



# Report from the Energy Frontier Hadron Collider Detector R&D

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Joint CPAD and Instrumentation Frontier Workshop  
Boulder, CO

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# Outline

- 1) **State of Knowledge at the Energy Frontier**
  - Higgs, SUSY, Exotica, etc....
- 2) **Physics Goals for the next two decades**
  - Plans and Projections for ATLAS and CMS
- 3) **Hadron Collider Evolution**
  - LHC Upgrades
- 4) **Detector Challenges to meet those Goals**
  - ATLAS and CMS upgrade strategies
- 5) **Ongoing R&D Summary**
  - Emphasis on US involvement
  - Many efforts here – no time for details



I predict everything !

the Nostradamus seal of approval



# Acknowledgments & Information



## Special Thanks To

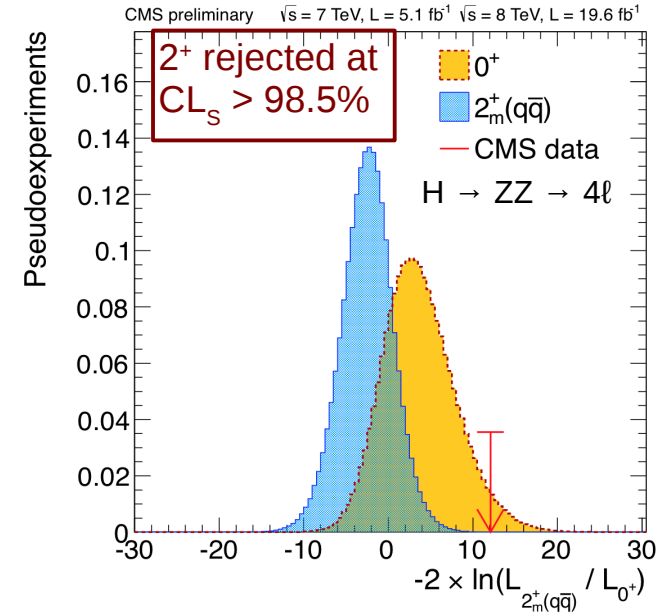
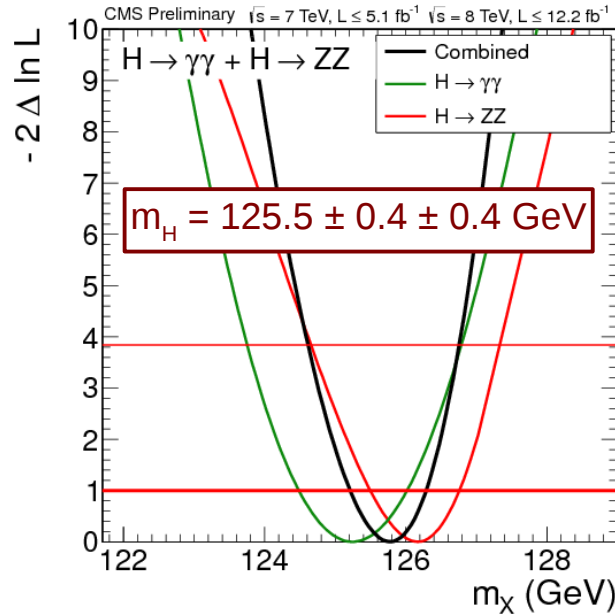
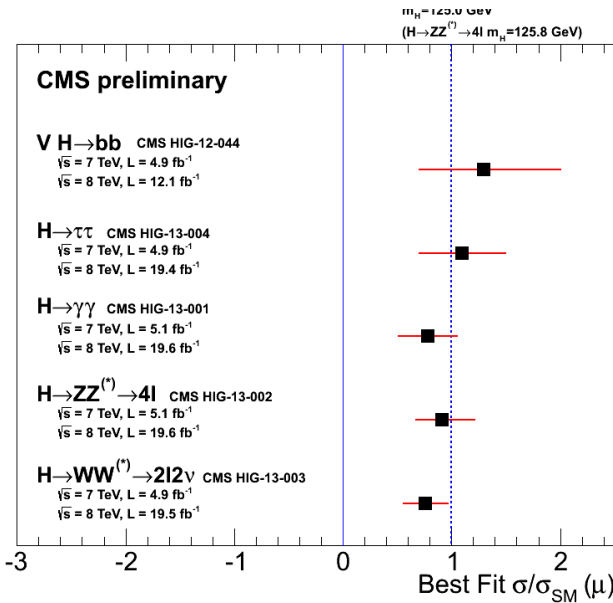
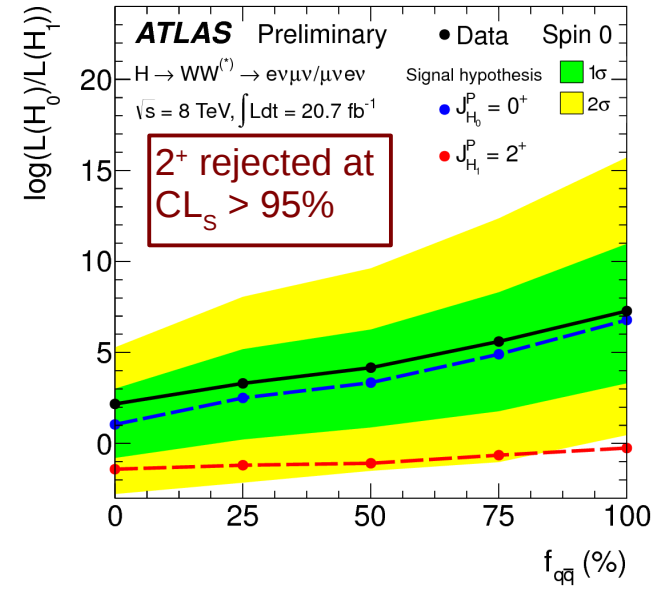
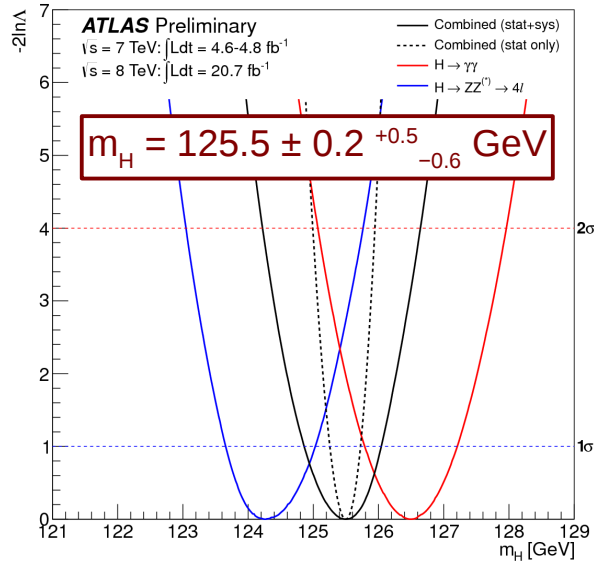
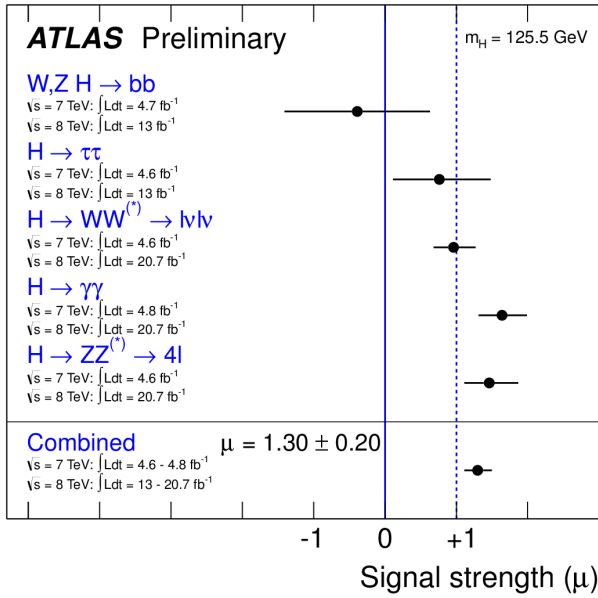
- Daniela Bortoletto, Abe Seiden

