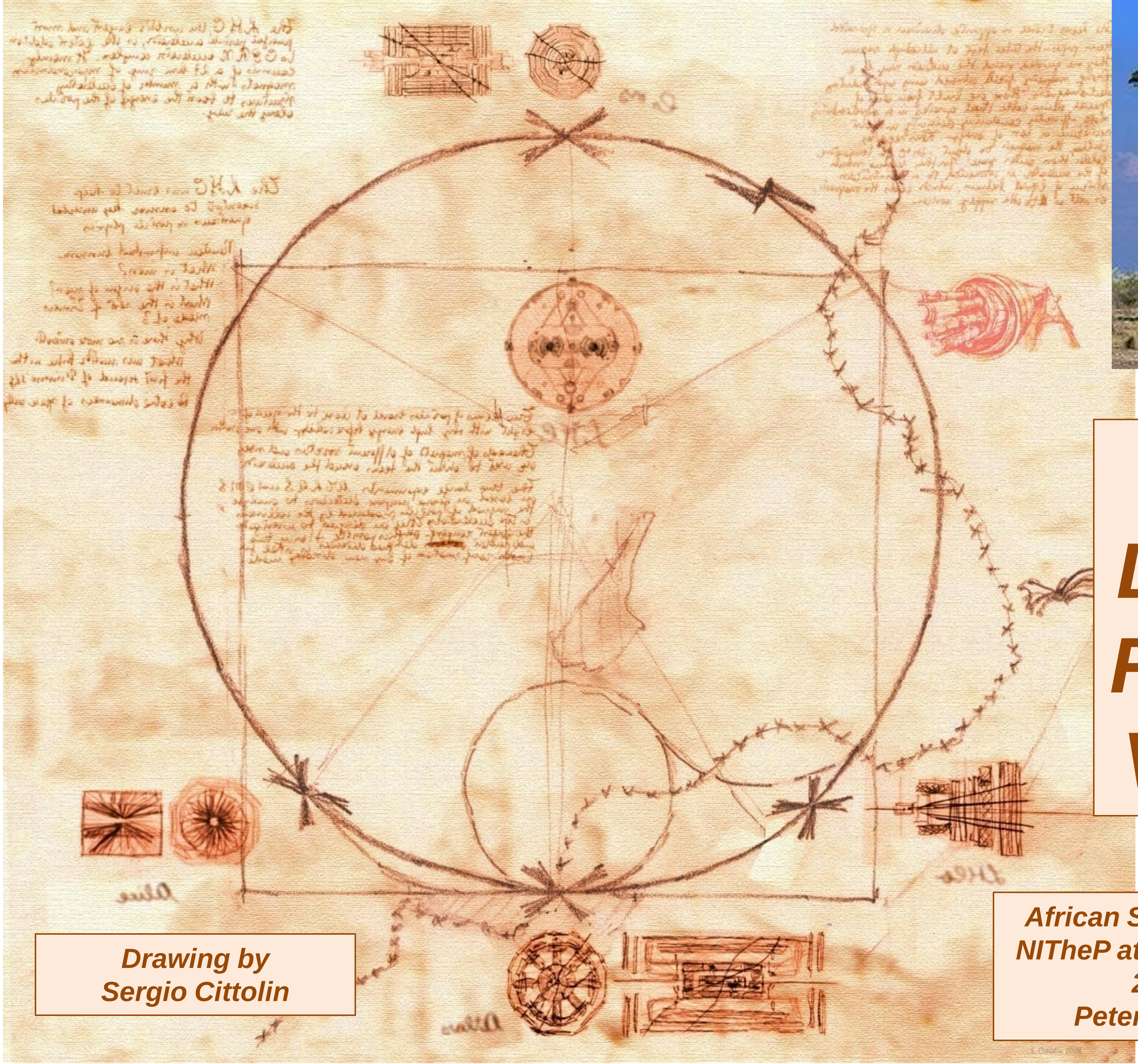
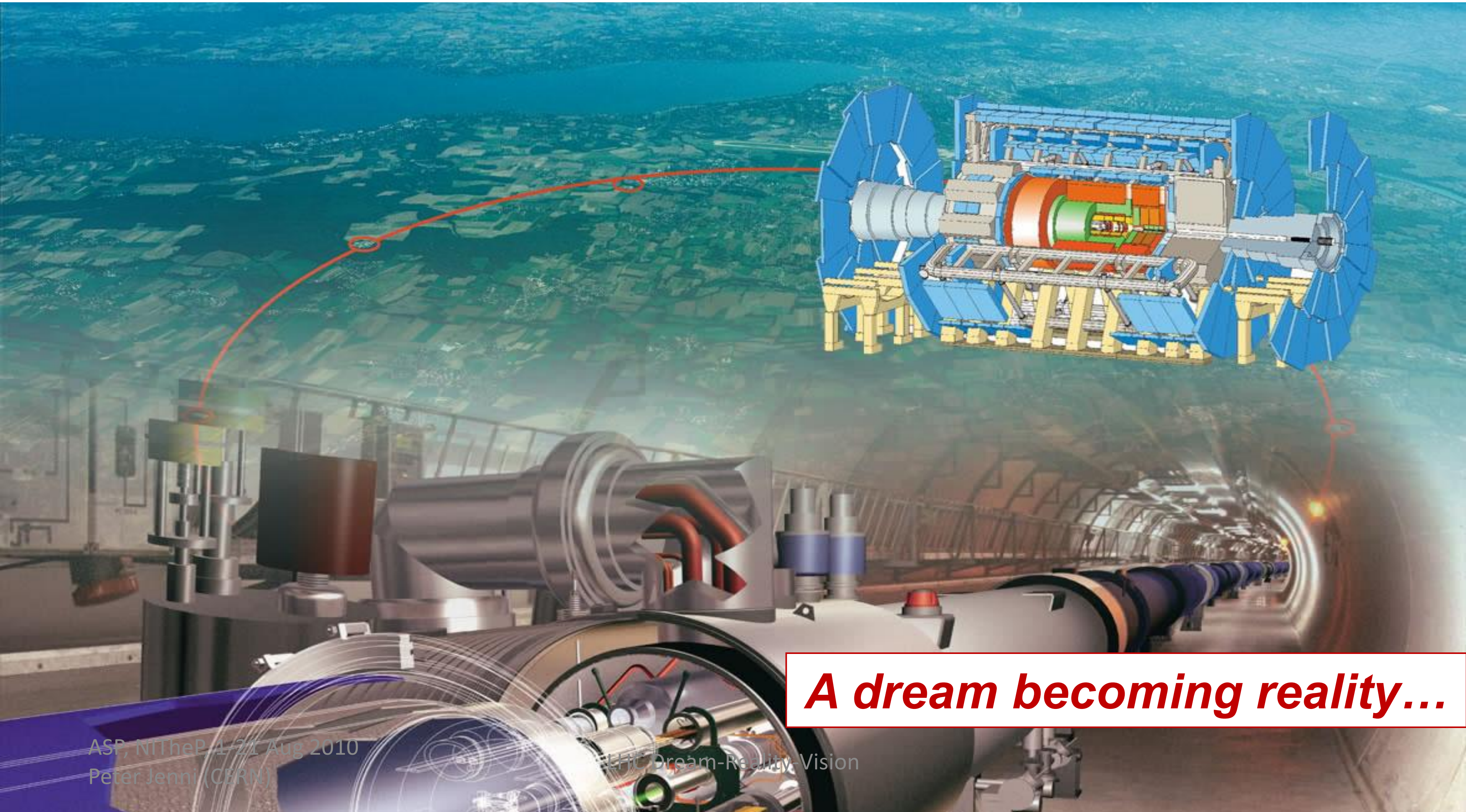


LHC: Dream Reality Vision

Drawing by Sergio Cittolin

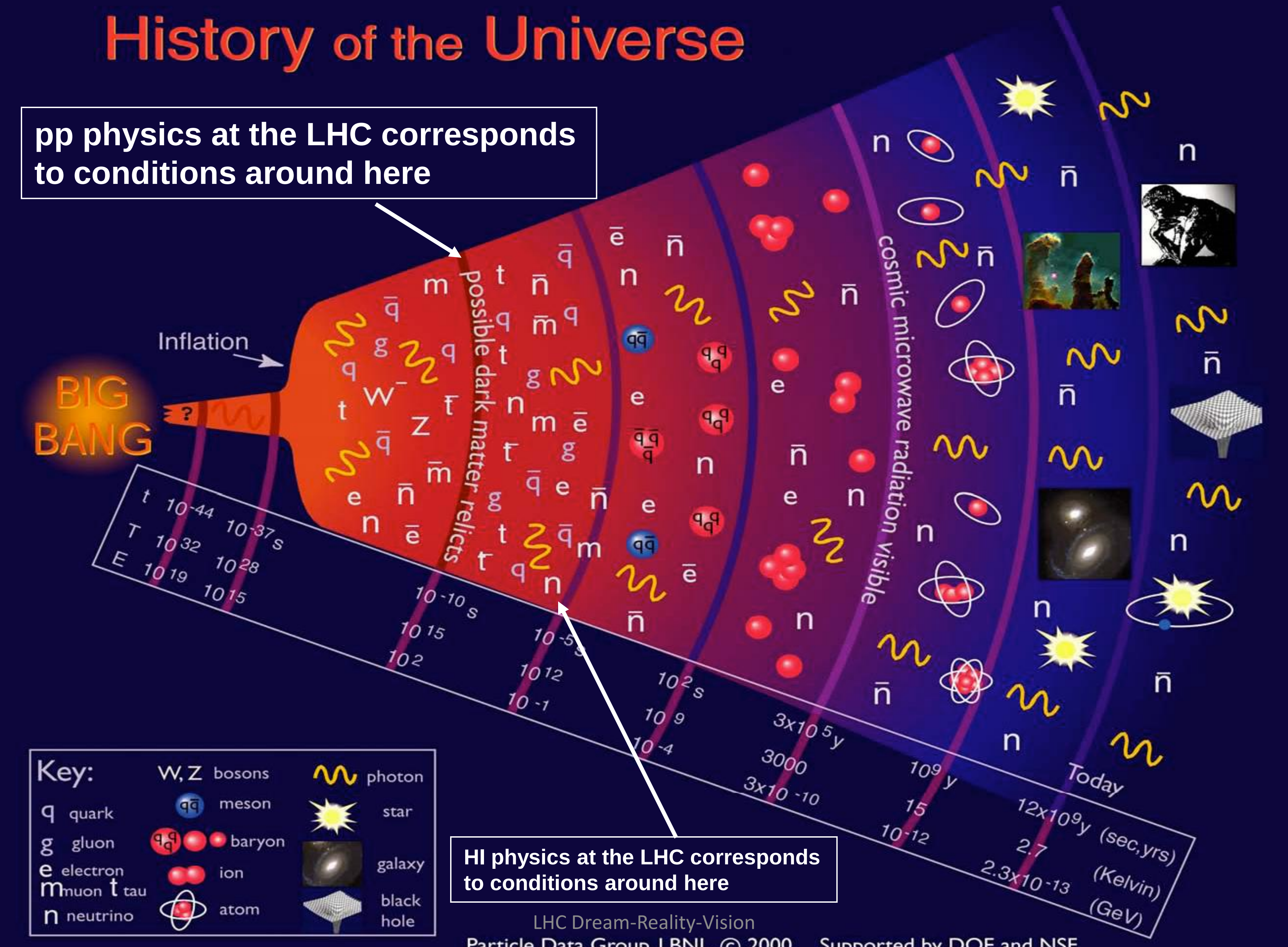
African School of Physics
NITheP at Stellenbosch, SA
20-8-2010
Peter Jenni, CERN

The Large Hadron Collider Project:
A Journey to Discover the Physics Shortly After the Big Bang



A dream becoming reality…

The Large Hadron Collider project has to be seen as a global scientific adventure, combining the accelerator and the experiments



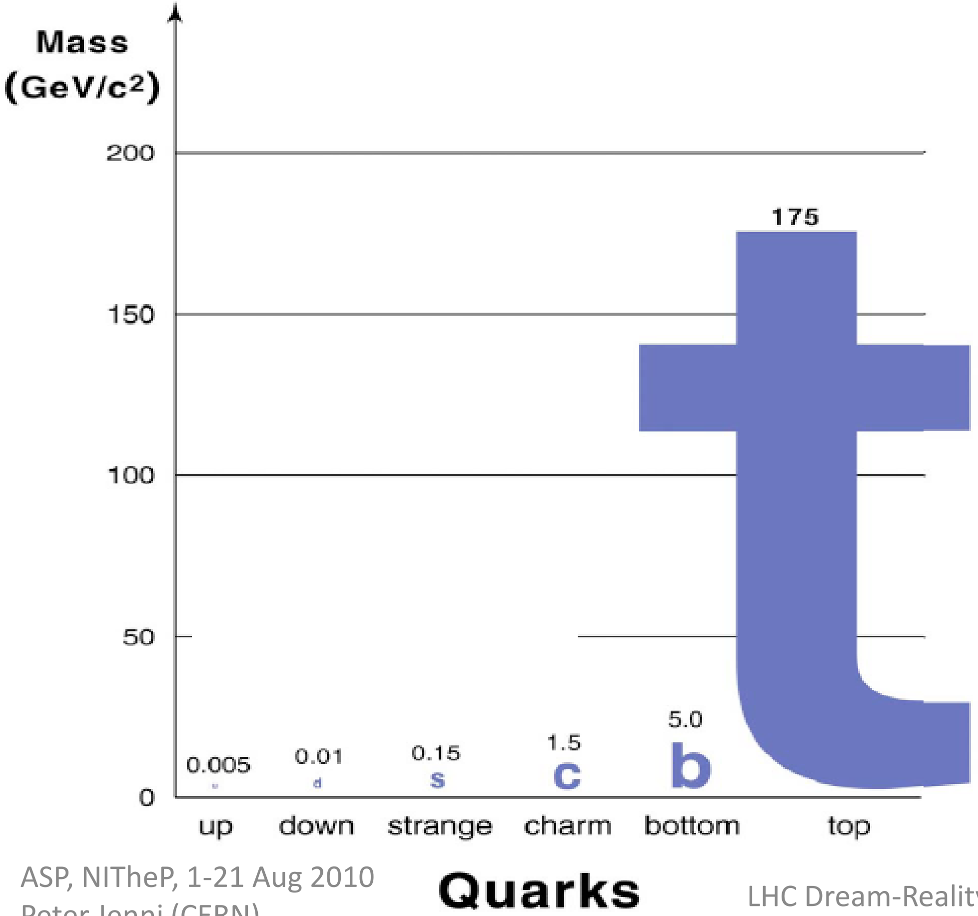
pp physics at the LHC corresponds to conditions around here

HI physics at the LHC corresponds to conditions around here

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)

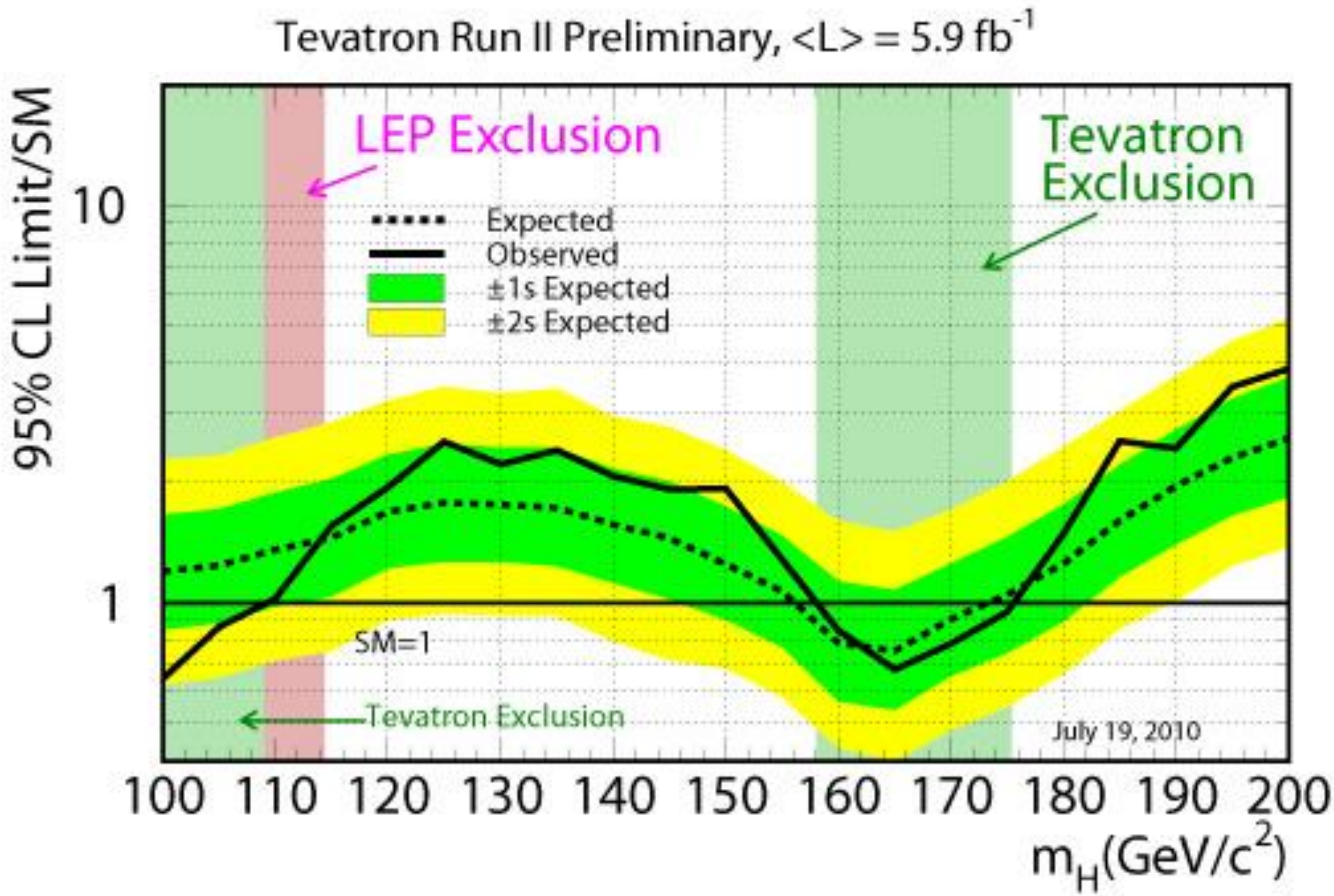
Peter Higgs



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

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

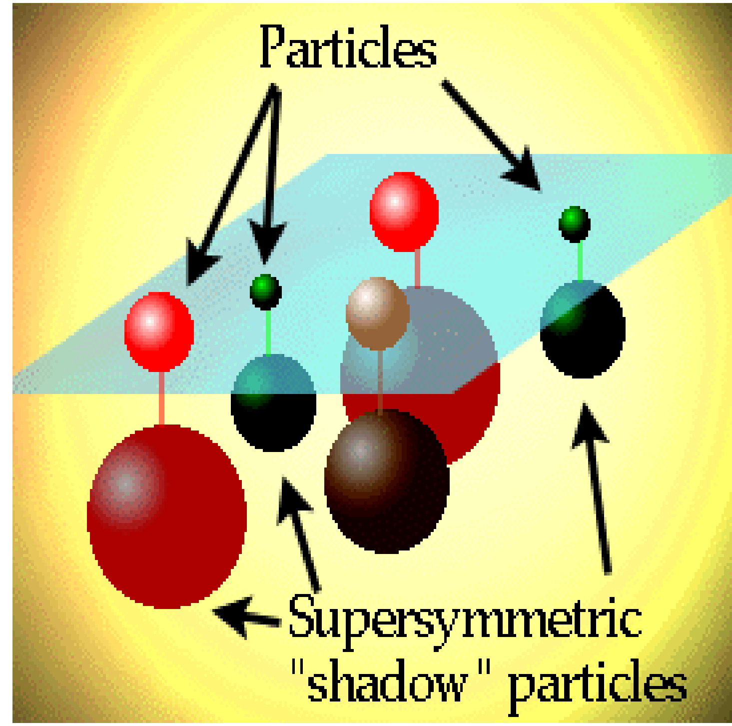
Francois Englert



(Status ICHEP 2010)

Supersymmetry (SUSY)

(Julius Wess and Bruno Zumino, 1974)



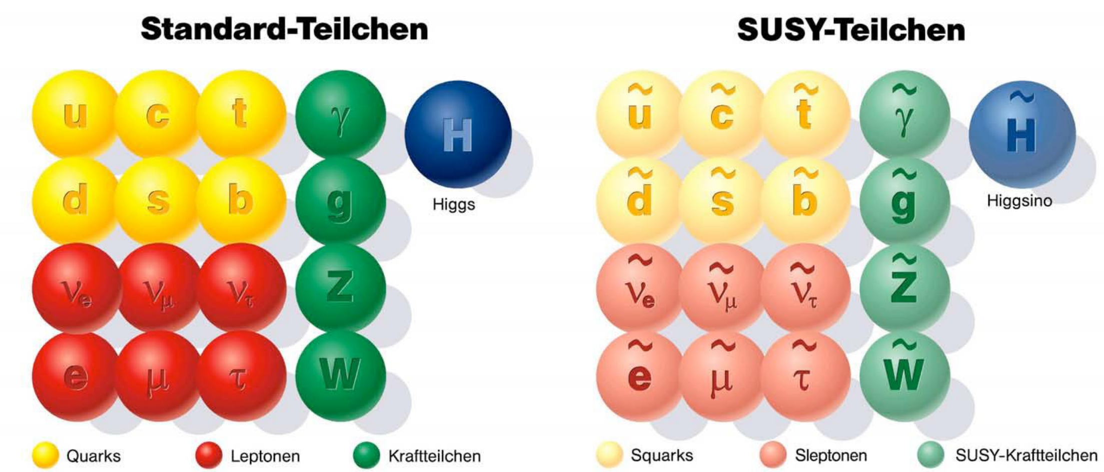
Establishes a symmetry between fermions (matter) and bosons (forces):

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

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

g (s=1) → $\tilde{g}$ (s=1/2) gluino

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



Motivation:

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

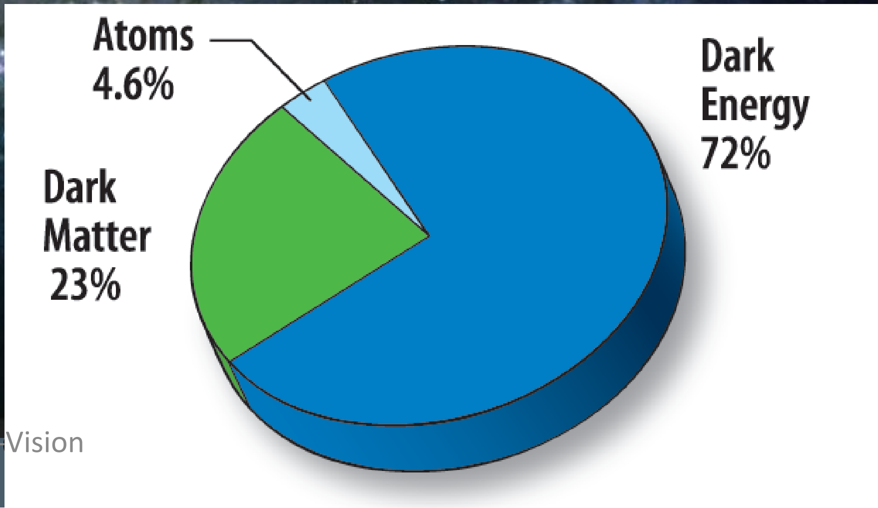
Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible
Dark Matter

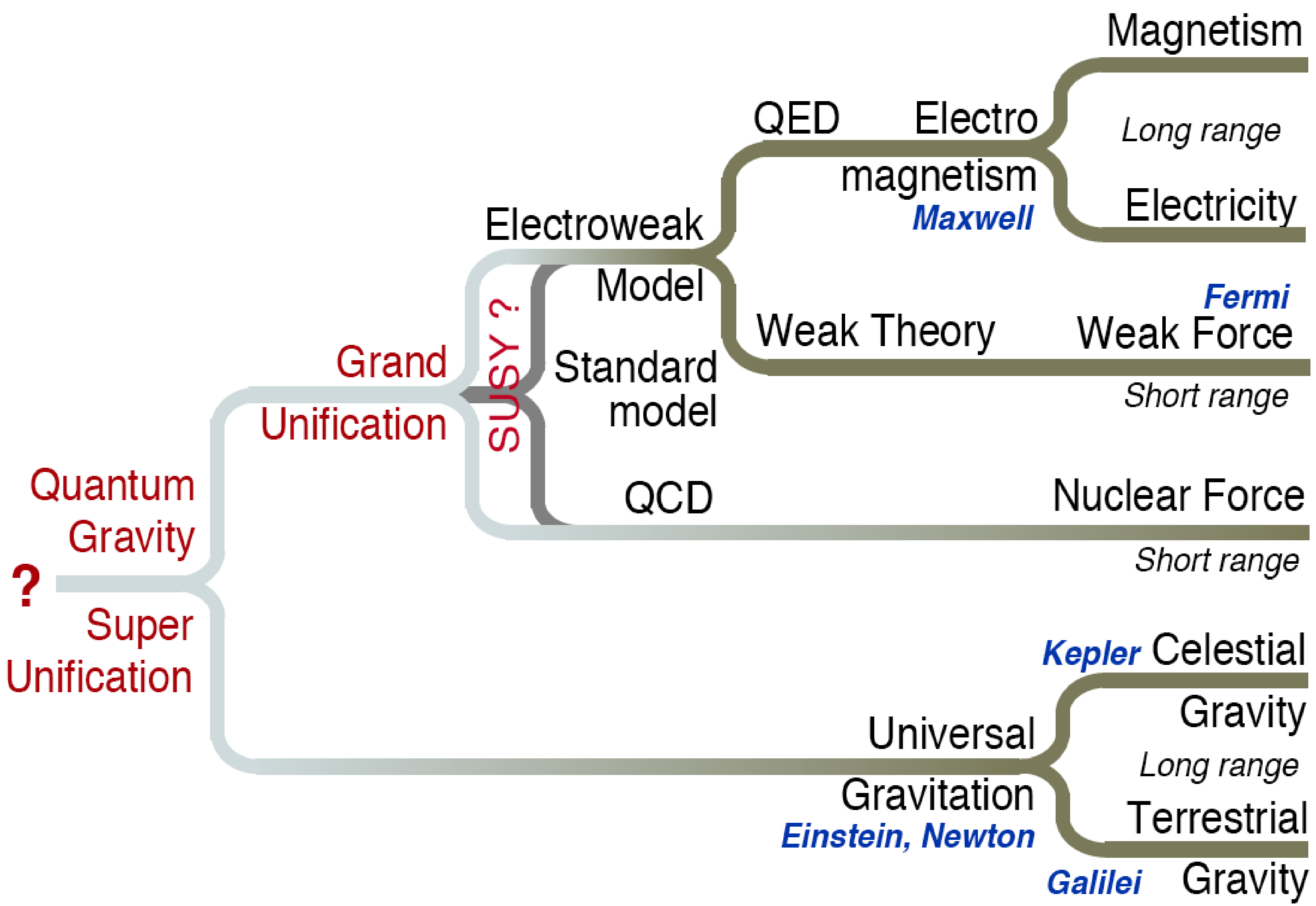
‘Supersymmetric’ particles ?

We shall look for them with the LHC

F. Zwicky 1898-1974



Unification of Forces



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**

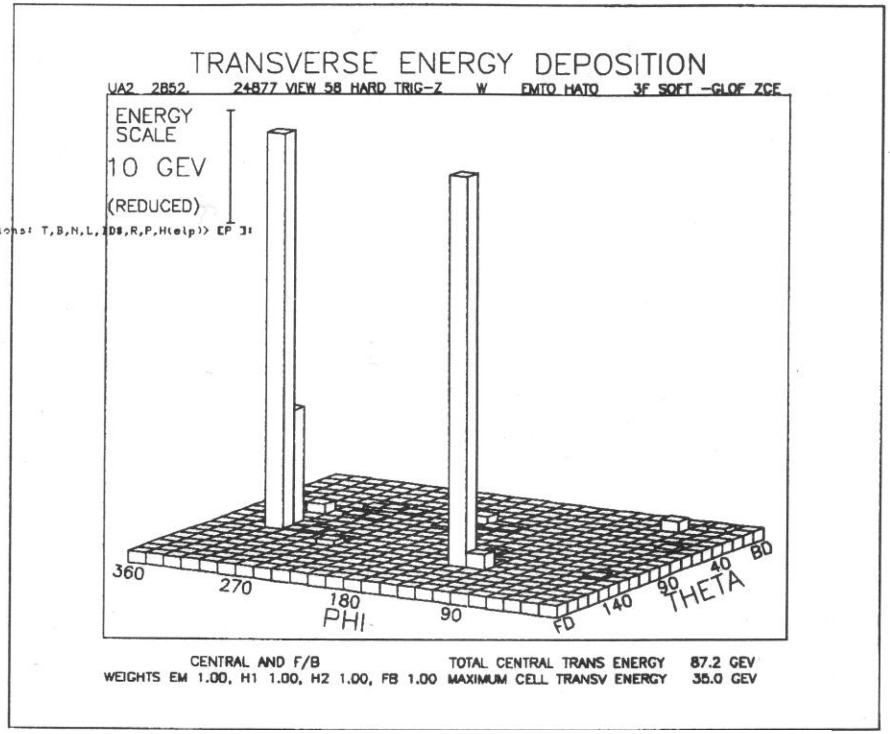
1981 **LEP was approved with a large and long (27 km) tunnel**

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

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

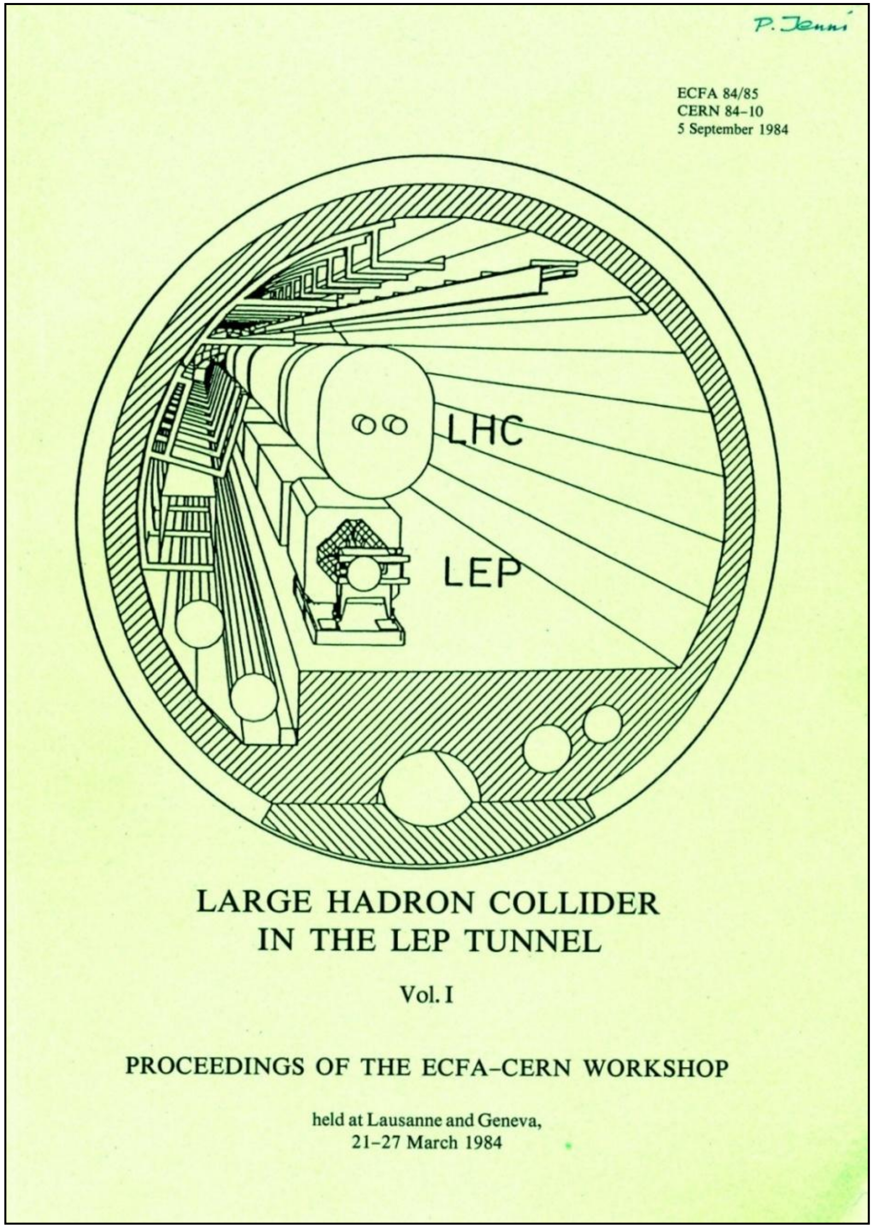
1987 La Thuile LHC Workshop

(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

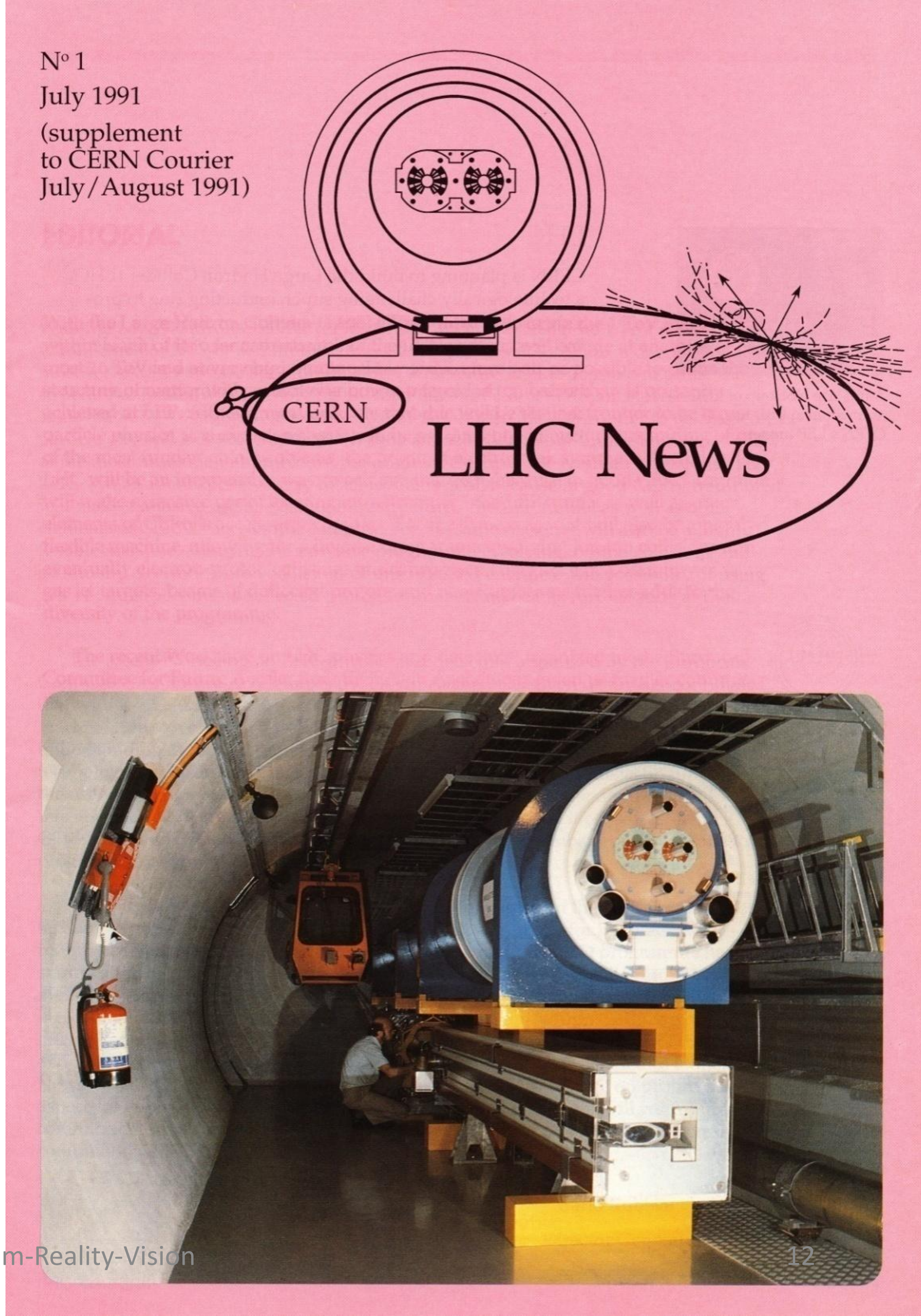
(J Mulvey main organizer, four Plenary talks and many study group reports: I Hinchliffe (physics), D Saxon (tracking), B Pope (high-performance detectors) and PJ (calorimetry and jets))

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



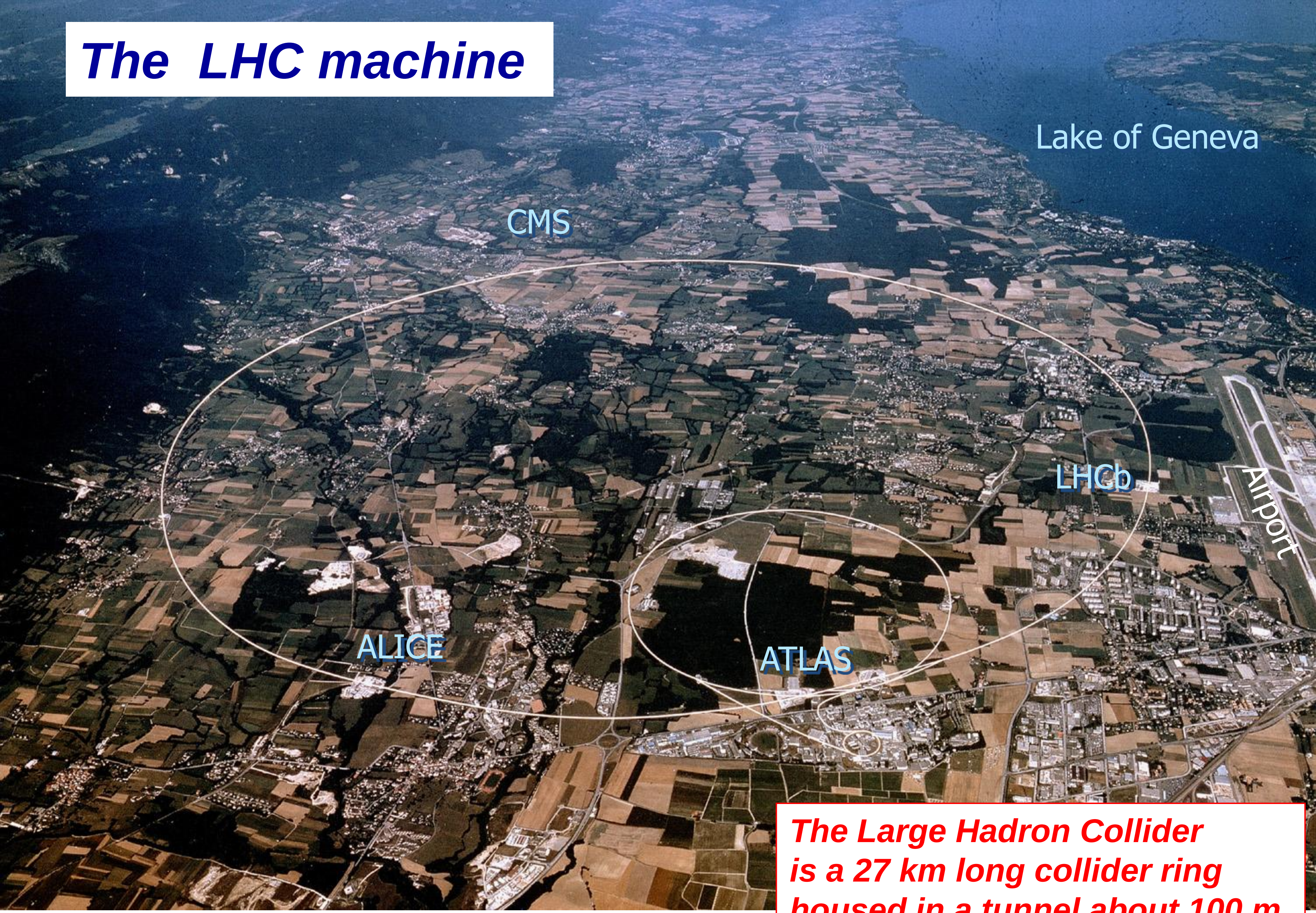
1991 December CERN Council:
'LHC is the right machine for advance of the subject and the future of CERN'
(thanks to the great push by DG C Rubbia)

1993 December proposal of LHC with commissioning in 2002



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

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

Main parameters of the machine

n. of protons per bunch → N; n. of bunches → k_b; n. of turns per second → f

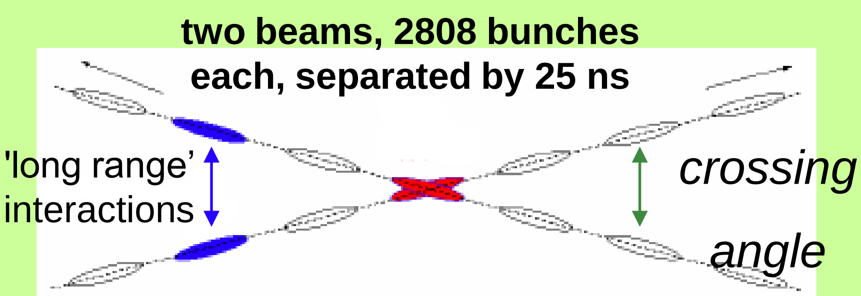
$$L = \frac{N^2 k_b f}{4\pi\sigma_x\sigma_y}$$

beam size at IP ($\sigma_{x,y}$ = 16 μm)

	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

$N = L \times \sigma(pp \to X)$

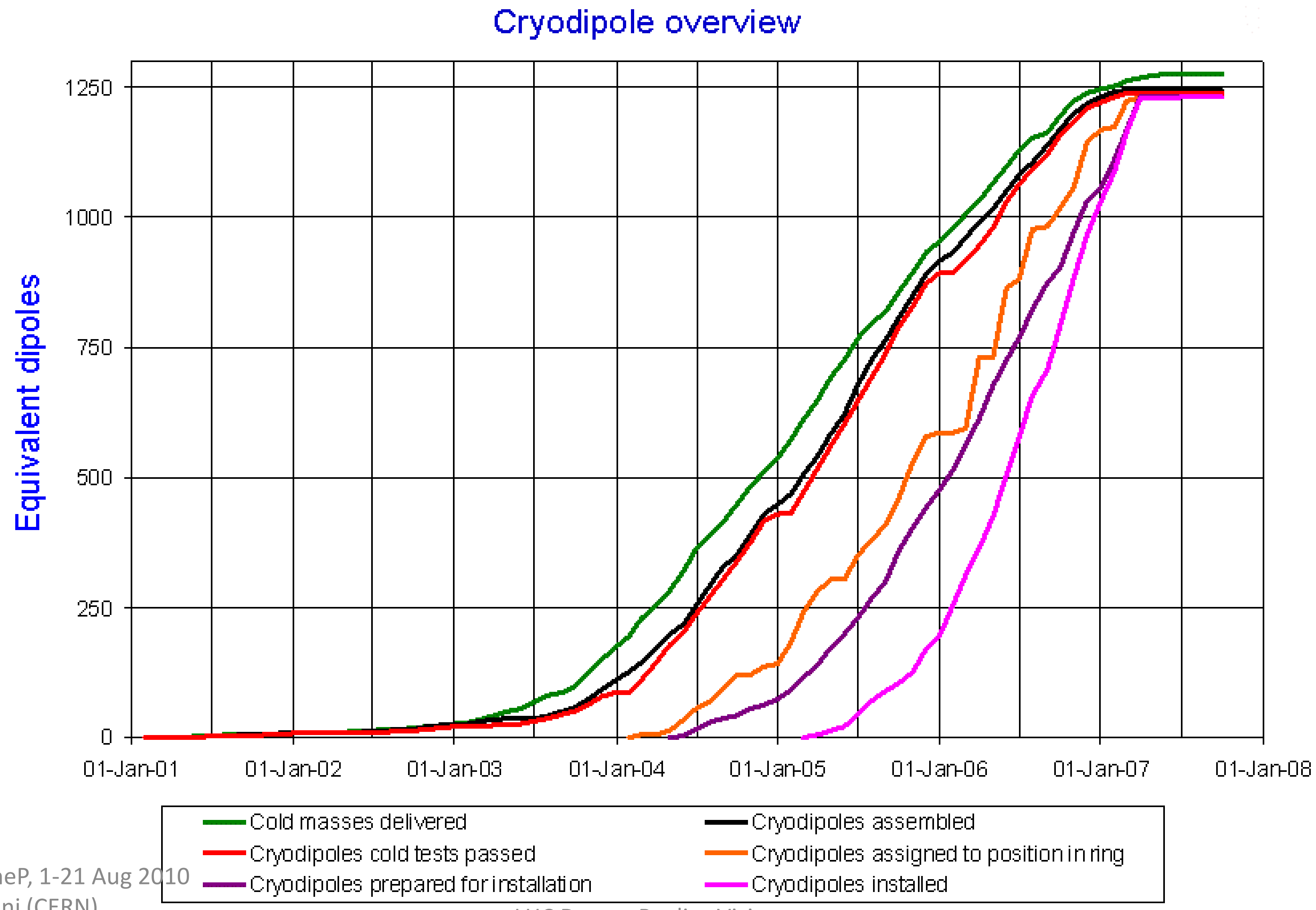
x200 Tevatron (→ Stored beam energy)



History of the dipole magnet construction and installation

LHC Progress Dashboard

Accelerator Technology Department

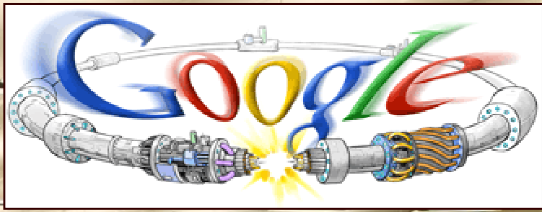


Updated 30 September 2007

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

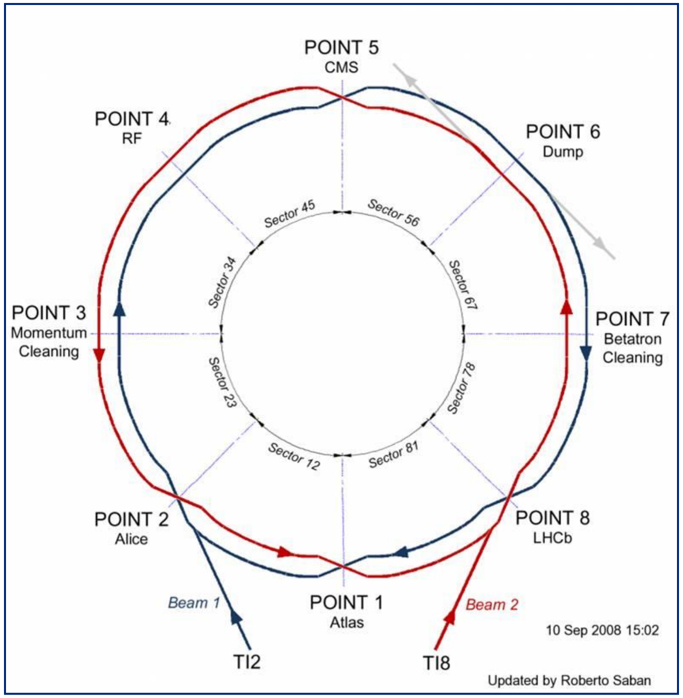
10 September 2008: LHC inauguration day

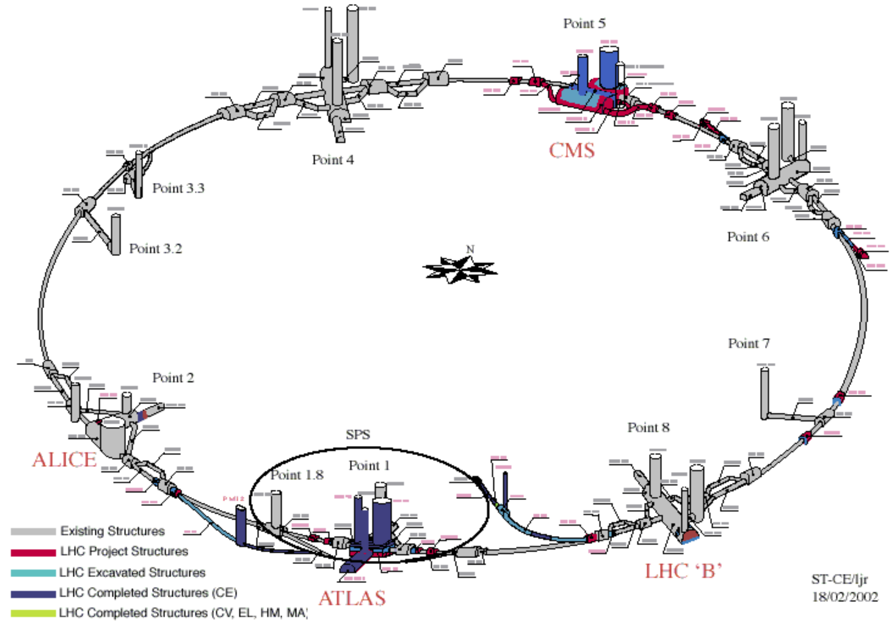
First (single) beams circulating in the machine

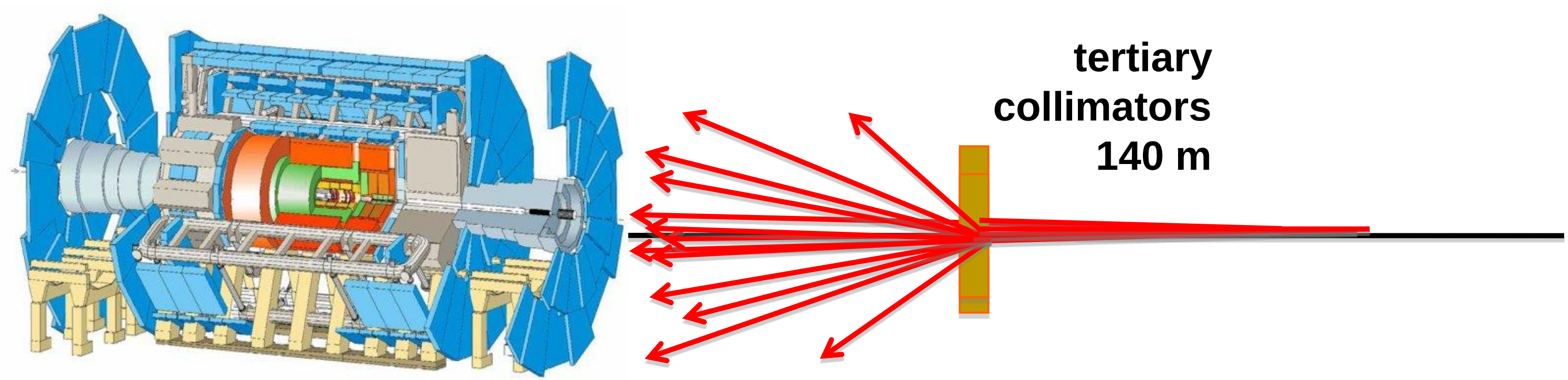


Five CERN DGs, from conception to realization: Schopper, Rubbia, Llewellyn Smith, Maiani, Aymar (from right to left)

First LHC Single Beam on 10th September 2008







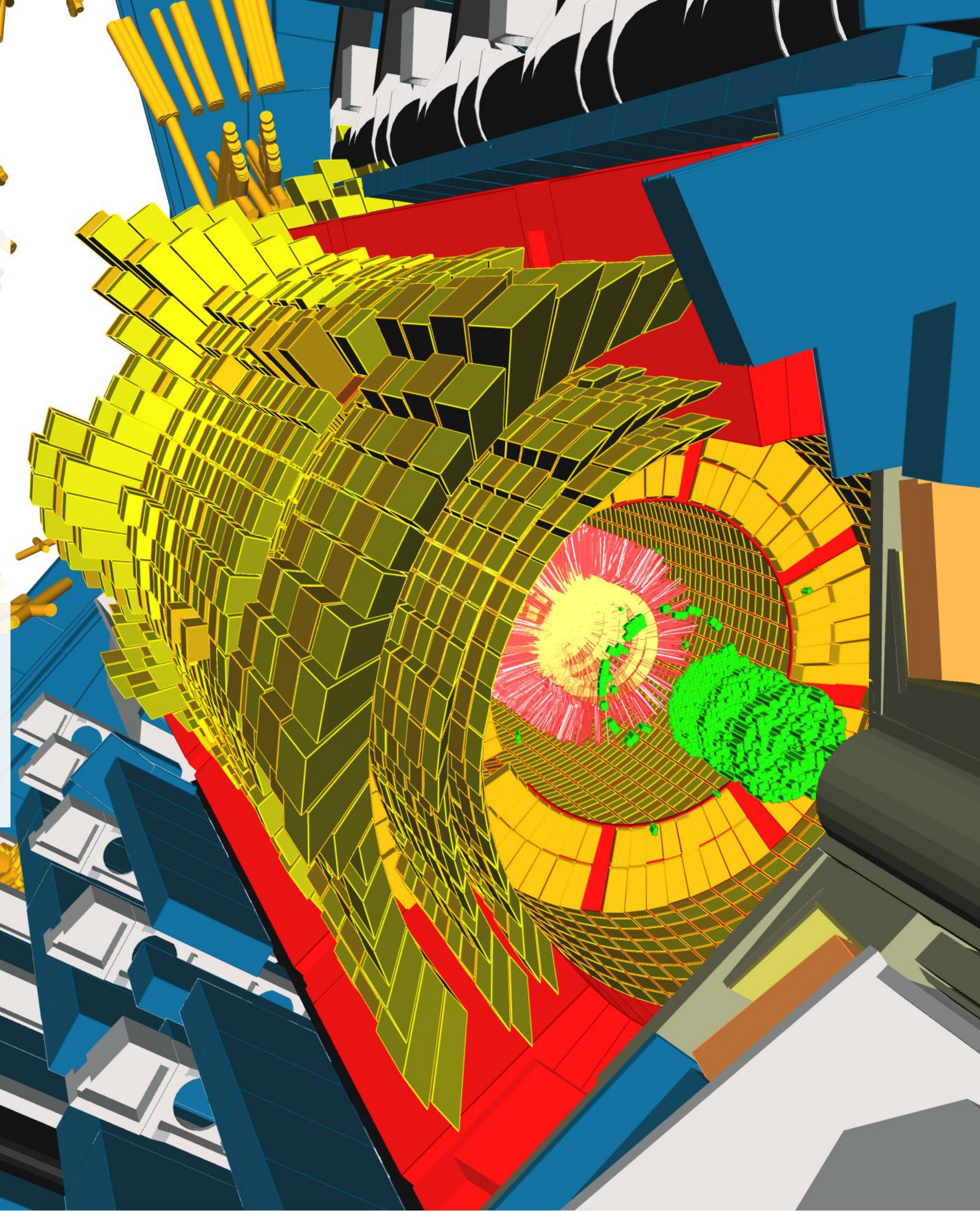
Excitement in the ATLAS Detector Control Room: The first LHC event on 10th September 2008

ATLAS Beam Splash Event

Avalanche of scattered particles from beam-on-collimator hits

Detectors fully lit, typically

- **300,000 SCT hits**
- **350,000 TRT hits (~all passing high-threshold)**
- **3000 TeV calo energy sum**
- **490,000 MDT hits**
- **320,000 RPC hits**
- **65,000 TGC hits**



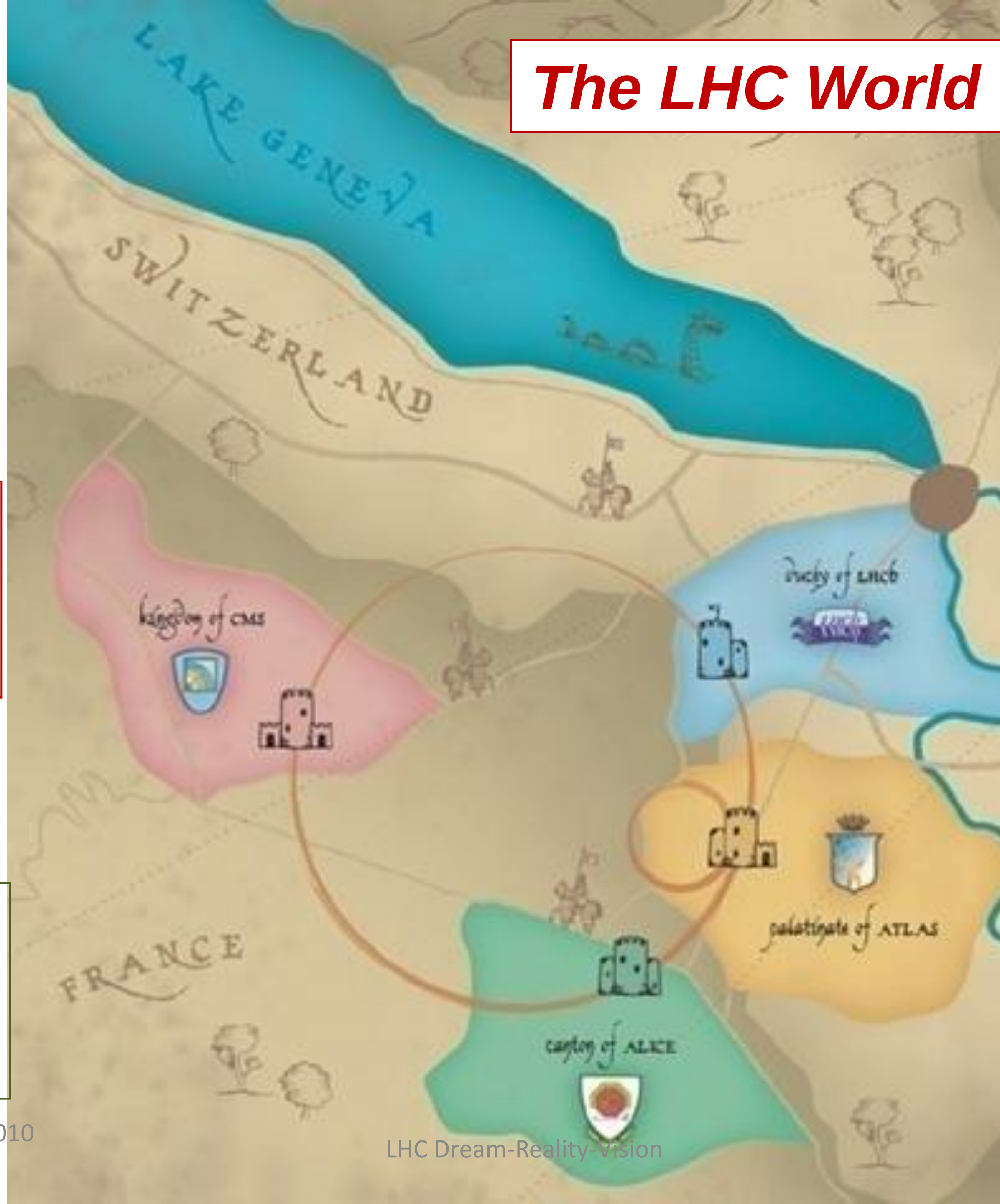
ATLAS EXPERIMENT

2009-11-20, 23:32 CET

Run 140370, Event 2666

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

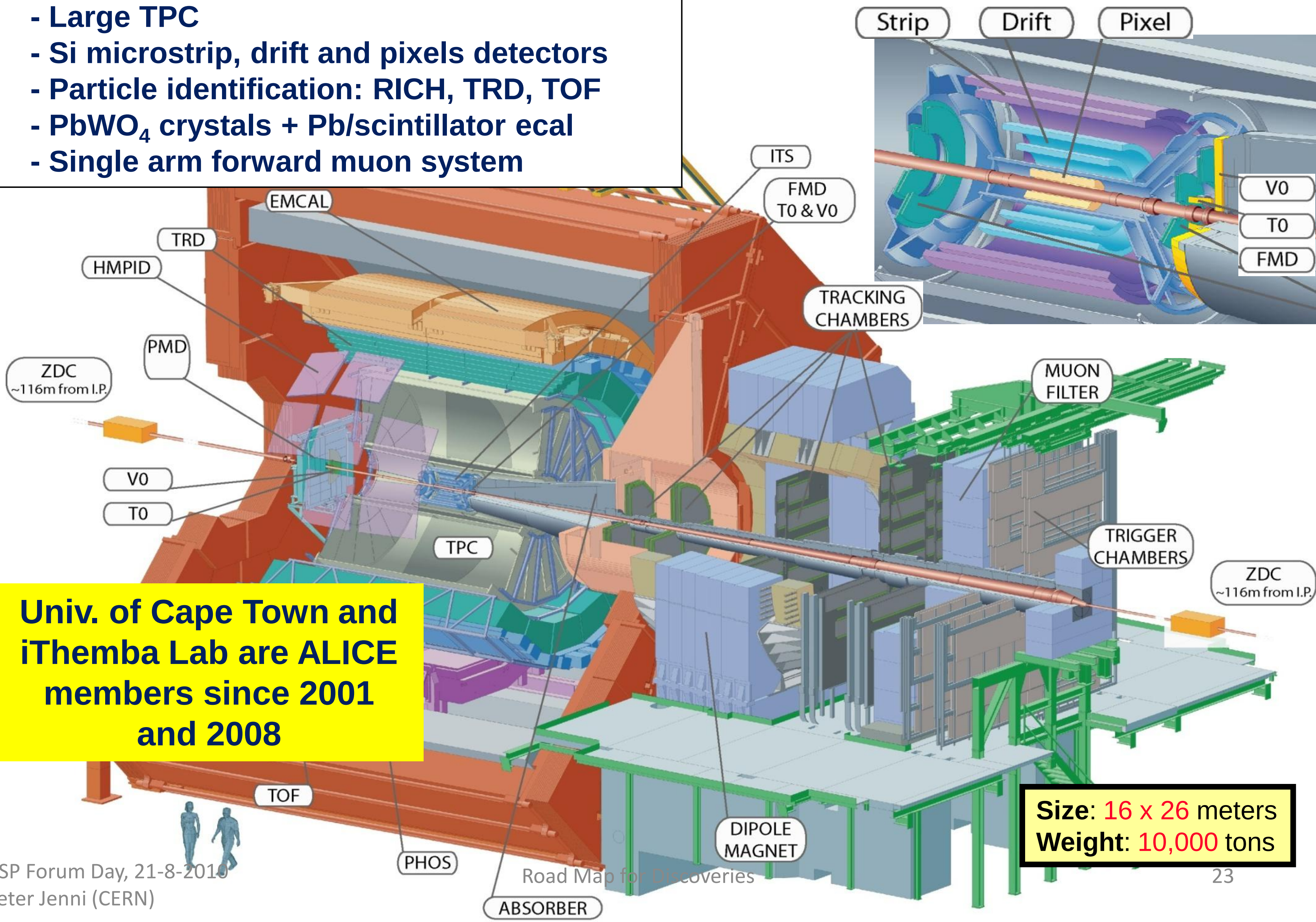
LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

ATLAS
3000 Physicists
174 Institutions
38 countries
550 MCHF

ALICE
1000 Physicists
105 Institutions
30 countries
150 MCHF

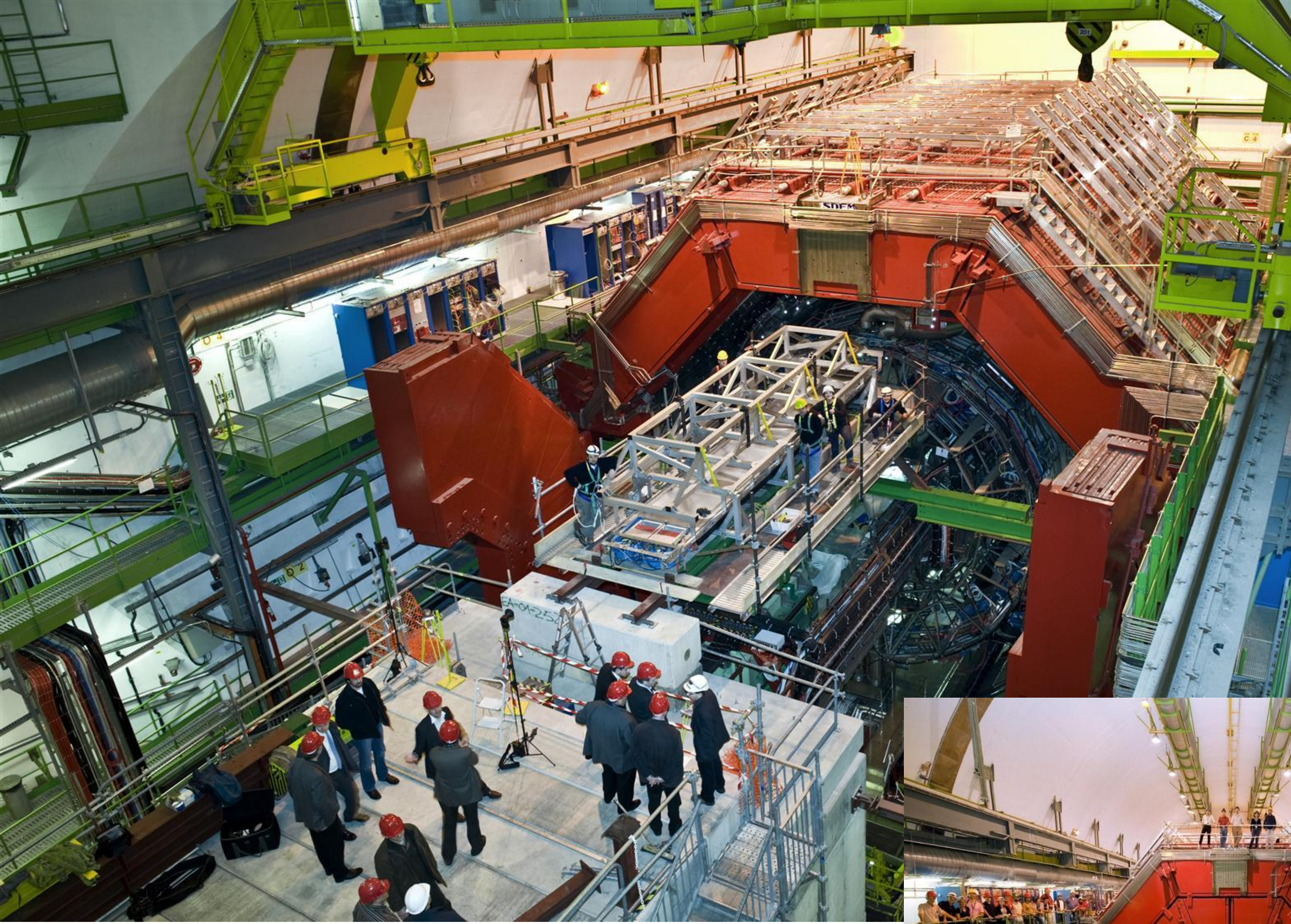
ALICE: study of quark-gluon plasma

- L3 solenoid
- Large TPC
- Si microstrip, drift and pixels detectors
- Particle identification: RICH, TRD, TOF
- $PbWO_4$ crystals + Pb/scintillator ecal
- Single arm forward muon system



Univ. of Cape Town and iThemba Lab are ALICE members since 2001 and 2008

Size: 16 x 26 meters
Weight: 10,000 tons

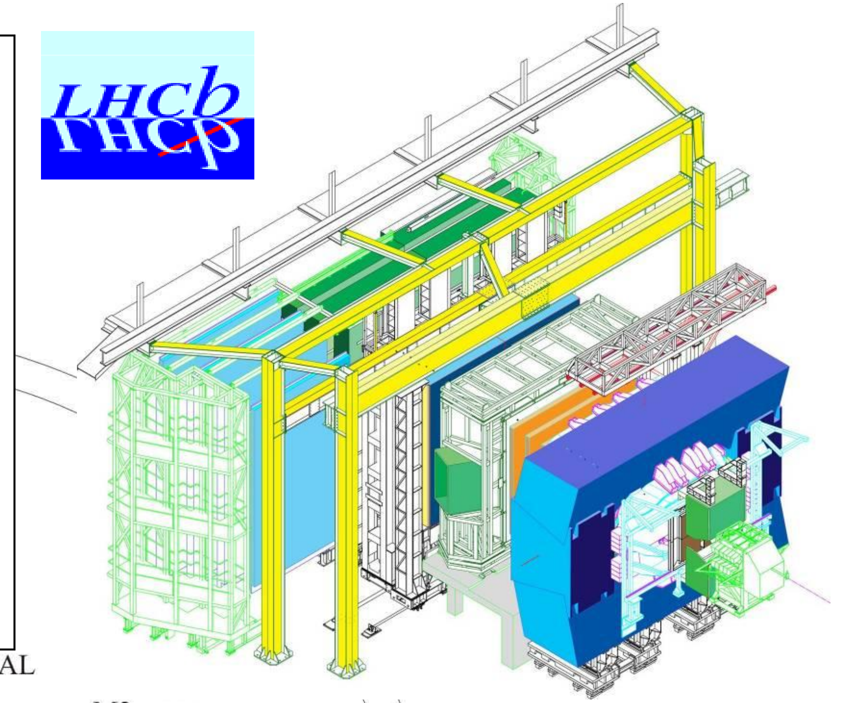


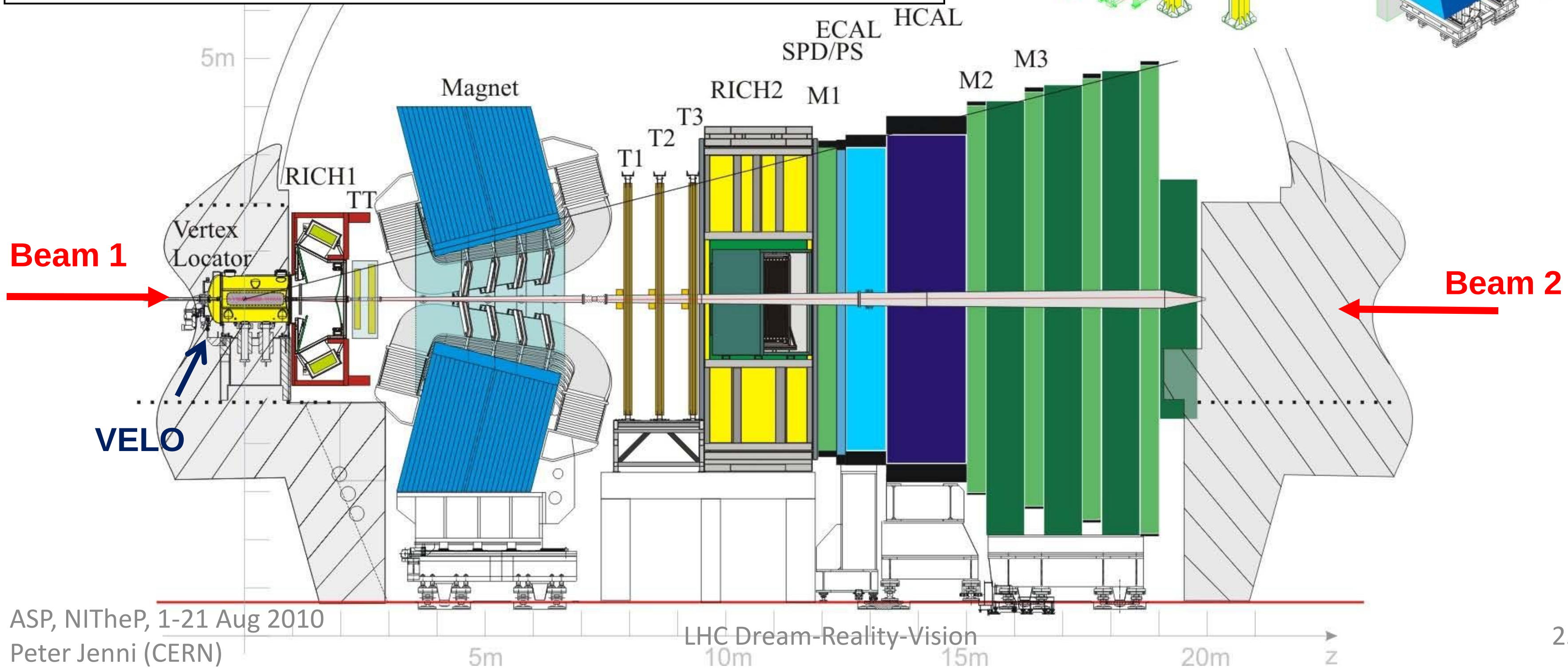
Installation of a ALICE TOF module May 2008

Formal end of ALICE installation July 2008

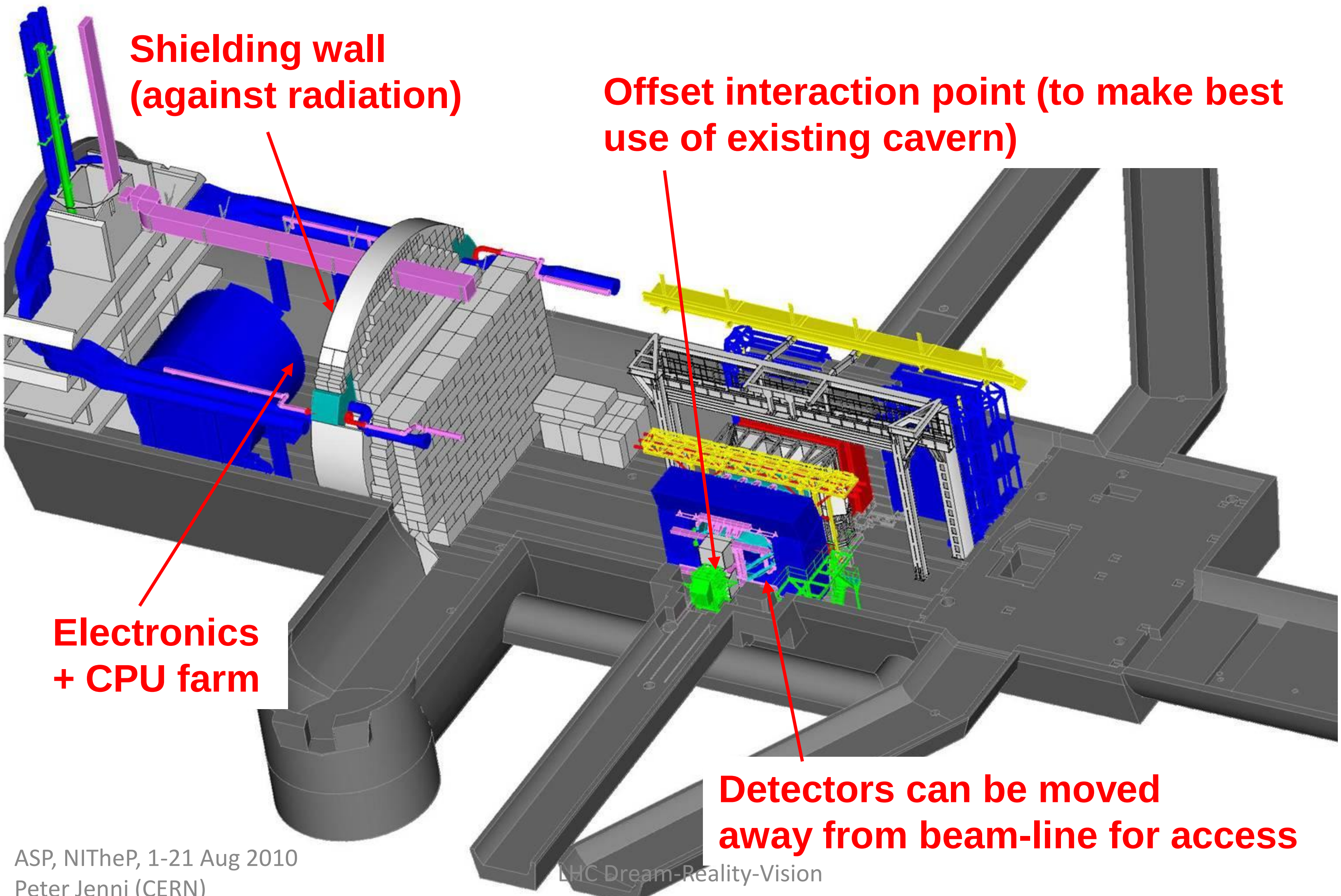
LHCb:
Study of B decays and CP Violation
(indirect search for New Physics)

