世界最高エネルギー加速器
LHCが次に狙うもの

素粒子物理の最前線は今

坂本　宏
東京大学名誉教授

自己紹介

- 坂本　宏(さかもと　ひろし) 66歳
- 東京大学名誉教授
- 略歴
  - 1982年京都大学大学院理学研究科博士後期課程修了
  - 1985年高エネルギー物理学研究所助手
  - 1993年京都大学大学院理学研究科助教授
  - 2001年東京大学素粒子物理国際研究センター教授
  - 2018年同定年退職
- sakamoto@icepp.s.u-tokyo.ac.jp
- http://www.icepp.s.u-tokyo.ac.jp/~sakamoto/

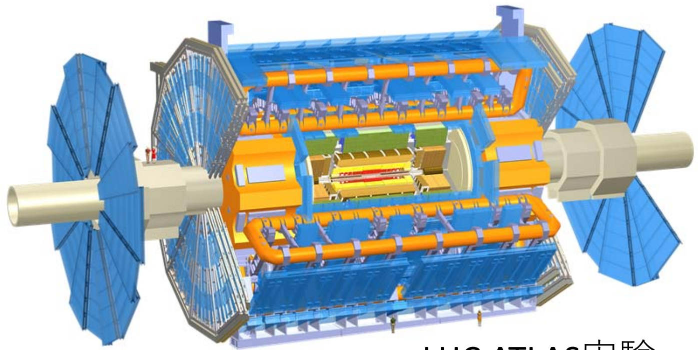
自己紹介～これまでに関わってきた実験

高エネルギー加速器研究機構

トリスタン加速器VENUS実験
陽子シンクロトロンE162実験
KEKB加速器Belle実験

ロナルドレーガンSSC研究所

欧州合同原子核研究機関(CERN)



LHC ATLAS実験

目次

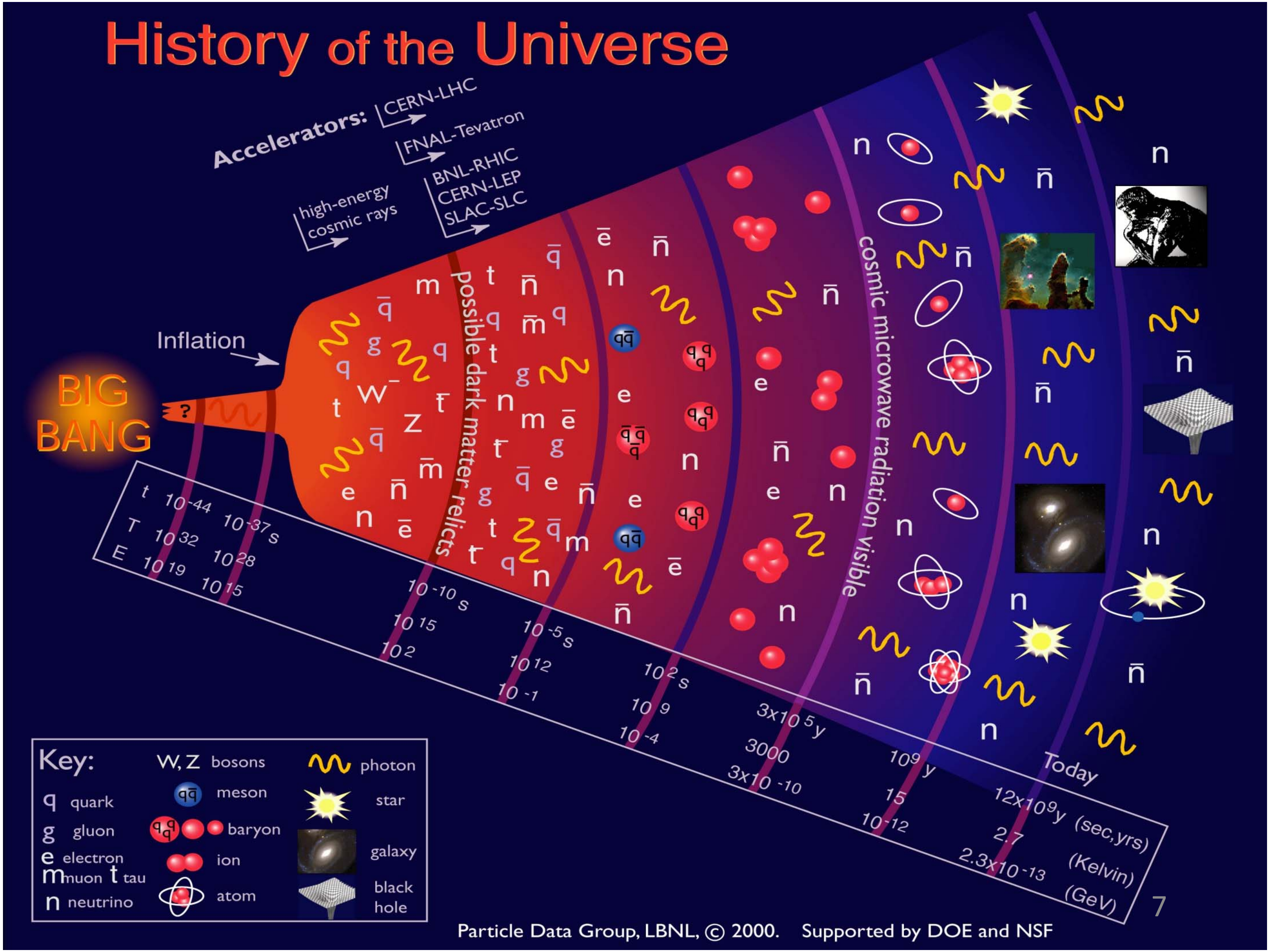
- 素粒子の世界
- 素粒子を調べる方法
- 素粒子を見る
- ヒッグス粒子の発見
- 素粒子の次の課題～標準模型を超えて
- 巨大科学のありかた

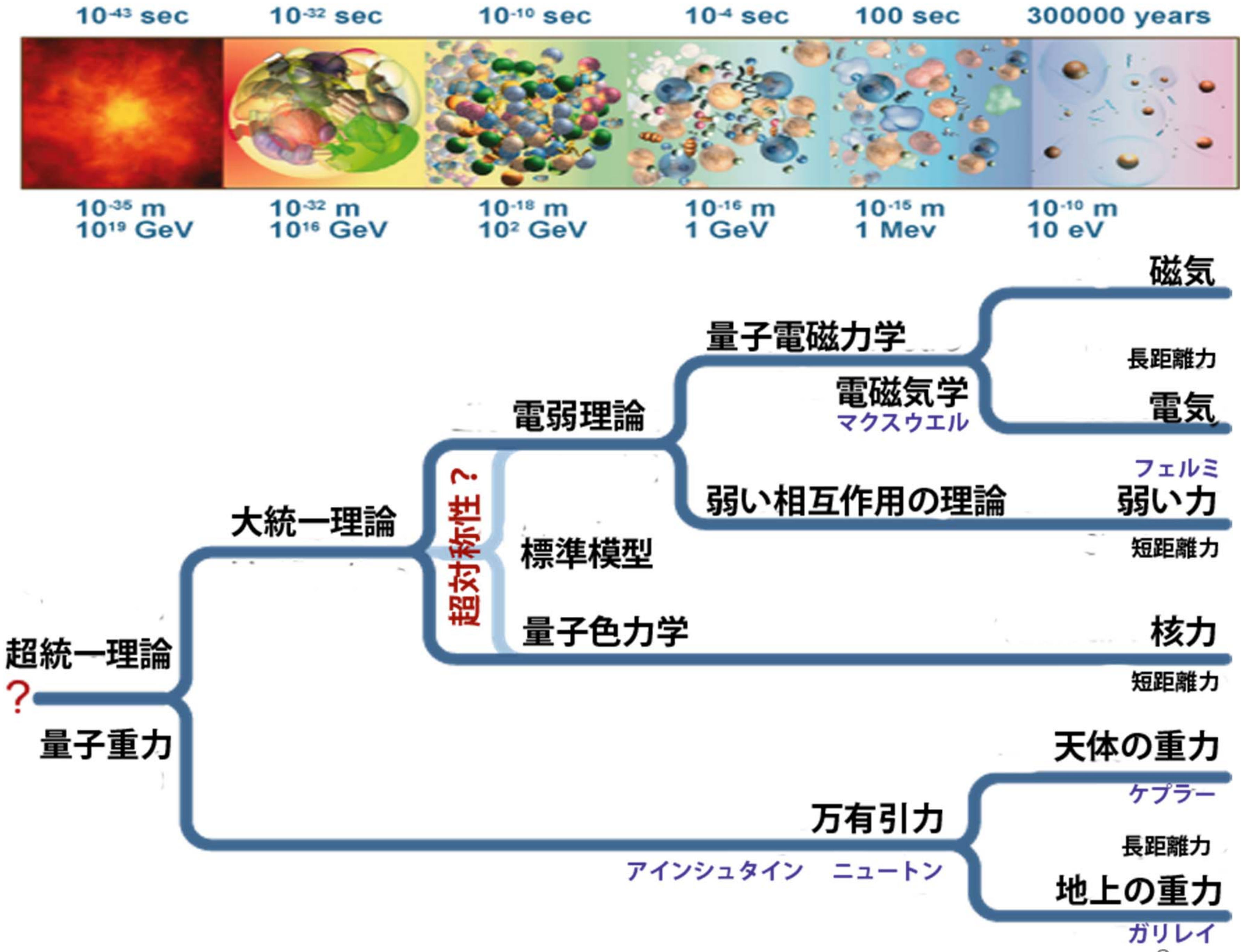
素粒子の世界

- 素粒子とは
  - ものの大きさ
  - 物質の階層
  - 原子核と電子
- 支配する法則
  - 相対論的量子力学
  - 素粒子の相互作用
- 素粒子の標準模型
  - クォークとレプトン
  - ゲージ粒子
  - ヒッグス機構


物質
原子
電子
陽子
クォーク
原子核
中性子
物質を構成する粒子
通常存在する粒子は全てこのグループに属す
これらの粒子はビッグバン直後に存在した。今では宇宙線や加速器によって作られる
レプトン
クォーク
第1世代
第2世代
第3世代
電子
電磁気と化学反応をつかさどる；電荷-1を持つ
電子ニュートリノ
電荷を持たない粒子で、ほぼ質量がない；毎秒何十億個があなたの体を通り抜けている
アップクォーク
電荷+2/3を持つ；陽子に2つ、中性子には1つ含まれる
ダウンクォーク
電荷-1/3を持つ；陽子に1つ、中性子には2つ含まれる
ミュー粒子
電子の重たい親戚；百万分の2秒だけ生きる
ミューニュートリノ
なにがしかの粒子の崩壊時にミュー粒子とともに作られる
チャームクォーク
アップクォークの重たい親戚；1974年に発見
ストレンジクォーク
ダウンクォークの重たい親戚；1964年に発見
タウ粒子
さらに重たい；非常に不安定。1975年に発見
タウニュートリノ
なにがしかの粒子の崩壊時にタウ粒子とともに作られる。2000年に発見
トップクォーク
さらに重たい；1995年に発見
ボトムクォーク
さらに重たい；ボトムクォークの測定は電弱理論の検証に重要。1977年に発見
力を伝える粒子
これらの粒子は自然界に存在する4つの基本的な力を伝える。重力量子はまだ発見されていない。
グルオン
クォーク間に働く強い力を伝える
クォークにのみ作用
原子核エネルギーの爆発的解放は強い力の結果
光子
光を形作る粒子；電磁力を伝える。
クォークと荷電レプトンに作用
電気・磁気・化学反応は全て電磁力の結果
ウィークボゾン
弱い力を伝える。
W⁻
W⁺
Z⁰
クォークとレプトンに作用
放射性崩壊の一部は弱い力の結果
重力量子
重力を伝える。
質量を持つ全ての粒子に作用
我々が経験する全ての重さは重力の結果
GRAPHICS: PETER CROWTHER

原版©CERN


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10 -44 10 -37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



http://cms.web.cern.ch/news/are-there-more-particles-left-findより和訳

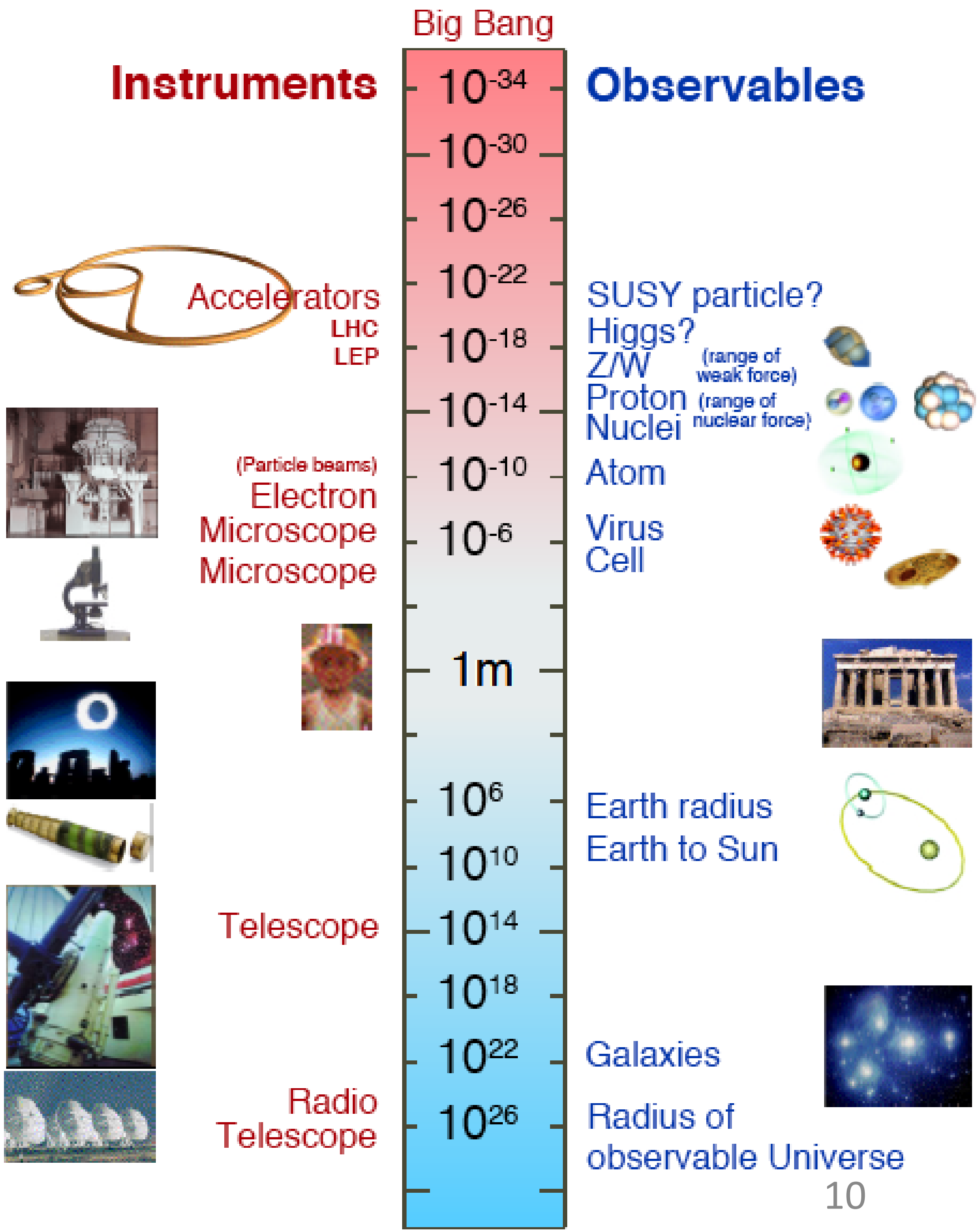
素粒子を調べる方法

- 光学顕微鏡と電子顕微鏡
- 加速器
- 衝突型加速器実験
- 大型ハドロン衝突器LHC

ドブロイ波長

$$\lambda = \frac{h}{mv} = \frac{h}{p} = \frac{2\pi}{k}$$

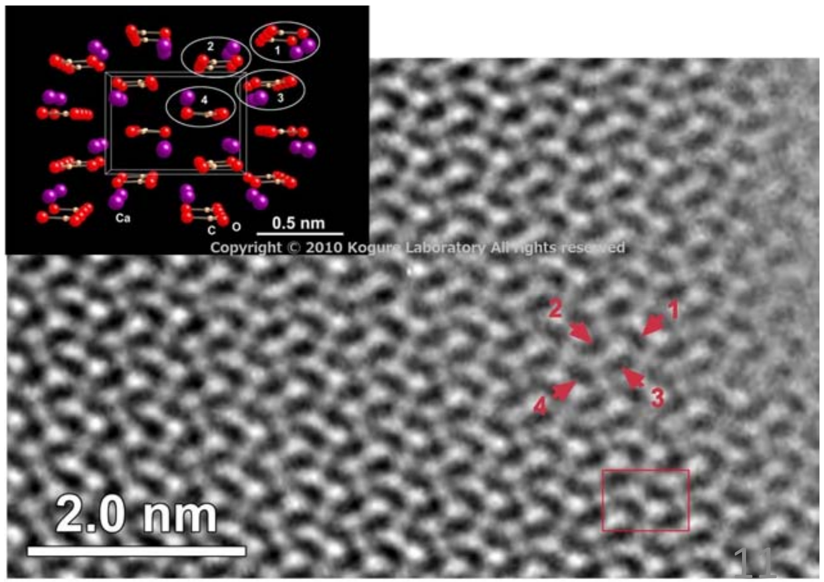
加速電圧	ドブロイ波長
100V	0.12nm(10^{-9}m)
1kV(10^{3}V)	0.03nm
1MV(10^{6}V)	0.84pm(10^{-12}m)
1GV(10^{9}V)	1.2fm(10^{-15}m)
1TV(10^{12}V)	1.2am(10^{-18}m)



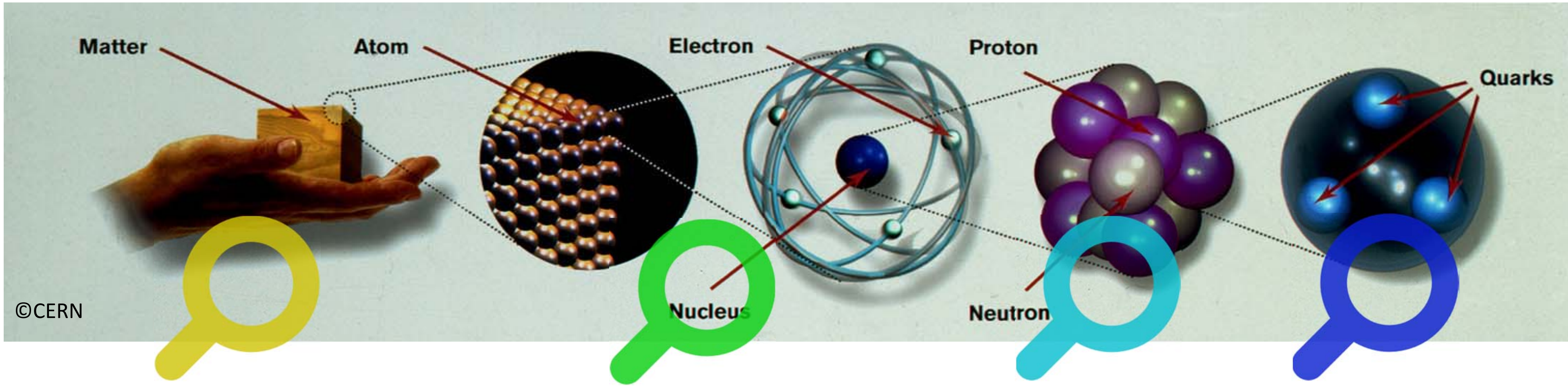
プリンス光学 顕微鏡 50-750倍

多機能電子顕微鏡「JEM-F200」 出典：物質・材料研究機構

http://bio-pandora.kinokoyama.com/box/vital/vital.html#



http://www-gbs.eps.s.u-tokyo.ac.jp/kogure/gallery/gallery-index.html



可視光	電子	核子	クォーク
~500nm	~0.01nm (10^{-11}m)	~1fm (10^{-15}m)	~1am (10^{-18}m)
~1eV	~1keV	~400MeV	~7TeV

The Olympus Museum : Microscopes

“Electron microscope” From Wikipedia

Superconducting Ring Cyclotron
RIKEN Nishina Center for
Accelerator-Based Science

Large Hadron Collider
CERN

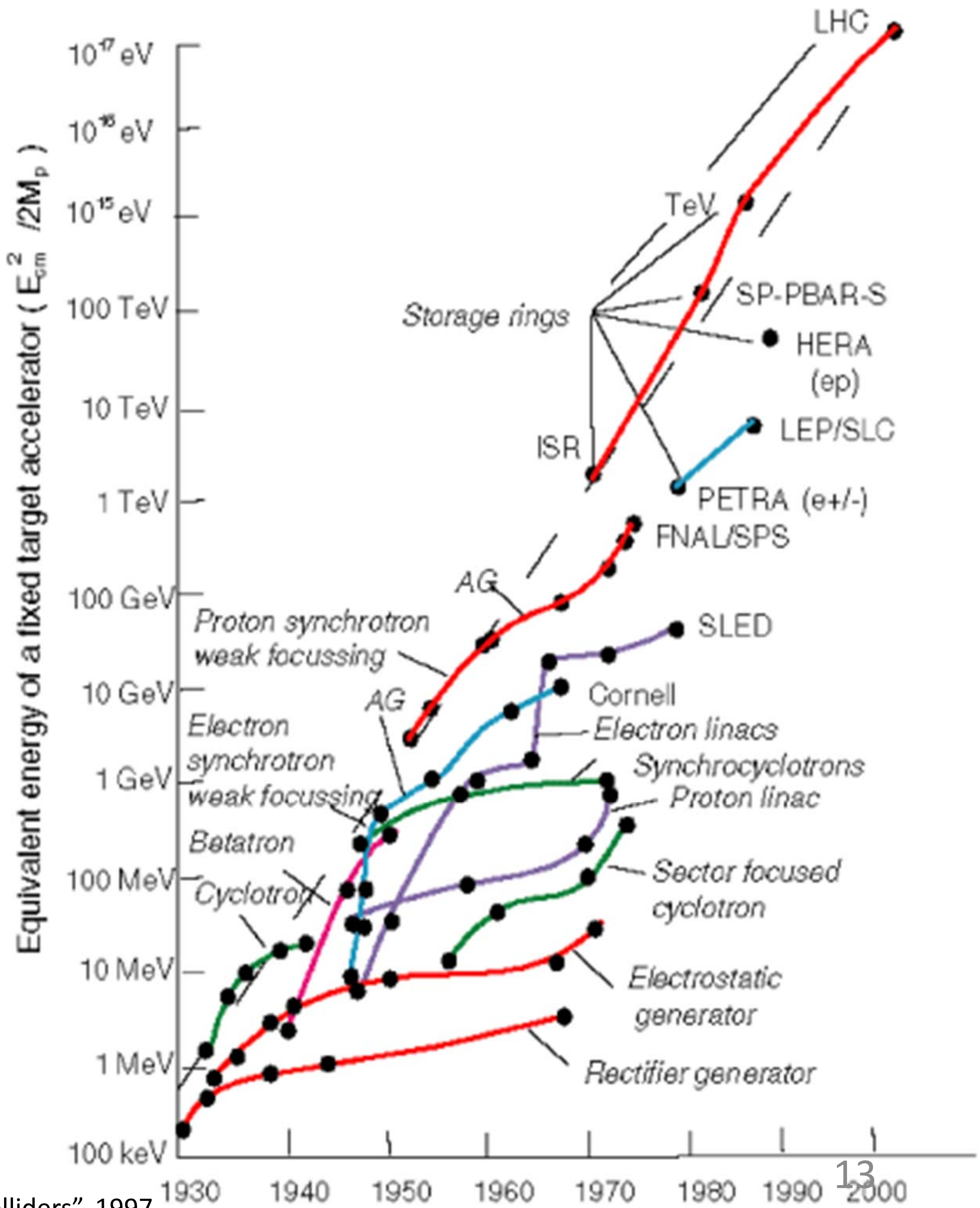
$m_1 = m_2 \cong 1GeV$の時
(陽子陽子衝突)

$$E_{CM} = \sqrt{m_1^2 + m_2^2 + 2E_{1lab}m_2}$$

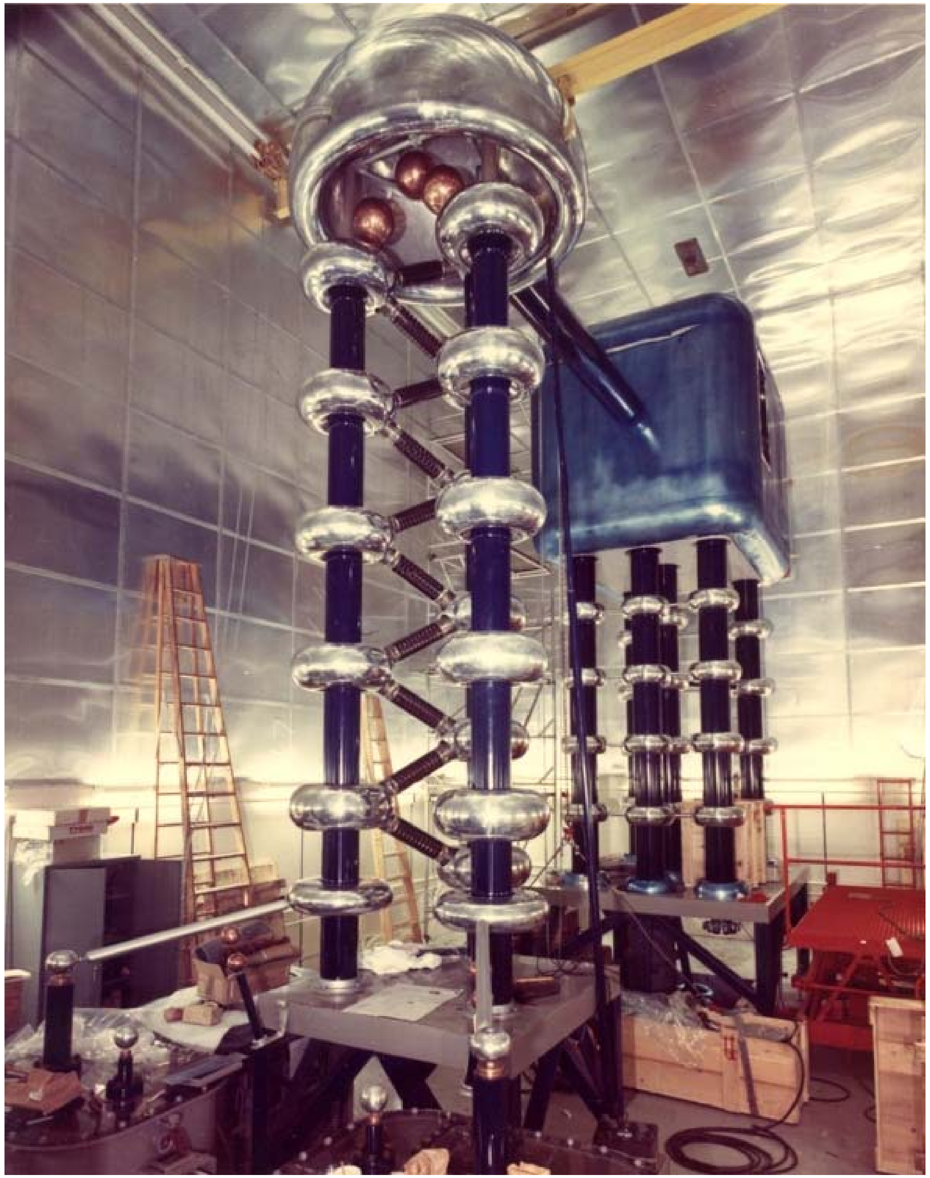
$$E_{1lab} = 100GeV \leftrightarrow E_{CM} = 14GeV$$
$$E_{1lab} = 1TeV \leftrightarrow E_{CM} = 44GeV$$

$$E_{1lab} = \frac{1}{2m_2}(E_{CM}^2 - m_1^2 - m_2^2)$$

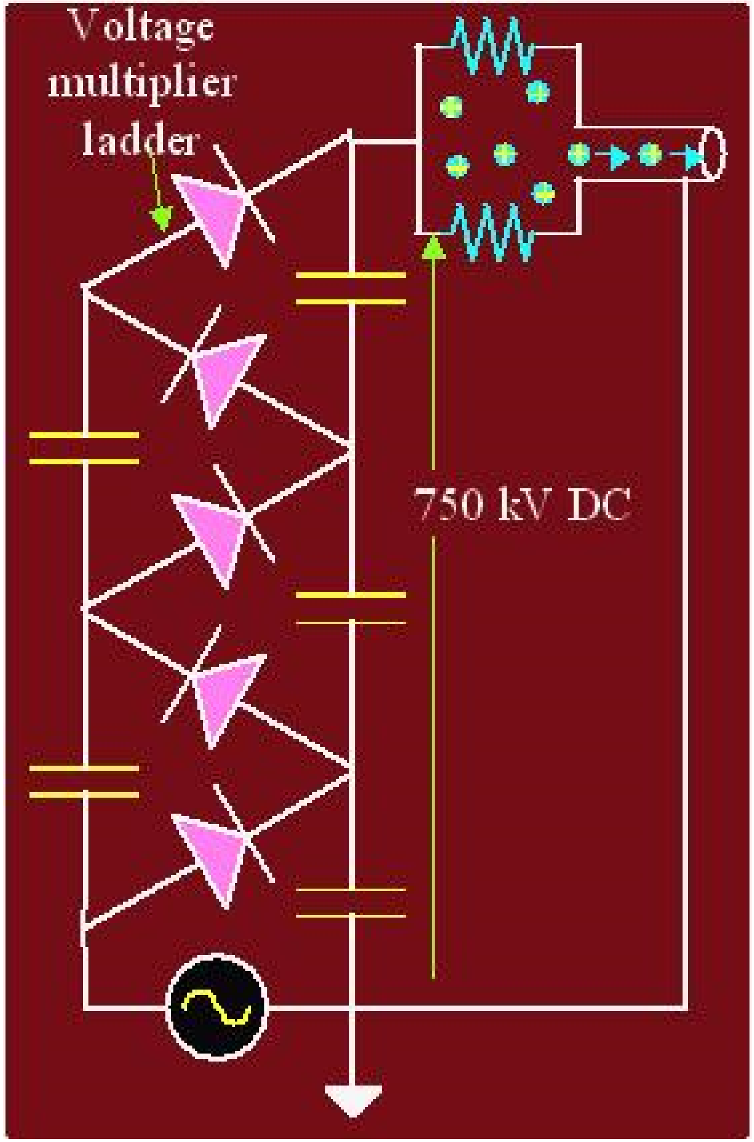
$$E_{CM} = 2TeV \leftrightarrow E_{1lab} = 2PeV$$
$$E_{CM} = 14TeV \leftrightarrow E_{1lab} = 98PeV$$



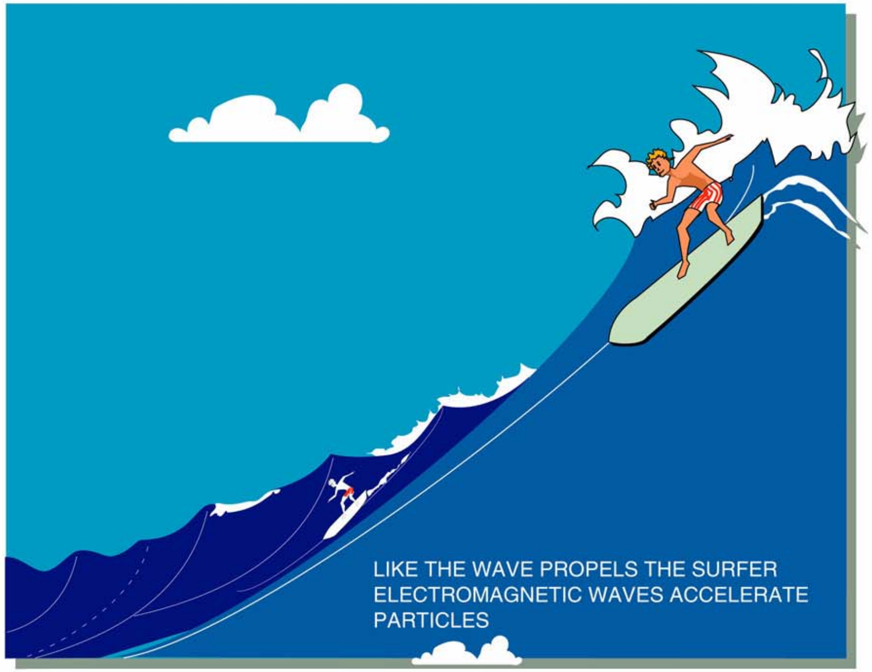
W. H. K. Panofsky, “Evolution of Particle Accelerators and Colliders”, 1997



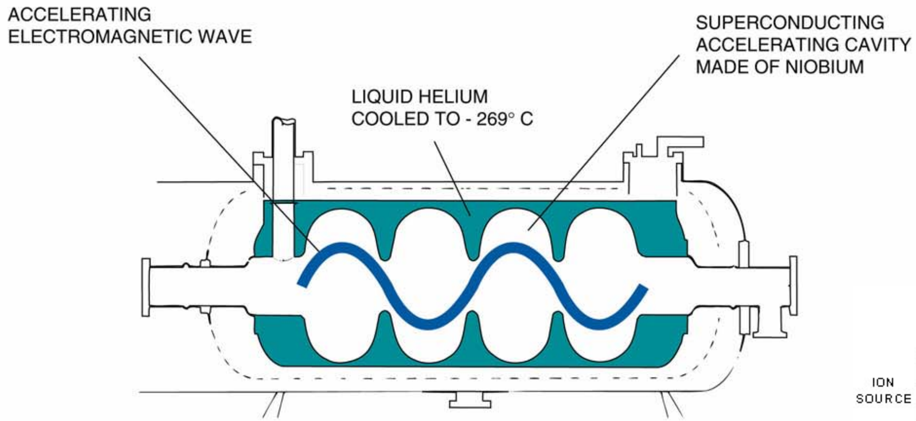
Cockcroft-Walton accelerator. Image credit: Brookhaven National Laboratory



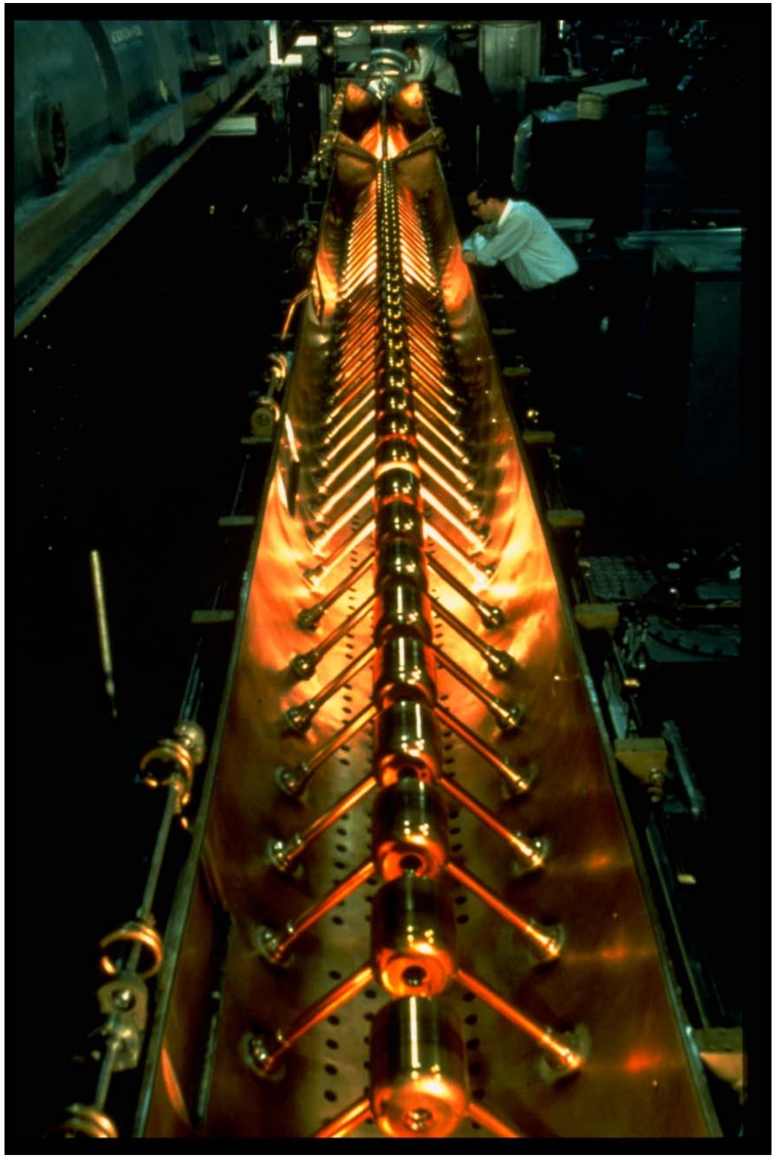
THE SUPRACONDUCTIVITY

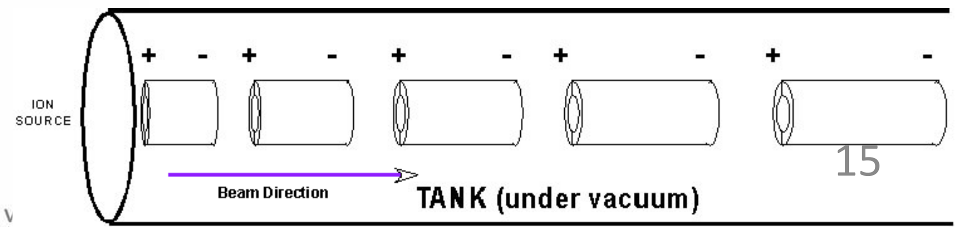


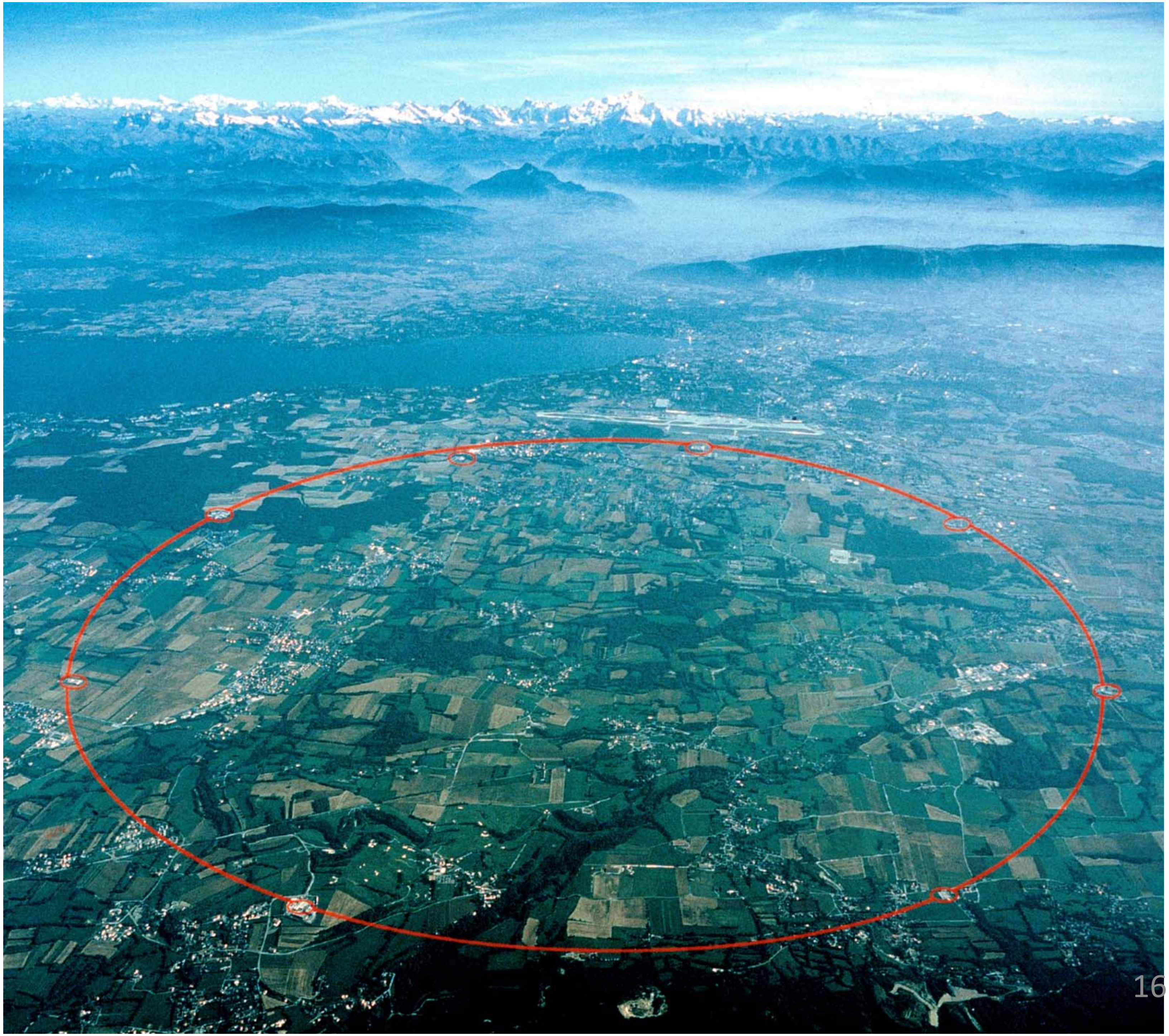
THE USE OF SUPRACONDUCTIVITY TO INCREASE PERFORMANCES AND CONSIDERABLY REDUCE ELECTRICITY CONSUMPTION



CERN AC _ Z31 V







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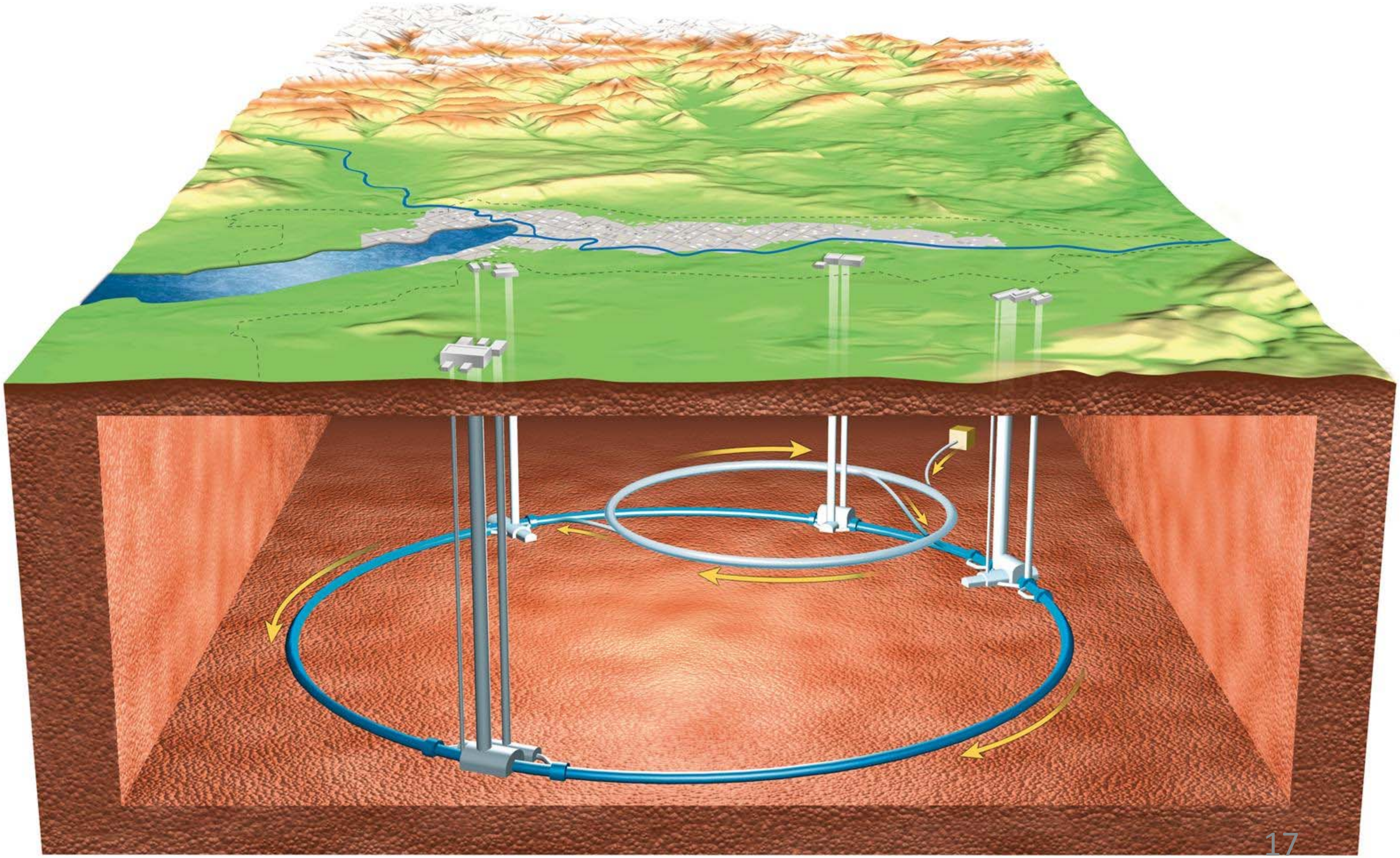
LHC Accelerator Tunnel



Accelerator Components

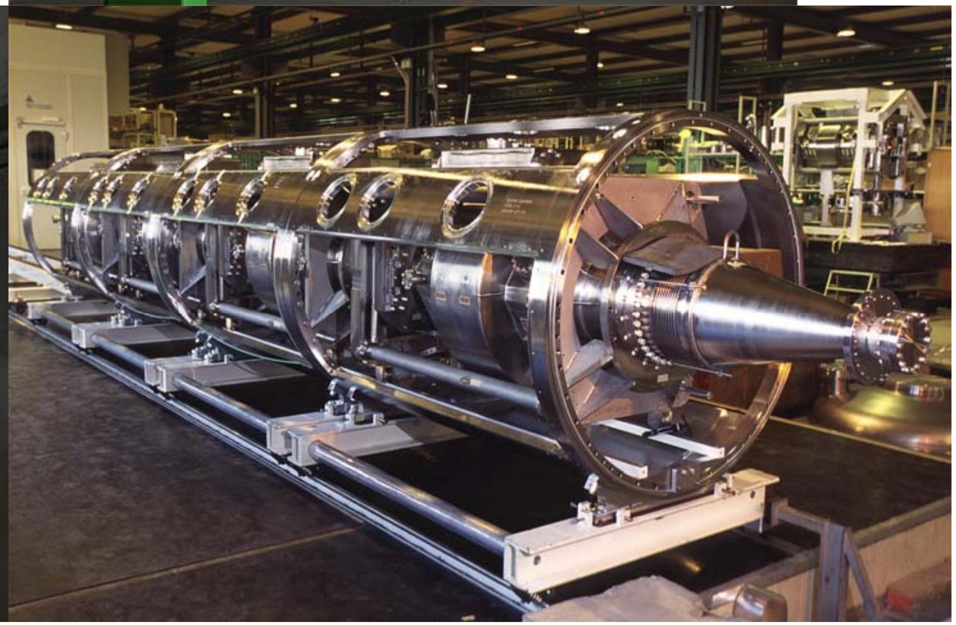
- 1232 Main Dipole Magnets
- 386 Main Quadrupole Magnets
- A few thousands of Correction Magnets.

