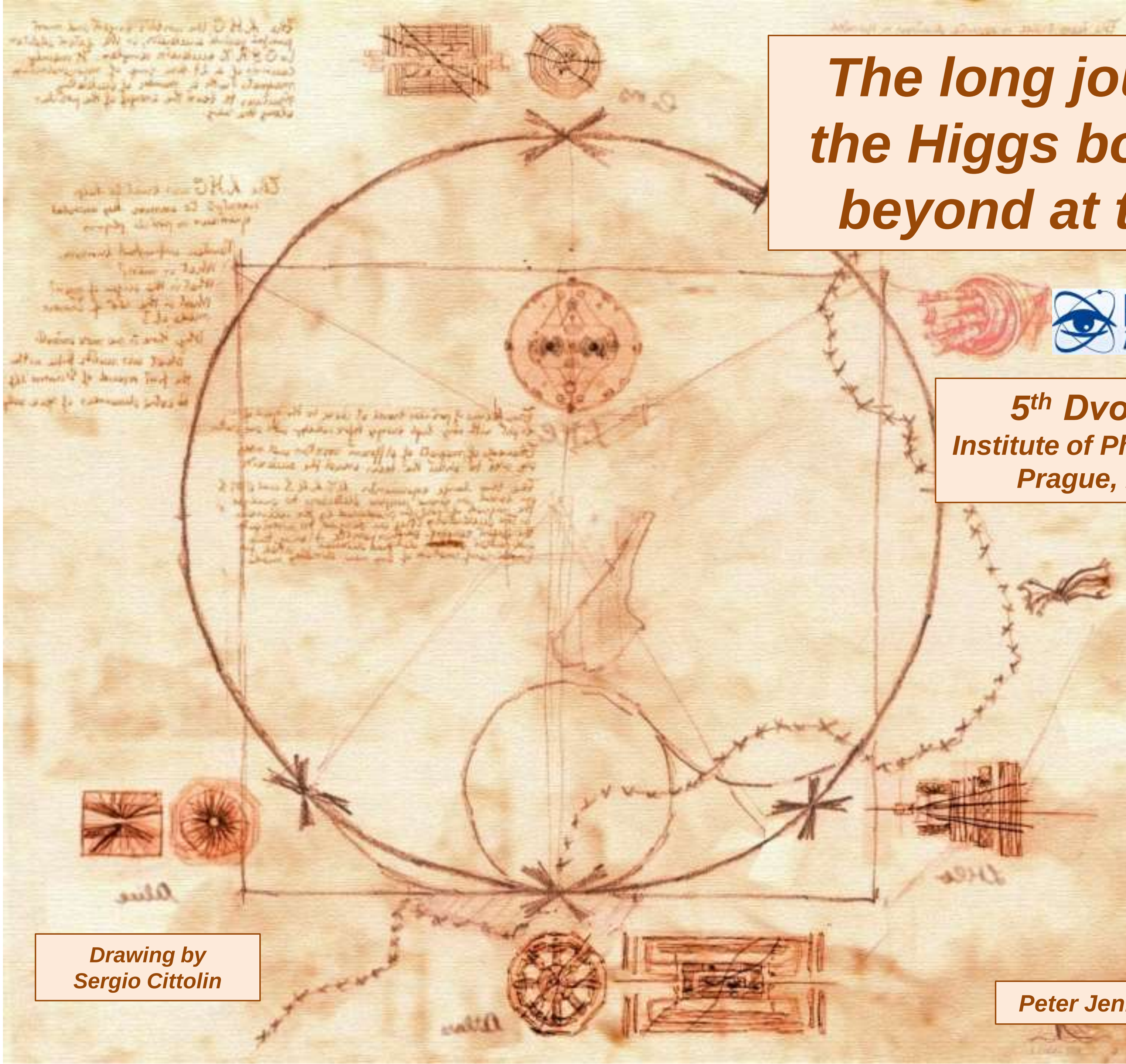
The long journey to the Higgs boson and beyond at the LHC



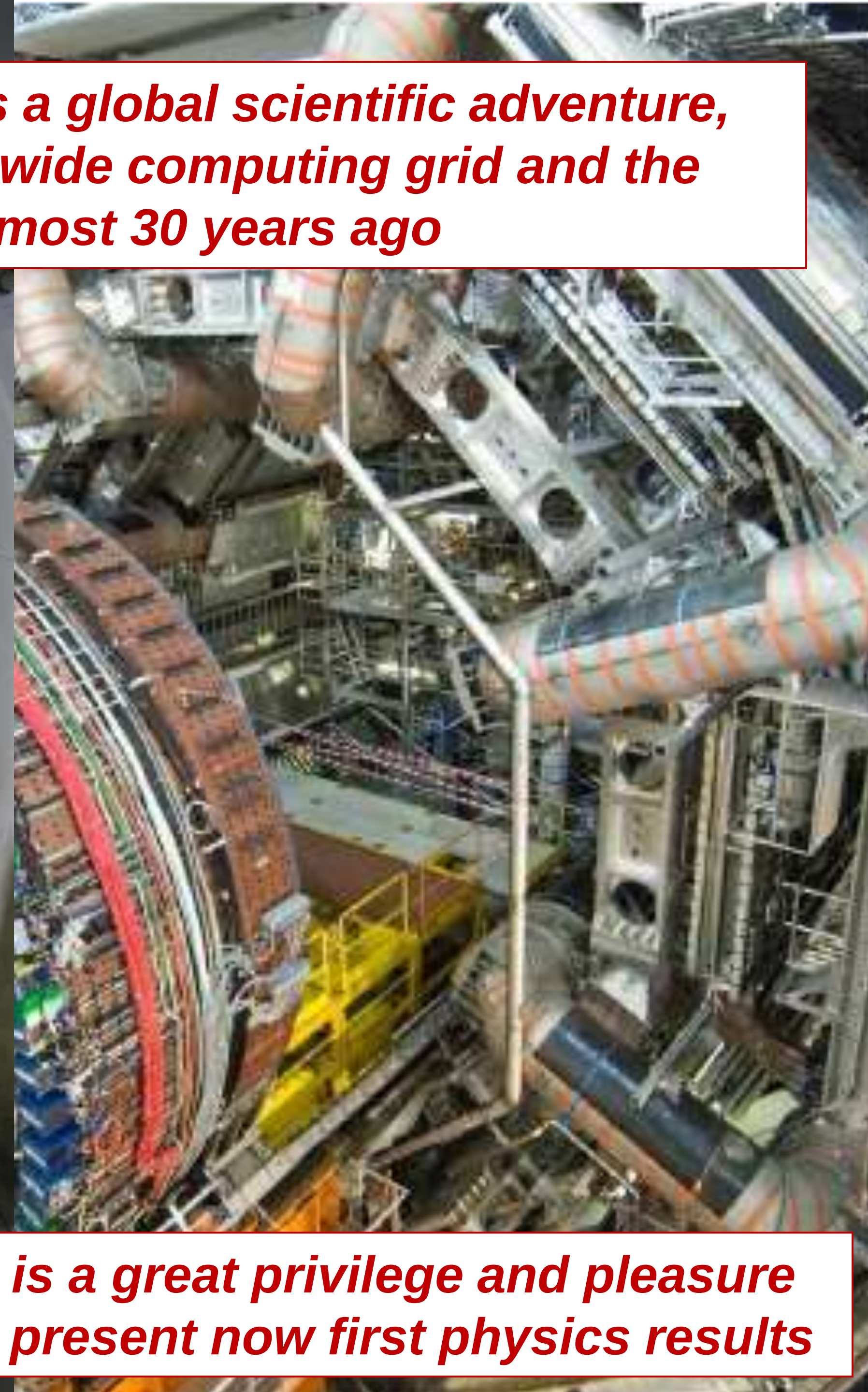
Drawing by
Sergio Cittolin

Fyzikální ústav
Akademie věd ČR, v. v. i.

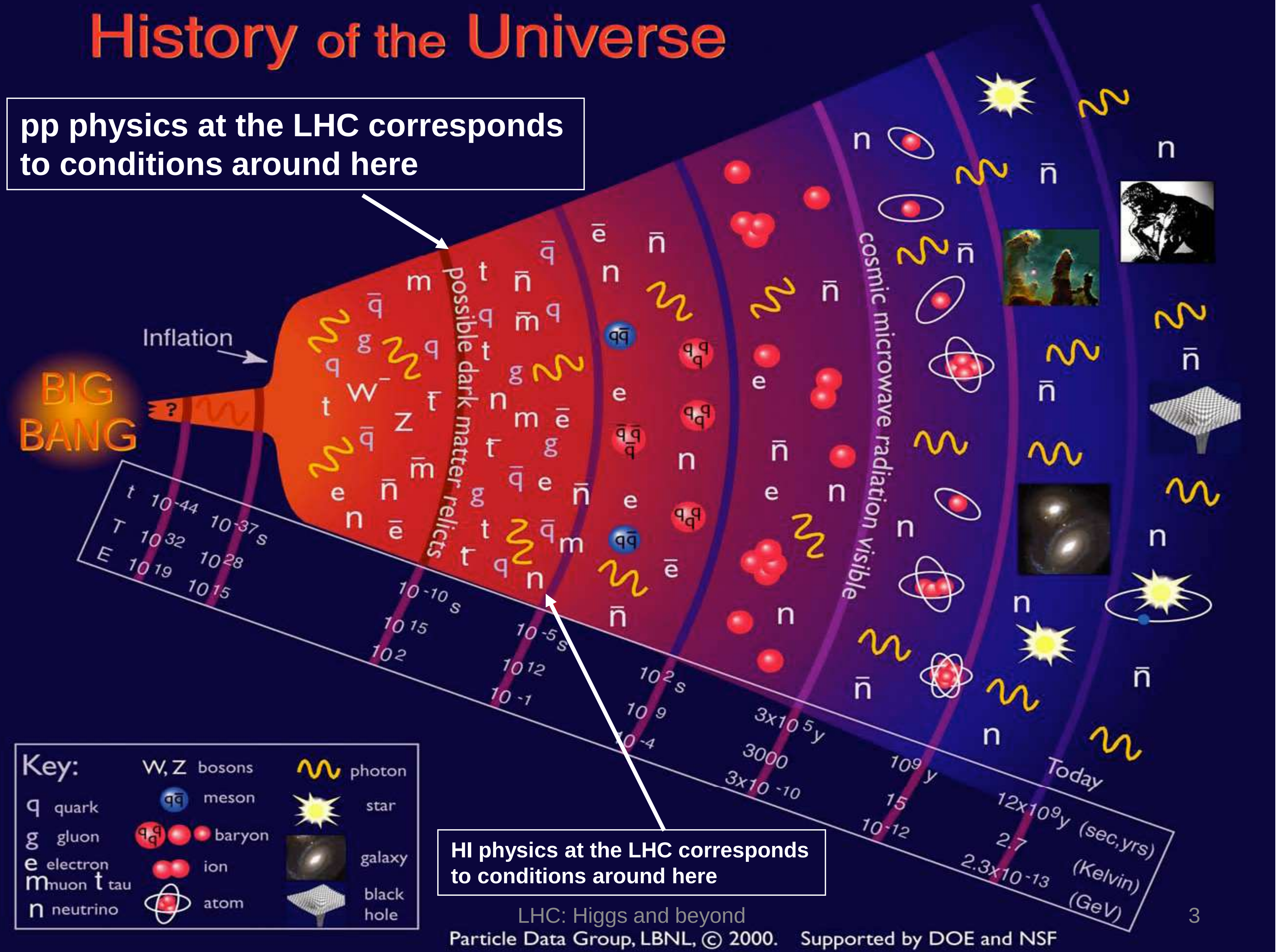
5th Dvořák Lecture
Institute of Physics of the AS CR
Prague, 12th June 2013

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

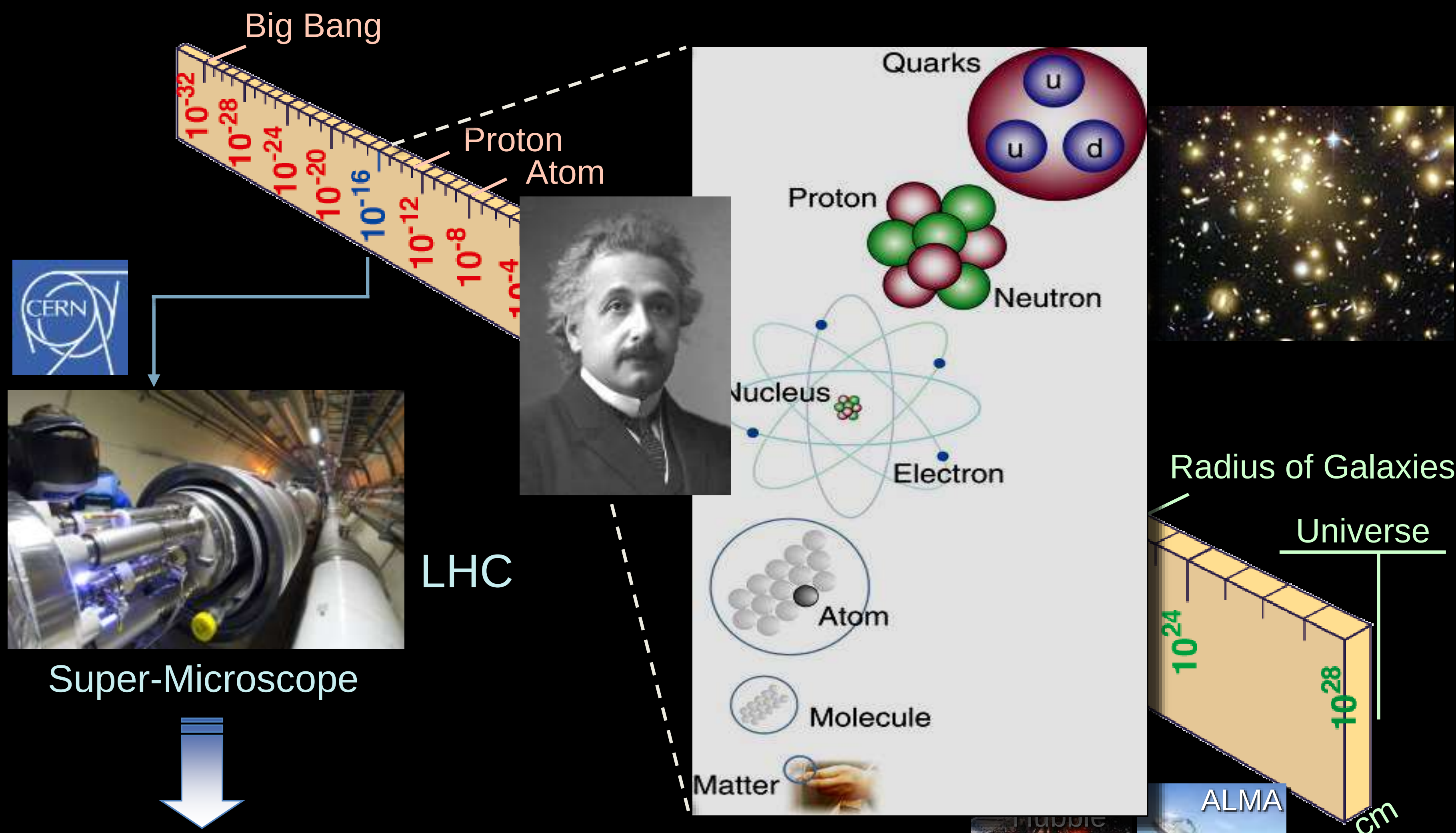


It is a great privilege and pleasure to present now first physics results



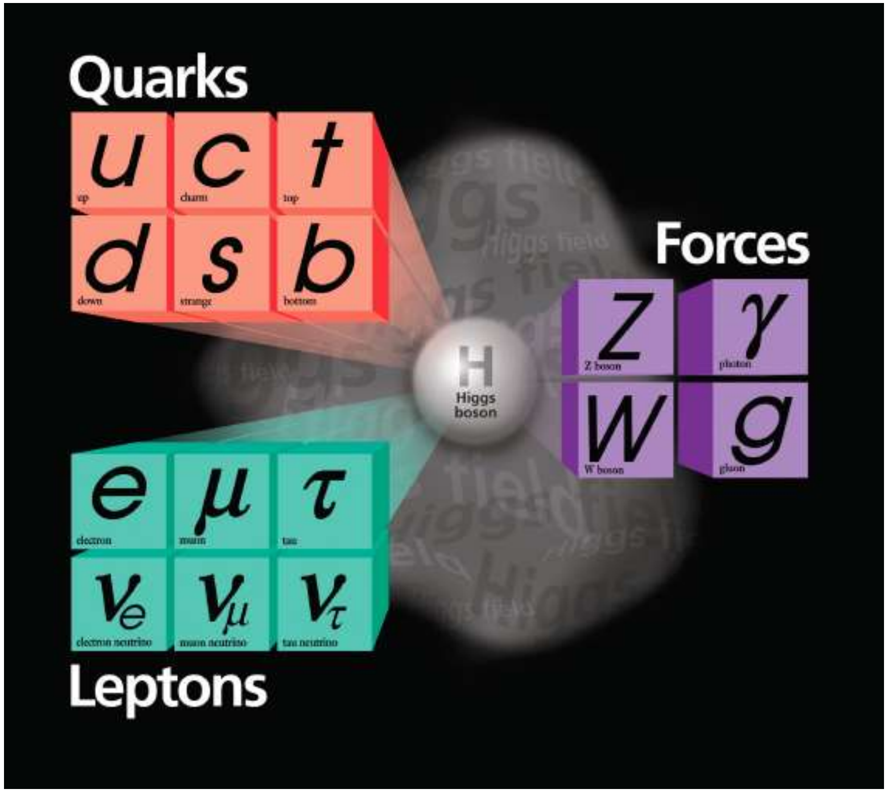
pp physics at the LHC corresponds to conditions around here

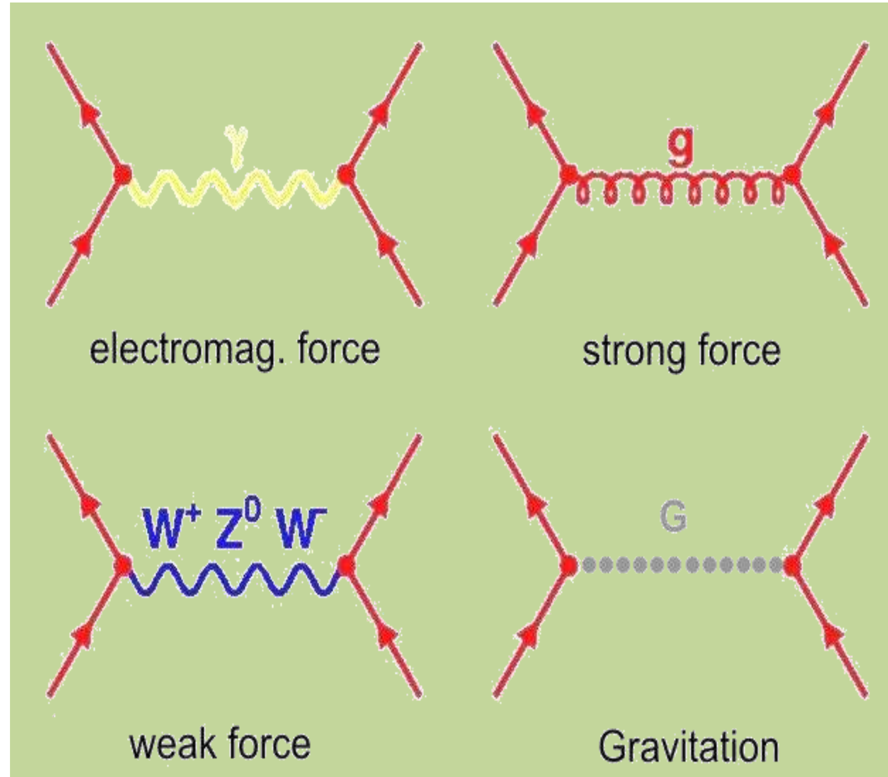
HI physics at the LHC corresponds to conditions around here



Study physics laws of first moments after Big Bang
increasing Symbiosis between Particle Physics,
Astrophysics and Cosmology

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)

However: 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 ? **(~✓)**

What is the nature of the Universe dark matter ?

Why is there so much less antimatter than matter in the Universe ?

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

What happe… …erse
~10…

Al… …n addition to the known four ?
Ar… …ional (microscopic) space dimensions ?
….

New Physics beyond the Standard Model is needed to answer these and other questions. The huge amount of precise experimental data collected so far indicate that 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)

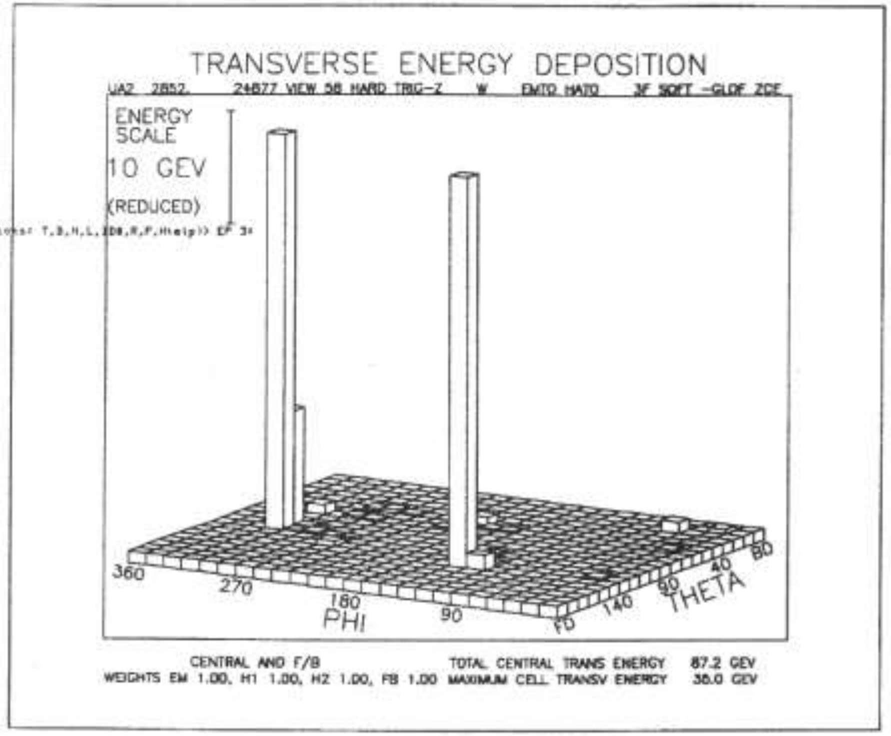
Some early key dates

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)

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

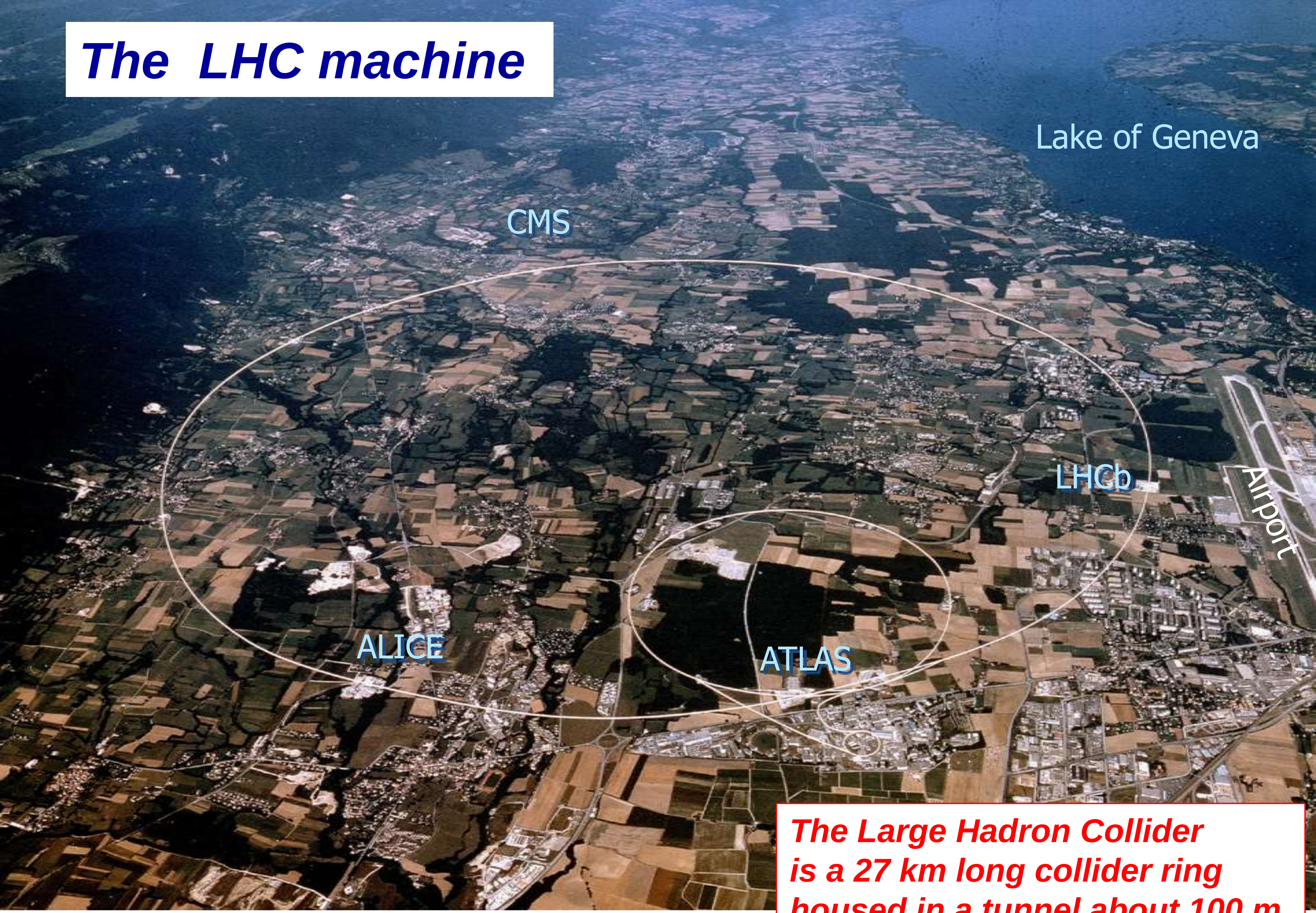
(Israel contributed all along to the full CERN programme and LHC)

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

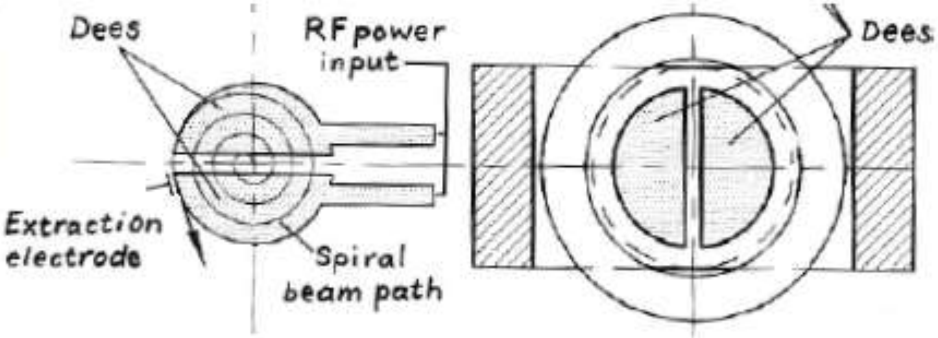


The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

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

Ernest Lawrence
(1901 - 1958)

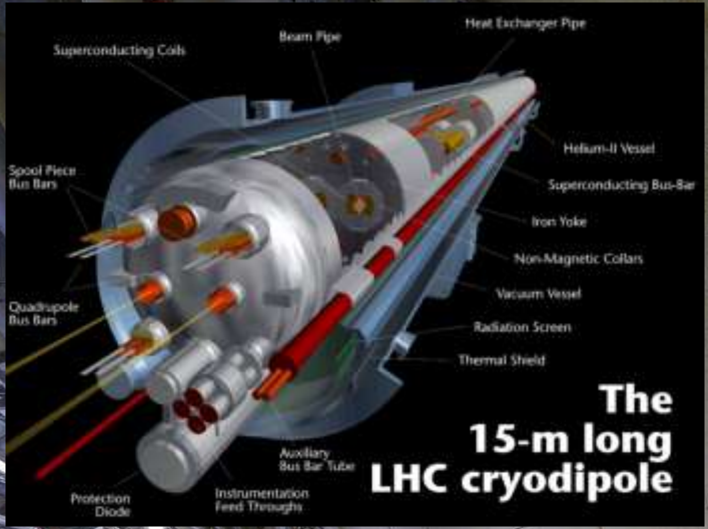
The first circular accelerator (Berkeley 1930)



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**

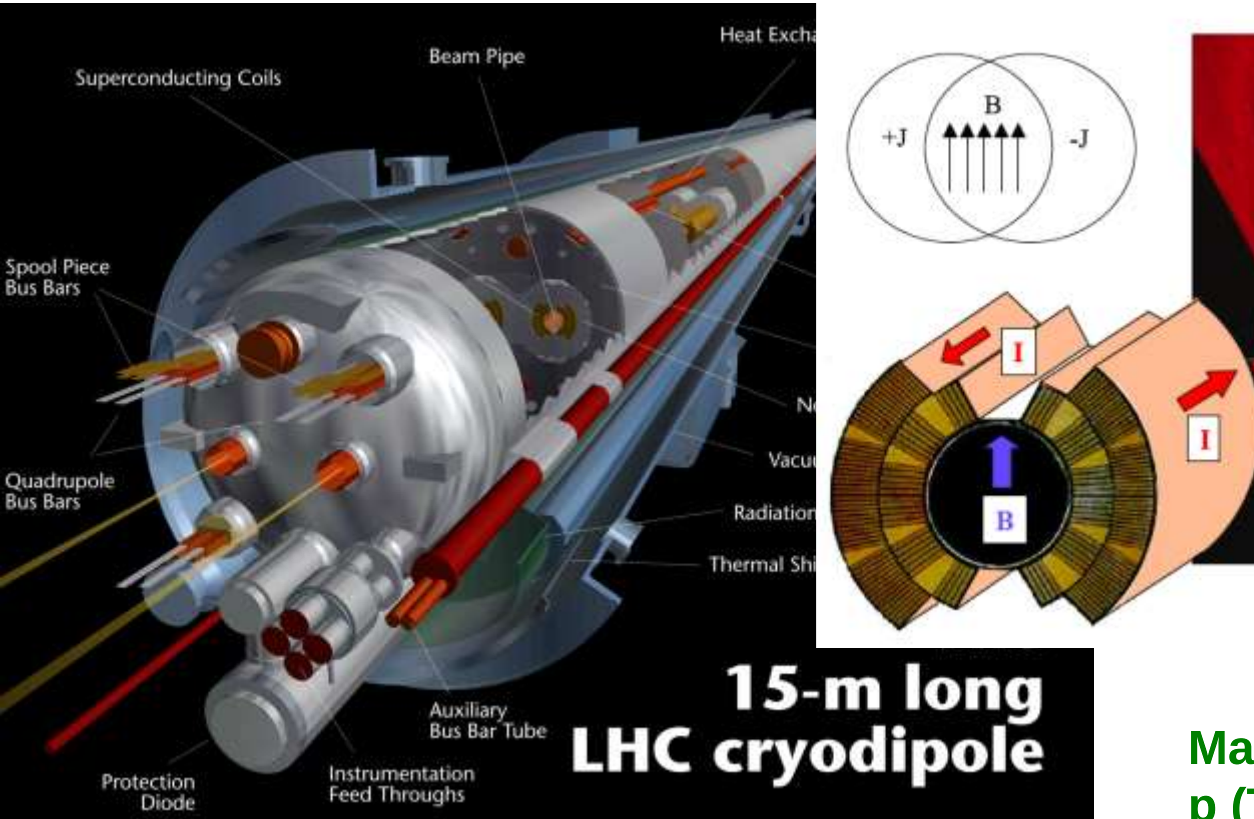
7600 km of Nb-Ti superconducting cable

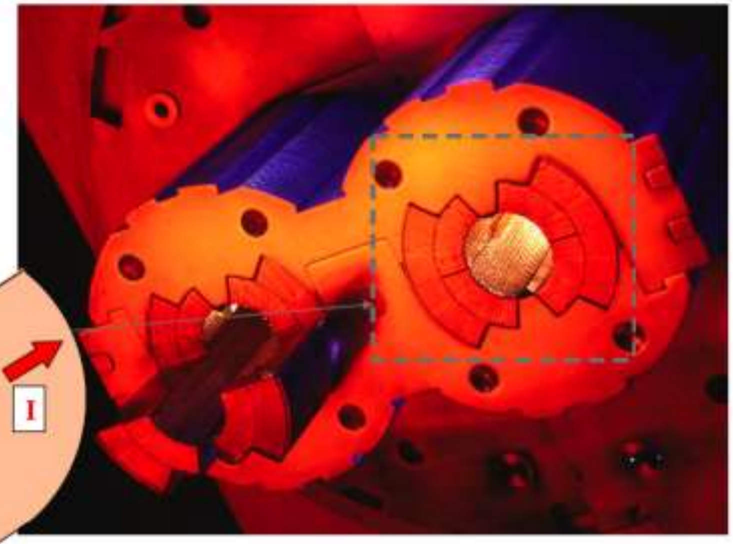


p(TeV) = 0.3 B(T) R(km)

LHC Construction Project Leader Lyndon Evans

LHC Accelerator Challenge: Dipole Magnets





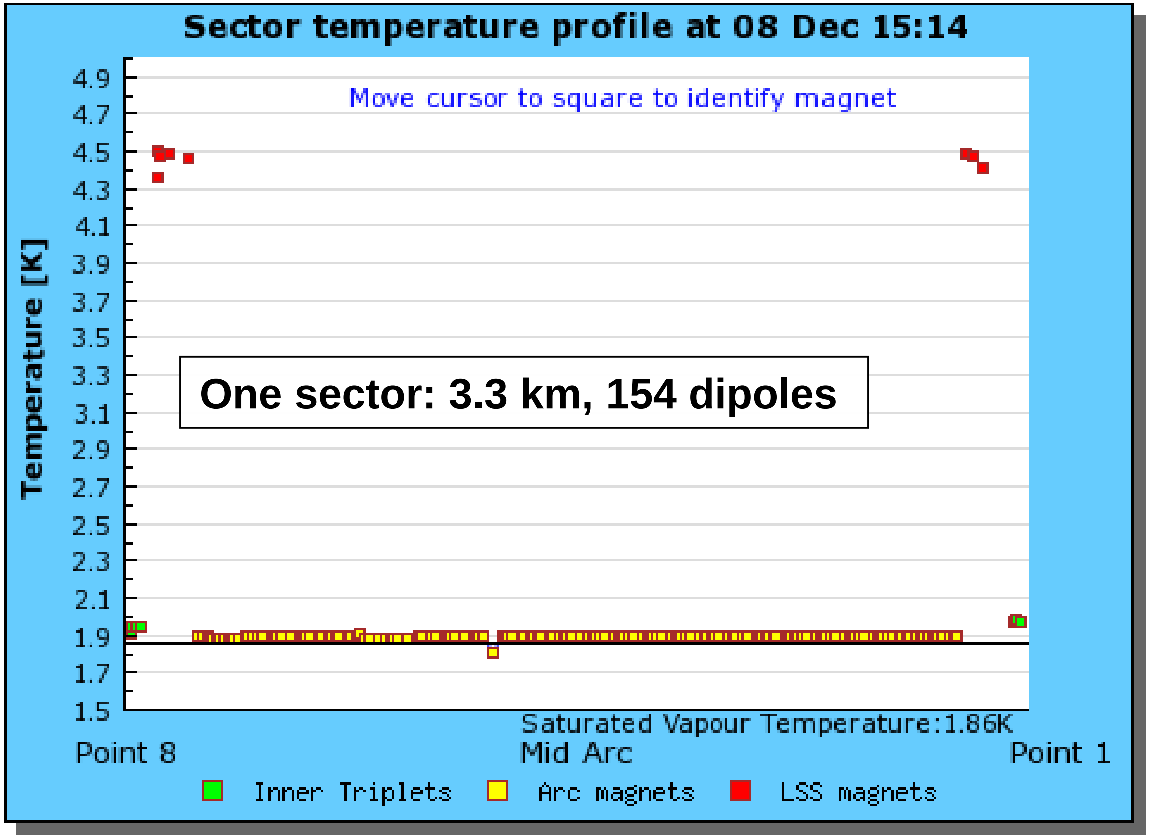
Magnetic Field for Dipoles
p (TeV) = 0.3 B(T) R(km)

For p = 7 TeV and R = 4.3 km
⇨ B = 8.4 T
⇨ Current 12 kA

Coldest Ring in the Universe ?
1.9 K (CMBR is about 2.7 K)

