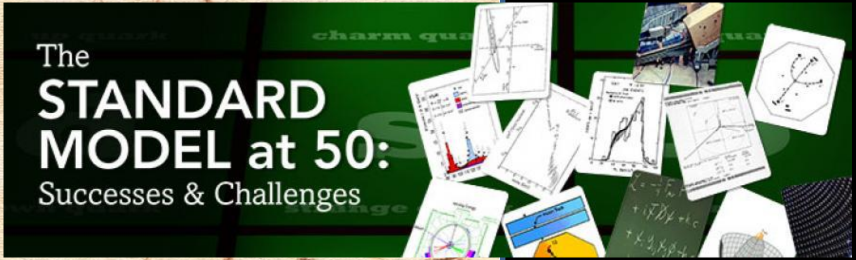
Critical Experiments Establishing the SM: Hadron Colliders

46th SLAC Summer Institute
Stanford, July 30 – Aug 10, 2018


The STANDARD MODEL at 50: Successes & Challenges

The plan:

Some highlights and comments from the experiments at the

ISR, the First Hadron Collider

CERN SPS $p\bar{p}$ Collider

FNAL Tevatron $p\bar{p}$ Collider

… and of course the LHC !

(except flavour physics, see the next talk by Dave Hitlin)

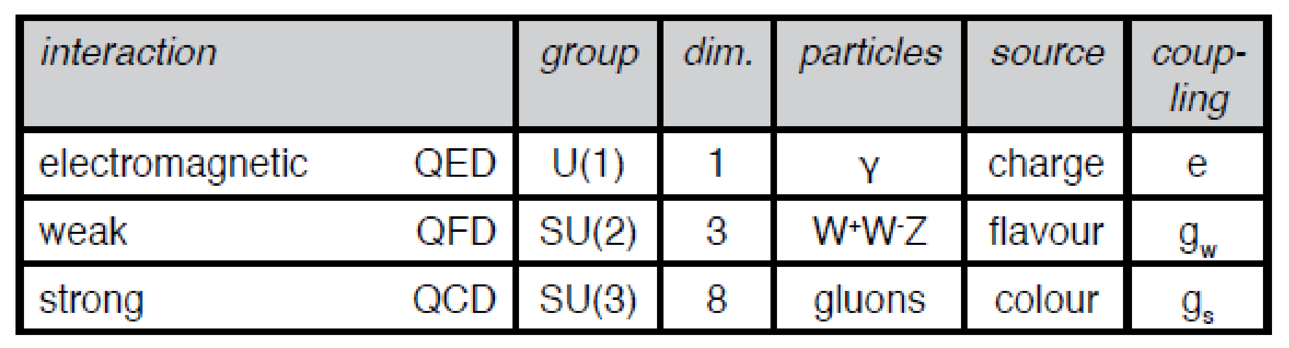
Apologies also right away: I had to make choices, and these are sometimes biased towards experiments I have had the privilege to participate…

Drawing by Sergio Cittolin

Peter Jenni, Freiburg and CERN

Some of the Pioneers of the Standard Model of Particle Physics…

Quark Model:
Murray Gell-Mann, George Zweig



interaction		group	dim.	particles	source	coup-ling
electromagnetic	QED	U(1)	1	γ	charge	e
weak	QFD	SU(2)	3	W^+W^-Z	flavour	g_w
strong	QCD	SU(3)	8	gluons	colour	g_s

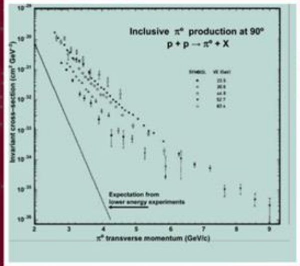
Scalar fields can generate mass:
Robert Brout, François Englert, Peter Higgs, Gerald Guralnik, Carl Hagen, Tom Kibble

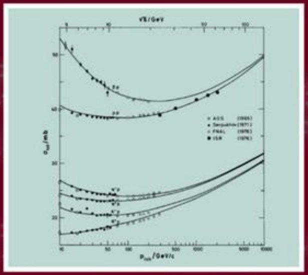
But please don't forget all the experimentalists who established step by step the SM as a reality … !

Gauge theory of the weak interaction:
Sheldon Glashow, Abdus Salam, Steven Weinberg

Gauge theory of the strong interaction, asymptotic freedom:
David Gross, David Politzer, Frank Wilczek

Interaction point with crossing angle



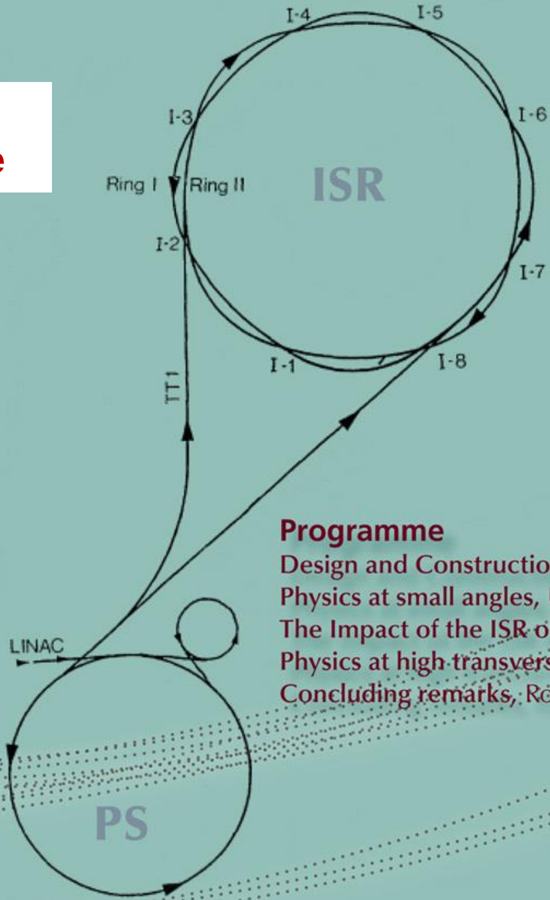


40th Anniversary of the First Proton-Proton Collisions

in the CERN Intersecting Storage Rings (ISR)

Colloquium *January 18th, 2011 at 14:30 CERN Council Chamber*

(Now it is 47 years ago)



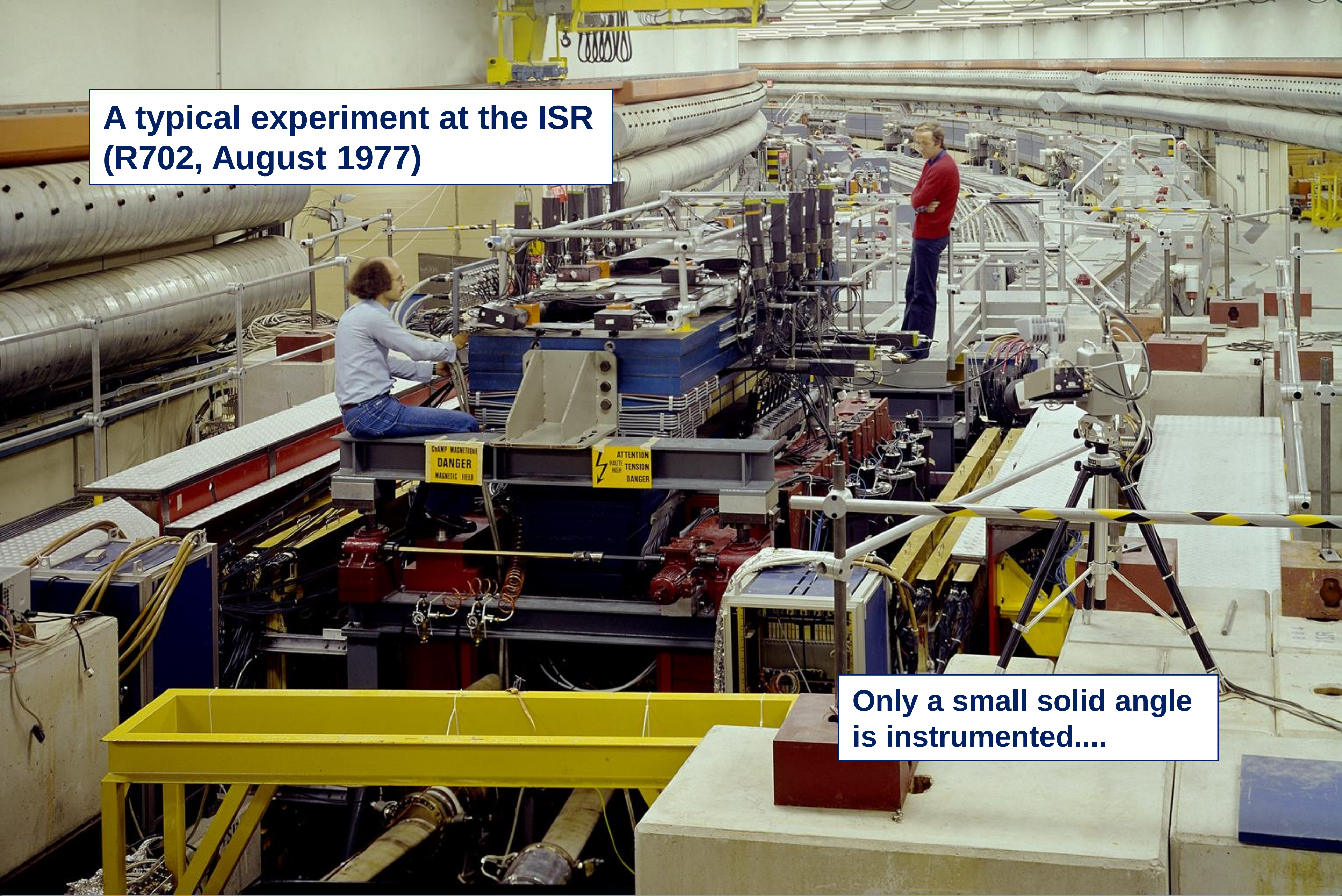
ISR 1971-1984

(up to 63 GeV collision energy, achieved a peak luminosity 1.4 x $10^{32}cm^{-2}s^{-1}$, well above the design)

Programme

Design and Construction of the ISR, Kurt Hübner
Physics at small angles, Ugo Amaldi (TERA-Novara)
The Impact of the ISR on Accelerator Physics and Technology, Philip J.Bryant
Physics at high transverse momentum, Pierre Darriulat (VATLY-Hanoi)
Concluding remarks, Rolf Heuer

A typical experiment at the ISR (R702, August 1977)



Only a small solid angle is instrumented....

Burton Richter's experiment: search for open charm in pp by oppositely charged eμ events (from semi-leptonic decays of charmed meson pairs)

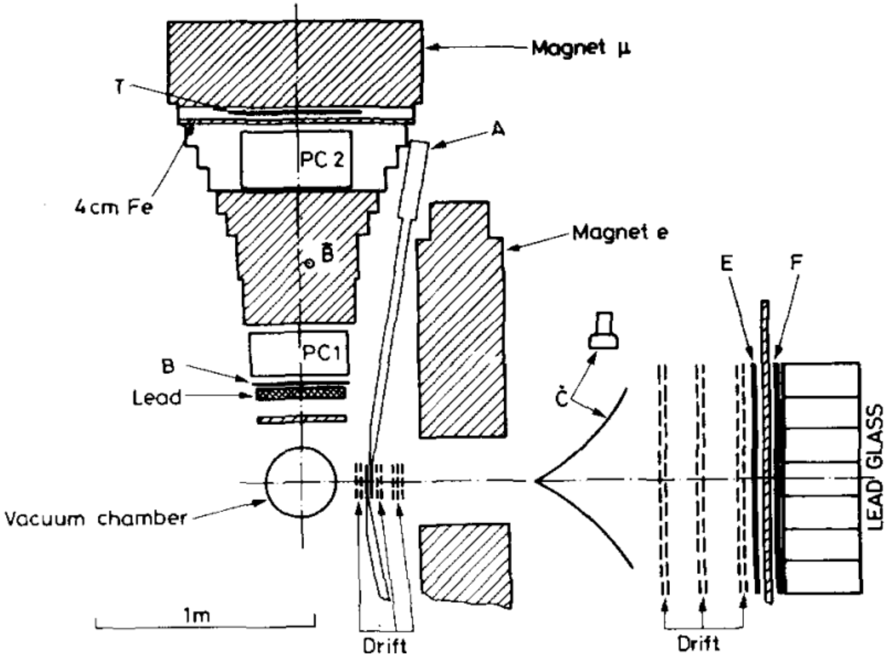


Fig. 1. View of the apparatus transverse to the beams. A second complete electron spectrometer (not shown) is placed symmetrically to the left.

Burton Richter in 1977 with the future CERN DG Christopher Llewellyn Smith

Burton Richter’s experiment: search for open charm in pp by oppositely charged eμ events (from semi-leptonic decays of charmed meson pairs)

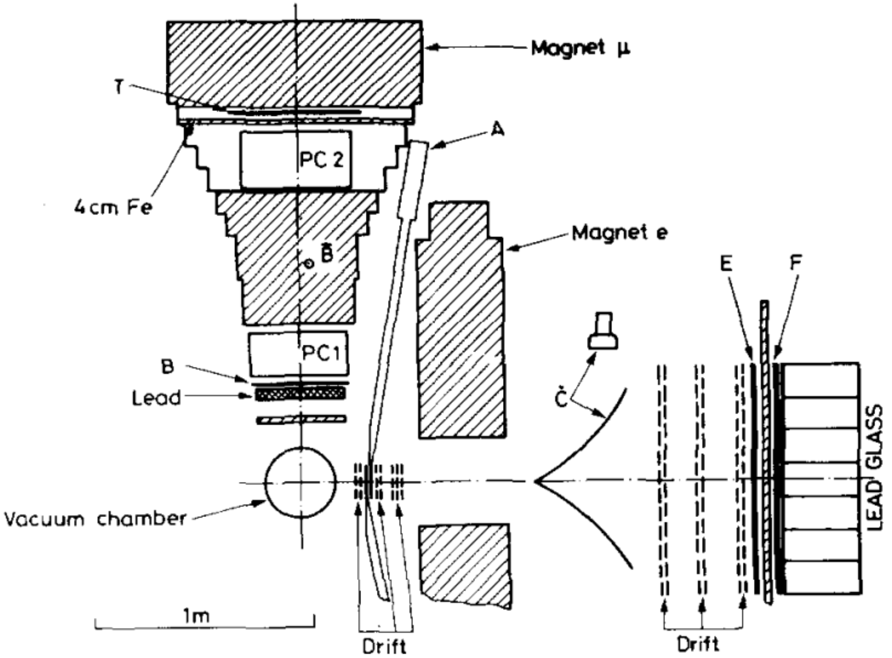


Fig. 1. View of the apparatus transverse to the beams. A second complete electron spectrometer (not shown) is placed symmetrically to the left.

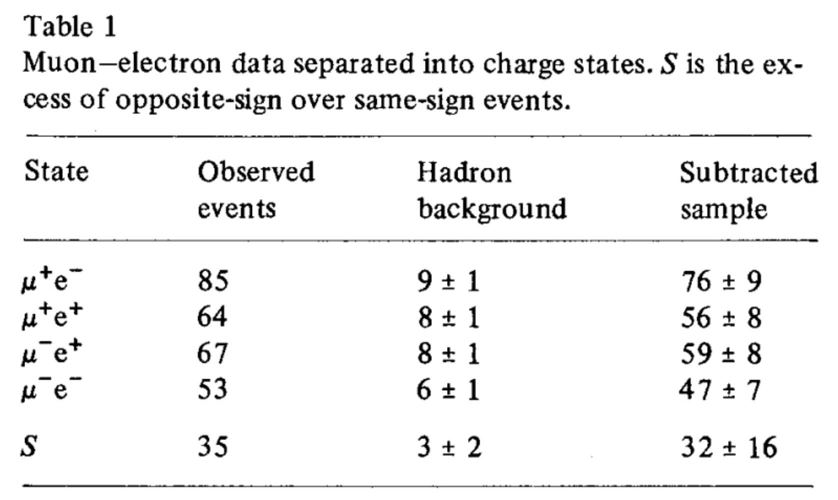


Table 1
Muon–electron data separated into charge states. *S* is the excess of opposite-sign over same-sign events.

State	Observed events	Hadron background	Subtracted sample
μ^+e^-	85	9 ± 1	76 ± 9
μ^+e^+	64	8 ± 1	56 ± 8
μ^-e^+	67	8 ± 1	59 ± 8
μ^-e^-	53	6 ± 1	47 ± 7
S	35	3 ± 2	32 ± 16

Statistics were treated simply at that time…

R702, Phys. Lett. B 77 (1978) 339

The other comment here, valid in general for the ISR: a few years earlier, the experiments could have made nice discoveries …

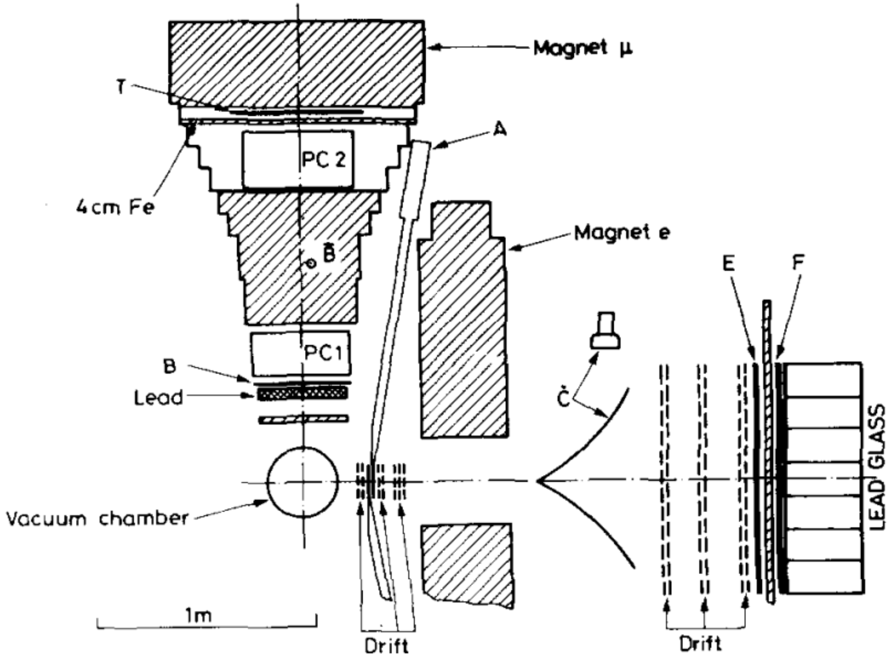


Fig. 1. View of the apparatus transverse to the beams. A second complete electron spectrometer (not shown) is placed symmetrically to the left.

A.G. Clark et al. / Electron pair production at the ISR 45

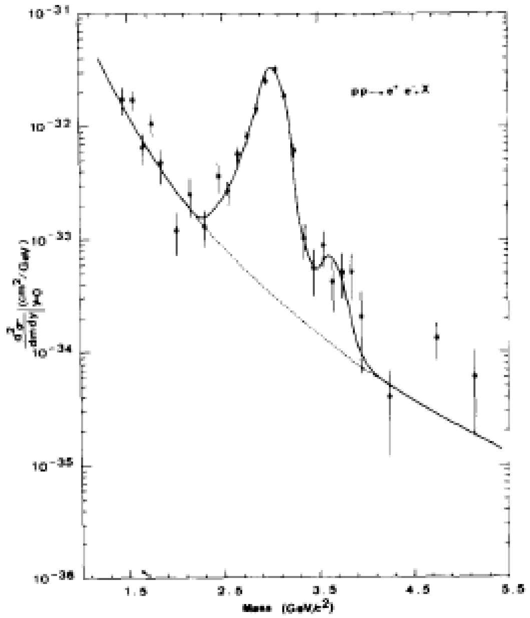
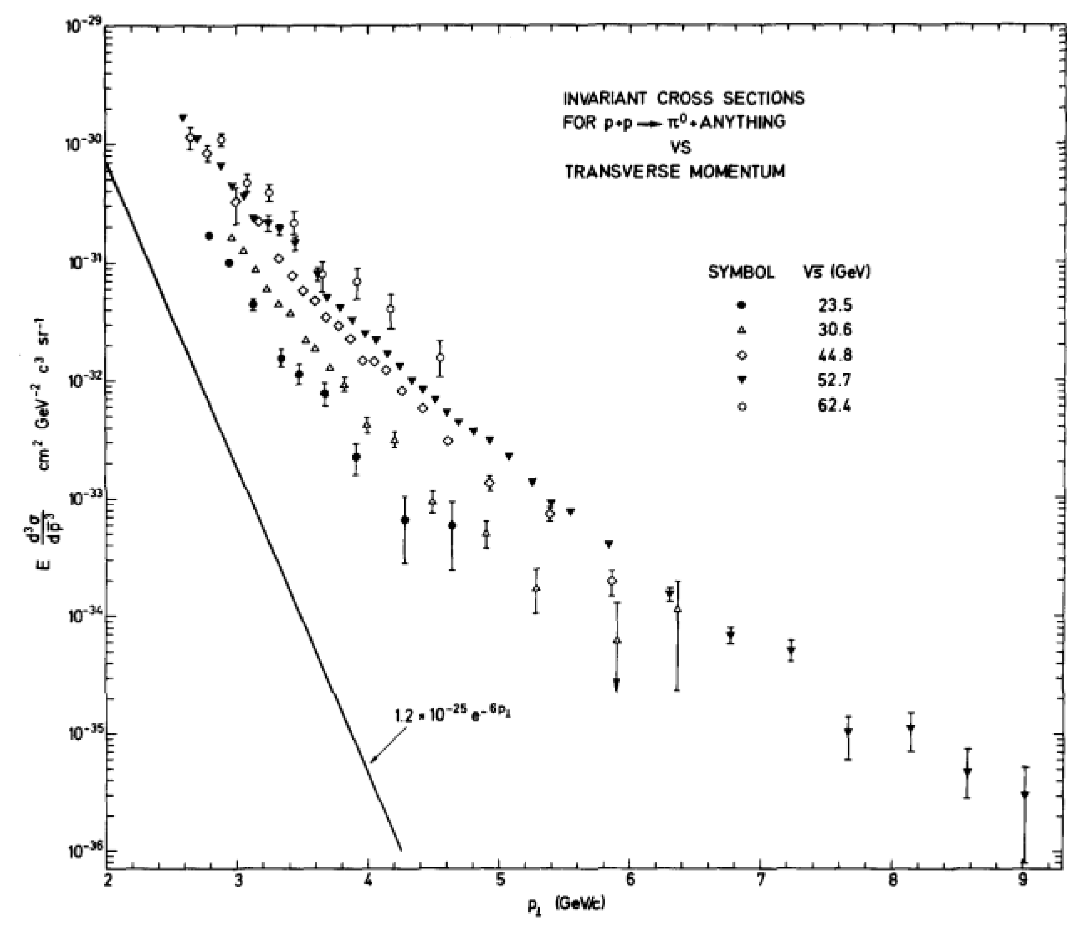
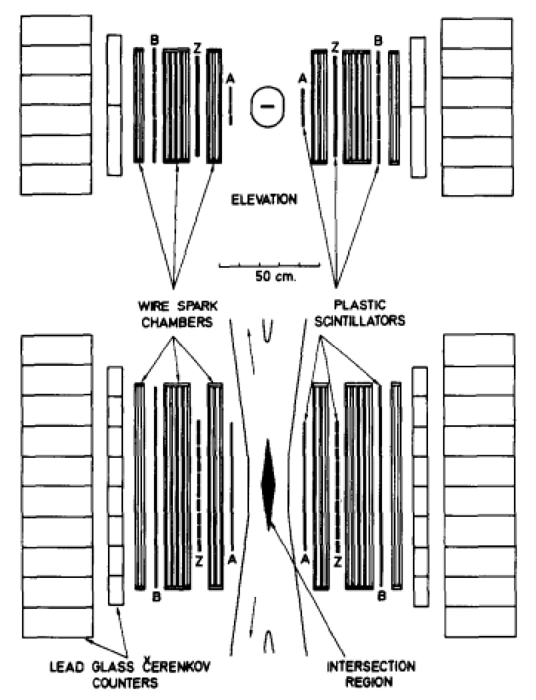


Fig. 12. The cross section $(d^2\sigma/dmdy)_{y=0}$ for inclusive electron pair production is displayed as a function of the pair mass. The line is the result of the fit described in subsect. 4.2.

R702, Nucl. Phys. B 142 (1978) 29

The pioneering legacy result from the ISR: Large transverse momentum phenomena became evident, characteristic of parton scattering at hadron colliders

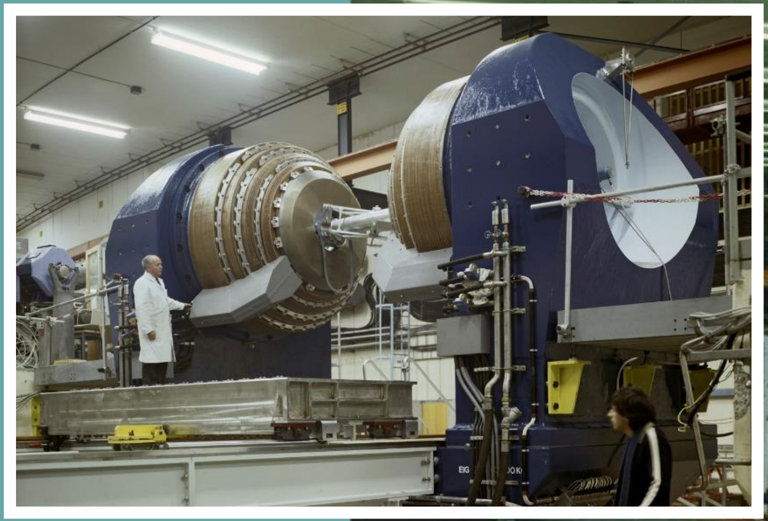


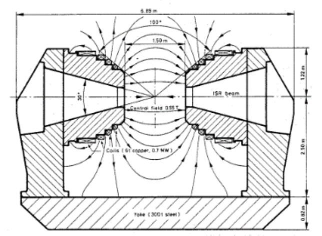


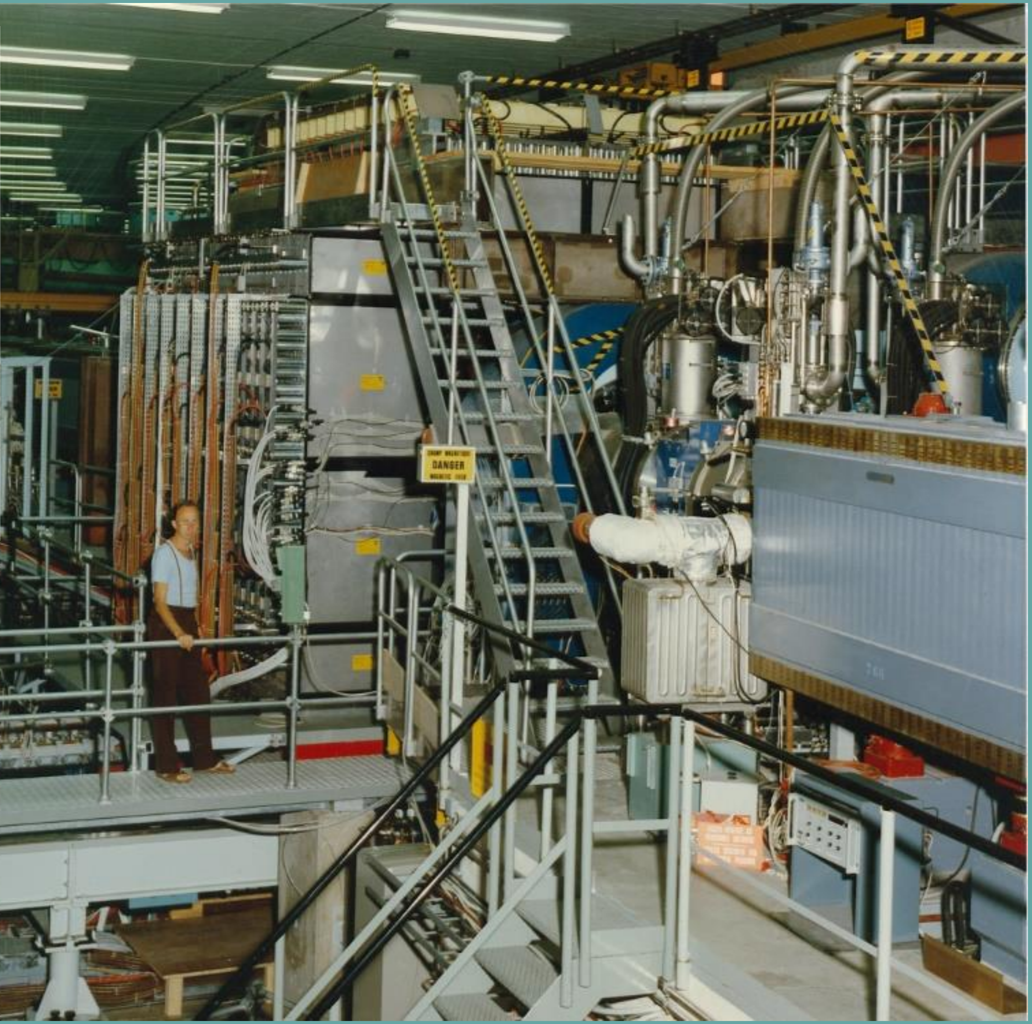
Phys. Lett. B 46 (173) 471

Observed by 3 experiments, shown is the 1973 inclusive π^o cross-section at 90º by R103 in 1973

The last generation detectors, here the Axial Field Spectrometer R807/8, were closer to general purpose collider detectors as we know them now

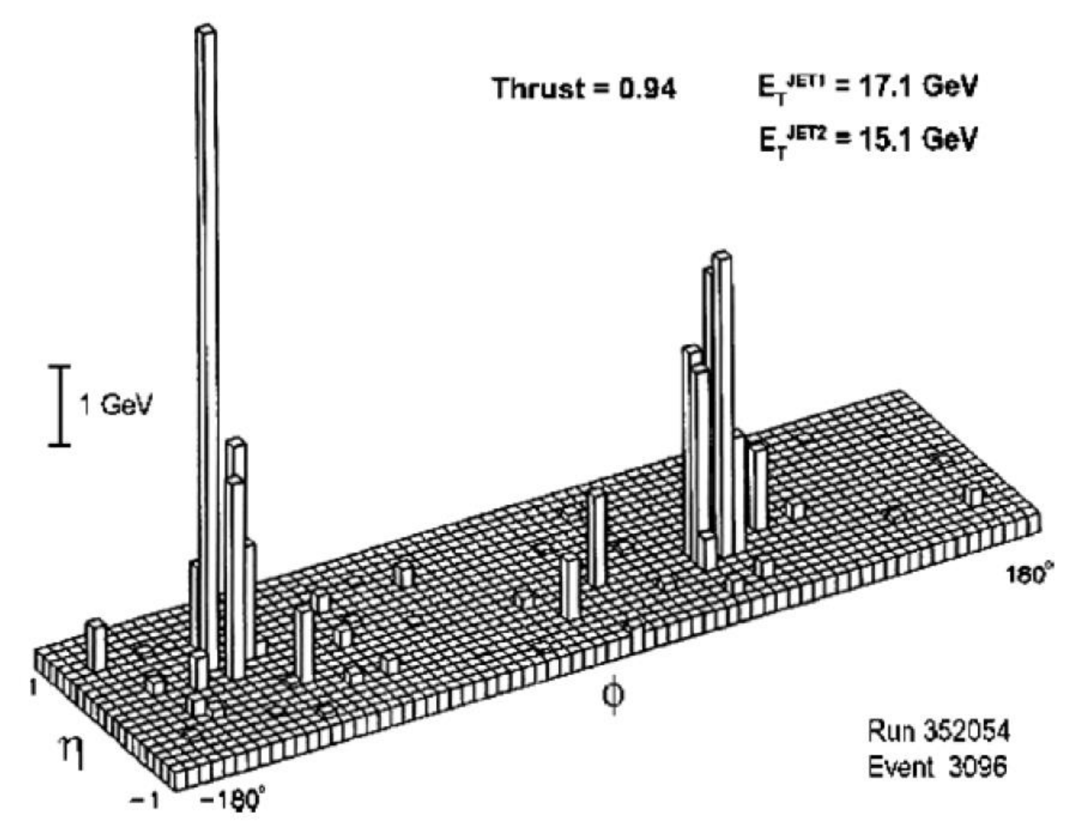






AFS approaching 4π coverage, with a Uranium-scintillator calorimeter

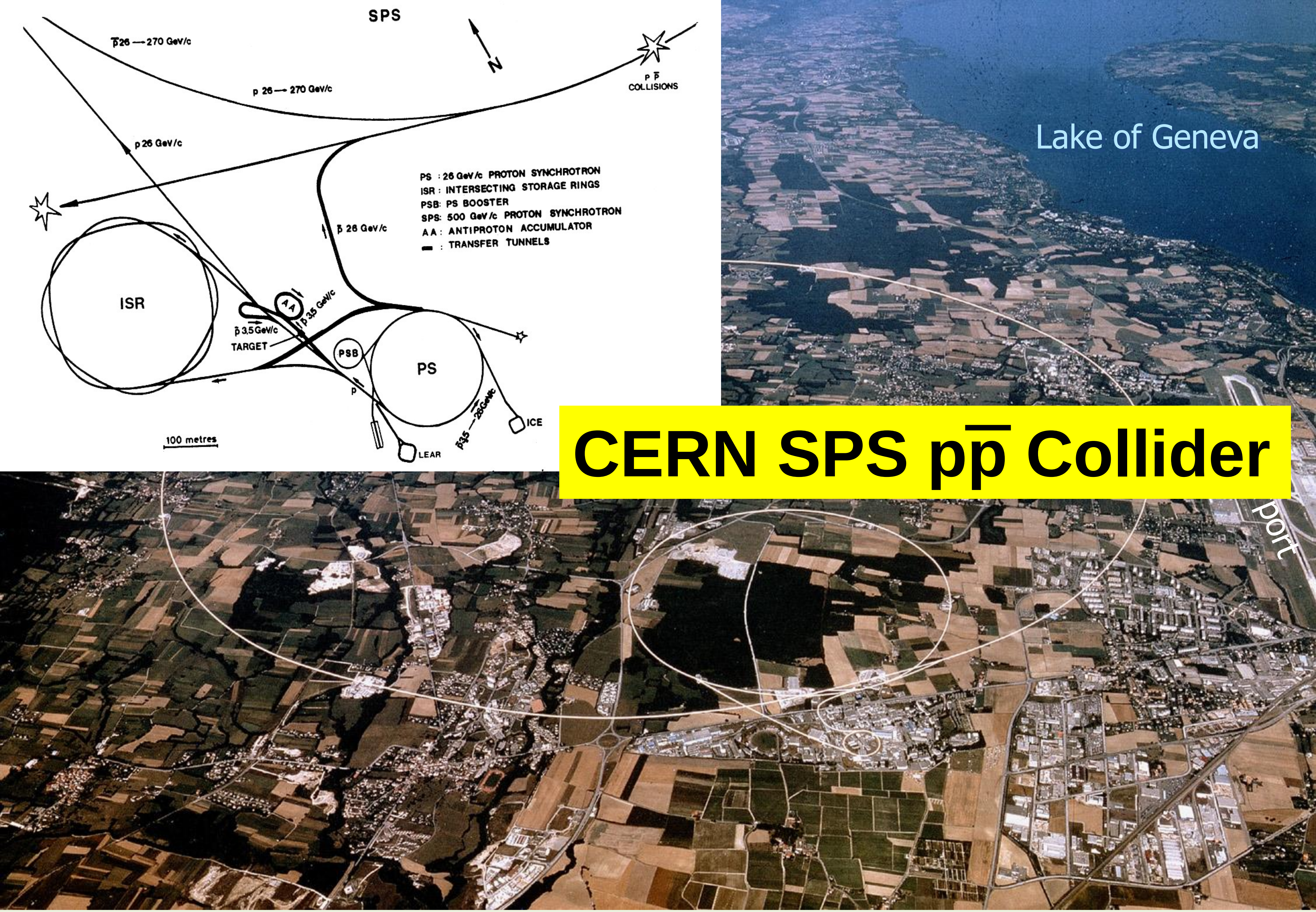
When the ISR closed down 1983/4, evidence for two-jet events became clear...

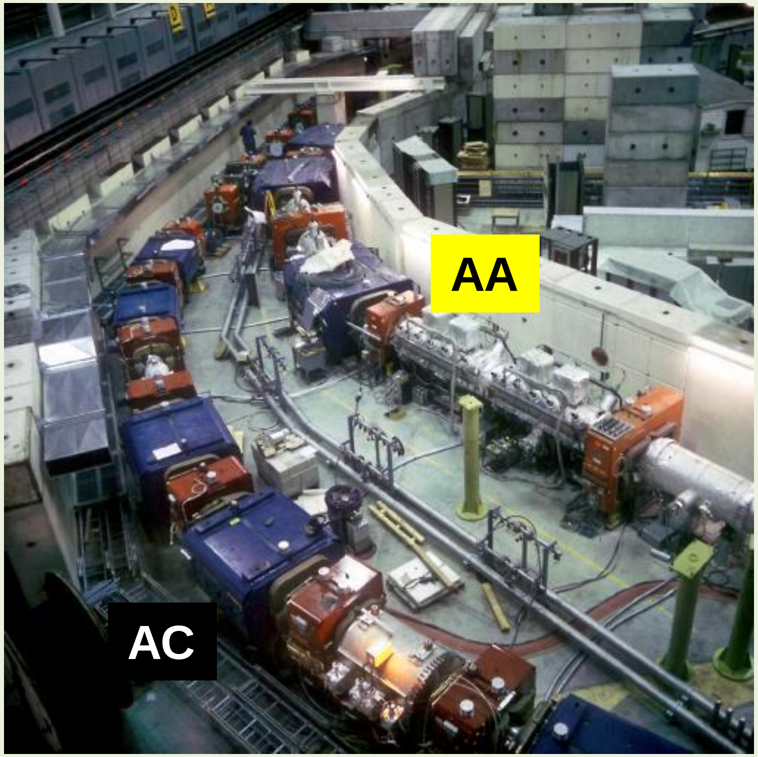


A 'lego plot' from the AFS experiment showing the two-jet in the calorimeter energy map

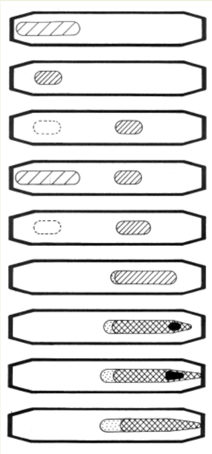
… but by then the focus of attention for hard scattering had already turned to the CERN SPS proton-antiproton collider with its higher energy

CERN SPS $p\bar{p}$ Collider

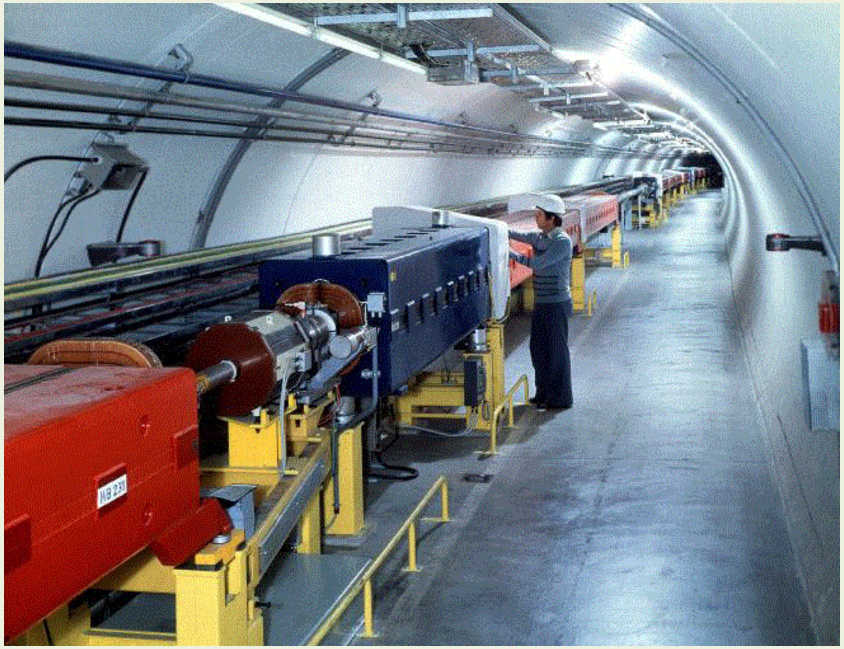




The crucial challenge was to stack as much as possible antiprotons over many hours to reach high luminosities

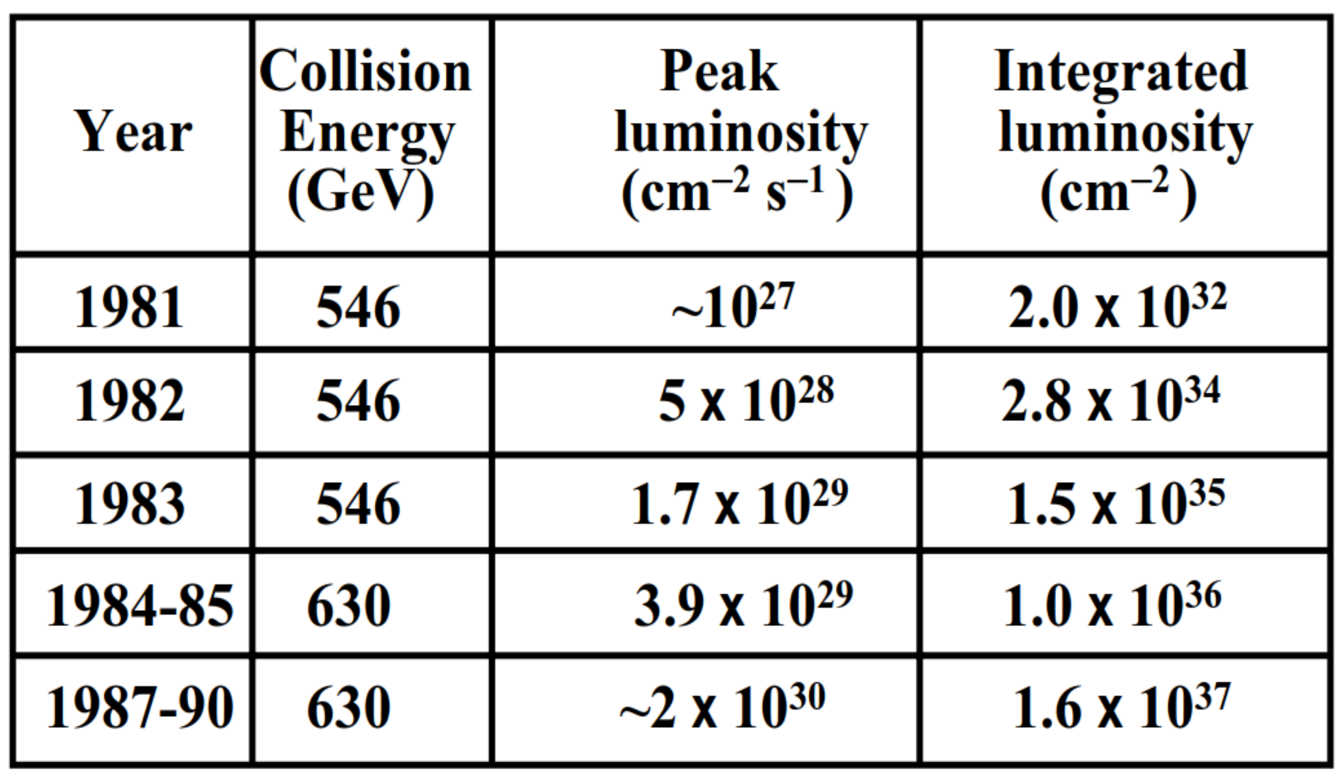


A view of the CERN SPS, 450 GeV



The CERN Antiproton Accumulator (AA) 3.5 GeV large-aperture ring for antiproton storage and cooling, and the Antiproton Collector (AC) added for the second phase

CERN SPS Proton-Antiproton Collider operation (1981 – 1990)



Year	Collision Energy (GeV)	Peak luminosity (cm^{-2} s^{-1})	Integrated luminosity (cm^{-2})
1981	546	$\sim 10^{27}$	2.0 x 10^{32}
1982	546	5 x 10^{28}	2.8 x 10^{34}
1983	546	1.7 x 10^{29}	1.5 x 10^{35}
1984-85	630	3.9 x 10^{29}	1.0 x 10^{36}
1987-90	630	$\sim$2 x 10^{30}	1.6 x 10^{37}

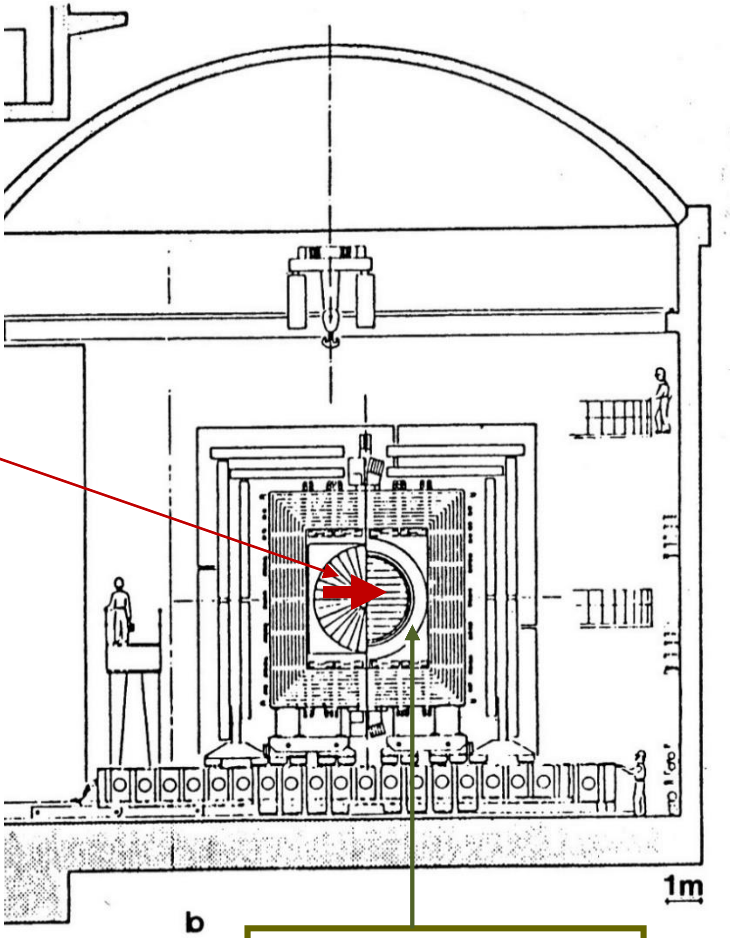
Unambiguous jets

W discovery

Z discovery

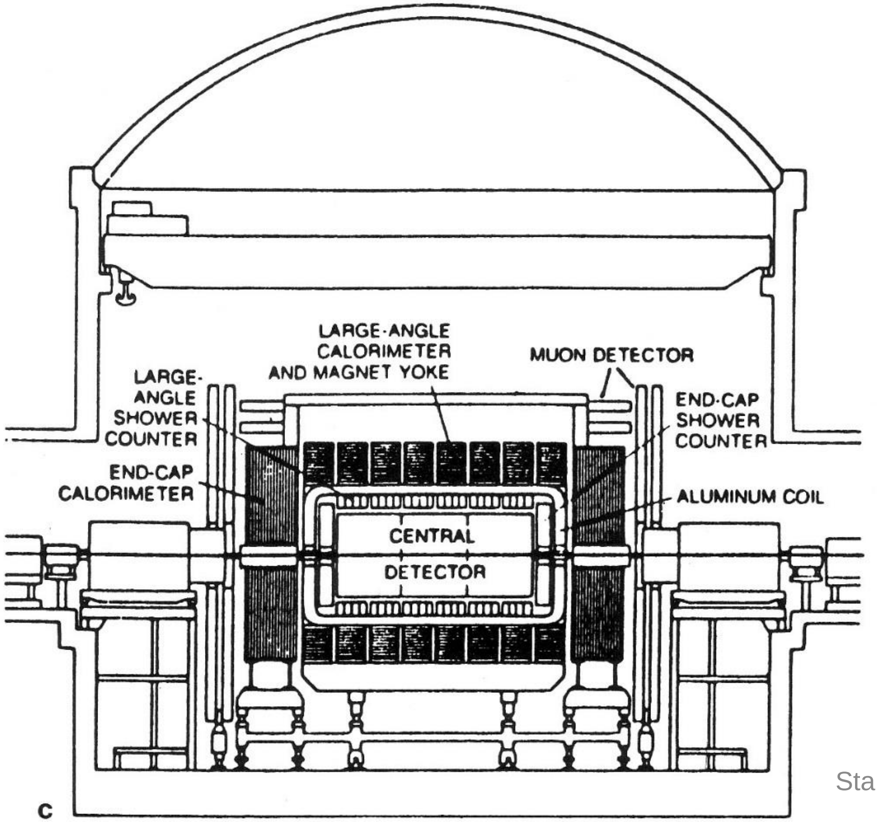
Searches for top, SUSY, and m_W measurements, B^o – B^o mixing

The UA1 detector, pioneering a first hermetic hadron collider detector approach at the CERN pp Collider (January 1981)



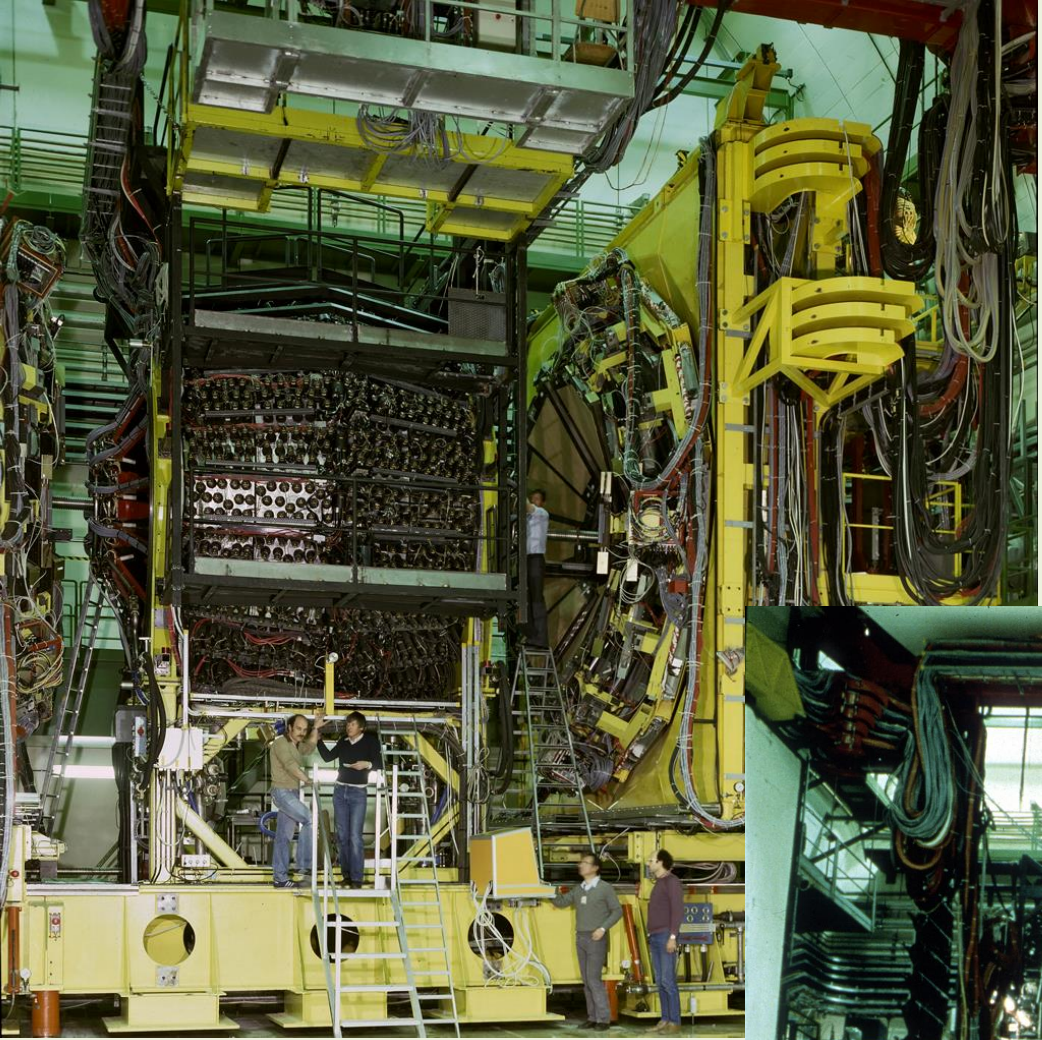
Magnetic field direction

Central electromagnetic calorimeter



The UA1 detector, pioneering a first hermetic hadron collider detector approach at the CERN pp Collider (January 1981)

The UA2 detector
('highly' segmented, central calorimeter with pointing cells, but no muon detection)

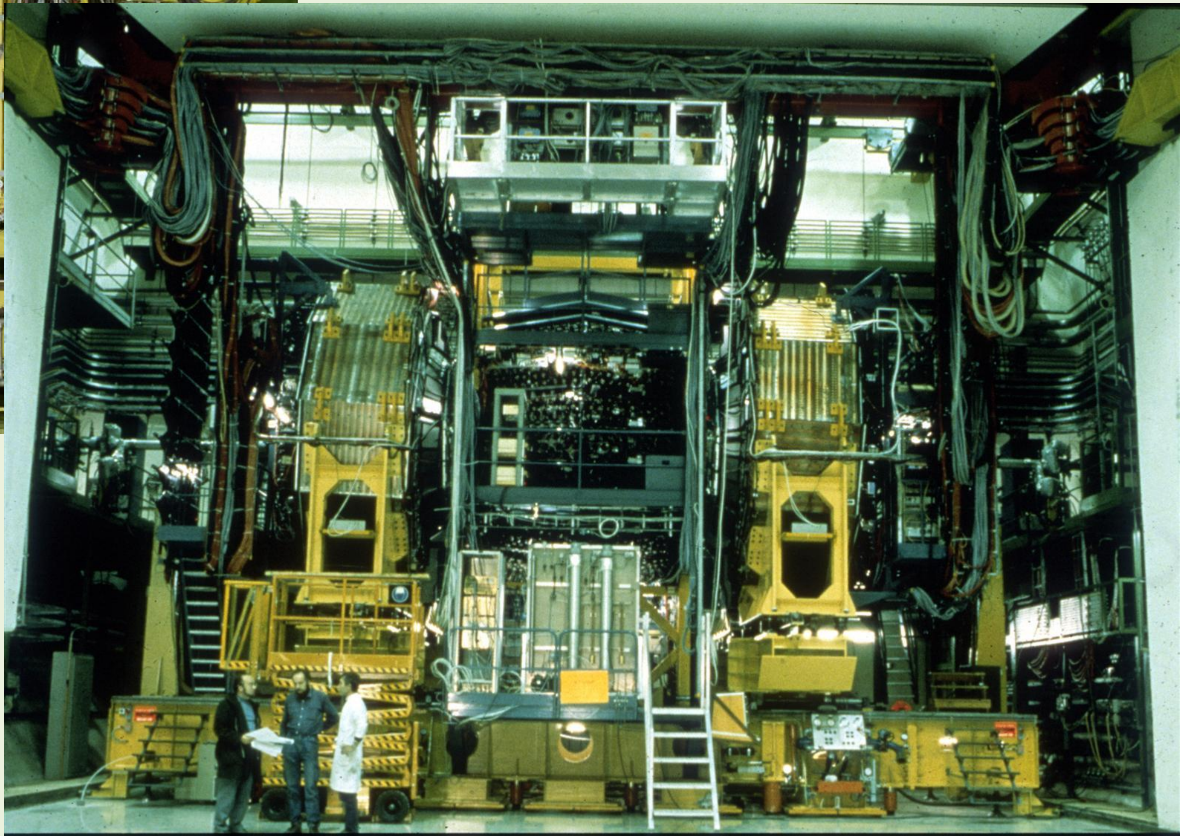


UA2 1981-85

(toroid forward magnets)

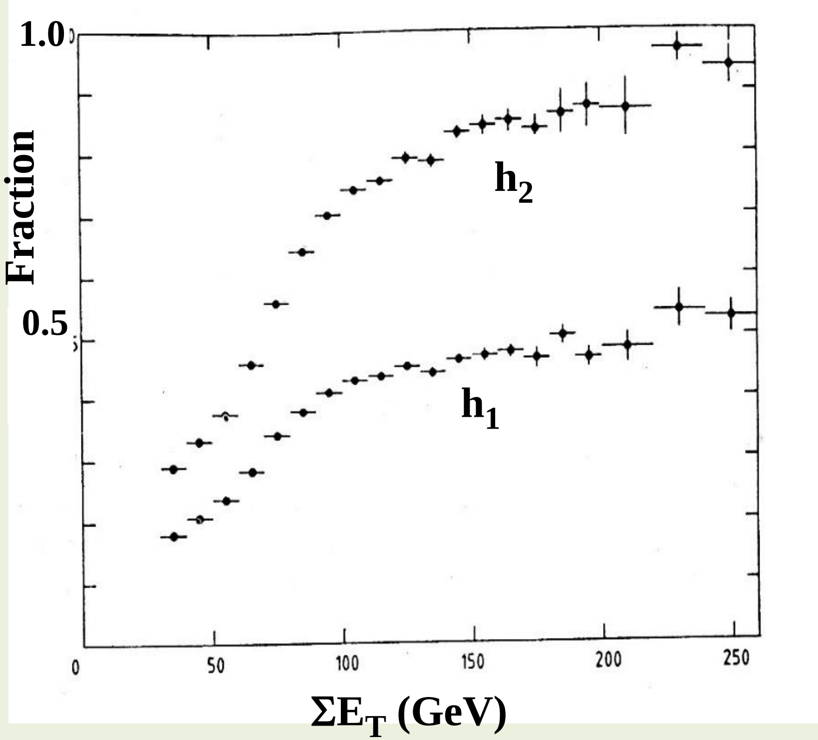
UA2' 1987-90

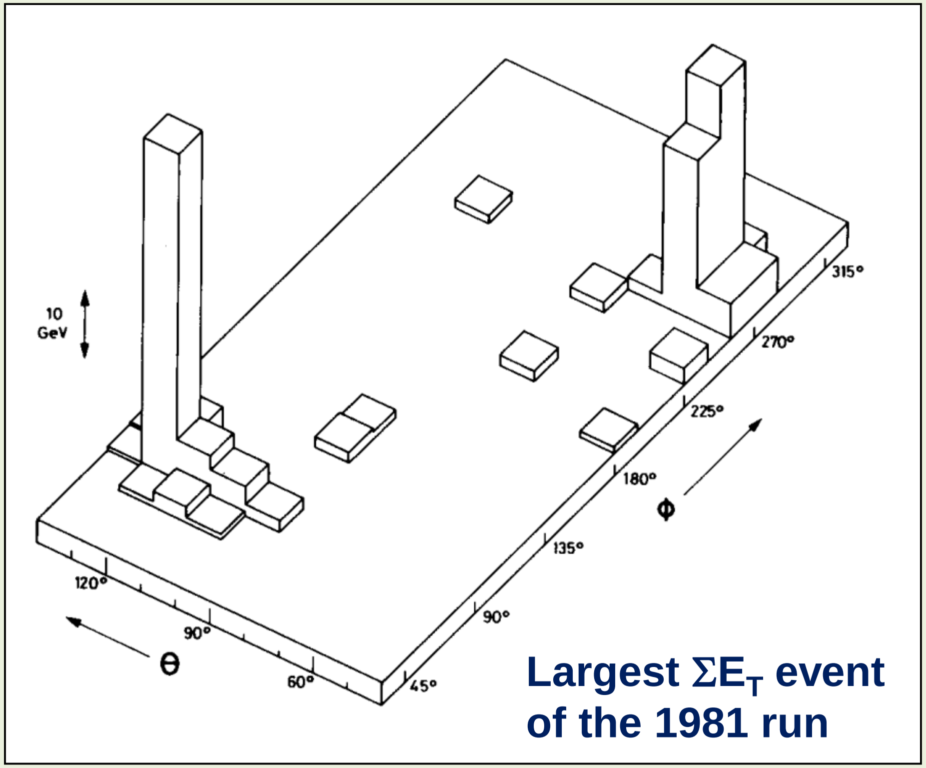
(fully non-magnetic, upgraded with new hermetic end-cap calorimeters for ET_{miss} …)



Emergence of two-jet processes in UA2 events with large transverse energy in the central calorimeter

UA2, Phys. Lett. B 118 (1982) 203





Largest ΣE_T event of the 1981 run

$$h_1 = \frac{E_T^1}{\Sigma E_T}$$ fraction of total $\mathbf{E_T}$ carried by leading cluster

$$h_2 = \frac{E_T^1 + E_T^2}{\Sigma E_T}$$ fraction of total $\mathbf{E_T}$ carried by the two leading clusters

At that time: jet = cluster = adjacent cells above a threshold

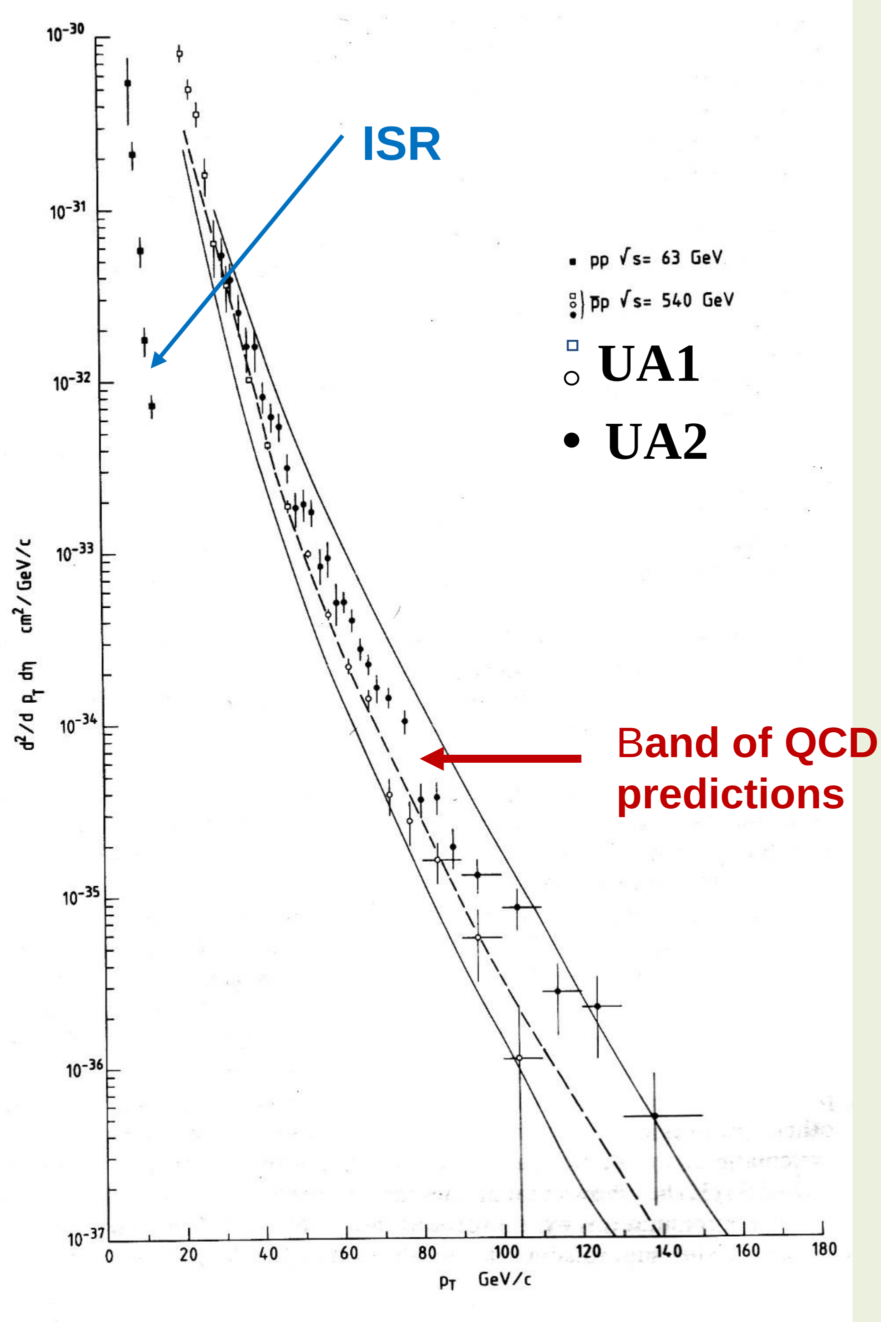
Early differential cross-section measurements for inclusive jet production at 90° compared to QCD calculations (1983-1985)

Relative contributions of parton scattering processes:

$$\bar{q} + q \to \bar{q} + q \qquad 1.0$$

$$\left.\begin{array}{l}\bar{q} + g \to \bar{q} + g \\ g + q \to g + q\end{array}\right\} \qquad 1.2$$

$$g + g \to g + g \qquad 6.0$$

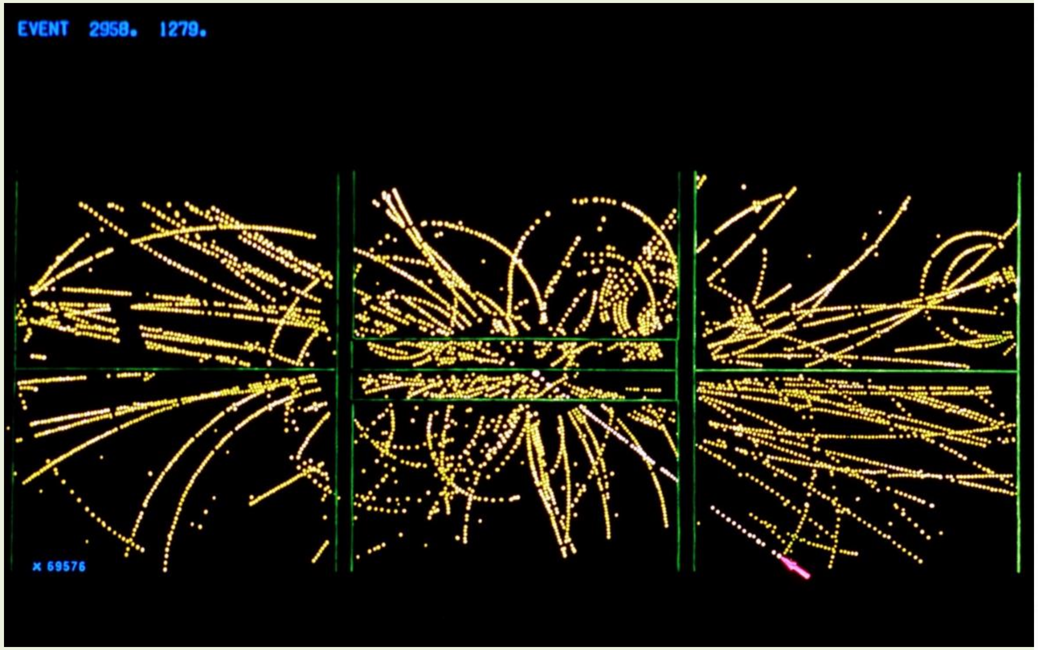


ISR

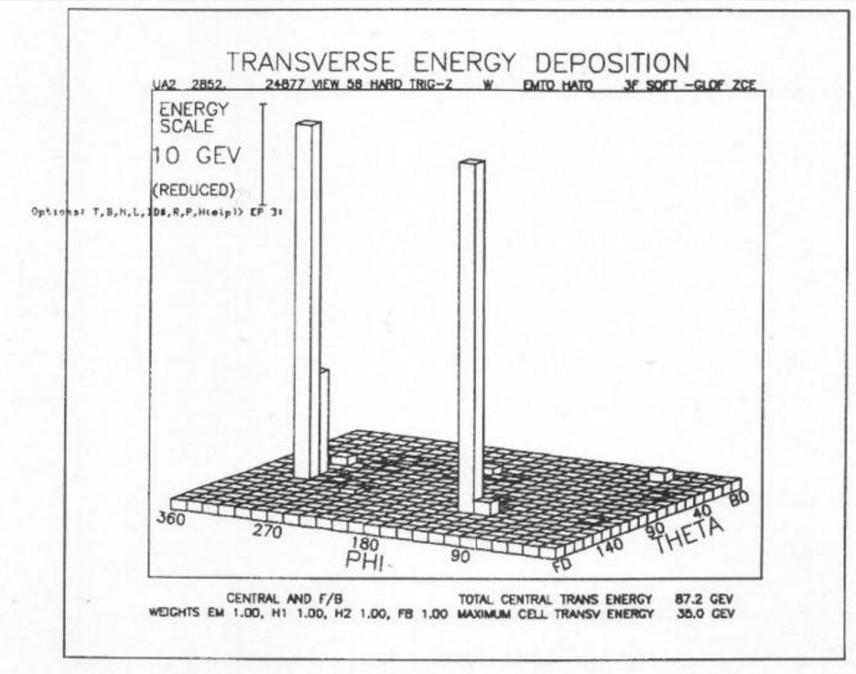
Band of QCD predictions

W and Z boson discovery (1982/3)

W discovery press conference 25 January 1983 with Rubbia, van der Meer, Schopper, Gabathuler, Darriulat

