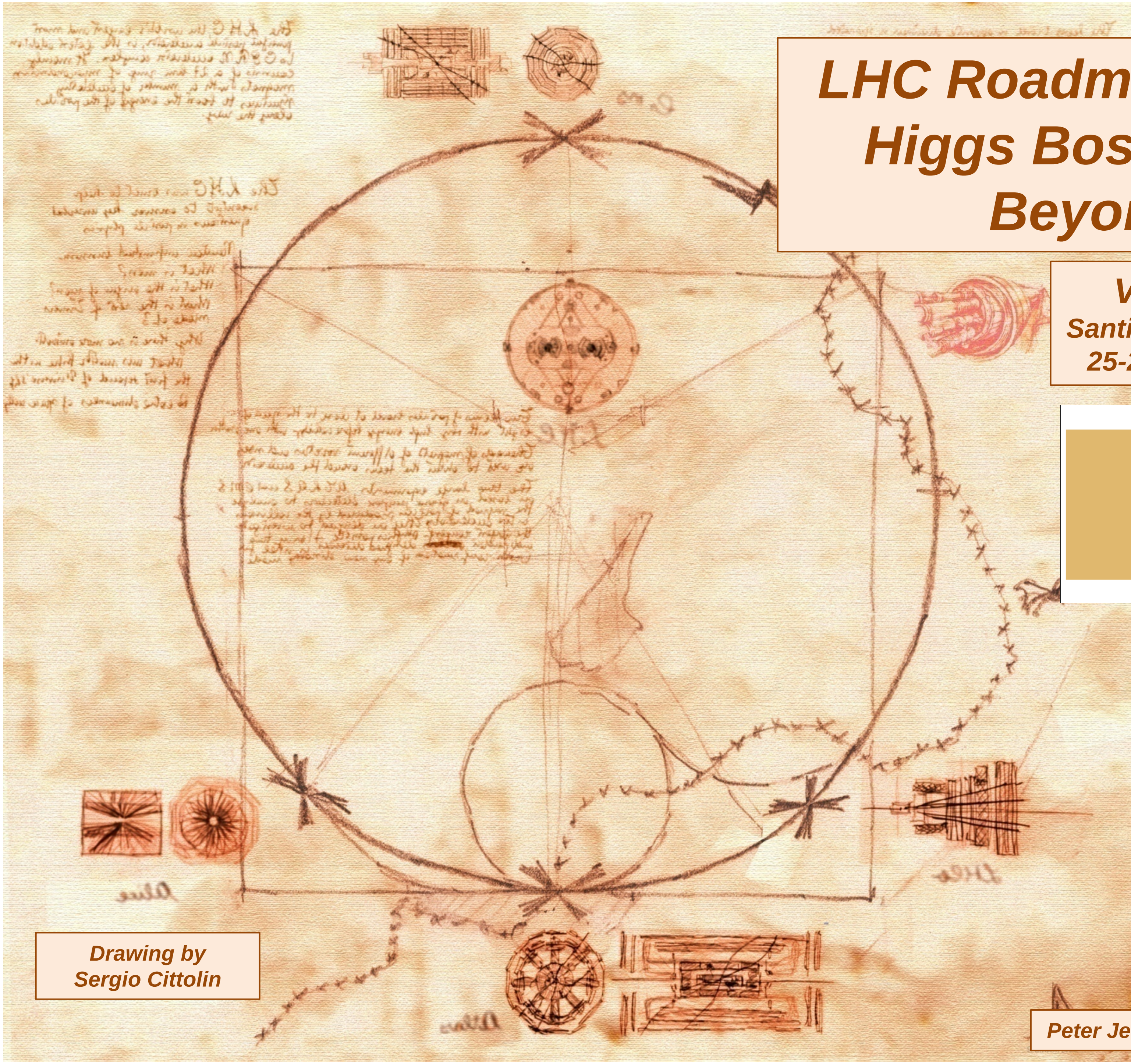
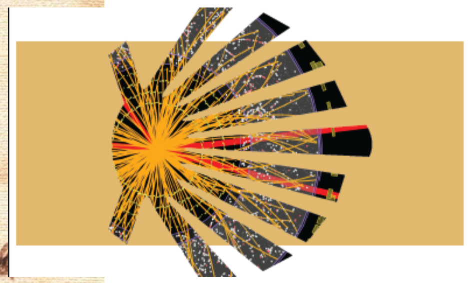


LHC Roadmap to the Higgs Boson and Beyond

V CPAN Days

Santiago de Compostela

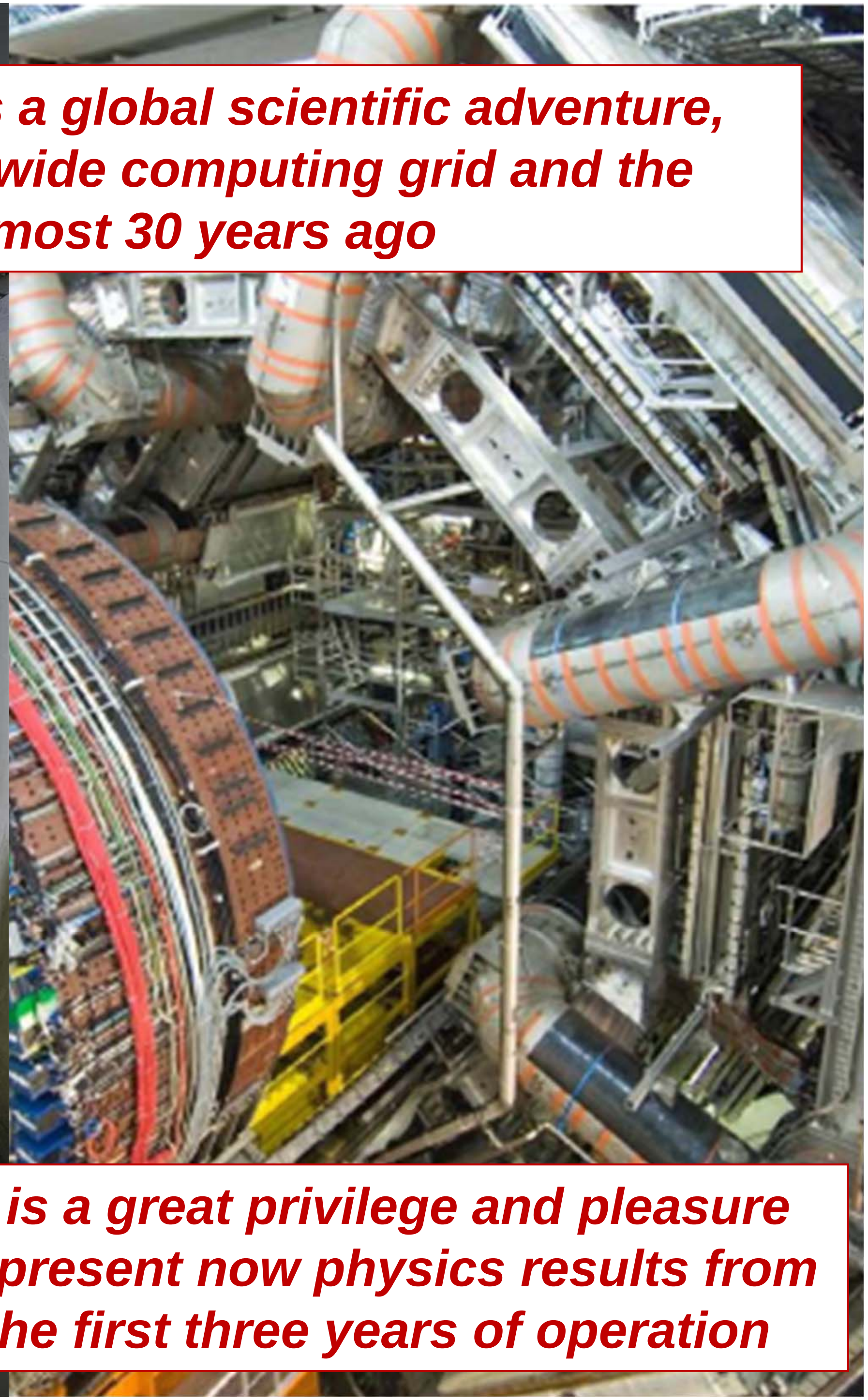
25-27 November 2013



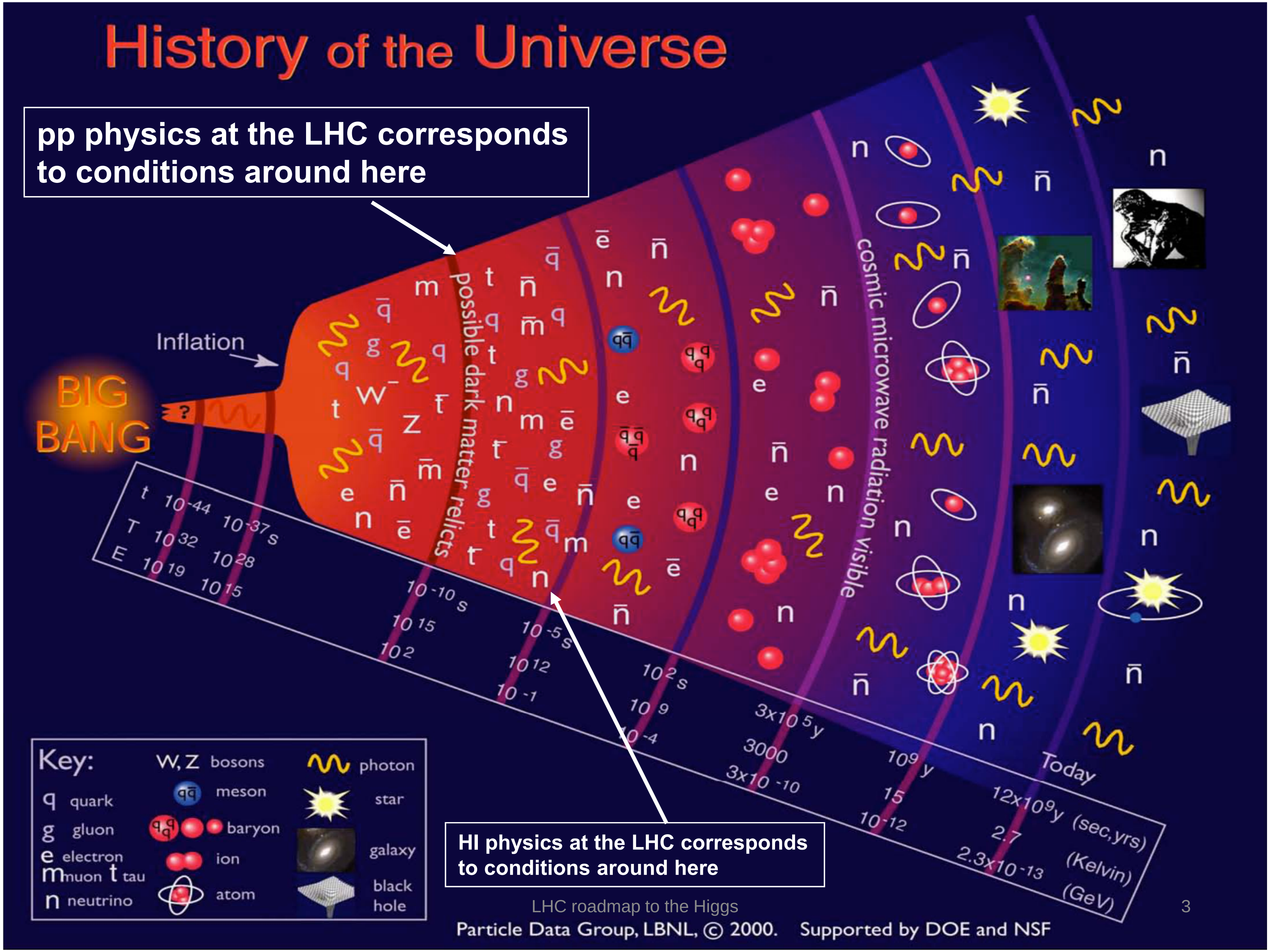
Drawing by Sergio Cittolin

Peter Jenni, Freiburg and CERN

The Large Hadron Collider project is a global scientific adventure, combining the accelerator, a worldwide computing grid and the experiments, initiated almost 30 years ago



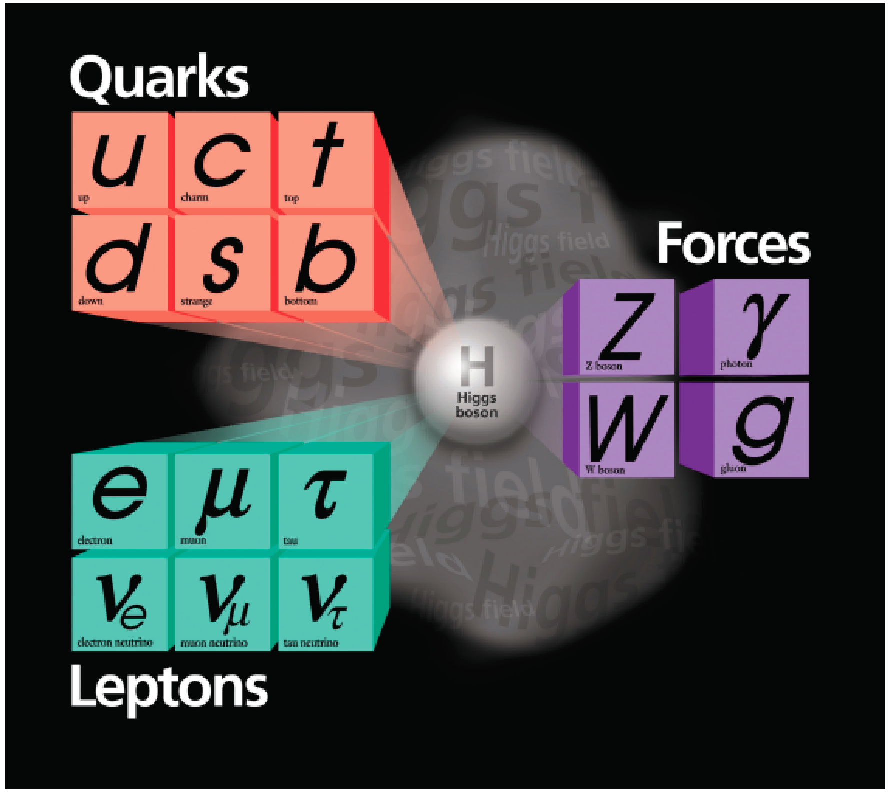
It is a great privilege and pleasure to present now physics results from the first three years of operation

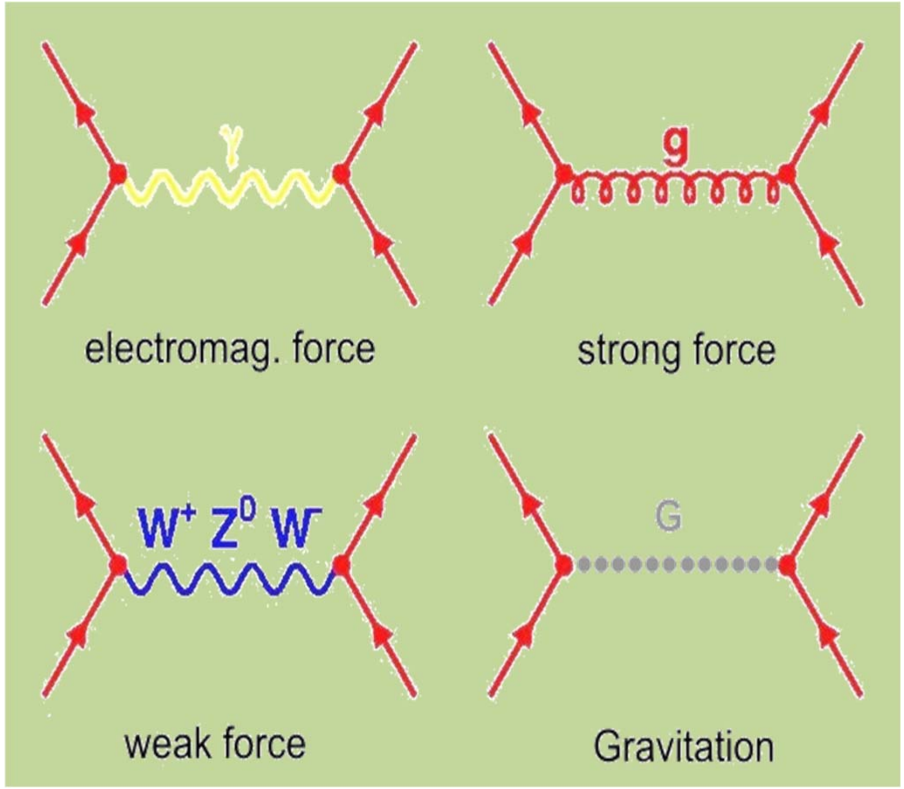


pp physics at the LHC corresponds to conditions around here

HI physics at the LHC corresponds to conditions around here

The Standard Model of Particle Physics



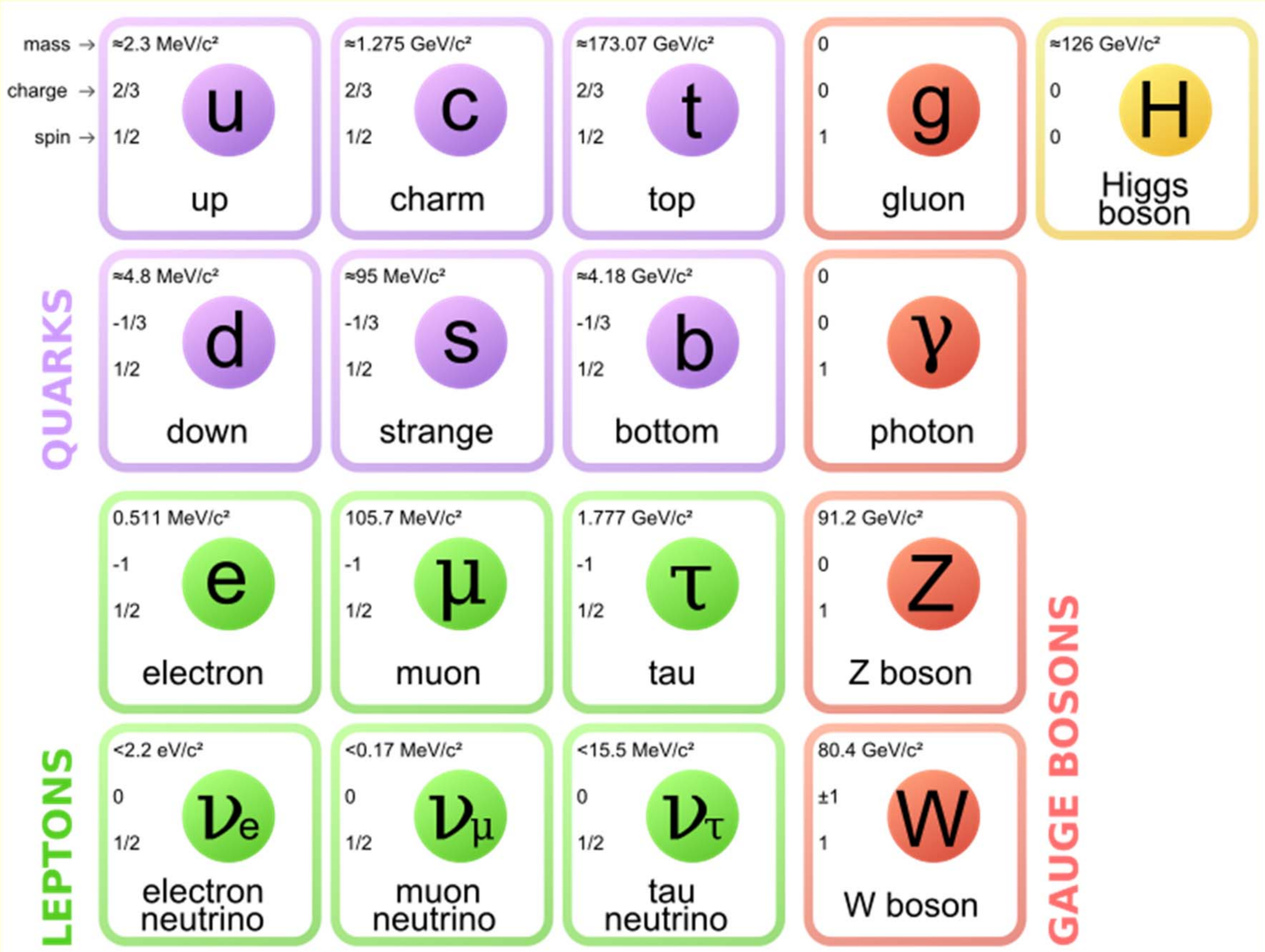


(i) Constituents of matter: quarks and leptons

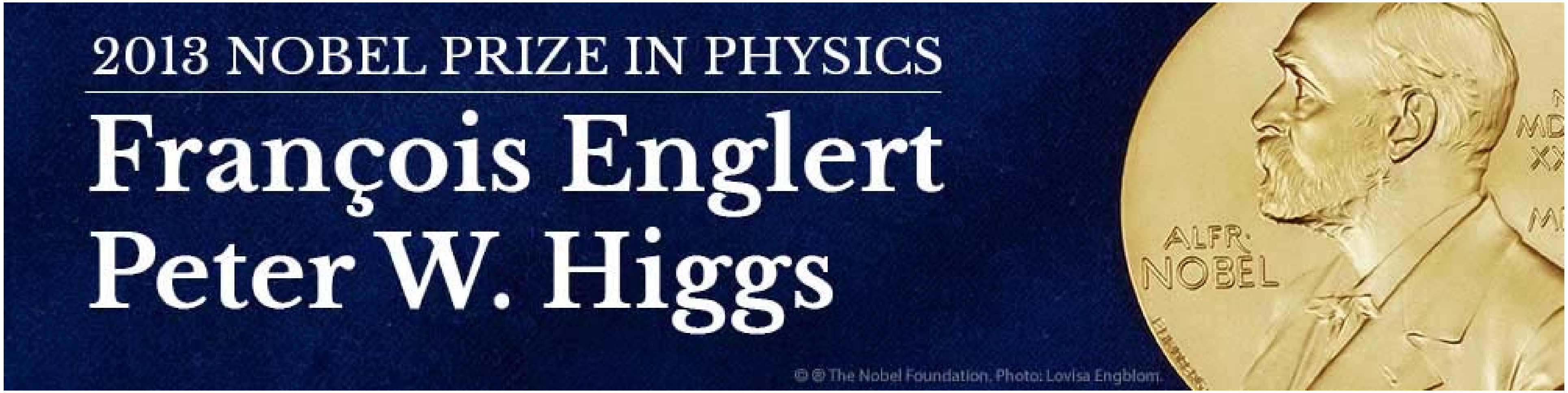
(ii) Four fundamental forces
(described by quantum field theories, except gravitation)

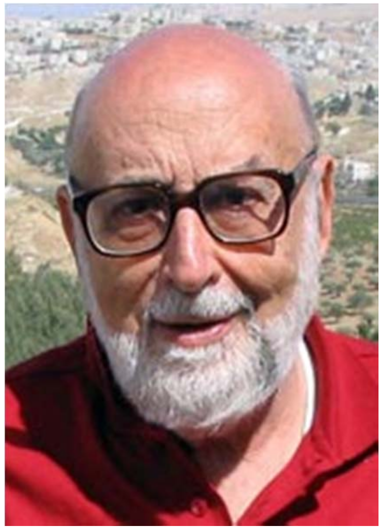
(iii) The Higgs field (problem of mass)

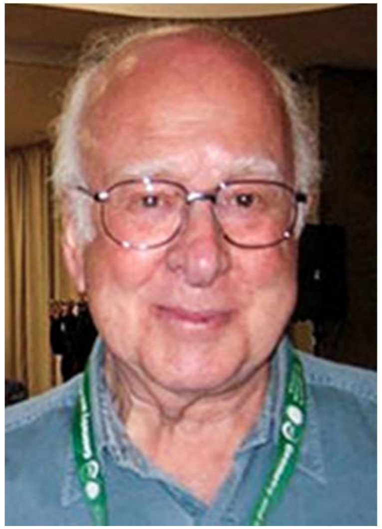
Standard Model of Elementary Particles



On Tuesday 8th October 2013:

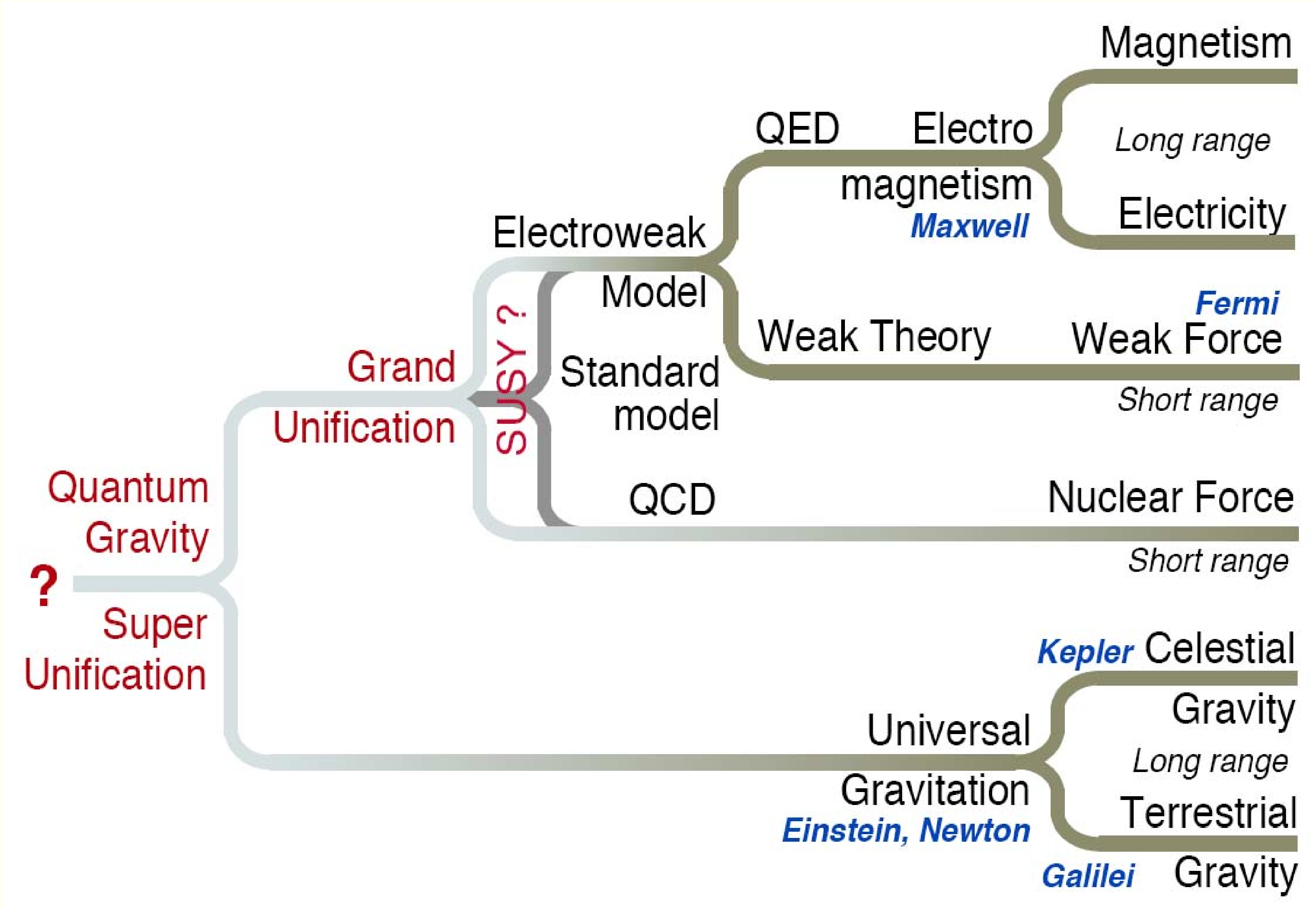






"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Unification of Forces



The SM is not a complete theory

Some of the outstanding questions in fundamental physics addressed, at least in part, with the LHC are:

What is the origin of the elementary particle masses ? (~✔)

What is the nature of the Universe dark matter ?

Why is only matter observed in the Universe as primary constituents and not anti-matter ?

What are the features of the primordial plasma present ~10 μs after the Big Bang ?

What happened in the first moments of the Universe ~10^{-11} s after the Big Bang ?

Are there other forces in addition to the known four ?
Are there additional (microscopic) space dimensions ?
….

The SM is not a complete theory

Some of the outstanding questions in fundamental physics addressed, at least in part, with the LHC are:

What is the origin of the elementary particle masses ? (~✔)

What is the nature of the Universe dark matter ?

Why is only matter observed in the Universe as primary constituents and not anti-matter ?

What are the features of the primordi… present ~10 μs after the Big B…

What happ… … the Universe ~10…

Are th… …er forces in addition to the known four ?
Are there additional (microscopic) space dimensions ?

….

New Physics beyond the Standard Model is needed to answer these and other questions. This New Physics could manifest itself at the ~ TeV energy scale being explored by the LHC

How the LHC came to be …

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

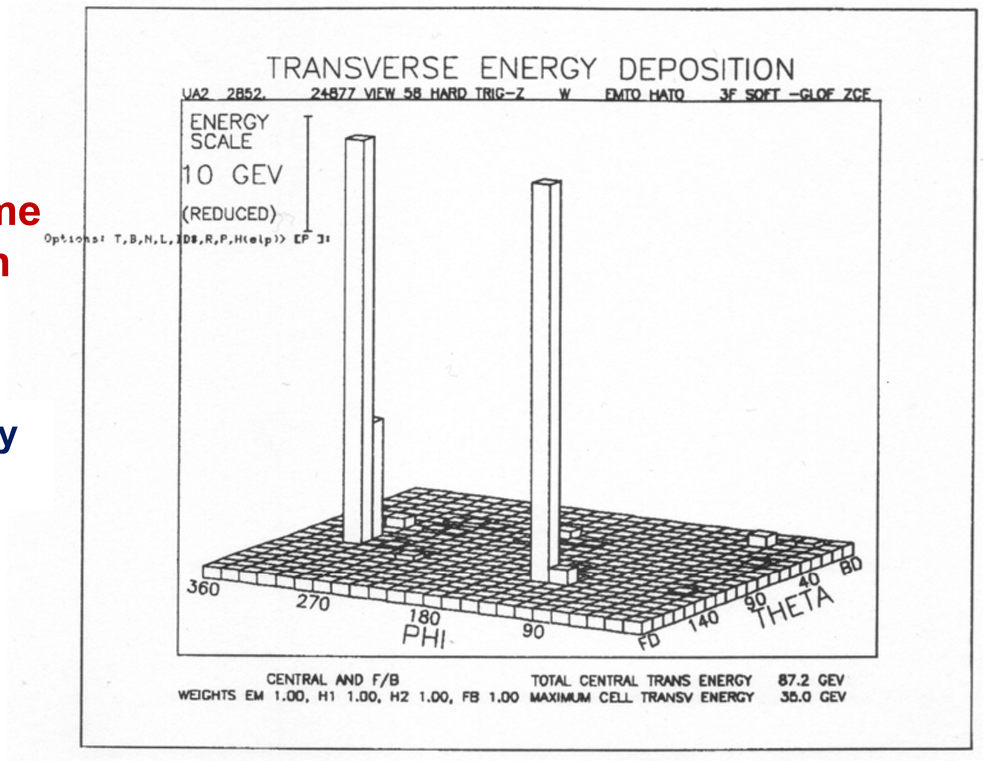
Some early key dates

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) tunnel**

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 → ee online display from one of the detectors (UA2)

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

1987 La Thuile Workshop

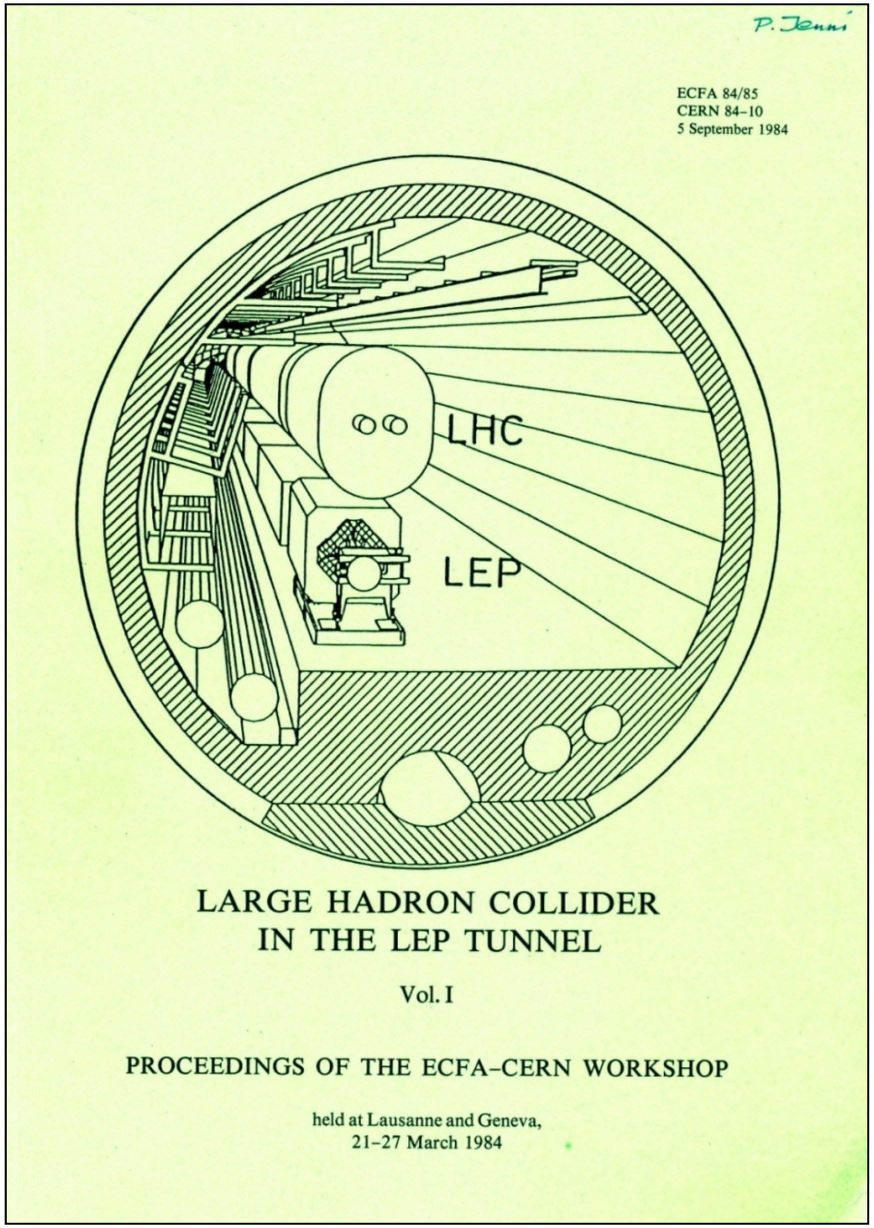
Many LHC colleagues were already involved in this WS set up by Carlo Rubbia as part of the Long Range Planning Committee

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 1st October 1992, more than 20 years ago



ATLAS and CMS were born with Letters of Intent (LoI), submitted on 1st October 1992, more than 20 years ago

Spokesperson Fabiola Gianotti, celebrating 20 years of ATLAS on 1st October 2012

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)

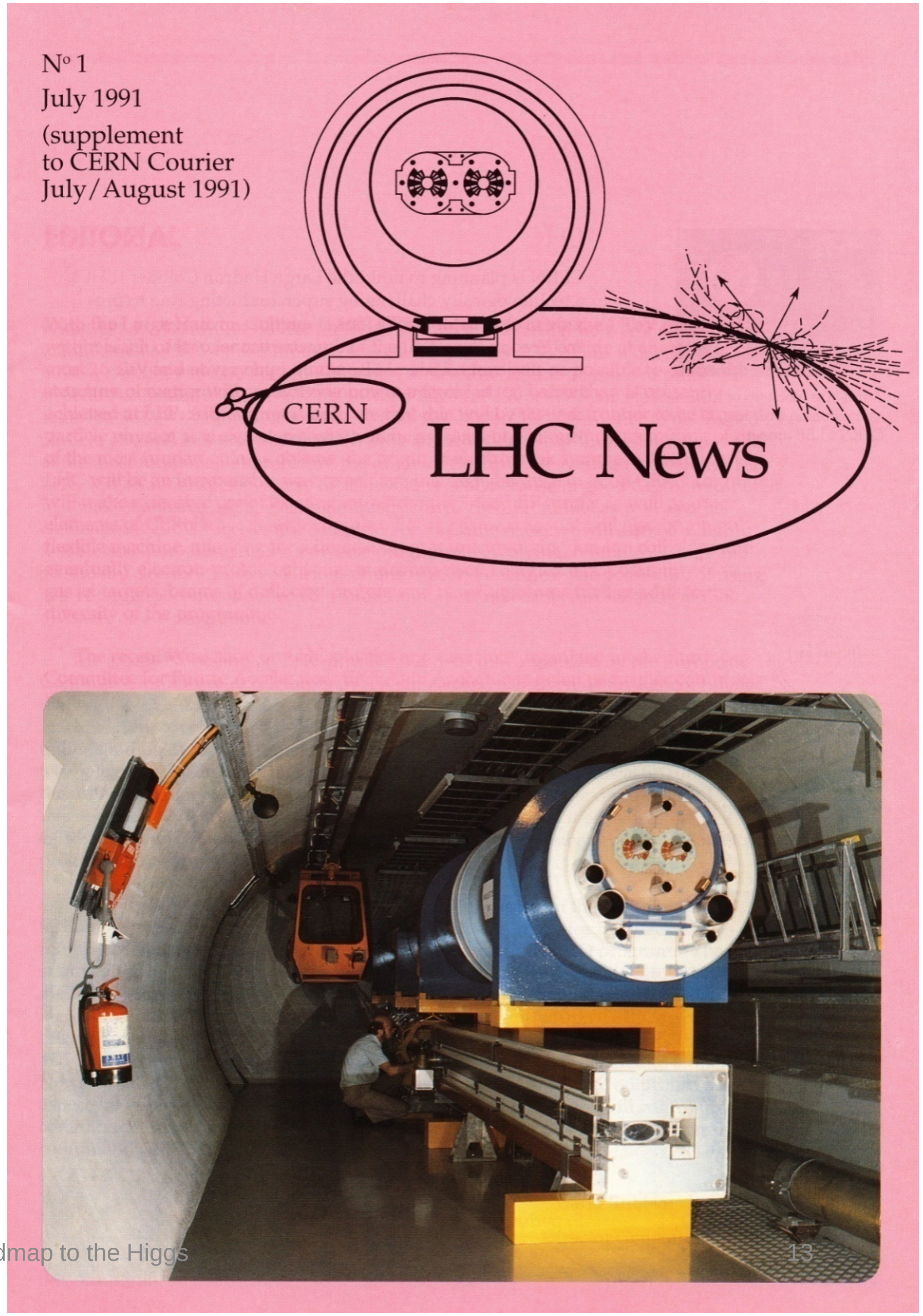
1993 December proposal of LHC with commissioning in 2002

1994 June Council:

Staged construction was proposed by DG Chris Llewellyn Smith, 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

