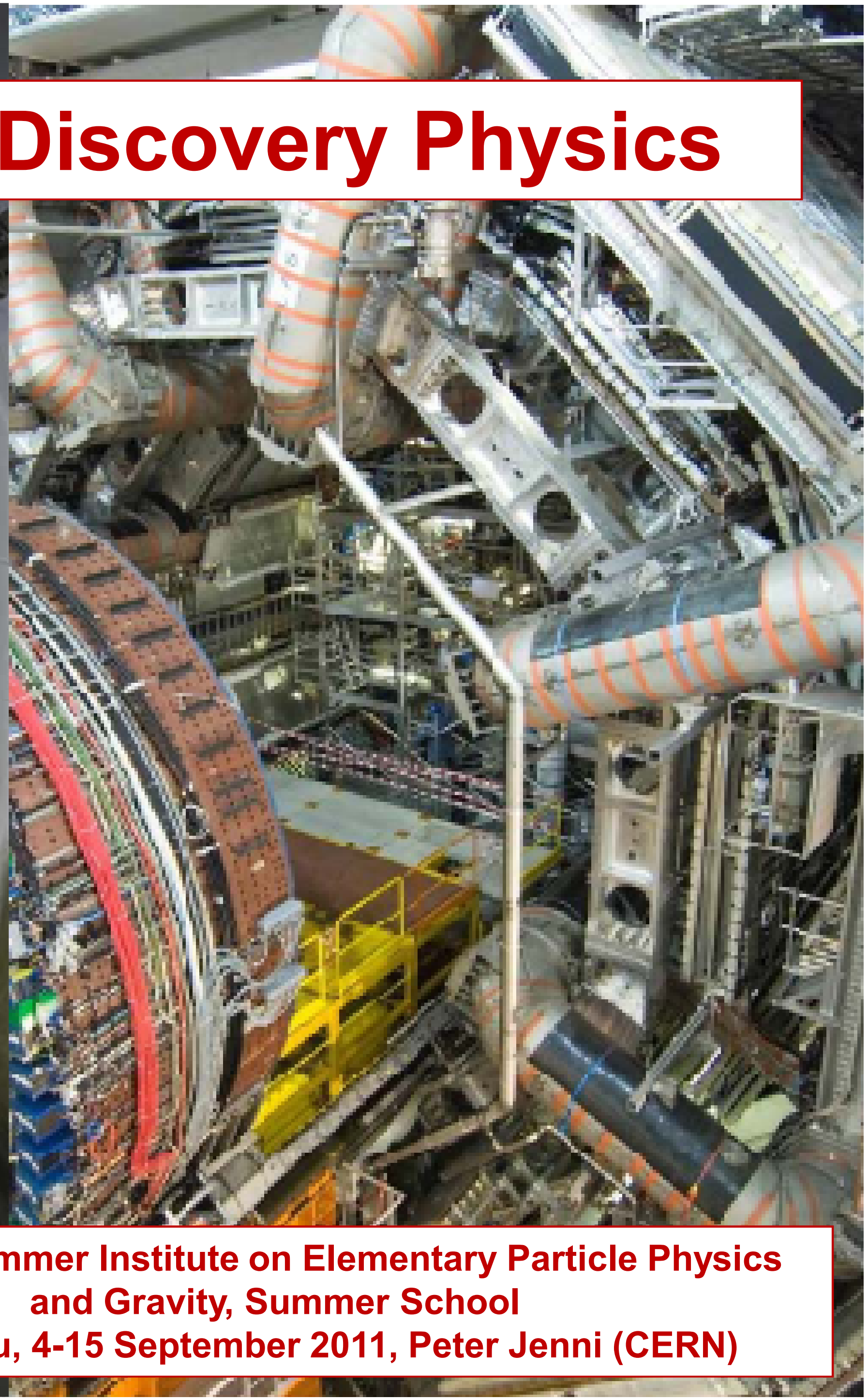
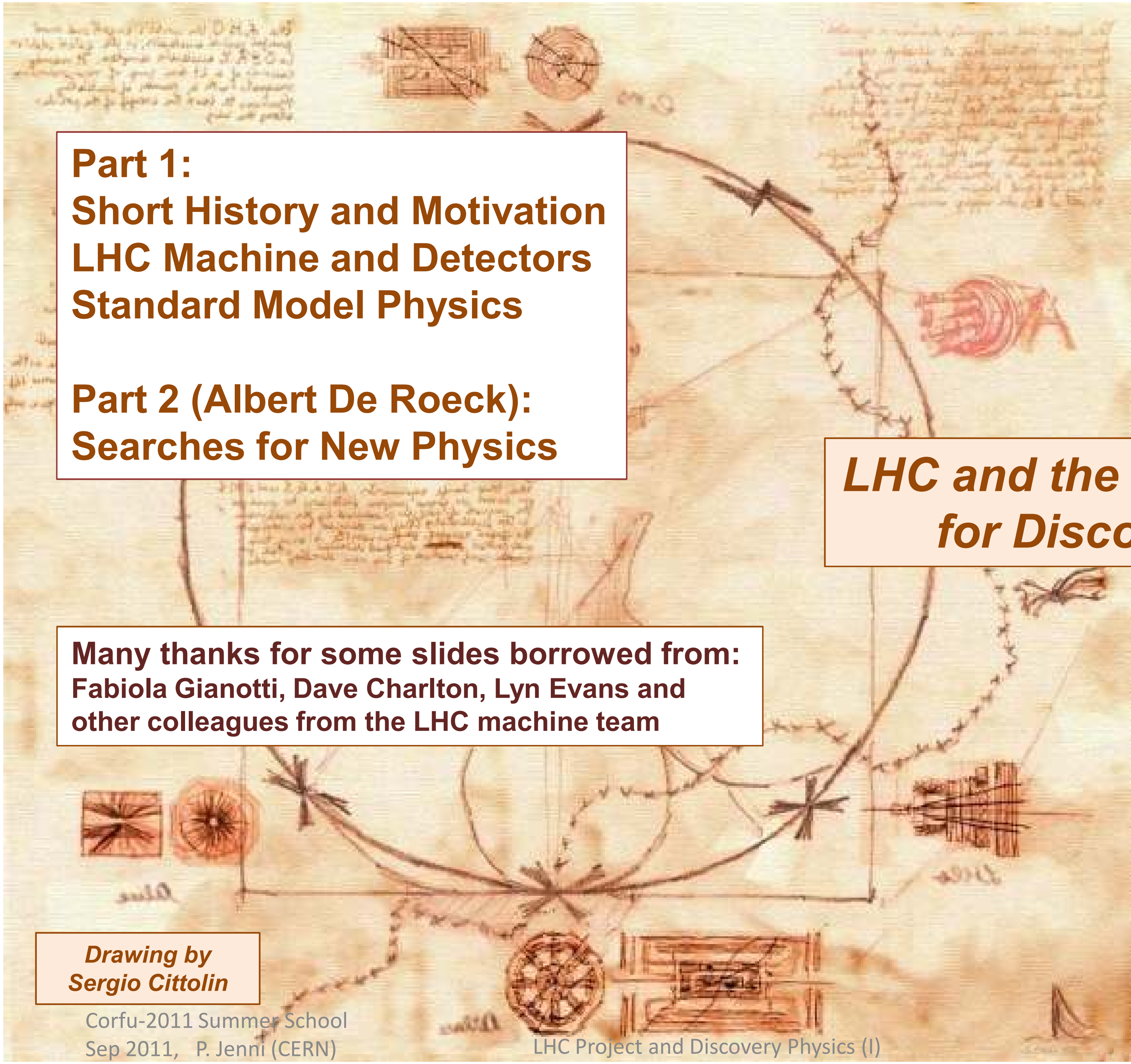
The LHC Project and Discovery Physics



11th Corfu Summer Institute on Elementary Particle Physics and Gravity, Summer School
EISA, Corfu, 4-15 September 2011, Peter Jenni (CERN)



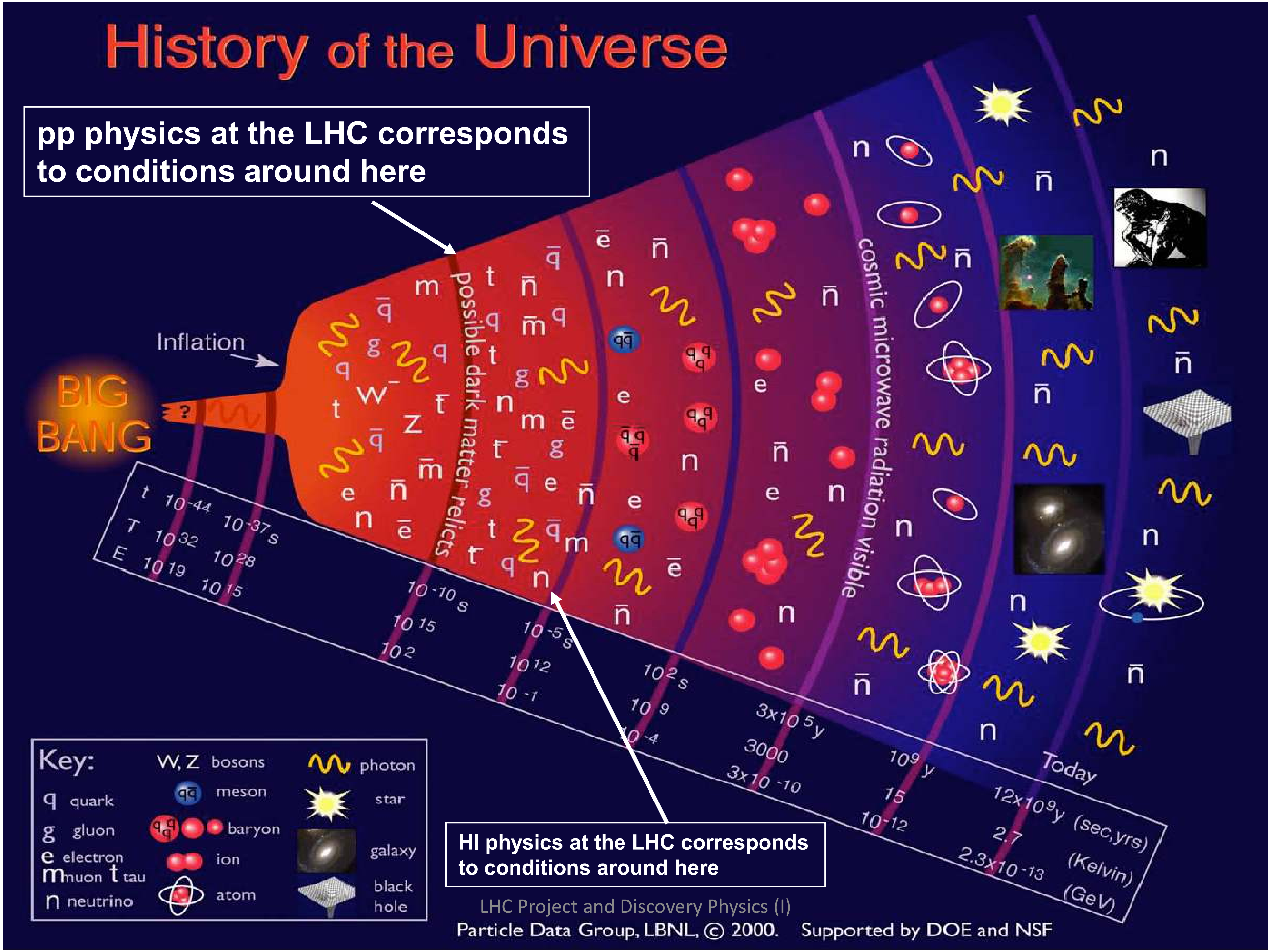
Part 1:
Short History and Motivation
LHC Machine and Detectors
Standard Model Physics

Part 2 (Albert De Roeck):
Searches for New Physics

LHC and the Road Map for Discoveries

Many thanks for some slides borrowed from:
Fabiola Gianotti, Dave Charlton, Lyn Evans and other colleagues from the LHC machine team

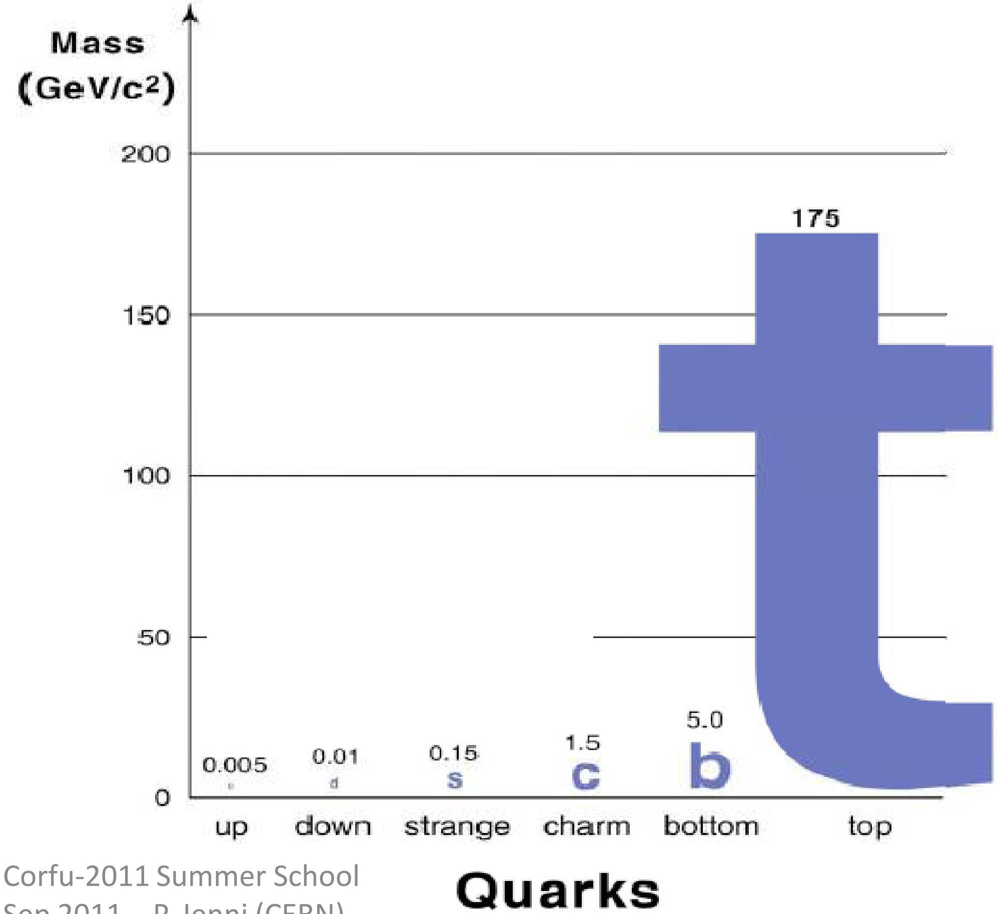
Drawing by Sergio Cittolin


History of the Universe
pp physics at the LHC corresponds to conditions around here
HI physics at the LHC corresponds to conditions around here
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 10 2 s 3x10 5 y 10 9 y Today 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10 -12 2.3x10 -13 (GeV)
Key:
W, Z bosons
q quark
g gluon
e electron
m muon t tau
n neutrino
meson
baryon
ion
atom
photon
star
galaxy
black hole
LHC Project and Discovery Physics (I)
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

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

The mass mystery could be solved with the 'Higgs mechanism' which predicts the existence of a new elementary particle, the 'Higgs' particle (theory 1964, P. Higgs, R. Brout and F. Englert)

Peter Higgs



The Higgs (H) particle has been searched for since decades at accelerators, but not yet found…

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

Francois Englert

Supersymmetry (SUSY)

(Julius Wess and Bruno Zumino, 1974)

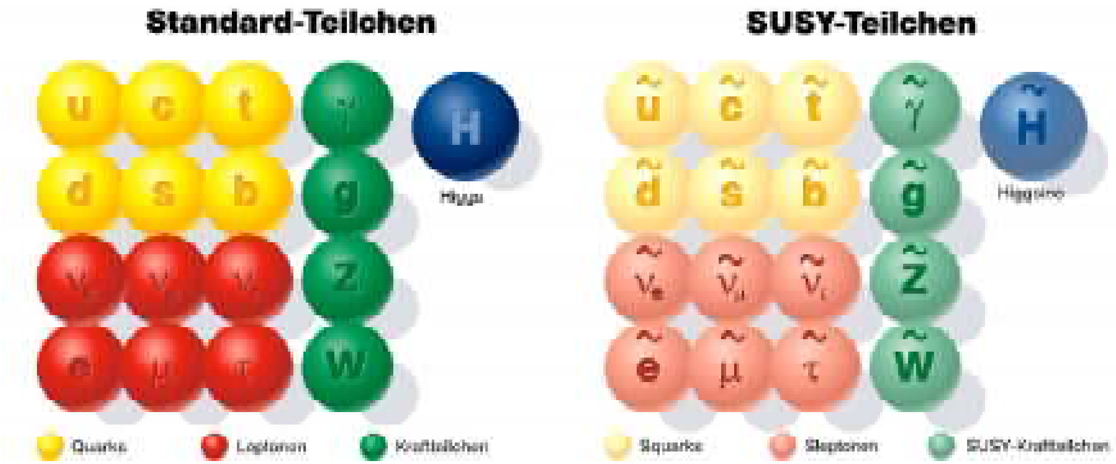
Establishes a symmetry between fermions (matter) and bosons (forces):

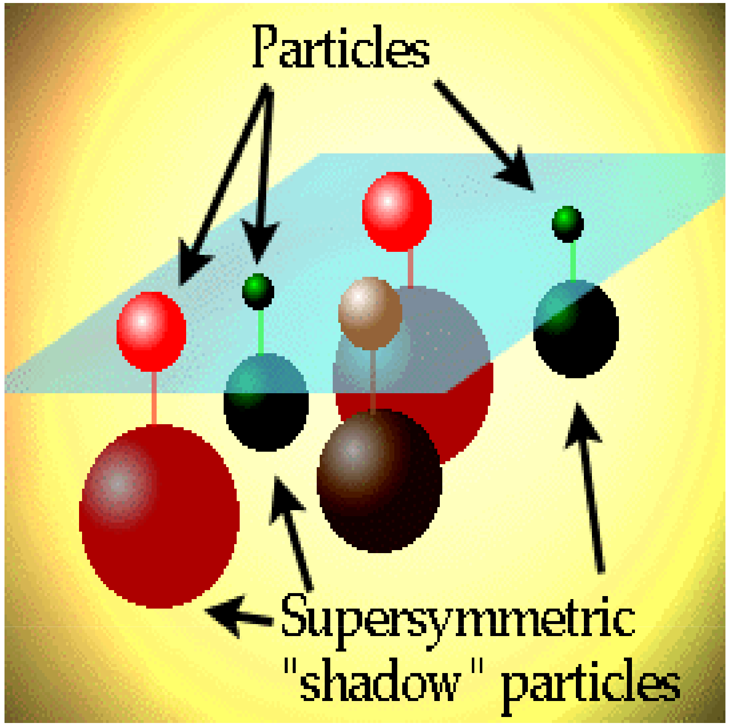
- Each particle p with spin s has a SUSY partner $\tilde{p}$ with spin s -1/2

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

g (s=1) → $\tilde{g}$ (s=1/2) gluino

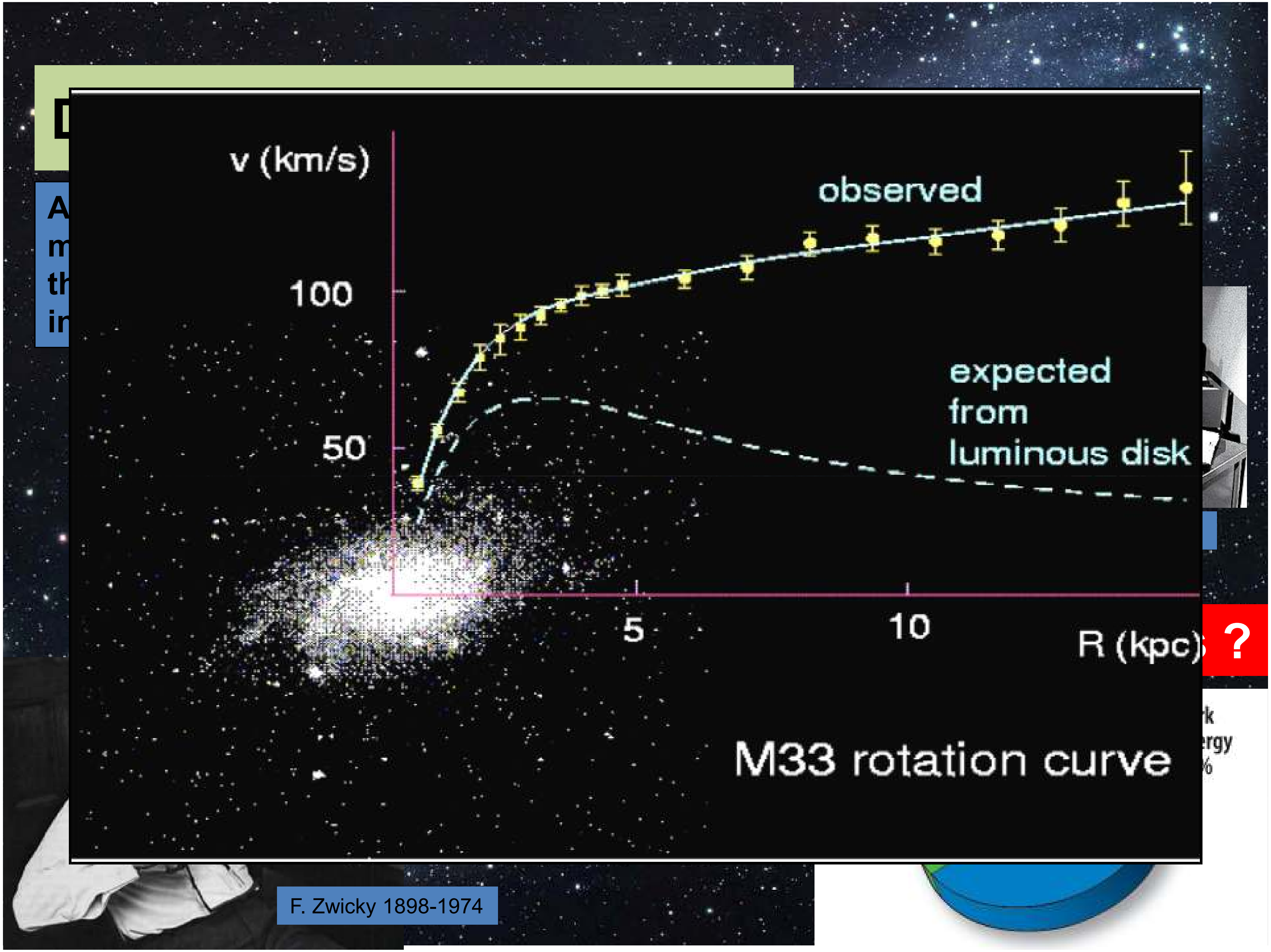
Our known world **Maybe a new world?**



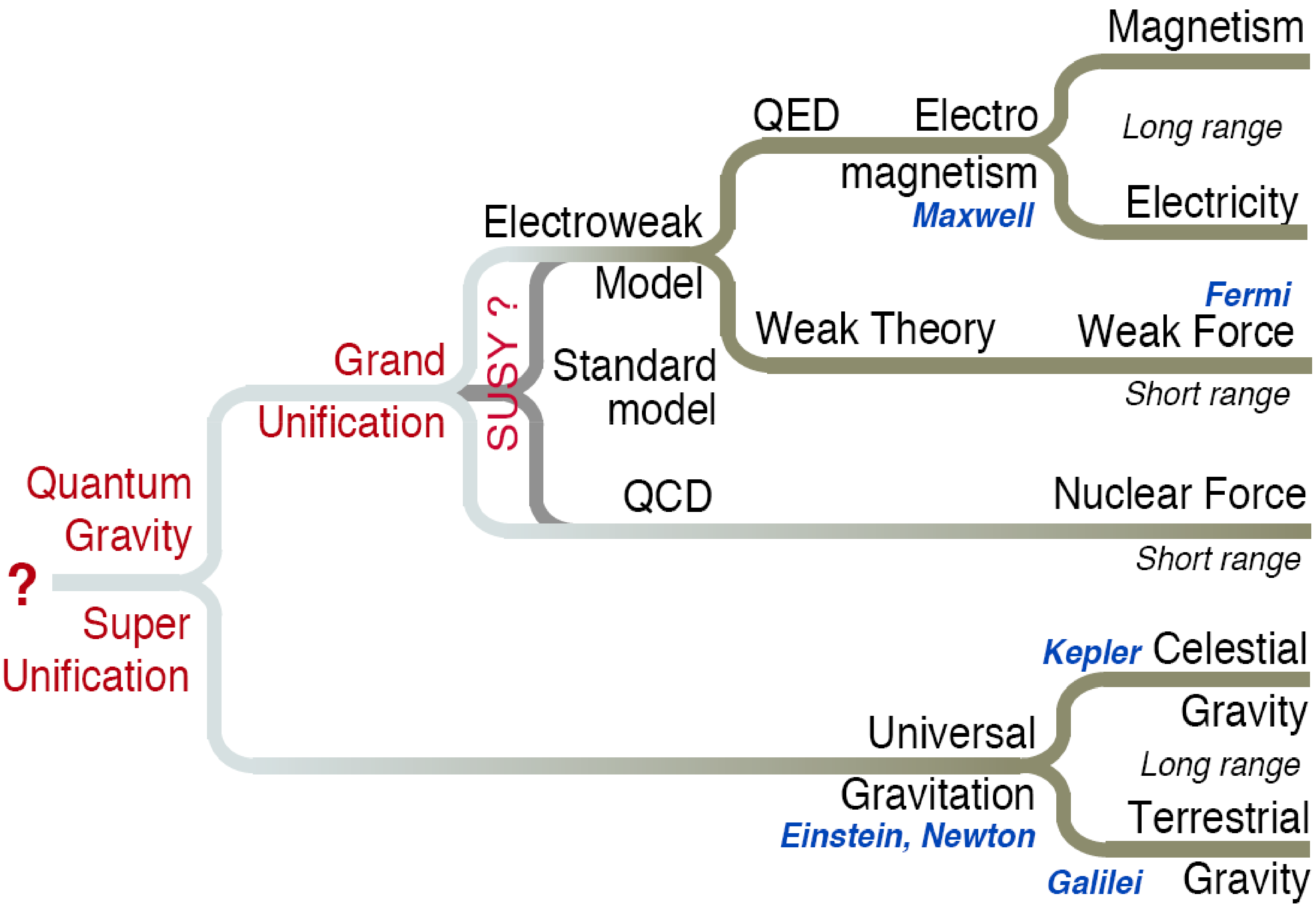


Motivation:

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


v (km/s)
100
50
5
10
R (kpc)
observed
expected
from
luminous disk
M33 rotation curve
?
F. Zwicky 1898-1974

Unification of Forces



Most exciting: searches for physics Beyond the Standard Model (BSM) (see Albert De Roeck's lecture)

How the LHC came to be …

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

Some early key dates

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

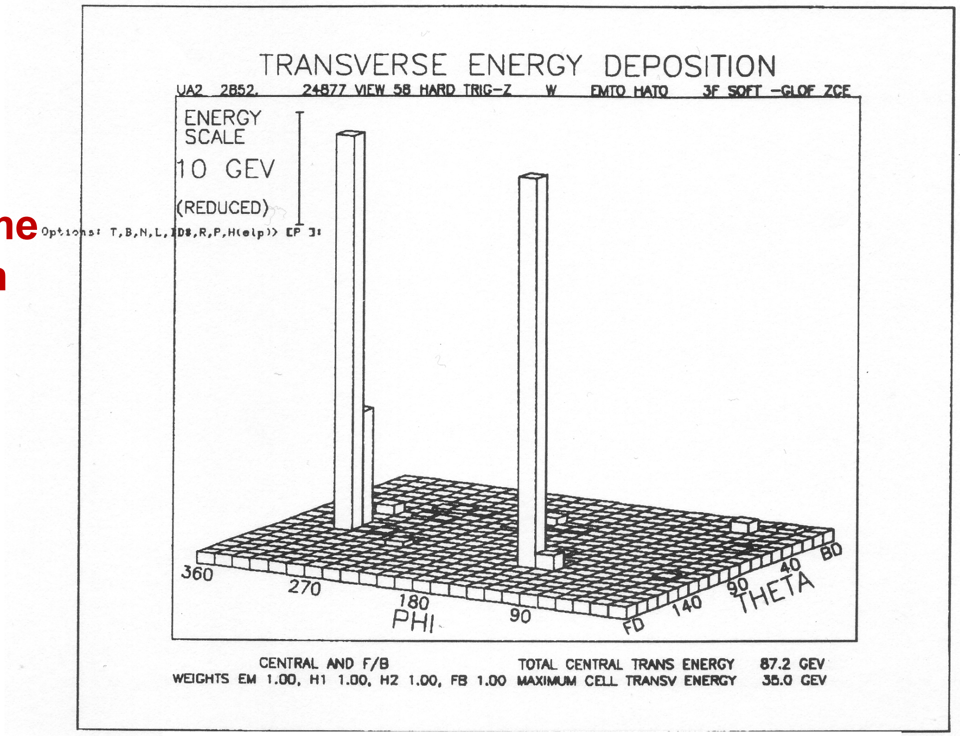
1981 **LEP was approved with a large and long (27 km) tunnel**

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

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

This also triggered a famous quote from a 1983 New York Times editorial:

'Europe: 3 - US Not Even Z-Zero'



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

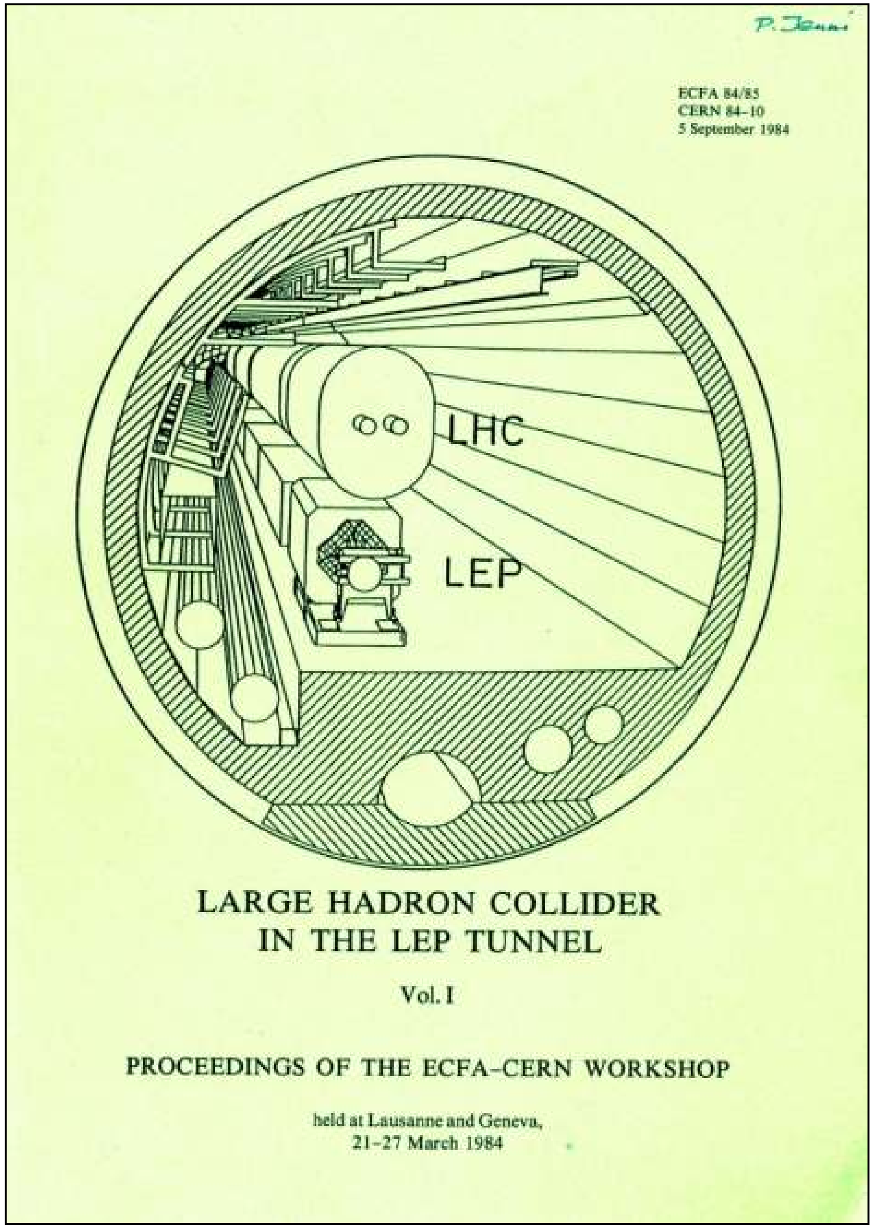
1984 For the community it all started in a way with the 1st CERN – ECFA Workshop Lausanne on the feasibility of a hadron collider in the future LEP tunnel

1987 La Thuile LHC Workshop

Many LHC colleagues were already involved in this, a clear evolution started for detectors away from a 4μ iron-ball experiment (C Rubbia) towards multi-purpose detectors…)

1989 ECFA Study Week in Barcelona for LHC instrumentation

At this conference a few decided to start setting up a structure for an LHC proto-Collaboration….


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

1991 December CERN Council:
‘LHC is the right machine for advance of the subject and the future of CERN’
(thanks to the great push by DG C Rubbia)

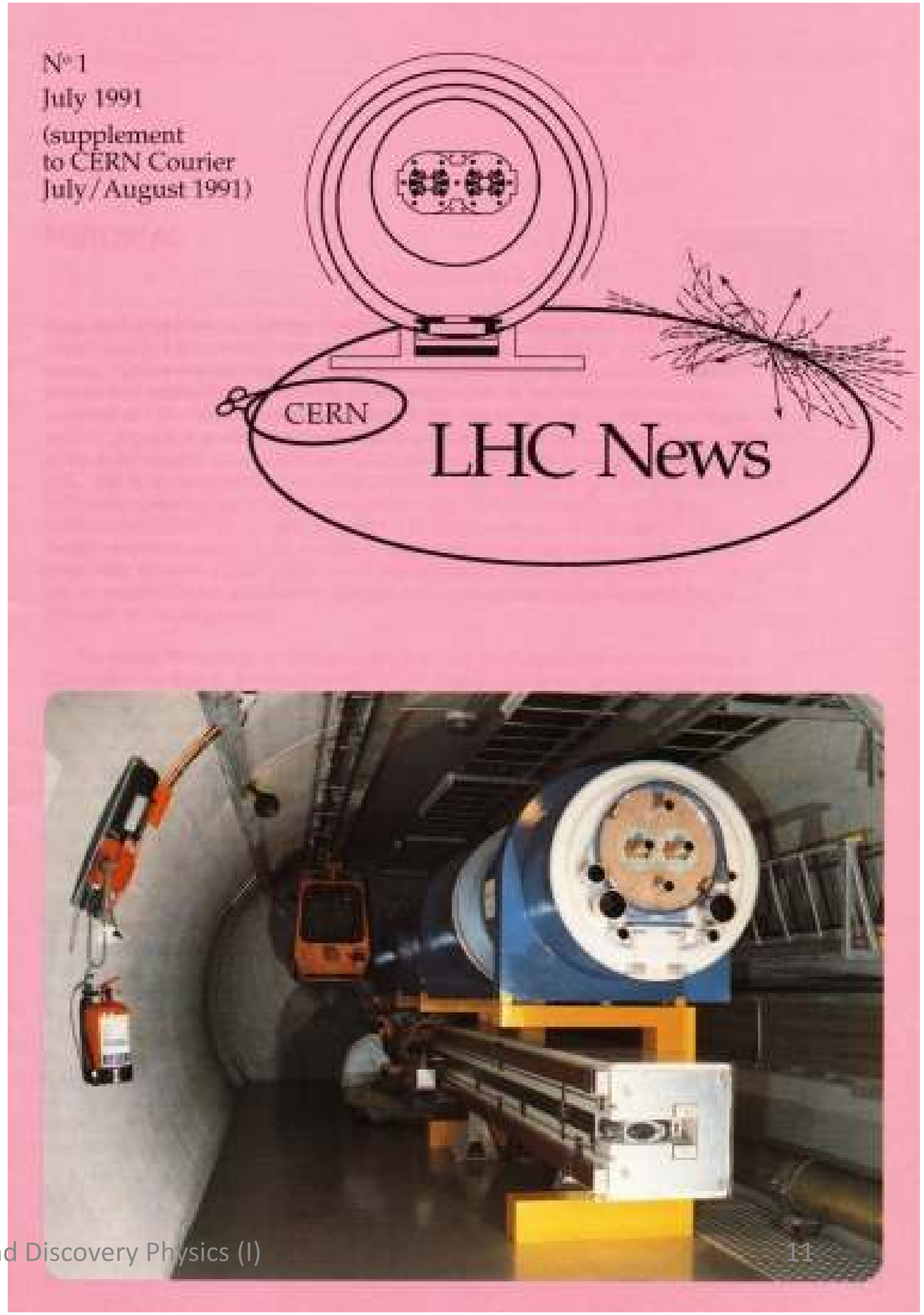
1993 December proposal of LHC with commissioning in 2002

1994 June Council:

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

16 December 1994 Council:

(Two-stage) construction of LHC was approved



The two-stage approval 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 coming years, including also the experiments

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

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

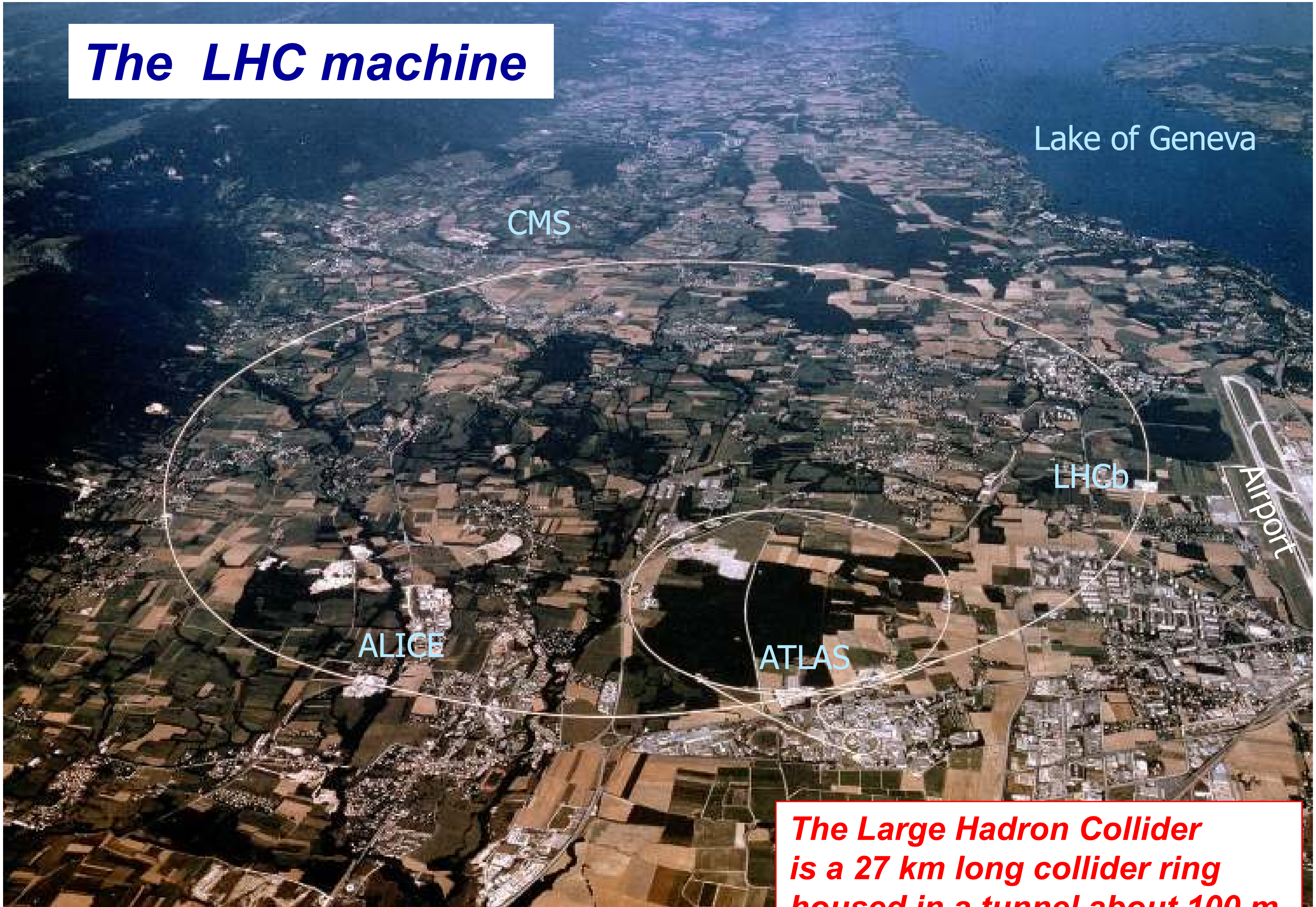
1997

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

Delivery of the last dipole for the LHC injection lines from Russia (15th June 2001)

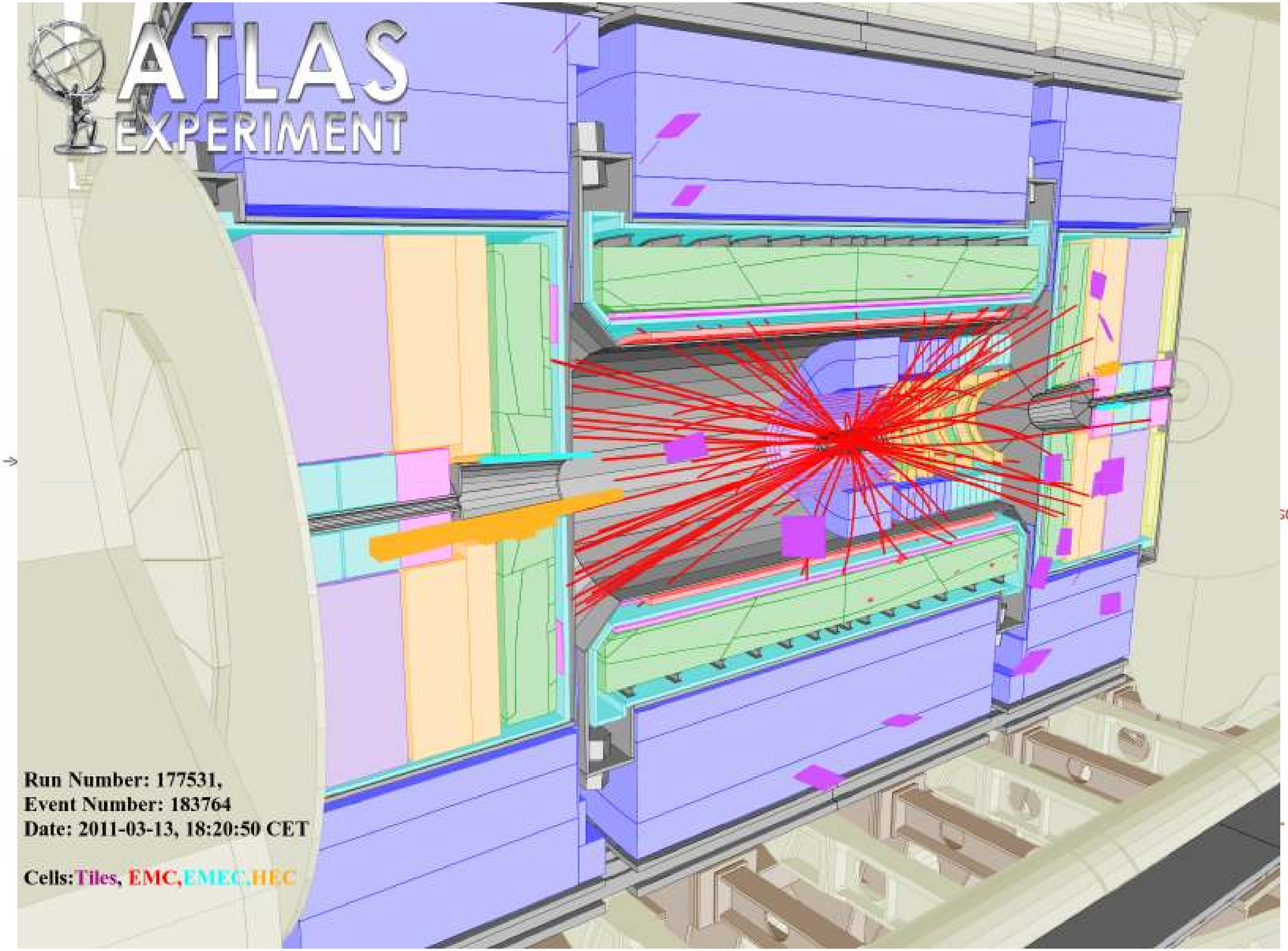
The first picture on the Web in 1992 !

The LHC machine



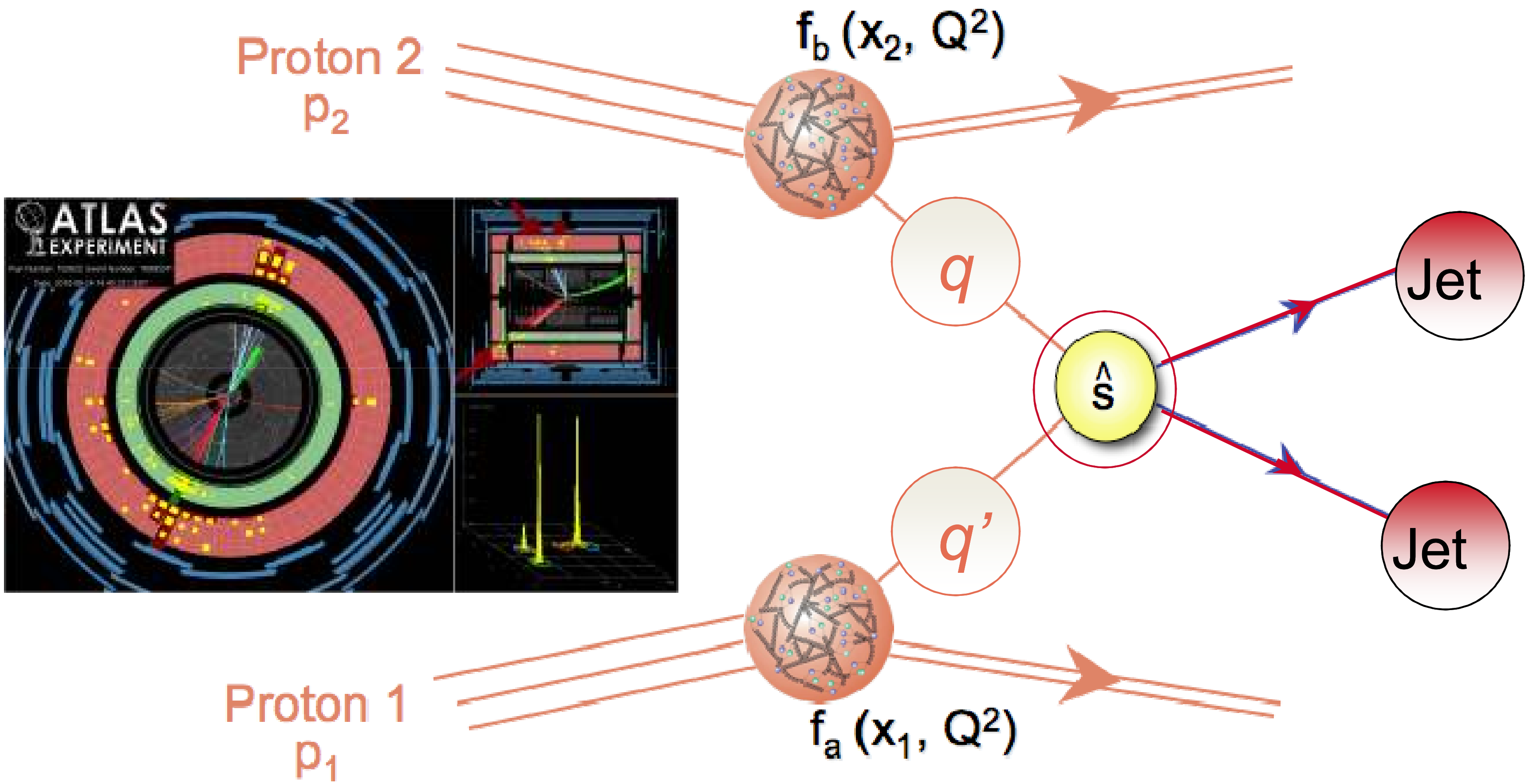
The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

CERN's particle accelerator chain



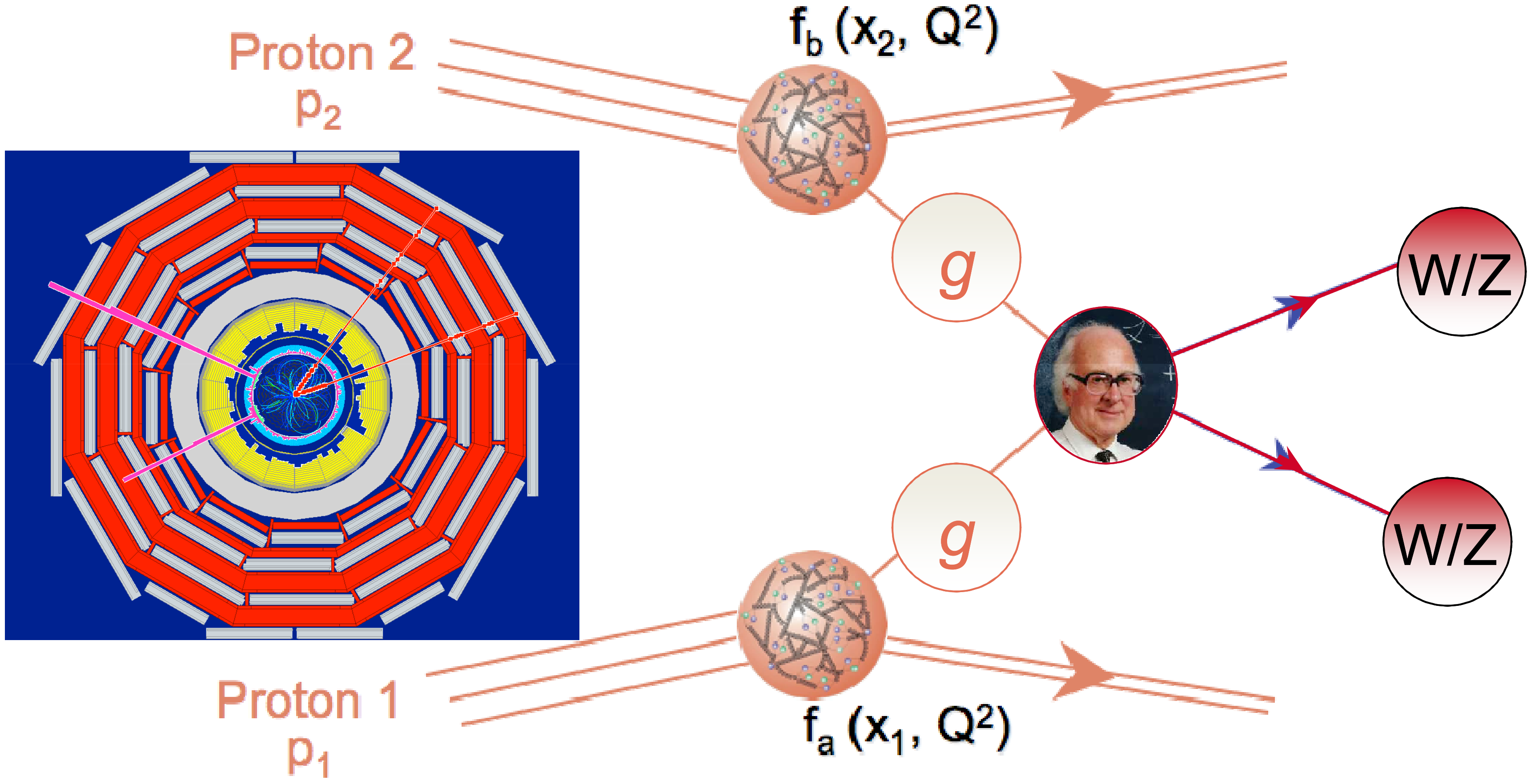
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

Basic processes at LHC



$$d\sigma(p_1p_2 \to c\;d) = \int_0^1 dx_1 dx_2 \sum_{a,b} (f_a\,(x_1,\,Q^2)\,f_b\,(x_2,\,Q^2)\,d\hat{\sigma}^{ab\to cd})$$

What we are looking for…

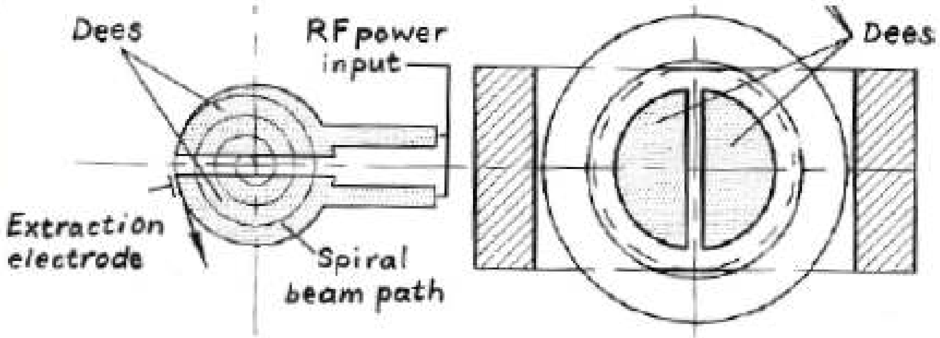


The first cyclotron and the Berkeley one

Ernest Lawrence
(1901 - 1958)

The first circular accelerator (Berkeley 1930)

184” 1946



A Particle Accelerator

New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the RF cavity, used to accelerate the particles has also to change.