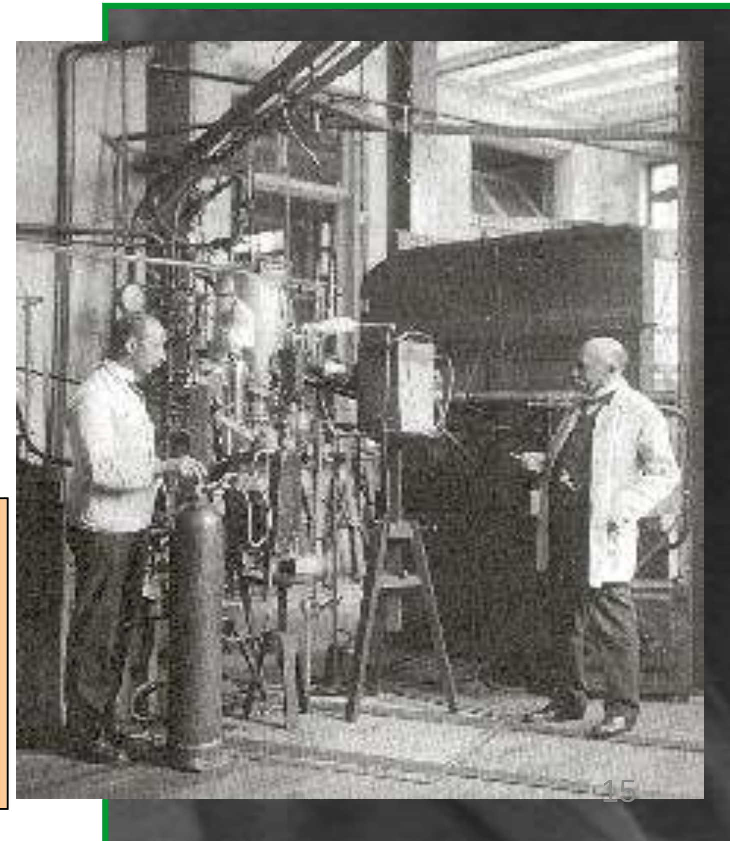
LHC magnets are cooled with pressurized superfluid helium

The LHC is the largest cryogenic system on earth, cooler than outer space



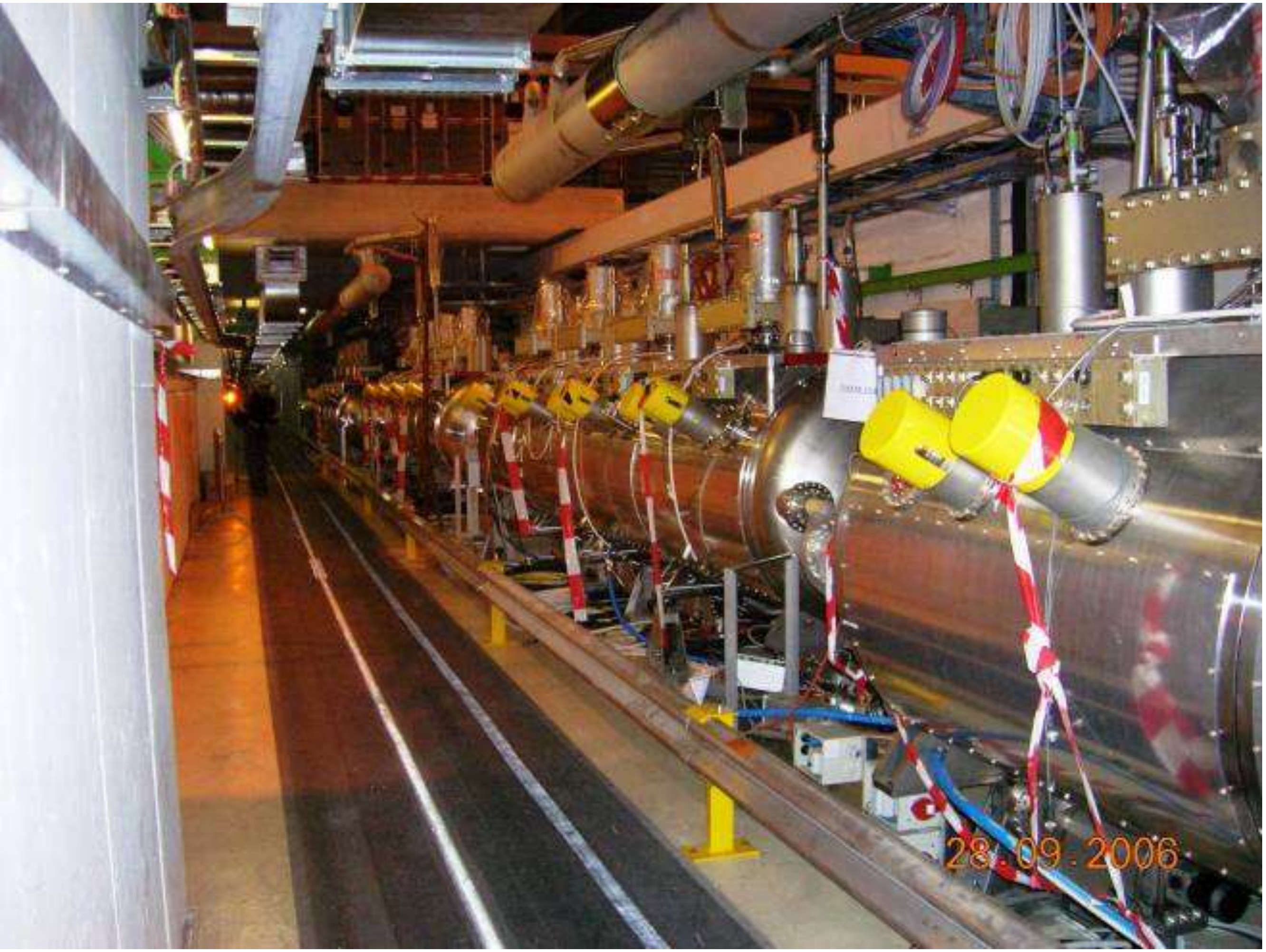
Magnets cooled down in a bath of ~120 tons of superfluid Helium (excellent thermal conductor)

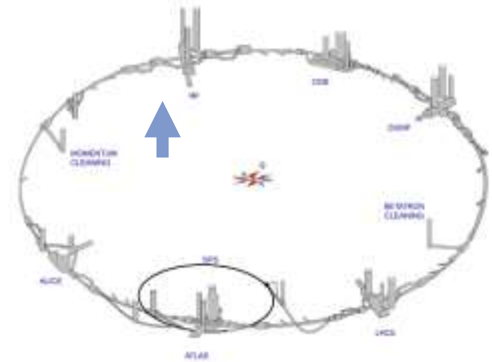
H K Onnes
Nobel Prize in Physics 1913



- **105 years ago, on 10 July 1908: Heike K Onnes first liquefied Helium (60 ml in 1 hour) in Leiden**
- **LHC today: 32000 He liters liquefied per hour by eight big cryogenic plants (the largest refrigerator in the world)**

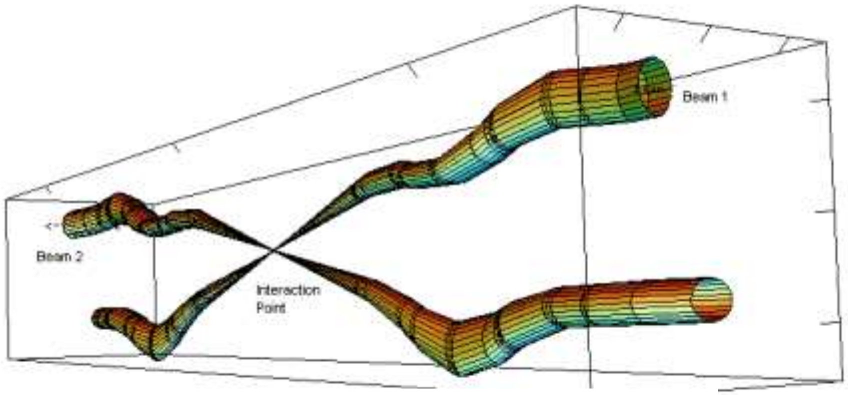
The particle beams are accelerated by superconducting Radio-Frequency (RF) cavities





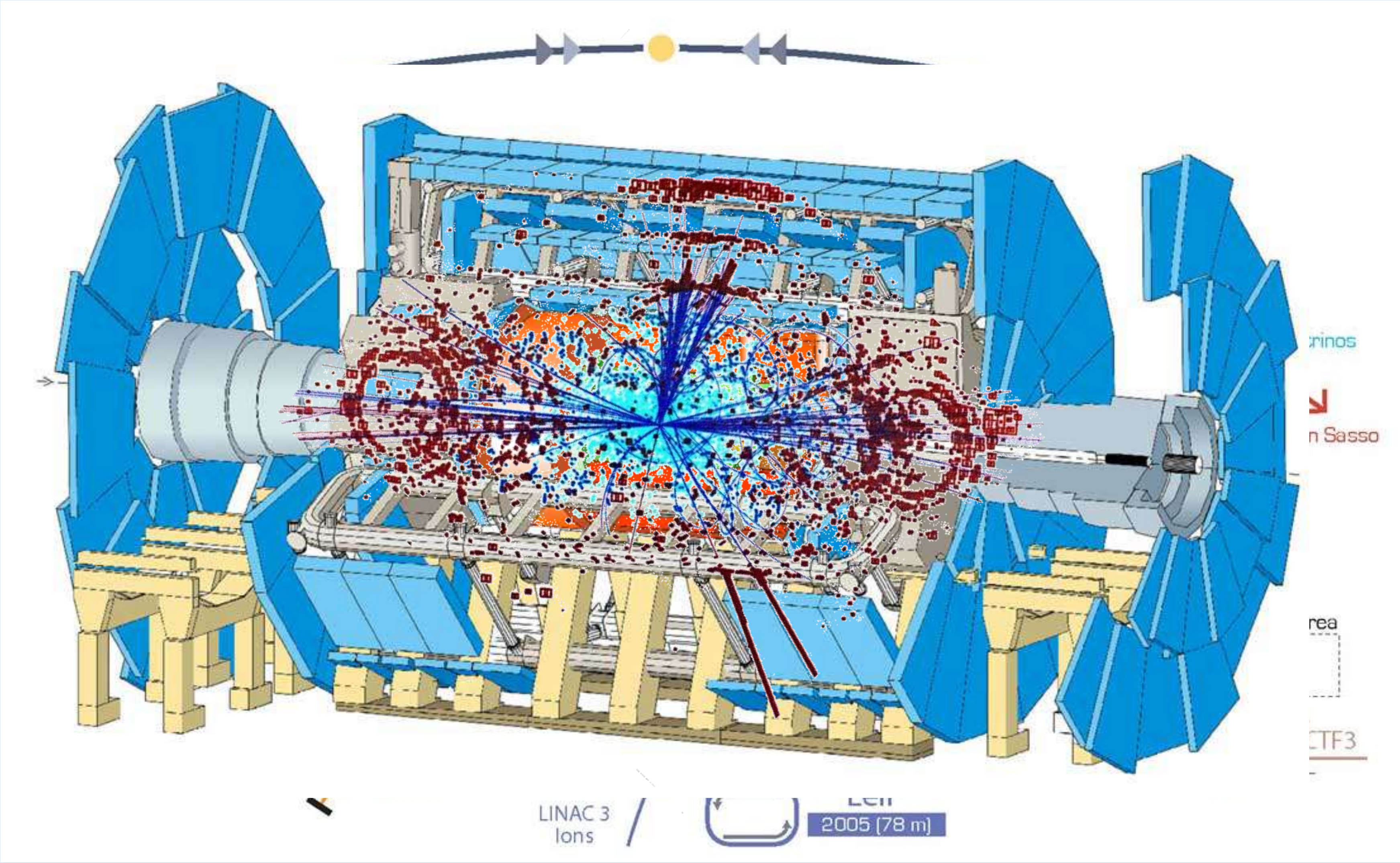
Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the ~ $1/m^4$ behaviour of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

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

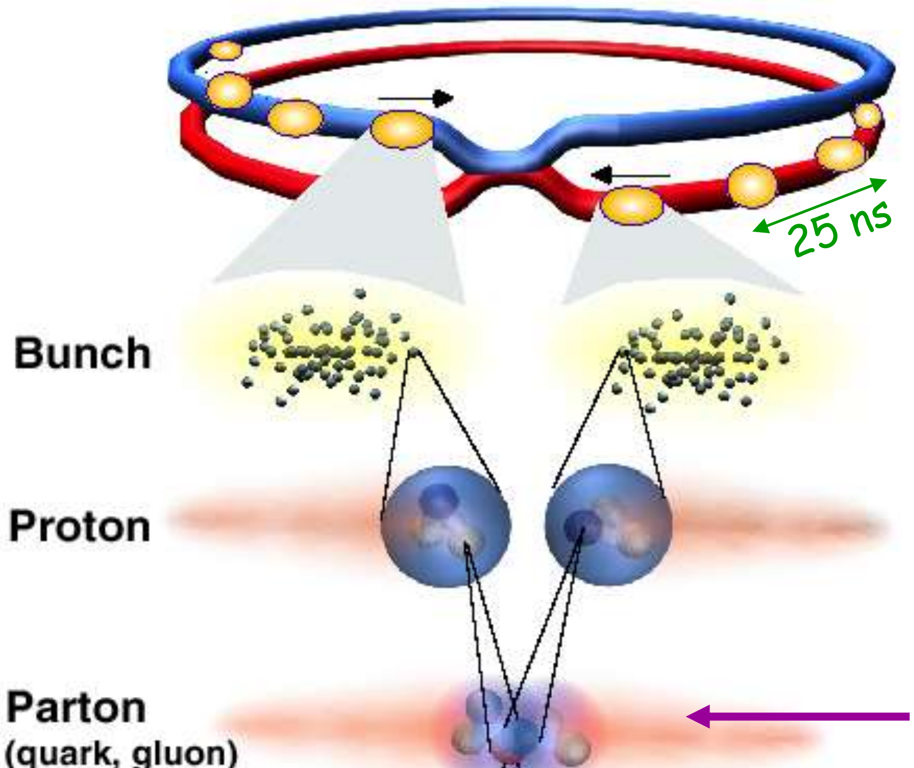


Relative beam sizes around the collision point

CERN's particle accelerator chain



Collisions at LHC



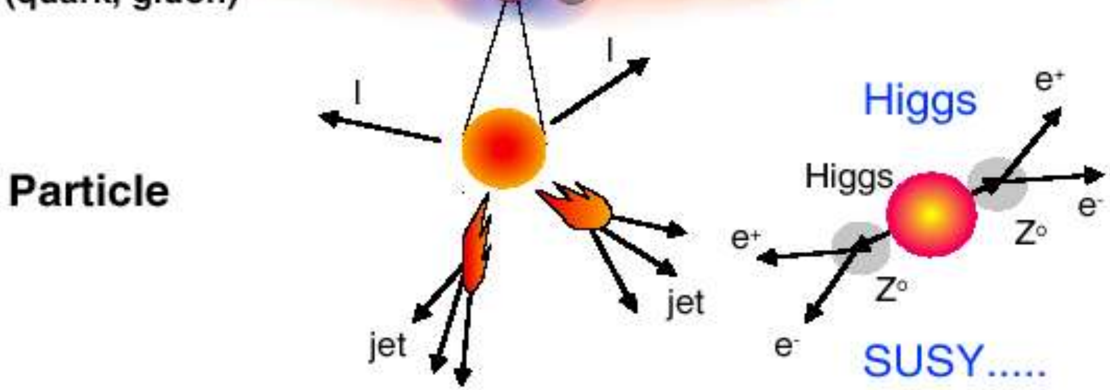
Proton-Proton	
Protons/bunch	**10^{11}**
Beam energy	**7 TeV ($7x10^{12}$ eV)**
Luminosity	**10^{34} cm^{-2} s^{-1}**

Event rate:

N = L x σ (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

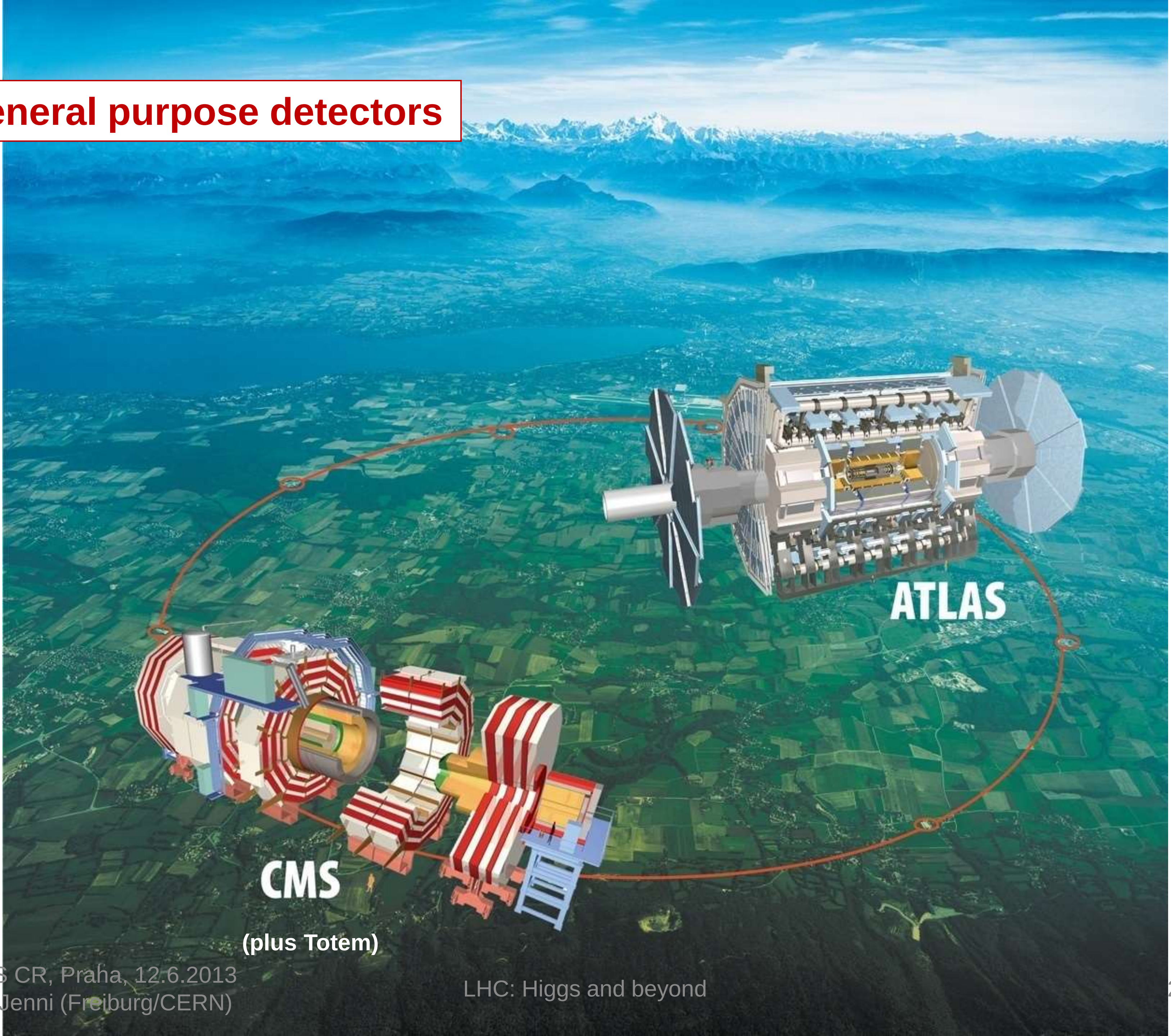
→ very powerful detectors needed

However: the SM is not a complete theory

Some of the outstanding questions in fundamental physics are

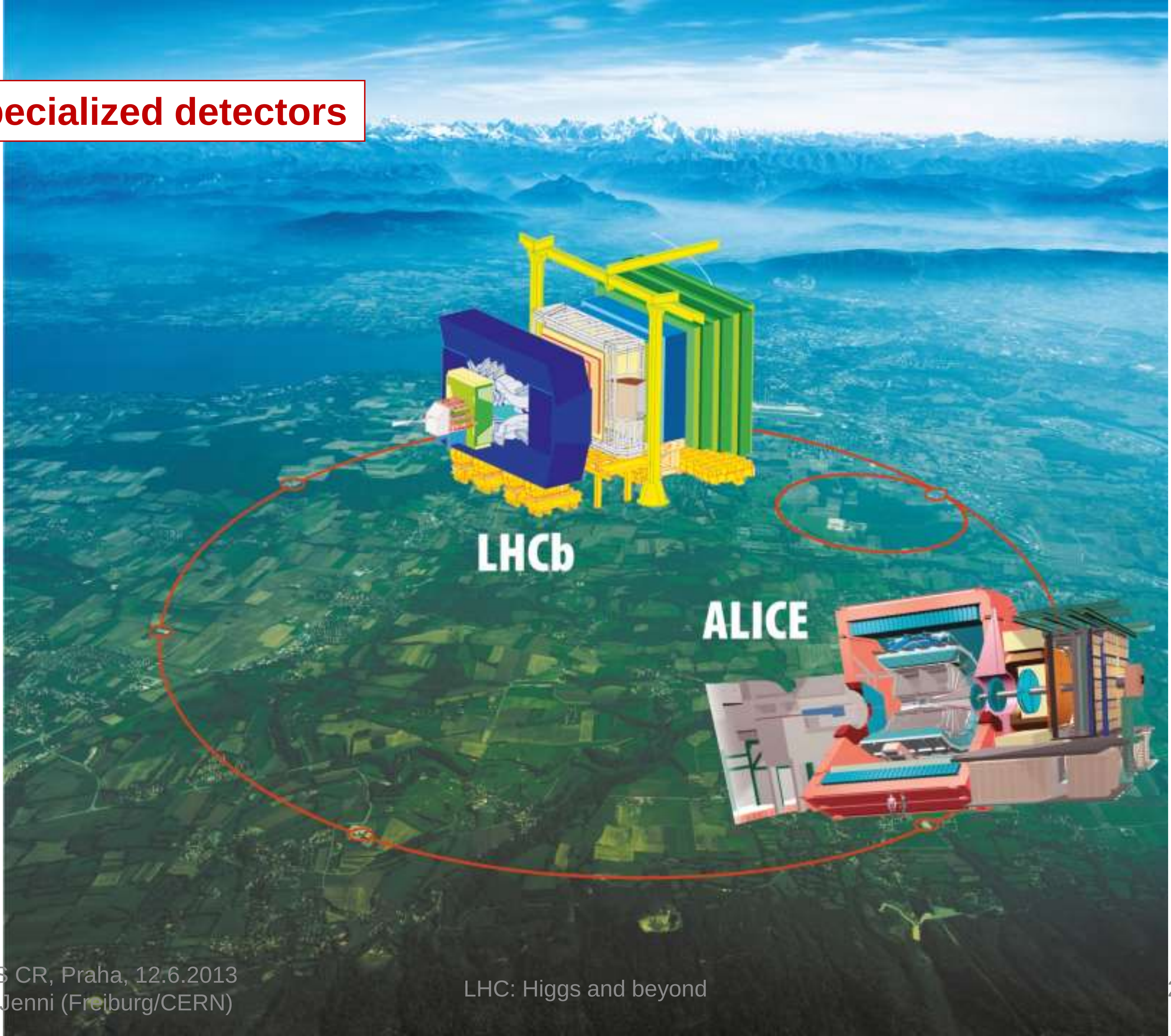
What is the origin of the elementary particle masses ?	**ATLAS, CMS**
What is the nature of the Universe dark matter ?	**ATLAS, CMS**
Why is there so much less antimatter than matter in the Universe ?	**LHCb**
What are the features of the primordial plasma present ~10 μs after the Big Bang ?	**ALICE**
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**
….	

General purpose detectors



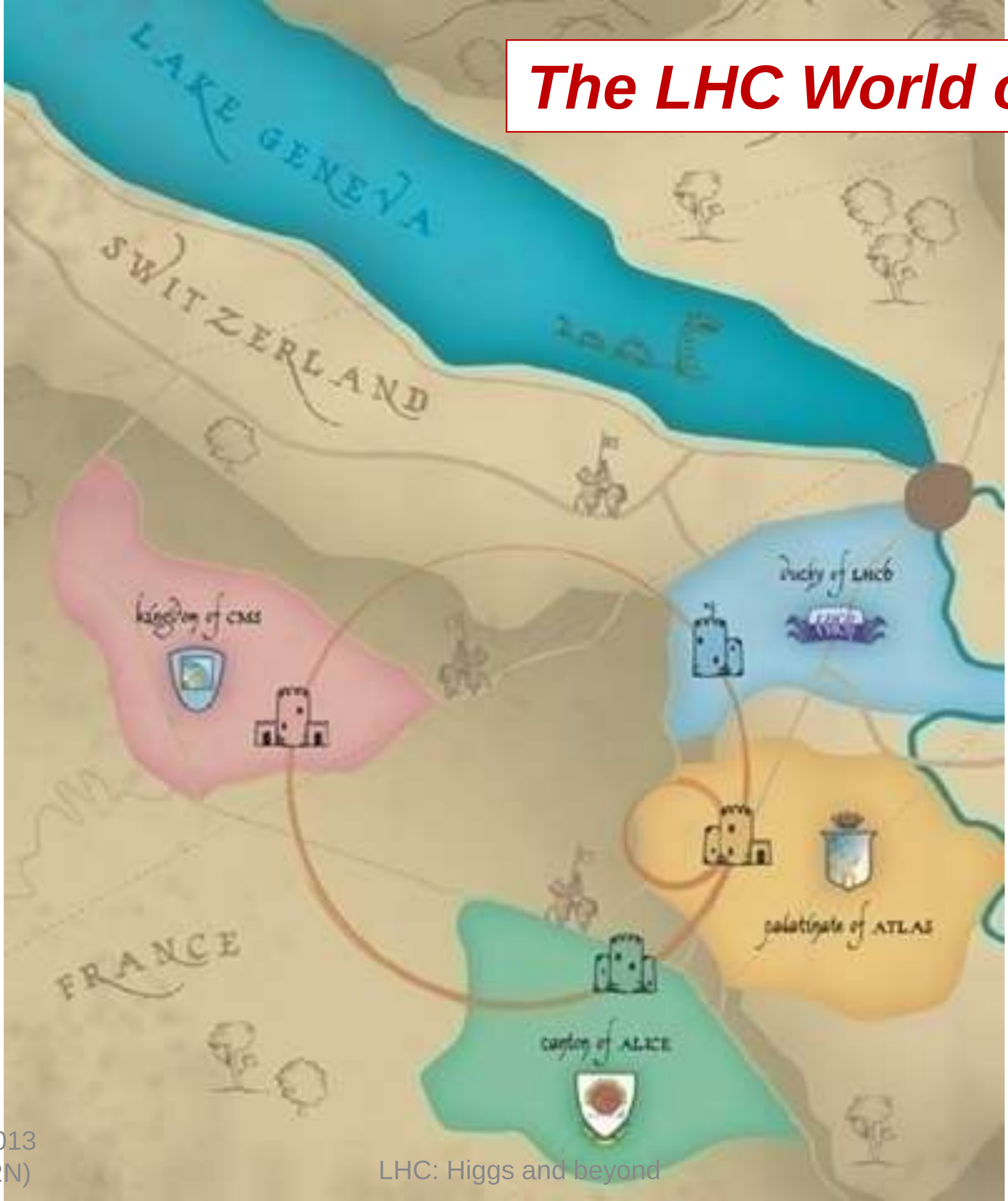
(plus Totem)

Specialized detectors



The LHC World of CERN

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

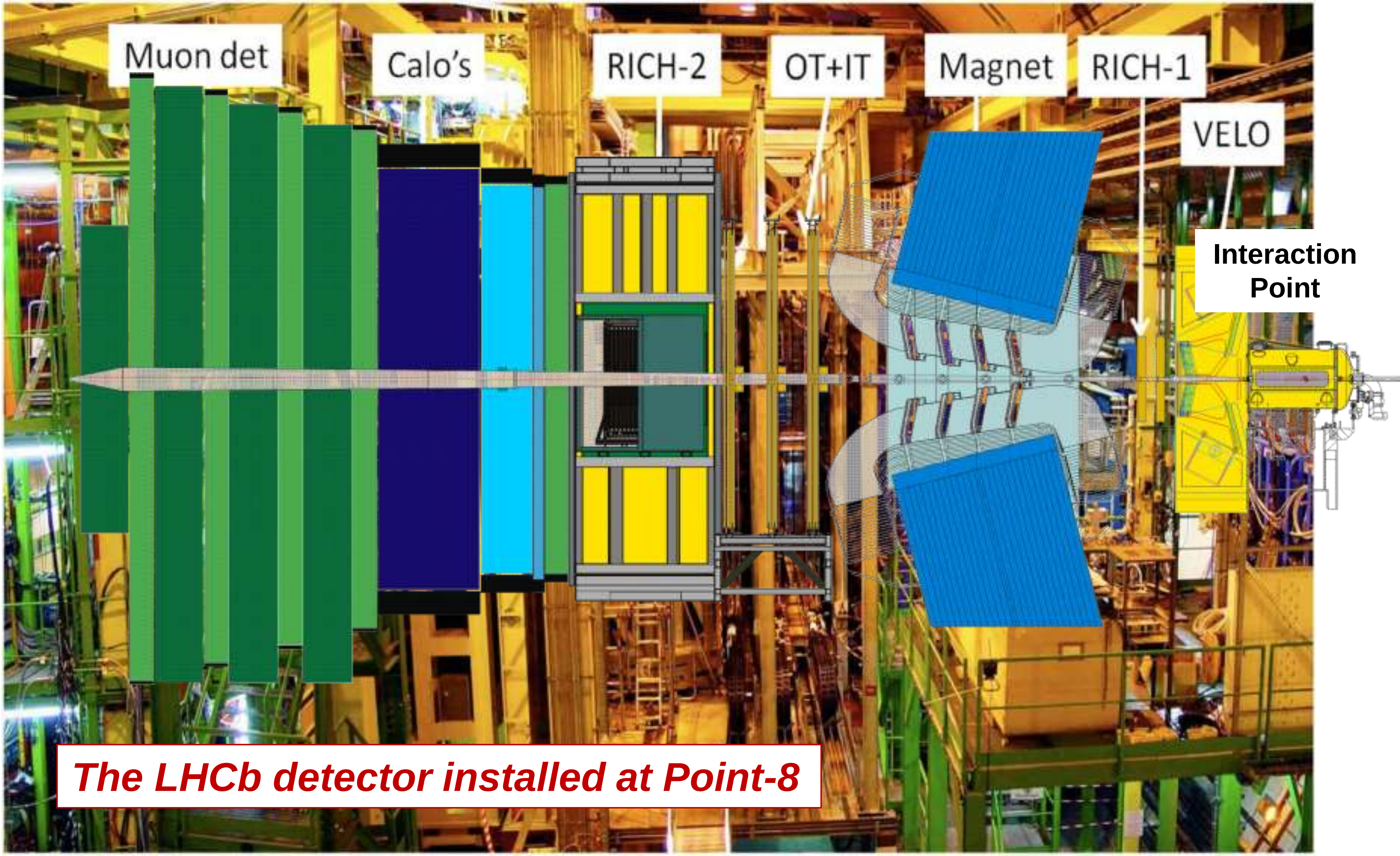


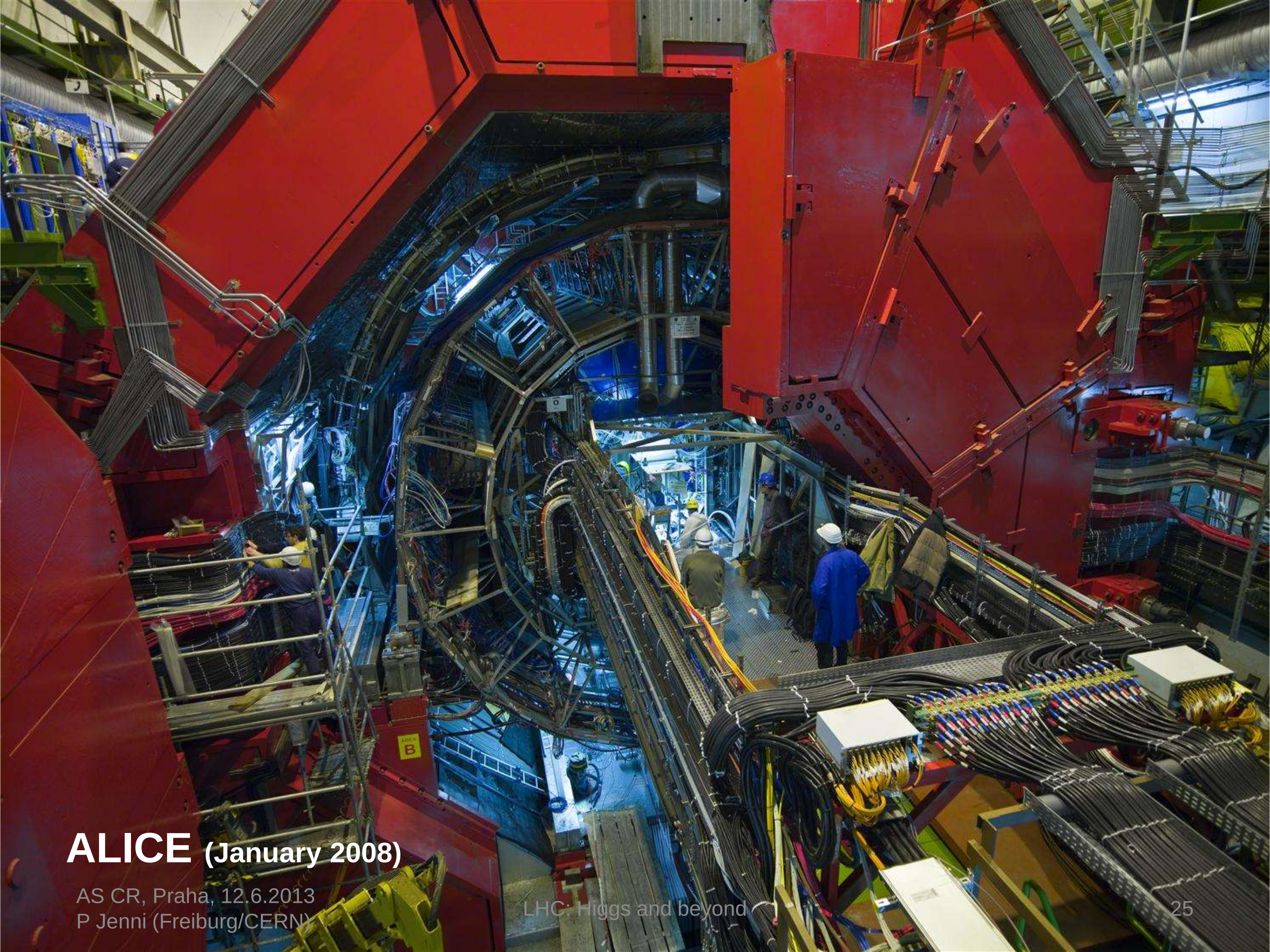
CMS
3000 Physicists
184 Institutions
38 countries
550 MCHF

LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

ATLAS
3000 Physicists
176 Institutions
38 countries
550 MCHF

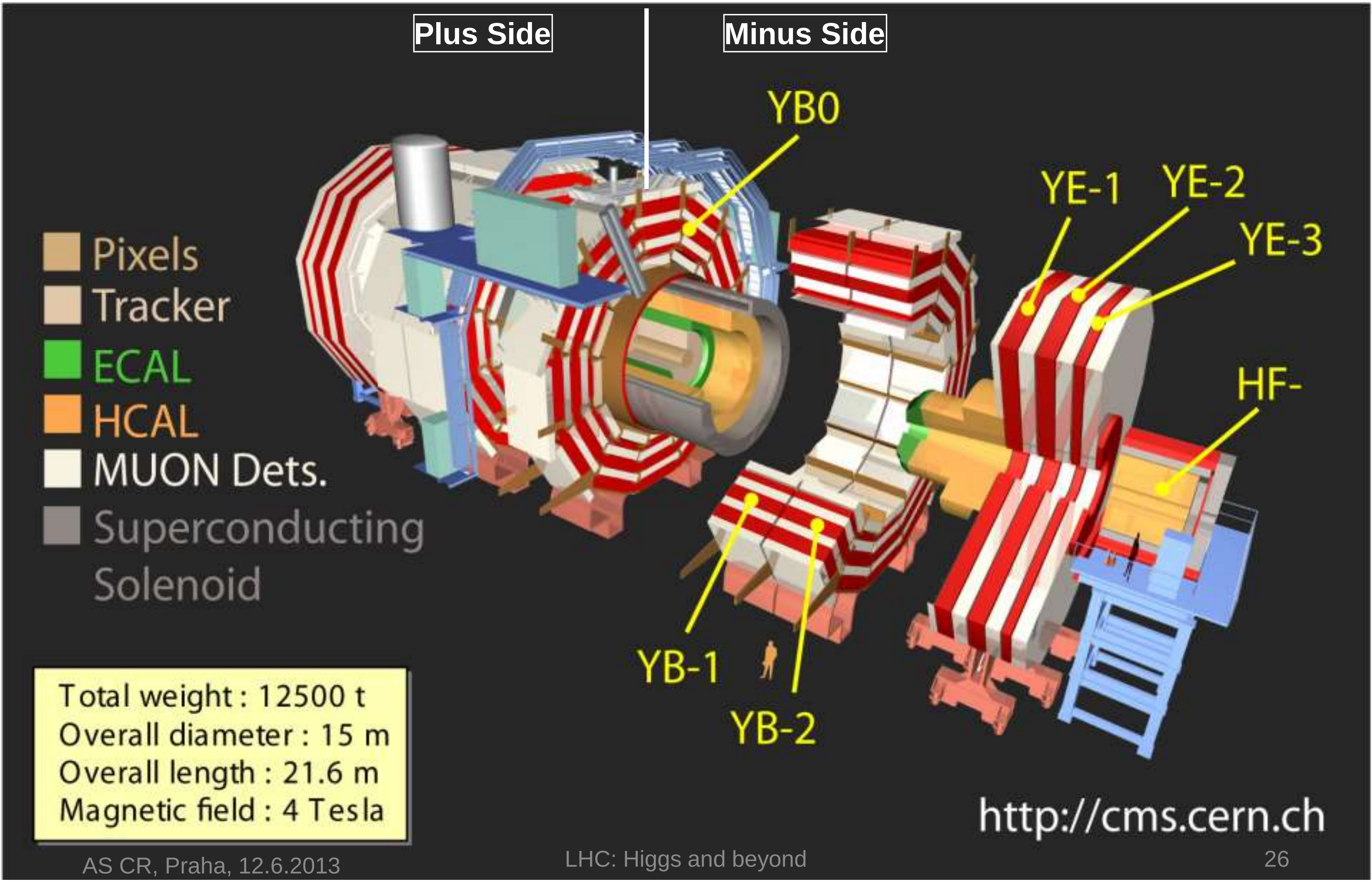
ALICE
1300 Physicists
130 Institutions
35 countries
160 MCHF


