Future Searches for New Physics at the LHC with ATLAS and CMS

Beate Heinemann

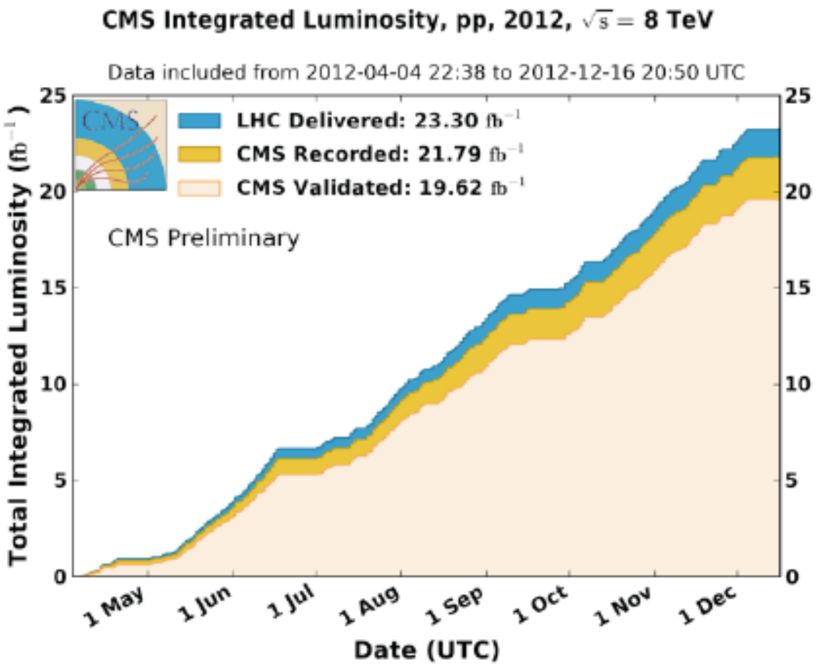
University of California, Berkeley
Lawrence Berkeley National Laboratory

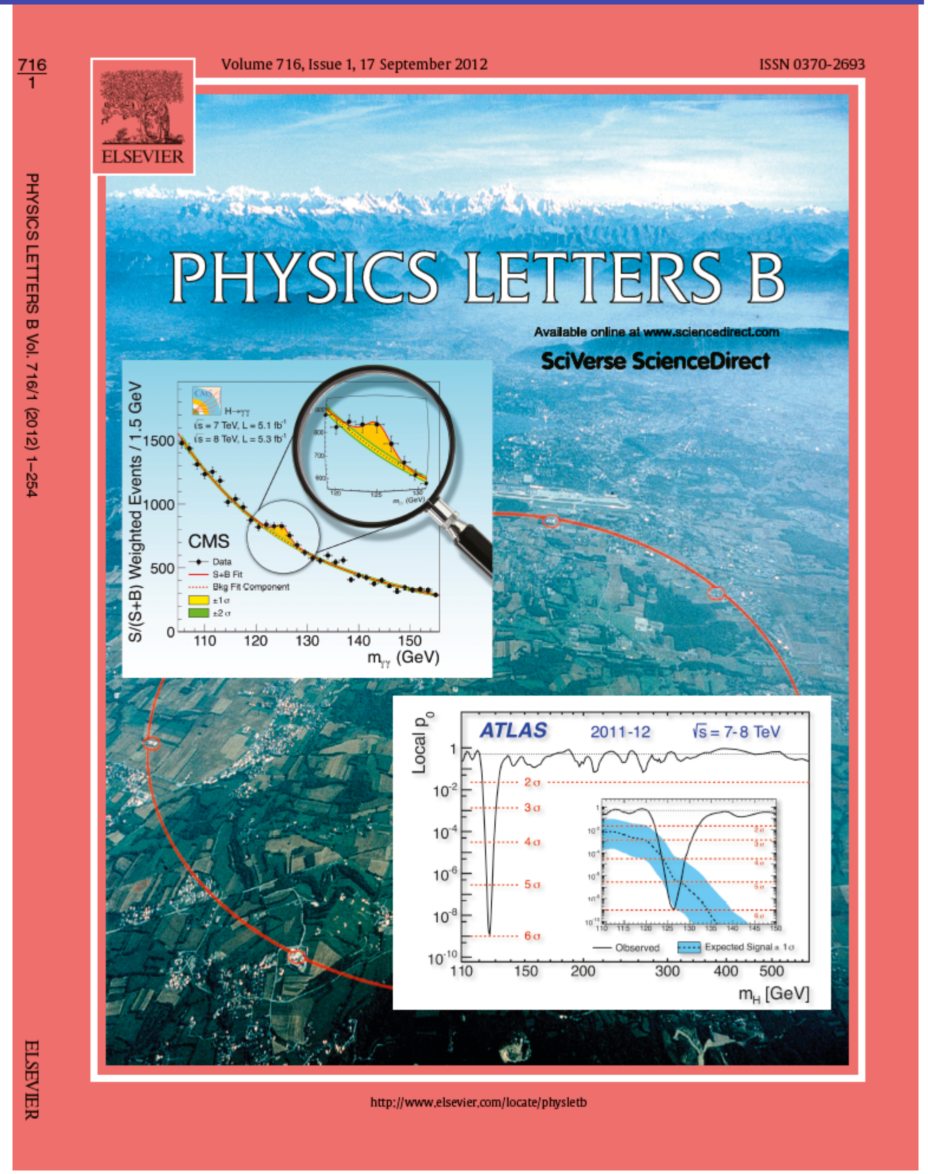
on behalf of the ATLAS and CMS collaborations

Snowmass on the Mississippi, Minneapolis, July 31st 2013

Introduction

LHC Run 1





- 25 fb^{-1}of 7+8 TeV pp data
- Higgs boson found!
  - Looks like SM at first glance
- Stringent limits set on physics beyond the SM
- Many precise measurements of SM processes

ATLAS Supersymmetry Searches

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: EPS 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.4 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt\,[\mathrm{fb}^{-1}]$		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q},\ \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g},\ \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g},\ \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\to qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$	1.1 TeV	$m(\tilde{\chi}_1^0)$<650 GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	$\tan\beta<15$	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\tan\beta>18$	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	0	Yes	4.8	$\tilde{g}$	619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.14 TeV	$m(\tilde{\chi}_1^0)$ <200 GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1,\ \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-630 GeV	$m(\tilde{\chi}_1^0)$<100 GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1,\ \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	430 GeV	$m(\tilde{\chi}_1^{\pm})=2\ m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^{\pm})$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1,\ \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2,\ \tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R},\ \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$	180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu),\ \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	600 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W^*\tilde{\chi}_1^0 Z^*\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	315 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	857 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	0	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$	700 GeV	1 mm<$c\tau$<1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_\tau+X,\ \tilde{\nu}_\tau\to e+\mu$	2 e, μ	0	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X,\ \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e, \mu + \tau$	0	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to W\tilde{\chi}_1^0,\ \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu,\ e\mu\tilde{\nu}_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$	760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\to W\tilde{\chi}_1^0,\ \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e,\ e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$	350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6 jets	-	4.6	$\tilde{g}$	666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1 t,\ \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

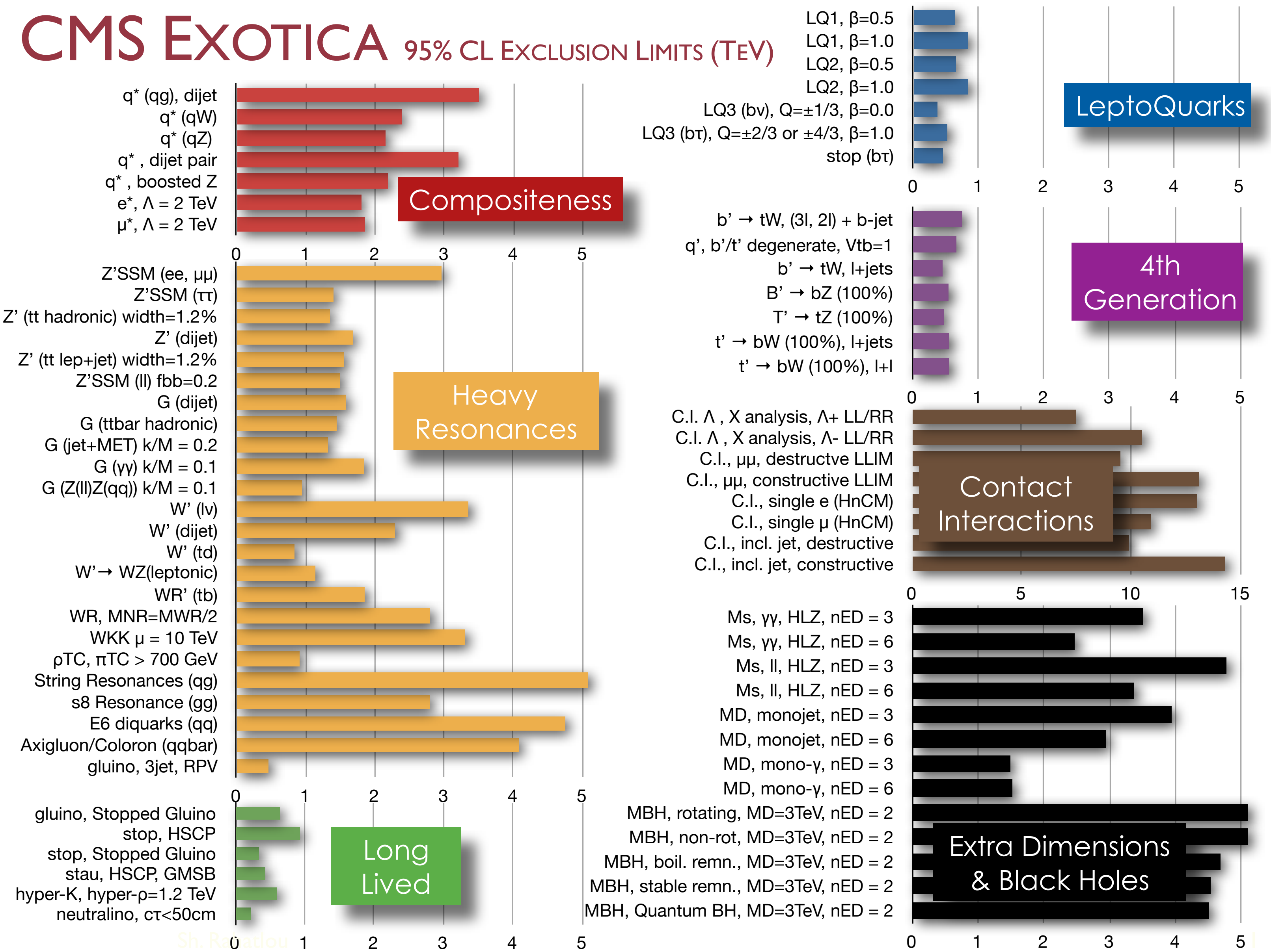
Mass scale [TeV] (axis: 10^{-1}, 1)

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

*similar results obtained by CMS

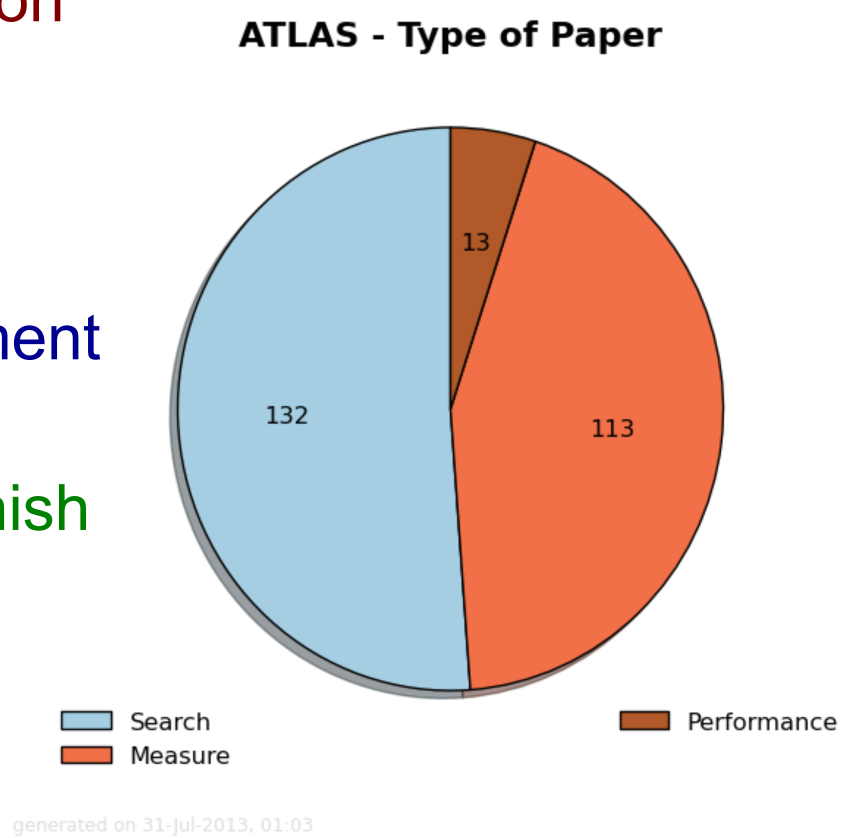
CMS Exotics Searches



*similar results obtained by ATLAS

Run-1 Publications

- ATLAS and CMS have published 510 papers based on run-1 collision data to date
  - Split about 50/50 between searches and measurements
  - Expect >100 more per experiment on run-1 data
    - as 7 and 8 TeV analyses finish
  - Behind every paper there is a PhD thesis!
    - Often more than one…
- Huge interest in the field
  - Higgs observation papers have >1300 citations each
    - they are merely one year old!

