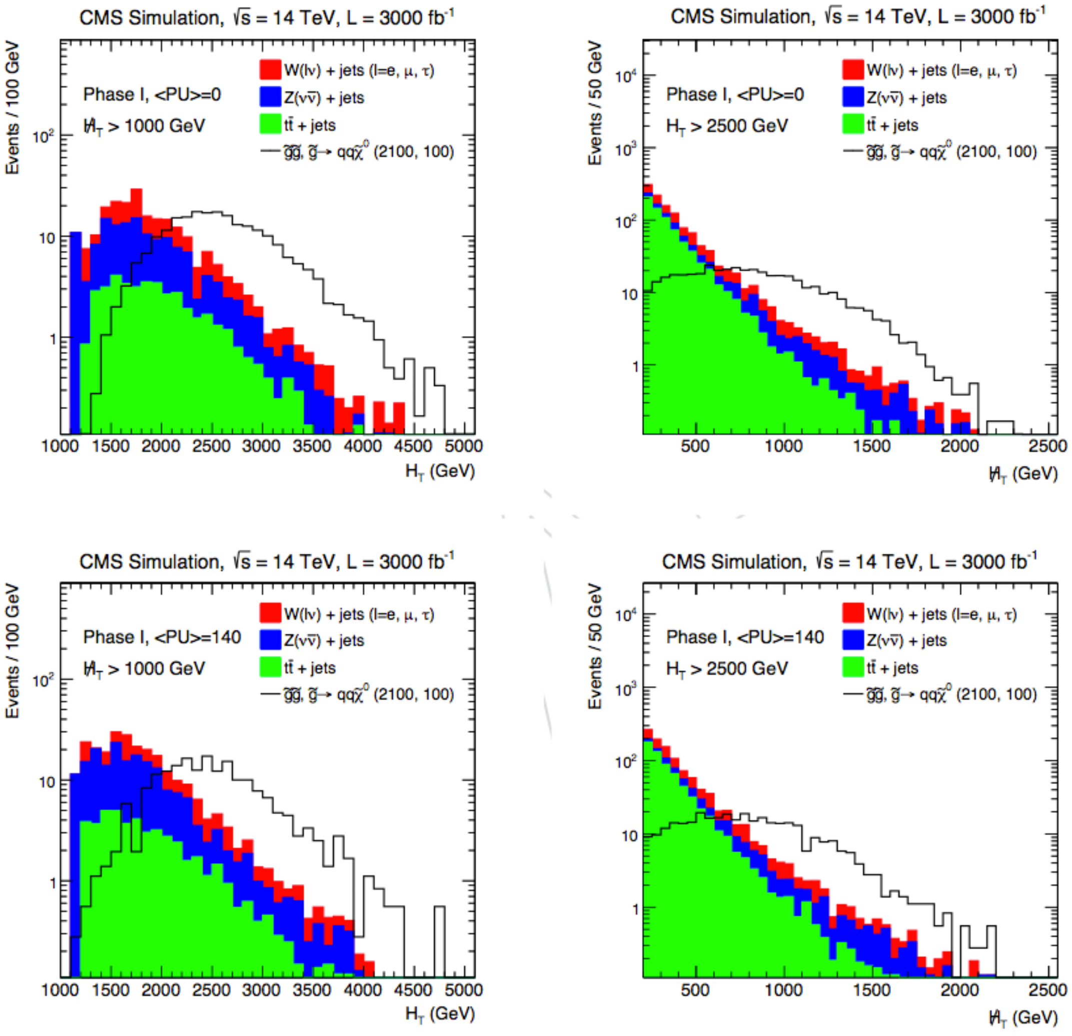
Search region binned in H_T and MHT for $n_{jets} \geq 6$