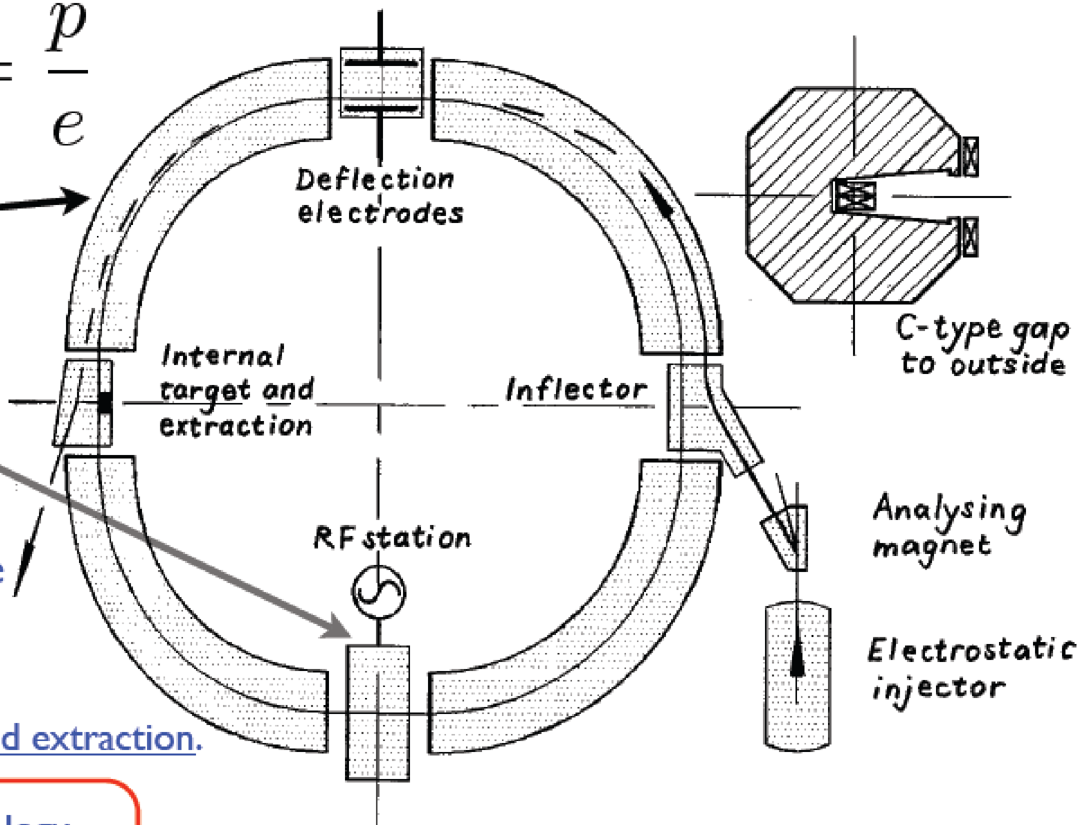
Particle rigidity: $B\rho = \dfrac{p}{e}$

B = B(t) magnetic field from the bending magnets

p = p(t) particle momentum varies by the RF cavity

e electric charge

ρ constant radius of curvature

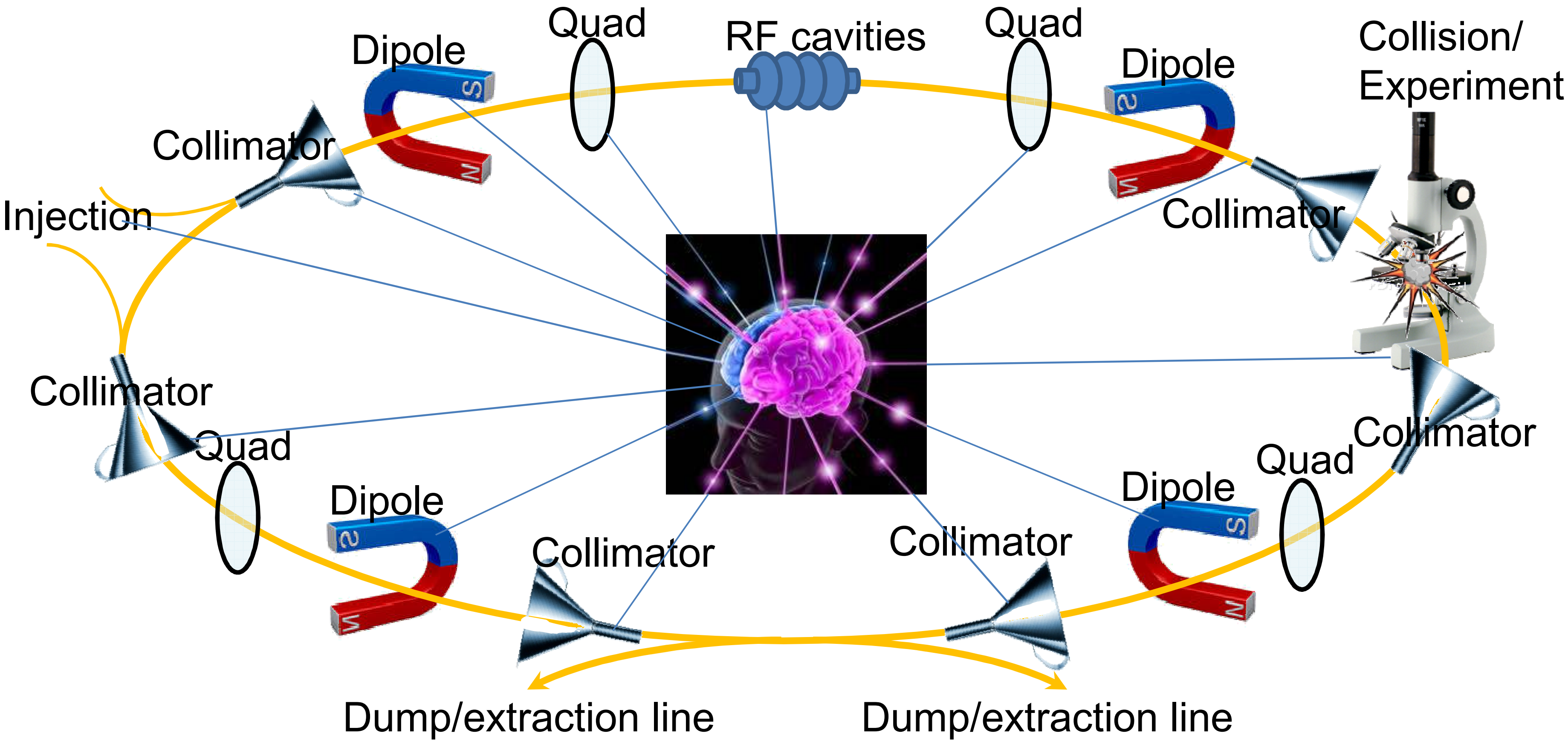


New magnetic elements for injection and extraction.

Bending strength limited by used technology to max ~ 1 T for room temperature conductors

Weak focusing machine: no quadrupoles yet
Strong focusing machine, using quadrupoles, were proposed in 1952

Pedagogical sketch of a hadron machines

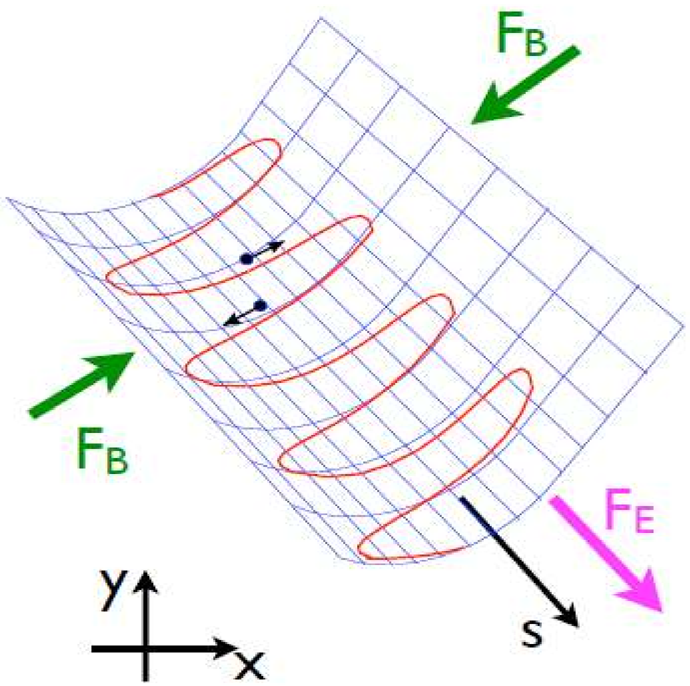


Goal: producing the highest number of collisions at the highest energy, in the safest way…

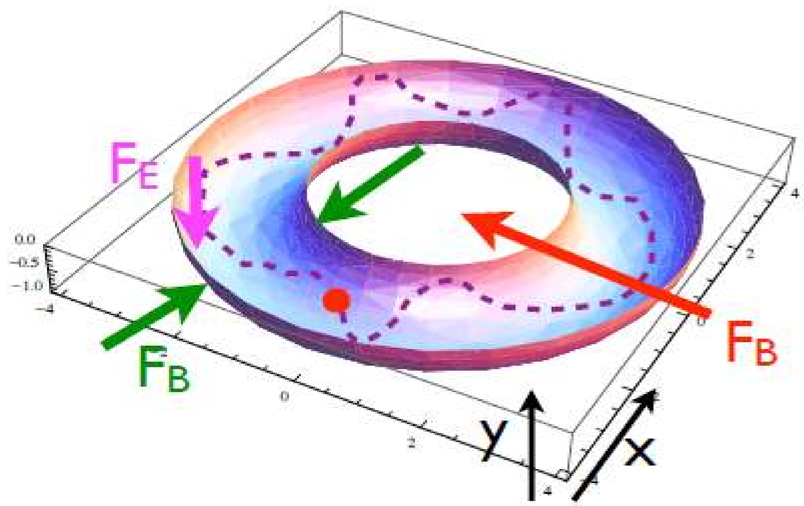
Forces acting on the beam particles

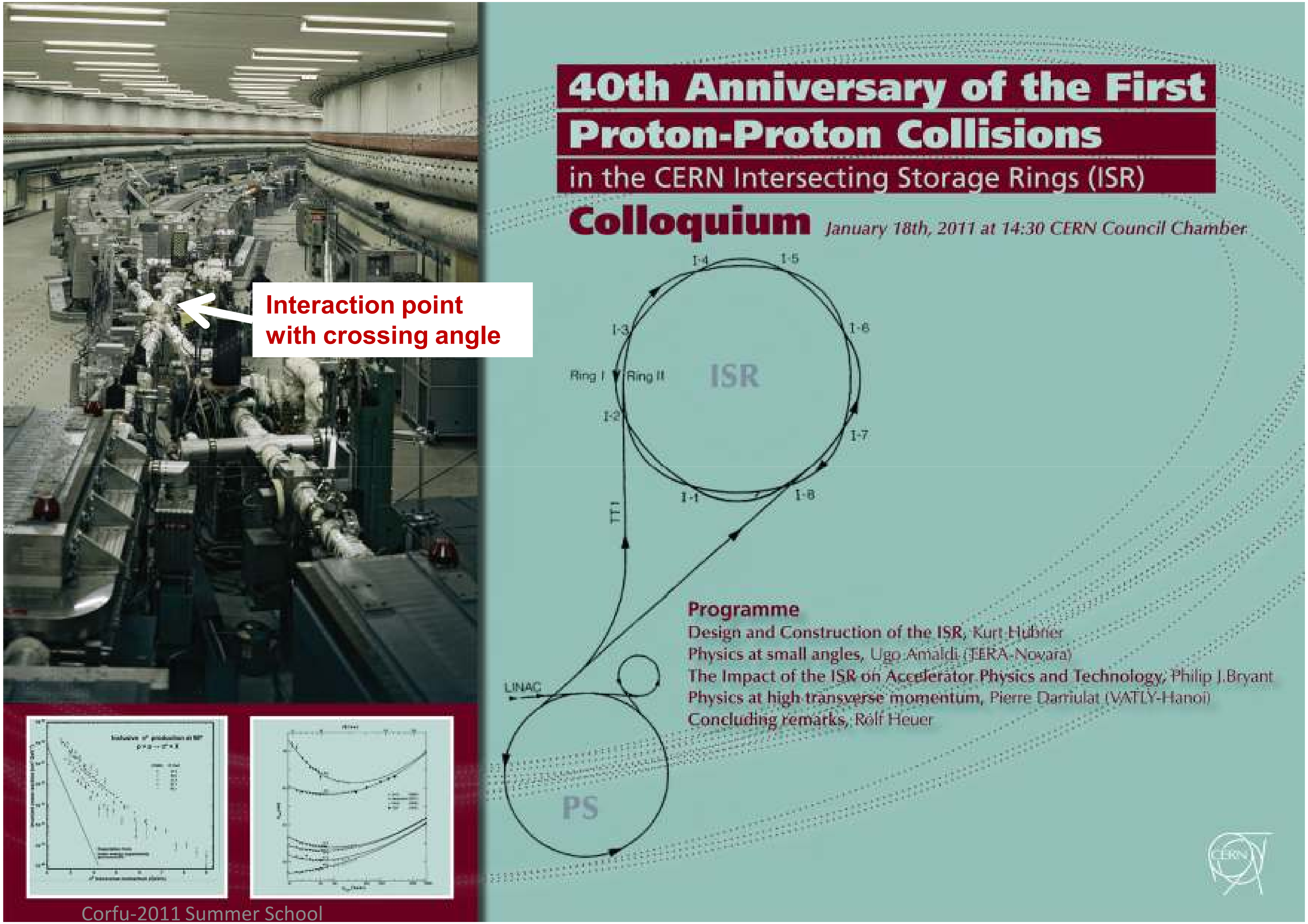
$$\overline{F(t)} = \underbrace{q\left(\overline{E(t)}\right.}_{F_E} + \underbrace{\overline{v(t)} \otimes \overline{B(t)}}_{F_B}\left.\right)$$

Linear Accelerator



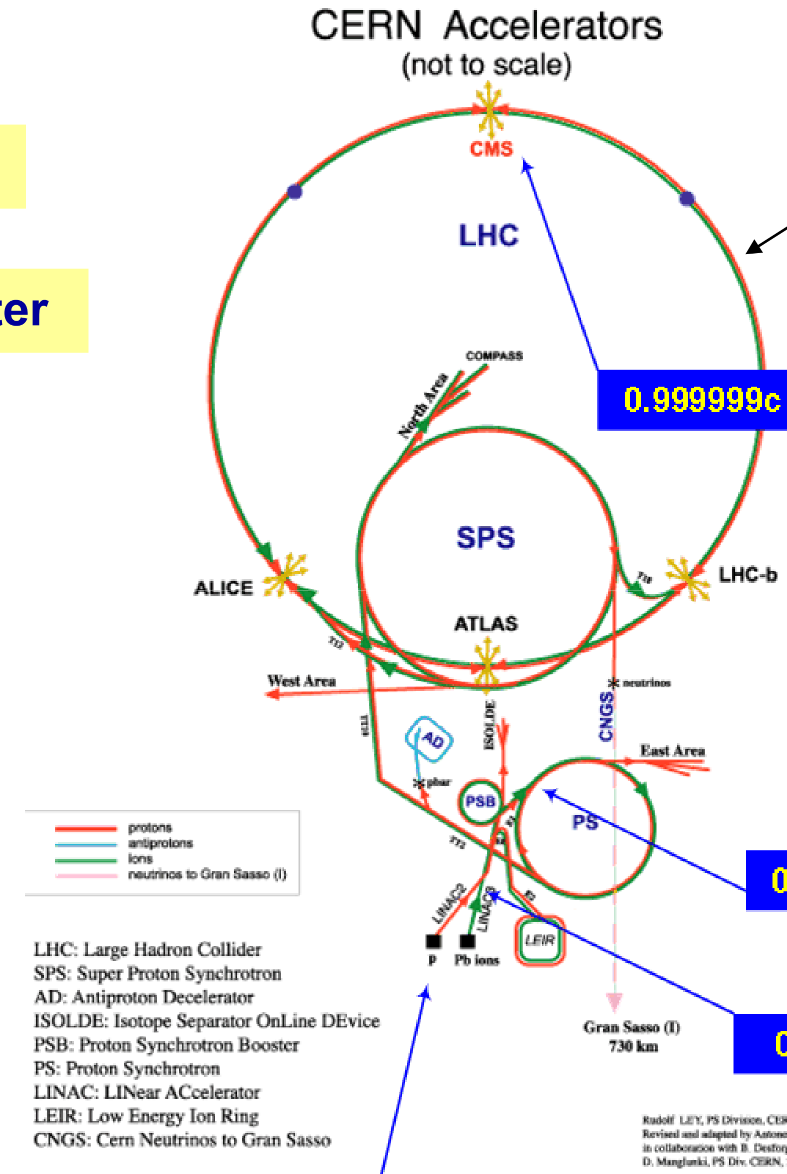
Circular Accelerator




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
ISR
Ring I
Ring II
I-1
I-2
I-3
I-4
I-5
I-6
I-7
I-8
TT1
LINAC
PS
Programme
Design and Construction of the ISR, Kurt Hubner
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

The full LHC accelerator complex

Linac
↓
Booster
↓
PS
↓
SPS
↓
LHC



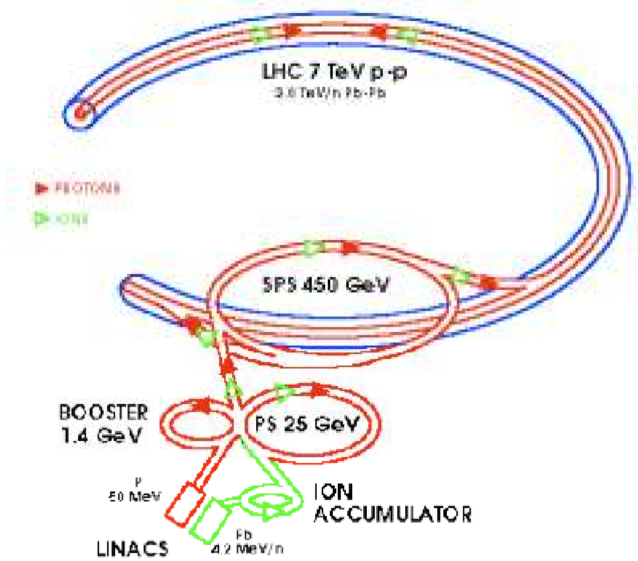
LHC ring is divided into 8 sectors

0.999999c by here

0.87c by here

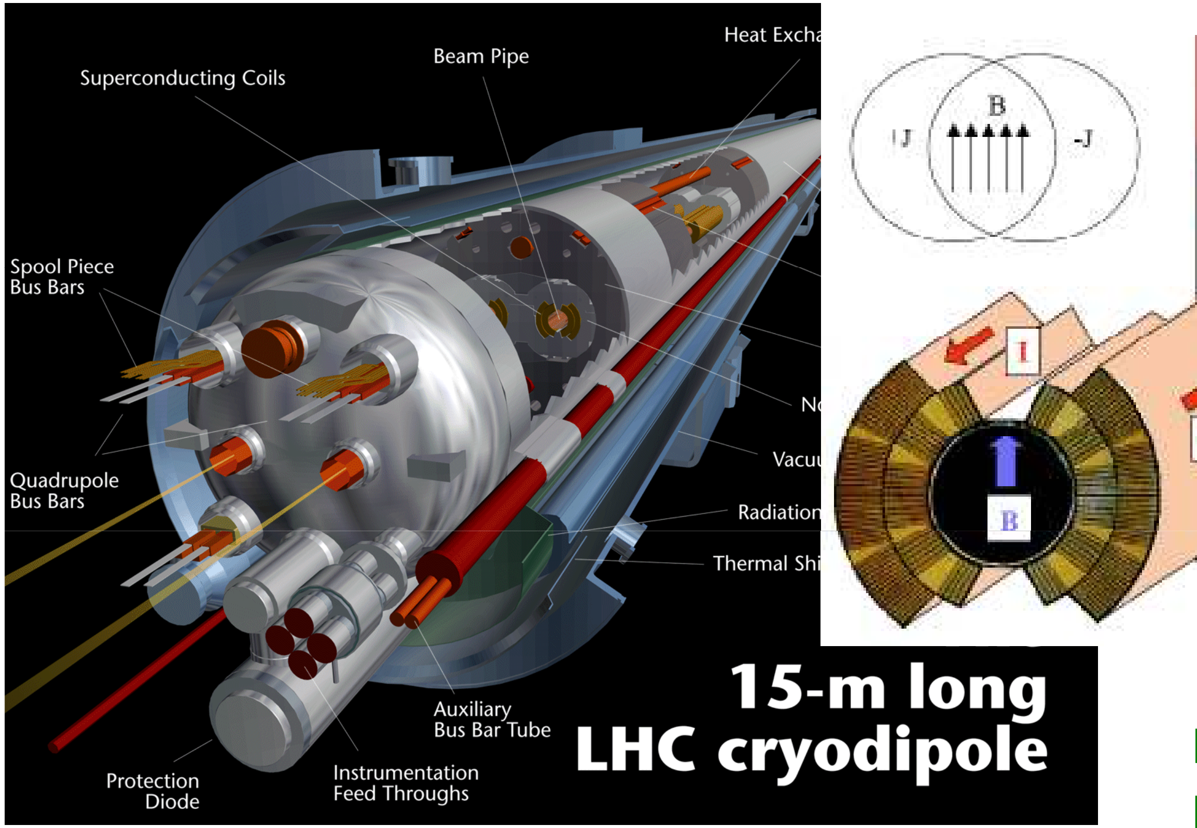
0.3c by here

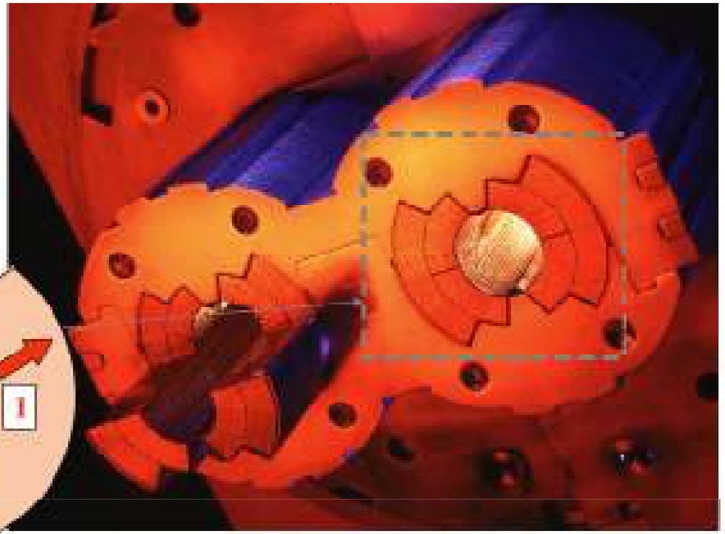
Start the protons out here



> 50 years of CERN history still alive and operational

LHC Accelerator Challenge: Dipole Magnets





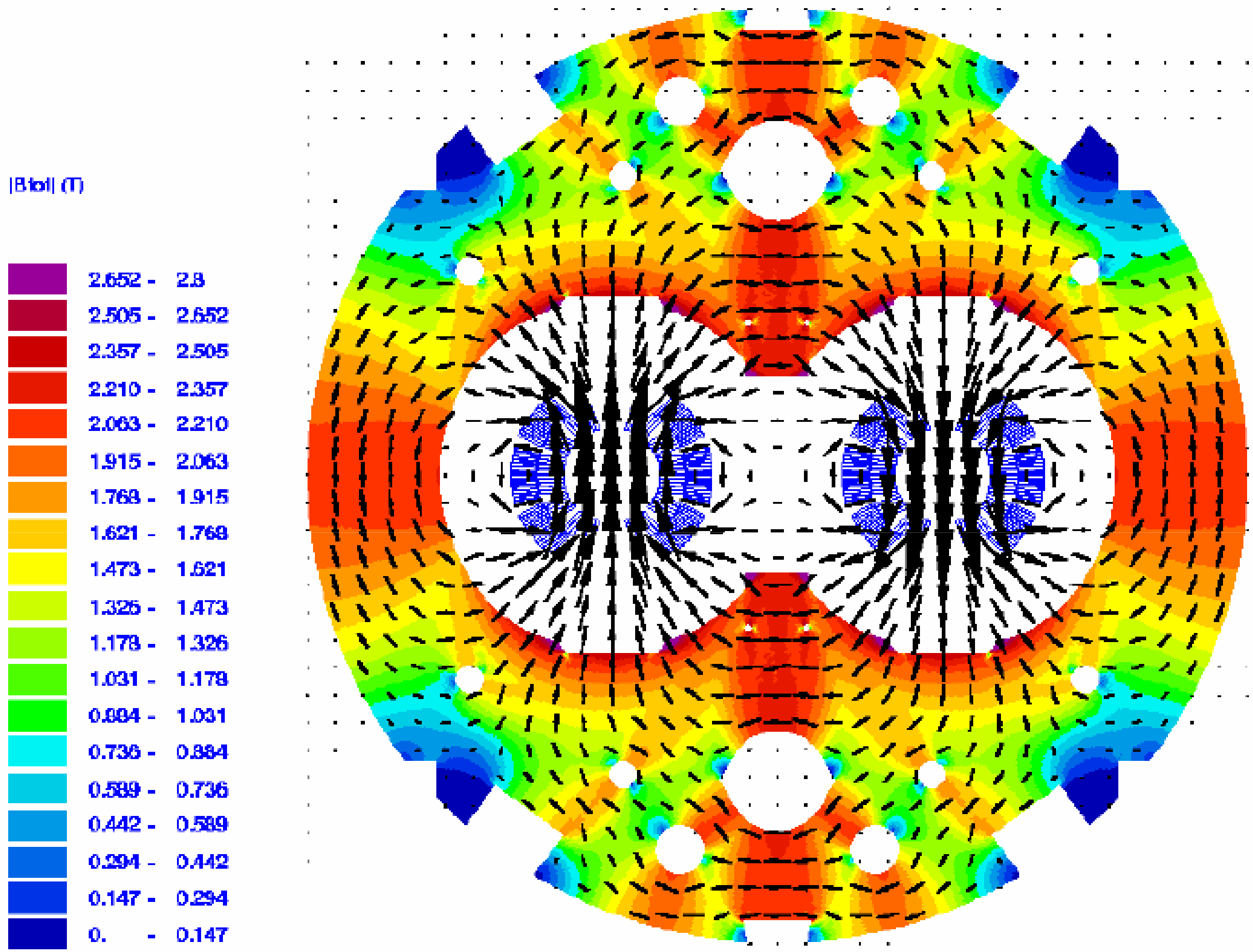
Magnetic Field for Dipoles
p (TeV) = 0.3 B(T) R(km)

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

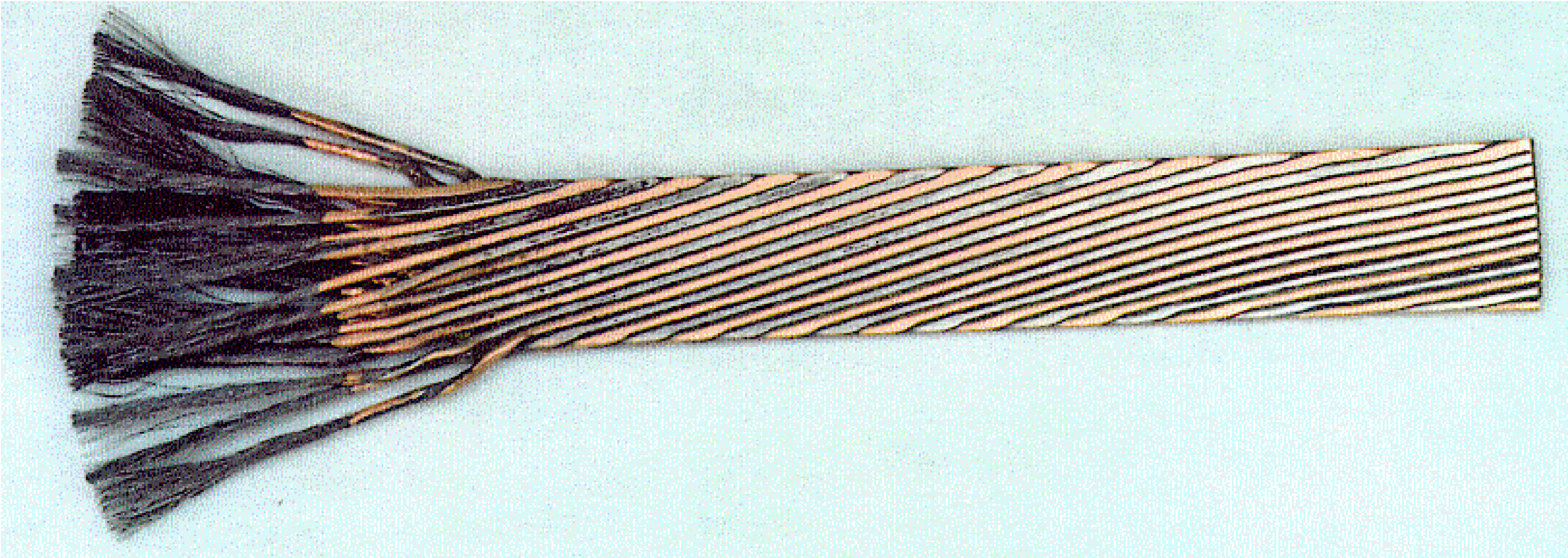
Coldest Ring in the Universe ?
1.9 K (CMBR is about 2.7 K)

LHC magnets are cooled with pressurized superfluid helium

Dipole magnetic flux plot



Sample of superconducting cable



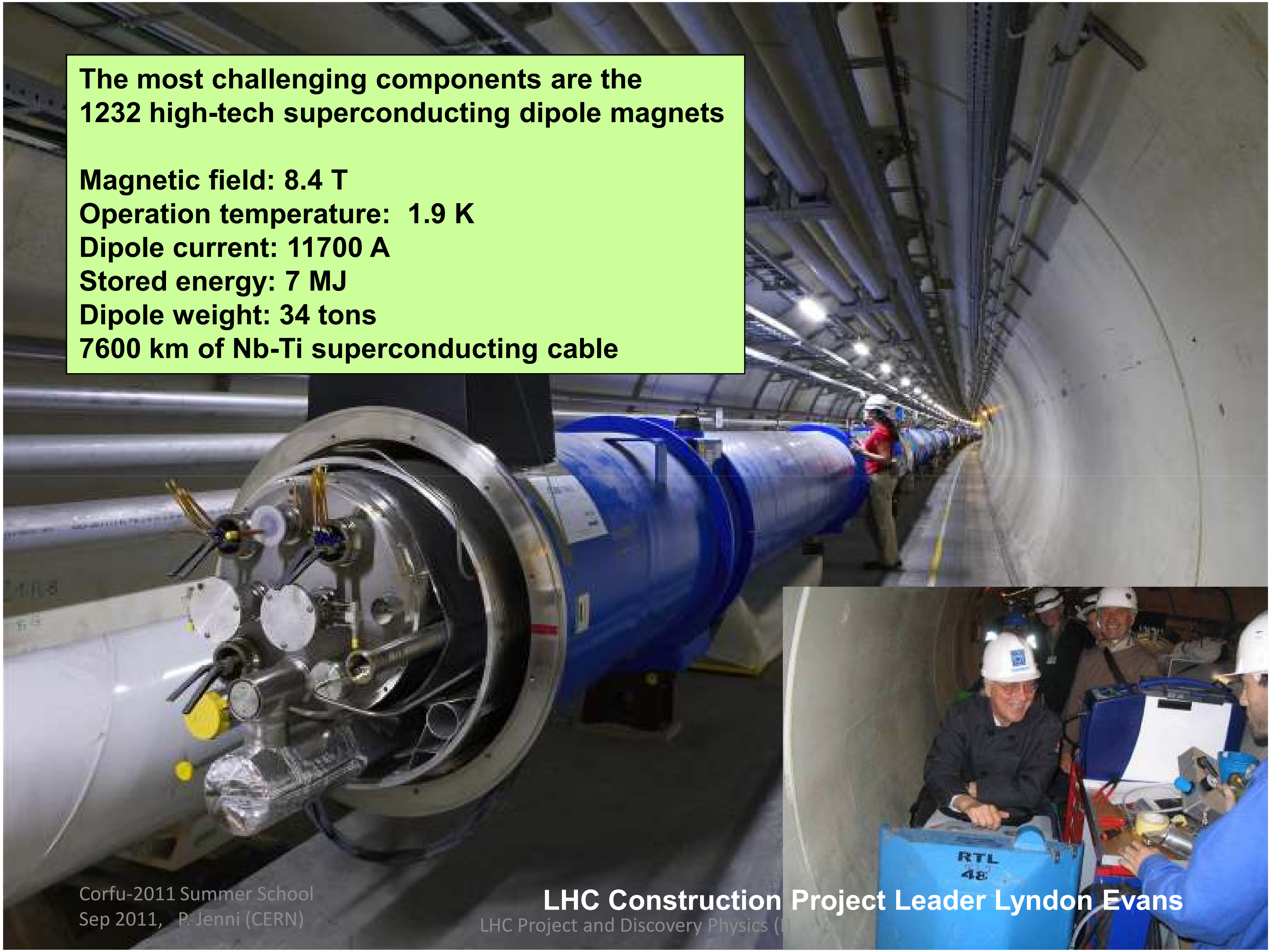
Production of superconducting wires & cables

Manufacturing of superconducting coils

Assembly of dipole cold masses

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

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



LHC Construction Project Leader Lyndon Evans

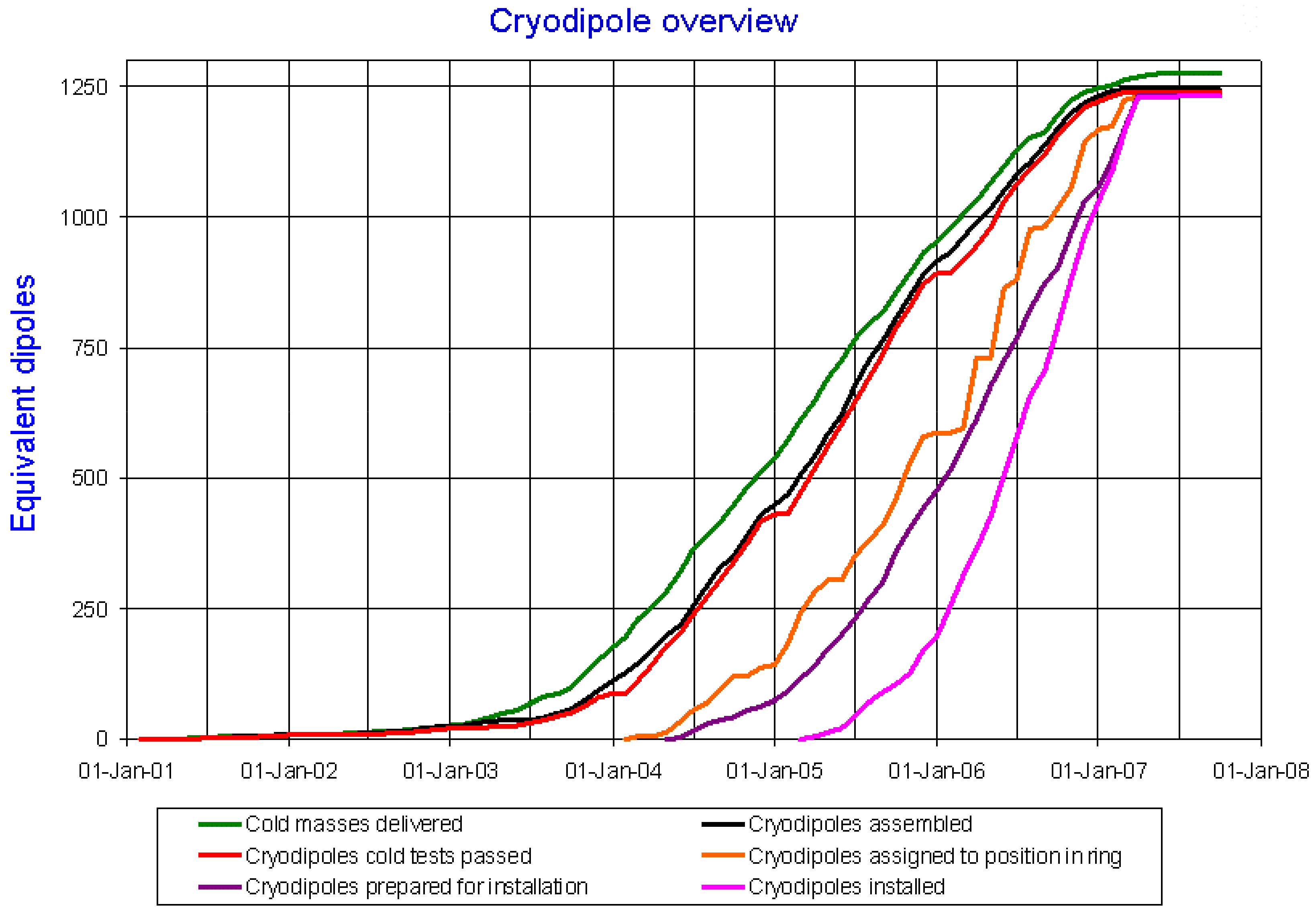
Descent of the last dipole magnet, 26 April 2007

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

LHC Progress Dashboard

History of the dipole magnet construction and installation

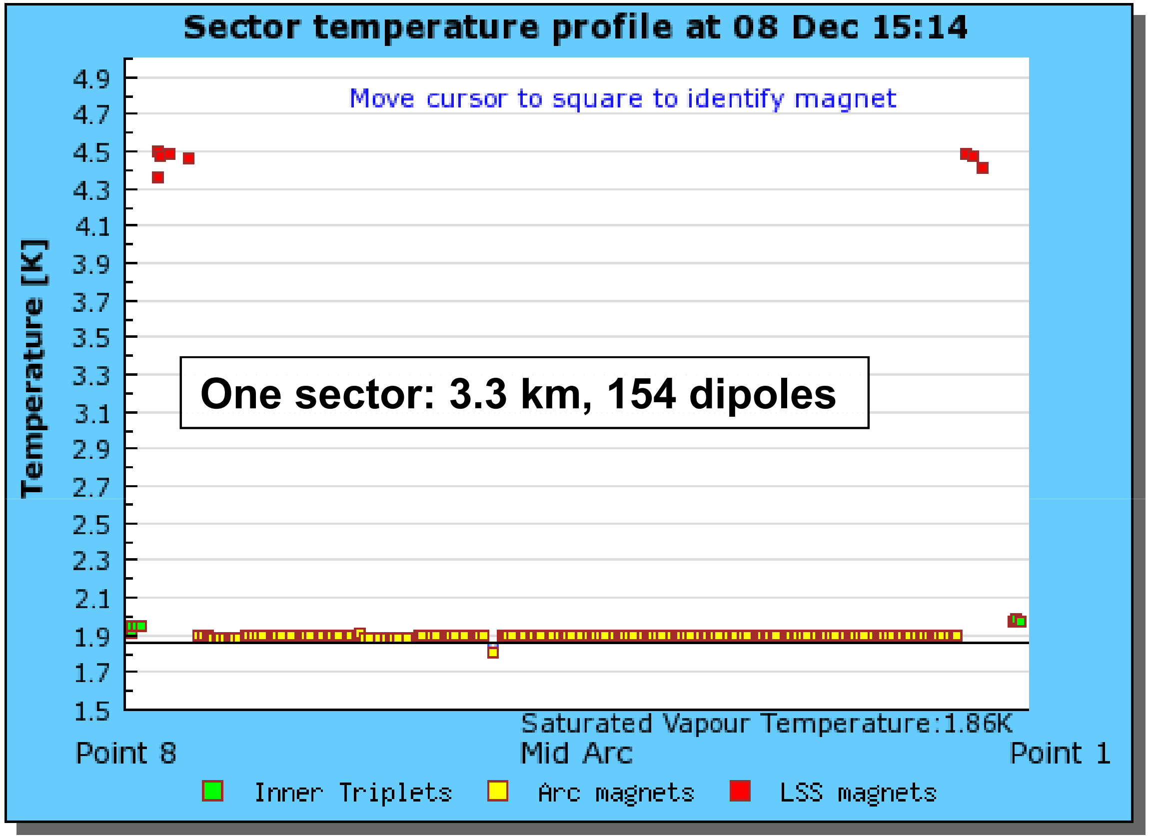
Accelerator Technology Department



Updated 30 September 2007

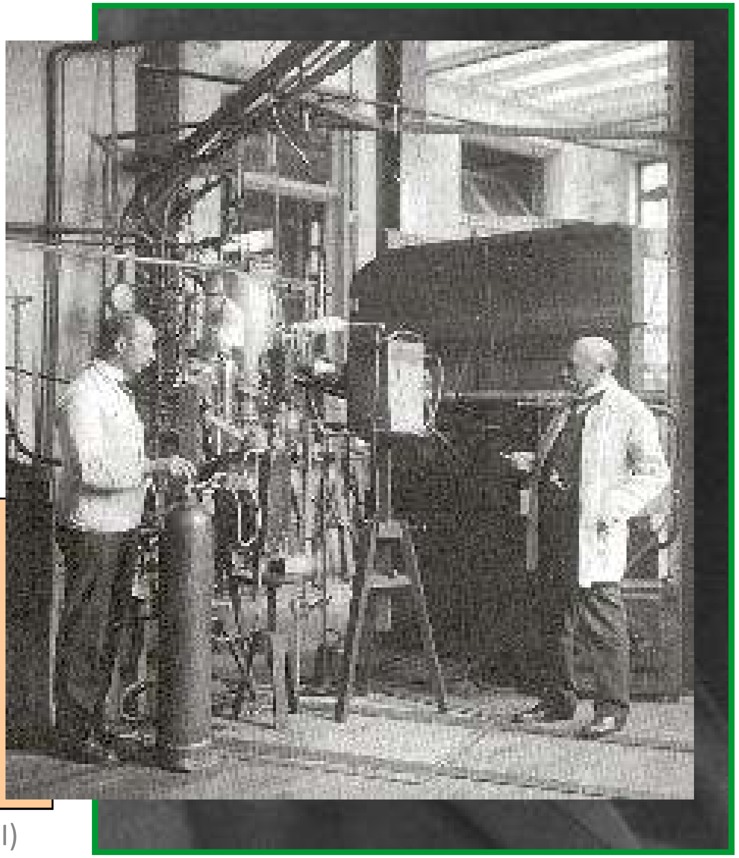
Data provided by D. Tommasini AT-MCS, L. Bottura AT-MTM

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



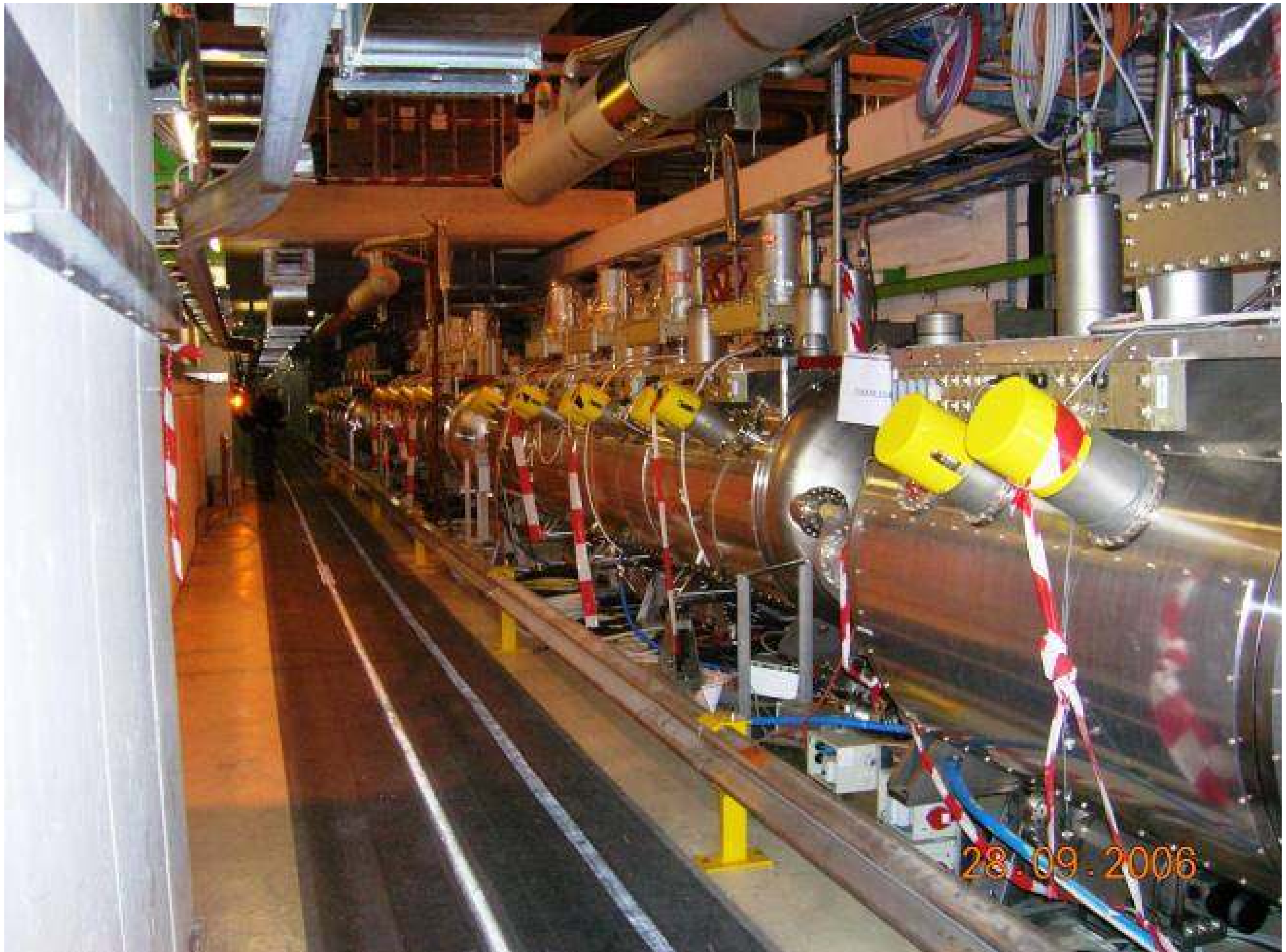
Magnets cooled down in a bath of ~120 tons of superfluid Helium (excellent thermal conductor)

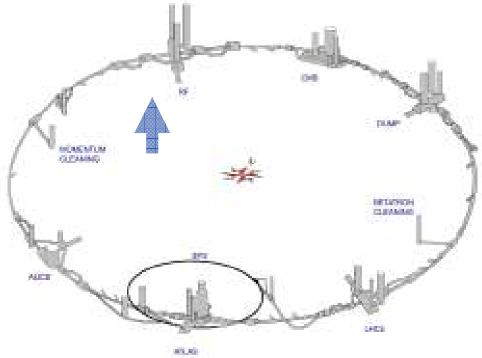
H K Onnes
Nobel Prize in Physics 1913



- **~100 years ago, on 10 July 1908: Heike K Onnes first liquefied Helium (60 ml in 1 hour) in Leiden**
- **LHC today: 32000 He liters liquefied per hour by eight big cryogenic plants (the largest refrigerator in the world)**

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

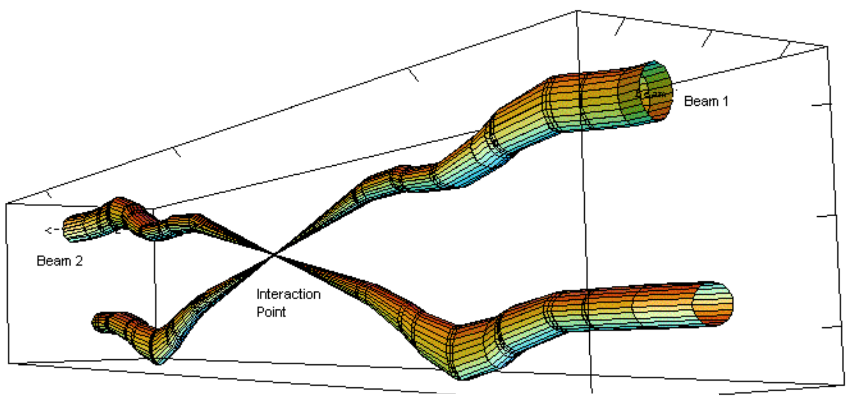




Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the ~ $1/m^4$ behaviour of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

	LHC at 7 TeV	LEP at 100 GeV
Synchrotron radiation loss	6.7 keV/turn	3 GeV/turn
Peak accelerating voltage	16 MV/beam	3600 MV/beam

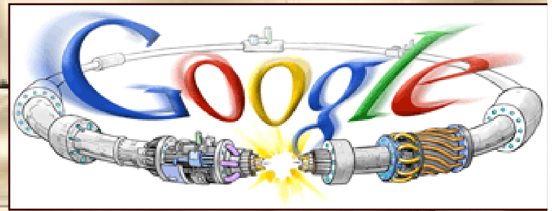
Special quadrupole magnets ('Inner Triplets') are focussing the particle beams to reach highest densities ('luminosity') at their interaction point in the centre of the experiments