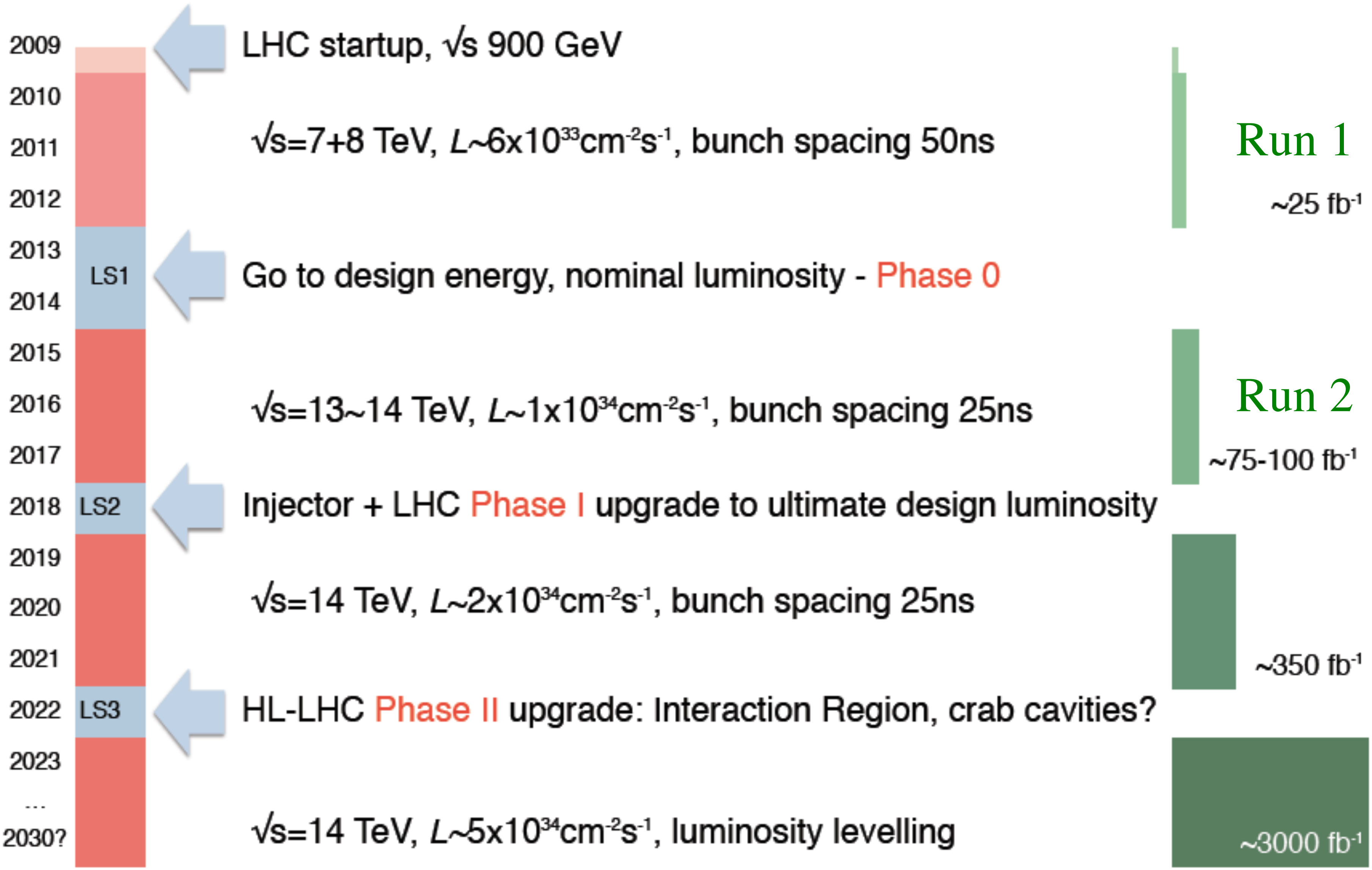


US role in LHC, ATLAS and CMS

- US has made critical contributions to LHC machine
  - E.g. Inner Triplet magnets
- US is single biggest collaborator in both ATLAS and CMS
  - ATLAS: 583 US authors (20% of total)
    - 175 US graduate students
  - CMS: 678 US authors (31%)
    - 247 US graduate students
- US Contributions
  - Major contributions to design, construction and operation of most subdetectors
  - Making major impact on physics analyses
  - Providing leadership in all areas

Future Plans for LHC and ATLAS and CMS Detector Upgrades

LHC Roadmap



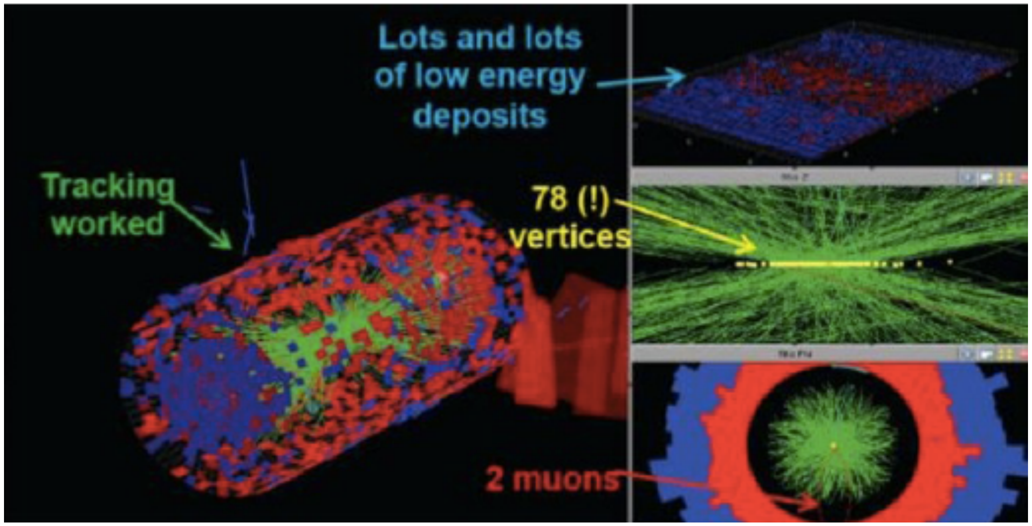
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
...
2030?
LS1
LS2
LS3
LHC startup, √s 900 GeV
√s=7+8 TeV, L~6x10^33cm^-2s^-1, bunch spacing 50ns
Go to design energy, nominal luminosity - Phase 0
√s=13~14 TeV, L~1x10^34cm^-2s^-1, bunch spacing 25ns
Injector + LHC Phase I upgrade to ultimate design luminosity
√s=14 TeV, L~2x10^34cm^-2s^-1, bunch spacing 25ns
HL-LHC Phase II upgrade: Interaction Region, crab cavities?
√s=14 TeV, L~5x10^34cm^-2s^-1, luminosity levelling
Run 1
~25 fb^-1
Run 2
~75-100 fb^-1
~350 fb^-1
~3000 fb^-1

LHC Roadmap

Year	Phase	Event	Average # of simultaneous pp collisions
2009		LHC startup, √s 900 GeV	
2010–2012		√s=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns	20
2013–2014	LS1	Go to design energy, nominal luminosity - Phase 0	
2015–2017		√s=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	~25
2018	LS2	Injector + LHC Phase I upgrade to ultimate design luminosit	
2019–2021		√s=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	~50-80
2022	LS3	HL-LHC Phase II upgrade: Interaction Region, crab cavities	
2023 … 2030?		√s=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling	~140

Detector Upgrades

- Detectors will need to be upgraded to be able to cope with higher luminosity, e.g.
  - Improve trigger capabilities
    - better discriminate the desired signal events from background as early as possible in trigger decision
  - Upgrade and/or replace detectors as they e.g.
    - Cannot handle higher rate due to bandwidth limitations
    - Suffer from radiation damage making them less efficient



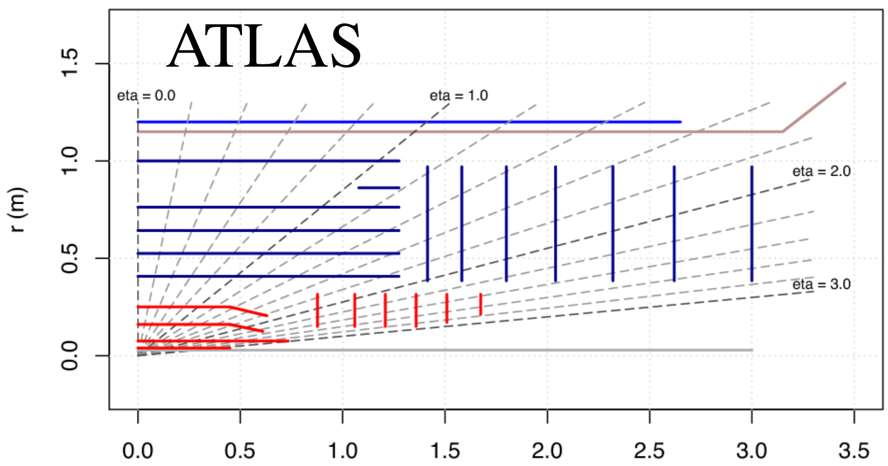
Detector Upgrades: Phase-0, Phase-I and Phase-II

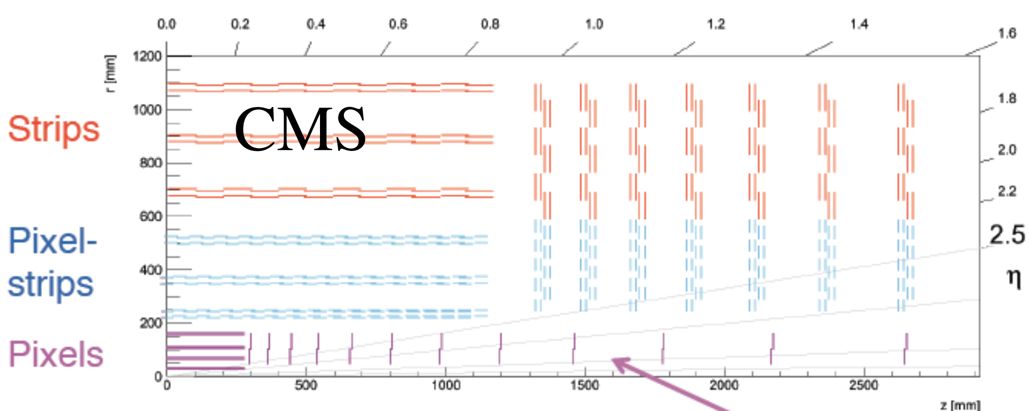
- Phase-0
  - 4th Si Pixel layer (IBL)
  - Complete muon coverage
  - Repairs (TRT, LAr and Tile)
  - New beampipe and infrastructure updates
- Phase-I
  - Fast Track Trigger (FTK)
  - Muon New Small Wheel (NSW)
  - LAr cal. electronics
- Phase-II
  - New pixel and strip tracker
  - Calorimeter
  - Muon system
  - Trigger system
  - Computing
  - …

- Phase-0
  - Complete muon coverage
  - Colder tracker
  - Photodetectors in HCAL
  - New beampipe and infrastructure updates
- Phase-I
  - New Si pixel tracker
  - L1 trigger upgrade
  - HCAL electronics
- Phase-II
  - New pixel and strip tracker
  - Calorimeter
  - Muon system
  - Trigger system
  - Computing
  - …

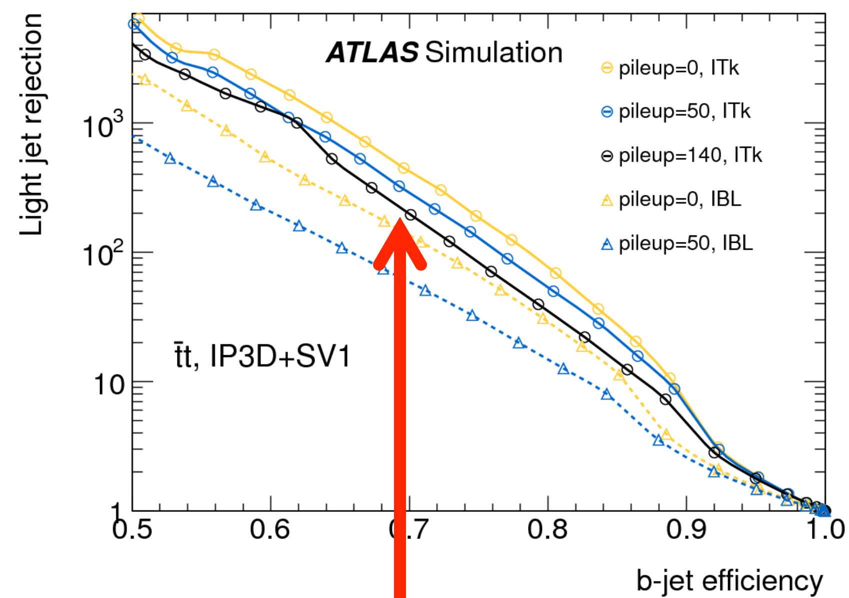
Tracking during Phase-2

- New inner trackers needed after 300 fb^{-1}
- Performance as good or better than current detectors even for 140 pp interactions per crossing



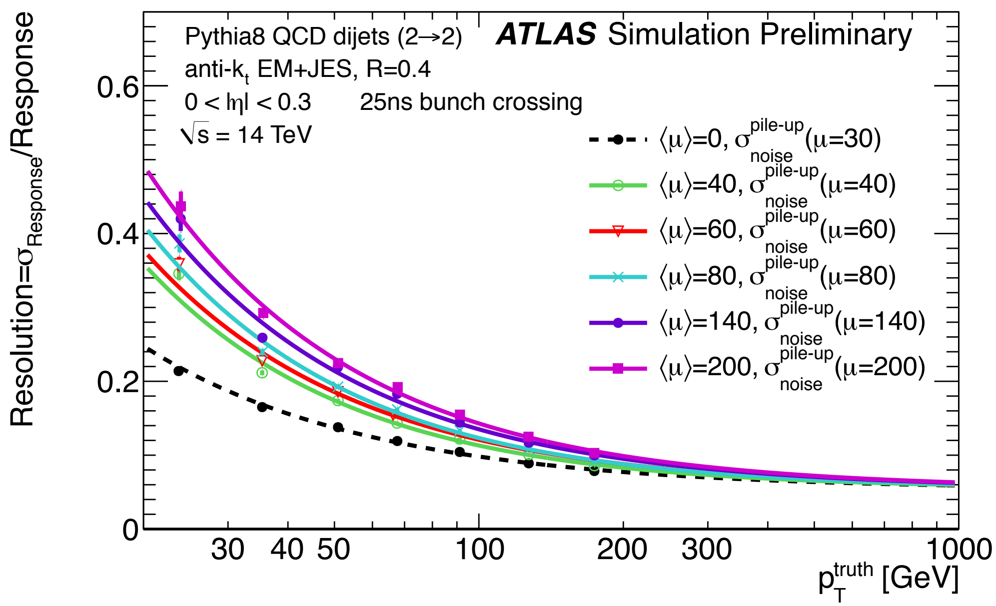


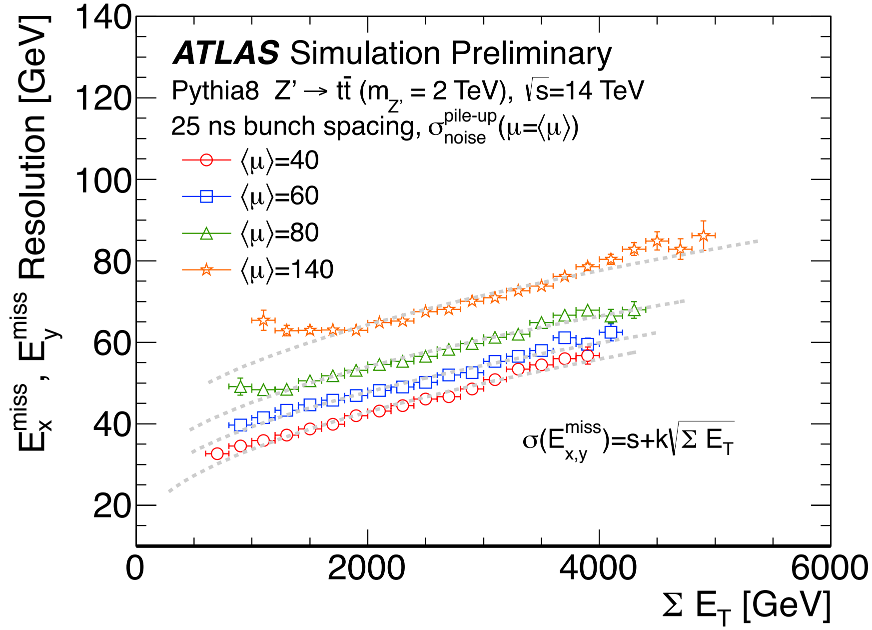
Possible tracker layout with forward pixel disks