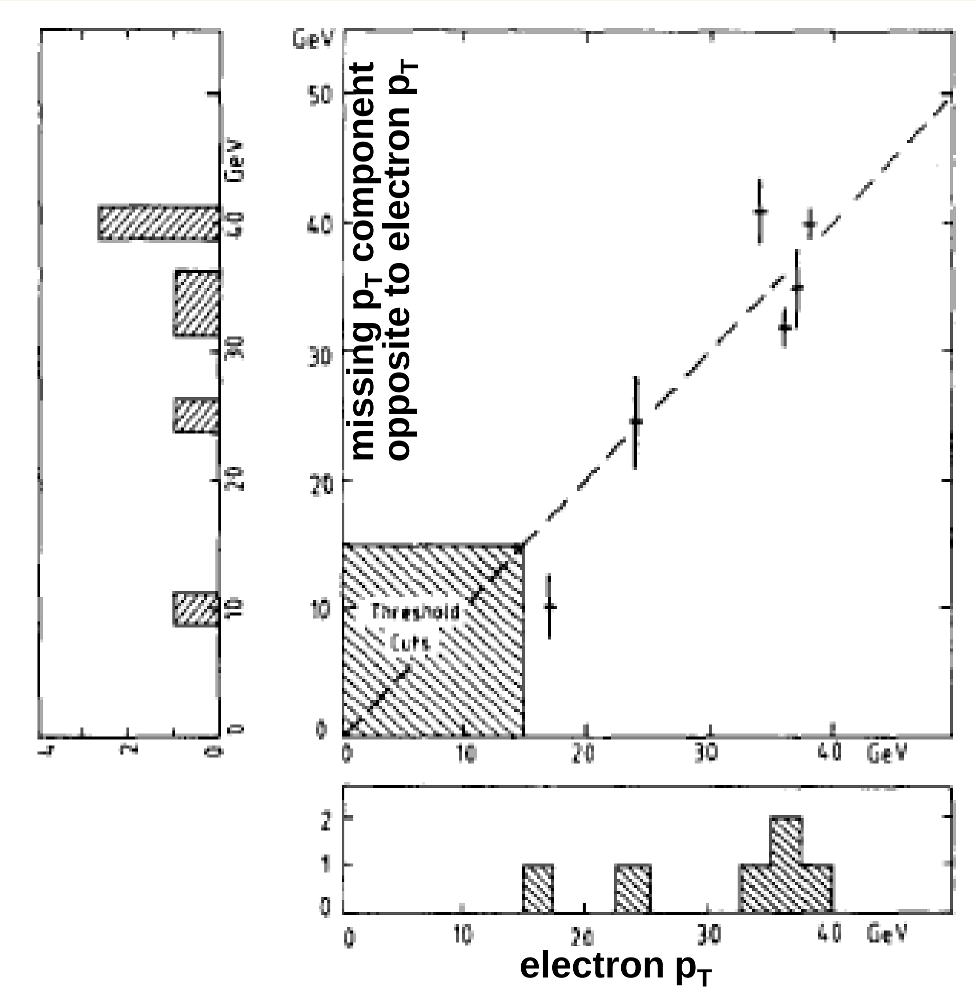


UA1 W → eν event, the arrow points to the electron, 1982

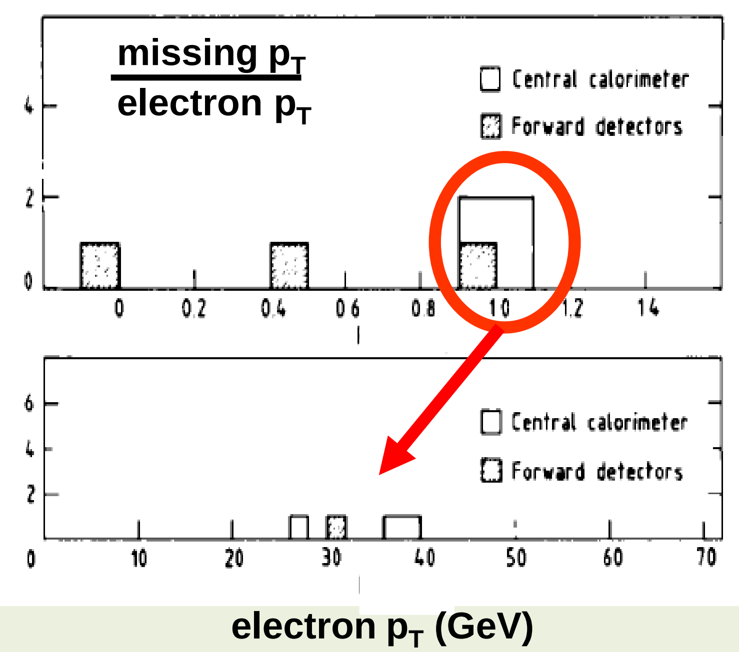


UA2 online display of a Z → ee event, 1983

UA1



UA2



The W → eν results presented on 20 and 21 January 1983 by both teams at CERN

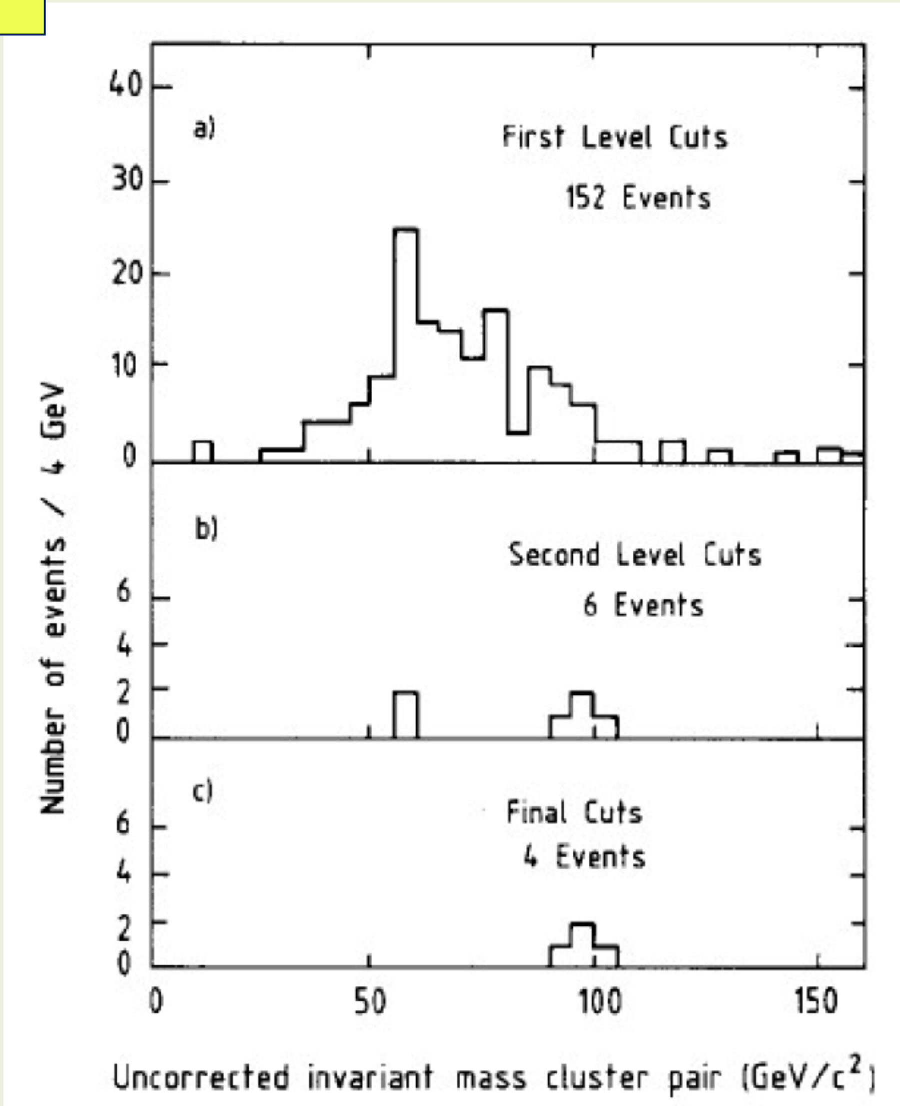
$W^{\pm}$

UA1, Phys. Lett. B 122 (1983) 103

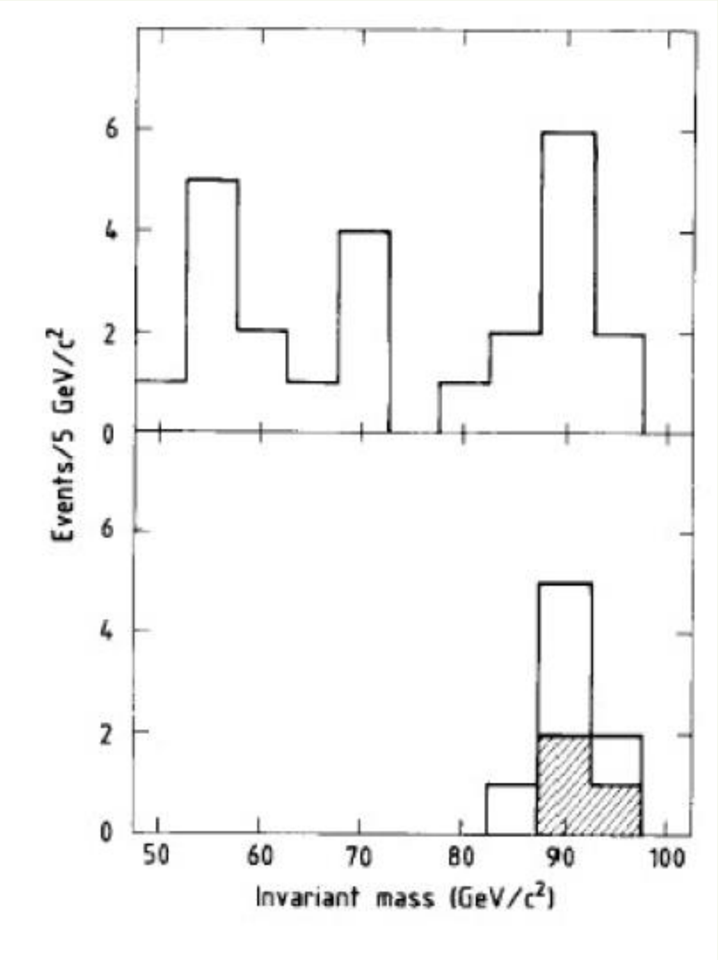
UA2, Phys. Lett. B 122 (1983) 476

Z°

UA1



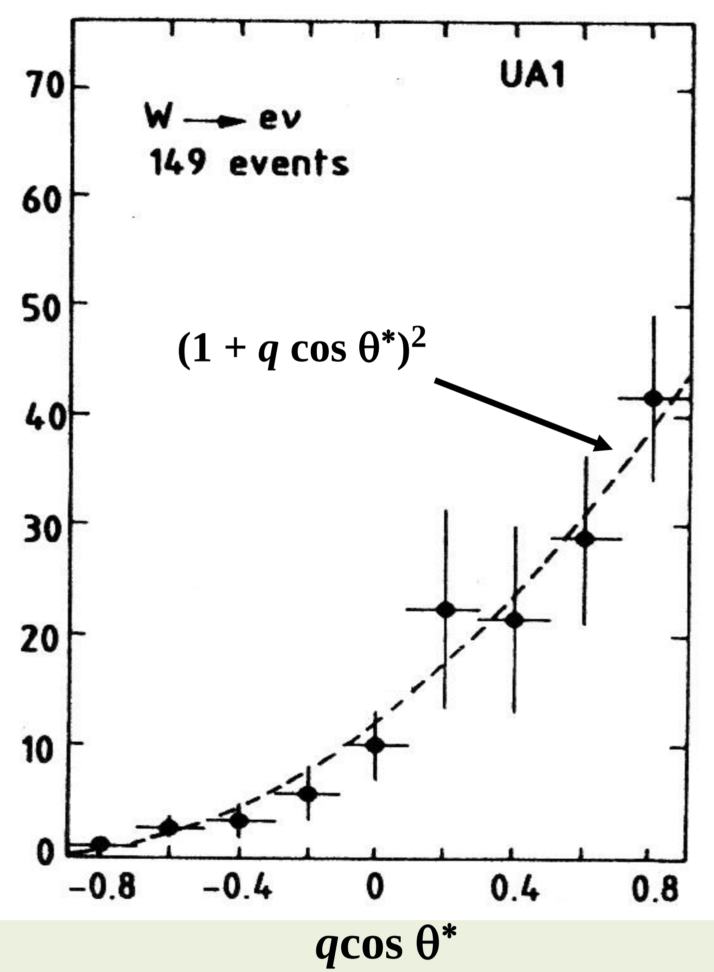
UA2

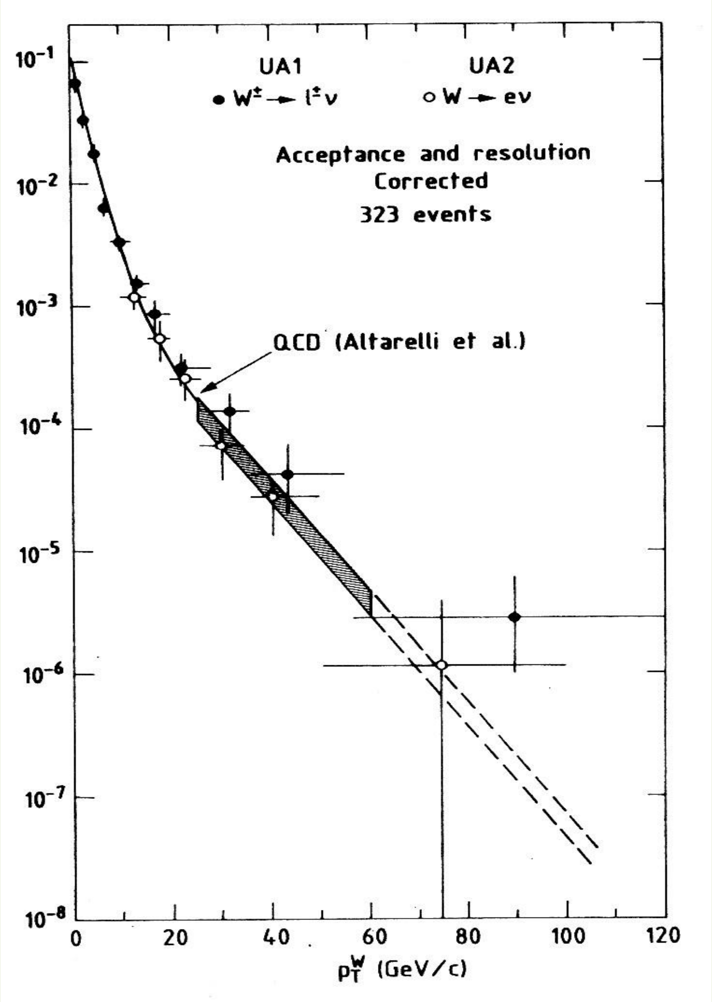


The Z → ee results presented in May and June 1983 at CERN

UA1, Phys. Lett. B 126 (1983) 398

UA2, Phys. Lett. B 129 (1983) 130





W± polarization along antiproton direction (V – A coupling)

p_T^W distribution was predicted from QCD

At the end of the CERN proton-antiproton collider, the first ‘precise’ measurement of the W mass by UA2

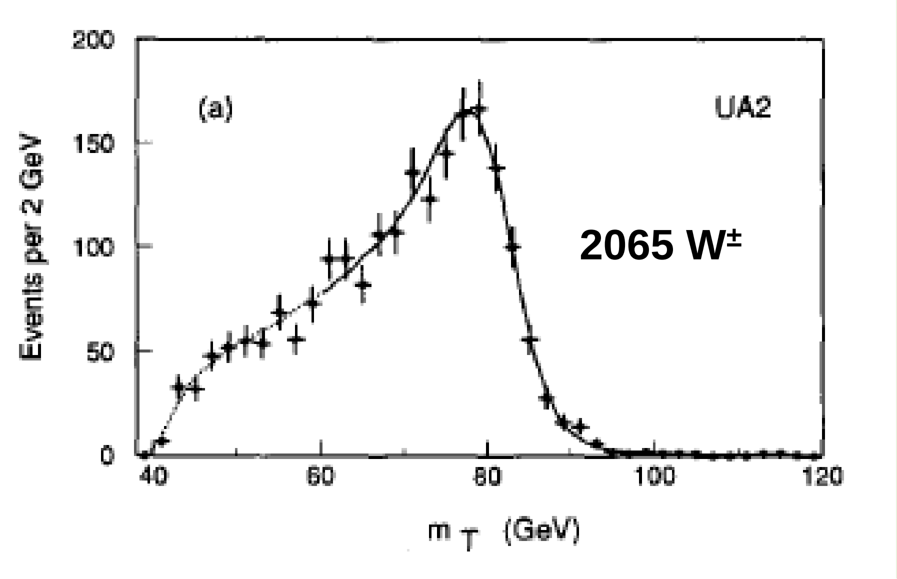
Exploit a precise measurement of the ratio $r = m_W / m_Z$ to avoid the the calorimeter calibration uncertainty and use the precise measurement for m_Z from LEP and SLD
(direct m_W fit 80.84 ± 0.22 GeV ±1% calibration)

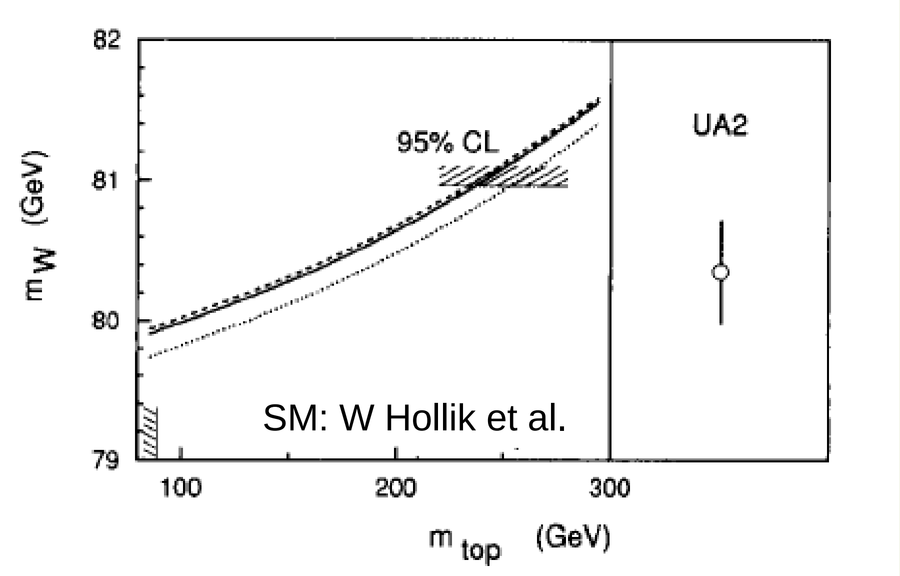
$r = 0.8813 \pm 0.0036 \pm 0.0019$

yielding $m_W = 80.35 \pm 0.33 \pm 0.17$ GeV

This gave a bound on the mass of the top quark in the frame of the Standard Model, five years before the top quark discovery at Fermilab

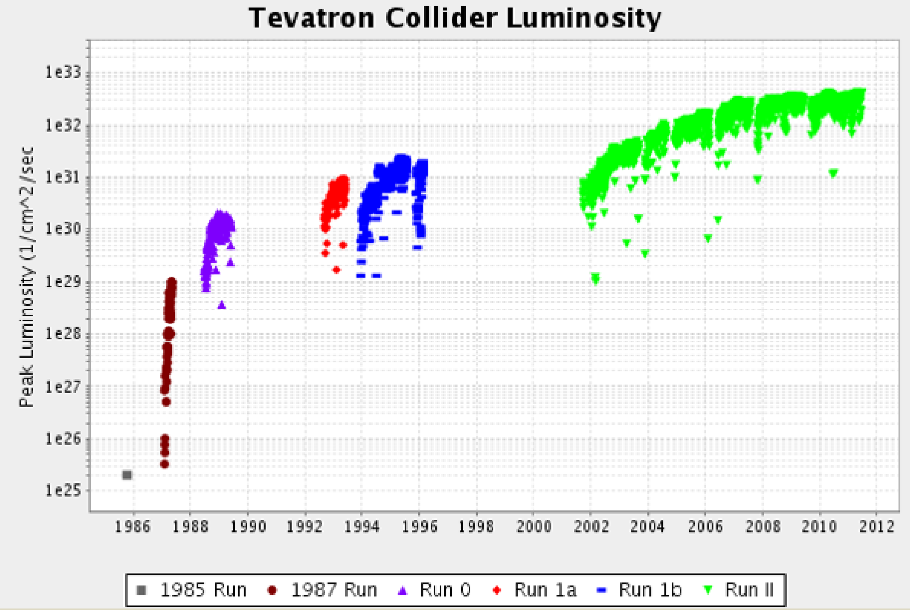
$m_{top} = 160 \ ^{+50}_{-60}$ GeV

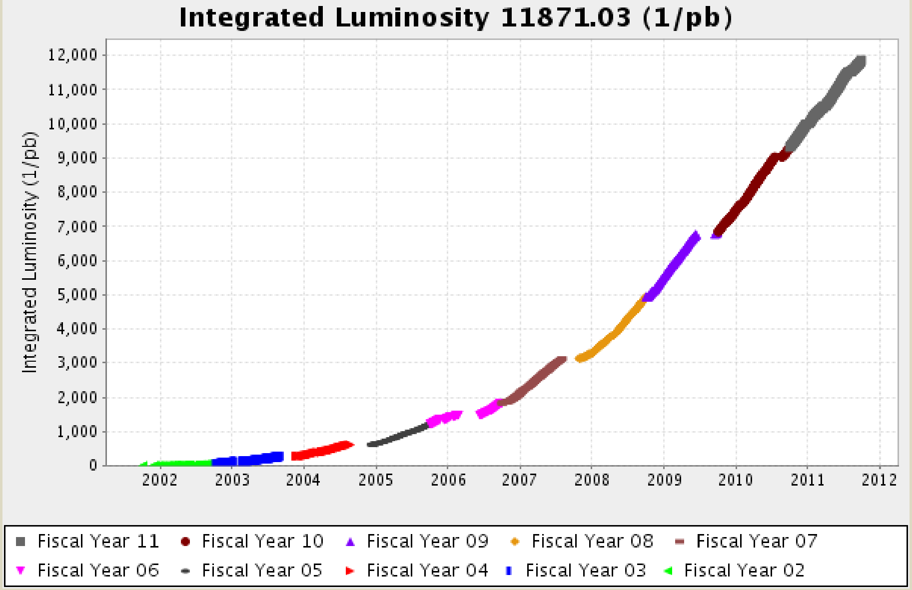




Tevatron, CDF and DØ: a Legacy Impact on the SM

Tevatron proton-antiproton Collider run and performance history





<u>Run 0</u> (1987 – 1988):

1.8 TeV, CDF only, 4 pb^{-1}

<u>Run I</u> (1992 – 1996):

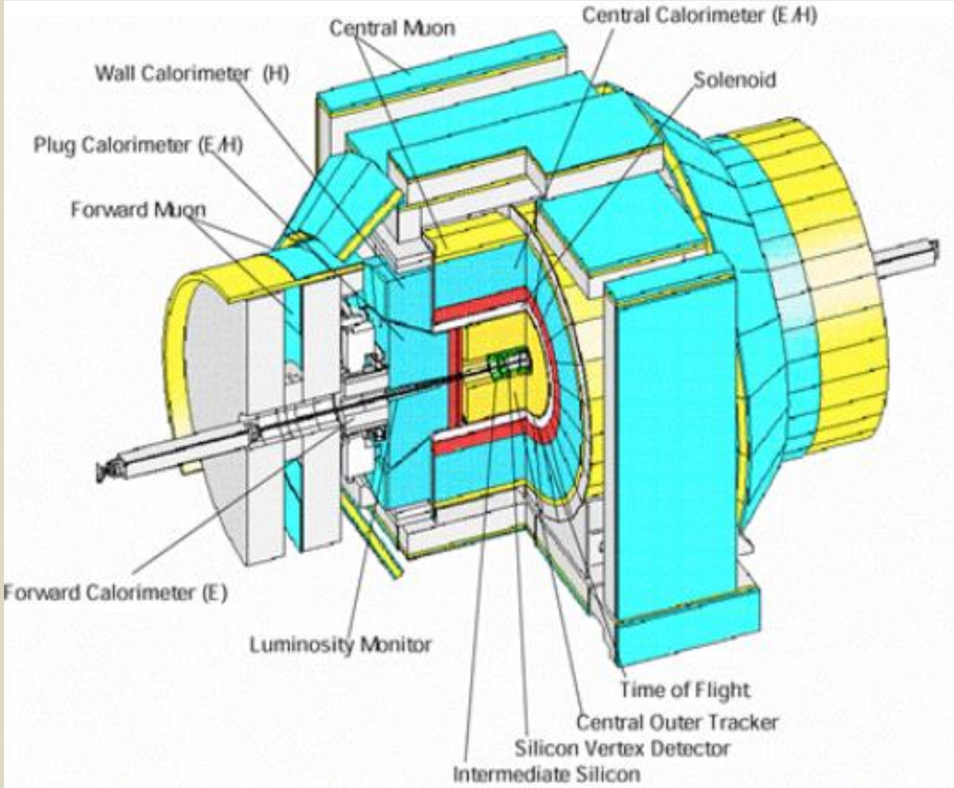
1.8 TeV, CDF+DØ: 120 pb^{-1}

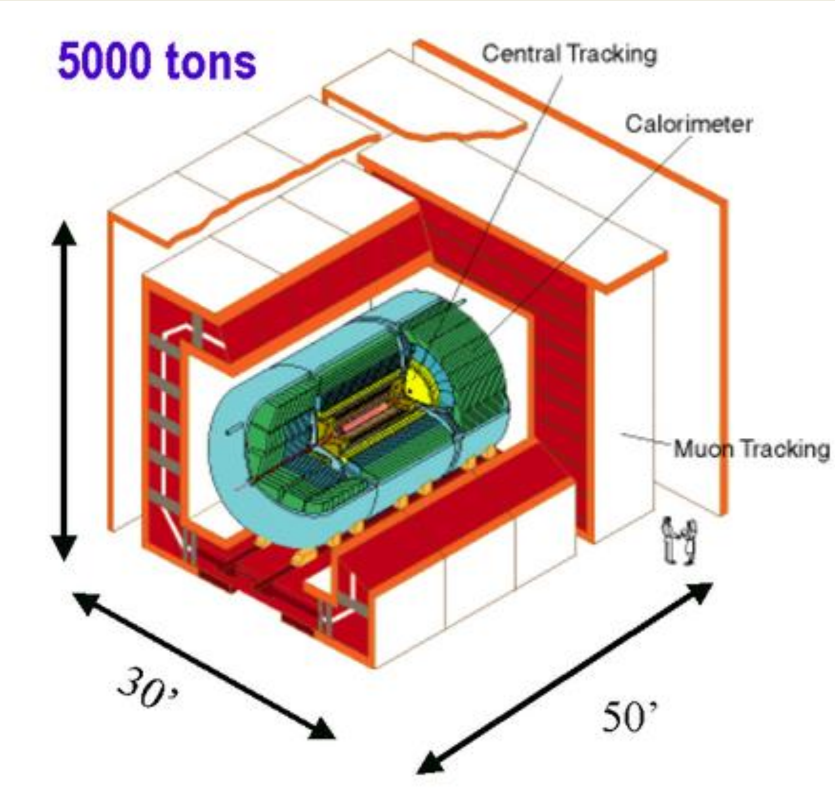
<u>Run II</u> (2001 – 2011):

1.96 TeV, 12 fb^{-1}

→ Superb performance with added Main Injector, Recycler Ring …

The initial detectors (Run I) already were designed like general-purpose experiments, with a complexity and sophistication well beyond what has been done before. (Shown are drawings for the Run II detectors.)





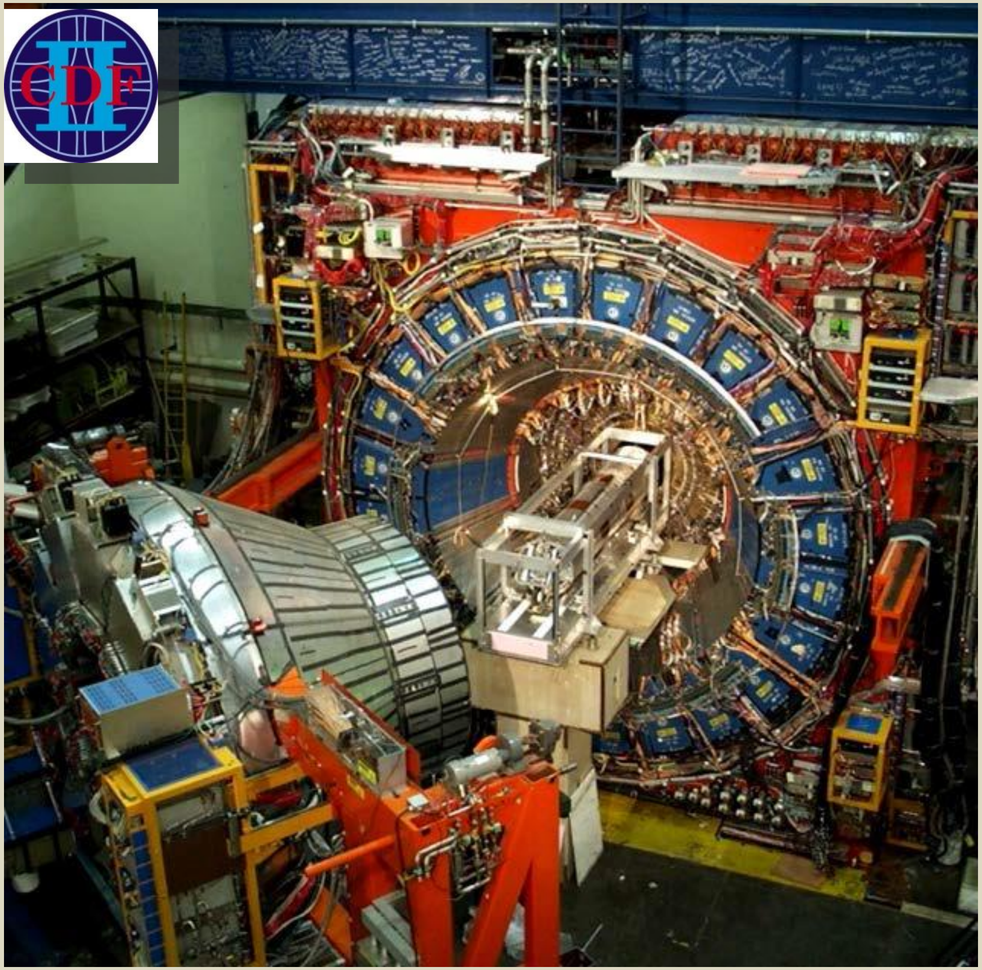
CDF

DØ

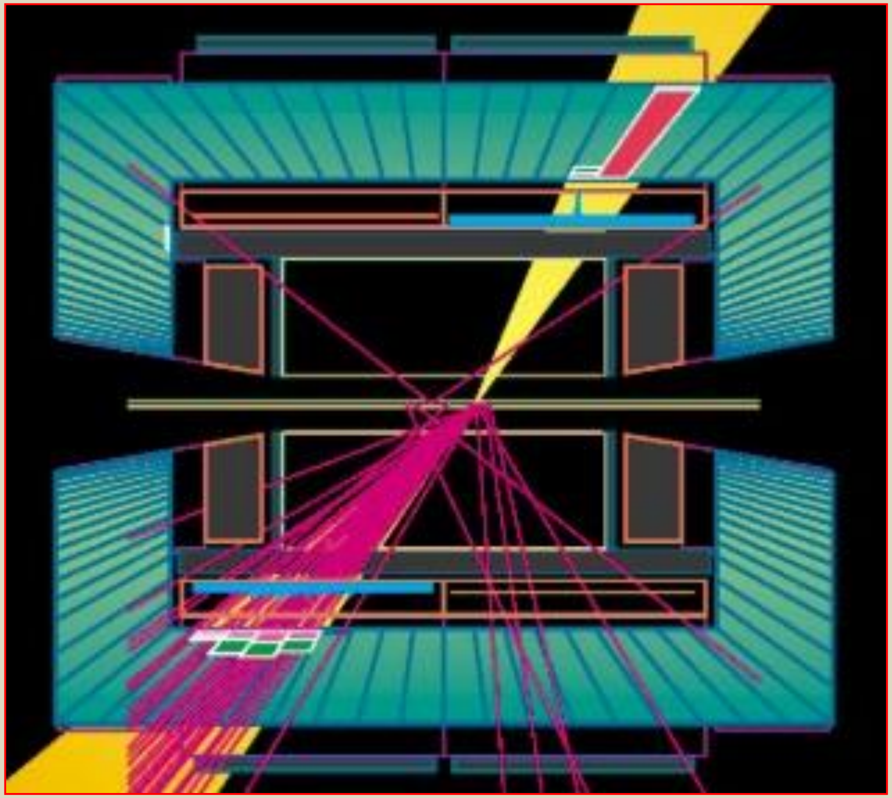
Major detector upgrades for Run II:

CDF: new tracker, new Si vertex detector, upgraded endcap/forward calorimeters, muons, FE electronics and track-triggers

DØ: solenoid, fiber tracker, Si vertex and preshower detectors, new fwd muon detectors.

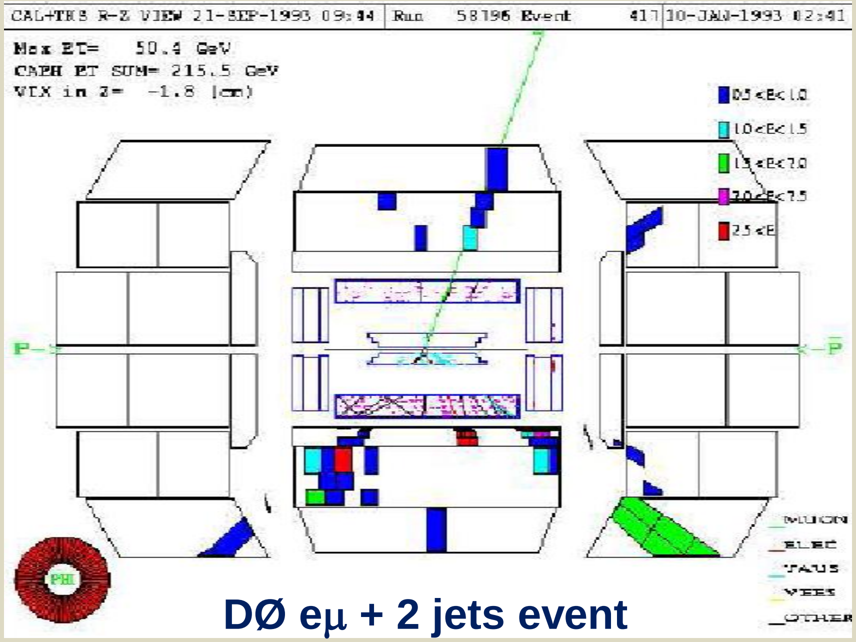


The CDF and D0 Collaborations pioneered many of the modern analysis methods that are now used and further developed at LHC

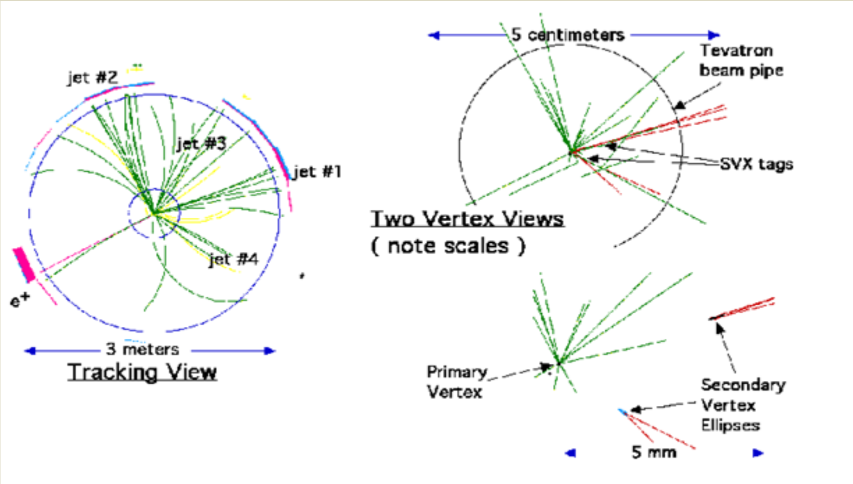


Top quark discovery: Major step establishing the Standard Model

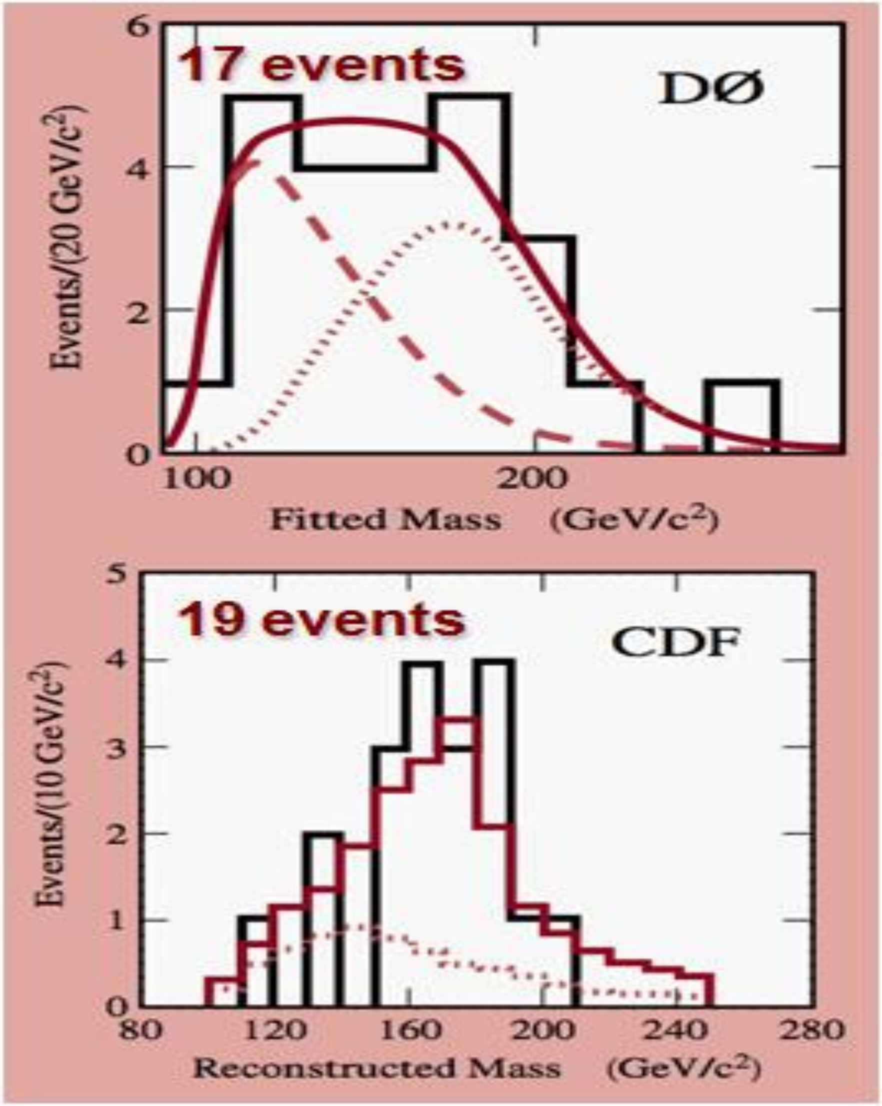
(CDF and DØ, 24th February 1995 papers submitted, 2nd March 1995 joint seminar)



DØ eμ + 2 jets event



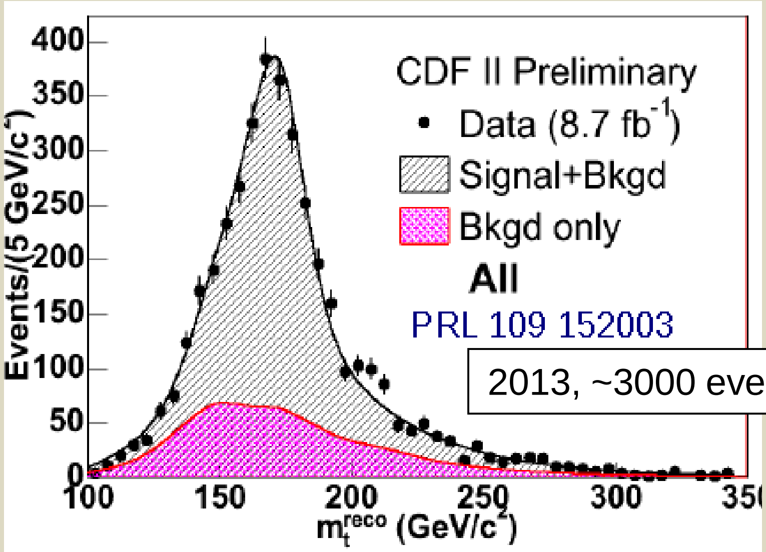
CDF secondary vertices b-jet event



1995, CDF and DØ experiments, Fermilab

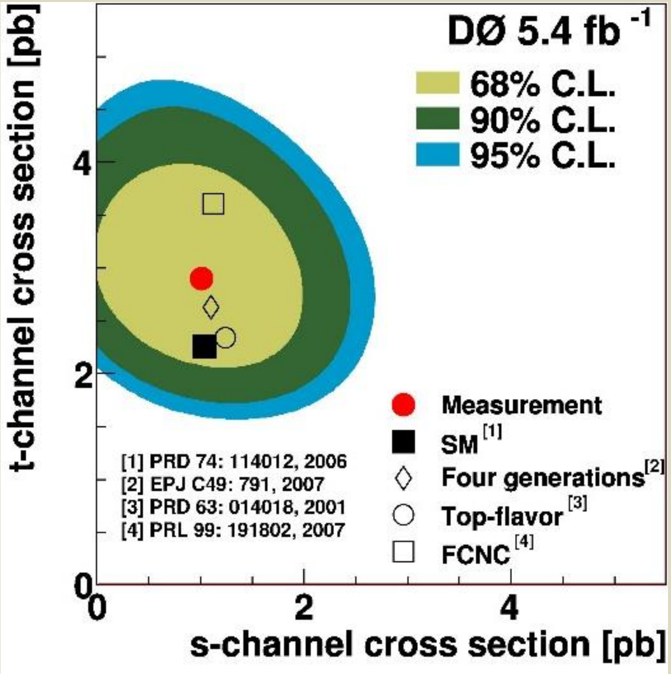
CDF Phys. Rev. Lett. 74 (1995) 2626
D0 Phys. Rev. Lett. 74 (1995) 2632

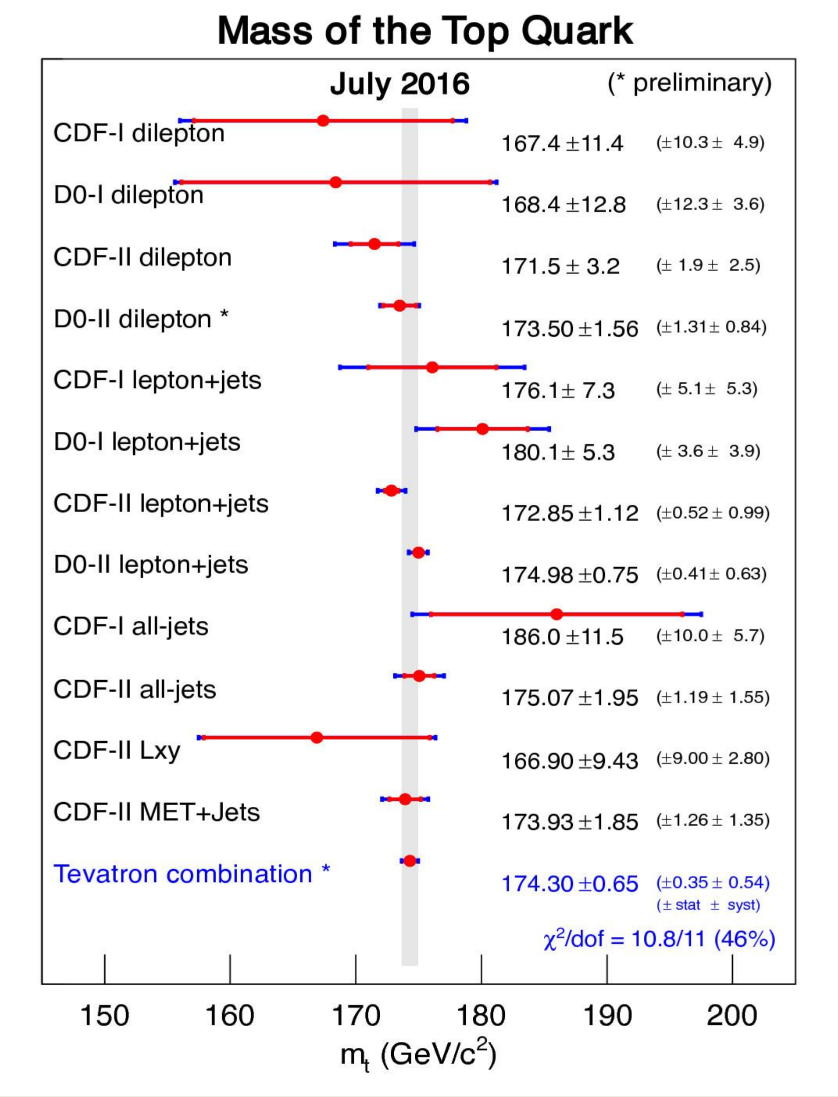
A very rich harvest of top physics followed, just a few examples…



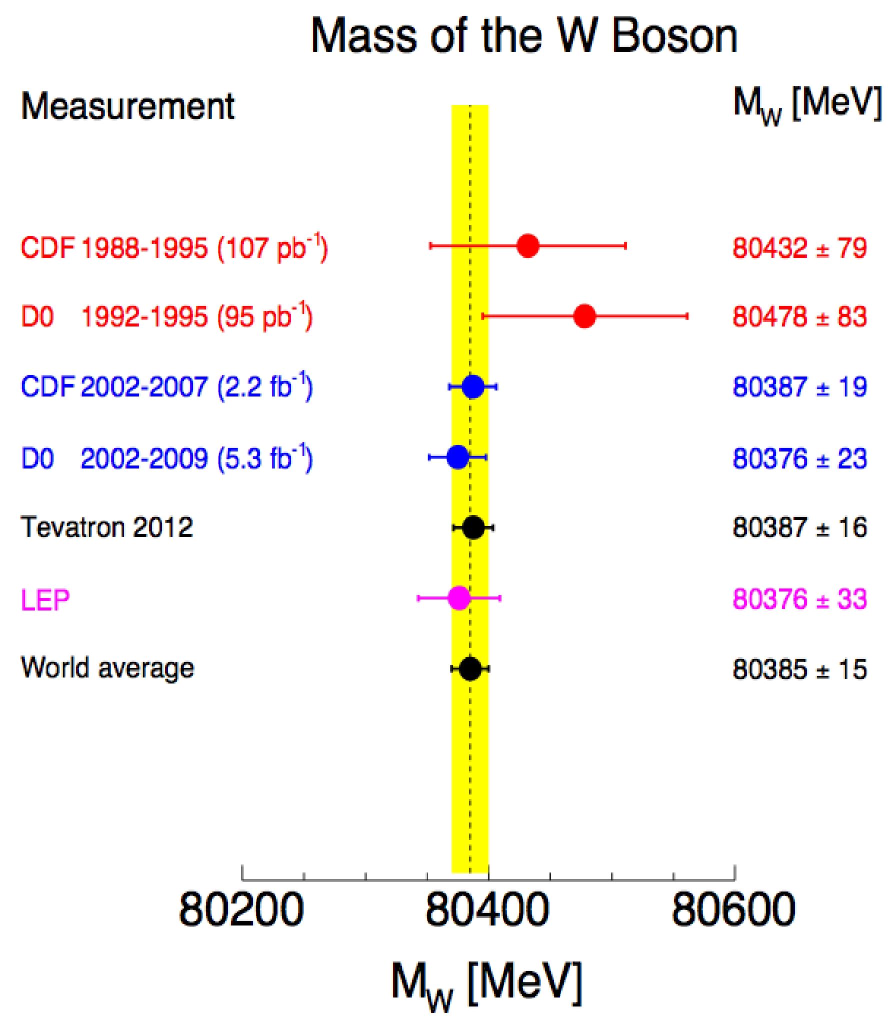
2013, ~3000 events

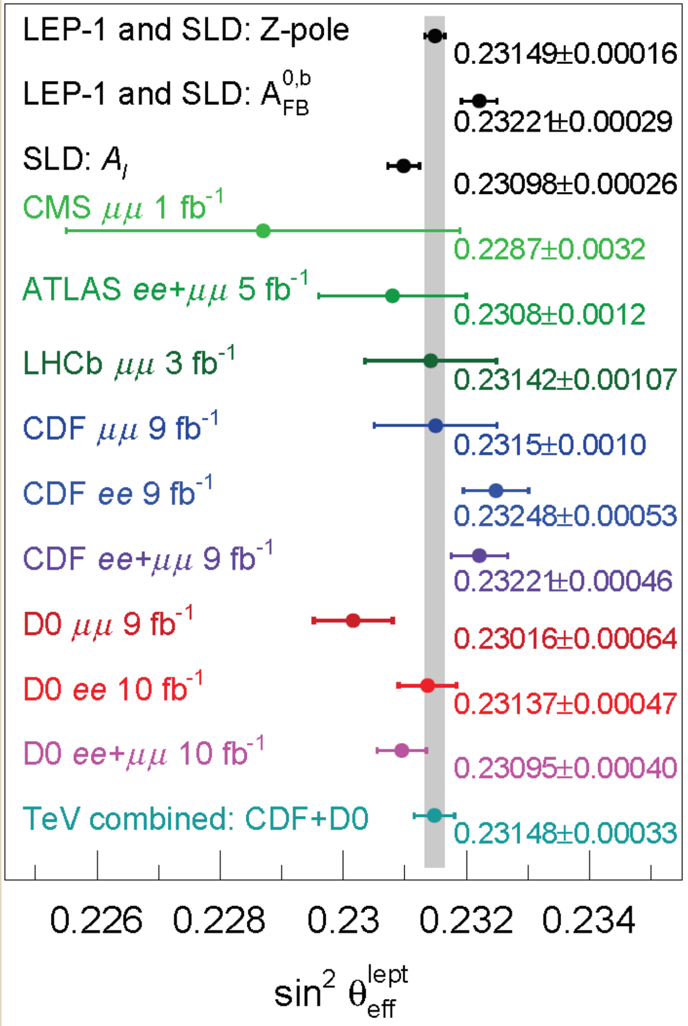
Single t production discovered 2009, thanks to sophisticated MV methods





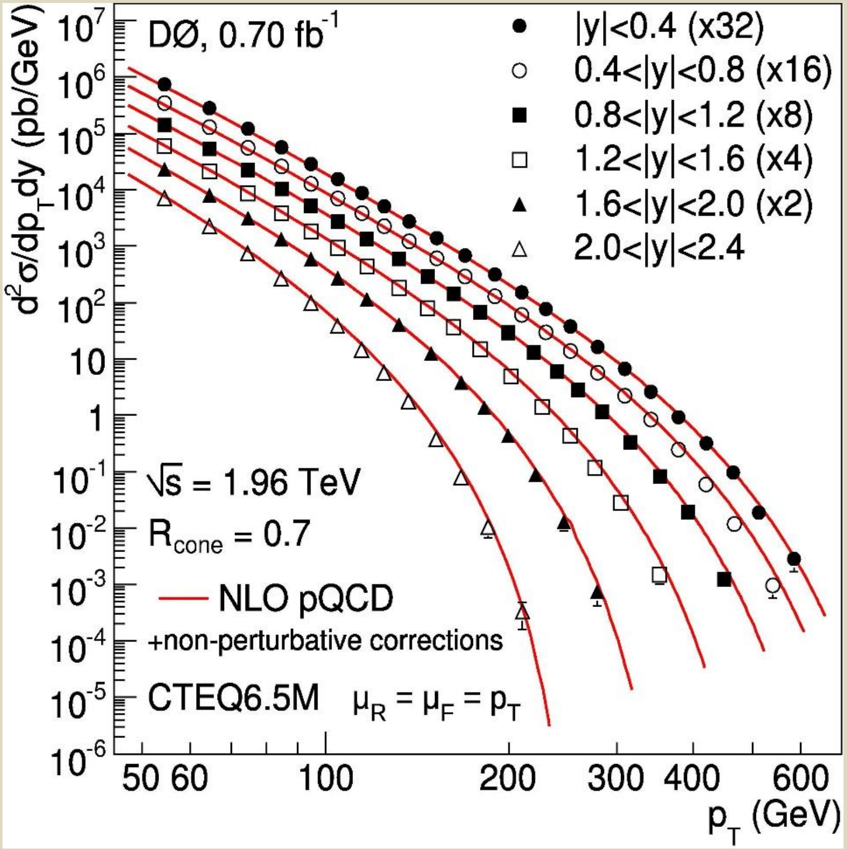
The Tevatron experiments set a standard for electro-weak precision measurements, also critical for Standard Model consistency checks



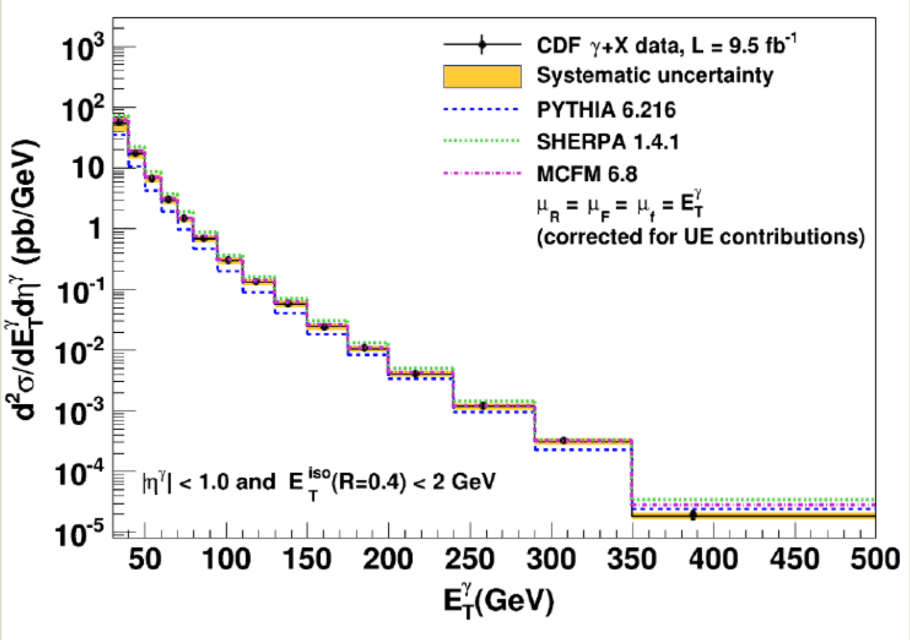


New 2018 result !

A rich harvest also on QCD hard scattering results, like for example detailed inclusive jet and prompt isolated photon cross-sections as shown here from D0 and CDF



Differential cross-sections for inclusive jets

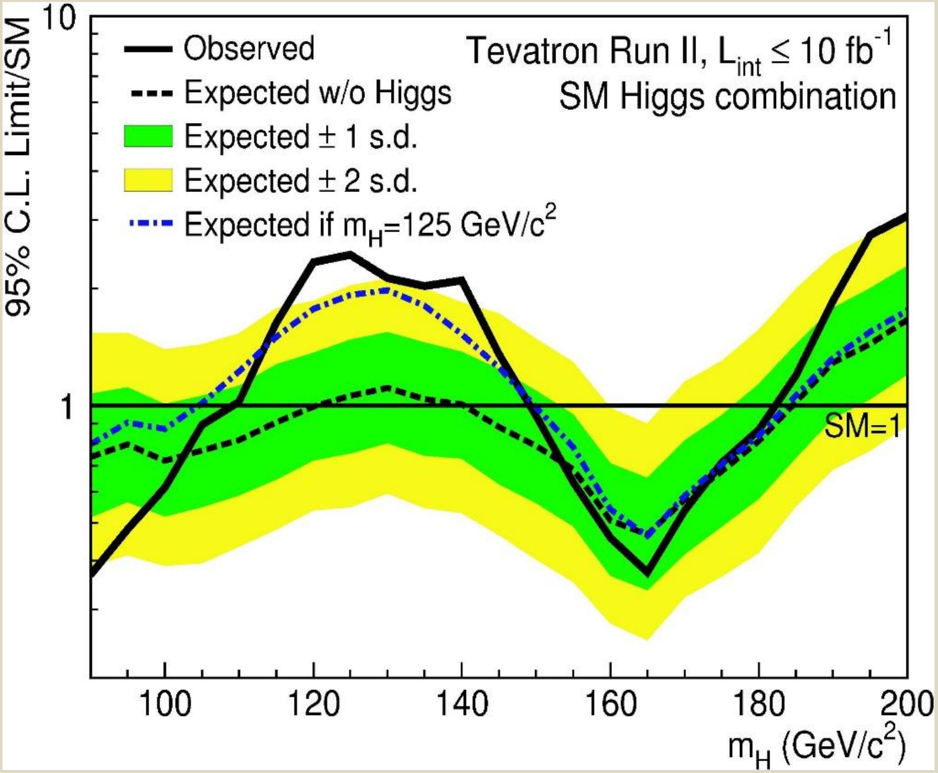


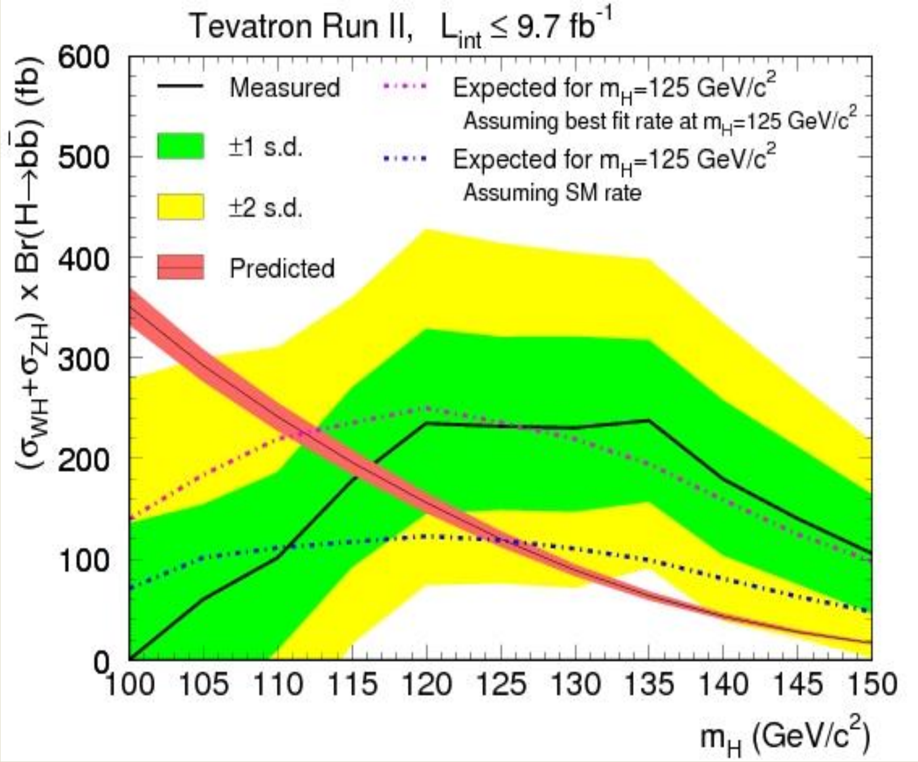
Differential cross-sections for prompt isolated photons

(As mentioned before, all the heavy flavour physics and the BSM searches are beyond the scope of this talk)

The hunt for the Higgs boson

CDF and D0 combined
Phys. Rev. Lett. 109 (2012) 071804



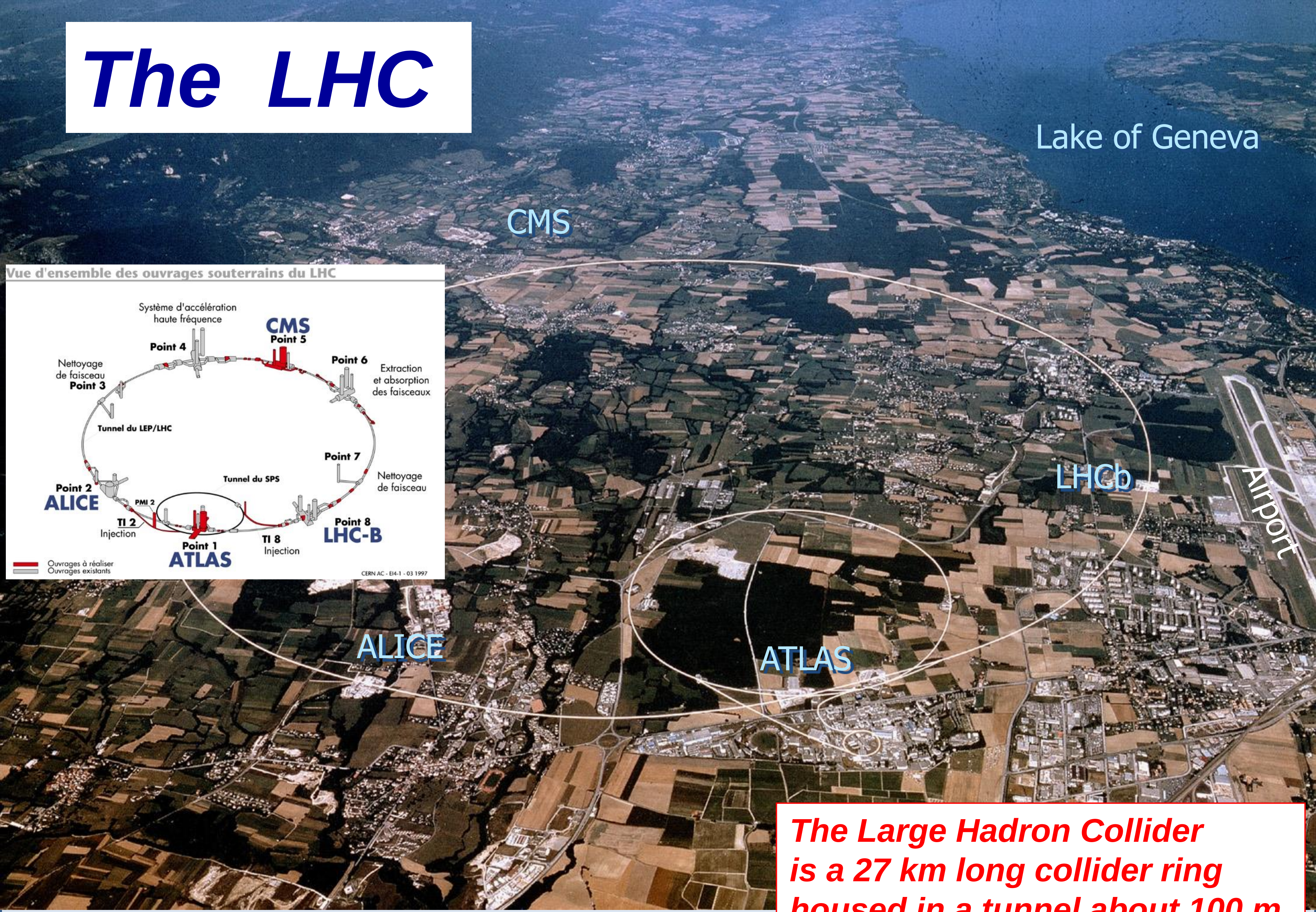


To quote Paul Grannis in his June 2018 Fermilab Users Meeting 'Tevatron Highlights' talk:

'The Higgs was discovered in 2012 at LHC in the $\gamma\gamma$ & ZZ decays. Simultaneously, CDF & DØ obtained the first 3σ evidence for H→bb using the combined W(lν)H, Z(ll)H and Z($\nu\nu$)H channels. This preceded the LHC evidence for fermionic Higgs decays by 4 years and was the first direct evidence for the Higgs Yukawa coupling.'

(Of course I could not say it better …)

The LHC



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

The first picture on the Web in 1992 !

How the LHC came to be …

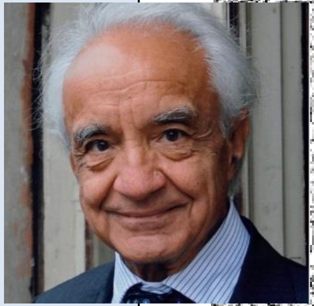
Some very early key dates

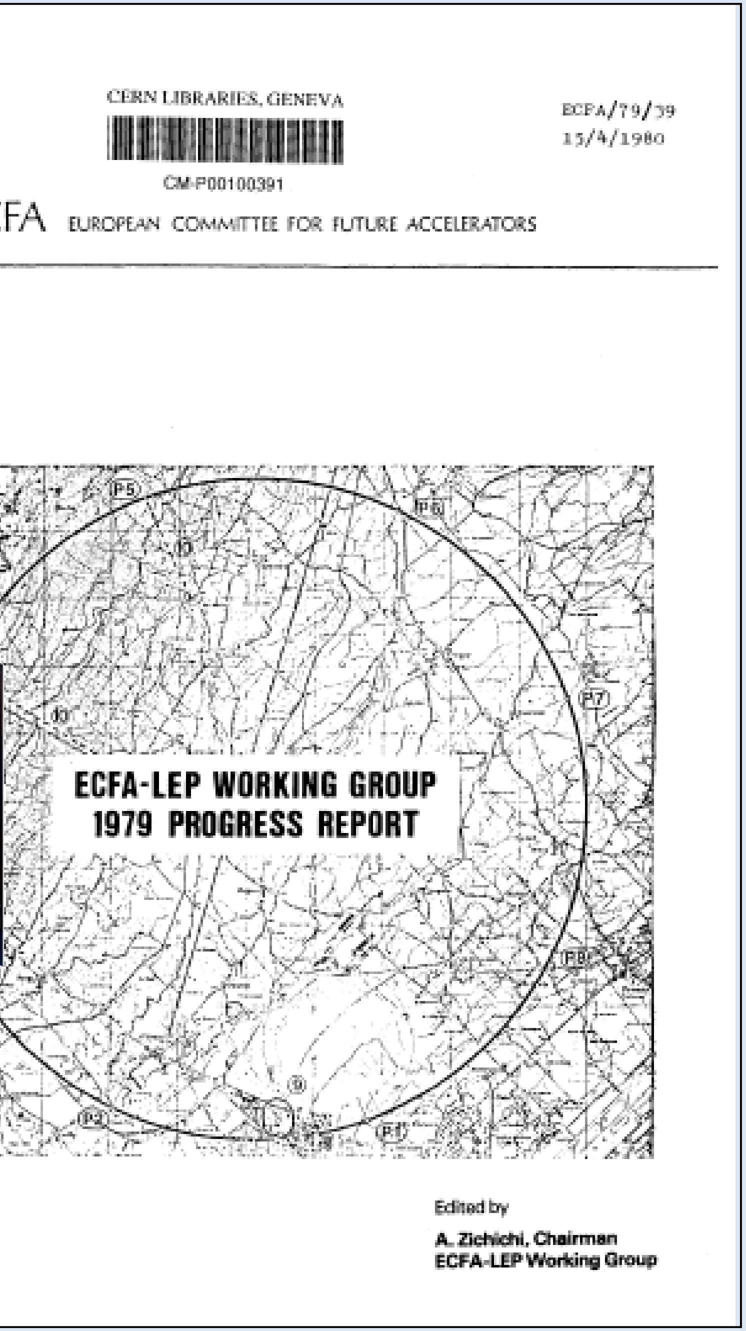
1977 The community talked about the LEP project, and it was already mentioned that a new tunnel could also house a hadron collider in the far future

1979 LEP White Book:

ECFA-LEP Working Group 1979 chaired by A Zichichi

‘Tunnel with 27 km circumference and a diameter of 5 m, with a view to the replacement of LEP at the end of its activities by a proton-proton Collider using cryogenic magnets’





ECFA/79/39
15/4/1980

ECFA EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

ECFA-LEP WORKING GROUP
1979 PROGRESS REPORT

Edited by
A. Zichichi, Chairman
ECFA-LEP Working Group

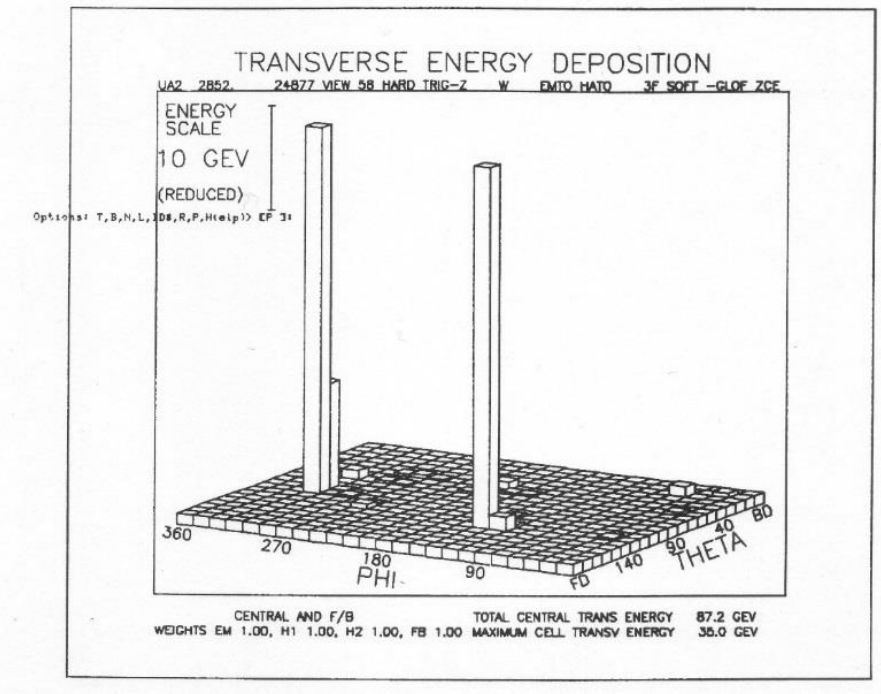
1981 LEP was approved with a large and long (27 km) ring tunnel

Herwig Schopper
CERN DG 1981 - 1988

1983 The early 1980s were crucial

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

A very early Z → ee online display from one of the detectors (UA2)



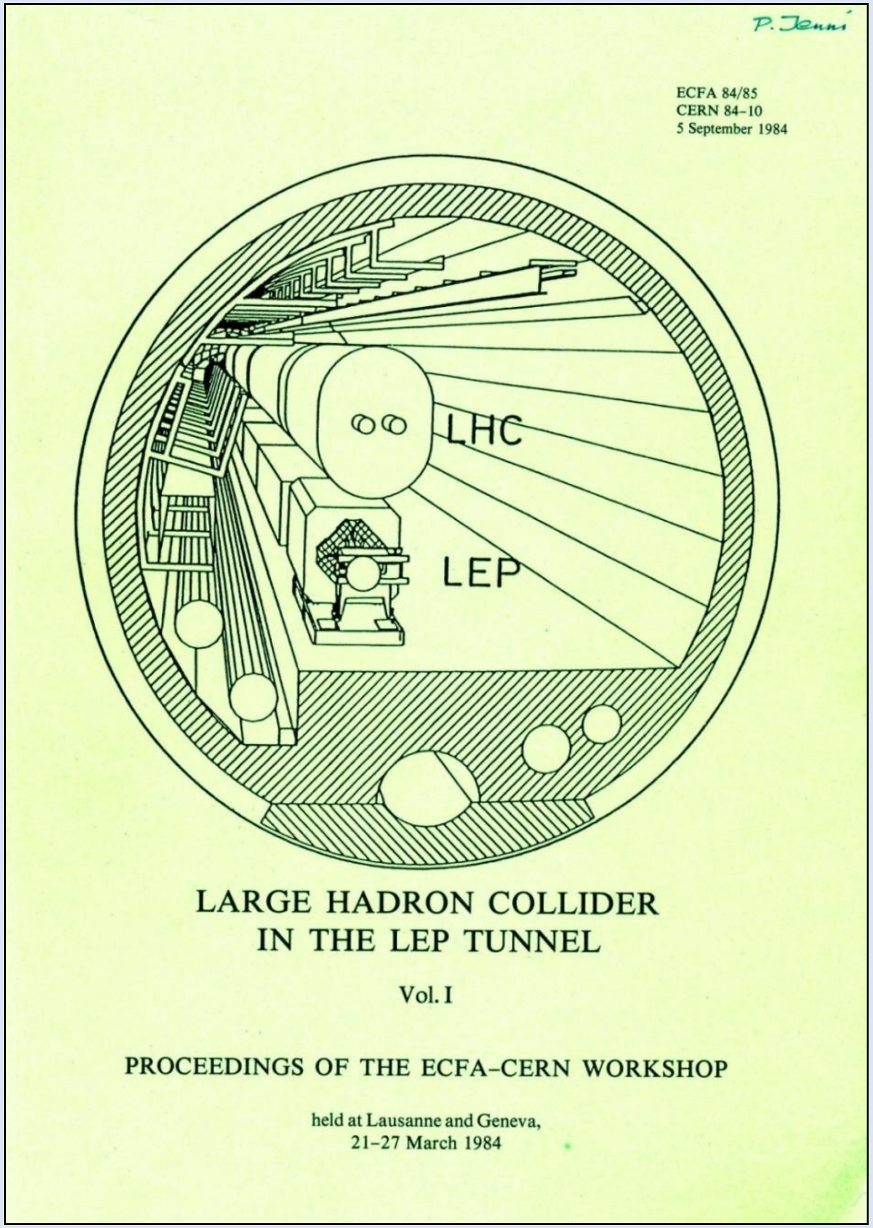
1984 For the community it all started with the CERN - ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel

Giorgio Brianti was leading the LHC machine studies until 1993

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

1987 La Thuile Workshop

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



P. Jenni

ECFA 84/85
CERN 84-10
5 September 1984

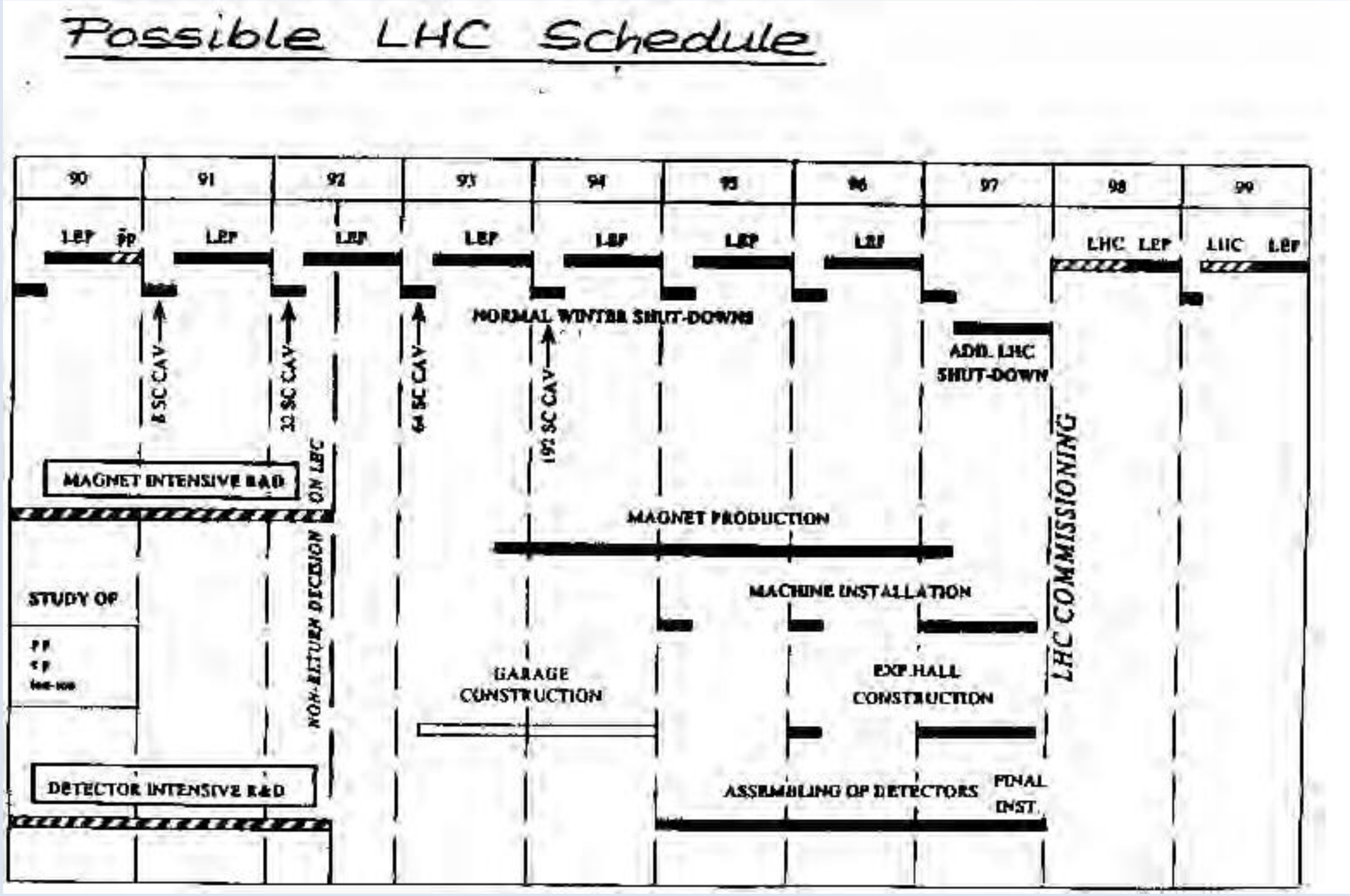
LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984

