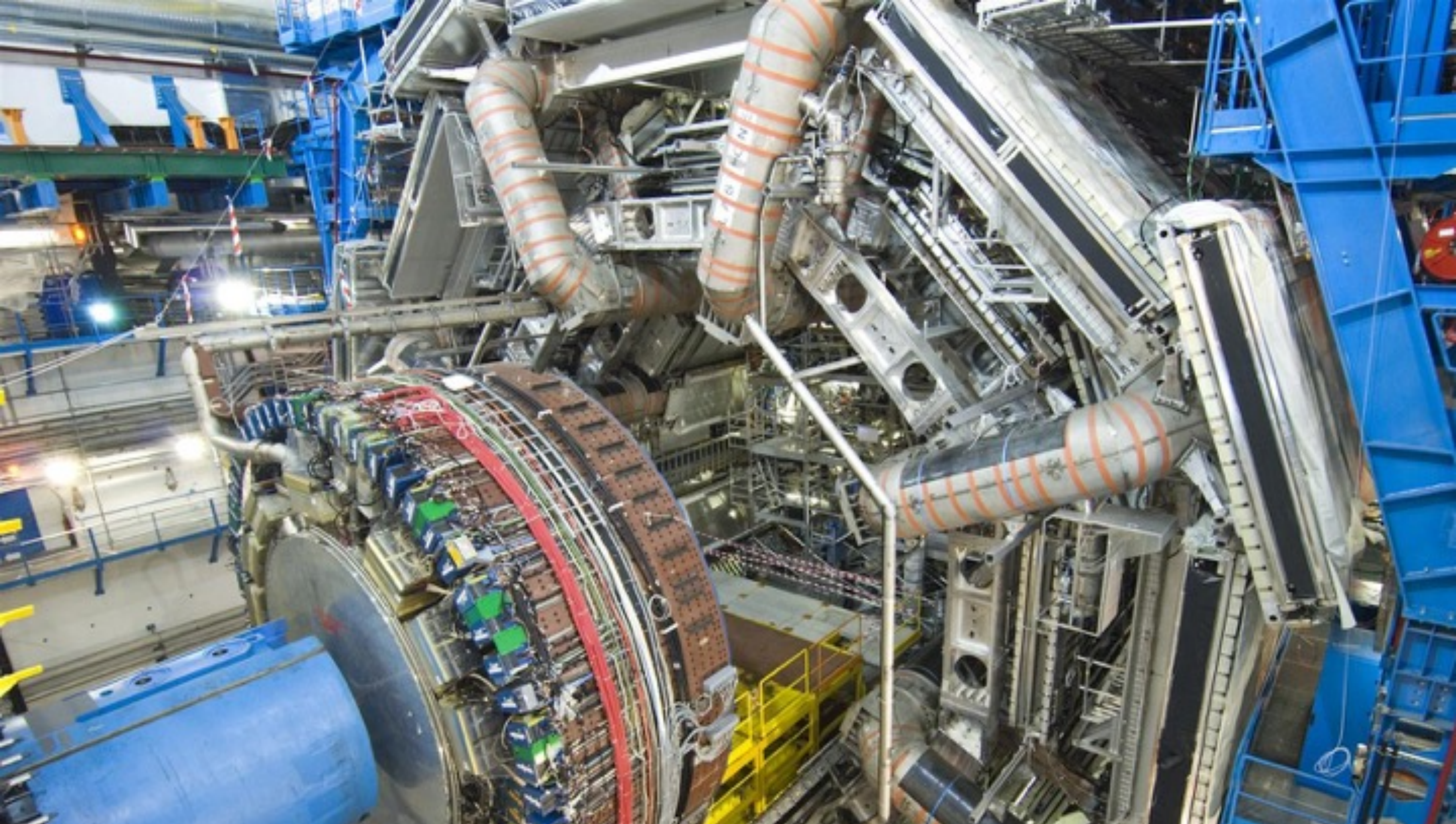
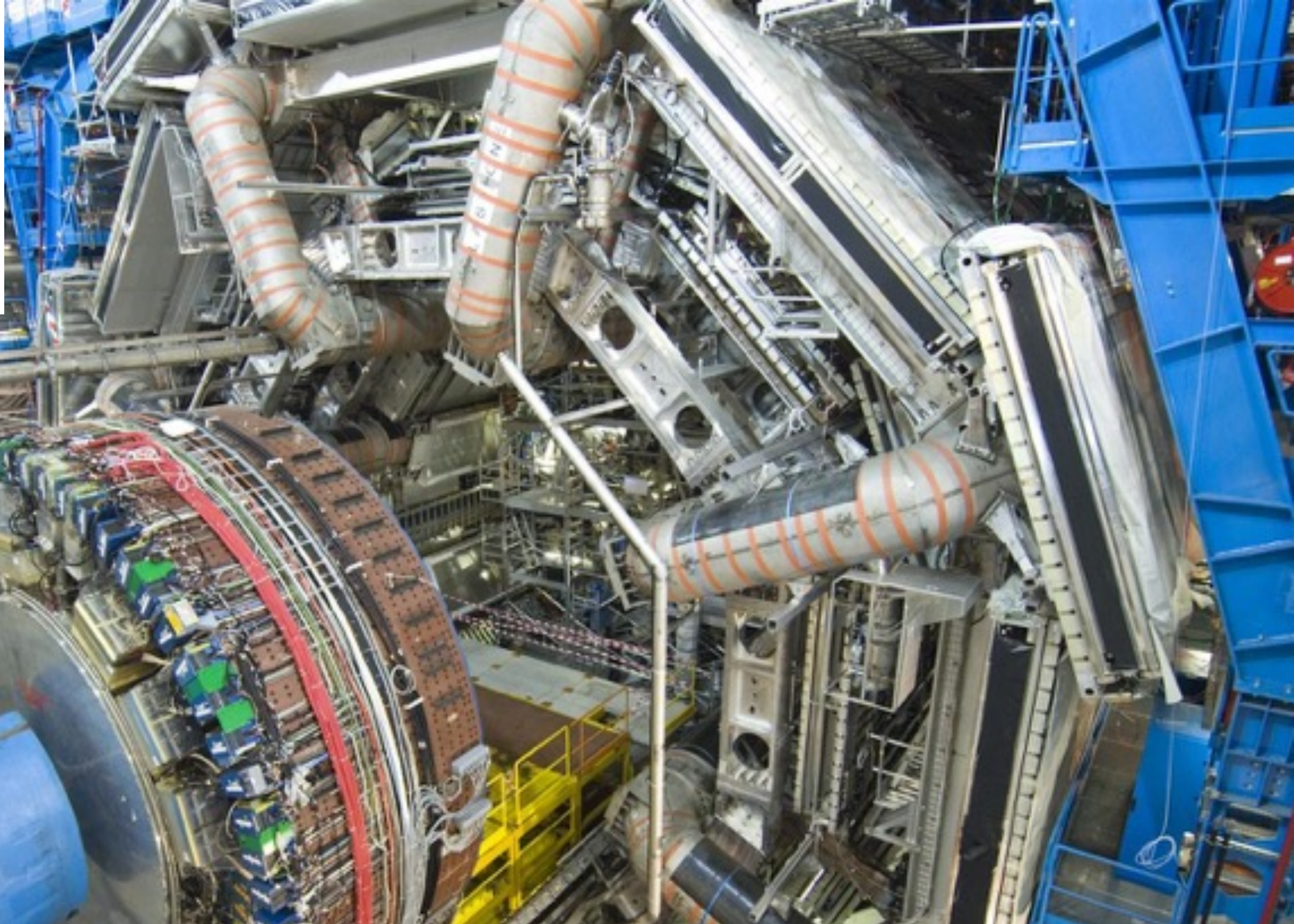


Physics at the LHC: a historical perspective and a pedagogical view on how this is done. The role of theory and experiment

D. Froidevaux (CERN)



***Physics at the LHC*: 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 2015

♥ 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

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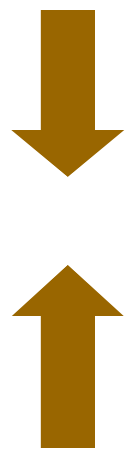

Huge success of Standard Model in particle physics:

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!

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Still incompatible today from a theoretical viewpoint

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

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Observations (measurements: build detectors)

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

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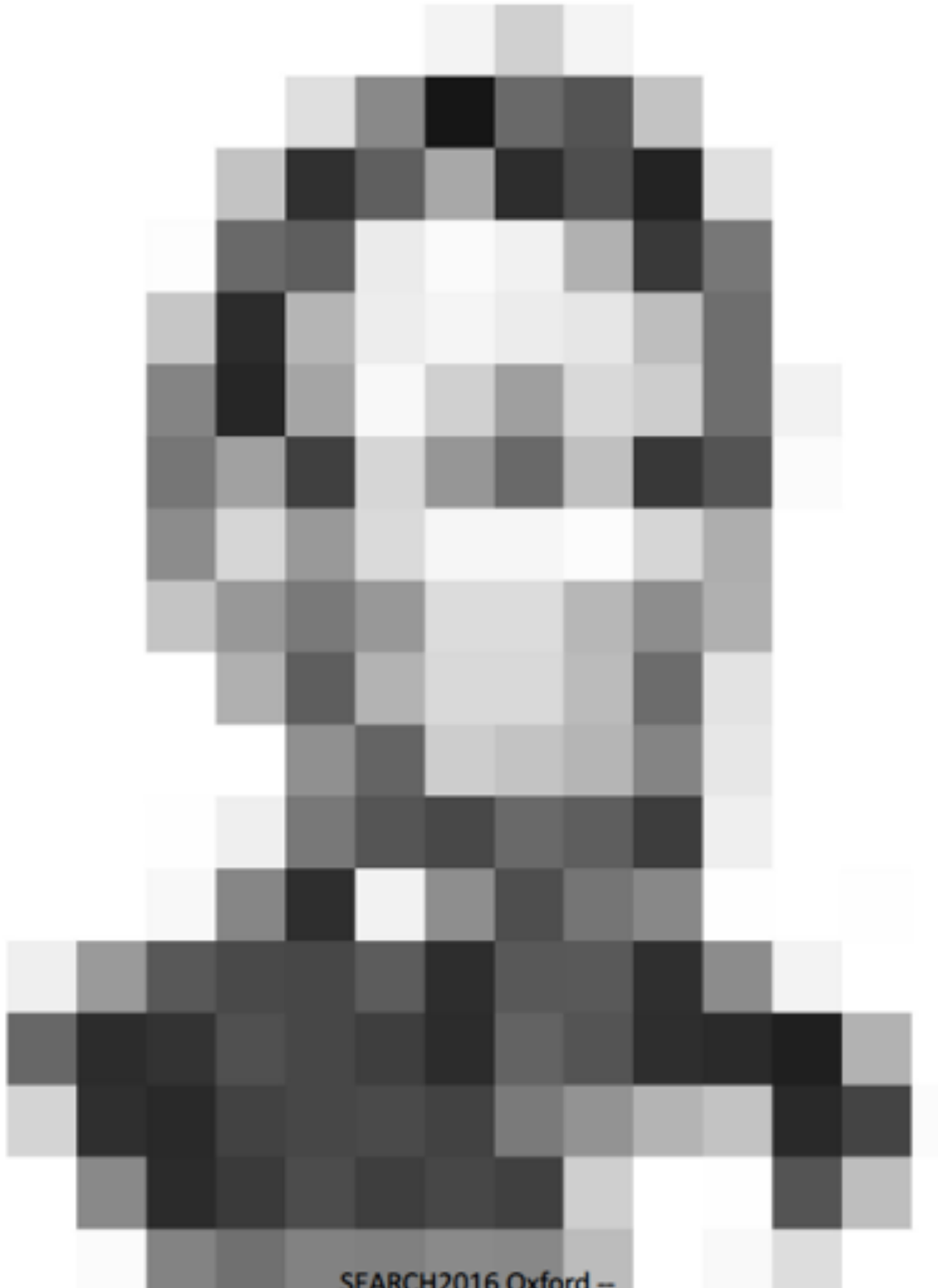
Perception & understanding *with a roadmap*

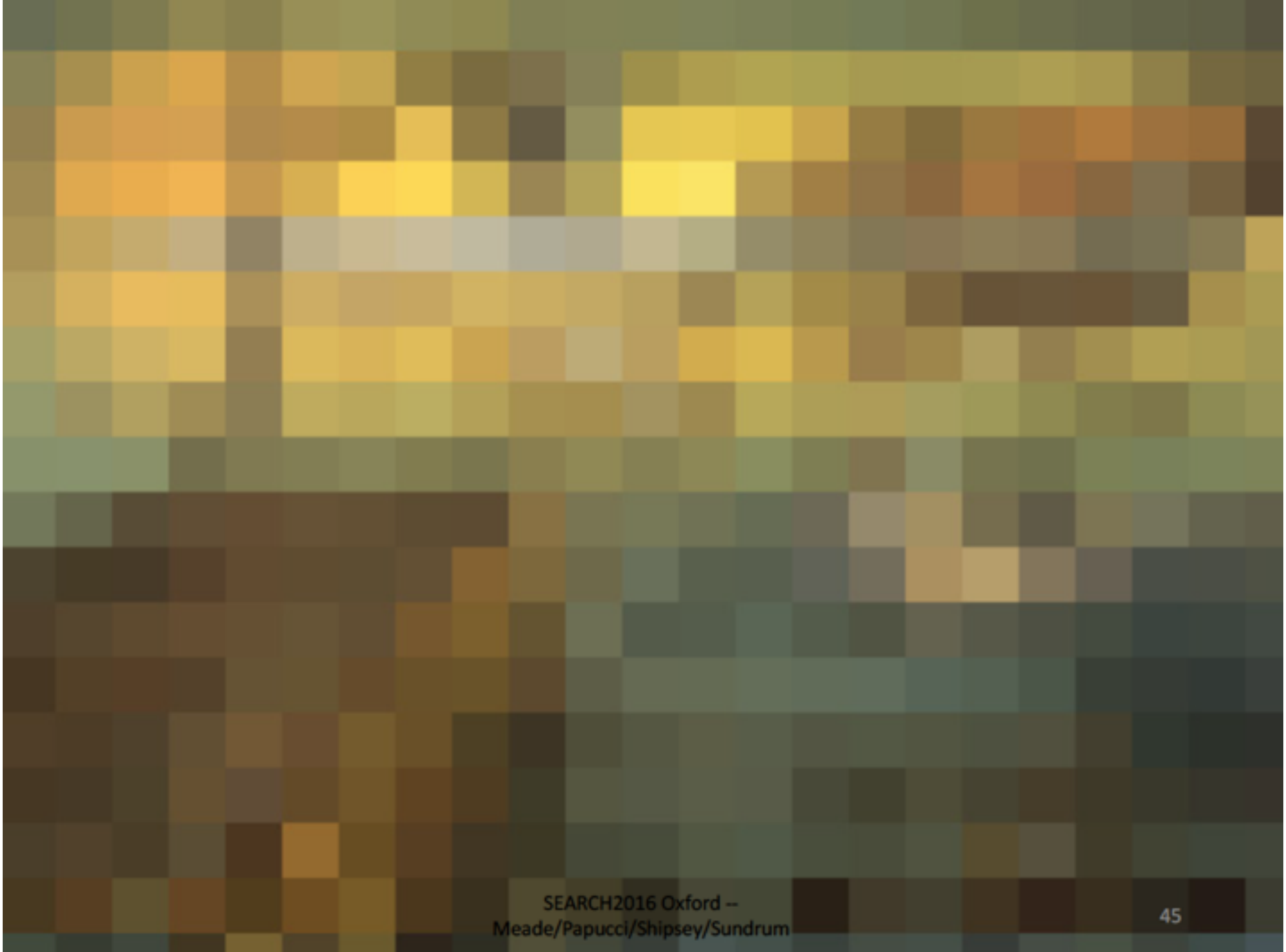
Perception is a dynamic combination of top-down (theory) and bottom-up (data driven) processing

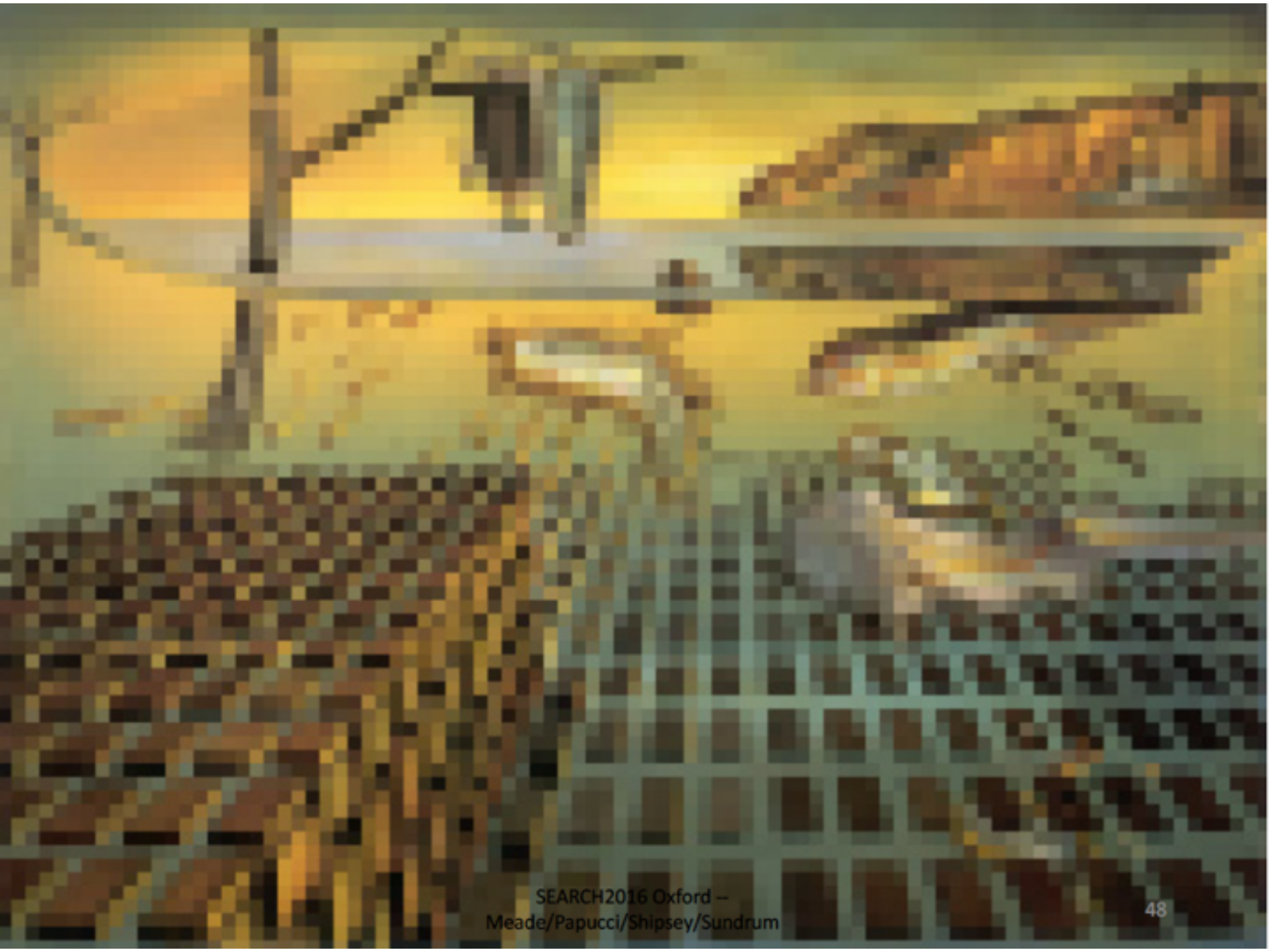
- The need for detail (quality and quantity of the data) depends on the *distinctiveness* of the object and the *level of familiarity*