## More Information

- **ATLAS**
  - > physics documents <https://twiki.cern.ch/twiki/bin/view/AtlasPublic>
  - > Phase-1 LOI [CERN-LHCC-2011-012](#)
  - > Phase-2 LOI [CERN-LHCC-2012-022](#)
- **CMS**
  - > physics documents <http://cms.web.cern.ch/news/cms-physics-results>
  - > Phase-1 HCAL TDR [CERN-LHCC-2012-015](#)
  - > Phase-1 Pixels TDR [CERN-LHCC-2012-016](#)
- **General**
  - > HEPAP Facilities Report <http://science.energy.gov/hep/hepap/reports/>
  - > European Strategy [homepage](#)



# The Higgs (or something like it)





# Still Seeking SUSY

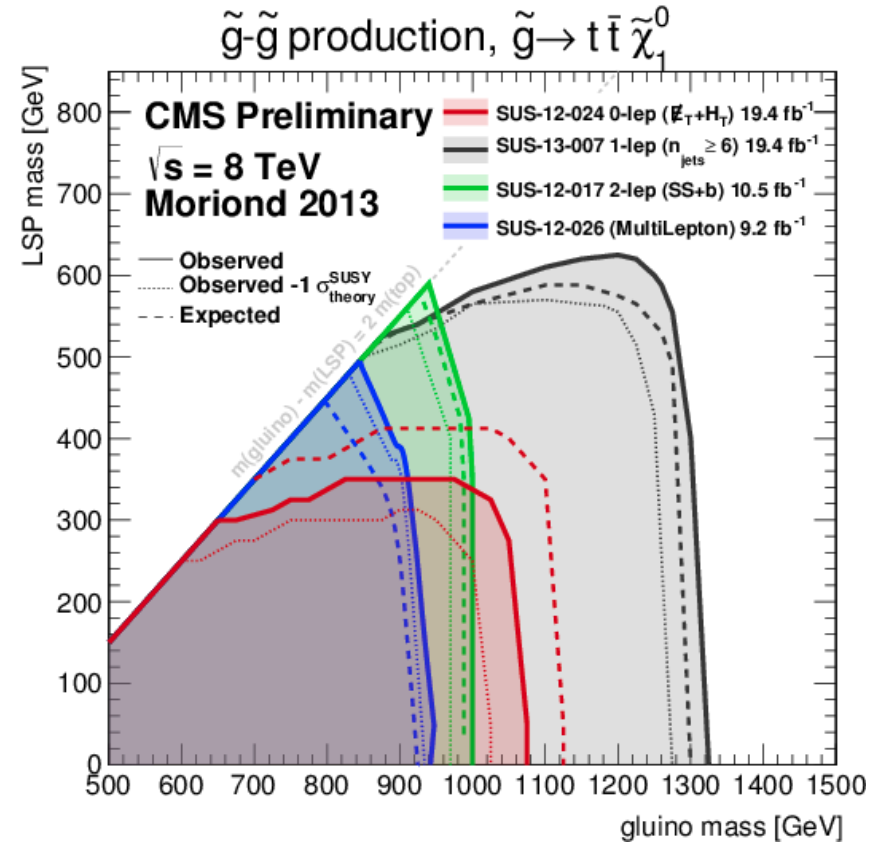


**ATLAS SUSY Searches\* - 95% CL Lower Limits (Status: March 26, 2013)**

Search Category	Search Description	Lower Limit [TeV]	Notes
Inclusive searches	MSUGRA/CMSSM : 0 lep + $\tilde{f}$ s + $E$	1.30 TeV	$\tilde{q} = \tilde{g}$ mass
	MSUGRA/CMSSM : 1 lep + $\tilde{f}$ s + $E$	1.24 TeV	$\tilde{q} = \tilde{g}$ mass
	Pheno model : 0 lep + $\tilde{f}$ s + $E$	1.19 TeV	$\tilde{g}$ mass ( $m(\tilde{q}) < 2 \text{ TeV, light } \tilde{\chi}_1^0$ )
	Pheno model : 0 lep + $\tilde{f}$ s + $E$	1.29 TeV	$\tilde{q}$ mass ( $m(\tilde{g}) < 2 \text{ TeV, light } \tilde{\chi}_1^0$ )
	Glauino med. $\tilde{\chi}^0 \rightarrow q\bar{q}\tilde{\chi}^0$ : 1 lep + $\tilde{f}$ s + $E$	900 GeV	$\tilde{g}$ mass ( $m(\tilde{q}) < 200 \text{ GeV, } m(\tilde{g}) = \frac{1}{2}(m(\tilde{q}) + m(\tilde{g}))$ )
	GMSB (NLSP) : 2 lep (OS) + $\tilde{f}$ s + $E$	1.24 TeV	$\tilde{g}$ mass ( $\tan\beta < 15$ )
	GMSB (NLSP) : 1-2 $\tau$ + $\tilde{f}$ s + $E$	1.46 TeV	$\tilde{g}$ mass ( $\tan\beta > 15$ )
	GGM (bino NLSP) : $\gamma\gamma$ + $E$	1.67 TeV	$\tilde{g}$ mass ( $m(\tilde{q}) > 50 \text{ GeV}$ )
	GGM (wino NLSP) : $\gamma$ + lep + $E$	619 GeV	$\tilde{g}$ mass
	GGM (higgsino-bino NLSP) : $\gamma$ + b + $E$	900 GeV	$\tilde{g}$ mass ( $m(\tilde{q}) > 220 \text{ GeV}$ )
3rd gen. squarks gluino mediated	$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$ : 0 lep + 3 b-jets + $E$	690 GeV	$\tilde{g}$ mass ( $m(\tilde{H}) > 200 \text{ GeV}$ )
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ : 2 SS-lep + (0-3b)-jets + $E$	645 GeV	$F^{\prime}$ scale ( $m(\tilde{G}) > 10^4 \text{ eV}$ )
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ : 0 lep + multi- $\tilde{f}$ s + $E$	1.24 TeV	$\tilde{g}$ mass ( $m(\tilde{q}) < 200 \text{ GeV}$ )
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ : 0 lep + 3 b-jets + $E$	900 GeV	$\tilde{g}$ mass (any $m(\tilde{q})$ )
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ : 0 lep + 3 b-jets + $E$	1.03 TeV	$\tilde{g}$ mass ( $m(\tilde{q}) < 300 \text{ GeV}$ )
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ : 0 lep + 3 b-jets + $E$	1.15 TeV	$\tilde{g}$ mass ( $m(\tilde{q}) < 200 \text{ GeV}$ )
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ : 0 lep + 3 b-jets + $E$	620 GeV	$\tilde{b}$ mass ( $m(\tilde{q}) < 120 \text{ GeV}$ )
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ : 0 lep + 2-b-jets + $E$	430 GeV	$\tilde{b}$ mass ( $m(\tilde{q}) = 2 m(\tilde{q}_1)$ )
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ : 2 SS-lep + (0-3b)-jets + $E$	167 GeV	$\tilde{t}$ mass ( $m(\tilde{q}) = 55 \text{ GeV}$ )
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ : 2 SS-lep + (0-3b)-jets + $E$	160-410 GeV	$\tilde{t}$ mass ( $m(\tilde{q}) = 0 \text{ GeV, } m(\tilde{q}_1) = 150 \text{ GeV}$ )
3rd gen. squarks direct production	$\tilde{t}(\text{light}), \tilde{t} \rightarrow b\bar{c}$ : 1/2 lep + (b-jet) + $E$	160-440 GeV	$\tilde{t}$ mass ( $m(\tilde{q}) = 0 \text{ GeV, } m(\tilde{q}_1) = 10 \text{ GeV}$ )
	$\tilde{t}(\text{medium}), \tilde{t} \rightarrow b\bar{c}$ : 2 lep + b-jet + $E$	200-610 GeV	$\tilde{t}$ mass ( $m(\tilde{q}_1) = 0$ )