b-tag ε=70%
light q rejection: 120

Jet and Etmiss resolution at high pileup

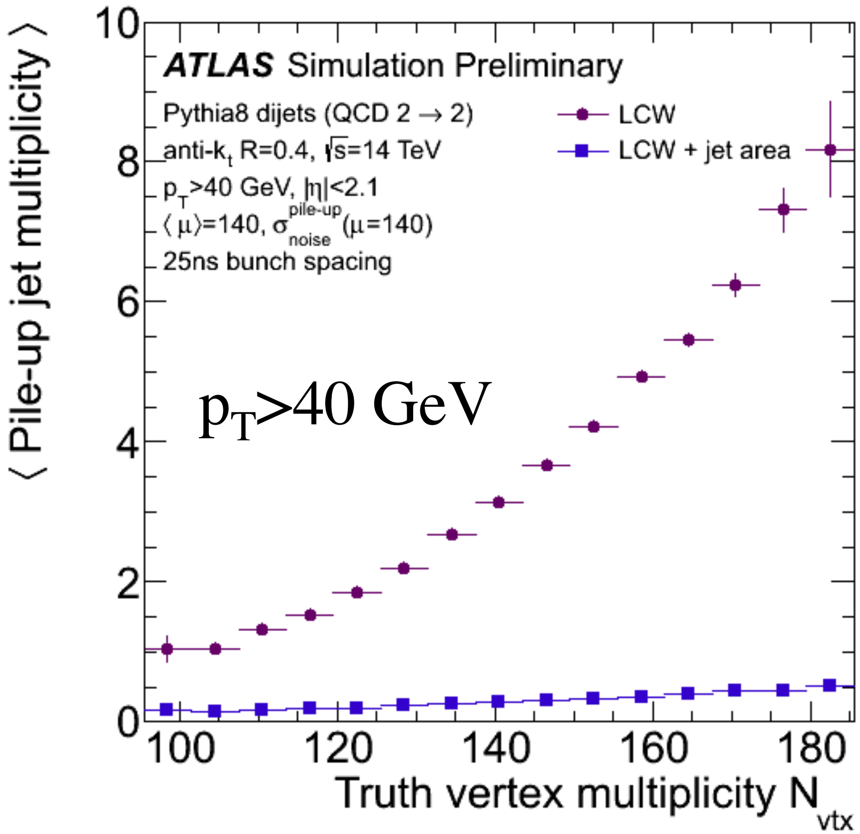


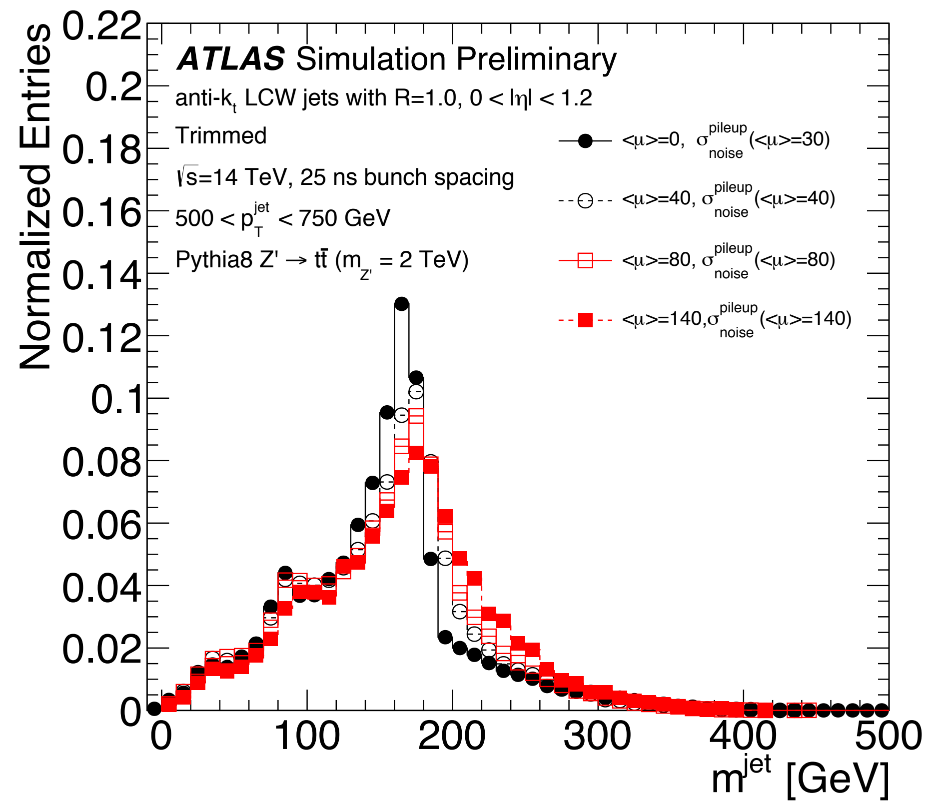


- Jet and E_T^{miss} resolution degrades moderately with increasing pileup
  - Performance still sufficient for physics measurements and searches

more details: see talk by A. Schwartzman in QCD parallel session Saturday

Jet counting and substructure at high pileup





- Jet multiplicity is controlled with clever pileup suppression techniques
- Jet substructure can still be resolved thanks to “trimming” techniques
  - Important for searches with boosted massive objets (e.g. top, W, H)

Future Prospects for New Physics Searches

Many questions follow from Higgs discovery!

- **Is it *the* Higgs boson?**
  - Does it couple to matter exactly as predicted?
  - Does it couple to gauge bosons exactly as predicted?
  - Are there more Higgs bosons?
- **Does the Higgs boson decay to non-SM particles?**
  - E.g. to Dark Matter?
- **How do bosons interact with each other?**
  - Does Higgs boson contribute as expected in SM?
  - Are there new gauge groups?
- **What protects the Higgs mass from being m_{Planck}?**
  - Is Nature Supersymmetric?
    - Is Dark Matter a SUSY particle?
  - Are there new generations of fermions?
  - Is there some other new dramatic physics coming in at the TeV scale
    - Are there extra dimensions of space?
    - Is there a new strong interaction?

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Next Talk

- **How do bosons interact with each other?**
  - Does Higgs boson contribute as expected in SM?
  - Are there new gauge groups?
- **What protects the Higgs mass from being m_{Planck}?**
  - Is Nature Supersymmetric?
    - Is Dark Matter a SUSY particle?
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  - Is there some other new dramatic physics coming in at the TeV scale
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    - Is there a new strong interaction?

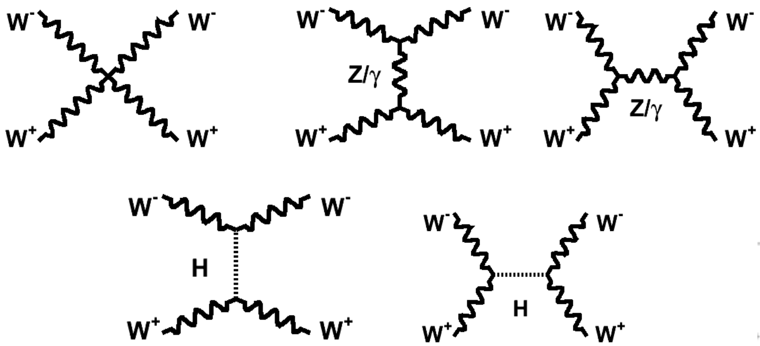
This Talk

Studies of Future Physics Prospects

- Studies have been performed for $\sqrt{s}$=14 TeV for integrated luminosities of 300 fb^{-1} (LHC) and 3000 fb^{-1} (HL-LHC)
  - Many were done a year ago for European Strategy study
  - Many new studies done newly for this Snowmass meeting
- Studies should be considered conservative
  - Analyses were based on parametric simulation (ATLAS) or extrapolated from Run-1 (CMS) for a given set of cuts
    - Much less elaborate than current Run-1 analyses
    - Better results can be obtained when cuts are reoptimized
      - Gain by making cuts harder to reject more background
  - Various treatments of systematic uncertainties studied to provide range of predictions
    - See talk by M. Klute

CMS and ATLAS white papers:
arXiv:1307.7135 and 1307.7292

How do bosons interact with each other?



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

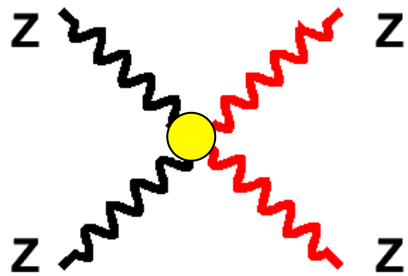
Terms which grow with energy cancel for E >> M_H

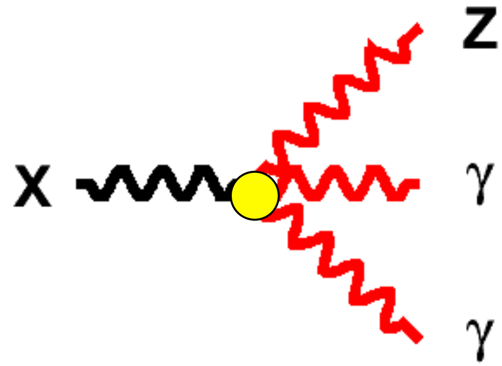
This cancellation requires M_H < 800 GeV

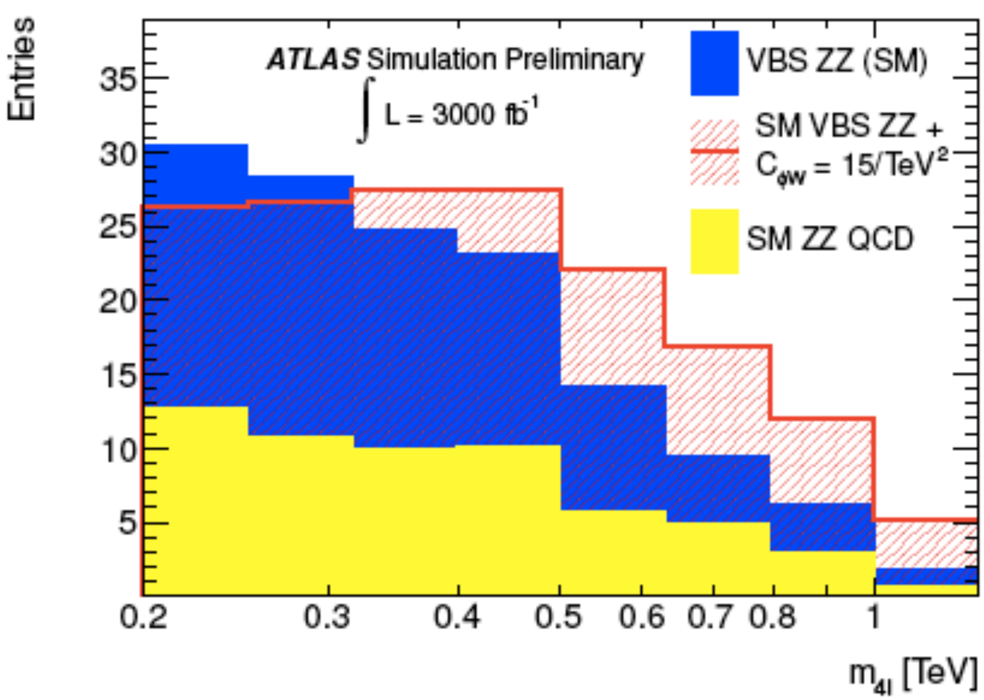
- In SM there is an exact cancellation between terms for longitudinal vector boson scattering
  - Cross section does not grow with energy due to Higgs
- Long history of studying trilinear gauge couplings at LEP and Tevatron
  - Excellent probe of structure of EWK interaction
- **LHC allows for the first time study of quartic couplings**
  - Understand if Higgs boson plays the expected role in this area

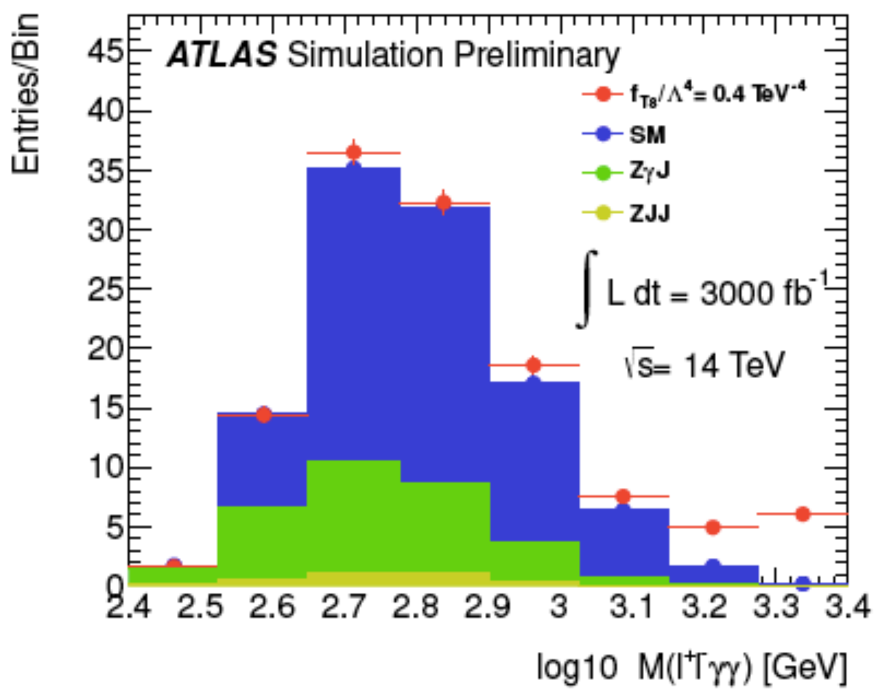
Probing Quartic Gauge Boson Couplings

- Vector boson scattering: ZZ, WZ, W±W±,…
- 3-boson production, e.g. Zγγ



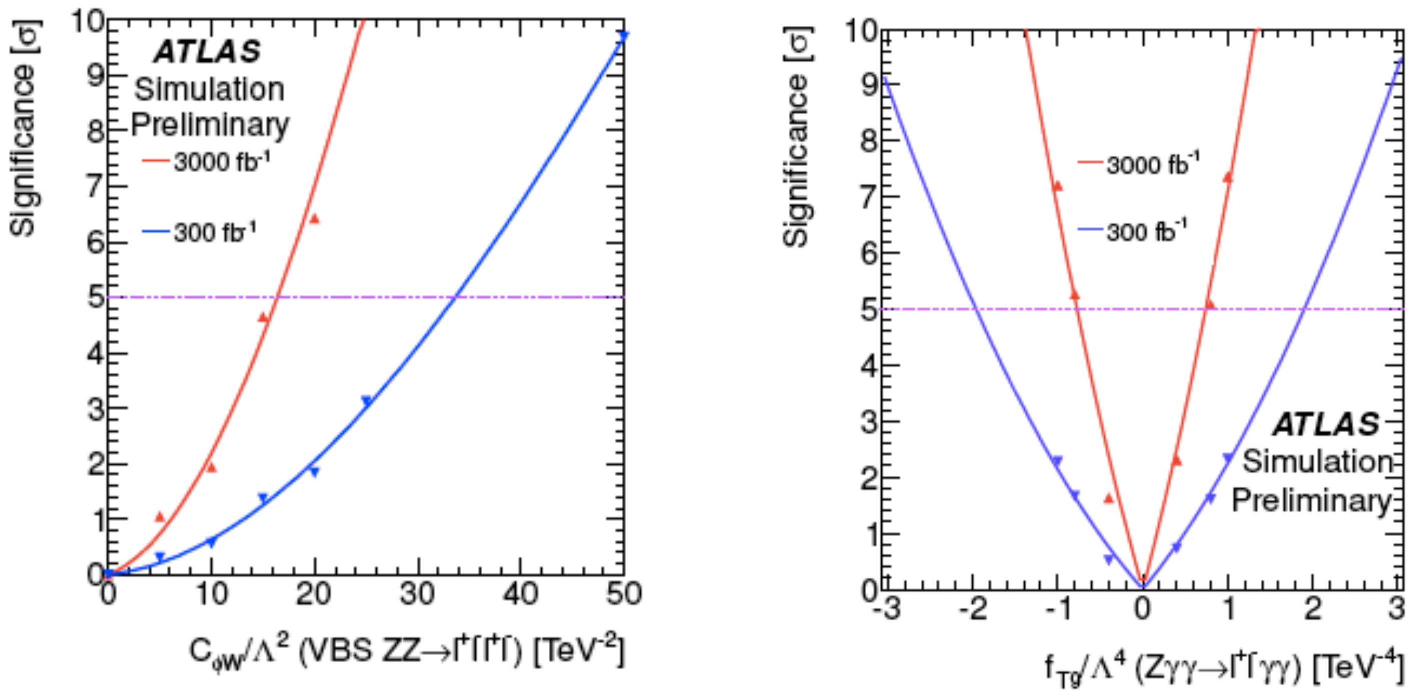






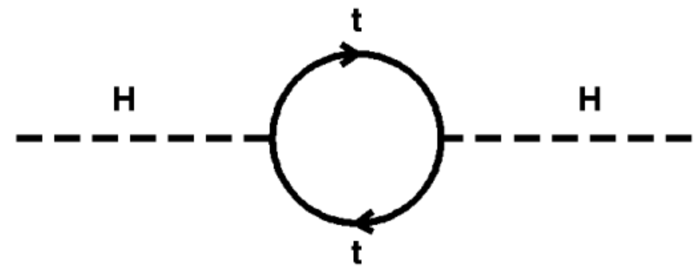
Quartic Gauge Boson Couplings

- Use framework of effective operators to parameterize new physics as quartic coupling, e.g
  - ZZ: dimension-6 operator $\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2}\mathrm{Tr}(W^{\mu\nu}W_{\mu\nu})\phi^\dagger\phi.$
  - Zγγ: dimension-8 operator $\mathcal{L}_{T,9} = \frac{f_{T9}}{\Lambda^4}B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$
- If new physics discovered with 300 fb^{-1} can measure coupling with 5% accuracy with 3000 fb^{-1}



What protects Higgs mass from being m_{Planck}?