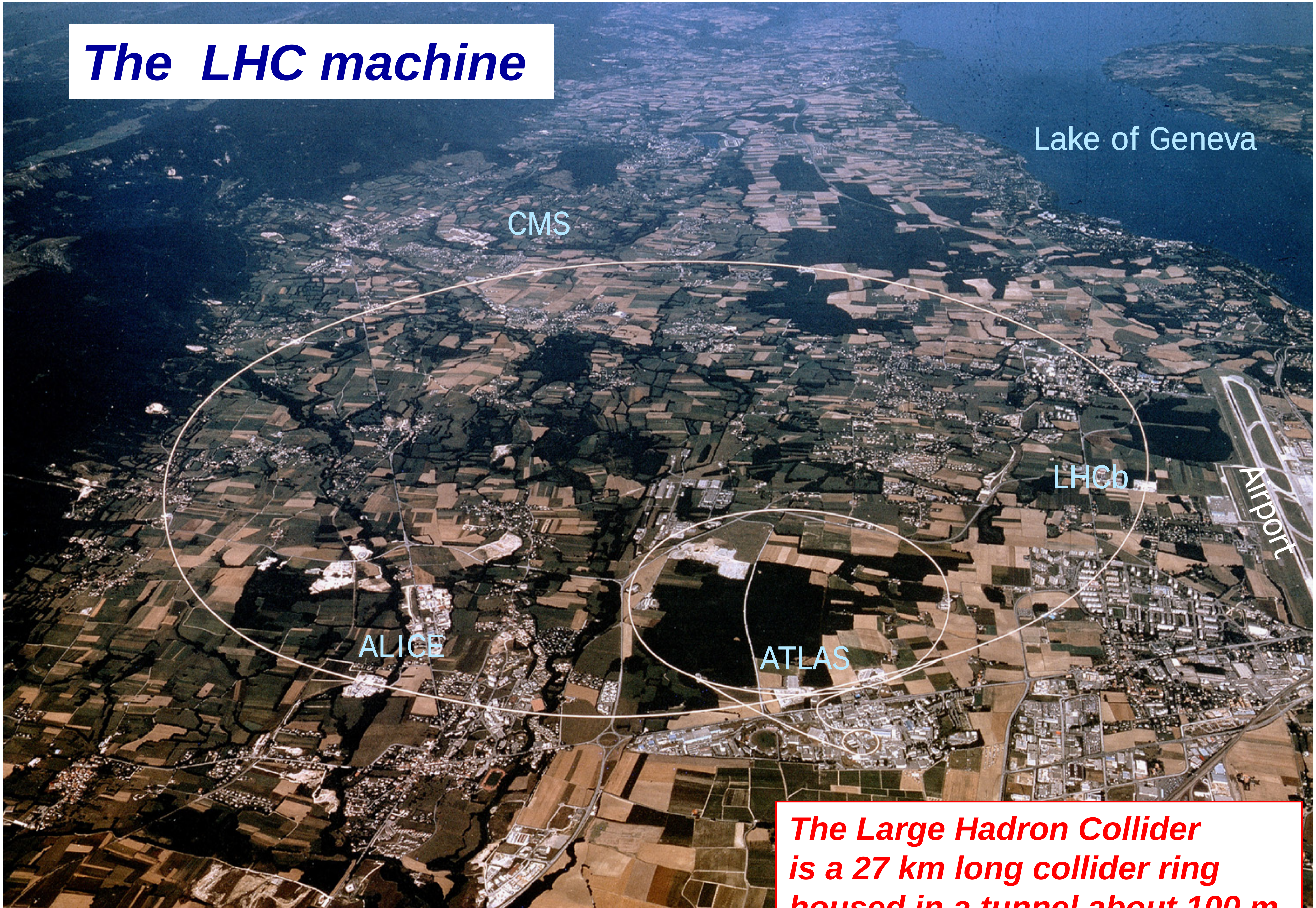
(Israel contributed all along to the full CERN programme and LHC)

1997

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 (15th June 2001), with L Maiani and A Skrinsky in the centre

The LHC machine



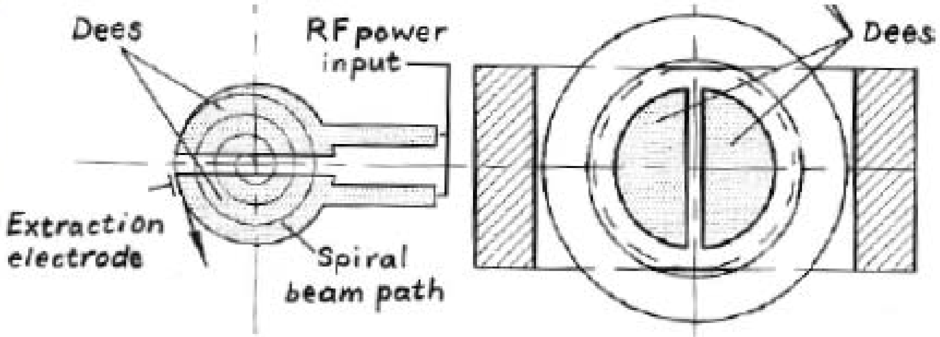
The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

The first cyclotron, and the famous 184” one of Berkeley

Ernest Lawrence
(1901 - 1958)

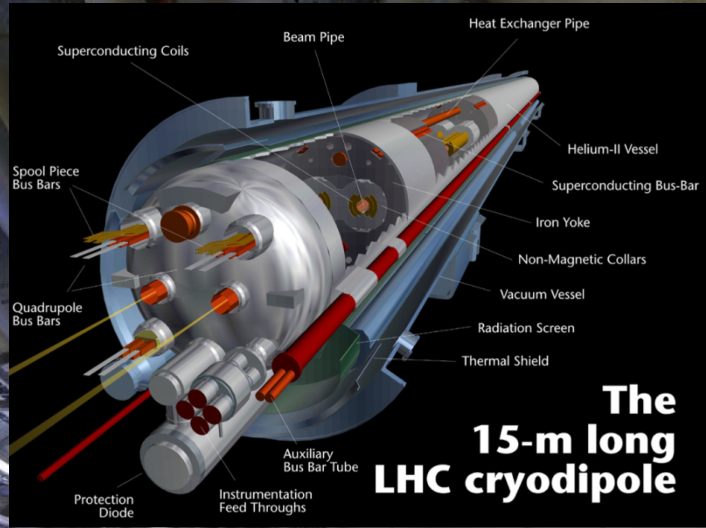
The first circular accelerator
(Berkeley 1930)

184” 1946



The most challenging components were the 1232 high-tech superconducting dipole magnets

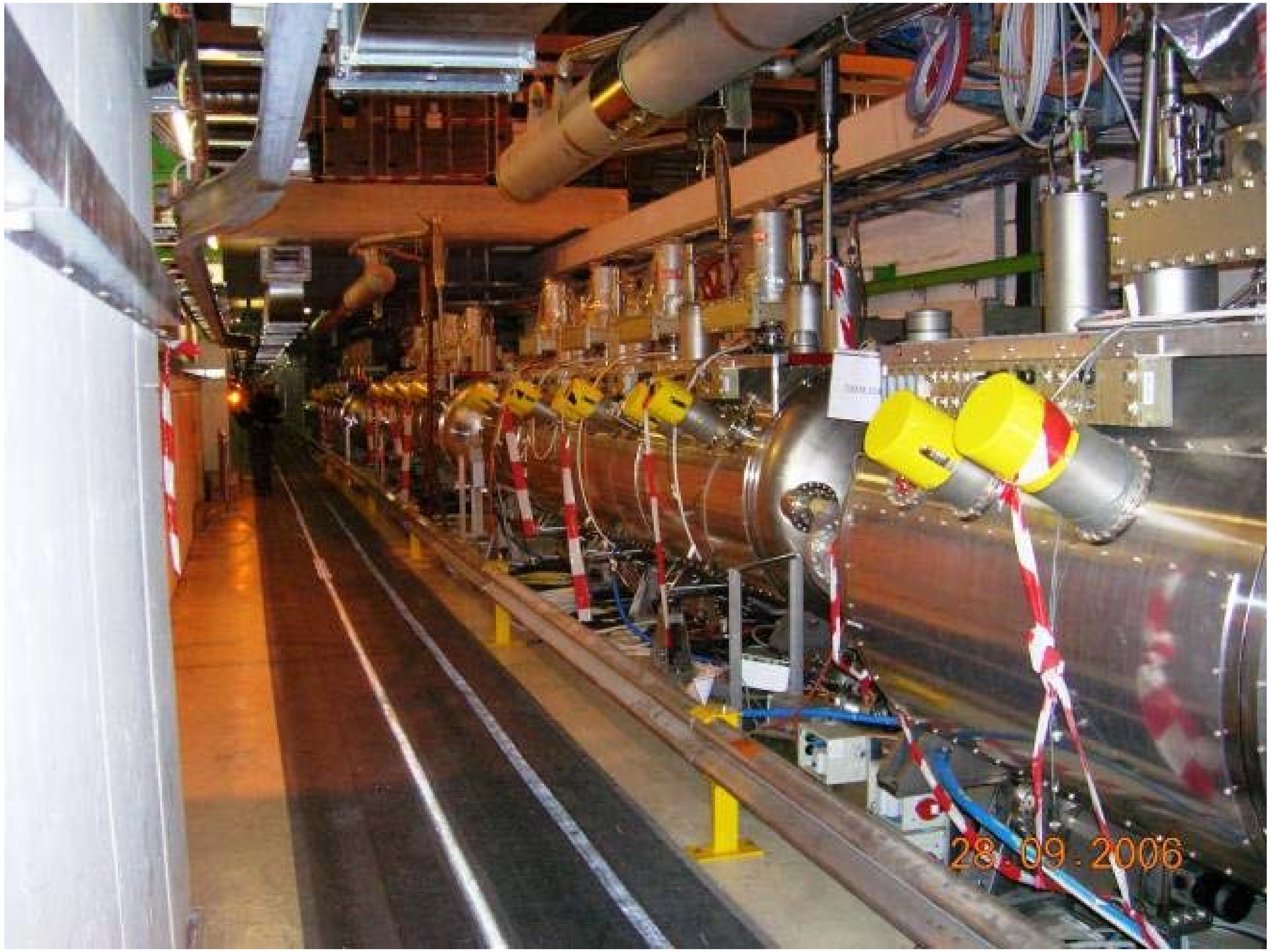
Magnetic field:	8.4 T
Operation temperature:	1.9 K
(120 tons of superfluid Helium)	
Dipole current:	11700 A
Stored energy:	7 MJ
Dipole weight:	34 tons
7600 km of Nb-Ti superconducting cable	

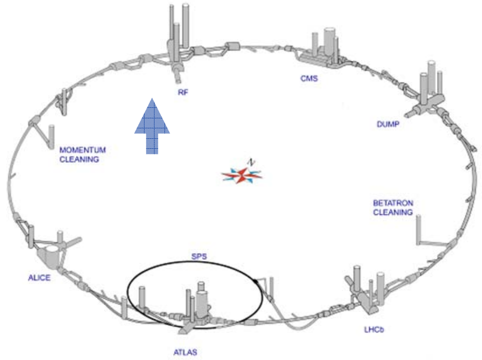


p(TeV) = 0.3 B(T) R(km)

LHC Construction Project Leader Lyndon Evans

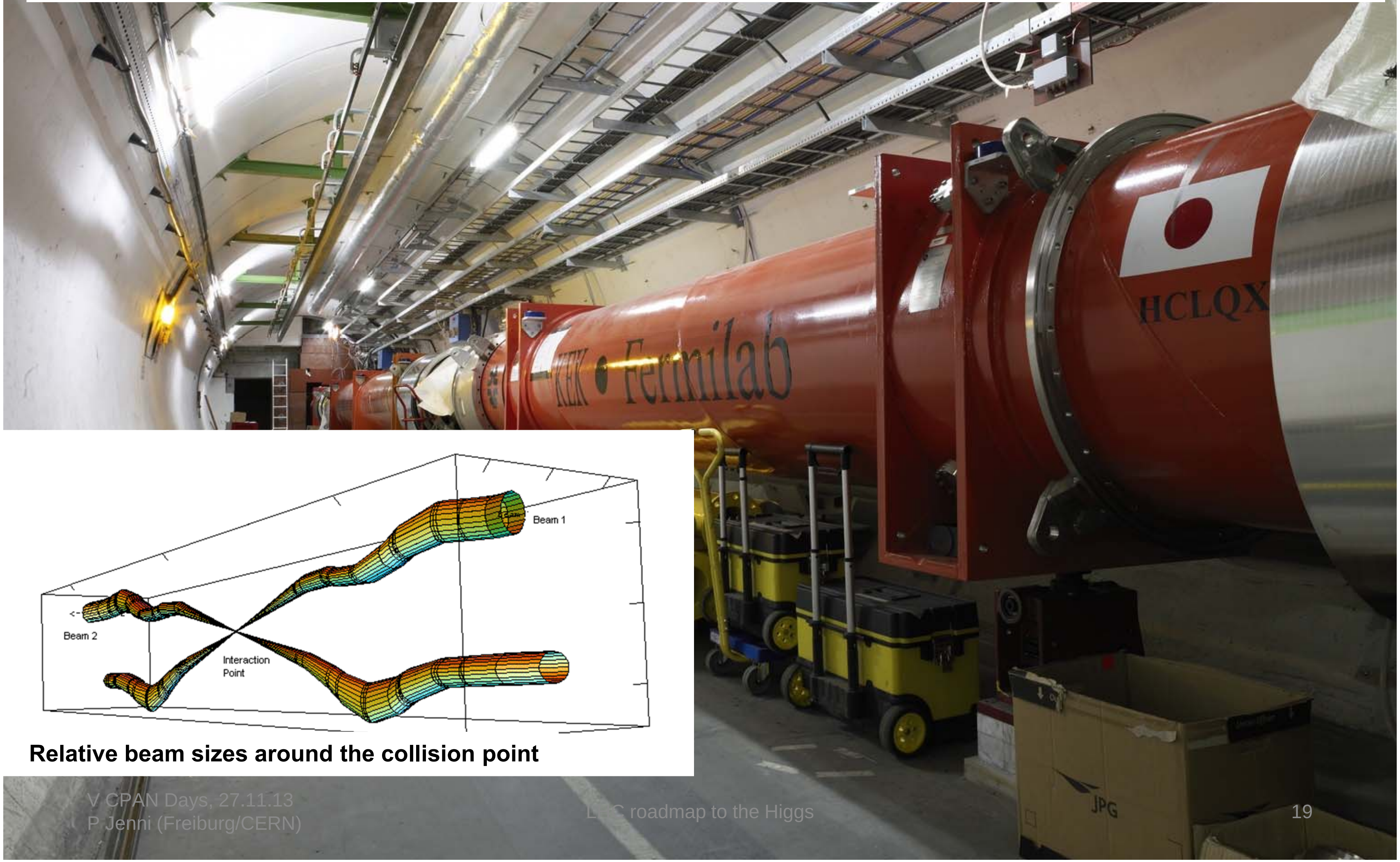
The particle beams are accelerated by superconducting Radio-Frequency (RF) cavities





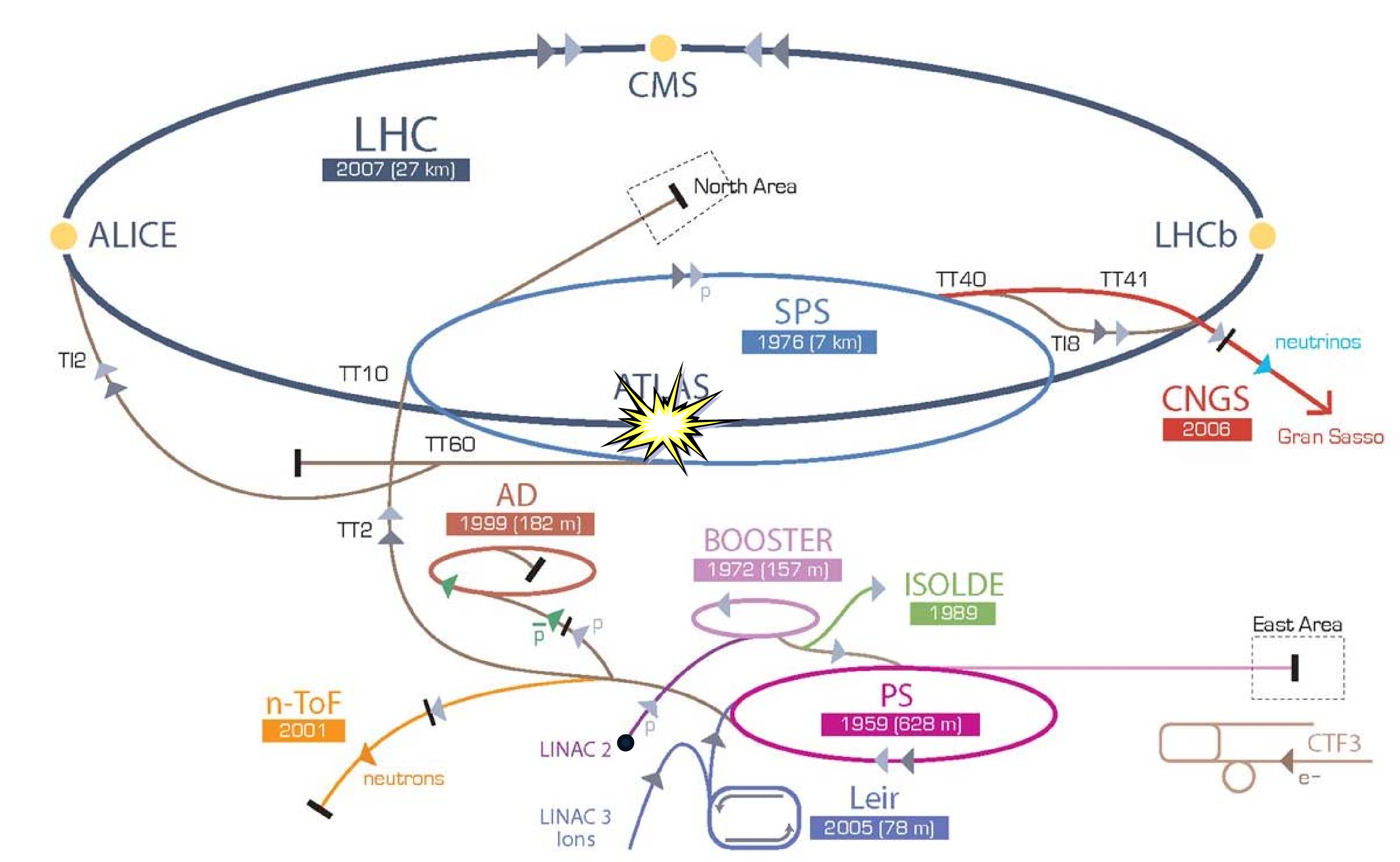
Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the ~ $1/m^4$ behaviour of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

Special quadrupole magnets ('Inner Triplets') are focussing the particle beams to reach highest densities ('luminosity') at their interaction point in the centre of the experiments

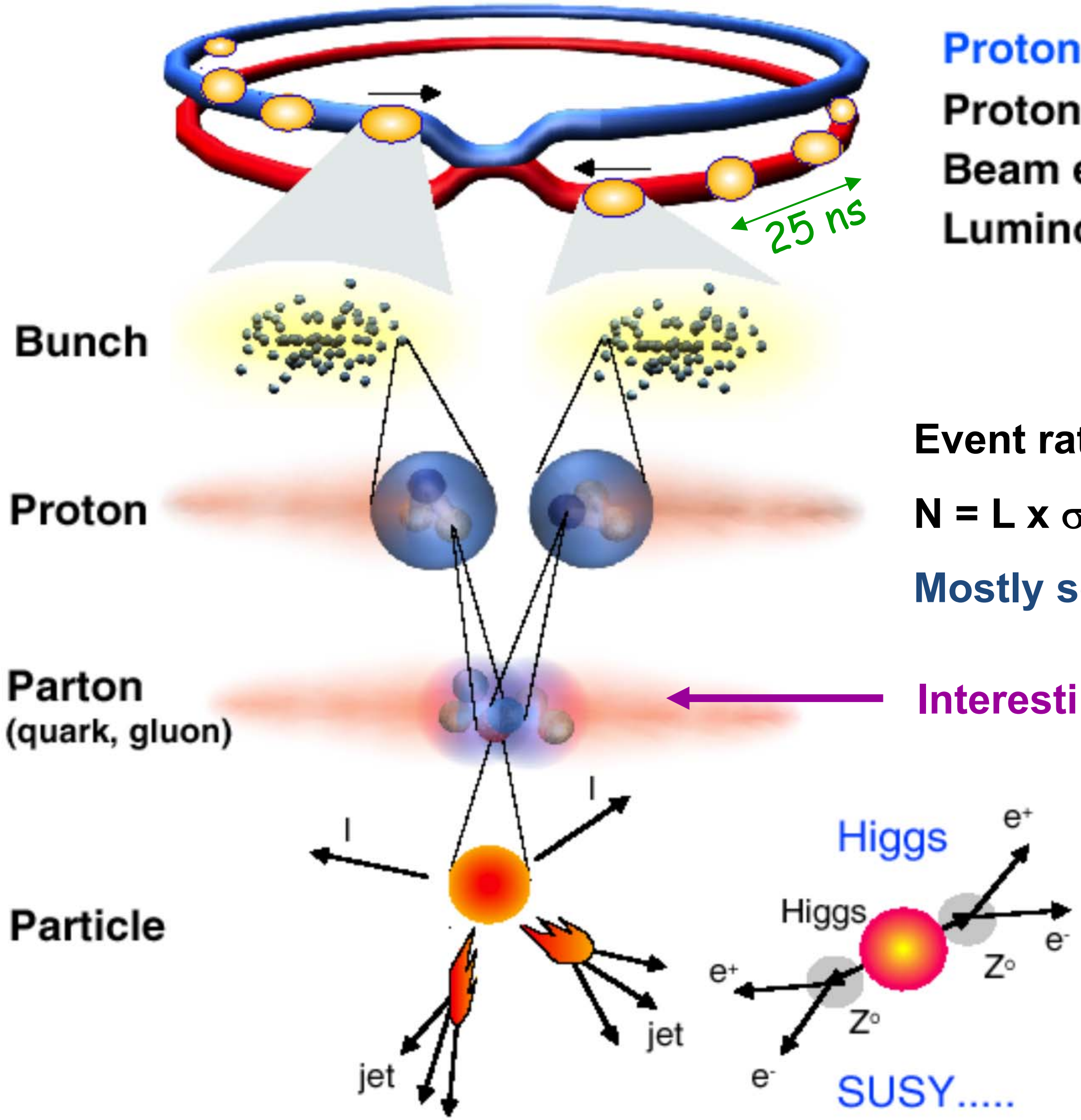


Relative beam sizes around the collision point

CERN's particle accelerator chain



Collisions at LHC



Proton-Proton	
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

$N = L \times \sigma$ (pp) ≈ 10^9 interactions/s

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

Selection of 1 in 10,000,000,000,000

→ very powerful detectors needed

The SM is not a complete theory

Some of the outstanding questions in fundamental physics are

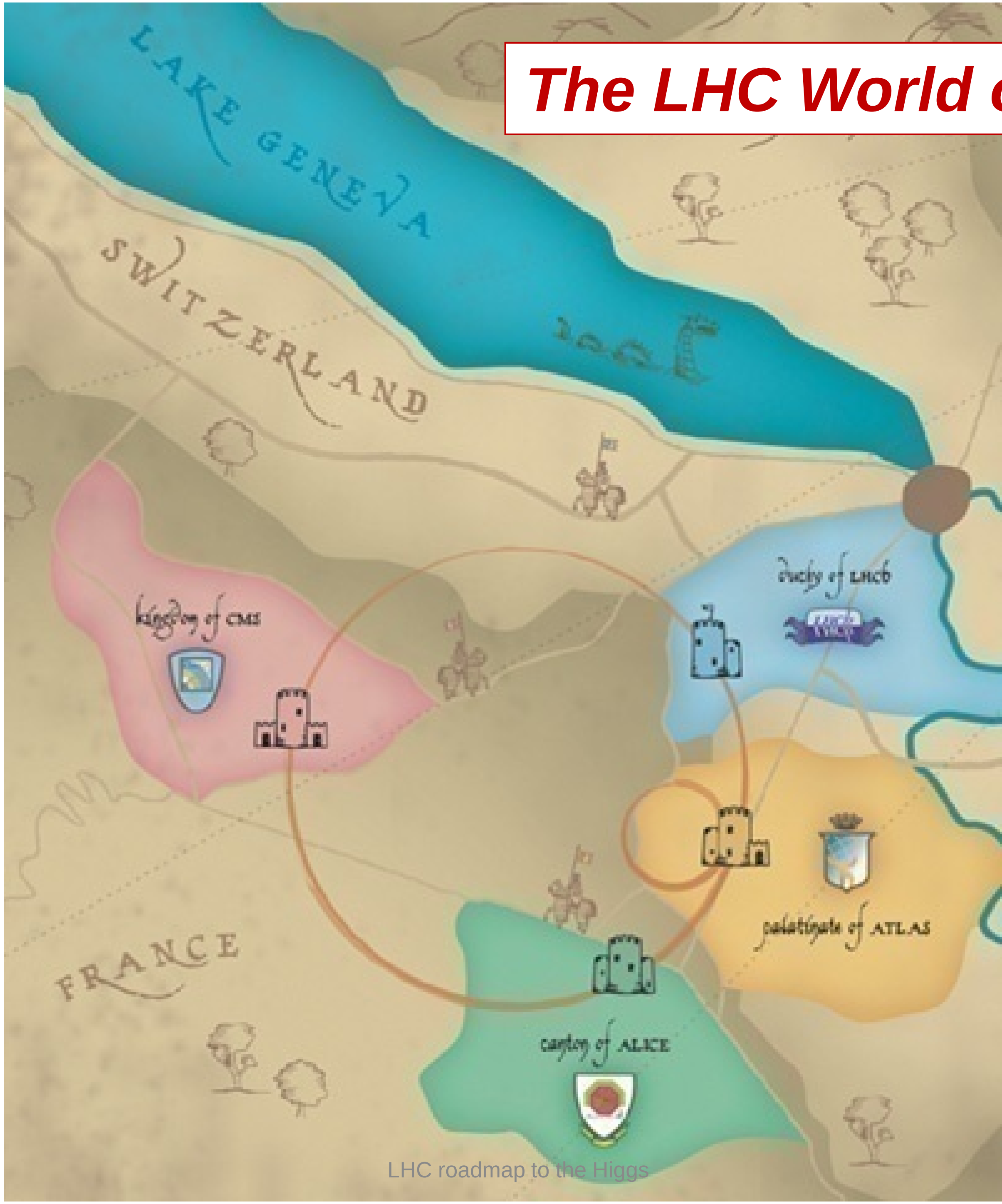
What is the origin of the elementary particle masses ?	ATLAS, CMS
What is the nature of the Universe dark matter ?	ATLAS, CMS
Why is only matter observed in the Universe as primary constituents and not anti-matter ?	LHCb
What are the features of the primordial plasma present ~10 μs after the Big Bang ?	ALICE
What happened in the first moments of the Universe ~10^{-11} s after the Big Bang ?	ATLAS, CMS
Are there other forces in addition to the known four ? Are there additional (microscopic) space dimensions ? ….	ATLAS, CMS

The LHC World of CERN

Plus smaller local earldoms
LHCf (point-1)
TOTEM (point-5)
Moedal (point-8)

CMS
3000 Physicists
184 Institutions
38 countries
550 MCHF

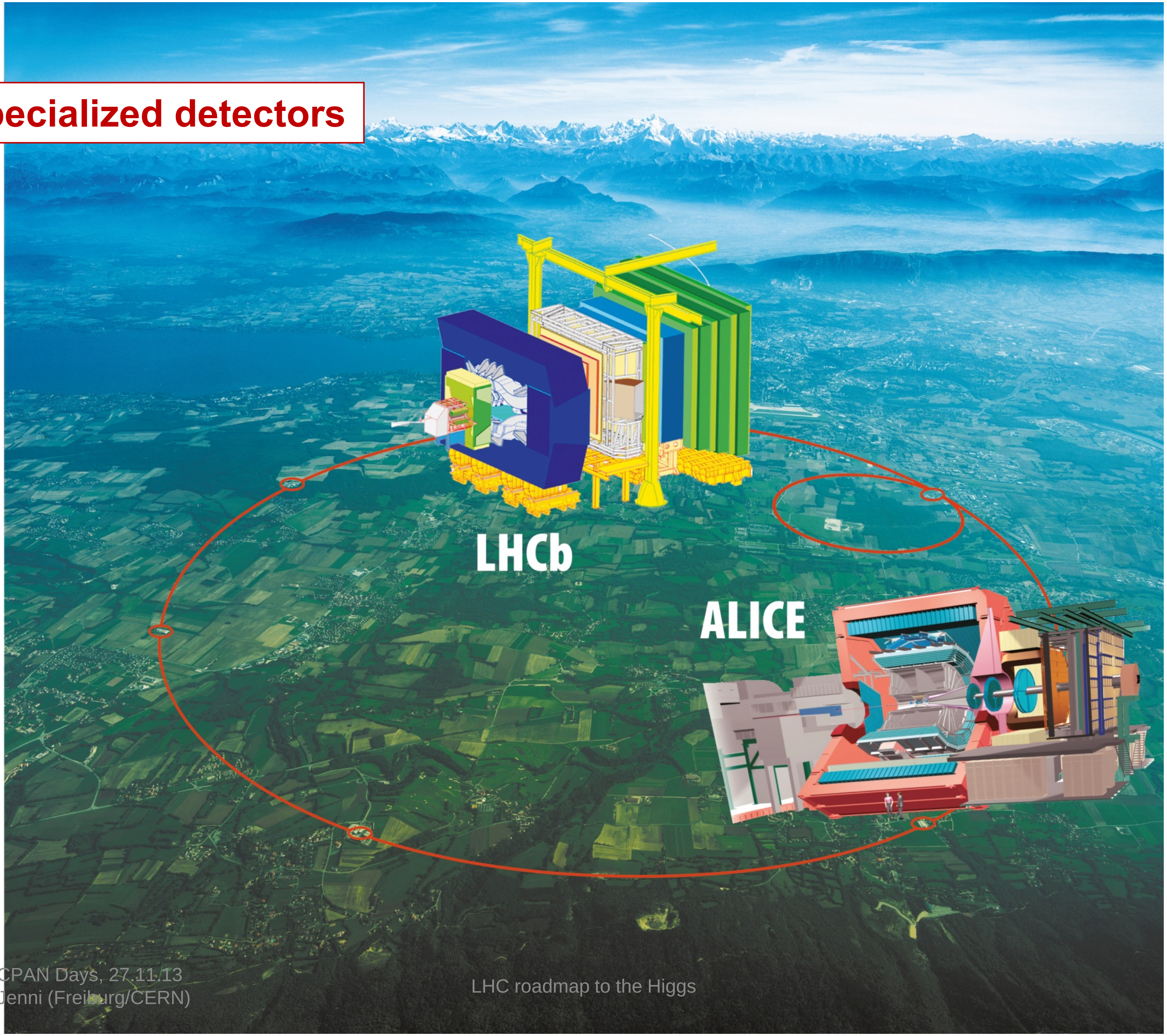
ALICE
1300 Physicists
130 Institutions
35 countries
160 MCHF



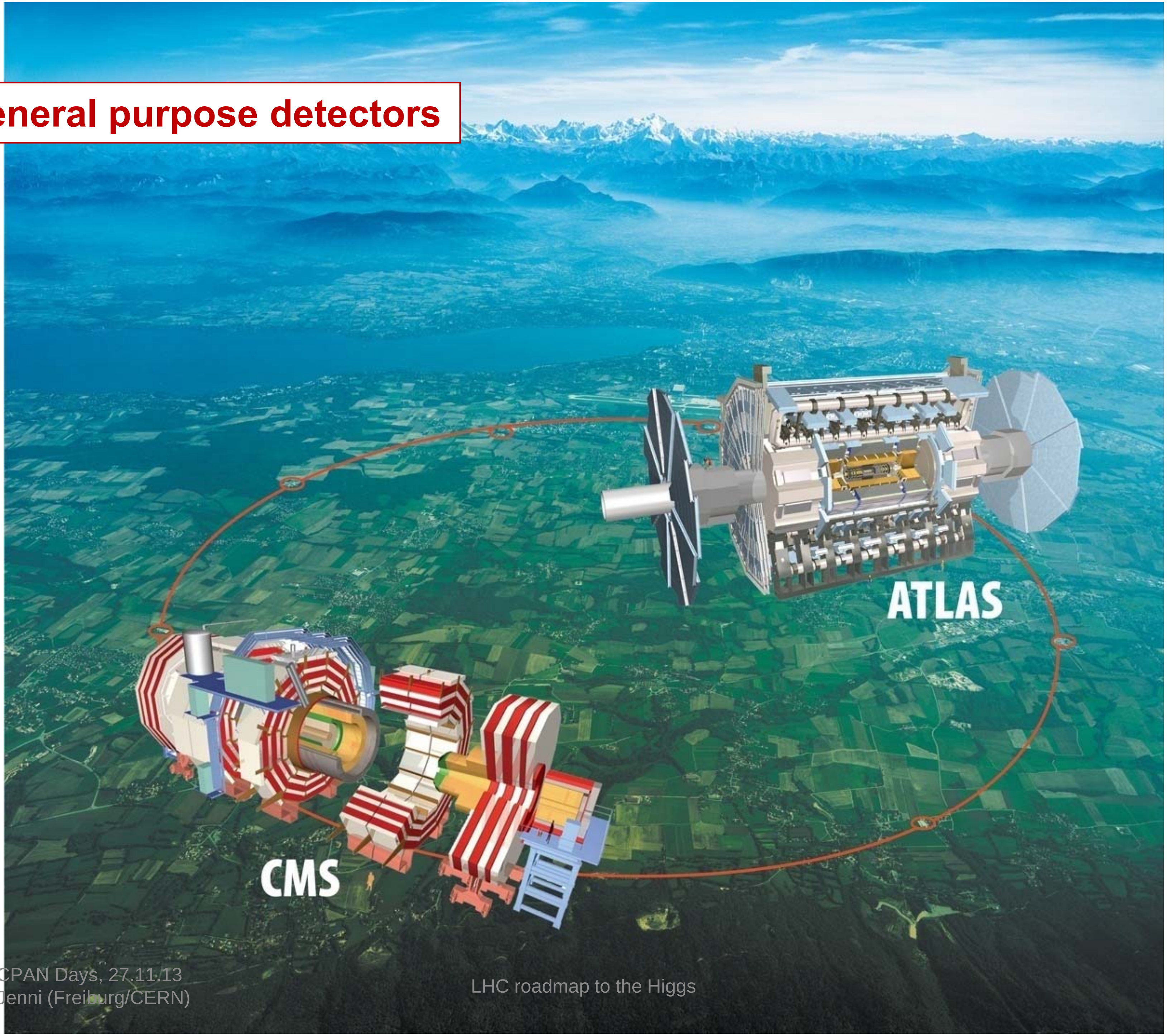
LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