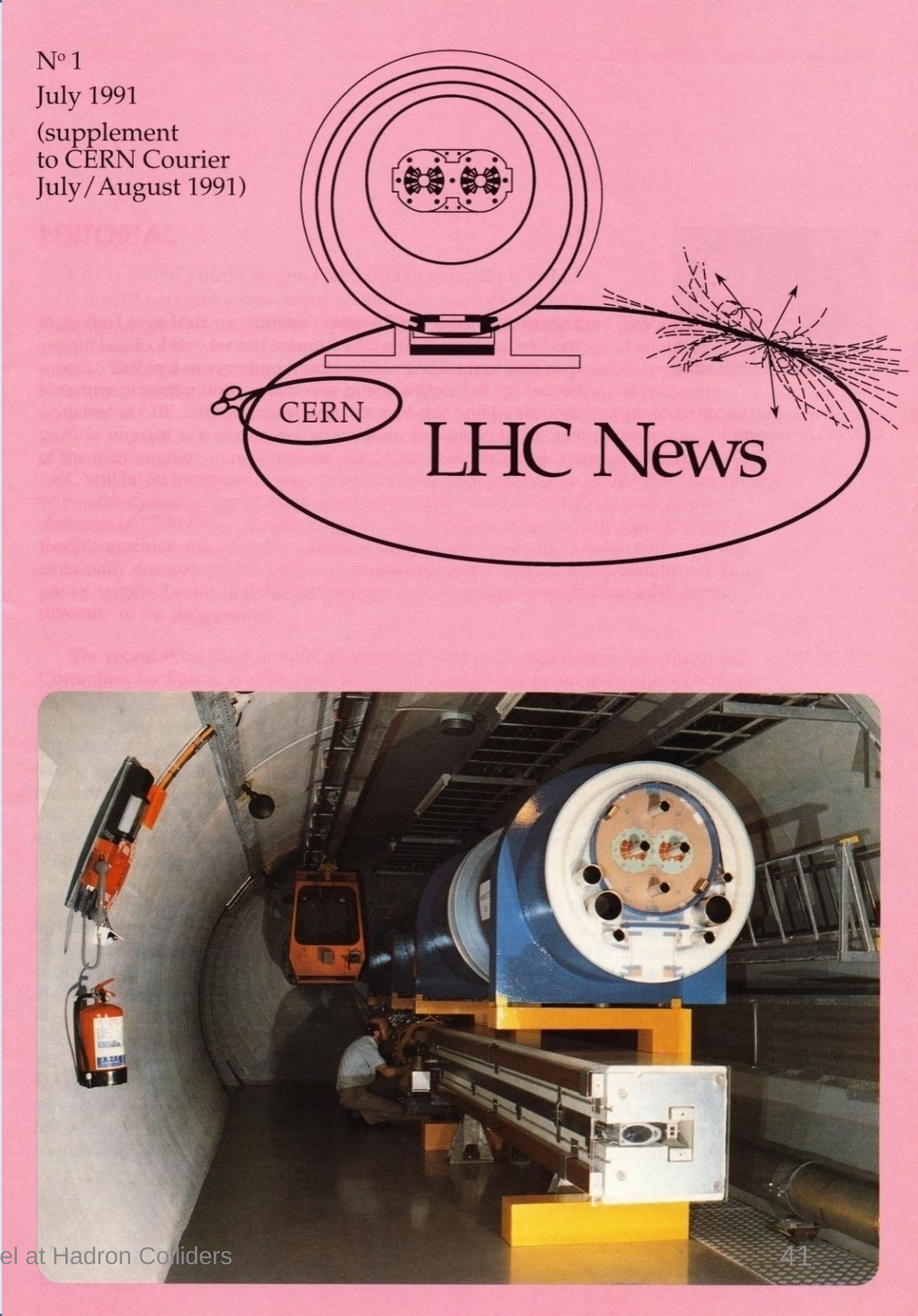
From a very early talk about the LHC, must have been around 1987 …



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

Minister Boris Saltykov and DG Carlo Rubbia signing an updated Cooperation Agreement Russia and CERN (28 June 1993)

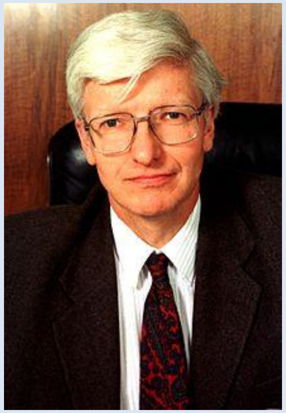


Nº 1
July 1991
(supplement
to CERN Courier
July/August 1991)

CERN

LHC News

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



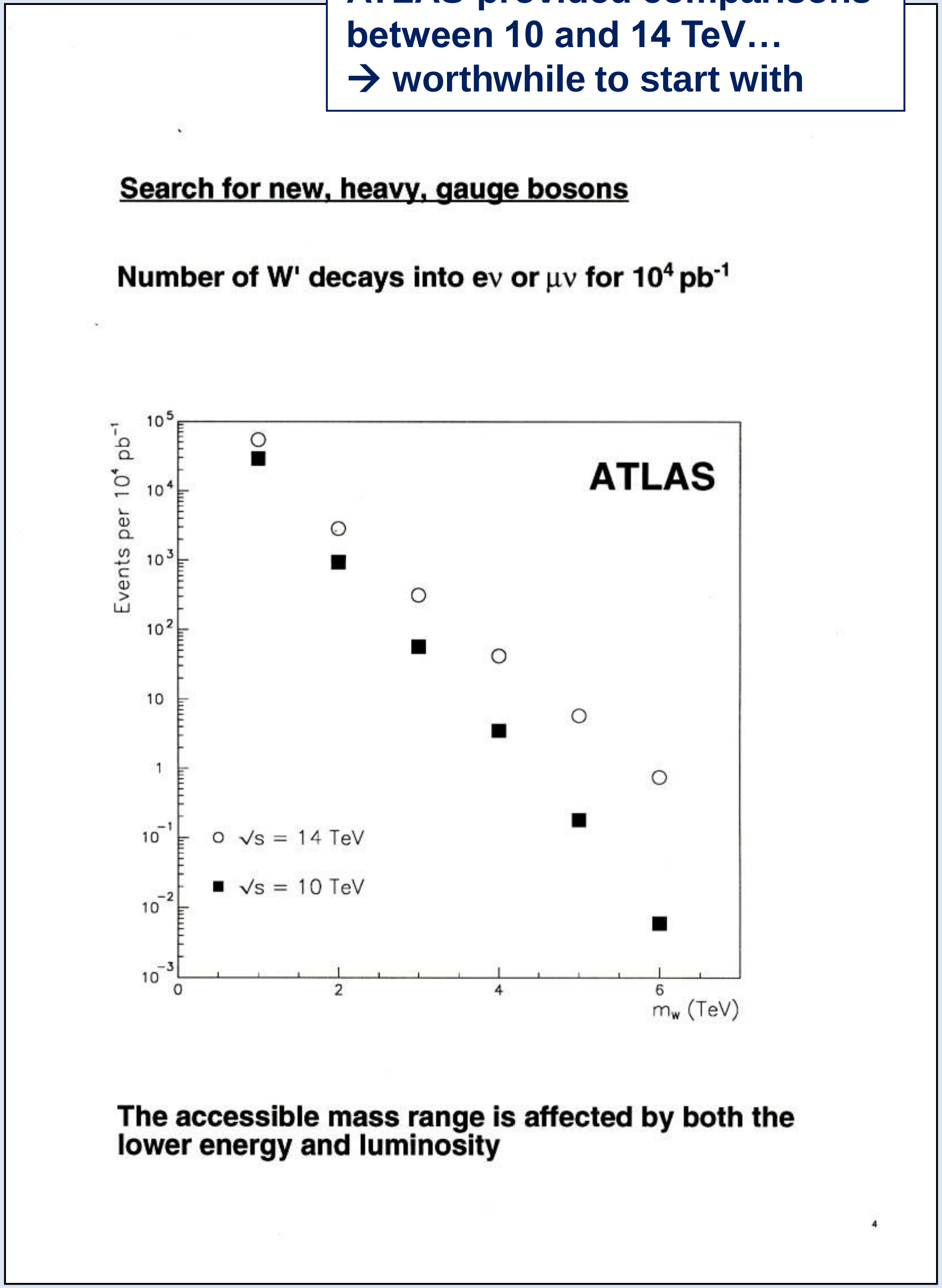
June 1994 Council:

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

16 December 1994 Council:

Two-stage construction of LHC was approved

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



Search for new, heavy, gauge bosons

Number of W' decays into eν or μν for 10^4 pb^{-1}

The accessible mass range is affected by both the lower energy and luminosity

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

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

1996

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

Signature of the Japan-CERN agreement on 1st June 1995

(K Yosana – Japanese Minister, H Curien – Council President, C Llewellyn-Smith – CERN DG, with the famous Daruma doll)

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

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

1996

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

Signature of the US-CERN machine and experiments protocols on 19th December 1997:
R Eisenstein (NSF), C Llewellyn Smith (CERN DG), M Krebs (DOE)

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

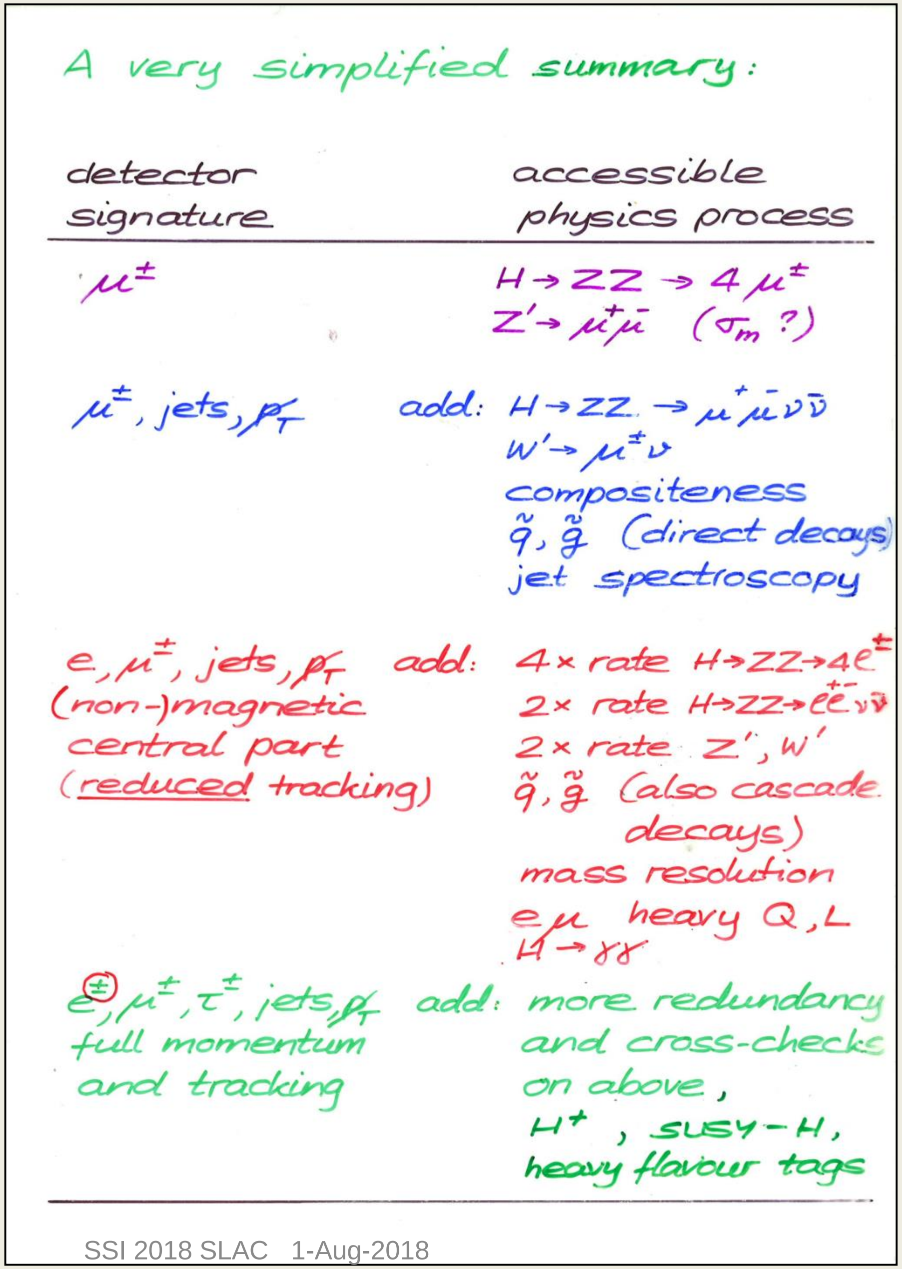
(Israel contributed all along to the full CERN programme and LHC)

1996

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

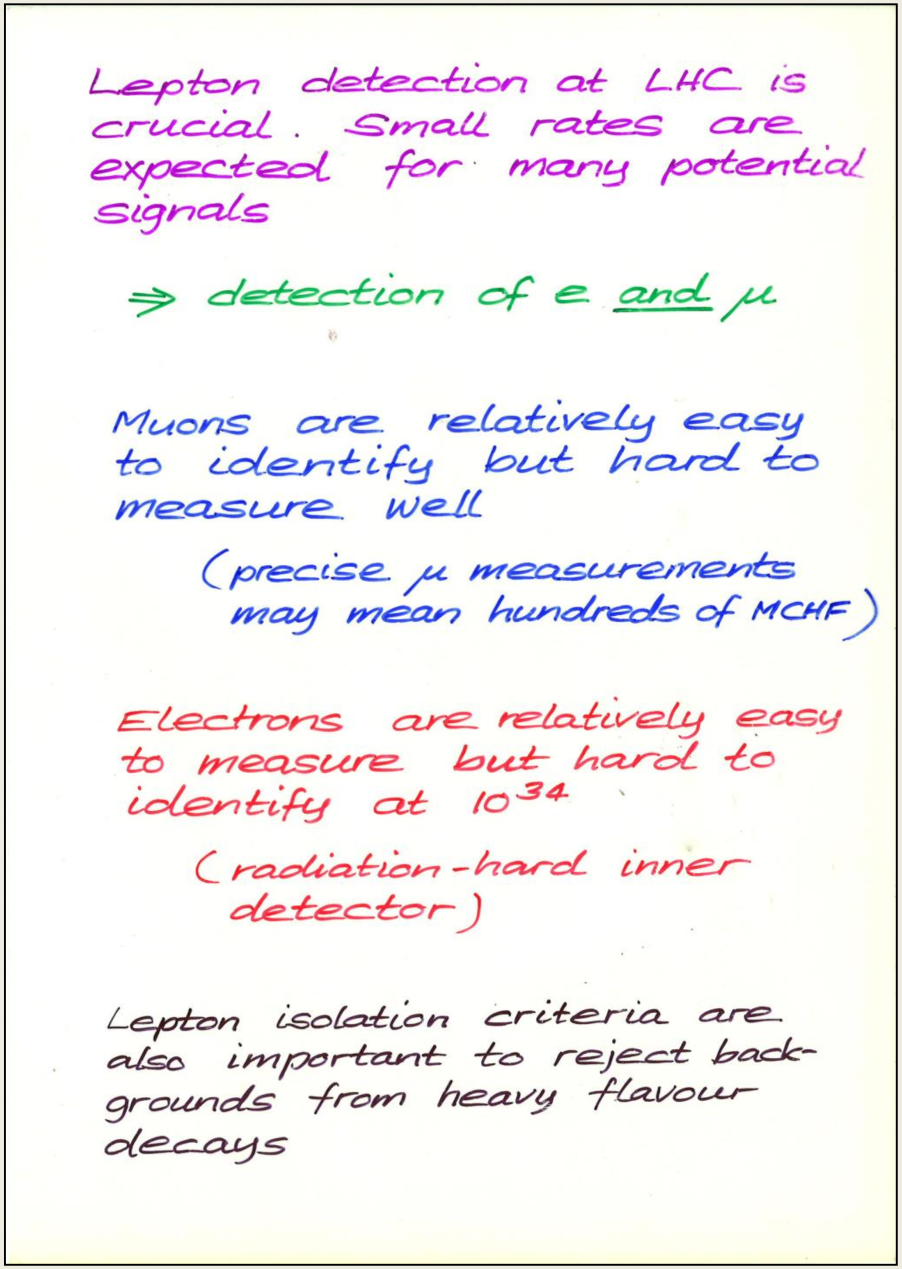
Delivery of the last dipole for the LHC injection lines from Russia (15th June 2001), with L Maiani and A Skrinsky in the centre

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



A very simplified summary:

detector signature	accessible physics process
$\mu^\pm$	$H \to ZZ \to 4\mu^\pm$ $Z' \to \mu^+\mu^-$ (σ_m ?)
$\mu^\pm$, jets, $p\!\!\!/_T$	add: $H \to ZZ \to \mu^+\mu^-\nu\bar{\nu}$ $W' \to \mu^\pm\nu$ compositeness $\tilde{q}, \tilde{g}$ (direct decays) jet spectroscopy
e, $\mu^\pm$, jets, $p\!\!\!/_T$ (non-)magnetic central part (reduced tracking)	add: 4× rate $H \to ZZ \to 4e^\pm$ 2× rate $H \to ZZ \to e^+e^-\nu\bar{\nu}$ 2× rate Z', W' $\tilde{q}, \tilde{g}$ (also cascade decays) mass resolution $e\mu$ heavy Q, L $H \to \gamma\gamma$
$e^\pm$, $\mu^\pm$, $\tau^\pm$, jets, $p\!\!\!/_T$ full momentum and tracking	add: more redundancy and cross-checks on above, H^+, SUSY-H, heavy flavour tags



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

⇒ detection of e and μ

Muons are relatively easy to identify but hard to measure well

(precise μ measurements may mean hundreds of MCHF)

Electrons are relatively easy to measure but hard to identify at 10^{34}

(radiation-hard inner detector)

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

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

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

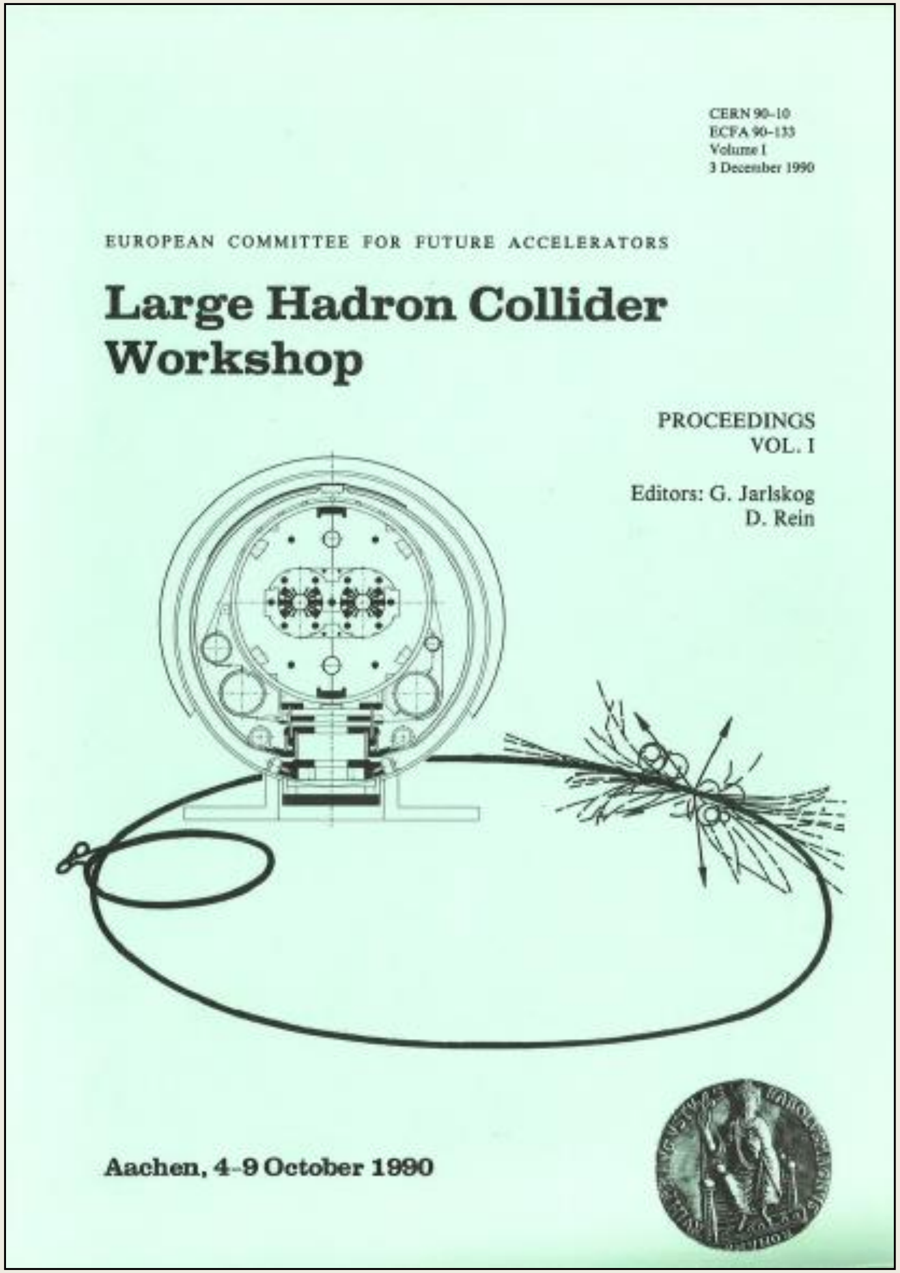
1987 La Thuile Workshop

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

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



CERN 90-10
ECFA 90-133
Volume I
3 December 1990

EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS

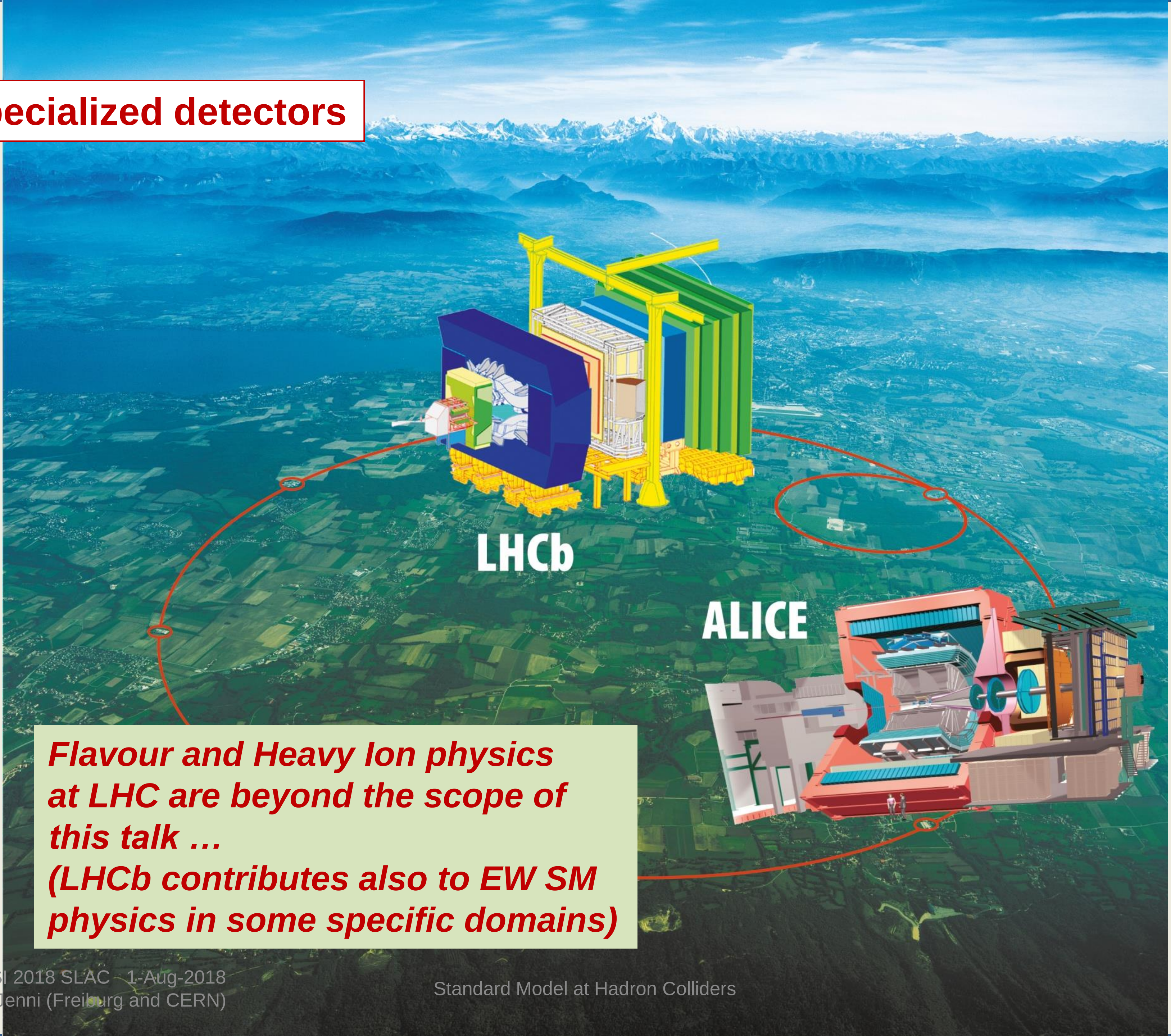
Large Hadron Collider Workshop

PROCEEDINGS
VOL. I

Editors: G. Jarlskog
D. Rein

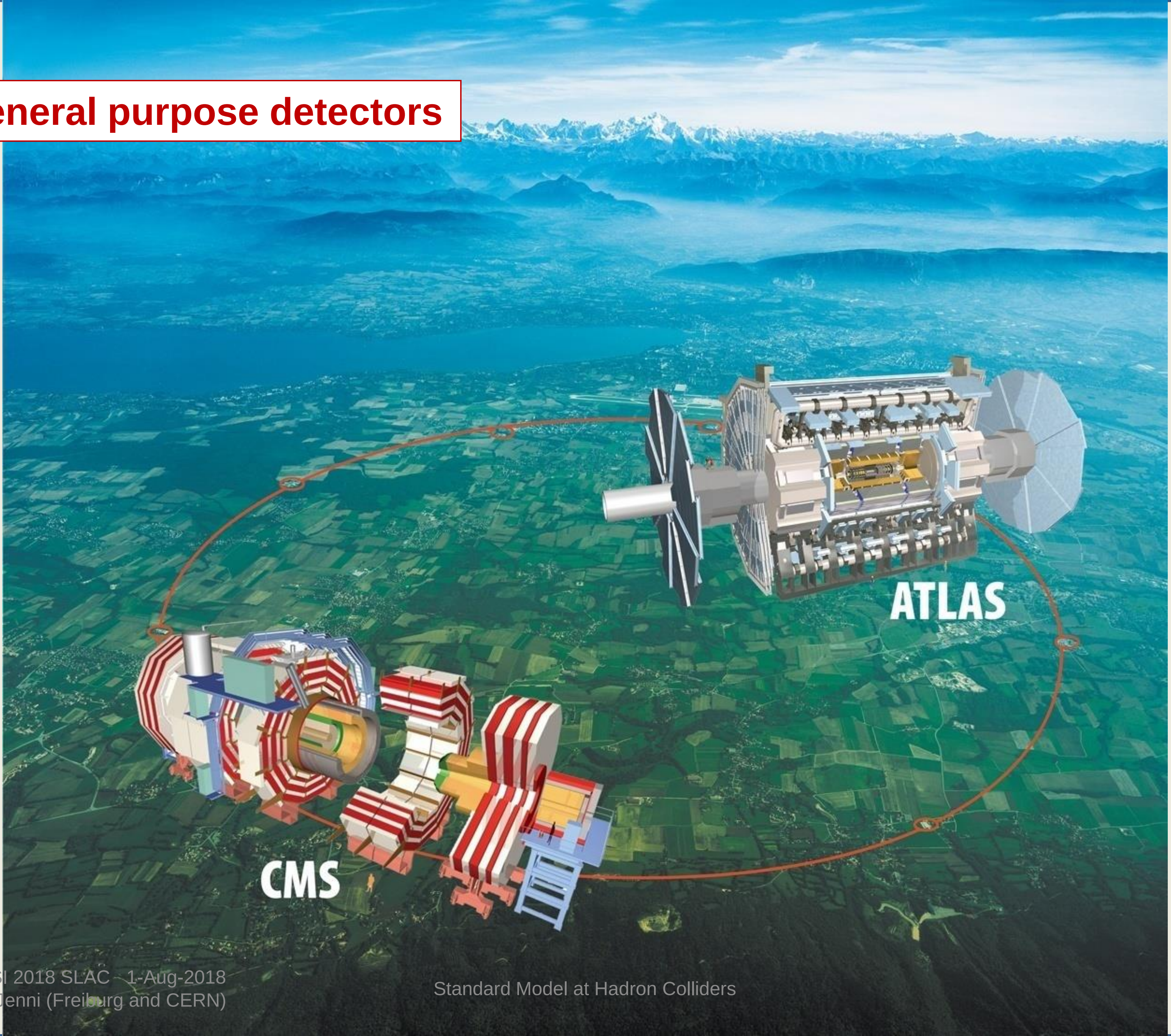
Aachen, 4-9 October 1990

Specialized detectors

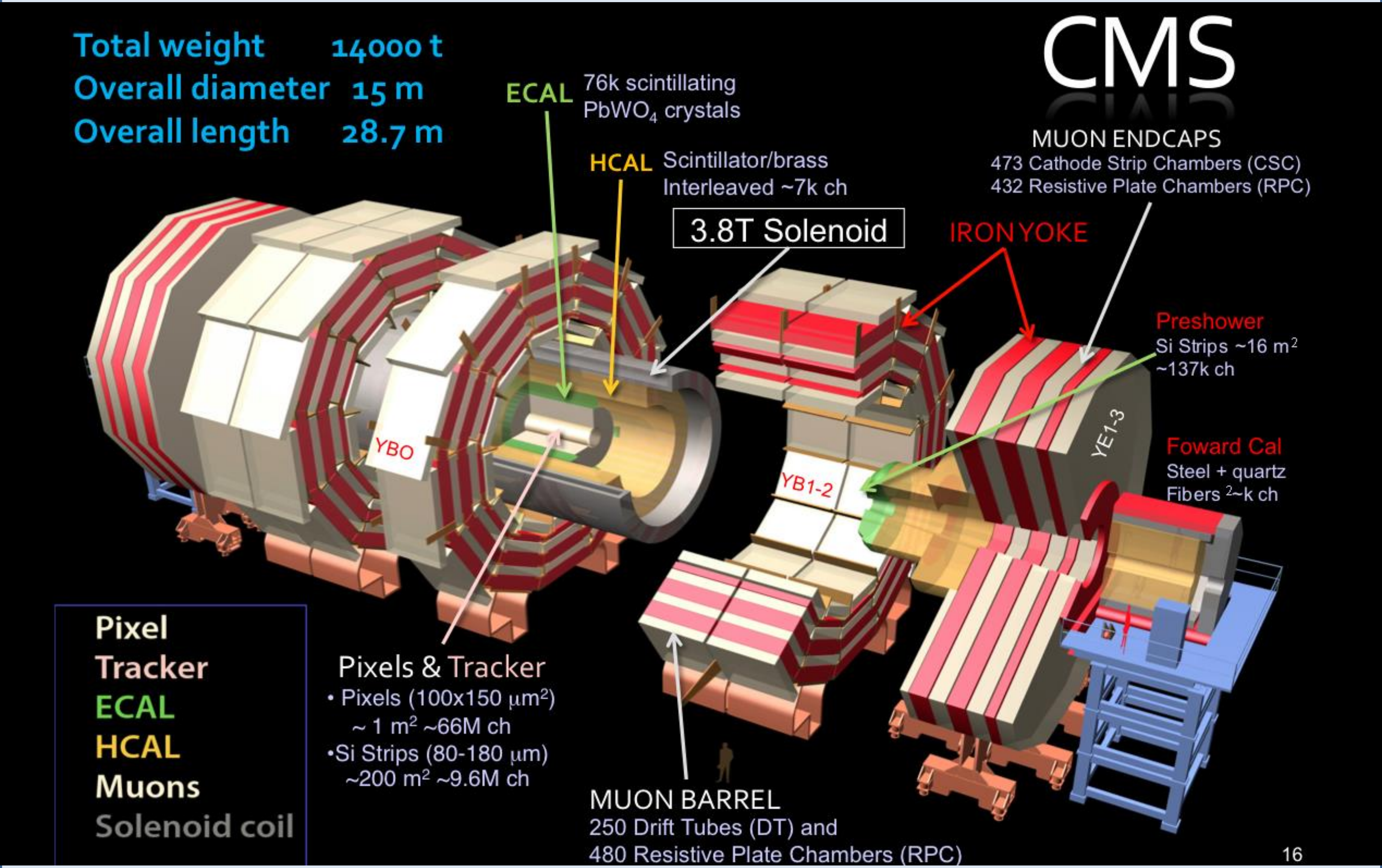


Flavour and Heavy Ion physics at LHC are beyond the scope of this talk …
(LHCb contributes also to EW SM physics in some specific domains)

General purpose detectors



Exploded View of CMS



Total weight 14000 t

Overall diameter 15 m

Overall length 28.7 m

CMS

ECAL 76k scintillating $PbWO_4$ crystals

HCAL Scintillator/brass Interleaved ~7k ch

3.8T Solenoid

MUON ENDCAPS

473 Cathode Strip Chambers (CSC)

432 Resistive Plate Chambers (RPC)

IRON YOKE

Preshower

Si Strips ~16 m^2

~137k ch

Foward Cal

Steel + quartz

Fibers ^{2}~k ch

Pixel

Tracker

ECAL

HCAL

Muons

Solenoid coil

Pixels & Tracker

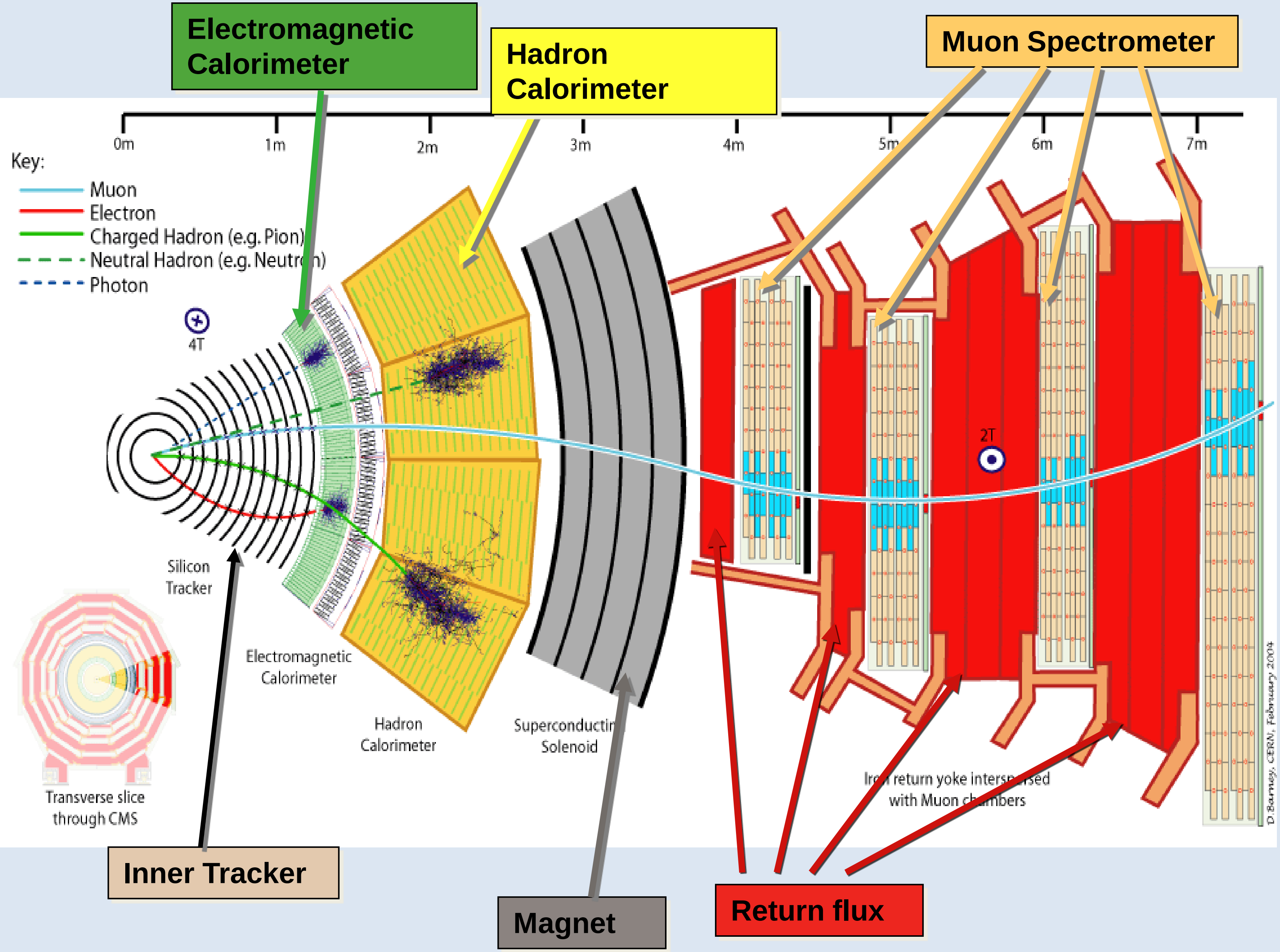
- Pixels (100x150 μm^2) ~ 1 m^2 ~66M ch
- Si Strips (80-180 μm) ~200 m^2 ~9.6M ch

MUON BARREL

250 Drift Tubes (DT) and

480 Resistive Plate Chambers (RPC)

Main components of the CMS detector



Electromagnetic Calorimeter

Hadron Calorimeter

Muon Spectrometer

Inner Tracker

Magnet

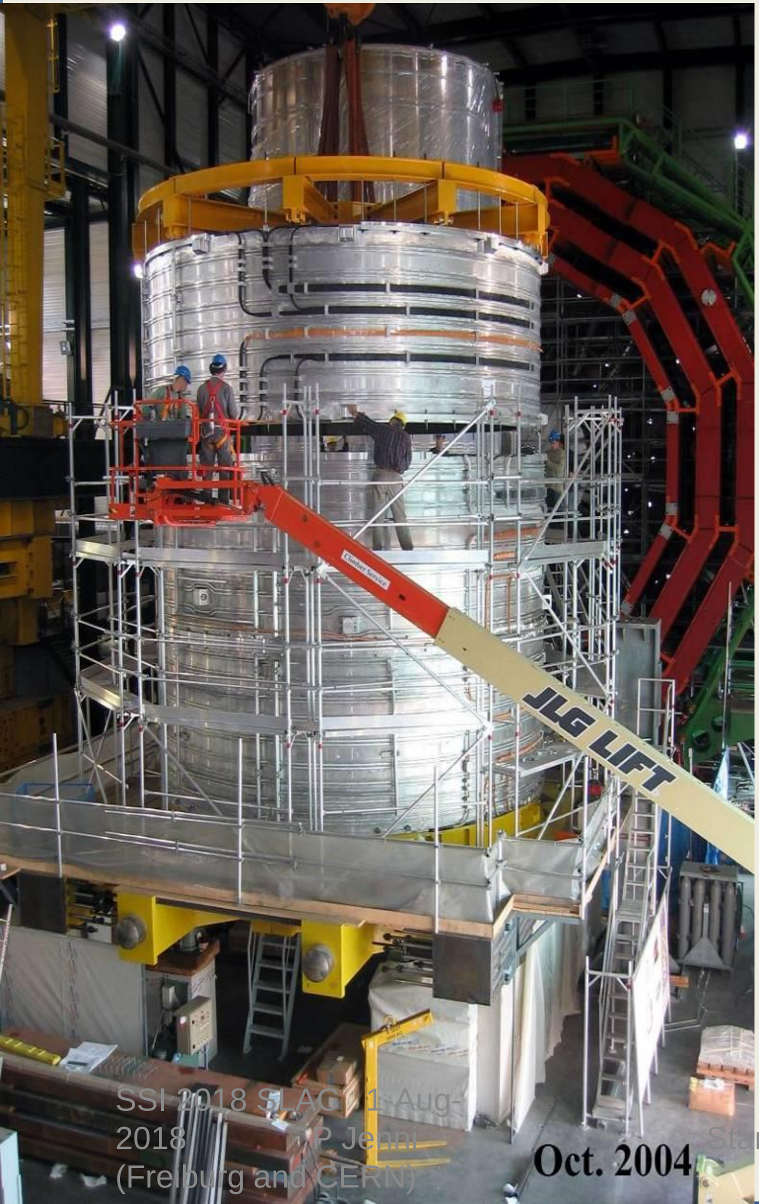
Return flux

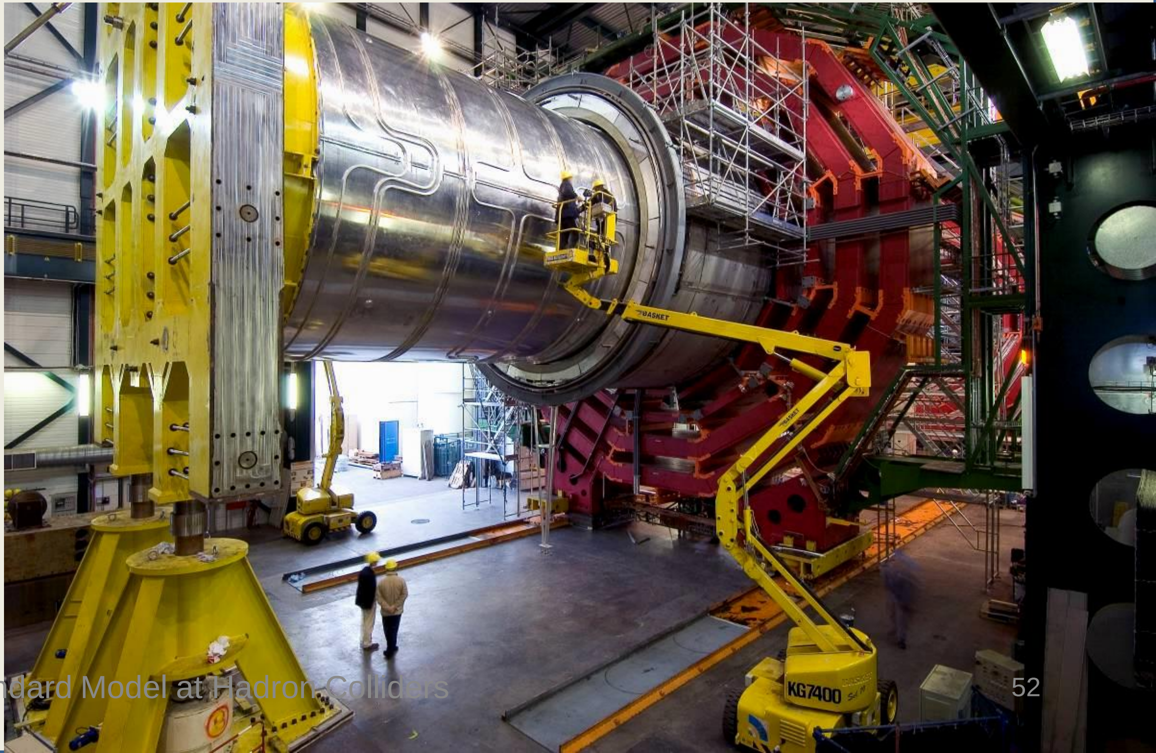
An Example of an Engineering Challenge: CMS Solenoid

CMS solenoid:

Magnetic length	**12.5 m**
Diameter	**6 m**
Magnetic field	**4 T**
Nominal current	**20 kA**
Stored energy	**2.7 GJ**

Tested at full current in Summer 2006



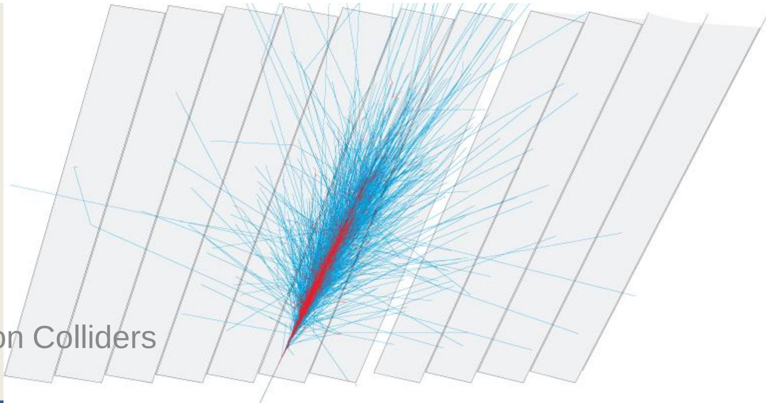


CMS Electron and Photon calorimeter: 76 000 $PbW0_4$ crystals

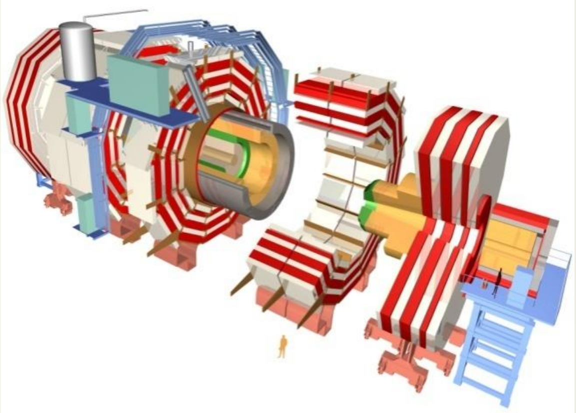
End-cap was on the critical path for many years, but it was completed just in time before final closure, a major achievement by CMS

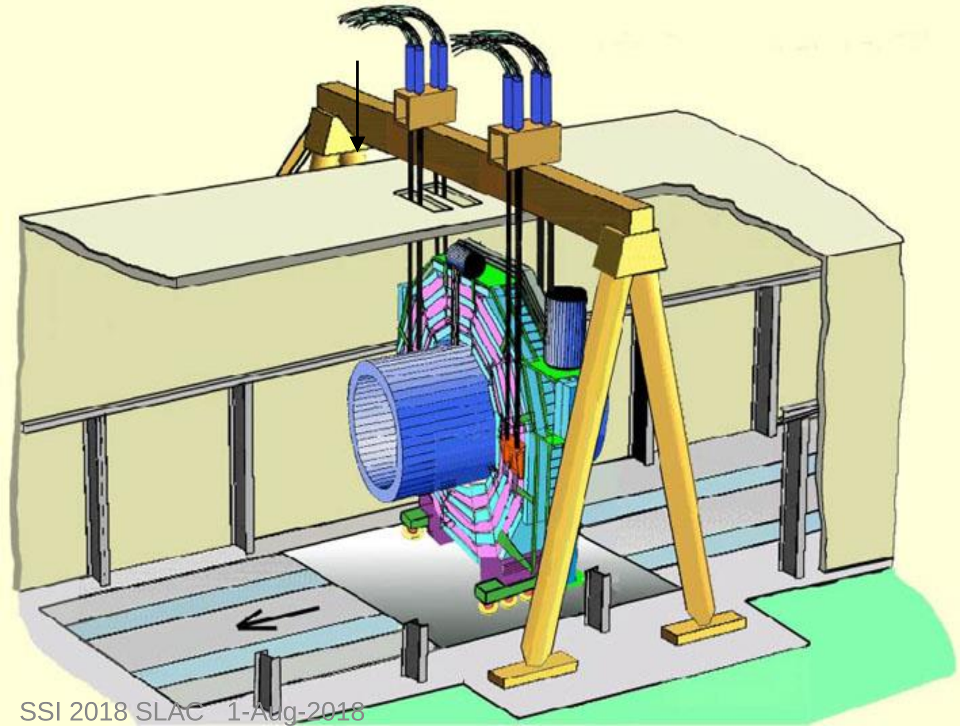
Barrel ECAL Installation Completed: 27 July 07

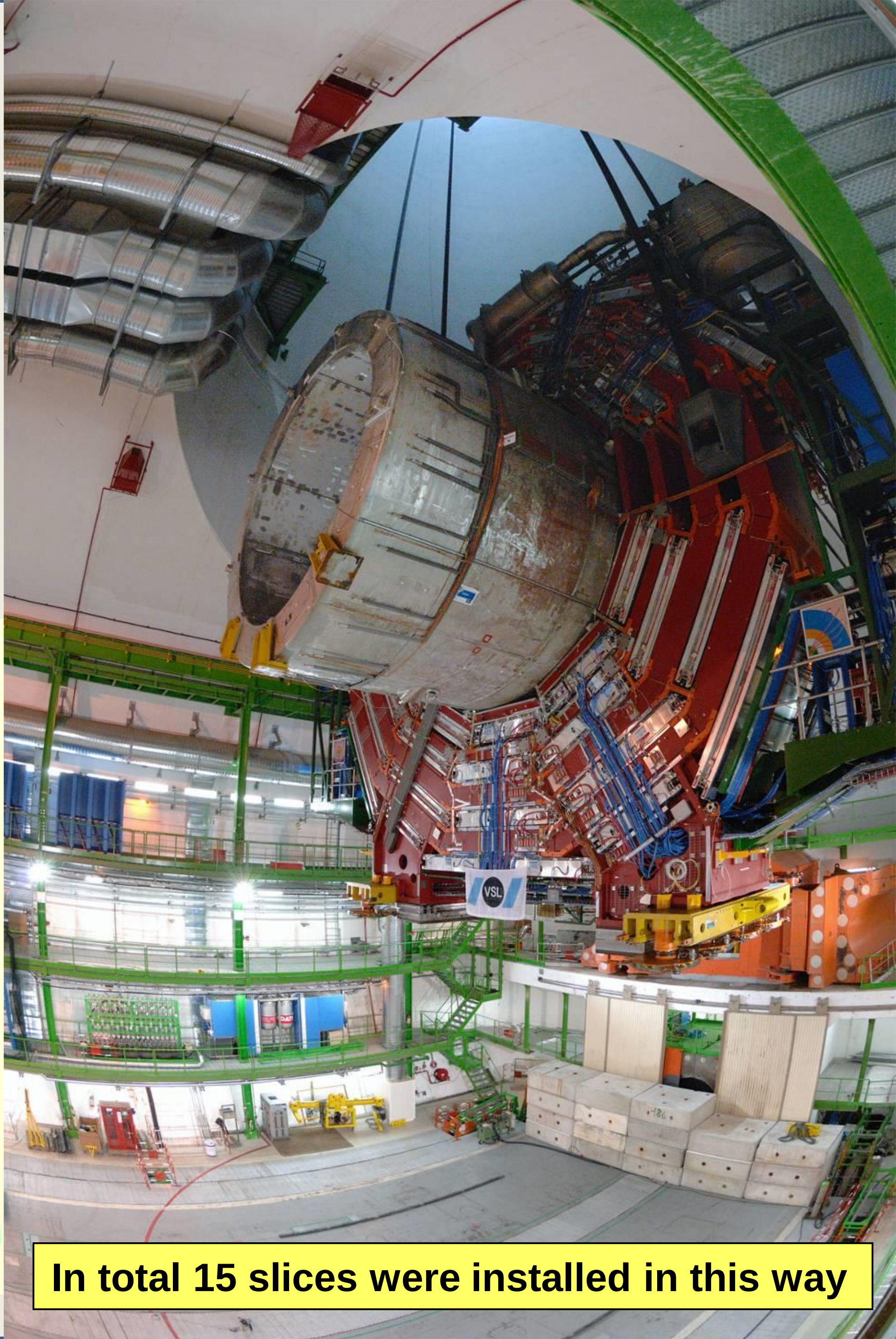
18 SMs installed and tested in 12 working days!



The central, heaviest slice (2000 tons) with the solenoid magnet, lowered into the underground cavern in Feb. 2007







In total 15 slices were installed in this way

CMS before closure 2008

In the following I often take ATLAS as example, but many things are of course similar for the sister experiment CMS

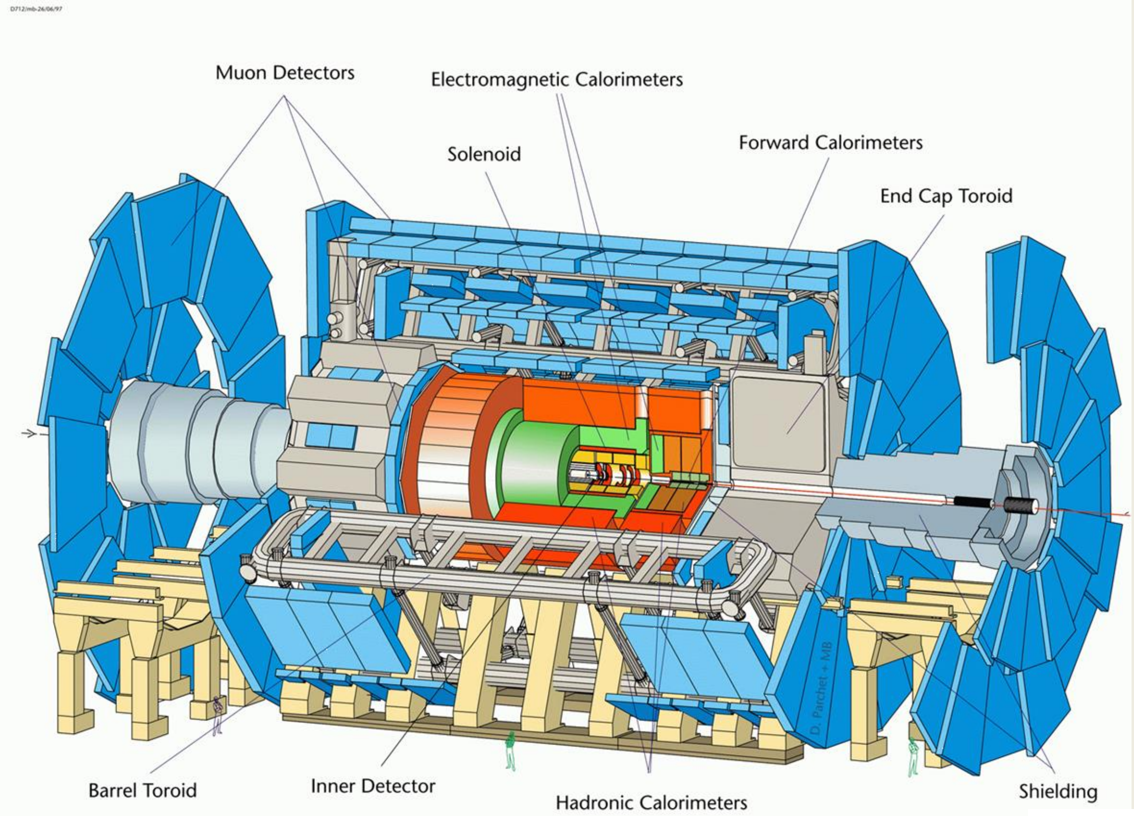
ATLAS Collaboration

(Status June 2018)

38 Countries
182 Institutions
2900 Scientific authors total
(1000 Students)

**Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizo a, UT Arlington, UT Austin, Athens,
NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berli Birmingham, UAN Bogota, Bologna,
Bonn, Boston, Brandeis, Brazil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Bu charest, Cambridge, Carleton, CERN,
China IHEP-NJU-THU, China USTC-SDU-SJTU, Chicago, Chile, Clermo NBI Copenhagen, Cosenza,
AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, NCSR De TU Dresden, JINR Dubna, Duke,
Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow nion Haifa, Harvard, Heidelberg,
Hiroshima IT, Hong Kong, NTHU Hsinchu, Indiana, Inns anbul Bogazici, KEK, Kobe, Kyoto,
Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, L MW London, RHBNC London, UC London,
Louisiana Tech, Lund, UA Madrid, Mainz, Man usetts, MIT, Melbourne, Michigan, Michigan SU,
Milano, Minsk NAS, Minsk NCPHEP, Mo occo, FIAN Moscow, ITEP Moscow, MEPhI Moscow,
MSU Moscow, LMU Munich, MPI M ples, New Mexico, New York, Nijmegen, Northern Illinois,
BINP Novosibirsk, Ohio SU, Okayama, lomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, LPNHE Paris VI
and VII, Pavia, Pennsylvania, NPI Peters gh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II,
Rome III, Rutherford Appleton Laborat y, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC,
South Africa, Stockholm, KTH Stockhol y Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP,
Tokyo MU, Tokyo Tech, Tomsk, Toronto, Trento, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBCVancouver,
Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan**

Similar world-spanning Collaboration for CMS



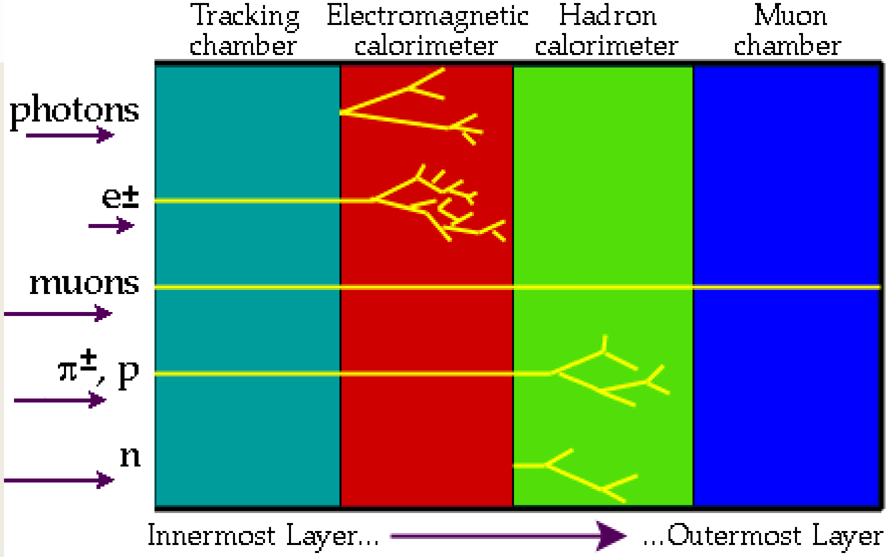
ATLAS

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



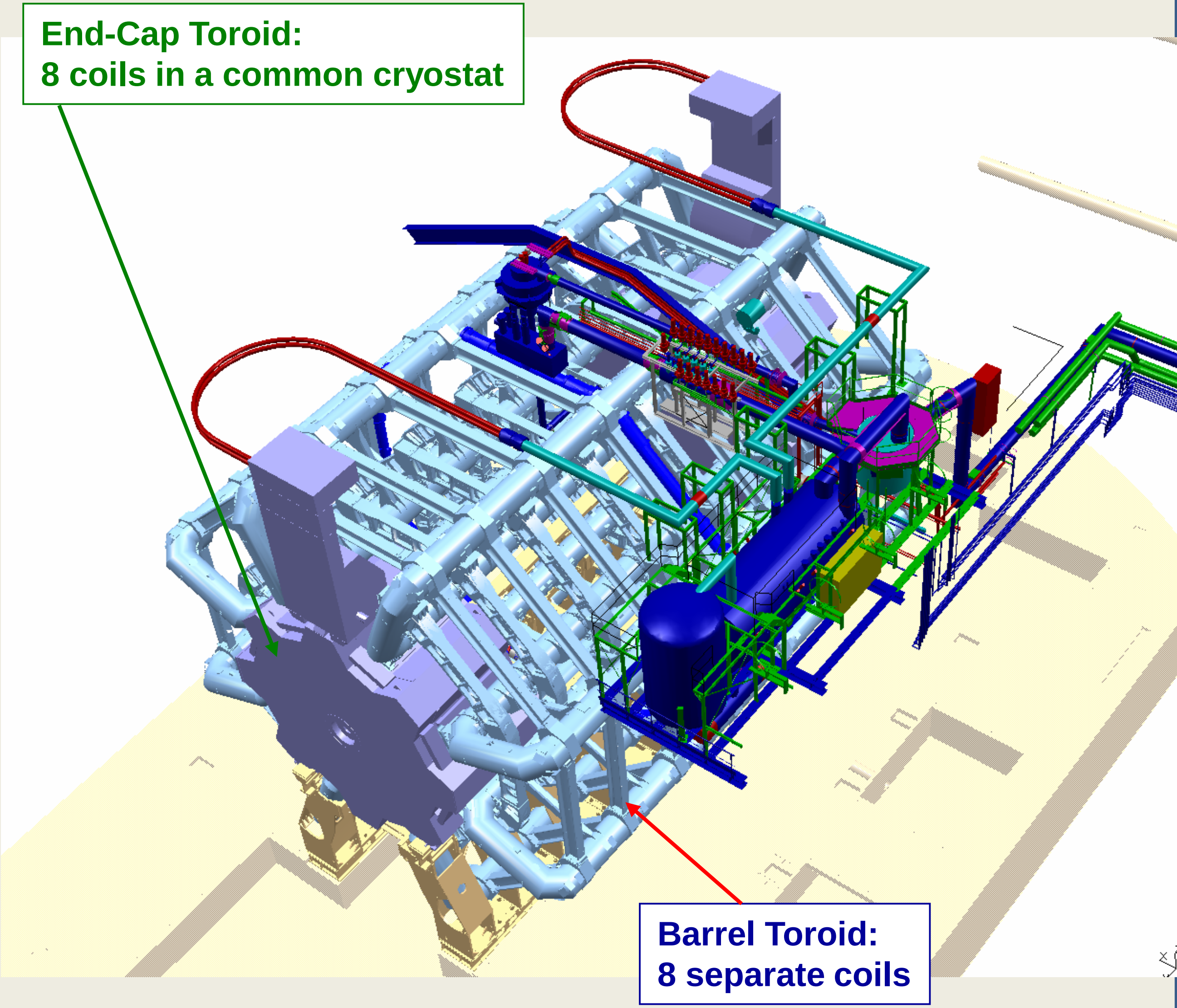
Point-1 Civil Engineering 1998-2003
(cavern 56 x 32 x 35 m^3)

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

ATLAS Toroid Magnet System

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

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



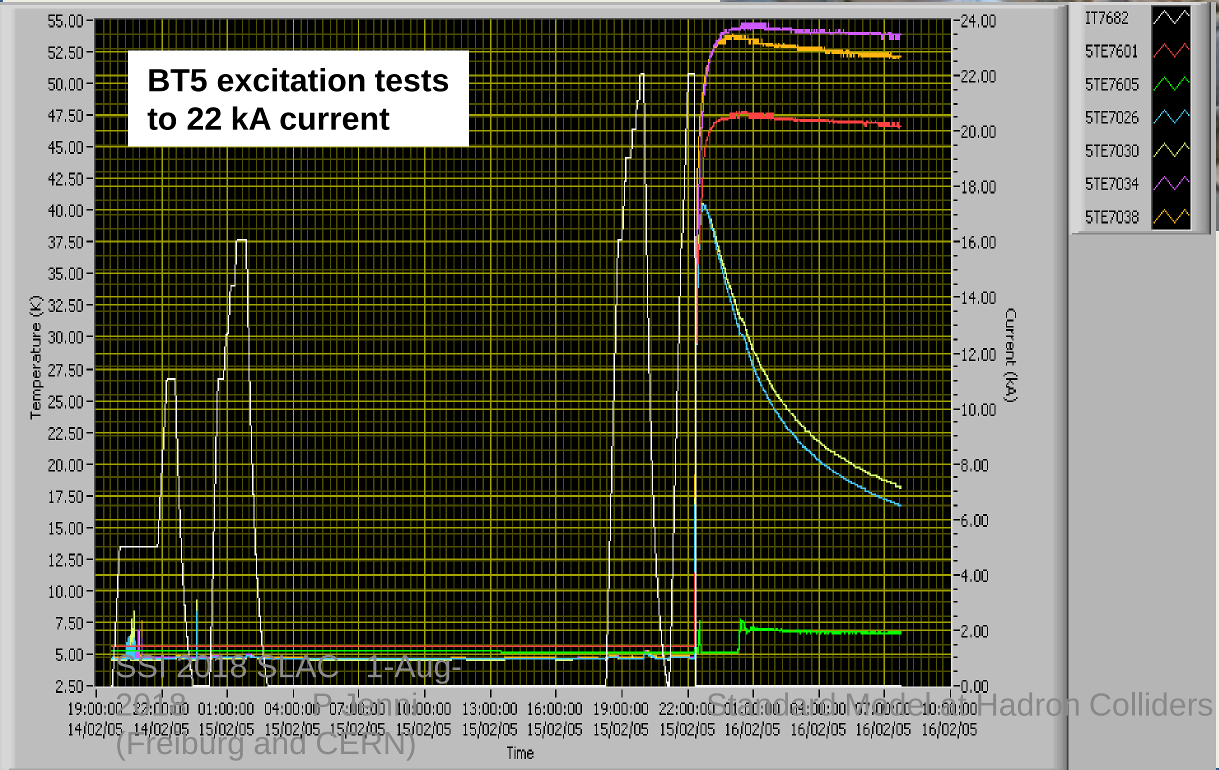
End-Cap Toroid:
8 coils in a common cryostat

Barrel Toroid:
8 separate coils

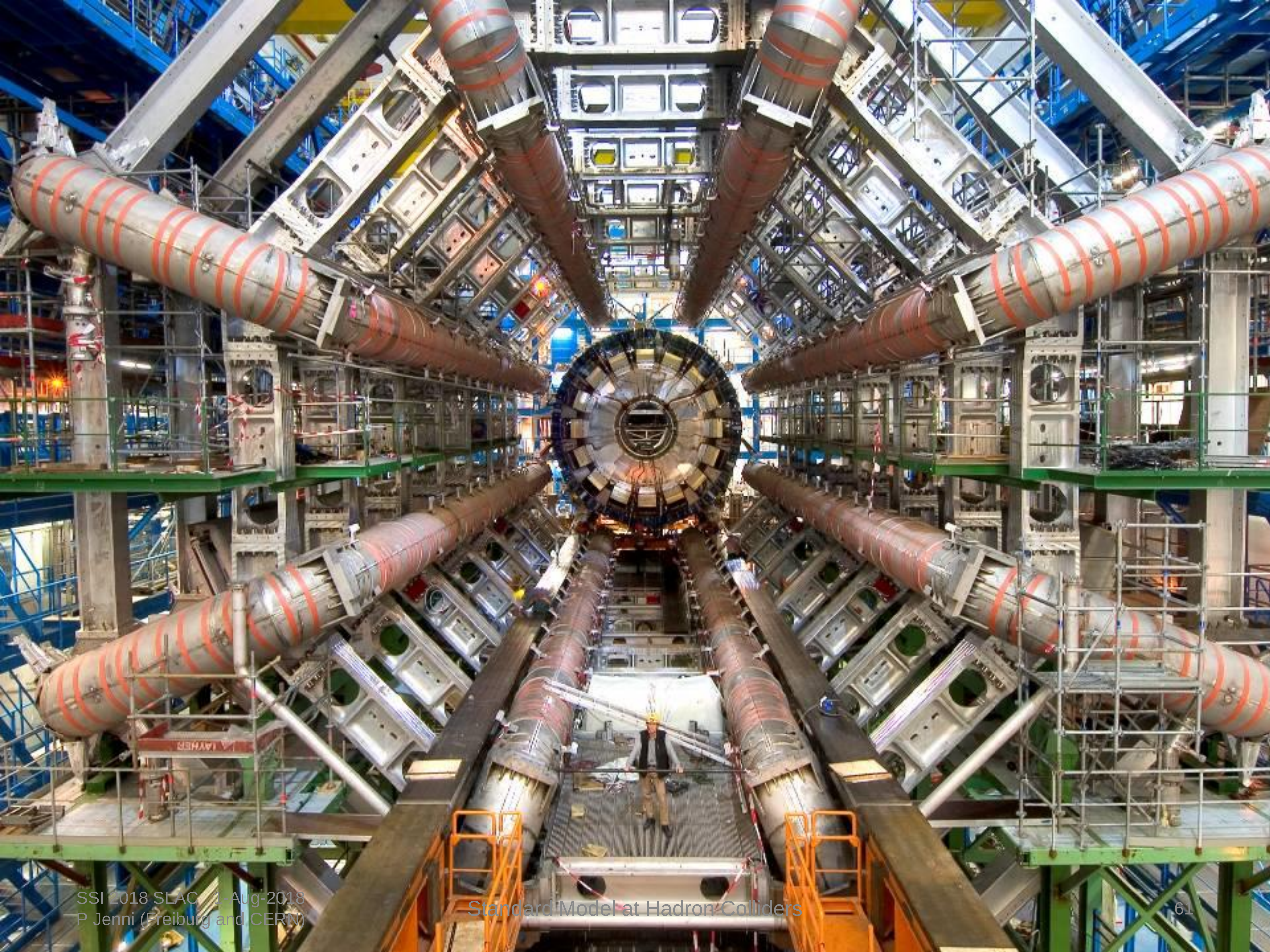
ATLAS Barrel Toroid construction

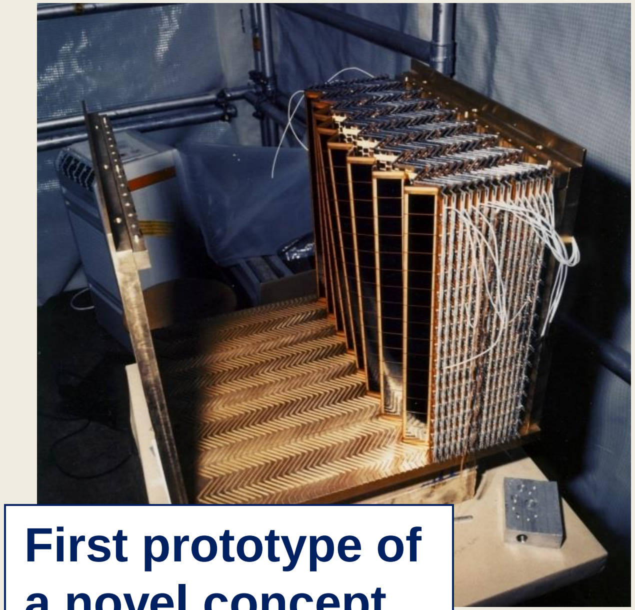
Series integration and tests of the 8 coils at the surface were finished in June 2005

BT test area

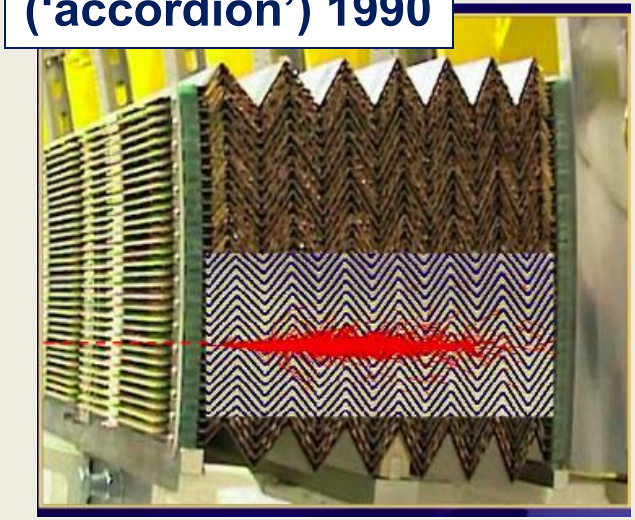


BT5 excitation tests to 22 kA current





First prototype of a novel concept (‘accordion’) 1990

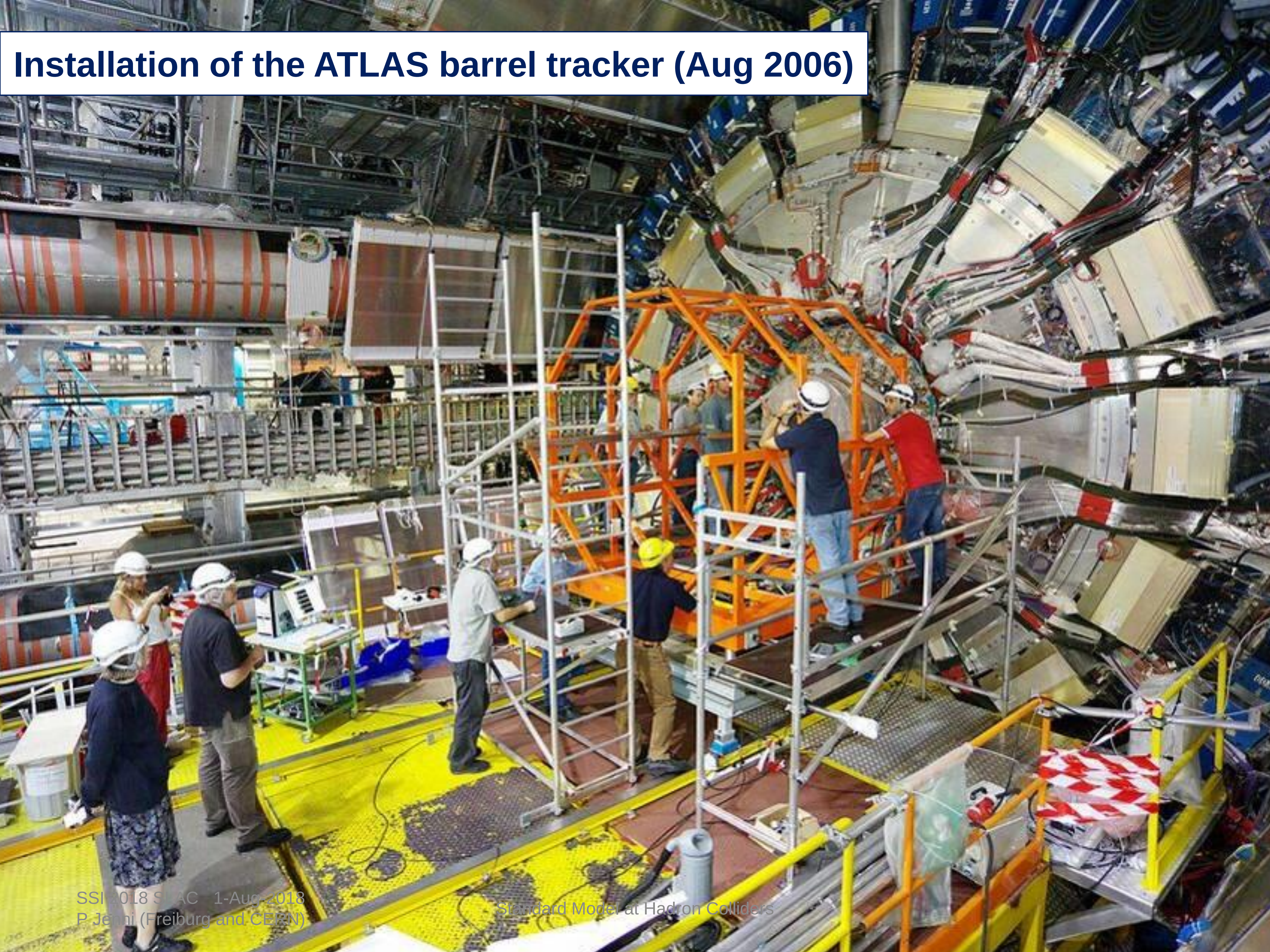


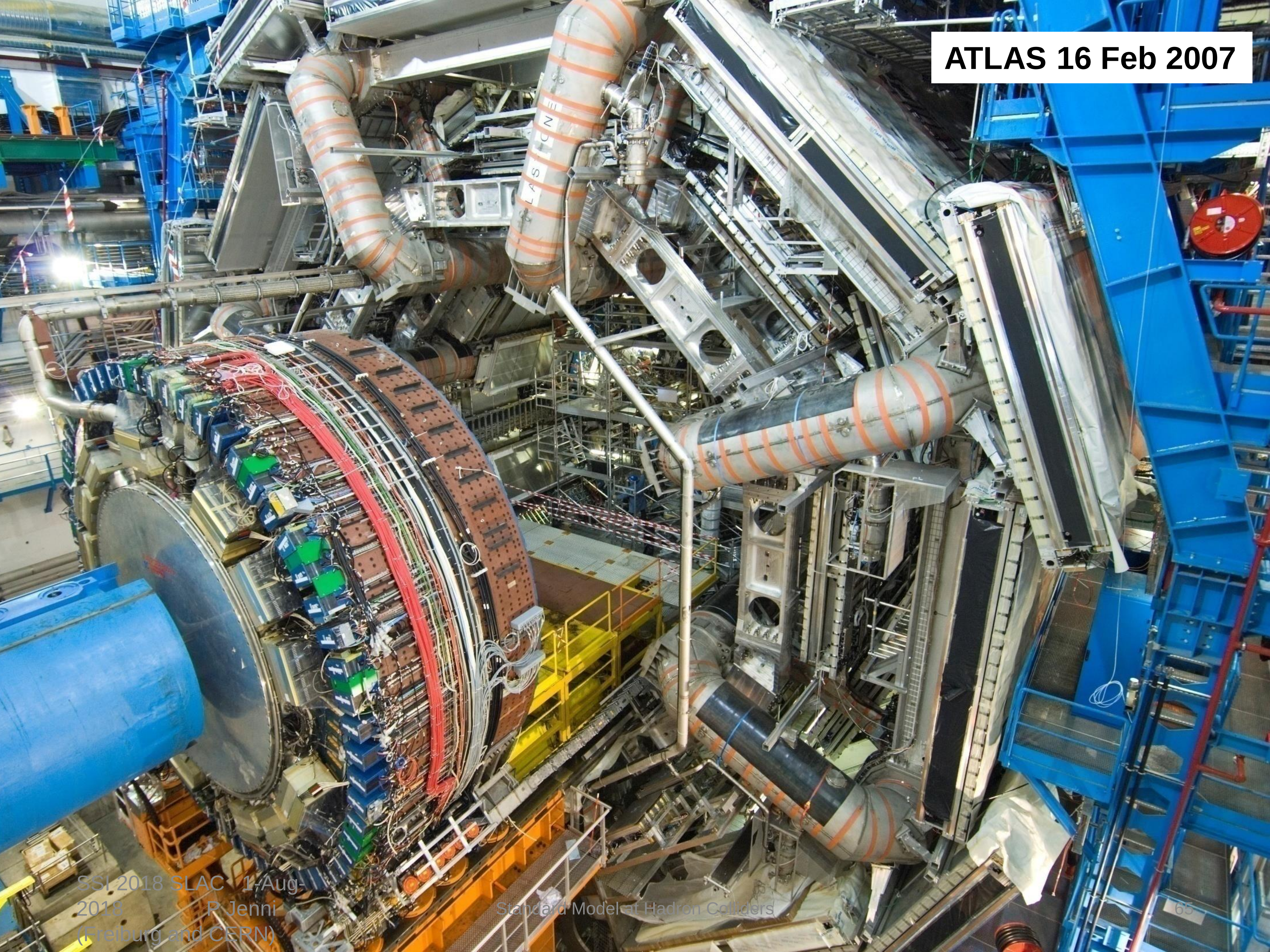
LAr EM Calorimeter construction 1999 - 2004

