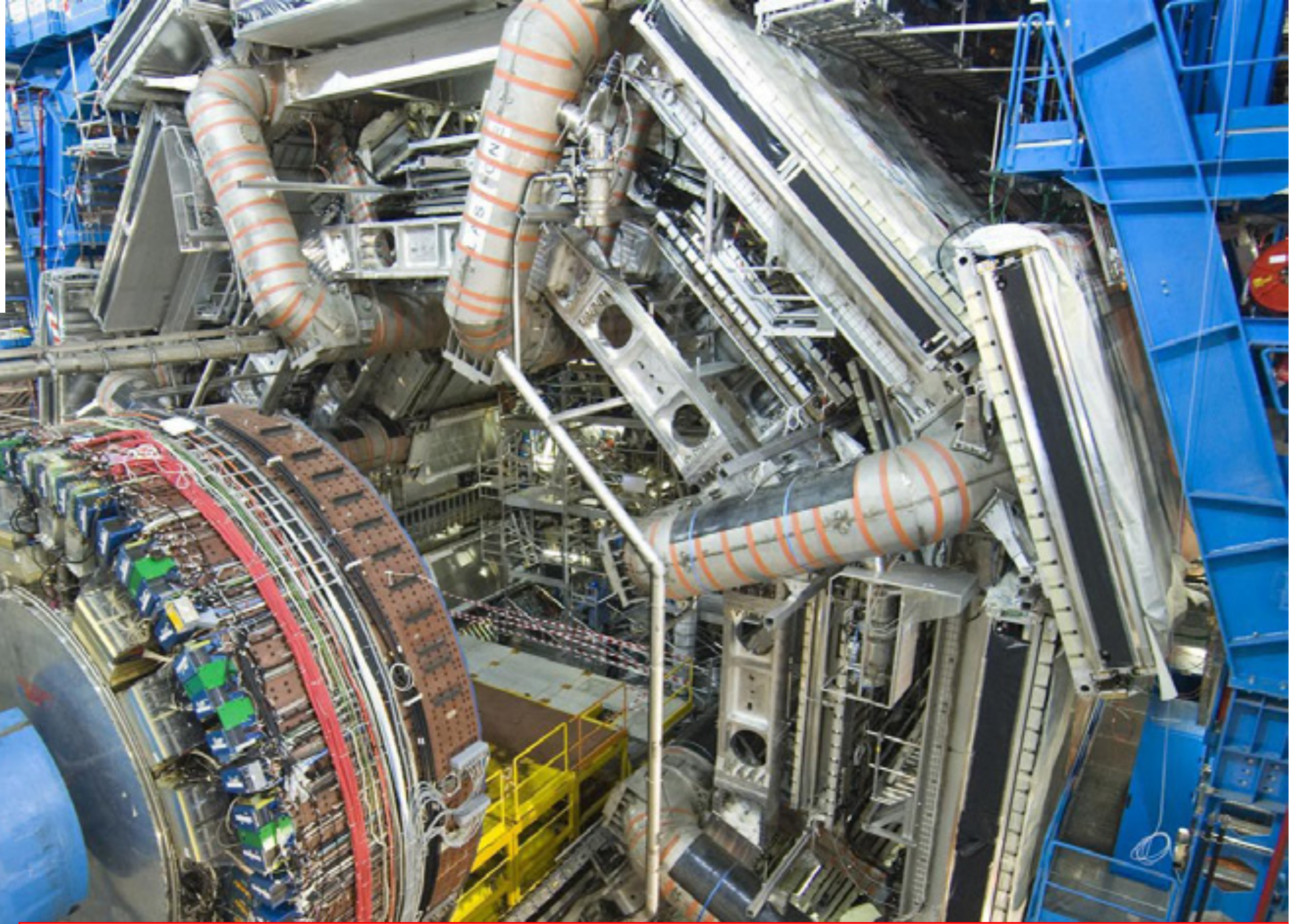

<u>*Particle physics at CERN and the LHC*</u>*:*
a historical perspective and a pedagogical view on how this is done. The role of theory and experiment.

D. Froidevaux (CERN)

Experimental particle physics: 40 years from 1976 to 2016

♥ I believe we are often at least partially shaped by circumstance in our major choices when growing from childhood to adulthood. From 1971 to 1976, I moved from mathematics, to theoretical physics, to finally experimental particle physics

♥ The French often say "un expérimentateur = un théoricien raté"

♥ I also was attracted to astrophysics but at the time it looked a lot like zoology, i.e. extending the catalogue of observations without an underlying predictive theory of the evolution of the universe

♥ Initially and naively, I believed fundamental research meant regular major advances in our understanding of the laws of nature

♥ With experience (and listening to the Nobel lecture by D. Gross in 2004), I slowly realised that the years 1976 to 2010 have brought our understanding of fundamental physics a few small but also very important steps forward on a staircase which is most likely without end and uncovers itself to our eyes and brains only gradually

Outstanding Questions in Particle Physics *circa* 2011

Quarks and leptons:
- why 3 families ?
- masses and mixing
- *CP* violation in the lepton sector
- matter and antimatter asymmetry
- baryon and charged lepton number violation

EWSB
- Does the Higgs boson exist?

Physics at the highest E-scales:
- how is gravity connected with the other forces ?
- do forces unify at high energy ?

Dark matter:
- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- one type or more ?
- only gravitational or other interactions ?

Neutrinos:
- ν masses and and their origin
- what is the role of $H(125)$?
- Majorana or Dirac ?
- *CP* violation
- additional species → sterile ν ?

The two epochs of Universe's accelerated expansion:
- primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is Λ so small?) or gravity modification ?

Outstanding Questions in Particle Physics *circa* 2016

... there has never been a better time to be a particle physicist!

Higgs boson and EWSB
- ❑ m_H natural or fine-tuned ?
  → if natural: what new physics/symmetry?
- ❑ does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate CP ?
- ❑ cosmological EW phase transition

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
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The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ?
  which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

This is a golden time to do particle/astroparticle physics!!

«Αποσκοτησών με».

Στα νέα ελληνικά: «Βγάλε με από το σκοτάδι», μεταφορικά μιλώντας.

(Διογένης, (410-323) προ Χριστού).

«Get me out of the obscurity »

«Ουδέν άλλο έχουσα ες Άδου η ψυχή έρχεται πλην της παιδείας και τροφής»

Στα νέα ελληνικά : «Η ψυχή έρχεται στον Άδη χωρίς να κουβαλάει τίποτε άλλο πέρα από την παιδεία και την αγωγή της».

(Πλάτωνας 427-347 προ Χριστού)

«Our soul reaches death wearing only its education and life experience».

«Όπου της αιτίας απολείπει ο λόγος, εκείθεν άρχεται το απορείν»,

(Πλούταρχος)

Στα νέα ελληνικά : «Όπου απουσιάζει η λογική από την αιτία, από εκεί αρχίζει η απορία».

«The questioning begins where logic is absent from the cause».

This is a golden time to do particle/astroparticle physics!!

I hope to convince you that fundamental research is exciting!

Αρχάς είναι των όλων ατόμους και κενόν, τα δ' άλλα πάντα νενομίσθαι.

Δημόκριτος, 470-370 π.Χ., Αρχαίος Έλληνας φιλόσοφος

μτφρ: τα άτομα και το κενό είναι η αρχή των πάντων και τα υπόλοιπα είναι κατασκευάσματα του νου

«The atoms and the vacuum are the beginning of everything, the remainder is just a figment of the spirit».

Η επιστήμη και η τέχνη ανήκουν σε όλο τον κόσμο, και μπροστά τους εξαφανίζονται όλα τα σύνορα.

Βόλφγκανγκ Γκαίτε, 1749-1832, Γερμανός ποιητής & φιλόσοφος

«Science and art belong to all, and facing them all boundaries are wiped out».

This is a golden time to do particle/astroparticle physics!!

But we must remain humble and explain our goals to all!

Η επιστήμη μας έκανε θεούς πριν να γίνουμε άξιοι να είμαστε άνθρωποι.

Jean Rostand, 1894-1977, Γάλλος επιστήμονας & φιλόσοφος

«Science makes us gods before we deserve to be called human beings».

Χωρίς αμφιβολία, οι θεμελιωτές της σύγχρονης επιστήμης υπήρξαν κατά κανόνα άνθρωποι που η αγάπη τους για την αλήθεια υπερέβαινε την αγάπη τους για την εξουσία.

C.S. Lewis, 1898-1963, Ιρλανδός συγγραφέας

«Undoubtedly, the founders of today's science were people whose love for truth superseded their love for power».

Δεν υπάρχει εθνική επιστήμη ακριβώς όπως δεν υπάρχει εθνικός πίνακας πολλαπλασιασμού. Ό,τι είναι εθνικό δεν είναι επιστήμη.

Άντον Τσέχωφ, 1860-1904, Ρώσος συγγραφέας

«There is no such thing as national science, in the same way as there are no national multiplication tables. Any thing national in nature is not science».

Huge success of Standard Model in particle physics:

Predictions in agreement with measurements to 0.1%

Magnetic moment of electron:

agreement to 11 significant digits between theory and experiment!

Discovery of W, Z, top quark, ν_τ After prediction by theory!

Still incompatible today from a theoretical viewpoint

Main success of general relativity:

Predictions in agreement with measurements to 0.1%

Endless loop of experimental physicist: measure, simulate, talk to theorists …

Observations (measurements: build detectors)

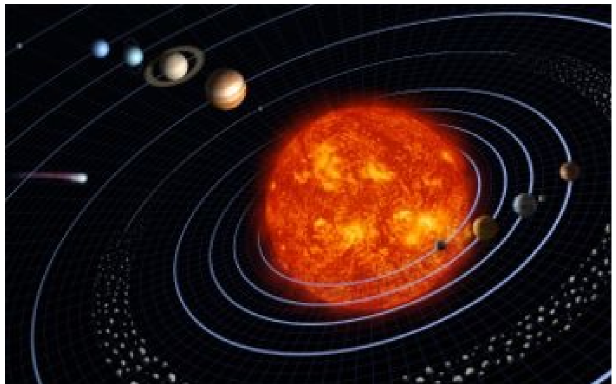
- An apple falls from a tree
- There are four forces + matter particles

Models (simulations)

- $P=GmM/R^2$
- Standard Model

Predictions (theories, ideas)

- Position of planets in the sky
- Higgs boson, supersymmetric particles

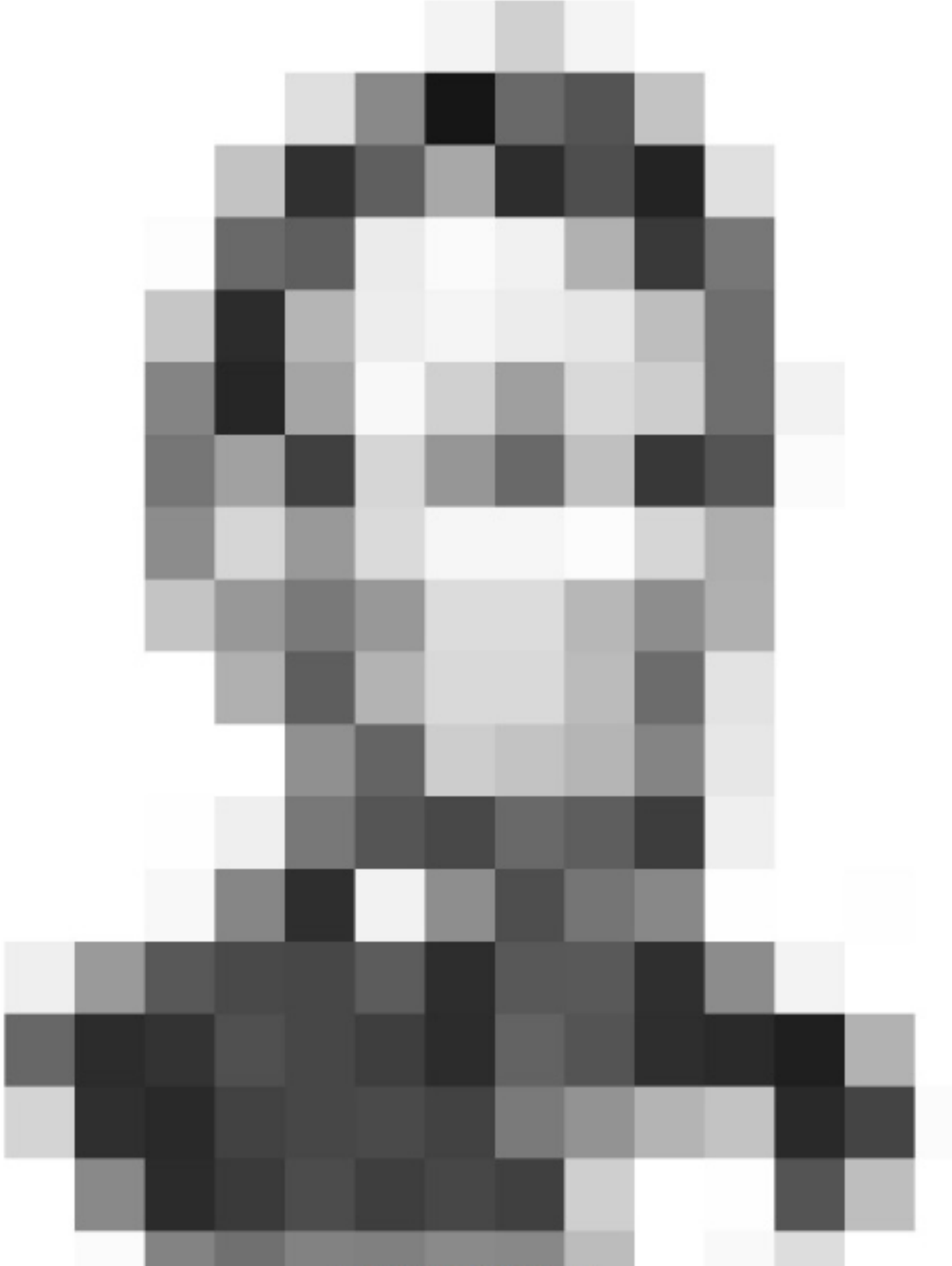


Perception & understanding *with a roadmap*

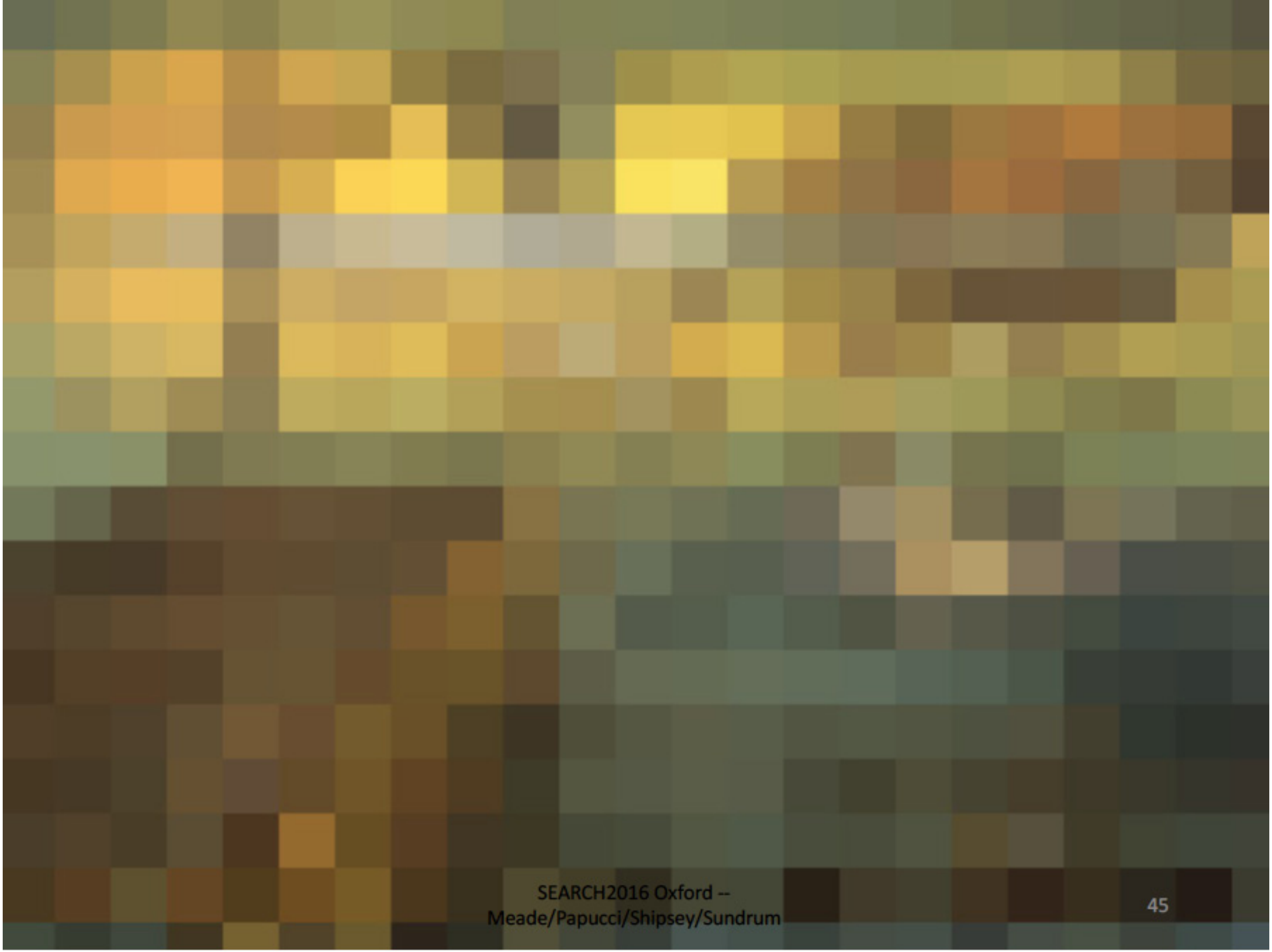
Perception is a dynamic combination of top-down (theory) and bottom-up (data driven) processing

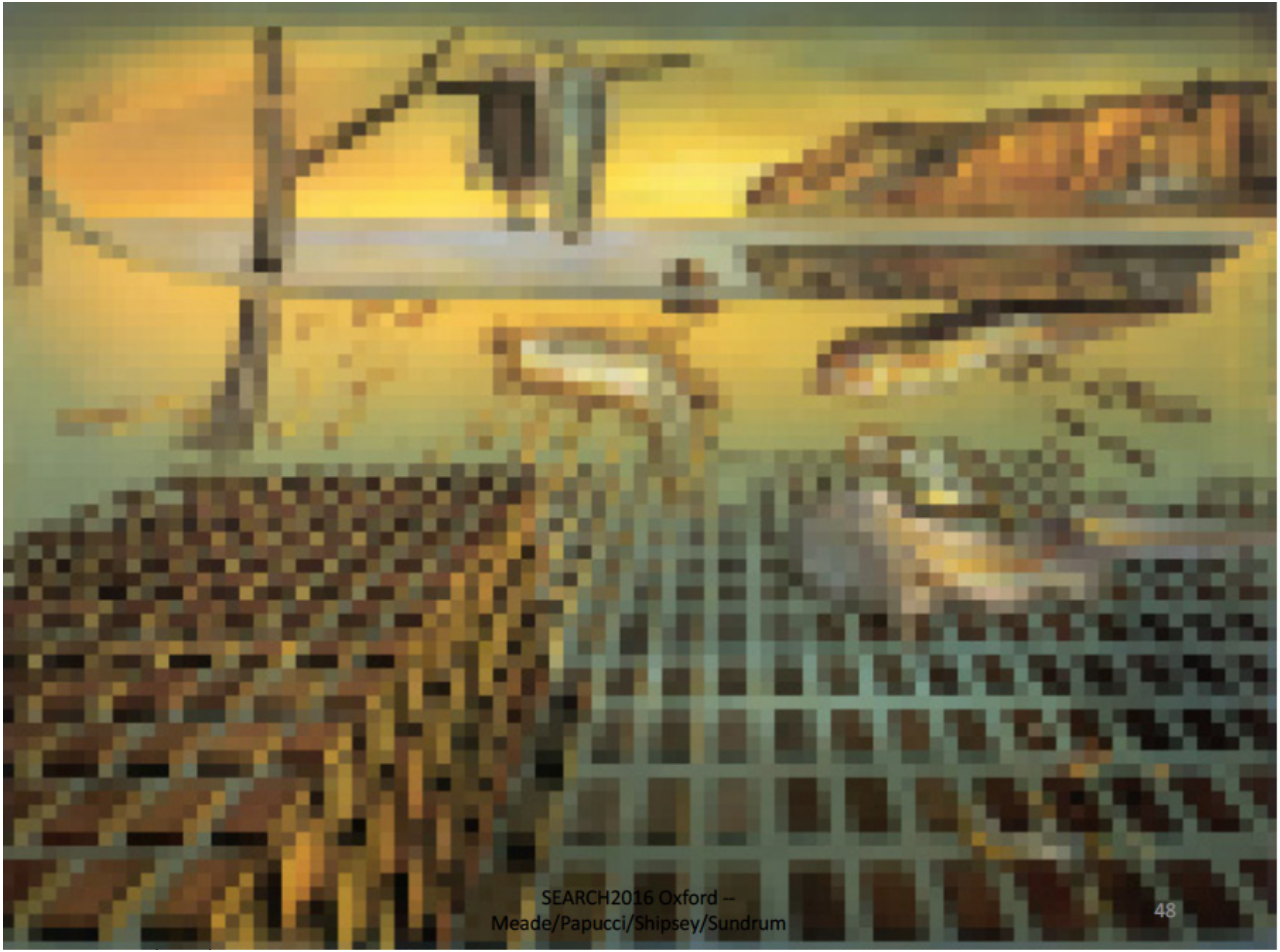
- The need for detail (quality and quantity of the data) depends on the *distinctiveness* of the object and the *level of familiarity*