ATLAS
3000 Physicists
177 Institutions
38 countries
550 MCHF

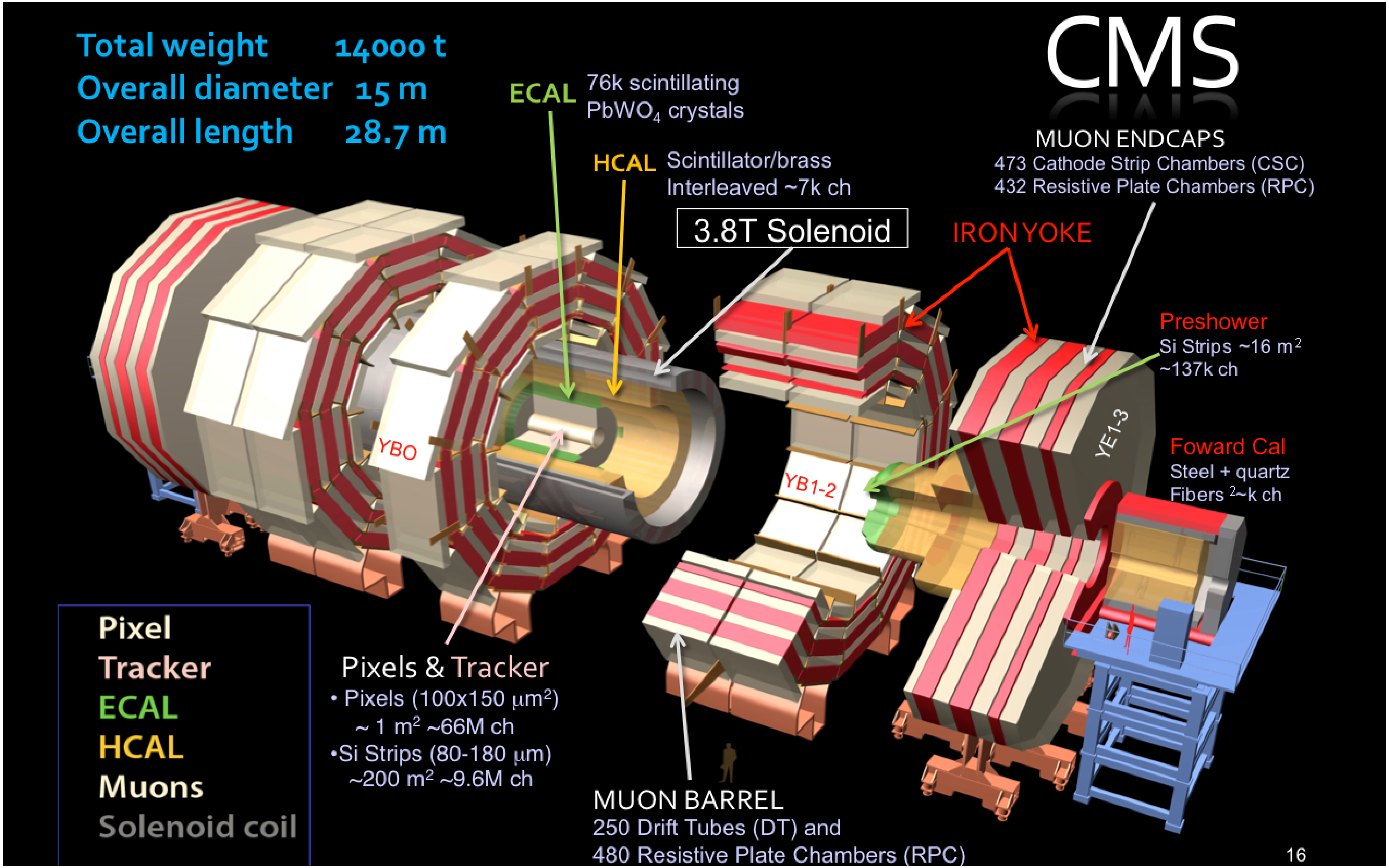
Specialized detectors



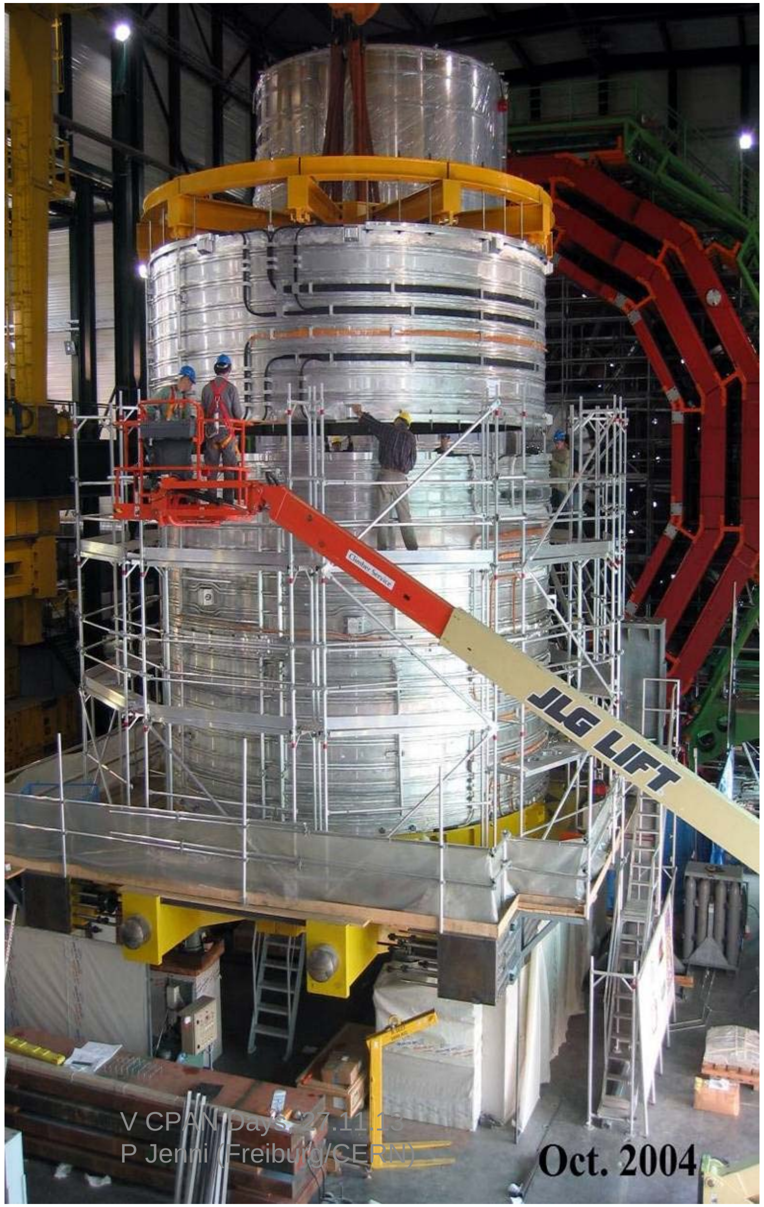
General purpose detectors



Exploded View of CMS

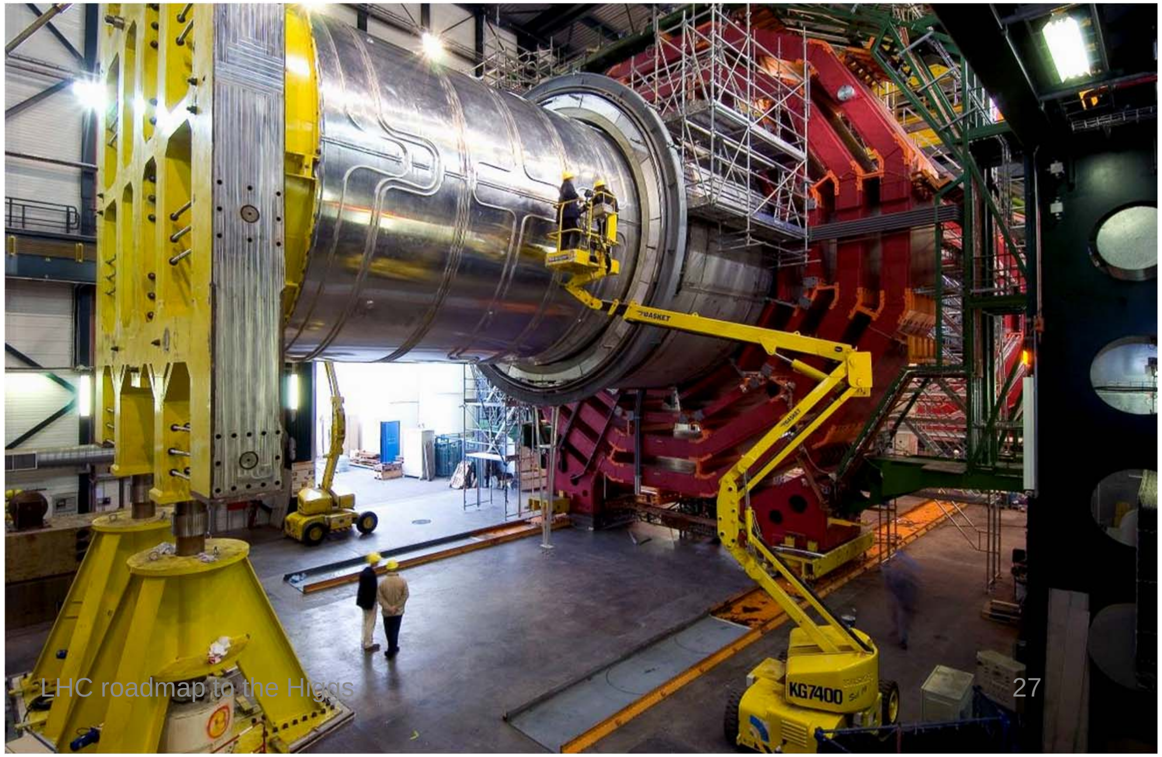


An Example of an Engineering Challenge: CMS Solenoid

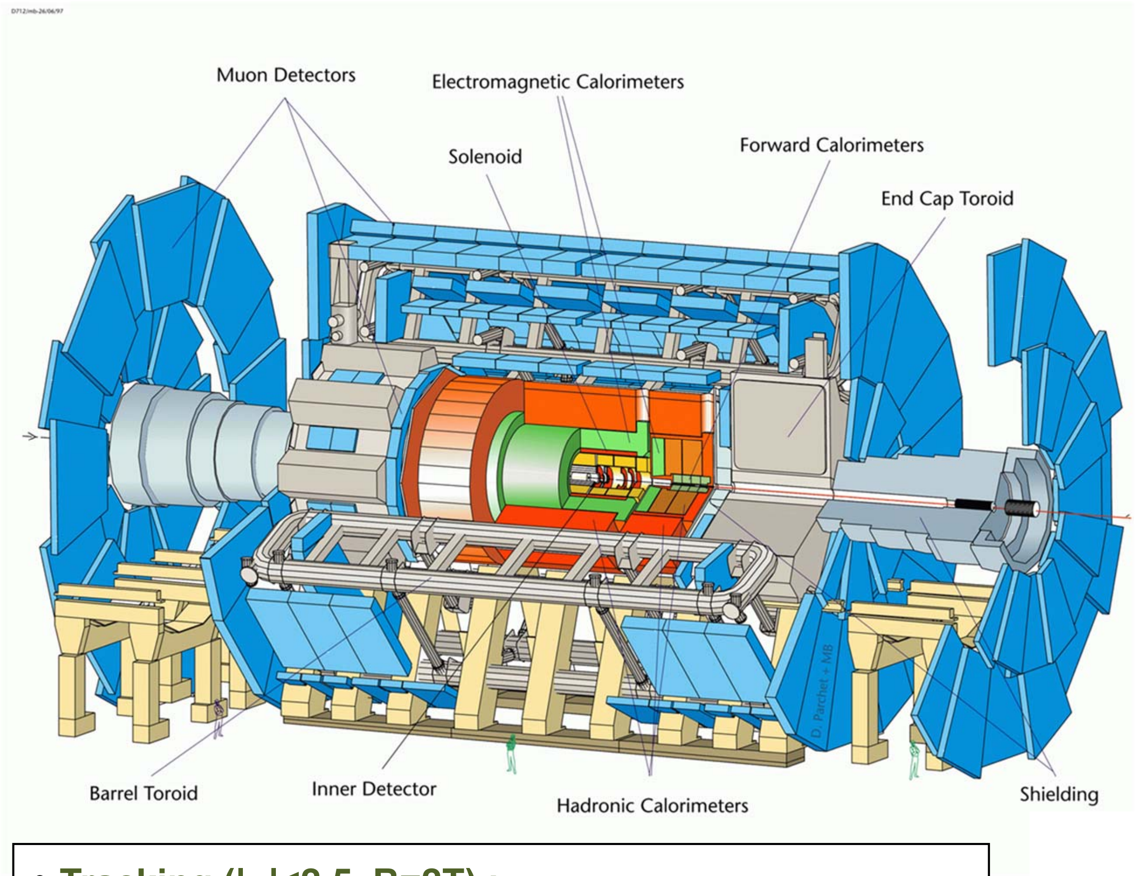


<u>CMS solenoid:</u>	
Magnetic length	**12.5 m**
Diameter	**6 m**
Magnetic field	**4 T**
Nominal current	**20 kA**
Stored energy	**2.7 GJ**

Tested at full current in Summer 2006



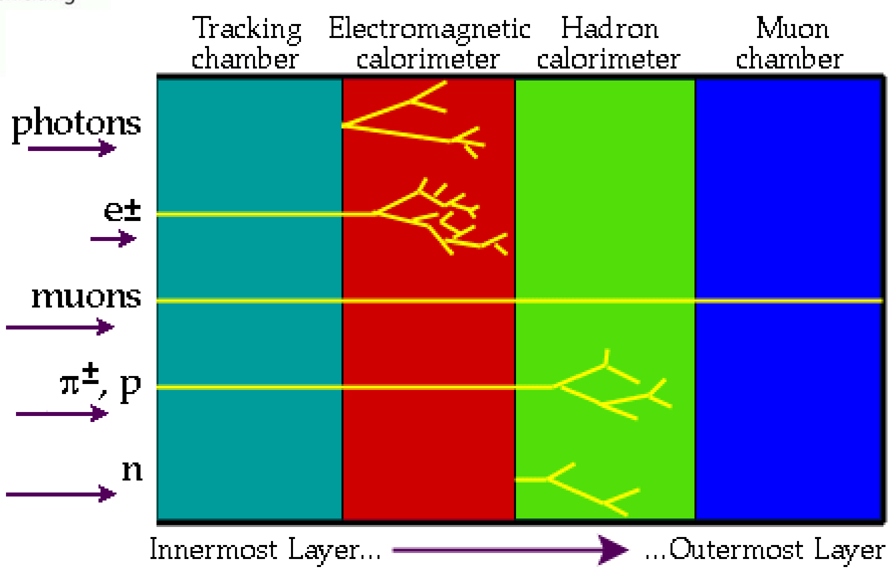
CMS before closure 2008

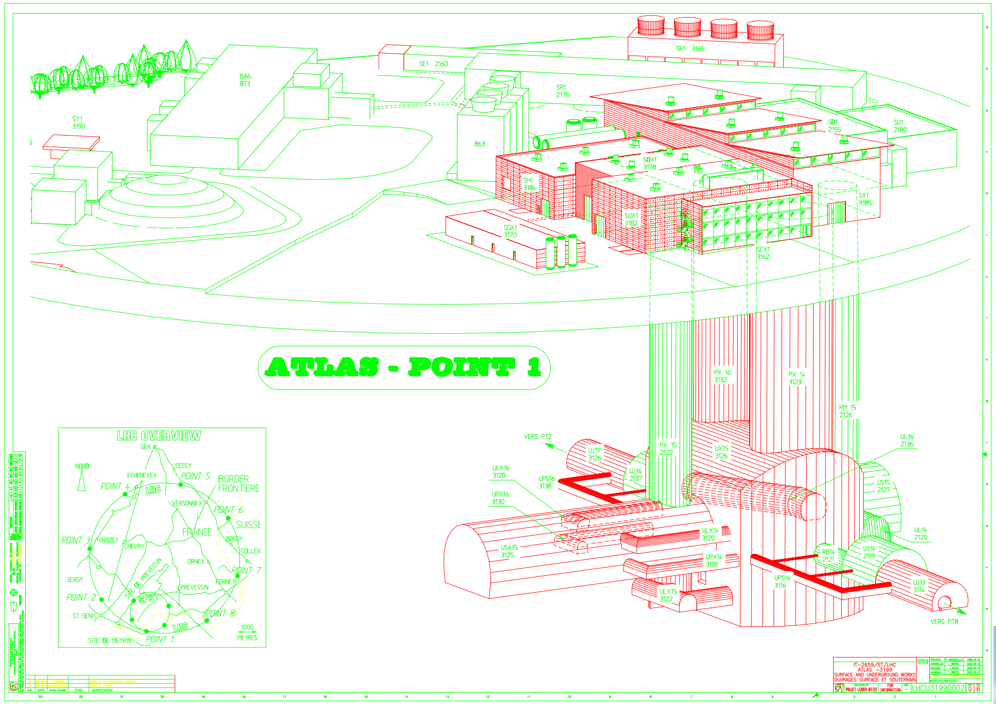


ATLAS

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

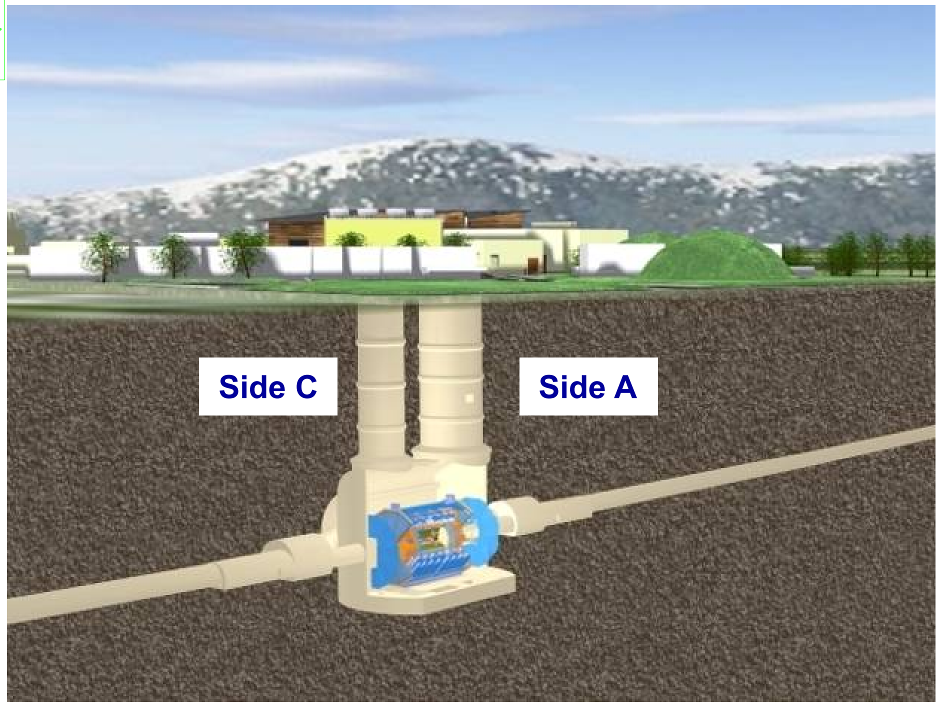
- **Tracking (|η|<2.5, B=2T) :**
  - -- Si pixels and strips
  - -- Transition Radiation Detector (e/π separation)
- **Calorimetry (|η|<5) :**
  - -- EM : Pb-LAr
  - -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)
- **Muon Spectrometer (|η|<2.7) :**
  - -- air-core toroids with muon chambers



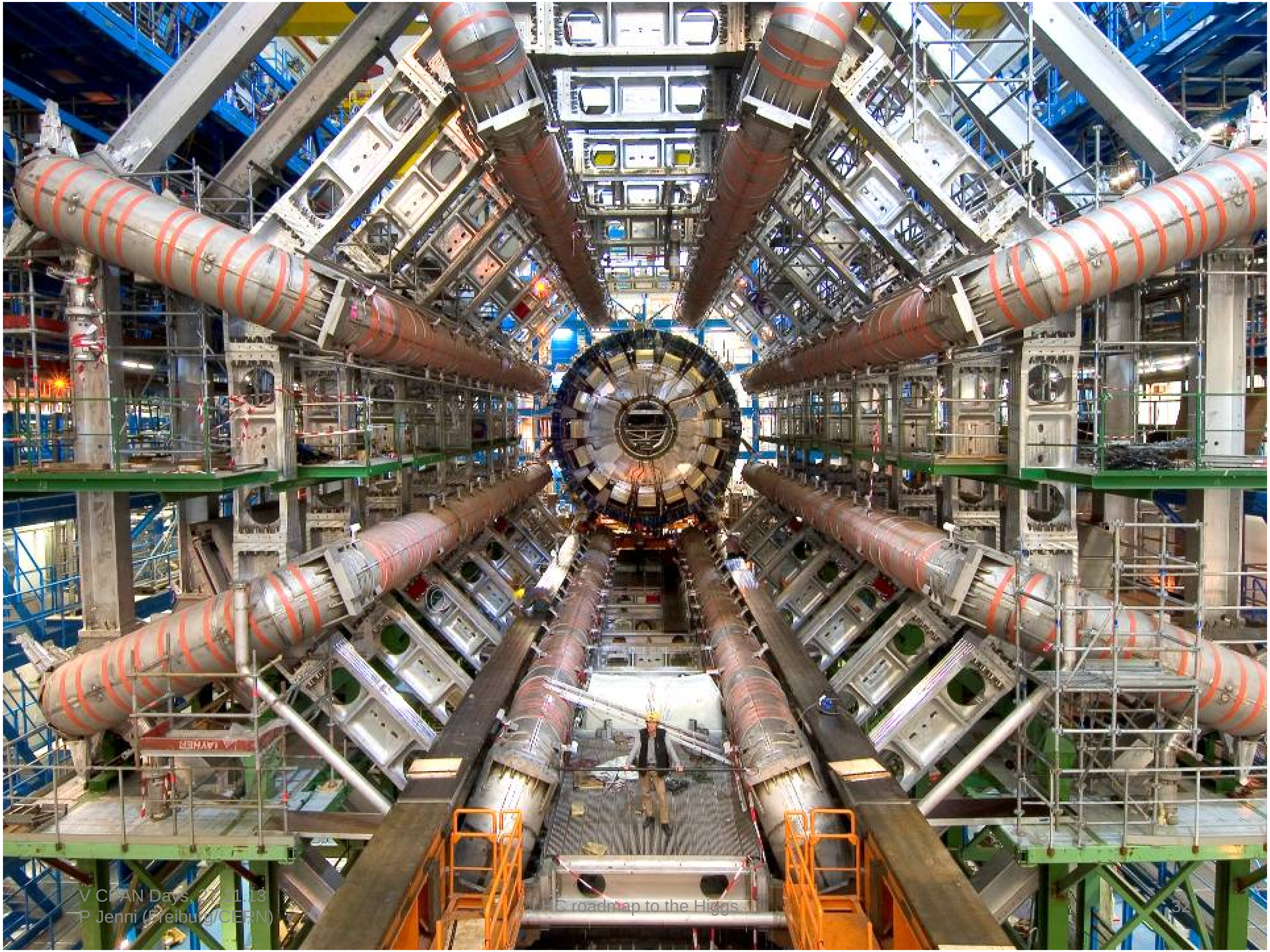


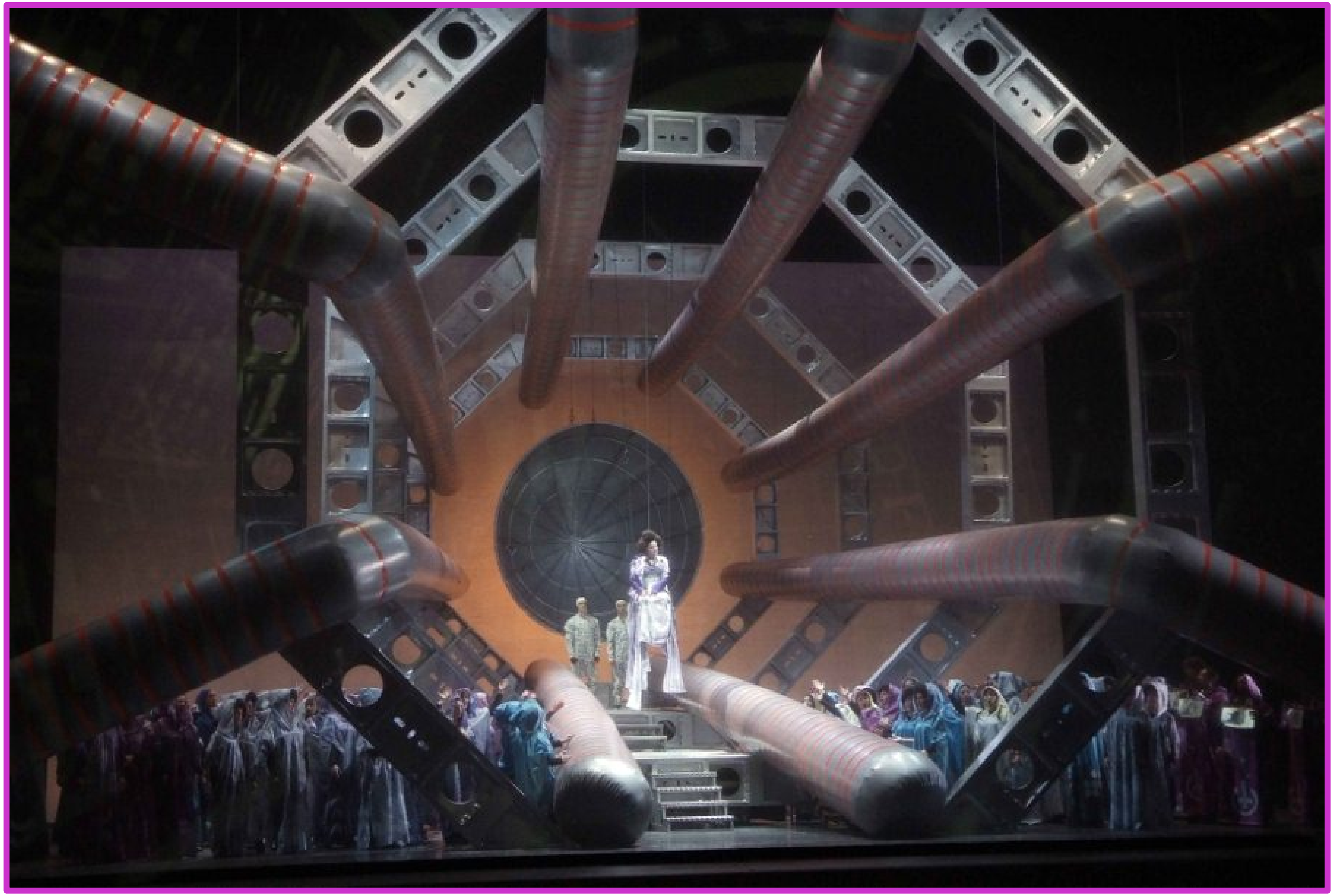
The Underground Cavern at Point-1 for the ATLAS Detector

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



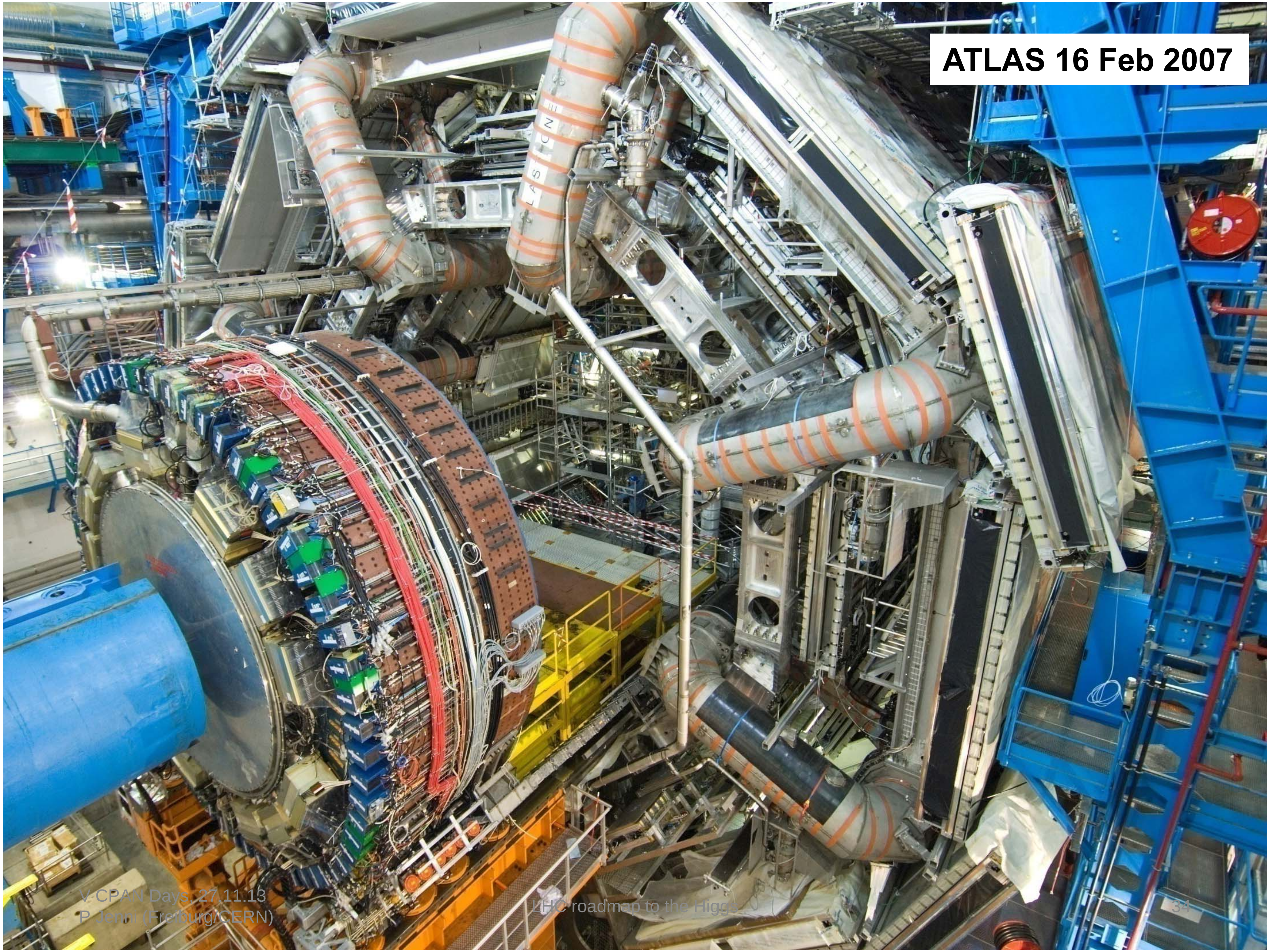

LHC Point 1 - UX 15 Cavern - Concrete walls 6th lift - 20-02-2003 - CERN ST-CE

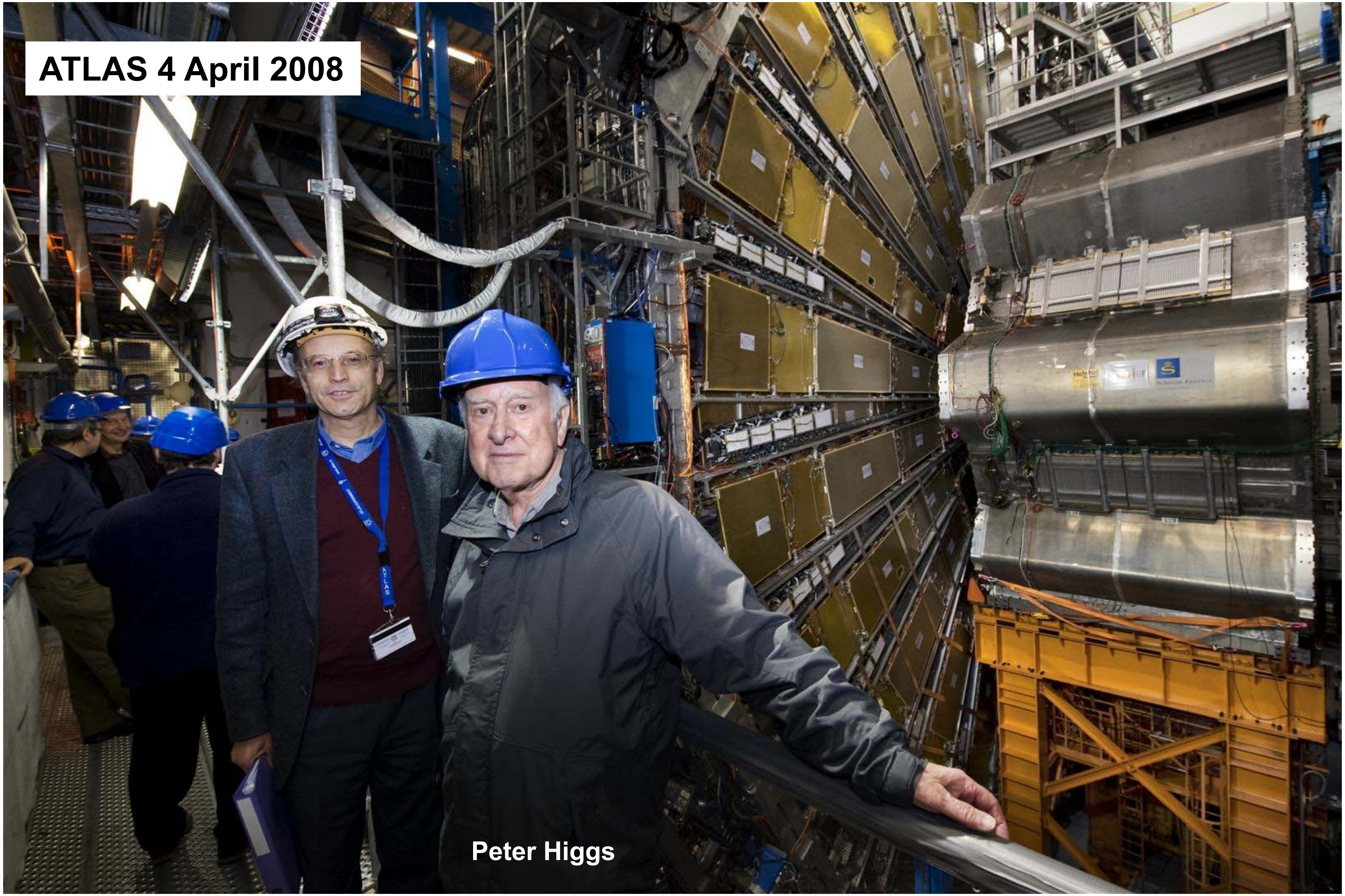




Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009

ATLAS 16 Feb 2007



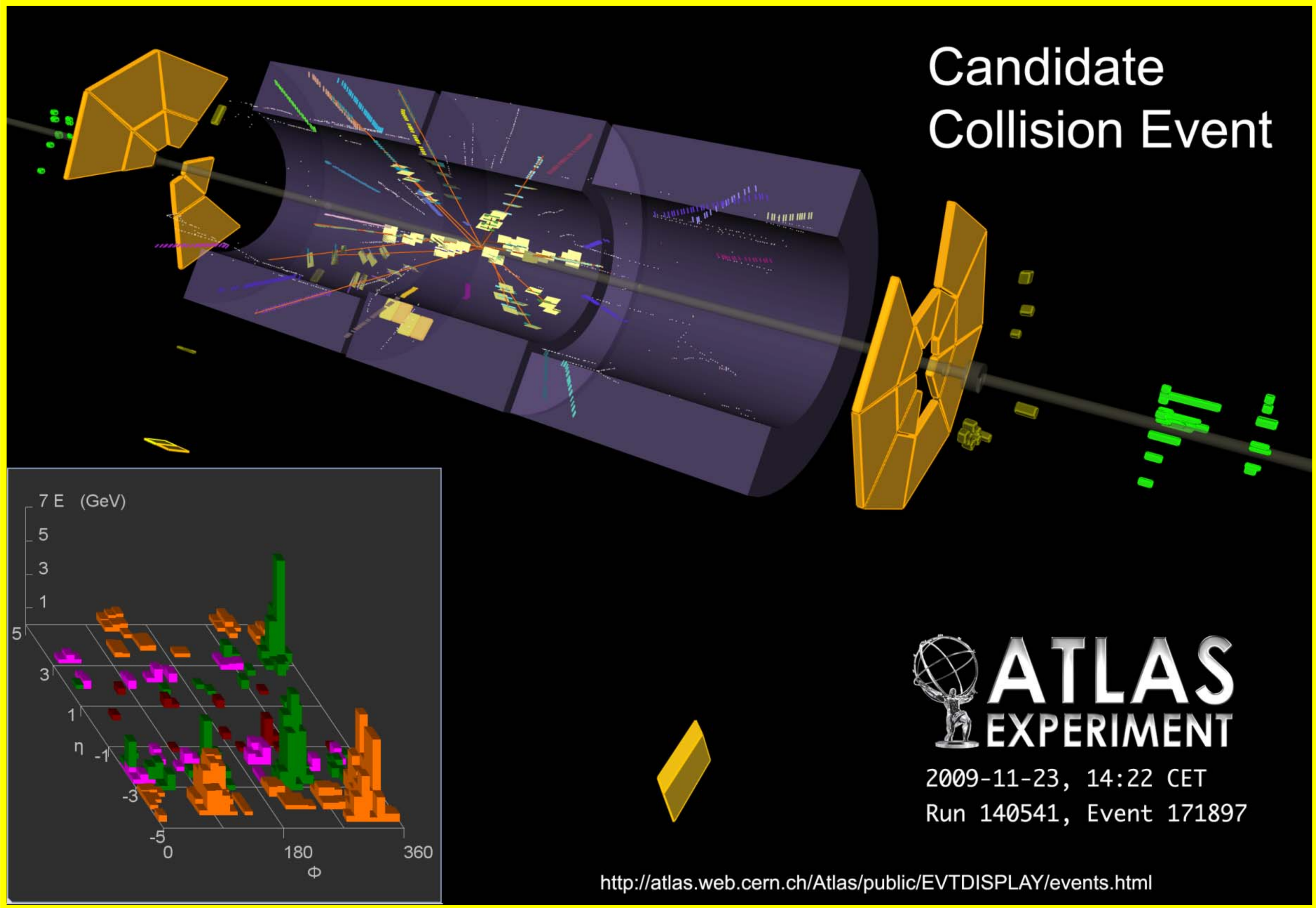

ATLAS 4 April 2008
Peter Higgs

Interconnections of two magnets

One (superconductor) joint failed on 19th September 2008, and it caused a catastrophic He-release that made serious collateral damage to sector 3-4 of the LHC machine

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

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



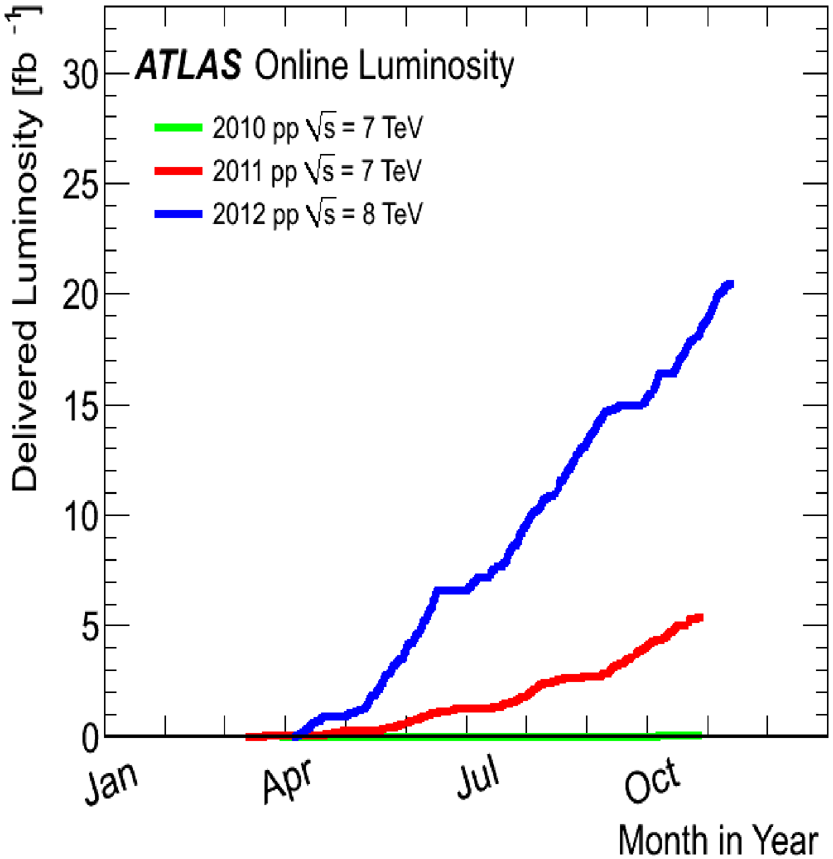
A well-deserved toast to all who have built such a marvelous machine, and to all who operate it so superbly

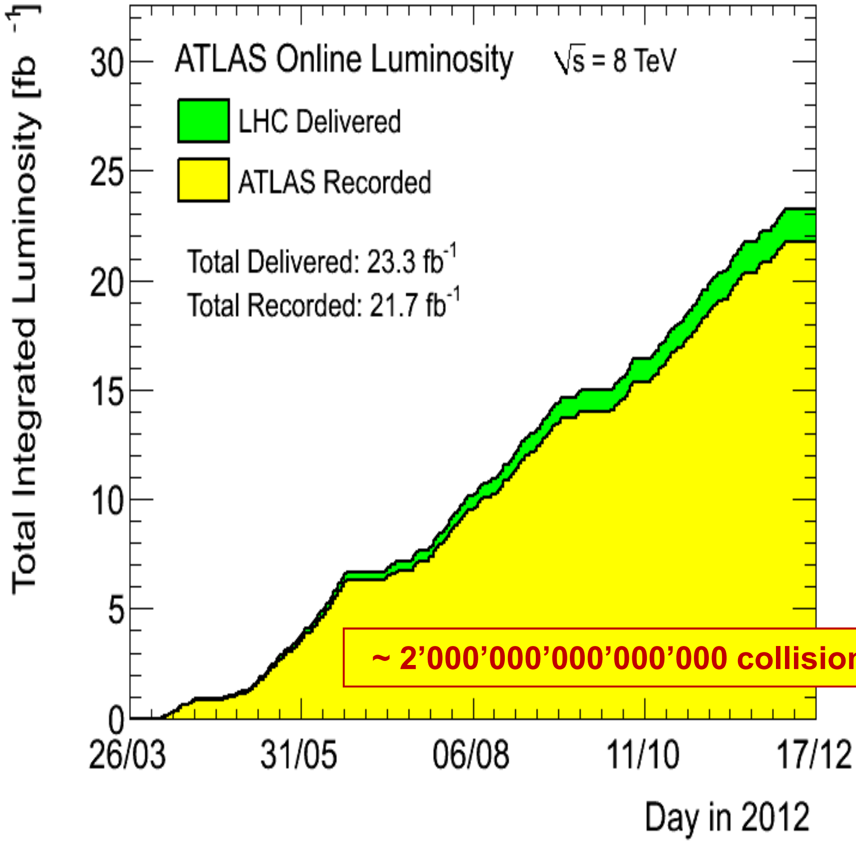
(first 7 TeV collisions on 30th March 2010)

The LHC and experiments performances were simply fantastic over the last three years

Total integrated luminosity

$$N_{events} = \sigma \int L \, dt$$



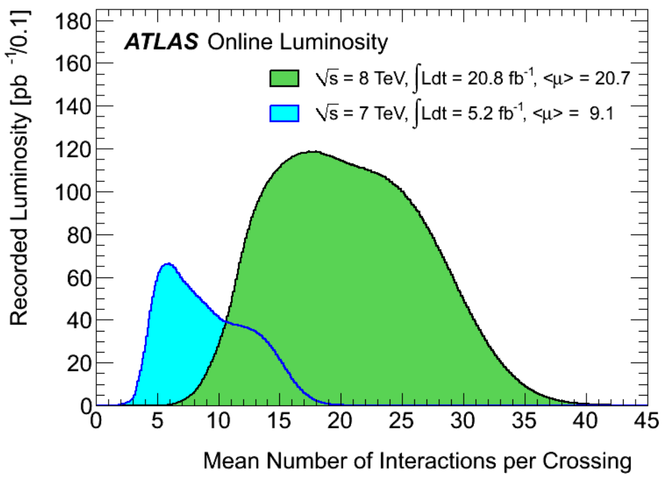


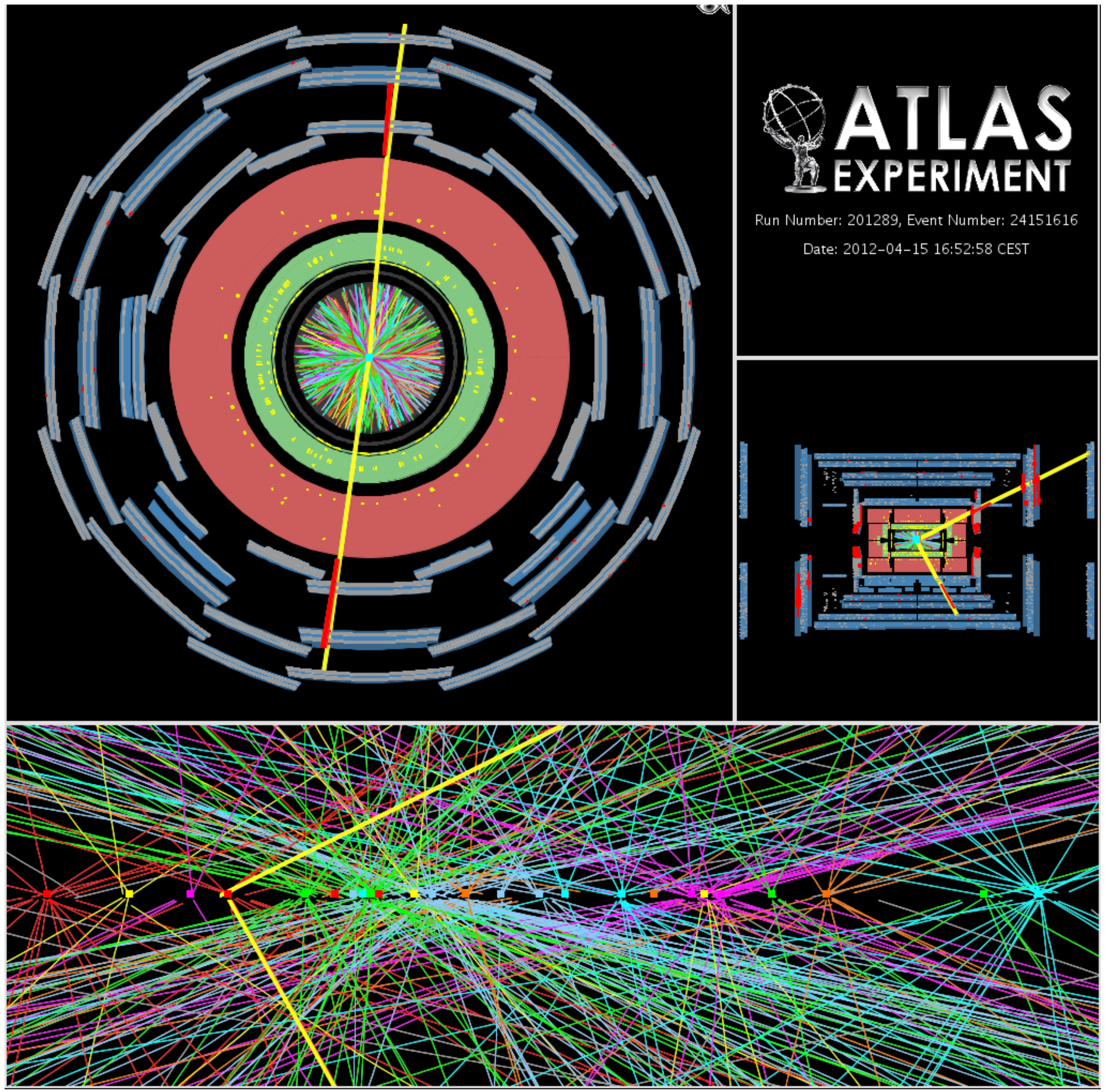
~ 2'000'000'000'000'000 collisions

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:

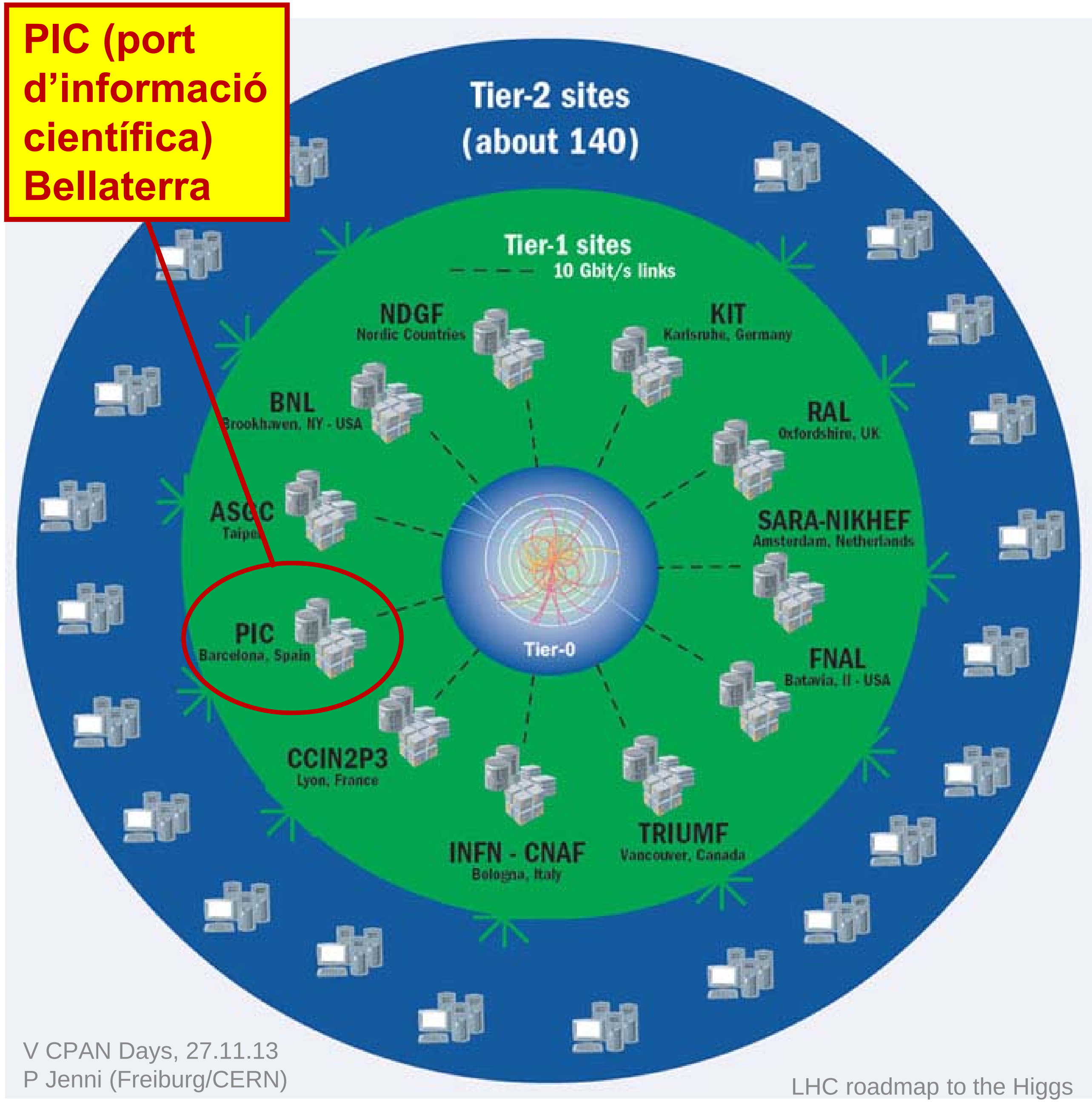
- **Trigger**
- **Pile-up**
- **Maintain accuracy of the the measurements in this environment**





Inner Detector for a Z → μμ event with 25 primary vertices

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

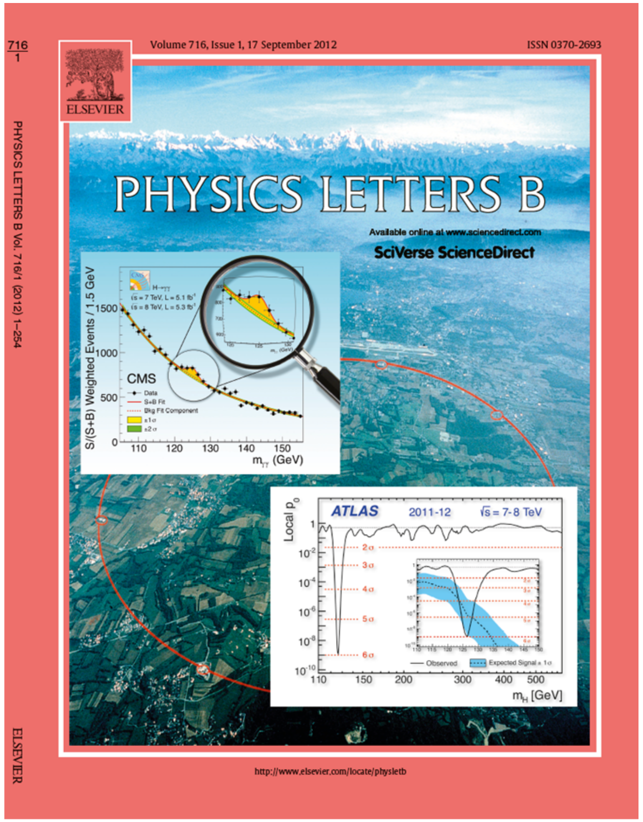
Physics Highlights

ATLAS and CMS have already published together about 550 papers in scientific journals (and many more as public conference notes…)

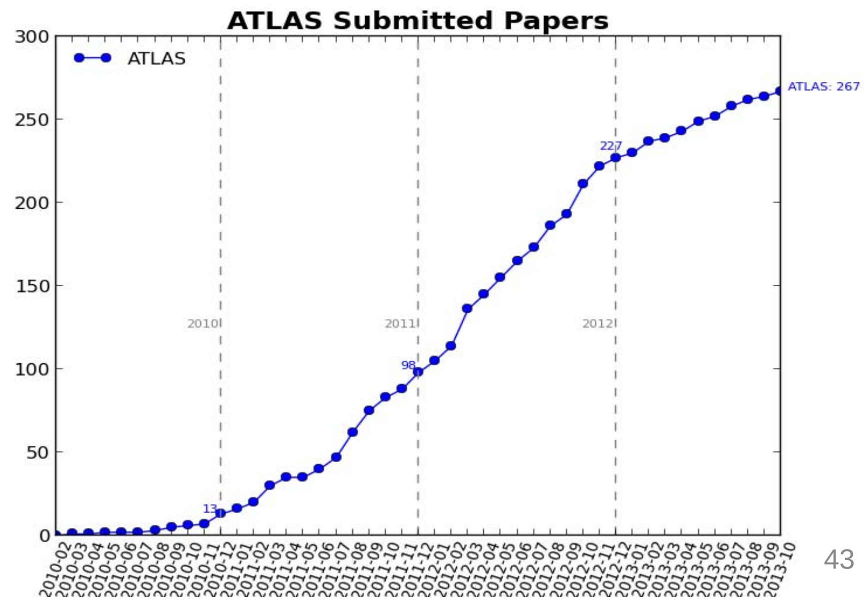
The other experiments, ALICE, LHCb, LHCf, and TOTEM total another 220 journal publications together

It is clearly not possible to cover all these results…

No attempt is made to show in a democratic way, for example, CMS and ATLAS results, only examples are given that are meant to represent the others as well where applicable...



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?ln=en



Physics Highlights:

General event properties

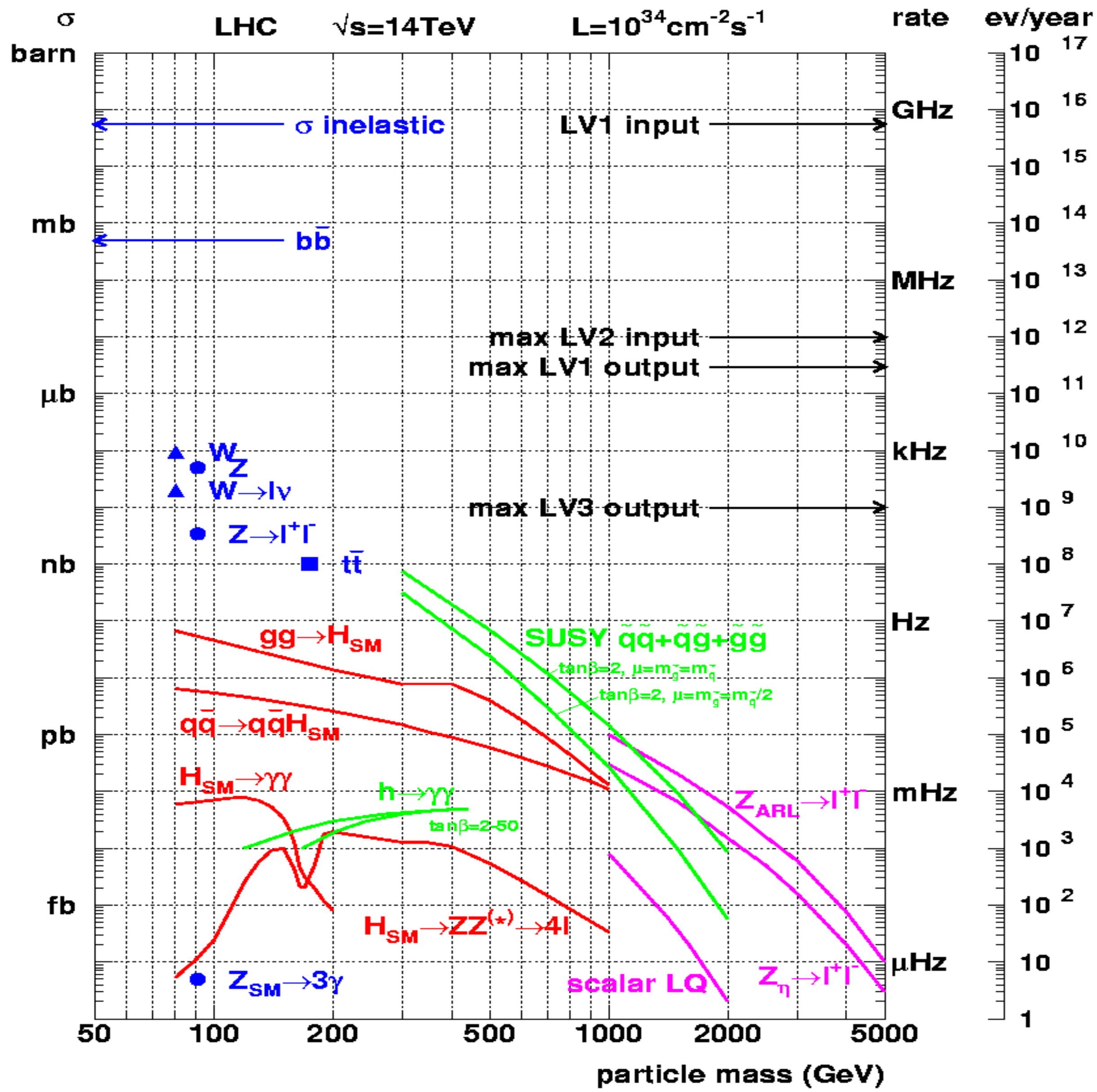
Heavy flavour physics

Standard Model physics including QCD jets

Higgs searches

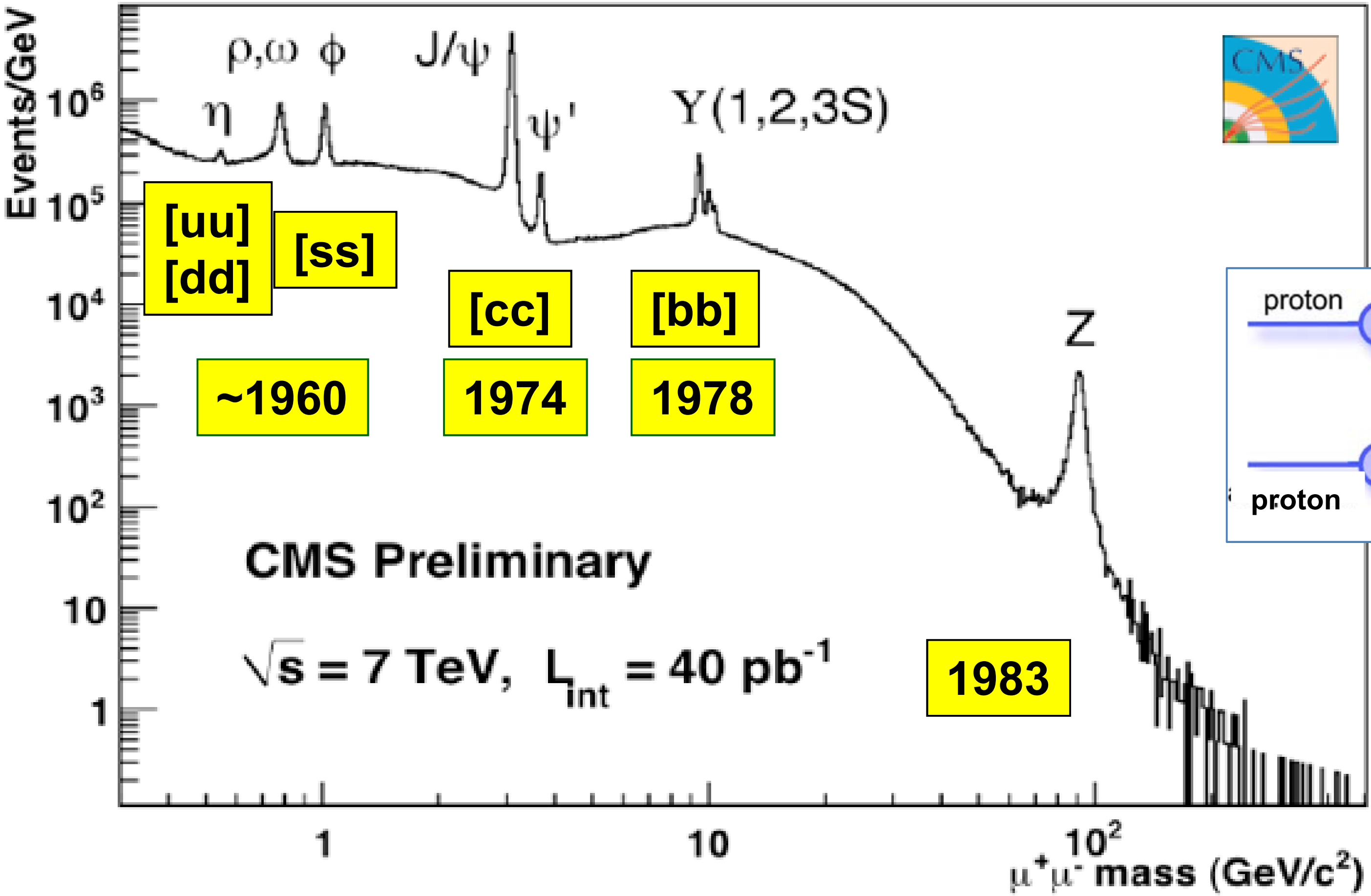
Searches for SUSY

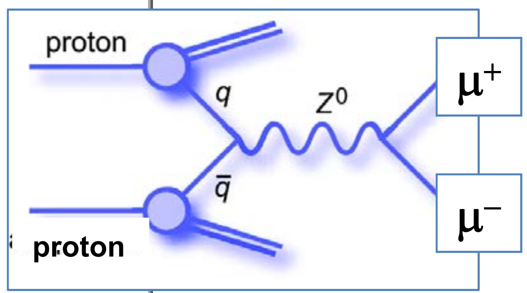
Searches for ‘exotic’ new physics



2010

Data corresponding to ~40 pb^{-1} collected
→ re-discovery of the Standard Model

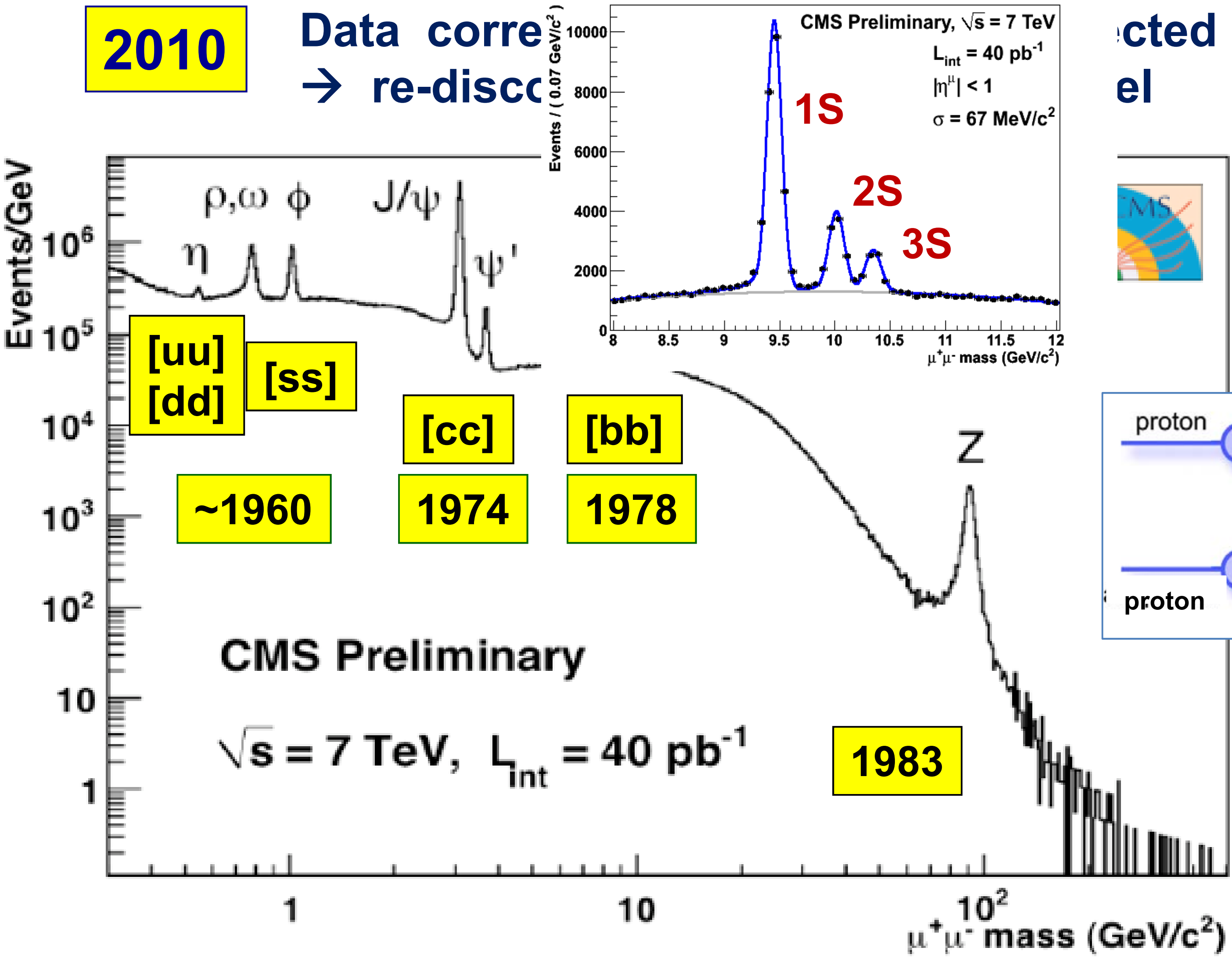


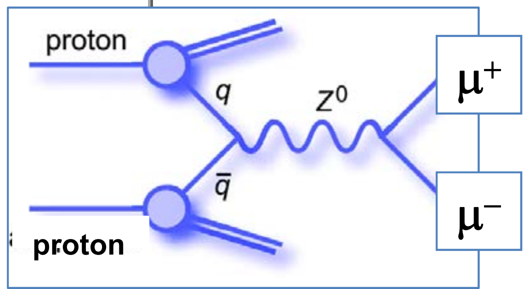


The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear "online"

2010

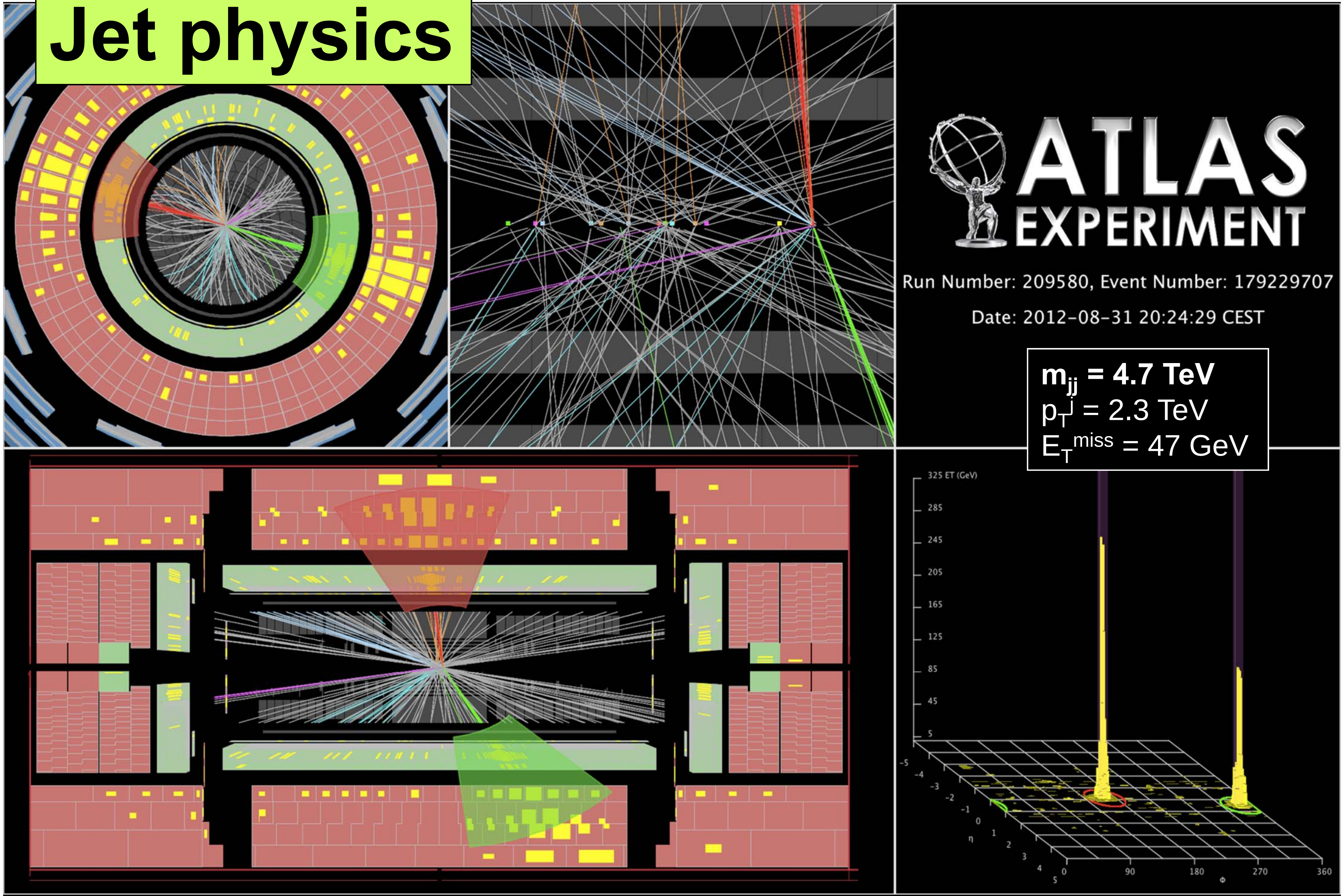
Data corre... cted
→ re-disco... el





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

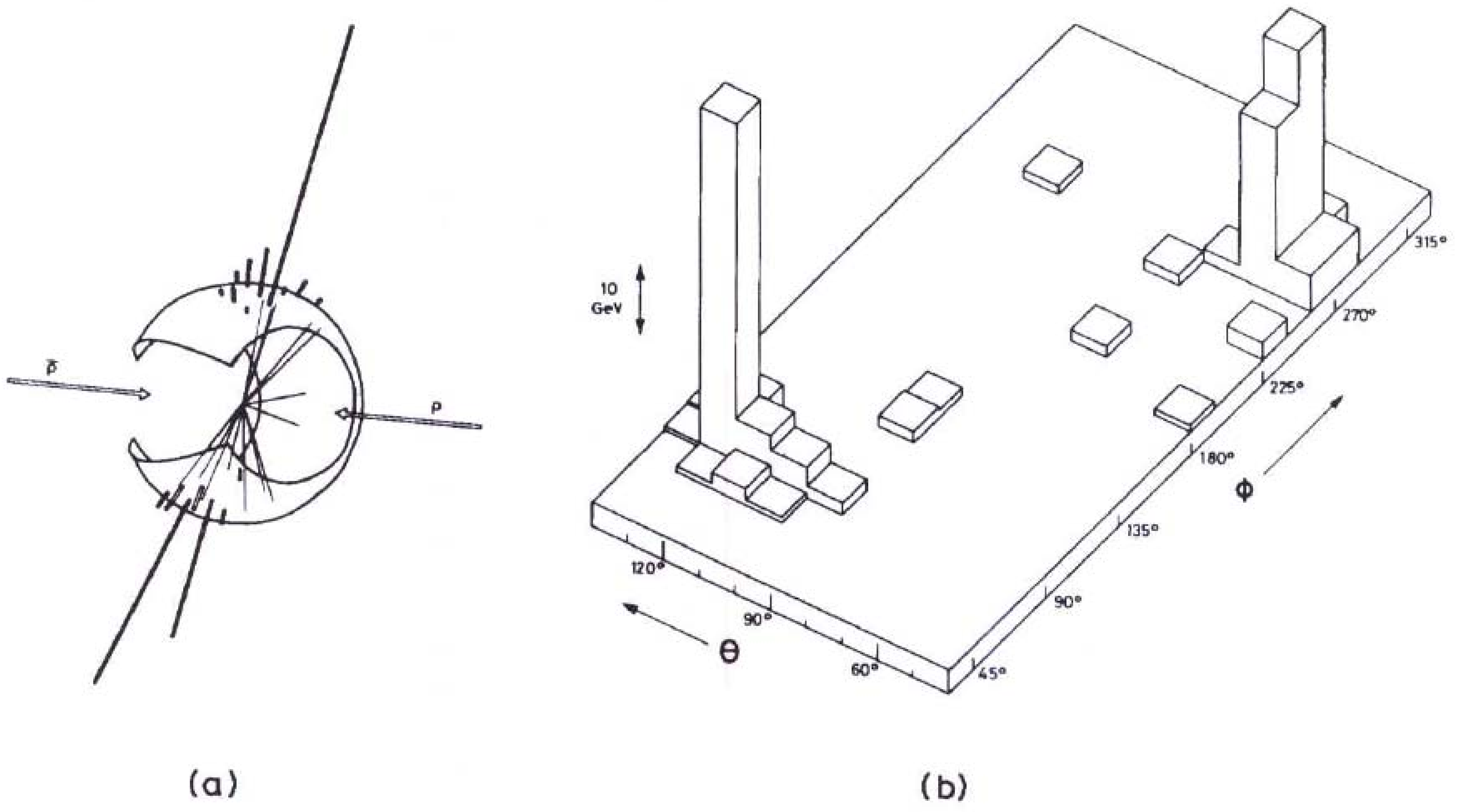
Jet physics

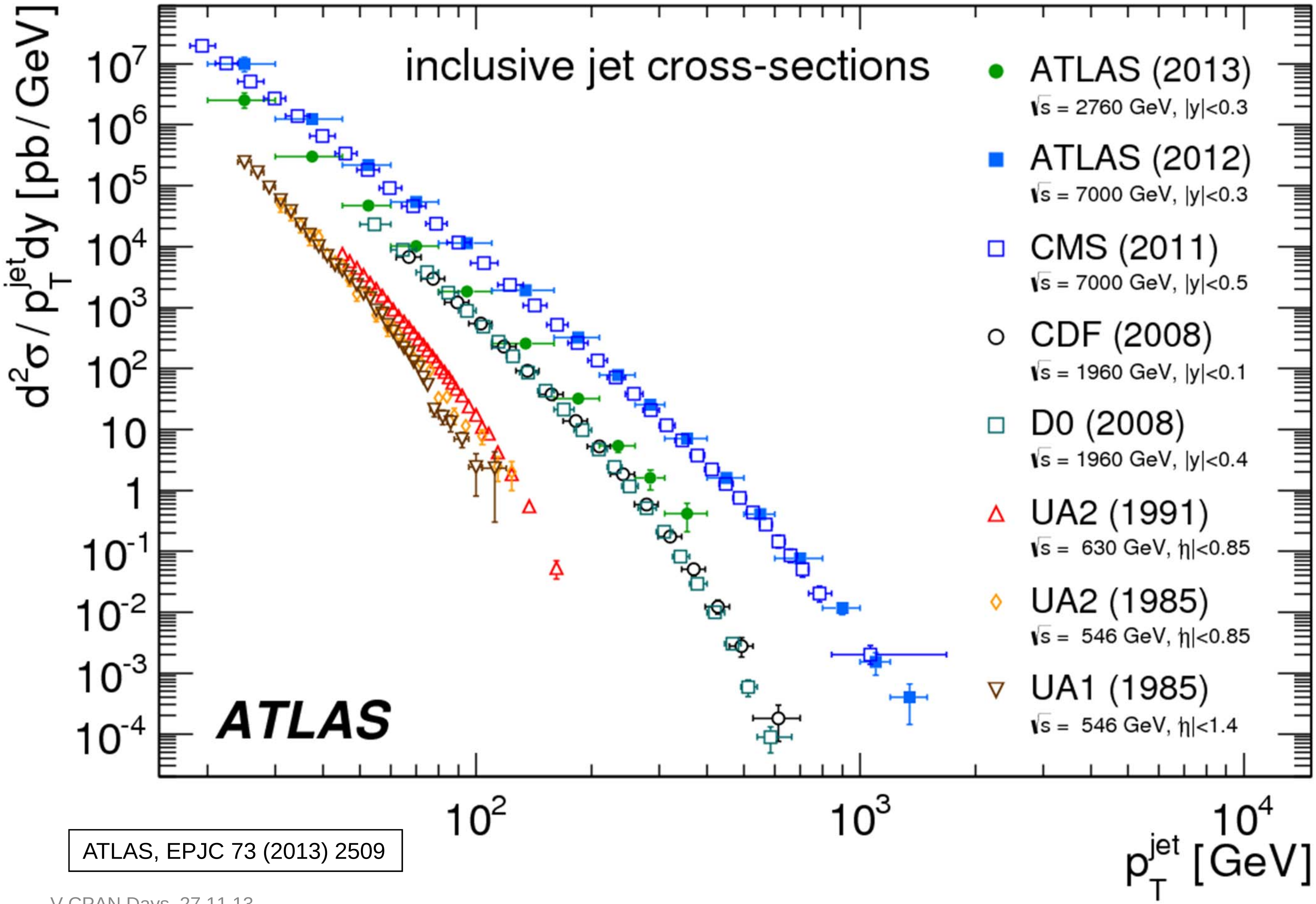


m_{jj} = 4.7 TeV
p_T^j = 2.3 TeV
E_T^{miss} = 47 GeV

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

Volume 118B, number 1, 2, 3 PHYSICS LETTERS 2 December 1982

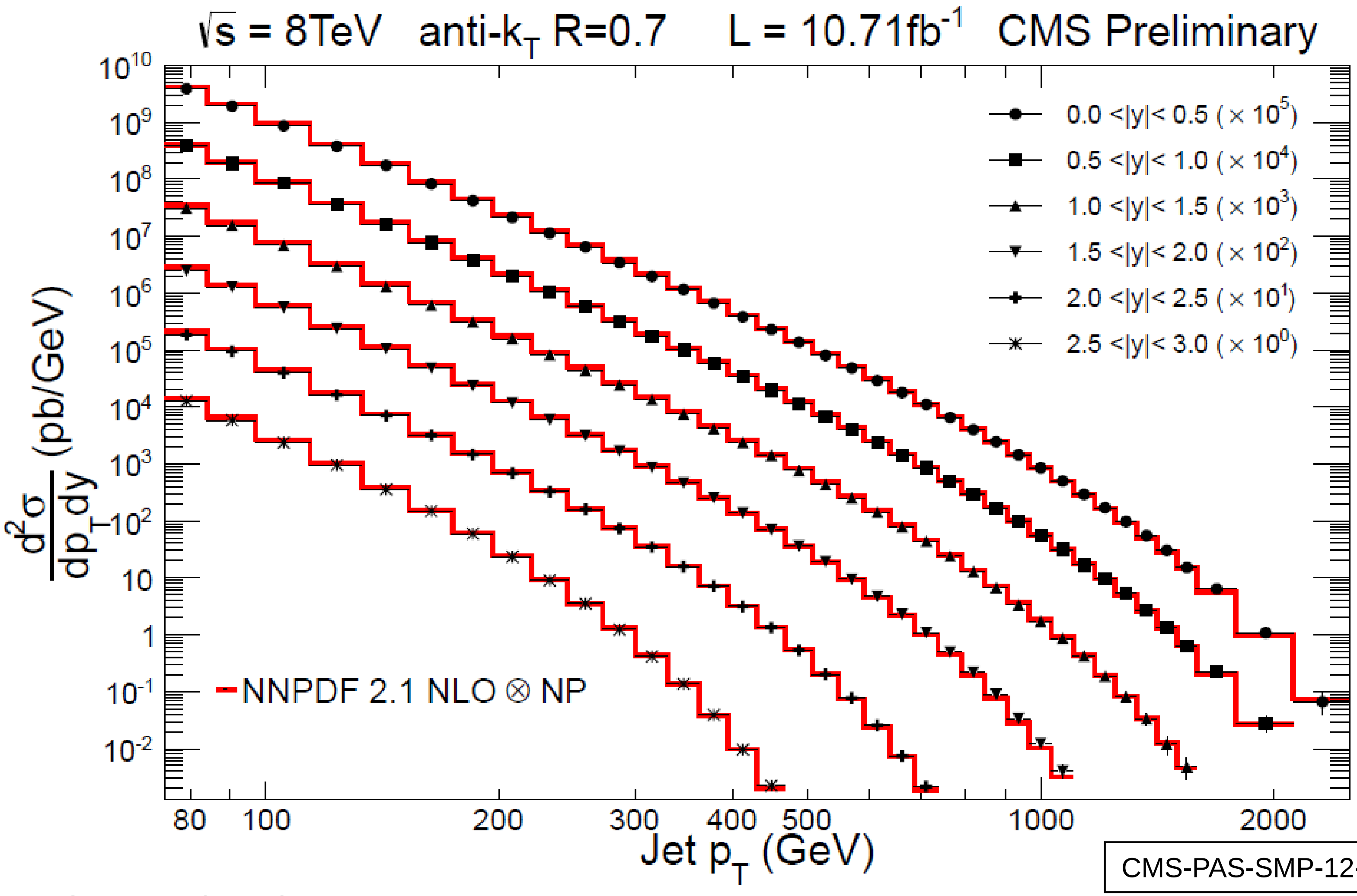




ATLAS, EPJC 73 (2013) 2509

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

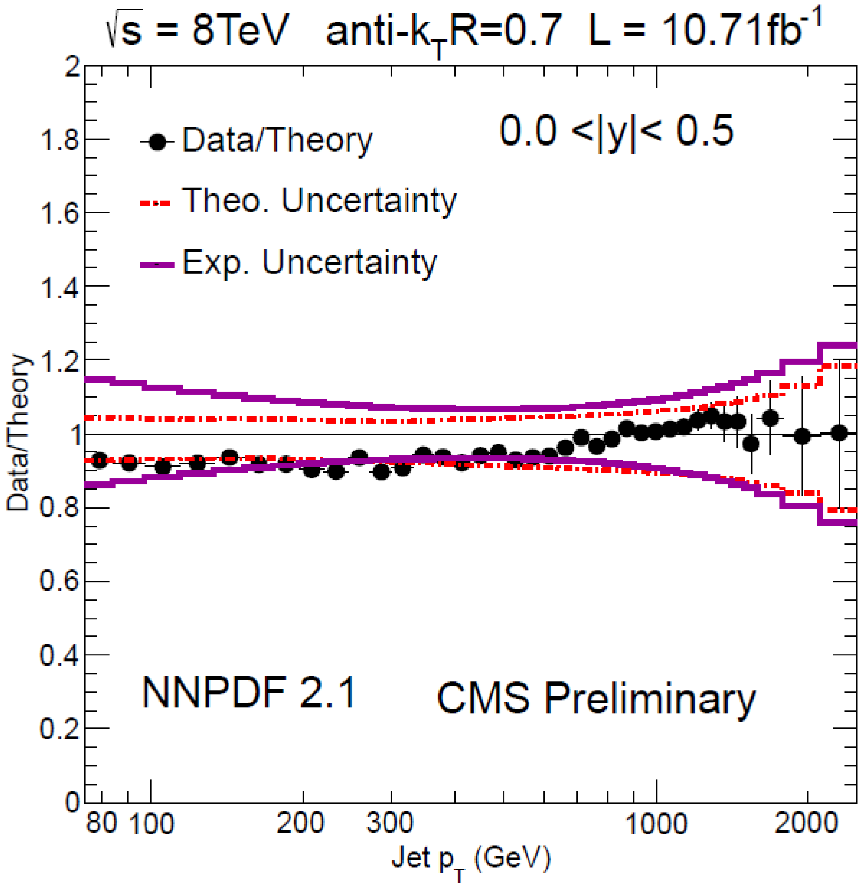
Example: The inclusive jet cross sections as a function of the jet P_T in rapidity bins