Insertion of the solenoid into the LAr EM calorimeter barrel cryostat

February 2004

Installation of the ATLAS barrel tracker (Aug 2006)





ATLAS 16 Feb 2007

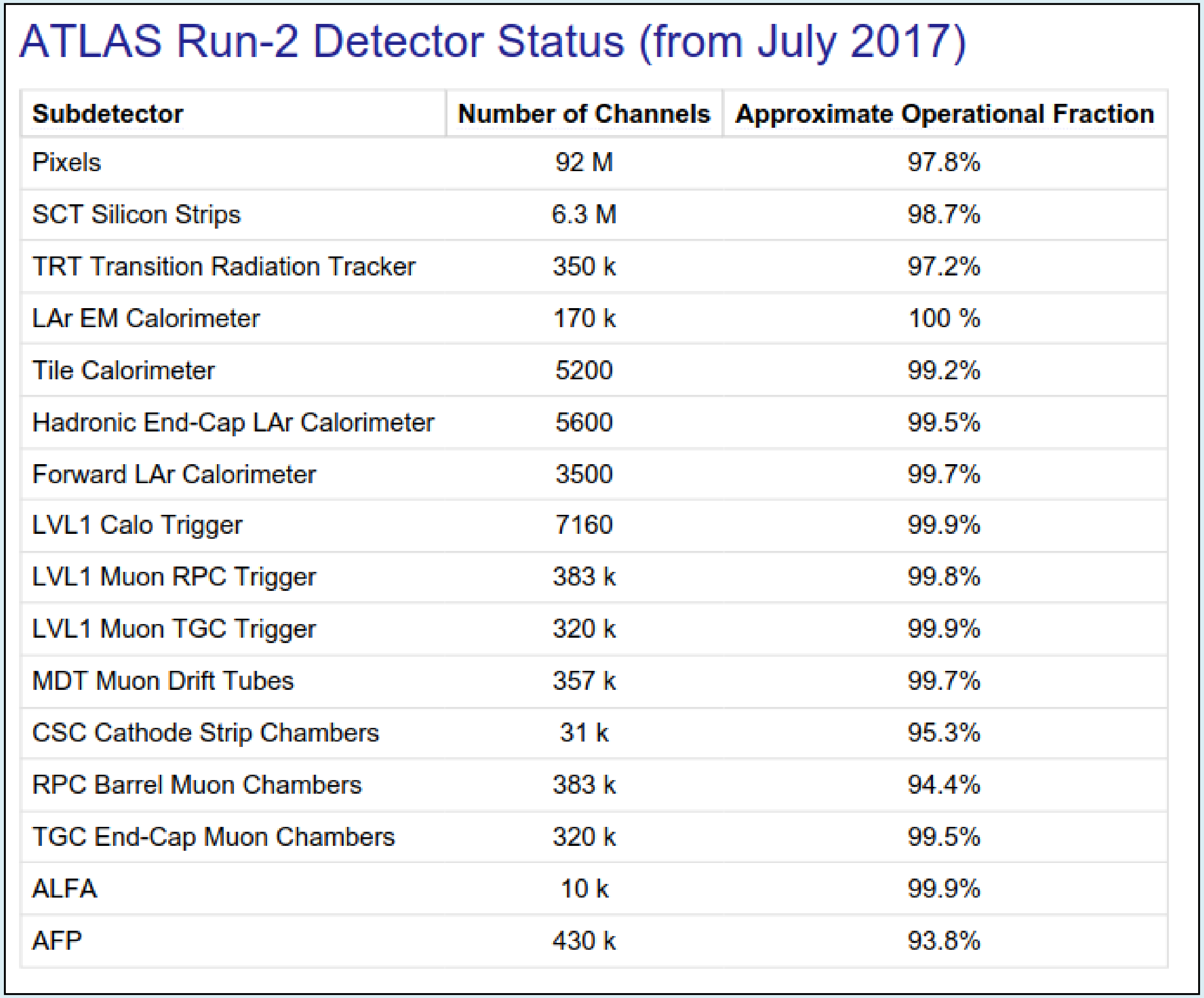
Famous visitors in ATLAS and CMS

Francois Englert
6 Dec 2007

Peter Higgs
4 April 2008

Steven Weinbeg
7 July 2009

Typical channel counts and operational status of the ATLAS and CMS experiments (100 M channels, 99% working, in very rough numbers…)

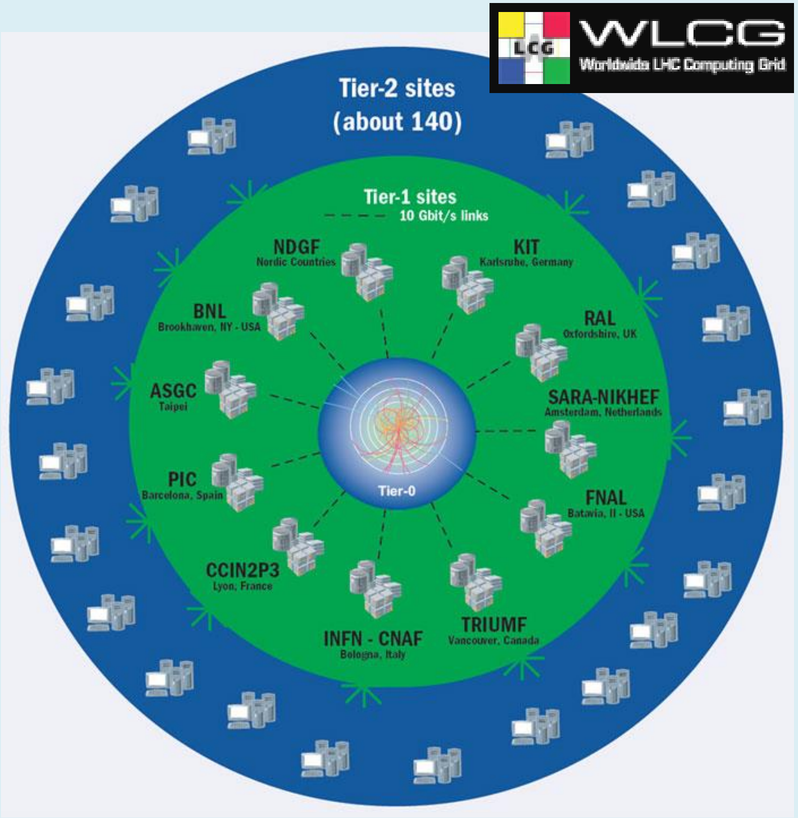


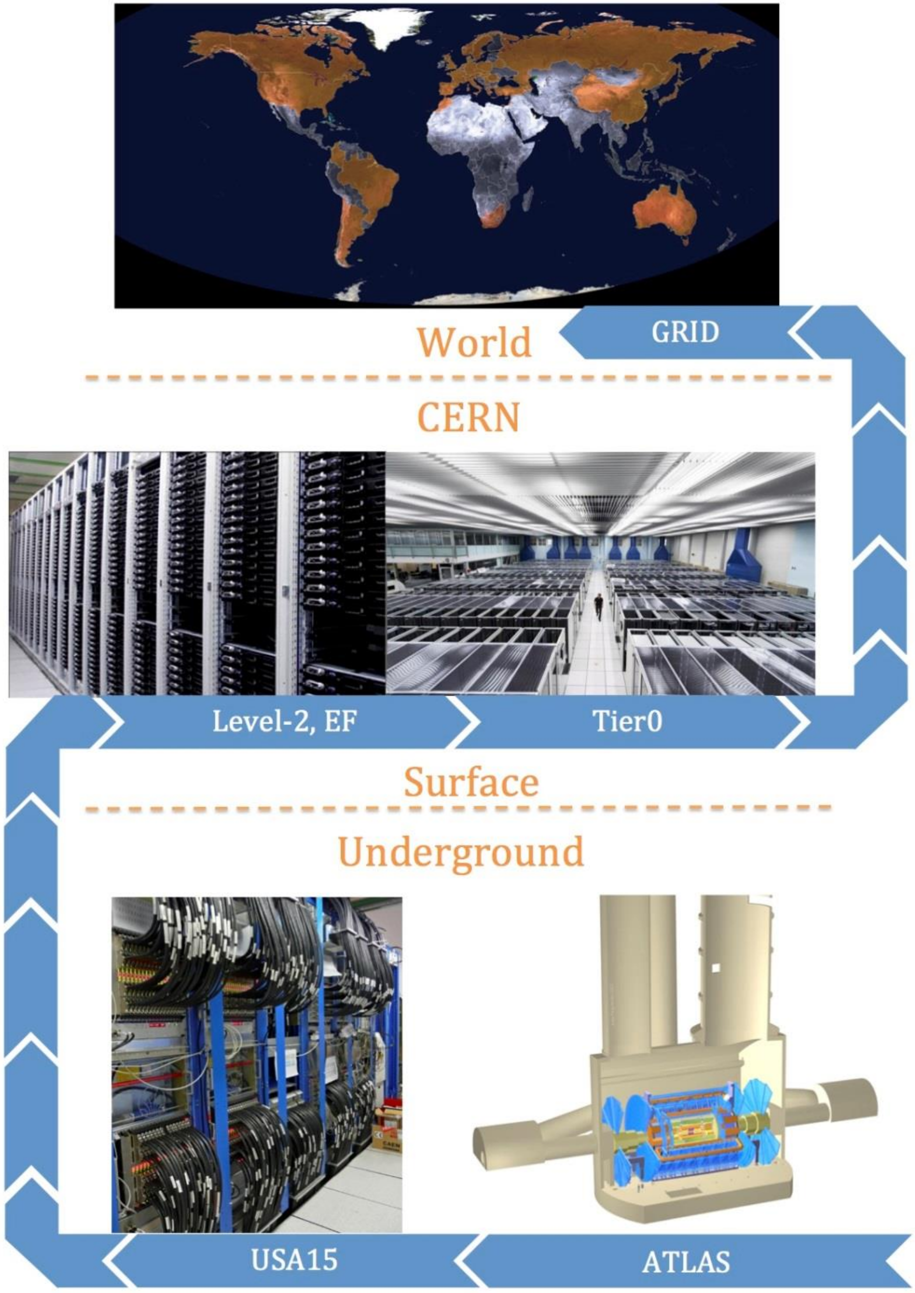
ATLAS Run-2 Detector Status (from July 2017)

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	92 M	97.8%
SCT Silicon Strips	6.3 M	98.7%
TRT Transition Radiation Tracker	350 k	97.2%
LAr EM Calorimeter	170 k	100 %
Tile Calorimeter	5200	99.2%
Hadronic End-Cap LAr Calorimeter	5600	99.5%
Forward LAr Calorimeter	3500	99.7%
LVL1 Calo Trigger	7160	99.9%
LVL1 Muon RPC Trigger	383 k	99.8%
LVL1 Muon TGC Trigger	320 k	99.9%
MDT Muon Drift Tubes	357 k	99.7%
CSC Cathode Strip Chambers	31 k	95.3%
RPC Barrel Muon Chambers	383 k	94.4%
TGC End-Cap Muon Chambers	320 k	99.5%
ALFA	10 k	99.9%
AFP	430 k	93.8%

Trigger, DAQ, Software and Computing

(An absolutely essential part of the success story, only left out for time…)



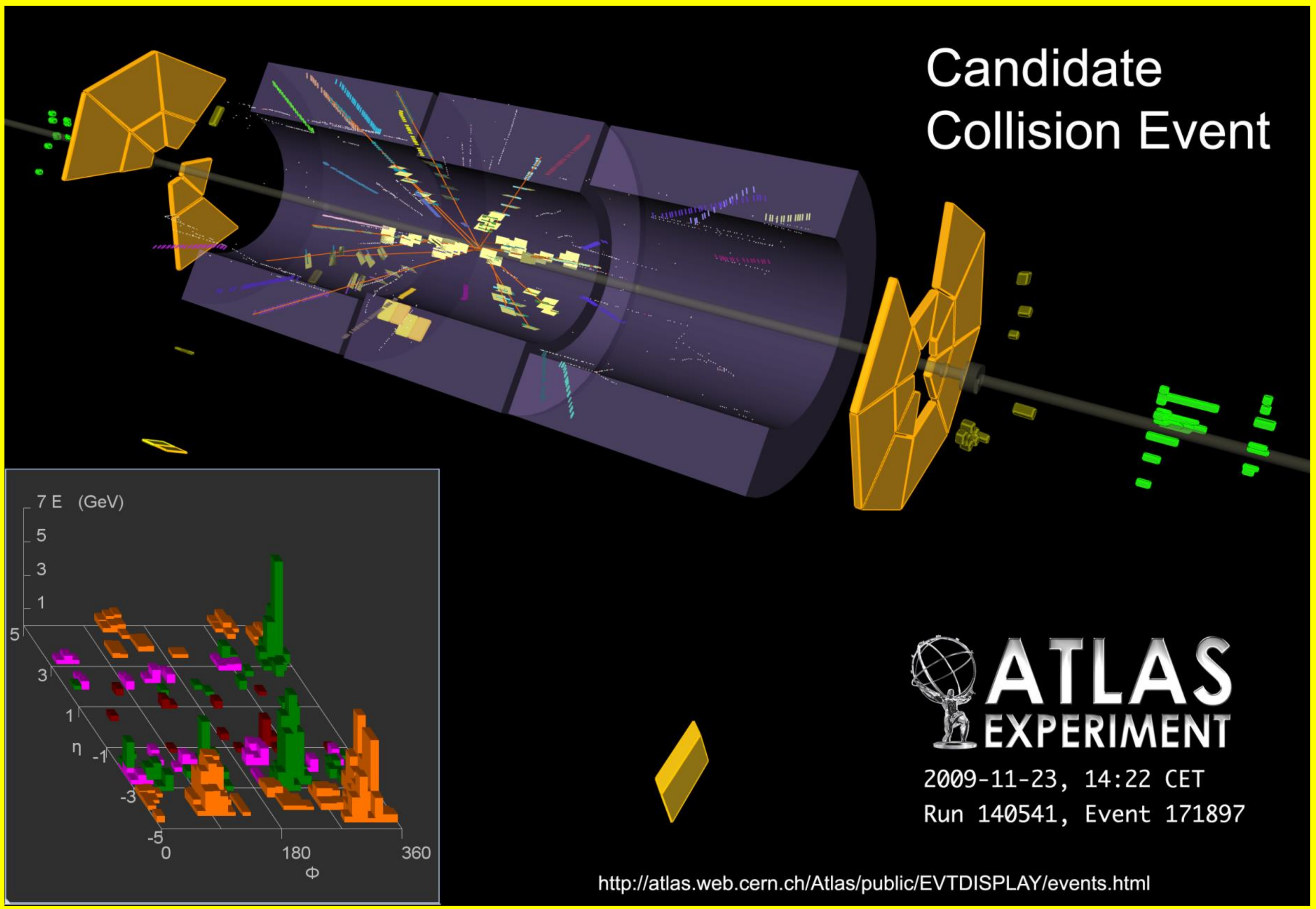


Data flow

Expecting in the ATLAS Control Room the first LHC beam to collide on November 23rd, 2009....

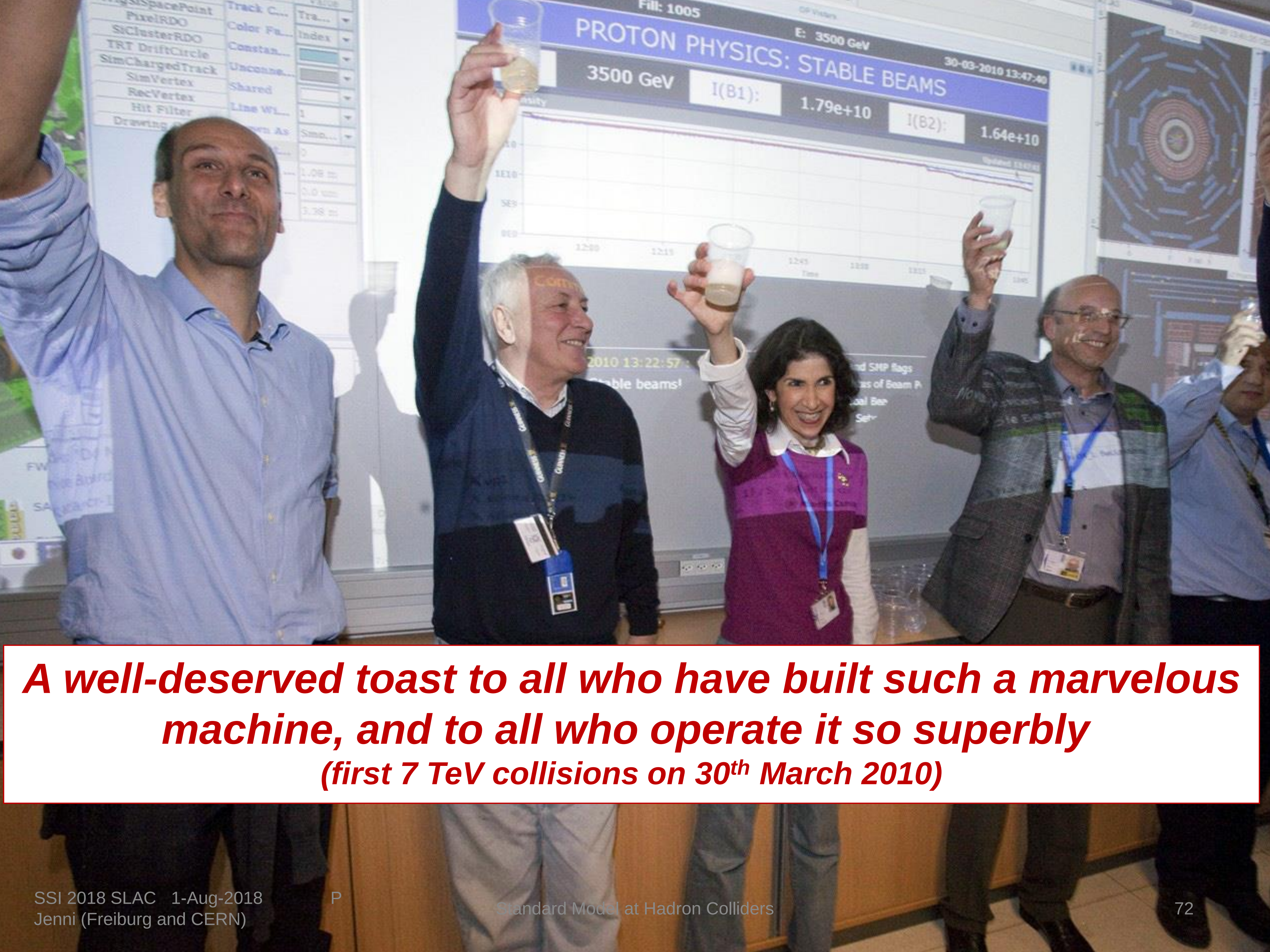
The joy in the ATLAS Control Room when the first LHC beam collided on November 23^{rd}, 2009....

First collisions in ATLAS 23rd November 2009 with LHC beams at the injection energy of 450 GeV



2009-11-23, 14:22 CET
Run 140541, Event 171897

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html



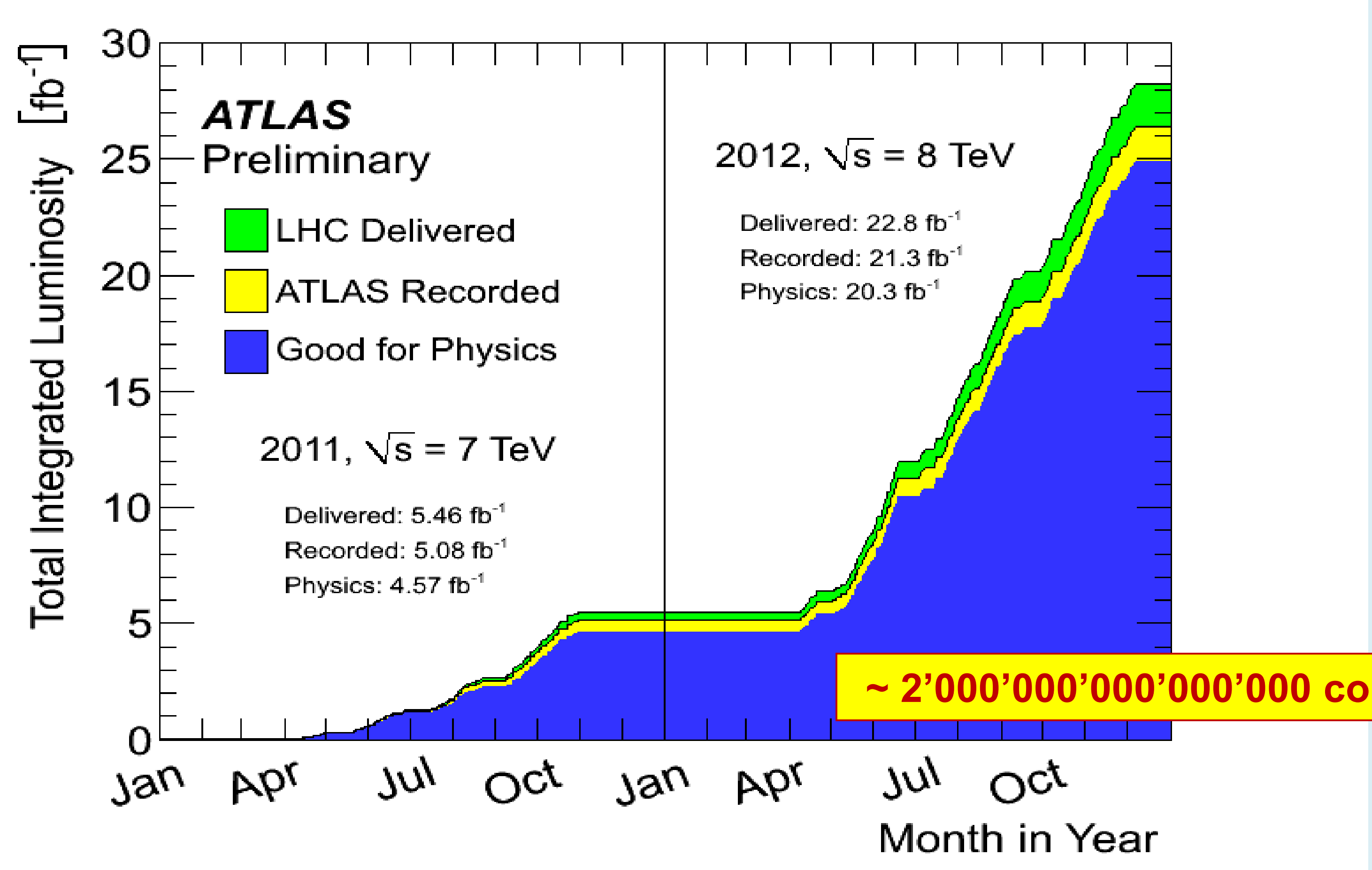
A well-deserved toast to all who have built such a marvelous machine, and to all who operate it so superbly

(first 7 TeV collisions on 30th March 2010)

The LHC and experiments performances were simply fantastic over the three years of Run-1

Total integrated luminosity

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

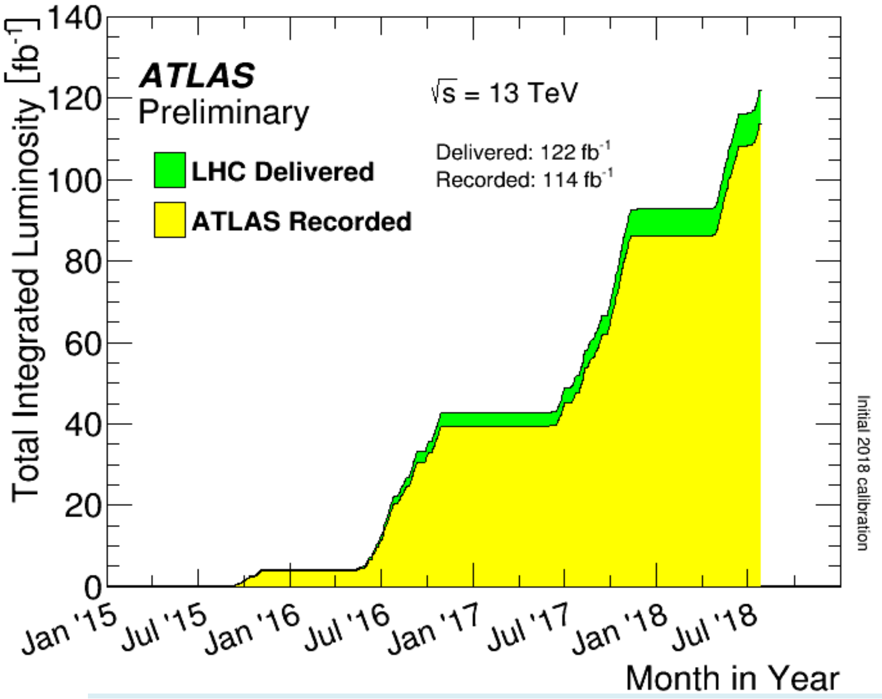


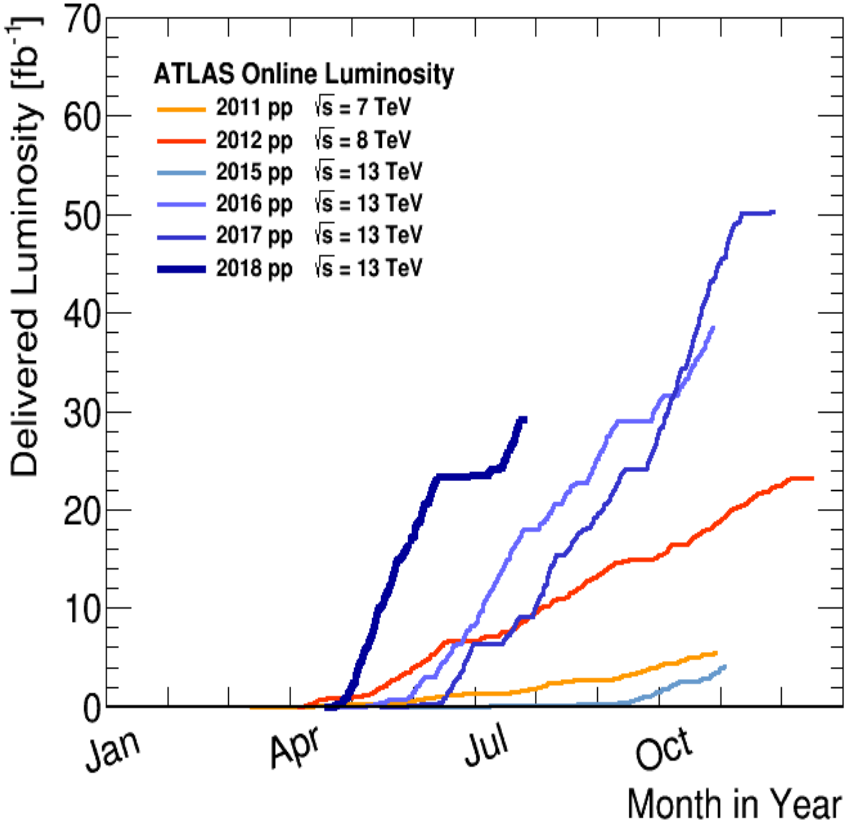
~ 2’000’000’000’000’000 collisions

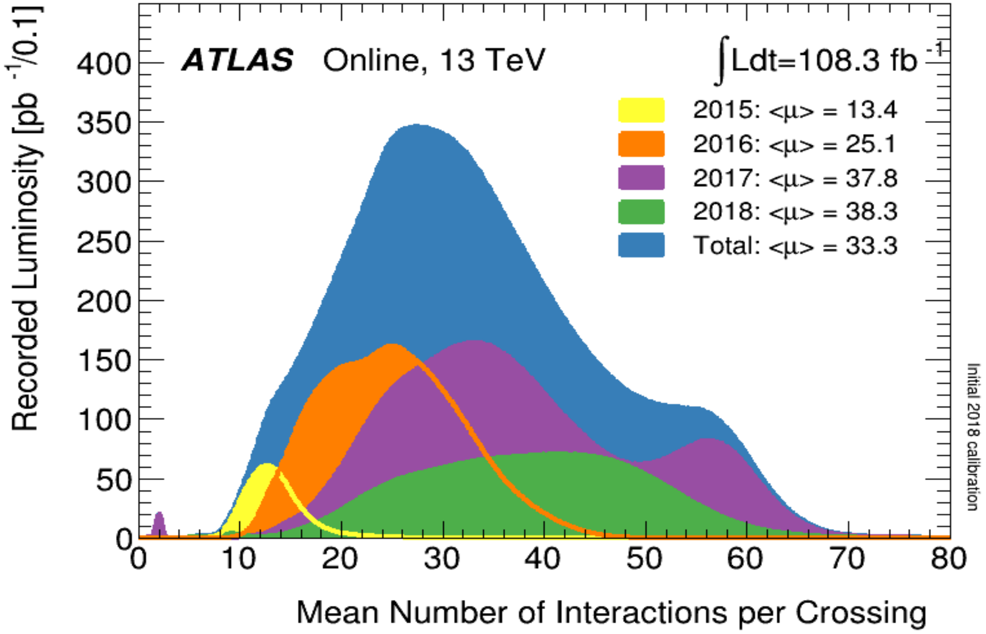
ATLAS and CMS record typically 94% of the stably delivered luminosity, and use up to 90% of the LHC luminosity in the final analyses!

The LHC and ATLAS performances for Run-2 (2015-2018) at 13 TeV (similar for CMS)

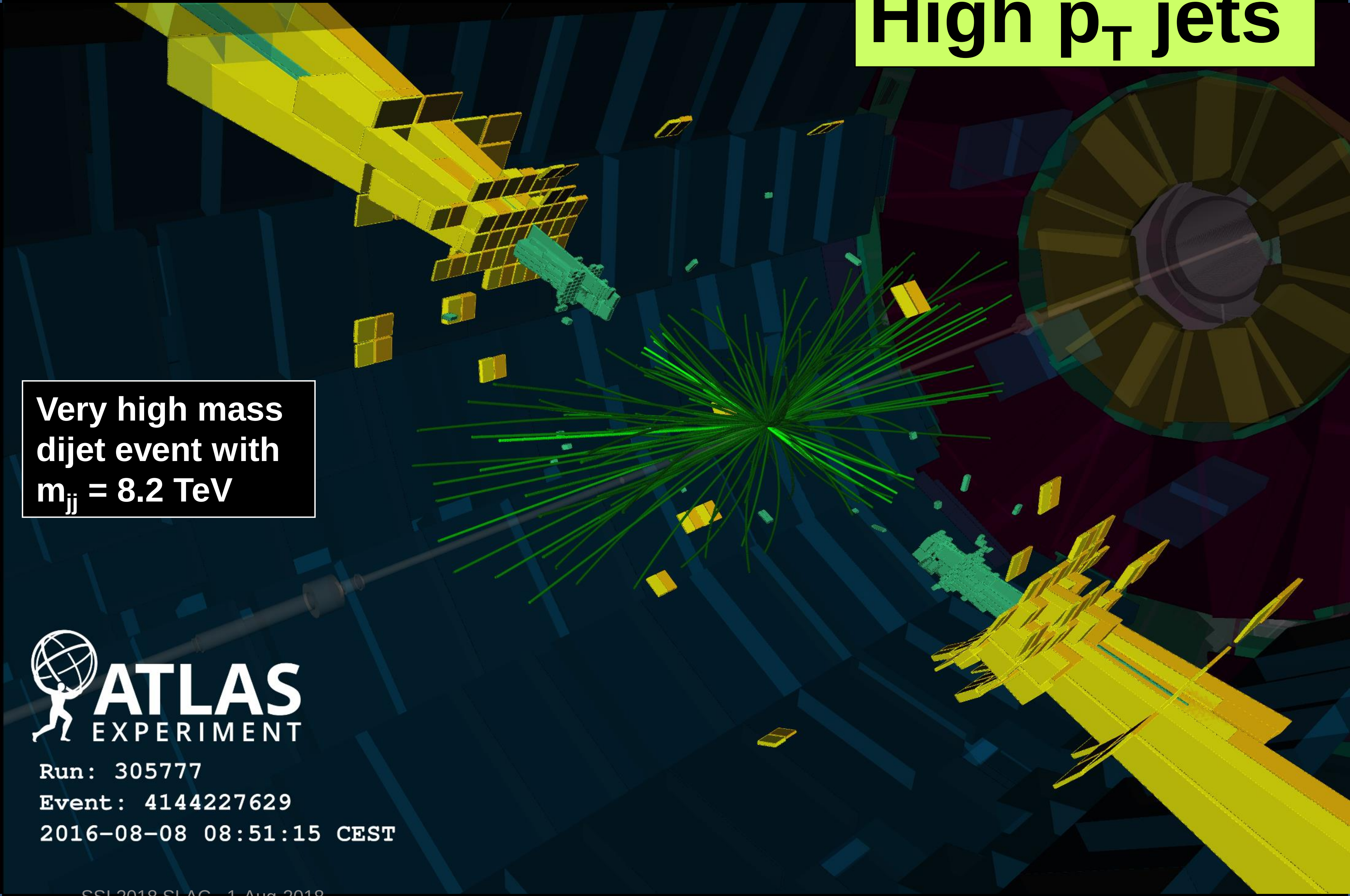
The machine worked outstandingly well and delivered in 2016 about 40 fb^{-1} and in 2017 about 50 fb^{-1} of stable data, and we may get even more 2018 !



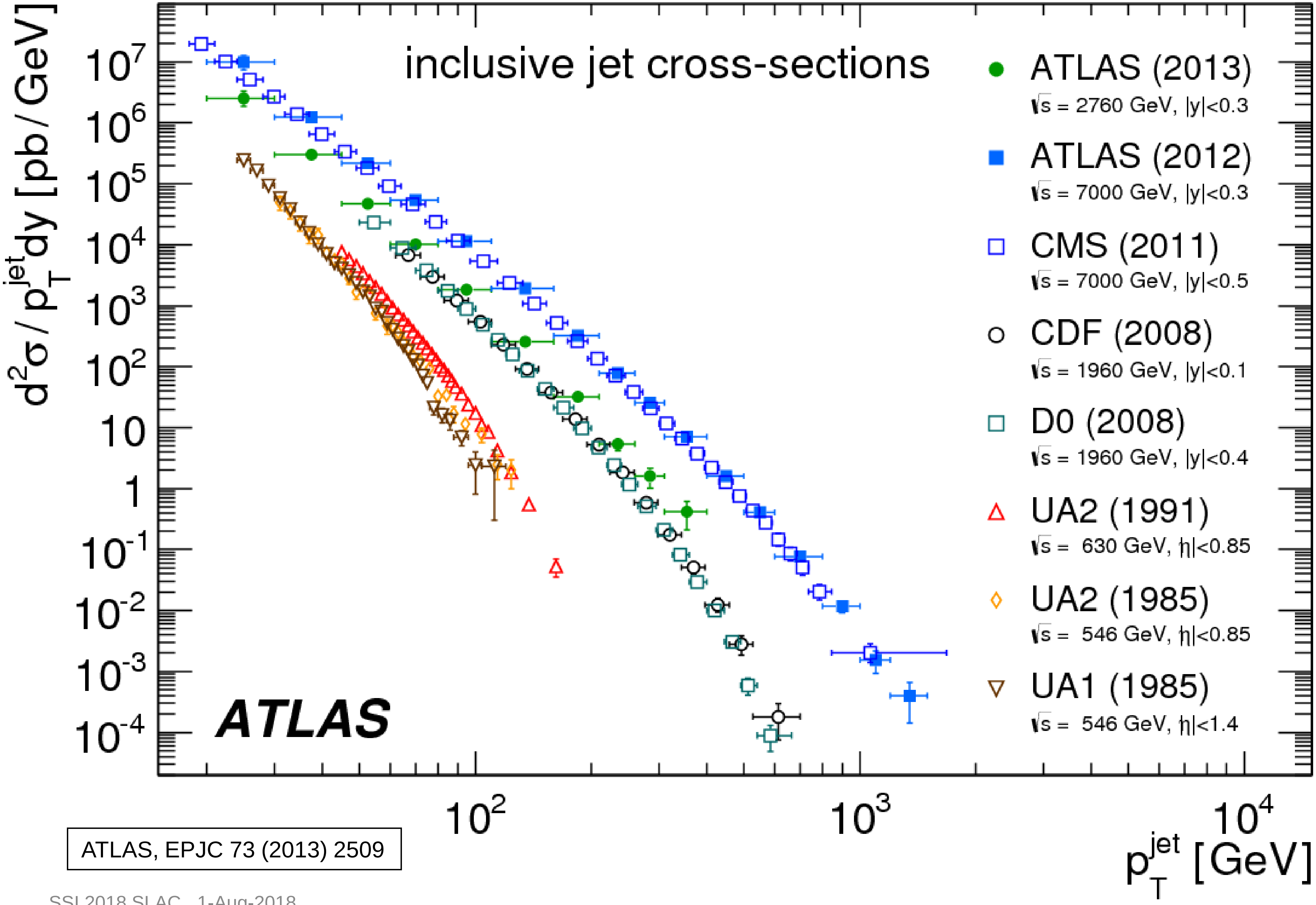




High p_T jets

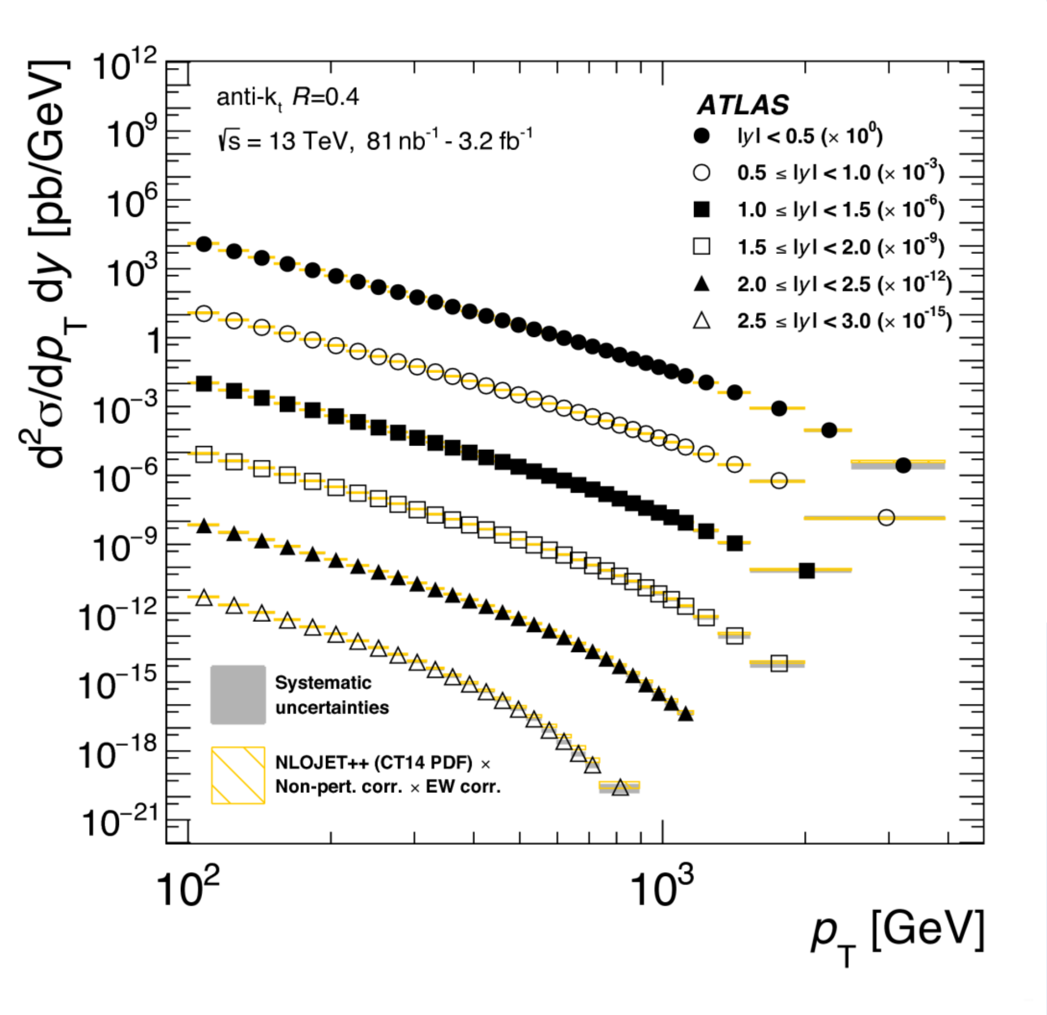


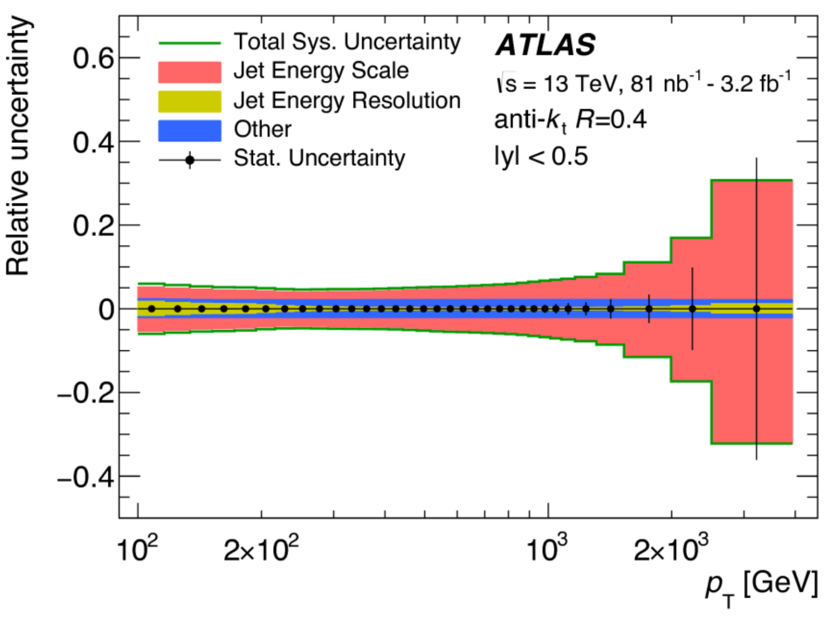
Very high mass dijet event with m_{jj} = 8.2 TeV



ATLAS, EPJC 73 (2013) 2509

A more recent example of a QCD analysis: Inclusive jet cross-section at 13 TeV

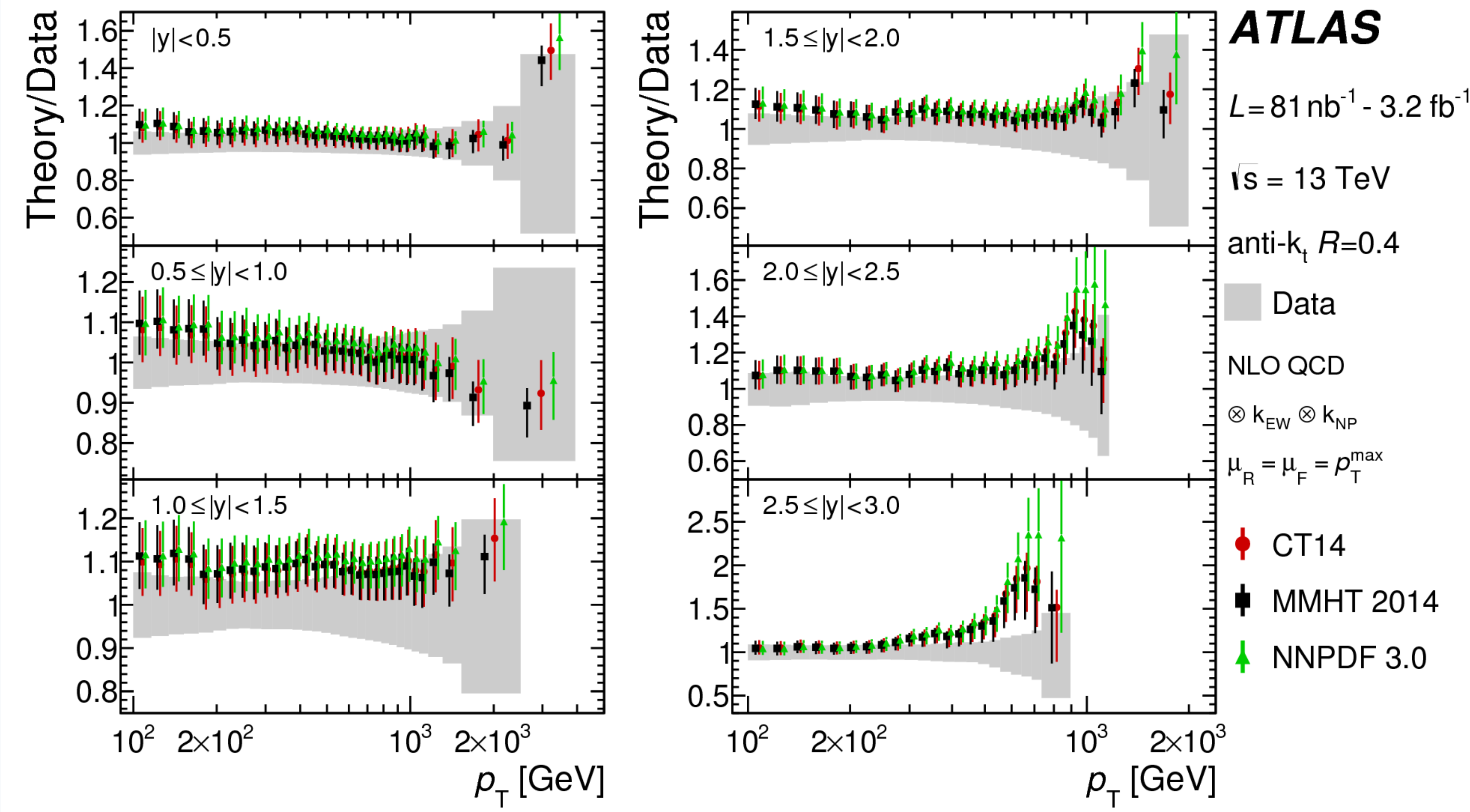




Jet energy scale (JES) and jet energy resolution (JER) uncertainties

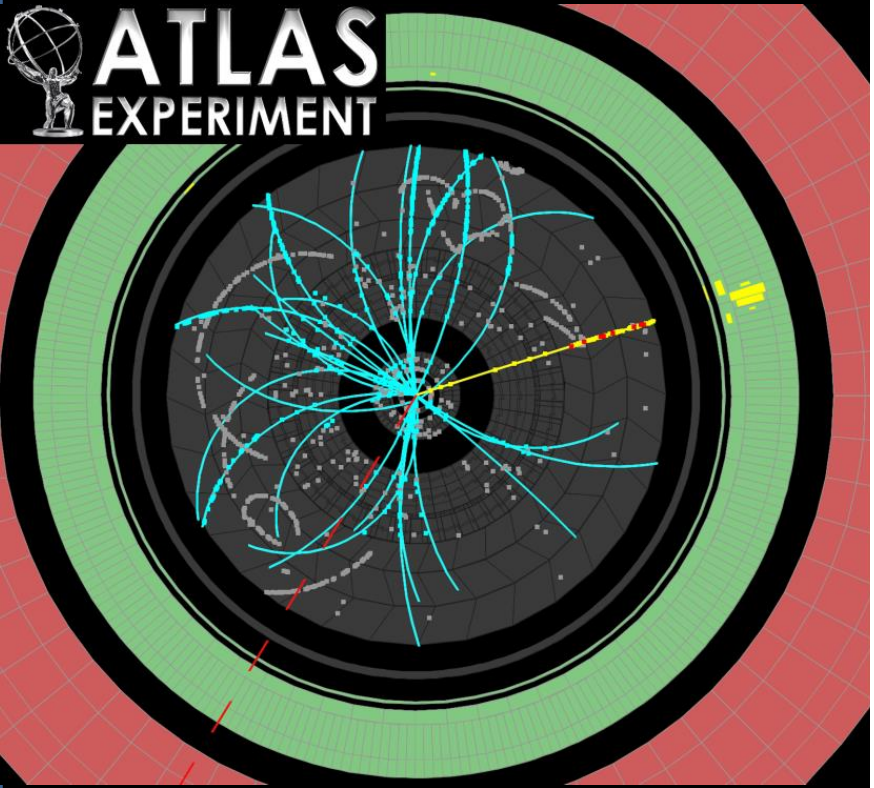
arXiv:1711.02692[hep-exp], published in JHEP 05(2018)195

An example of a QCD analysis: Inclusive jets at 13 TeV compared to different NLO pQCD calculations

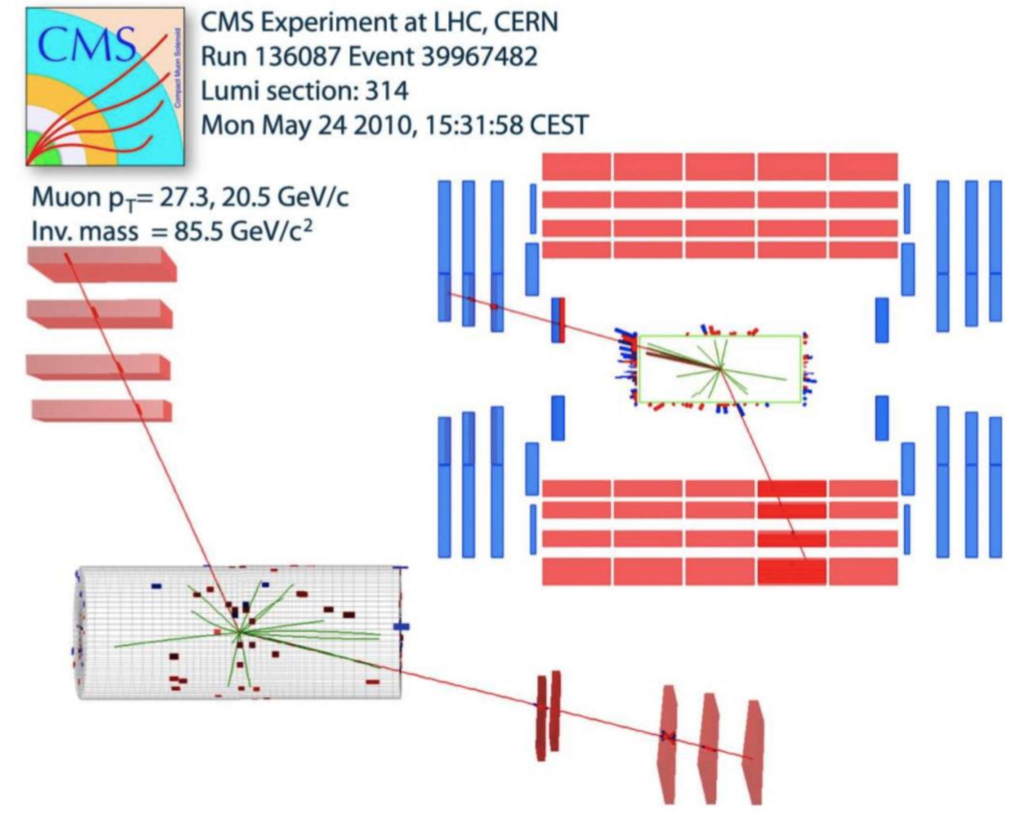


arXiv:1711.02692[hep-exp], published in JHEP 05(2018)195

‘Standard Candles’ for the LHC physics: W and Z bosons

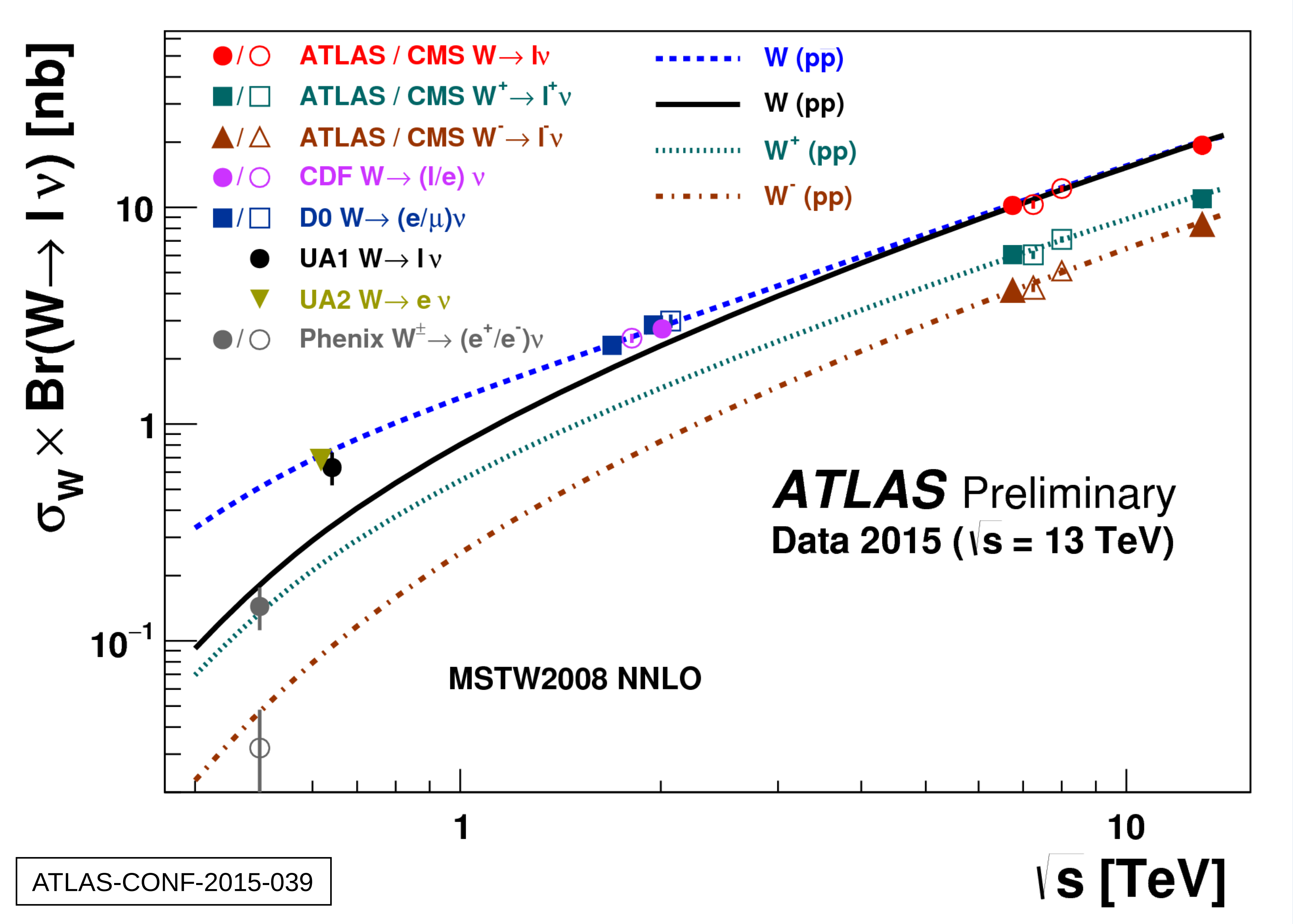


W → eν candidate

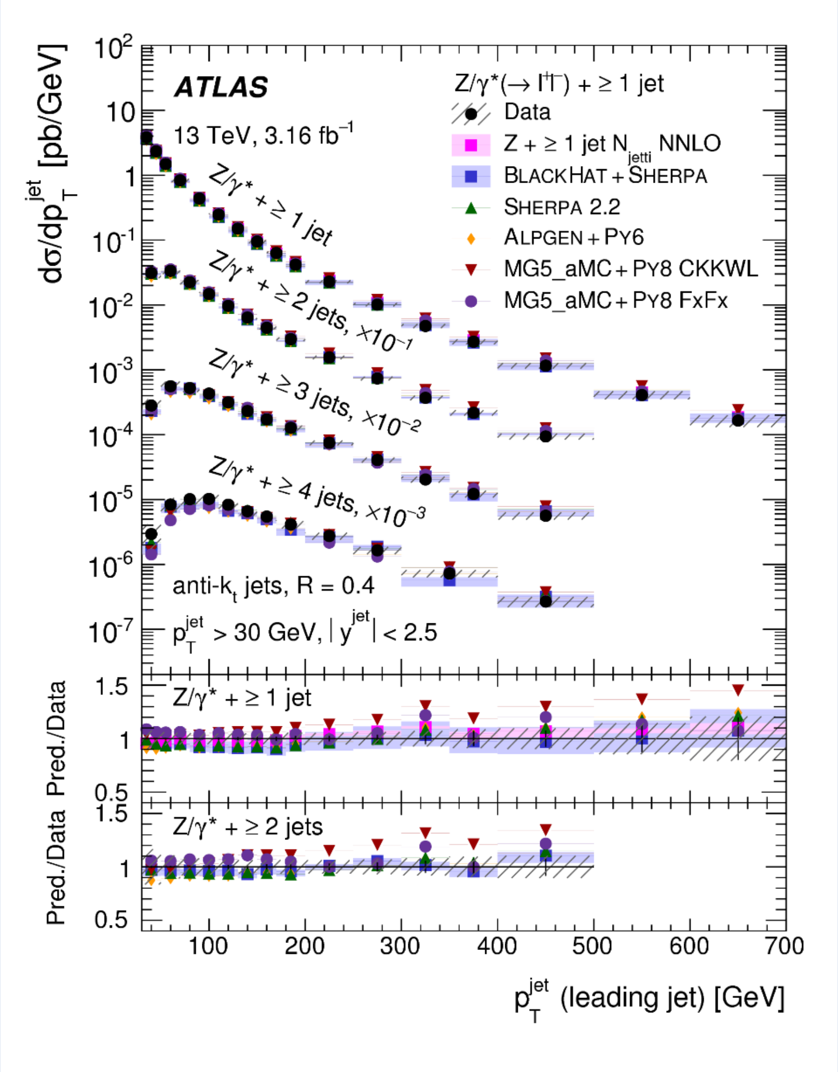


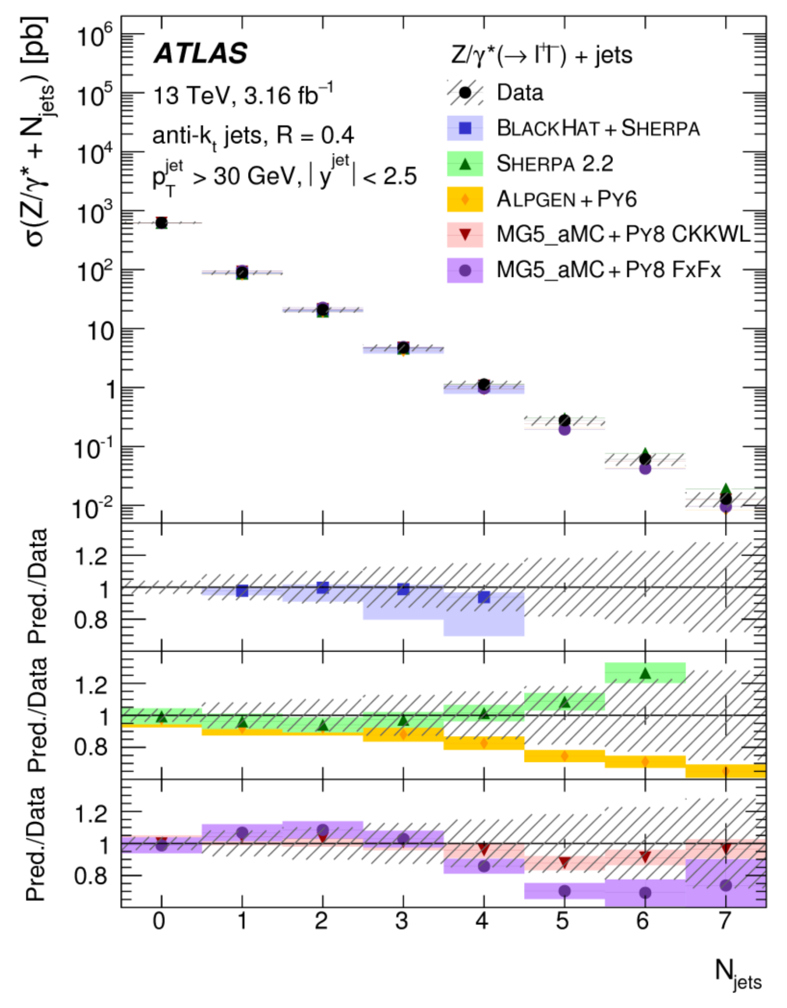
Candidate Z → $\mu^+\mu^-$

W cross section measurements in pp collisions



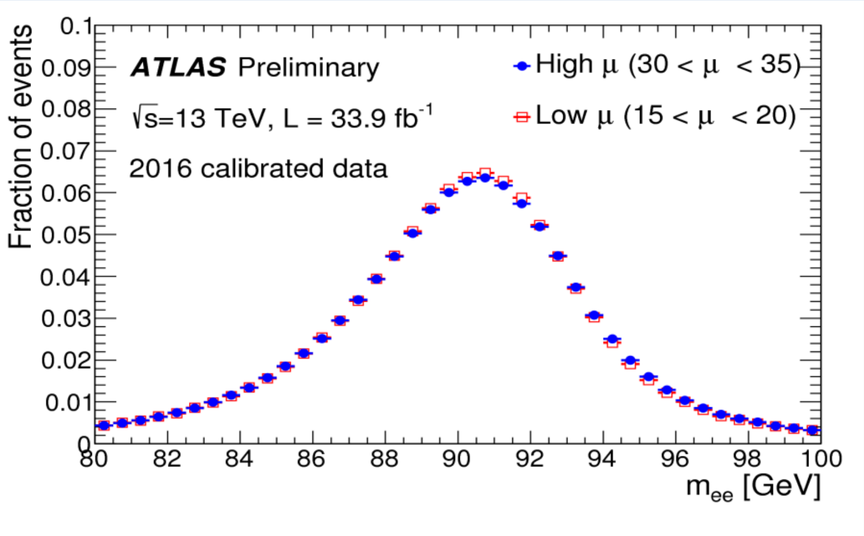
Example of detailed IVB + jets QCD measurements

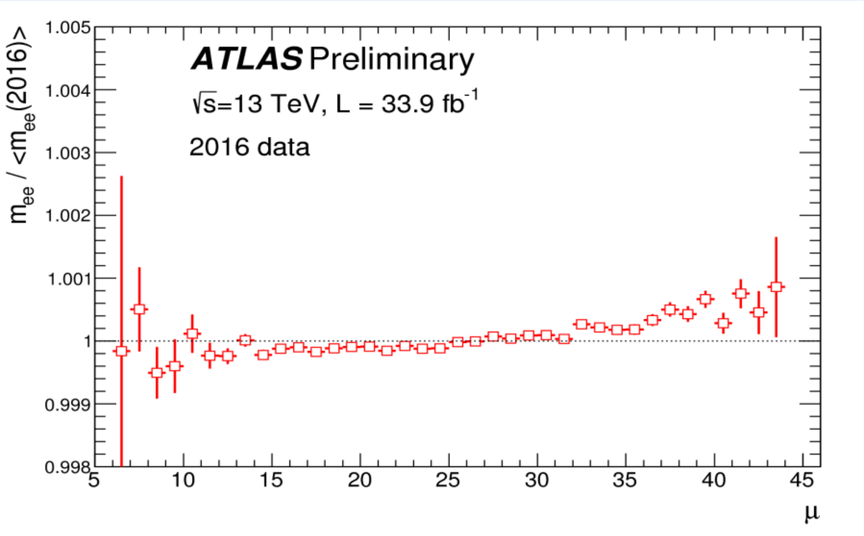


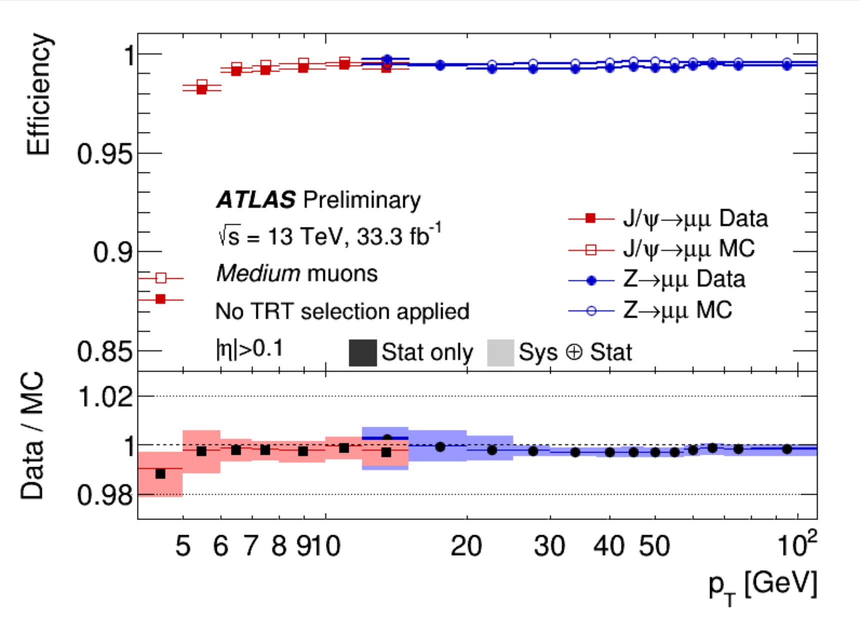


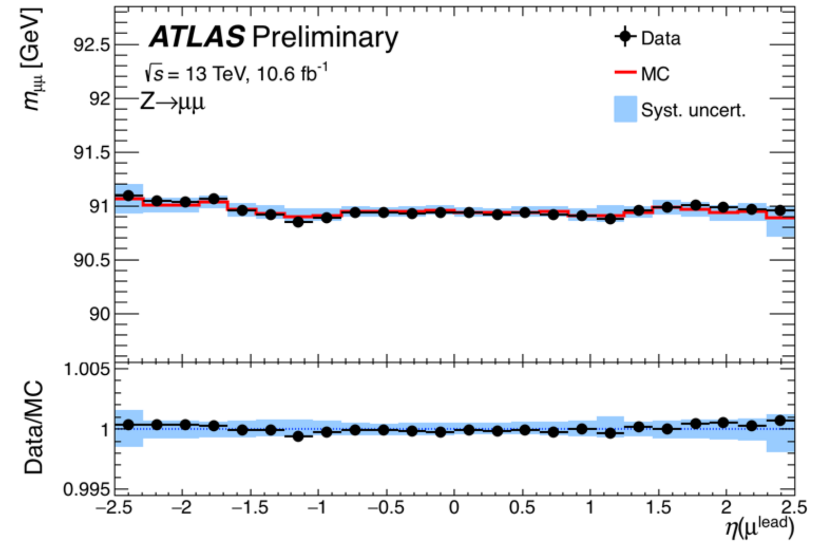
Eur. Phys. J. C77 (2017) 361

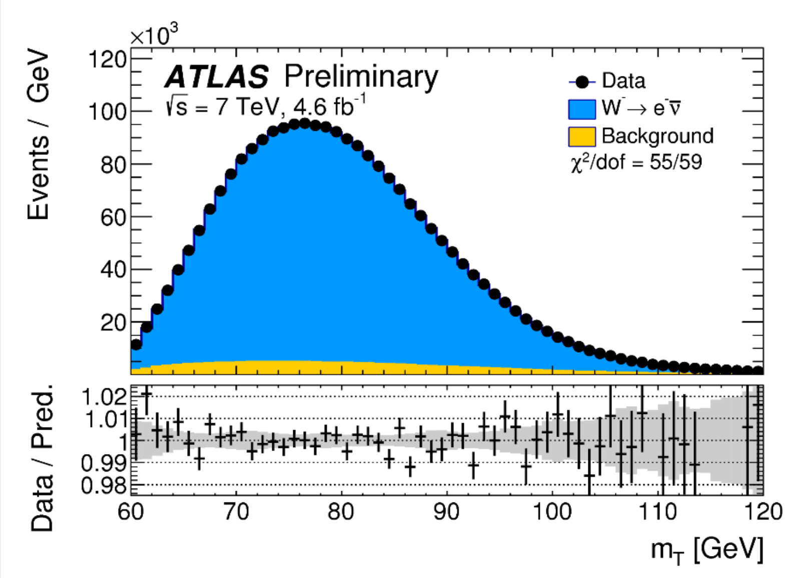
Detailed performance studies for electrons and muons (mass scales, efficiencies, dependence on pile-up …) are most important for precision measurements, as examples some plots from ATLAS

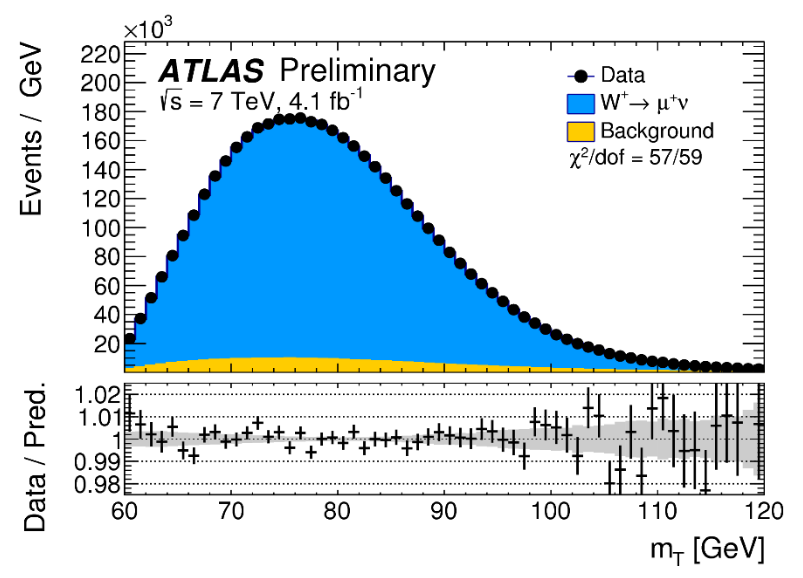










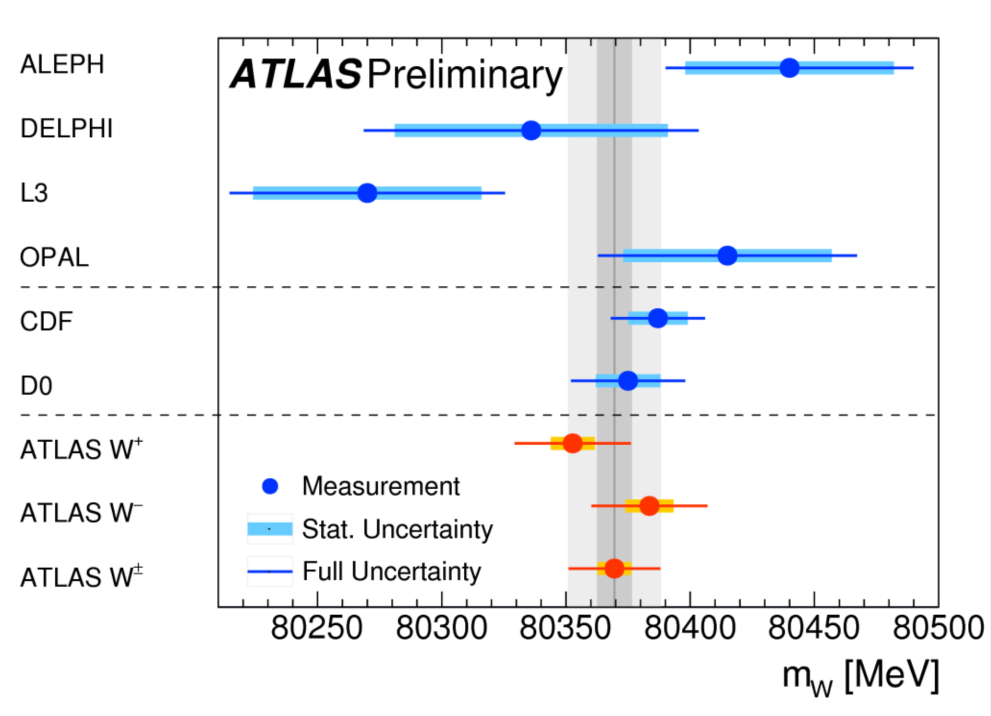


$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}p_{\mathrm{T}}^{\nu}(1-\cos(\phi^{\ell}-\phi^{\nu}))}$$