Relative beam sizes around the collision point

10 September 2008: LHC inauguration day

First (single) beams circulating in the machine



Five CERN DGs, from conception to realization: Schopper, Rubbia, Llewellyn Smith, Maiani, Aymar (from right to left)

Interconnections of two magnets

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

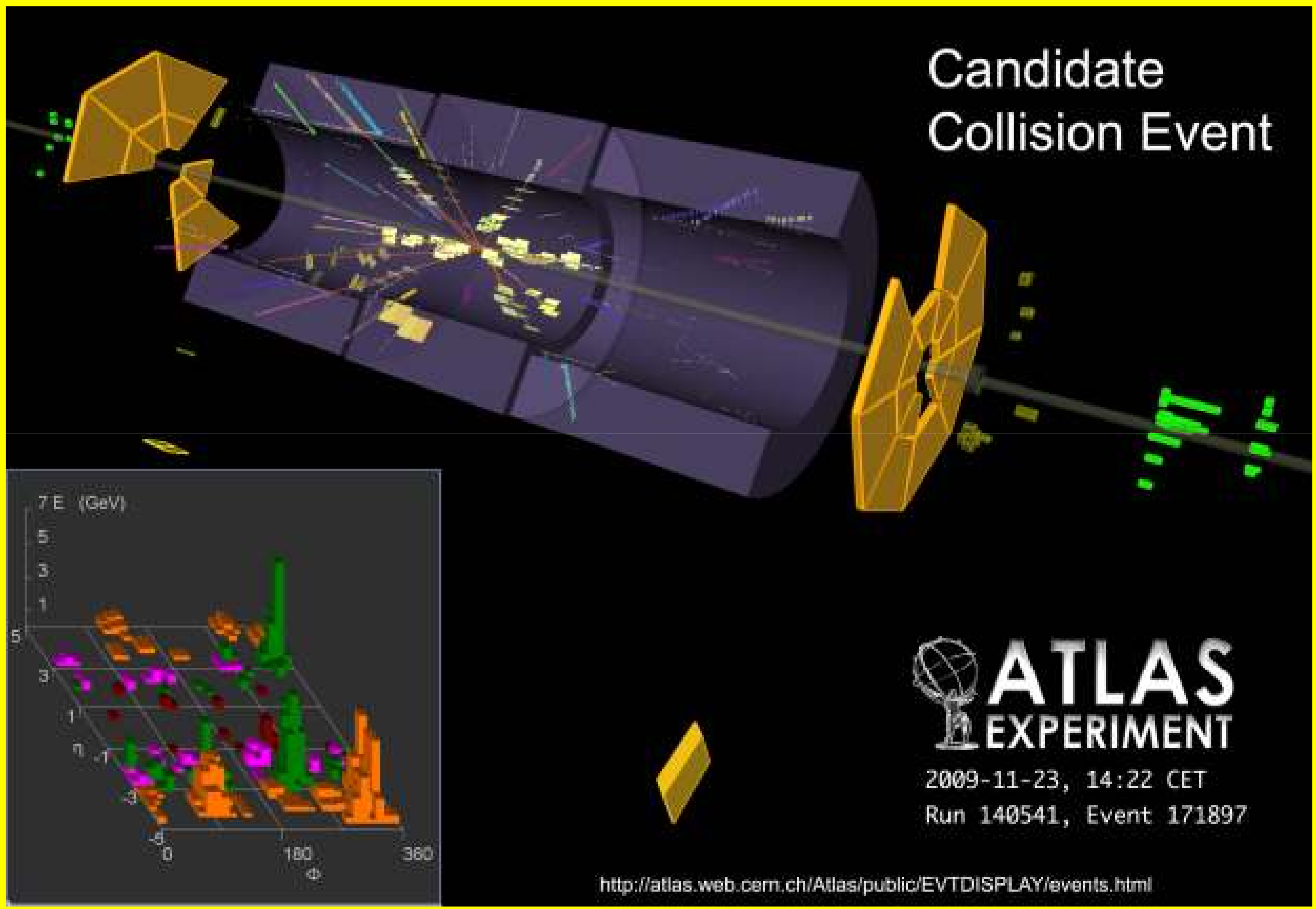
Examples of collateral damage

High pressure build-up damaged the magnet interconnects and the super-insulation

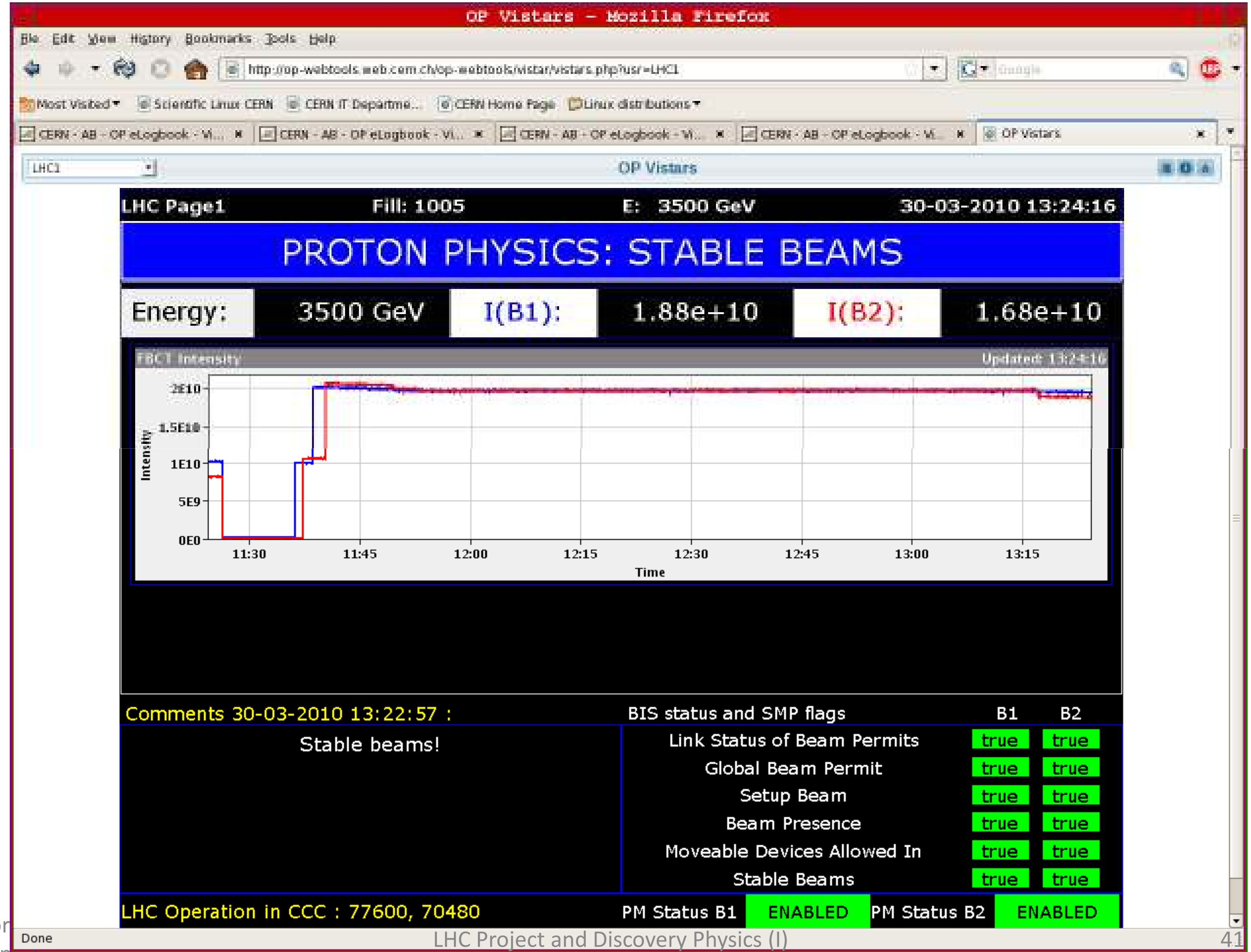
Perforation of the beam tubes resulted in pollution of the vacuum system with soot from the vaporization and with debris from the super insulation.

ATLAS Control Room when the first LHC beam collided....

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



High-energy operation with 3.5 TeV beams started on 30th March 2010




Fill: 1005
PROTON PHYSICS: STABLE BEAMS
E: 3500 GeV
30-03-2010 13:47:40
3500 GeV
I(B1):
1.79e+10
I(B2):
1.64e+10

Collision energy

Tevatron ($p\bar{p}$)

1.96 TeV

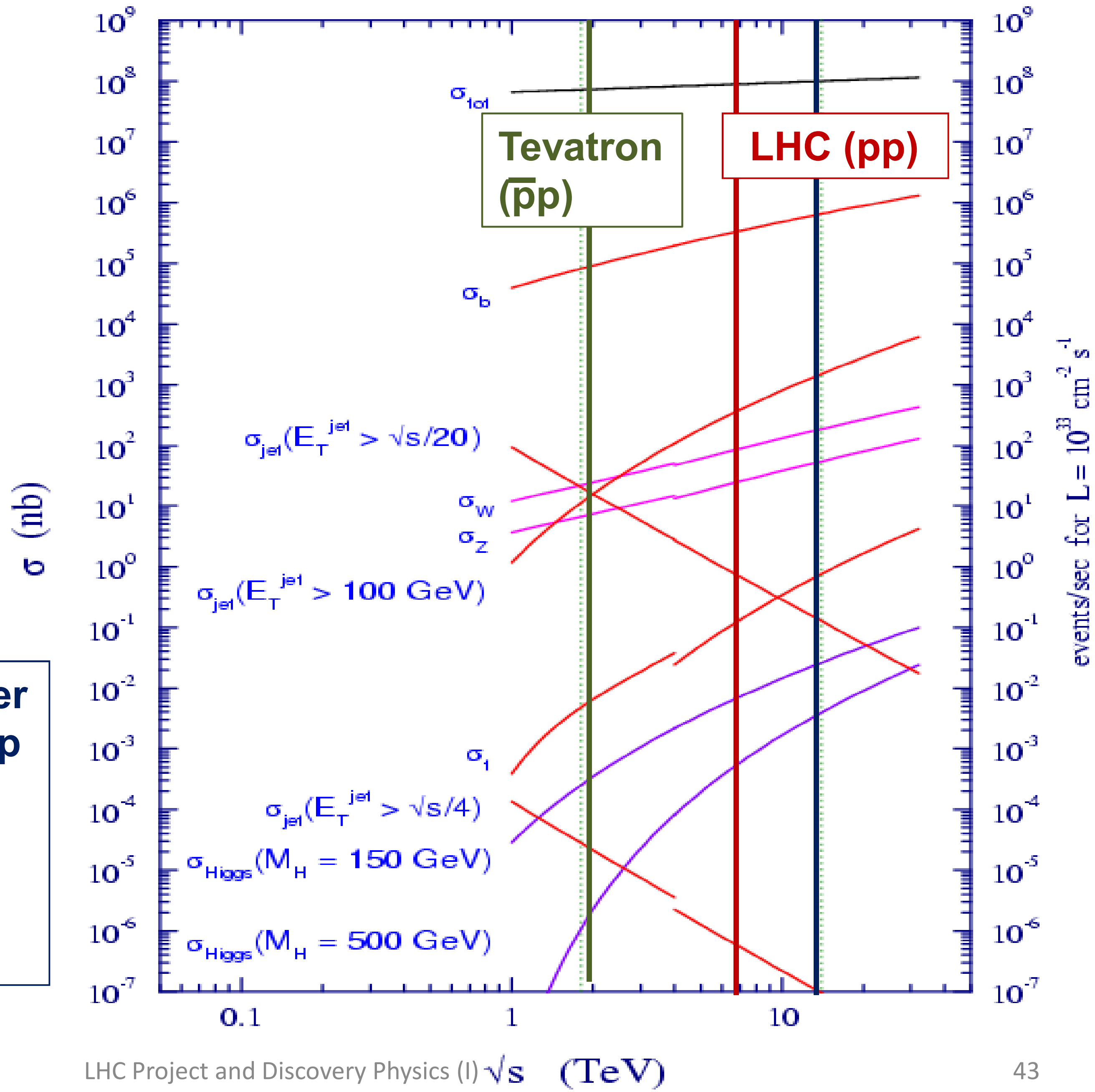
LHC (pp)

initially 7 TeV
later 14 TeV

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

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

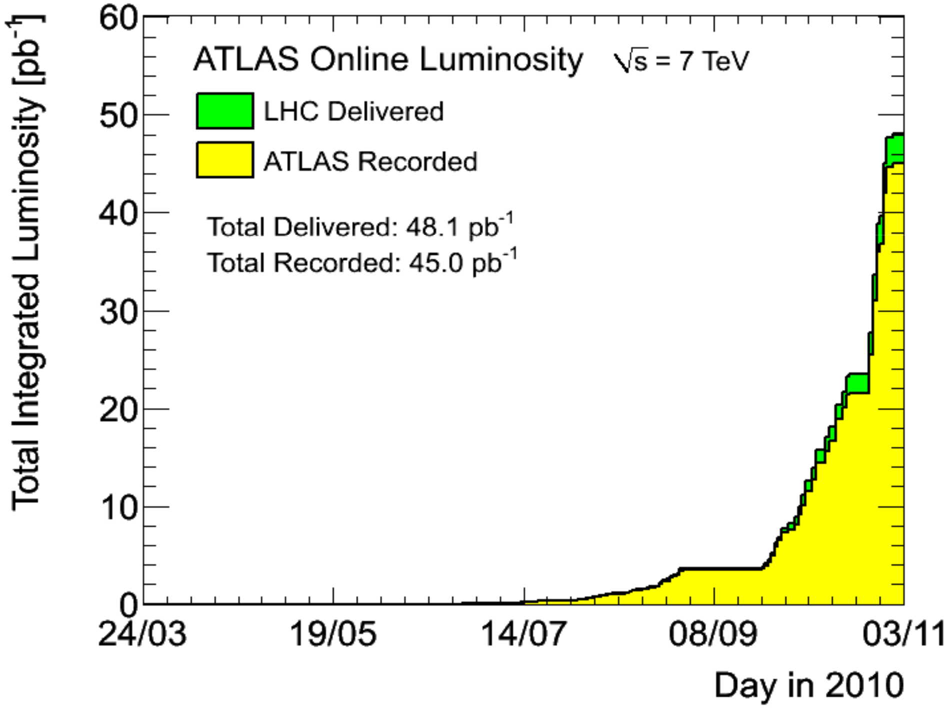
Some bench-mark cross-sections

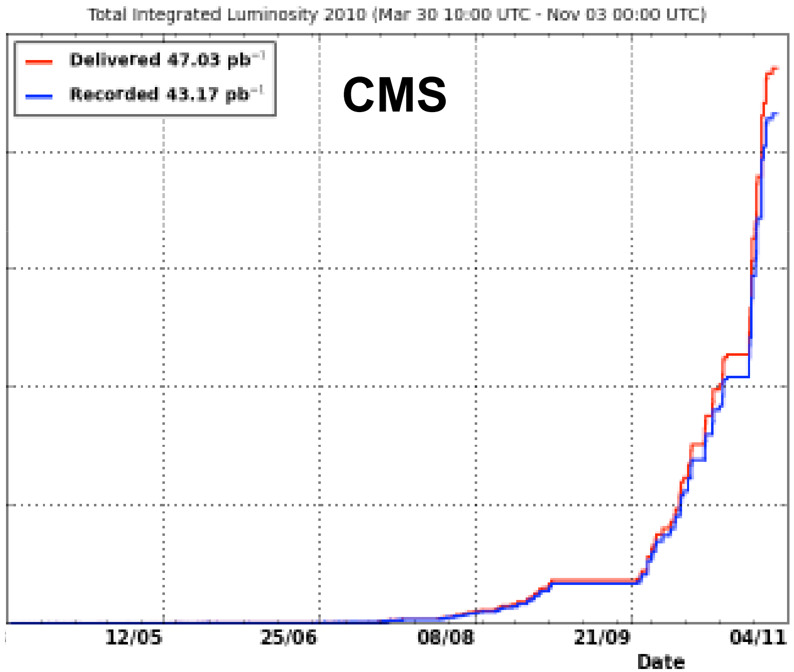


The LHC has performed over 2010 in a superb way at 7 TeV collision energy, and delivered a good sample of data in stable pp beam operation (~ 48 pb^{-1} integrated luminosity)

The high-luminosity general-purpose experiments ATLAS and CMS both have operated efficiently (recorded typically 92 – 94 % of the luminosity delivered in stable conditions)

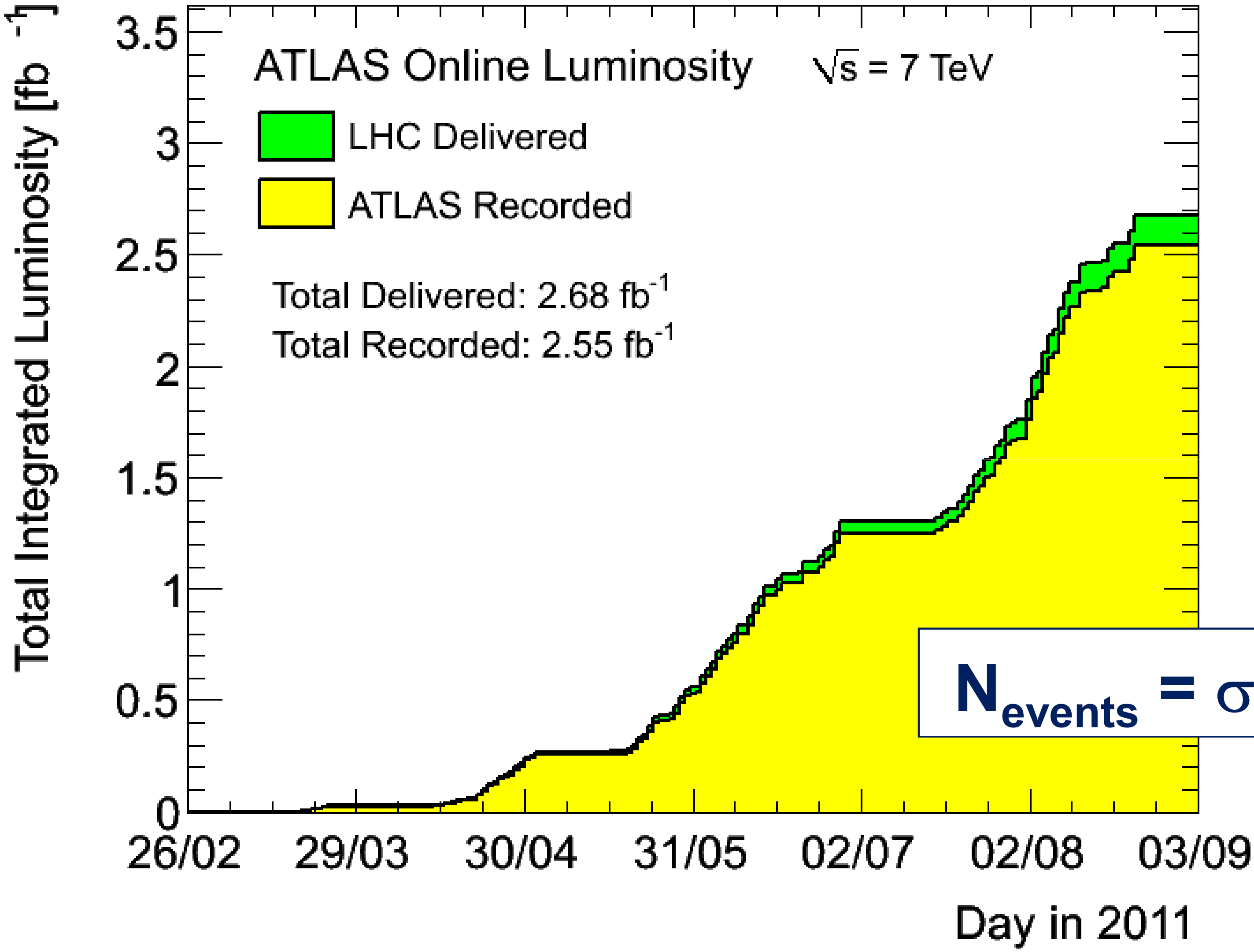
After all data quality criteria, published physics results for the full 2010 data sets are typically based on an integrated luminosity of 35 – 40 pb^{-1} (syst. luminosity errors 3-5%)





(In addition the LHC delivered in 2010 about 10 μb^{-1} of PbPb collisions at 2.76 TeV/nucleon, not covered in this talk)

Integrated Luminosity in ATLAS 2011



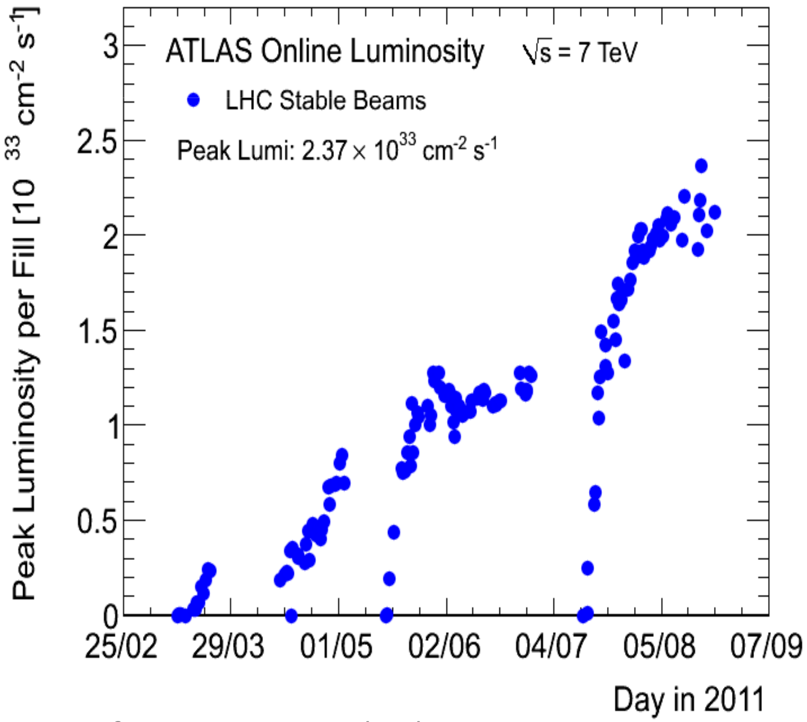
$$N_{events} = \sigma \int L \, dt$$

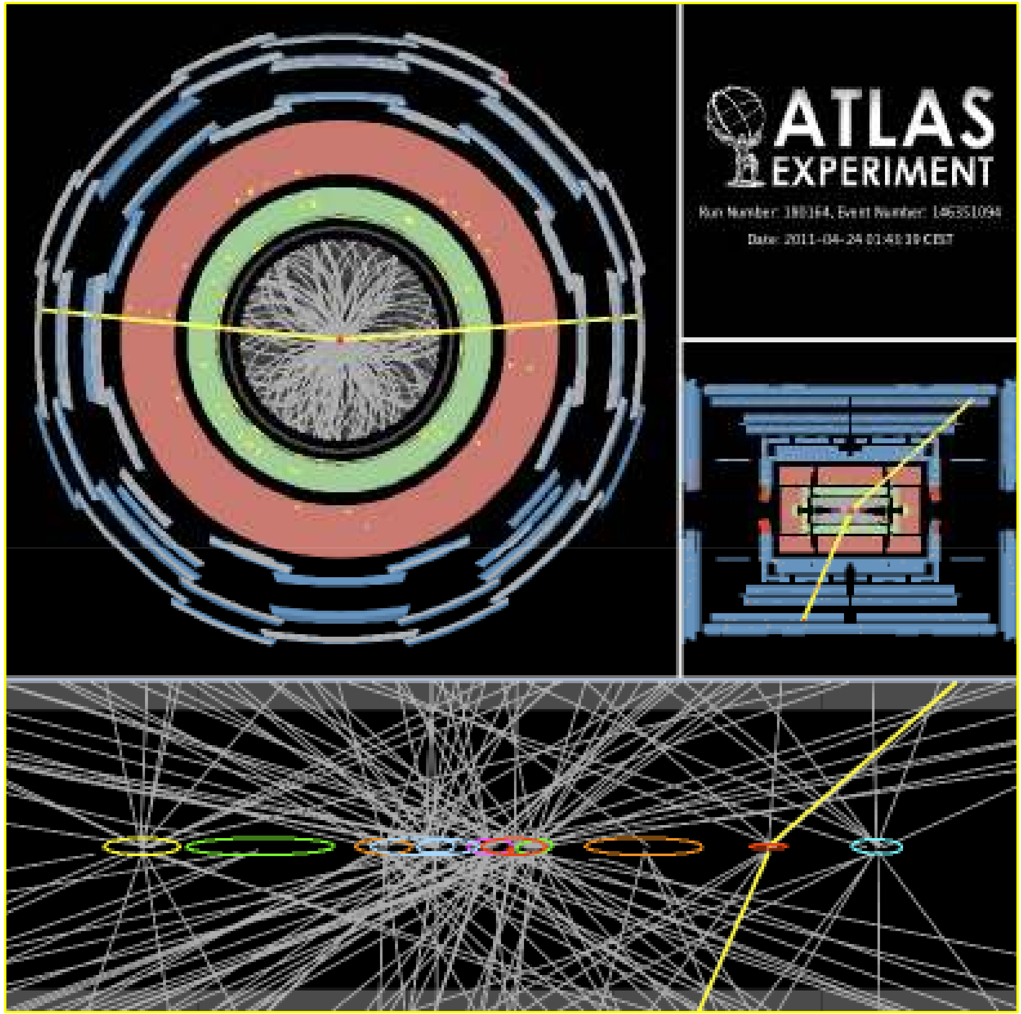
Current LHC Operation:

1380 bunches per beam

50 ns bunch spacing

up to 1.7 x 10^{11} protons per bunch

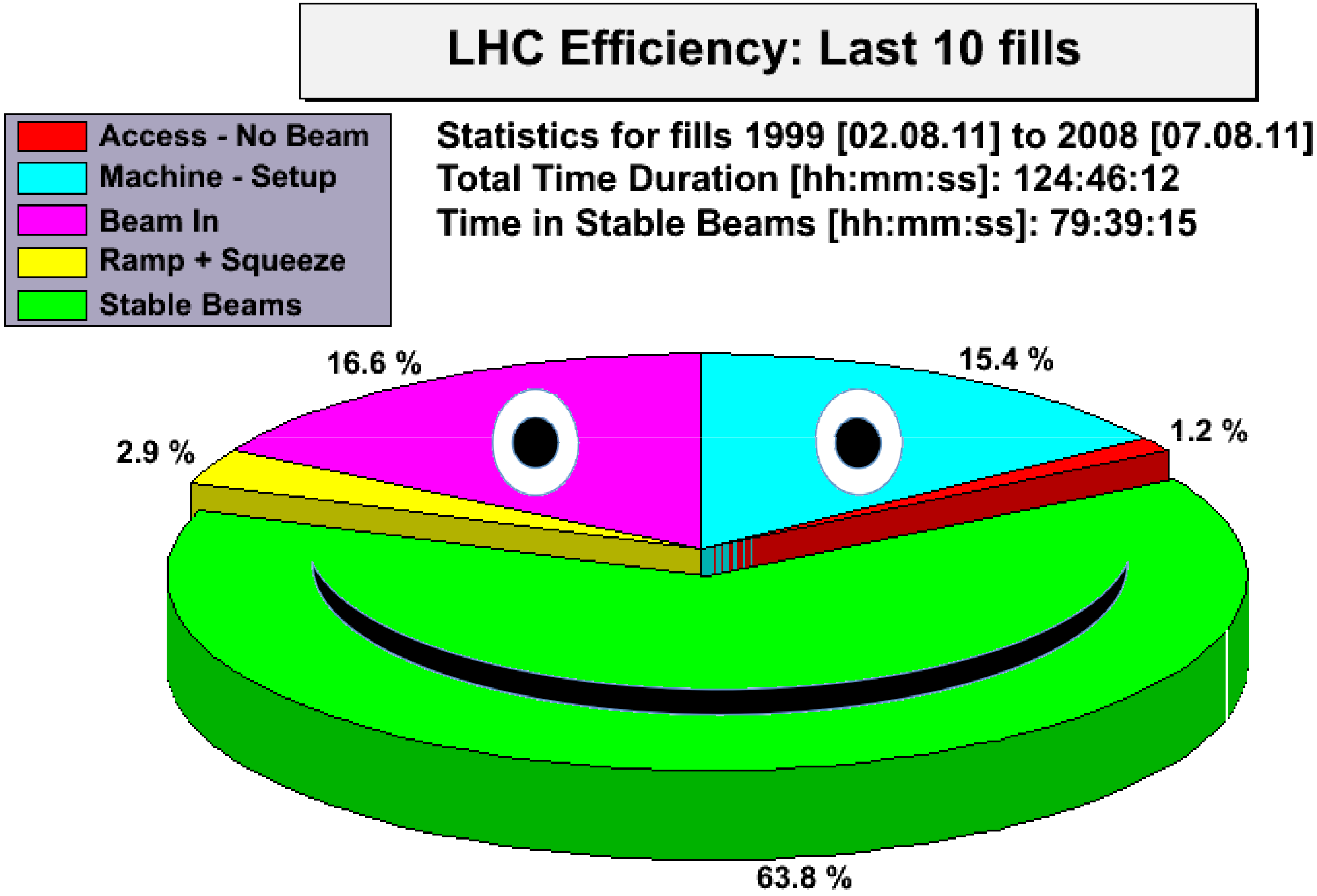




Z→μμ event with 11 primary vertices

(Typical peak pile-up per bunch crossing: 10)

A great LHC week…



Road Map of Expected Hadron Collider Performances

End 2010	**Tevatron**	**2 TeV**	**7 fb^{-1} (analysed)**
	LHC	**7 TeV**	**45 pb^{-1}**
End 2011	**Tevatron**	**2 TeV**	**10 fb^{-1} (analysed)**
	LHC	**7 TeV**	**4 fb^{-1}**
End 2012	**LHC**	**7 TeV**	**10 fb^{-1}**
End 2015	**LHC**	**14 TeV**	**30 fb^{-1}**
End 2017	**LHC**	**14 TeV**	**100 fb^{-1}**
Early 2020s	**LHC**	**14 TeV**	**500 fb^{-1}**
2030	**(s)LHC**	**14 TeV**	**3000 fb^{-1} (ultimately…)**

(These are round numbers and estimates, just to give a rough idea…)

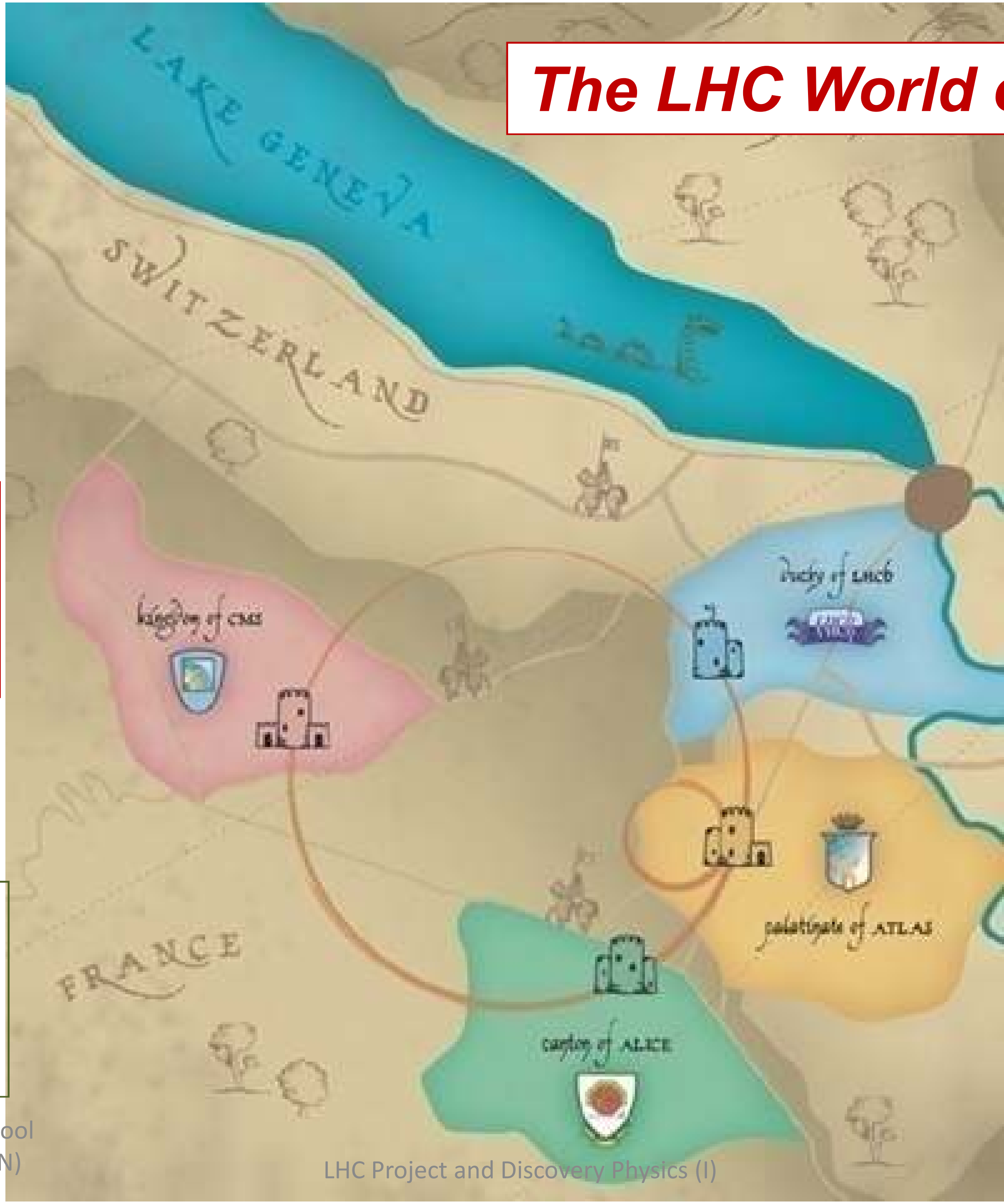
(1 fb^{-1} = 1000 pb^{-1})

The LHC World of CERN

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

CMS
2900 Physicists
184 Institutions
38 countries
550 MCHF

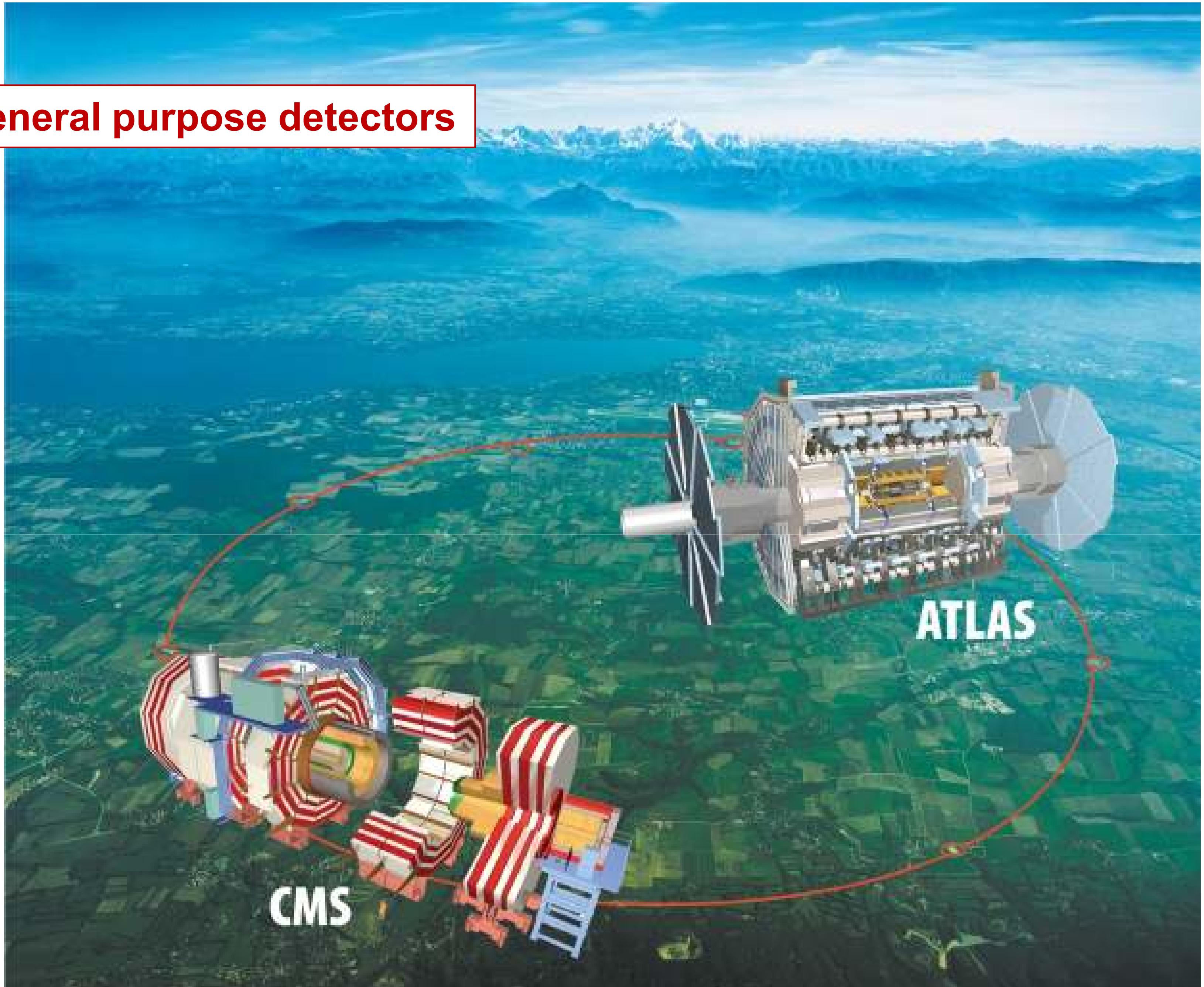
ALICE
1000 Physicists
105 Institutions
30 countries
150 MCHF



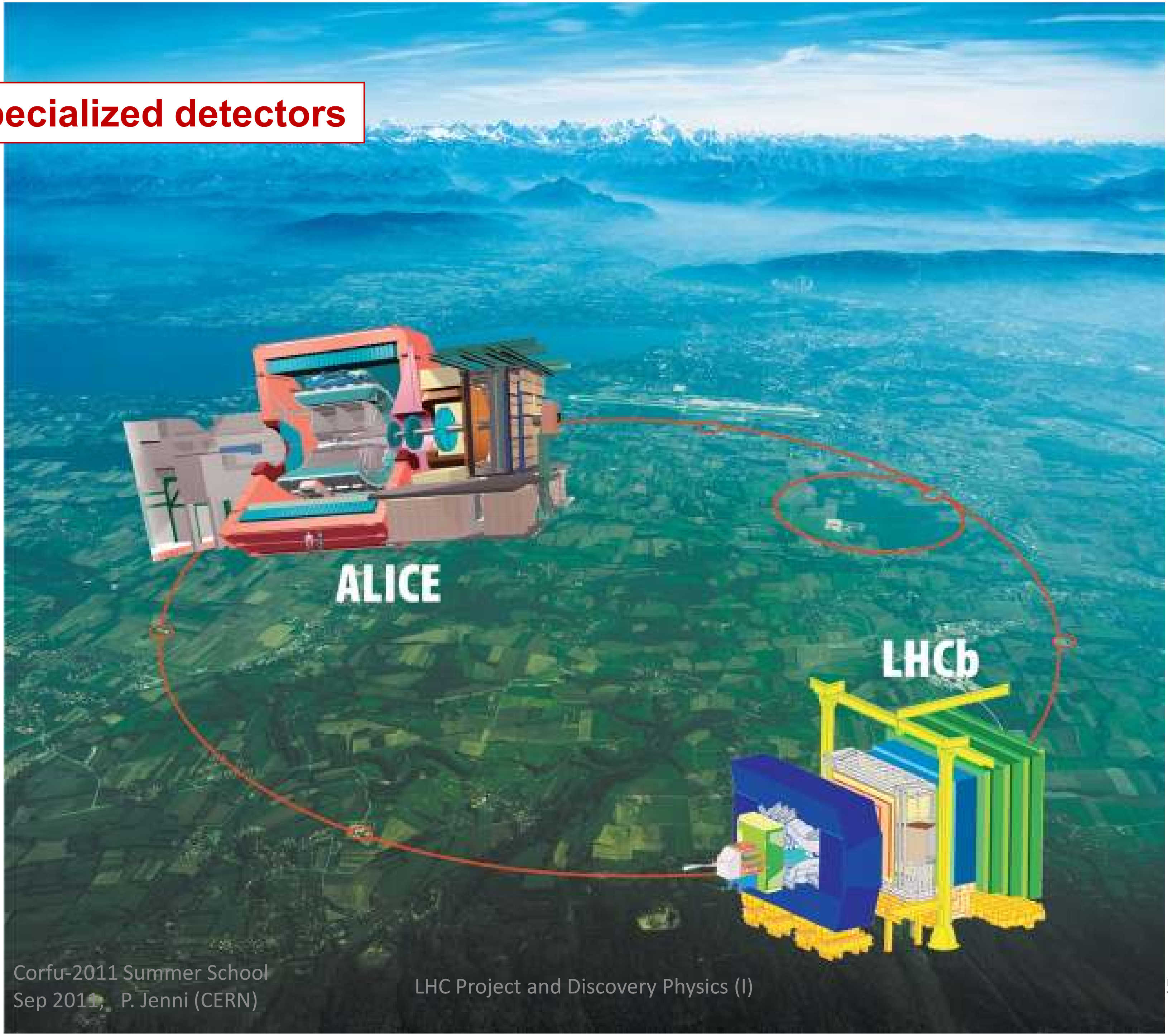
LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

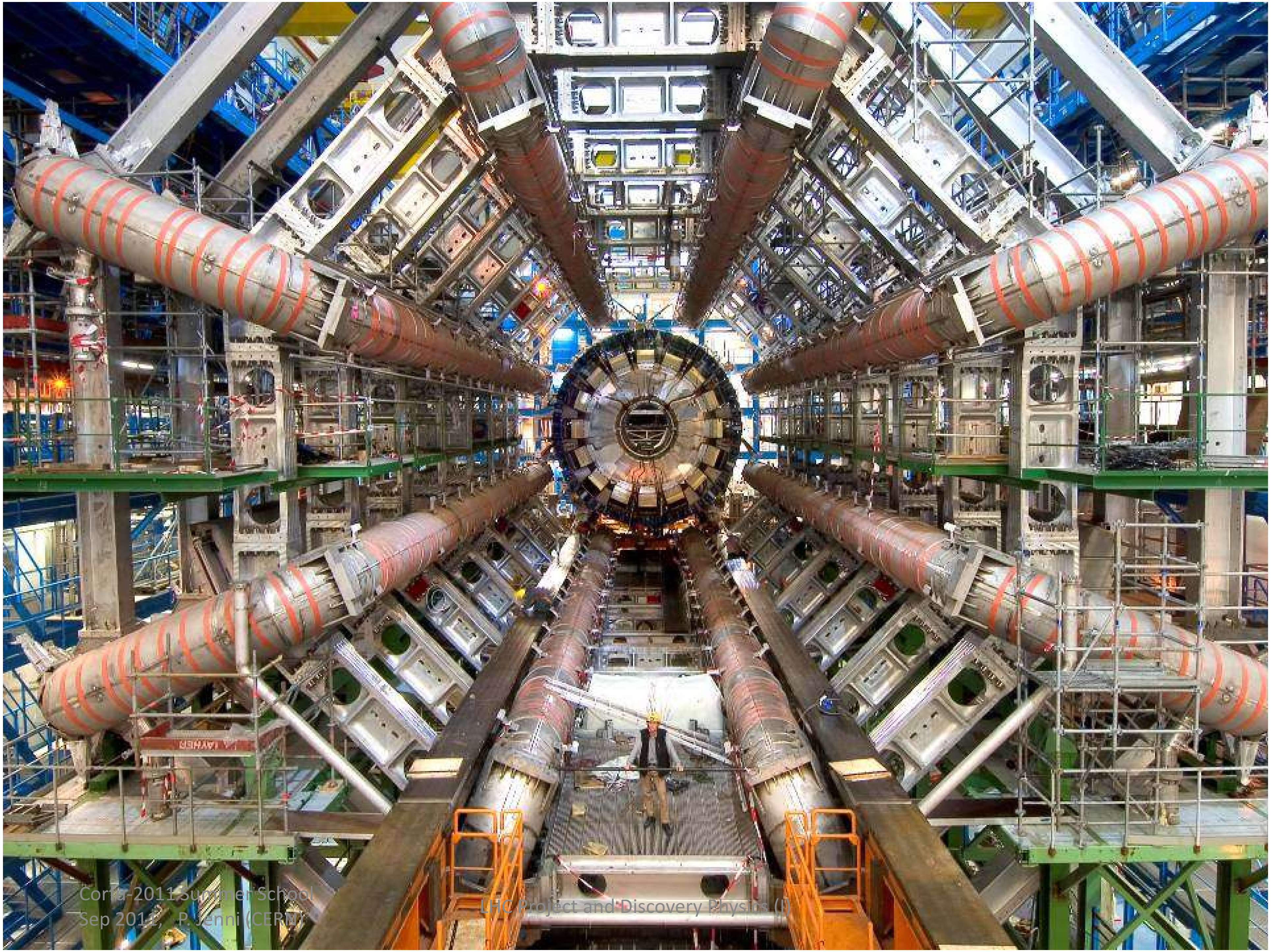
ATLAS
3000 Physicists
174 Institutions
38 countries
550 MCHF

General purpose detectors

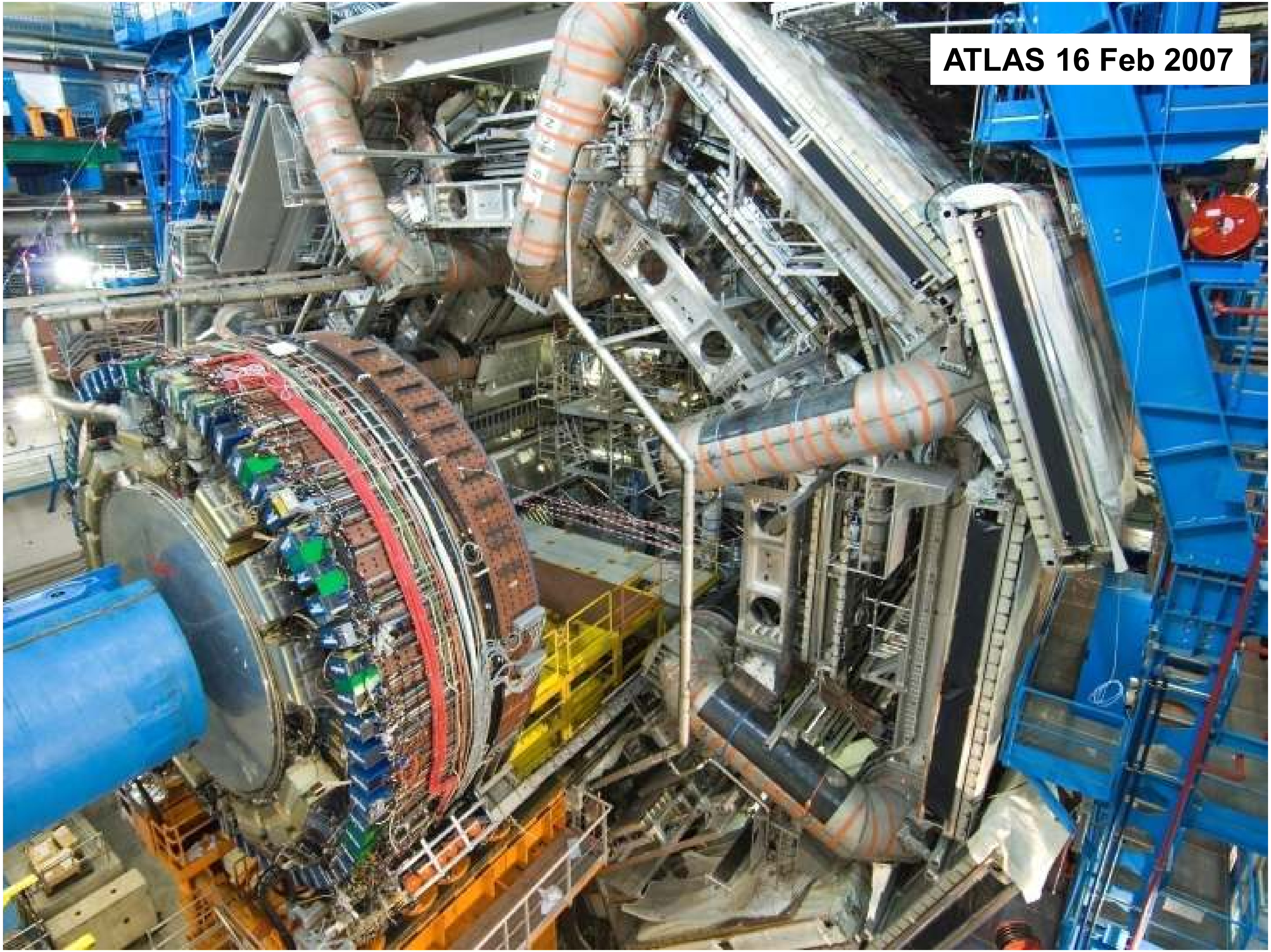


Specialized detectors





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


ATLAS 16 Feb 2007

CMS before closure

Strategy toward physics

Before data taking starts:

- Strict quality controls of detector construction to meet physics requirements
- Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation)
- Detailed simulations of realistic detector "as built and as installed" (including misalignments, material non-uniformities, dead channels, etc.) → test and validate calibration/alignment strategies
- Experiment commissioning with cosmics in the underground cavern

With the first data:

- Commission/calibrate detector/trigger in situ with physics (min.bias, Z→ll, …)
- "Rediscover" Standard Model, measure it at $\sqrt{s}$ = 7 TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators)
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

↓

Prepare the road to discoveries …

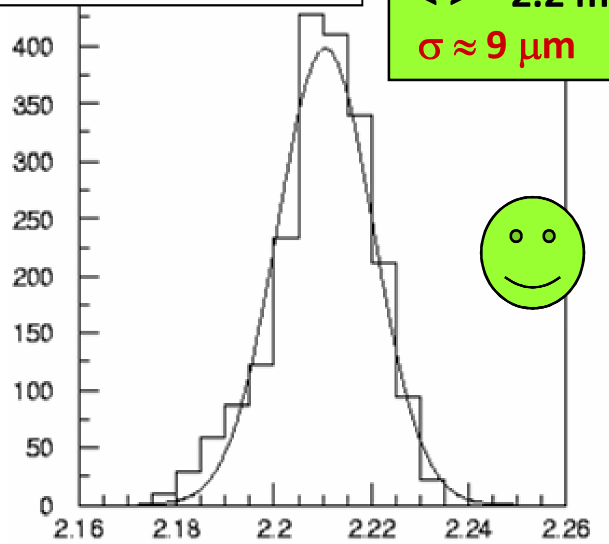
Example: ATLAS LAr em Accordion Calorimeter

Construction quality

Thickness of Pb plates must be uniform to 0.5% (~10 μm)

