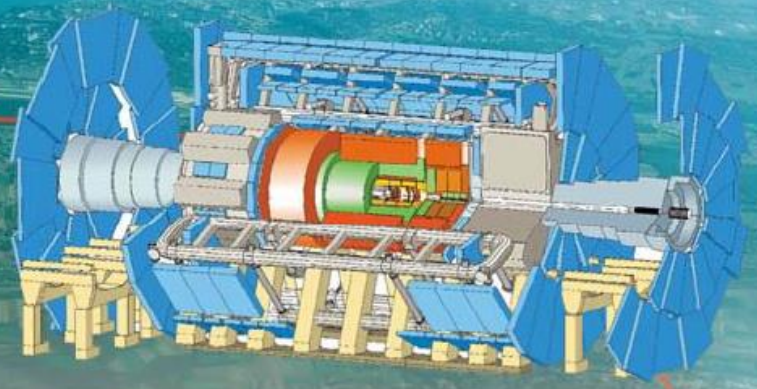
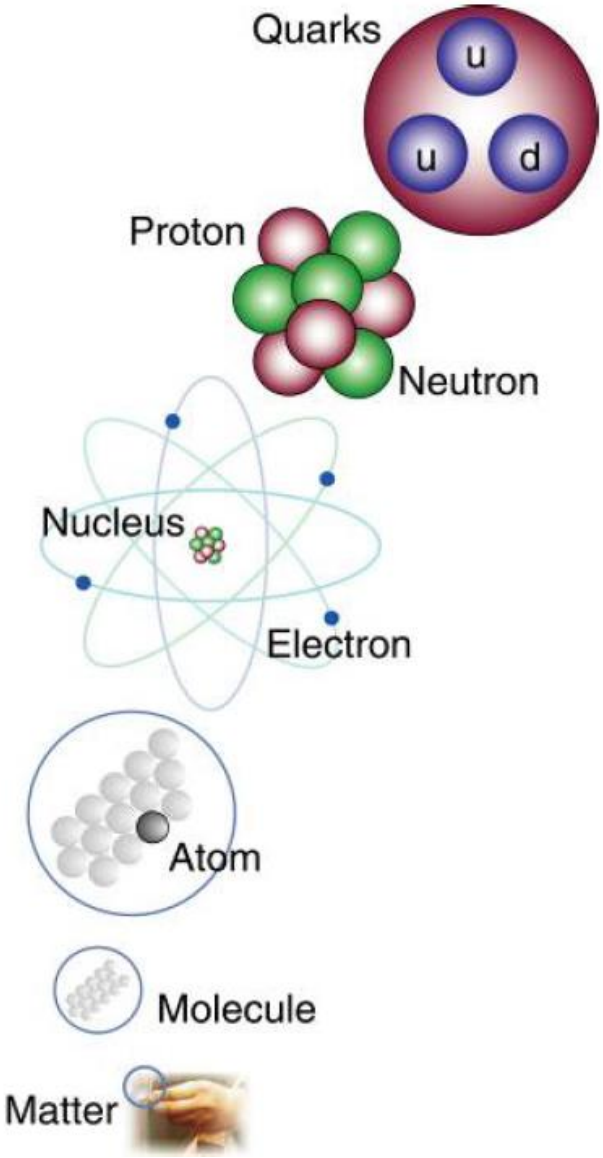
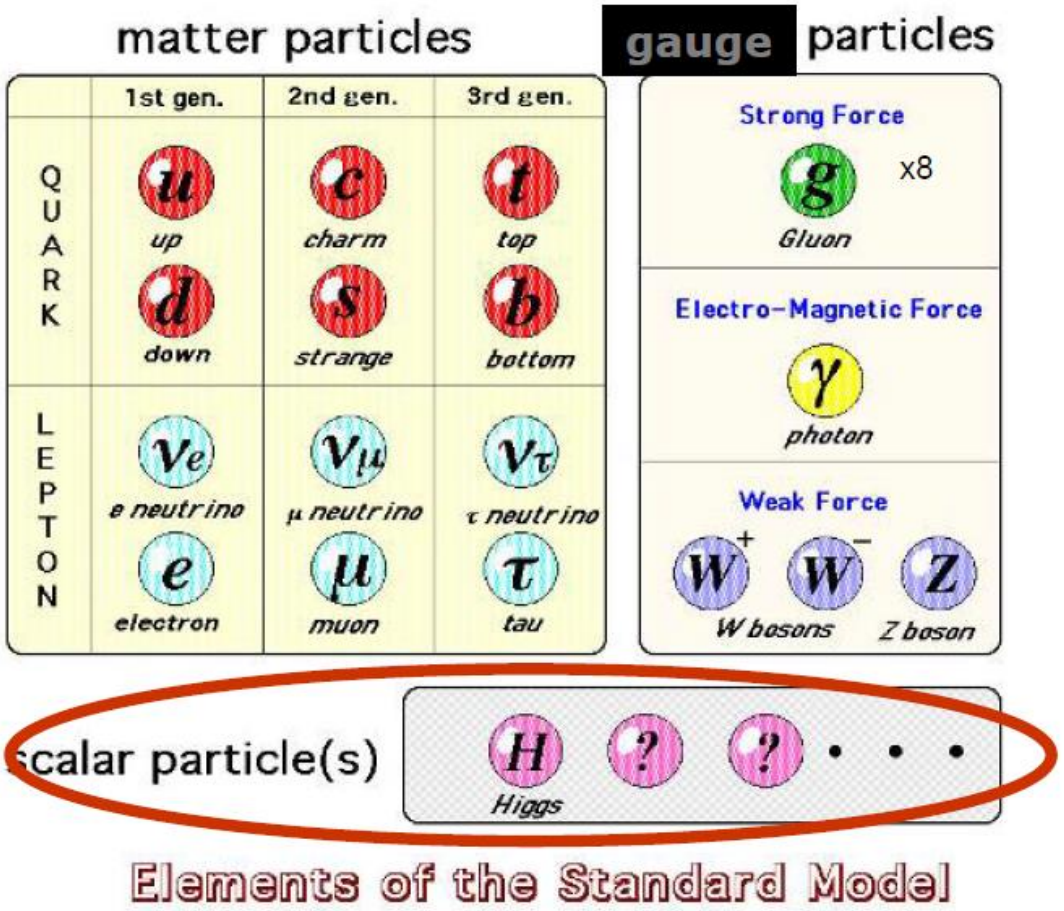
Odkrycie cząstki Higgsa przez eksperymenty LHC: jakie trudności musielismy pokonać?

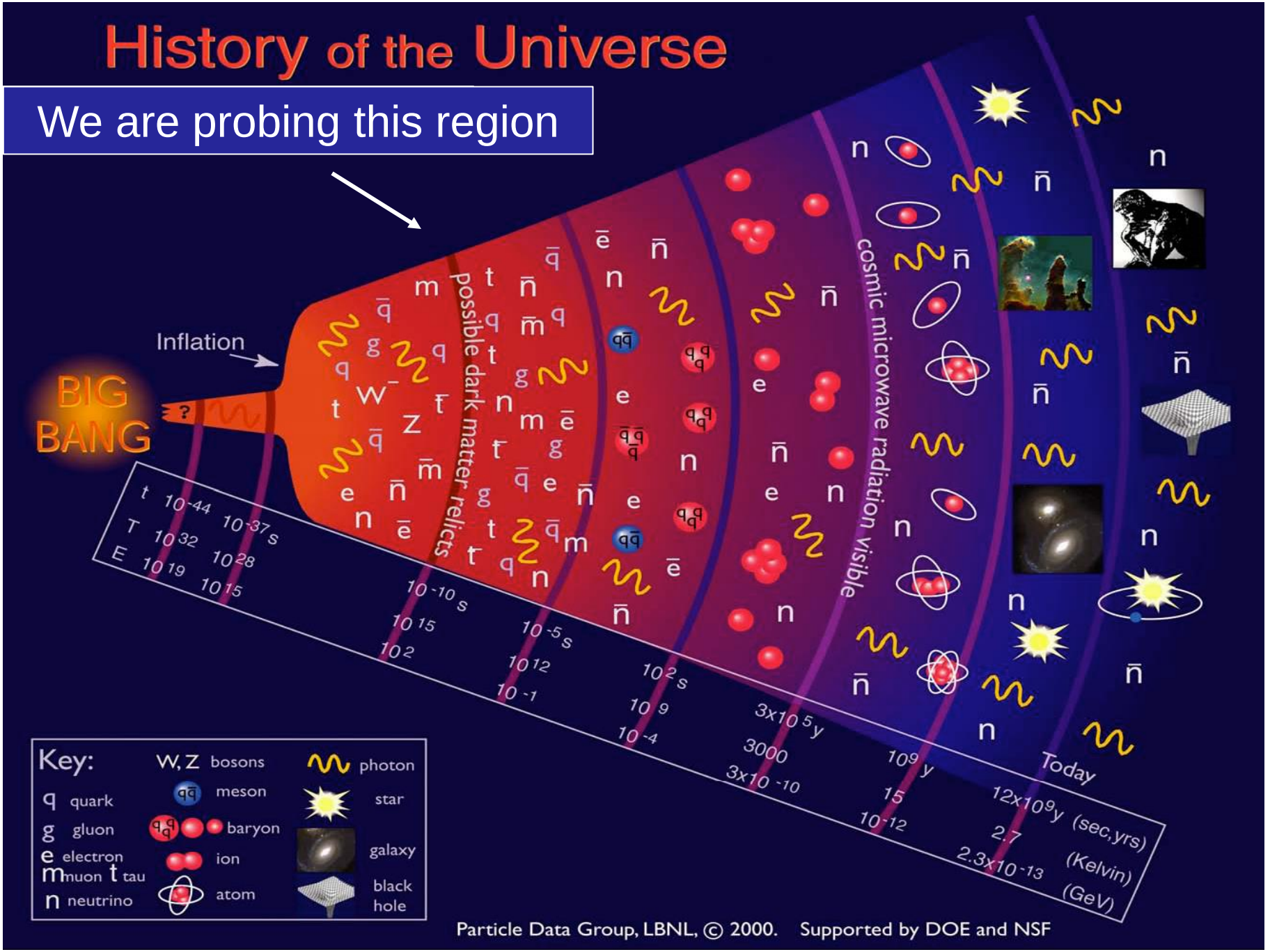


Czyli Wielka Przygoda z Fizyką i nie tylko……

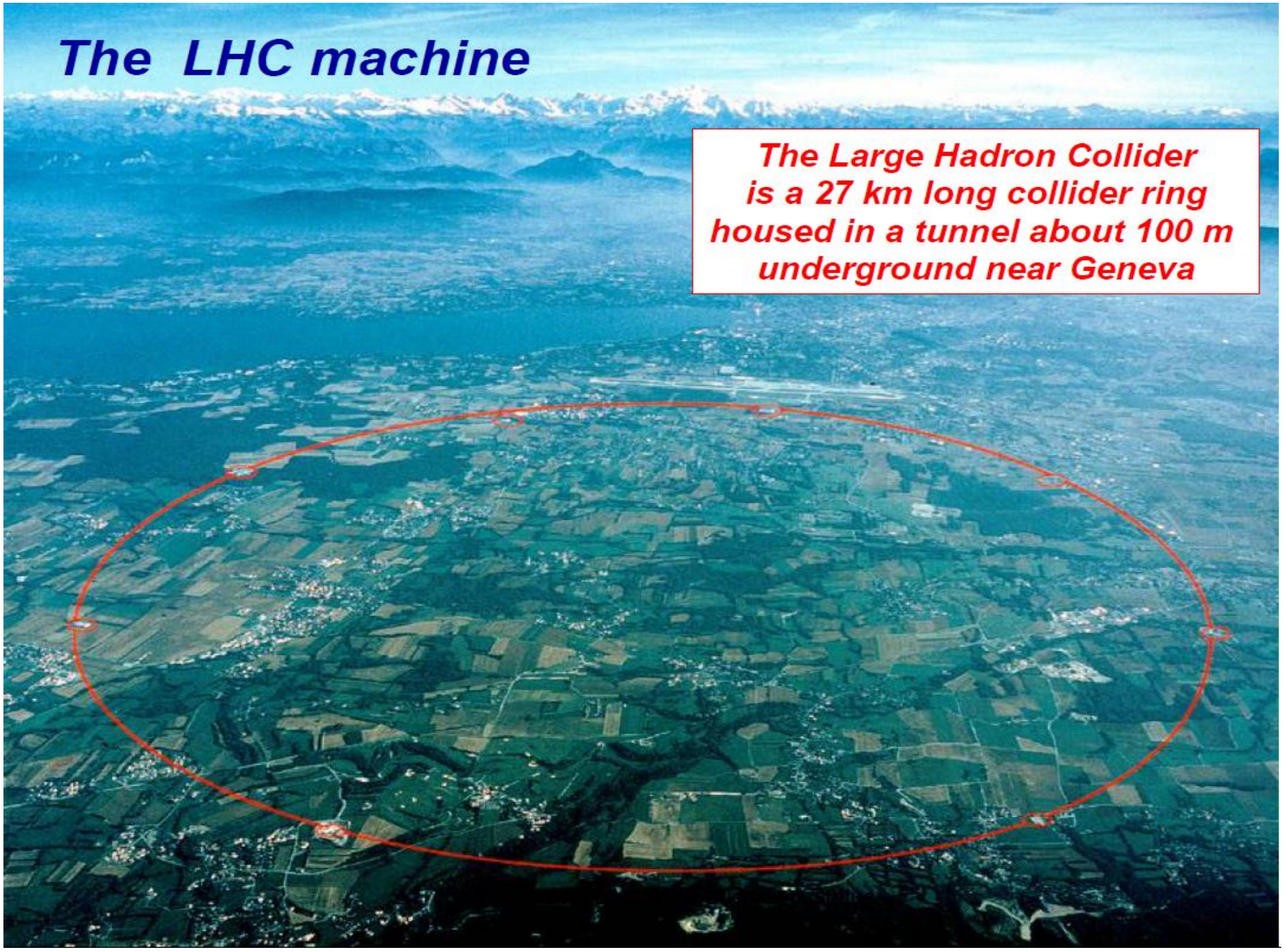
Cząstki elementarne, pola cechowania i ich oddziaływania






History of the Universe
We are probing this region
BIG BANG
Inflation
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
12x109 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

The LHC machine




Coldest Ring in the Universe ?
1.9 K (CMBR is about 2.7 K)
LHC magnets are cooled with pressurized superfluid helium