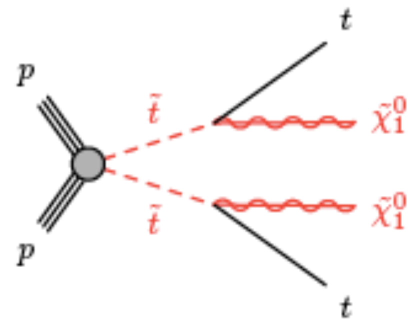
- Known possible answers:
  - SUSY: top squark at m≲1 TeV
    - … and gluino with m≲3 TeV
  - vector-like top quarks
    - e.g. Little Higgs theories
  - extra spatial dimensions or some other dramatic new physics at a mass scale of a few TeV

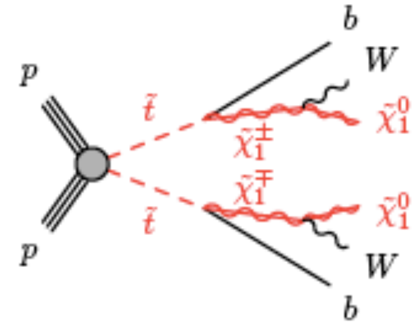


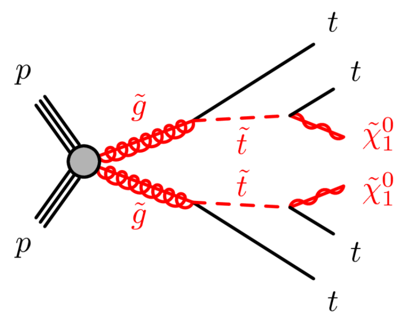
- **Can directly search for these particles at LHC!**
  - If we see nothing at LHC the electroweak scale is finetuned at ~1% level

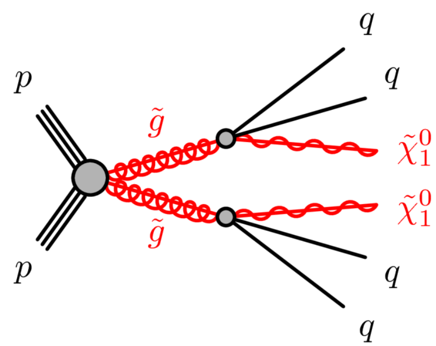
SUSY particles and processes

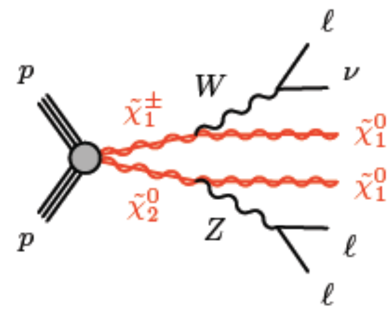
- Top squarks
  - Produced directly or in gluino decays
    - if gluino mass low enough
  - Decay via top quarks or via charginos to final states of W's and b's
- Gluinos
  - Decay via jets + E_T^{miss}
  - Meta-stable case
- Charginos and neutralions
  - Trilepton signature



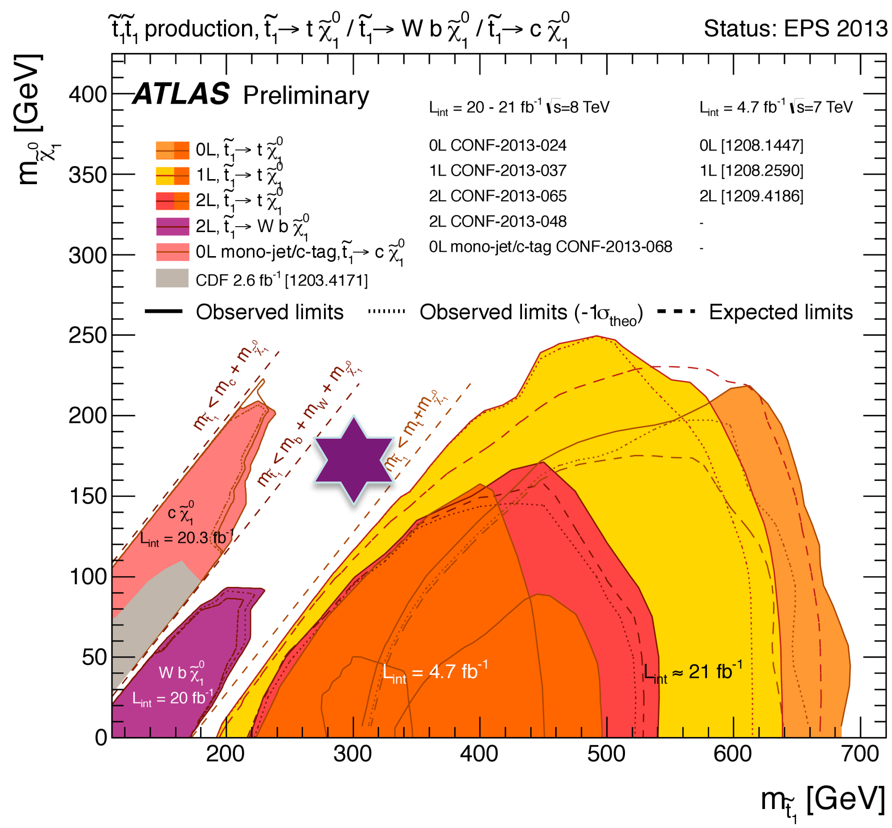


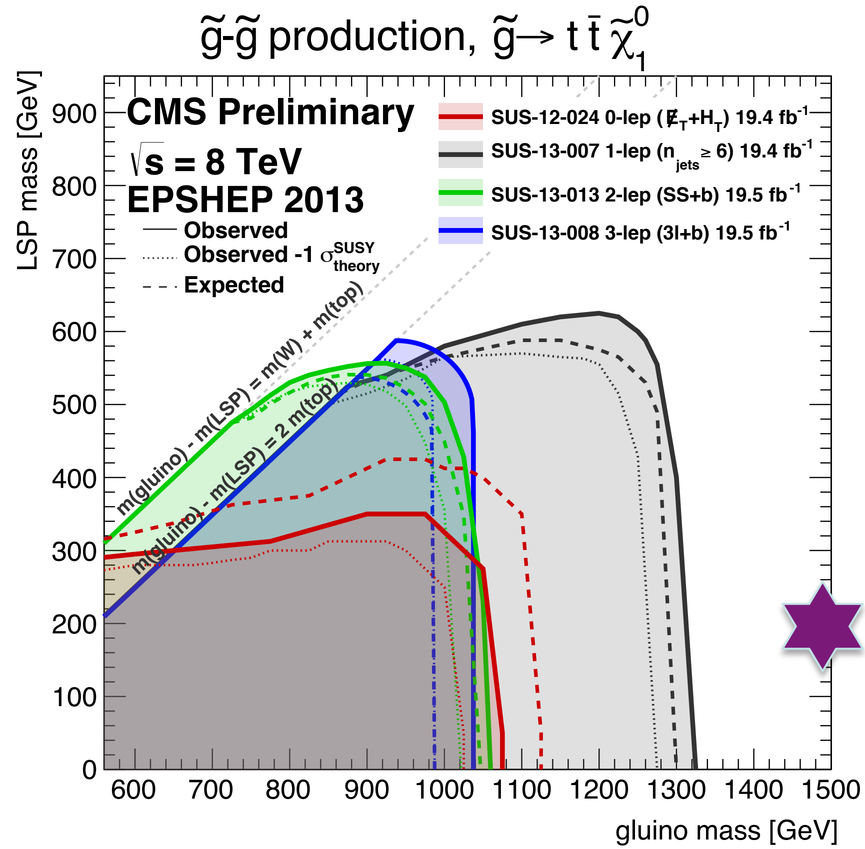






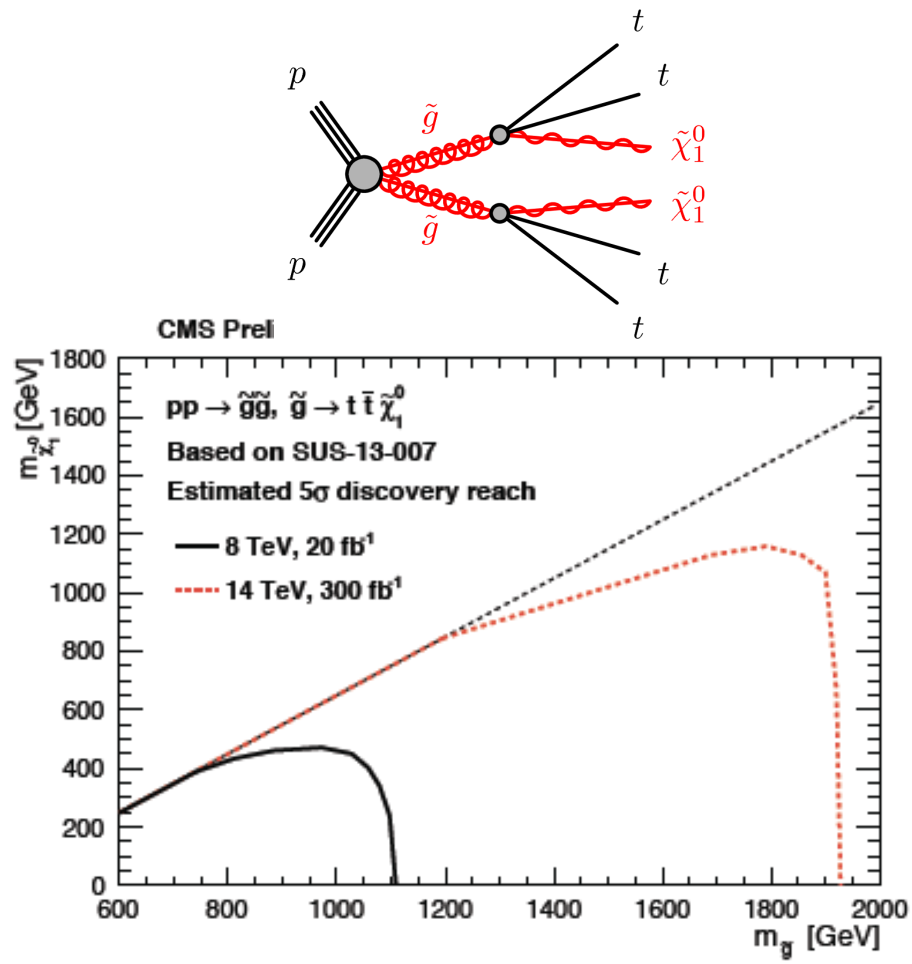
Run-1 constraints on top squarks

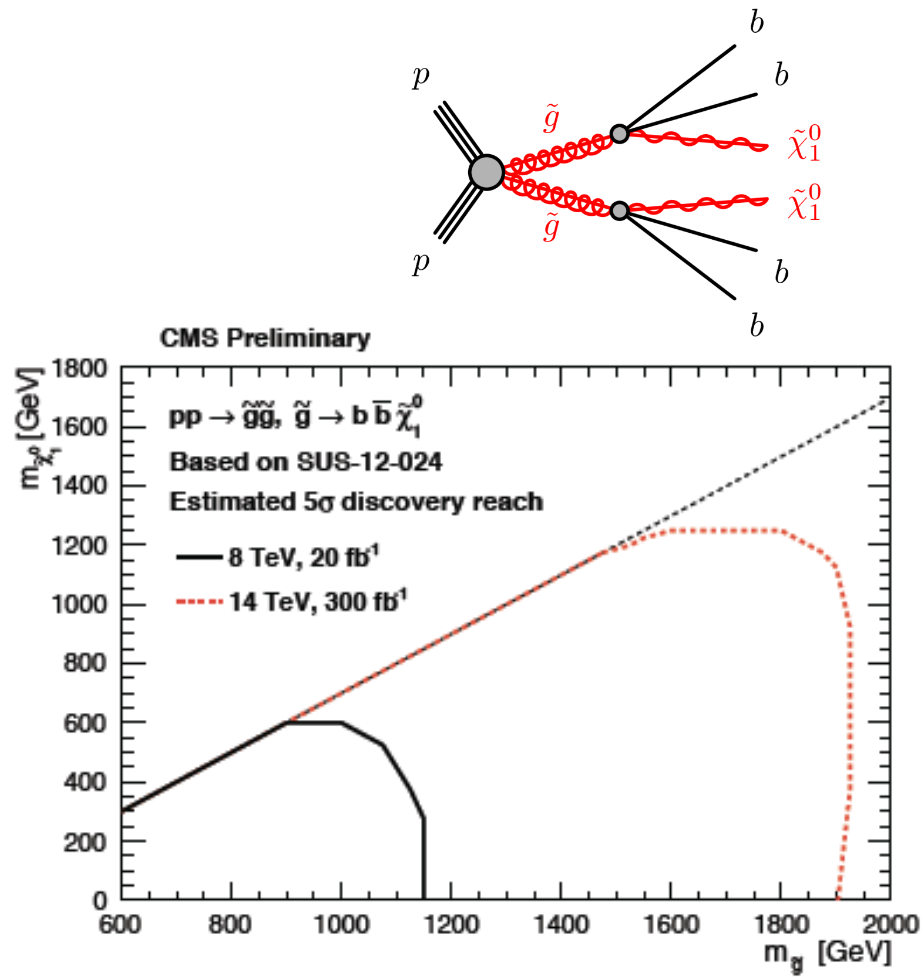




- Vigorously probed using many different analyses
- However, **pretty natural** scenarios still allowed, e.g
  - **M(g)=1.5 TeV, m(t)=300 GeV, m(LSP)=150 GeV**
- LHC (and HL-LHC) will be able to discover such scenarios