	$\tilde{t}(\text{heavy}), \tilde{t} \rightarrow t\bar{c}$ : 1 lep + b-jet + $E$	320-660 GeV	$\tilde{t}$ mass ( $m(\tilde{q}_1) = 0$ )
	$\tilde{t}(\text{heavy}), \tilde{t} \rightarrow t\bar{c}$ : 0 lep + 6(2b)-jets + $E$	500 GeV	$\tilde{t}$ mass ( $m(\tilde{q}_1) = 0$ )
	$\tilde{t}(\text{natural GMSB}) : Z(\rightarrow ll) + b\text{-jet} + E$	520 GeV	$\tilde{t}$ mass ( $m(\tilde{q}_1) > 150 \text{ GeV}$ )
	$\tilde{t}_1, \tilde{t}_2 \rightarrow t_1 + Z : Z(\rightarrow ll) + 1 \text{ lep} + b\text{-jet} + E$	520 GeV	$\tilde{t}$ mass ( $m(\tilde{t}_1) = m(\tilde{q}_1) + 180 \text{ GeV}$ )
	$\tilde{t}(\text{heavy}), \tilde{t} \rightarrow t\bar{c}$ : 2 lep + $E$	85-195 GeV	$\tilde{t}$ mass ( $m(\tilde{q}_1) = 0$ )
	$\tilde{t}(\text{heavy}), \tilde{t} \rightarrow t\bar{c}$ : 2 lep + $E$	110-340 GeV	$\tilde{t}$ mass ( $m(\tilde{q}_1) < 10 \text{ GeV, } m(\tilde{q}_2) = \frac{1}{2}(m(\tilde{q}_1) + m(\tilde{q}_2))$ )
	$\tilde{t}(\text{heavy}), \tilde{t} \rightarrow t\bar{c}$ : 2 lep + $E$	180-330 GeV	$\tilde{t}$ mass ( $m(\tilde{q}_1) < 10 \text{ GeV, } m(\tilde{q}_2) = \frac{1}{2}(m(\tilde{q}_1) + m(\tilde{q}_2))$ )
	$\tilde{t}(\text{heavy}), \tilde{t} \rightarrow t\bar{c}$ : 2 lep + $E$	600 GeV	$\tilde{t}$ mass ( $m(\tilde{q}_1) = m(\tilde{q}_2) = 0, m(\tilde{q}_3) \text{ as above}$ )
EW direct	$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \tilde{l} \nu(\tilde{\nu}), \tilde{N}(\tilde{\nu}\nu) : 3 \text{ lep} + E$	315 GeV	$\tilde{\chi}_1^0$ mass ( $m(\tilde{q}_1) = m(\tilde{q}_2) = 0, m(\tilde{q}_3) \text{ as above}$ )
	$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W^+ \tilde{\chi}_1^+ \tilde{\chi}_2^0$ : 3 lep + $E$	220 GeV	$\tilde{\chi}_1^0$ mass ( $m(\tilde{q}_1) = m(\tilde{q}_2) = 0, \text{ sleptons decoupled}$ )
	Direct $\tilde{\chi}_1^0$ pair prod. (AMS $\beta$ ) : long-lived $\tilde{\chi}_1^0$	985 GeV	$\tilde{g}$ mass
	Stable $\tilde{\tau}$ , R-hadrons : low $\beta$ , $\beta\gamma$	300 GeV	$\tilde{\tau}$ mass ( $5 < \tan\beta < 20$ )
	GMSB, stable $\tilde{\tau}$ : low $\beta$	230 GeV	$\tilde{\chi}_1^0$ mass ( $0.4 < \tau(\tilde{\chi}_1^0) < 2 \text{ ns}$ )
	GMSB, stable $\tilde{\tau}$ : low $\beta$	700 GeV	$\tilde{q}$ mass ( $1 \text{ mm} < c\tau < 1 \text{ m, } \tilde{g} \text{ decoupled}$ )
	LFV : $pp \rightarrow V + X, V_s \rightarrow e(\mu) + \tau$ resonance	1.81 TeV	$V_s$ mass ( $\lambda_{311} = 0.10, \lambda_{322} = 0.05$ )
	LFV : $pp \rightarrow V + X, V_s \rightarrow e(\mu) + \tau$ resonance	1.10 TeV	$V_s$ mass ( $\lambda_{311} = 0.10, \lambda_{322} = 0.05$ )
	BFV : $pp \rightarrow V + X, V_s \rightarrow e(\mu) + \tau$ resonance	1.2 TeV	$\tilde{q} = \tilde{g}$ mass ( $c\tau_{\tilde{q}} < 1 \text{ mm}$ )
	BFV : $pp \rightarrow V + X, V_s \rightarrow e(\mu) + \tau$ resonance	760 GeV	$\tilde{\chi}_1^0$ mass ( $m(\tilde{q}_1) > 300 \text{ GeV, } \lambda_{311} > 0$ )
Long-lived particles	$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W^+ \tilde{\chi}_1^+ \tilde{\chi}_2^0$ : 4 lep + $E$	350 GeV	$\tilde{\chi}_1^0$ mass ( $m(\tilde{q}_1) > 80 \text{ GeV, } \lambda_{311} > 0$ )
	$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W^+ \tilde{\chi}_1^+ \tilde{\chi}_2^0$ : 3 lep + $E$	666 GeV	$\tilde{g}$ mass
	$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ : 3-jet resonance pair	440 GeV	$\tilde{g}$ mass (any $m(\tilde{q})$ )
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ : 2 SS-lep + (0-3b)-jets + $E$	100-287 GeV	sgluon mass (incl. limit from 1110.2693)
	Scalar gluon : 2-jet resonance pair	781 GeV	$M^*$ scale ( $m_s < 80 \text{ GeV, limit of } < 687 \text{ GeV for D5}$ )
	WIMP interaction (D5, Dirac $\tilde{\chi}$ ) : 'monojet' + $E$	781 GeV	$M^*$ scale