The full LHC accelerator complex

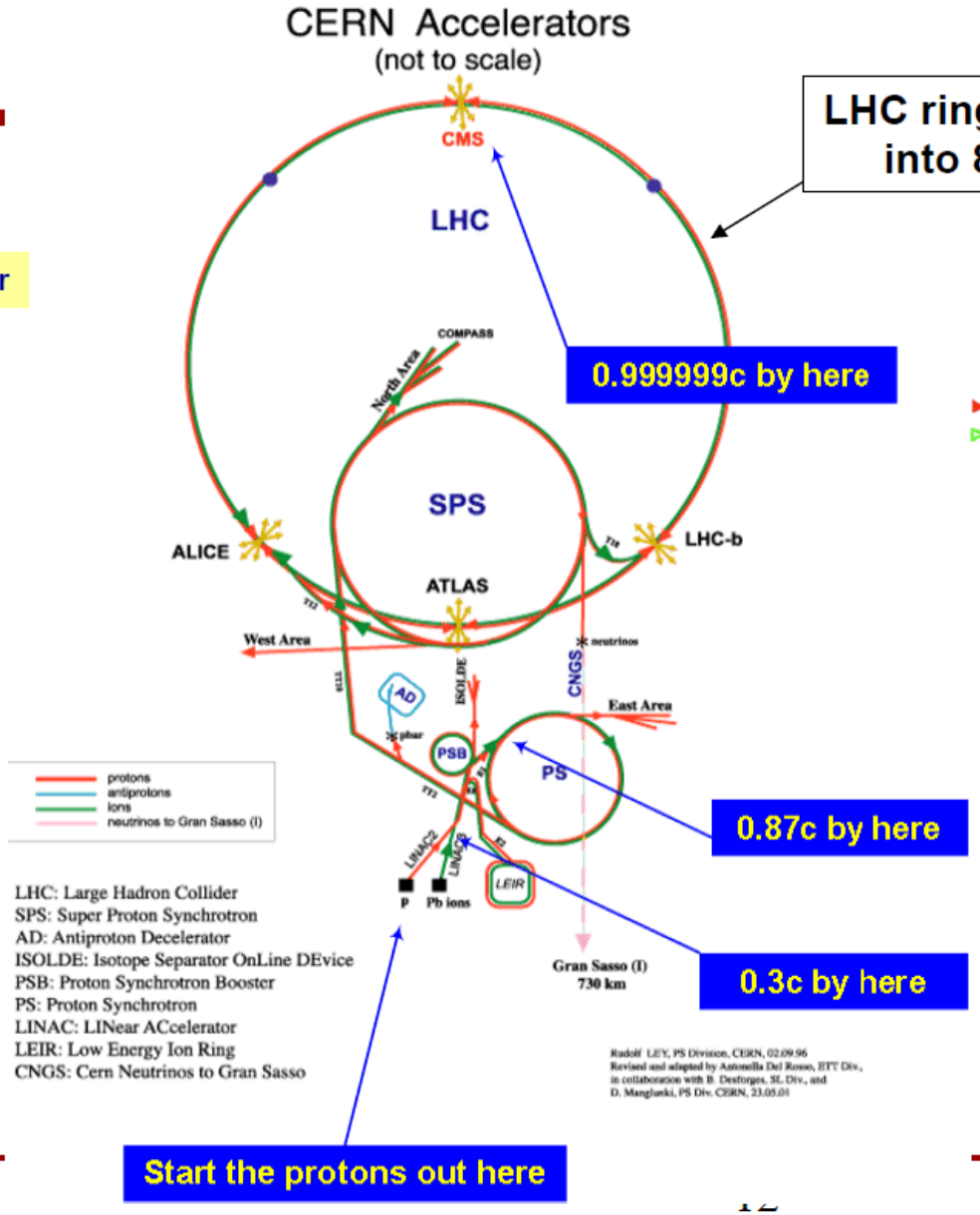
Linac

Booster

PS

SPS

LHC



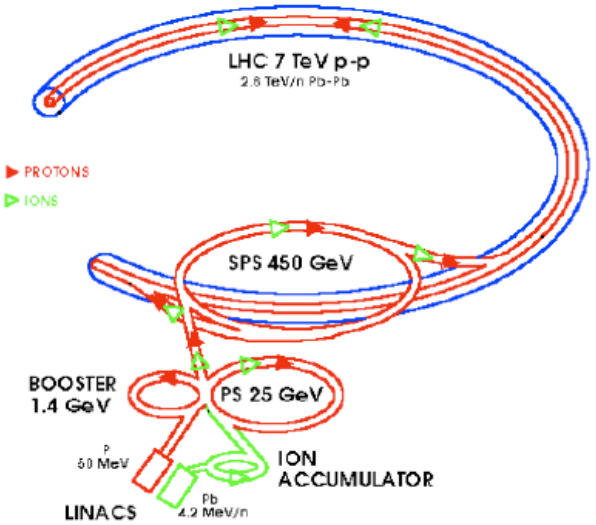
LHC ring is divided into 8 sectors

0.999999c by here

0.87c by here

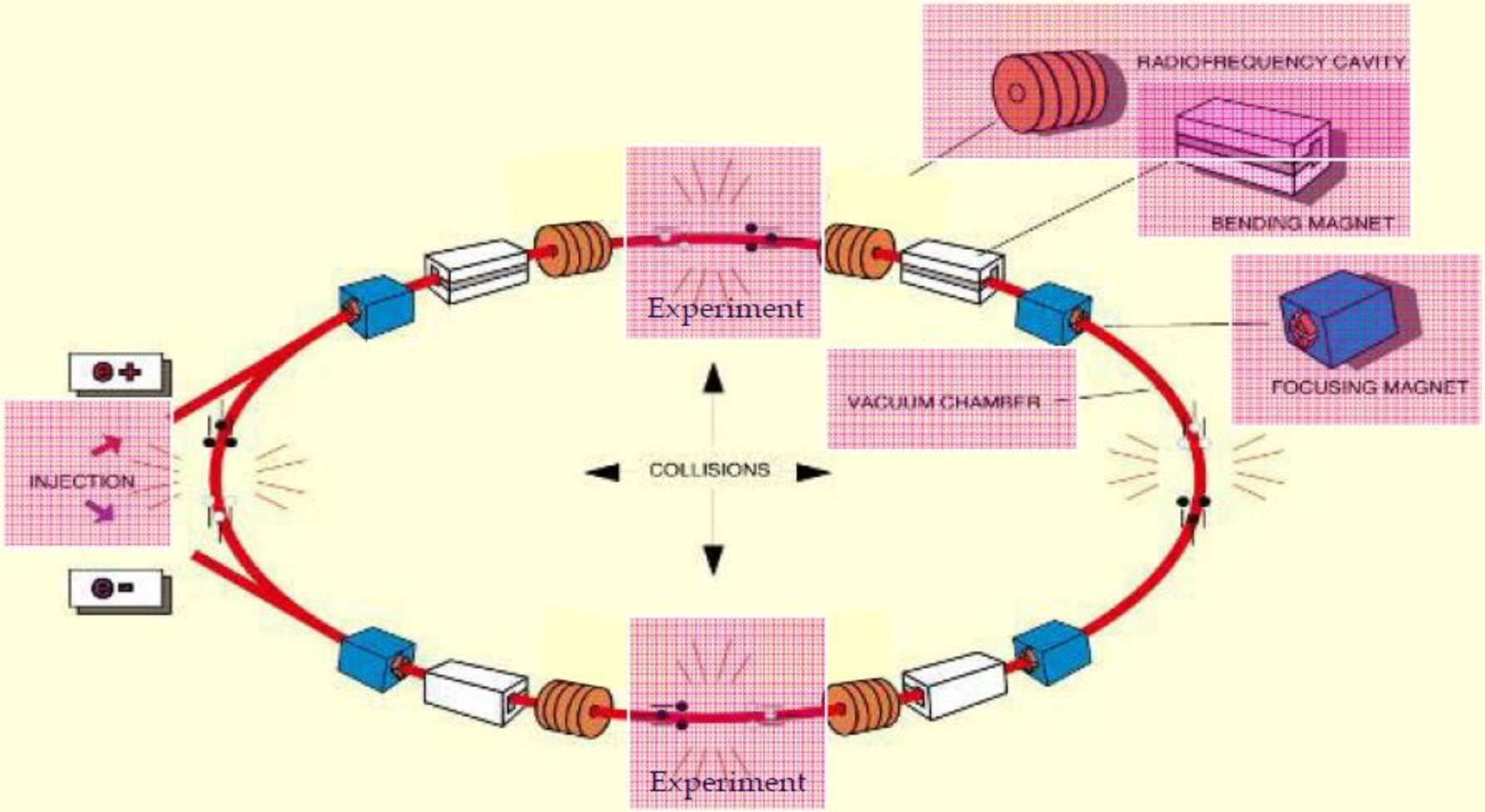
0.3c by here

Start the protons out here



> 50 years of CERN history still alive and operational

LHC **circular machine** with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 7 TeV will take about 20 minutes



- pp $\sqrt{s} = 14$ TeV $L_{design} = 10^{34}$ cm^{-2} s^{-1} (after 2010)

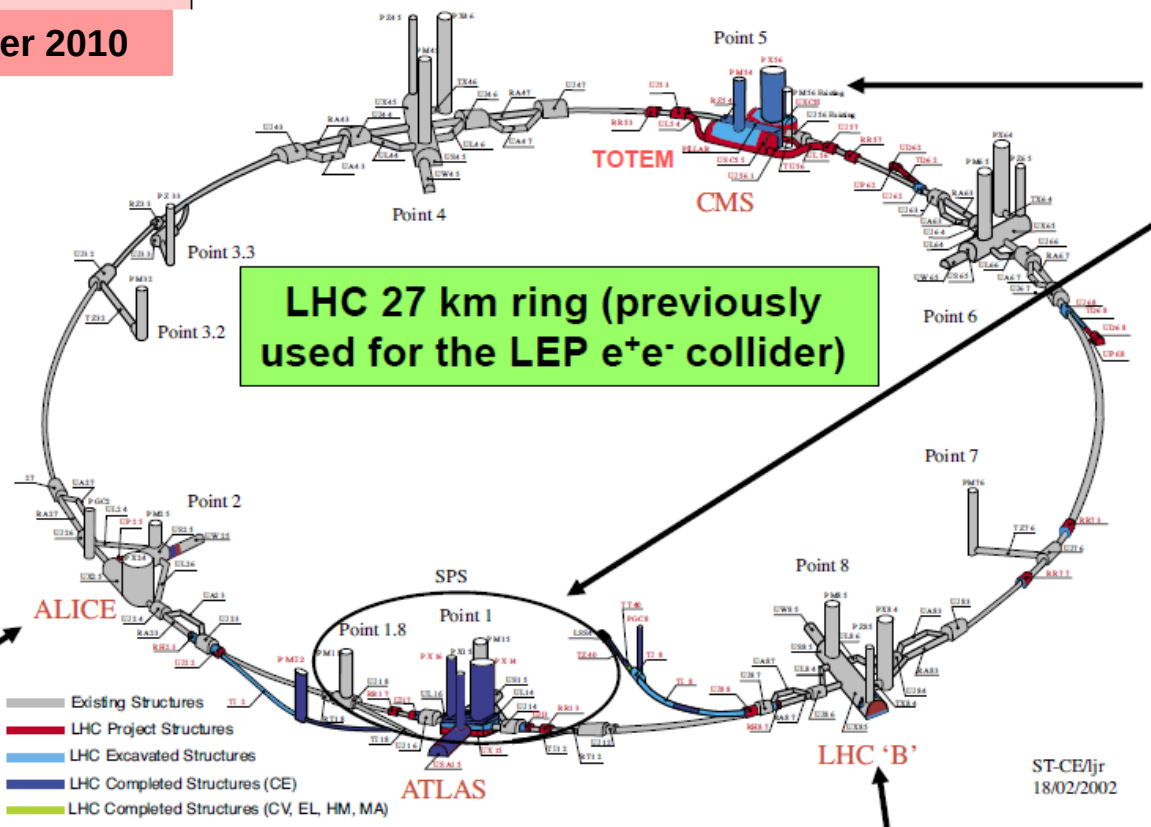
  $L_{initial}$ < few x 10^{33} cm^{-2} s^{-1} (before)

Note: $\sqrt{s}$ is x7 Tevatron, L_{design} is x100 Tevatron

- Heavy ions (e.g. Pb-Pb at $\sqrt{s} \sim 1000$ TeV)

First collisions:

November 2010



ATLAS and CMS : pp, general purpose

LHC 27 km ring (previously used for the LEP e^+e^- collider)

ALICE : ion-ion, p-ion

LHCb : pp, B-physics, CP-violation

LHC: jeszcze jeden zderzacz?

	Start	Type	Max proton energy [GeV]	Length [m]	B Field [Tesla]	Lumi [$cm^{-2}s^{-1}$]	Stored beam energy [MJoule]
TEVATRON Fermilab Illinois USA	1983	p-pbar	980	6300	4.5	$4.3\ 10^{32}$	1.6 for protons
HERA DESY Hamburg	1992	p – e+ p – e-	920	6300	5.5	$5.1\ 10^{31}$	2.7 for protons
RHIC Brookhaven Long Island	2000	Ion-Ion p-p	250	3834	4.3	$1.5\ 10^{32}$	0.9 per proton beam
LHC CERN	2008	Ion-Ion p-p	7000 Now 4000	26800	8.3	10^{34} Now 7.7×10^{33}	**362 per beam**
Factor			7	4	2	**50**	**100**

What does this mean?

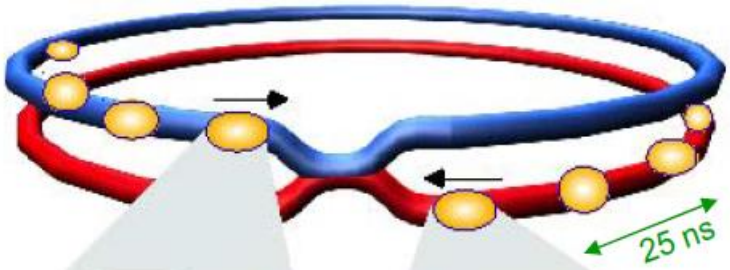
The energy of an 200 m long fast train at 155 km/hour corresponds to the energy of 360 MJoule stored in one LHC beam

360 MJoule: the energy stored in one LHC beam corresponds approximately to…

- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate

It's how ease the energy is released that matters most !!