Systematic uncertainty: assume 30% similar to 8 TeV analysis

SUSY: Jets + MHT Search – Pileup Dependence

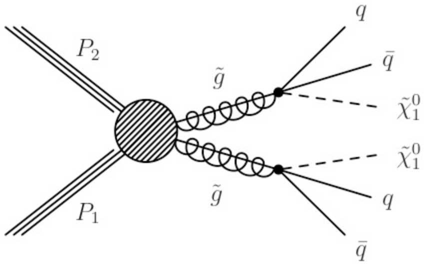
No pileup

140 pileup

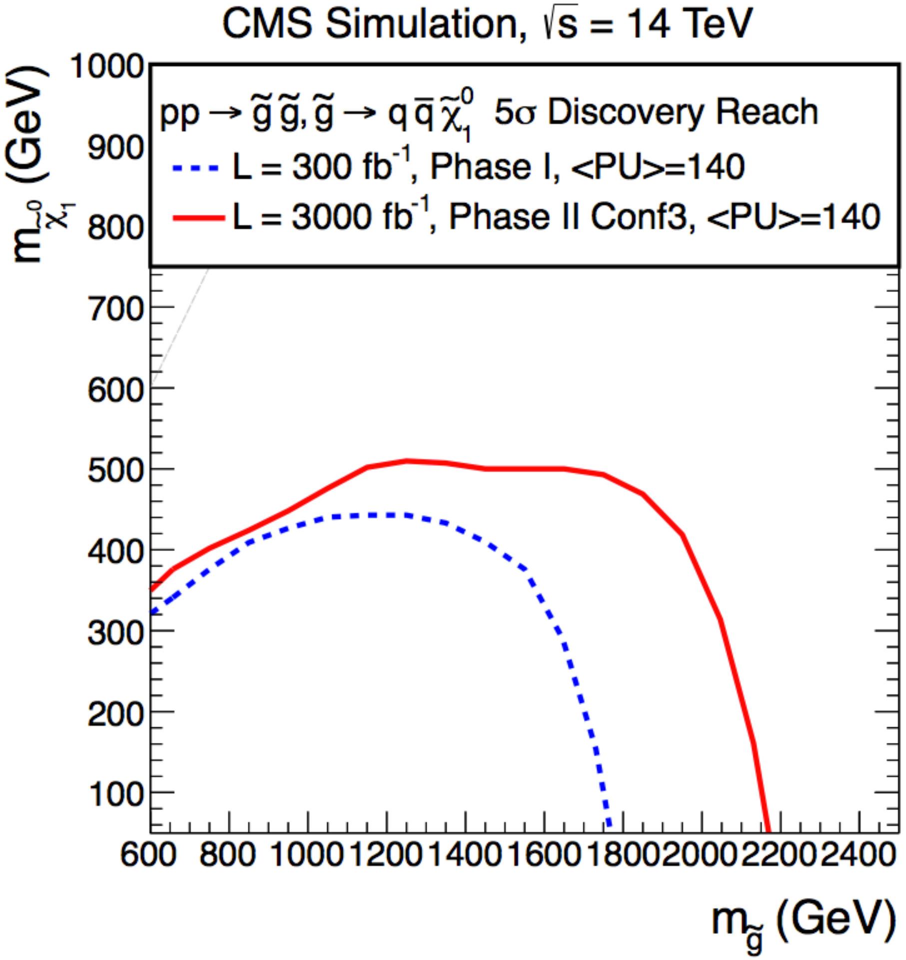


→ This analysis is not very pileup-dependent

SUSY: Jets + MHT Search – Result

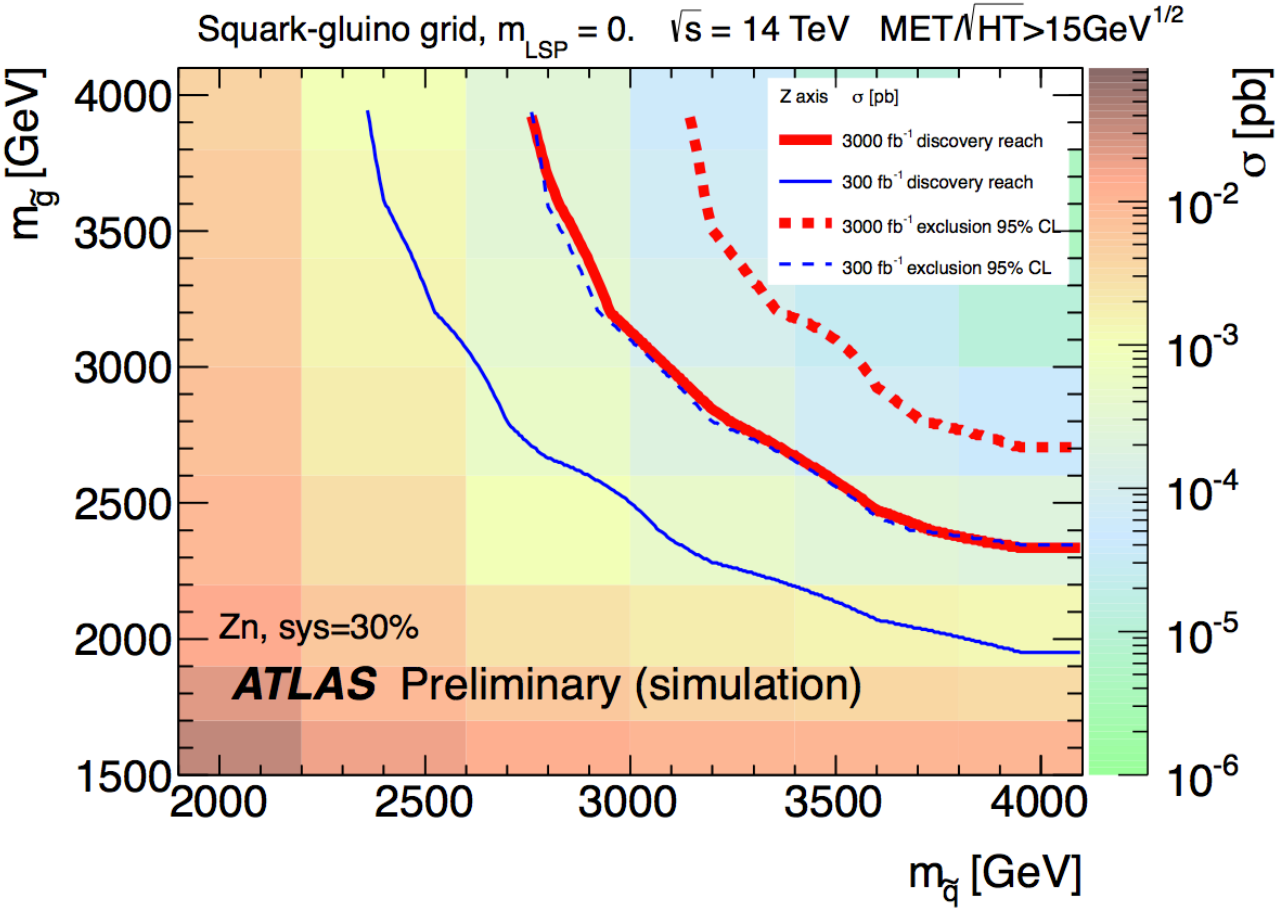


Sensitive to
gluino masses up to 2.2 TeV and
LSP masses up to 500 GeV



Gain of ~400 GeV in gluino mass
discovery reach when
going from 300 fb^{-1} to 3000 fb^{-1}

SUSY: Jets + MHT Search – Result



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}

Search for ttbar Resonances – Analysis Strategy

Extra Dimensions can lead to **wide ttbar resonances**, e.g. Kaluza-Klein gluon (g_{KK}) via the process pp → g_{KK} → ttbar

Topcolor Z' scenarios arising in models of strong electroweak symmetry breaking through top quark condensation can lead to **narrow resonances** from heavy Z'→ ttbar

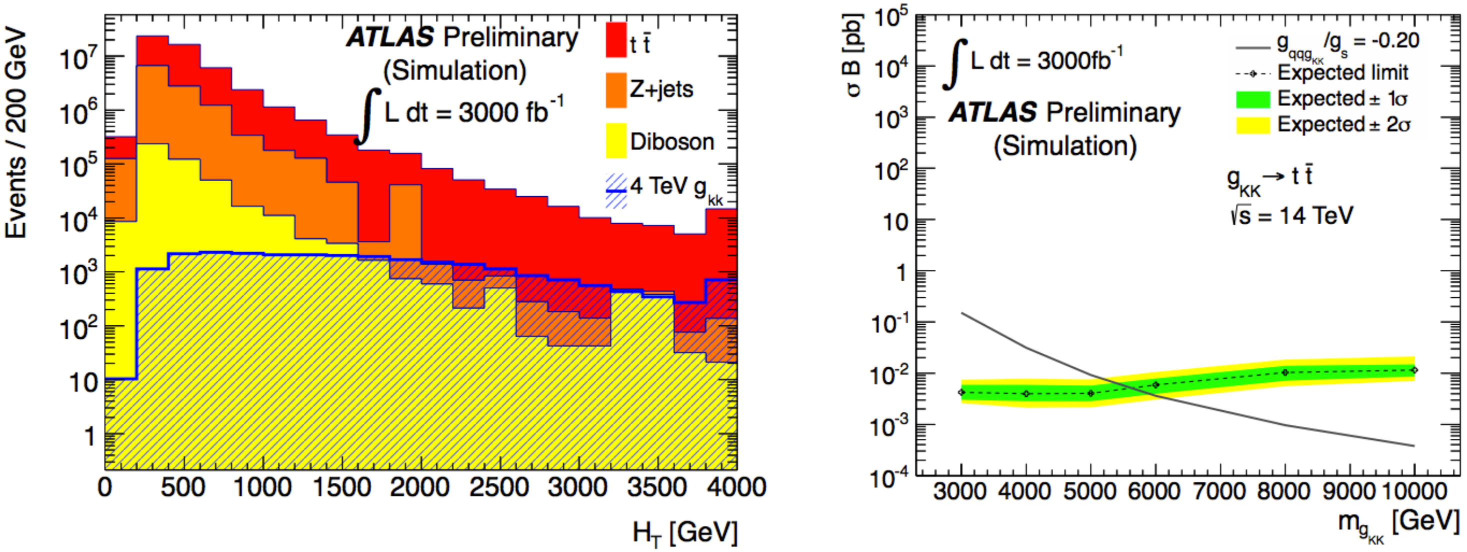
Both models lead to **similar final states**:

- di-leptonic ttbar → 2 leptons + MET
  - → clean final state, but more difficult reconstruction of ttbar inv. mass
  - → less affected by the merging of top quark decay products in case of boosted ttbar (leptons are easier to identify close to a b–jet)
- semi-leptonic ttbar → 1 lepton + MET
  - → more complete reconstruction, but higher background