$L_{int} = (4.4 - 20.7) \text{ fb}^{-1}$   
 $\sqrt{s} = 7, 8 \text{ TeV}$

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



**Strongly Produced**  
**Weakly Produced**

$\tilde{q}, \tilde{g}$   
 $\tilde{\chi}_i^0, \tilde{\chi}_i^\pm$

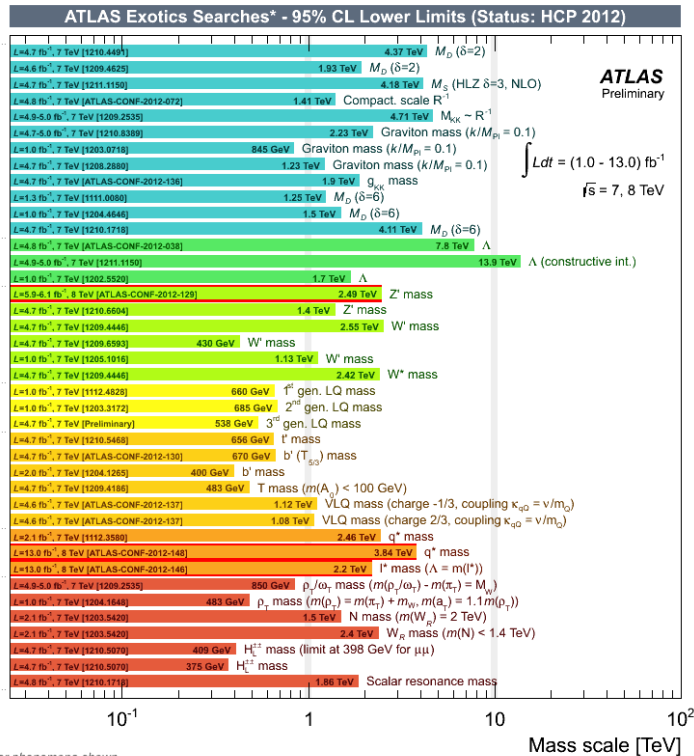
**> 1 TeV**  
**> 200 - 300+ TeV**



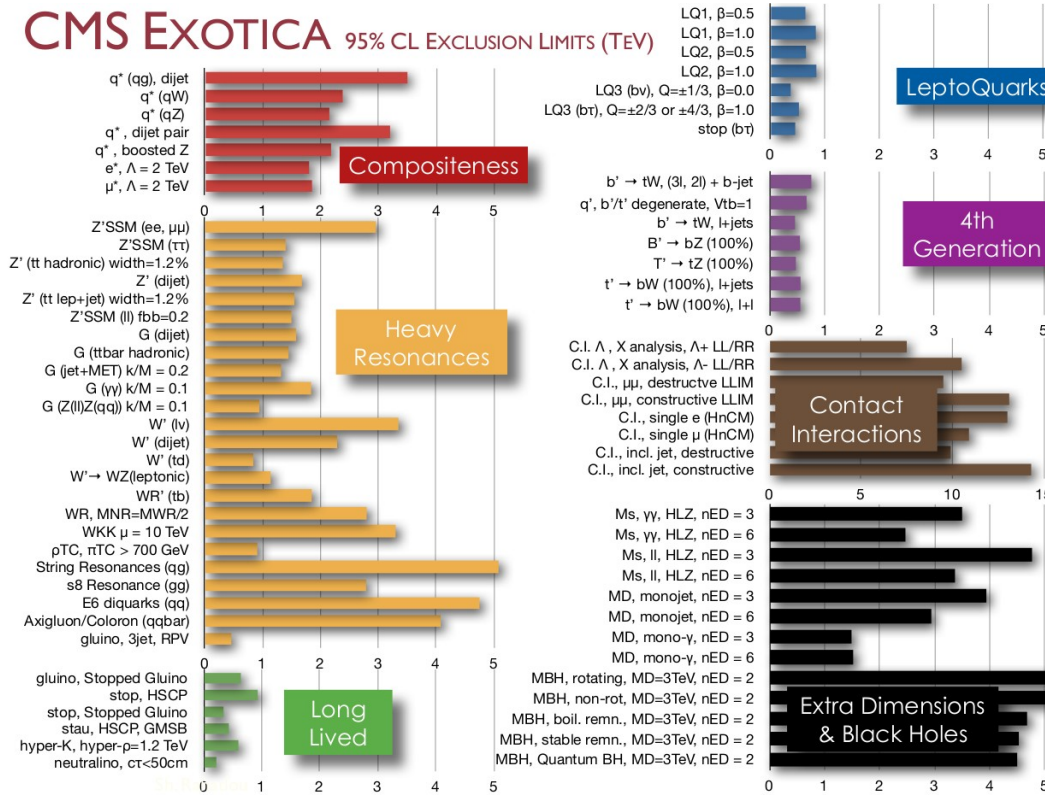




# Other Searches



## CMS EXOTICA 95% CL EXCLUSION LIMITS (TeV)



No Hints Yet !

# Goals & Projections: Higgs

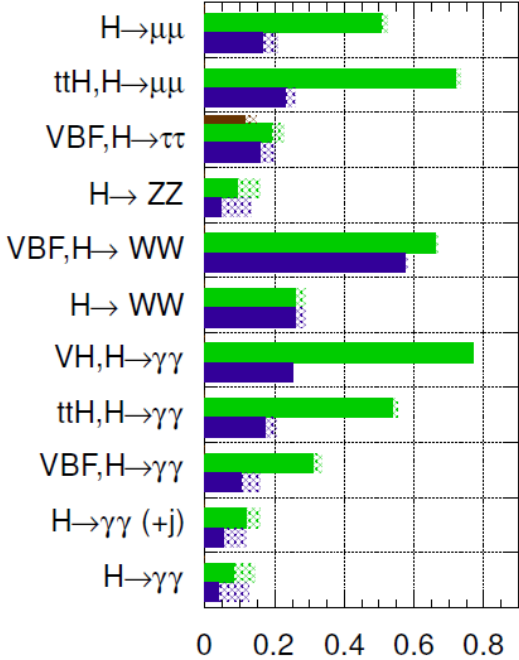
## Measure the Properties of the newly-discovered Boson

- couplings, partial width ratios, spin
- Higgs self-coupling under study:  $3\sigma/\text{exp}$  possible

ATLAS Simulation

$\sqrt{s} = 14 \text{ TeV}$ :  $\int Ldt=300 \text{ fb}^{-1}$ ;  $\int Ldt=3000 \text{ fb}^{-1}$

$\int Ldt=300 \text{ fb}^{-1}$  extrapolated from 7+8 TeV

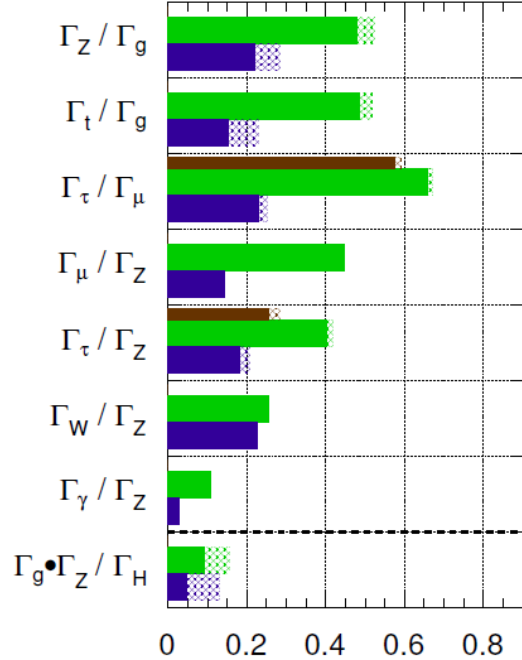


$\frac{\Delta\mu}{\mu}$

ATLAS Simulation

$\sqrt{s} = 14 \text{ TeV}$ :  $\int Ldt=300 \text{ fb}^{-1}$ ;  $\int Ldt=3000 \text{ fb}^{-1}$

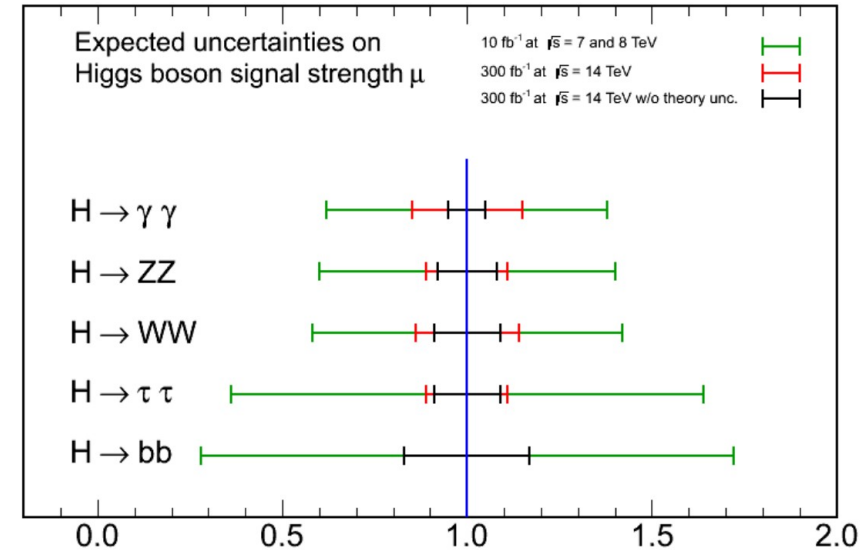
$\int Ldt=300 \text{ fb}^{-1}$  extrapolated from 7+8 TeV



$$\frac{\Delta(\Gamma_X/\Gamma_Y)}{\Gamma_X/\Gamma_Y} \sim 2 \frac{\Delta(\kappa_X/\kappa_Y)}{\kappa_X/\kappa_Y}$$