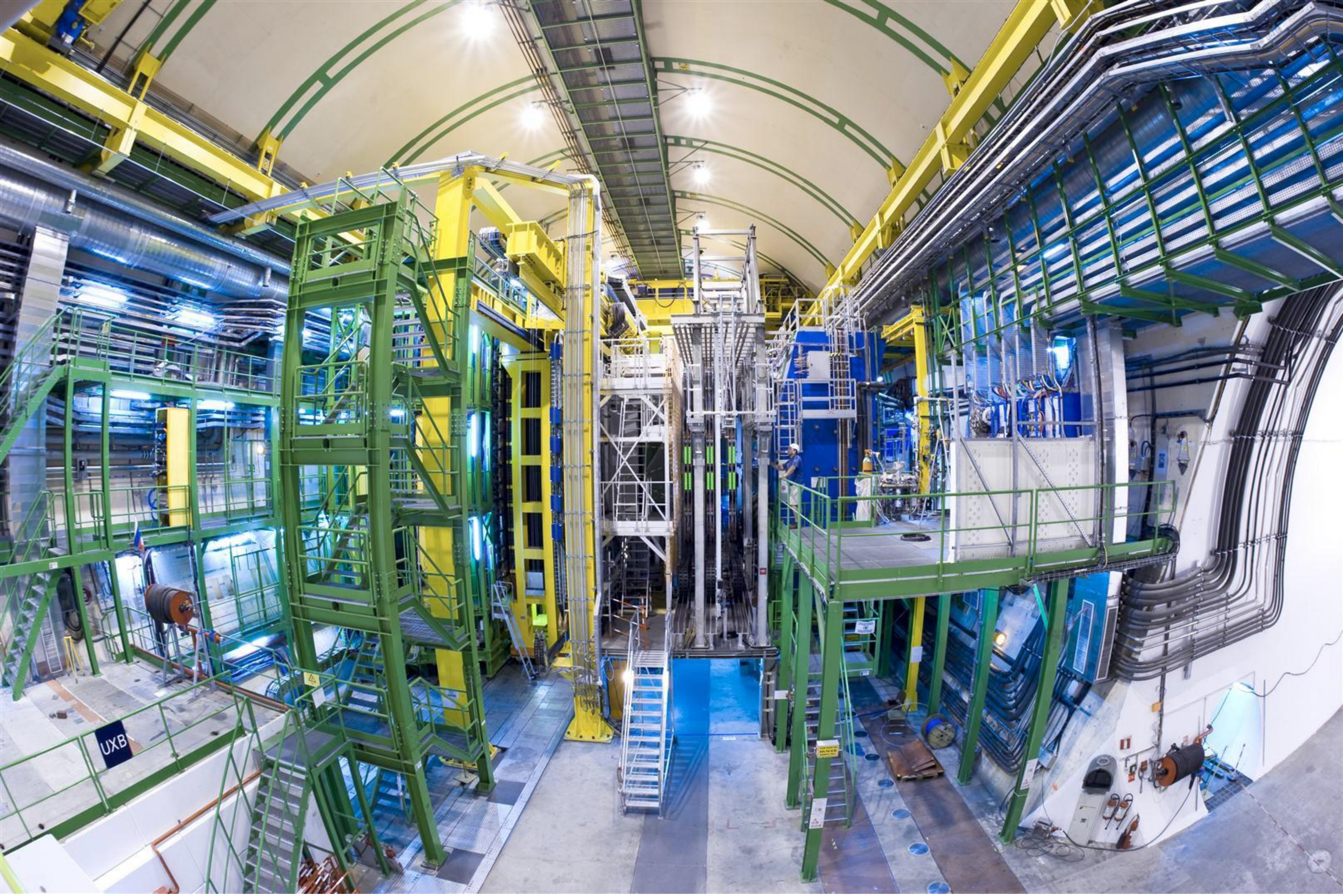
- Dipole magnet (4 T.m)
- Particle Identification (2 RICH)
- 21 layer of Si microstrip vertex locator (VELO)
- Tracking: Silicon + long straw tubes
- Shashlik (Pb/scint) em calorimeter
- HCAL (Fe/scint),
- MWPC muon system

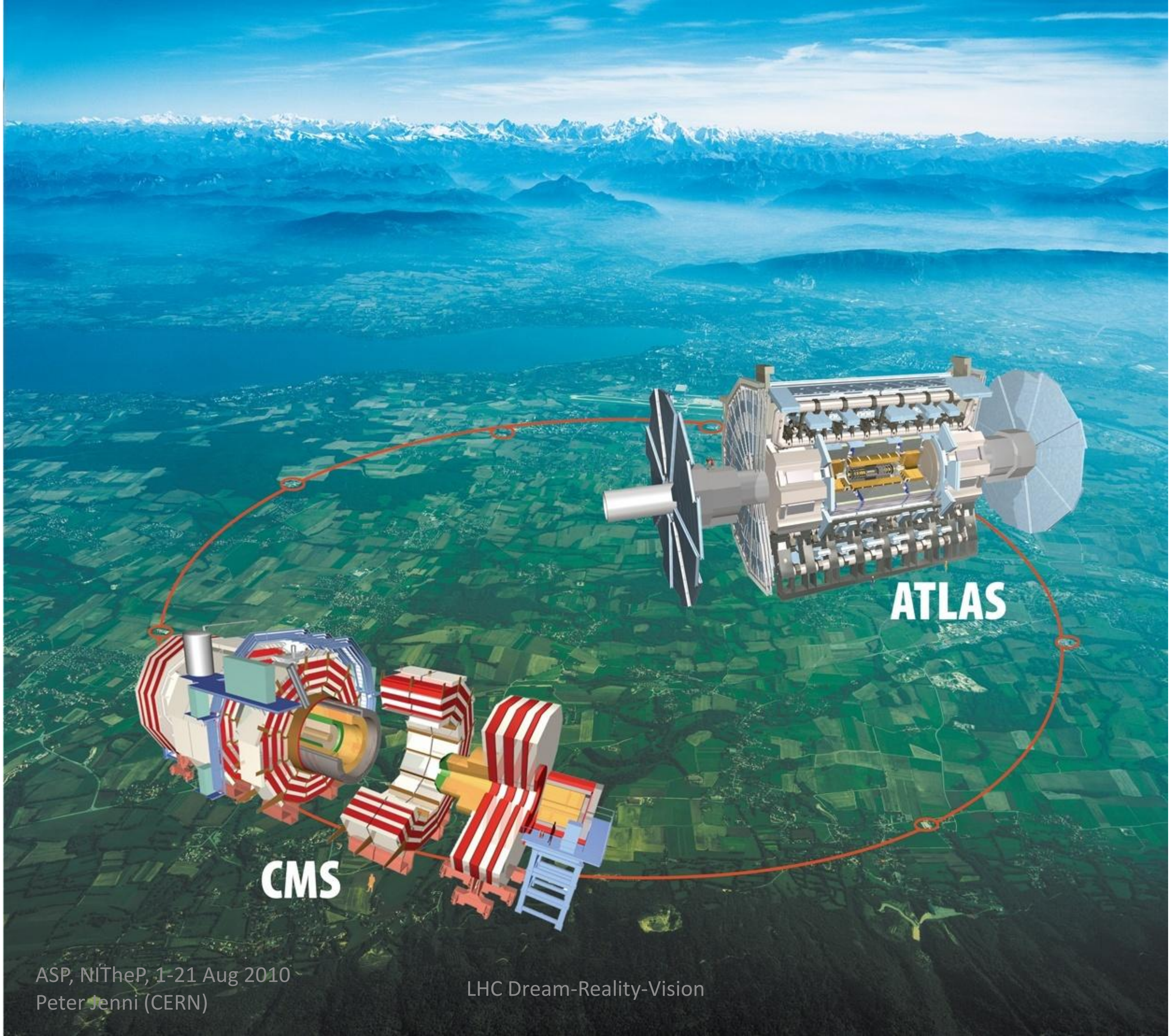




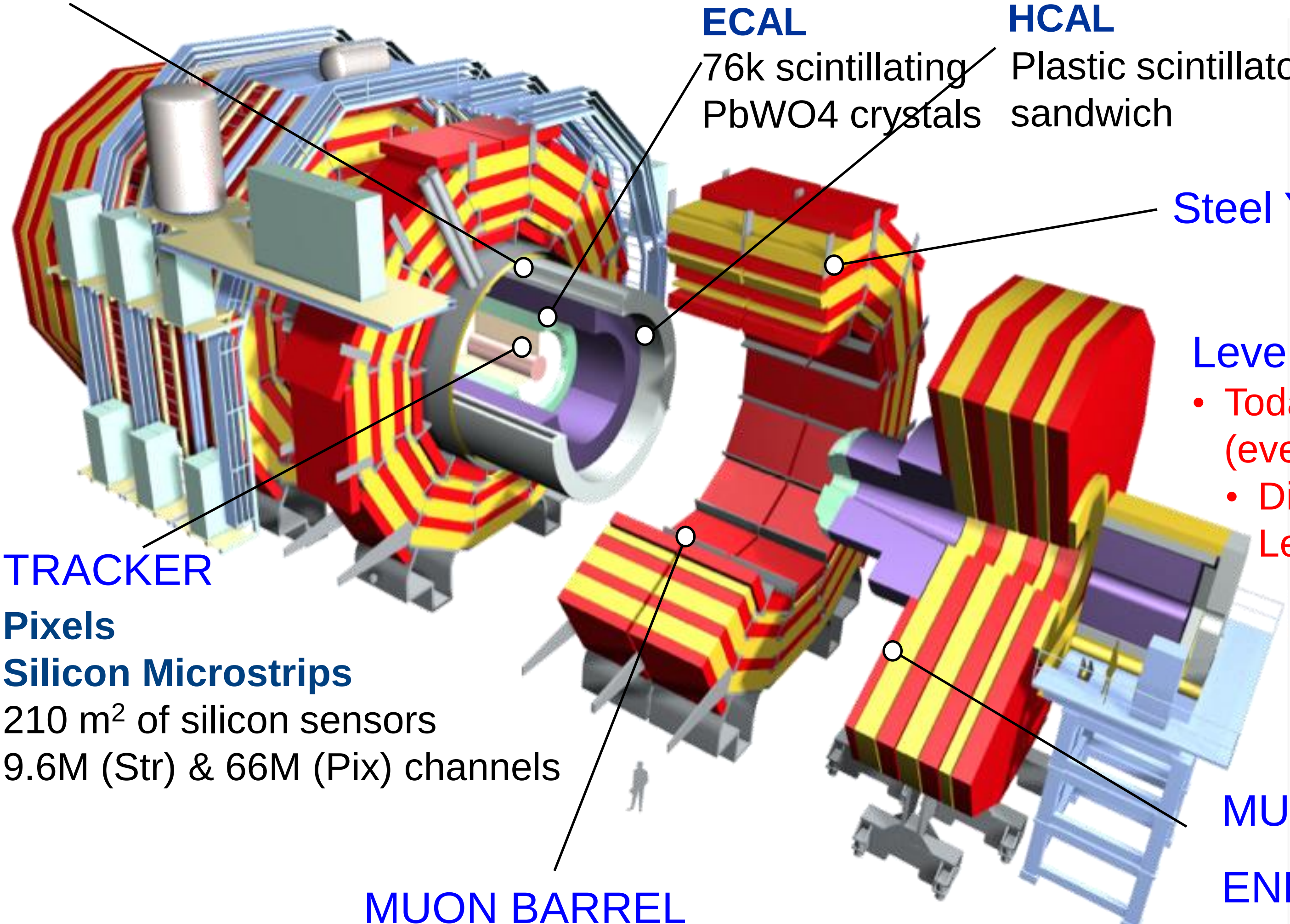
LHCb in its cavern (~100 m deep)



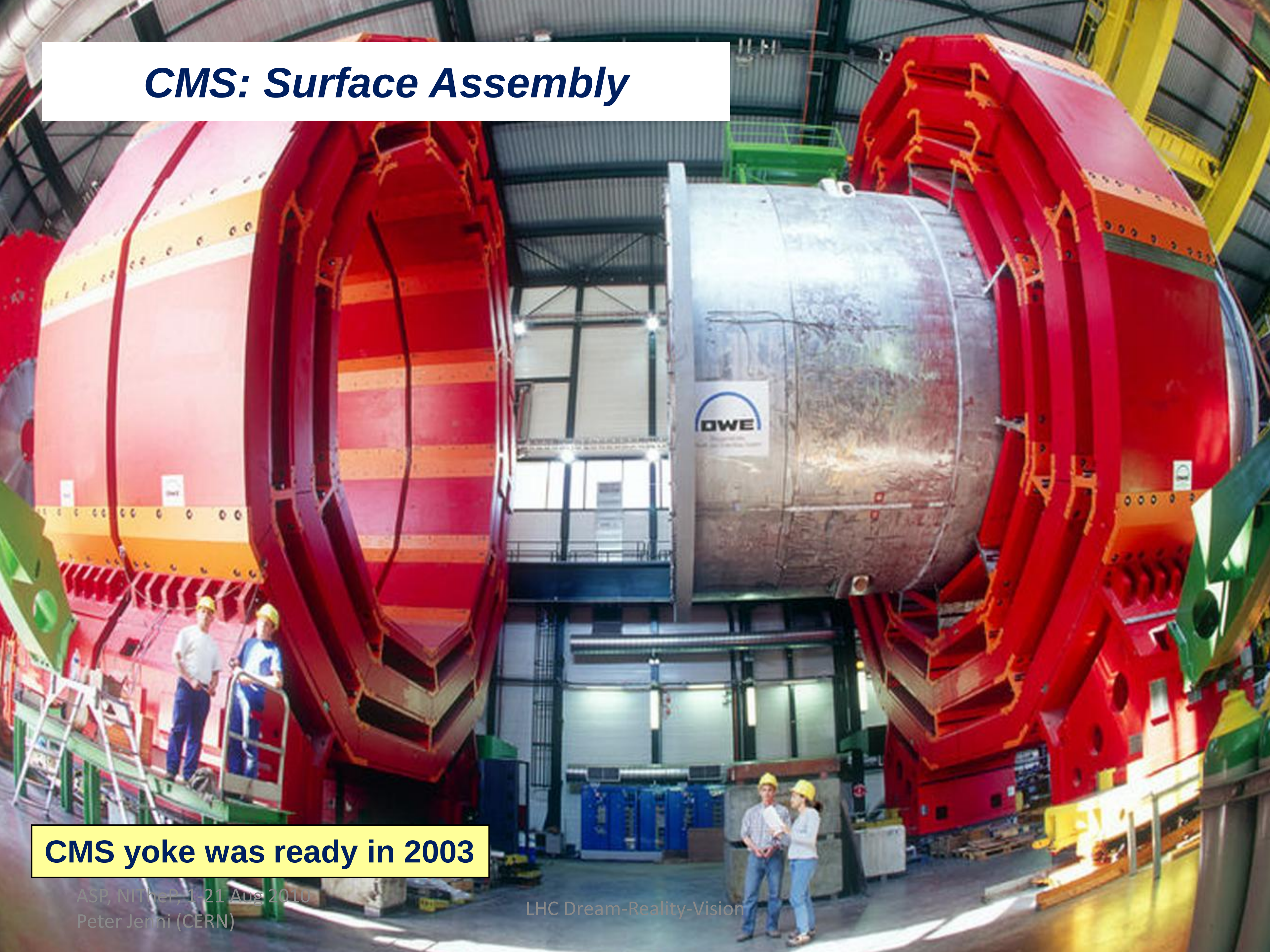

UXB


ATLAS
CMS

CMS Detector

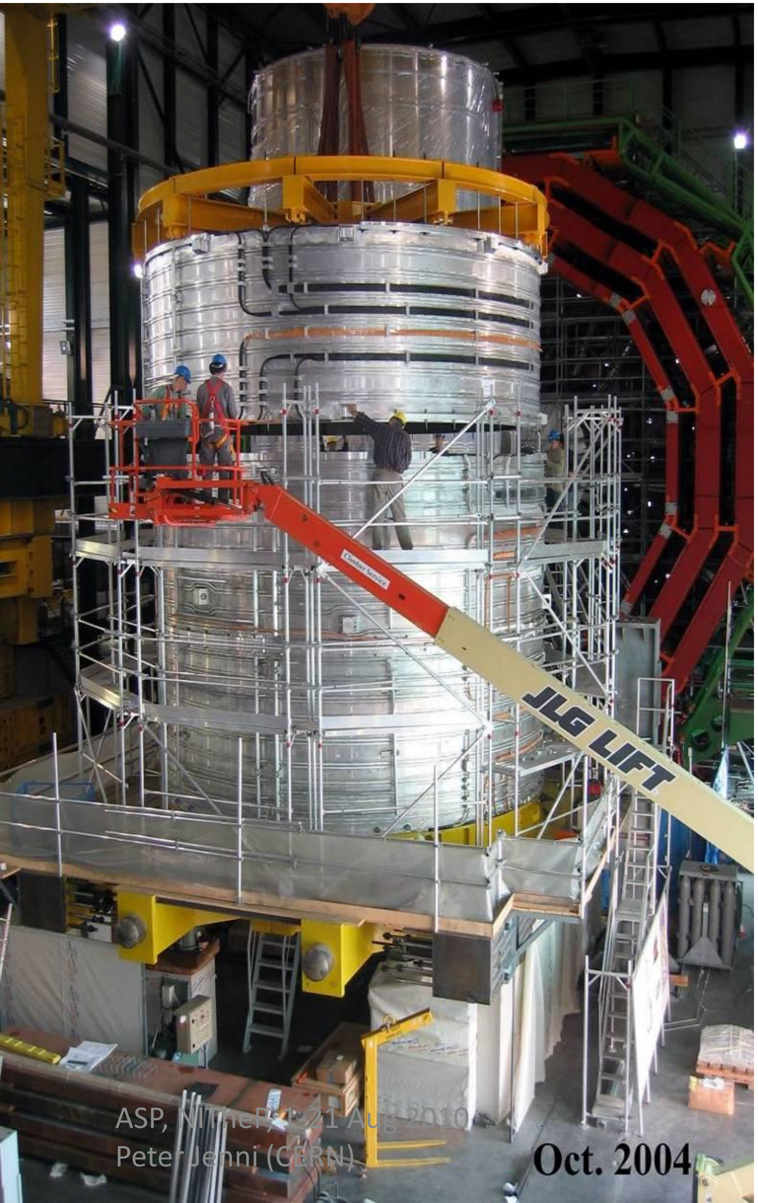


CMS: Surface Assembly



CMS yoke was ready in 2003

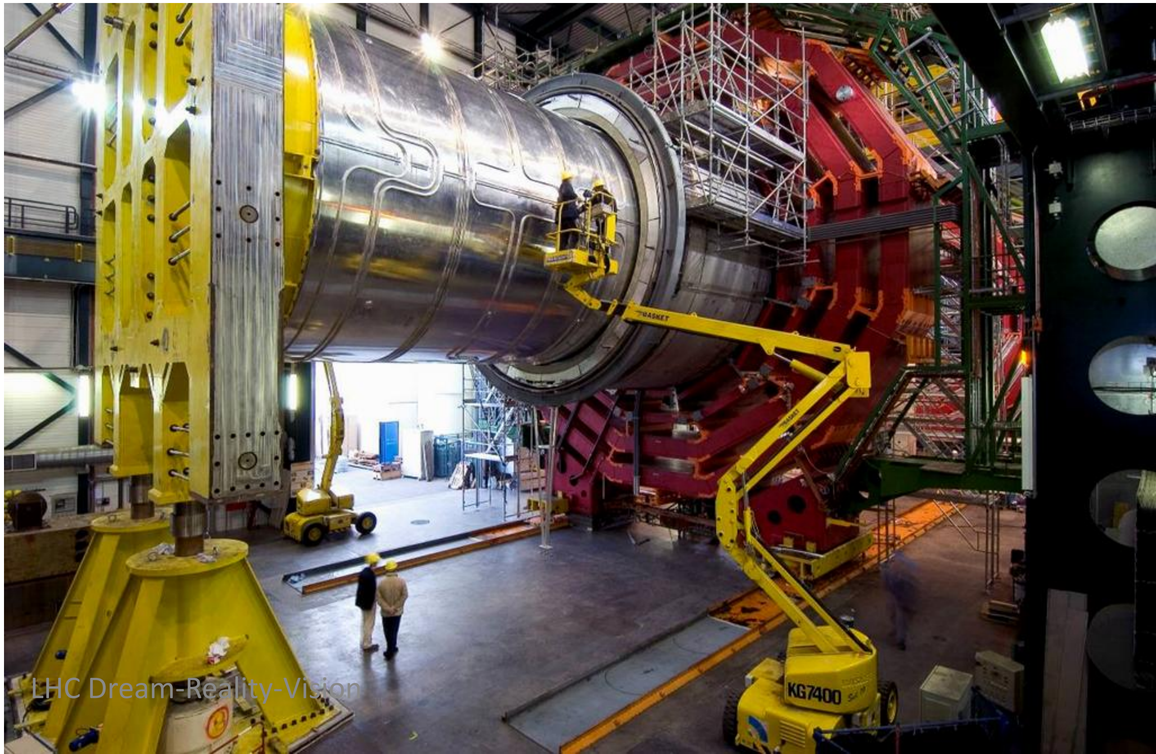
Example of an Engineering Challenge: CMS Solenoid



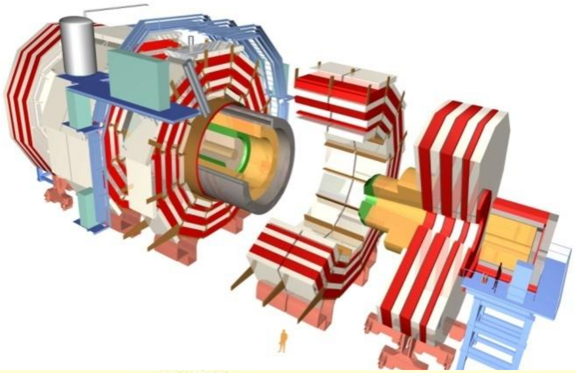
CMS solenoid:

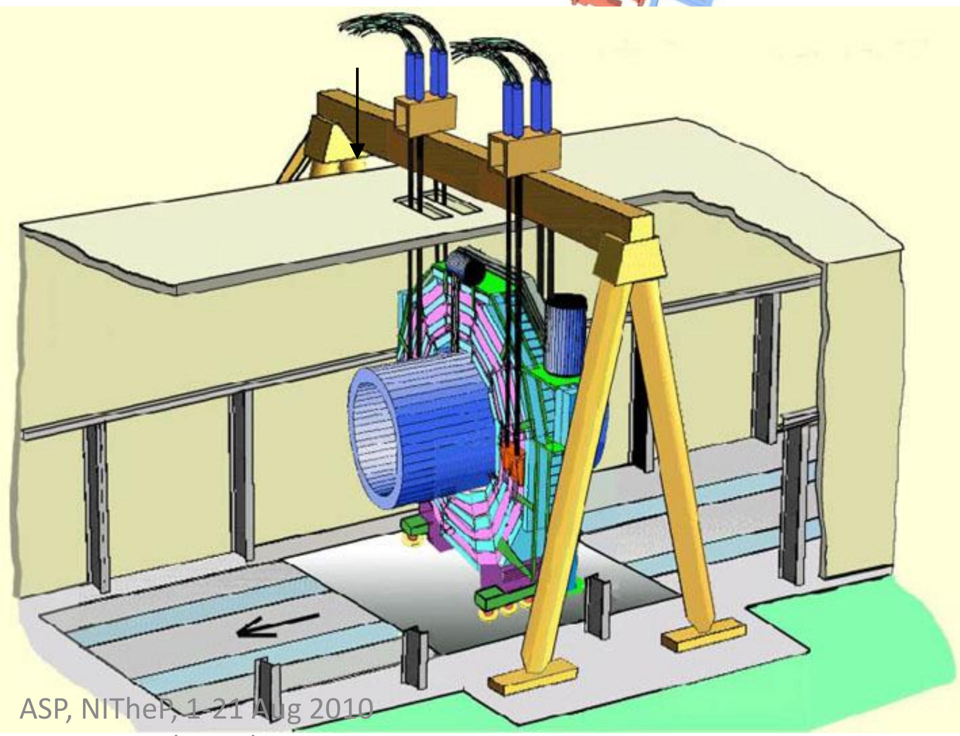
Magnetic length	**12.5 m**
Diameter	**6 m**
Magnetic field	**4 T**
Nominal current	**20 kA**
Stored energy	**2.7 GJ**

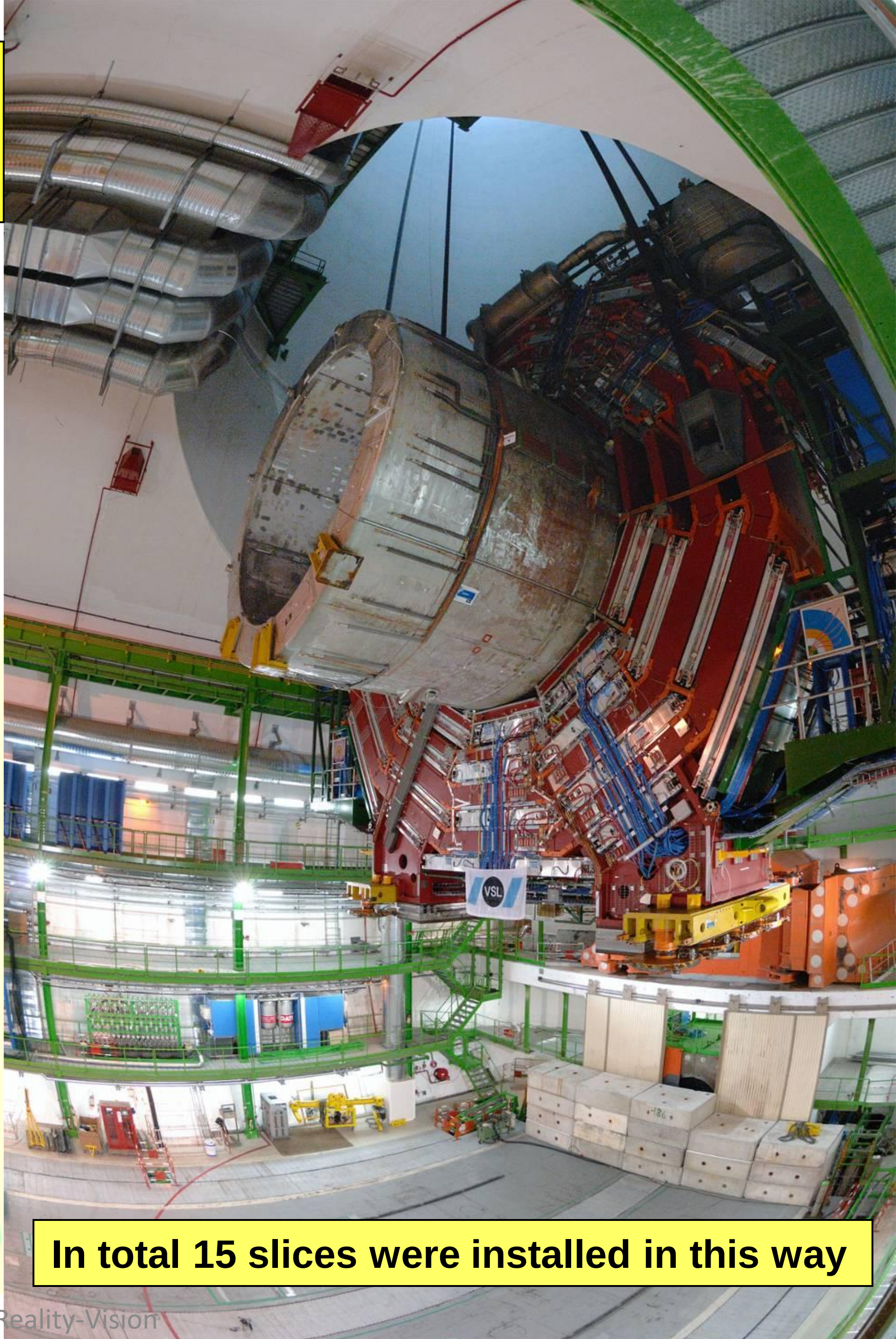
Tested at full current in Summer 2006



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



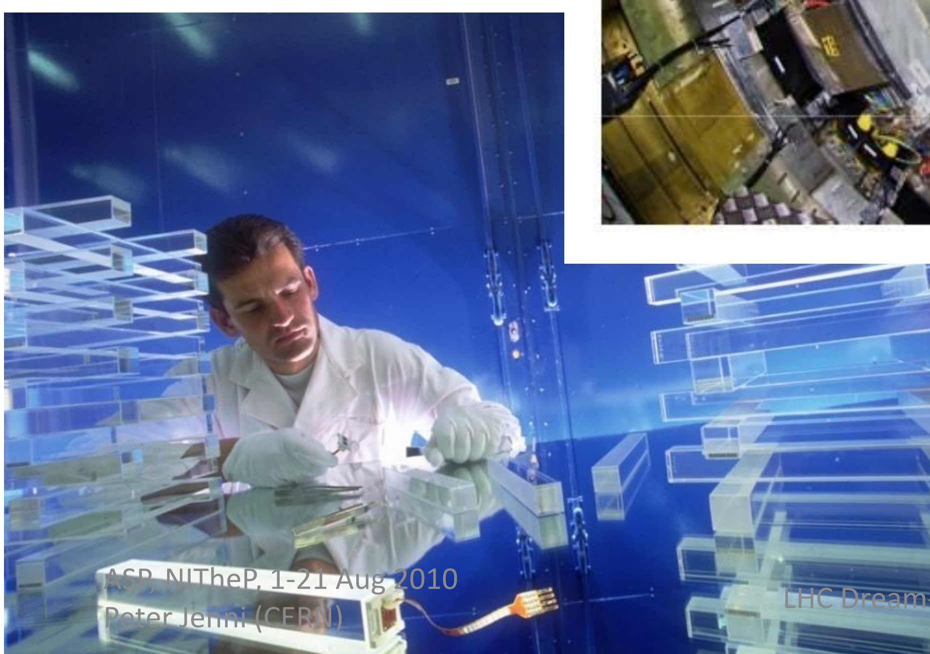


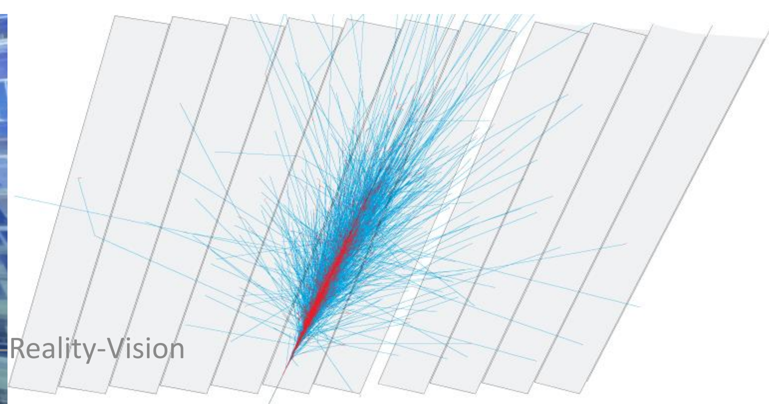


In total 15 slices were installed in this way

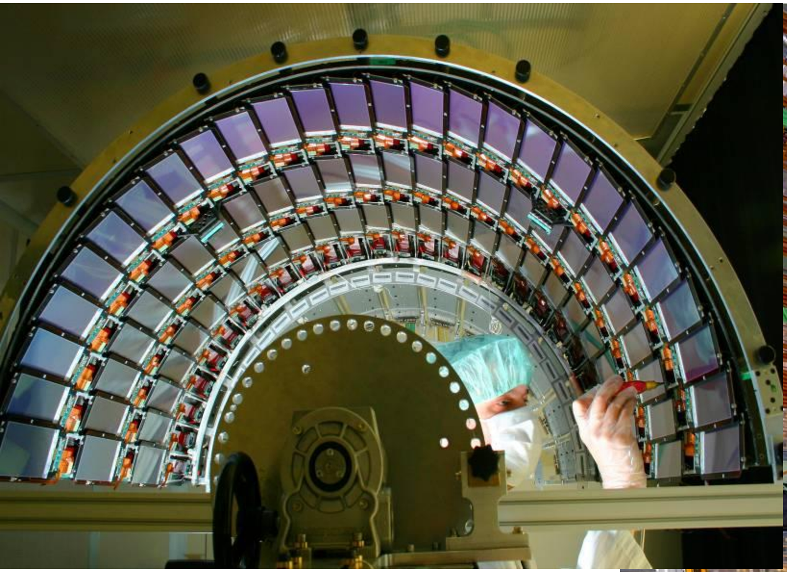
CMS Electron and Photon calorimeter: 76 000 $PbWO_4$ crystals

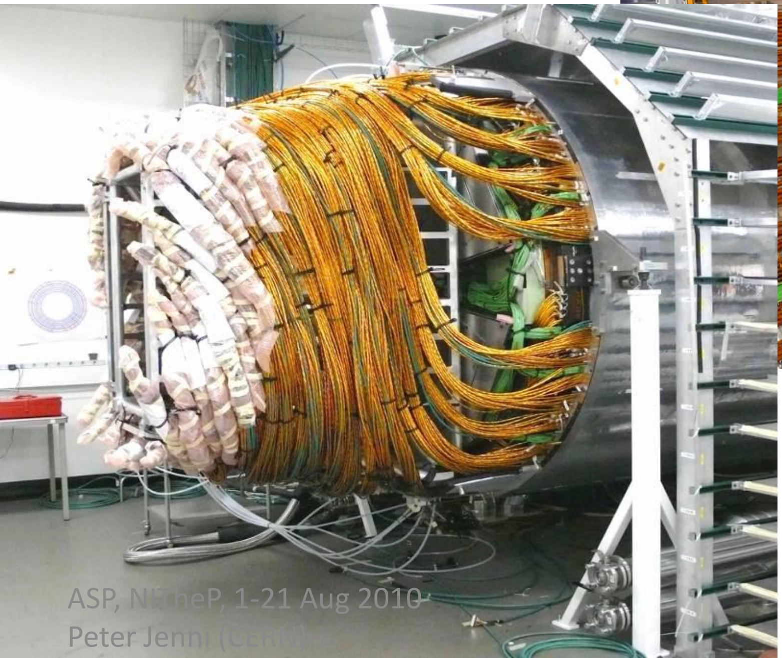
The End-cap was on the critical path for many years, but it was completed just in time before final closure, a major achievement by CMS

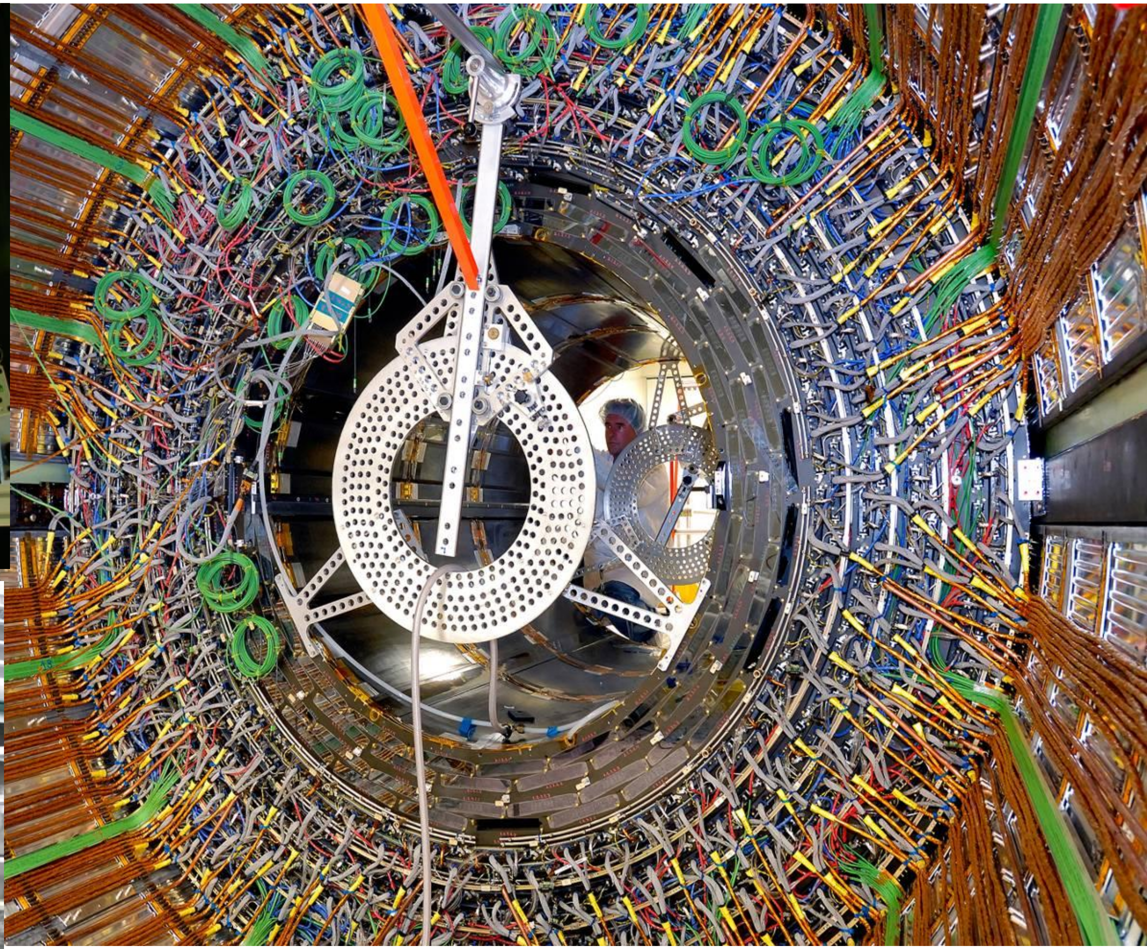




CMS Silicon Tracker







The Silicon tracker (200m^2) has 10 M channels
Operating temperature -15°C

CMS before closure

The Birth of ATLAS

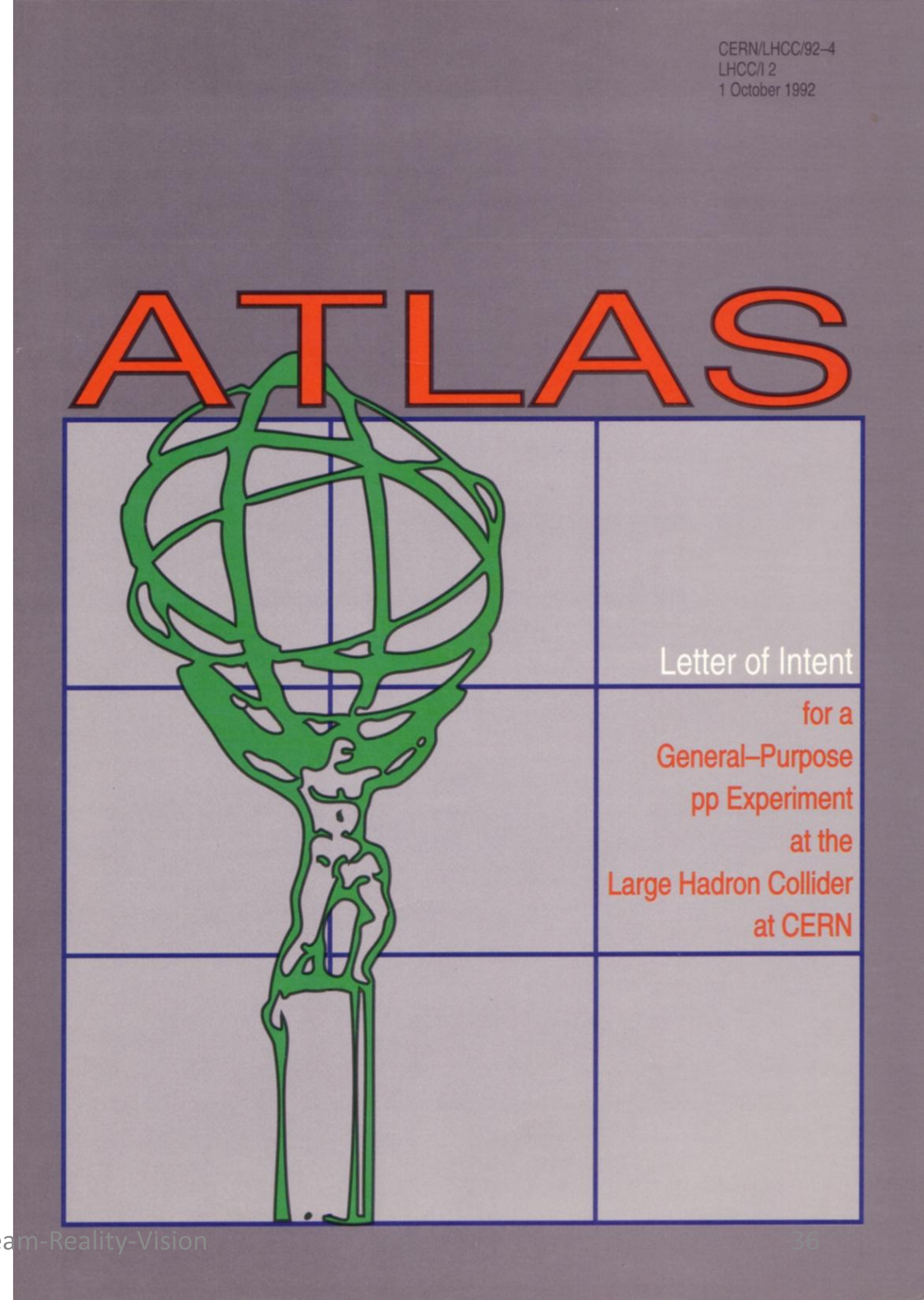
March 1992
Evian Meeting with EoI presentations

March 1992 – Summer 1992
Merging of EAGLE and ASCOT, two proto-collaborations

September 1992
Decision on the name

October 1992
ATLAS LoI submitted to the LHCC

Official birth of the ATLAS Collaboration



ATLAS Collaboration

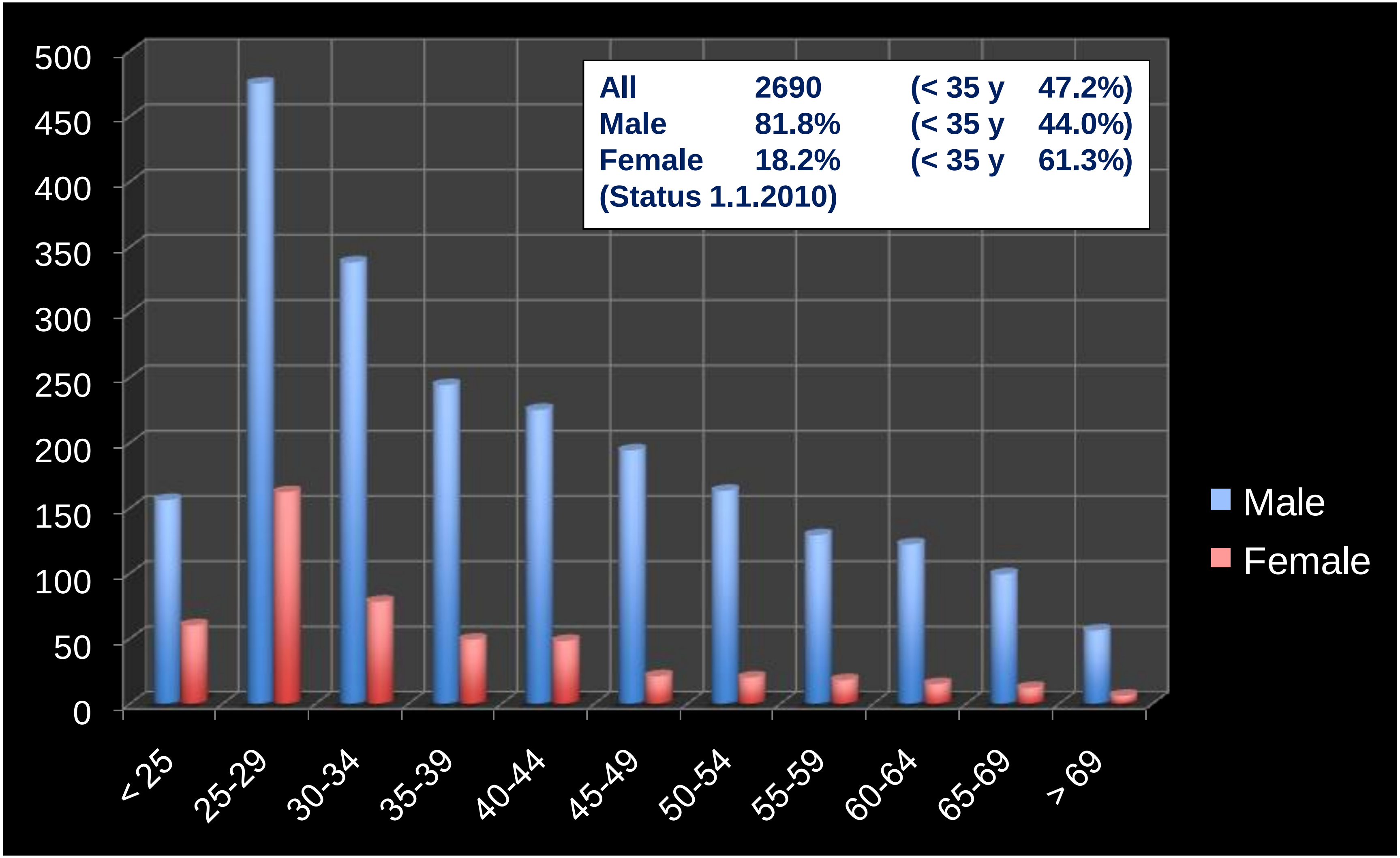
(Status August 2010)

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

In July 2010 South Africa was unanimously admitted as Collaboration member, with the Institutes of the University of Johannesburg and the University of the Witwatersrand (and open to others in the future)

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

Age distribution of the ATLAS population

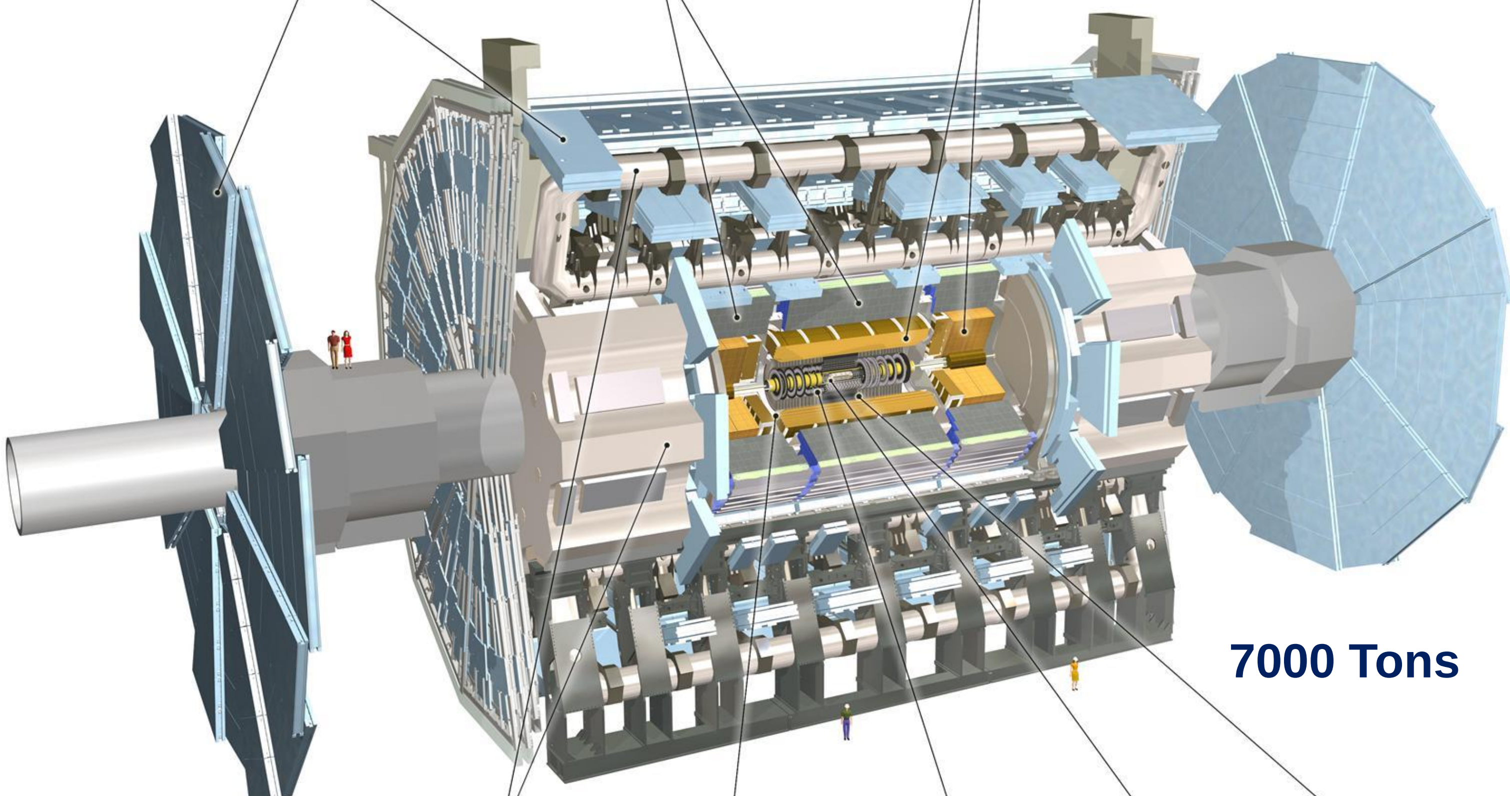


ATLAS superimposed to
the 5 floors of building 40

ATLAS Detector

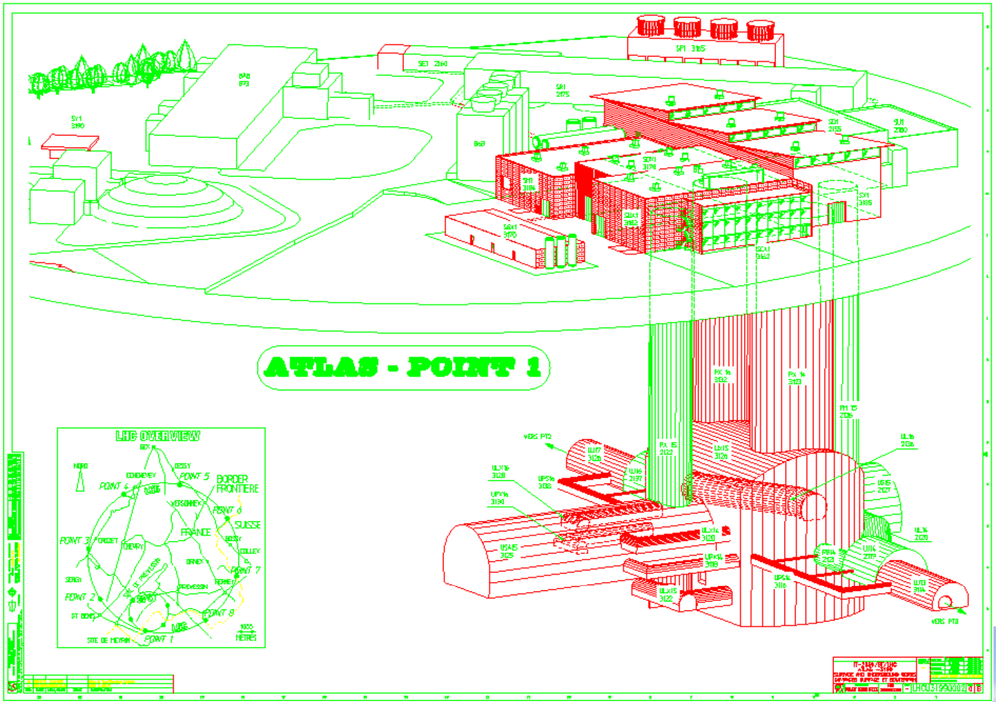
45 m

24 m

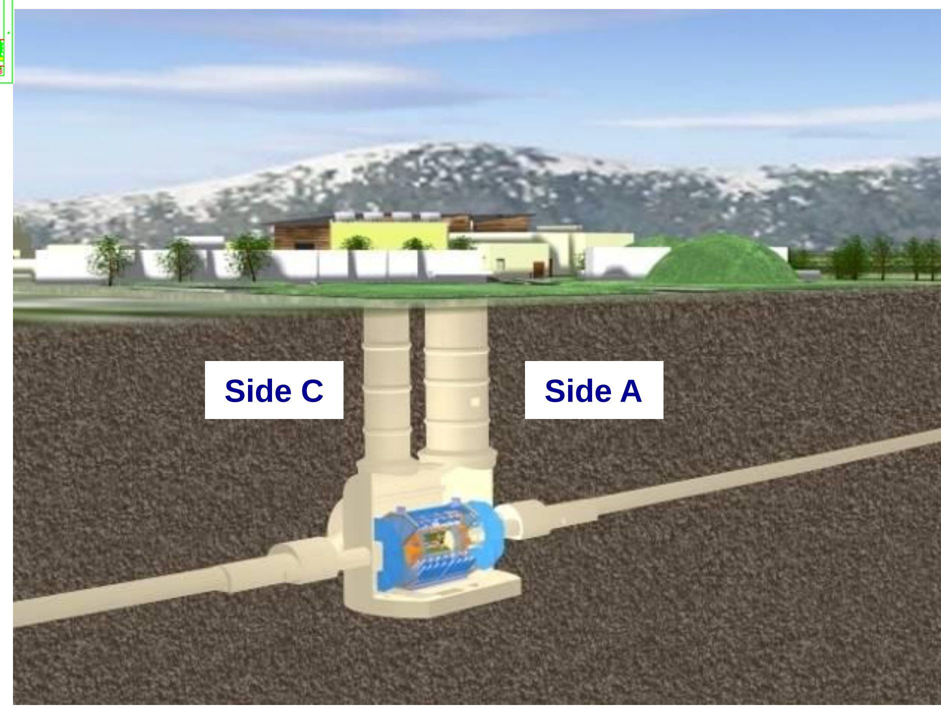


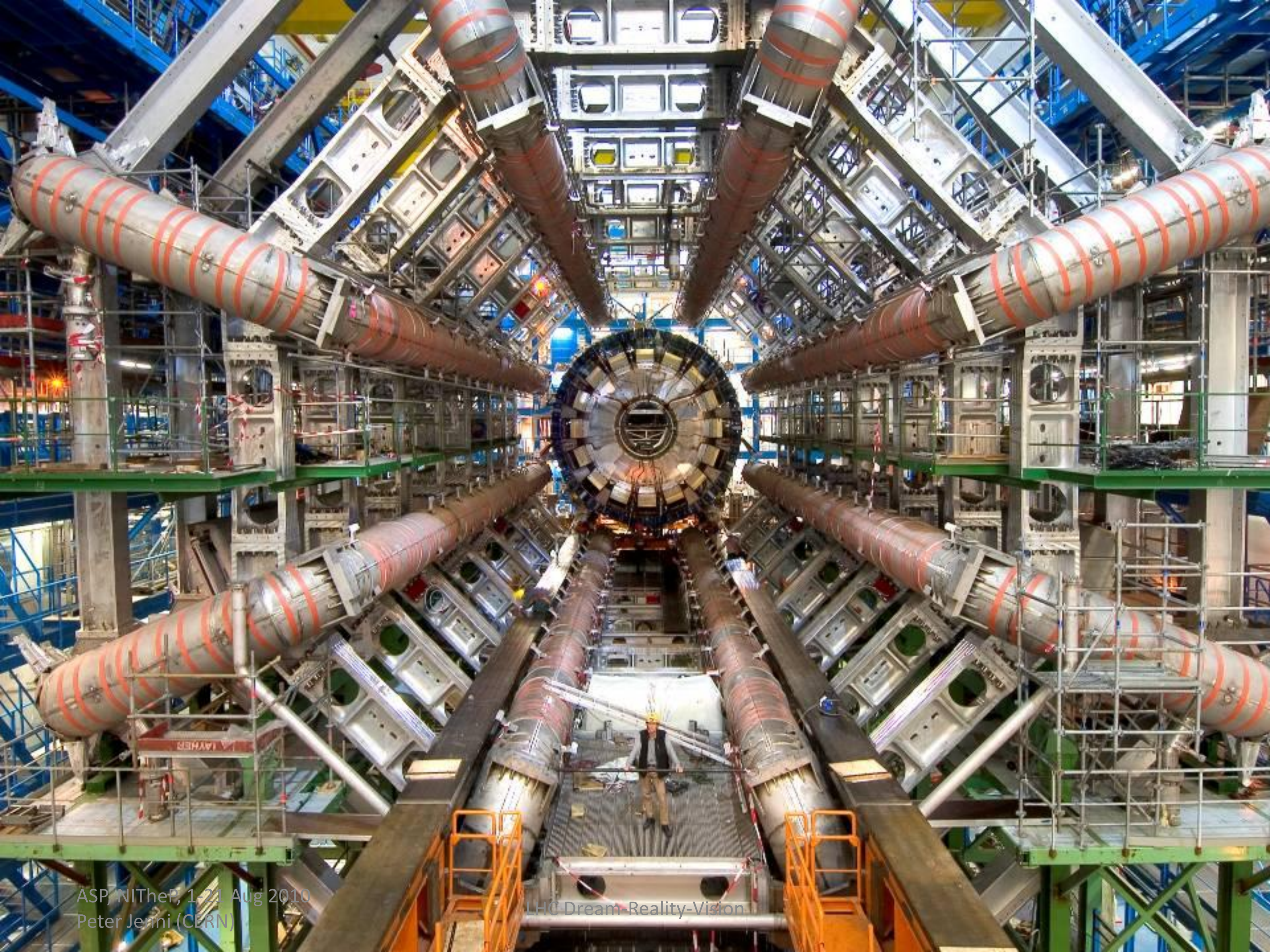
7000 Tons

The Underground Cavern at Point-1 for the ATLAS Detector

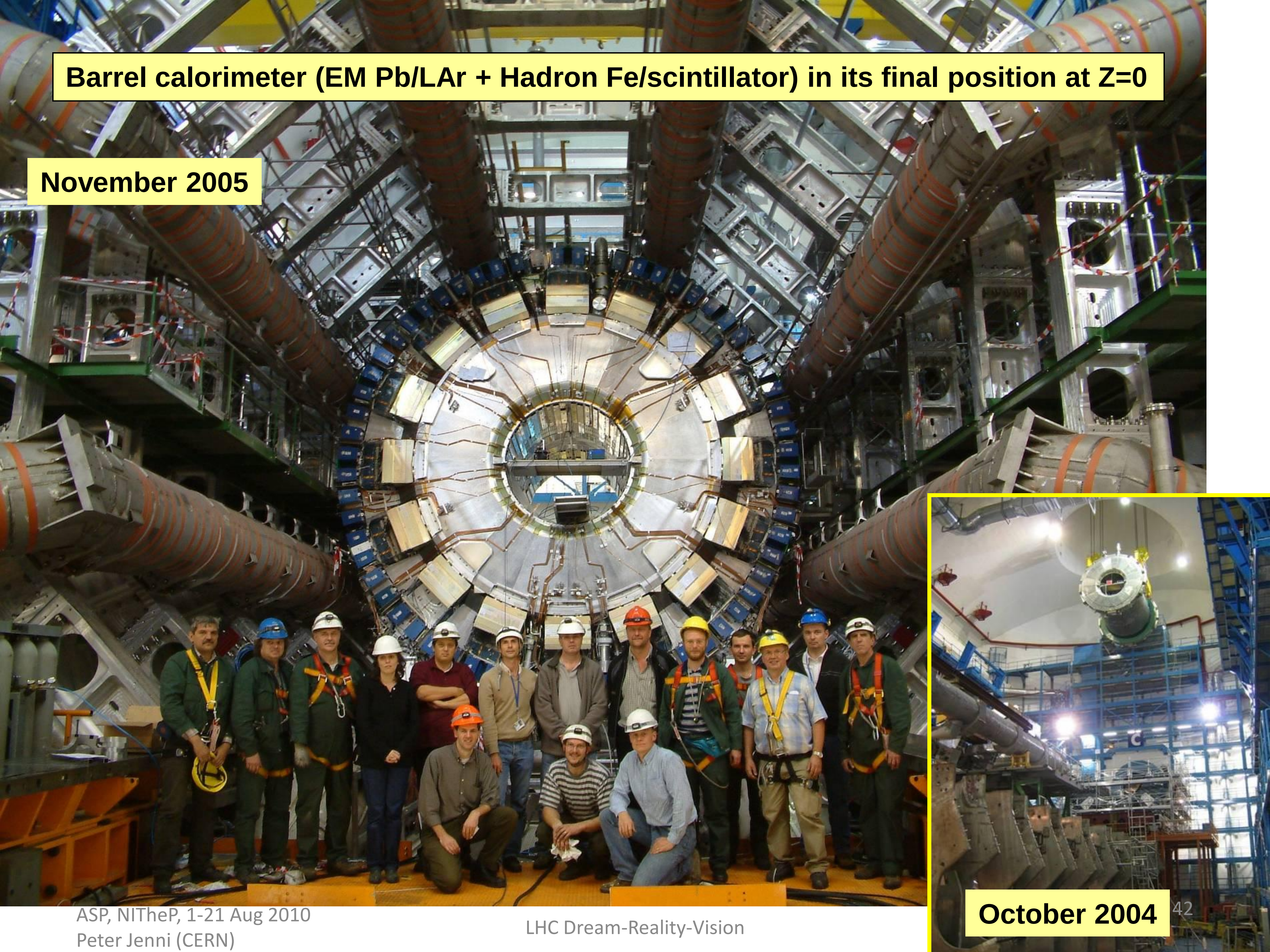


Length = 55 m
Width = 32 m
Height = 35 m



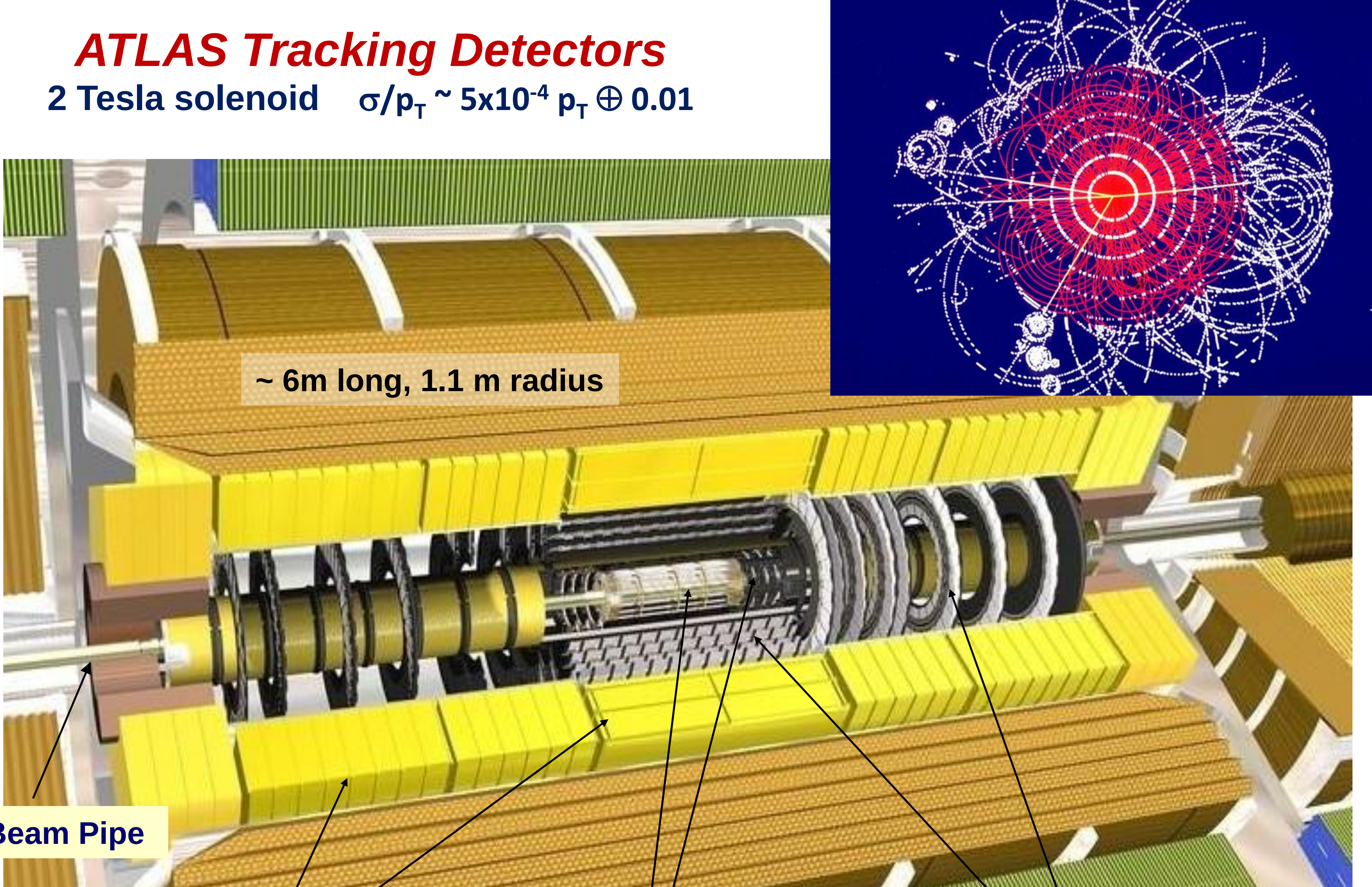


Barrel calorimeter (EM Pb/LAr + Hadron Fe/scintillator) in its final position at Z=0



ATLAS Tracking Detectors

2 Tesla solenoid $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$

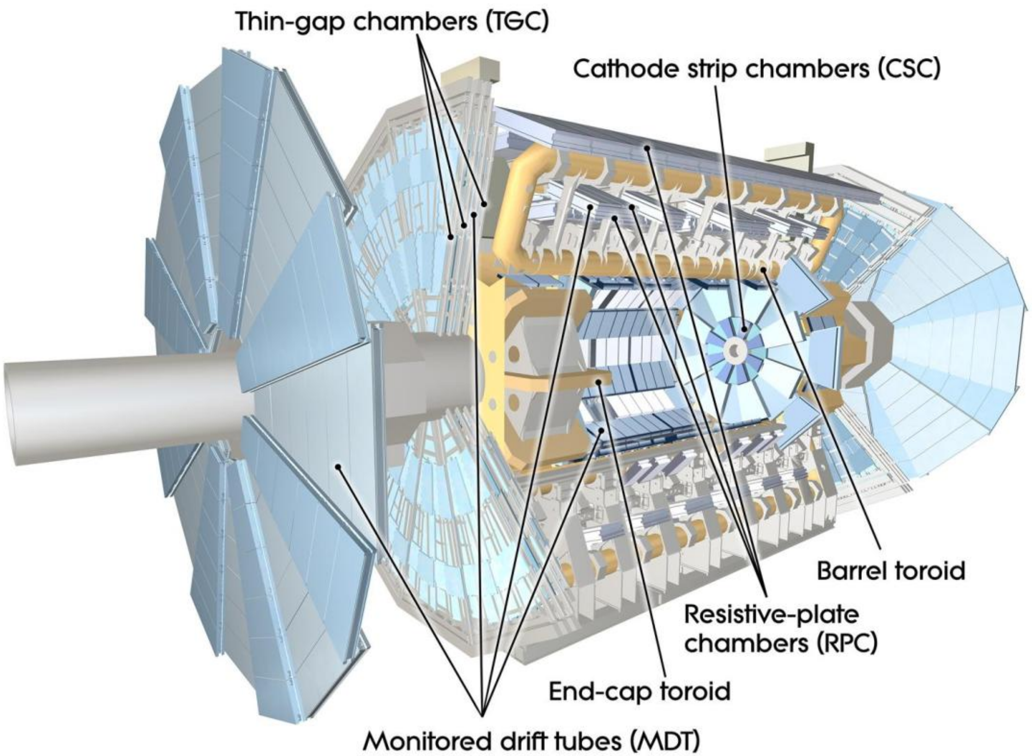


Installation of the ATLAS barrel tracker (Aug 2006)

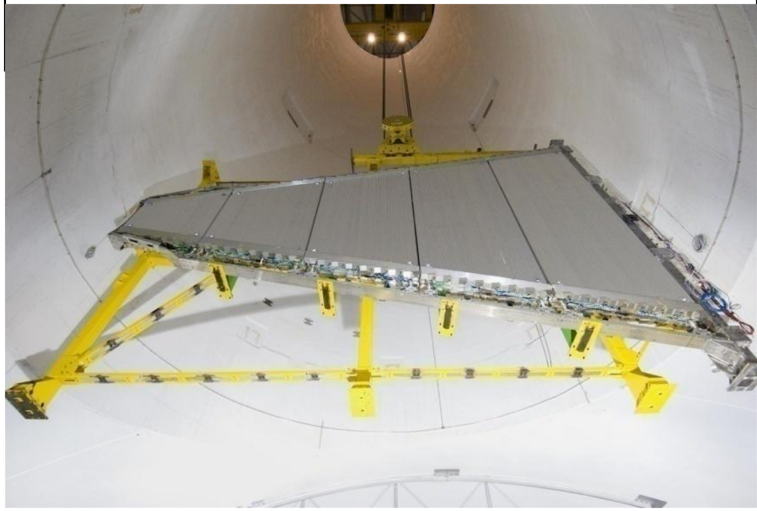
Muon System

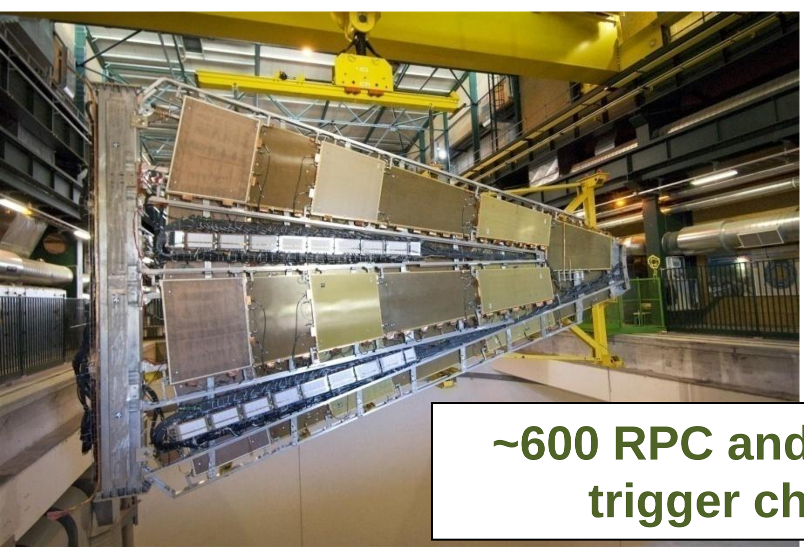
Stand-alone momentum resolution
ΔpT/pT < 10% up to 1 TeV