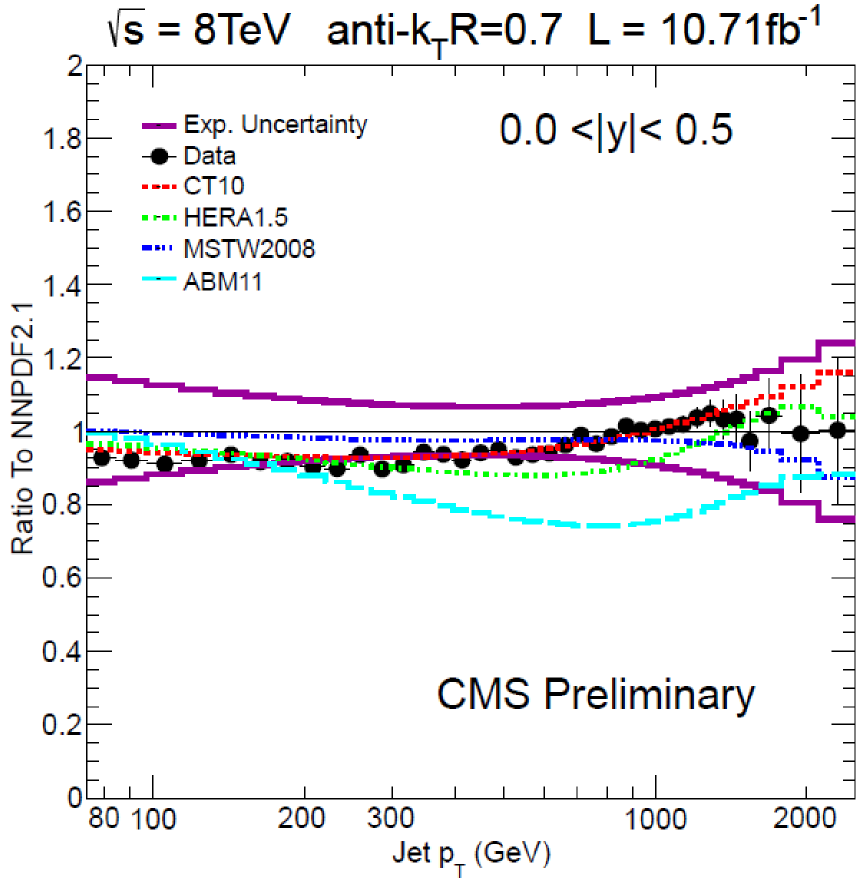


CMS-PAS-SMP-12-012

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

Example: The inclusive jet cross sections as a function of the jet P_T in rapidity bins



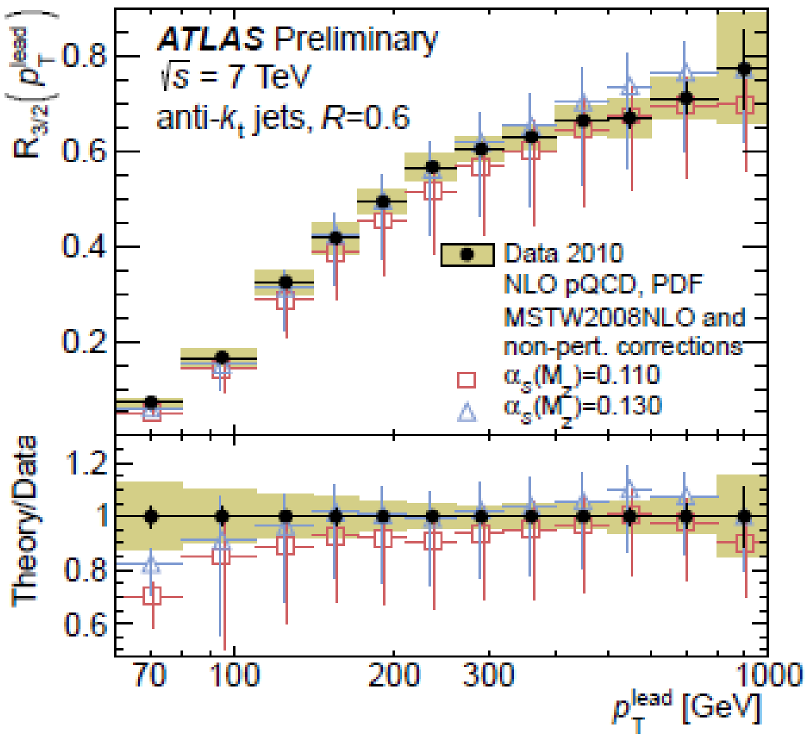


CMS-PAS-SMP-12-012

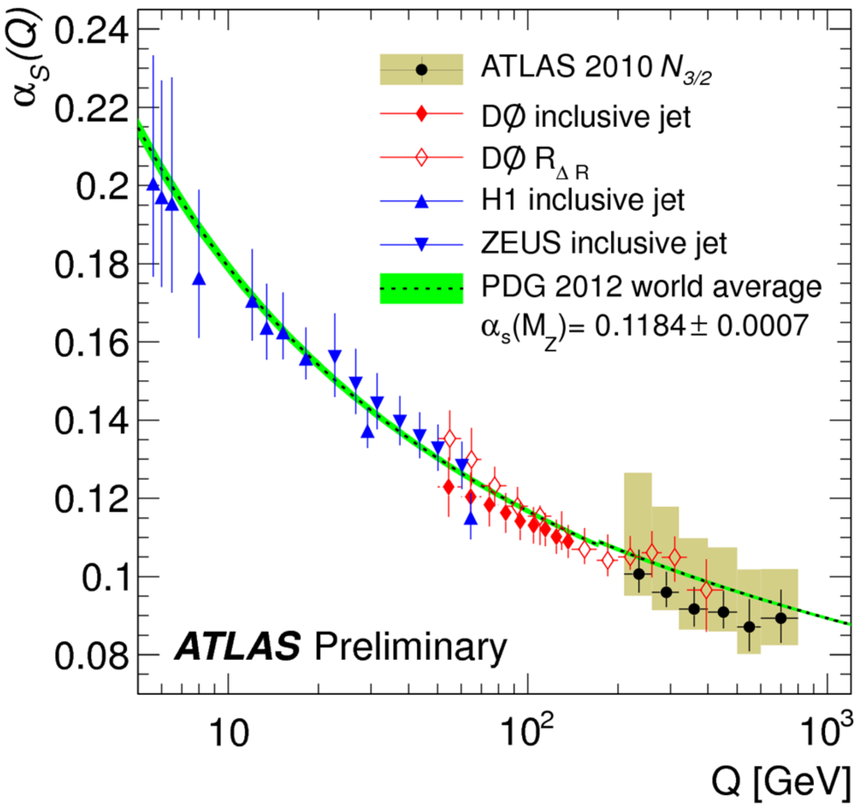
Cross-section ratios of multi-jets allow one to determine α_s

$$R_{3/2}(p_T^{\rm lead}) = \frac{d\sigma_{N_{\rm jet}\geq 3}/dp_T^{\rm lead}}{d\sigma_{N_{\rm jet}\geq 2}/dp_T^{\rm lead}}$$

$p_T > 40$ GeV and $|y| < 2.8$.



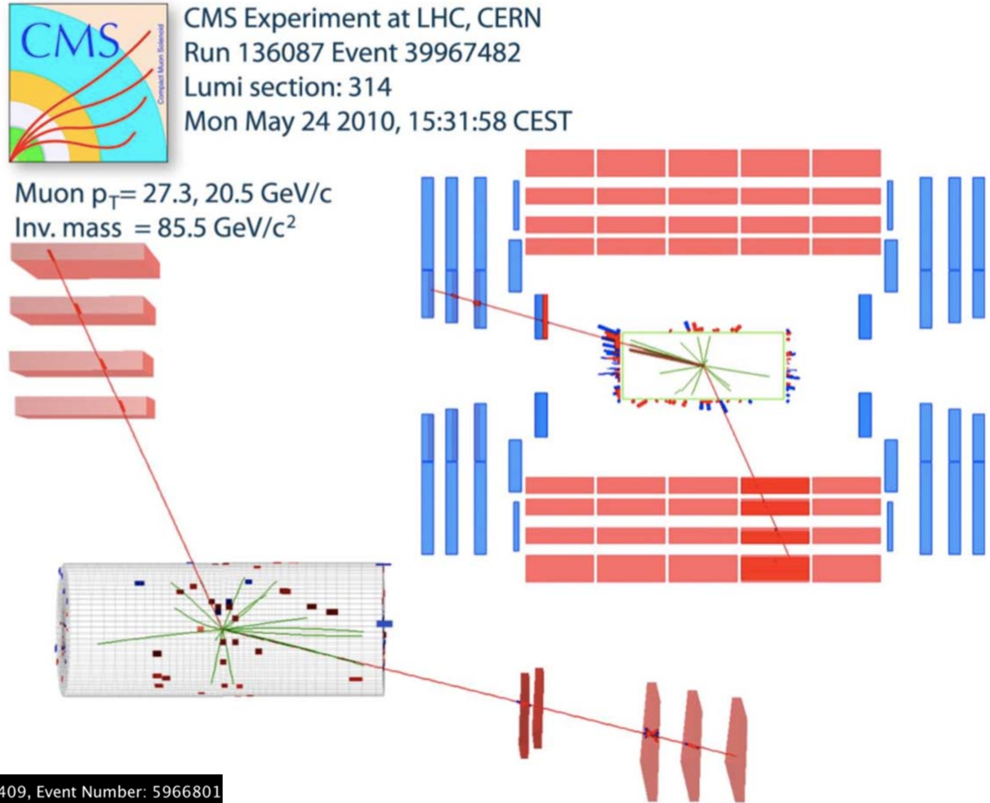
$$\alpha_s(M_Z) = 0.111 \pm 0.006(\text{exp.})\ ^{+0.016}_{-0.003}(\text{theory}).$$



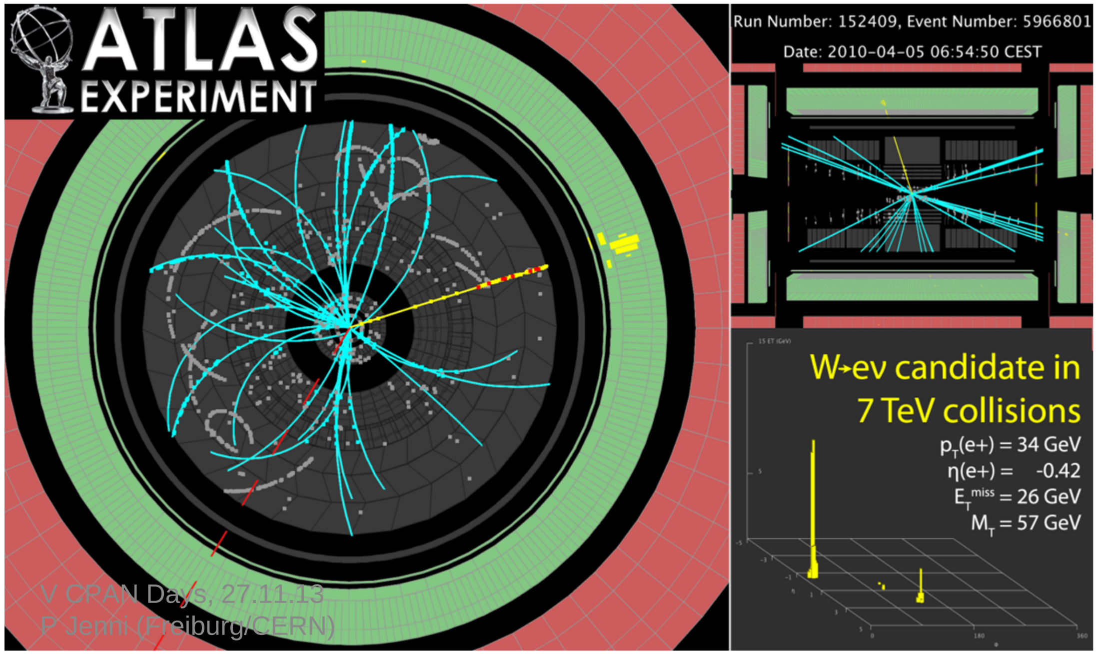
ATLAS-CONF-2013-041

Standard Model Physics

Candidate Z → $\mu^+\mu^-$



W → eν candidate



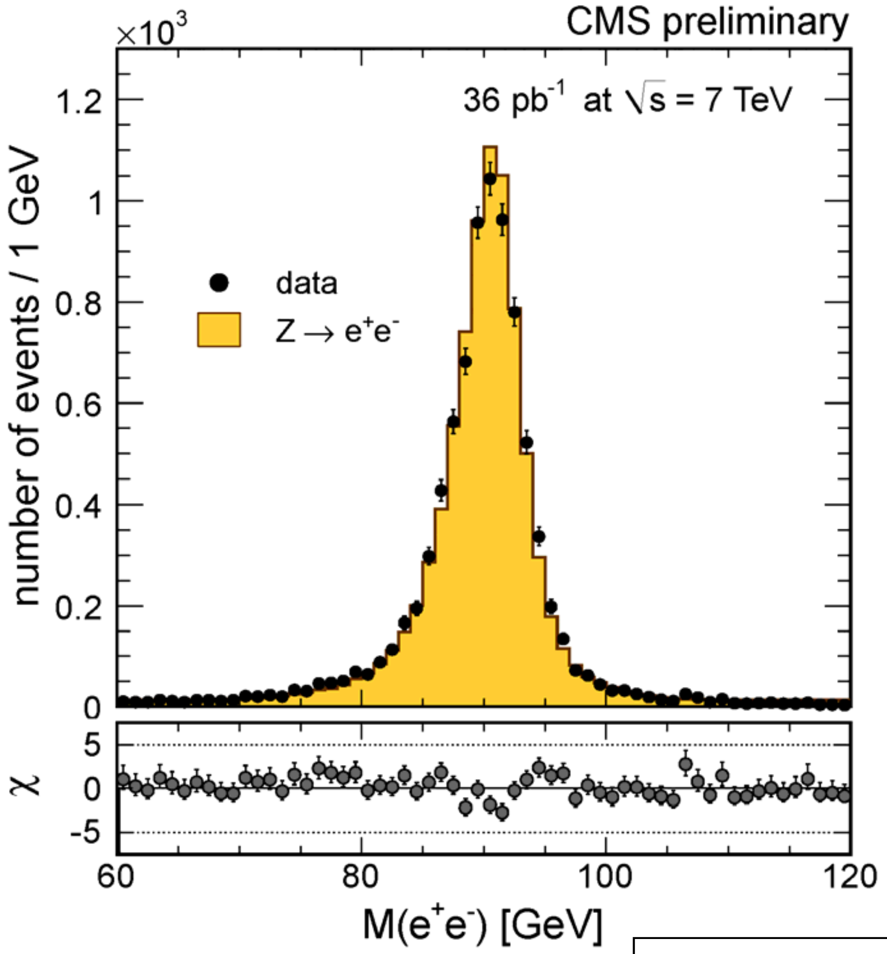
Today each ATLAS and CMS have in their data more than:

100 M W→ $\mu\nu$, eν events
10 M Z → $\mu\mu$, ee events

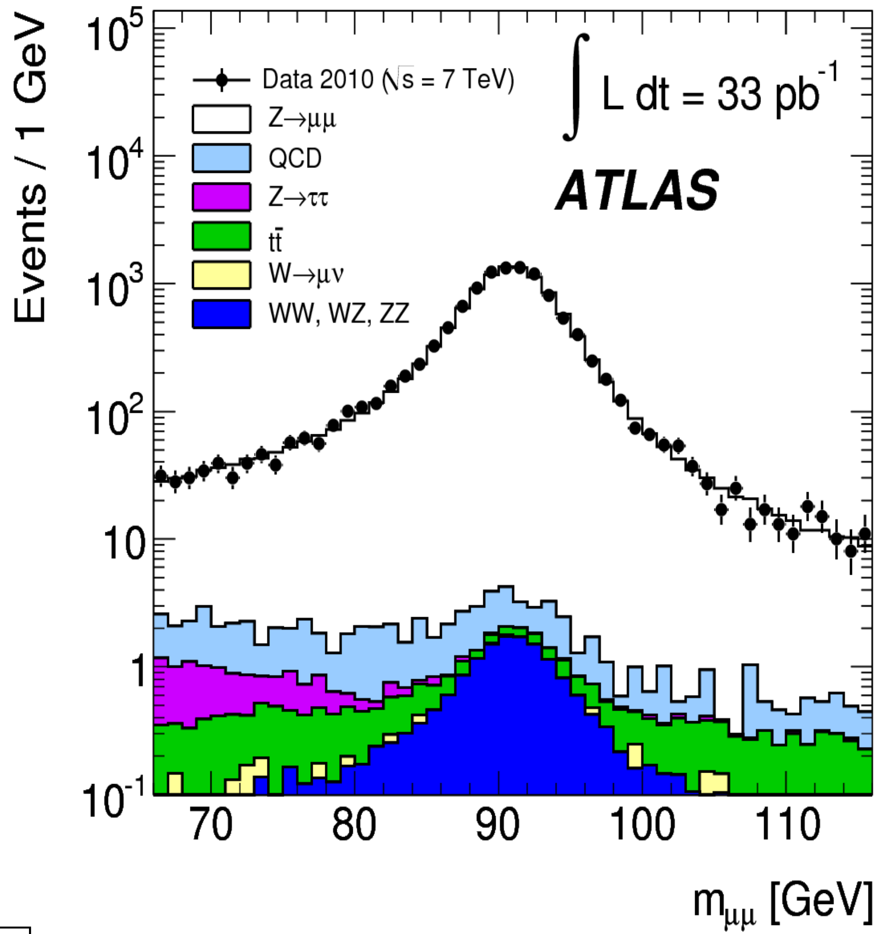
after all selection cuts

Z and W production

Phys Rev D85 (2012) 072004



JHEP 10 (2011) 132

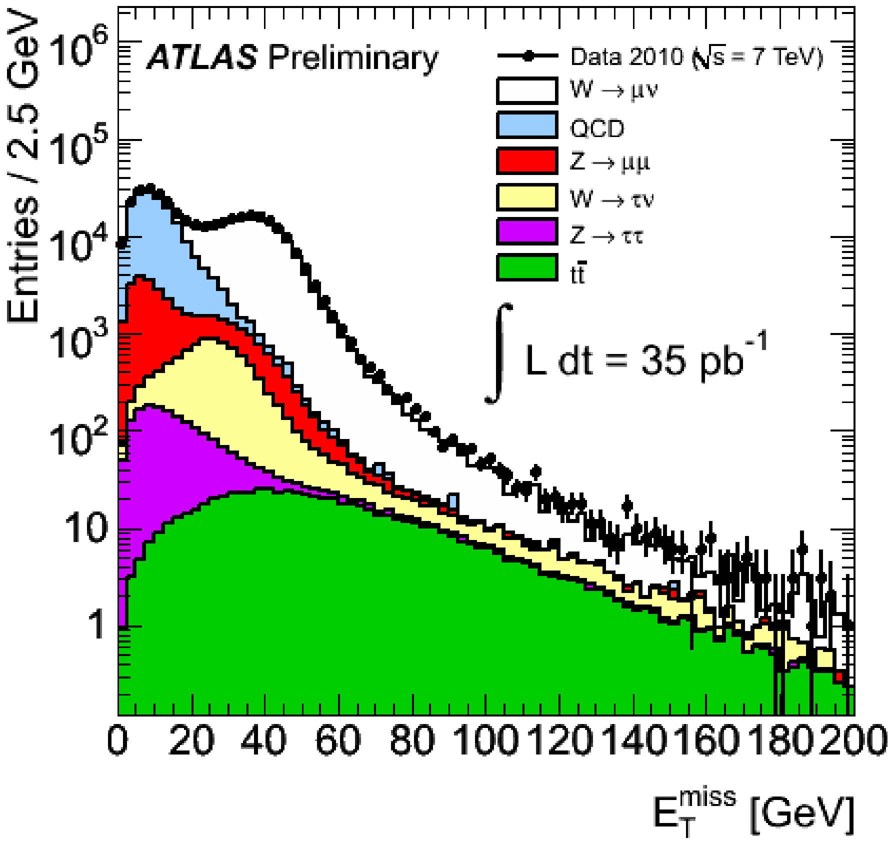


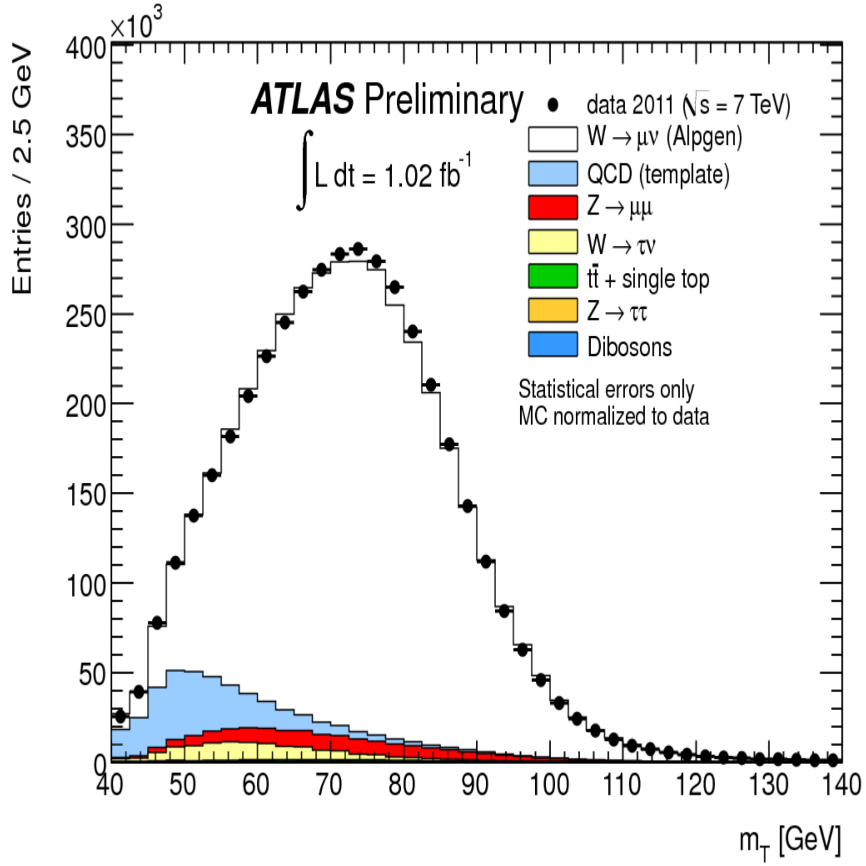
Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

W transverse mass

μ with p_T>20 GeV, E_T^{miss}>25 GeV



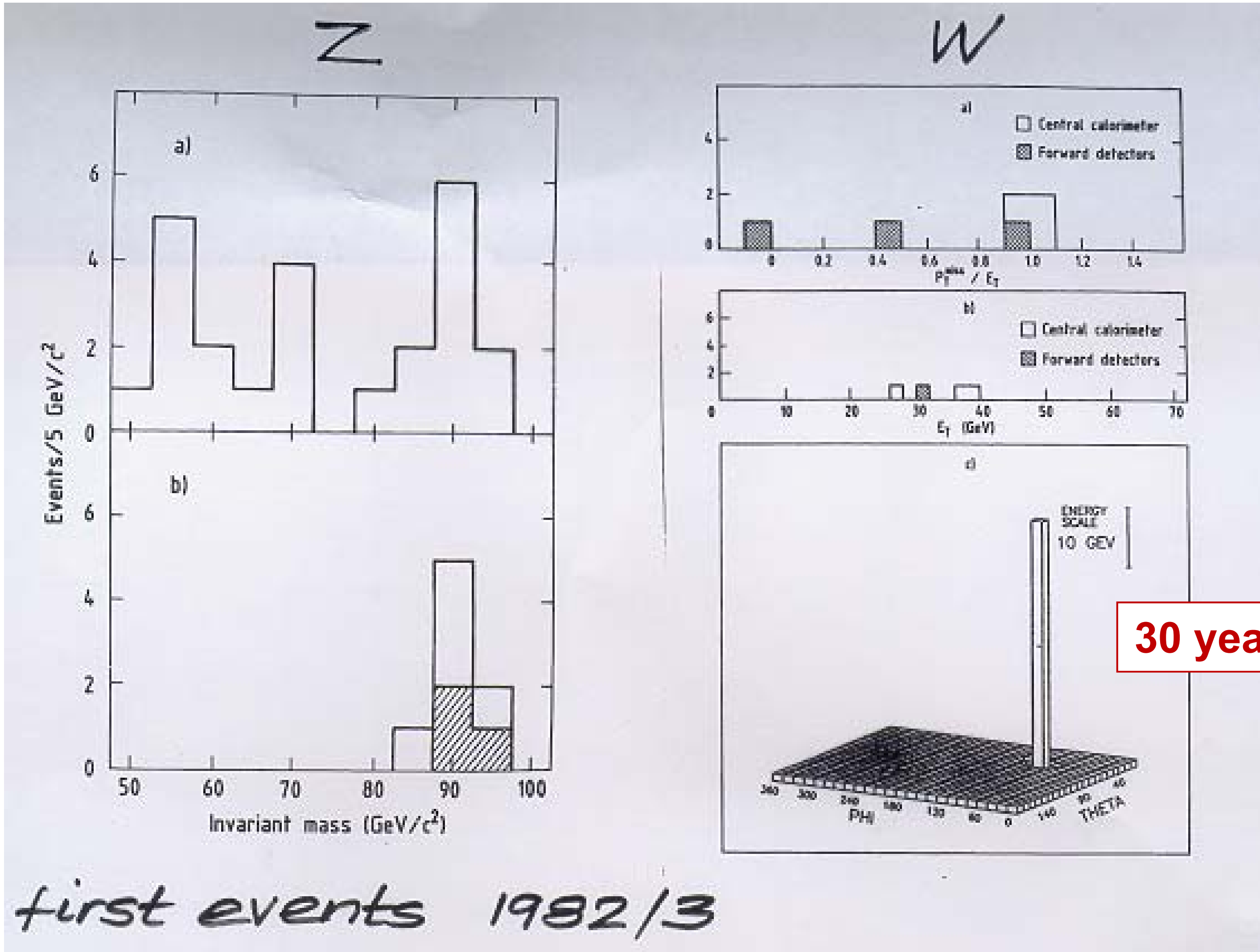


Missing transverse energy from the W → μ + ν decays

ATLAS-CONF-2011-041

$$m_T = \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

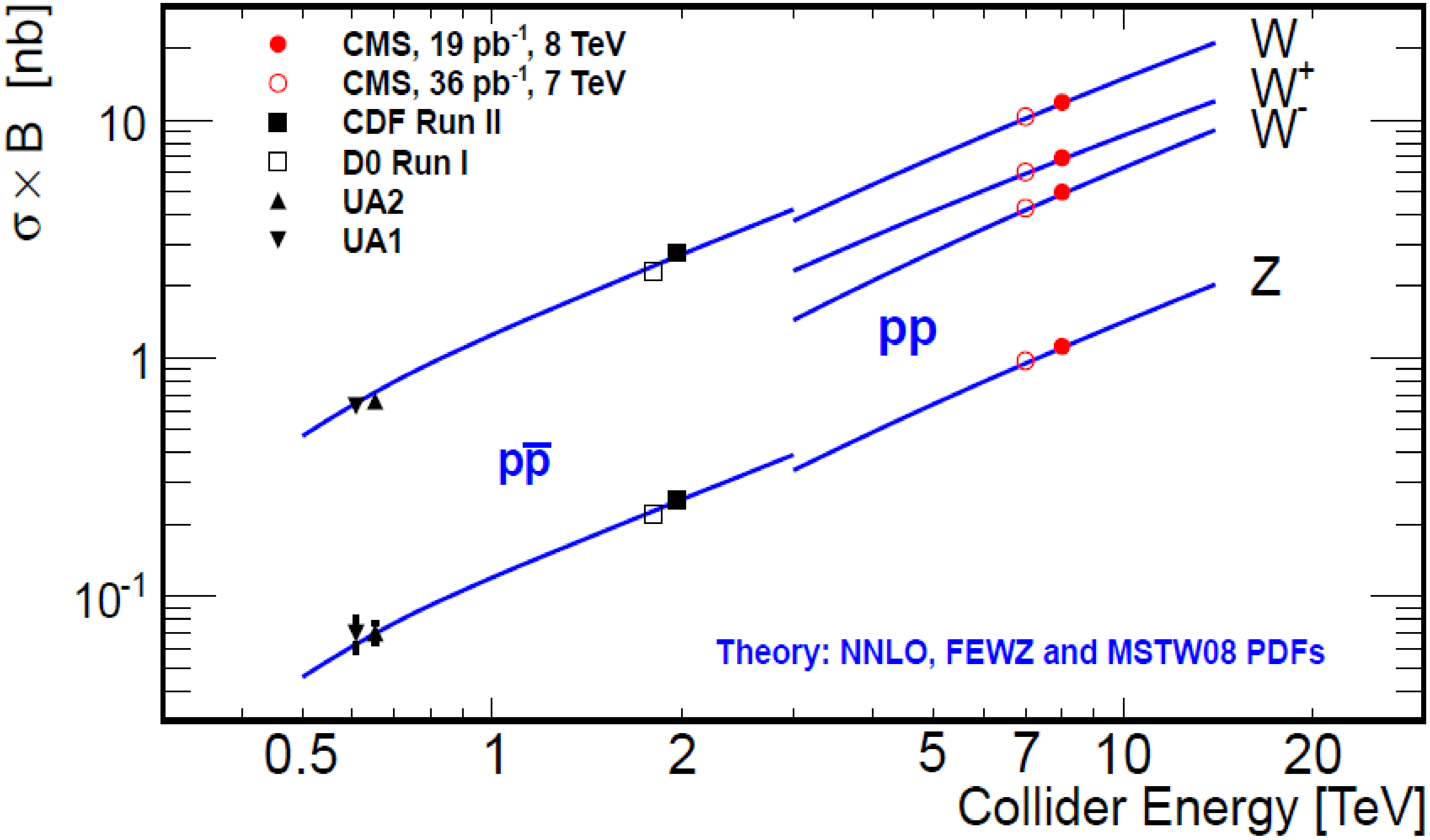
What a contrast to the Intermediate Vector Boson discovery distributions in 1982 and 1983 by UA1 and UA2 …



30 years ago!

(here are shown the UA2 distributions)

Cross section measurements

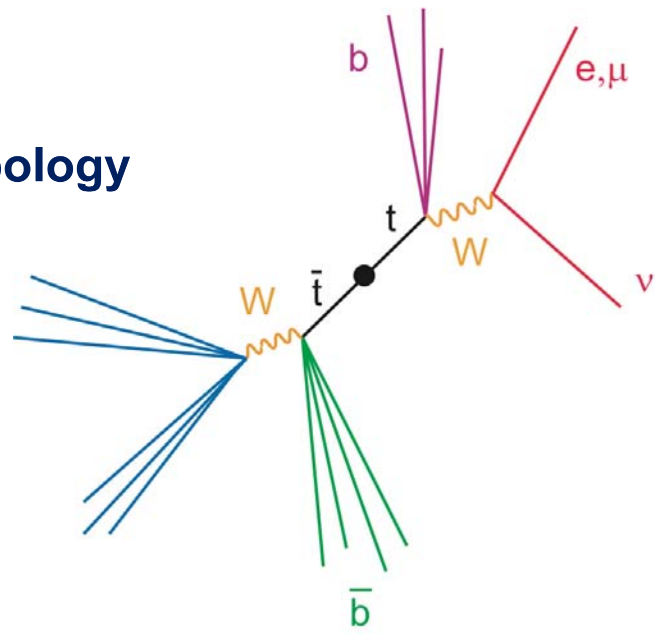


CMS-PAS-SMP-12-011

Top measurements

- **Complete set of ingredients to investigate production of ttbar, which is the next step in verifying the SM at the LHC:**
  - **e, μ, E_T^{miss}, jets, b-tag**

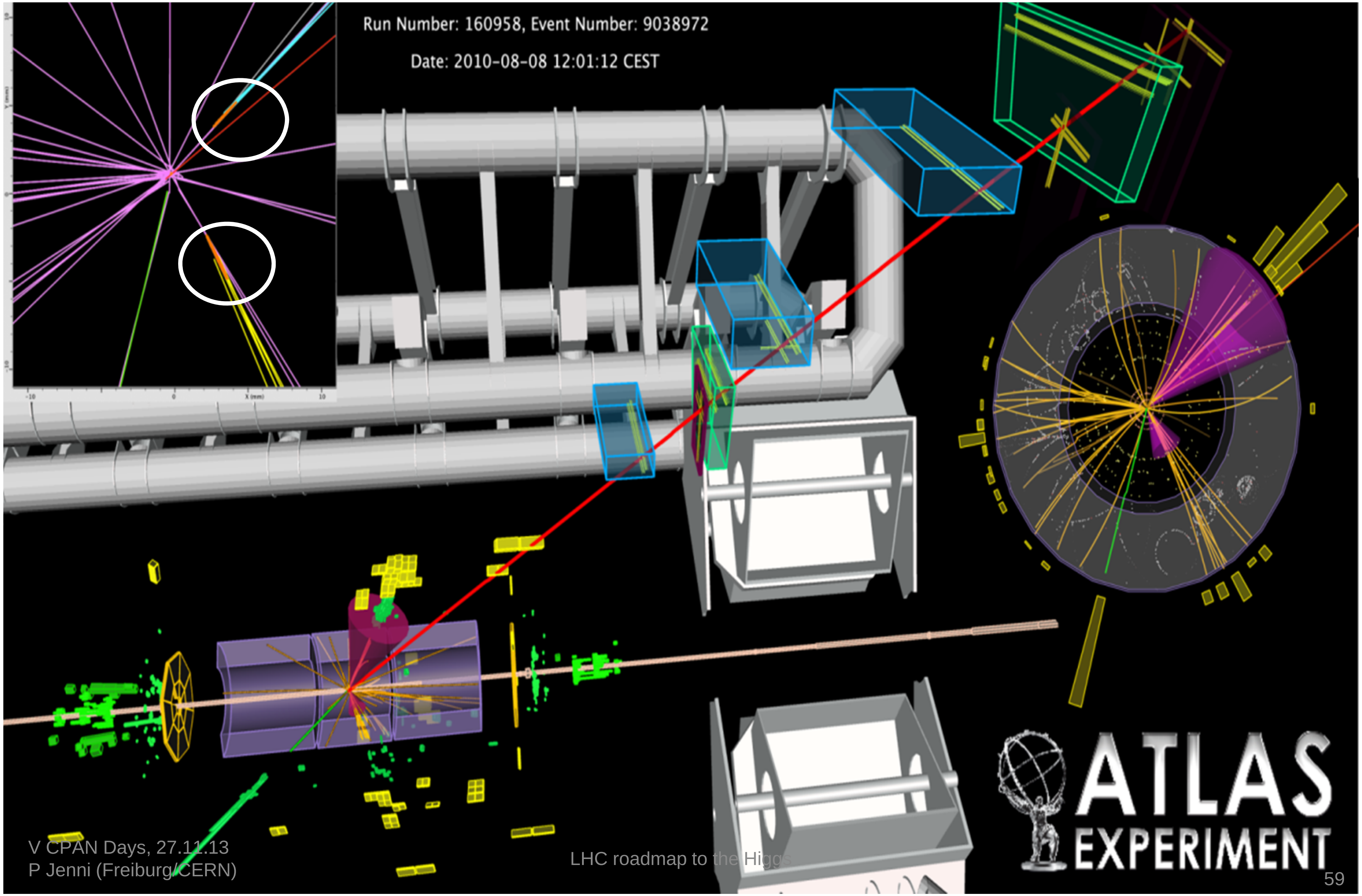
- **Assume all tops decay to Wb: event topology then depends on the W decays:**
  - **one lepton (e or μ), E_T^{miss}, jjbb (37.9%)**
  - **di-lepton (ee, $\mu\mu$ or eμ), E_T^{miss}, bb (6.5%)**

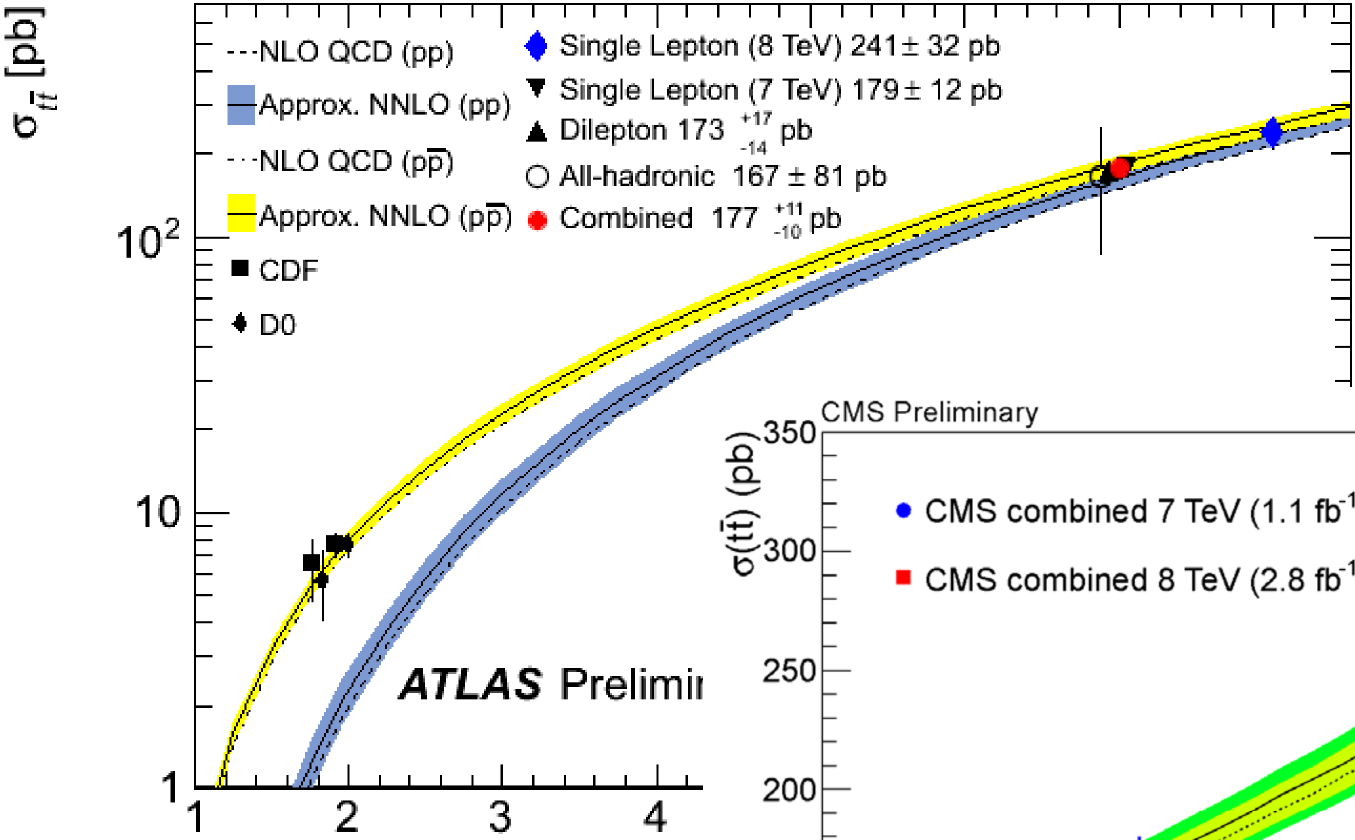


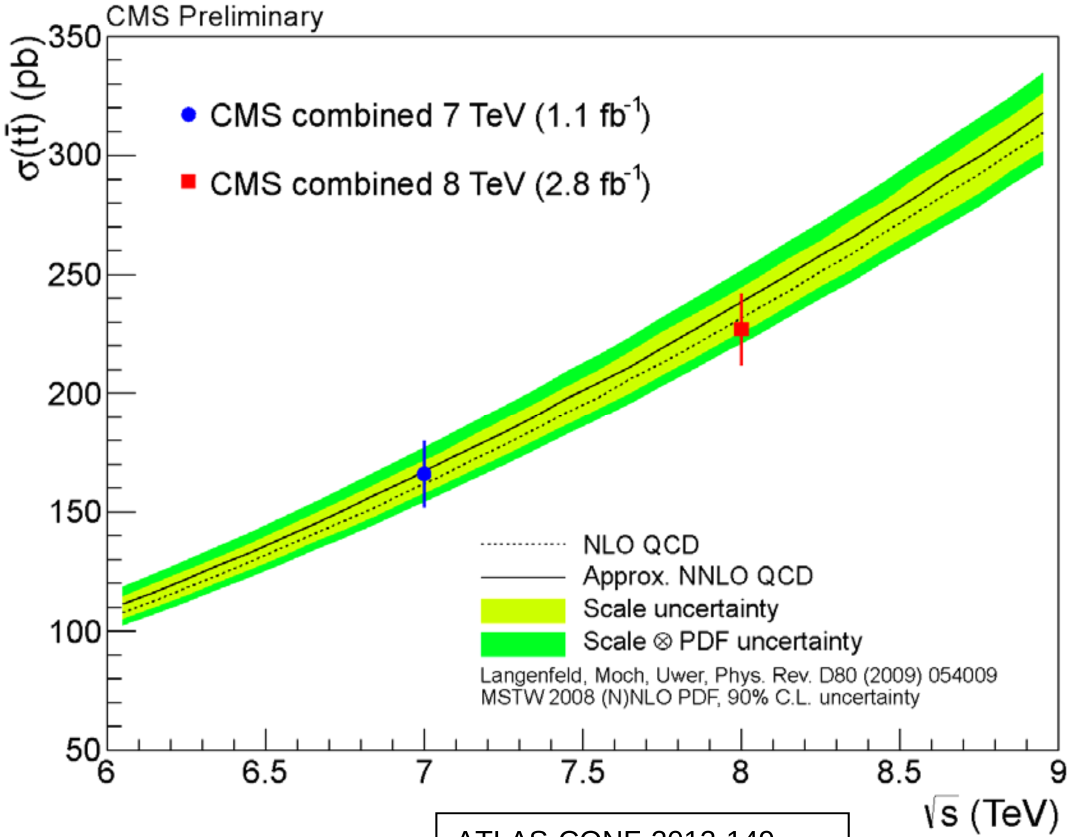
- **Data-driven methods to control QCD and W+jets backgrounds**