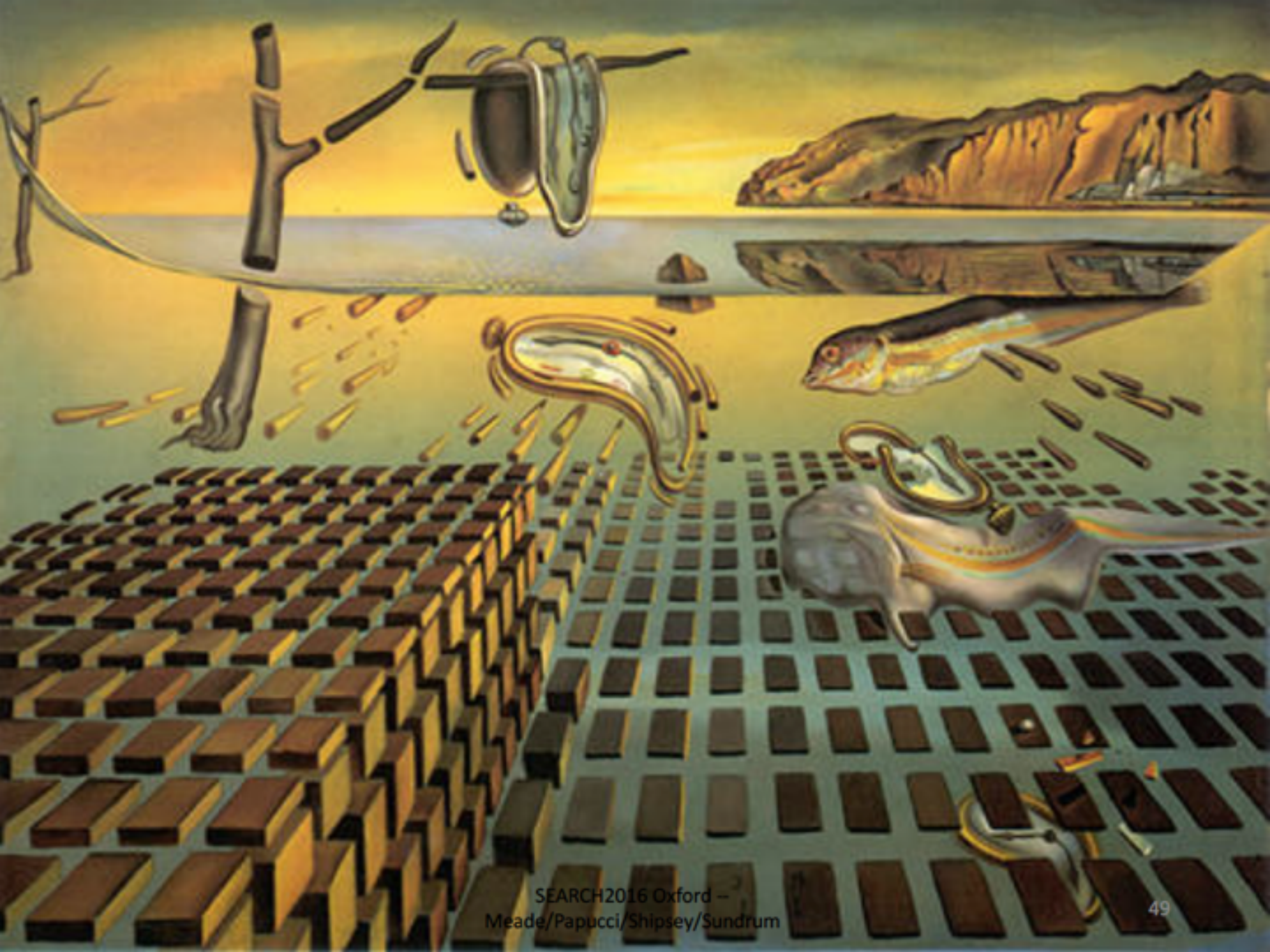
When we know the characteristics and context of what to expect (W,t,H) a little data goes a long way (top-down dominates)



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)	w/o a roadmap (data driven)
	
For the discovery of (W/Z, top quark, Higgs boson), a little data goes a long way (top-down dominates)	**For the discovery of new physics, need a lot of data and many different viewpoints (bottom-up dominates)**

Main questions I wish you to reflect on for the tutorial today and perhaps more importantly on the longer term to make the right choices for your professional life!

- ♥ As experimentalists, we should guided by what theory tells us to design our experiments. Why is this important?

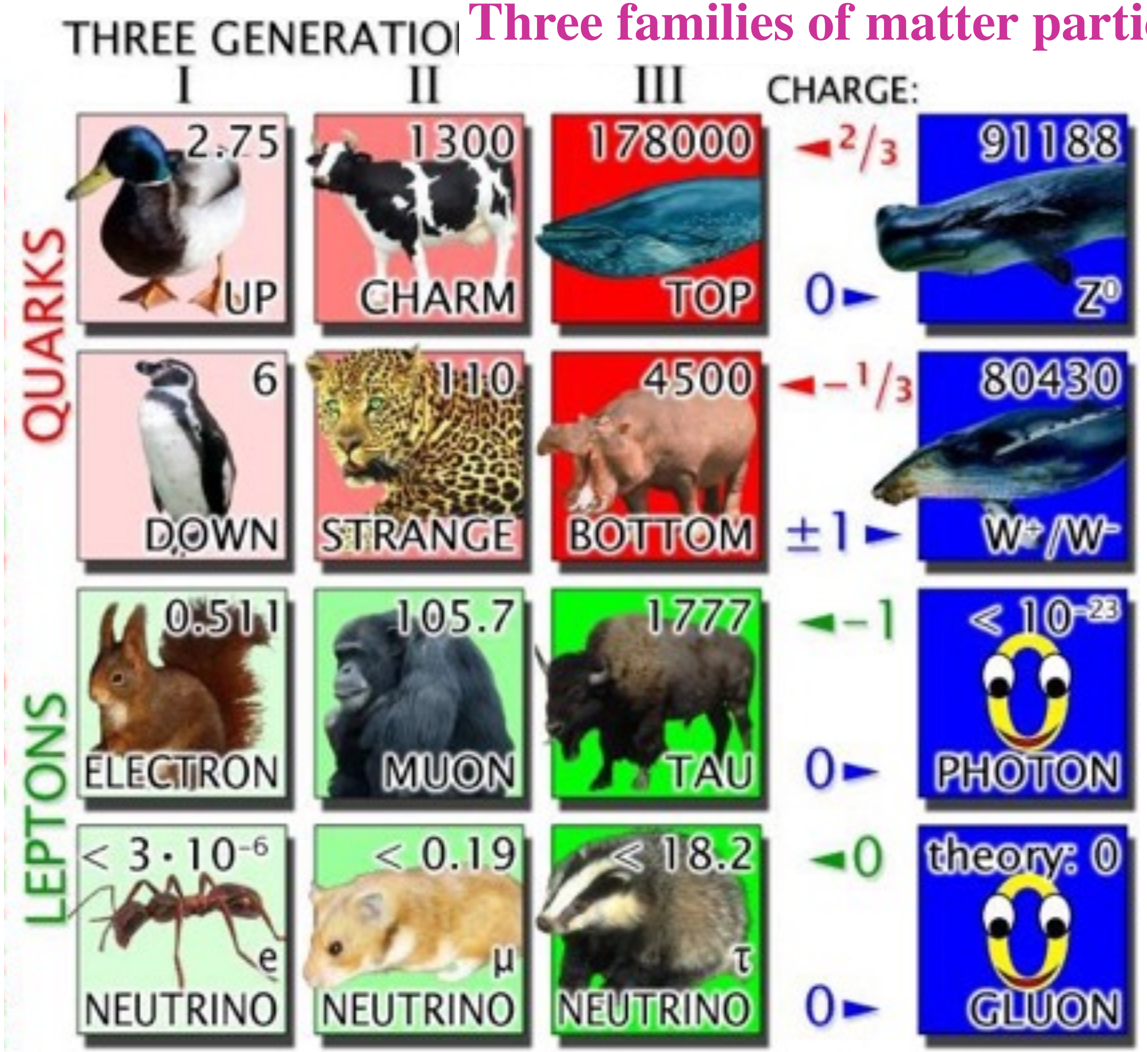
- ♥ But our (general-purpose) experiments should be as unbiased as possible by theory when probing a new energy frontier. Why? Answer is simple enough (only nature knows what lies beyond the horizon of our knowledge).

- ♥ The real question is: how to achieve the above? Which are the main ingredients? Elements of answers are: trigger of the experiment, quality of experimental measurements, simulation of physics processes of all types at the interaction point and simulation of physics processes occurring in the detector when particles traverse it.

- ♥ Are there any other ingredients? Yes! I will illustrate these tomorrow in more detail with a few examples. They are related to the interplay between theory and experiment.

The zoo of elementary particles in the Standard Model

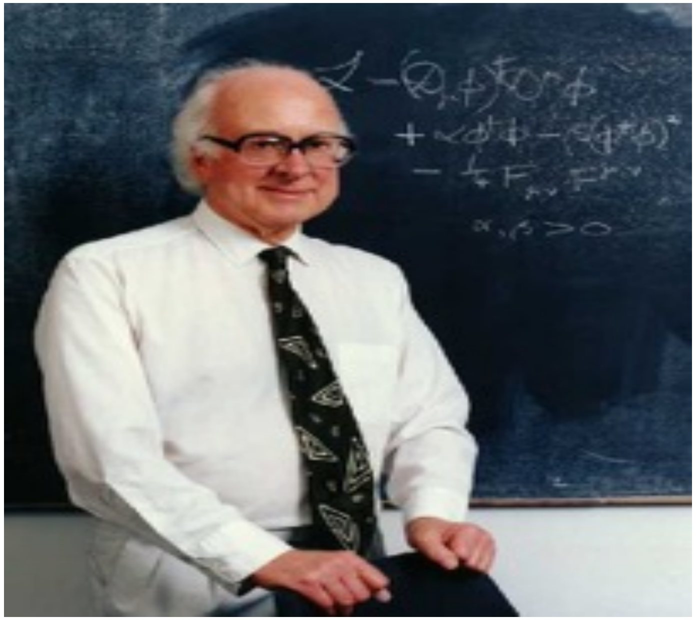
Three families of matter particles



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?



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Higgs boson has been with us for many decades as:

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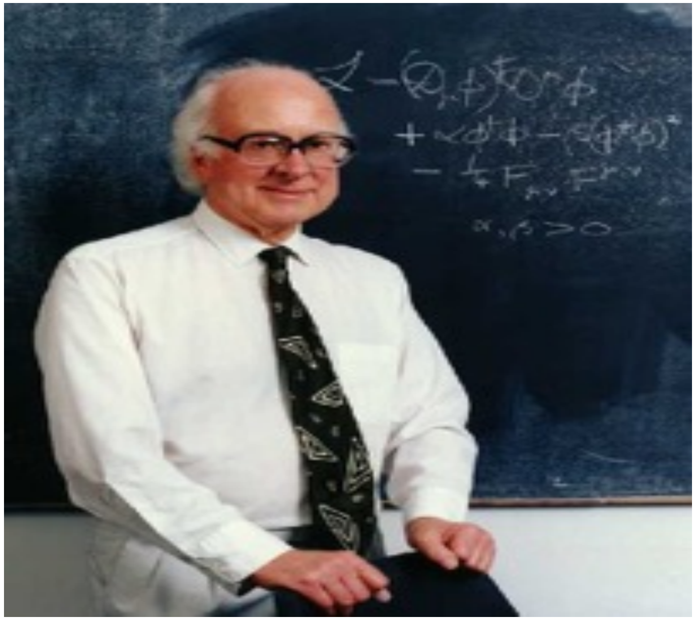

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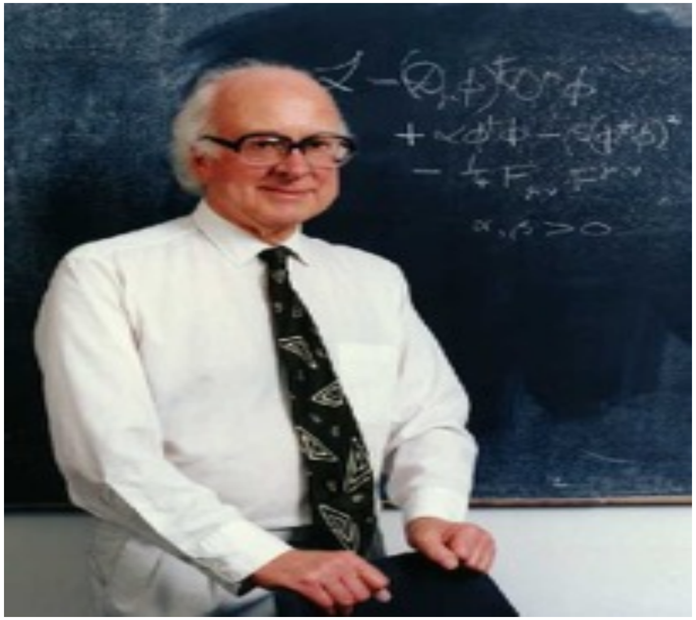

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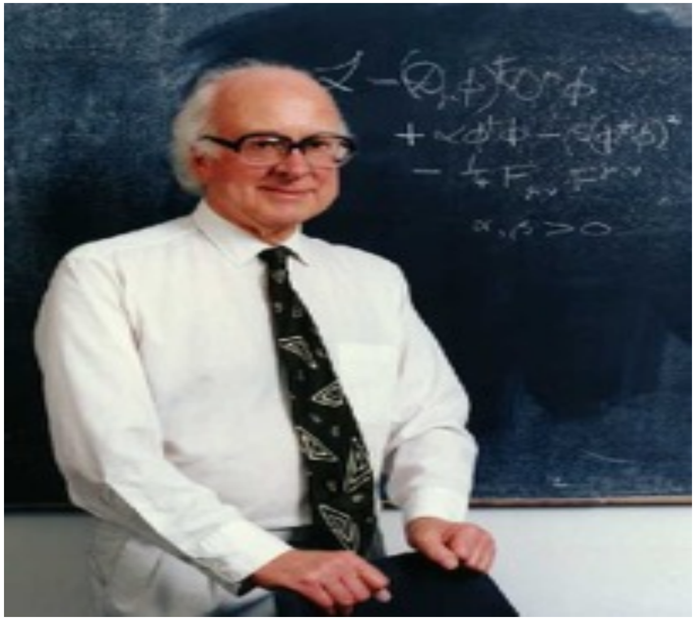

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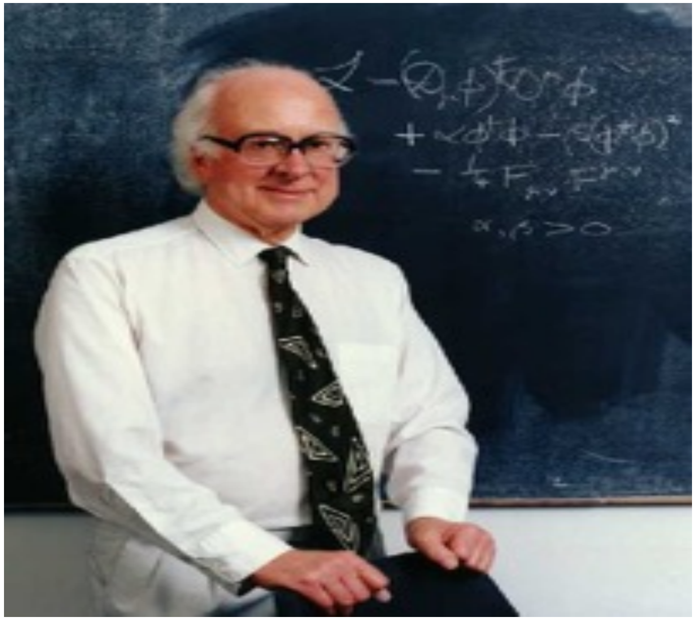

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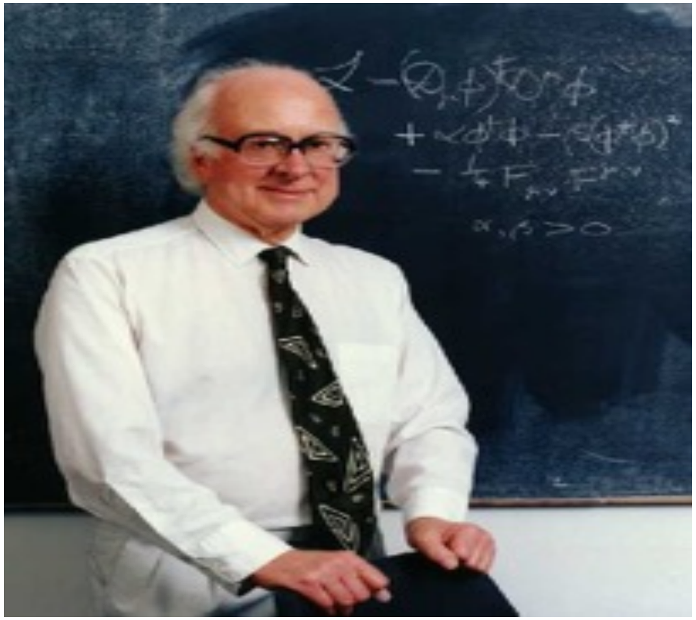

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The giant challenge of the LHC

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 . 10^{14} (1 ng of H^+)

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700 MJ dissipated in 88 μs ≅ 8 TW

Total world electrical capacity ≅ 3.8 TW

90 kg of TNT per beam

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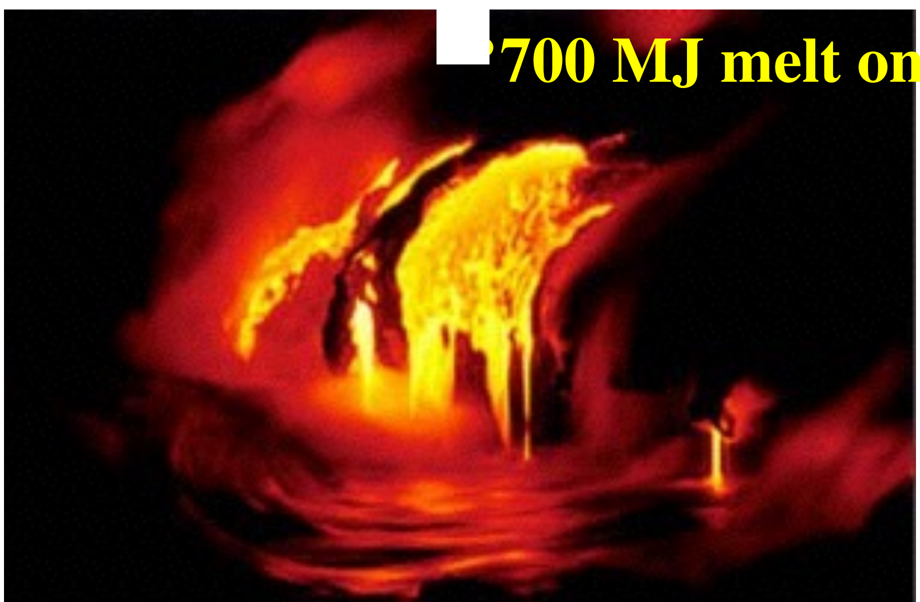

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Is the LHC an efficient machine?

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

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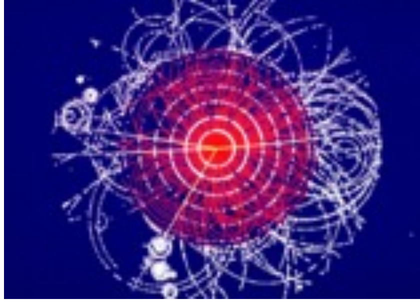


Energy of 100 Higgs bosons

―――――――――――――――― $\cong 10^{-20}$

Total energy provided by EDF

140 MW during 2000 hours: 100 000 GJ

A laughingly small efficiency?