Collisions at LHC



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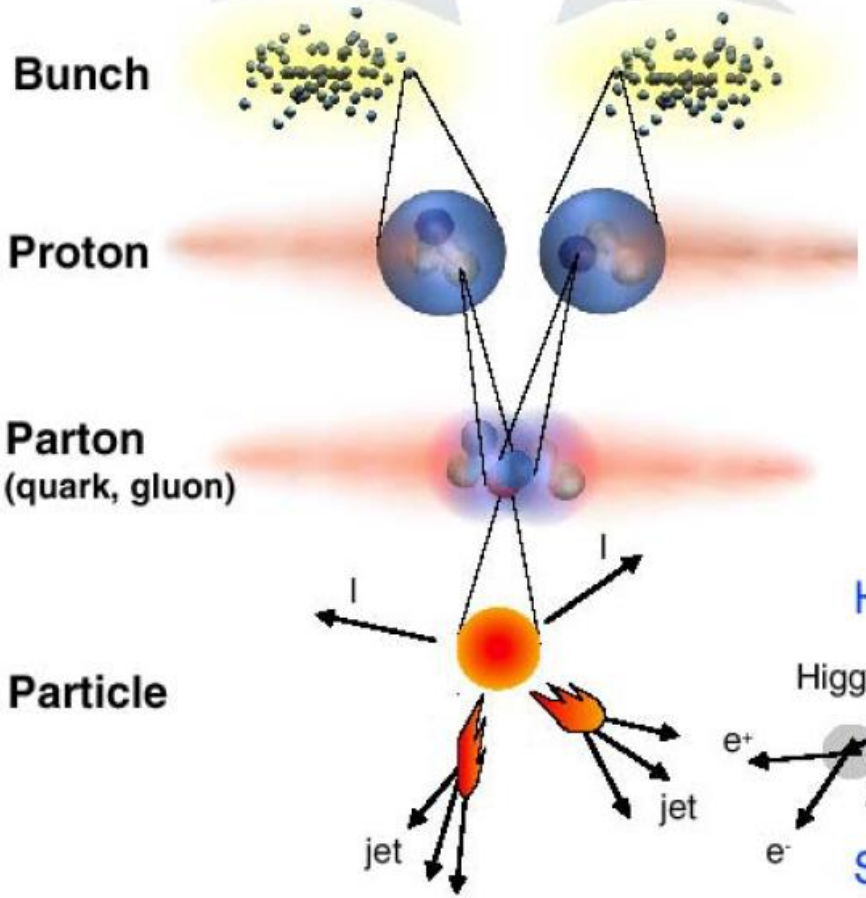
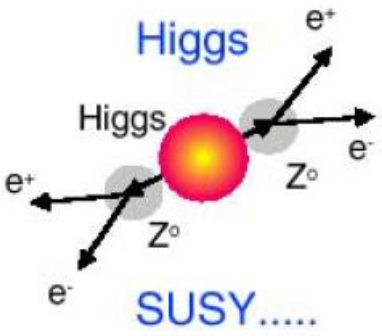
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}





In the experiments:

10^9 pp interactions per second

~ 1500 particles (p,n, π) produced in the detectors at each bunch-crossing

Selection of 1 in

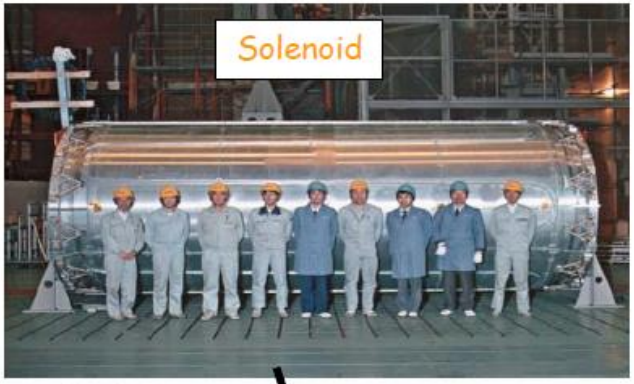
10,000,000,000,000

Detektory eksperymentów fizyki wysokich energii

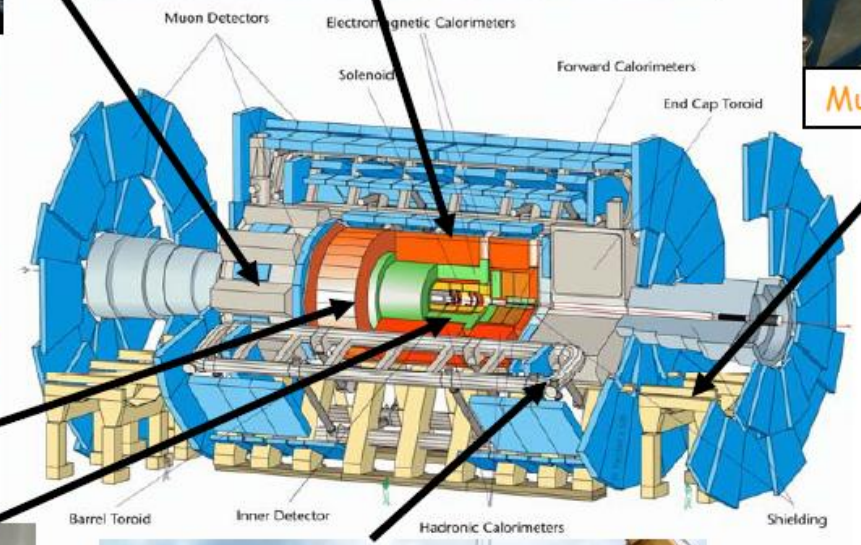
- **Detektory** pozwalają na obserwację (rejestrację) serii oddziaływań, podjęcie decyzji czy oddziaływanie jest interesujące, identyfikację produkowanych cząstek, pomiar ich energii i pędu.

- Detektory dla zderzeń przy wysokich energiach muszą być duże, zbudowane z różnych poddetektorów (każdy dedykowany do rejestracji pewnego określonego typu sygnału). Niektóre poddetektory umieszczone są w polu magnetycznym (aby umożliwić pomiar pędu).

- **Metody pomiarowe** to pomiar absorpcji energii, rekonstrukcja toru na podstawie „śladów" zostawionych w poszczególnych warstwach detektorów, itd. itd...



ATLAS

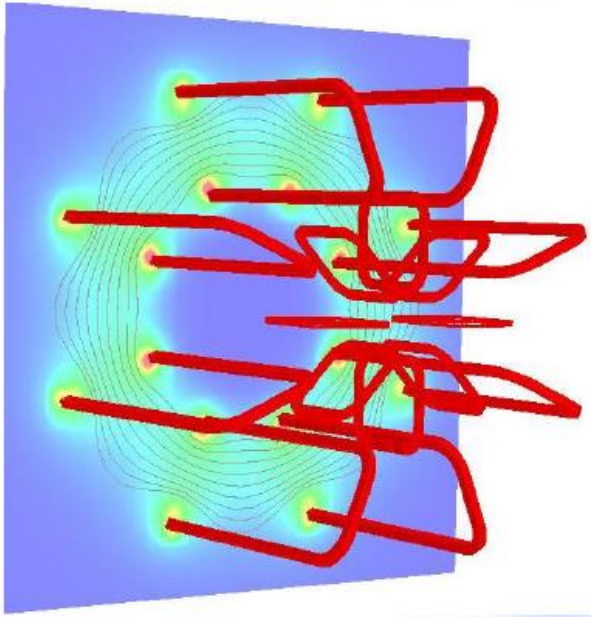


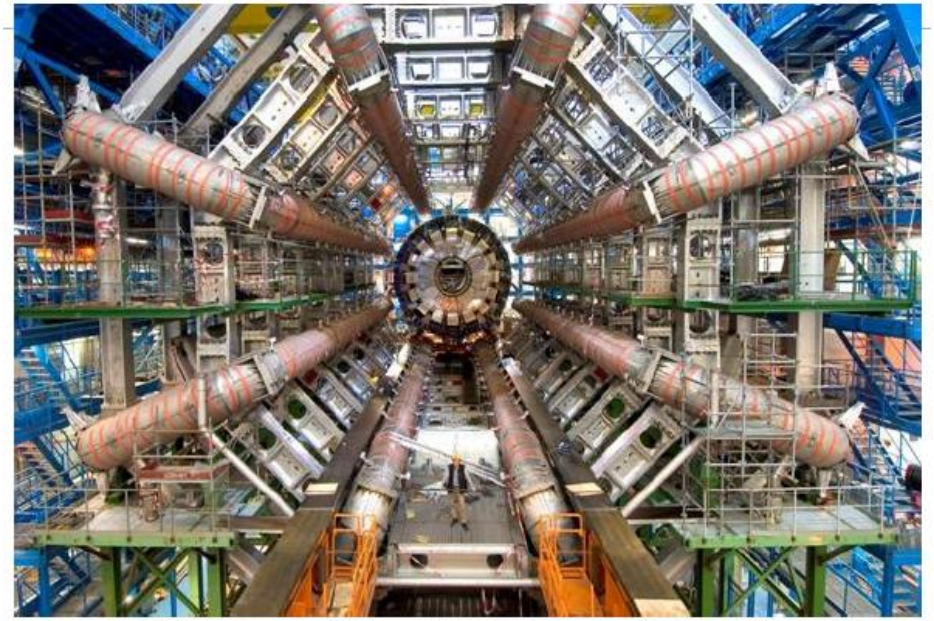
zdjecia

rok 2003

Długość : ~ 40 m
Promień : ~ 10 m
Waga : ~ 7000 ton

Toroid





$$qvB = \frac{p}{R}v$$

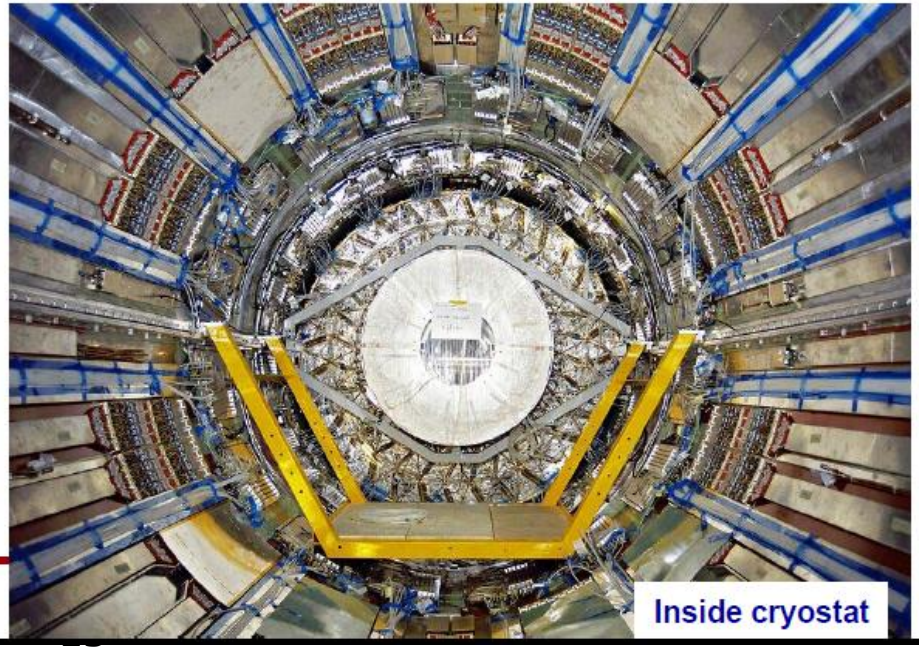
$$B[\mathsf{T}]\cdot R[\mathsf{m}] = 3.3356\cdot p\left[\mathsf{GeV/c}\right]$$

TRT+SCT barrel travelled to the pit, 24th Aug 2006

Through the parking area

A tight fit between BT and EC Calorimeter

From the trolley to the support rails



Inside cryostat


Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Morocco
Netherlands
Norway
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR
ATLAS
Collaboration

38 countries, 177 Institutions
~2900 scientific authors
~1800 with PhD, ~1100 students

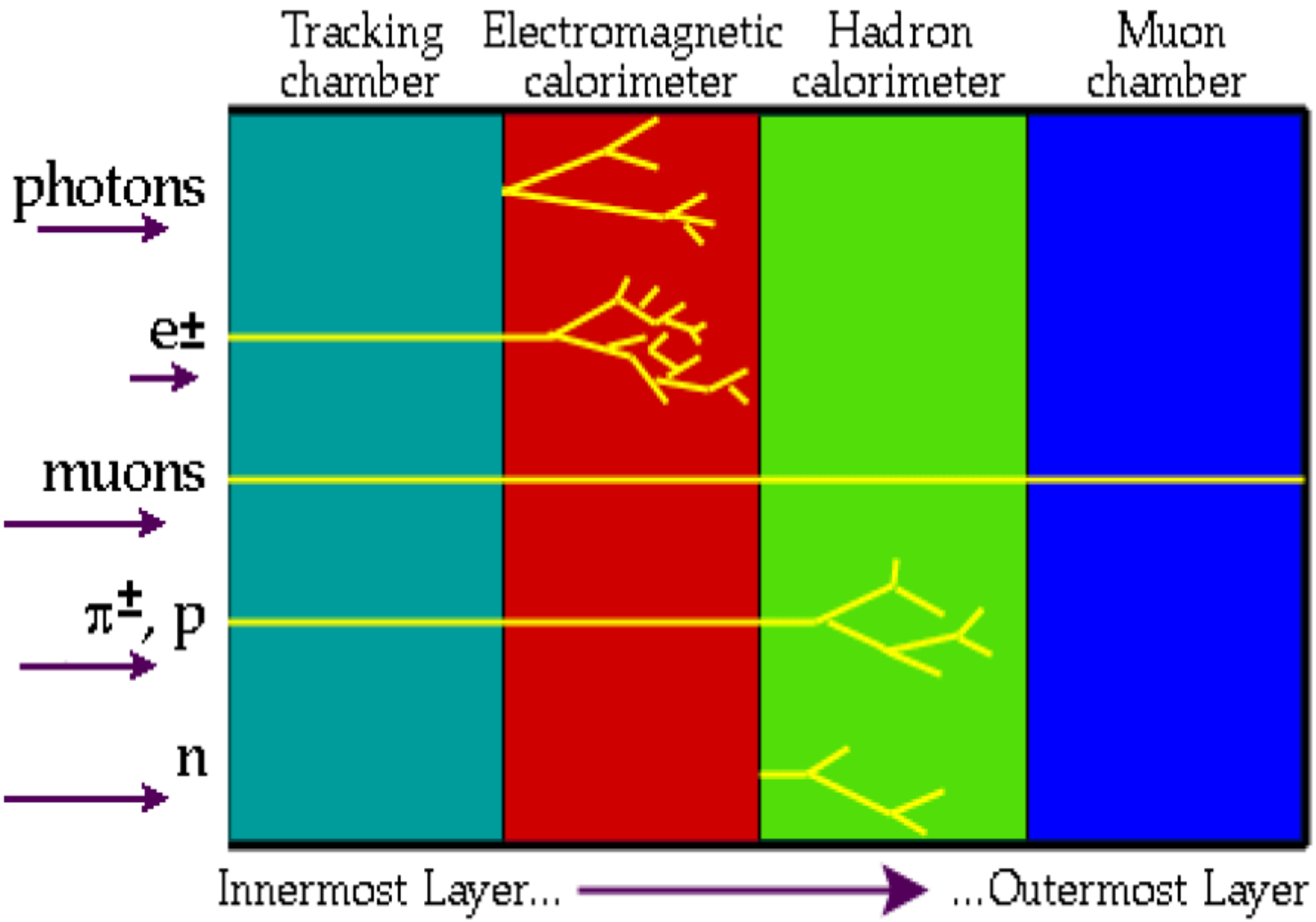
Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brazil Cluster, Brookhaven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