Energy Frontier R&D

CMS Projection



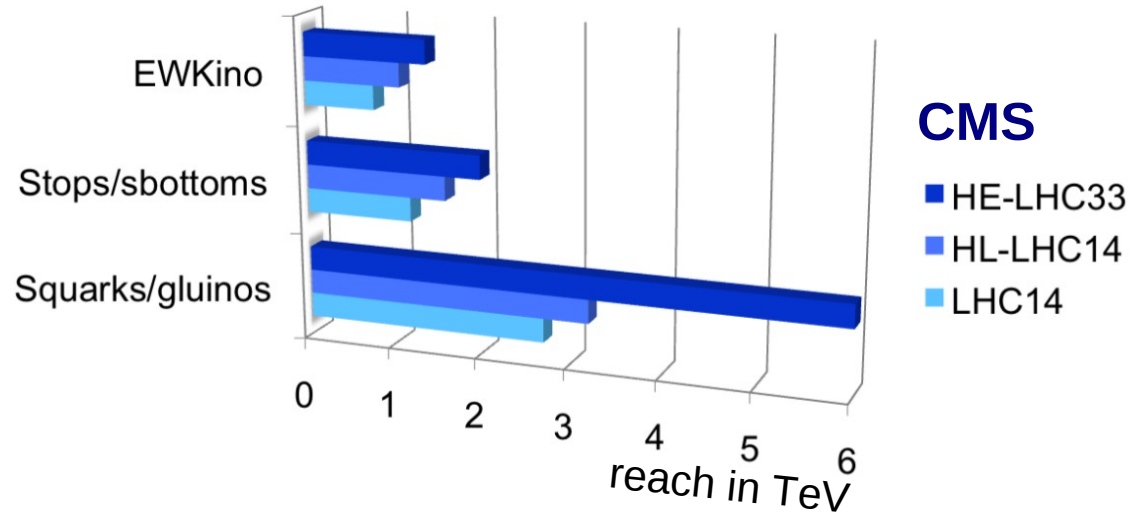
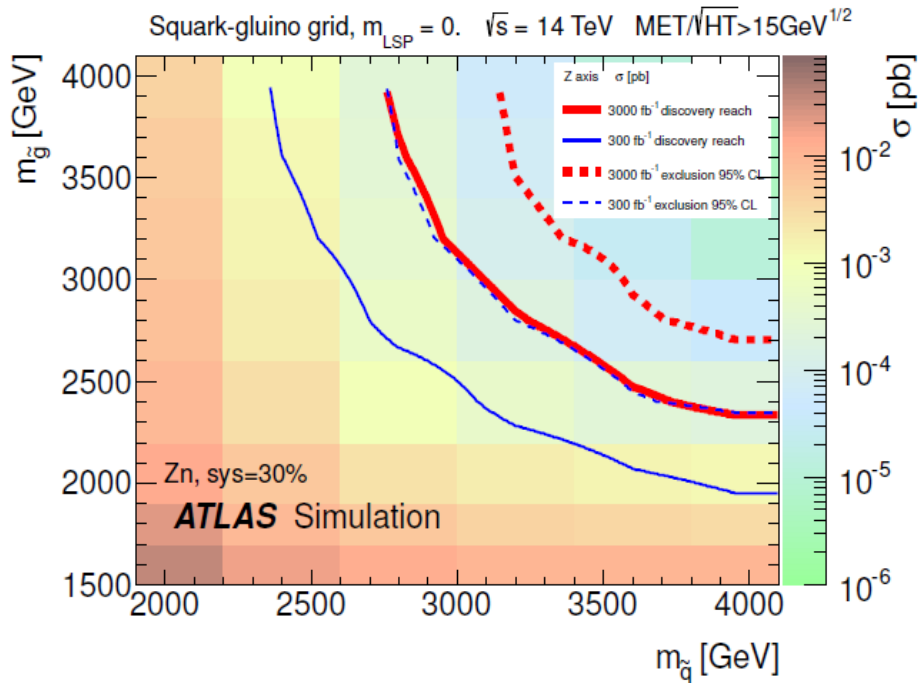


# Goals & Projections: SUSY, etc.



## Continue Searches for New Particles/Deviations from the SM

- LHC will remain the energy frontier of the Energy Frontier



### ATLAS: Weak Boson Scattering

Res. Mass	Coupling	300 $\text{fb}^{-1}$	3000 $\text{fb}^{-1}$
500	$g = 1.0$	$2.4\sigma$	$7.5\sigma$
1 TeV	$g = 1.75$	$1.7\sigma$	$5.5\sigma$
1 TeV	$g = 2.5$	$3.0\sigma$	$9.4\sigma$

### CMS: Lepto-Quarks ( $\ell\ell jj$ )

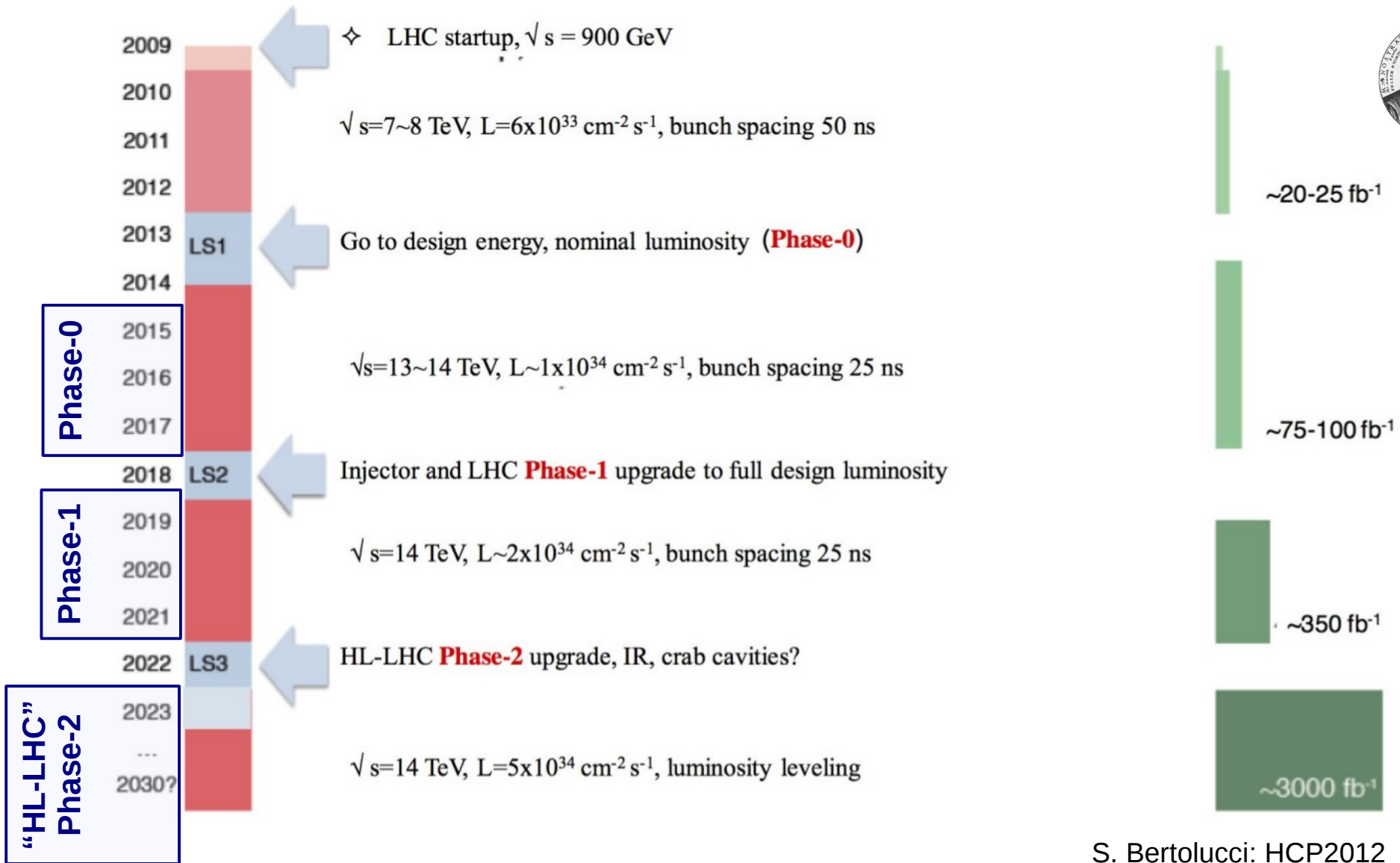
M Reach	LHC	3000 $\text{fb}^{-1}$	33 TeV
Low S/B	1.6 TeV	1.8 TeV	2.5 TeV
High S/B	1.7 TeV	2.3 TeV	3.5 TeV