Precision measurement of the W mass recently published by ATLAS

m_W = 80.370 ± 0.019 GeV

arXiv:1701.07240[hep-exp], EPJ C78 (2018) 110

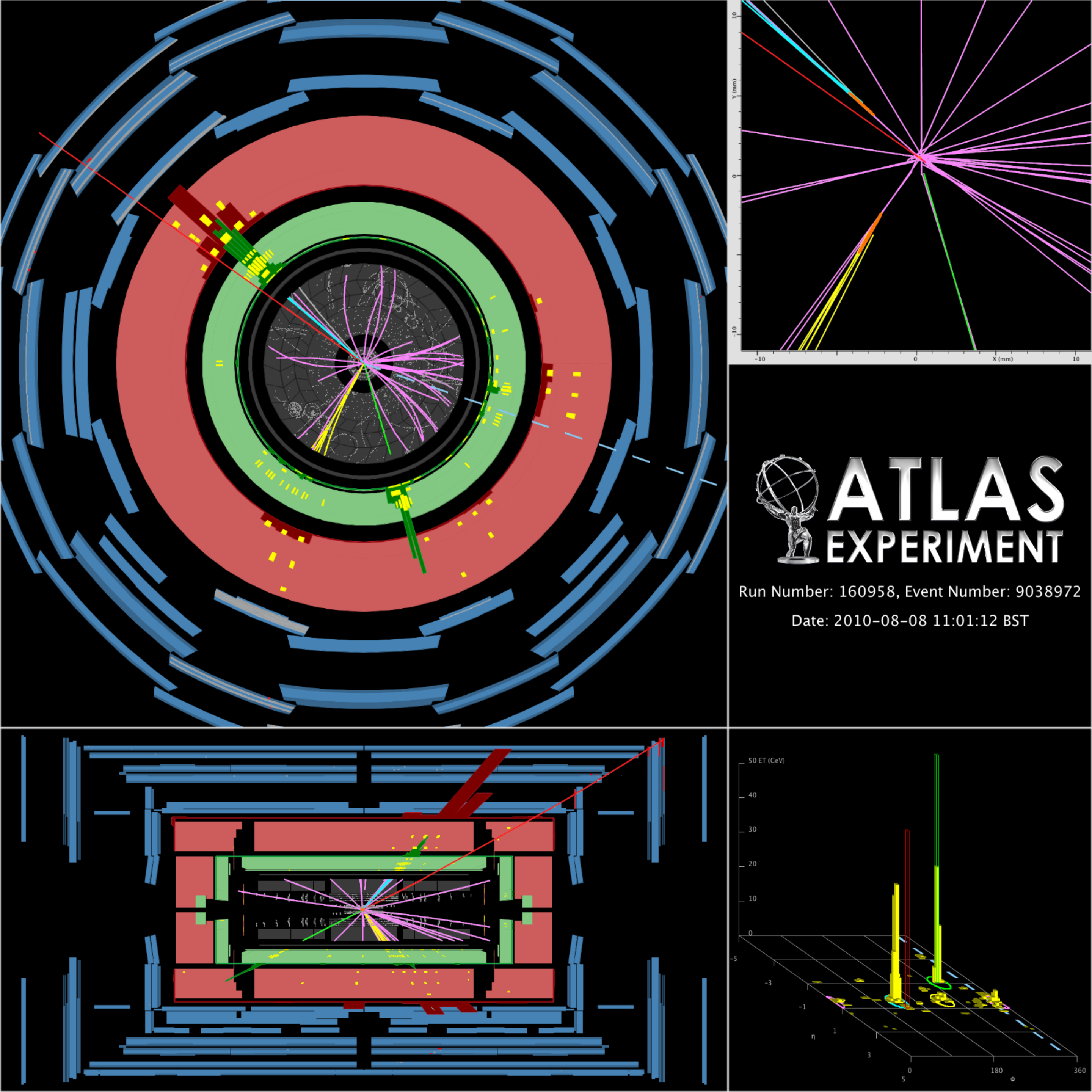


Top

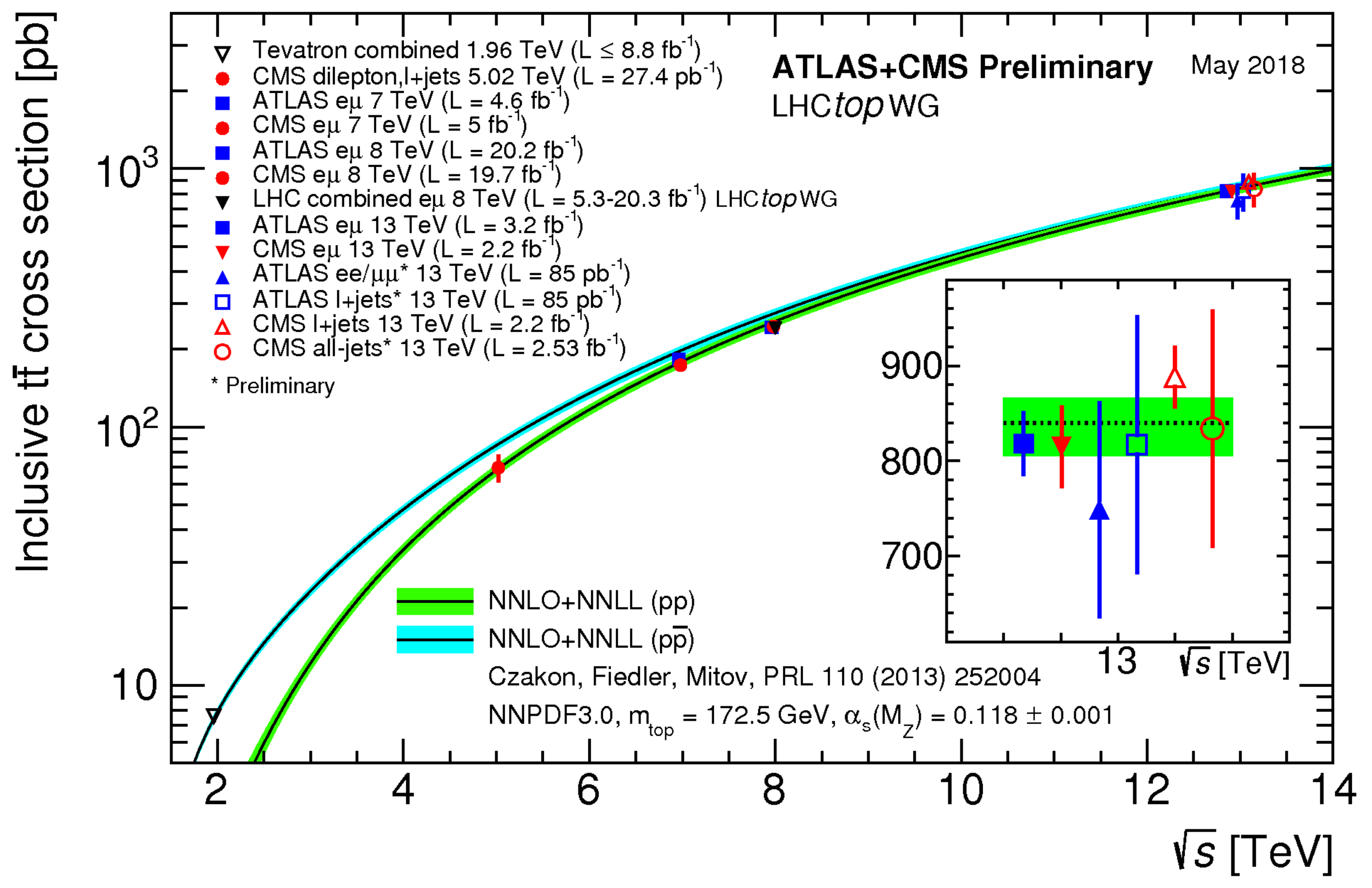
$t\bar{t}$ candidate event

Cleanest event topology with both W decaying leptonically:

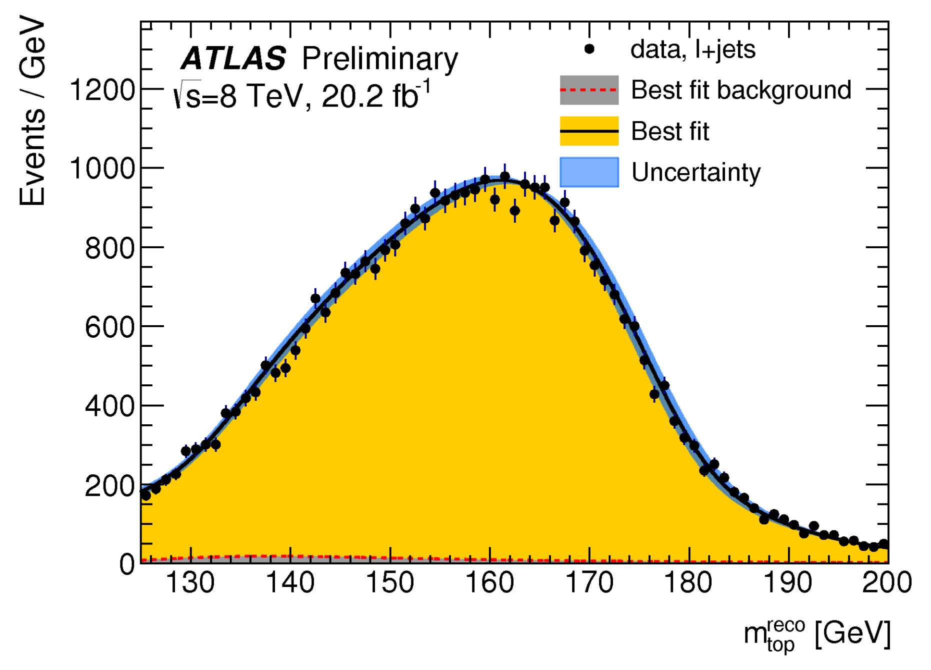
e + μ + 2 b-jets + ETmiss

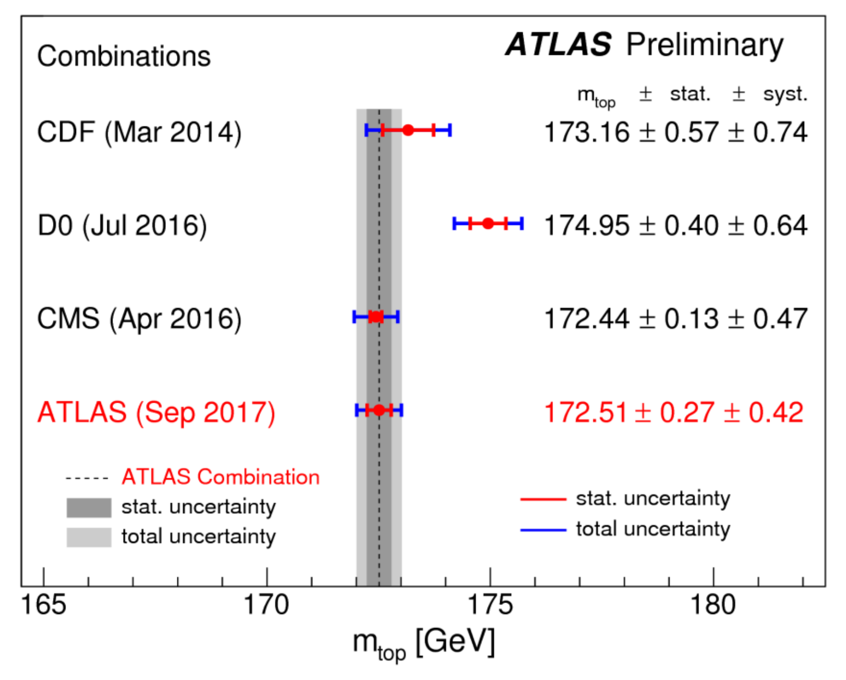


$t\bar{t}$ pair production cross-sections (May 2018)



An example of a m_t measurement at LHC





Tevatron combination [July 2016, 1608.01881]
m_{top} = 174.30 ± 0.35 ± 0.54 GeV

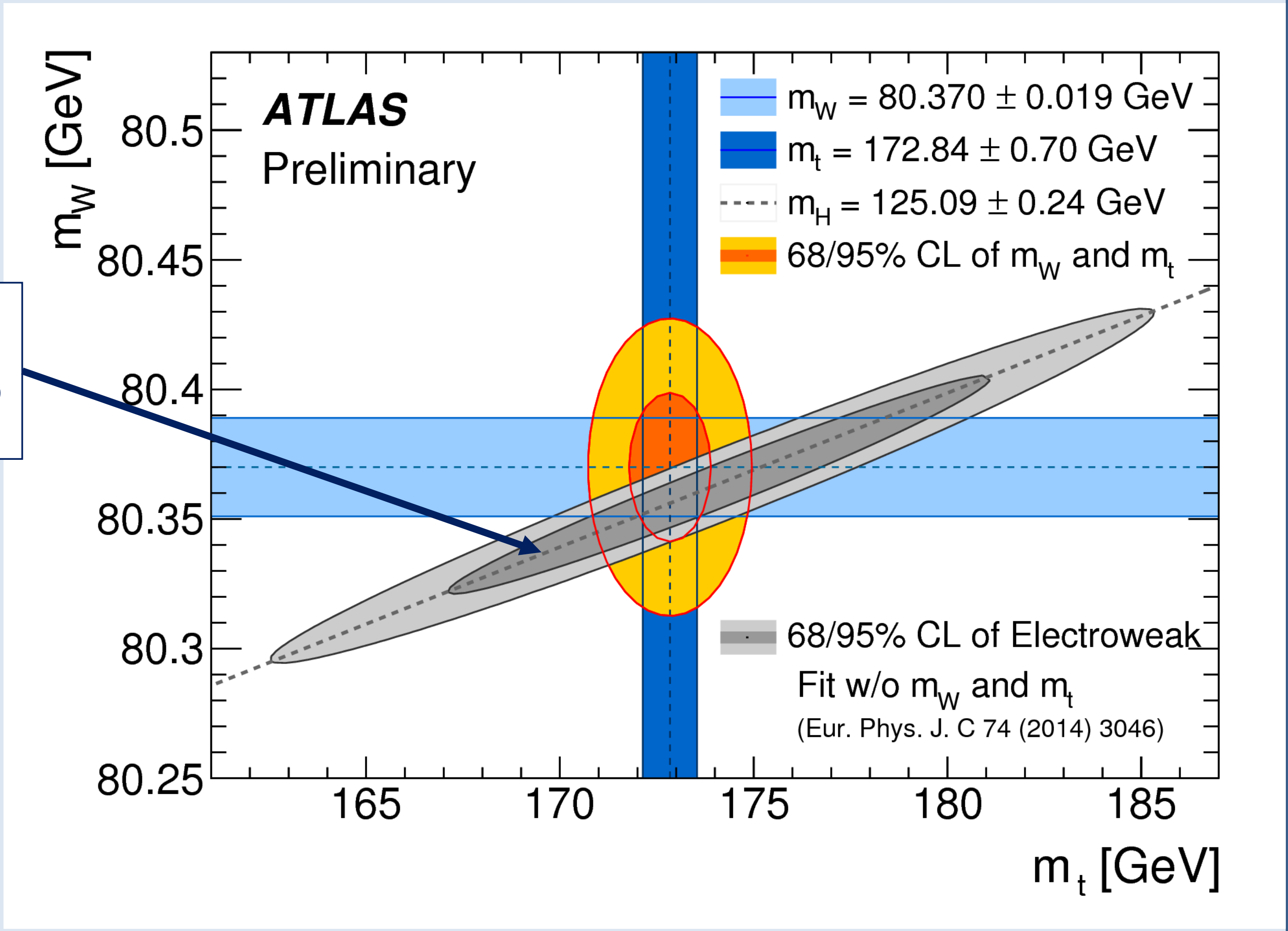
ATLAS-CONF-2017-071

m_{top} = 172.51 ± 0.27 ± 0.42 GeV

Standard Model consistency

G fitter

M.Baak et al, Eur. Phys. J C 74(2014) 3046

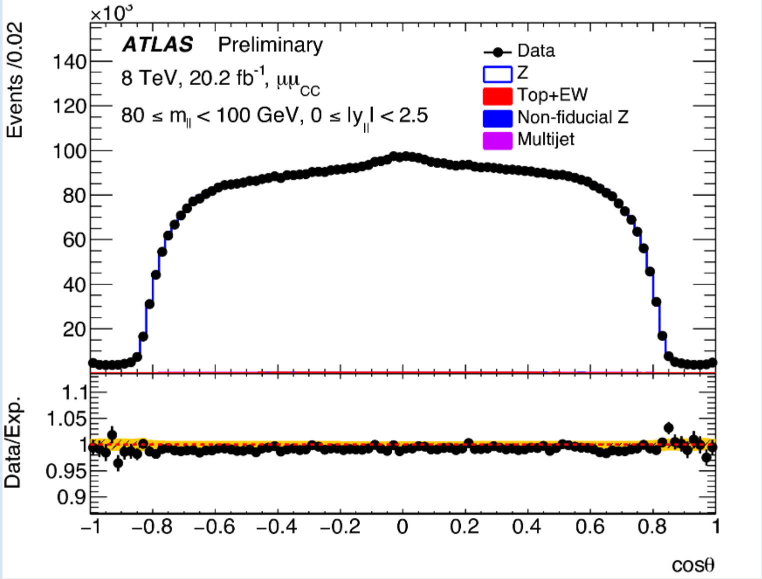


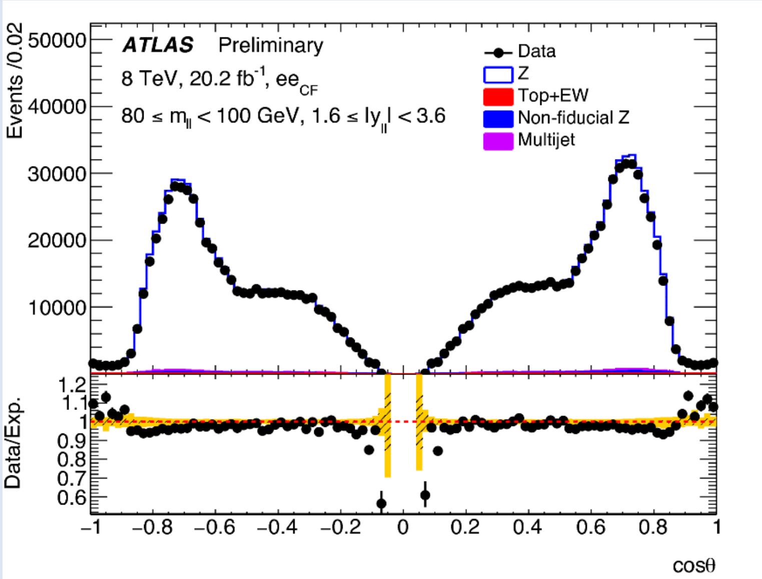
Global EW fit using $m_H = 125.09 \pm 0.24$ GeV compared to W and top mass measurements

Well supported by the new mass measurement of W, top, and H

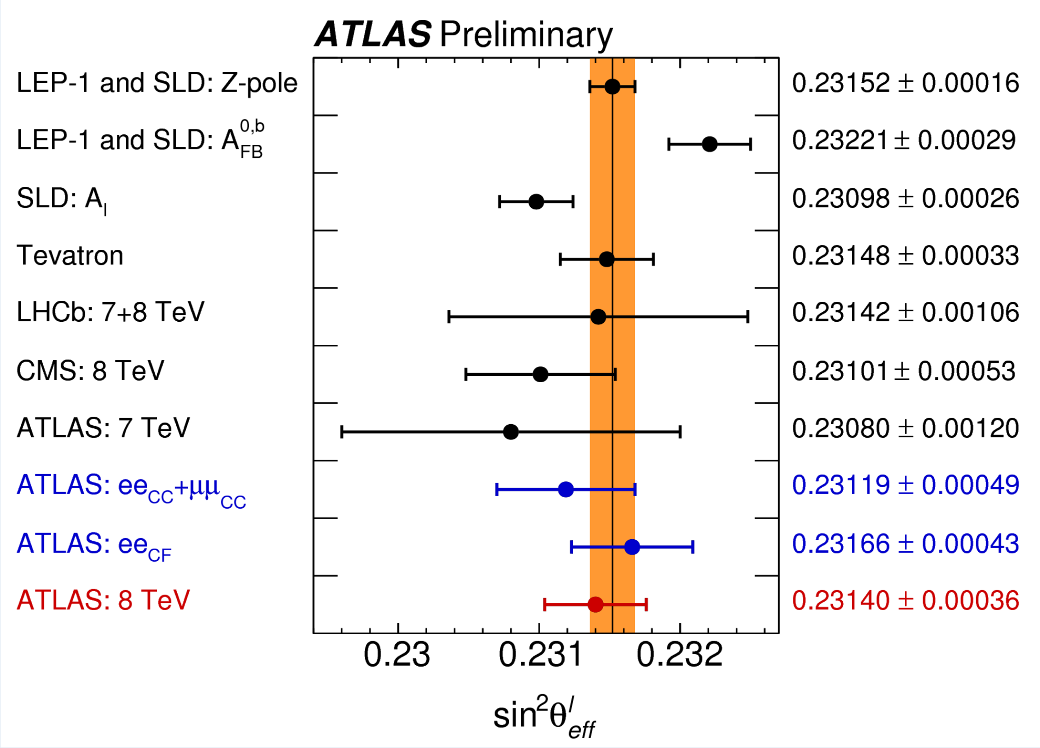
Effective leptonic weak mixing angle $\sin^2\theta^l_{eff}$

Exploit sensitivity in the Drell-Yan Z cross-section using lepton pair decays





(two examples, scattering in the CS frame)

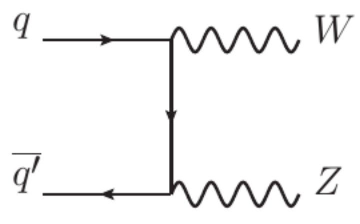


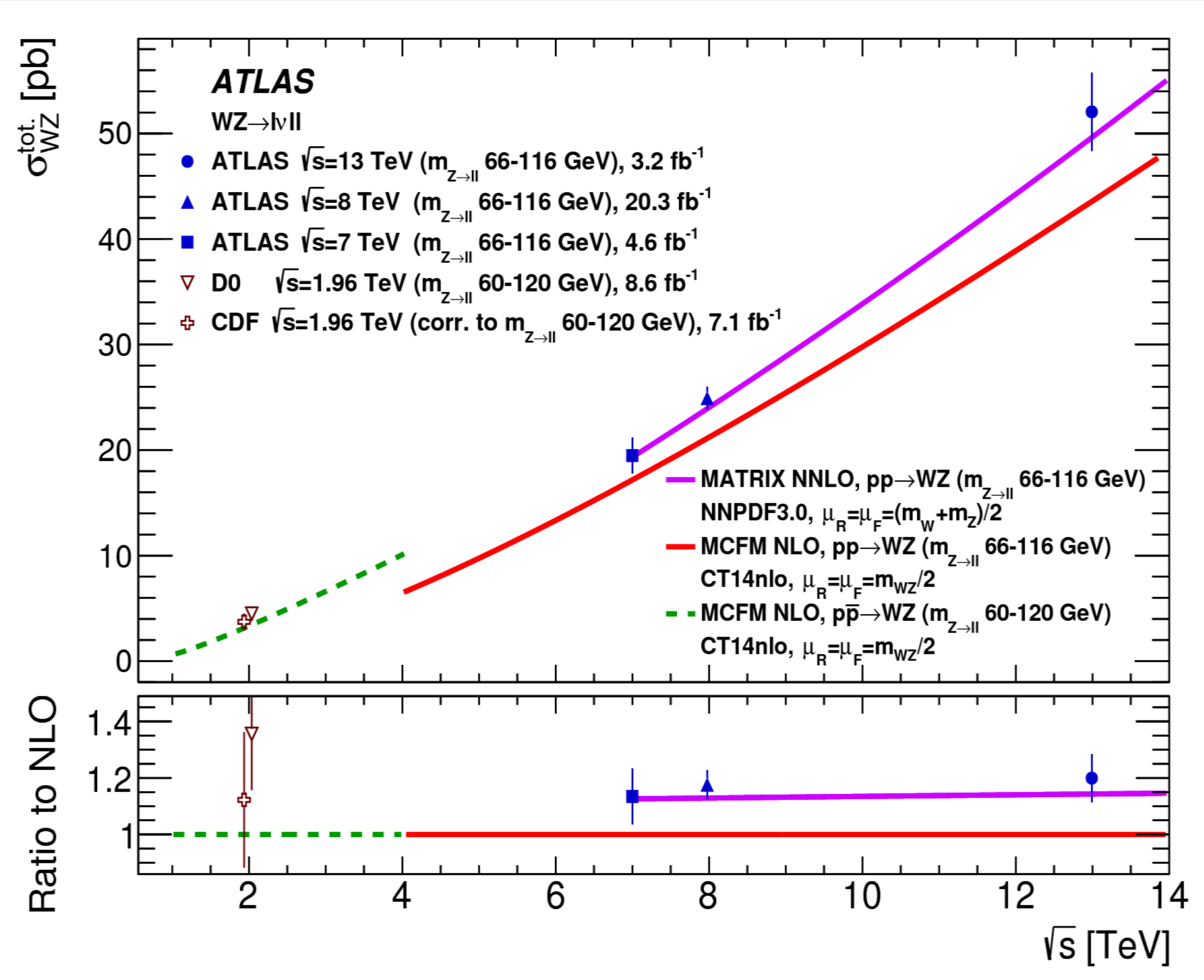
ATLAS-CONF-2018-037

EW boson pair productions

An example:
ZW at 13 TeV

→ NNLO calculations are required to describe the data



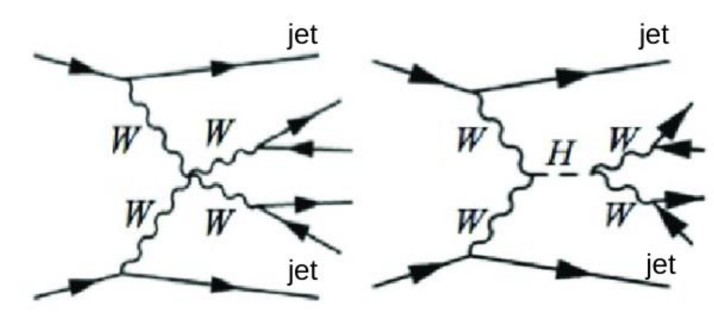


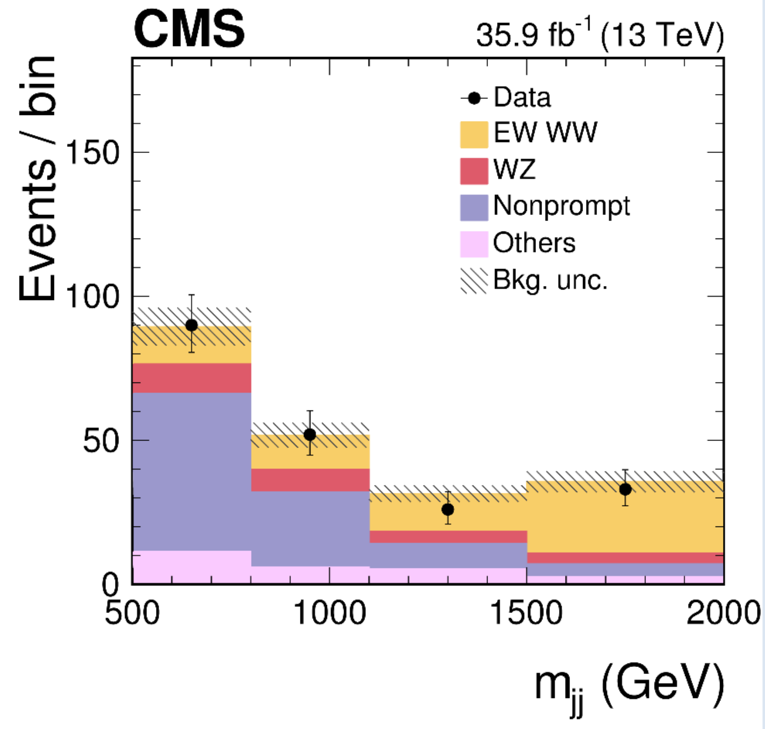
Phys. Lett. B 762 (2016) 1

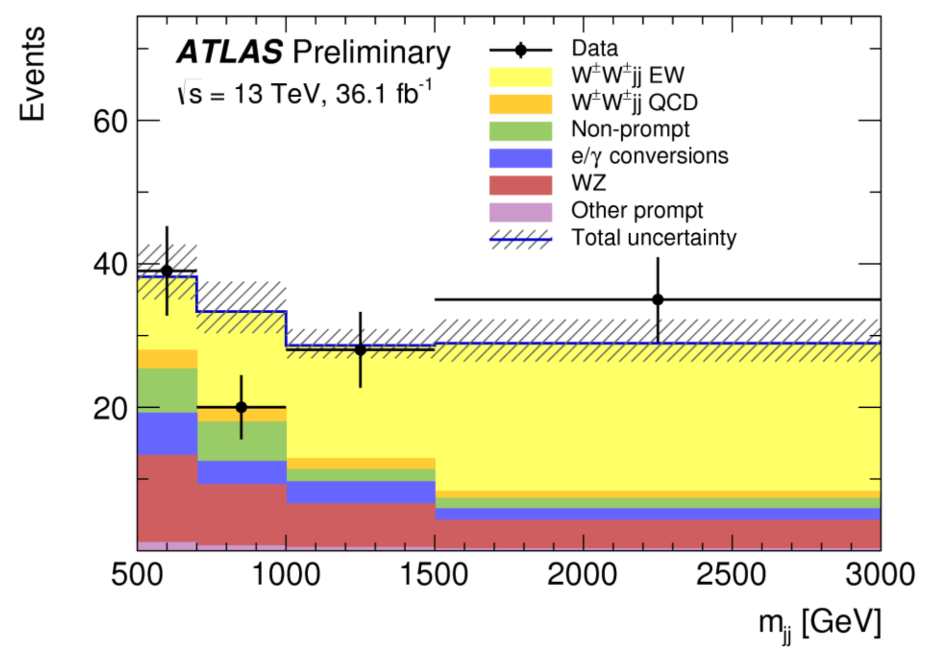
ZZ and ZW are very important processes to probe the EW boson self-couplings, they could reveal physics beyond the Standard Model

Observation of $W^{\pm}W^{\pm}jj$

Important process as part of (future) EW symmetry breaking studies has been observed well above 5σ at the LHC (i.e. restoring of unitarity by the H boson in WW scattering)



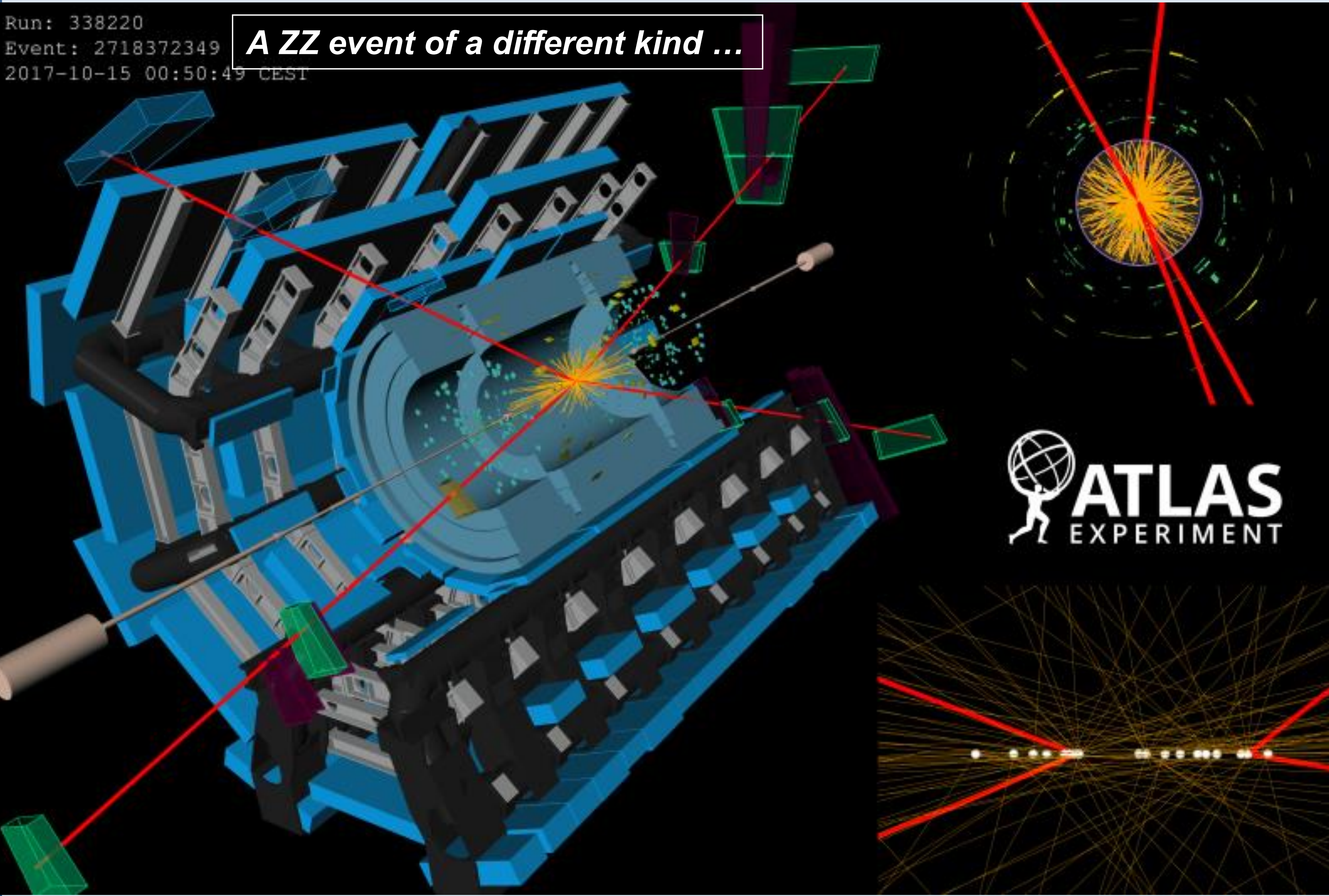


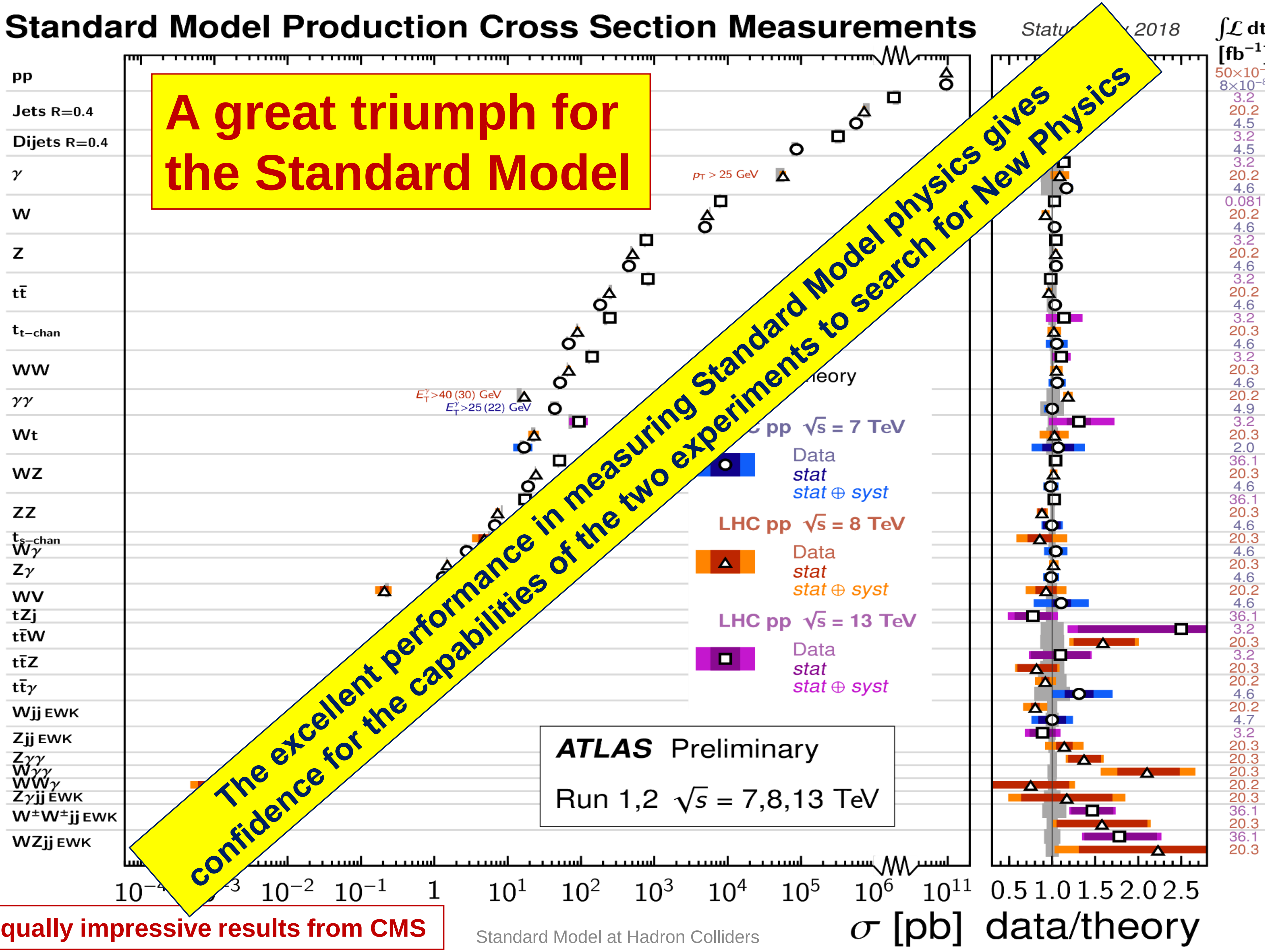


Phys. Rev. Lett. 120 (2018) 081801

ATLAS-CONF-2018-030

A ZZ event of a different kind …





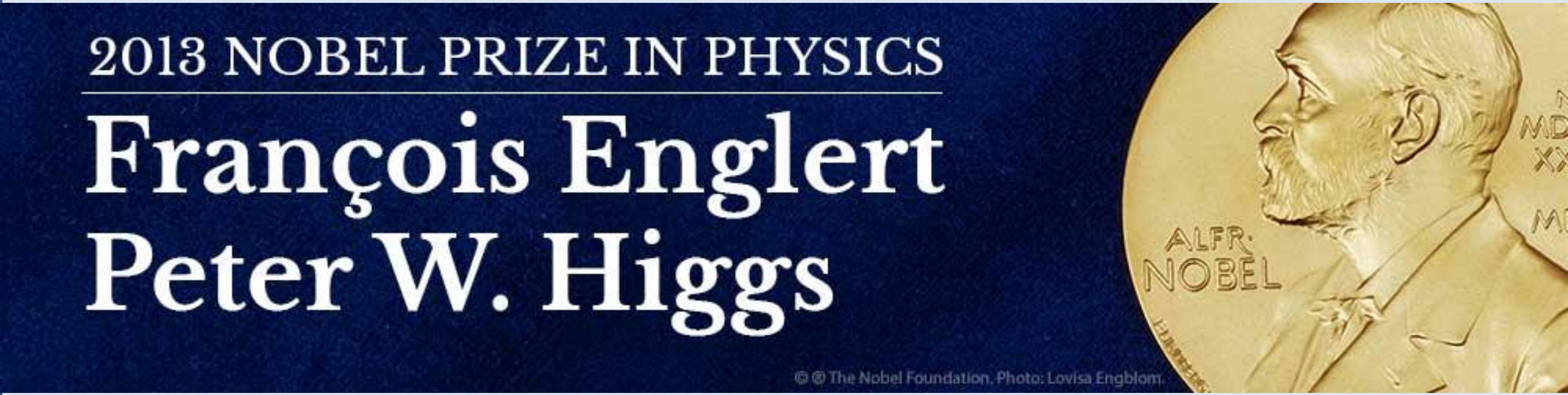
A great triumph for the Standard Model

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

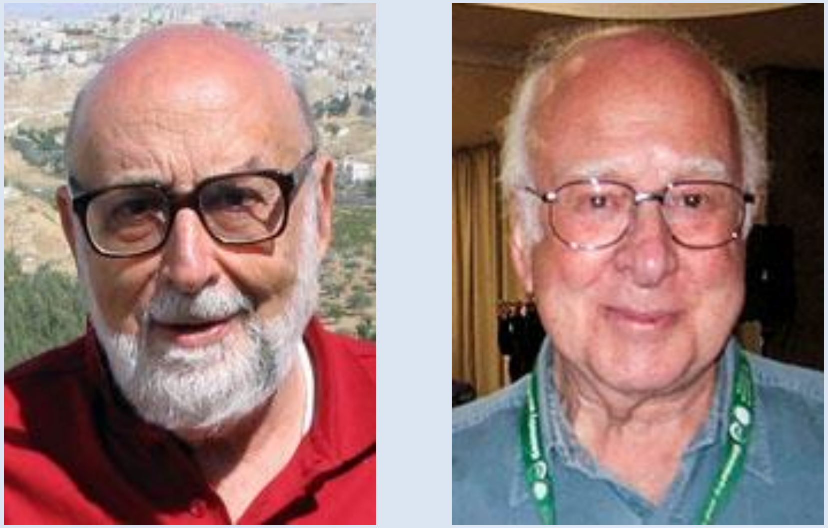
Equally impressive results from CMS

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

Announced on 8th October, celebrated on 10th December 2013

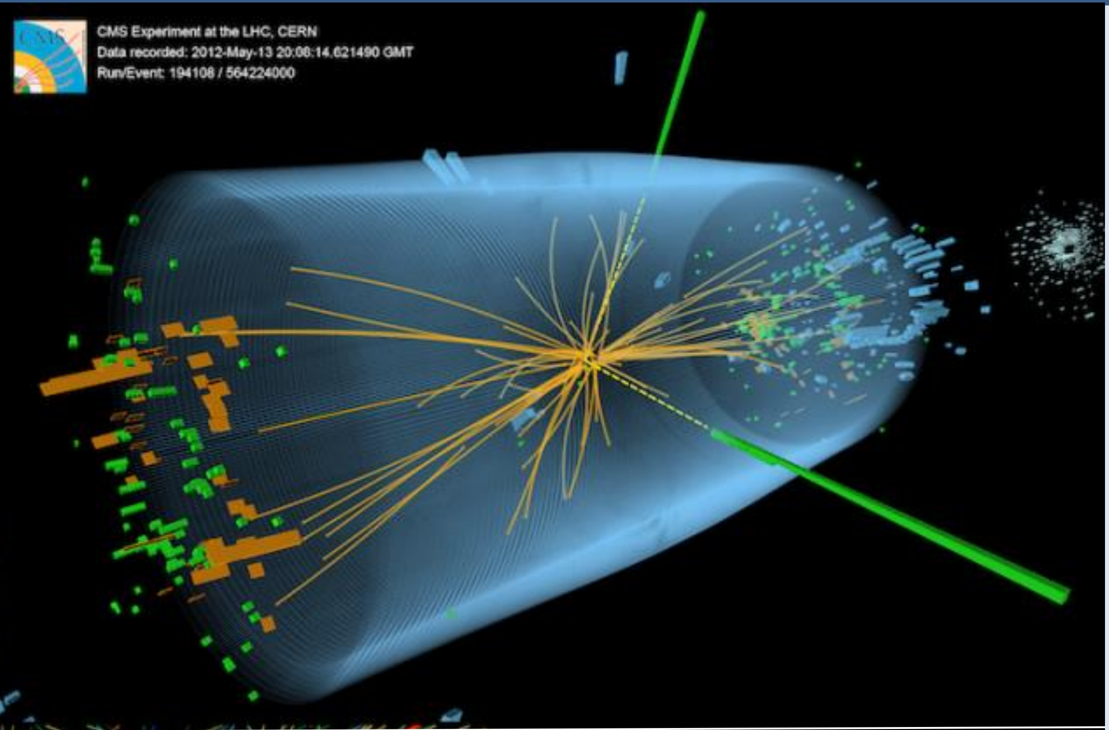


© The Nobel Foundation. Photo: Lovisa Engblom.

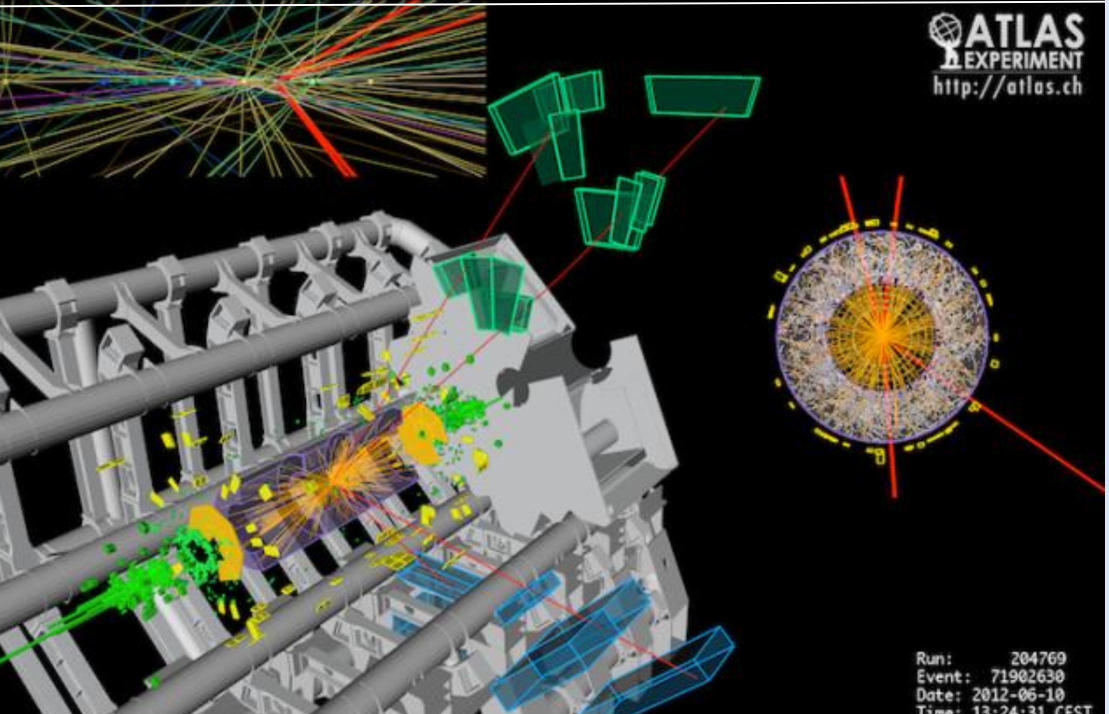


"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Event candidates as predicted for the boson of the Brout-Englert-Higgs field



Candidate for a CMS $H \rightarrow \gamma\gamma$ event

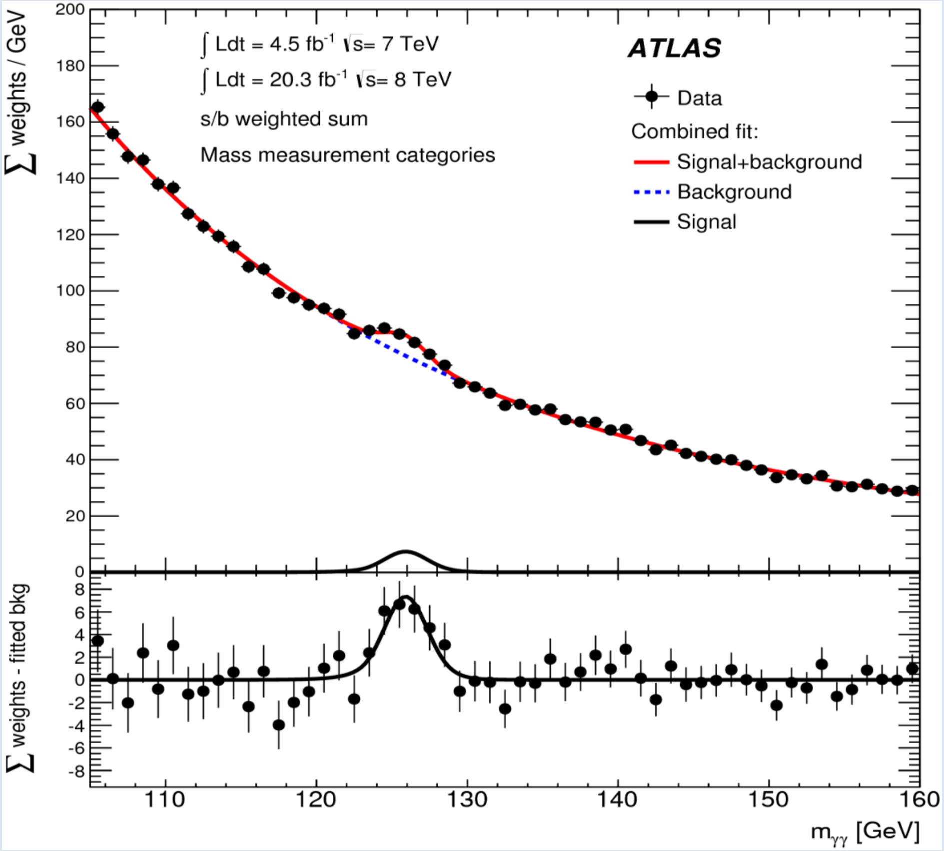


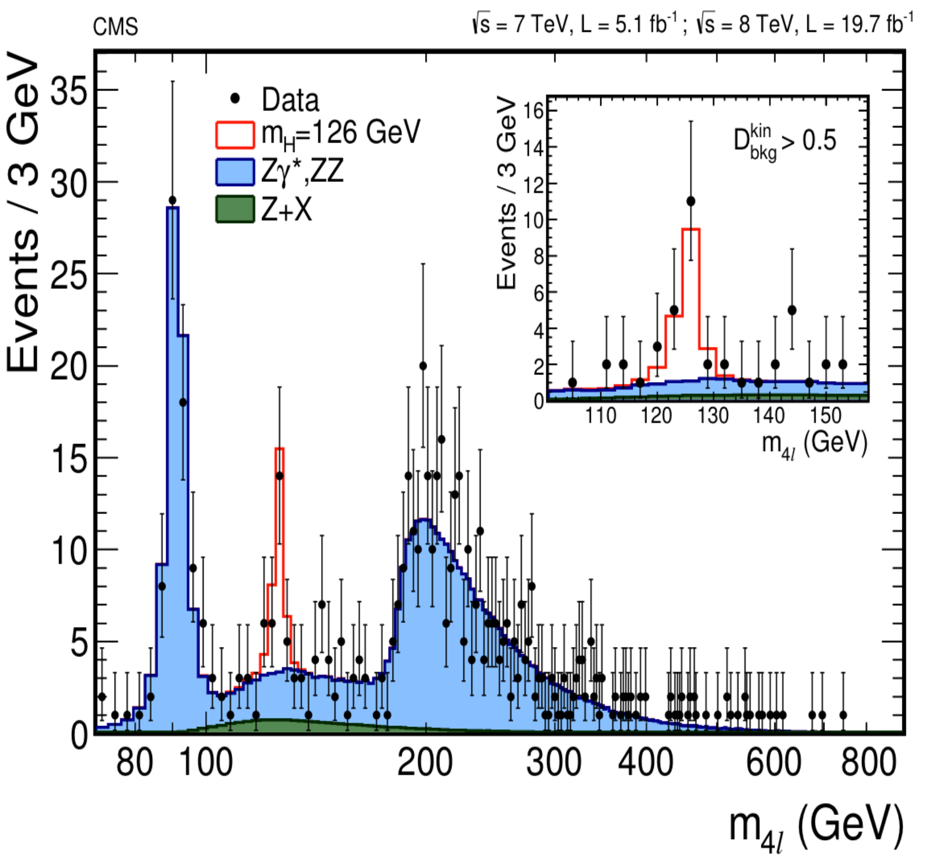
Candidate for an ATLAS $H \rightarrow Z Z^{*} \rightarrow \mu\mu\ \ \mu\mu$ event

LHC Run-1 signal peaks ('Run-1 legacy')

H → $\gamma\gamma$

H → $ZZ^{(*)}$ → 4l (4e, 4μ, 2e2μ)



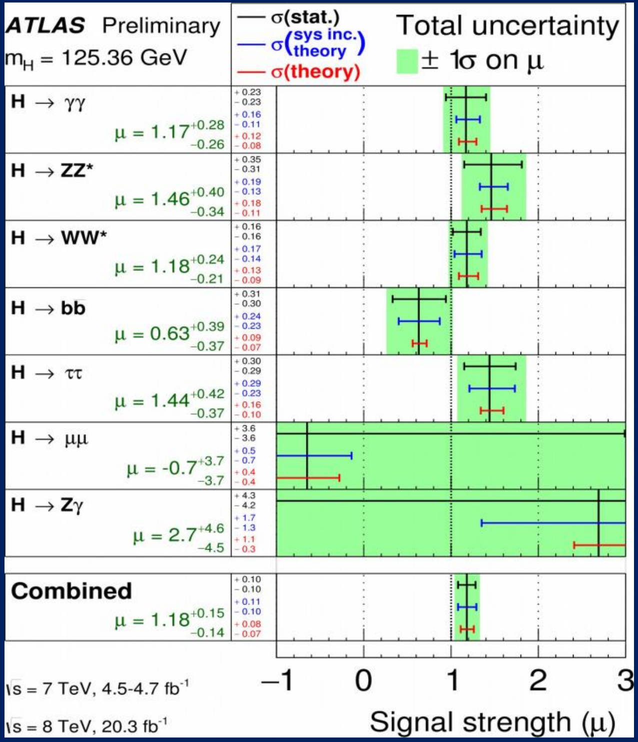


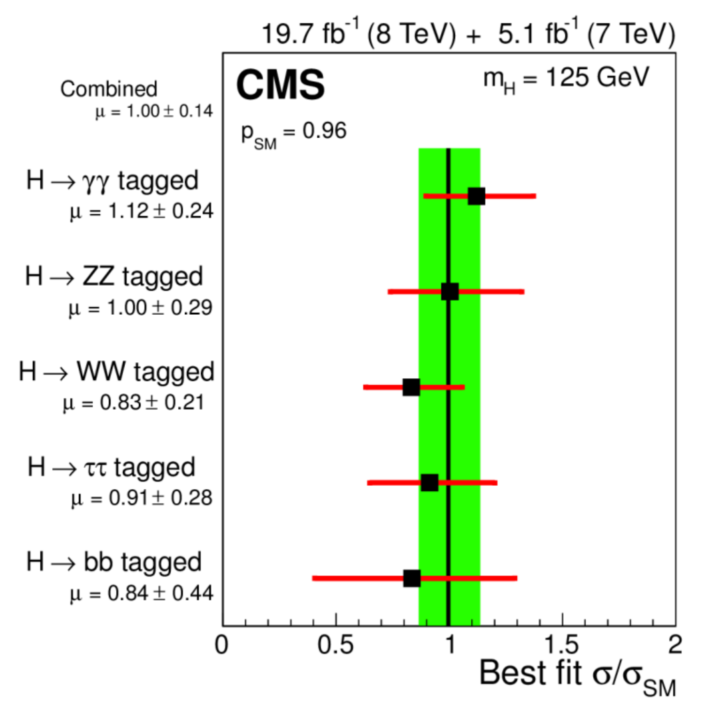
Phys. Rev. D 90 (2014) 052004

Phys. Rev. D 89 (2014) 092007

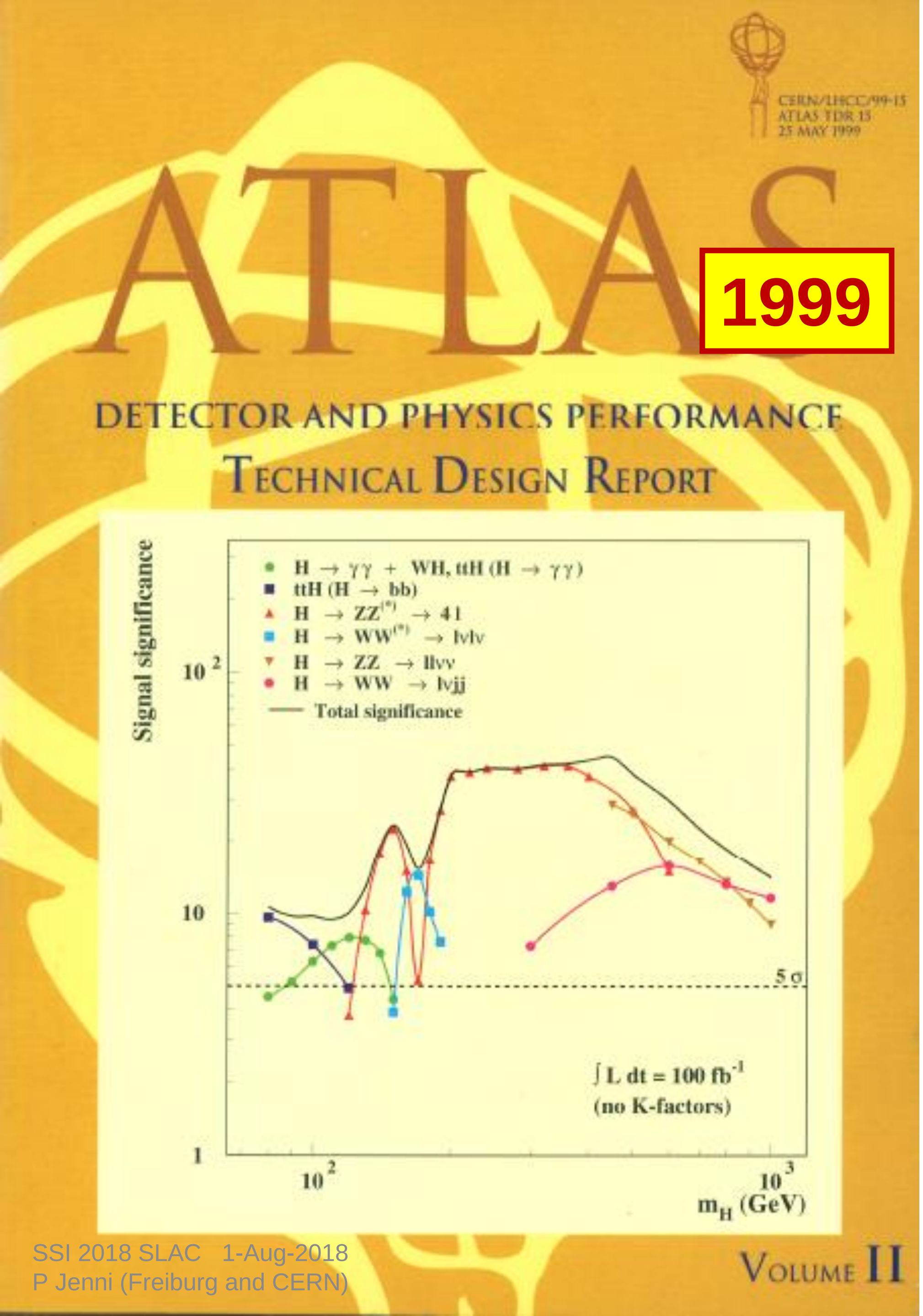
Complementary technologies provided comparable performances in term of significance of the signals ('Run-1 legacy') !

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





A dream becoming true much faster than anticipated long ago



CERN/LHCC/99-15
ATLAS TDR 15
25 MAY 1999

ATLAS

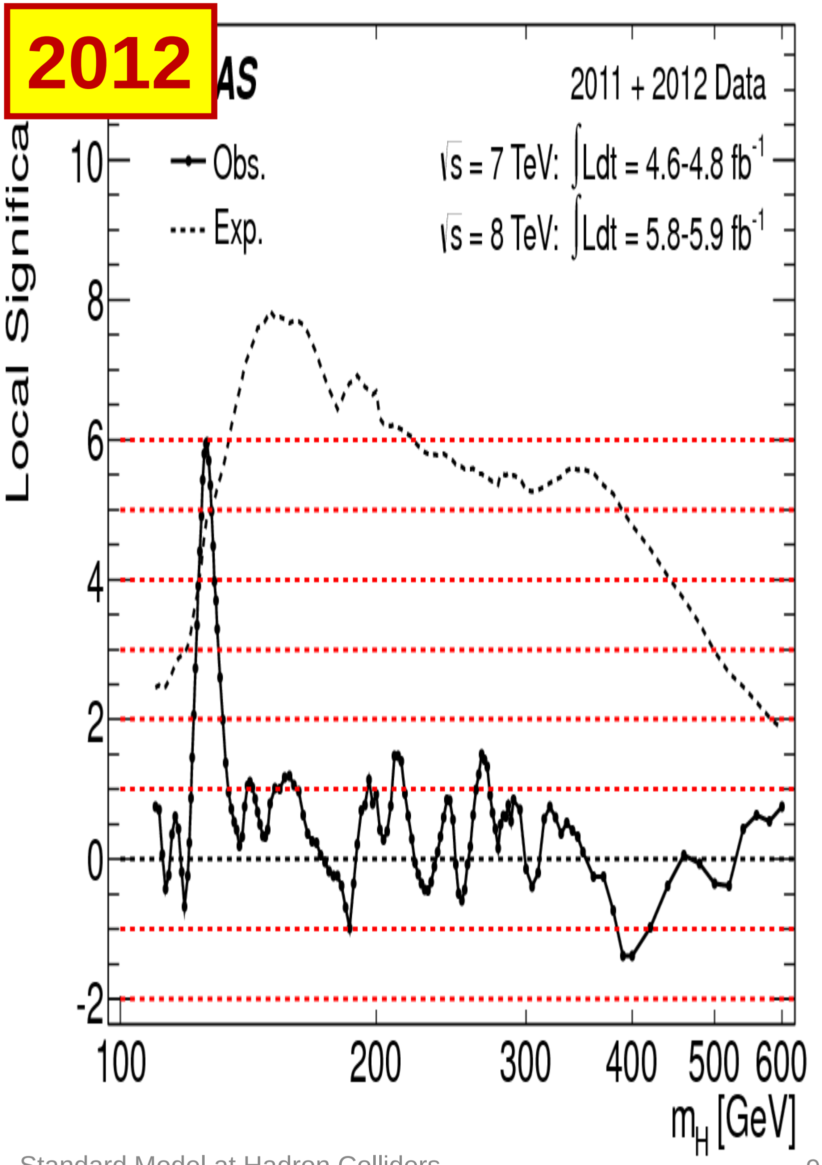
DETECTOR AND PHYSICS PERFORMANCE

TECHNICAL DESIGN REPORT

VOLUME II

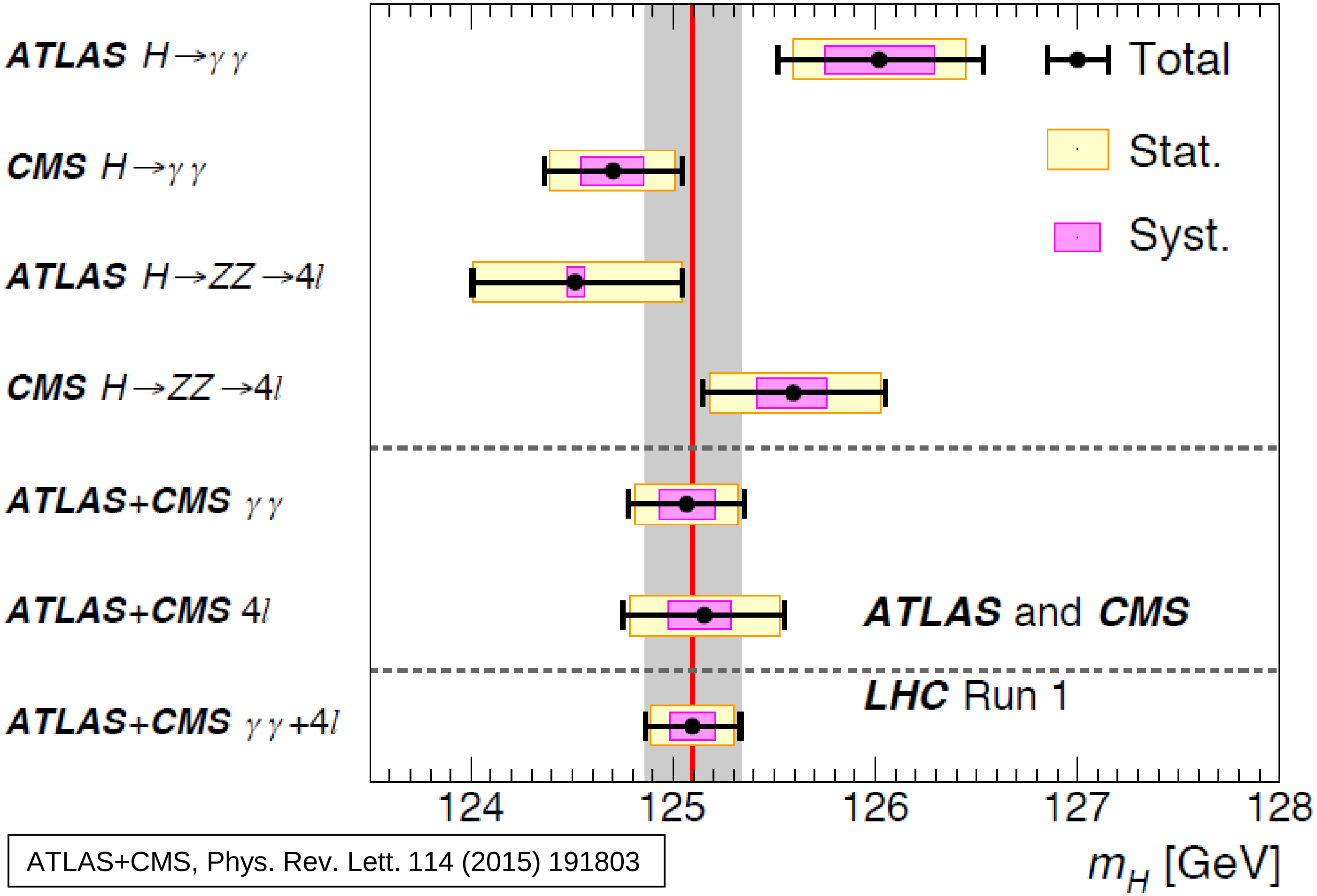
1999

2012



ATLAS and CMS combined Run-1 mass measurements

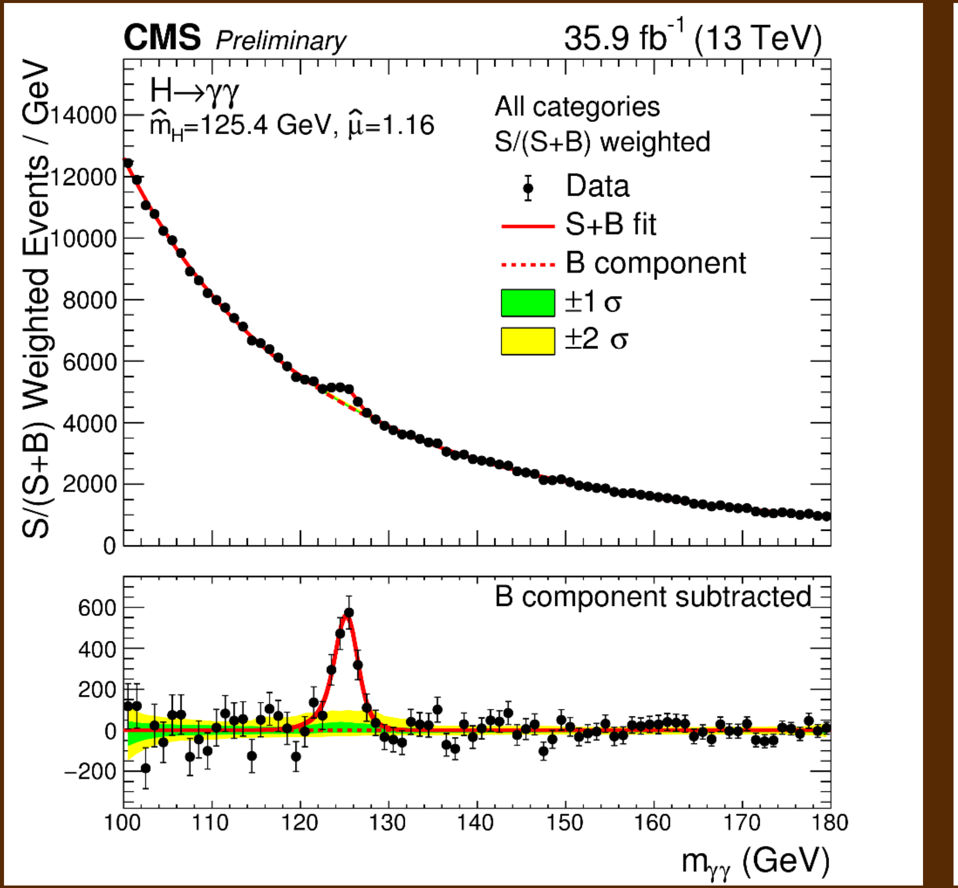
$$m_H = 125.09 \pm 0.24\ (\pm 0.21\ \mathrm{stat} \pm 0.11\ \mathrm{syst})\ \mathrm{GeV}$$