France
Georgia
Germany
Greece
Israel
Italy
Japan
Switzerland
Taiwan
Turkey

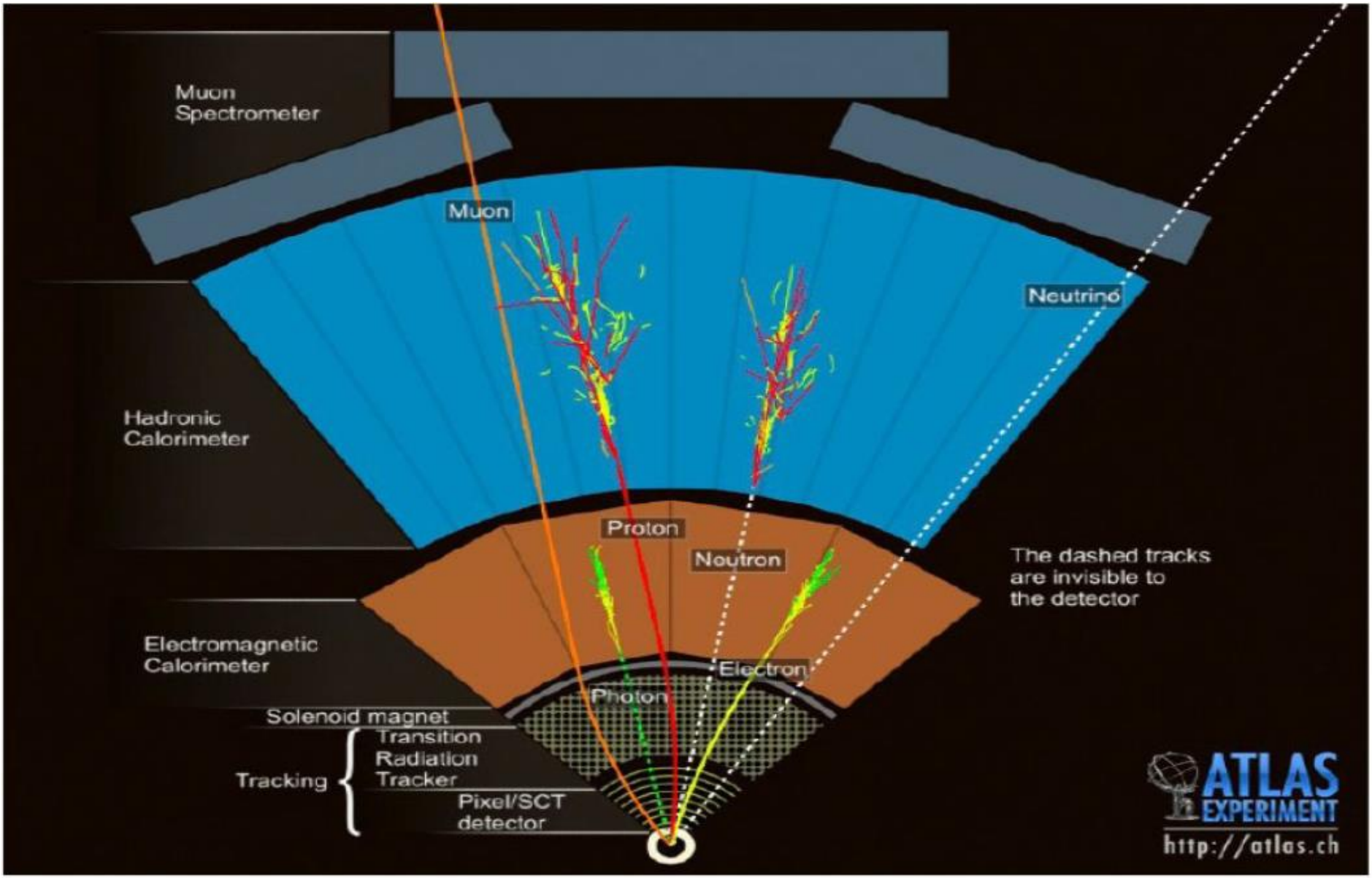
ATLAS

East Asian collaborating institutes from China (5 institutes), Japan (16 institutes), Taiwan (1 institute) and Hong Kong SAR (3 institutes) joining ; some Vietnam students via French institutes

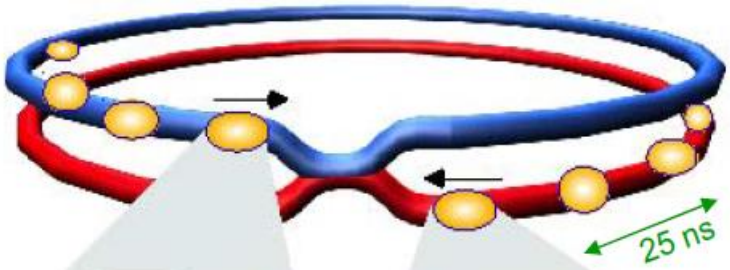
General purpose detectors



Particle identification



Collisions at LHC



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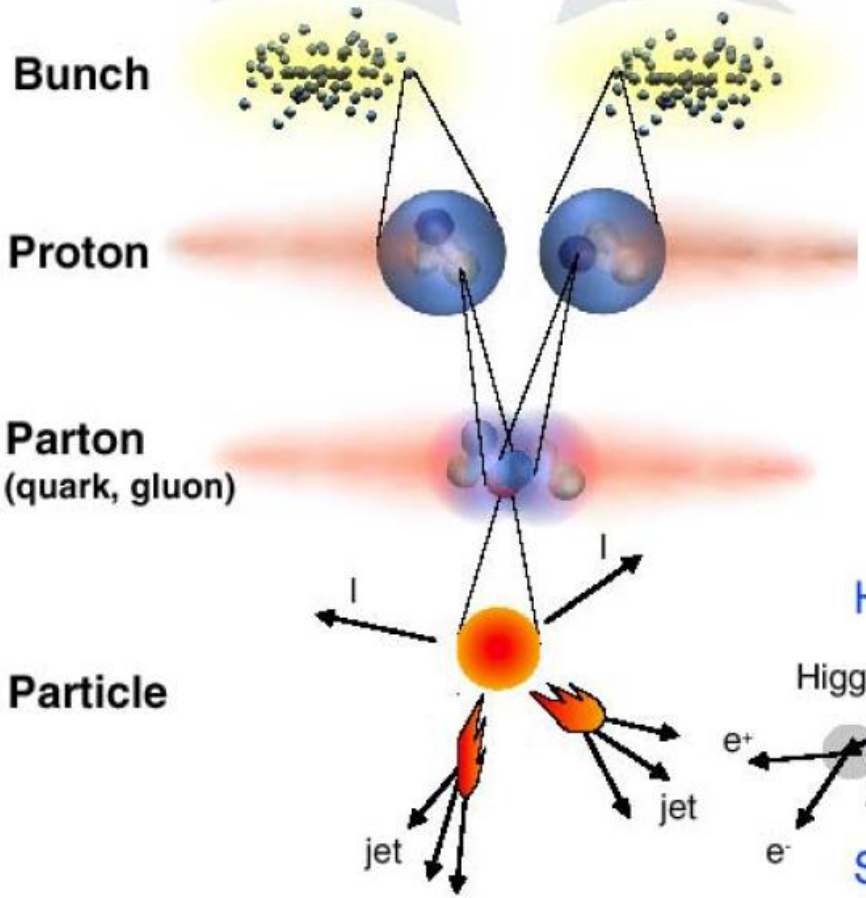


In the experiments:

10^9 pp interactions per second

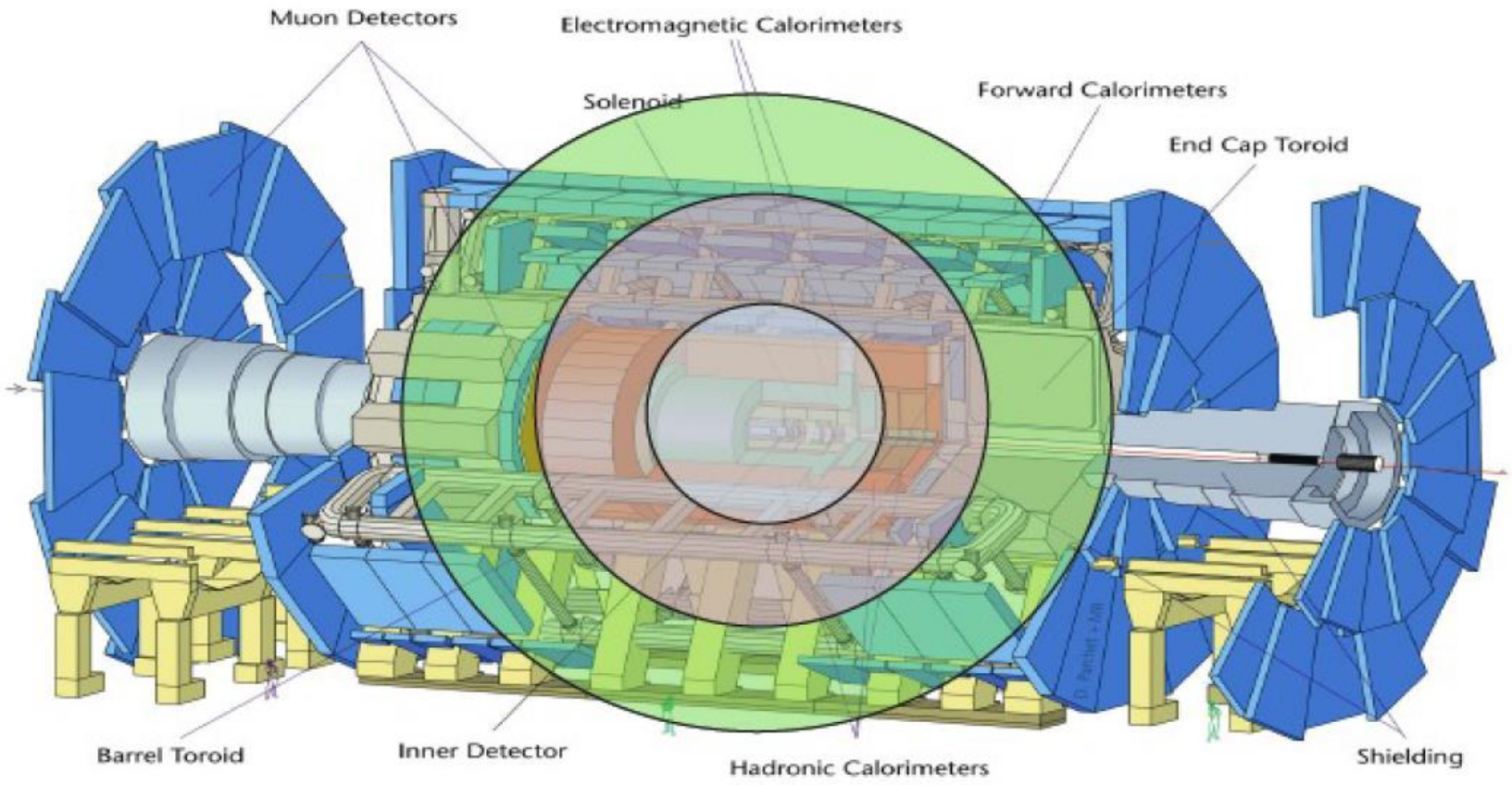
~ 1500 particles (p,n, π) produced in the detectors at each bunch-crossing

Selection of 1 in

10,000,000,000,000

- Interactions every 25 ns …
  - In 25 ns particles travel 7.5 m

c=30cm/ns; in 25ns, s=7.5m



: 7000 t

44 m

- Cable length ~100 meters …
  - In 25 ns signals travel 5 m

Jak w ciągu 1 sekundy wybrać 1 spośród 10^7 ?

Co to znaczy niewielka część?

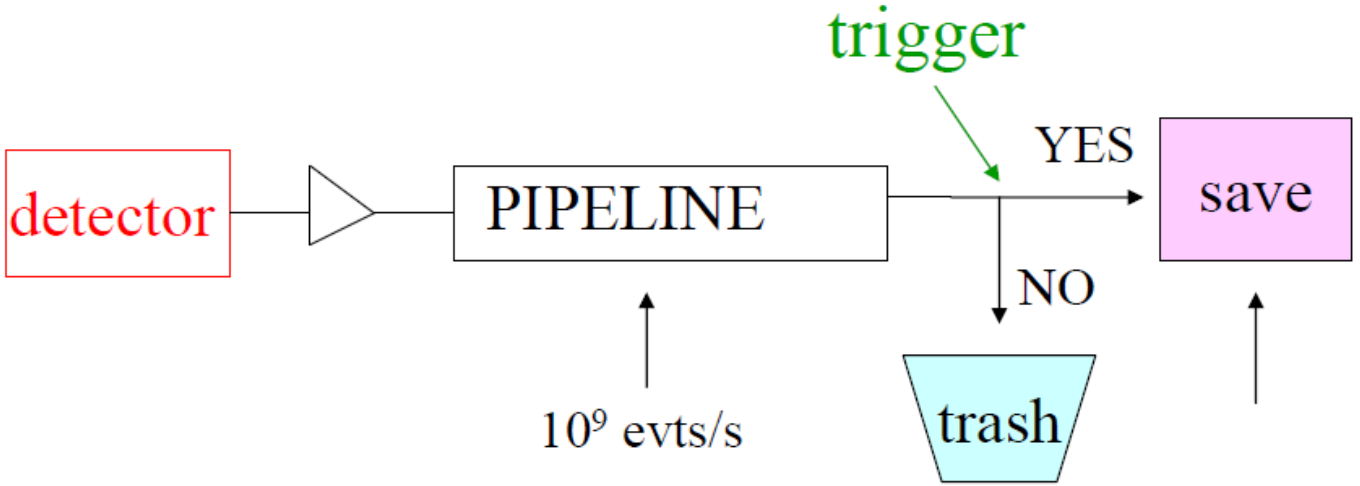
- 25ns $\Rightarrow$ 40 x 10^6/s zderzeń
- 23 oddział/zderzenie $\Rightarrow$ 23 x 40 x 106 /sek ~ 10^9 /sek oddział
- możemy zarejestrować tylko ~ 100/sek zderzeń $\Rightarrow$ **redukcja 10^7**

Ile informacji trzeba przetworzyć?