2-6 Tm |η|<1.3   4-8 Tm 1.6<|η|<2.7

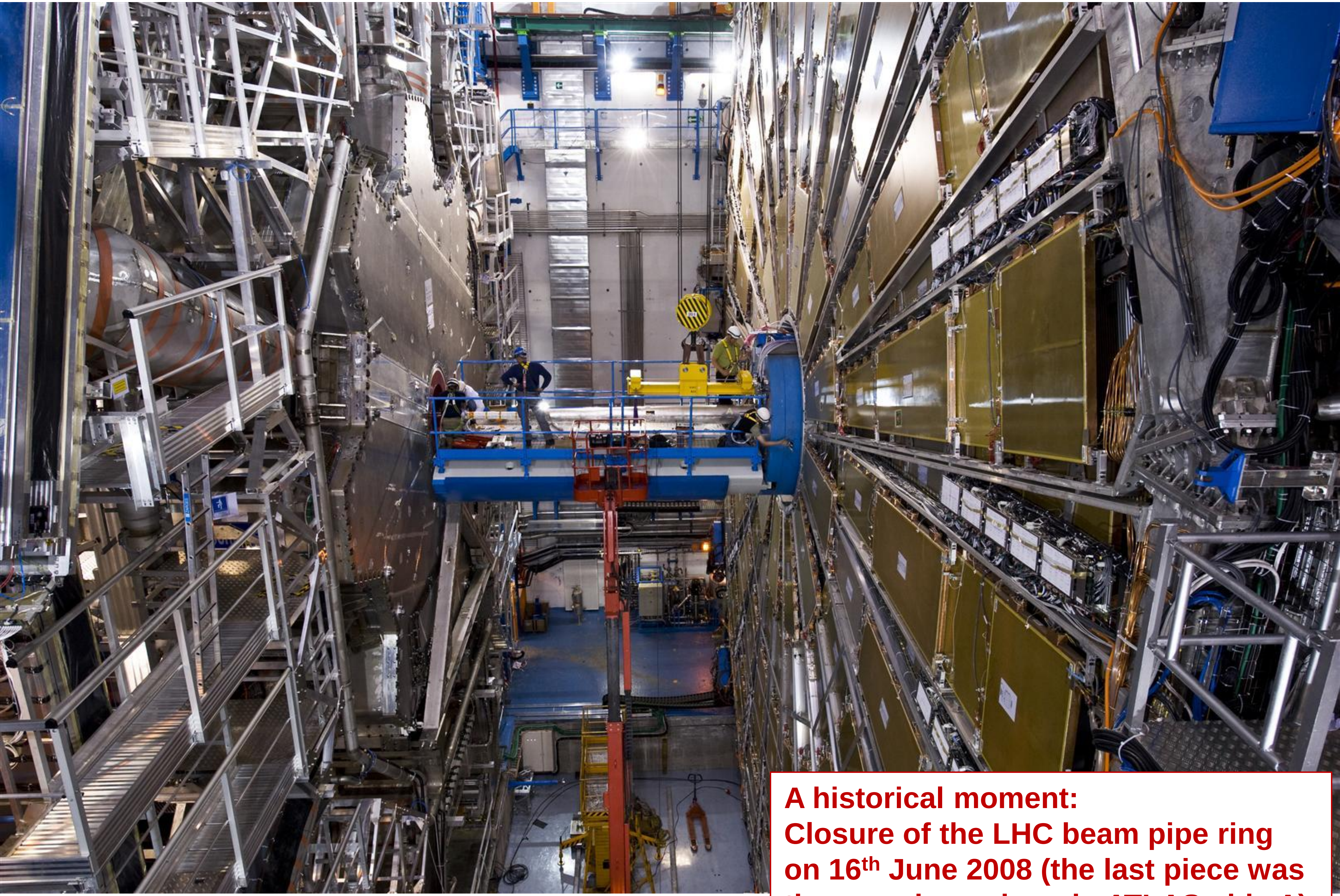


~1200 MDT precision chambers for track



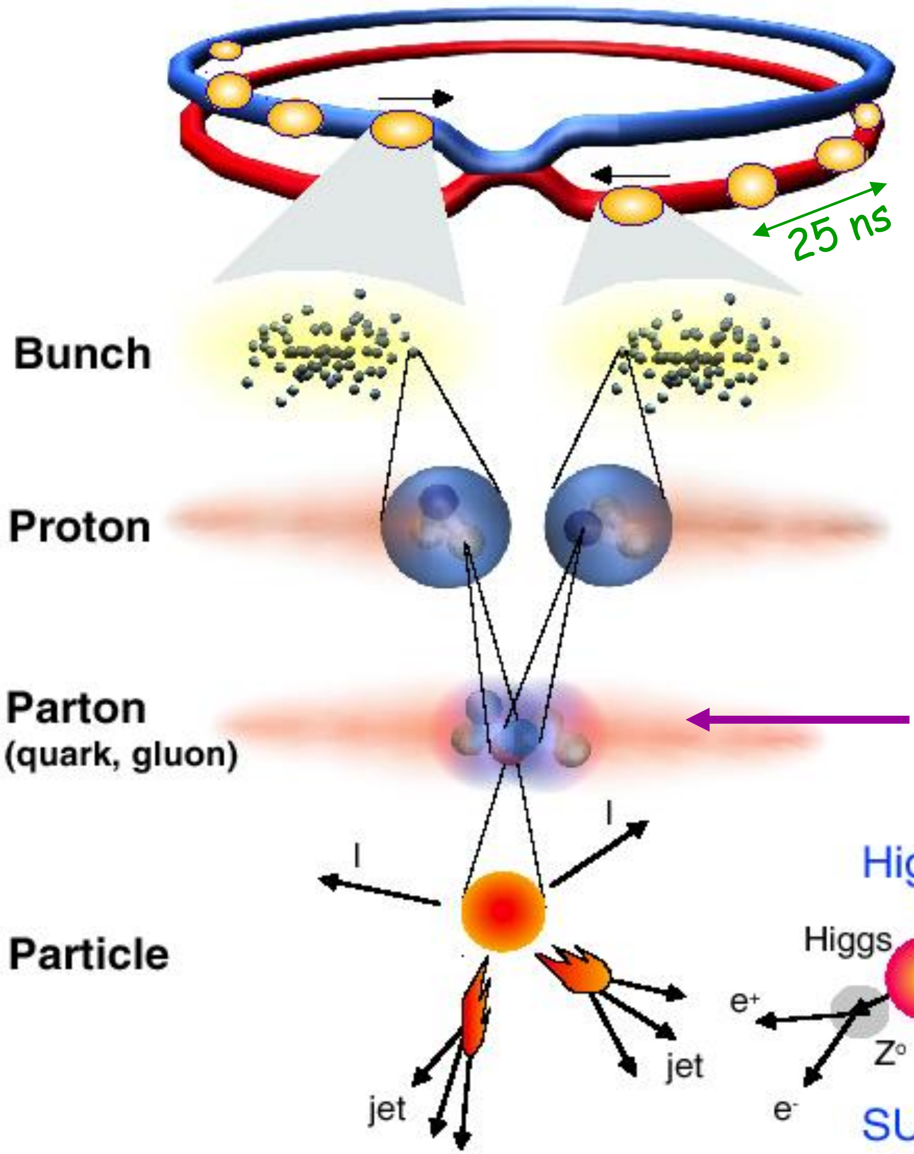


~600 RPC and ~3600 TGC trigger chambers



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

Collisions at LHC



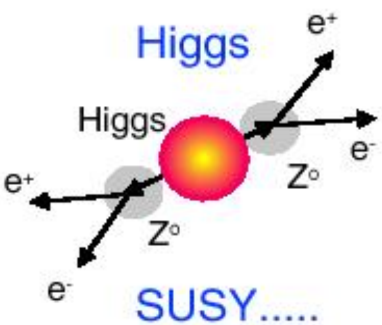
Proton-Proton	
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

N = L x σ (pp) ≈ 10^9 interactions/s

Mostly soft (low p_T) events

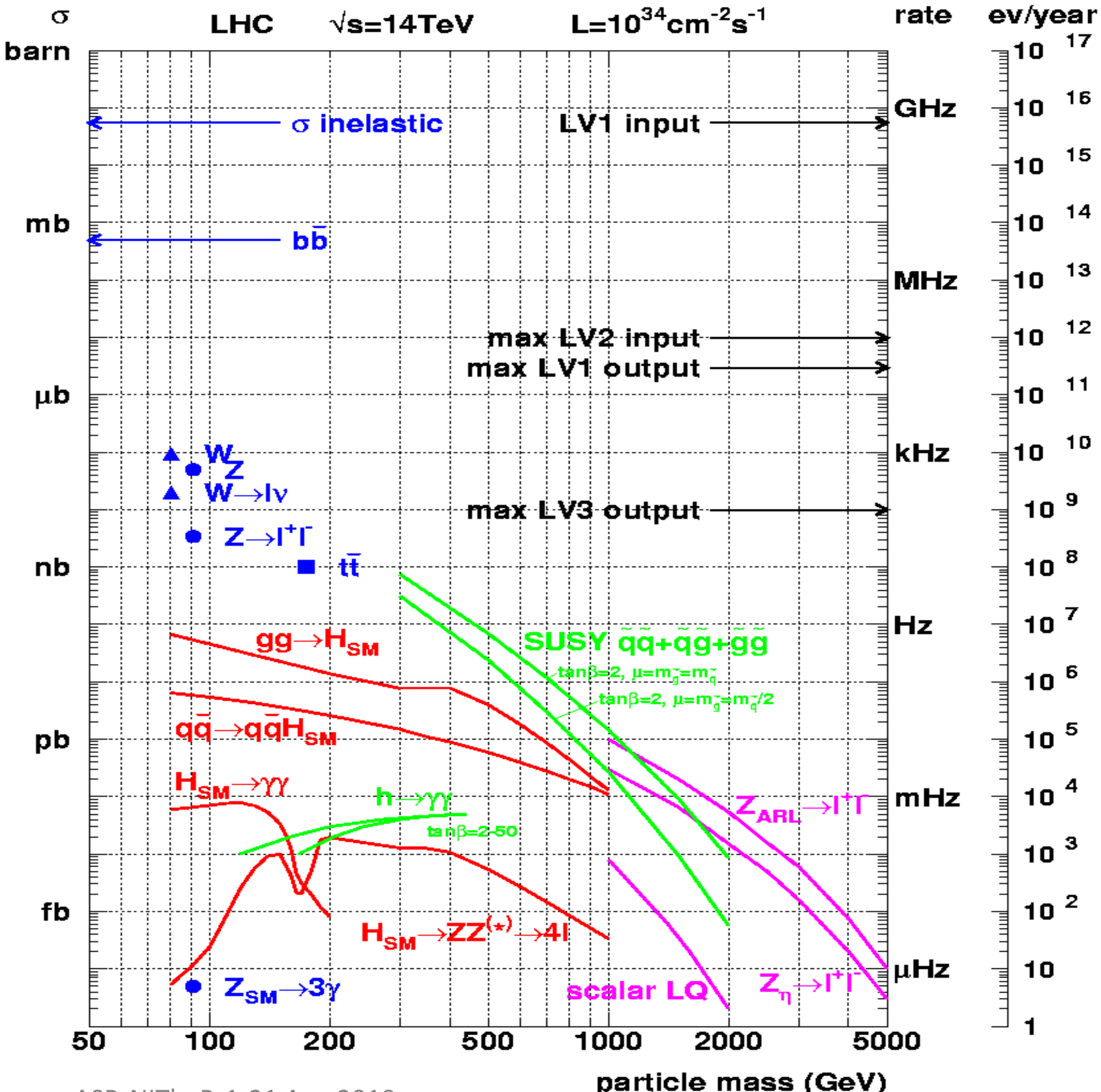
Interesting hard (high-p_T) events are rare



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

→ very powerful detectors needed

Cross Sections and Production Rates

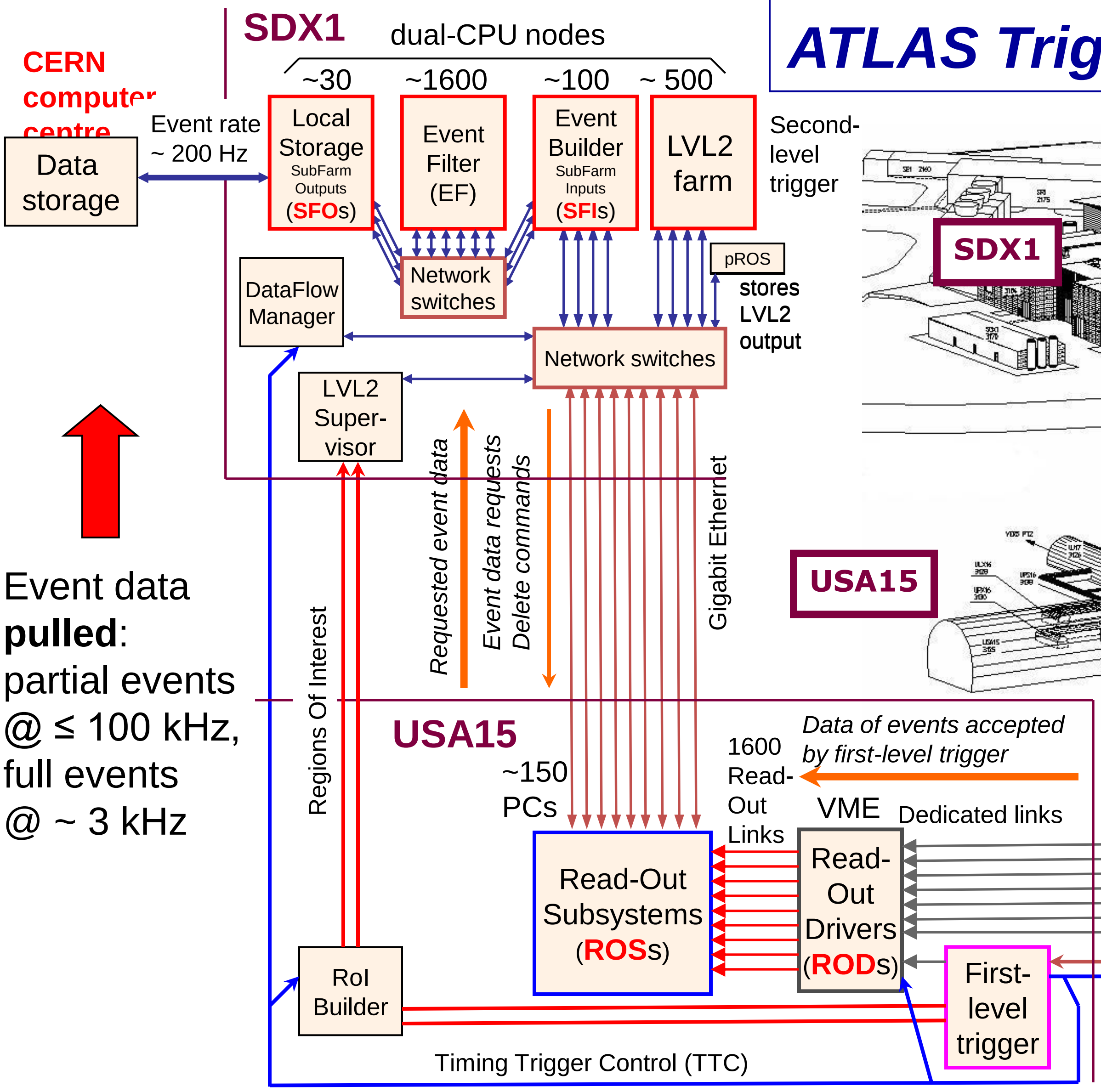


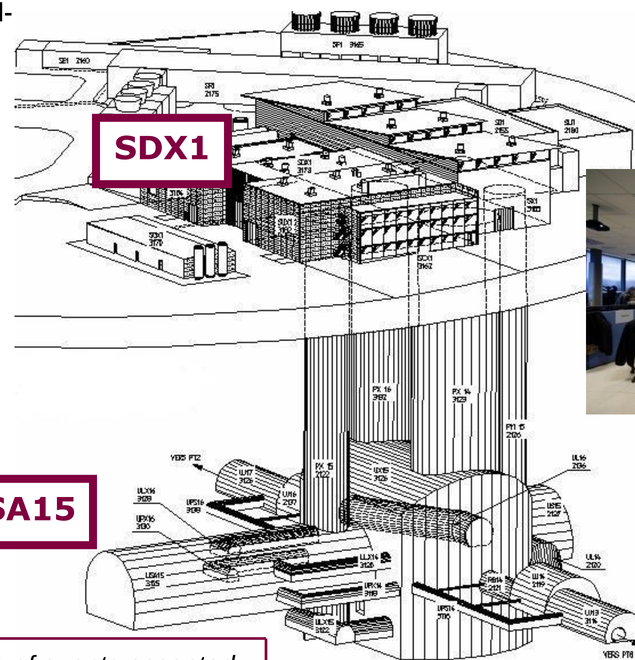
"Well known" processes, don't need to keep all of them …

New Physics

This we want to keep!

As an example: ATLAS Trigger / DAQ Data Flow

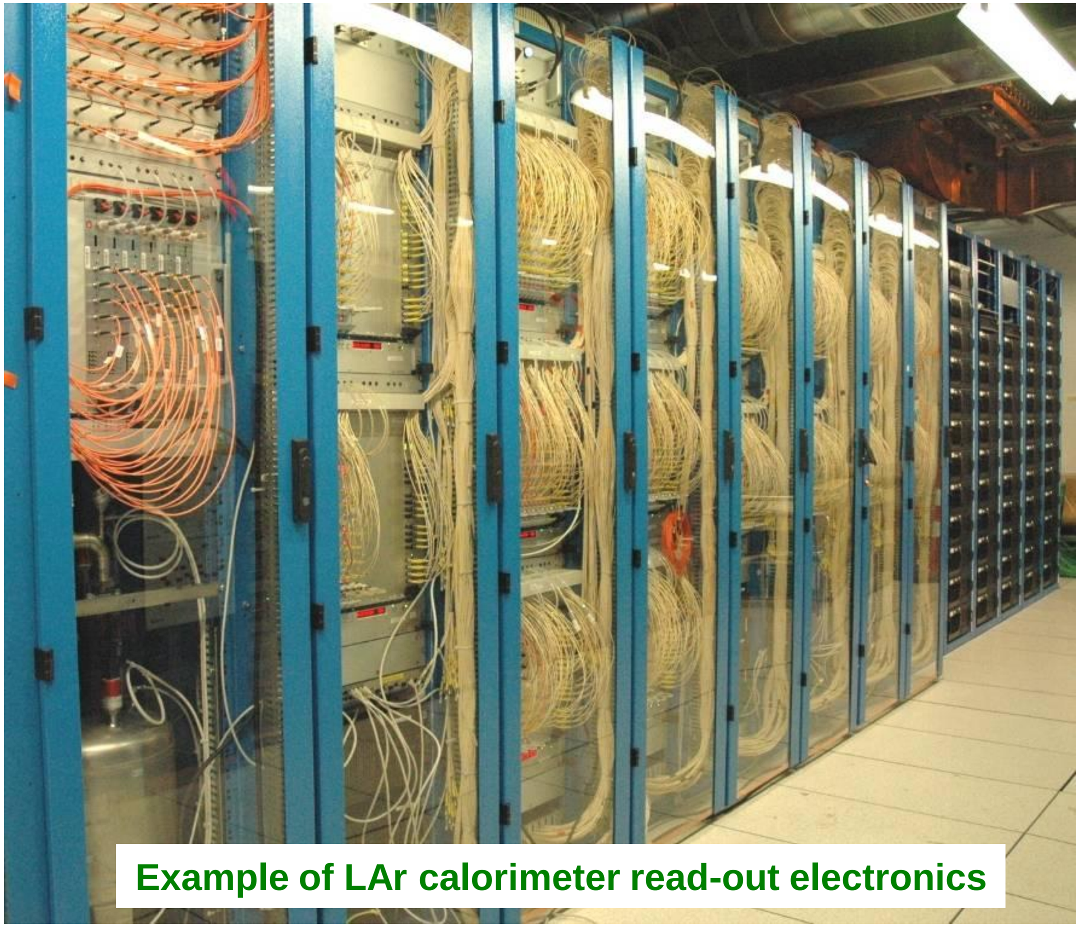




Event data pushed @ ≤ 100 kHz, 1600 fragments of ~ 1 kByte each

The read-out electronics, trigger, DAQ and detector control systems have been brought into operation gradually over the past years, along with the detector commissioning with cosmics

(Examples from ATLAS)

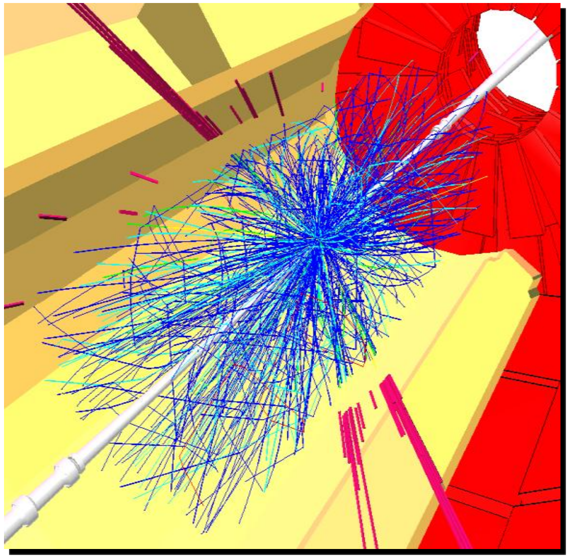


Example of LAr calorimeter read-out electronics

Example of Level-1 Trigger electronics

In total about 300 racks with electronics in the underground counting rooms

Worldwide LHC Computing Grid (wLCG)



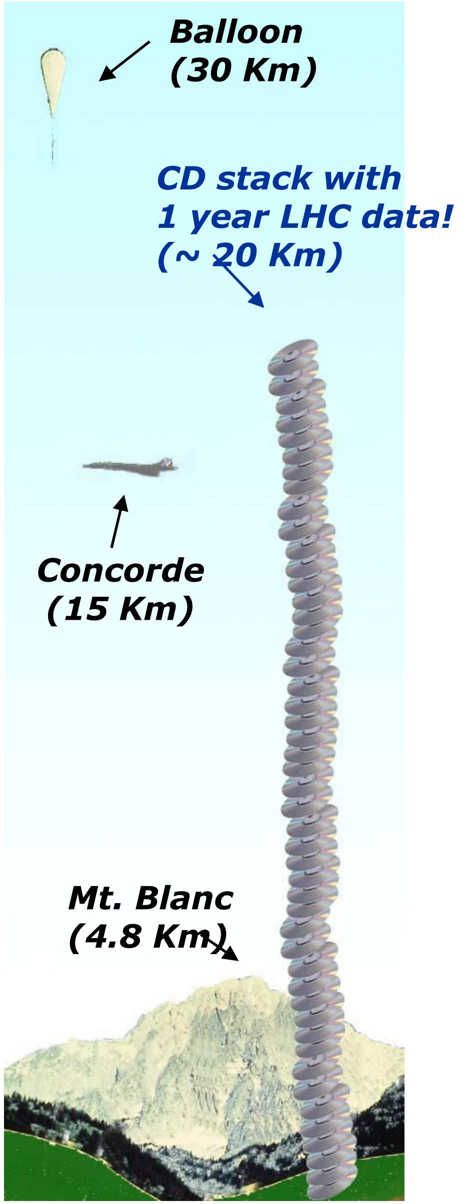
WLCG is a worldwide collaborative effort on an unprecedented scale in terms of storage and CPU requirements, as well as the software project's size

GRID computing developed to solve problem of data storage and analysis

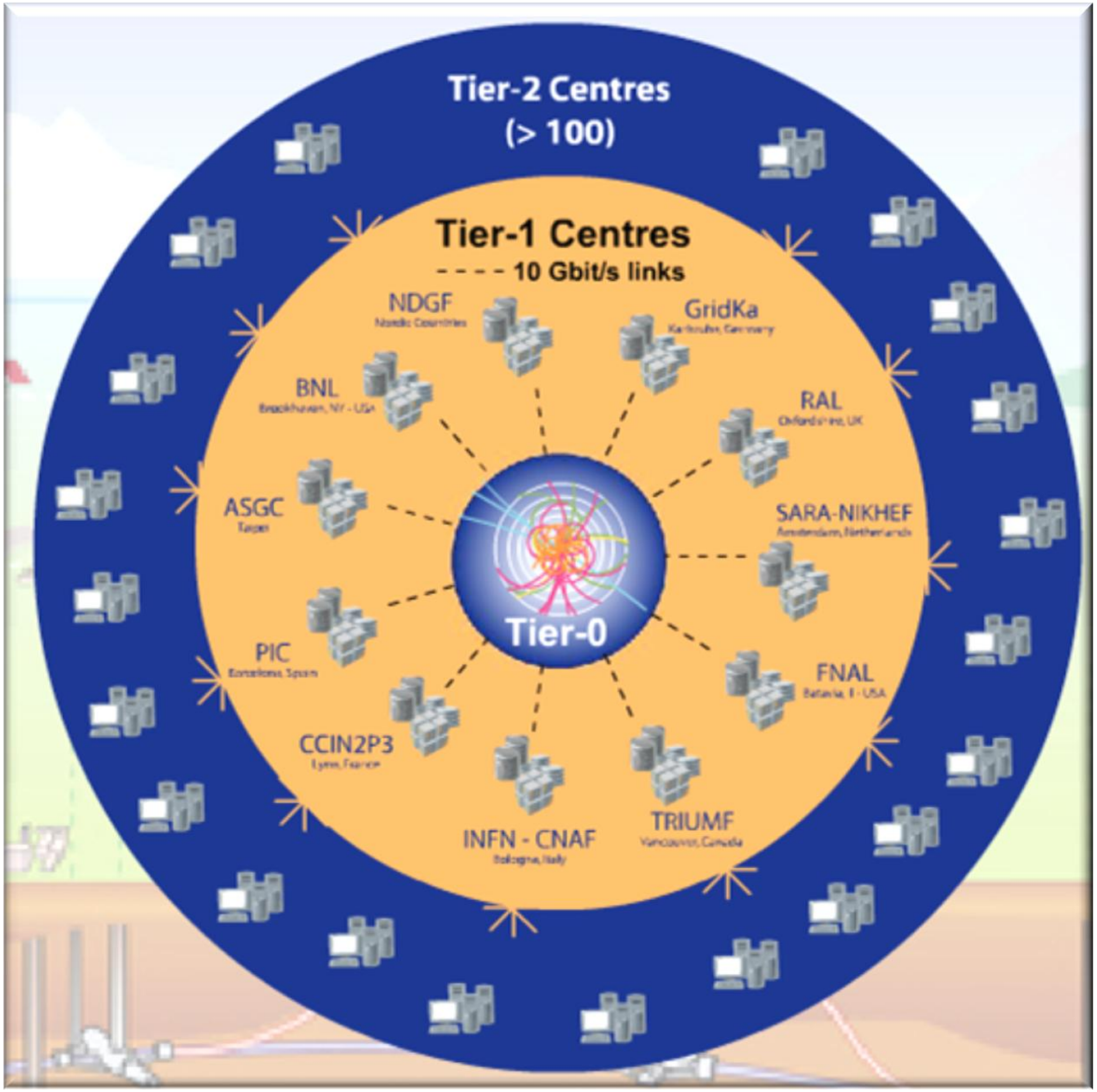
LHC data volume per year: 10-15 Petabytes

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

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

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 $\sqrt{s}$ = 10 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 …

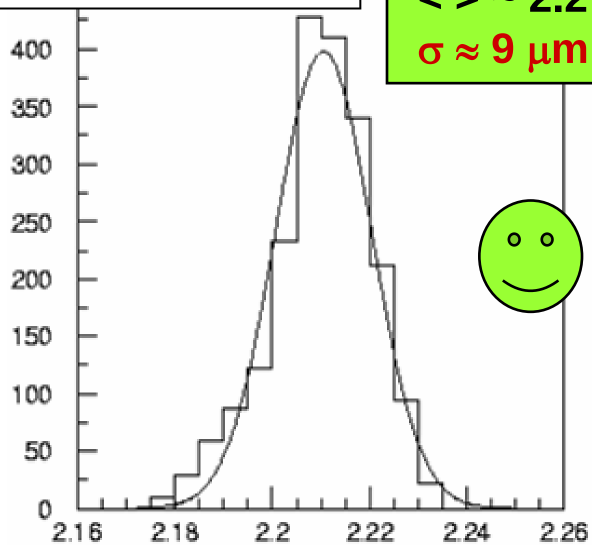
Example: ATLAS LAr em Accordion Calorimeter

Construction quality

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

End-cap: 1536 plates

< > ~ 2.2 mm
σ ≈ 9 μm

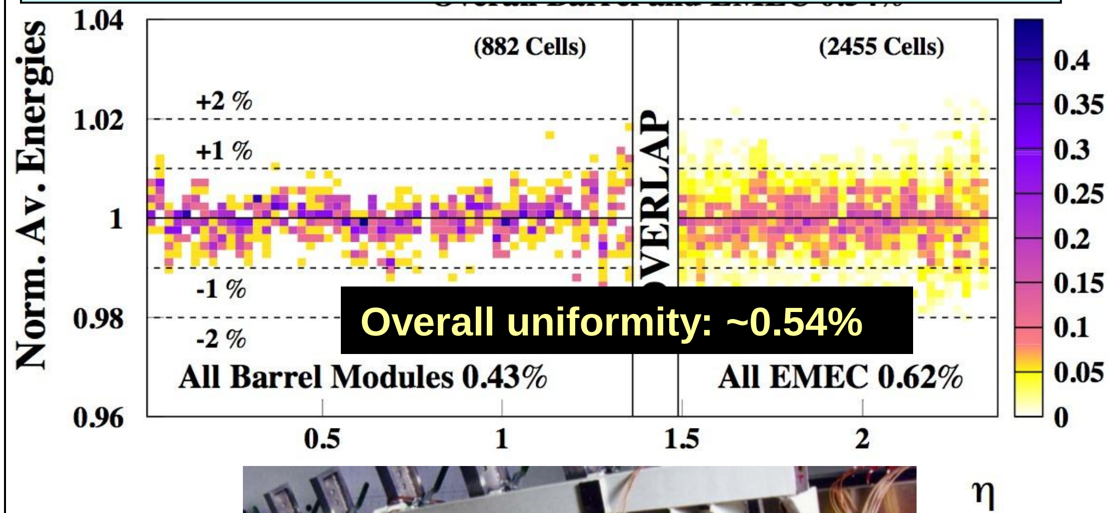


Absorber thickness (mm)

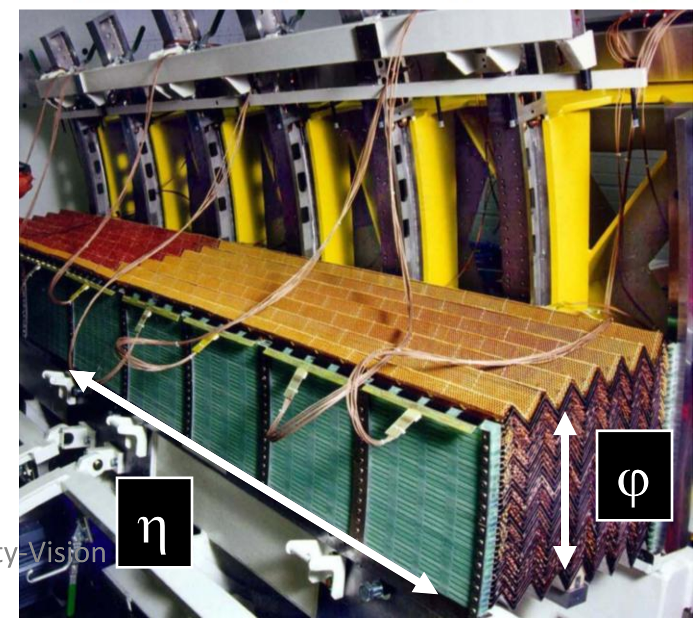
Test-beam measurements

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)



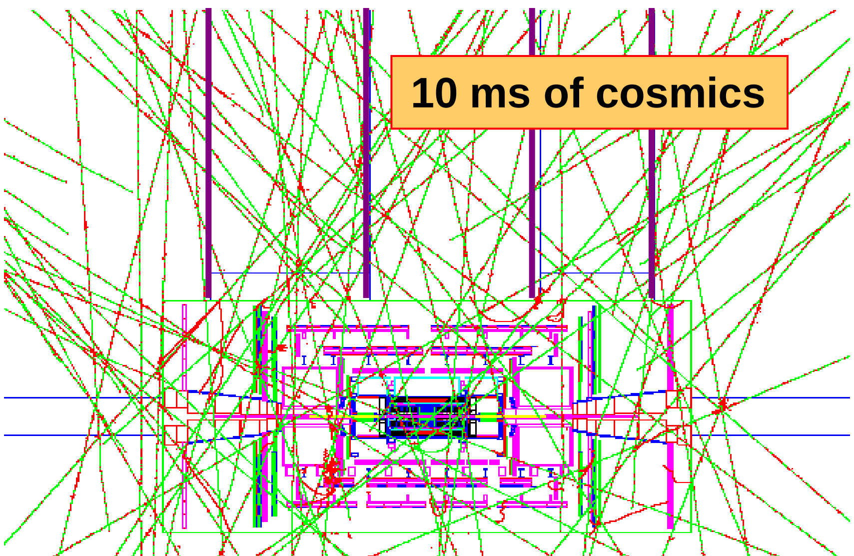
1 barrel module:
Δη x Δφ = 1.4 x 0.4
≈ 3000 channels



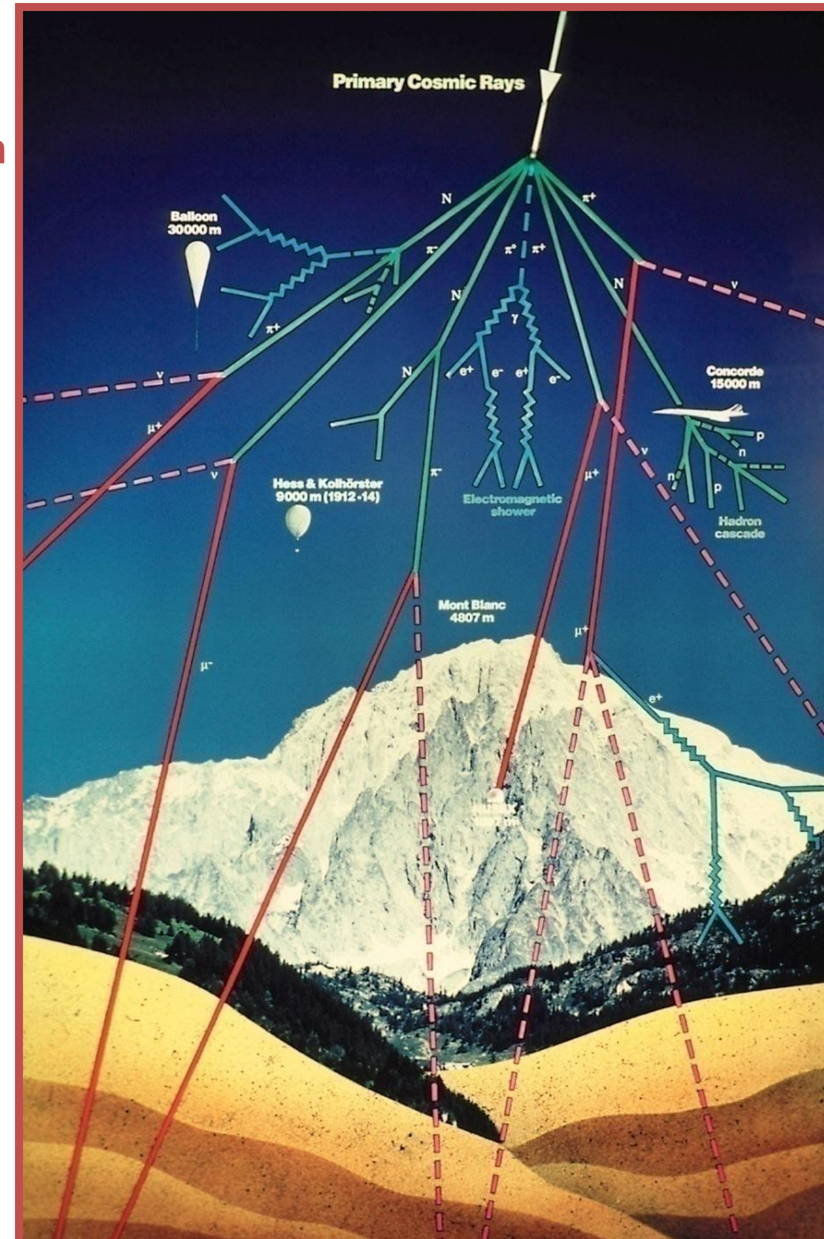
Commissioning with cosmics in the underground caverns
(were the first real data in situ …)

Started in 2005 along the installation. Was very useful to:

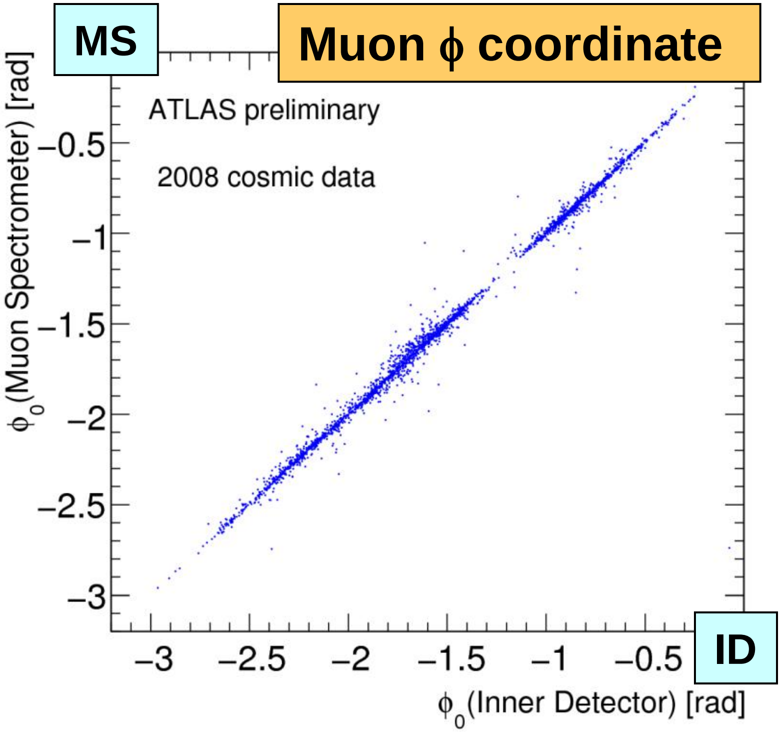
- **Run an increasingly more complete detector with final trigger, data acquisition and monitoring systems. Data analyzed with final software**
- **Shake-down and debug the experiment in its final position → fix problems**
- **Perform calibration and alignment studies**
- **Gain global operation experience in situ before collisions start**

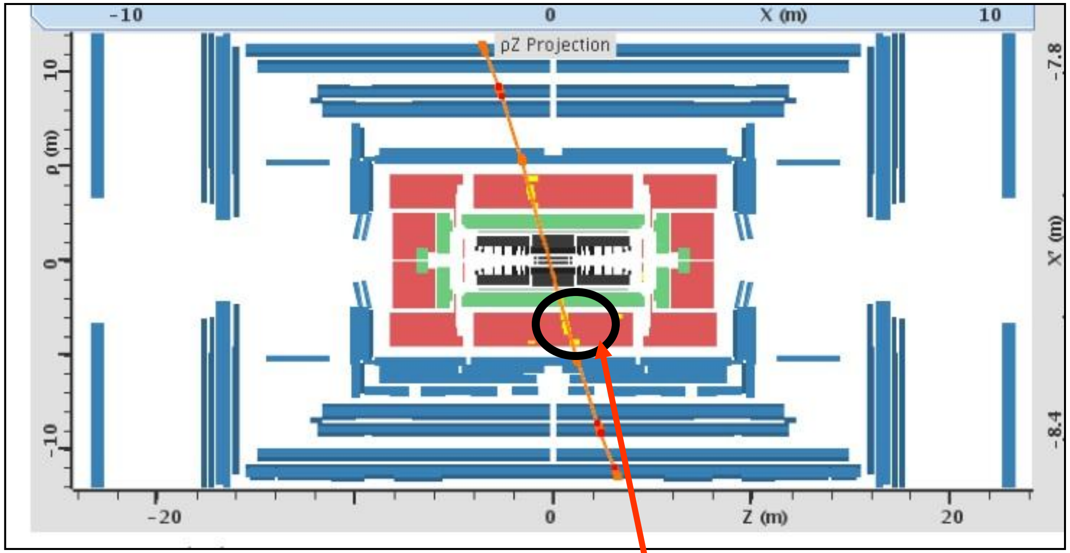


Rate of cosmics in ATLAS: 0.5- few 100 Hz (depending on sub-detector size and location)

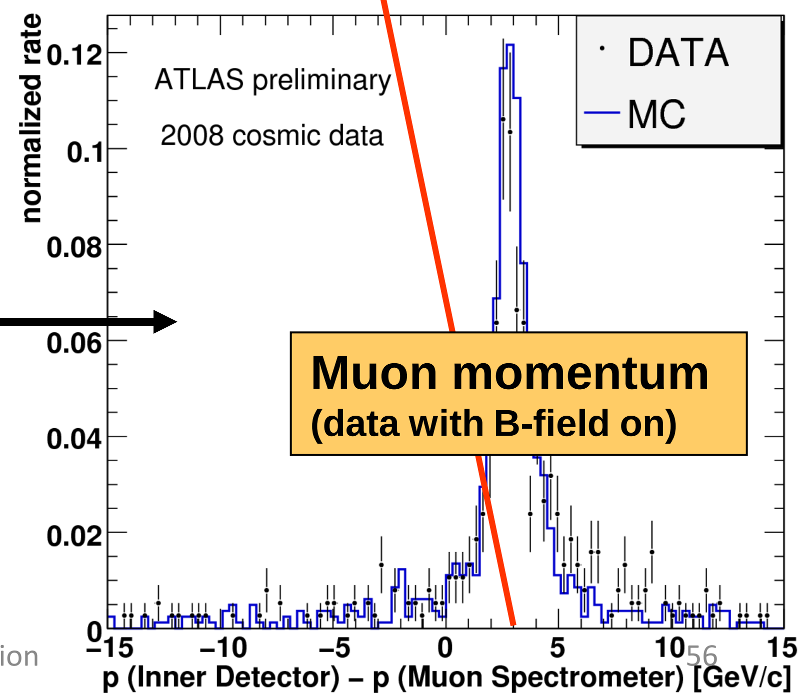


Correlation between measurements in the ATLAS Inner Detector and Muon Spectrometer





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)



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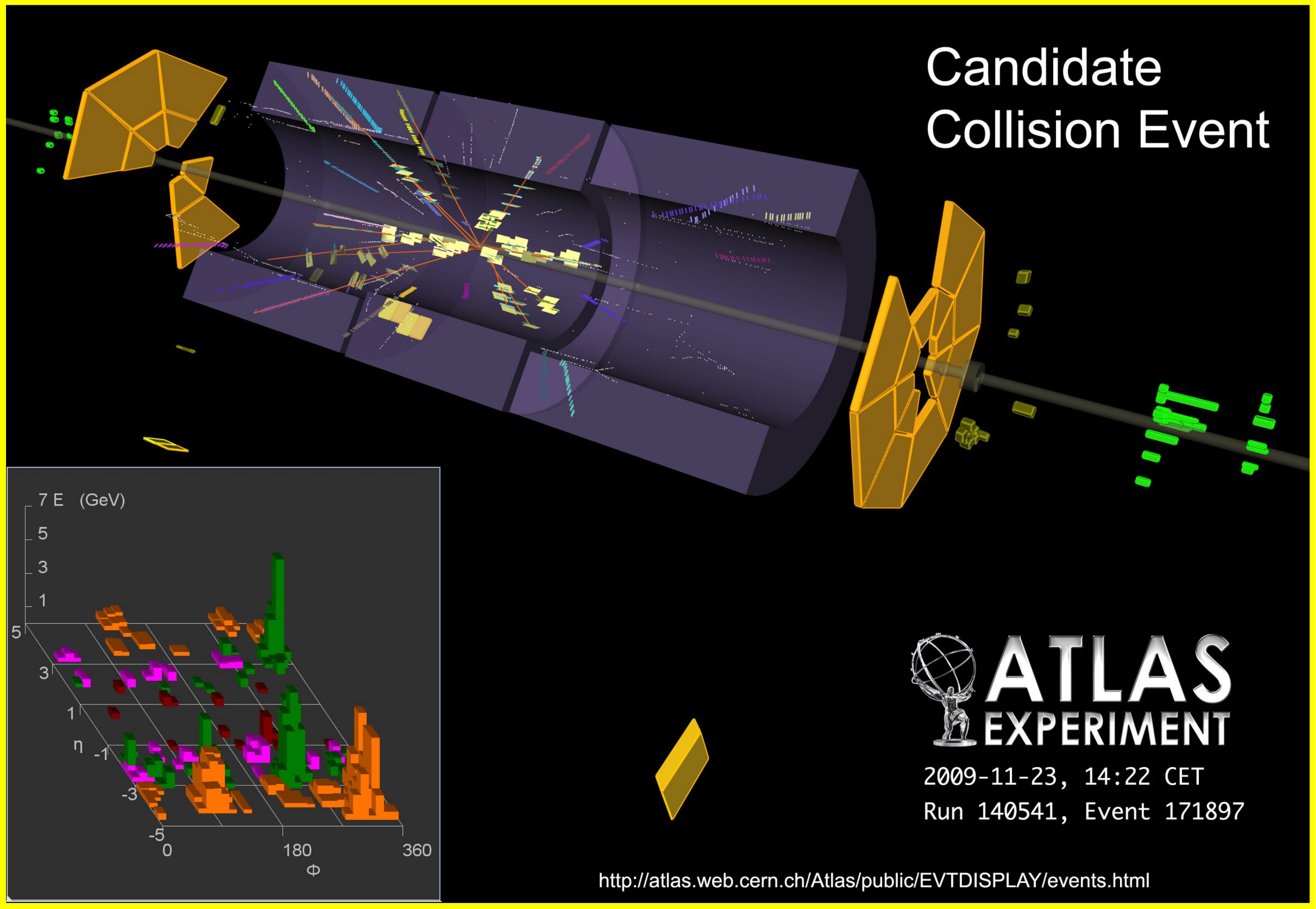
- Validate and tune tools (e.g. MC generators)
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

↓

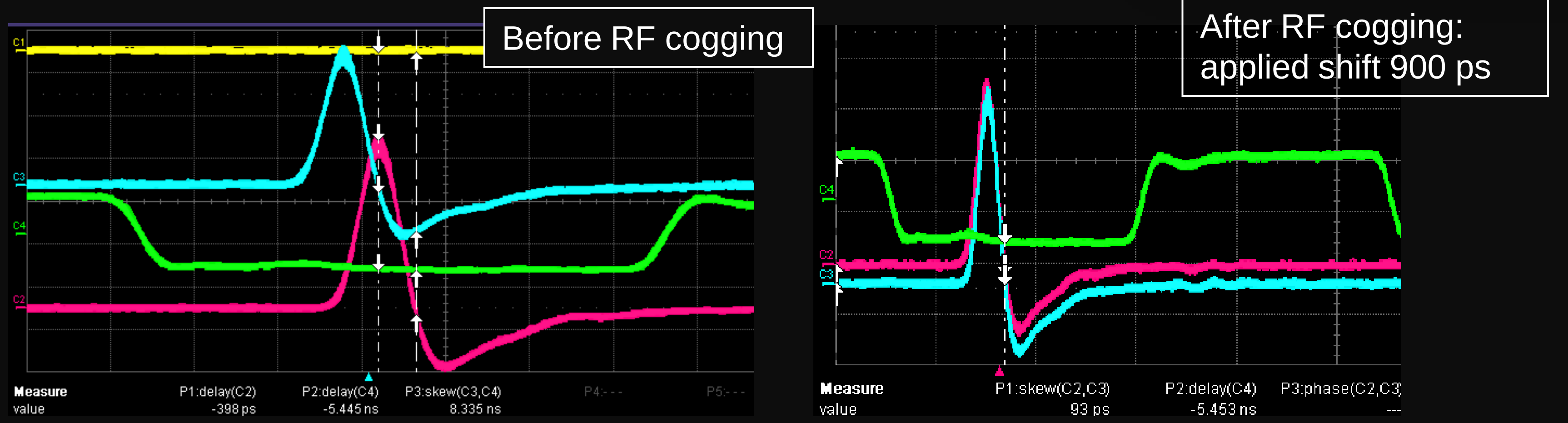
Prepare the road to discoveries …

First collisions at the LHC end of November 2009



Example of an early "handshake" between ATLAS and the LHC operation team

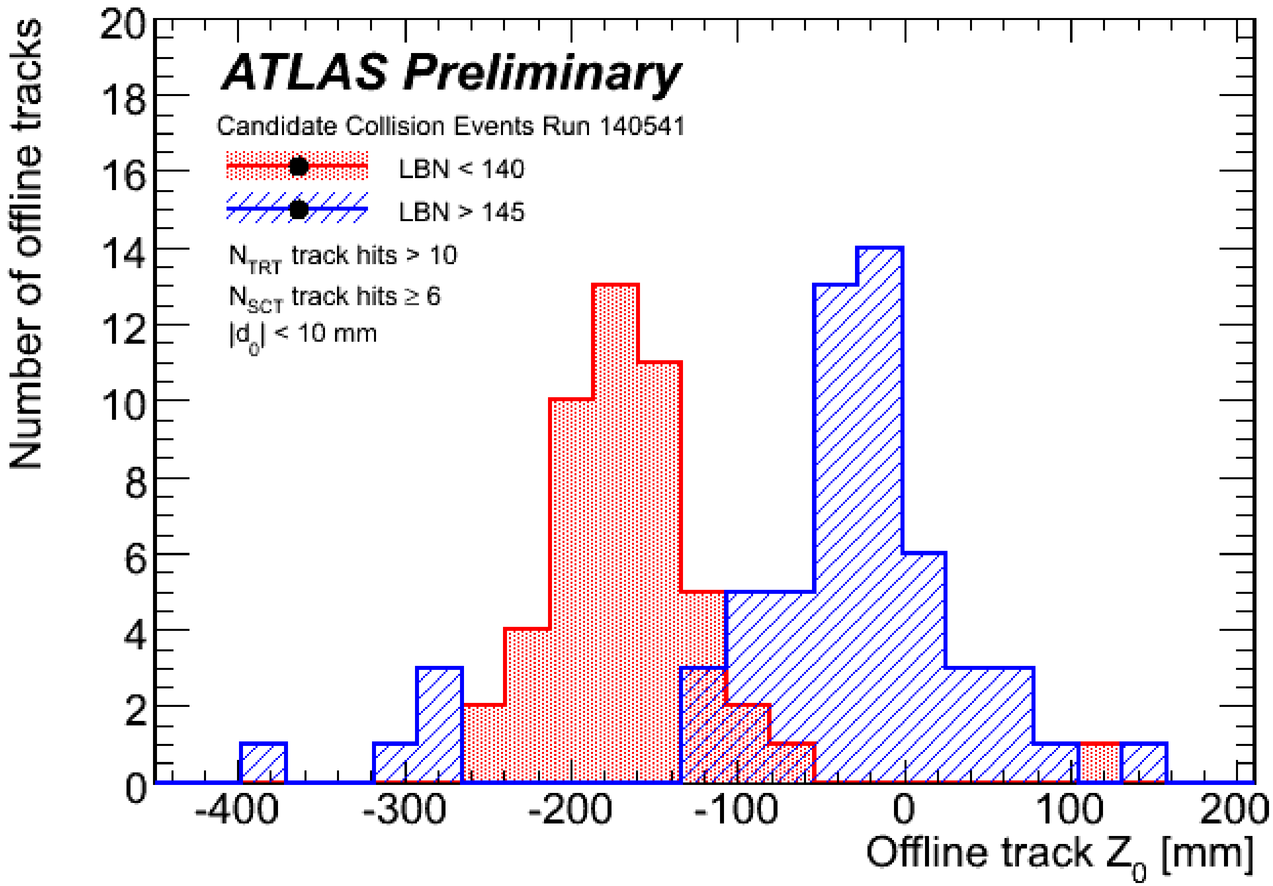
First collision events on 23 November:
ATLAS beam pickups showed phase shift of 900 ps, causing the primary vertex to be shifted by -13.5 cm in Z → based on this information, the machine team corrected the RF cogging



Beam pickup scope shots, beam 1 & 2

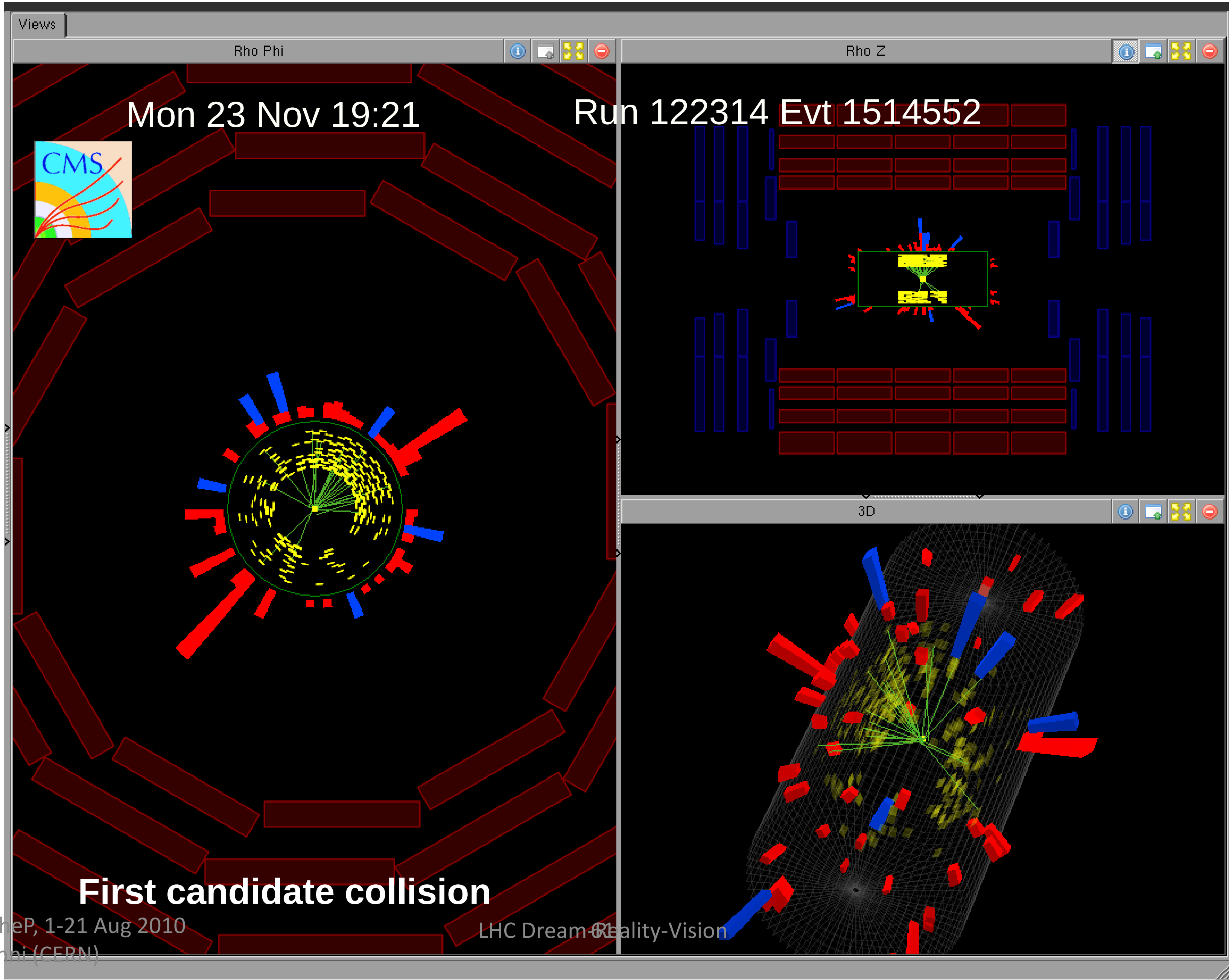
Bunches stable within 20 ps (rms)

Track *Z* distribution of collision candidate events as obtained before and after RF cogging. Observed shift: ~ +12 cm

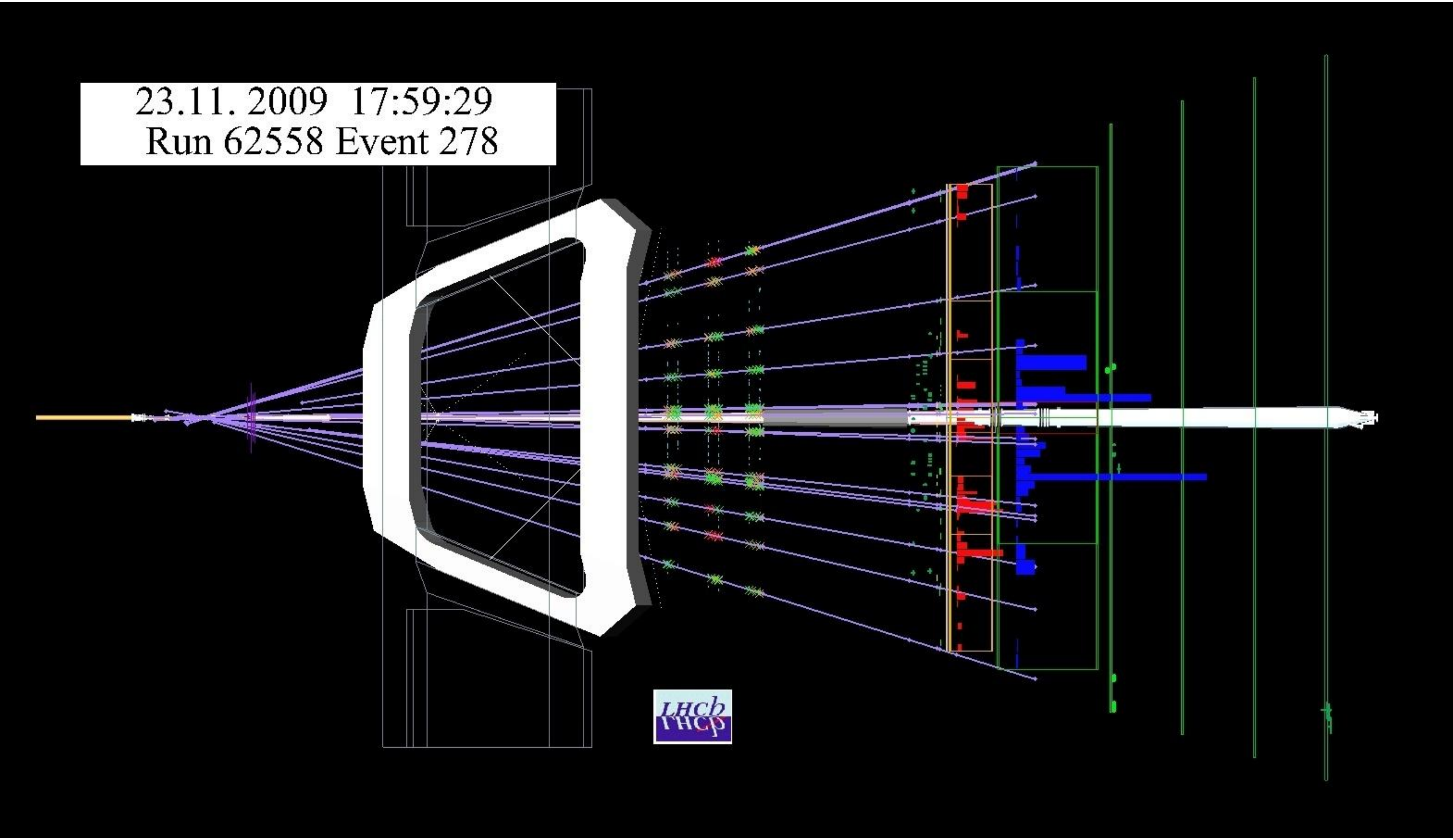


(Note: beams were not yet stable → Pixels off and SCT at reduced voltage)

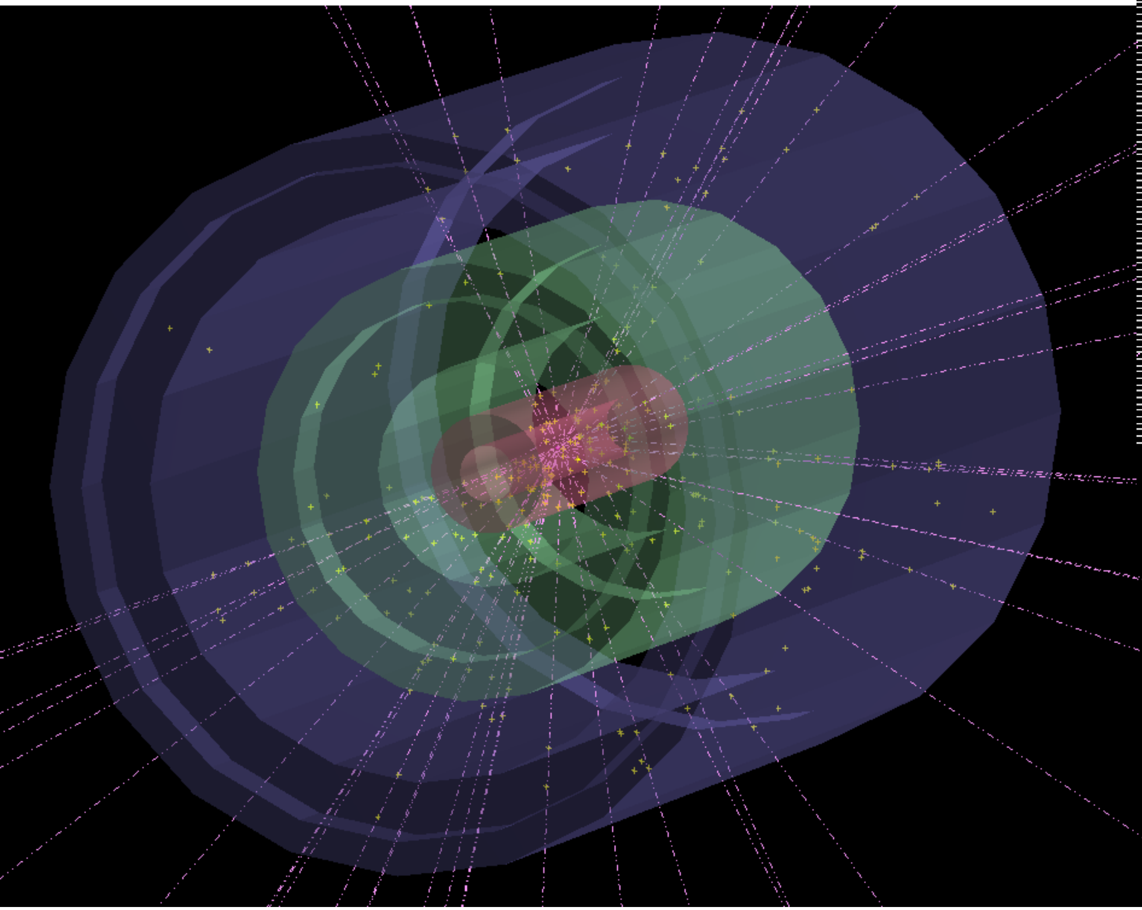
CMS event from the first day

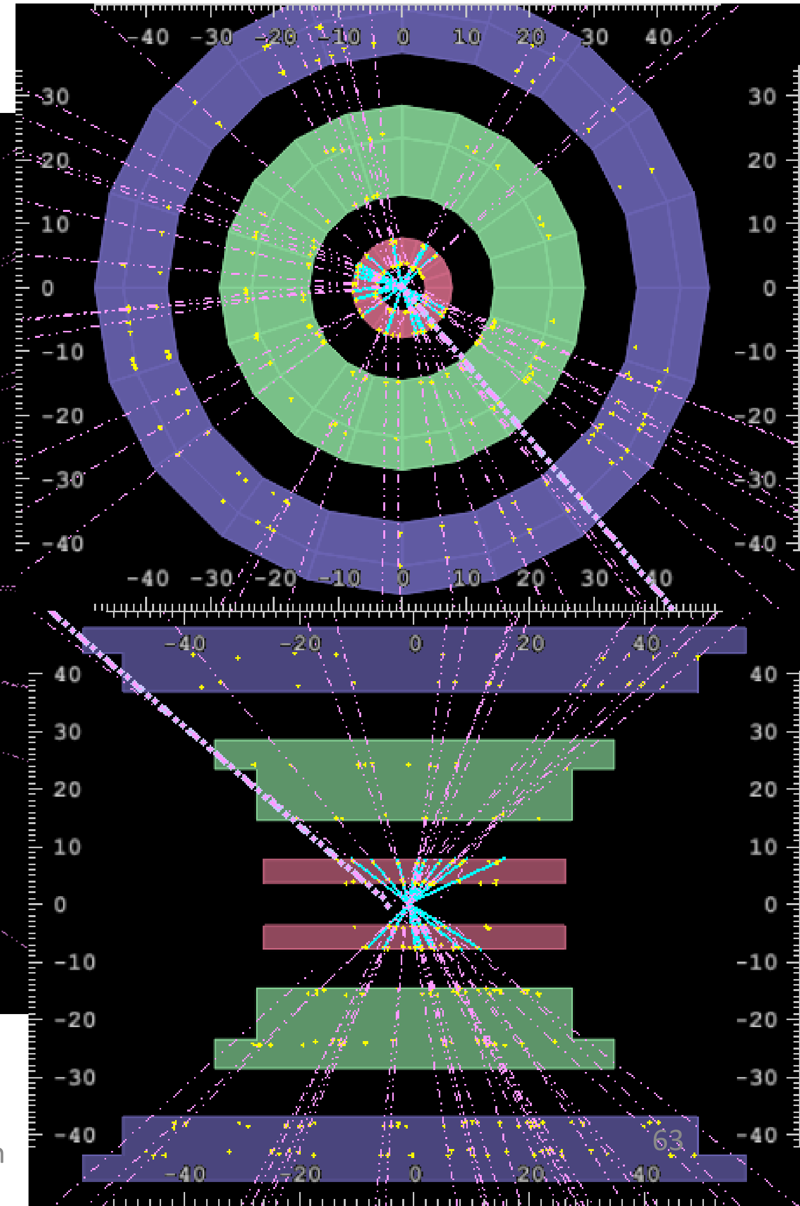


LHCb event from the first day

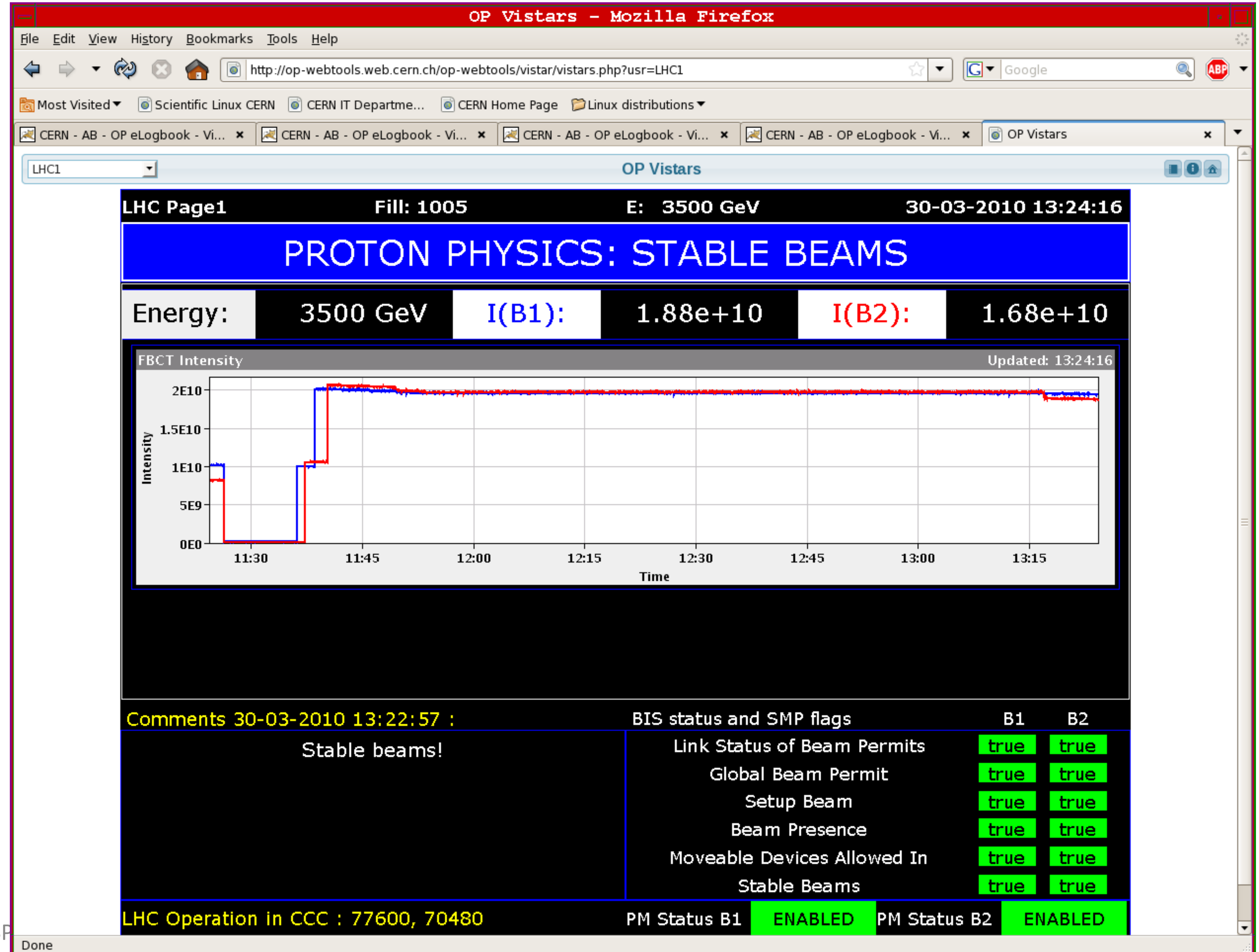


A high multiplicity ALICE event from the first day…

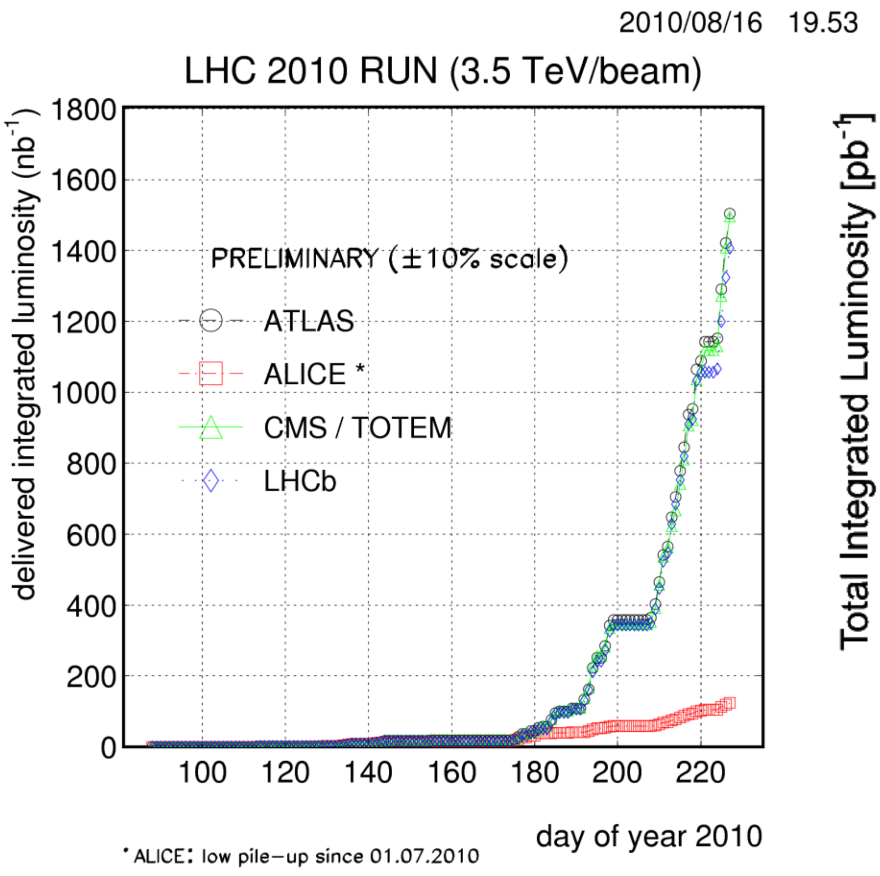


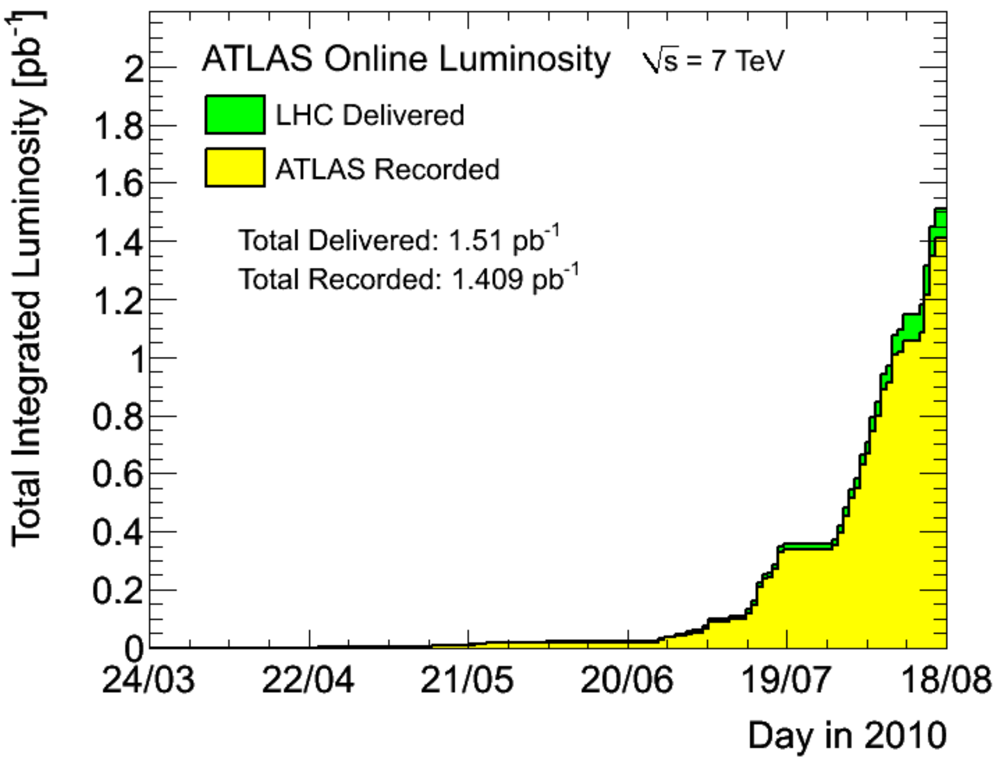


High-energy operation with 3.5 TeV beams started on 30th March 2010



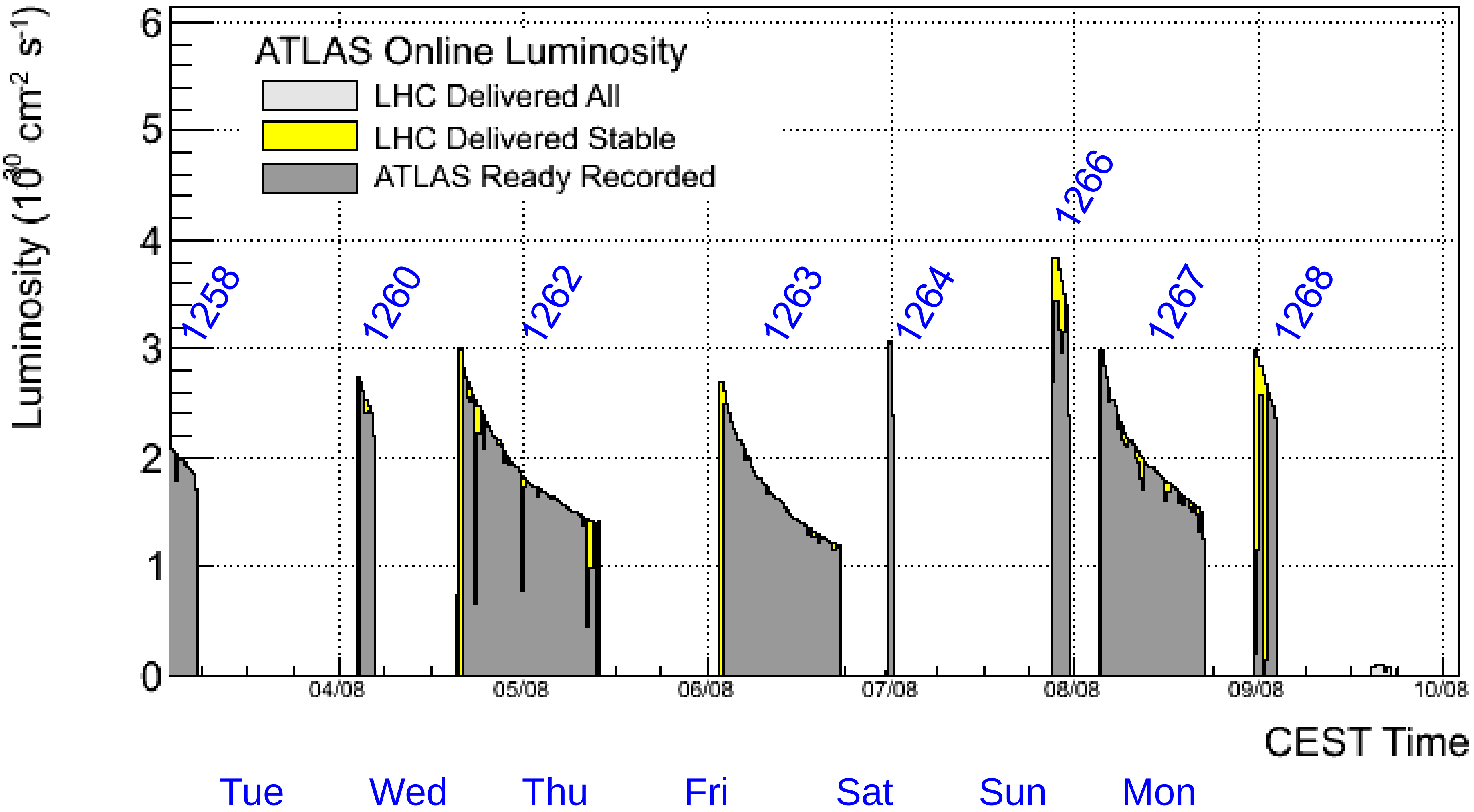
Accumulated data so far (integrated luminosity)