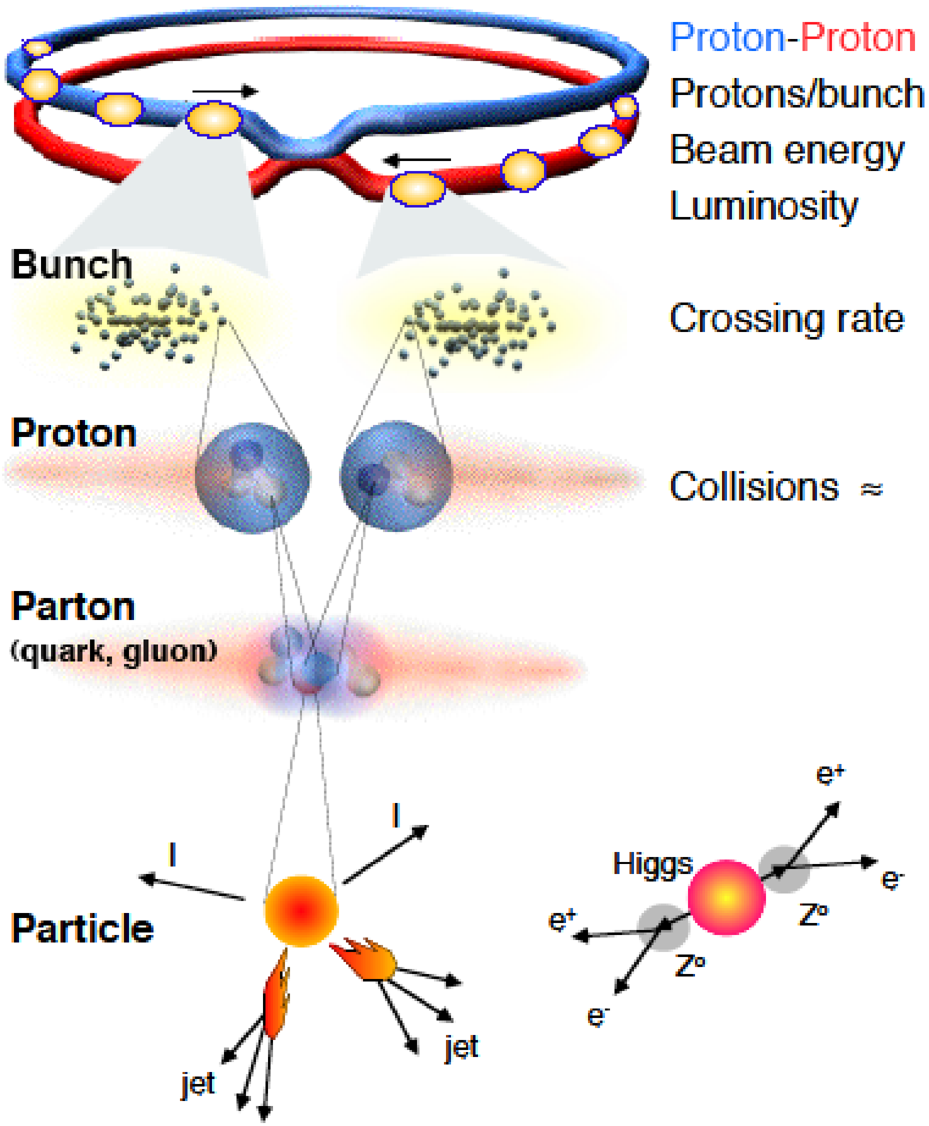
Beam Dump

- 7TeV proton energy (1.1uJ)
- 1.1×10^{11} protons/bunch
- 2800 bunches
- 345MJ/beam = 900t $\times$ 100km/h

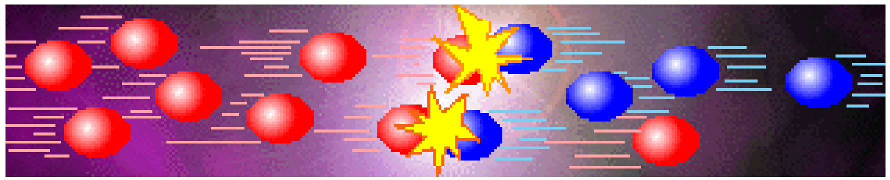
RF System

- 400MHz Radio Frequency
- 2MV Accelerating Field
- 16 RF Units



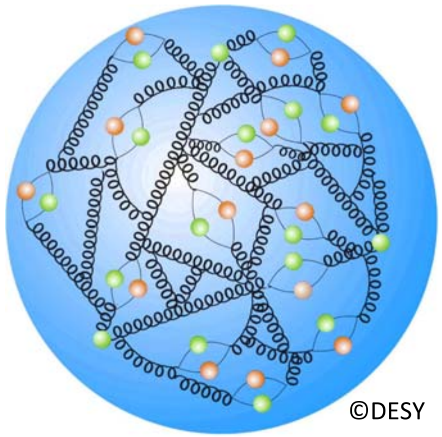


Proton-Proton	(2835 x 2835 bunches)
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz



Higgs

SUSY.....



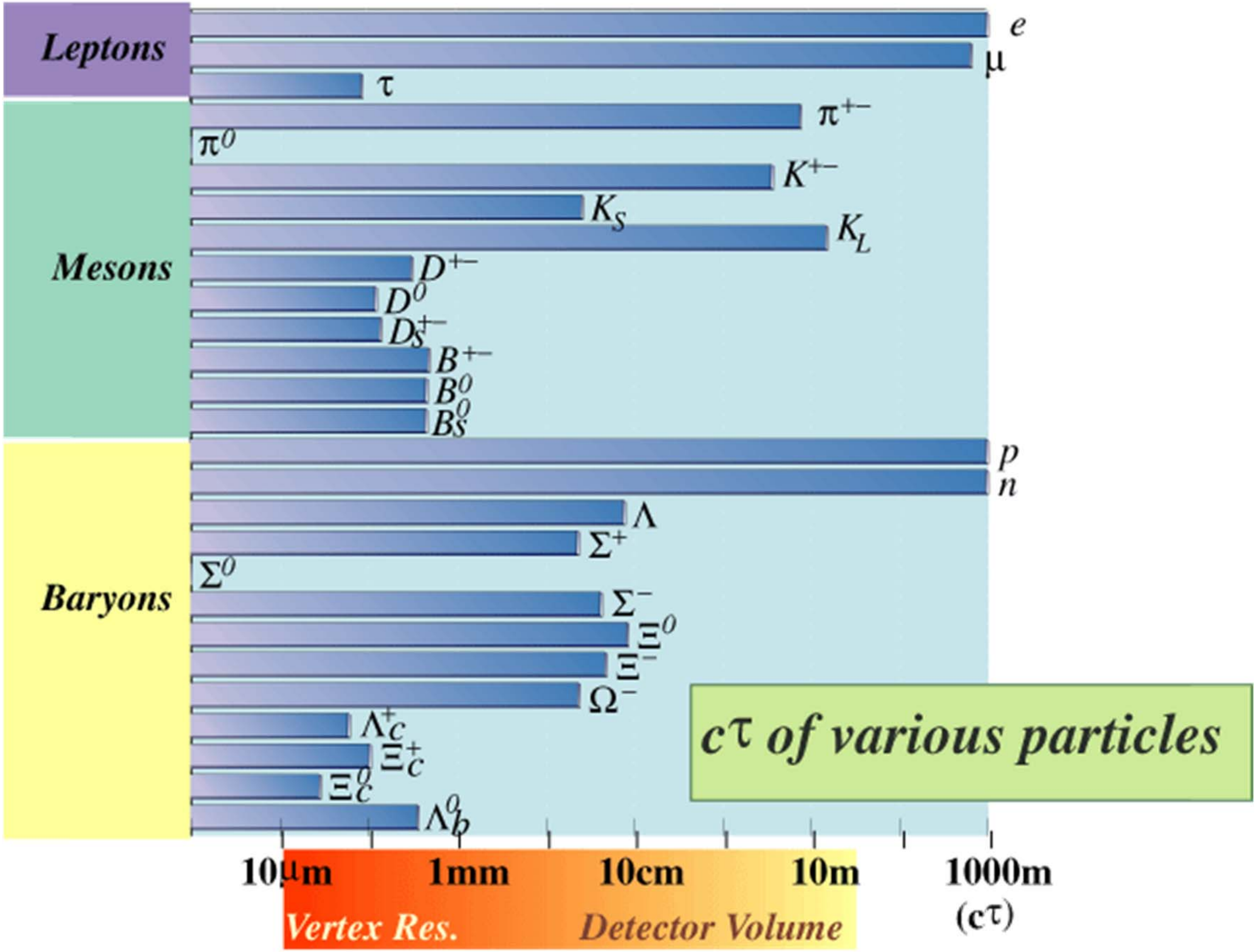
©DESY

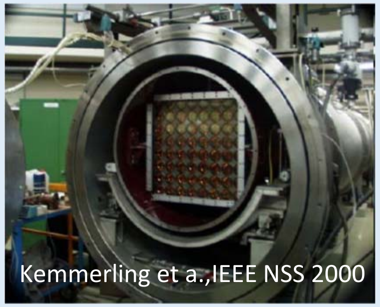
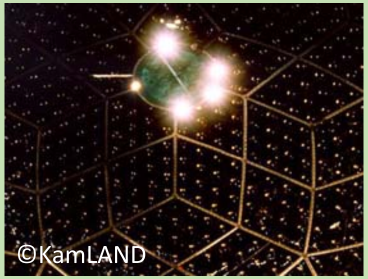
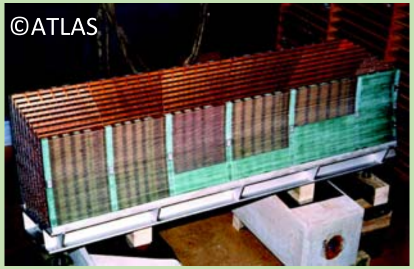
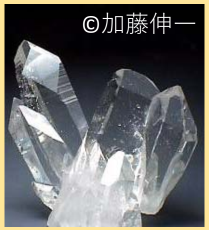
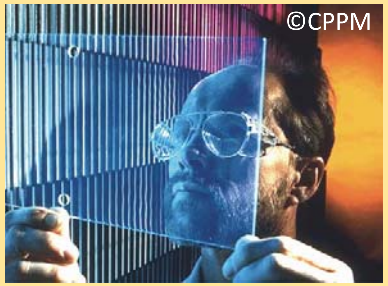
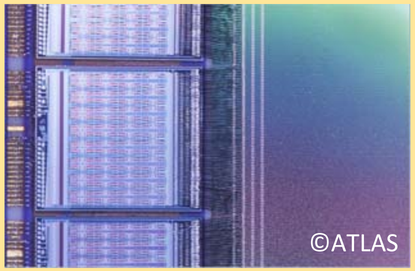
Selection of 1 in 10,000,000,000,000

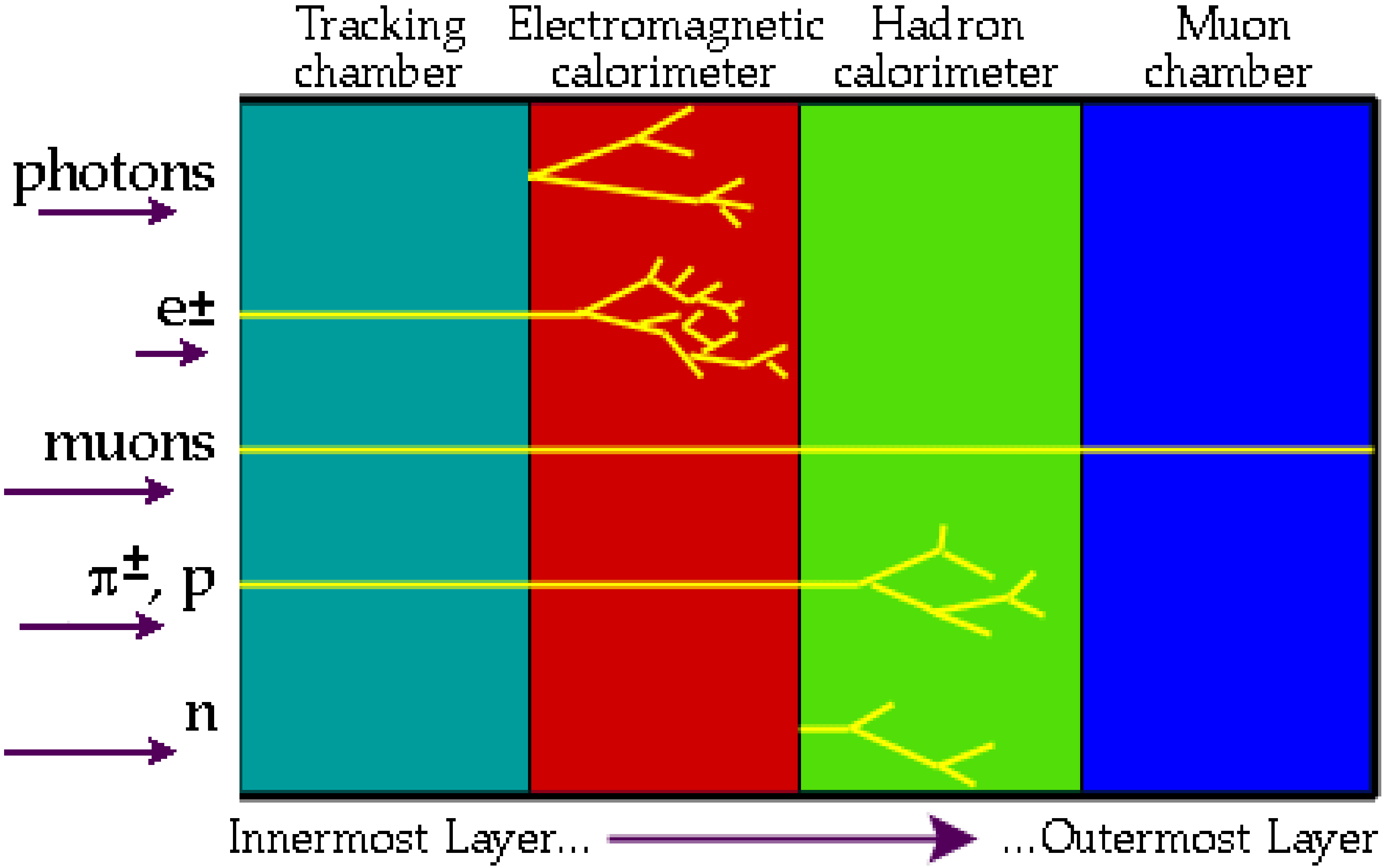
Monika Wielers
RAL PPD

(素)粒子を見る

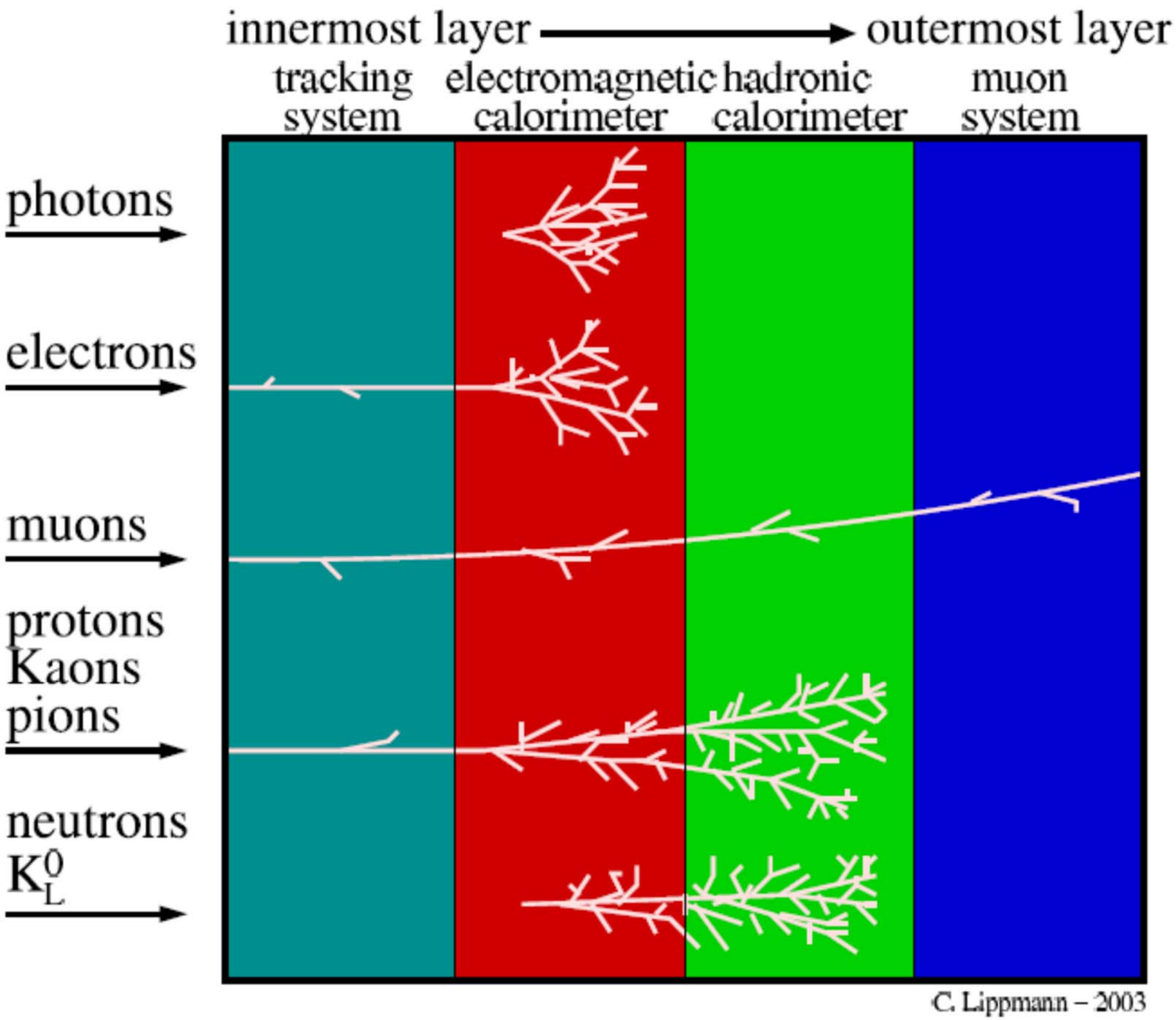
- 衝突型加速器実験
  - 生成される粒子
  - 検出される粒子
- 粒子と物質の相互作用
  - 電離
  - 励起
  - 輻射
- 飛跡の検出
- シャワーの検出


Leptons
e
μ
τ
Mesons
π+−
π0
K+−
KS
KL
D+−
D0
Ds+−
B+−
B0
Bs0
Baryons
p
n
Λ
Σ+
Σ0
Σ−
Ξ0
Ξ−
Ω−
Λc+
Ξc+
Ξc0
Λb0
cτ of various particles
10μm
1mm
10cm
10m
1000m
(cτ)
Vertex Res.
Detector Volume

過程→ ↓媒質	 励起	 電離	 輻射
 気体	 ガスシンチレータ	 ドリフトチューブ	 ガスチェレンコフ
 液体	 液体シンチレータ	 液体アルゴンカロリメータ	 水チェレンコフ
 固体	 プラスチックシンチレータ	 半導体検出器	 エアロジェルチェレンコフ

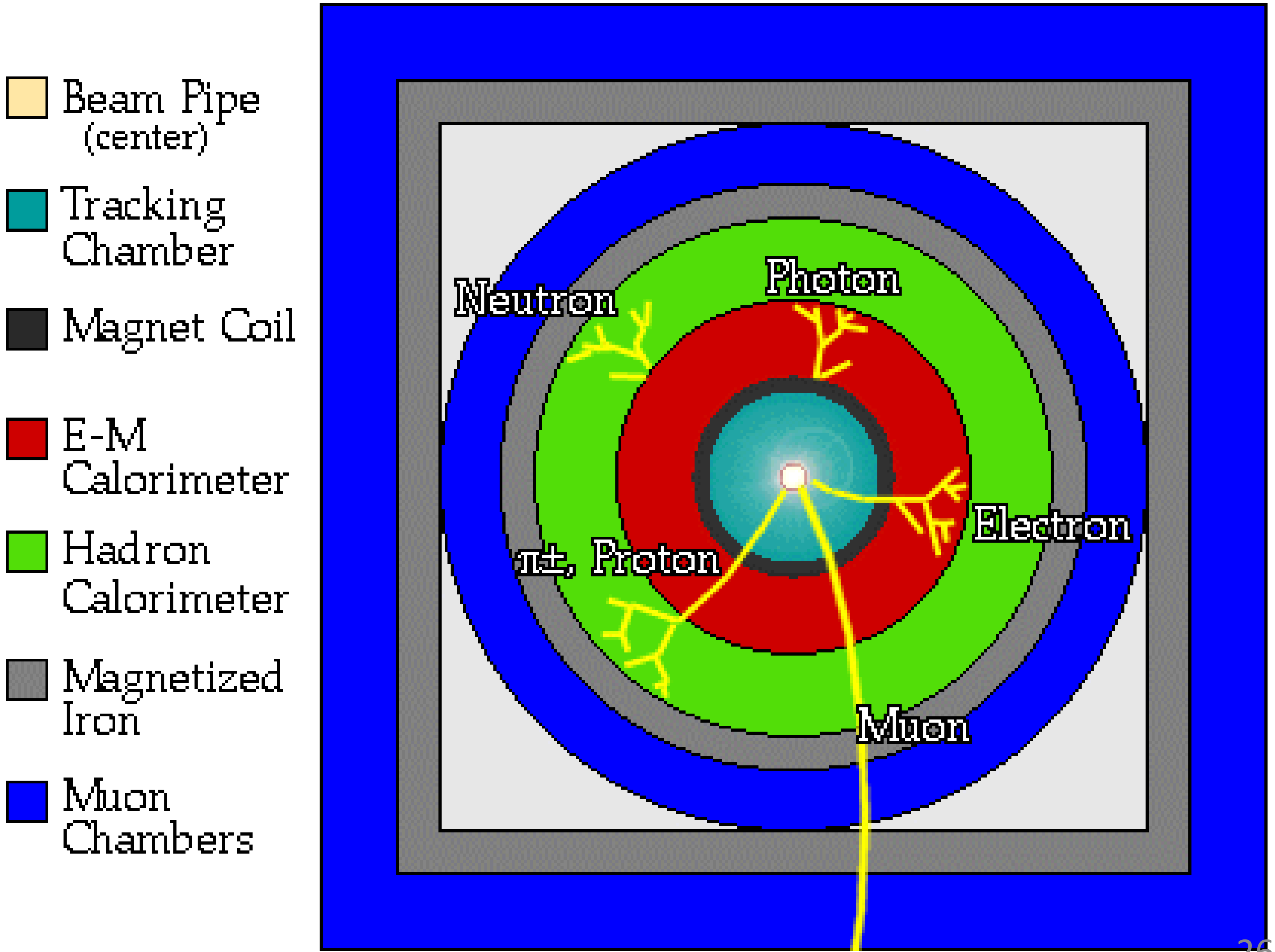


http://www.particleadventure.org/component_detector.html

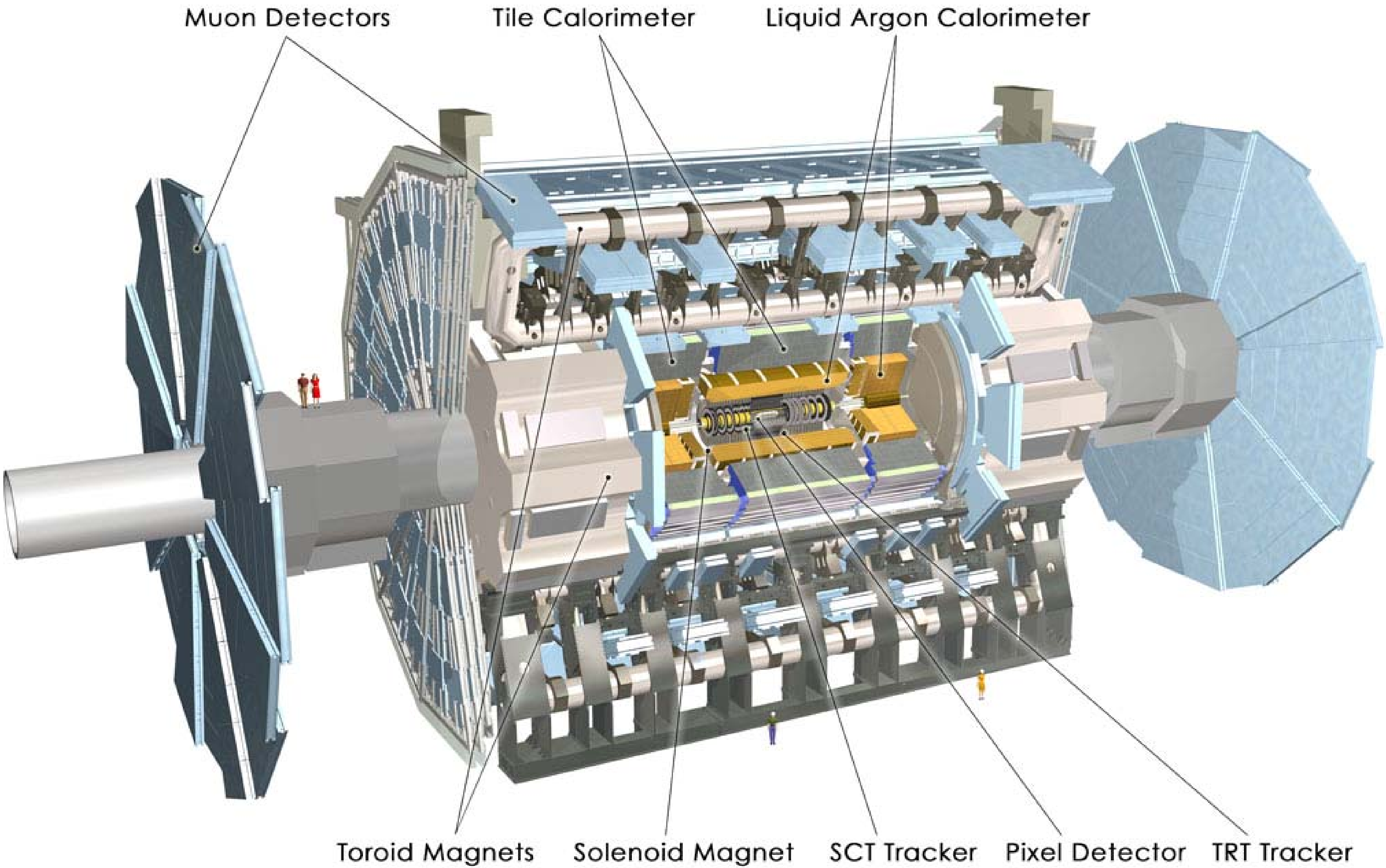


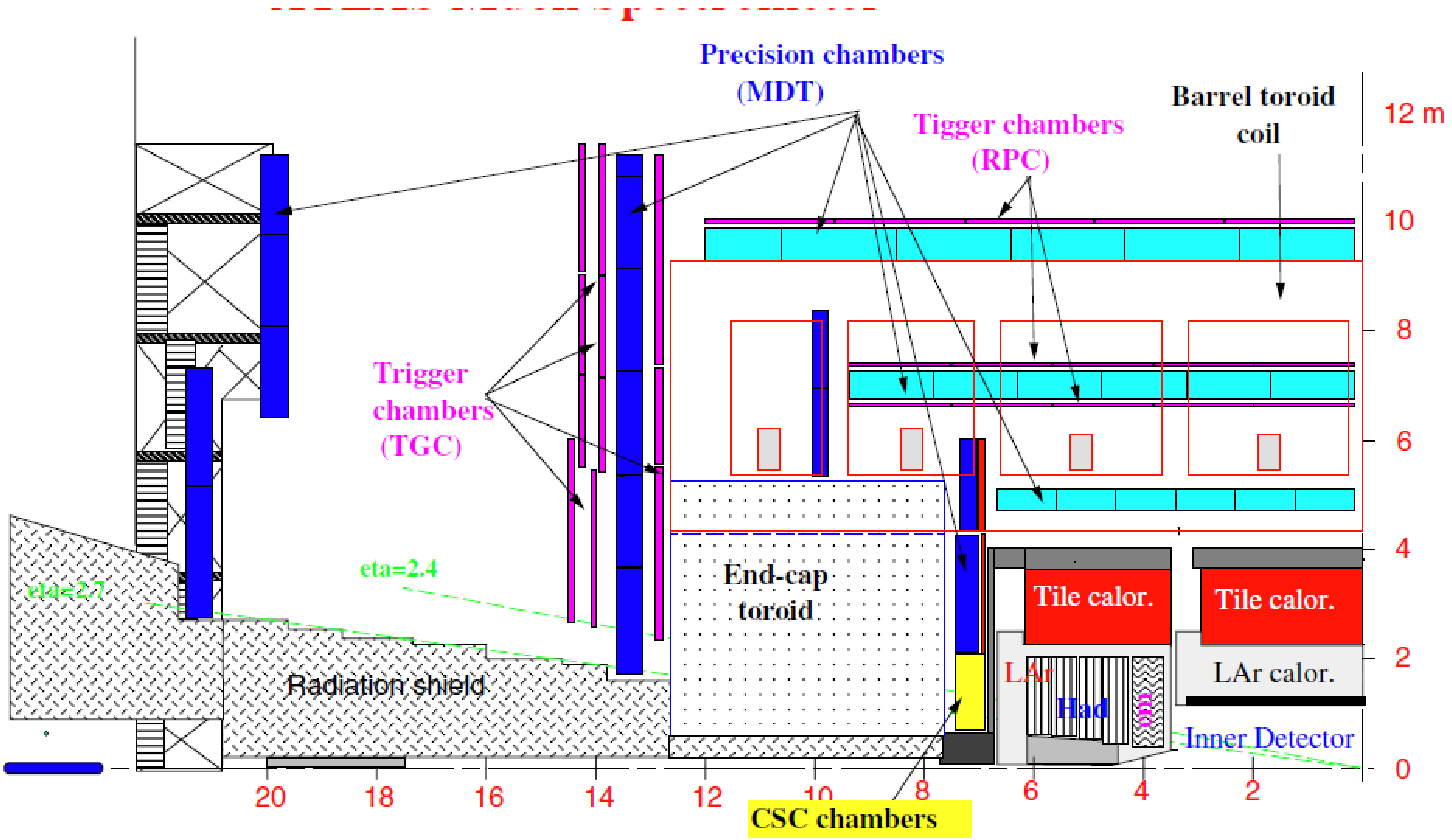
Review of Searches for Rare Processes and Physics Beyond the Standard Model at HERA
David M. South, Monica Turcato, arXiv:1605.03459 [hep-ex]

A detector cross-section, showing particle paths

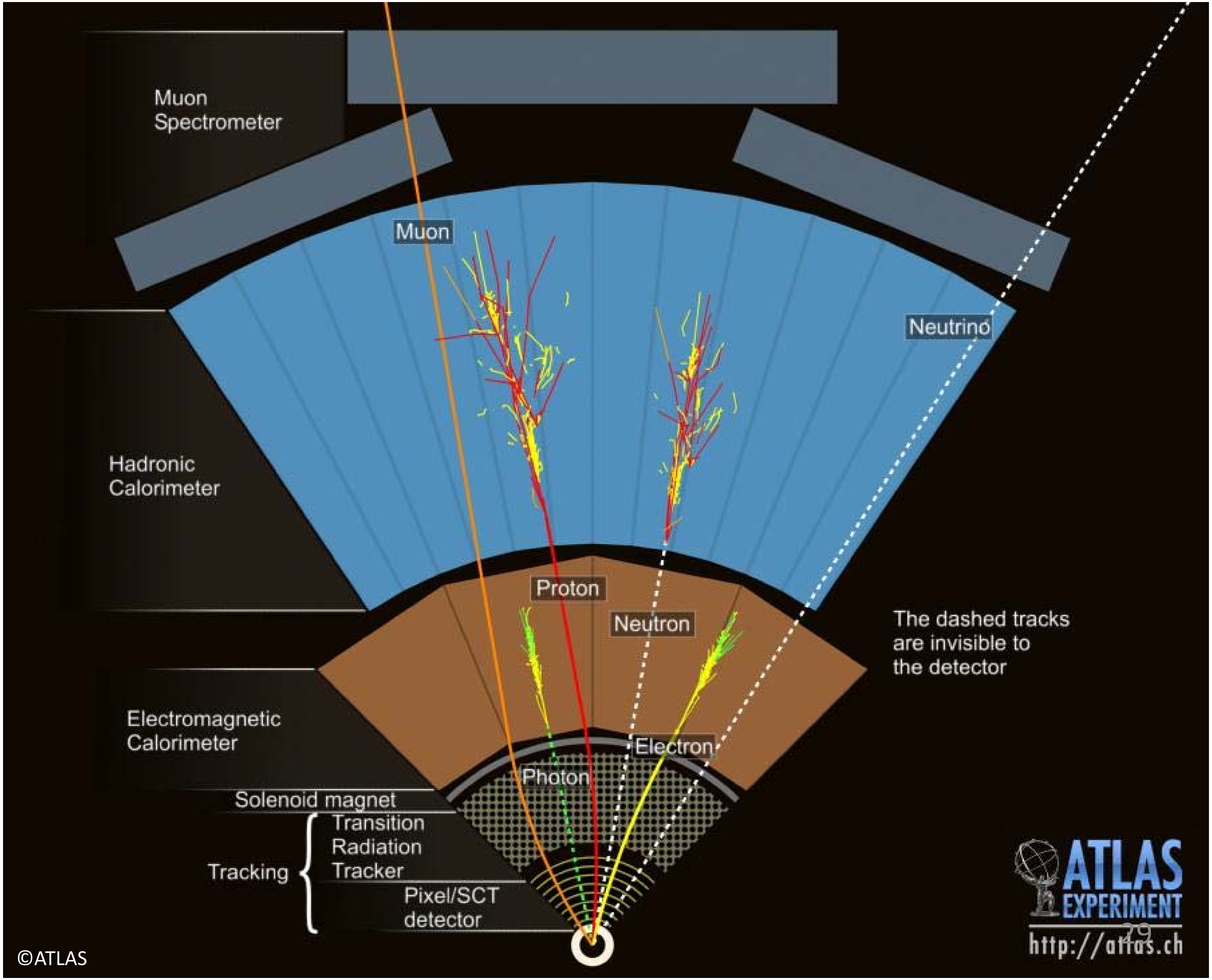


https://www.researchgate.net/figure/Scheme-of-a-typical-particle-detector-transverse-view-for-colliding-beam-experiments_fig5_41217416