End-cap: 1536 plates

< > ~ 2.2 mm
σ ≈ 9 μm

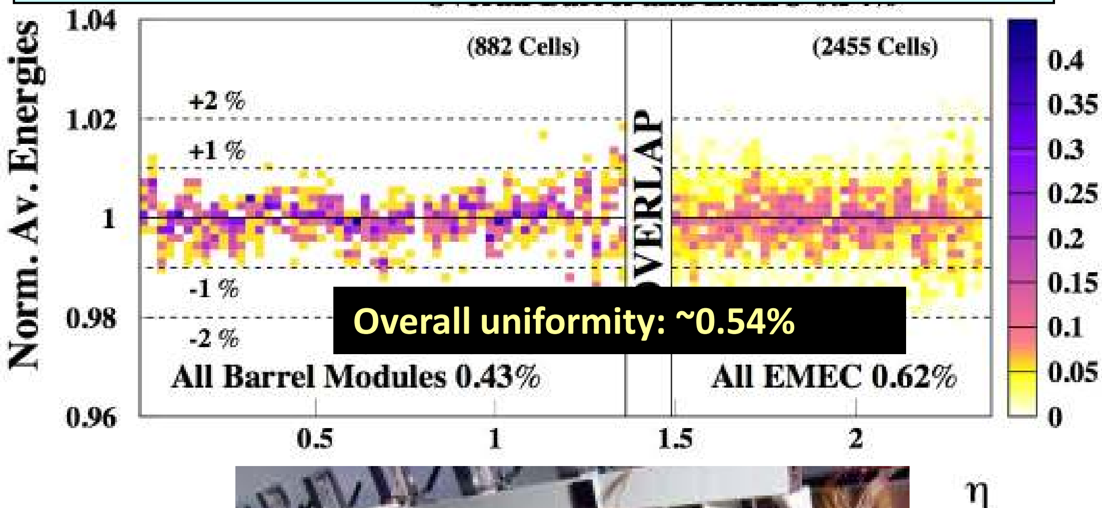


Absorber thickness (mm)

Test-beam measurements

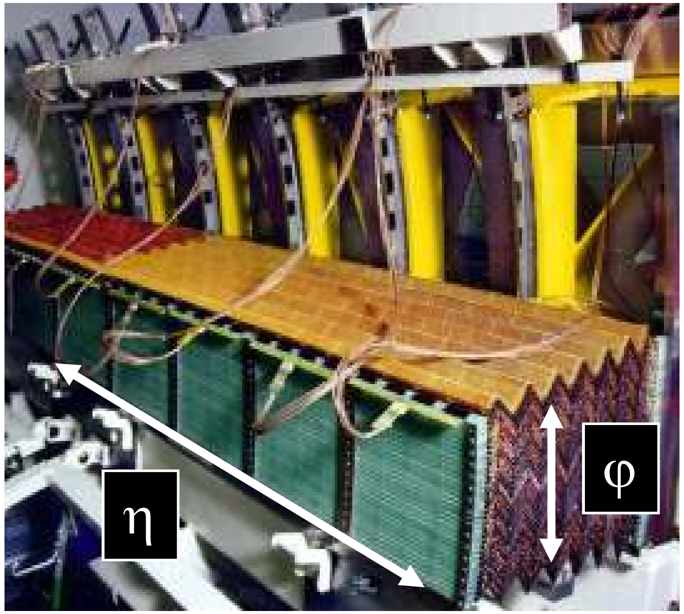
4 (out of 32) barrel modules and 3 (out of 16) end-cap (EMEC) modules tested with beams

Scans with 120-245 GeV electrons (all 7 tested modules)

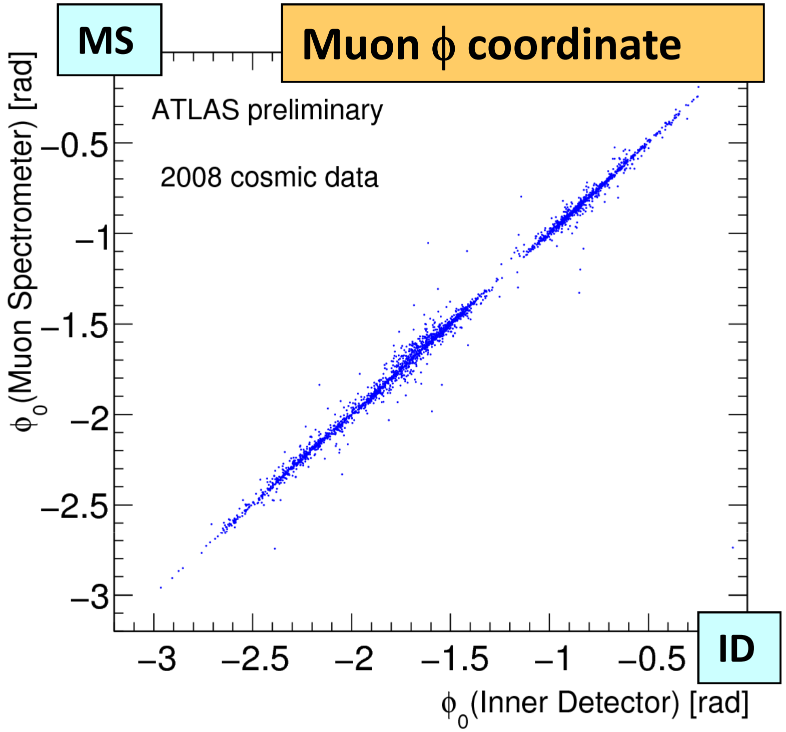


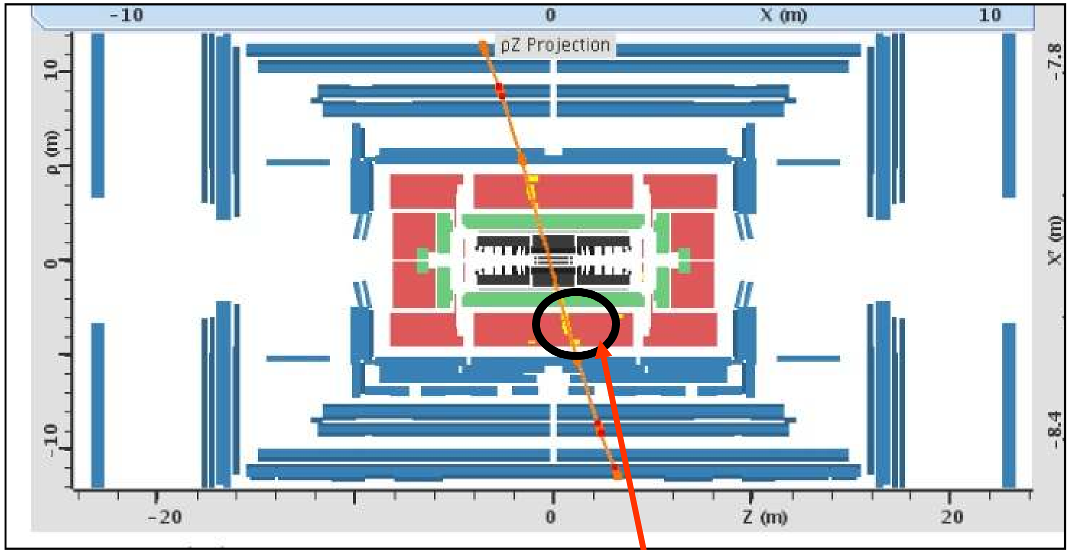
Overall uniformity: ~0.54%

1 barrel module:
Δη x Δφ = 1.4 x 0.4
≈ 3000 channels

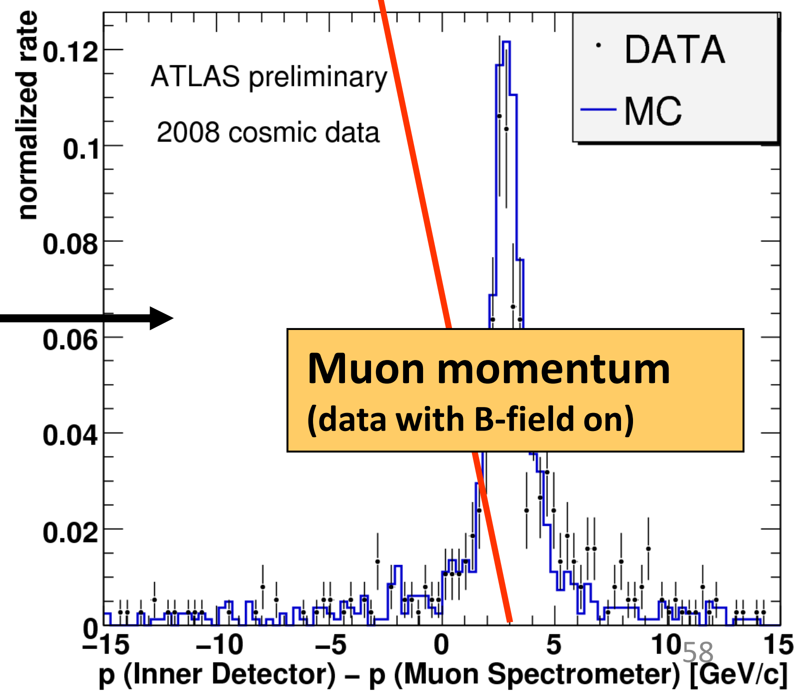


Correlation between measurements in the ATLAS Inner Detector and Muon Spectrometer





Difference between the muon momentum measured in the ID and in the MS for tracks in the bottom part of the detector (~ 3 GeV energy loss in the calorimeter)



Strategy toward physics

Before data taking starts:

- Strict quality controls of detector construction to meet physics requirements ✓
- Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation) ✓
- Detailed simulations of realistic detector "as built and as installed" (including misalignments, material non-uniformities, dead channels, etc.) → test and validate calibration/alignment strategies ✓
- Experiment commissioning with cosmics in the underground cavern ✓

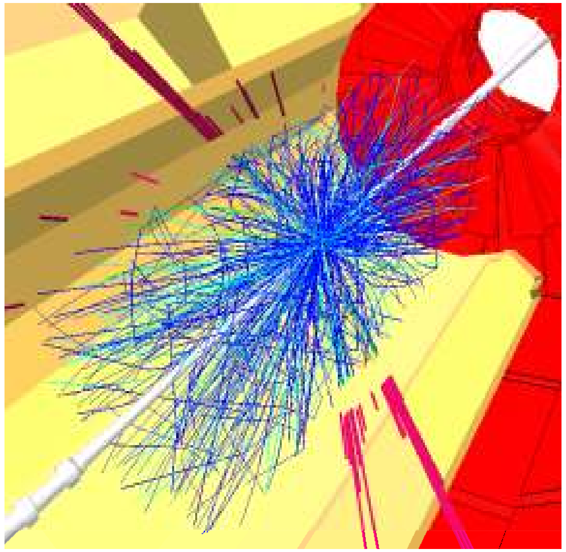
With the first data:

- Commission/calibrate detector/trigger in situ with physics (min.bias, Z→ll, …)
- "Rediscover" Standard Model, measure it at √s = 7 TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators)
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

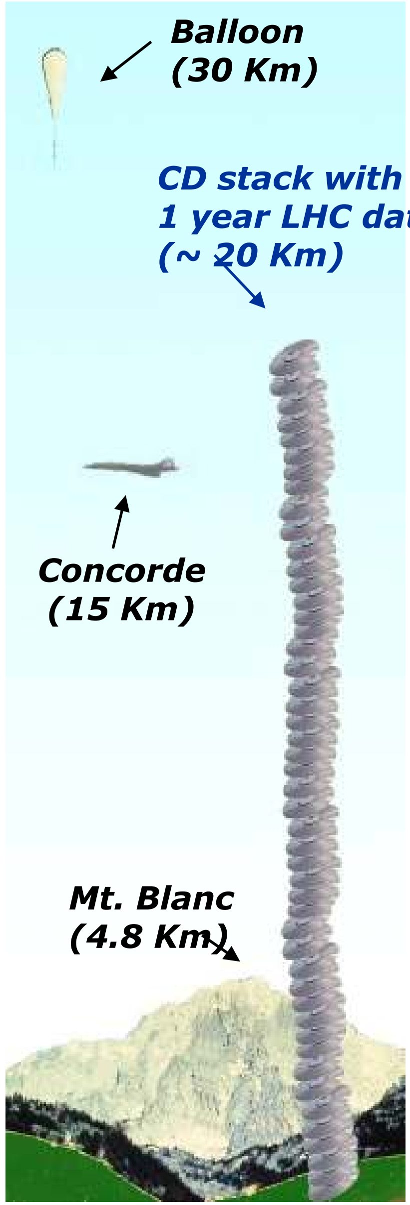
↓

Prepare the road to discoveries …

*Worldwide LHC Computing Grid (**wLCG**)*



WLCG is a worldwide collaborative effort on an unprecedented scale in terms of storage and CPU requirements, as well as the software project's size



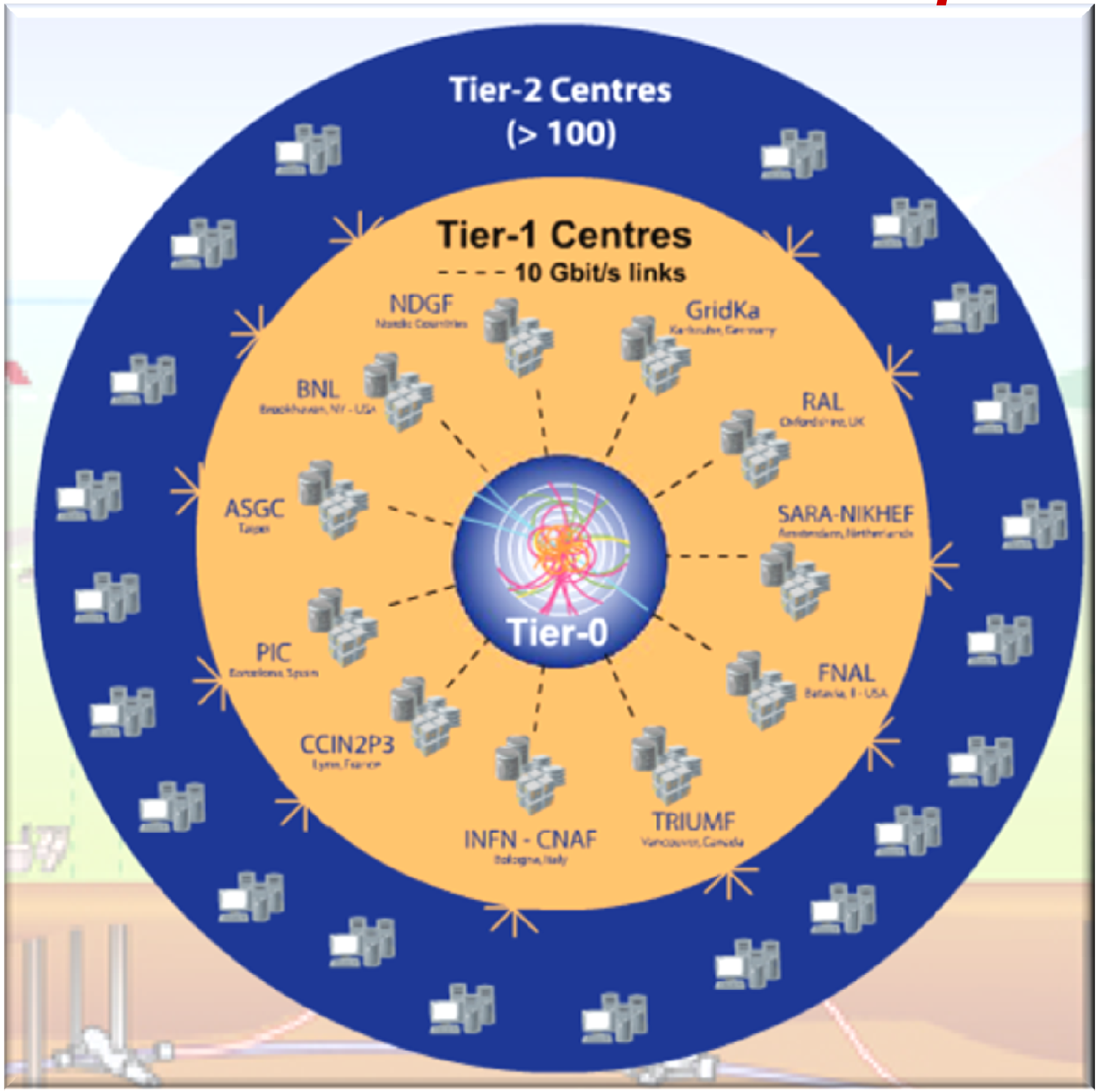
GRID computing developed to solve problem of data storage and analysis

LHC data volume per year: 10-15 Petabytes

One CD has ~ 600 Megabytes
1 Petabyte = 10^9 MB = 10^{15} Byte

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

The Worldwide LHC Computing Grid (wLCG)



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

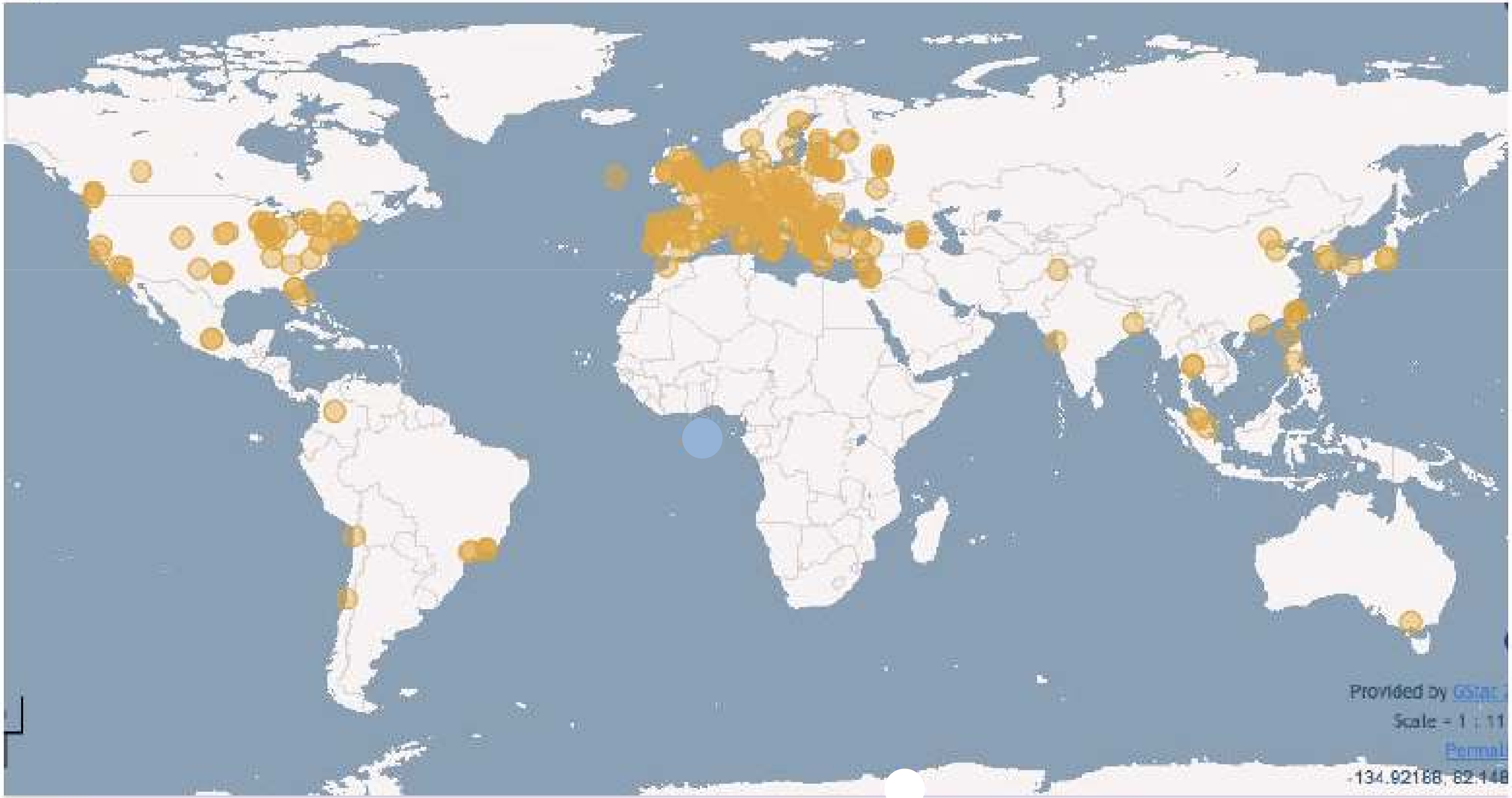
Tier-1 (11 centres):
- Permanent storage
- Re-processing
- Analysis
- Simulation

Tier-2 (federations of ~130 centres):
- Simulation
- End-user analysis

Today's WLCG

- More than 170 computing facilities in 34 countries
  - More than 100k Processing Cores
  - More than 50PB of disk

WLCG
Worldwide LHC Computing Grid



Computing Grid Delivers Physics

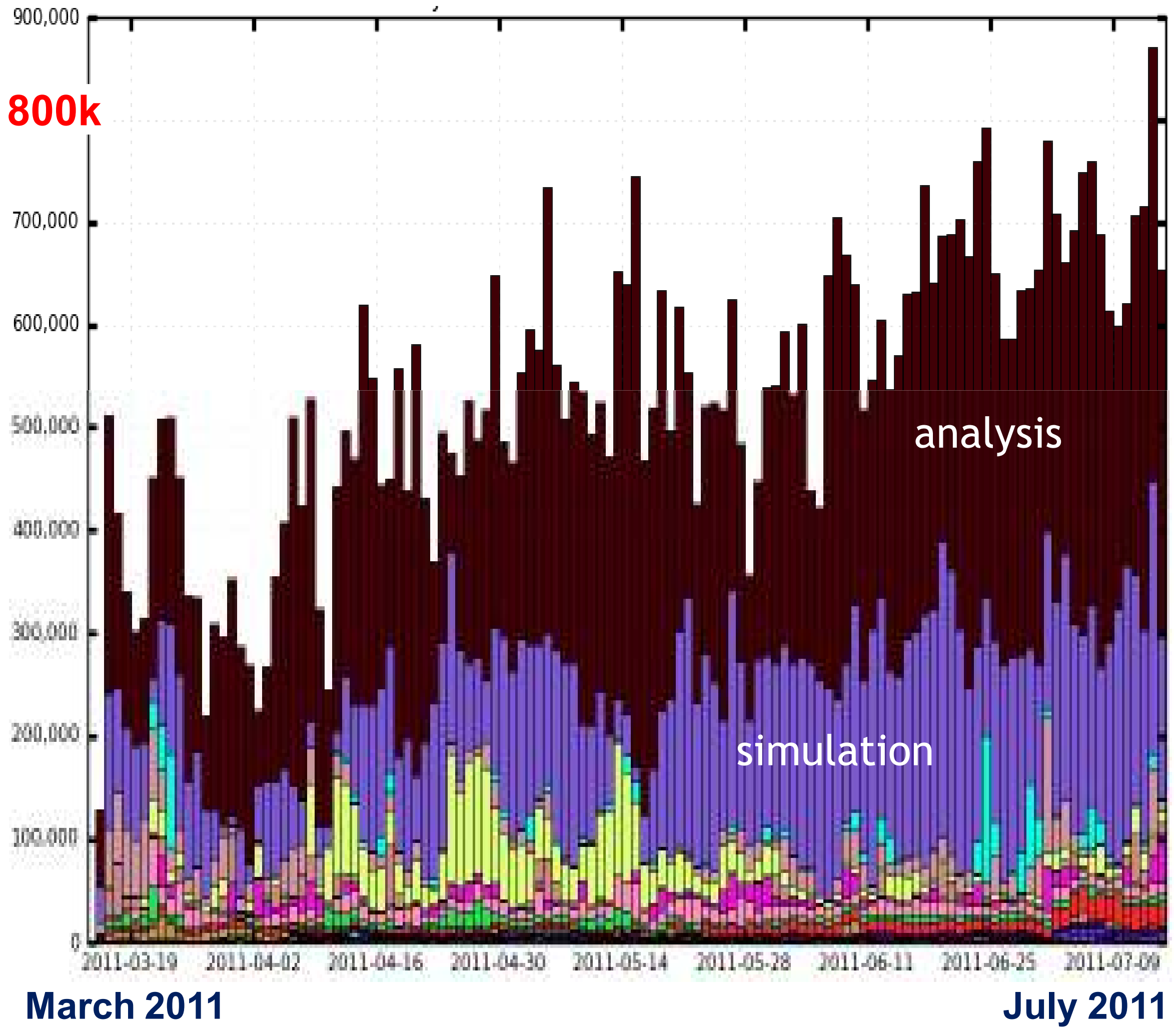
(Example from ATLAS)

Data preparation:
- First-pass reco. at Tier-0 within ~2 days
- Calibration/DQ good for physics analysis
- Data analysable on Grid within ~1 week

Tier-1 and Tier-2's process close to one M jobs per day alone for ATLAS (as example):
- simulation
- re-reconstruction (campaigns)
- group production (ntuples...)
- physics analysis

The high quality of the wLCG computing system allows LHC experiments to show results on data taken just after few weeks already

ATLAS jobs per day across all Tier-1 & Tier-2s



A few examples of the Physics Roadmap

General event properties

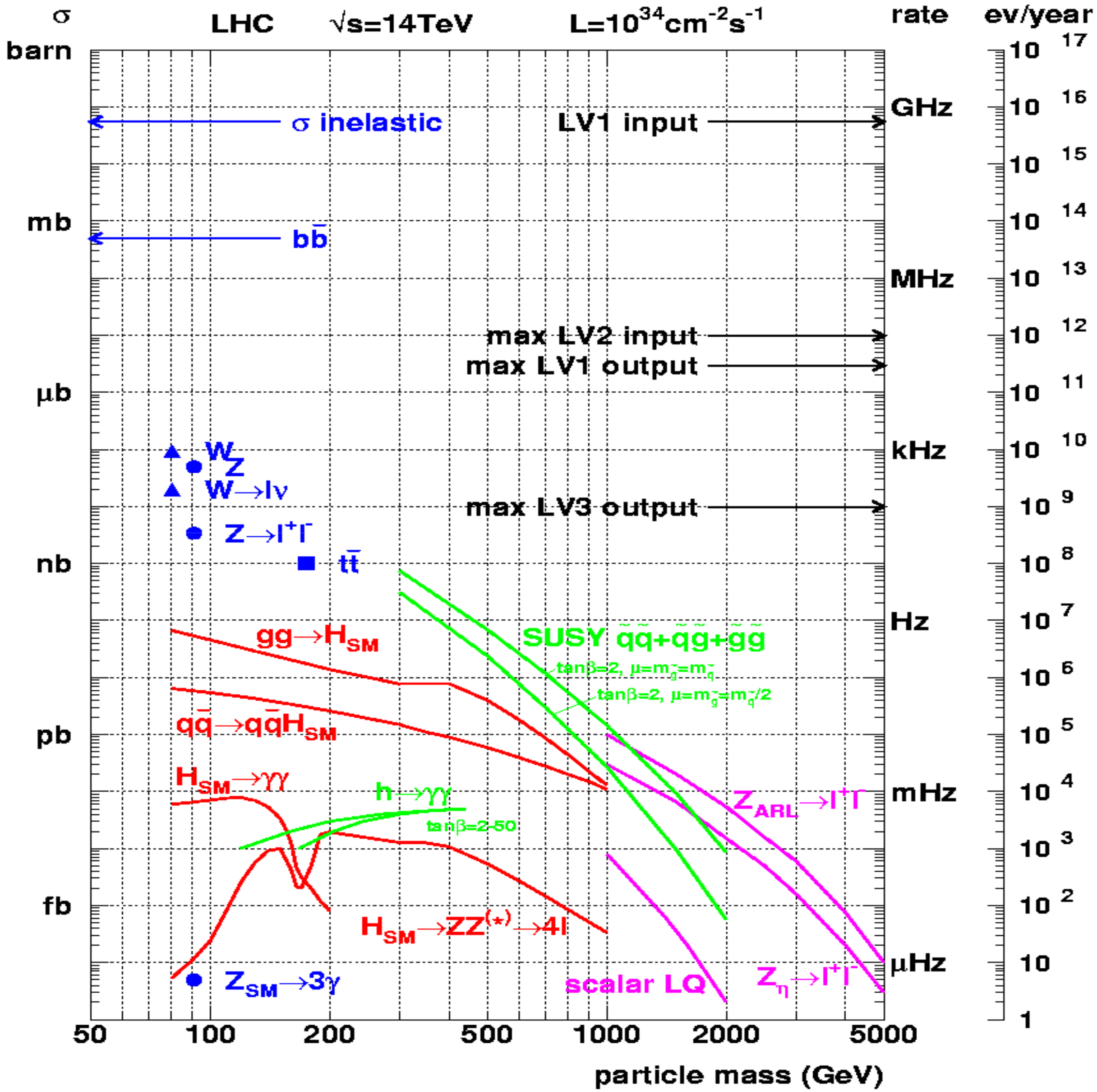
Heavy flavour physics

Standard Model physics including QCD jets

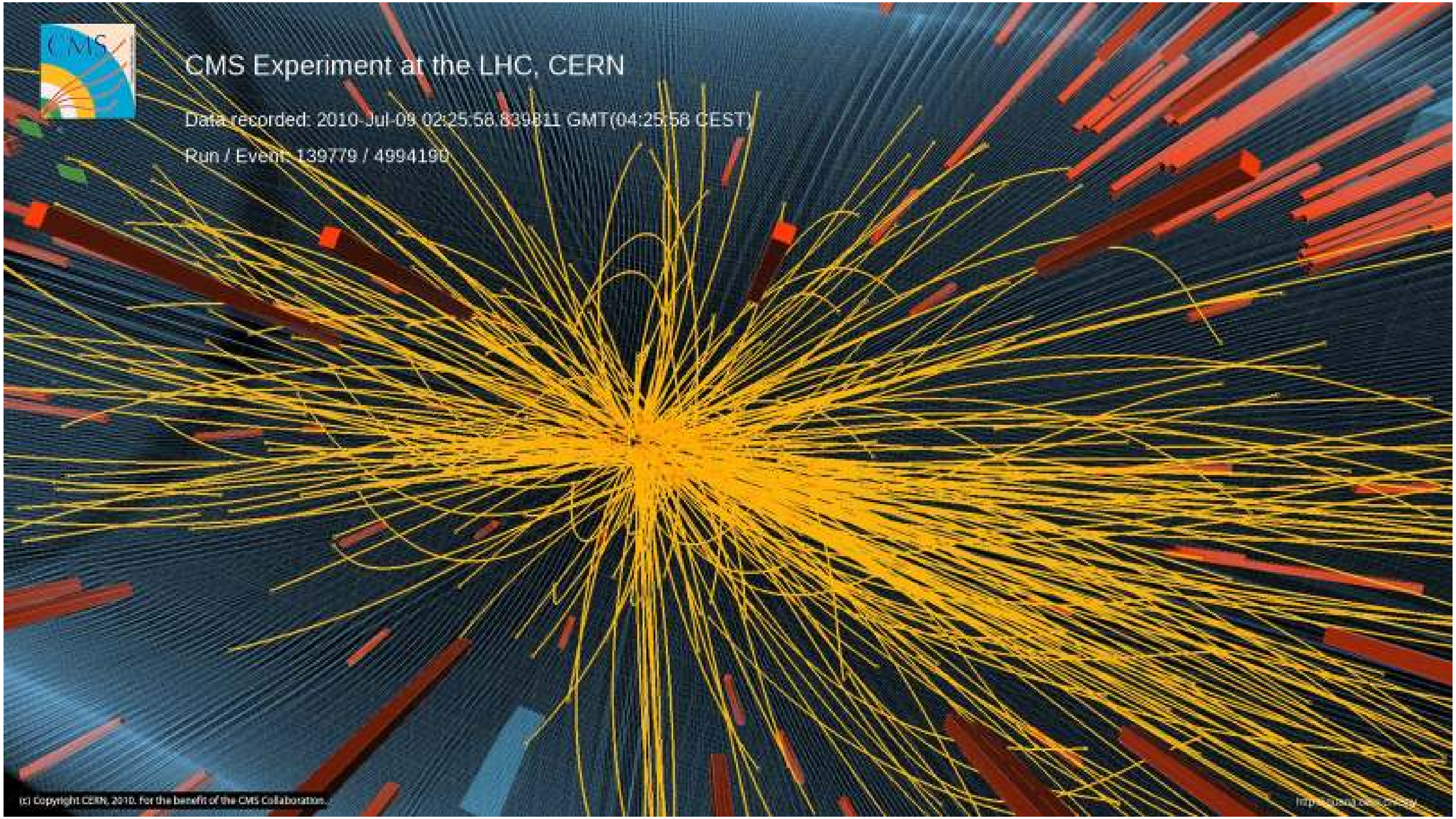
Higgs searches

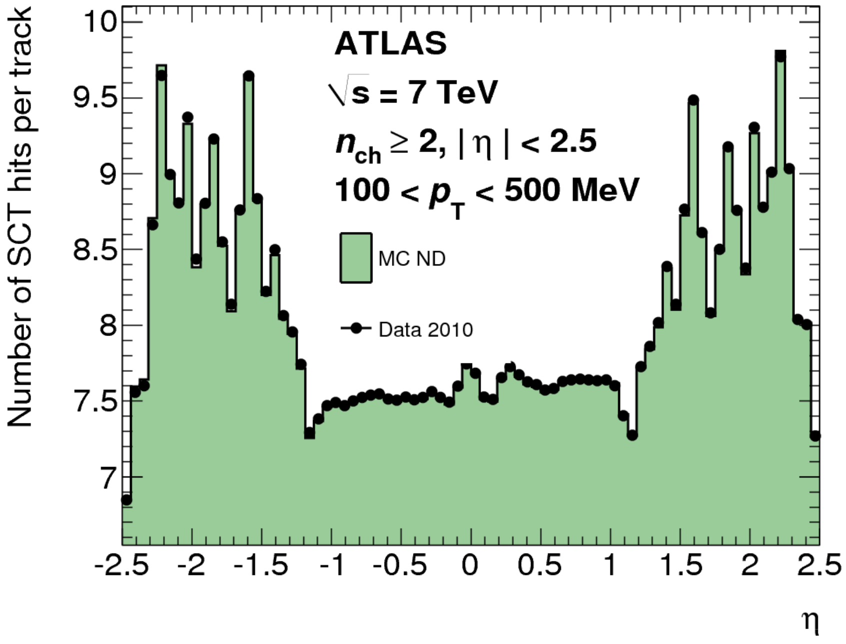
Searches for SUSY

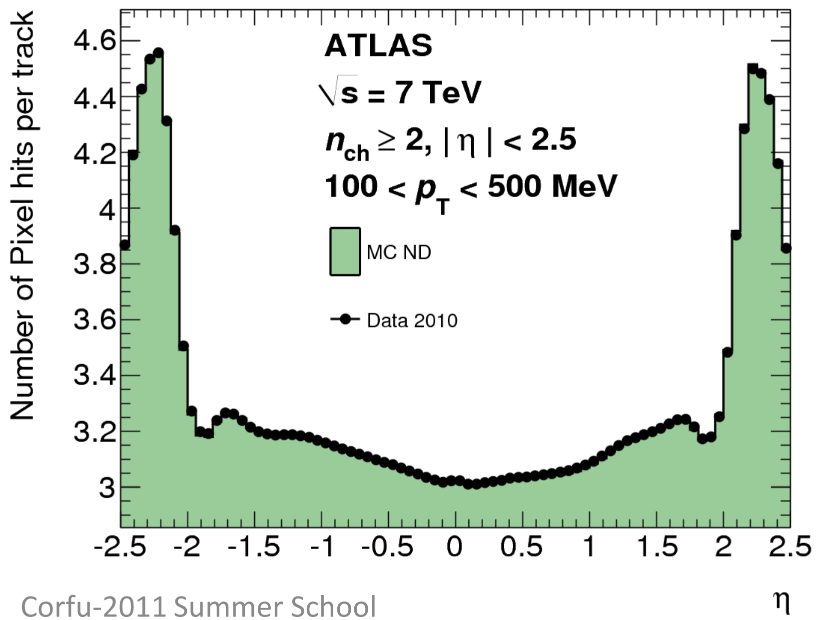
Examples of searches for ‘exotic’ new physics



General Event Properties



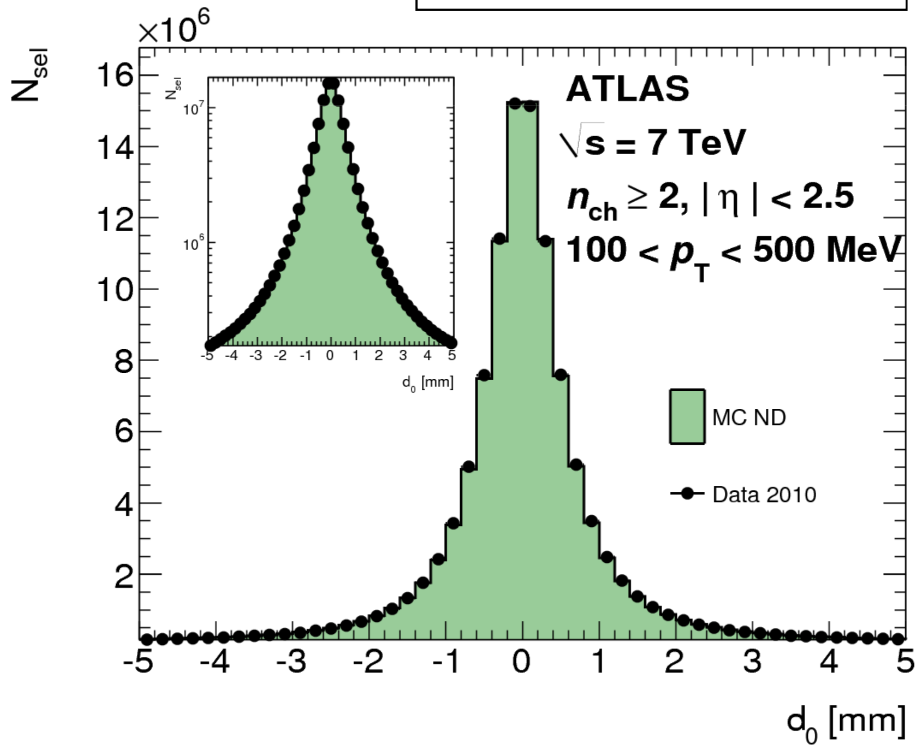




The tracking detector simulations are in a mature state, charged track measurements are well understood

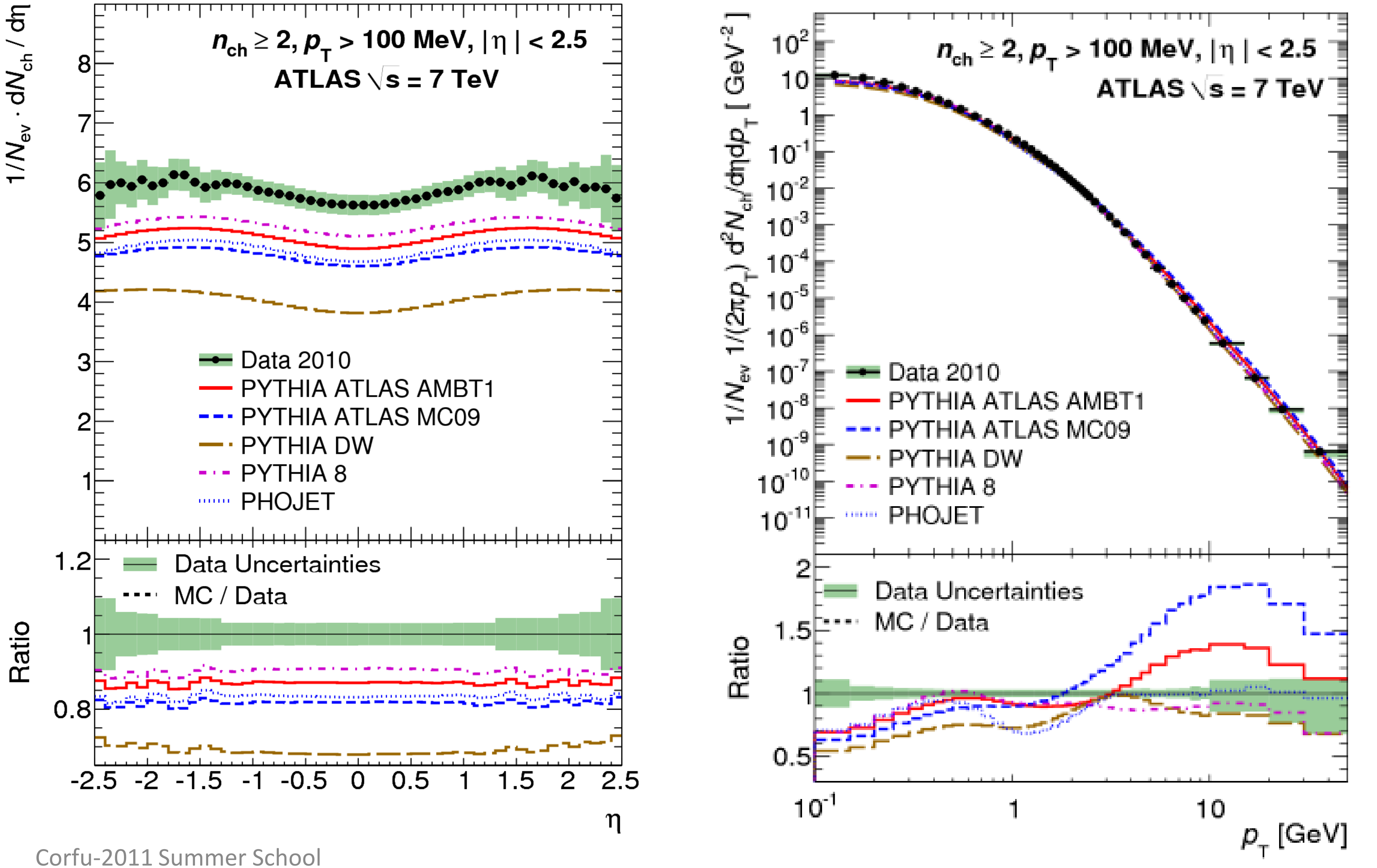
Example shows the ATLAS description of minimum bias tracks (silicon and pixel hits, transverse impact parameter)

New J. Phys. 13 (2010) 053033

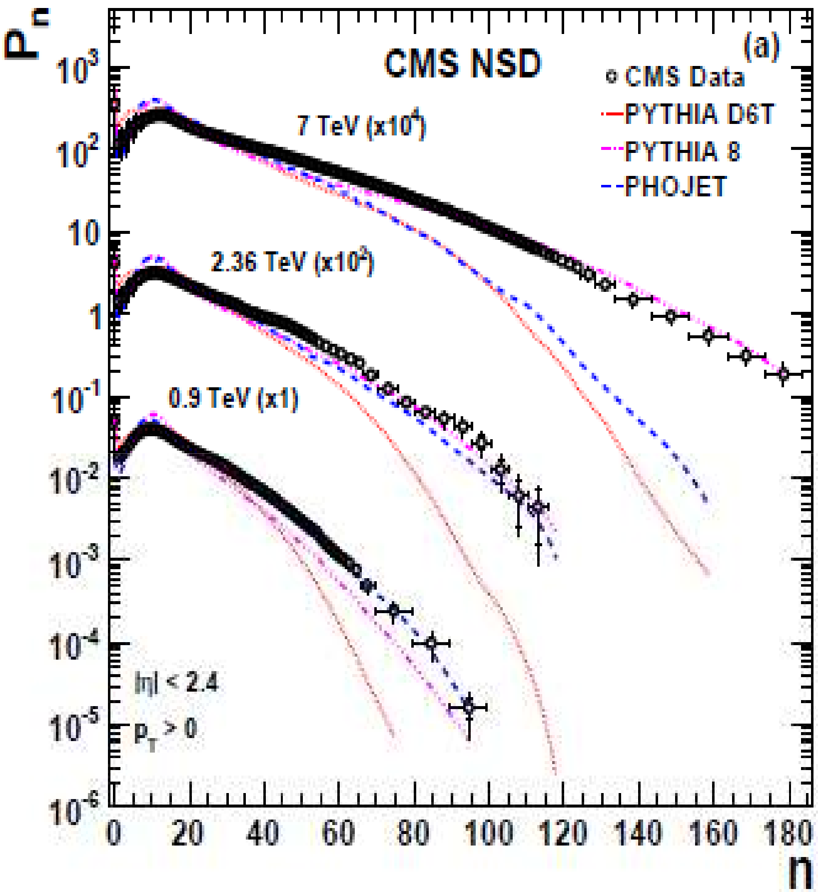


Charged-particle multiplicities as a function of pseudorapidity η and transverse momentum p_T for minimum bias events selected as specified, and compared to various Monte Carlo models

New J. Phys. 13 (2010) 053033

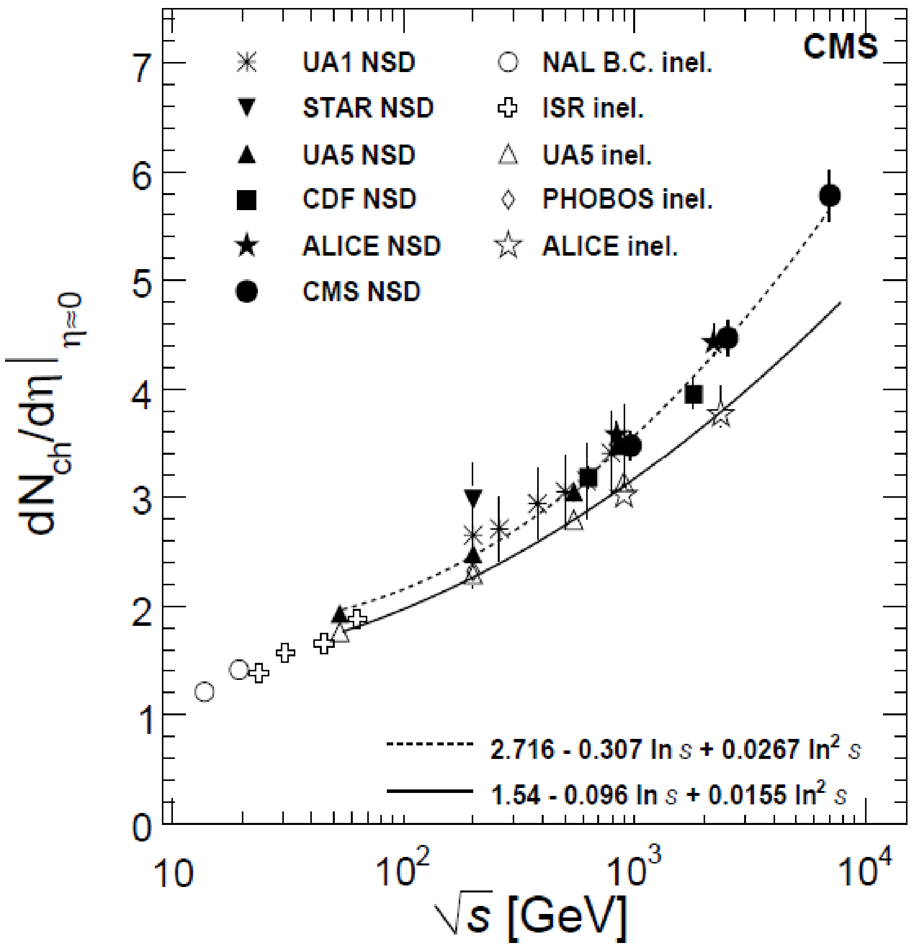


Charged hadron multiplicities at the three different √s



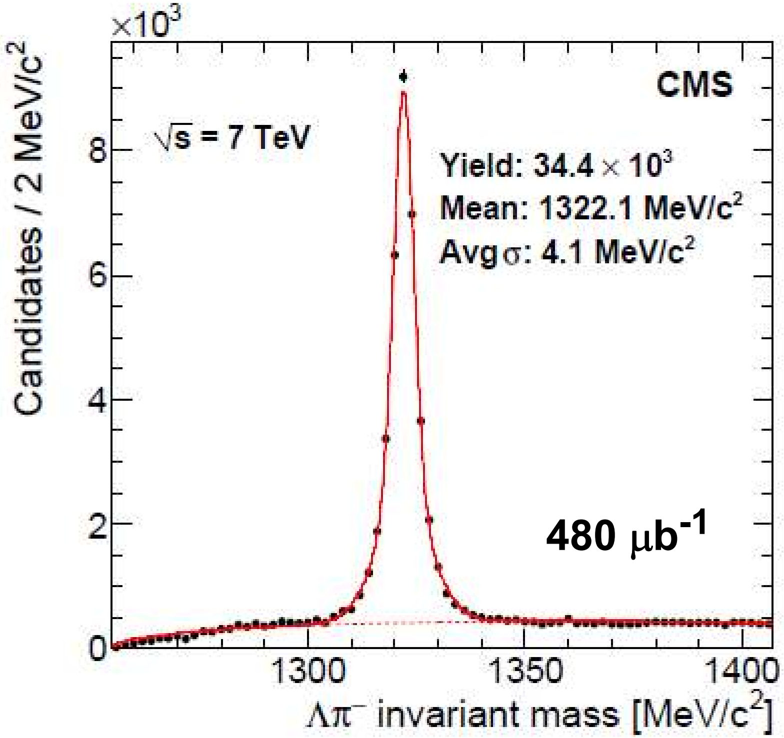
JHEP 01 (2011)079

Average charged particle density for the central η region (pp and p$\bar{p}$)