Gluino reach if decay via top/bottom

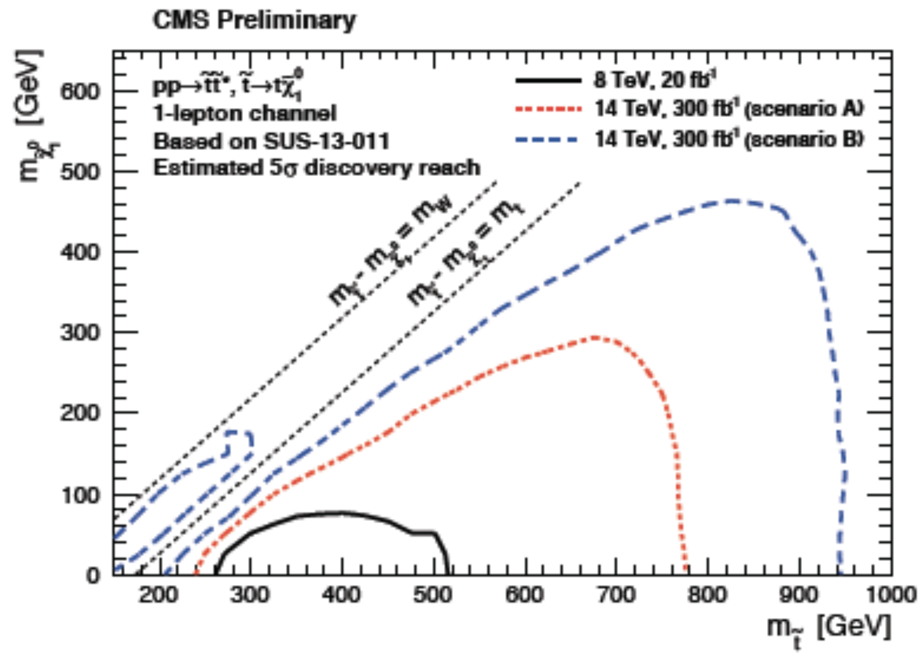


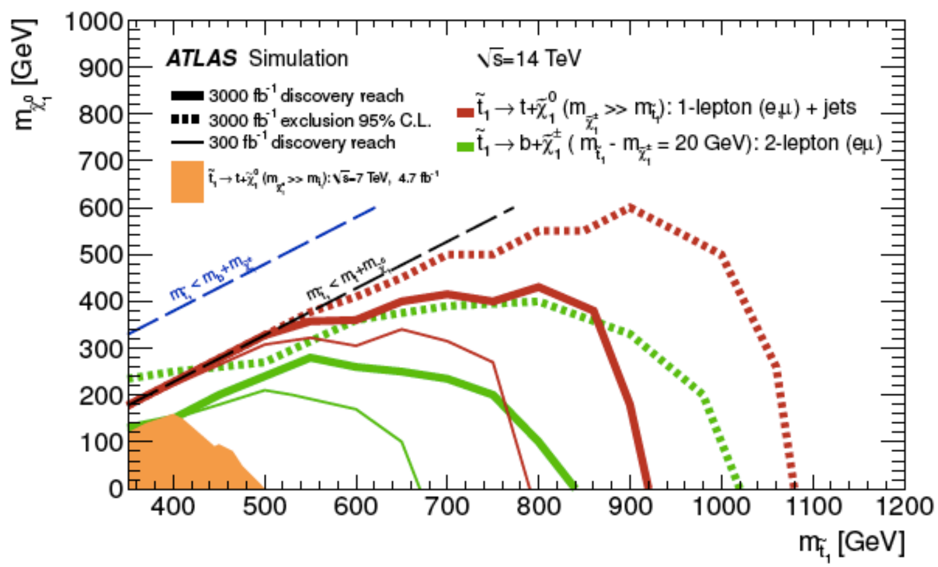


- With 300 fb^{-1} will reach about 2 TeV in gluino mass both in top- and b-decay signatures
  - 3000 fb^{-1} study ongoing

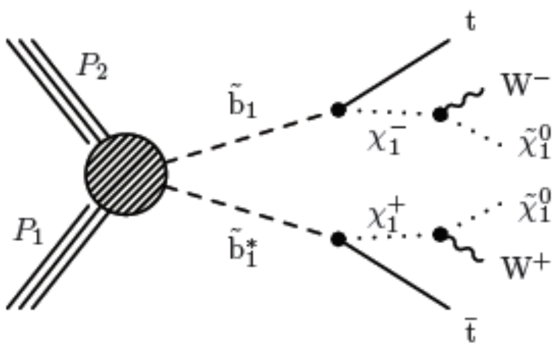
Top squark discovery potential

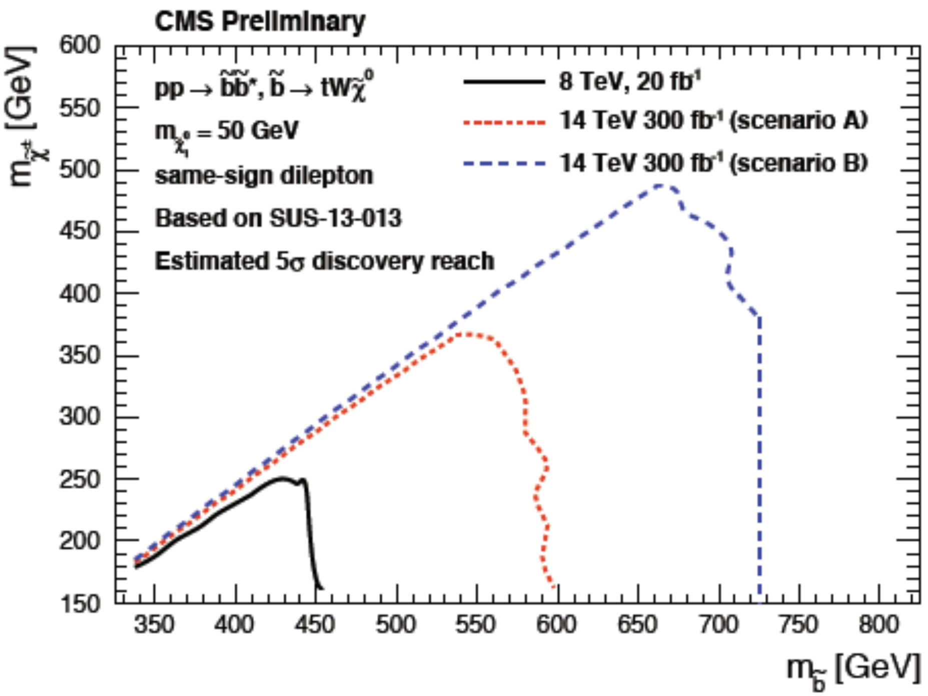
- Challenging analysis due to large top background
  - Systematic uncertainties matter
- 300 fb^{-1}:
  - Discovery up to 800-900 GeV in direct production
- 3000 fb^{-1}:
  - Reach improved by ~140 GeV in m(stop) and ~100 GeV in m(LSP)
- Expect further improvements with reoptimization





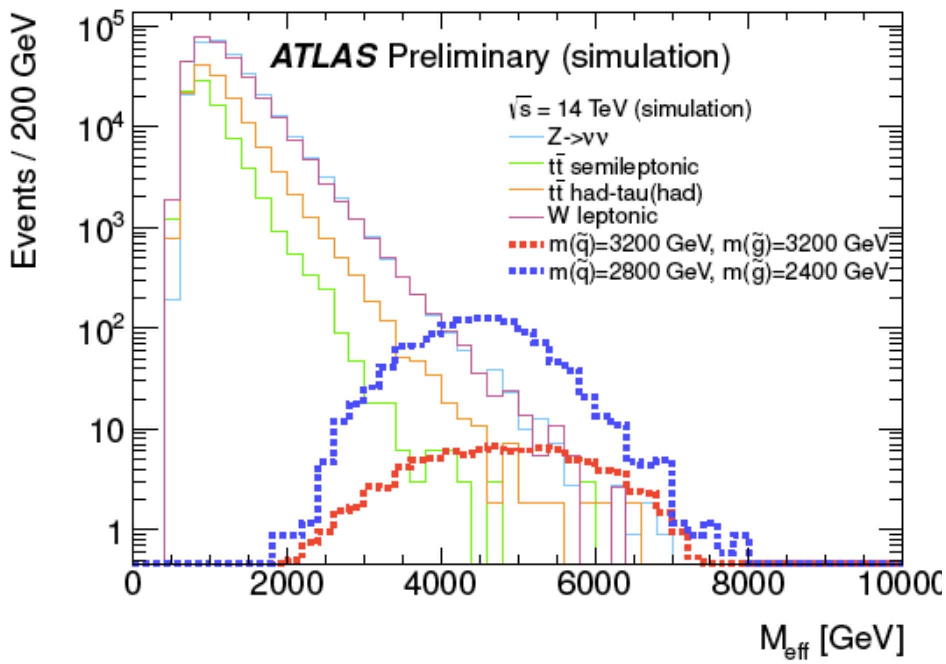
Bottom squark discovery potential

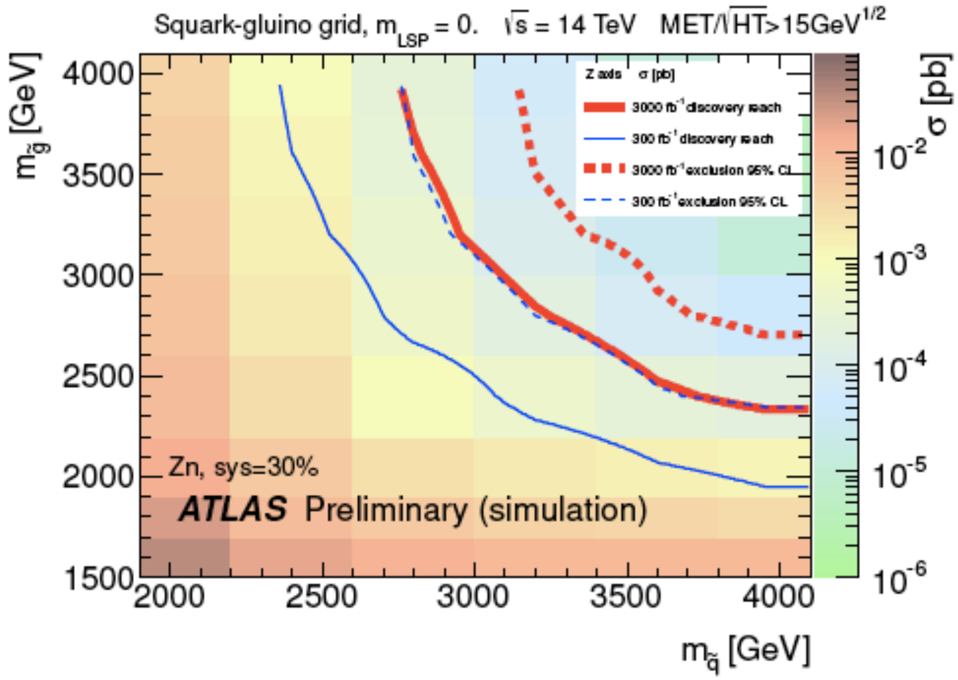




- Sbottom also supposedly light due to mixing with stop
- Discovery with 300 fb^{-1} for masses up to 600-700 GeV
  - Scenario A: syst. errors as today
  - Scenario B: syst. errors scaled with 1/√L (but at least 10%)

Generic Squarks and Gluinos

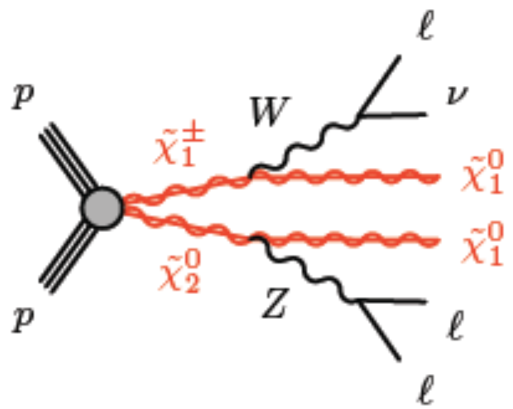


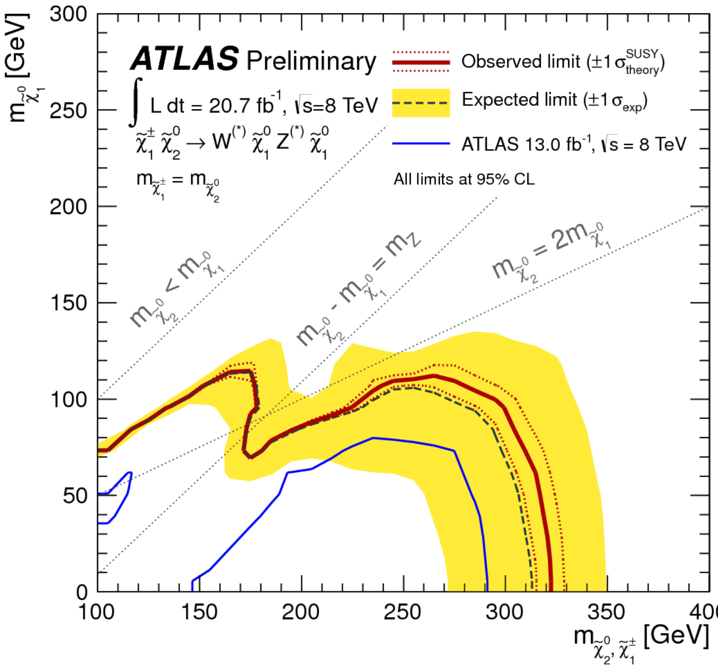


- Search for large E_T^{miss} and large M_{eff}
- Current limit ~1.2 TeV at 95% CL:
  - Will be extended to 2.3 (2.7) TeV with LHC (HL-LHC) if we don't discover it
- Discovery potential extended by 400 GeV with HL-LHC

Weak SUSY Production

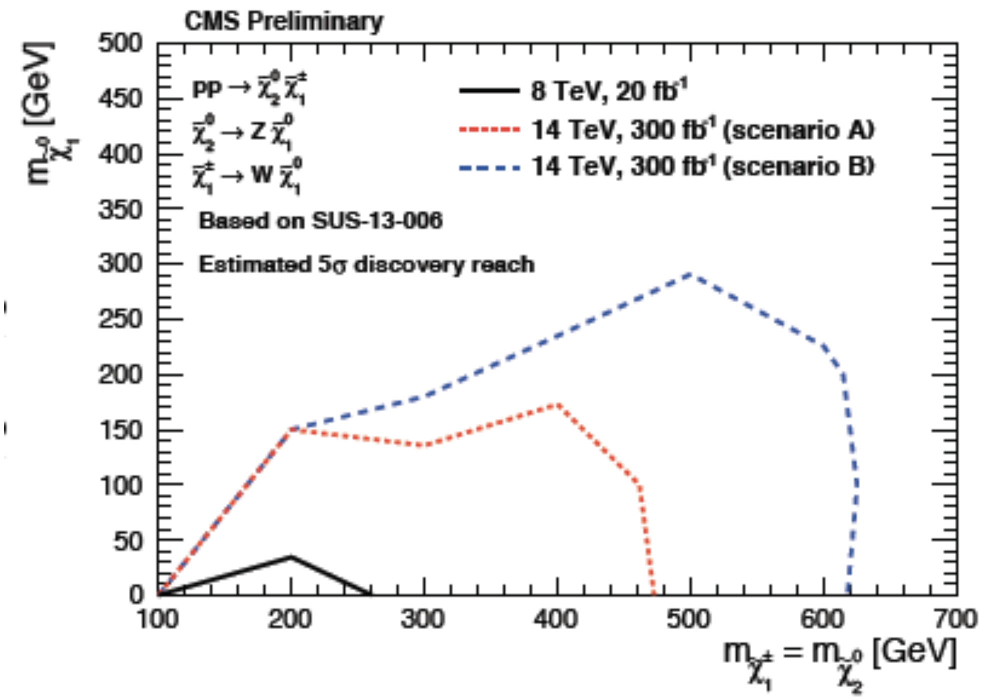
- Further motivations for new physics at weak scale
  - Unification of couplings, Dark Matter, …
- E.g. in "split-SUSY" squarks are heavy but gauginos are at ~low mass
  - Search for those directly
- Classic search
  - Chargino+neutralino production