Muon det
Calo's
RICH-2
OT+IT
Magnet
RICH-1
VELO
Interaction Point
The LHCb detector installed at Point-8



ALICE (January 2008)

Exploded View of CMS



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 before closure 2008

ATLAS Collaboration

38 Countries
176 Institutions
3000 Scientific participants total
(1000 Students)

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, Brasil 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, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, 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, 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

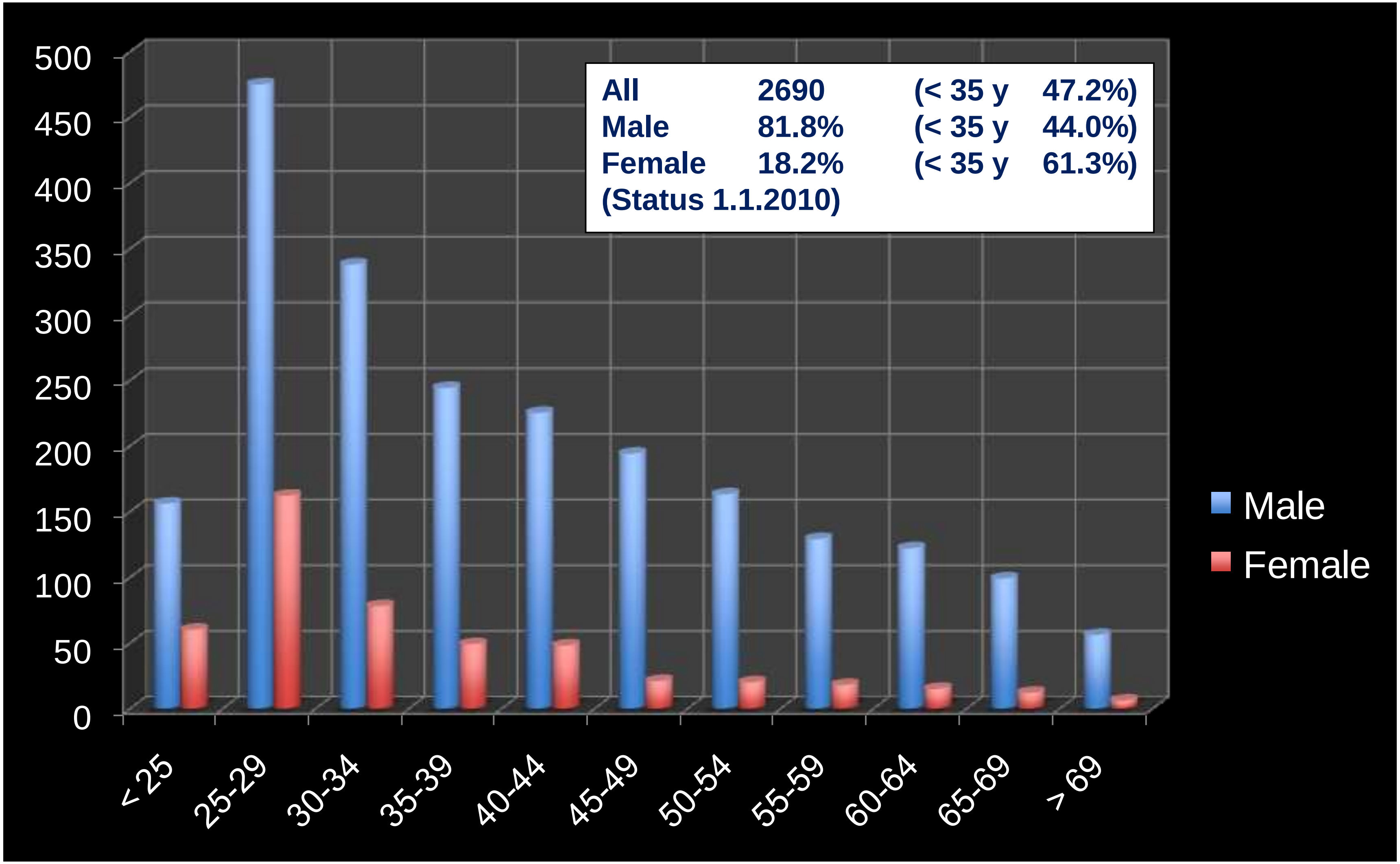
ATLAS Collaboration

38 Countries
176 Institutions
3000 Scientific participants total
(1000 Students)

It is a great pleasure to collaborate with ~75 colleagues, junior and senior, from the four Czech Universities since the very first days

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, Brasil 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, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, 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, **ASCR 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, 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

Age distribution of the ATLAS population

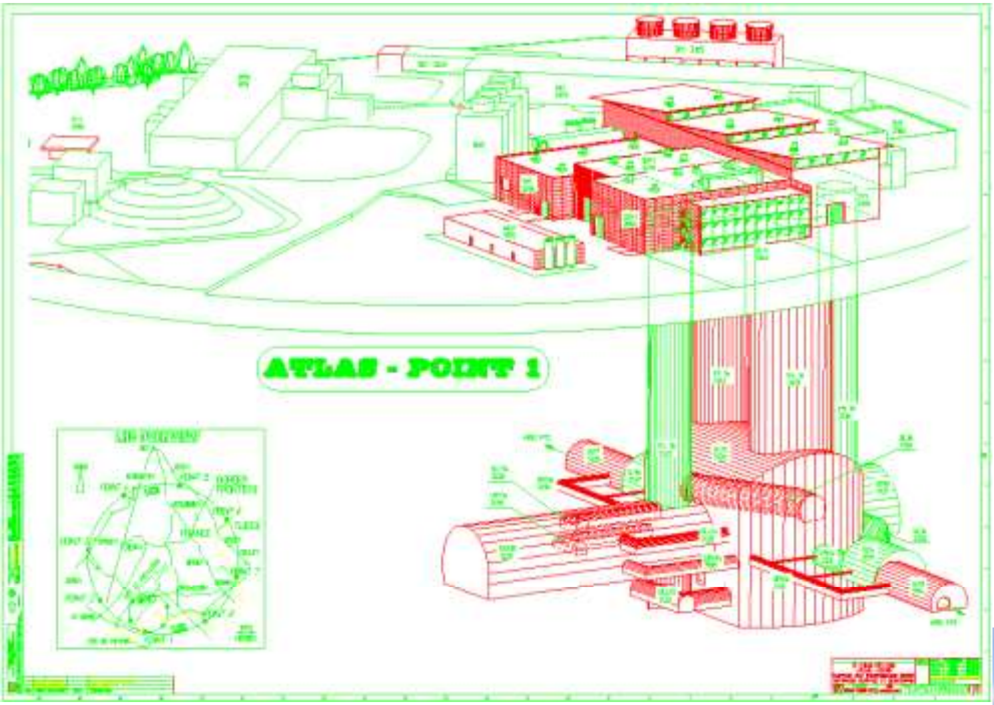


ATLAS has a long-standing, excellent, cooperation with the Czech teams, since the official start of the project in 1992

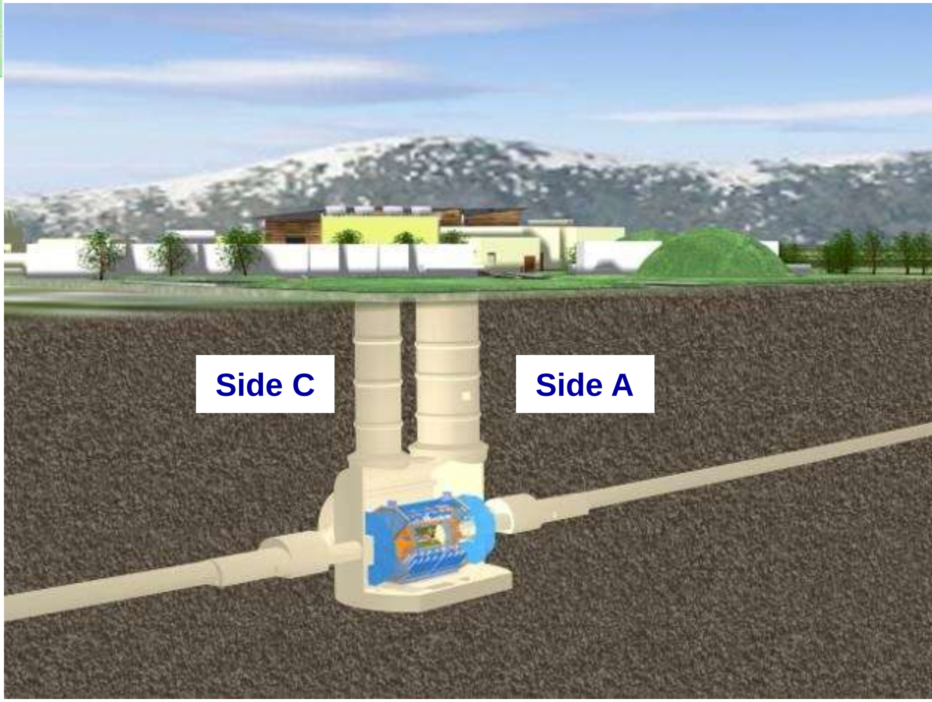
An important milestone was the ATLAS Collaboration meeting in Prague 2003, just before we started installing the detector

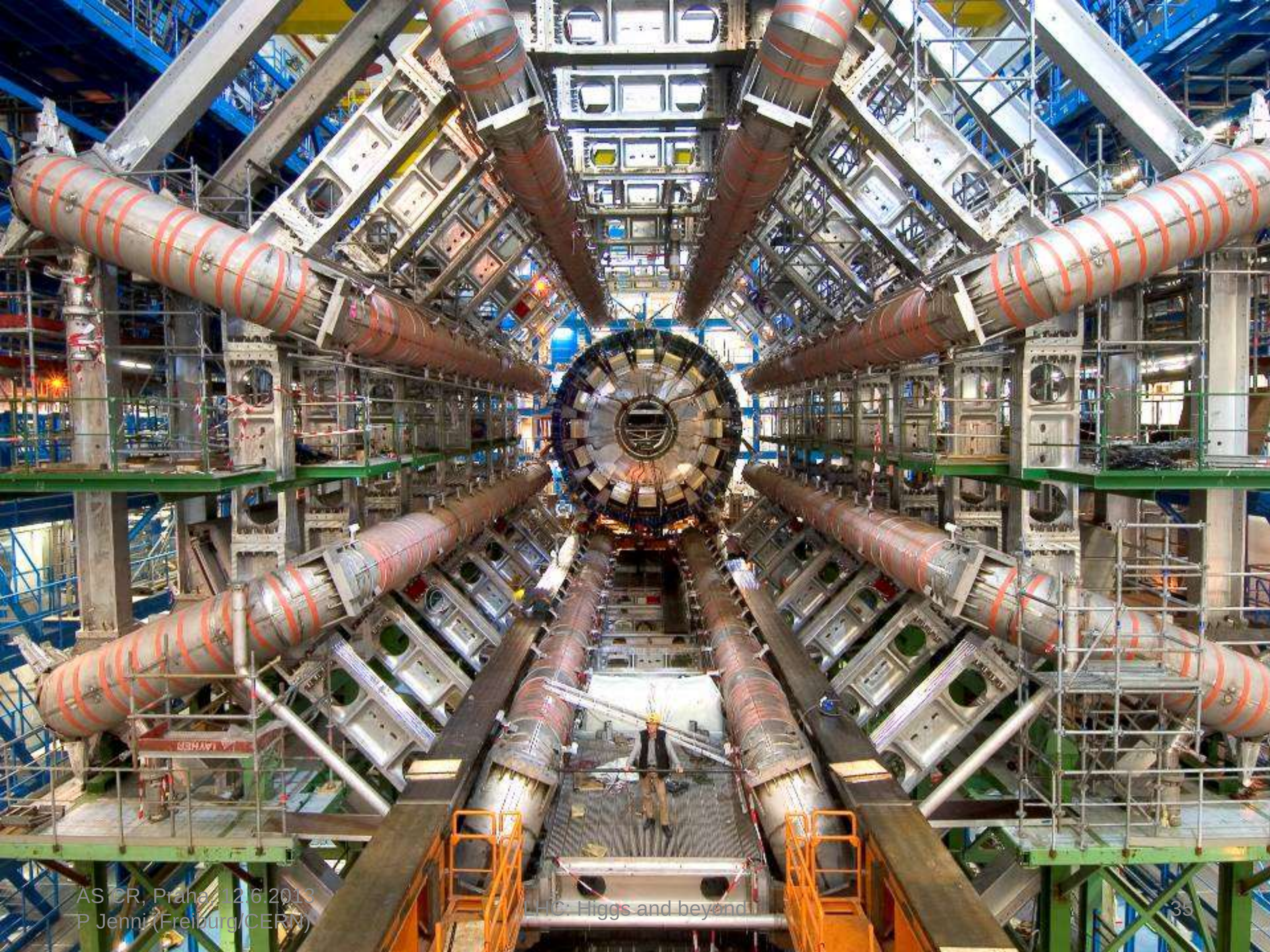
Professor J Niederle (1939-2010) opening the ATLAS Overview Week in Prague

The Underground Cavern at Point-1 for the ATLAS Detector



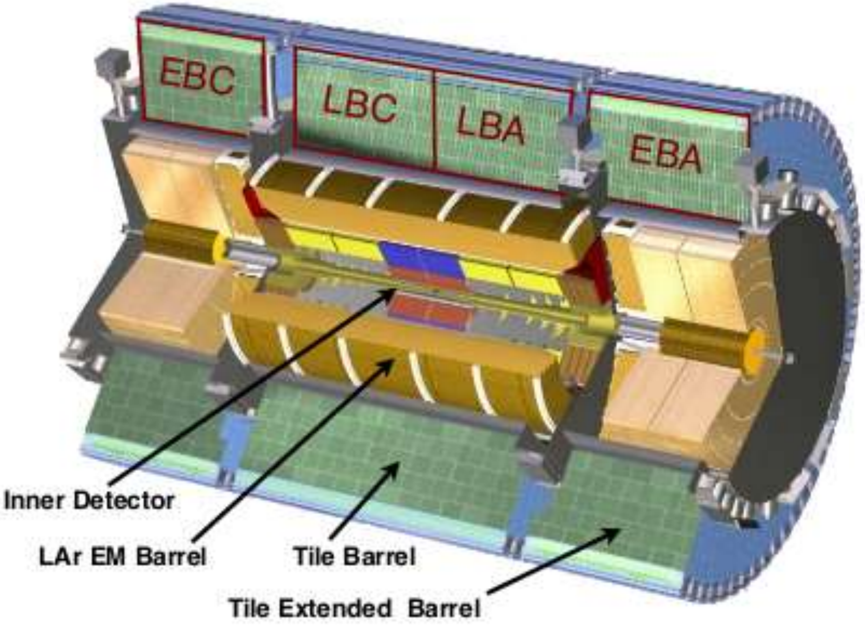
Length = 55 m
Width = 32 m
Height = 35 m



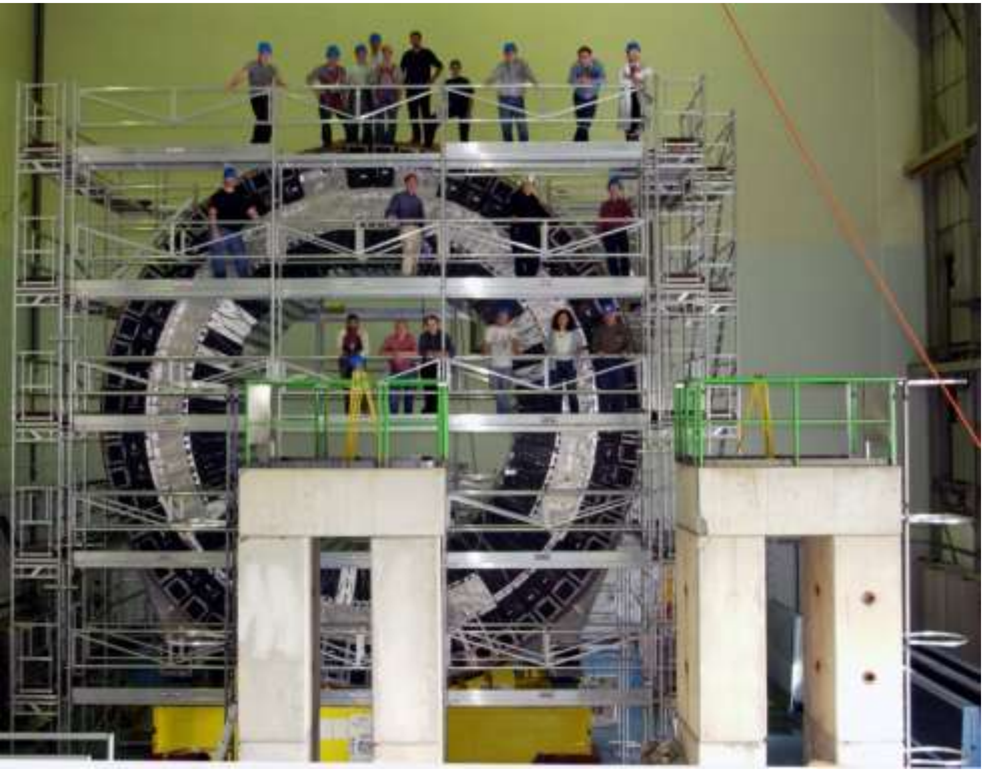


Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009

Tile Calorimeter

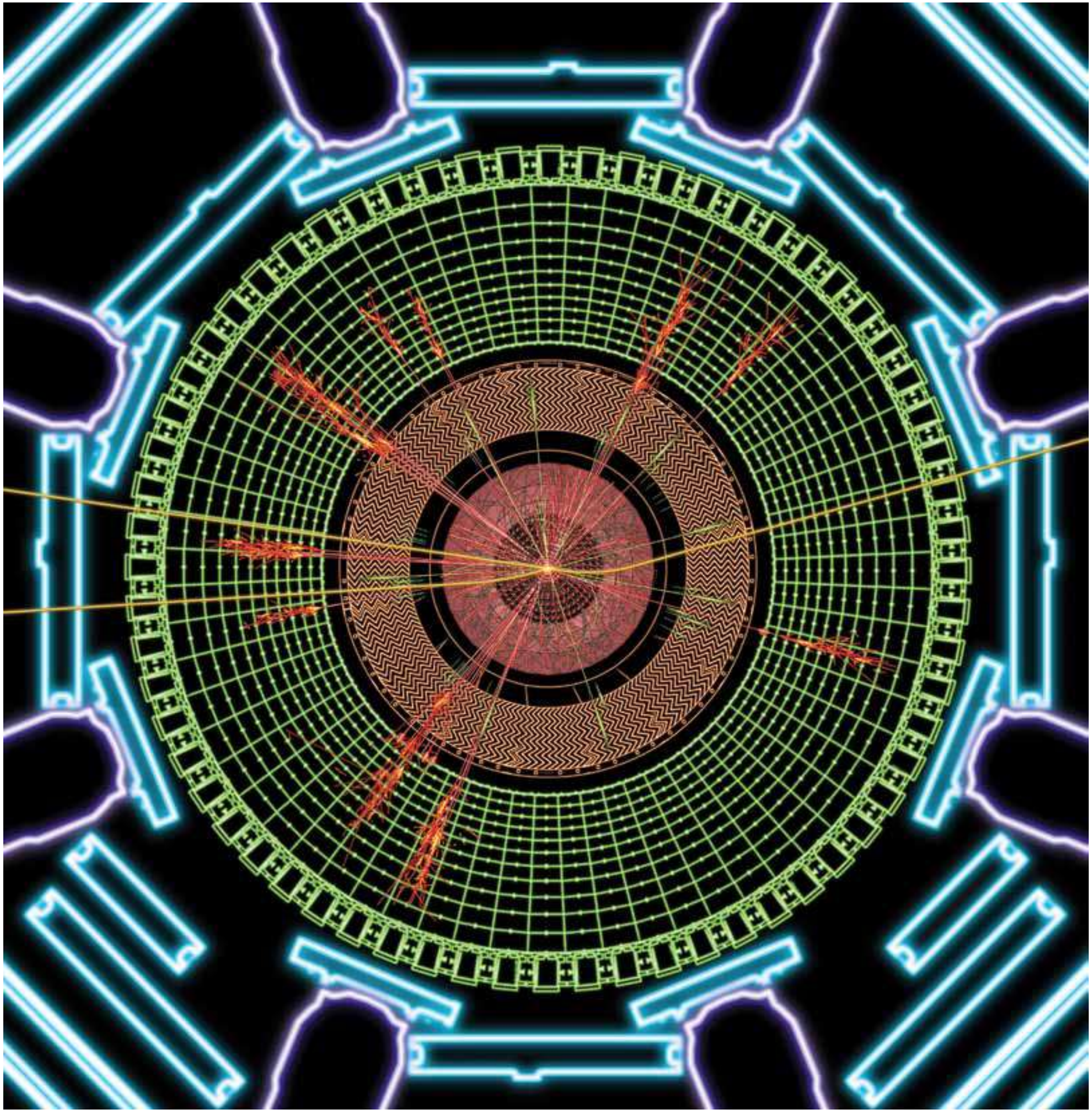


EBC pre-assembly on the surface, April 2003



Rupert Leitner Project Leader 2001-2004

An artistic view of the ATLAS Tile Calorimeter with simulated em and hadronic showers

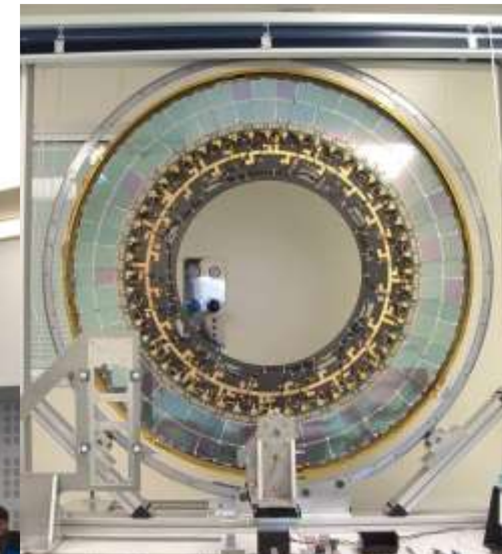


Tile Calorimeter sub-module construction in Prague 1999

Czech Deputy Prime Minister Petr Mares visiting the Tile Calorimeter pre-assembly (Dec 2003)

Transport of part of the Barrel Tile Calorimeter to the experimental area Point-1 (Sep 2004)

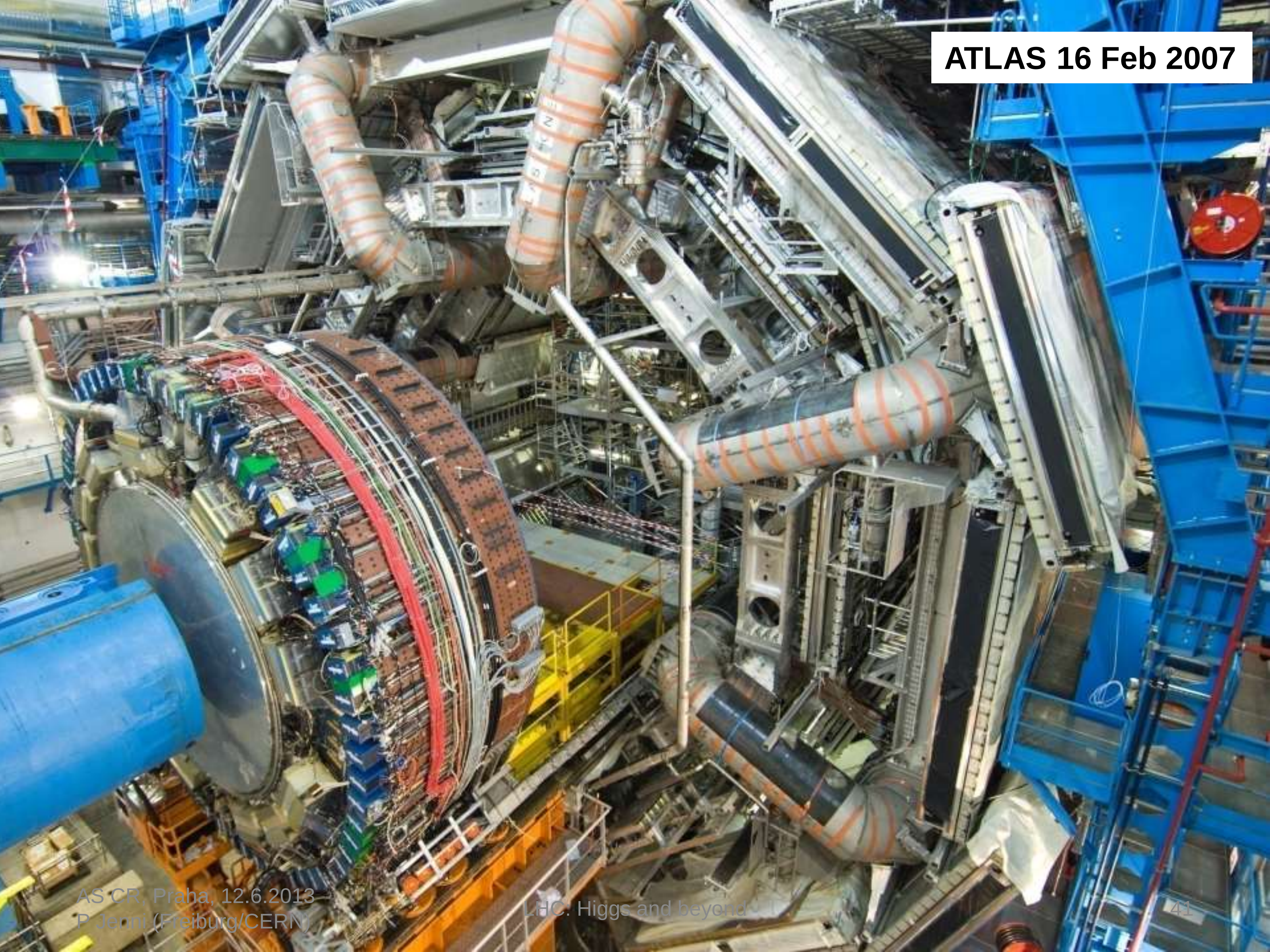
The Prague groups (and Czech industry) are also important collaborators on the semiconductor tracking system (SCT and Pixels)

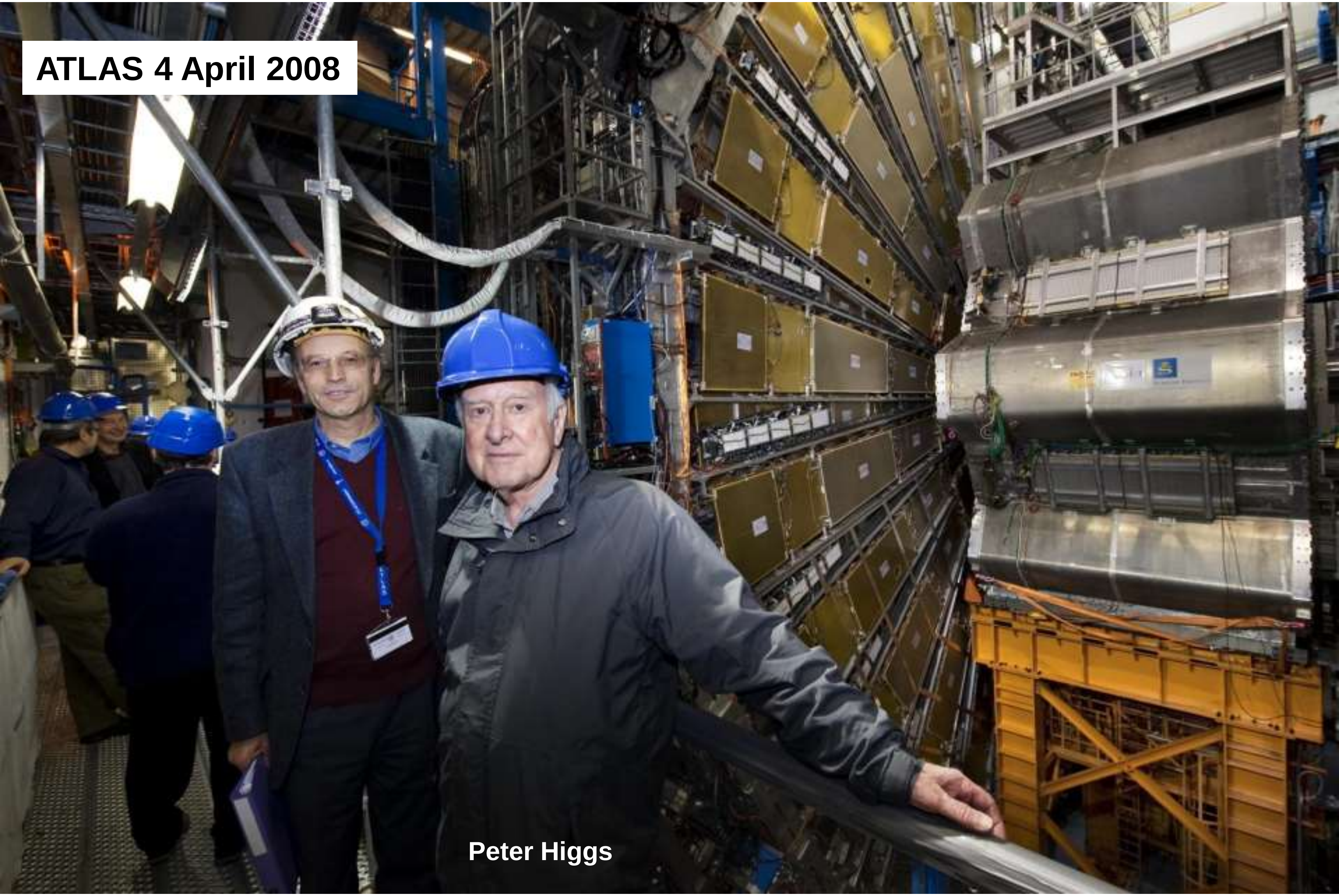


ATLAS Supplier Award ceremony for 'On Semiconductor' (ex 'Tesla') in 2007

Also 'Skoda Hute' received the same award in 2004 for their shielding work, another important expertize of Czech groups in radiation matters

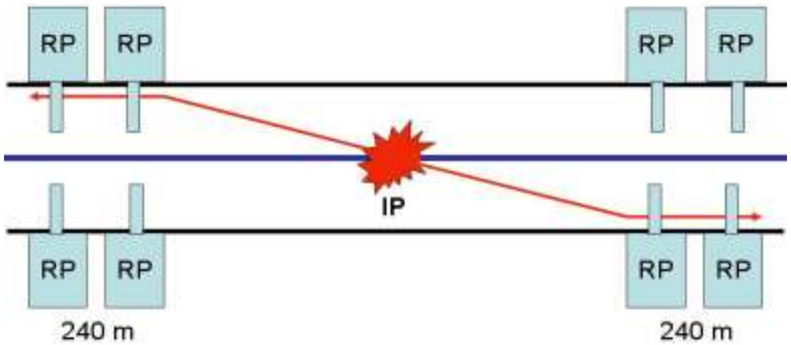
ATLAS 16 Feb 2007




ATLAS 4 April 2008
Peter Higgs

ATLAS Roman Pots (ALFA)

There is also a strong involvement of Czech colleagues and industry in ALFA since the Palacky University in Olomouc joined ATLAS in 2008

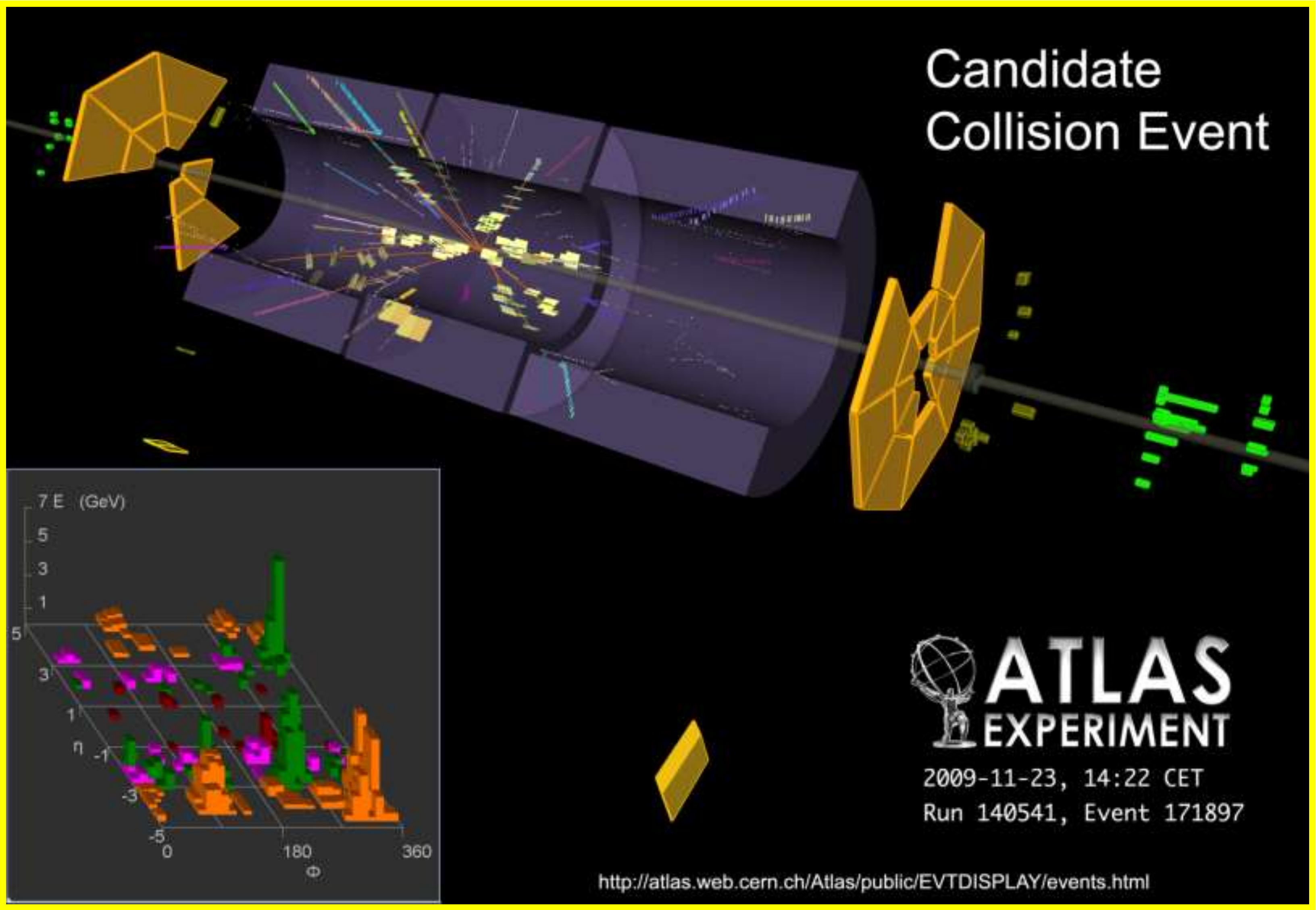


Absolute
Luminosity
For
ATLAS

Roman Pots mechanics, based on Czech work in the Totem experiment

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

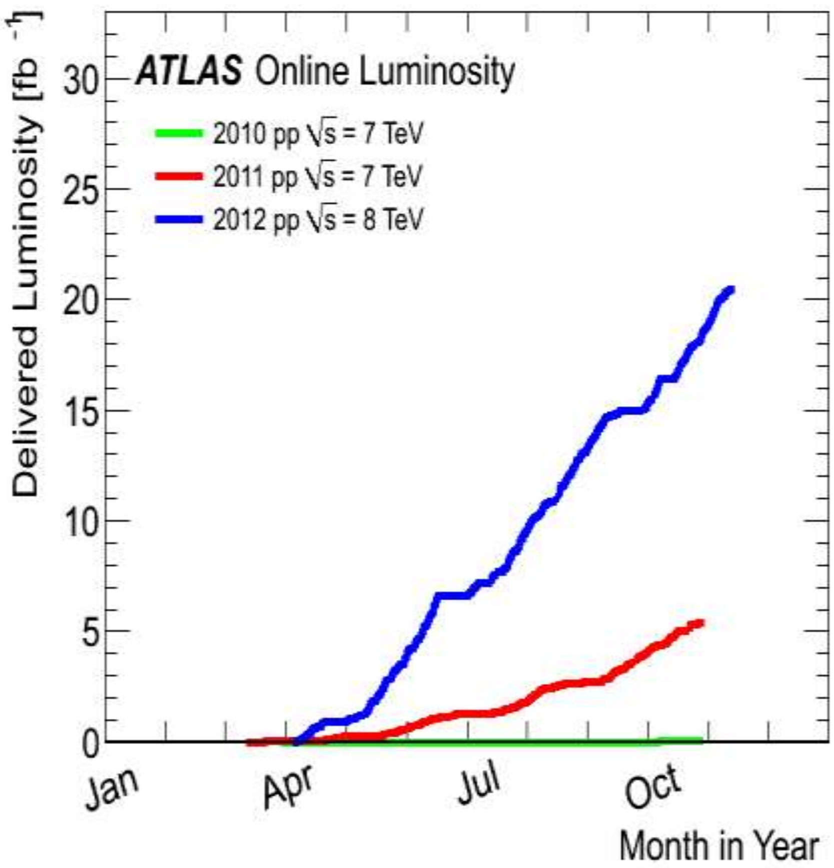
First collisions at the LHC end of November 2009 with beams at the injection energy of 450 GeV