Search for ttbar Resonances – Results

di-leptonic selection

(similar results for single-lepton selection)



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)

(in TeV)

Mass reach for Kaluza-Klein gluons or Z′ can be enhanced by 50% with 3000 fb^{-1}

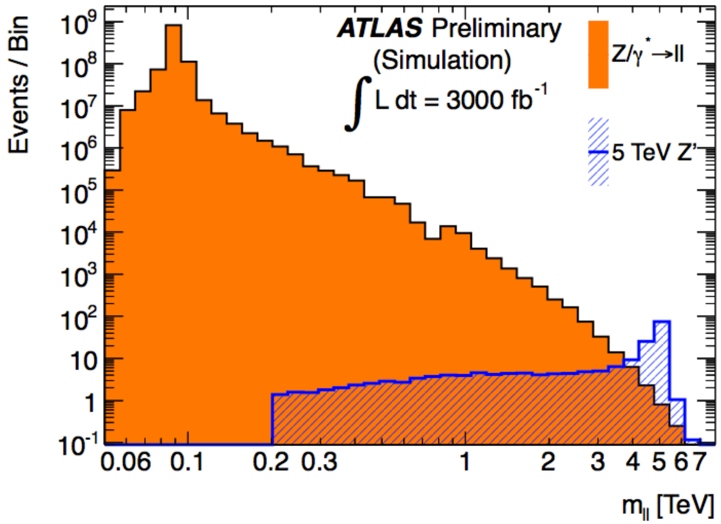
Search for Z’ with di-lepton Resonances

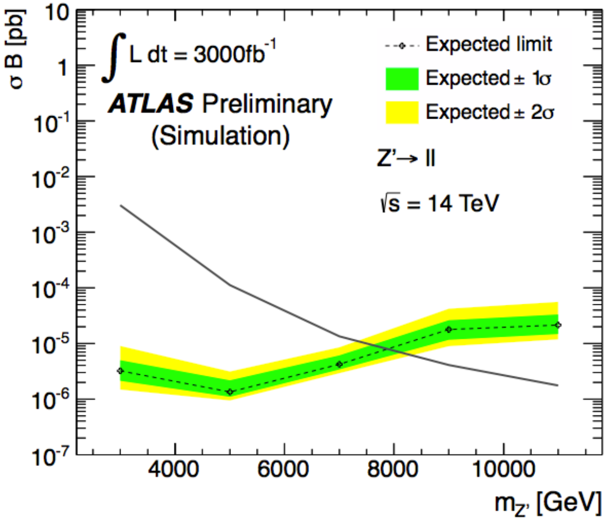
Z′ can decay to di-leptons

→ main background: SM Drell-Yan (ttbar, di-boson smaller, but considered)

→ Upgraded detector should be able to suppress electrons from γ conversions

ee final state (similar results for $\mu\mu$)





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

(in TeV)

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

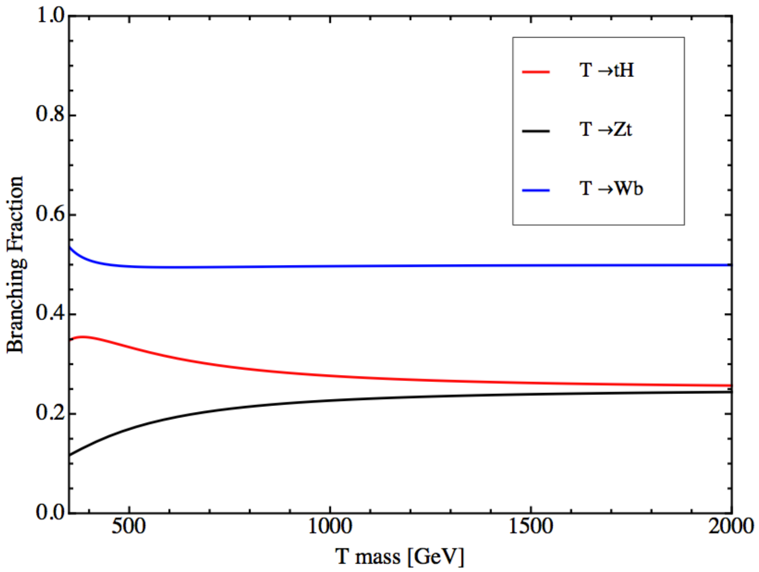
Vector-like Charge 2/3 Quark Search – Motivation

Vector-like quarks differ from SM quarks in their electroweak couplings:

- SM quarks have V-A coupling to the W
  → Left and right-handed states couple differently to the W
  Vector-like quarks have only vector-coupling to the W

→ 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:1309.0026 and performed in:

- Single-lepton channel
- Multi-lepton channel

Vector-like Charge 2/3 Quark Search – Event Selection

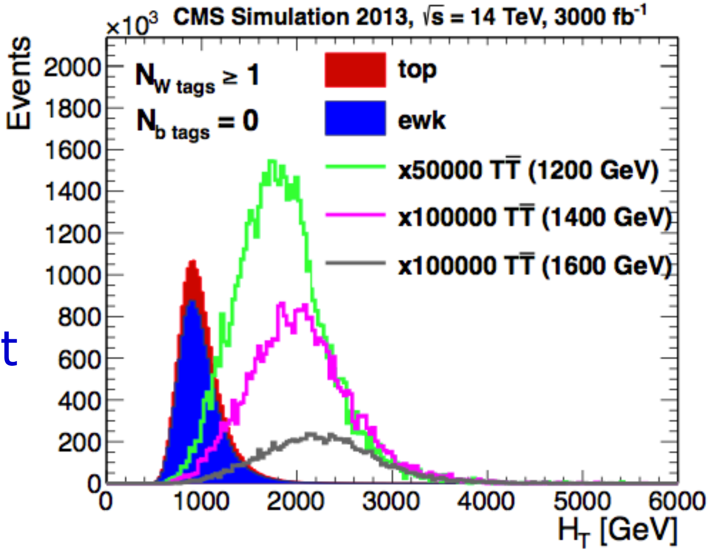
Single-lepton channel:

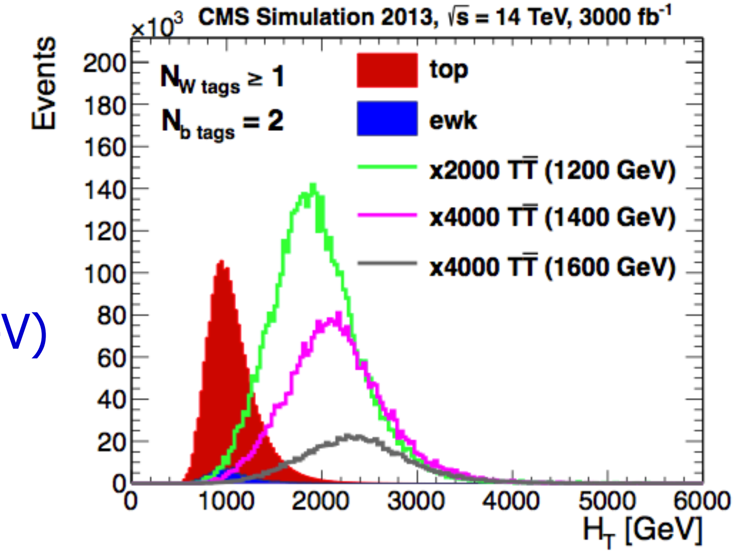
- 1 lepton (e or μ) with $p_T > 30$ GeV
- MET > 20 GeV
- $0 \leq n_{b\text{-jet}} \leq 3$
- p_T (leading b-jet) > 150 GeV
- $n_{jet} > 3$ with $p_T > 200, 90, 50$ GeV + at least 1 W-jet
- or $n_{jet} > 4$ with $p_T > 200, 90, 50,35$ GeV + no W-jet