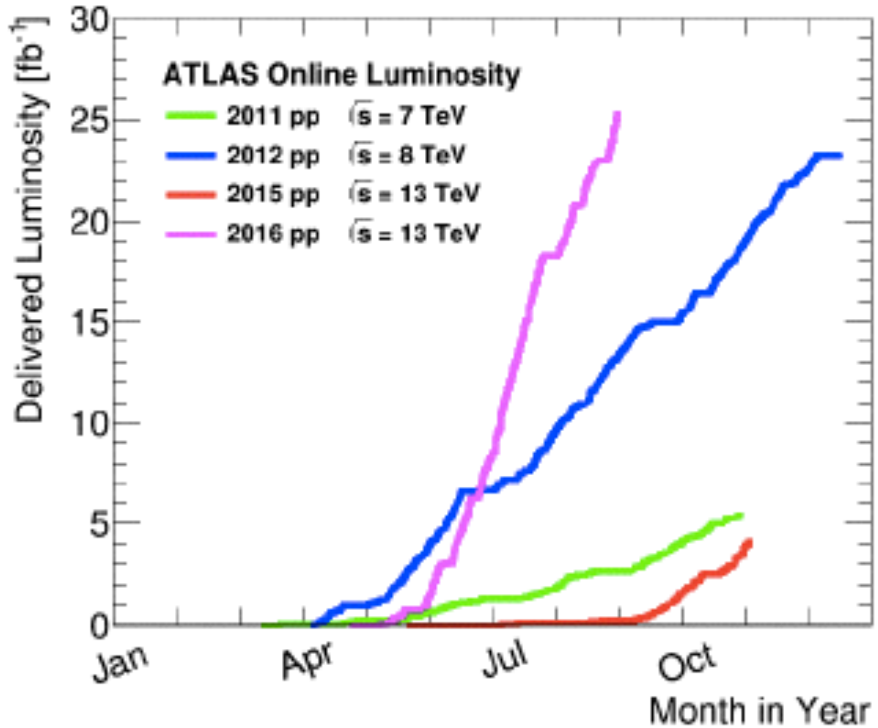
No, an incredible tool produced by humanity to improve our understanding of the fundamental properties of nature

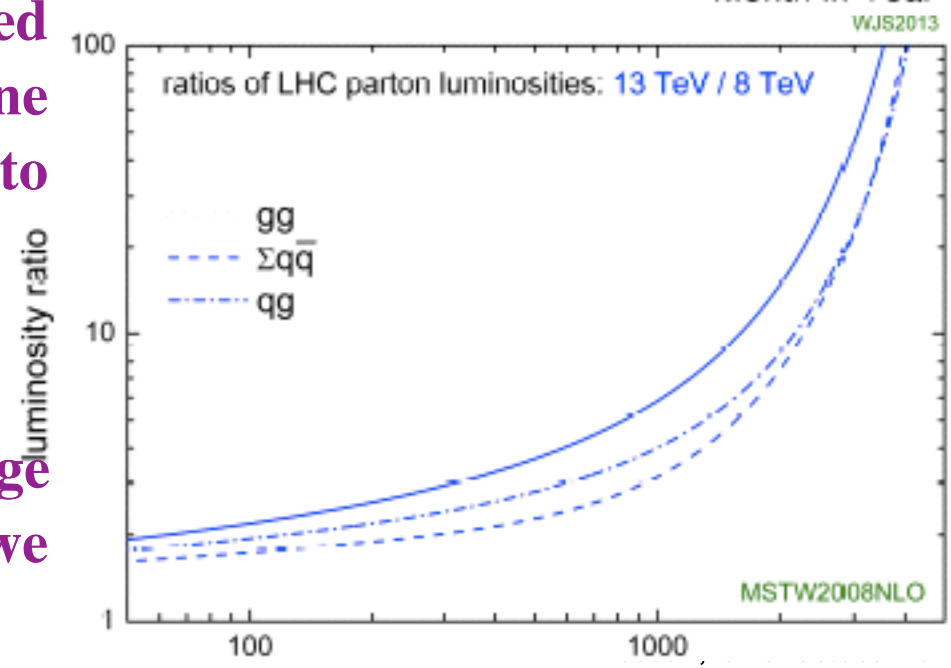
♥ Exceptional performance of the LHC this year!

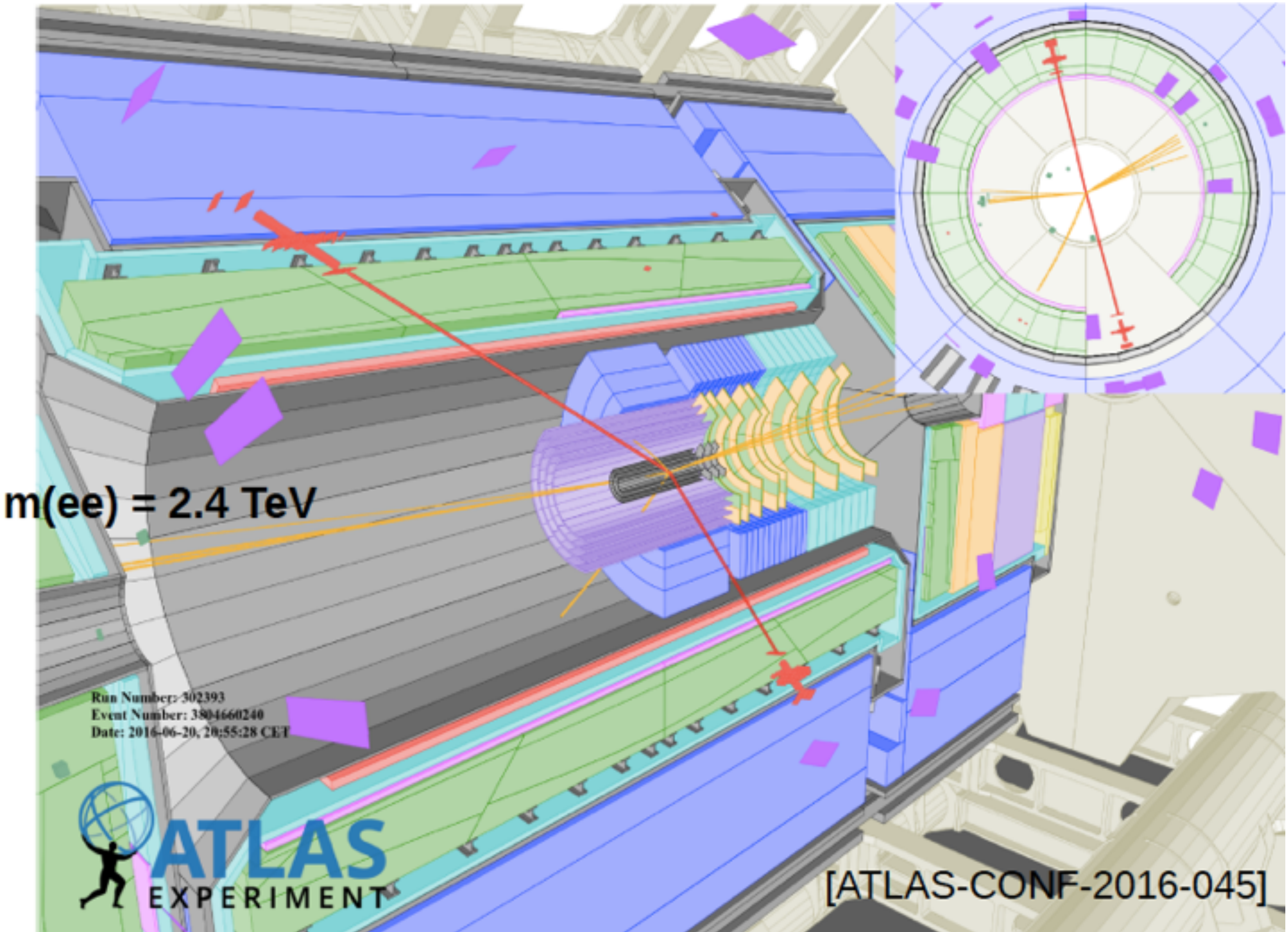
♥ Experiments will collect more than 30 fb^{-1} of data for physics. In one year, supersede statistics of 7/8 TeV data by more than a factor of 3!

♥ 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!

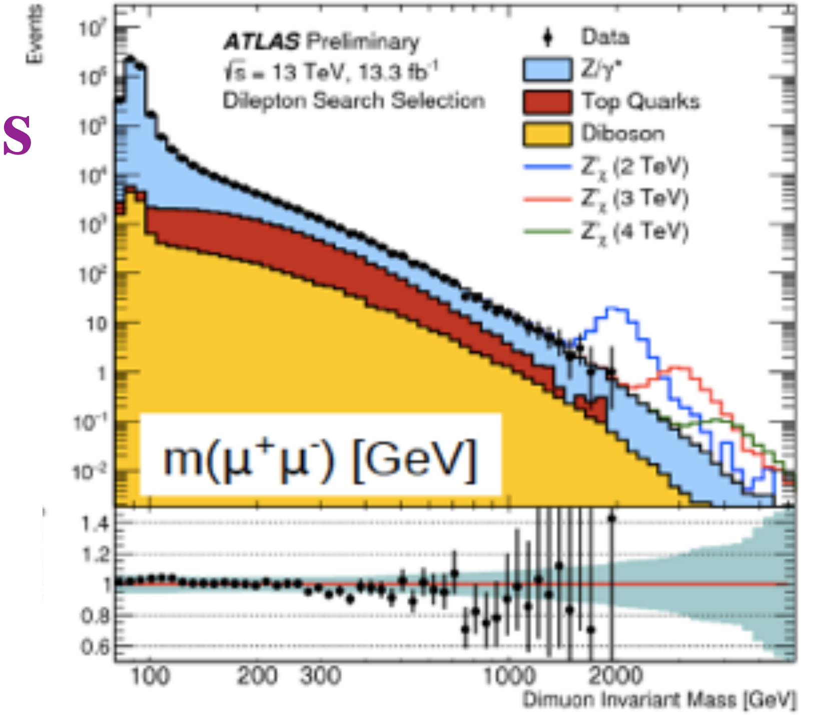


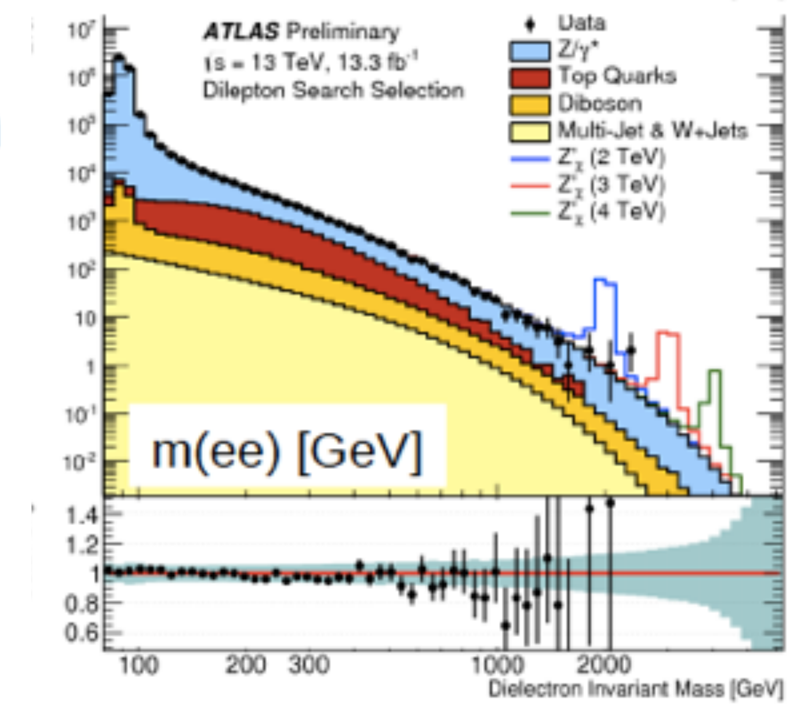


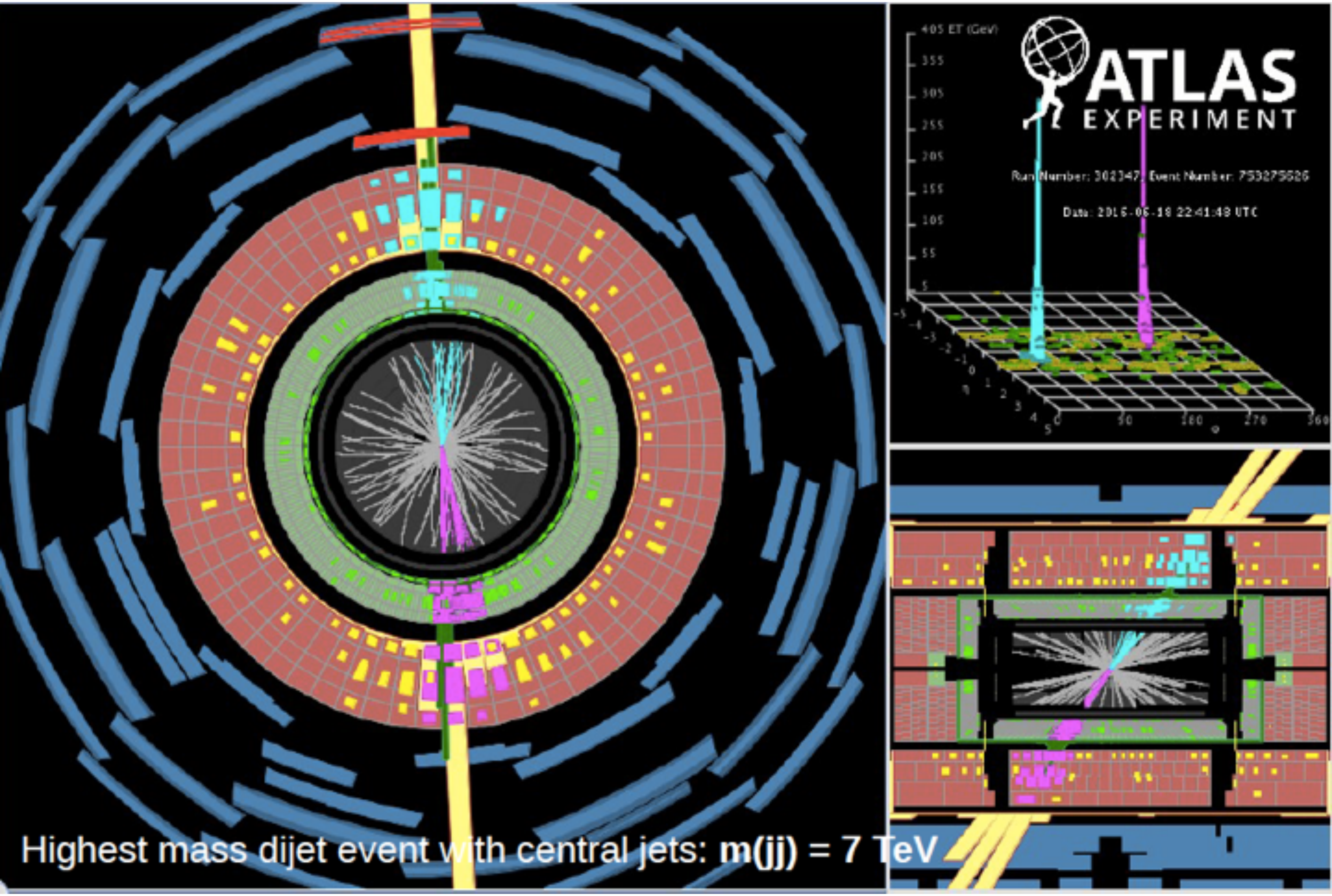

m(ee) = 2.4 TeV
Run Number: 302393
Event Number: 3804660240
Date: 2016-06-20, 20:55:28 CET
ATLAS
EXPERIMENT
[ATLAS-CONF-2016-045]

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.

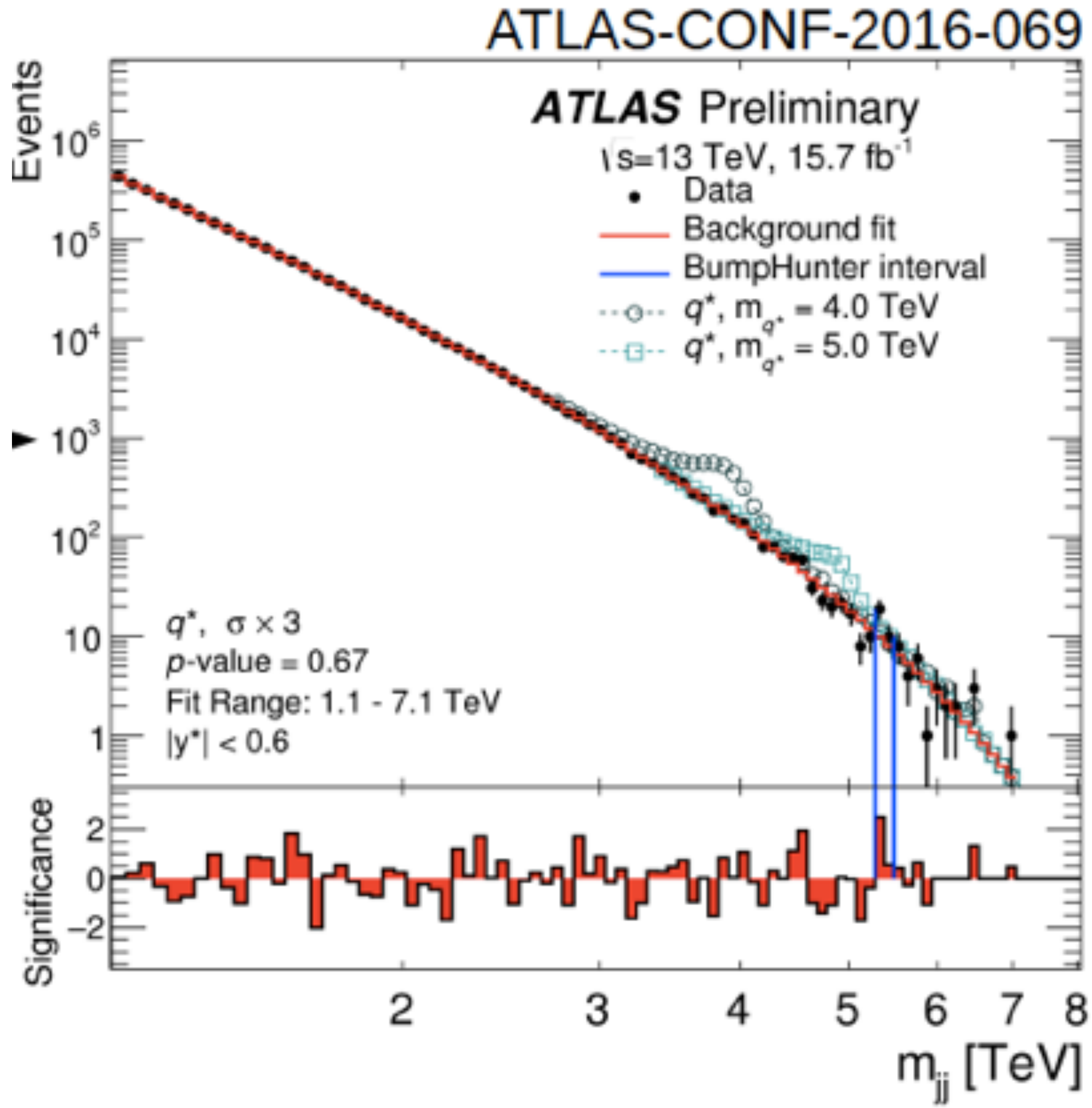


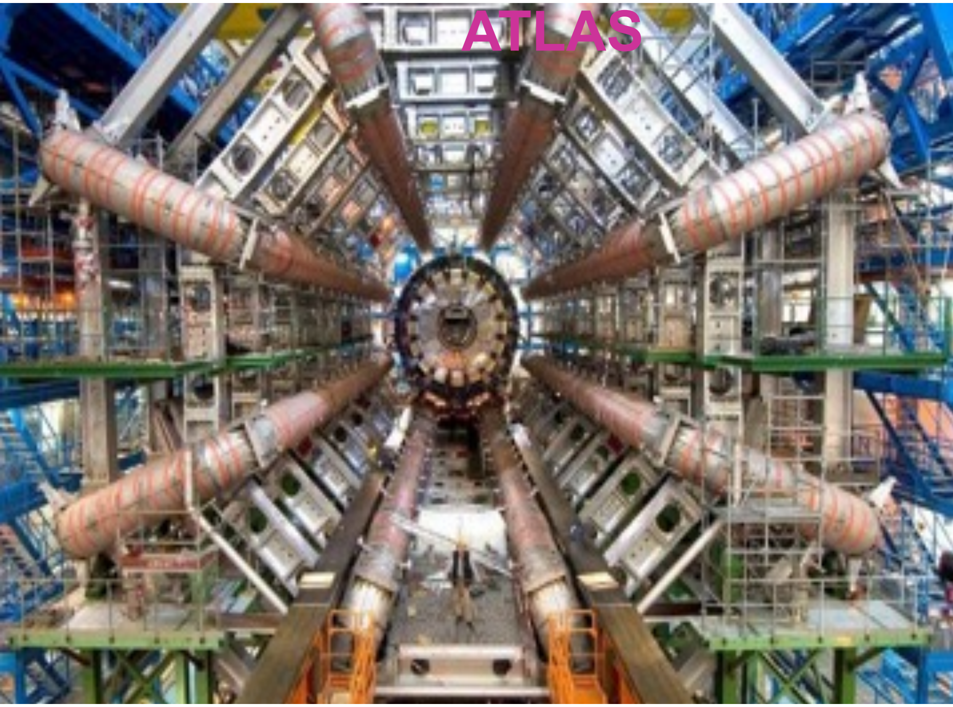


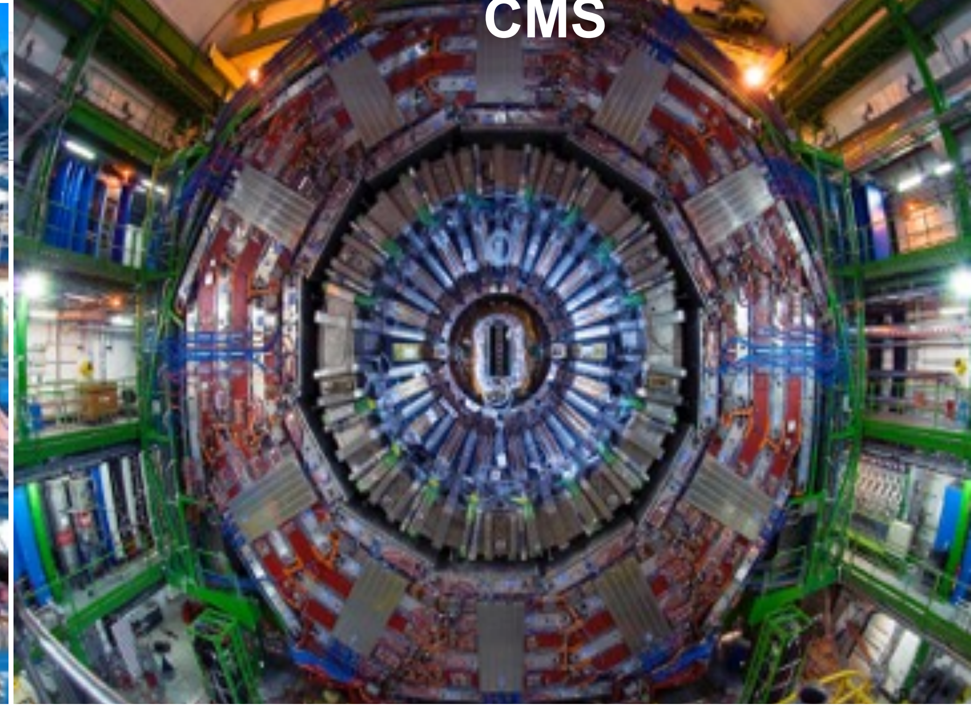

ATLAS
EXPERIMENT
Run Number: 302347, Event Number: 753275626
Date: 2016-06-18 22:41:48 UTC
405 ET (GeV)
Highest mass dijet event with central jets: **m(jj) = 7 TeV**