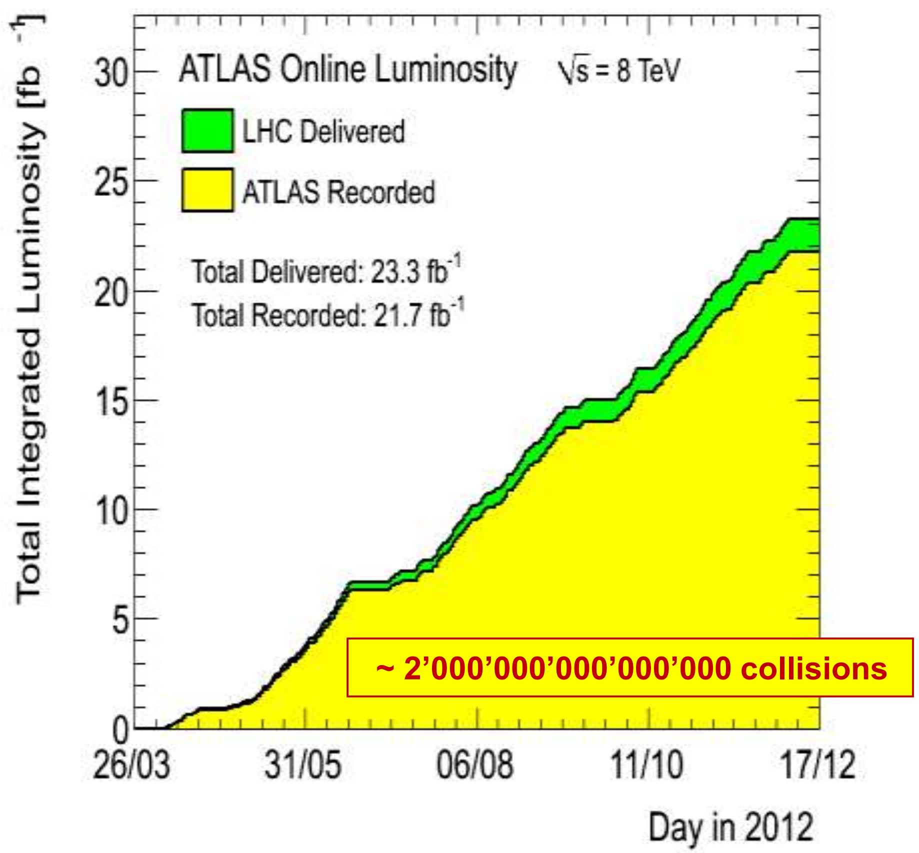


The LHC and experiments performances were simply fantastic over the last three years

Total integrated luminosity

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

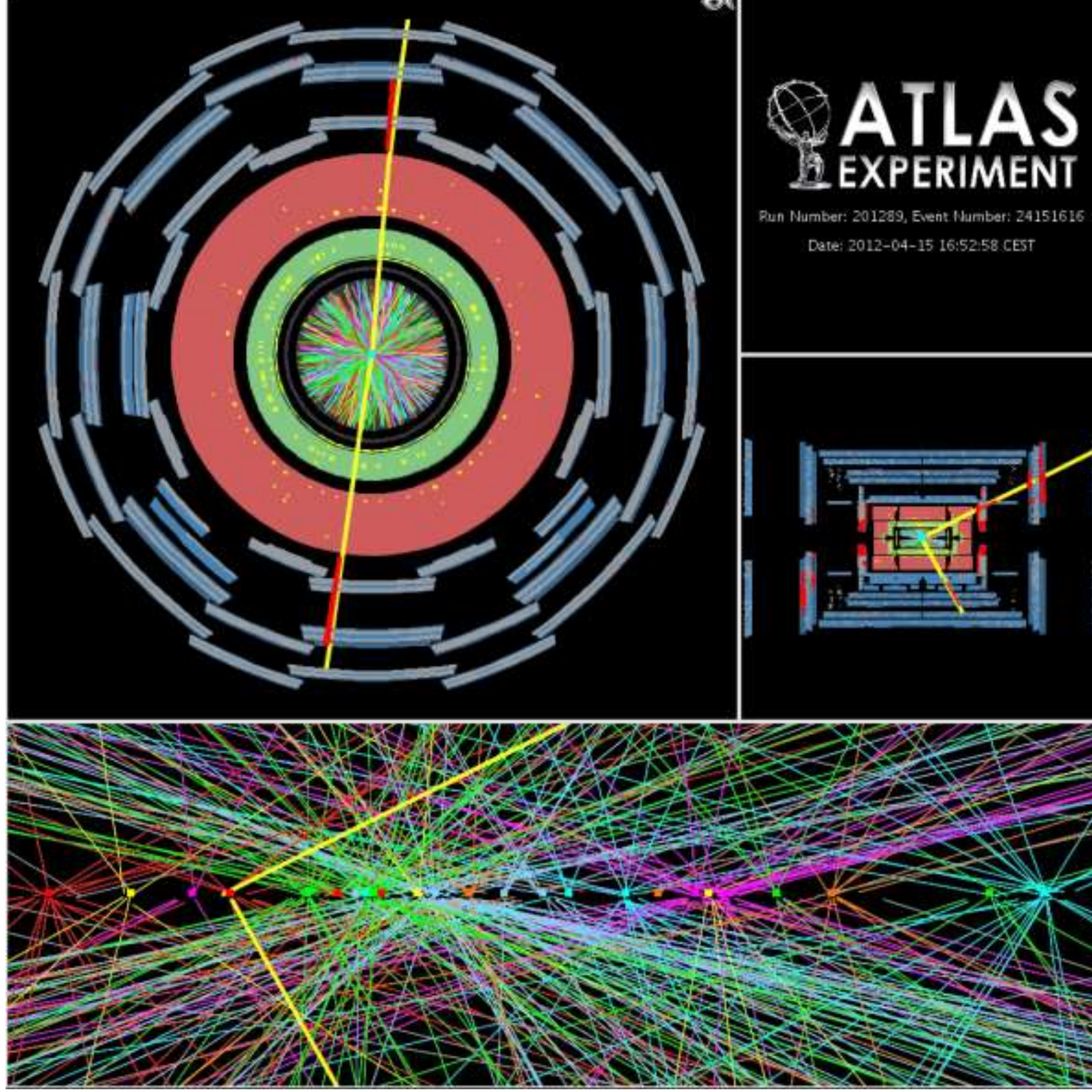


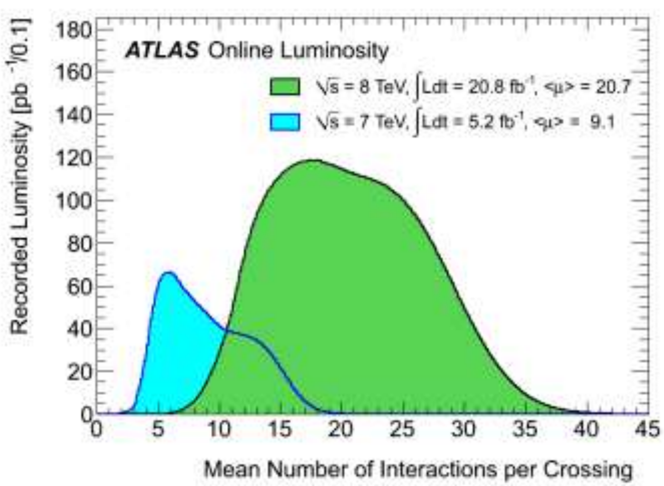


The experiment records typically 94% of the stably delivered luminosity, and uses up to 90% of the LHC luminosity in the final analyses!

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

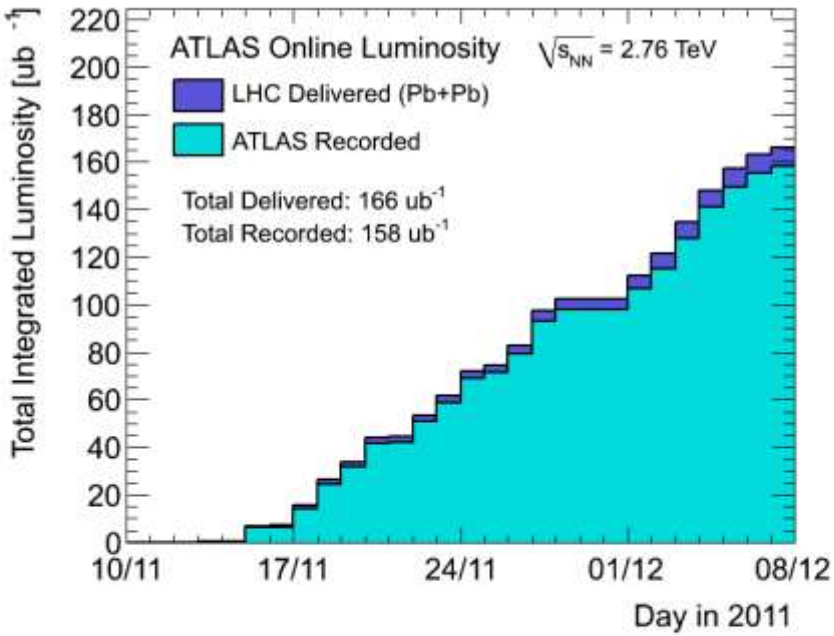
- **Trigger**
- **Pile-up**
- **Maintain accuracy of the the measurements in this environment**

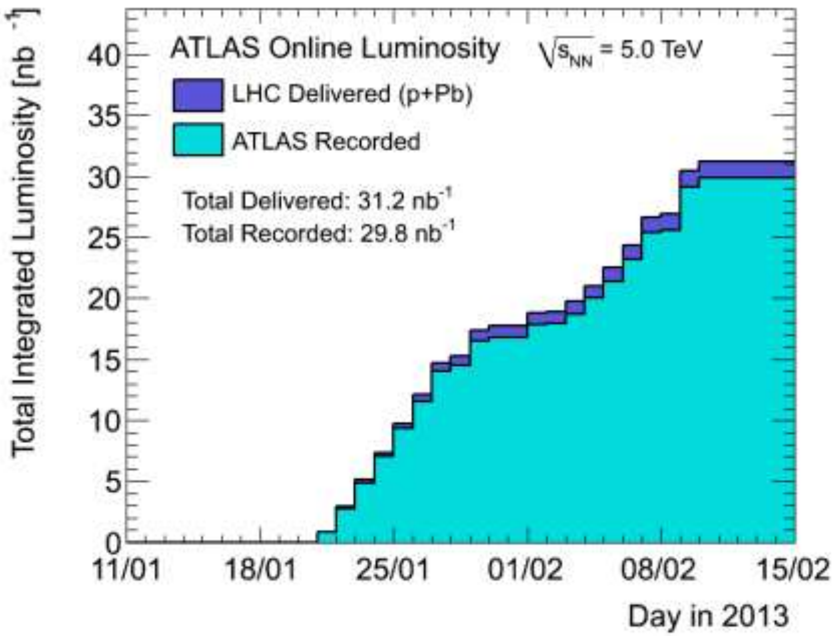




Inner Detector for a Z → μμ event with 25 primary vertices

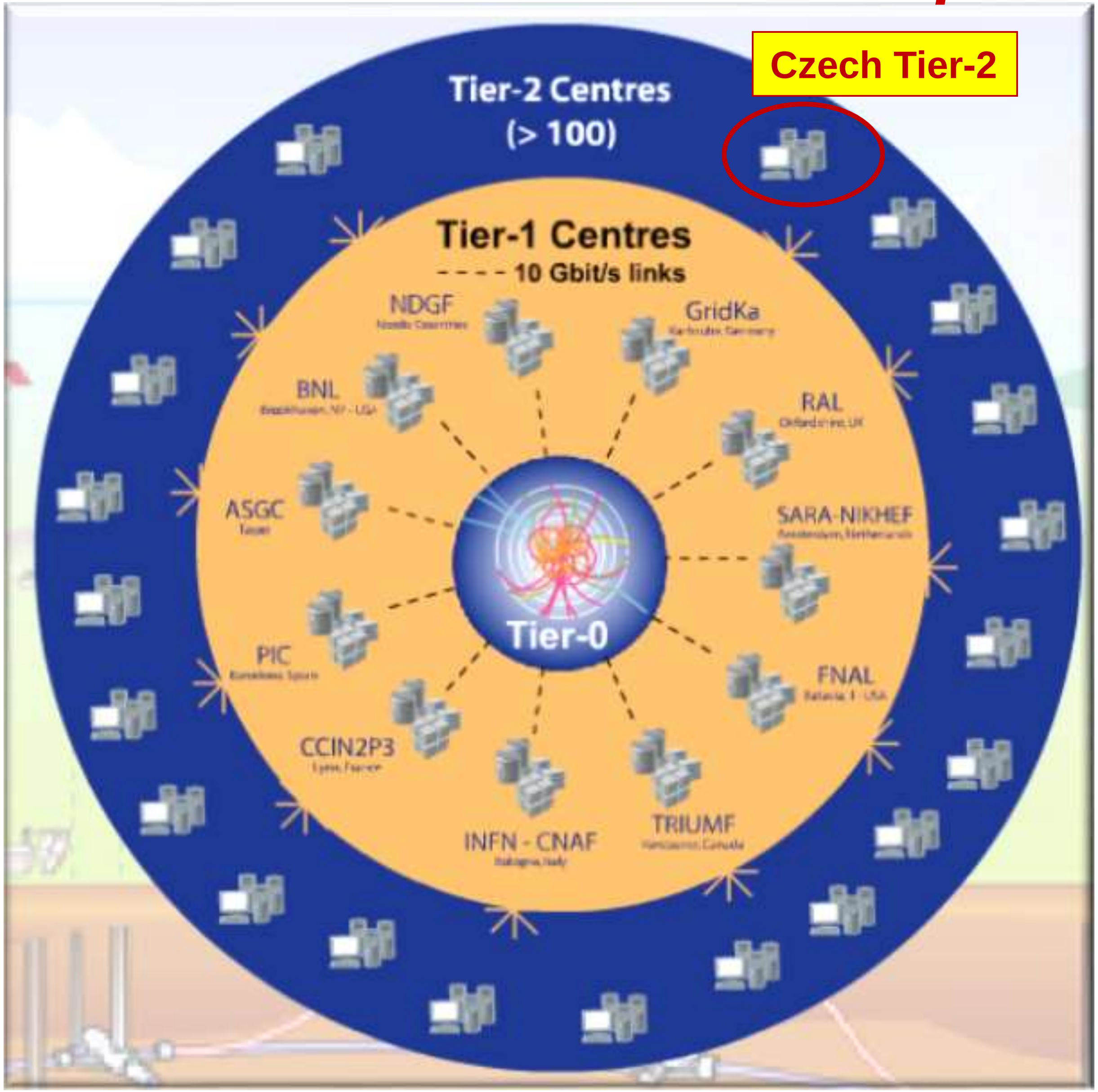
LHC and ATLAS have also been operated very successfully as Pb-Pb and as p-Pb colliders





Czech ATLAS scientists are very active in this rich field of quark-gluon plasma physics

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

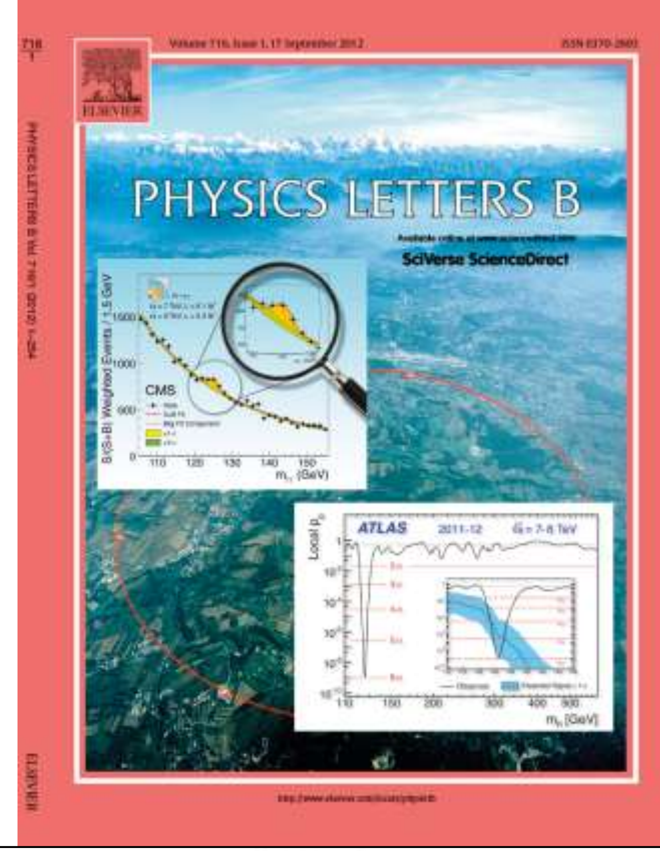
Physics Highlights

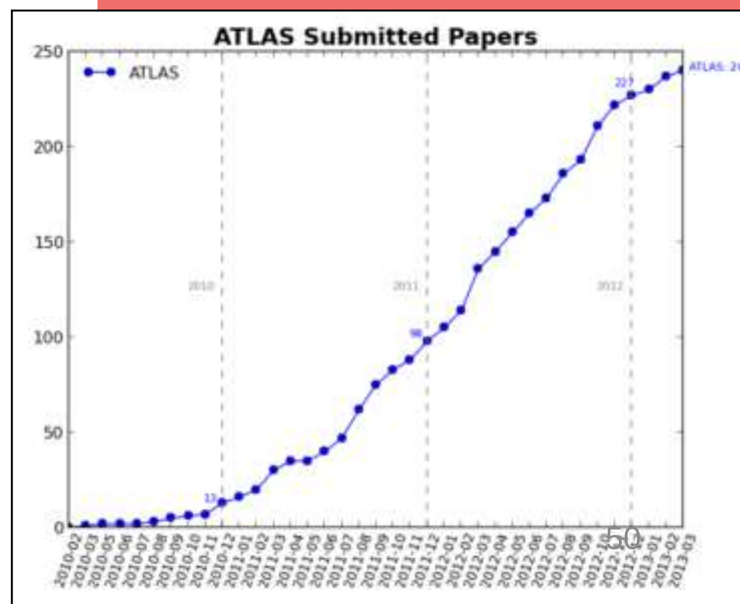
ATLAS and CMS have already published together more than 400 papers in scientific journals (and many more as public conference notes…)

The other experiments, ALICE, LHCb, LHCf, and TOTEM total another 150 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, but 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

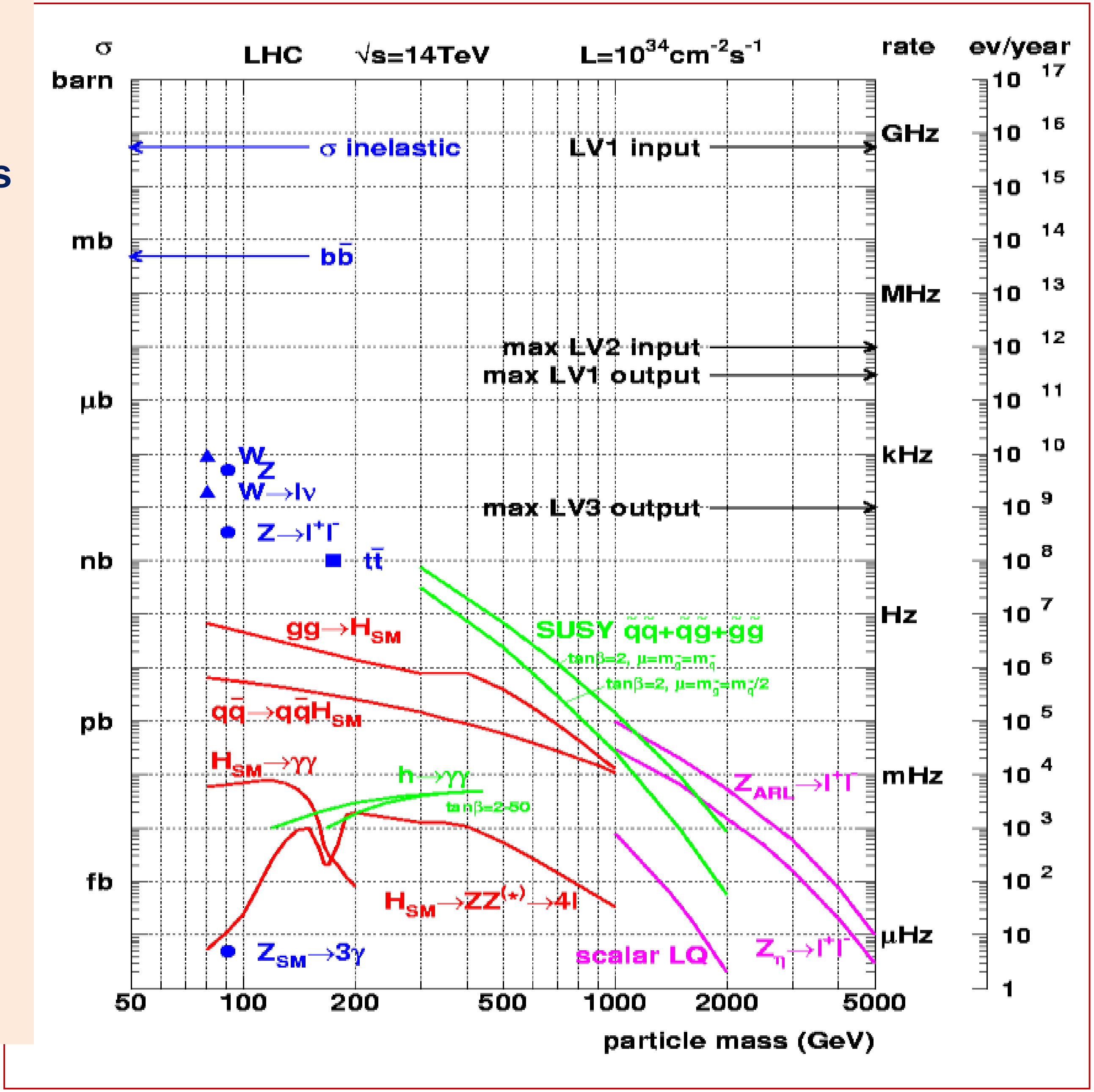
Heavy flavour physics

Standard Model physics including QCD jets

Higgs searches

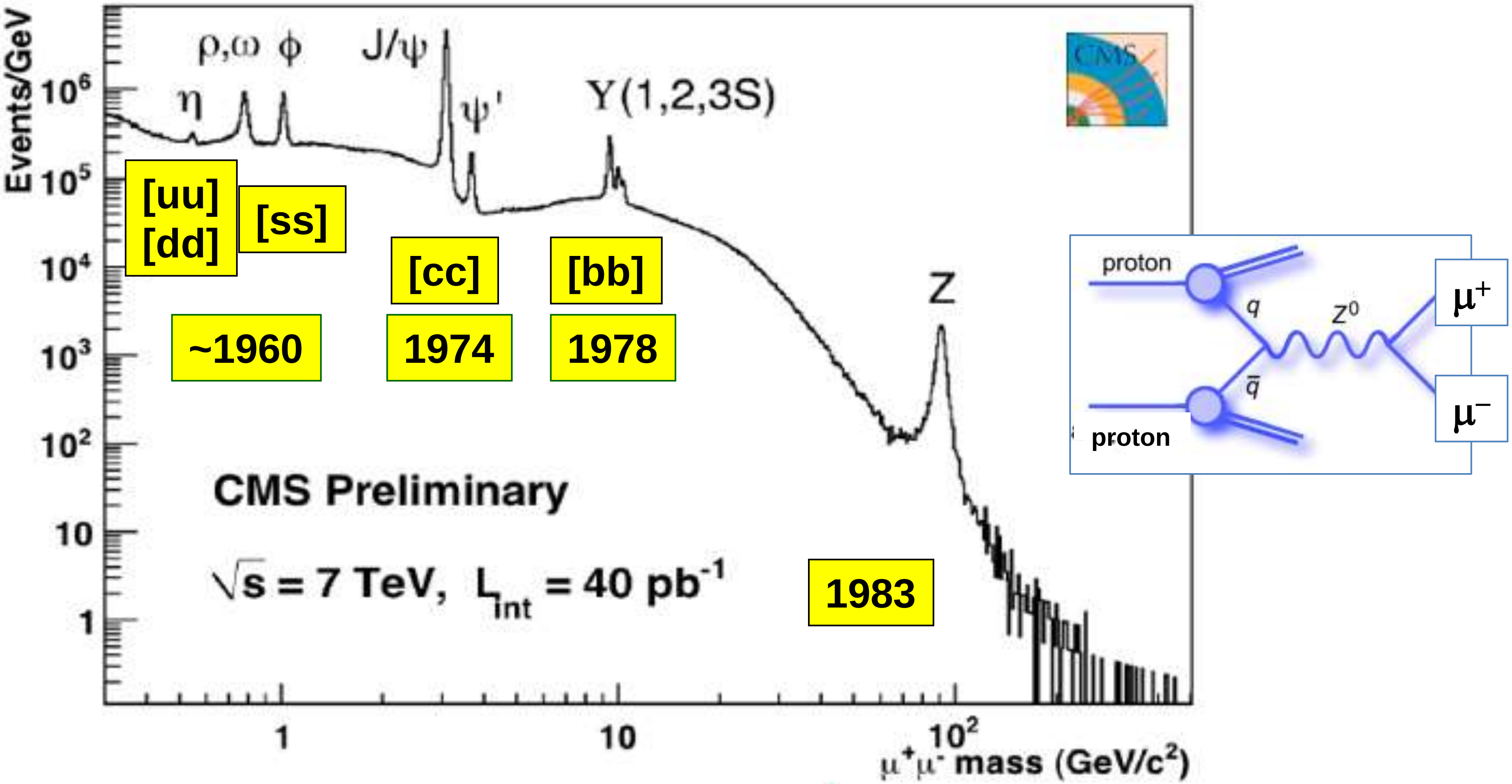
Searches for SUSY

Searches for 'exotic' new physics



2010

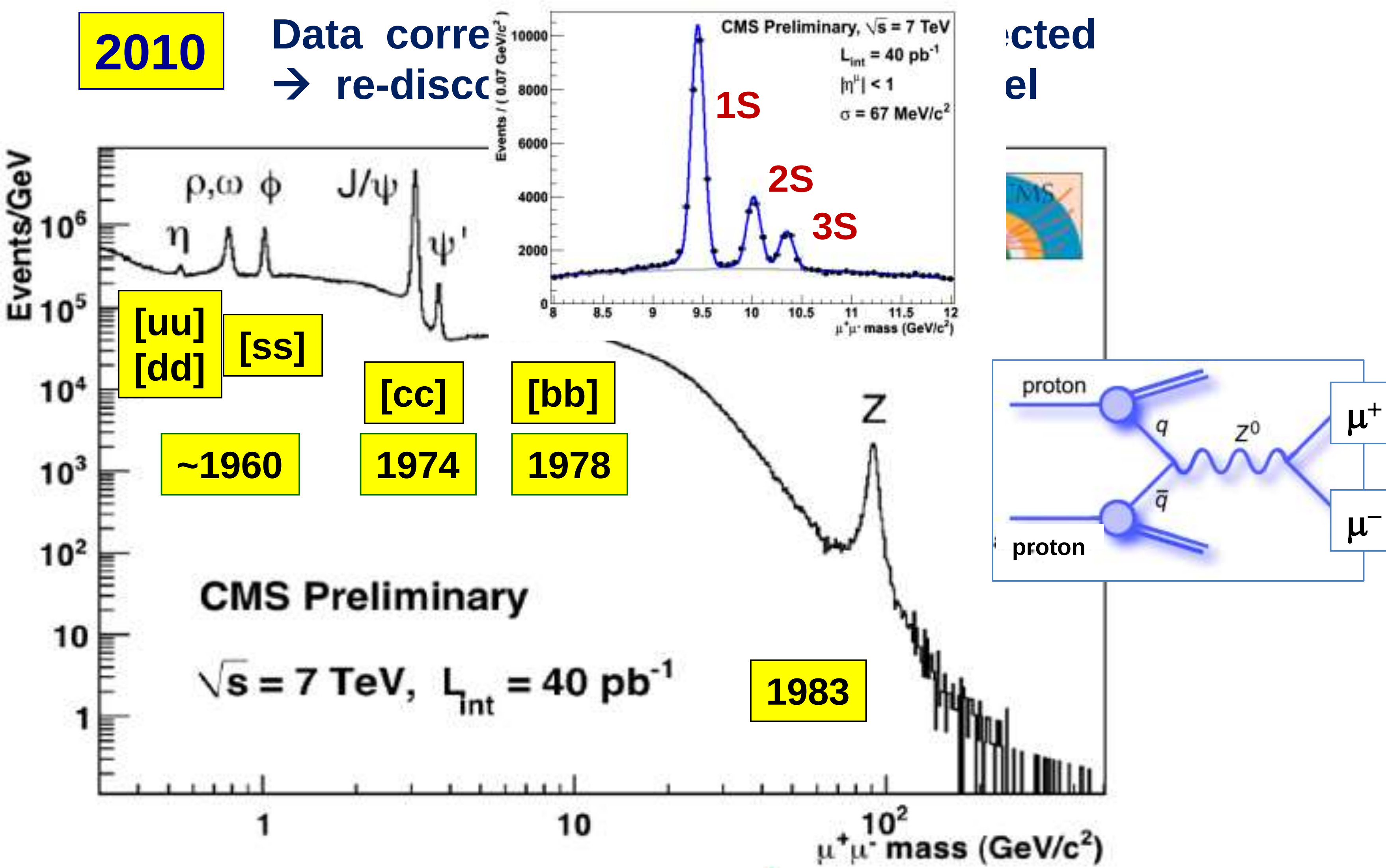
Data corresponding to ~40 pb^{-1} collected
→ re-discovery of the Standard Model



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

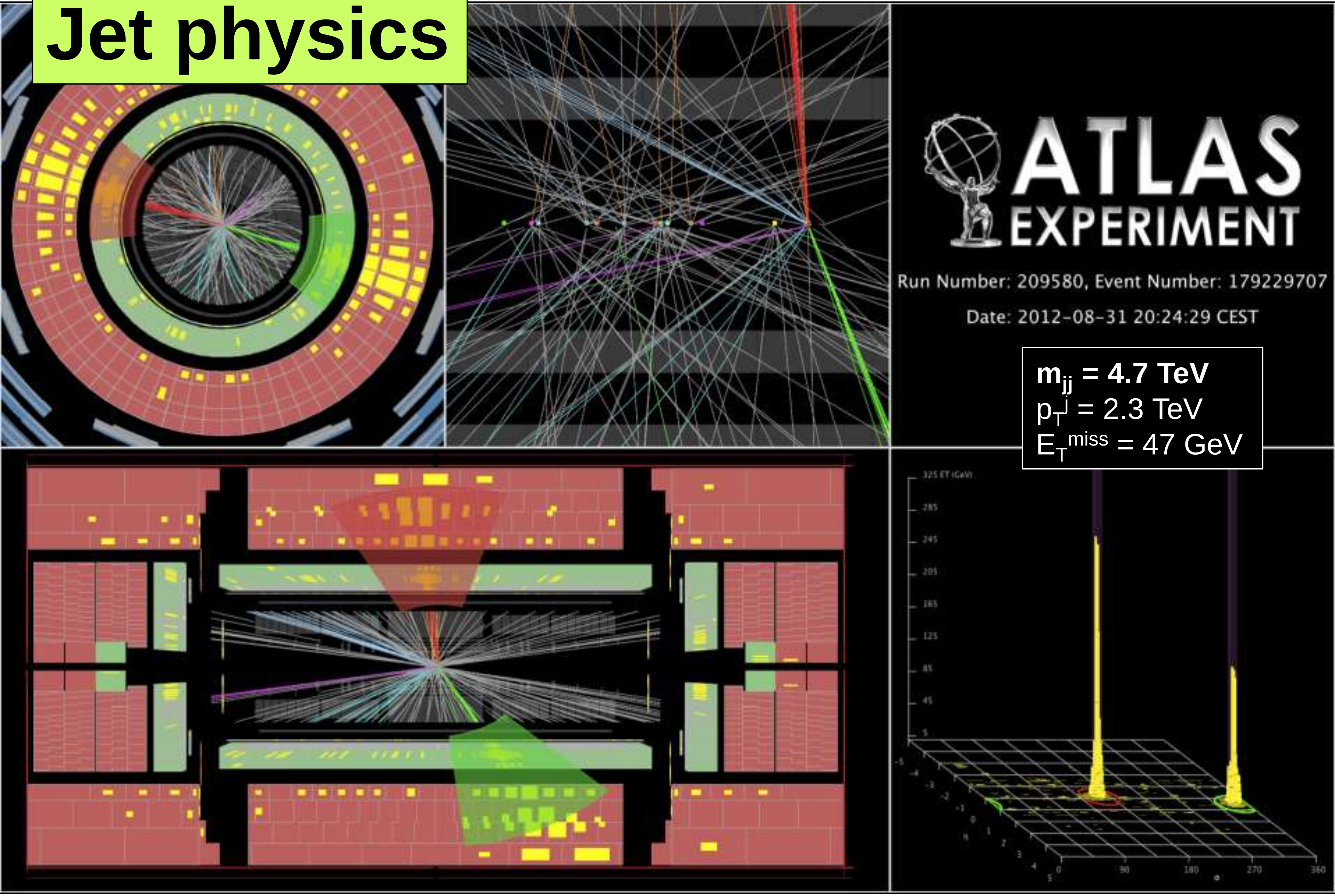
2010

Data corre… …cted
→ re-disco… …el

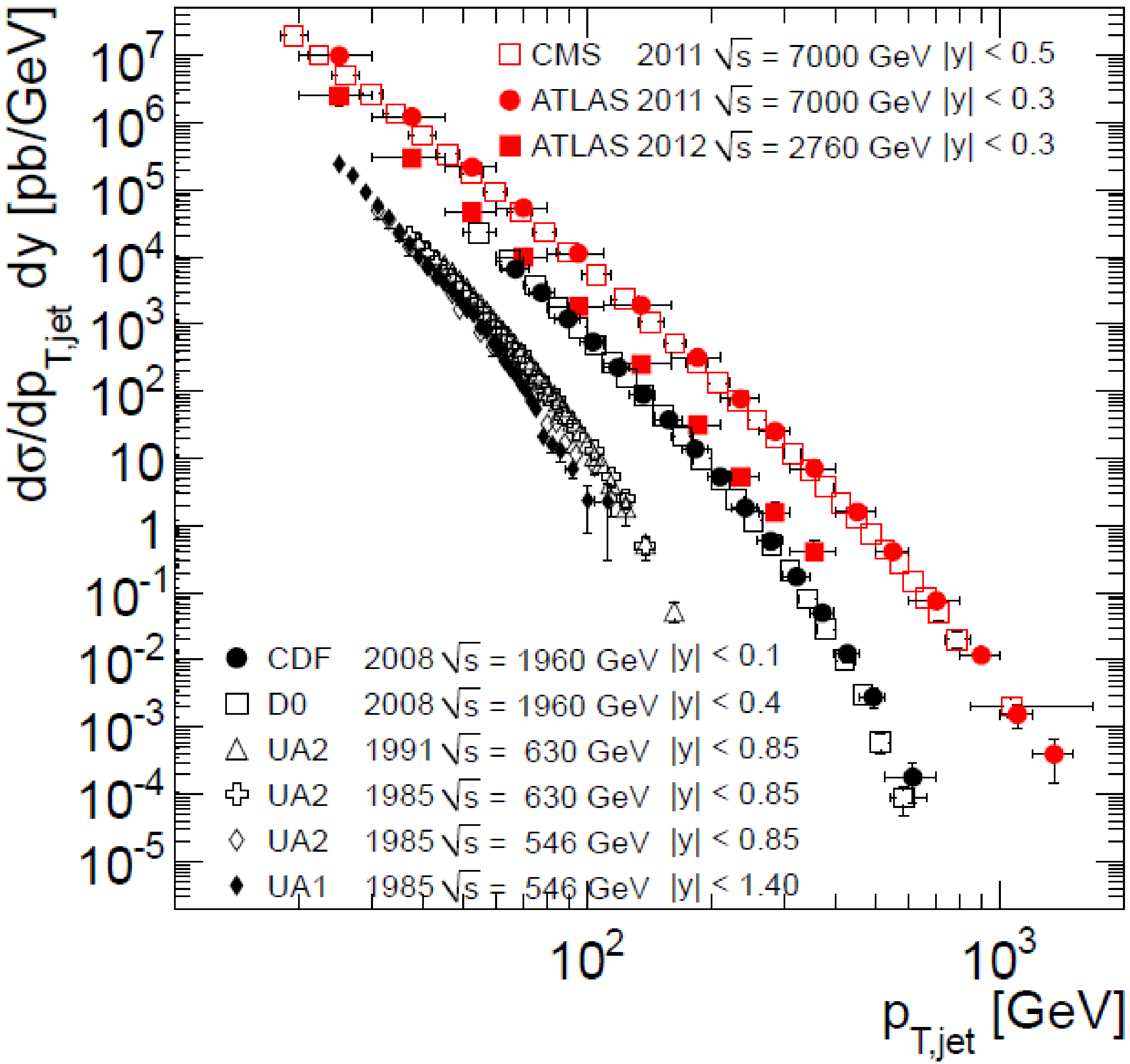


The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear “online”