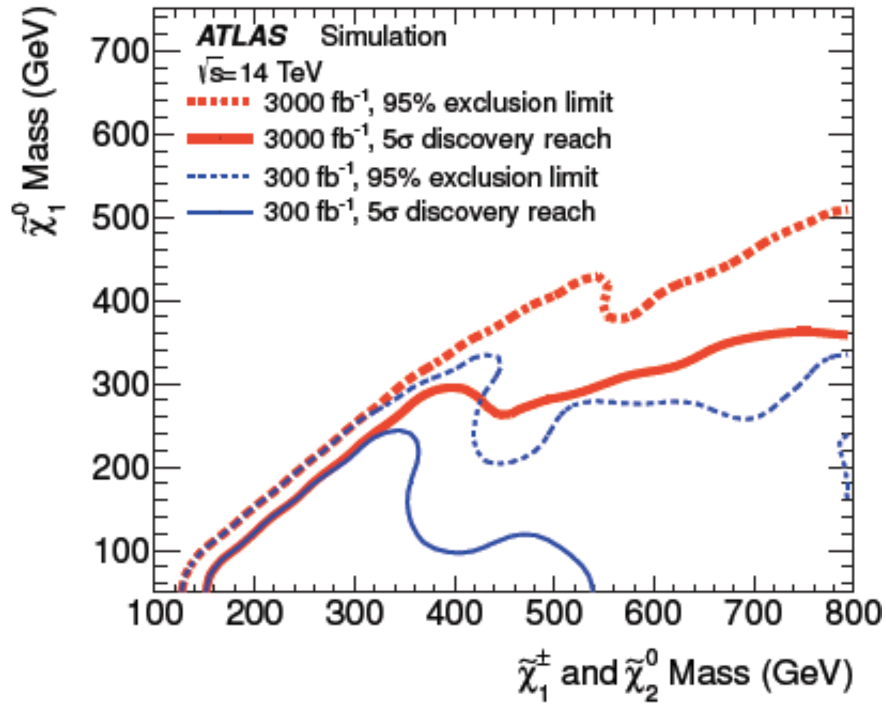




Current limits not yet very restrictive, e.g. no constraints for m(LSP)>100 GeV

Future Prospects for Weak SUSY Production

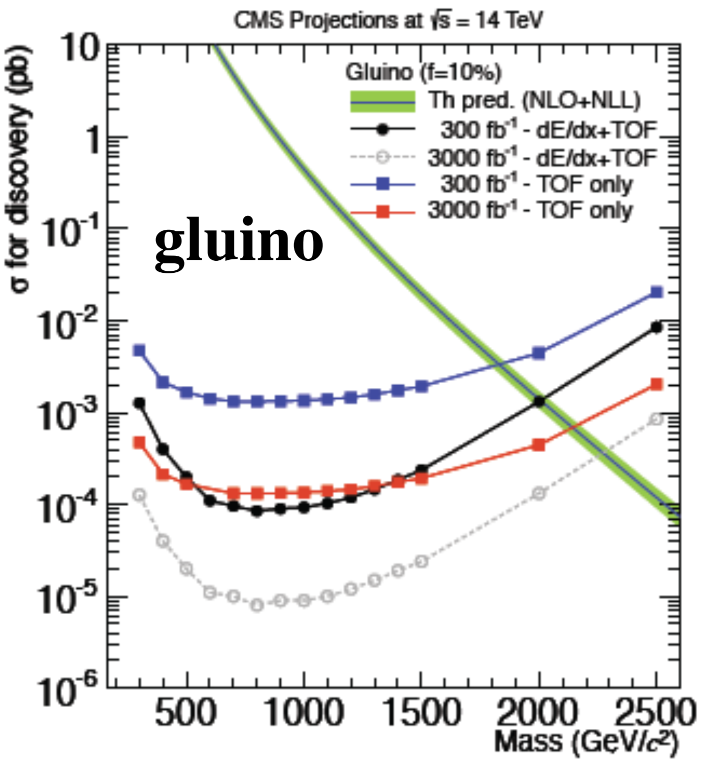


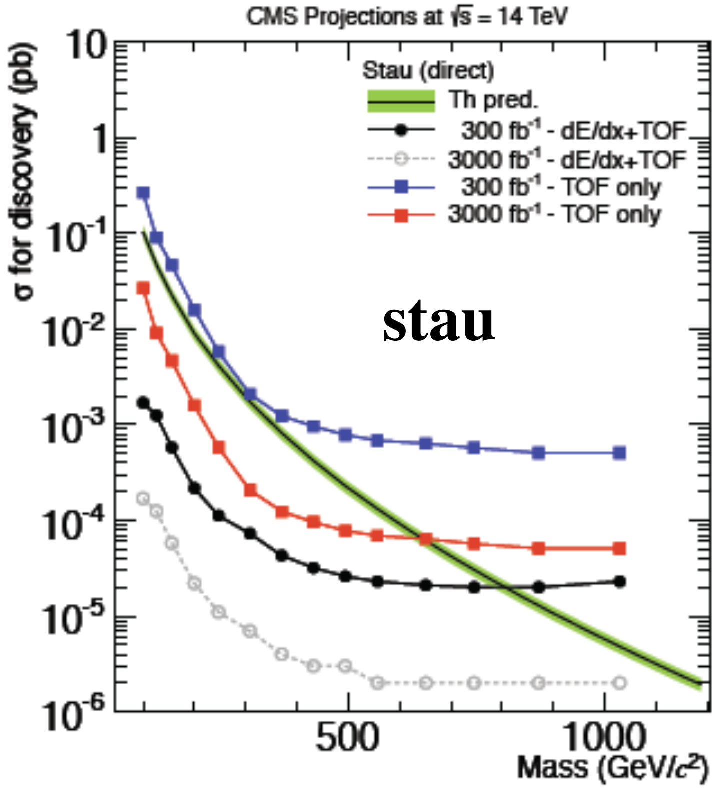


- Probe chargino masses of ~500 GeV with 300 fb^{-1}
  - for m(LSP)<100-200 GeV
- Dramatic improvement with HL-LHC:
  - Reach >800 GeV for m(LSP)<300 GeV

Metastable Gluinos and Staus

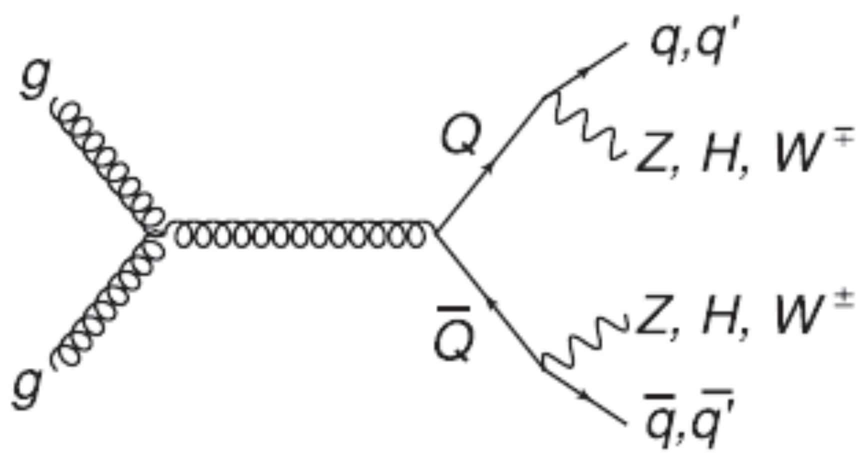
- Metastable sparticles occur in many scenarios of new physics
  - E.g. Split-SUSY $\tilde{g}$, GMSB stau, ….

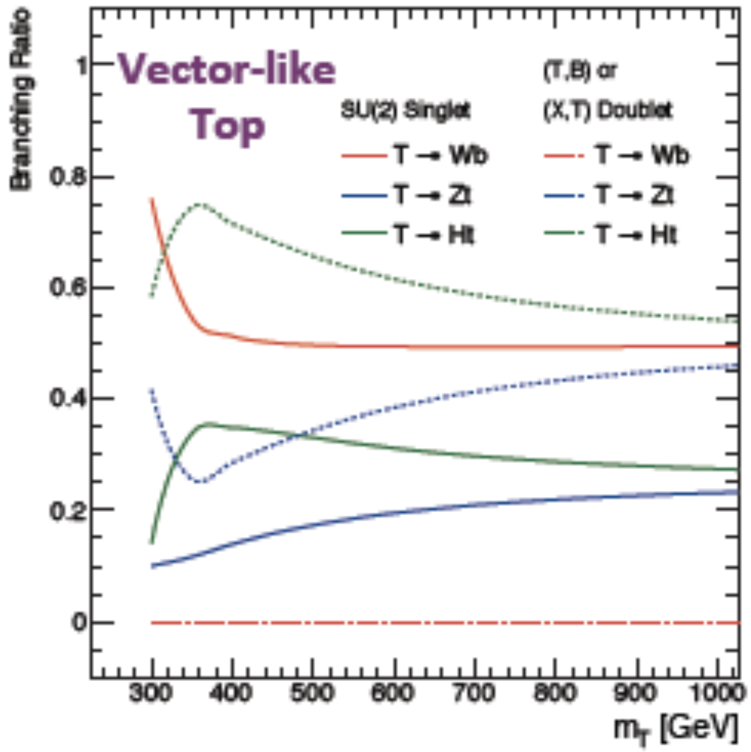




	$M(\tilde{g})$ [TeV]	$M(\tilde{\tau})$ [TeV]
Run-1 data 95% CL limit	>1.0	0.27
300 fb^{-1} 5σ discovery	1.8-2.0	~0.8
3000 fb^{-1} 5σ discovery	2.1-2.3	~1.2

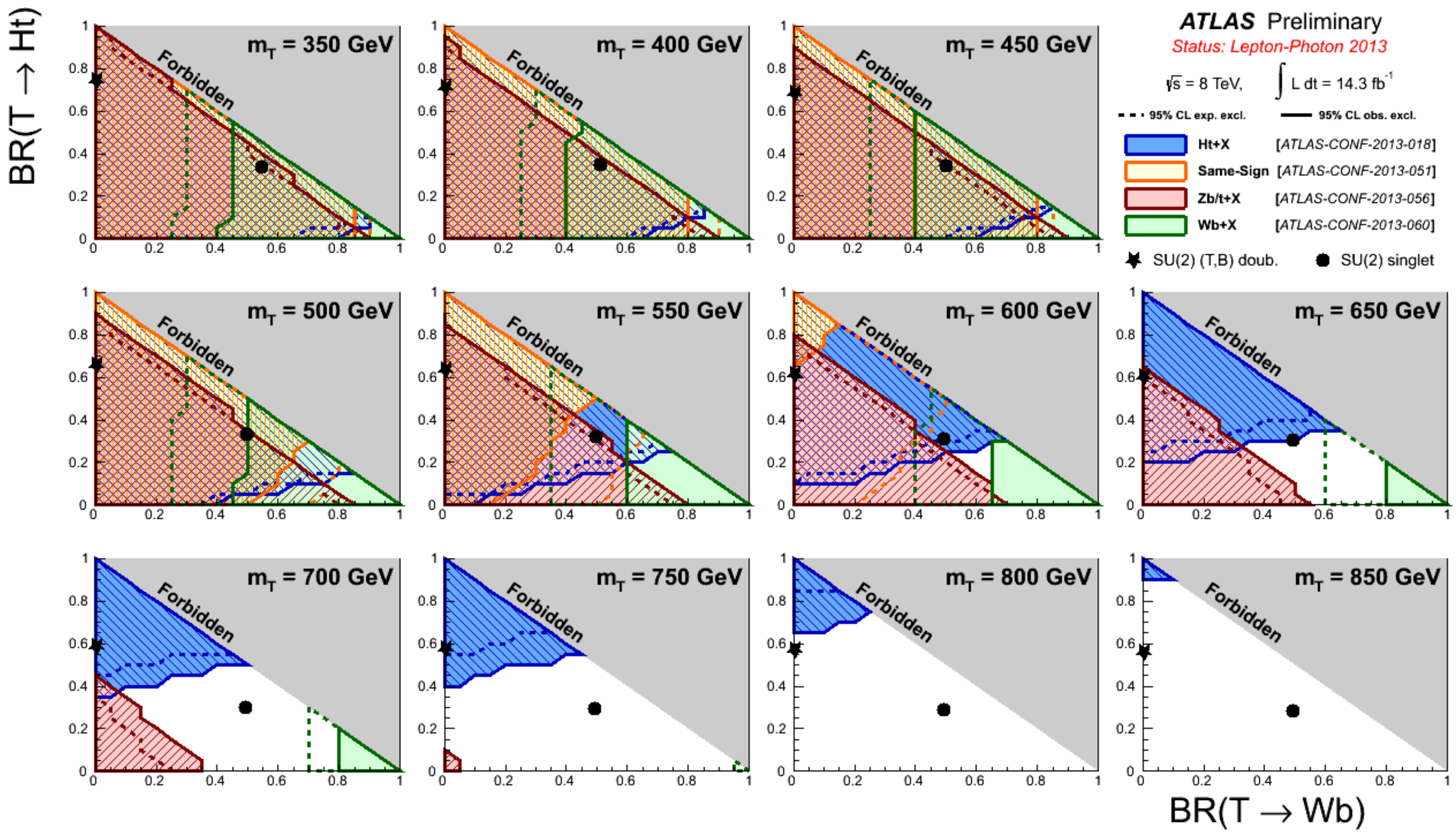
Vector-like Top Quarks





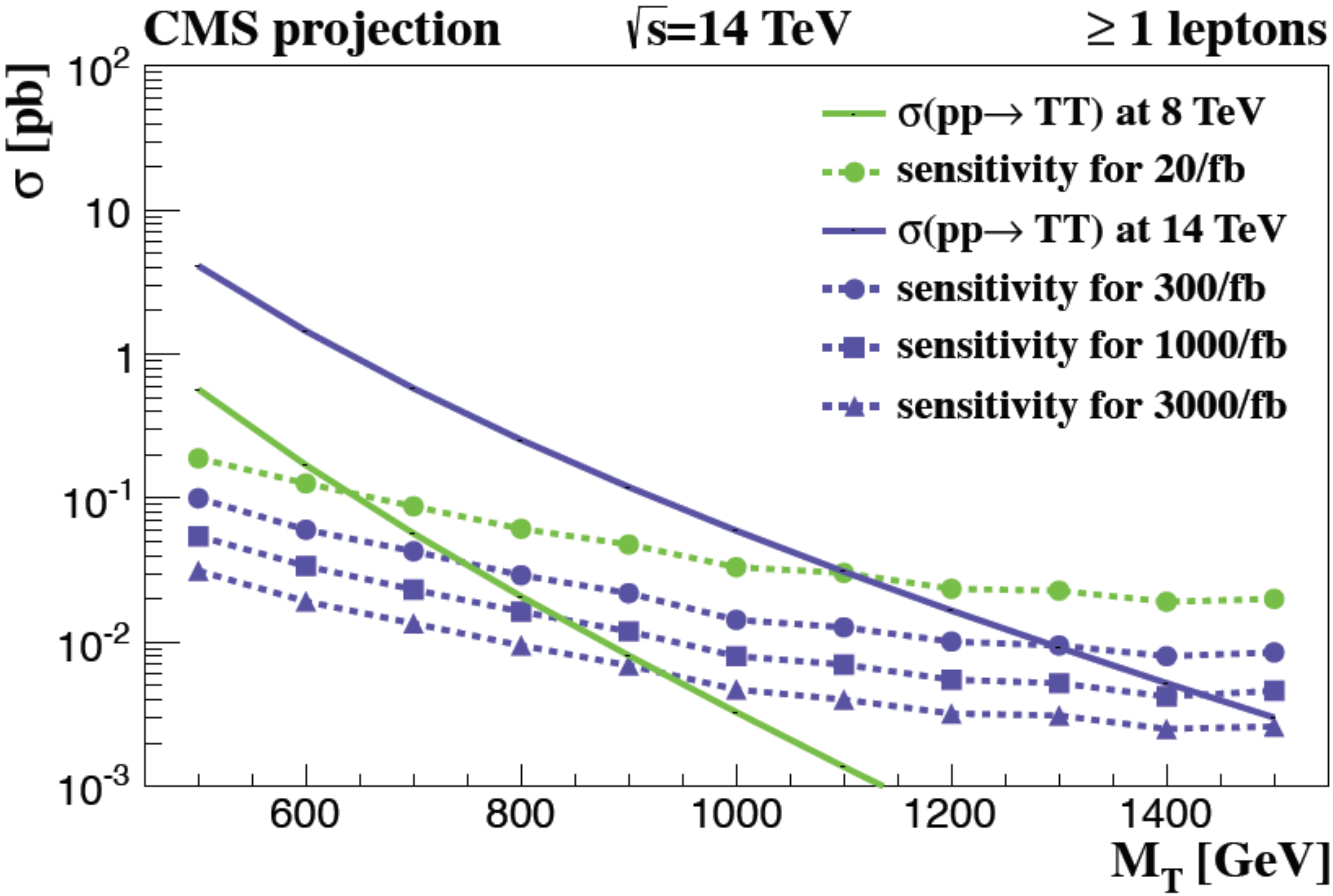
- Colored spin-1/2 fermions
  - transform the same for left- and right-handed under EW gauge group
- Provide alternative solution to little hierarchy problem
- Appear in many BSM models, e.g.
  - Little Higgs, Extra Dimensions,…