Search in bins of $n_{b\text{-jet}}$, n_{jet} , $n_{W\text{-jet}}$

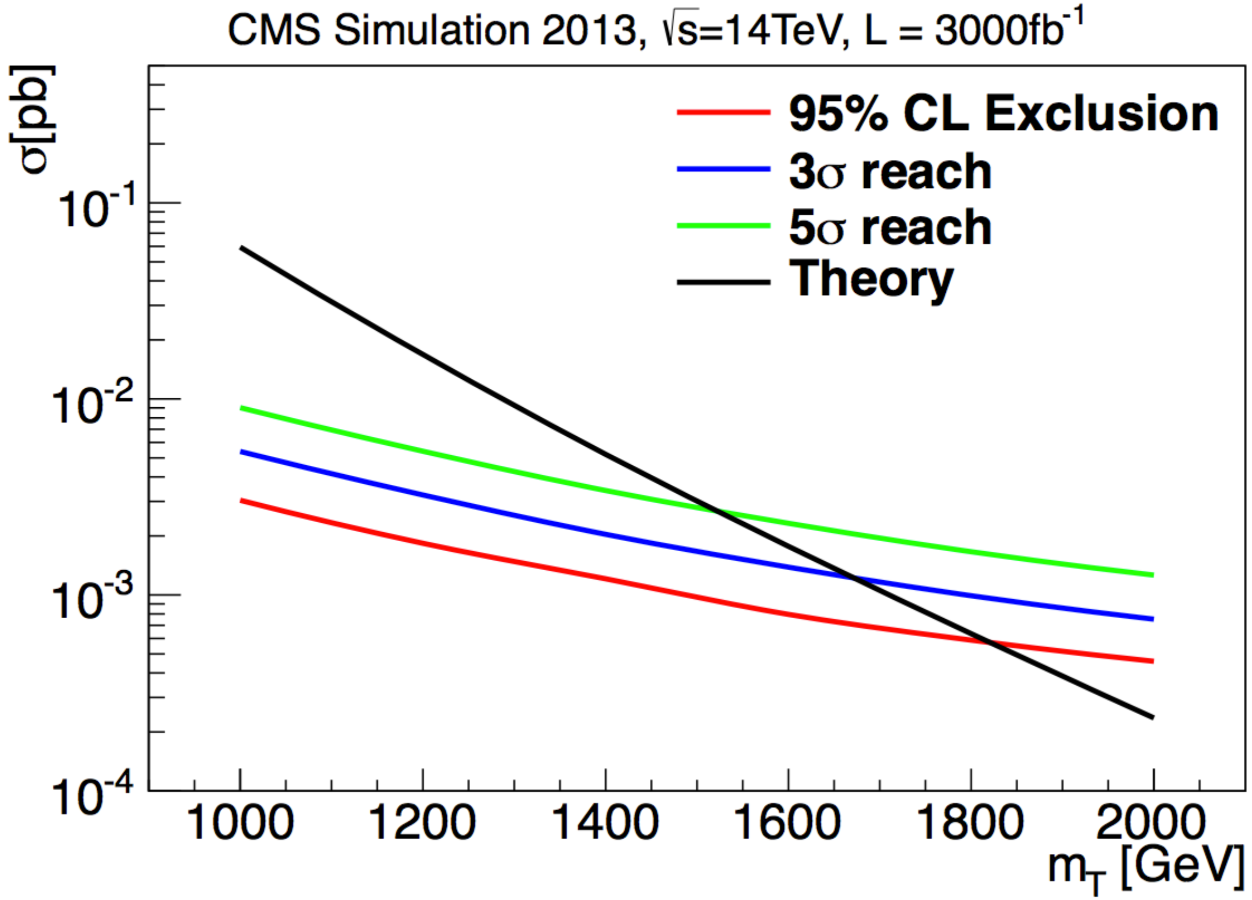
Multi-lepton channel:

- ≥ charged leptons (e/μ) with p_T >30 GeV
- define jet constituents:
- two: W-tagged jets (W-jet p_T>200 GeV)
- three - top-tagged jets (top-jet p_T>300 GeV)
- 4 Exclusive signal regions
  - 2 leptons: OS23, OS5+, SS
  - 3 leptons





Vector-like Charge 2/3 Quark Search – Result



Combined 5σ discovery reach up to T masses of 1500 GeV

(compared to ~700 GeV (2σ) exclusion limit @ 8 TeV)

Summary

Several BSM scenarios have been studied

- **Vector boson scattering:**
  - BSM contribution discovery at TeV scale possible with 300 fb^{-1}
  - **If BSM discovered with 300 fb^{-1}**, then the coefficients on the new operators can be measured with **5% precision with 3000 fb^{-1}**
- **Supersymmetry and naturalness:**
  - Gain up to 200 GeV in chargino/neutralino mass sensitivity
  - Gain up to 200 GeV in 3rd gen. mass sensitivity → exclusion region covers almost all of the estimated "natural" region

  → **Most interesting mass range for neutralinos/charginos/stops can be covered!** (Caveat – SMS with 100% BR is ideal case)
  - Gain up to 400 GeV in gluino and squark mass sensitivity
- **VBF searches** might be used for **dark matter** detection, but depend crucially on **forward tracking** (CMS) for pileup mitigation
- **Large Extra Dimensions and topcolor Z':** gain up to 50% in mass reach for KK gluons or Z' to several TeV
- **Vector-like charge 2/3 quark** search can probe masses up to 1.5 TeV

Conclusion and Outlook

The general purpose detectors at the LHC have world-beating sensitivity across a huge range of physics topics

- Our sensitivity greatly exceeds all previous experiments in an enormous range of channels already now
- We will have out-performed both simulations and expectations with 300 fb^{-1}
- The results from ATLAS and CMS will continue to set the agenda across the energy frontier for the foreseeable future