Jet physics



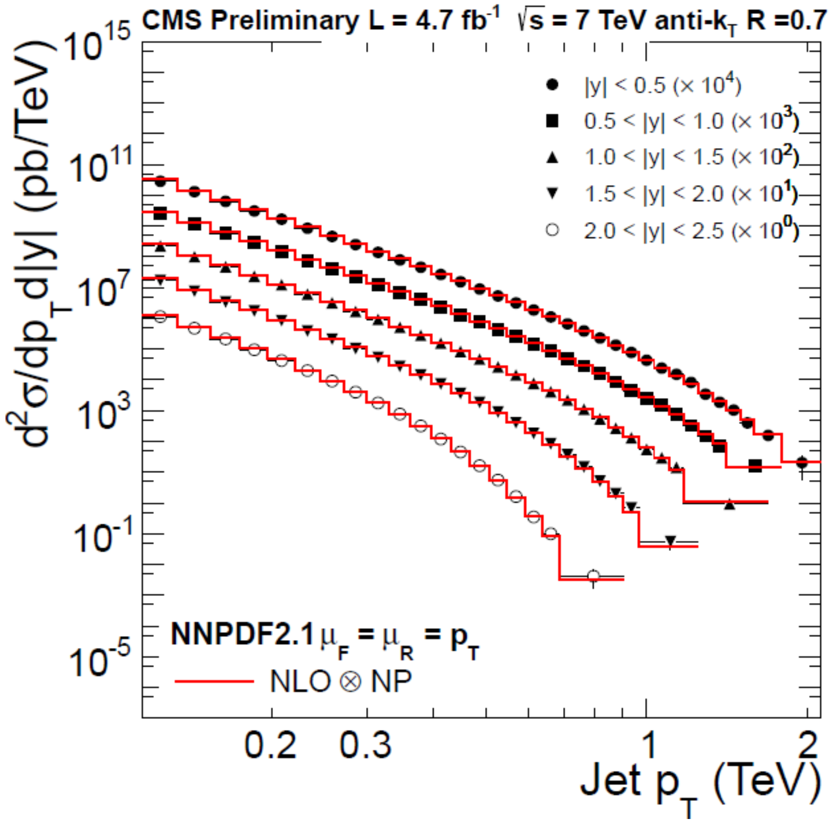
m_{jj} = 4.7 TeV
p_T^j = 2.3 TeV
E_T^{miss} = 47 GeV

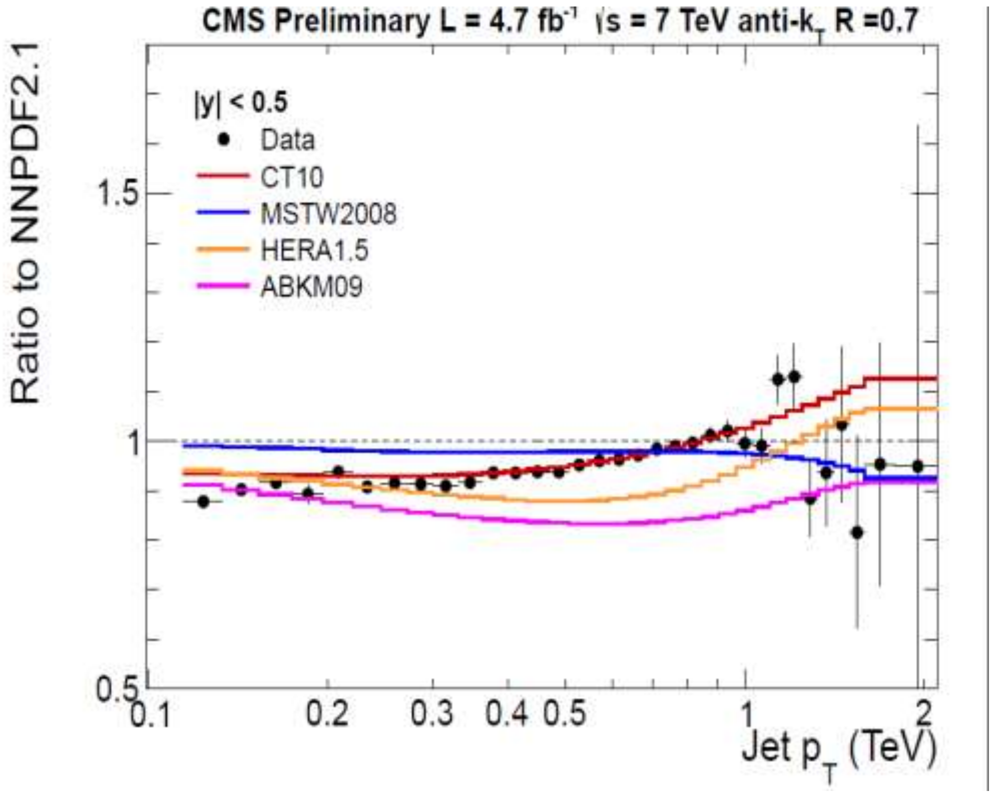


dσ/dp_T,jet dy [pb/GeV]
CMS 2011 √s = 7000 GeV |y| < 0.5
ATLAS 2011 √s = 7000 GeV |y| < 0.3
ATLAS 2012 √s = 2760 GeV |y| < 0.3
CDF 2008 √s = 1960 GeV |y| < 0.1
D0 2008 √s = 1960 GeV |y| < 0.4
UA2 1991 √s = 630 GeV |y| < 0.85
UA2 1985 √s = 630 GeV |y| < 0.85
UA2 1985 √s = 546 GeV |y| < 0.85
UA1 1985 √s = 546 GeV |y| < 1.40
p_T,jet [GeV]

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

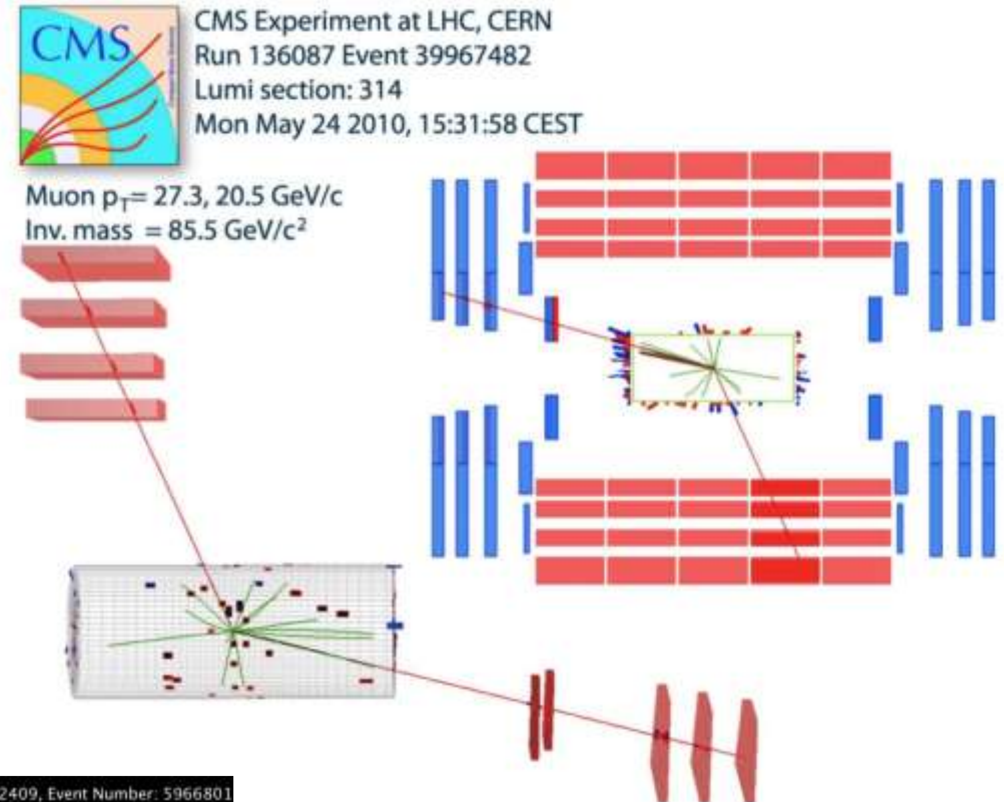
Example: The inclusive jet cross sections as a function of the jet P_T in rapidity bins





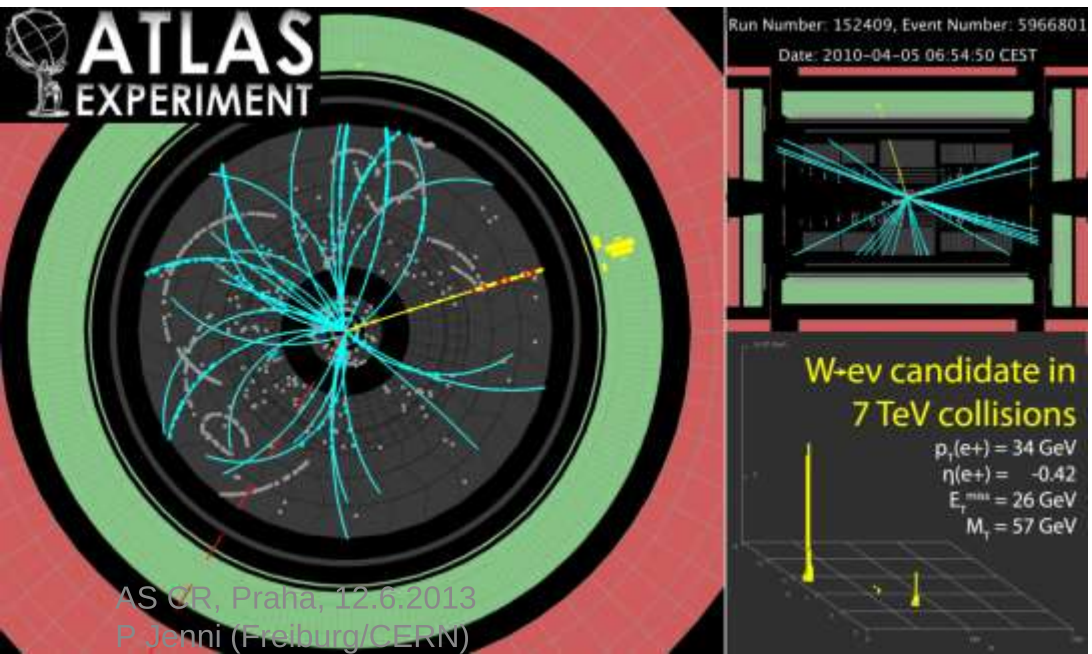
CMS-PAS-QCD-11-004

Standard Model Physics



Candidate Z → $\mu^+\mu^-$

W → eν candidate



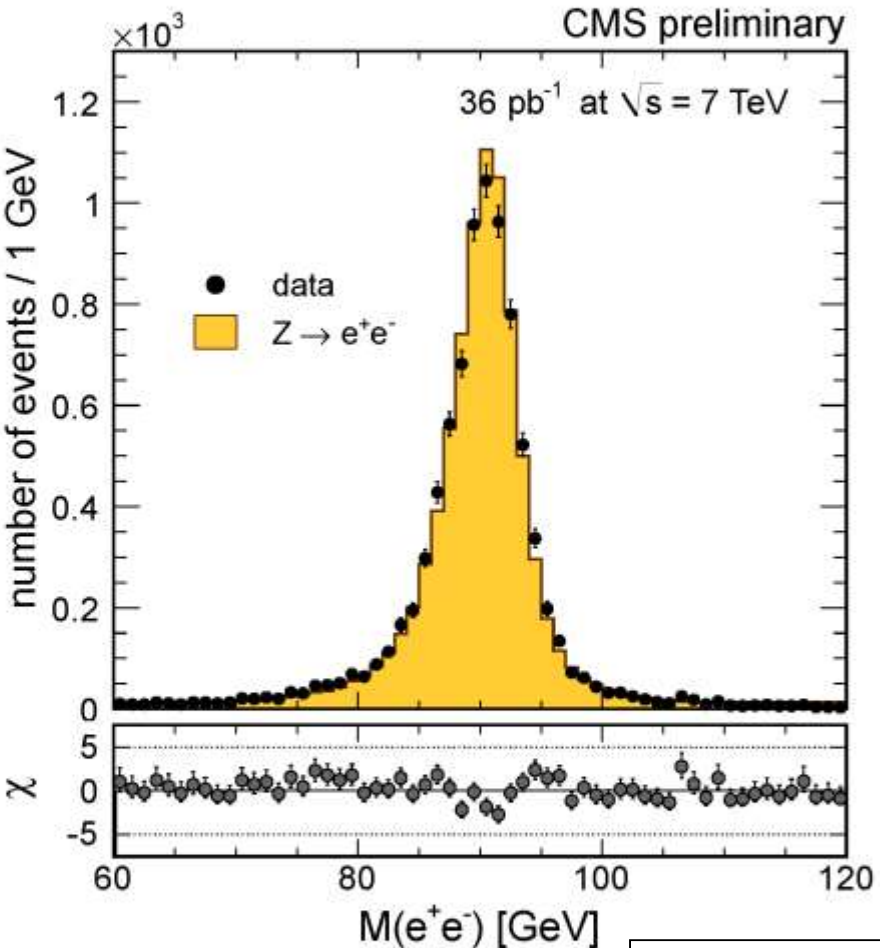
Today each ATLAS and CMS have in their data more than:

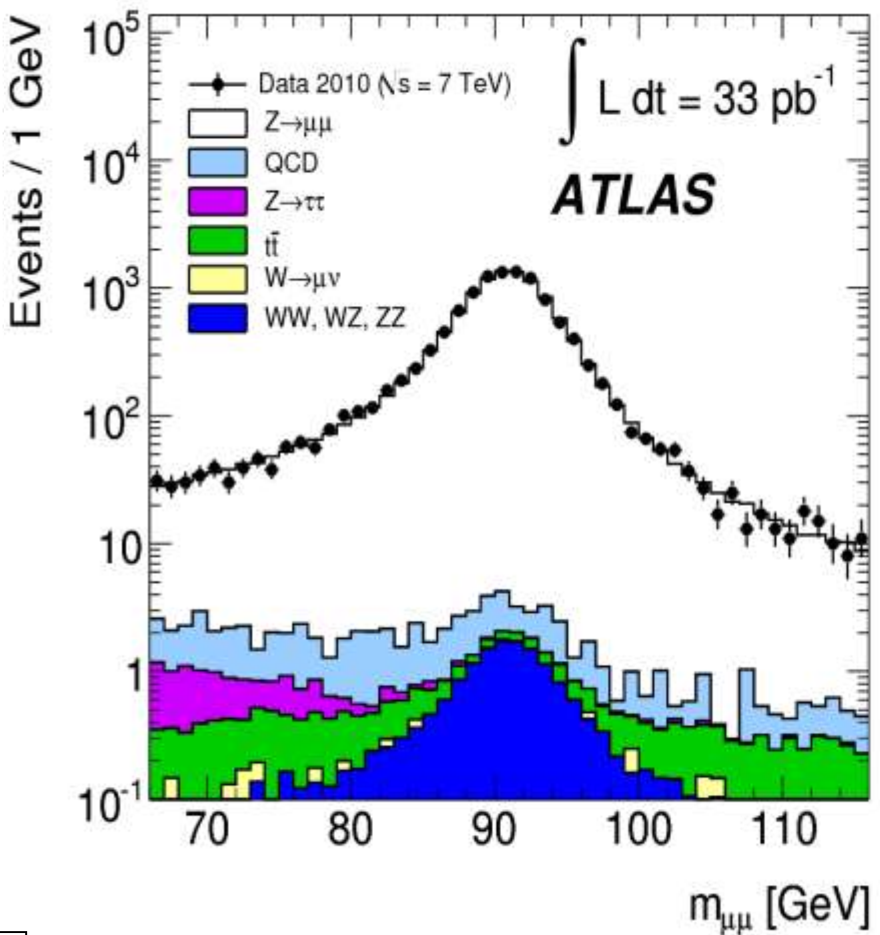
100 M W→ μν, eν events
10 M Z → μμ, ee events

after all selection cuts

Z and W production

Phys Rev D85 (2012) 072004





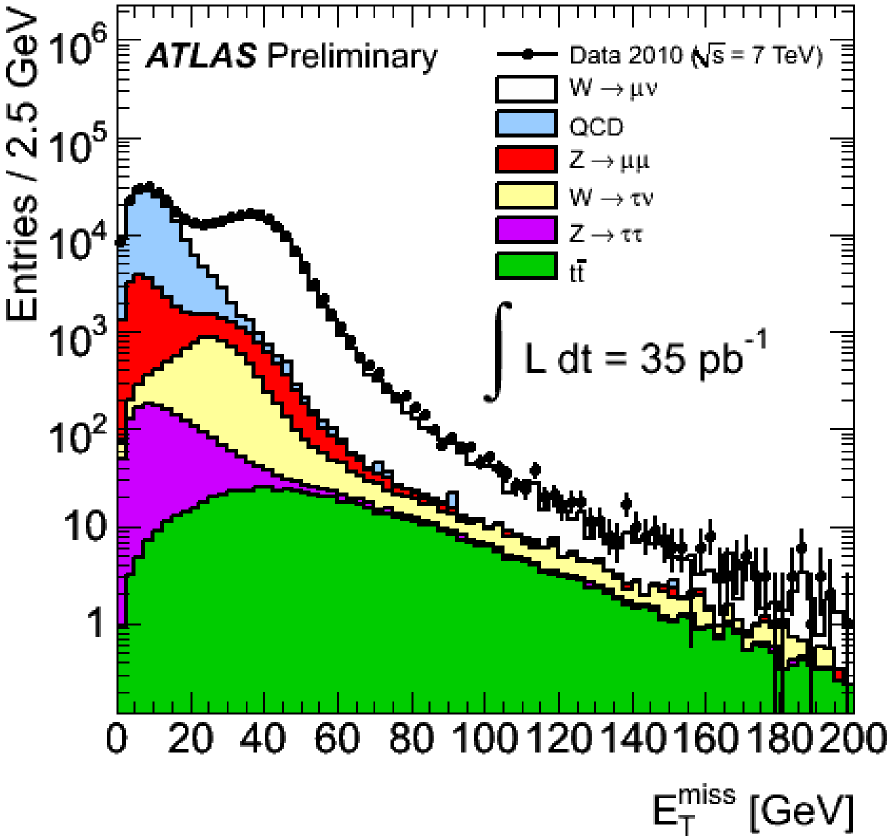
JHEP 10 (2011) 132

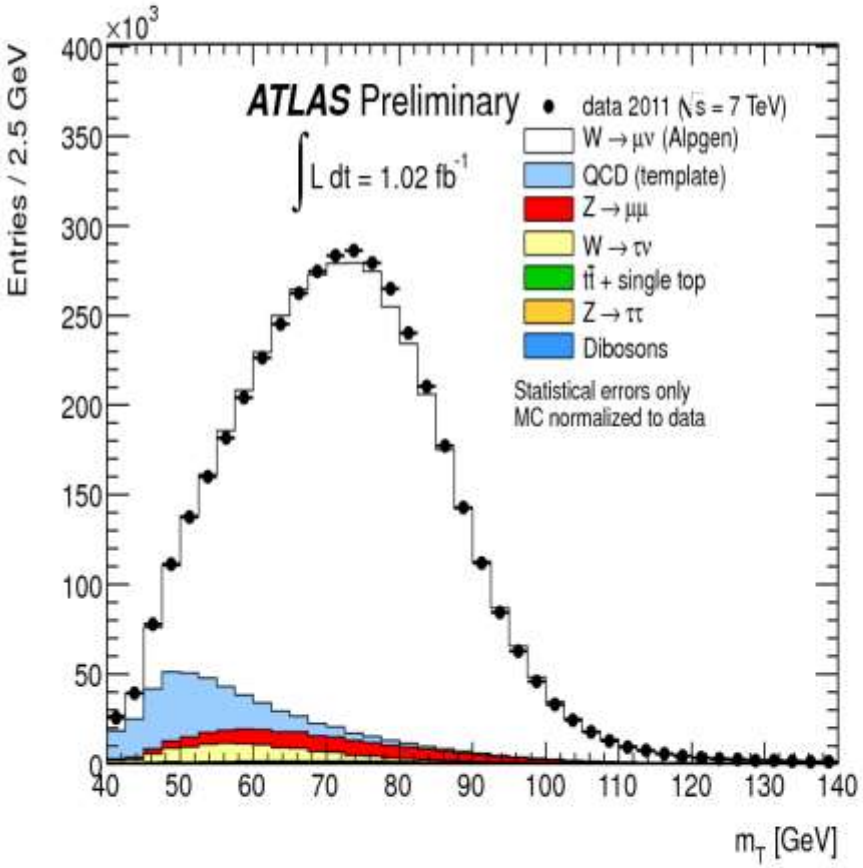
Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)

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

W transverse mass

μ with p_T>20 GeV, E_T^{miss}>25 GeV



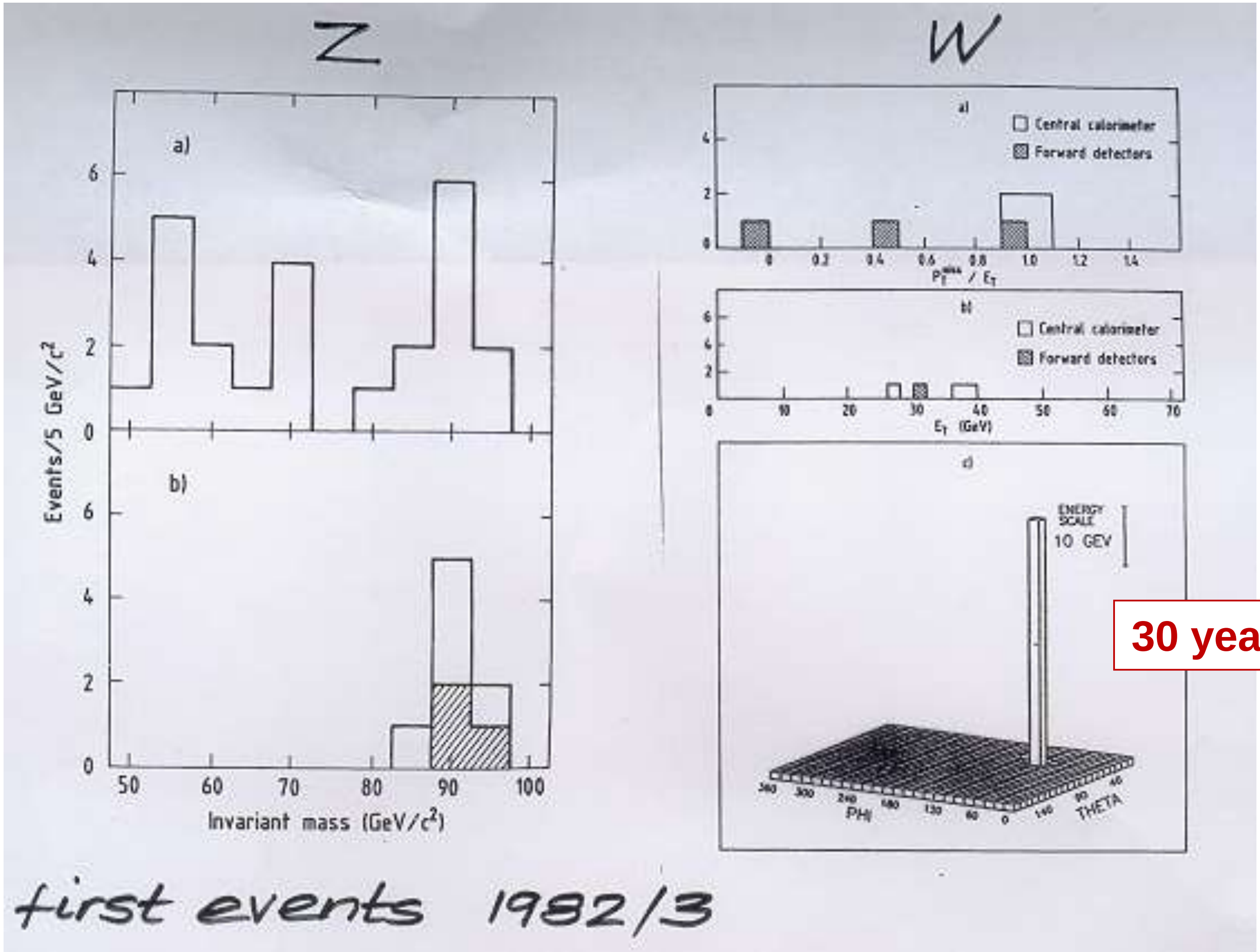


Missing transverse energy from the W → μ + ν decays

ATLAS-CONF-2011-041

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

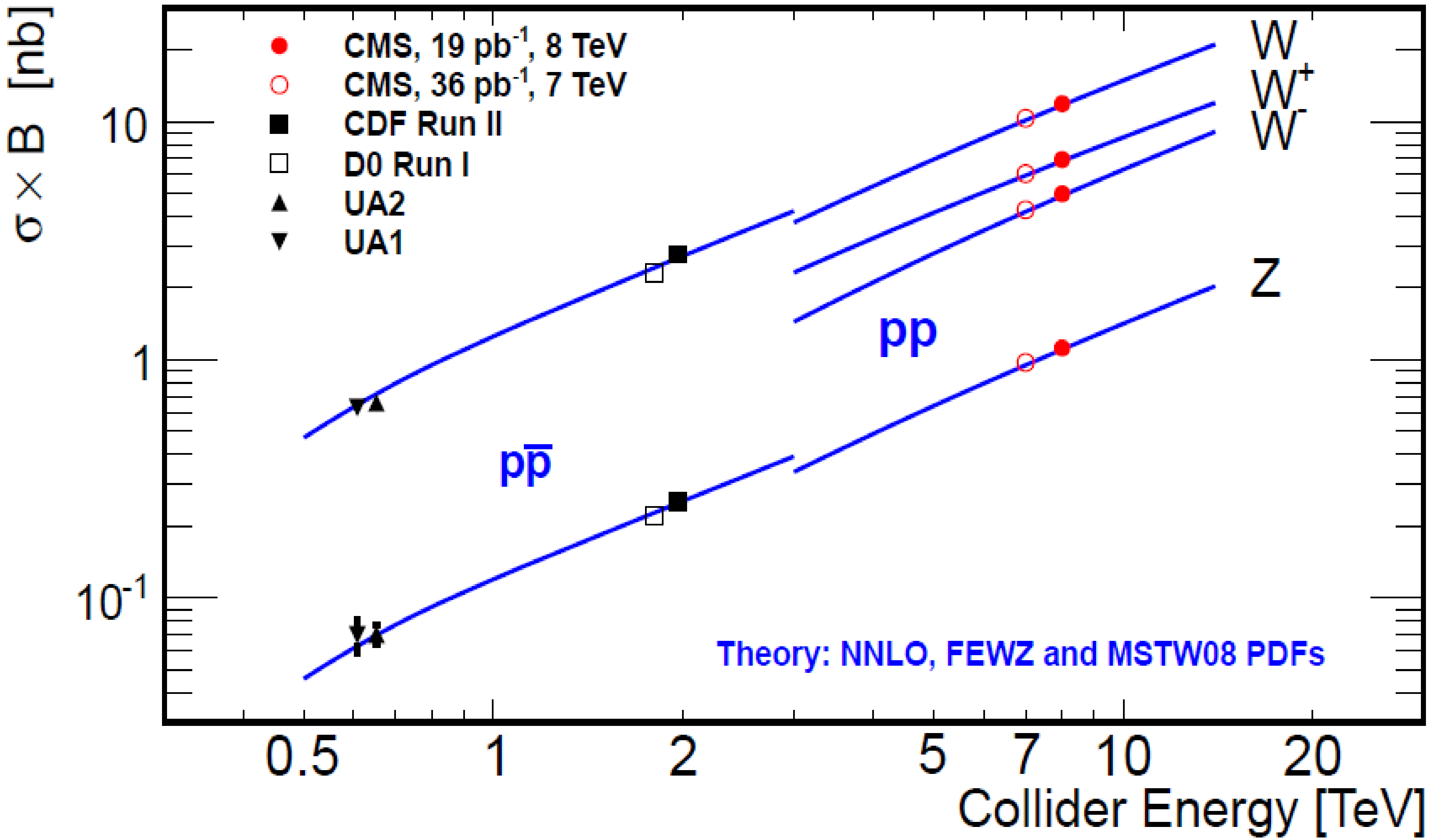
What a contrast to the Intermediate Vector Boson discovery distributions in 1982 and 1983 by UA1 and UA2 …



30 years ago!

(here are shown the UA2 distributions)

Cross section measurements

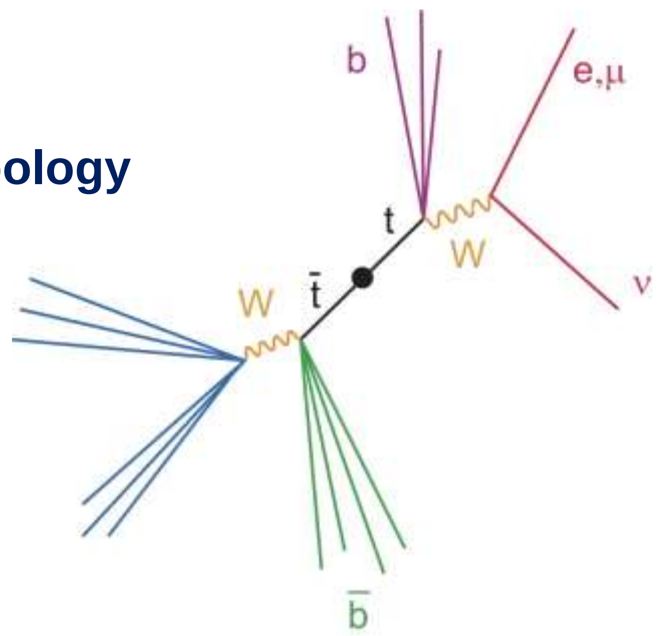


CMS-PAS-SMP-12-011

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, μμ or eμ), E_T^{miss}, bb (6.5%)**

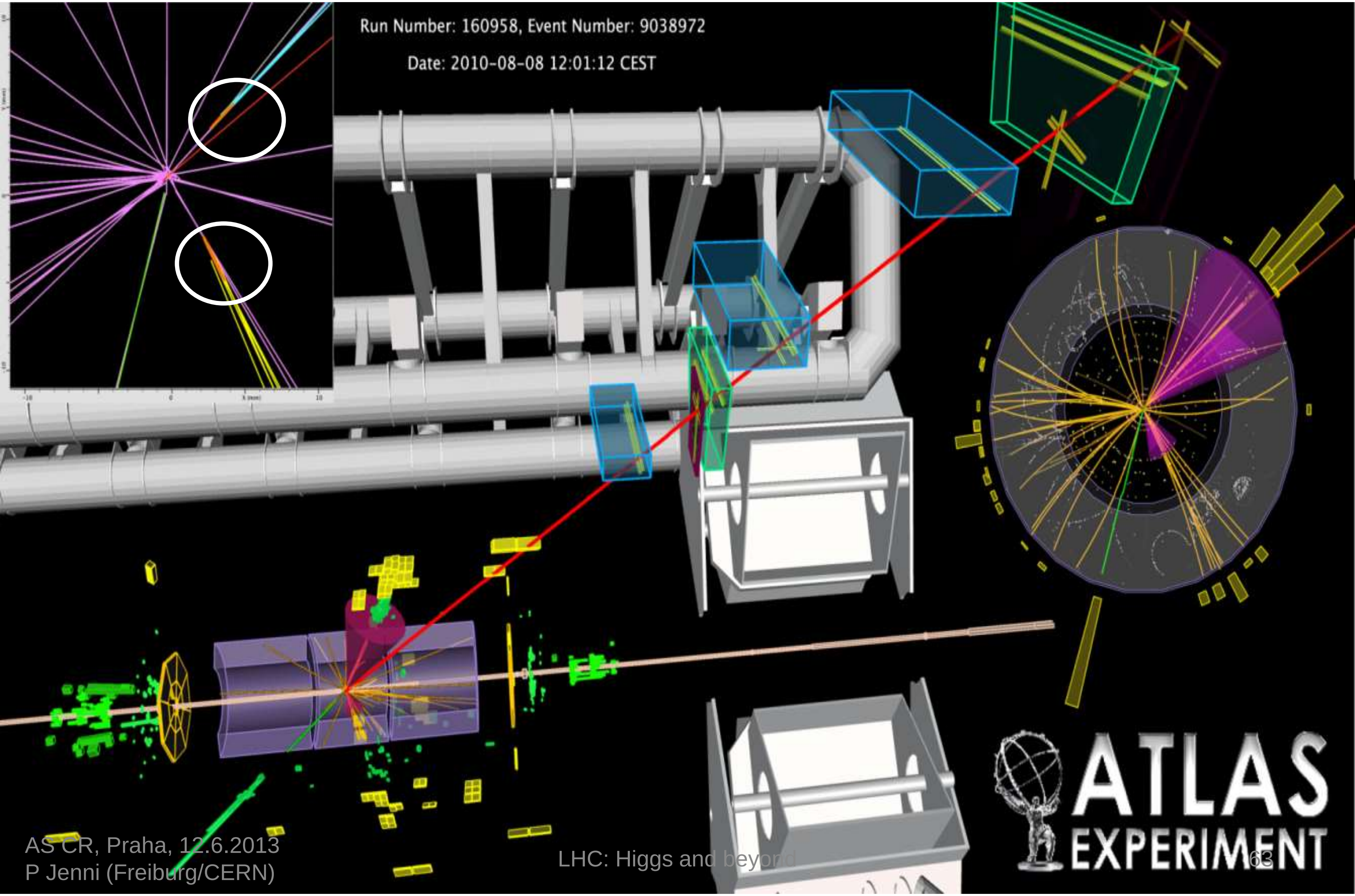


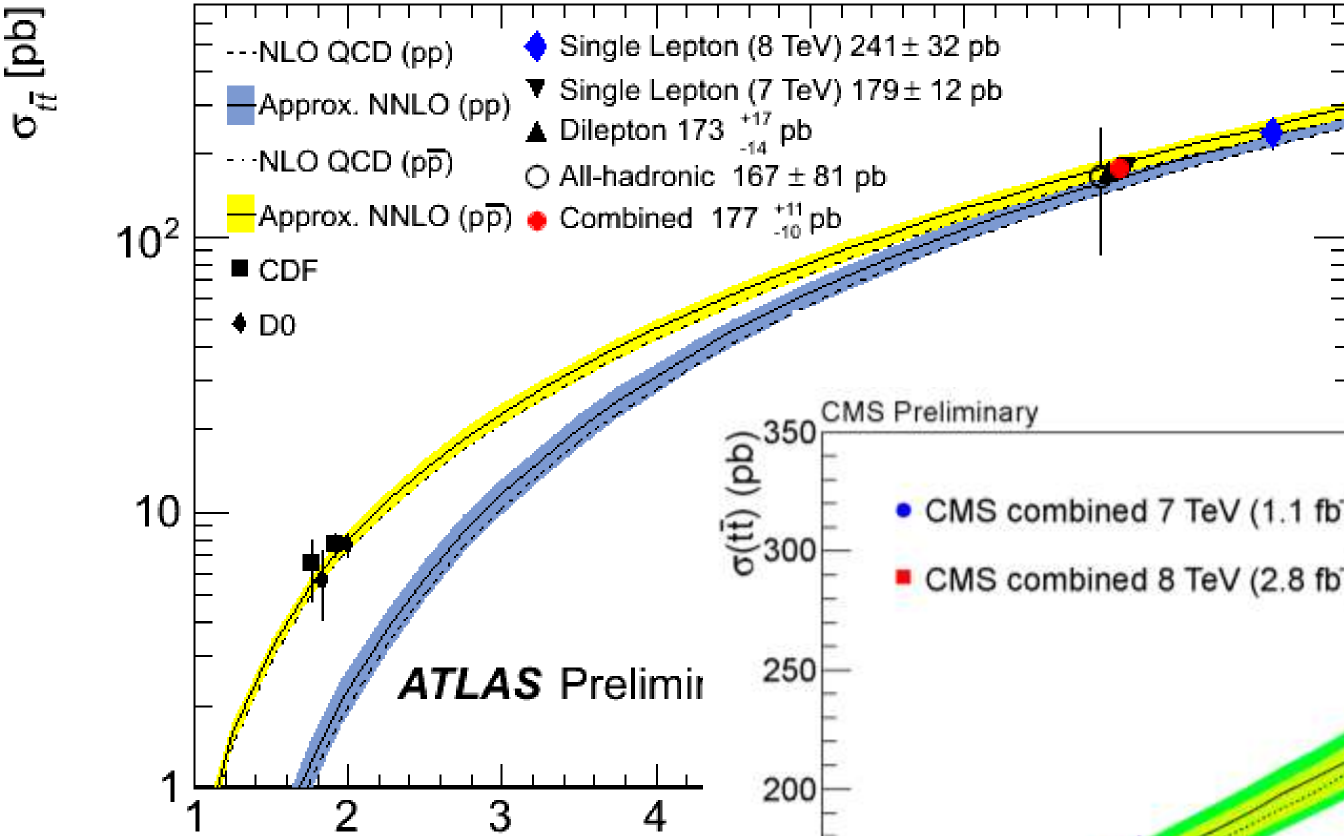
- **Data-driven methods to control QCD and W+jets backgrounds**