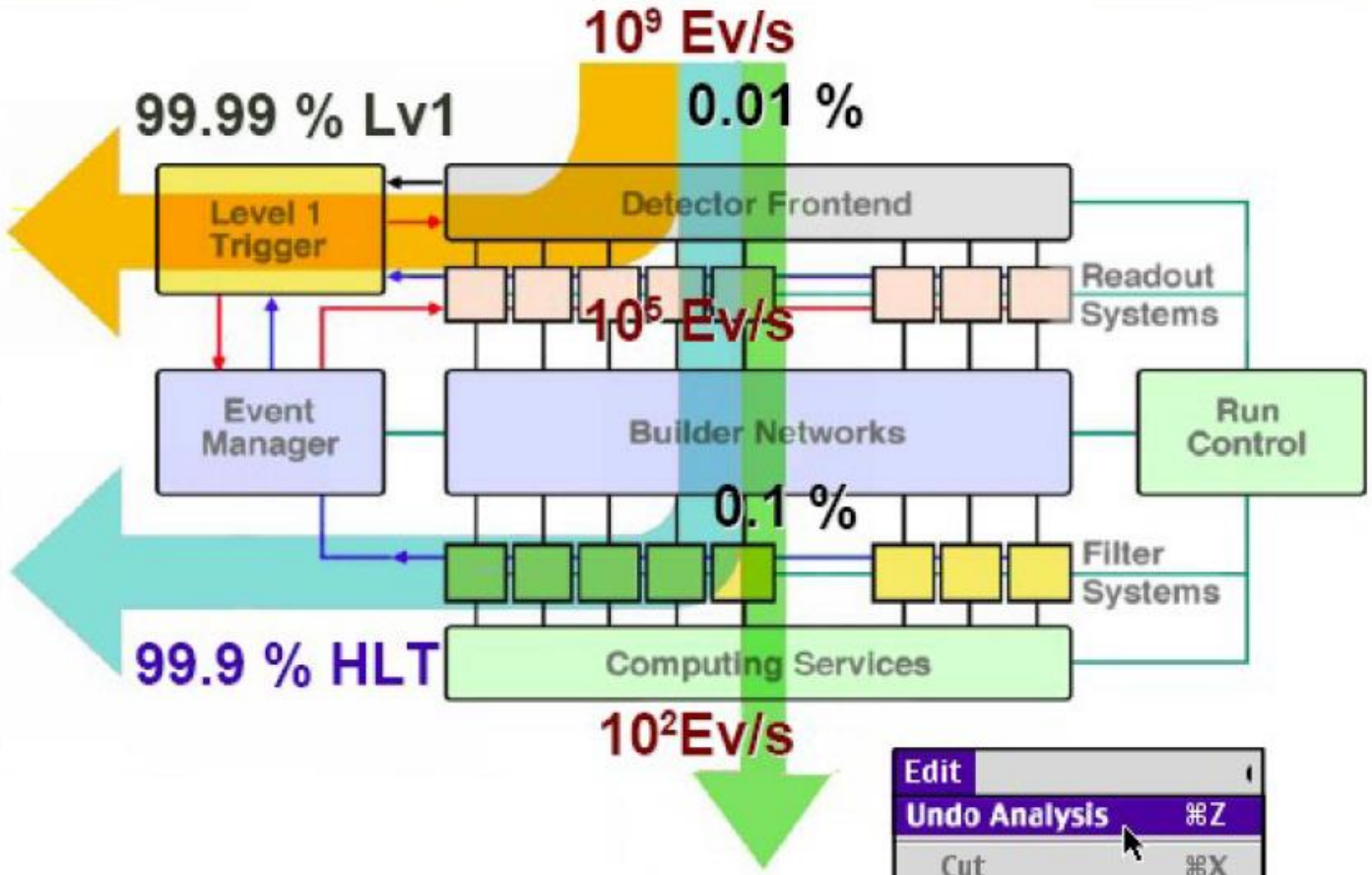
trigger elektron: 8bit x 40MHz x 7500 ~ 3 000 Gbit/sek

Czy można podjąć decyzje w 25ns?

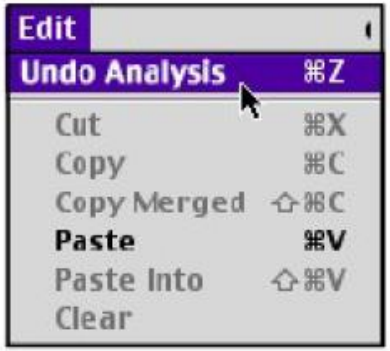
nie można: czas rejestracji w detektorze dłuższy (ok. 50 x 25ns)
informacje trzeba wysłać do procesora (ok. 15 x 25ns)
informacje trzeba przetworzyć (ok. 10 x 25ns)



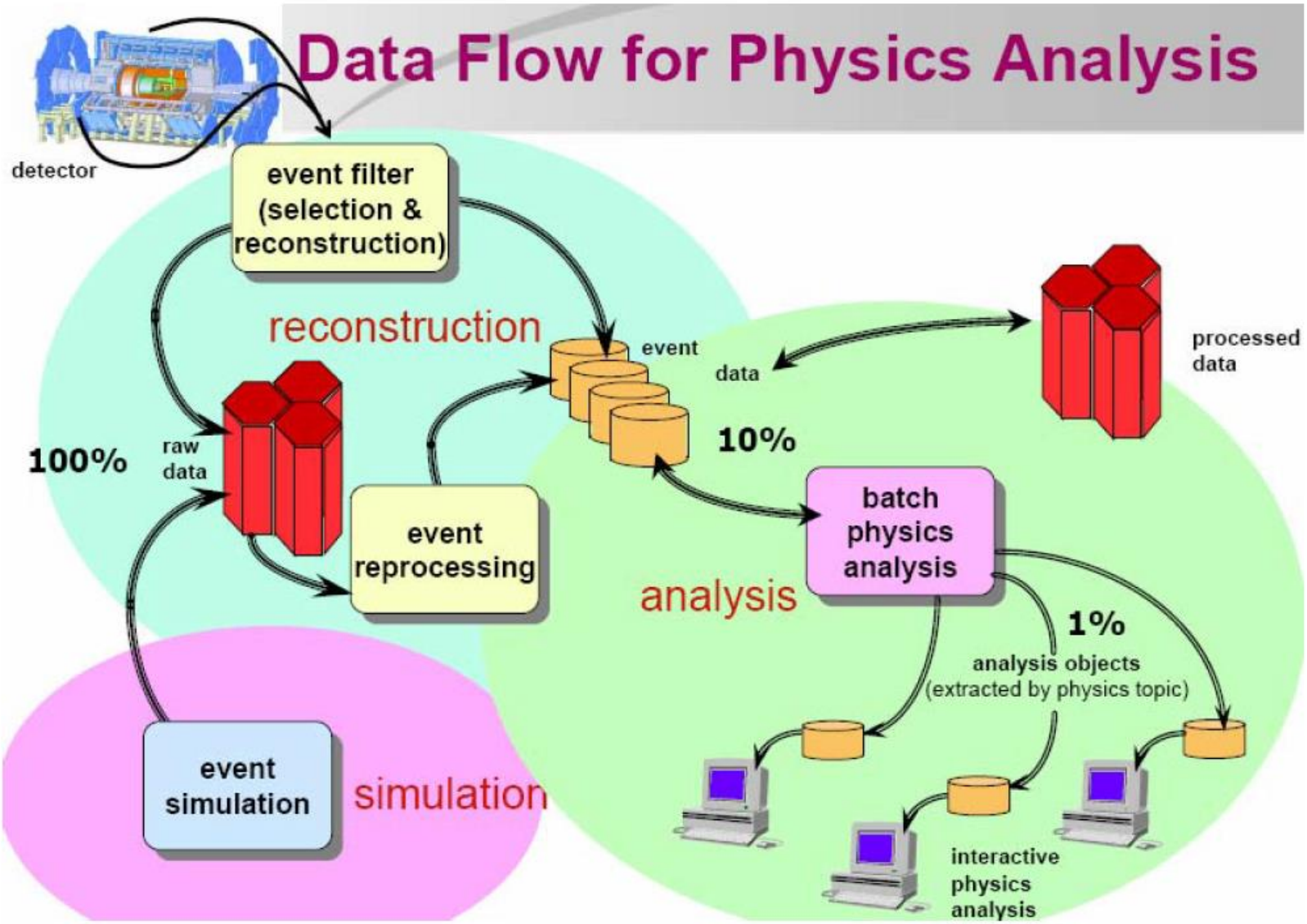
Trigger


10⁹ Ev/s
99.99 % Lv1
0.01 %
Level 1 Trigger
Detector Frontend
Readout Systems
10⁵ Ev/s
Event Manager
Builder Networks
Run Control
0.1 %
Filter Systems
99.9 % HLT
Computing Services
10²Ev/s


Edit
ayer Se
Can't Undo ⌘Z
Cut ⌘X
Copy ⌘C
Copy Merged ⇧⌘C
Paste ⌘V
Paste Into ⇧⌘V
Clear


Edit
Undo Analysis ⌘Z
Cut ⌘X
Copy ⌘C
Copy Merged ⇧⌘C
Paste ⌘V
Paste Into ⇧⌘V
Clear

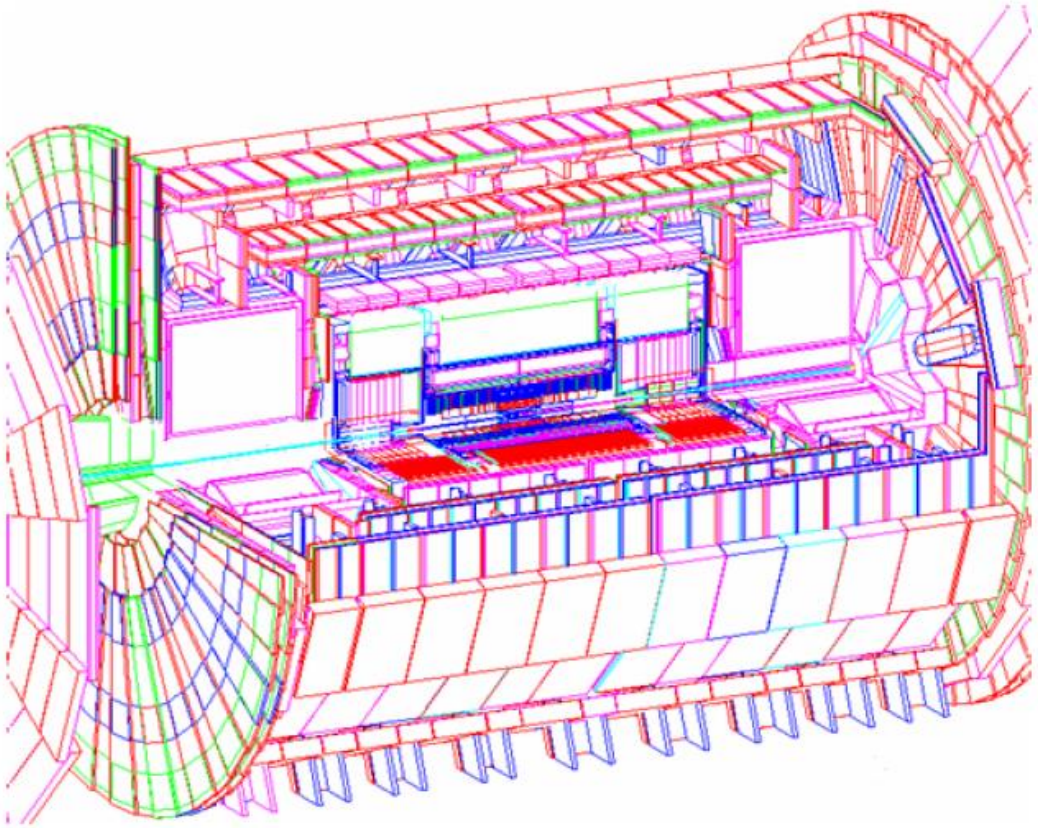
Data Flow for Physics Analysis



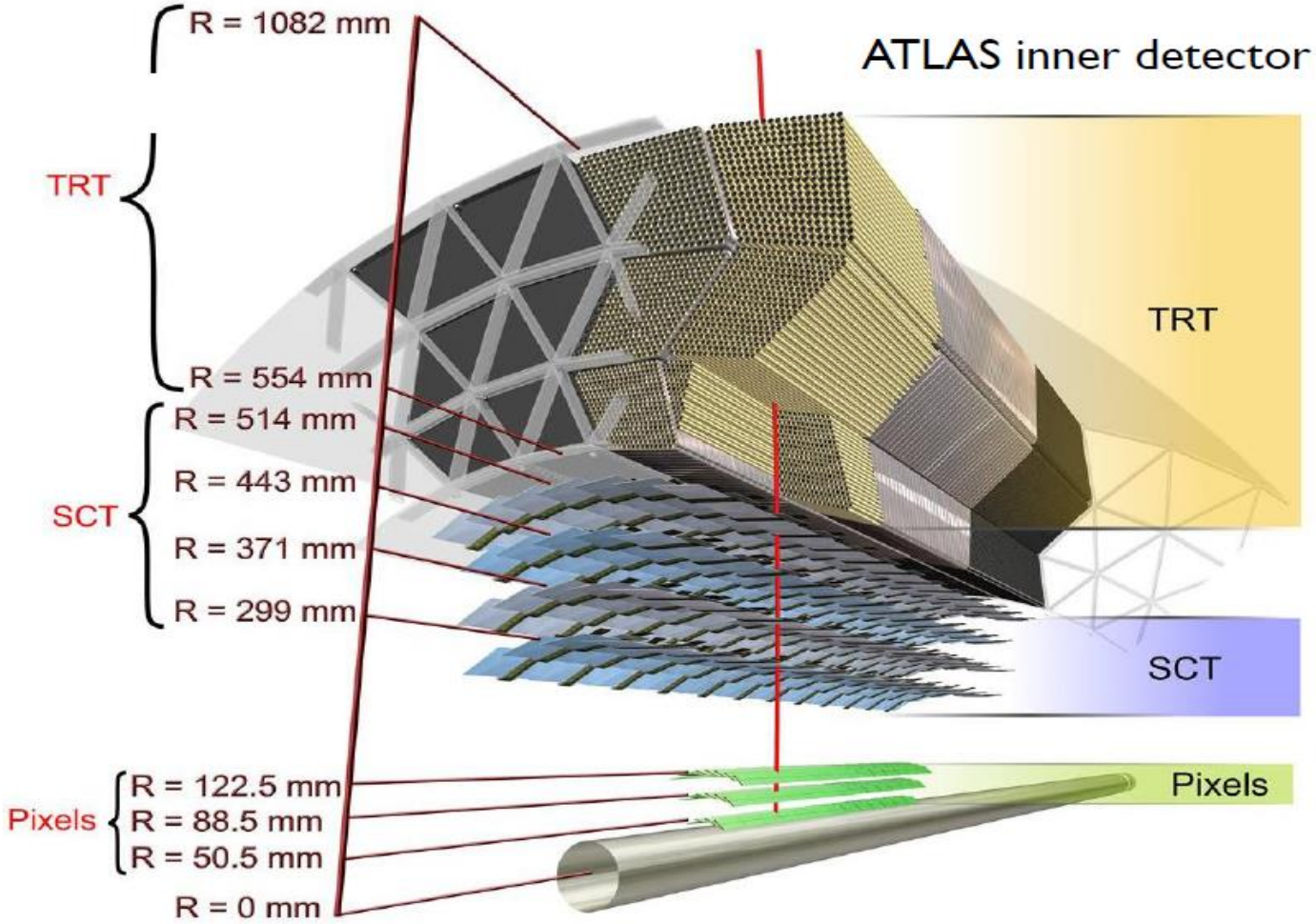
Model detektora
i symulacja oddziaływania cząstek z jego materiałem