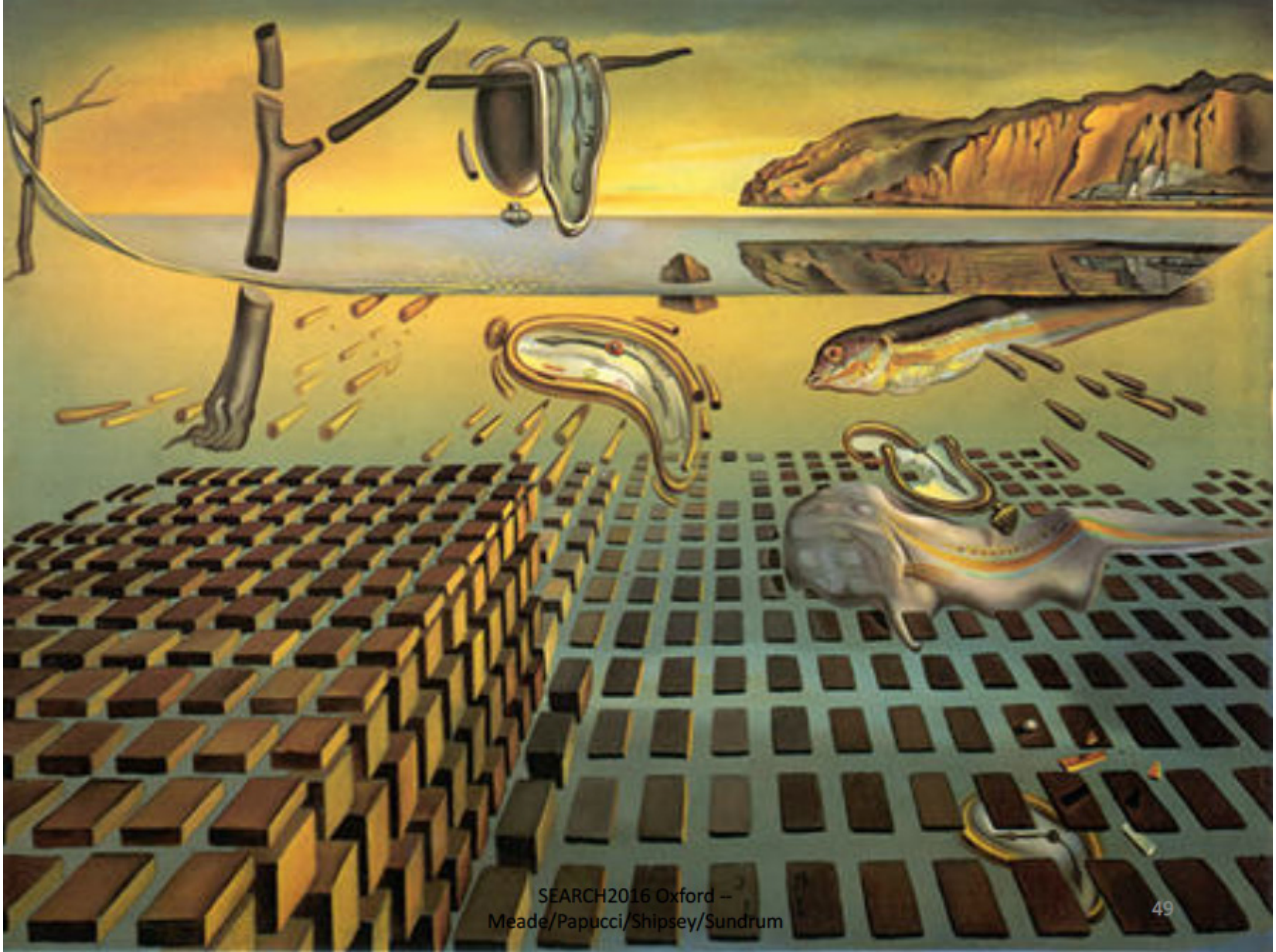
When we know the characteristics and context of what to expect (W,t,H) a little data goes a long way (top-down dominates)



SEARCH2016 Oxford --
Meade/Papucci/Shipsey/Sundrum



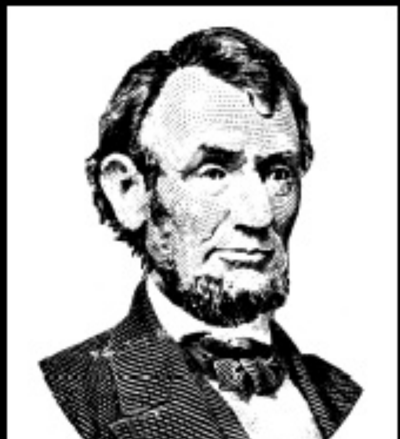




Perception & understanding

Experimental physics can be viewed as an incubator for new ideas to help in the recognition of a Dali painting

With a roadmap (theory)



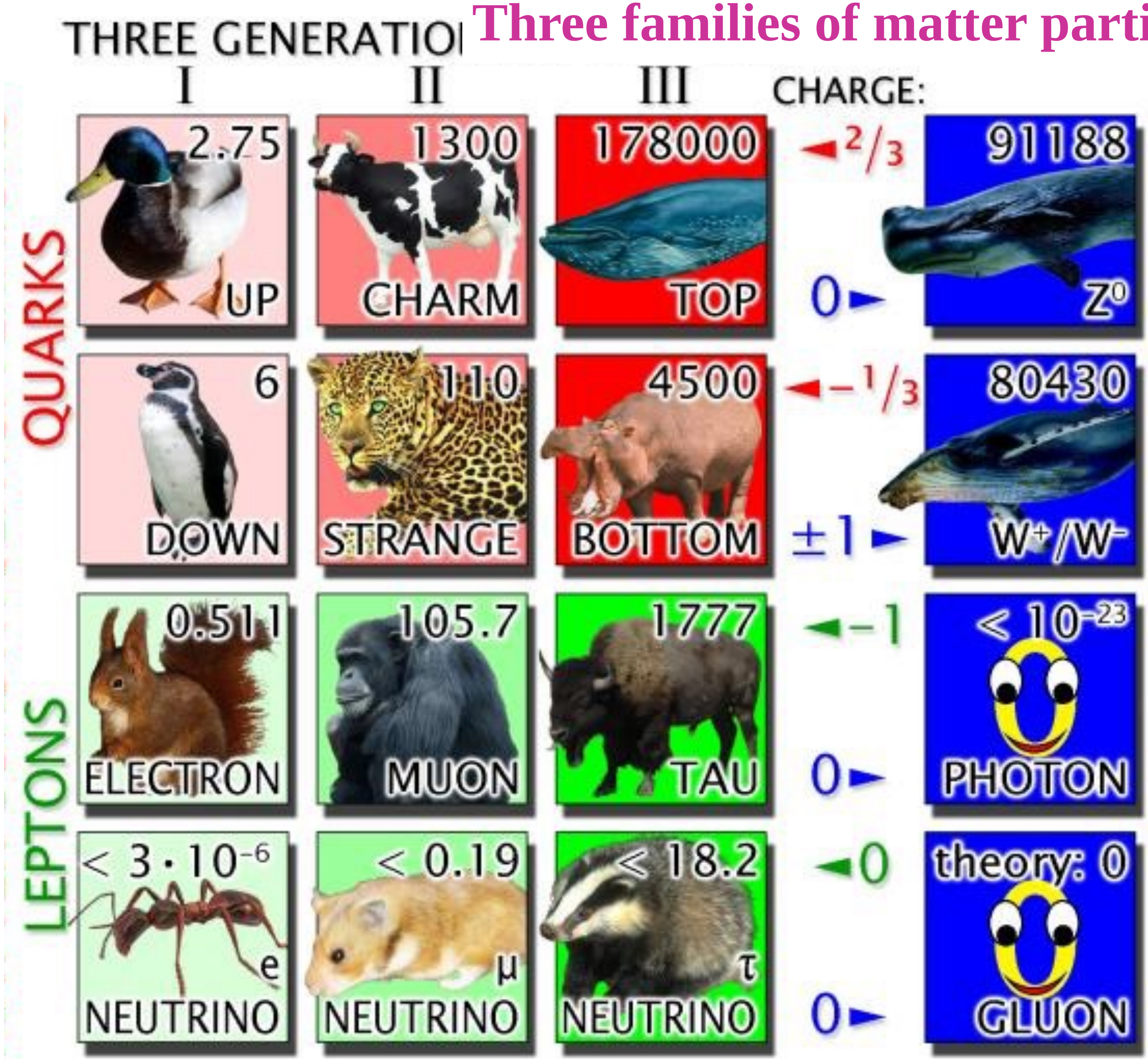
For the discovery of (W/Z, top quark, Higgs boson), a little data goes a long way (top-down dominates)

w/o a roadmap (data driven)

For the discovery of new physics, need a lot of data and many different viewpoints (bottom-up dominates)

The zoo of elementary particles in the Standard Model

Three families of matter particles



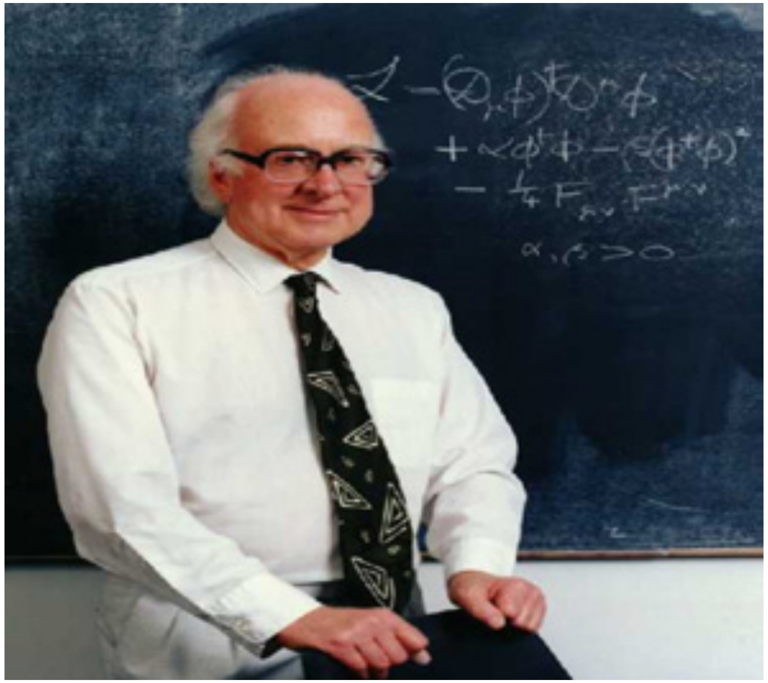
Masses are in MeV or millions of electron-volts.

The weights of the animals are proportional to the weights of the corresponding particles.

What about the Higgs boson?

Higgs boson has been with us for many decades as:

1. a theoretical concept,
2. a scalar field linked to the vacuum,
3. the dark corner
   of the Standard Model,
4. an incarnation of the Communist Party, since it controls the masses (L. Alvarez-Gaumé in lectures for CERN summer school in Alushta),
5. a painful part of the first chapter of our Ph. D. thesis



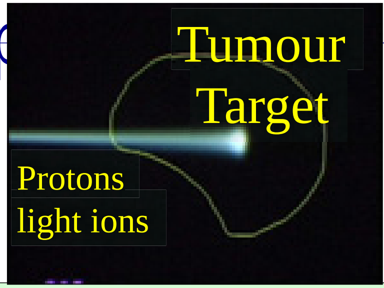
Will the Higgs boson change our life ?

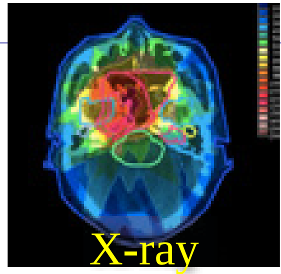
It already has !

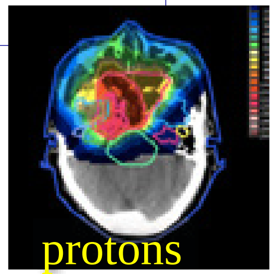
Complex, high-tech instruments needed in particle physics → cutting-edge technologies developed at CERN and collaborating Institutes → transferred to

Examples of applications: medical imaging, cancer therapy, solar panels, materials science, airport scanners, cargo screening, food sterilization, nuclear waste transmutation, analysis of historical relics, etc. etc. … not to mention the WE

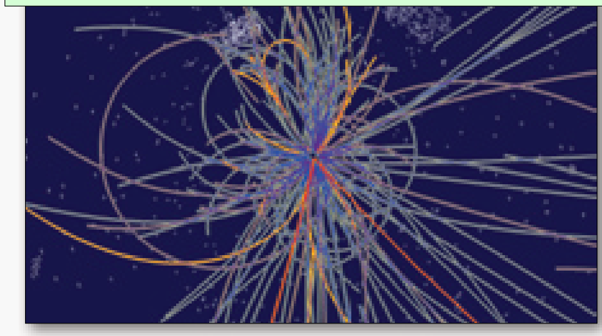
Hadron Therap



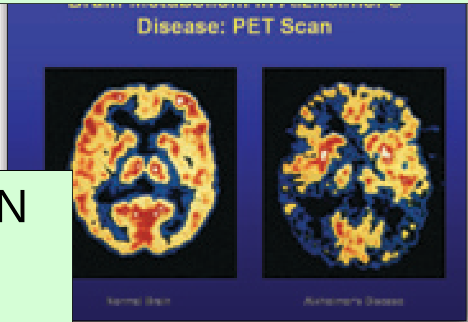




Particle accelerators: ~30’000 worldwide, of which ~17’000 used for medical applications
E.g. Hadron Therapy: > 50000 patients treated in Europe (14 facilities)



Imaging



e.g. PET scanner (based on CERN technology) is main cancer diagnostic technique since 2000

CERN : the largest particle physics laboratory

International Organization based in Geneva

Mission:

- science: fundamental research in particle physics (many discoveries, e.g. Higgs boson)
- technology and innovation → transferred to society (e.g. the World Wide Web, medical applications)
- training and education
- bringing the world together: ~ 12500 scientists, > 110 nationalities

CERN staff member T. Berners-Lee, inventor of the WEB, with Kofi Annan and CERN DG Luciano Maiani

Samuel Ting, Nobel prize, 1976

Carlo Rubbia, Nobel prize, 1984

George Charpak, Nobel prize, 1992

CERN was founded in 1954: 12 European St
Today: 22 Member States

Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

Associate Member States: Cyprus, Pakistan, Serbia, Turkey, Ukraine, soon India

Observers to Council: India, Japan, Russia, USA, EU, JINR, UNESCO

~ 2300 staff, 3700 on payroll

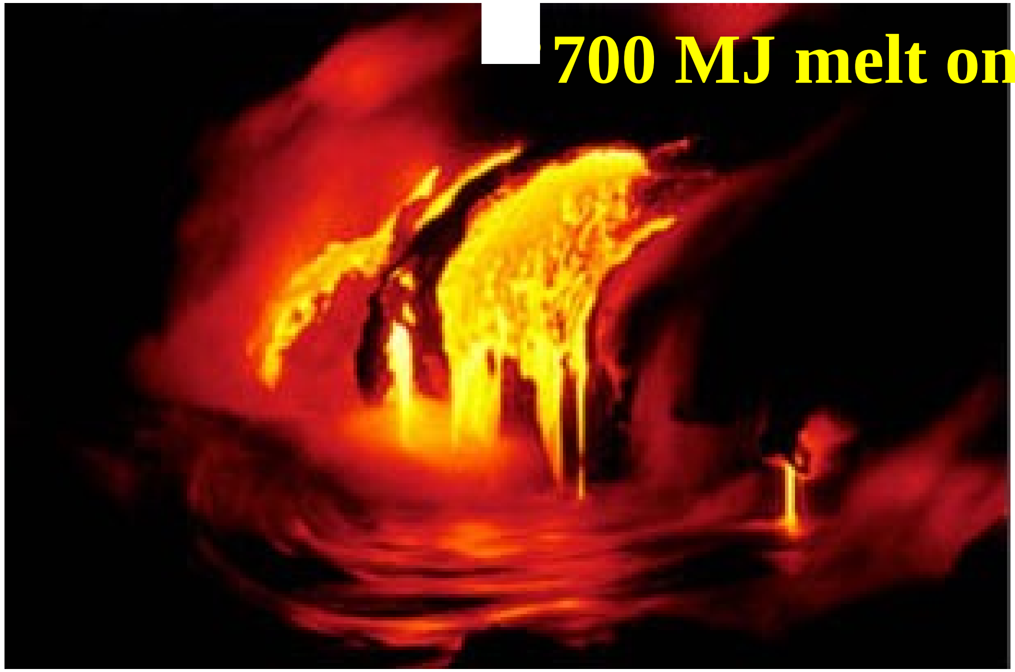
~ 12500 users

Budget (2016) ~1100 MCHF (~ 1 cappuccino/year per European citizen): each Member State contributes in proportion to its income.

The giant challenge of the LHC

Collision energy	7 TeV (1 eV = 1,6 × 10^{-19} Joule)
Number of bunches	2808
Protons per bunch	$1.15 \cdot 10^{11}$
Total number of protons	$6.5 \cdot 10^{14}$ (1 ng of H^+)

Energy stored in the two beams:	724 MJoule
Energy to heat and melt one ton of copper:	700 MJoule

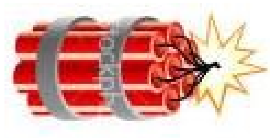


700 MJ melt one ton of copper

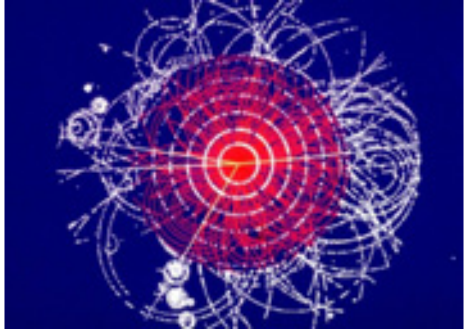
700 MJ dissipated in 88 μs ≅ 8 TW

Total world electrical capacity ≅ 3.8 TW

90 kg of TNT per beam



Is the LHC an efficient machine?



$$\frac{\text{Energy of 100 Higgs bosons}}{\text{Total energy provided by EDF}} \cong 10^{-20}$$

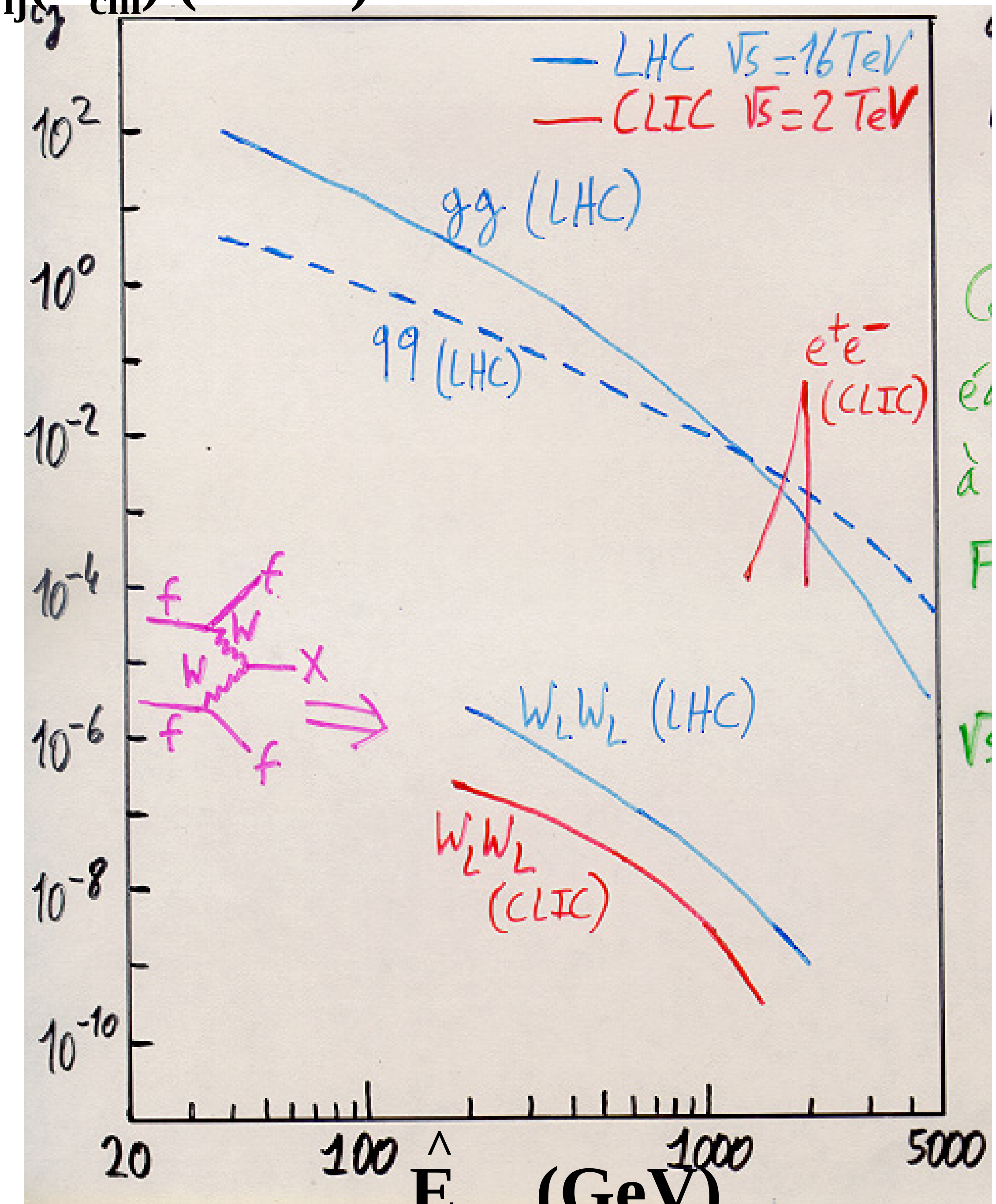
140 MW during 2000 hours: 100 000 GJ

A laughingly small efficiency?