# LHC Roadmap (tentative)



S. Bertolucci: HCP2012





# Accelerator Evolution



Parameter	Tevatron Run 2	LHC 2012	Phase-0	Phase-1	Phase-2	HE-LHC
$\sqrt{s}$	1.96 TeV	8 TeV	13–14 TeV	14 TeV	14 TeV	33 TeV
$\epsilon_n$	7–11 $\mu\text{m}$	2.2 $\mu\text{m}$	1.4 $\mu\text{m}$	2.5 $\mu\text{m}$	2.5 $\mu\text{m}$	2.59 $\mu\text{m}$
$\beta^*$	0.28 m	0.6 m	0.4 m	0.3 m	0.15 m	0.6 m
crossing angle	0	290 $\mu\text{rad}$	300 $\mu\text{rad}$	~450 $\mu\text{rad}$	590 $\mu\text{rad}$	188 $\mu\text{rad}$
bunch length	30 cm	9 cm	7.55 cm	7.55 cm	7.55 cm	6.5 cm
$N_p$ / bunch	$2.9 \times 10^{11}$ / $8 \times 10^{10}$	$1.6 \times 10^{11}$	$1.15 \times 10^{11}$	$2.0 \times 10^{11}$	$2.0 \times 10^{11}$	$1.3 \times 10^{11}$
spacing	396 ns	50 ns	25 ns	25 ns	25 ns	50 ns
luminosity	$4.3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$	$0.76 \times 10^{34}$	$2.0 \times 10^{34}$	$2\text{--}3 \times 10^{34}$	$5\text{--}7 \times 10^{34}$ (levelled)	$2 \times 10^{34}$
pileup	2	35	48	>80	140	76
int. lumi.	$12 \text{ fb}^{-1}$	$22 \text{ fb}^{-1}$	$75 \text{ fb}^{-1}$	$350 \text{ fb}^{-1}$	$3000 \text{ fb}^{-1}$	$300 \text{ fb}^{-1}$



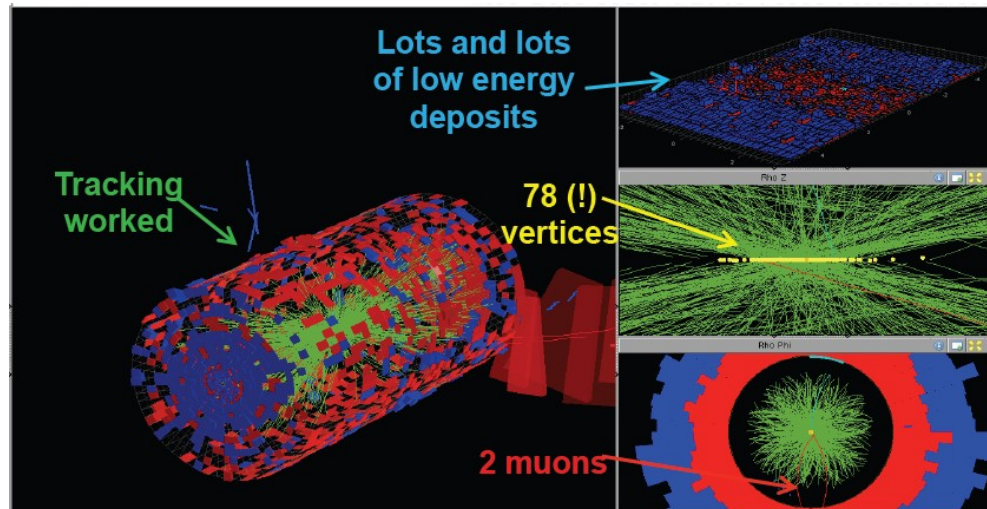
# Challenges for the Detectors



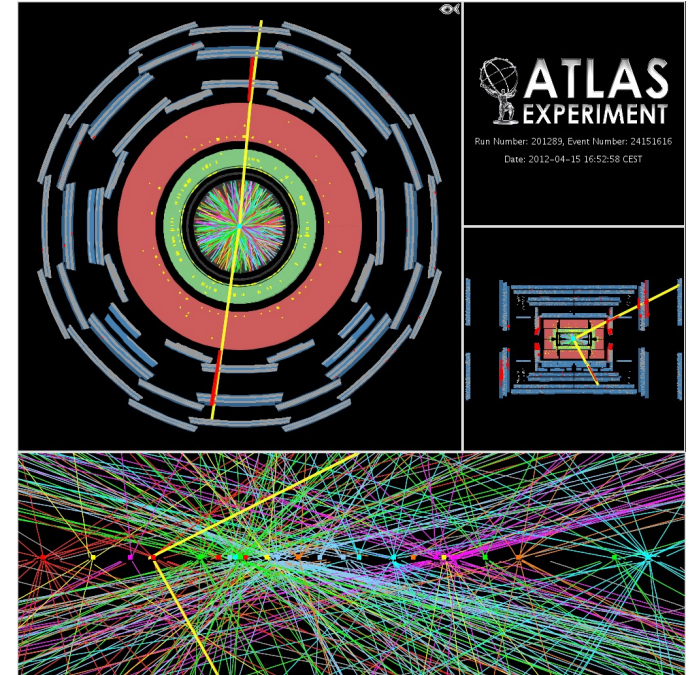
## 1. Instantaneous Luminosity

- event complexity
- data volume

CMS:  $Z \rightarrow \mu\mu$  with 78 vertices



ATLAS:  $Z \rightarrow \mu\mu$  with 25 vertices



## 2. Integrated Luminosity

- radiation damage

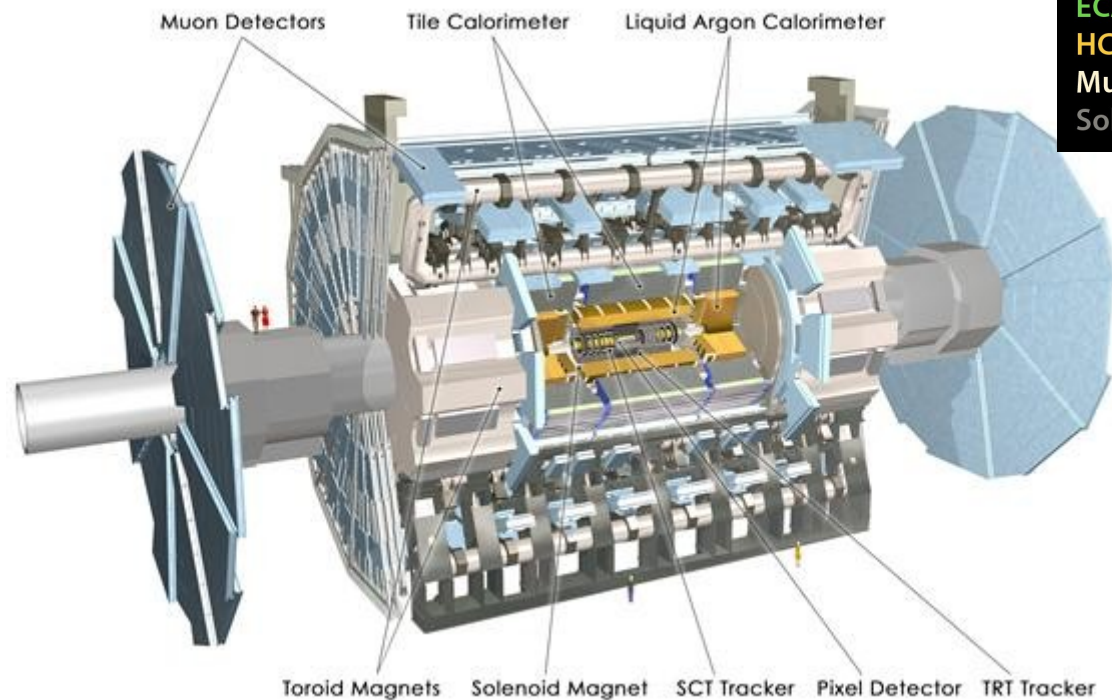
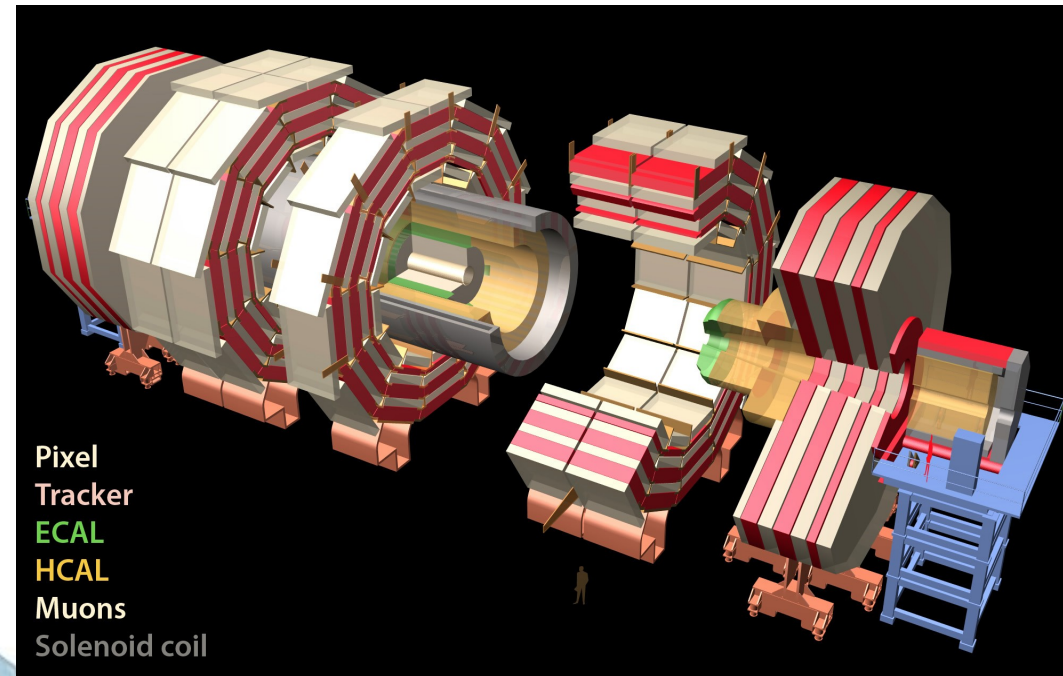
## 3. Component Activation

