## The Story of the LHC Project, the Higgs Discovery and Beyond

1494

**CPPM Marseille** Luminy, 13<sup>th</sup> November 2015





Peter Jenni, Freiburg and CERN



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Drawing by Sergio Cittolin

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The Large Hadron Collider project is a global scientific adventure, which was initiated some 30 years ago, combining the accelerator, the experiments, a worldwide computing grid, and with lots of motivation from our theory colleagues





Experiments at CERN with the Large Hadron Collider allow us to study fundamental particle physics in conditions that we can control, and with measurements that we can reproduce and verify



## The Standard Model of Particle Physics



- (i) Constituents of matter: quarks and leptons
- (ii) Four fundamental forces (described by quantum field theories, except gravitation)
- (iii) The Brout-Englert-Higgs field (problem of mass, broken symmetry)





A most basic question is why particles (and

charm

Quarks

bottom

top

LHC, Higgs Boson, and Beyond

down

up

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strange

**Peter Higgs** 



**Francois** 

Englert

### Why do we need a Higgs?

Elementary particles are point-like, without any internal structure

The natural consequence would be that they are massless, but we know experimentally that this is not the case!

The above-mentioned theorists, together with others, postulated in 1964 a solution which <u>spontaneously breaks this symmetry</u> (initially between the gauge bosons, i.e. the massless photon and the heavy W and Z bosons)



A field was proposed that fills all space (vacuum) that has the following effects:

- Bosons can acquire a mass
- Fermions can acquire a mass
- The weak and the electromagnetic forces are very different in their properties
- A new massive scalar elementary particle (the Higgs, H) must exist (however with a mass that is not predicted by this theory)

The discovery of this H particle would verify this bold theory !

Announced on 8<sup>th</sup> October and celebrated on 10<sup>th</sup> December 2013:

# 2013 NOBEL PRIZE IN PHYSICS François Englert Peter W. Higgs





"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

The Nobel Foundation, Photo: Lovisa Engl

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The protons, neutrons, and many others like pions, kaons ... are not elementary particles

They are objects that are composed of quarks, bound together by the strong force mediated by the gluons

Their mass is mainly due to the 'binding energy' holding them together ...

Quark Model 1964

Murray Gell-Mann George Zweig





G Zweig



### How the LHC came to be ....

(see a nice article by Chris Llewellyn Smith in Nature 448, p281)

#### Some early key dates

- 1977 The community talked about the LEP project, and it was already mentioned that a new tunnel could also house a hadron collider in the far future
- 1981 LEP was approved with a large and long (27 km) ring tunnel



Herwig Schopper CERN DG 1981 - 1988

#### **1983** The early 1980s were crucial

The real belief that a 'dirty' hadron collider can actually do great discovery physics came from UA1 and UA2 with their W and Z boson discoveries at CERN

#### A very early $Z \rightarrow$ ee online display from one of the detectors (UA2)

LHC, Higgs Boson, and Beyond





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LHC, Higgs Boson, and Beyond

underground near Geneva

1984 For the community it all started with the CERN - ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel

1986 LAA R&D on new detector technologies started, later followed by the DRDC

#### **1987 La Thuile Workshop**

Many LHC colleagues were already involved in this WS set up by Carlo Rubbia as part of the Long Range Planning Committee





Fig.

13

Possible LHC Schedule



CPPM, AMU, 13-Nov-2015 P Jenni (Freiburg and CERN) 1991 December CERN Council: 'LHC is the right machine for advance of the subject and the future of CERN' (thanks to the great push by DG C Rubbia)

1993 December proposal of LHC with commissioning in 2002



1994 In order to have any chance at all of approval, the idea of a staged construction was worked out by the then new CERN DG Chris Llewellyn-Smith

> ATLAS provided comparisons between 10 and 14 TeV... → worthwhile to start with

June 1994 Council:

Staged construction was proposed, but some countries could not yet agree, so the Council session vote was suspended until