No, an incredible tool produced by humanity to improve our understanding of the fundamental properties of nature

How do different accelerators compare?

$F_{ij}(E_{cm})$ (GeV^{-1})



$\hat{E}_{cm}$ (GeV)

Parton luminosities

where Ecm is the centre-of-mass energy of two "partons" i and j,

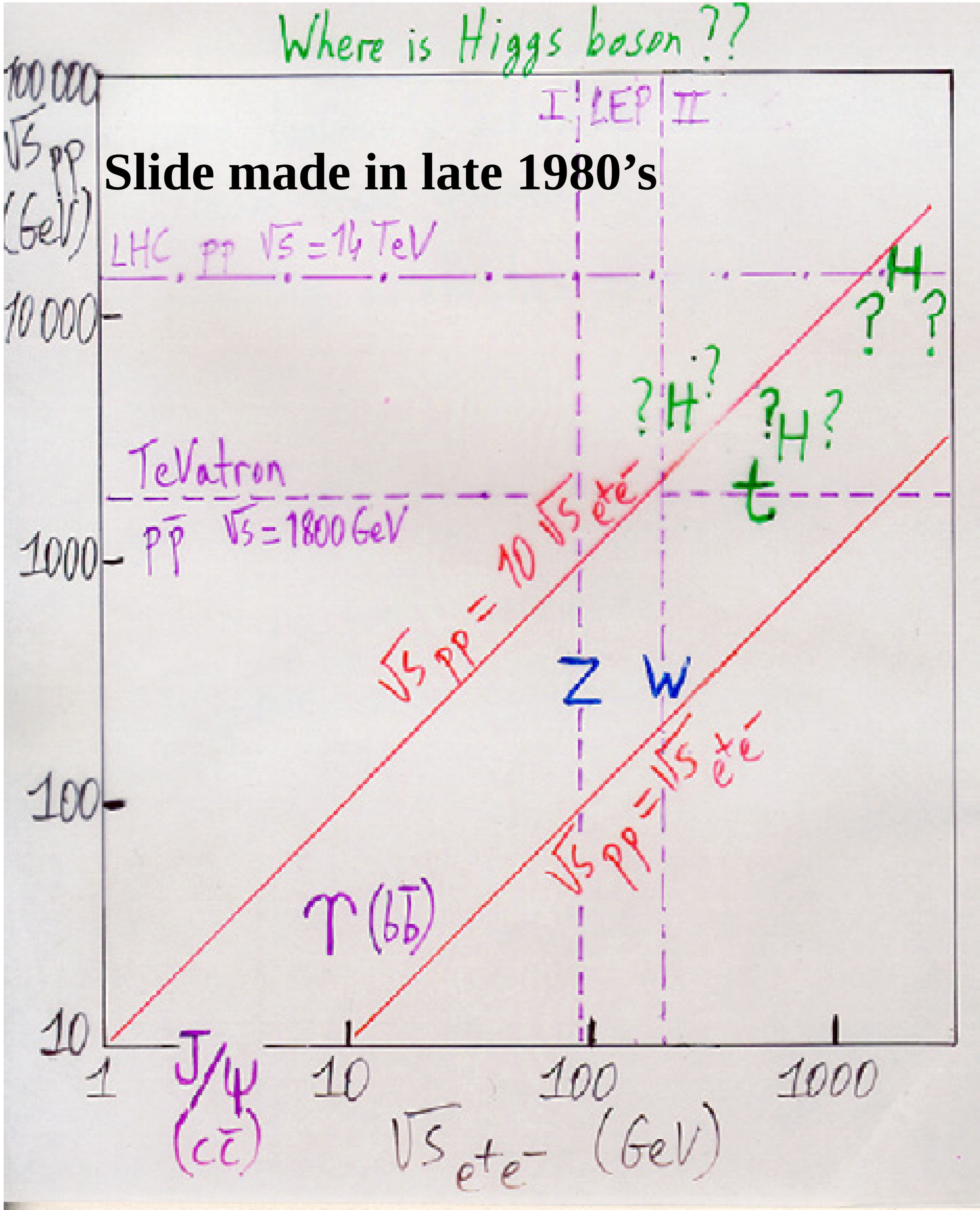
are useful to compare intrinsic potential of different machines

Important to note that:

1. **as centre-of-mass energy grows, processes without beam-energy constraint such as vector-boson fusion become also important at e^+e^- machines;**
2. **Proton-proton collisions are equivalent to e^+e^- collisions for**

$$\sqrt{s}_{pp} \approx 5 \sqrt{s}_{e+e-}$$

How do different accelerators compare?



All particles in plot were discovered first at hadron machines with one notable exception:

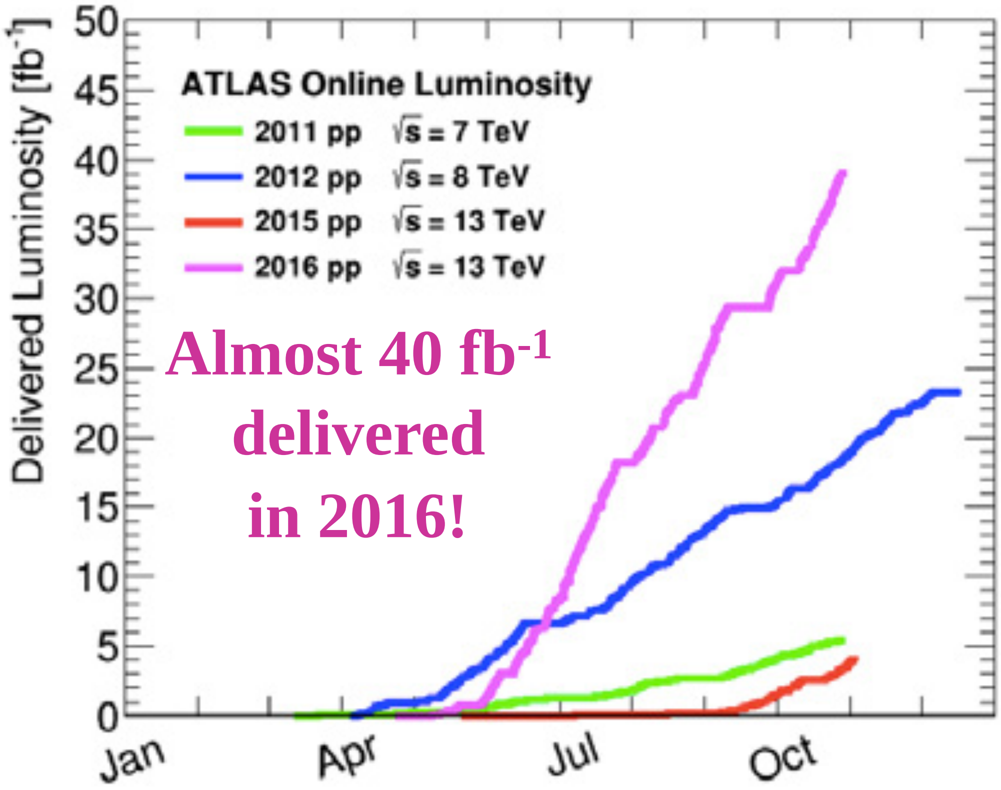
the τ-lepton was (and could have been) observed only in vector-boson decays at the CERN proton-antiproton collider.

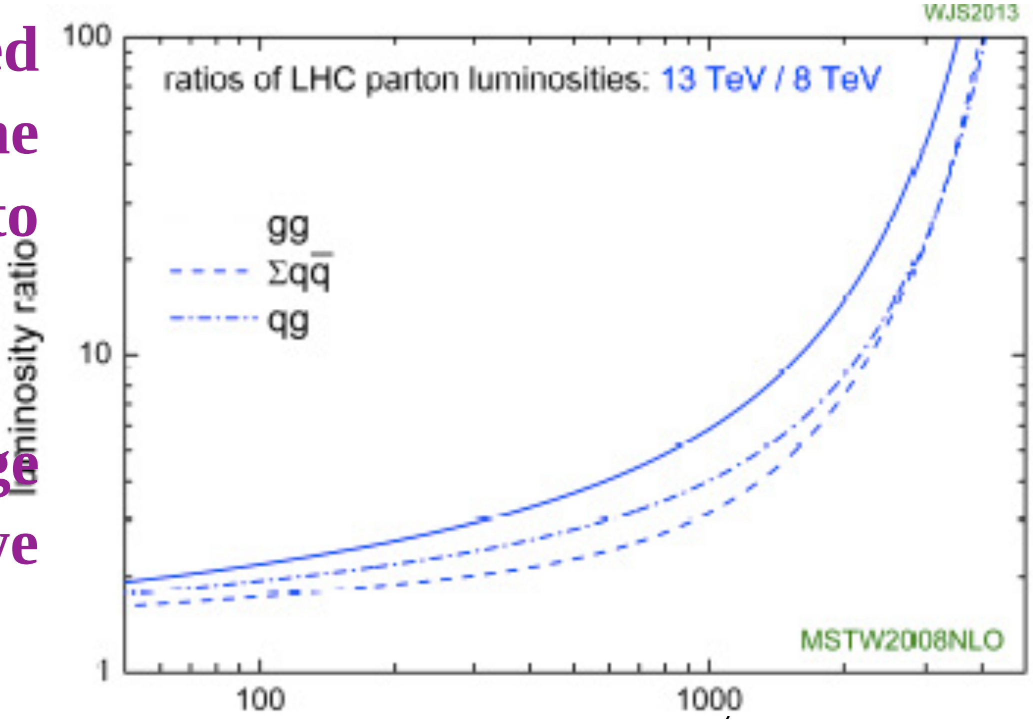
♥ Exceptional performance of the LHC this year!

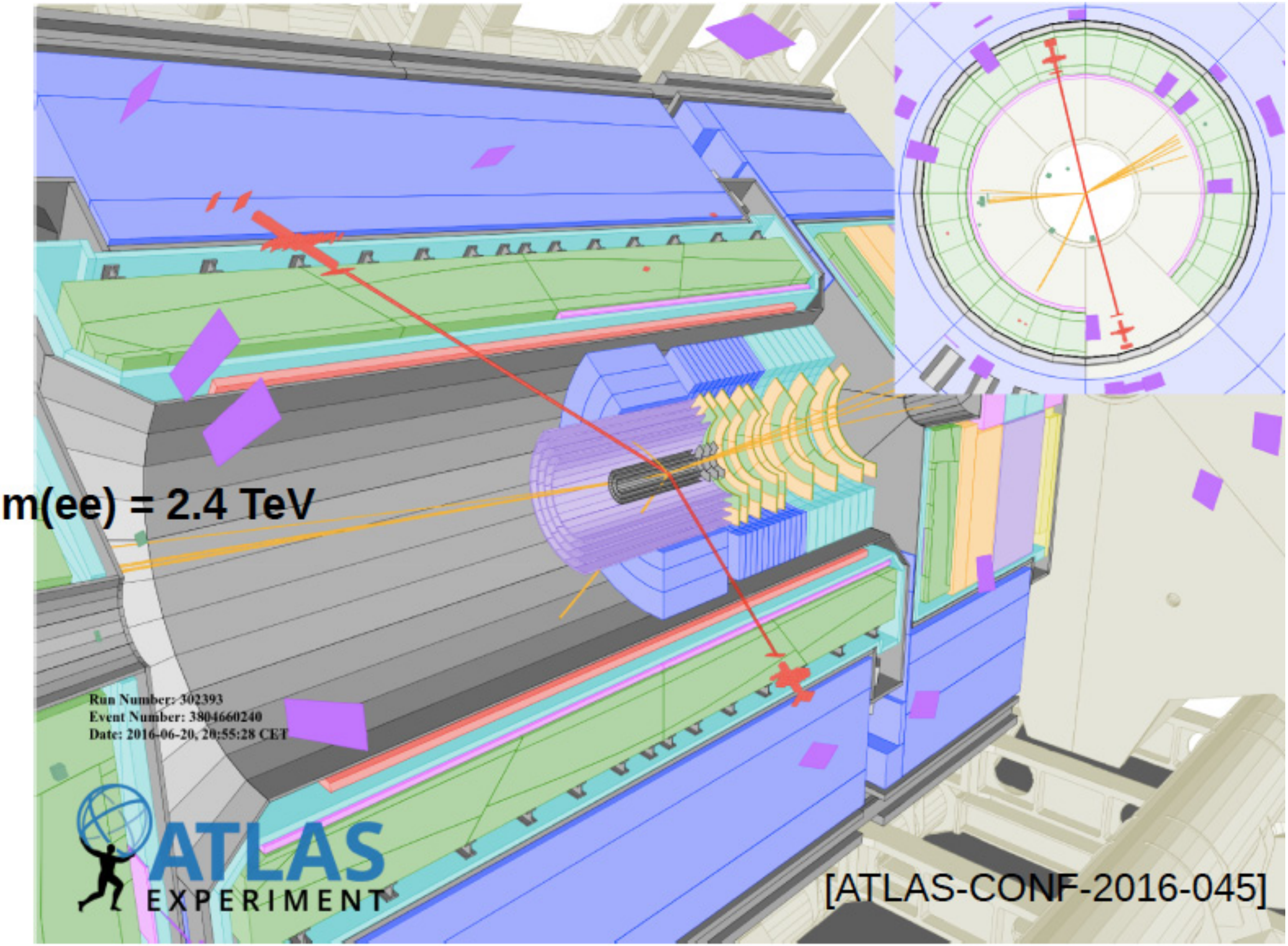
♥ Experiments have collected more than 30 fb^{-1} of data for physics. In one year, supersede statistics of 7/8 TeV data by more than a factor of 3!

♥ But there is more to the 2015-2016 operations than the integrated luminosity: the energy of the machine is now 13 TeV, it might rise further to 14 (15?) TeV in the coming years.

♥ The gains in cross section at the edge of the phase space can be as large as we wish to dream!