Benefits of the HL-LHC

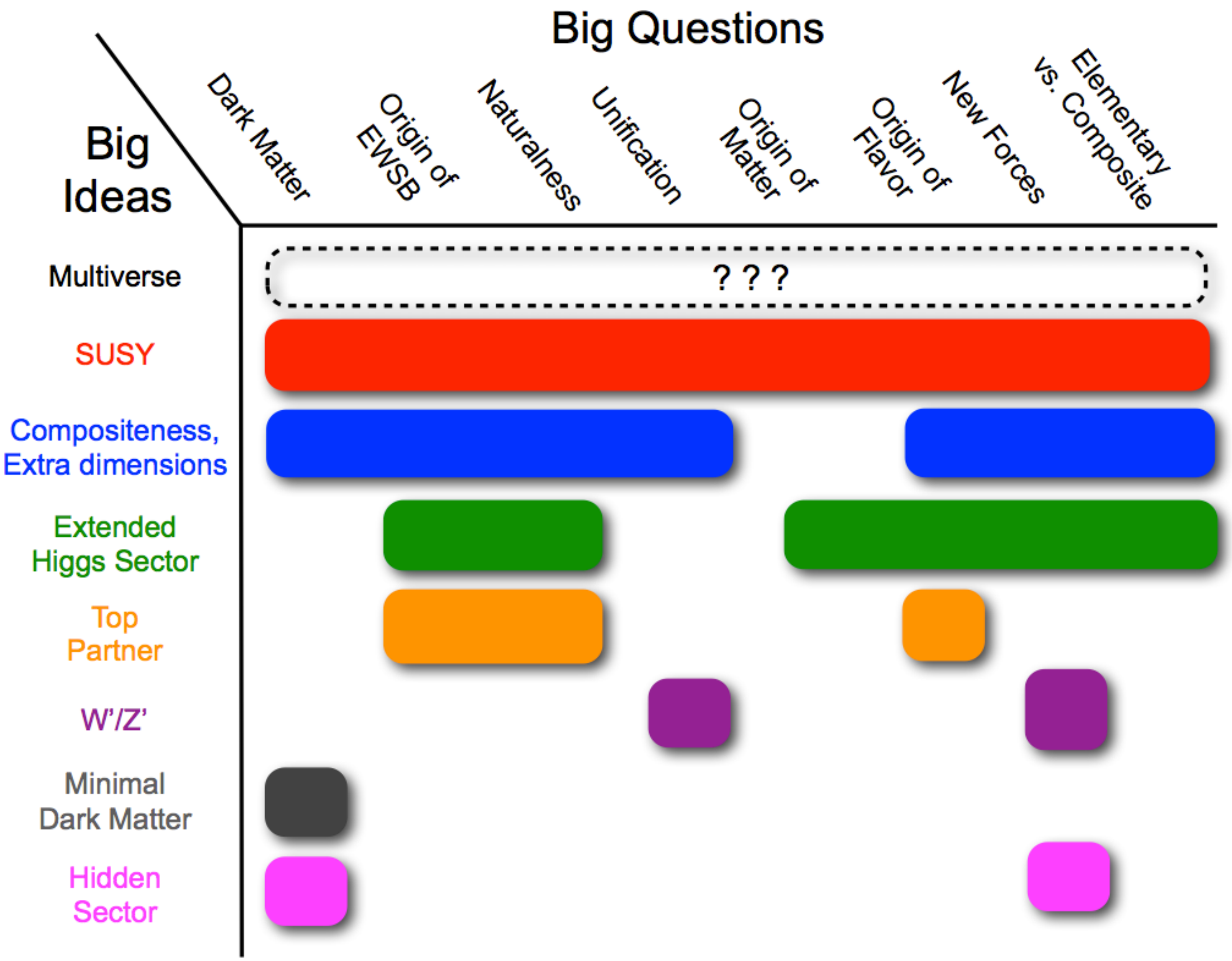
- Reduced statistical and systematic uncertainties in searches through further improvement of detector modeling and understanding (precise measurement) of background processes
- Increased sensitivity to low cross section processes (e.g. electroweak processes, dark matter production) and rare decays
- Probe a significant part of the interesting range of phase space for new physics
- Possibility for 5σ discovery for cases where we might see some kind of excess with 300 fb^{-1}

Thank you for listening…

… backup slides follow!

Why do we want HL-LHC?

We are searching for answers for big questions in particle physics and cosmology!

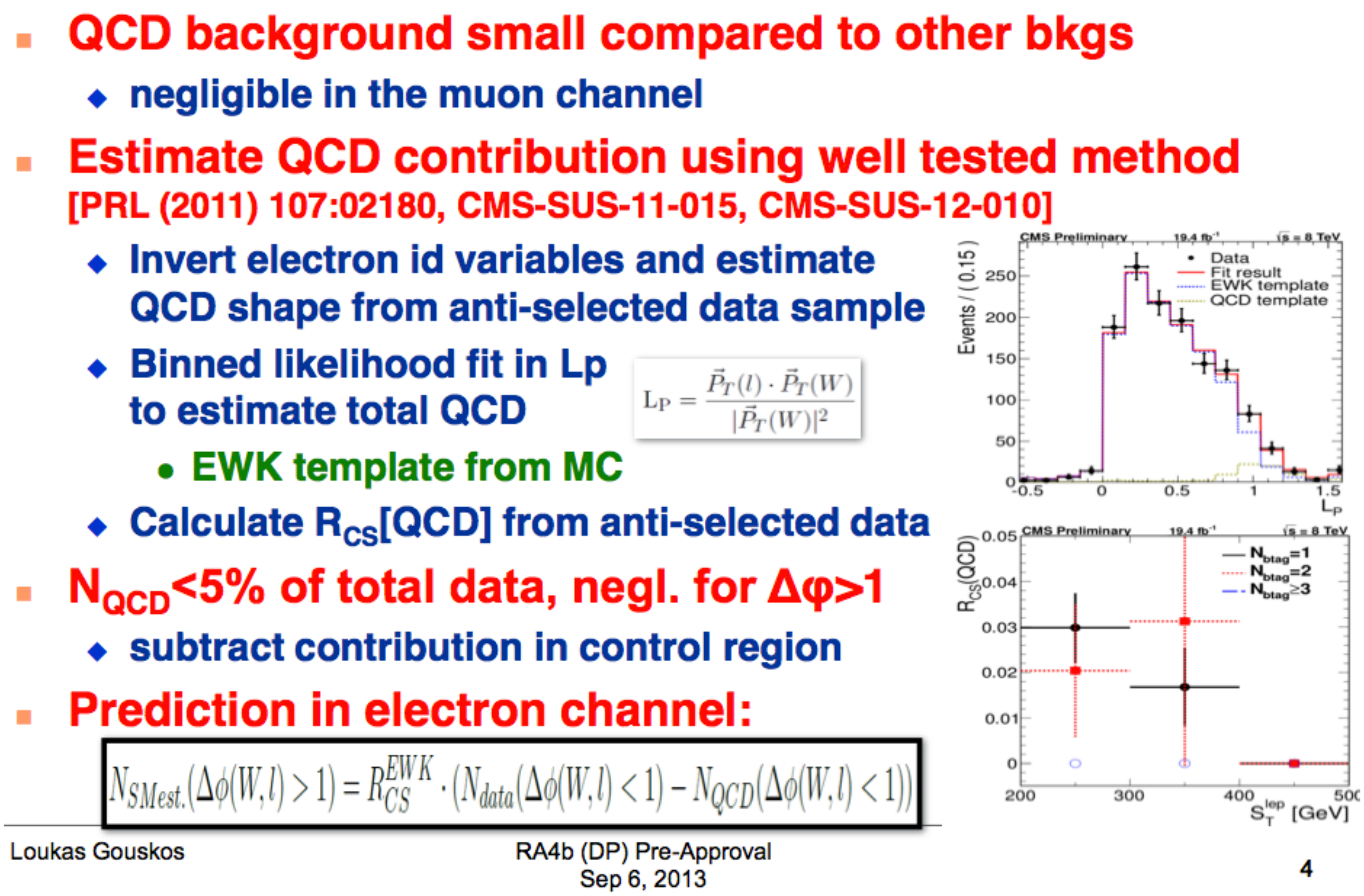


Big Questions

Big Ideas	Dark Matter	Origin of EWSB	Naturalness	Unification	Origin of Matter	Origin of Flavor	New Forces	Elementary vs. Composite
Multiverse	? ? ?	? ? ?	? ? ?	? ? ?	? ? ?	? ? ?	? ? ?	? ? ?
SUSY	●	●	●	●	●	●	●	●
Compositeness, Extra dimensions	●	●	●	●		●	●	●
Extended Higgs Sector		●	●		●	●	●	●
Top Partner		●	●			●		
W'/Z'				●			●	
Minimal Dark Matter	●							
Hidden Sector	●						●	