16 December 1994 Council:

## Two-stage construction of LHC was approved



The two-stage approval of LHC was understood to be modified in case sufficient CERN non-member state contributions would become available

A lot of LHC campaigns and negotiations took place in the years 1995 - 1997, including also the experiments

Japan, Russia, India, Canada and the USA were agreeing in that phase to contribute to the LHC

(Israel contributed all along to the full CERN programme and LHC)

### **1996**

December Council approved finally the single-stage 14 TeV LHC for completion in 2005



Delivery of the last dipole for the LHC injection lines from Russia (15<sup>th</sup> June 2001), with L Maiani and A Skrinsky in the centre



### Descent of the last dipole magnet, 26 April 2007



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30'000 km underground transports at a speed of 2 km/h!



### The particle beams are accelerated by superconducting Radio-Frequency (RF) cavities





Note: The acceleration is not such a big issue in pp colliders (unlike in ring e<sup>+</sup>e<sup>-</sup> colliders), because of the ~  $1/m^4$ dependance of the synchrotron radiation energy losses [~ E<sup>4</sup><sub>beam</sub>/Rm<sup>4</sup>] Special quadrupole magnets ('Inner Triplets') are focussing the particle beams to reach highest densities ('Iuminosity') at their interaction point in the centre of the experiments

Contraction of the second seco





## Collisions at the LHC



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#### 1989 ECFA Study Week in Barcelona for LHC instrumentation

1990 Large Hadron Collider Workshop Aachen (CERN - ECFA)

1992 CERN – ECFA meeting 'Towards the LHC Experimental Programme' in Evian

ATLAS and CMS were born with Letters of Intent (LoI), submitted on 1<sup>st</sup> October 1992



### **Detectors for particle physics**

Cover the whole angular range around the collision point to detect as much of the particles produced in the collision as possible. **Dual role of detectors:** 

Select potentially interesting collision events

Provide as much information about these events for the analysis as possible

A typical cylindrical layout of a collider detector

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#### Arguing after the mid-1980s of being ambitious and design a general purpose detector ...

A very simplified summary:		
detector	accessible	
signature	physics process	
· m <sup>±</sup>	$\begin{array}{l} H \rightarrow ZZ \rightarrow 4 \mu^{\pm} \\ Z' \rightarrow \mu^{\pm} \mu^{\pm} (\sigma_{m}?) \end{array}$	
$\mu^{\pm}$ , jets, $p_{T}$ add.	H→ZZ.→μμνν W'→μ <sup>±</sup> ν compositeness q̃, g̃ (direct decays)	
e_u <sup>±</sup> , jets, p <sub>+</sub> add:	jet spectroscopy 4× rate H>ZZ>48t	
(non-)magnetic	2× rate H>ZZ>levi	
central part ( <u>reduced</u> tracking)	2× rate Z', W' g,g (also cascade	
	mass resolution	
	en heavy Q,L H-88	
E, µt, tt, jets, g, ada	1: more redundancy	
and tracking	on above,	
5	Ht, SUSY-H,	
	heavy flavour tags	

Lepton detection at LHC is crucial Small rates are expected for many potential signals

> detection of e and µ

Muons are relatively easy to identify but hard to measure well

> (precise u measurements may mean hundreds of MCHF)

Electrons are relatively easy to measure but hard to identify at 10<sup>34</sup>

(radiation-hard inner detector)

Lepton isolation criteria are also important to reject backgrounds from heavy flavour decays

### The birth of ATLAS

March 1992 – Summer 1992

#### Merging of EAGLE and ASCOT

September 1992: Decision on the name

1 <sup>st</sup> round		2 <sup>nd</sup> round	
ATLAS	31	ATLAS	40
ALICE	12	ALICE	13
ACE	5		
ALEX	5		
LHD	0		

October 1992:

ATLAS Lol submitted to the LHCC (as well as the CMS Lol)

Note that J.J. Aubert was the LHCC Chairperson 1992 - 95



For the experiments it was a long way convincing the LHCC, but finally, on 16<sup>th</sup> November 1995, our referees were happy, and Hugh Montgomery, ATLAS main referee at that time, gave us the following 'official leak' from the committee...