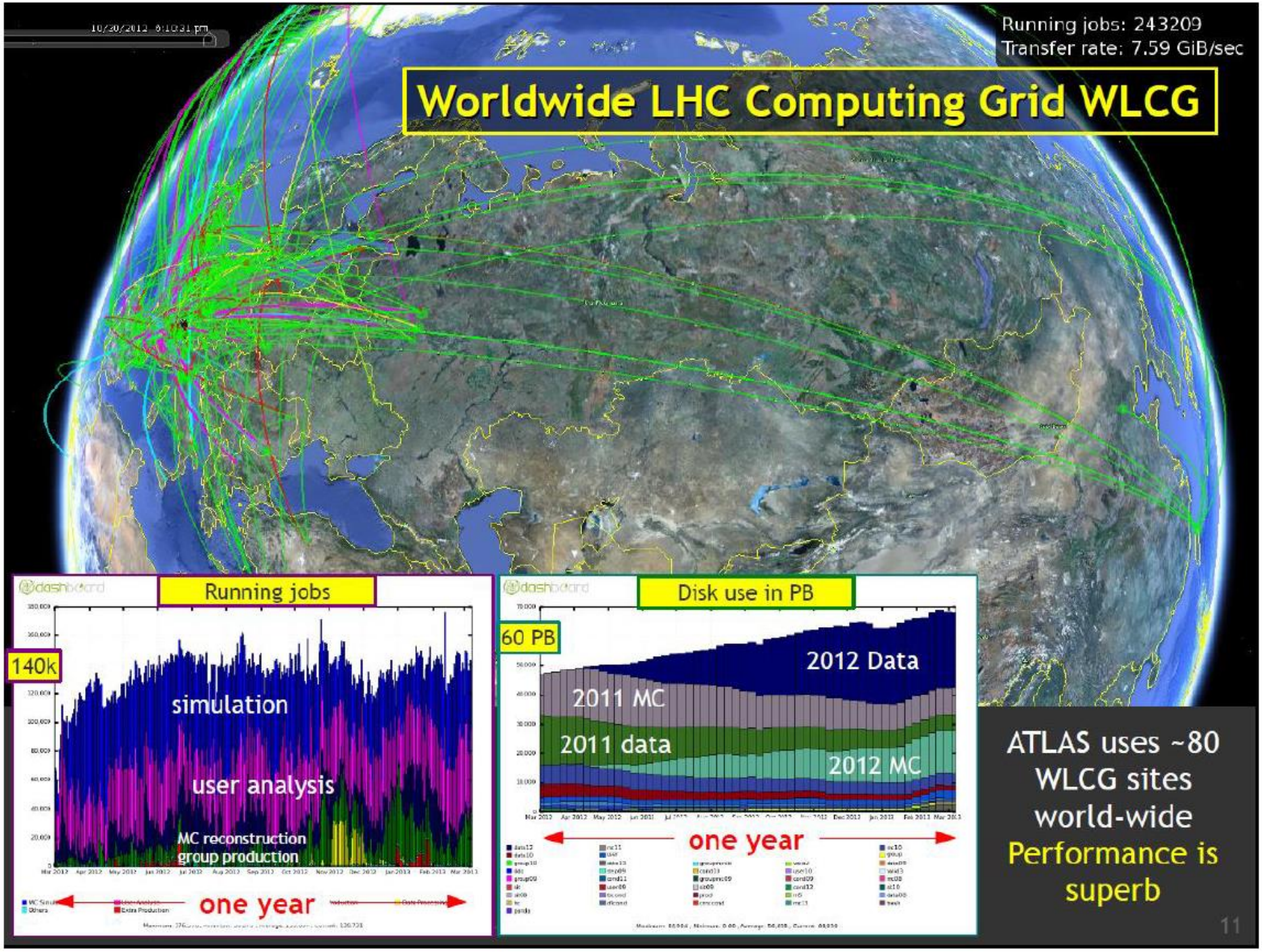
Jaka jest skala problemu?

- **25,5 millionów** oddzielnych elementów
- **23 000** różnych obiektów geometrycznych
- **4 673** różnych typów geometrycznych
- kontrolowanie nakładających się na siebie przypadków
- **1 000 000** sygnałów w detektorze na przypadek

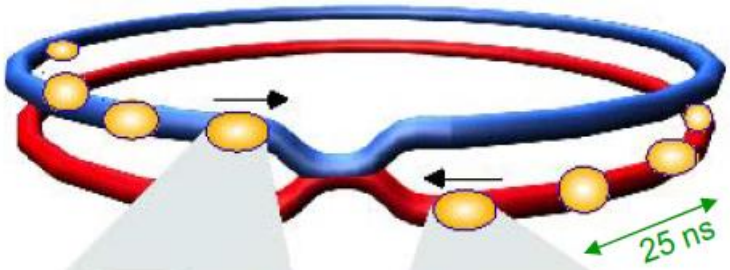


Model detektora




10/30/2012 8:10:31 pm
Running jobs: 243209
Transfer rate: 7.59 GiB/sec
Worldwide LHC Computing Grid WLCG
Running jobs
140k
simulation
user analysis
MC reconstruction
group production
one year
Disk use in PB
60 PB
2012 Data
2011 MC
2011 data
2012 MC
one year
ATLAS uses ~80 WLCG sites world-wide
Performance is superb

Collisions at LHC



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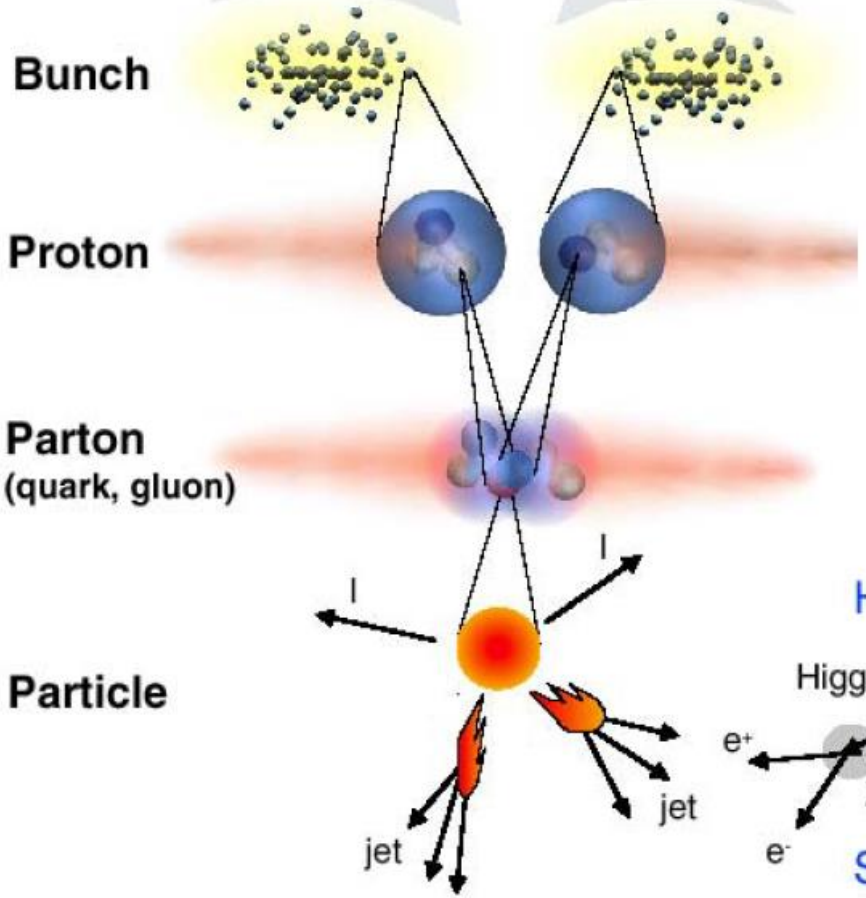

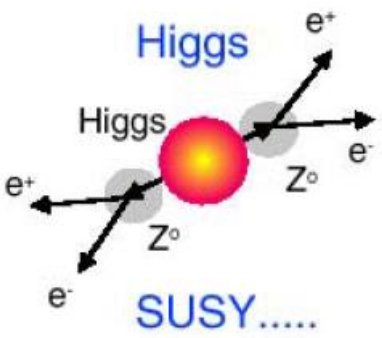

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10^9 pp interactions per second

~ 1500 particles (p,n, π) produced in the detectors at each bunch-crossing

Selection of 1 in

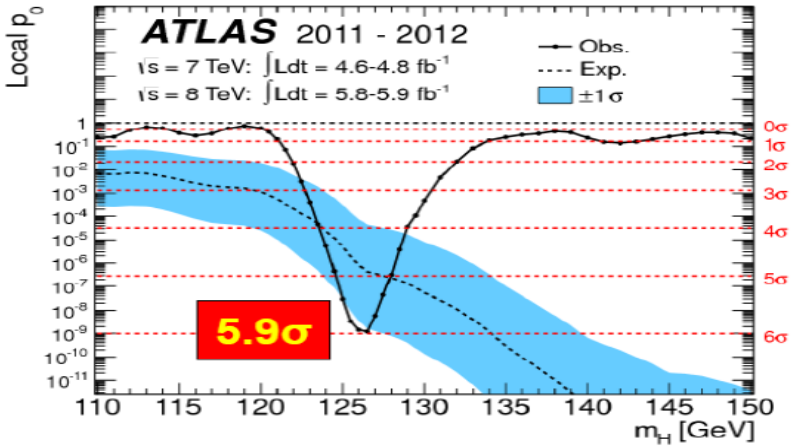
10,000,000,000,000

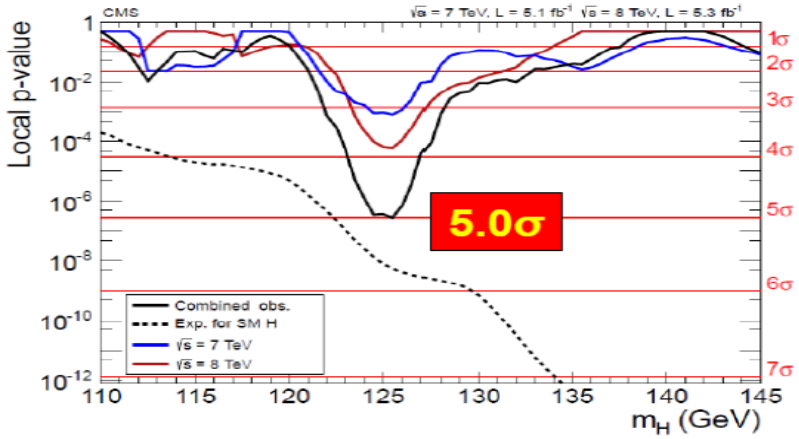
Higgs-like particle: 4-th July 2012

We are living a privileged moment in the history of HEP.

OUR FIRST FUNDAMENTAL SCALAR (?)

The discovery came at half of the design energy, much more several pile-up and one-third of integrated luminosity than was originally judged as necessary.





ATLAS PLB 716 (2012) 1-29, Sept 17 (2012)

Largest local excess:
5.9σ at m_H= 126.5 GeV

H→γγ, bb, ττ, WW(lνlν, lνqq), ZZ(4l, llνν, llqq)

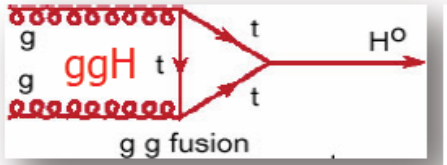
CMS PLB 716 (2012) 30-61, Sept 17 (2012)

Largest local excess:
5.0σ at m_H= 125.5 GeV

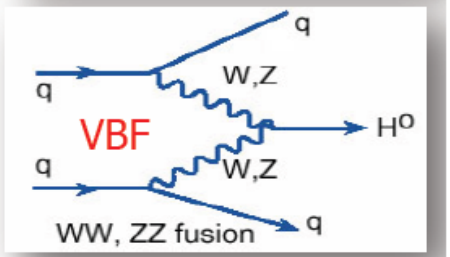
H→γγ, bb, ττ, WW(lνlν), ZZ(4l, llττ, llνν, llqq)