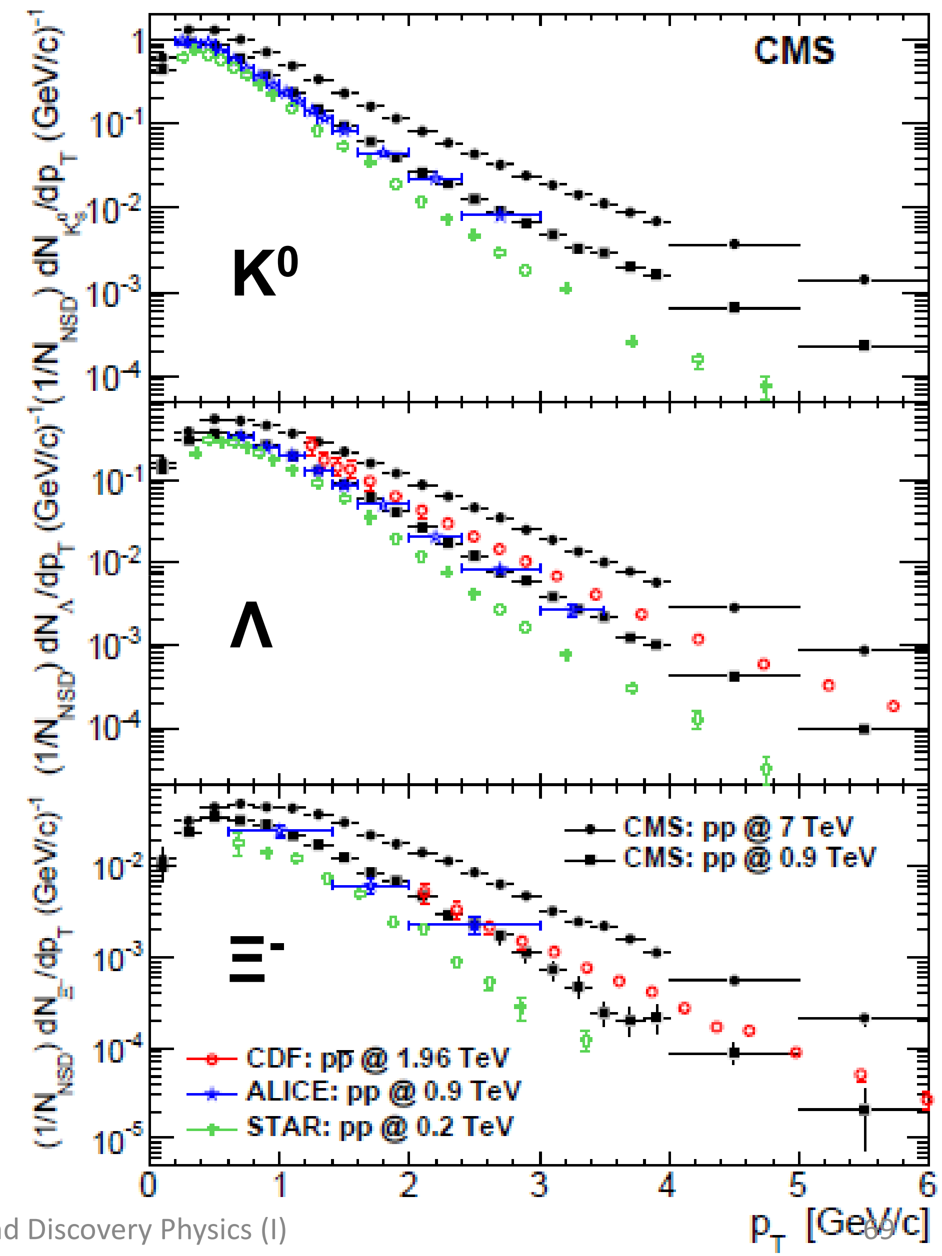
Phys. Rev. Lett. 105 (2010) 022002

Strange particle production spectra

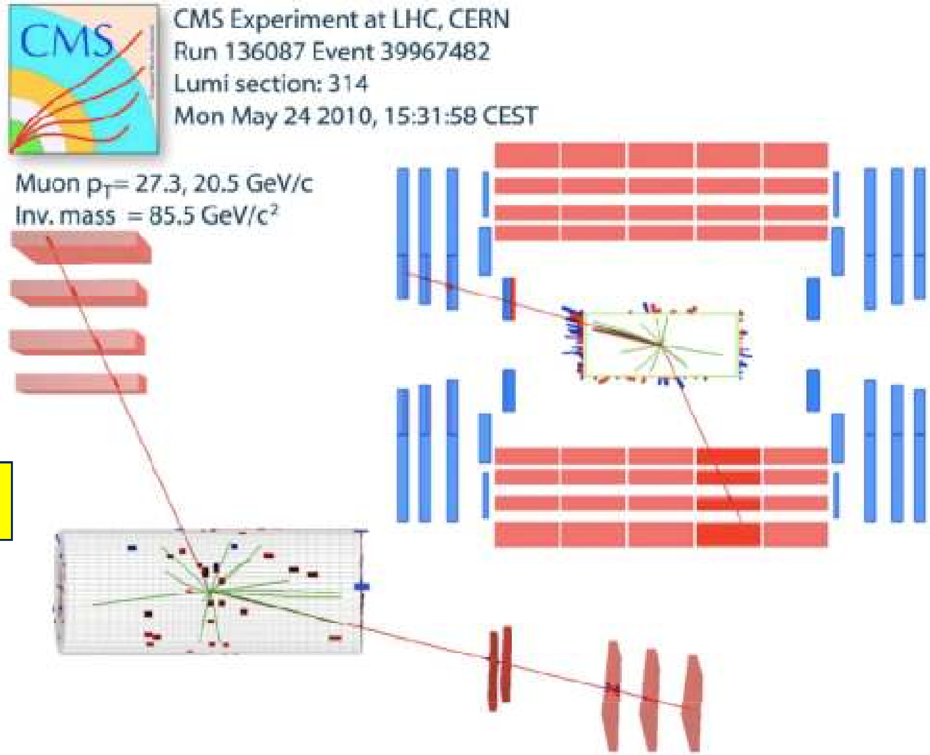


Example $\Xi^- \rightarrow \Lambda\pi^-$

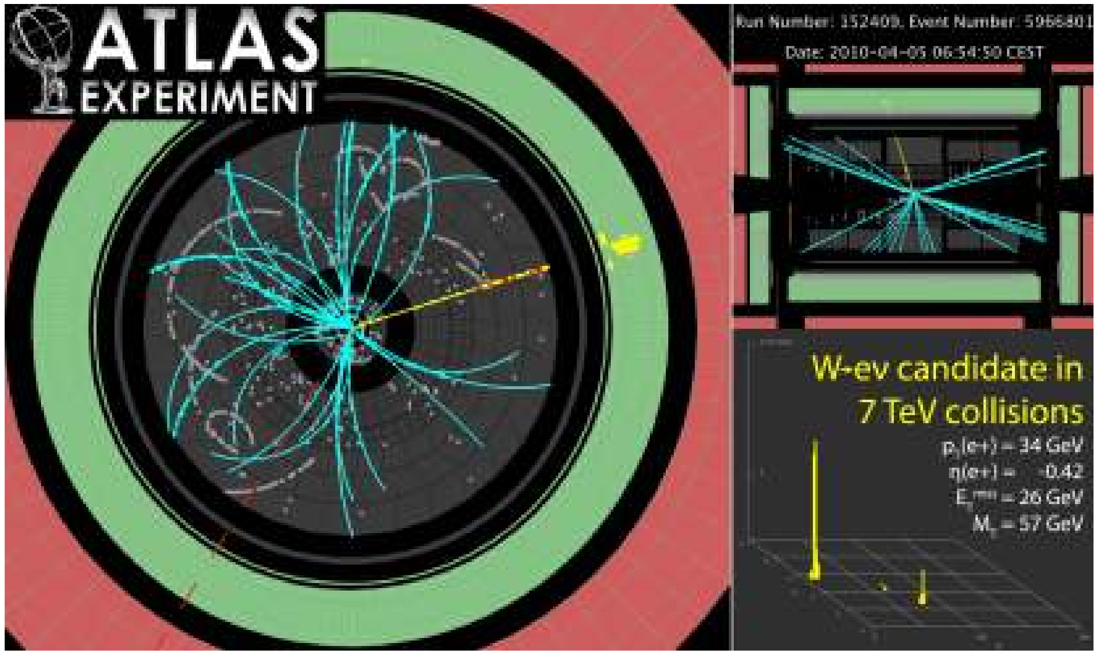
JHEP 05 (2011) 064

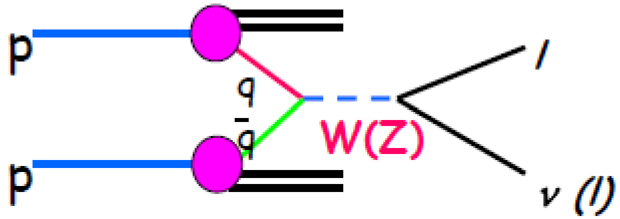


Standard Model Physics



CMS candidate Z → $\mu^+\mu^-$

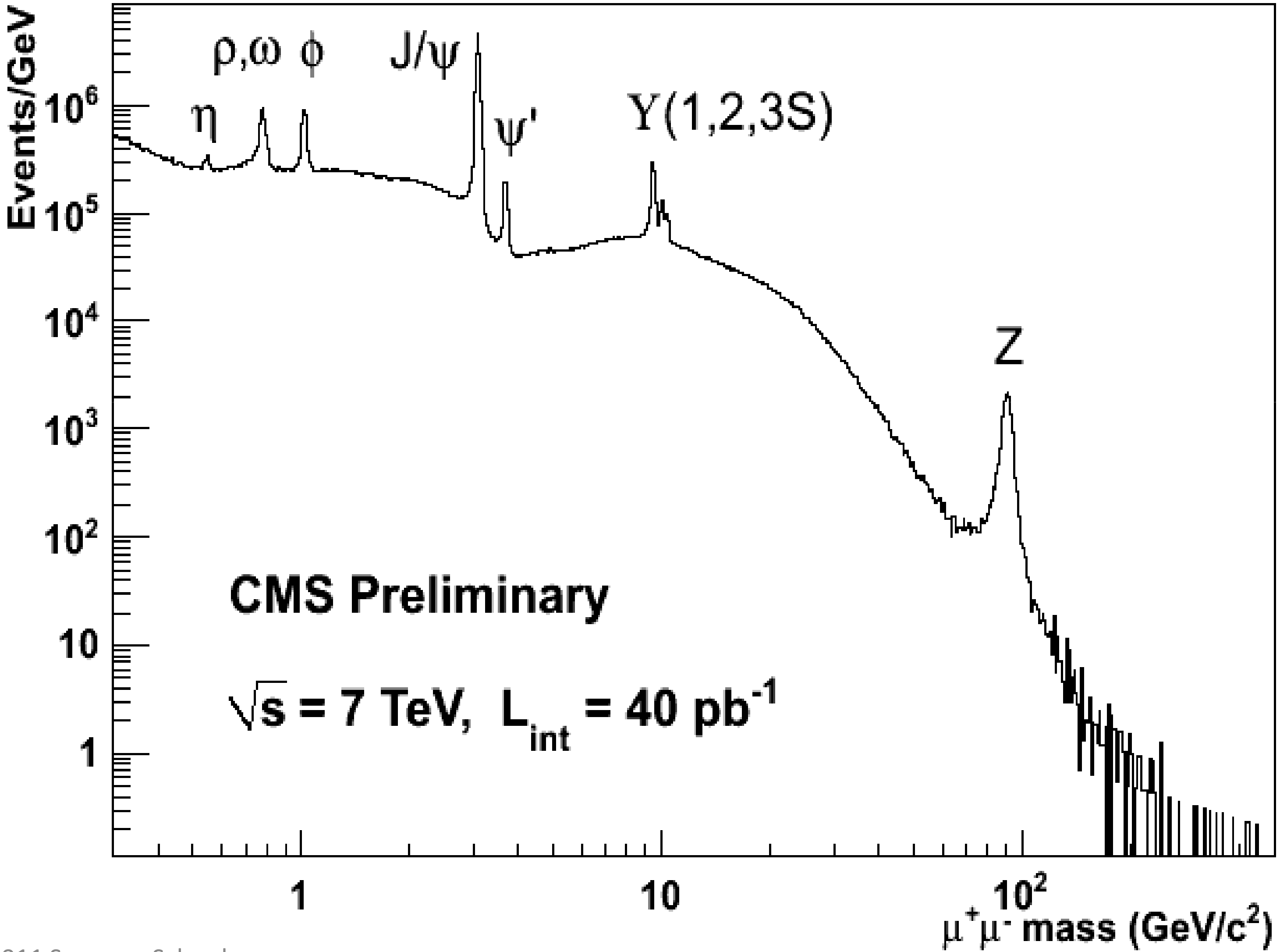




ATLAS W → eν candidate

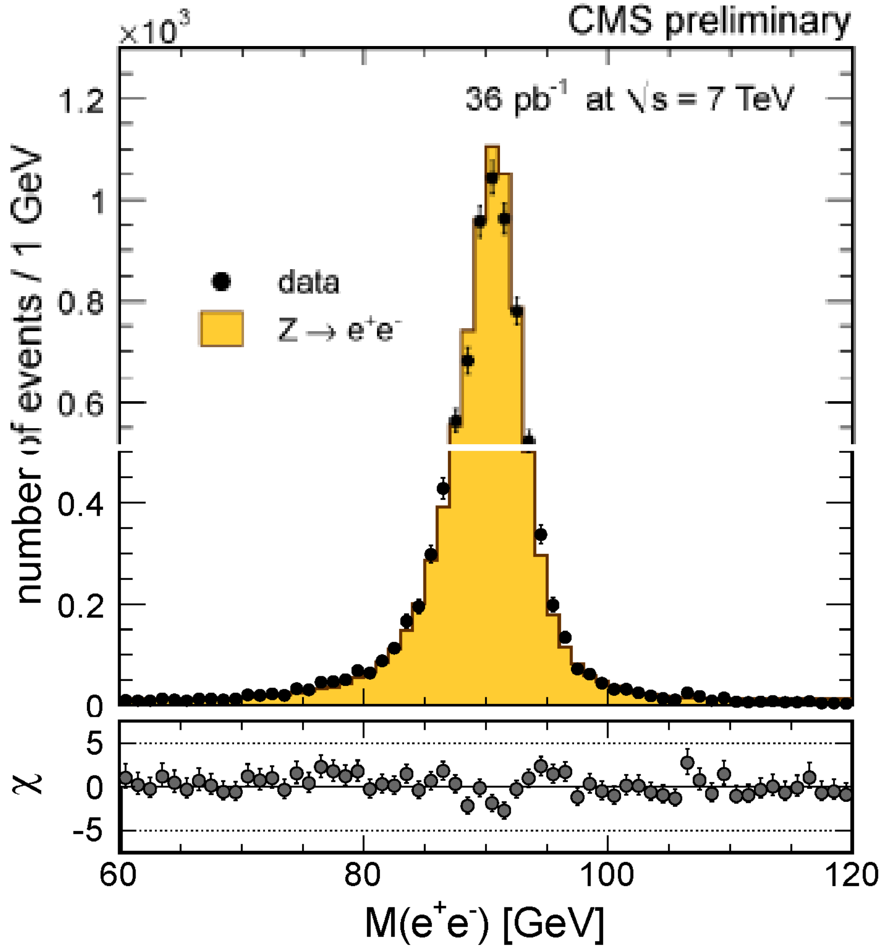
Di-lepton invariant mass spectra

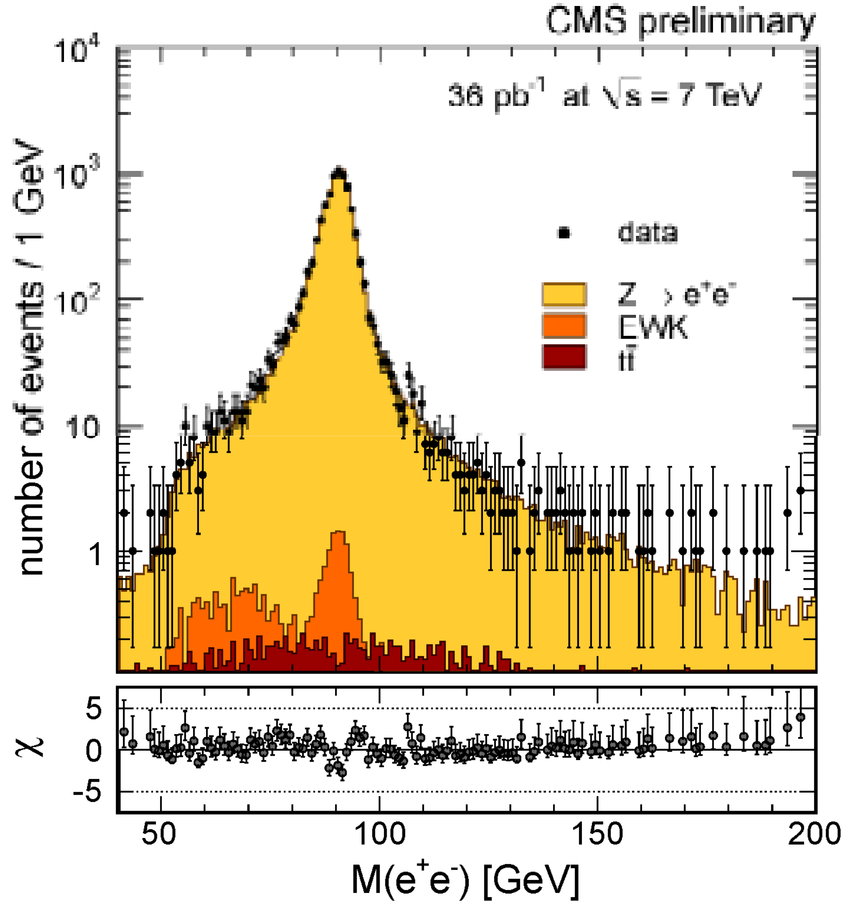
The di-muon spectrum recalls a long period of particle physics:



Z and W production

Sub. to JHEP
arXiv:1107.4789[hep-ex]

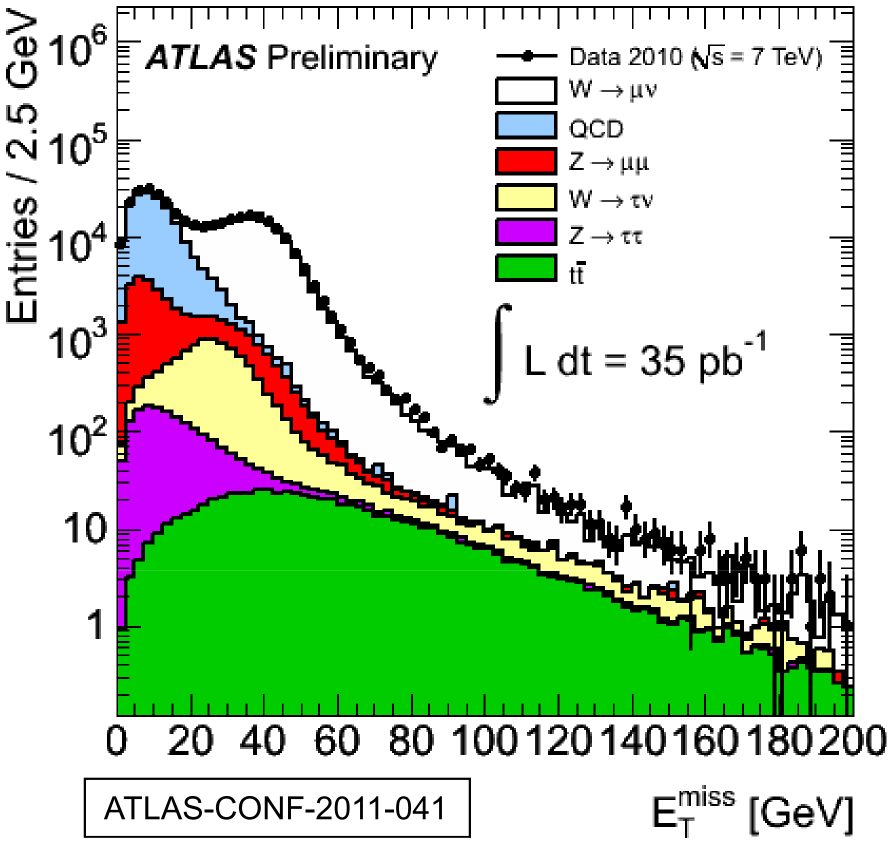




Z peak (di-lepton pair mass distributions)

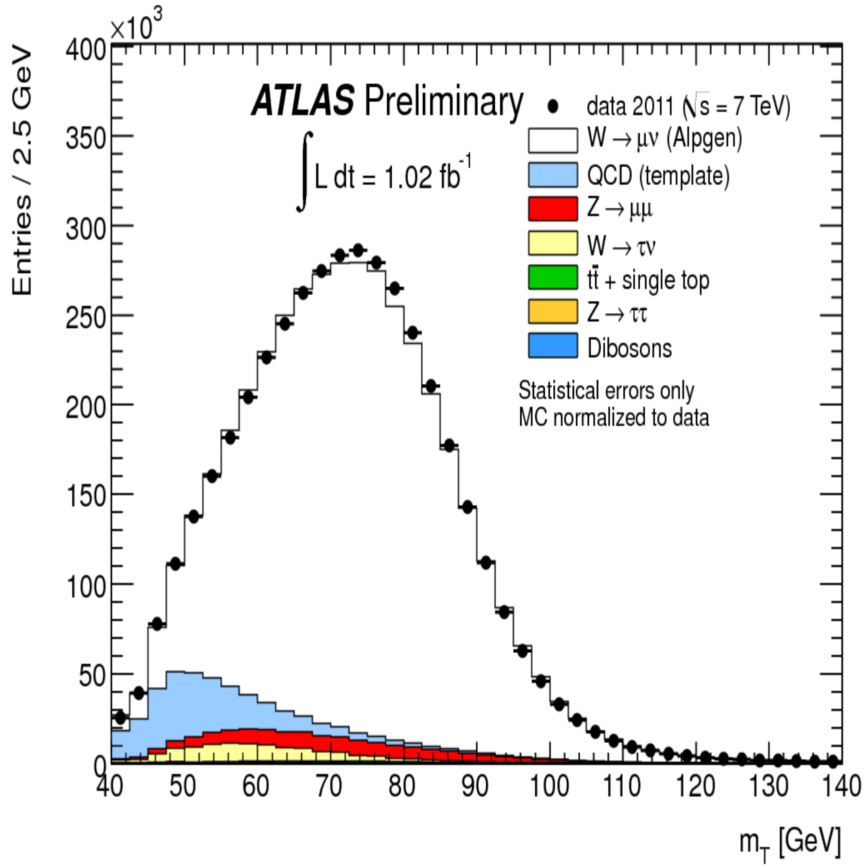
$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

W transverse mass



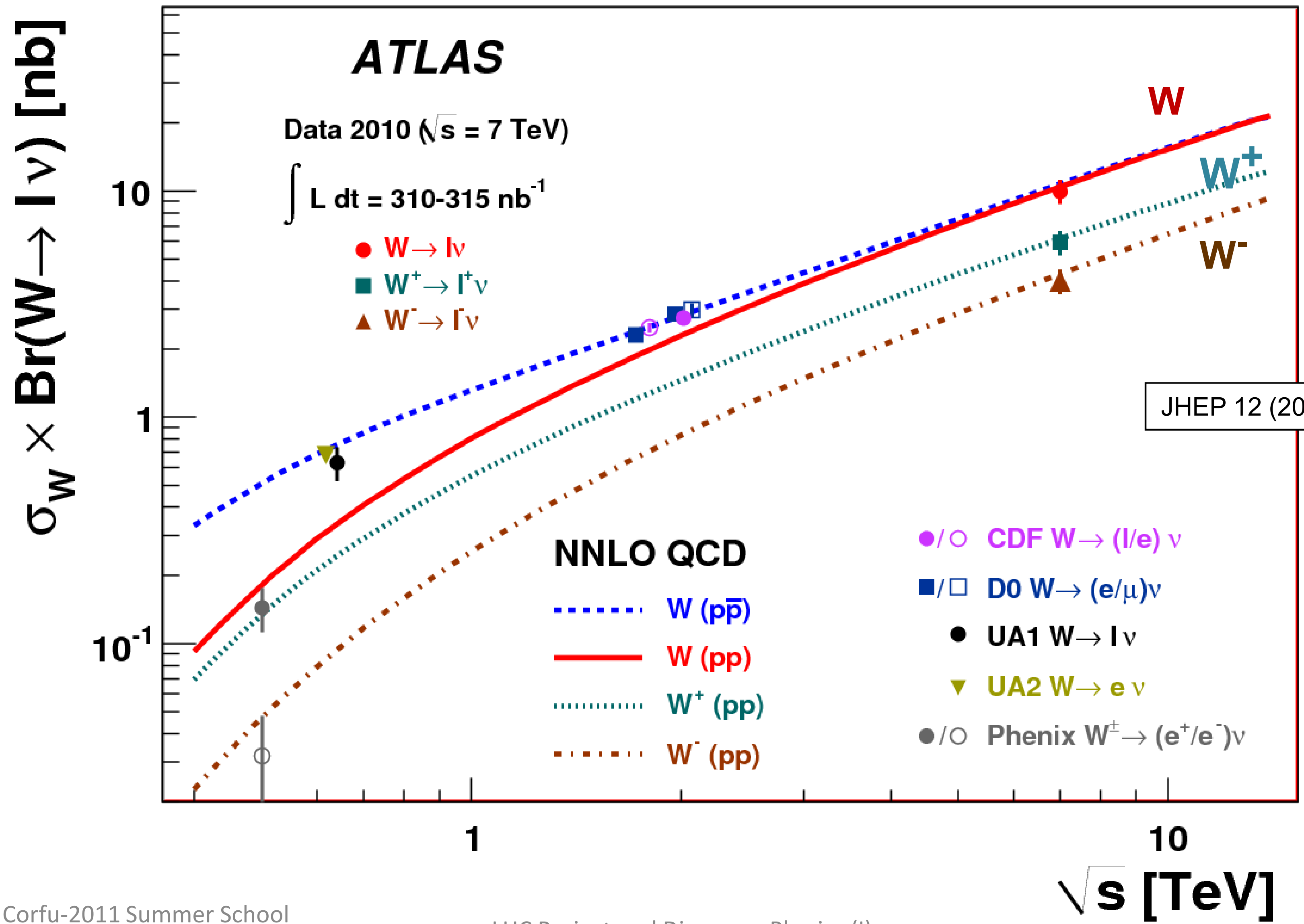
Missing transverse energy from the W → μ + ν decays

μ with p_T>20 GeV, E_T^{miss}>25 GeV



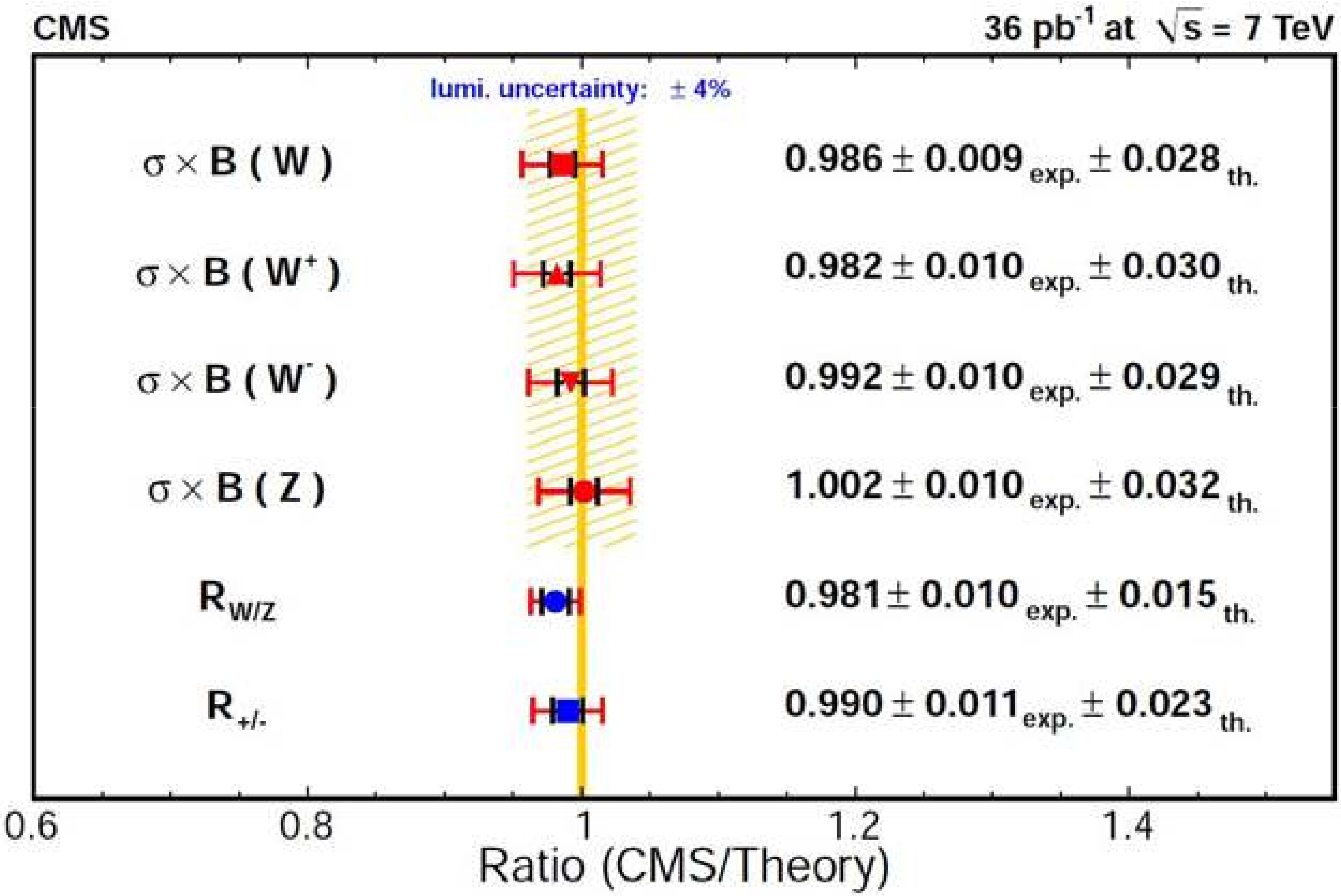
$$m_T = \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

Very early W cross section measurement with e and μ



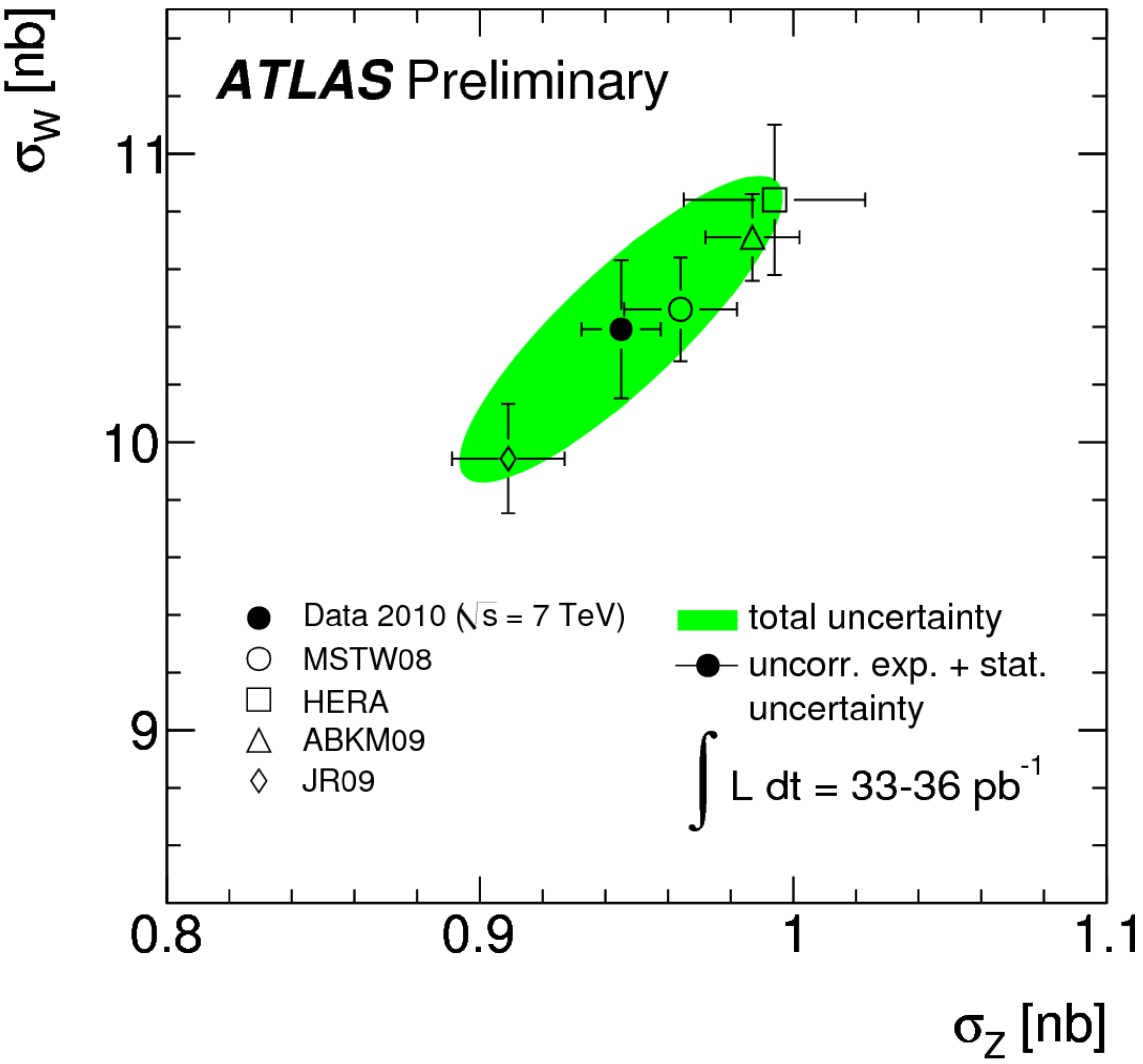
JHEP 12 (2010) 060

Full 2010 data set measurements from CMS



Sub. to JHEP
arXiv:1107.4789[hep-ex]

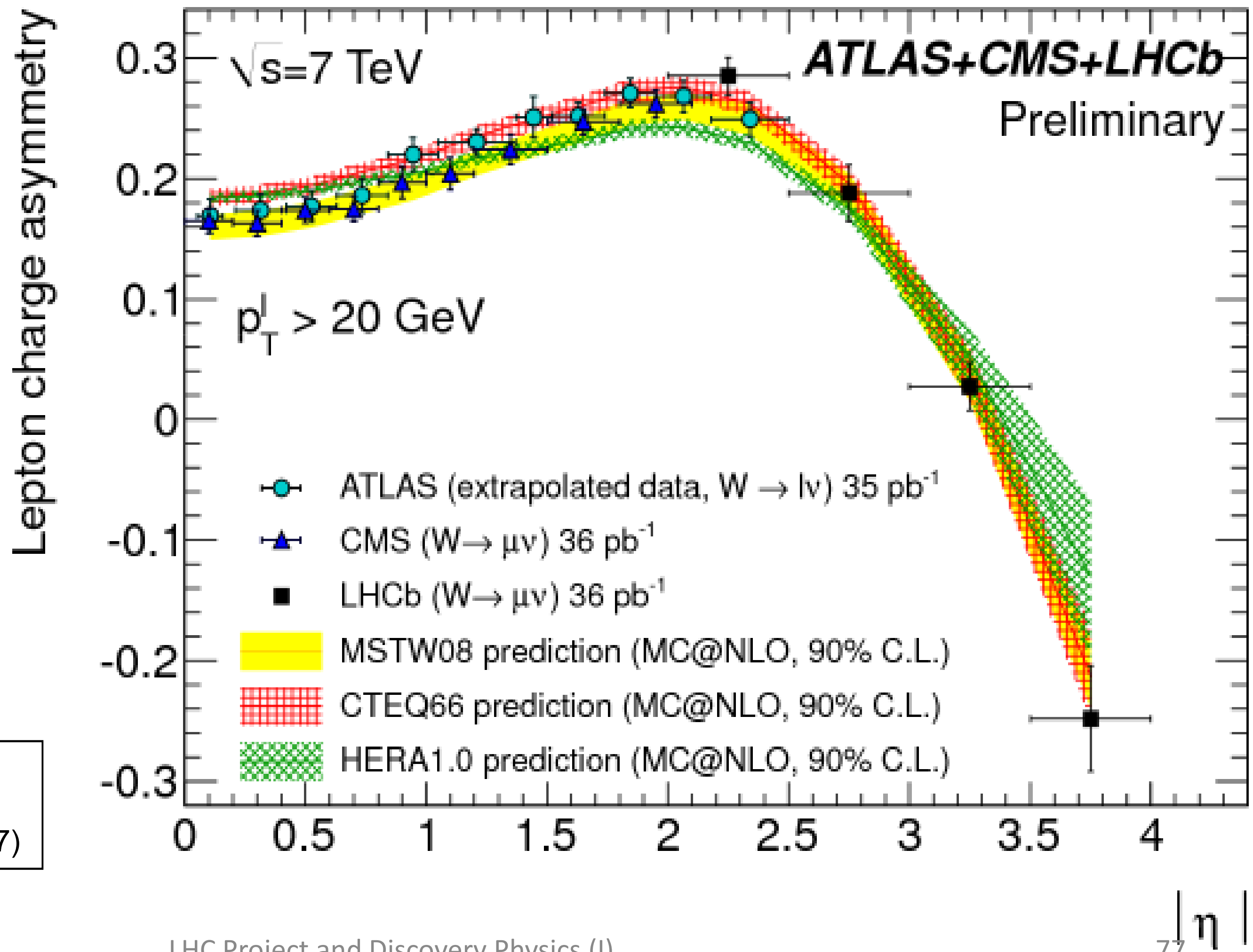
Full 2010 data set from ATLAS



ATLAS-CONF-2011-041

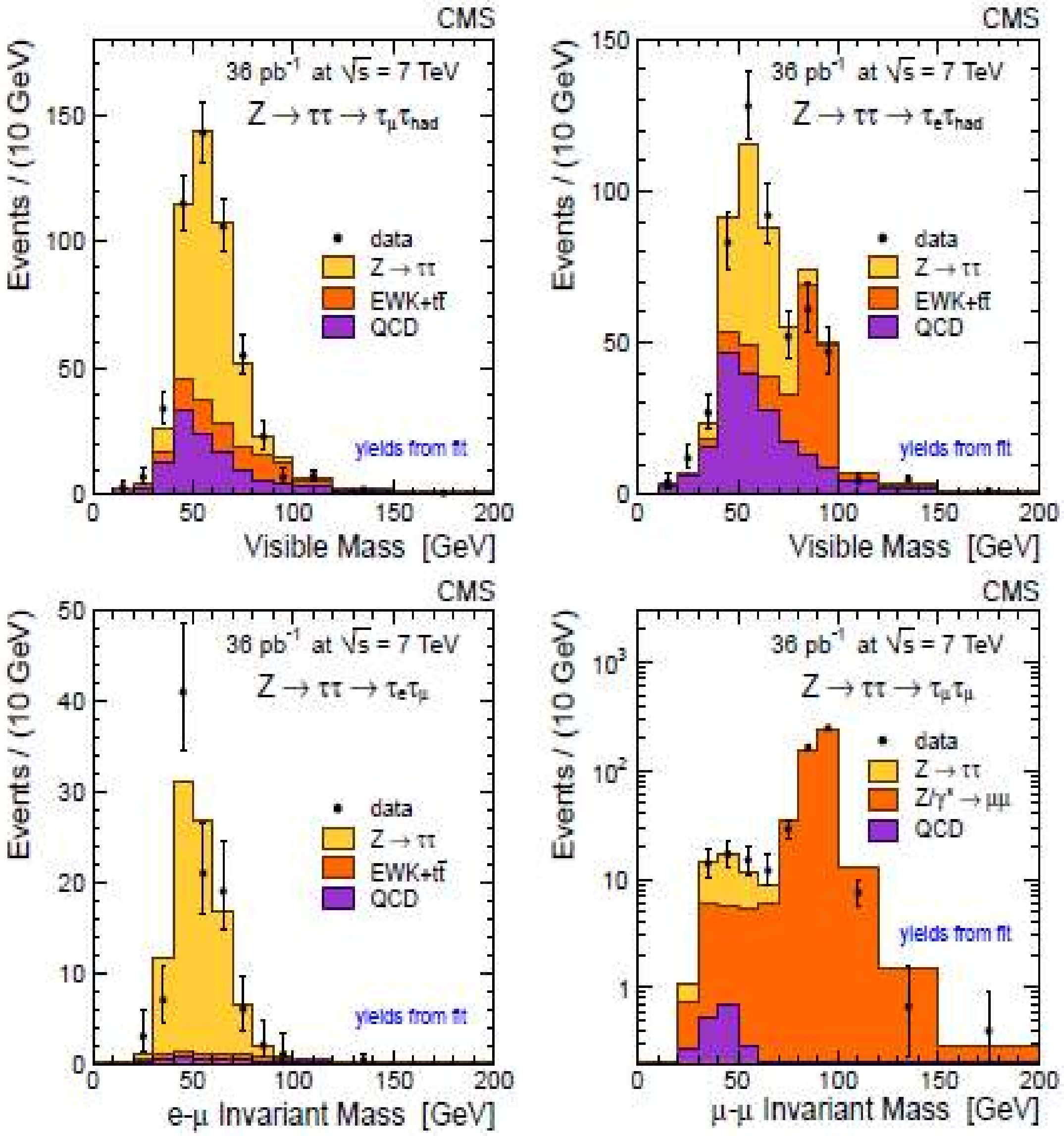
Lepton charge asymmetry from W decays in pp collisions at 7 TeV

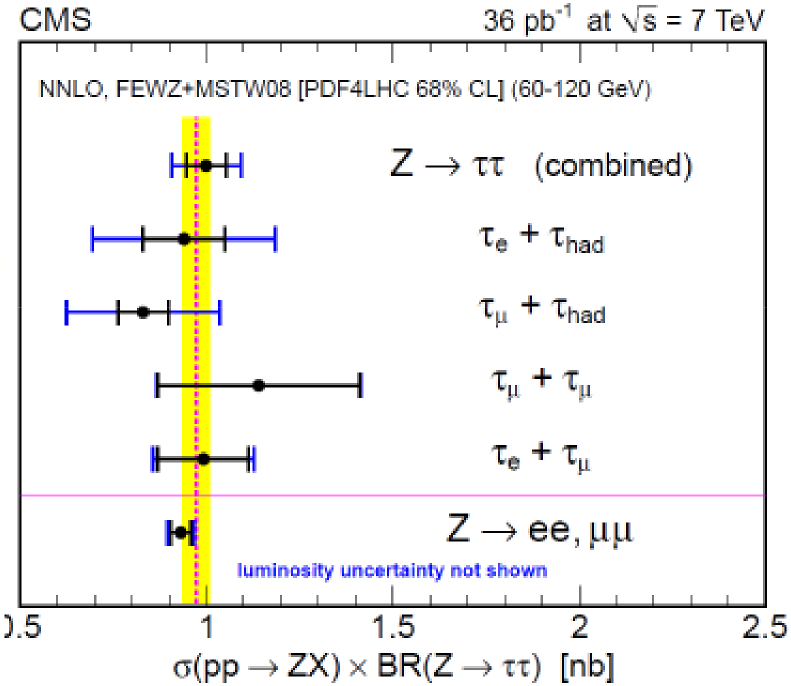
$$A(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})},$$



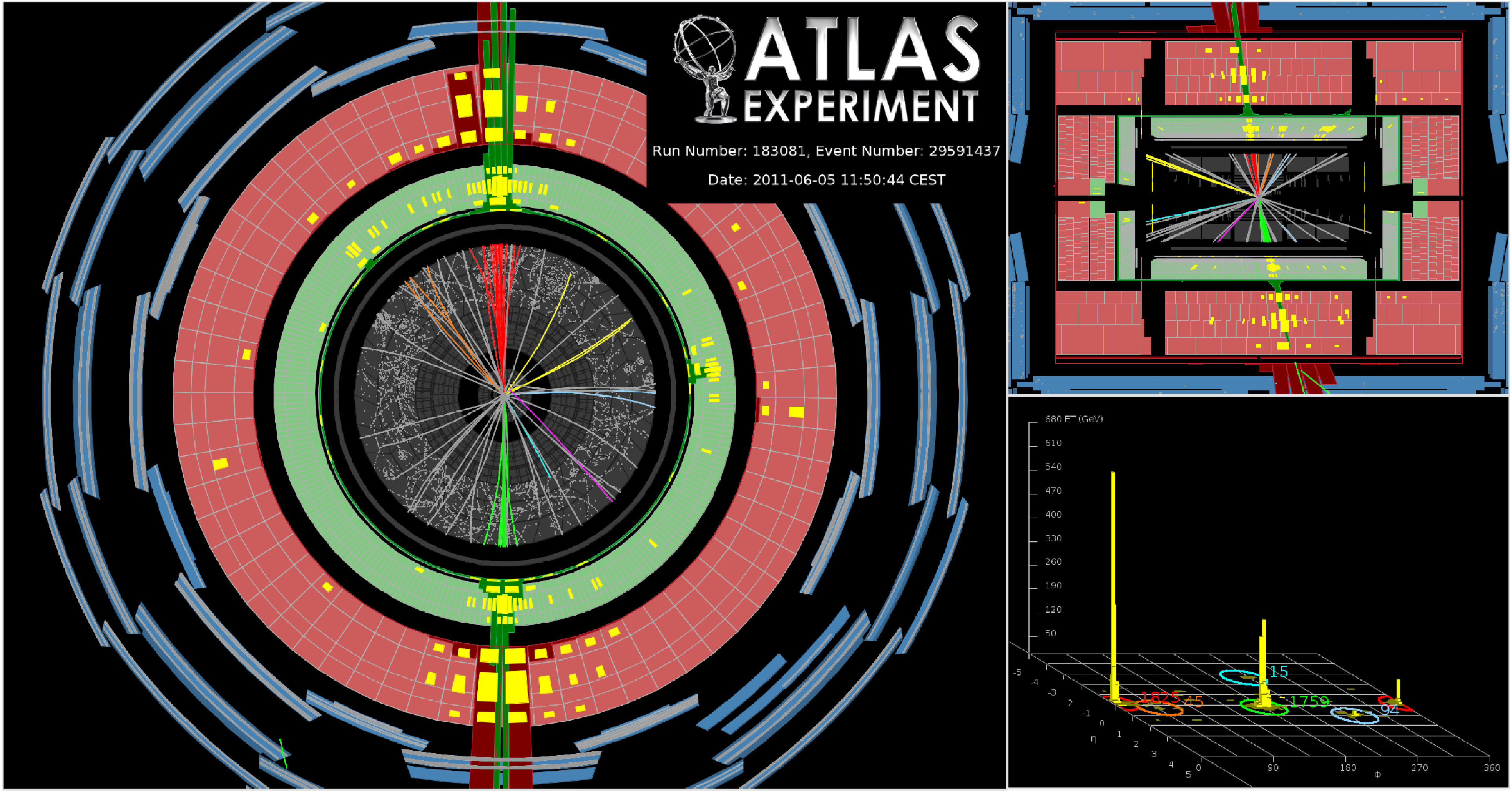
ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006 (aXiv:1103.3407)

Example of using τ's





Sub. to JHEP
arXiv:1104.1617[hep-ex]

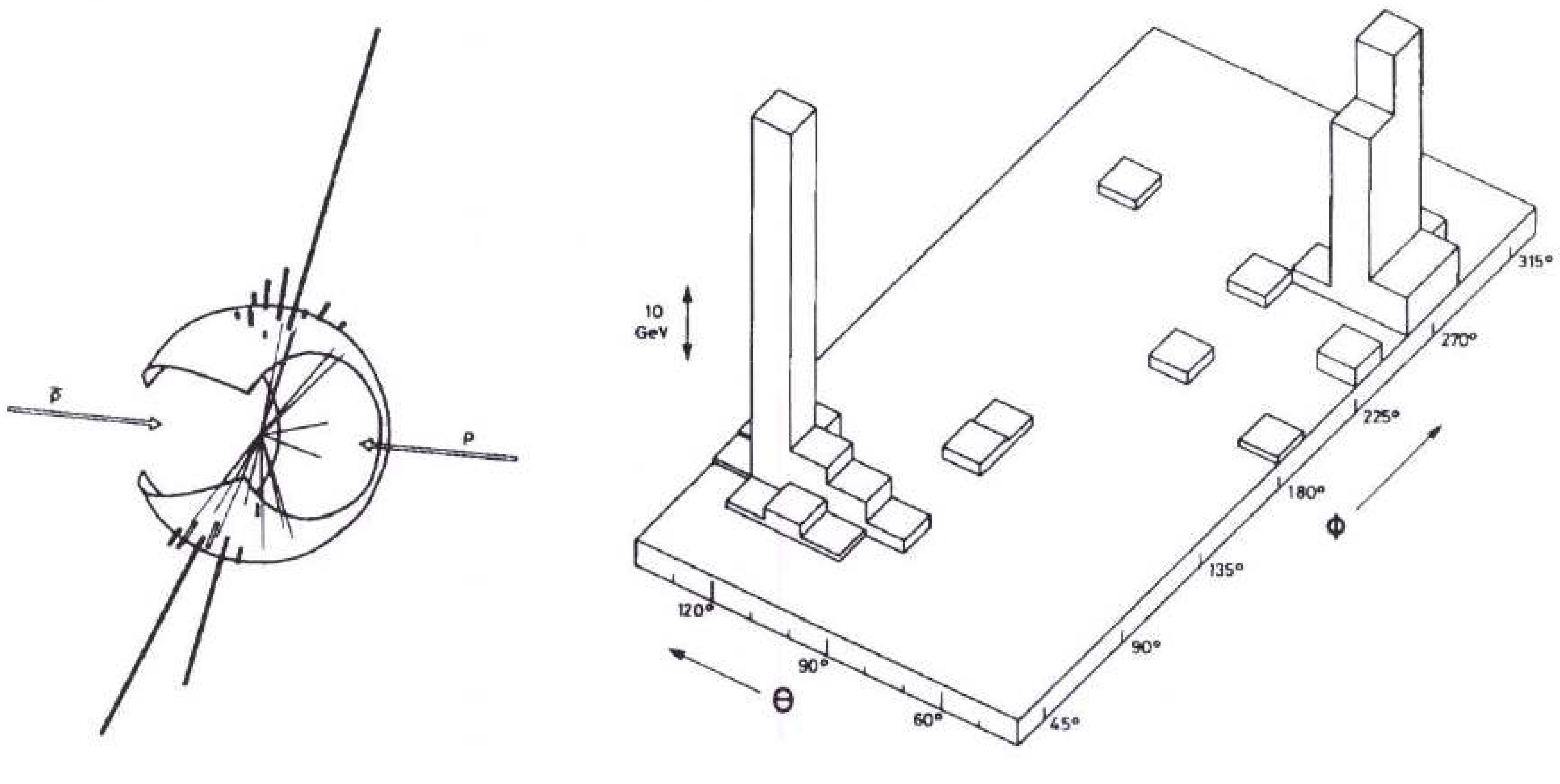


Jets with 1.9 and 1.7 TeV transverse momenta (p_T)

Jets

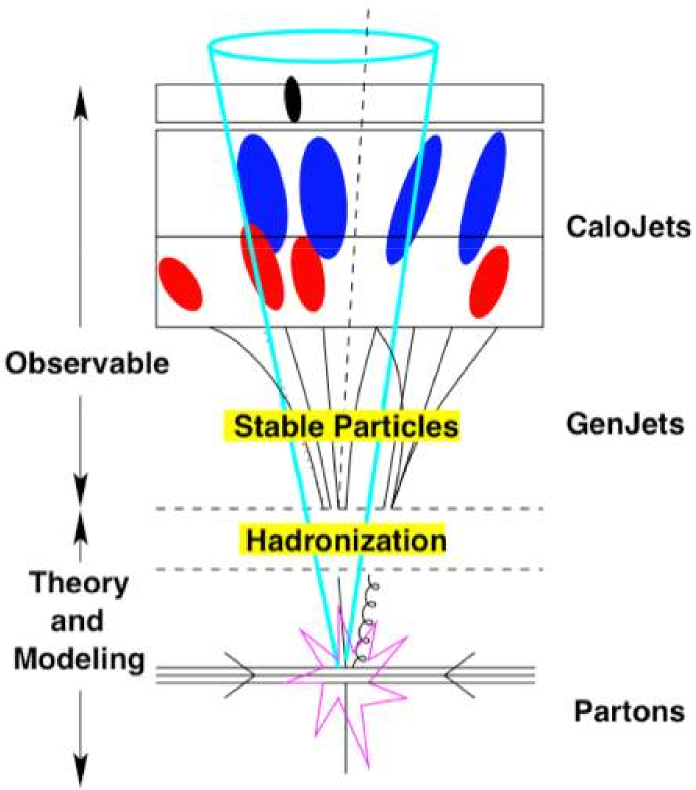
Note also that the event displays have become more sophisticated since the first spectacular events, hand-drawn, at a hadron collider …

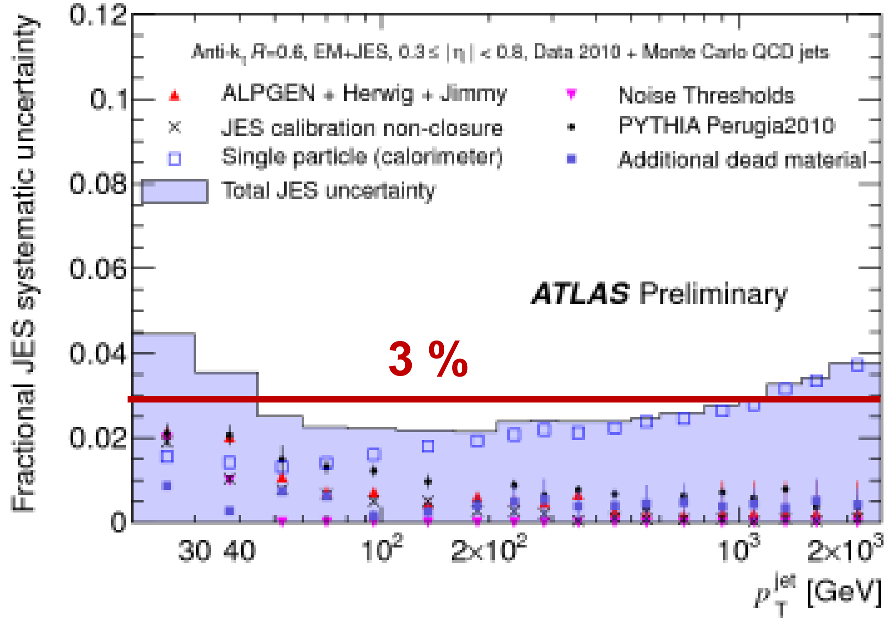
Volume 118B, number 1, 2, 3 PHYSICS LETTERS 2 December 1982