The LHCC recommendations meant in particular that ATLAS and CMS could now proceed in developing their series of Technical Design Reports

11/16/95 Official Feak The LHCC recommends the projects, logether with ATLAS + CMS the 1 milestone, leading the Subsystem Technical Derig- Reposts Second

Bohne

Good continue trou metil the final success !

Anything worked out fine, and we produced a large series of TDRs...



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 Our Ref.

 Our Ref.
 DG/mnd/2540
 **Dr Peter Jenni** PPE Division CERN

Geneva, 1st July 1997

Dear Peter,

Following the thorough discussion of the status of ATLAS and CMS by Council and its Committees two weeks ago, the way is now open for construction to begin. I am therefore pleased to inform you that I have decided to *i*) set the cost ceiling for ATLAS at 475 MCHF (1995 prices), and *ii*) approve the TDR of the ATLAS calorimeters on the following basis formulated by the LHCC and endorsed by the Research Board at its meeting on 12th June:

"The LHCC recommends general approval of the ATLAS Calorimetry Technical Design Report describing design, performance, construction, and installation in 2004. The review identified some concerns in limited areas, which require resolution (LHCC 97–27). The LHCC considers that the schedules and milestones given in the TDR are reasonable, and these will be used by the committee to measure and regulate the future progress of the project."

Yours sincerely,

Chi

Chris Llewellyn Smith

### The SM is not a complete theory

### Some of the outstanding questions in fundamental physics were/are





## ALICE (Status January 2008)

Study primordial plasma of quarks and gluons with heavy ion collisions in the LHC (Pb-Pb, p-Pb)

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First signs of new physics could also come from accurate measurements of clean processes for which the Standard Model makes very precise predictionsthe known SM processes are at play





Measured deviations could indicate that something more than just the known SM processes are at play

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### An Example of an Engineering Challenge: CMS Solenoid



CMS solenoid:	
Magnetic length	12.5 m
Diameter	6 m
Magnetic field	4 T
Nominal current	20 kA
Stored energy	2.7 GJ
Tested at full current in Summer 2006	



CMS Electron and Photon calorimeter: 76 000 PbW0<sub>4</sub> crystals

End-cap was on the critical path for many years, but it was completed just in time before final closure, a major achievement by CMS

#### Barrel ECAL Installation Completed: 27 July 07



liggs Boson, and Beyond



## ATLAS Collaboration

39 Countries 178 Institutions 2820 Scientific authors total (~1000 Students)

# The CPPM group has been a founding member of ATLAS in 1992



Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Brazil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Harvard, Heidelberg, Hiroshima IT, Hong Kong, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubliana, QMW London, RHBNC London, UC London, Louisiana Tech, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, LMU Munich, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, NPI Petersburg, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, Trento, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan



The Underground Cavern at Point-1 for the ATLAS Detector (excavation started in 1998)

Length = 55 m Width = 32 m Height = 35 m





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## ATLAS Toroid Magnet System

Barrel Toroid parameters 25.3 m length 20.1 m outer diameter 8 coils 1.08 GJ stored energy 370 tons cold mass 830 tons weight 4 T on superconductor 56 km Al/NbTi/Cu conductor 20.5 kA nominal current 4.7 K working point

End-Cap Toroid parameters 5.0 m axial length 10.7 m outer diameter 2x8 coils 2x0.25 GJ stored energy 2x160 tons cold mass 2x240 tons weight 4 T on superconductor 2x13 km Al/NbTi/Cu conductor 20.5 kA nominal current 4.7 K working point



#### One of many ingredients to make the experiment affordable ...



... initial ideas of a toroid with 12 coils were 'descoped' to a 8 coil design (which turned out to be an excellent choice also to have more 'air' in the air-core spectrometer)

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#### The B0 Model Coil Reaching Full Current of 20.5 kA in July 2001



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## ATLAS Barrel Toroid construction

Series integration and tests of the 8 coils at the surface were finished in June 2005



5TE7026

5TE7030

5TE7034

5TE7038





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## Liquid Argon Calorimeters

## First end-cap EM module during stacking at CPPM in 2001



- a very stable and radiation-hard detector
- relatively easy to calibrate
- a lot of freedom in spacial resolution
- but quite a challenge to construct....