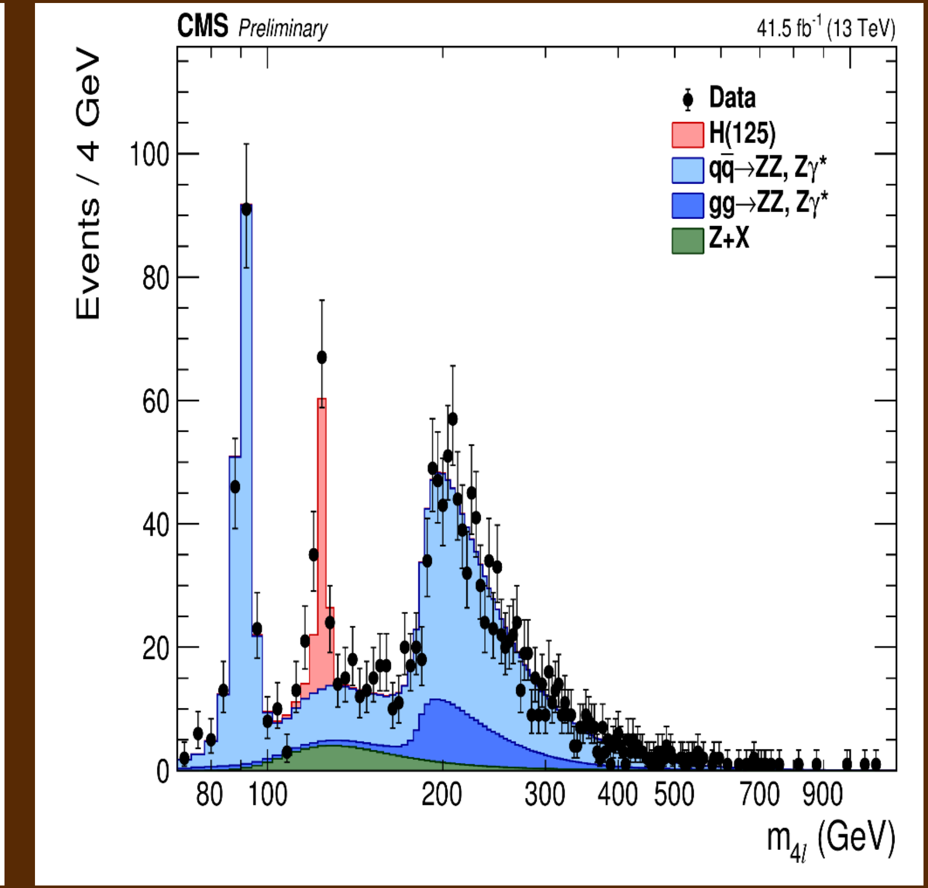


ATLAS+CMS, Phys. Rev. Lett. 114 (2015) 191803

Accuracy already ~ 0.2%

CMS Higgs signals from Run-2

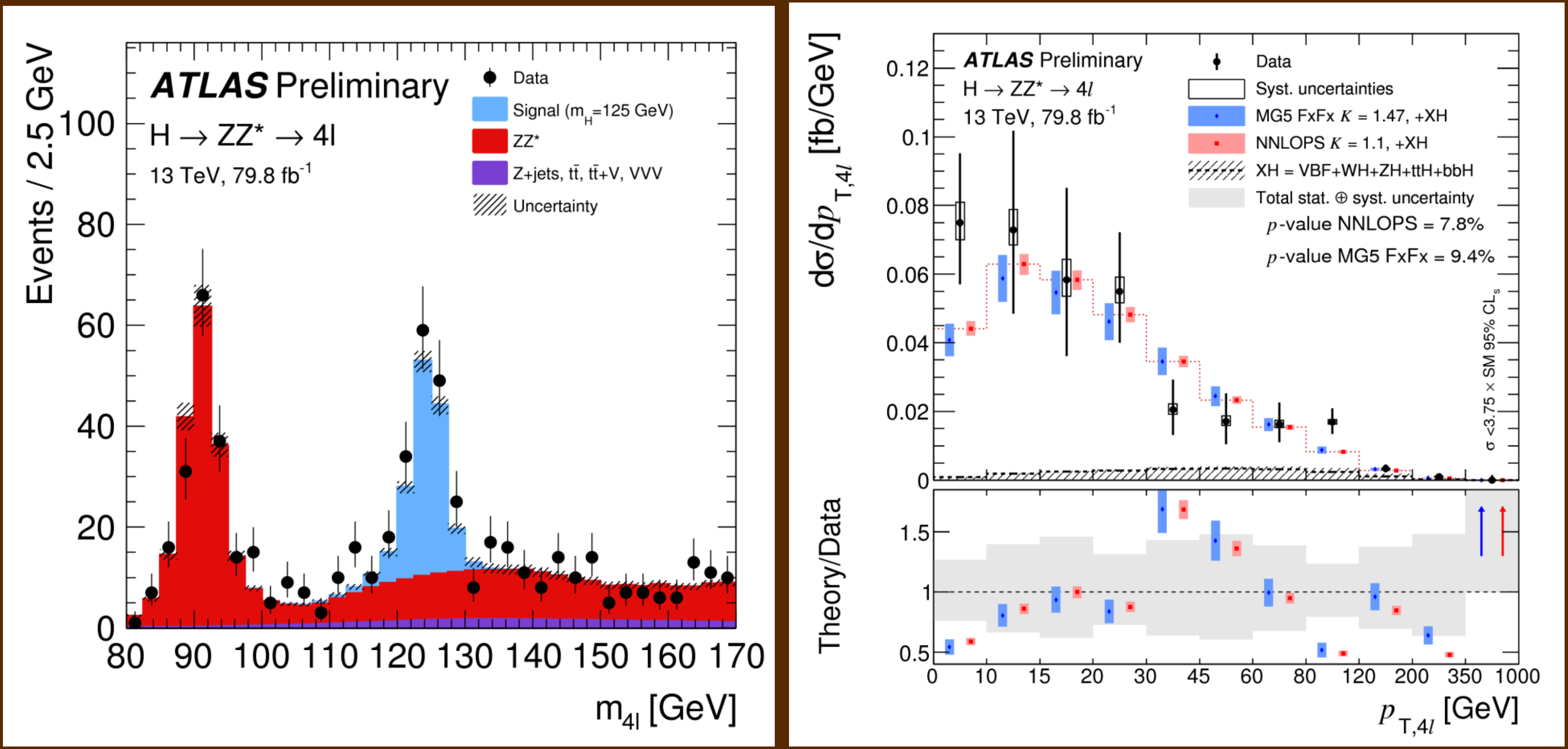




CMS-HIG-16-040, submitted to JHEP

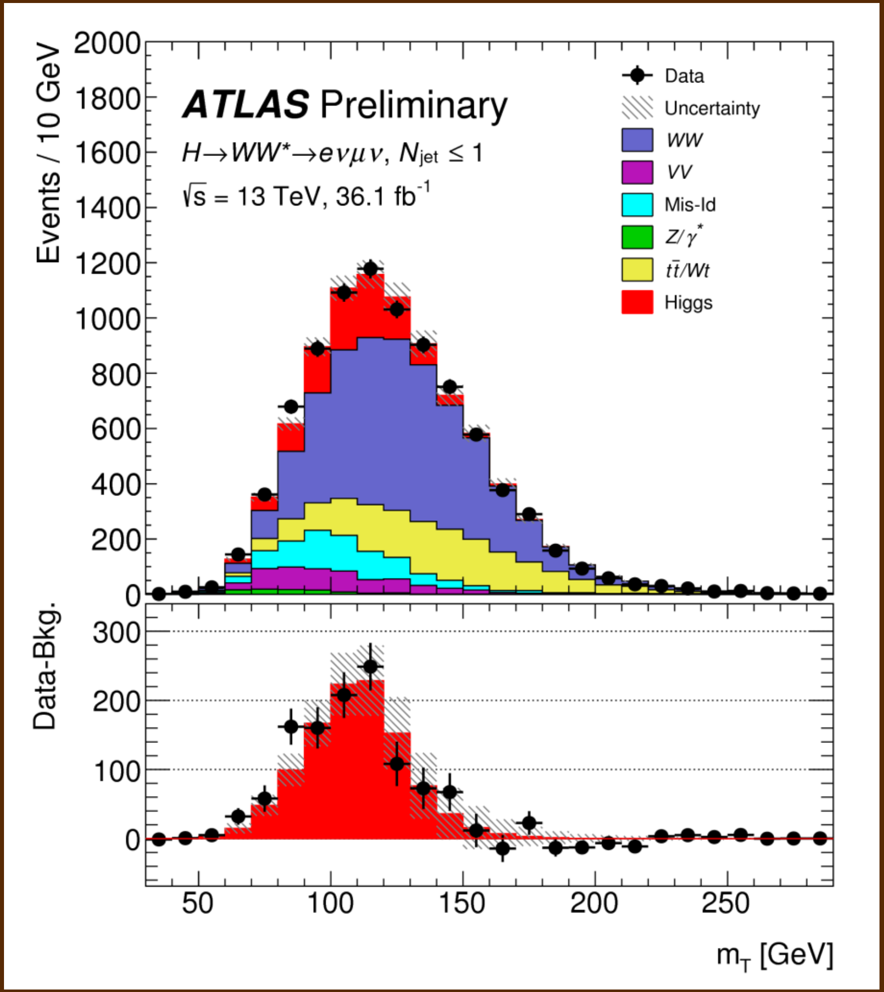
CMS-PAS-HIG-18-001

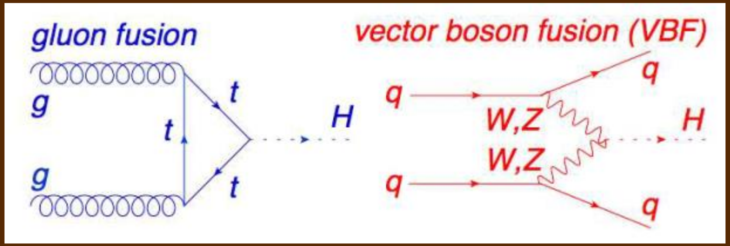
ATLAS H → 4 lepton including 2017 data, differential cross-section measurement

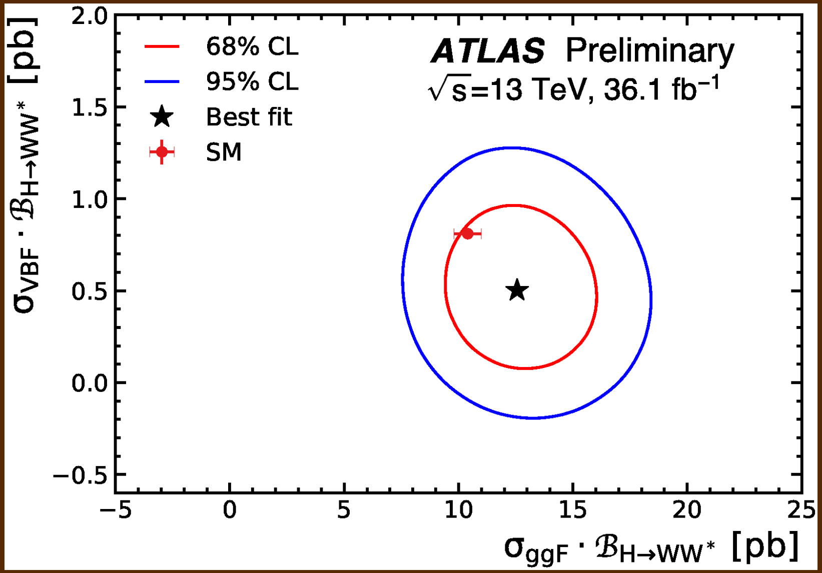


ATLAS-CONF-2018-018

H → WW* at 13 TeV with 2015/6 data (eνμν channel)



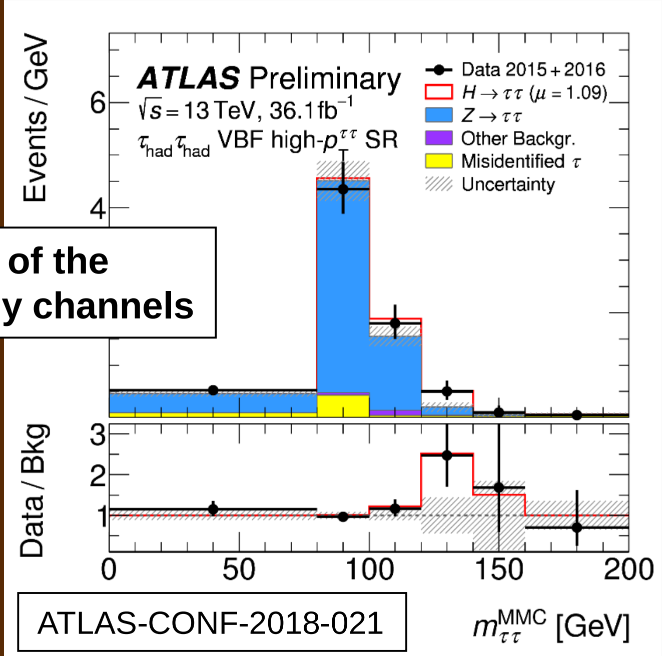




ATLAS-CONF-2018-004

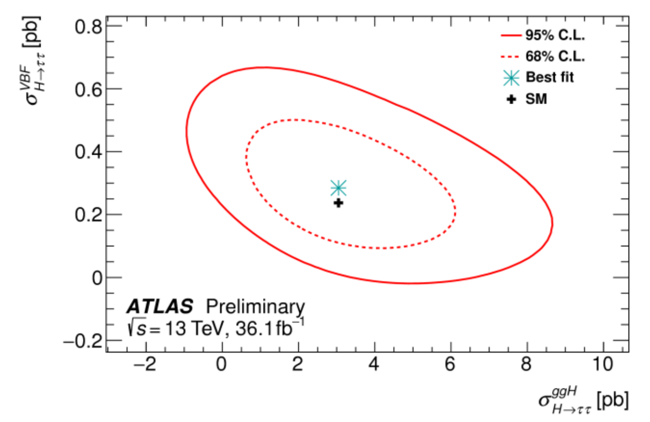
Observation of H → ττ decay consistent with SM in combined Run-1 and Run-2 (2016) data

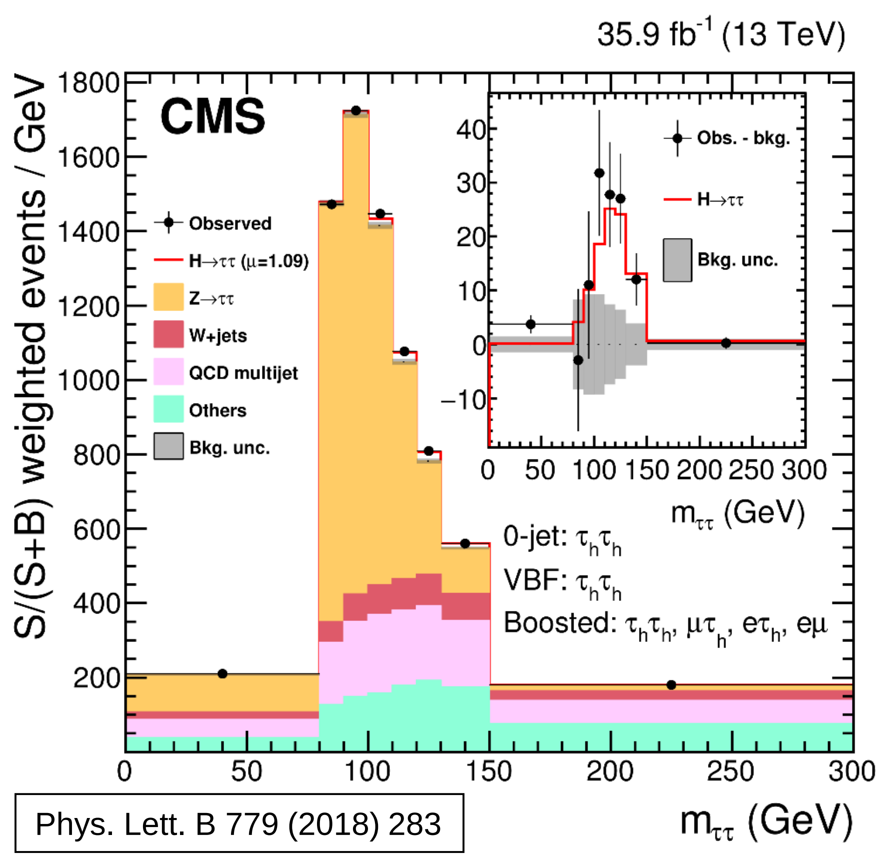
6.4 σ observed (5.4 σ expected)



ATLAS-CONF-2018-021

One of the many channels

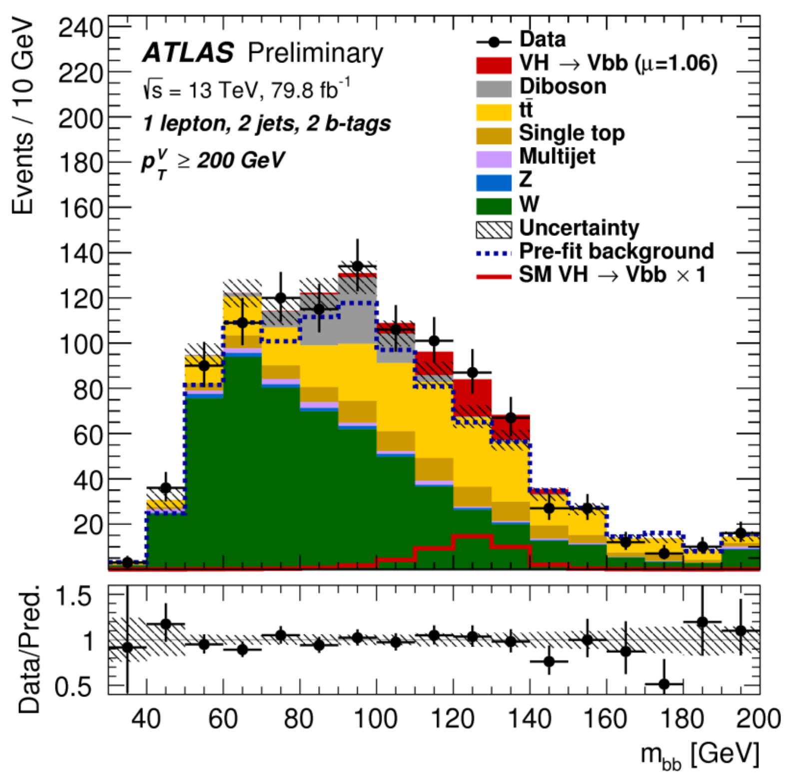


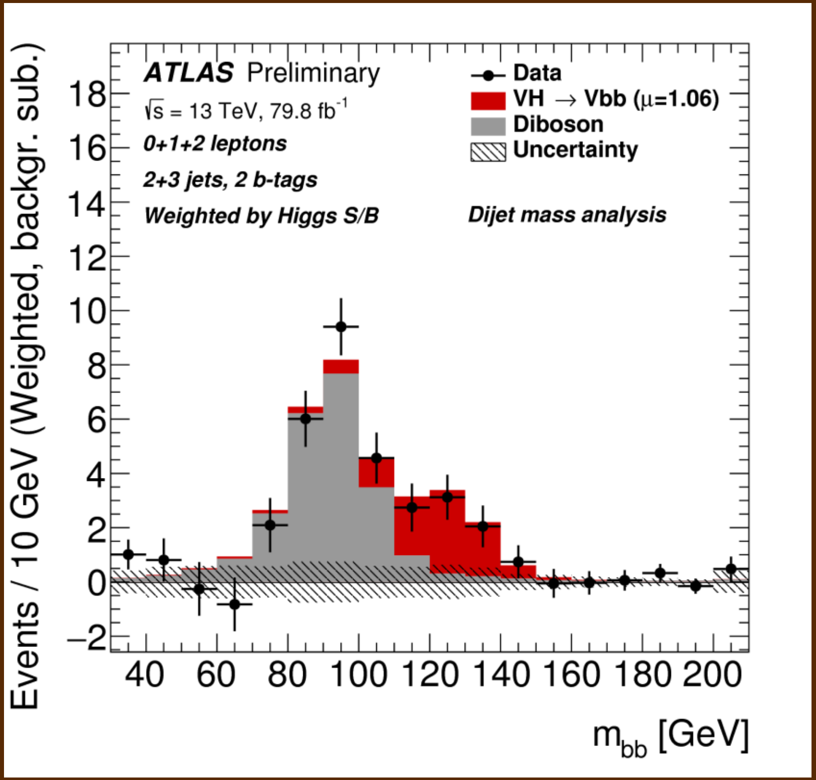


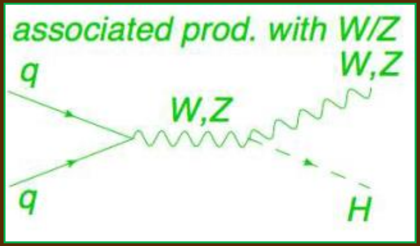
Phys. Lett. B 779 (2018) 283

5.9 σ observed (same as expected)

Observation of H → bb decay consistent with the SM in combined Run-1 and Run-2 data





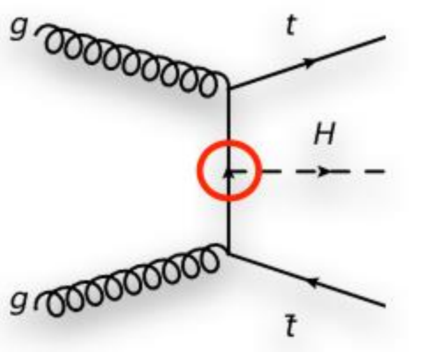


ATLAS-CONF-2018-036

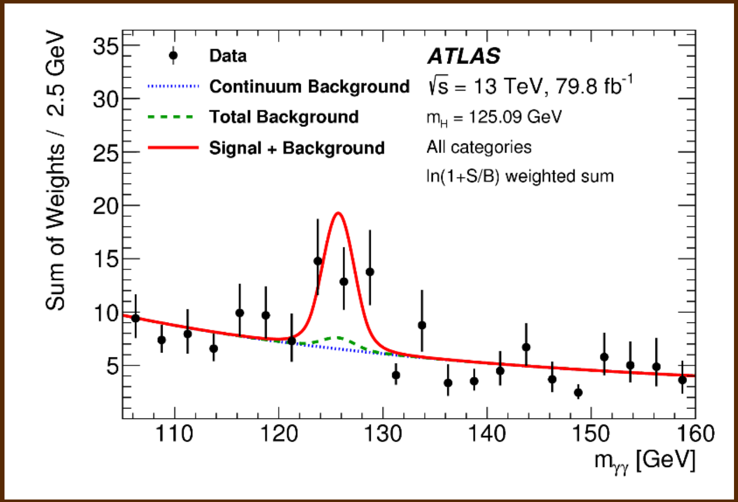
5.4 σ observed (5.5 σ expected)

$\mu = 1.01 \pm 0.12\ ^{+0.16}_{-0.15}$

Observation of ttH combined Run-1 and Run-2 (2017) data

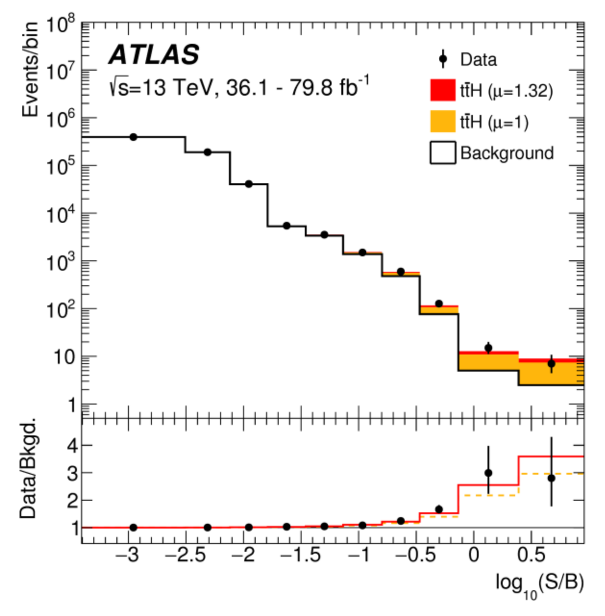


Cross-section is only about 1% of pp → H



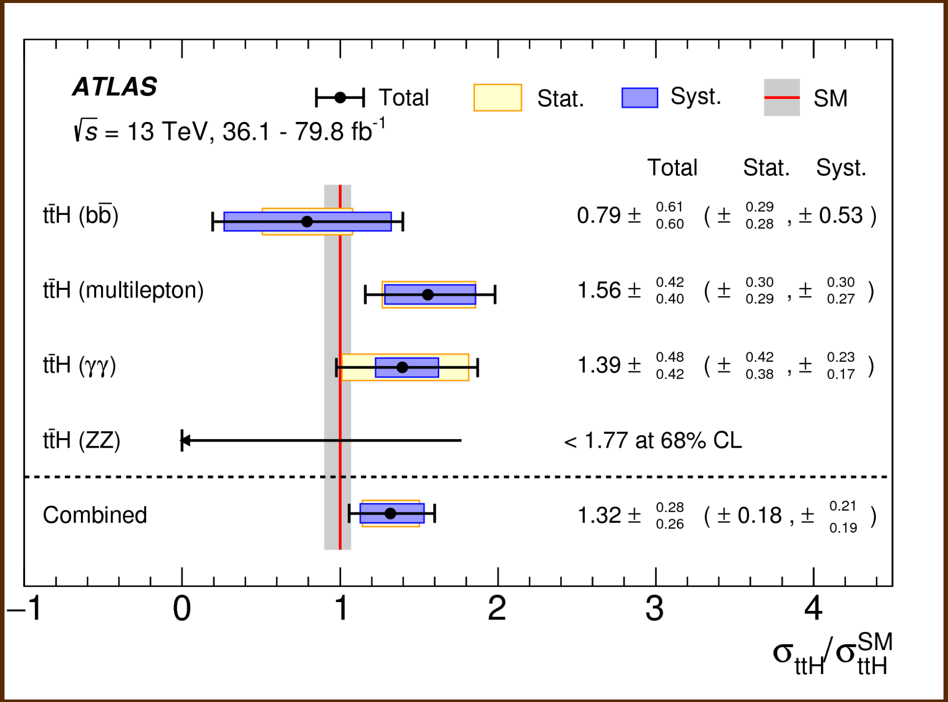
Direct evidence that the heaviest known particle, the top quark, interacts with the predicted large strength with the Higgs boson

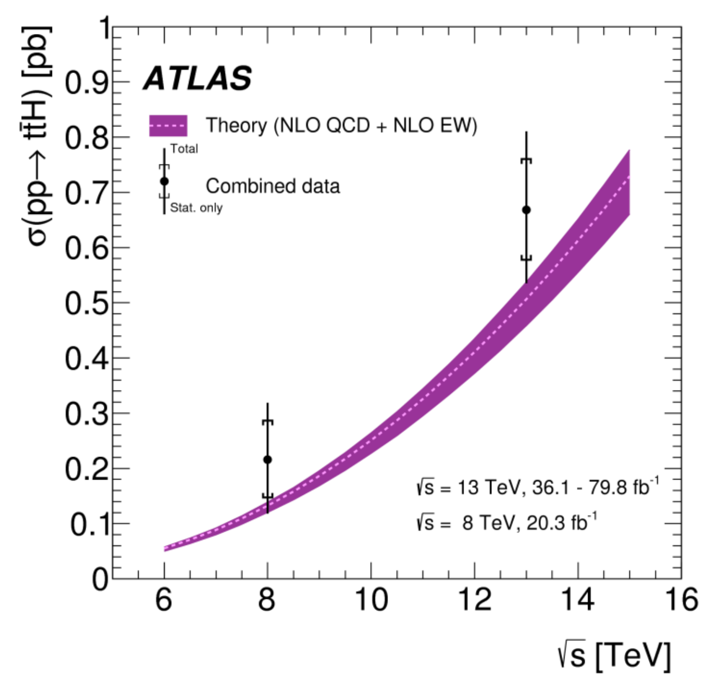
A very sophisticated analysis considering H decays into bb, WW, ττ, γγ, and ZZ, employing Machine Learning methods



arXiv:1806.00425[hep-exp], submitted to Phys. Lett. B

Observation of ttH combined Run-1 and Run-2 (2017) data





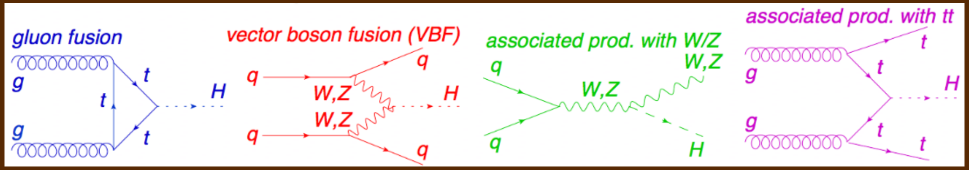
Significance from the combined analysis of all channels: 6.3 σ observed (5.1 σ expected)

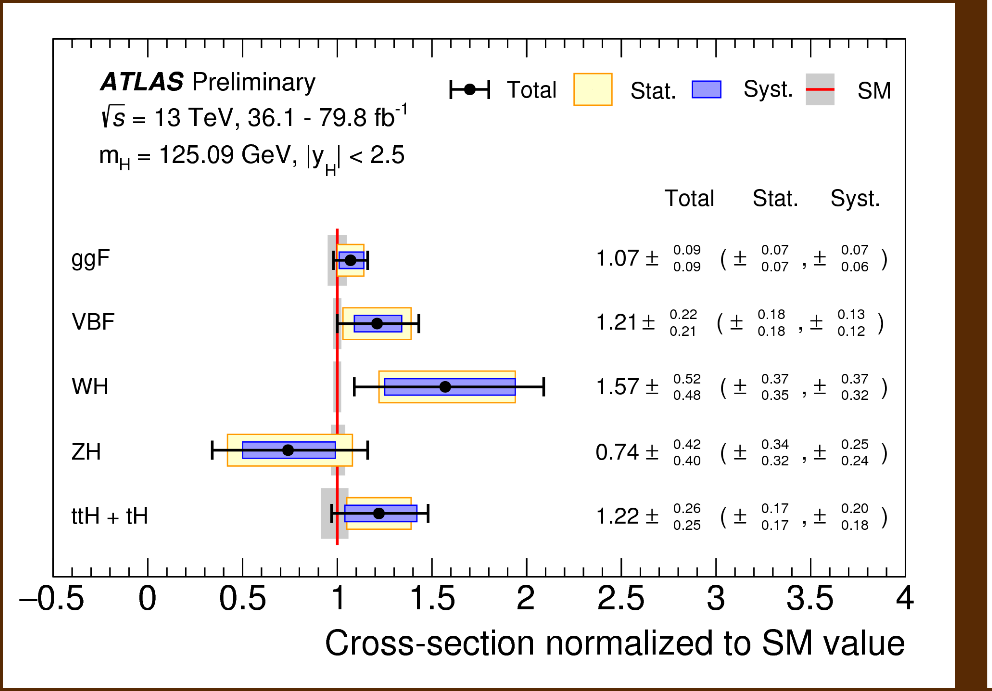
arXiv:1806.00425[hep-exp], submitted to Phys. Lett. B

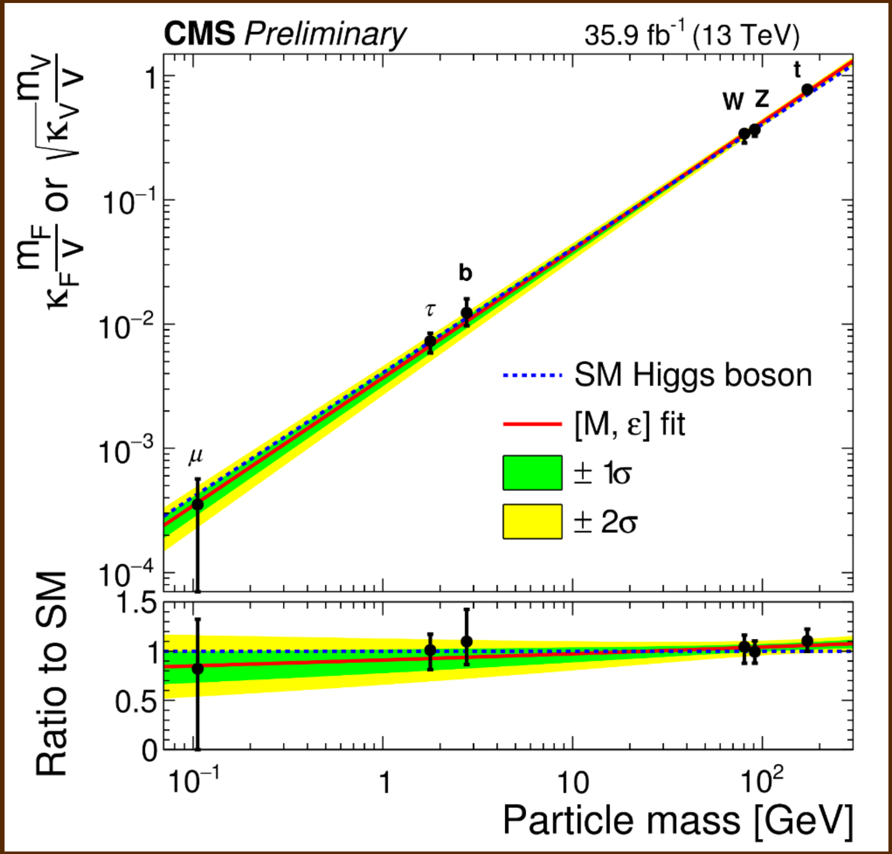
See also CMS: Phys. Rev. Lett. 120 (2018) 231801 data up to 2016: 5.2 σ observed (4.2 σ expected)

Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production modes	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-lepton	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

Higgs boson production modes and couplings (partial Run-2 data)







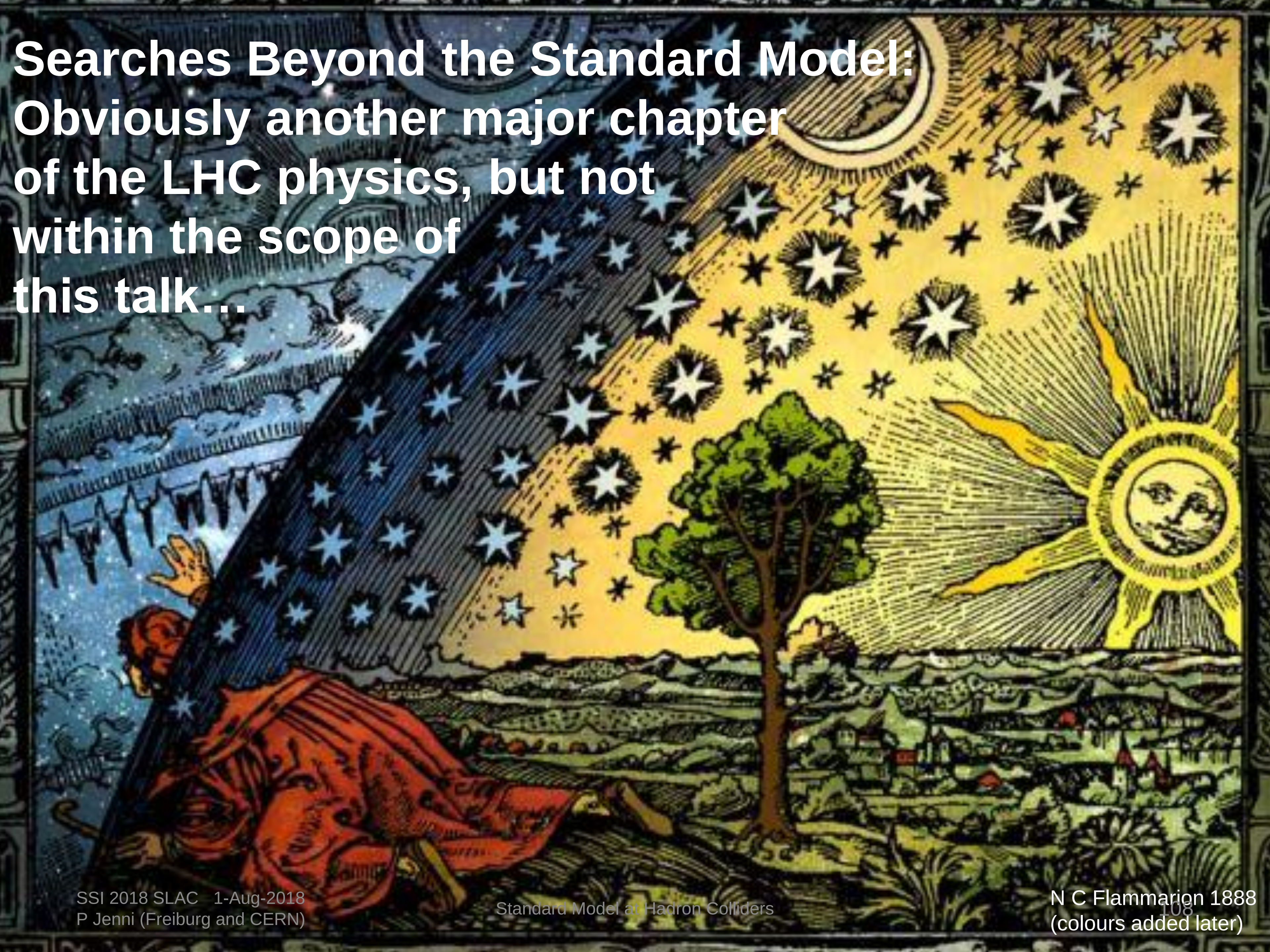
$\mu = 1.13^{+0.09}_{-0.08}$

ATLAS-CONF-2018-031

$\mu = 1.17 \pm 0.10$

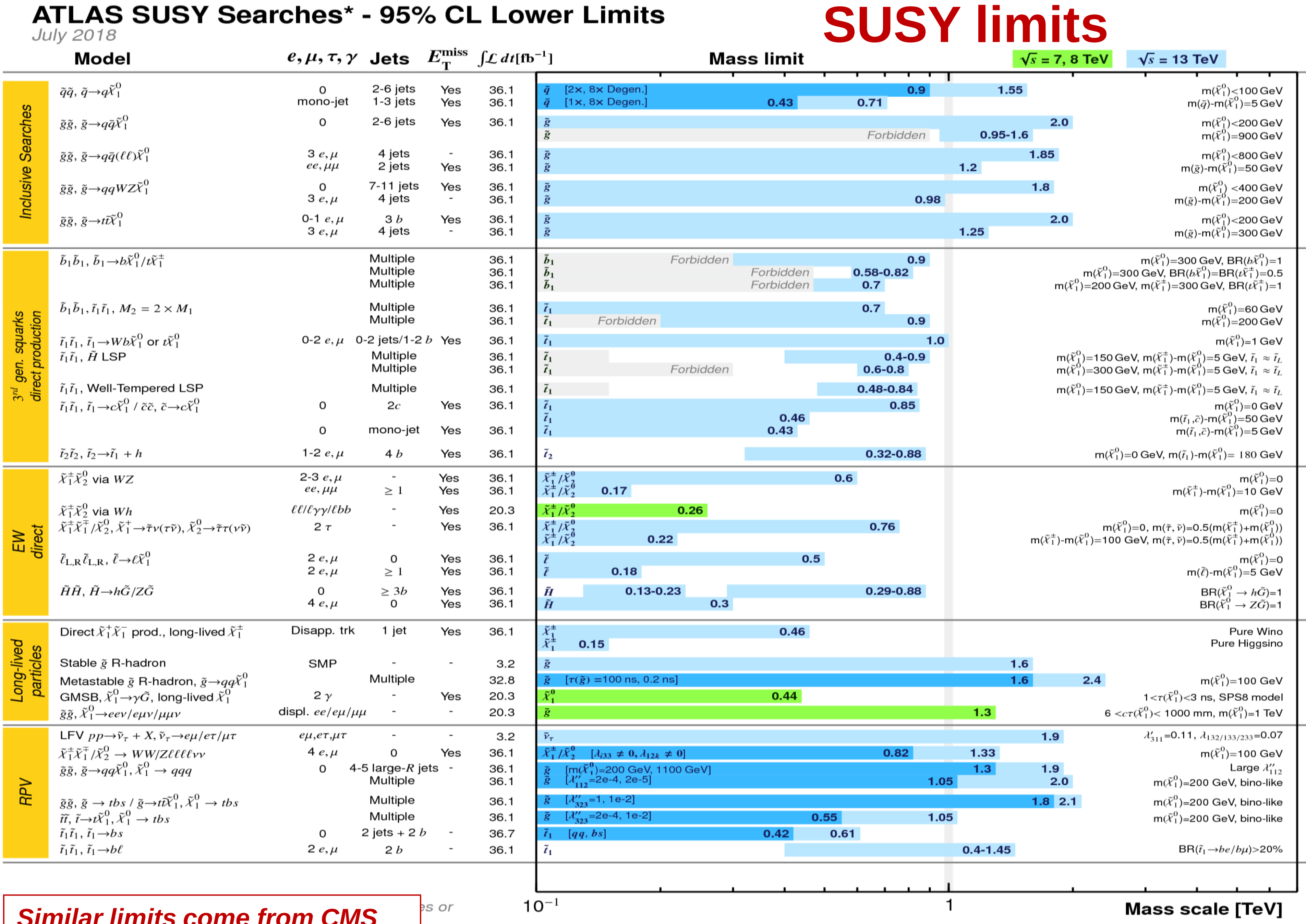
CMS-PAS-HIG-17-031

Searches Beyond the Standard Model: Obviously another major chapter of the LHC physics, but not within the scope of this talk…



N C Flammarion 1888
(colours added later)

SUSY limits

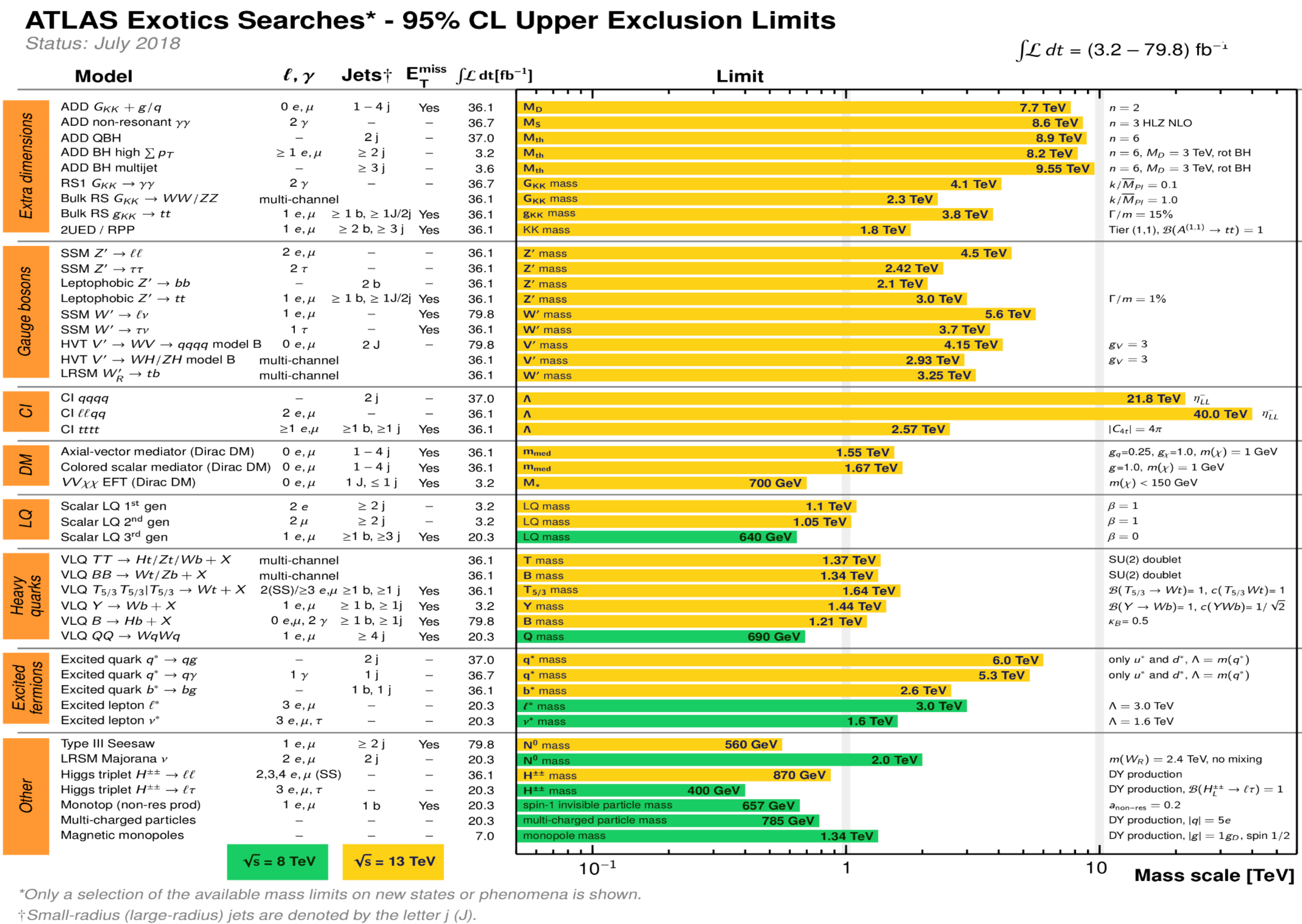


ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit	
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	$m(\tilde{\chi}_1^0)<100$ GeV
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	$m(\tilde{q})-m(\tilde{\chi}_1^0)=5$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}_1^0)<200$ GeV
						$\tilde{g}$ Forbidden 0.95-1.6	$m(\tilde{\chi}_1^0)=900$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.85	$m(\tilde{\chi}_1^0)<800$ GeV
		$ee, \mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	$m(\tilde{g})-m(\tilde{\chi}_1^0)=50$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	$m(\tilde{\chi}_1^0) <400$ GeV
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 0.98	$m(\tilde{g})-m(\tilde{\chi}_1^0)=200$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}_1^0)<200$ GeV
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.25	$m(\tilde{g})-m(\tilde{\chi}_1^0)=300$ GeV
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	$m(\tilde{\chi}_1^0)=300$ GeV, $BR(b\tilde{\chi}_1^0)=1$
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	$m(\tilde{\chi}_1^0)=300$ GeV, $BR(b\tilde{\chi}_1^0)=BR(t\tilde{\chi}_1^\pm)=0.5$
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	$m(\tilde{\chi}_1^0)=200$ GeV, $m(\tilde{\chi}_1^\pm)=300$ GeV, $BR(t\tilde{\chi}_1^\pm)=1$
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1, M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	$m(\tilde{\chi}_1^0)=60$ GeV
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	$m(\tilde{\chi}_1^0)=200$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	$m(\tilde{\chi}_1^0)=1$ GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	$m(\tilde{\chi}_1^0)=150$ GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=5$ GeV, $\tilde{t}_1 \approx \tilde{t}_L$
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	$m(\tilde{\chi}_1^0)=300$ GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=5$ GeV, $\tilde{t}_1 \approx \tilde{t}_L$
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	$m(\tilde{\chi}_1^0)=150$ GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=5$ GeV, $\tilde{t}_1 \approx \tilde{t}_L$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$	0	2c	Yes	36.1	$\tilde{t}_1$ 0.85	$m(\tilde{\chi}_1^0)=0$ GeV
						$\tilde{t}_1$ 0.46	$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)=50$ GeV
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)=5$ GeV
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)=$ 180 GeV
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e, μ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6	$m(\tilde{\chi}_1^0)=0$
		$ee, \mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=10$ GeV
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.26	$m(\tilde{\chi}_1^0)=0$
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76	$m(\tilde{\chi}_1^0)=0$, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=100$ GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	$m(\tilde{\chi}_1^0)=0$
		2 e, μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	$m(\tilde{\ell})-m(\tilde{\chi}_1^0)=5$ GeV
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	$BR(\tilde{\chi}_1^0 \to h\tilde{G})=1$
		4 e, μ	0	Yes	36.1	$\tilde{H}$ 0.3	$BR(\tilde{\chi}_1^0 \to Z\tilde{G})=1$
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 0.46	Pure Wino
						$\tilde{\chi}_1^\pm$ 0.15	Pure Higgsino
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6	
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	$m(\tilde{\chi}_1^0)=100$ GeV
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44	$1<\tau(\tilde{\chi}_1^0)<3$ ns, SPS8 model
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	$6 < c\tau(\tilde{\chi}_1^0)<$ 1000 mm, $m(\tilde{\chi}_1^0)=1$ TeV
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	$\lambda'_{311}=0.11$, $\lambda_{132/133/233}=0.07$
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e, μ	0	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.82 1.33	$m(\tilde{\chi}_1^0)=100$ GeV
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [$m(\tilde{\chi}_1^0)$=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like
	$\tilde{g}\tilde{g}, \tilde{g} \to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	$BR(\tilde{t}_1\to be/b\mu)>20\%$

Similar limits come from CMS



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

$\int \mathcal{L}\, dt = (3.2 - 79.8)\ \mathrm{fb}^{-1}$

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit	
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 M_D 7.7 TeV	$n = 2$
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$
	Bulk RS $g_{KK} \rightarrow tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$
	2UED / RPP	$1\ e, \mu$	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2\ e, \mu$	–	–	36.1	🟨 Z' mass 4.5 TeV	
	SSM $Z' \rightarrow \tau\tau$	$2\ \tau$	–	–	36.1	🟨 Z' mass 2.42 TeV	
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	36.1	🟨 Z' mass 2.1 TeV	
	Leptophobic $Z' \rightarrow tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 Z' mass 3.0 TeV	$\Gamma/m = 1\%$
	SSM $W' \rightarrow \ell\nu$	$1\ e, \mu$	–	Yes	79.8	🟨 W' mass 5.6 TeV	
	SSM $W' \rightarrow \tau\nu$	$1\ \tau$	–	Yes	36.1	🟨 W' mass 3.7 TeV	
	HVT $V' \rightarrow WV \rightarrow qqqq$ model B	$0\ e, \mu$	2 J	–	79.8	🟨 V' mass 4.15 TeV	$g_V = 3$
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel			36.1	🟨 V' mass 2.93 TeV	$g_V = 3$
	LRSM $W'_R \rightarrow tb$	multi-channel			36.1	🟨 W' mass 3.25 TeV	
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV η_{LL}^-	
	CI $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	🟨 Λ 40.0 TeV η_{LL}^-	
	CI $tttt$	$\geq 1\ e,\mu$	≥ 1 b, ≥ 1 j	Yes	36.1	🟨 Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV
	Colored scalar mediator (Dirac DM)	$0\ e, \mu$	$1-4$ j	Yes	36.1	🟨 m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV
	$VV\chi\chi$ EFT (Dirac DM)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi) < 150$ GeV
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$
	Scalar LQ 3rd gen	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$
Heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel			36.1	🟨 T mass 1.37 TeV	SU(2) doublet
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel			36.1	🟨 B mass 1.34 TeV	SU(2) doublet
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \rightarrow Wt + X$	2(SS)/$\geq 3\ e,\mu$	≥ 1 b, ≥ 1 j	Yes	36.1	🟨 $T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt)$= 1, $c(T_{5/3}Wt)$= 1
	VLQ $Y \rightarrow Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1j	Yes	3.2	🟨 Y mass 1.44 TeV	$\mathcal{B}(Y \rightarrow Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$
	VLQ $B \rightarrow Hb + X$	$0\ e,\mu$, $2\ \gamma$	≥ 1 b, ≥ 1j	Yes	79.8	🟨 B mass 1.21 TeV	κ_B= 0.5
	VLQ $QQ \rightarrow WqWq$	$1\ e, \mu$	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV	
Excited fermions	Excited quark $q^* \rightarrow qg$	–	2 j	–	37.0	🟨 q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	$1\ \gamma$	1 j	–	36.7	🟨 q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	36.1	🟨 b^* mass 2.6 TeV	
	Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV
Other	Type III Seesaw	$1\ e, \mu$	≥ 2 j	Yes	79.8	🟨 N^0 mass 560 GeV	
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$
	Monotop (non-res prod)	$1\ e, \mu$	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2

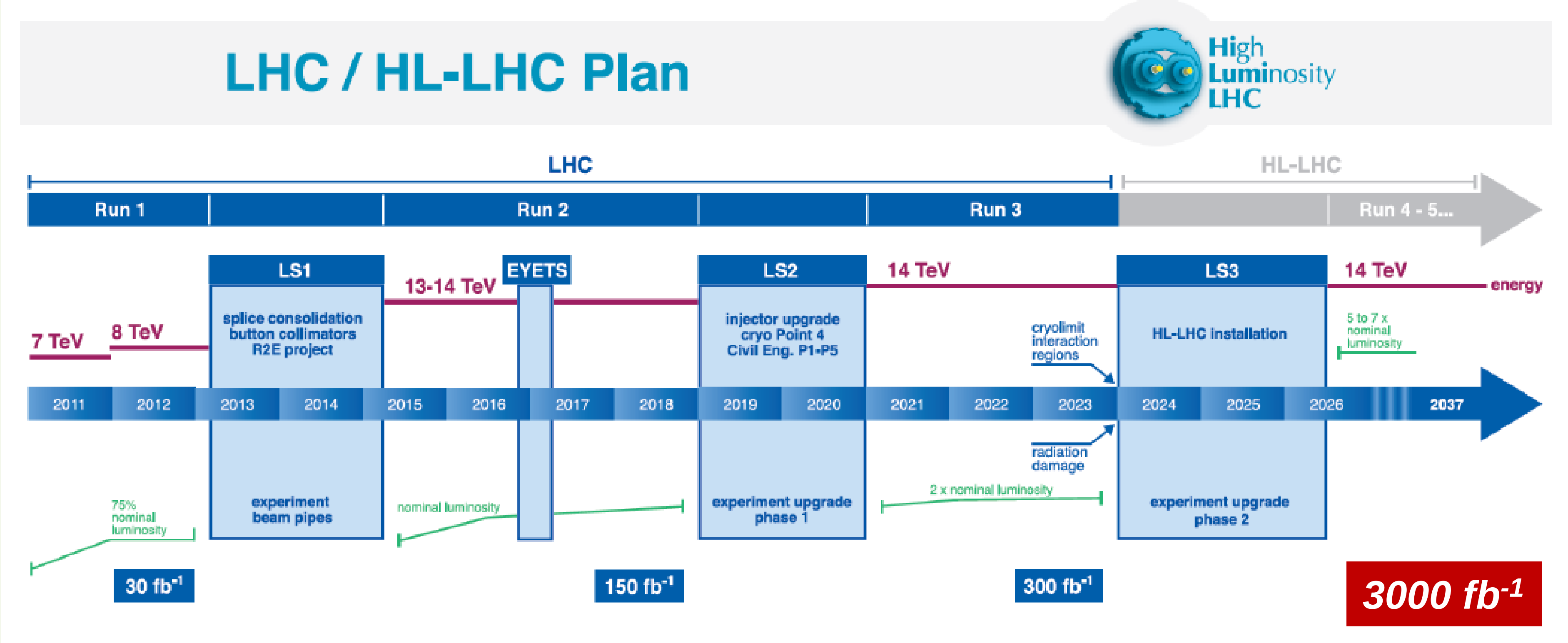
🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Similar limits come from CMS

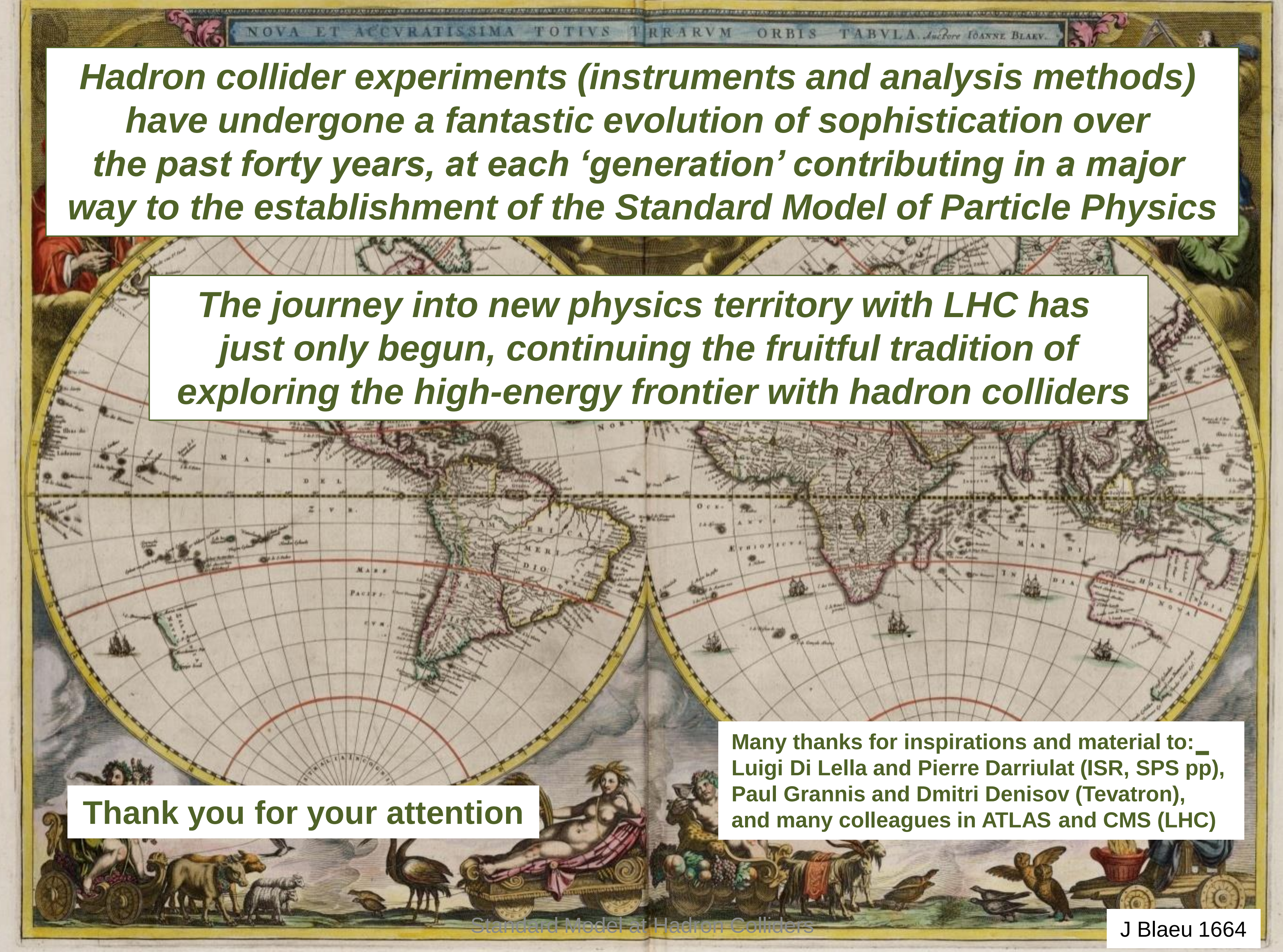


We are here

Phase-0 upgrades

Phase-1 upgrades

Major Phase-2 detector and machine upgrades to accumulate a factor 10 integrated luminosity



Hadron collider experiments (instruments and analysis methods) have undergone a fantastic evolution of sophistication over the past forty years, at each 'generation' contributing in a major way to the establishment of the Standard Model of Particle Physics

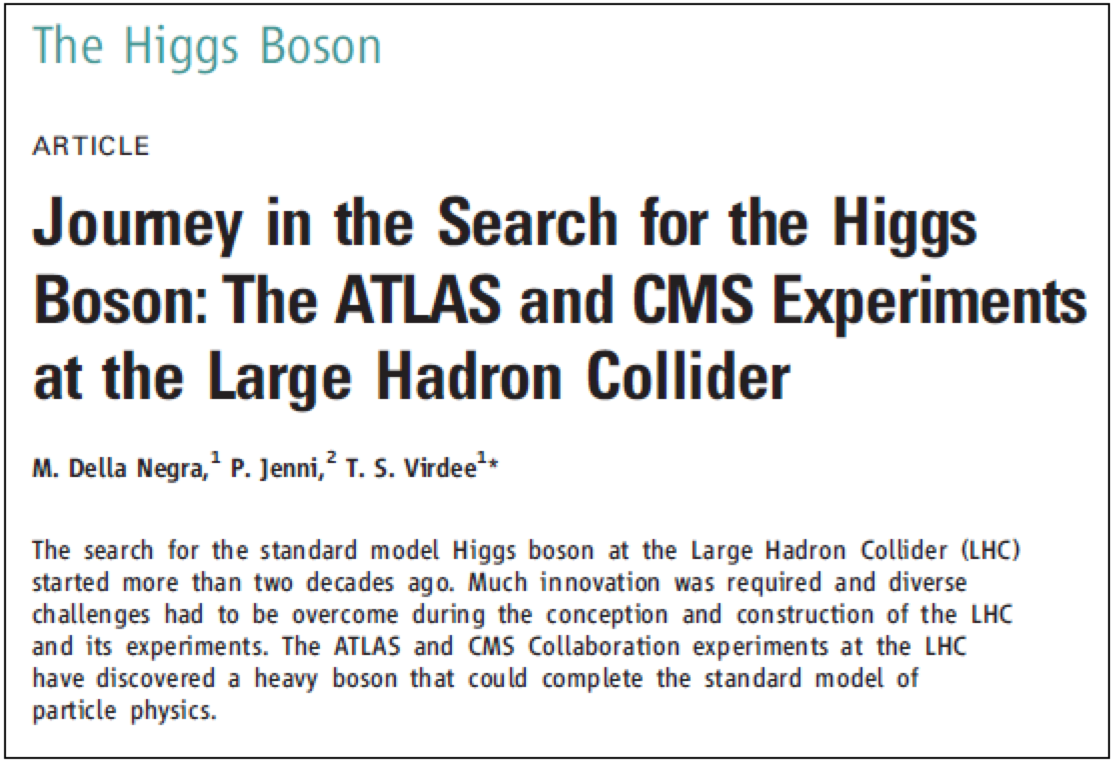
The journey into new physics territory with LHC has just only begun, continuing the fruitful tradition of exploring the high-energy frontier with hadron colliders

Thank you for your attention

Many thanks for inspirations and material to:
Luigi Di Lella and Pierre Darriulat (ISR, SPS pp),
Paul Grannis and Dmitri Denisov (Tevatron),
and many colleagues in ATLAS and CMS (LHC)

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

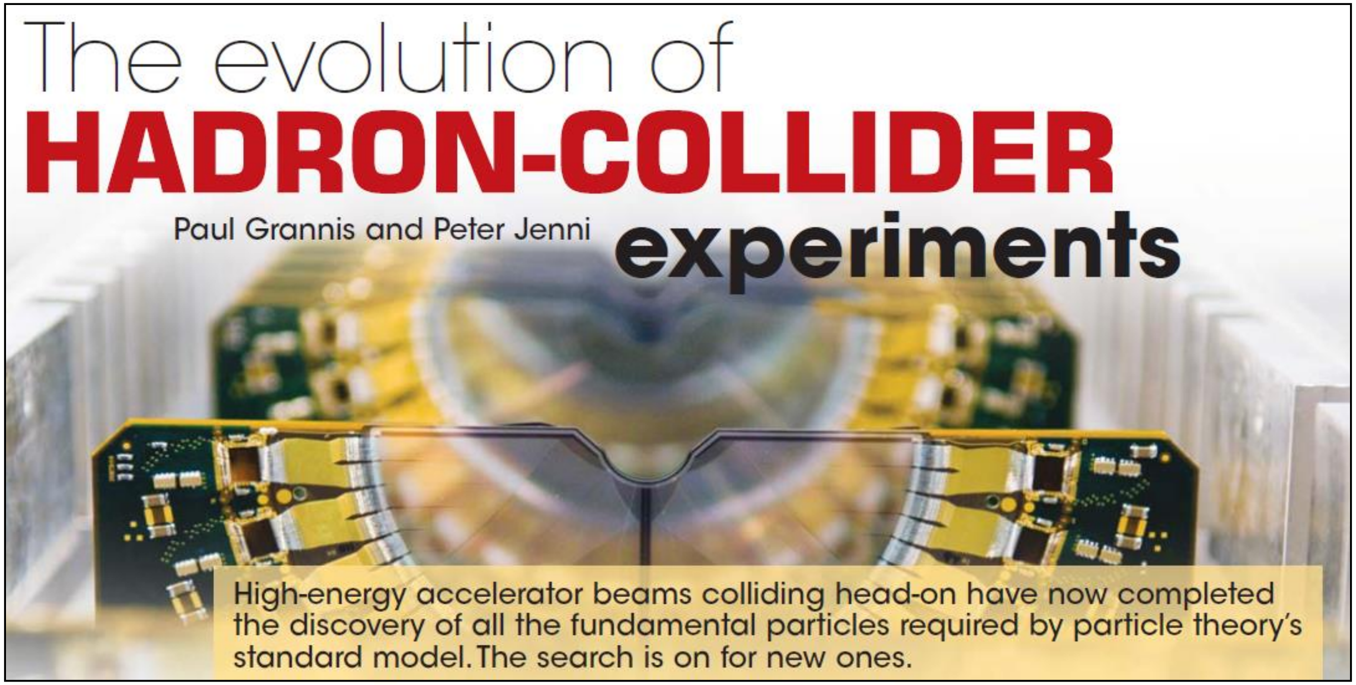
M. Della Negra,[1] P. Jenni,[2] T. S. Virdee[1]*

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

Further reading:



The evolution of HADRON-COLLIDER experiments

Paul Grannis and Peter Jenni

High-energy accelerator beams colliding head-on have now completed the discovery of all the fundamental particles required by particle theory's standard model. The search is on for new ones.

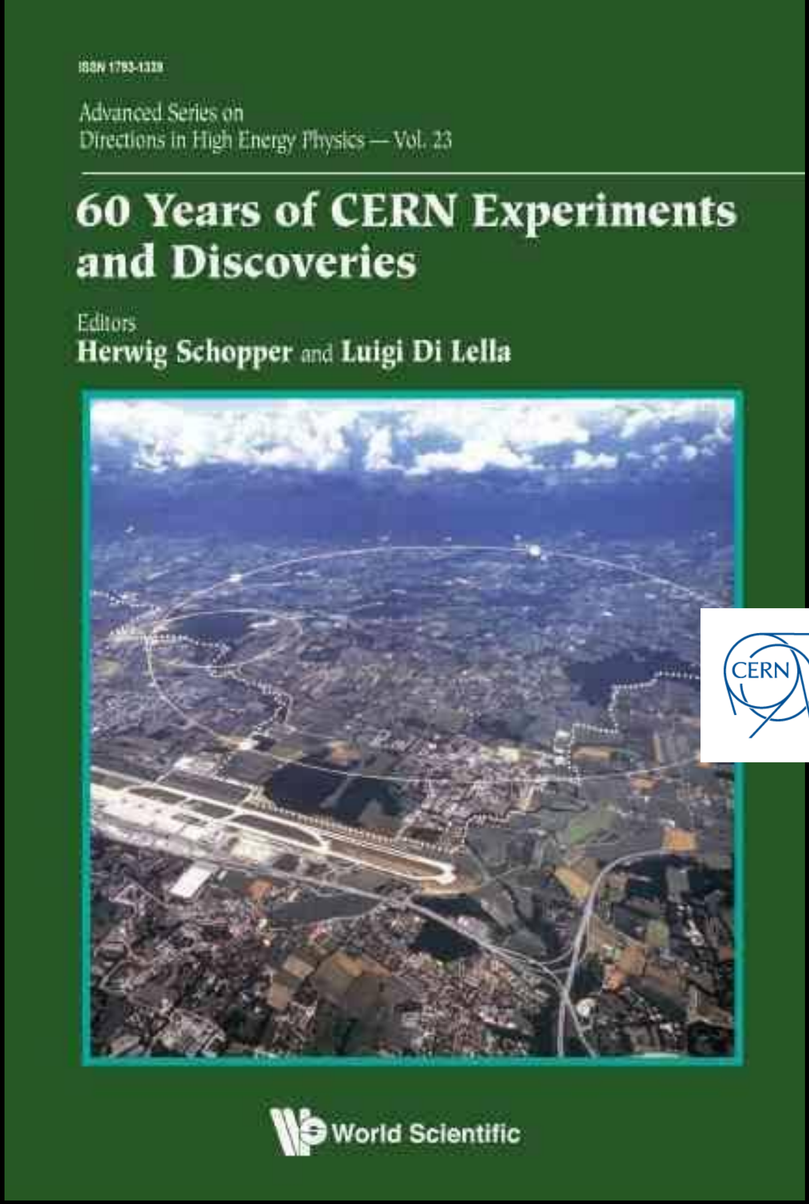
physics today

The evolution of hadron-collider experiments

Paul Grannis and Peter Jenni

Citation: Phys. Today **66**(6), 38 (2013); doi: 10.1063/PT.3.2010
View online: http://dx.doi.org/10.1063/PT.3.2010
View Table of Contents: http://www.physicstoday.org/resource/1/PHTOAD/v66/i6
Published by the American Institute of Physics.