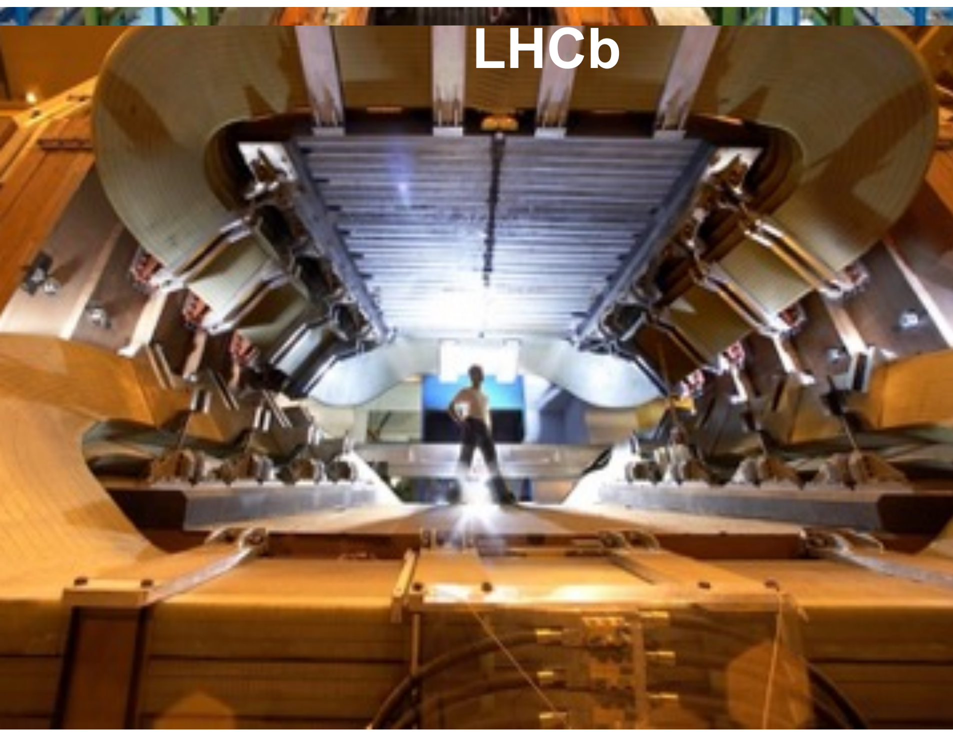
Search for high-mass resonances decaying to jets

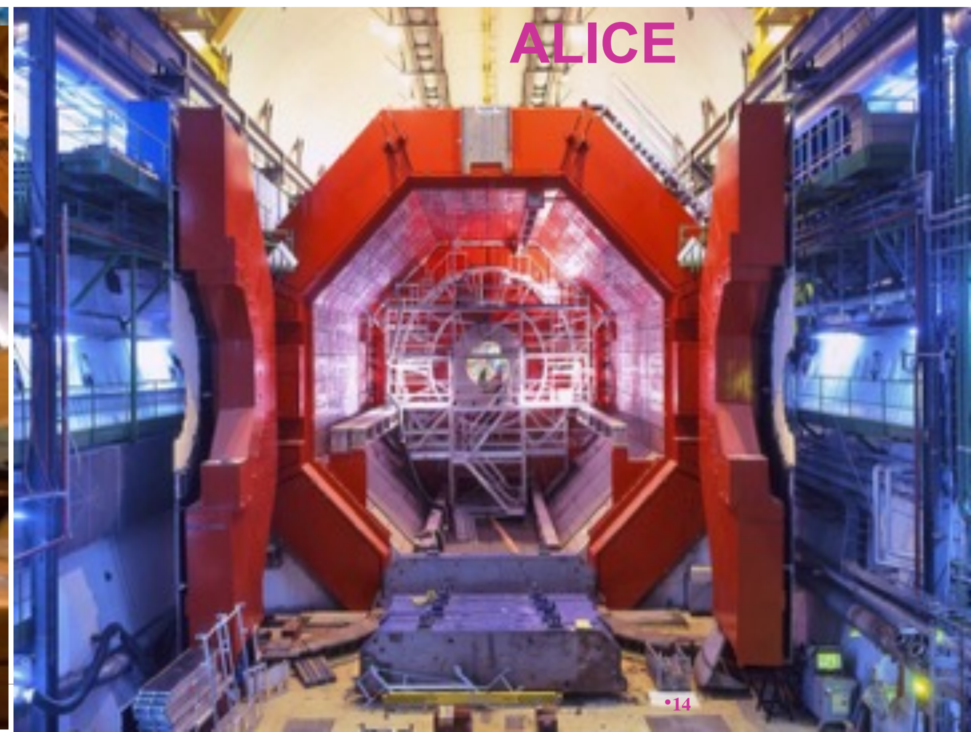
- W'/Z', excited quarks, strong gravity, DM-mediator
- Look for resonance above phenomenological fit of the data




ATLAS


CMS


LHCb


ALICE

Physics at the LHC: the environment

Time-of-flight

Physics at the LHC: the environment

Time-of-flight

Interactions every 25 ns …

Physics at the LHC: the environment

Time-of-flight

Interactions every 25 ns …

- In 25 ns particles travel 7.5 m

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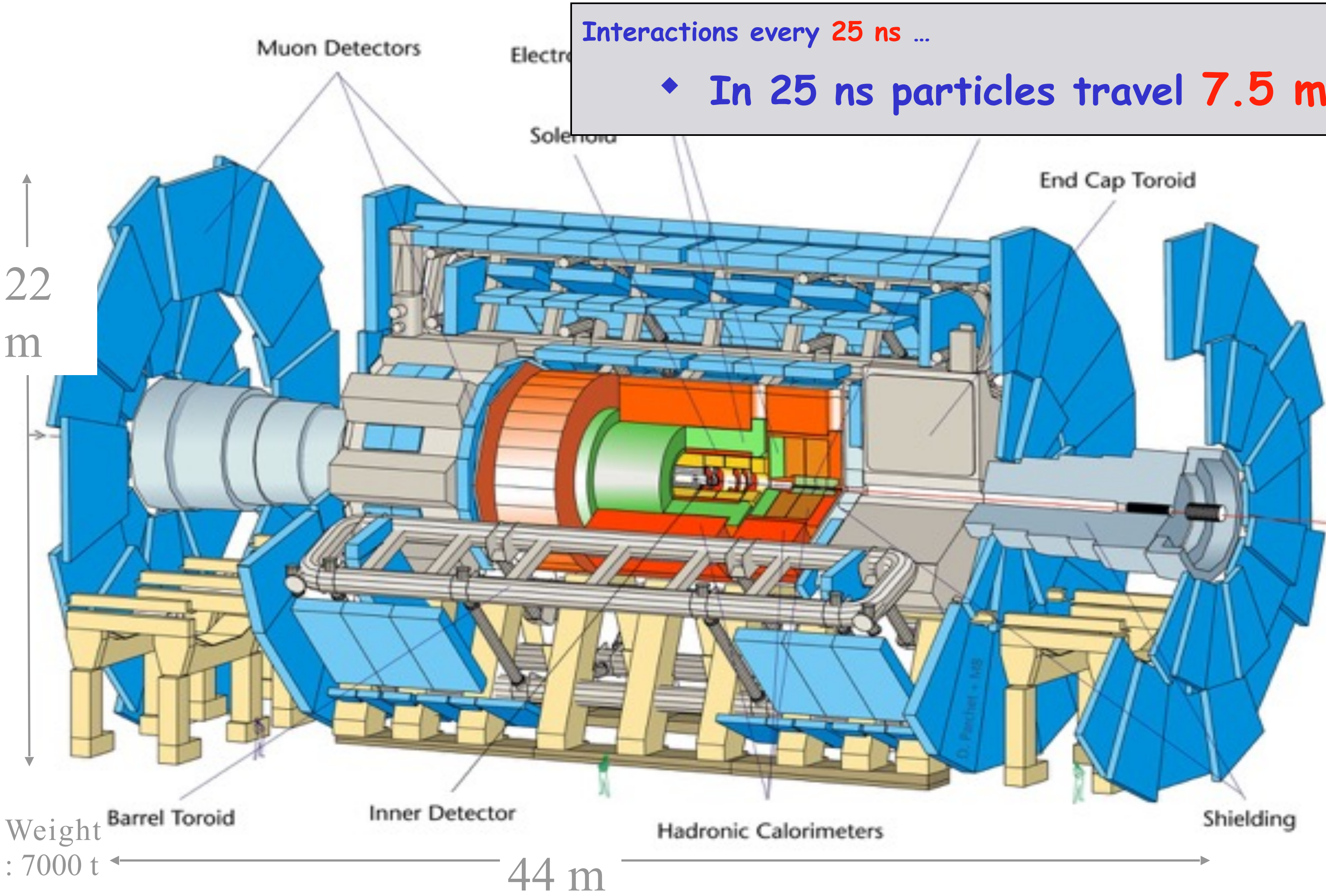

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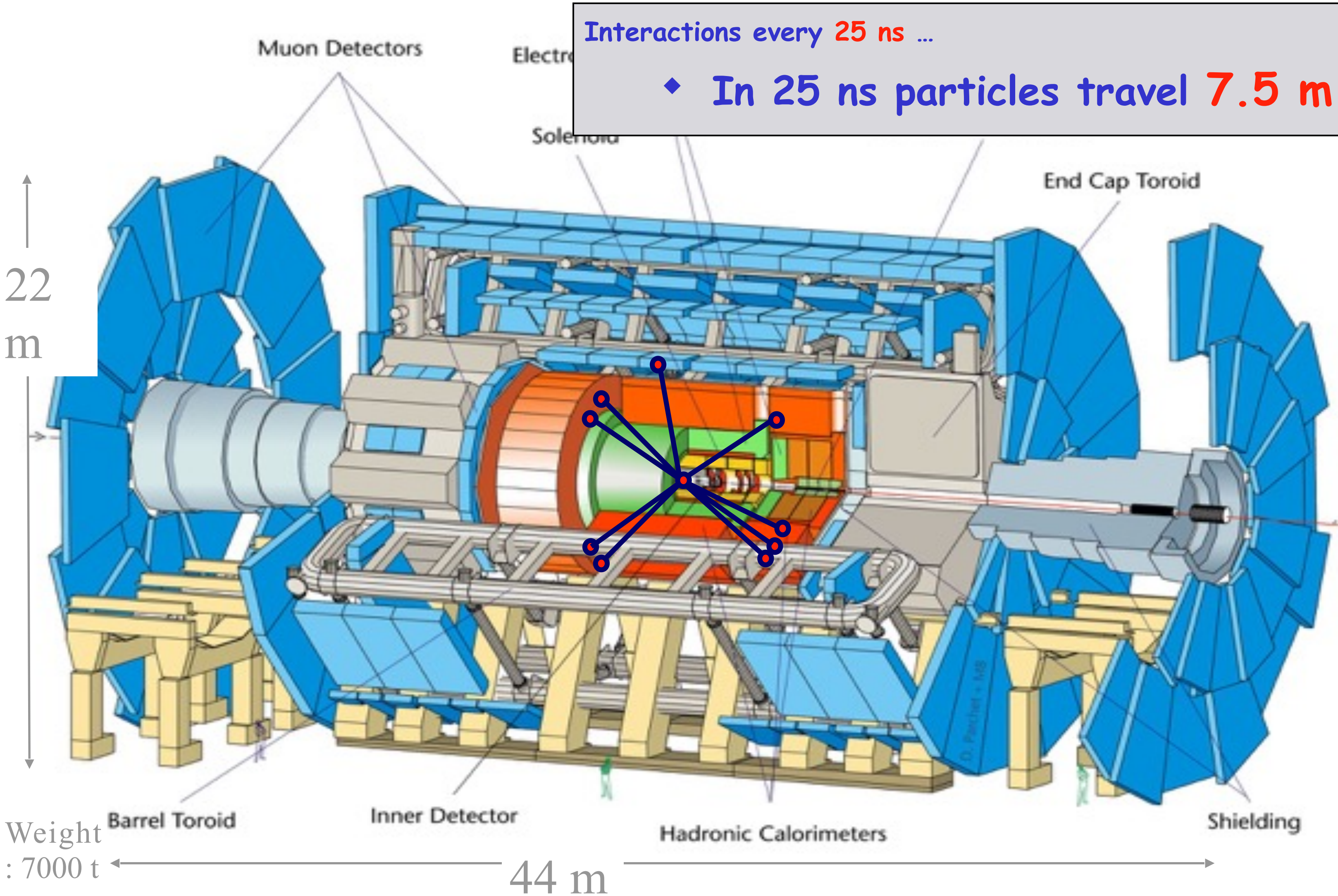

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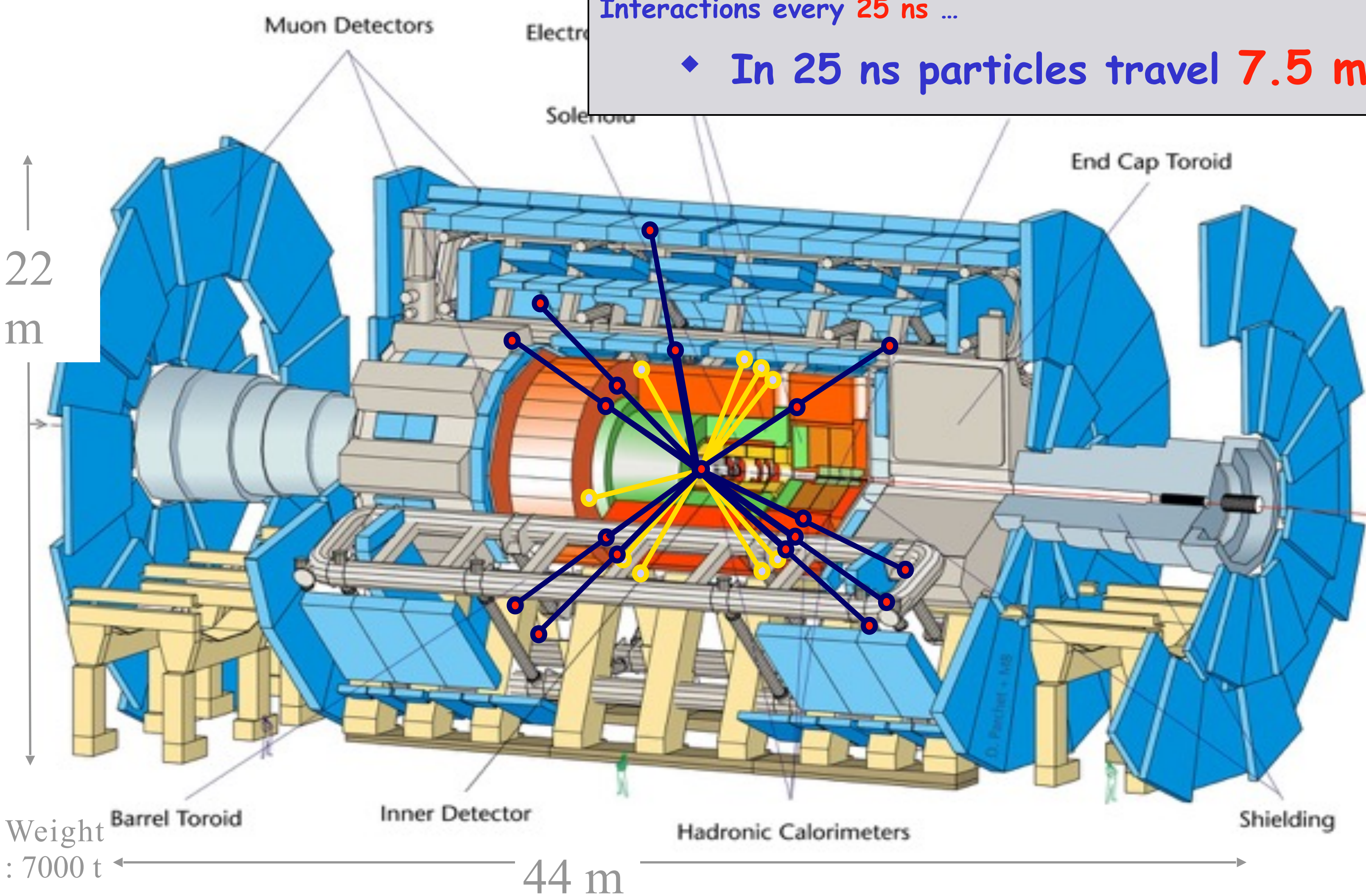

