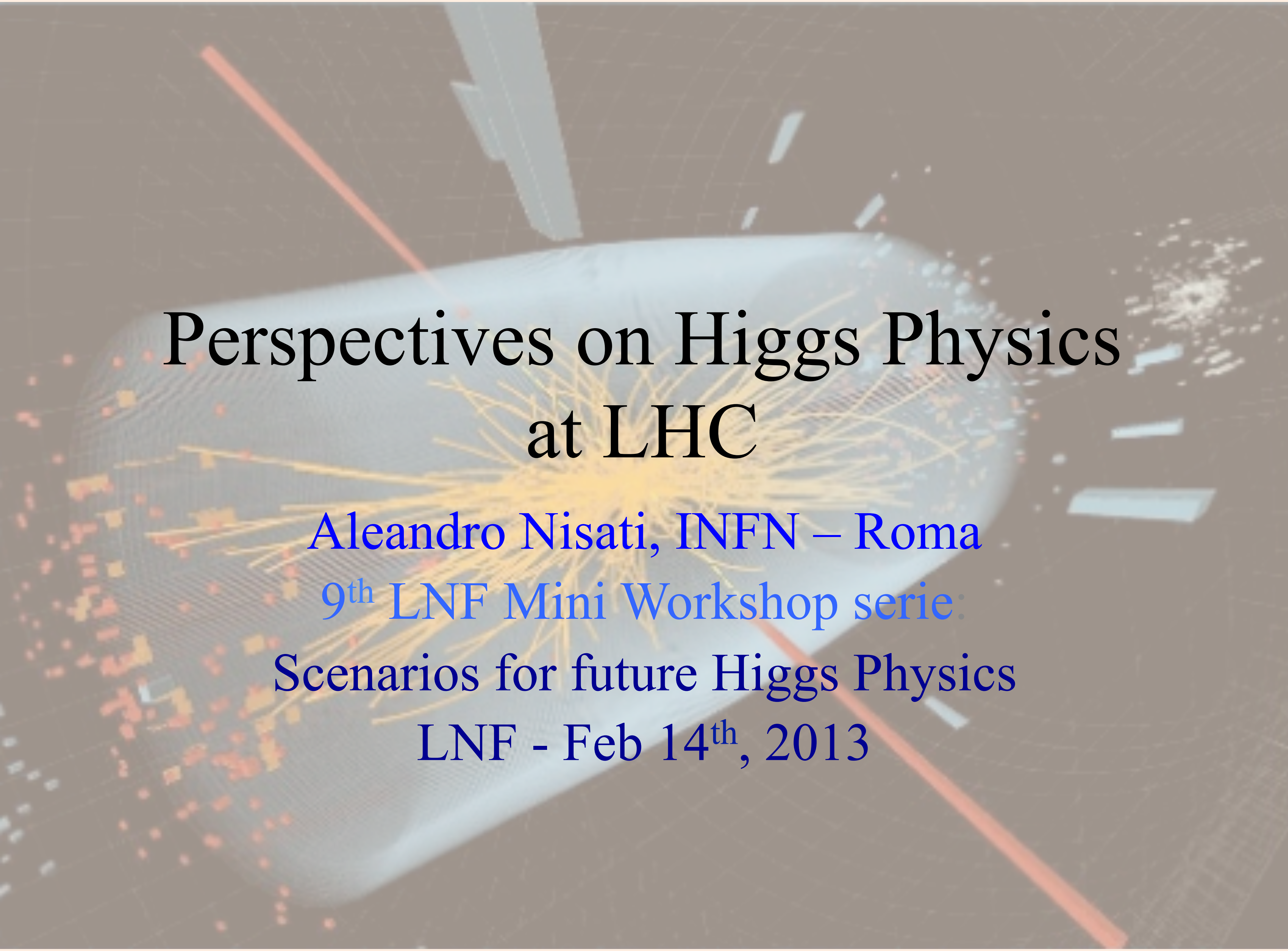


Perspectives on Higgs Physics at LHC

Aleandro Nisati, INFN – Roma

9th LNF Mini Workshop serie:

Scenarios for future Higgs Physics

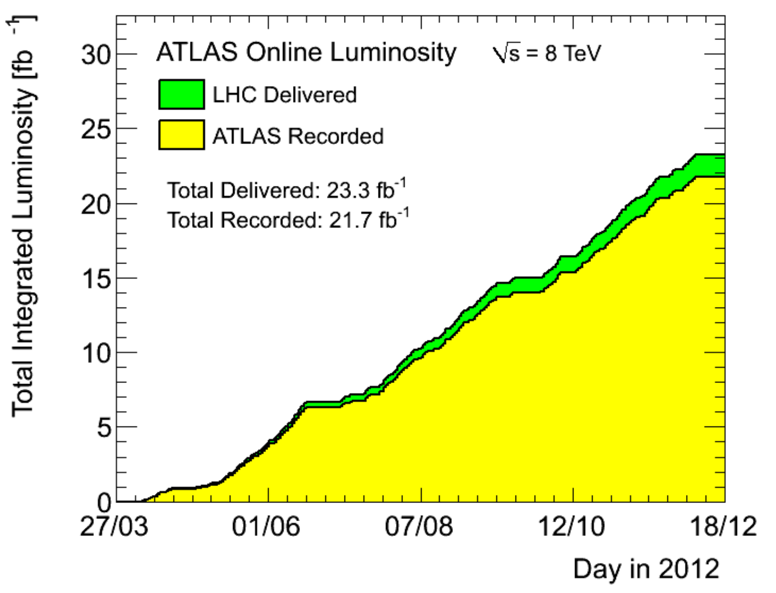
LNF - Feb 14th, 2013

outline

- Physics at the Large Hadron Collider
- Latest results from ATLAS and CMS on the new Higgs-like particle
- Priorities after the discovery of the new boson
- “European Strategy”: the LHC Upgrade plan
- Physics at the HL-LHC
- Higgs boson physics at the HL-LHC
- Vector Boson Scattering at HL-LHC

Physics at the Large Hadron Collider

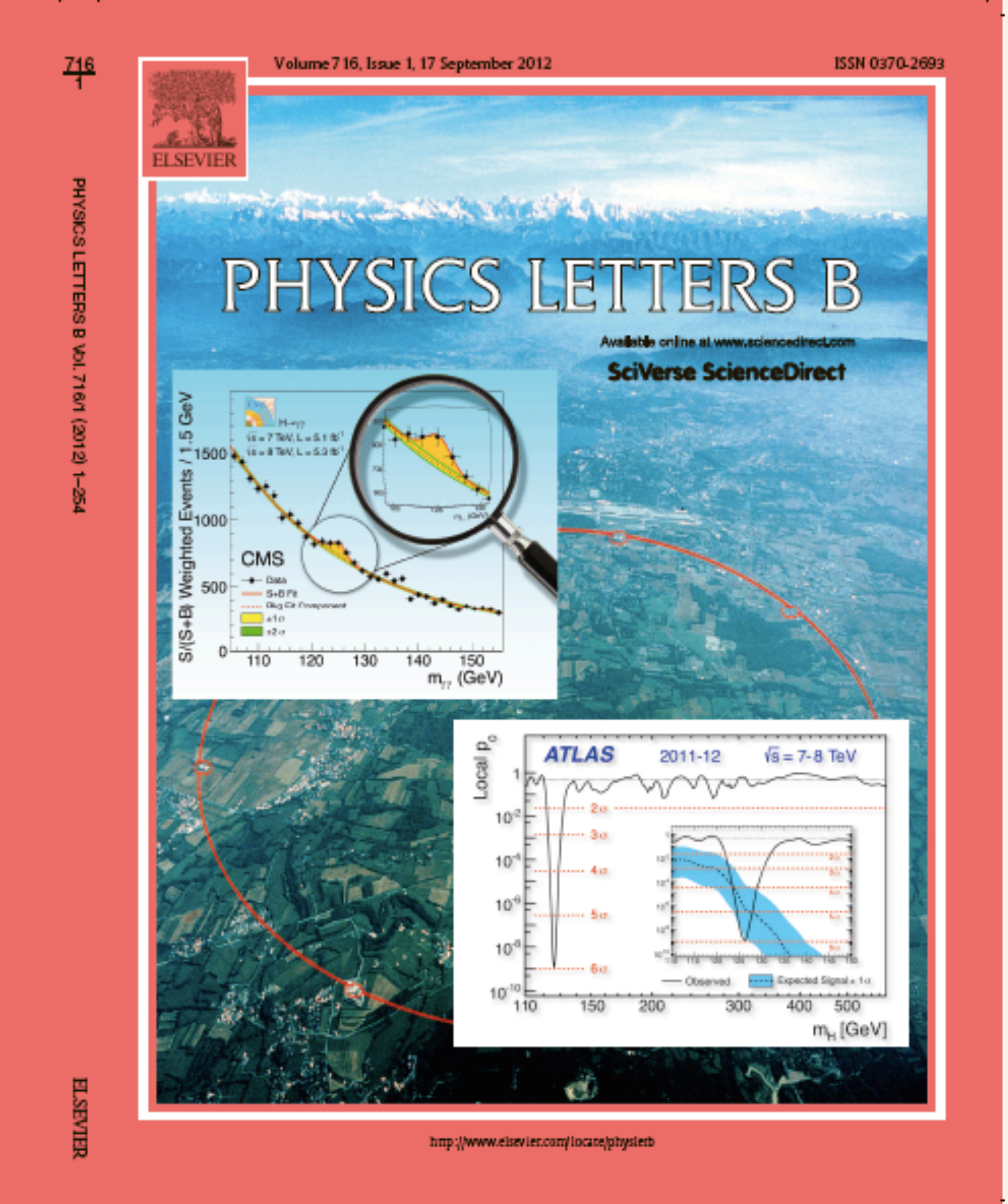
- The LHC operations at high-energy started in 2010
- Excellent performance of the machine and of the four main experiments on the ring, ATLAS and CMS in particular
- Collected in 2011 + 2012 about 5.5 fb^{-1} ($\sqrt{s} = 7$ TeV) + 22 fb^{-1} ($\sqrt{s} = 8$ TeV) by ATLAS and CMS



- A lot of solid outstanding experimental results are available:
- agreement between Standard Model (SM) and data in the EW and QCD sectors
- Discovery of a new particle, SM Higgs boson candidate, with mass around 125 GeV
- Exclusion of a wide range of parameters values in Supersimmetry (SUSY) models
- Exclusion of new heavy objects with mass up to 2-3 TeV

The successful Standard Model

The Standard Model predictions are confirmed by experimental data within uncertainties



716

Volume 716, Issue 1, 17 September 2012

ISSN 0370-2693

ELSEVIER

PHYSICS LETTERS B

Available online at www.sciencedirect.com

SciVerse ScienceDirect

PHYSICS LETTERS B Vol. 716/1 (2012) 1–254

ELSEVIER

http://www.elsevier.com/locate/physletb

ATLAS

Physics Letters B
Volume 716, Issue 1, 17
September 2012, Pages 1–29

Results based on:

- 4.8 fb-1 of data at $\sqrt{s} = 7$ TeV
- 5.9 fb-1 of data at $\sqrt{s} = 8$ TeV

CMS

Physics Letters B
Volume 716, Issue 1, 17
September 2012, Pages 30–61

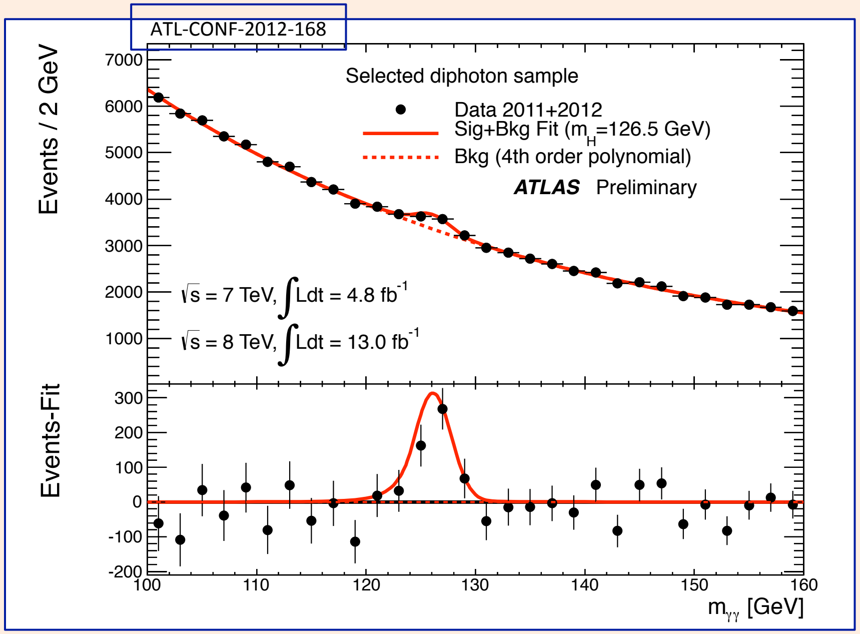
Results based on:

- 5.1 fb-1 of data at $\sqrt{s} = 7$ TeV
- 5.3 fb-1 of data at $\sqrt{s} = 8$ TeV

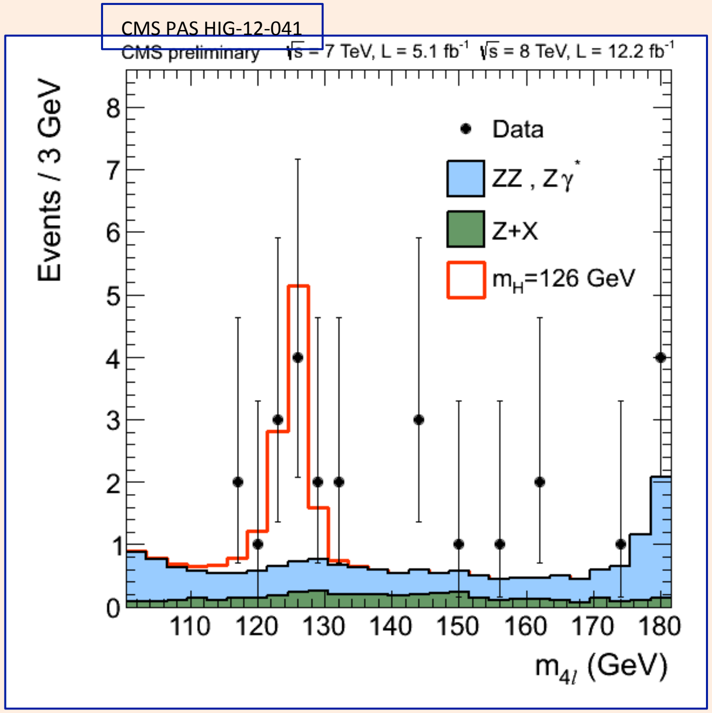
Latest results from ATLAS and CMS

- Since ICHEP 2012, ATLAS has presented three new results:
  - Update of H→γγ with 13 fb^{-1} data (including the 4.8 fb^{-1} of 7 TeV data)
  - Update of H→ZZ(*)→4-leptons with 13 fb^{-1} data (including the 4.6 fb^{-1} of 7 TeV data)
  - Update of H→WW(*)→lνlν with 13 fb^{-1} data
  - Update of VH,H→bbbar with 13 fb^{-1} data (including the 4.6 fb^{-1} of 7 TeV data)
  - Update of H→ττ with 13 fb^{-1} data(including the 4.6 fb^{-1} of 7 TeV data)
  - Update of the Higgs boson combination and physics properties using the latest results from H→γγ and H→ZZ*→4-leptons
- Since ICHEP 2012, CMS has presented new result on
  - H→ZZ(*)→4-leptons with 13 fb^{-1} data
  - H→WW(*)→lνlν with 13 fb^{-1} data
  - H→ττ with 13 fb^{-1} data
  - Associated production H→bbbar with 13 fb^{-1} data
  - Combination of the above channels including H→γγ (“ICHEP” data)

Latest results from ATLAS and CMS


ATL-CONF-2012-168

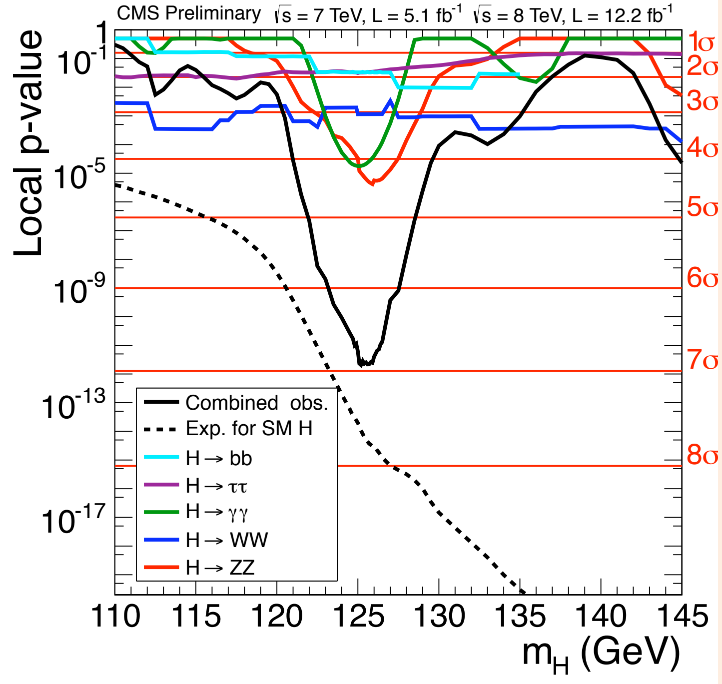
Invariant mass distribution of diphoton candidates for the combined √s= 7 TeV and √s= 8 TeV data samples. The fit to the data is the sum of a signal component fixed to m_H = 126.5 GeV and a background component described by a fourth-order Bernstein polynomial. Bottom inset: display of the residuals of the data with respect to the fitted background.


CMS PAS HIG-12-041

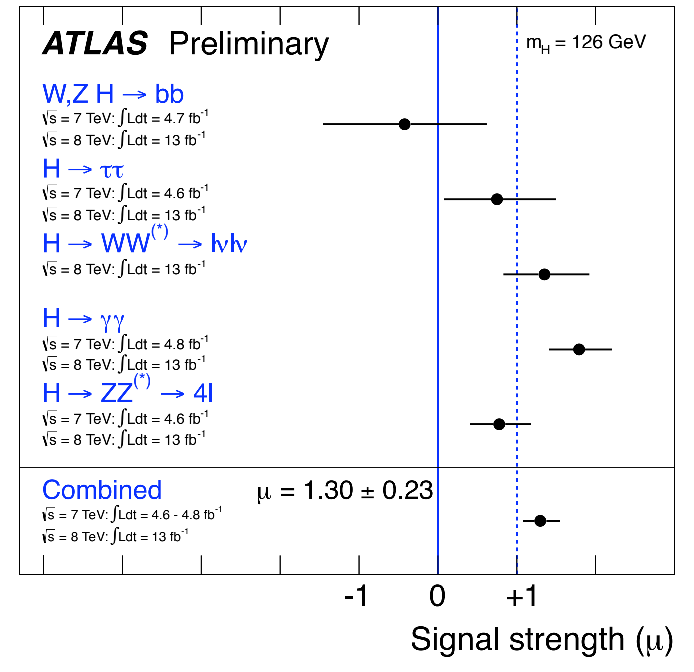
Four-lepton reconstructed mass for the sum of the 4e, 4μ, and 2e2μ channels. Points represent the data, shaded histograms represent the background and unshaded histogram the signal expectations

Latest results from ATLAS and CMS

CMS PAS HIG-12-045



ATL-CONF-2012-170



The observed local p-value for the five decay modes and the overall combination as a function of the SM Higgs boson mass in the range 110–1000 GeV (left) and 110–145 GeV (right). The dashed lines show the expected local p-values for a SM Higgs boson with a mass m_H.

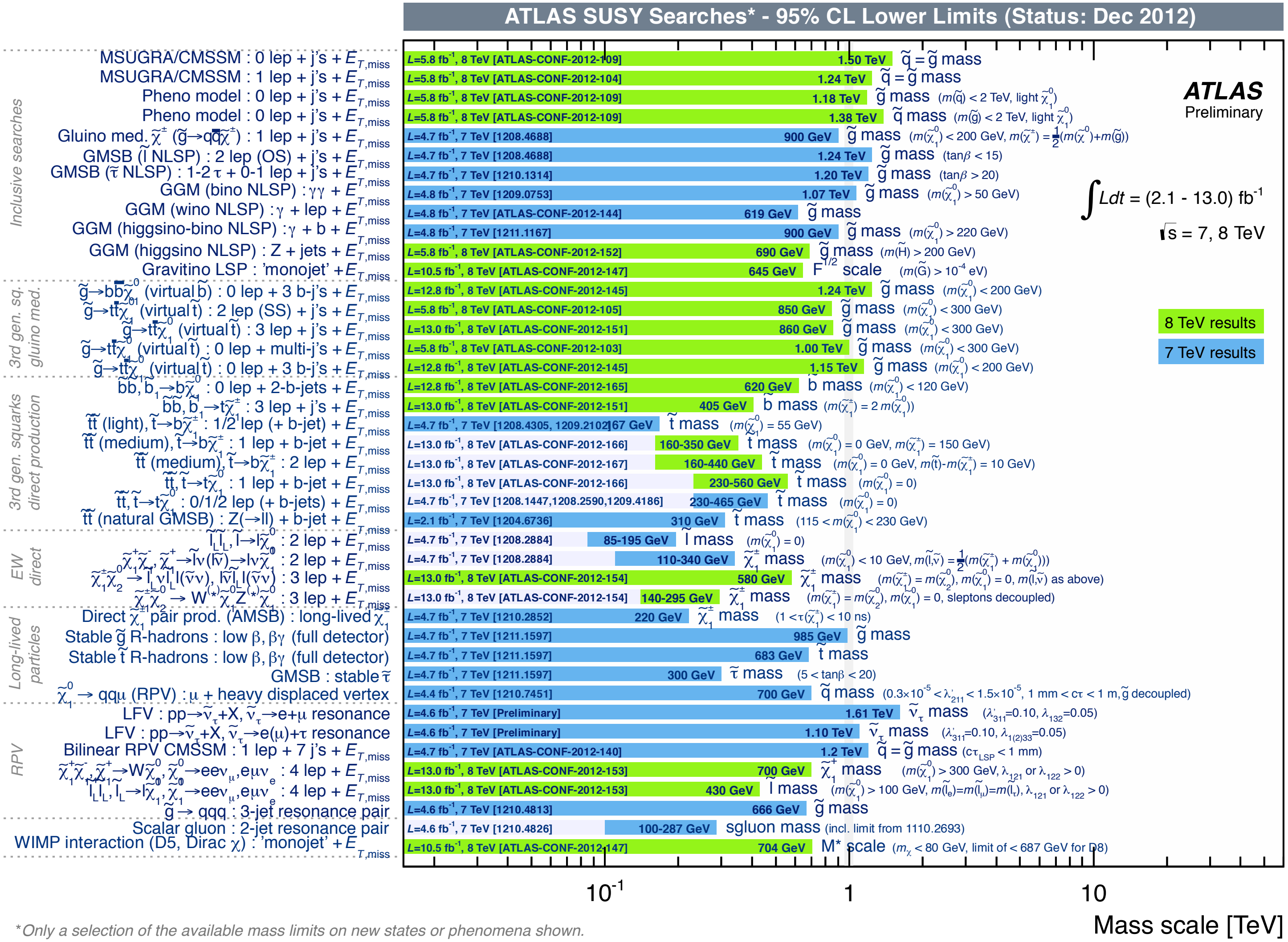
Local significance: 6.9 σ

Measurements of the signal strength parameter mu for mh at 126 GeV for the individual channels and their combination.