Vector-like Top: Present



Currently probing up to about 600-800 GeV

Vector-like Top: future

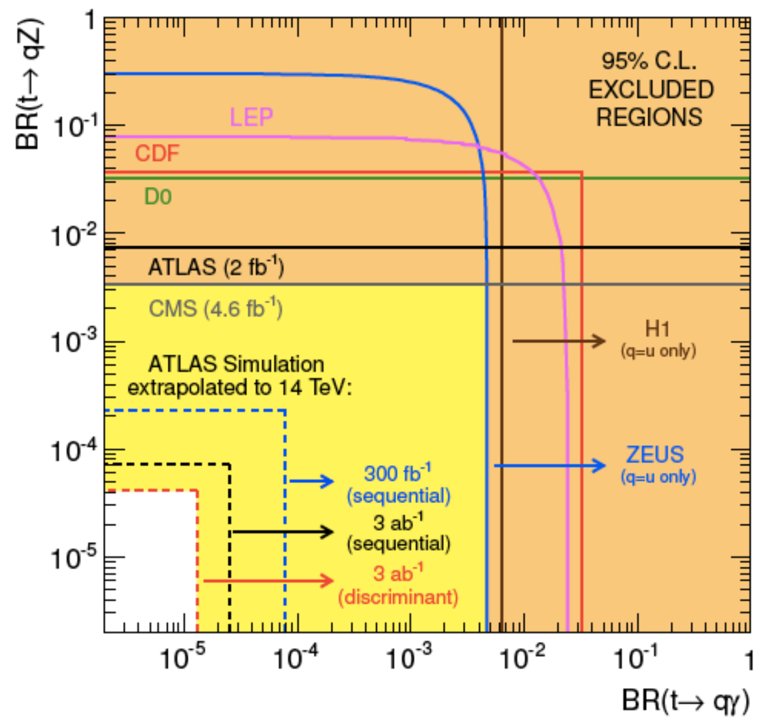


- Probe >1.5 TeV with 3000 fb^{-1}

Rare decays of the top quark

Process	SM	QS	2HDM	FC 2HDM	MSSM	R̸	TC2	RS
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}	—	$\sim 10^{-11}$
$t \to uZ$	8.0×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}	—	$\sim 10^{-9}$
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}	—	$\sim 10^{-11}$
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}	$\sim 10^{-6}$	$\sim 10^{-9}$
$t \to cZ$	1.0×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}	$\sim 10^{-4}$	$\sim 10^{-5}$
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8.5×10^{-5}	2×10^{-4}	$\sim 10^{-4}$	$\sim 10^{-9}$

- LHC is a top factory
  - In 3000 fb^{-1} 0.5 billion observed ttbar events per experiment
- In SM top quark decays to Wb nearly 100%
  - Observing decays to other modes clear sign of new physics
  - Interesting region starts at $\sim 10^{-4}$
- HL-LHC will probe $\sim 3\times10^{-5}$ at least

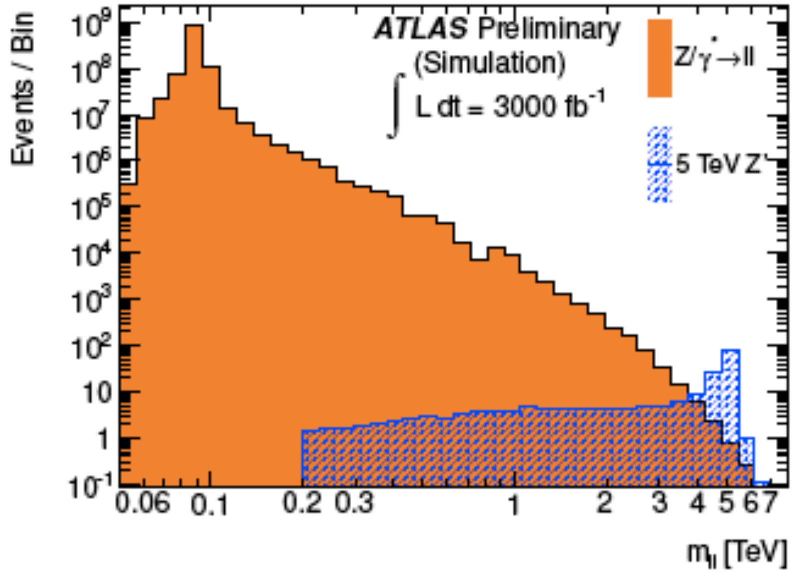


Is there some other new physics coming in dramatically at the TeV scale?

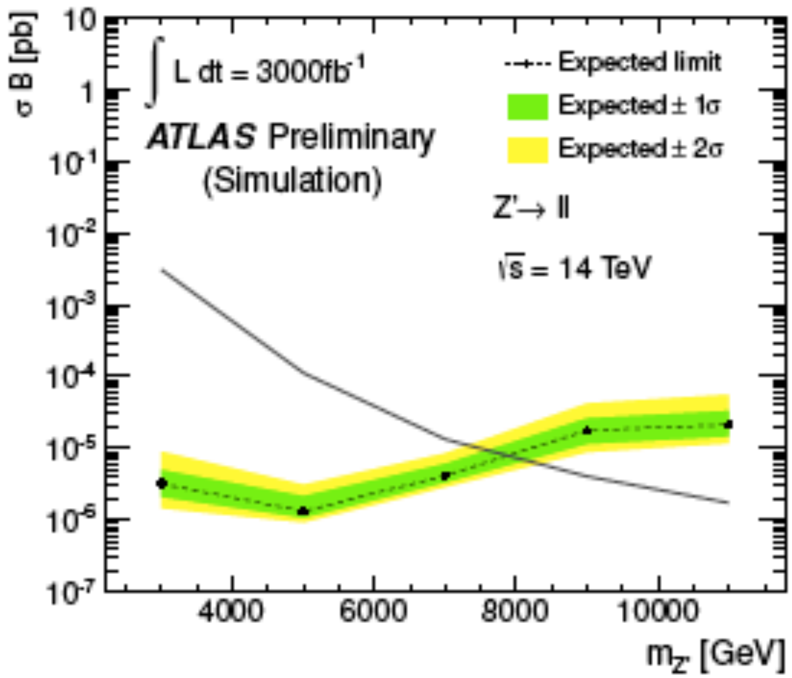
- E.g. large or warped extra dimensions provide alternative solution to naturalness problem
  - Bring Planck scale down to TeV scale
- Main signatures
  - Resonances of dilepton, diphoton, ditop production
    - via KK graviton or KK gluon exchange
    - Also common signatures for extended gauge groups (Z')
  - Monojet or monophoton
    - Due to graviton emission
  - Many hard particles
    - Black holes
- All of them are pursued in run-1 data analyses
  - Future prospects for dilepton and ditop resonances

Dilepton resonances: limits

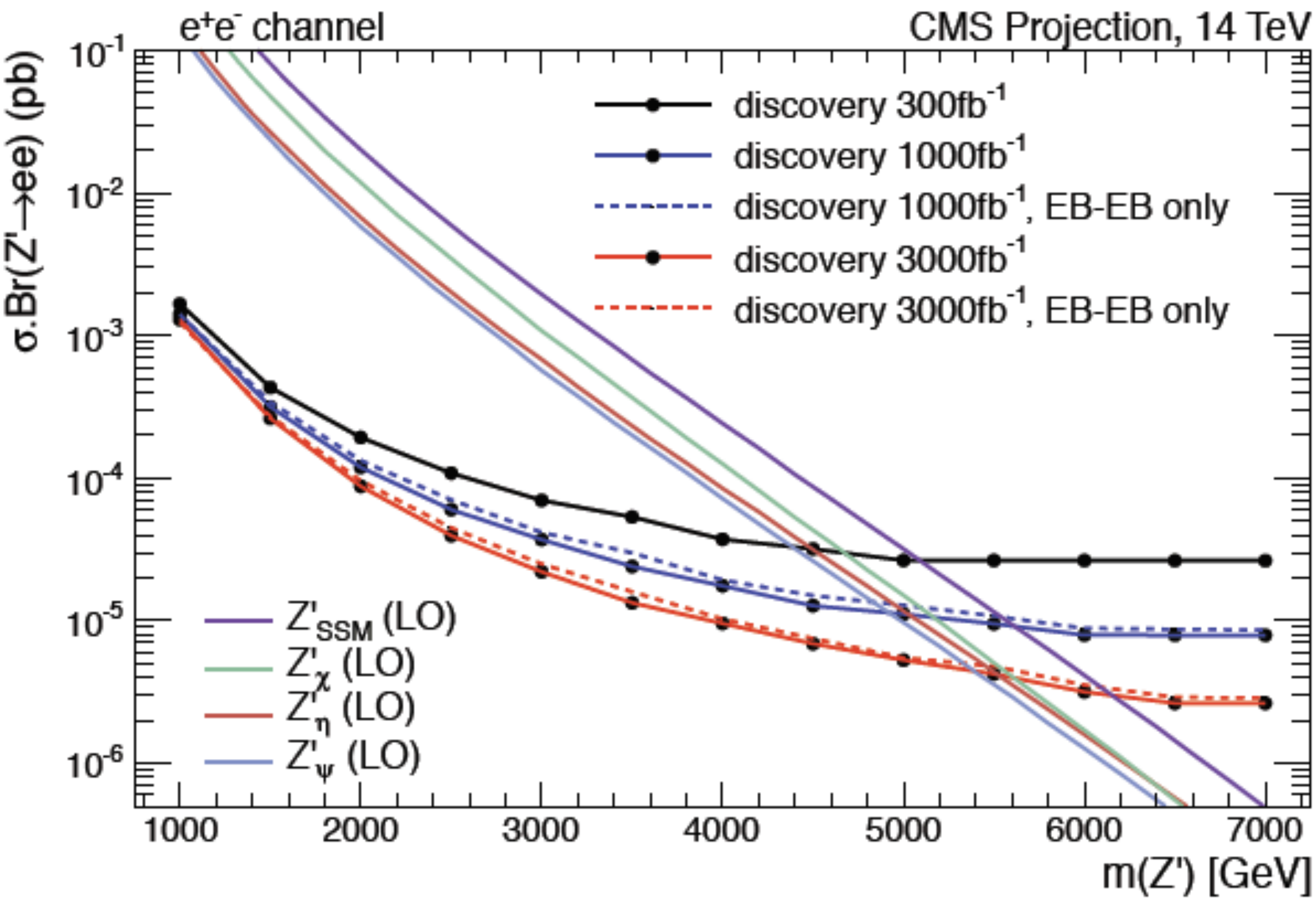
- Current limits are on σxBR are ~0.3 fb
  - Expect to improve by a factor of ~100 with HL-LHC
  - Probe Z'_{SSM} up to masses of 7.8 TeV



95% CL limits on:		
	Z'-> ee (TeV)	Z'->μμ (TeV)
Run-1 data	2.79	2.48
300 fb^{-1}	6.5	6.4
3000 fb^{-1}	7.8	7.6



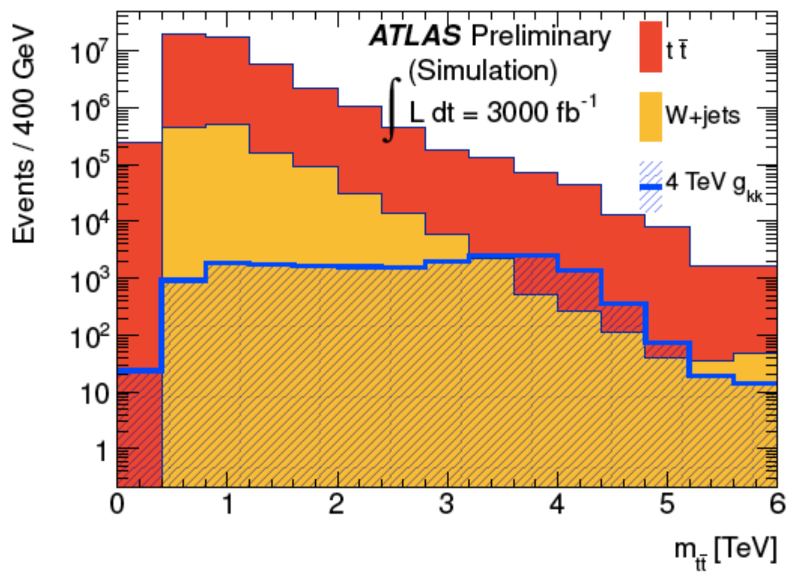
Dilepton resonances: discovery potential



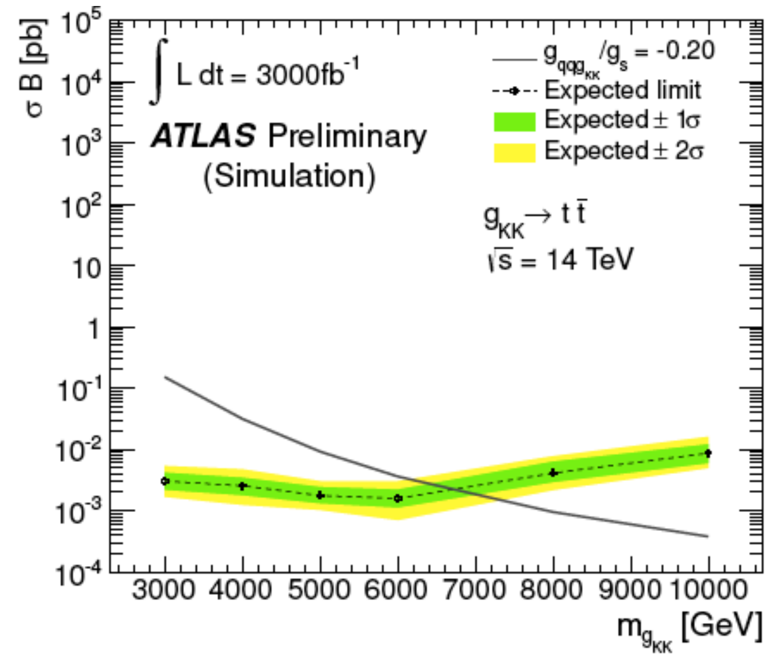
	Z'_{SSM} ee	Z'_{SSM} μμ
300 fb^{-1}	5.1 TeV	5.2 TeV
3000 fb^{-1}	6.2 TeV	6.4 TeV

Ditop resonances: limits

- Current limits are on σxBR are ~0.1 pb
  - Expect to improve by a factor of ~100 with HL-LHC
  - Probe KK gluons up to masses of ~6.7 TeV

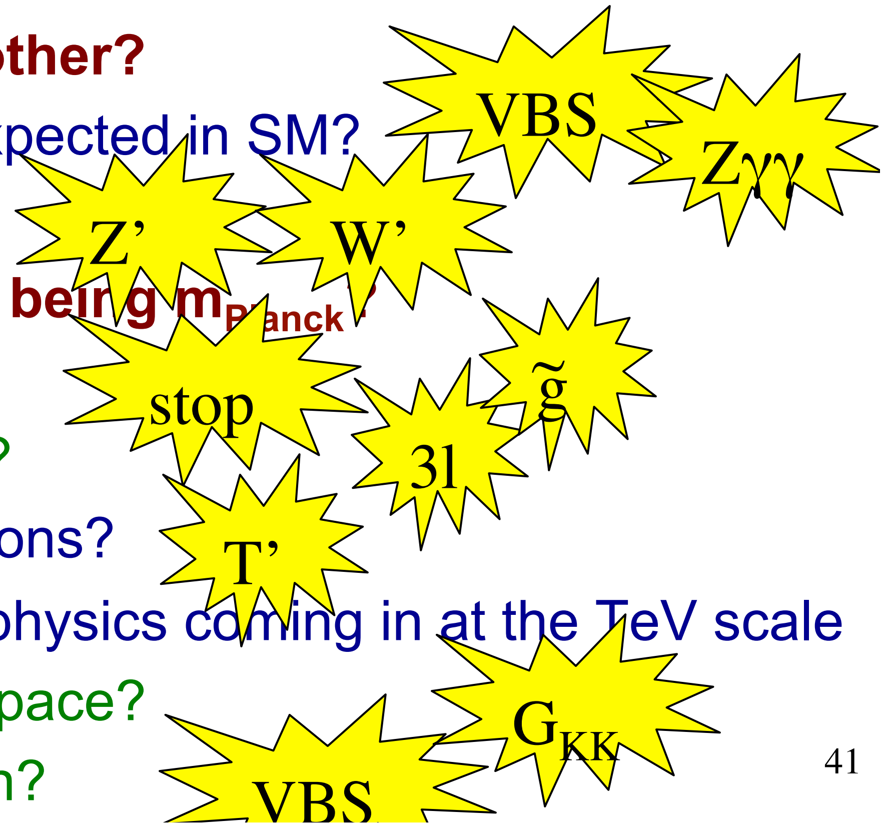


95% CL limits on:		
	Z' (TeV)	g_{KK} (TeV)
Run-1 data	1.8	2.0
300 fb^{-1}	3.3	4.3
3000 fb^{-1}	5.5	6.7



Many questions follow from Higgs discovery!