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#### Full EM end-cap wheel after isertion and cabling in the end-cap cryostat in 2003

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The Pixel tracker is an other high-tech area where the CPPM team is strongly involved since the conception...







Insertion in June 2007



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#### Interconnections of two magnets

One (superconductor) joint failed on 19<sup>th</sup> September 2008, and it caused a catastrophic He-release that made serious collateral damage to sector 3-4 of the LHC machine (required a 15 months repair period)

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LHC incident



The joy in the ATLAS Control Room when the first LHC beam collided on November 23<sup>rd</sup>, 2009....

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#### First collisions at the LHC end of November 2009 with beams at the injection energy of 450 GeV



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## The experiments record typically 94% of the stably delivered luminosity, and use up to 90% of the LHC luminosity in the final analyses!

Excellent LHC performance is a (nice) challenge for the experiment:

- Trigger
- Pile-up

Recorded Luminosity [pb <sup>-1</sup>/0.1]

180

160

140

5

10

- Maintain accuracy of the the measurements in this environment

 $\sqrt{s} = 8 \text{ TeV}, \int \text{Ldt} = 20.8 \text{ fb}^{-1}, <\mu > = 20.7$ 

 $\sqrt{s} = 7 \text{ TeV}, \int \text{Ldt} = 5.2 \text{ fb}^{-1}, <\mu > = 9.1$ 



Inner Detector for a Z  $\rightarrow \mu\mu$  event with 25 primary vertices

15

20

25

Mean Number of Interactions per Crossing

30

35

40

45

ATLAS Online Luminosity

#### Start of Run-2 at 13 TeV collision energy



## The Worldwide LHC Computing Grid (WLCG)

GRID computing developed to solve problem of data storage and analysis

## LHC data volume per year: ~25 Petabytes

One CD has ~ 600 Megabytes 1 Petabyte =  $10^9 \text{ MB} = 10^{15} \text{ Byte}$  $\rightarrow$  Stack of 30 km of CDs !



## **CPPM contributed strongly to the whole data flow area**

#### (Note: the WWW is from CERN...)

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LHC, Higgs Boson, and Beyond

**Data flow** 

## The Worldwide LHC Computing Grid (WLCG)





Tier-0 (CERN): Data recording Initial data reconstruction Data distribution

Tier-1 (12 centres): •Permanent storage •Re-processing Analysis •Simulation

**Tier-2 (68 federations** of >100 centres):

- Simulation
- End-user analysis

### The Worldwide LHC Computing Grid (WLCG)





Tier-0 (CERN):
Data recording
Initial data reconstruction
Data distribution

Tier-1 (12 centres): • Permanent storage • Re-processing • Analysis • Simulation

Tier-2 (68 federations of >100 centres):

- Simulation
- End-user analysis

## LHC Physics Highlights

ATLAS and CMS have already published together close to 1000 papers in scientific journals (and many more as public conference notes...)

The other experiments, ALICE, LHCb, LHCf, and TOTEM total another 500 journal publications together

Note that all public results are available from the experiments Web pages, and from the CERN Document Server http://cdsweb.cern.ch/collection/LHC%20Experiments?In=en

and on the public physics web sites of the Collaborations





#### Very basic measurement: the total cross-section



But remember, only once in about 10<sup>13</sup> of the collisions a detectable Higgs is produced

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#### First inelastic cross-section measurement at 13 TeV LHC





## Data corresponding to ~40 pb<sup>-1</sup> collected $\rightarrow$ re-discovery of the Standard Model



#### The di-muon spectrum recalls a long period of particle physics: Well known quark-antiquark resonances (bound states) appear "online"

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## Note also that the event displays have become more sophisticated since the first spectacular events, hand-drawn, at a hadron collider ...