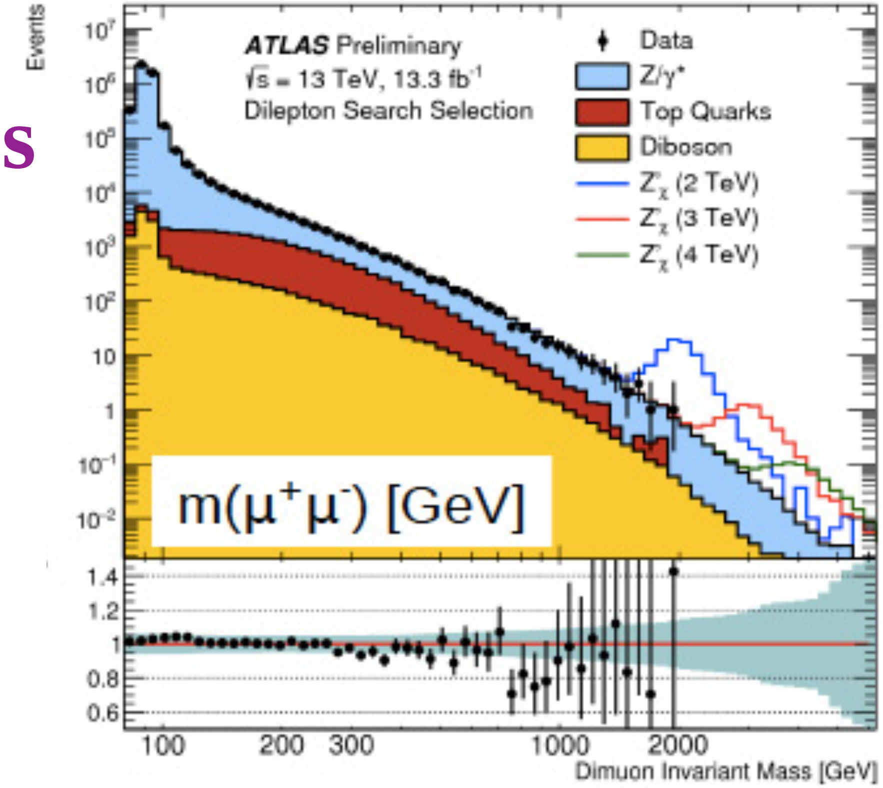


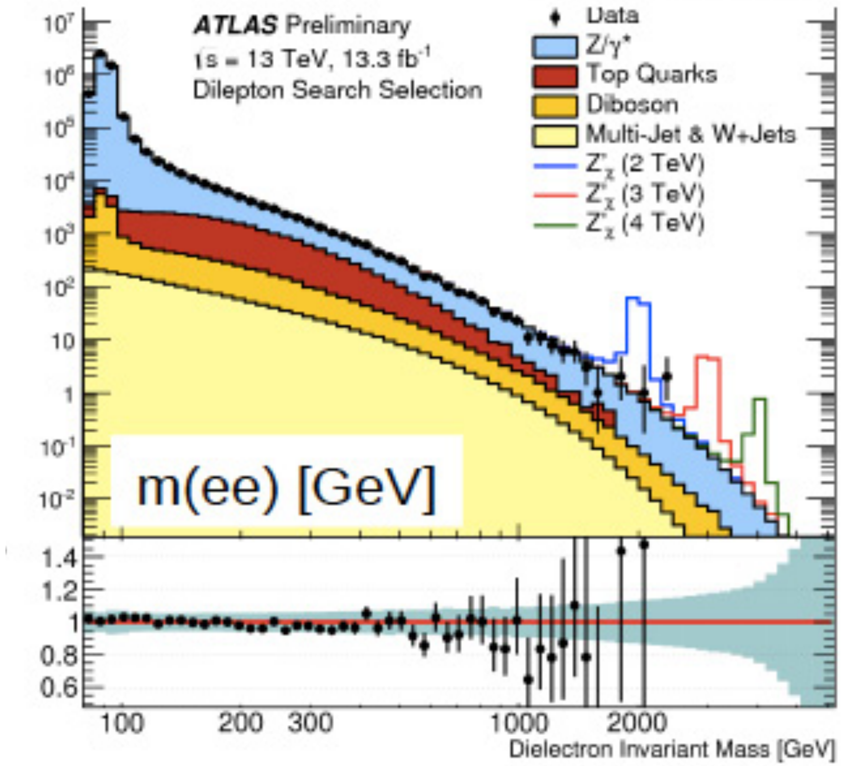


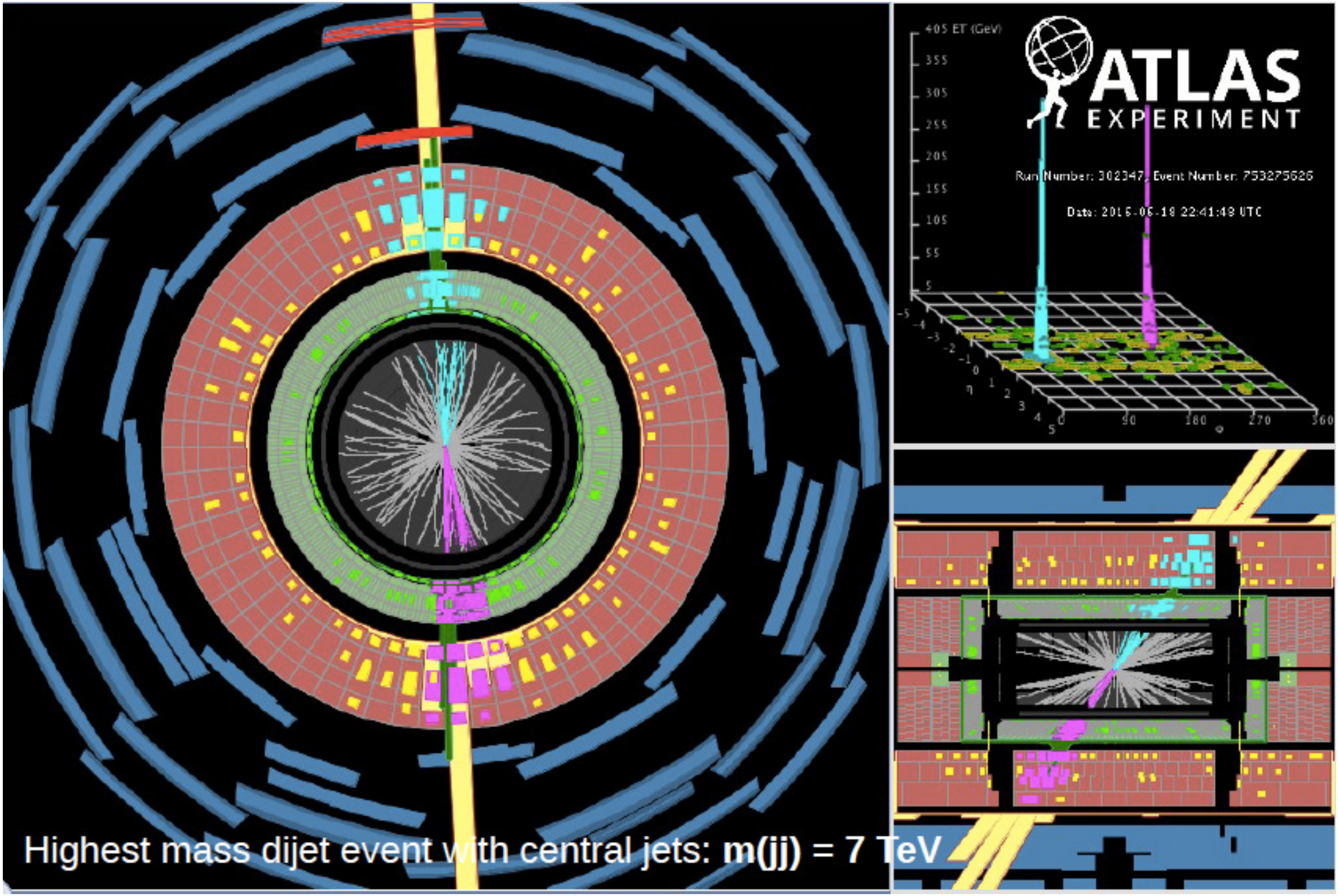

m(ee) = 2.4 TeV
Run Number: 302393
Event Number: 3804660240
Date: 2016-06-20, 20:55:28 CEST
ATLAS
EXPERIMENT
[ATLAS-CONF-2016-045]

Search for high-mass resonances decaying to leptons

- Dimuon channel:
  - → 30 µm muon spectrometer alignment critical (ATLAS)
  - → Resolution 10-15% at p_T = 1 TeV
- Dielectron channel:
  - → Excellent resolution: < 2% at high momentum
  - → Poor charge measurement → no charge requirement
- Fit of the entire dilepton spectrum, incl. Z peak.



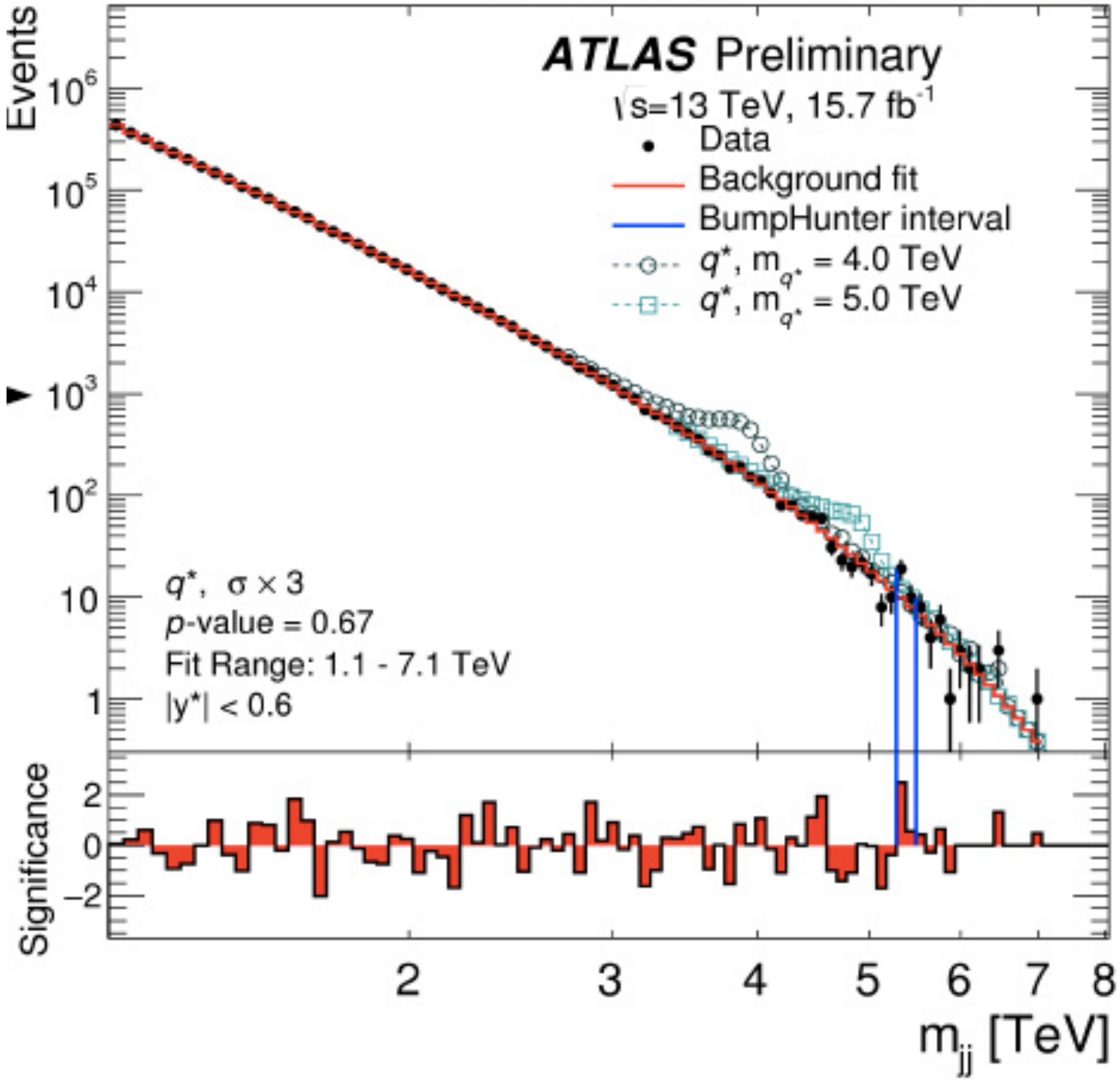


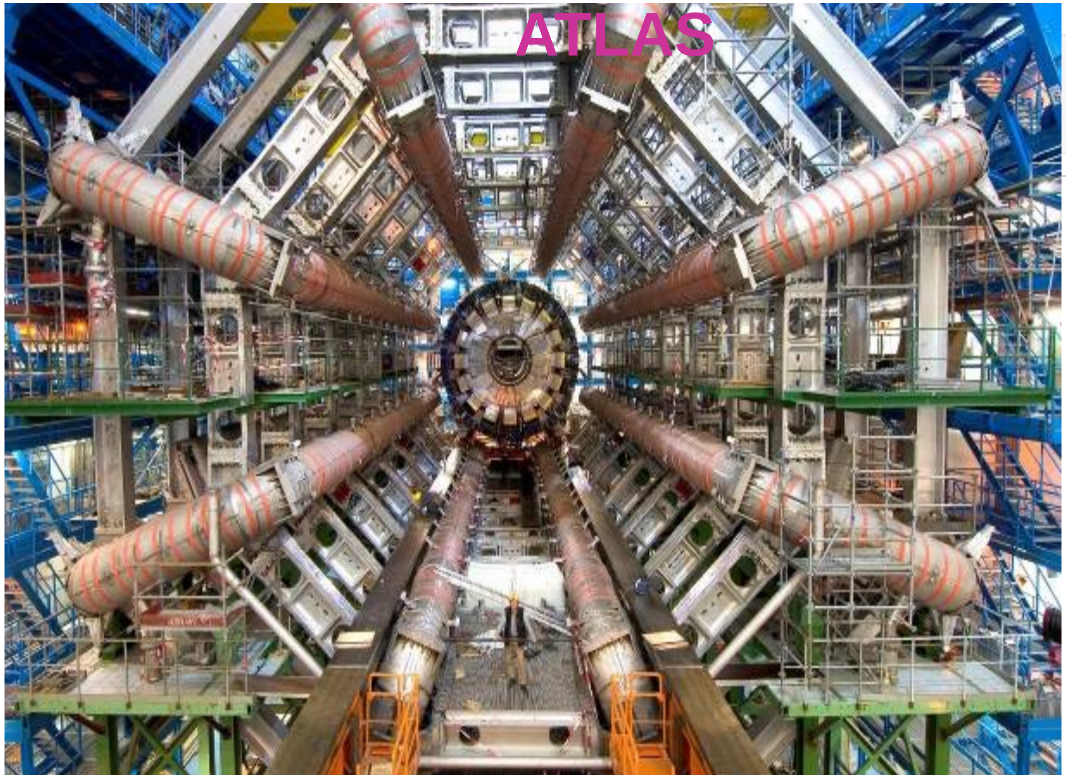

405 ET (GeV)
355
305
255
205
155
105
55
5
ATLAS
EXPERIMENT
Run Number: 302347, Event Number: 753275626
Date: 2016-06-18 22:41:48 UTC
η
φ
0
90
180
270
360
Highest mass dijet event with central jets: **m(jj) = 7 TeV**

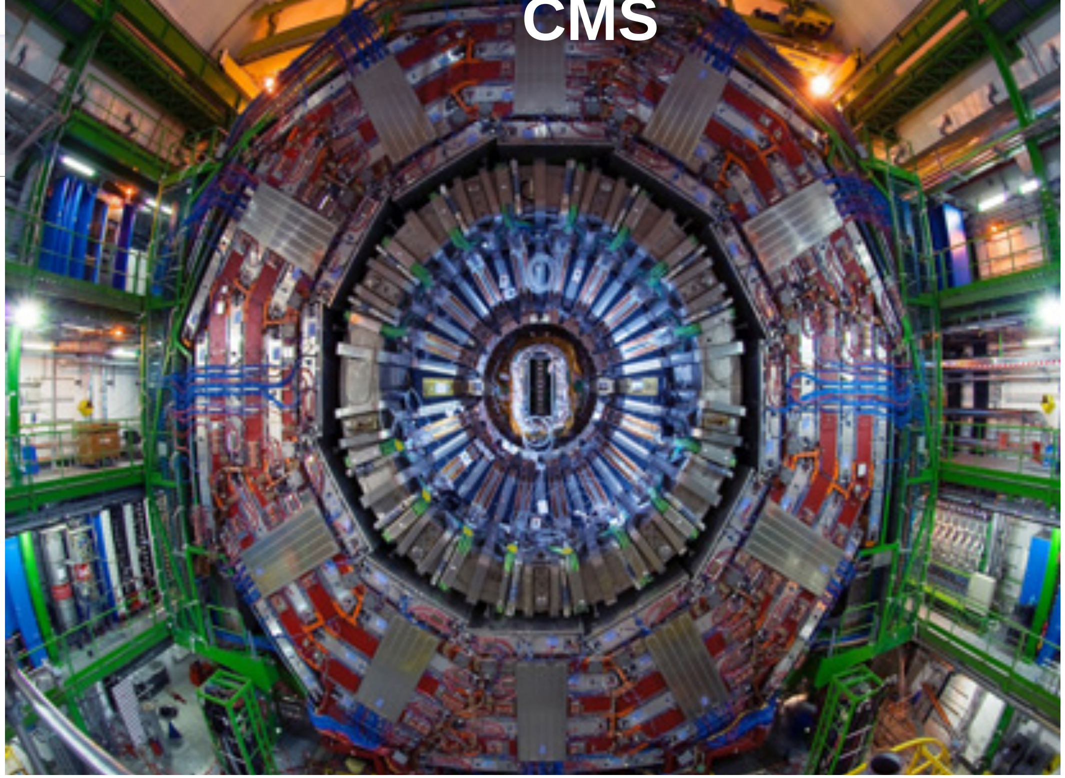
Search for high-mass resonances decaying to jets

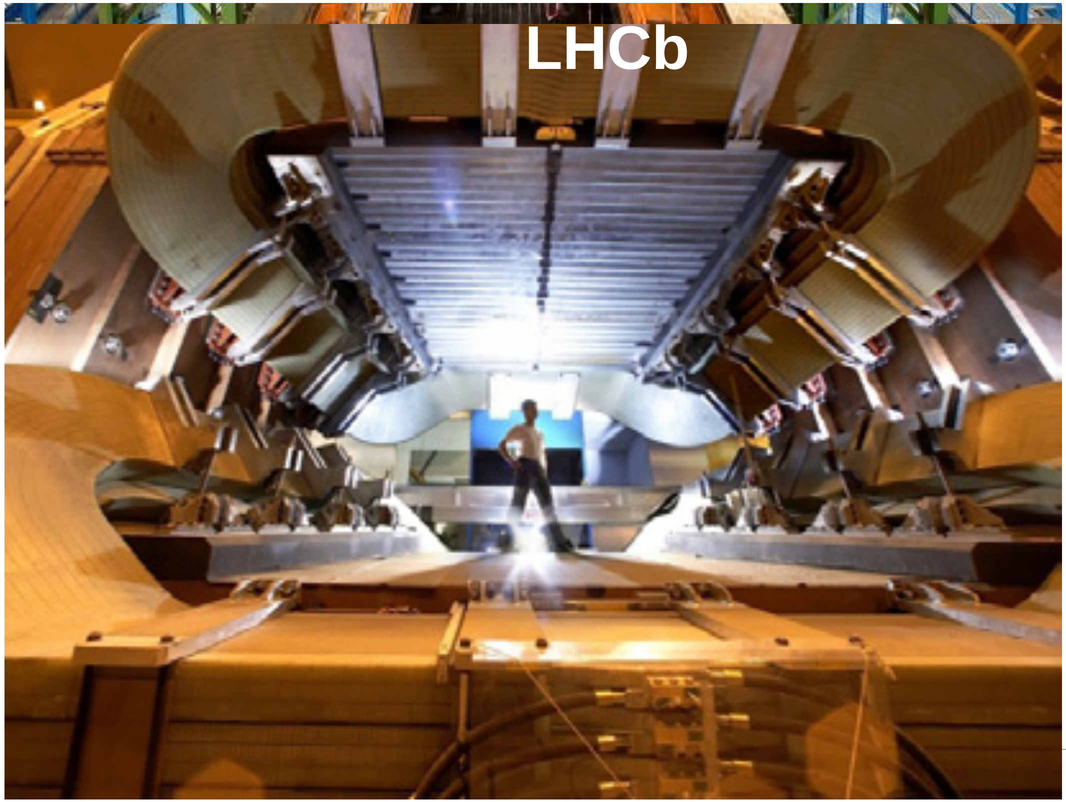
- W'/Z', excited quarks, strong gravity, DM-mediator
- Look for resonance above phenomenological fit of the data