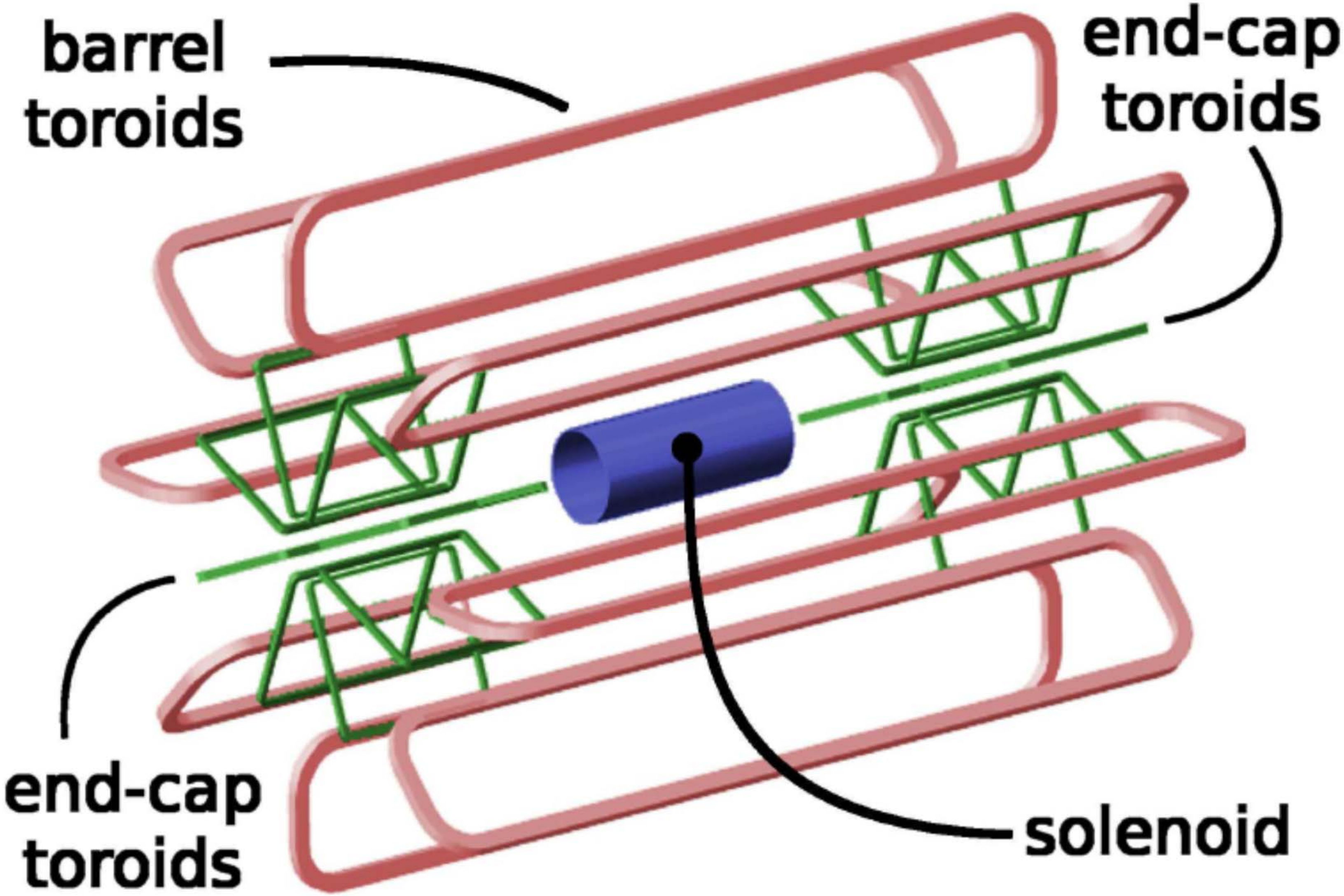

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker



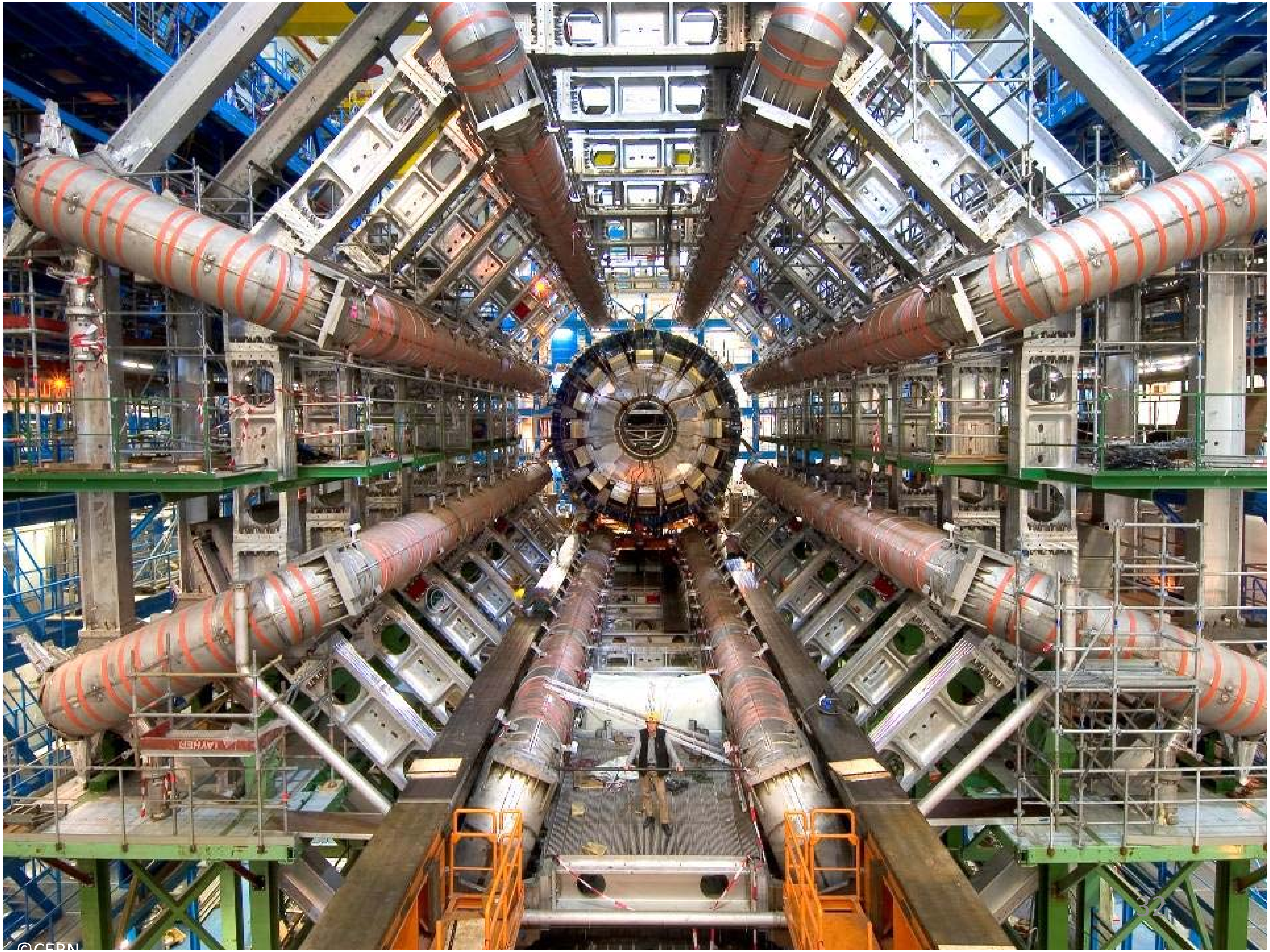
Precision chambers
(MDT)
Barrel toroid
coil
Tigger chambers
(RPC)
12 m
10
8
6
4
2
0
Trigger
chambers
(TGC)
eta=2.4
eta=2.7
End-cap
toroid
Tile calor.
Tile calor.
LAr
Had
LAr calor.
Inner Detector
Radiation shield
20
18
16
14
12
10
8
6
4
2
CSC chambers



Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Transition Radiation Tracker
Tracking
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch
©ATLAS


barrel
toroids
end-cap
toroids
end-cap
toroids
solenoid


8400A
Toshiba
Dec. 26, 2000
KEK



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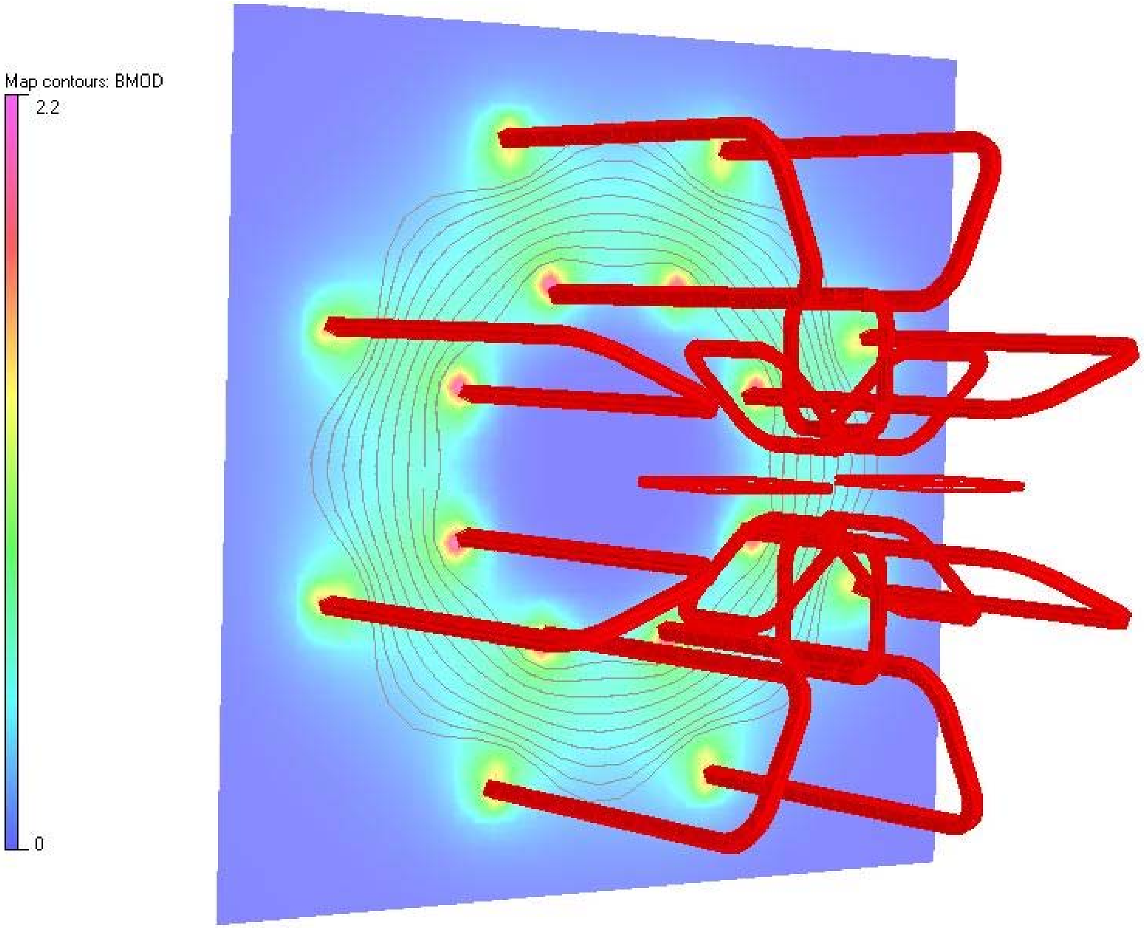
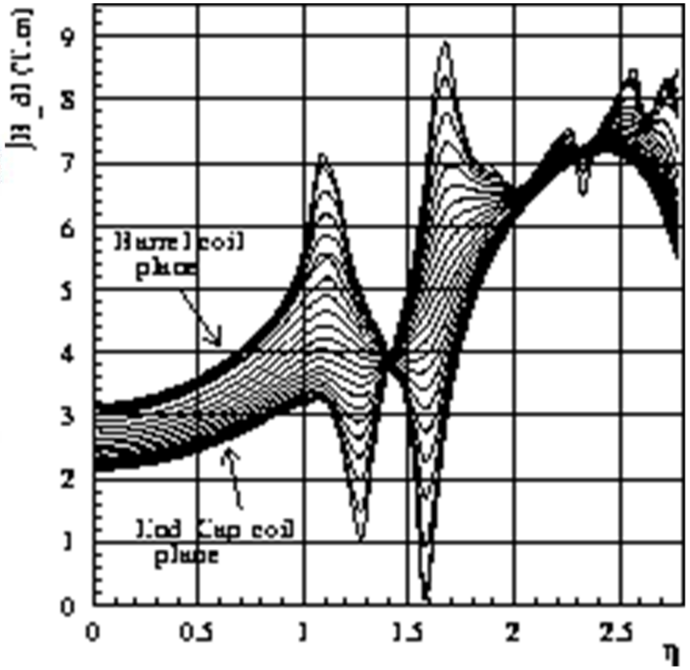
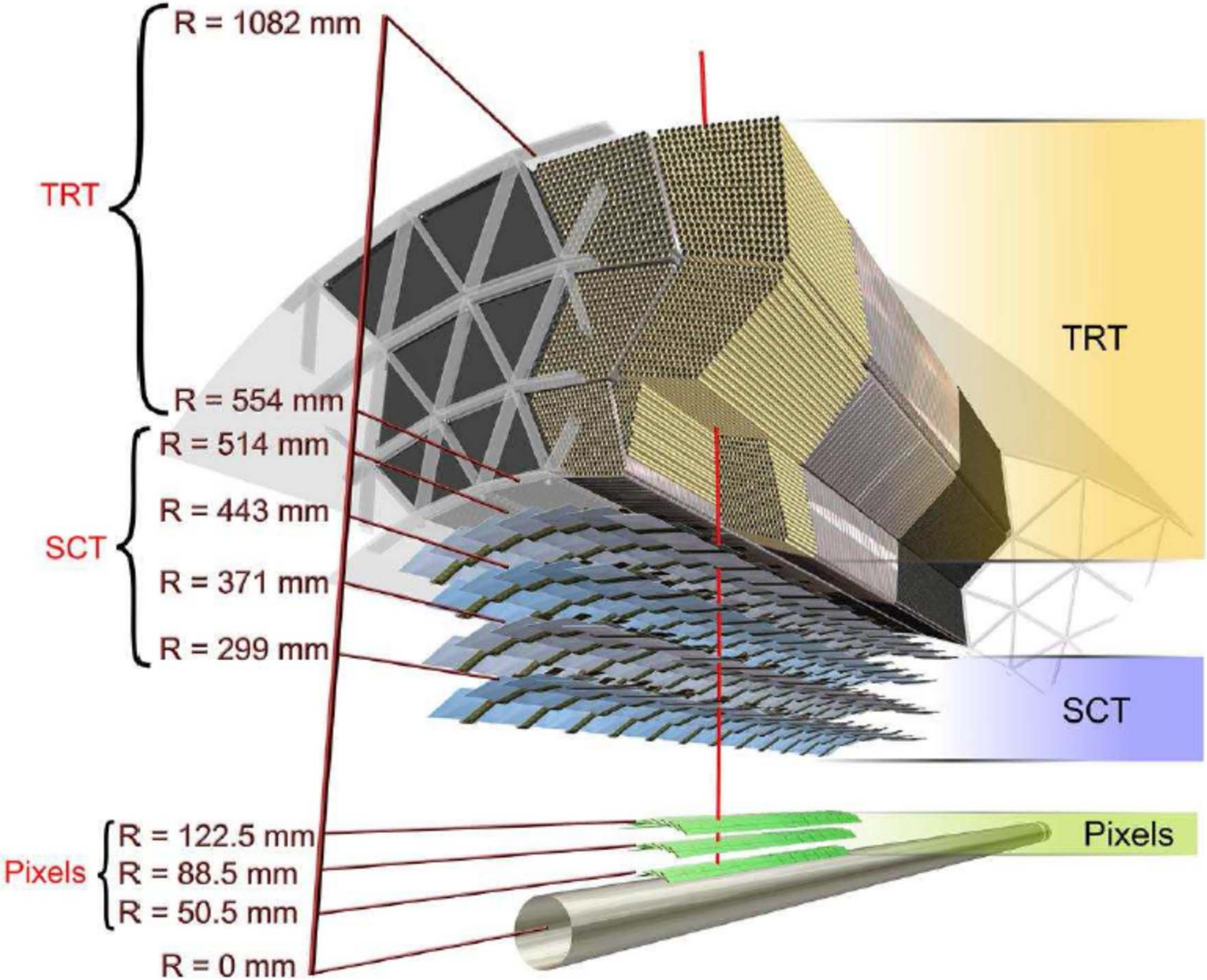
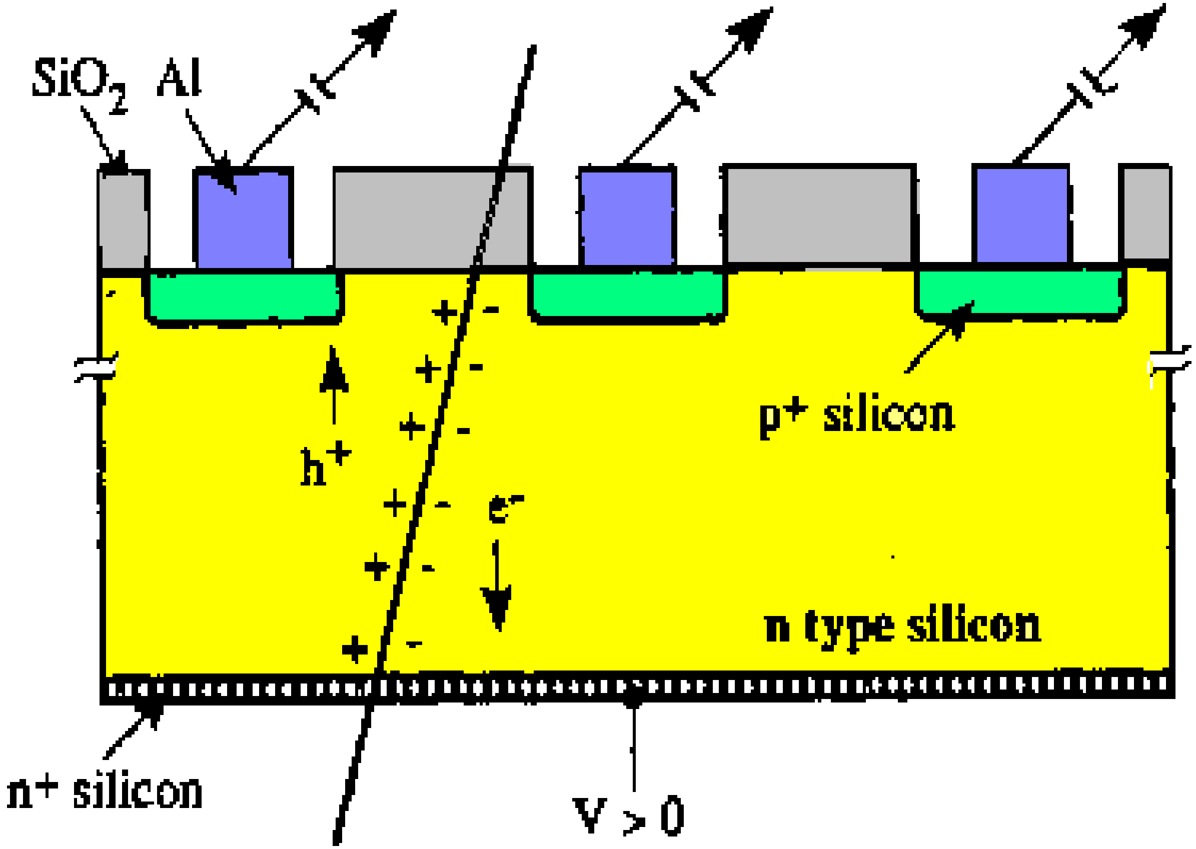

Map contours: BMOD
2.2
0

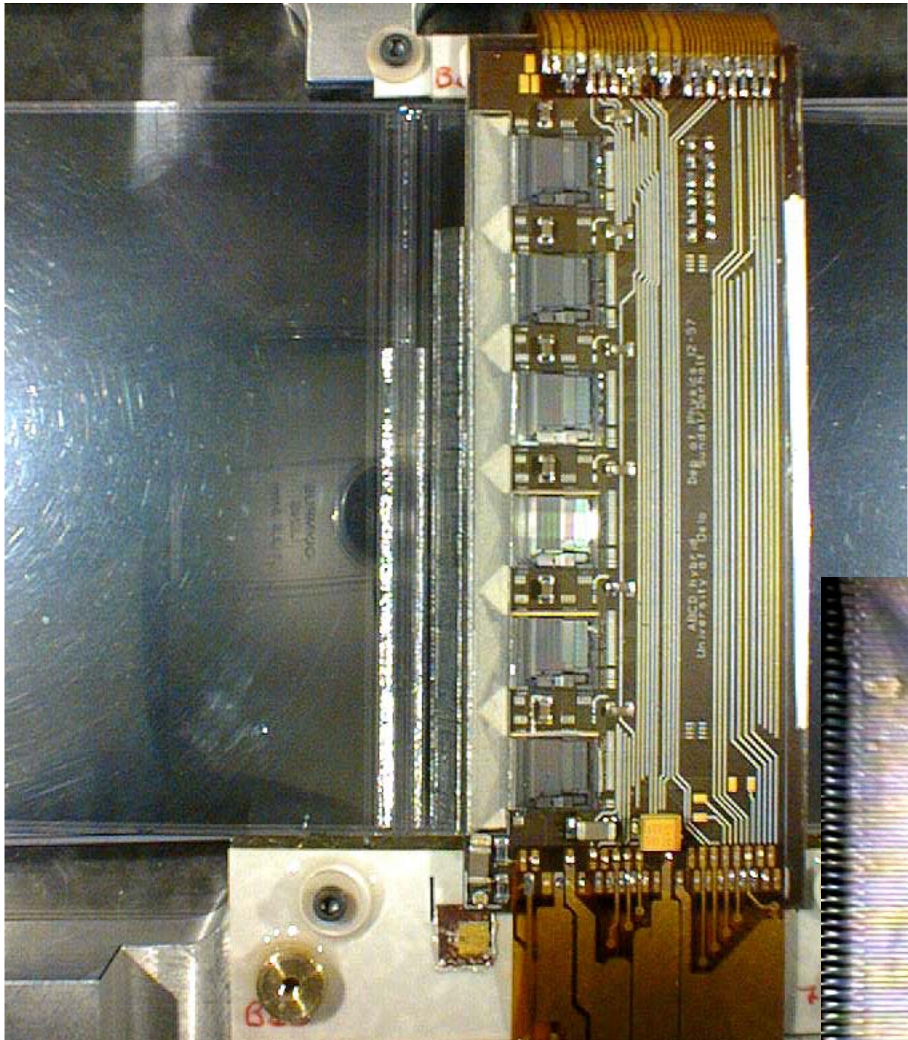

0
1
2
3
4
5
6
7
8
9
0
0.5
1
1.5
2
2.5
η

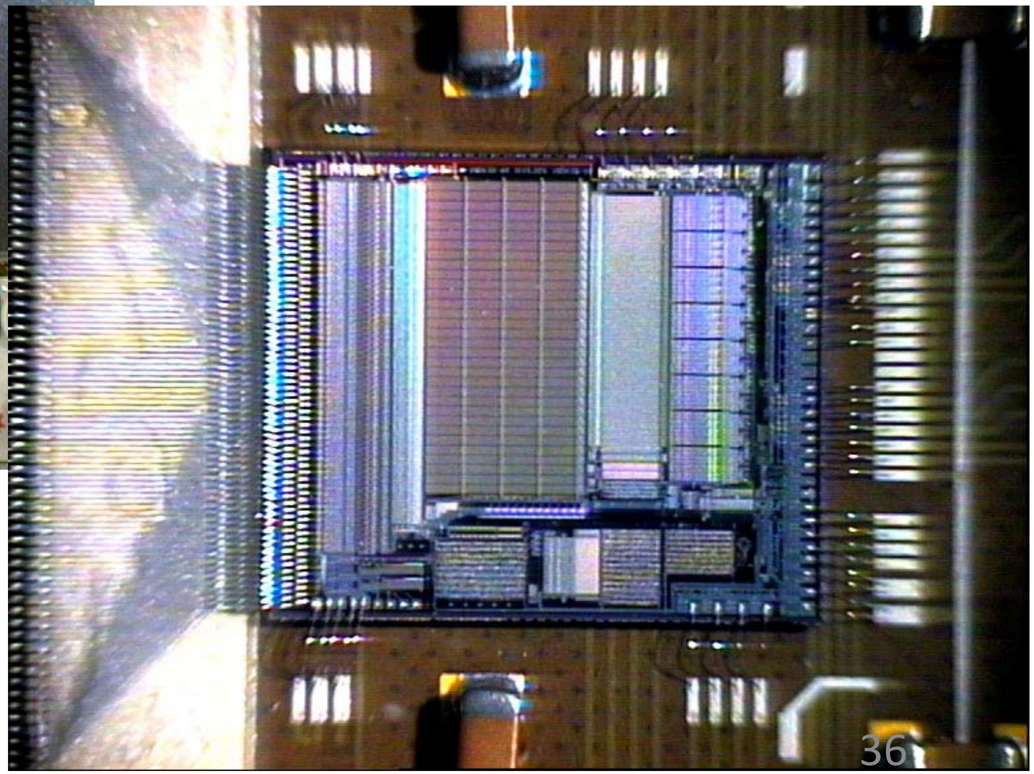


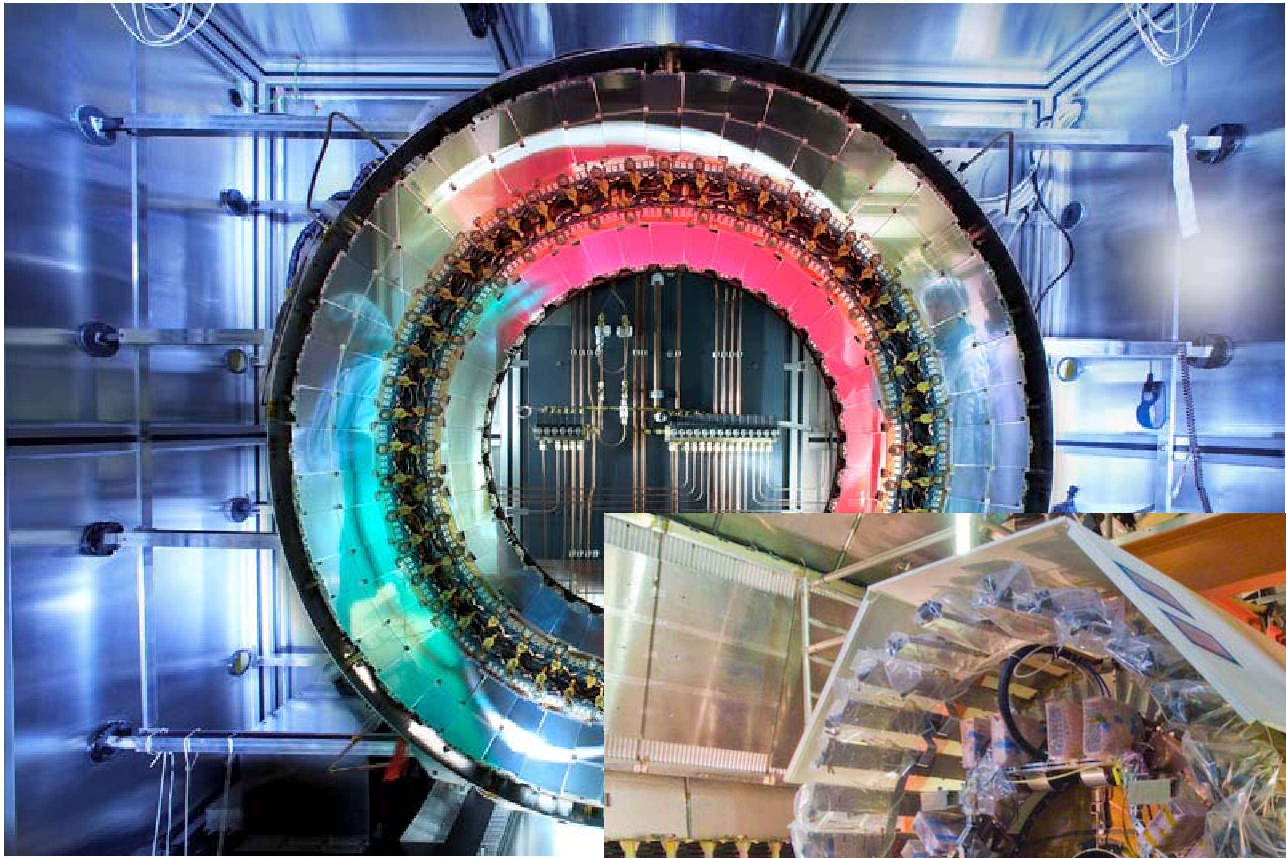
R = 1082 mm
TRT
R = 554 mm
R = 514 mm
R = 443 mm
SCT
R = 371 mm
R = 299 mm
R = 122.5 mm
Pixels
R = 88.5 mm
R = 50.5 mm
R = 0 mm
TRT
SCT
Pixels