### Very detailed jet measurements are now available from LHC that can be compared with QCD calculations ...

Example: The di- jet cross sections as a function of the jet  $P_T$  in rapidity bins



#### JHEP 05 (2014) 059

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# Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2})^2}$$

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# What a contrast to the Intermediate Vector Boson discovery distributions in 1982 and 1983 by UA1 and UA2 with just a few events ...

#### Some 30 years ago!



#### The UA1 W $\rightarrow$ ev events

#### The UA2 distributions

### W cross section measurements



# tt pair production cross-sections



### Top quark mass measurements



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#### Very happy faces after the announcement of the discovery on 4<sup>th</sup> July 2012 at CERN and at ICHEP Melbourne



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# **Candidate for a H** $\rightarrow \gamma\gamma$ **event**



CMS Experiment at the LHC, CERN Data recorded: 2012-May-13 20:08:14.621490 GMT Run/Event: 194108 / 564224000

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# **Candidate for a H \rightarrow Z Z<sup>\*</sup> \rightarrow \mu\mu \mu\mu <b>event**



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# How significant is the signal ?

Observed data compared to the probability that the background fluctuates to fake the observed excess of events



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# Fingerprints for a Standard Model Higgs Boson: 1) Signal strength $\mu = \sigma / \sigma_{sm}$



# **Fingerprints for a Standard Model Higgs Boson:** 2) Leading production processes at the LHC



# **Fingerprints for a Standard Model Higgs Boson:** 3) Coupling strengths



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# Fingerprints for a Standard Model Higgs Boson: 4) Spin-parity tests (scalar particle with $J^P = 0^+$ )

Testing decay angular distributions against alternative J<sup>P</sup> hypothesis (example)





#### EPJC 75 (2015) 476

Alternative J<sup>P</sup> assignments are disfavoured at more than 99.9%

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#### Complementary technologies provided comparable performances in term of significance of the signals !

Experiment	AT	ATLAS		CMS	
Decay mode/combination	Expected	Observed	Expected	Observed	
	(σ)	(σ)	(σ)	(σ)	
γγ	4.6	5.2	5.3	5.6	
ZZ	6.2	8.1	6.3	6.5	
WW	5.8	6.1	5.4	4.7	
bb	2.6	1.4	2.6	2.0	
ττ	3.4	4.5	3.9	3.8	





# Supersymmetry (SUSY)

(Julius Wess and Bruno Zumino, 1974)

Establishes a symmetry between fermions (matter) and bosons (forces):

- Each particle p with spin s has a SUSY partner  $\tilde{p}$ with spin s -1/2
- Examples

 $q (s=1/2) \rightarrow \tilde{q} (s=0)$ squark  $g(s=1) \rightarrow \tilde{g}(s=1/2)$  gluino



**Julius Wess** (1934 - 2007)



**Bruno Zumino** (1923 - 2014)



#### Motivation:

- Unification (fermions-bosons, *matter-forces*)
- Solves some deep problems of the Standard Model



# **Dark Matter in the Universe**

Astronomers found that most of the matter in the Universe must be invisible Dark Matter



# **'Supersymmetric' particles ?**

F. Zwicky 1898-1974 LHC, Higgs Boson, and Beyond



### In practice SUSY searches at LHC are rather complicated

Missing

Energy

**Transverse** 

Events/50 GeV/10 fb<sup>-1</sup>

10

 $10^{4}$ 

10

102

10

0

500

• Complex (and model-dependent) squark/gluino cascades



- Focus on signatures covering large classes of models while strongly rejecting SM background
  - large missing  $E_T$
  - High transverse momentum jets
  - Leptons
    - Perform separate analyses with and without lepton veto (0-lepton / 1-lepton / 2-leptons )
  - B-jets: to enhance sensitivity to third-generation squarks
  - Photons: typically for models with the gravitino as LSP