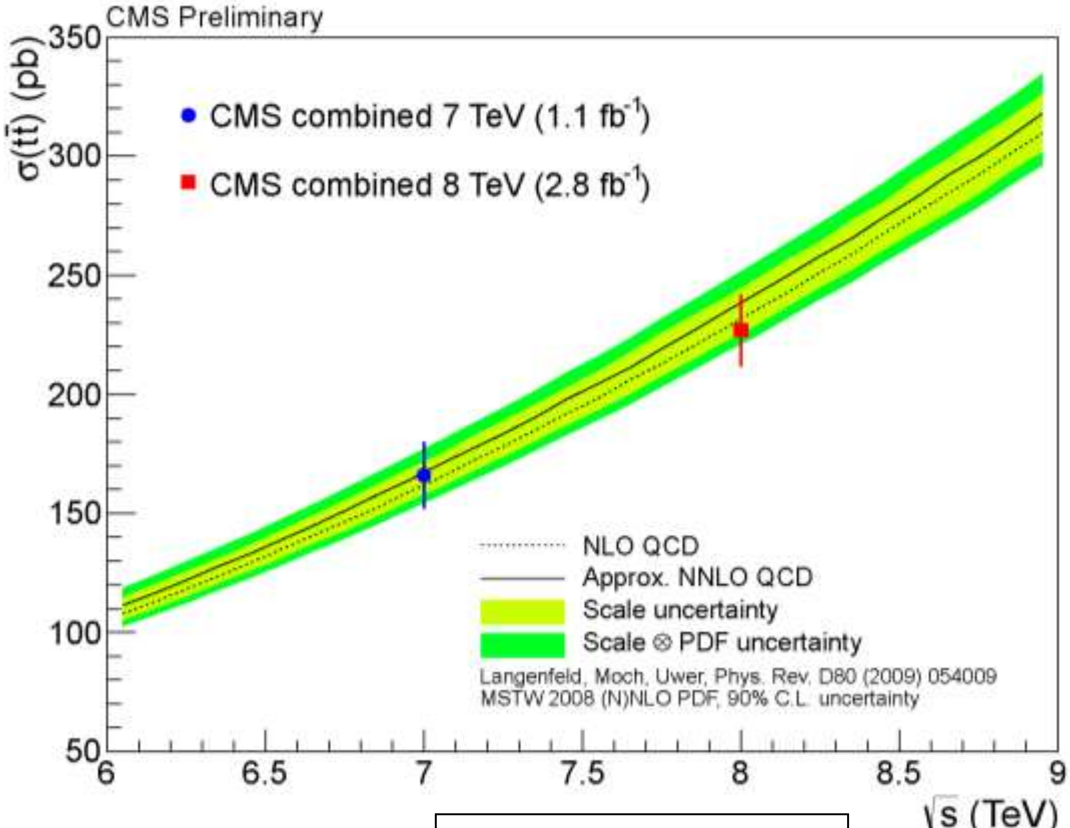
Czech ATLAS colleagues are experts in top physics

$t\bar{t}$ candidate event

e + μ + 2 jets (b-tagged) +ETmiss



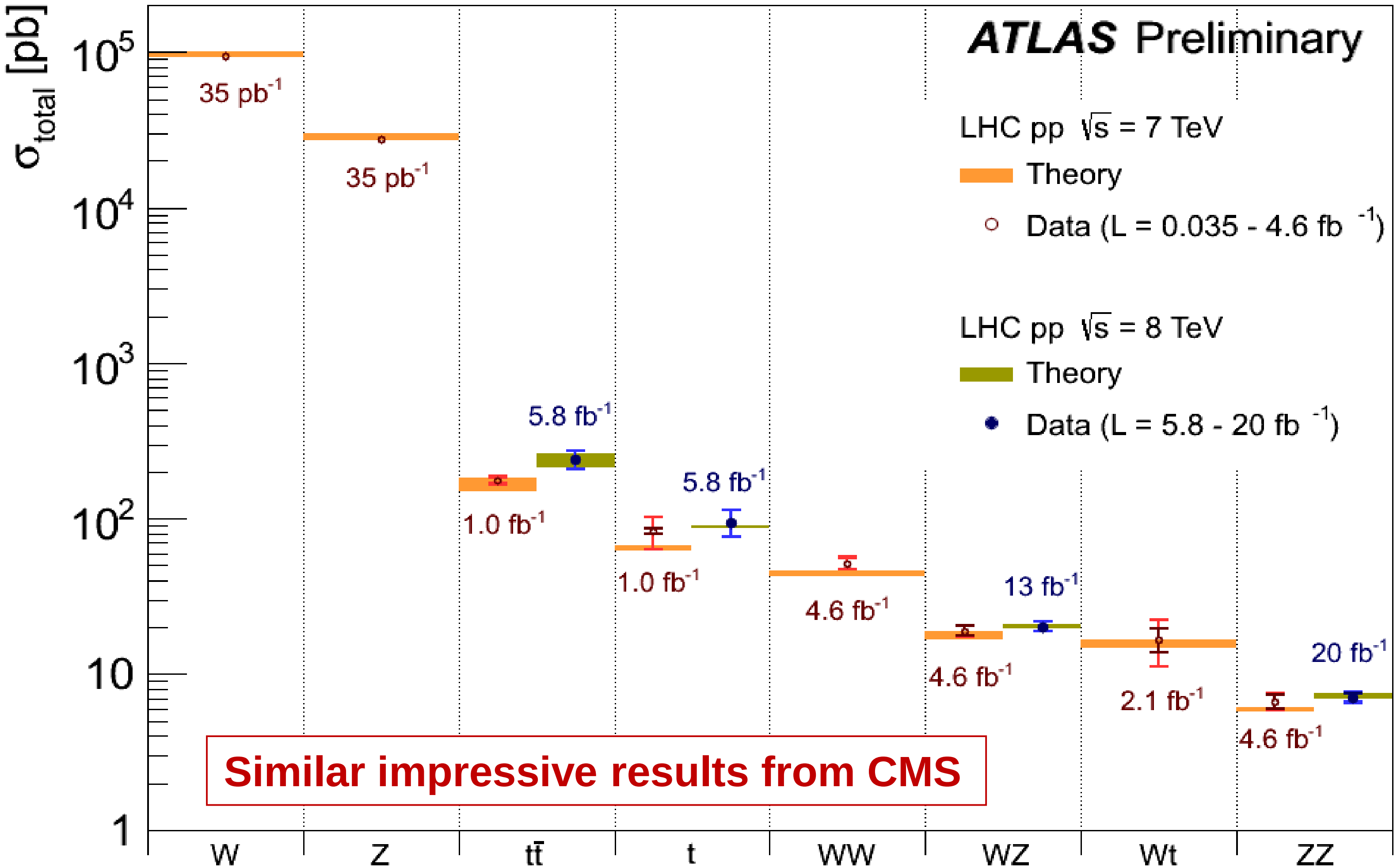




tt pair production cross-sections

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

A summary of Standard Model measurements



Czech ATLAS colleagues contributed strongly to the di-boson analyses

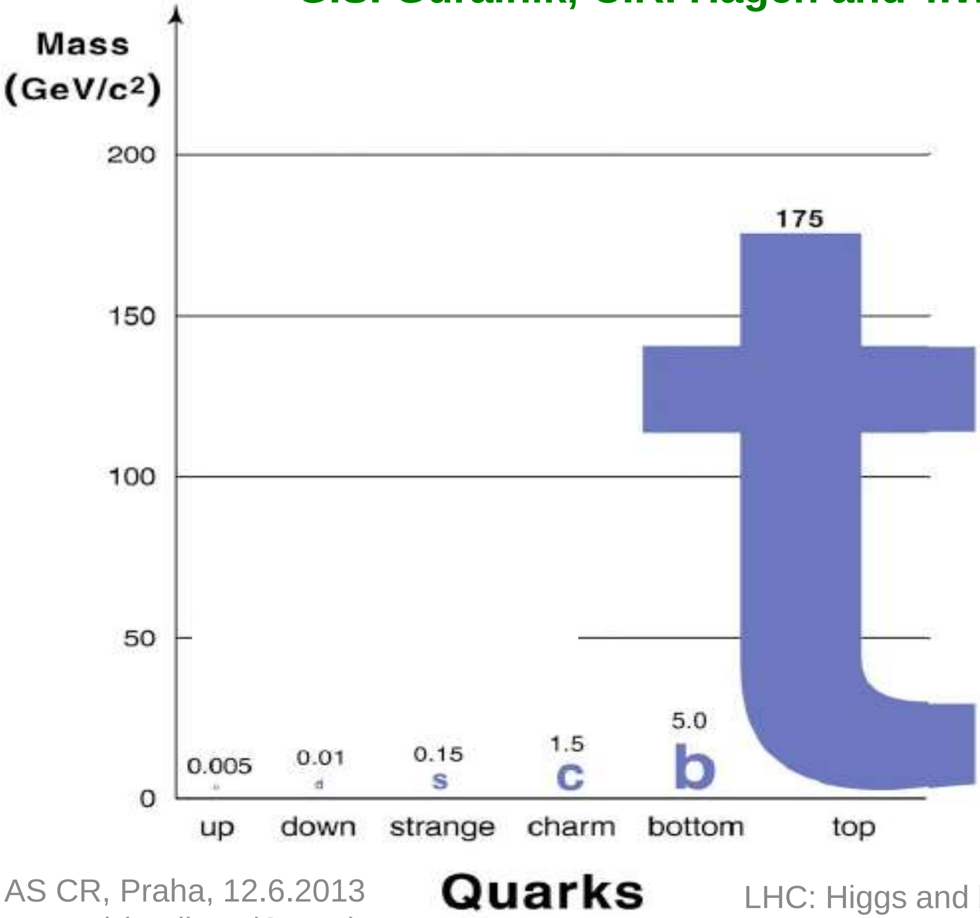
The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics


HIGGS BOSON

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

**The mass mystery 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



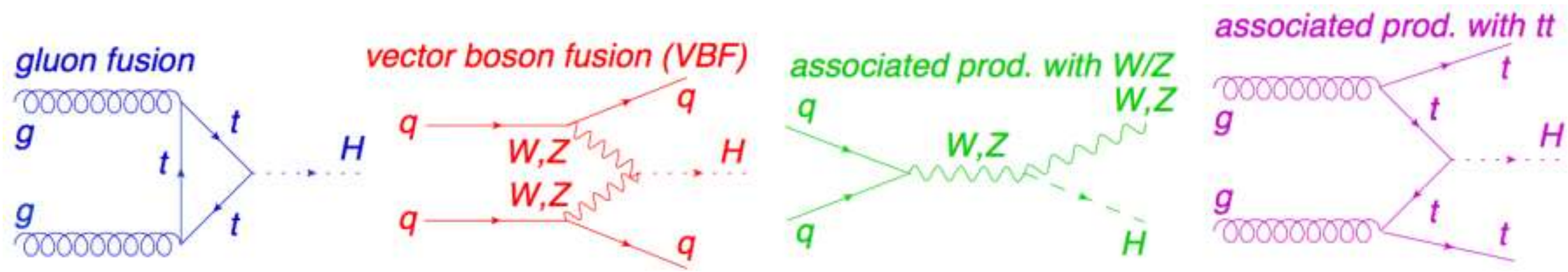
The Higgs (H) particle has been searched for since decades at accelerators …

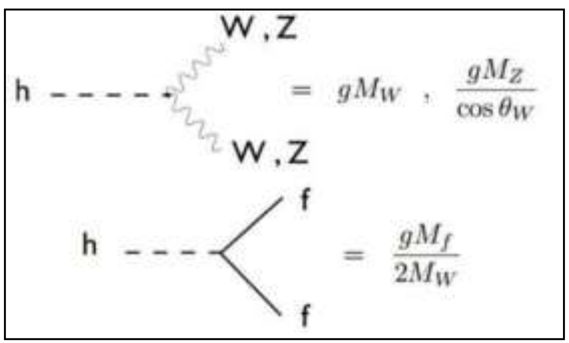
The LHC has sufficient energy to produce it for sure, if it exists

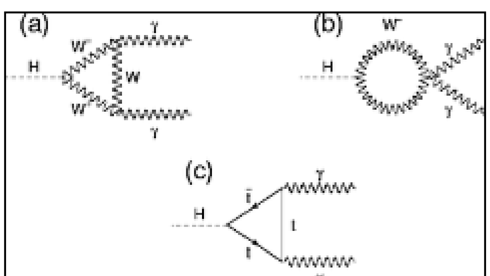
Francois Englert

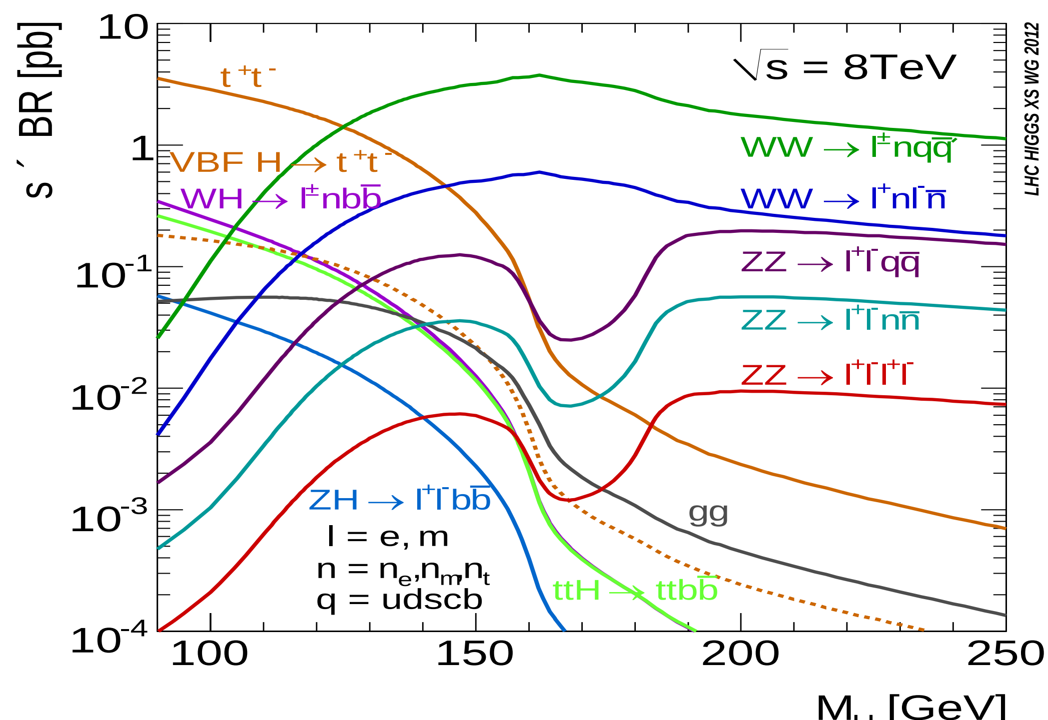
Search for the boson (H) of the EW symmetry breaking

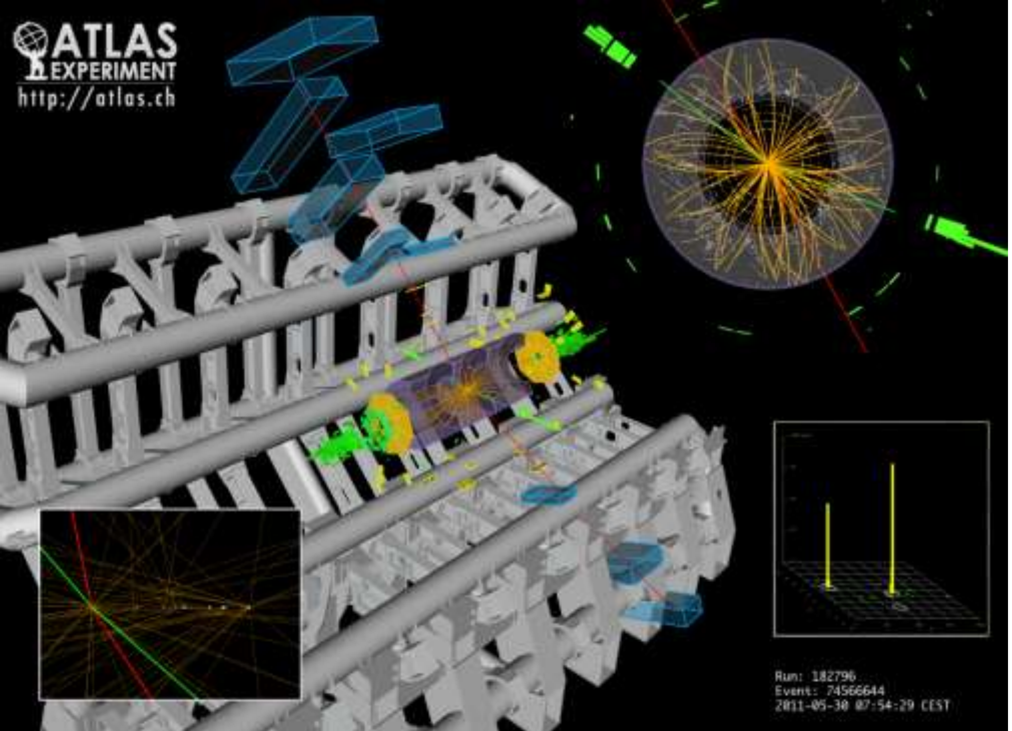
SM H boson production cross sections times observable decay branching ratios at 8 TeV







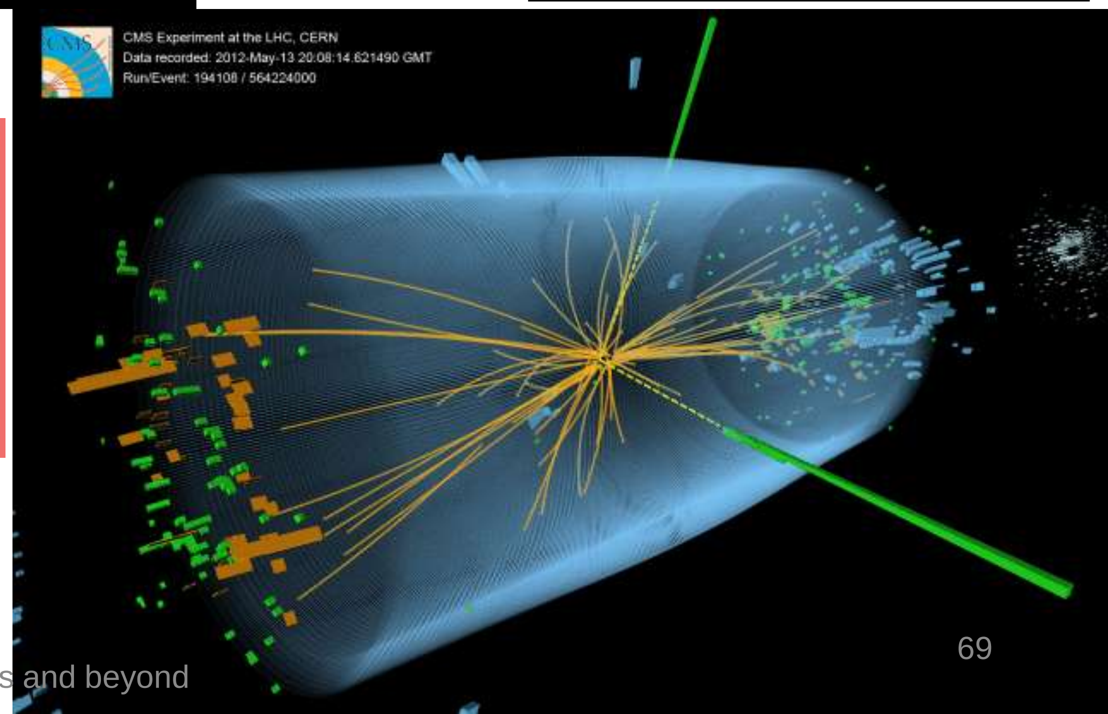




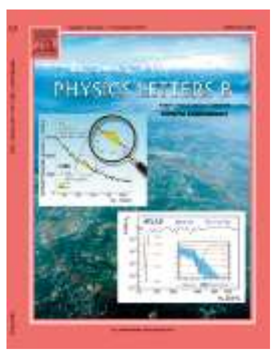
The Higgs(-~~like~~) boson

Candidate event for H → ZZ* → ee μμ

Candidate event for H → γγ



ATLAS and CMS have announced the discovery of a new boson together on 4th July 2012, published in a special issue of Physics Letter B

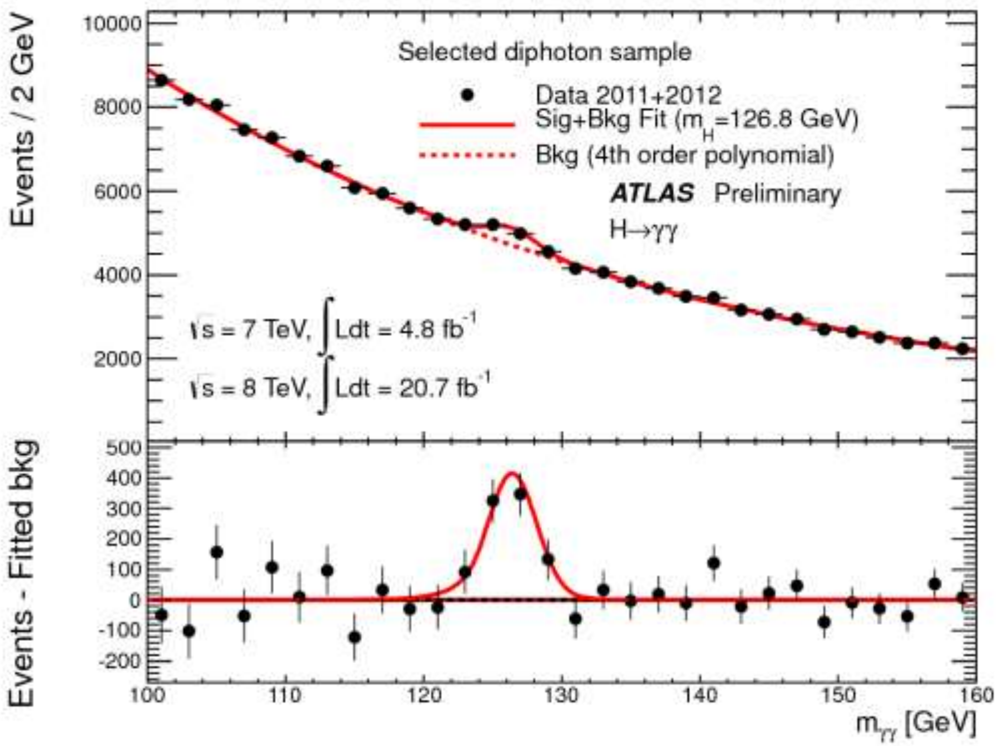


Phys. Lett. B 716 (2012) 1

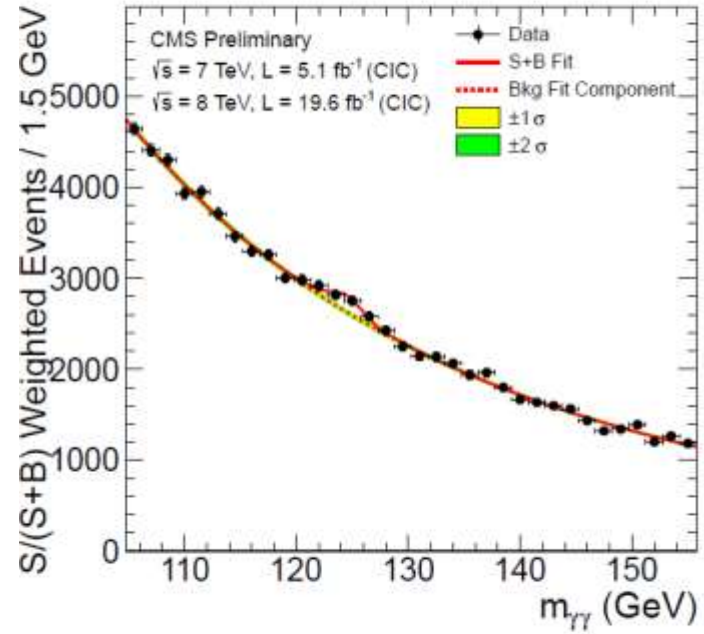
Phys. Lett. B 716 (2012) 30

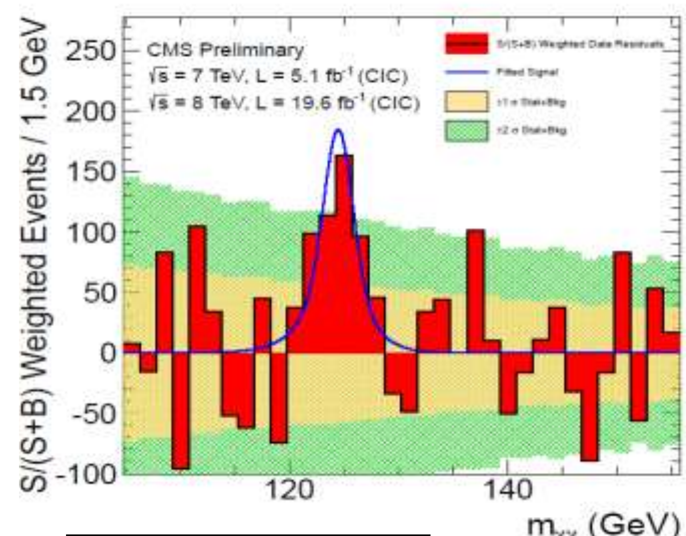
$H \rightarrow \gamma\gamma$

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



ATLAS-CONF-2013-012

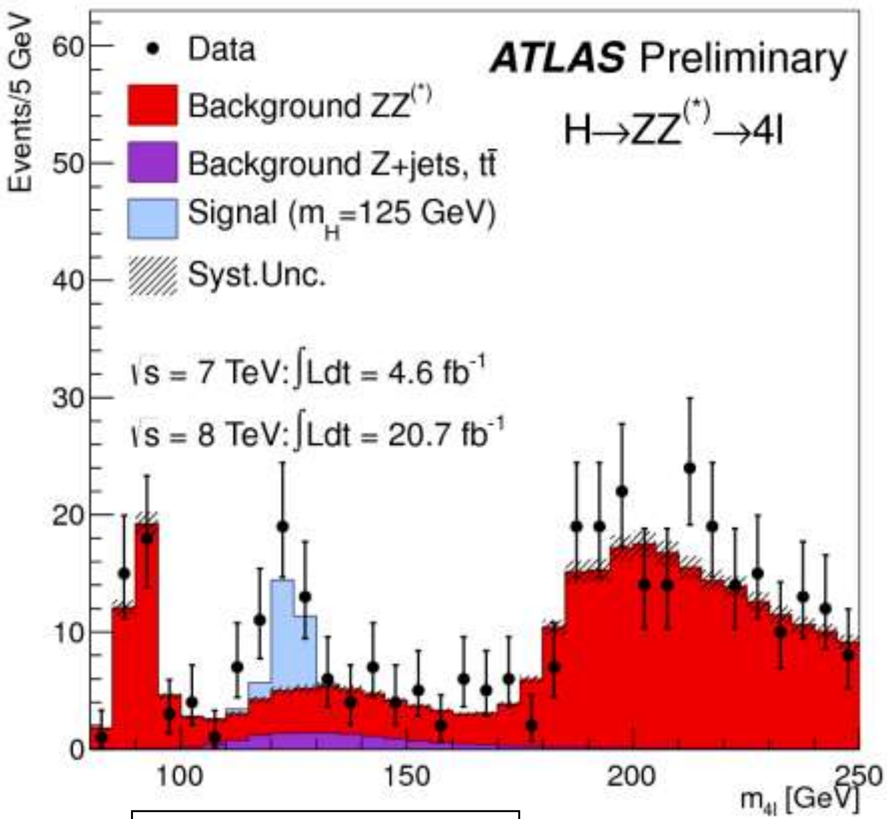




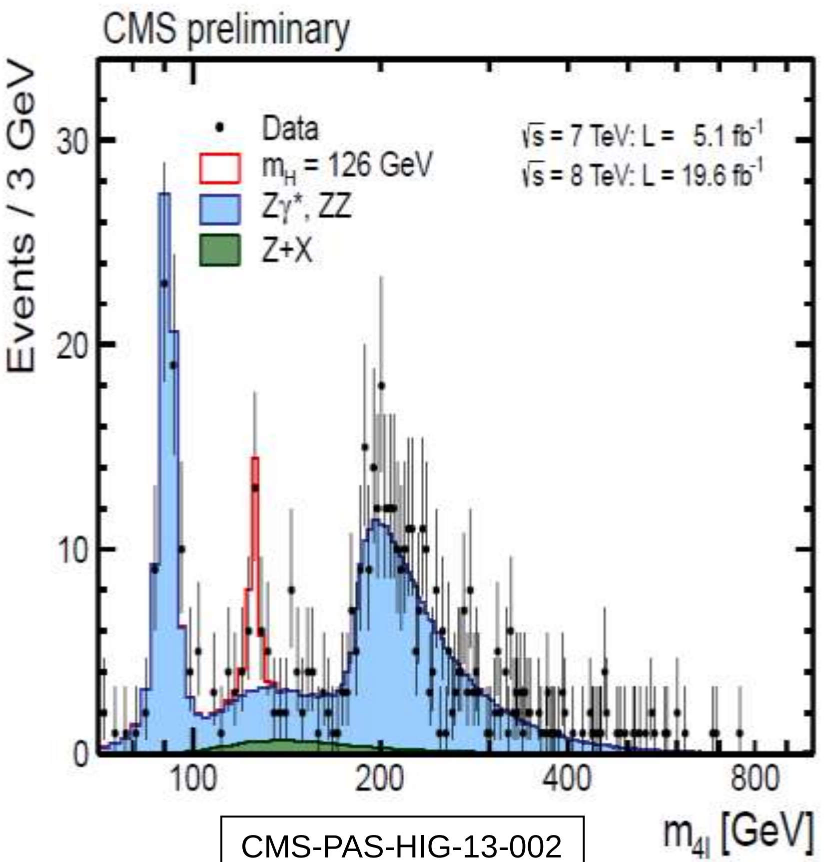
CMS-PAS-HIG-13-001

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (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

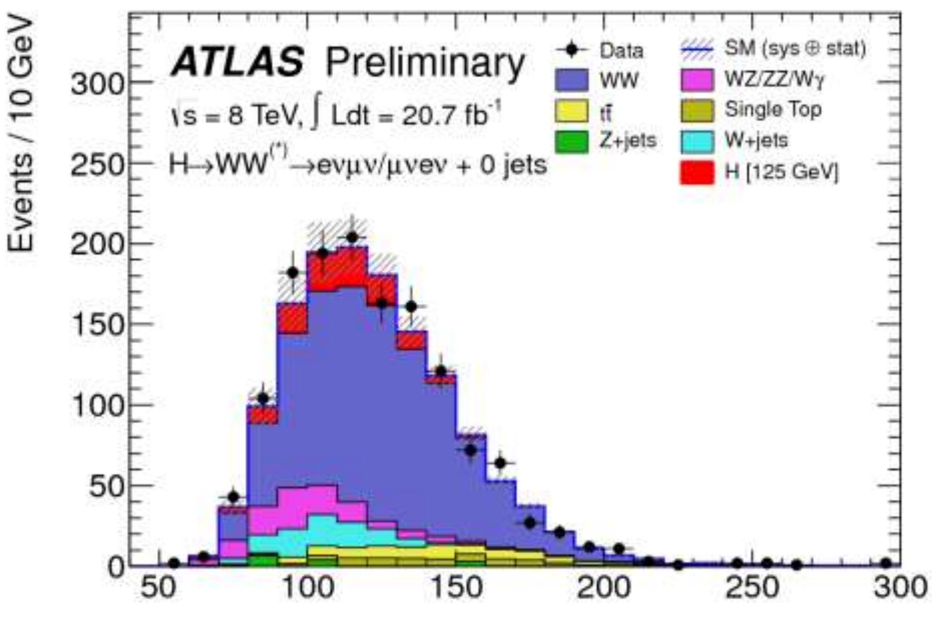


CMS-PAS-HIG-13-002

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

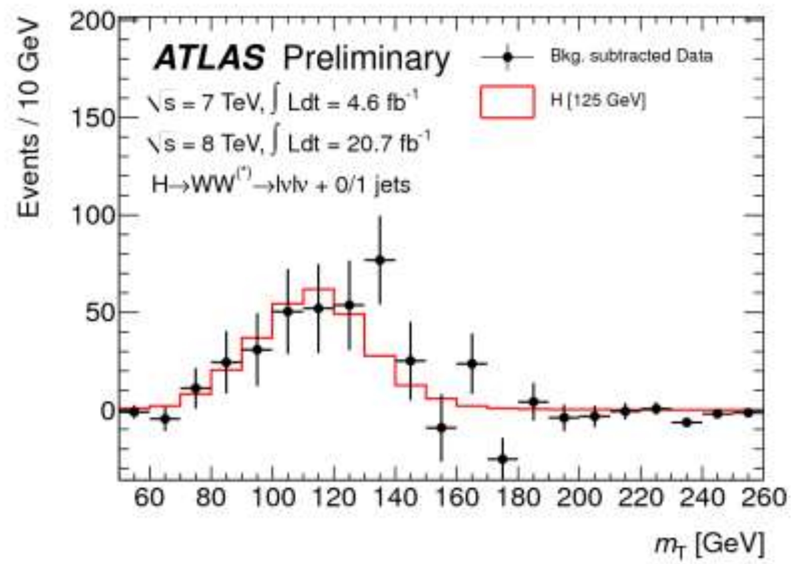
- Very sensitive channel over ~ 125-180 GeV (σ ~ 200 fb)
- Challenging: 2ν → no mass reconstruction/peak → "counting channel"
- 2 isolated opposite-sign leptons, use eνμν only for 2012 data, large E_T^{miss}
- Main backgrounds: WW, top, Z+jets, W+jets
- Topological cuts against "irreducible" WW background

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



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

To get a feeling for the number of events, this is for all categories the summed, background-subtracted distributions



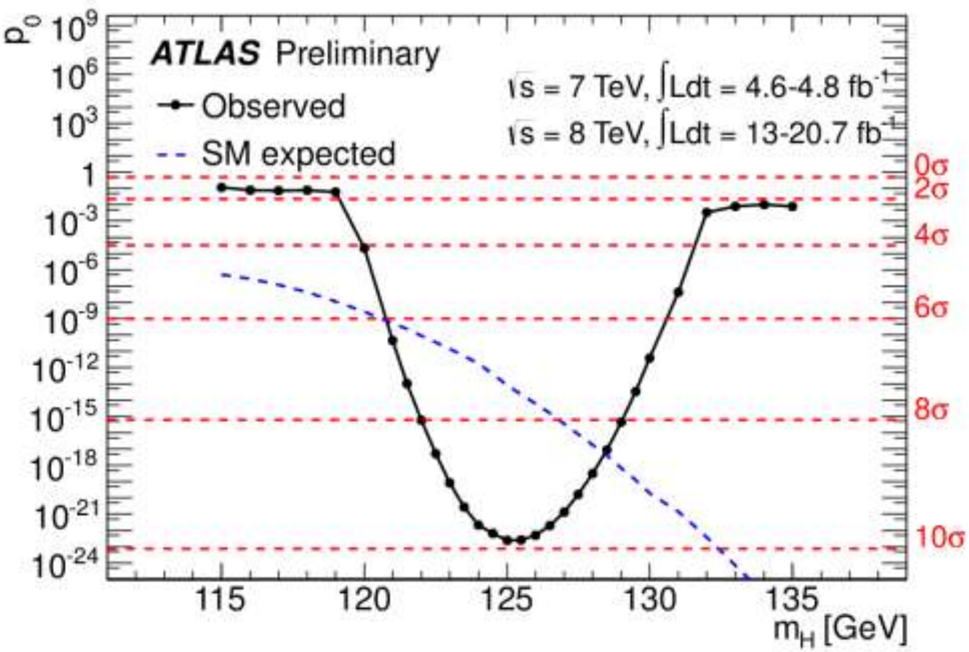
ATLAS-CONF-2013-030

How significant is the signal for the new particle ?