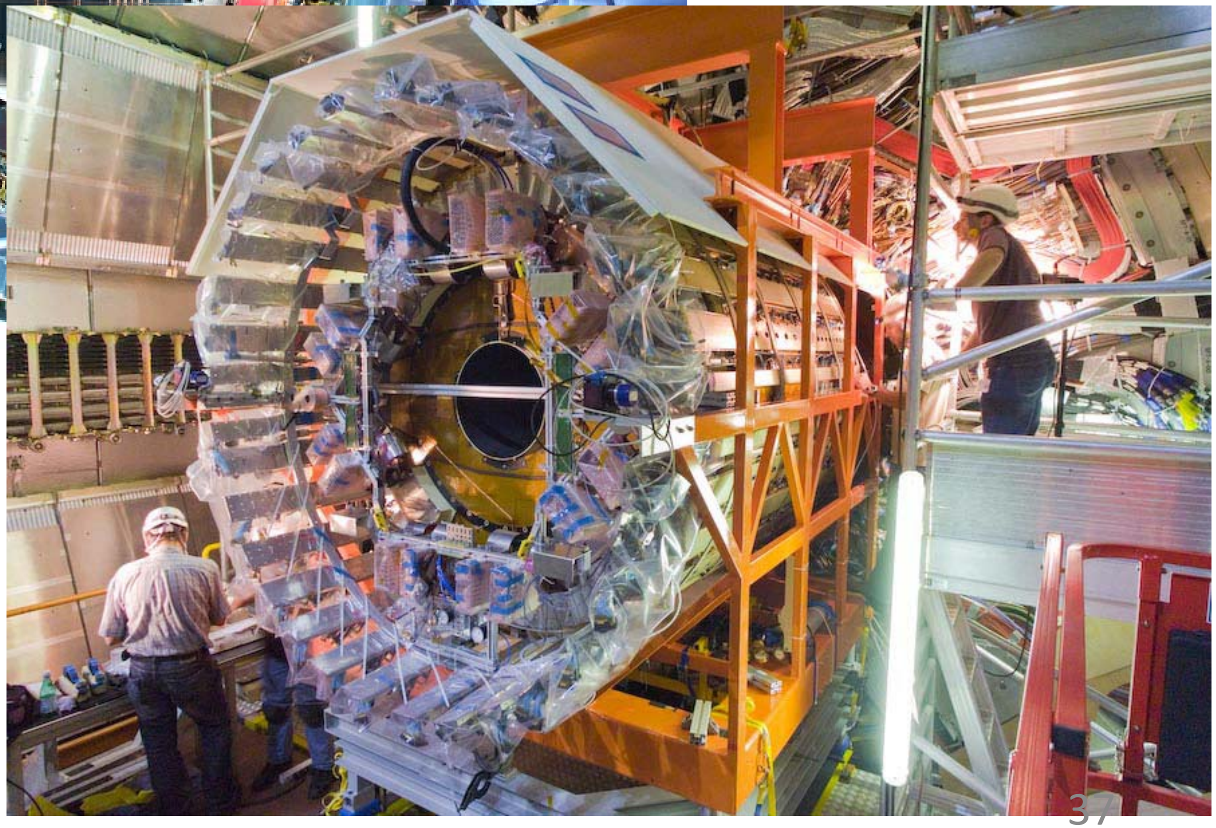


SiO2
Al
p+ silicon
h+
e-
n type silicon
n+ silicon
V > 0

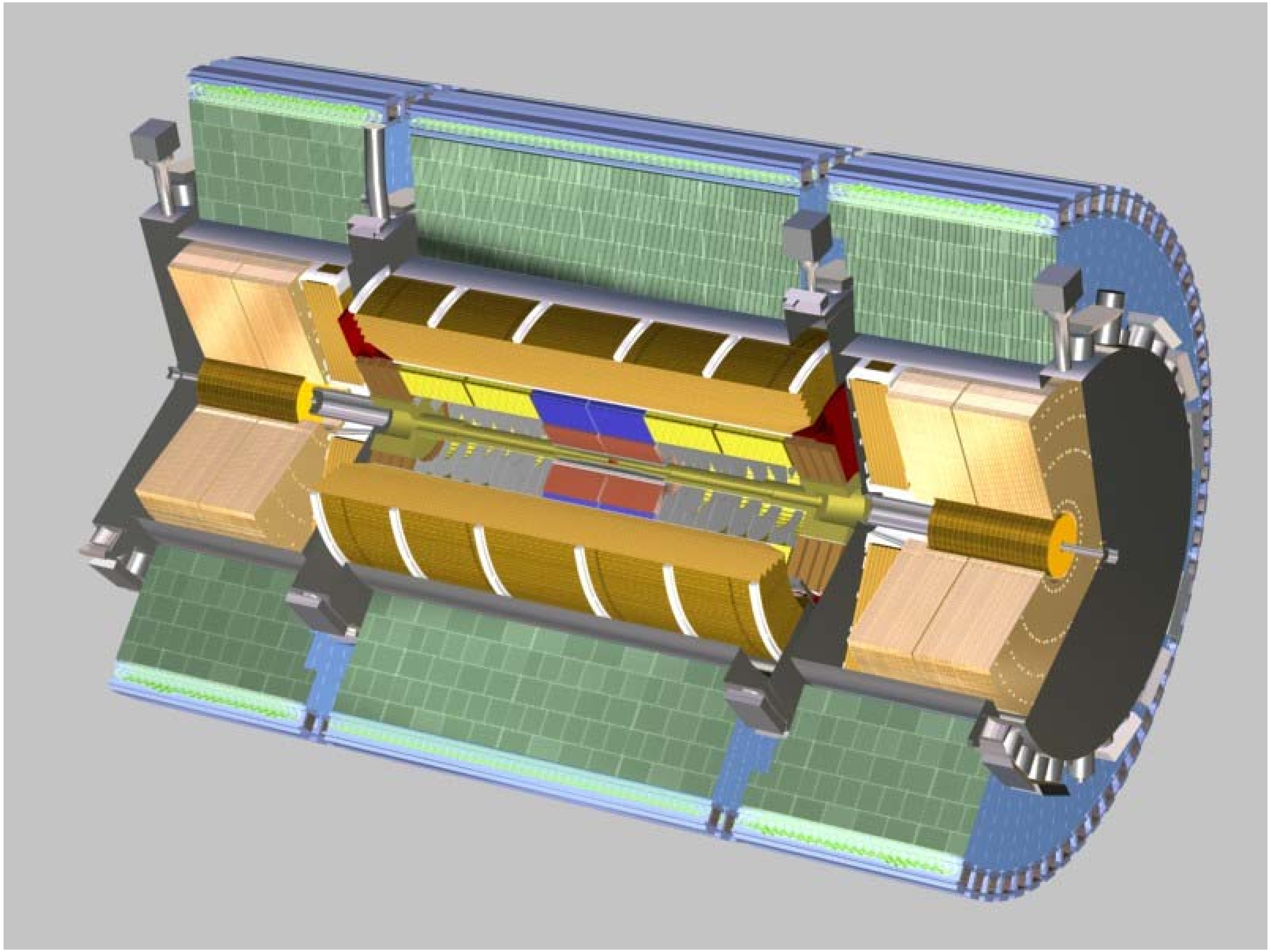


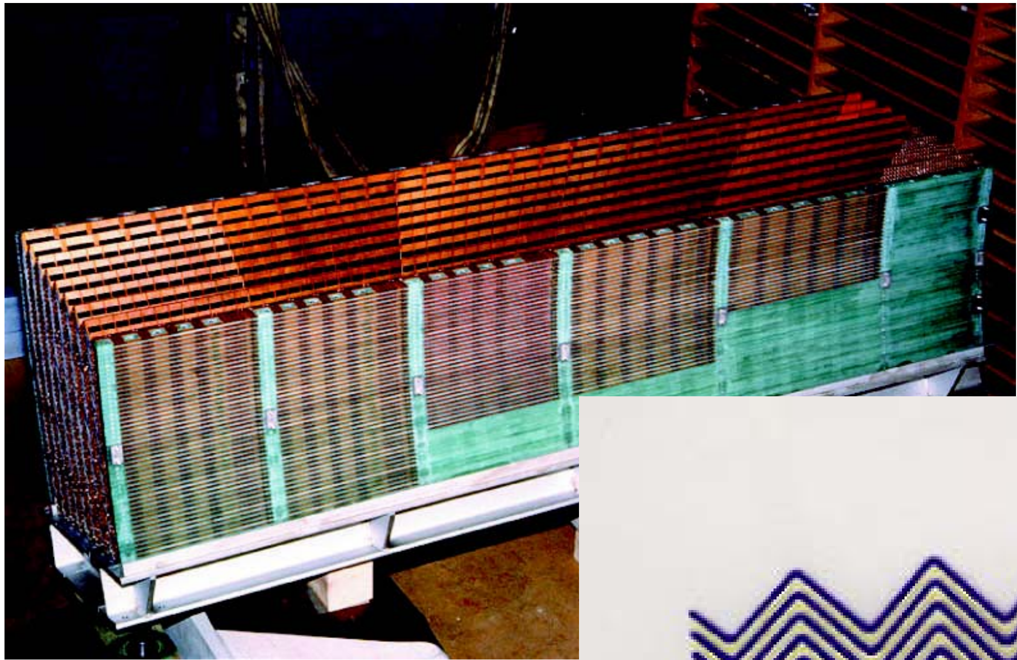


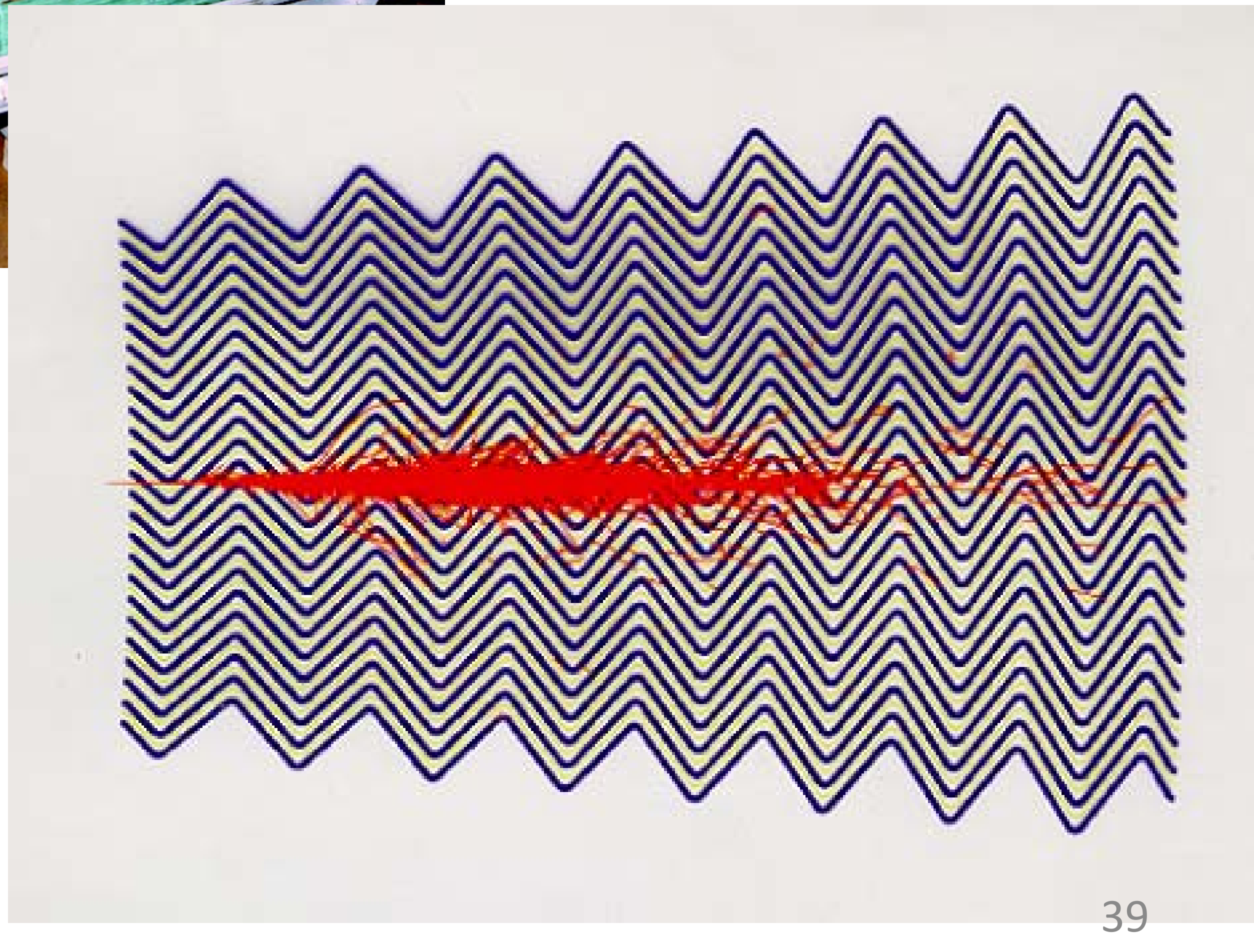


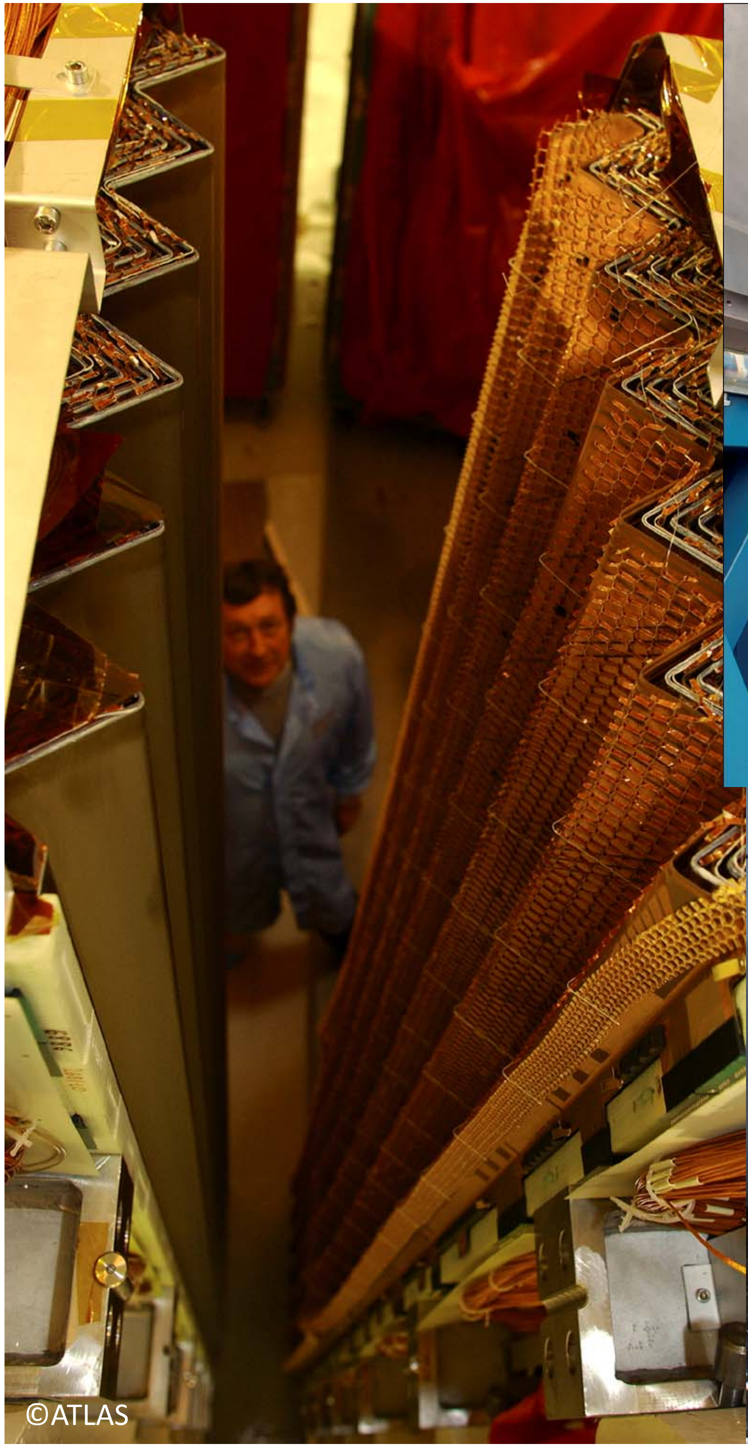


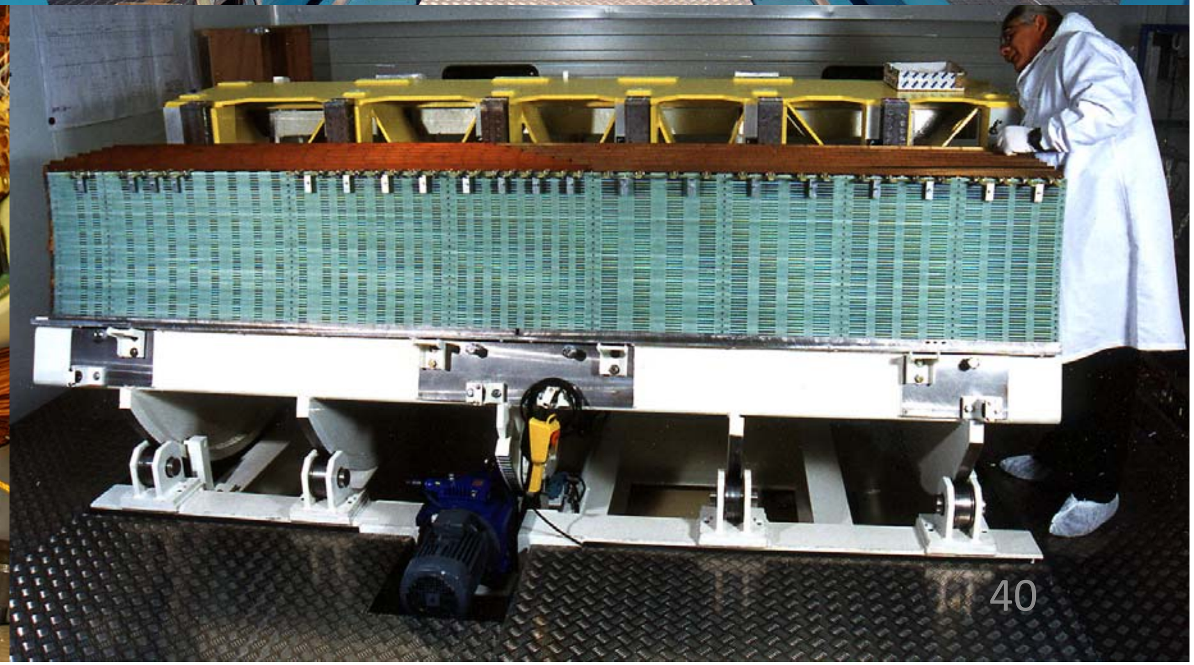
©ATLAS

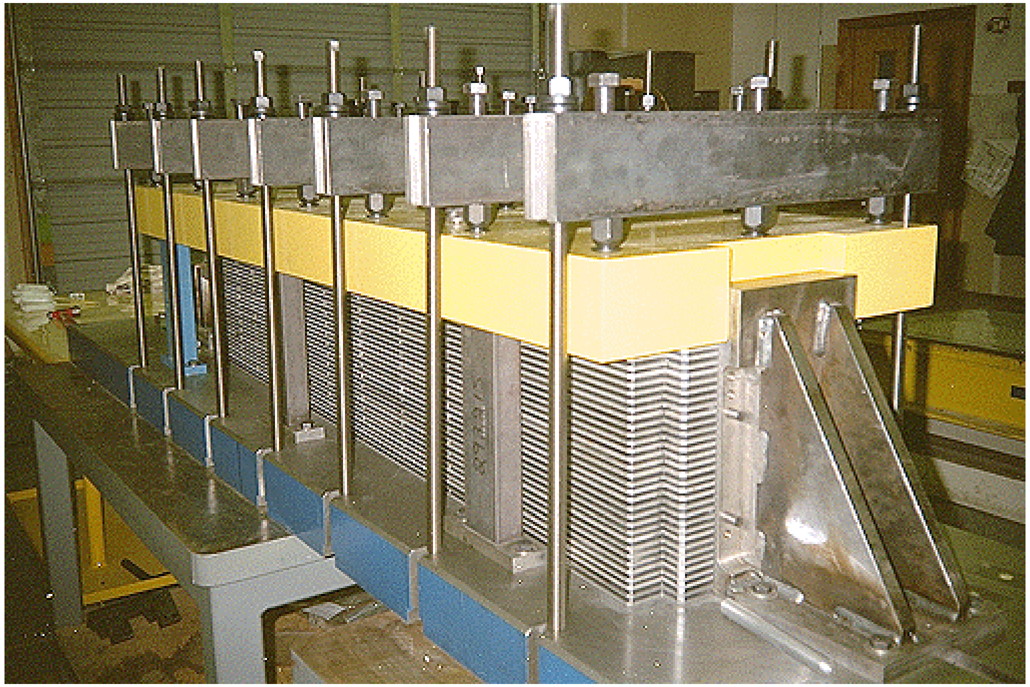


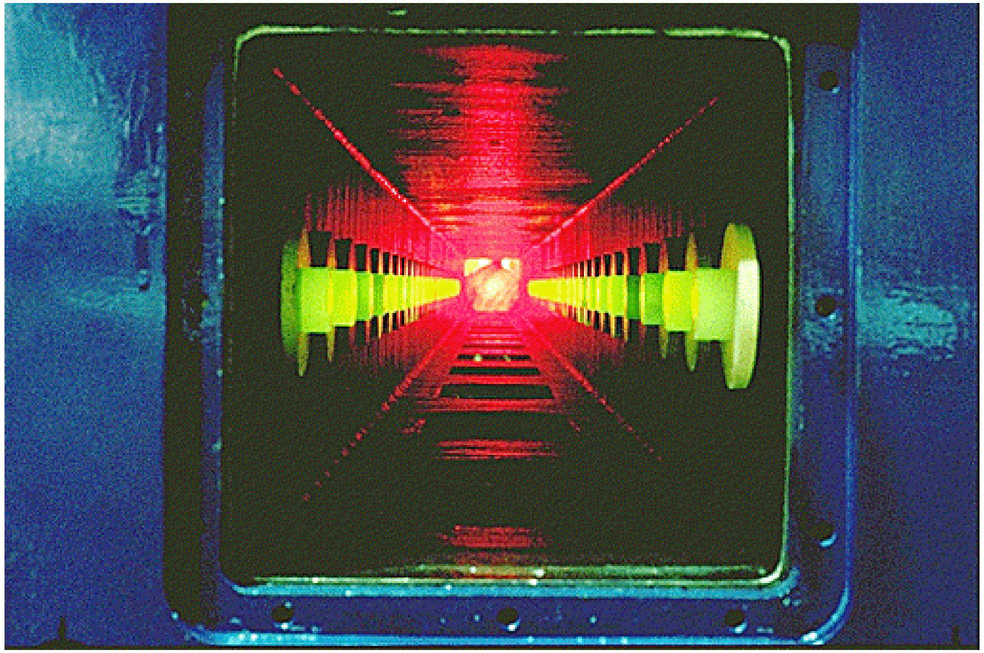


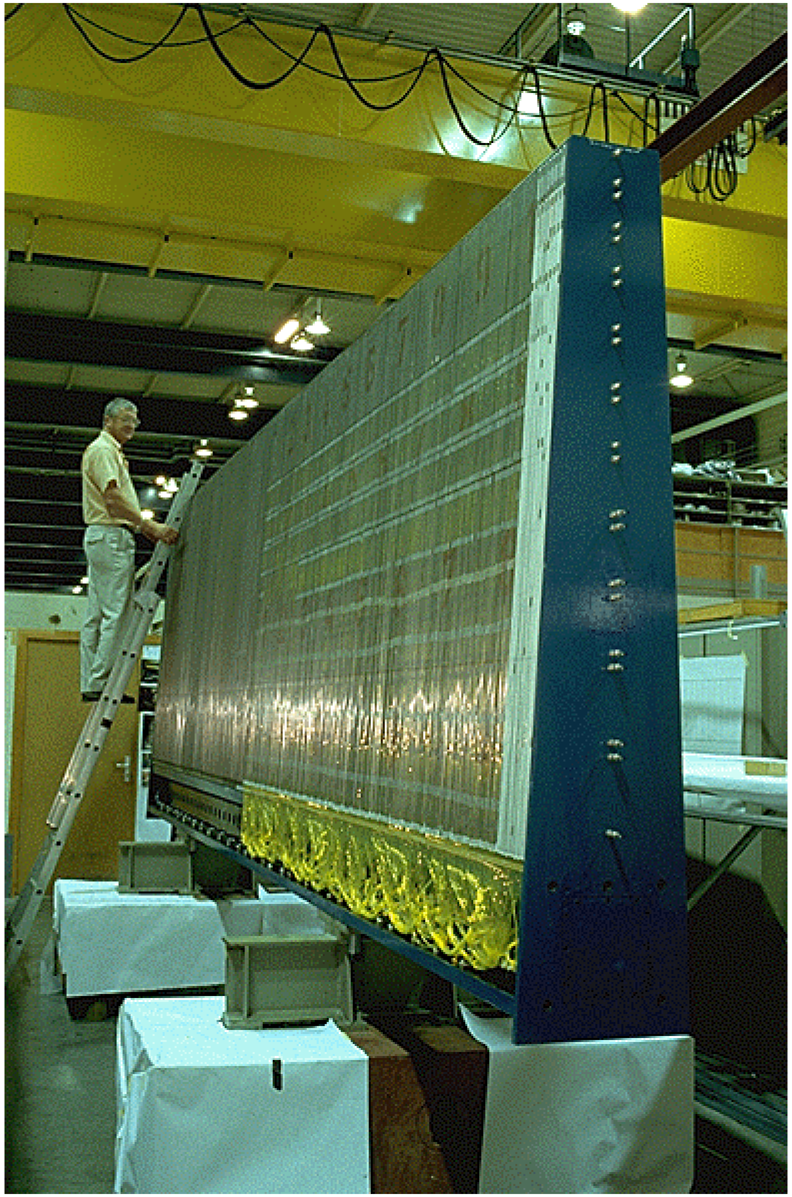


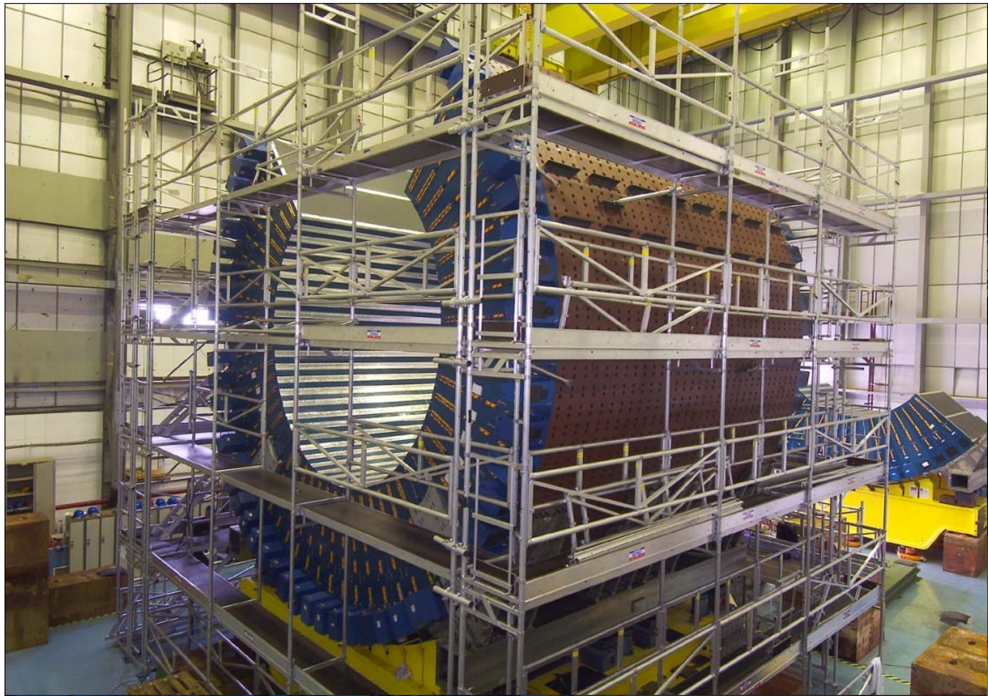


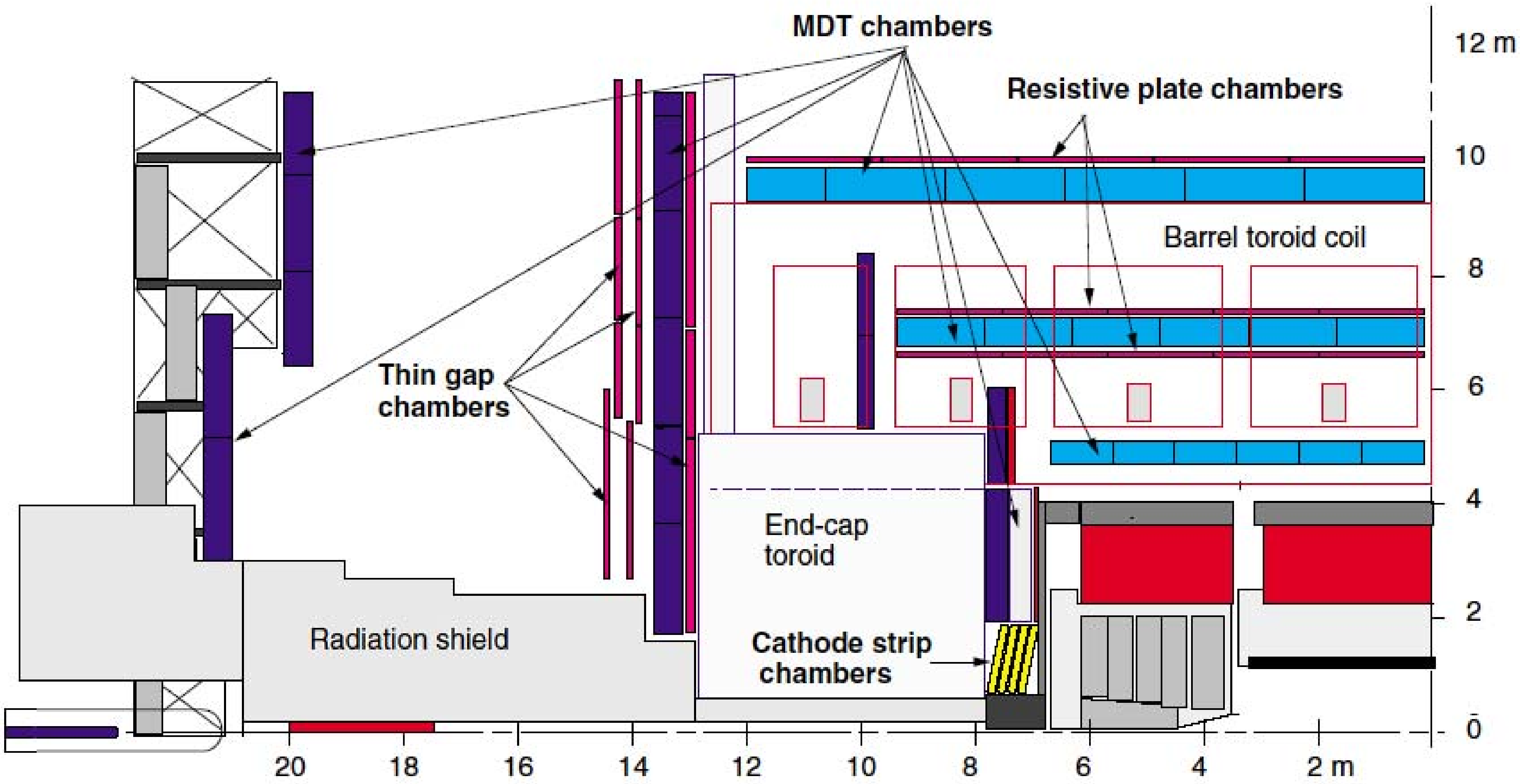


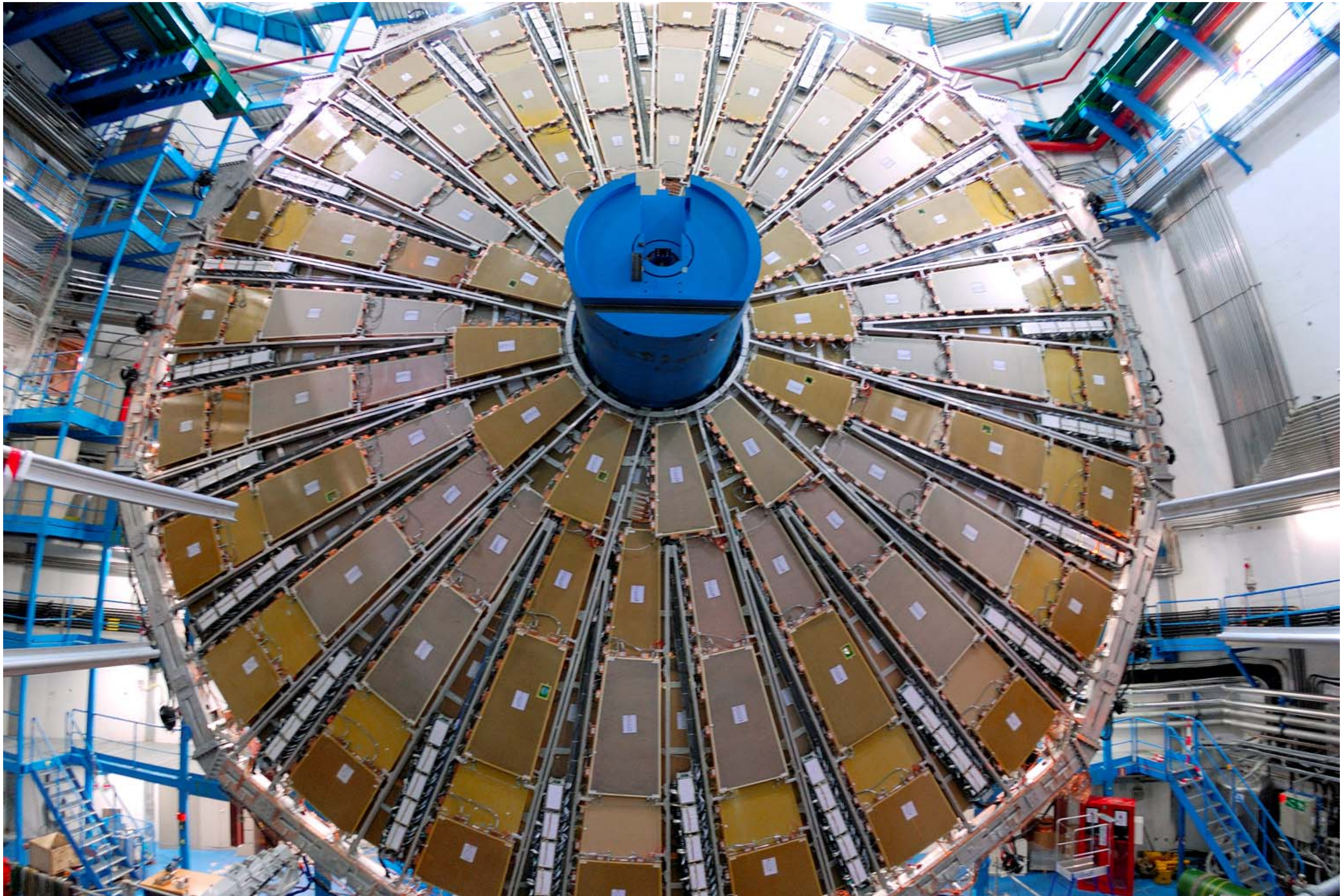






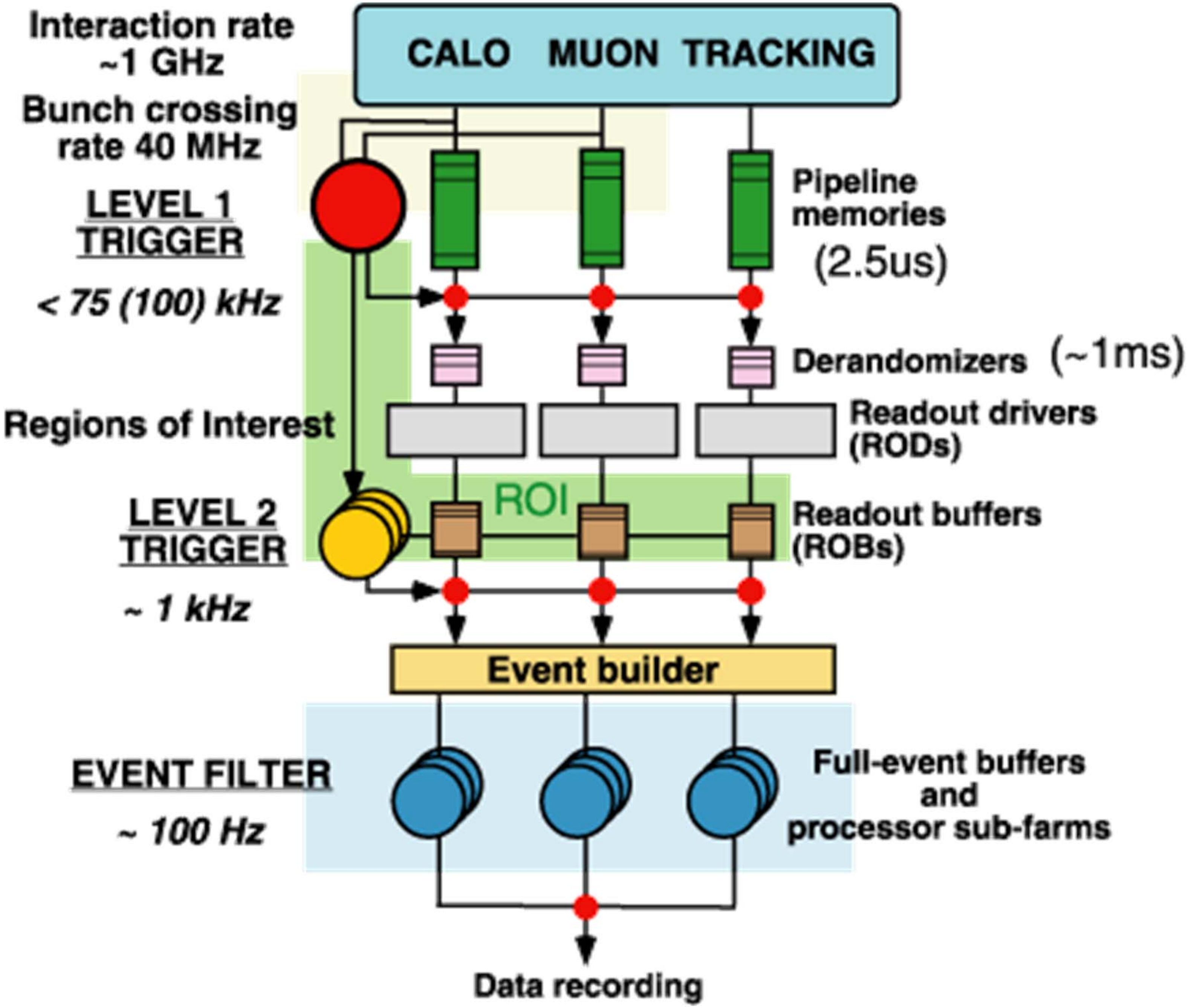



MDT chambers
12 m
Resistive plate chambers
10
Barrel toroid coil
8
Thin gap
chambers
6
4
End-cap
toroid
2
Radiation shield
Cathode strip
chambers
0
20
18
16
14
12
10
8
6
4
2 m

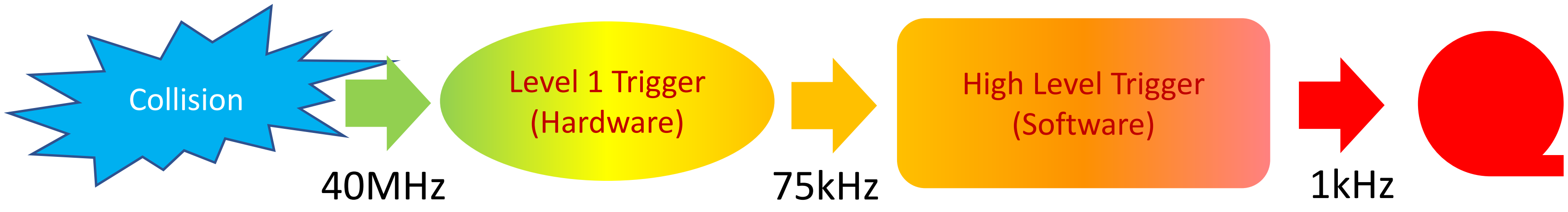


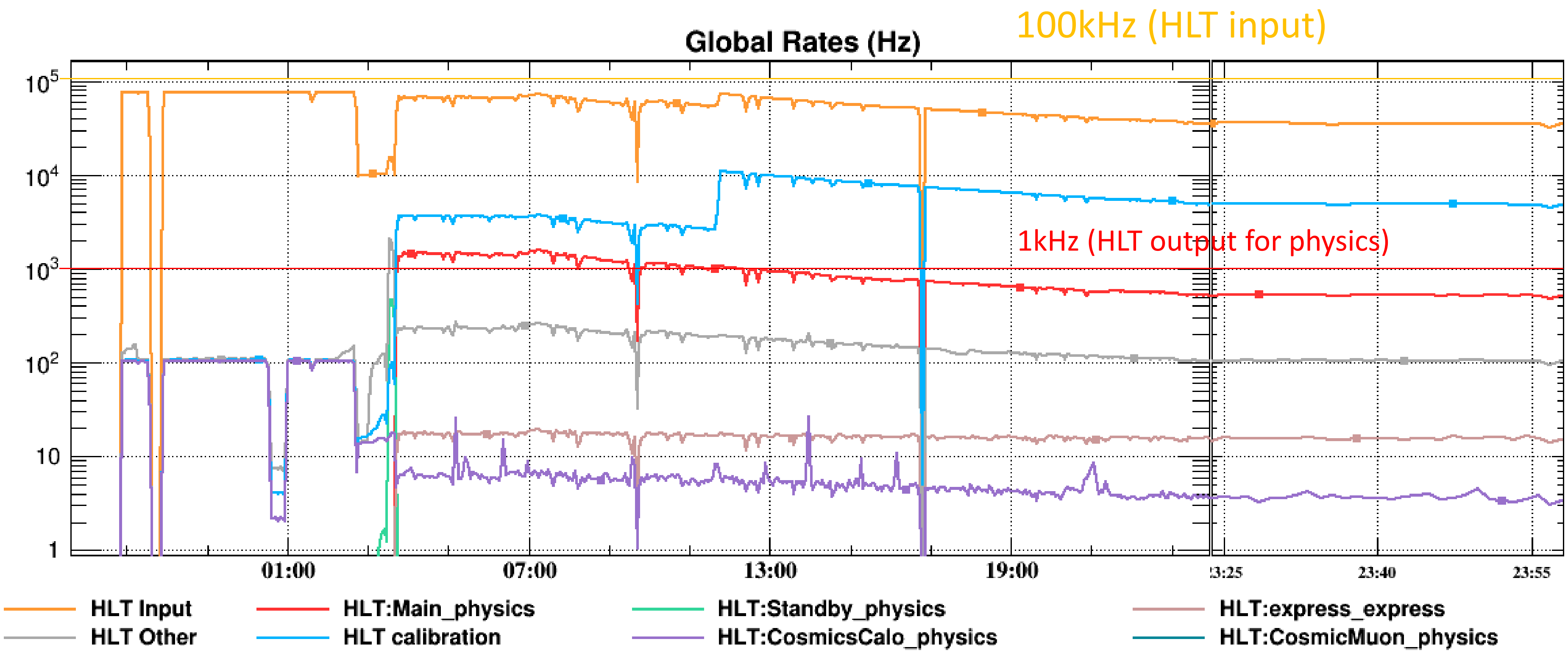
ATLAS Run-2 Detector Status (from July 2017)

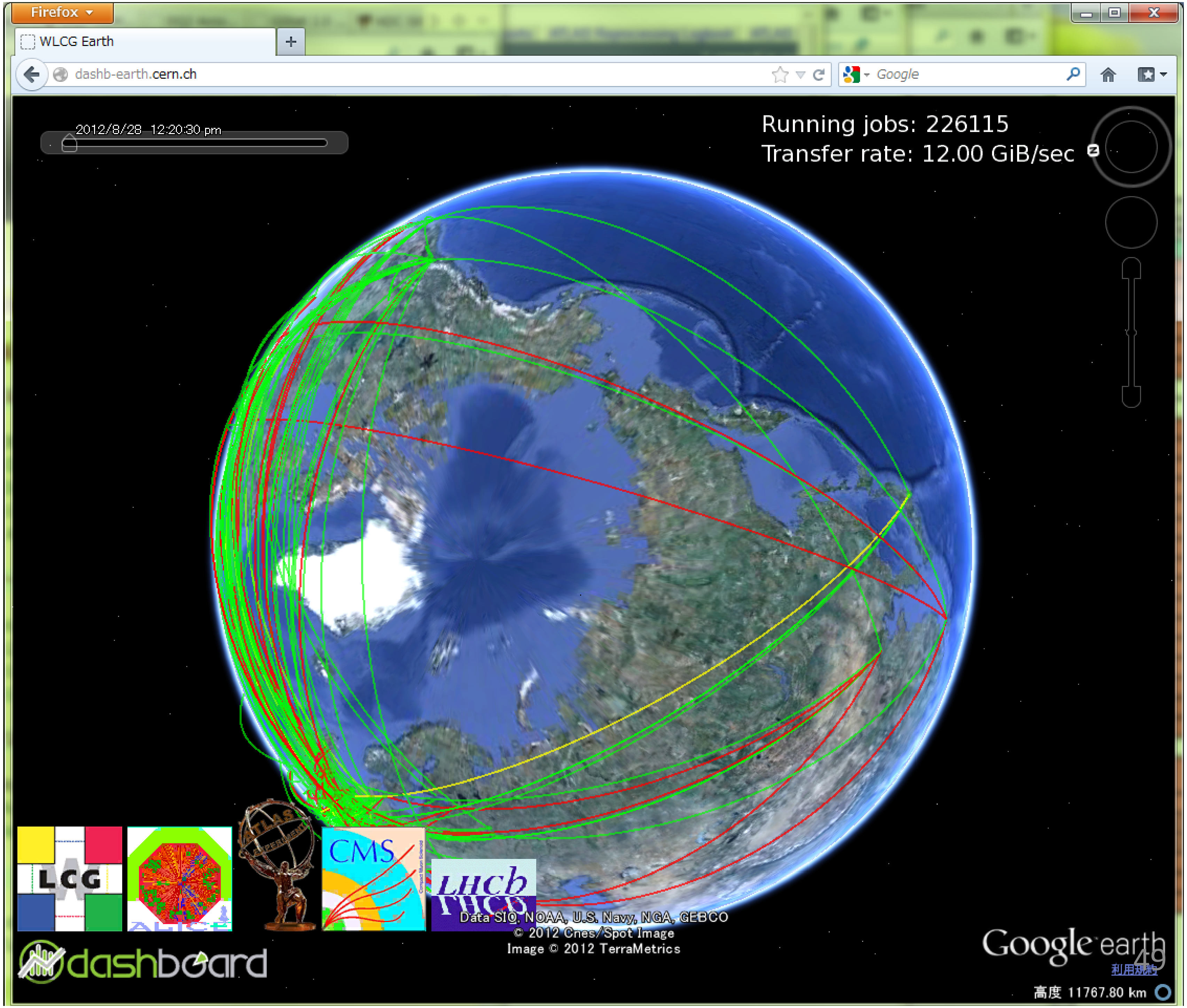
Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	92 M	97.8%
SCT Silicon Strips	6.3 M	98.7%
TRT Transition Radiation Tracker	350 k	97.2%
LAr EM Calorimeter	170 k	100 %
Tile Calorimeter	5200	99.2%
Hadronic End-Cap LAr Calorimeter	5600	99.5%
Forward LAr Calorimeter	3500	99.7%
LVL1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

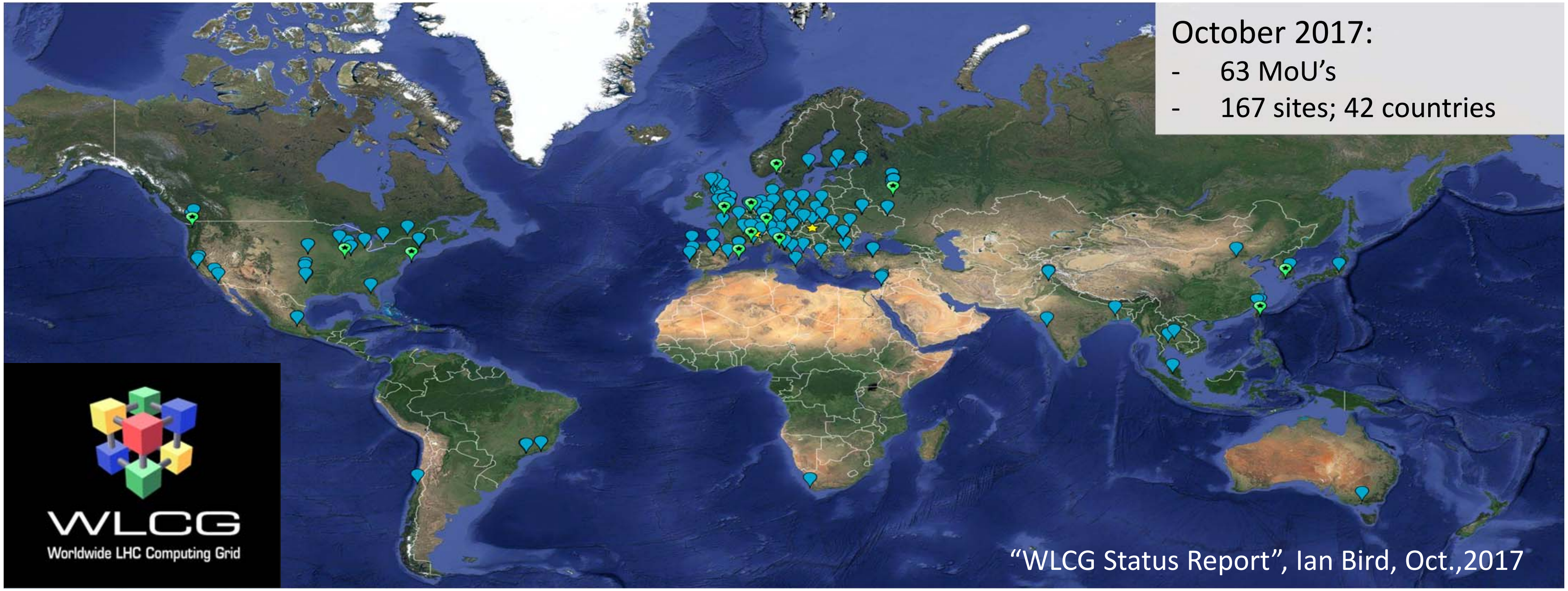

Interaction rate
~1 GHz
Bunch crossing
rate 40 MHz
CALO MUON TRACKING
LEVEL 1
TRIGGER
< 75 (100) kHz
Pipeline
memories
(2.5us)
Derandomizers (~1ms)
Regions of Interest
Readout drivers
(RODs)
ROI
LEVEL 2
TRIGGER
~ 1 kHz
Readout buffers
(ROBs)
Event builder
EVENT FILTER
~ 100 Hz
Full-event buffers
and
processor sub-farms
Data recording

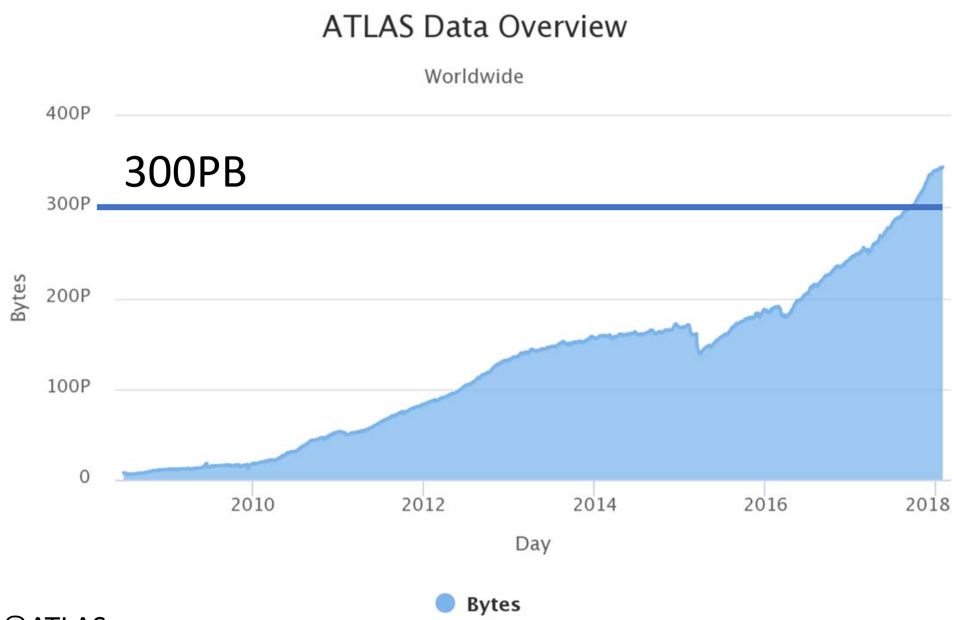
Trigger System

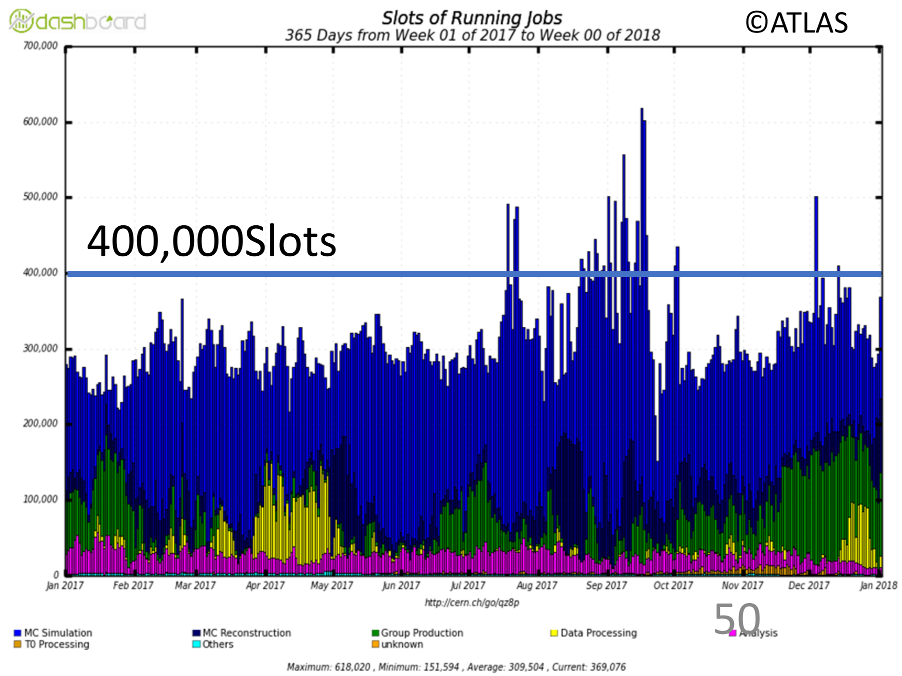


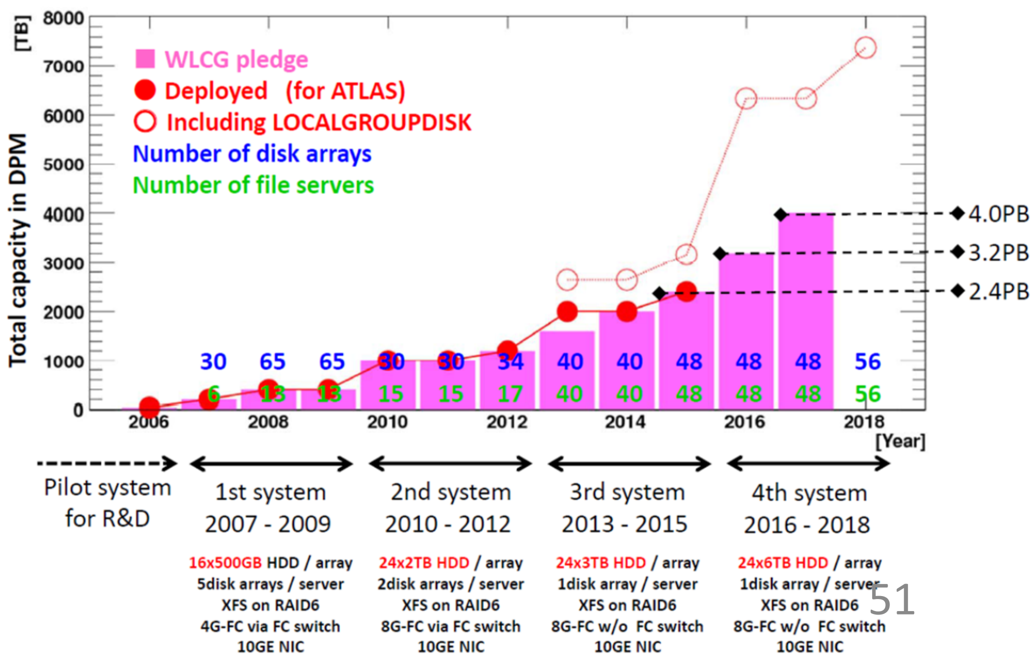



Firefox
WLCG Earth
dashb-earth.cern.ch
Google
2012/8/28 12:20:30 pm
Running jobs: 226115
Transfer rate: 12.00 GiB/sec
LCG
CMS
LHCb
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2012 Cnes/Spot Image
Image © 2012 TerraMetrics
Google earth
利用規約
高度 11767.80 km
dashboard