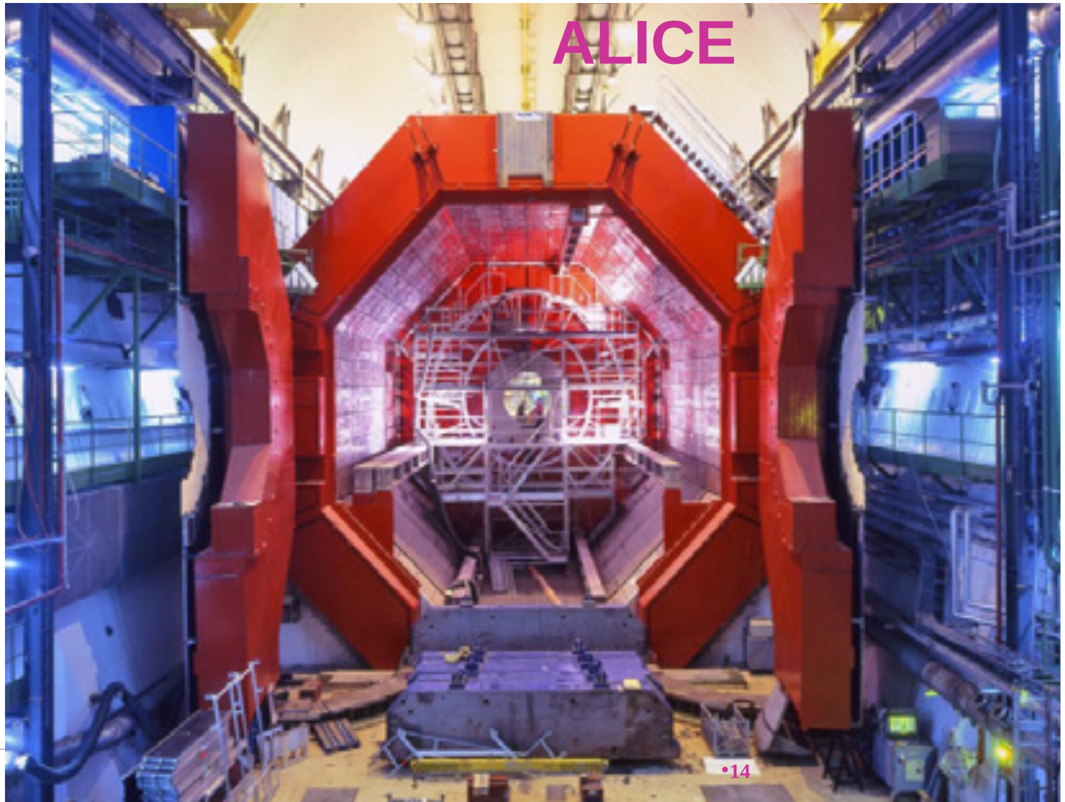
ATLAS-CONF-2016-069




ATLAS

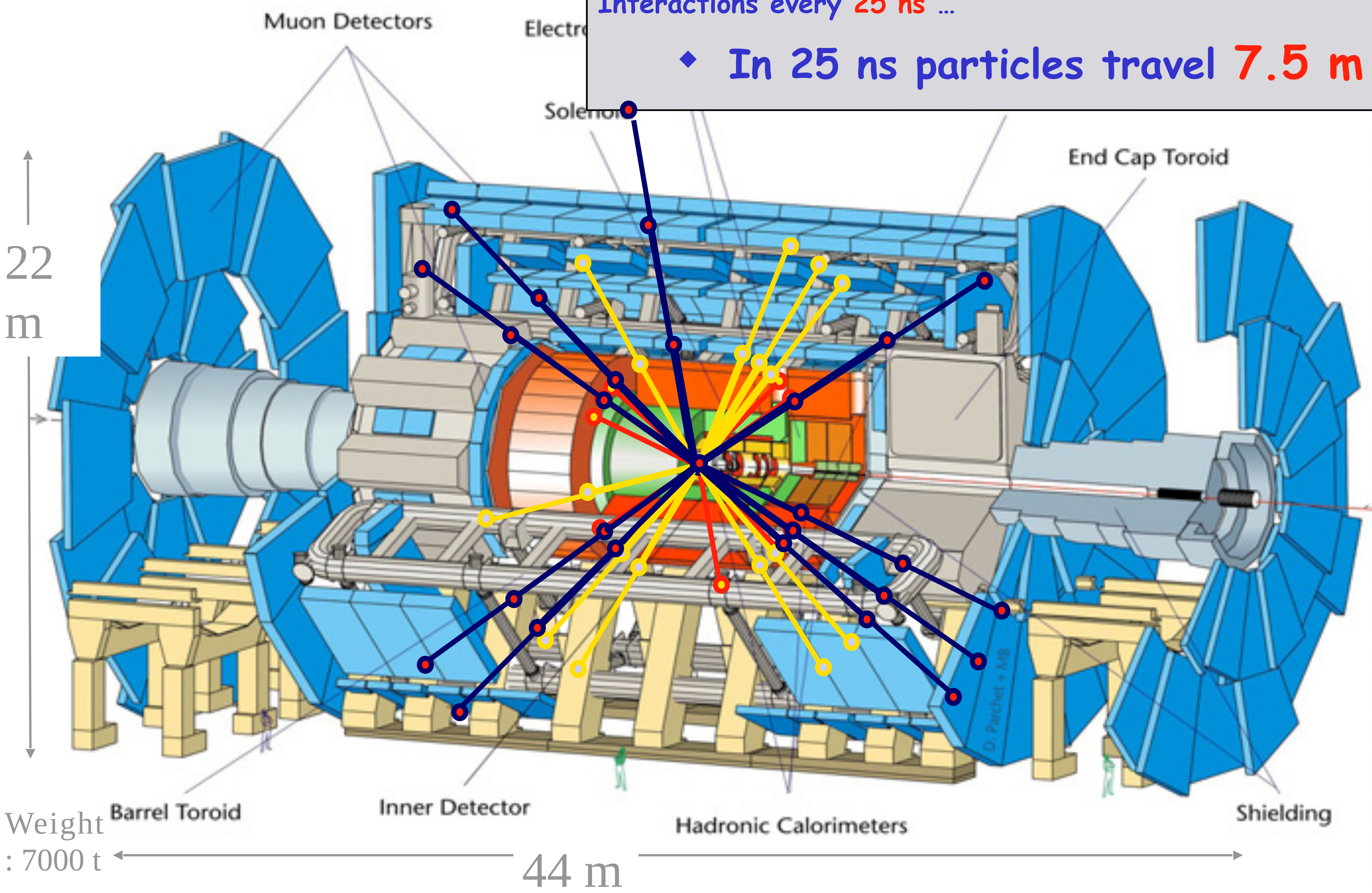

CMS


LHCb


ALICE

Physics at the LHC: the environment

Time-of-flight



Interactions every 25 ns …

- In 25 ns particles travel 7.5 m

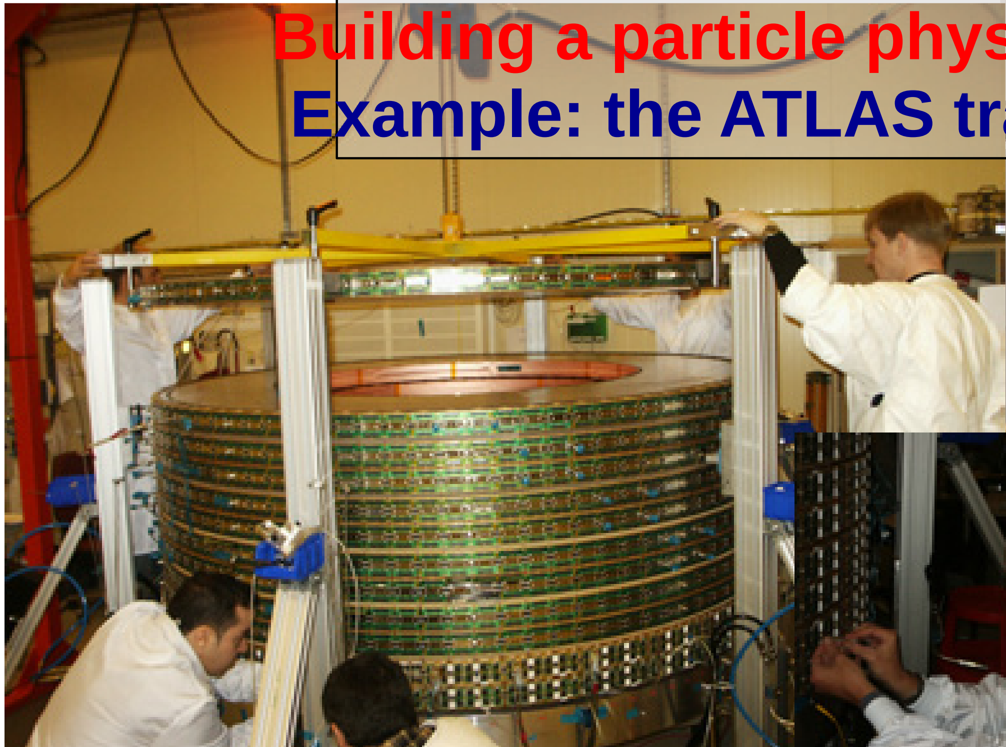
Cable length ~100 meters …

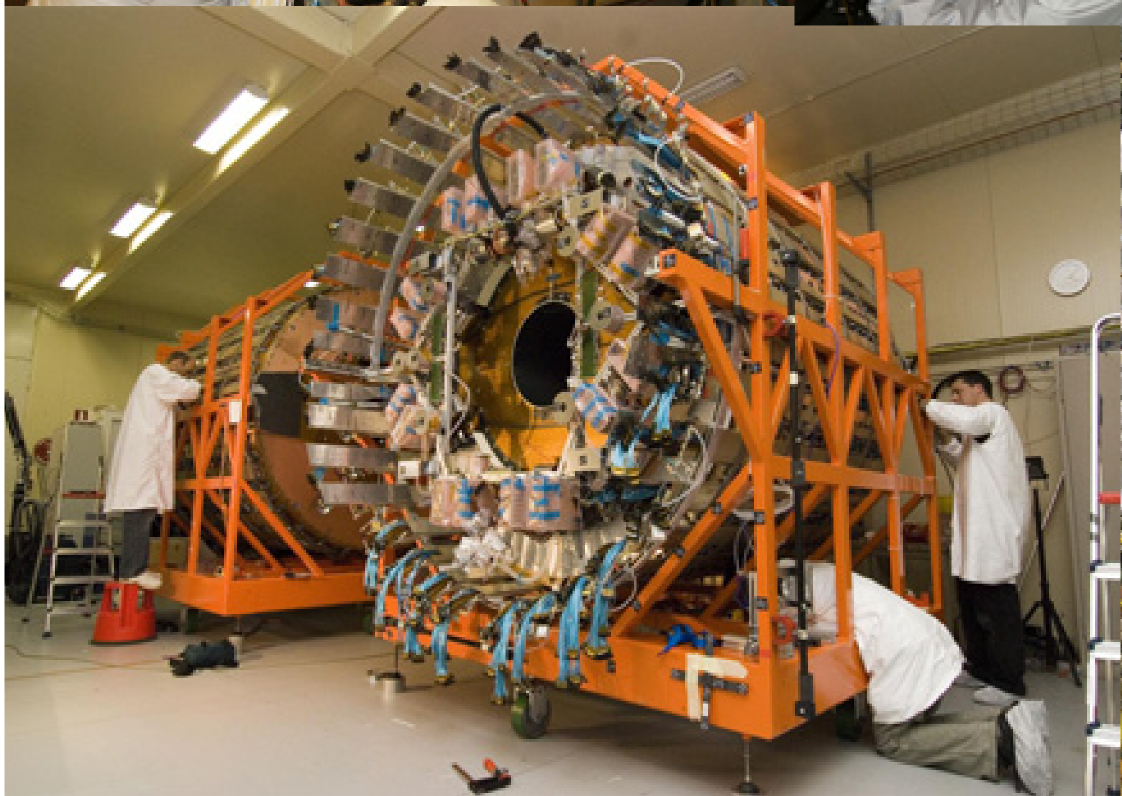
- In 25 ns signals travel 5 m

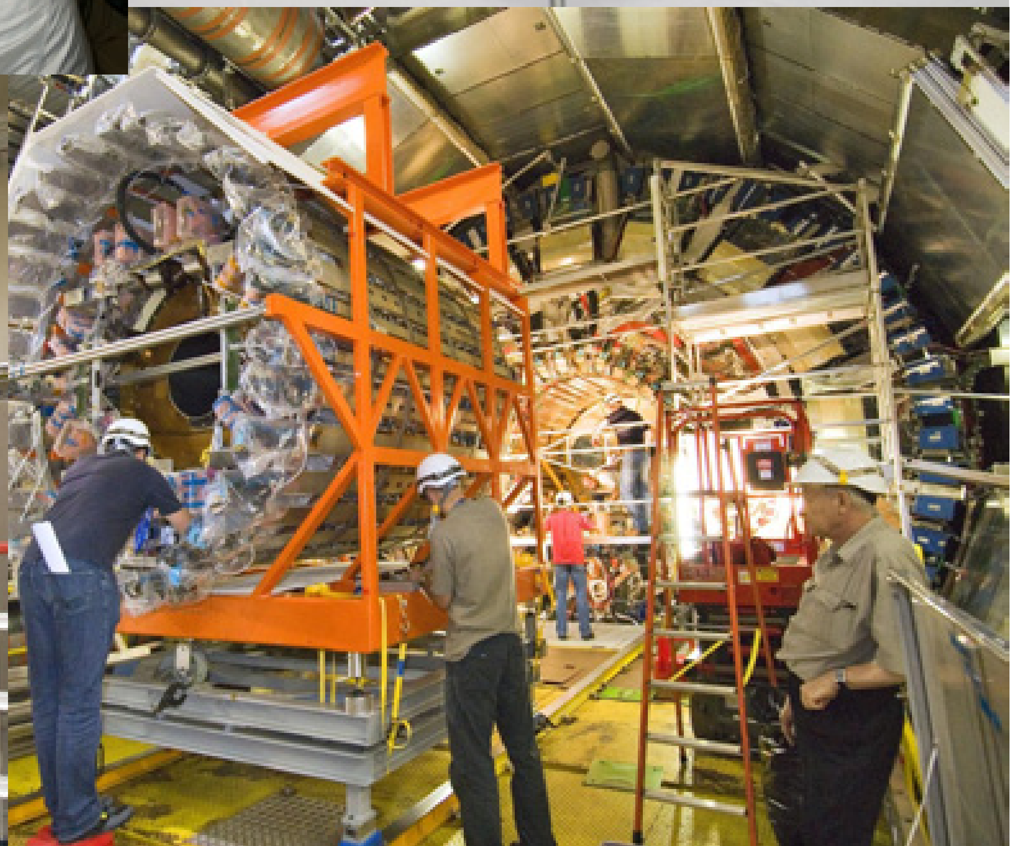
D. Froidevaux (CERN)

Building a particle physics detector is fascinating!

Example: the ATLAS transition radiation detector







The operation of a particle physics experiment is fascinating!

Example: arrival of the first proton beams in ATLAS in September 2008

What does the operation of an experiment at the LHC mean?

Analogy:

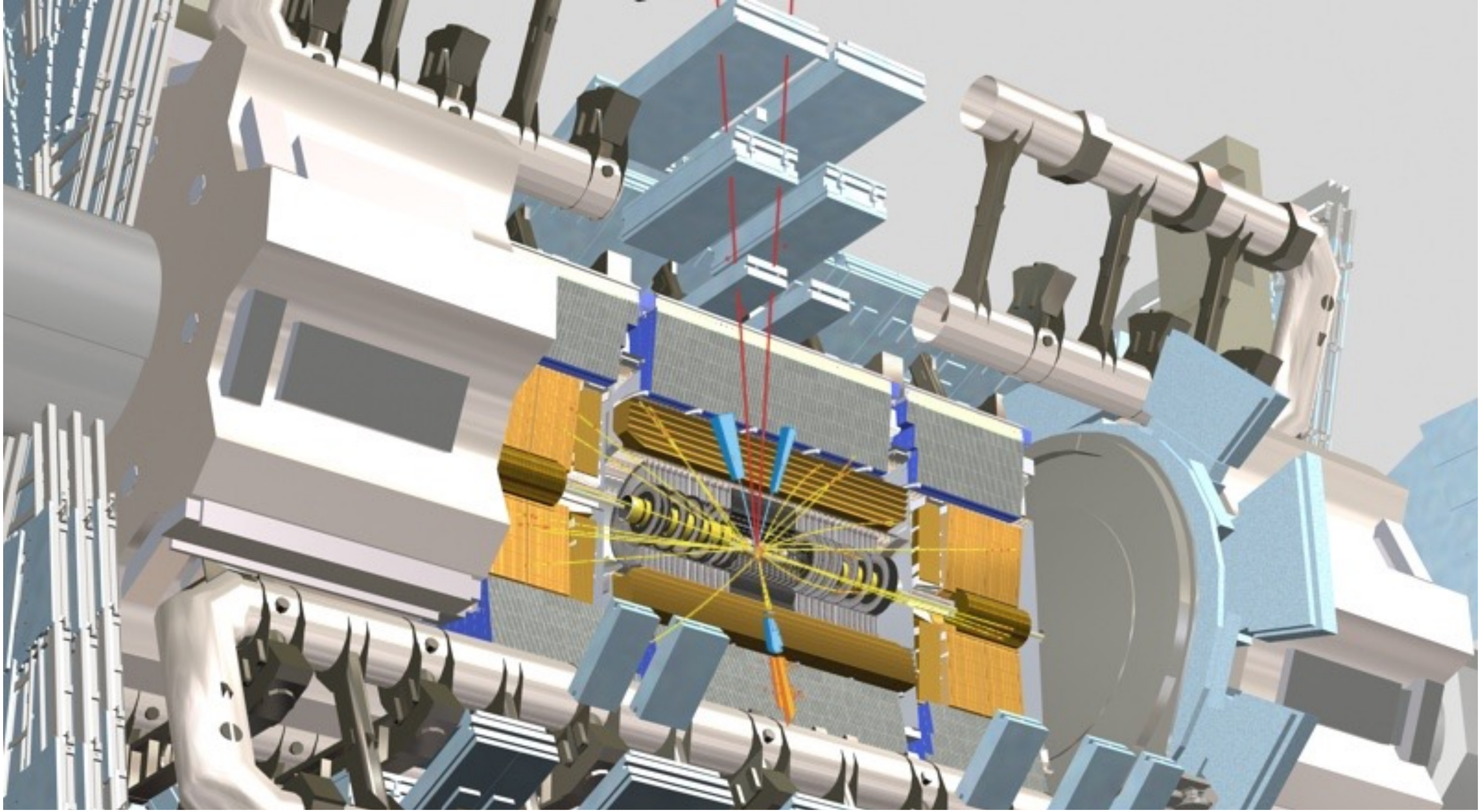
3D digital camera with 100 Megapixels built only once. It is its own prototype. It must survive in an environment close to that of the heart of a nuclear reactor (no commercial components allowed!)

- **40 million pictures per second (taken day and night, 24h/24h, 7 days a week). Each picture is taken in energy density conditions corresponding to those prevailing in the first moments of the life of our universe**
- **Amount of information: 10,000 encyclopedias per second**
- **First selection of pictures: 100,000 times per second**
- **The size of each picture is about 1 MByte**
- **Each picture is analysed by a worldwide network of about 50,000 processors**
- **Every second, the camera records on magnetic tape the 200-300 most interesting, which corresponds to 10 million GByte/year (or about three million DVDs/year)**
- **Each and every day, thousands of physicists look carefully time and time again at some of these pictures.**

What do physicists do with their pictures?

Analogy with sport:
one can understand the rules of football by observing pictures
A good camera provides details by zooming in
By collecting many pictures,
one can find rare events and analyse them

In physics, one does not know who is the referee, nature plays this role and does not obey rules pre-established by us!



Data analysis and the search for the Higgs boson are indeed fascinating activities: our university education has prepared us for this more than for the 25 years of preparation!

Example (simulation): a Higgs boson decaying to two electrons and two muons in the ATLAS detector

Interlude: difference between simulation and reality

Simulation tools are vital components for the design, optimisation and construction of large instruments such as the LHC and its experiments:

- simulations allow us to make precise predictions of the behaviour of our detectors
- simulations allow us to extrapolate from what we know today and to project ourselves towards unknown realms:
  - towards higher energies (from Chicago to CERN)
  - towards new physics searches (from the Standard Model to supersymmetry which may hold the keys to the dark matter problem)

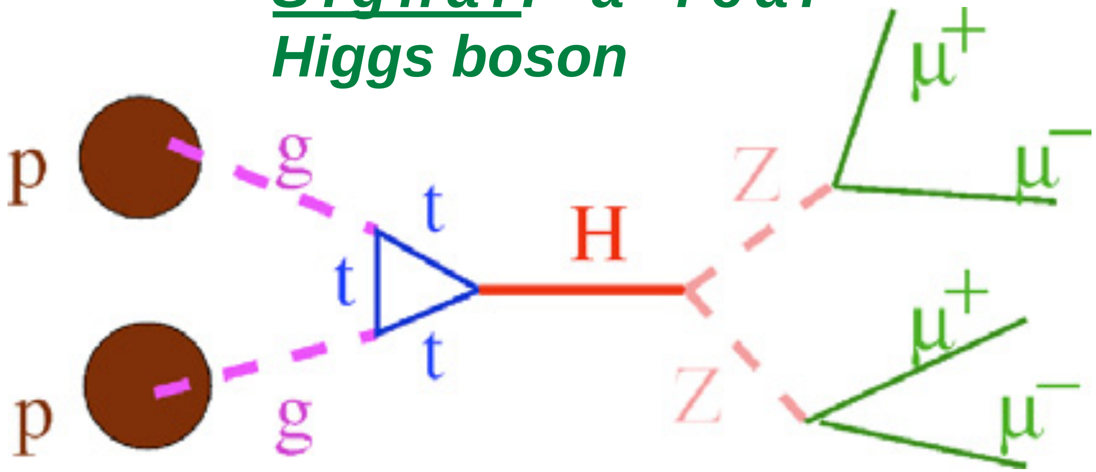
Now at last we have pictures of these new realms!

But not yet of new physics…
Patience and doubt are the names of the game.