Production cross-section

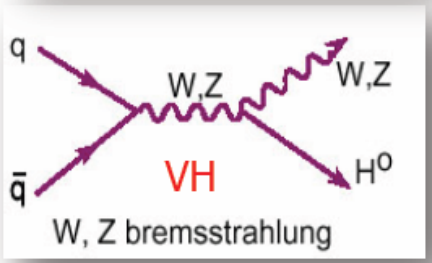
87%



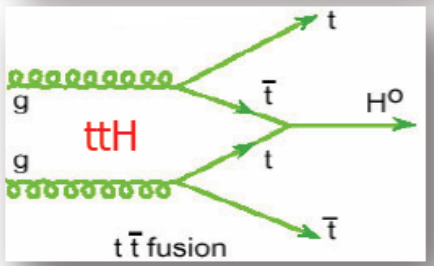
7.1%



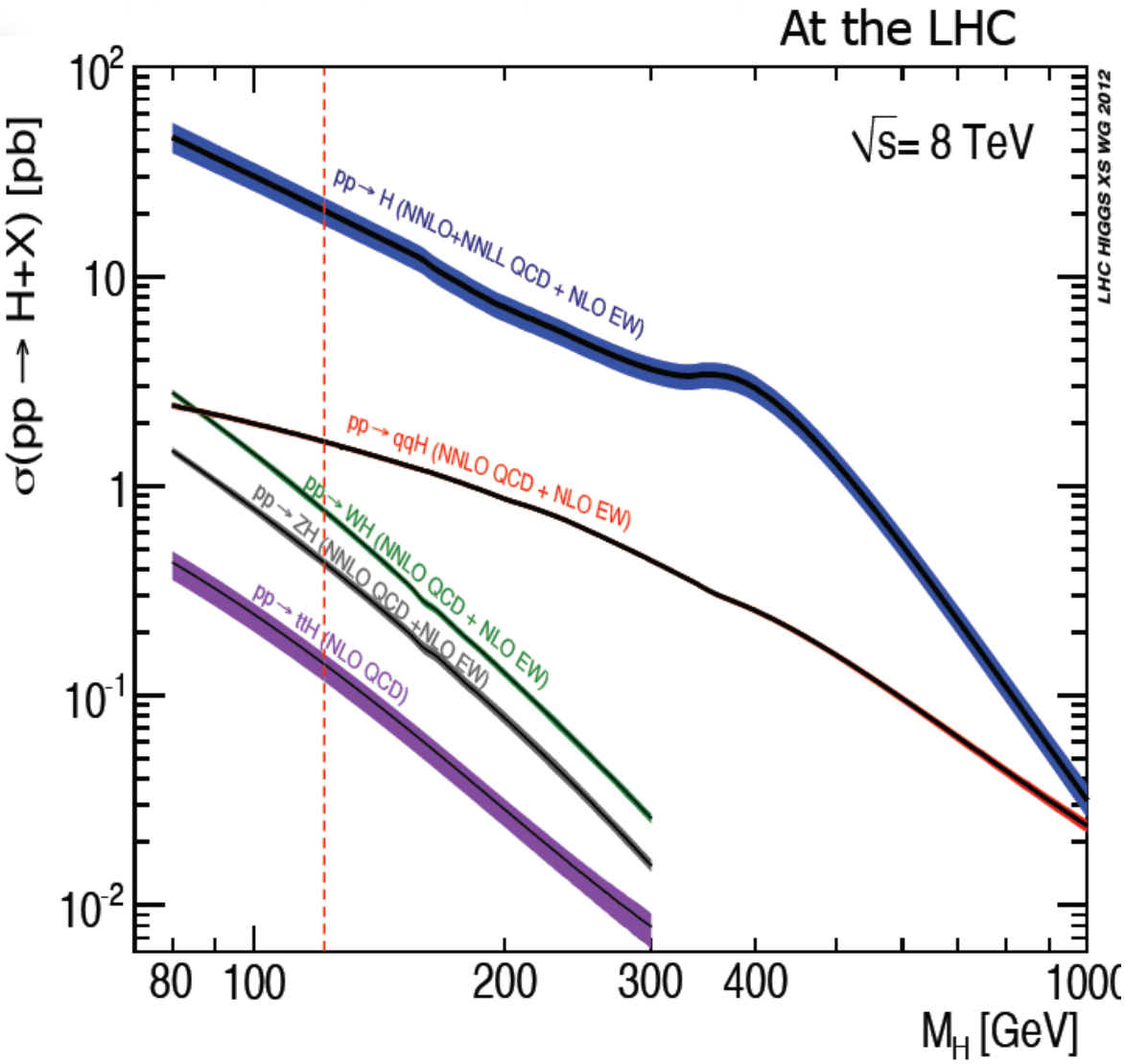
4.9%



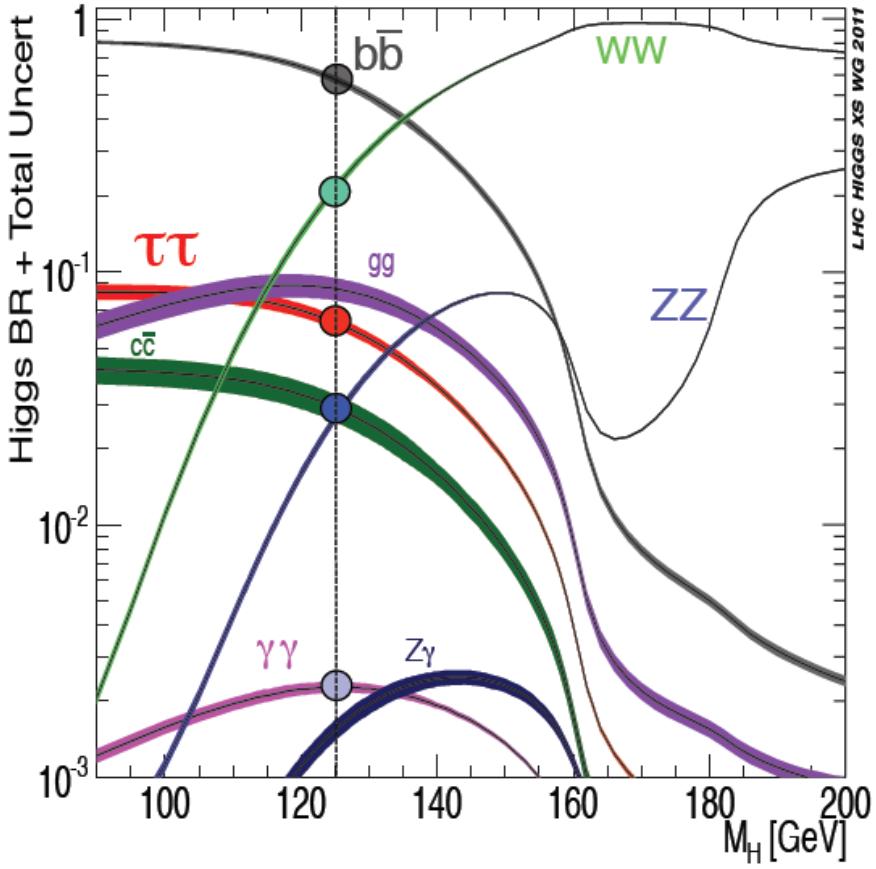
0.6%



σ/σ_{tot} (M_H = 125 GeV)



Decay channels



$\Delta M/M \sim 1\text{-}2\%$ High resolution

$H \to \gamma\gamma$ Rare, S/B < 1

$H \to ZZ^* \to 4\ell$ Very rare, S/B >> 1

$\Delta M/M \sim 10\text{-}20\%$ Medium resolution

$H \to bb$ Abundant, S/B << 1

$H \to \tau\tau$ Abundant, S/B < 1

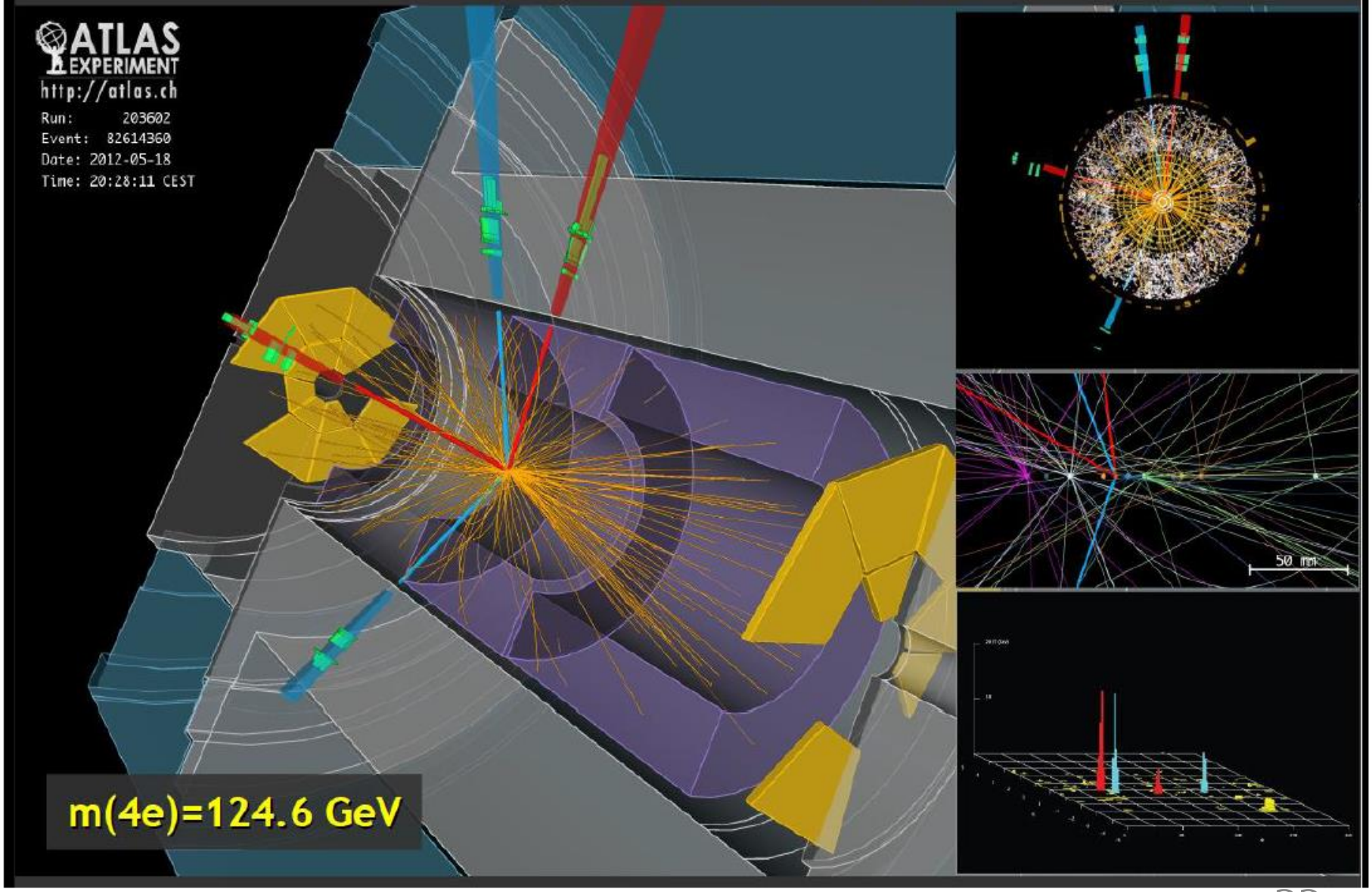
$\Delta M/M > 30\%$ Low resolution

$H \to WW^* \to 2\ell 2\nu$ Very abundant, S/B < 1

4 production modes × 5 decay modes ($\gamma\gamma$, ZZ, WW, $\tau\tau$, bb)

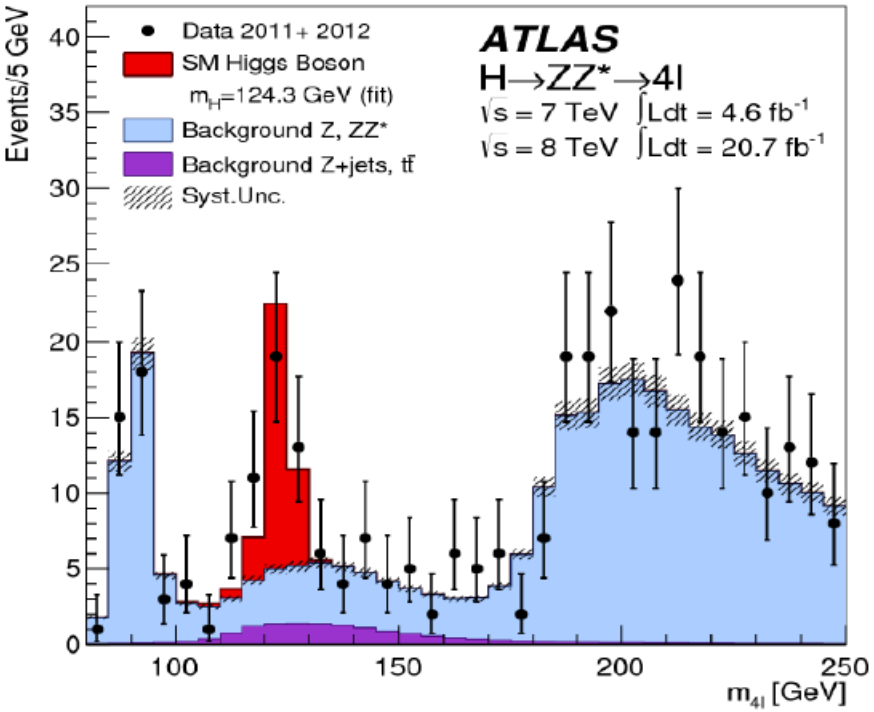
~ 100 exclusive final states (production, decay, event categories) are contributing for $M_H \sim 125$ GeV !

H → eeee candidate

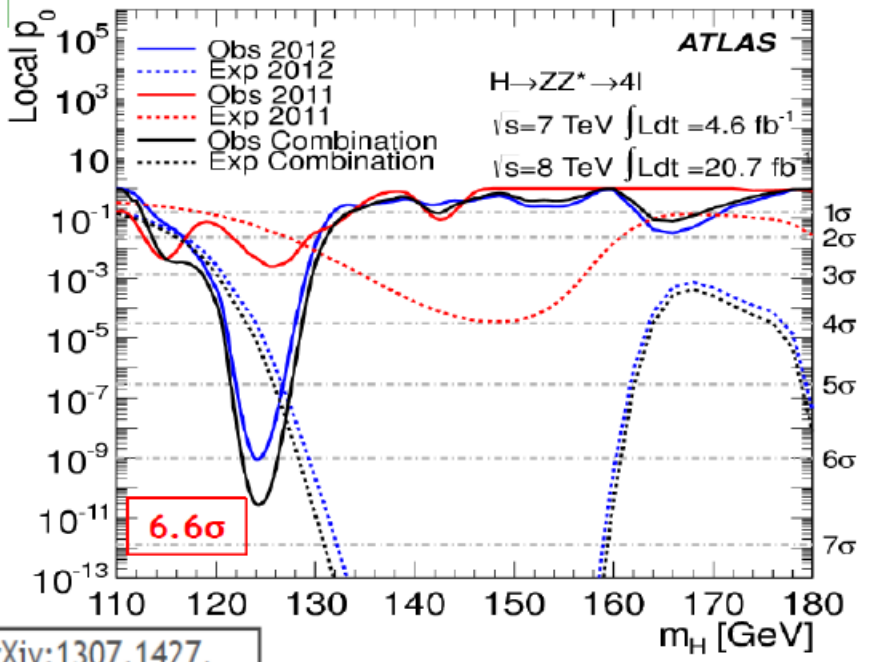


H->ZZ*->4l

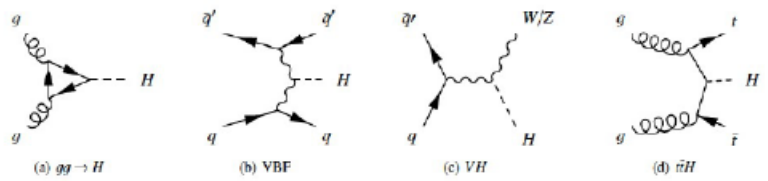
"Golden" channel, high S/B, excellent mass resolution, but low statistics