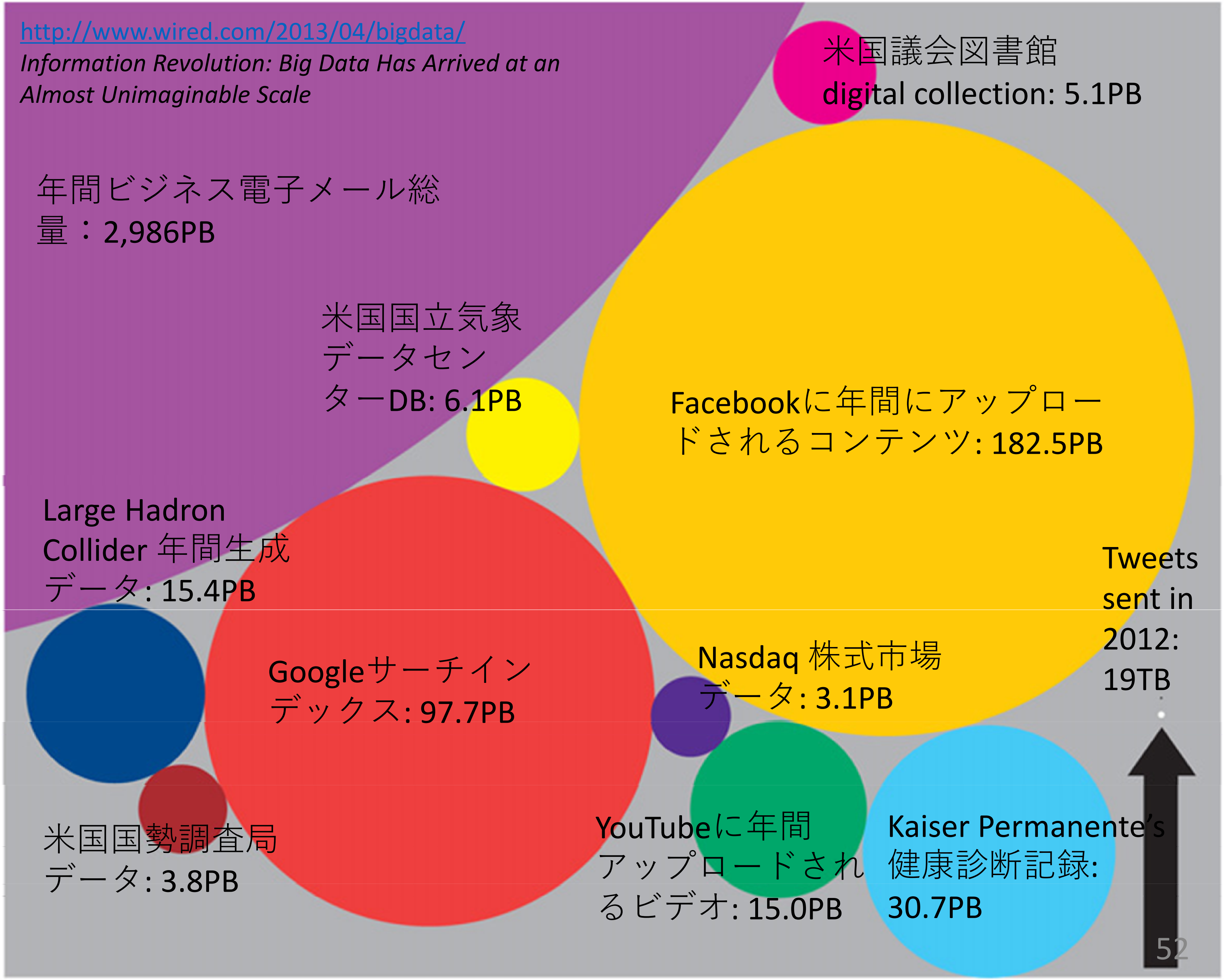

October 2017:
- 63 MoU's
- 167 sites; 42 countries
WLCG
Worldwide LHC Computing Grid
"WLCG Status Report", Ian Bird, Oct.,2017


ATLAS Data Overview
Worldwide
400P
300P
200P
100P
0
Bytes
300PB
2010
2012
2014
2016
2018
Day
Bytes


dashboard
Slots of Running Jobs
365 Days from Week 01 of 2017 to Week 00 of 2018
400,000Slots
Jan 2017
Feb 2017
Mar 2017
Apr 2017
May 2017
Jun 2017
Jul 2017
Aug 2017
Sep 2017
Oct 2017
Nov 2017
Dec 2017
Jan 2018
http://cern.ch/go/qz8p
MC Simulation
MC Reconstruction
Group Production
Data Processing
Analysis
T0 Processing
Others
unknown
Maximum: 618,020 , Minimum: 151,594 , Average: 309,504 , Current: 369,076



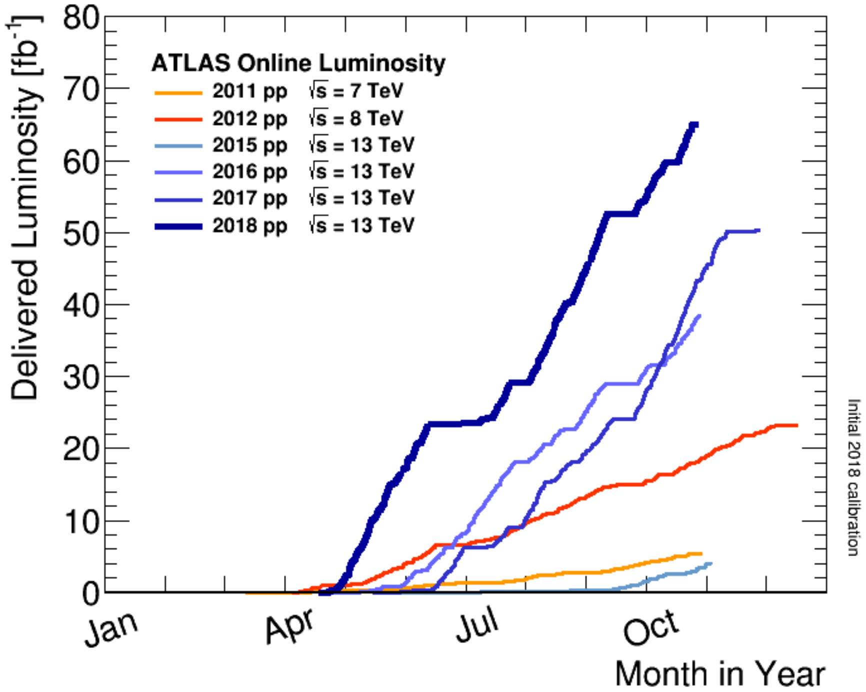
[TB]
Total capacity in DPM
8000
7000
6000
5000
4000
3000
2000
1000
0
WLCG pledge
Deployed (for ATLAS)
Including LOCALGROUPDISK
Number of disk arrays
Number of file servers
4.0PB
3.2PB
2.4PB
30 65 65 30 30 34 40 40 48 48 48 56
6 13 13 15 15 17 40 40 48 48 48 56
2006
2008
2010
2012
2014
2016
2018
[Year]
Pilot system
for R&D
1st system
2007 - 2009
2nd system
2010 - 2012
3rd system
2013 - 2015
4th system
2016 - 2018
16x500GB HDD / array
5disk arrays / server
XFS on RAID6
4G-FC via FC switch
10GE NIC
24x2TB HDD / array
2disk arrays / server
XFS on RAID6
8G-FC via FC switch
10GE NIC
24x3TB HDD / array
1disk array / server
XFS on RAID6
8G-FC w/o FC switch
10GE NIC
24x6TB HDD / array
1disk array / server
XFS on RAID6
8G-FC w/o FC switch
10GE NIC

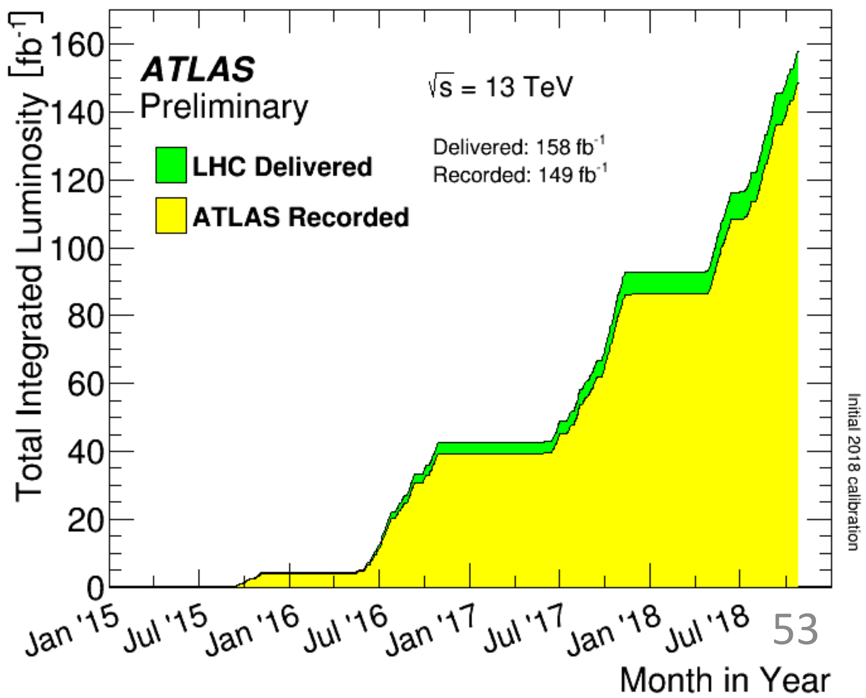


http://www.wired.com/2013/04/bigdata/
Information Revolution: Big Data Has Arrived at an Almost Unimaginable Scale
米国議会図書館 digital collection: 5.1PB
年間ビジネス電子メール総量：2,986PB
米国国立気象データセンターDB: 6.1PB
Facebookに年間にアップロードされるコンテンツ: 182.5PB
Large Hadron Collider 年間生成データ: 15.4PB
Tweets sent in 2012: 19TB
Googleサーチインデックス: 97.7PB
Nasdaq 株式市場データ: 3.1PB
米国国勢調査局データ: 3.8PB
YouTubeに年間アップロードされるビデオ: 15.0PB
Kaiser Permanente's 健康診断記録: 30.7PB

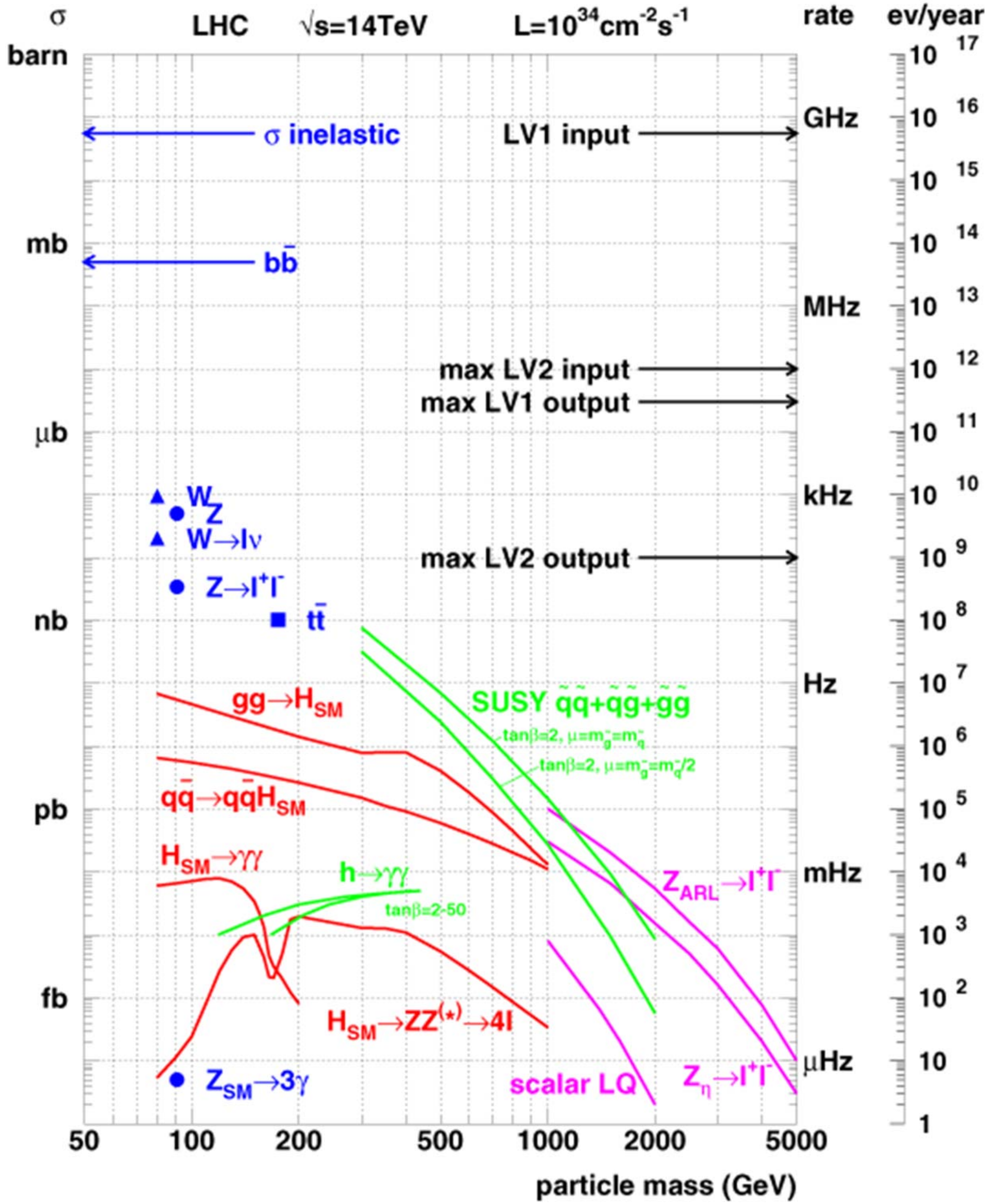
積分ルミノシティ

- fb (フェントバーン)
  - 1b = $10^{-28}m^2$　面積の単位
  - およそ原子核の大きさ
  - 1fb = 10^{-15}b=$10^{-43}m^2$
- fb^{-1}
  - $1fb^{-1}$は1fbの事象が1回発生するだけの衝突回数





瞬間ルミノシティ
$10^{34}cm^{-2}s^{-1} = 10nb^{-1}/s$
１年は10^7秒(効率30%として)
積分すると$10^{34}cm^{-2}s^{-1} \times 10^7$ =
$10nb^{-1}/s \times 10^7 = 100fb^{-1}$


σ barn
LHC √s=14TeV L=10^34 cm^-2 s^-1
rate ev/year
σ inelastic
LV1 input
GHz
mb
bb̄
MHz
max LV2 input
max LV1 output
μb
kHz
W
Z
W→lν
max LV2 output
Z→l+l-
nb
tt̄
Hz
gg→H_SM
SUSY q̃q̃+q̃g̃+g̃g̃
tanβ=2, μ=m_g̃=m_q̃
tanβ=2, μ=m_g̃=m_q̃/2
qq̄→qq̄H_SM
pb
H_SM→γγ
h→γγ
tanβ=2-50
mHz
Z_ARL→l+l-
fb
H_SM→ZZ(*)→4l
μHz
Z_SM→3γ
scalar LQ
Z_η→l+l-
50 100 200 500 1000 2000 5000
particle mass (GeV)
10^17 10^16 10^15 10^14 10^13 10^12 10^11 10^10 10^9 10^8 10^7 10^6 10^5 10^4 10^3 10^2 10 1

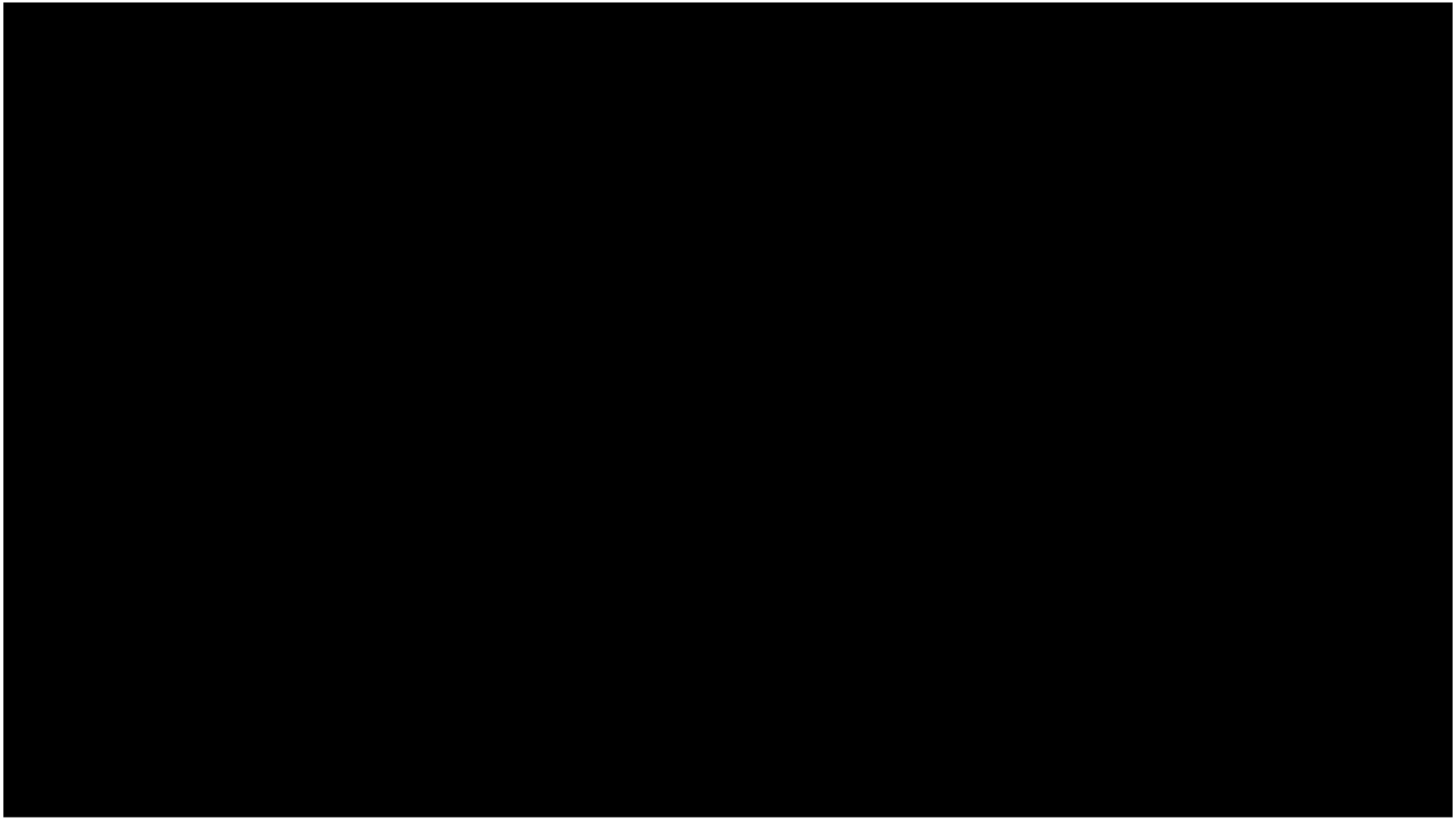
ヒッグス粒子の発見

- ヒッグス粒子とは
- ヒッグス粒子の生成
- ヒッグス粒子の崩壊
- ヒッグス粒子の信号
- ヒッグス粒子に関する最新の結果

A quasi-political Explanation of the Higgs Boson; for Mr Waldegrave, UK Science Minister 1993.

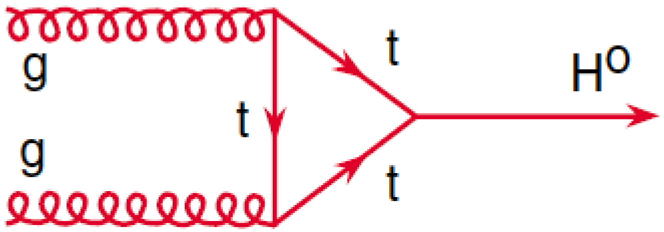
from David J. Miller, Physics and Astronomy, University College London.
(cartoons courtesy of CERN).

http://www.hep.ucl.ac.uk/~djm/higgsa.html

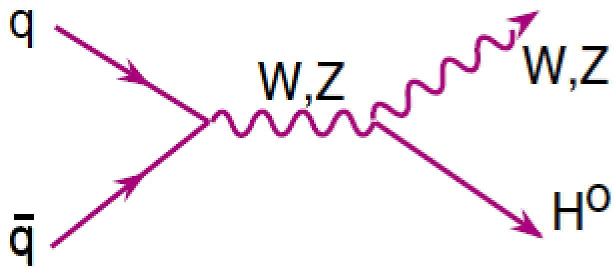


The Higgs Mechanism, CERN-VIDEO-2011-189-001

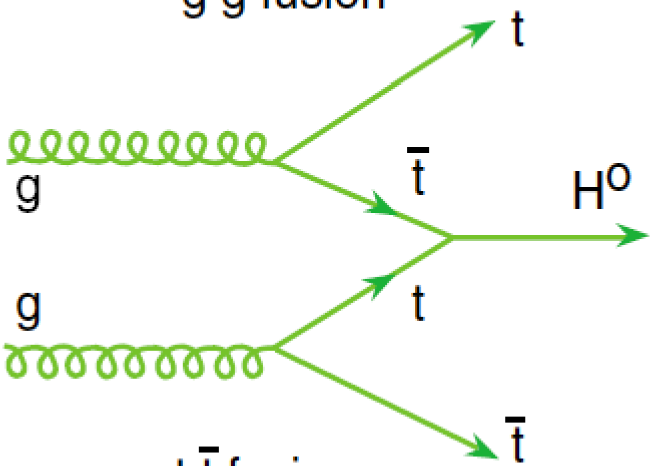
ヒッグス粒子を作る



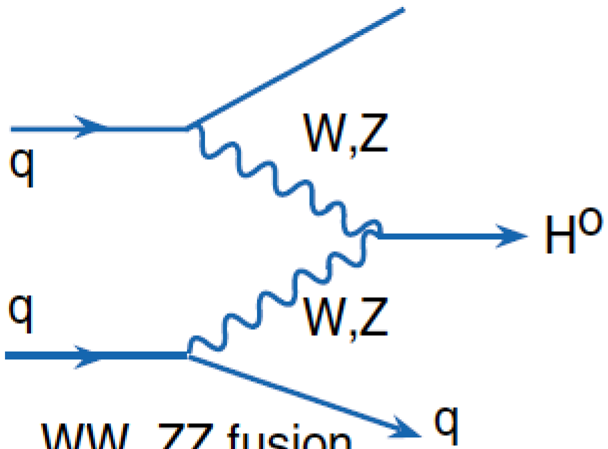
g g fusion



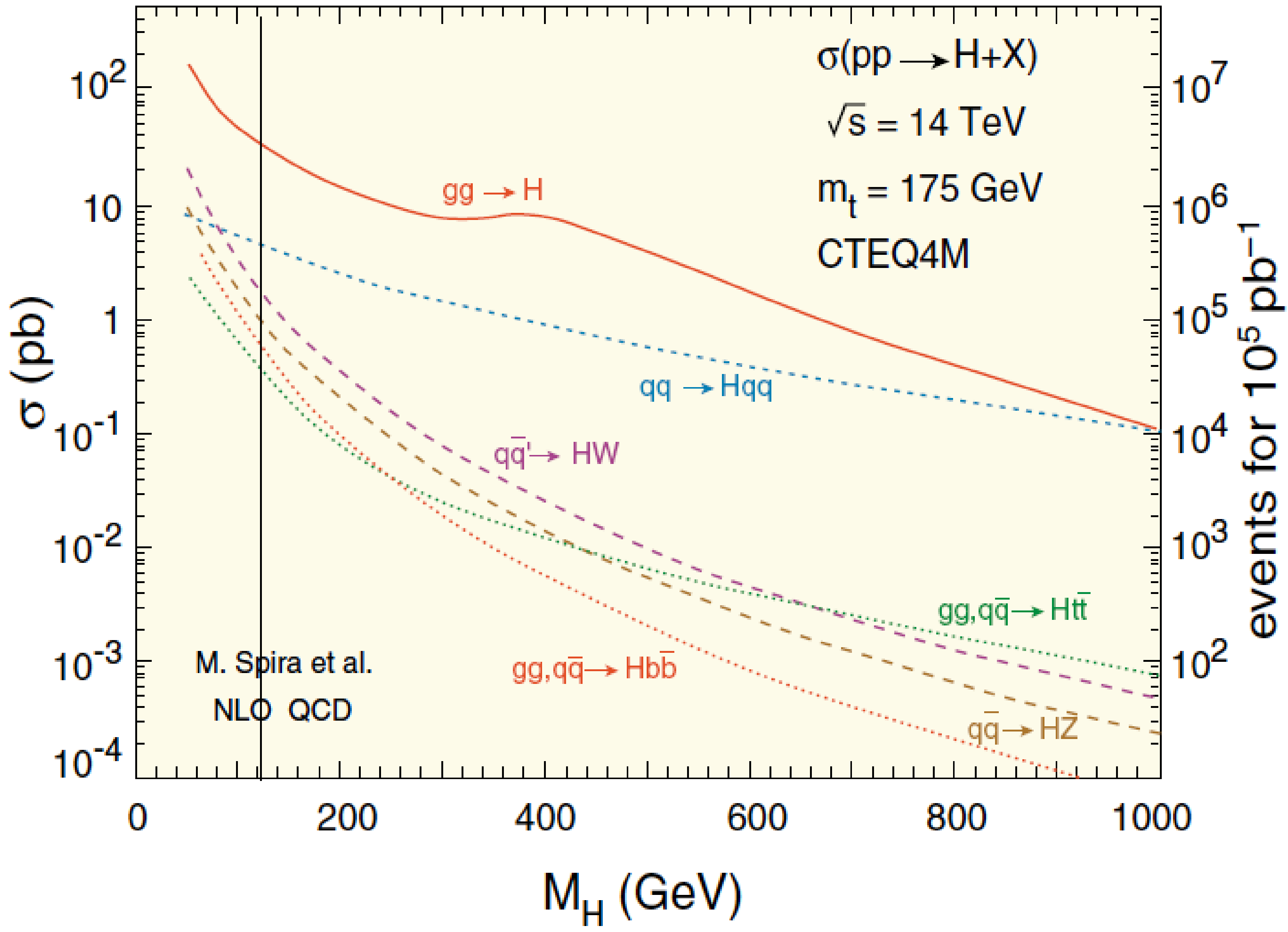
W, Z bremsstrahlung



t $\bar{t}$ fusion

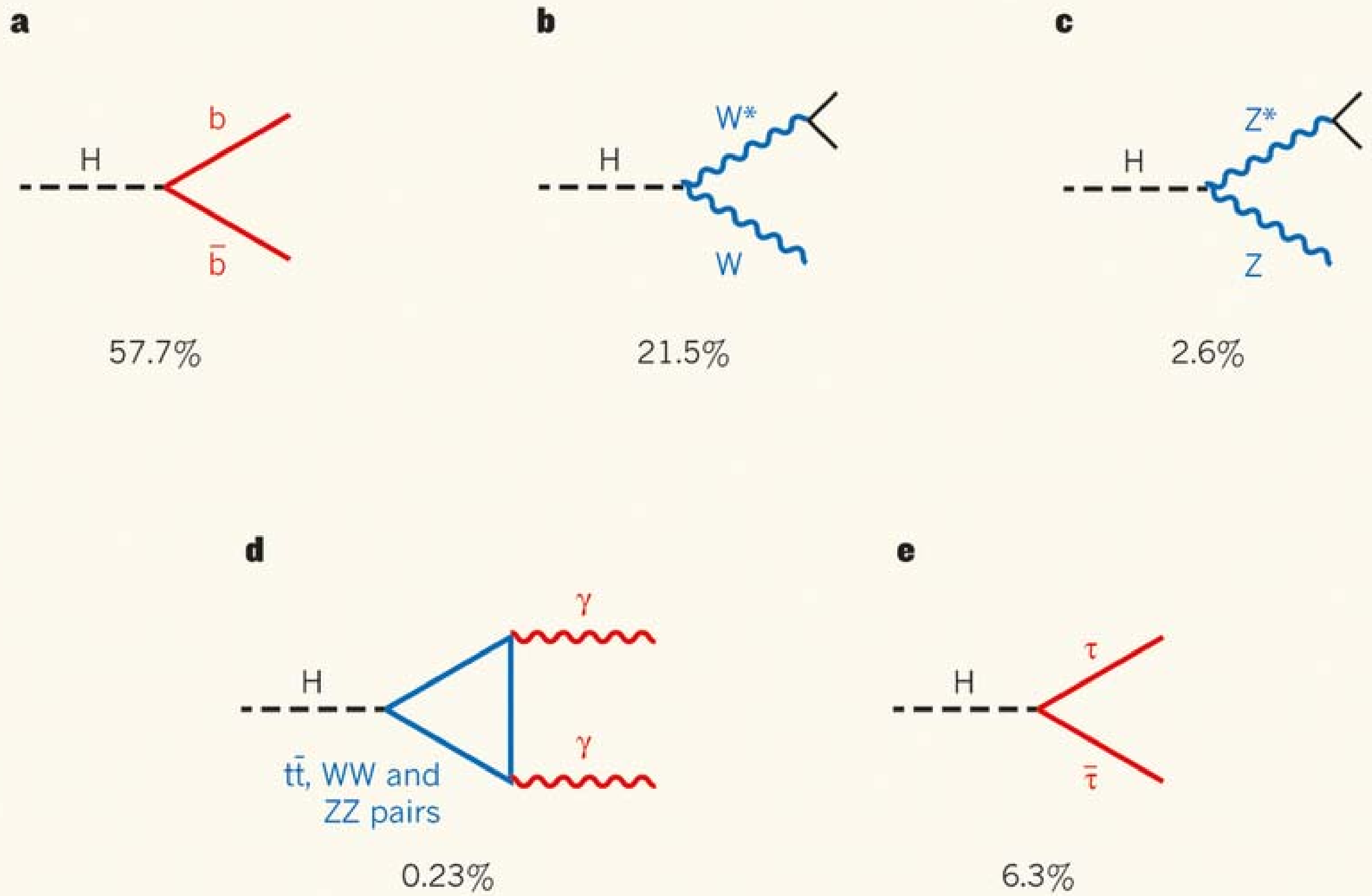


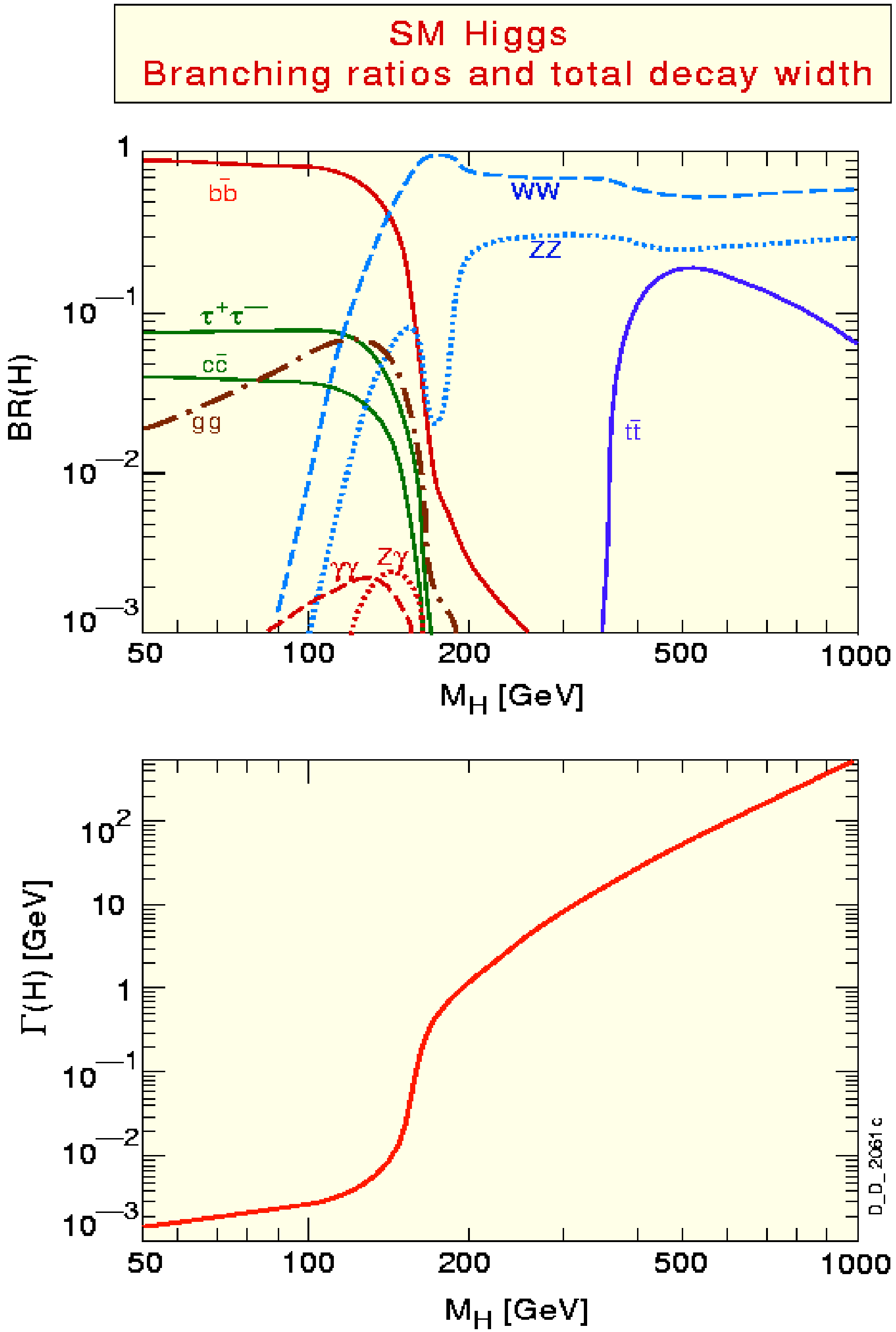
WW, ZZ fusion

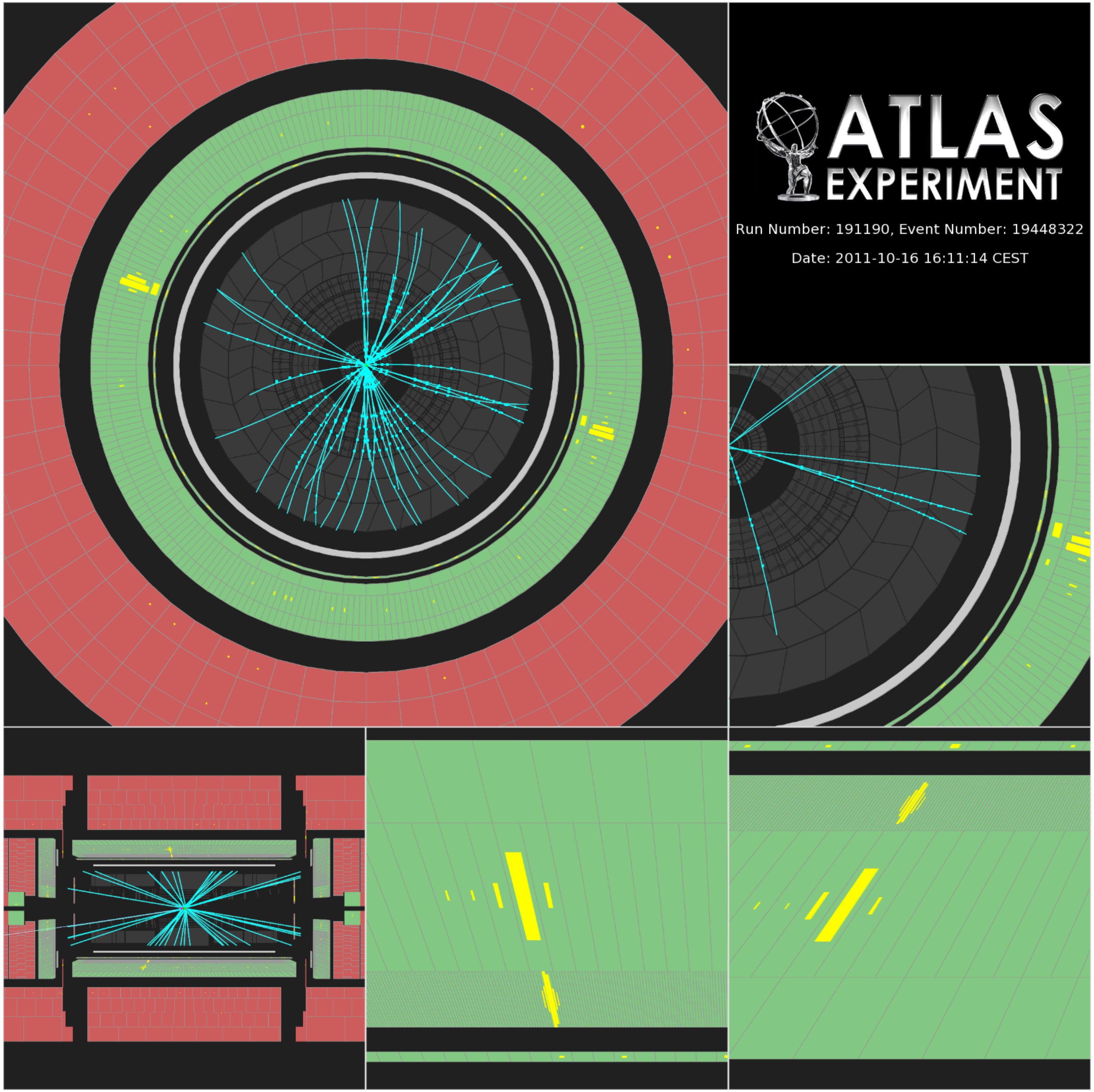


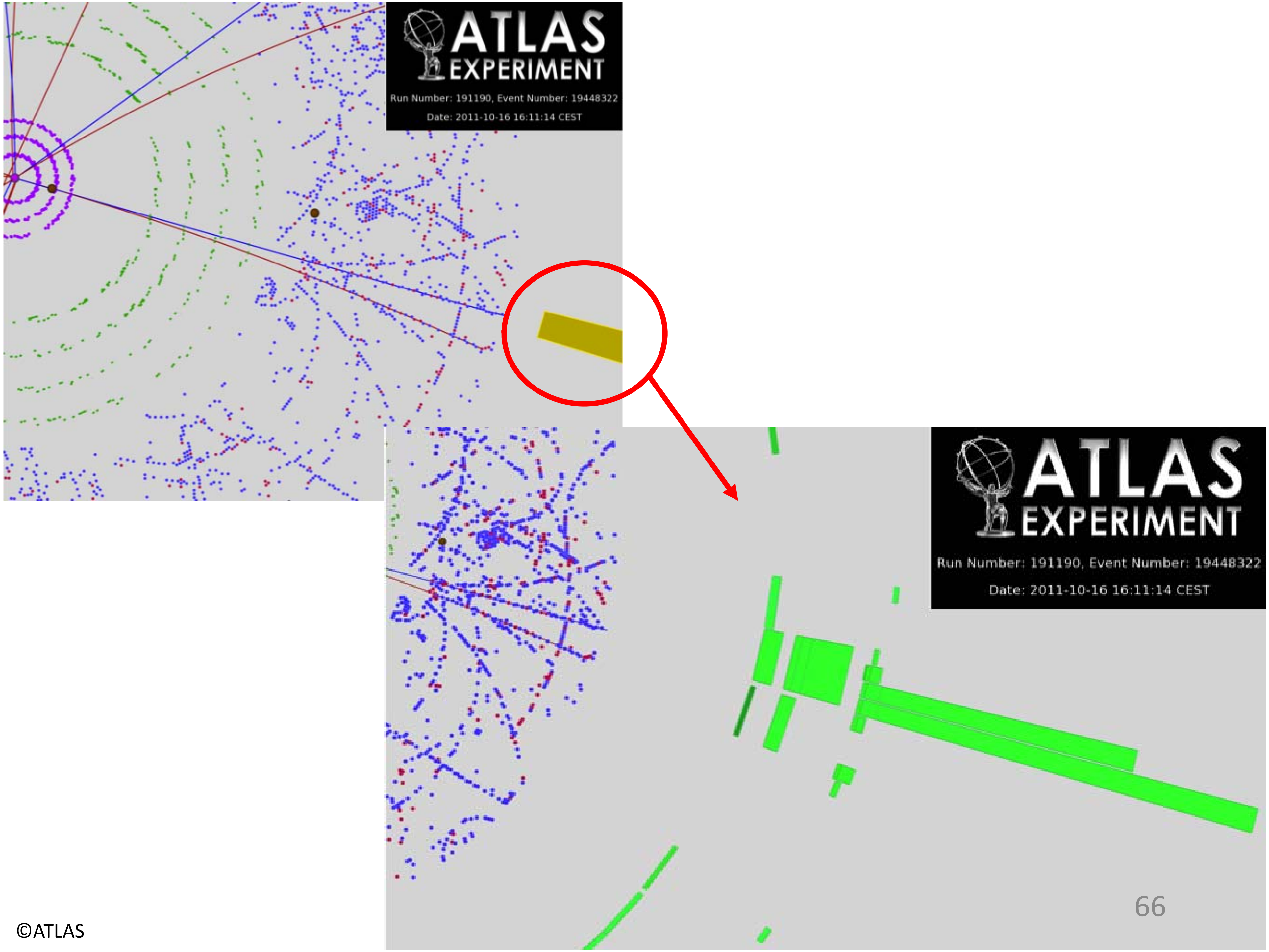
σ(pp → H+X)
√s = 14 TeV
m_t = 175 GeV
CTEQ4M
gg → H
qq → Hqq
qq̄' → HW
gg,qq̄ → Htt̄
gg,qq̄ → Hbb̄
qq̄ → HZ
M. Spira et al.
NLO QCD
σ (pb)
events for 10^5 pb^-1
M_H (GeV)
0
200
400
600
800
1000
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^7
10^6
10^5
10^4
10^3
10^2