$t\bar{t}$ candidate event

e + μ + 2 jets (b-tagged) +ETmiss





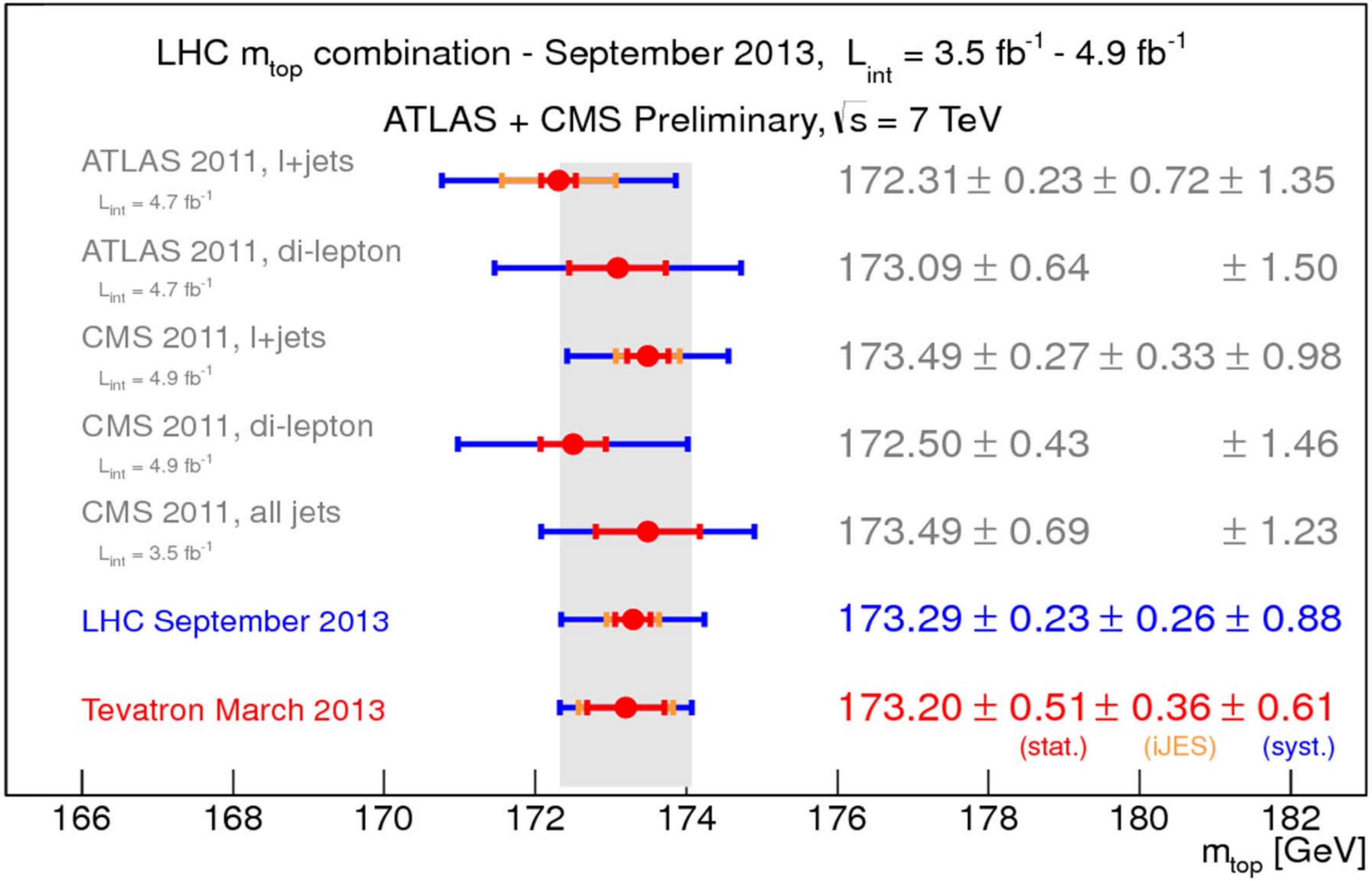


$t\bar{t}$ pair production cross-sections

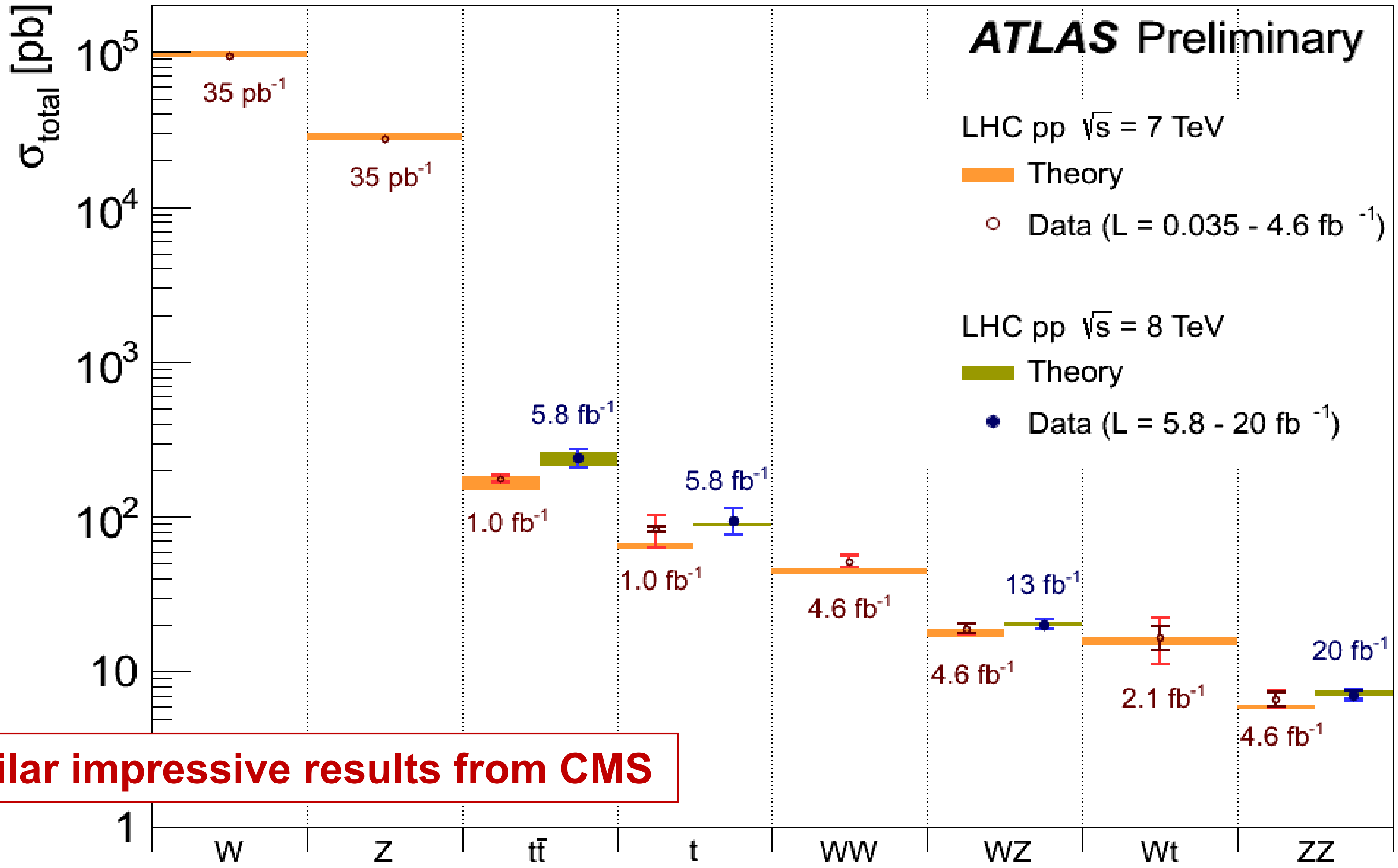
ATLAS-CONF-2012-149
CMS-PAS-TOP-12-006, 007

Top quark mass measurements

ATLAS-CONF-2013-102
CMS-PAS-TOP-13-005



A summary of Standard Model measurements



Similar impressive results from CMS

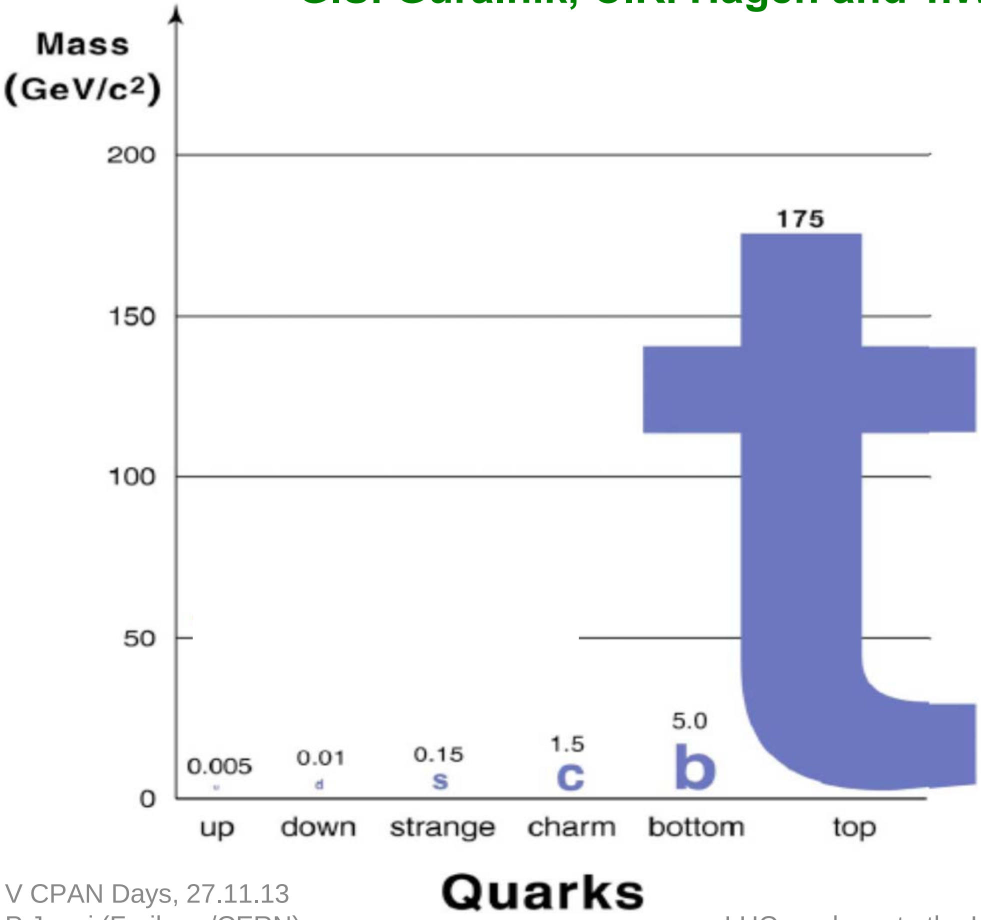
The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics


HIGGS BOSON

A most basic question is why particles (and matter) have masses (and so different masses)

The mass mystery for fundamental particles could be solved with the 'EW symmetry breaking mechanism' which predicts the existence of a new elementary particle, the 'Higgs' particle (theory 1964: R. Brout and F. Englert; P.W. Higgs; G.S. Guralnik, C.R. Hagen and T.W.B. Kibble)

Peter Higgs

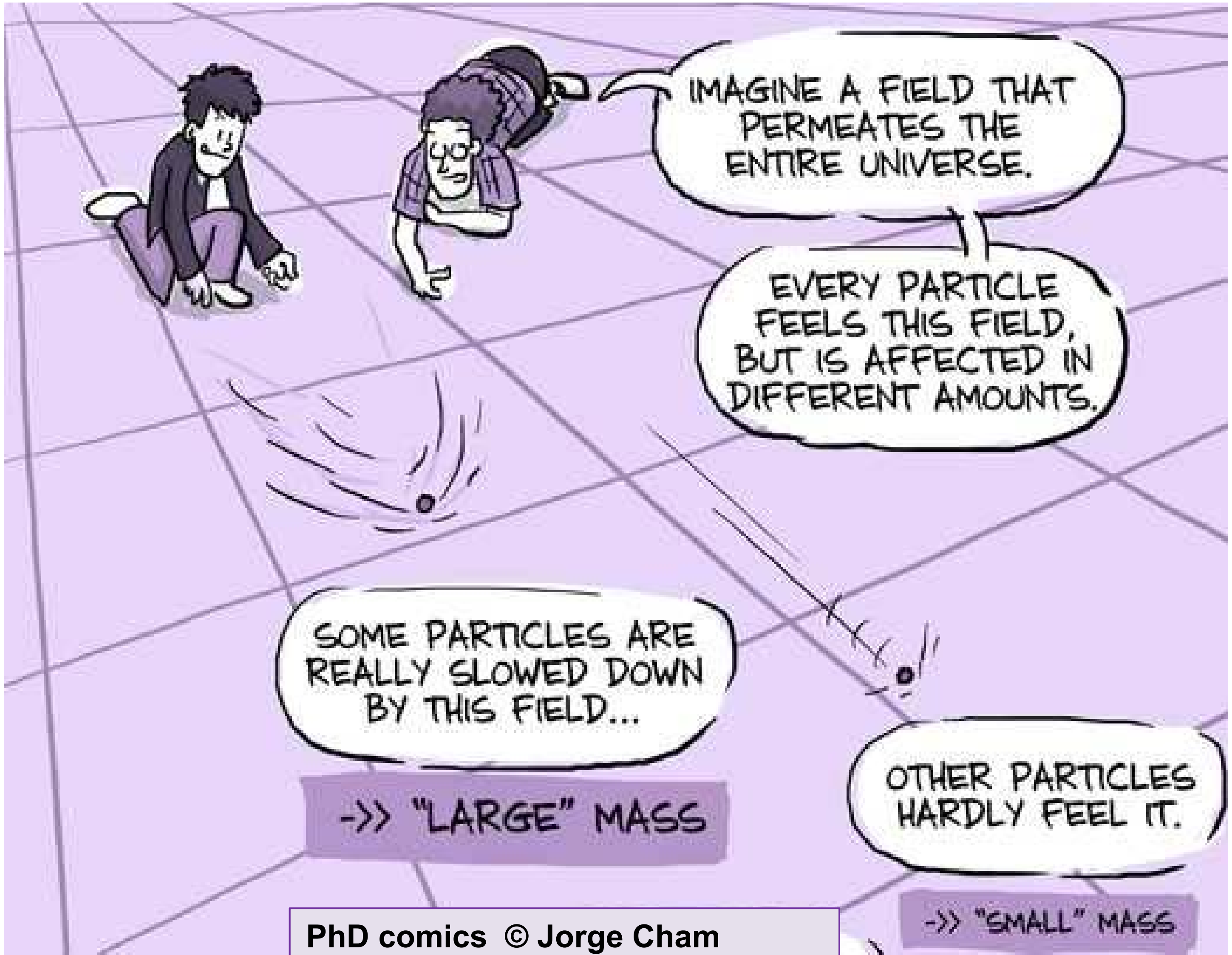


The Higgs (H) particle has been searched for since decades at accelerators …

The LHC has sufficient energy to produce it for sure, if it exists

Francois Englert

A cartoon 'illustrating' the scalar Brout-Englert-Higgs field filling all space that affects elementary particles, and 'gives' them their mass by interacting with them



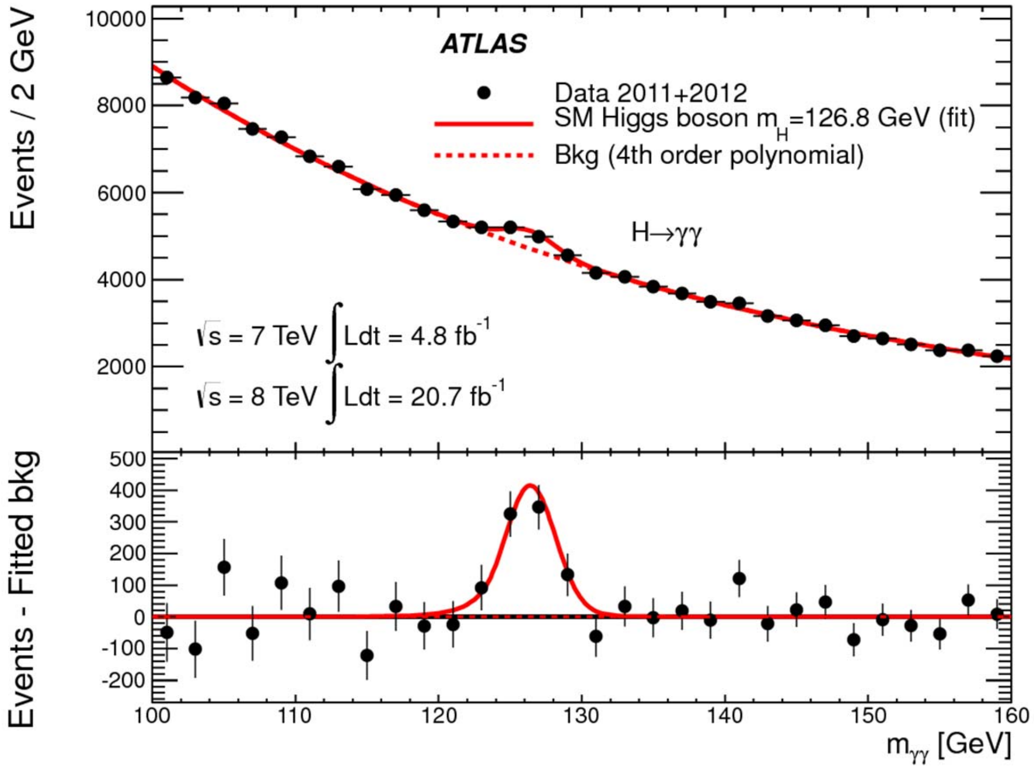
PhD comics © Jorge Cham
http://www.phdcomics.com/higgs/

Very happy faces after the announcement of the discovery on 4th July 2012 at CERN and at ICHEP Melbourne

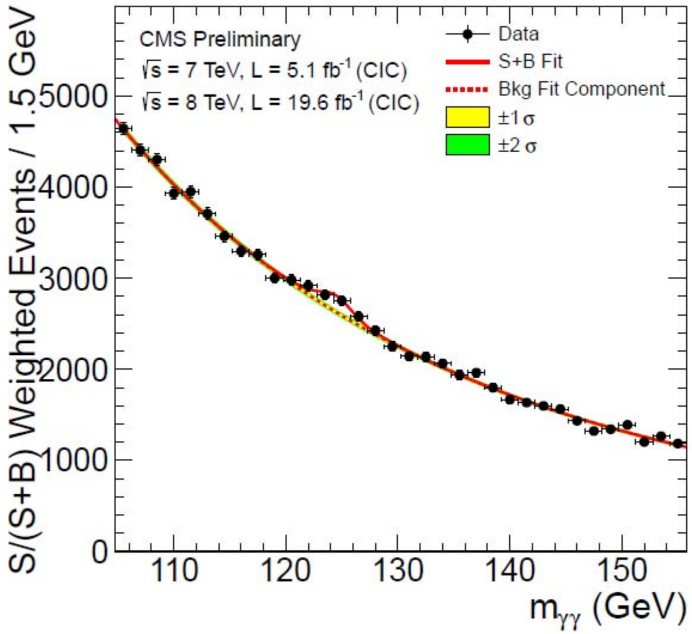
ICHEP2012
Melbourne

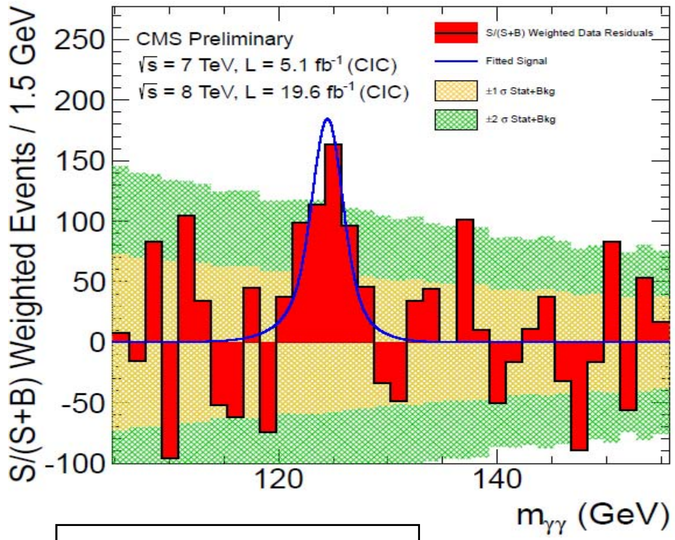
H → γγ

- Small cross-section: σ ~ 40 fb
- Expected S/B ~ 0.02
- Simple final state: two high-p_T isolated photons
- Main background: γγ continuum (irreducible) and fake γ from γj and jj events (reducible)



ATLAS-CONF-2013-012 and Phys. Lett. B 726 (2013) 88-119

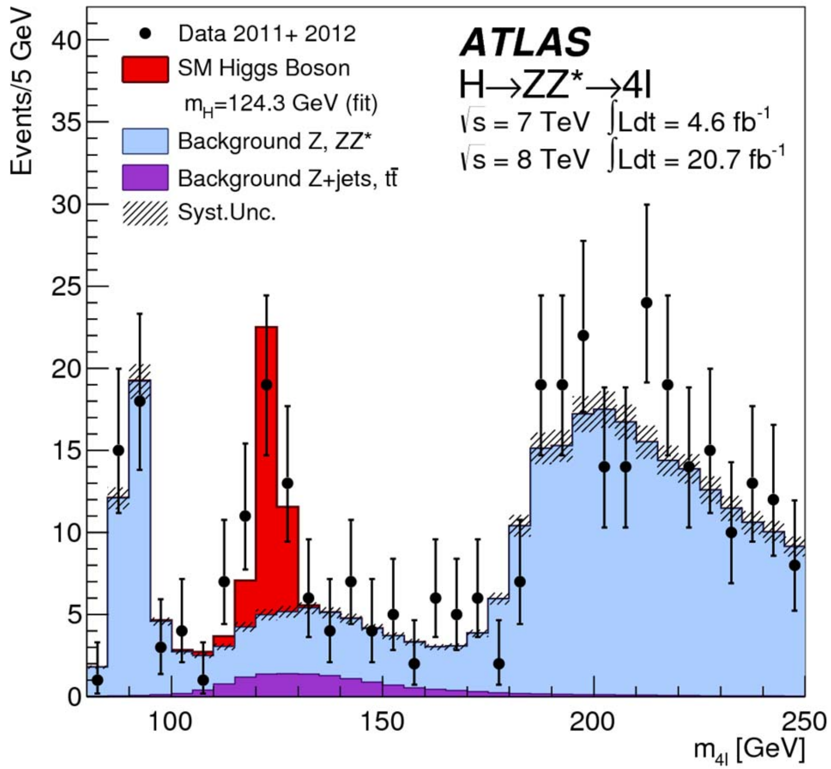




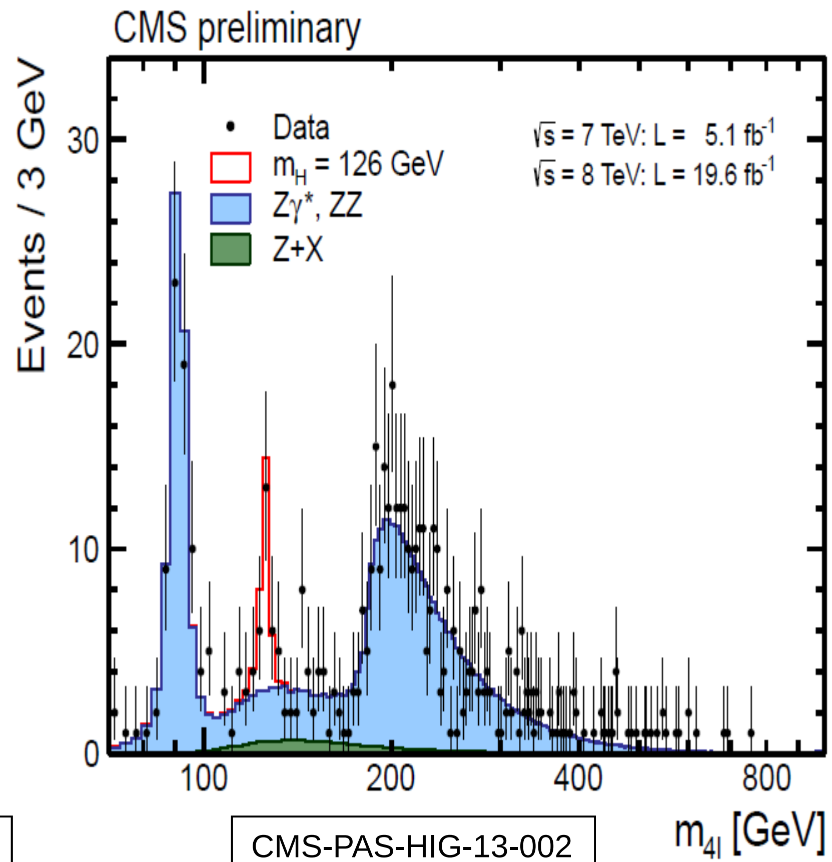
CMS-PAS-HIG-13-001

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (4e, 4μ, 2e2μ)

- Rare process, small cross section: σ ~ 2-5 fb
- However: pure: S/B ~ 1
- 4 leptons:
- Main background: $ZZ^{(*)}$ (irreducible)
  In addition: Zbb, Z+jets, tt with two leptons from b-quarks or jets



ATLAS-CONF-2013-013 and Phys. Lett. B 726 (2013) 88-119



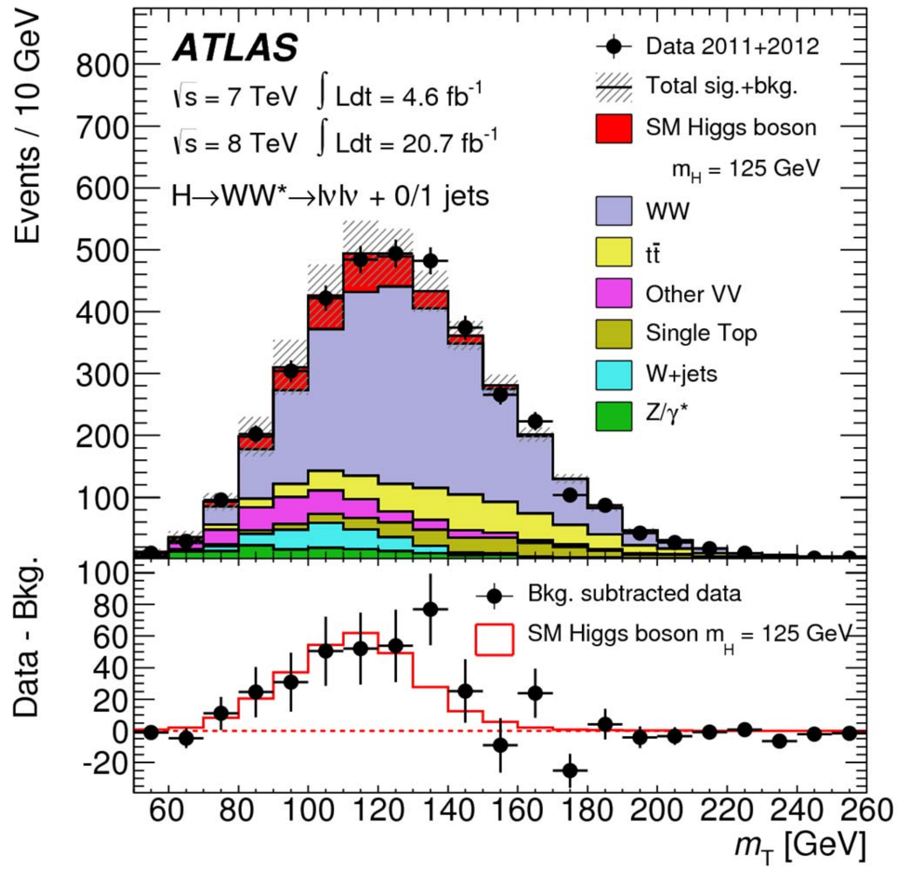
CMS-PAS-HIG-13-002

H → WW$^{(*)}$ → lνlν (eνeν, μνμν, eνμν)

- Very sensitive channel over ~ 125-180 GeV (σ ~ 200 fb)
- Challenging: 2ν → no mass reconstruction/peak → "counting channel"
- 2 isolated opposite-sign leptons, use eνμν only for 2012 data, large E_T^{miss}
- Main backgrounds: WW, top, Z+jets, W+jets
- Topological cuts against "irreducible" WW background

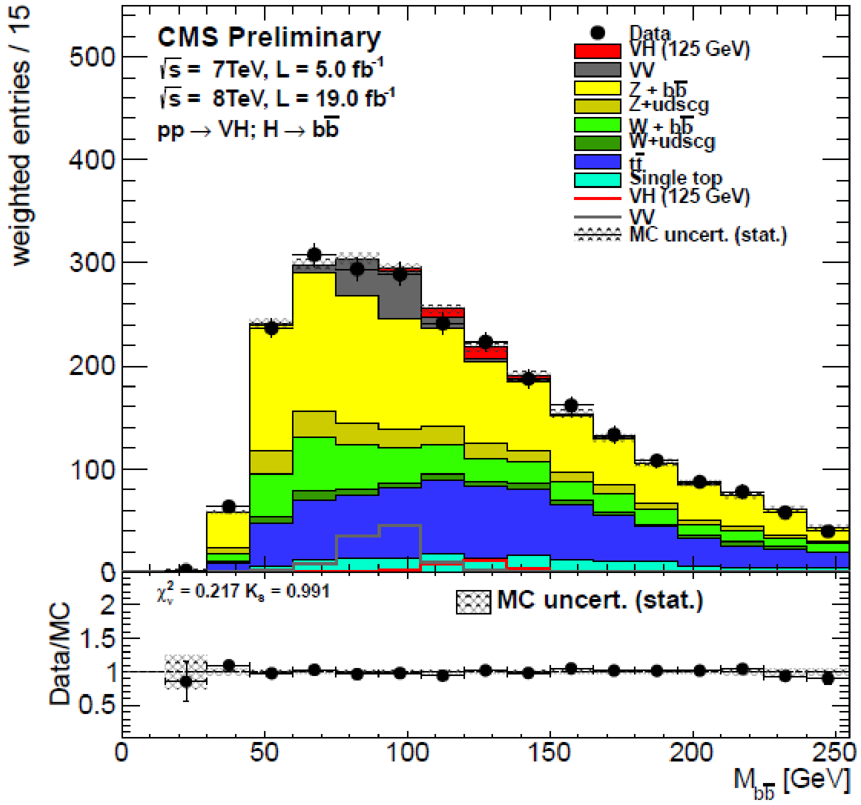
(Just an example distributions from several categories used in both experiments)

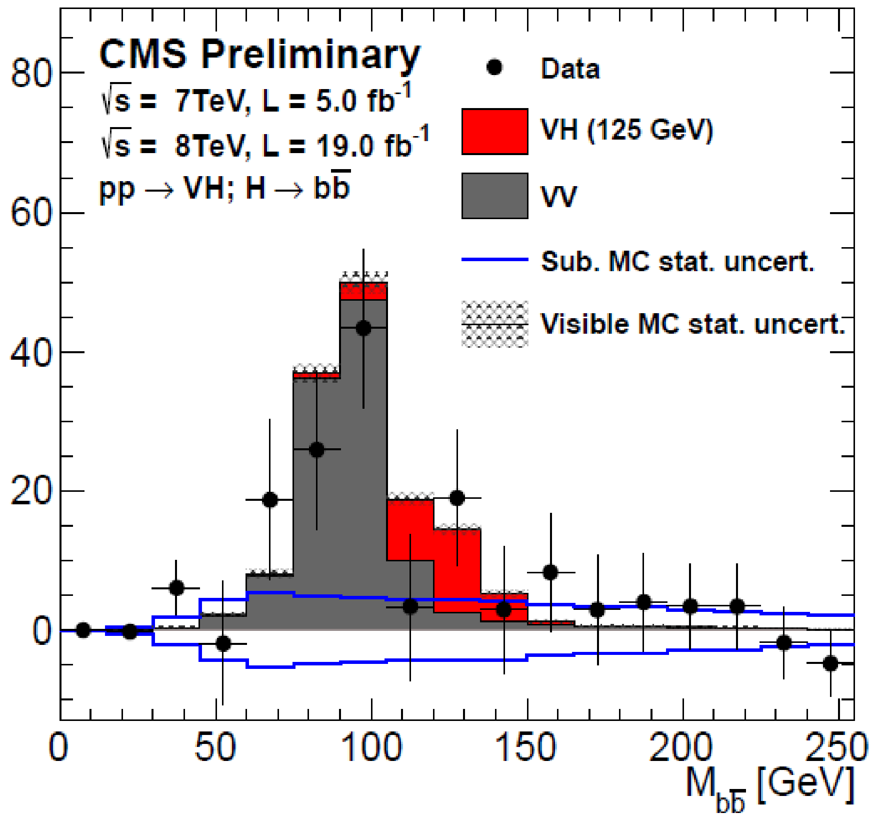
ATLAS-CONF-2013-030 and Phys. Lett. B 726 (2013) 88-119



$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

H search in the bb channel, for H produced in association with a W or Z





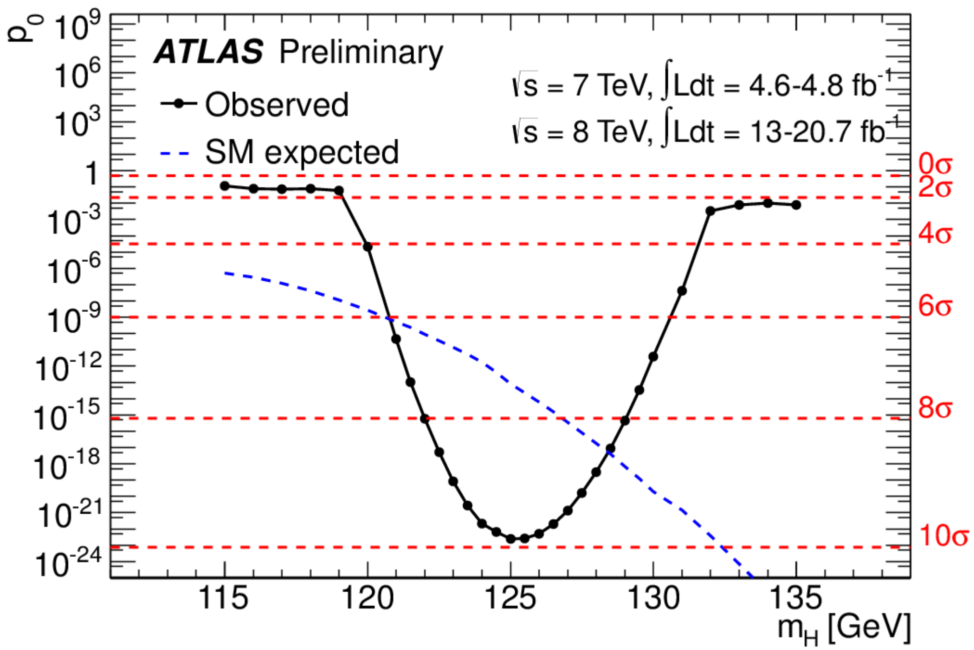
CMS-PAS-HIG-13-012, arXiv:1310.3687v1[hep-ex], submitted to Phys Rev D

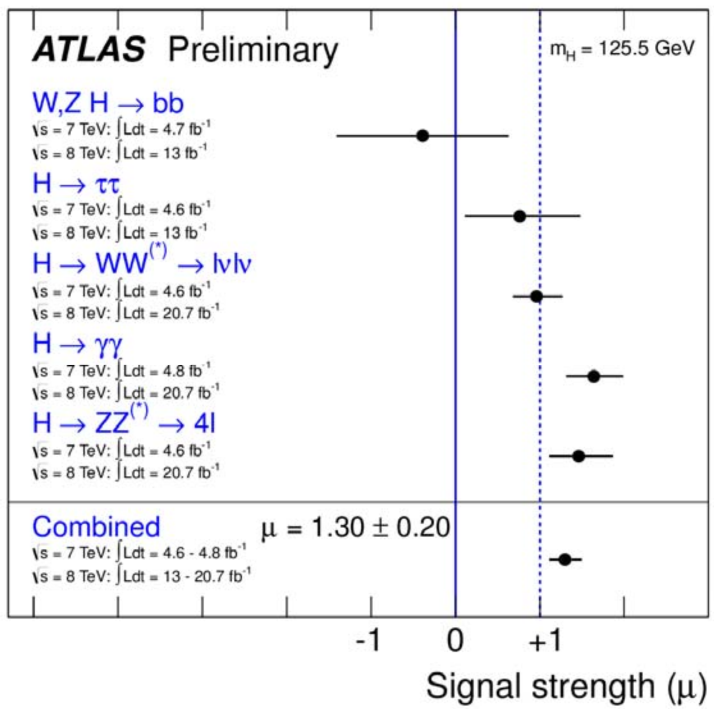
How significant is the signal for the new particle ?

Mass = 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV [ATLAS]
125.7 ± 0.3 (stat) ± 0.3 (syst) GeV [CMS]

Observed data compared to the probability that the background fluctuates to fake the observed excess of events, and what is expected from a SM Higgs

Signal strength
μ = 0 background only hypothesis
μ = 1 SM Higgs hypothesis





ATLAS-CONF-2013-034

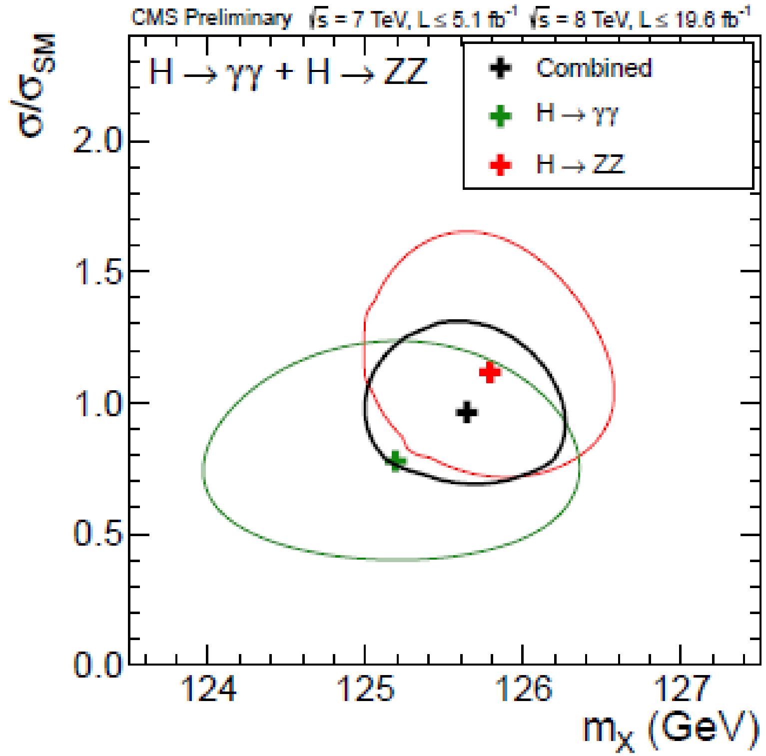
CMS-PAS-HIG-13-005

μ = 1.30 ± 0.20 [ATLAS]
μ = 0.80 ± 0.14 [CMS]

How significant is the signal for the new particle ?