Spares



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60 Years of CERN Experiments
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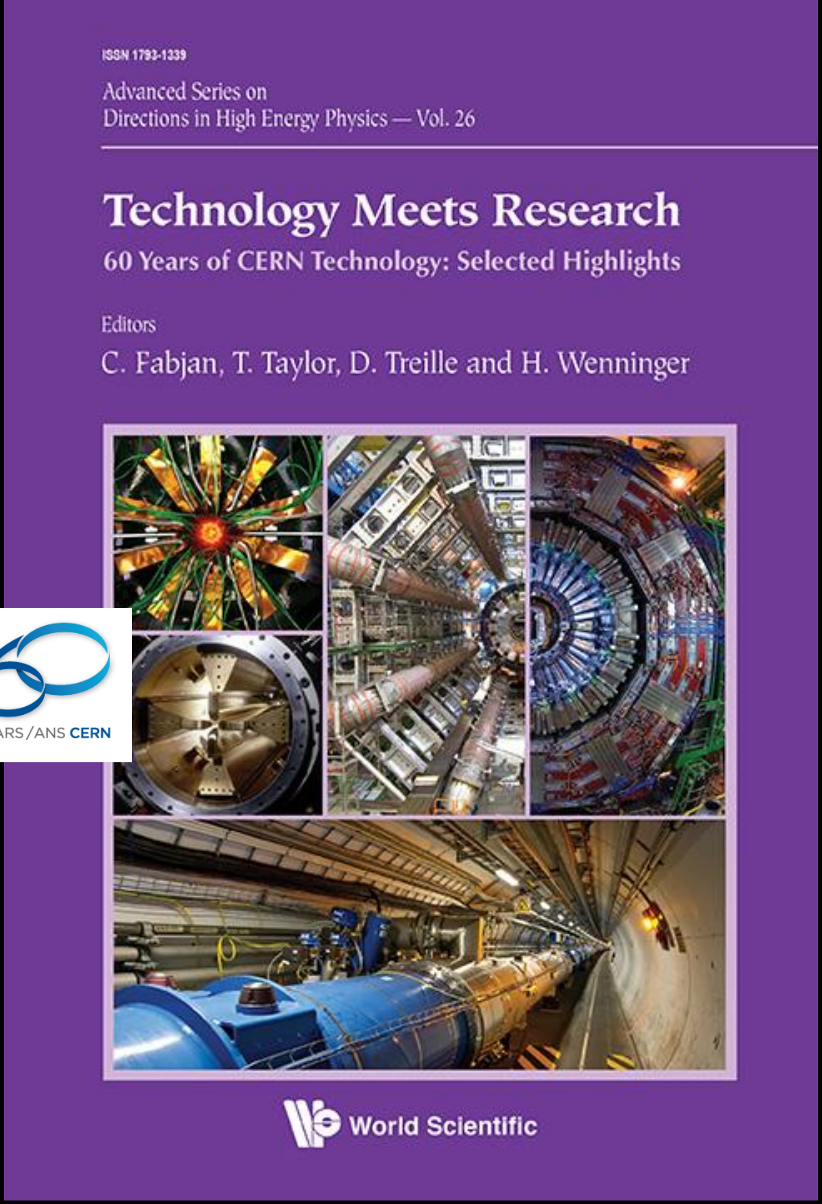
World Scientific



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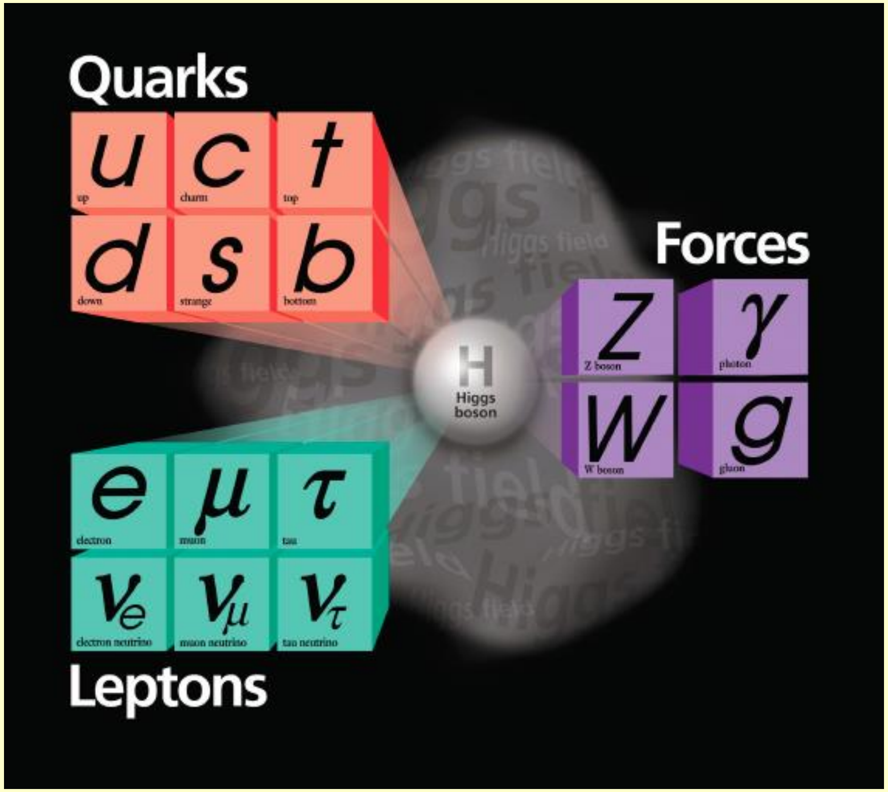
World Scientific

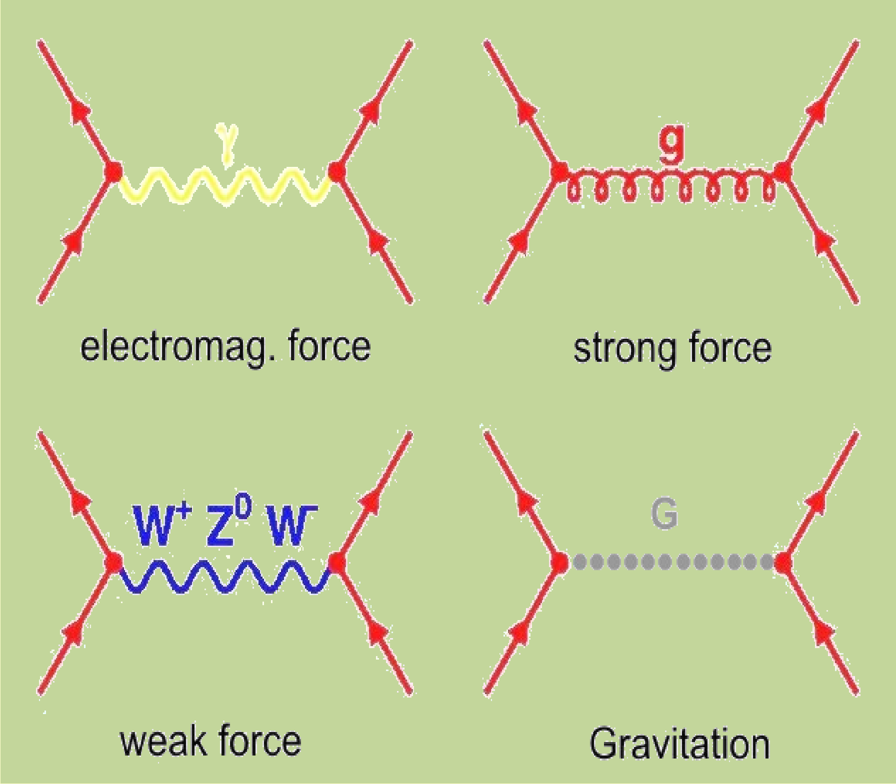
Chapter 1, p. 1-30, P.Jenni and T.S.Virdee:
The discovery of the Higgs Boson at the LHC

Chapter 8, p. 263-326, G.Brianti and P.Jenni:
The Large Hadron Collider: The Energy Frontier

OPEN ACCESS

The Standard Model of Particle Physics



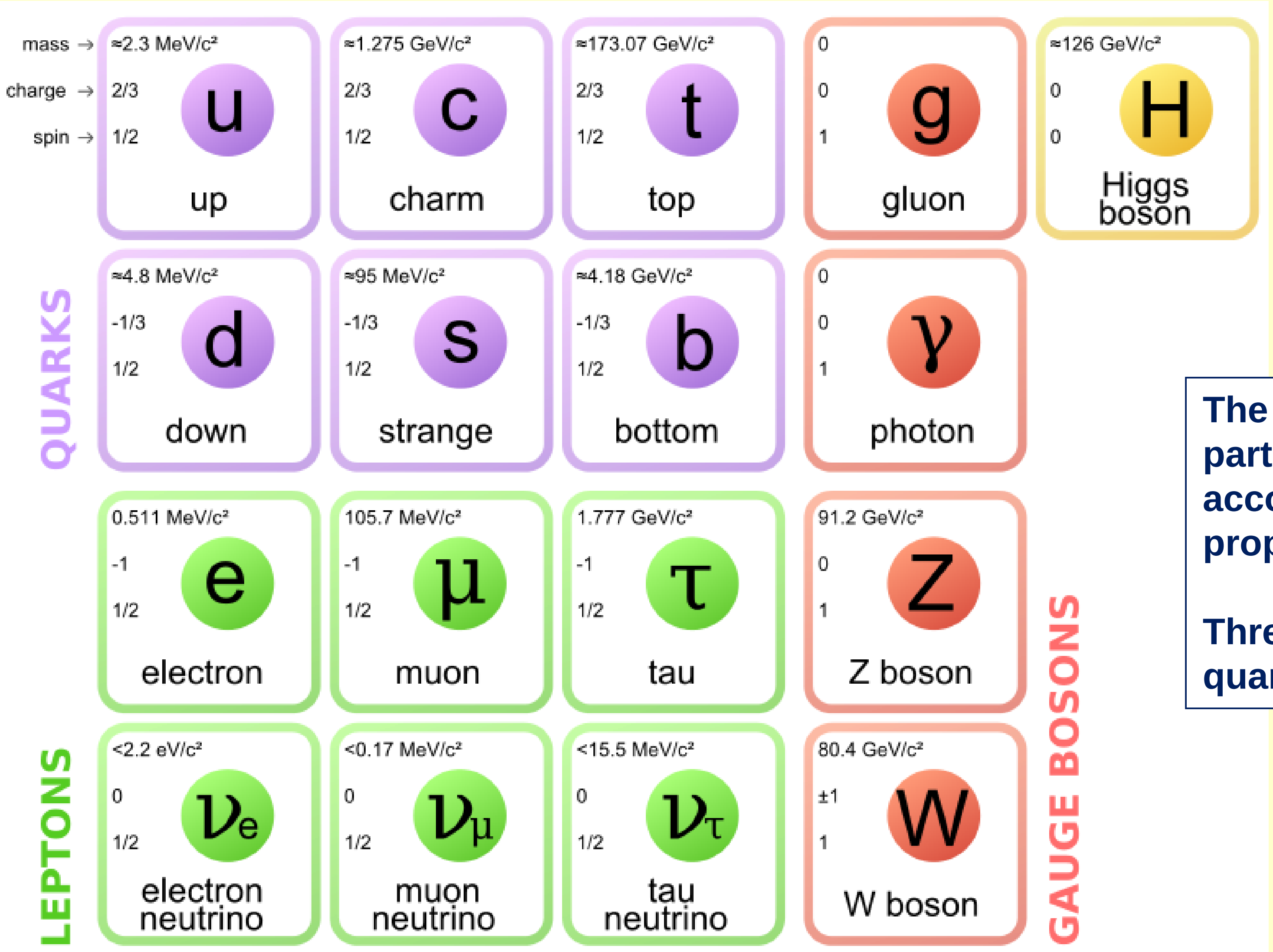


(i) Constituents of matter: quarks and leptons

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

(iii) The Brout-Englert-Higgs field (problem of mass, broken symmetry)

Standard Model of Elementary Particles



mass → charge → spin →	≈2.3 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈173.07 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c² 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c² -1 1/2 e electron	105.7 MeV/c² -1 1/2 μ muon	1.777 GeV/c² -1 1/2 τ tau	91.2 GeV/c² 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	80.4 GeV/c² ±1 1 W W boson	

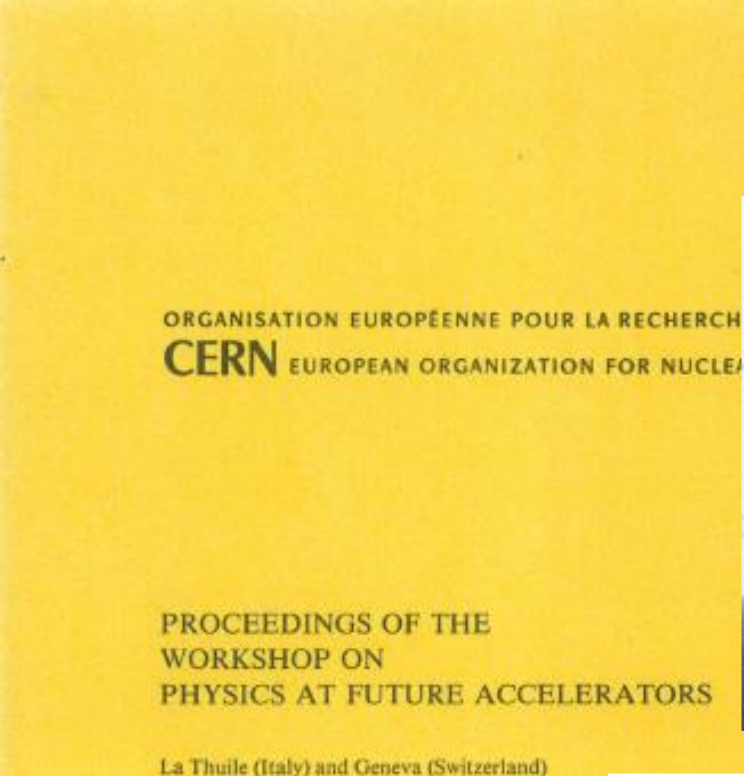
← *Fermionen* → ← *Bosonen* →

The elementary particles arranged according to their properties

Three families of quarks and leptons

La Thuile 7 – 13 January 1987

(Carlo Rubbia's Long Range Planning Committee)



CERN 87-07
Vol. I
4 June 1987

ORGANISATION EUROPÉENNE POUR LA RECHERCH
CERN EUROPEAN ORGANIZATION FOR NUCLE

PROCEEDINGS OF THE
WORKSHOP ON
PHYSICS AT FUTURE ACCELERATORS

La Thuile (Italy) and Geneva (Switzerland)
7 – 13 January 1987

Vol. I

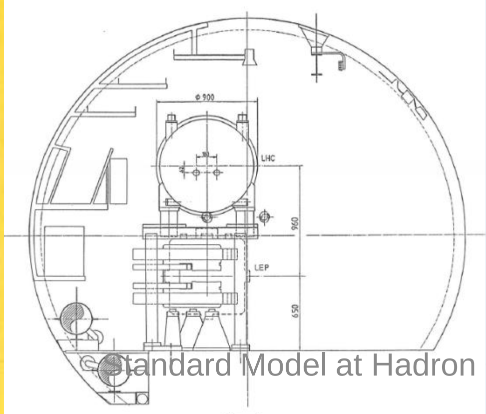
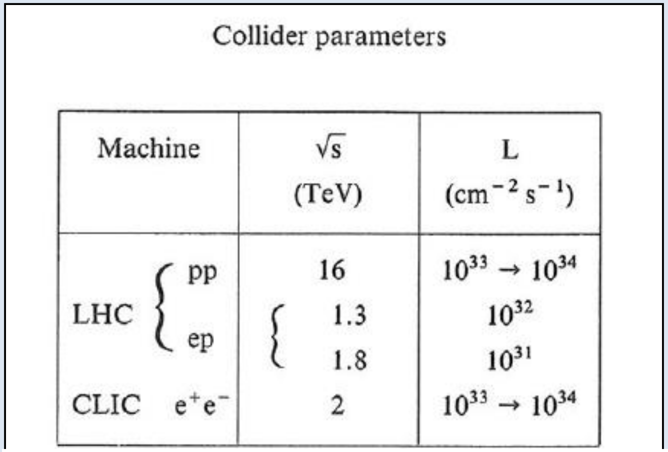
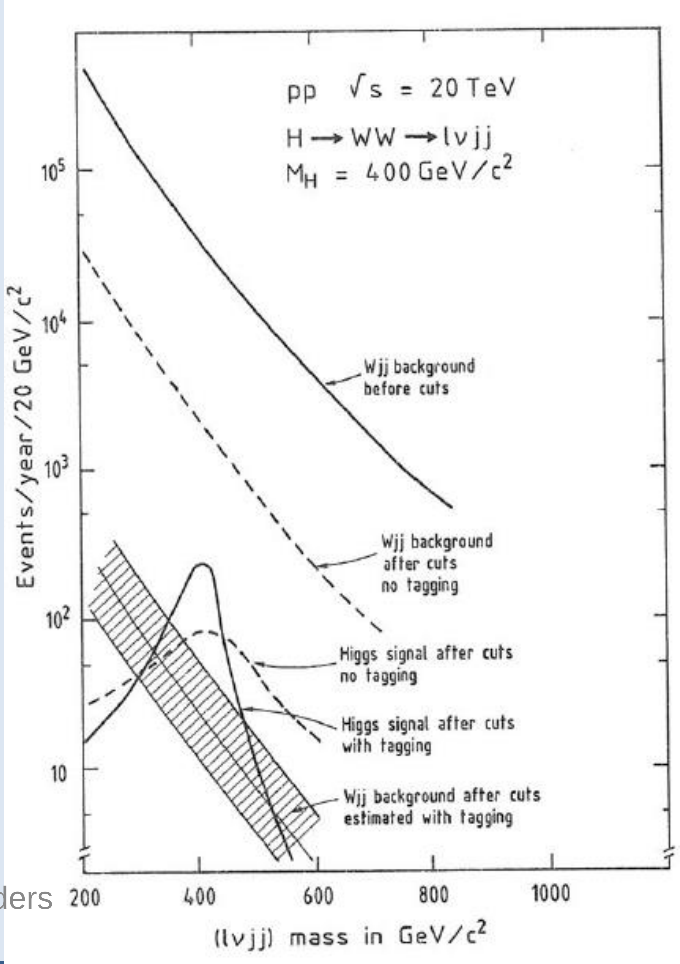


Fig. 1



Collider parameters

Machine		$\sqrt{s}$ (TeV)	L ($cm^{-2} s^{-1}$)
LHC	pp	16	$10^{33} \rightarrow 10^{34}$
	ep	1.3	10^{32}
		1.8	10^{31}
CLIC	e^+e^-	2	$10^{33} \rightarrow 10^{34}$

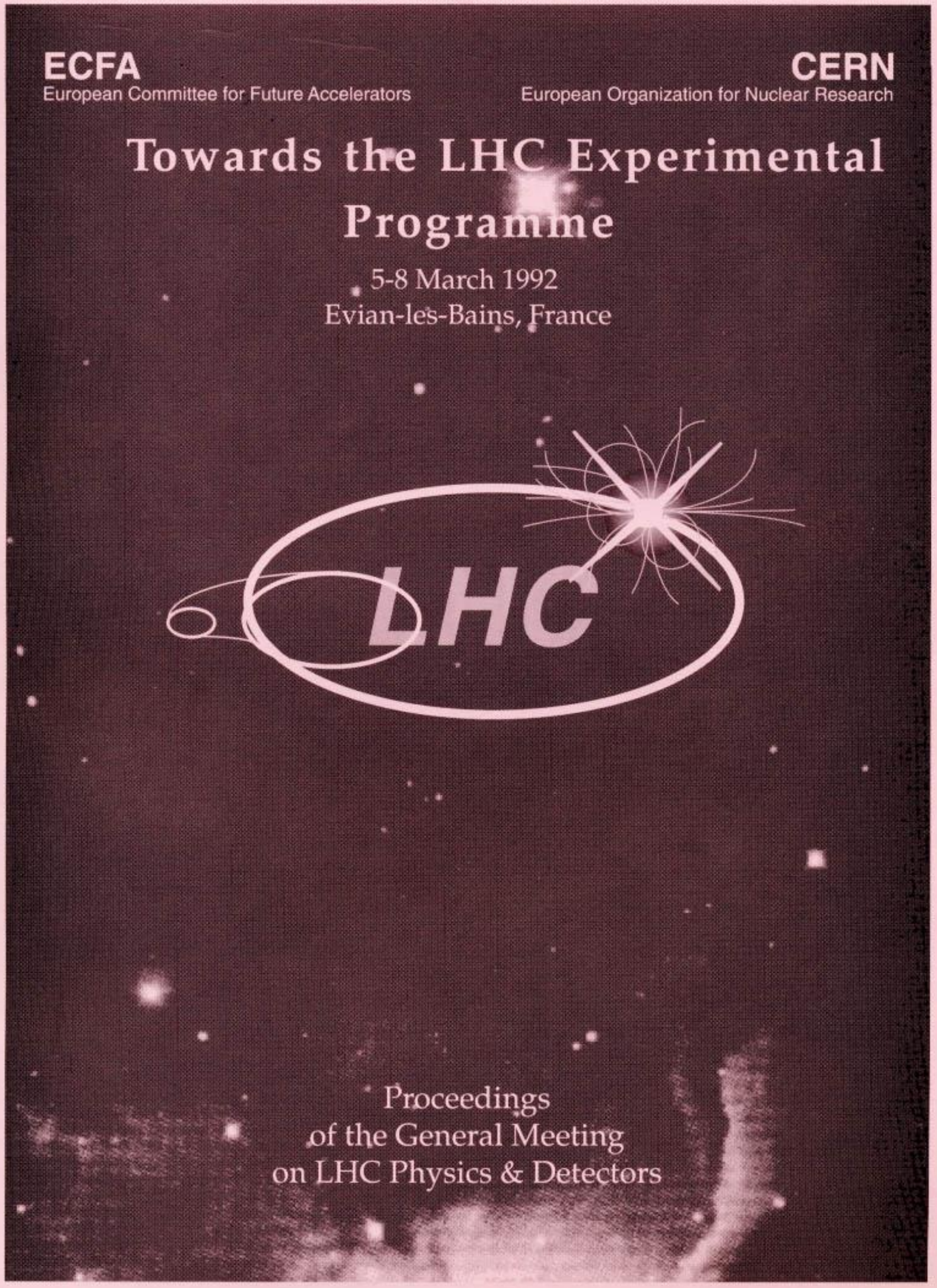


March 1992

Evian Meeting with EoI presentations

ASCOT	pp	Norton
CMS	pp	Della Negra / Desportes
EAGLE	pp	PJ
L3+1	pp	Ting / Pauss

LHC Beauty Collider	Schlein
B extracted beam	Carboni
B gas jet	Nakada
Neutrino at LHC	Vannucci
LHC HI	Schukraft
DELPHI LHC HI	Jarlskog



ECFA
European Committee for Future Accelerators

CERN
European Organization for Nuclear Research

Towards the LHC Experimental Programme

5-8 March 1992
Evian-les-Bains, France

Proceedings
of the General Meeting
on LHC Physics & Detectors

There was a symposium on 15th December at CERN marking the 25th anniversary of the LHC experimental programme

The talks (slides and videos) by several of the funders of the LHC and experiments are available at:

25 years since Evian

LHC EXPERIMENTAL
PROGRAMME

15 DECEMBER 2017
11:00 hrs – 16:00 hrs
MAIN AUDITORIUM

https://indico.cern.ch/e/Symposium-25Years-LHC

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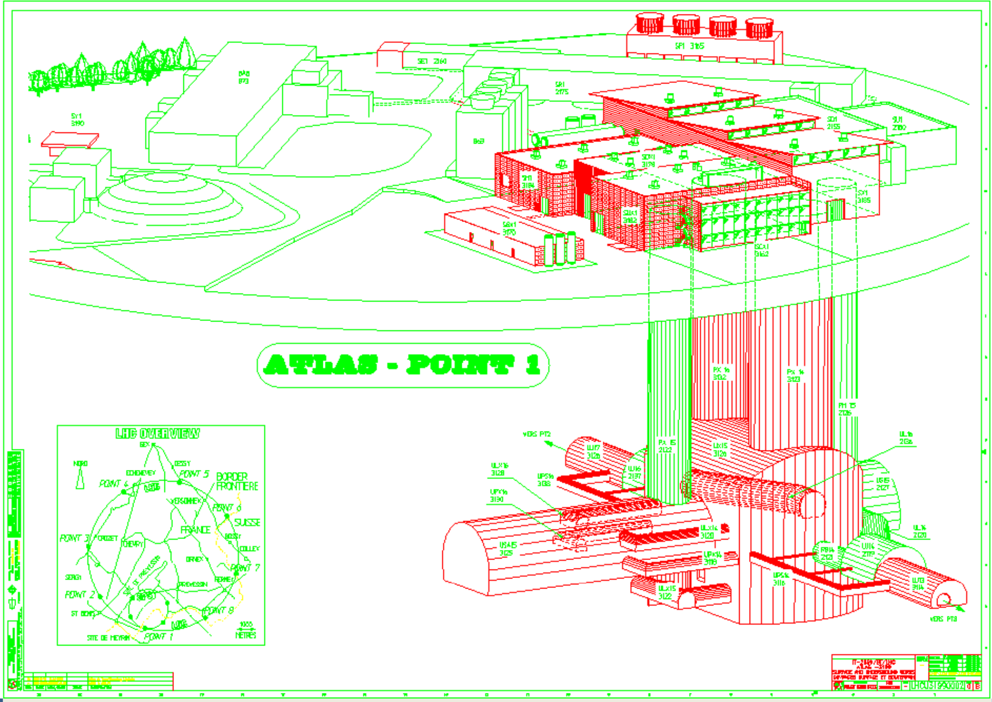
CERN

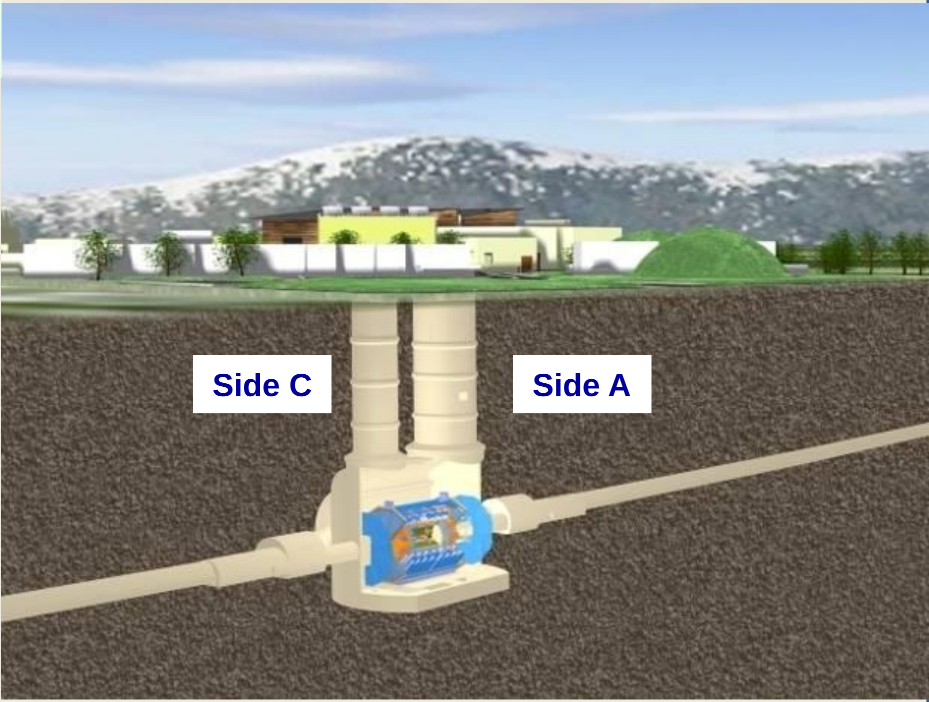
https://indico.cern.ch/event/653848/timetable/#20171215.detailed

The Underground Cavern at Point-1 for the ATLAS Detector

(excavation started in 1998)

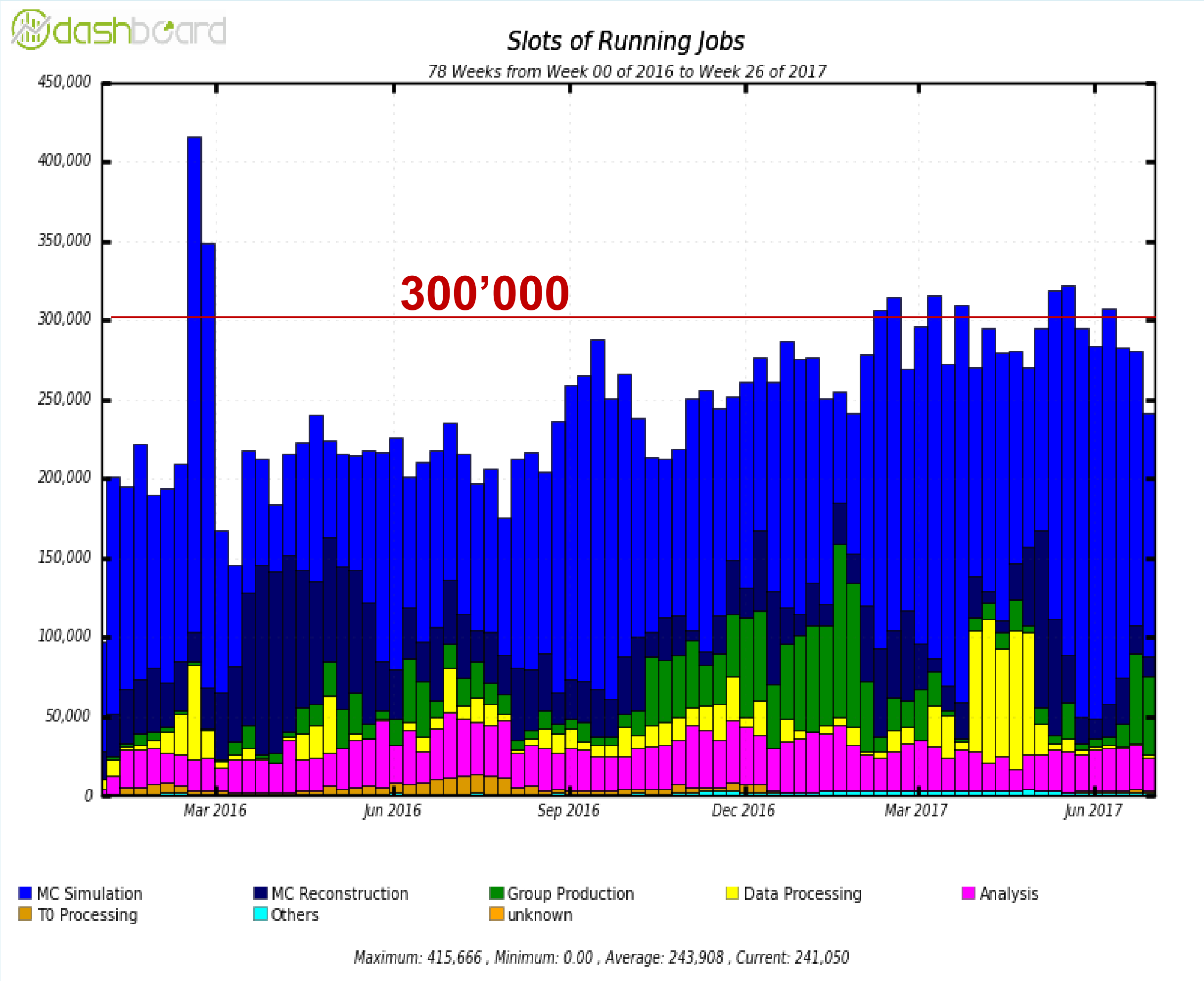
Length = 55 m
Width = 32 m
Height = 35 m



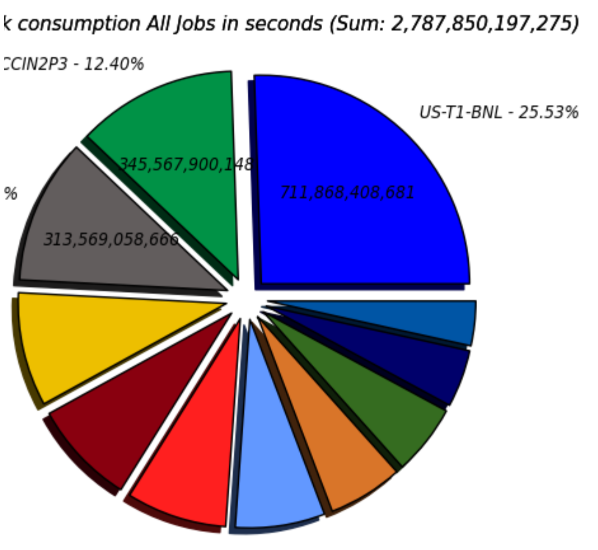


A historical moment on 16th June 2008: Closure of the LHC ring (the last beam pipe piece was the one shown here in ATLAS on side A)

Weekly averages of cores running for ATLAS

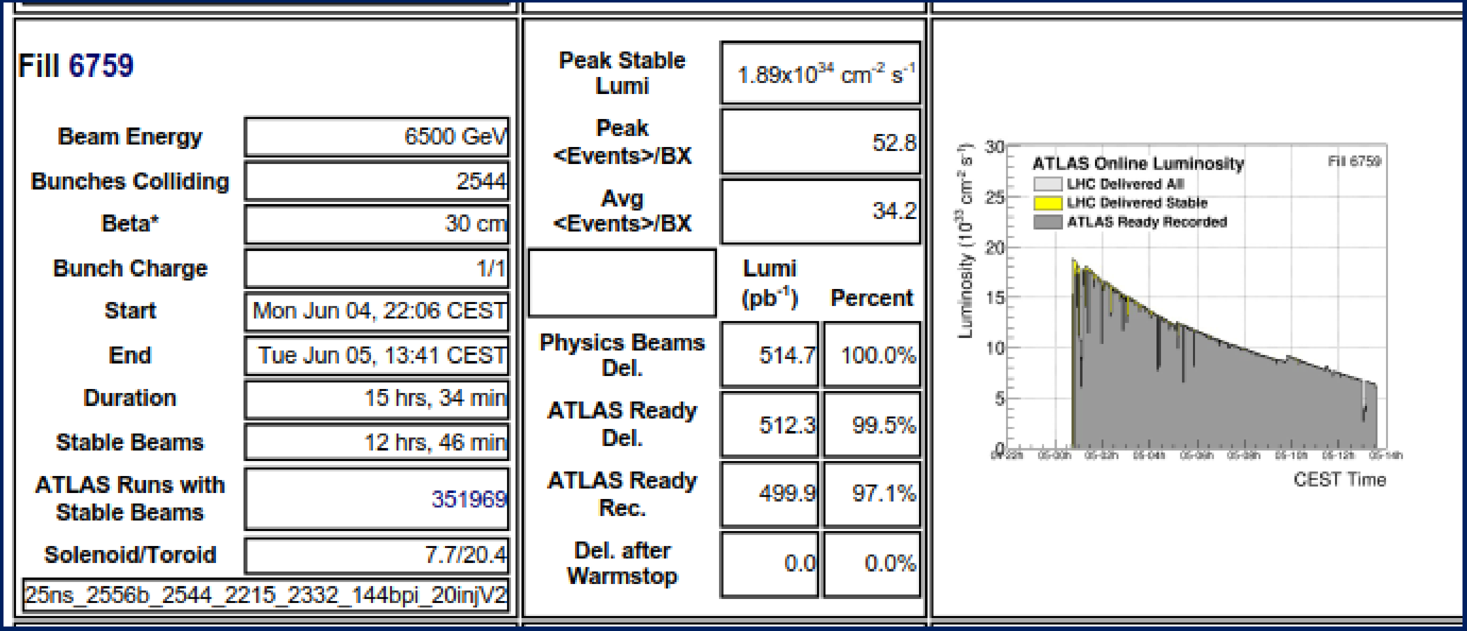


Wall clock consumption for all jobs in the 11 Tier-1s



LHC and ATLAS performance 2018 run

Example of an excellent LHC with 0.5 fb^{-1} recorded by ATLAS



Fill 6759

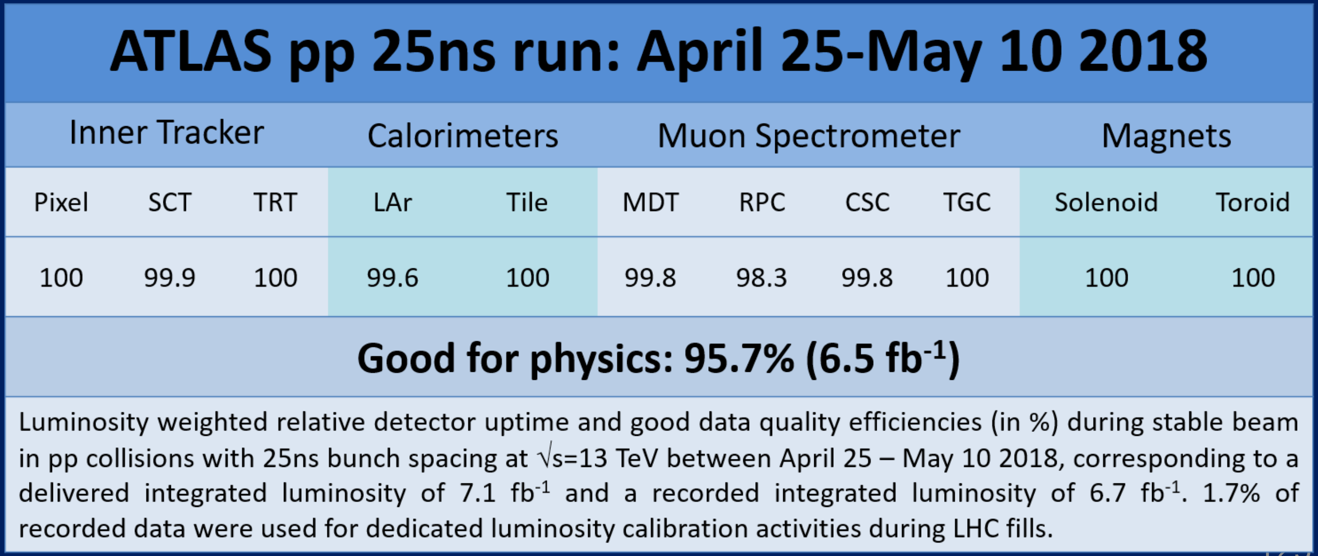
Beam Energy	6500 GeV
Bunches Colliding	2544
Beta*	30 cm
Bunch Charge	1/1
Start	Mon Jun 04, 22:06 CEST
End	Tue Jun 05, 13:41 CEST
Duration	15 hrs, 34 min
Stable Beams	12 hrs, 46 min
ATLAS Runs with Stable Beams	351969
Solenoid/Toroid	7.7/20.4

25ns_2556b_2544_2215_2332_144bpi_20injV2

Peak Stable Lumi	1.89x10^{34} cm^{-2} s^{-1}
Peak <Events>/BX	52.8
Avg <Events>/BX	34.2

	Lumi (pb^{-1})	Percent
Physics Beams Del.	514.7	100.0%
ATLAS Ready Del.	512.3	99.5%
ATLAS Ready Rec.	499.9	97.1%
Del. after Warmstop	0.0	0.0%

Overall data quality for the first part of the 2018 run



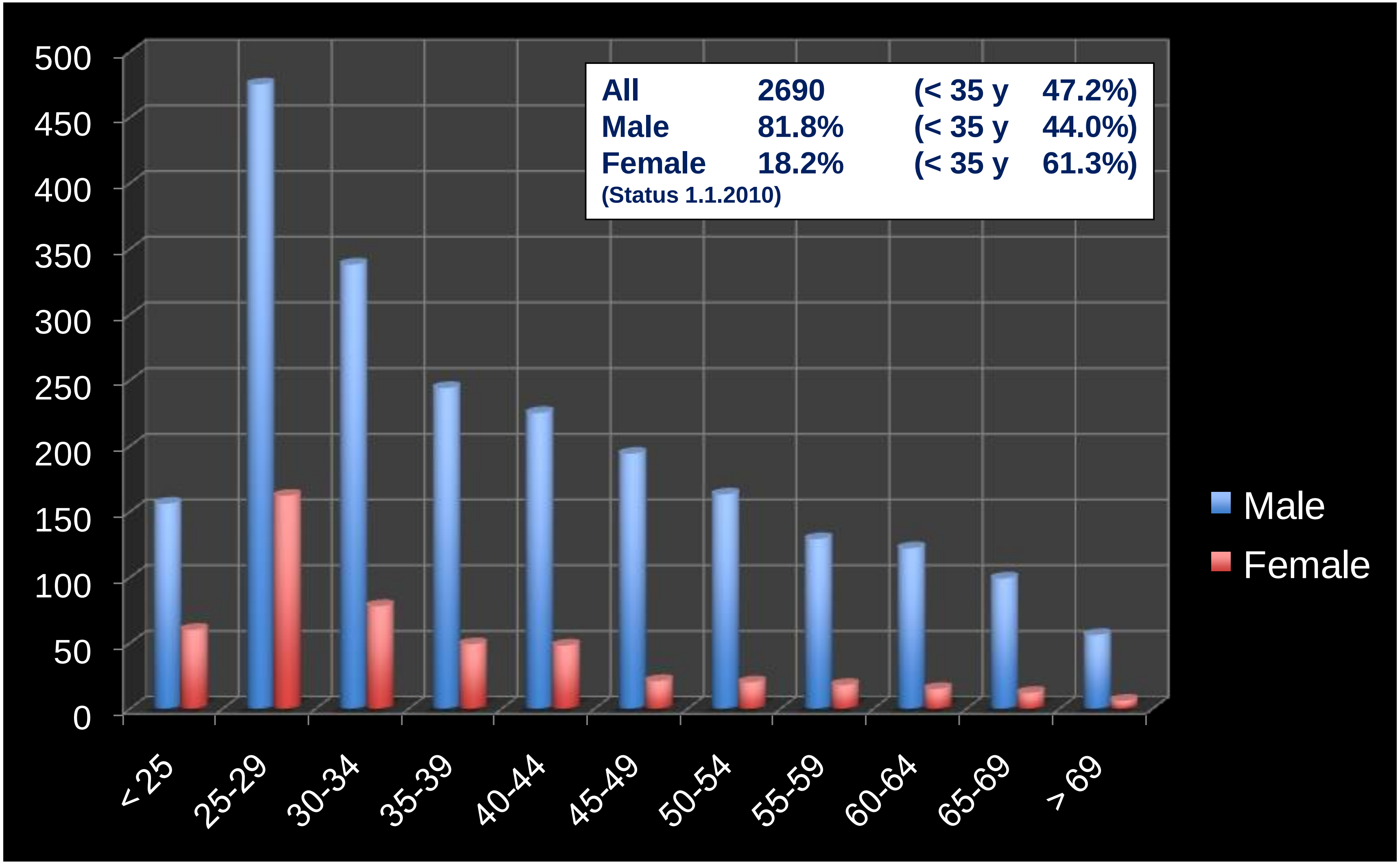
ATLAS pp 25ns run: April 25-May 10 2018

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.9	100	99.6	100	99.8	98.3	99.8	100	100	100

Good for physics: 95.7% (6.5 fb^{-1})

Luminosity weighted relative detector uptime and good data quality efficiencies (in %) during stable beam in pp collisions with 25ns bunch spacing at √s=13 TeV between April 25 – May 10 2018, corresponding to a delivered integrated luminosity of 7.1 fb^{-1} and a recorded integrated luminosity of 6.7 fb^{-1}. 1.7% of recorded data were used for dedicated luminosity calibration activities during LHC fills.

Age distribution of the ATLAS population

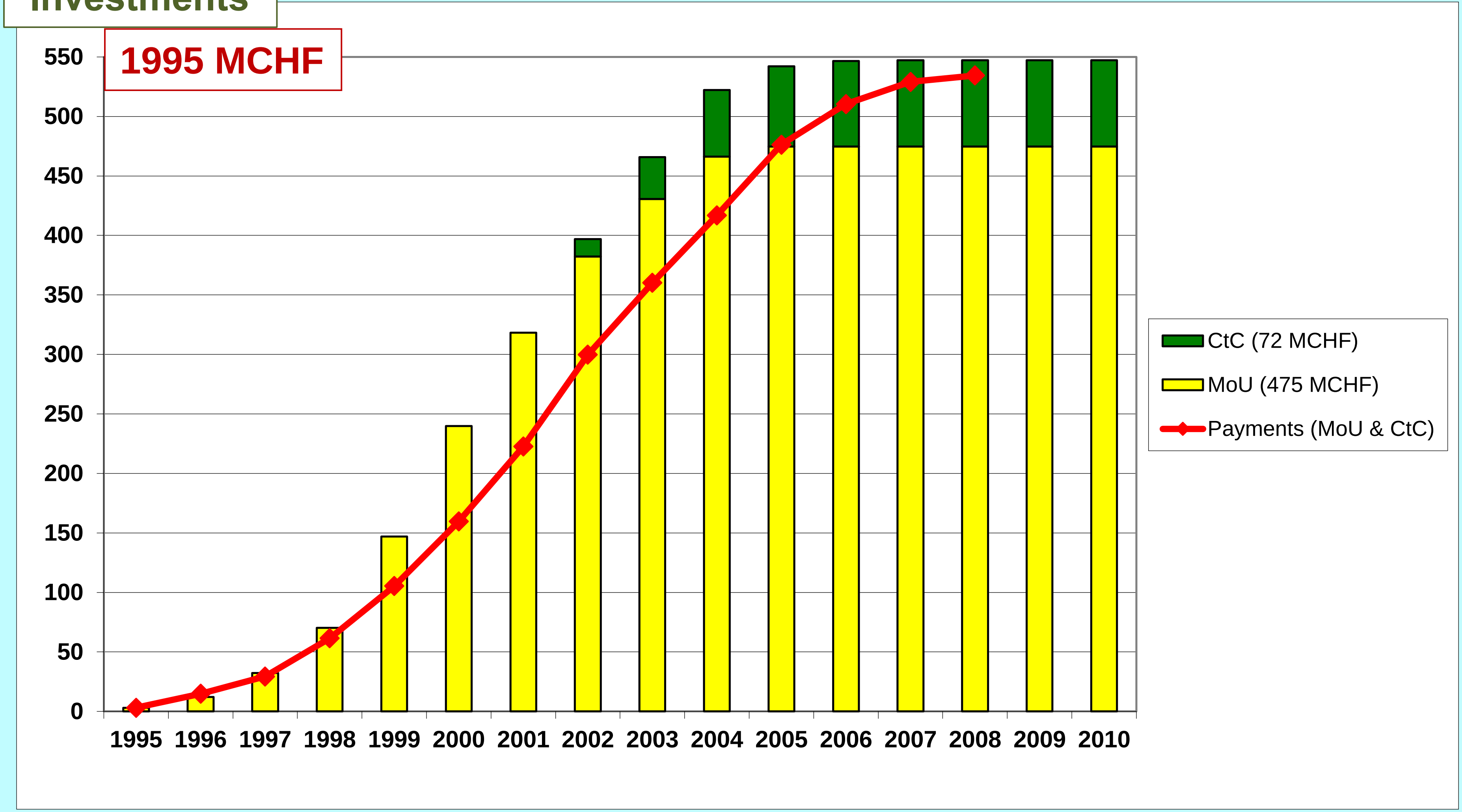


All	**2690**	**(< 35 y**	**47.2%)**
Male	**81.8%**	**(< 35 y**	**44.0%)**
Female	**18.2%**	**(< 35 y**	**61.3%)**

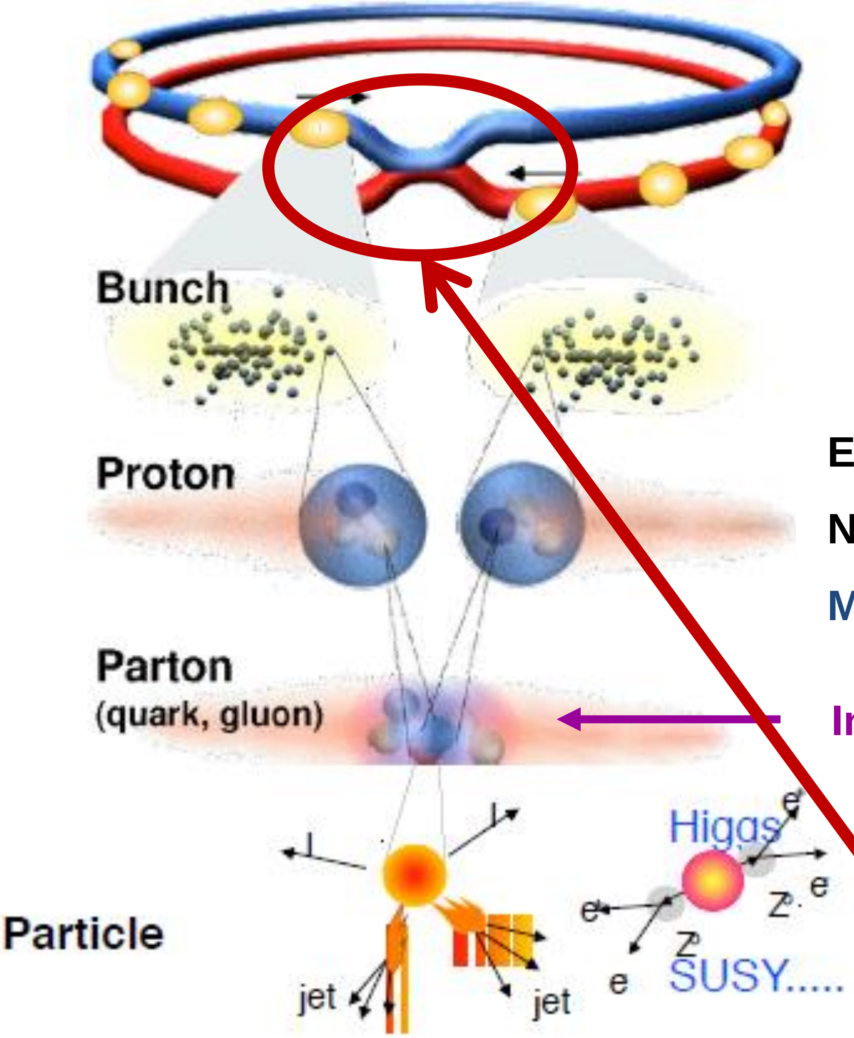
(Status 1.1.2010)

Overview of the integrated financial evolution of the 'CORE' costs of ATLAS (Constr. MoU deliverables and Common Fund, Cost-to-Completion, in 1995 MCHF)

'Investments'



Collisions at the LHC



Proton - Proton	2808 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34}cm^{-2}s^{-1}
Crossing rate	40 MHz

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

New physics rate ≈ .00001 Hz

Event selection:
1 in 10,000,000,000,000

→ Interesting events are very, very rare
→ One needs highly sophisticated instruments to find them

Physics Highlights

General event properties

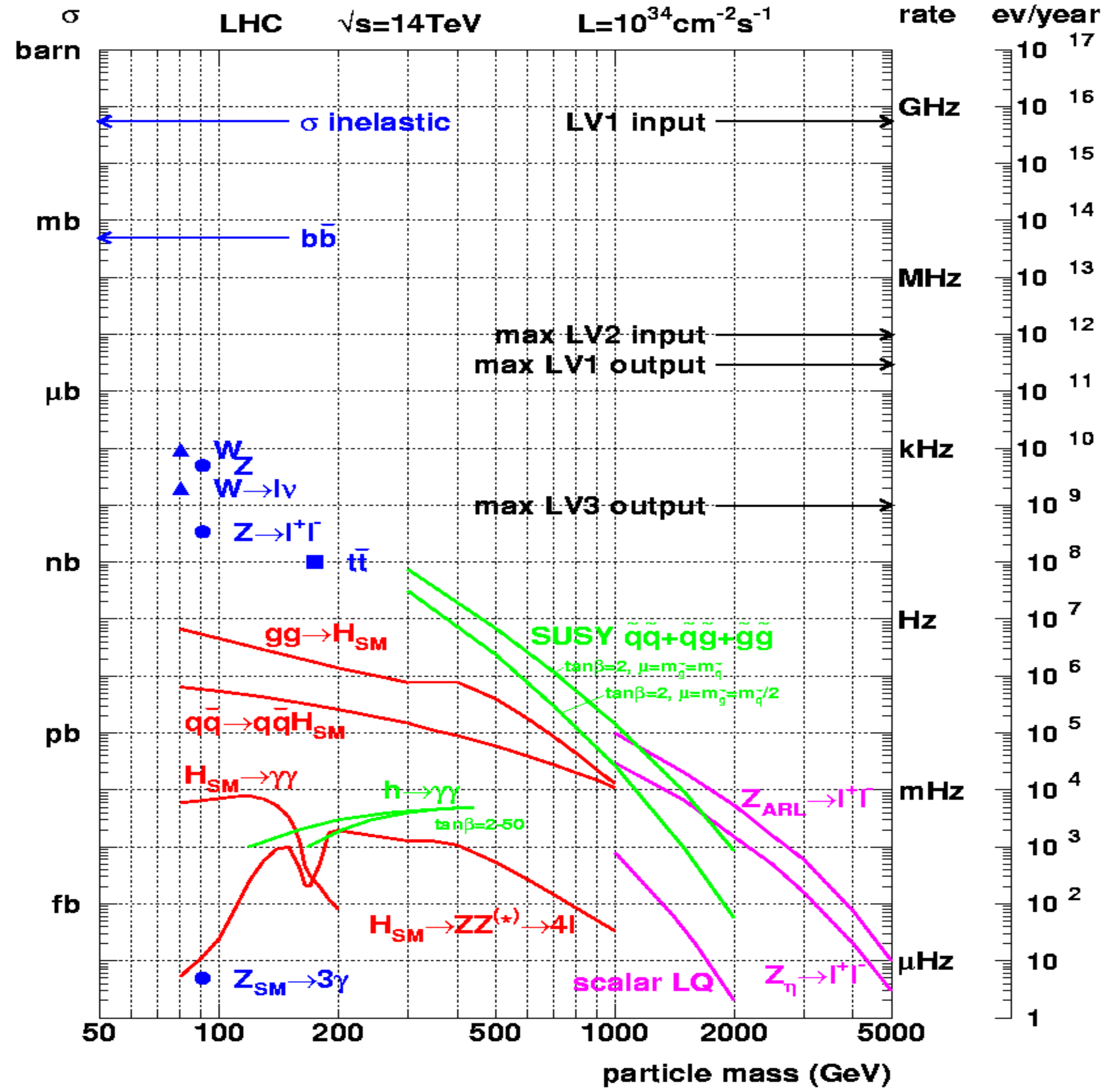
Heavy flavour physics

Standard Model physics including QCD jets

Higgs searches

Searches for SUSY

Searches for 'exotic' new physics



Collision energy

Tevatron ($p\bar{p}$)

1.96 TeV

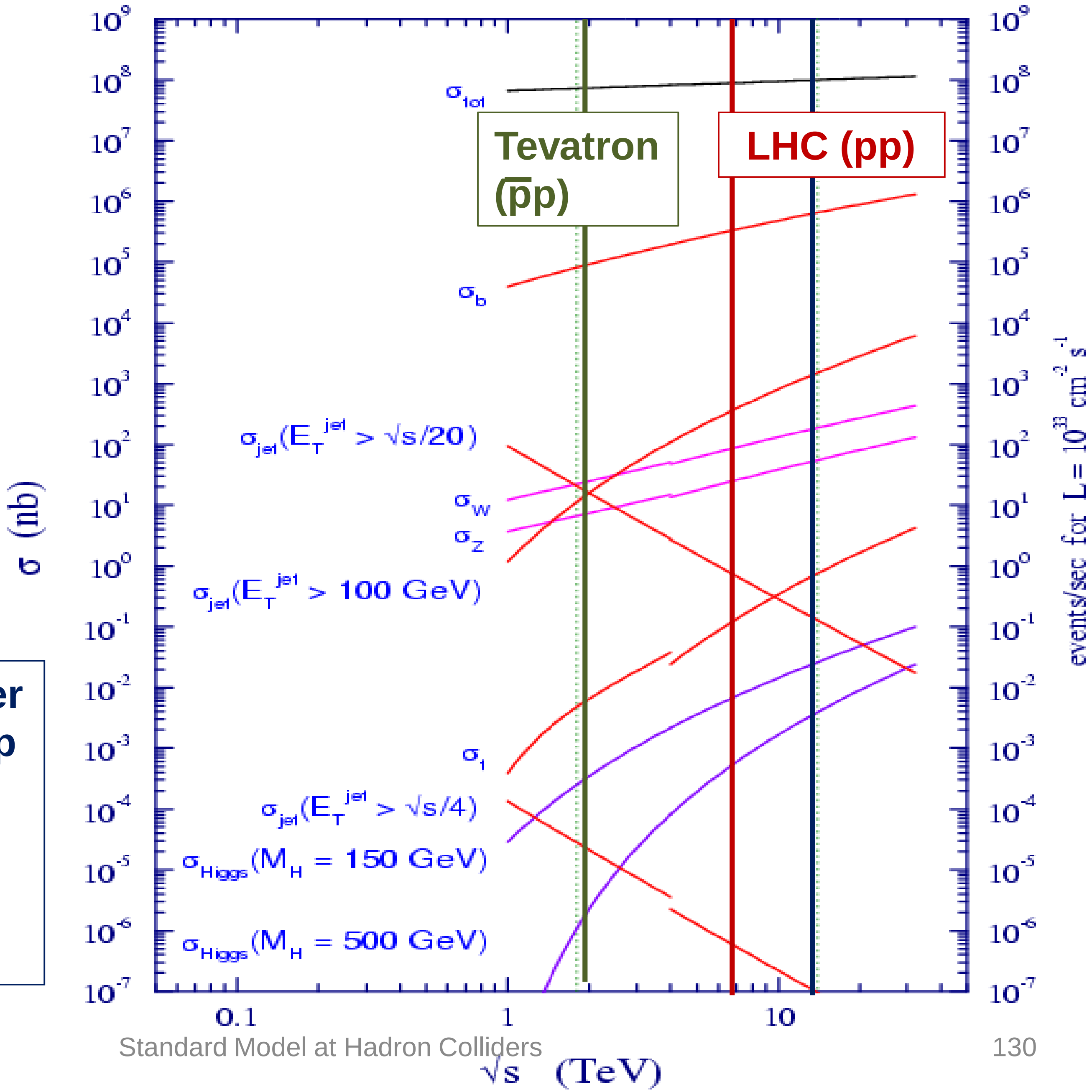
LHC (pp)

initially 7 TeV
later 14 TeV

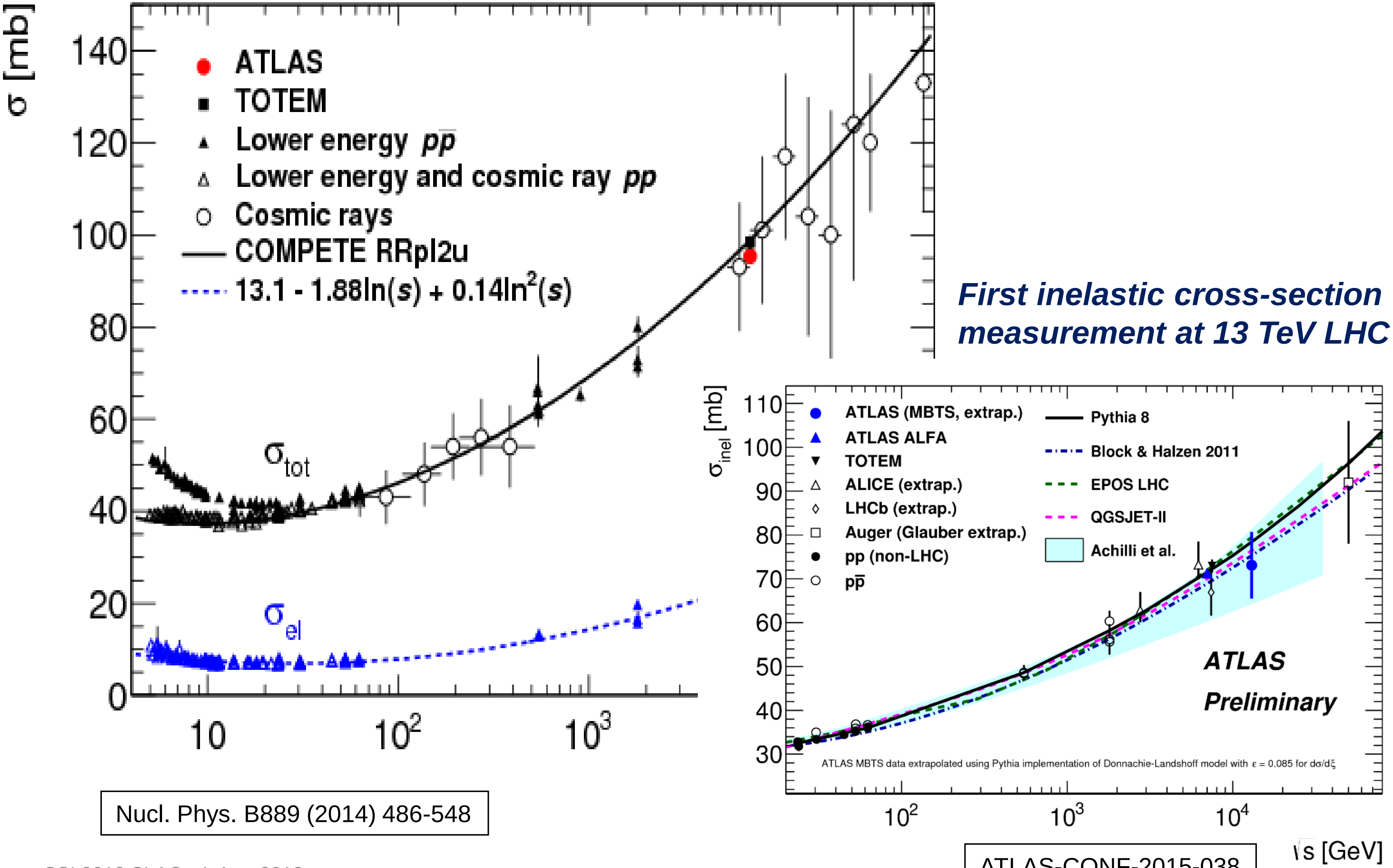
The other key parameter for setting the road map for discoveries is the integrated luminosity

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

Some bench-mark cross-sections



Very basic measurement: the total cross-section



First inelastic cross-section measurement at 13 TeV LHC

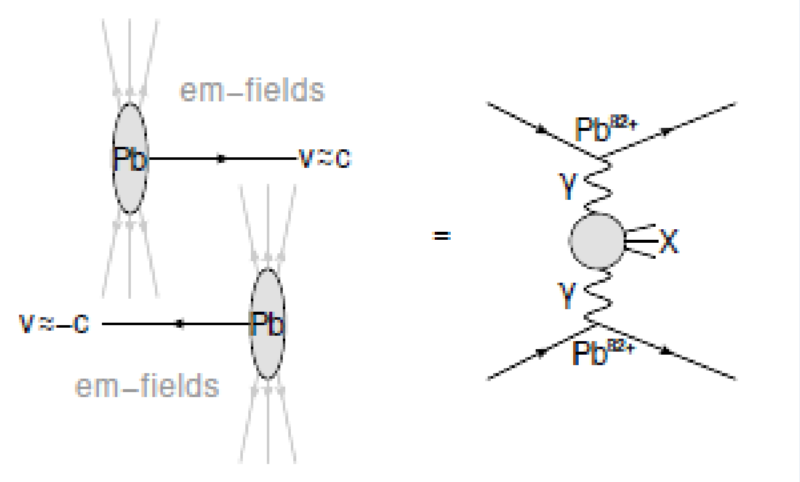
Nucl. Phys. B889 (2014) 486-548

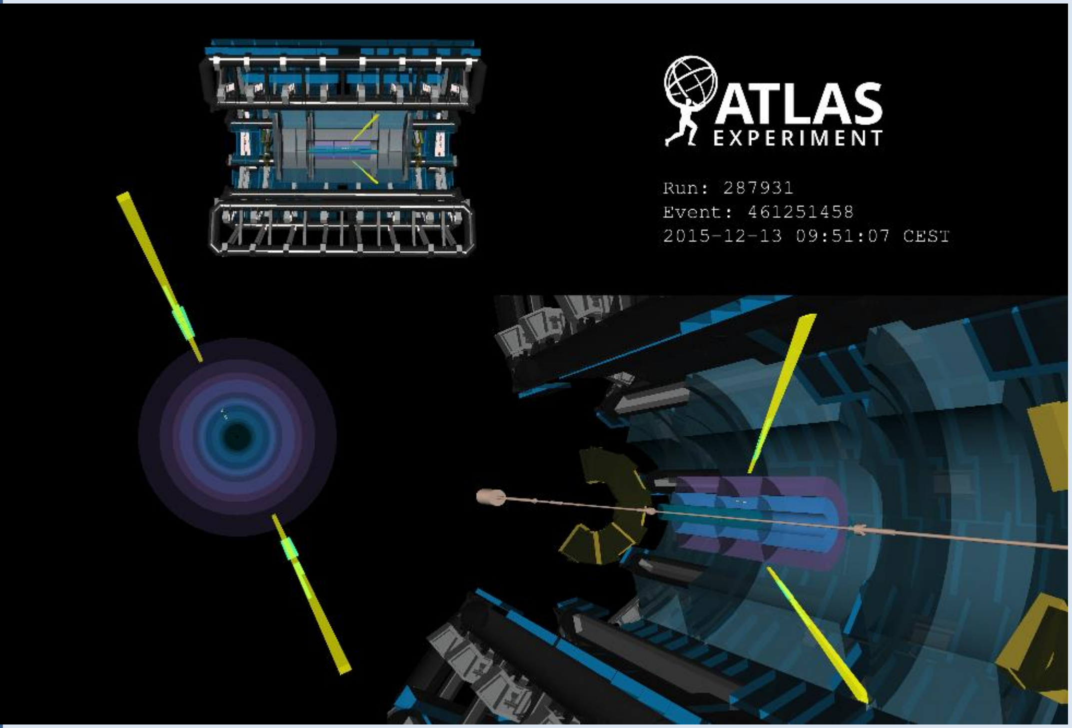
ATLAS-CONF-2015-038

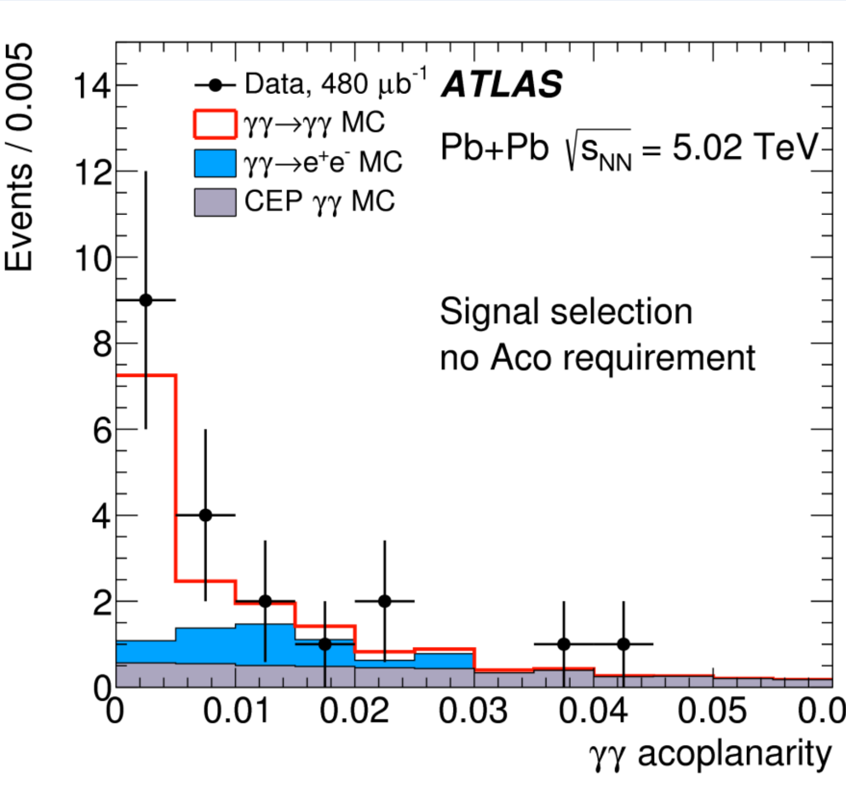
An example of physics that was certainly not anticipated at the time of the conception of ATLAS:

Evidence of light-by-light scattering in heavy ion collisions

arXiv:1702.01625[hep-exp] accepted by Nature Physics

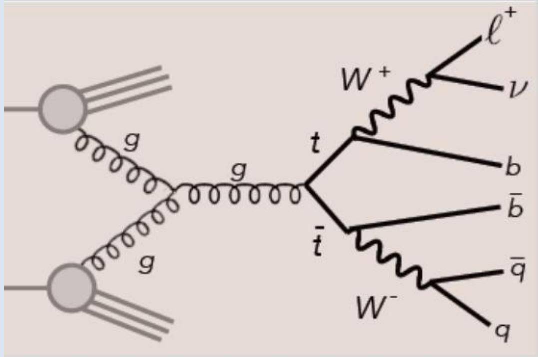


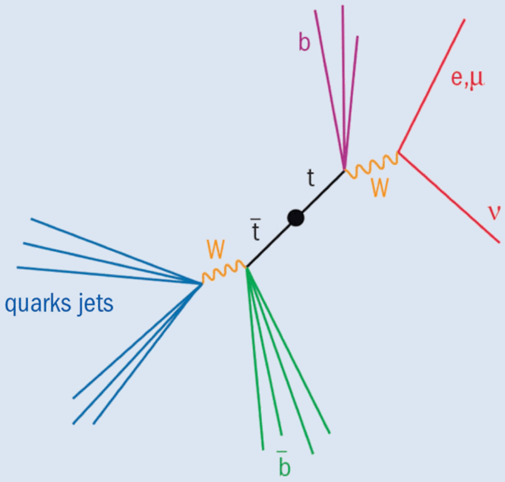


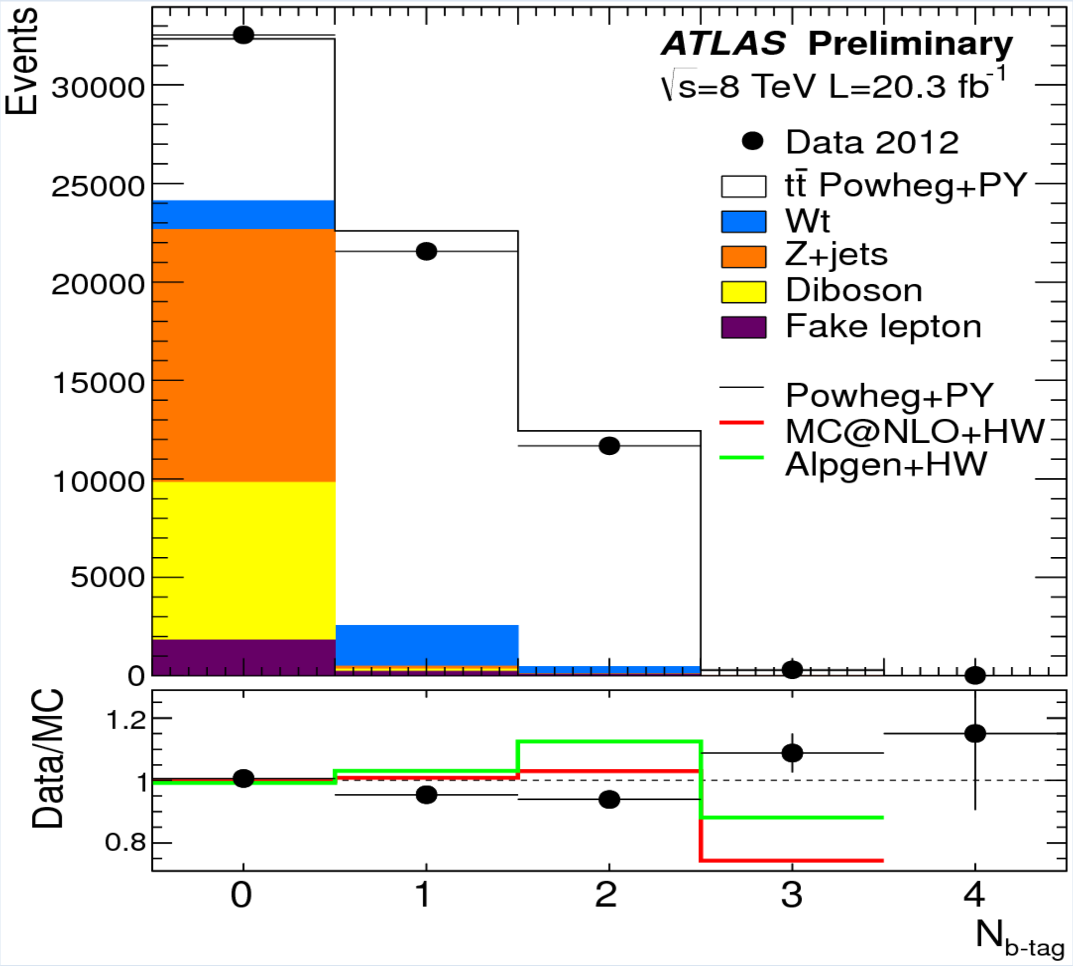


Top

Example signal distribution

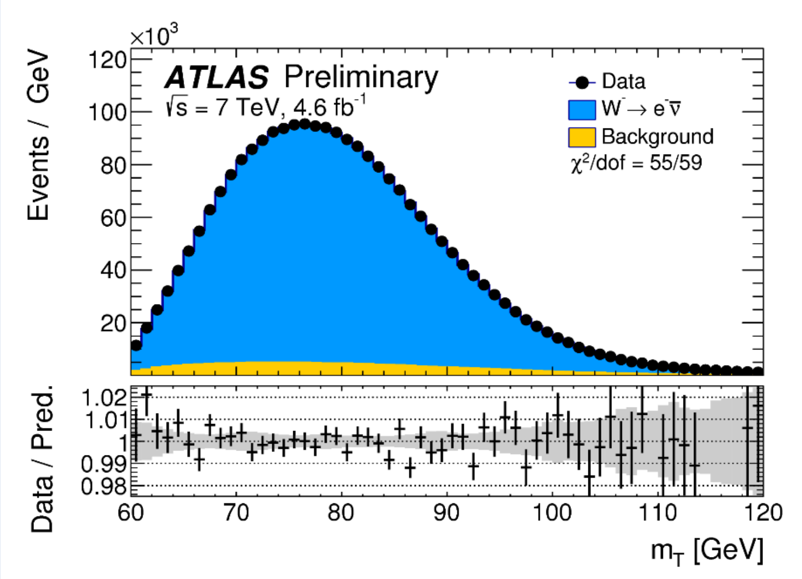


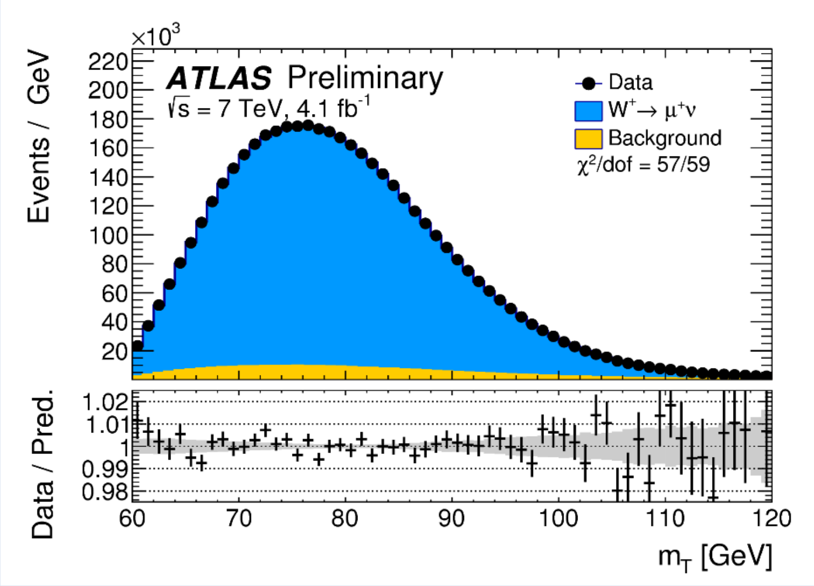




$t\bar{t}$ – production with b-tagged e-μ events

ATLAS-CONF-2013-097



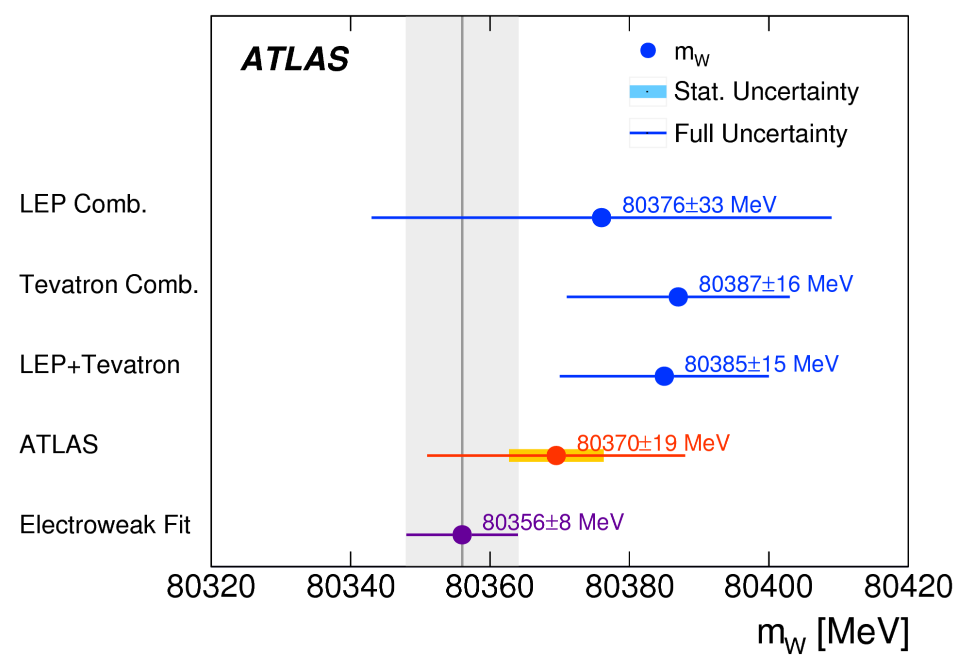


$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

Precision measurement of the W mass recently published by ATLAS

$m_W = 80.370 \pm 0.019$ GeV

arXiv:1701.07240[hep-exp], EPJ C78 (2018) 110

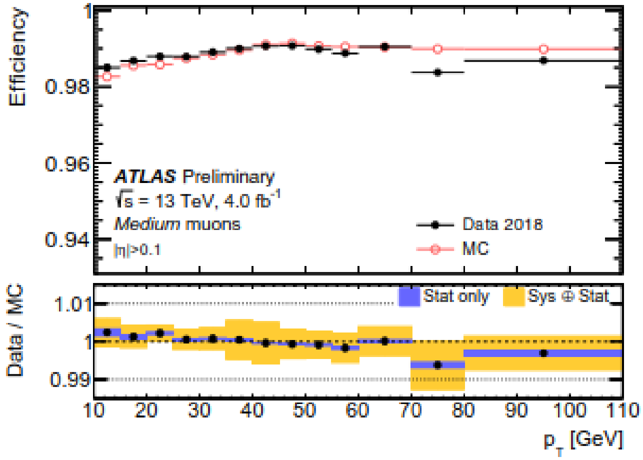


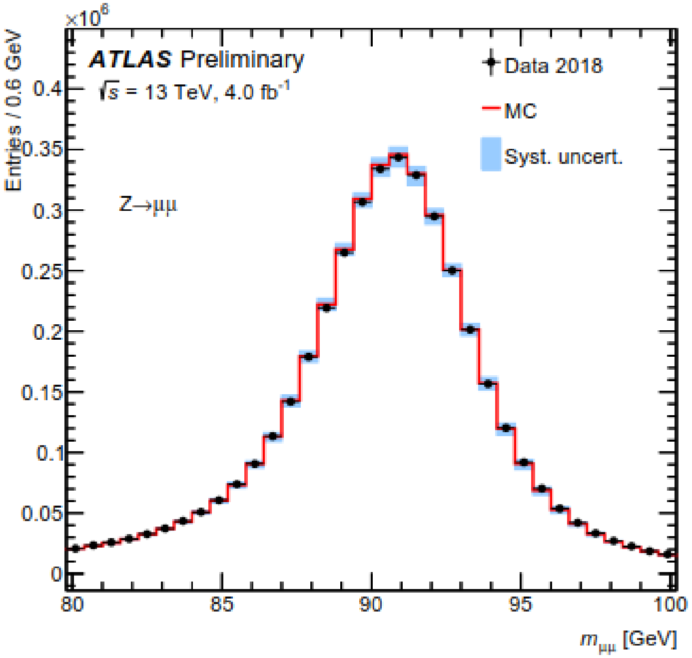
Electron and muon reconstruction performance with 2018 data

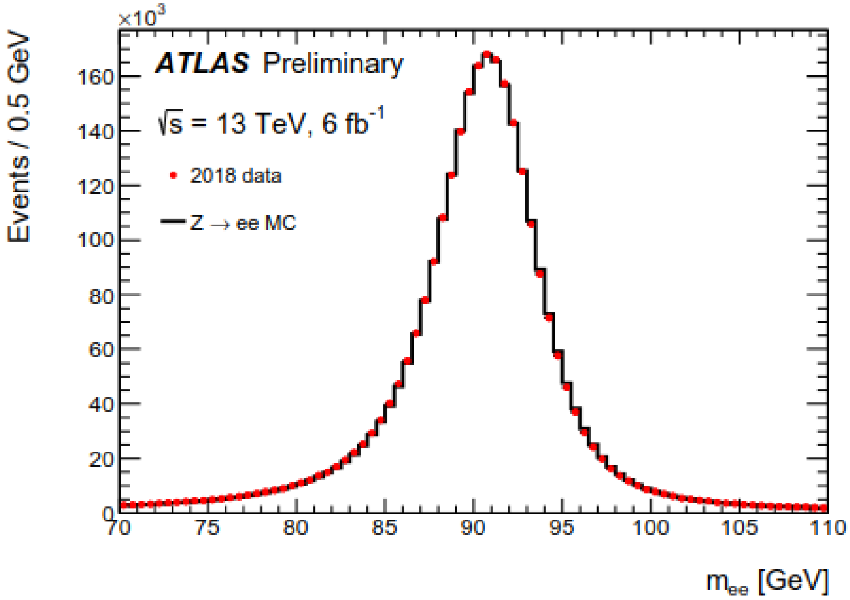
- validate electron and muon reconstruction performance with 2018 data using $Z \to \ell\ell$ events