ヒッグス粒子を壊す

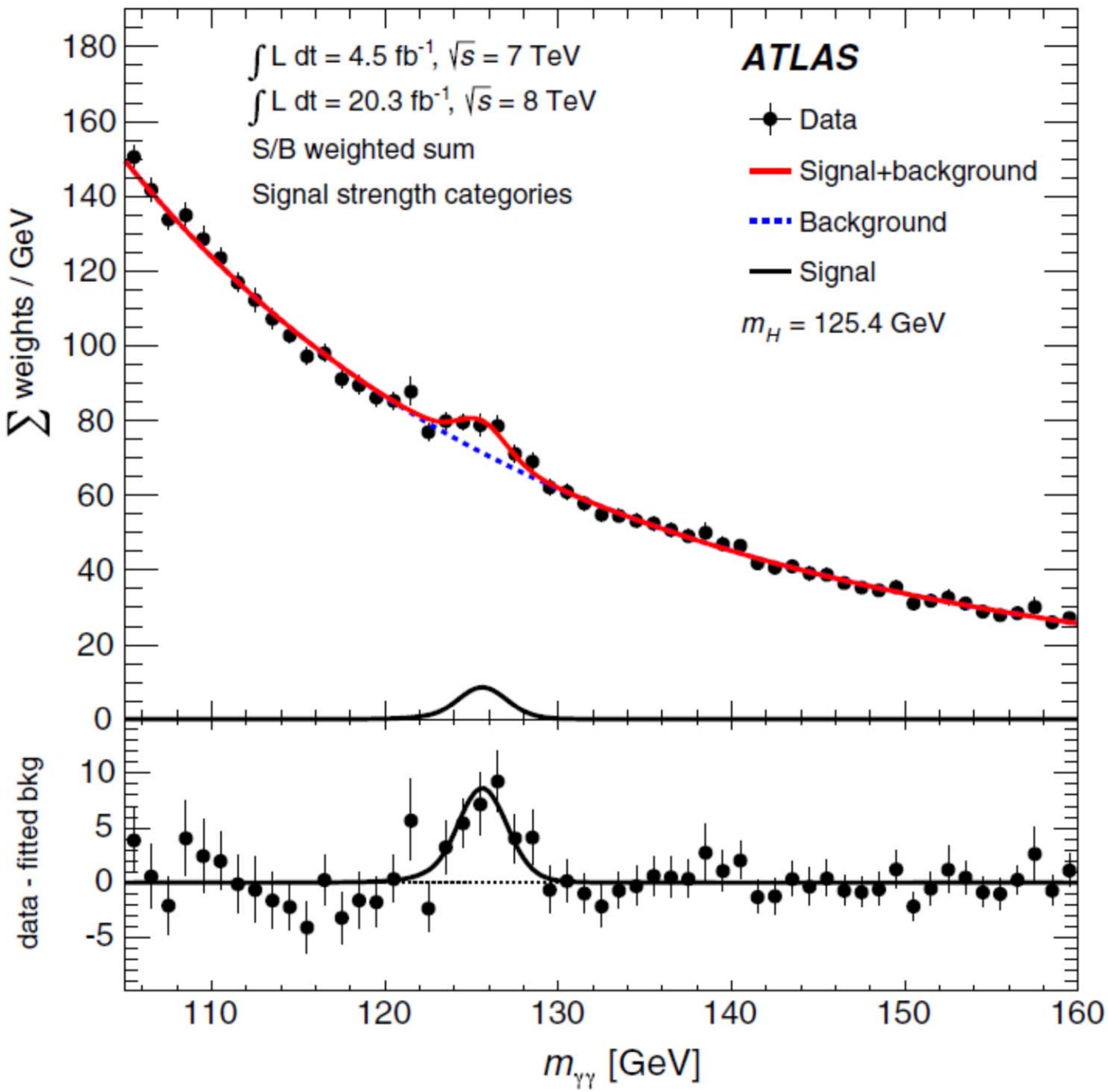


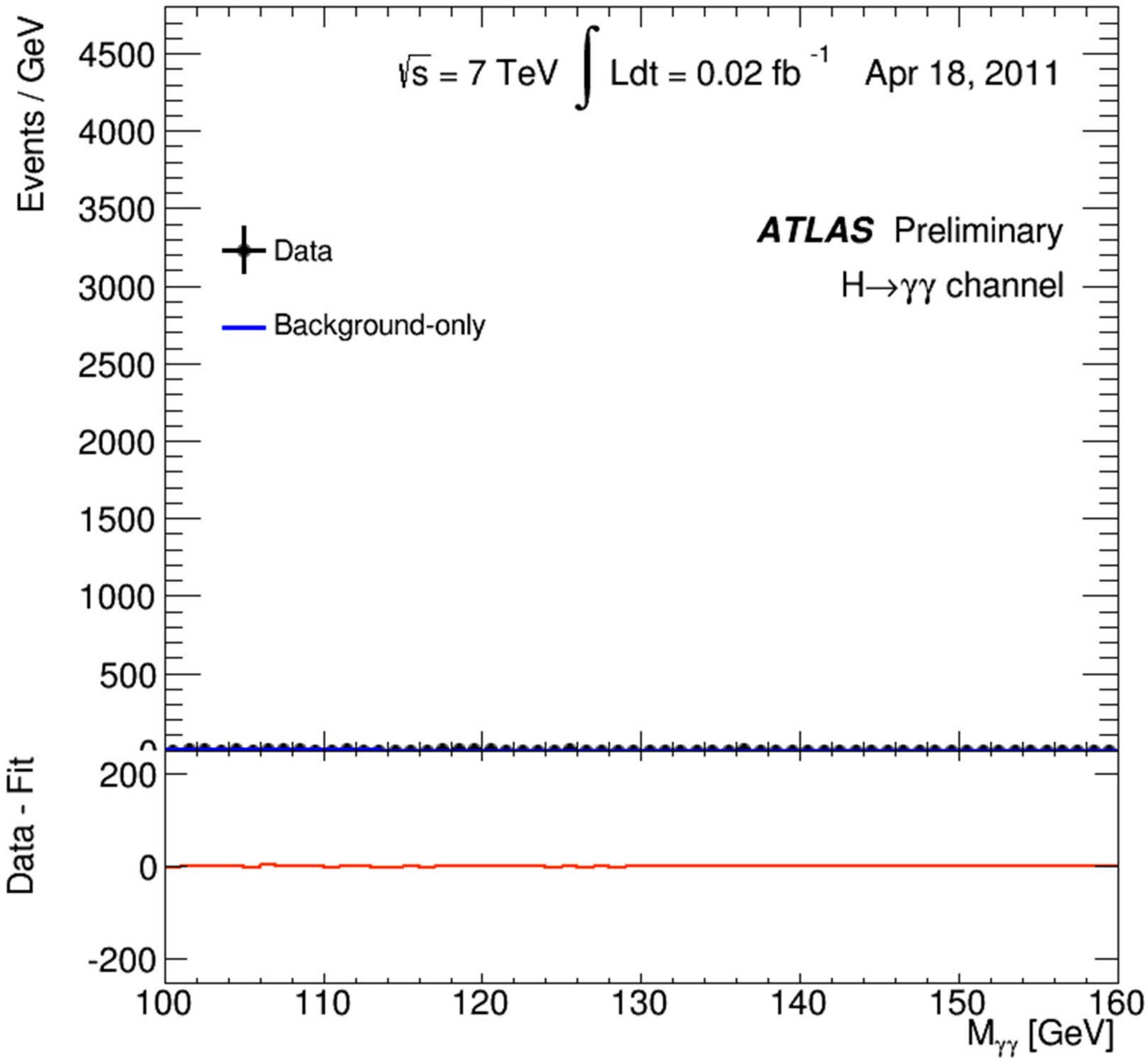

SM Higgs
Branching ratios and total decay width
BR(H)
1
10⁻¹
10⁻²
10⁻³
bb̄
WW
ZZ
τ⁺τ⁻
cc̄
gg
tt̄
γγ
Zγ
50
100
200
500
1000
M_H [GeV]
Γ(H) [GeV]
10²
10
1
10⁻¹
10⁻²
10⁻³
D_D_2061 c


ATLAS
EXPERIMENT
Run Number: 191190, Event Number: 19448322
Date: 2011-10-16 16:11:14 CEST

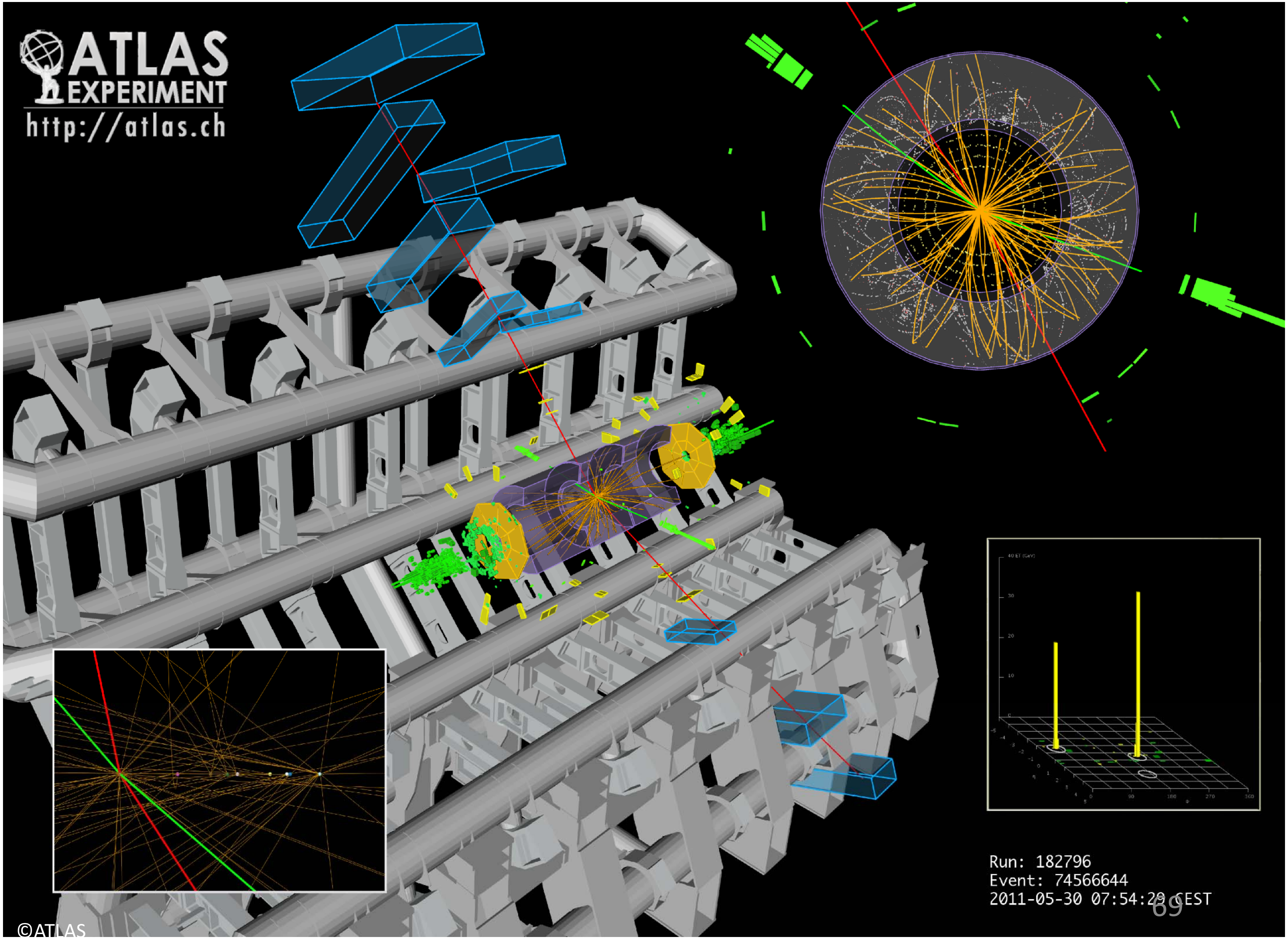

ATLAS EXPERIMENT
Run Number: 191190, Event Number: 19448322
Date: 2011-10-16 16:11:14 CEST
ATLAS EXPERIMENT
Run Number: 191190, Event Number: 19448322
Date: 2011-10-16 16:11:14 CEST

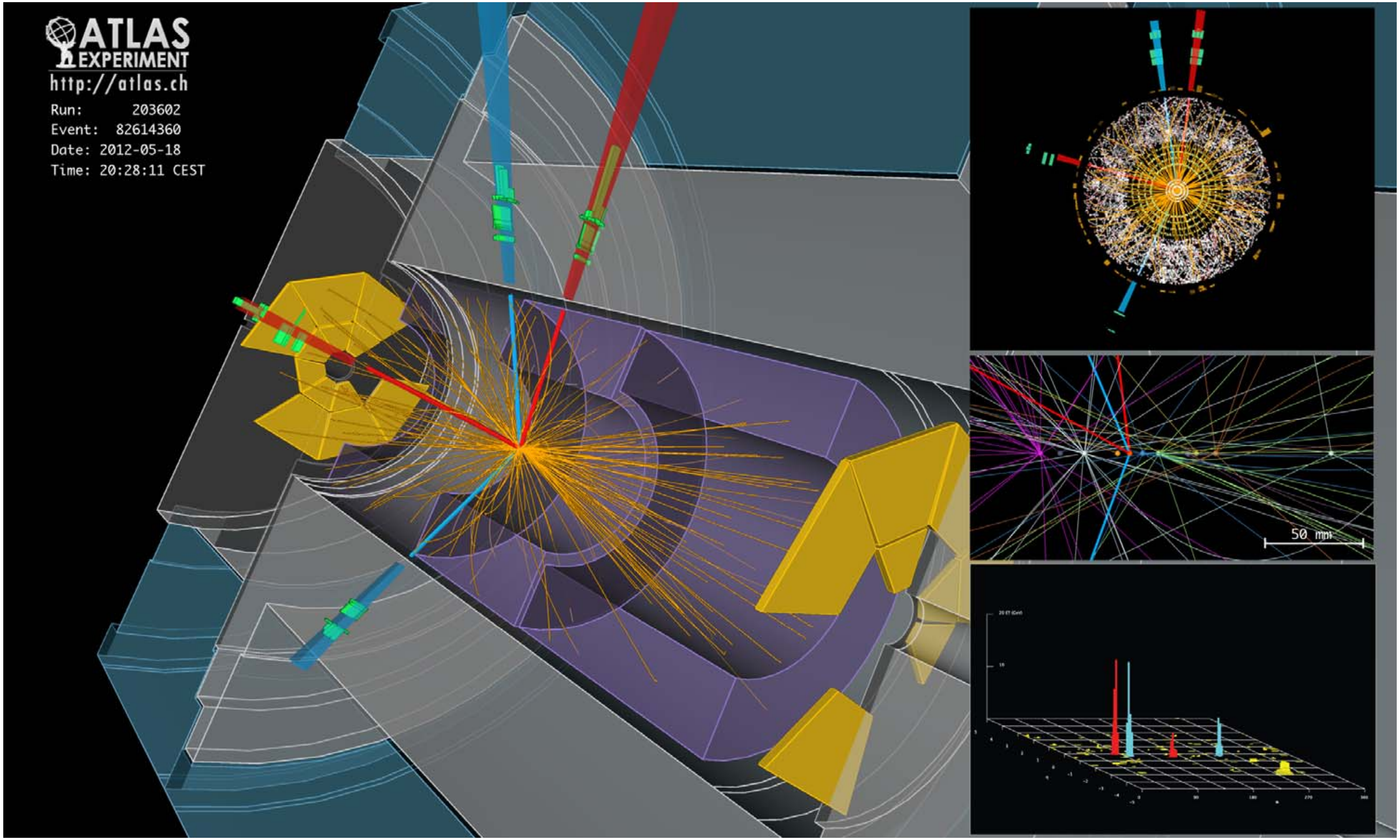
PHYSICAL REVIEW D **90**, 112015 (2014)

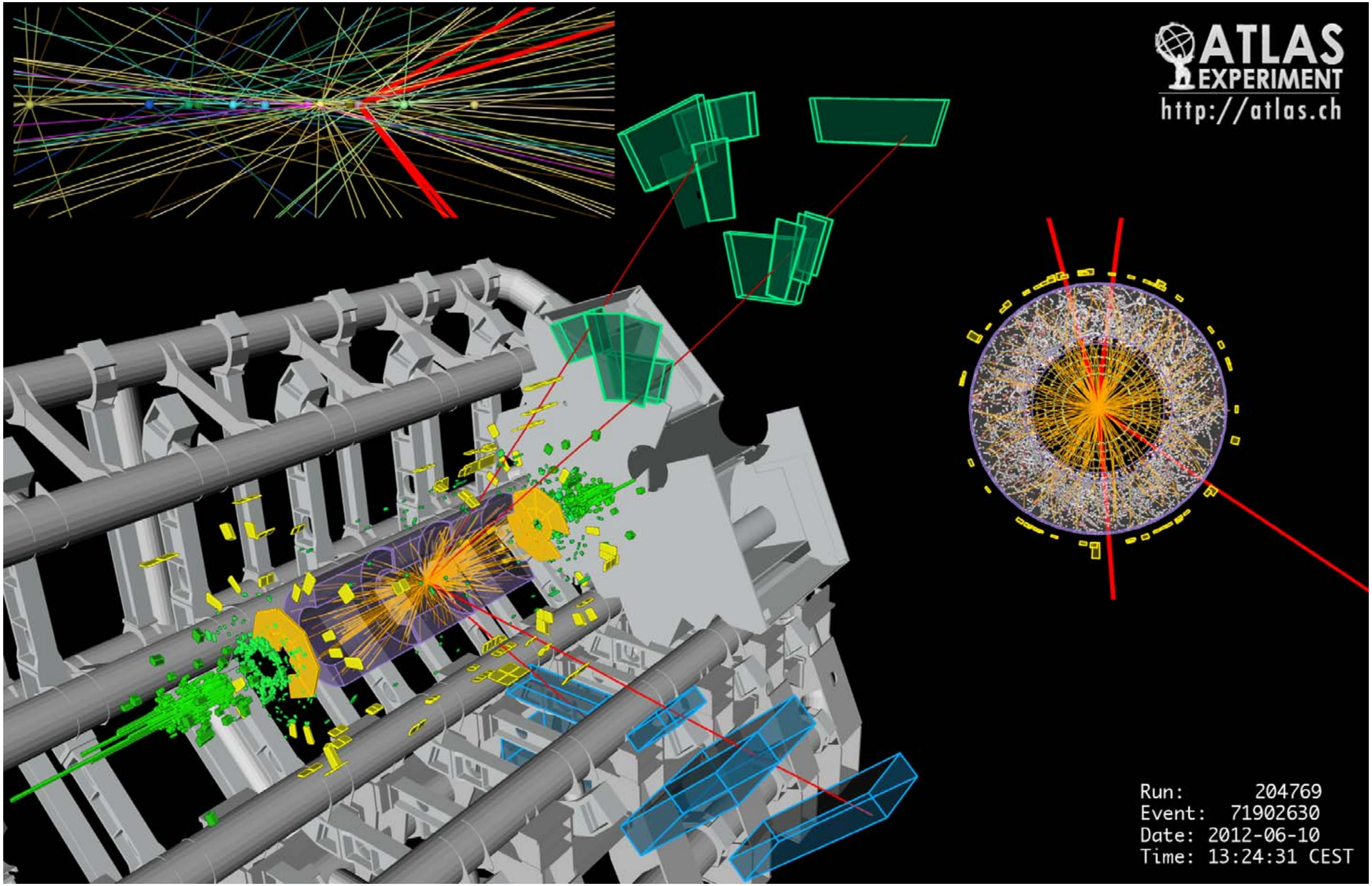




Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
√s = 7 TeV ∫ Ldt = 0.02 fb -1 Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Data - Fit
200
0
-200
100
110
120
130
140
150
160
M γγ [GeV]


ATLAS
EXPERIMENT
http://atlas.ch
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST
©ATLAS


ATLAS
EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
50 mm


ATLAS EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

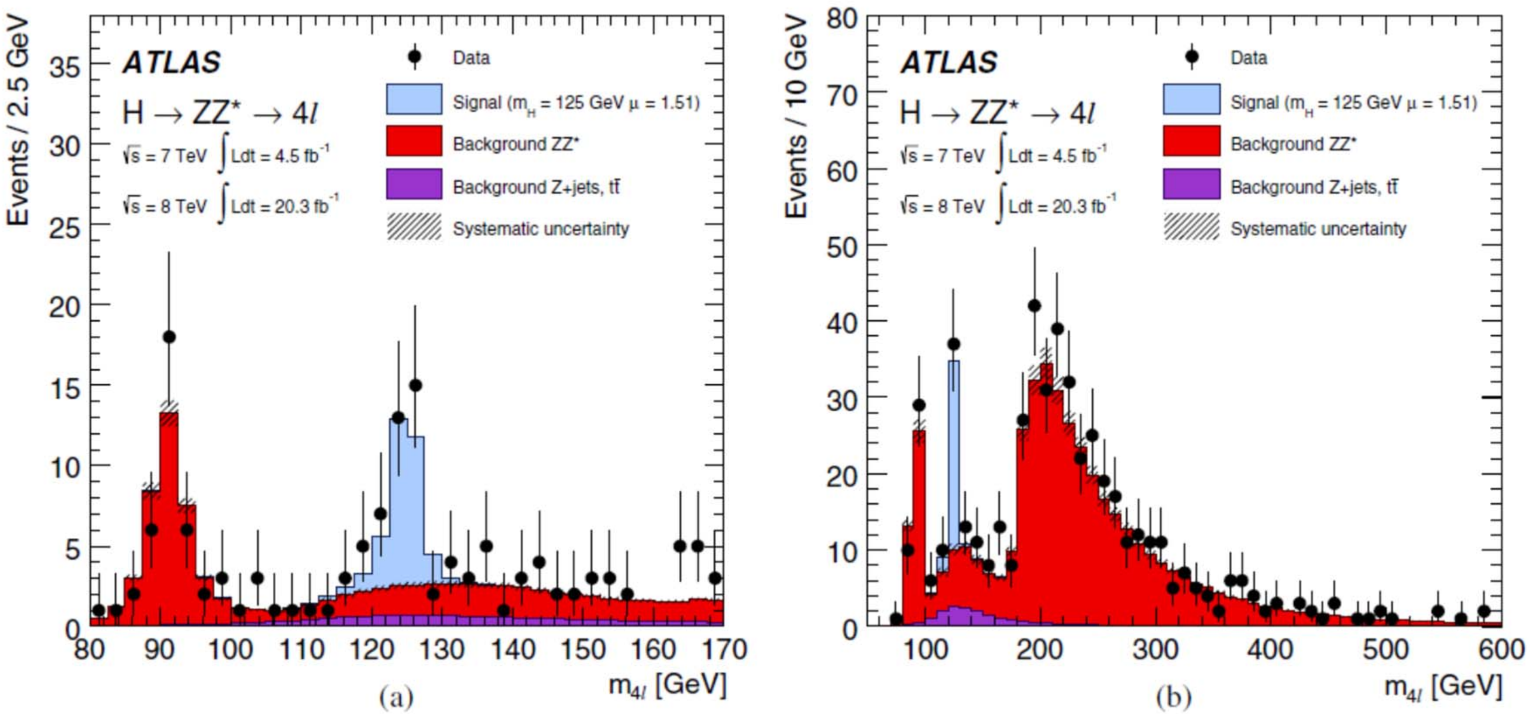
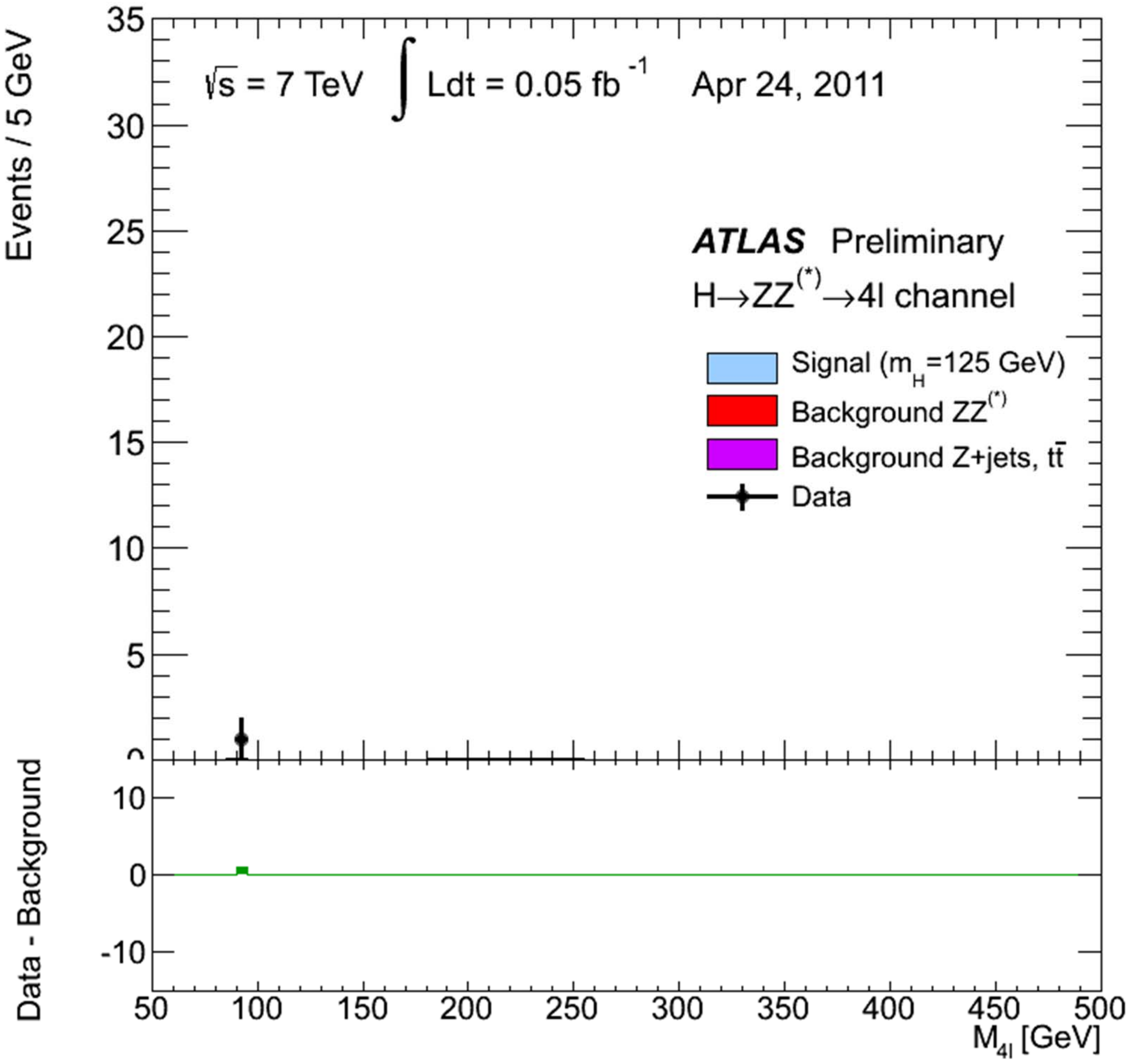
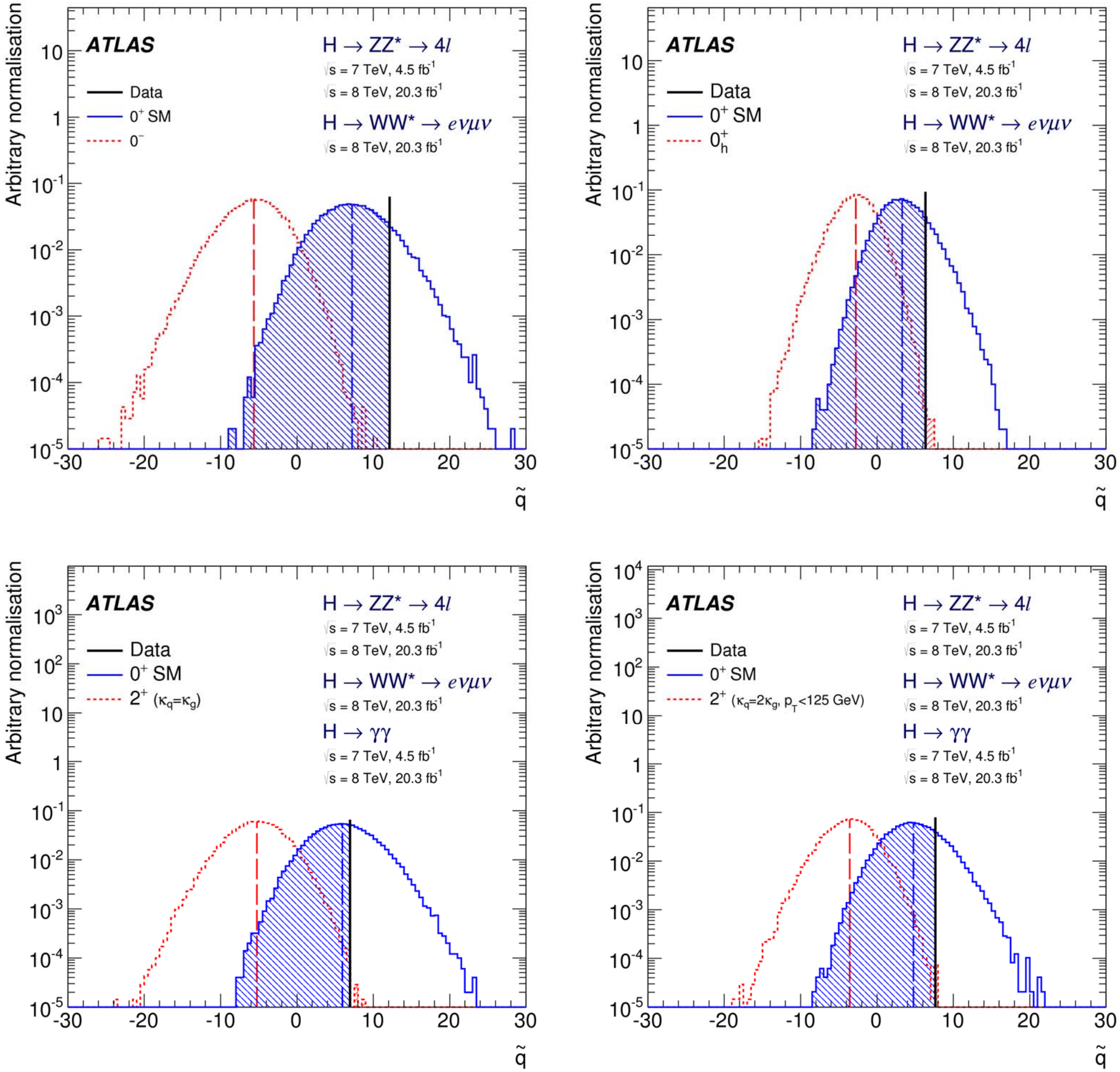


FIG. 13 (color online). The distribution of the four-lepton invariant mass, $m_{4\ell}$, for the selected candidates (filled circles) compared to the expected signal and background contributions (filled histograms) for the combined $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data for the mass ranges: (a) 80–170 GeV, and (b) 80–600 GeV. The signal expectation shown is for a mass hypothesis of $m_H = 125$ GeV and normalized to $\mu = 1.51$ (see text). The expected backgrounds are shown separately for the ZZ^* (red histogram), and the reducible $Z+$jets and $t\bar{t}$ backgrounds (violet histogram); the systematic uncertainty associated to the total background contribution is represented by the hatched areas.

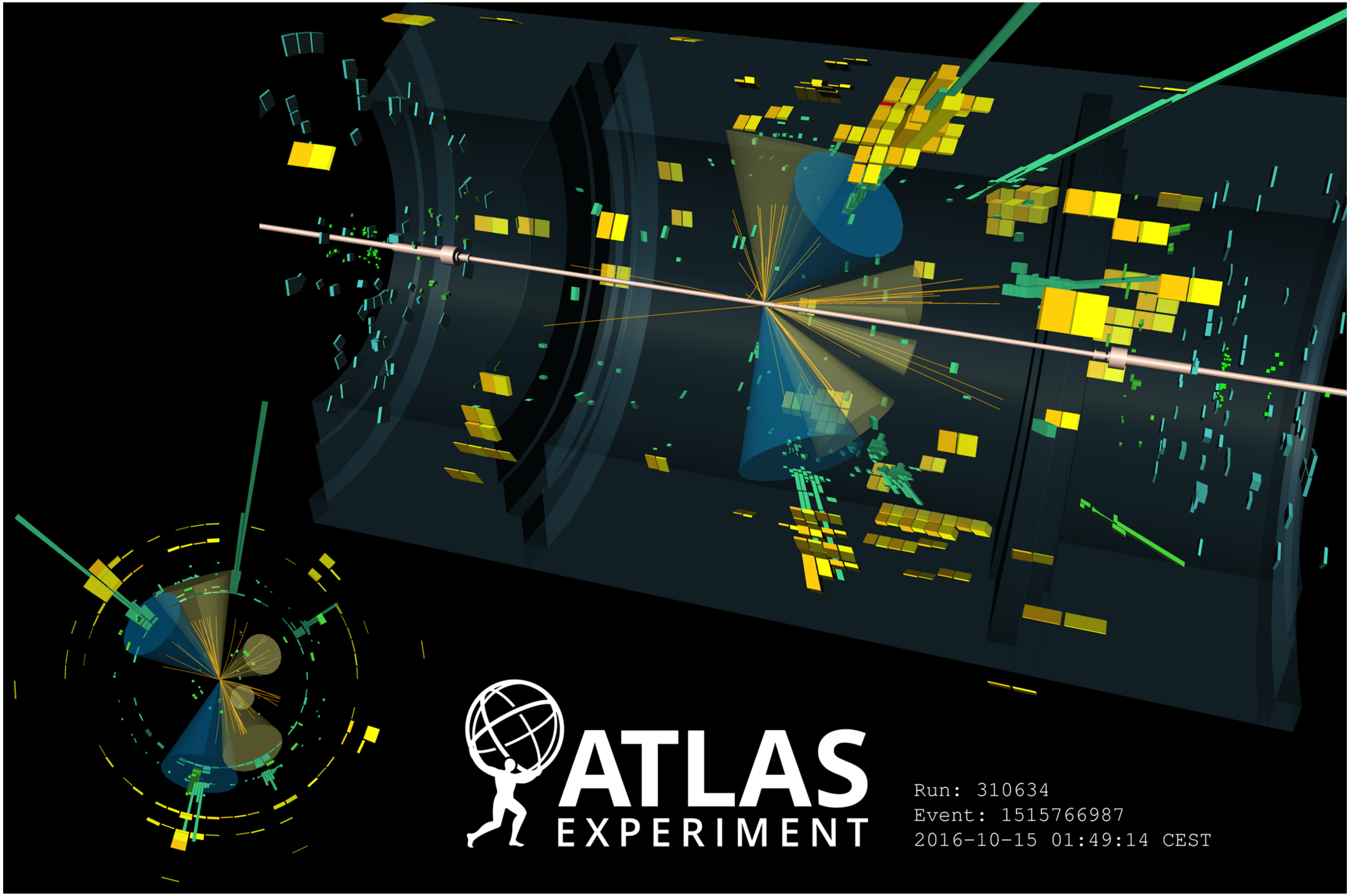
- Analysis based on:
  - 2011 *pp* data: 3,365,473,349 events
  - 2012 *pp* data: 8,445,206,327 events



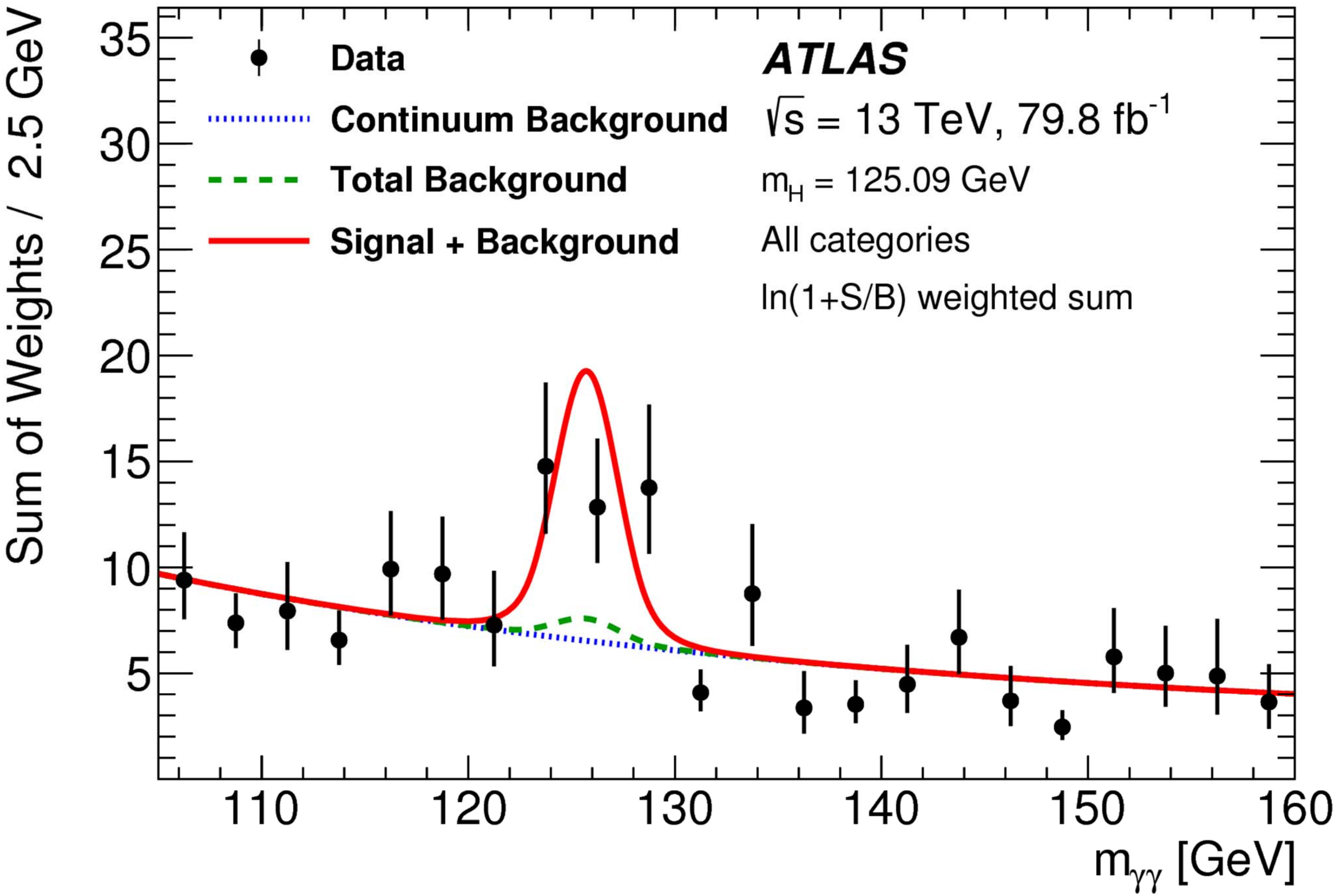
Events / 5 GeV
√s = 7 TeV ∫ Ldt = 0.05 fb^-1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M_4l [GeV]



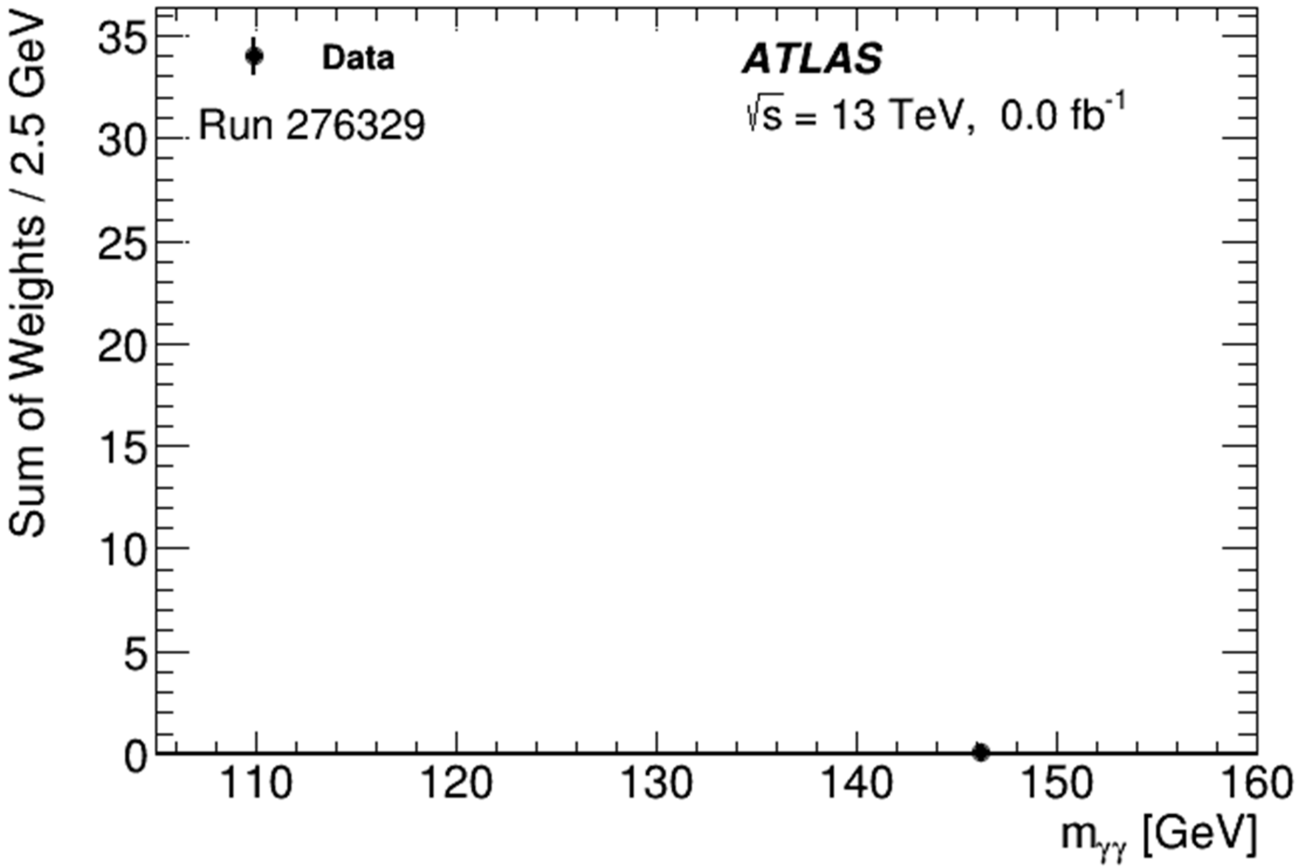
Study of the spin and parity of the Higgs boson in di-boson decays with the ATLAS detector, Eur. Phys. J. C75 (2015) 476