No pictures of Higgs boson itself: only of its decay products

Sometimes (rarely) the Higgs boson decays to four muons:

***Signal*: a real Higgs boson**

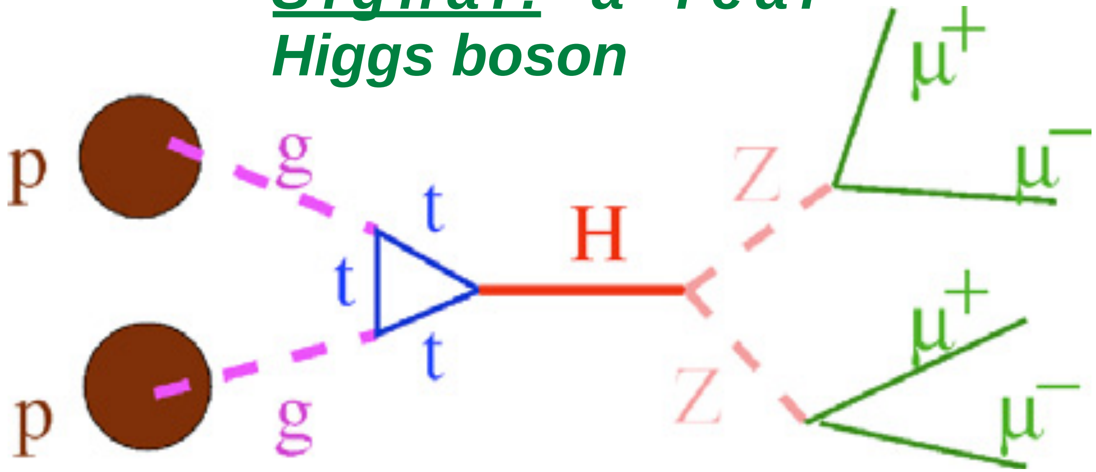


So let's look for four muons with high energy because the Higgs boson mass is larger than 114 GeV (inheritance from LEP machine and experiments)

No pictures of Higgs boson itself

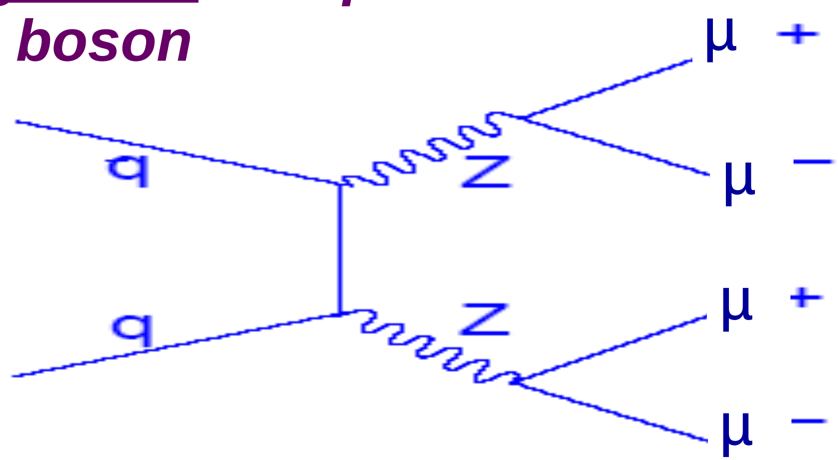
Sometimes the Higgs boson decays into four muons:

***Signal:* a real Higgs boson**



But four muons may also be produced without any Higgs boson (process predicted by the Standard Model and therefore constituting an irreducible background)

***Background:* a pseudo Higgs boson**

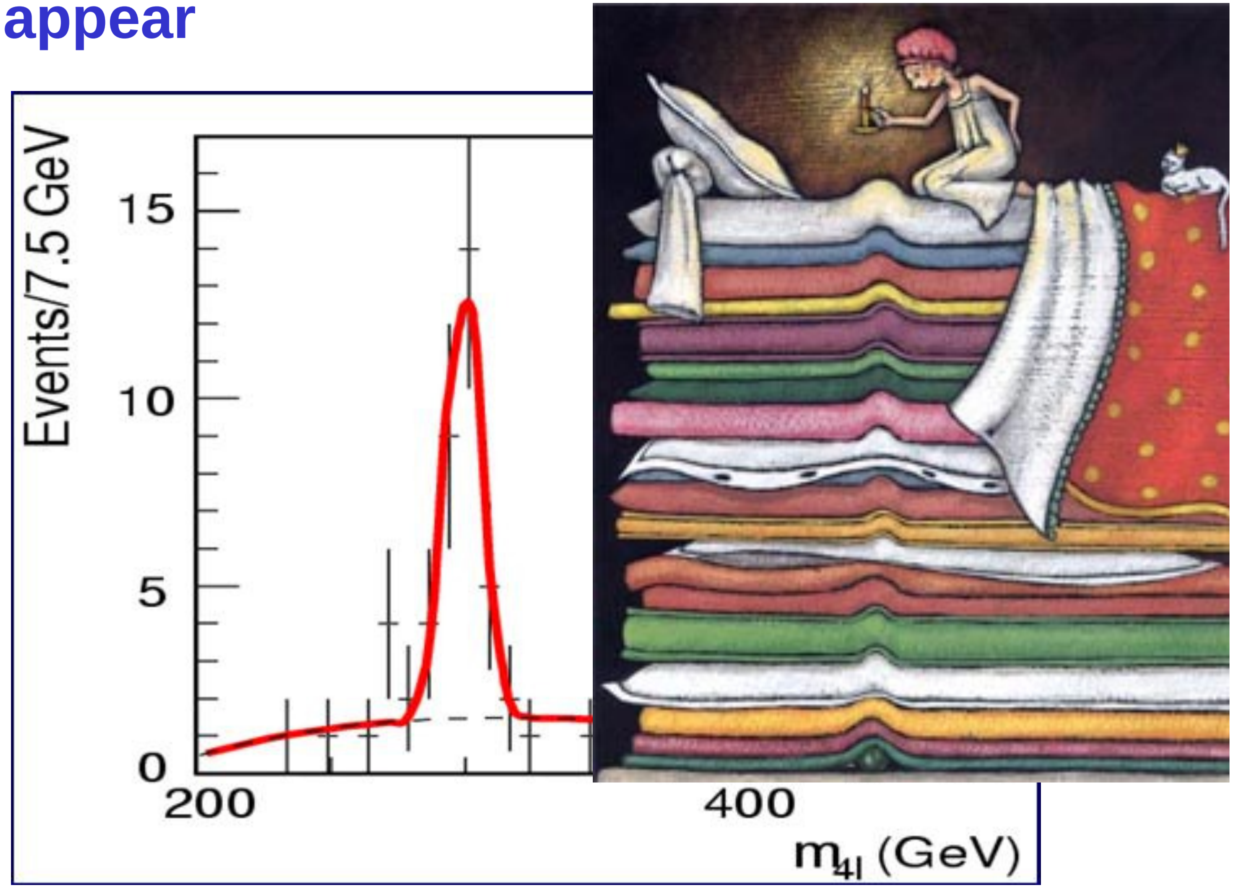


No pictures of Higgs boson itself:
but how can we find it? how can we eliminate background?

- We have to use the precise measurements obtained with each of the four muons to find back their parents (Z bosons) through the simple laws of energy and momentum conservation (in a relativistic world)
- We therefore calculate the mass of the "particle" which might have given birth to the four muons. The Higgs boson should manifest itself as a narrow peak (it has a definite mass and a narrow width) above the background which will itself appear at all possible masses

- Example: m_H = 300 GeV

We have had to wait until summer 2012 to to be sure that we have observed a Higgs boson, because it is produced very rarely and hides very well!

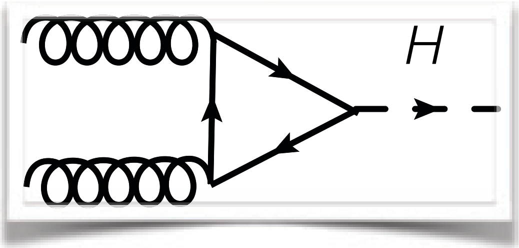


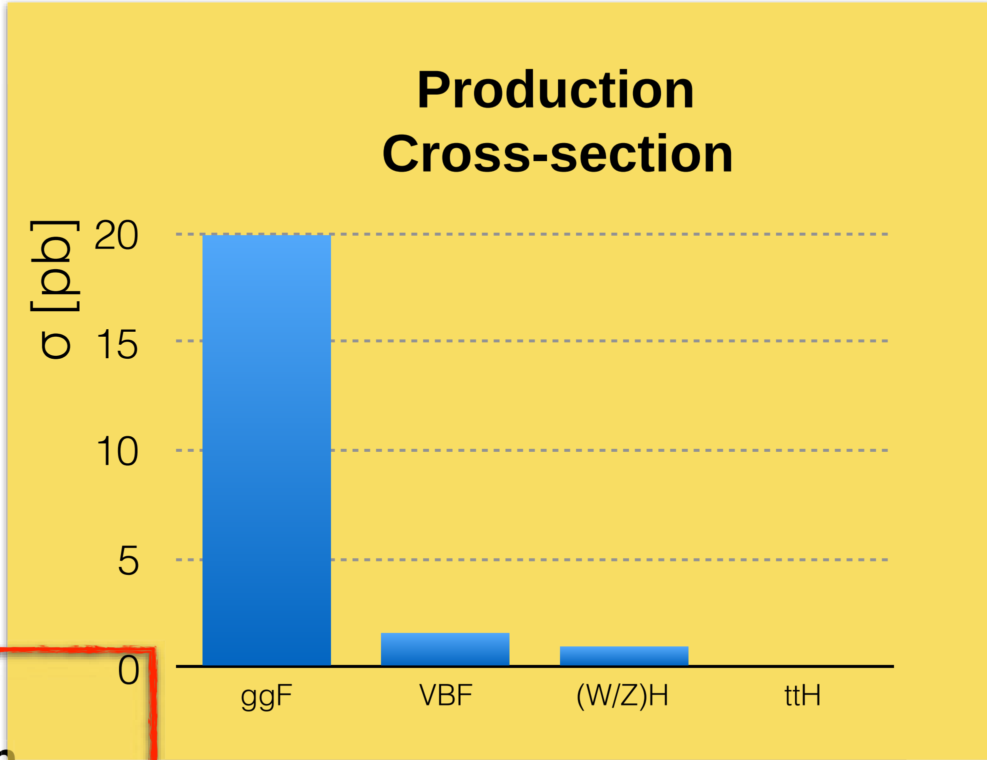
How to find a Higgs boson

Thanks to Heather Gray!

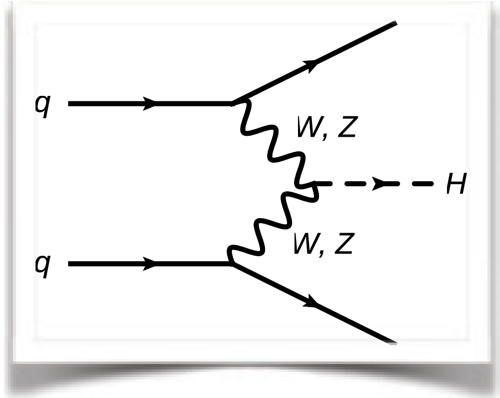
Choose your channel I

Gluon fusion

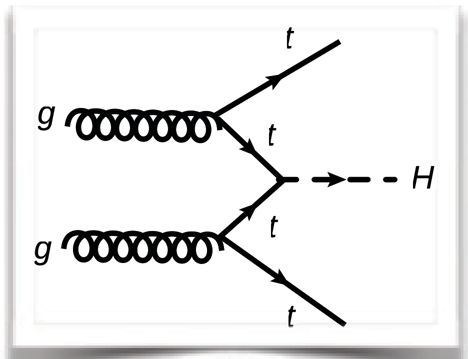




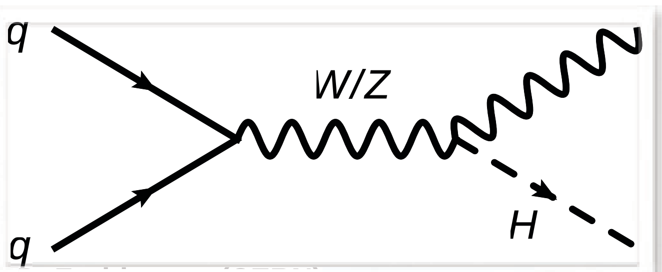
Vector Boson Fusion (VBF)