From Snowmass summary paper 2013

Gluino (l+b) – QCD background



- QCD background small compared to other bkgs
  - negligible in the muon channel
- Estimate QCD contribution using well tested method [PRL (2011) 107:02180, CMS-SUS-11-015, CMS-SUS-12-010]
  - Invert electron id variables and estimate QCD shape from anti-selected data sample
  - Binned likelihood fit in Lp to estimate total QCD
    - EWK template from MC
  - Calculate R_{CS}[QCD] from anti-selected data
- N_{QCD}<5% of total data, negl. for Δφ>1
  - subtract contribution in control region
- Prediction in electron channel:

$$L_P = \frac{\vec{P}_T(l)\cdot\vec{P}_T(W)}{|\vec{P}_T(W)|^2}$$

$$\boxed{N_{SMest.}(\Delta\phi(W,l)>1) = R_{CS}^{EWK}\cdot\left(N_{data}(\Delta\phi(W,l)<1) - N_{QCD}(\Delta\phi(W,l)<1)\right)}$$

Gluino (l+b) Search – Analysis Overview

Baseline selection:

- 1 lepton [e/mu] with p_T>20 GeV, $|\eta|<2.4$
- veto 2nd loose lepton
- $N_{jet} \geq 6$ with p_T> 40 GeV, $|\eta|<2.4$
- $N_{b\text{-}jet} \geq 2$
- H_T > 500 GeV
- S_T^{lep}>250 GeV
- $\Delta\Phi(W,l)$> 1

Search regions binned in:

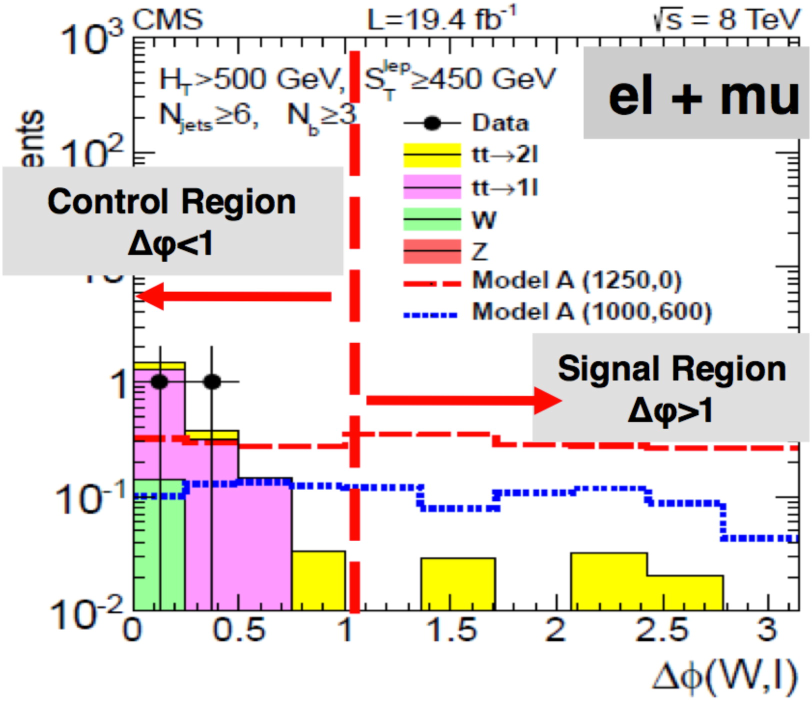
- $N_{b\text{-}jet}$
- S_t^{lep}

based on 8 TeV analysis
CMS-PAS-SUS-13-007
with optimized signal regions

Gluino (l+b) Search – Method

Delta phi method:

The angle between W and lepton is larger for signal than for background



Control Region
Δφ<1

Signal Region
Δφ>1

Jets + MHT Search – Search Regions

For simplicity, use inclusive bins in n_{jets}, HT and MHT

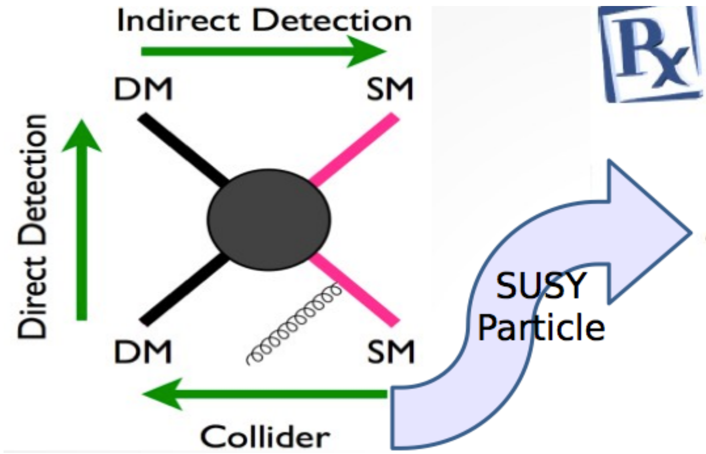
- most sensitive is $n_{jets} \geq 6$ for T1qqqq

The following search bins are used:

- 300fb^{-1}
  - R1: HT>=2100 GeV && MHT>=700 GeV (high gluino mass)
  - R2: HT>=1100 GeV && MHT>=600 GeV (high LSP mass)
  - R3: HT>=1600 GeV && MHT>=700 GeV (medium gluino and LSP masses)
  - R4: HT>=800 GeV && MHT>=400 GeV (low gluino mass and LSP masses)
- 3000fb^{-1}
  - R1: HT>2500 GeV && MHT>=1000 GeV (high gluino mass)
  - R2: HT>1600 GeV && MHT>=700 GeV (high LSP mass)
  - R3: HT>2000 GeV && MHT>=1000 GeV (medium gluino and LSP masses)
  - R4: HT>=800 GeV && MHT>=400 GeV (low gluino and low LSP masses)
  - R5: HT>=1100 GeV && MHT>=600 GeV (low gluino and high LSP masses)

VBF Dark Matter Search – Motivation

Determination of the N1 composition is important to understand the early universe cosmology