Mass = 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV [ATLAS]
125.7 ± 0.3 (stat) ± 0.3 (syst) GeV [CMS]

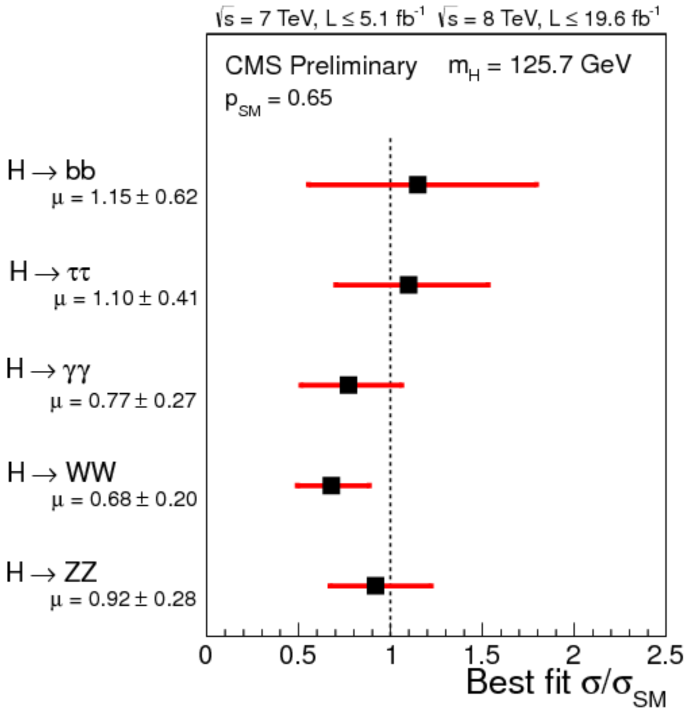
Mass measurements in the two high-resolution channels from CMS



ATLAS-CONF-2013-034

CMS-PAS-HIG-13-005

Signal strength
$\mu = 0$ background only hypothesis
$\mu = 1$ SM Higgs hypothesis

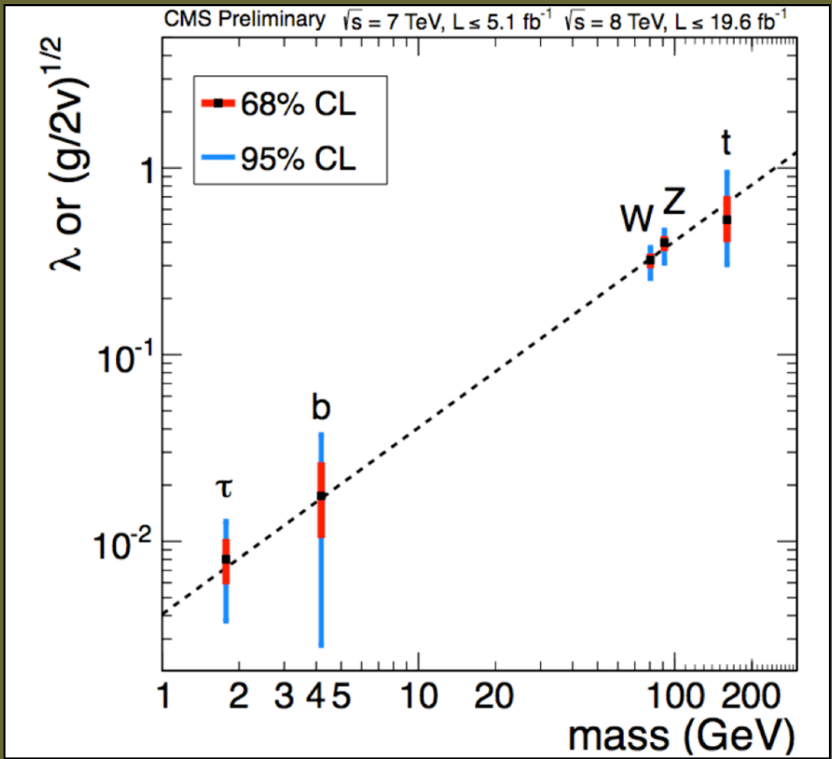


$\mu = 1.30 \pm 0.20$ [ATLAS]
$\mu = 0.80 \pm 0.14$ [CMS]

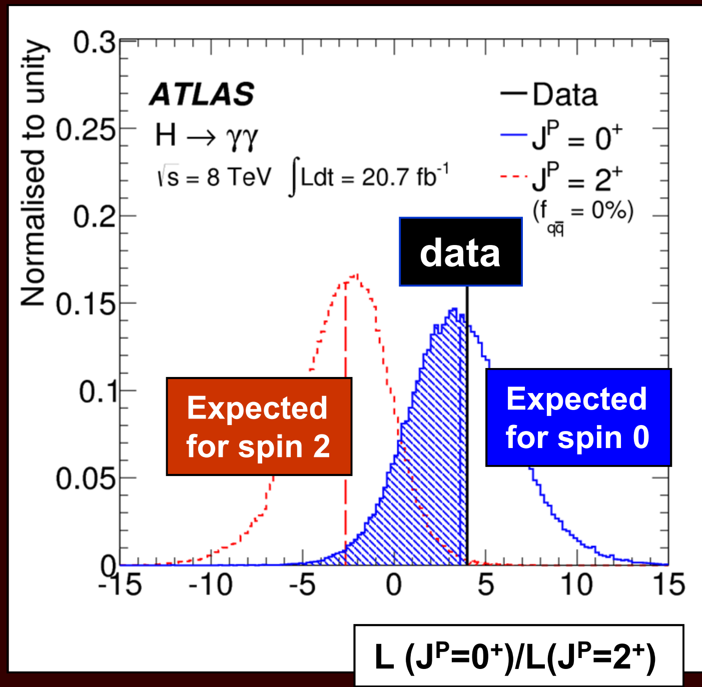
Is the new particle a Higgs boson ?

ATLAS and CMS have verified the two "fingerprints" (… to copy F Gianotti)

1) To accomplish its job (providing mass) it interacts with other particles (in particular W, Z) with strength proportional to their masses



2) It has spin zero (scalar)



Hypothesis	Rejection (C.L.)
0^-	97.8%
1^+	99.97%
1^-	99.7%
2^+	99.9%

Detailed studies of the production and decay properties have started in order to characterize the new particle

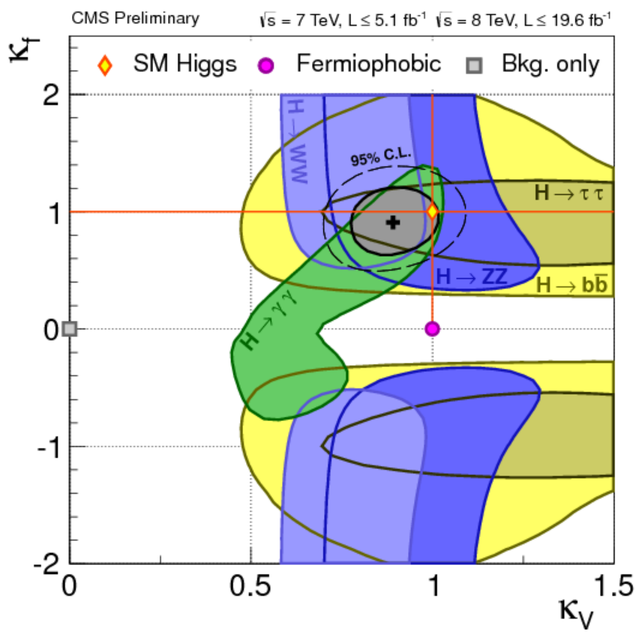
It will be important to understand with great precision if it is the only scalar boson of the Standard Model 'Brout-Englert-Higgs' mechanism to break the electroweak symmetry, or if it is only part of a broader physics picture going *Beyond the Standard Model*

These studies will be among the most central ones in the decades to come both at the LHC and at possible other future colliders

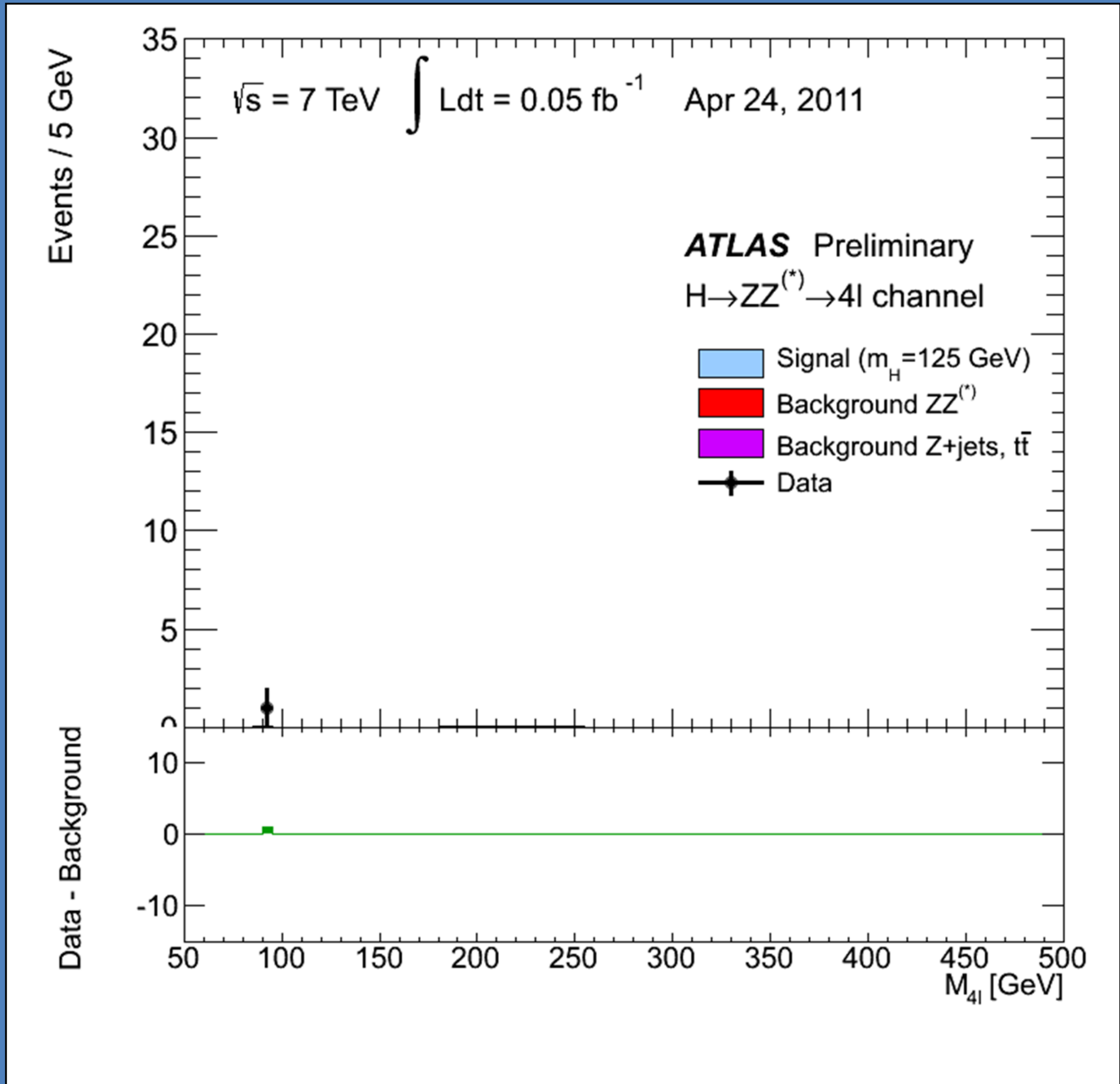
For the experts, today:

Couplings
Production modes
Spin-parity

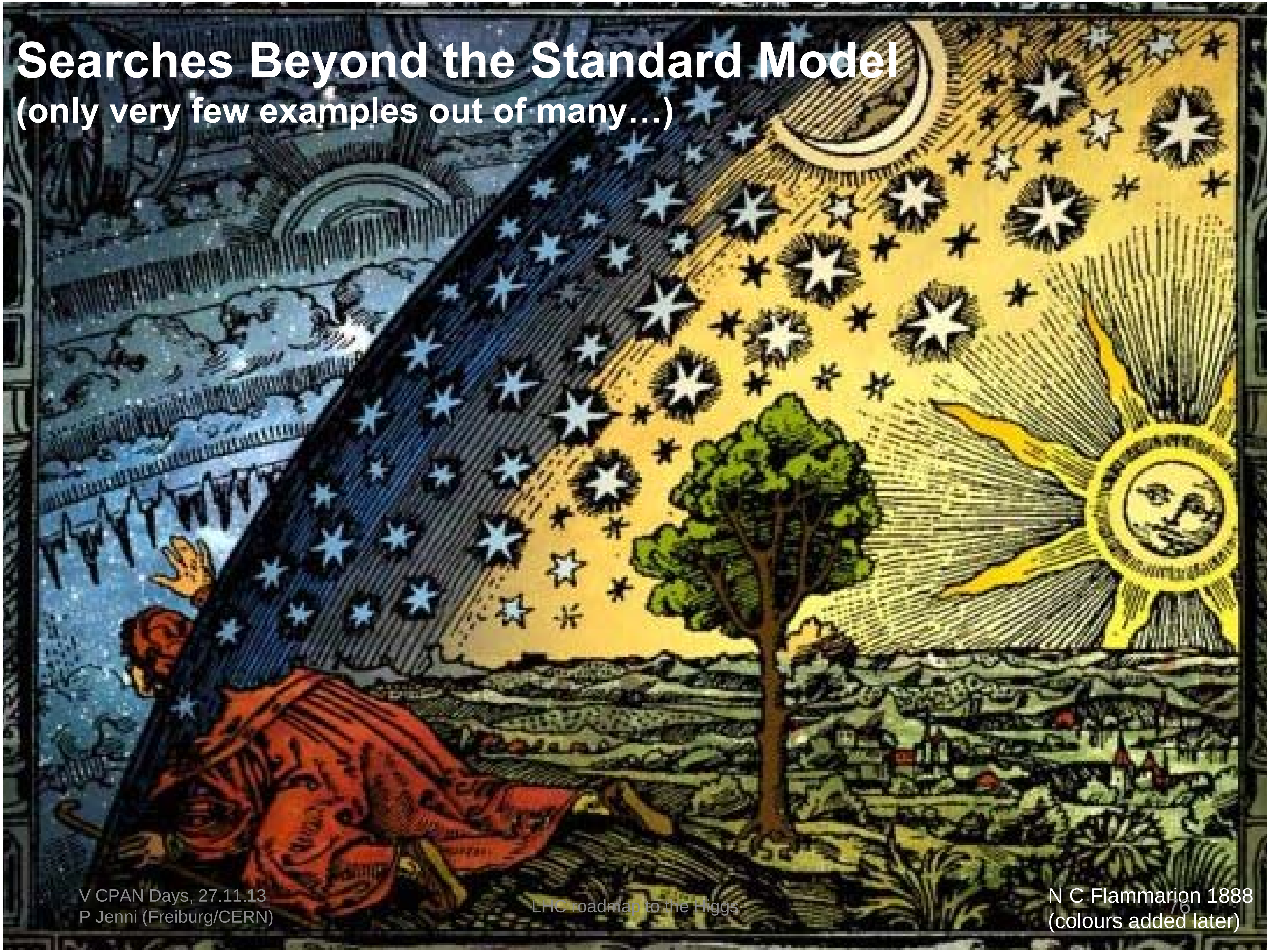
all support at the 2-3 σ level the SM Higgs with present limited statistics



Birth and evolution of a signal: $H \rightarrow 4l$



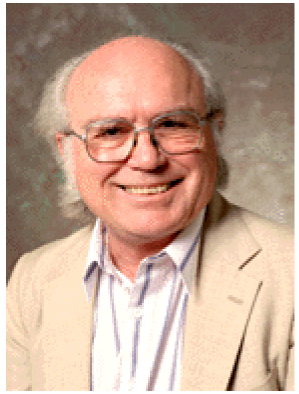
Searches Beyond the Standard Model
(only very few examples out of many…)



N C Flammarion 1888
(colours added later)

Supersymmetry (SUSY)

(Julius Wess and Bruno Zumino, 1974)



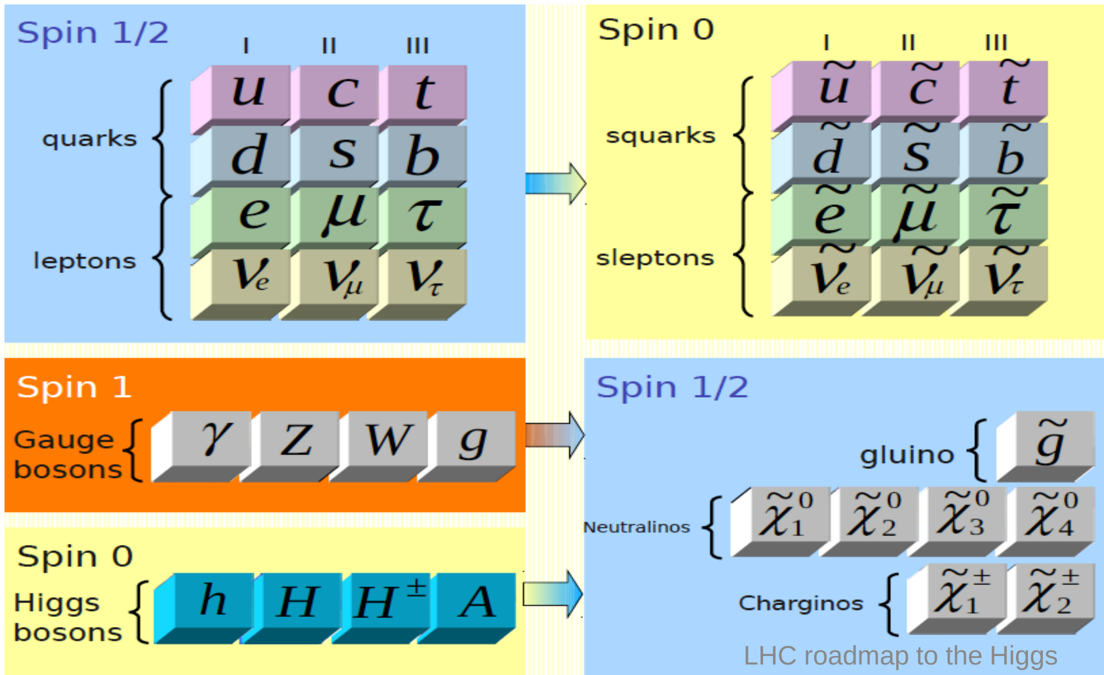
Establishes a symmetry between fermions (matter) and bosons (forces):

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

- Examples

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

Our known world… **Maybe a new world?**



Motivation:

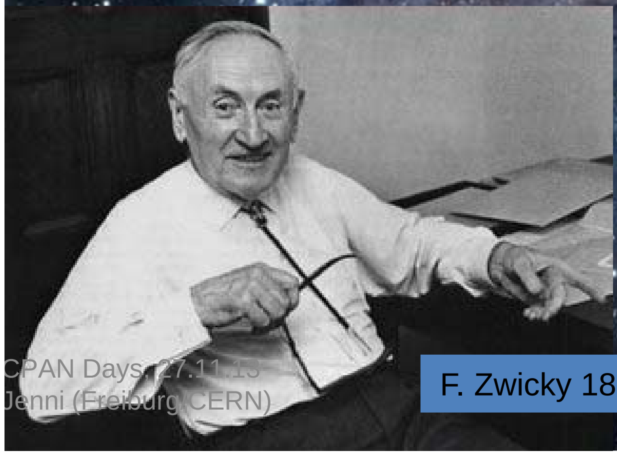
- Unification (fermions-bosons, matter-forces)
- Solves some deep problems of the Standard Model

Dark Matter in the Universe

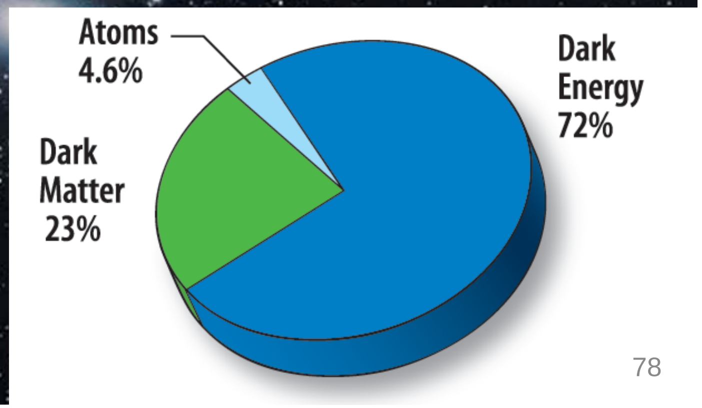
Astronomers found that most of the matter in the Universe must be invisible Dark Matter

Vera Rubin ~ 1970

'Supersymmetric' particles ?

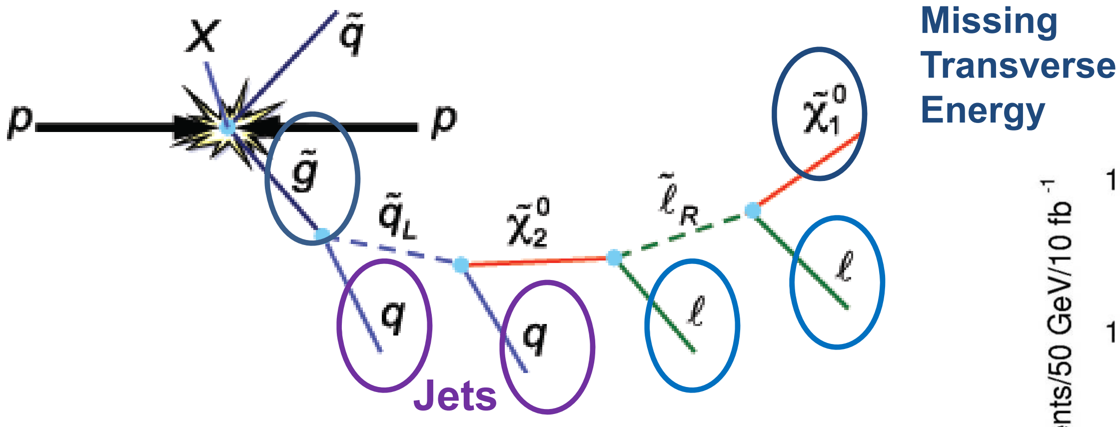


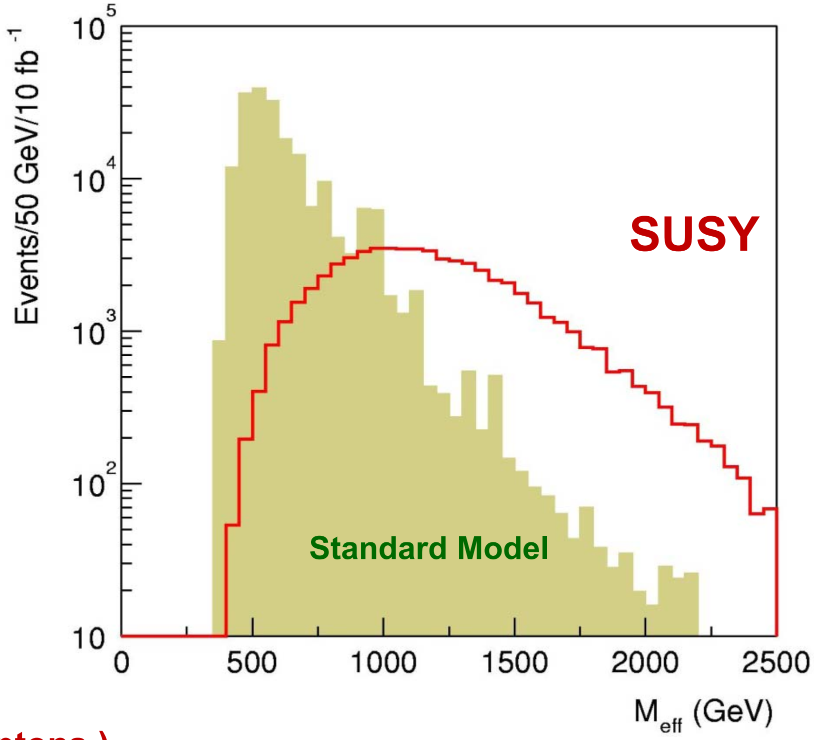
F. Zwicky 1898-1974



In practice SUSY searches at LHC are rather complicated

- 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

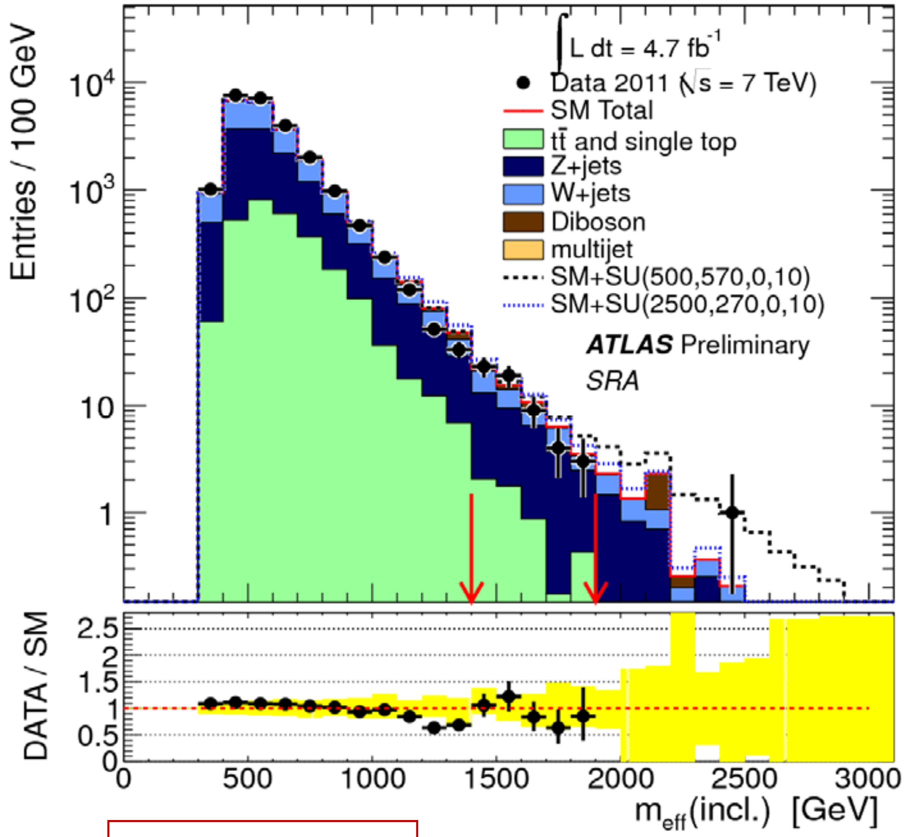
Meff = Etmiss + Σ pT(jets)

An <u>example</u> from the 2011 data, to show the principle, final results will be quoted for updated analyses including 2012 data

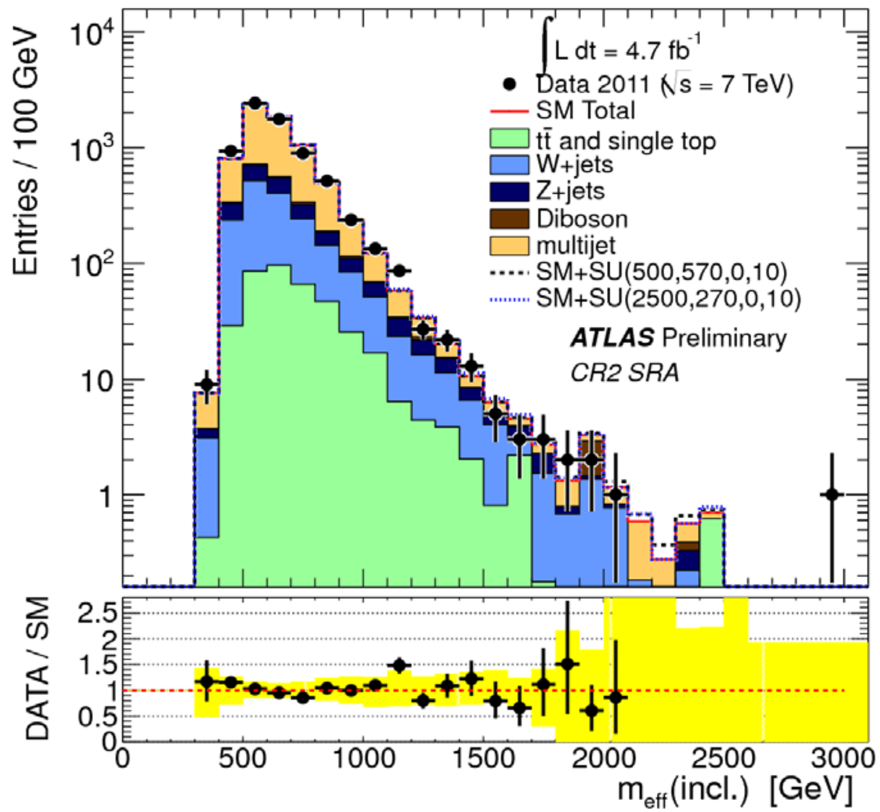
- **0-lepton + 2−6 jets + high MET (based on Et-miss+jet triggers)**
- **0-lepton + 6−9 (multi-)jets + MET (based on multi-jet triggers)**
- **1-lepton + 3,4 jets + high MET (based on lepton triggers)**

Example: O-leptons + 2-6 Jets analysis

ATLAS-CONF-2012-033, 037, and 041



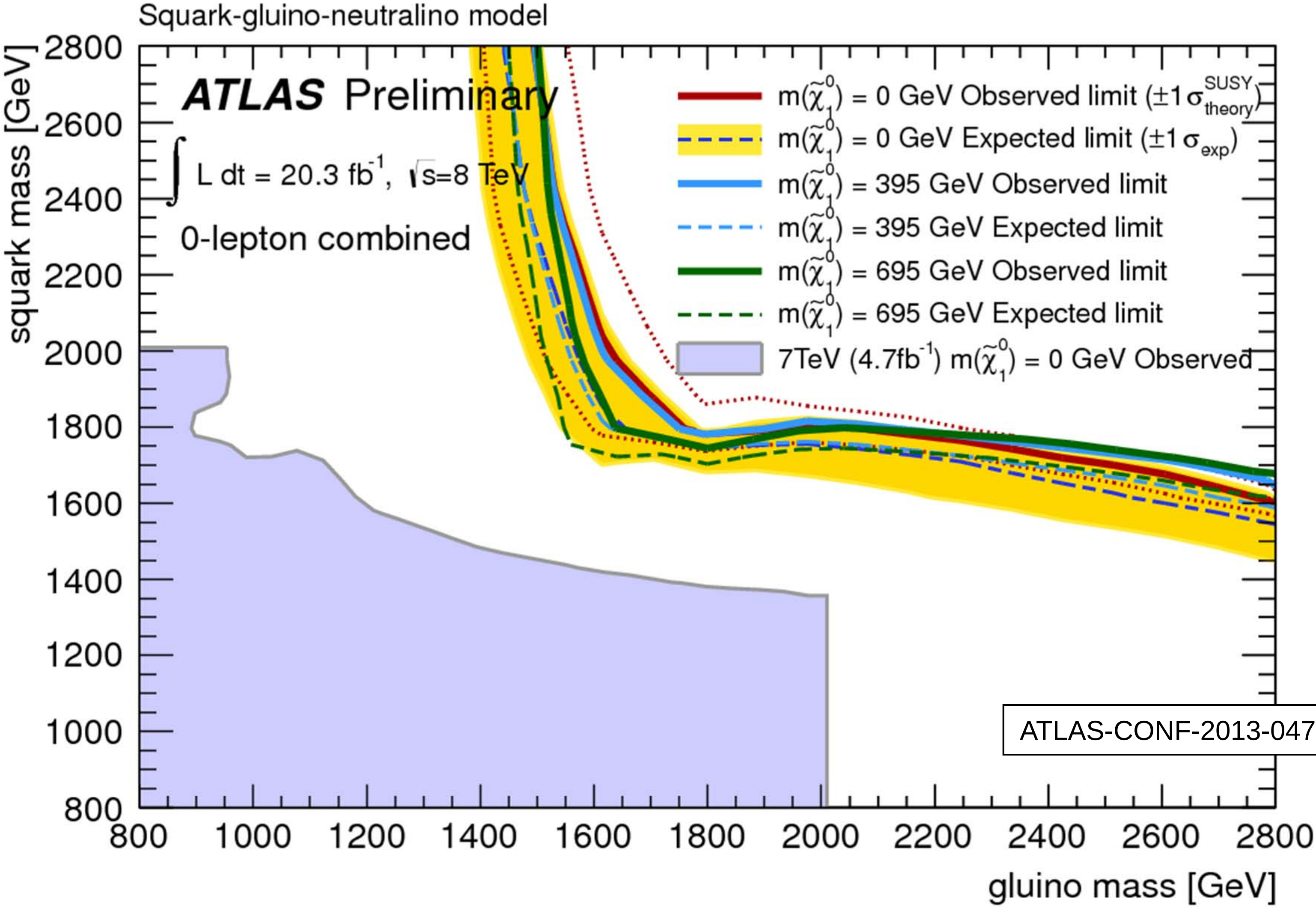
A signal region



A control region where no signal is expected

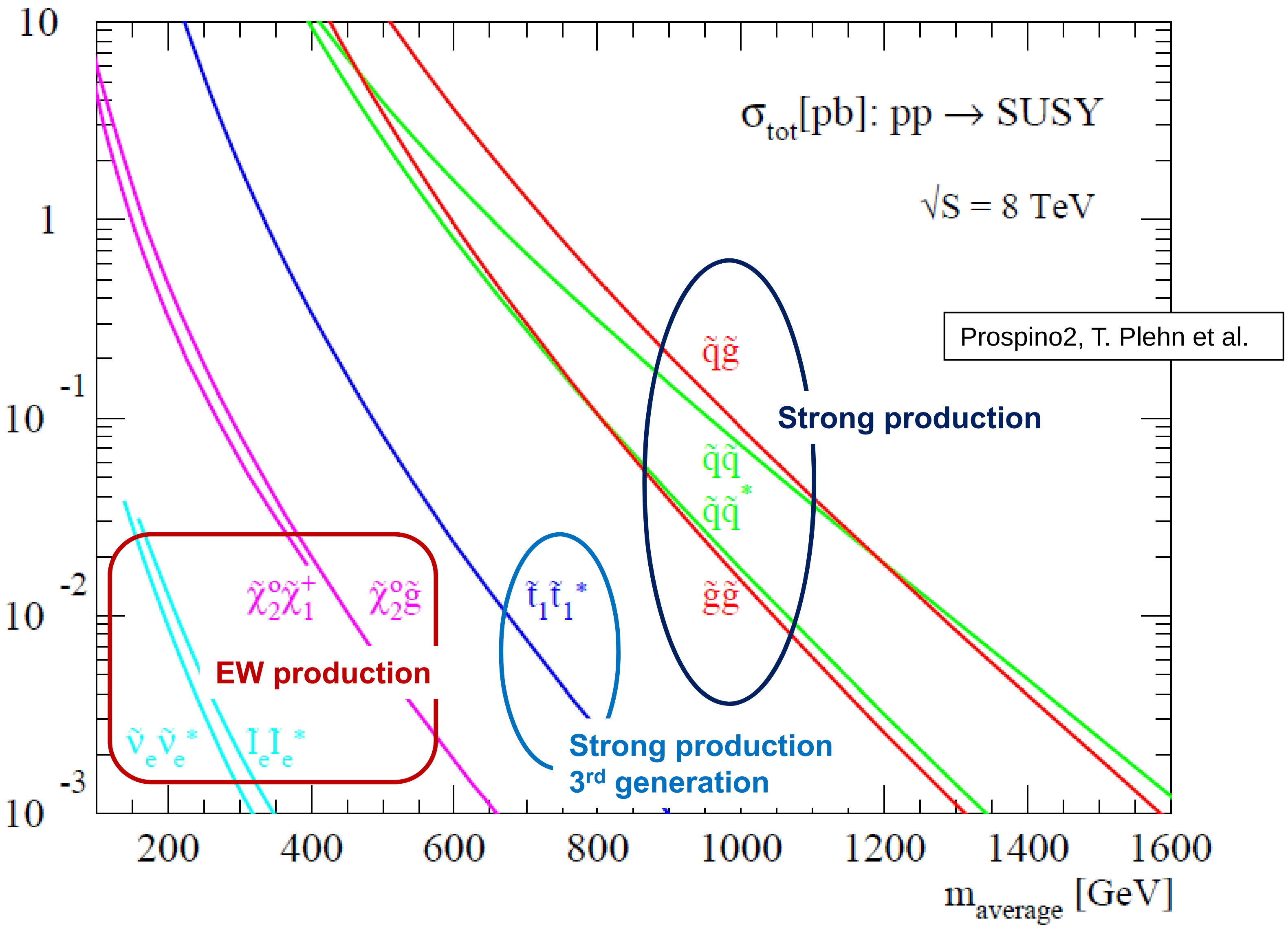
Interpretation of the results

Consider phenomenological MSSM models containing only squarks of 1st and 2nd generation, gluino and light neutralinos



ATLAS-CONF-2013-047

Expected production cross-sections at LHC



SUSY limits

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LP 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	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	$m(\tilde{\chi}_1^0)$ [illegible]	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	[illegible]	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	[illegible]	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	[illegible]	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	[illegible] $m(\tilde{\chi}_1^0)$	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), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ [illegible]	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^\pm)$=10 GeV	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ [illegible]	$m(\tilde{\chi}_1^0)$<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	$\tilde{t}_1$ [illegible] 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
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	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	[illegible]	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	[illegible]	[illegible]	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	[illegible]	[illegible]	[illegible]	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	[illegible]	[illegible]	[illegible]	$\tilde{\chi}_1^\pm$ 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	[illegible]	[illegible]	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
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W^*\tilde{\chi}_1^0Z^*\tilde{\chi}_1^0$	3 e,μ	[illegible]	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 $\tilde{\chi}_1^\pm$	0	1 jet	Yes	4.7	$\tilde{\chi}_1^\pm$ 220 GeV	1<$\tau(\tilde{\chi}_1^\pm)$<10 ns	1210.2852
	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 $\tilde{\tau}$	1-2 μ	0	-	15.9	$\tilde{\tau}$ 385 GeV	5<$\tan\beta$<50	ATLAS-CONF-2013-058
	Direct $\tilde{\tau}\tilde{\tau}$ prod., stable $\tilde{\tau}$ or $\tilde{\ell}$	1-2 μ	0	-	15.9	$\tilde{\tau}$ 395 GeV	$m(\tilde{\tau})$=$m(\tilde{\ell})$	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] (10^{-1} … 1)