Signal significance 6.6σ, expected 4.4σ (SM)



arXiv:1307.1427, accepted by PLB

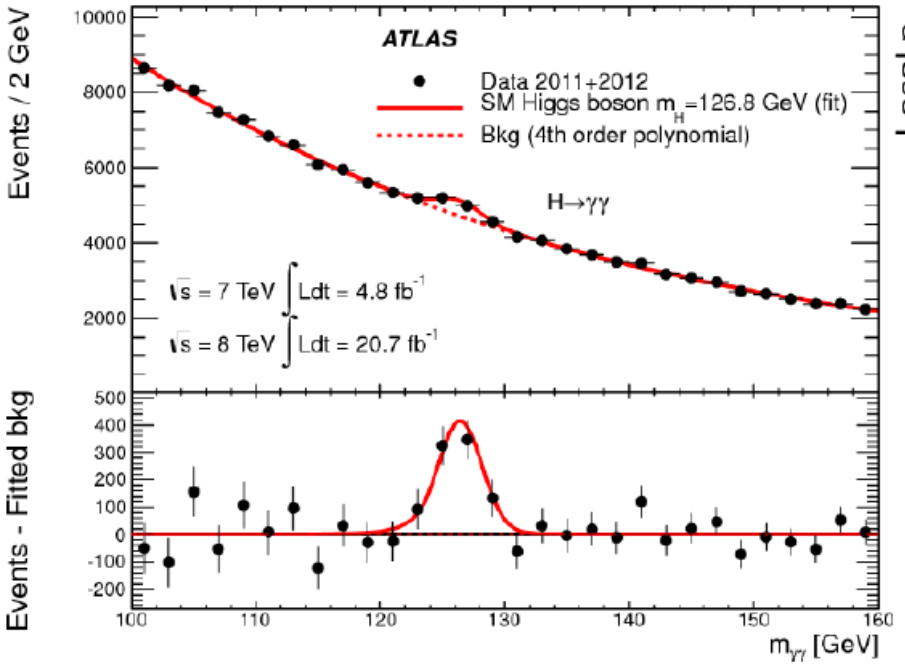


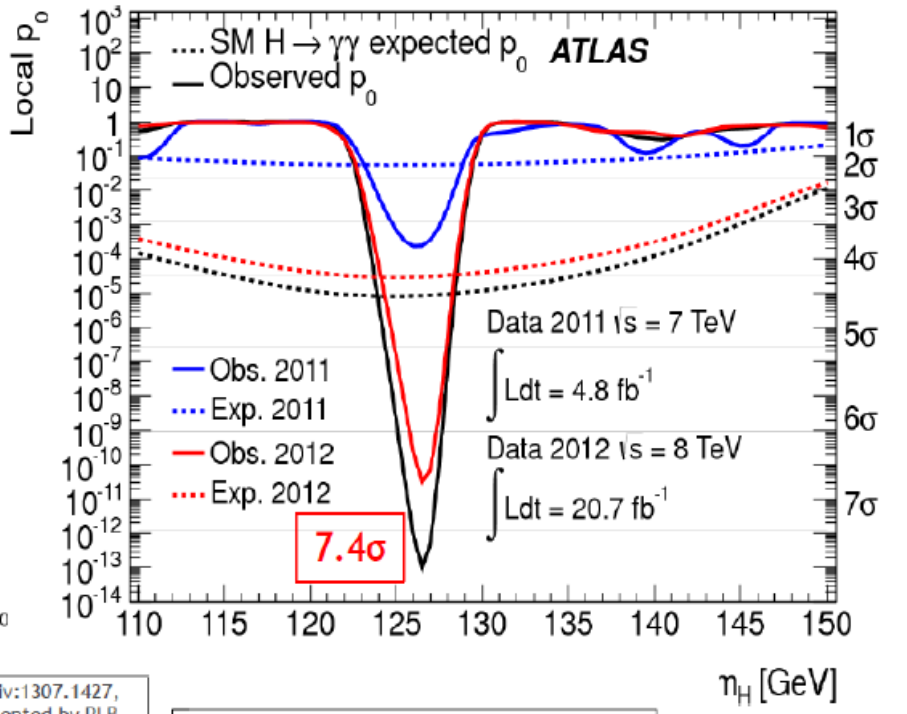
Again, categorisation of events to enhance VBF and VH sensitivity

H->γγ

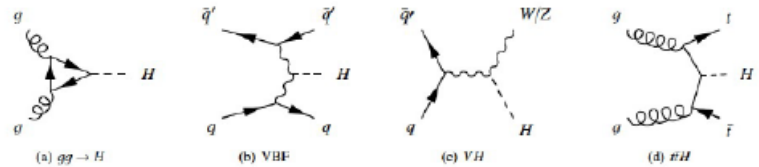
Excellent mass resolution (γ pointing in calorimeter), poor S/B

Signal significance 7.4σ, expected 4.3σ (SM)

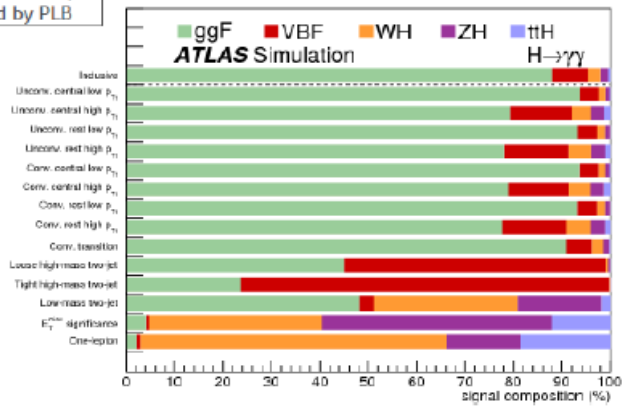




arXiv:1307.1427, accepted by PLB

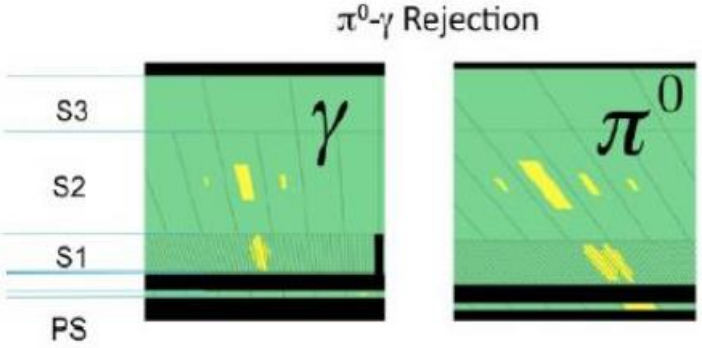


Subdivide into categories, including vector-boson fusion (VBF) and (W/Z)H (=VH) targeted selections



Shower shapes and vertex reconstruction

Photon ID 2 – Photon shower shapes and background rejection

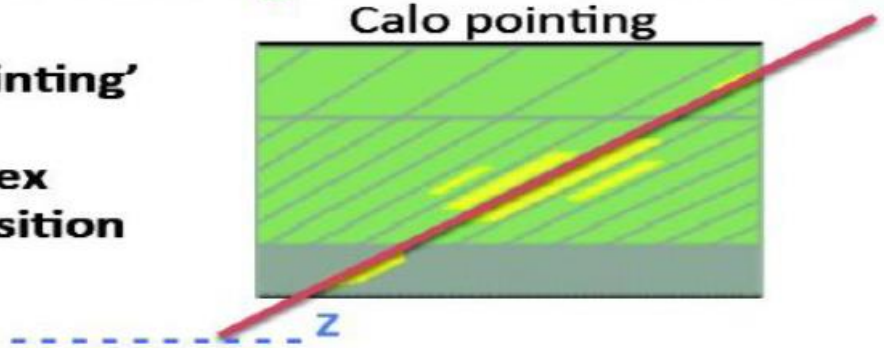


- Photons shower shape distributions in LAr sampling layers - different for signal and background (π^0)

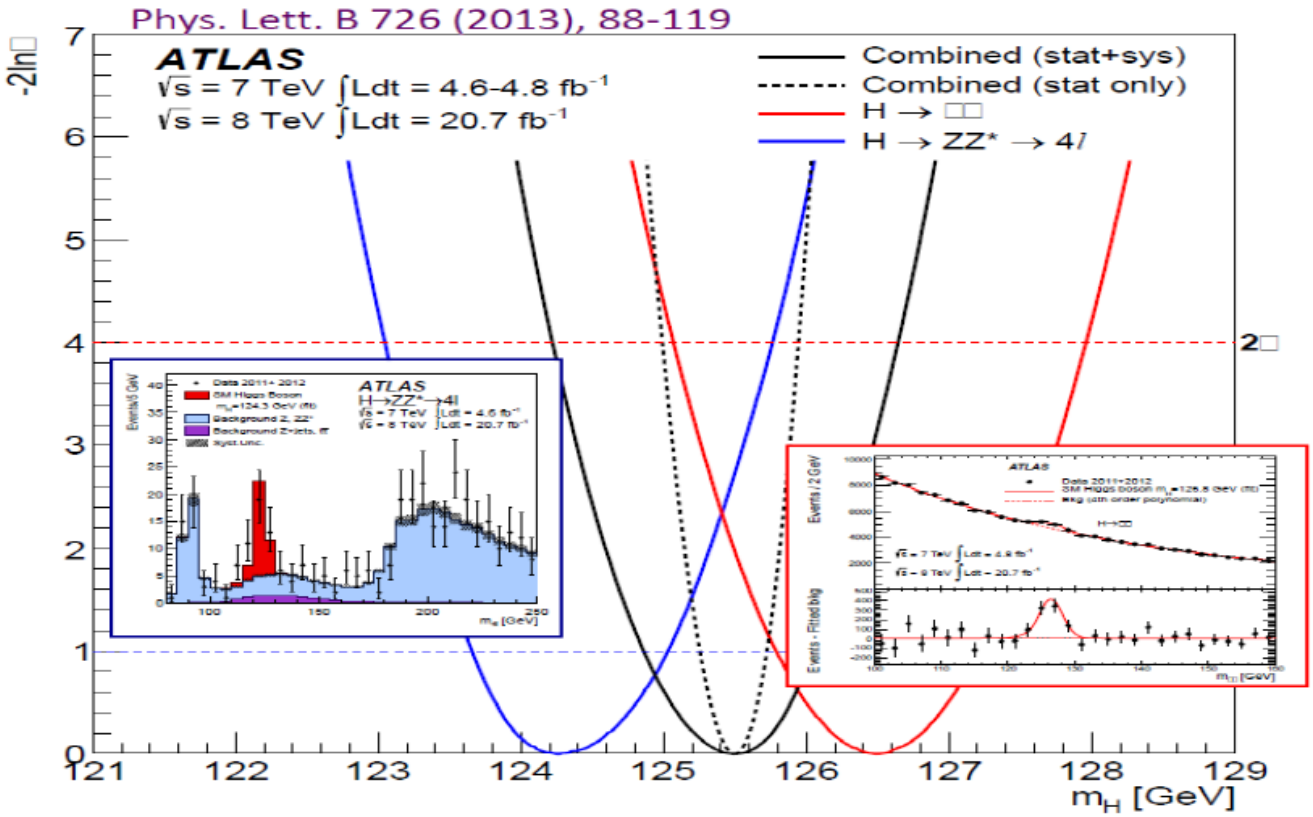
Vertex Reconstruction

$$m_{\gamma\gamma}^2 = 2 * E_1 E_2 (1 - \cos \alpha)$$

- Vertex reconstructed through likelihood combination
  - Calorimeter 'pointing'
  - Σ tracks pT^2
  - Conversion vertex
  - Mean vertex position



Mass measurement



4ℓ: $M_H = 124.3 \pm \mathbf{0.6}_{stat} \pm 0.4_{sys}$ GeV

$\gamma\gamma$: $M_H = 126.8 \pm 0.2_{stat} \pm \mathbf{0.7}_{sys}$ GeV

Combined: $M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{sys}$ GeV

Which Higgs boson we discovered

- Higgs boson was discovered in ZZ*, $\gamma\gamma$, and WW* decays
- Higgs boson mass is ~125.6 GeV
  - measured in $H \rightarrow ZZ^* \rightarrow 4l$, and $H \rightarrow \gamma\gamma$
  - ATLAS: $M_H = 125.5 \pm 0.2\ (stat) \pm 0.6\ (syst)$ GeV
  - CMS: $M_H = 125.7 \pm 0.3\ (stat) \pm 0.3\ (syst)$ GeV
- ATLAS and CMS data strongly favor $J^P = 0^+$ SM quantum numbers
  - All alternative J^P models tried are excluded at >95%CL
- Signal strength $\mu = \sigma/\sigma_{SM}$ and all couplings are consistent with 1
  - ATLAS: $\mu = 1.33 \pm 0.20$
  - CMS: $\mu = 0.80 \pm 0.14$
  - Tevatron: $\mu = 1.44 \pm 0.60$
- >3σ evidence for V-boson mediated (VBF) production
- **All measured properties are compatible with SM Higgs hypothesis**

What do we want to measure?

$$\mathcal{L}_{EW}^{SM} = -\frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu} - -\frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$+\bar{L}\gamma^\mu \left(i\partial_\mu - \frac{1}{2} g \tau_a W^a_\mu - \frac{1}{2} g' Y B_\mu \right) L$$

$$+\bar{R}\gamma^\mu \left(i\partial_\mu - -\frac{1}{2} g' Y B_\mu \right) R$$

$$- \left| \left(i\partial_\mu - \frac{1}{2} g \tau_a W^a_\mu - \frac{1}{2} g' Y B_\mu \right) \Phi \right|^2$$

$$+\mu^2 |\Phi|^2 - \lambda |\Phi|^4$$

$$-(\sqrt{2}\lambda_d \bar{L}\Phi R + \sqrt{2}\lambda_u \bar{L}\Phi_c R + h.c.)$$

+ L_{BSM} (eventually)

a) Discriminate models with extended Higgs sectors from SM Higgs sector?

b) Determine remaining (effective) parameters in SM Lagrangian (Higgs couplings and quartic gauge boson couplings) ?

Zapraszam w czwartek, 8.05, na konwersatorium PTF

Collecting few numbers …..

Number of turns of the LHC ring made by protons in one second: ~ 11000

Number of proton-proton interactions per second : 1 billion

Number of particles produced per collision : more than 1000

Machine temperature : 1.9 K (the largest cryogenic system in the world)

Weight of CMS experiment: ~ 13000 tons (30% more than the Tour Eiffel)

Amount of cables used to transfer the detector signals in ATLAS : ~ 3000 km

Data recorded by experiments in 1 year: 20 km of CD

Number of involved physicists : > 4000 (from the 5 continents !)

Total cost (accelerator plus experiments) : ~ 5000 MCHF

The most ambitious project in particle physics ever and one of the most ambitious in science in general