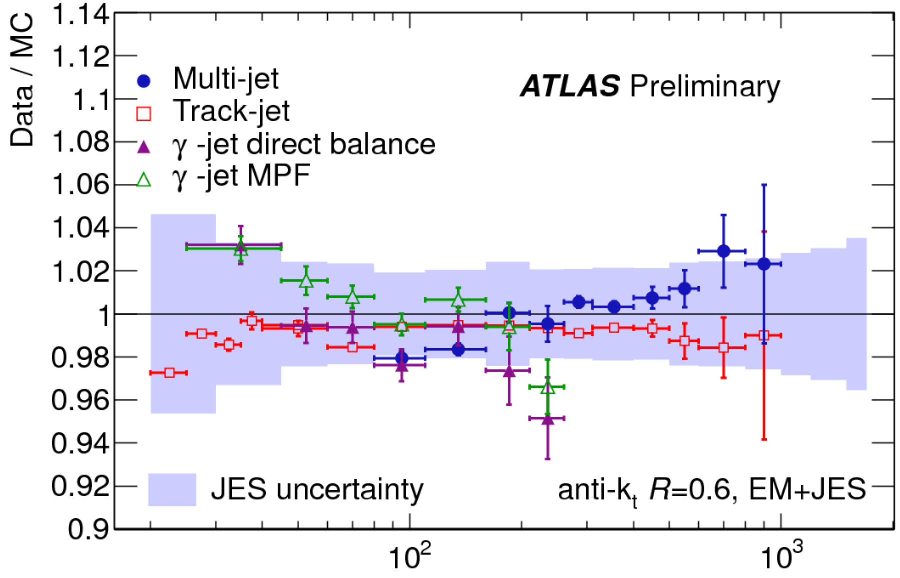


(a) (b)

A considerable effort went into understanding the Jet Energy Scale (JES), the dominant source of uncertainties for most jet measurements







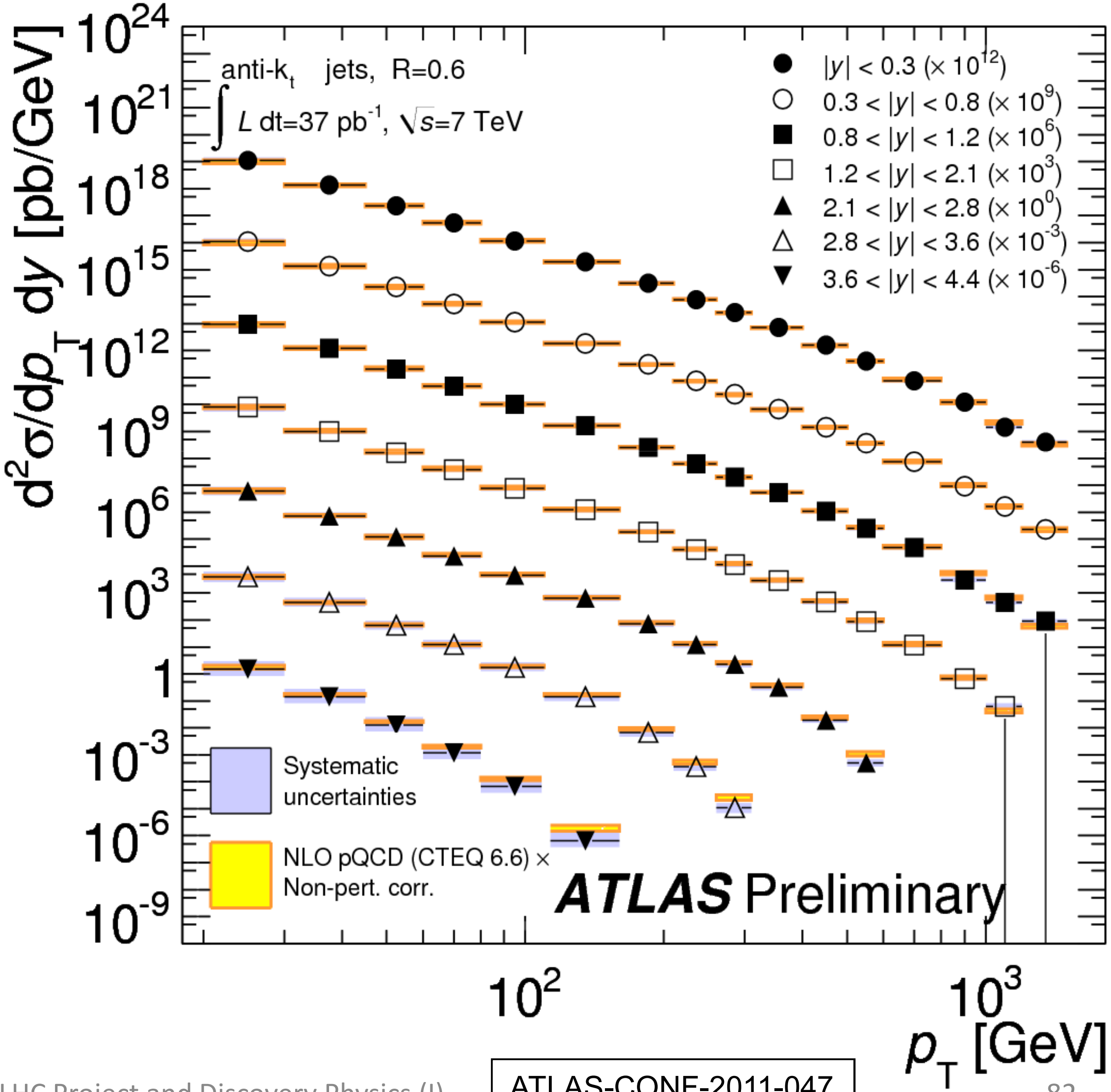
ATLAS-CONF-2011-032

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

Inclusive jet cross sections in various rapidity intervals

The data are spanning:

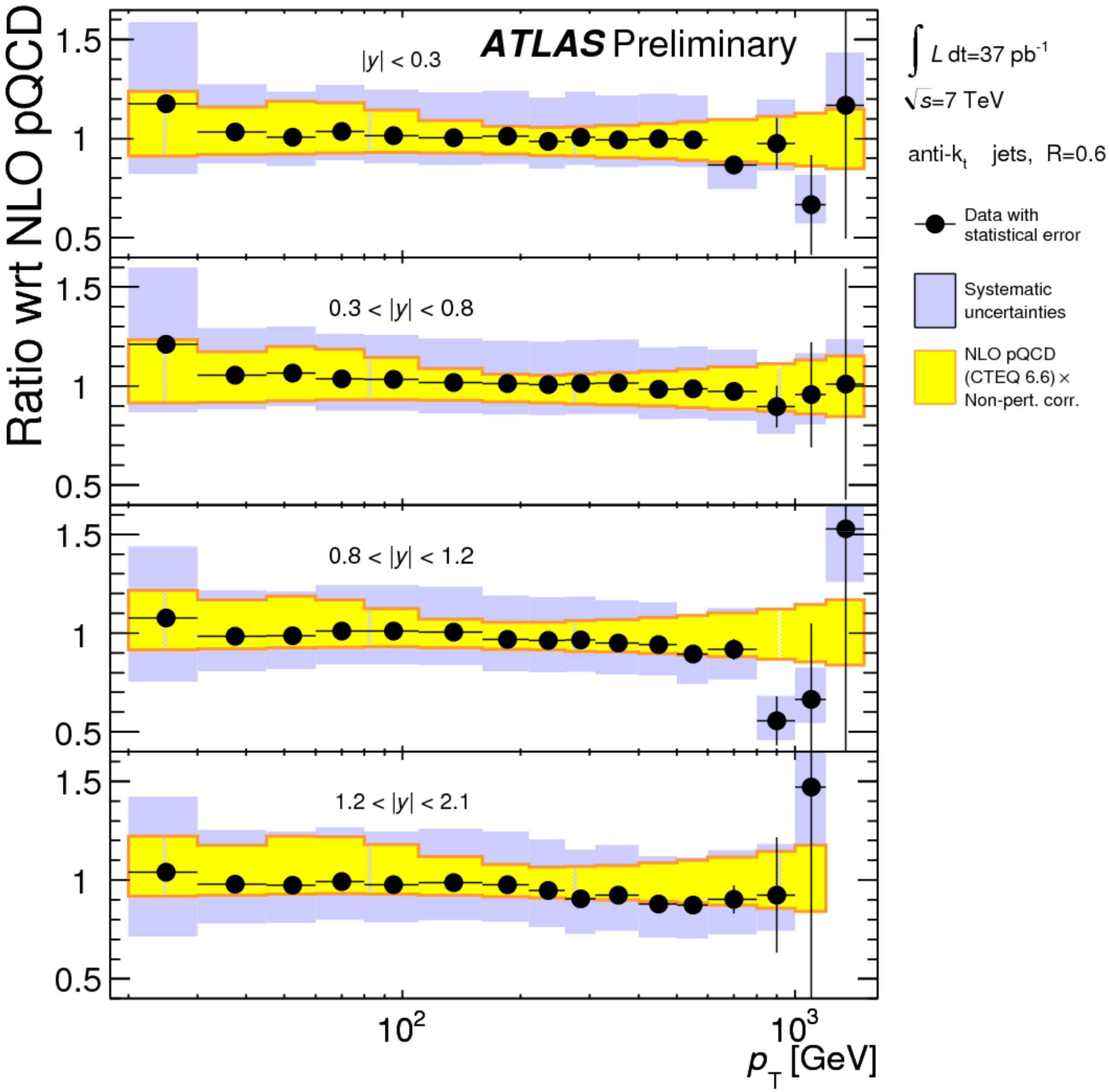
- **20 GeV < p_T < 1500 GeV**
- **|η| < 4.4**
- **Up to 12 orders of magnitudes in cross-sections**



ATLAS-CONF-2011-047

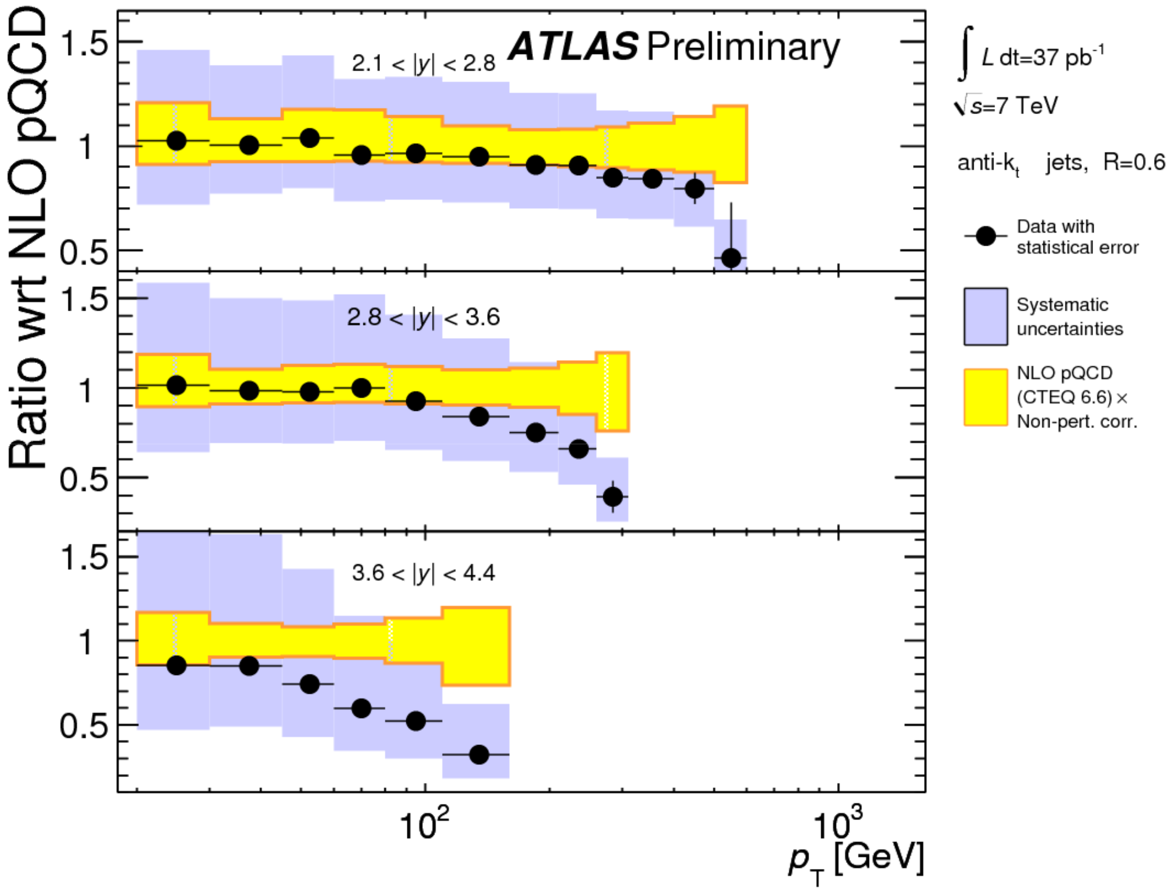
Systematic uncertainty dominated by JES

Good agreement between data and NLO pQCD with various PDFs globally…



ATLAS-CONF-2011-047

Systematic uncertainty dominated by JES

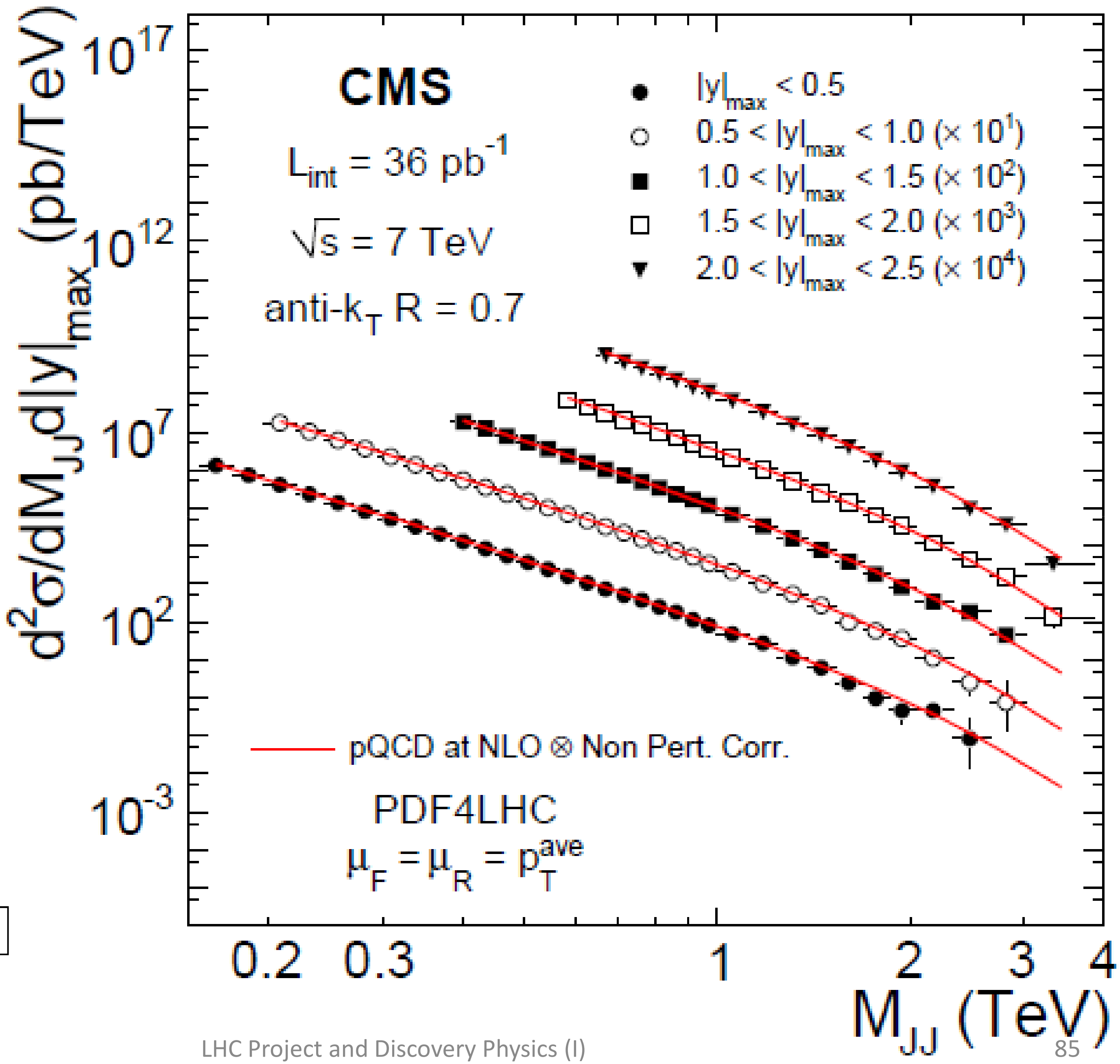


… except in some specific regions, for example in the forward directions

→Should be able soon to constrain PDFs

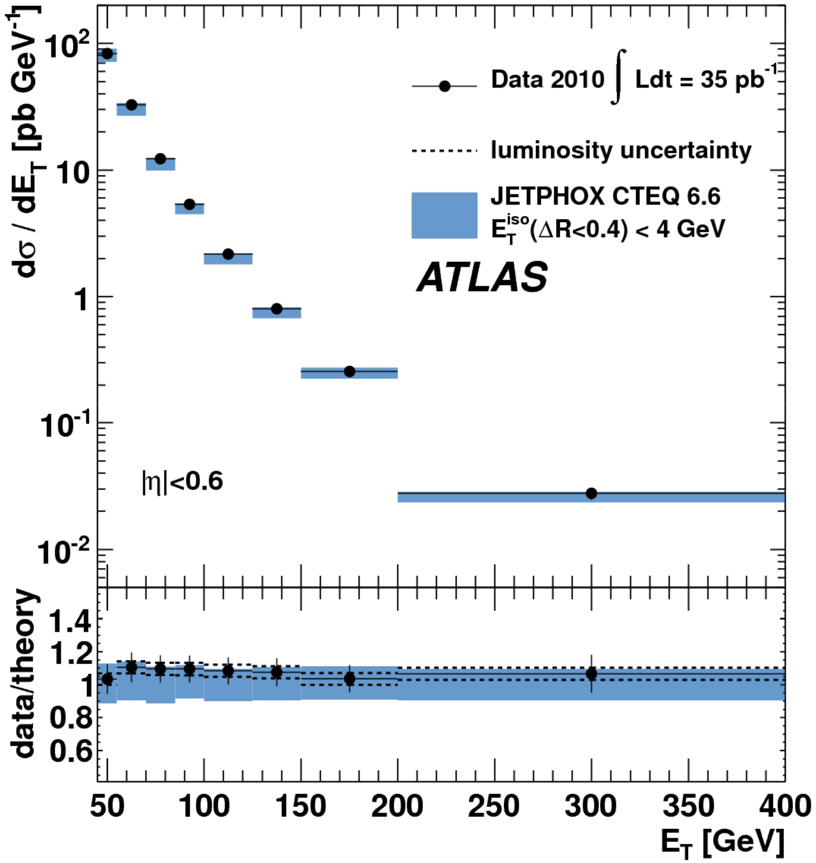
ATLAS-CONF-2011-047

Di-jet cross-sections in various rapidity intervals



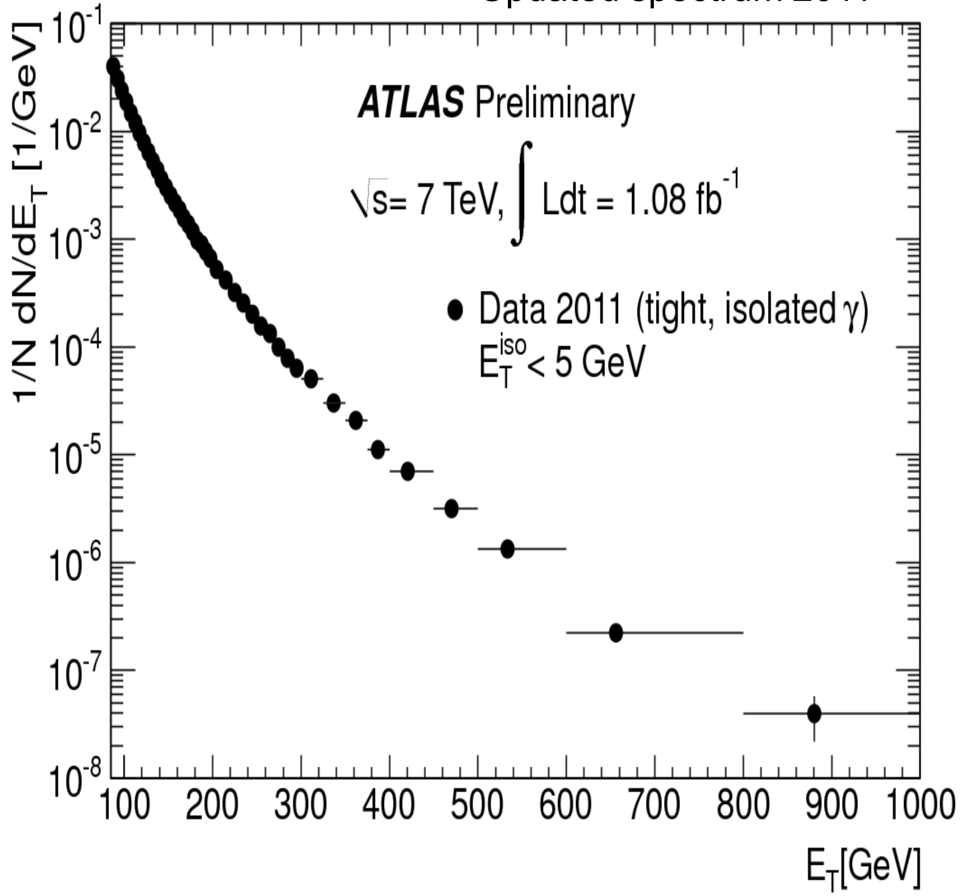
Phys. Lett. B700 (2011) 187

Example of inclusive isolated prompt photon cross-sections



Sub. To Phys. Lett. B
arXiv:1108.0251v1[hep-ex]

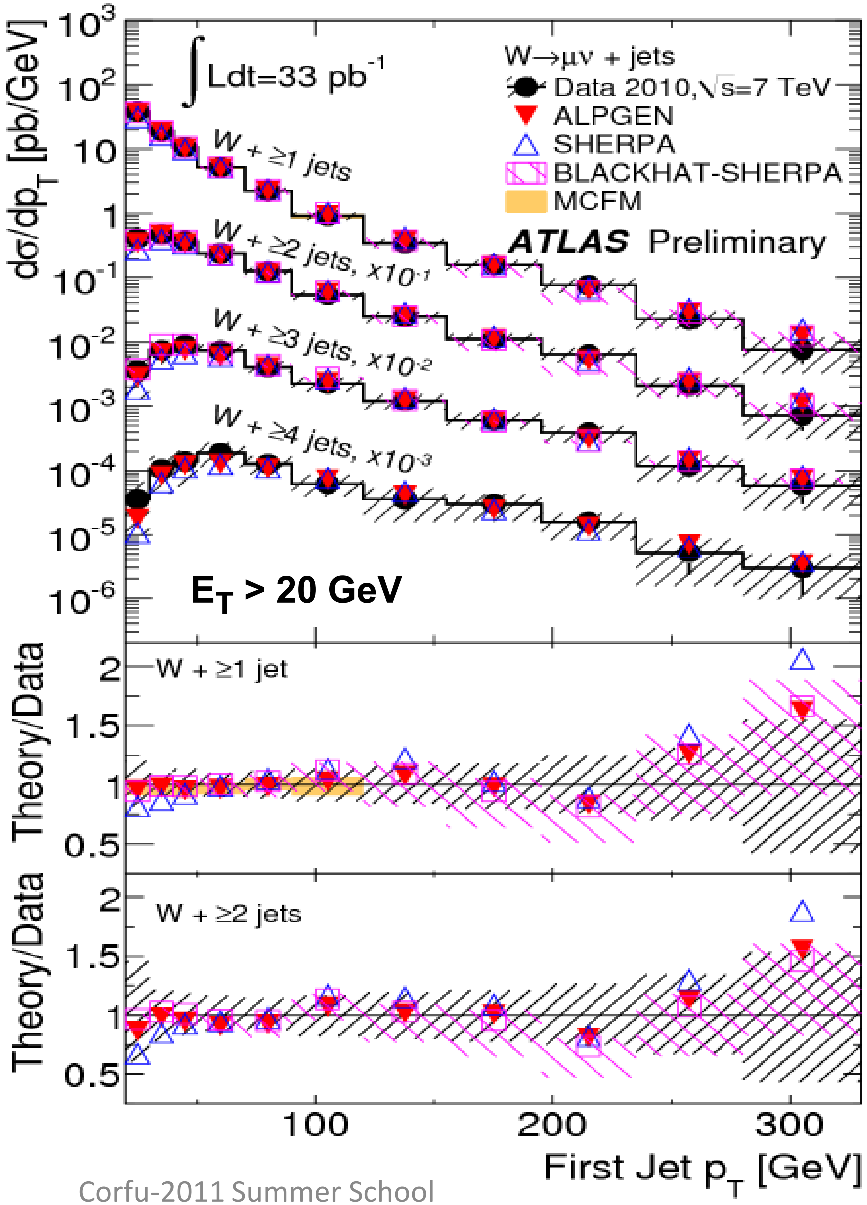
Updated spectrum 2011

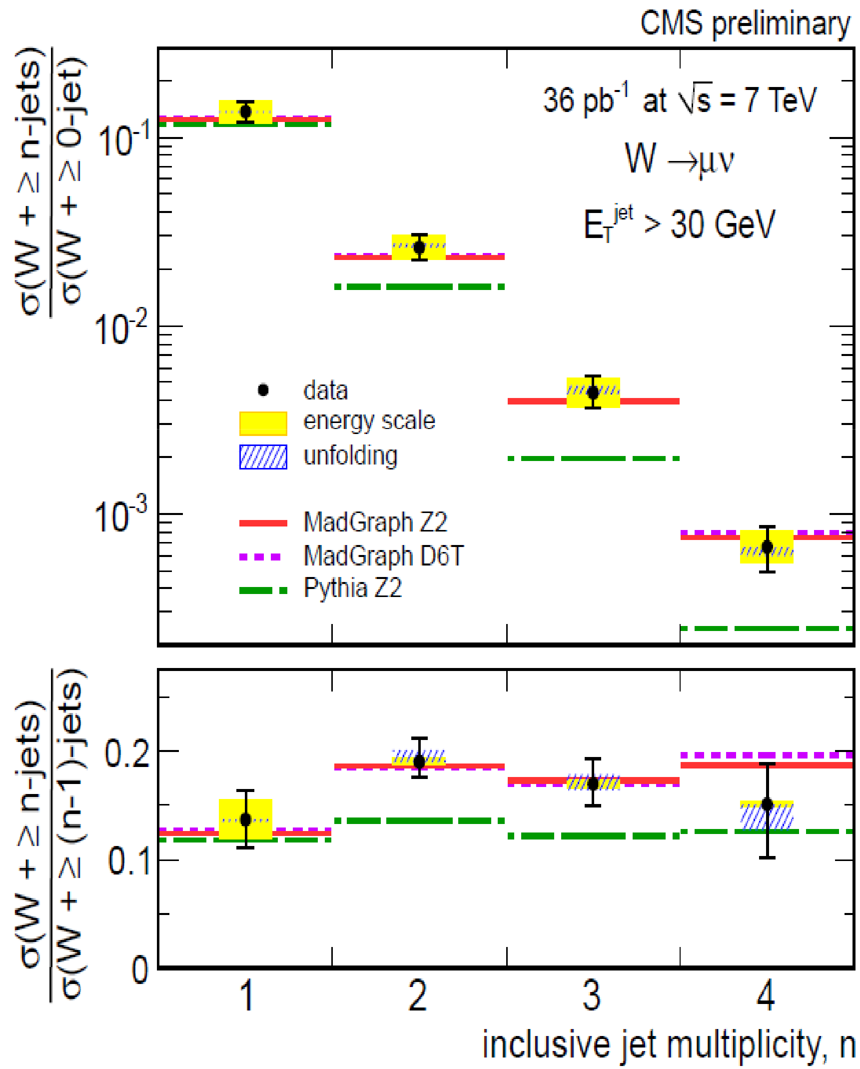


W + jet(s) production

Both an interesting QCD measurement as well as a dominant background to searches

ATLAS-CONF-2011-060



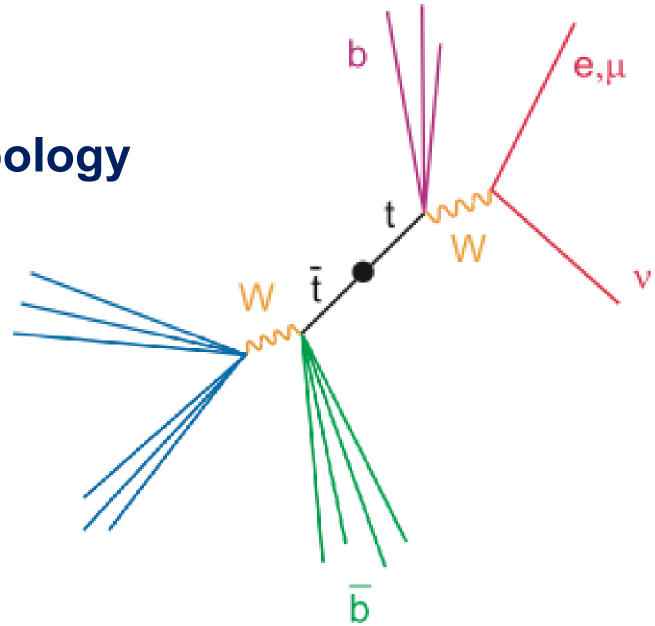


CMS PAS EWK 10-012

Early LHC measurements of the top cross section

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

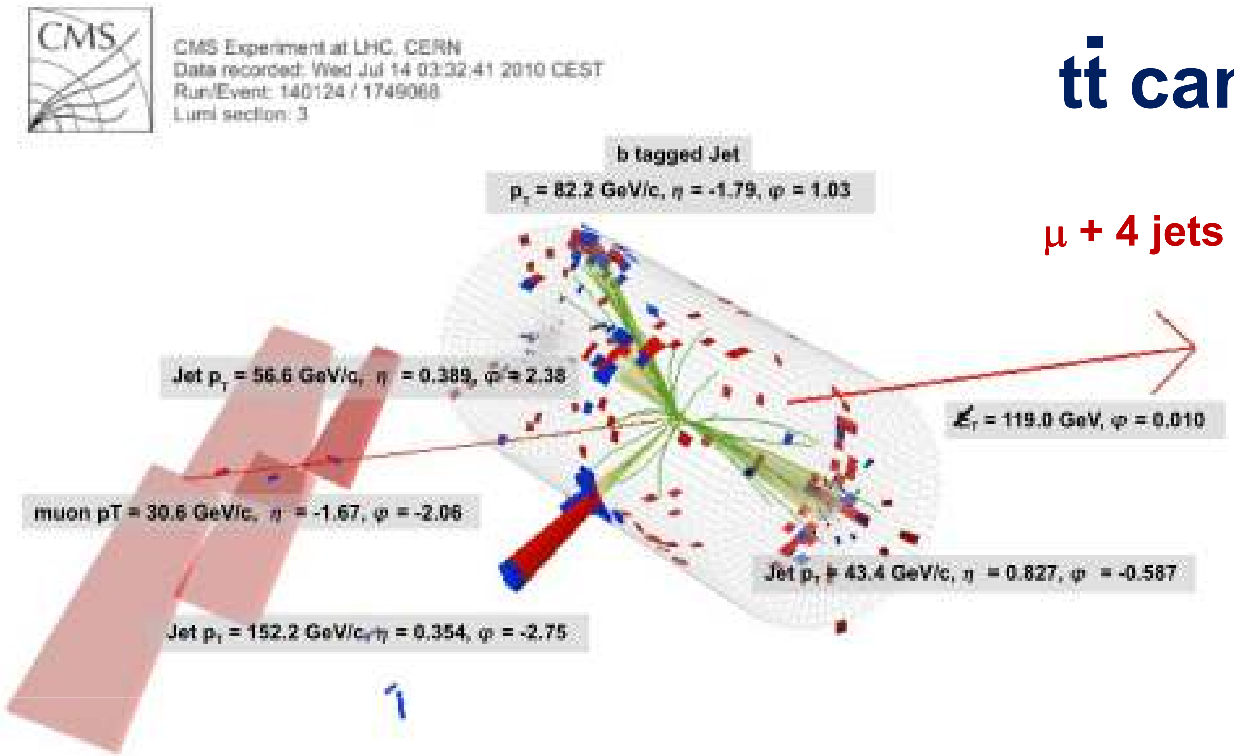
- **Assume all tops decay to Wb: event topology then depends on the W decays:**
  - **one lepton (e or μ), E_T^{miss}, jjbb (37.9%)**
  - **di-lepton (ee, $\mu\mu$ or eμ), E_T^{miss}, bb (6.46%)**



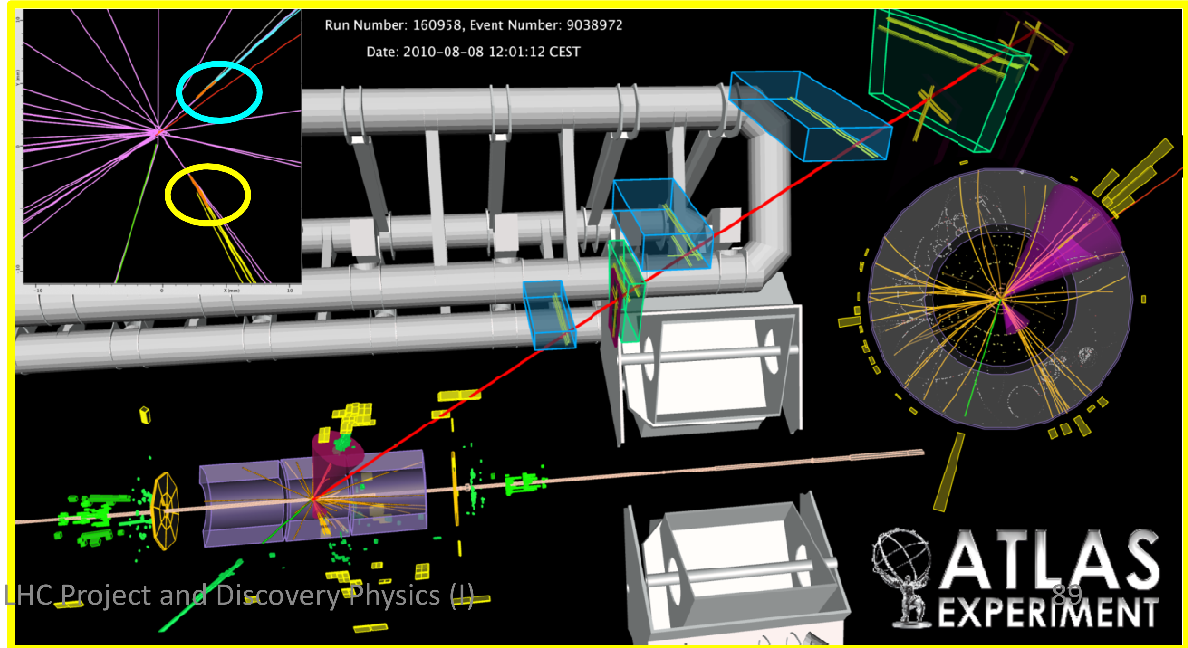
- **Data-driven methods to control QCD and W+jets backgrounds**

$t\bar{t}$ candidate events

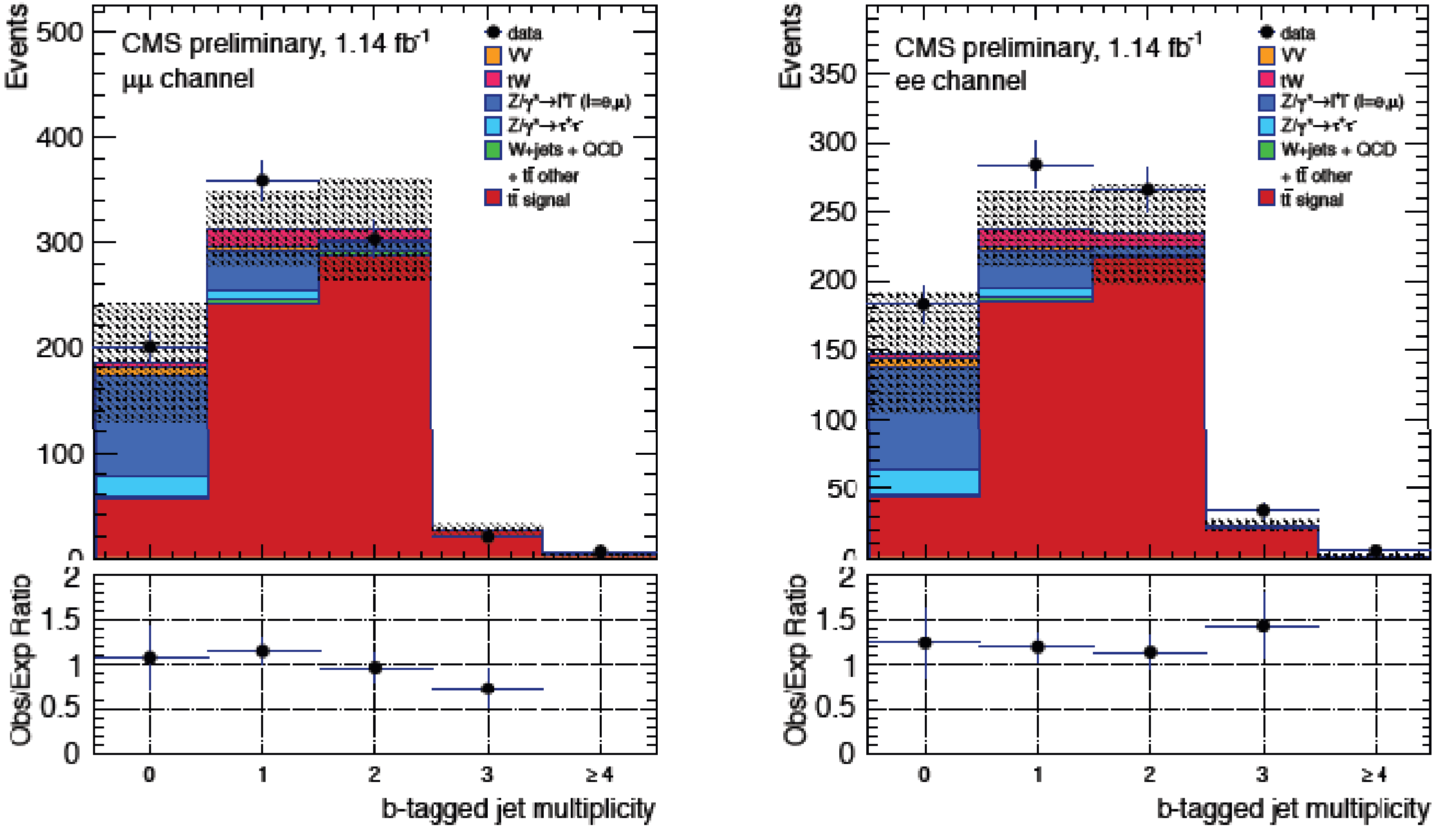
μ + 4 jets (one b-tagged) +ETmiss



e + μ + 2 jets (b-tagged) +ETmiss



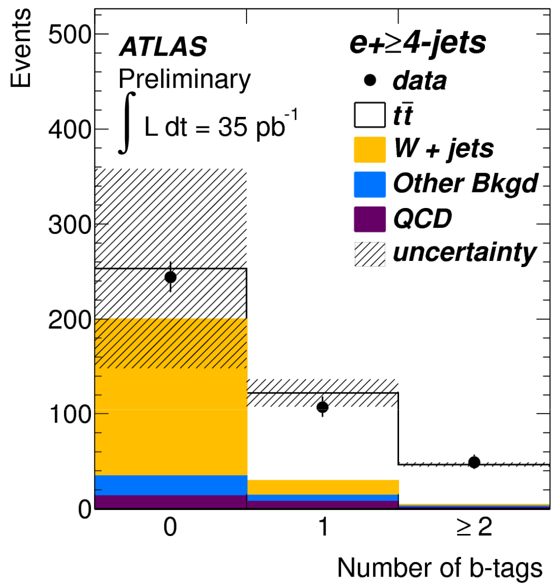
2 leptons + jets + ETmiss



CMS-PAS-TOP-11-005

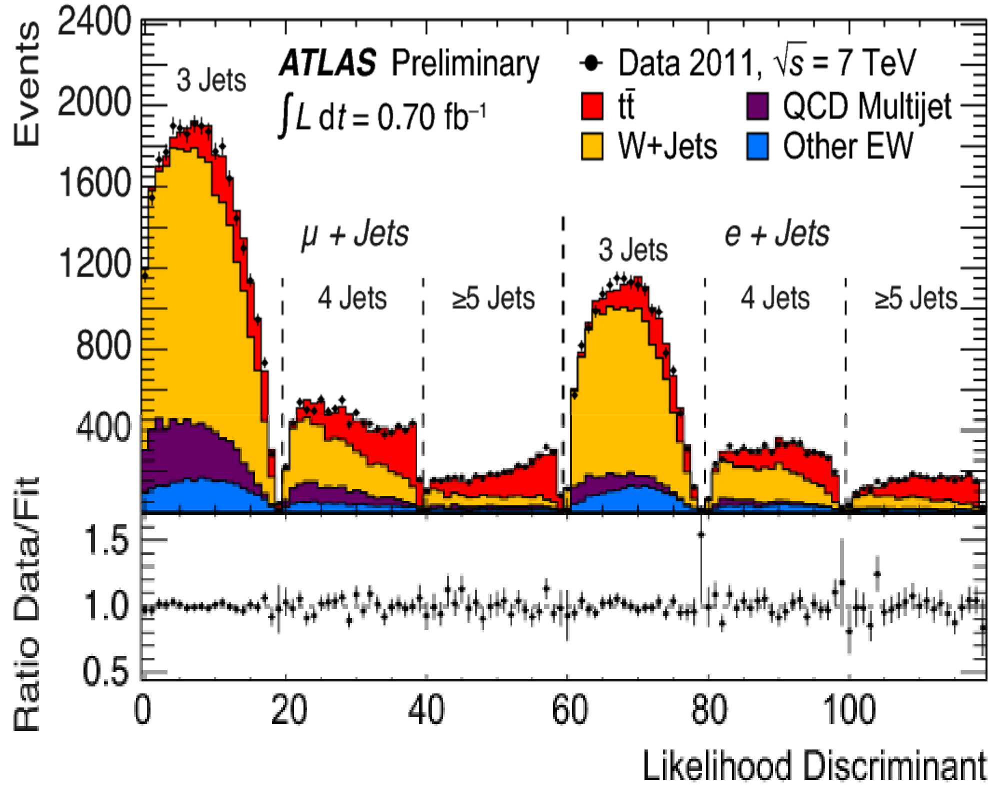
1 lepton + 4 jets + ETmiss

'Classical analysis'

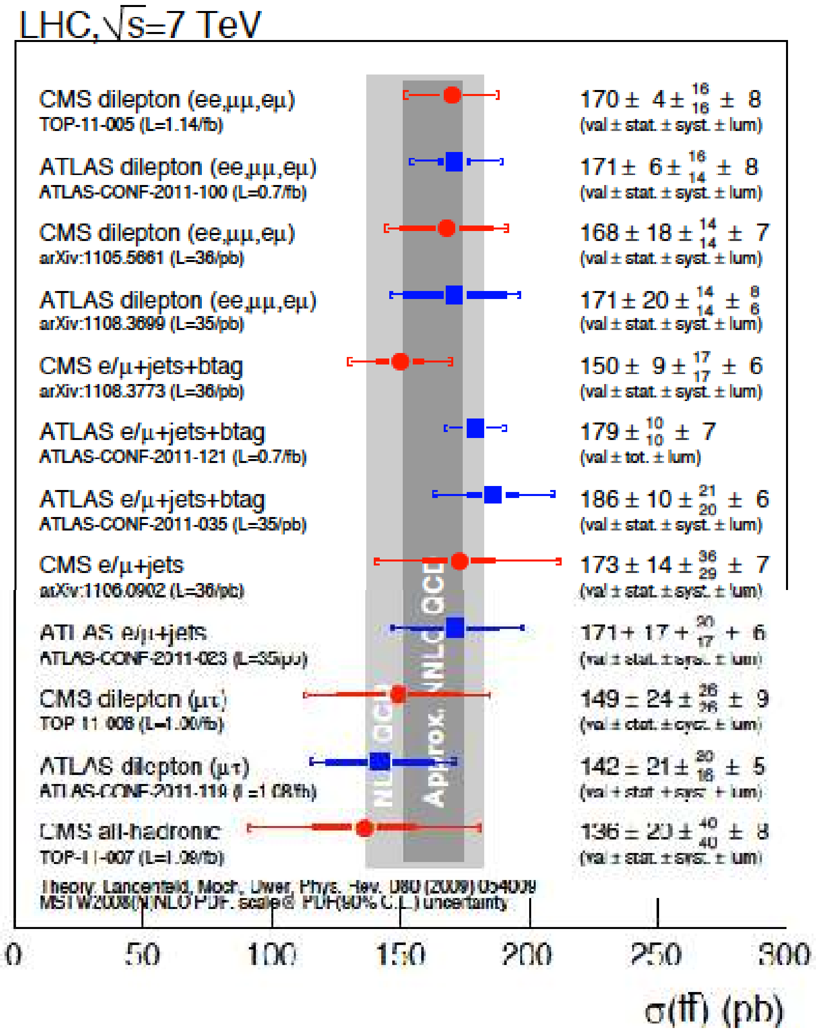


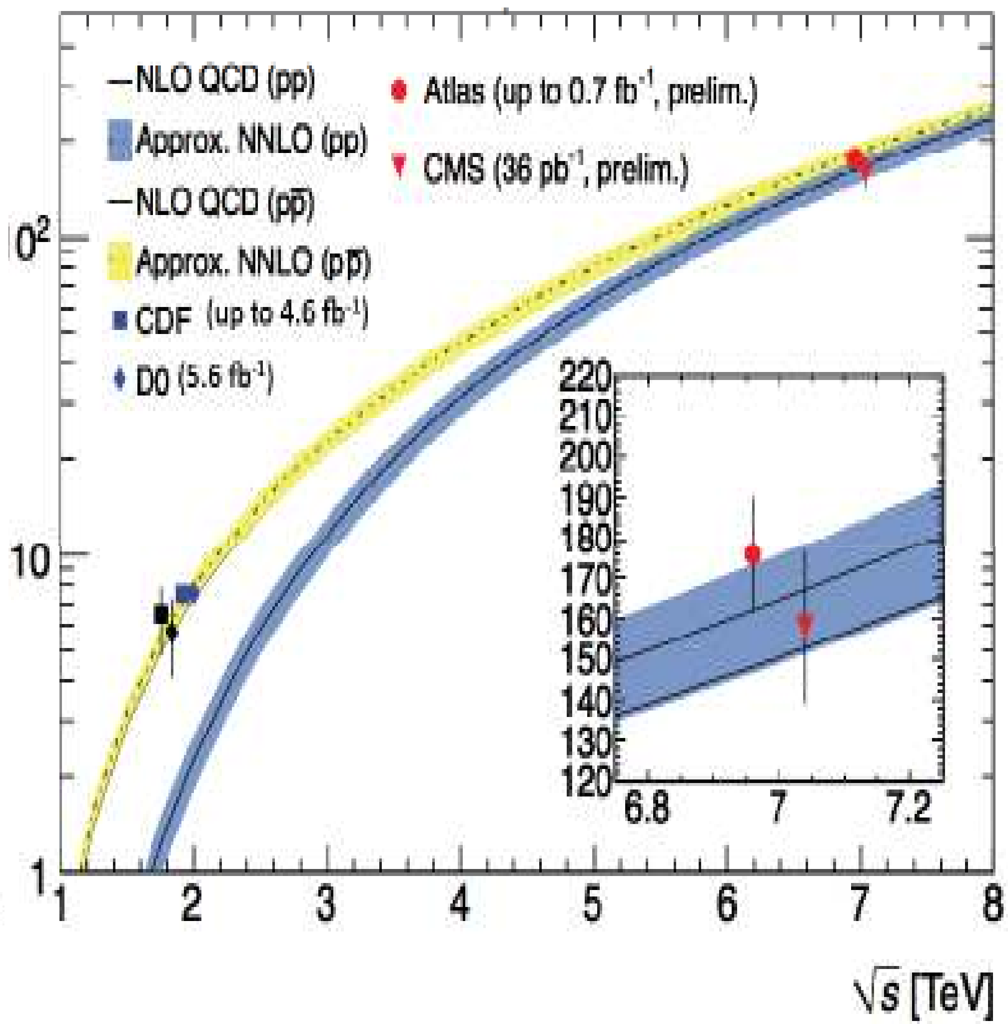
ATLAS-CONF-2011-035

Updated results with global kinematical fit



ATLAS-CONF-2011-121

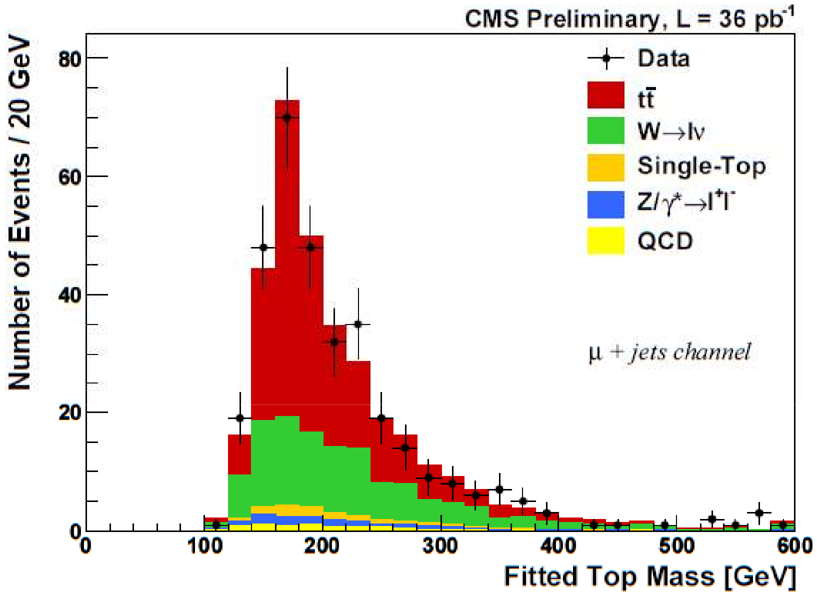




(ATLAS and CMS have also made first single top cross-section measurements in agreement with NLO QCD expectations)

Examples of first measurements of Top quark properties

CMS mass measurement with l + jets (kinematic fit, 4 or more jets)