2500

**SUSY** 

**Standard Model** 

1000

1500

2000

Meff = Etmiss +  $\Sigma$  pT(jets)

M<sub>eff</sub> (GeV)

#### ATLAS SUSY Searches\* - 95% CL Lower Limits

010	lius. July 2015	0 11 T 0	· · · · · · · · · · · · · · · · · · ·	rmiss	fe Hin-		$\sqrt{s} = 7$ , o lev	
	Model	ε,μ,ι,γ	Jets	T		$\frac{1}{\sqrt{s}} = \frac{1}{\sqrt{s}} = 1$	Reference	
Inclusive Searches	$ \begin{array}{l} MSUGRA/CMSSM \\ \tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_{1}^{0} \\ \tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_{1}^{0} \\ (compressed) \\ \tilde{q}\tilde{q}, \tilde{q} \rightarrow q (\ell \ell / \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q \tilde{\chi}_{1}^{1} \rightarrow q q W^{\pm} \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q \tilde{\chi}_{1}^{\pm} \rightarrow q q W^{\pm} \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow q q (\ell \ell / \ell \nu / \nu \nu) \tilde{\chi}_{1}^{0} \\ GMSB (\ell  NLSP) \\ GGM (bino  NLSP) \\ GGM (higgsino-bino  NLSP) \\ GGM (higgsino-bino  NLSP) \\ GGM (higgsino  NLSP) \\ GGM (higgsino  NLSP) \\ GGM (higgsino  NLSP) \\ GGM (higgsino  NLSP) \\ \end{aligned} $	$\begin{array}{c} 0{\text{-}}3 \ e, \mu / 1{\text{-}}2 \ \tau \\ 0 \\ \text{mono-jet} \\ 2 \ e, \mu \ (\text{off-}Z) \\ 0 \\ 0{\text{-}}1 \ e, \mu \\ 2 \ e, \mu \\ 1{\text{-}}2 \ \tau + 0{\text{-}}1 \ \ell \\ 2 \ \gamma \\ \gamma \\ 2 \ e, \mu \ (Z) \end{array}$	2-10 jets/3 <i>b</i> 2-6 jets 1-3 jets 2-6 jets 2-6 jets 2-6 jets 0-3 jets 0-3 jets 1 <i>b</i> 2 jets 2 jets	Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20 20 20.3 20.3 20.3	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	1507.05525 1405.7875 1507.05525 1503.03290 1405.7875 1507.05525 1501.03555 1407.0603 1507.05493 1507.05493 1507.05493	
3 <sup>ru</sup> gen. § med.	$\begin{array}{c} \tilde{g}\tilde{g}, \tilde{g} \rightarrow b \bar{b} \tilde{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow t \bar{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow t \bar{\chi}_{1}^{0} \\ \tilde{g}\tilde{g}, \tilde{g} \rightarrow b \bar{t} \tilde{\chi}_{1}^{1} \end{array}$	0 0 0-1 <i>e</i> , μ 0-1 <i>e</i> , μ	3 <i>b</i> 7-10 jets 3 <i>b</i> 3 <i>b</i> 3 <i>b</i>	Yes Yes Yes Yes	20.3 20.1 20.3 20.1 20.1	Ref         Ref <th ref<="" td="" th<=""><td>1407.0600 1308.1841 1407.0600 1407.0600</td></th>	<td>1407.0600 1308.1841 1407.0600 1407.0600</td>	1407.0600 1308.1841 1407.0600 1407.0600
3 <sup>ru</sup> gen. squarks direct production	$ \begin{split} \tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 \\ \tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow t \tilde{\chi}_1^{\tilde{\tau}} \\ \tilde{t}_1 \tilde{i}_1, \tilde{i}_1 \rightarrow b \tilde{\chi}_1^{\tilde{\tau}} \\ \tilde{t}_1 \tilde{i}_1, \tilde{i}_1 \rightarrow b \tilde{\chi}_1^{\tilde{\tau}} \\ \tilde{t}_1 \tilde{i}_1, \tilde{i}_1 \rightarrow c \tilde{\chi}_1^0 \\ \tilde{t}_1 \tilde{i}_1, \tilde{i}_1 \rightarrow c \tilde{\chi}_1^0 \\ \tilde{t}_1 \tilde{i}_1 (natural GMSB) \\ \tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z \end{split} $	0 2 $e, \mu$ (SS) 1-2 $e, \mu$ 0 $e, \mu$ 2 $e, \mu$ (Z) 3 $e, \mu$ (Z)	2 b 0-3 b 1-2 b 0-2 jets/1-2 l nono-jet/c-ta 1 b 1 b	Yes Yes Yes 4 Yes Yes Yes Yes	20.1 20.3 20.3 20.3 20.3 20.3 20.3 20.3	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	1308.2631 1404.2500 1209.2102, 1407.0583 1506.08616 1407.0608 1403.5222 1403.5222	