- constraints on detector manipulation





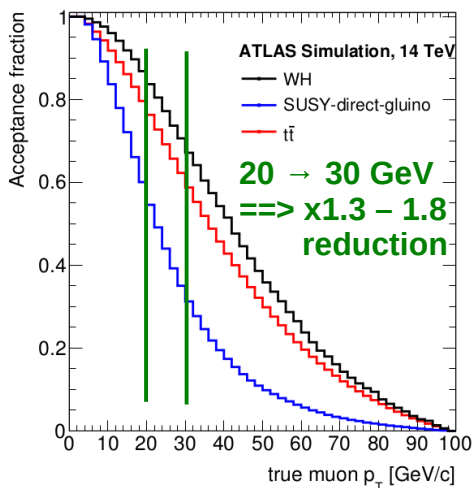
# Current ATLAS & CMS Detectors



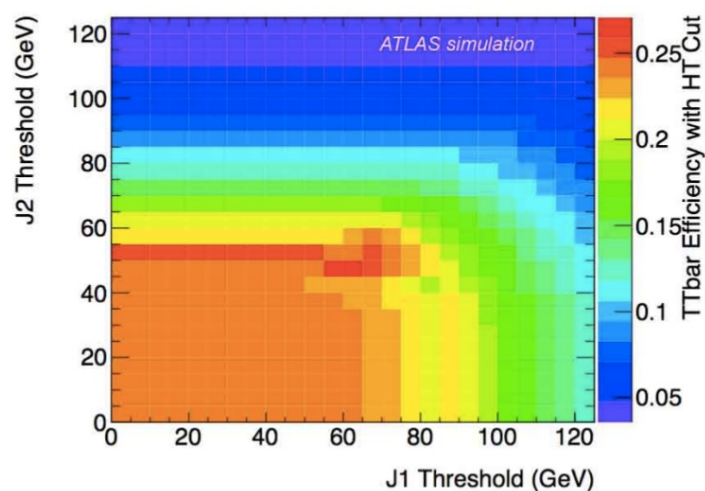
# Object Reconstruction

Example Channels	Objects Required
W, Z, $t\bar{t}$	<ul style="list-style-type: none"> <li>single <math>e, \mu</math> triggers with <math>p_T \sim 20</math> GeV</li> <li>di-jet triggers in the 60–80 GeV range</li> </ul>
$HH \rightarrow b\bar{b}\gamma\gamma$ & $t\bar{t}H, H \rightarrow \gamma\gamma$	<ul style="list-style-type: none"> <li>photons with <math>E_T \sim 25</math> GeV</li> <li>retain/improve current b-ID performance</li> </ul>
VBF, $H \rightarrow \tau\tau$	<ul style="list-style-type: none"> <li>retain/improve <math>\tau</math>-ID performance</li> </ul>
VBF: $H \rightarrow \gamma\gamma$ & $H \rightarrow WW$	<ul style="list-style-type: none"> <li>retain forward jet capabilities</li> </ul>
squarks, gluons, stops	<ul style="list-style-type: none"> <li>missing Energy + b-ID</li> </ul>

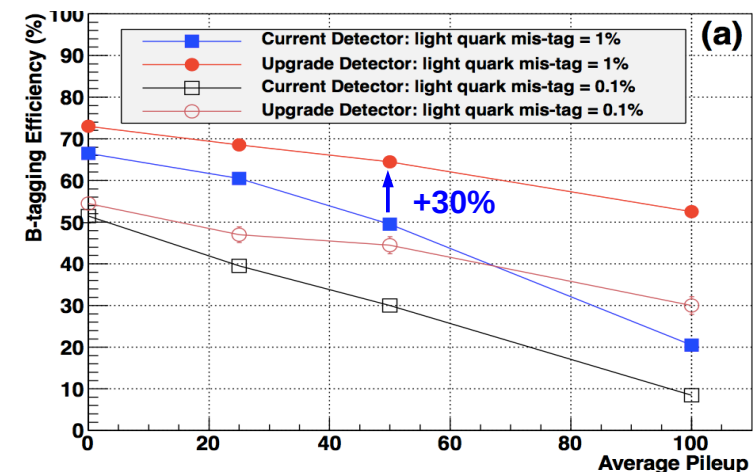
ATLAS:  $\mu$  Thresholds



ATLAS: jj Trigger Thresholds ( $t\bar{t}$ )



CMS: Phase-1 b-tag improvements







# ATLAS & CMS Upgrade Overview



Phase	ATLAS Upgrades	CMS Upgrades
Phase 0	<ul style="list-style-type: none"> <li>• new insertable b-layer pixels (IBL) + services</li> <li>• new Al beam pipe</li> <li>• new low voltage power supplies for calorimeters</li> <li>• finish installation of EE muon chambers (staged)</li> <li>• topological triggering at Level-1</li> <li>• dataflow improvements (merge L2/EF/EB)</li> <li>• new evaporative cooling plant</li> <li>• added neutron shielding</li> </ul>	<ul style="list-style-type: none"> <li>• new beam pipe (necessary for pixel repl. 2016/17)</li> <li>• complete muon coverage (4th endcap layer)</li> <li>• barrel drift tube electronics</li> <li>• replace HCAL forward photo-detectors (new PMTs)</li> <li>• replace outer HCAL photo-detectors (SiPMs)</li> <li>• Level-1 trigger upgrade</li> <li>• DAQ improvements</li> </ul>
Phase 1	<ul style="list-style-type: none"> <li>• new Small Wheel (nSW) for forward muon system</li> <li>• higher granularity calo information to Level-1</li> <li>• fast tracking trigger (FTK) at Level-2</li> <li>• expanded topological capabilities at Level-1</li> </ul>	<ul style="list-style-type: none"> <li>• pixel detector replacement (2016/17)</li> <li>• HCAL electronics/granularity upgrade</li> <li>• complete Level-1 trigger upgrade</li> </ul>
Phase 2 (tentative)	<ul style="list-style-type: none"> <li>• complete tracker replacement (all silicon)</li> <li>• calorimeter electronics upgrade (fully digital)</li> <li>• muon system/electronics upgrades</li> <li>• forward calorimeter upgrade/replacement</li> <li>• track trigger at Level-1</li> <li>• overhaul of trigger architecture</li> </ul>	<ul style="list-style-type: none"> <li>• complete tracker replacement</li> <li>• forward region: tracking, calorimeters, muons</li> <li>• track trigger at Level-1</li> <li>• further trigger upgrades</li> </ul>

note: lots of standard maintenance and improvements at each phase

**Phase 0: all projects now in production**

**Phase 1: R&D well advanced for most projects**

**Phase 2: R&D started for many projects**

**Summary of Main  
US R&D Efforts  
in the following slides**





# (some) Joint ATLAS–CMS R&D



## Common CERN RD Projects

- **RD42 Diamond Detectors** <http://rd42.web.cern.ch/rd42/>
- **RD50 Silicon Detectors** <http://rd50.web.cern.ch/rd50/>
- **New 65 nm Chip Design** **27 Nov, 2012 meeting**