$\mu = 1.30 \pm 0.23$ for $m_H = 126$ GeV

Searches for New Physics: SUSY

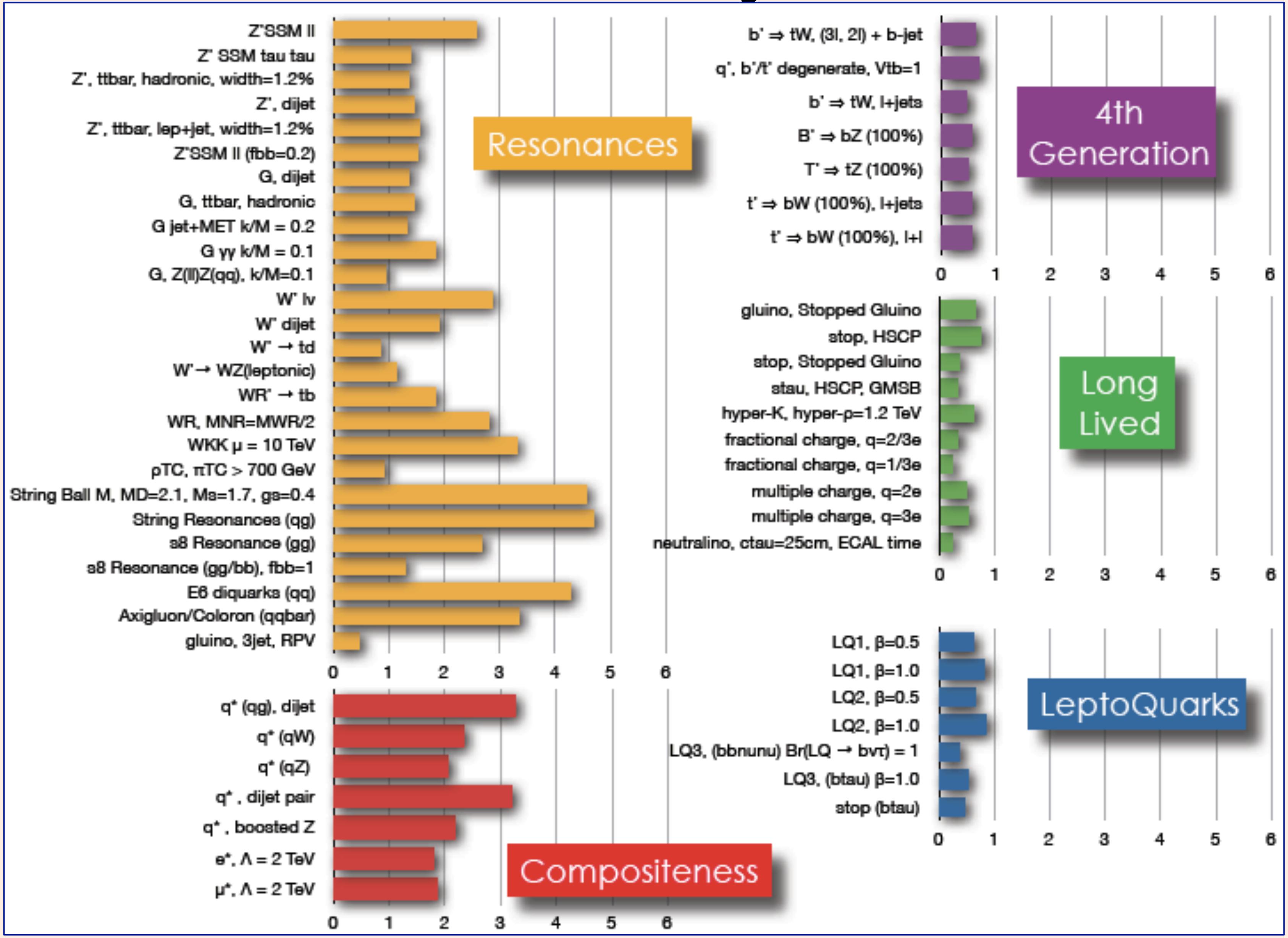
ATLAS



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

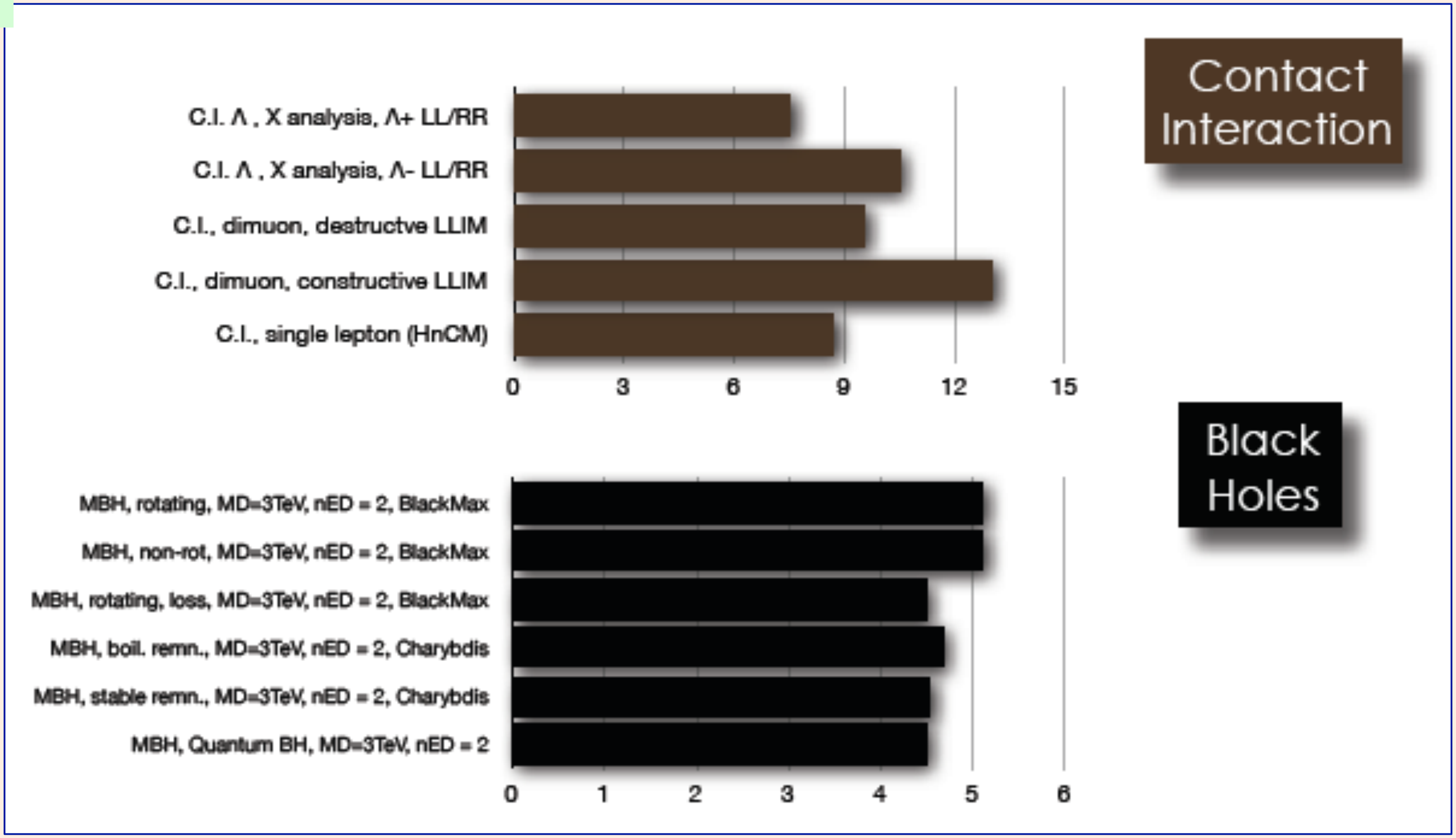
Searches for New Physics: Exotics

CMS



Searches for New Physics: Exotics

CMS



The priorities for collider physics after July 4th

- The recently discovered new particle drives to a number of fundamental open points that are top priority for the physics programme for the LHC and future energy frontier accelerators:
  1. Precision measurement of the mass of this new particle
  2. Determination of the quantum numbers spin and parity, J^P, and CP violation
  3. Measurement of couplings to elementary fermions and bosons
  4. Measurement of the self-coupling strength
  5. Comparison of these physics properties with those predicted by Standard Model
  6. Search for possible partners (neutral and/or charged) of this boson
  7. Is this particle a fundamental object, or it is composite?

The priorities for collider physics after July 4th

- The investigations of the electroweak symmetry breaking cannot be limited to the study of the Higgs sector only: several points still to be addressed. Among these:
  - The dependence with energy of the Vector Boson Scattering cross section (WW, WZ and ZZ)
  - The hierarchy problem, that motivated new theories beyond SM, such as SUperSYmmetry, Extra-Dimensions, Technicolor models

The priorities for collider physics after July 4th

- This enriches the collider physics programme:

8. Analyse the Vector Boson scattering cross section to study whether the cross-section regularization is operated by the Higgs boson (as predicted by SM) or by other processes associated to pyisics beyond SM;
9. Continue the search for SUSY particles, in particular search for third generation squarks: to be effective, the mass of the stop quark cannot be too different from the on of the top quark; also continue the search for gauginos and for 1st and 2nd generation squarks;
10. Continue the search for heavy resonances decaying to photon, lepton or quark pairs, and for deviations from SM of physics distributions highly sensitive to New Physcs (di-jet angular distribution,…)

The European Strategy for Particle Physics

- These themes have been widely discussed in the context of the Symposium on the European Strategy for Particle Physics, held on September 10 to 12, 2012.
- Many proposals have been submitted (collider energy frontier physics, heavy flavour physics, neutrino and astroparticle physics, etc. etc.)

CERN Council Open Symposium on

European Strategy for Particle Physics

10 – 12 September 2012, Kraków, Poland

AGH UST, IFJ PAN, The M. Smoluchowski Scientific Consortium, Kraków

Foundation for the AGH University of Science and Technology

The European Strategy for Particle Physics

- These themes have been widely discussed in the context of the Symposium on the European Strategy for Particle Physics, held on September 10 to 12, 2012.
- Many proposals have been submitted (collider energy frontier physics, heavy flavour physics, neutrino and astroparticle physics, etc. etc.)

Meeting of the Strategy Group for Particle Physics held in Erice from 21 to 25 January

See talk from Roy Aleksan

The European Strategy for Particle Physics

- High Energy Frontier:

Name	beams	collider geometry	√s, TeV	luminosity	Operation (years)
HL-LHC	pp	circular	14	3000 fb^{-1}	2024-2030
HE-LHC	pp	circular	26-33	100-300 fb^{-1}/year	After 2035
VHE-LHC	pp	circular	40-100	-	After 2035
LEP3	e^+e^-	circular	0.240	$1 \cdot 10^{34}$ $cm^{-2}s^{-1}$	After 2024
ILC	e^+e^-	linear	0.250→1.0	~$1 \cdot 10^{34}$ $cm^{-2}s^{-1}$	~ 2030
CLIC	e^+e^-	linear	0.500→3.0	2-$6 \cdot 10^{34}$ $cm^{-2}s^{-1}$	After 2030
TLEP	e^+e^-	circular	0.24-0.350	$5 \cdot 10^{34}$ $cm^{-2}s^{-1}$	After 2035
LHeC	$e^-(e^+)p$	circular		O(100 fb^{-1})	After 2022
γγ-collider	γγ				?
μ-collider	$\mu^+\mu^-$	circular			?