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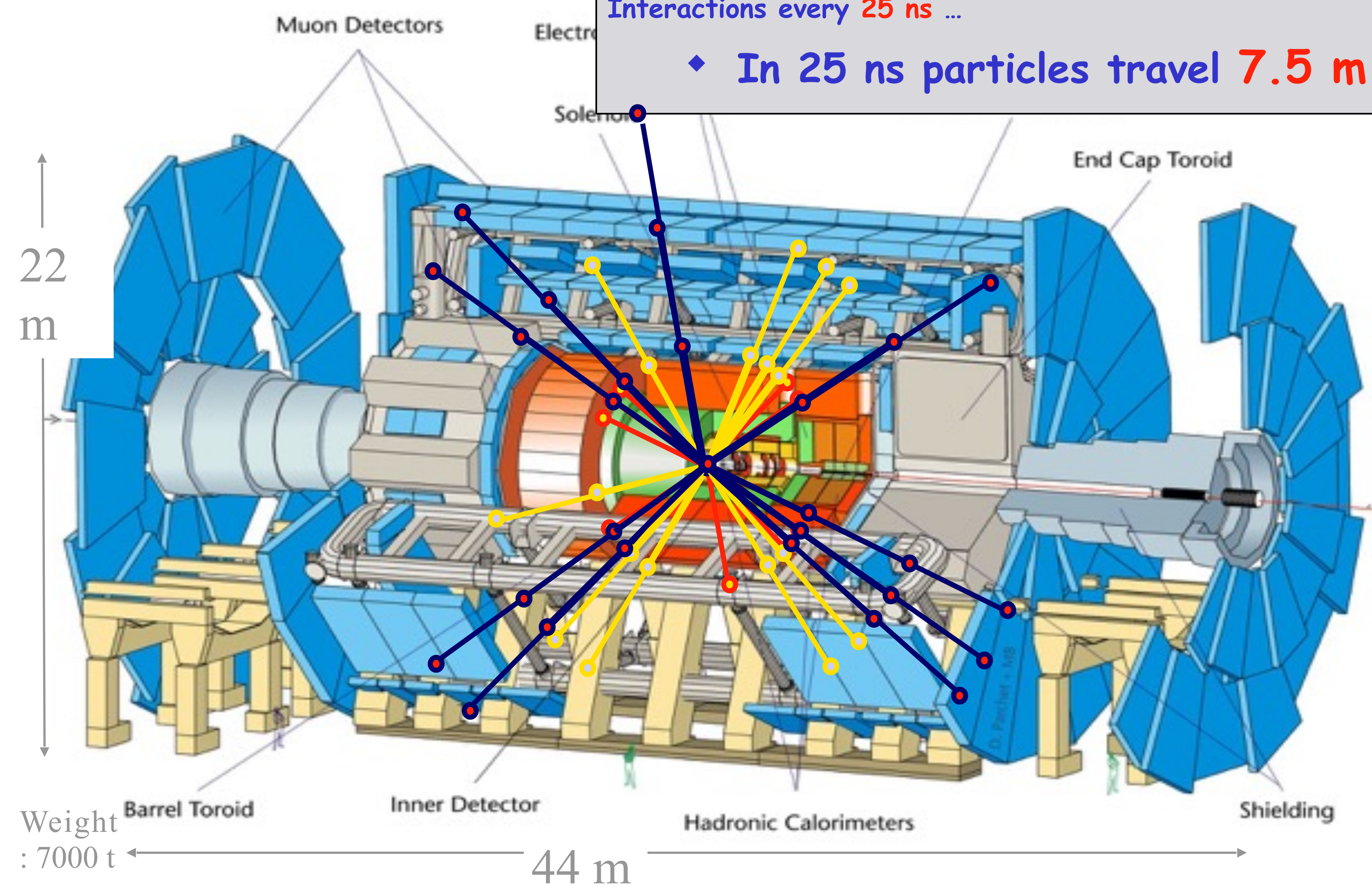

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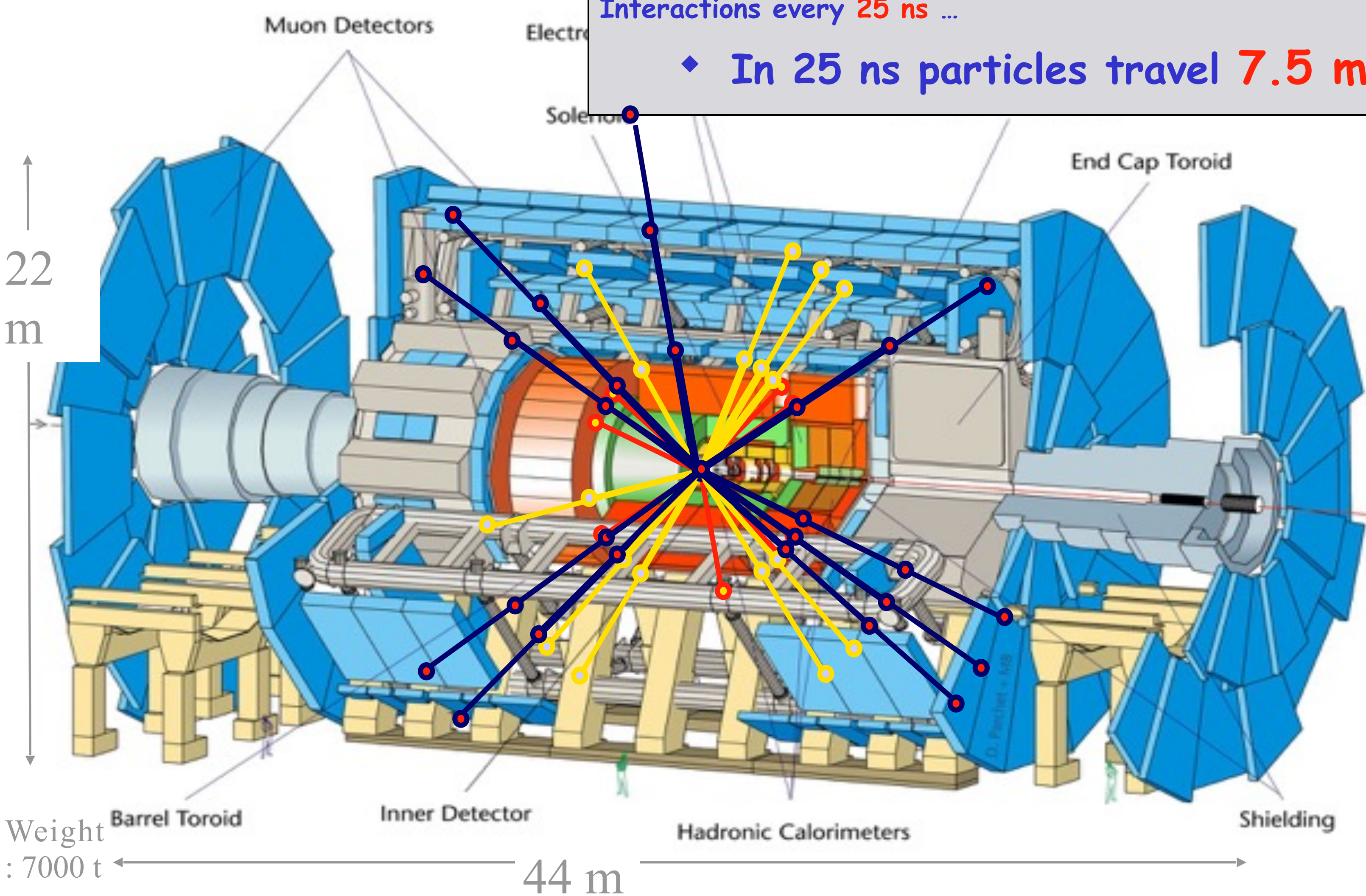


Interactions every 25 ns …

- In 25 ns particles travel 7.5 m

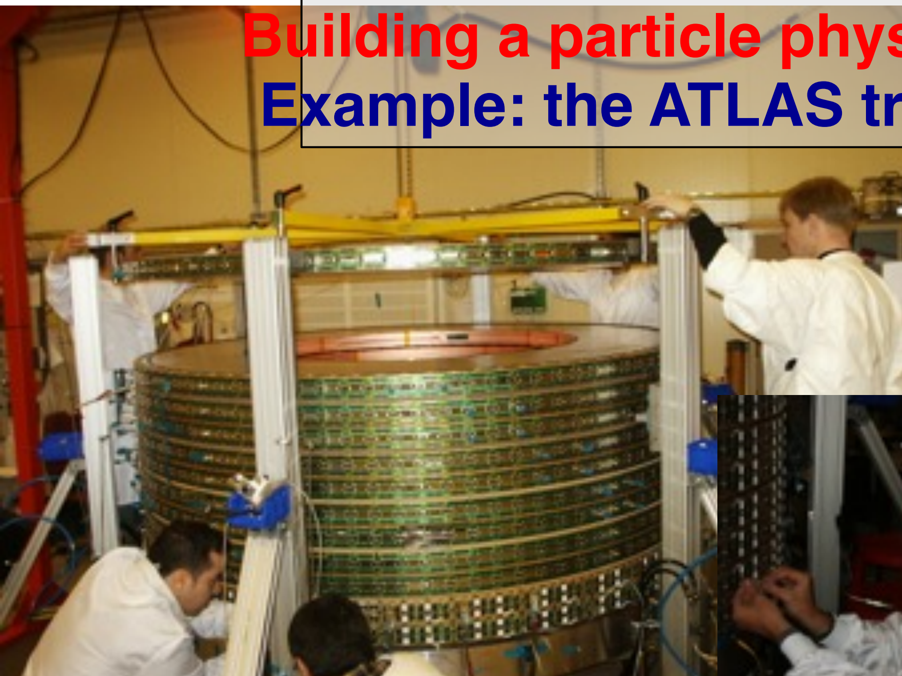
Cable length ~100 meters …

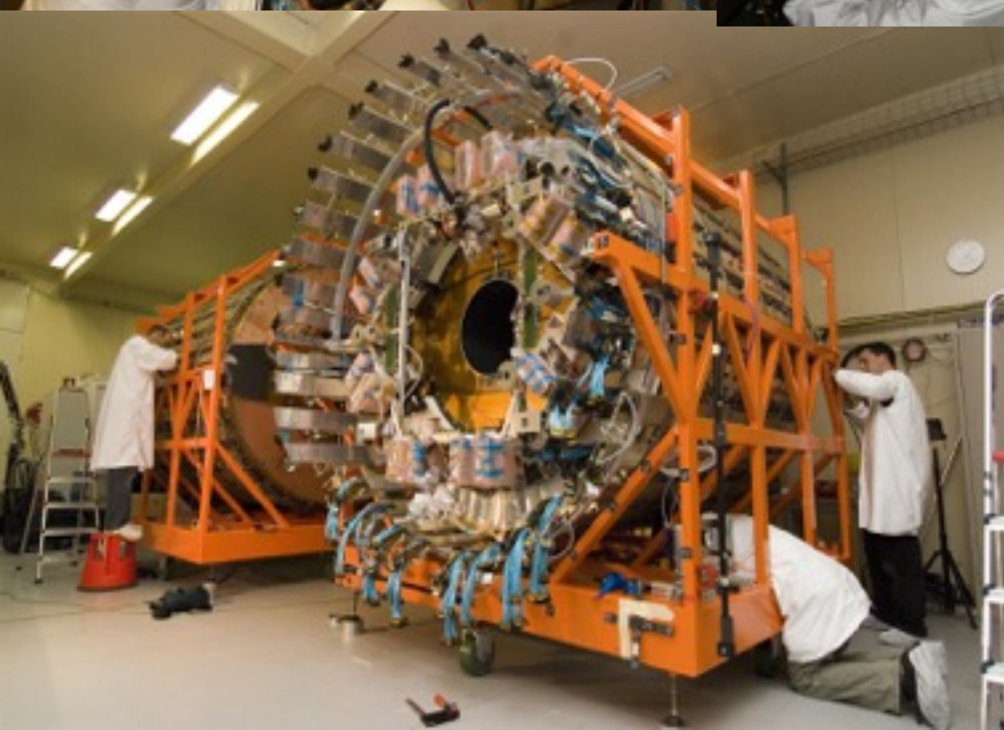
- In 25 ns signals travel 5 m

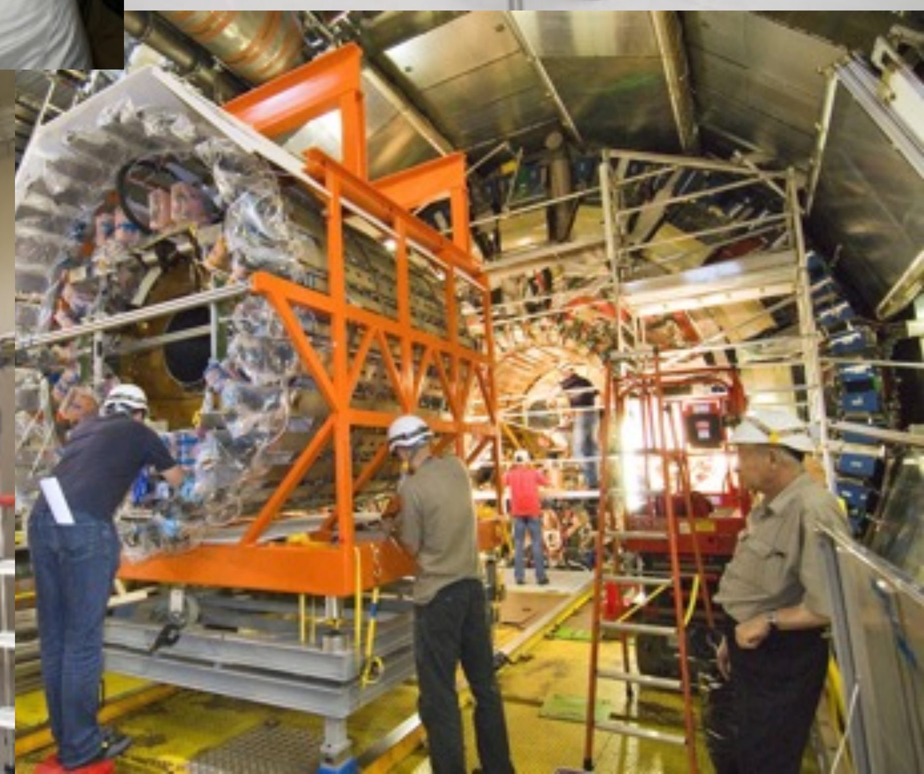
•

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:

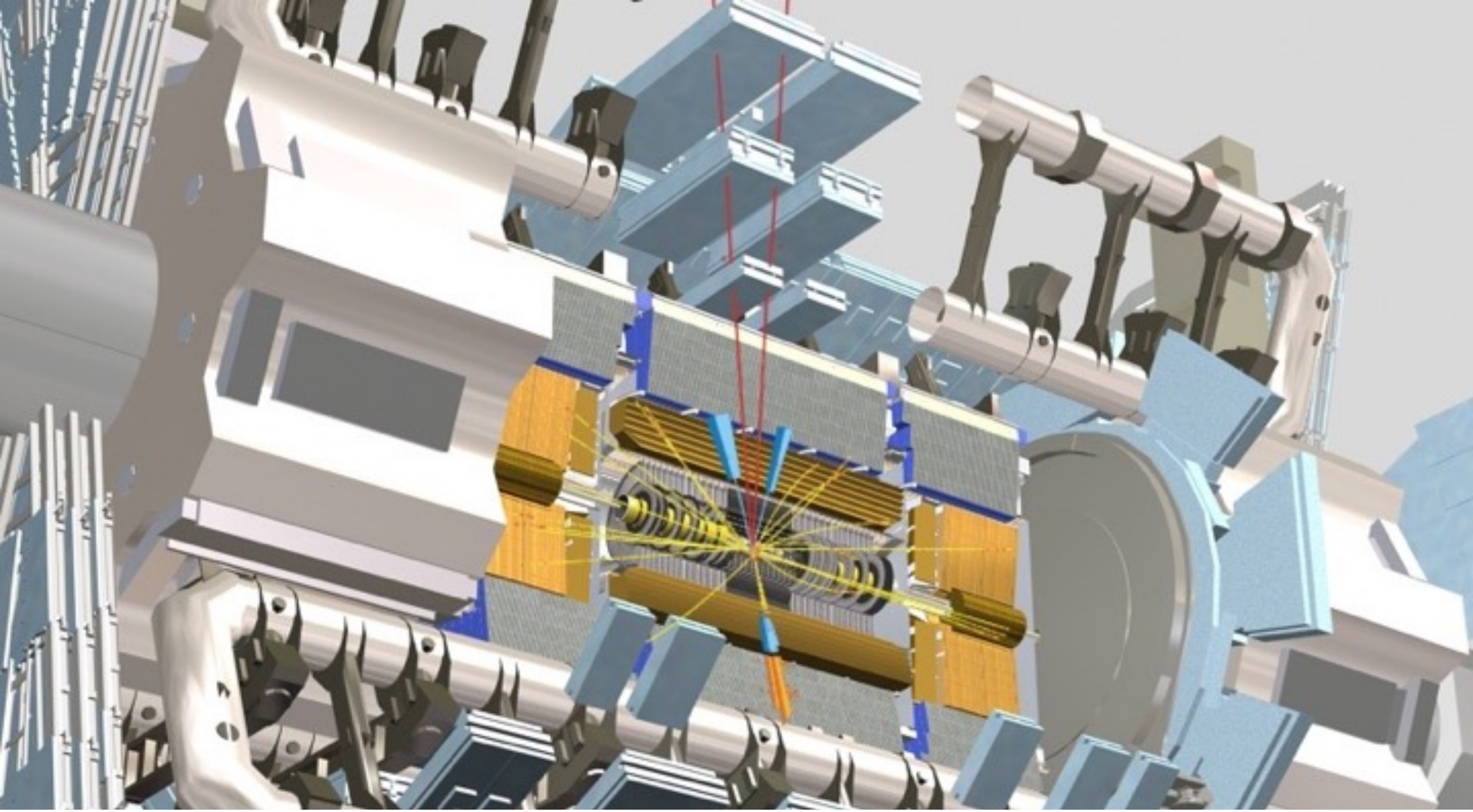
3D digital camera with 100 Megapixels built only once. It is its own prototype. It must survive in an environment close to that of the heart of a nuclear reactor (no commercial components allowed!)