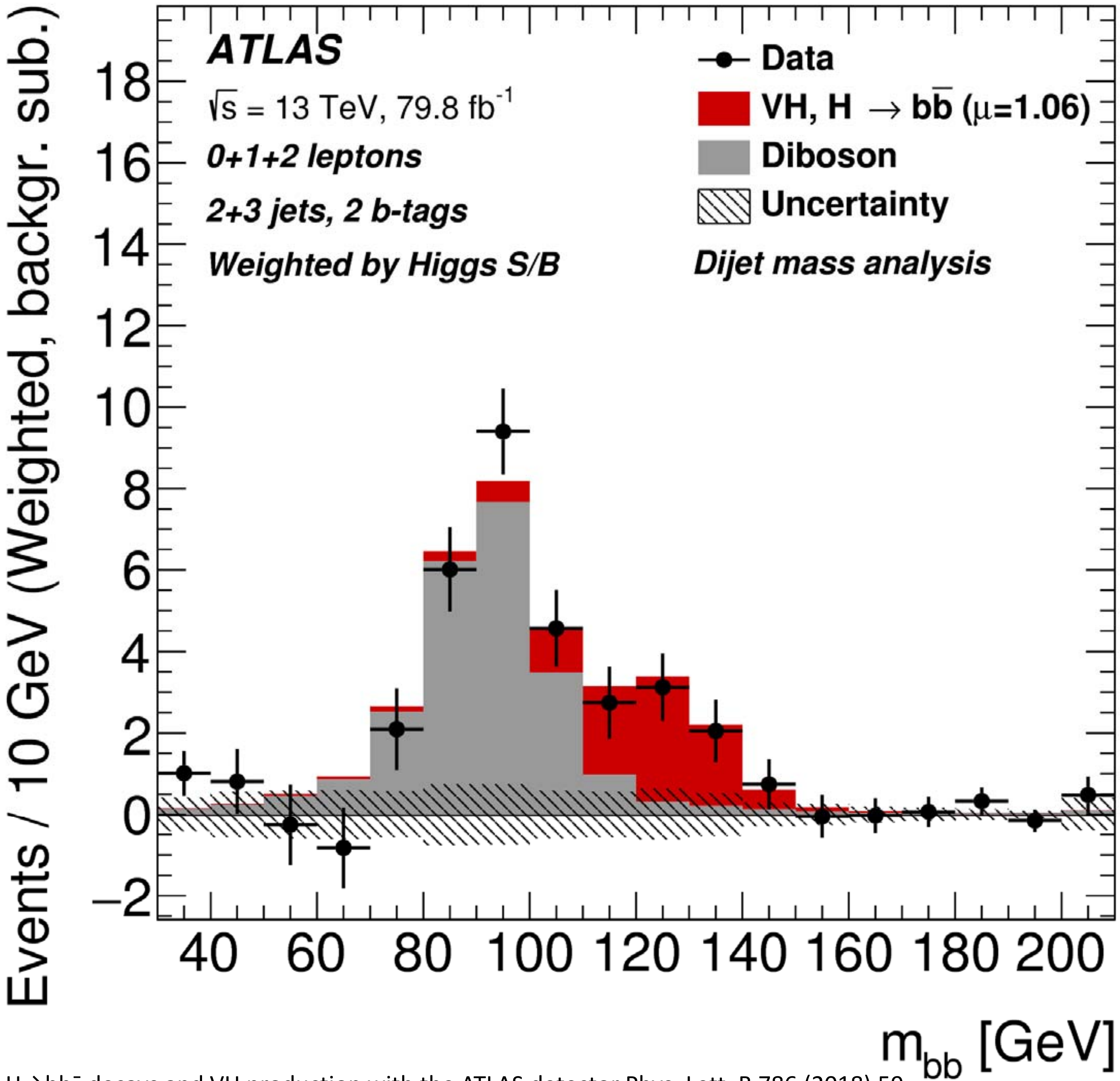


 Phys. Lett. B 784 (2018) 173

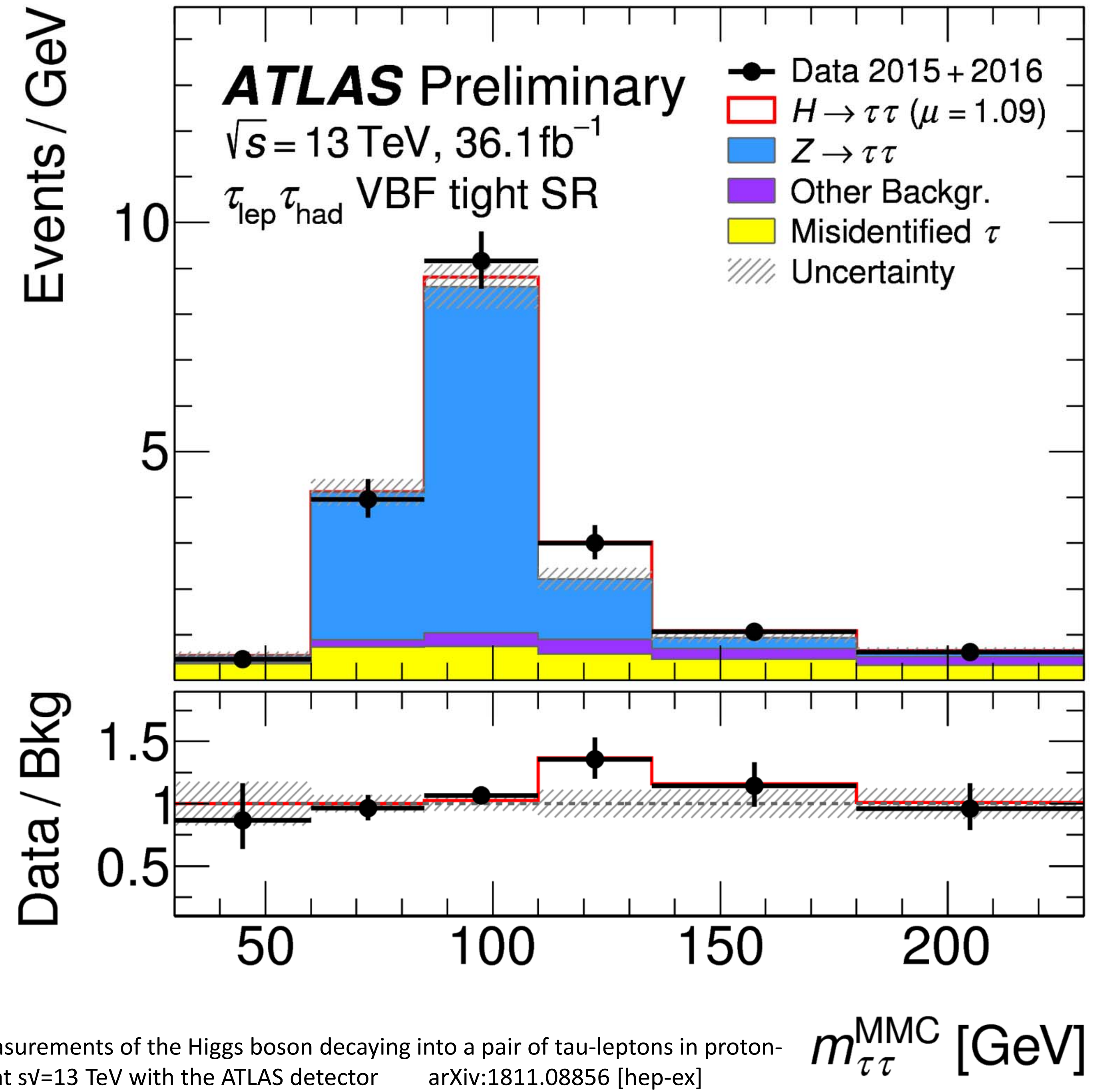


Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector
Phys. Lett. B 784 (2018) 173

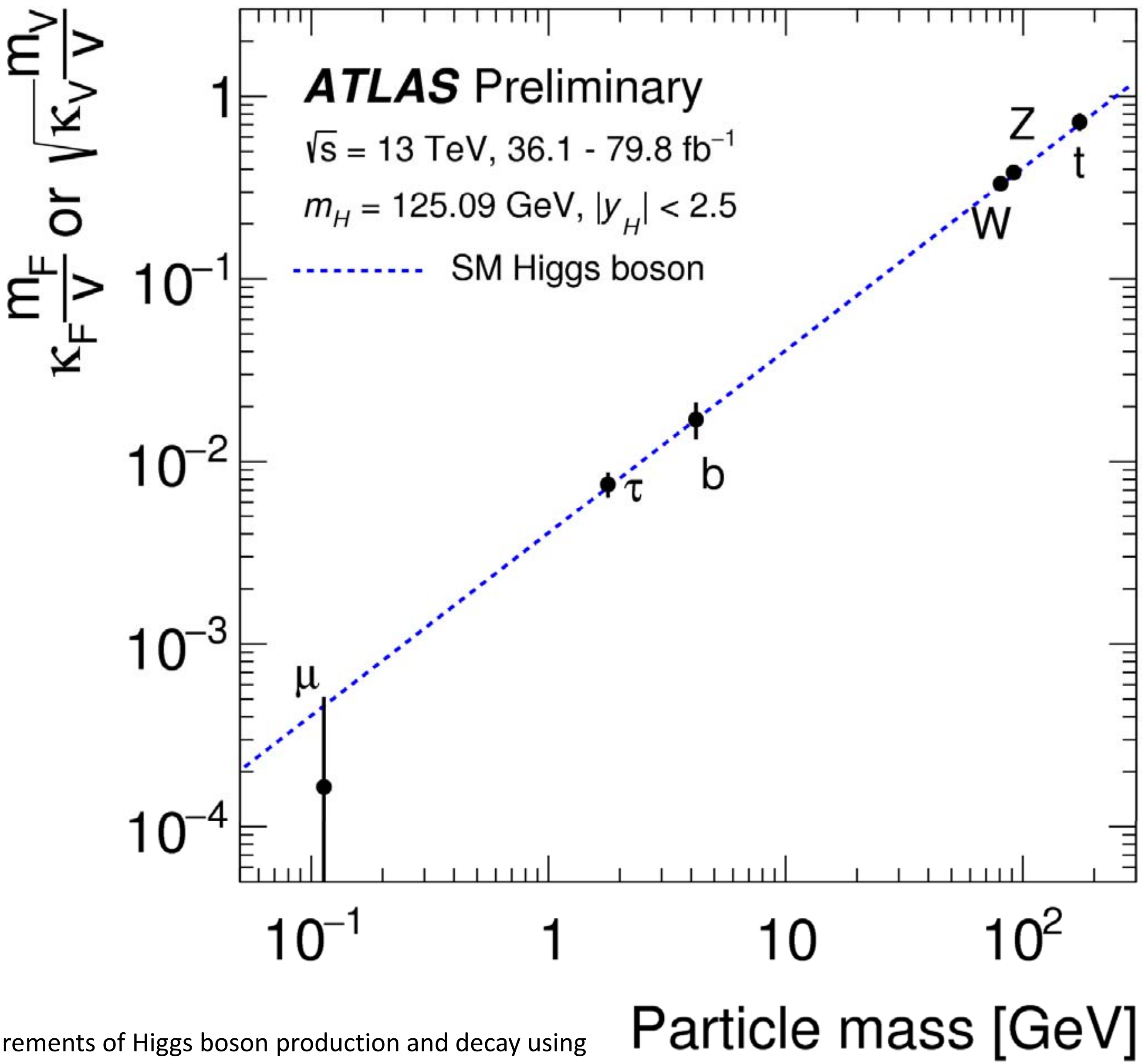

Data
ATLAS
Run 276329
$\sqrt{s}$ = 13 TeV, 0.0 fb^{-1}
Sum of Weights / 2.5 GeV
0
5
10
15
20
25
30
35
110
120
130
140
150
160
$m_{\gamma\gamma}$ [GeV]



Observation of H→bb⁻ decays and VH production with the ATLAS detector Phys. Lett. B 786 (2018) 59



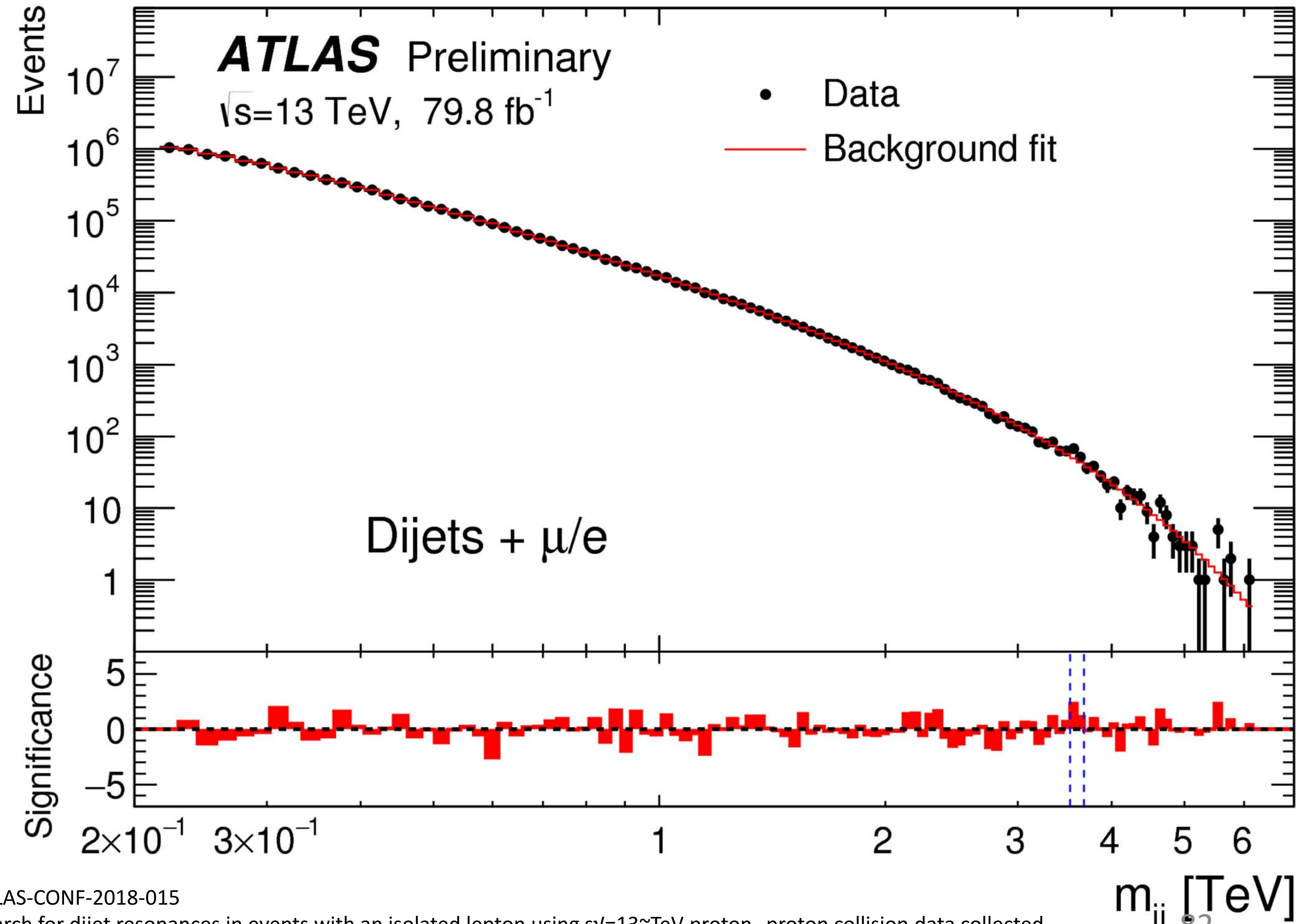
Cross-section measurements of the Higgs boson decaying into a pair of tau-leptons in proton-proton collisions at s√=13 TeV with the ATLAS detector arXiv:1811.08856 [hep-ex]



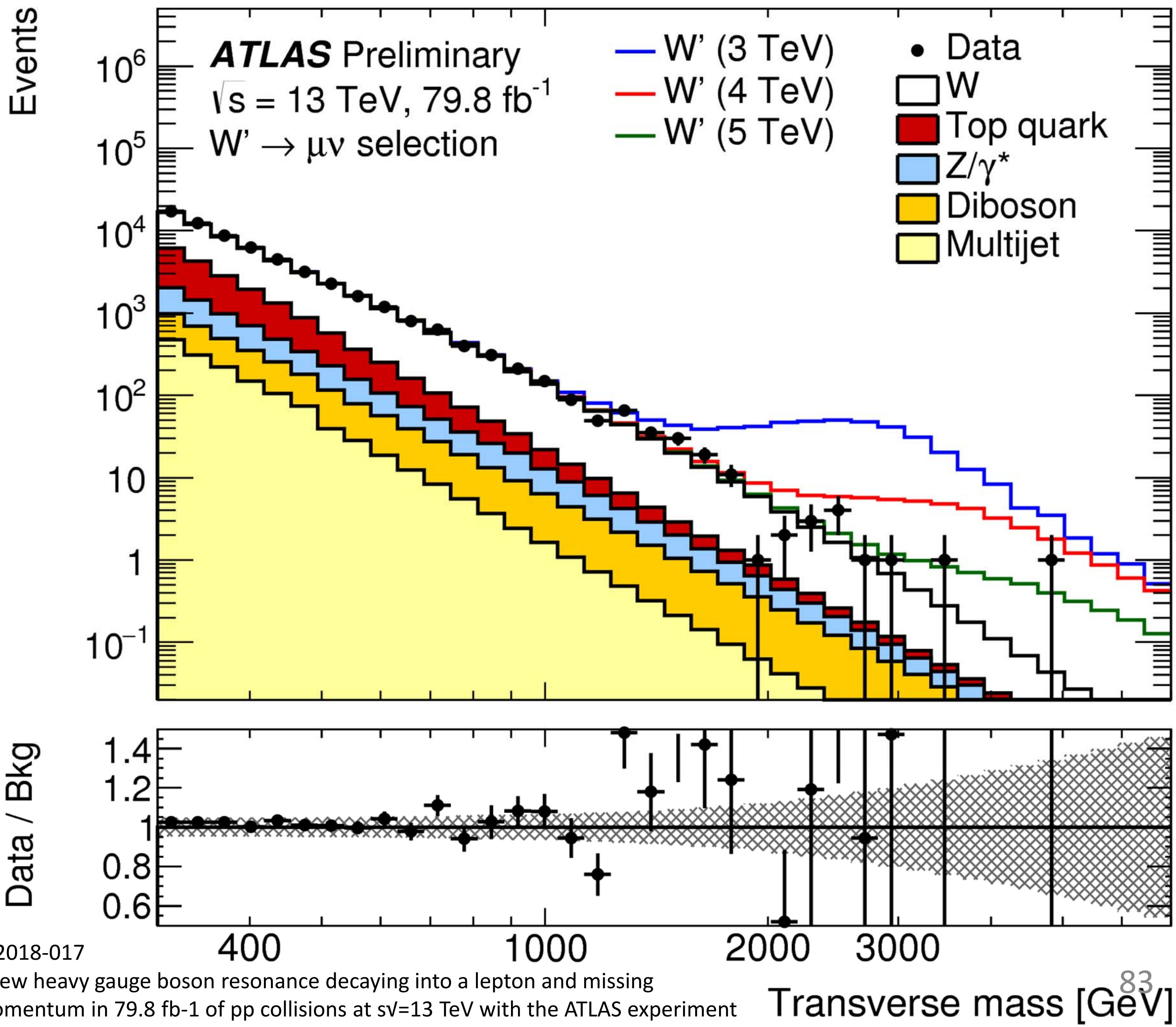
Combined measurements of Higgs boson production and decay using up to 80 fb−1 of proton--proton collision data at s√= 13 TeV collected with the ATLAS experiment ATLAS-CONF-2018-031

標準模型を超えて

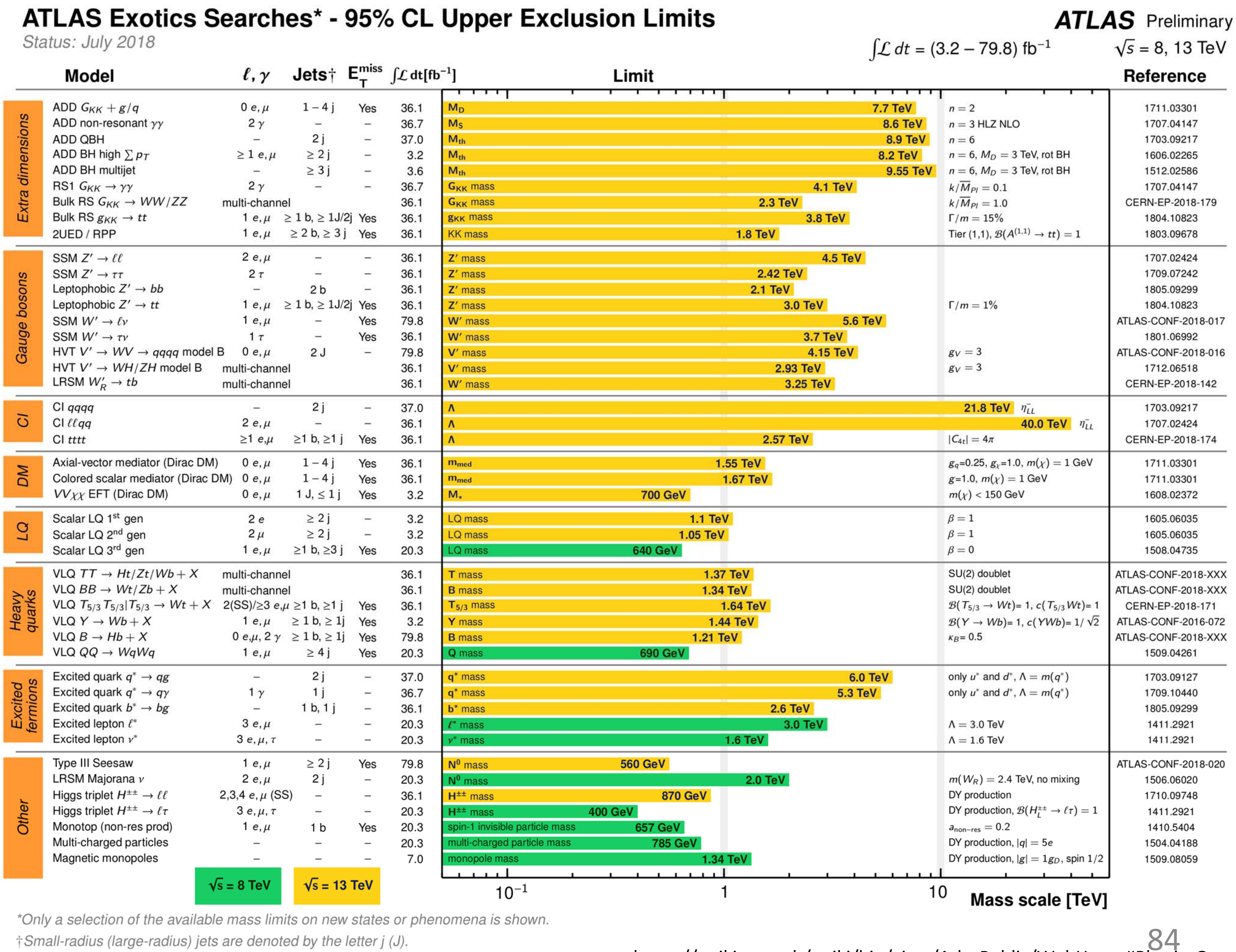
- 標準模型は非常に成功した模型
  - 低エネルギー事象を高精度で再現
- 標準模型は不完全
  - 多くの疑問に答えていない
- 標準模型を超えた(BSM)理論の候補
  - 力の大統一
  - 超対称性
  - 余剰次元
- 素粒子実験の次の課題
  - 直接新粒子を発見する
  - 間接的に標準模型の予測とのずれから
- LHCアップグレード



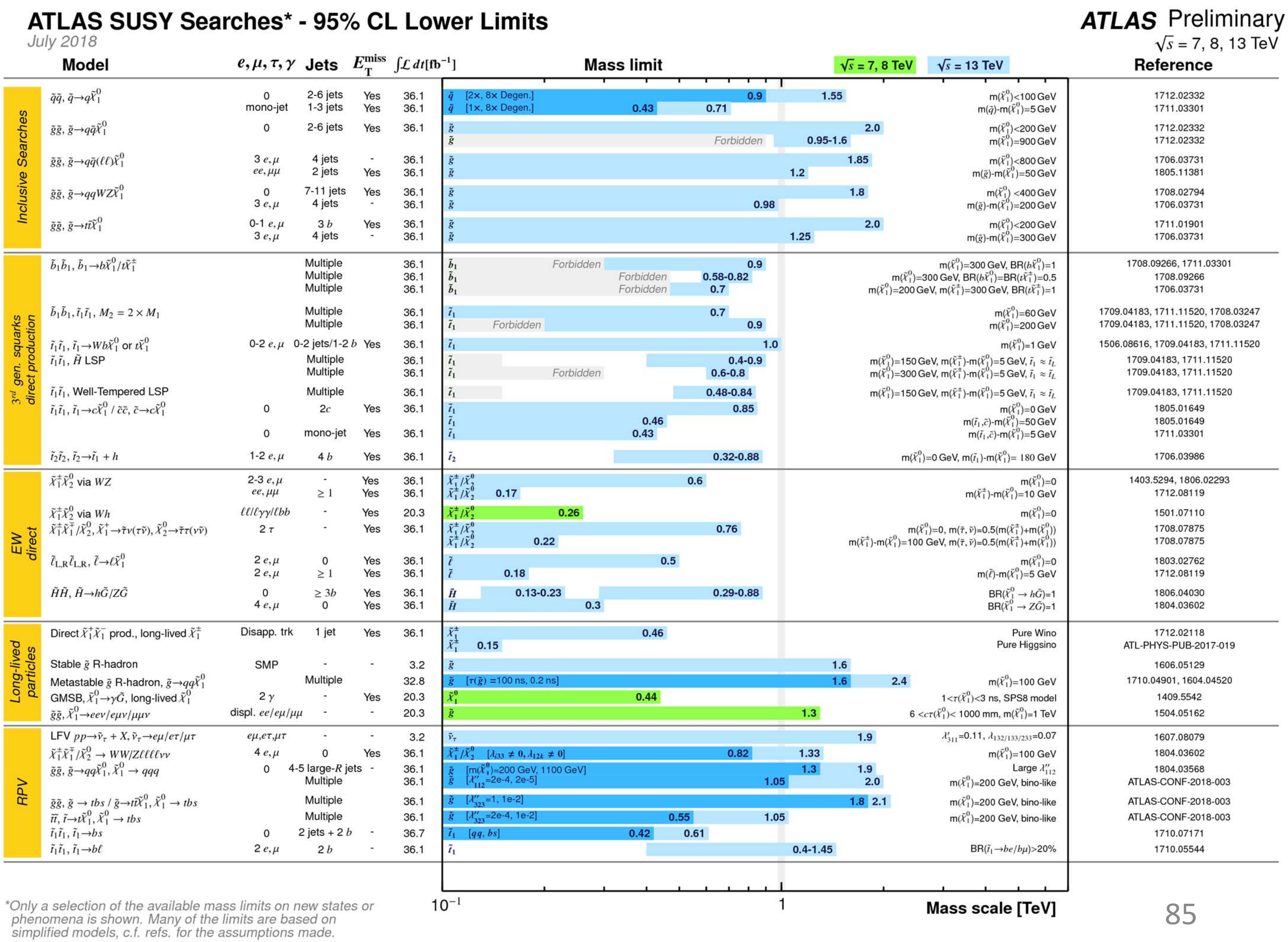
ATLAS-CONF-2018-015
Search for dijet resonances in events with an isolated lepton using s√=13~TeV proton--proton collision data collected by the ATLAS detector

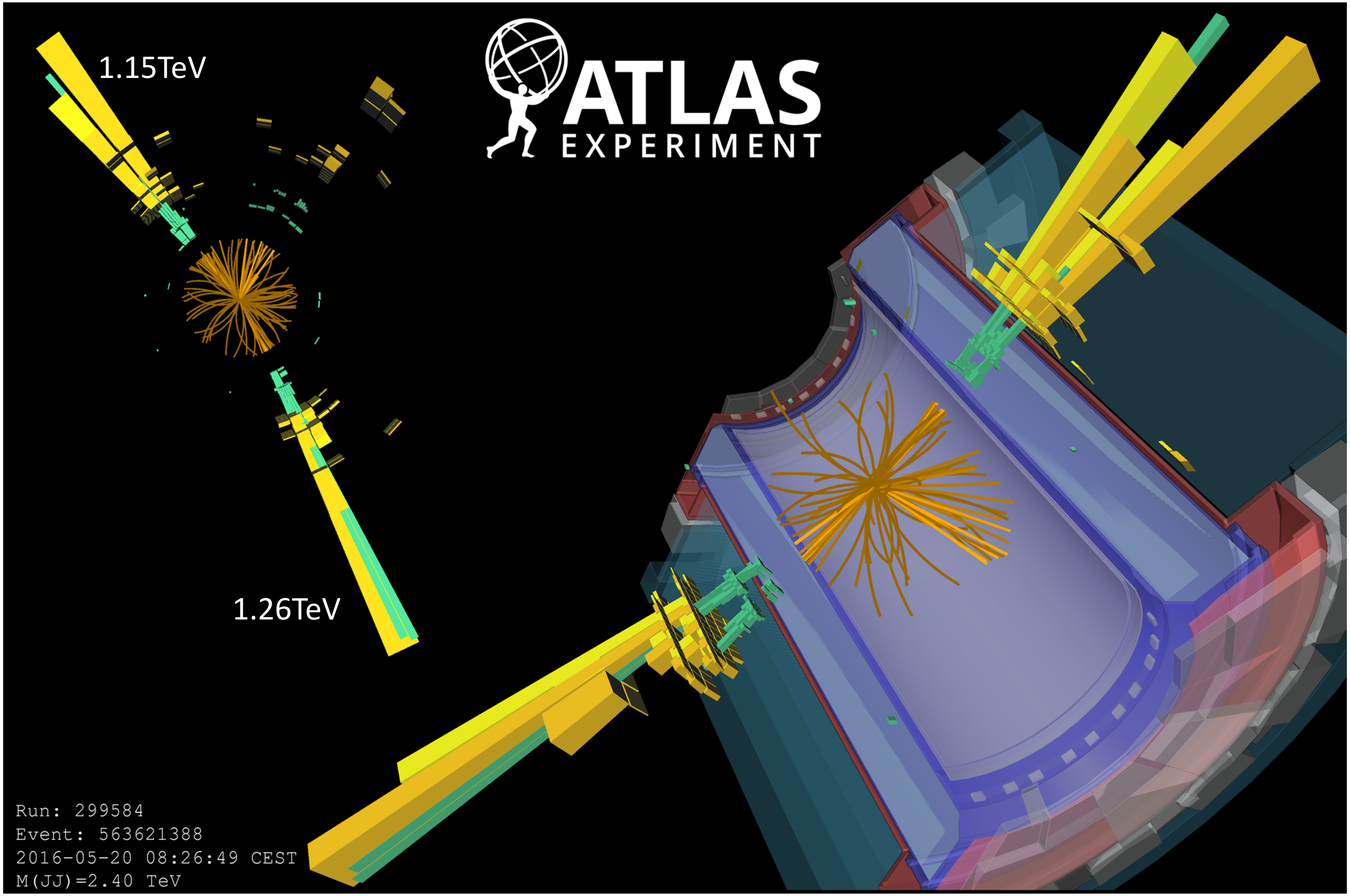


ATLAS-CONF-2018-017
Search for a new heavy gauge boson resonance decaying into a lepton and missing transverse momentum in 79.8 fb-1 of pp collisions at s√=13 TeV with the ATLAS experiment

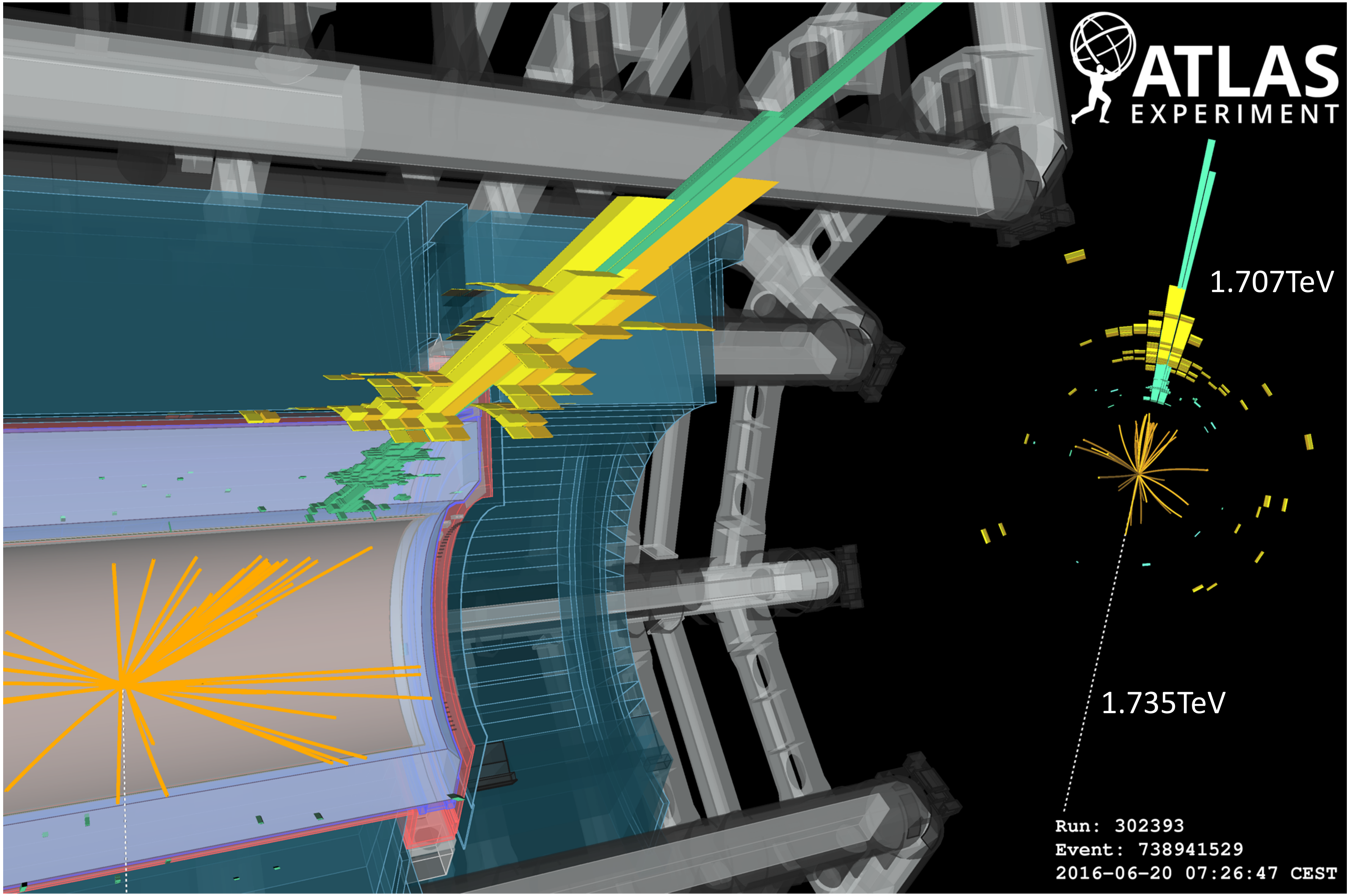


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#PhysicsGroups

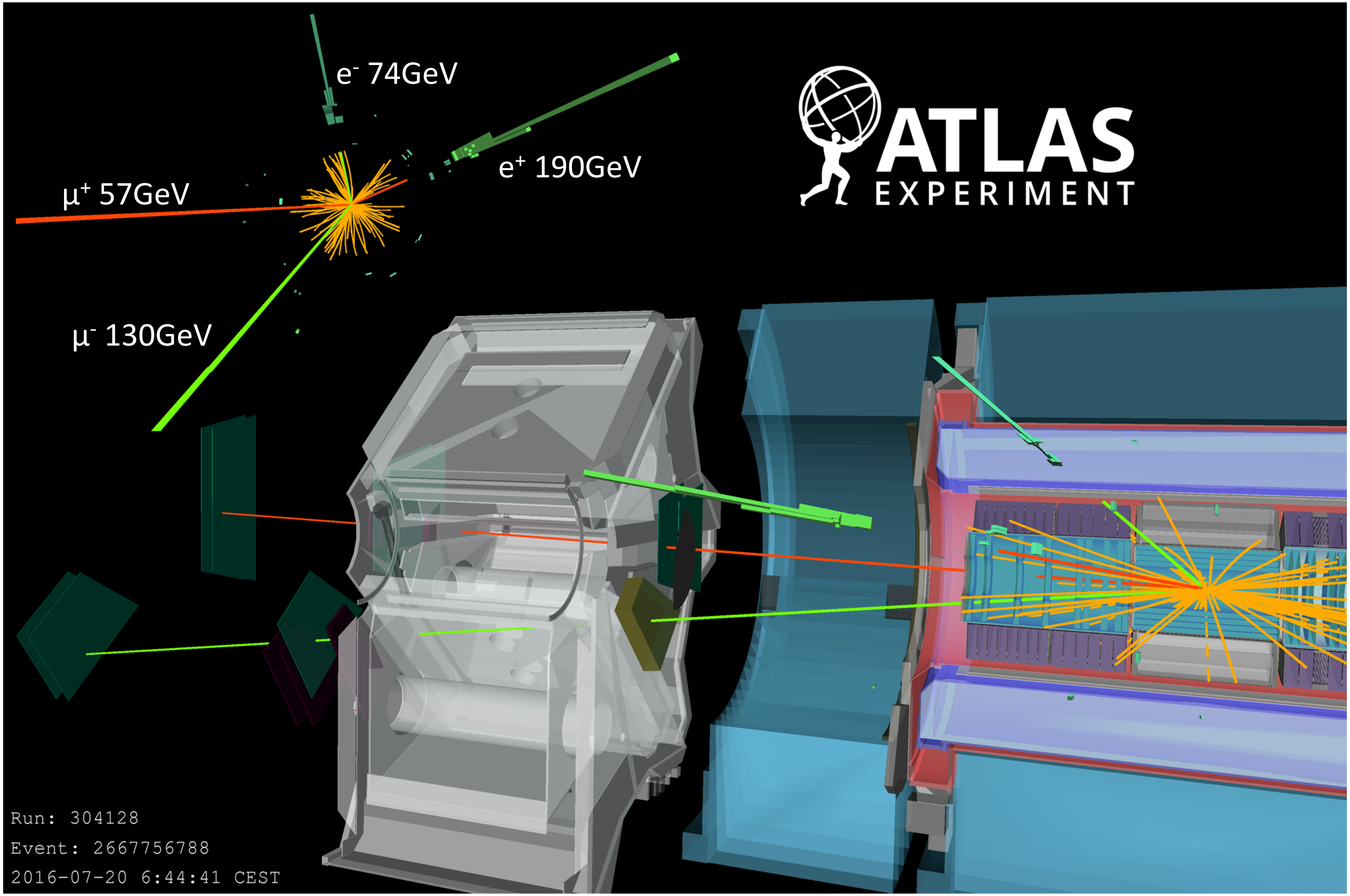

ATLAS SUSY Searches* - 95% CL Lower Limits
July 2018
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model
e, μ, τ, γ
Jets
E_T^miss
∫L dt[fb^-1]
Mass limit
√s = 7, 8 TeV
√s = 13 TeV
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Forbidden
10^-1
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-055/figaux_05.png

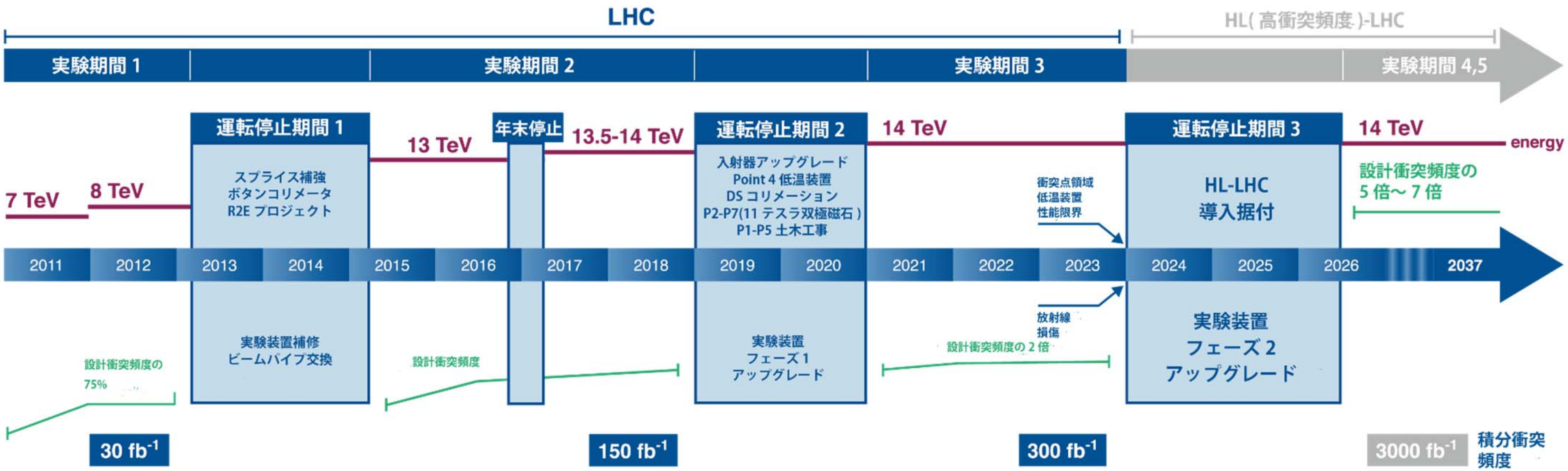


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2017-060/figaux_01.png

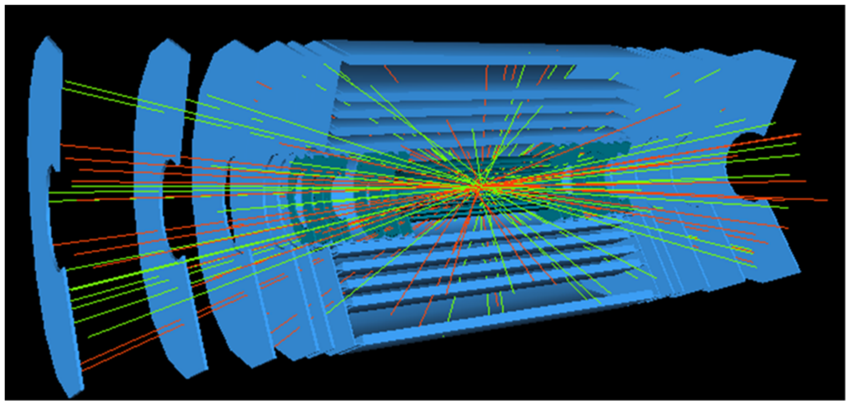


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2017-053/figaux_01.png

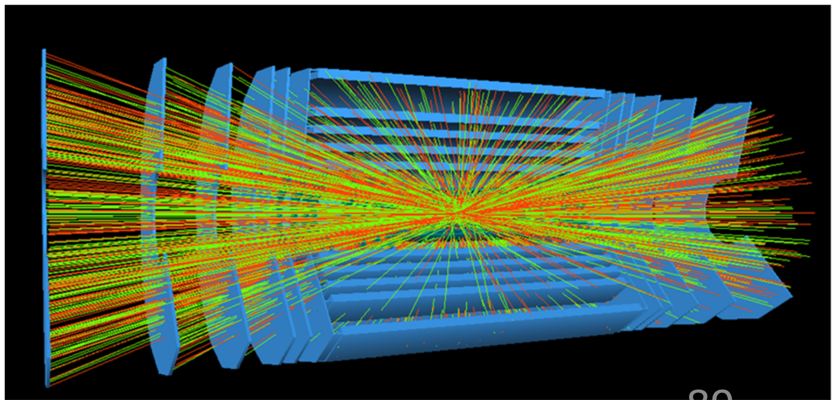
LHC / HL-LHC Plan

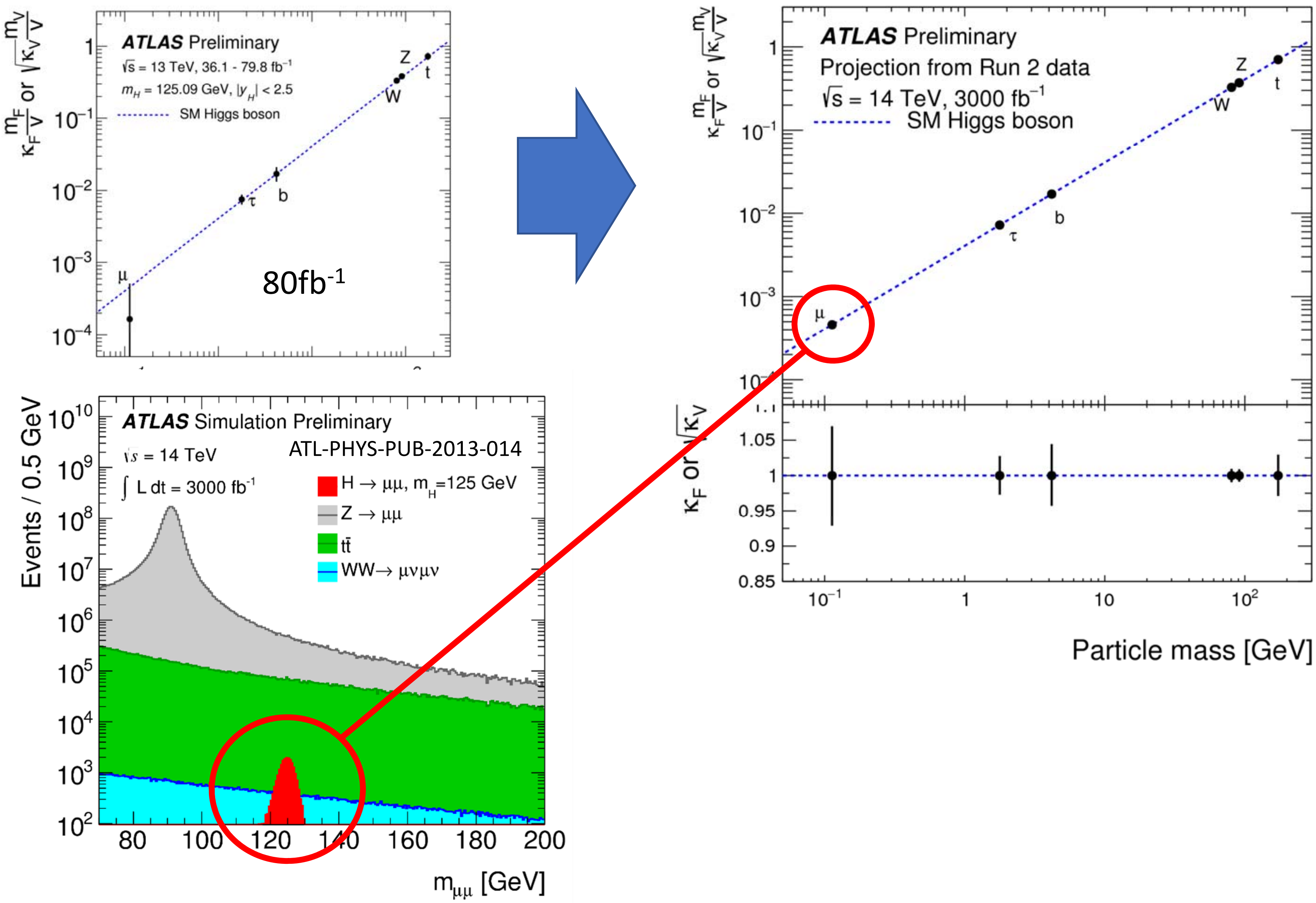


~23 collisions per crossing ($5x10^{33}cm^{-2}s^{-1}$)