℞ to Probe Ωh^2

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

$s_W = \sin(\theta_W) \quad c_W = \cos(\theta_W)$

$s_\beta = \sin(\beta) \quad c_\beta = \cos(\beta)$

$M_1 << M_2,\ \mu \ \Rightarrow \ \tilde{\chi}_1^0 \approx \tilde{B}$ Pure Bino

$M_2 << M_1,\ \mu \ \Rightarrow \ \tilde{\chi}_1^0 \approx \tilde{W}$ Pure Wino

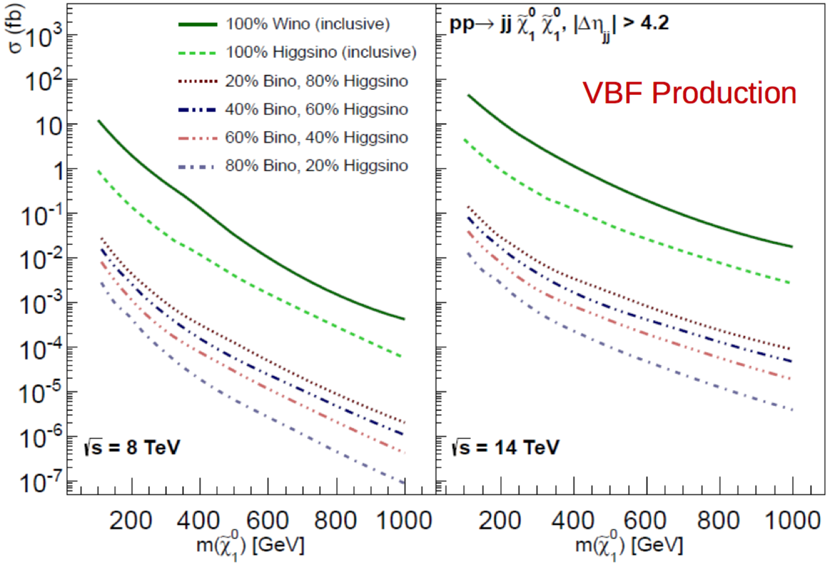
$\mu << M_1,\ M_2 \ \Rightarrow \ \tilde{\chi}_1^0 \approx \tilde{H}_h + \tilde{H}_d$

Pure Higgsino

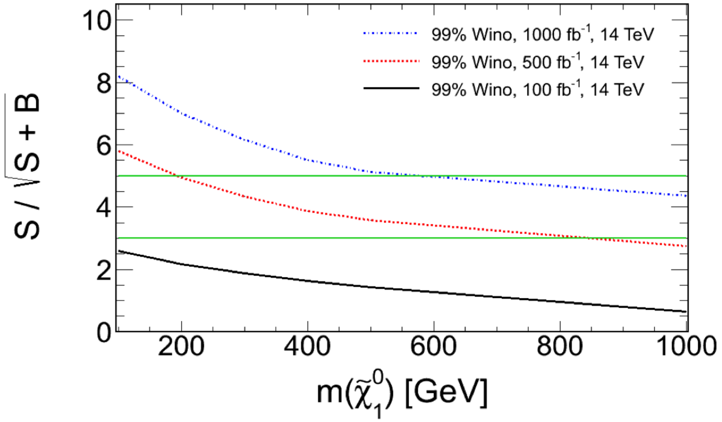
From A. Gurrola, Snowmass Seattle

VBF Dark Matter Search – Prediction from Pheno Paper

Largest cross section from 100% Wino



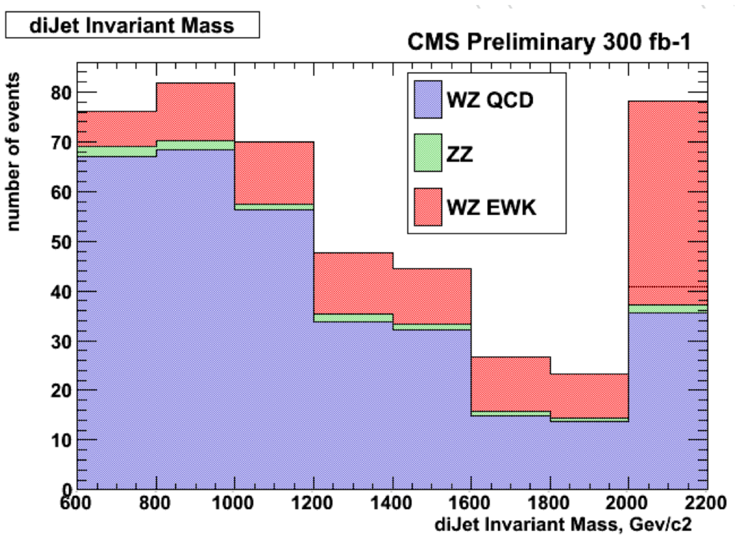
Pheno paper (1301.7779) predicts 5σ discovery (omitting influence of syst. unc.)