I'll focus on examples of physics perspectives at the High Luminosity-LHC (HL-LHC)

The European Strategy for Particle Physics

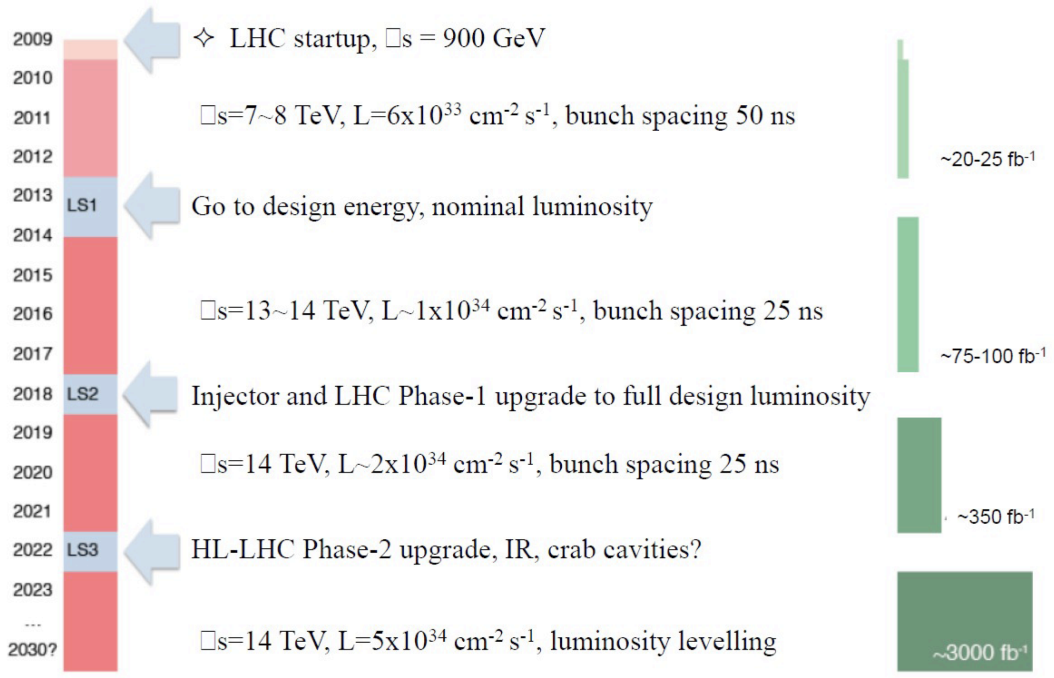
- High Energy Frontier:

See talks from Frank Zimmermann and Patrick Janot

Name	beams	collider geometry	$\sqrt{s}$, TeV	luminosity	Operation (years)
HL-LHC	pp	circular	14	3000 fb^{-1}	2024-2030
HE-LHC	pp	circular	26-33	100-300 fb^{-1}/year	After 2035
VHE-LHC	pp	circular	40-100	-	After 2035
LEP3	e^+e^-	circular	0.240	$1 \cdot 10^{34}$ cm^{-2}s^{-1}	After 2024
ILC	e^+e^-	linear	0.250→1.0	~$1 \cdot 10^{34}$ cm^{-2}s^{-1}	~ 2030
CLIC	e^+e^-	linear	0.500→3.0	2-$6 \cdot 10^{34}$ cm^{-2}s^{-1}	After 2030
TLEP	e^+e^-	circular	0.24-0.350	$5 \cdot 10^{34}$ cm^{-2}s^{-1}	After 2035
LHeC	$e^-(e^+)p$	circular		O(100 fb^{-1})	After 2022
γγ-collider	γγ				?
μ-collider	$\mu^+\mu^-$	circular			?

See talk from Marco Zanetti

The LHC Upgrade plan



✧ LHC startup, $\sqrt{s}$ = 900 GeV

$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns

Go to design energy, nominal luminosity

$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

Injector and LHC Phase-1 upgrade to full design luminosity

$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

HL-LHC Phase-2 upgrade, IR, crab cavities?

$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity levelling

About 350 fb^{-1} are expected at the end of the LHC Programme

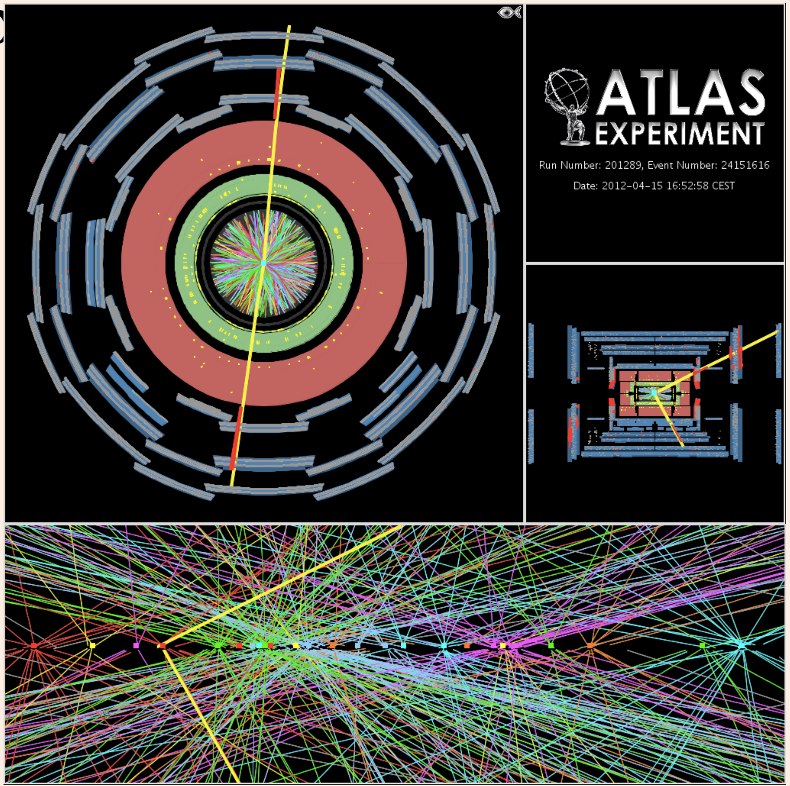
- 300 fb^{-1} have been assumed as baseline in the studies made by ATLAS and CMS

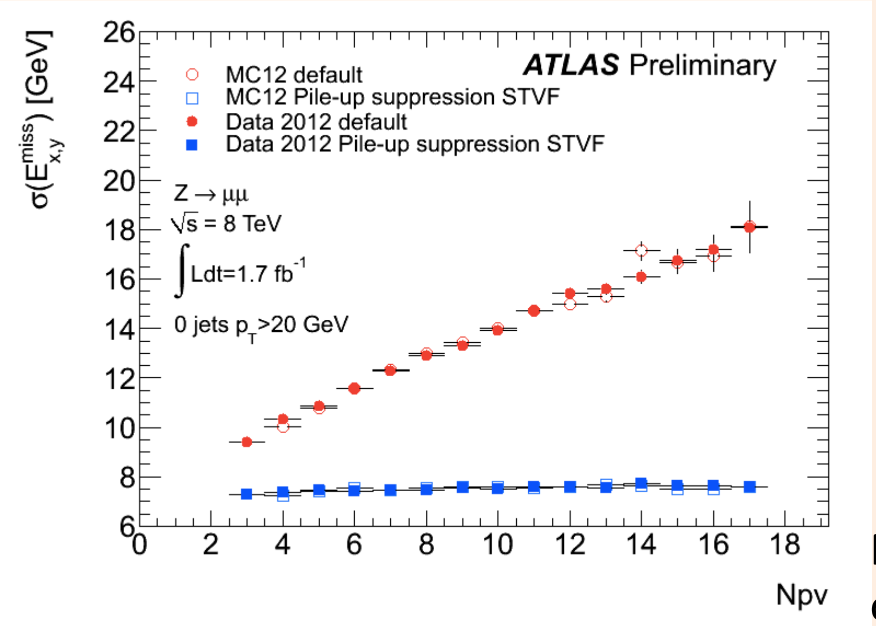
- Experimental challenges
  - The average number of proton-proton collisions per triggered events is about 140
  - The trigger has to cope with the effects induced by the large pile-up
  - The inner detector has to be fast and with high granularity and redundancy, to cope with the effects from large occupancy
  - The detector has to be (even more) radiation hard

Event pileup at the LHC

- Present ATLAS and CMS detectors have been designed for <μ> ~ 23 pp interactions / bunch-crossing
  - And continue to do an excellent job with 35

Z→μμ decay in a large pileup event





Missing transverse energy resolution as a function of the number of the reconstructed vertices

- But cannot handle (an average of) 140 events of pileup

Physics at HL-LHC

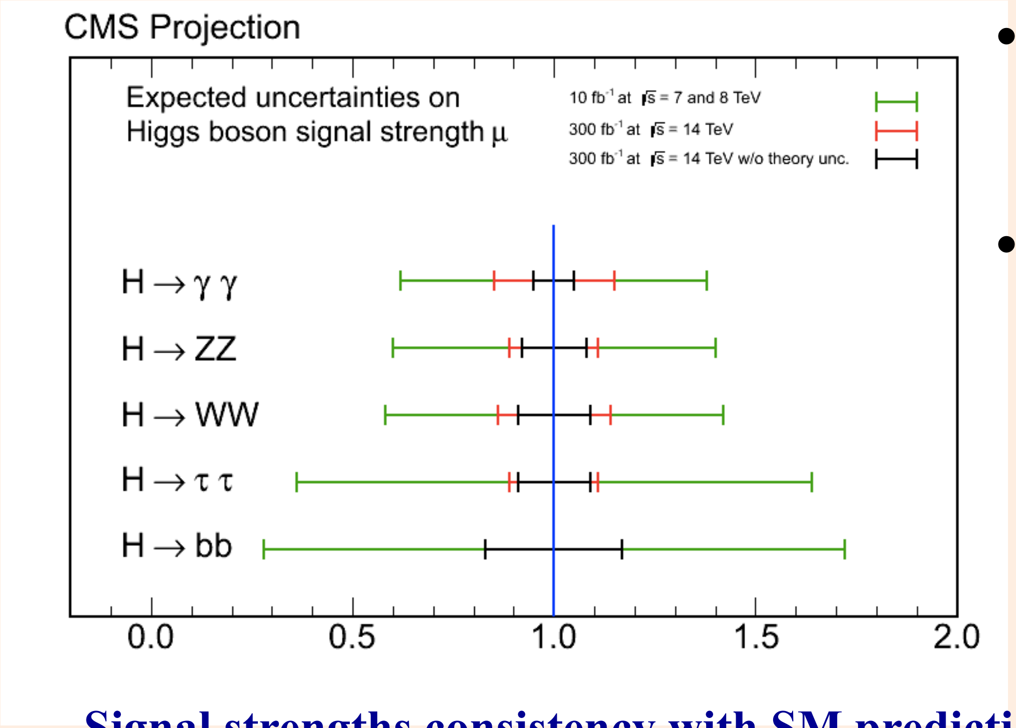
- On the basis of what discussed in the previous slides, ATLAS and CMS presented two documents for the Symposium in Cracow, subsequently updated in October 2012 for the Briefing Book
- These documents focused on:
  - Higgs couplings, spin/CP and self-couplings
  - Vector Boson Scattering
  - SUSY
  - Exotics
  - SM: Vector Boson TGCs and top quark FCNC

Approaches adopted for physics perspectives estimation

- ATLAS: perform physics simulation with a fast procedure based on simple functions applied to physics objects (electrons, photons, muons, tau, jets, b-jets, missing transverse energy) to mimic the effects from energy (momentum) resolution; acceptance, identification and reconstruction efficiencies, b-tagging efficiencies, fake rates
- CMS: the upgraded detector will compensate the effects from event pile-up; assume three different scenarios:
  - Scenario 1: all systematic uncertainties are kept unchanged wrt those in current data analyses
  - Scenario 2: the theoretical uncertainties are scaled by a factor of 1/2, while other systematic uncertainties are scaled $\sqrt{L}$;
  - Scenario 3: set theoretical uncertainties to zero, to demonstrate their interplay with the experimental uncertainties;
  - ➔ The truth will be most likely somewhere between Scenario 1 and 2

Higgs Couplings at the LHC

- The LHC programme will be completed by about 2021 with an integrated luminosity around 300 fb^{-1}.
- Important progress can be made on the analysis of the physics properties of the Higgs-like boson recently discovered



- Estimated precision of the signal strength determination for a SM Higgs boson
- Projections for L=300 fb^{-1} and √s = 14 TeV

├──┤ Current data

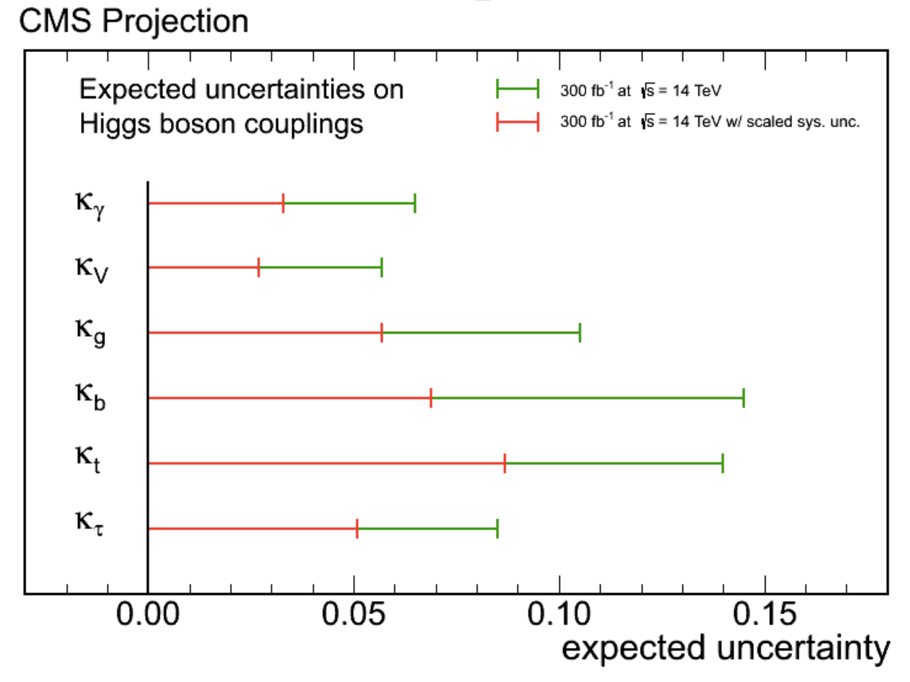
├──┤ Scenario 1

├──┤ Scenario 3

Signal strengths consistency with SM predictions can be tested with 10% accuracy

Higgs Couplings at the LHC

- Production cross section and decay pp→H, H→XX proportional to $\Gamma_p\Gamma_x/\Gamma_H$ (Γ_p partial width involving production couplings)
- Measurements of couplings at the LHC need a minimal theory input
- Measurements of coupling ratios c_x/c_f, extracted from Γ_x/Γ_y, are model independent