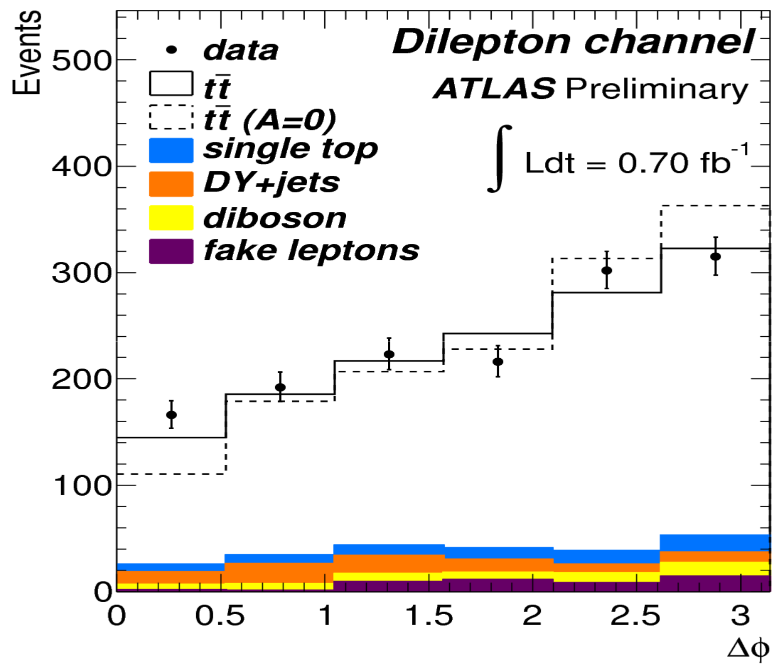


Result when combined with di-lepton analysis

$$m_t = 173.4 \pm 1.9(\text{stat}) \pm 2.7(\text{syst})\ \text{GeV}.$$

CMS-PAS-TOP-10-009

ATLAS t-tbar spin correlation as measured in di-lepton events (Δϕ between leptons in azimuthal plane in the t-tbar lab frame)

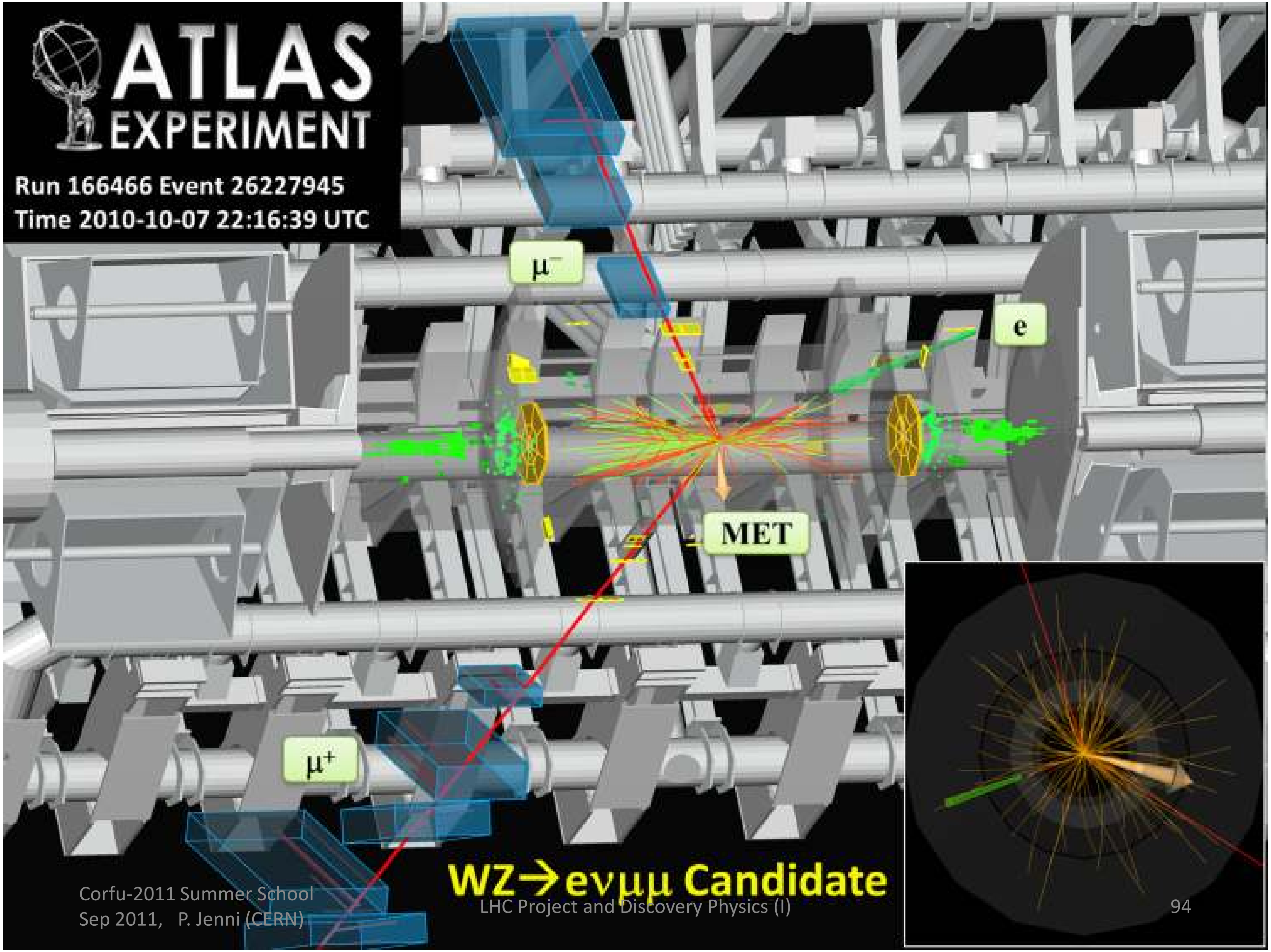


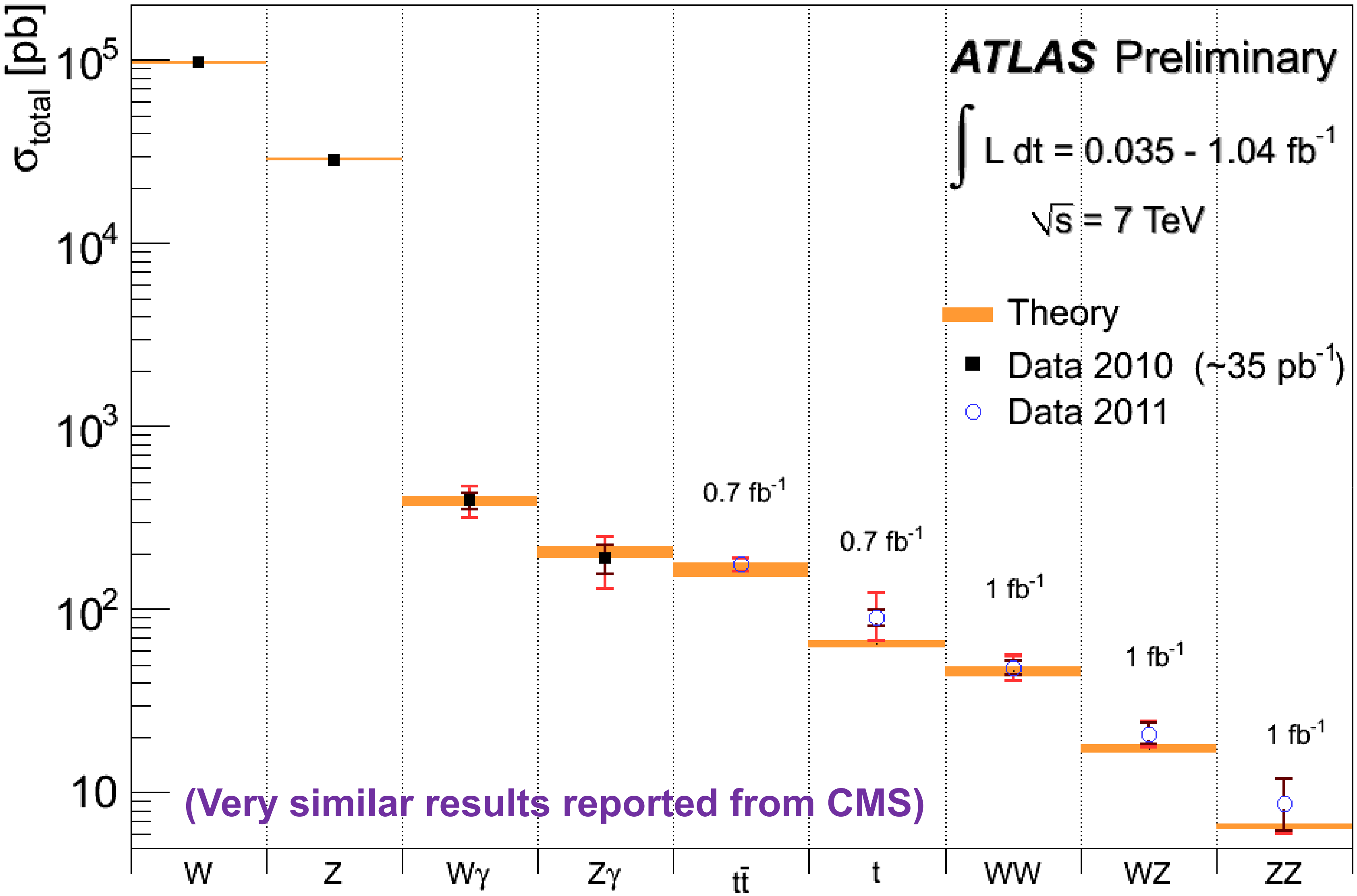
$$C_{\text{helicity}} = 0.34^{+0.15}_{-0.11}$$

(SM predicts ~ 0.32)

ATLAS-CONF-2011-117

(Soon) competitive with TeVatron…


ATLAS EXPERIMENT
Run 166466 Event 26227945
Time 2010-10-07 22:16:39 UTC
μ⁻
e
MET
μ⁺
WZ→eνμμ Candidate



σtotal [pb]
10^5
10^4
10^3
10^2
10
ATLAS Preliminary
∫ L dt = 0.035 - 1.04 fb-1
√s = 7 TeV
Theory
Data 2010 (~35 pb-1)
Data 2011
0.7 fb-1
0.7 fb-1
1 fb-1
1 fb-1
1 fb-1
(Very similar results reported from CMS)
W
Z
Wγ
Zγ
tt̄
t
WW
WZ
ZZ

Strategy toward physics

Before data taking starts:

- Strict quality controls of detector construction to meet physics requirements ✓
- Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation) ✓
- Detailed simulations of realistic detector "as built and as installed" (including misalignments, material non-uniformities, dead channels, etc.)
  $\rightarrow$ test and validate calibration/alignment strategies ✓
- Experiment commissioning with cosmics in the underground cavern ✓

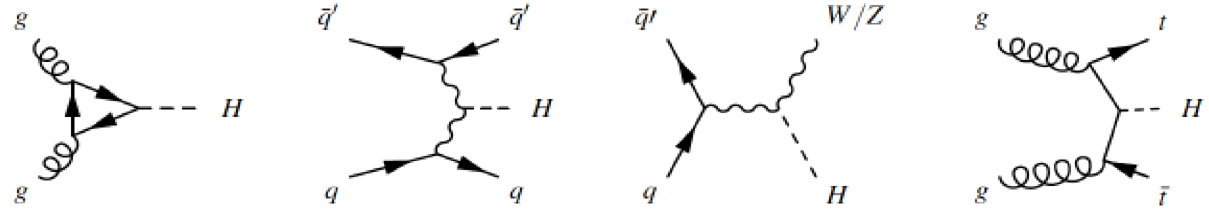
With the first data:

- Commission/calibrate detector/trigger in situ with physics (min.bias, $Z \rightarrow ll$, …) ✓
- "Rediscover" Standard Model, measure it at $\sqrt{s}$ = 7 TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators) ✓
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

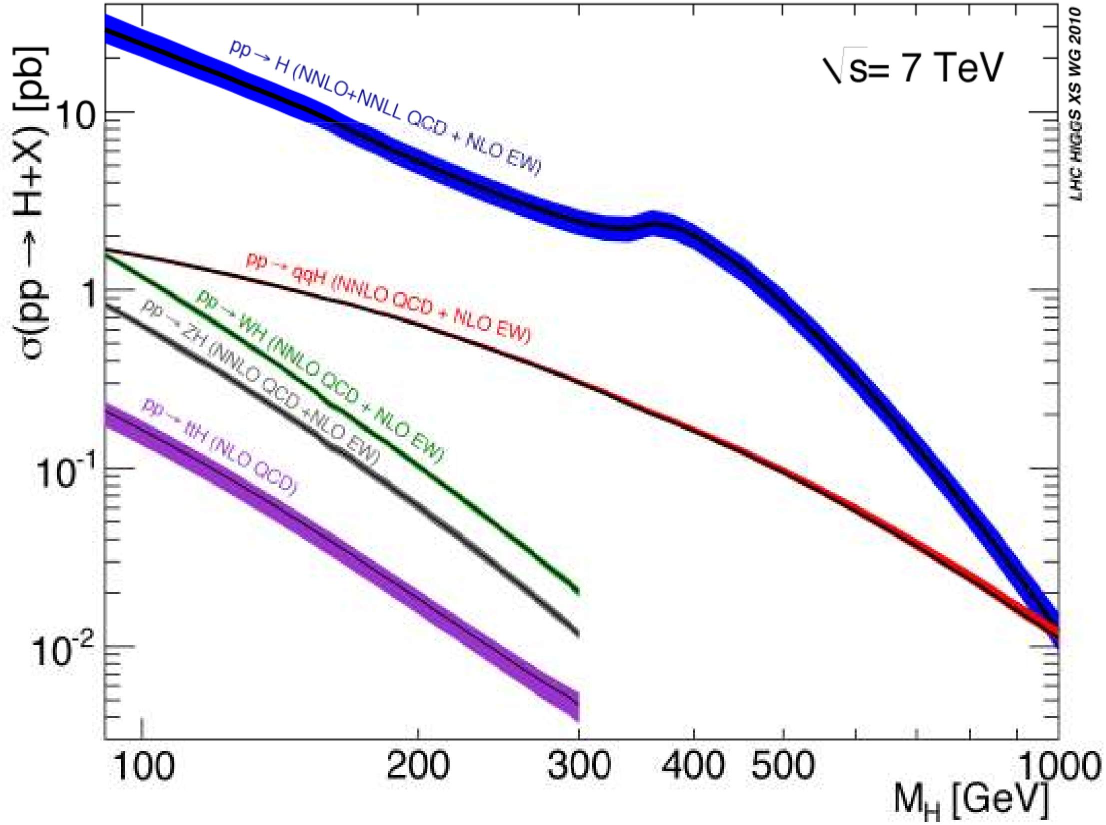
↓

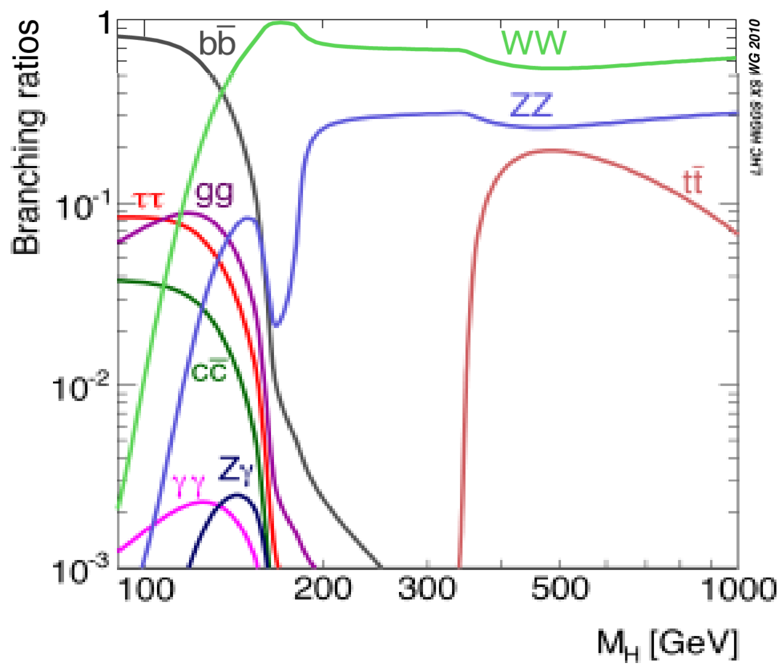
Prepare the road to discoveries …

The Higgs Hunt at LHC



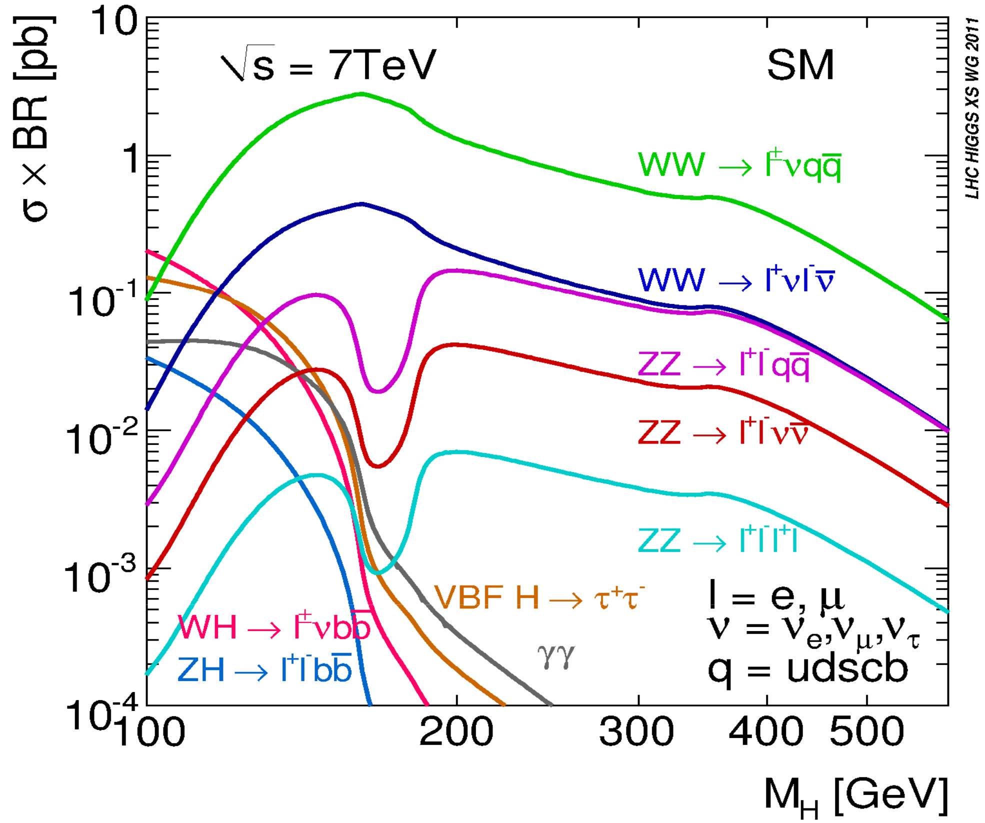
(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$





Higgs cross-sections (ATLAS example)

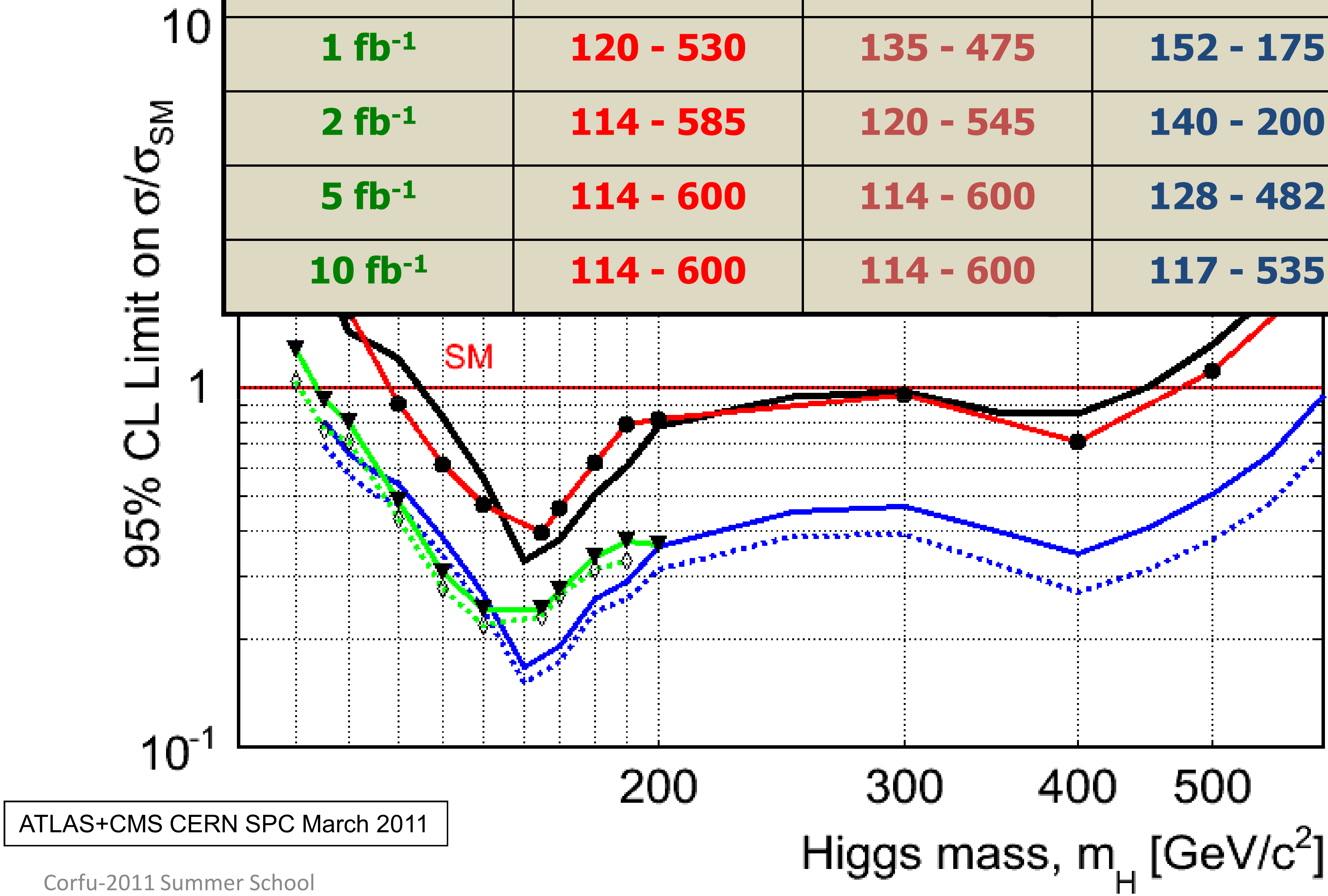
- **H→γγ: rare channel, but the best for low mass**
- **H→WW(*):**
  - **→lνlν: very important in the intermediate mass range**
  - **→ lνqq: highest rate, important at high mass**
- **H→ZZ(*):**
  - **→ 4l: golden channel**
  - **→ llνν: good for high mass**
  - **→ llbb: also high mass**
- **H→ττ: good signal/background, important at low mass, rare, and experimentally challenging**
- **Associated prod. H→ bb-bar**
  - **ttH, WH, ZH**
  - **It is useful for the discovery**
  - **It is very important for Higgs property studies if SM Higgs is discovered**



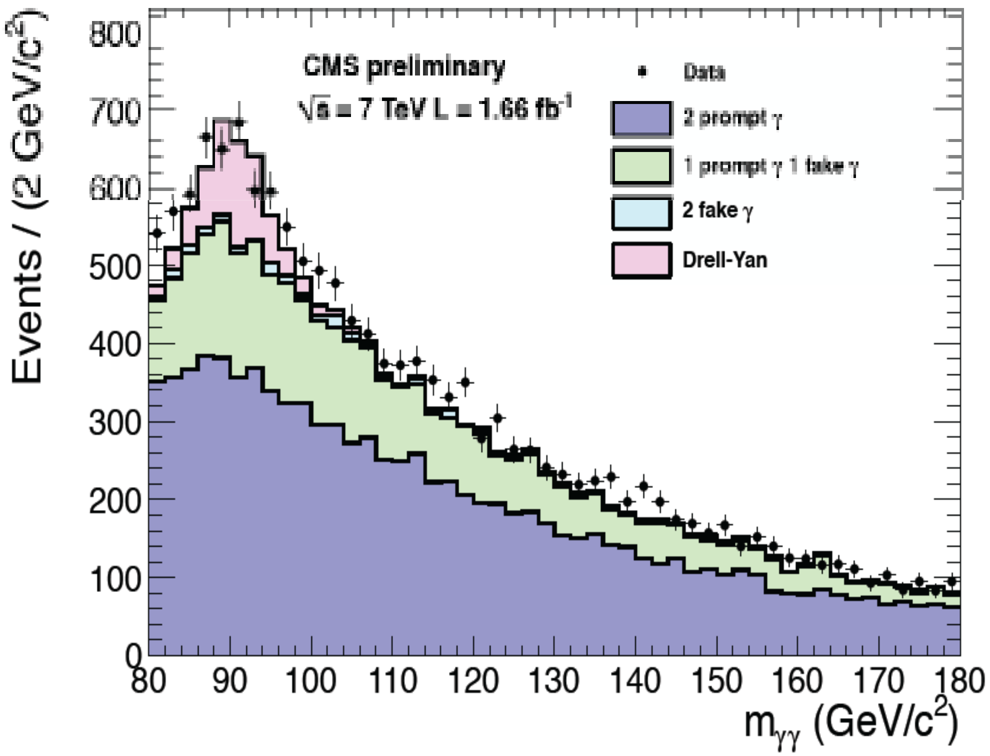
Events expected to be produced per 1 fb^{-1}

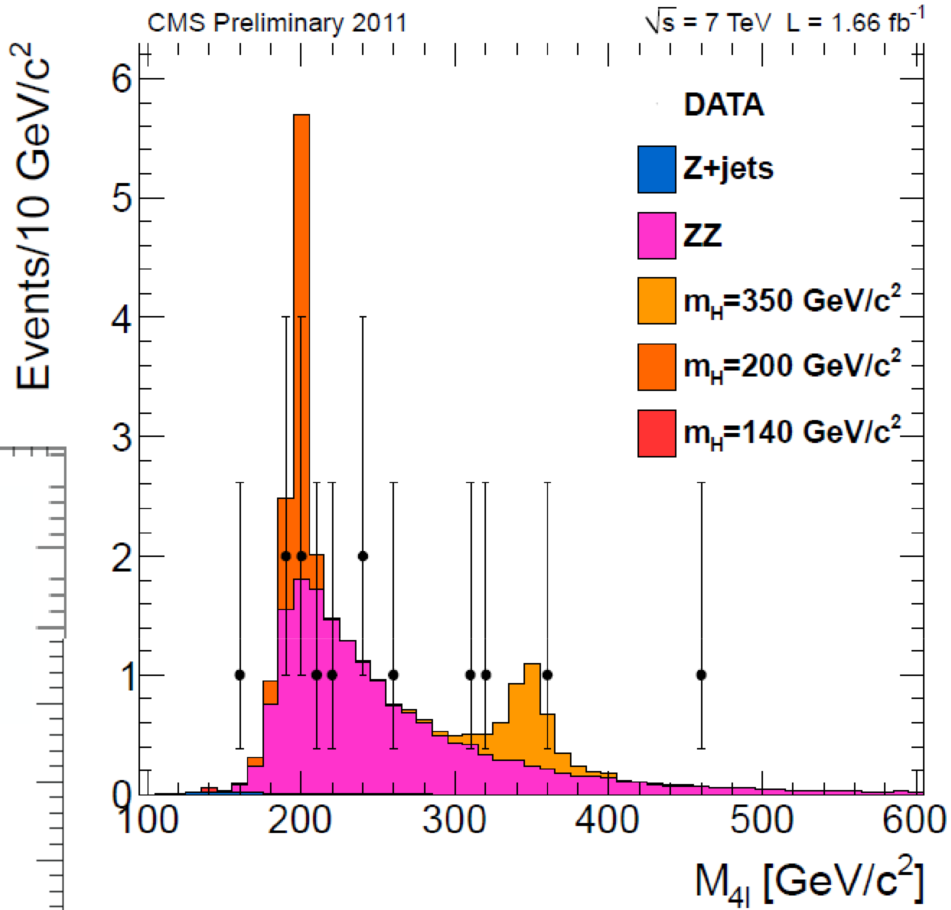
m_H, GeV	WW→lνlν	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

ATLAS+CMS 7 TeV	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

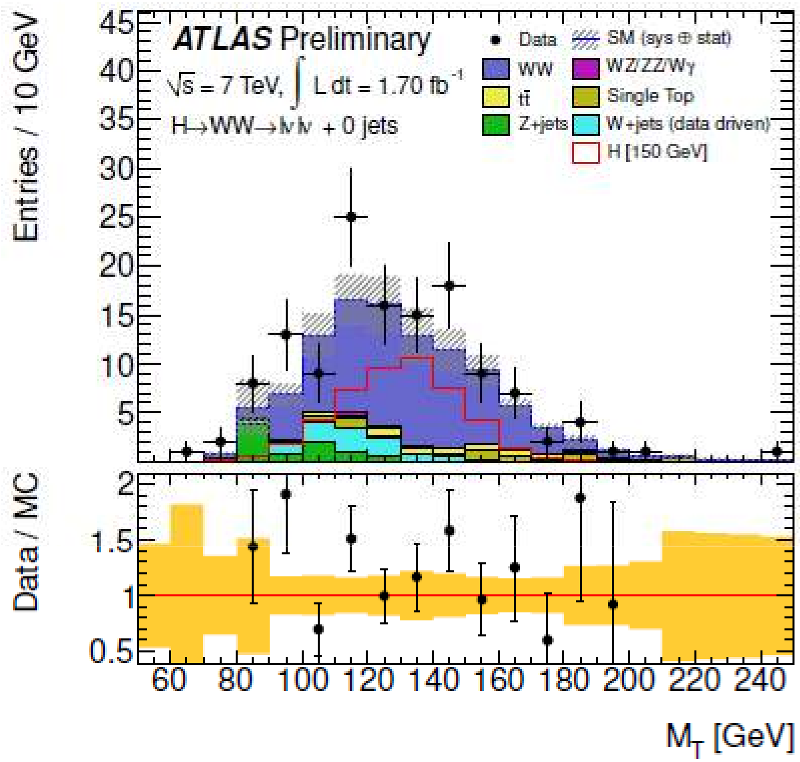


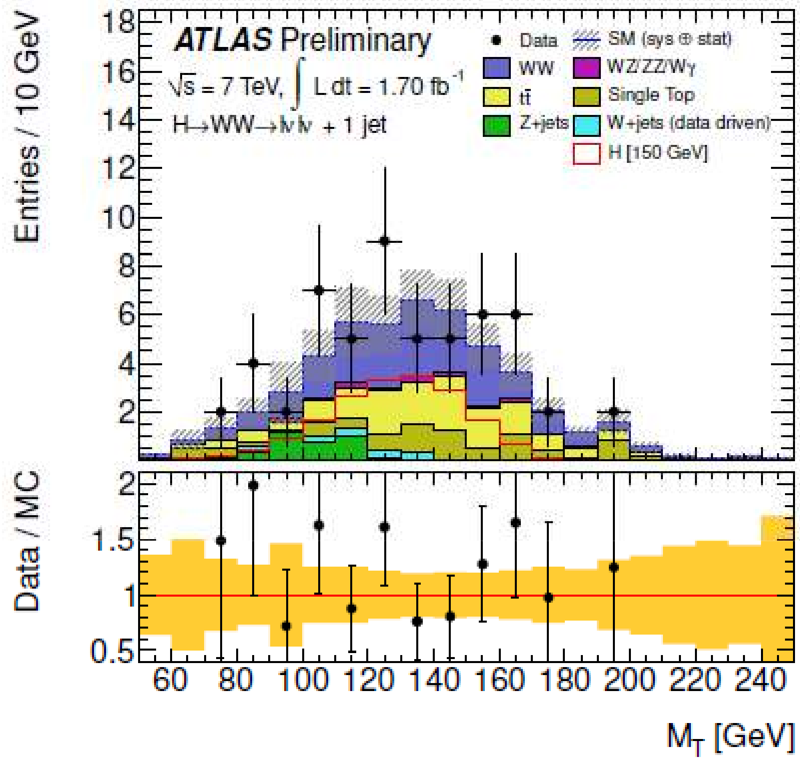
Two examples of ‘easy’ searches (where one would expect a mass peak)



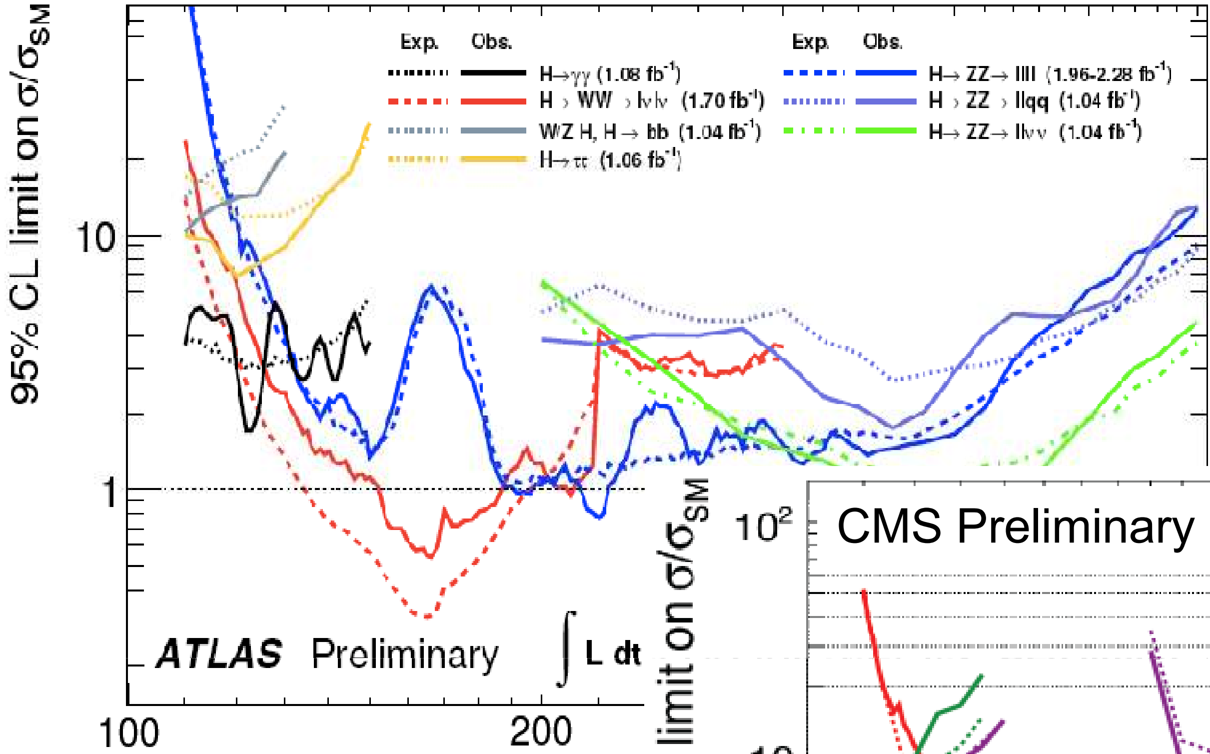


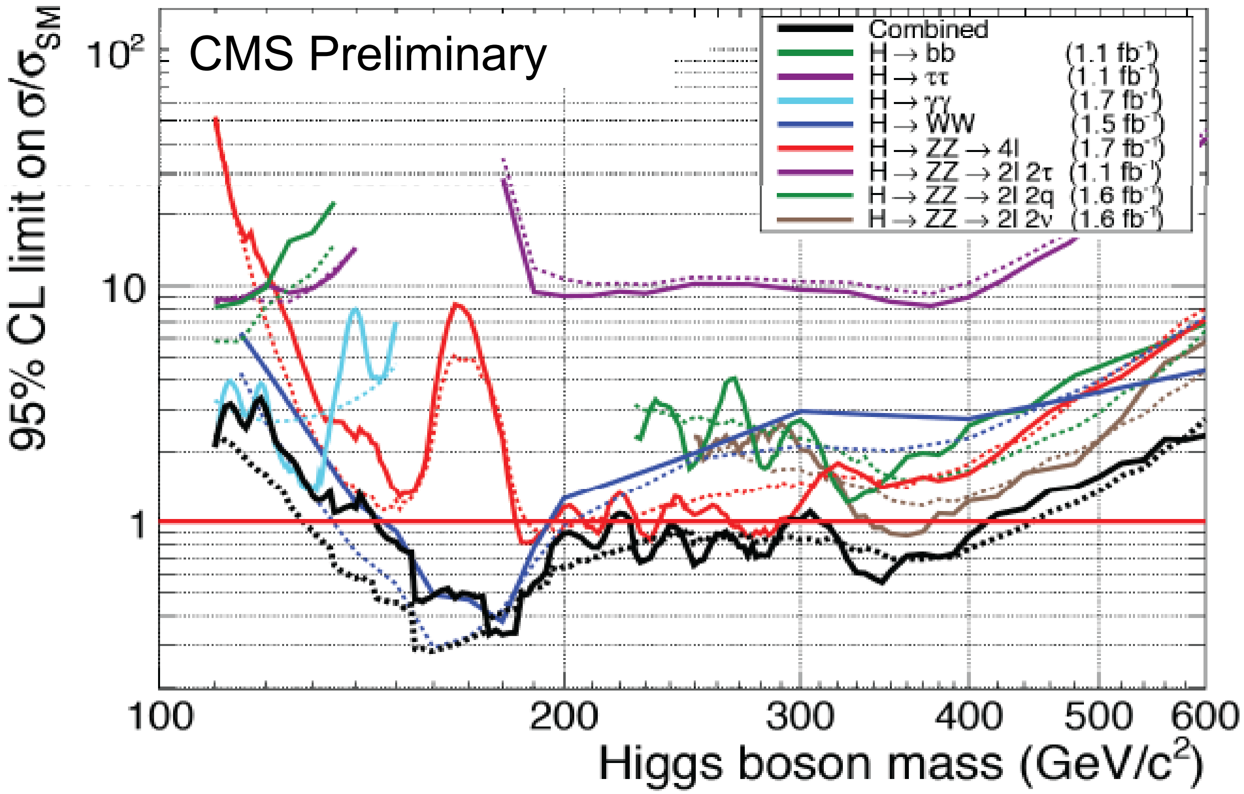
An example of ‘difficult’ search channel (no peak, counting experiment)





	WW	ttbar	Total SM back.	Data	Higgs m_H=150
0-jet	43±6	2.2±1.4	53±9	70	34±7
1-jet	10±2	6.9±1.9	23±4	23	12±3



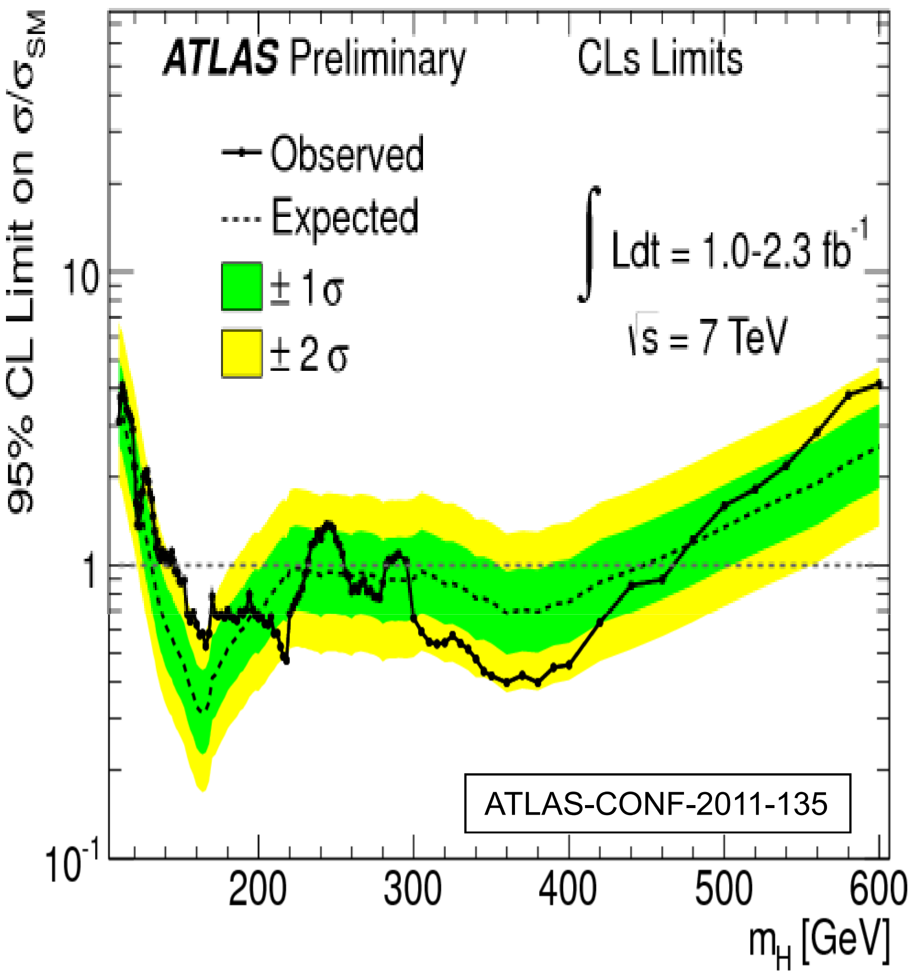


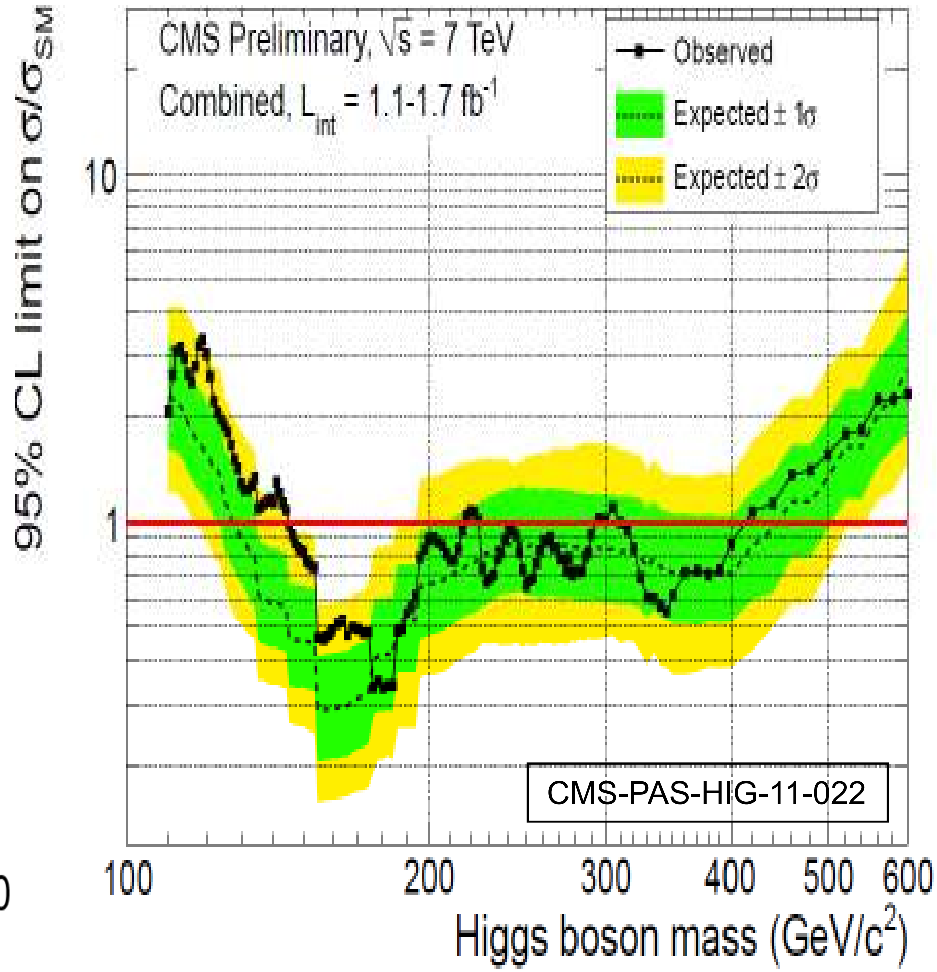
Higgs searches are the focal point at this year's conferences

Here last week's status (LP 2011 Mumbai)

The situation is evolving fast with the excellent LHC performance, new results can be expected in the near future well along the shown expectations...

Status of Lepton Photon Conference Mumbai, 22nd Aug 2011

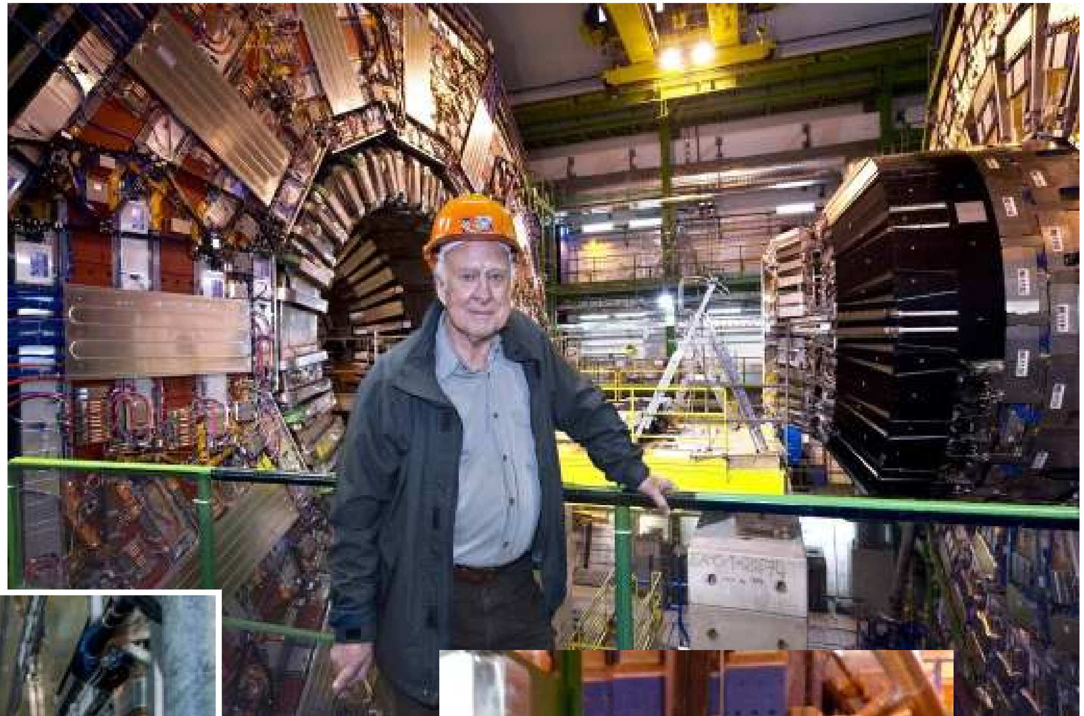




95% CL exclusions SM Higgs mass ranges (GeV)

	ATLAS	CMS
Expected	131 – 447	130 – 447
Data	146 – 232, 256 – 282, 296 – 466	145 – 216, 226 – 288, 310 - 400

The first "Higgs" events observed jointly in CMS and ATLAS … (April 2008)



somewhat later, even in ALICE…

Most exciting: searches for physics Beyond the Standard Model (BSM) (see Albert De Roeck's lecture)

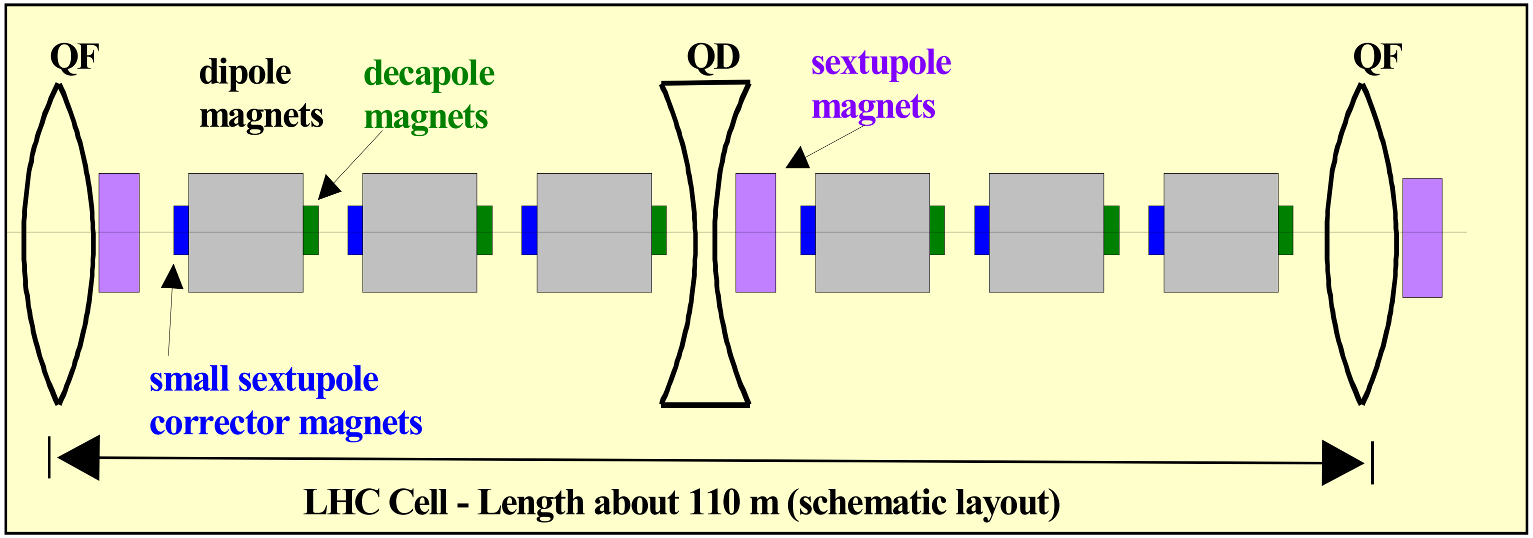
Note that all public results from CMS and ATLAS are available at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Exciting times are ahead of us!

Thank You!

Spares

Beam transport (LHC arcs)



Dipole- and Quadrupole magnets

- Particle trajectory stable for particles with nominal momentum

Sextupole magnets

- To correct the trajectories for off-momentum particles
- Particle trajectories stable for small amplitudes (about 10 mm)

Multipole-corrector magnets

- Sextupole - and decapole corrector magnets at end of dipoles
- Particle trajectories can become unstable after many turns (even after 10^6 turns)

Not only dipoles ….