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

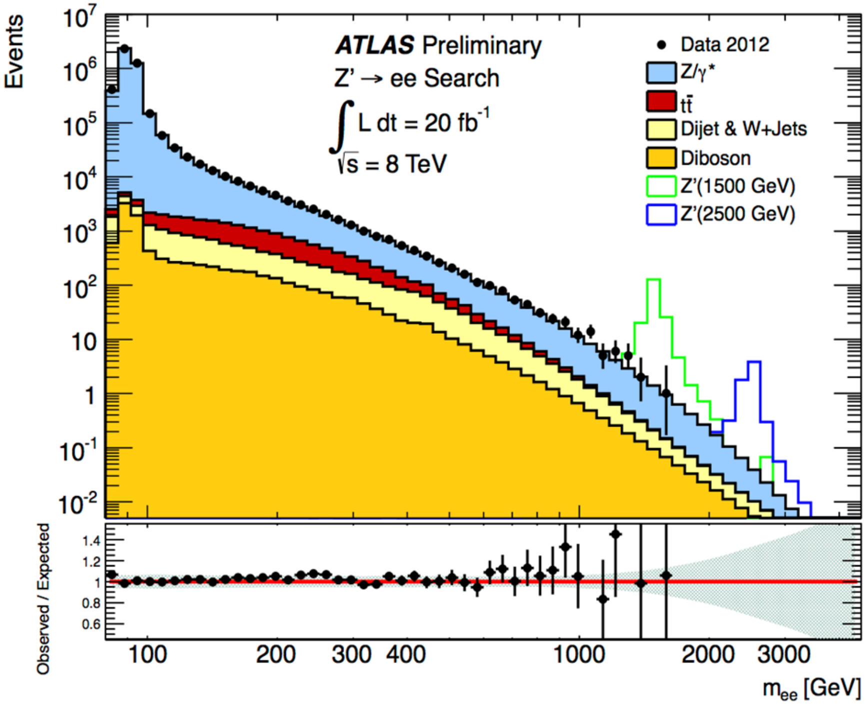
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Very similar limits come from CMS

Searches for heavy W and Z like particles

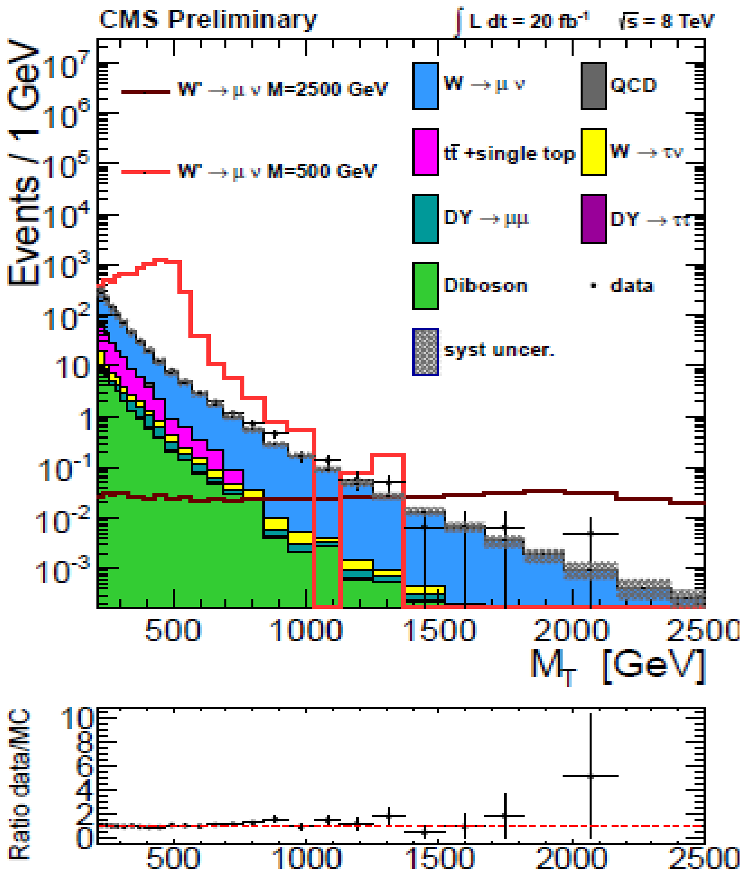
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z': Di-lepton pairs



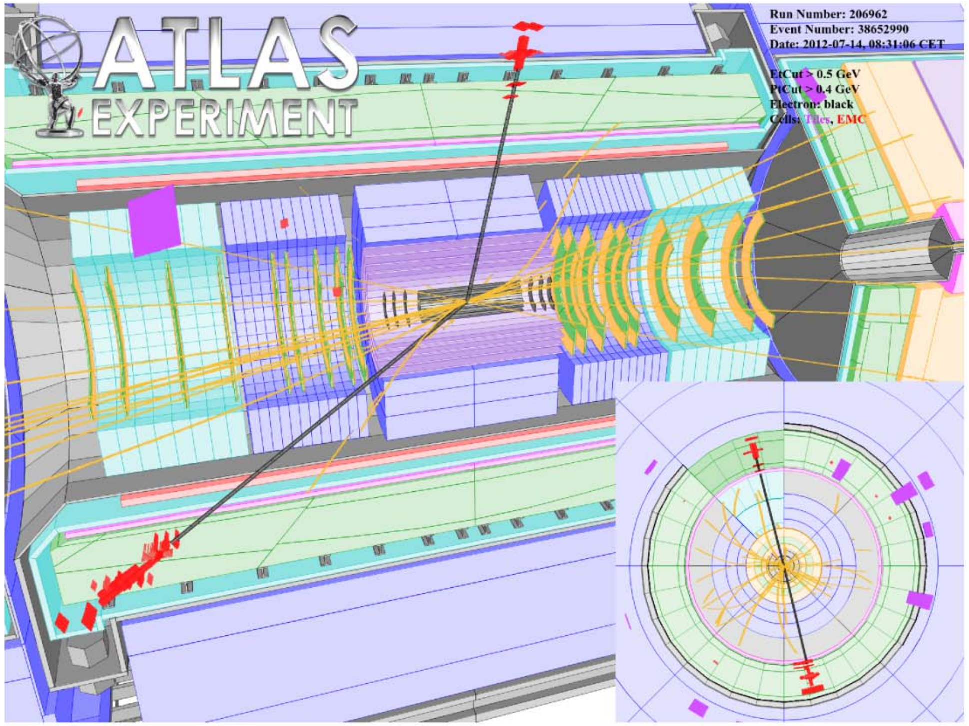
ATLAS-CONF-2013-017

W': Lepton + ETmiss

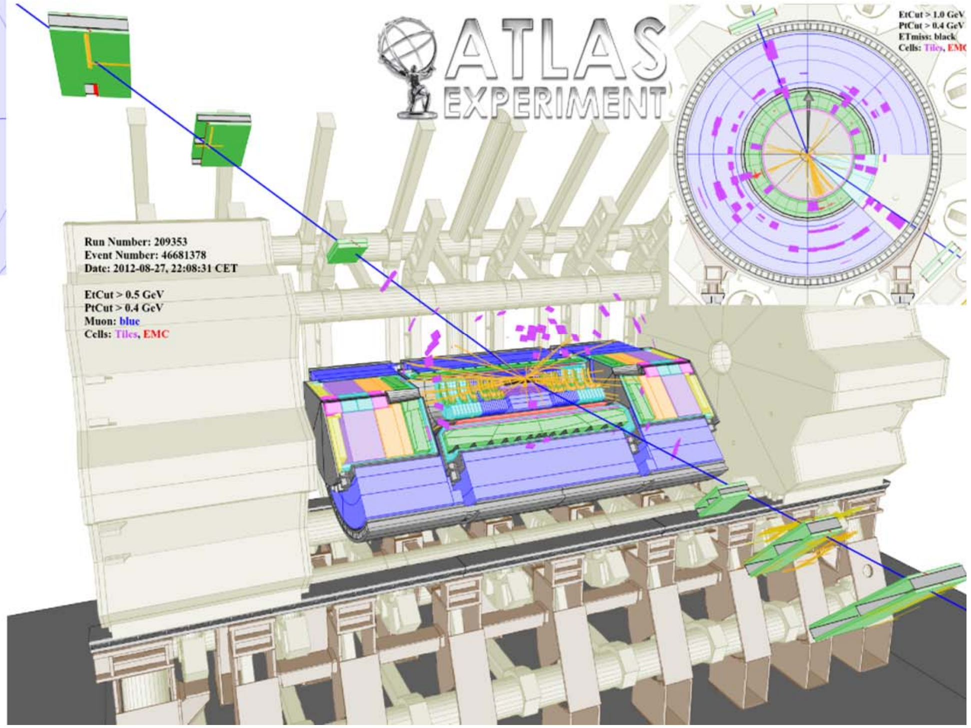


CMS-EXO-12-060

The highest mass di-lepton events from ATLAS

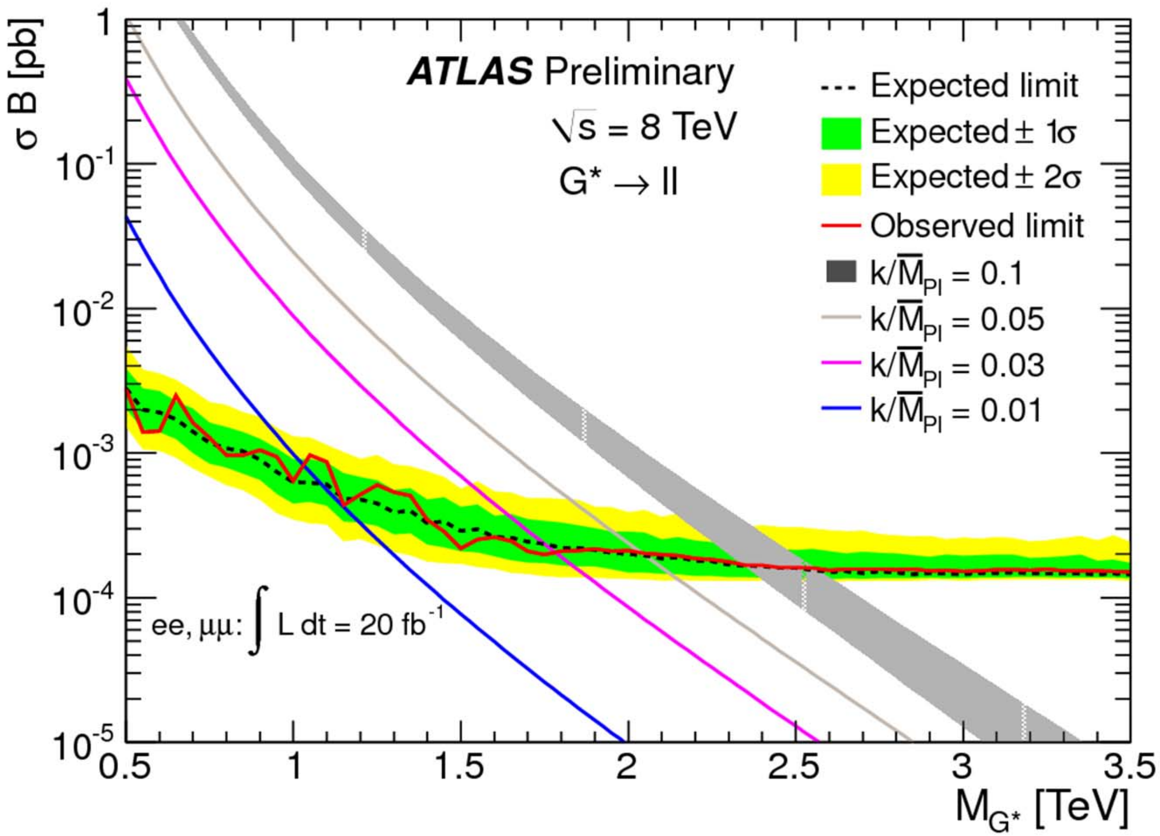


m (e^+e^-) = 1.54 TeV



m ($\mu^+\mu^-$) = 1.84 TeV

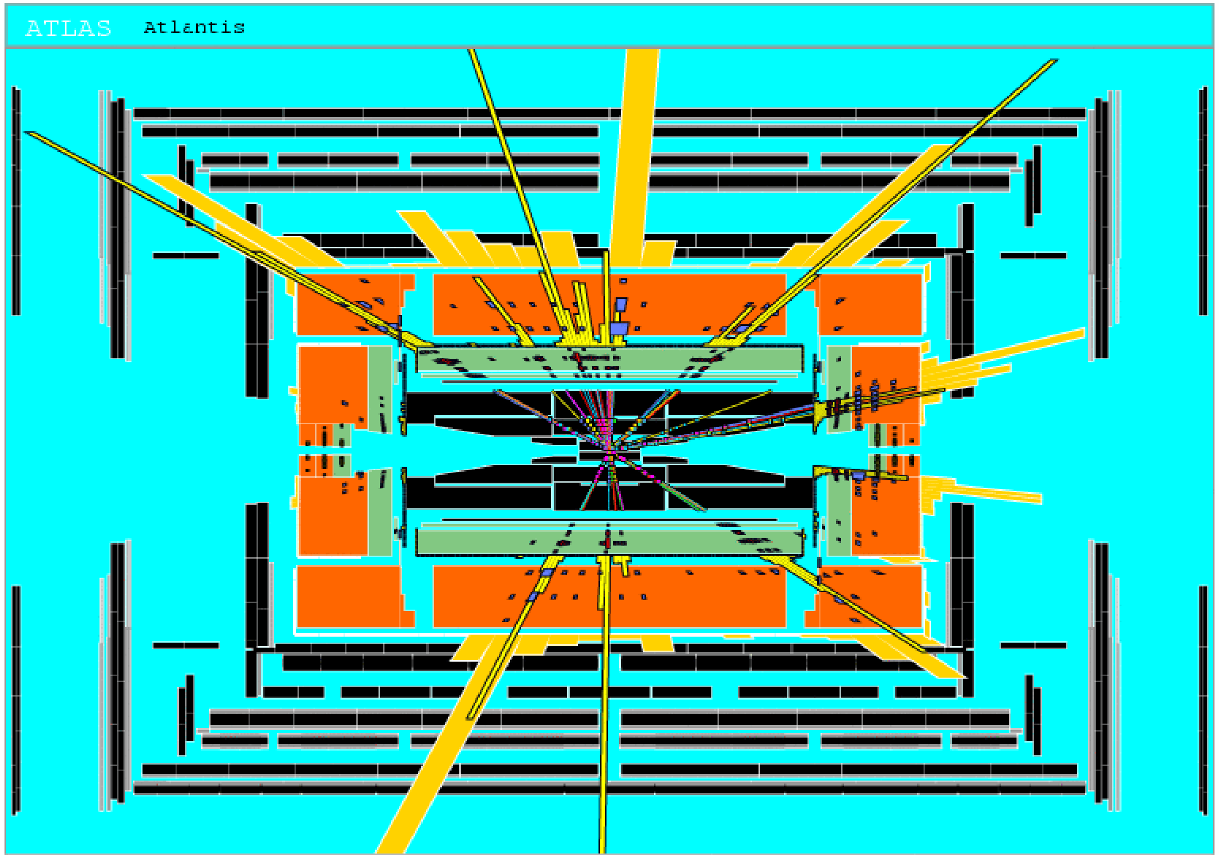
Lower mass limits, at 95% CL, for spin-2 Randall-Sundrum Gravitons



ATLAS-CONF-2013-017

R Sundrum
L Randall
F Gianotti

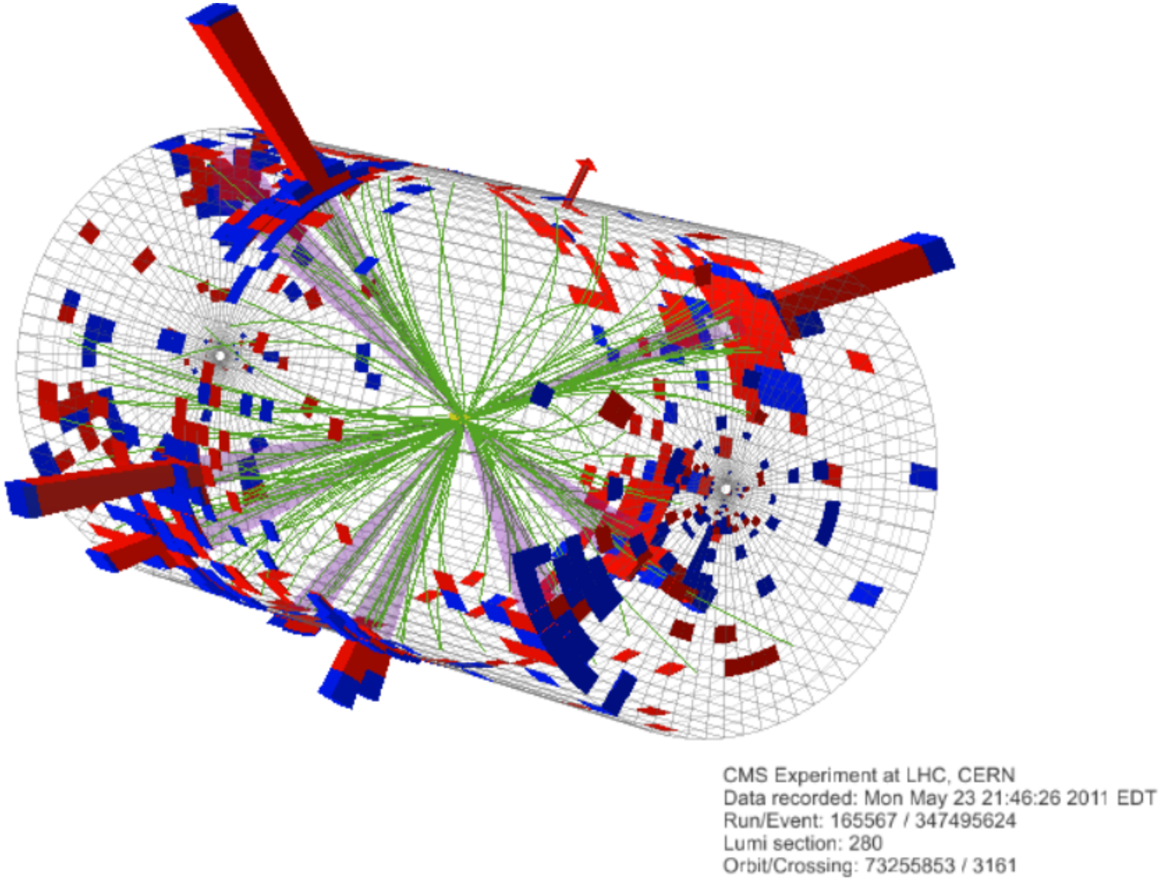
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



Simulation of a black hole event with M_{BH} ~ 8 TeV in ATLAS

They decay immediately through Stephen Hawking radiation

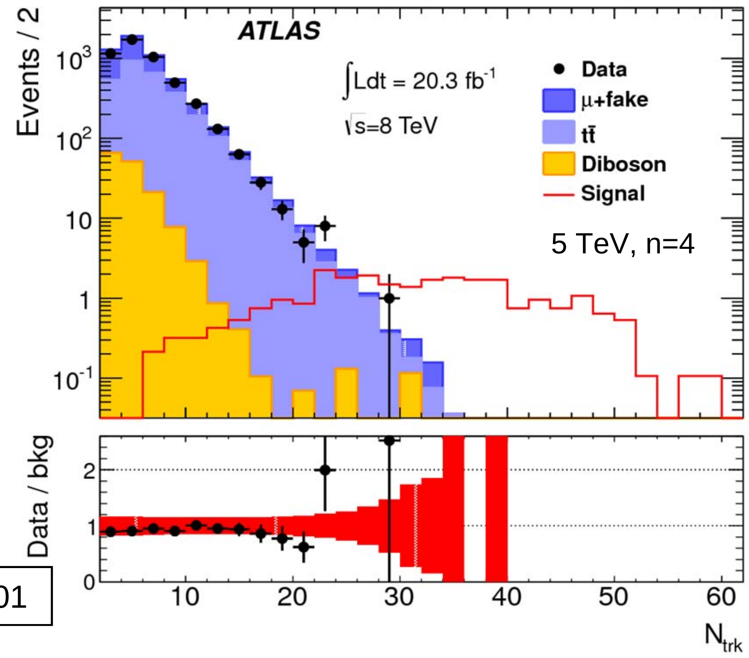
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



A real 'candidate' event of a 'black hole' in CMS with 9 jets and ST = 2.6 TeV

They decay immediately through Stephen Hawking radiation

Search for Microscopic Black Hole production in models wth large extra dimensions
(Arkani-Hamed, Dimopoulos, Dvali)



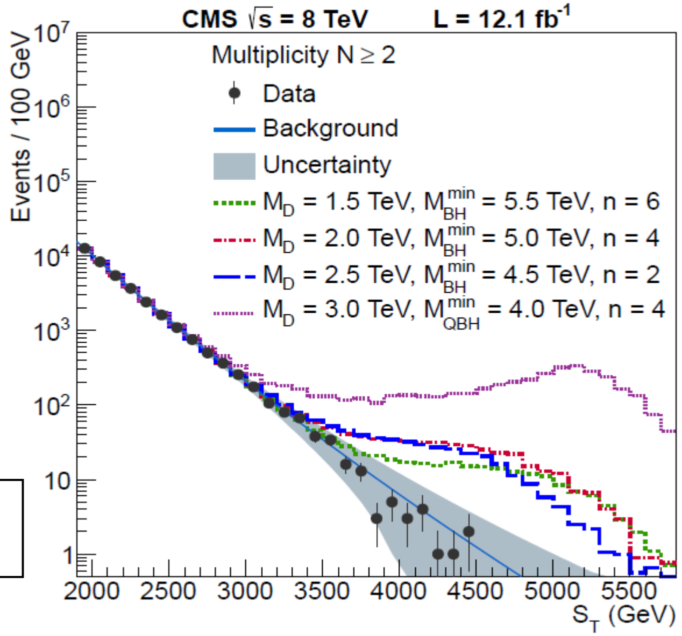
Decay into many objects (jets, leptons, photons)

Phys Rev D88 (2013) 072001

<u>Examples:</u> (ATLAS) two same sign muons and large multiplicity, (CMS) any three objects

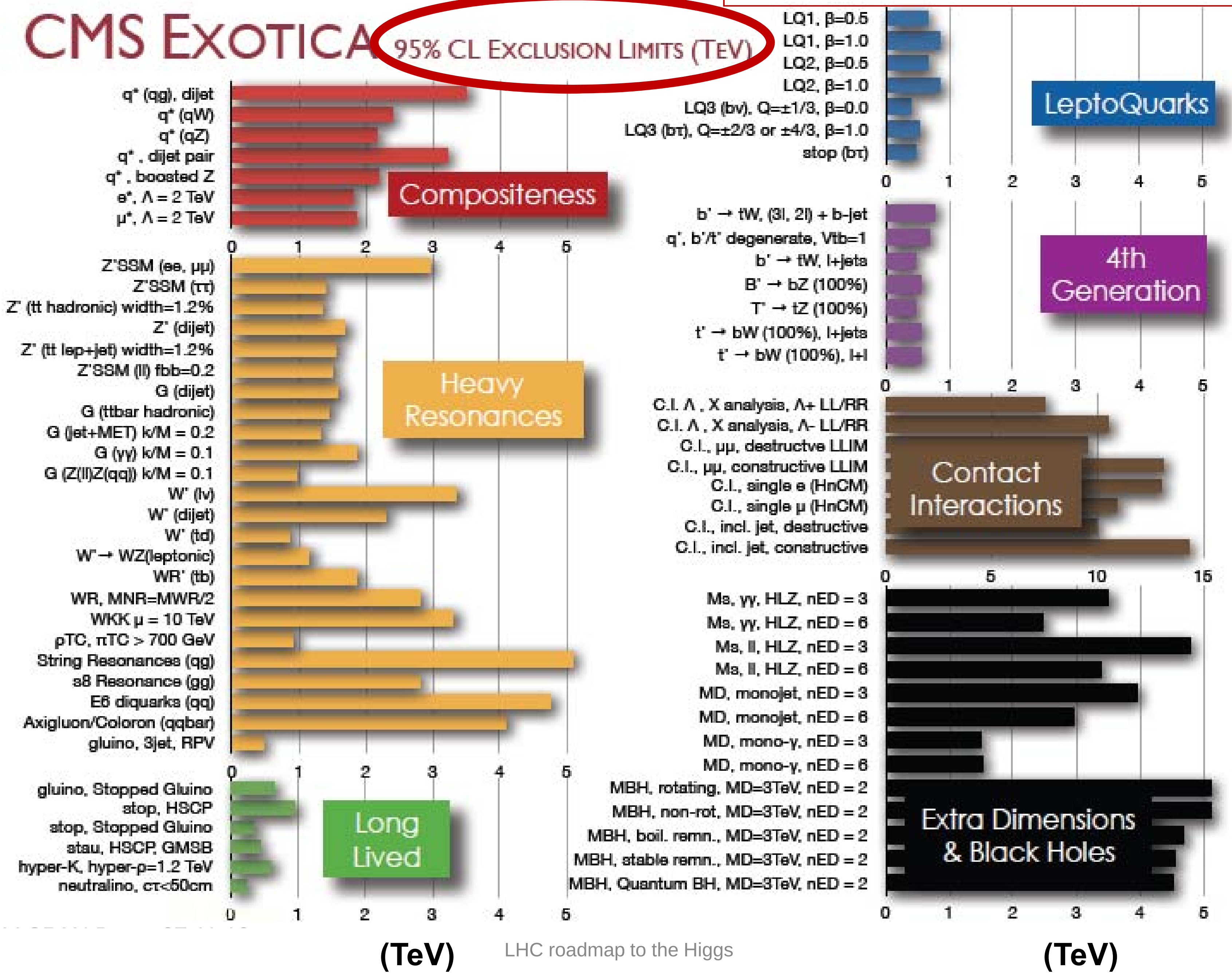
($S_T = \Sigma P_T$: scalar sum of the E_T of the N objects in the event)

No deviation is seen for events with at least 3 objects with > 50 GeV pT

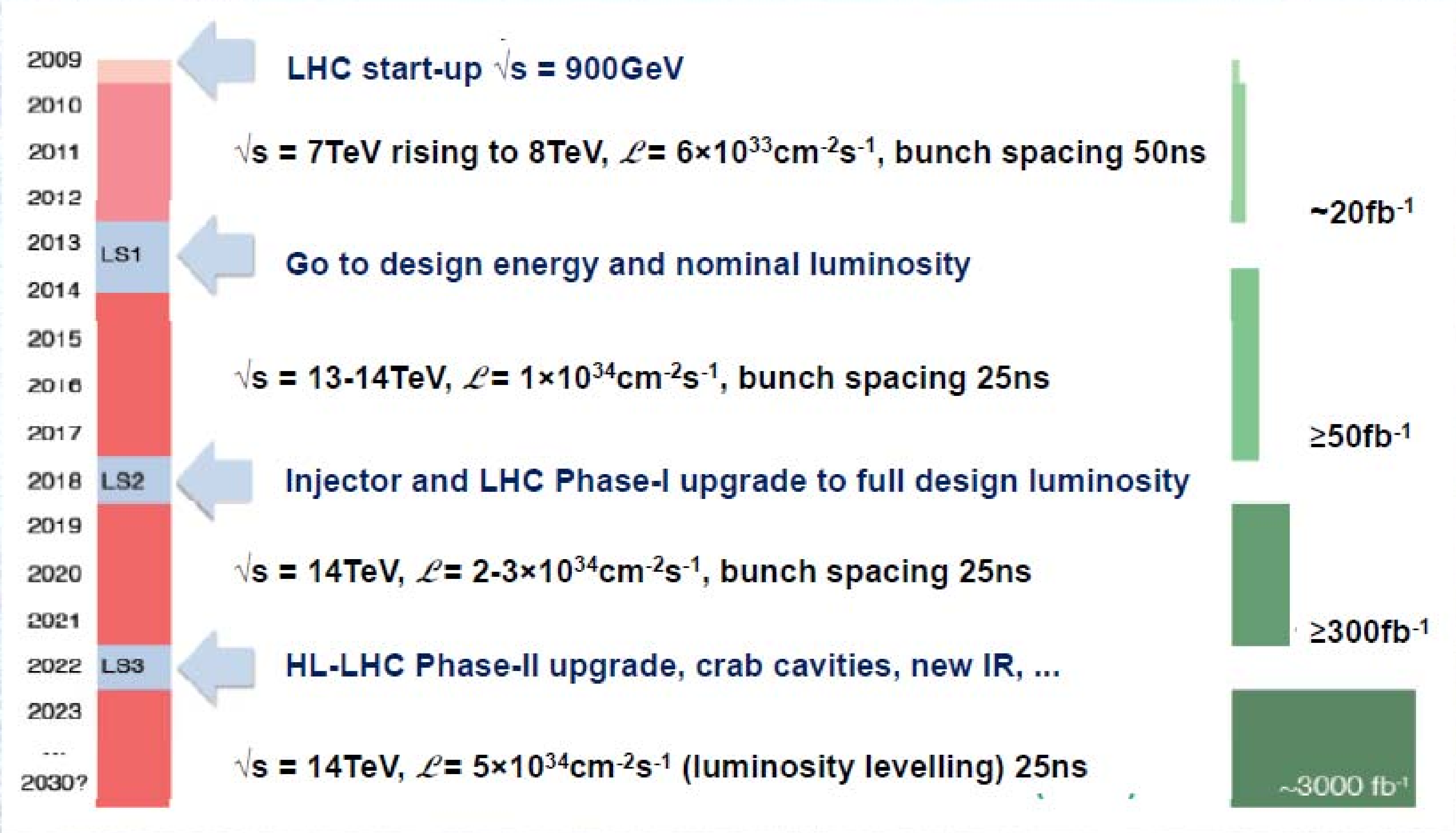


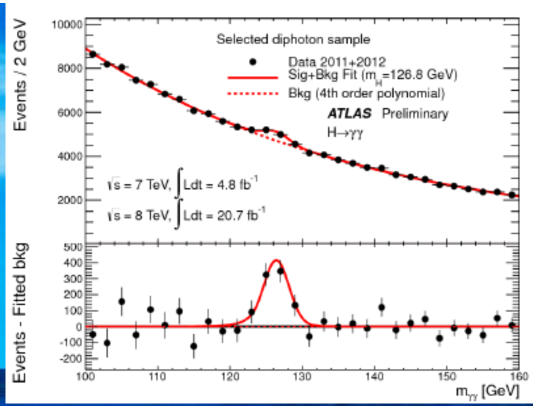
Submitted to JHEP
arXiv:1303.5338v1[hep-ex]

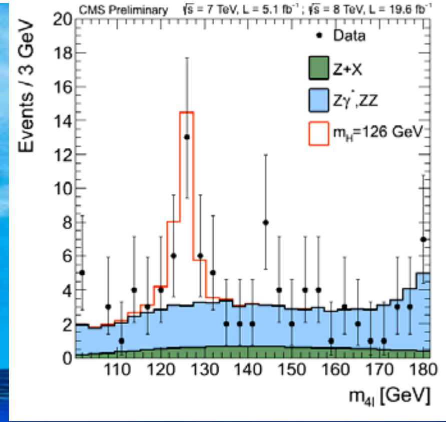
Similar results exist from ATLAS



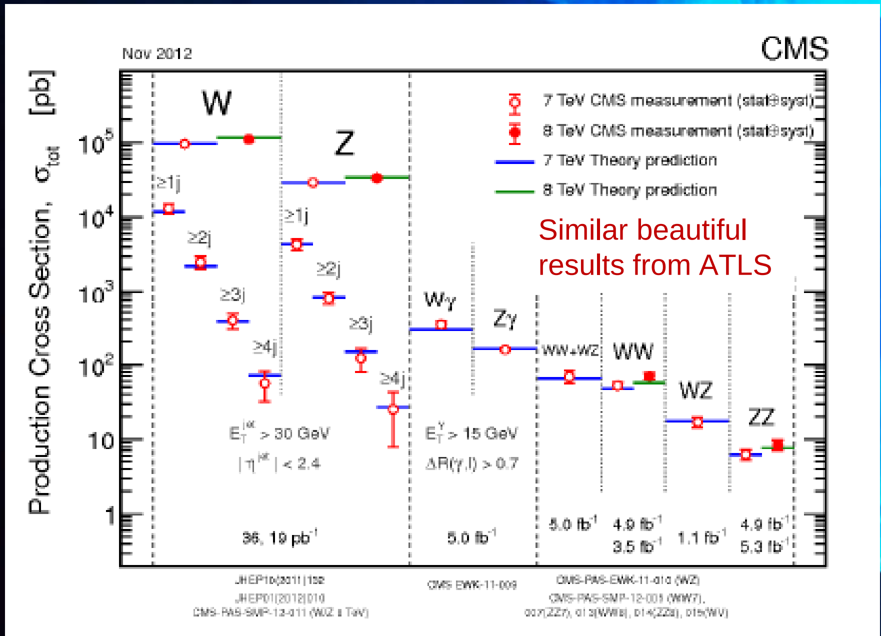
LHC Schedule and Upgrade

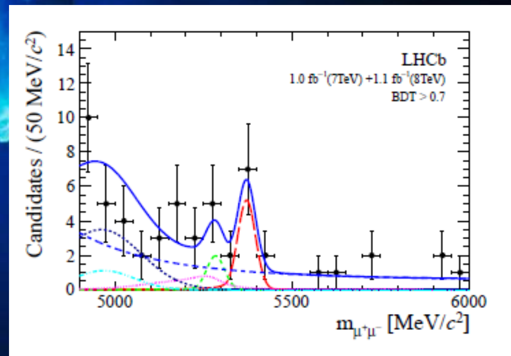






The High Energy Frontier





©Ralph A. Clevenger/CORBIS

Collider options for the high energy frontier

pp colliders

	Years	E_{cm} TeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Int. Luminosity fb^{-1}
Design LHC	2014-21	14	1-2	300
HL-LHC	2024-30	14	5	3000
HE-LHC	>2035	26-33*	2	100-300/y
V-LHC**	>2035	42-100		

* 16-20 T dipole field
** 80 km Tunnel

e+e- colliders

	Years	E_{cm} GeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Tunnel length km
ILC 250	<2030	250	0.75	
ILC 500		500	1.8	~30
ILC 1000		1000		~50
CLIC 500	>2030	500	2.3(1.3)	~13
CLIC 1400		1400(1500)	3.2(3.7)	~27
CLIC 3000		3000	5.9	~48
LEP3	>2024	240	1	LEP/LHC ring
TLEP	>2030	240	5	80 (ring)
TLEP		350	0.65	80 (ring)

Other options:

$\mu^+\mu^-$ and $\gamma\gamma$ colliders with similar physics as e^+e^- colliders

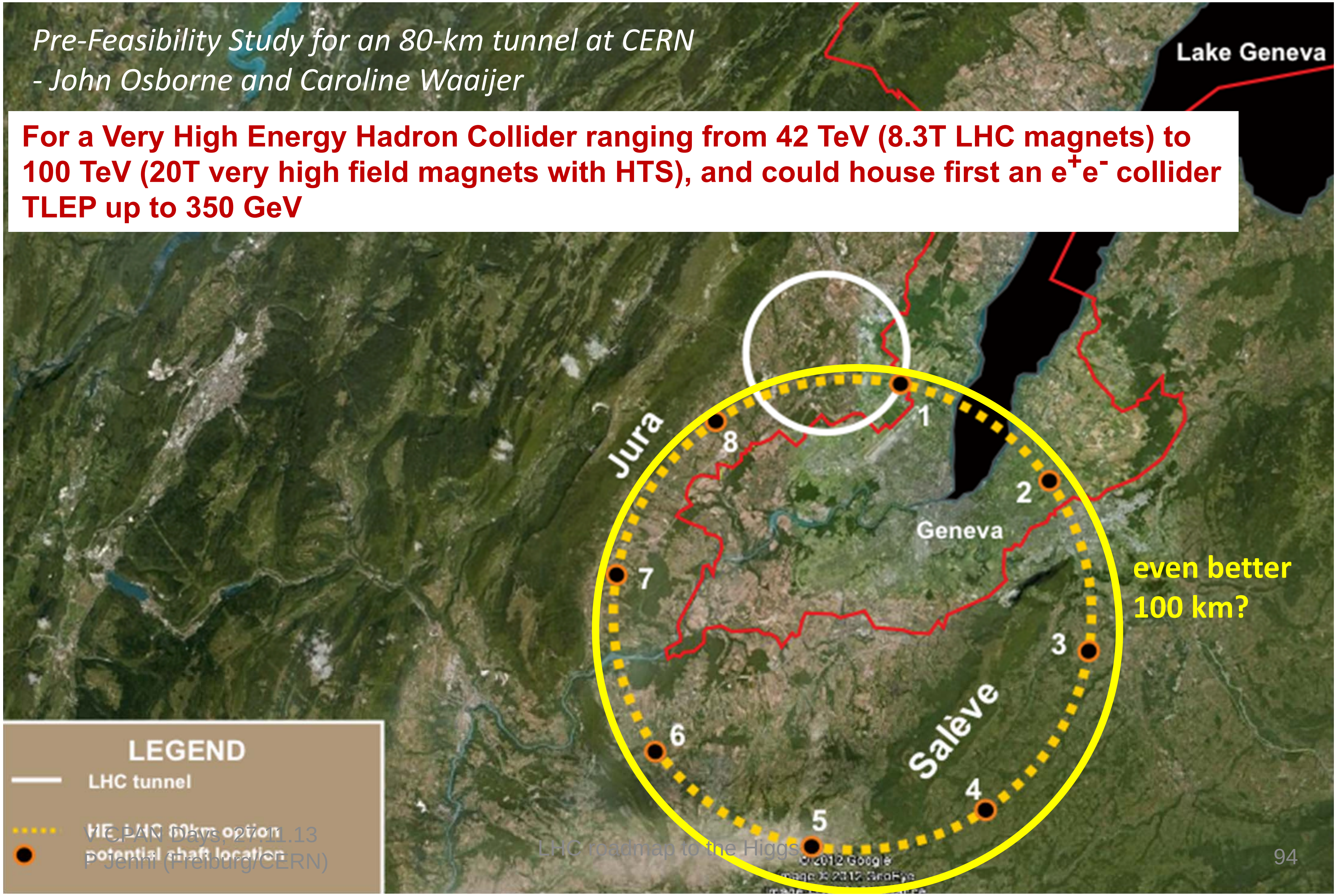
LHeC for ep collisions

See European Strategy for Particle Physics for references
http://council.web.cern.ch/council/en/EuropeanStrategy/ESParticlePhysics.html

Options for preliminary studies at CERN (FCC)

Pre-Feasibility Study for an 80-km tunnel at CERN
- John Osborne and Caroline Waaijer

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^+e^- collider TLEP up to 350 GeV



Time line of the LHC project

1984	Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne.
1987	Workshop on Physics at Future Accelerators, La Thuile, Italy. The Rubbia "Long-Range Planning Committee" recommends the Large Hadron Collider as the right choice for CERN's future.
1990	European Committee for Future Accelerators (ECFA) LHC Workshop, Aachen (discussion of physics, technologies and designs for LHC experiments)
1992	General Meeting on LHC Physics and Detectors, Evian les Bains (4 general-purpose experiment designs presented along with their physics performance)
1993	Three Letters of Intent submitted to the CERN peer review committee LHCC. ATLAS and CMS selected to proceed to a detailed technical proposal.
1994	The LHC accelerator approved for construction
1996	ATLAS and CMS Technical Proposals approved.
1997	Formal approval for ATLAS and CMS to move to construction (materials cost ceiling of 475 MCHF)
1997	Construction commences (after approval of detailed engineering design of subdetectors (magnets, inner tracker, calorimeters, muon system, trigger and data acquisition))
2000	Assembly of experiments commences, LEP accelerator is closed down to make way for the LHC.
2008	LHC experiments ready for pp collisions. LHC starts operation. An incident stops LHC operation.
2009	LHC restarts operation, pp collisions recorded by LHC detectors
2010	LHC collides protons at high energy (centre of mass energy of 7 TeV)
2012	LHC operates at 8 TeV: discovery of a Higgs-like boson.

It took a long time, and we already had a tunnel…

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

Thank you for your attention

J Blaeu 1664

Further reading:

The Higgs Boson

ARTICLE

Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider

M. Della Negra,[1] P. Jenni,[2] T. S. Virdee[1]*

The search for the standard model Higgs boson at the Large Hadron Collider (LHC) started more than two decades ago. Much innovation was required and diverse challenges had to be overcome during the conception and construction of the LHC and its experiments. The ATLAS and CMS Collaboration experiments at the LHC have discovered a heavy boson that could complete the standard model of particle physics.

Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider
M. Della Negra *et al.*
Science **338**, 1560 (2012);
DOI: 10.1126/science.1230827

http://www.sciencemag.org/content/338/6114/1560.full.html