- **Is it *the* Higgs boson?**
  - Does it couple to matter exactly as predicted?
  - Does it couple to gauge bosons exactly as predicted?
  - Are there more Higgs bosons?
- **Does the Higgs boson decay to non-SM particles?**
  - E.g. to Dark Matter?
- **How do bosons interact with each other?**
  - Does Higgs boson contribute as expected in SM?
  - Are there new gauge groups?
- **What protects the Higgs mass from being m_{Planck}?**
  - Is Nature Supersymmetric?
    - Is Dark Matter a SUSY particle?
  - Are there new generations of fermions?
  - Is there some other new dramatic physics coming in at the TeV scale
    - Are there extra dimensions of space?
    - Is there a new strong interaction?



Do we have to know results from 13 TeV run to decide on HL-LHC?

- Compare scenarios depending on what we know by 2017
  - Assume about 50 fb^{-1} by 2017 analyzed

	Observation in 2017	Want HL-LHC?
A	Found 5σ excess in data in at least one BSM signature	
B	Found 3σ excess in data in at least one BSM signature	
C	Found no excess in data >2σ but deviation in Higgs by 3σ	
D	Found no excess in data and no deviation in Higgs either	

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D	Found no excess in data and no deviation in Higgs either	✓

Do we have to know results from 13 TeV run to decide on HL-LHC?

- Compare scenarios depending on what we know by 2017

ed

- Improve **precision on Higgs couplings** by factor 2-3
- First chance to study **Higgs self coupling**
- Significantly **extend reach for new physics** in many areas
- Capitalize on **major past investment** and incrementally upgrade **working machine and detectors**

		Want HL-LHC?
A		✓✓✓
B		✓✓
C		✓✓
D	Found no excess in data and no deviation in Higgs either	✓

European Strategy

- In 2012 European Strategy convened to plan the future of particle physics in Europe
  - Endorsed by CERN council in May 2013

Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

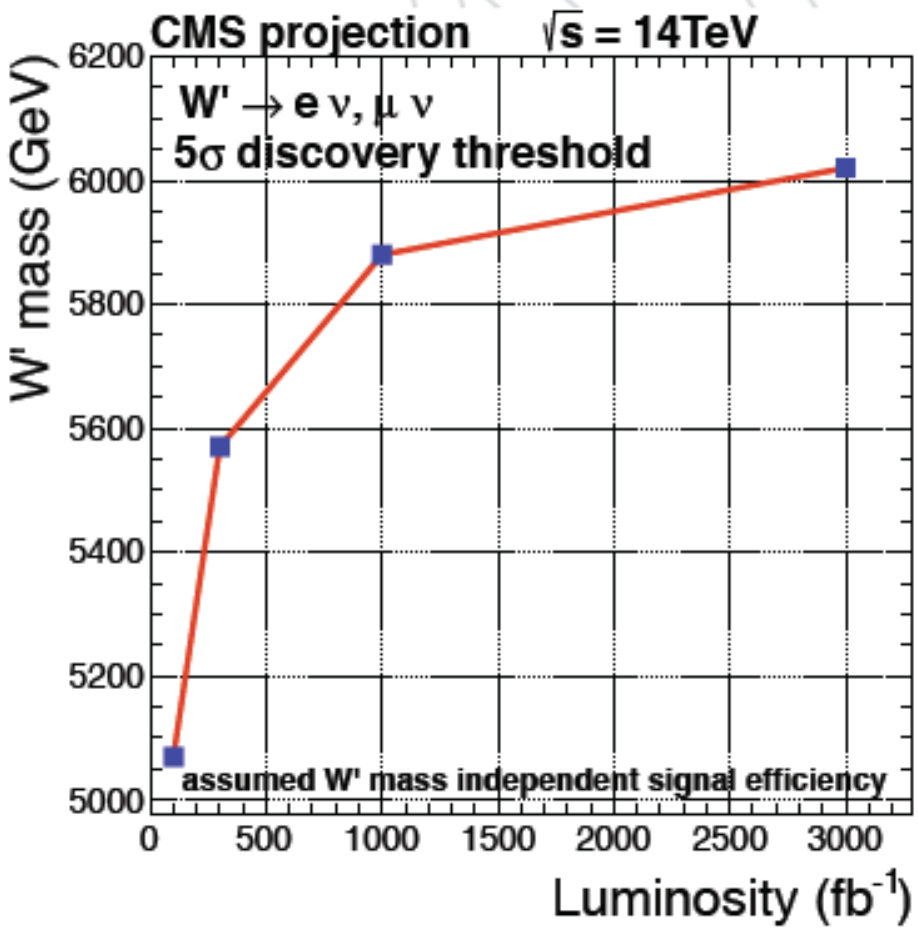
European Strategy
Update

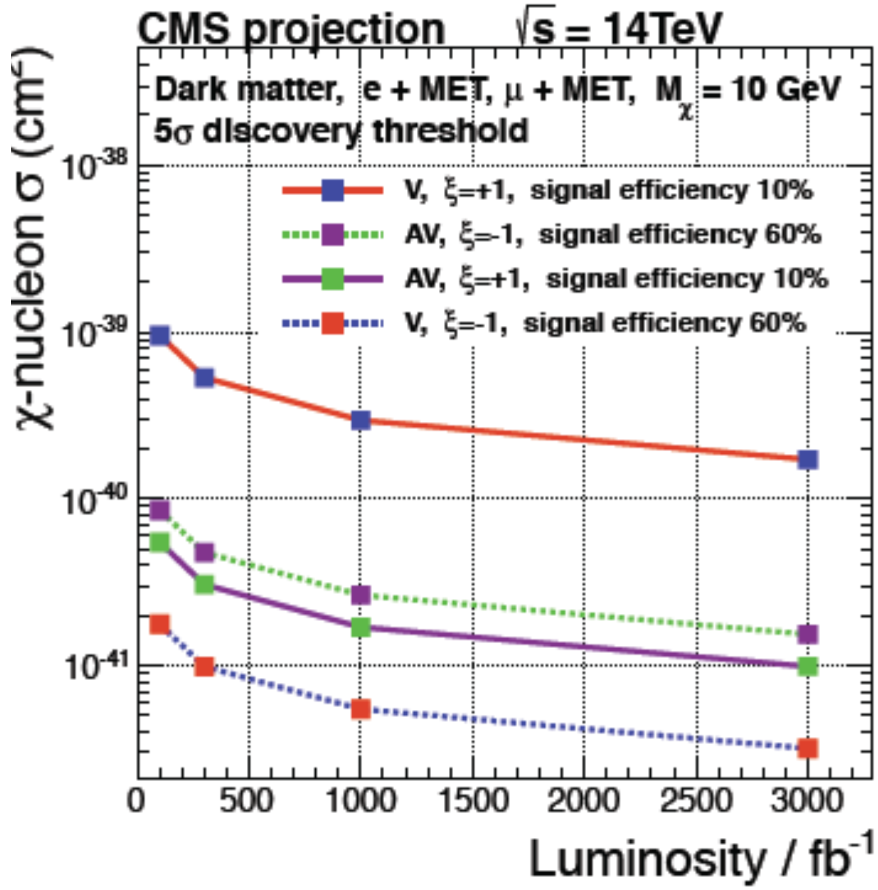
Conclusions

- **LHC run-1 has been tremendous success**
  - Higgs discovery and severe constraints on BSM physics
    - >500 publications on vast range of topics
- **Future LHC running will be even more exciting**
  - Probe Higgs boson precisely (see M. Klute's talk)
  - Significantly extend discovery reach for BSM physics
    - Is EWK scale *natural*?
- **HL-LHC natural next step to fully exploit LHC**
  - Capitalize on major past investments
  - Significantly extends LHC potential
    - Regardless of additional LHC discoveries!
  - Upgrades needed to LHC machine and ATLAS and CMS
    - Construction should start in 2017 to be ready for 2022
  - US is a very important partner in this global endeavor

Backup Slides

Monoleptons: W' and Dark Matter

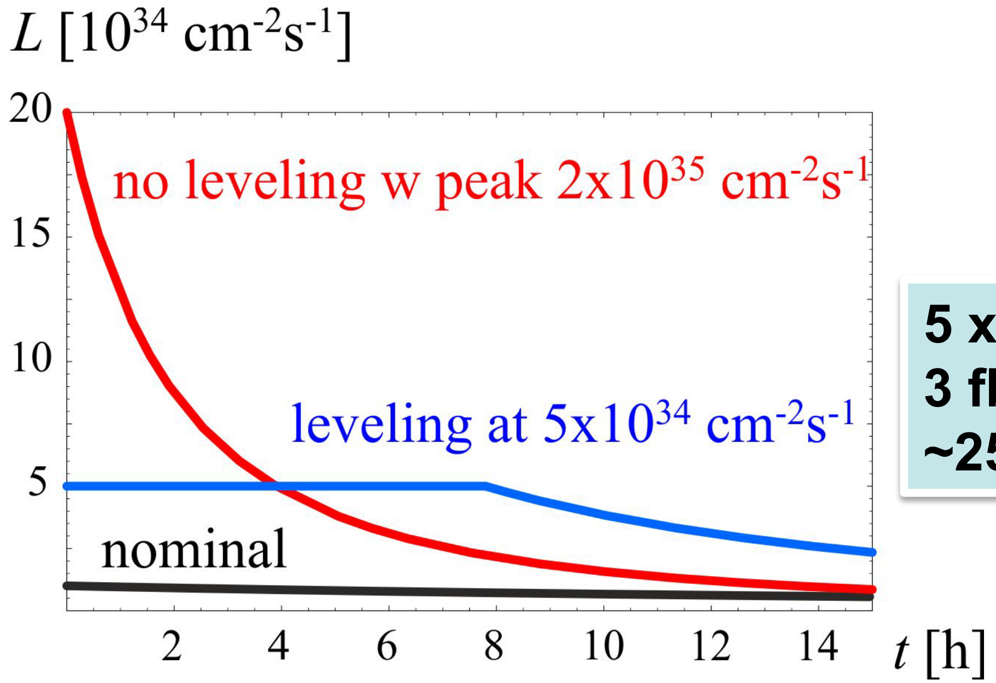




- W' discovery potential increased to 6 TeV for 3 ab^{-1}
- Also probe dark matter cross section:
  - Improvement from 300 fb^{-1} to 3000 fb^{-1}: factor 3-5

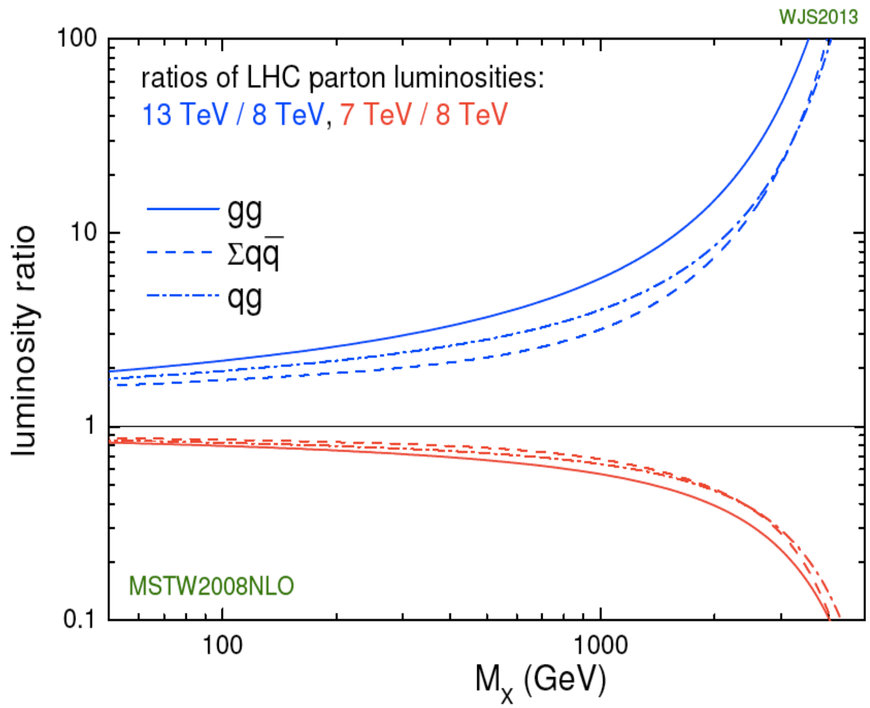
HL-LHC

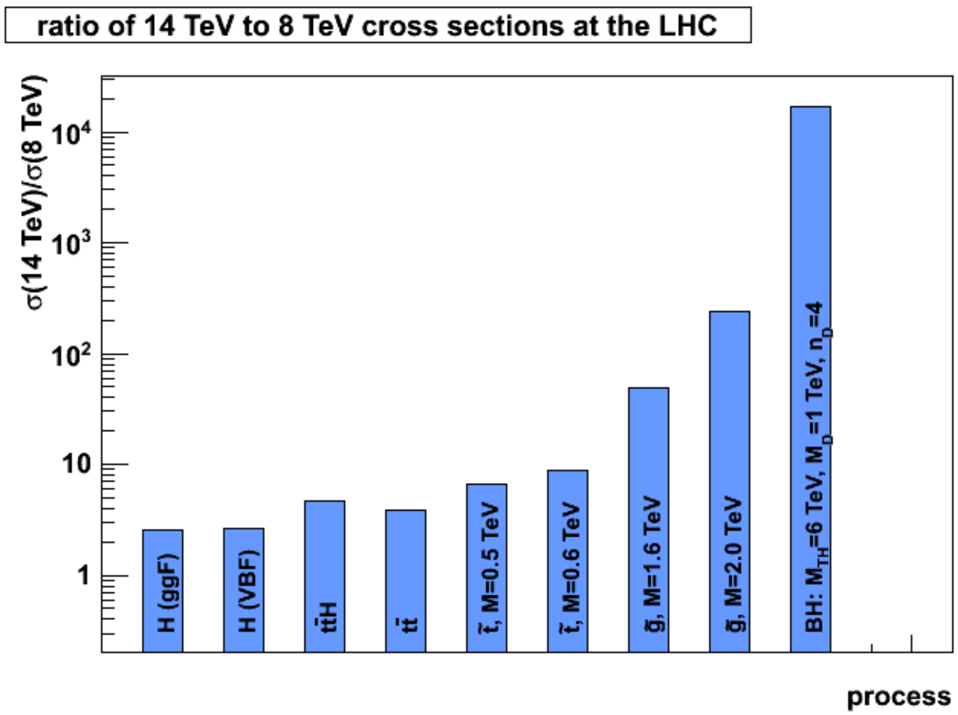
- 3000 fb^{-1} delivered in the order of 10 years
- High "virtual" luminosity with levelling anticipated
- Challenging demands on the injector complex
  - major upgrades foreseen (Linac 4, Booster 2GeV, PS and SPS)



5×10^{34} $cm^{-2}s^{-1}$ levelled luminosity
3 fb^{-1} per day
~250 fb^{-1} /year

Run-2 Physics Cross Sections





- Increase in cross section by factor ~10 for M~2 TeV
- Discovery of TeV scale particles possible with a few fb^{-1}