Note the high efficiency of recorded data (93.3%)

Typical fill structure of the LHC for a good week (2-8 Aug)

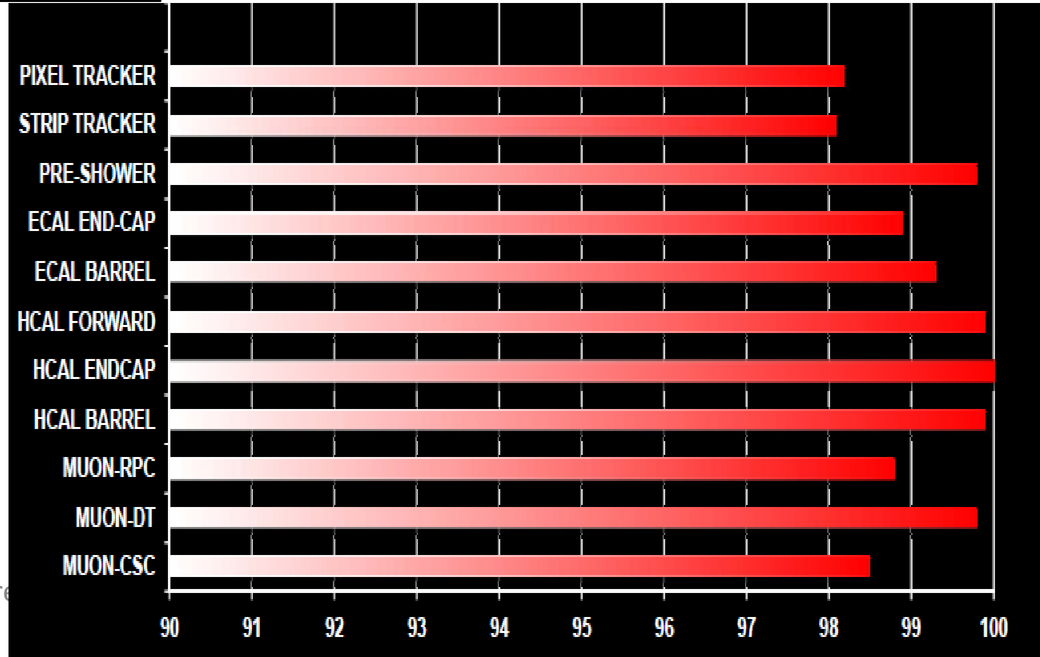


Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	97.4%
SCT Silicon Strips	6.3 M	99.2%
TRT Transition Radiation Tracker	350 k	98.0%
LAr EM Calorimeter	170 k	98.5%
Tile calorimeter	9800	97.3%
Hadronic endcap LAr calorimeter	5600	99.9%
Forward LAr calorimeter	3500	100%
LVL1 Calo trigger	7160	99.9%
LVL1 Muon RPC trigger	370 k	99.5%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	98.5%
RPC Barrel Muon Chambers	370 k	97.0%
TGC Endcap Muon Chambers	320 k	98.6%

The complex detectors take data with an impressive fraction of operational channels, and high efficiencies

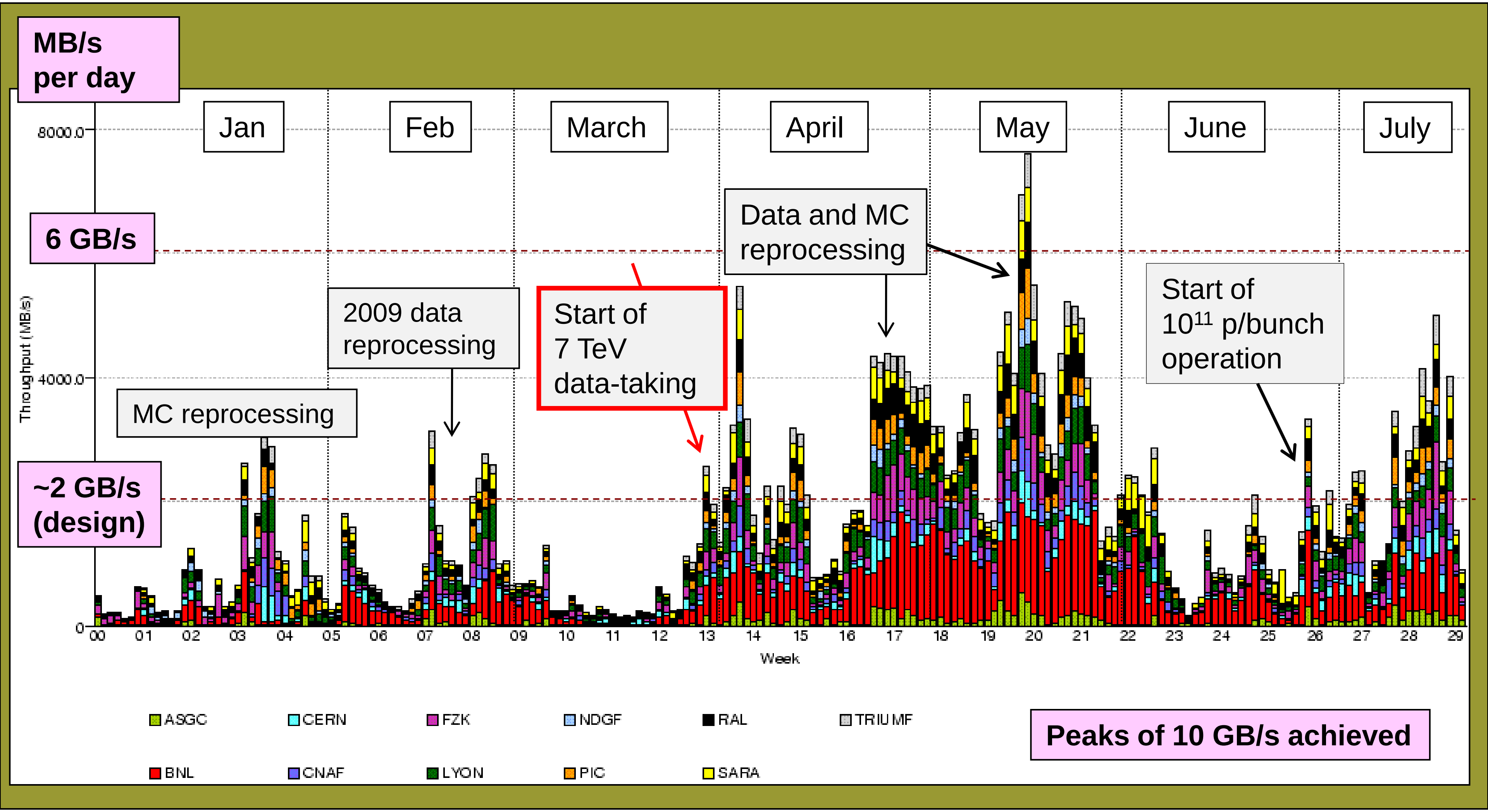
ATLAS EXPERIMENT
http://atlas.ch

CMS



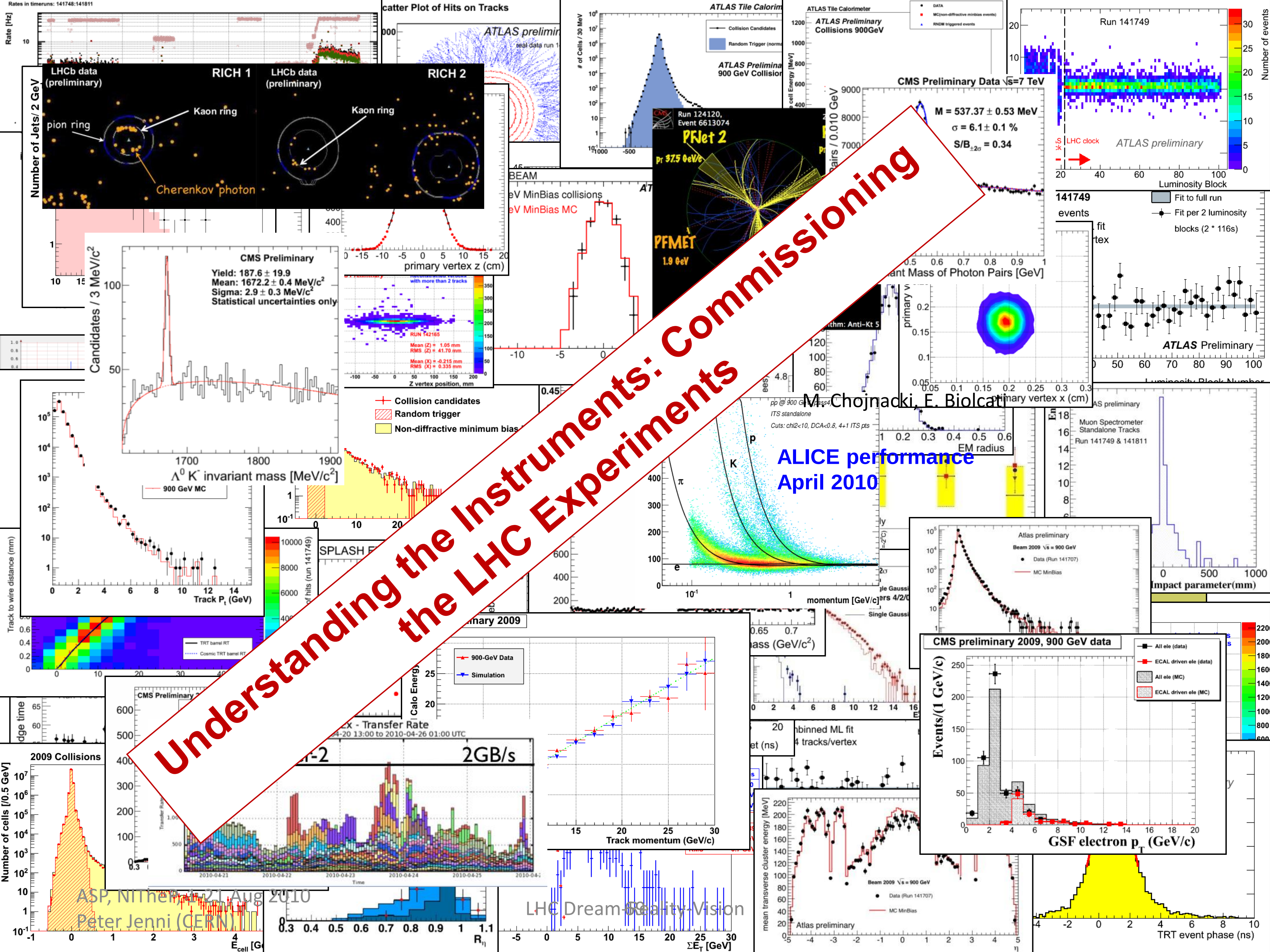
Worldwide data distribution and analysis

Total throughput of ATLAS data through the Grid: from 1st January until mid-July



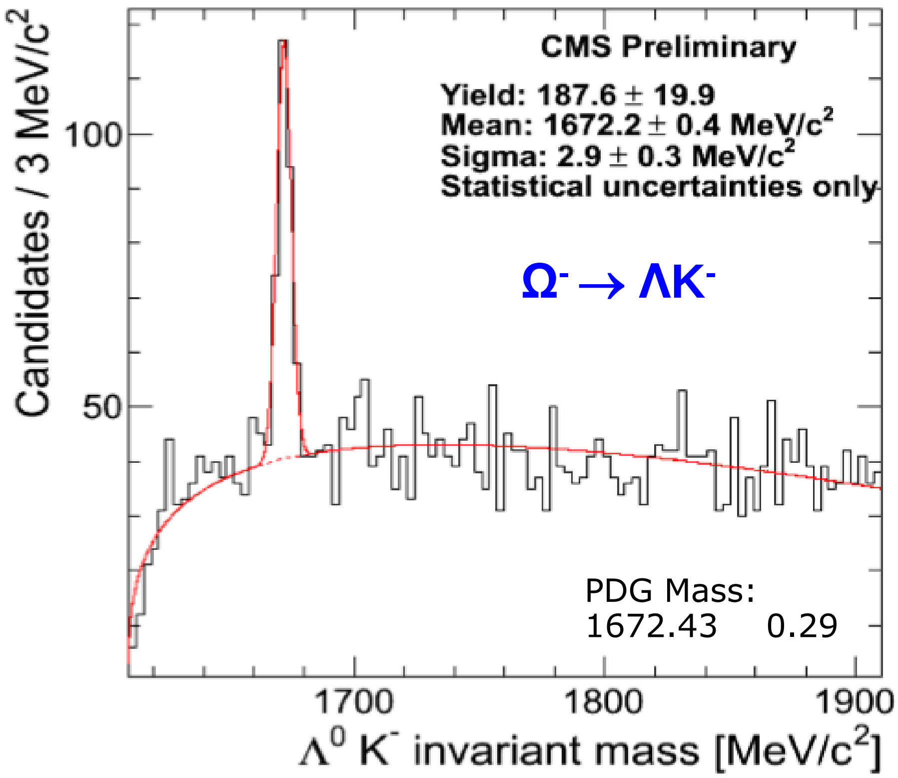
GRID-based analysis in June-July 2010:
> 1000 different users, ~ 11 million analysis jobs processed

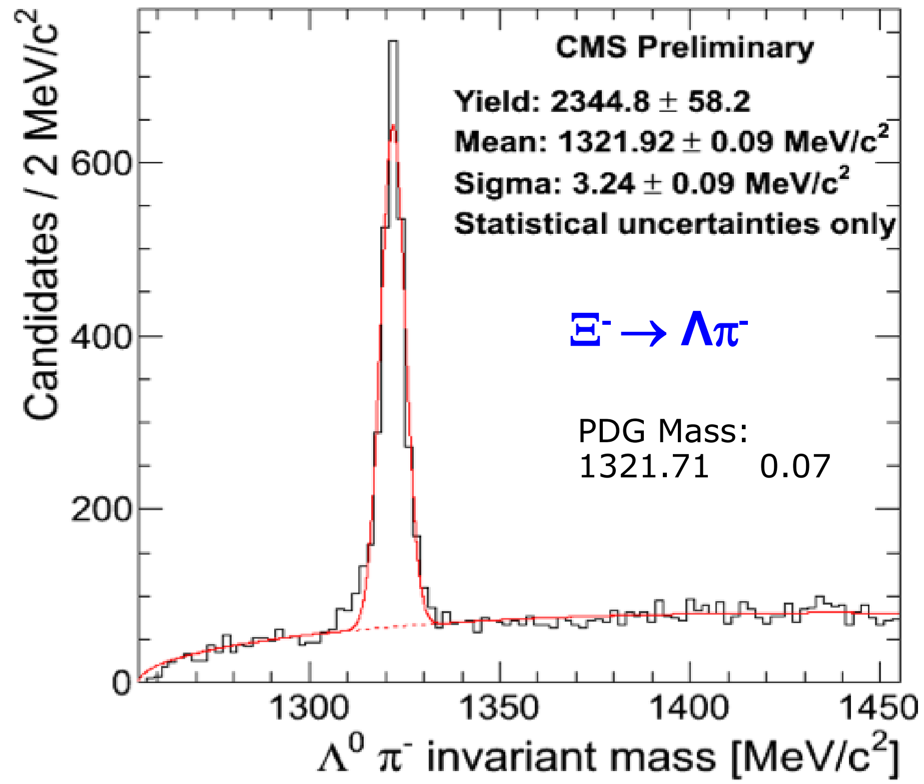
Understanding the Instruments: Commissioning the LHC Experiments



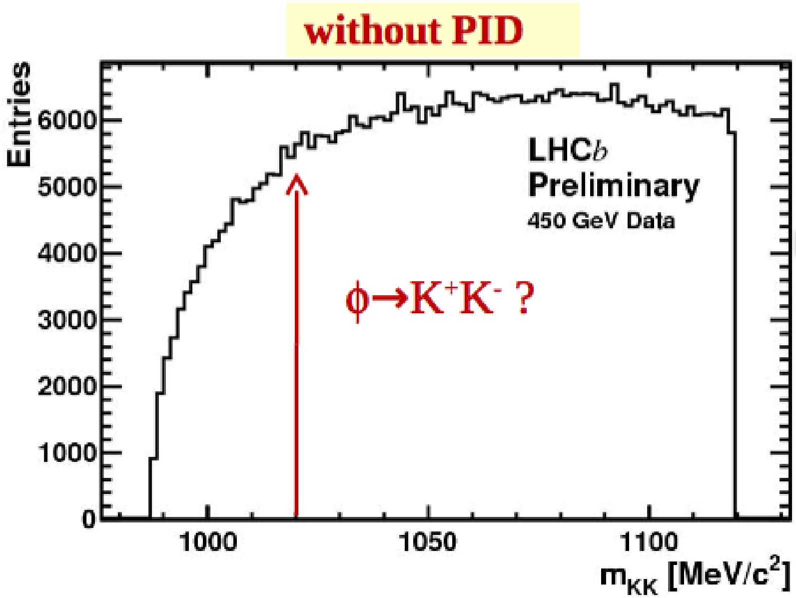
Enormous amount of tracking work, exploiting to the best also 100s of millions of cosmics, has led already to excellent performance for all experiments

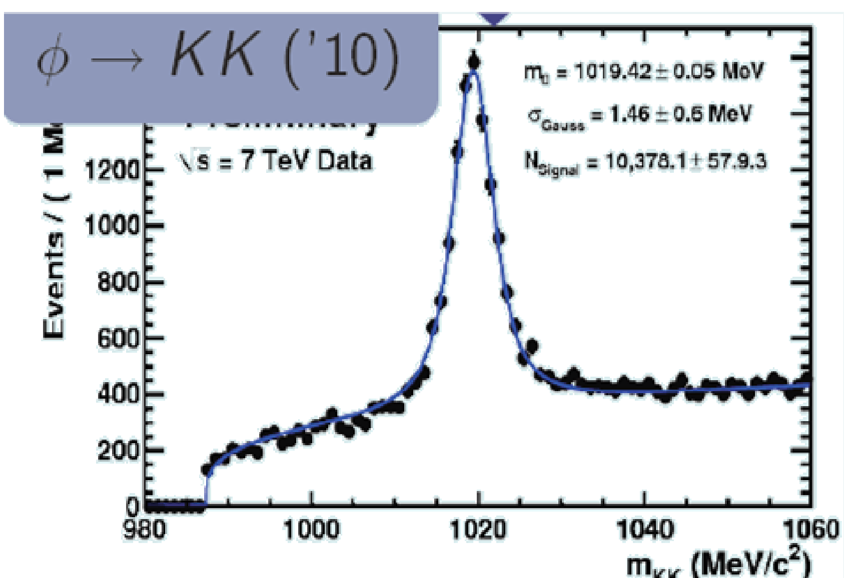
Here just a two examples from CMS, but ATLAS, LHCb and ALICE have a nice collection as well…



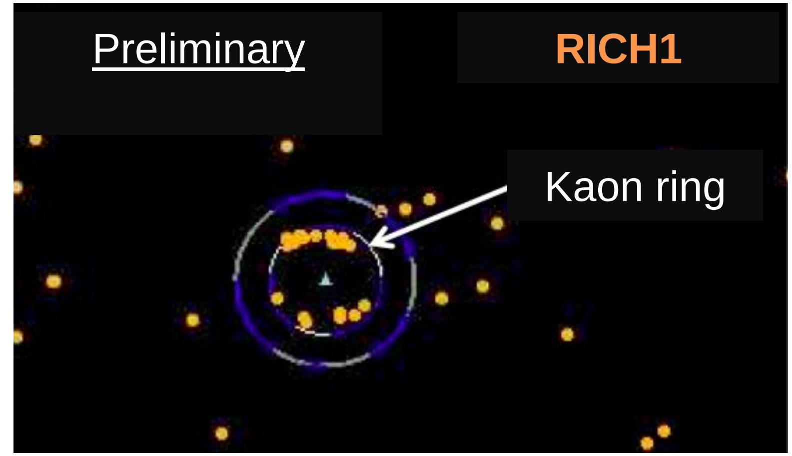


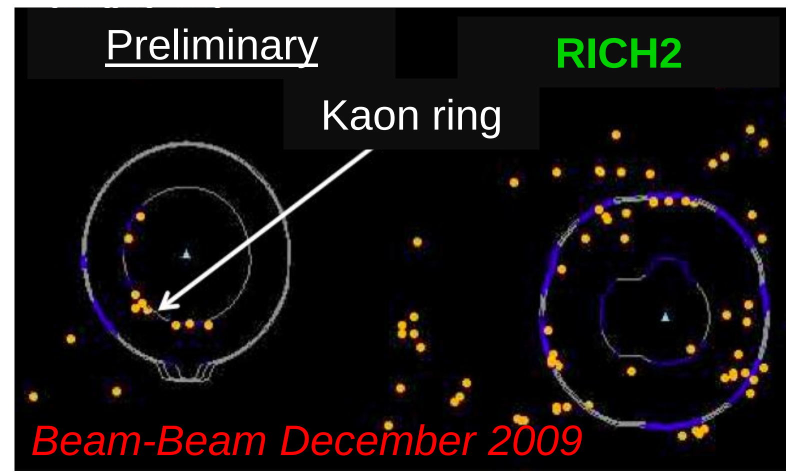
LHCb RICH detectors





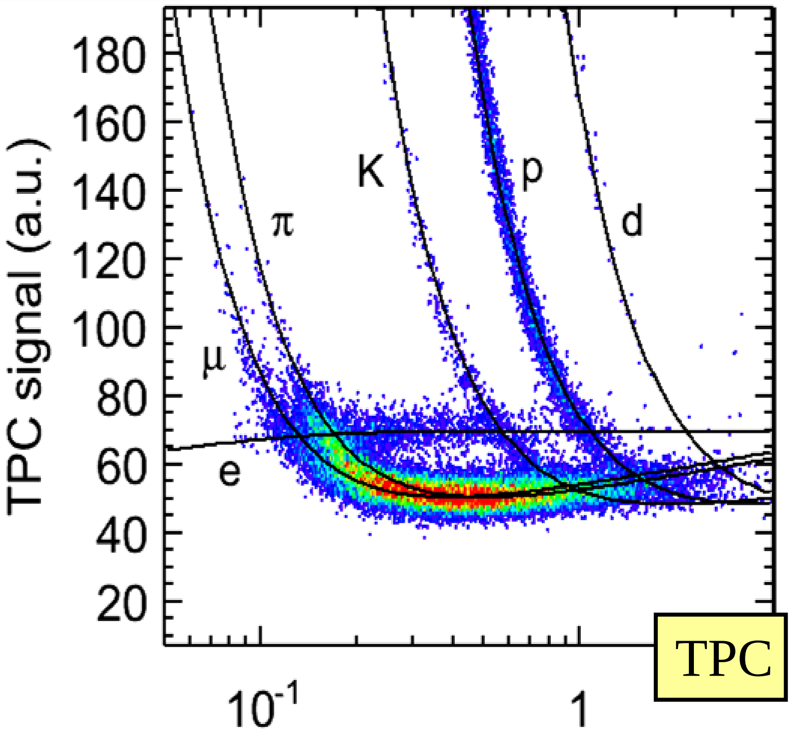
With RICHes PID!

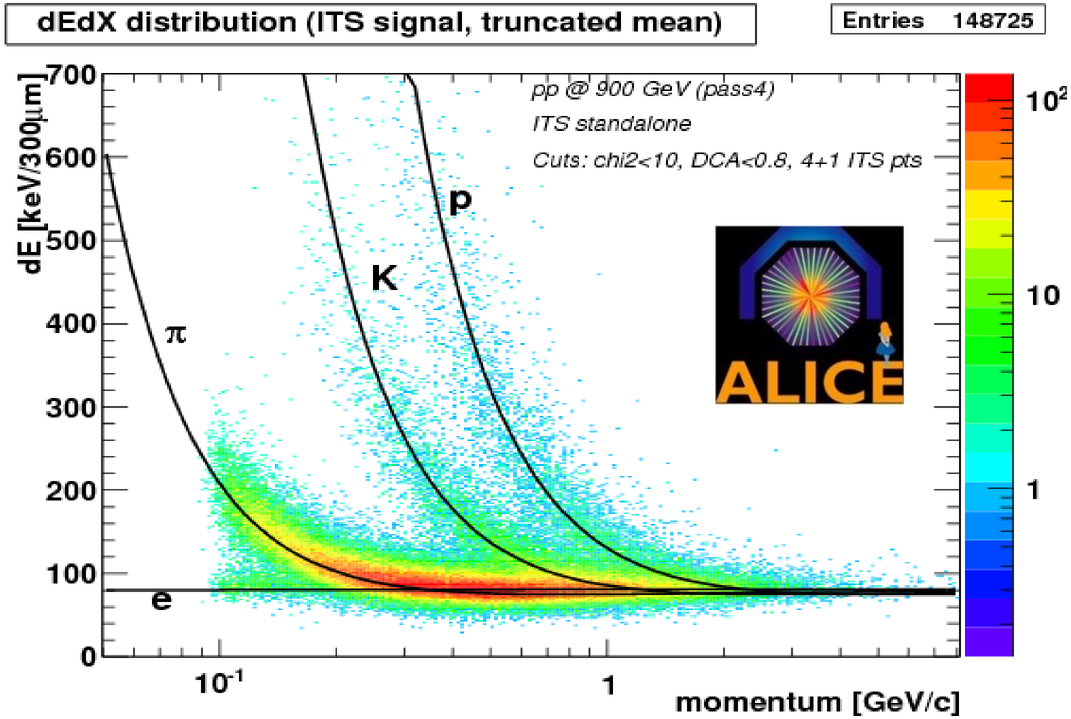


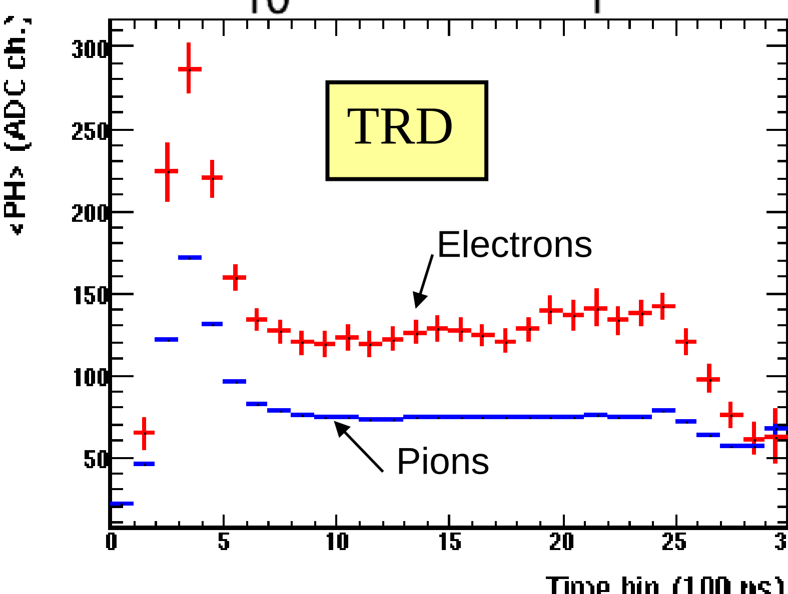


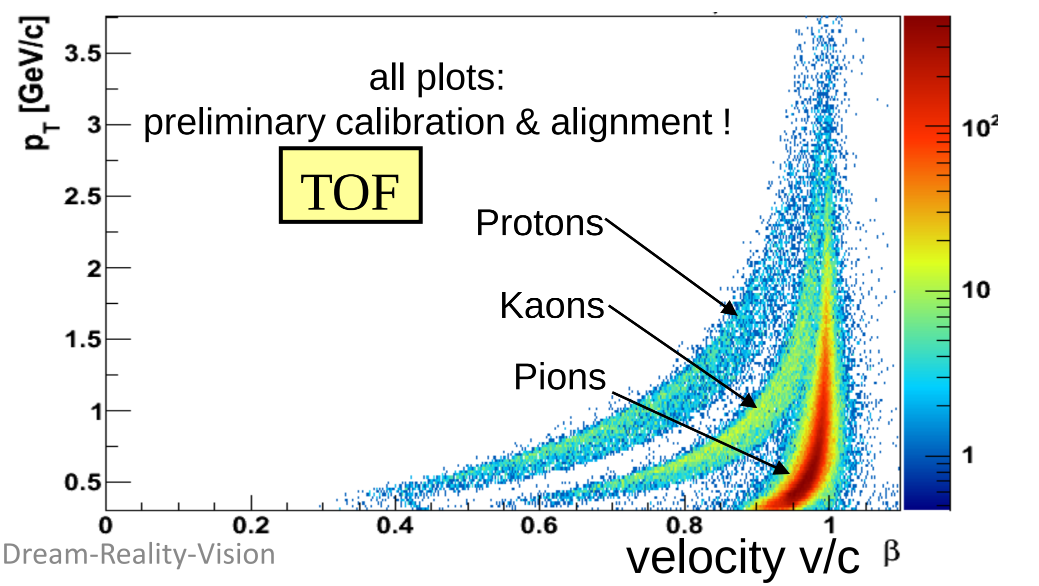
- RICH (Ring Imaging CHerenkov)
  - allow K-π identification from ~ 2 to 100 GeV
- Particle IDentification with RICHes
  - orange points: photon hits
  - Continuous lines: expected distribution for each particle hypothesis

ALICE particle identification

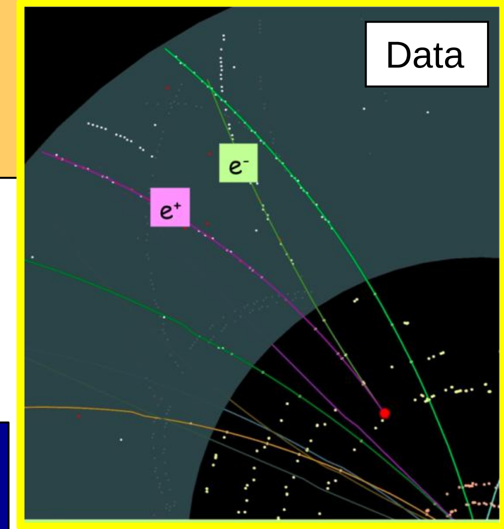




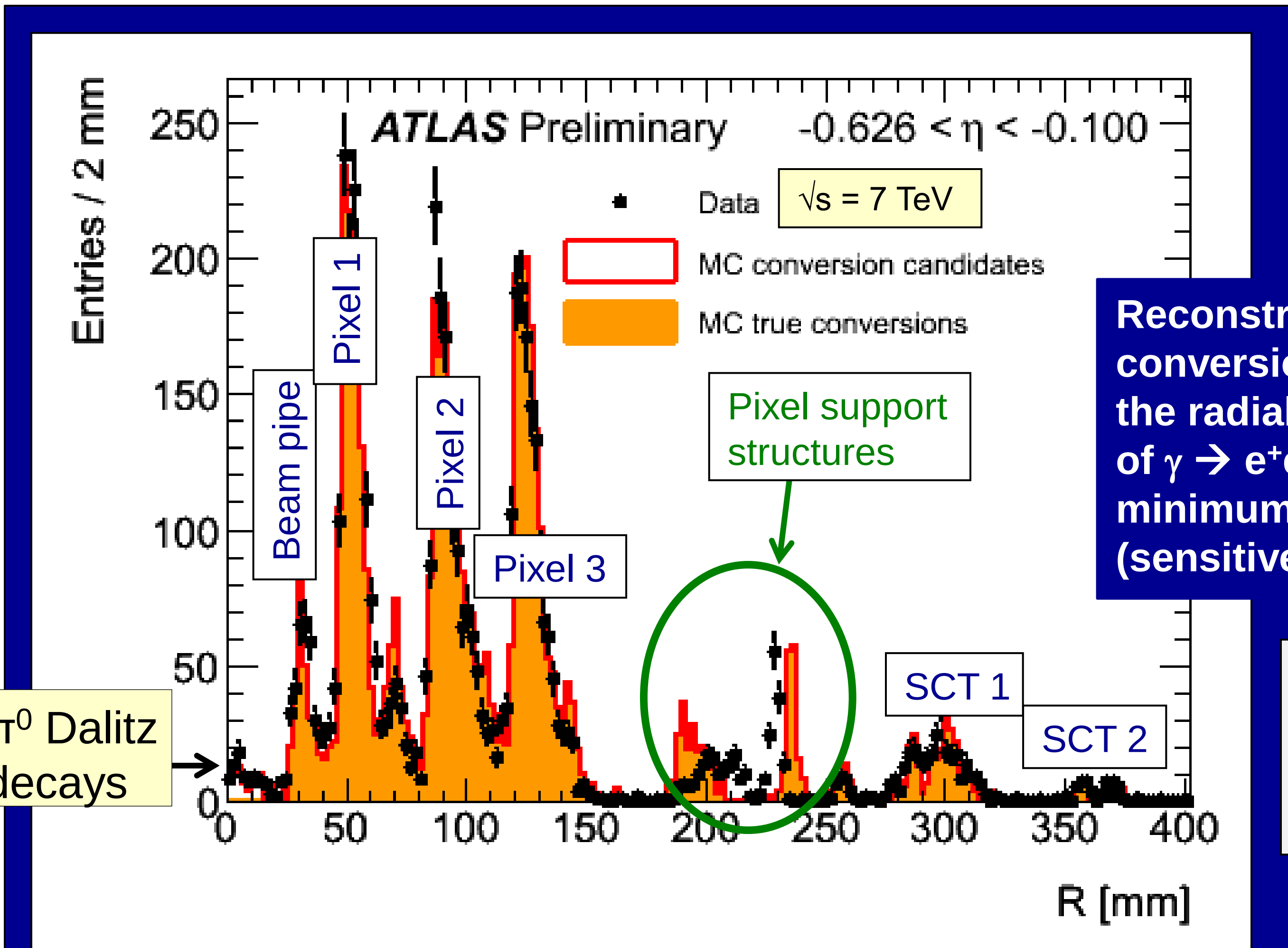




Mapping the Inner Detector material with $\gamma \rightarrow e^+e^-$ conversions and hadron interactions
… and using data to find geometry imperfections in the simulation



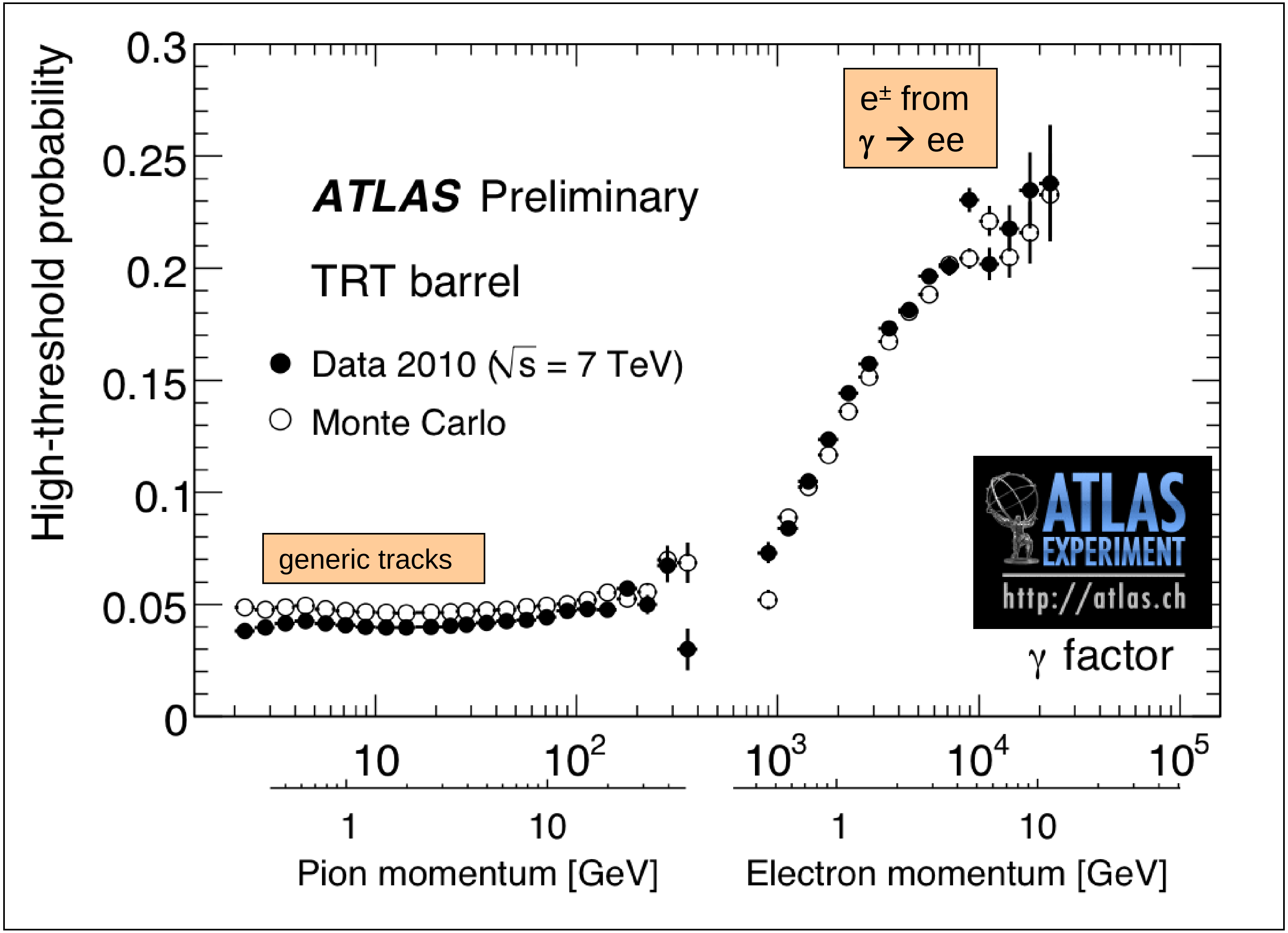
Goal is to know material to better than 5%
(over-constraining with several methods)
Present understanding: at the level of ~ 10%



π^0 Dalitz decays

Reconstructed conversion point in the radial direction of $\gamma \rightarrow e^+e^-$ from minimum bias events (sensitive to X_0)

Data show that Pixel supports are displaced in the simulation → to be fixed



Transition radiation intensity proportional to particle relativistic factor $\gamma = E/mc^2$.
Onset for $\gamma \sim 1000$ (MC tuned with test-beam data only)

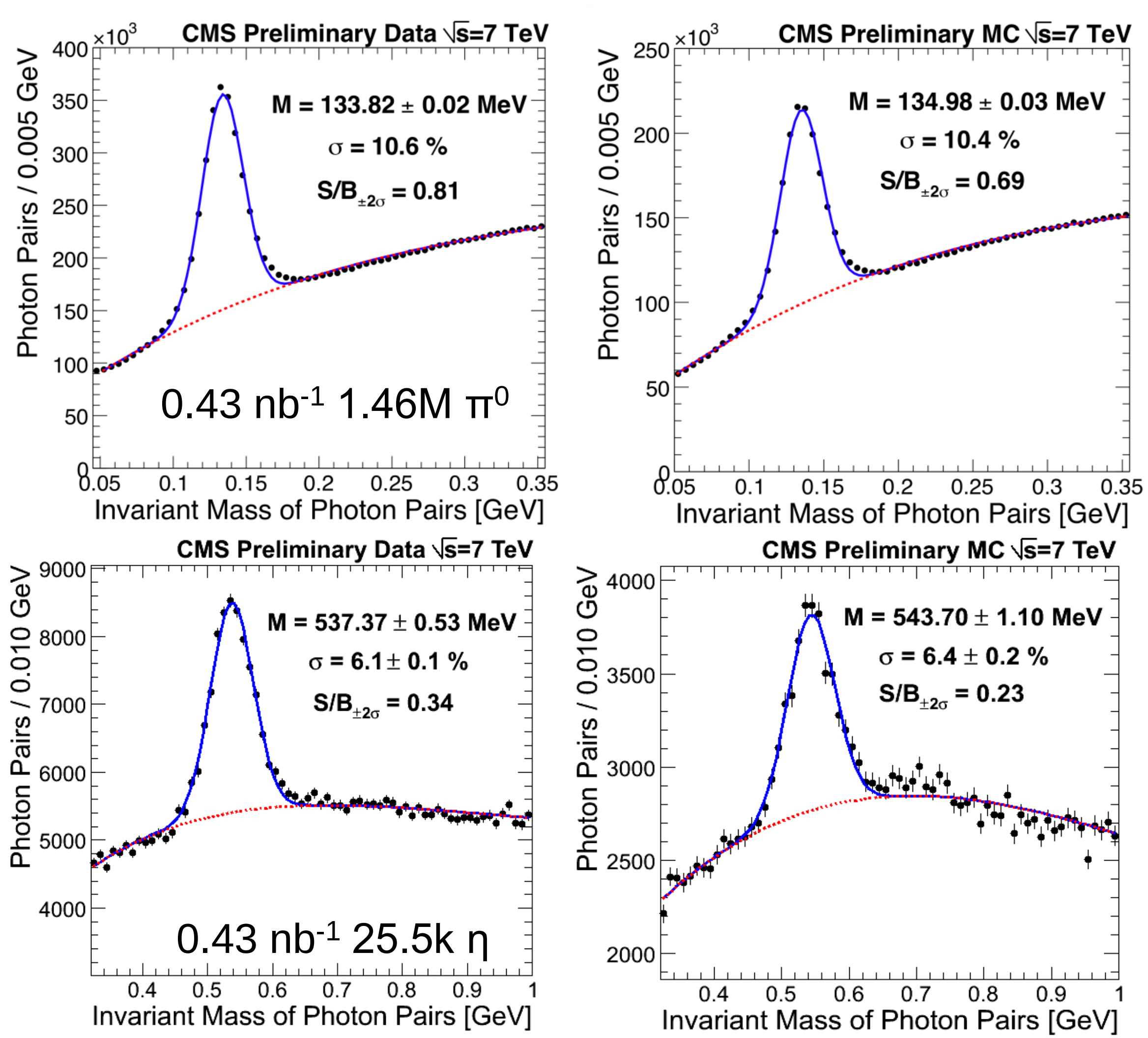
Low mass di-photons: π^0 and η

MC based correction applied according to cluster η and energy

1.46M of $\pi^0 \rightarrow \gamma\gamma$
$P_T(\gamma) > 0.4$ GeV,
$P_T(pair) > 1$ GeV

25.5K $\eta \rightarrow \gamma\gamma$
$P_T(\gamma) > 0.5$ GeV,
$P_T(pair) > 2.5$ GeV

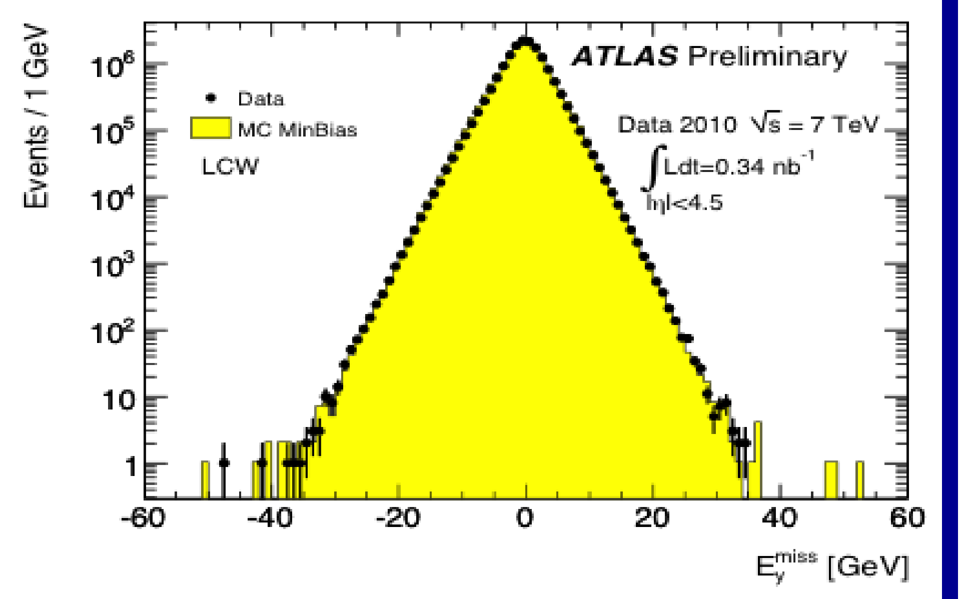
Numbers refer to ~10% of the currently available statistics.
Very useful tool to intercalibrate the crystals.



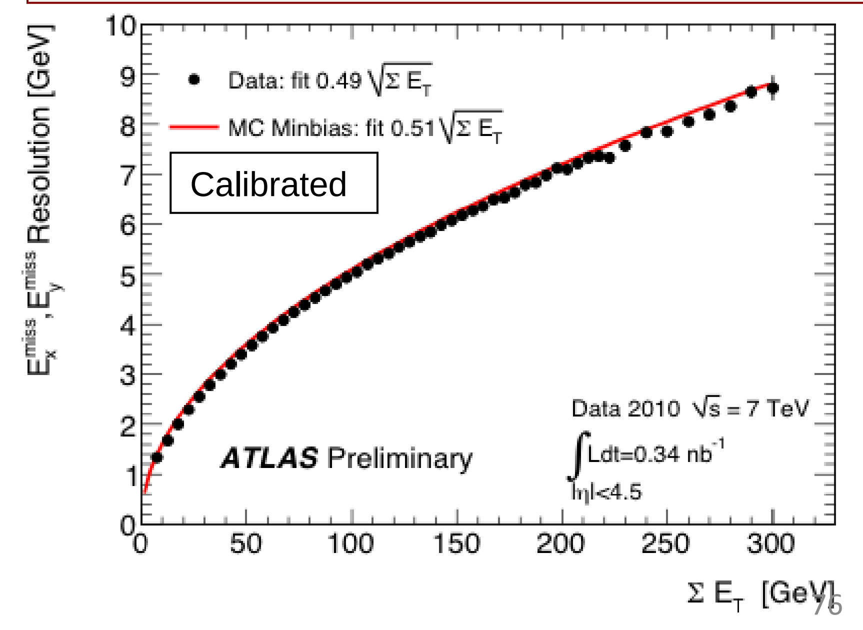
Missing transverse energy in the calorimeters

Calibrated E_T^{miss} from minimum-bias events (expect no real E_t^{miss})

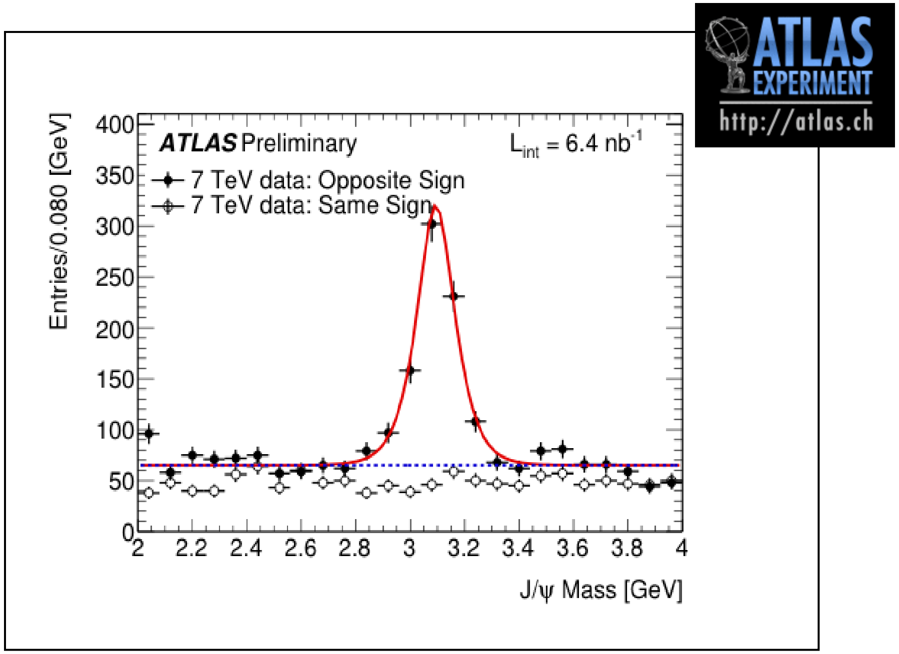
Sensitive to the calorimeter performance (noise, coherent noise, dead cells, mis-calibrations, cracks, etc.) as well as to cosmics and beam-related backgrounds

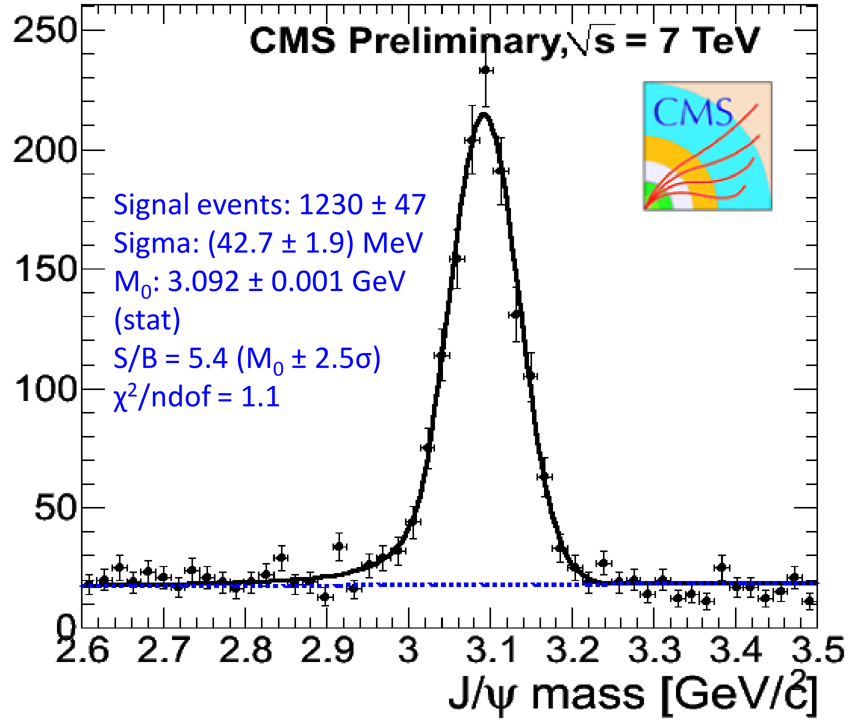


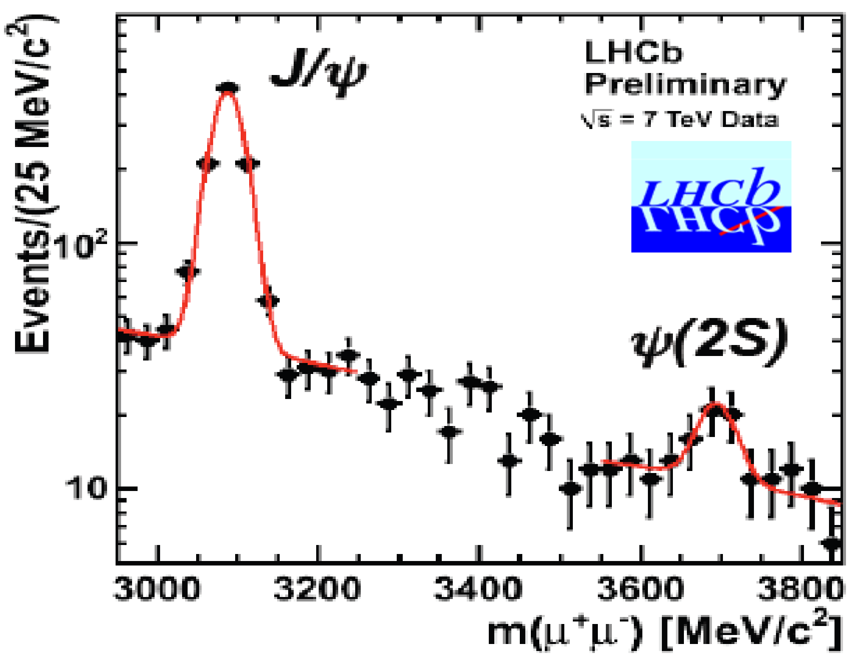
Measured over ~ full calorimeter coverage (360^0 in φ, |η| < 4.5, ~ 200k cells)

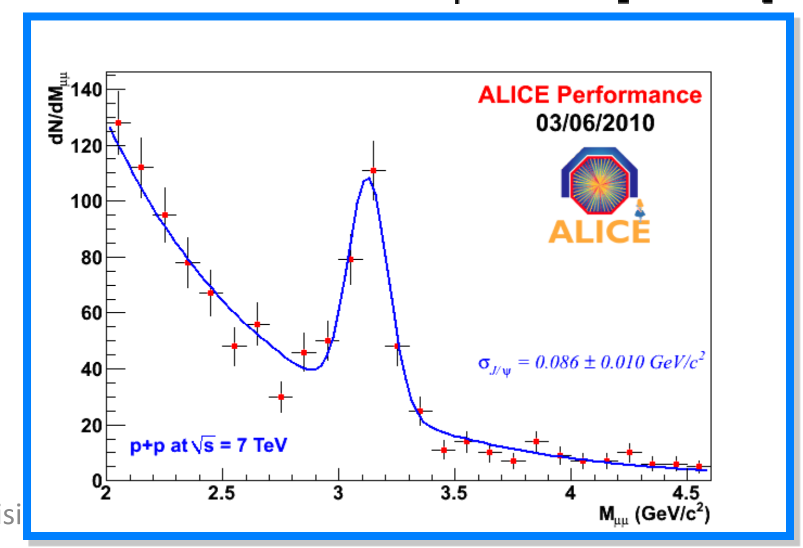


J/ψ Production



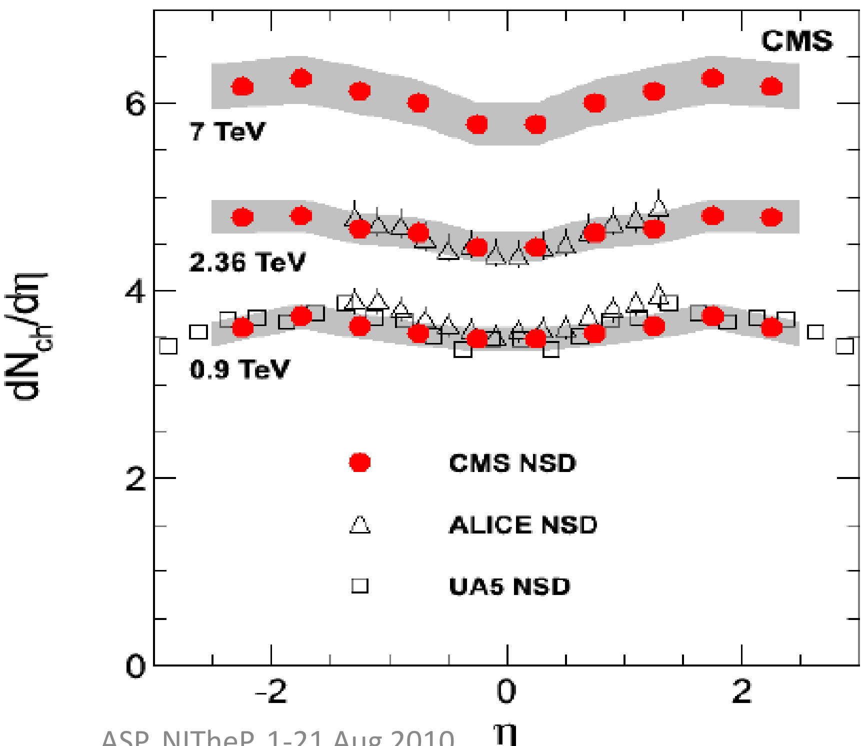


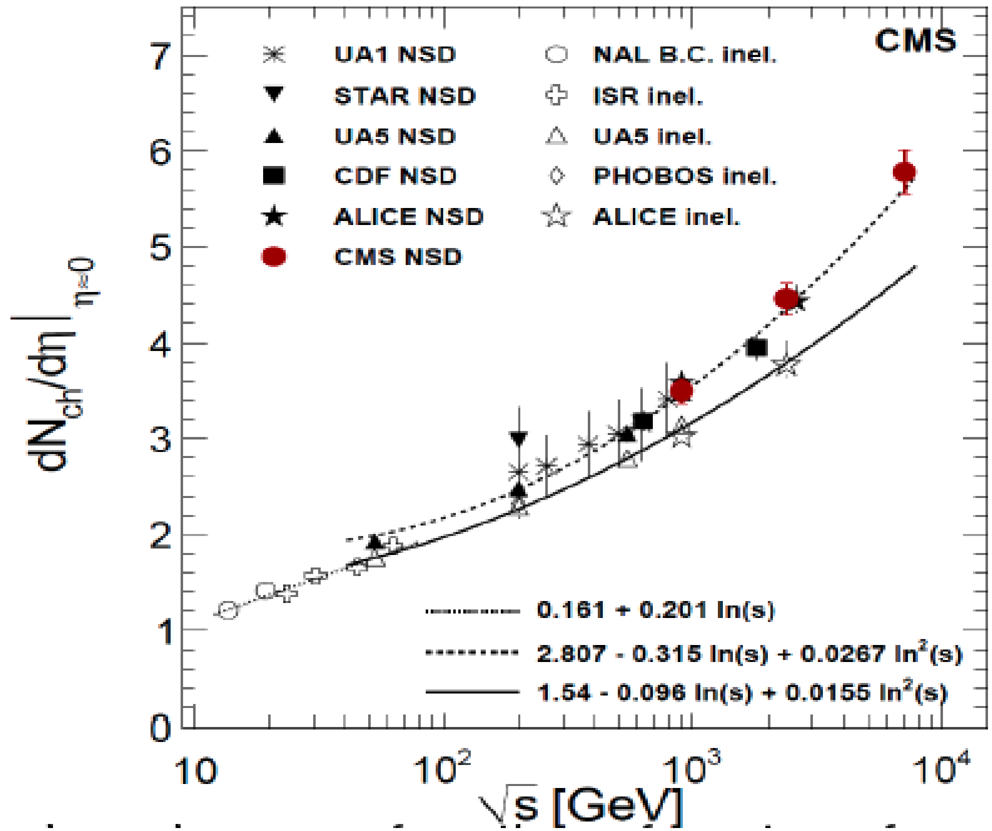




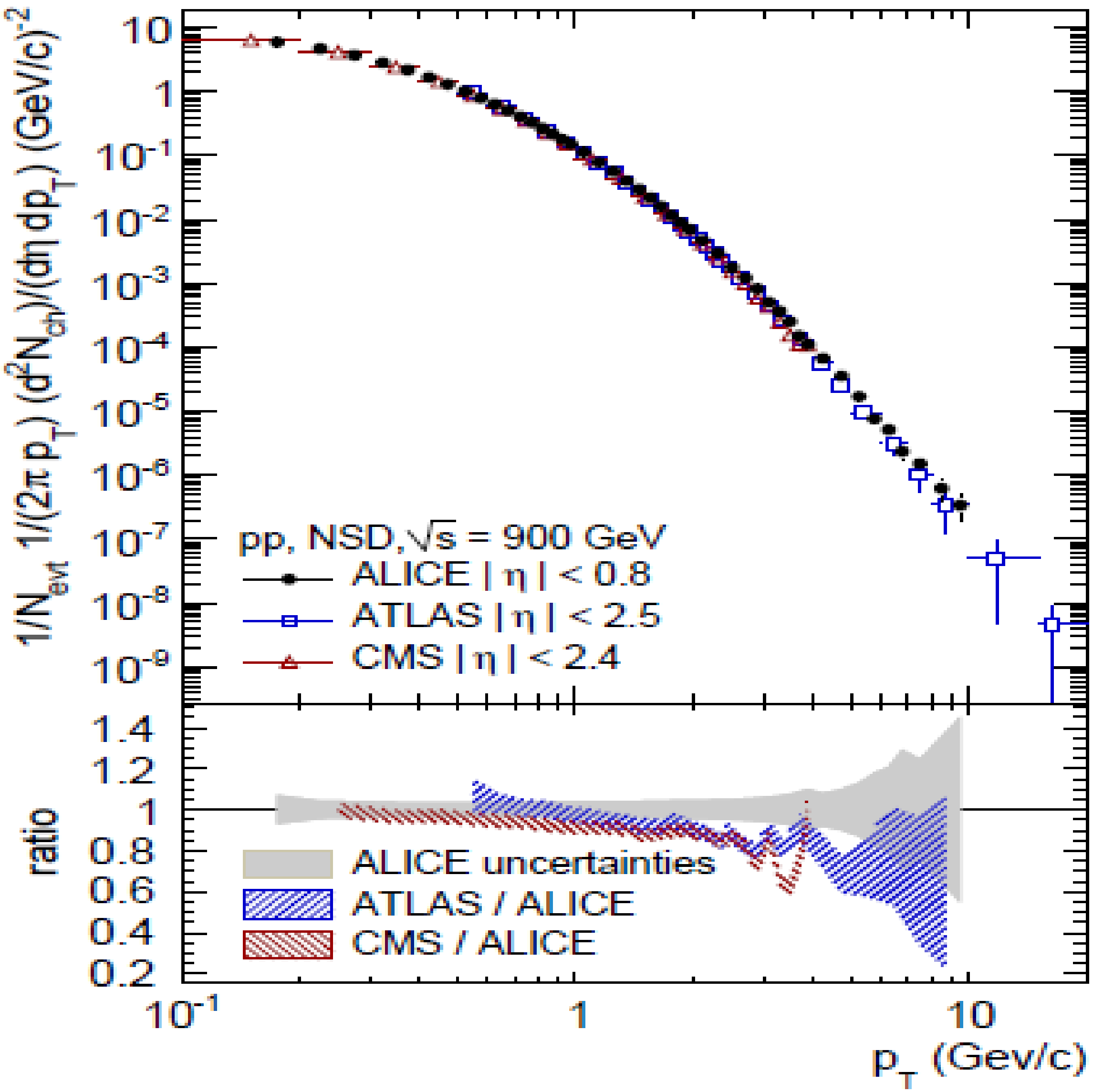
Understanding the Environment: Minimum Bias Events at LHC

Global minimum bias results from ALICE and CMS





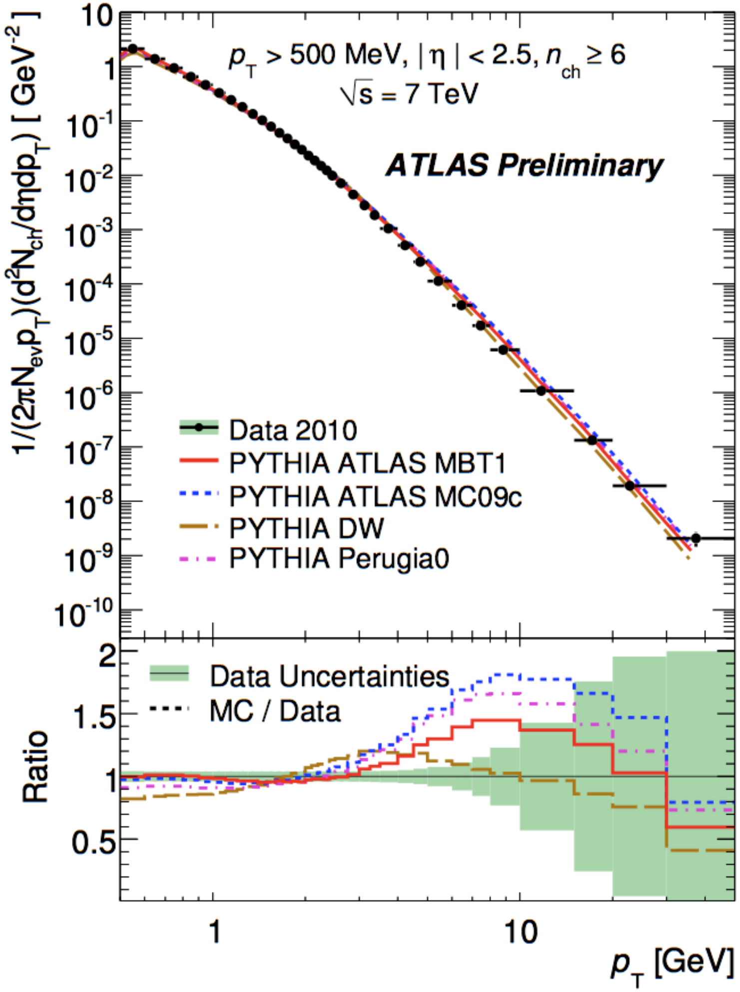
Charged particle transverse momentum distributions

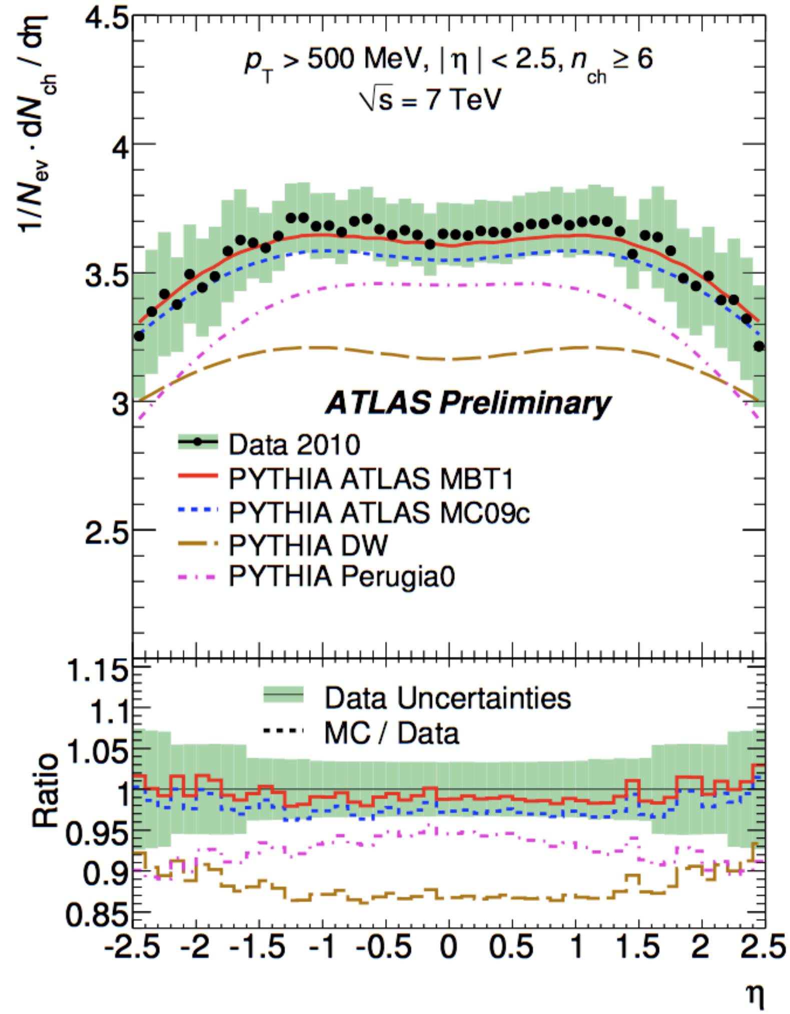


Data with minimal model dependence can be used for detailed MC tuning

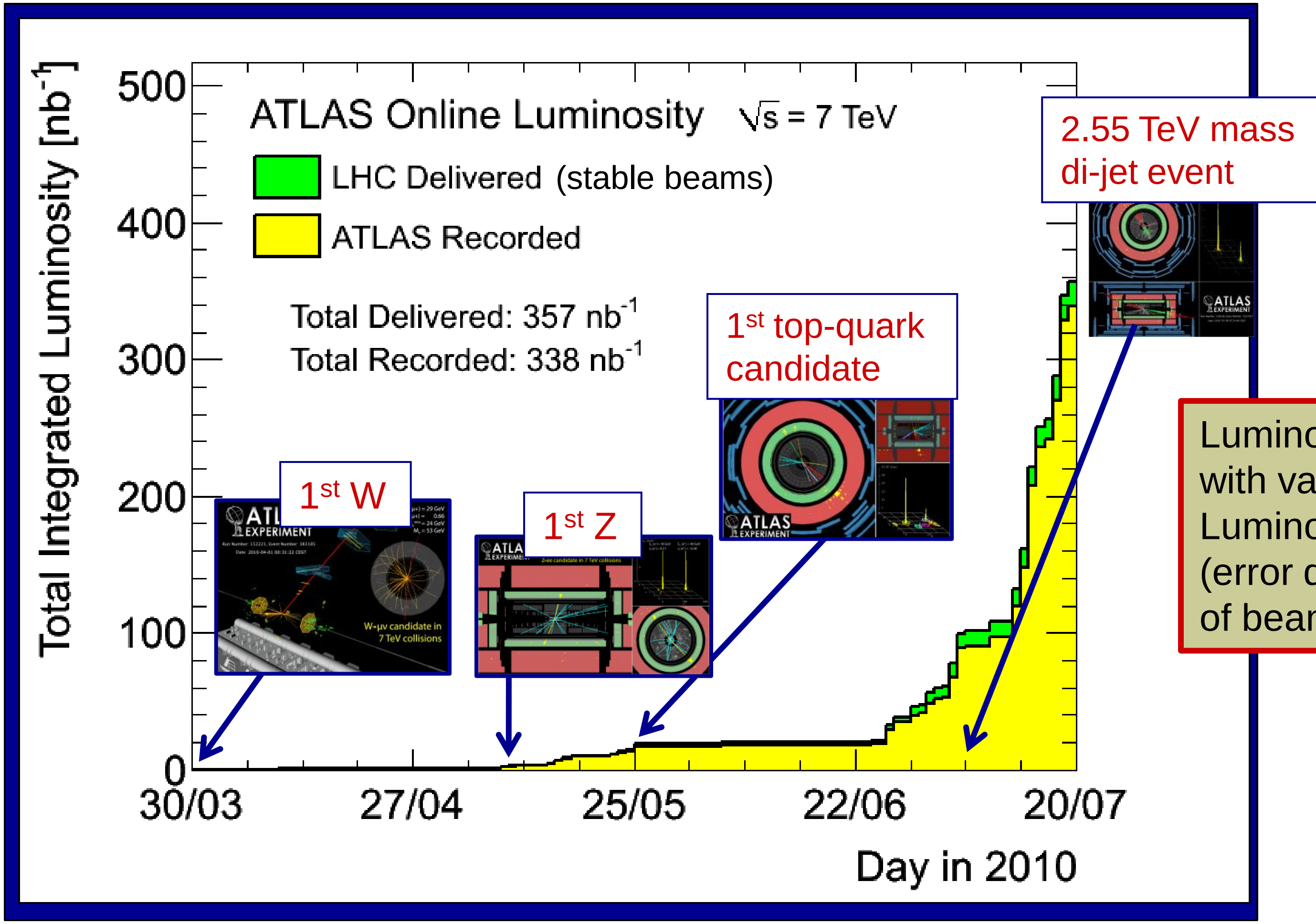
Used for the tune

- ATLAS UE data at 0.9 and 7 TeV
- ATLAS charged particle densitites at 0.9 and 7 TeV
- CDF Run I underlying event analysis (leading jet)
- CDF Run I underlying event "Min-Max" analysis
- D0 Run II dijet angular correlations
- CDF Run II Min bias
- CDF Run I Z pT





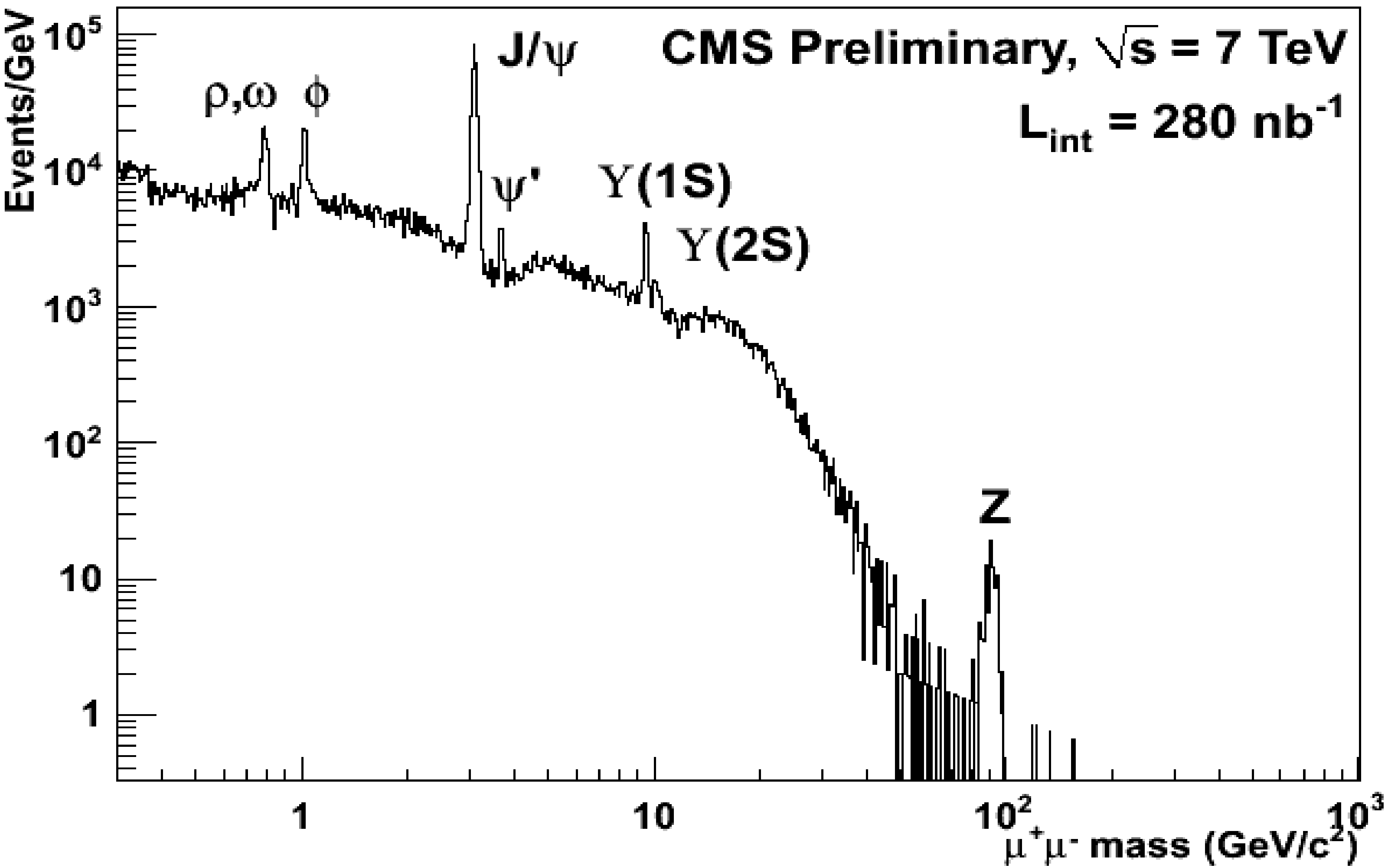
Integrated luminosity vs time
(from first √s =7 TeV collisions on 30 March to beginning of ICHEP on 22 July 2010)



Luminosity detectors calibrated with van der Meer scans. Luminosity known today to 11% (error dominated by knowledge of beam currents)

Most up-to-date LHC physics results were made public at the ICHEP Conference in Paris end of July 2010

More than 30 years of physics history resumed in one plot from LHC …



Collision energy

Tevatron ($p\bar{p}$)