Mass = 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV [ATLAS]
125.8 ± 0.4 (stat) ± 0.4 (syst) GeV [CMS]

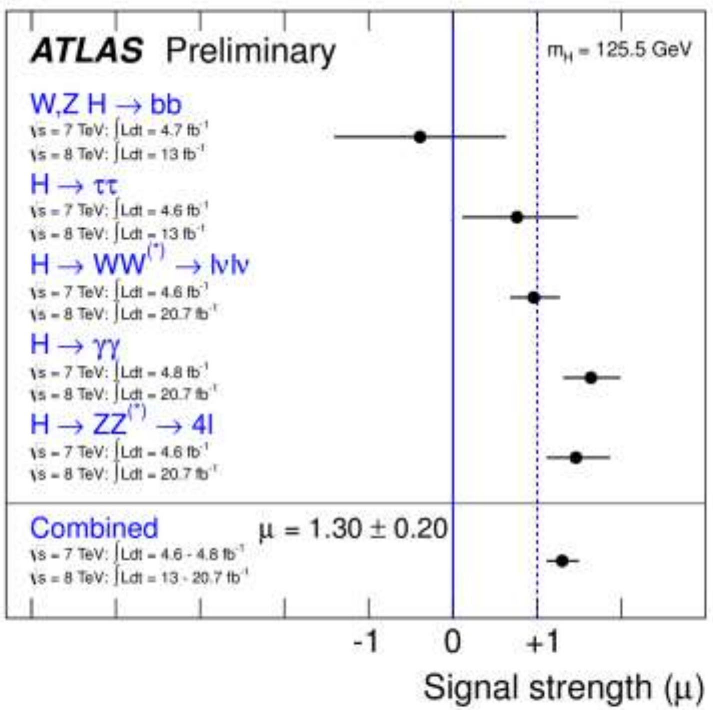
Observed data compared to the probability that the background fluctuates to fake the observed excess of events, and what is expected from a SM Higgs

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



ATLAS-CONF-2013-034

CMS: Moriond QCD presentation



$\mu = 1.30 \pm 0.20$ [ATLAS]
$\mu = 0.88 \pm 0.21$ [CMS]

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

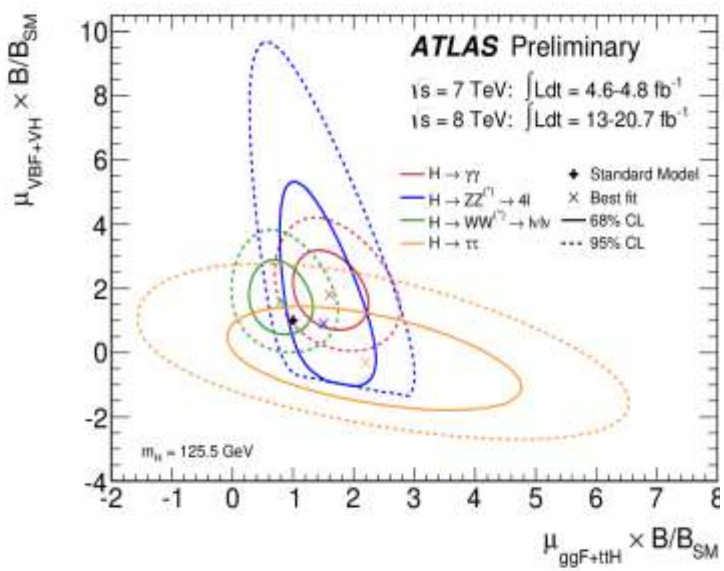
It will be important to understand with great precision if it is the only scalar boson of the Standard Model 'Brout-Englert-Higgs' mechanism to break the electroweak symmetry, or if it is only part of a broader physics picture going *Beyond the Standard Model*

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

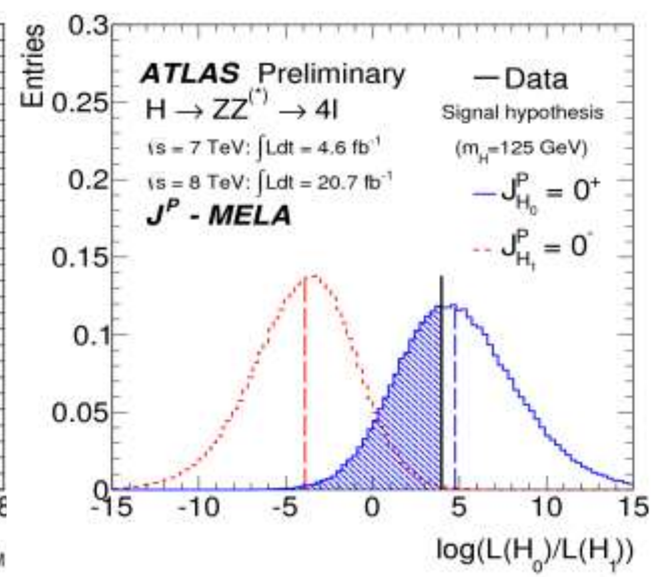
For the experts:

Couplings
Production modes
Spin-parity

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

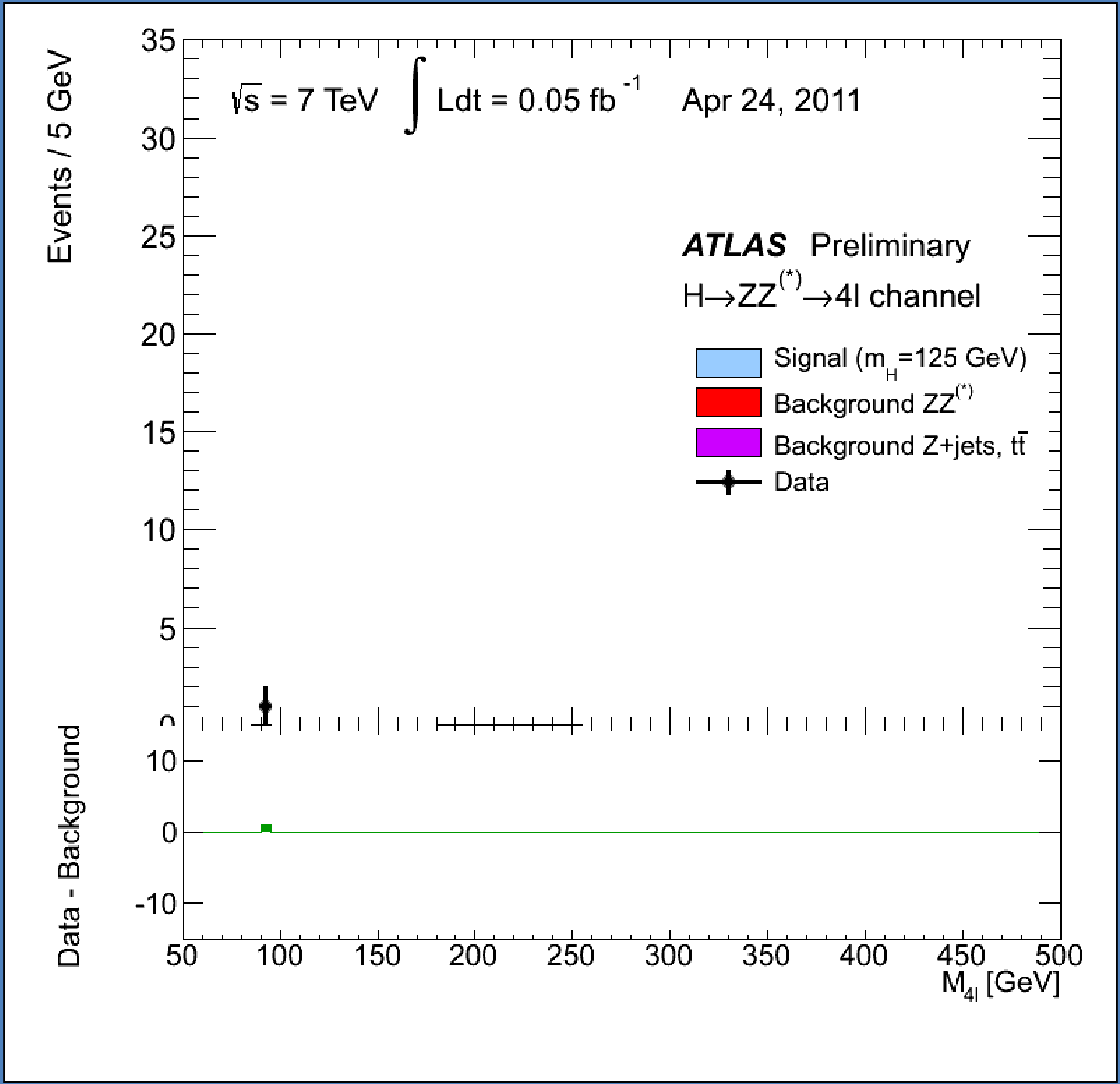


ATLAS-CONF-2013-034

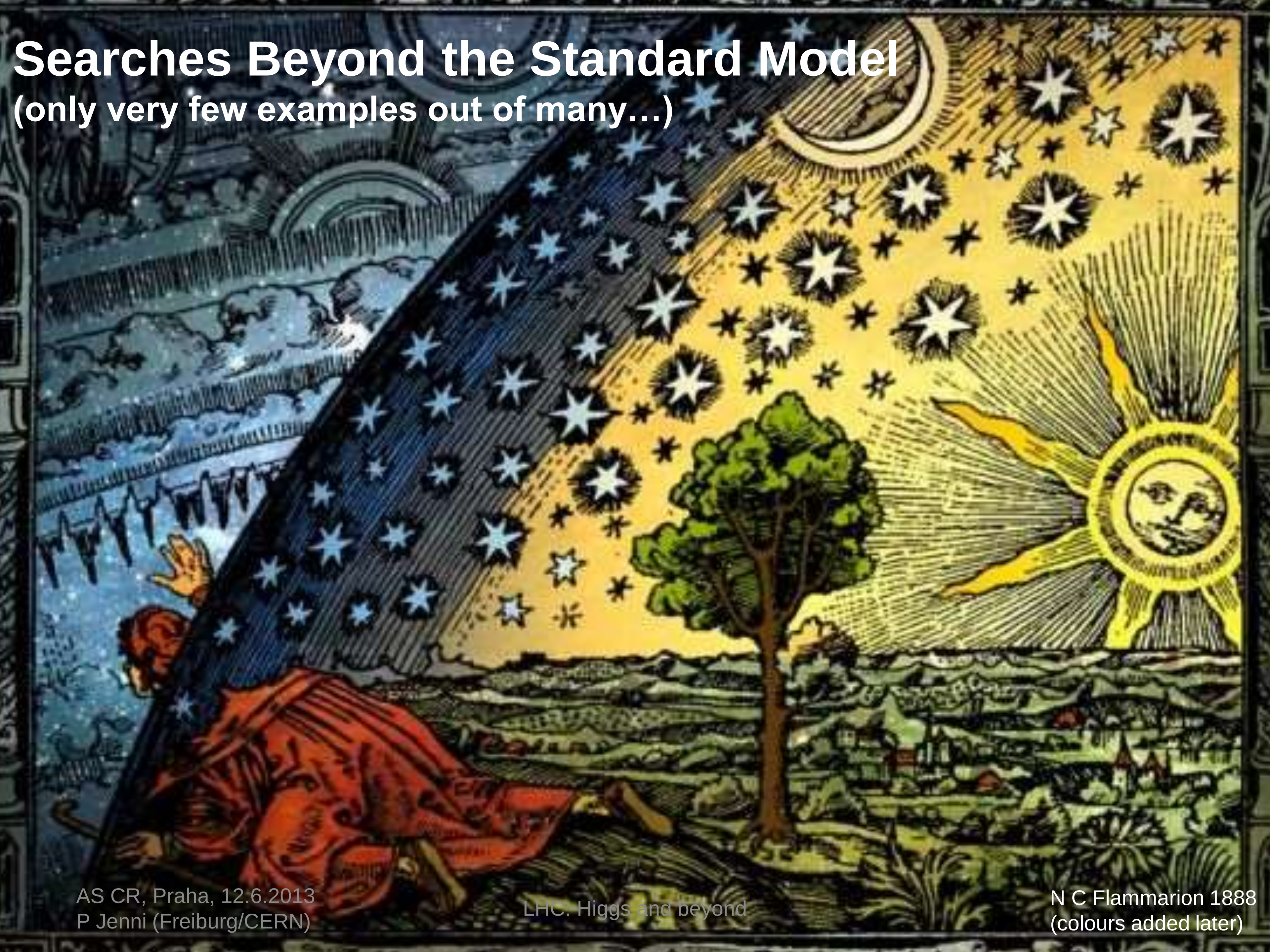


ATLAS-CONF-2013-013

Birth and evolution of a signal: H→ 4l



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



N C Flammarion 1888
(colours added later)

Supersymmetry (SUSY)

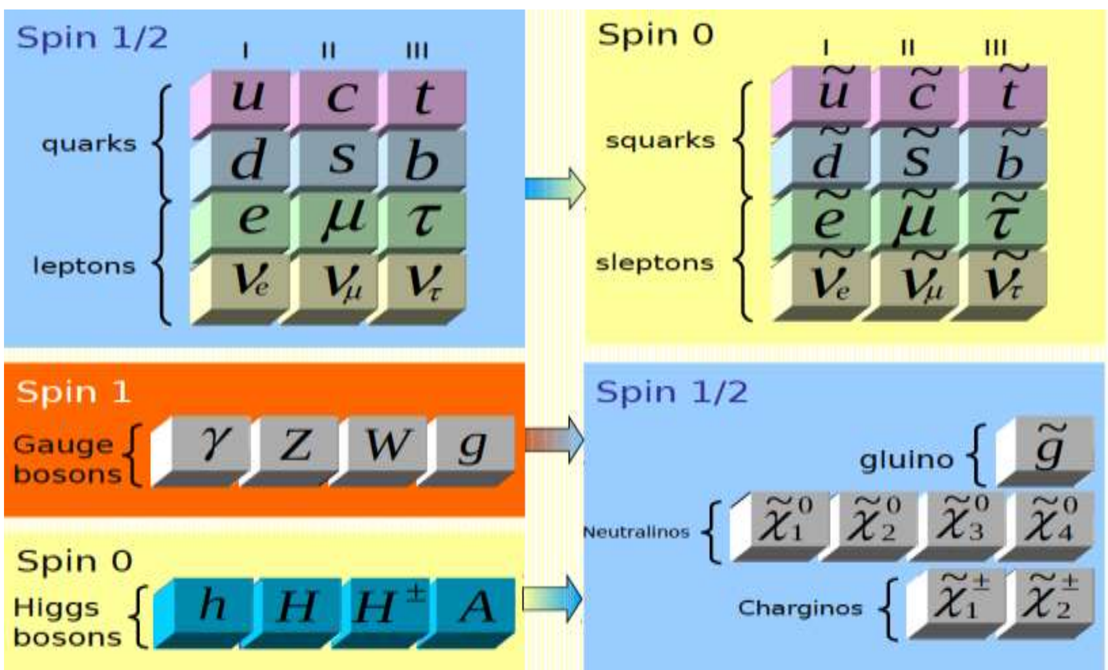
(Julius Wess and Bruno Zumino, 1974)

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

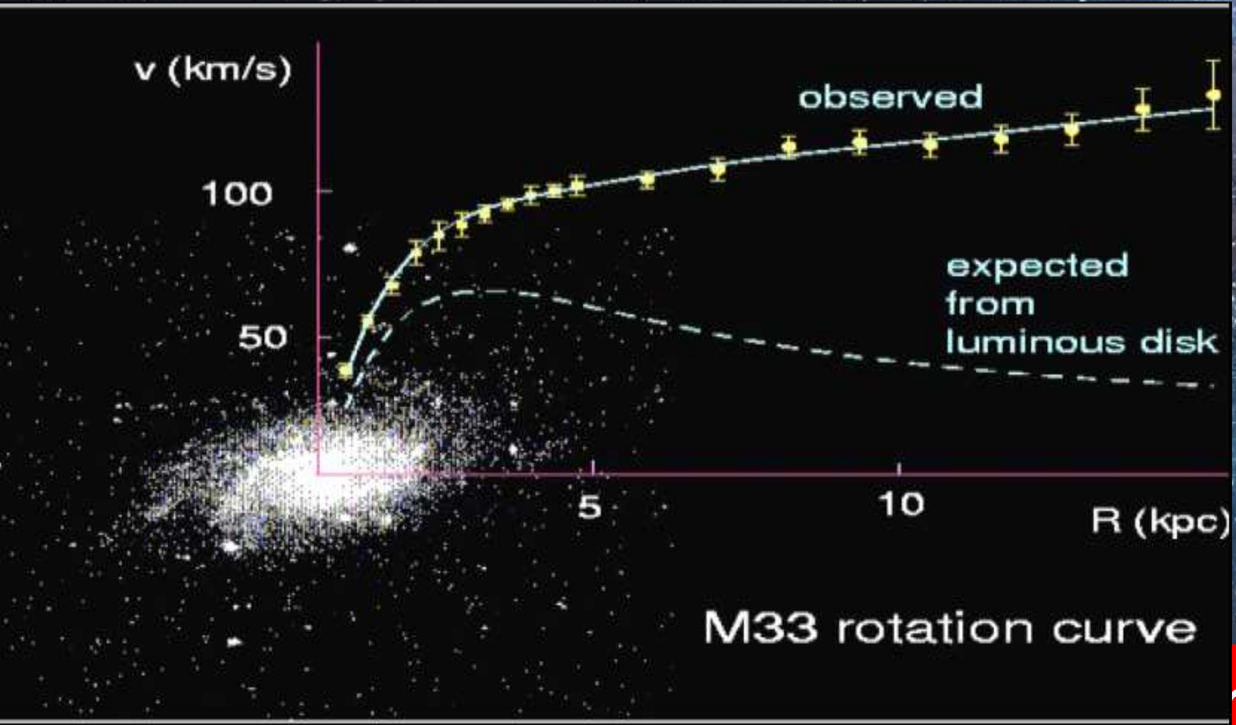
Our known world… **Maybe a new world?**



Motivation:

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

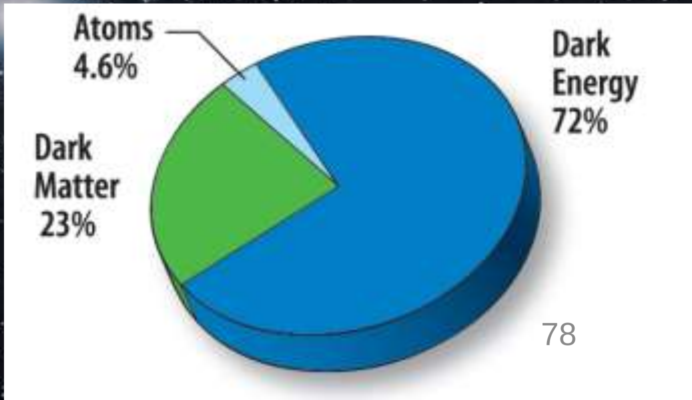
Dark Matter in the Universe



Vera Rubin ~ 1970

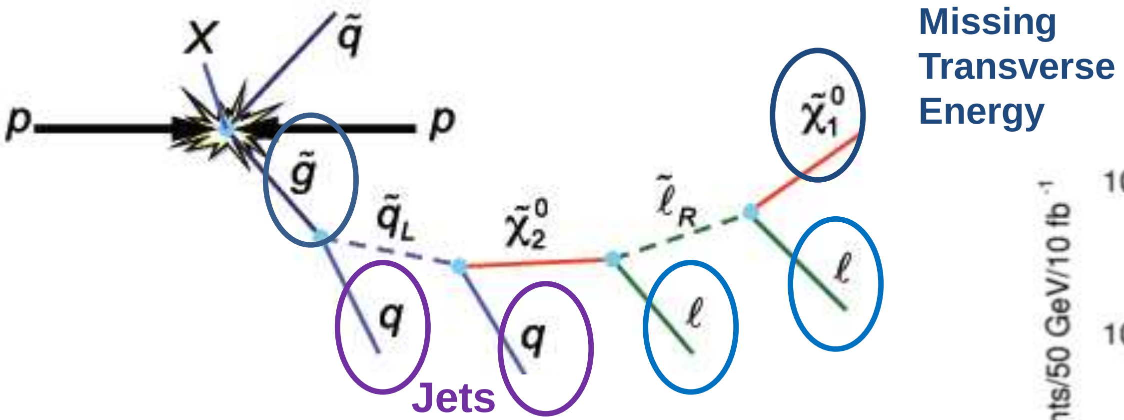
metric’ particles ?

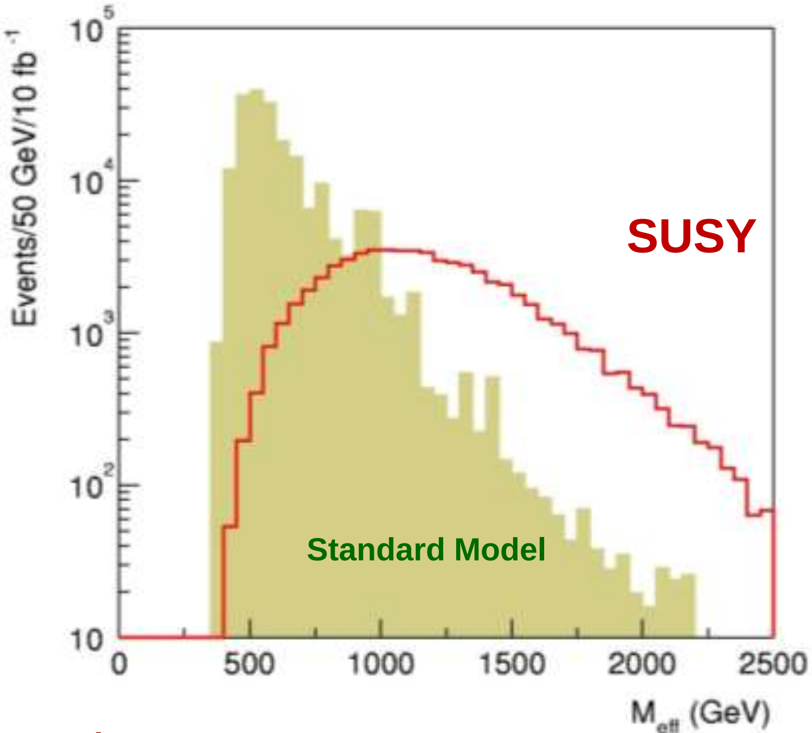
F. Zwicky 1898-1974



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**

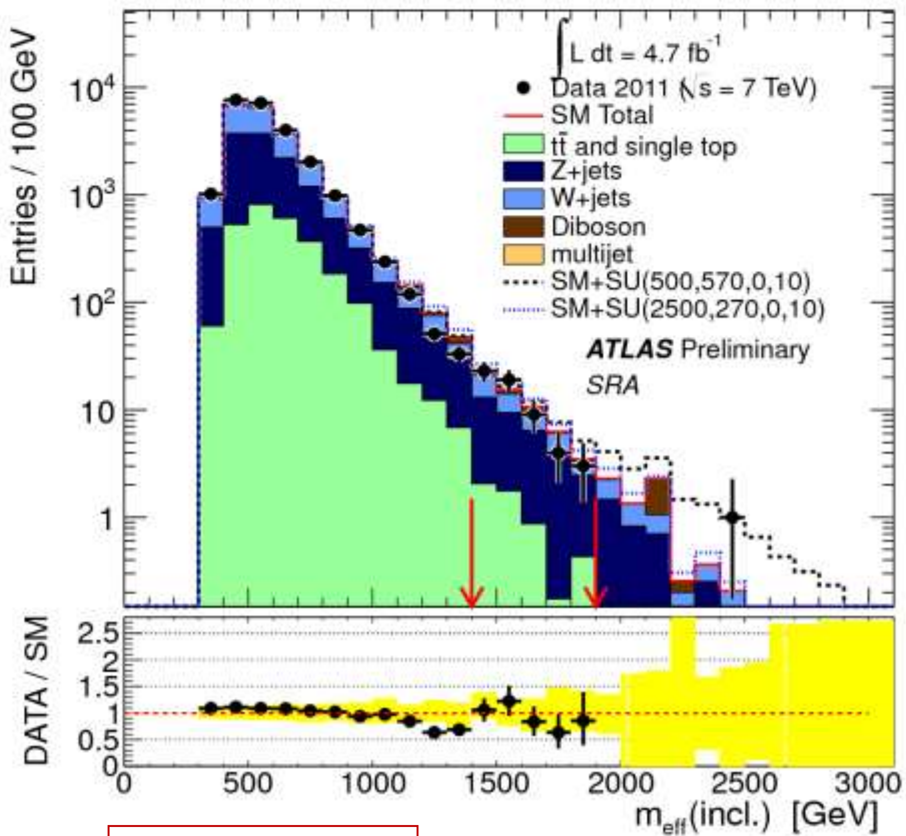
Meff = Etmiss + Σ pT(jets)

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

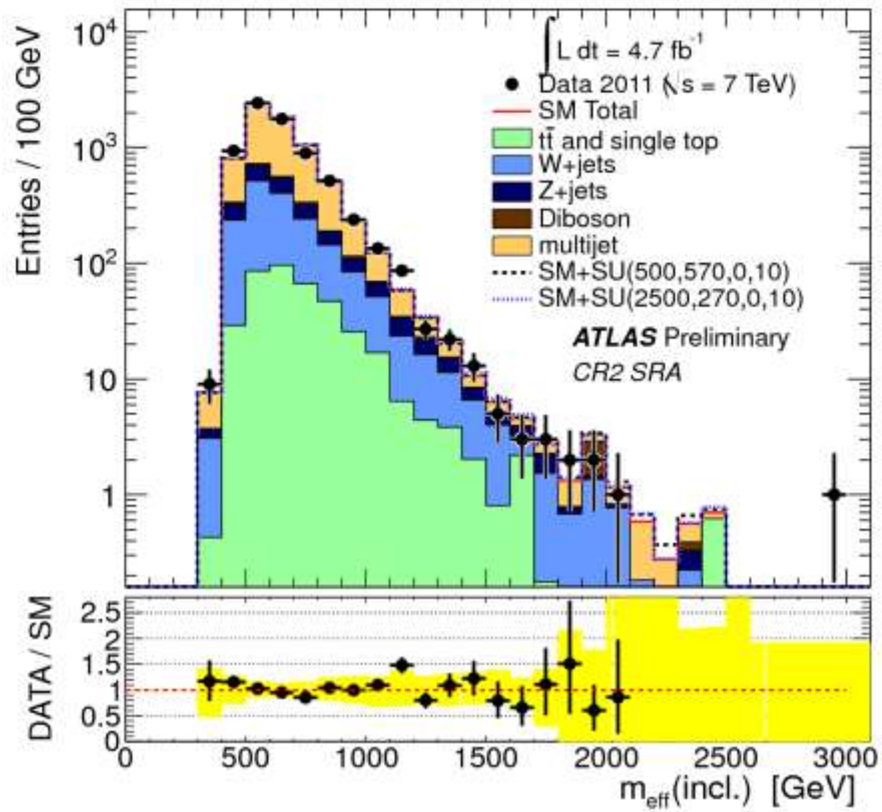
- **0-lepton + 2−6 jets + high MET (based on Et-miss+jet triggers)**
- **0-lepton + 6−9 (multi-)jets + MET (based on multi-jet triggers)**
- **1-lepton + 3,4 jets + high MET (based on lepton triggers)**

Example: O-leptons + 2-6 Jets analysis

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



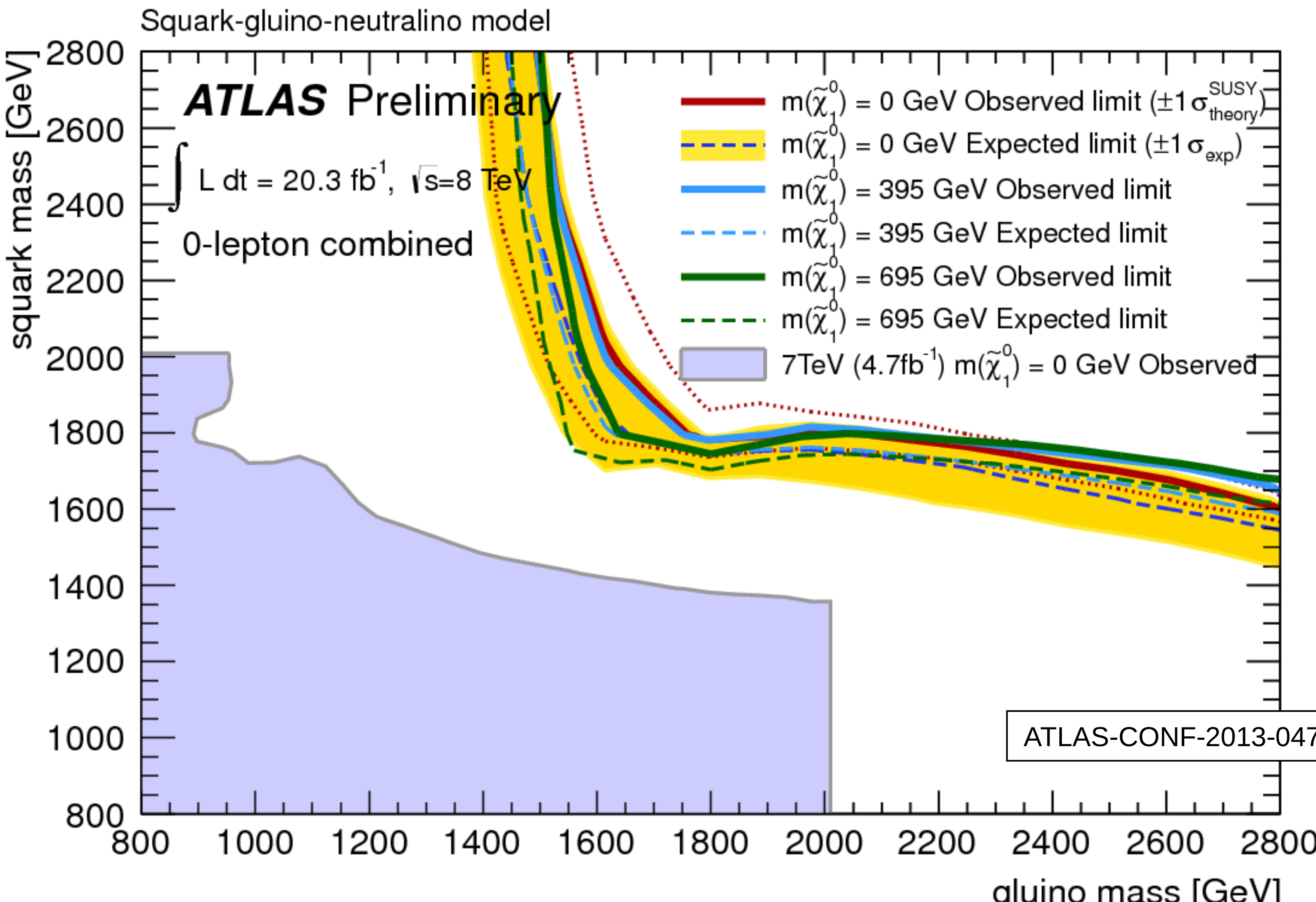
A signal region



A control region where no signal is expected

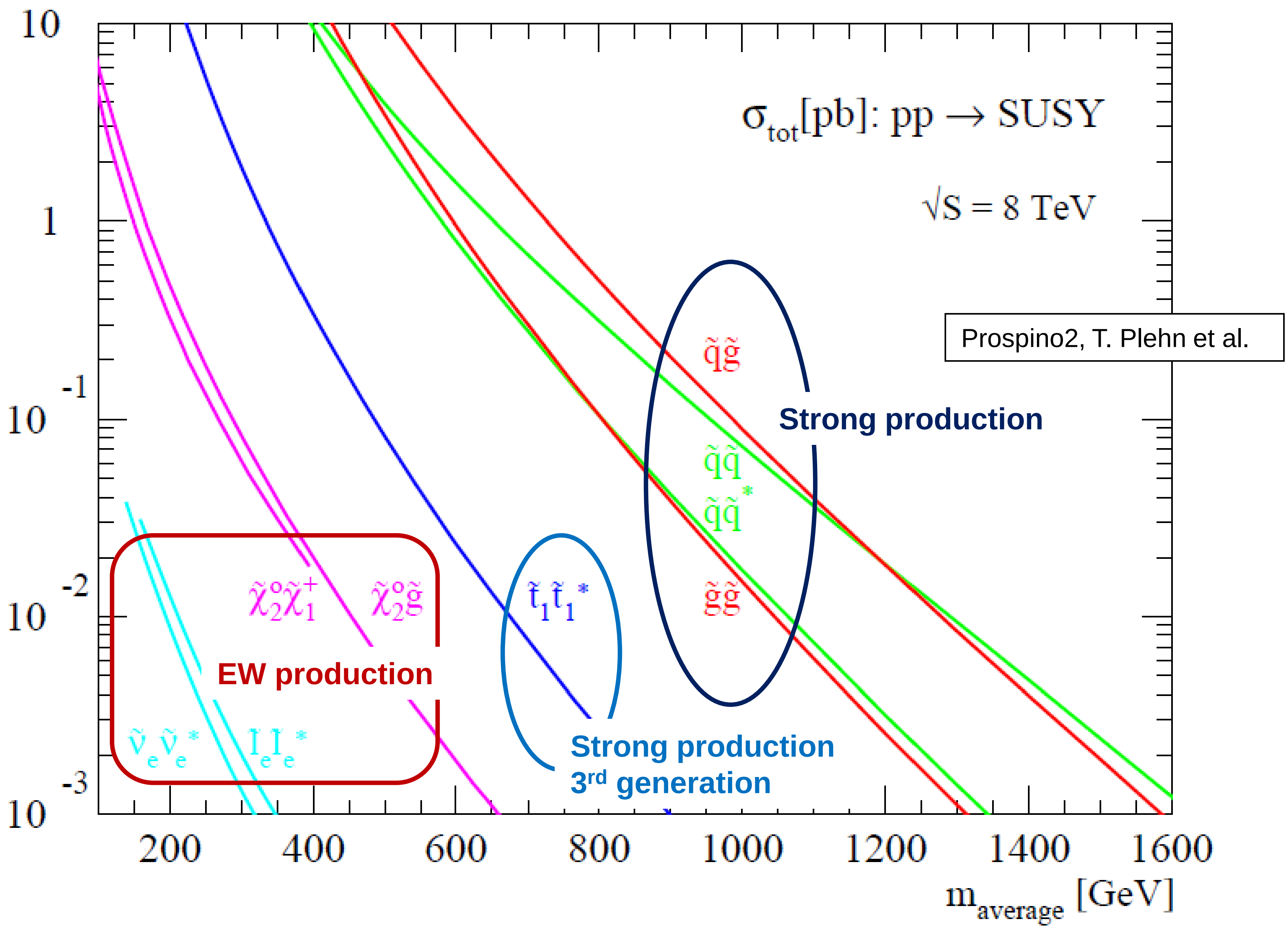
Interpretation of the results

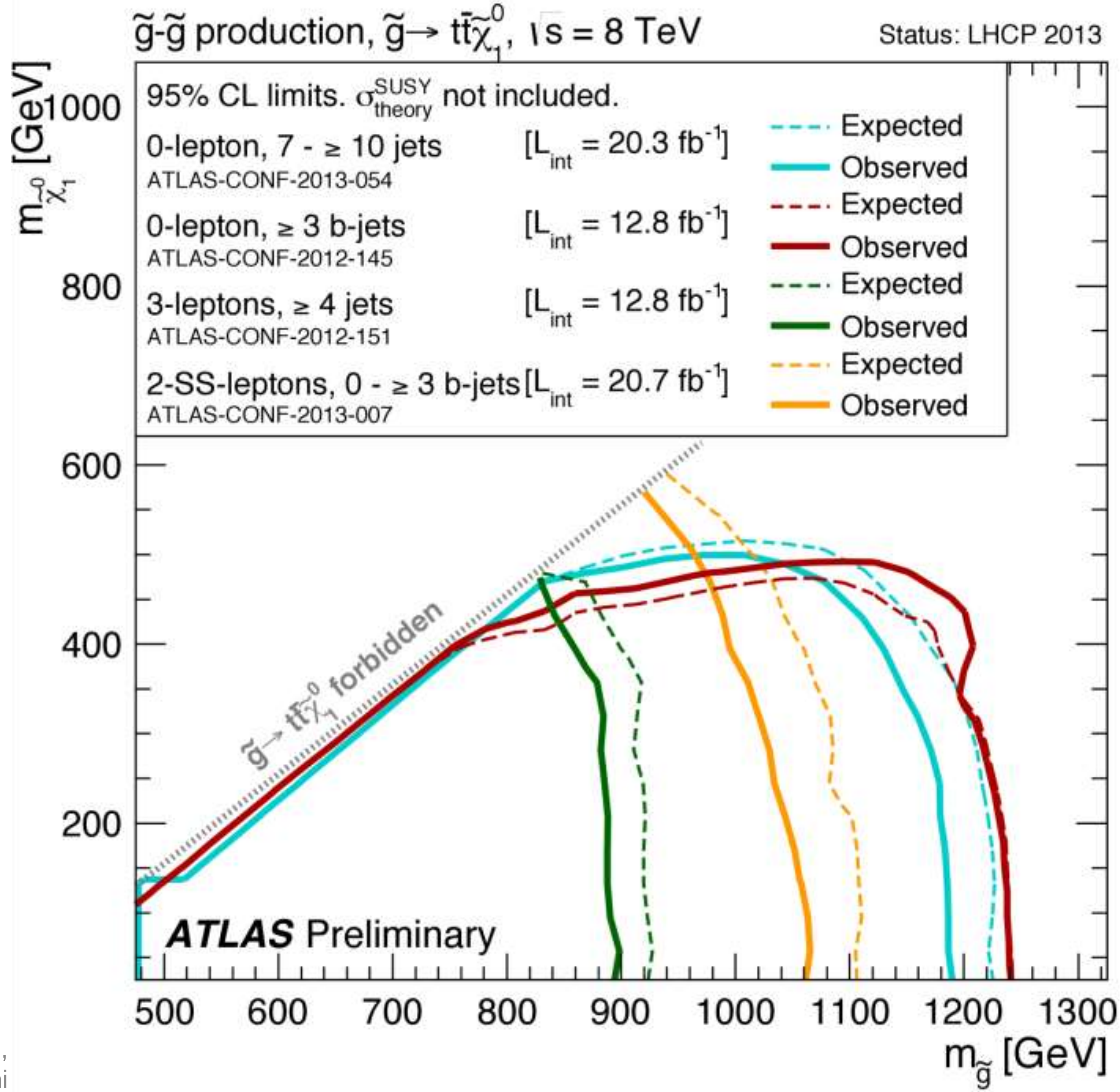
Consider phenomenological MSSM models containing only squarks of 1st and 2nd generation, gluino and light neutralinos