## Versatile Link Project

- **rad-hard, bi-directional optical link at ~5 Gbs**
- <https://espace.cern.ch/project-versatile-link/public/default.aspx>

## QIE10: Charge Integrating ADC with TDC

- **studying adapting Fermilab design for ATLAS TileCal and CMS HCAL**

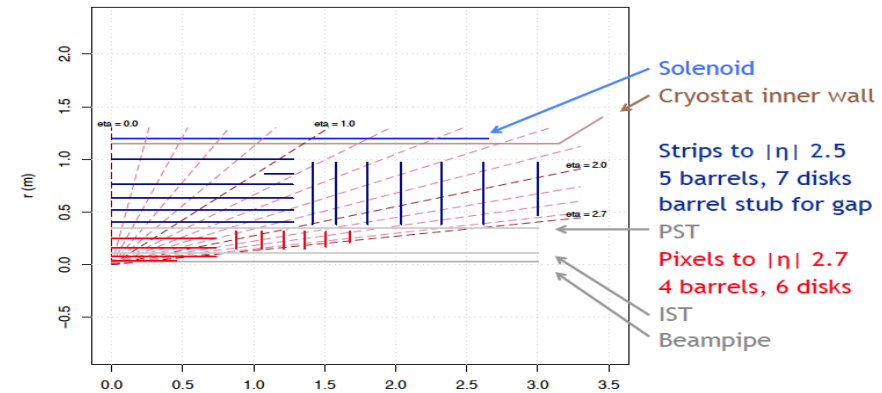
## Many other Joint Efforts

- **xTCA, Power, ...**

## Tracking

- Pixels: large wafers, edge reduction, rad hardness, electronics, optical transmission
- Strips: mechanics, cooling, powering, electronics, DAQ

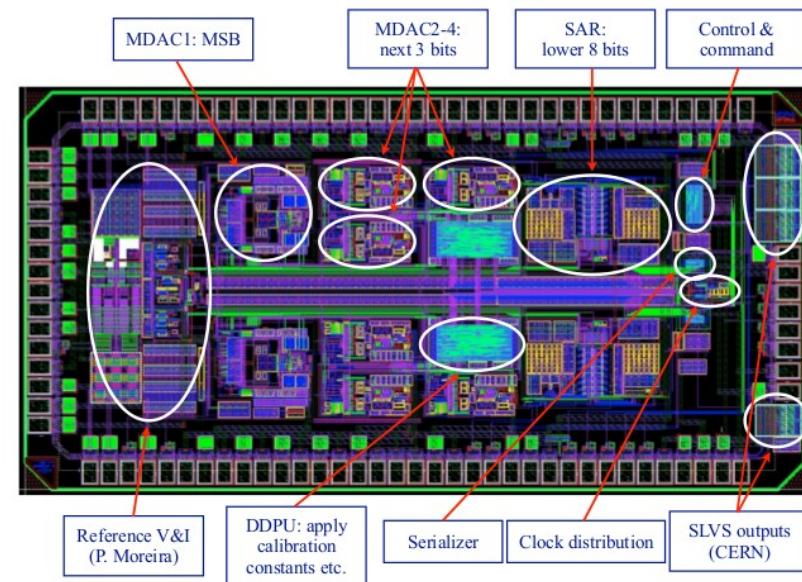
Lol tracker layout



## Calorimetry

- rad-hard ADC (Phase 1) for Liquid Argon
- QIE ASIC for TileCal
- detector development for Forward Calorimetry

## Nevis12: dual 12-bit ADC



## Trigger

- Level-1 Track Trigger

## Timeline

- Ph-1 TDRs: summer-fall 2013

## Tracker

- rad-hard sensors/electronics, cooling, DC-DC powering

## Forward Calorimetry

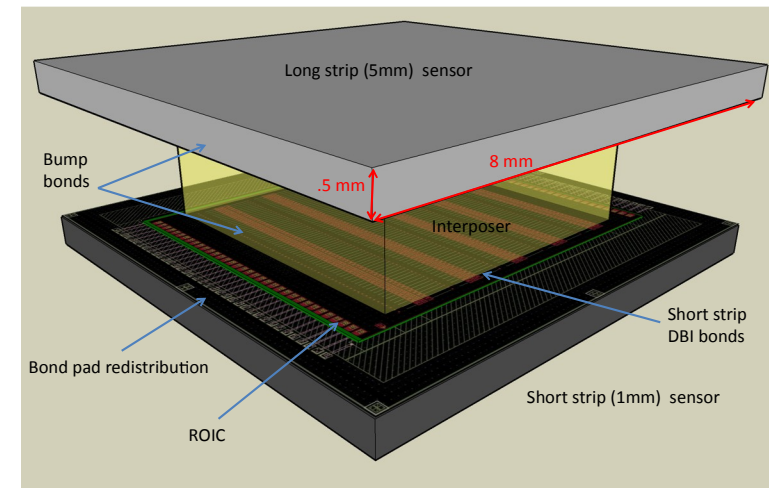
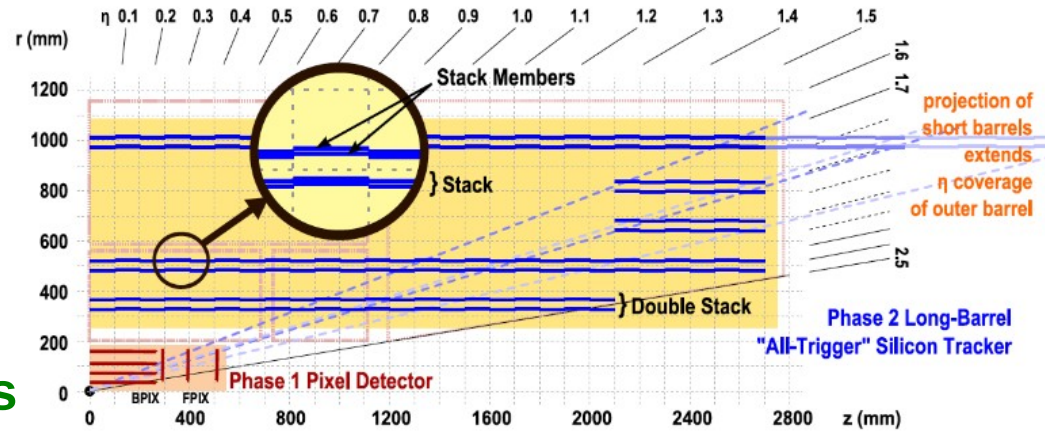
- rad-hard crystals/ceramics, fibers
- GaAs photosensors
- readout schemes

## Trigger

- Level-1 Track Trigger

## Timeline

- Ph-2 Technical Proposal: 2014
- TDRs: ~2016





# Conclusions



## Strong Physics Case for LHC Upgrade Program

- continued studies of Higgs-like particle
- direct detection of new particles at highest mass scales

## Accelerator Plan can provide data to meet our goals

- $350 \text{ fb}^{-1}$      $L \rightarrow 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$     by ~2021    (Phase 1)
- $3000 \text{ fb}^{-1}$      $L \sim 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  (levelled)    by ~2030    (Phase 2)

## ATLAS and CMS upgrades to deal with this data

- event pileup, radiation damage, activation
- Phase 1: projects well-defined, moving into construction phase
- Phase 2: R&D needed in many areas
  - > rad hard detectors & electronics; data transmission; powering;...
  - > a lot of ongoing effort in the US