1.96 TeV

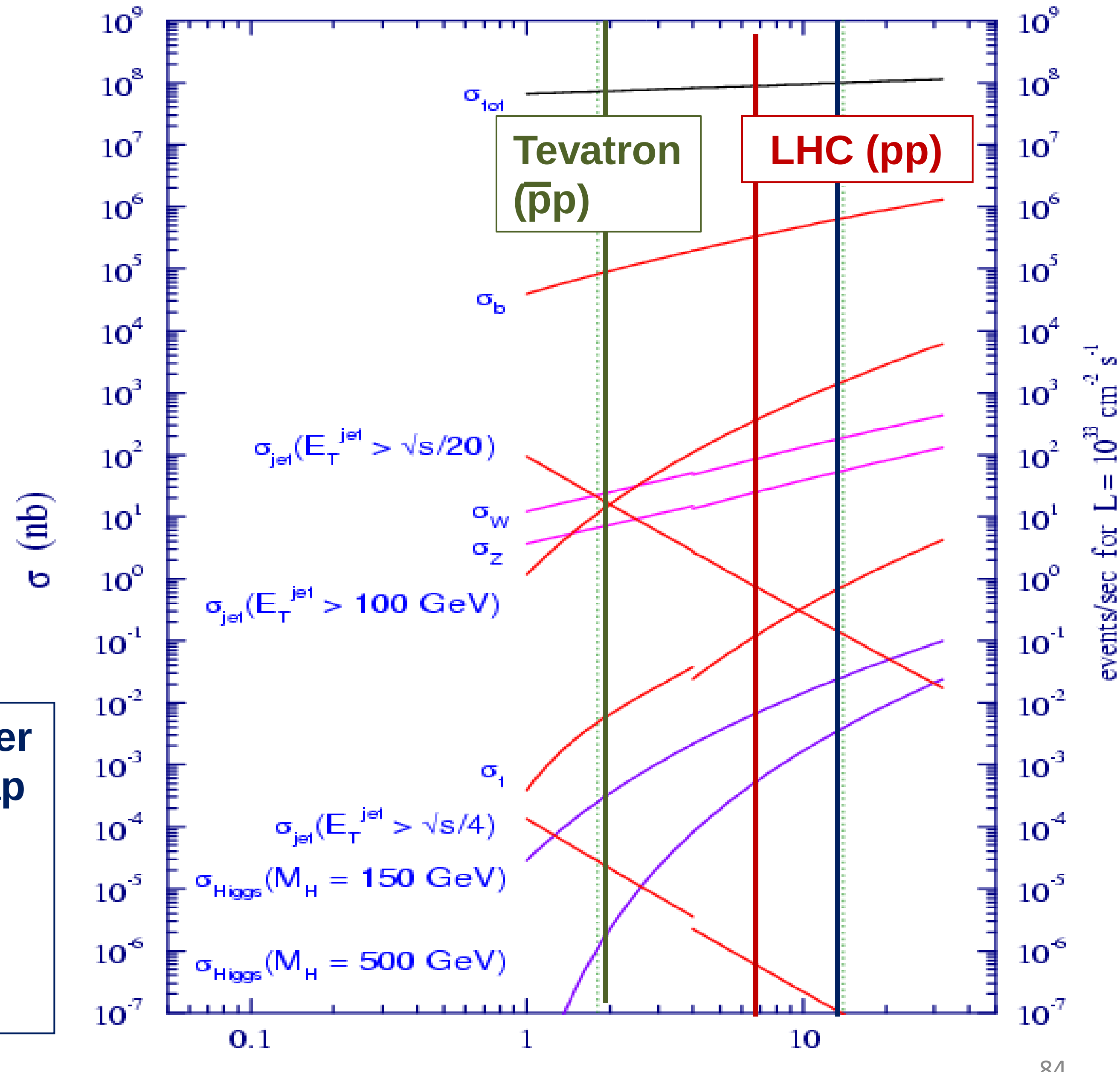
LHC (pp)

initially 7 TeV
later 14 TeV

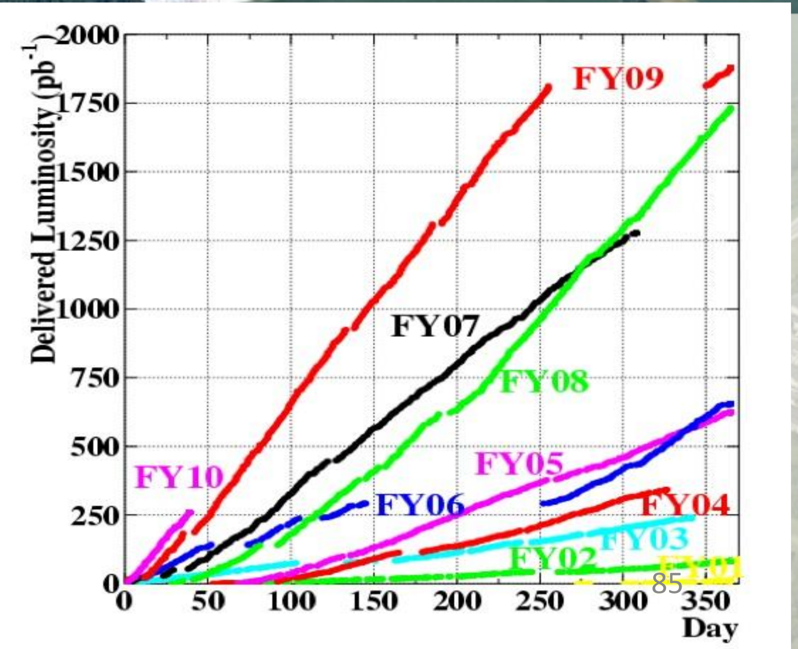
The other key parameter for setting the road map for discoveries is the integrated luminosity

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

Some bench-mark cross-sections



The Tevatron at Fermilab is performing in a superb way, and has still a major potential for great physics in the near future

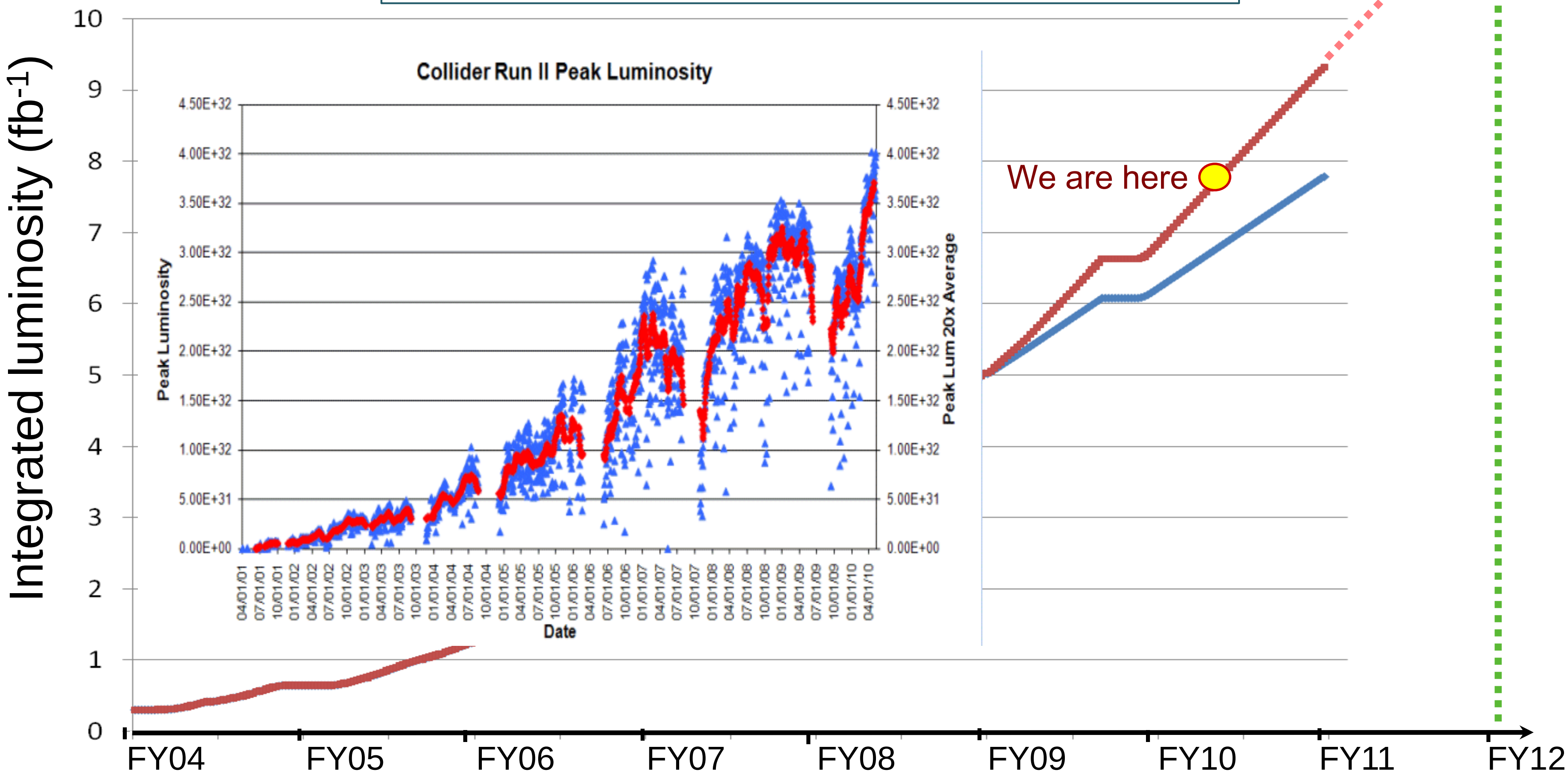


The Tevatron is a very mature machine with well understood detectors operated by collaborations with highly developed analysis skills

Projection for the Tevatron

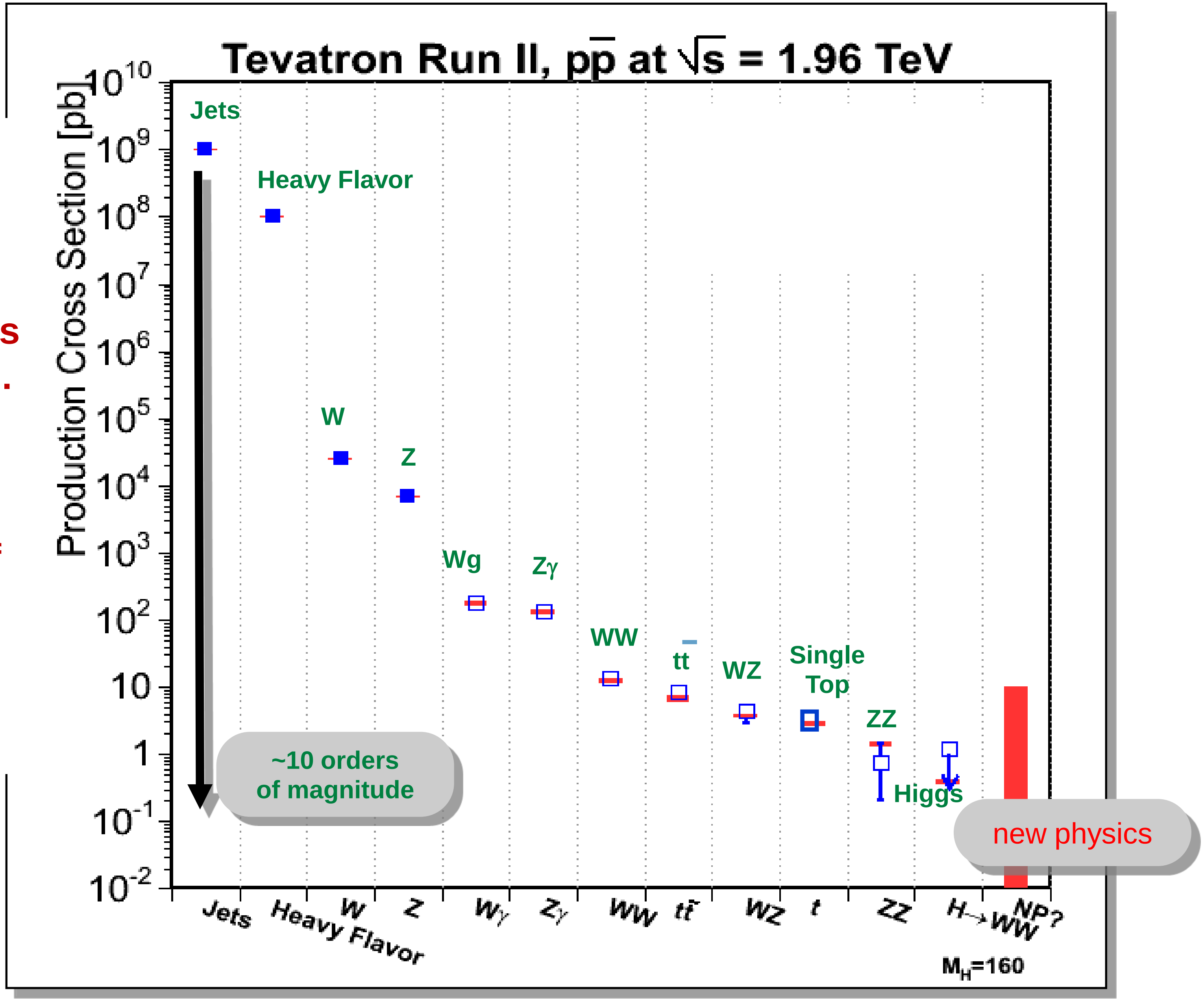
Expect about 2 fb^{-1} per year from now on → **~12 fb^{-1}**

→Reach at the end of 2011 some 10 – 12 fb^{-1} analyzable/delivered integrated luminosity



The Tevatron experiments have explored an impressive range of physics over the years…

…both in direct observations of processes as well as in precision measurements

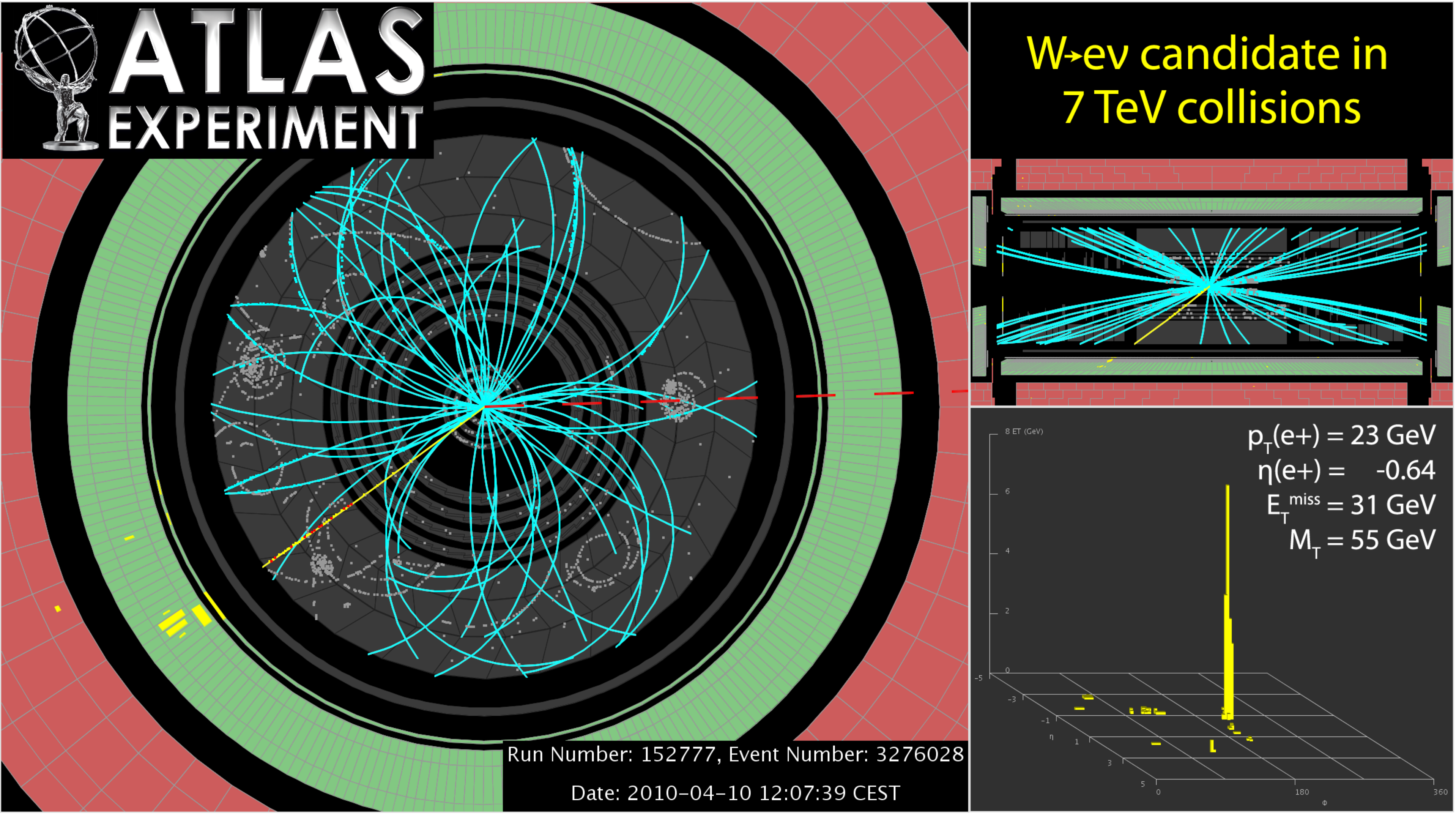


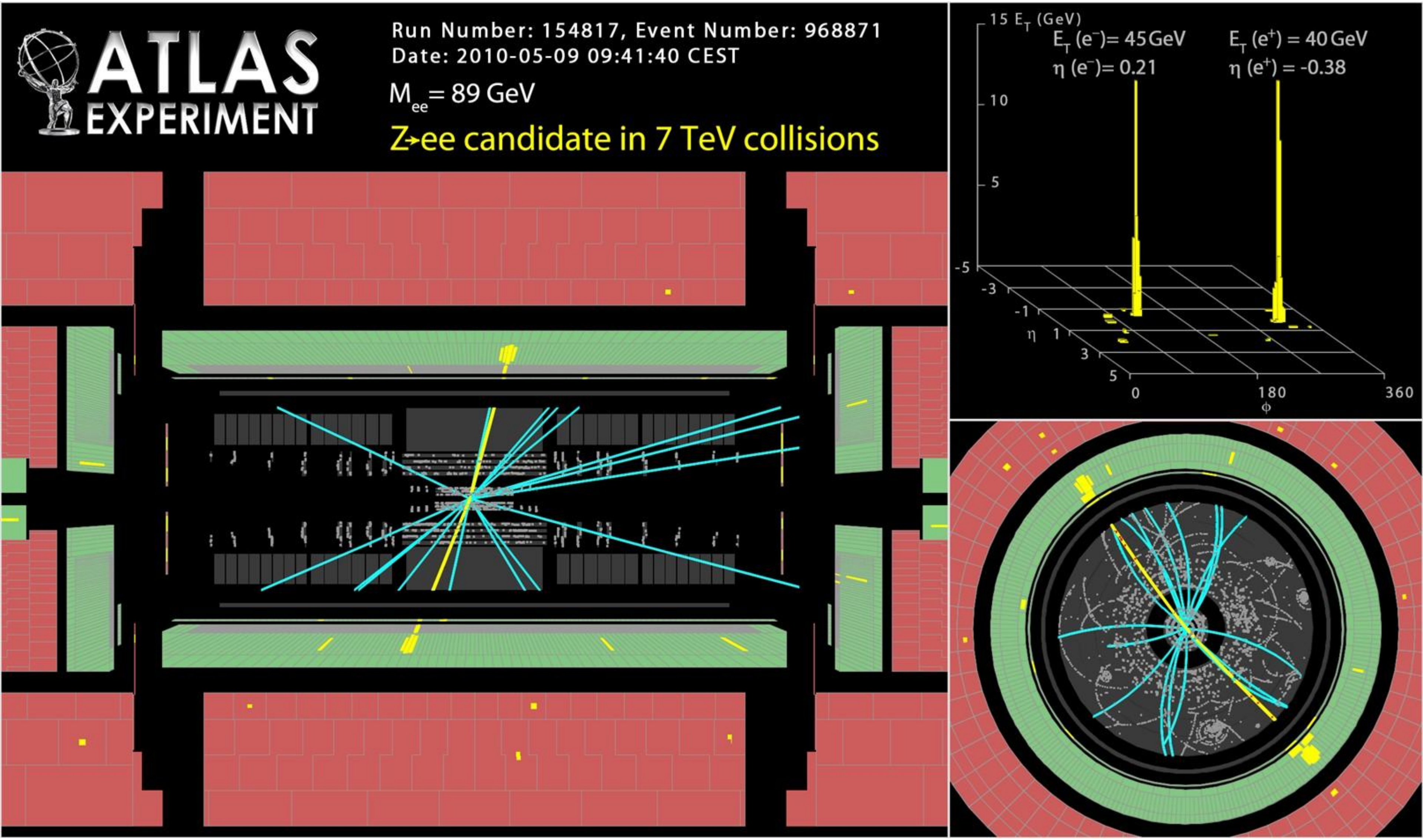
Road Map of Expected Hadron Collider Performances

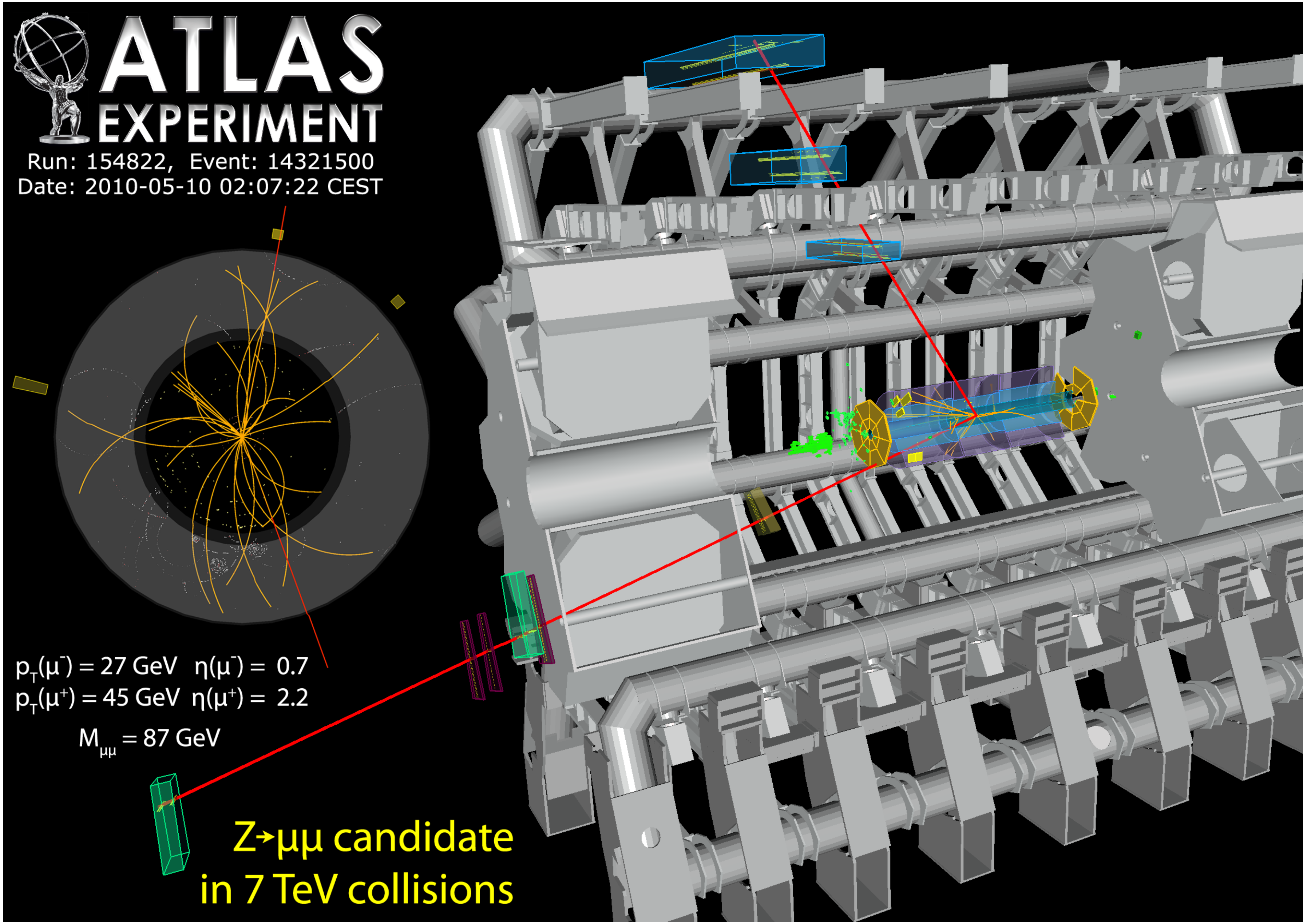
Now	Tevatron	2 TeV	7 fb^{-1} (analysed)
	LHC	7TeV	1 pb^{-1}
End 2011	Tevatron	2 TeV	10 fb^{-1}
	LHC	7 TeV	1 fb^{-1}
End 2014	LHC	14 TeV	30 fb^{-1}
End 2017	LHC	14 TeV	100 fb^{-1}
Early 2020ies	LHC	14 TeV	500 fb^{-1}
2030	(s)LHC	14 TeV	3000 fb^{-1} (ultimately…)

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

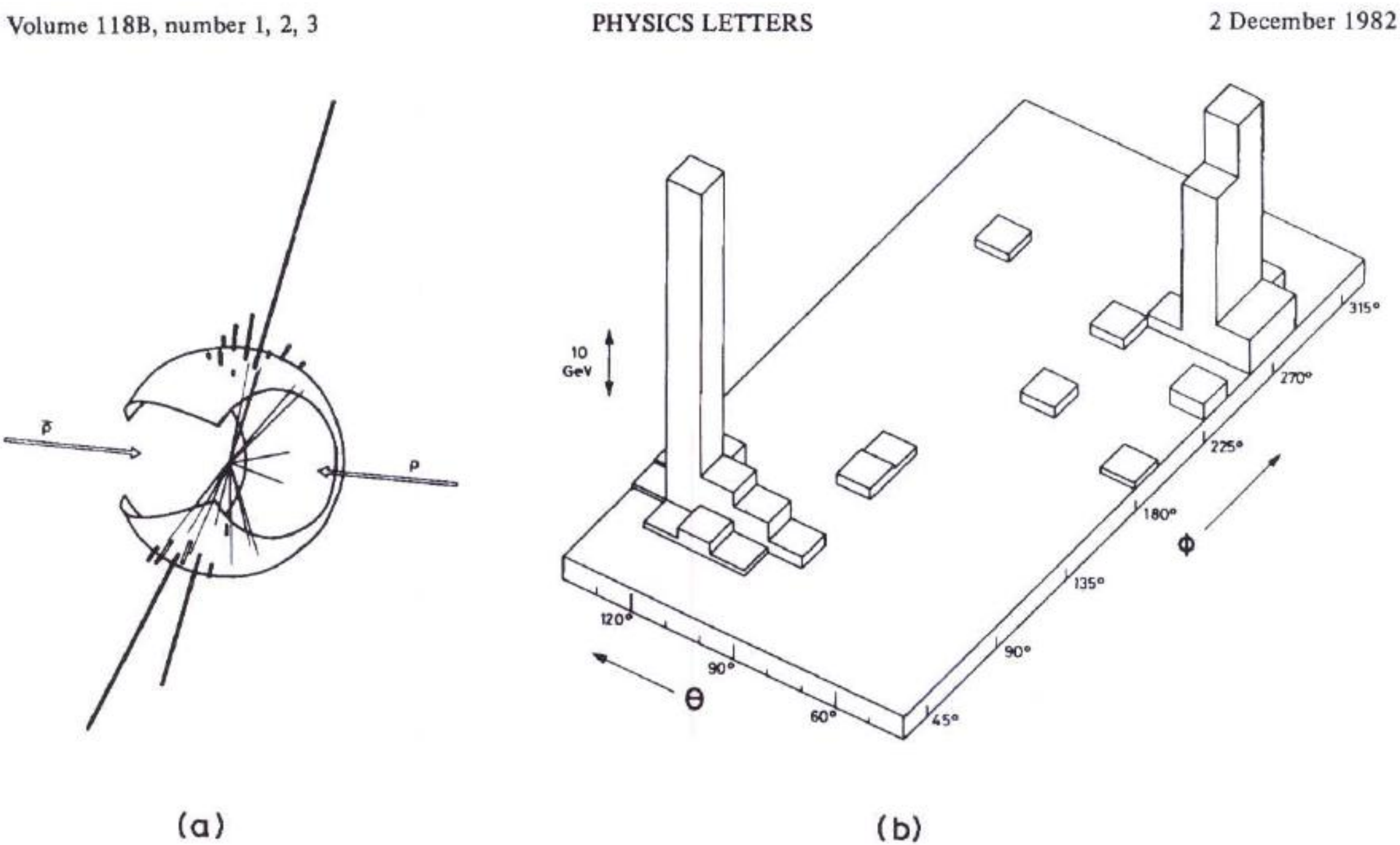
(1 fb^{-1} = 1000 pb^{-1})


ATLAS EXPERIMENT
W→eν candidate in 7 TeV collisions
Run Number: 152777, Event Number: 3276028
Date: 2010-04-10 12:07:39 CEST
$p_T(e+) = 23$ GeV
$\eta(e+) = -0.64$
$E_T^{miss} = 31$ GeV
$M_T = 55$ GeV
ET (GeV)
η
Φ
0
180
360

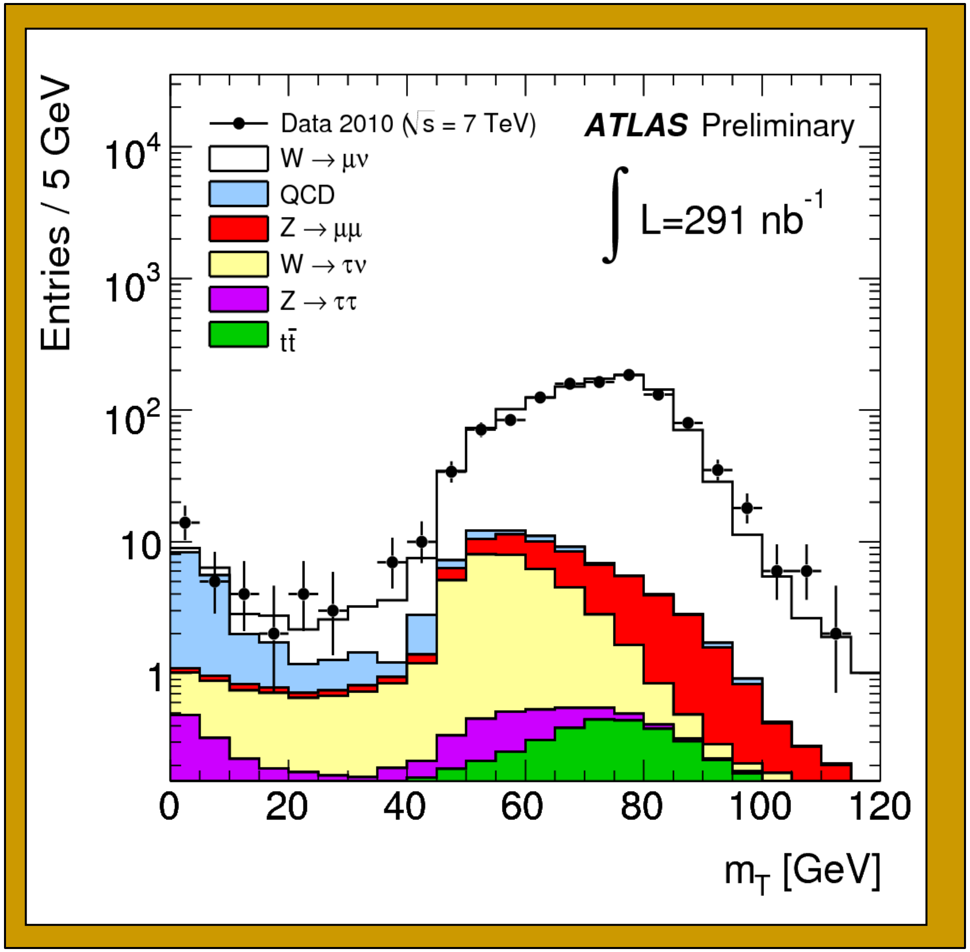

ATLAS EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M_{ee} = 89 GeV
Z→ee candidate in 7 TeV collisions
15 E_T (GeV)
E_T (e^-)= 45GeV
η (e^-)= 0.21
E_T (e^+) = 40GeV
η (e^+) = -0.38
10
5
-5
-3
-1
η
1
3
5
0
180
360
ϕ

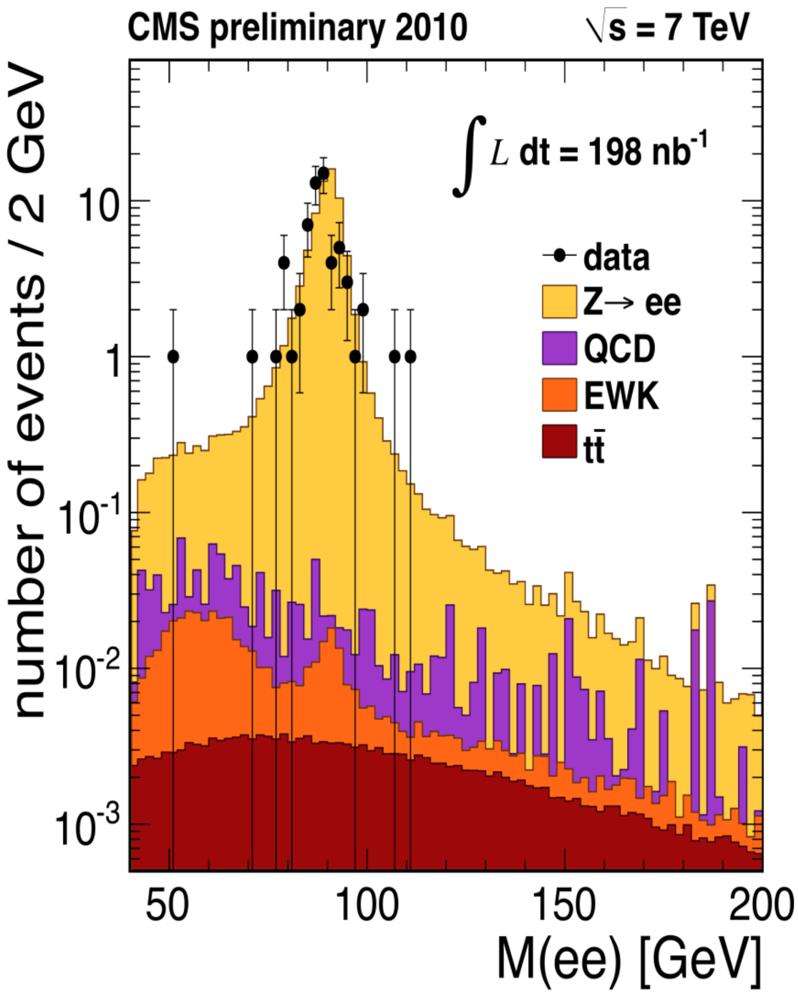

ATLAS EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions

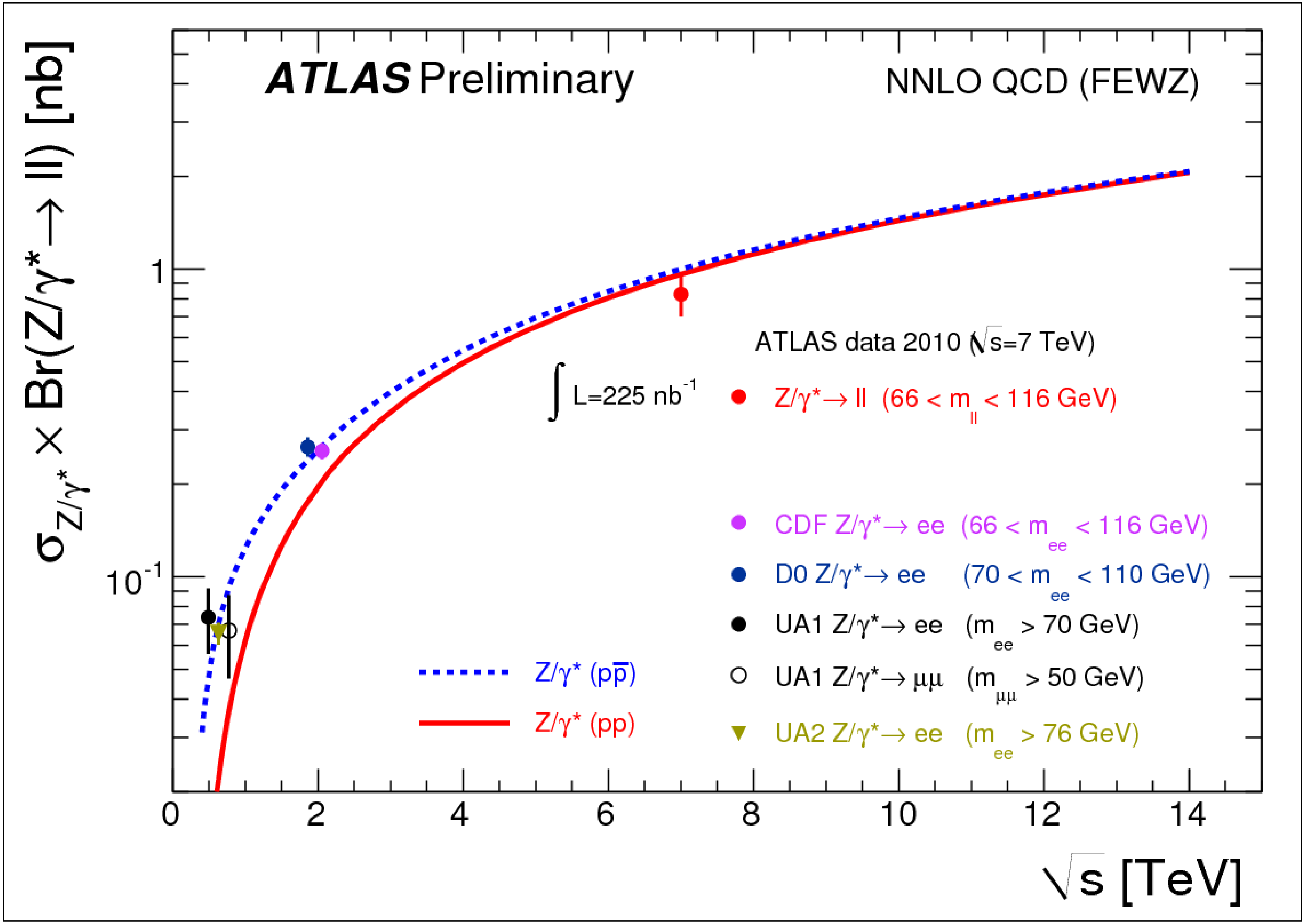
Note also that the event displays have become more sophisticated since the first spectacular events, hand-drawn, at a hadron collider …



Examples of the first W and Z distributions and measurements from ATLAS and CMS at the LHC



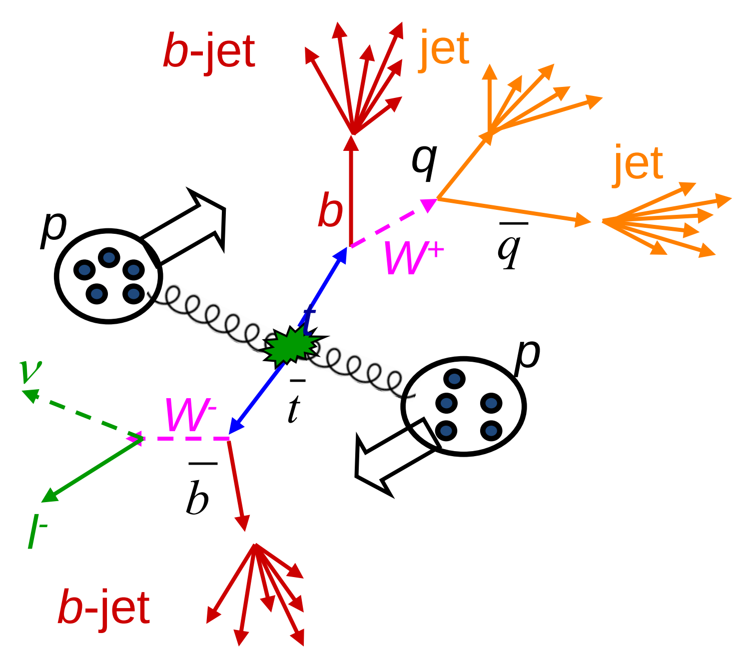



ATLAS Preliminary
NNLO QCD (FEWZ)
$\sigma_{Z/\gamma^*} \times Br(Z/\gamma^* \rightarrow ll)$ [nb]
1
10^{-1}
0
2
4
6
8
10
12
14
$\sqrt{s}$ [TeV]
ATLAS data 2010 ($\sqrt{s}$=7 TeV)
$\int L = 225\ nb^{-1}$
$Z/\gamma^* \rightarrow ll$ ($66 < m_{ll} < 116$ GeV)
CDF $Z/\gamma^* \rightarrow ee$ ($66 < m_{ee} < 116$ GeV)
D0 $Z/\gamma^* \rightarrow ee$ ($70 < m_{ee} < 110$ GeV)
UA1 $Z/\gamma^* \rightarrow ee$ ($m_{ee} > 70$ GeV)
UA1 $Z/\gamma^* \rightarrow \mu\mu$ ($m_{\mu\mu} > 50$ GeV)
UA2 $Z/\gamma^* \rightarrow ee$ ($m_{ee} > 76$ GeV)
Z/γ^* ($p\bar{p}$)
Z/γ^* (pp)

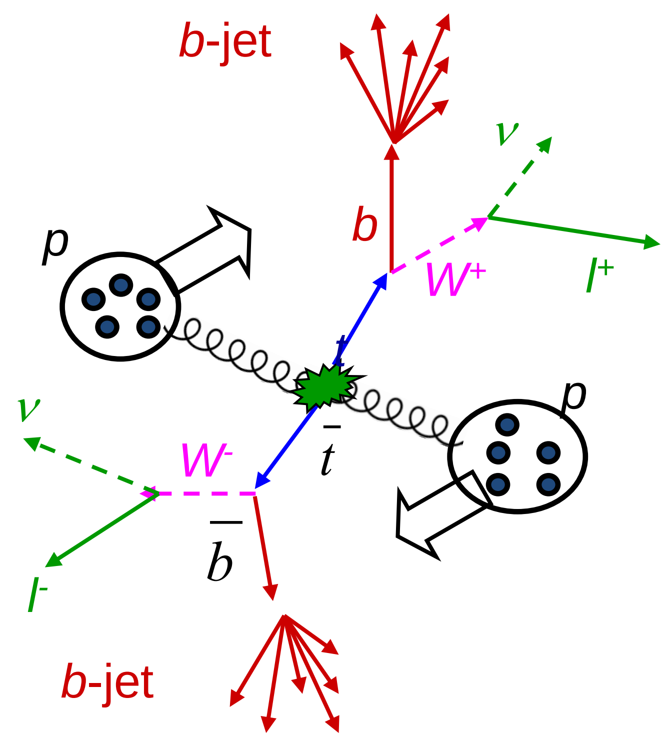
First Top Events from LHC

Up to ICHEP just a handful of candidates have been identified

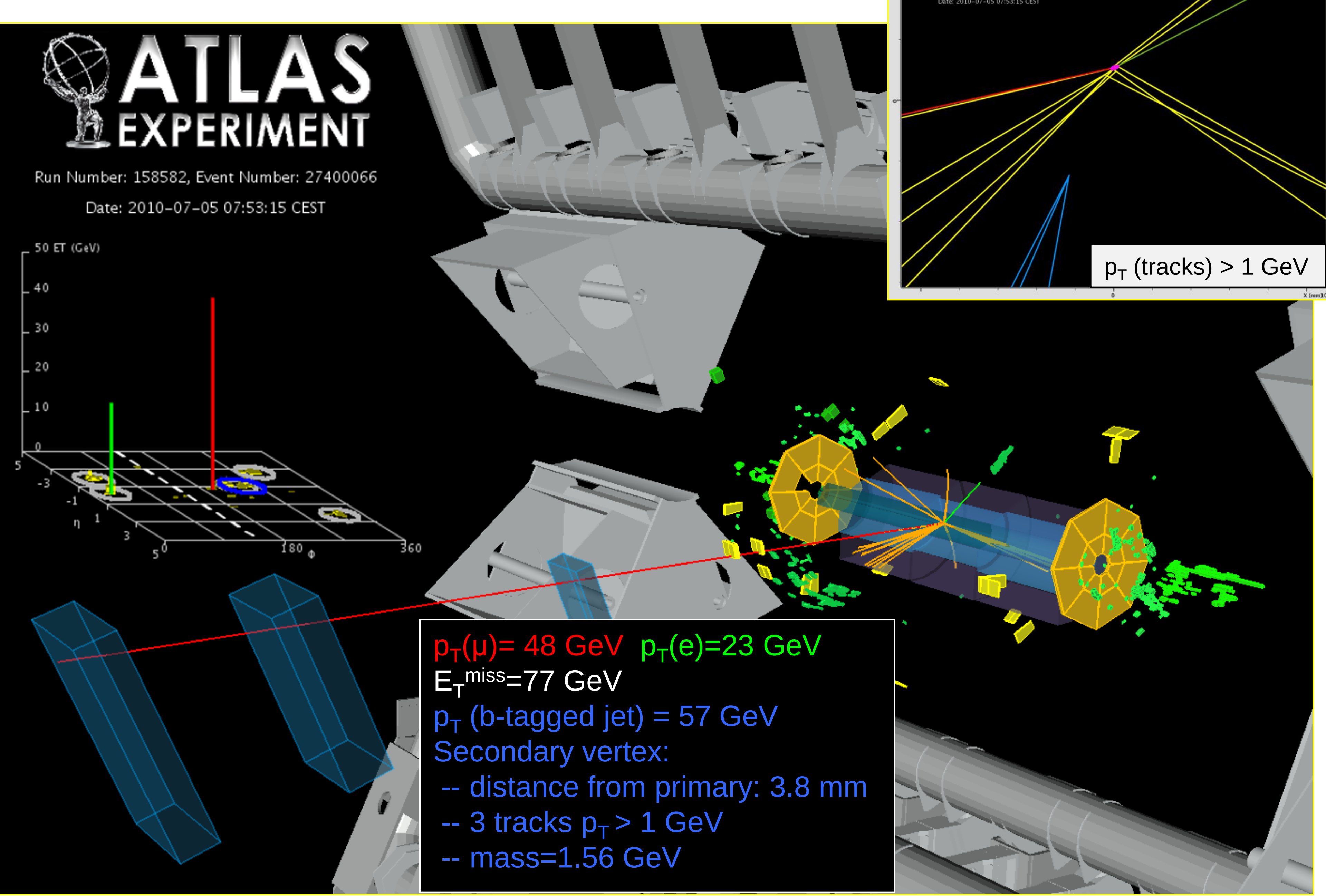
Standard channel with one lepton and jets in the final state, b-tagged



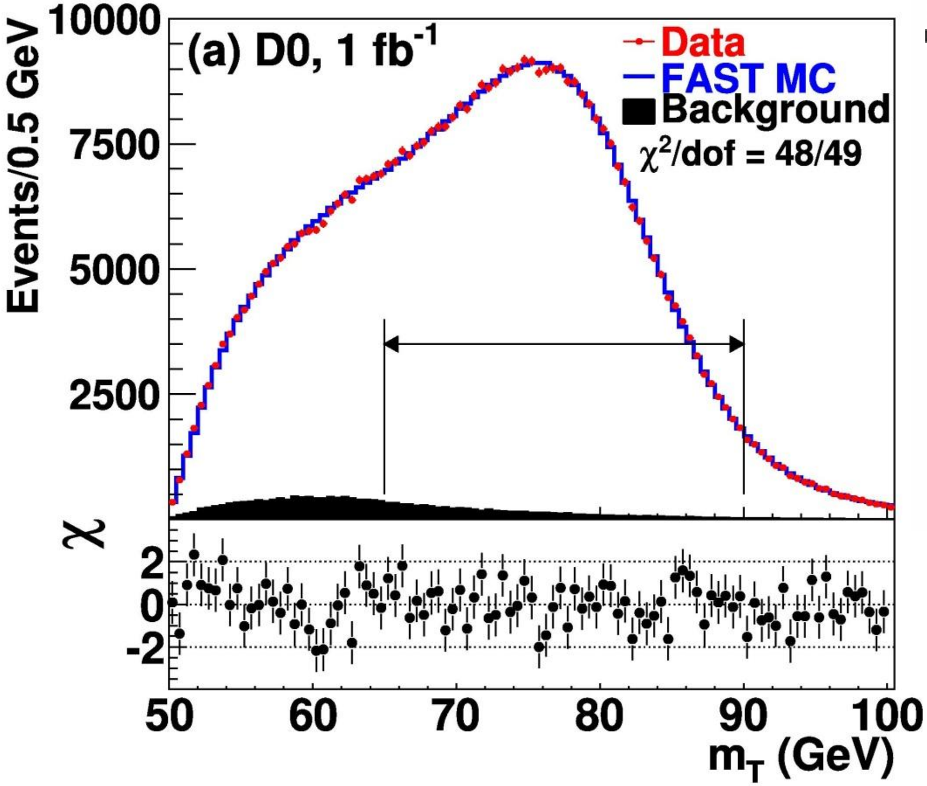
'Golden' channel with two leptons and jets in the final state, b-tagged



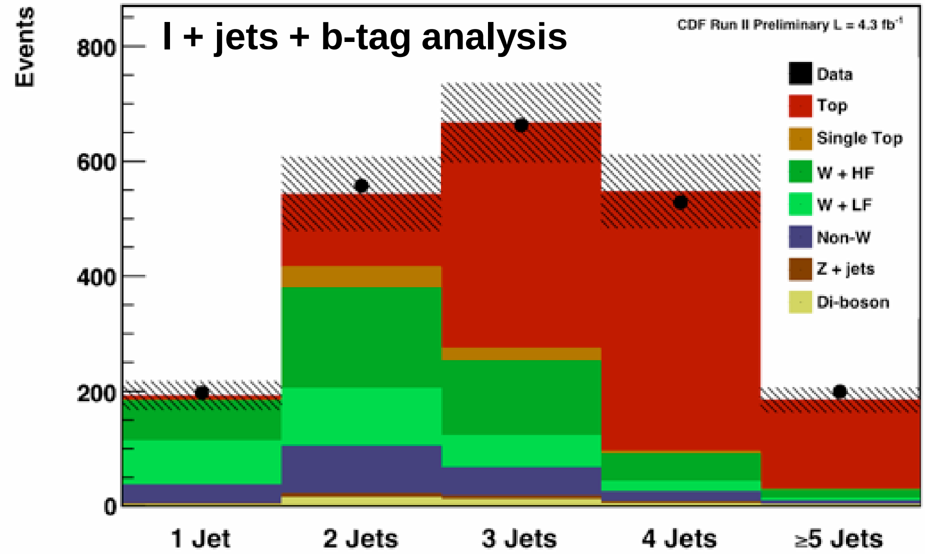
eμ + jets candidate

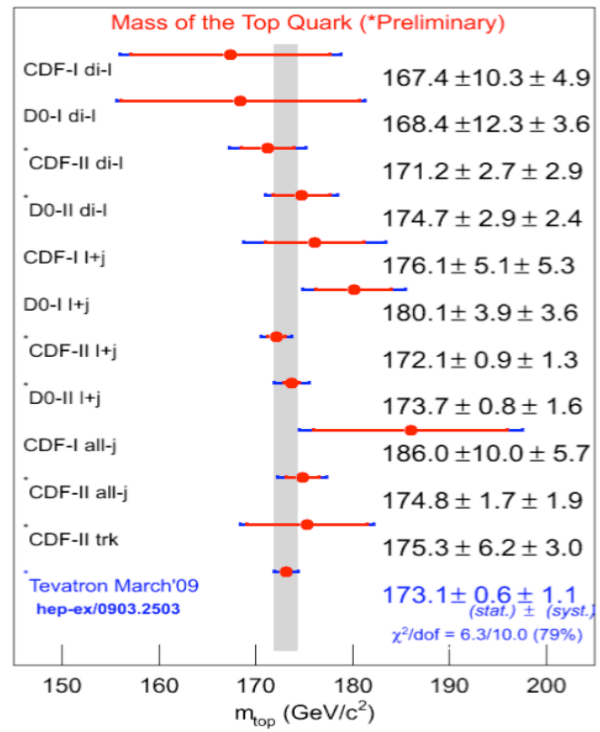


$p_T(\mu)$= 48 GeV $p_T(e)$=23 GeV
E_T^{miss}=77 GeV
p_T (b-tagged jet) = 57 GeV
Secondary vertex:
-- distance from primary: 3.8 mm
-- 3 tracks p_T > 1 GeV
-- mass=1.56 GeV



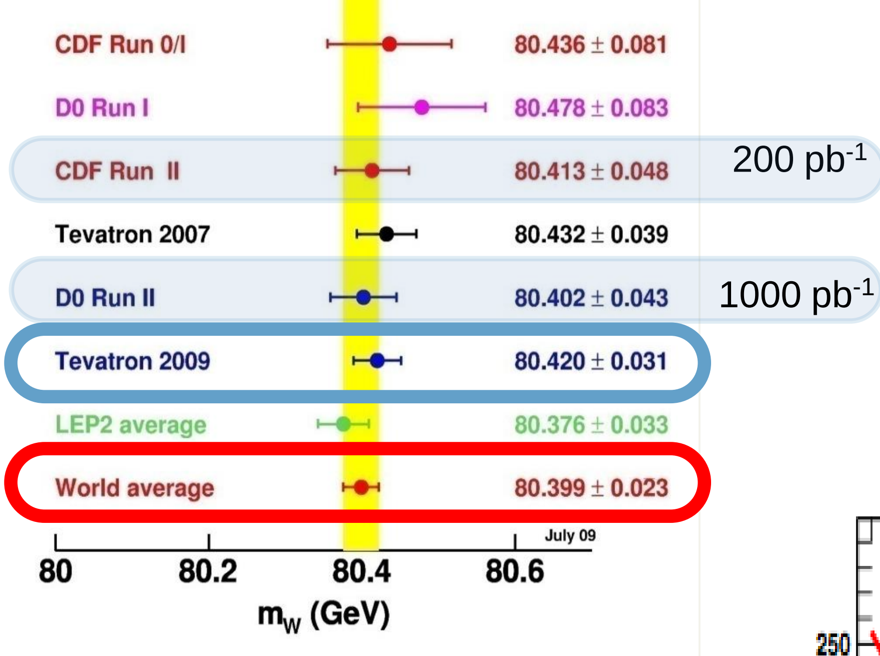
499830 W → eν candidates



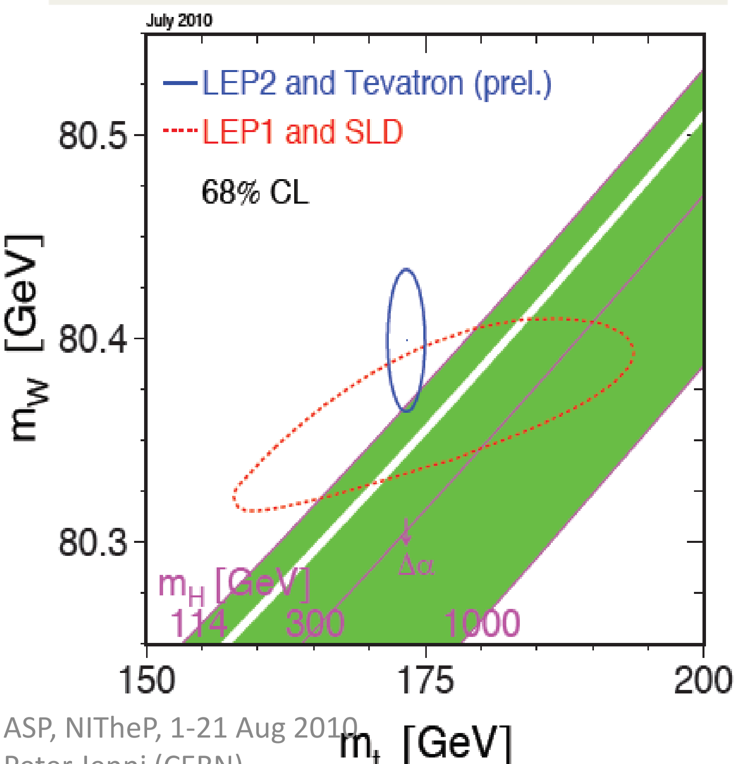


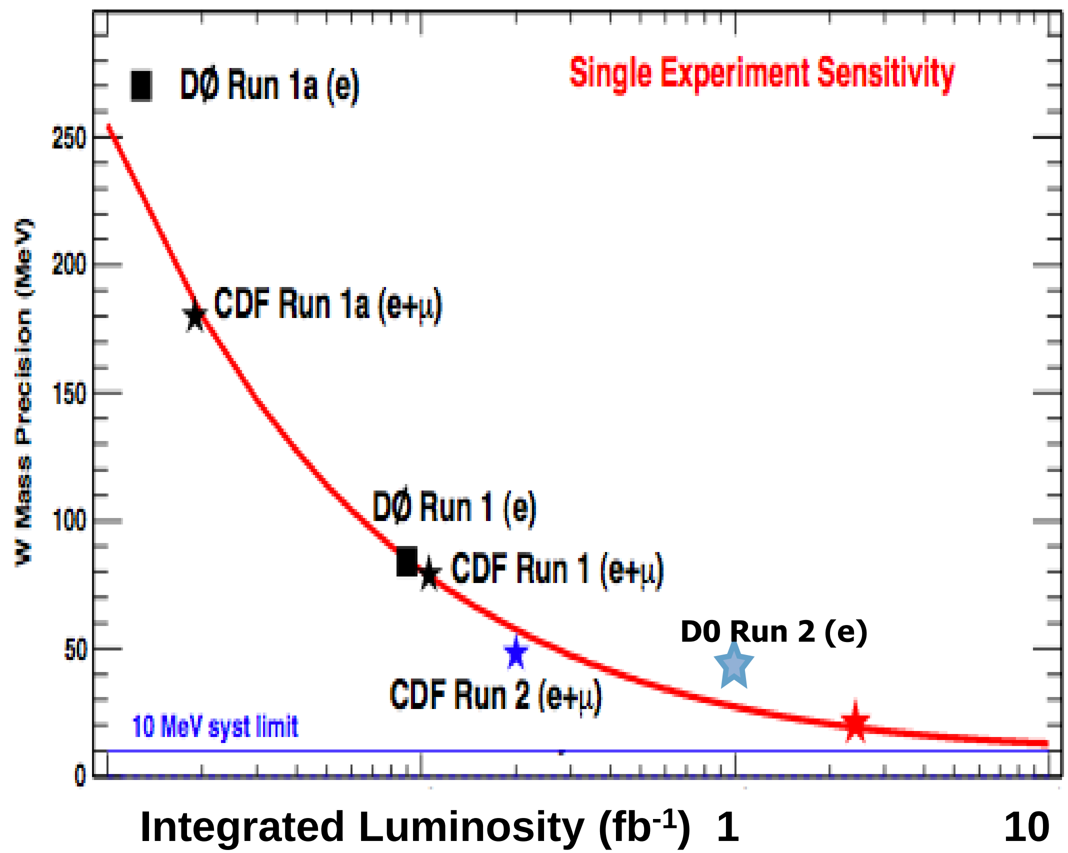
W, Z, and top analyses are in a very mature and advanced state at theTevatron, giving a wealth of detailed QCD and EW results

It will take some time to LHC to match this precision (~ 2013)

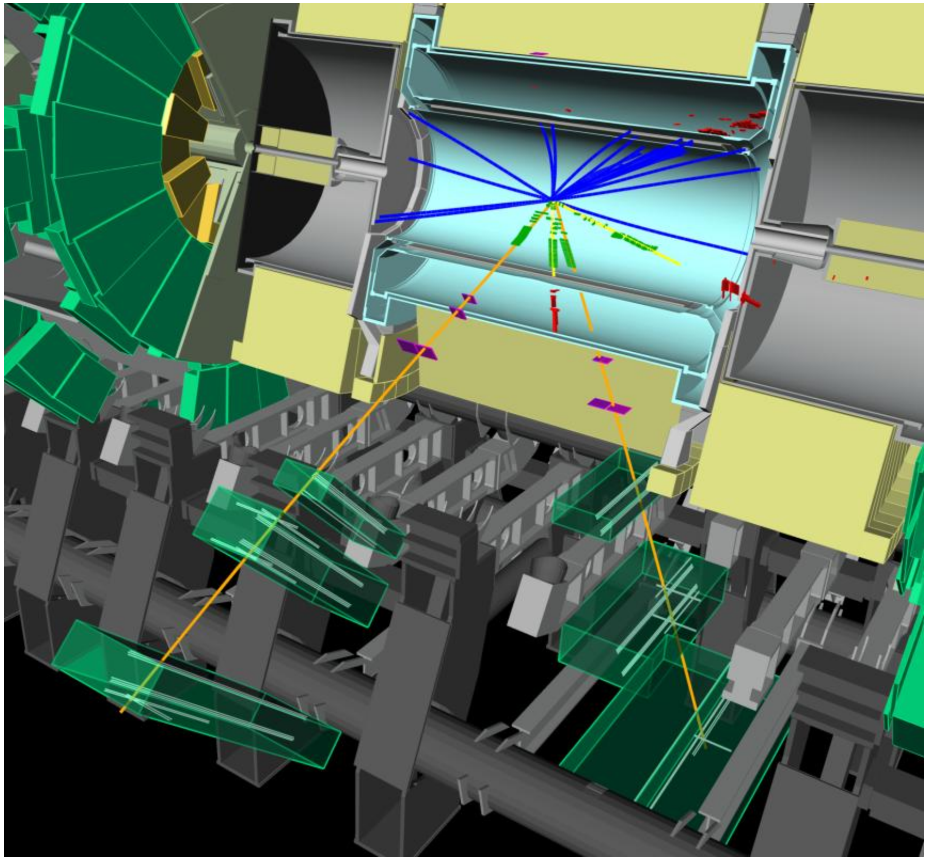


The W and Top mass measurements are testing the (consistency of the) Standard Model and the Higgs hypothesis

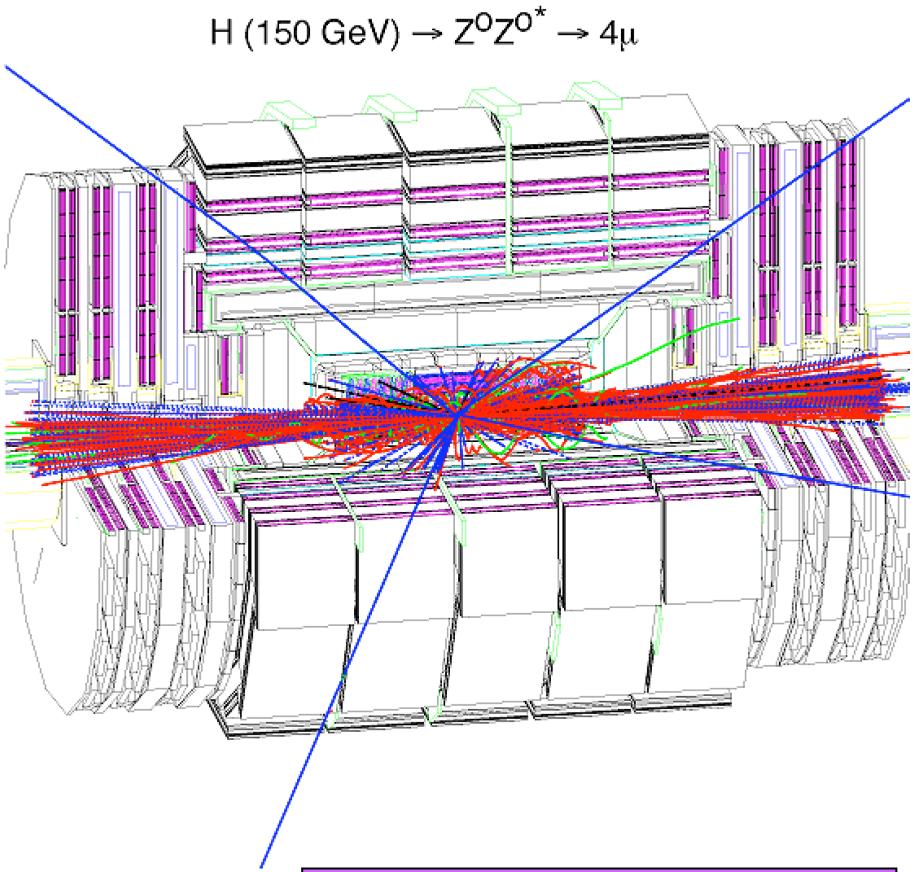




Higgs search

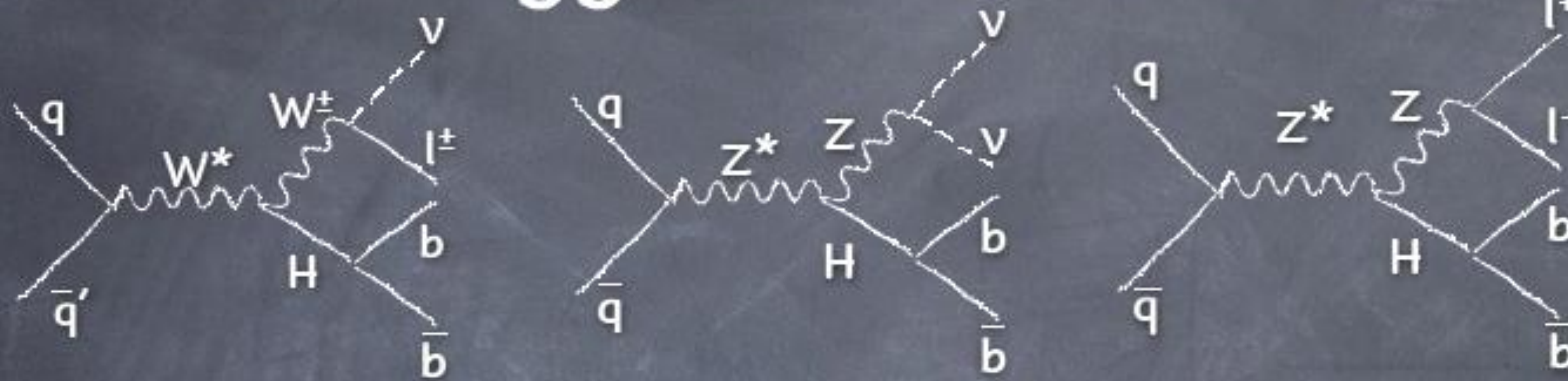


Simulation of a 130 GeV mass
H $\rightarrow$ $\mu\mu$ ee event in ATLAS

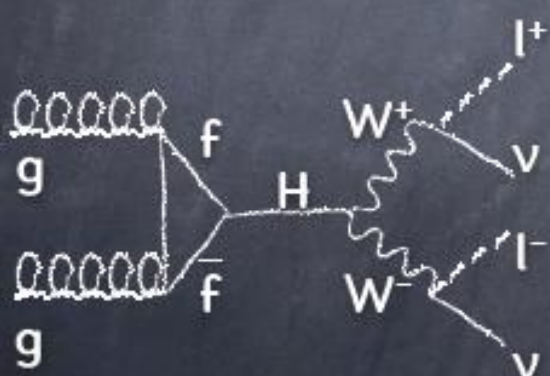


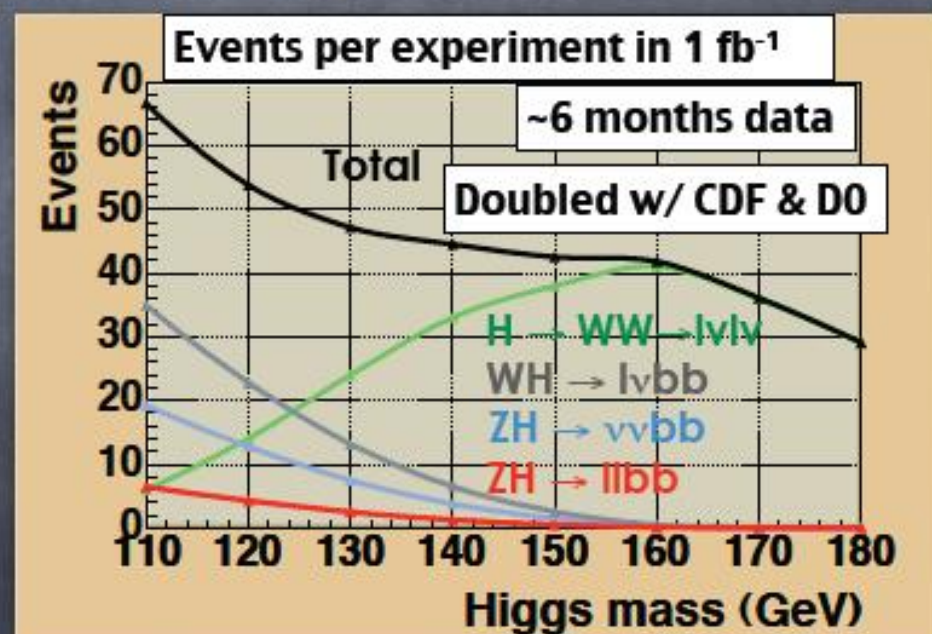
Simulation of a 150 GeV mass
H $\rightarrow$ $\mu\mu$ $\mu\mu$ event in CMS

SM Higgs at the Tevatron



Main decay modes

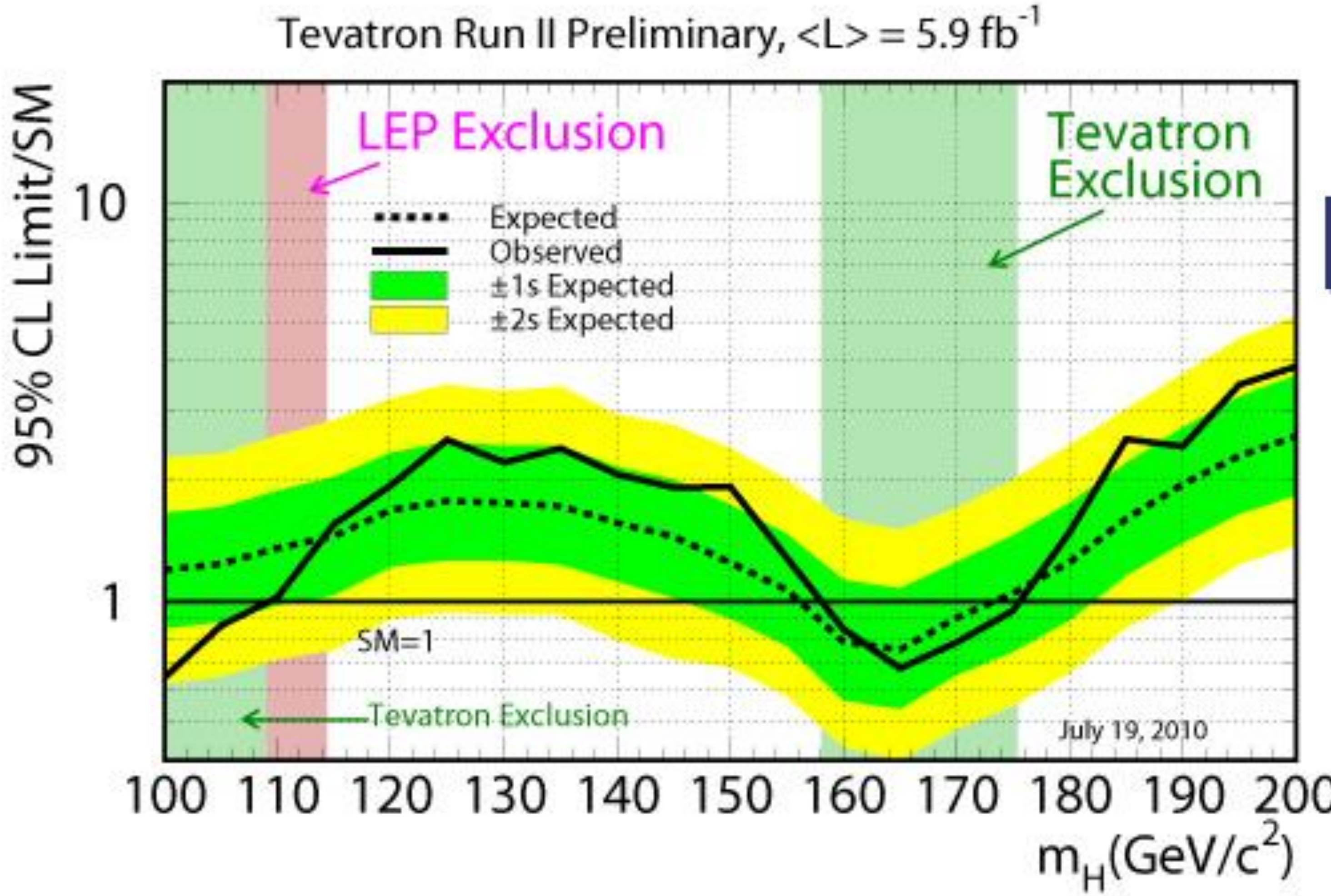




Ben Kilminster, ICHEP 2010

8

The new combined result published recently sets a new combined 95% CL exclusion for 158 – 175 GeV



Combining the two experiments at this advanced stage turns out to be very powerful for the Tevatron

Prospects for Higgs evidence

~16 fb^{-1} :*

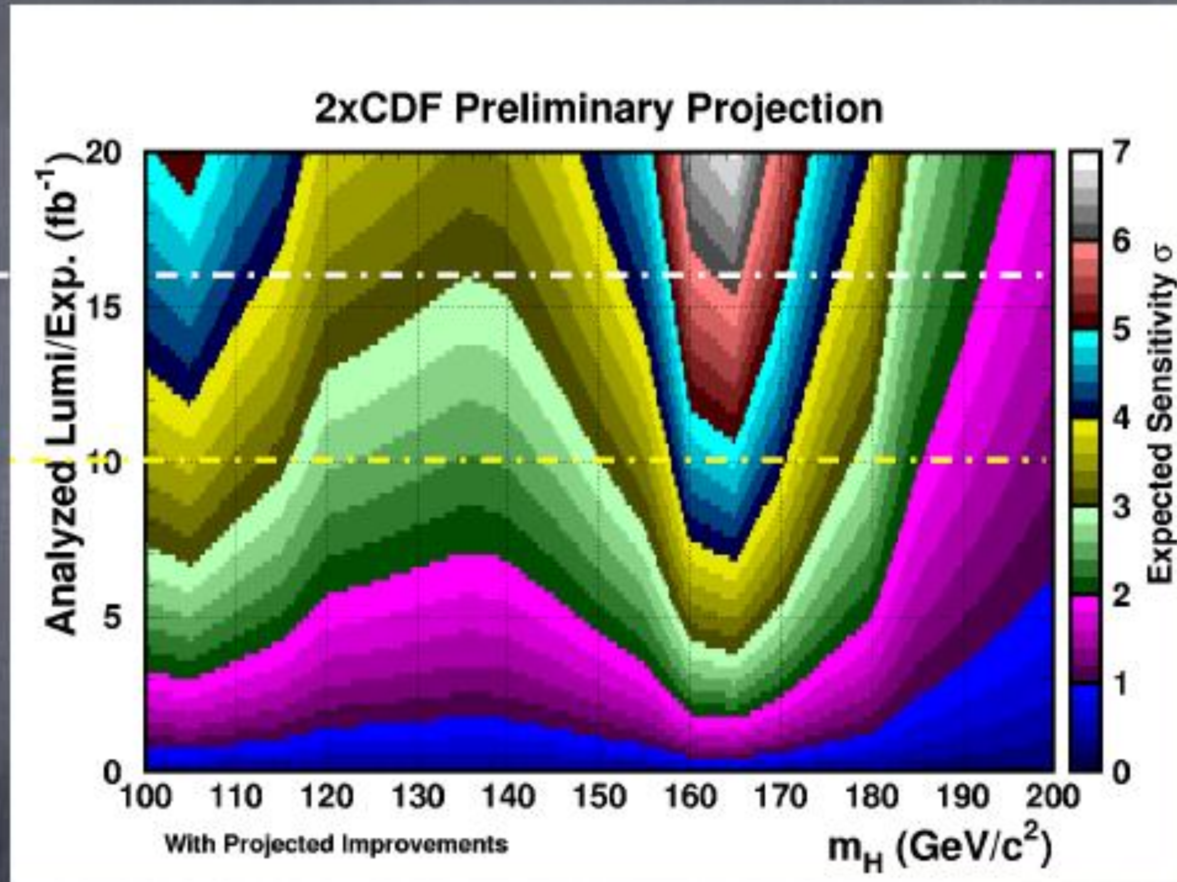
> 3 σ expected sensitivity from 100 – 185 GeV