Vector Boson Scattering – Event Selection for WZ Channel

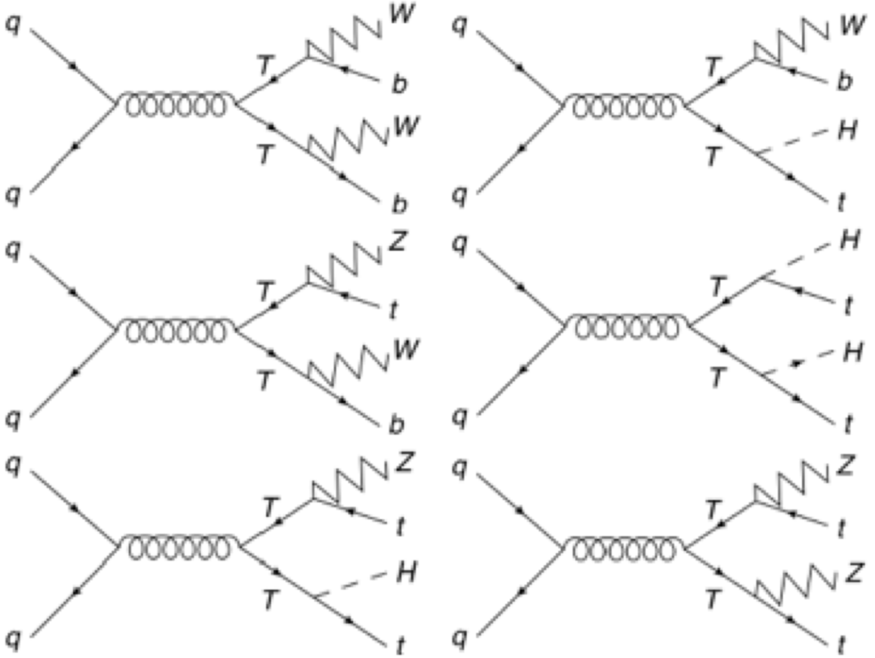
Event selection for WZ Channel

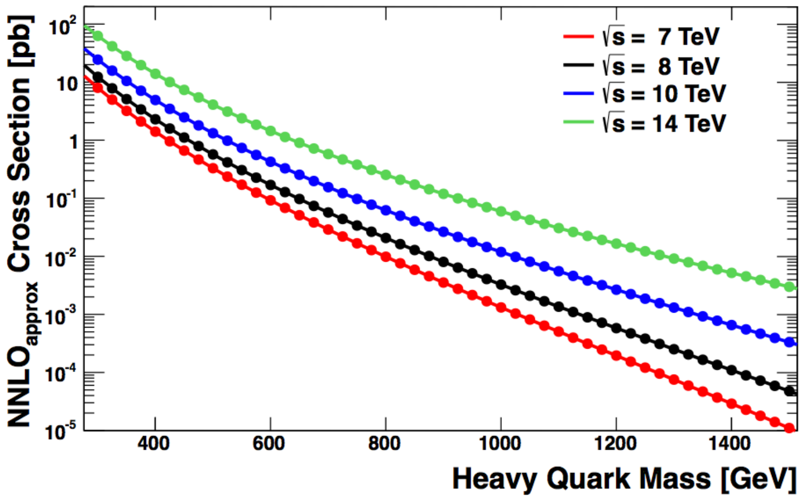
- Three identified leptons (e or μ) with $p_T > 20$ GeV and $|\eta| < 2.4$
- 2 leptons must be OSSF pair (from Z) with $|m_{ll} - m_Z| < 20$ GeV and $m_{ll} > 20$ GeV
- Reject events with additional leptons with $p_T > 10$ GeV
- $\Delta R(ll') > 0.04$
- $\Delta R(lj') > 0.4$
- MET > 30 GeV (300 fb^{-1} only)
- Two parton “jets” from quarks or gluons with
  - $p_T > 50$ GeV and $|\eta| < 4.7$
  - $\Delta\eta_{jj} > 4.0$
  - $m_{jj} > 600$ GeV



Vector-like Charge 2/3 Quark Search – Production Mechanism and CS

Decays to two vectorbosons and two 3rd generation quarks

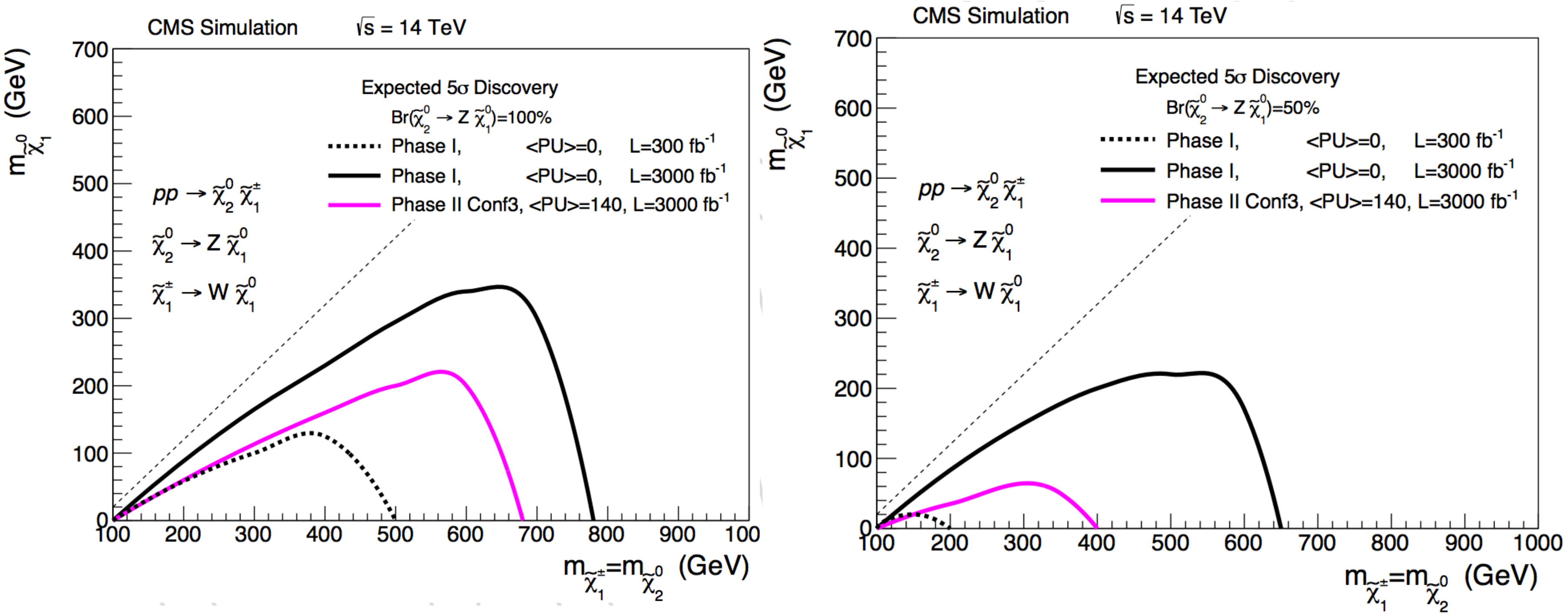




Cross section rises by order of magnitude from 8 → 14 TeV

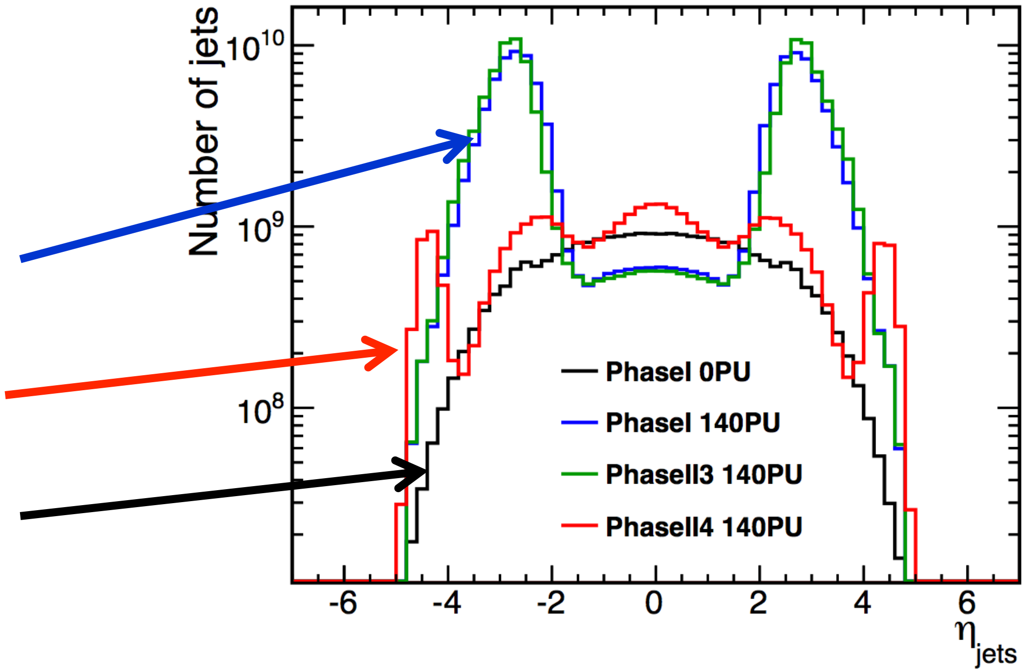
Search for direct $\chi^{\pm}\chi^{0}$ Production – Interpretation

Comparison of 100% to 50% branching ratio to WZ+LSPs final state



VBF Dark Matter Search – Necessity of the forward Tracker

Number of jets rises dramatically in forward region without tracking



140 PU

140 PU
with forward tracking

0PU

In addition:

Background after VBF selection partly in forward region

→ tracking in forward region leads to higher lepton acceptance

→ better S/B ratio