- Measure the scaling factor k_i: $c_i^{meas} = k_i \times c_i^{SM}$
- Estimated precision of the measurement of k_γ, k_V, k_g, k_b, k_t, and k_τ
- Projections for L=300 fb^{-1} and $\sqrt{s}$ = 14 TeV

🟩 Scenario 1

🟥 Scenario 2

Couplings consistency with SM predictions can be tested with 3→12% accuracy

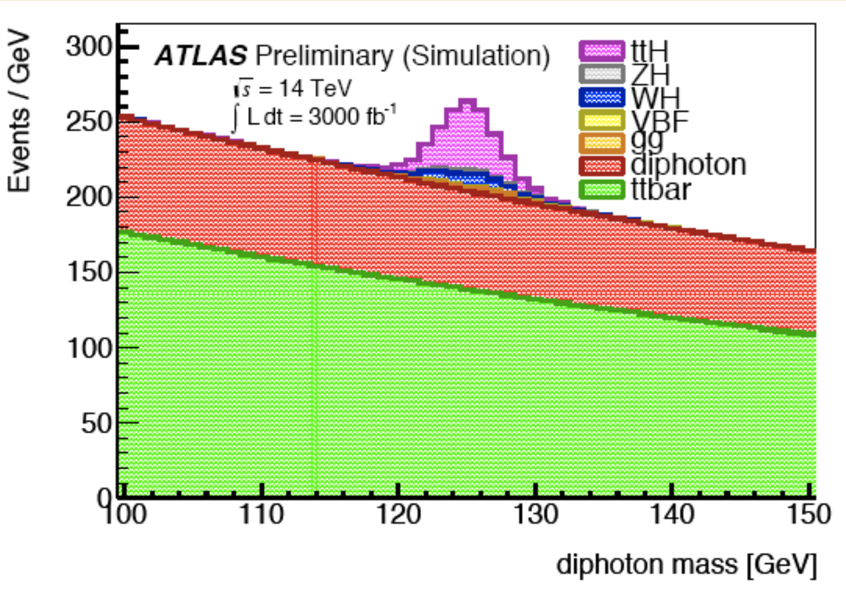
Higgs Couplings at the HL-LHC

- ATLAS has performed projection studies to HL-LHC, assuming 3000 fb^{-1} of data
- focused on the main channels already under study with LHC data, plus a few rare decay channels sensitive to top and muon couplings

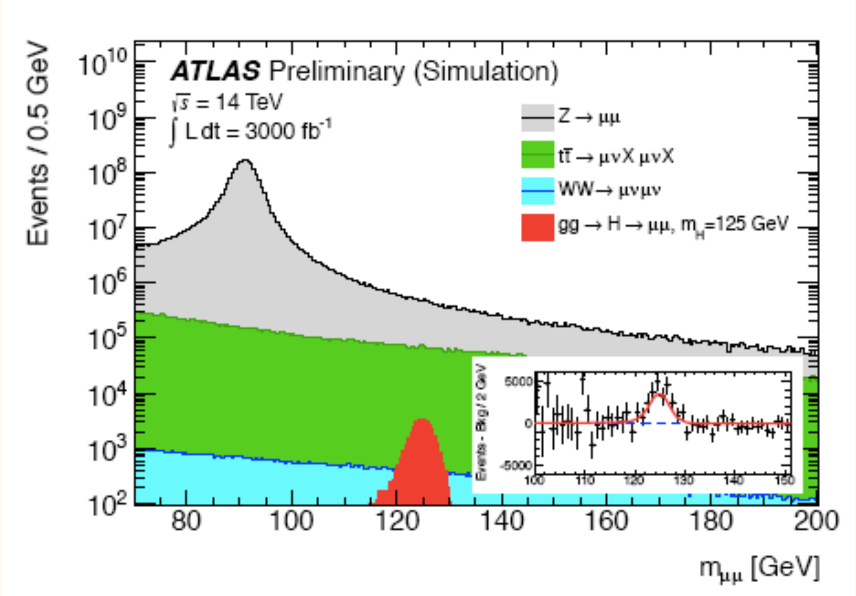
	ggF	VBF H	WH	ZH	ttH
H→γγ	✓	✓	✓	✓	✓
H→ZZ*	✓				
H→WW*	✓	✓	✓		
H→ττ	**extrap.**	✓			
H→μμ	✓				✓

- ZH,H→bb was studied, but S/B is bad and it it very difficult at present to estimate systematic uncertainties at $L=5x10^{34}\ cm^{-2}\ s^{-1}$ → not included in the available ES ATLAS studies

ttH, H$\rightarrow\gamma\gamma$ and H$\rightarrow\mu\mu$

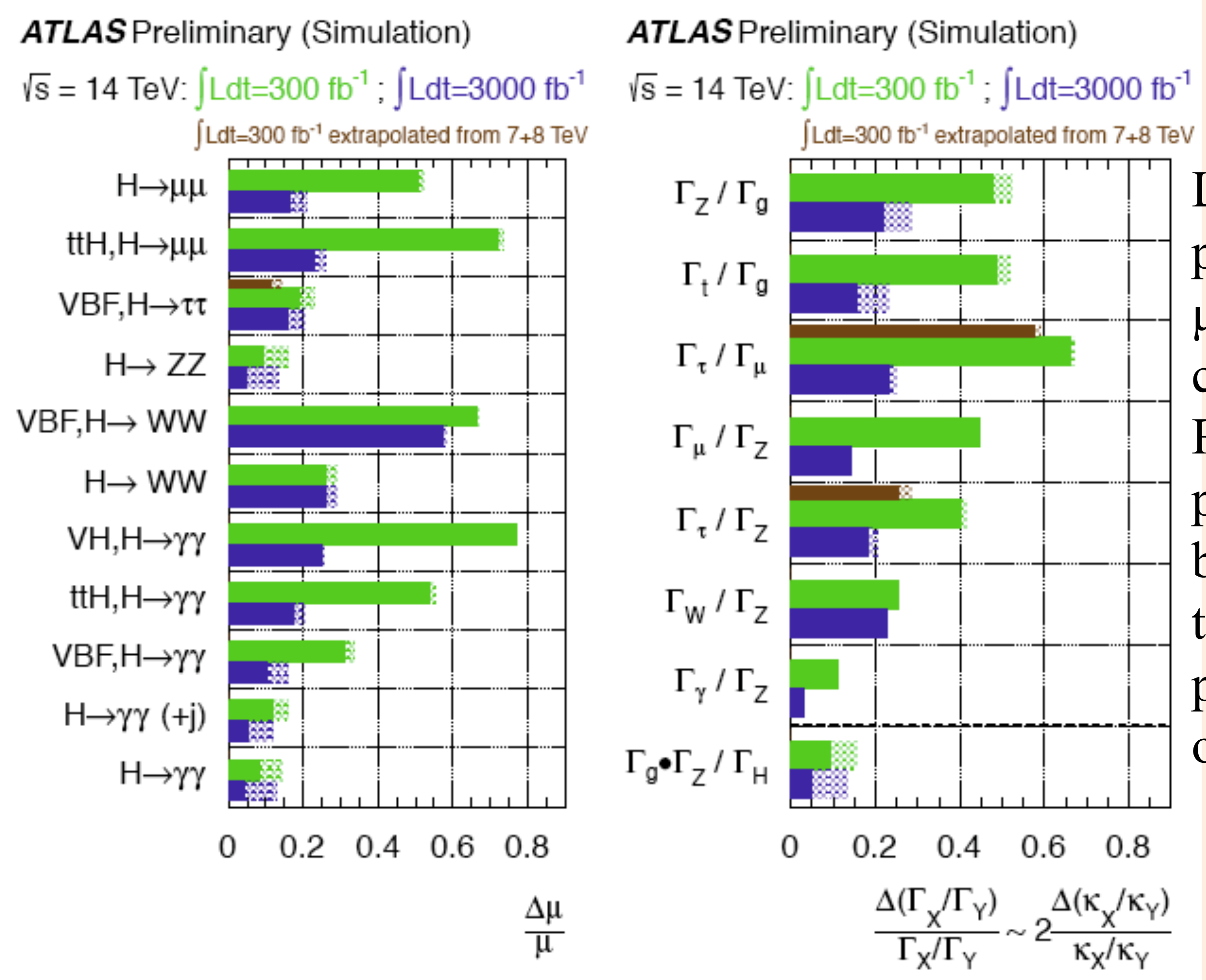


- Important for H-top coupling measurement
- Require multi-jet high-p_T jets
- Analyse 1-lepton and 2- lepton events
- Require very high luminosity
  - S/$\sqrt{B}$ ~ 6
  - A factor 2 better than 300 fb^{-1}



- One of the best channels to study Higgs boson couplings to fermions
- Very rare: deviations from the expected rate would indicate new physics
  - Large background from Z$\rightarrow\mu\mu$
- Analysis included background modeling uncertainties
- More than 6 sigma at L=3000 fb^{-1}

Higgs Couplings at the HL-LHC



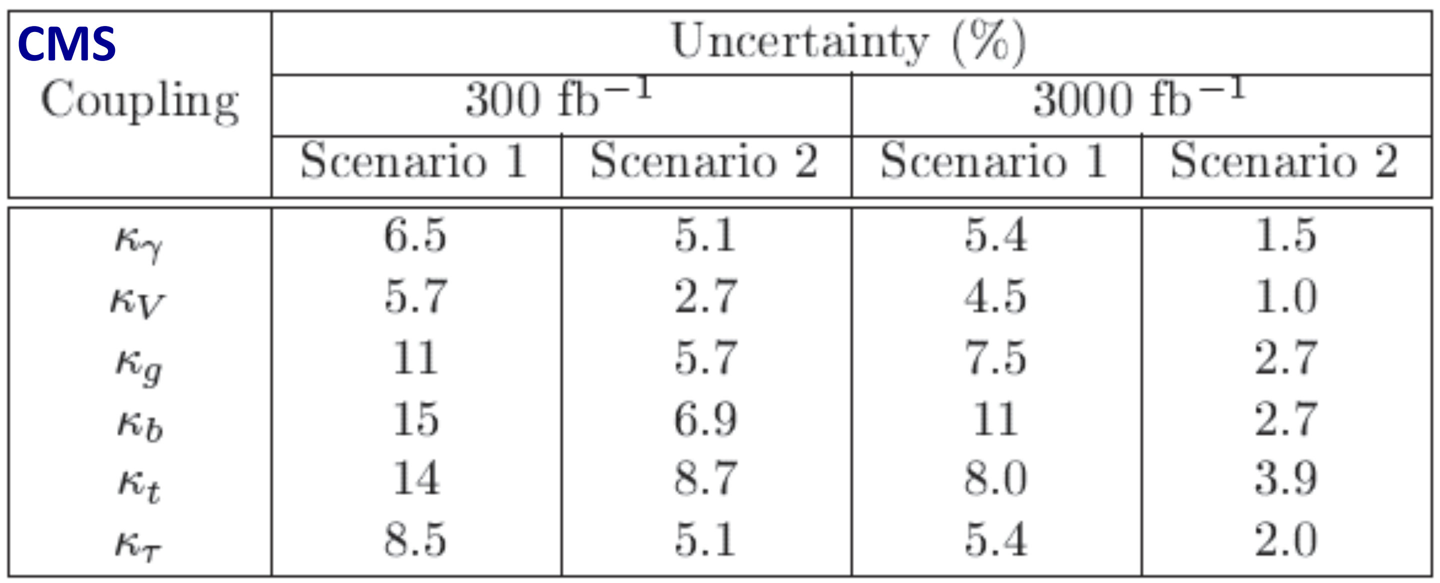
Left: Expected measurement precision on the signal strength $\mu = (\sigma\times BR)=(\sigma\times BR)_{SM}$ in all considered channels.