EW direct	$ \begin{array}{l} \tilde{\ell}_{L,R} \tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\ell} \nu (\ell \tilde{\nu}) \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau} \nu (\tau \tilde{\nu}) \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{0} \rightarrow \ell_{L} \nu \tilde{\ell}_{L} \ell (\tilde{\nu} \nu), \ell \tilde{\nu} \tilde{\ell}_{L} \ell (\tilde{\nu} \nu) \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} Z \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{2}^{+} \tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} \Lambda \tilde{\chi}_{1}^{0}, h \rightarrow b \tilde{b} / W W / \tau t \\ \tilde{\chi}_{2}^{+} \tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} \Lambda \tilde{\chi}_{2}^{0}, \tilde{\chi}_{2}^{0} \rightarrow \tilde{\chi}_{R} \ell \\ \text{GGM (wino NLSP) weak prod.} \end{array} $	2 e,μ 2 e,μ 2 τ 3 e,μ 2-3 e,μ r/γγ e,μ,γ 4 e,μ 1 e,μ + γ	0 0 0-2 jets 0-2 b 0	Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	1403.5294 1403.5294 1407.0350 1402.7029 1403.5294, 1402.7029 1501.07110 1405.5086 1507.05493	
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}$ Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}$ Stable, stopped $\tilde{g}$ R-hadron Stable $\tilde{g}$ R-hadron GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{\epsilon}, \tilde{\mu}) + \tau$ GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ , long-lived $\tilde{\chi}_1^0$ $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow eev/e\mu v/\mu\mu v$ GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$	$ \begin{array}{c} \overset{\pm}{l} & \text{Disapp. trk} \\ \overset{\pm}{l} & \text{dE/dx trk} \\ & 0 \\ \text{trk} \\ (e,\mu) & 1\text{-}2\mu \\ & 2\gamma \\ \text{displ. } ee/e\mu/\mu \\ \text{displ. vtx + je} \end{array} $	1 jet 1-5 Jets - - - μμ - ts -	Yes Yes - - Yes -	20.3 18.4 27.9 19.1 19.1 20.3 20.3 20.3	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	1310.3675 1506.05332 1310.6584 1411.6795 1411.6795 1409.5542 1504.05162 1504.05162	
RPV	$ \begin{array}{c} LFV pp \rightarrow \tilde{\mathbf{v}}_{\tau} + X, \tilde{\mathbf{v}}_{\tau} \rightarrow e\mu/e\tau/\mu\tau \\ Bilinear \ RPV \ CMSSM \\ \tilde{X}_1^+ \tilde{X}_1^-, \tilde{X}_1^+ \rightarrow W \tilde{X}_1^0, \tilde{X}_1^0 \rightarrow ee\tilde{v}_{\mu}, e\mu \tilde{v}, \\ \tilde{X}_1^+ \tilde{X}_1^-, \tilde{X}_1^+ \rightarrow W \tilde{X}_1^0, \tilde{X}_1^0 \rightarrow \tau\tau \tilde{v}_e, e\tau \tilde{v}, \\ \tilde{g}s, \tilde{g} \rightarrow qqq \\ \tilde{g}s, \tilde{g} \rightarrow q\tilde{x}_1^0, \tilde{X}_1^0 \rightarrow qqq \\ \tilde{g}s, \tilde{g} \rightarrow \tilde{t}_1, \tilde{t}_1 \rightarrow bs \\ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs \\ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b\ell \end{array} $	$e\mu,e\tau,\mu\tau \\ 2 e,\mu (SS) \\ e 4 e,\mu \\ 3 e,\mu+\tau \\ 0 \\ 2 e,\mu (SS) \\ 0 \\ 2 e,\mu \\ $	- 0-3 b - - 6-7 jets 6-7 jets 0-3 b 2 jets + 2 b 2 b	- Yes Yes - - Yes - -	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	Pr     1.7 TeV     X <sup>1</sup> <sub>311</sub> =0.11, X <sub>132/133/233</sub> =0.07 $\tilde{t}, \tilde{g}$ 1.35 TeV     m( $\tilde{q}$ )=m( $\tilde{g}$ ), $c_{T_{LSP}} < 1$ mm $\tilde{t}_1^+$ 750 GeV     m( $\tilde{t}_1^0$ )>0.2×m( $\tilde{t}_1^+$ ), $\lambda_{121} \neq 0$ $\tilde{t}_1^+$ 450 GeV     m( $\tilde{t}_1^0$ )>0.2×m( $\tilde{t}_1^+$ ), $\lambda_{133} \neq 0$ g     917 GeV     BR(t)=BR(t)=BR(t)=BR(c)=0%       g     850 GeV     m( $\tilde{t}_1^0$ )=600 GeV       g     850 GeV     BR( $\tilde{t}_1 \rightarrow be/\mu$ )>20%	1503.04430 1404.2500 1405.5086 1502.05686 1502.05686 1404.250 ATLAS-CONF-2015-026 ATLAS-CONF-2015-015	
Other	Scalar charm, $\tilde{c} \rightarrow c \tilde{\chi}_1^0$	0	2 c	Yes	20.3	e <b>490 GeV</b> m(ℓ <sub>1</sub> <sup>0</sup> )<200 GeV	1501.01325	