ATLAS-CONF-2013-047

Expected production cross-sections at LHC

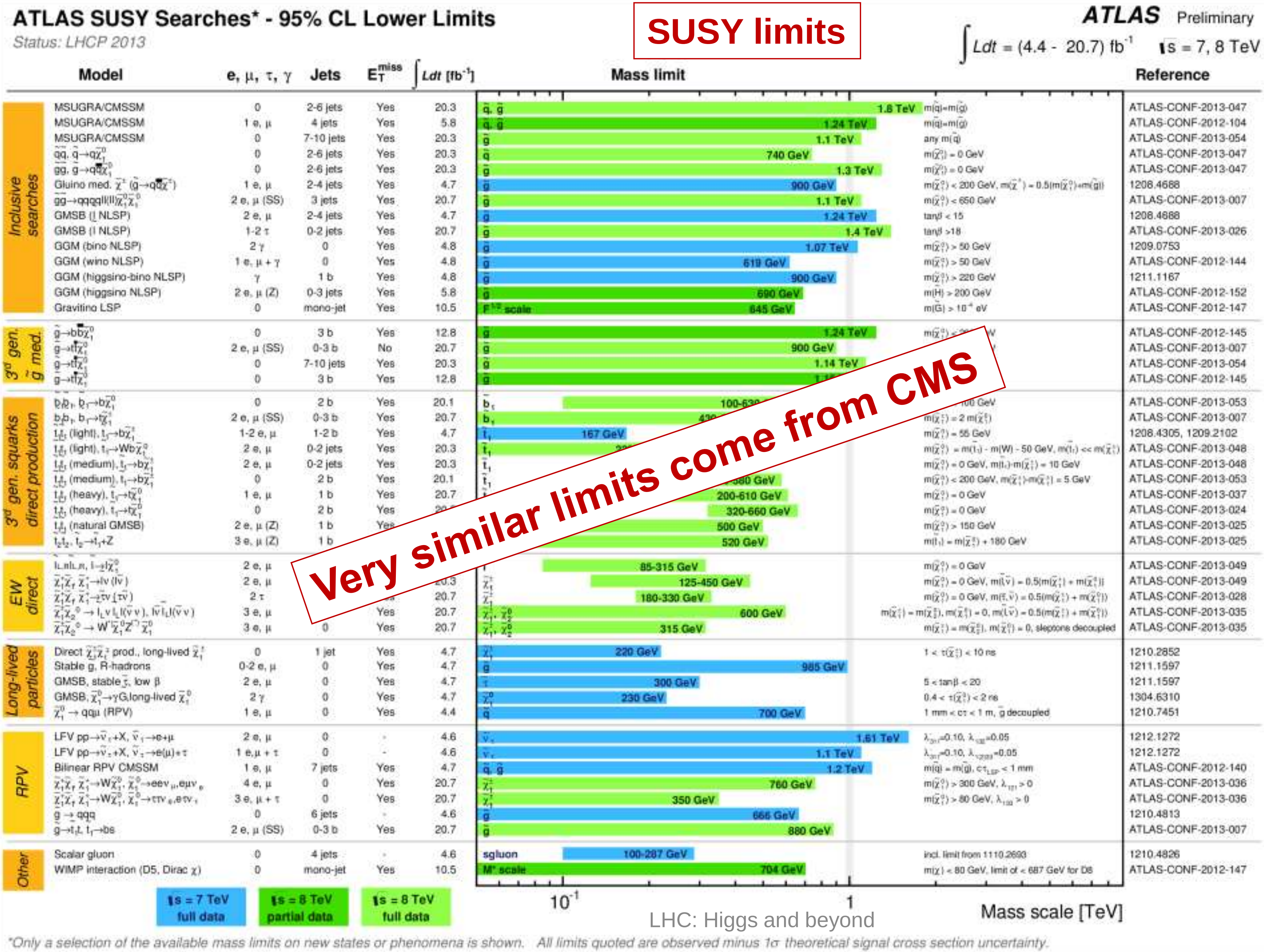




g̃-g̃ production, g̃→ tt̄χ̃⁰₁, √s = 8 TeV
Status: LHCP 2013
95% CL limits. σ^SUSY_theory not included.
0-lepton, 7 - ≥ 10 jets [L_int = 20.3 fb⁻¹]
ATLAS-CONF-2013-054
0-lepton, ≥ 3 b-jets [L_int = 12.8 fb⁻¹]
ATLAS-CONF-2012-145
3-leptons, ≥ 4 jets [L_int = 12.8 fb⁻¹]
ATLAS-CONF-2012-151
2-SS-leptons, 0 - ≥ 3 b-jets [L_int = 20.7 fb⁻¹]
ATLAS-CONF-2013-007
Expected
Observed
Expected
Observed
Expected
Observed
Expected
Observed
g̃→ tt̄χ̃⁰₁ forbidden
ATLAS Preliminary
m_χ̃⁰₁ [GeV]
m_g̃ [GeV]
1000
800
600
400
200
500
600
700
800
900
1000
1100
1200
1300

AS CR,
P Jenni

SUSY limits



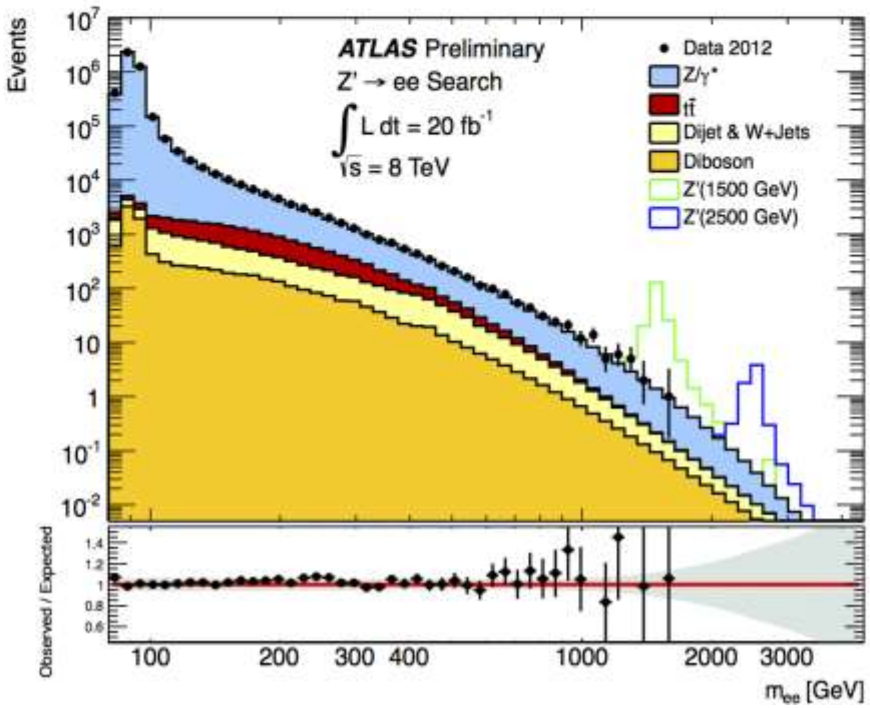
Very similar limits come from CMS

LHC: Higgs and beyond

Searches for heavy W and Z like particles

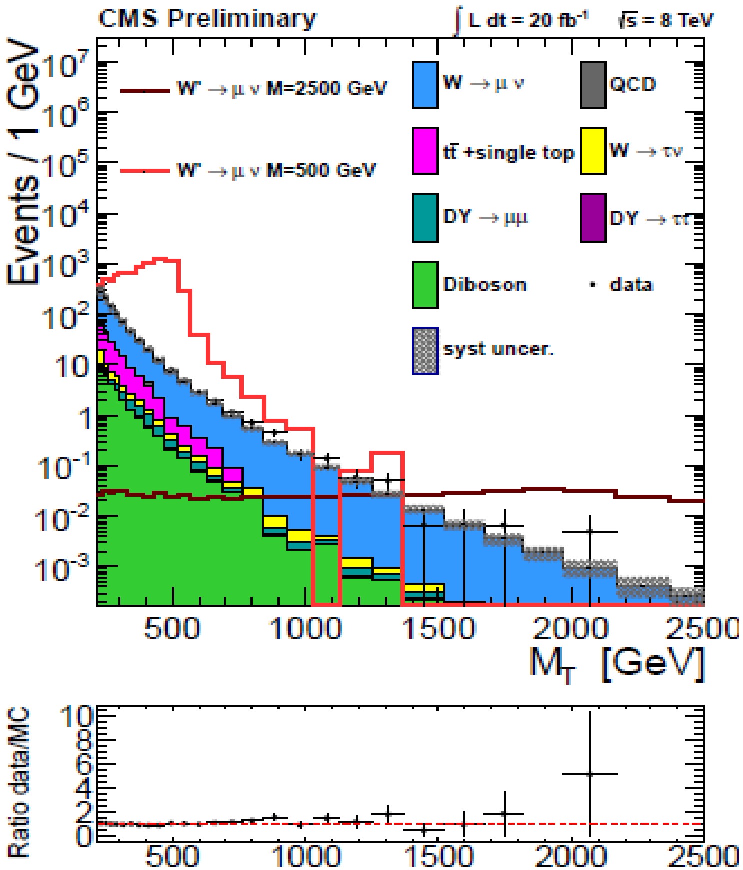
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z': Di-lepton pairs



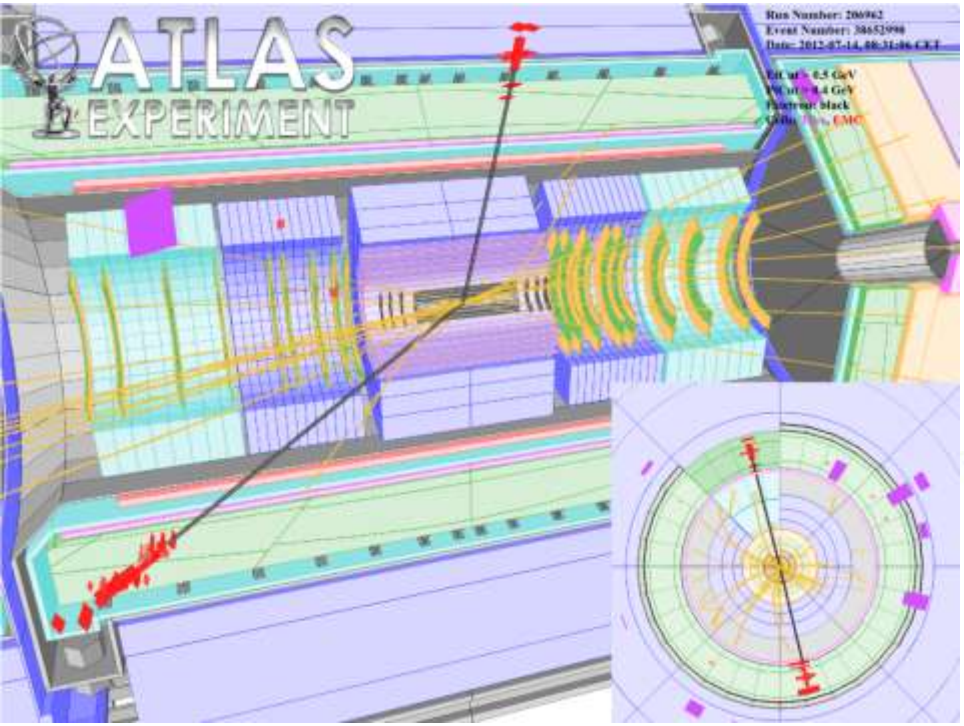
ATLAS-CONF-2013-017

W': Lepton + ETmiss

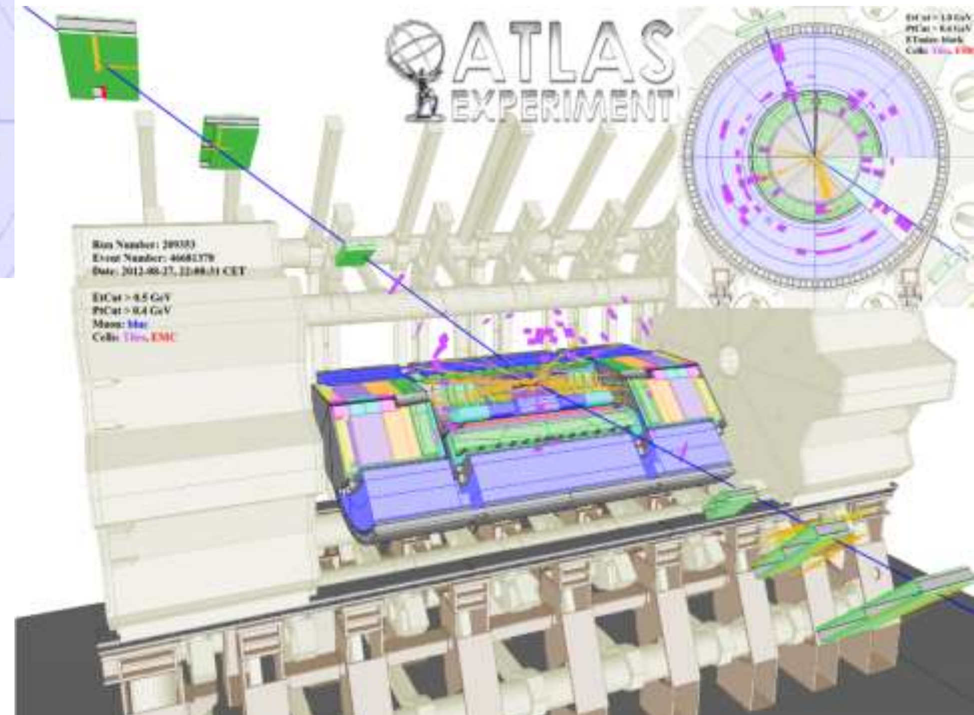


CMS-EXO-12-060

The highest mass di-lepton events from ATLAS

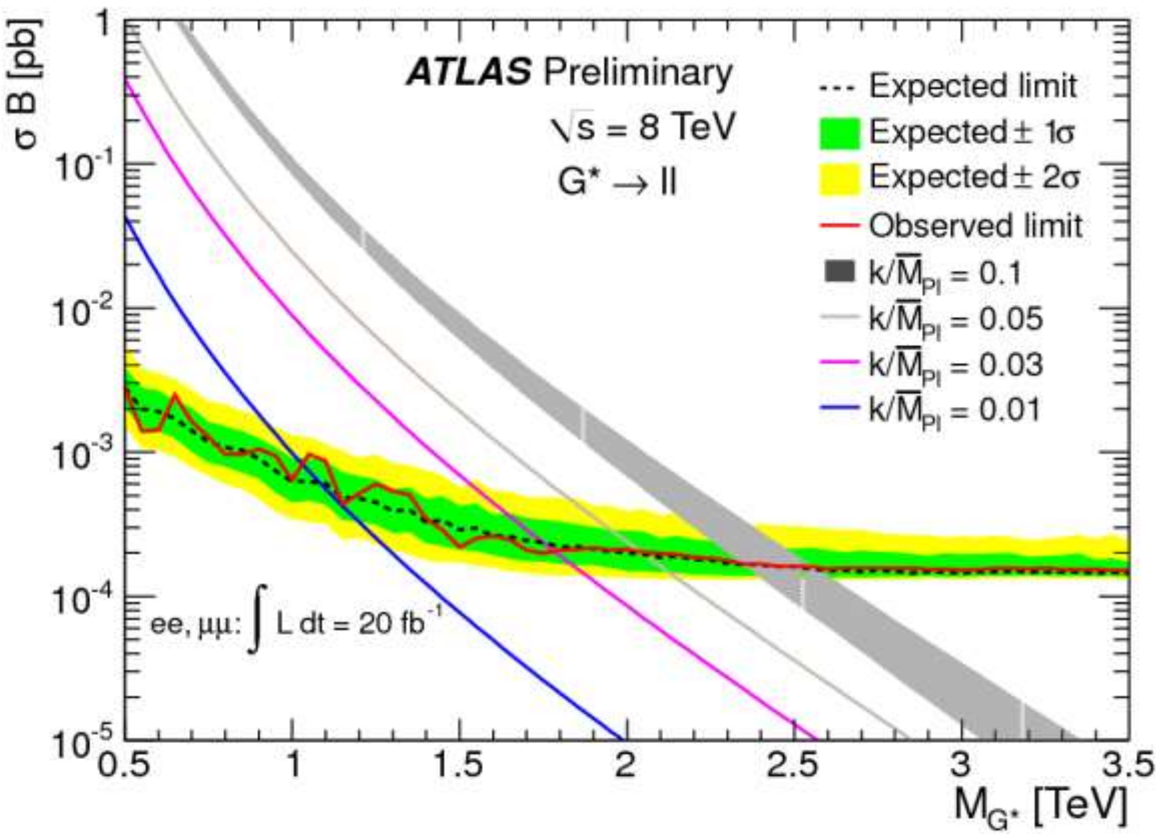


m (e^+e^-) = 1.54 TeV



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

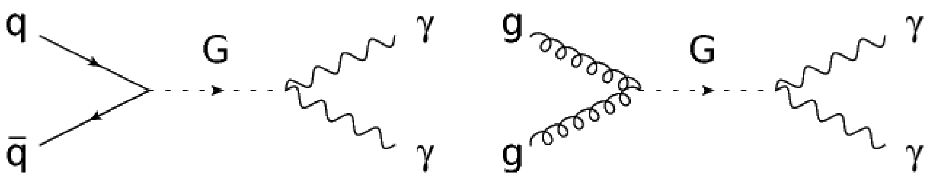
Lower mass limits, at 95% CL, for spin-2 Randall-Sundrum Gravitons



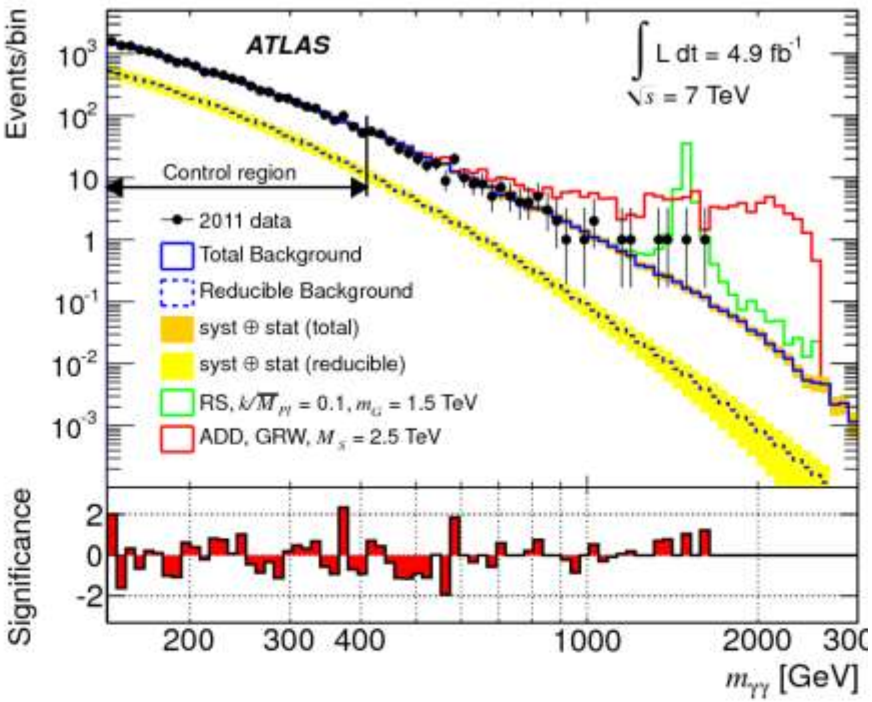
ATLAS-CONF-2013-017

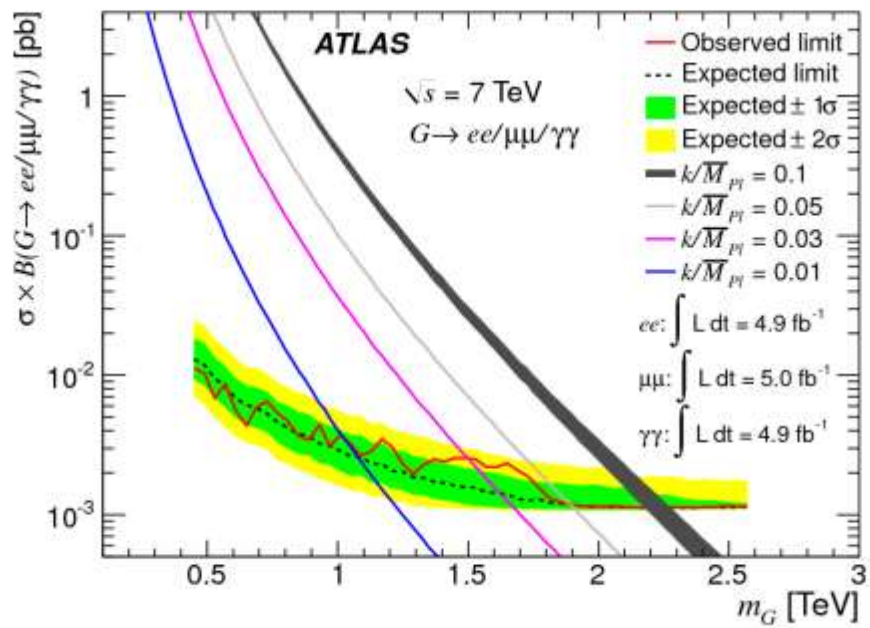
R Sundrum
L Randall
F Gianotti

New particles decaying into two photons



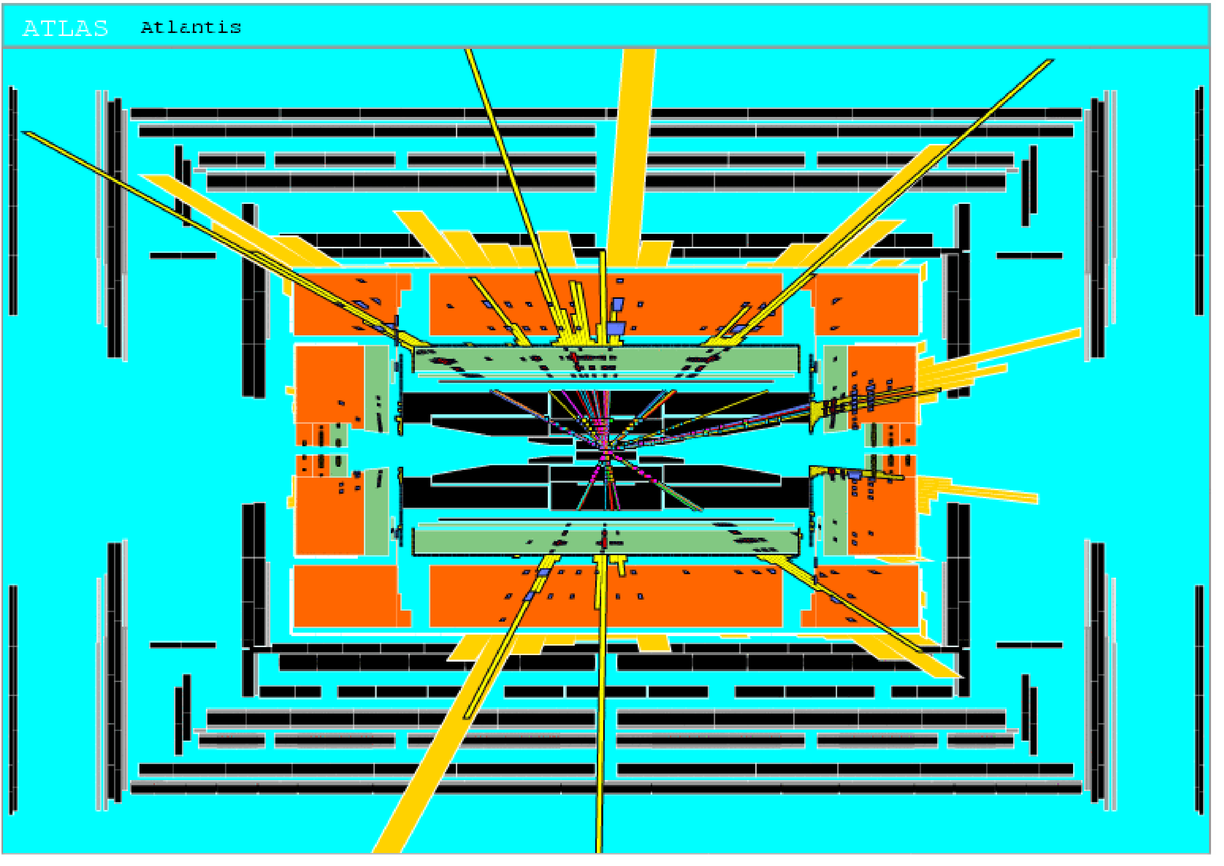
Example for a search of extra dimension signals (Kaluza-Klein Graviton in the Randall-Sundrum and Arkani-Hamed, Dimopoulos and Dvali models)





arXiv:1210.8389v12[hep-ex]

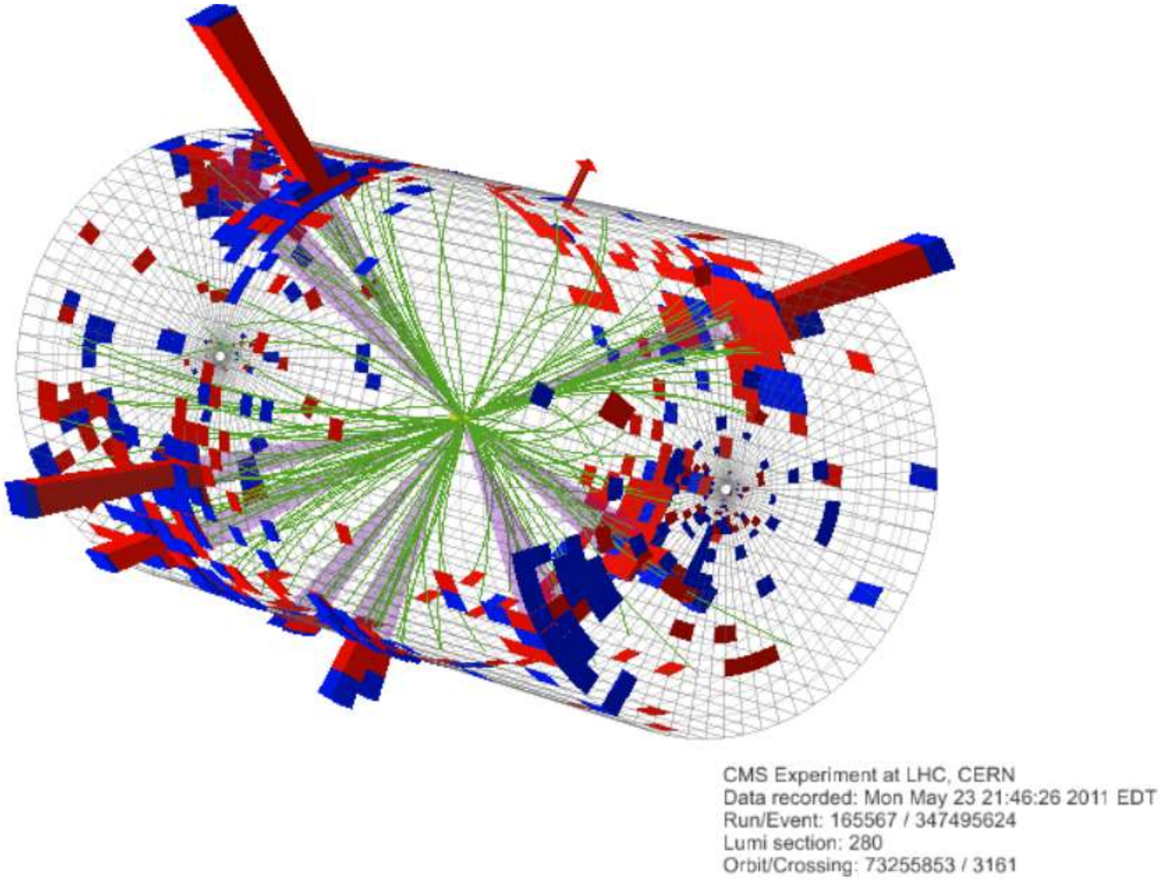
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



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

They decay immediately through Stephen Hawking radiation

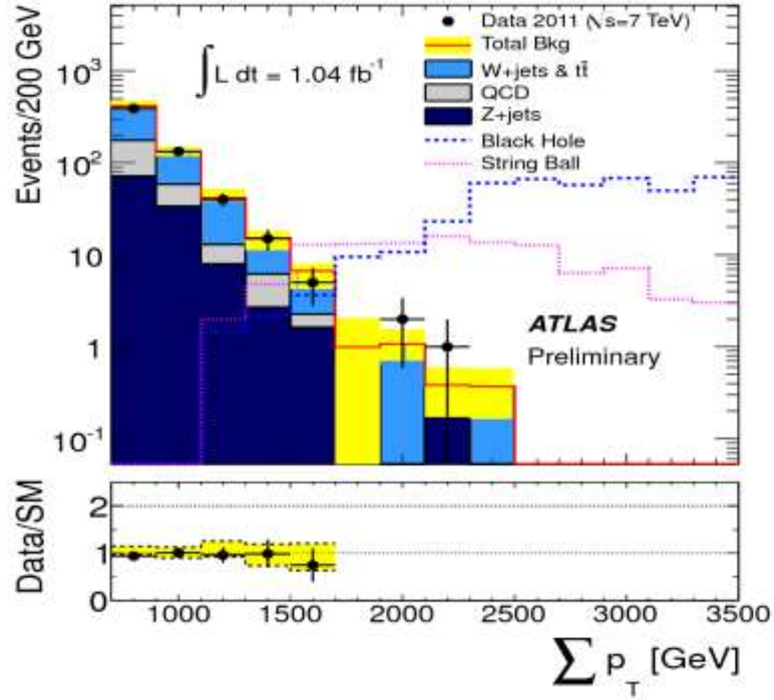
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



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)



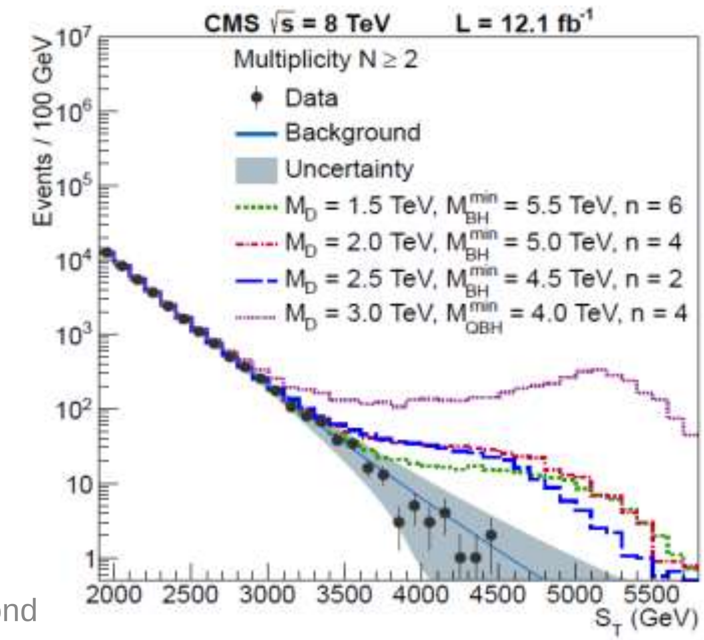
Decay into many objects (jets, leptons, photons)

ATLAS-CONF-2011-147
arXiv:1204.4646v1[hep-ex]

ΣP_T : scalar sum of the E_T of the N objects in the event

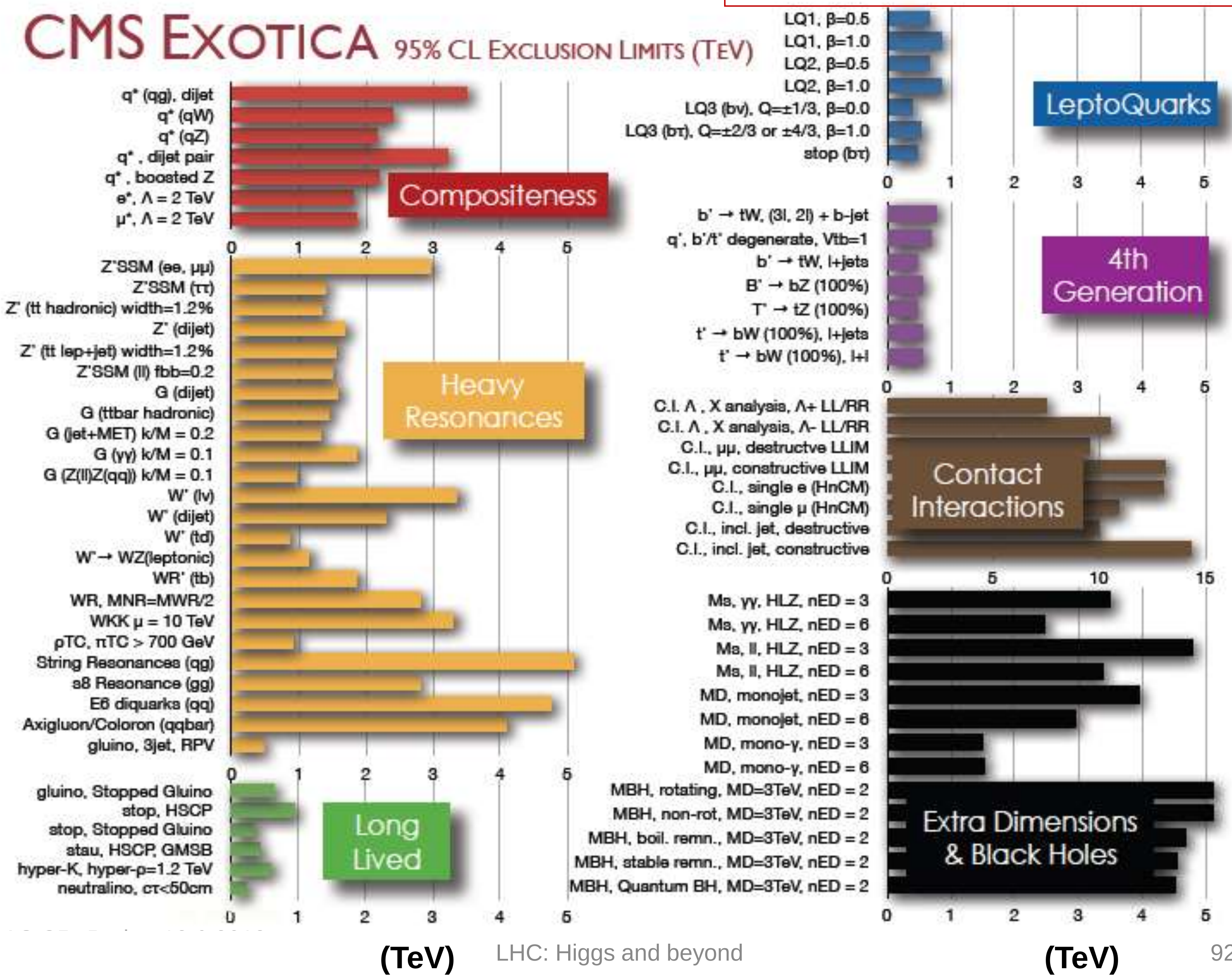
<u>Examples:</u> (ATLAS) at least one electron or muon and two or more jets, (CMS) any three objects

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

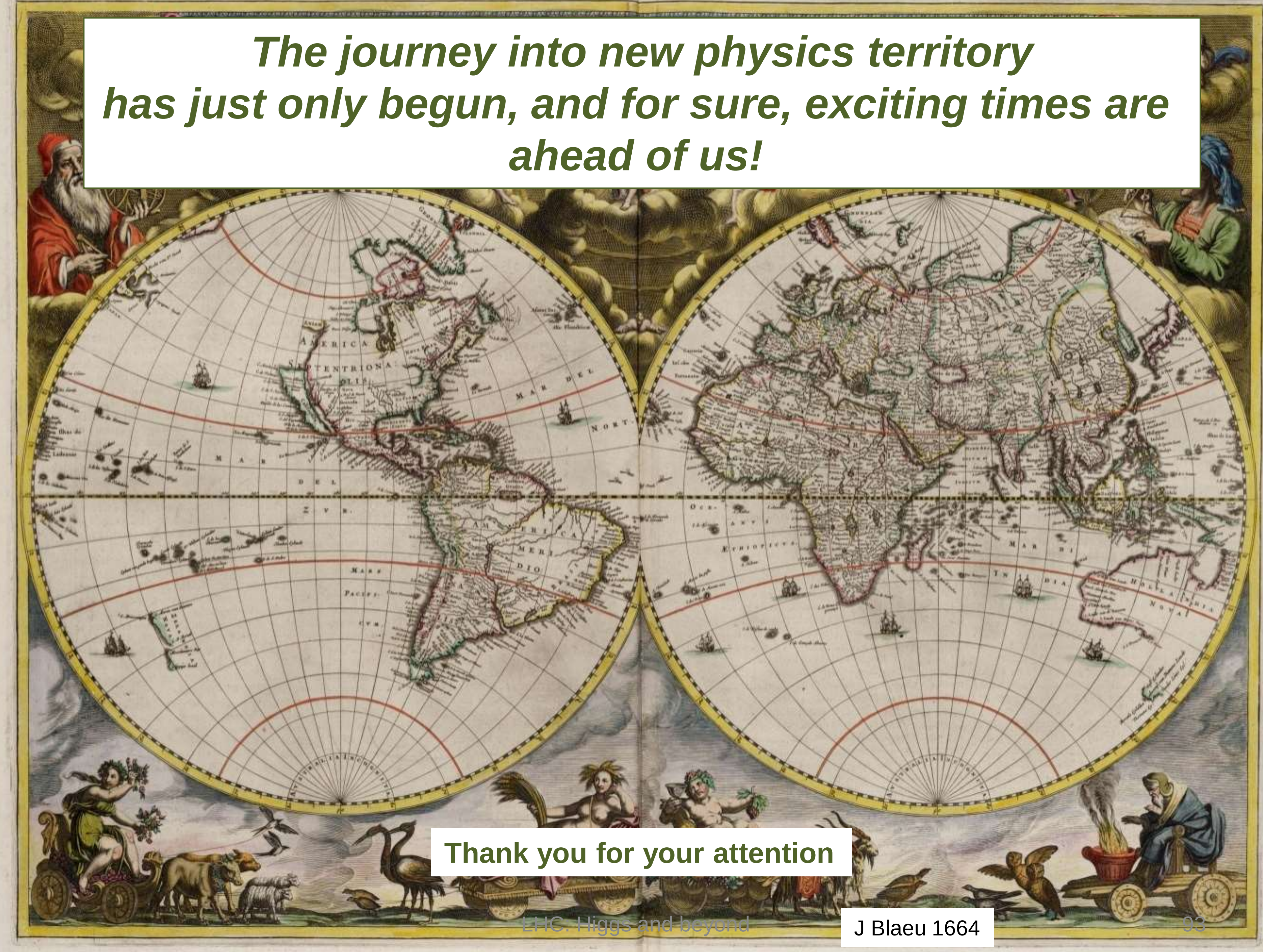


Submitted to JHEP
arXiv:1303.5338v1[hep-ex]

Similar results exist from ATLAS



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.

Science AAAS

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