- 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:

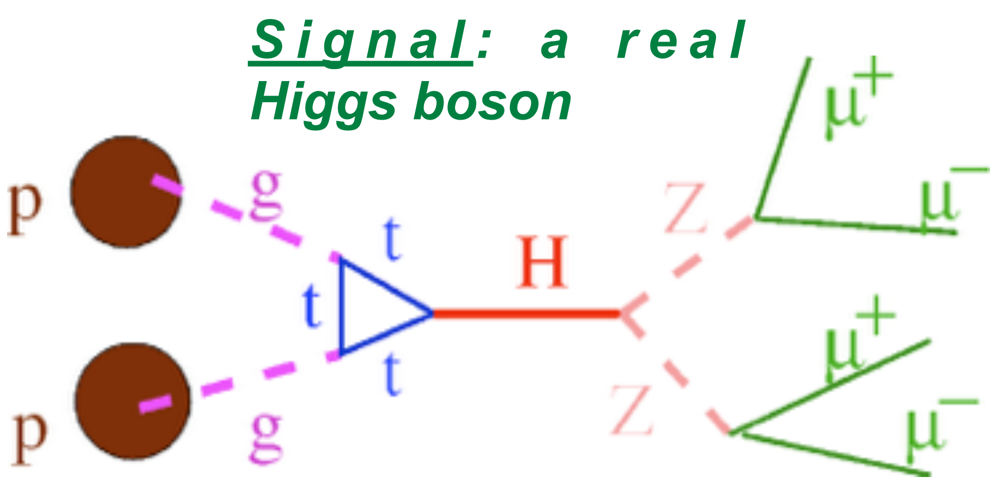
- simulations allow us to make precise predictions of the behaviour of our detectors
- simulations allow us to extrapolate from what we know today and to project ourselves towards unknown realms:
  - towards higher energies (from Chicago to CERN)
  - towards new physics searches (from the Standard Model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

Now we have acquired many 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:

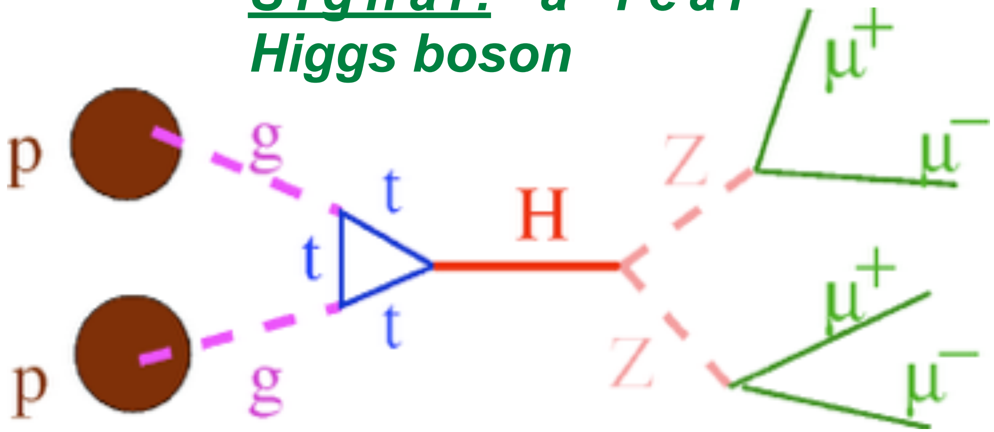


So let's look for four muons with high energy because the Higgs boson mass is larger than 114 GeV (inheritance from LEP machine and experiments)

No pictures of Higgs boson itself

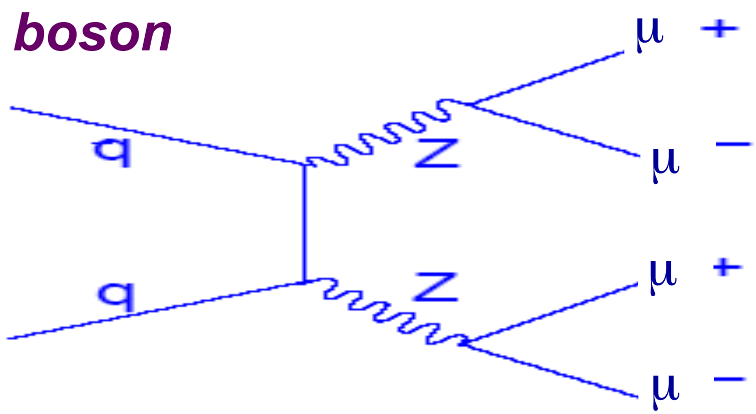
Sometimes the Higgs boson decays into four muons:

***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**

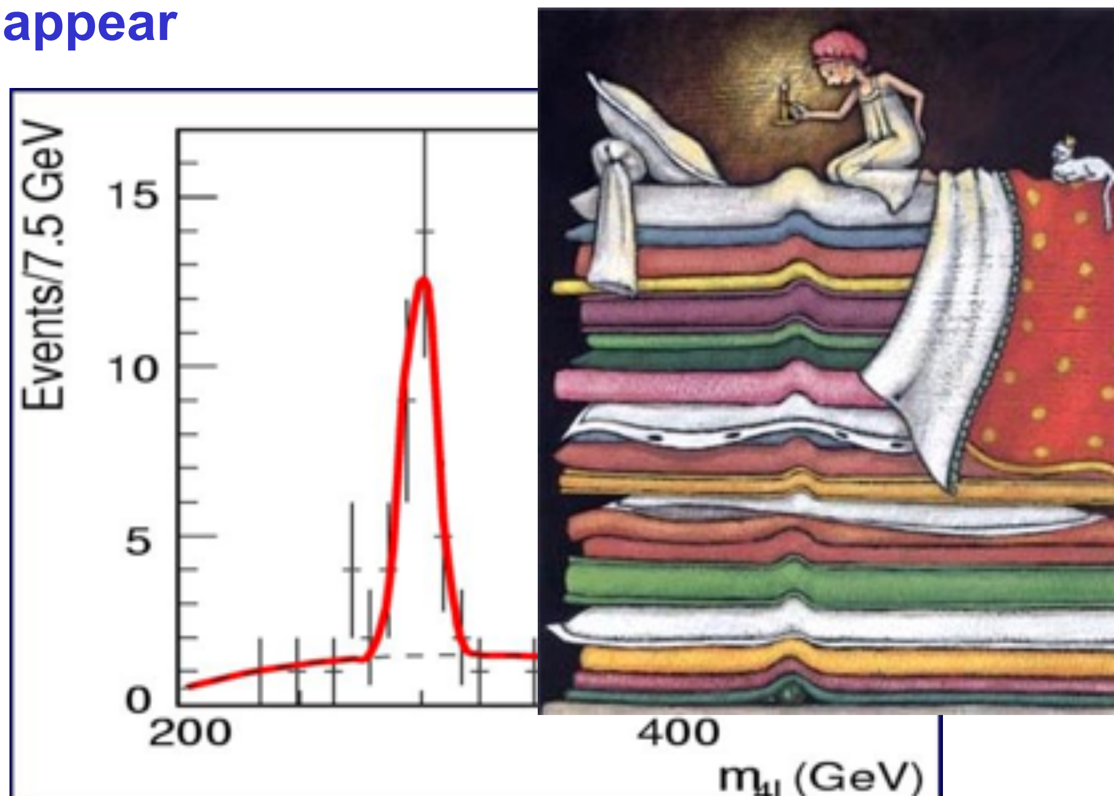


No pictures of Higgs boson itself:
but how can we find it? how can we eliminate background?

- 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!

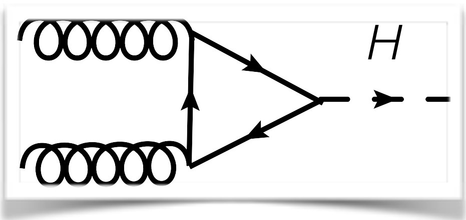


How to find a Higgs boson

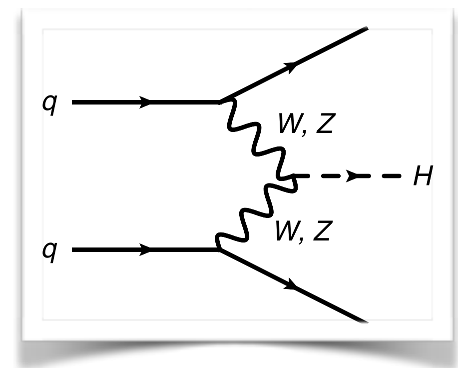
Thanks to Heather Gray!

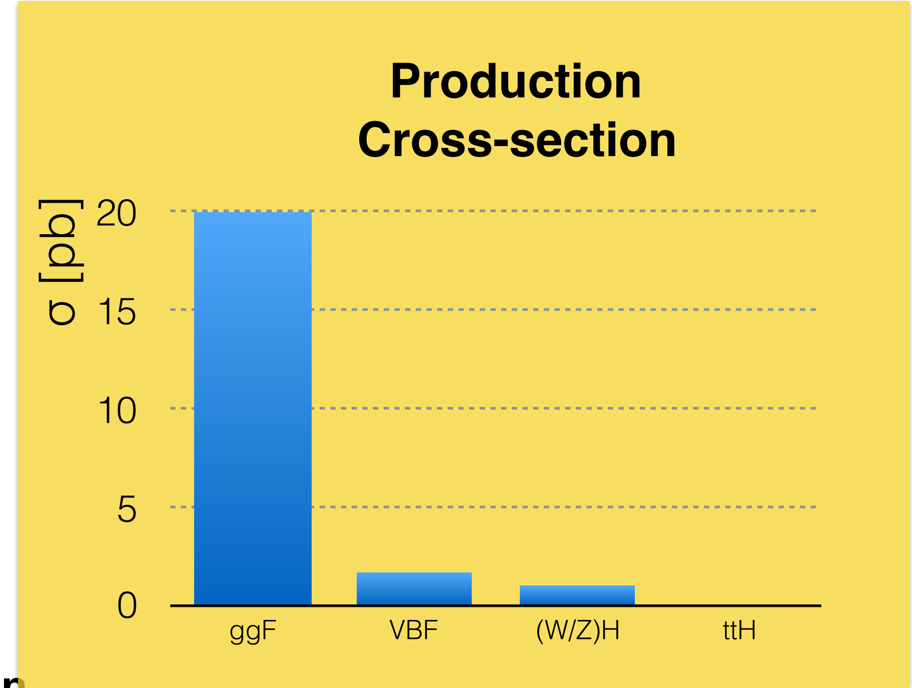
Choose your channel I

Gluon fusion

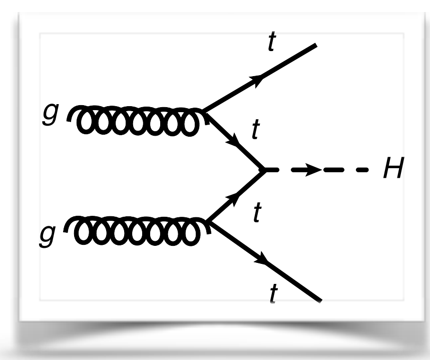


Vector Boson Fusion (VBF)

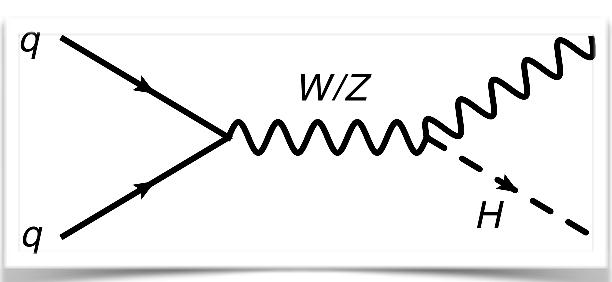




ttH Production

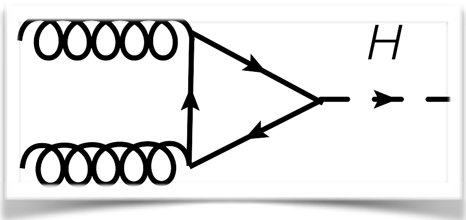


(W/Z) Production

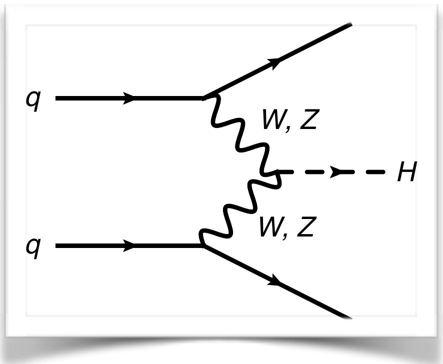


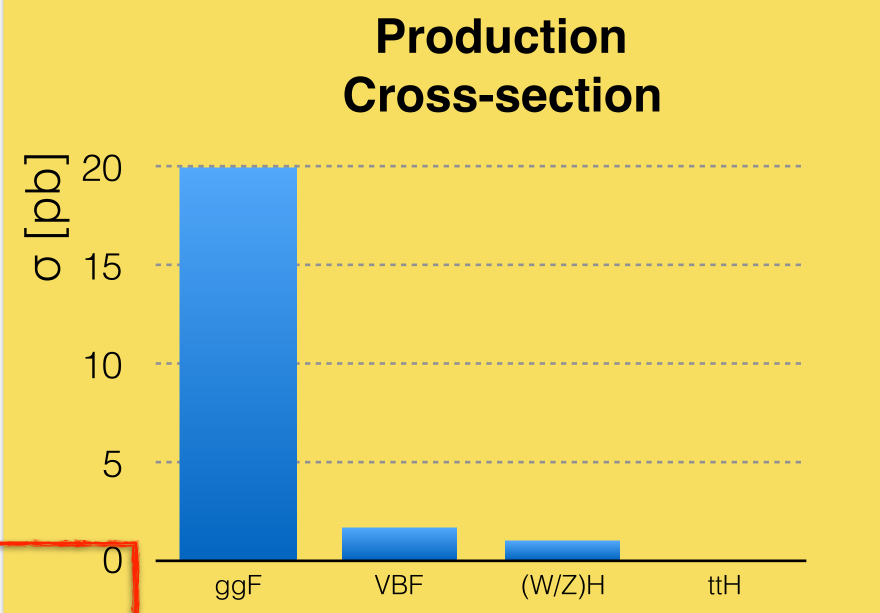
Choose your channel I

Gluon fusion

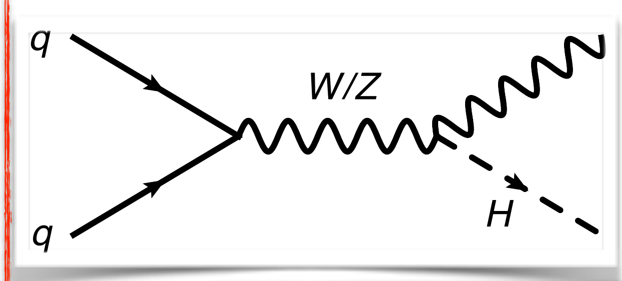


Vector Boson Fusion (VBF)

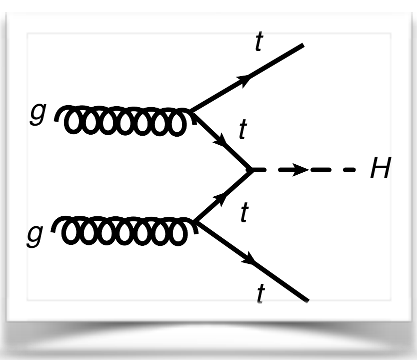




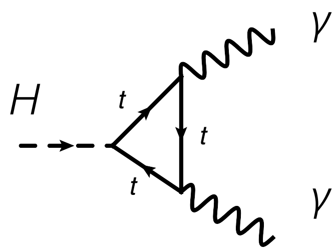
(W/Z) Production

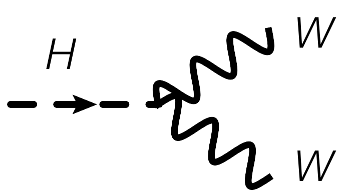


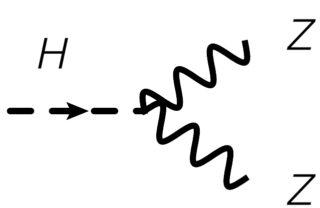
ttH Production

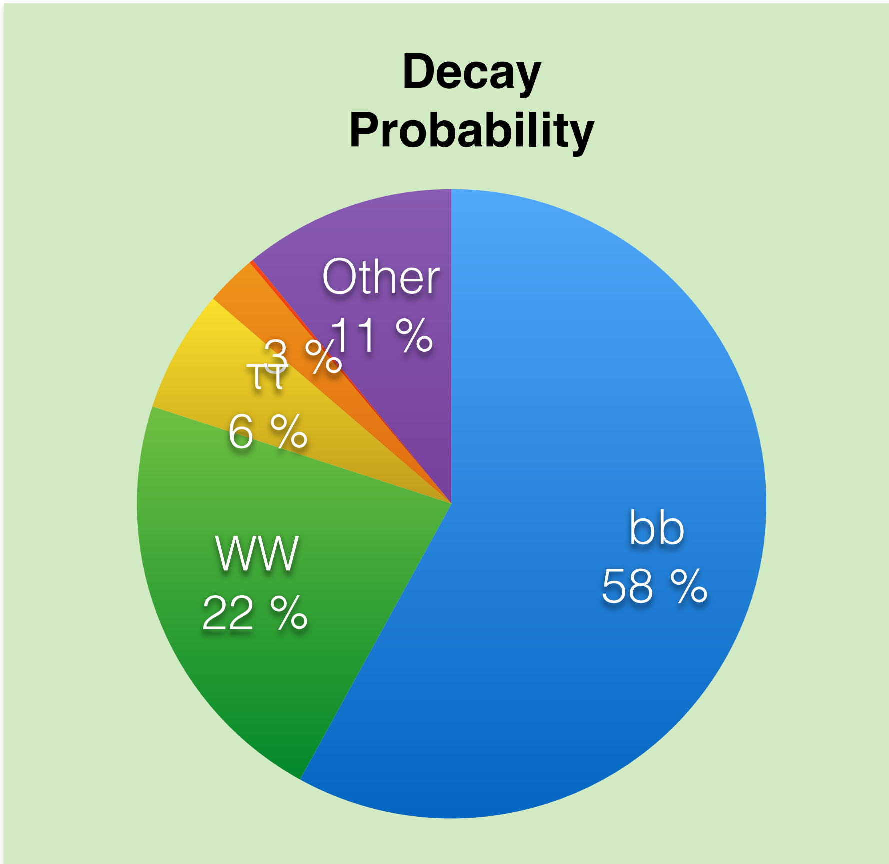


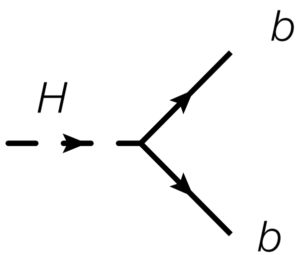
Choose your channel II

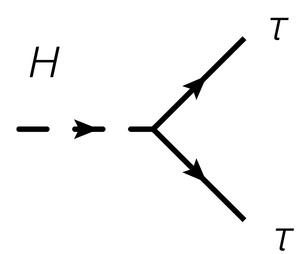






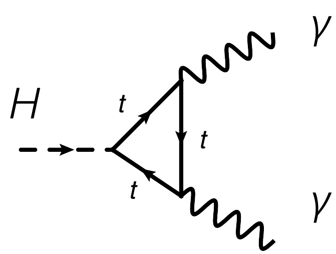


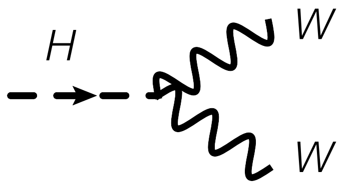


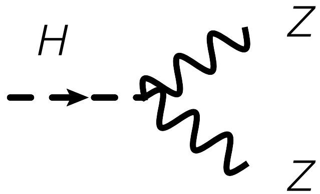


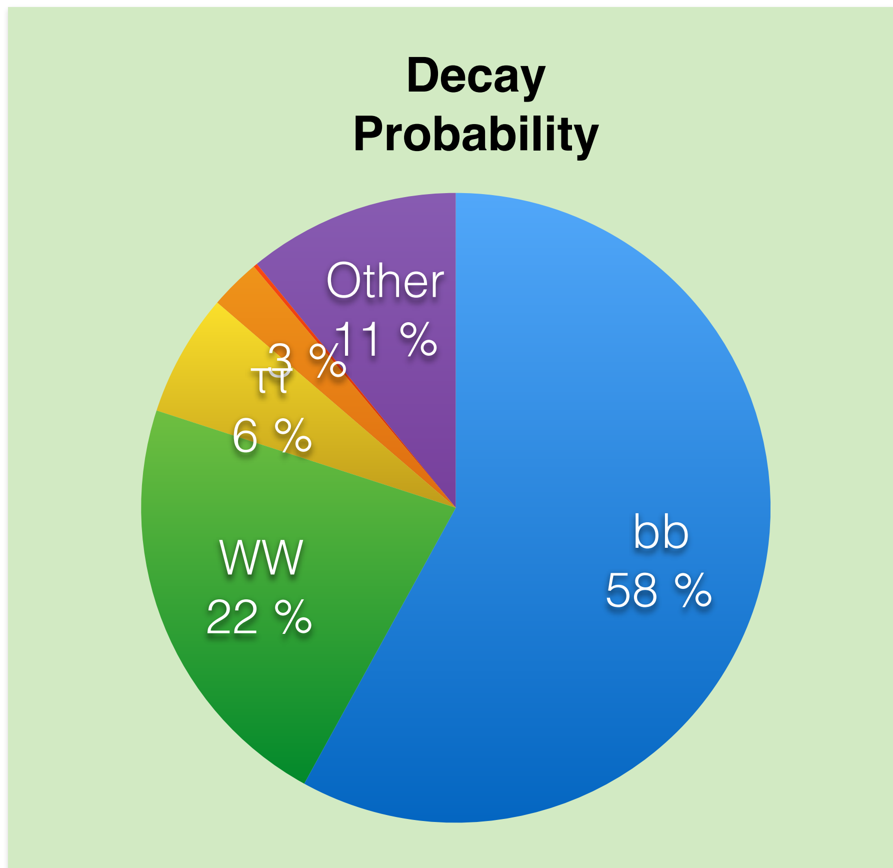
Choose your channel II

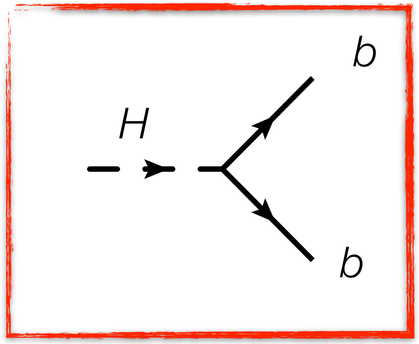
(あなたのチャンネルを選択)