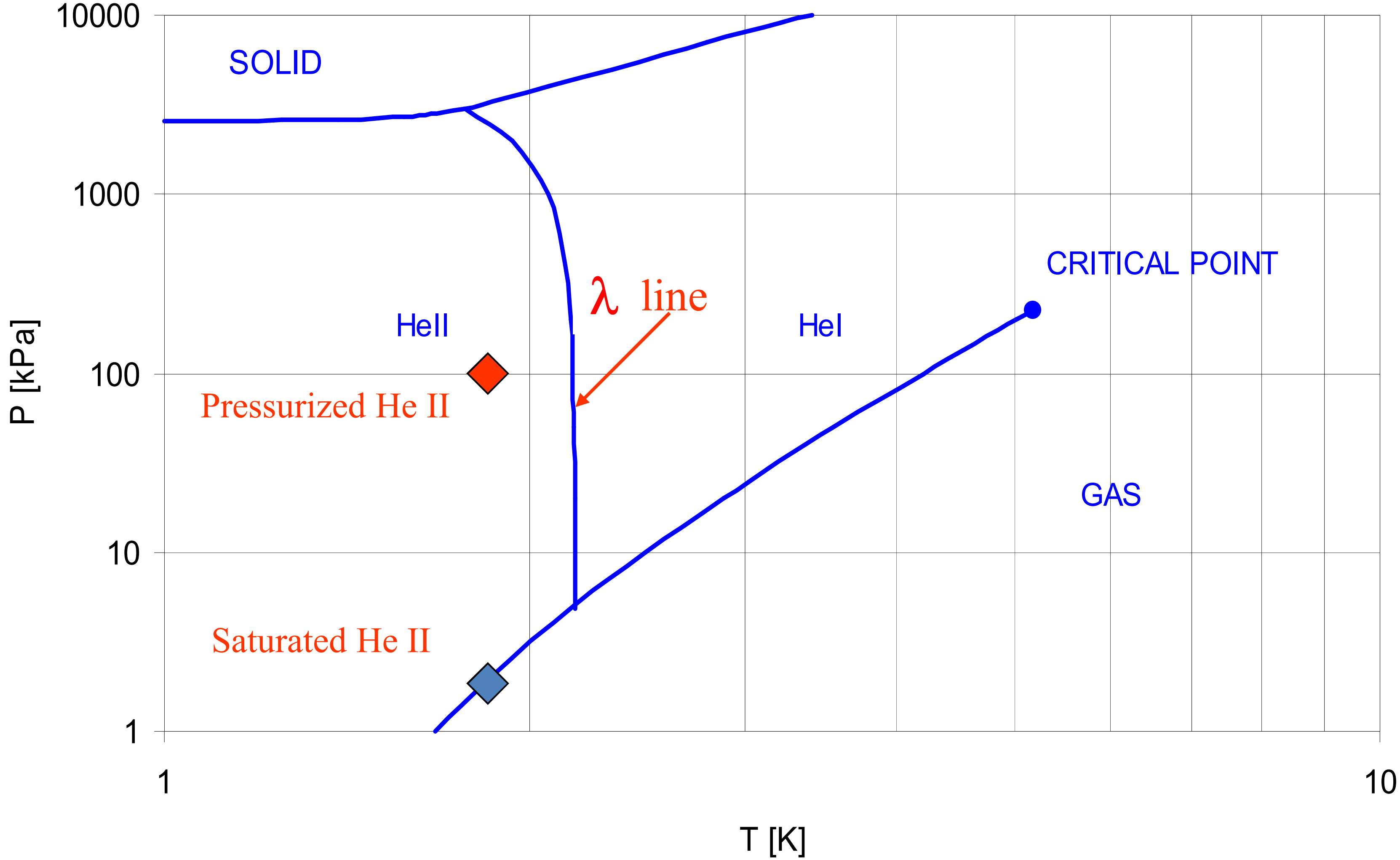
Dipoles	**1232**
Quadrupoles	**400**
Sextupoles	**2464**
Octupoles/decapoles	**1568**
Orbit correctors	**642**
Others	**376**
Total	**~ 6700**

Assembly of Short Straight Sections

Inner triplet quads assembly hall 181

Phase diagram of Helium

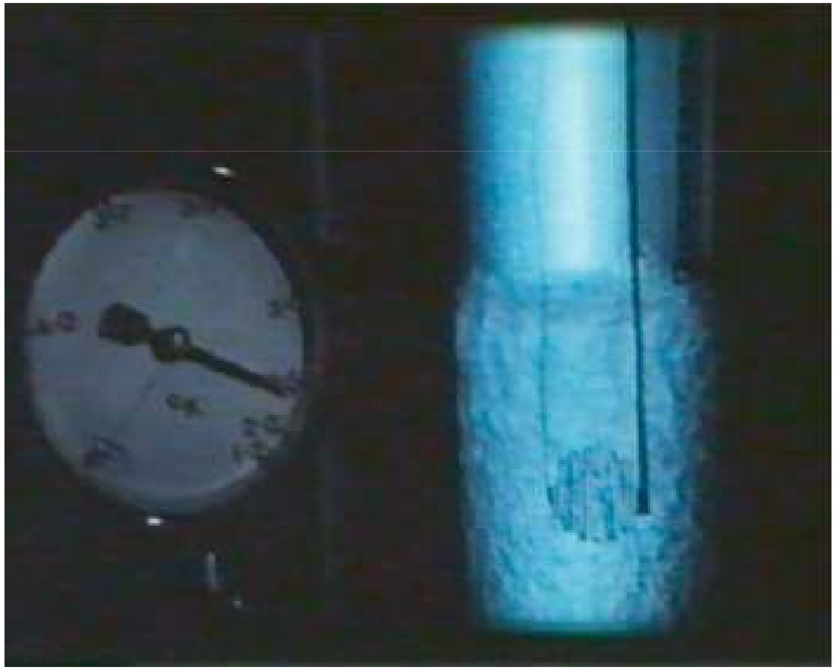
He II is a superfluid, it flows with zero viscosity



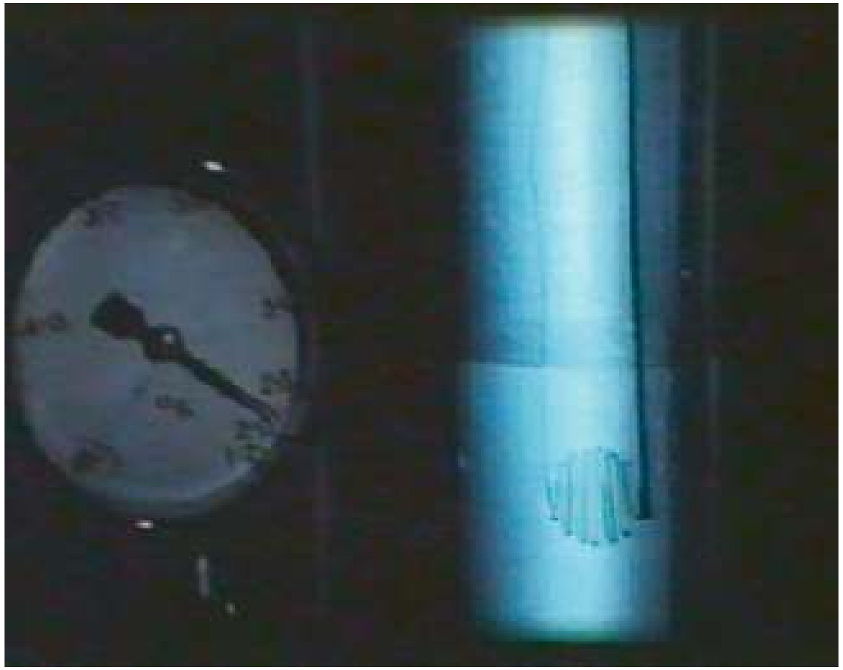
Discovery of superfluidity in He II (1938)

J.F. Allen & A.D. Misener (Cambridge)
P.L. Kapitsa (Moscow)

Vaporization of liquid helium



He I (T=2.4 K)



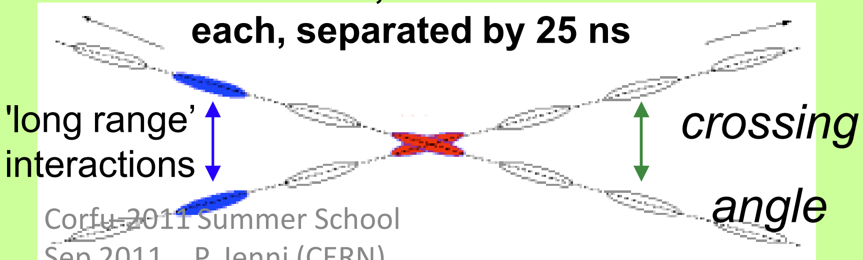
He II (T=2.1 K)

Main design parameters of the LHC

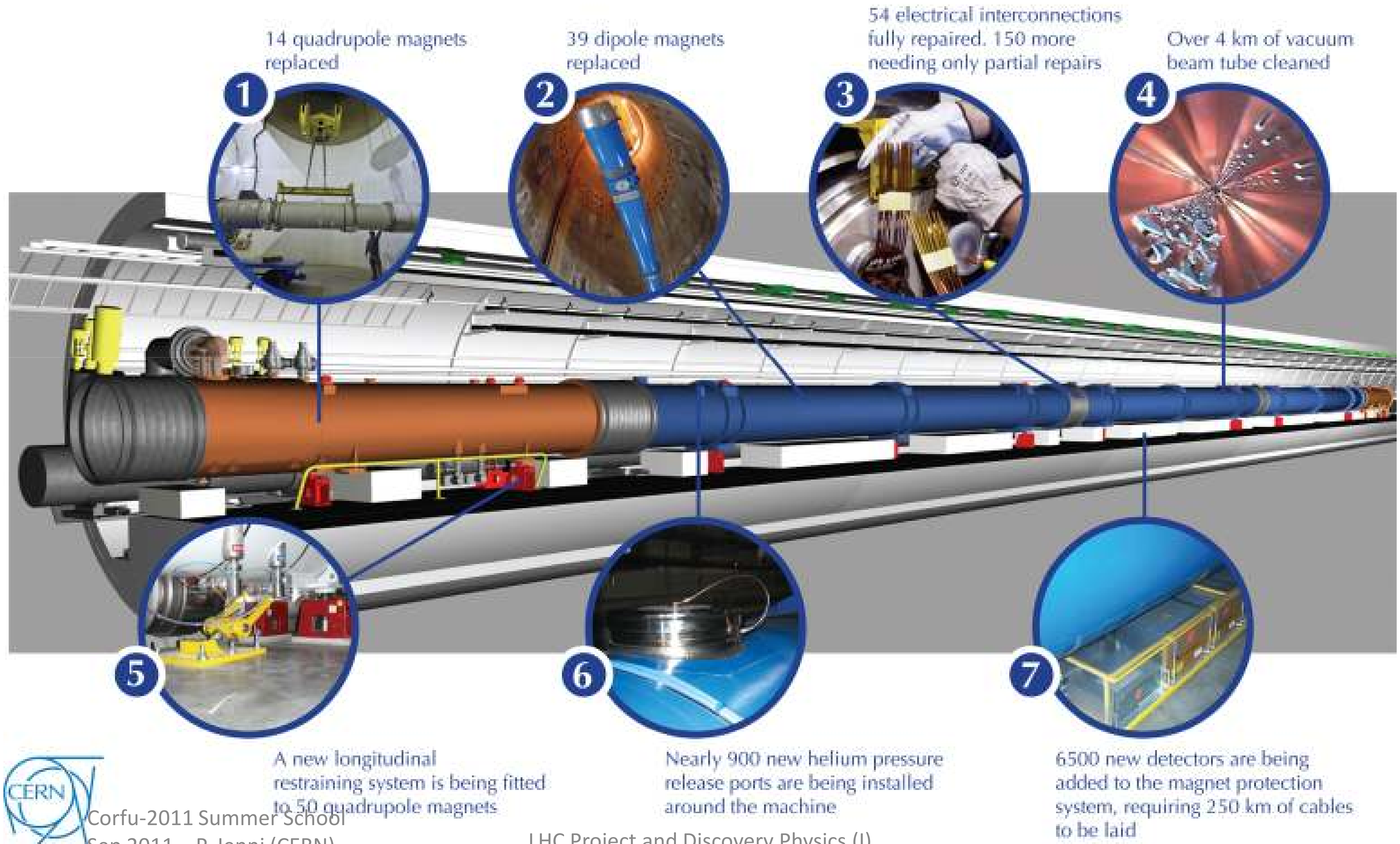
	Design operation	
Beam energy	7	TeV
Instantaneous luminosity L	10^{34}	$cm^{-2}s^{-1}$
Integrated luminosity/year	~ 100	fb^{-1}
Dipole field	8.4	T
Dipole current	11700	A
Circulating current/beam	0.53	A
Number of bunches	2808	
Bunch spacing	25	ns
Protons per bunch	10^{11}	
R.m.s. beam radius at IP1/5	16	μm
R.m.s. bunch length	7.5	cm
Stored beam energy	360	MJ
Crossing angle	300	μrad
Number of events per crossing	20	
Luminosity lifetime	10	hours

x200 Tevatron

two beams, 2808 bunches each, separated by 25 ns



The LHC repairs in detail



New rough draft 10 year plan

2022

Options

Installation of the HL-LHC hardware.

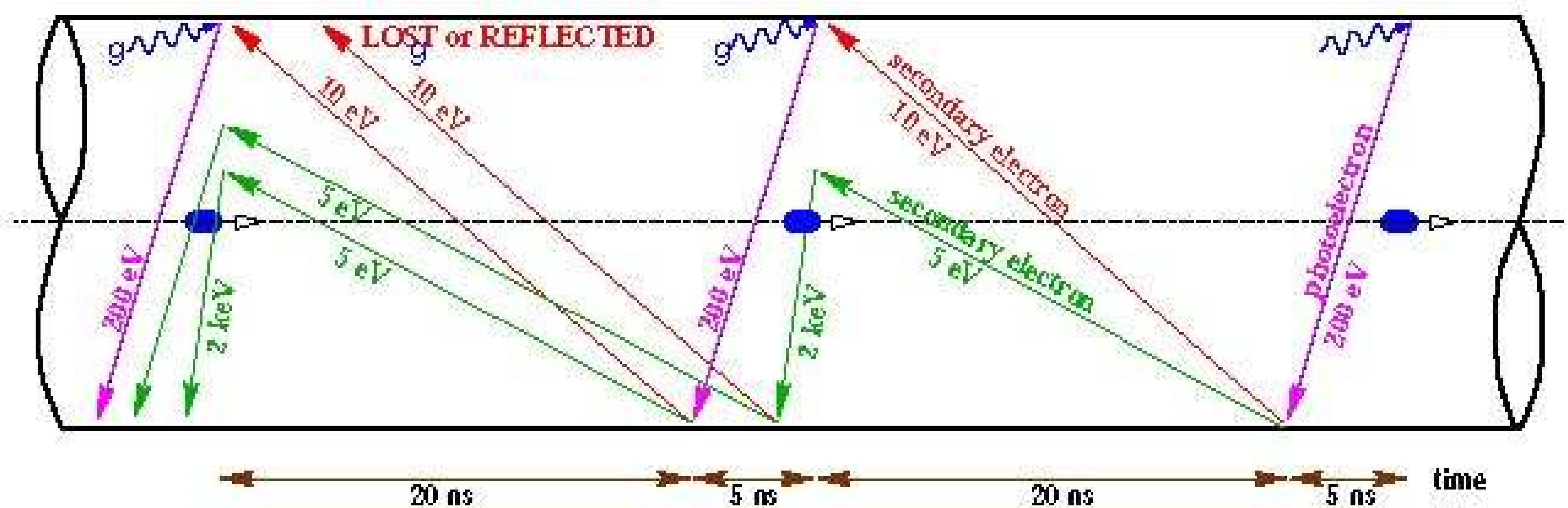
Installation of LHeC

Preparation for HE-LHC

Detector upgrades

Electron cloud

Reflection



Secondary emission yield [SEY]

Schematic of electron cloud build up in LHC arc beam pipe due to photoemission and secondary emission [F. Ruggiero]

Luminosity

- Single most important quantity
  - Drives our ability to detect new processes

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^2}{4\pi\sigma_x\sigma_y}$$

revolving frequency: f_{rev}=11245.5/s
#bunches: n_{bunch}=2808
#protons / bunch: N_p= 1.15 x 10^{11}
Area of beams: $4\pi\sigma_x\sigma_y$~40 μm

  - Rate of physics processes per unit time directly related:

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

Efficiency: optimized by experimentalist

Cross section σ: Given by Nature (calc. by theorists)

17 **Ability to observe something depends on N_{obs}**

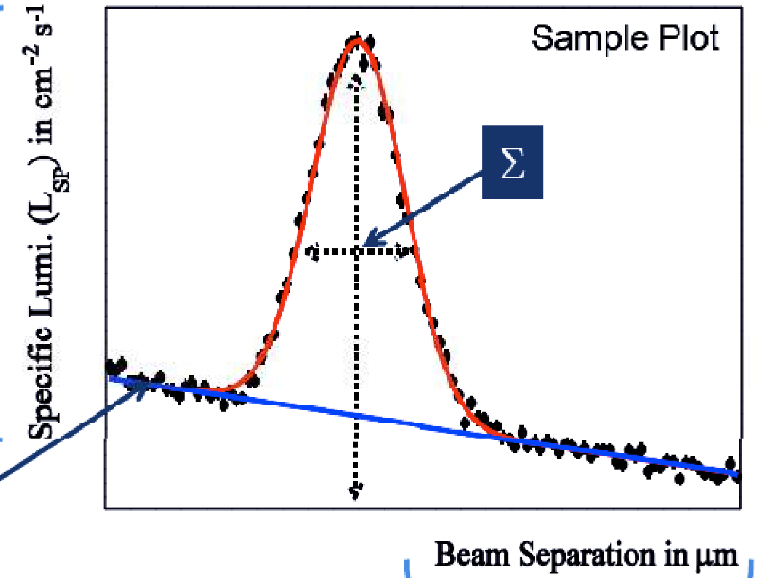
Principle: measure simultaneously

$L = f\ (I_1, I_2, \Sigma_x, \Sigma_y)$

R_{max} = **peak collision rate (arb. u.)**

From LUCID, ZDC,MBTS BCM,FCAL, HLT

$R_{max} \sim \mathcal{L}\ \sigma_{inel}\ \varepsilon_{det}$



Background

From LHC machine during the Van der Meer Scan (either from BPM or from Magnet Settings)

$$\mathscr{L} = \frac{n_b f_r I_1 I_2}{2\pi \Sigma_x \Sigma_y}$$

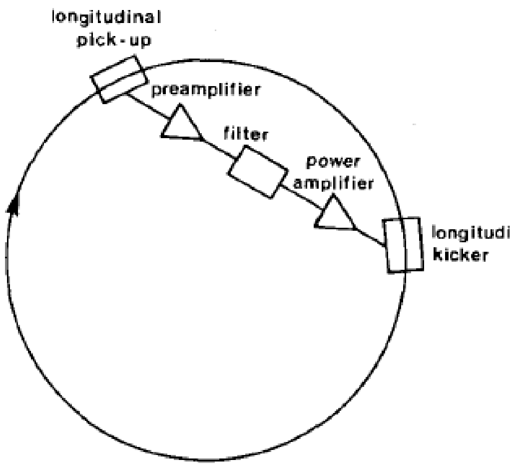
Simplest case: $\Sigma_x = (\sigma^2_{1x} + \sigma^2_{2x})^{1/2}$

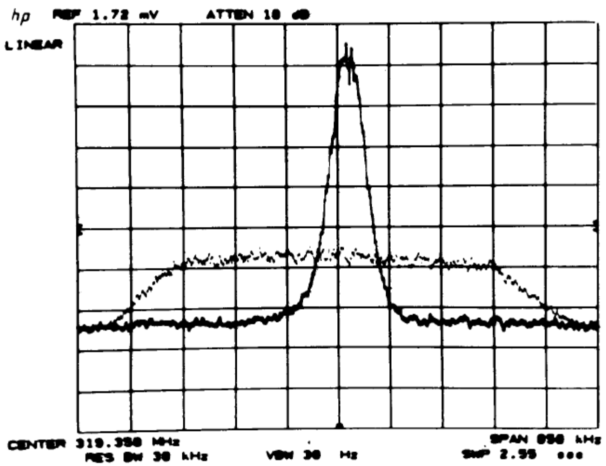
Simon van der Meer 1925 – 2011

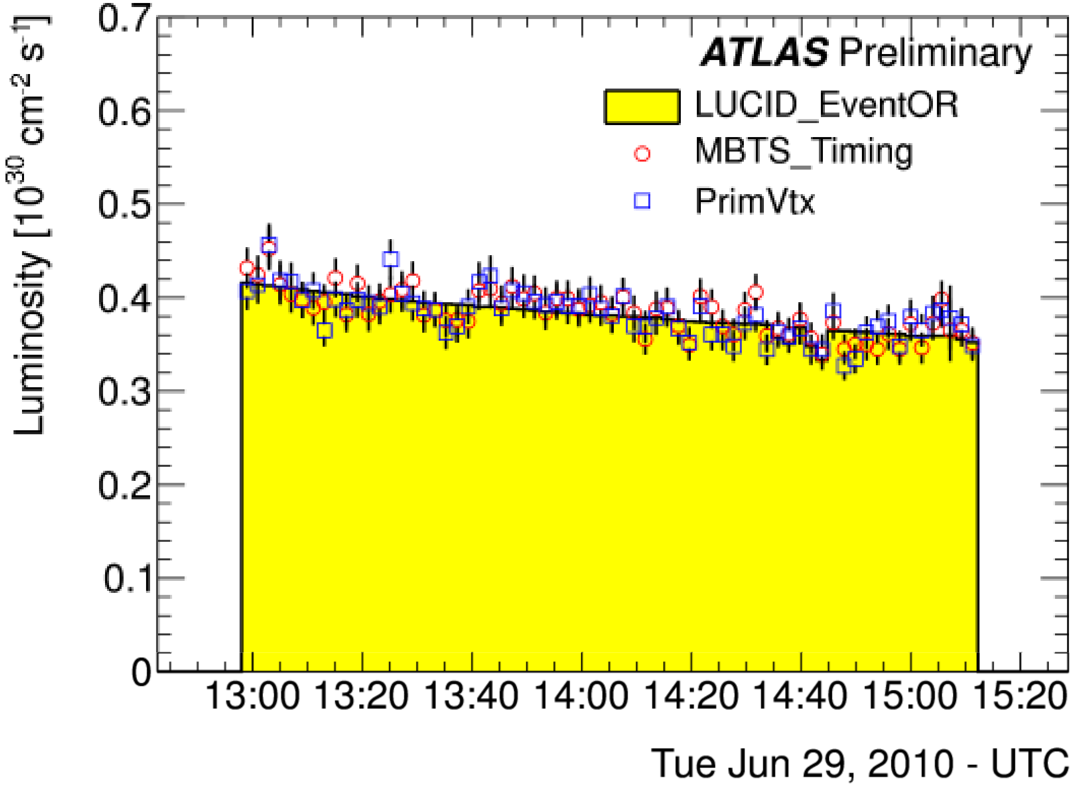
Nobel Prize in 1984 for the contributions that led to the discoveries of the W and Z)

(shared with Carlo Rubbia)

Van der Meer's crucial contribution was the stochastic cooling for accumulating enough anti-protons in conditions to be accelerated later in the SPS together with protons to provide the 630 GeV collisions needed to discover the W and Z







Initially the uncertainties for the 2010 results were 11 %, which would affect all cross-section results

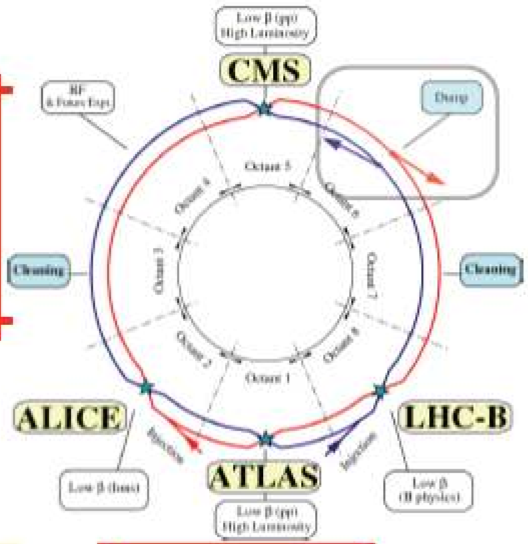
A big improvement has been recently achieved:

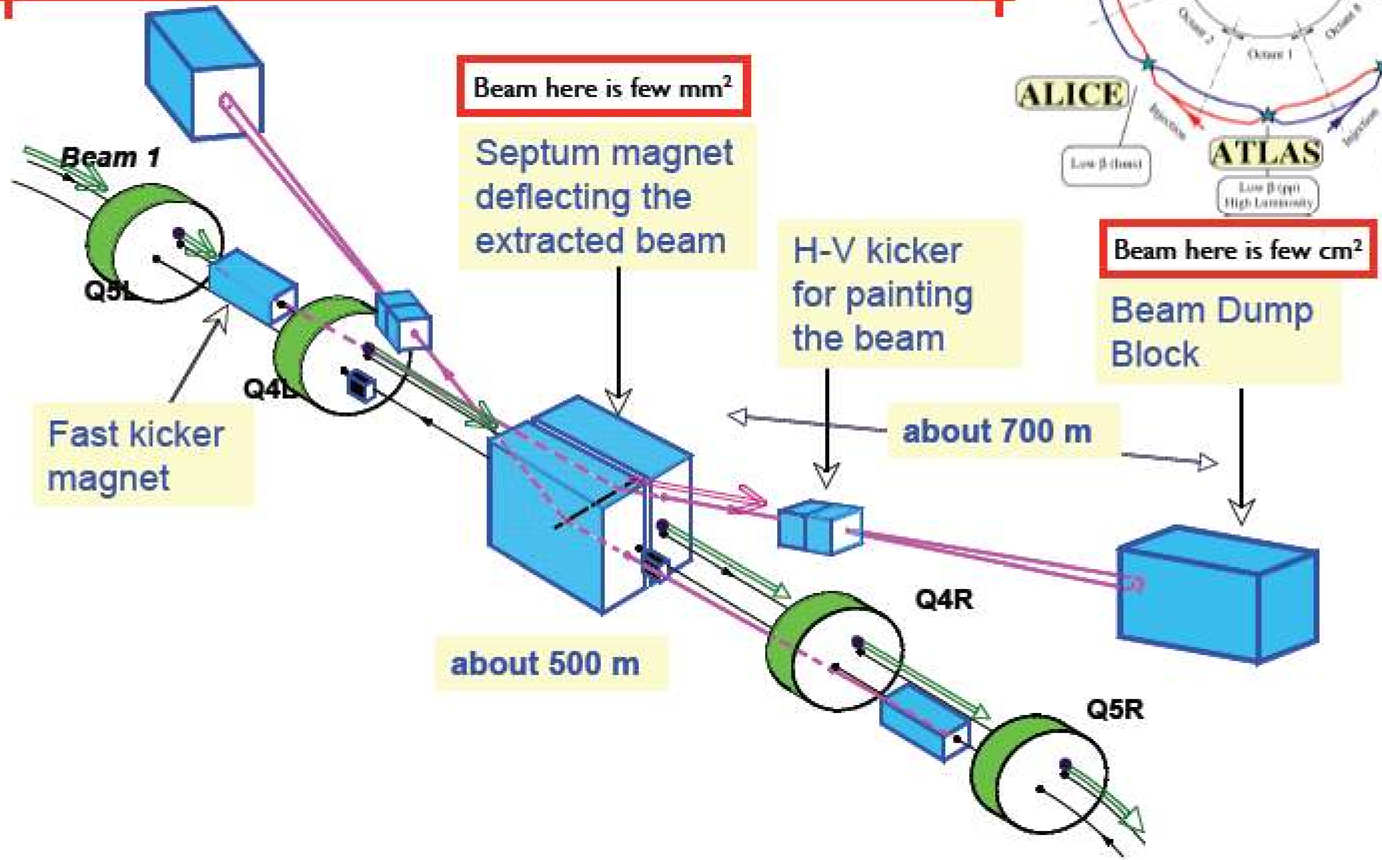
Uncertainty Source	$\delta\mathcal{L}/\mathcal{L}$
Statistical	< 0.1%
Bunch charge product	3.1%
Beam centering	0.1%
Emittance growth and other non-reproducibility	0.4%
Beam position jitter	0.2%
Length scale calibration	0.3%
Absolute ID length scale	0.3%
Fit model	0.2%
Transverse correlations	0.9%
μ dependence	0.6%
Long-term consistency	0.5%
Total	3.4%

Luminosity measured with 3.4% precision thanks to the use of several detectors (LUCID, Minimum-Bias-Trigger-Scintillators, Beam Condition Monitors, tracker)

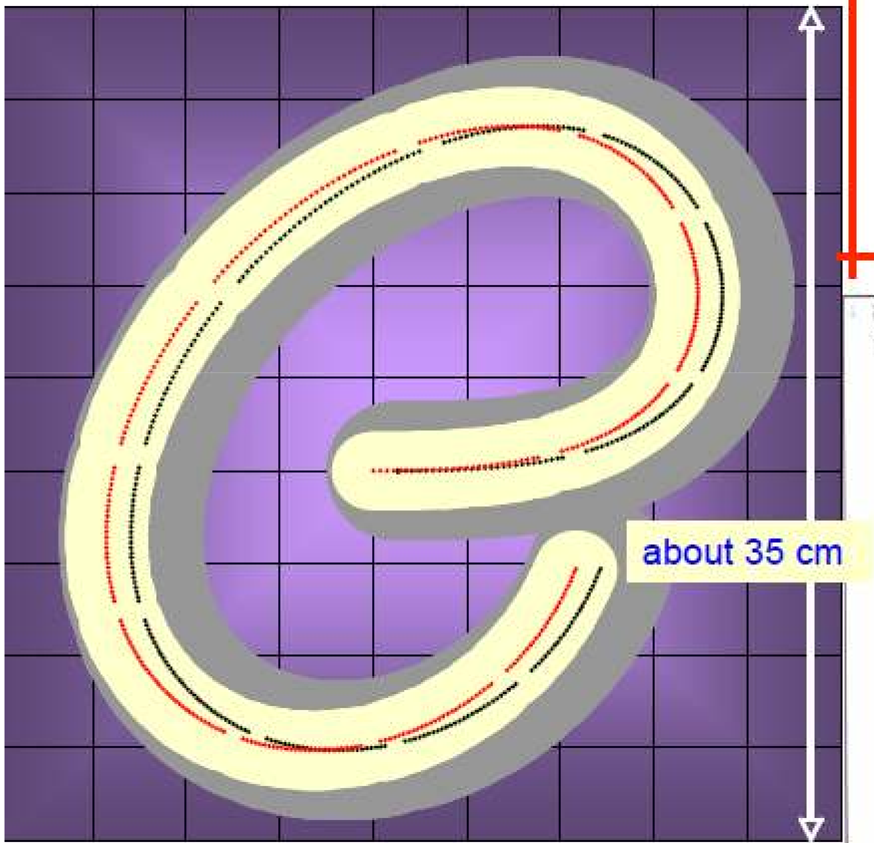
Beam extraction, emergency or not…

At the end of every "fill", when too low luminosity, or when BLM system triggers, both beams extracted on an external beam dump, in one turn.
Beam dump built to absorb full power at full energy.





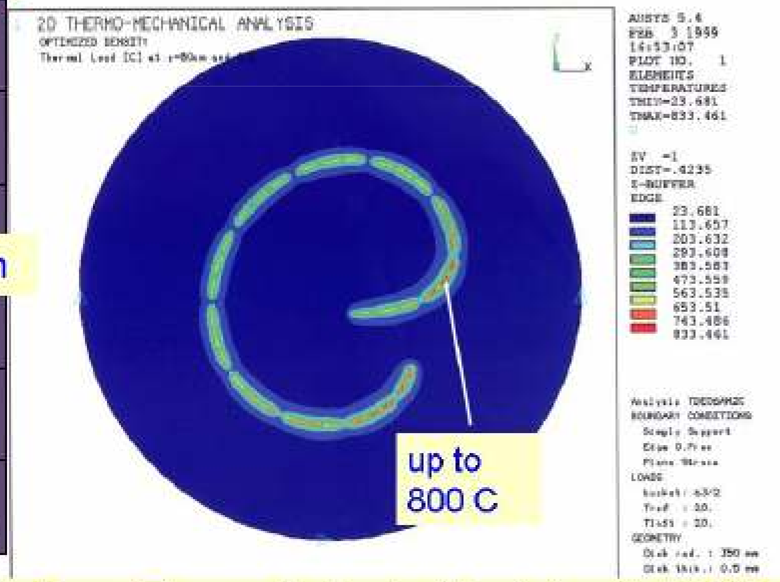
Spot size on the beam dump



To reduce energy deposition peak, proton swept by fast kickers to for a spiral on the transverse face of the dump.

Beam impact in less than 0.1 ms

Even like this, maximum temperature rise about 800 C.

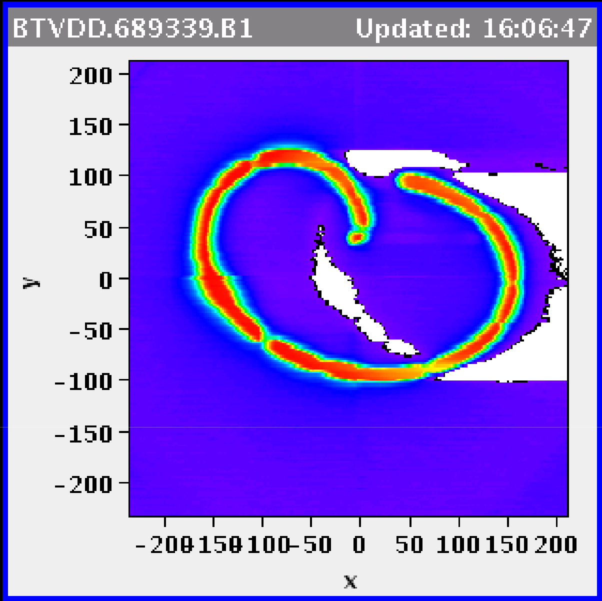


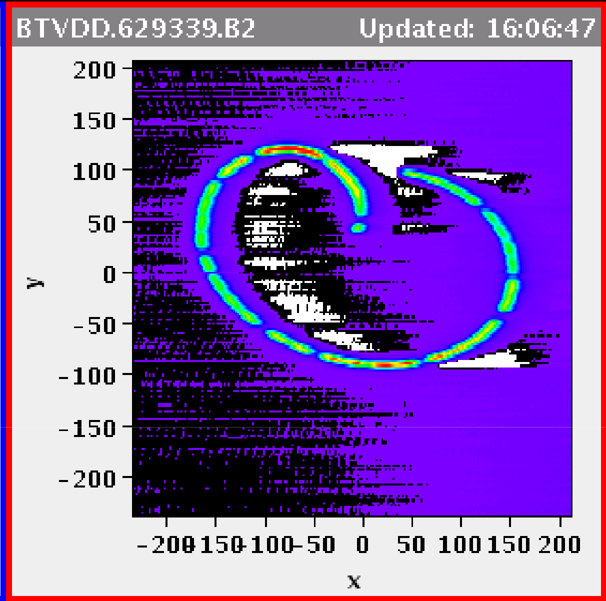
L.Bruno: Thermo-Mechanical Analysis with ANSYS

LHC Page1 | Fill: 1901 | E: 3500 GeV | 28-06-2011 16:07:54

PROTON PHYSICS: BEAM DUMP

Energy:	3500 GeV	I(B1):	2.52e+08	I(B2):	1.37e+09





Comments 28-06-2011 15:53:04 :

Will start dump handshake soon

Next: short access for BI

Then: setting up for 90 m optics

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	false	false
Setup Beam	false	false
Beam Presence	false	false
Moveable Devices Allowed In	true	true
Stable Beams	false	false

AFS: 50ns_1380b+1small_1318_39_1296_144bpi | PM Status B1 | ENABLED | PM Status B2 | ENABLED

Heavy Ion Collisions

Fully stripped Pb ions (208 Pb $^{82+}$)
With the full design field of the dipoles: 2.76 TeV/nucleon beams

Table 21.1: LHC beam parameters bearing upon the peak luminosity in the nominal ion scheme.

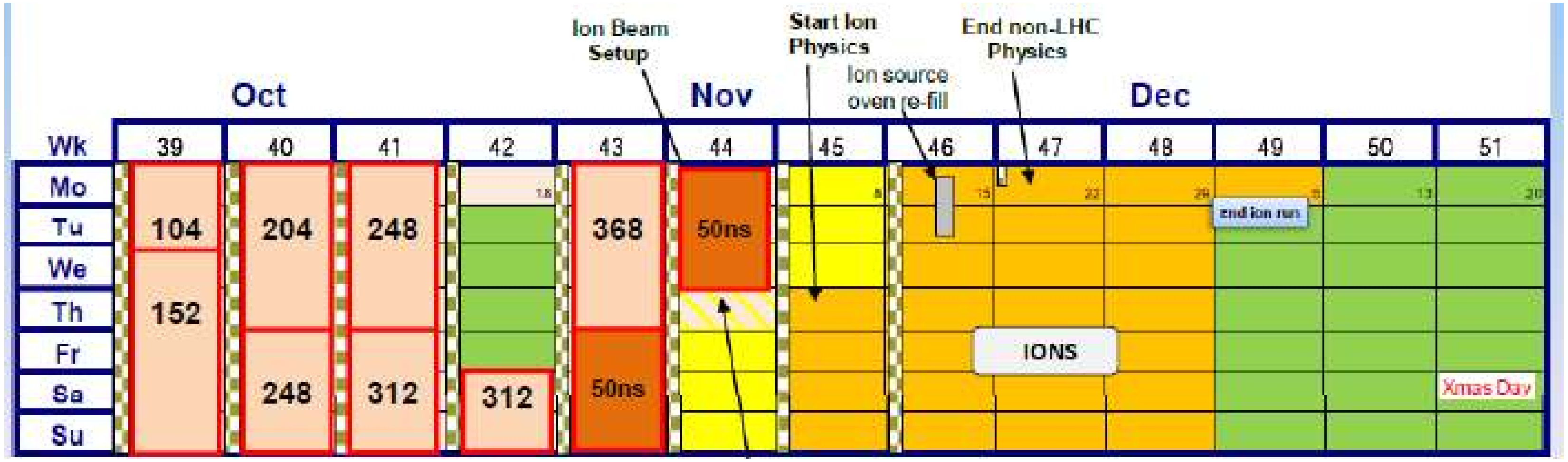
		Injection	Collision
Beam parameters			
Lead ion energy	[GeV]	36900	574000
Lead ion energy/nucleon	[GeV]	177.4	2759.
Relativistic "gamma" factor		190.5	2963.5
Number of ions per bunch		$7. \times 10^{7}$	
Number of bunches		592	
Transverse normalised emittance	[μm]	1.4[a]	1.5
Peak RF voltage (400 MHz system)	[MV]	8	16
Synchrotron frequency	[Hz]	63.7	23.0
RF bucket half-height		1.04×10^{-3}	3.56×10^{-4}
Longitudinal emittance (4σ)	[eV s/charge]	0.7	2.5[b]
RF bucket filling factor		0.472	0.316
RMS bunch length[c]	[cm]	9.97	7.94
Circulating beam current	[mA]	6.12	
Stored energy per beam	[MJ]	0.245	3.81
Twiss function $\beta_x = \beta_y = \beta^*$ at IP2	[m]	10.0	0.5
RMS beam size at IP2	μm	280.6	15.9
Geometric luminosity reduction factor F[d]		-	1
Peak luminosity at IP2	[cm^{-2}sec^{-1}]	-	$1. \times 10^{27}$

[a]The emittance at injection energy refers to the emittance delivered to the LHC by the SPS without any increase due to injection errors and optical mismatch.

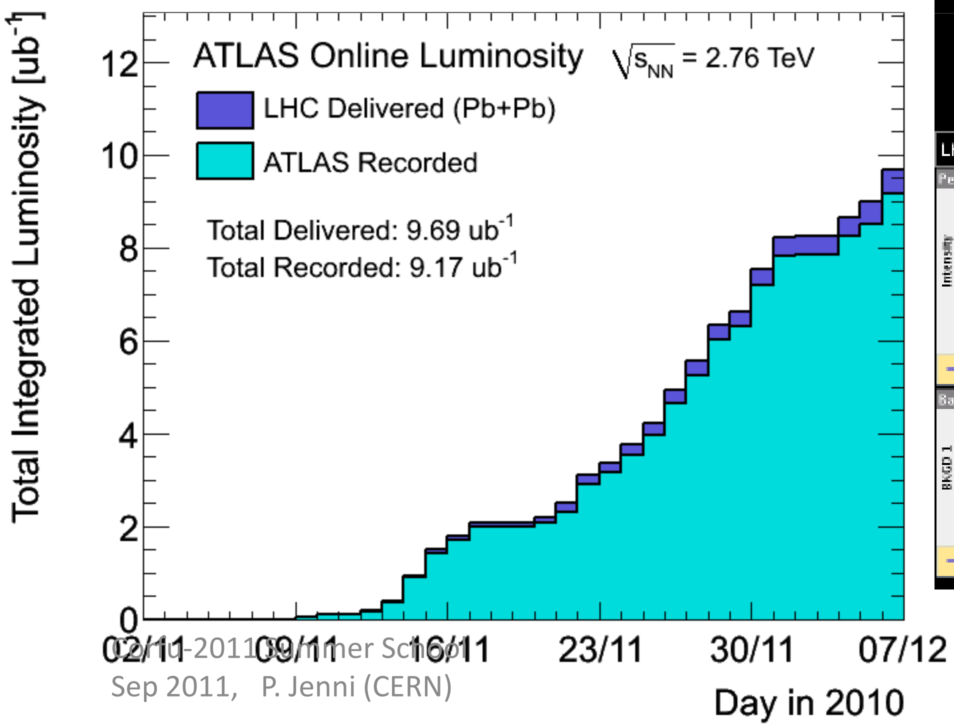
[b]The baseline operation assumes that the longitudinal emittance is deliberately blown up during, or before, the ramp in order to reduce the intra-beam scattering growth rates.

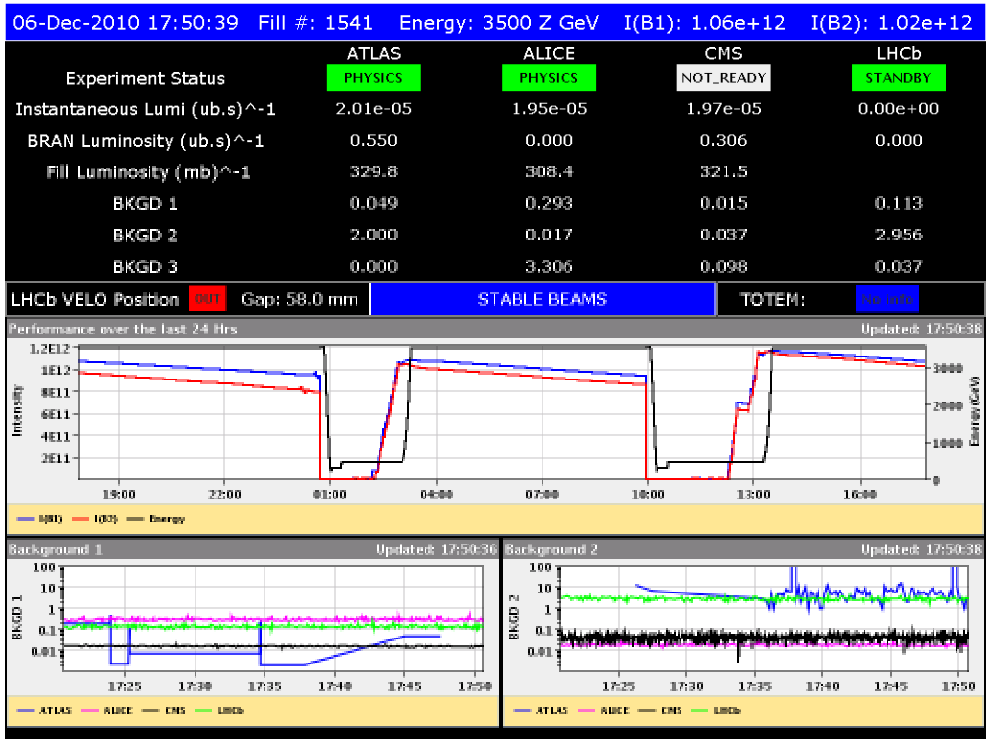
[c]Dimensions are given for Gaussian distributions. The real beam will not have a Gaussian distribution but more realistic distributions do not allow analytic estimates for the IBS growth rates.

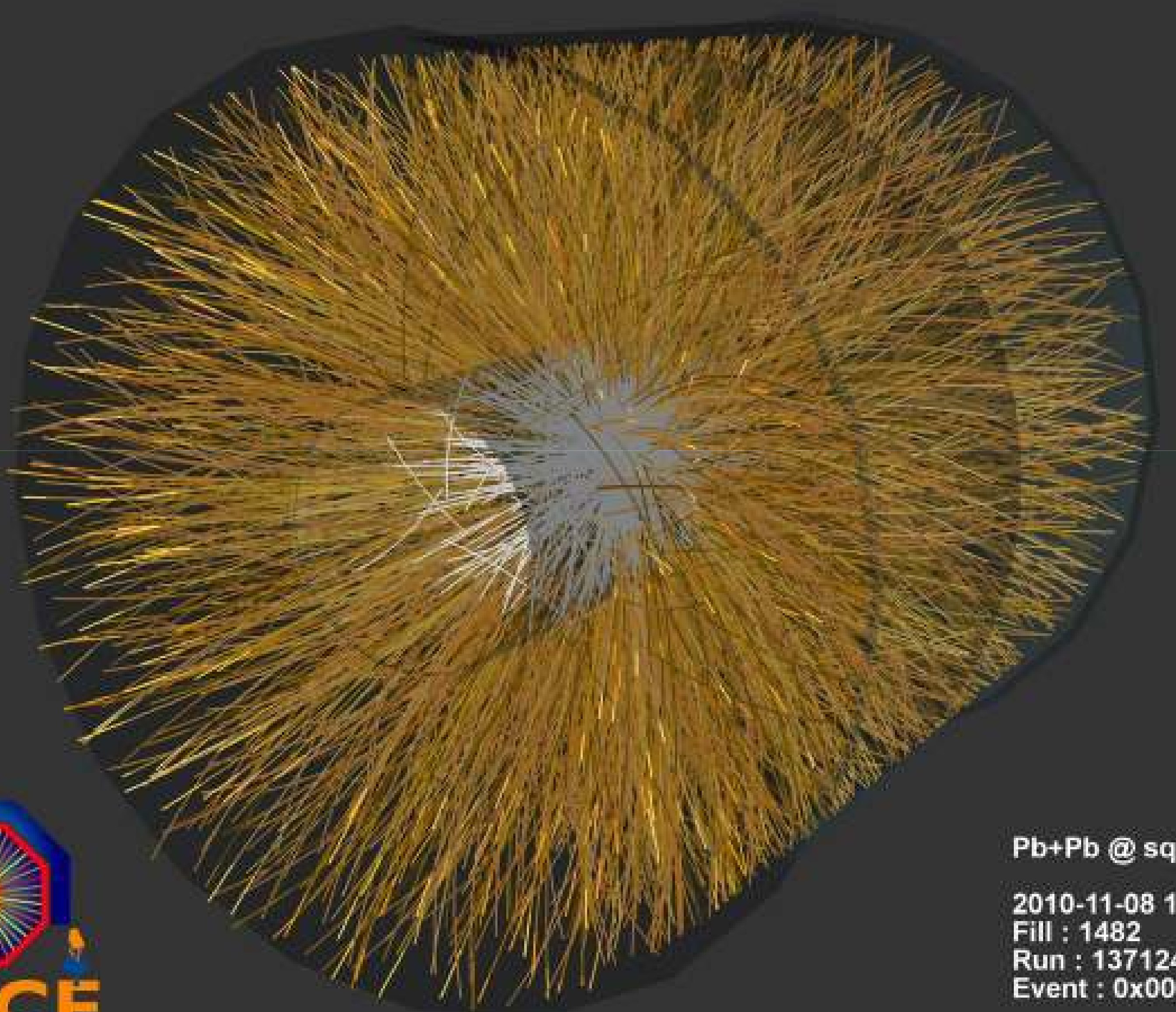
[d]The geometric luminosity reduction factor Equation 3.3 depends on the total crossing angle at the IP. The crossing angle for lead ions is discussed in Sec. 21.3.2



Heavy Ion running 2010

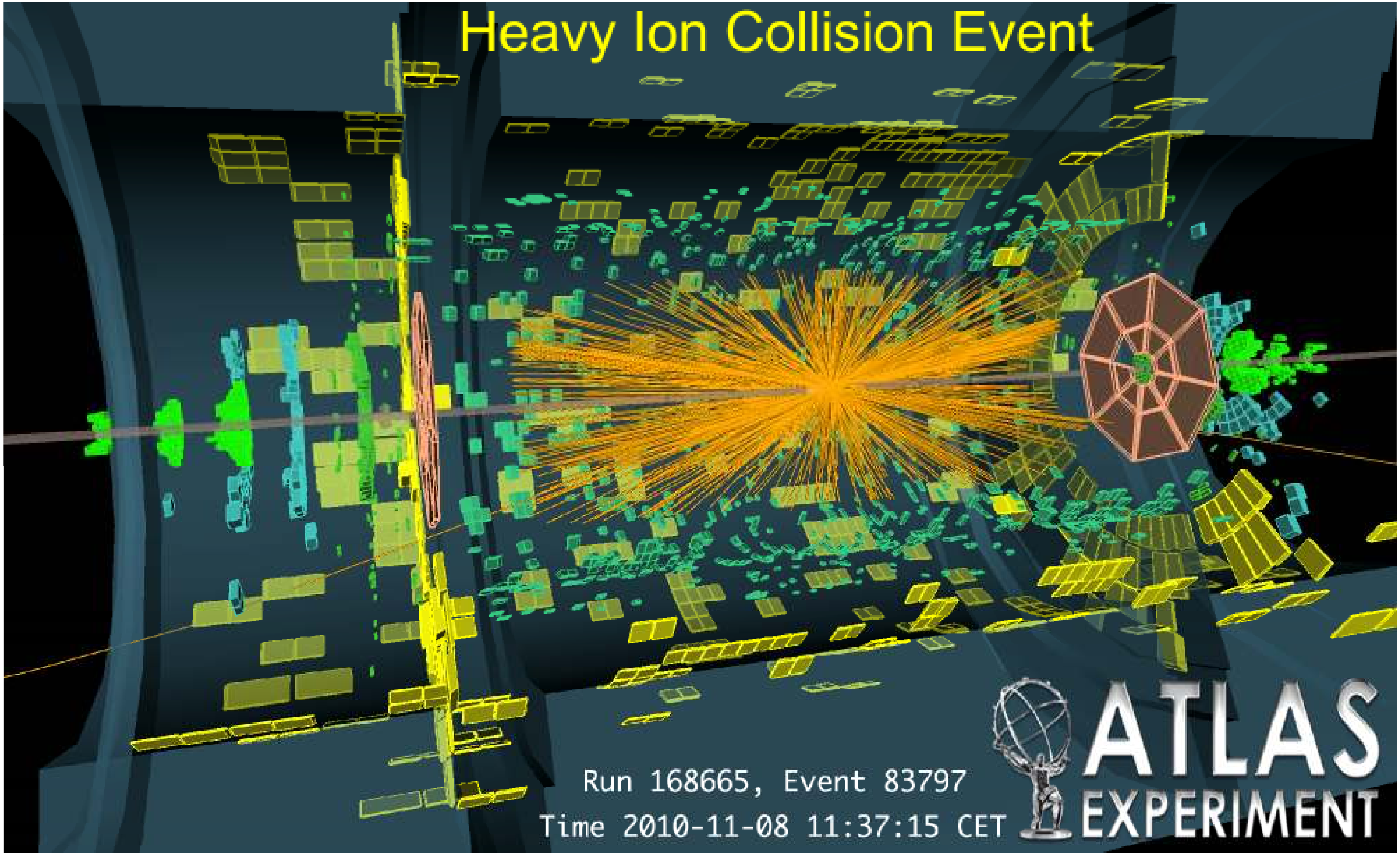






Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:29:52
Fill : 1482
Run : 137124
Event : 0x0000000042B1B693


Heavy Ion Collision Event
Run 168665, Event 83797
Time 2010-11-08 11:37:15 CET
ATLAS
EXPERIMENT