Right: Expected measurement precisions on ratios of Higgs boson partial widths without theory assumptions on the particle content in Higgs loops or the total width.

	300 fb^{-1}	3000 fb^{-1}
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)

Expected precision for the determination of the coupling scale factors k_V and k_F. No additional BSM contributions are allowed in either loops or in the total width (numbers in brackets include current theory systematic uncertainties).

Higgs Couplings at the HL-LHC



CMS Coupling	Uncertainty (%)			
	$300\ \text{fb}^{-1}$		$3000\ \text{fb}^{-1}$	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

- Coupling CMS projection: In the first one (Scenario 1) all systematic uncertainties are kept unchanged. In the second one (Scenario 2) the theoretical uncertainties are scaled by a factor of 1/2, while other systematical uncertainties are scaled by the square root of the integrated luminosity.

Couplings can be measured at the level of few %

Nice complementarity with ILC (γγ,μμ,tt,ZZ)

Higgs boson Self-Coupling

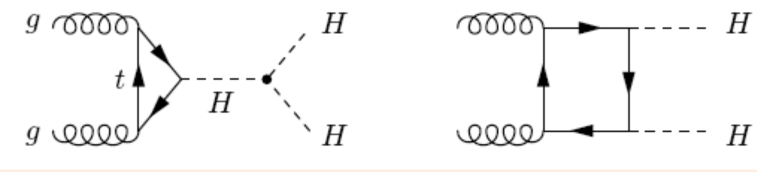
- The only way to reconstruct the scalar potential of the Higgs doublet field , that is responsible for spontaneous electroweak symmetry breaking, it is necessary to measure the Higgs boson self–interactions

$$V_H = \mu^2\Phi^\dagger\Phi + \frac{1}{2}\lambda(\Phi^\dagger\Phi)^2 \; ; \quad \lambda = \frac{M_H^2}{v^2} \text{ and } \mu^2 = -\frac{1}{2}M_H^2$$

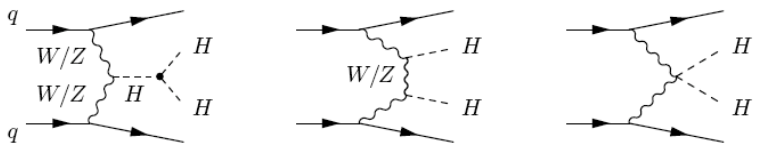
$$\boxed{\lambda_{HHH} = \frac{3M_H^2}{v}}$$

A. Djouadi, et al., Eur. Phys. J. C10 (1999), 45

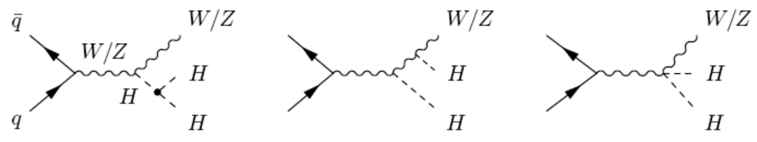
gluon-gluon fusion

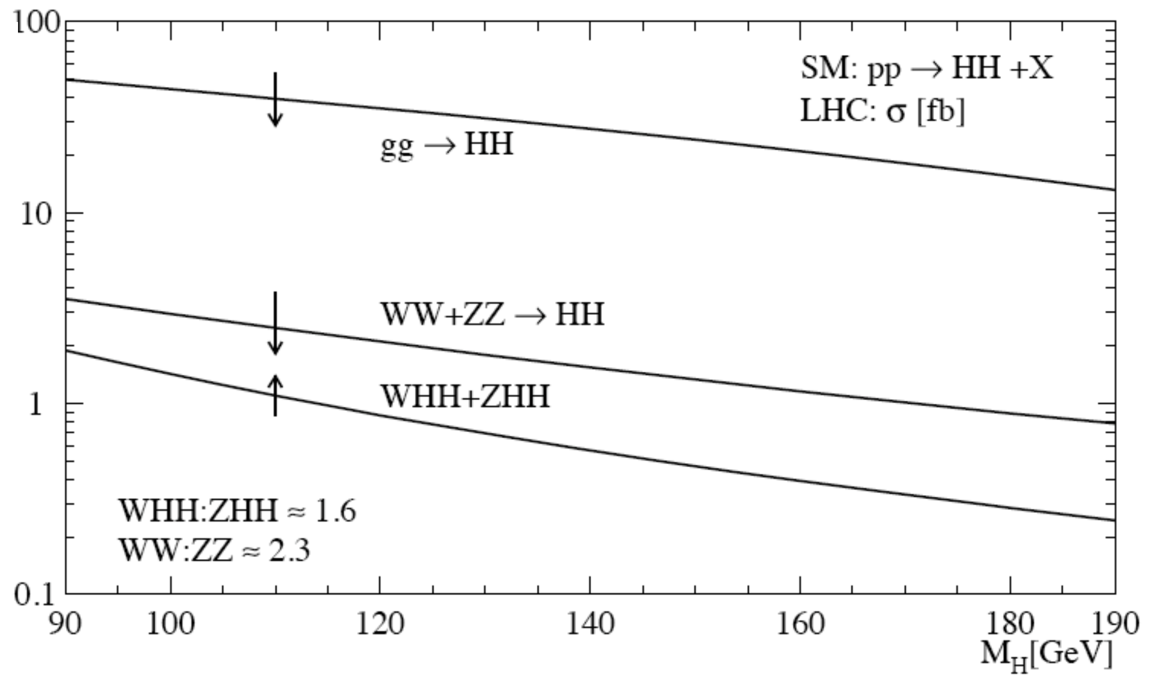


Vector Boson Fusion



Higgs-strahlung

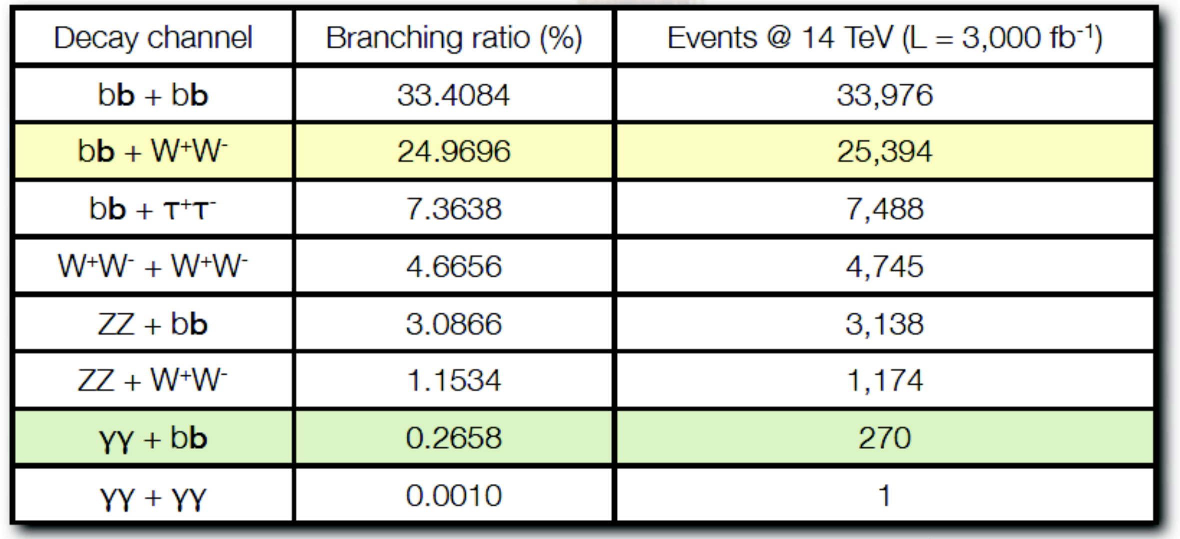




σ_{HH} (14 TeV) = 33.89 +18%-15% (QCD) ±7% (PDF+α_S) ±10% (EFT) fb ➔ +37.2 -29.8 fb

A. Djouadi, et al., http://arxiv.org/abs/1212.5581

Higgs Self-Coupling



Decay channel	Branching ratio (%)	Events @ 14 TeV (L = 3,000 fb^{-1})
bb + bb	33.4084	33,976
bb + W^+W^-	24.9696	25,394
bb + $\tau^+\tau^-$	7.3638	7,488
W^+W^- + W^+W^-	4.6656	4,745
ZZ + bb	3.0866	3,138
ZZ + W^+W^-	1.1534	1,174
$\gamma\gamma$ + bb	0.2658	270
$\gamma\gamma$ + $\gamma\gamma$	0.0010	1

Expected SM HH yields for proton-proton collisions at $\sqrt{s}$ = 14 TeV and L=3000 fb^{-1}

- The “trouble” with a 125 GeV Higgs: it decays in many final states with similar “small” B.R. This is very good for couplings, but opens real challenges for HH final states, characterized by small production rates.
- The selection of HH processes has to account for:
  - Final states experimentally clear and robust
  - Final states with large enough production rates

Two channels have been considered by ATLAS for the “European Strategy”:

1. **HH→bbWW**
2. **HH→bbγγ**

HH→bbWW

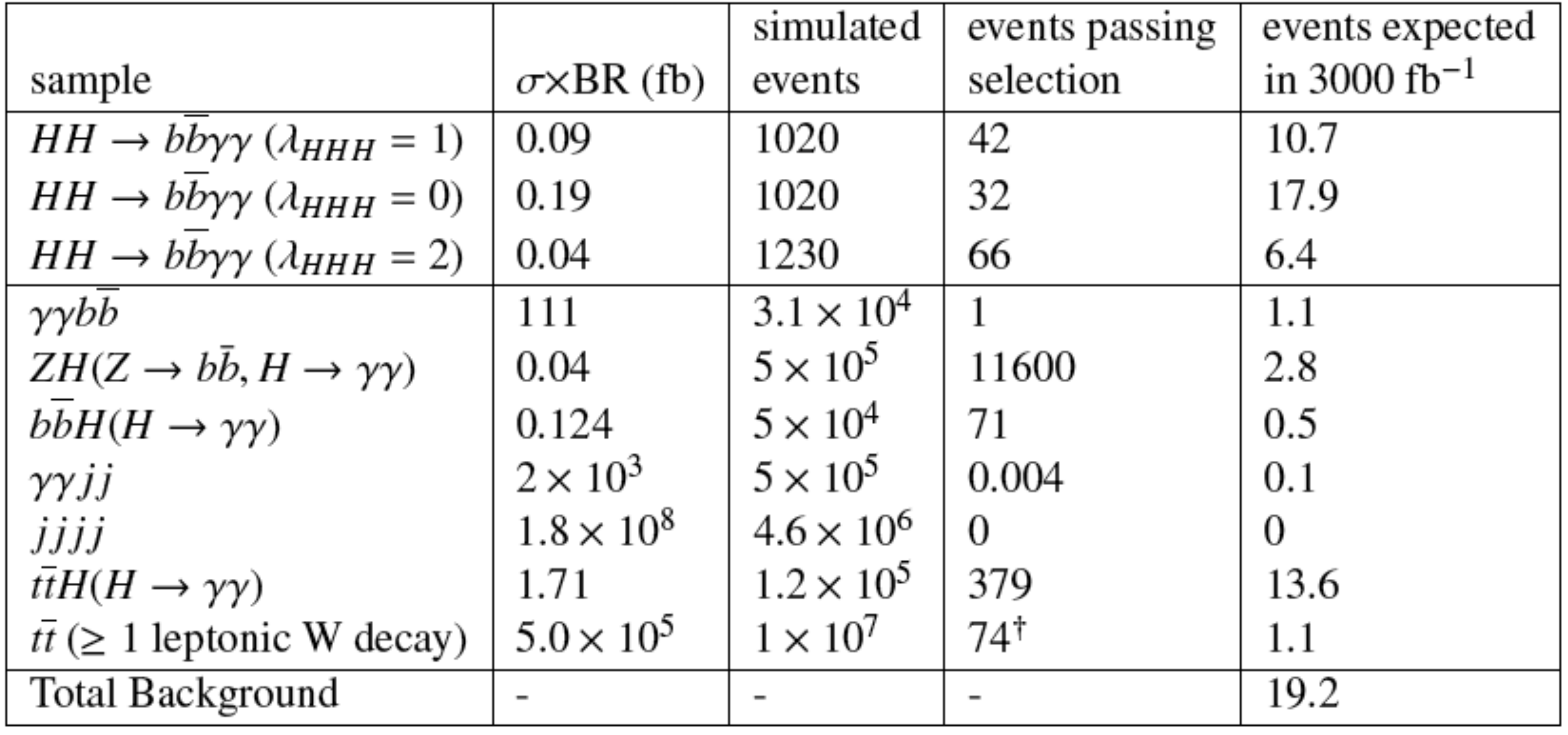
- BR ~ 25% → 2.6 × 10^4 events in 3000 fb^{-1} at 14 TeV;
  - This includes all W decay modes
- The ttbar process represents a severe background for this final state;
- Study done considering one W decaying hadronically, the other leptonically (e,μ; treated separately)
- Select events with high lepton p_T, large missing transverse energy, four high-p_T jets, of which two b-tagged;
- The result of the study shows how challenging is extract HH production from this channel
  - We select <~ 1000 signal events on top of 10^7 ttbar events
  - S/B in agreement with estimates performed by other authors (M.J. Dolan et al., arXiv:1206.5001v2 [hep-ph])