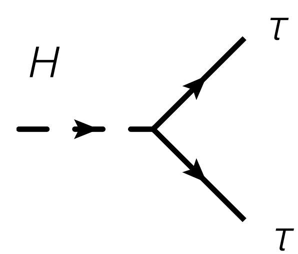




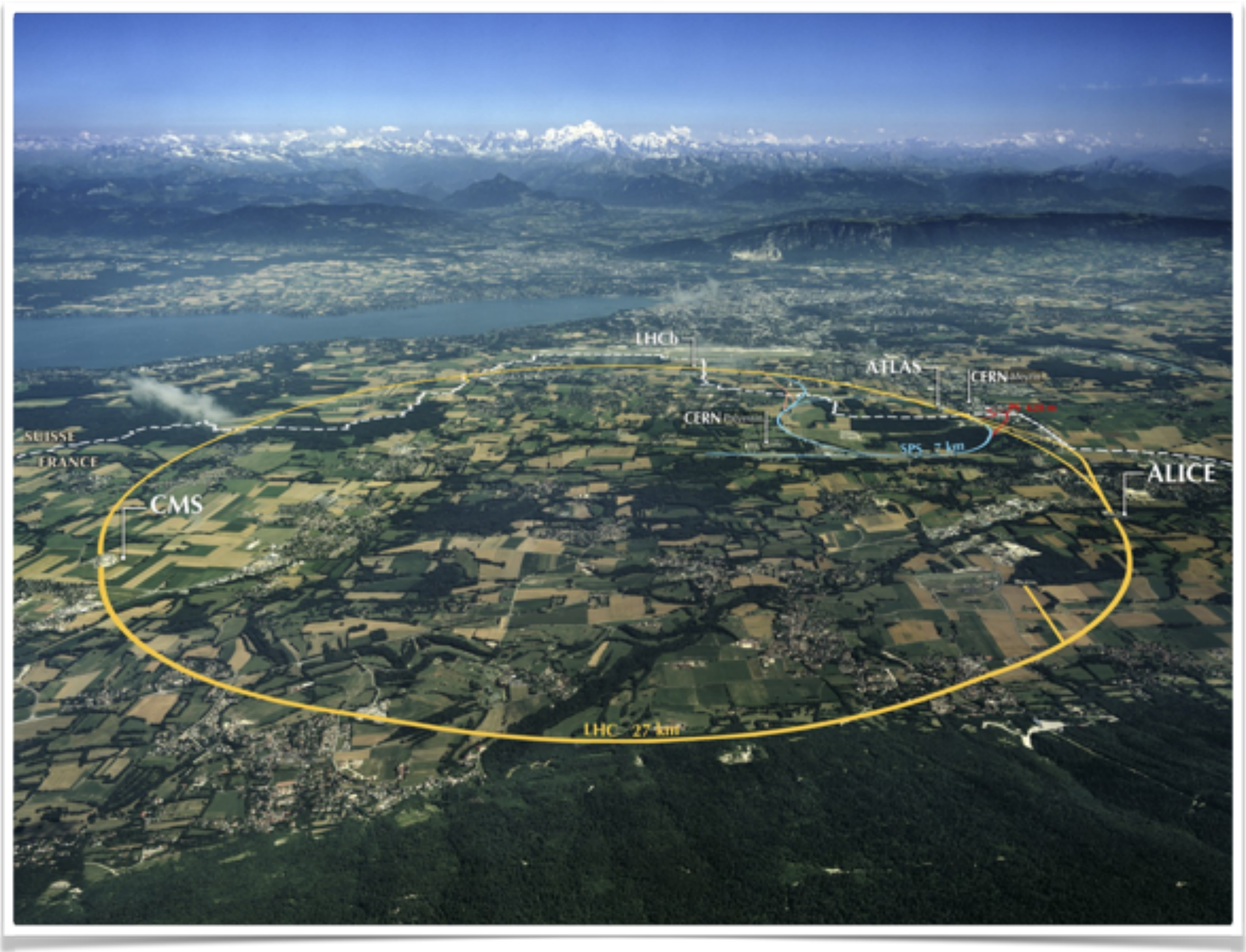




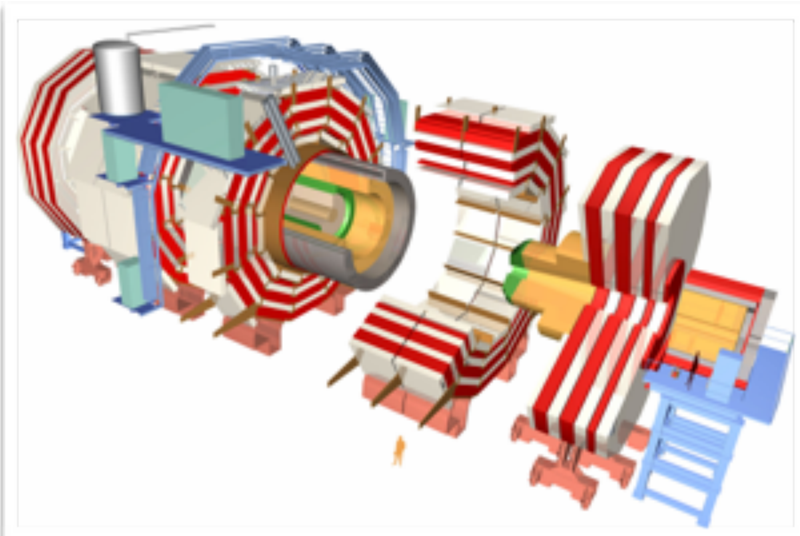




Build a multi-billion CHF collider

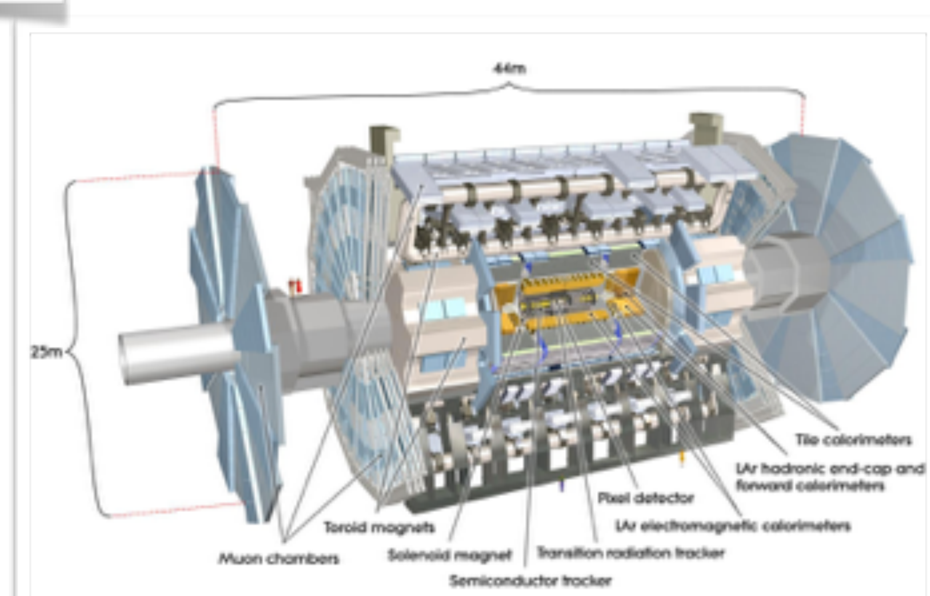


Add a couple of 0.5 billion CHF detectors

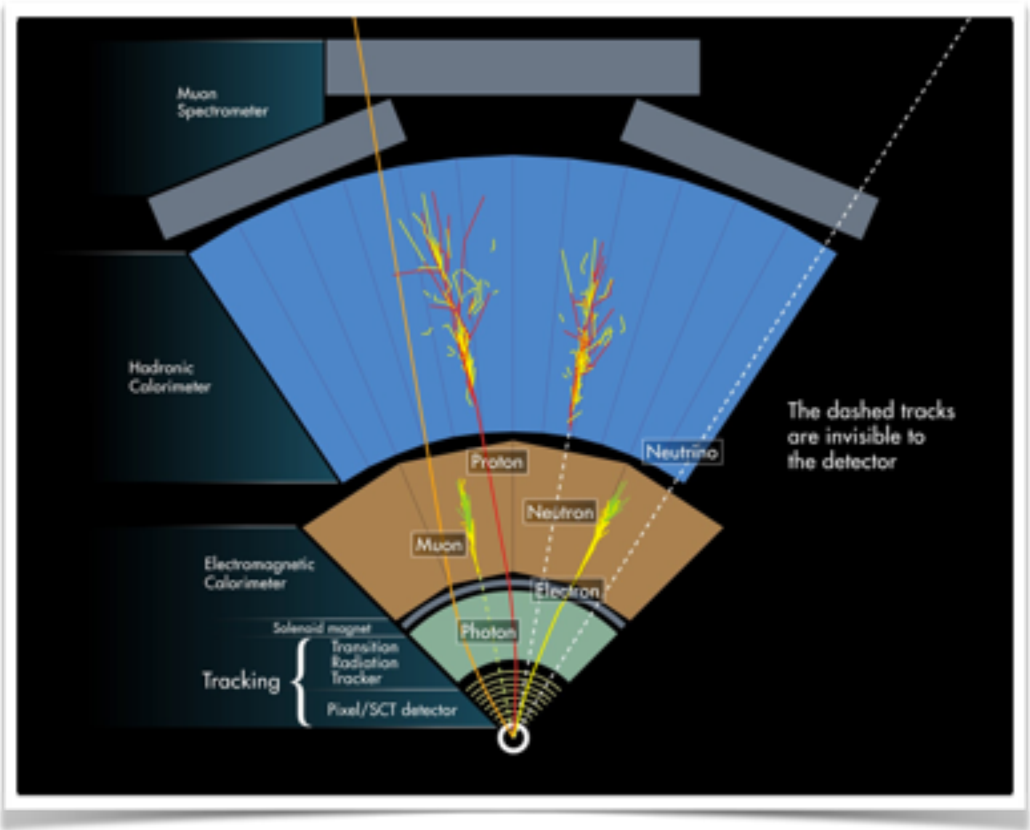


CMS
(Compact Muon Solenoid)

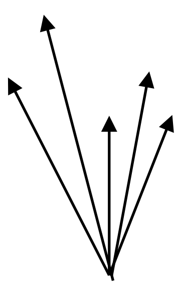
ATLAS
(A Toroidal ApparatuS)

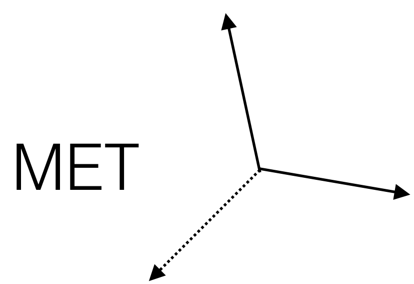


Reconstruction

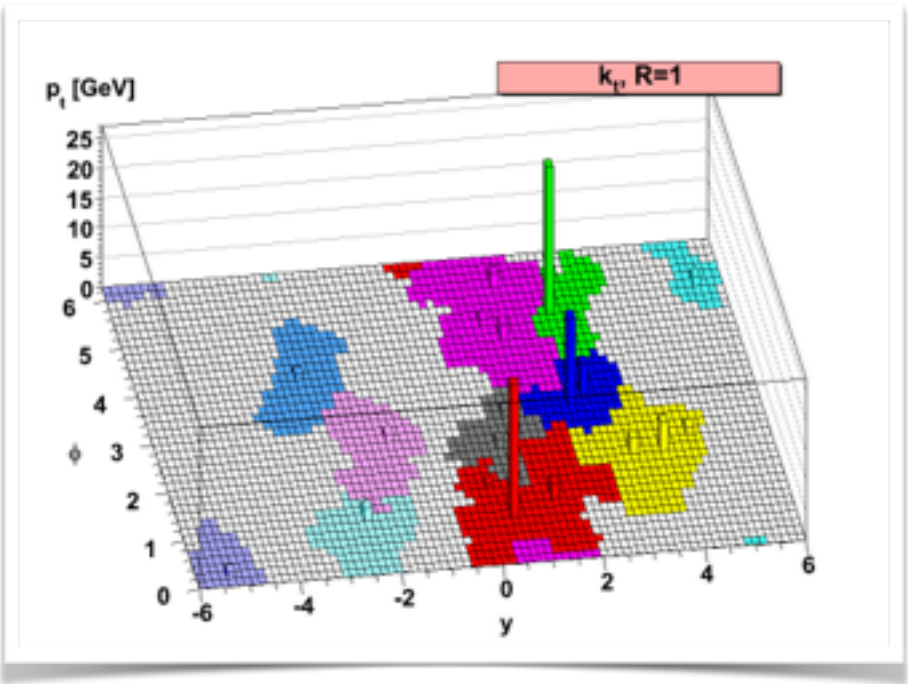


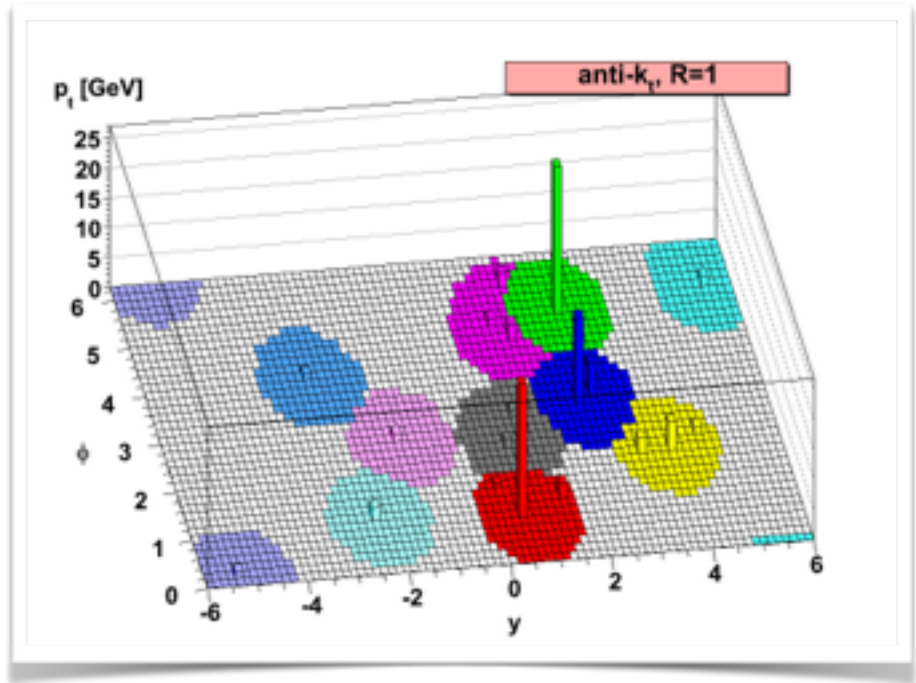
- Reconstruct electrons, muons, photons from energy deposits
- Reconstruct jets and tag b-jets with sophisticated algorithms
- Use conversation of (transverse) energy to calculate the missing energy (MET)





Jet reconstruction

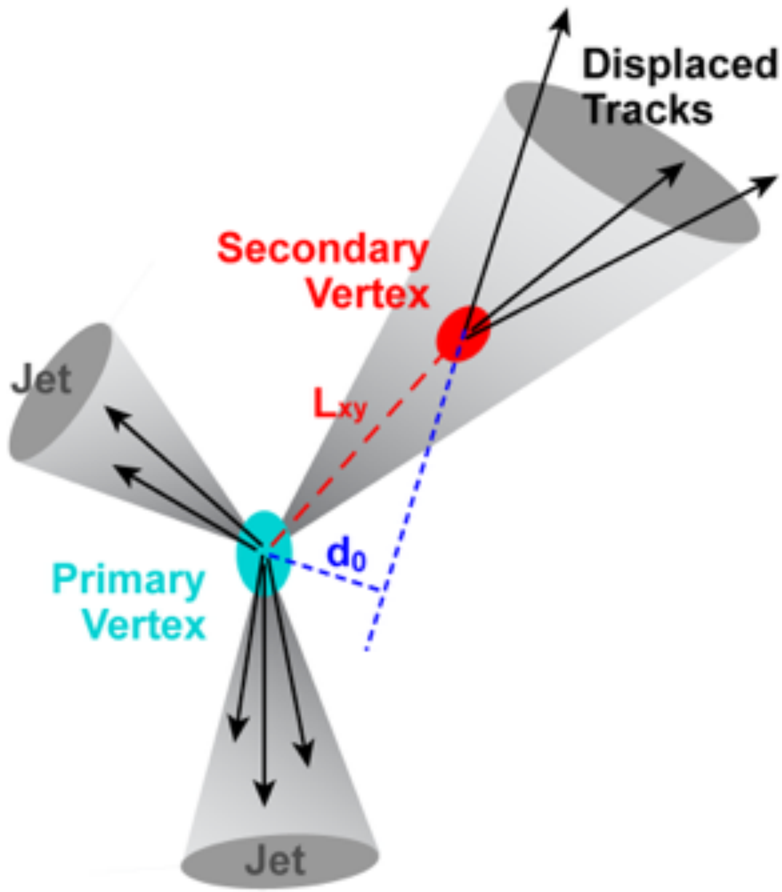




Jet reconstruction algorithms group energy deposits together in different ways to form jets (a lot of input from theory!)

b-jet identification

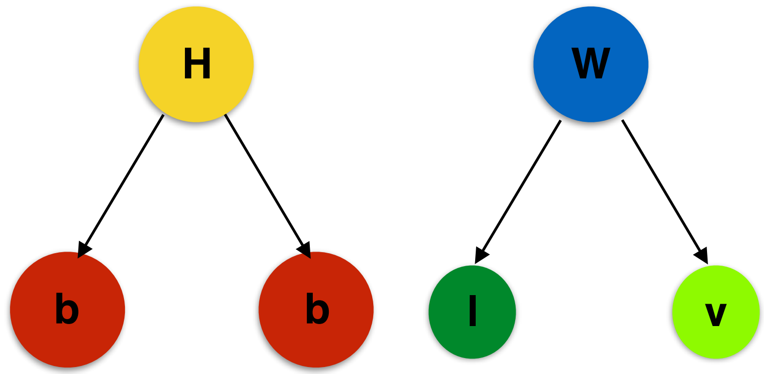
(ビージェット識別)



b-quarks have a longer lifetime than other elementary particles

identify b-jets by reconstructing displaced vertices from tracks

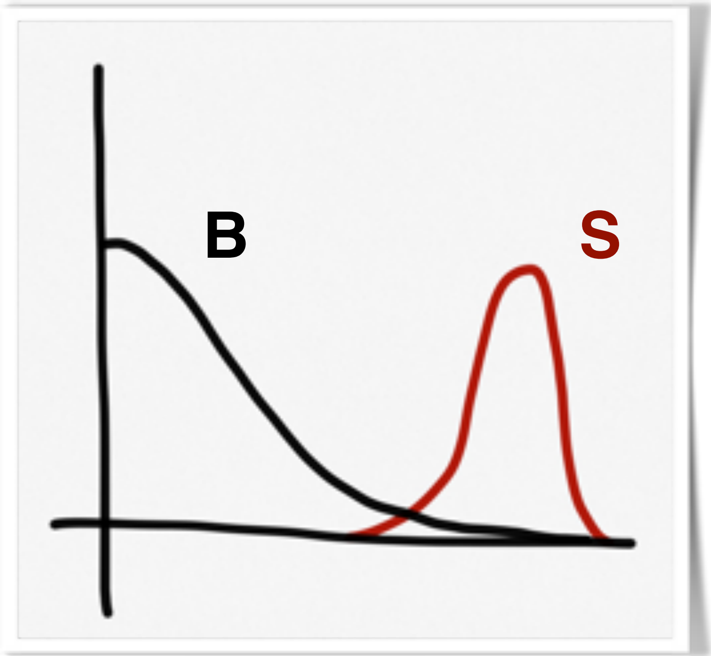
Choose your selection cuts



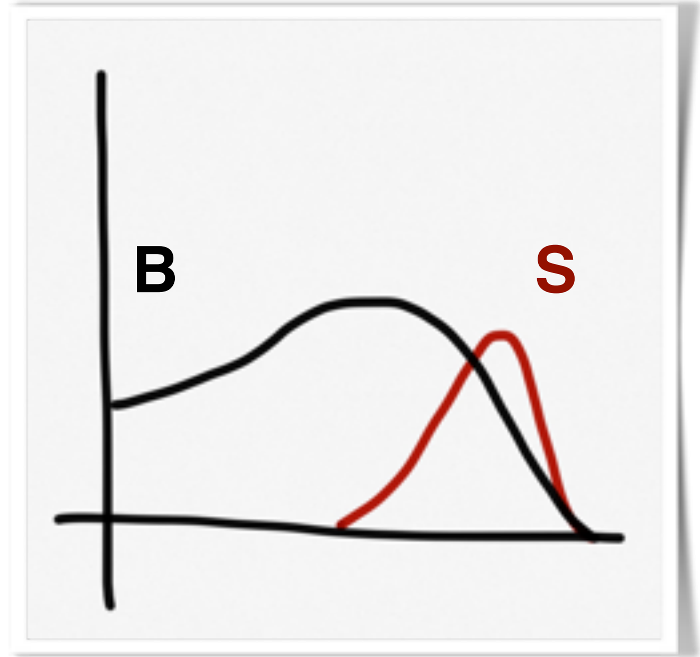
- Need events containing two b-jets, 1 lepton and MET
- $j_1 p_T > 45$ GeV; $j_2 p_T > 20$ GeV, MV1c > 80%
- l $p_T > 20$ GeV; isolated, MET > 20 GeV