- calibration derived from 2016 (μ) or 2017 (e) data

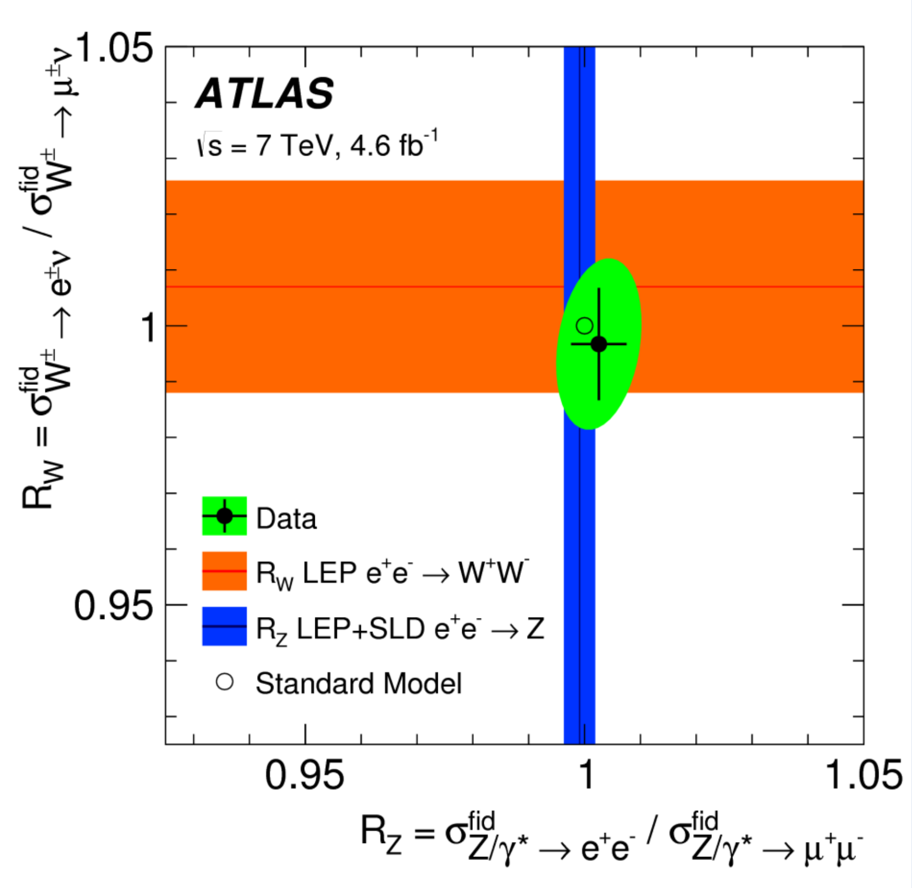
$\Longrightarrow$ excellent agreement between 2018 data and MC

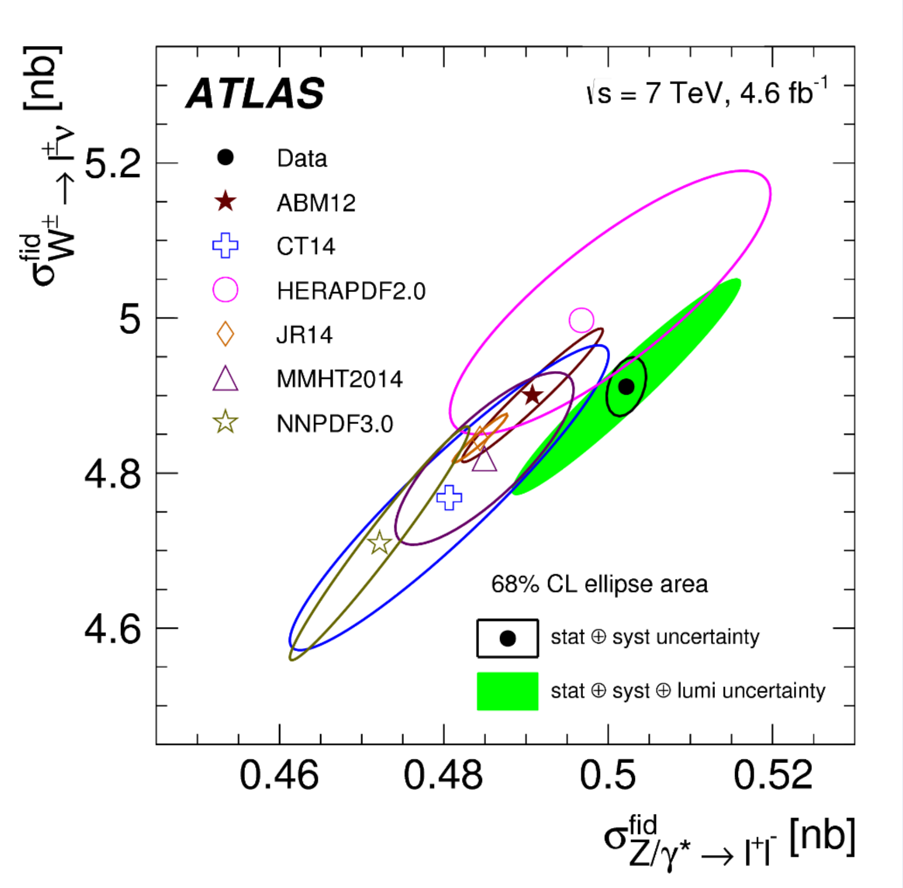






Testing in detail the predictions of the Standard Model





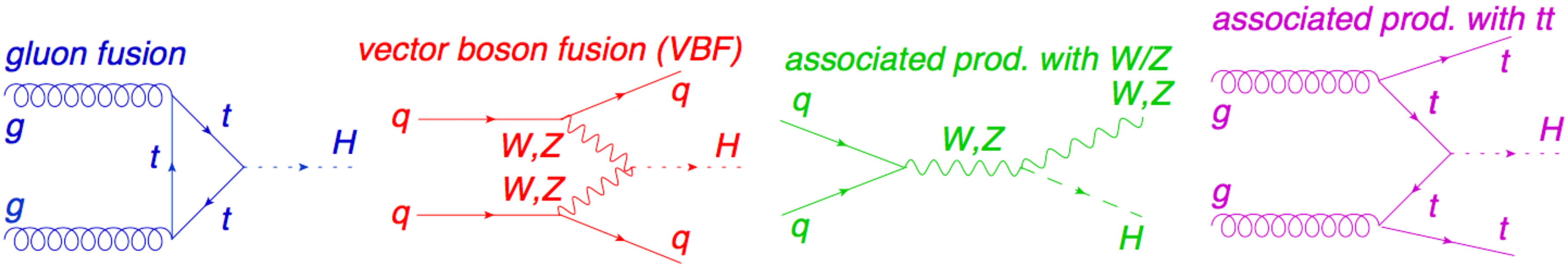
Lepton Universality

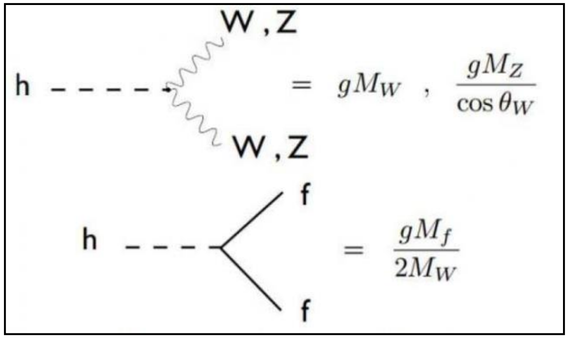
Cross-section predictions for different parton distributions

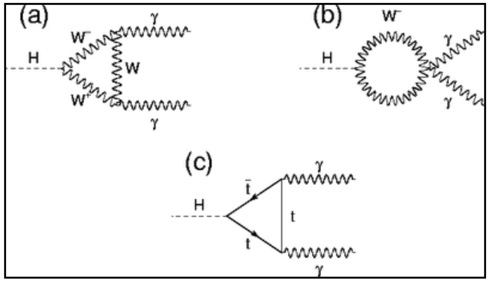
Eur. Phys. J. C77 (2017) 367

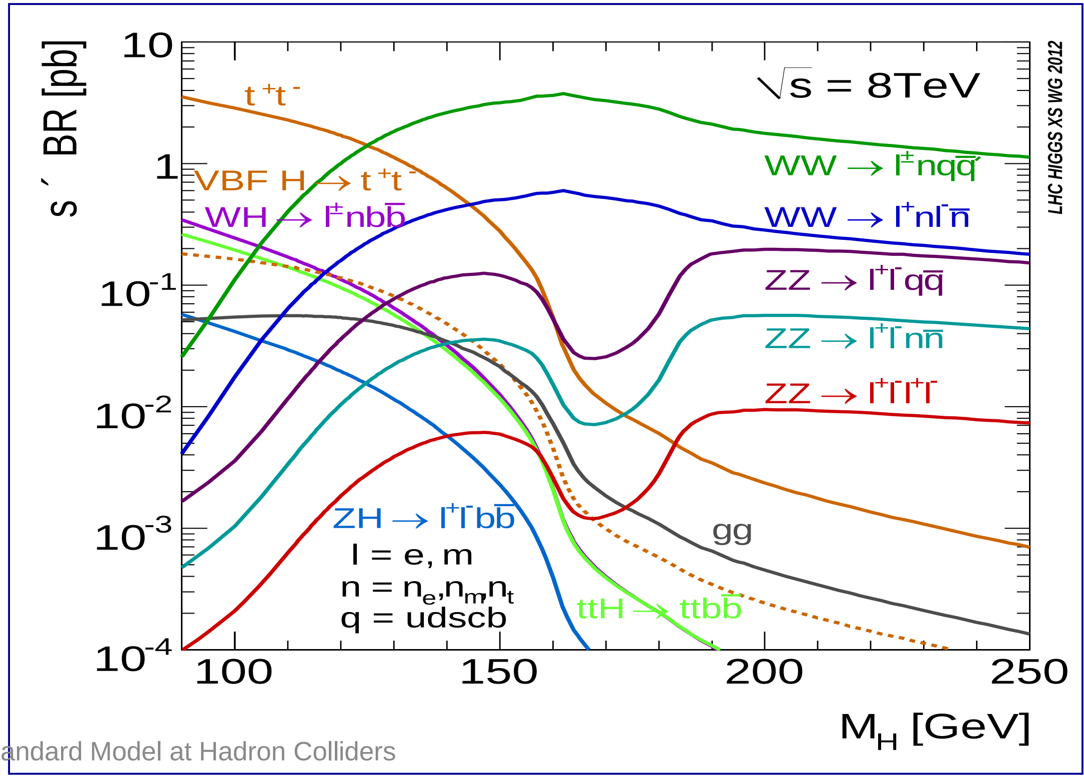
Search for the boson (H) of the EW symmetry breaking

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

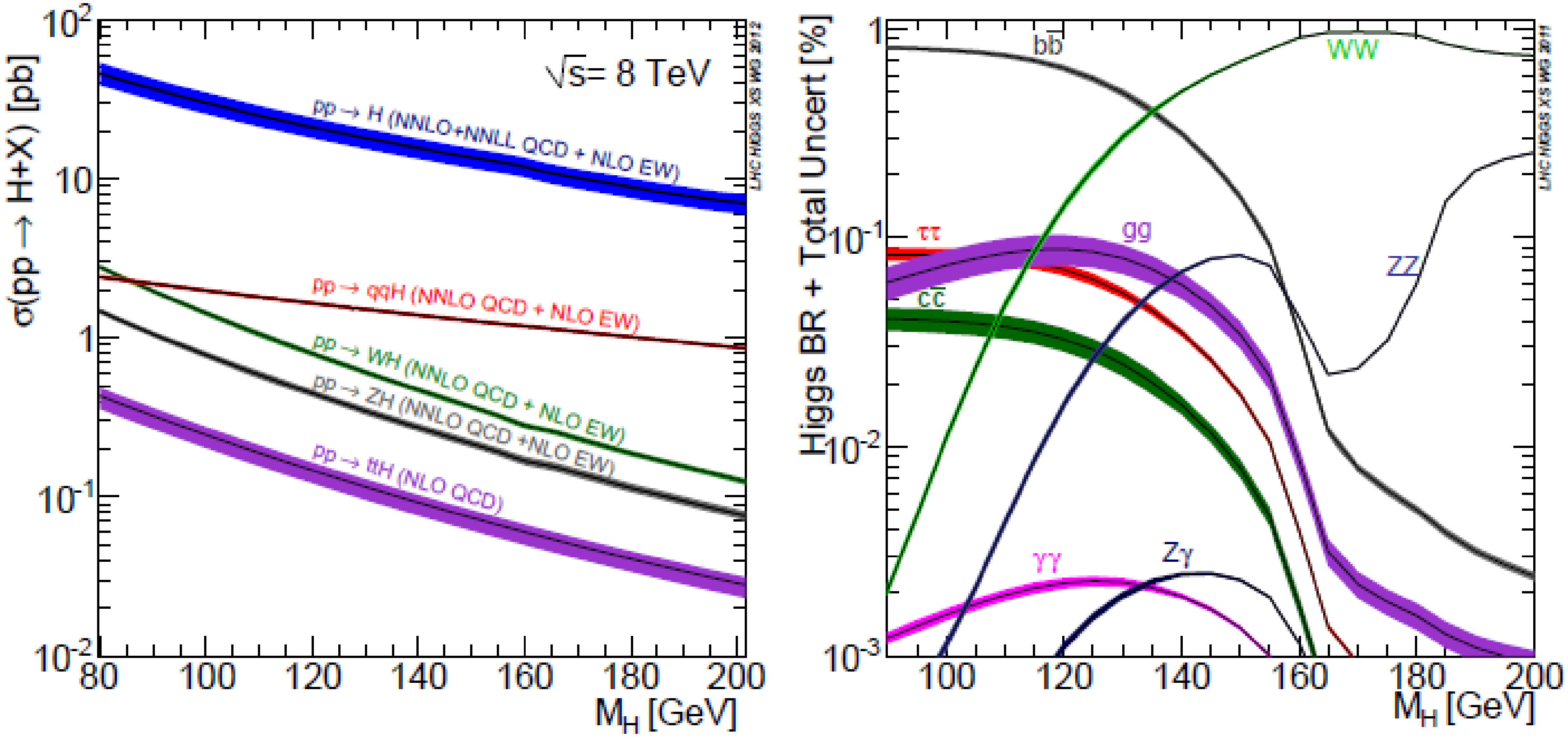




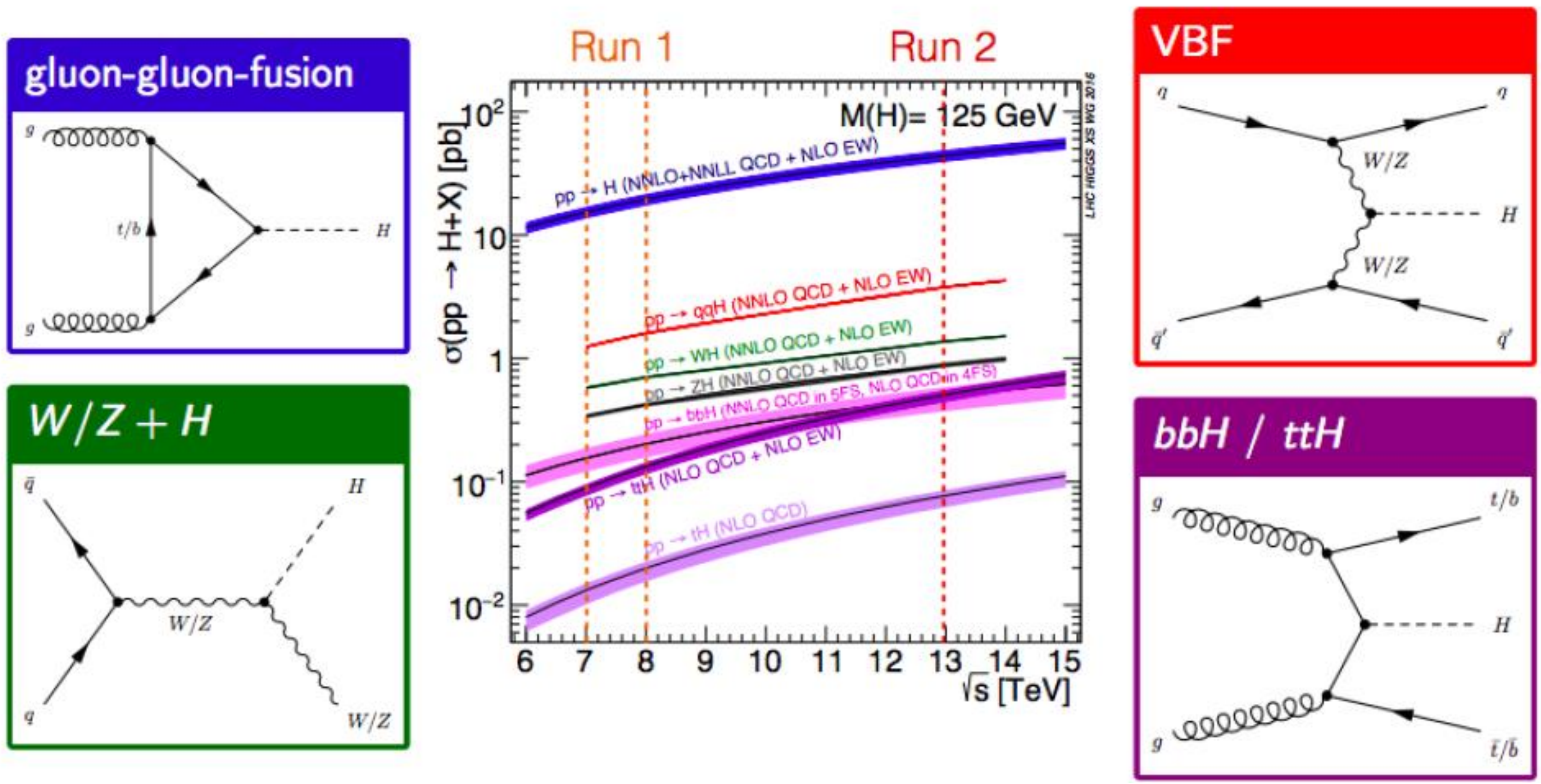


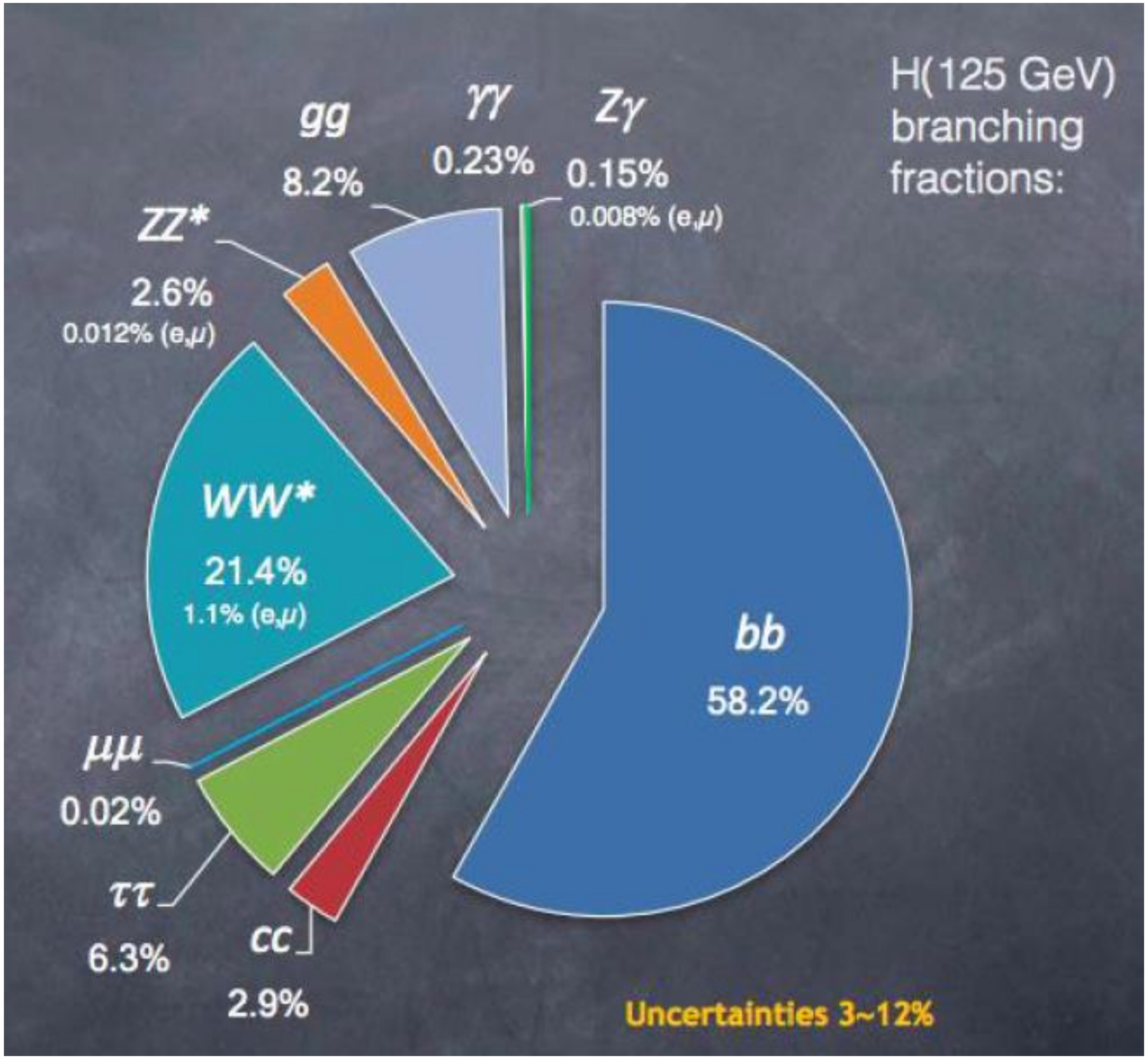


H production cross-sections at 8 TeV, and branching fractions

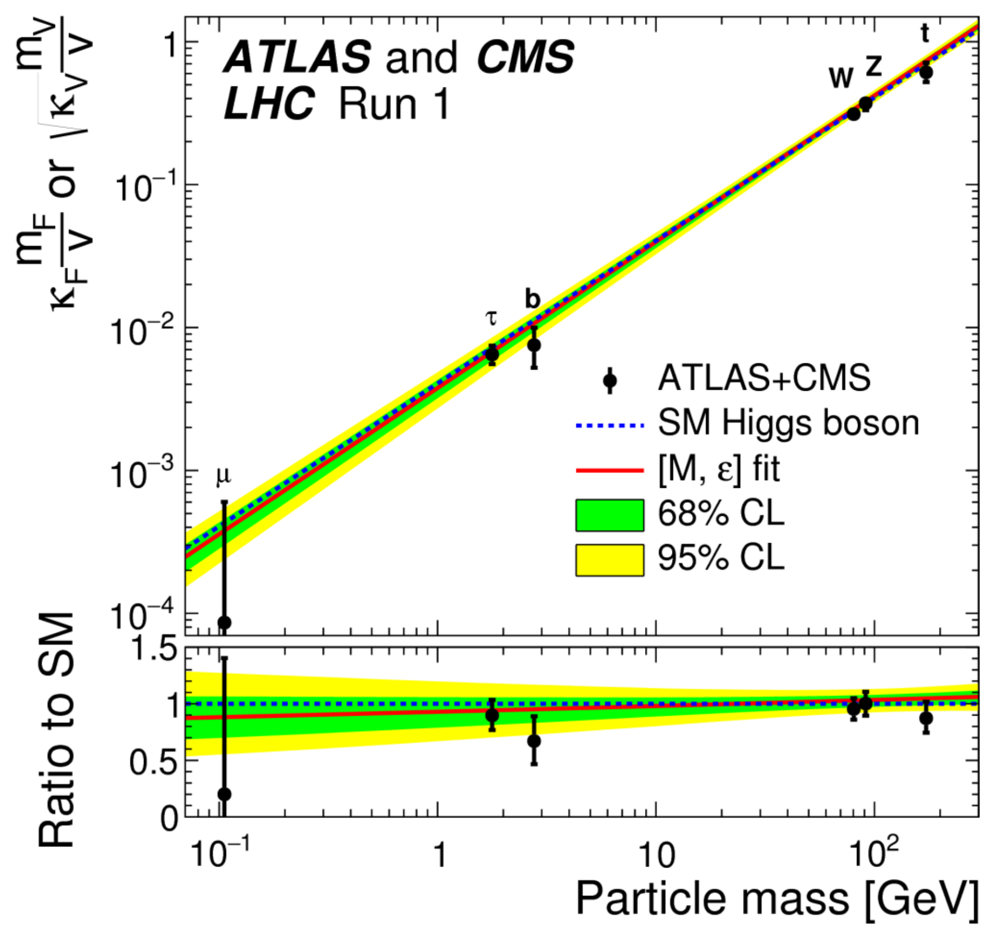


LHC Higgs cross-section working group, arXiv: 1101.0593 and 1201.3084
(the theoretical uncertainties are indicated by the width of the curves)


gluon-gluon-fusion
g
g
t/b
H
W/Z + H
q̄
q
W/Z
H
W/Z
Run 1
Run 2
M(H)= 125 GeV
LHC HIGGS XS WG 2016
σ(pp → H+X) [pb]
√s [TeV]
10²
10
1
10⁻¹
10⁻²
6
7
8
9
10
11
12
13
14
15
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD + NLO EW)
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → ttH (NLO QCD + NLO EW)
pp → tH (NLO QCD)
VBF
q
q
W/Z
H
W/Z
q̄′
q̄′
bbH / ttH
g
g
t/b
H
t̄/b̄


H(125 GeV)
branching
fractions:
gg
8.2%
γγ
0.23%
Zγ
0.15%
0.008% (e,μ)
ZZ*
2.6%
0.012% (e,μ)
WW*
21.4%
1.1% (e,μ)
bb
58.2%
μμ
0.02%
ττ
6.3%
cc
2.9%
Uncertainties 3~12%

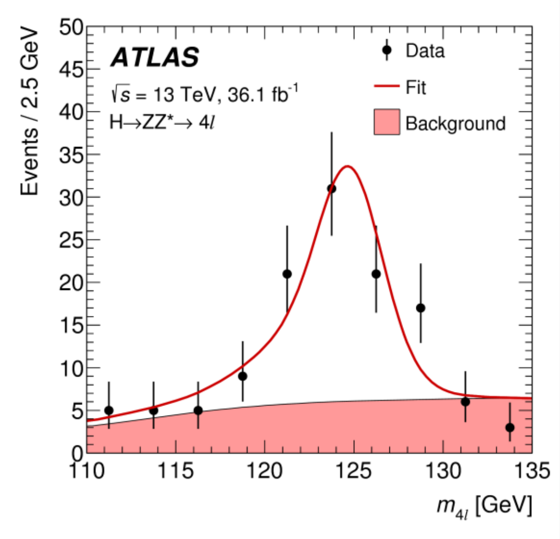
Fingerprints for a Standard Model BEH Boson:
ATLAS and CMS combined Run-1 coupling strengths

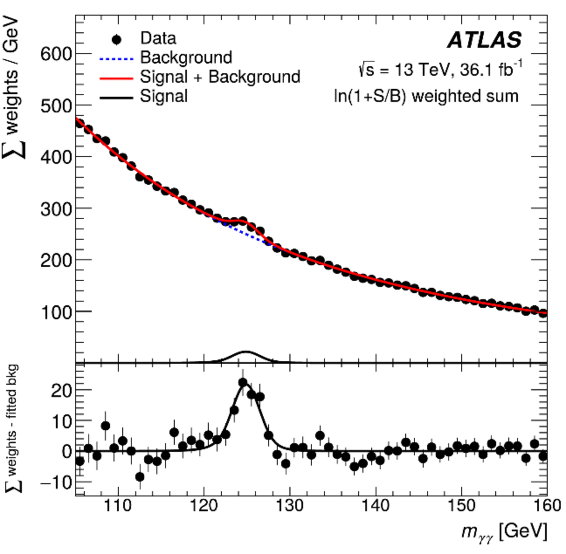


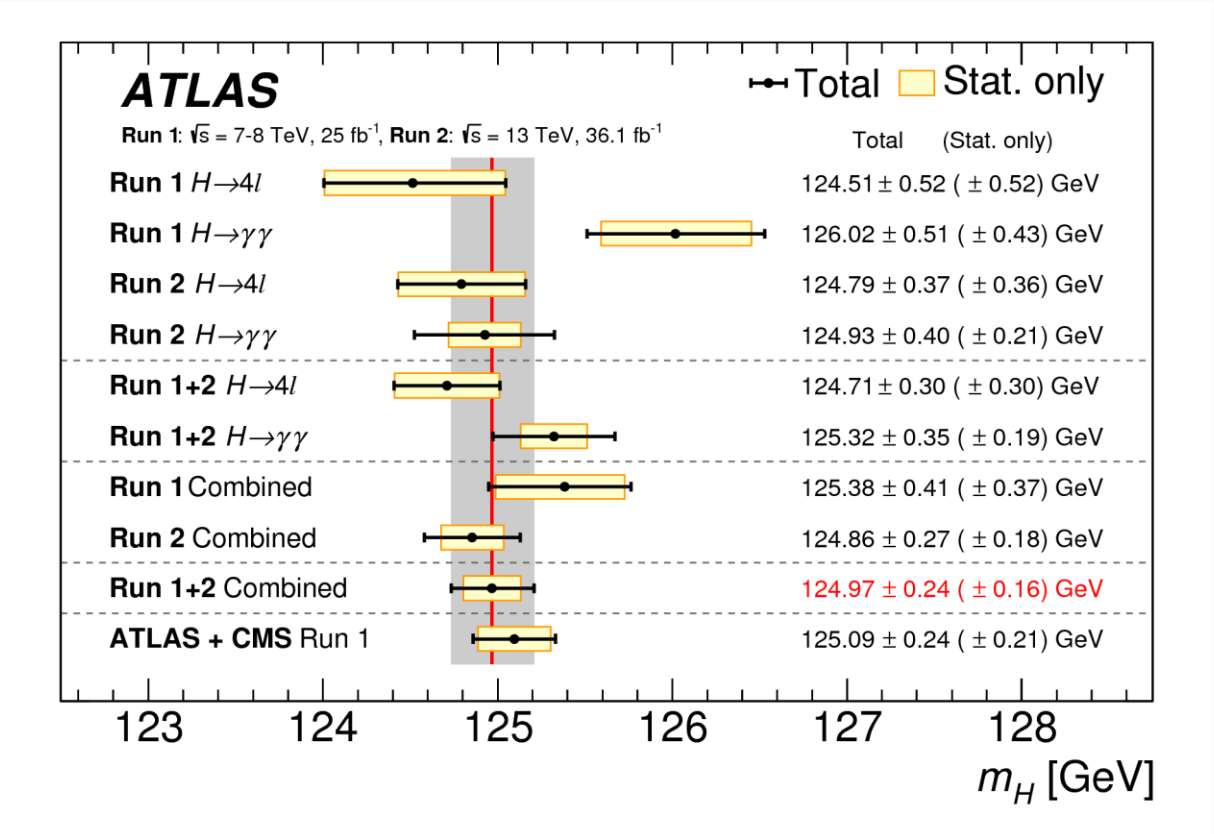
ATLAS+CMS JHEP 08 (2016) 045

Within the still rather limited precision the couplings scale with the particle masses as predicted by the SM

ATLAS m_H measurement Run-2 (2016) at 13 TeV

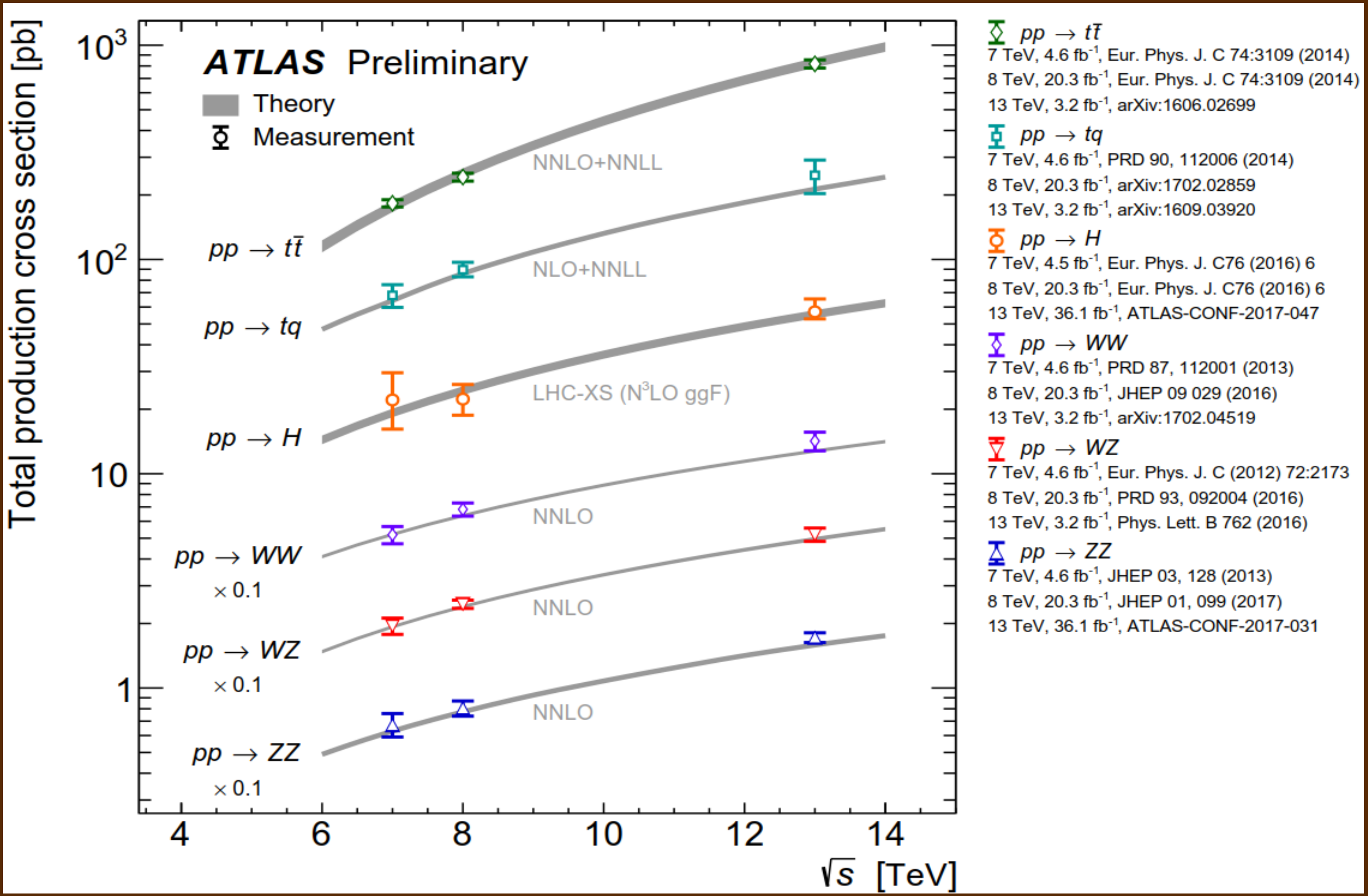






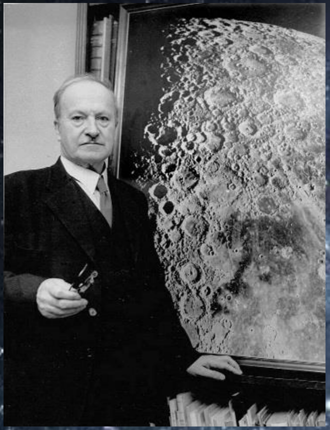
arXiv:1806.00242[hep-exp], submitted to Phys. Lett. B

Selection of SM cross-sections including from Run-2 (2015 and 2016)



Dark Matter in the Universe

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

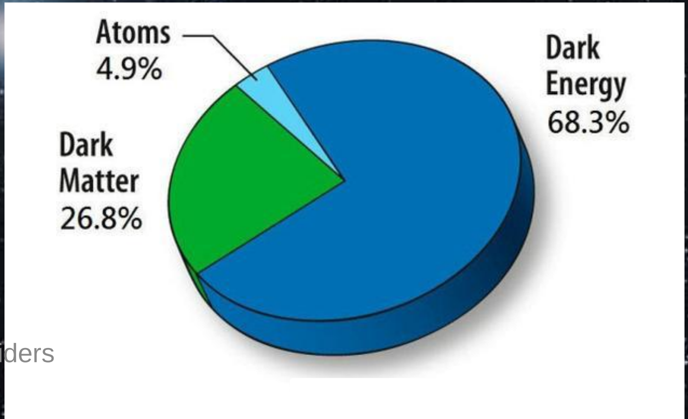


K. Lundmark 1889-1958

F. Zwicky 1898-1974

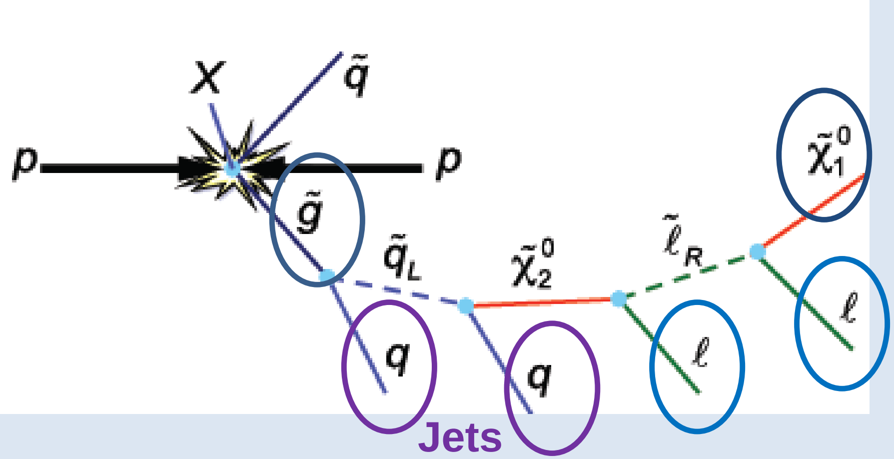
Vera Rubin ~ 1970

‘Supersymmetric’ particles ?

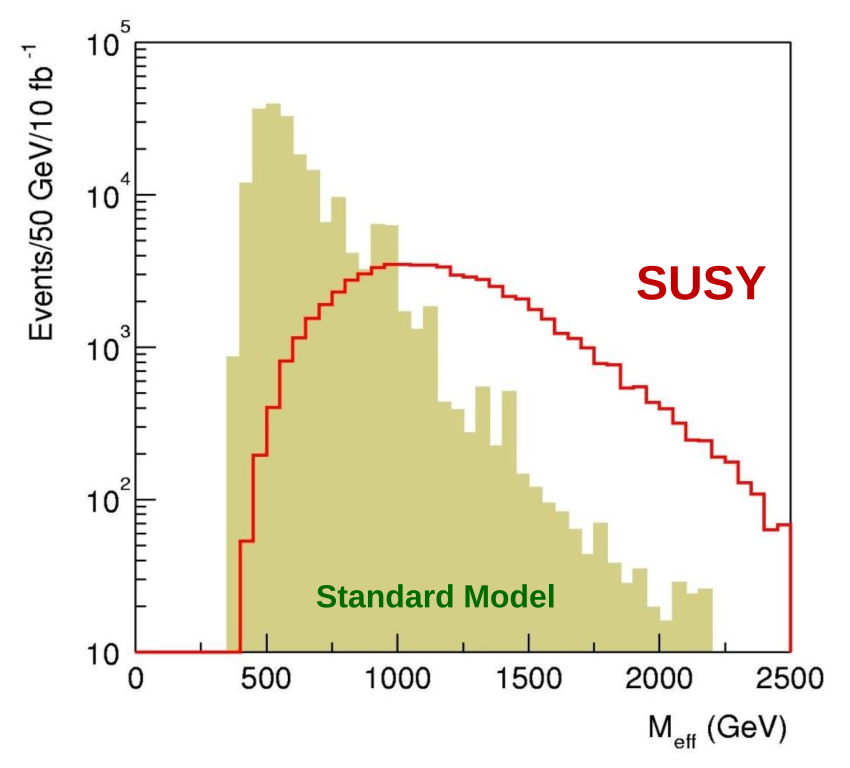


In practice SUSY searches at LHC are rather complicated

- Complex (and model-dependent): example squark/gluino cascades



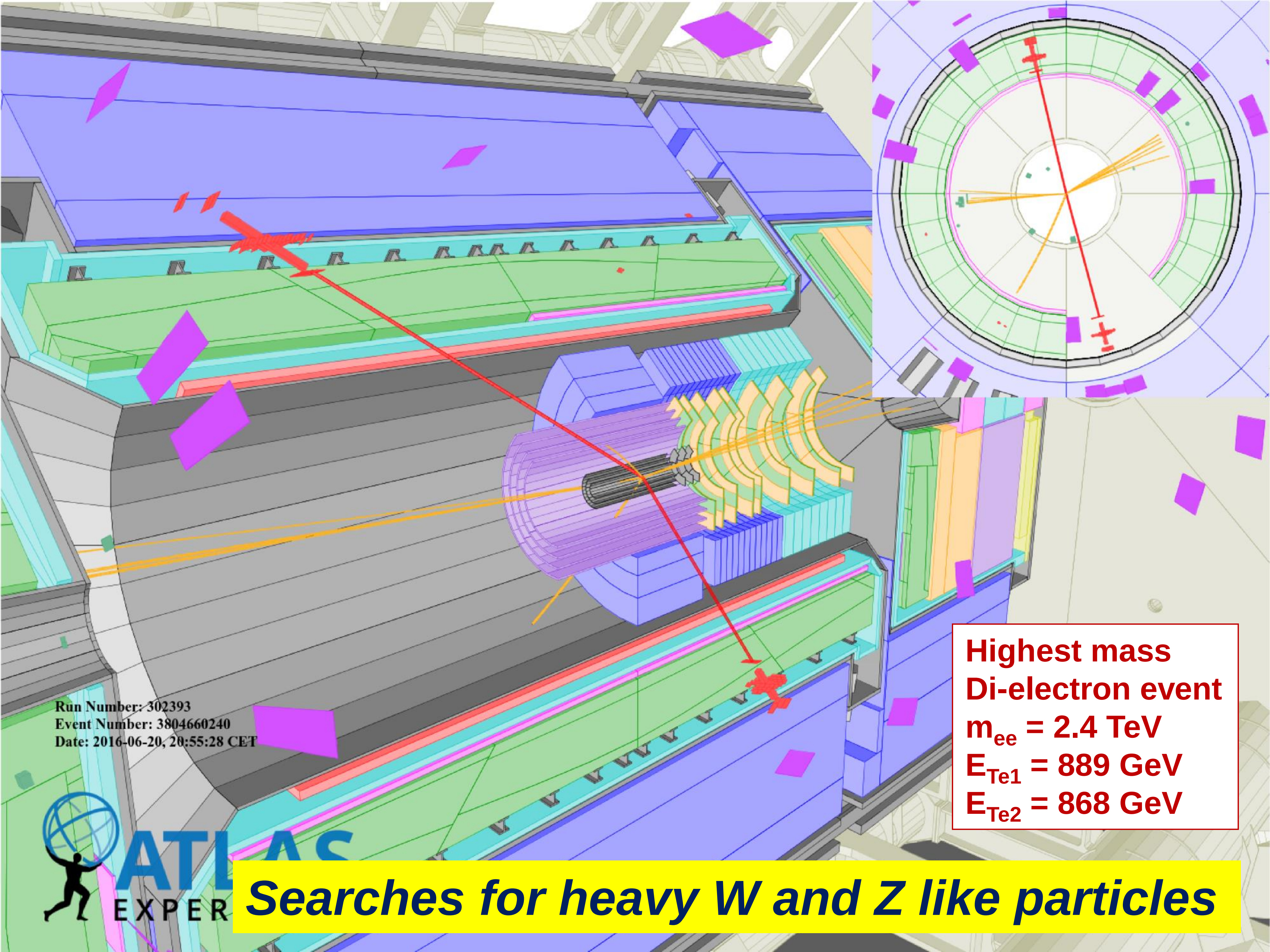
Missing Transverse Energy



Meff = Etmiss + Σ pT(jets)

- 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

Searches for heavy W and Z like particles

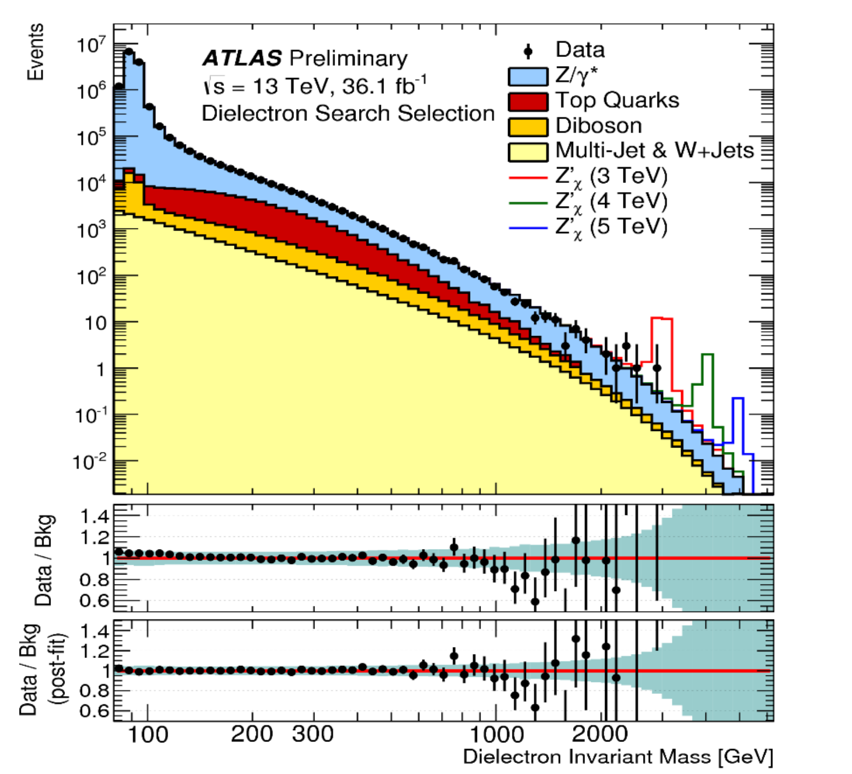


Highest mass
Di-electron event
m_{ee} = 2.4 TeV
E_{Te1} = 889 GeV
E_{Te2} = 868 GeV

Searches for heavy W and Z like particles

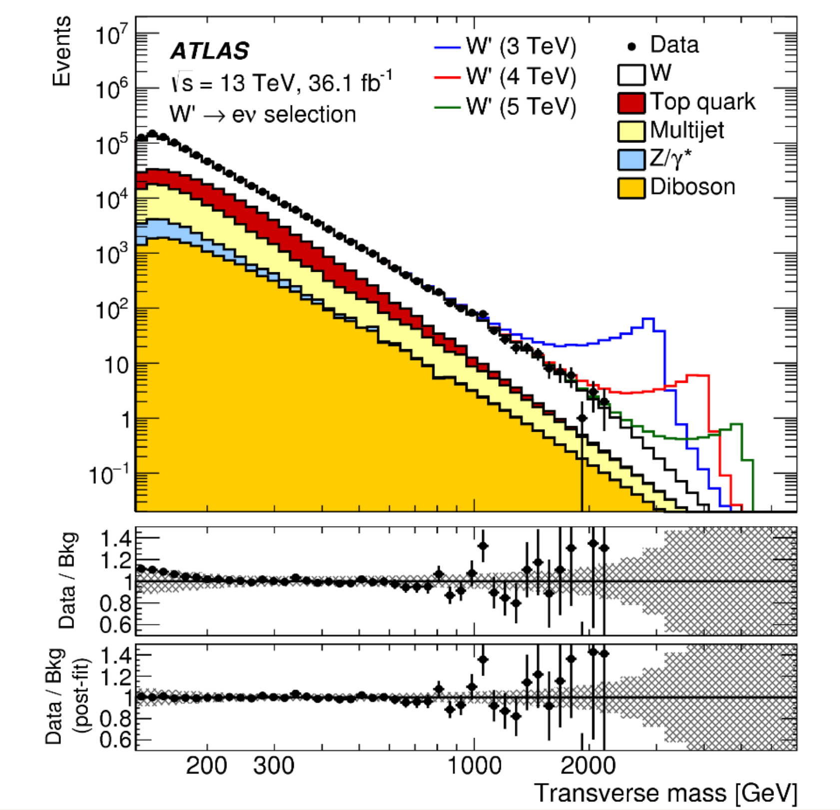
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z': Di-lepton pairs



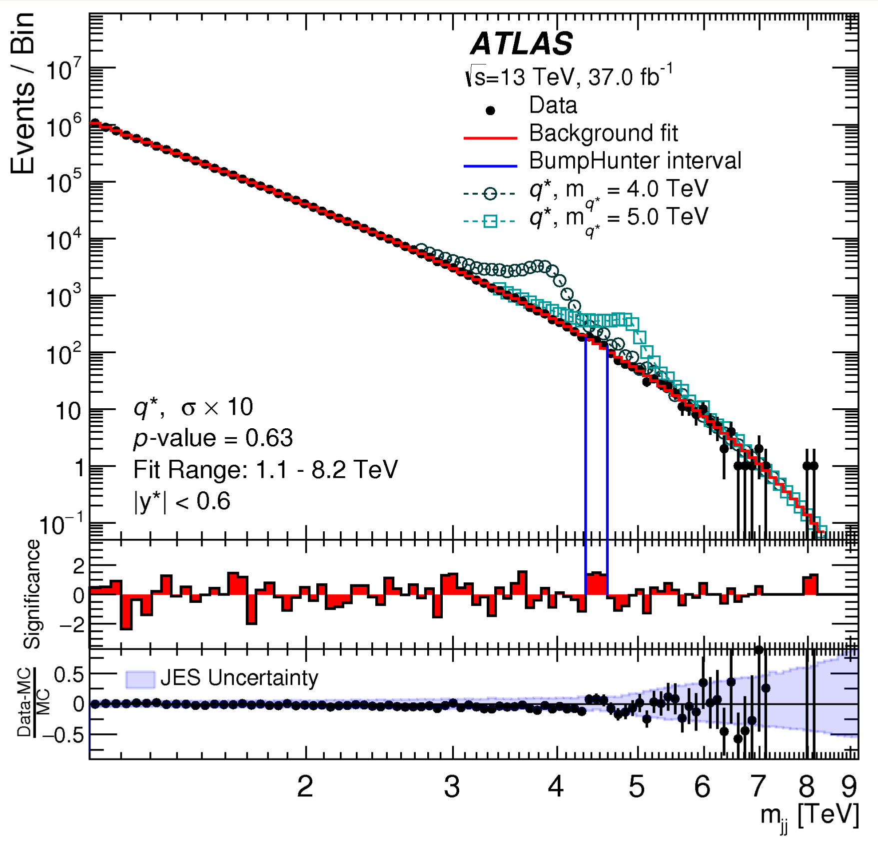
ATLAS-CONF-2017-027

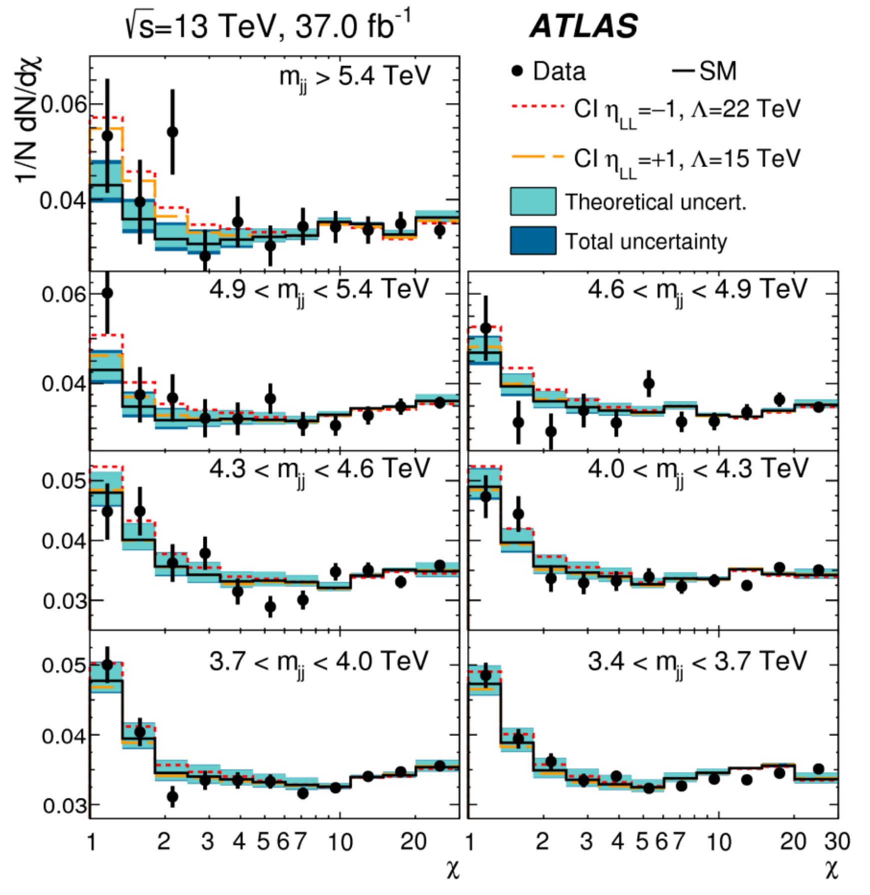
W': Lepton + ETmiss

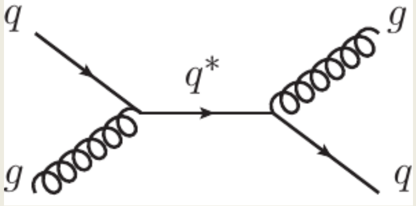


arXiv:1706.04786[hep-exp] subm. to EPJC

Searching for deviations from QCD
(Excited quarks, Black Holes, Compositeness…)





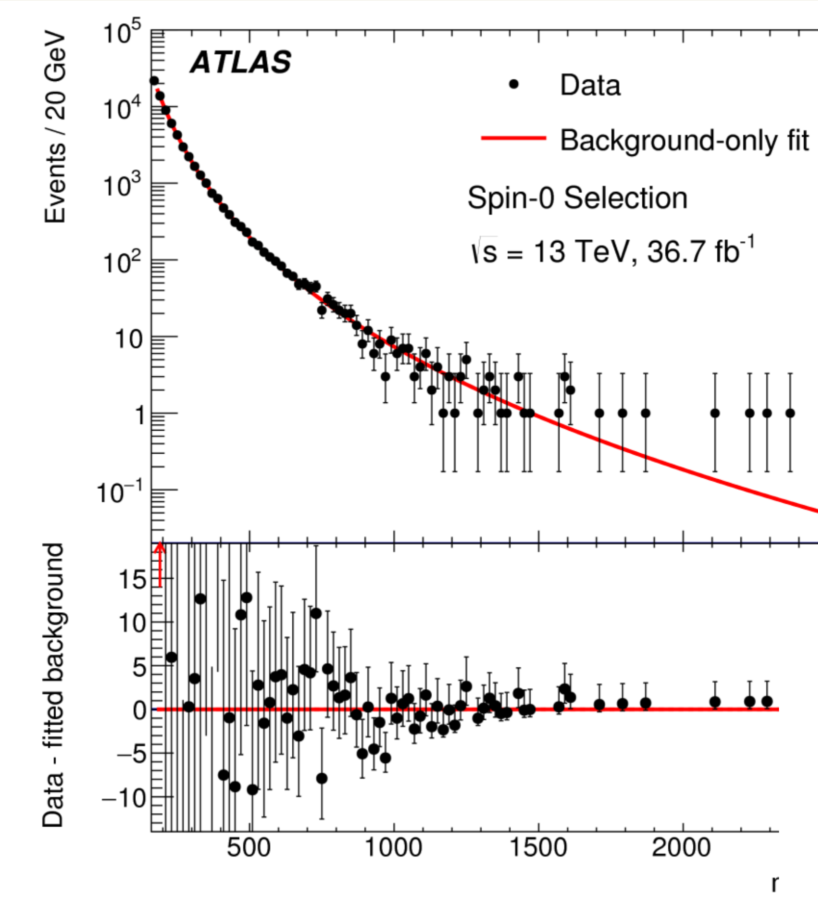


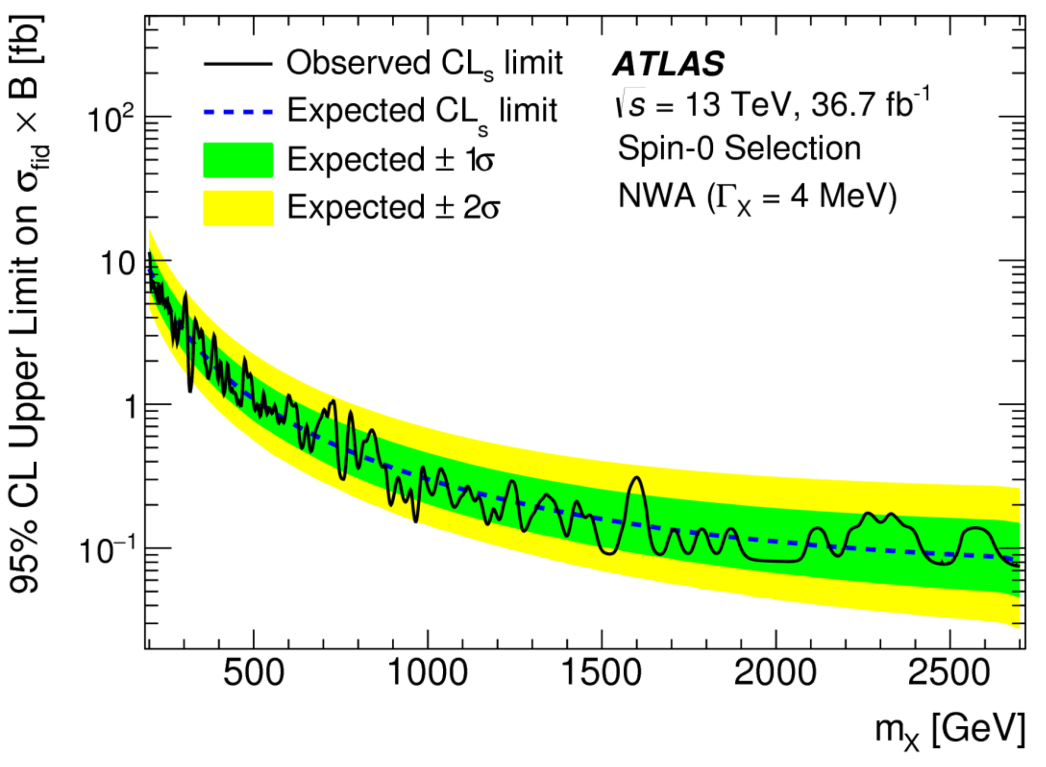
At 95% CL:
m(q*) > 6.0 TeV
Λ > 13 / 21 TeV

$$\chi = \exp(|y_1 - y_2|) = \frac{1 + \cos\vartheta^*}{1 - \cos\vartheta^*}$$

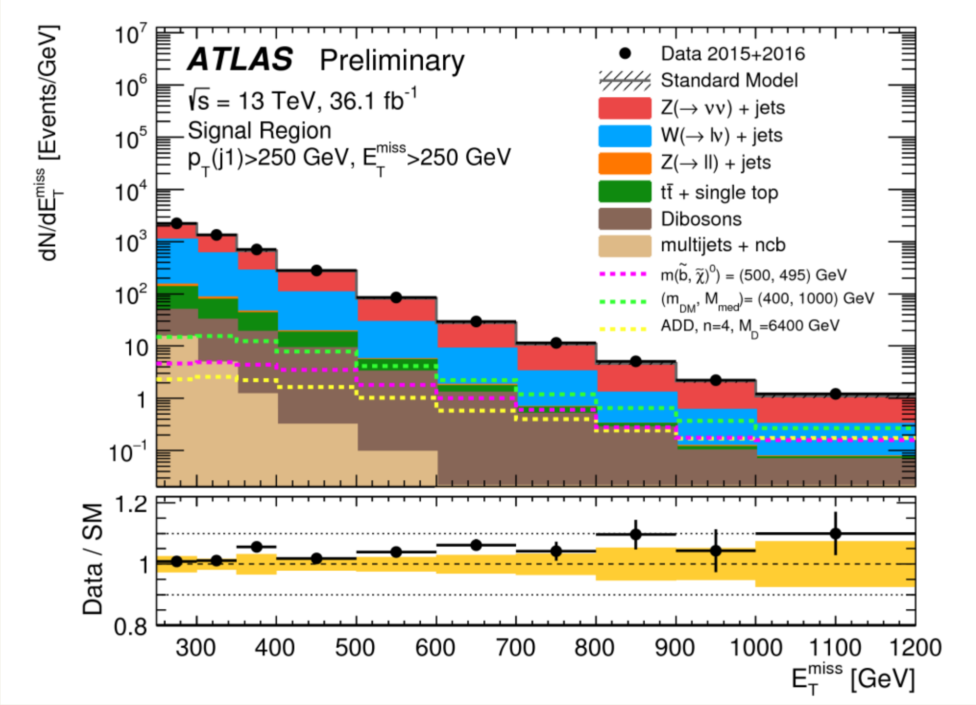
arXiv: 1703.09127 submitted to Phys. Rev. D (2017)

High mass di-photon resonance search





arXiv: 1707.04147[hep-exp]
subm. to Phys. Lett. B (2017)

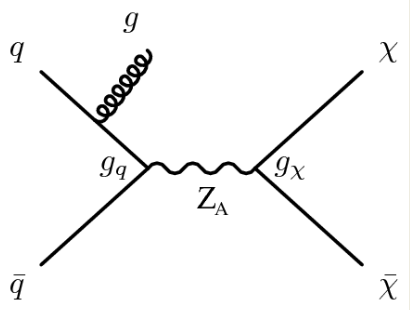


Example of a Dark Matter search at LHC

Complementary to direct DM searches

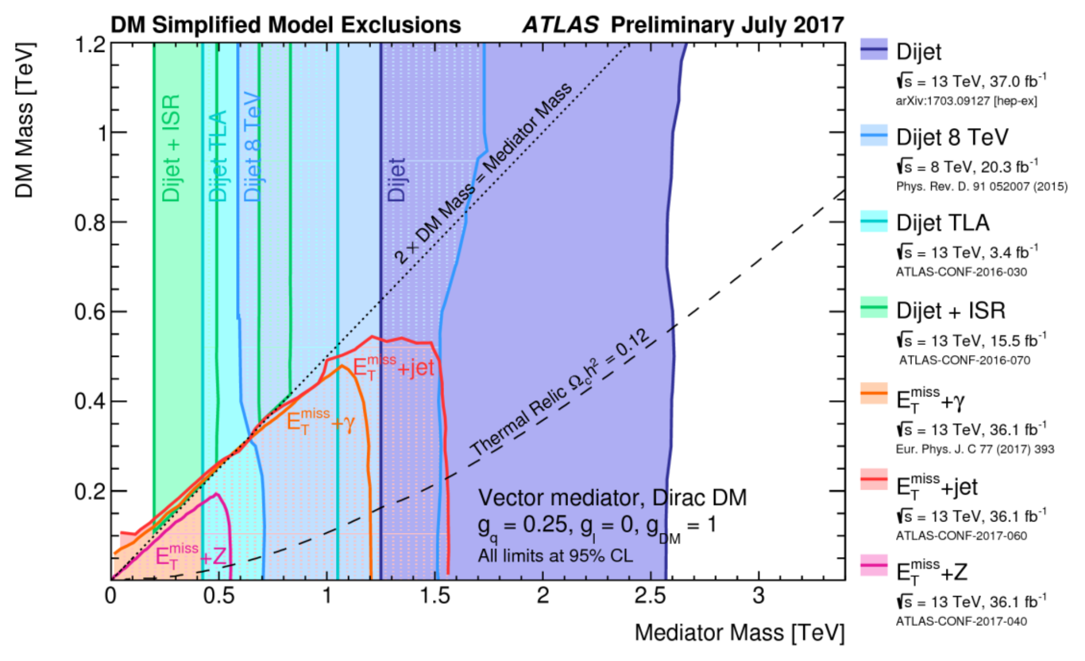
Rich phenomenology

Model-dependent limits, here shown in the $m_{mediator}$ vs m_{DM} plane



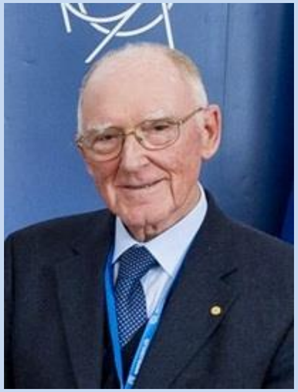
Monojet plus DM (ETmiss)

ATLAS-CONF-2017-060



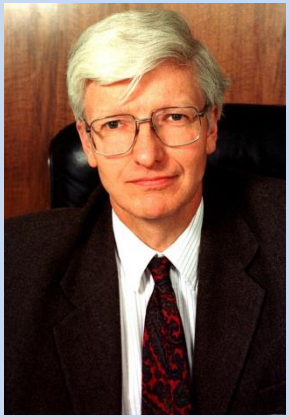
It was a very long road from first dreams to the fantastic scientific instrument we have now with the LHC and its experiments, and many visionaries deserve credit for it…

Herwig Schopper, CERN DG 1981 - 1988



Carlo Rubbia, CERN DG 1989 - 1993
Giorgio Brianti, first LHC Project Leader, until 1993

Sir Chris Llewellyn Smith, CERN DG 1994 - 1998
Lorenzo Foa († 2014), Research Director 1994 - 1998
Lyn Evans, LHC Project Leader 1994 - 2008

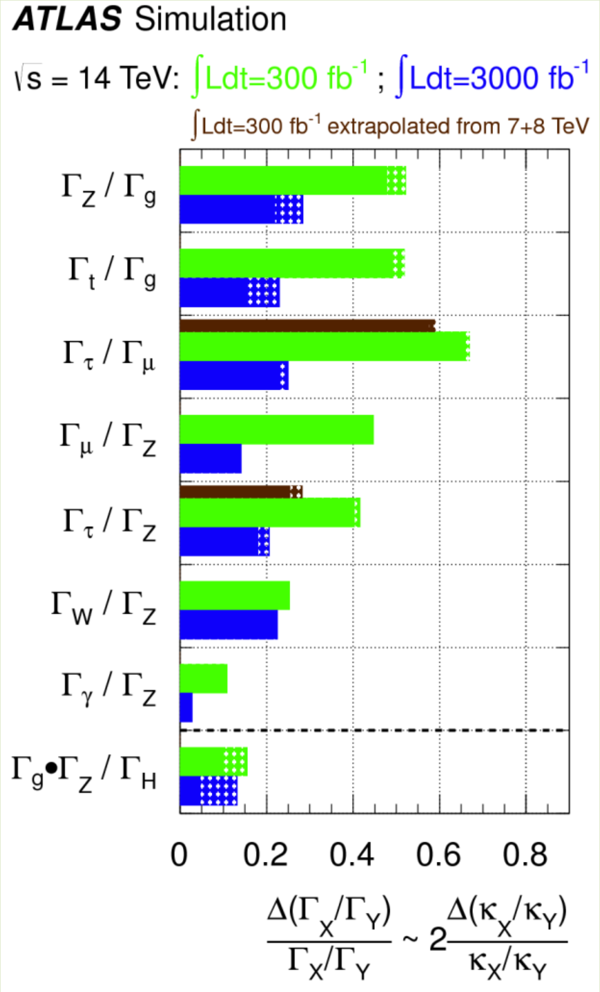


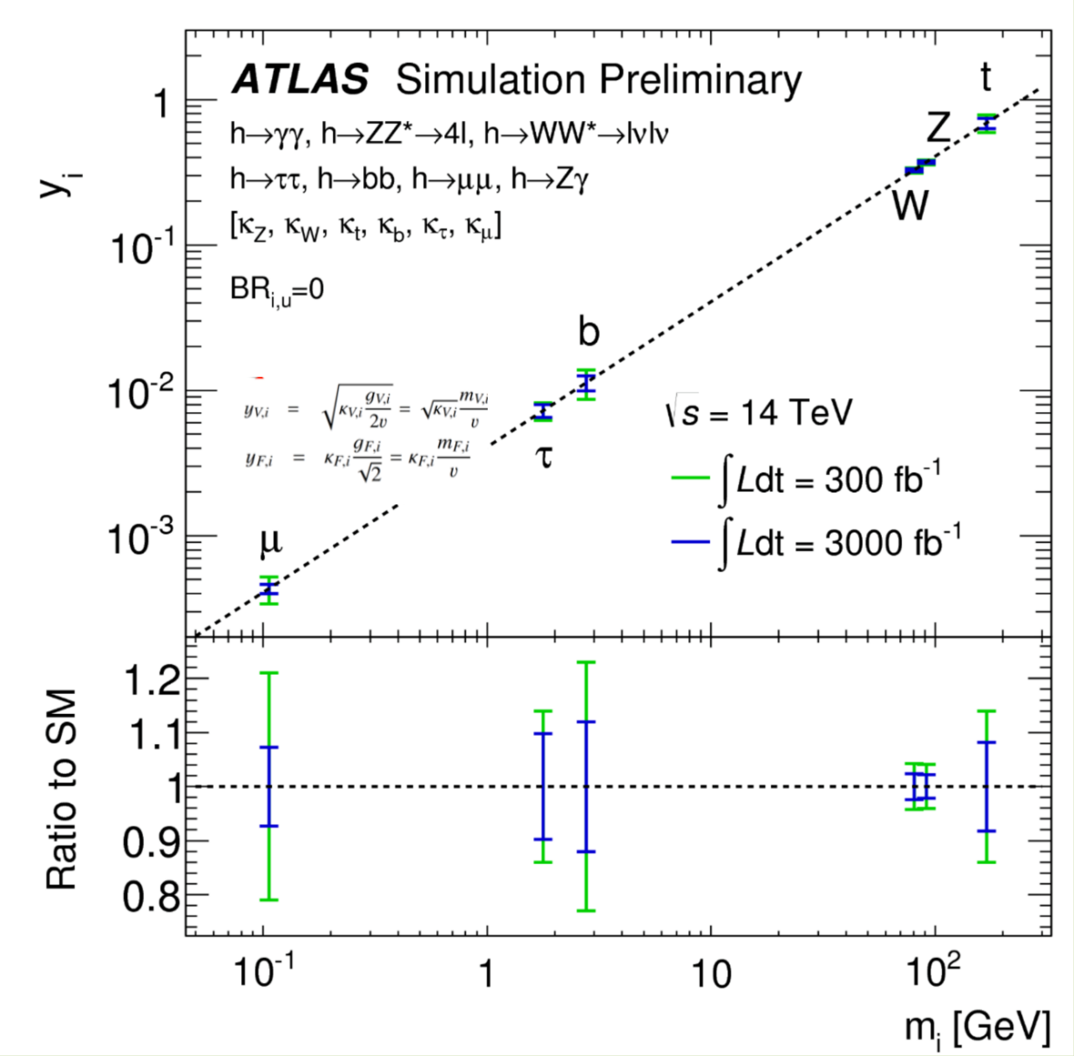
Luciano Maiani, CERN DG 1999 - 2003
Roger Cashmore, Research Director 1999 – 2003

Robert Aymar, CERN DG 2004 - 2008
Jos Engelen, Research Director 2004 - 2008

Rolf Dieter Heuer, CERN DG 2009 - 2015
Sergio Bertolucci, Research Director 2009 - 2015
Steve Myers, Director of Accelerators and Technology 2009 – 2013
(here shown together with the ATLAS and CMS Spokespersons Fabiola Gianotti and Joe Incandela, on the famous 4th July 2012)

Outlook for HL-LHC on the BEH physics



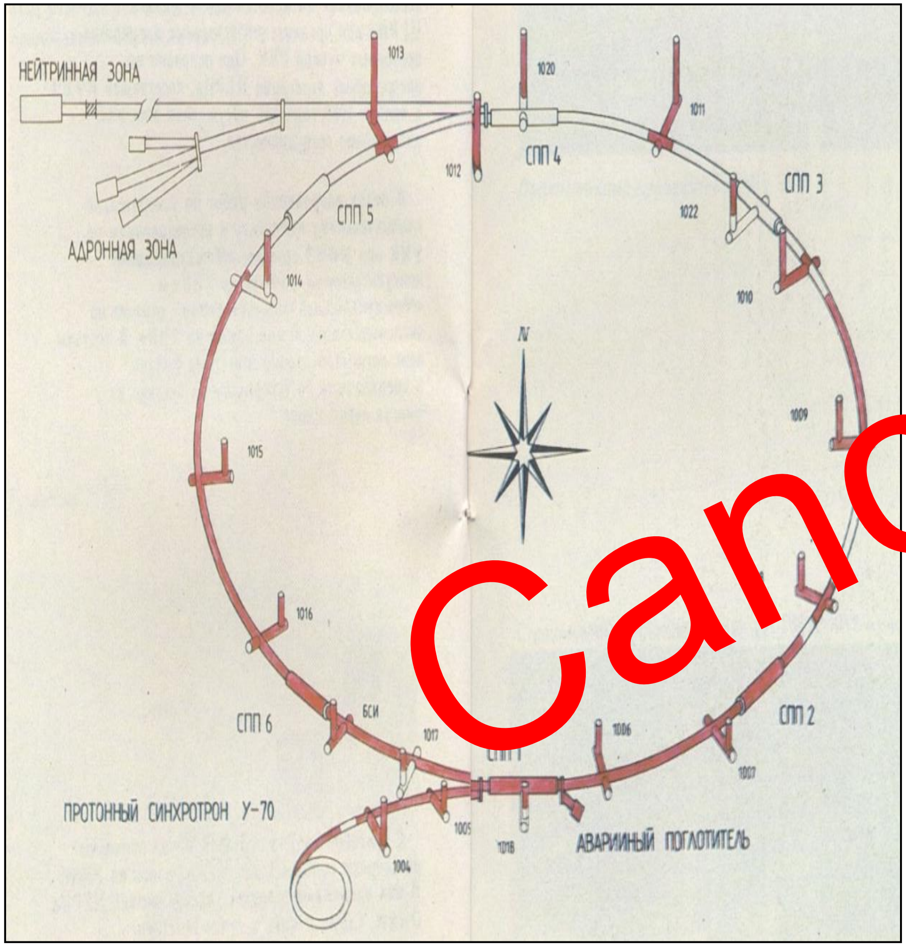


$$y_{V,i} = \sqrt{\kappa_{V,i}\frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v}$$

$$y_{F,i} = \kappa_{F,i}\frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i}\frac{m_{F,i}}{v}$$

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

Attempts to Reach Higher Energies: 90’s



Cancelled

3x3 TeV, UNK, USSR

20x20 TeV, SSC, USA