HH → $bb\gamma\gamma$

- BR ~ 0.27% , $\sigma \times$ BR ~ 0.09 fb → 260 HH events in 3000 fb^{-1} at 14 TeV;
- $bb\gamma\gamma$, Zbb, Hbb, ttbar are important backgrounds
- Select events with high-p_T photons, two jets b-tagged; reconstruct the invariant mass of the b-jets and of the photons and select events with $m_{\gamma\gamma}$ and $m_{bb} = m_Z$ within experimental mass resolution

HH → bbγγ

ATLAS Note: ATL-PHYS-PUB-2013-001



sample	$\sigma\times$BR (fb)	simulated events	events passing selection	events expected in 3000 fb^{-1}
$HH \rightarrow b\bar{b}\gamma\gamma$ ($\lambda_{HHH} = 1$)	0.09	1020	42	10.7
$HH \rightarrow b\bar{b}\gamma\gamma$ ($\lambda_{HHH} = 0$)	0.19	1020	32	17.9
$HH \rightarrow b\bar{b}\gamma\gamma$ ($\lambda_{HHH} = 2$)	0.04	1230	66	6.4
$\gamma\gamma b\bar{b}$	111	3.1×10^4	1	1.1
$ZH(Z \rightarrow b\bar{b}, H \rightarrow \gamma\gamma)$	0.04	5×10^5	11600	2.8
$b\bar{b}H(H \rightarrow \gamma\gamma)$	0.124	5×10^4	71	0.5
$\gamma\gamma jj$	2×10^3	5×10^5	0.004	0.1
$jjjj$	1.8×10^8	4.6×10^6	0	0
$t\bar{t}H(H \rightarrow \gamma\gamma)$	1.71	1.2×10^5	379	13.6
$t\bar{t}$ ($\geq$ 1 leptonic W decay)	5.0×10^5	1×10^7	$74^{\dagger}$	1.1
Total Background	-	-	-	19.2

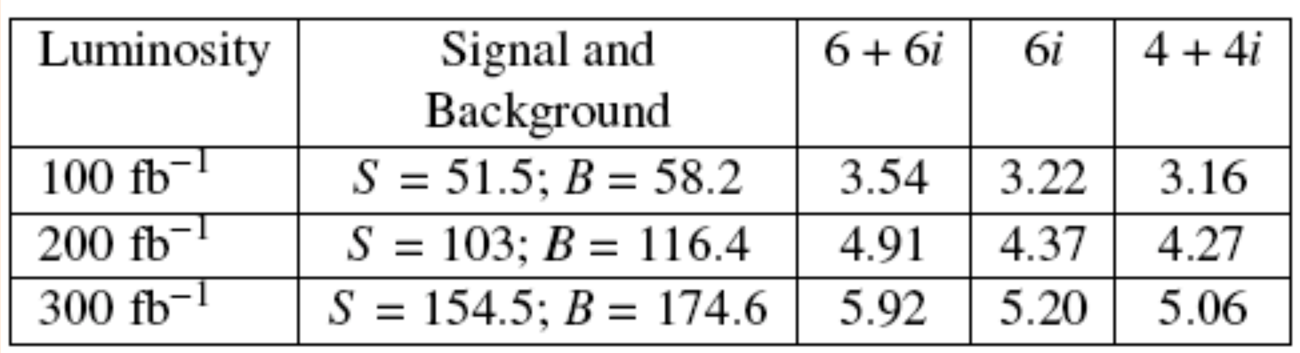
- Select 11 HH events with a total background yield of 19 events
- **Assuming that we can add another channel with similar performances (HH→ττbb ?) and two experiments, we can reach a measurement of the Higgs boson selfcoupling with an accuracy of ~30%**

Higgs boson CP

- Explore the ATLAS sensitivity to the CP-violating part of the HZZ scattering amplitude:

$$A(X \to VV) \sim \left(a_1 M_X^2 g_{\mu\nu} + a_2 (q_1 + q_2)_\mu (q_1 + q_2)_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right) \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}$$

- ε: polarisation vectors of the gauge bosons, form factors a1 and a2 refer to CP-even boson with mass M_X, a3 to a CP-odd boson
  - The presence of the two CP terms can lead to CP violation
  - In SM a1=1; a2=a3=0
- In this study we have set a1=1; a2=0, and varied a3



Luminosity	Signal and Background	$6+6i$	$6i$	$4+4i$
100 fb^{-1}	$S = 51.5; B = 58.2$	3.54	3.22	3.16
200 fb^{-1}	$S = 103; B = 116.4$	4.91	4.37	4.27
300 fb^{-1}	$S = 154.5; B = 174.6$	5.92	5.20	5.06

Expected significances in sigma to reject a CP-violating state in favour of 0+ hypothesis as a function of integrated luminosity for various strength of CP-violating contribution.

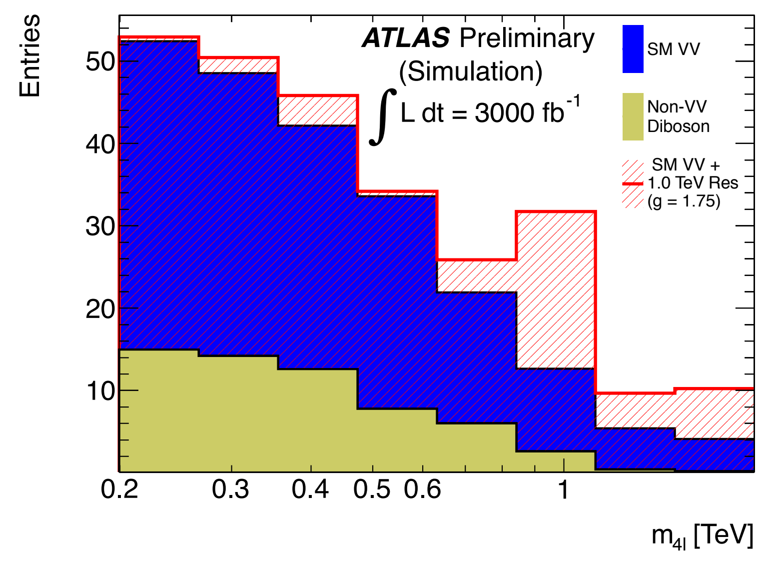
Precise measurement of smaller form factors which are more likely to be realized will require higher luminosities only accessible at HL-LHC. A similar conclusion can be drawn for the observation of anomalous form factor a2

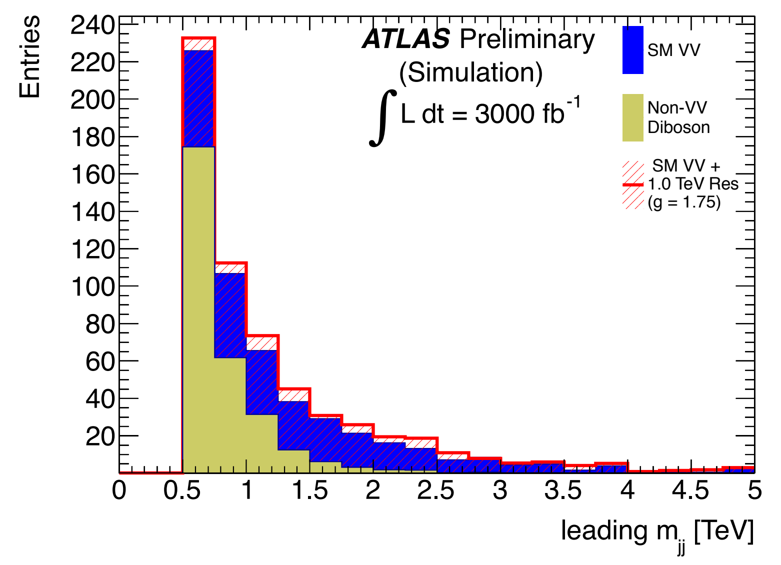
Vector Boson Scattering

- In the Standard Model, the Higgs boson preserves the unitarity of scattering amplitudes in longitudinal Vector Boson Scattering (VBS)
- However new physics can contribute to the regularization of of the VBS cross-section or else enhancing it.
  - Example: in Technicolor models predict the appearance of resonances in the V-V invariant mass distribution
- ➔ the study of VBS properties at the LHC is a mandatory step to test the effects of the SM Higgs boson (if the existence will be confirmed) or from New Physics BSM.

Vector Boson Scattering

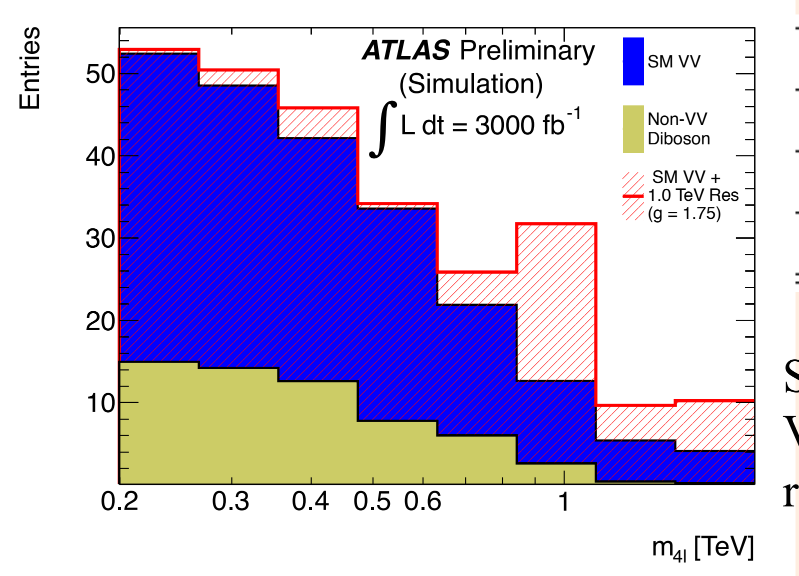
- At LHC VBS are tagged with two forward high-p_T jets on either side, the remnants of the quarks that have emitted the W/Z bosons in the central rapidity region: WW+2jets, WZ+2jets, ZZ+2jets
- ATLAS has performed preliminary studies of the process pp→ZZjj → 4l+jj within the “Pade’” unitarization (IAM, Inverse Amplitude Method) and using the WHIZARD generator (it allows to generate weak boson scattering mediated by a new high-mass resonance in presence of a Higgs boson with 126 GeV mass)

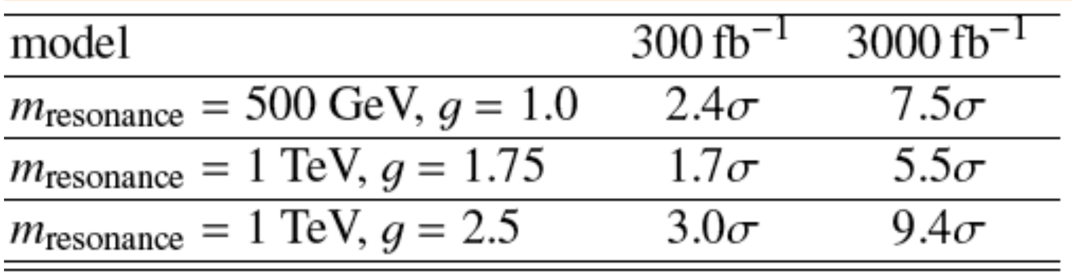




Vector Boson Scattering

- At LHC VBS are tagged with two forward high-p_T jets on either side, the remnants of the quarks that have emitted the W/Z bosons in the central rapidity region: WW+2jets, WZ+2jets, ZZ+2jets
- ATLAS has performed preliminary studies of the process pp→ ZZjj → 4l+jj within the "Pade'" unitarization (IAM, Inverse Amplitude Method) and using the WHIZARD generator (it allows to generate weak boson scattering mediated by a new high-mass resonance in presence of a Higgs boson with 126 GeV mass)





model	300 fb^{-1}	3000 fb^{-1}
$m_{\mathrm{resonance}} = 500$ GeV, $g = 1.0$	2.4σ	7.5σ
$m_{\mathrm{resonance}} = 1$ TeV, $g = 1.75$	1.7σ	5.5σ
$m_{\mathrm{resonance}} = 1$ TeV, $g = 2.5$	3.0σ	9.4σ

Summary of the expected sensitivity to anomalous VBS signal for a a few values of the mass of the resonance and of the coupling g.