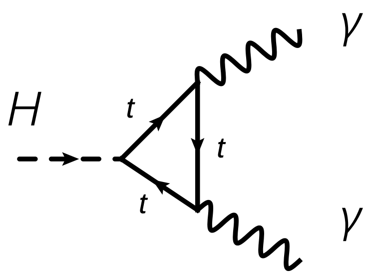
ttH Production

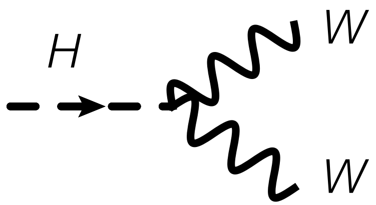


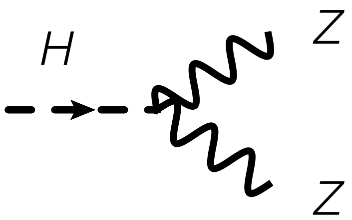
(W/Z) Production

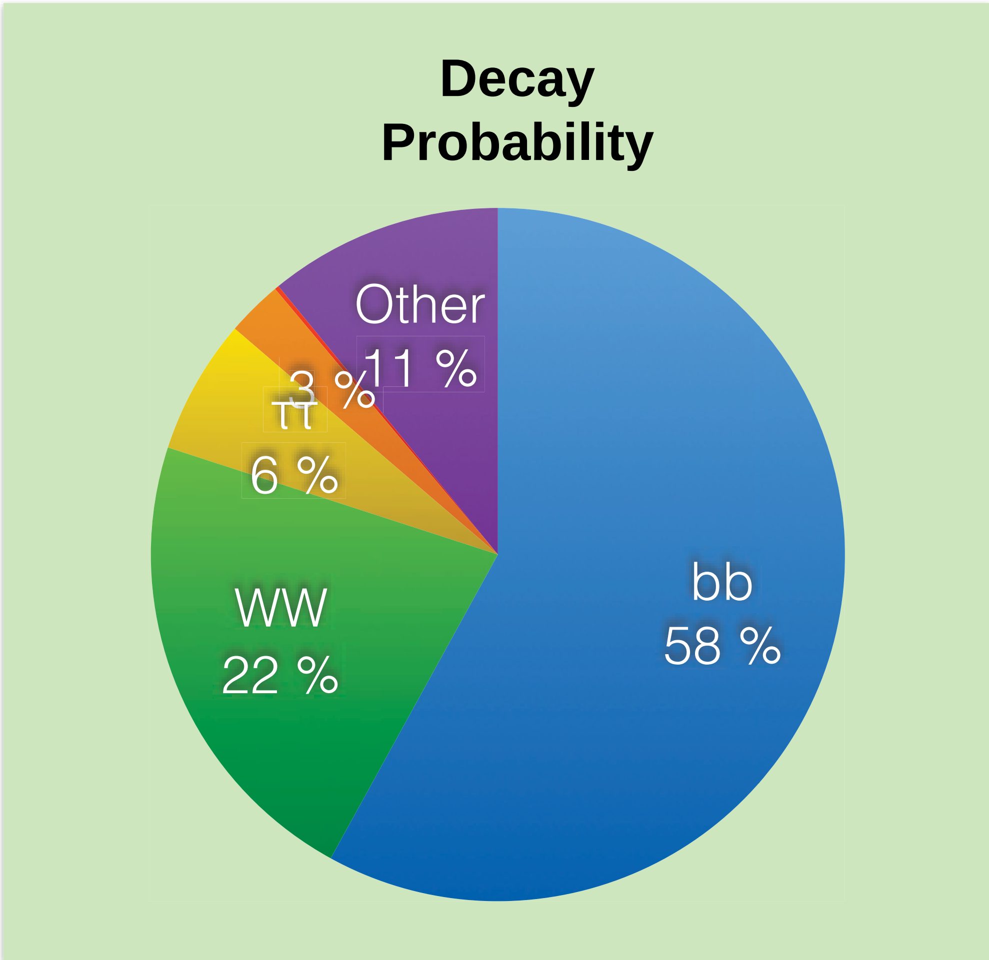


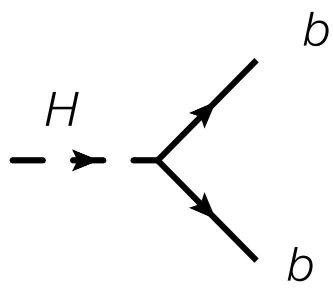
Choose your channel II

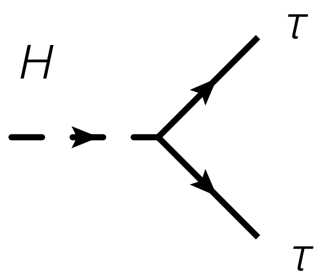




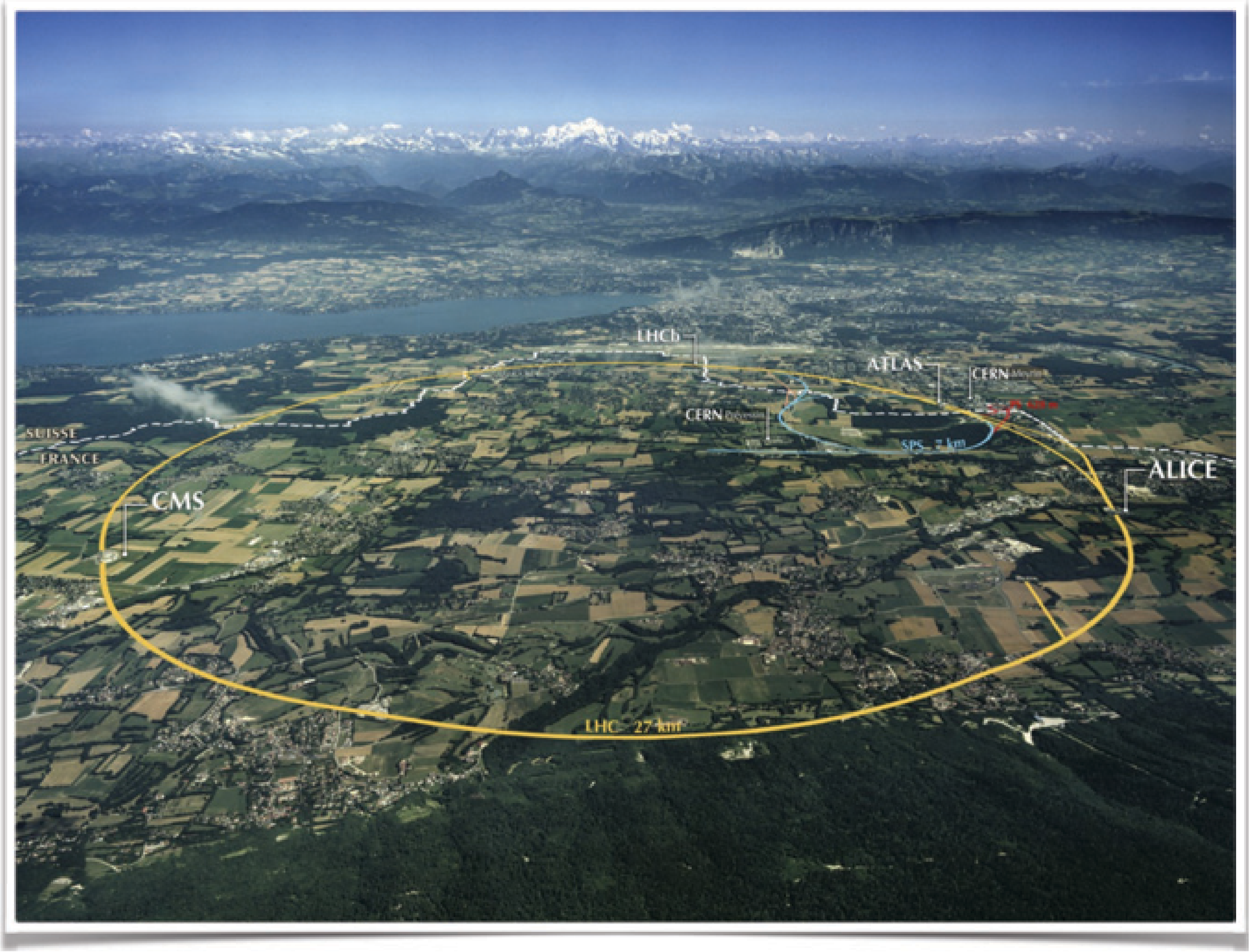




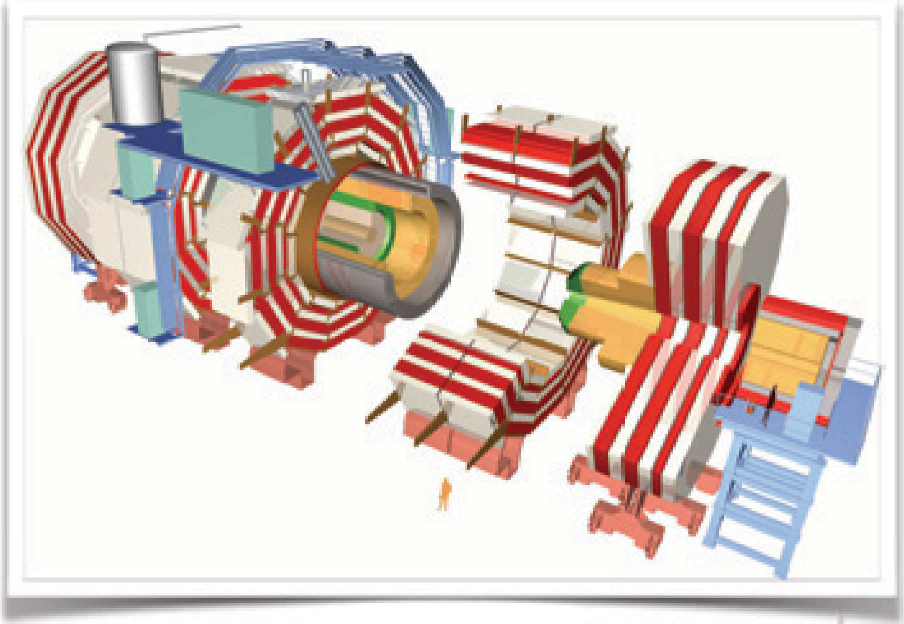




Build a multi-billion CHF collider

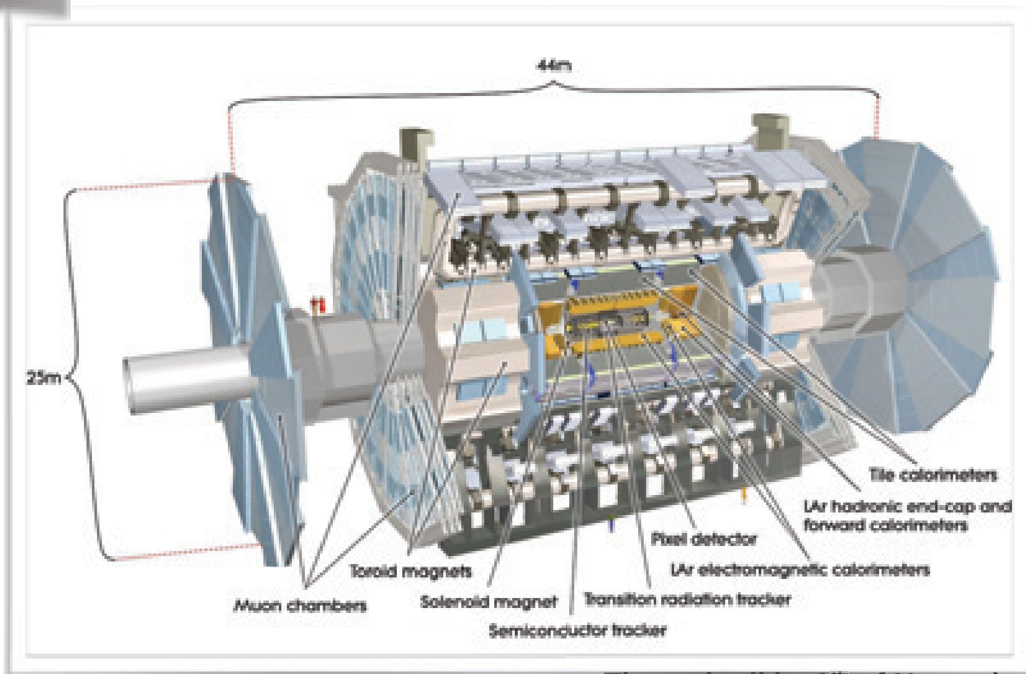


Add a couple of 0.5 billion CHF detectors

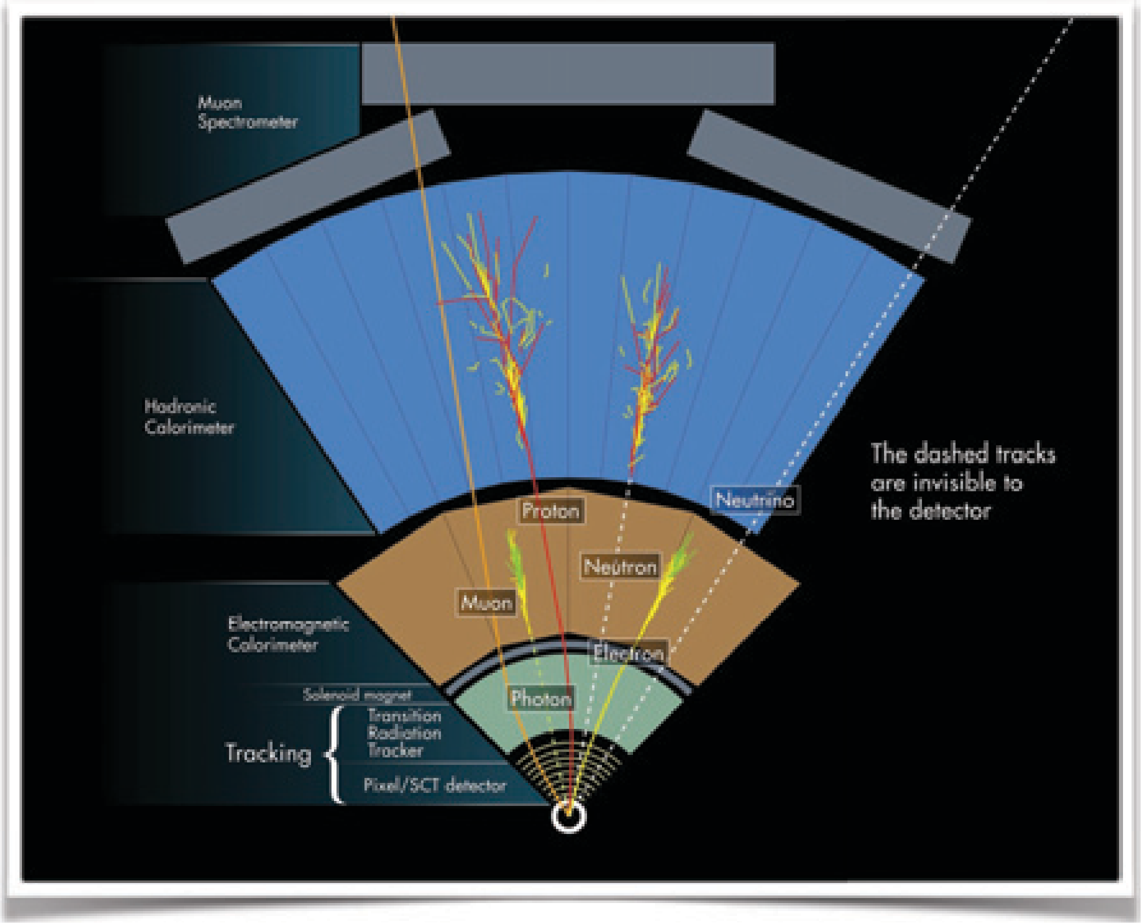


CMS
(Compact Muon Solenoid)

ATLAS
(A Toroidal ApparatuS)



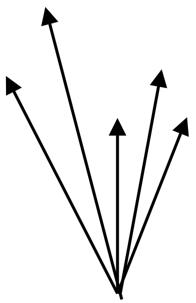
Reconstruction



- Reconstruct electrons, muons, photons from energy deposits

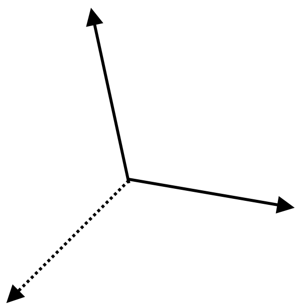
- Reconstruct jets and tag b-jets with sophisticated algorithms

- Use conversation of (transverse) energy to calculate the missing energy (MET)

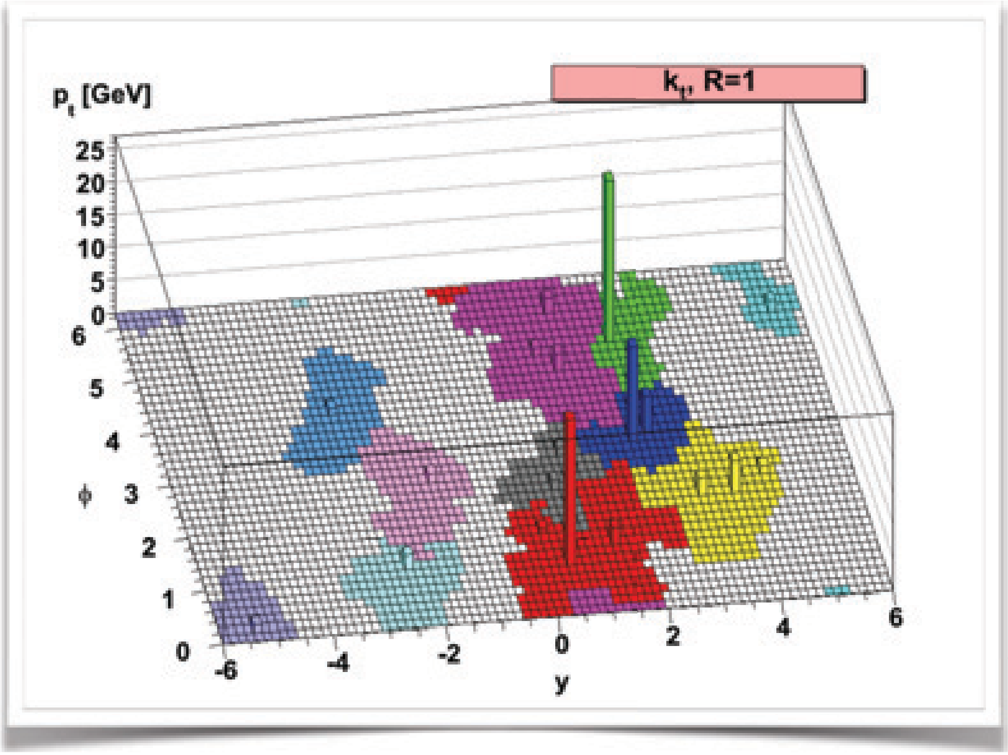


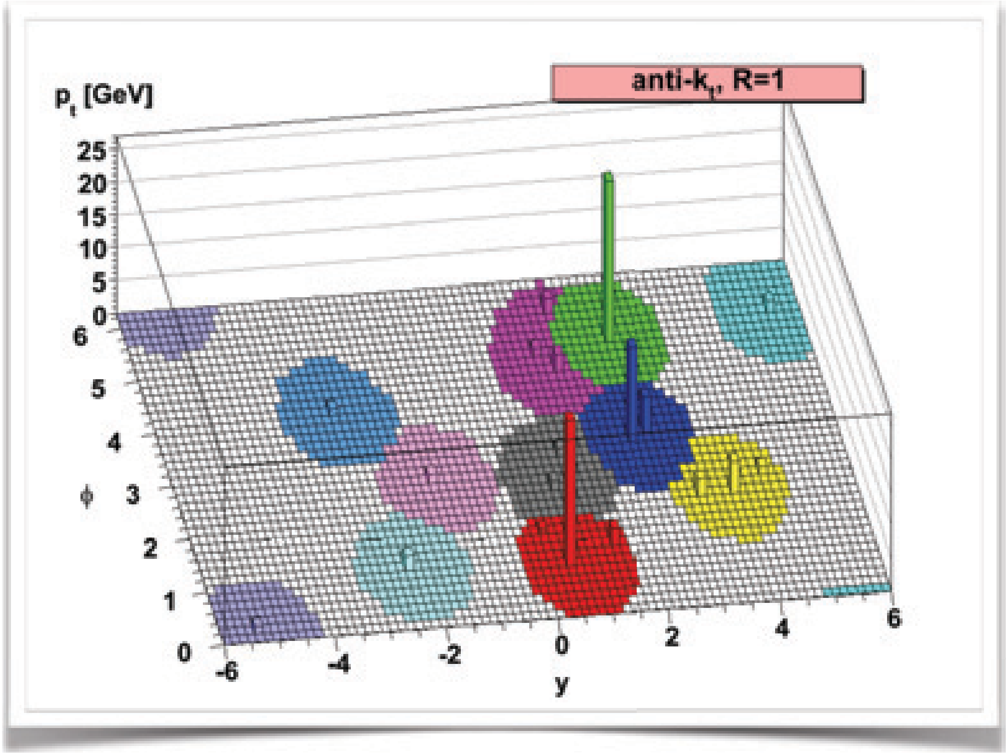
jet

MET



Jet reconstruction

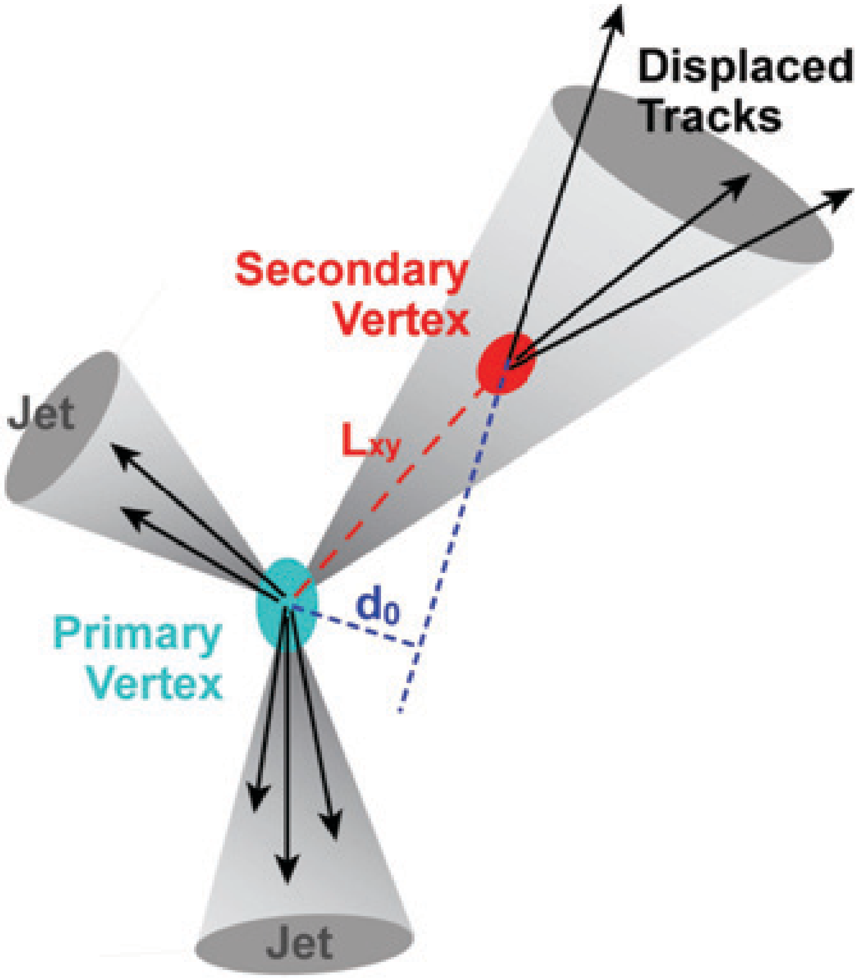




Jet reconstruction algorithms group energy deposits together in different ways to form jets (a lot of input from theory!)

b-jet identification

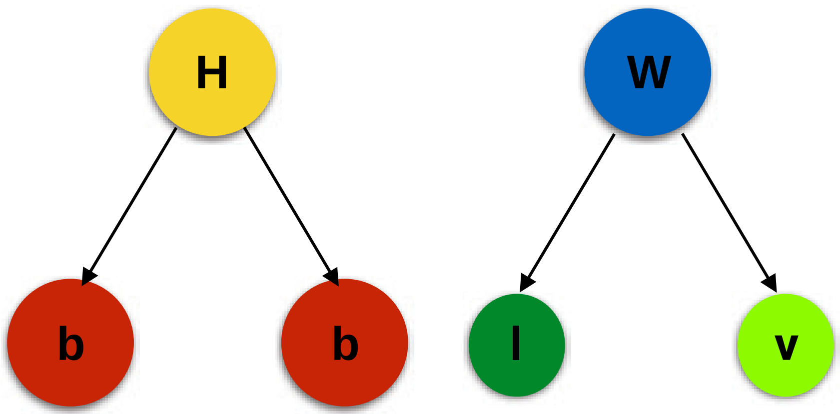
(□ □ □ □ □ □ □ □)



b-quarks have a longer lifetime than other elementary particles

identify b-jets by reconstructing displaced vertices from tracks

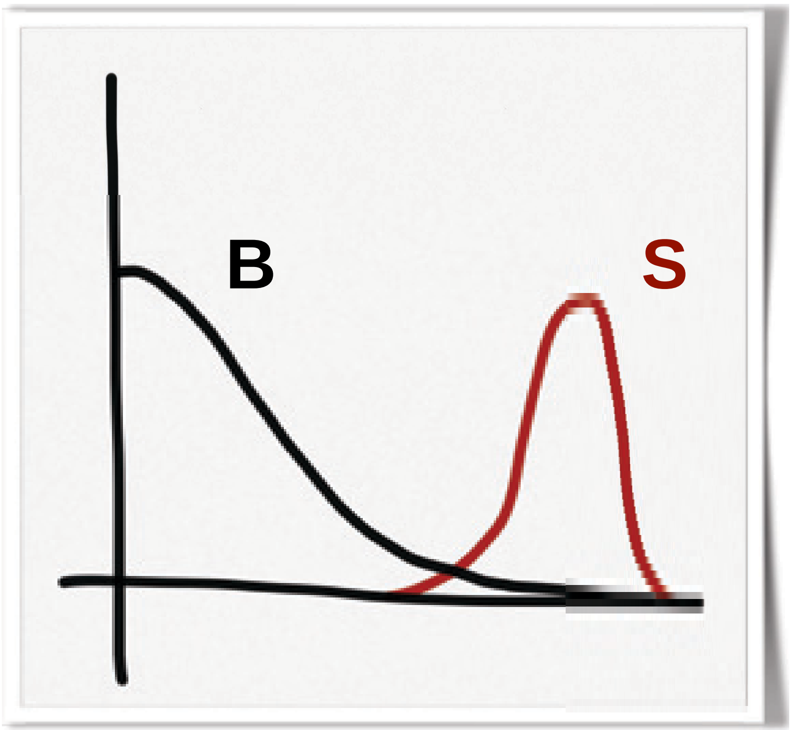
Choose your selection cuts



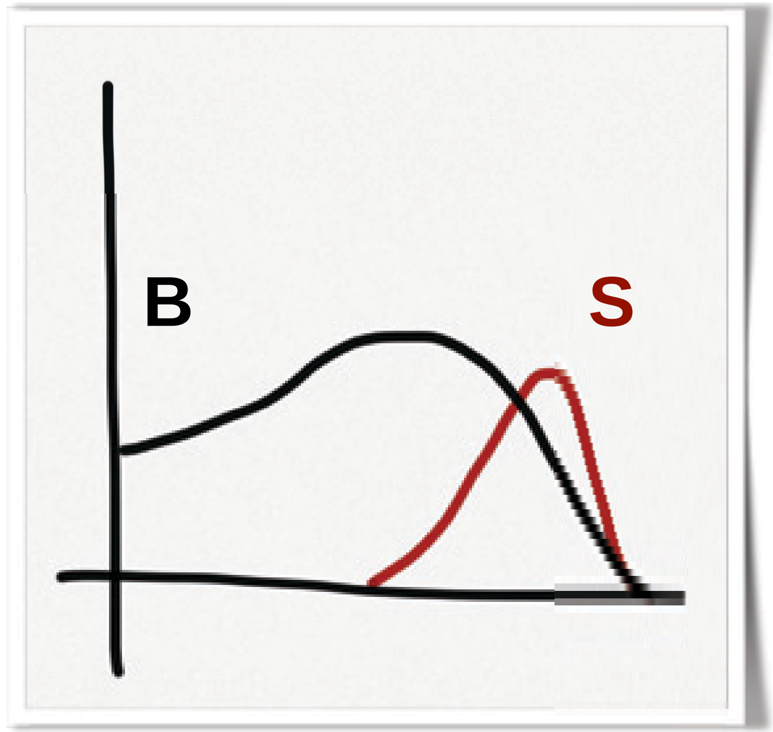
- Need events containing two b-jets, 1 lepton and MET
- $j_1 p_T$ > 45 GeV; $j_2 p_T$ > 20 GeV, MV1c > 80%
- l p_T > 20 GeV; isolated, MET > 20 GeV

Choose discriminating variable

Good discrimination



Poor discrimination

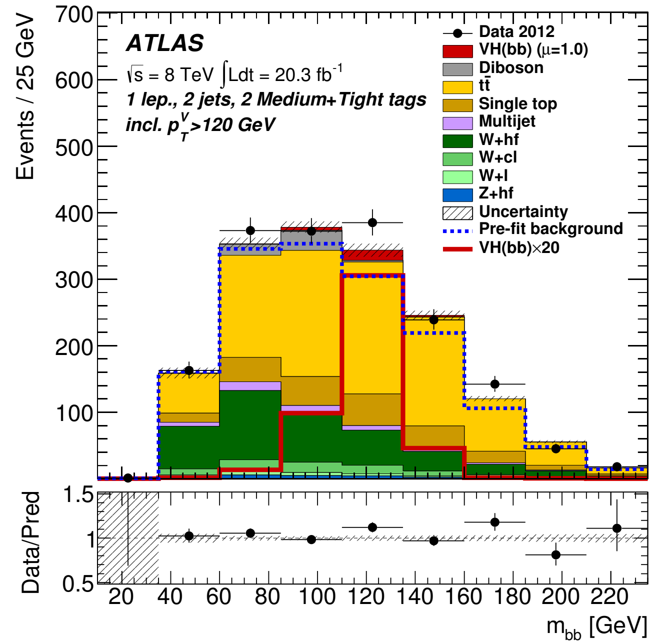


The better the discriminating variable, the larger the separation between signal and background

For the Higgs signal, a good and obvious variable is the mass

Backgrounds

- Background events are other events that look just like signal
- Two types of background
  - Reducible
    - Experimental: better isolation cut, improved b-tagging algorithm
    - Physics: different final state, e.g. additional lepton, jets
  - Irreducible = same final state as signal
    - Often different kinematics or need to apply kinematic cuts