4 σ @ 115 GeV

End of 2011:

> 2.4 σ expected sensitivity across mass range

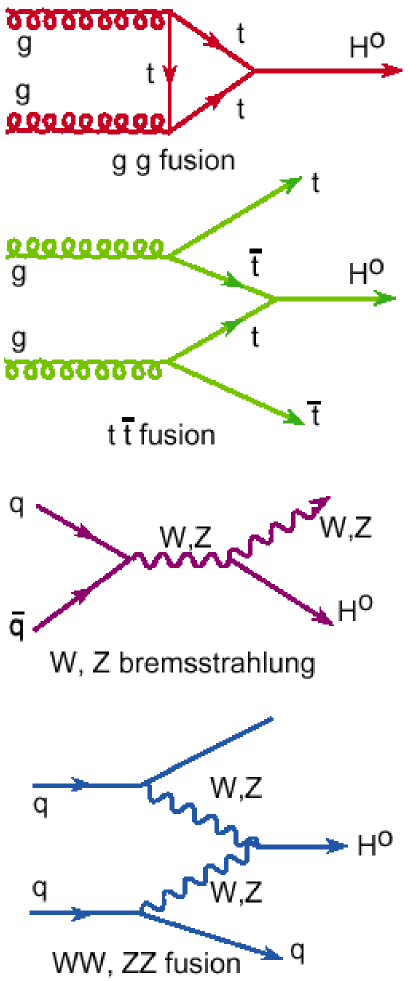
3 σ at 115 GeV



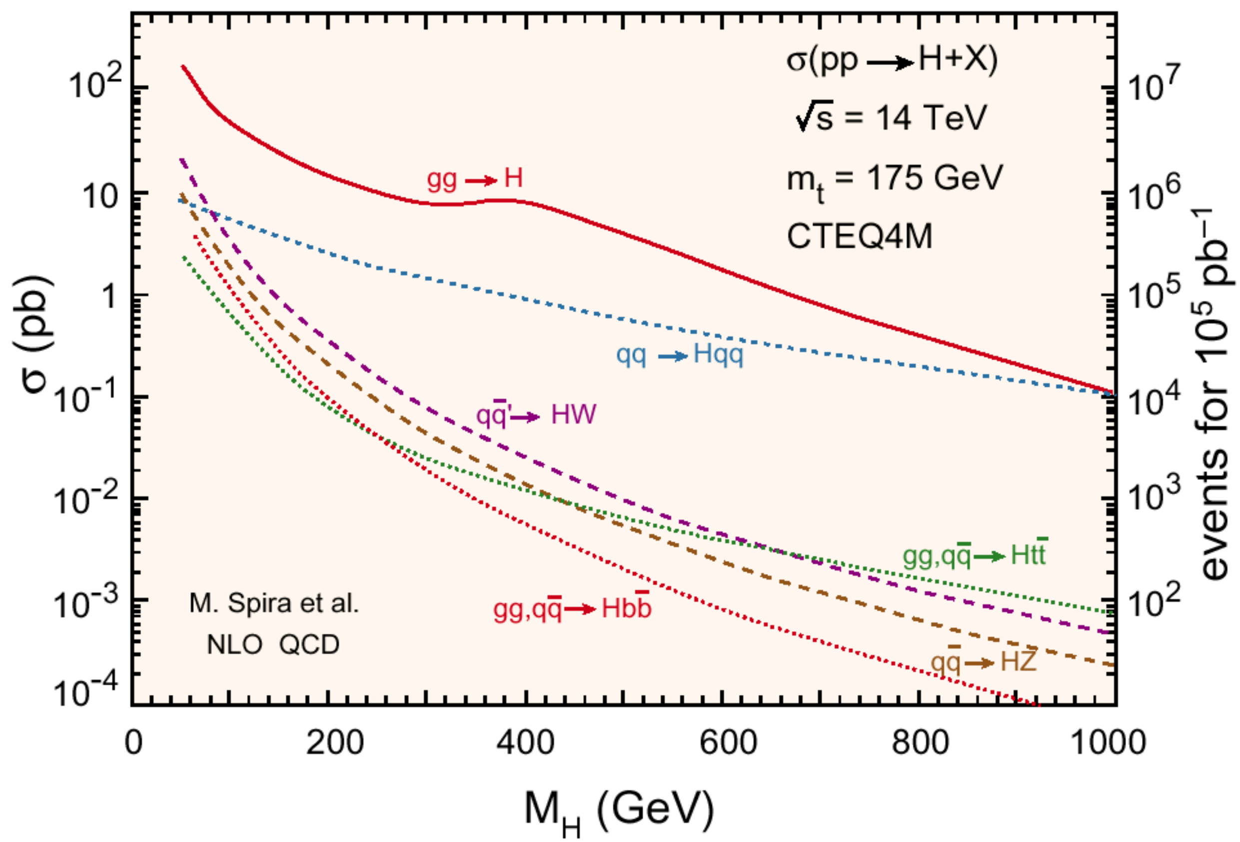
* 16 fb^{-1} : based on "Run III" proposal to run 3 more years

Ben Kilminster, ICHEP 2010 37

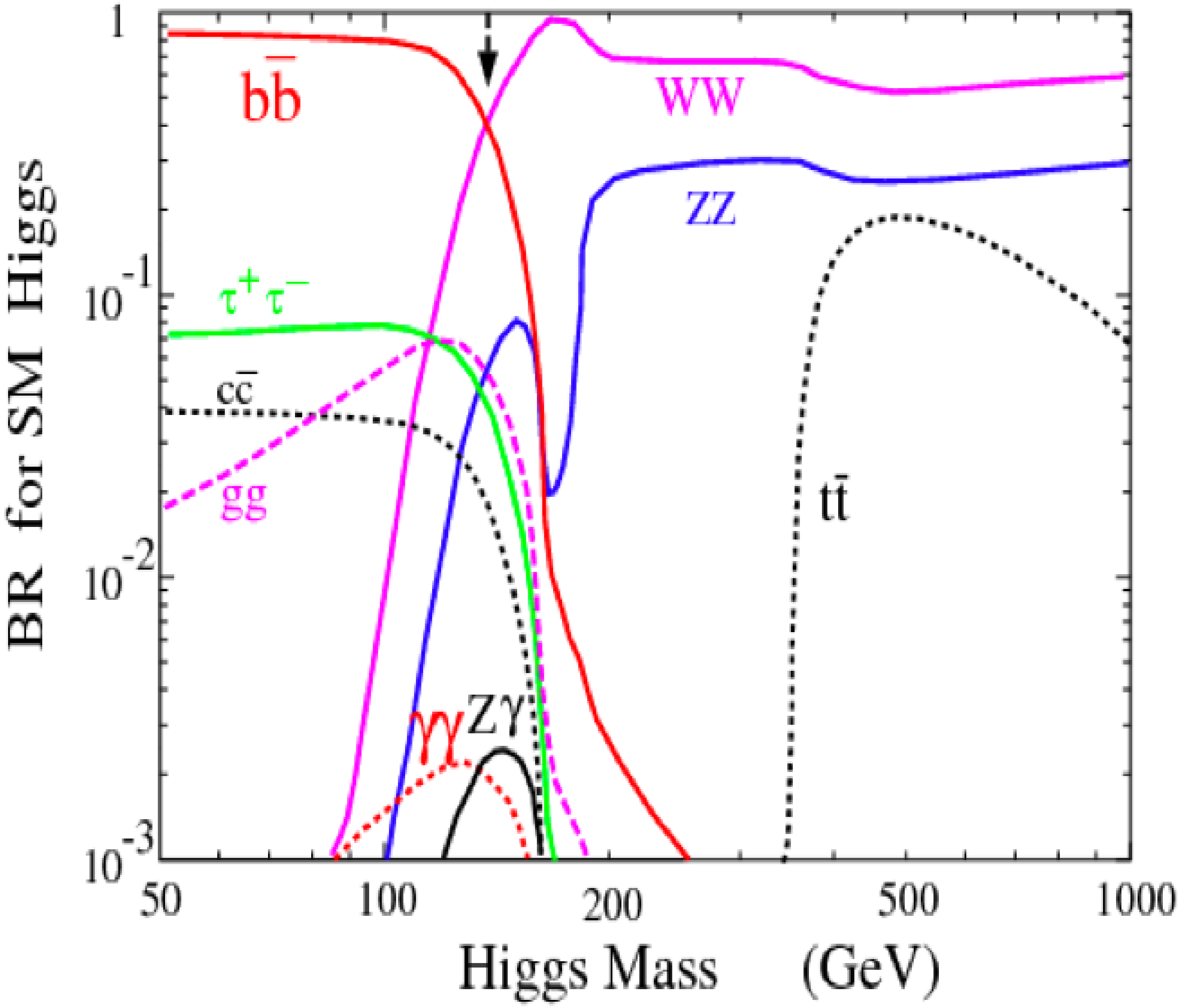
The Higgs Hunt at the LHC



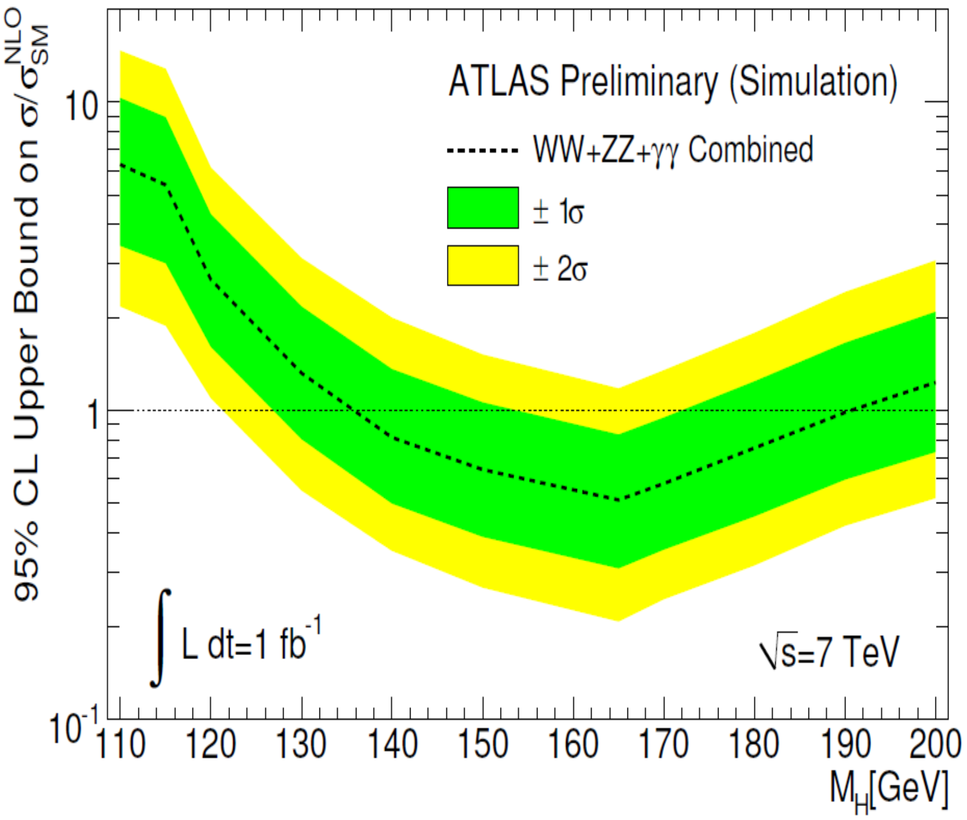
Higgs production cross sections at LHC

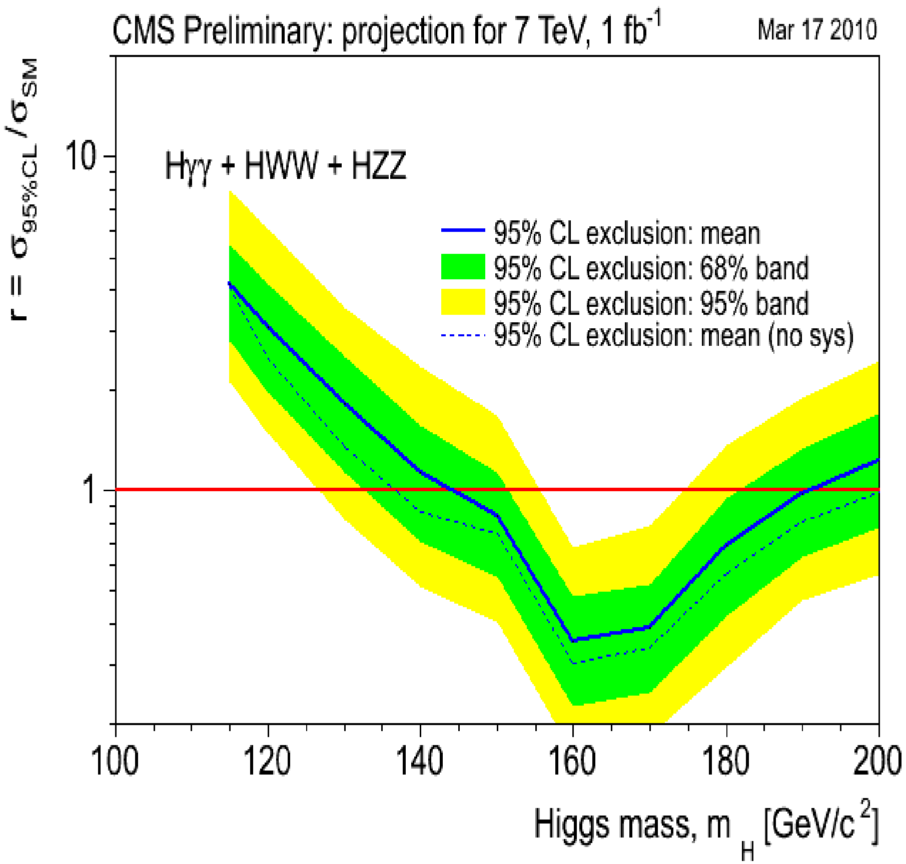


Higgs decay branching ratios



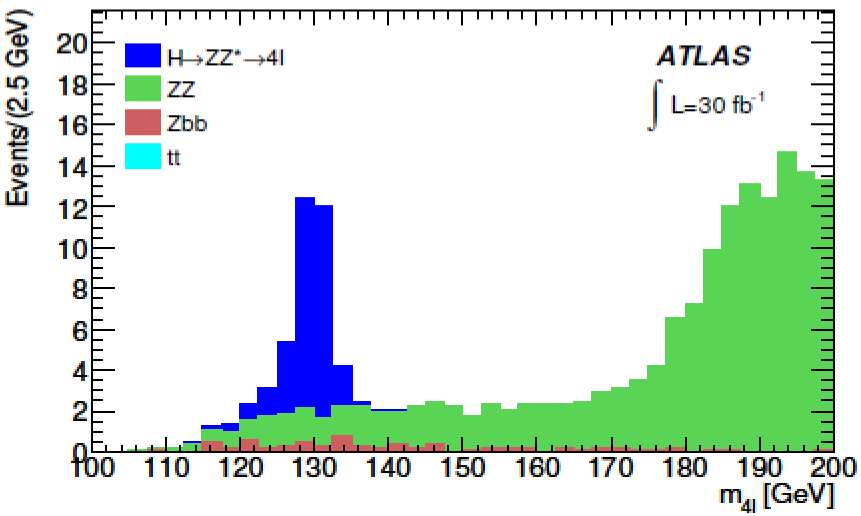
The first physics run with 7 TeV at the LHC, with the goal of 1 fb^{-1} towards the end of 2011, will be just 'catching up' the Tevatron

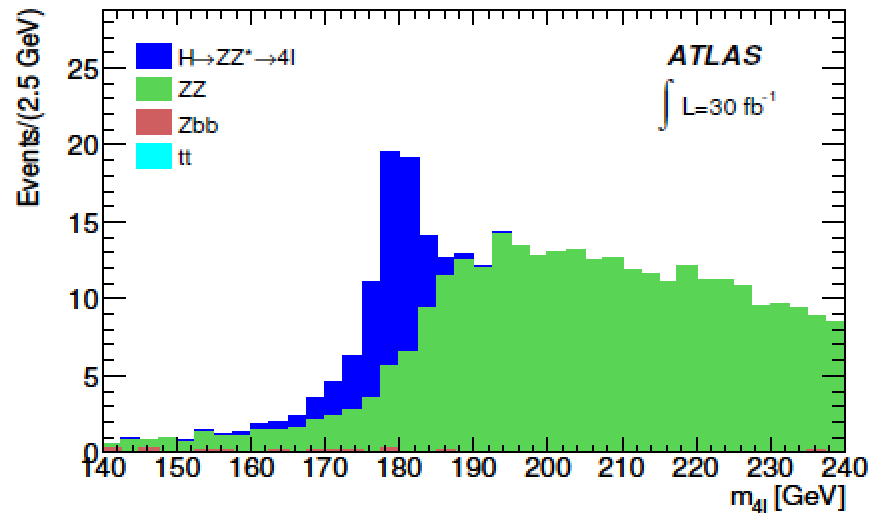


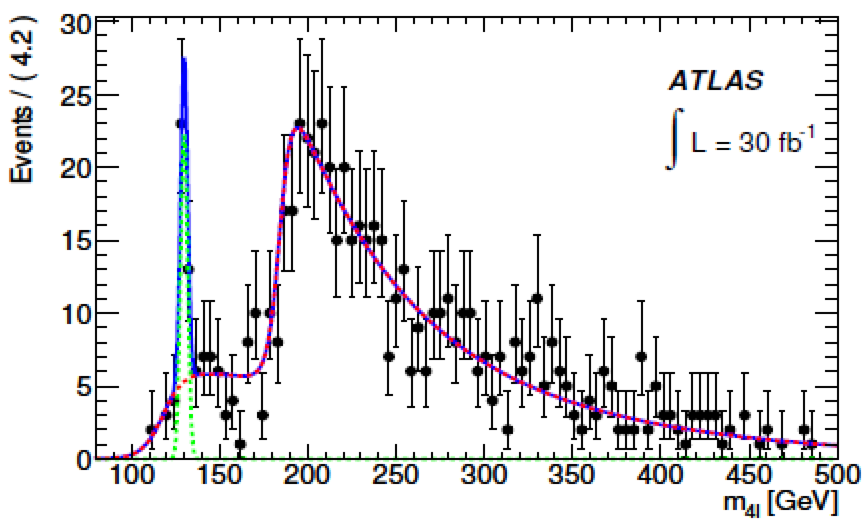


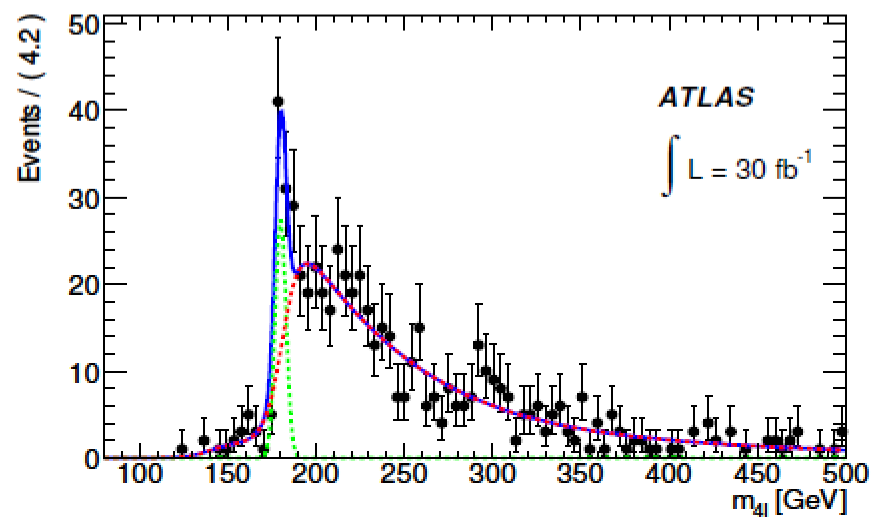
One can expect for the end of 2011 that ATLAS and CMS can exclude each the mass range 135 – 180 GeV, and that combined they could reach almost a 5 σ signal at a mass of 160 GeV

Higgs searches in the years 2014 and after … **14 TeV**





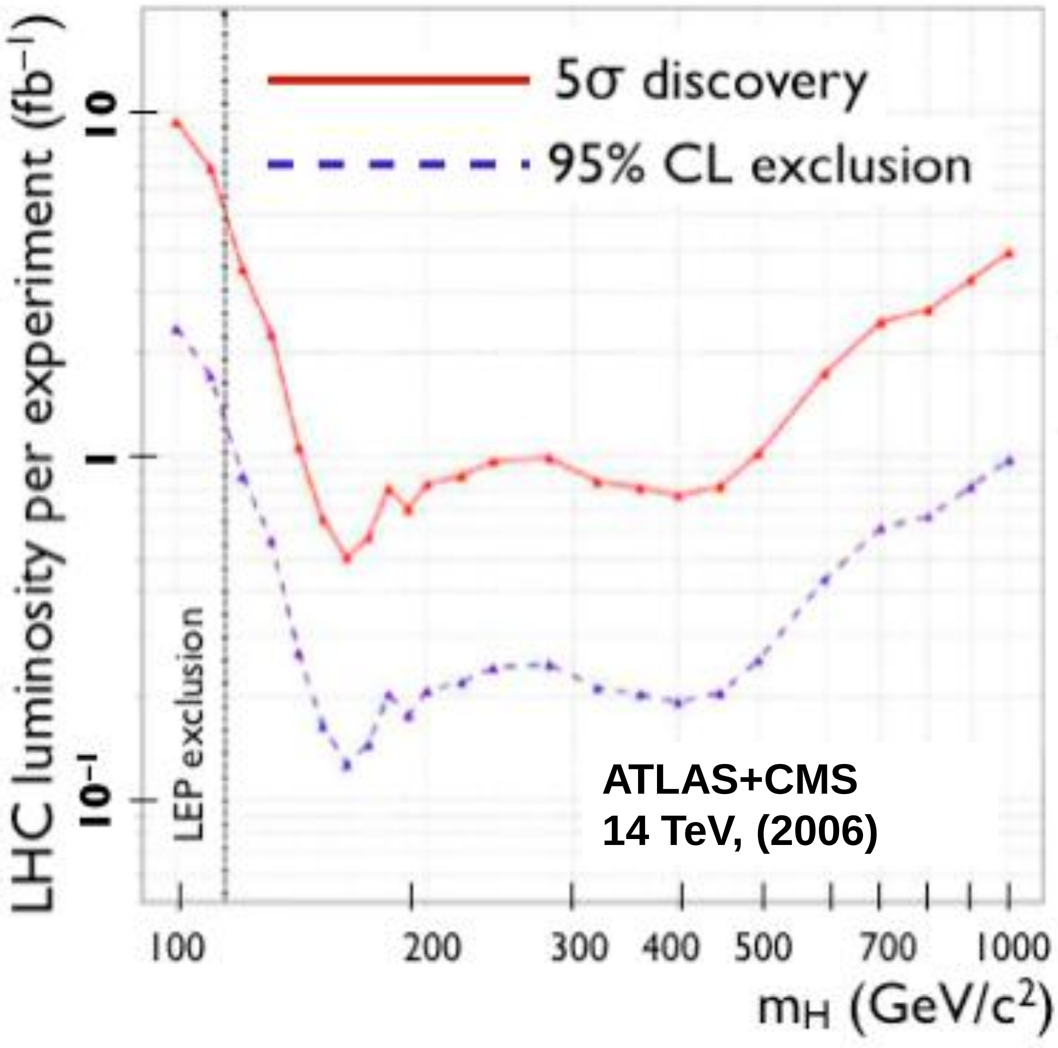




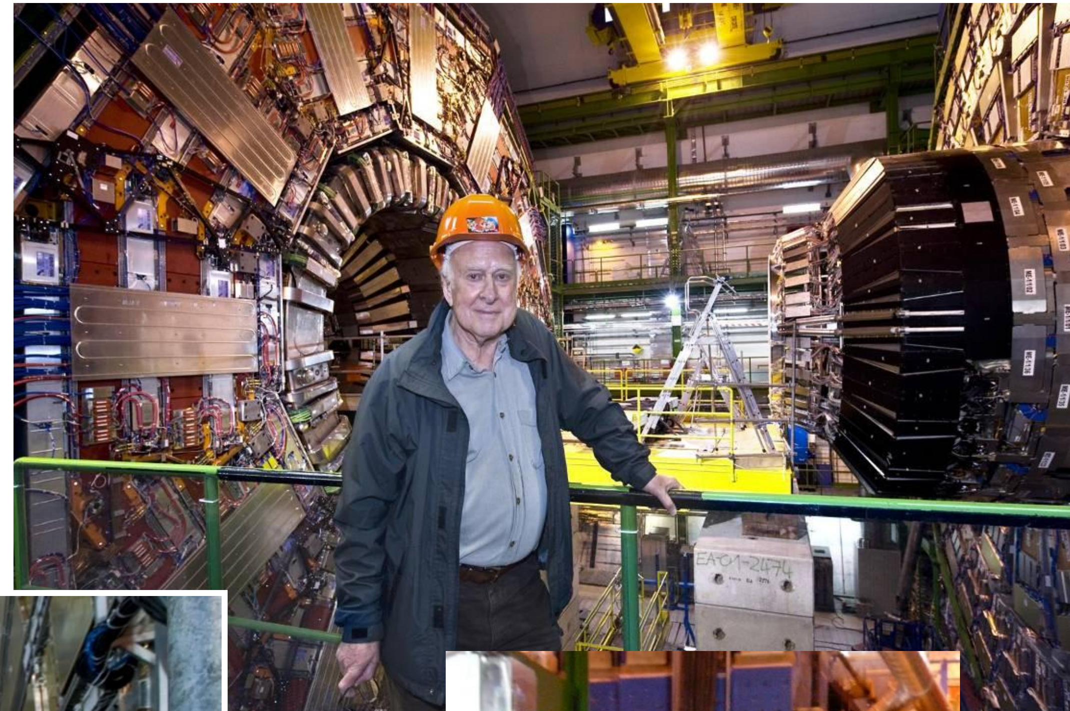
Examples for the 'gold-plated' 4 lepton channels (maybe sometimes in 2015), shown as smooth histogrammes and as a typical experimental distribution

Summing up the Higgs search at the LHC with an old plot (still ~ valid)

→Around 2015 we should be able to conclude…



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



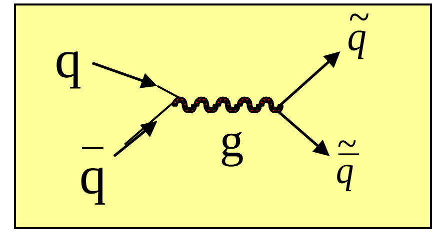
somewhat later, even in ALICE…

First discoveries at the LHC: Supersymmetry ?

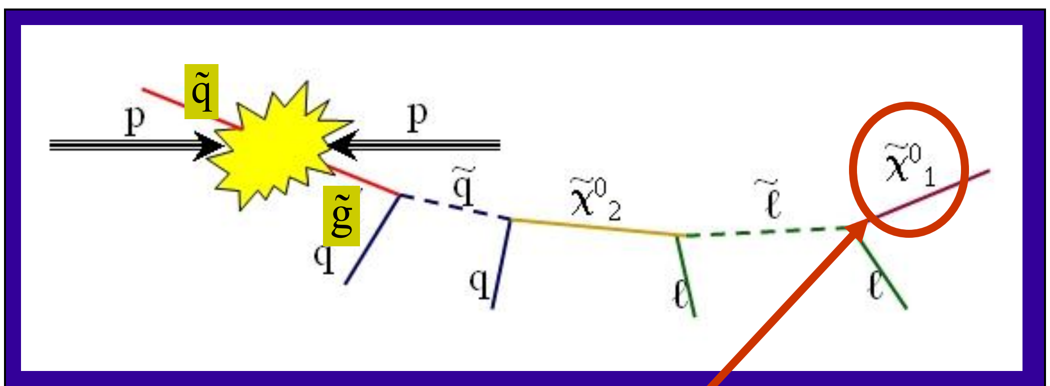
If it is at the TeV mass scale, it should be found "quickly" …. thanks to:

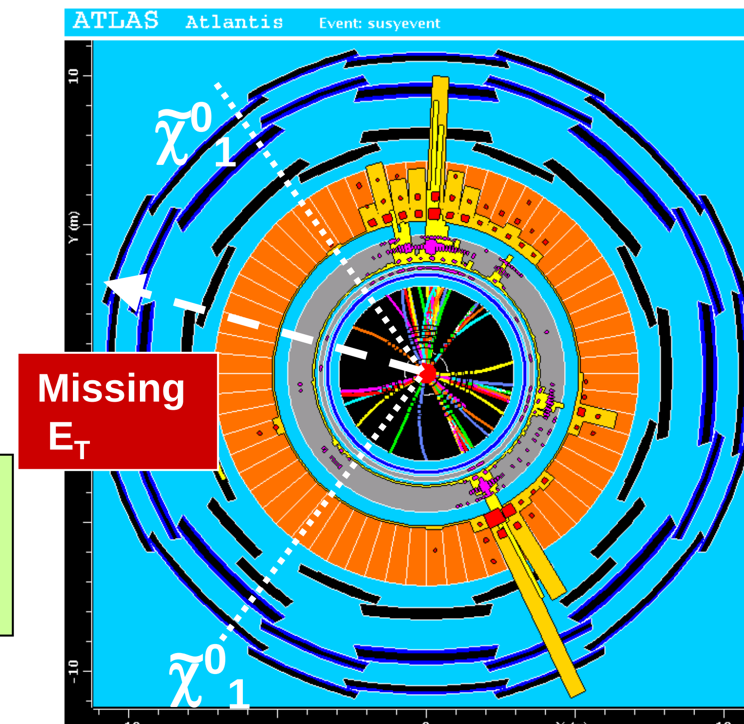
- **Large production rate for** $\tilde{q}\tilde{q}, \tilde{g}\tilde{q}, \tilde{g}\tilde{g}$ production

  For $m(\tilde{q},\tilde{g}) \sim 1$ TeV
  expect 1 event/day at $L=10^{31}\,cm^{-2}\,s^{-1}$



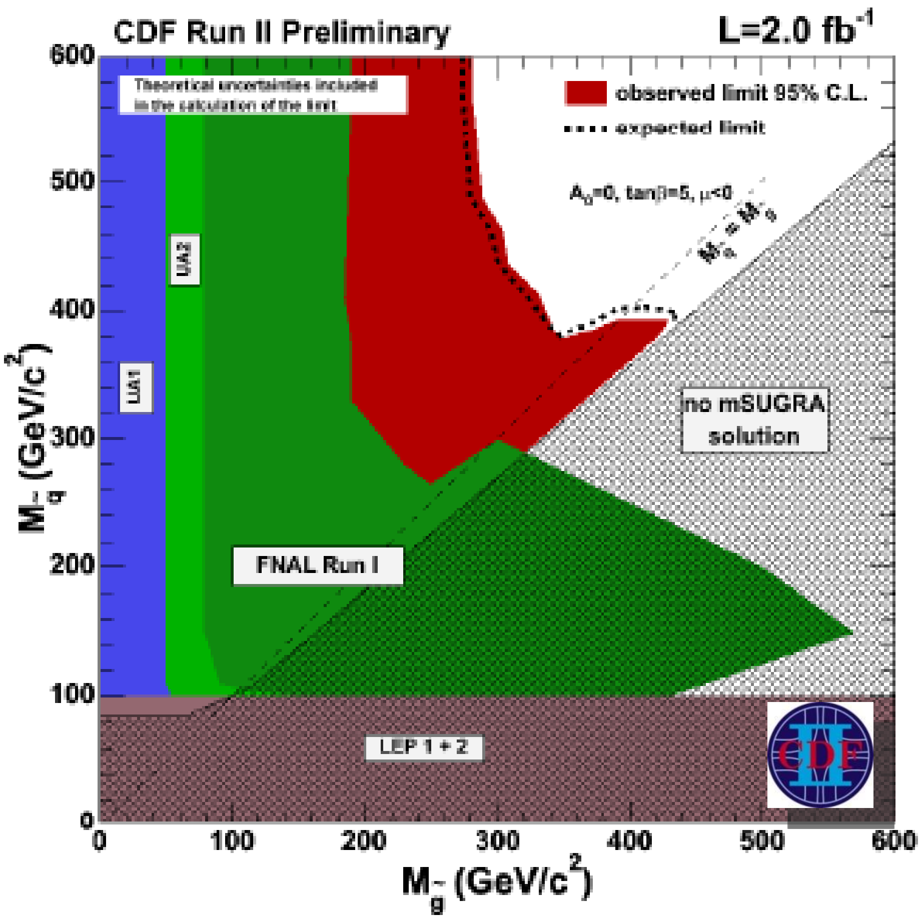
- **Spectacular final states (many jets, leptons, missing transverse energy)**

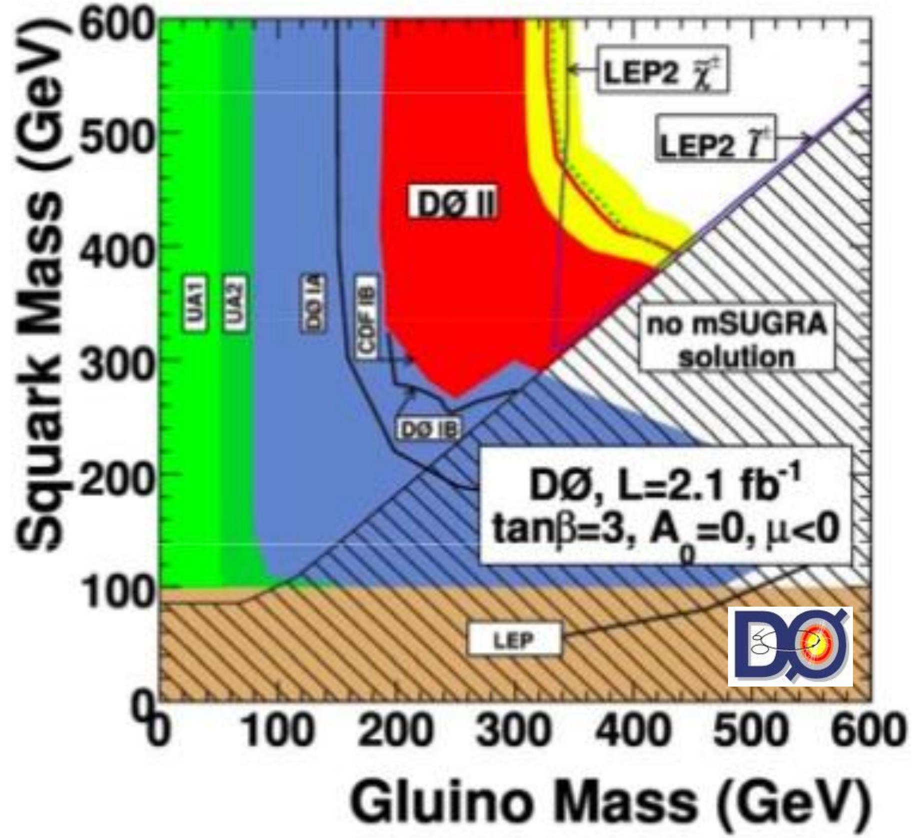




This particle (lightest neutralino) is stable, neutral and weakly interacting → escapes detection (like ν) → apparent missing energy in the final state

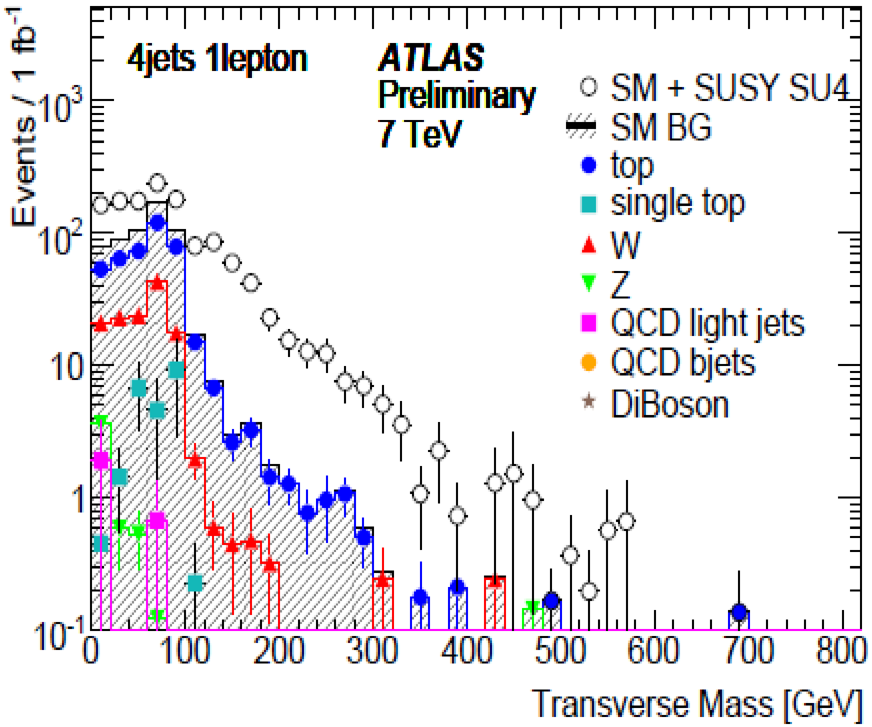
The Tevatron experiments have made very detailed studies investigating a large variety of possible signatures for SUSY

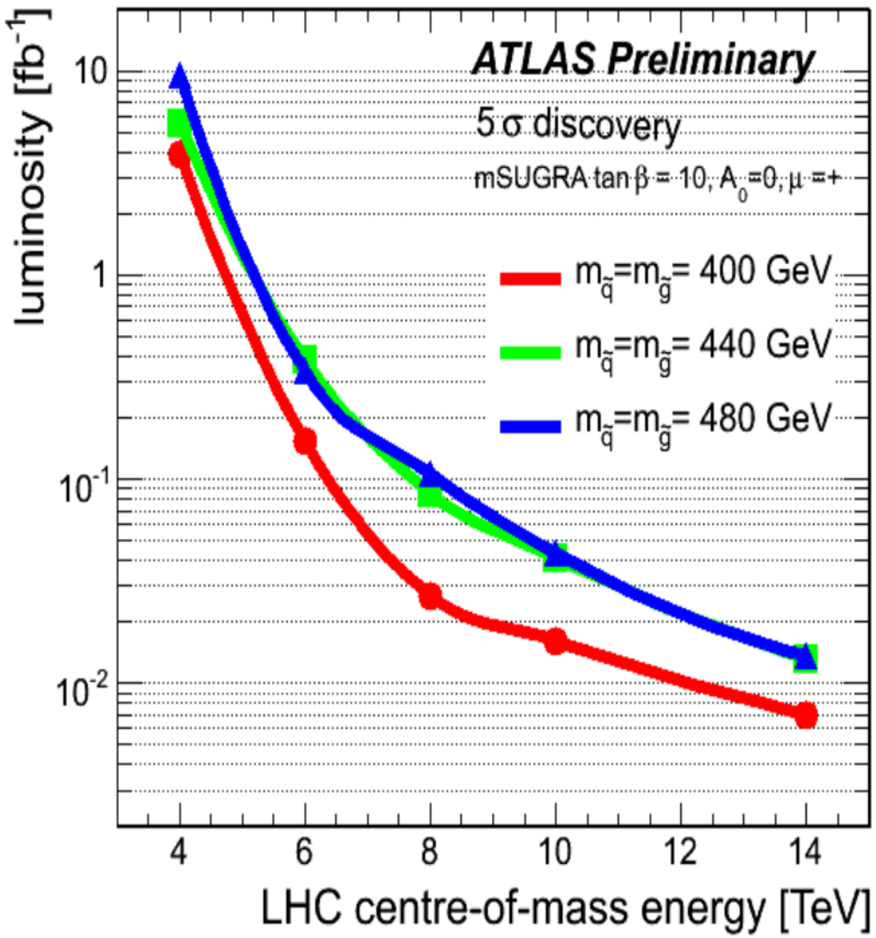




Exclusion plots (95% CL) for the most basic searches for squarks and gluinos

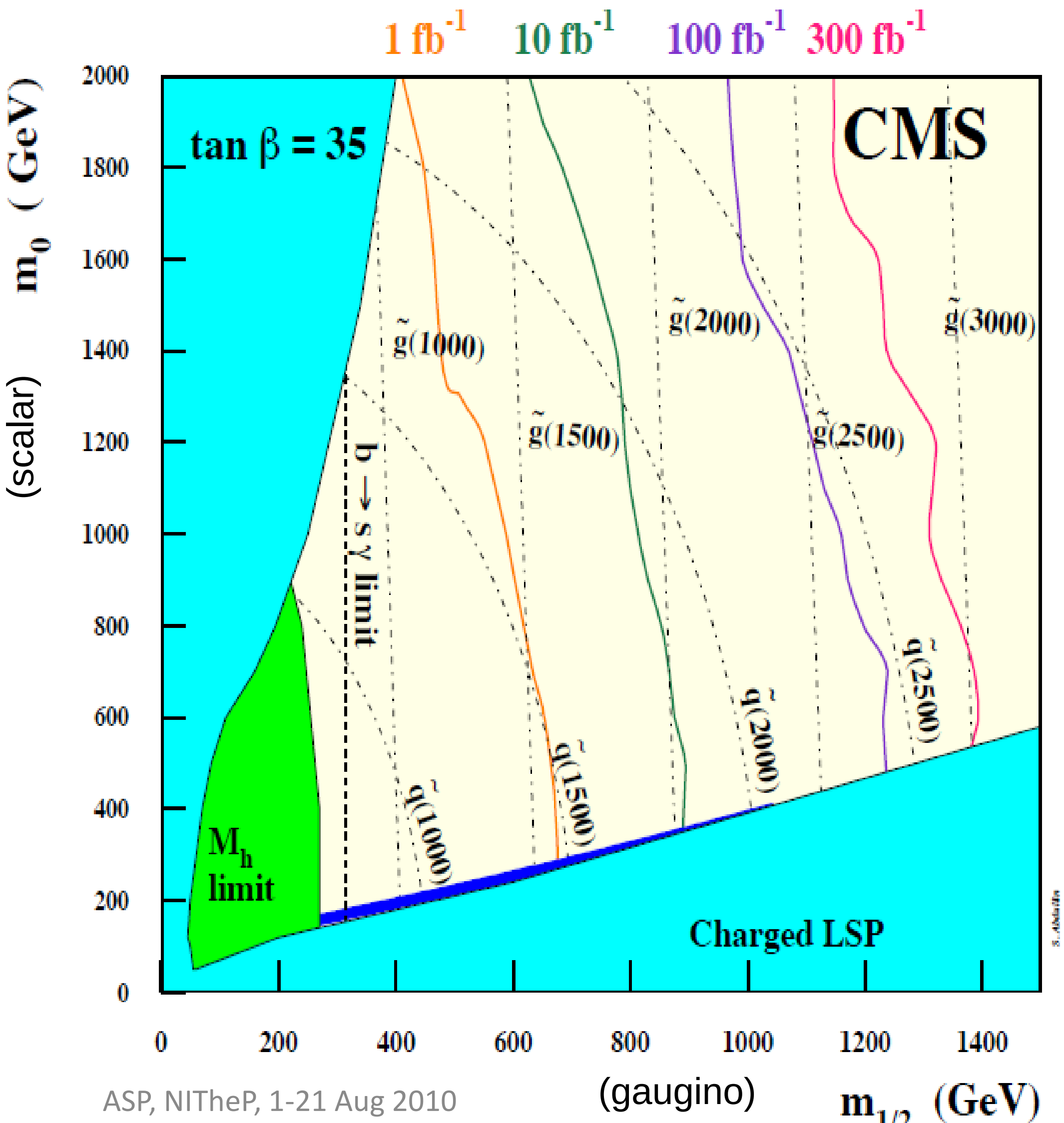
The initial LHC running will already match (maybe exceed) end of 2010 the Tevatron reach

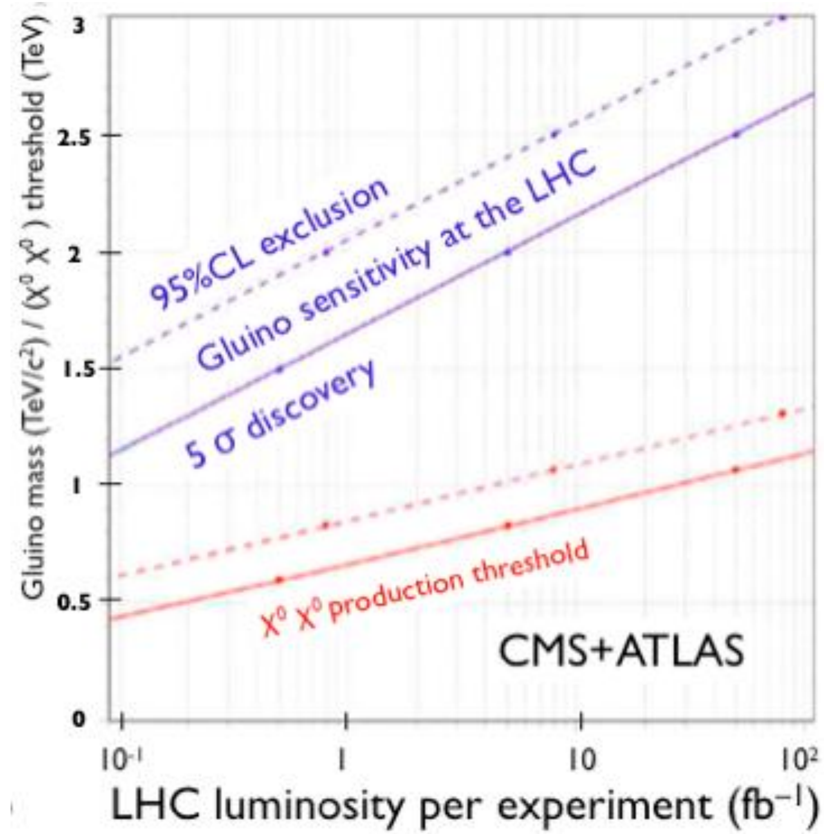




A typical example; note that the missing transverse energy performance enters directly the 'Transverse Mass', detectors must be well understood for these measurements

Ultimate discovery reach for SUSY particles at the LHC (indicative plots, model-dependent…)



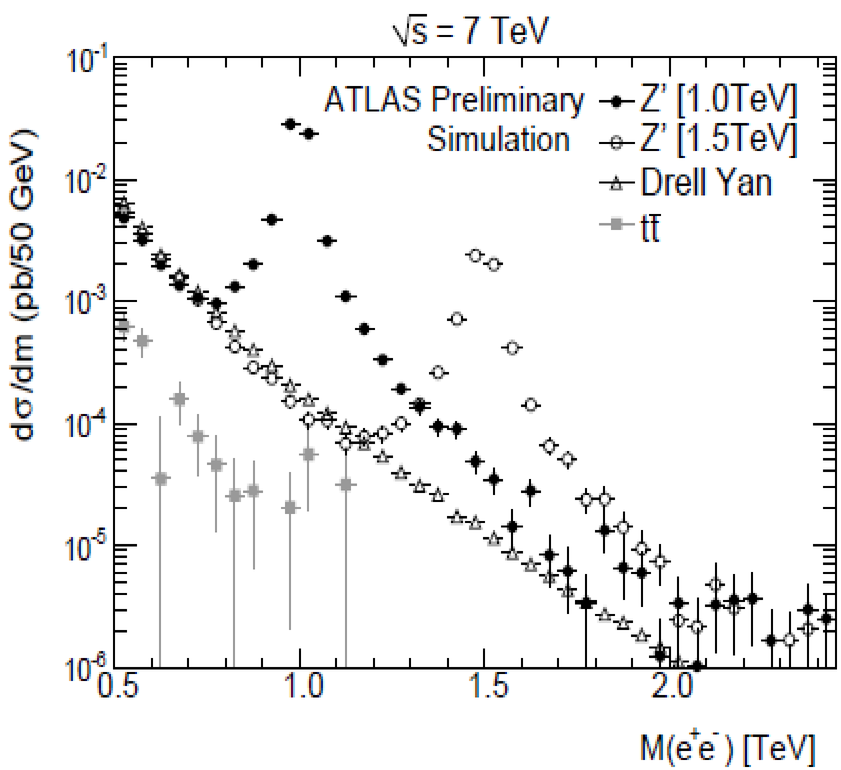


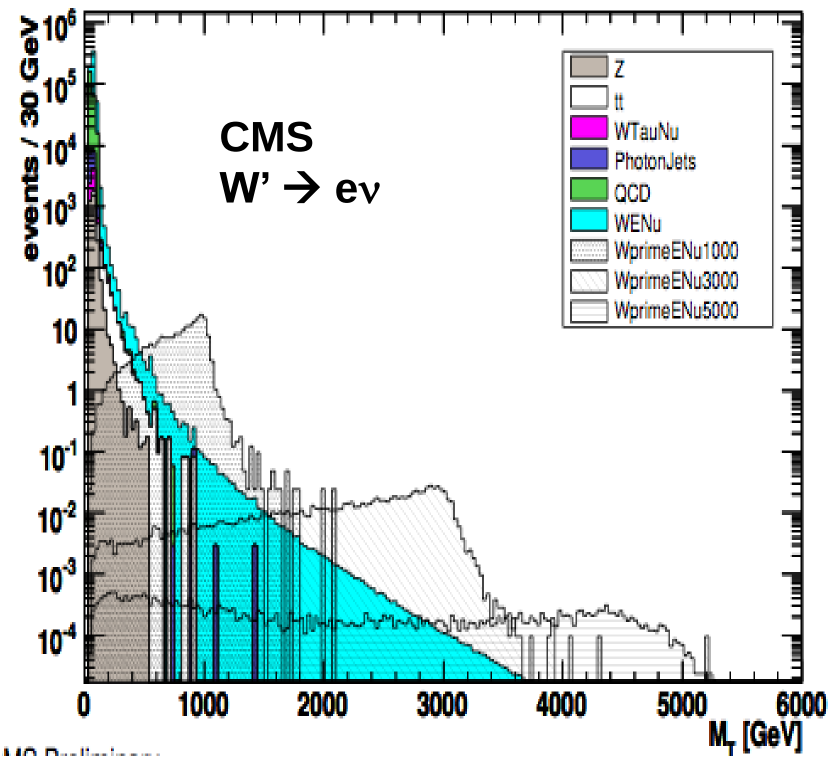
The mass scale probed for squarks and gluinos will be typically 2.5 TeV by 2017

An easy case for the LHC: searches for heavy Z' and W'

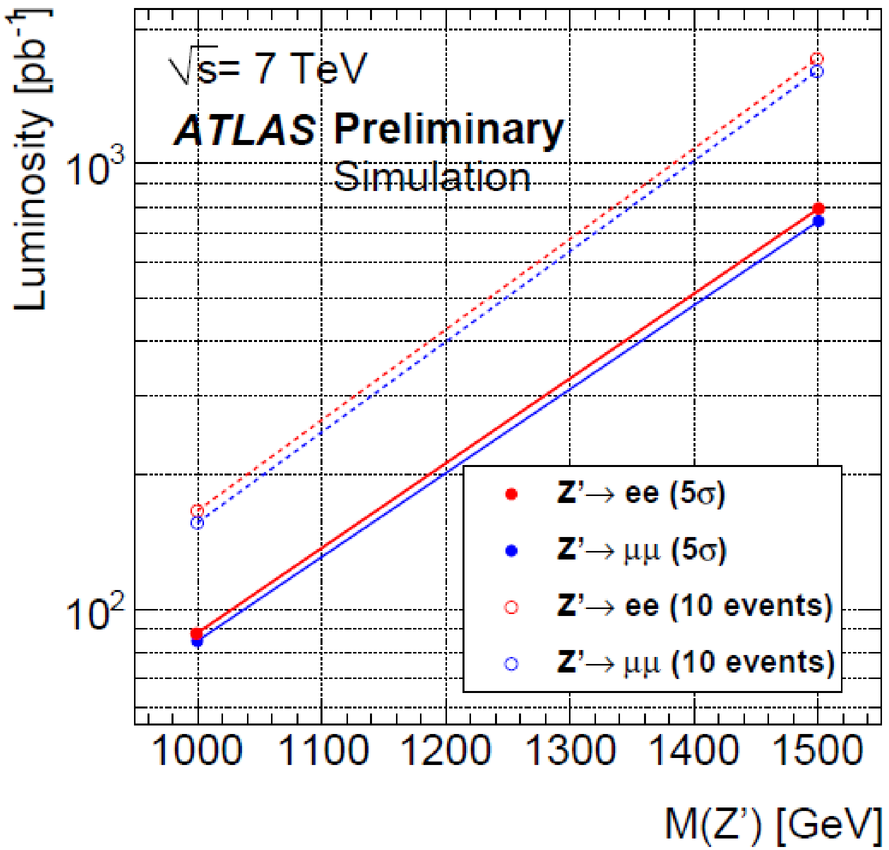
Leptonic decays with electrons or muons would give spectacular signatures

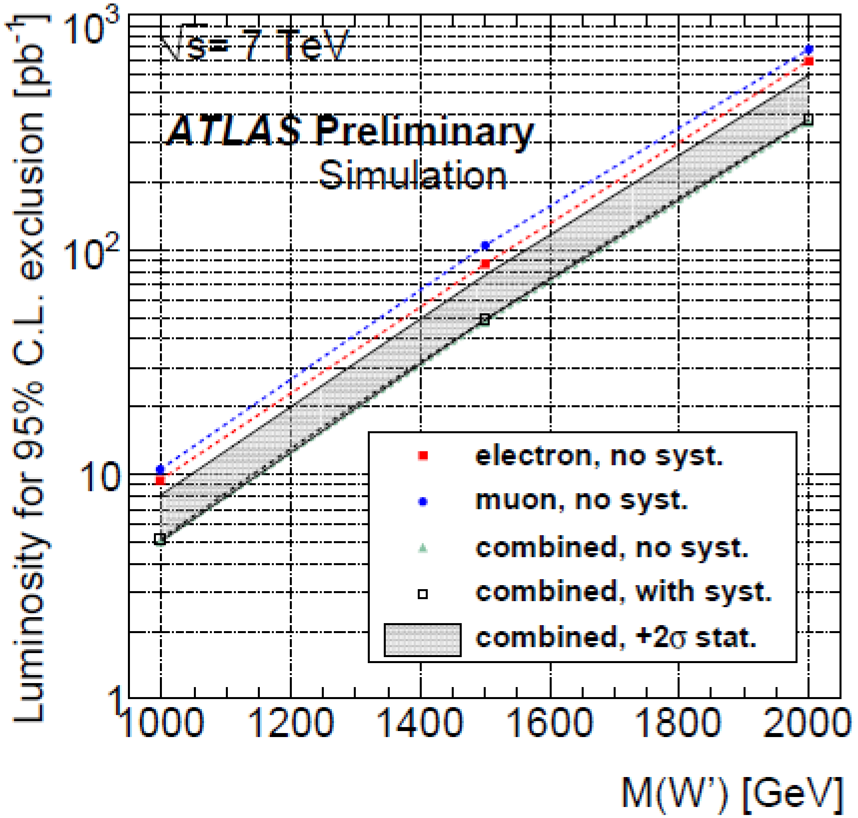
Many different models predict such objects, discoveries of a Z' and W' like particle would be a 'gold mine' for the field, other decay channels could contain yet more new particles!





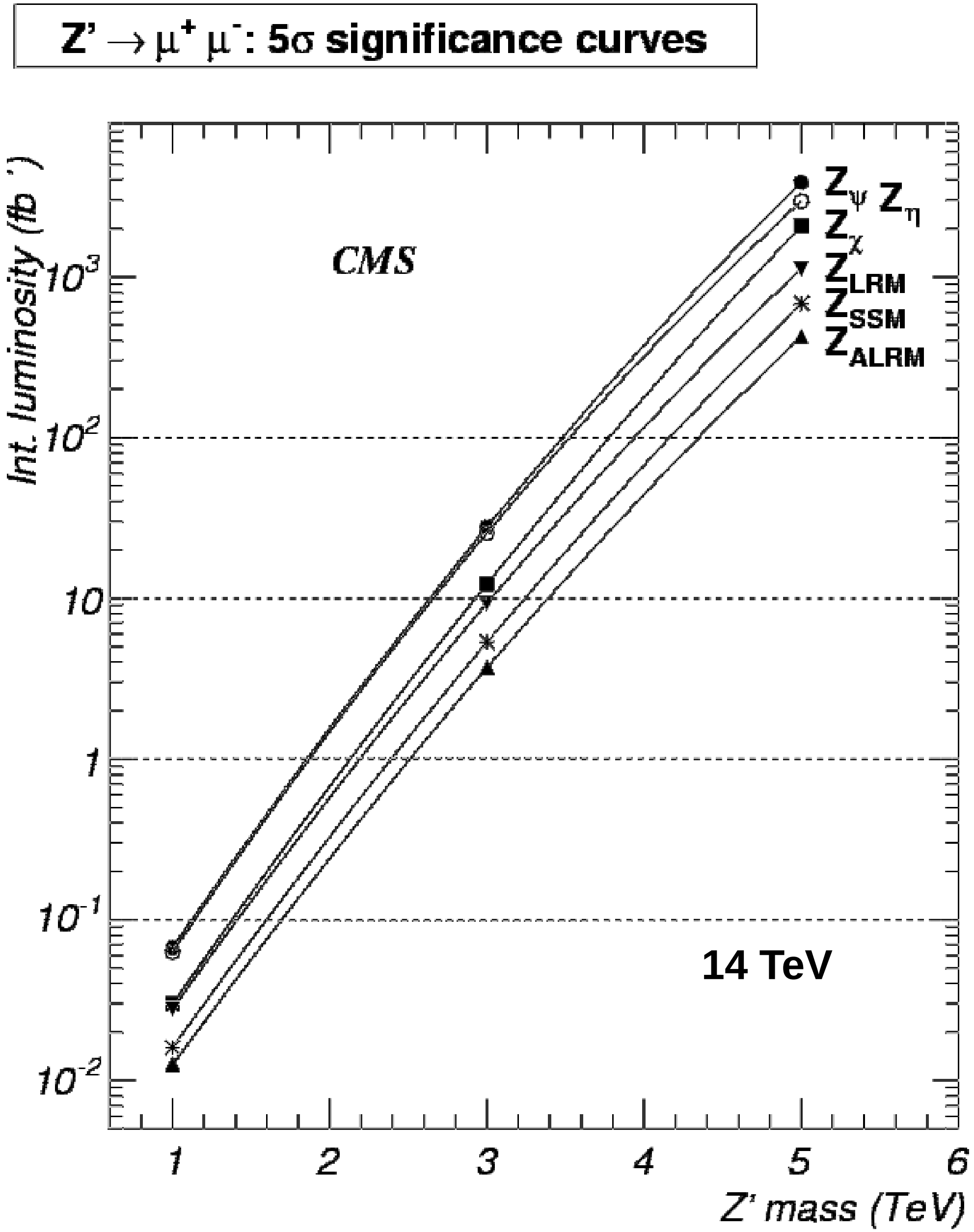
The LHC experiments will have access to the 1 TeV mass range very early on, still this year (2010)





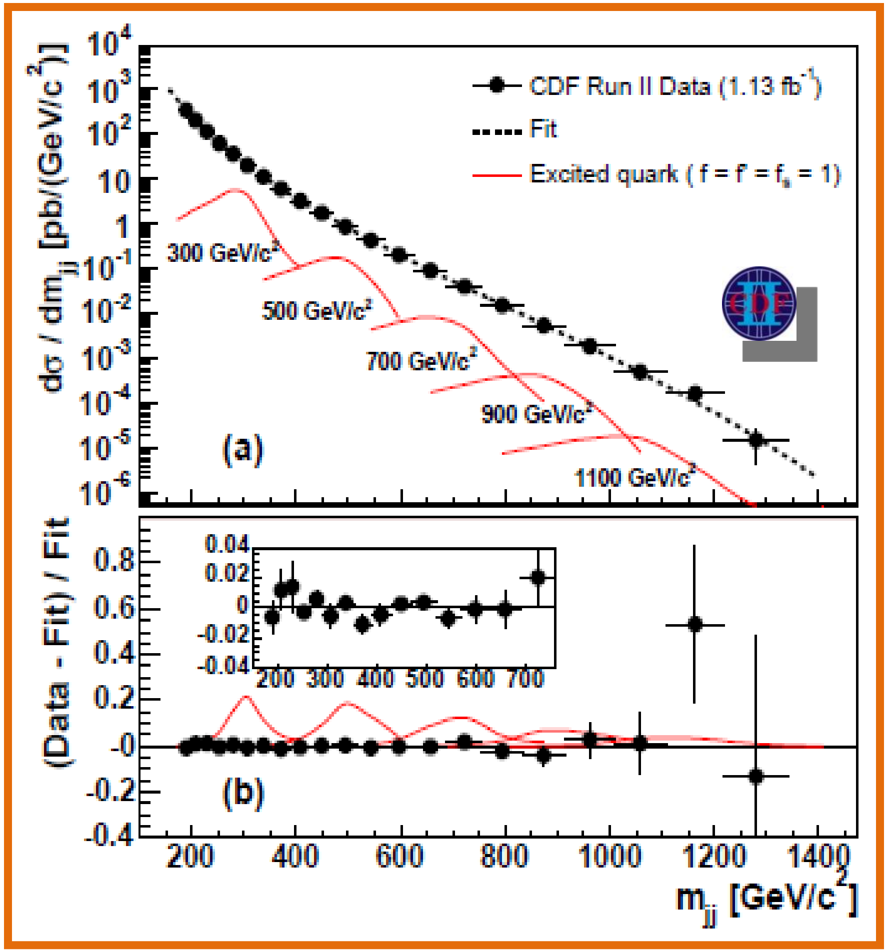
Discovery potential for ATLAS and CMS for the end of 2011, with 1 fb^{-1} at 7 TeV: up to 1.5 TeV for Z' and up to 1.9 TeV for W'

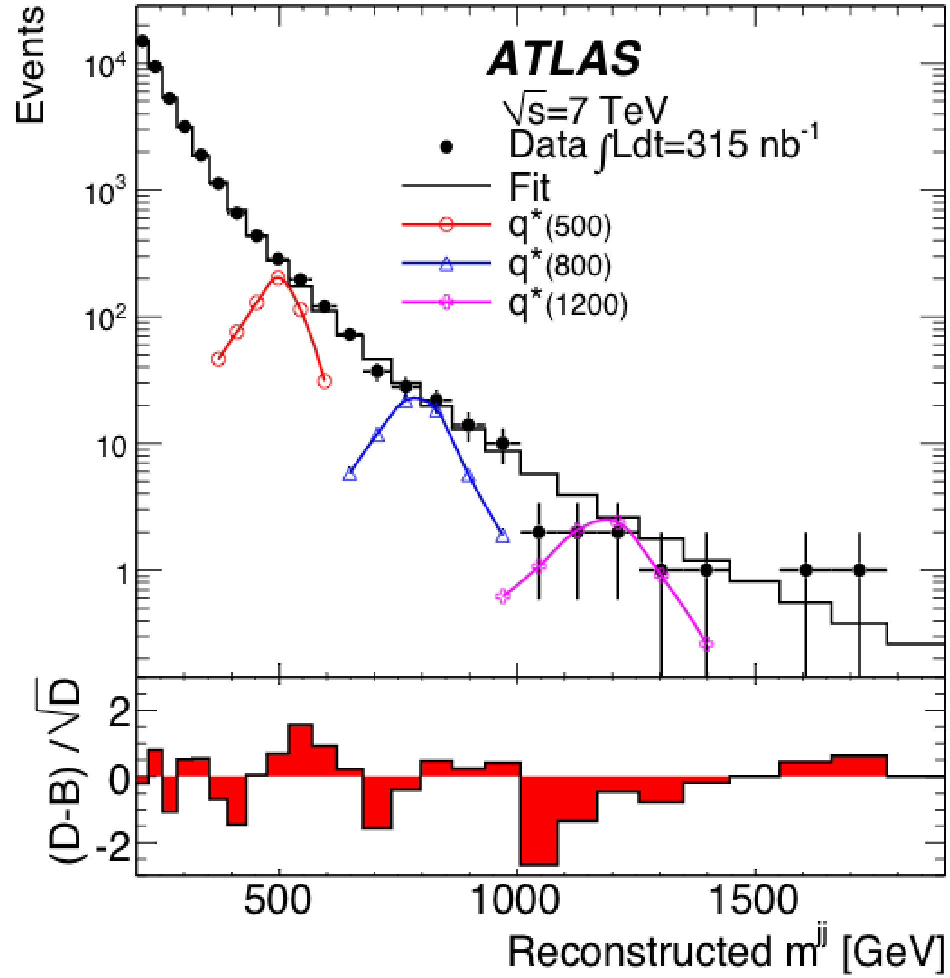
The ultimate discovery range at the LHC for heavy Z' and W' is very large, reaching 5 TeV and even beyond



(Note that the plot shows one channel for one experiment only)

Hunting for bumps in the di-jet mass distributions

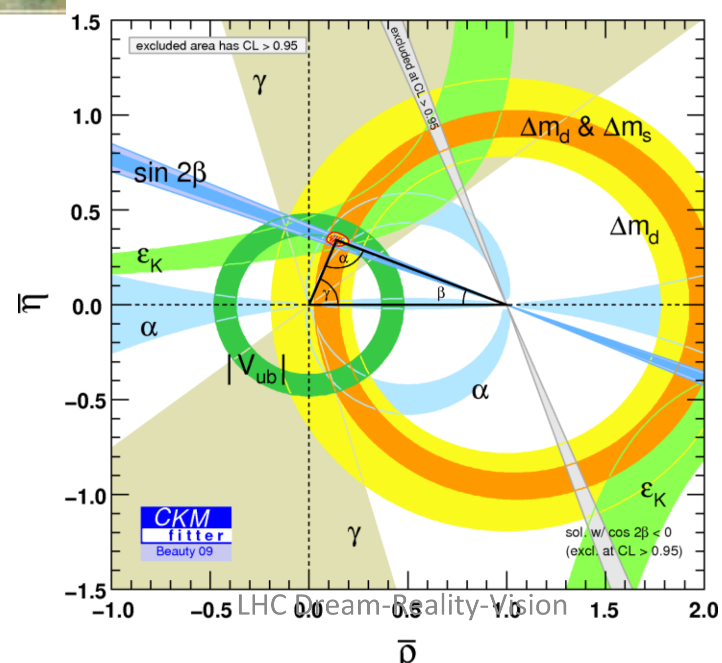




Best Tevatron limit m(Q*) > 870 GeV

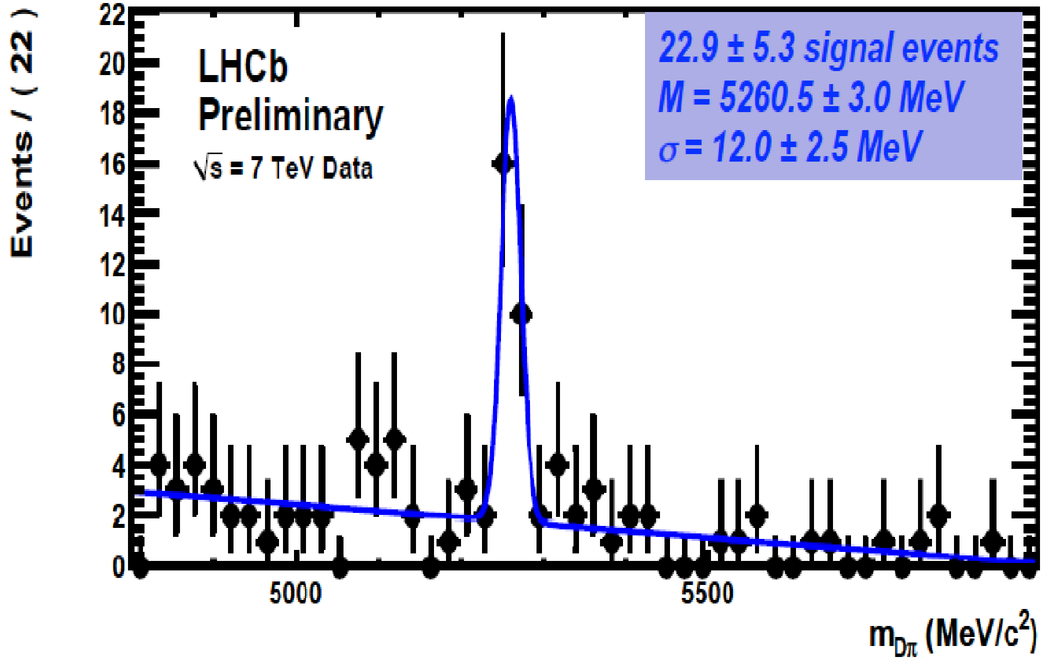
Even at this early stage the best LHC limit is already m(Q*) > 1.26 TeV

Early hints of news from 'Beyond the Standard Model' may come from 'beautiful' flavour physics...