~230 collisions per crossing ($5x10^{34}cm^{-2}s^{-1}$)



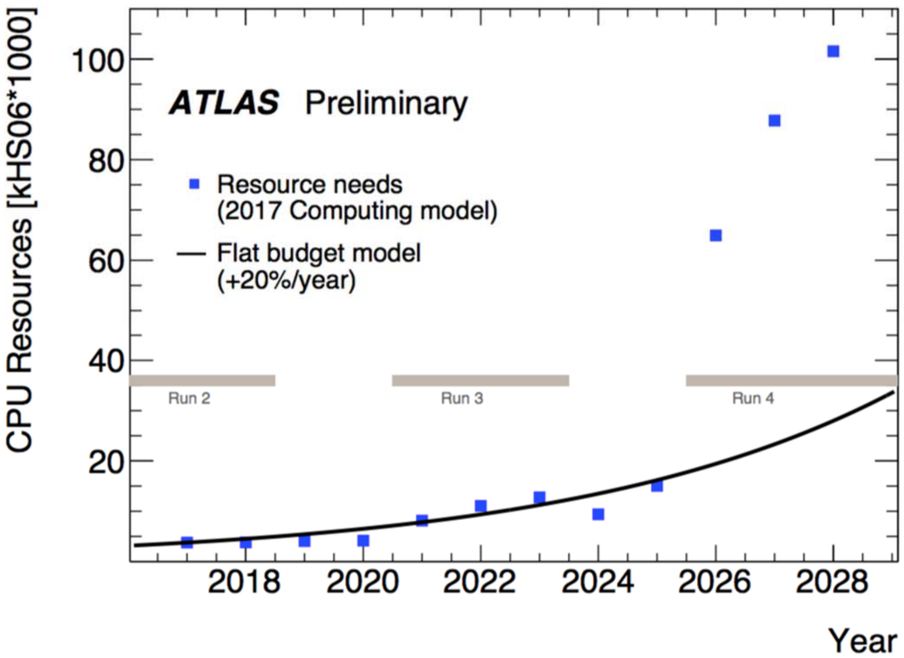


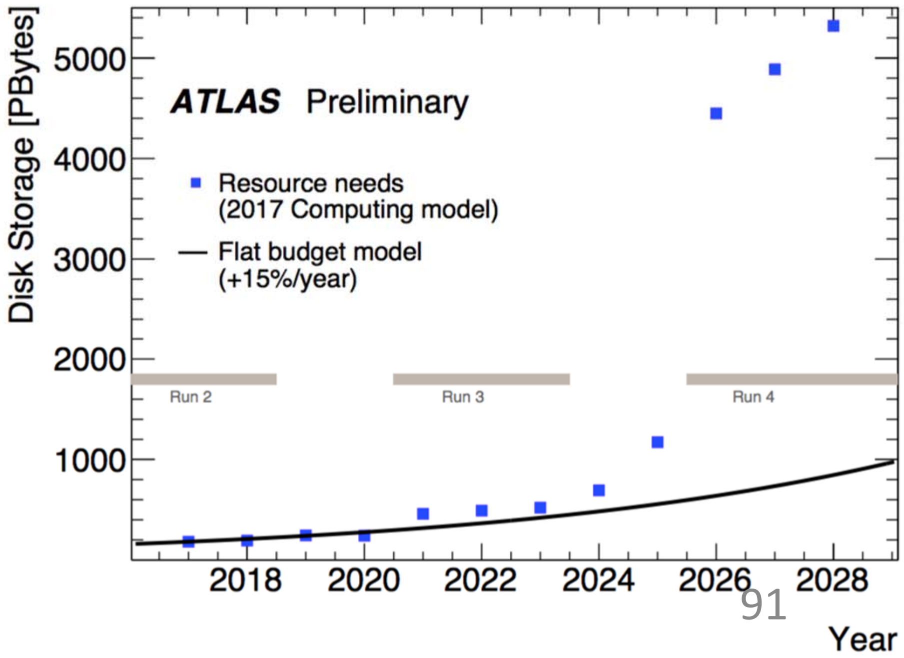
ATL-PHYS-PUB-2018-054

Projections for measurements of Higgs boson cross sections, branching ratios, coupling parameters and mass with the ATLAS detector at the HL-LHC

HL-LHCの挑戦

- 10倍のルミノシティ
  - 10倍の事象数
  - 10倍の事象サイズ(1交差あたり衝突数)
- 100倍のデータ処理
  - 価格低下だけではまかなえない
  - 革新的な技術の導入が必須





巨大科学のあり方

- LHCプロジェクトの規模
  - 時間
  - 経費
  - 人材
- 国際共同研究
  - コラボレーション(研究組織)
  - 研究拠点CERN
  - 国際分散情報基盤
- 運営原則
  - 徹底した民主主義
  - 全ての研究者の平等

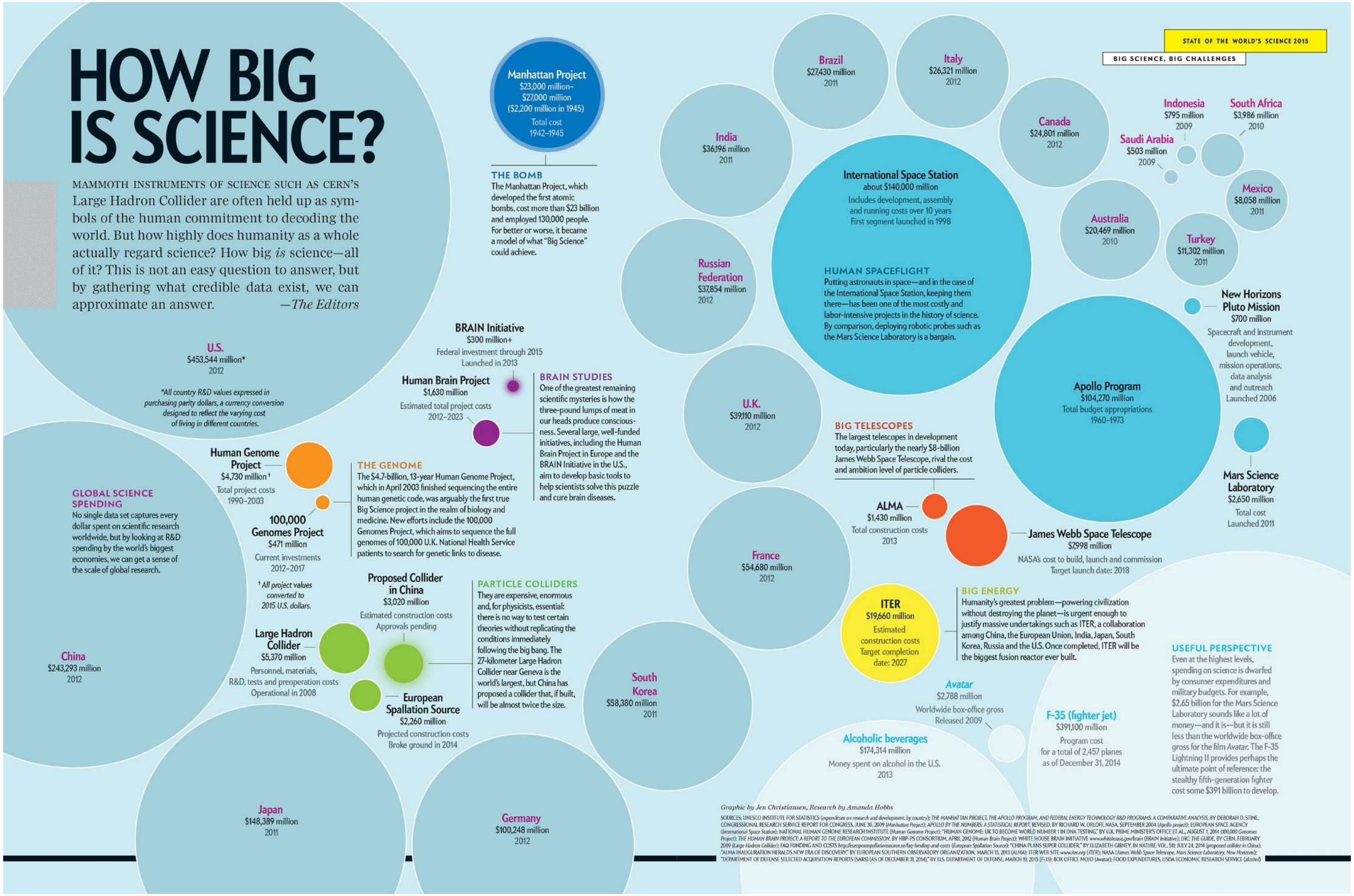
年	
1984	EC将来加速器ワークショップ：LHCをLEPトンネルに建設提案
1987	米レーガン大統領SSC計画サポートを表明
1988	CERNでLEPトンネル掘削完了
1992	ATLAS/CMS検出器 LoI(Letter of Intent)提出
1993	米下院20億ドル執行後SSC計画を停止
1994	CERN理事会LHC建設を承認
1995	日本政府LHCに出資
2000	LHC建設のためLEP運転停止・撤去
2003	ATLAS地下実験室完成
2005	CMS地下実験室完成
2008	LHCファーストビーム、電磁石結線事故
2009	LHCビーム復帰、ラン1開始
2012	ATLAS及びCMS、ヒッグス粒子発見
2015	LHCラン2開始

https://timeline.web.cern.ch/timelines/The-Large-Hadron-Collider

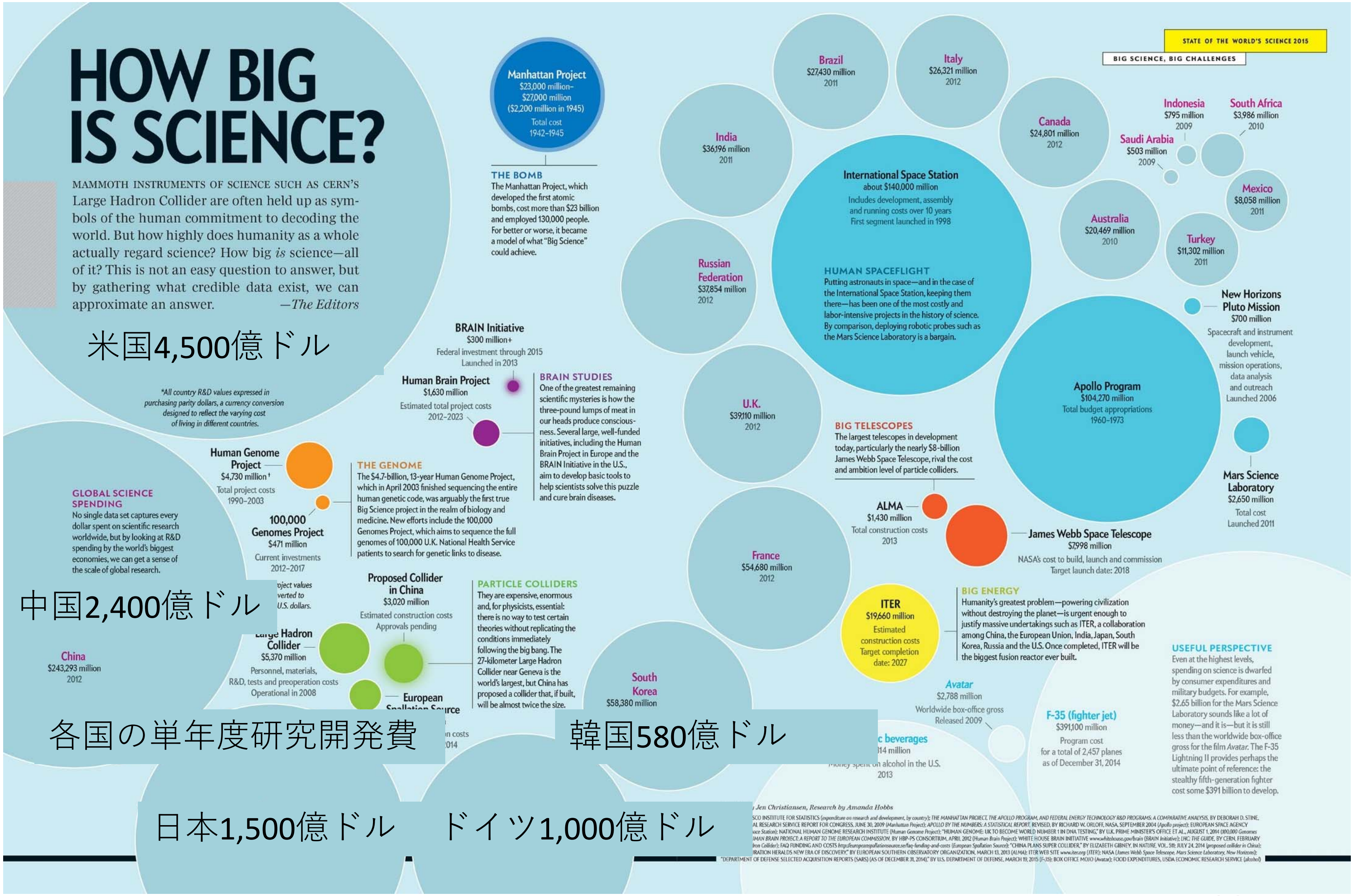
アトラス国際チームの財政分担・参加機関・研究者数（トップ10）

	Country	Budget MCHF	institutes	participants
1	United States	80.74 (17 %)	33	232 (18 %)
2	CERN	60.50 (13 %)	1	137 (10 %)
3	France	52.76 (11 %)	7	90 (6.9 %)
4	Italy	45.09 (9.6 %)	12	141 (11 %)
5	Germany	40.00 (8.5 %)	10	109 (8.3 %)
6	United Kingdom	34.11 (7.3 %)	12	105 (8.0 %)
7	日本	32.18 (7.0 %)	15	61 (4.7 %)
8	Russia	26.12 (5.6 %)	8	102 (7.8 %)
9	Switzerland	18.51 (4.0 %)	2	14 (1.1 %)
10	Canada	15.08 (3.2 %)	7	40 (3.1 %)
all	SUM	468.41 (100%)	149	1,306 (100 %)

https://www.scientificamerican.com/article/how-big-is-science/



https://www.scientificamerican.com/article/how-big-is-science/



米国4,500億ドル

中国2,400億ドル

各国の単年度研究開発費

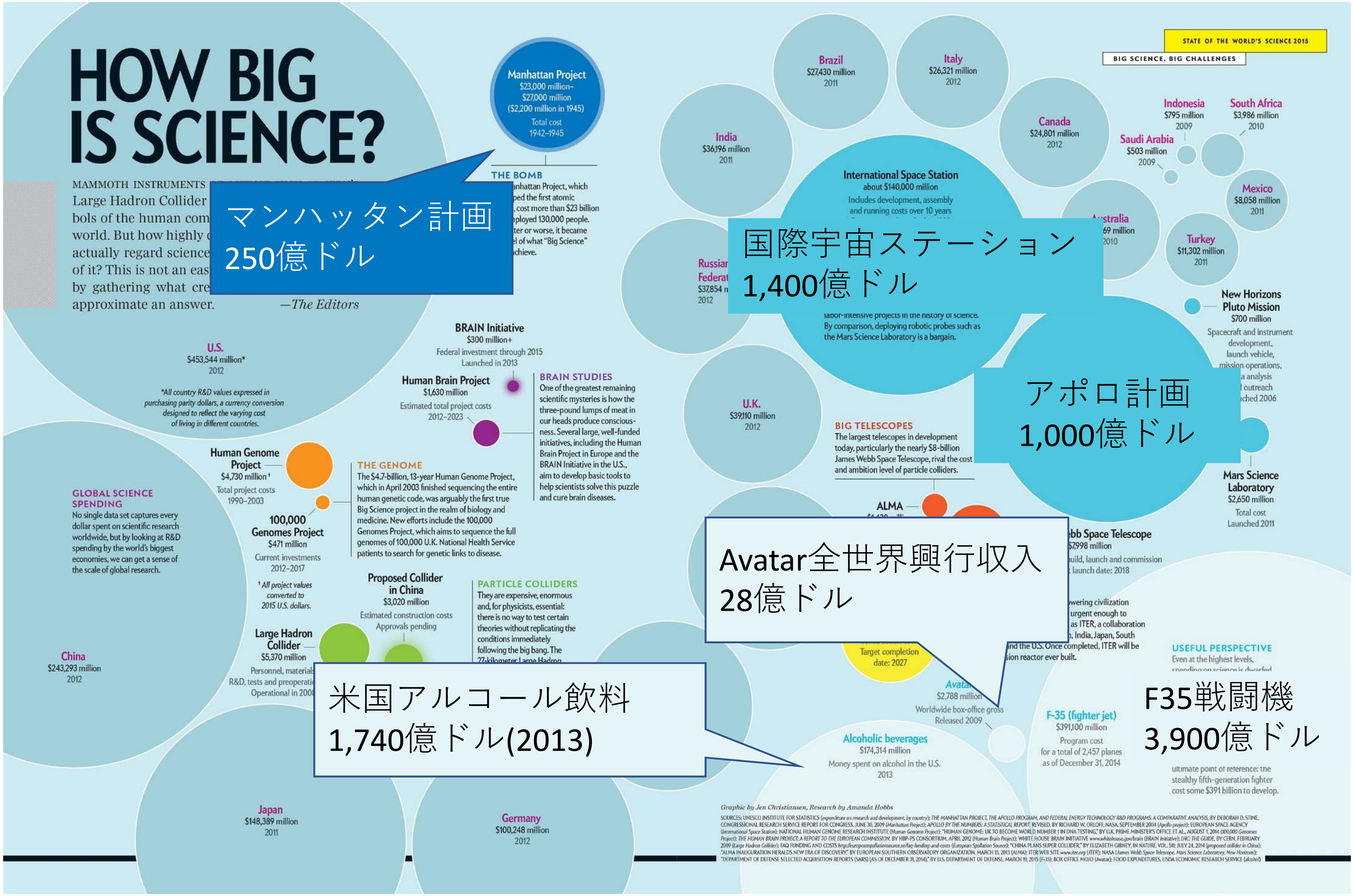
韓国580億ドル

日本1,500億ドル

ドイツ1,000億ドル

2015年USドル換算

https://www.scientificamerican.com/article/how-big-is-science/



マンハッタン計画
250億ドル

国際宇宙ステーション
1,400億ドル

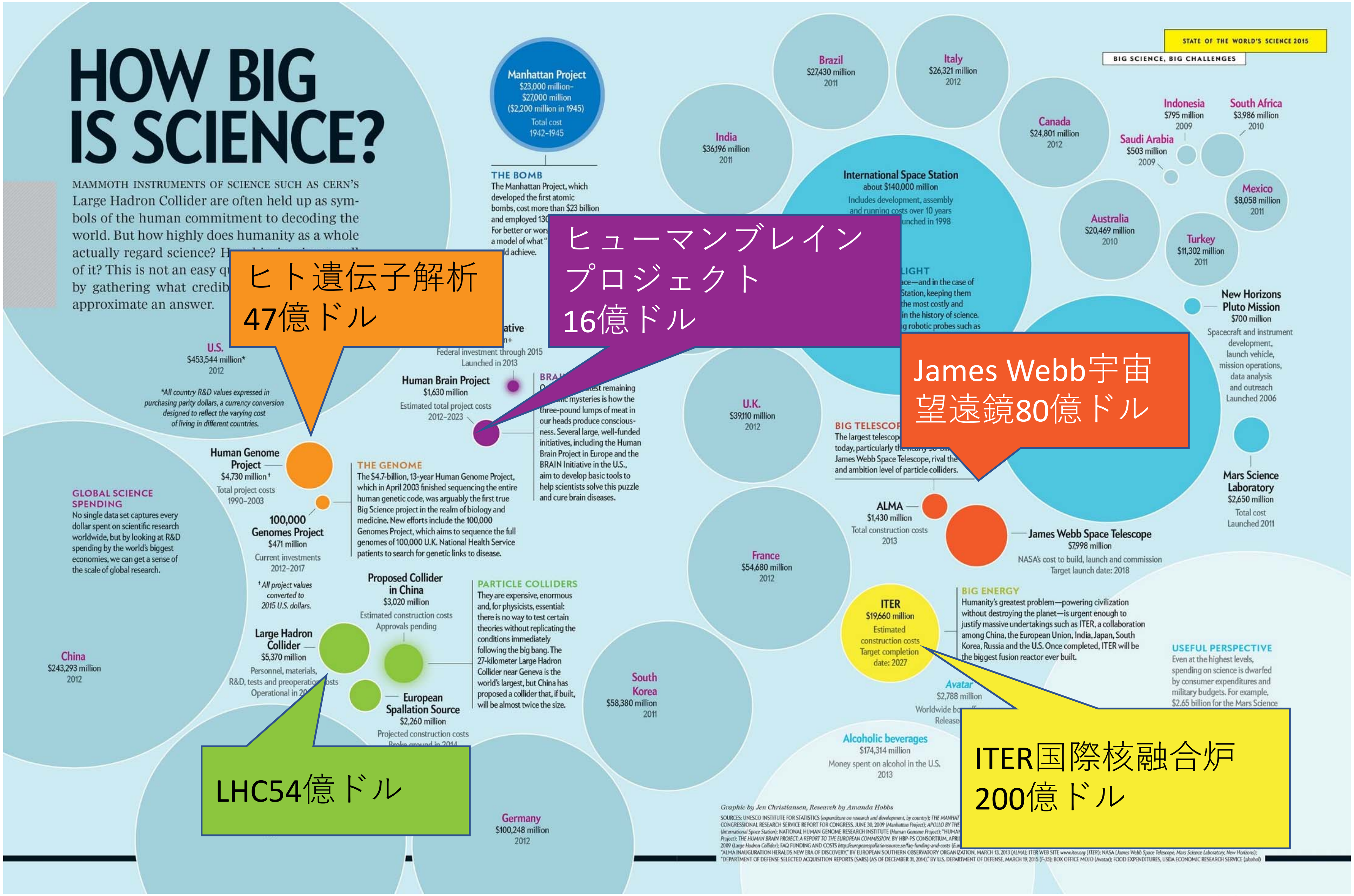
アポロ計画
1,000億ドル

Avatar全世界興行収入
28億ドル

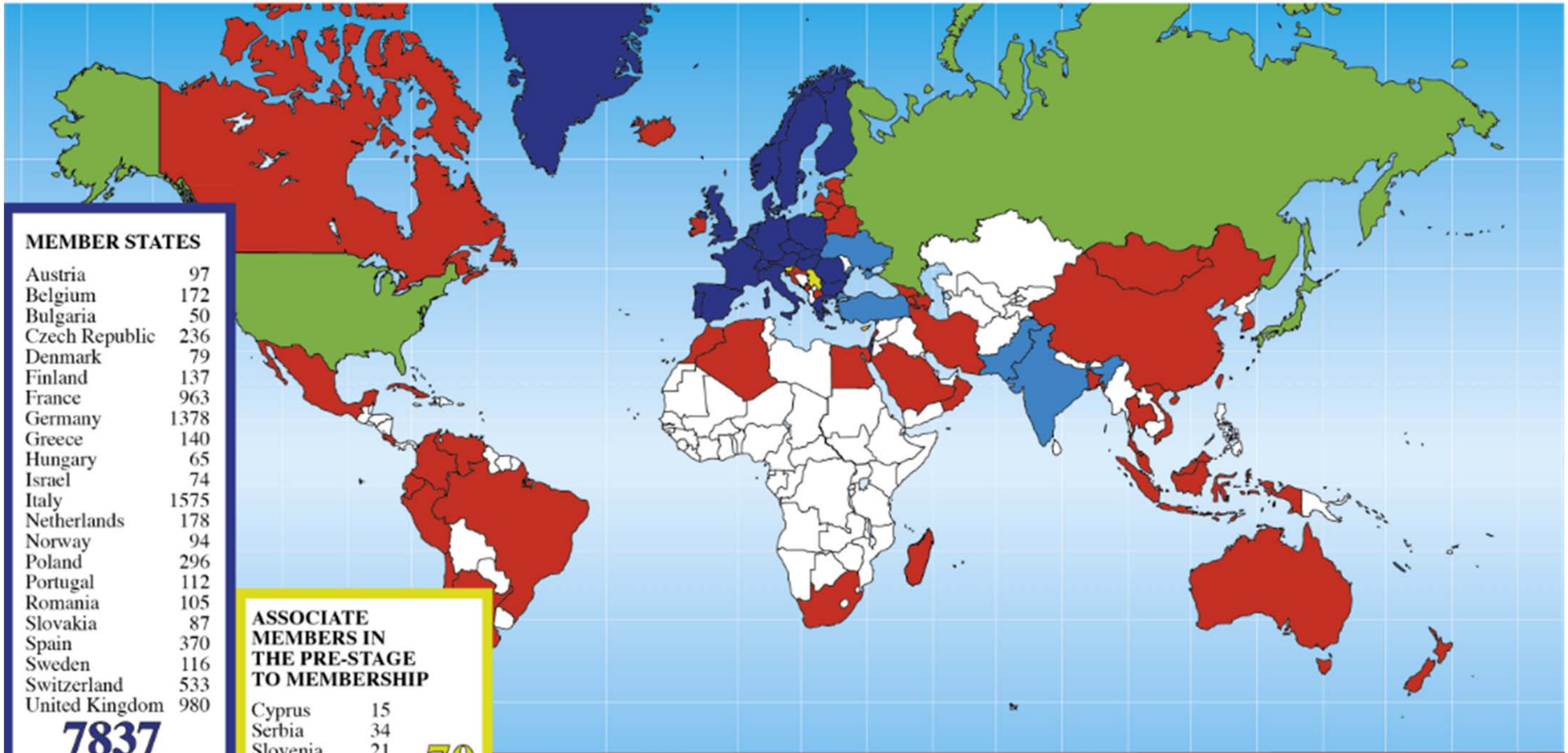
米国アルコール飲料
1,740億ドル(2013)

F35戦闘機
3,900億ドル

https://www.scientificamerican.com/article/how-big-is-science/



Distribution of All CERN Users by Location of Institute on 5 July 2017



MEMBER STATES

Austria	97
Belgium	172
Bulgaria	50
Czech Republic	236
Denmark	79
Finland	137
France	963
Germany	1378
Greece	140
Hungary	65
Israel	74
Italy	1575
Netherlands	178
Norway	94
Poland	296
Portugal	112
Romania	105
Slovakia	87
Spain	370
Sweden	116
Switzerland	533
United Kingdom	980

7837

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP

Cyprus	15
Serbia	34
Slovenia	21

70

ASSOCIATE MEMBERS

India	233
Pakistan	36
Turkey	131
Ukraine	37

437

OBSERVERS

Japan	263
Russia	1068
USA	2152

3483

OTHERS

Algeria	1
Argentina	23
Armenia	19
Australia	37
Azerbaijan	4
Bangladesh	4
Belarus	24
Brazil	136
Canada	191
Chile	24
China	243
Colombia	28
Costa Rica	1
Croatia	27
Cuba	3
Ecuador	2
Egypt	27
Estonia	19
Georgia	28
Hong Kong	26
Iceland	5
Indonesia	7
Iran	28
Ireland	9
Korea	160
Latvia	1
Lebanon	8
Lithuania	26
Madagascar	3
Malaysia	8
Malta	6
Mexico	68
Mongolia	2
Montenegro	4
Morocco	11
New Zealand	8
Oman	10
Peru	2
Saudi Arabia	1
Singapore	4
South Africa	60
Taiwan	74
Thailand	19
TFYROM	2
Venezuela	1
Viet Nam	1

1395

Physics Letters B 716 (2012) 1–29

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

L. Rumyantsev [64], Z. Rurikova [48], N.A. Rusakovich [64], J.P. Rutherfoord [7], P. Ruzicka [125], Y.F. Ryabov [121], M. Rybar [126], G. Rybkin [115], N.C. Ryder [118], A.F. Saavedra [150], I. Sadeh [153], H.F.-W. Sadrozinski [137], R. Sadykov [64], F. Safai Tehrani [132a], H. Sakamoto [155], G. Salamanna [75], A. Salamon [133a], M. Saleem [111], D. Salek [30], D. Salihagic [99], A. Salnikov [143], J. Salt [167], B.M. Salvachua Ferrando [6], D. Salvatore [37a,37b], F. Salvatore [149], A. Salvucci [104], A. Salzburger [30], D. Sampsonidis [154], B.H. Samset [117], A. Sanchez [102a,102b], V. Sanchez Martinez [167], H. Sandaker [14], H.G. Sander [81], M.P. Sanders [98], M. Sandhoff [175], T. Sandoval [28]

ATLAS共同研究における性別や地域の多様性に関する調査

メンバーの性別年齢分布

科学論文著者の性別年齢分布

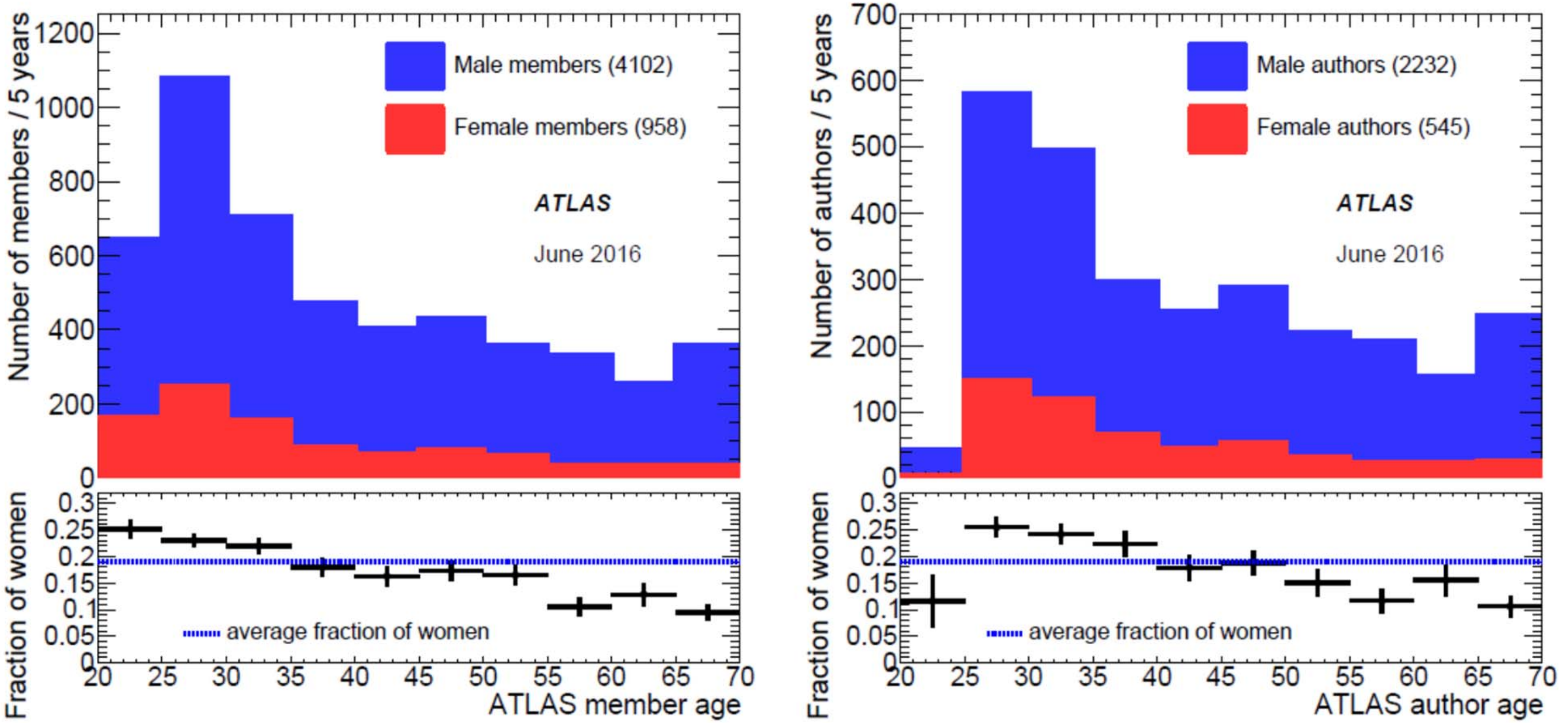


Figure 1: Age distribution of ATLAS members (left) and ATLAS scientific authors (right). The bottom panel shows the fraction of women as a function of age. The dotted line shows the average fraction of female ATLAS members of 19%.

"Studies related to gender and geographic diversity in the ATLAS Collaboration," The ATLAS Collaboration, ATL-GEN-PUB-2016-001

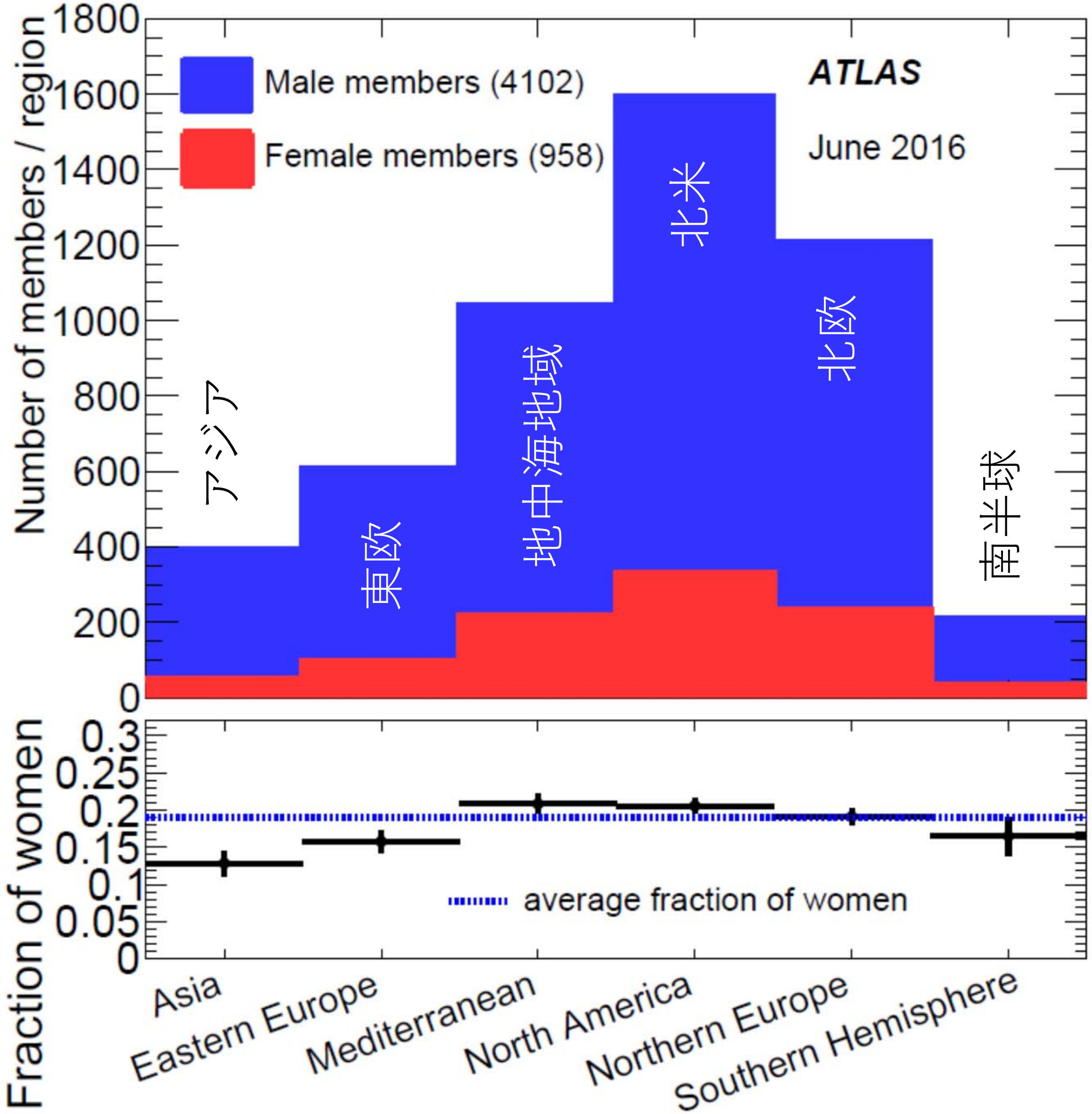


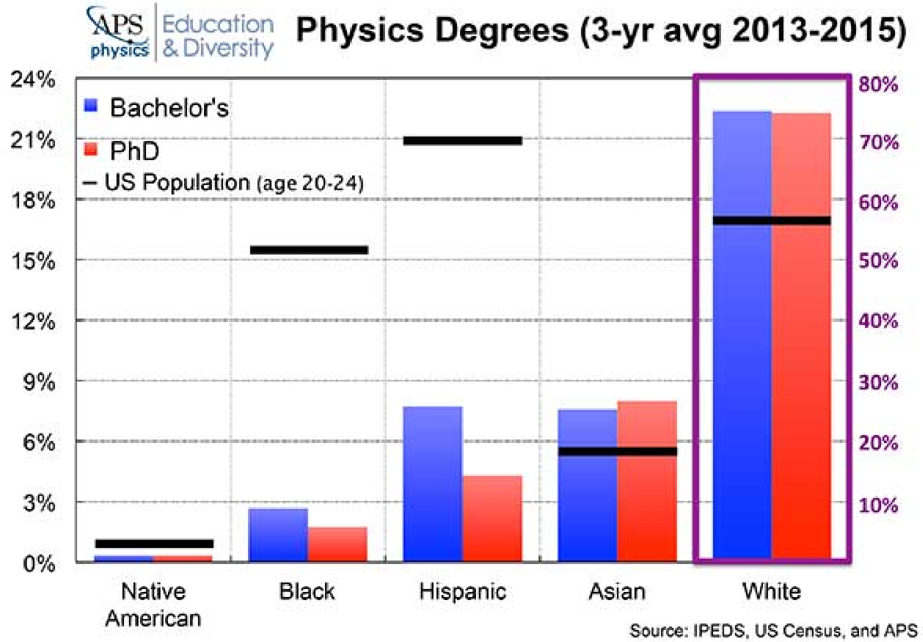
Figure 3: Region of affiliation of ATLAS members. The bottom panel shows the fraction of women as function of region. The dotted line shows the average fraction of female ATLAS members of 19%.

affiliation	% in ATLAS	% women by affiliation	% women by nationality
Romania	0,8%	46,7%	42,9%
Spain	2,9%	35,7%	35,6%
Greece	1,3%	34,6%	40,5%
Poland	1,2%	30,4%	31,3%
France	7,0%	29,2%	23,6%
Norway	0,9%	27,8%	28,6%
Netherland	1,9%	27,0%	11,1%
Switzerland	1,4%	25,9%	16,0%
Italy	7,7%	25,8%	31,9%
Sweden	1,8%	25,7%	26,7%
UK	10,1%	23,2%	18,1%
Portugal	0,9%	22,2%	20,8%
Germany	13,9%	20,7%	15,2%
Canada	3,8%	20,0%	22,2%
Israel	1,6%	18,8%	19,2%
USA	18,2%	16,1%	11,3%
China	1,3%	8,0%	12,0%
Czech	2,5%	6,3%	8,9%
Russia	3,4%	6,1%	6,1%
Japan	4,1%	4,9%	7,5%

ATLAS EXPERIMENT

"YOU ARE WELCOME HERE!"

Report of the ATLAS Diversity Study Group



Women in physics: Are we there yet?

https://www.quantumdiaries.org/2012/10/31/women-in-physics-are-we-there-yet/

まとめ

- 世界最高エネルギー衝突型加速器LHCとATLAS実験の紹介
- ヒッグス粒子の発見とその後
- 素粒子の標準模型を超えて～アップグレード
- 巨大科学のあり方

- LHCは現在運転停止
- 2021年に運転再開
- 2026年よりHL-LHC
- 2037年？まで実験継続