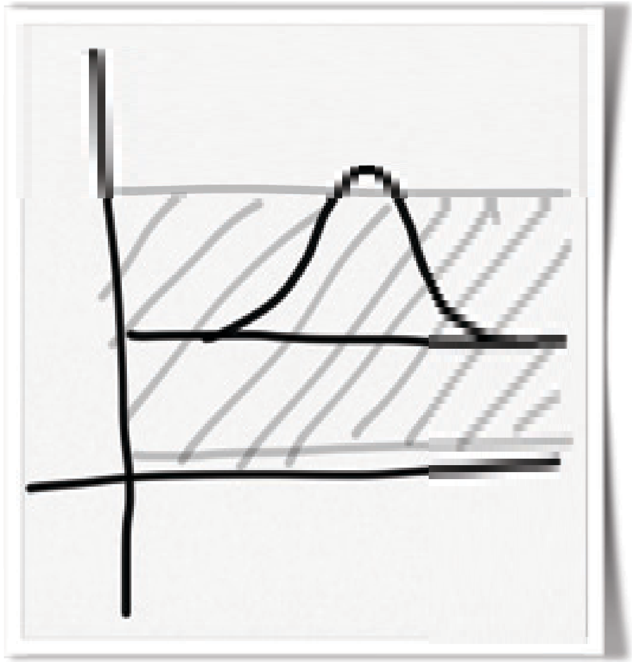
top

W+cl

W+bb

WZ

Background uncertainties

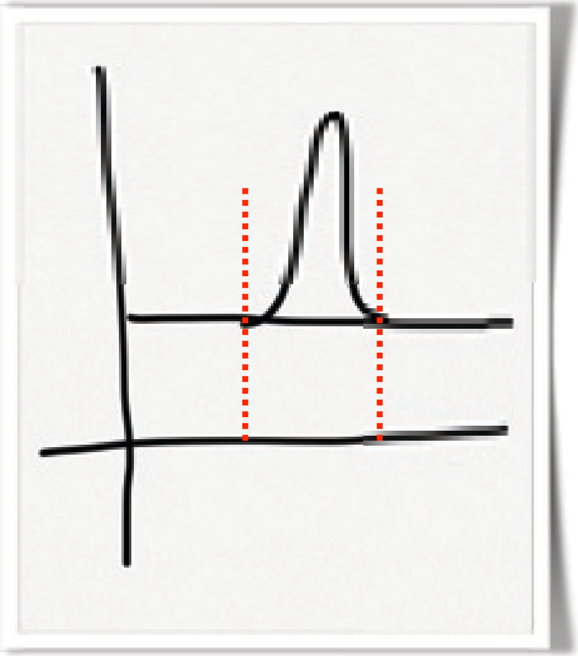


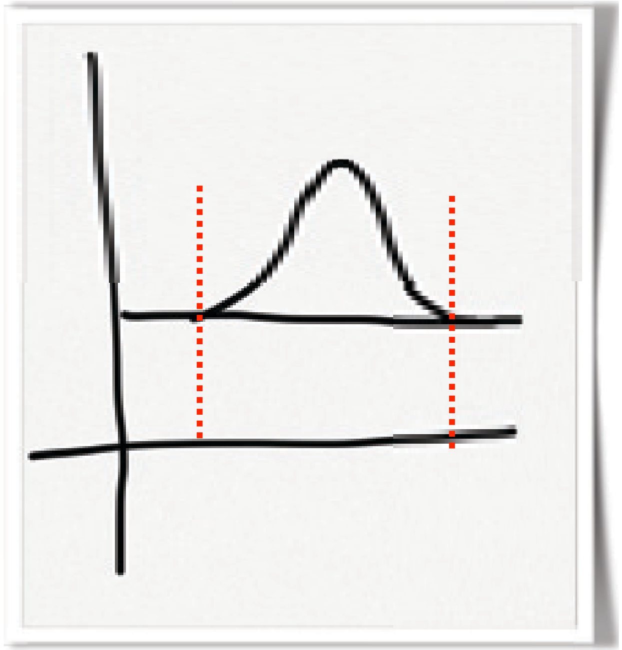
- Large uncertainties -> more difficult to extract the signal
- Uncertainties can be both statistical and systematic
- Decrease impact by either reducing background or reducing uncertainty: e.g. estimate in a control region

Systematic uncertainties

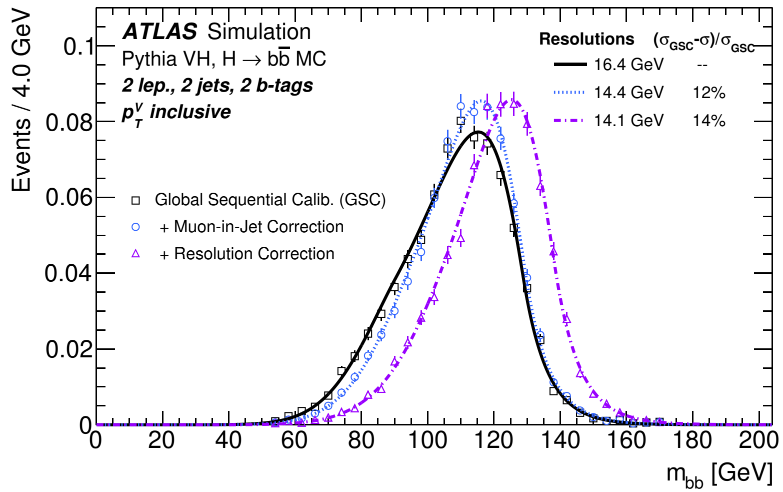
Z+jets	
Zl normalisation, 3/2-jet ratio	5%
Zcl 3/2-jet ratio	26%
Z+hf 3/2-jet ratio	20%
Z+hf/Zbb ratio	12%
$\Delta\phi(\mathrm{jet}_1, \mathrm{jet}_2)$, p_{T}^{V}, m_{bb}	S
W+jets	
Wl normalisation, 3/2-jet ratio	10%
Wcl, W+hf 3/2-jet ratio	10%
Wbl/Wbb ratio	35%
Wbc/Wbb, Wcc/Wbb ratio	12%
$\Delta\phi(\mathrm{jet}_1, \mathrm{jet}_2)$, p_{T}^{V}, m_{bb}	S
$t\bar{t}$	
3/2-jet ratio	20%
High/low-p_{T}^{V} ratio	7.5%
Top-quark p_{T}, m_{bb}, $E_{\mathrm{T}}^{\mathrm{miss}}$	S
Single top	
Cross section	4% (s-,t-channel), 7% (Wt)
Acceptance (generator)	3%–52%
m_{bb}, $p_{\mathrm{T}}^{b_1}$	S
Diboson	
Cross section and acceptance (scale)	3%–29%
Cross section and acceptance (PDF)	2%–4%
m_{bb}	S
Multijet	
0-, 2-lepton channels normalisation	100%
1-lepton channel normalisation	2%–60%
Template variations, reweighting	S

Improving sensitivity: mass resolution

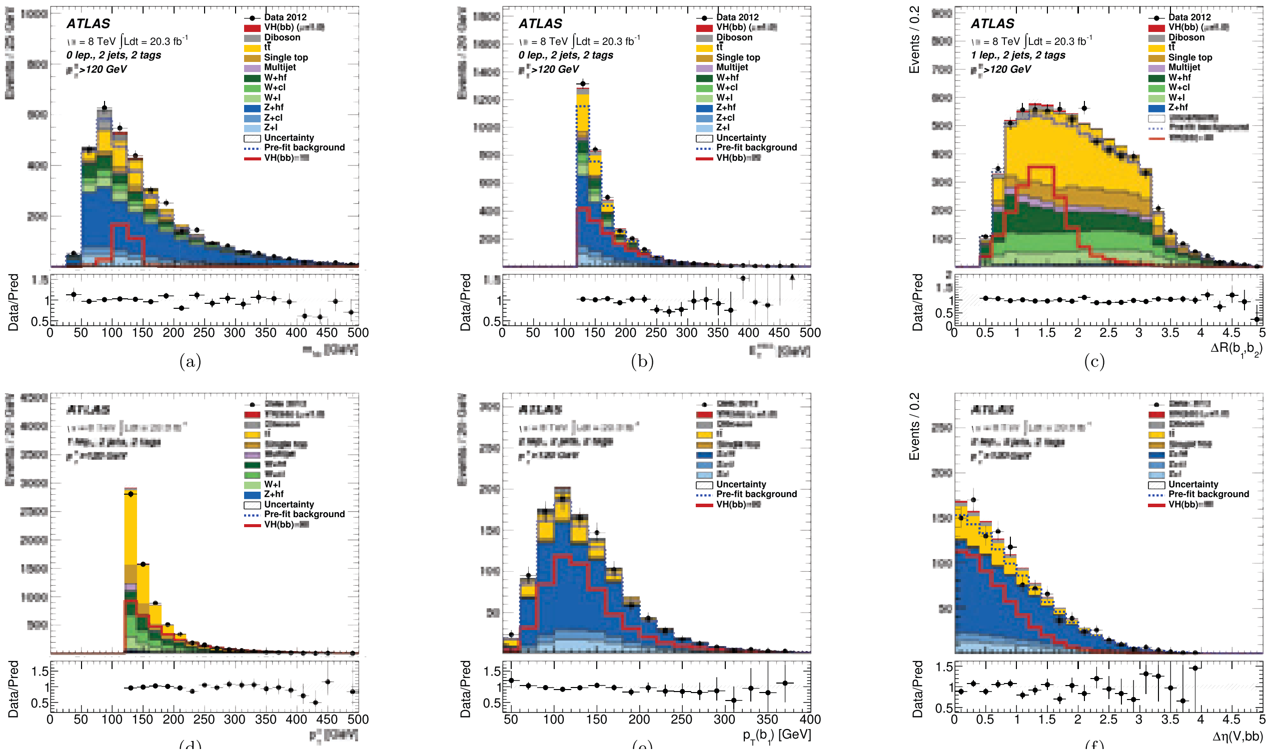


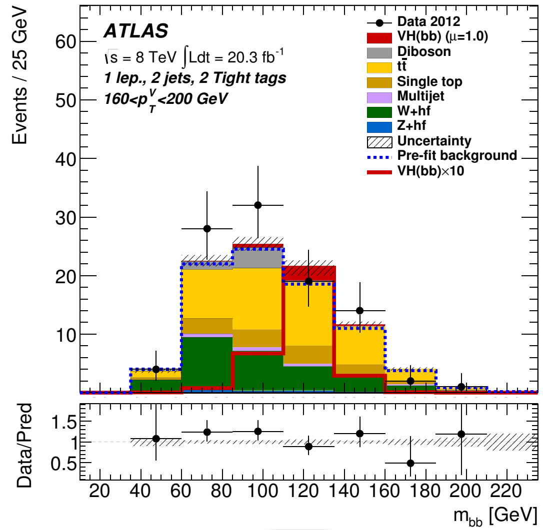


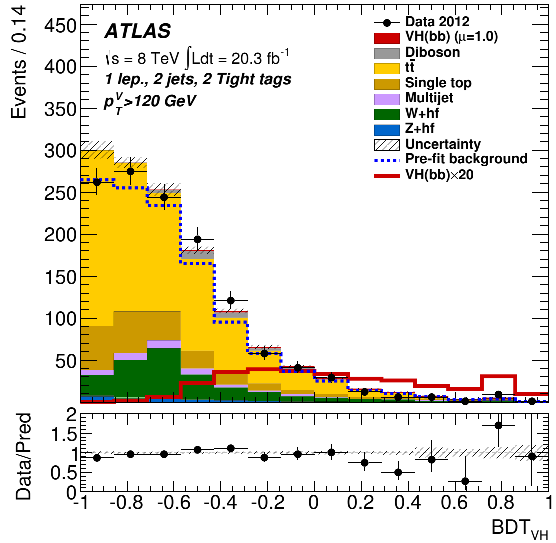
- The better the mass resolution, the smaller the amount of background that needs to be considered
- 14% improvement in resolution



Improving sensitivity: MVA



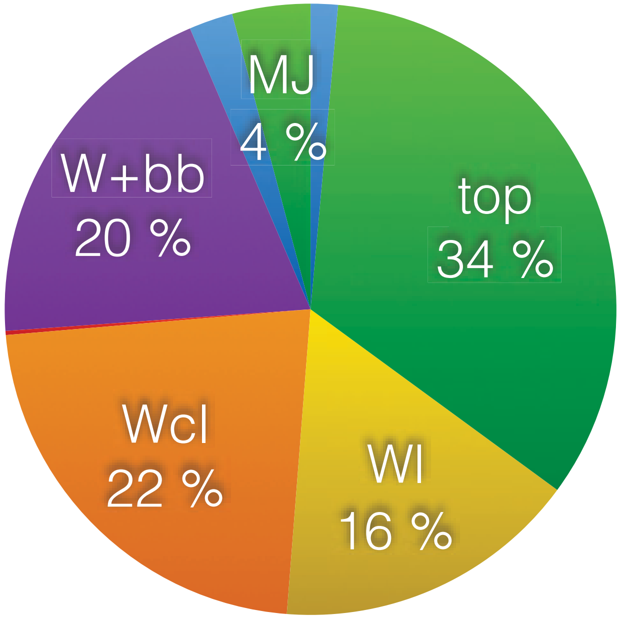




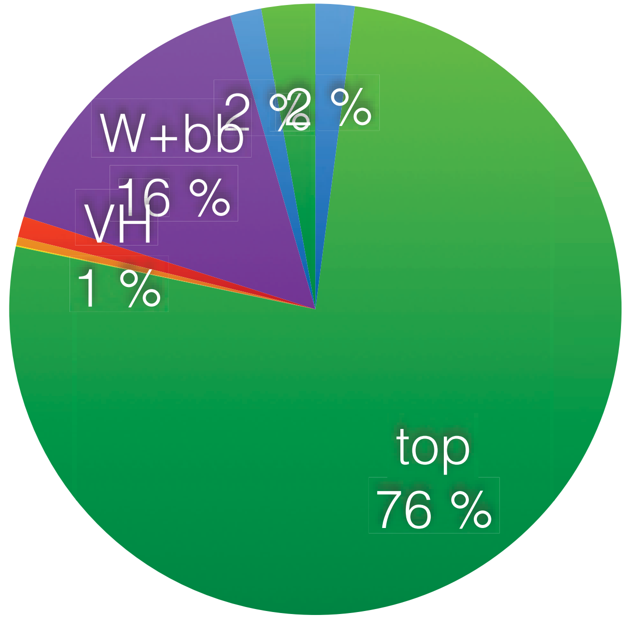
Multivariate techniques combine information from kinematic distributions into a single discriminating variable

Improving sensitivity: categories

loose b-tag



tight b-tag

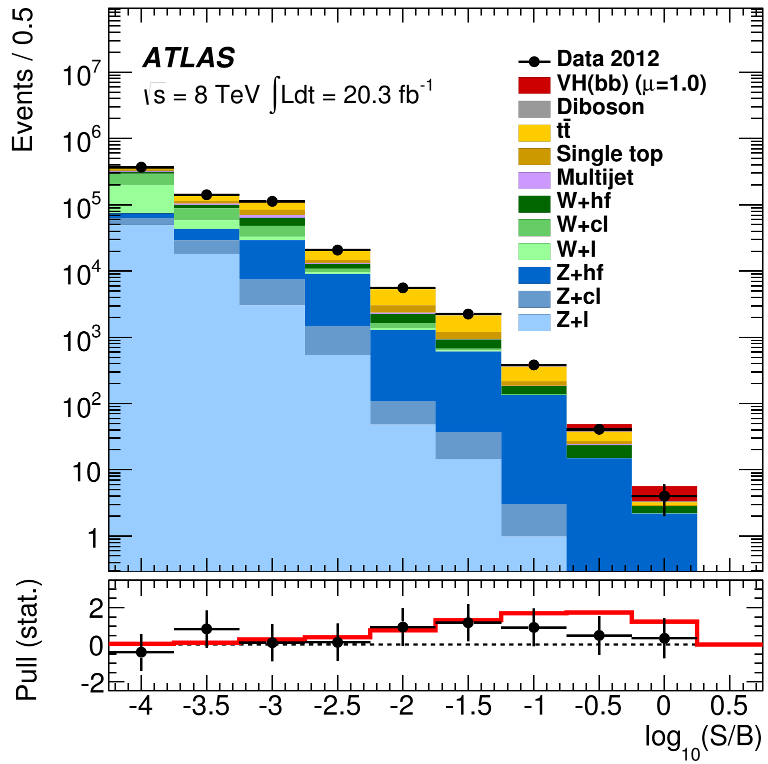


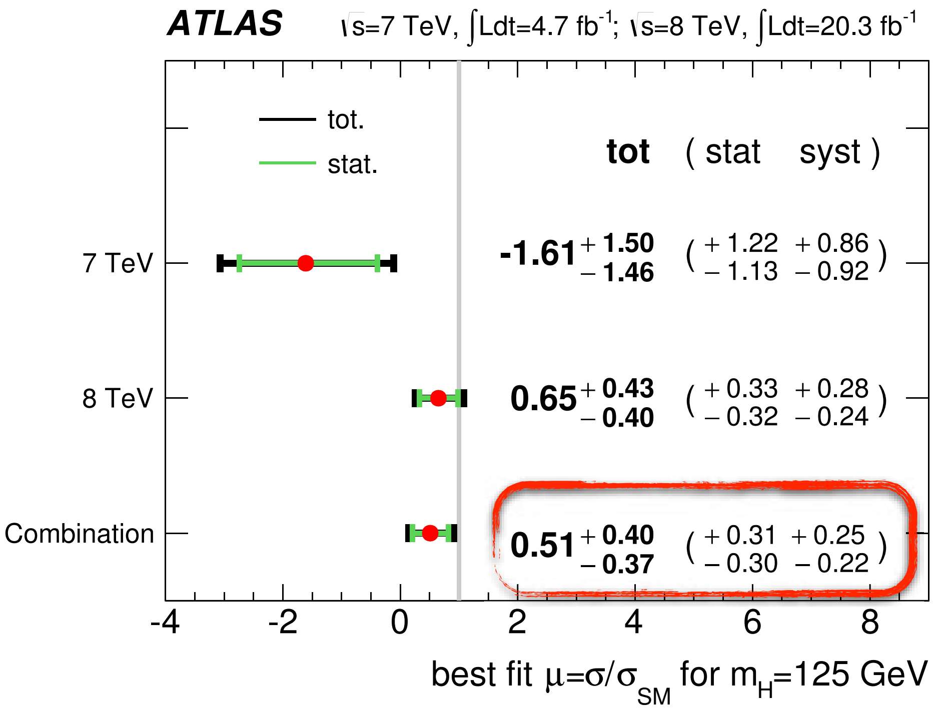
- Simple idea: add cuts to divide events into categories
  - Don't throw away any events
  - Separate out high S/B regions
  - Information to constrain backgrounds
- For VH(bb) we categorise depending on the number of jets x Higgs p_T x b-tagging quality
  - Huge improvement to sensitivity; largely from background constraint

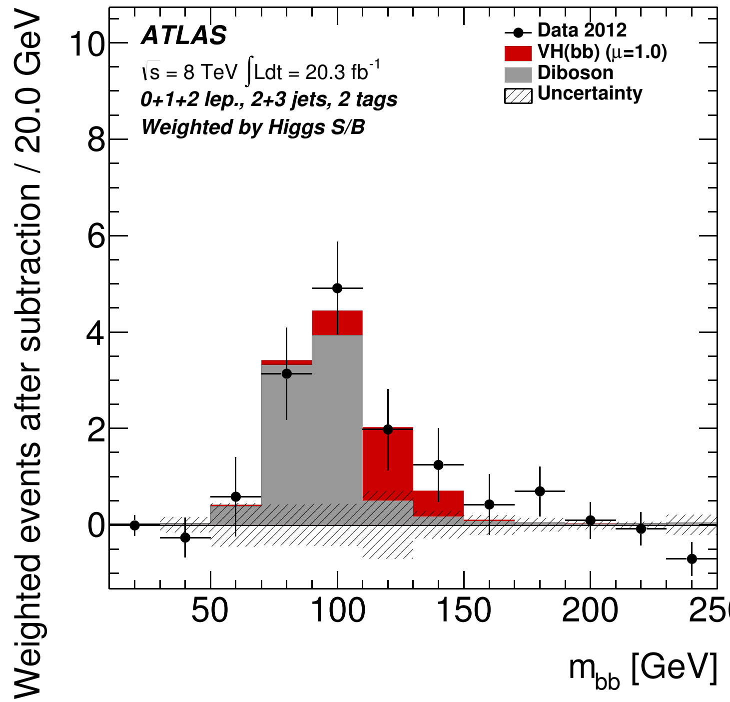
Process	Scale factor
$t\bar{t}$ 0-lepton	1.36 ± 0.14
$t\bar{t}$ 1-lepton	1.12 ± 0.09
$t\bar{t}$ 2-lepton	0.99 ± 0.04
Wbb	0.83 ± 0.15
Wcl	1.14 ± 0.10
Zbb	1.09 ± 0.05
Zcl	0.88 ± 0.12

Result

- Look for an excess over background prediction
- Fit rate with respect to the Standard Model prediction
  - $\mu = \sigma/\sigma_{SM}$
- Small excess, but a little smaller than the SM prediction
  - More data needed !







Conclusion on H to bb search

- A lightning tour of the >20 years of work it took to probe the Higgs coupling to b-quarks
- Discussed some key aspects of analysis design
  - Discriminating variable selection
  - Mass resolution
  - Background estimate
  - Systematic Uncertainties
- For bb, we're not quite there yet, but getting very close
  - Perhaps one of you will be the one to observe it ?