First fully reconstructed B mesons

$B^0 \rightarrow D^+\pi^- + B^+ \rightarrow D^0\pi^+$

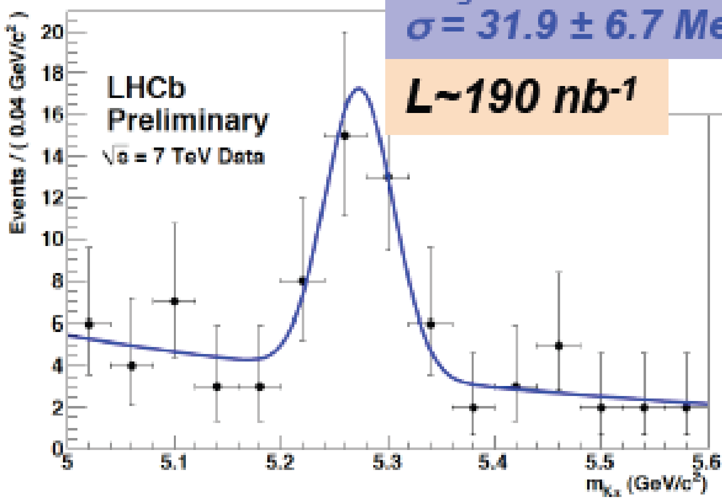


Calibration of the mass scale and B-field is ongoing

$B \rightarrow K\pi$

N_{sig} = 27.3 ± 6.1
σ = 31.9 ± 6.7 MeV

L~190 nb^{-1}



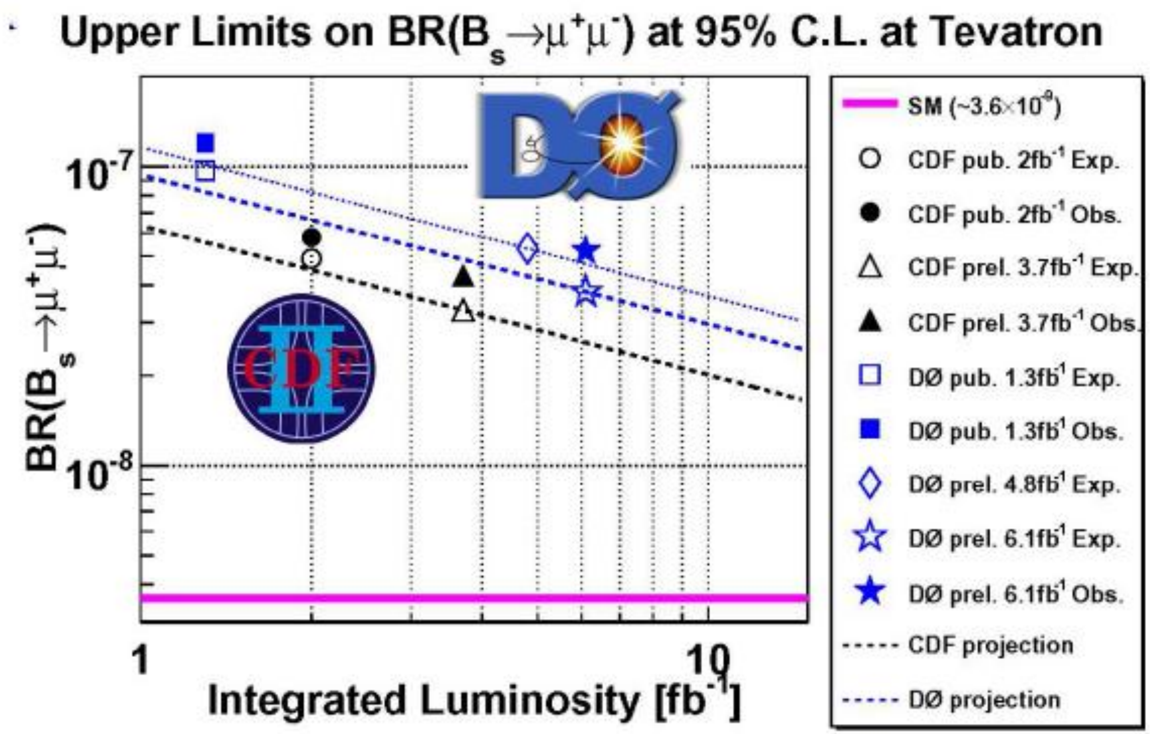
35

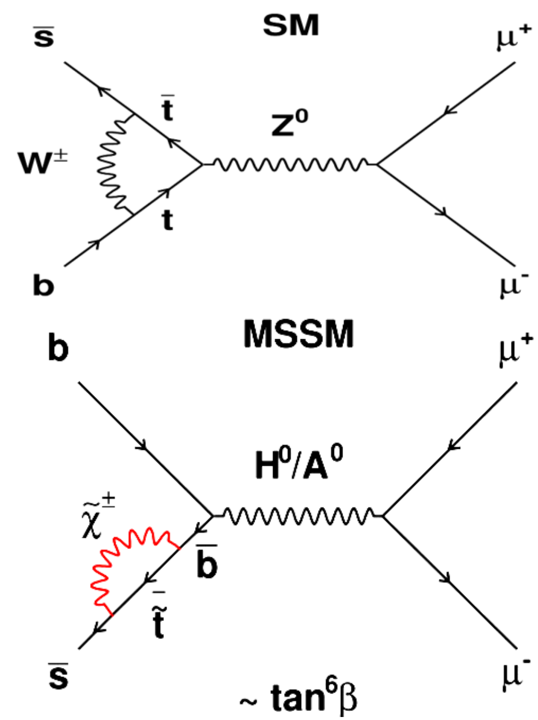
$B_s \rightarrow \mu\mu$

Small BR in SM: (3.2 0.2) $\times 10^{-9}$

Sensitive to NP

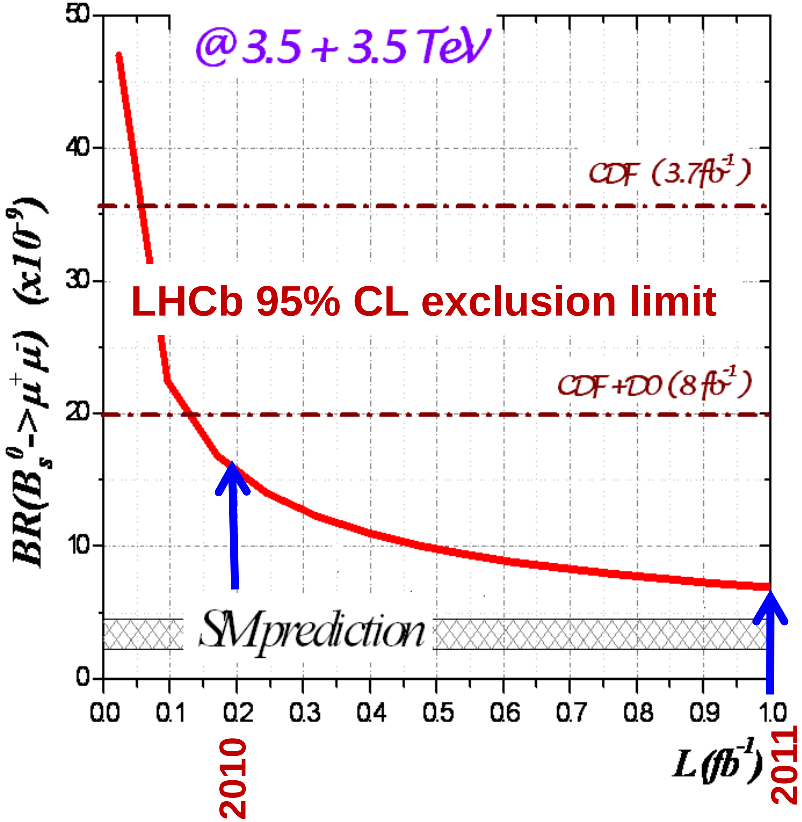
- **could be strongly enhanced in SUSY**
  - **In MSSM scales like ~$\tan^6\beta$**

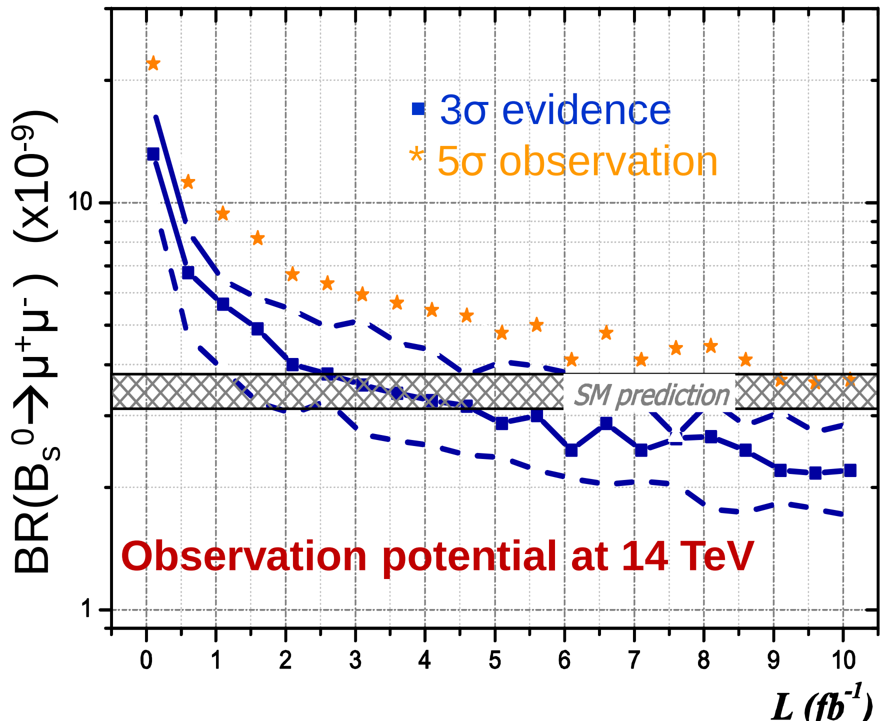




- CDF Preliminary, 3.7 fb^{-1}: $< 4.3 \cdot 10^{-8}$ at 95% C.L.
- DØ Preliminary, 6.1 fb^{-1}: $< 5.2 \cdot 10^{-8}$ at 95% C.L.

Physics reach for BR($B_s^0 \rightarrow \mu^+\mu^-$) as function of integrated luminosity
(and comparison with Tevatron)



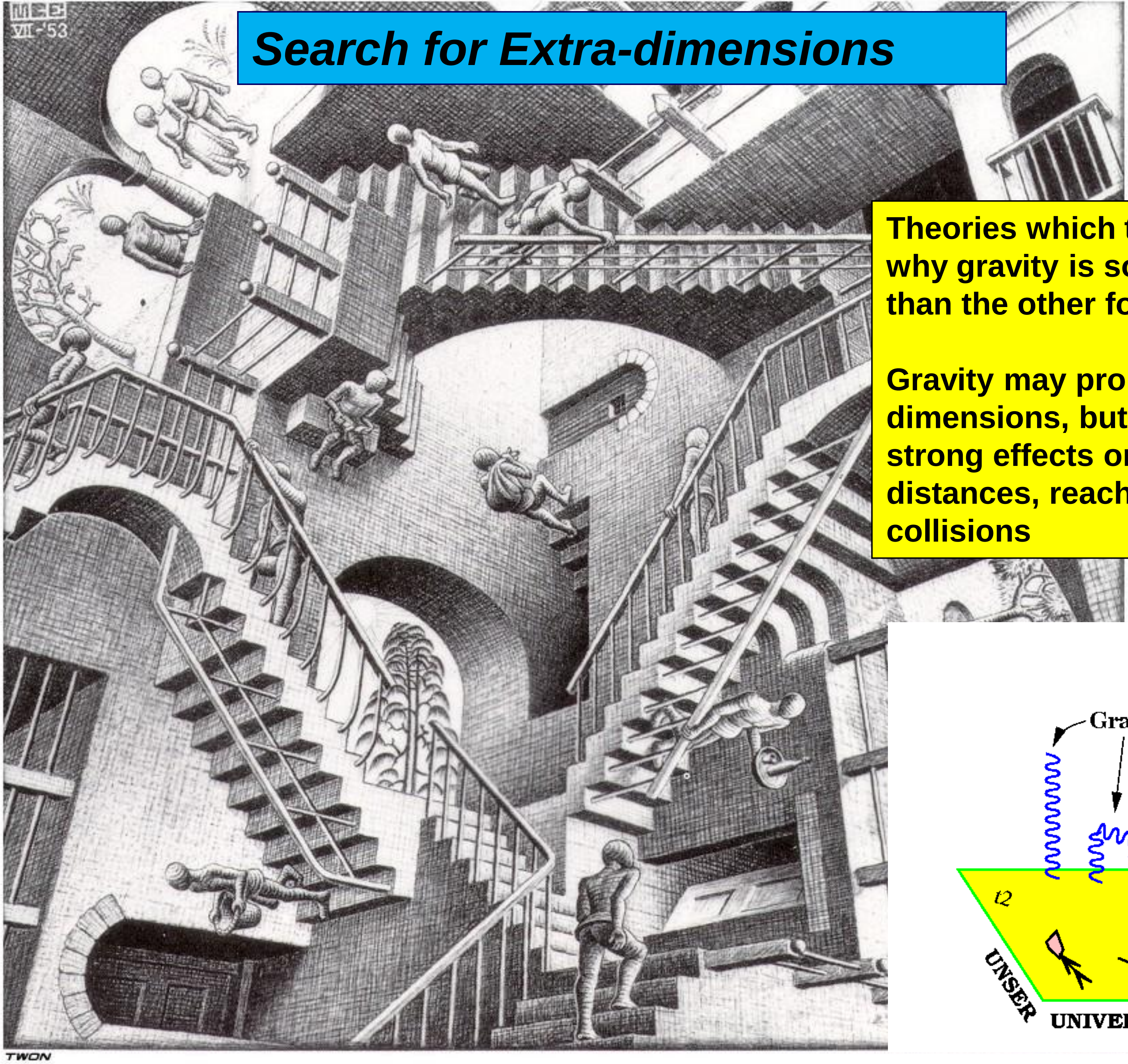


With ~0.2 fb^{-1} LHCb should improve on expected Tevatron limit

→ Collect ~3 fb^{-1} for 3σ evidence of SM value and ~10 fb^{-1} for 5σ observation of SM

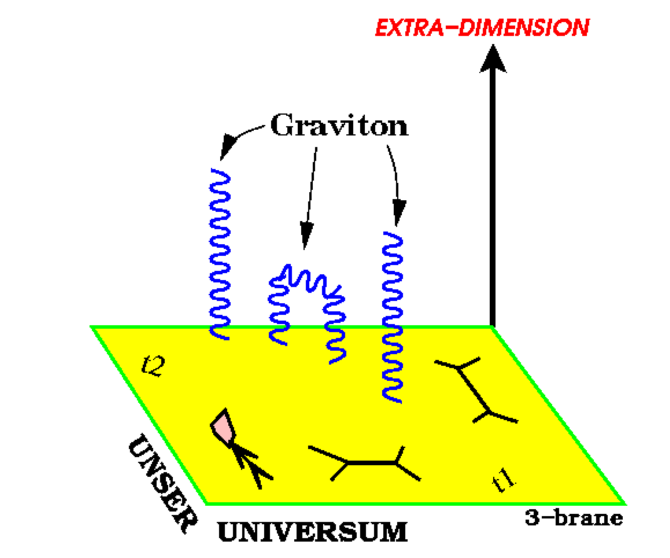
(Note: ATLAS/CMS will be competitive)

Search for Extra-dimensions

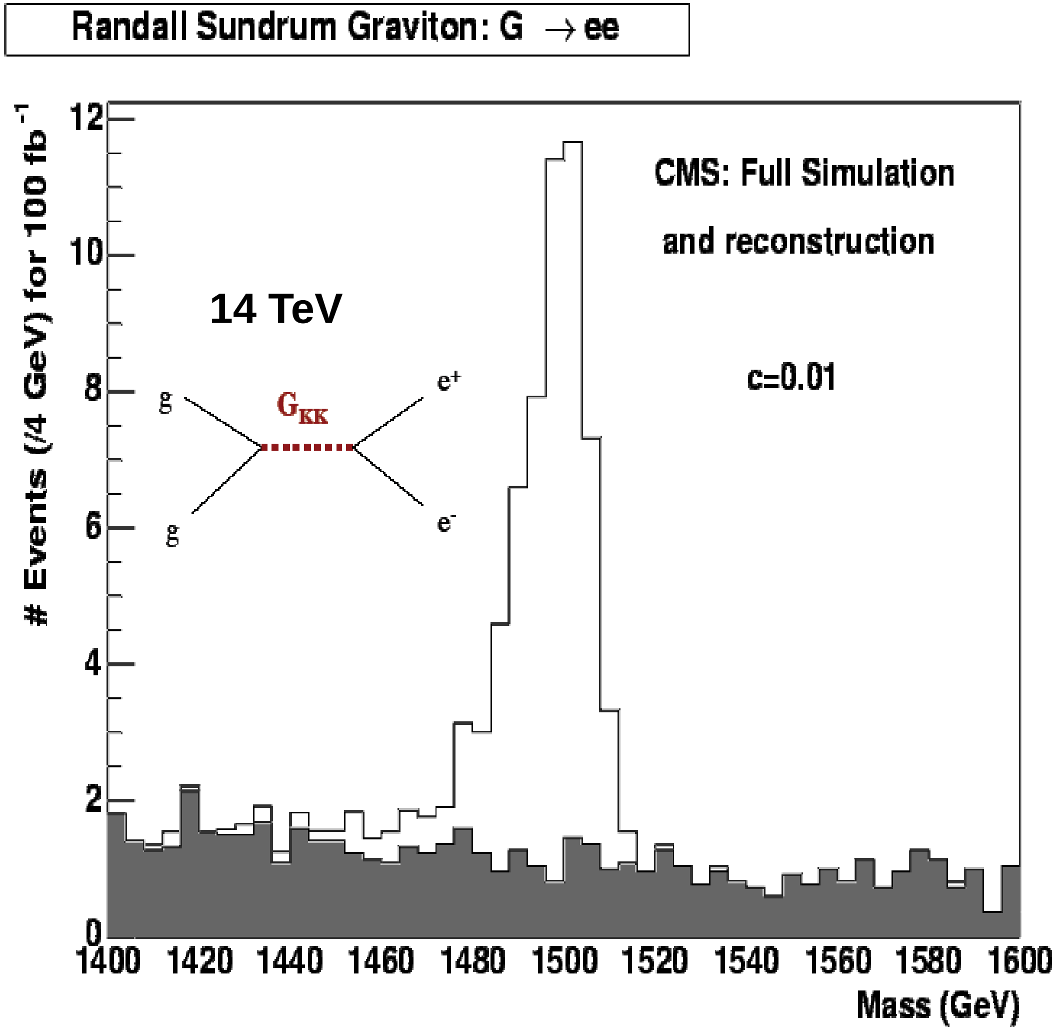


Theories which try to explain why gravity is so much weaker than the other forces

Gravity may propagate in 4+n dimensions, but we could see strong effects only at very small distances, reachable in pp LHC collisions



Warped Extra-dimensions (Randall-Sundrum models): production of narrow Graviton resonances



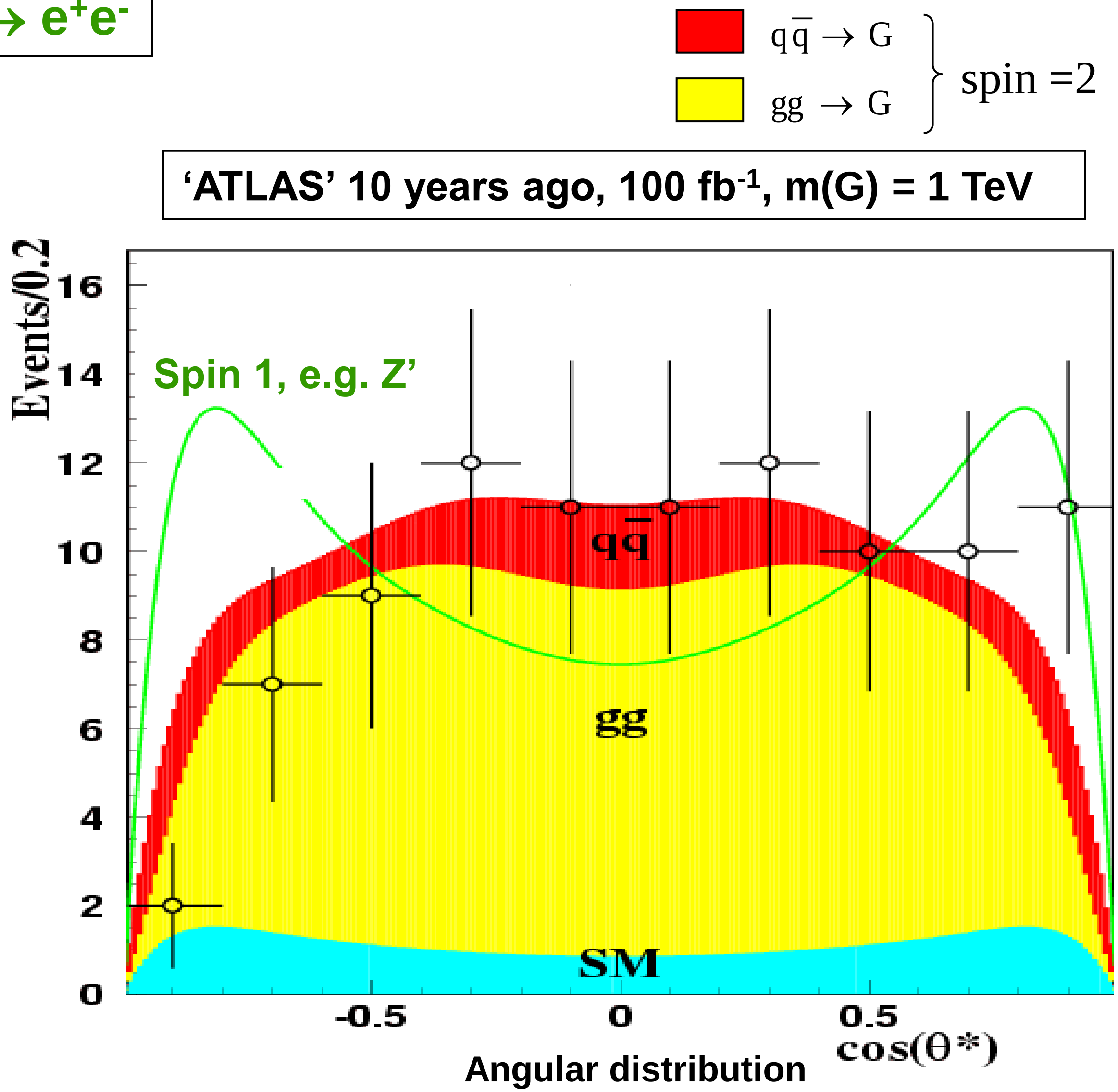
Sundrum
Randall
Gianotti

Signature: a resonance in the di-electron or di-muon final state, as well as di-photons, *a priori* easy for the experiments

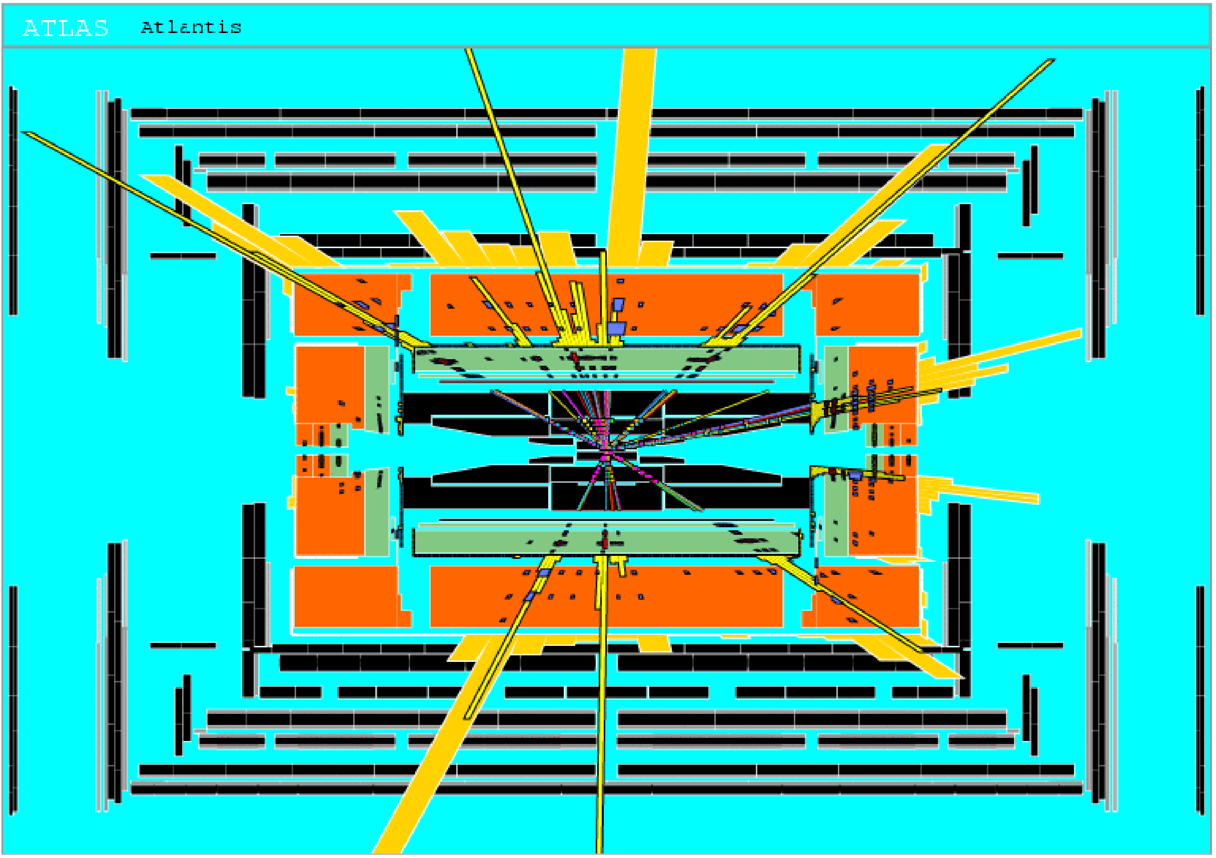
Caveat: new developments suggest that G_{KK} would couple dominantly to top anti-top…

$qq, gg \rightarrow G \rightarrow e^+e^-$

Lisa Randall visiting ATLAS



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



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

They decay immediately through Stephen Hawking radiation

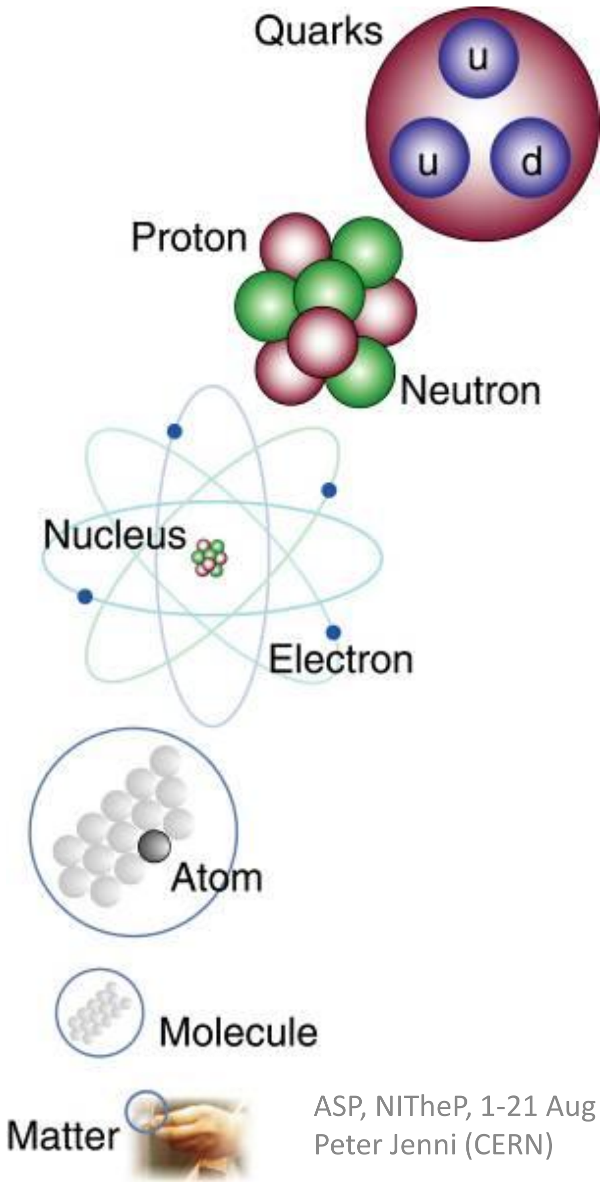
Exciting times are ahead of us!

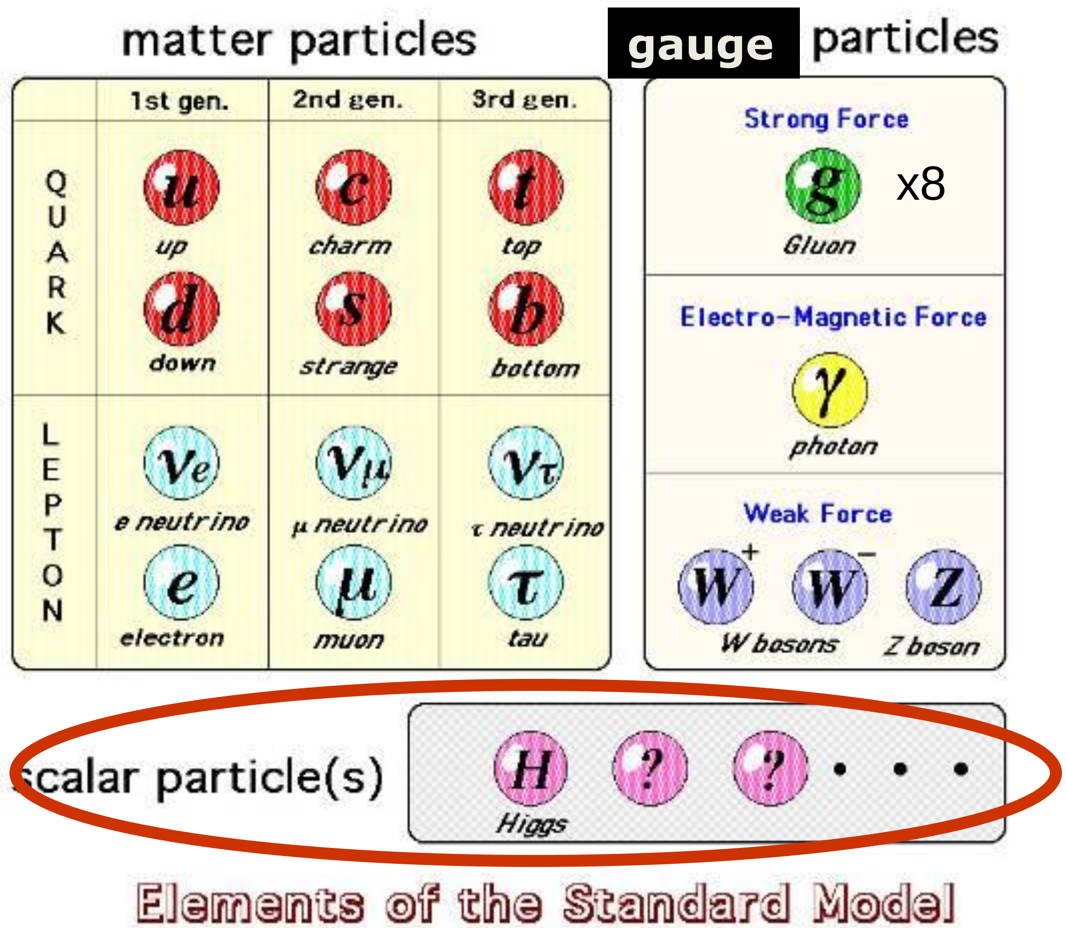
Hadron colliders, and in particular the LHC, will show us the way forward in our field

Thank you for your attention

Spares

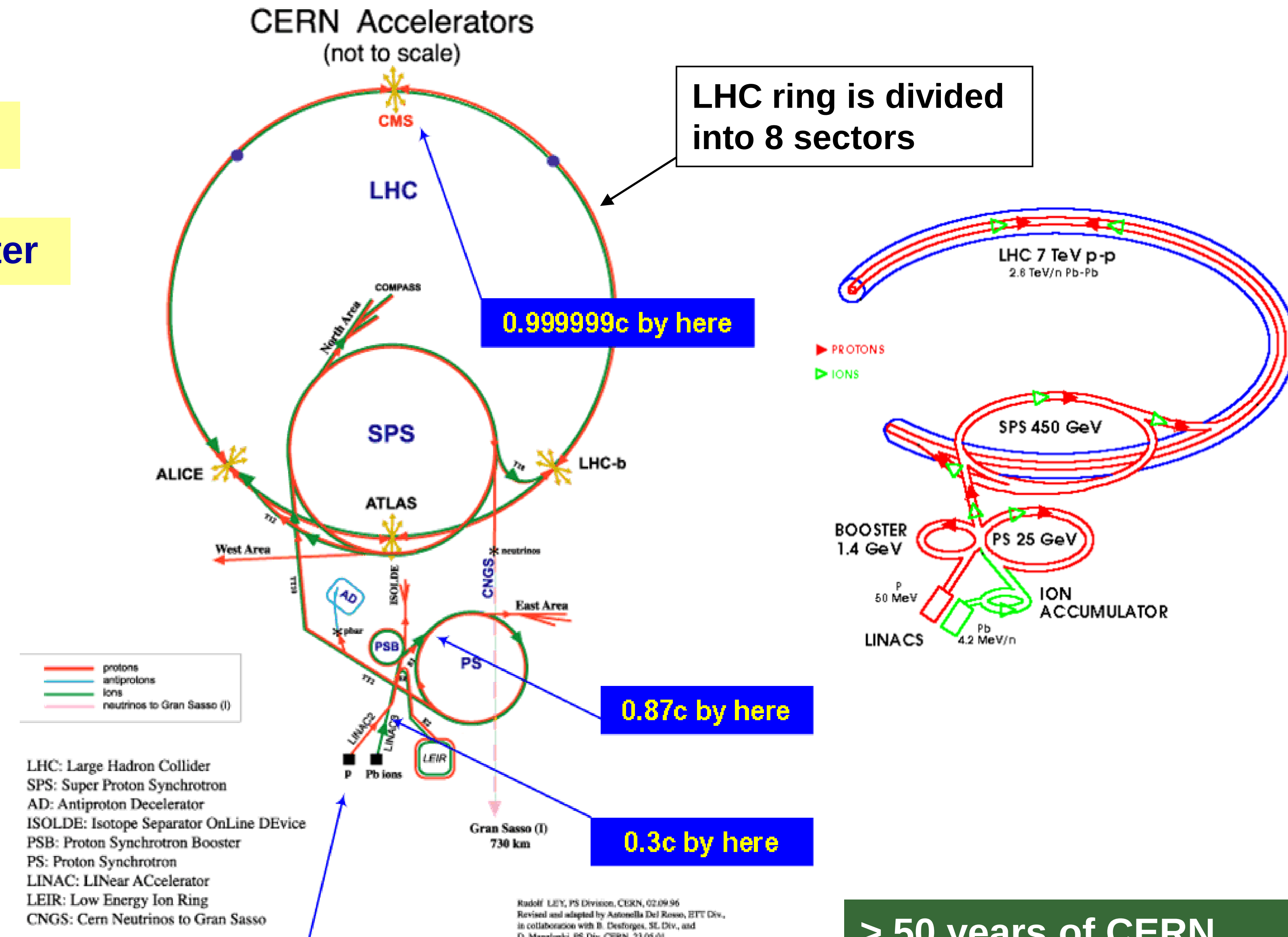
The study of elementary particles and fields and their interactions





The full LHC accelerator complex

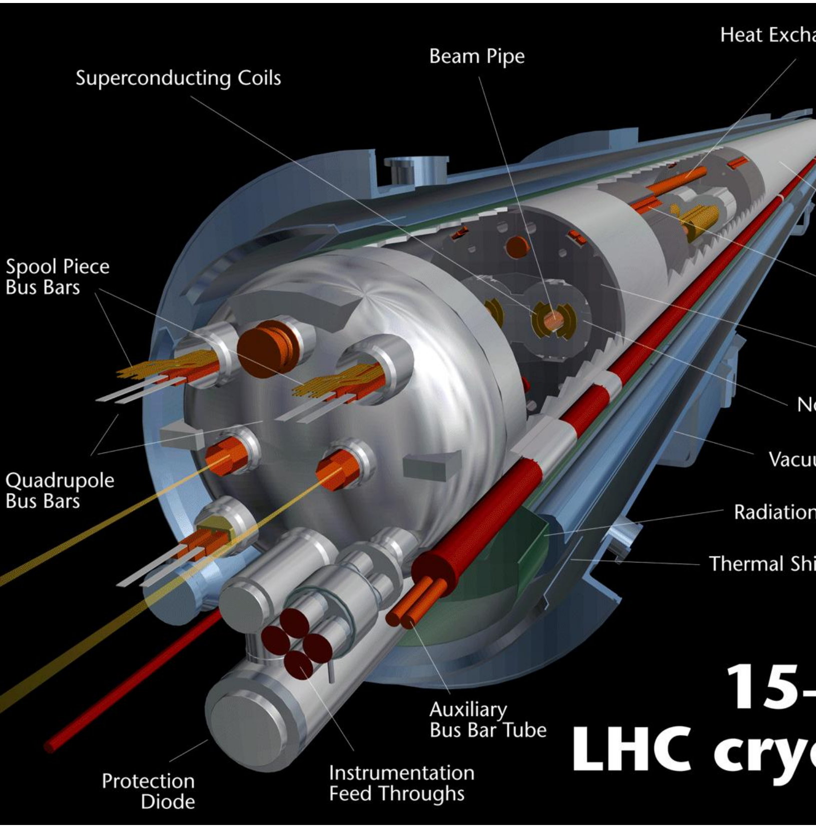
Linac
↓
Booster
↓
PS
↓
SPS
↓
LHC

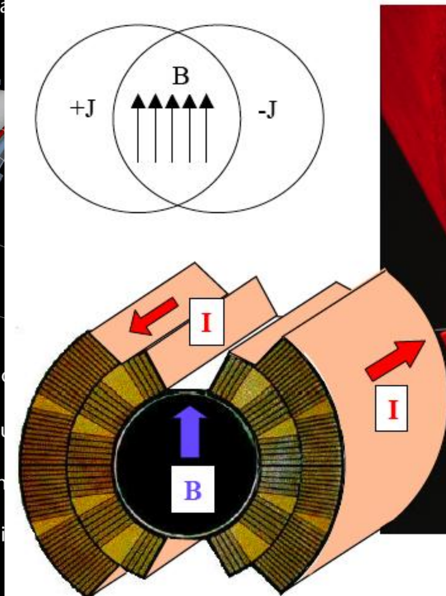


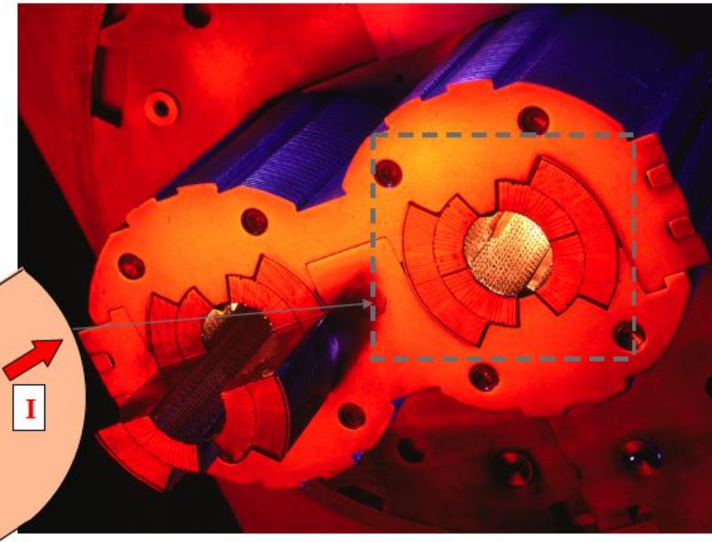
Start the protons out here

> 50 years of CERN history still alive and operational

LHC Accelerator Challenge: Dipole Magnets







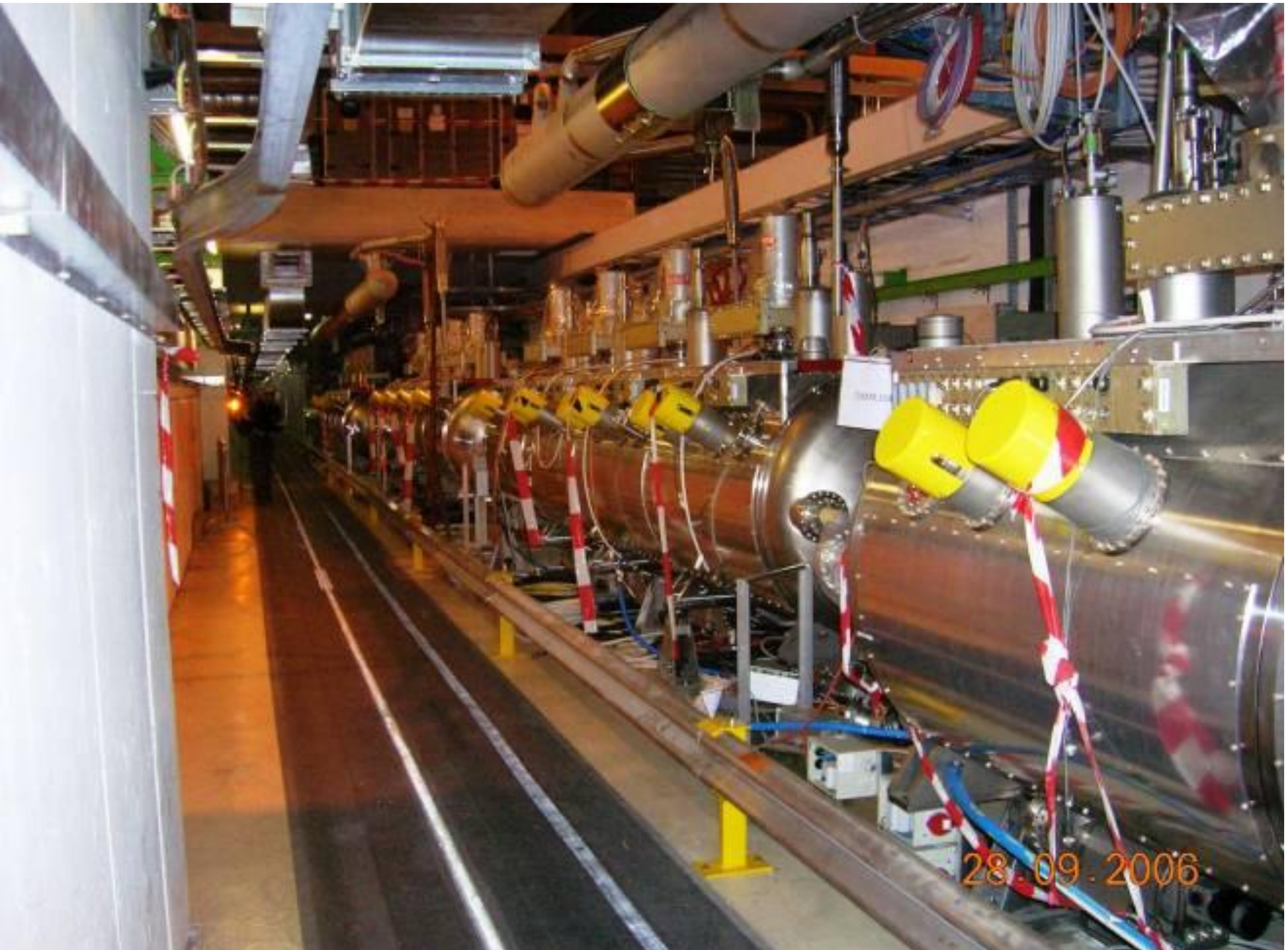
Magnetic Field for Dipoles
p (TeV) = 0.3 B(T) R(km)

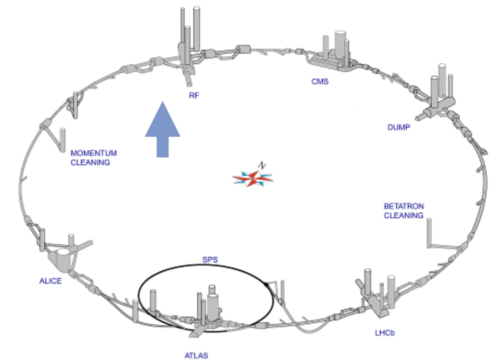
For p = 7 TeV and R = 4.3 km
➪ B = 8.4 T
➪ Current 12 kA

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

LHC magnets are cooled with pressurized superfluid helium

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

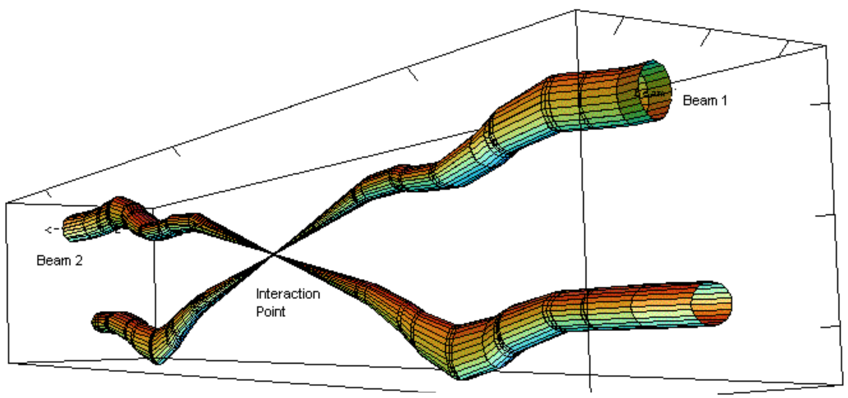




Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the ~ $1/m^4$ behaviour of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

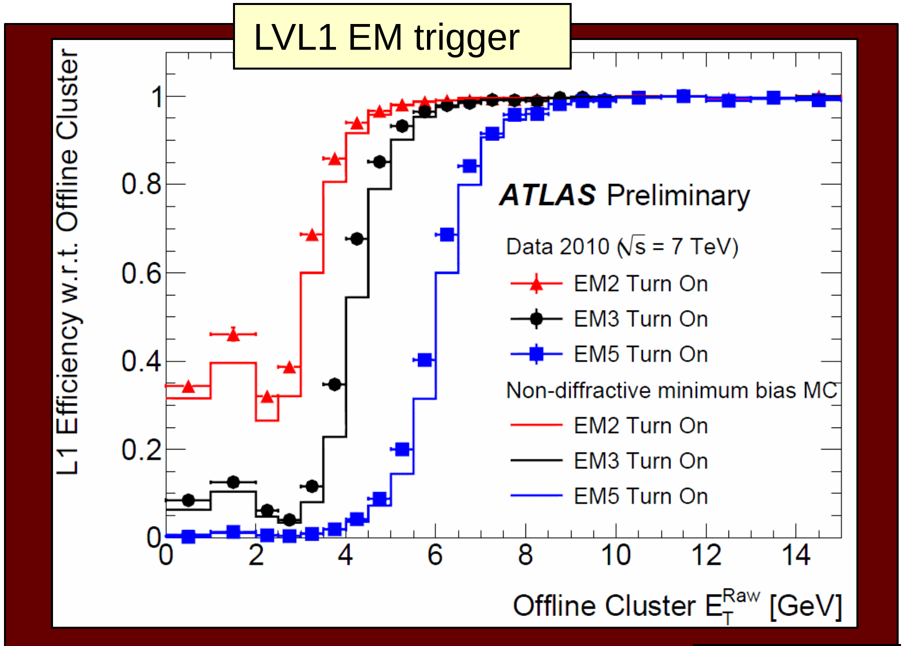
	LHC at 7 TeV	LEP at 100 GeV
Synchrotron radiation loss	6.7 keV/turn	3 GeV/turn
Peak accelerating voltage	16 MV/beam	3600 MV/beam

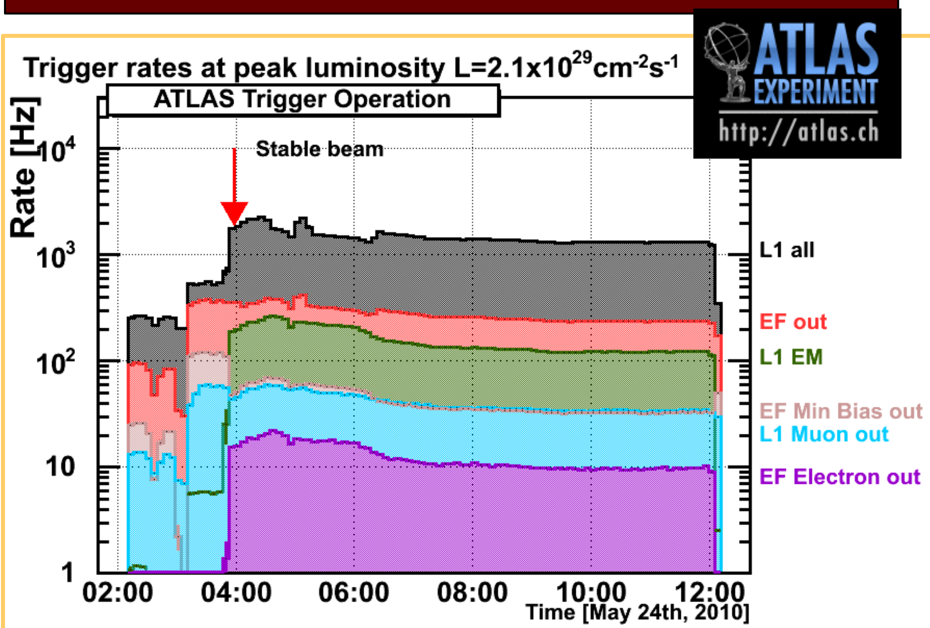
Special quadrupole magnets ('Inner Triplets') are focussing the particle beams to reach highest densities ('luminosity') at their interaction point in the centre of the experiments

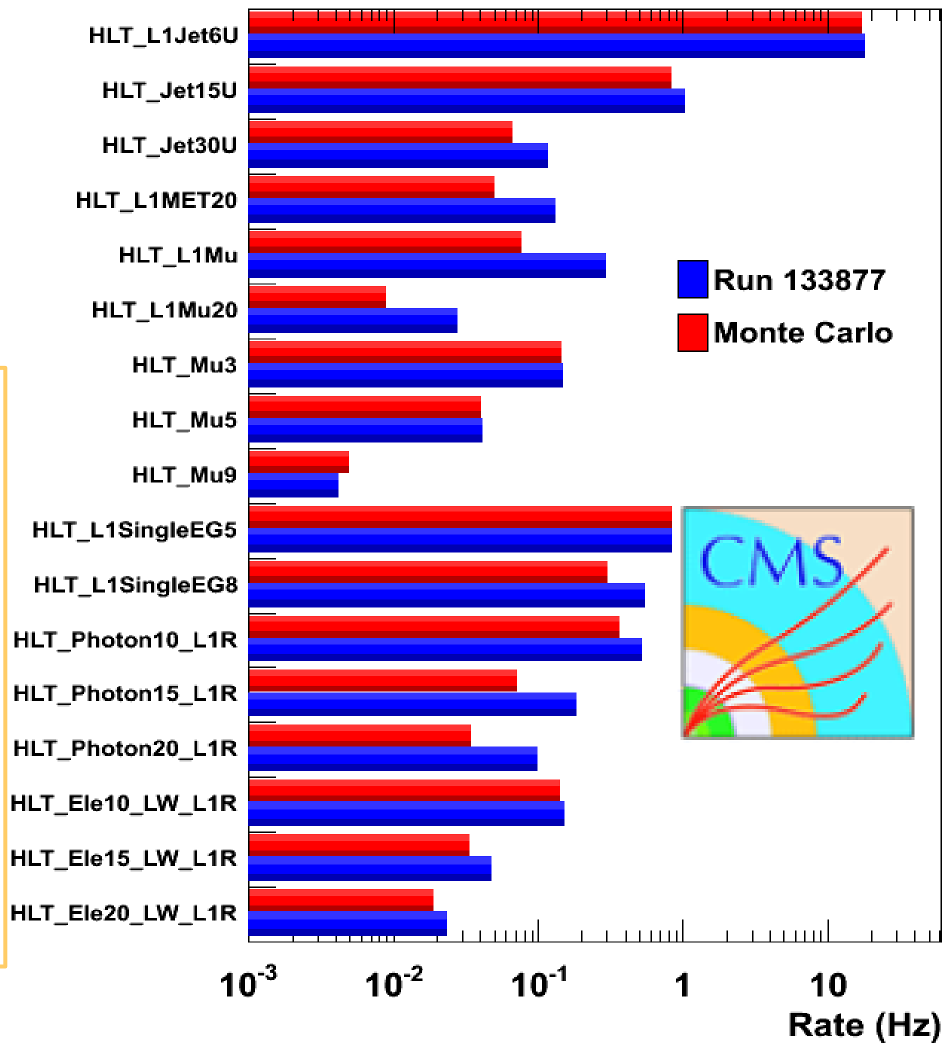


Relative beam sizes around the collision point

Triggers work and are well understood, but did not yet have a 'hard' job to do…



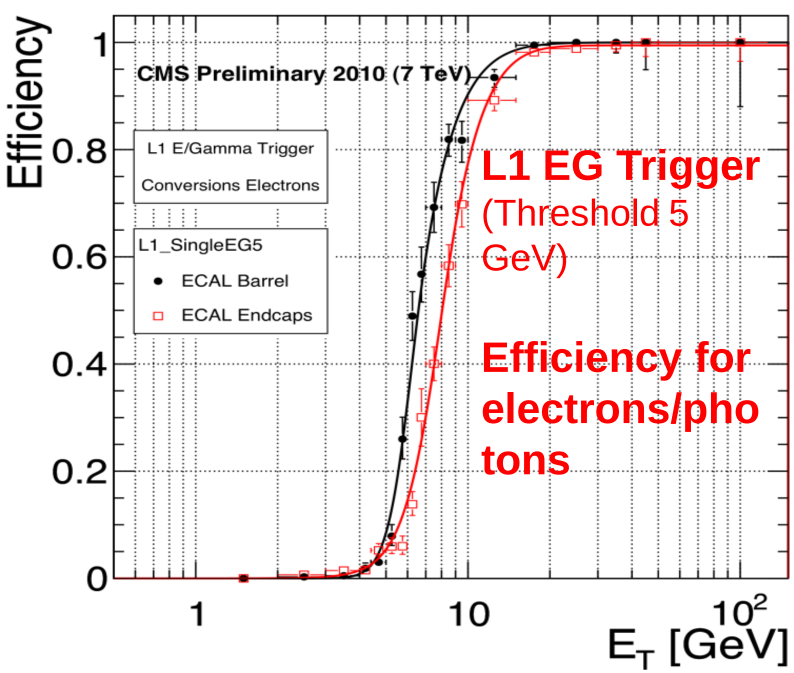


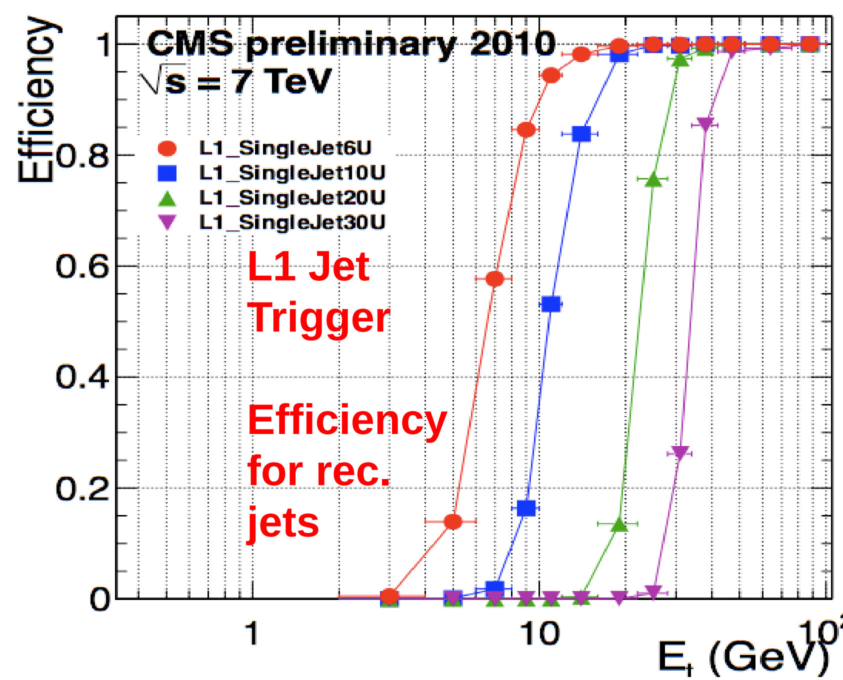


DAQ & L1 and HLT Triggers

- **L1/DAQ**
  - **L1 ~ 45kHz; Event size at DAQ 500 kB/evt (**after compression in HLT for StreamA **~250kB); 200-400Hz of data to storage.**
  - Timing has precision of 1 ns or better

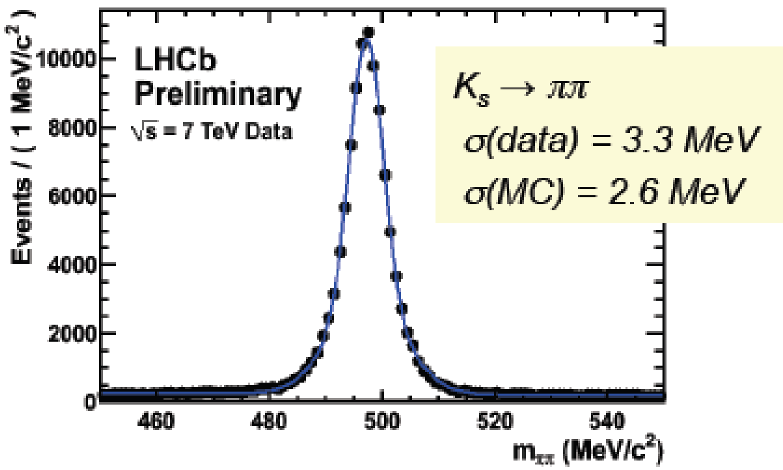
- **All L1 triggers have high efficiency and sharp turn-on curves**

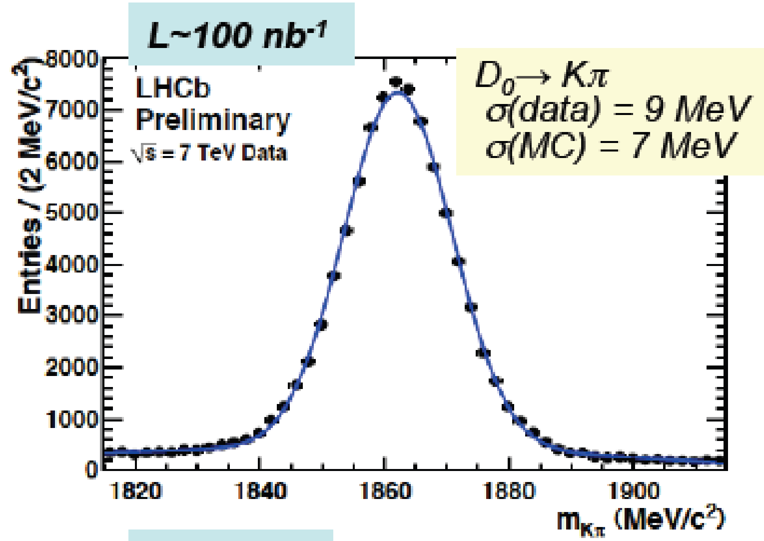


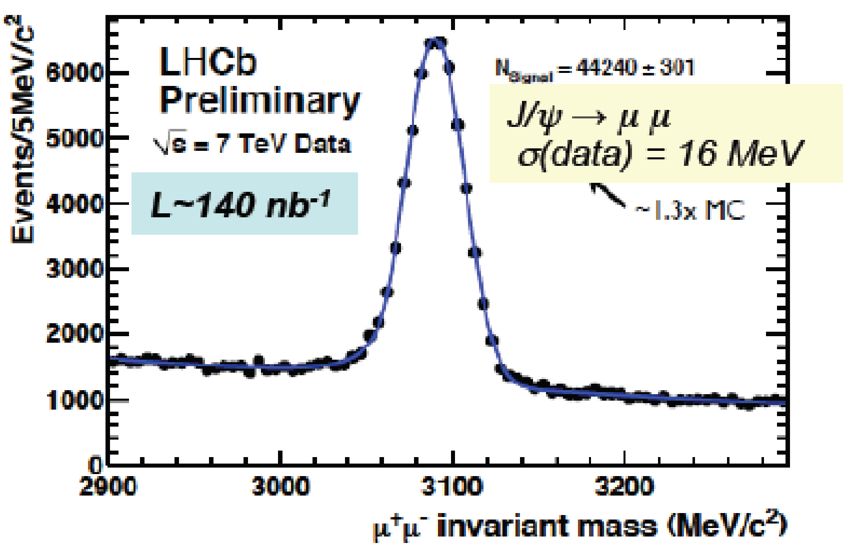


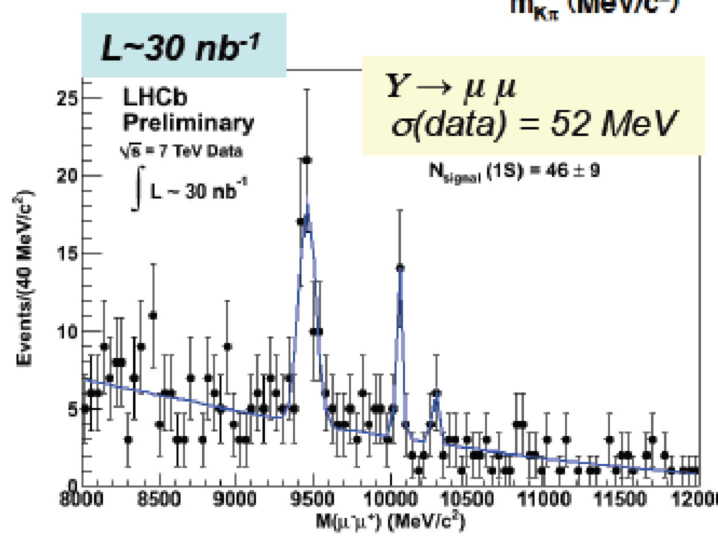
Signal peaks & present mass resolution

(Will be improved !!!)





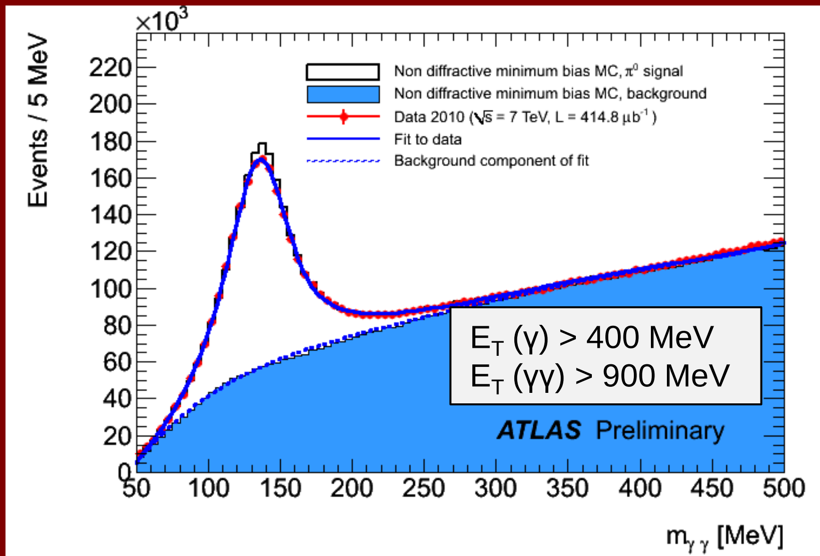


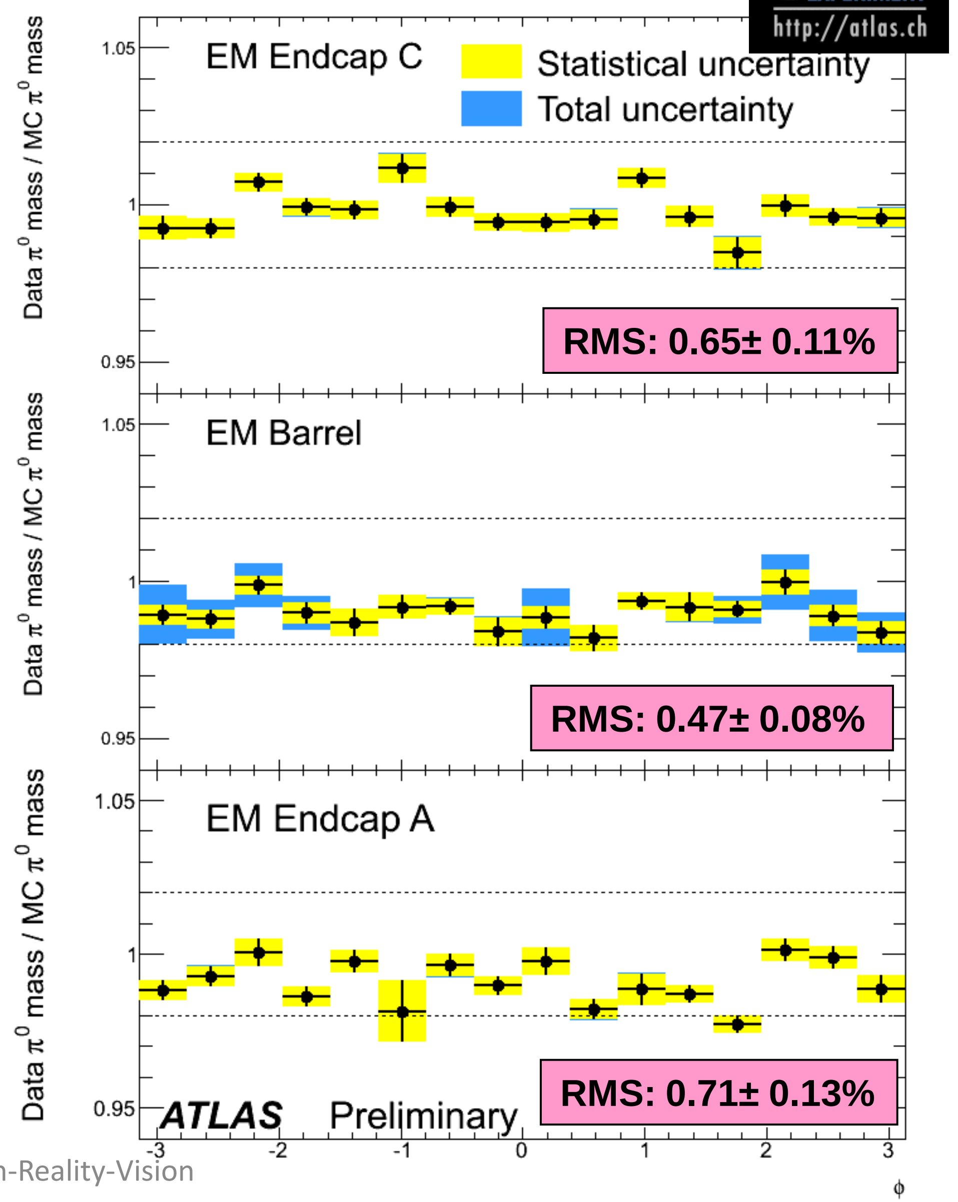


12

ICHEP, Paris 2010

Understanding the EM calorimeter response uniformity and E-scale with $\pi^0 \rightarrow \gamma\gamma$

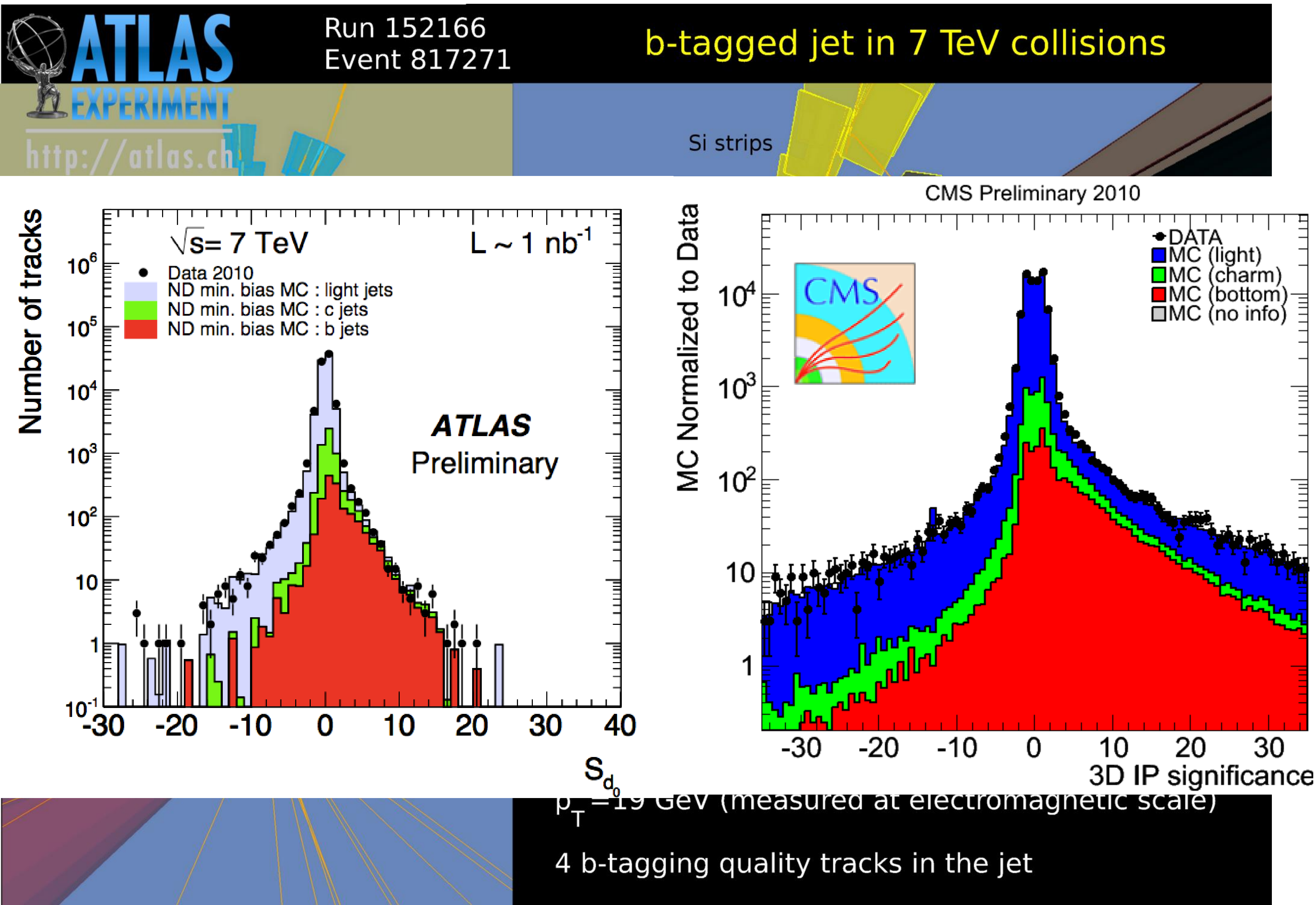




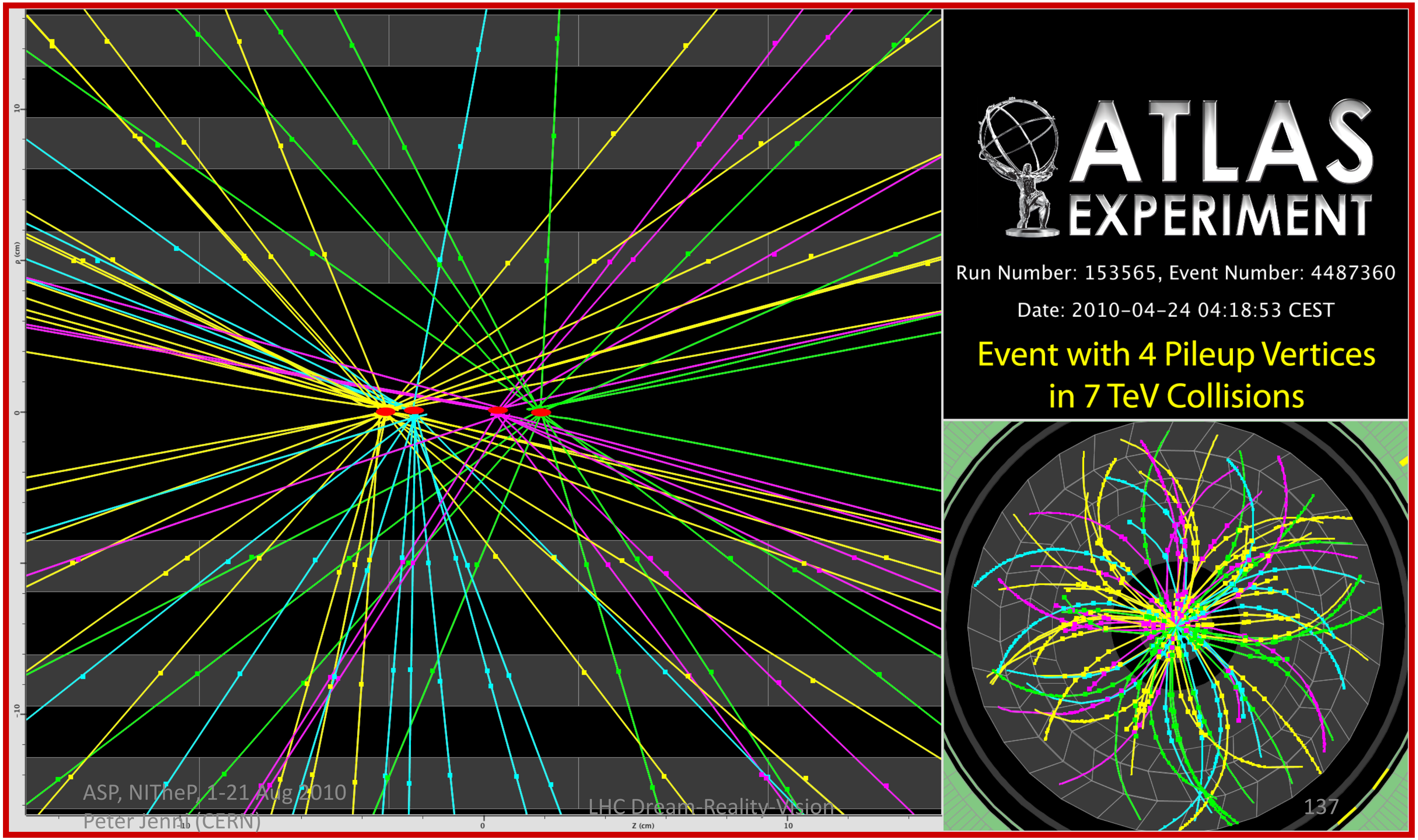
Fit results:
M= 135.05 ± 0.04 MeV (PDG: 134.98)
σ ~ 20 MeV
Systematics: m: 1%; σ~ 10%

E-scale in this range known to ~ 2 %
Response uniformity in φ in each calorimeter: ~ 0.7%

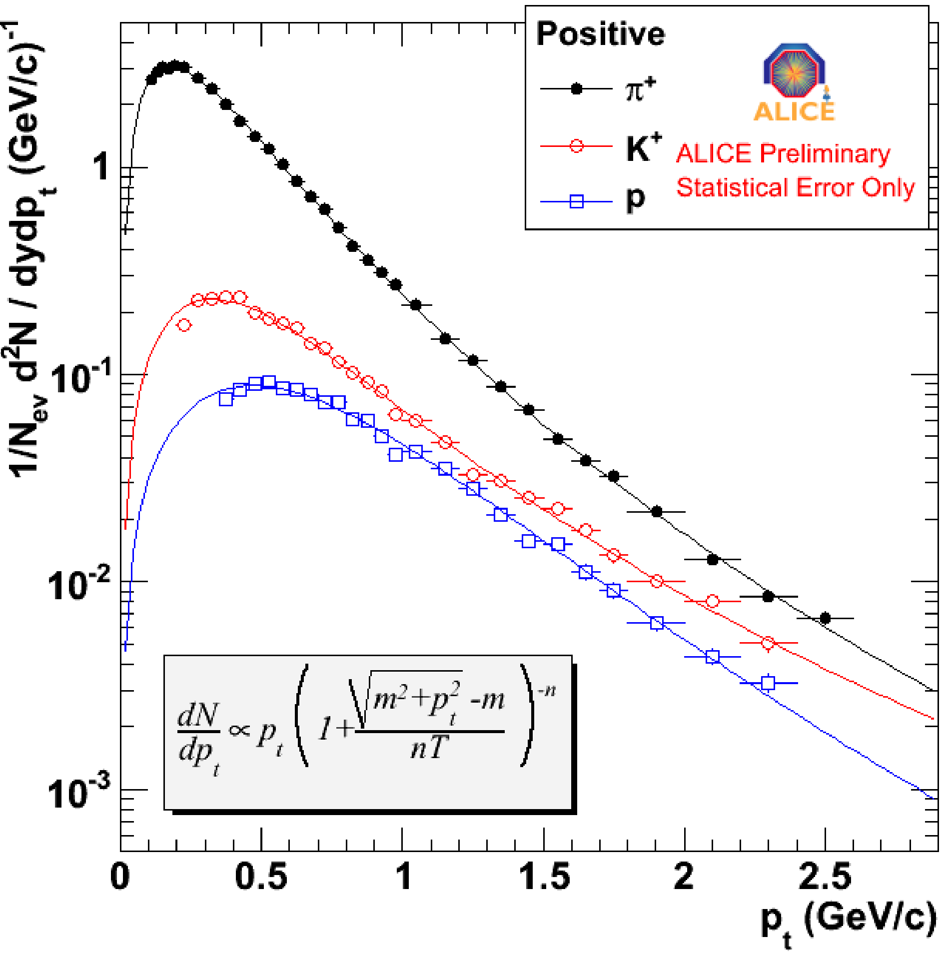
b - tagging

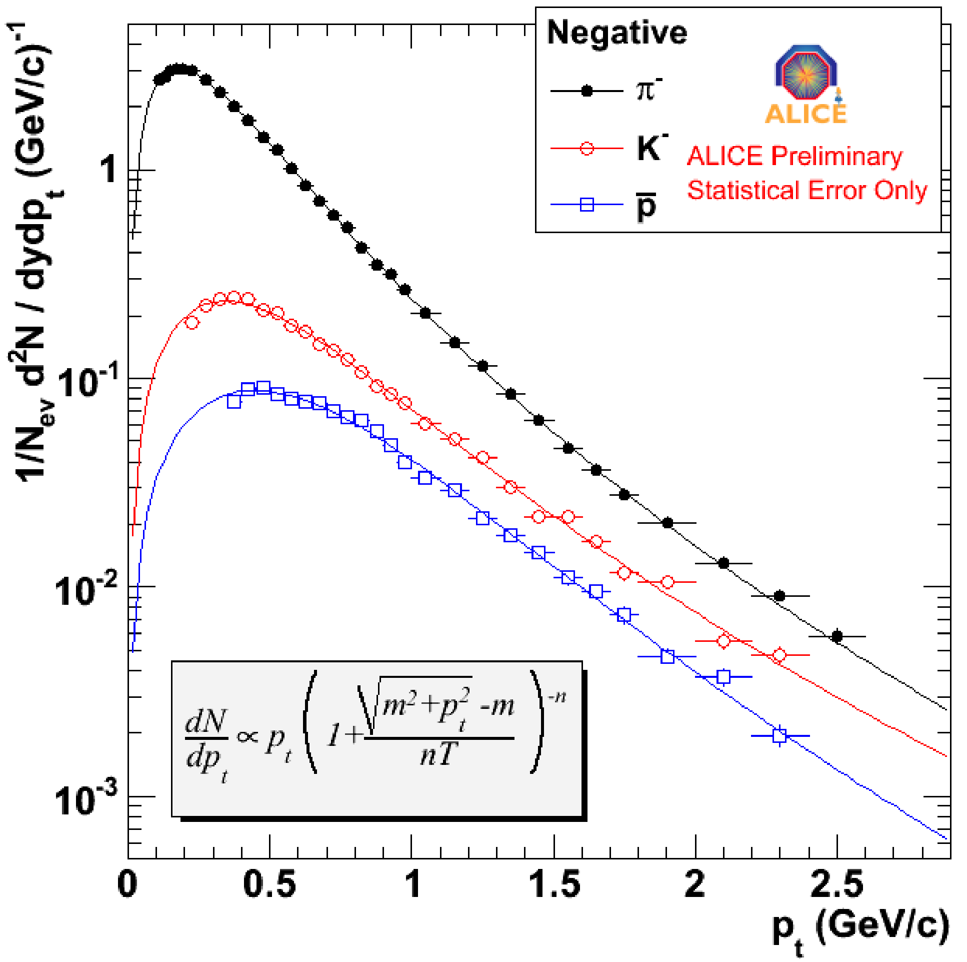

ATLAS EXPERIMENT
http://atlas.ch
Run 152166
Event 817271
b-tagged jet in 7 TeV collisions
Si strips
$\sqrt{s}$= 7 TeV
L ~ 1 nb^{-1}
Data 2010
ND min. bias MC : light jets
ND min. bias MC : c jets
ND min. bias MC : b jets
ATLAS Preliminary
Number of tracks
S_{d_0}
CMS Preliminary 2010
CMS
DATA
MC (light)
MC (charm)
MC (bottom)
MC (no info)
MC Normalized to Data
3D IP significance
p_T =19 GeV (measured at electromagnetic scale)
4 b-tagging quality tracks in the jet

Preparing for the future : pile-up reconstruction
4 pp interactions in the same bunch-crossing



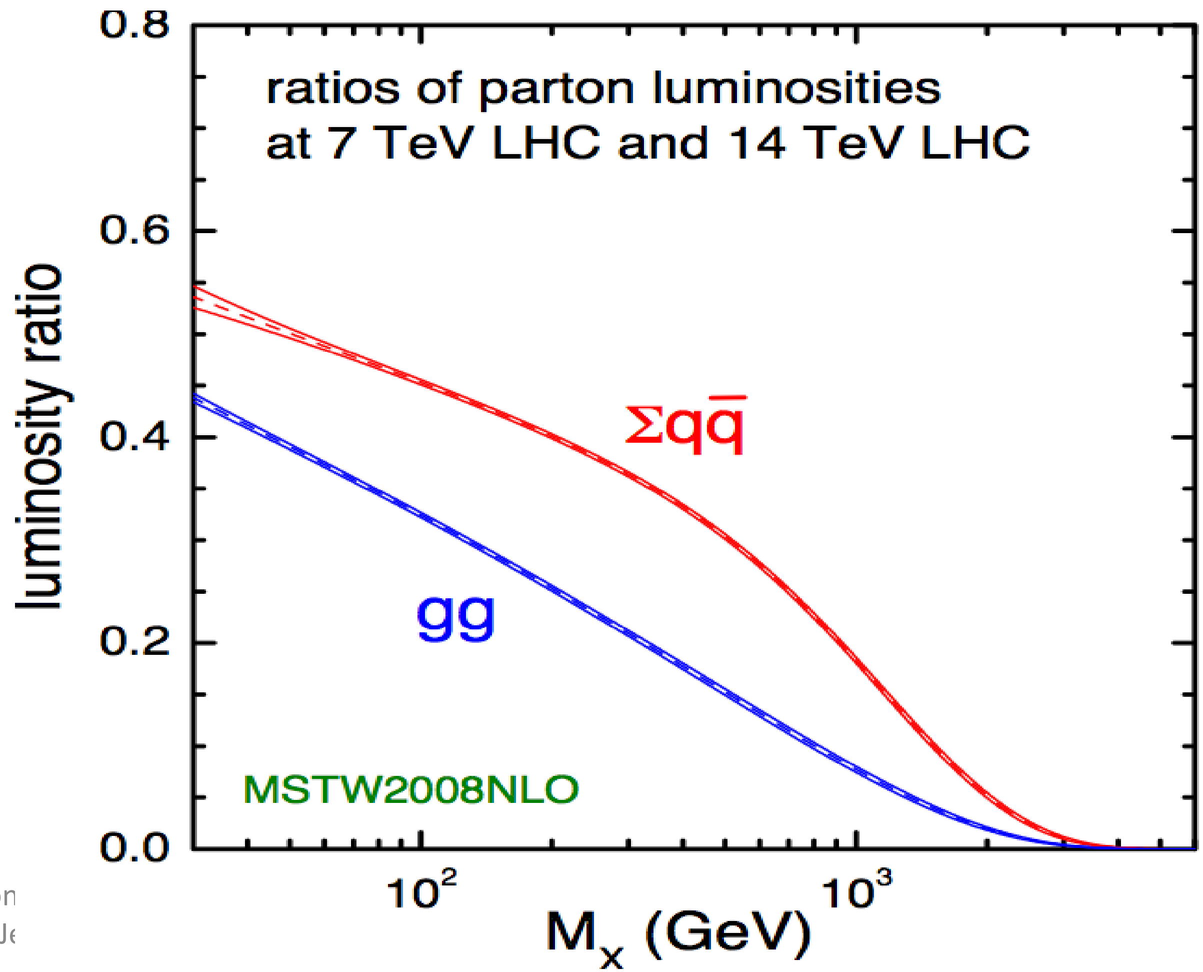
Stable: π, K, p at 900 GeV





Comparing 7 TeV to 14 TeV...