tes or phenomena is shown. All limits quoted are observed minus 1 or theoretical signal cross section uncertainty.



# Searches for heavy W and Z like particles

# These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z': Di-lepton pairs

W': Lepton + ETmiss



#### Lower mass limits, at 95% CL, for spin-2 Randall-Sundrum Gravitons





R Sundrum L Randall F Gianotti

Phys. Rev. D90 (2014) 052005

CPPM, AMU, 13-Nov-2015 P Jenni (Freiburg and CERN)



#### The search for high-mass objects is exciting with the much higher cross sections now in LHC Run-2



10<sup>°</sup>

10<sup>9</sup>

proton - (anti)proton cross sections



#### 13 TeV / 8 TeV inclusive pp cross-section ratio

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### LHC / HL-LHC Plan





Upgrade of DAQ detector readout

# LHC roadmap: Goal of 3'000 fb<sup>-1</sup> by mid 2030s



Year

CPPM, AMU, 13-Nov-2015 P Jenni (Freiburg and CERN) High Luminosity project (HL-LHC)
# **Examples of SUSY and** Z' mass reaches at HL-LHC



ATL-PHYS-PUB-2013-007, arXiv:1307.7292[hep-ex]

# **Outlook for HL-LHC on the Higgs physics**



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LHC, Higgs Boson, and Beyond

#### A very exciting dream for a facility in Europe after the LHC

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh) with possibility of e+-e- (FCC-ee) and p-e (FCC-he)



For a Very High Energy Hadron Collider ranging from 42 TeV (8.3T LHC magnets) to 100 TeV (20T very high field magnets with HTS), and could house first an e<sup>+</sup>e<sup>-</sup> collider up to 350 GeV



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### Cross sections vs $\sqrt{s}$



### The journey into new physics territory has just only begun, and for sure, exciting times are ahead of us!