Conclusions

- A data sample of 300 fb^{-1} at the LHC will allow to exclude strong deviations of the Higgs-like particle recently discovered from the Higgs boson predicted by Standard Model
- A complete investigation on the physics properties of this new boson will require the search for rare decay final states, selfcoupling processes, CP violation effects, as well as the reduction of experimental (and theoretical) uncertainties ➔ High-Luminosity LHC can provide the required statistics with an accuracy on the Higgs couplings around a few %;
- HL-LHC extends the searches of LHC of BSM physics, and offers the required data to study the properties of new particles if found at the LHC

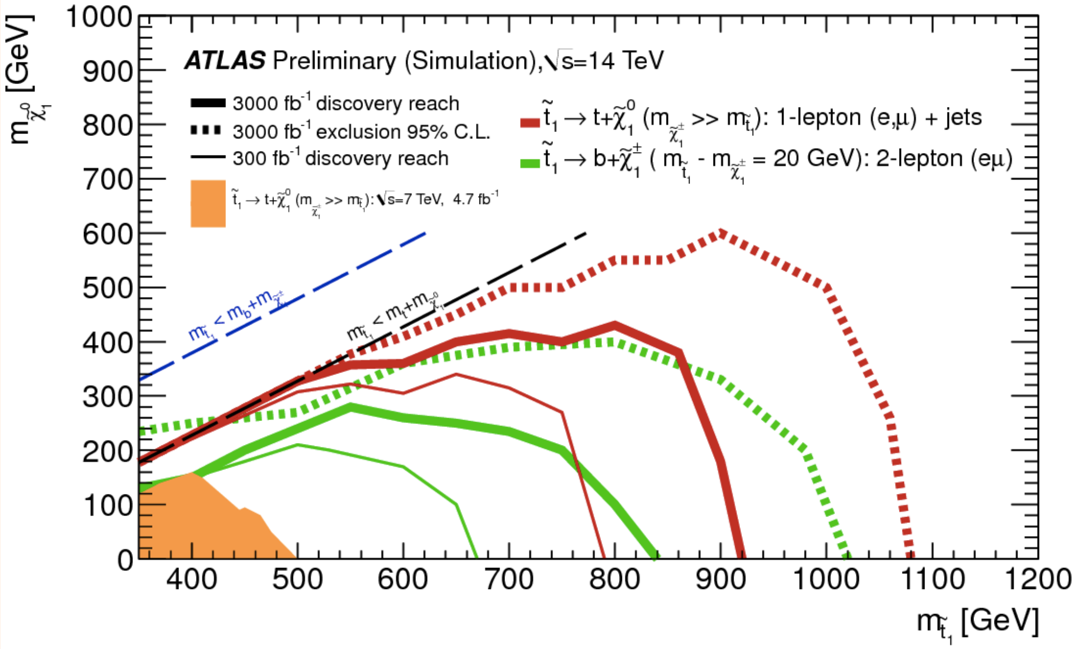
backup

SUSY Searches

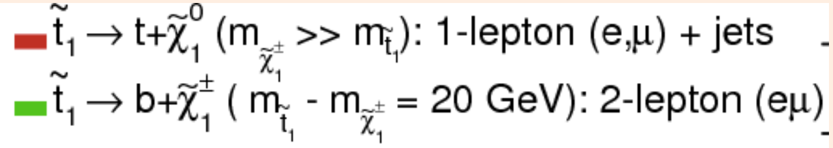
- So far there has been no sign of Supersymmetry at LHC
  - However only < 10% of the LHC expected data have been studied (and at $\sqrt{s}=7$ TeV)
  - 3rd generation squarks have low cross-sections
- If we find it:
  - We have a large set of new particles to study
  - Thus a SUSY discovery will mandate more luminosity
- If will not find it by 2020:
  - HL-LHC offers a 25% increase in mass reach
  - HL-LHC will explore a phase space no other machine will probe for decades

Searches for stop

- Probably this will be one of the most important points in SUSY for the immediate future: naturalness requires stop mass not larger than ~ 1 TeV
- Rates will be modest ➔ HL-LHC reprsents an ideal machine for this search



The 95% CL exclusion limits for 3000 fb^{-1} (dashed) and 5 sigma discovery reach (solid) for 300 fb^{-1} and 3000 fb^{-1} in the stop, neutralino_1 mass plane assuming:

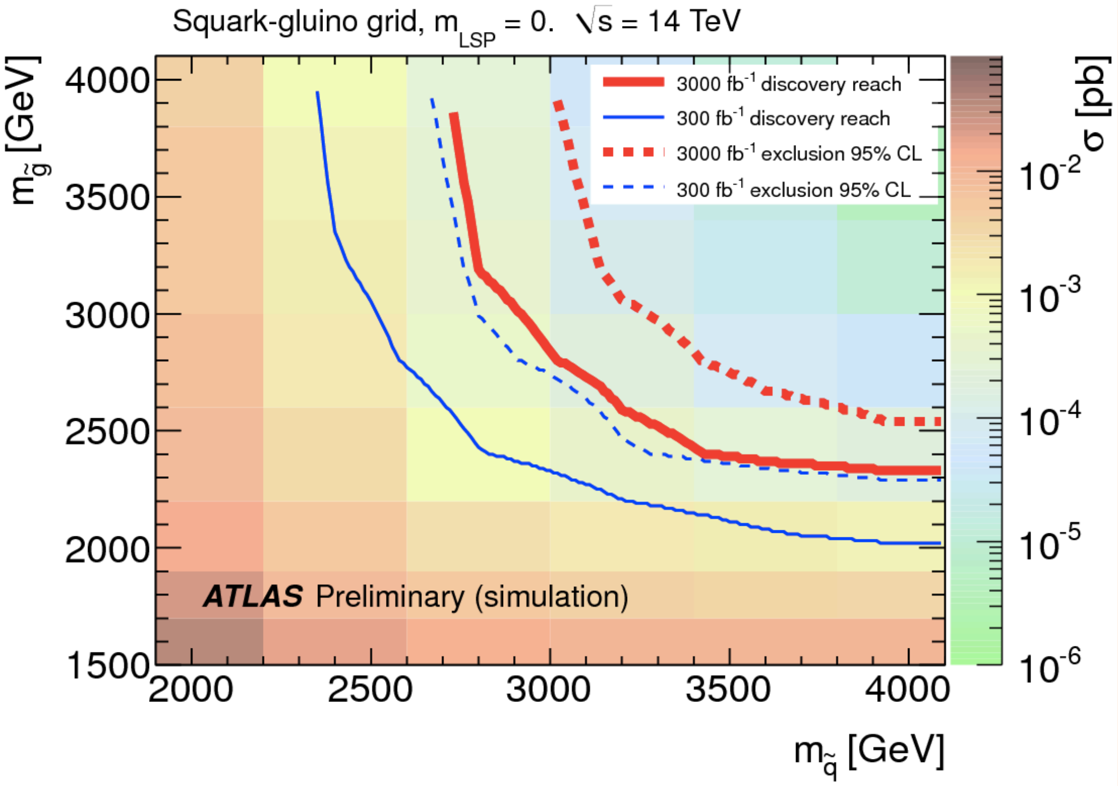


🟥 $\tilde{t}_1 \rightarrow t+\tilde{\chi}_1^0$ ($m_{\tilde{\chi}_1^\pm} >> m_{\tilde{t}_1}$): 1-lepton (e,μ) + jets

🟩 $\tilde{t}_1 \rightarrow b+\tilde{\chi}_1^\pm$ ($m_{\tilde{t}_1} - m_{\tilde{\chi}_1^\pm}$ = 20 GeV): 2-lepton (eμ)

Searches for squarks and gluinos

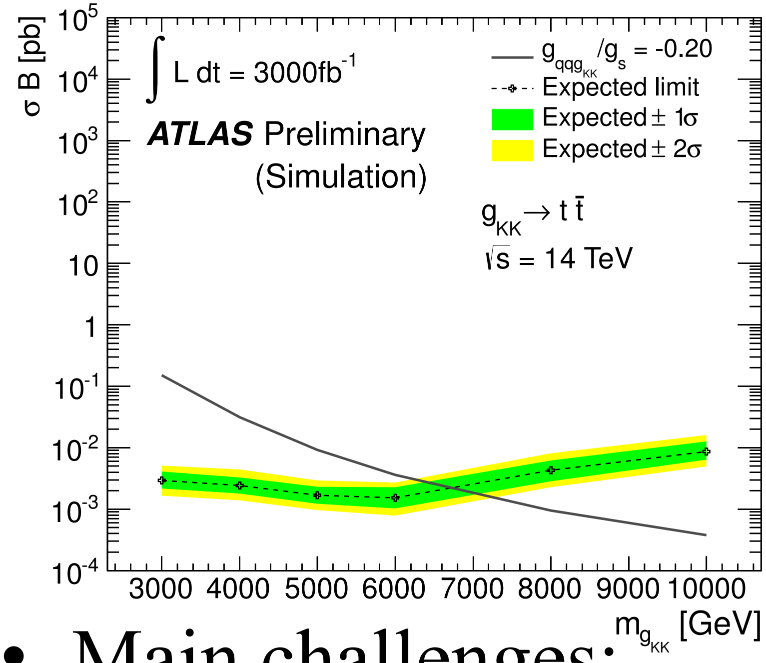
- HL-LHC gives tight limits:
  - – ~ 3 TeV for squarks
  - – ~ 2.5 TeV for gluinos
- This represents a 400 GeV rise in sensitivity with respect to the L=300 fb^{-1} case

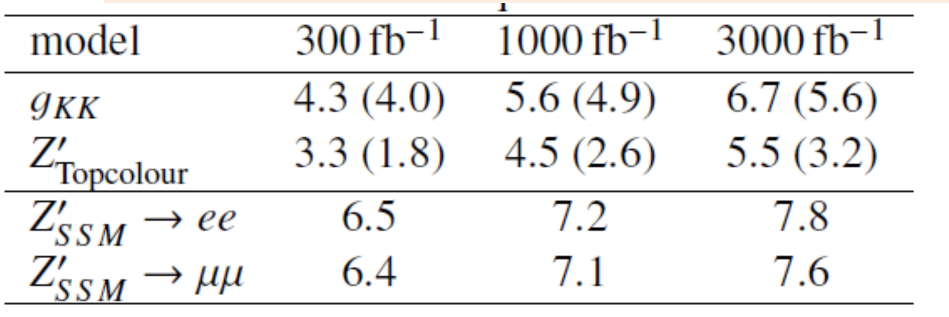


The 95% CL exclusion limits (solid lines) and 5 sigma discovery reach (dashed lines) in a simplified squark--gluino model with massless neutralino with 300 fb-1 (blue lines) and 3000 fb-1 (red lines). The colour scale shows √s=14 TeV NLO production cross section calculated by Prospino 2.1.

Exotics Searches

- Searches for ttbar resonances or Z’ leptons can exploit the physics potential offered by HL-LHC





model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{\text{Topcolour}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)
$Z'_{SSM} \to ee$	6.5	7.2	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6

Summary of the expected limits for g_{KK} → ttbar and Z'_{Topcolor} → ttbar searches in the lepton+jets (dilepton) channel and of Z'_{SSM} → ee and Z'_{SSM} → μμ searches in the Sequential Standard Model. All boson mass limits are quoted in TeV.

- Main challenges:
  - Reconstruct highly boosted top decays
  - Ensure lepton measurement at very high pT
    - Muon system alignment
    - Leakage from calorimeter (?)