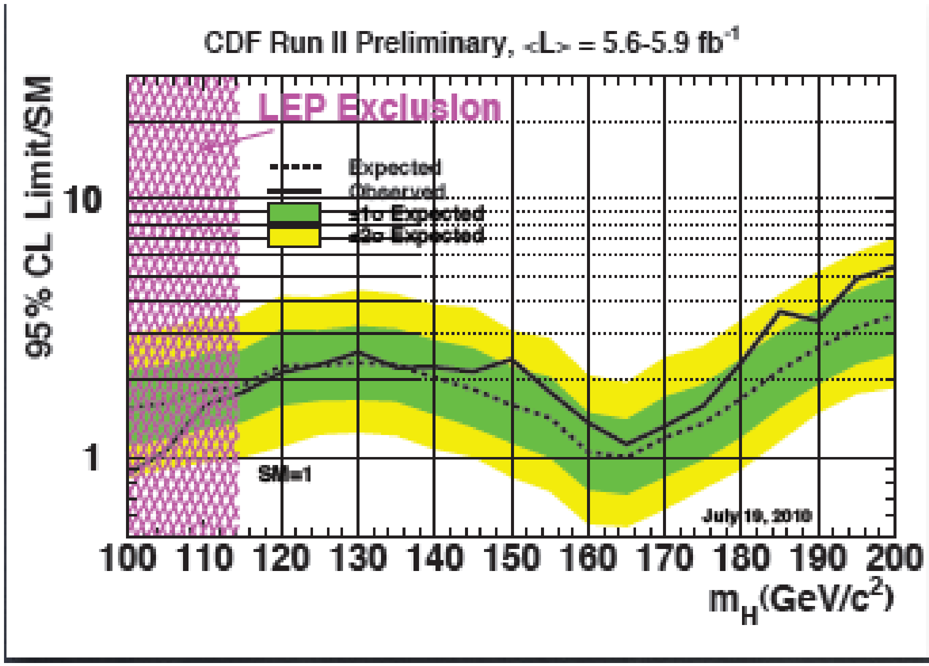
Ratios of cross-sections at 7/14 TeV for processes induced by gg and qq (from James Stirling)

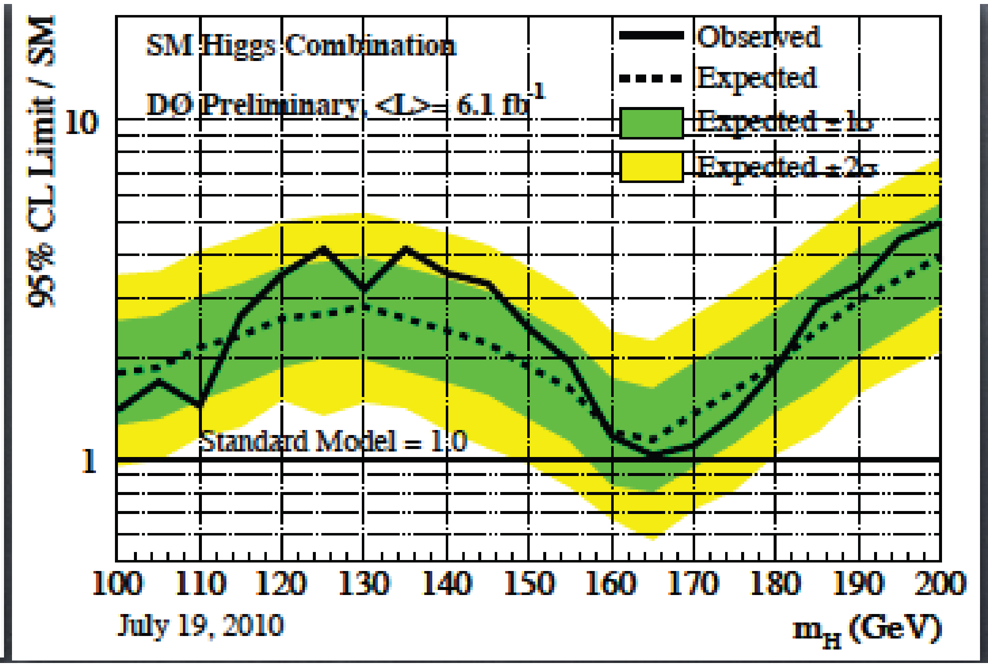


At lower energy it is of course more difficult to produce high mass objects...

Both Tevatron experiments have released new results (ICHEP)

The analyses are very sophisticated combining many final state channels and topologies, exploiting multi-variate analyses methods





Summary of low & high mass results

Channel	Expt	Dataset now	Increase since Nov. 2009 combination
H → WW	D0	6.7	24%
H → WW	CDF	5.9	23%
WH → lvbb	CDF	5.7	30%
WH → lvbb	D0	5.3	6%
ZH/WH→METbb	CDF	5.7	60%
ZH/WH→METbb	D0	6.4	23%
ZH → llbb	CDF	5.7	40%
ZH → llbb	D0	6.2	45%
H → γγ	CDF	5.4	New!
H → γγ	D0	4.2	0%
H → ττ	CDF	2.3	15%
H → ττ	D0	4.9	0%
ZH/WH→qqbb	CDF	4	100%
ttH	D0	2.1	0%

Each channel represents several "sub-channels"

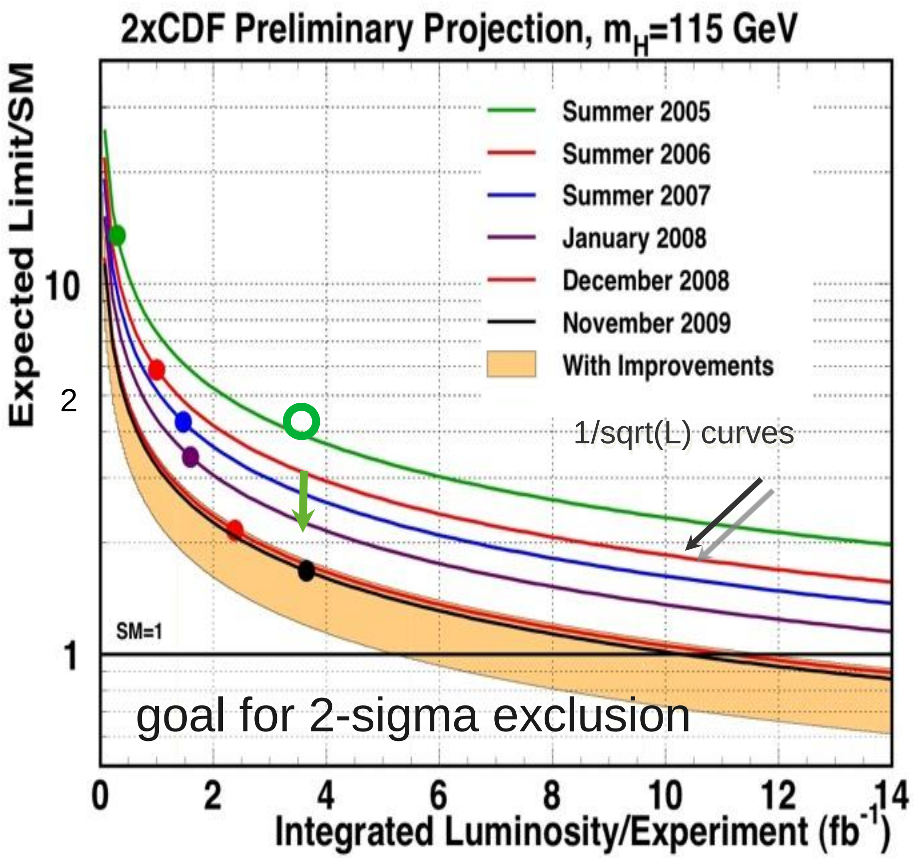
H→WW Sub-channels
opposite sign leptons + 0-jets
opposite sign leptons + 1-jets
opposite sign leptons + 2-jets
opposite sign leptons , low M_{ll}
same sign leptons
trileptons, no Z candidate
trileptons, Z candidate, 1-jet
trileptons, Z candidate, 2-jet
electron + hadronic tau
muon + hadronic tau
leptons + jets

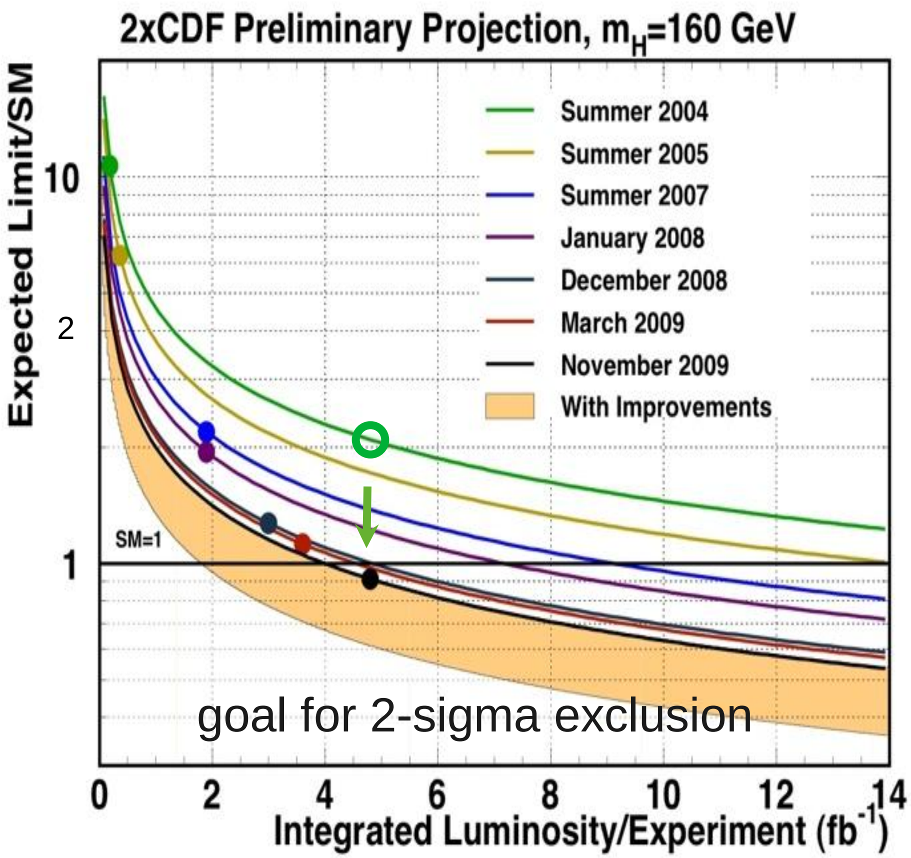
New

Ben Kilminster, ICHEP 2010

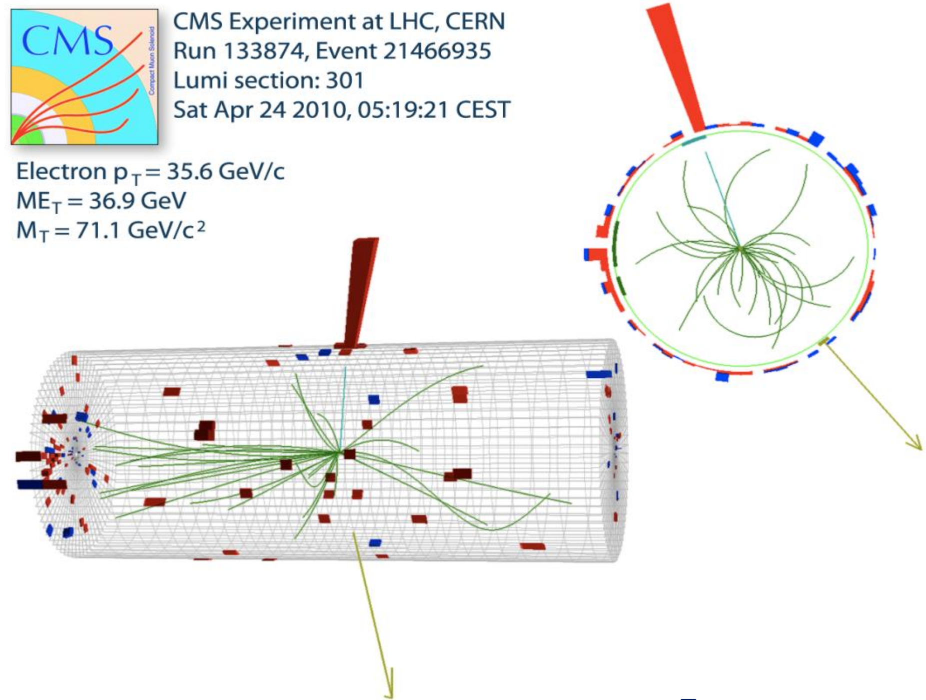
21

Tevatron Higgs Search Progress

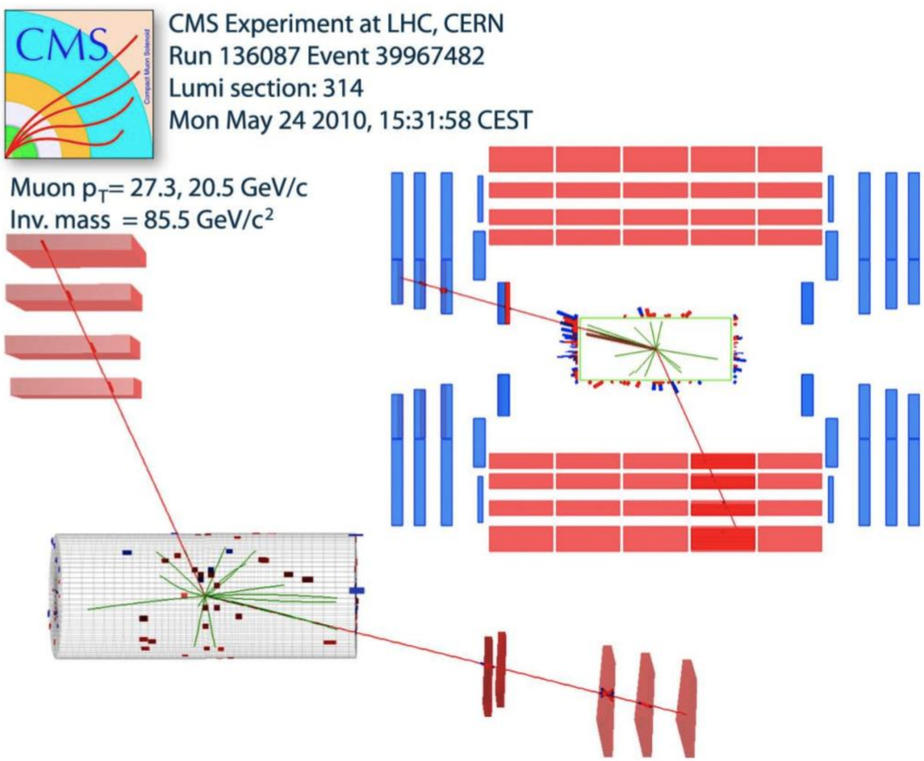




At the LHC we just enter the era of the W and Z …



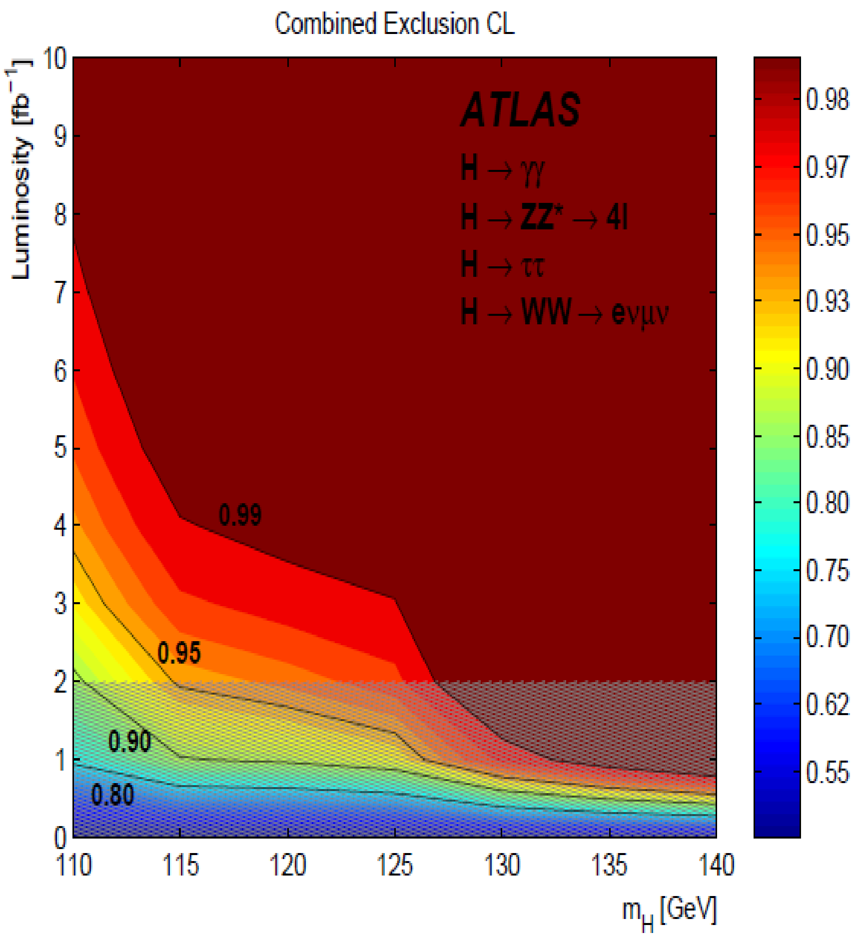
W → eν

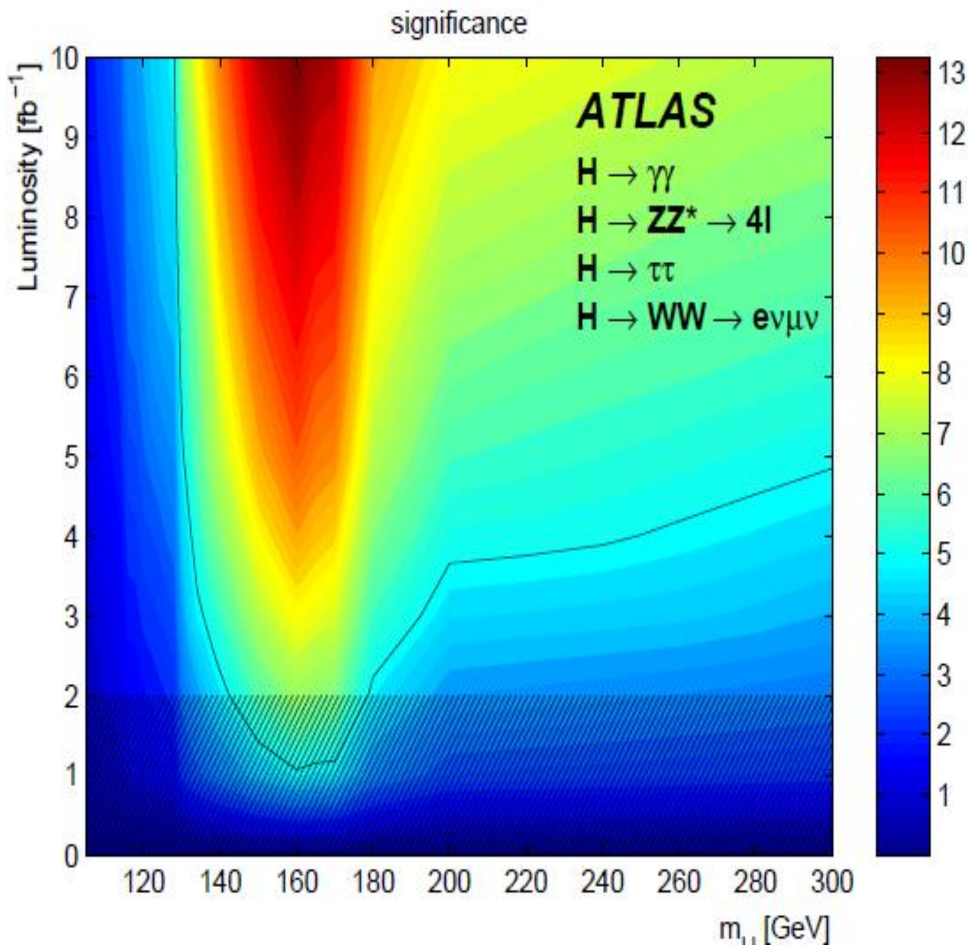


Z → $\mu^+\mu^-$

Combining several channels in a single experiment (ATLAS as example, of course CMS very similar)

14 TeV





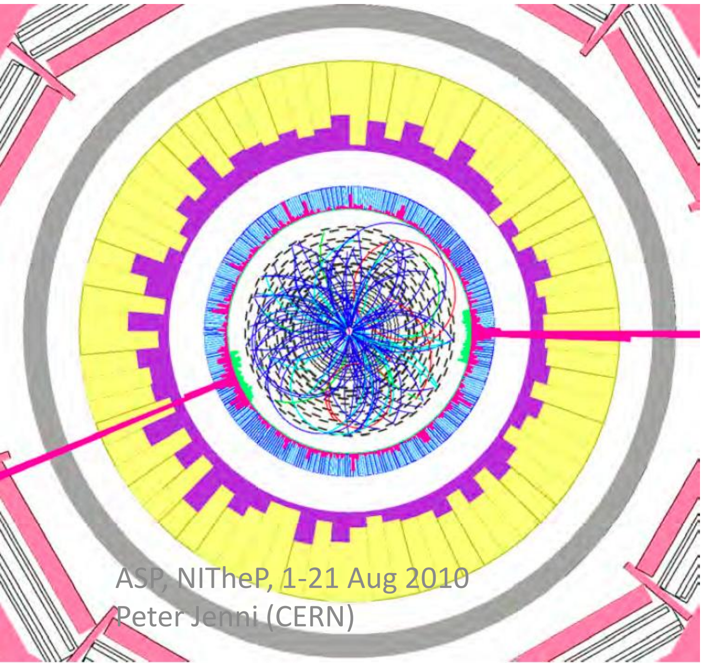
Exclusion confidence levels

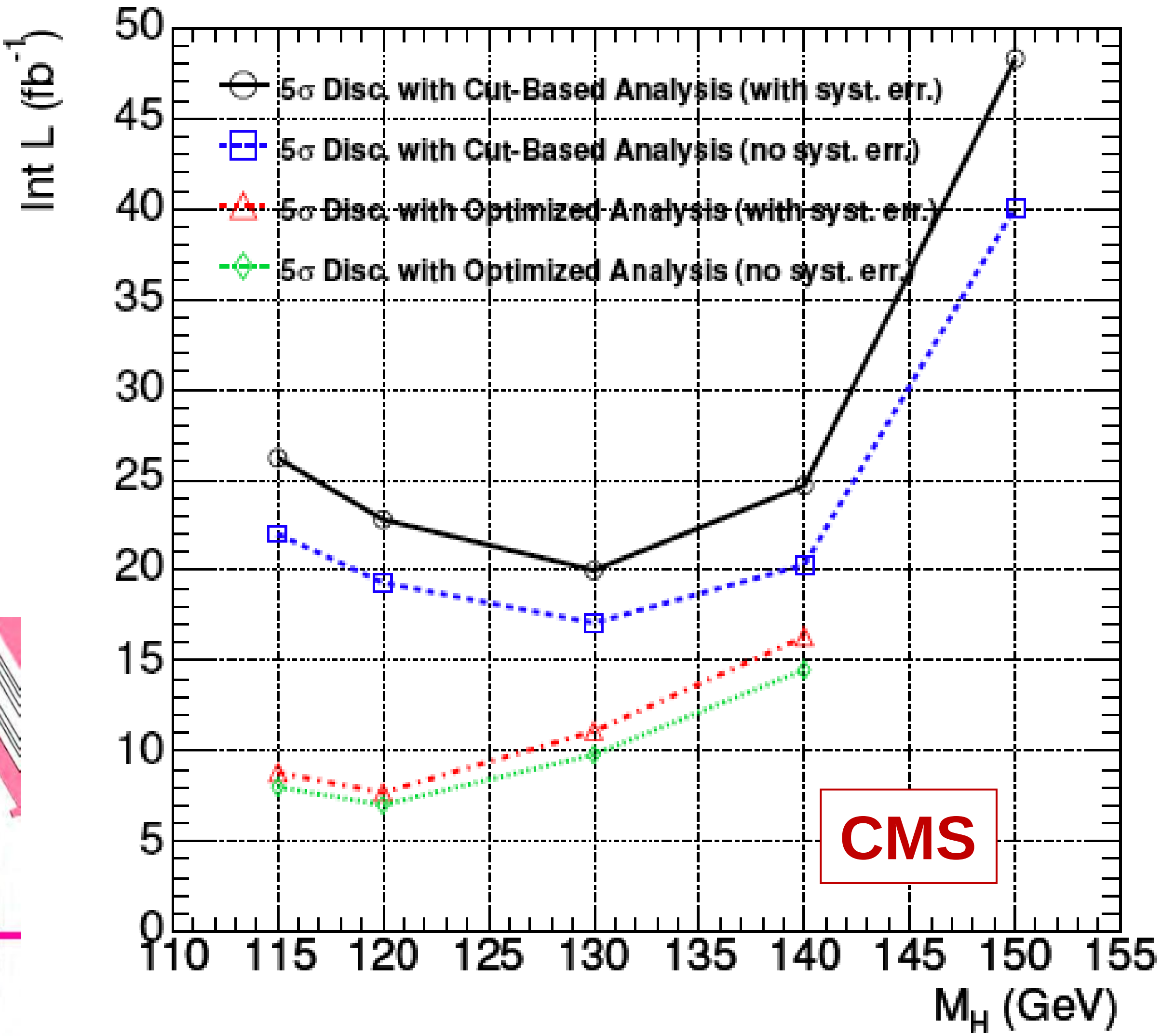
Discovery significance levels in σ

Example of another channel for the low mass region

***H* → $\gamma\gamma$**

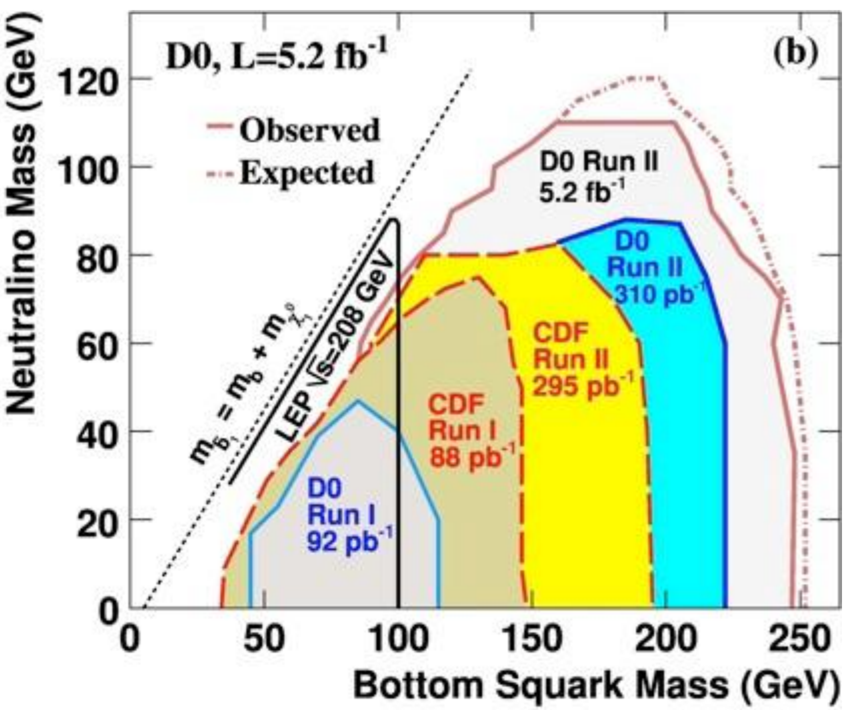
Optimized analysis: discovery with ~ 10 fb^{-1}

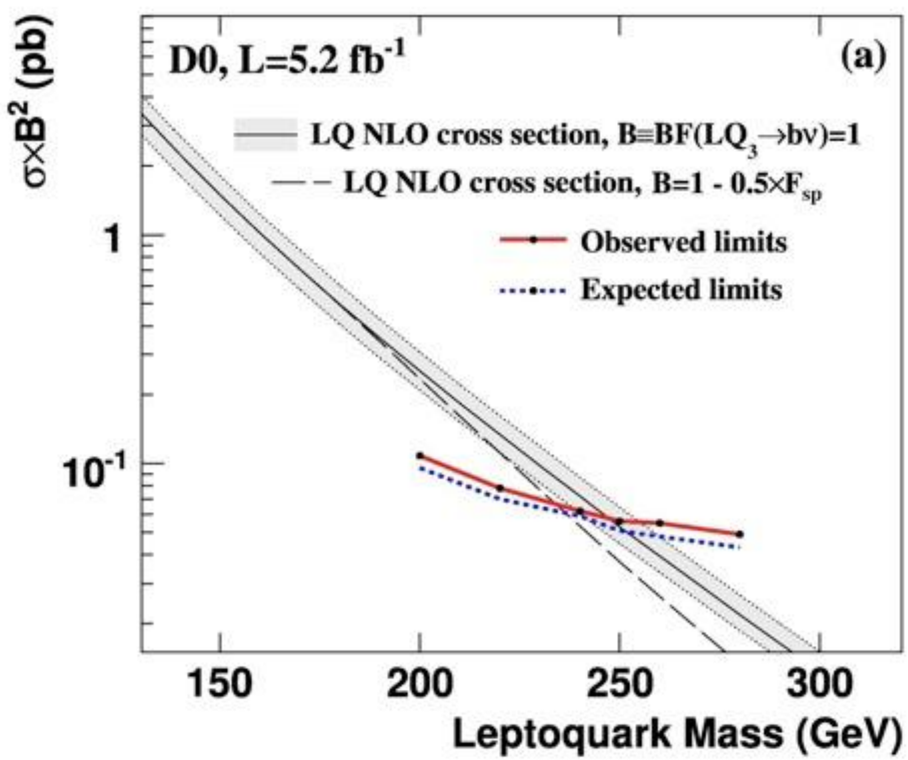




A very impressive spectrum of sophisticated searches have been reported from the Tevatron experiments, there is no way to do any justice here for this excellent work!

Just a few examples, which however also illustrate that it will be very difficult to push these searches much further, the LHC will have a much easier time thanks to the higher energy…

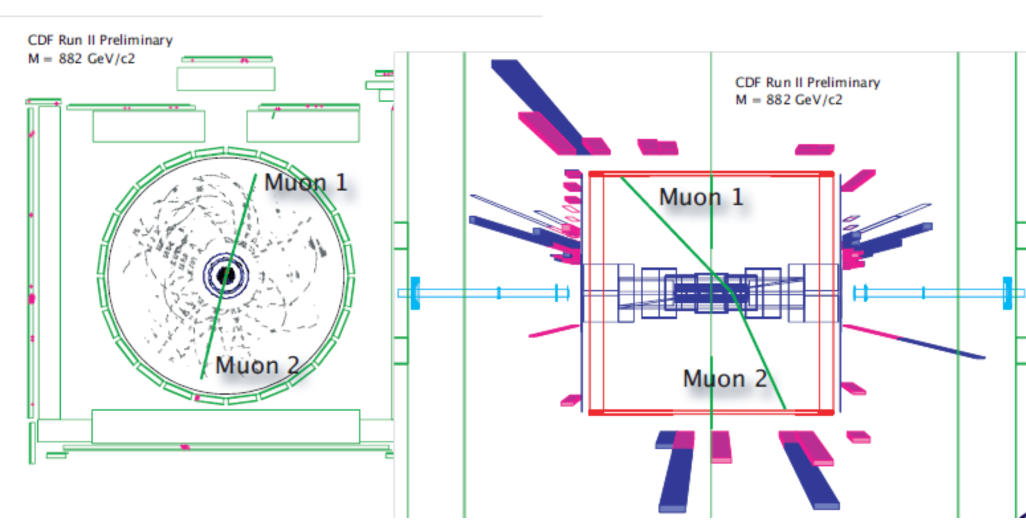


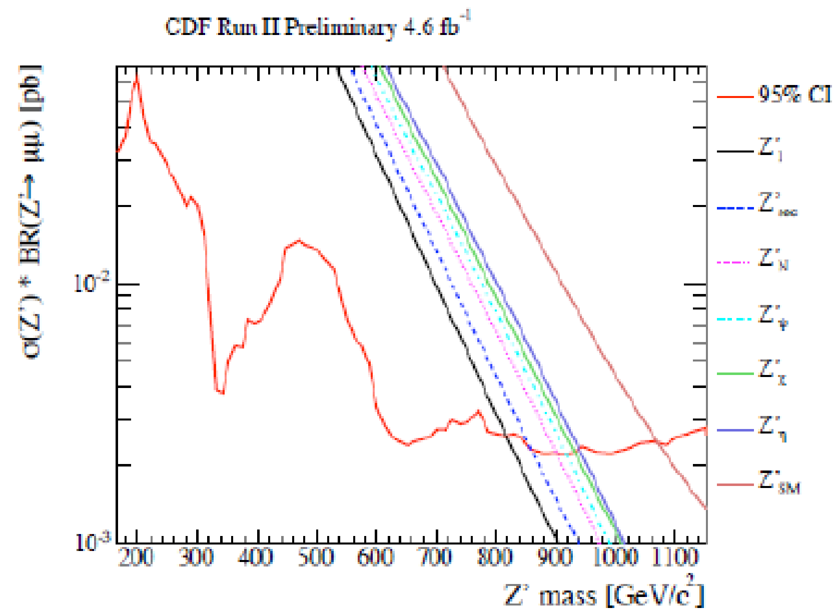


Search for new heavy particles decaying into lepton pairs or jet pairs

The Tevatron limits reach typically at 1 TeV, and cannot improved much further because of the Collider energy

highest mass event: $m_{\mu\mu}$ = 882 GeV **CDF**





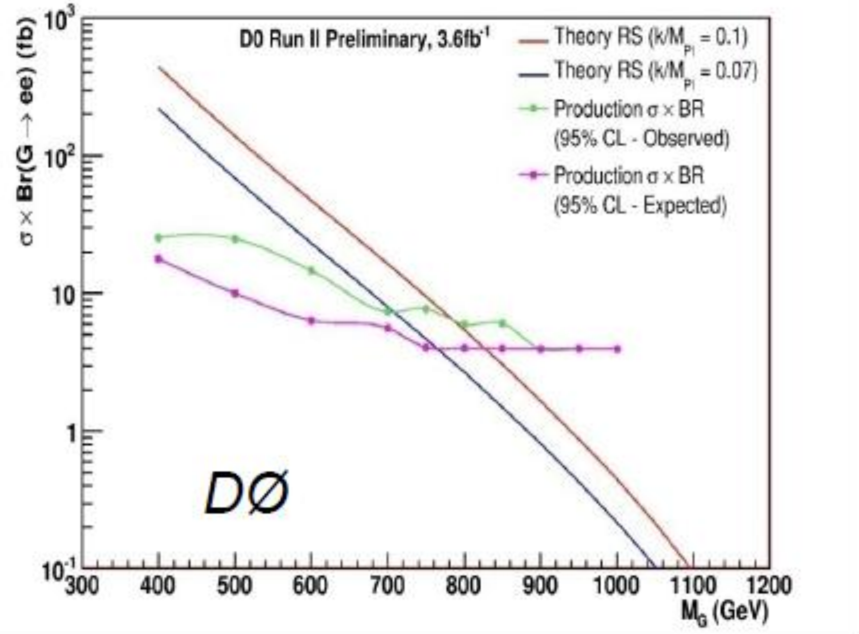
Z'_{SM} > 1.071 TeV (95% CL)

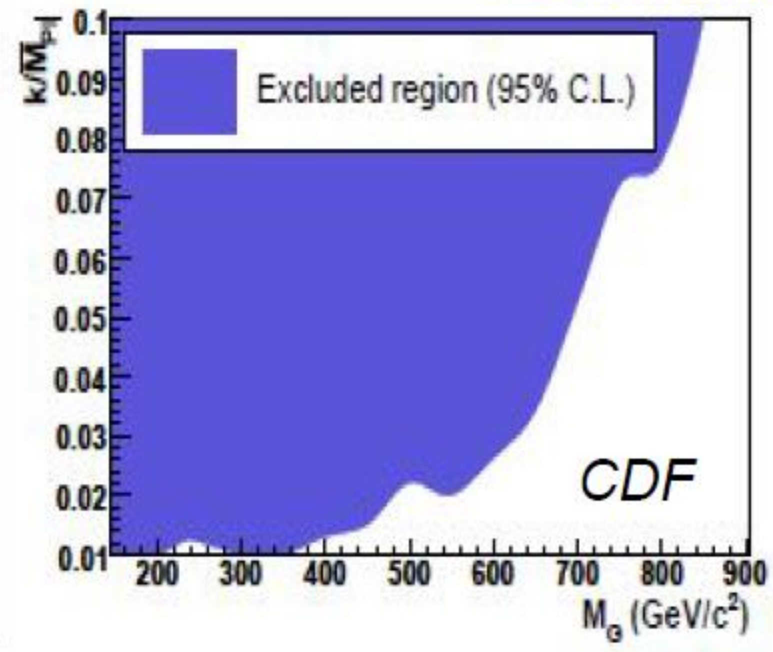
Limits on Graviton $q\,\bar{q} \rightarrow G_{RS} \rightarrow e\,e$

3.6 fb^{-1}

2.5 fb^{-1}

PRL 102, 031801(2009)



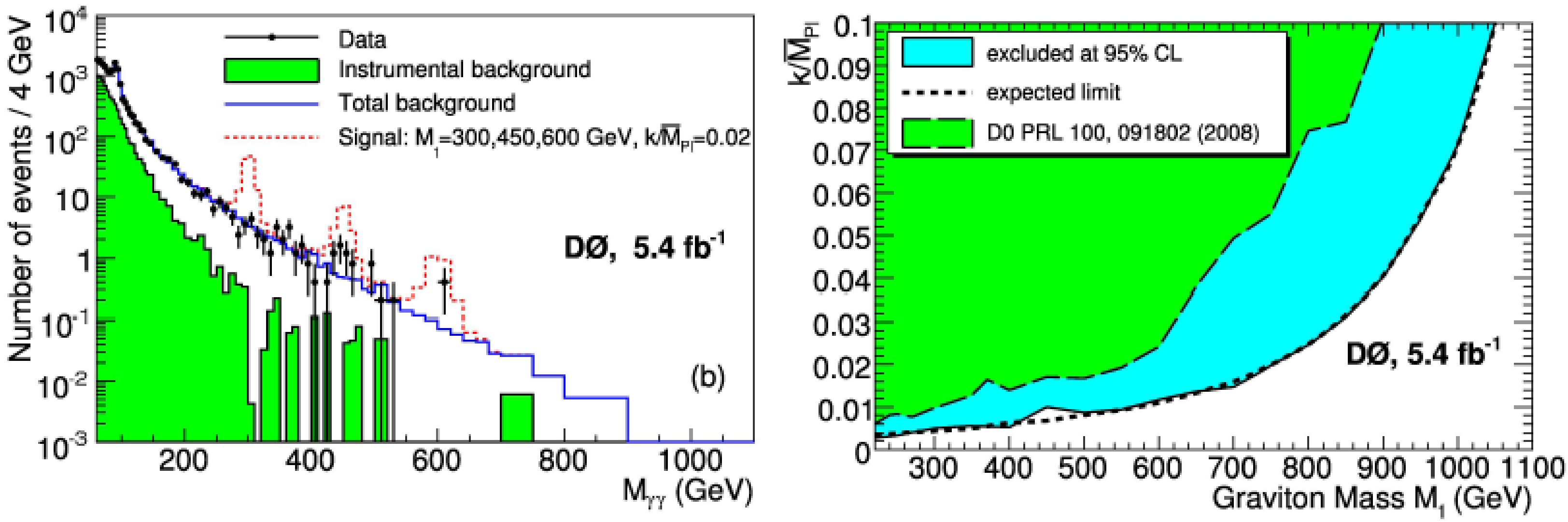


95%C.L.		RS	$(k/M_{pl}) = 0.1$
CDF	obs. = exp.		$M(G_{RS}) > 848$ GeV
D0	obs. (exp.)		$M(G_{RS}) > 786\ (826)$ GeV

(slide from
M-C Cousinou,
HCP2009)

Extra Dimensions

- a solution to a hierarchy problem (Arkani-Hamed,Dimopulous,Dvali'99)
- warped extra dimensions (Randall, Sundrum'99) :
  - Kaluza-Klein excitations of a graviton, G^*, are coupled to SM particles and narrow
  - $B(G^* \to \gamma\gamma) \approx 2B(G^* \to l^+l^-)$

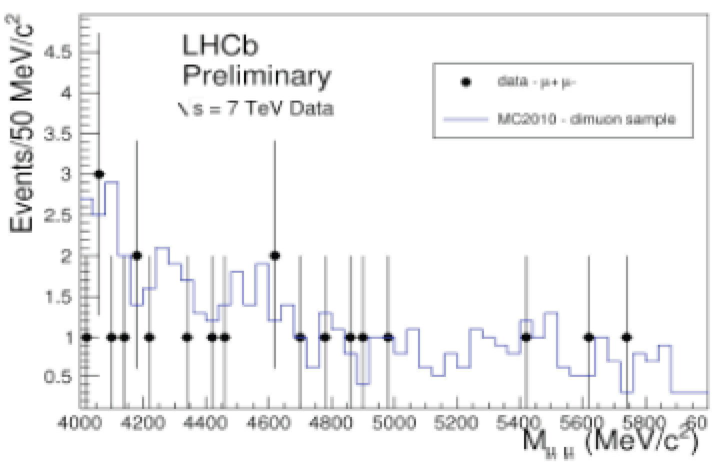


- excluded at 95% CL for $k/M_{Pl} = 0.1$:
  - D0'2010: $G^* \to \gamma\gamma, e^+e^-$: $M_{G*} <$ 1050 GeV PRL 104, 241802
  - CDF'2010: $G^* \to \gamma\gamma$: $M_{G*} <$ 976 GeV arXiv:0910.5170 [hep-ex]

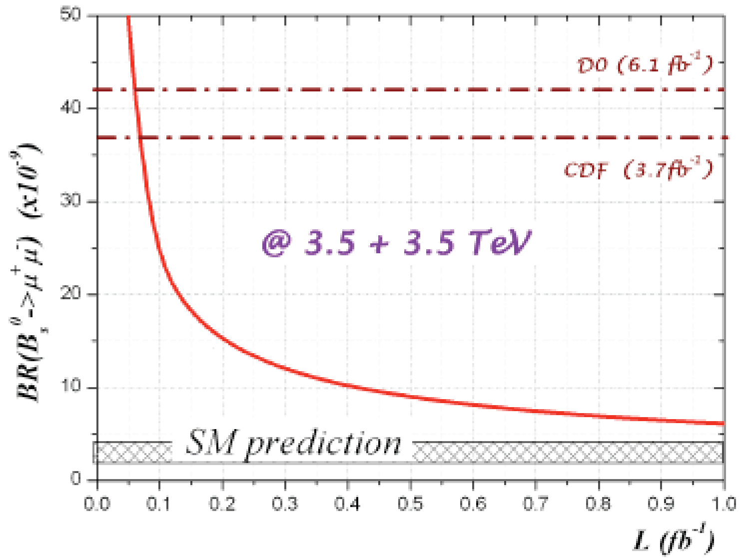
$B_s \rightarrow \mu\mu$

- *Super rare decay in SM with well predicted* $BR(B_s \rightarrow \mu\mu) = (3.2\pm0.2)\times10^{-9}$
  $BR(B_d \rightarrow \mu\mu) = (1.1\pm0.1)\times10^{-10}$
- *Sensitive to NP, in particular new scalars*
  In MSSM: $BR \propto \tan^6\beta / M^4_A$
- *For the SM prediction LHCb expects 10 signal in 1* fb^{-1}.

Background expected from MC is so far in good agreement with data



Exclusion limit @ 90% C.L.



Exclusion of SM enhancement up to $BR(B_s \rightarrow \mu\mu) \sim 7\times10^{-9}$ ***should be possible with*** $L\sim1\ fb^{-1}$

Current limit can be improved with < 100 pb^{-1}

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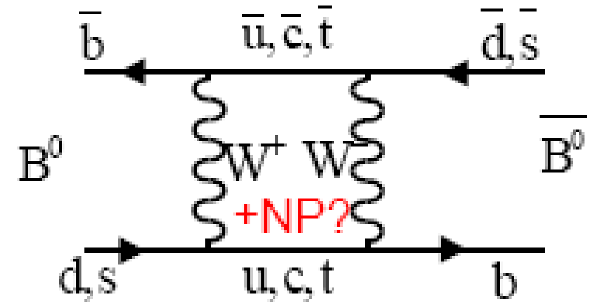
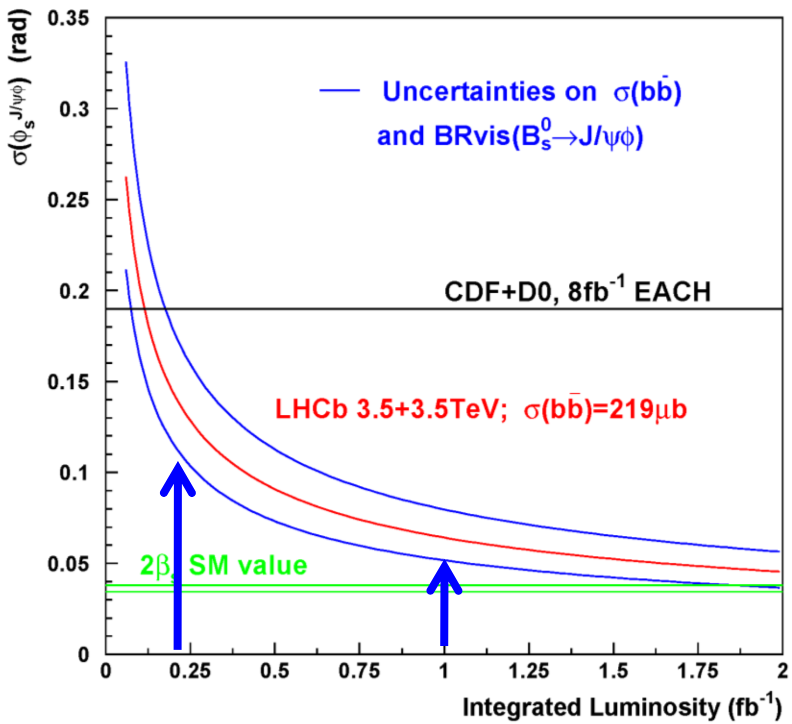
37

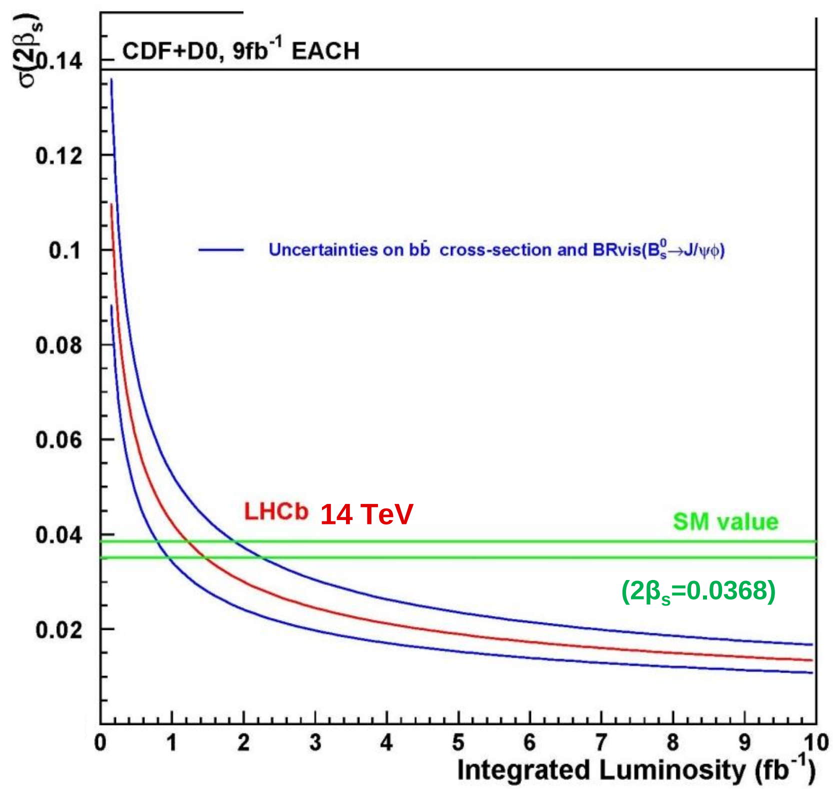
B_s-$\bar{B}_s$ mixing phase ϕ_s (from $B_s \to J/\psi\, \phi$)

Sensitive to New Physics effects in box diagrams

- $\phi_s = \phi_{s(SM)} + \phi_{s\,(NP)}$
- $\phi_{s(SM)} = -2\beta_s = -2\lambda^2\eta \sim -0.04$



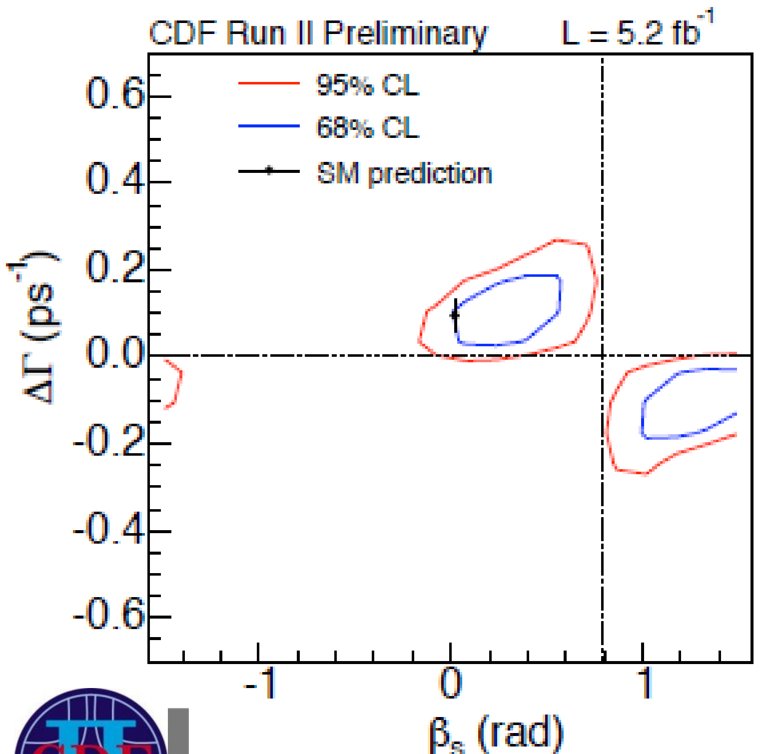


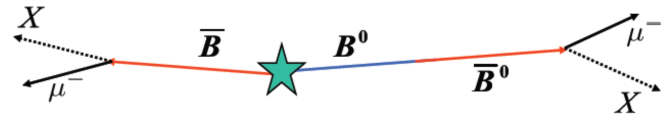


→ ***With ~0.2 fb^{-1} LHCb should improve on expected Tevatron limit***

Two new results which get a lot of attention (rightly so!)

Bs mixing phase (from $B_s \to J/\psi\ \phi$)





- Asymmetry in "same-sign" muons from decays of mixed neutral B mesons:

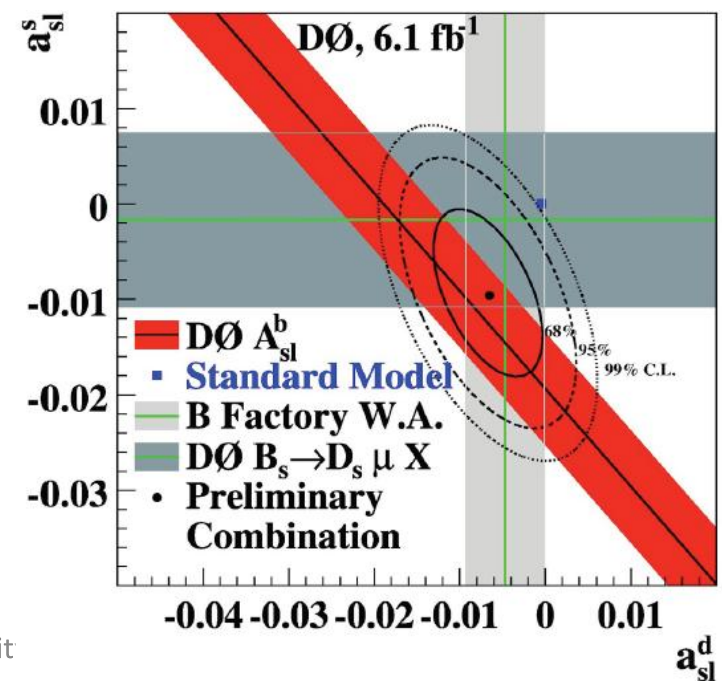
$$a^b_{sl} \equiv \frac{\Gamma(\bar{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\bar{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)}$$

$$A^b_{sl} \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

Grossman, Nir, Raz, Phys.Rev.Lett.97:151801,2006.

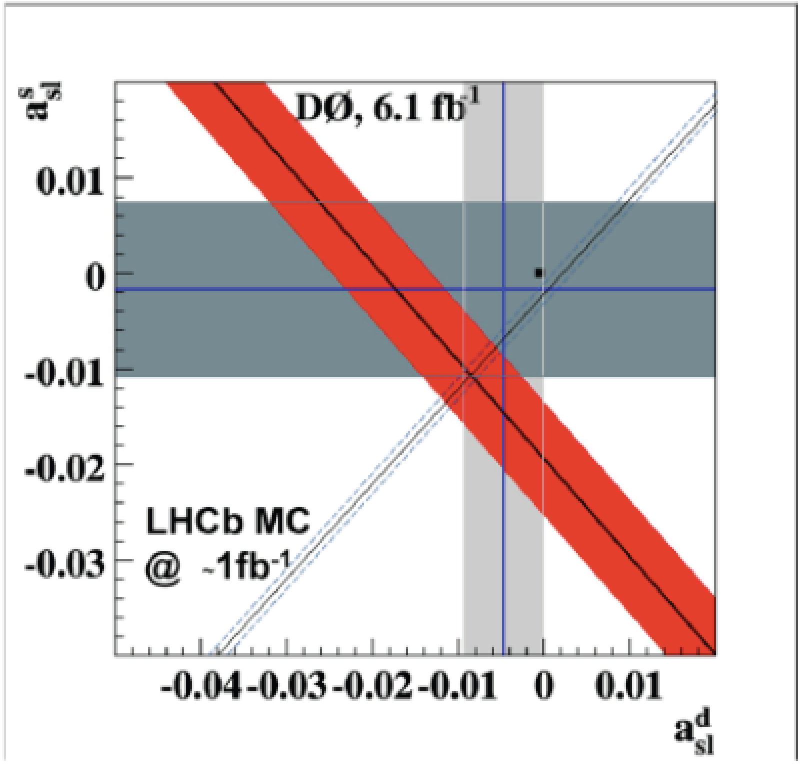
$$A^b_{sl} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\,\%$$

$$A^b_{sl}\,(\text{SM}) = \left(-2.3^{+0.5}_{-0.6}\right) \times 10^{-4}$$



$\Delta A_{fs} = (a_{fs}(B_s) - a_{fs}(B_d)) / 2$ @ LHCb using semileptonic decays $B_{d,s} \rightarrow D\mu\nu$

- *Provide constrain "orthogonal" to recent D^0 measurement*
- *With 100 pb^{-1} expect statistical precision similar to that of D0*



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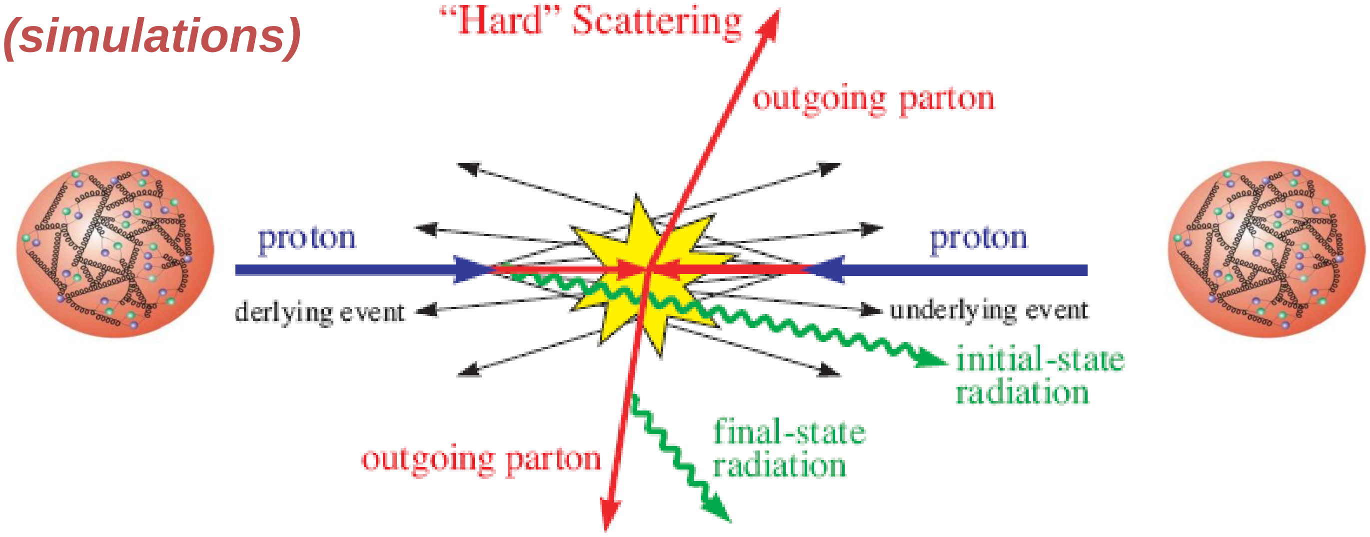
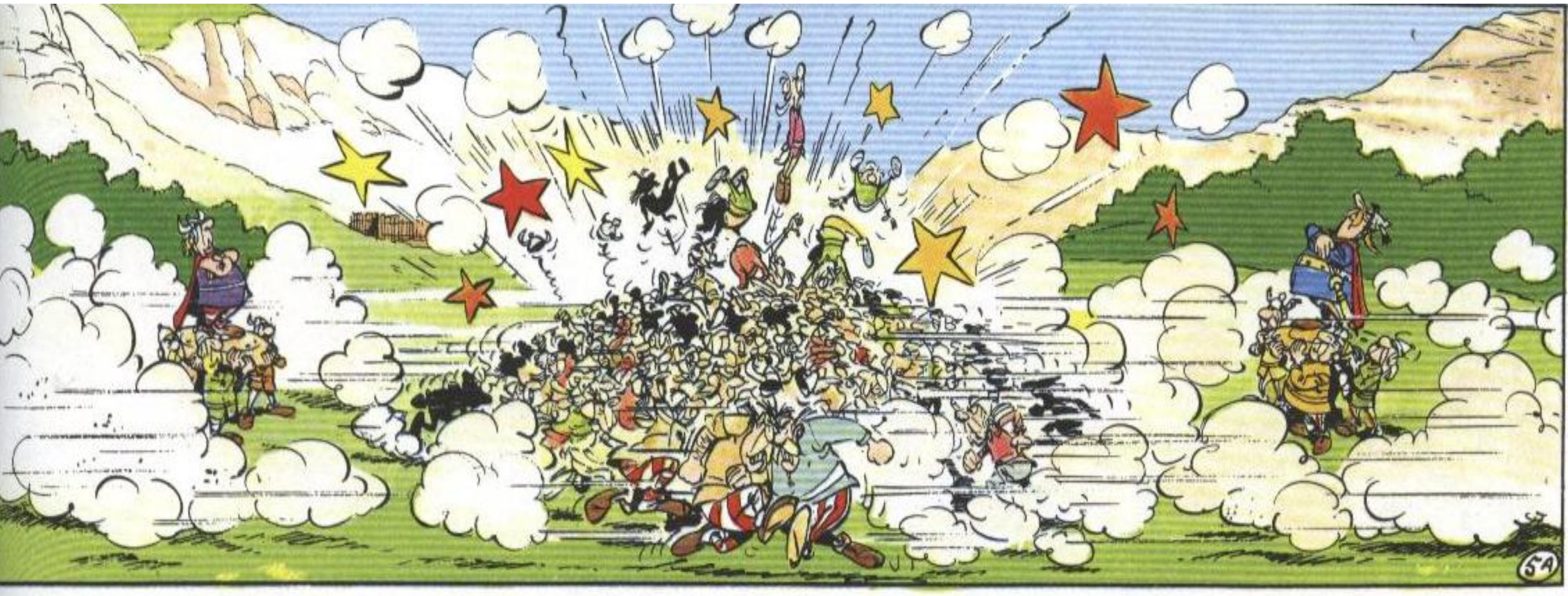
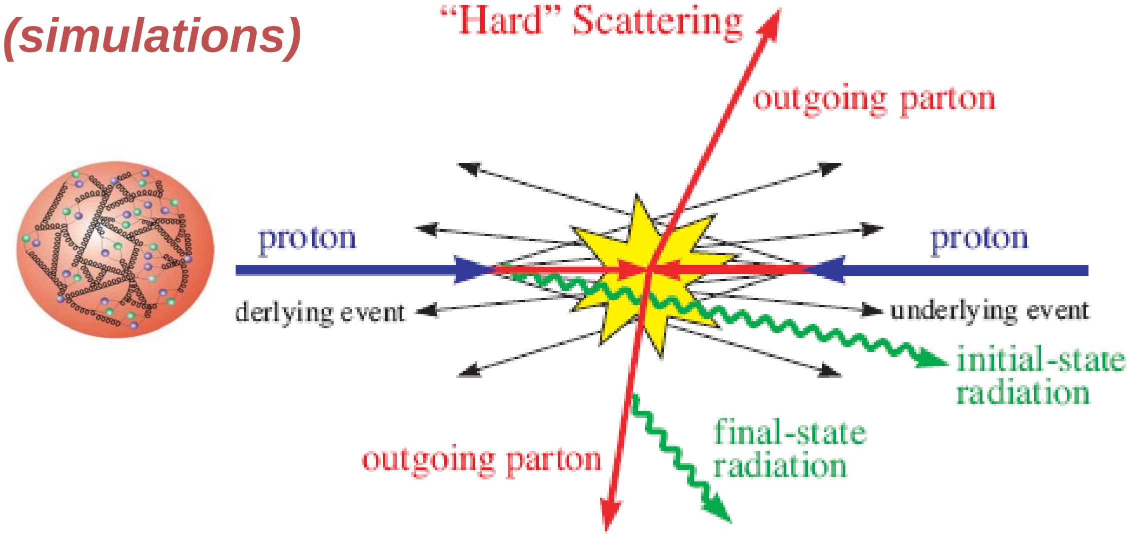
42

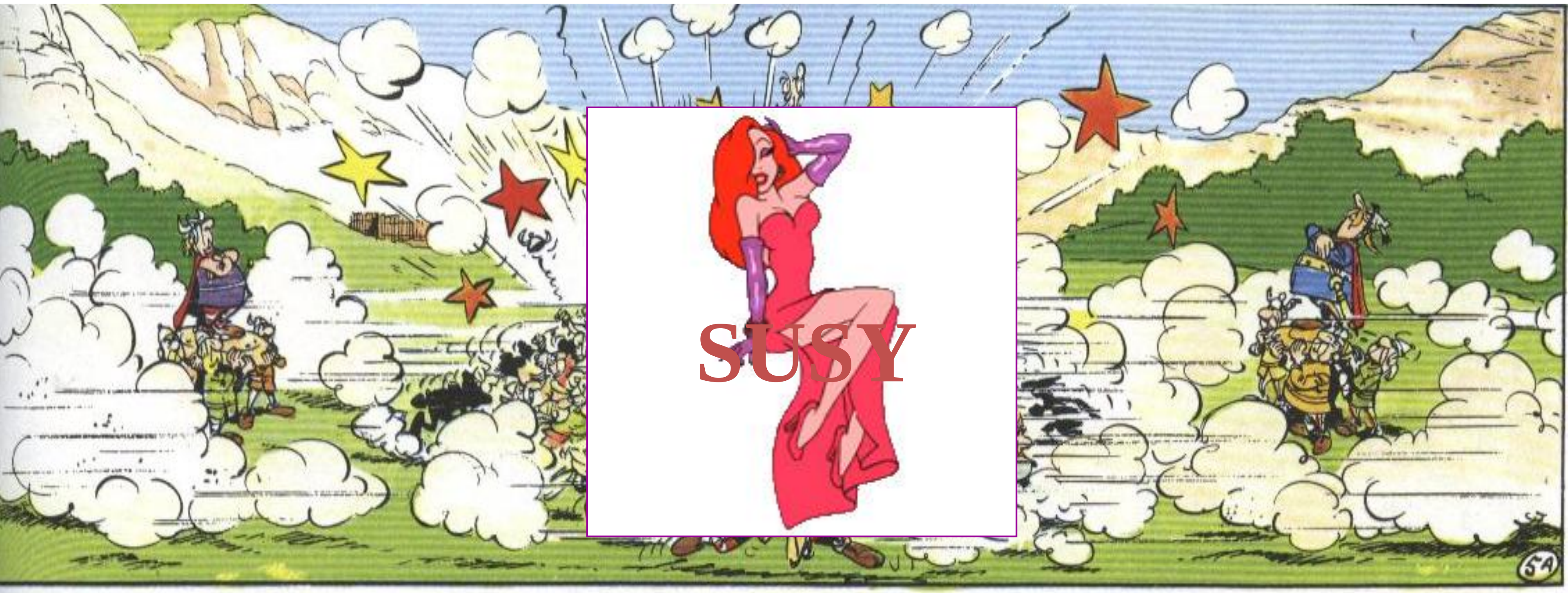
Examples of physics discoveries hoped for at the LHC (simulations)



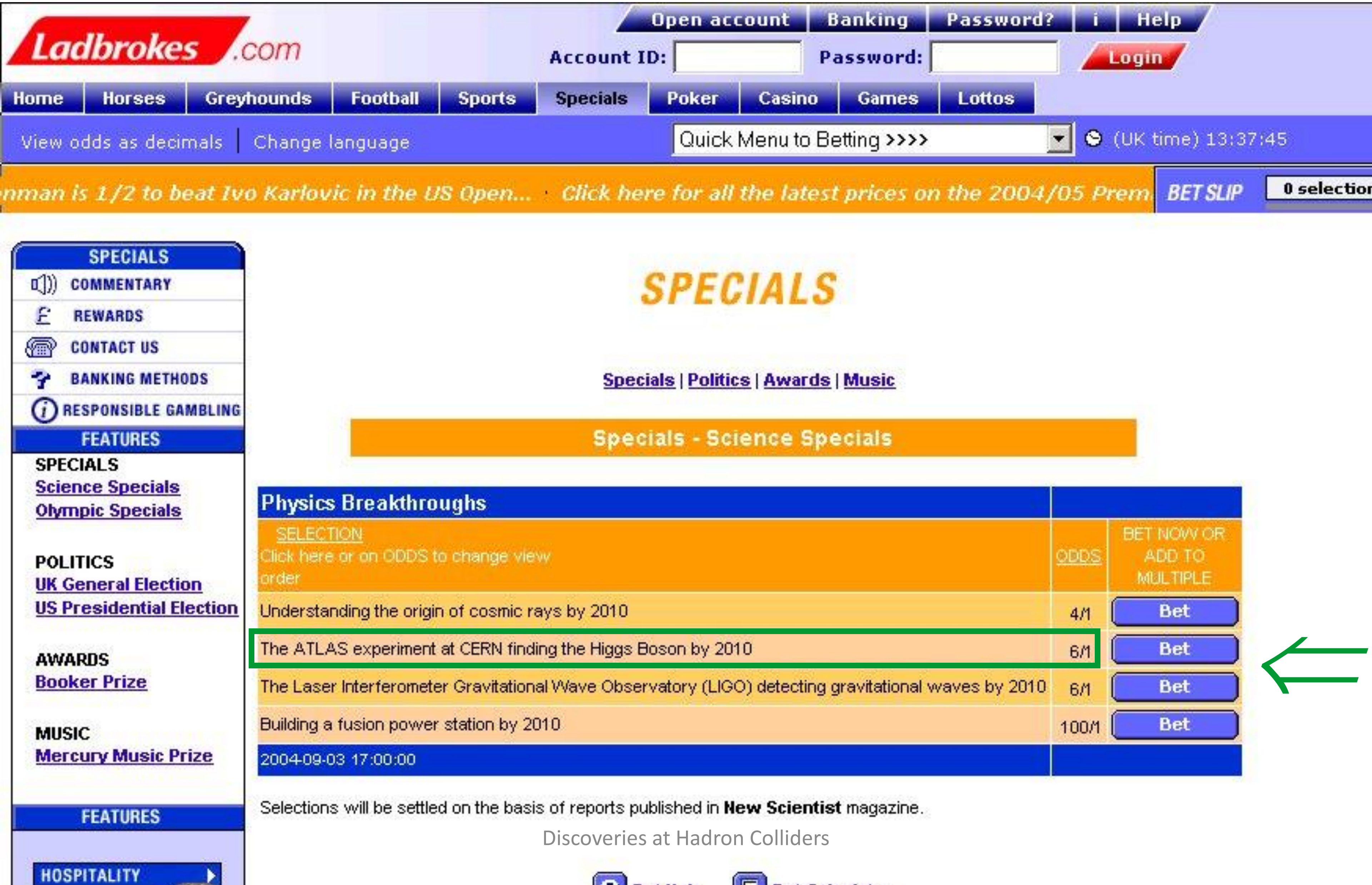


Examples of physics discoveries hoped for at the LHC (simulations)





Those of you who have placed Higgs discovery bets in 2004 have unfortunately little chance to recover their money…



μ + jets candidate