Choose discriminating variable

Good discrimination



Poor discrimination

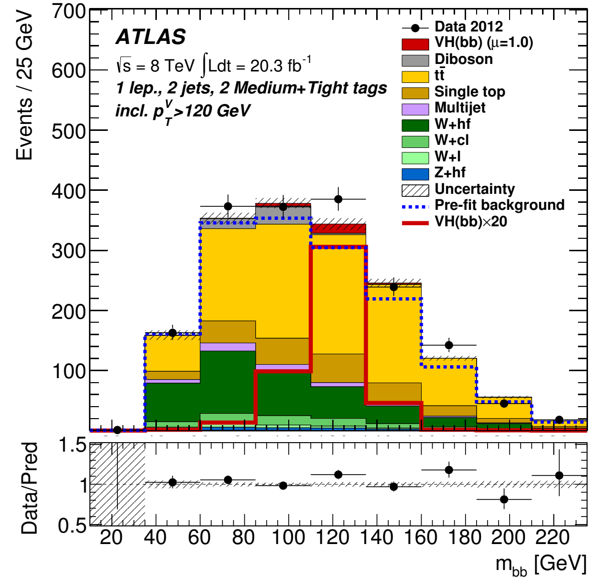


The better the discriminating variable, the larger the separation between signal and background

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



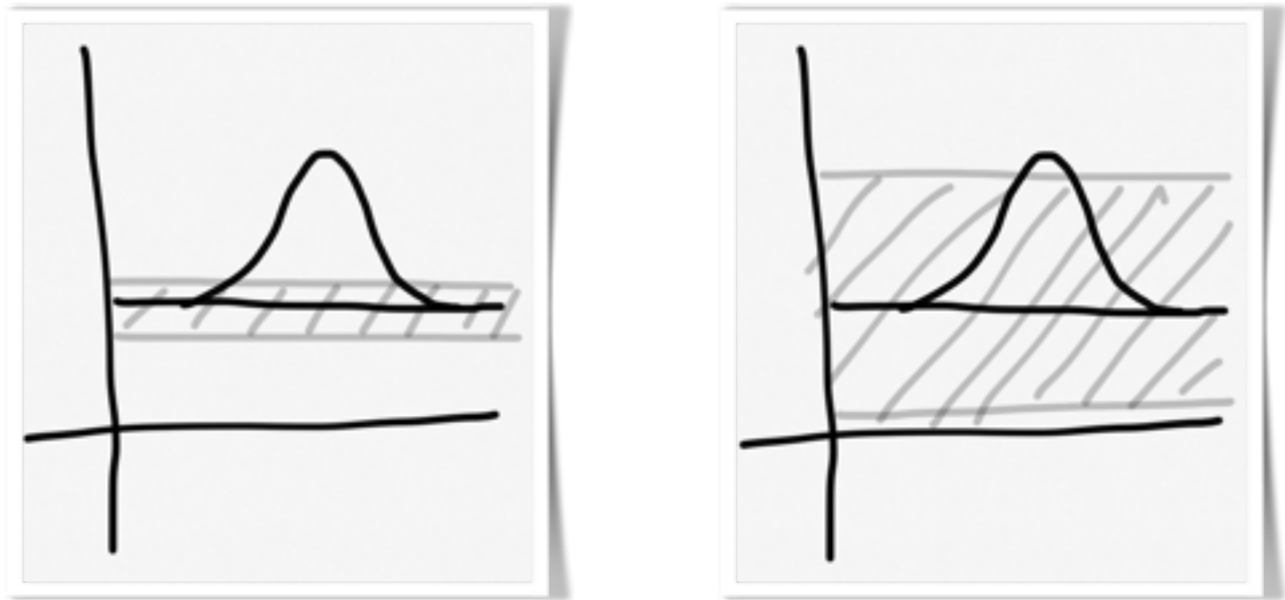
top

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

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
Leptons		0.01
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z + jets		0.07
W + jets		0.07
$t\bar{t}$		0.07
Single top quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
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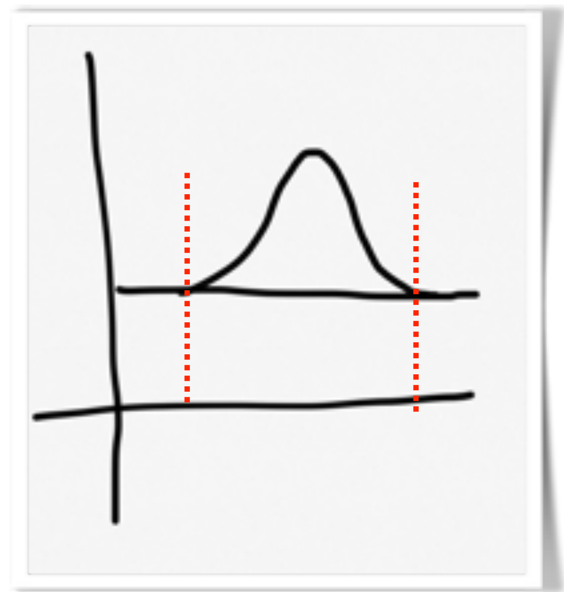
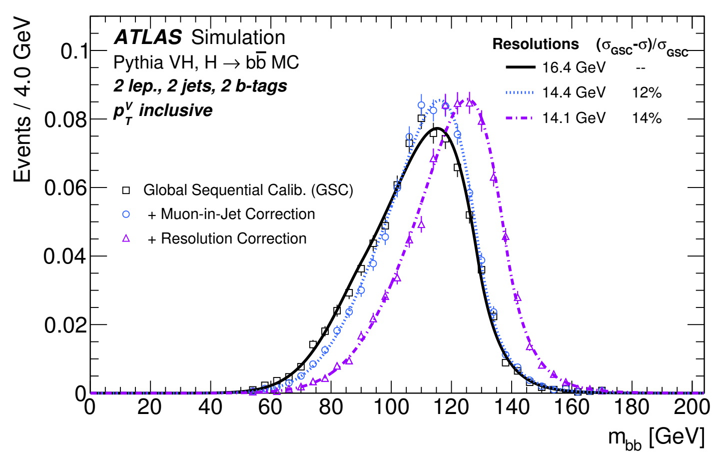
b-tagging	b-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01

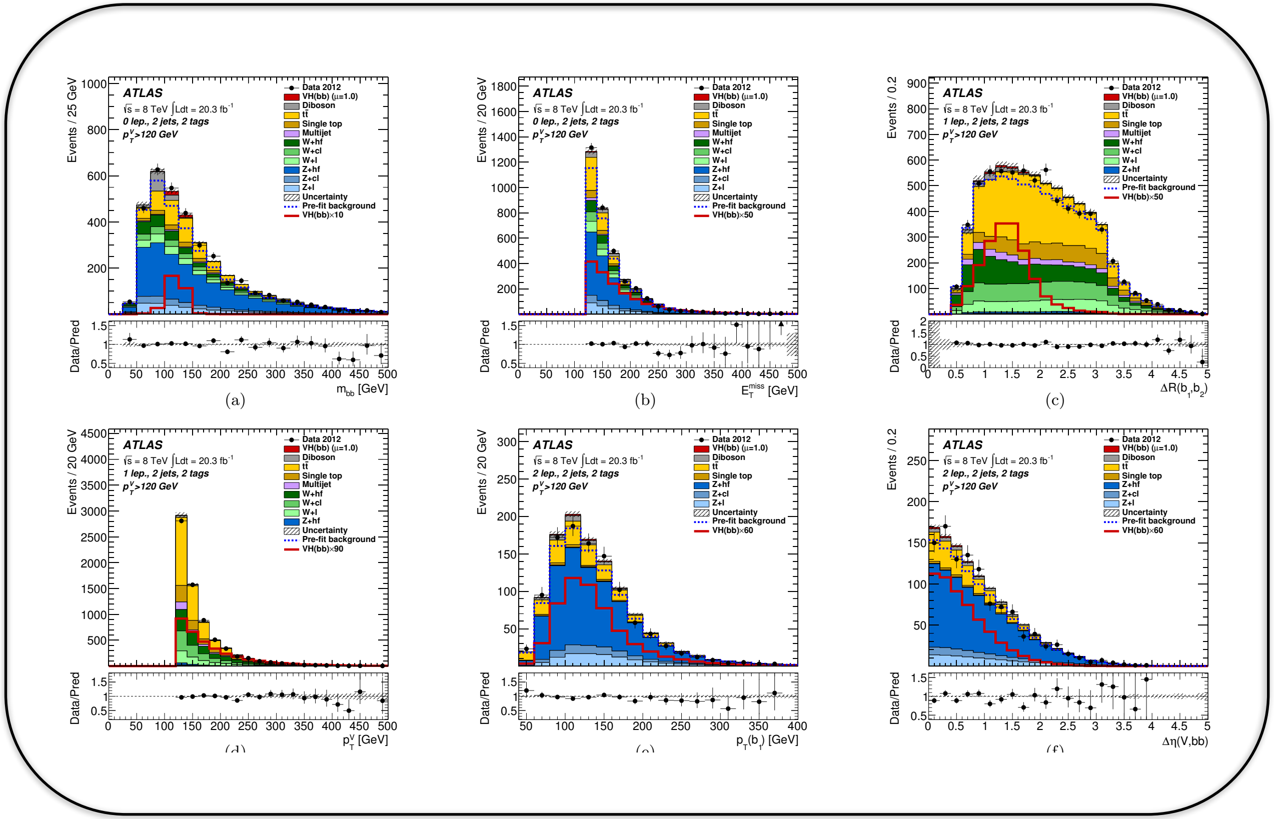
Improving sensitivity: mass resolution

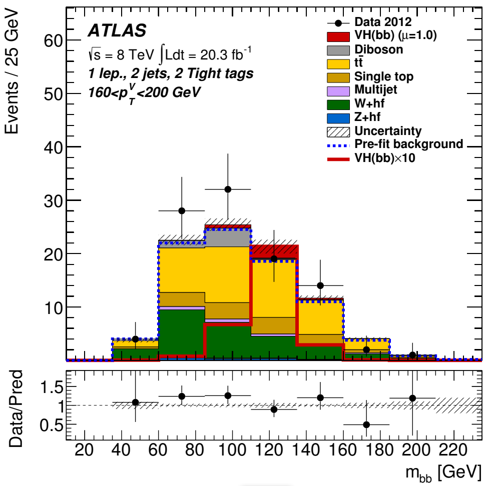


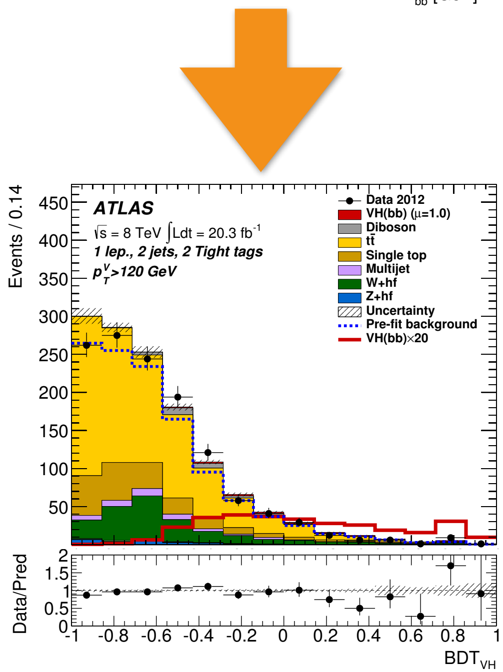
- The better the mass resolution, the smaller the amount of background that needs to be considered
- 14% improvement in resolution



Improving sensitivity: MVA



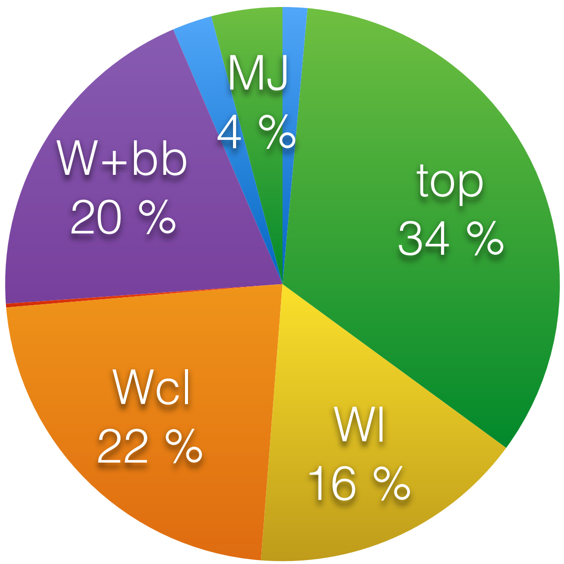




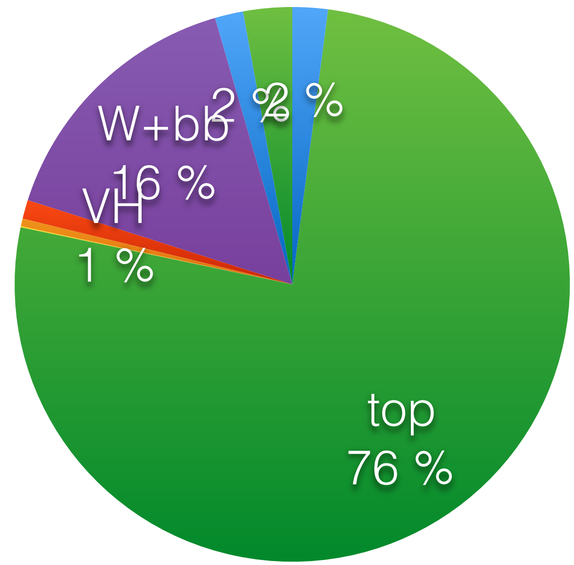
Multivariate techniques combine information from kinematic distributions into a single discriminating variable

Improving sensitivity: categories

loose b-tag



tight b-tag

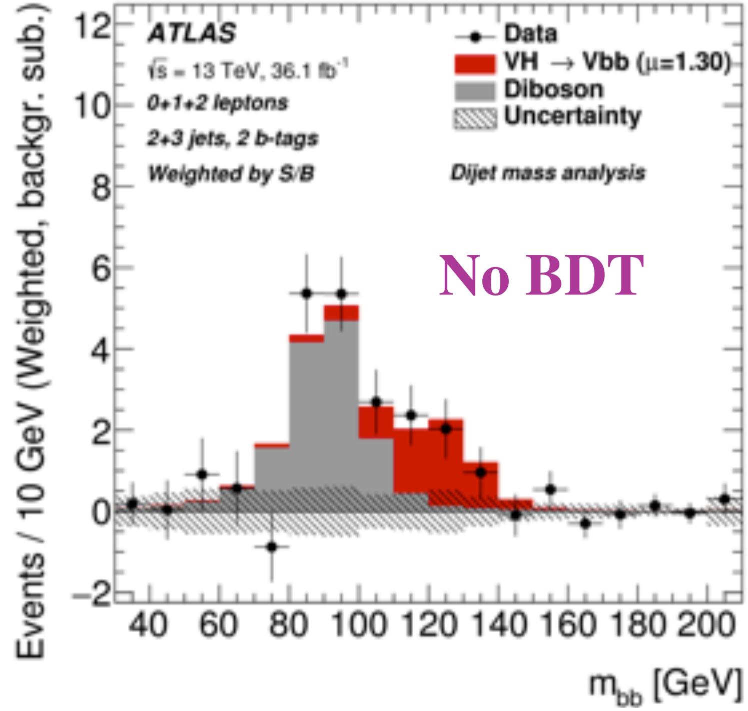


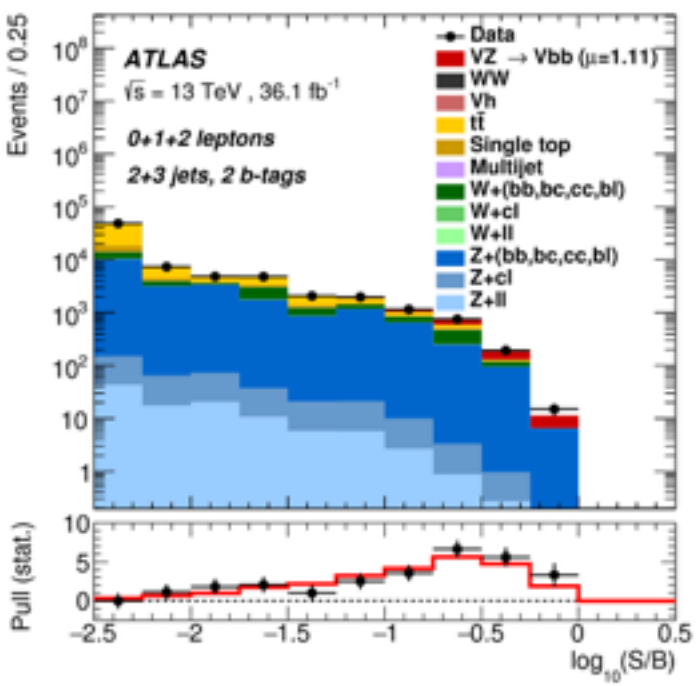
- Simple idea: add cuts to divide events into categories
  - Don't throw away any events
  - Separate out high S/B regions
  - Information to constrain backgrounds
- For VH(bb) we categorise depending on the number of jets x Higgs p_T x b-tagging quality
  - Huge improvement to sensitivity; largely from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

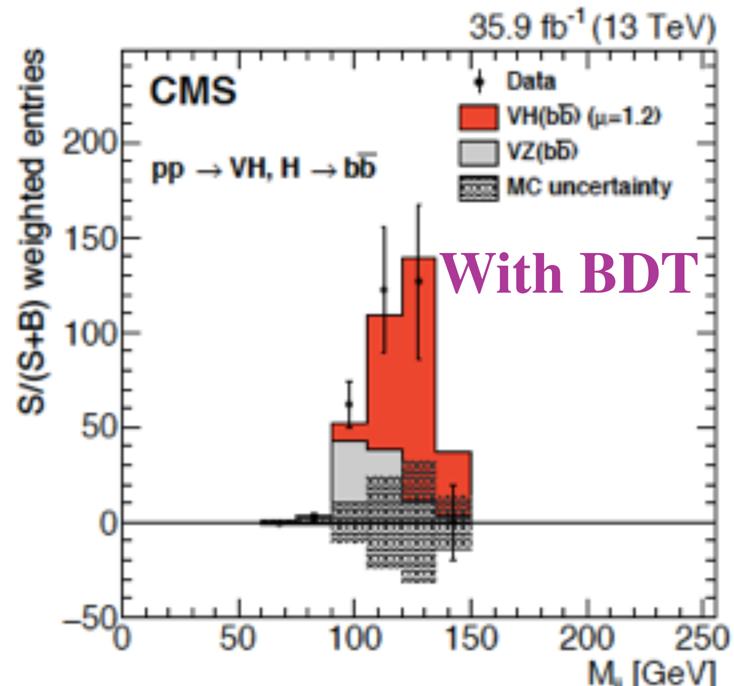
Process	Scale factor
$t\bar{t}$ 0-lepton	1.36 ± 0.14
$t\bar{t}$ 1-lepton	1.12 ± 0.09
$t\bar{t}$ 2-lepton	0.99 ± 0.04
Wbb	0.83 ± 0.15
Wcl	1.14 ± 0.10
Zbb	1.09 ± 0.05
Zcl	0.88 ± 0.12

Result

- Look for an excess over background prediction
- Fit rate with respect to the Standard Model prediction
    - $\mu = \sigma/\sigma_{SM}$
- Evidence for H to bb now observed in both ATLAS and CMS
    - More data needed to do real measurements in this channel!







D. Froidevaux

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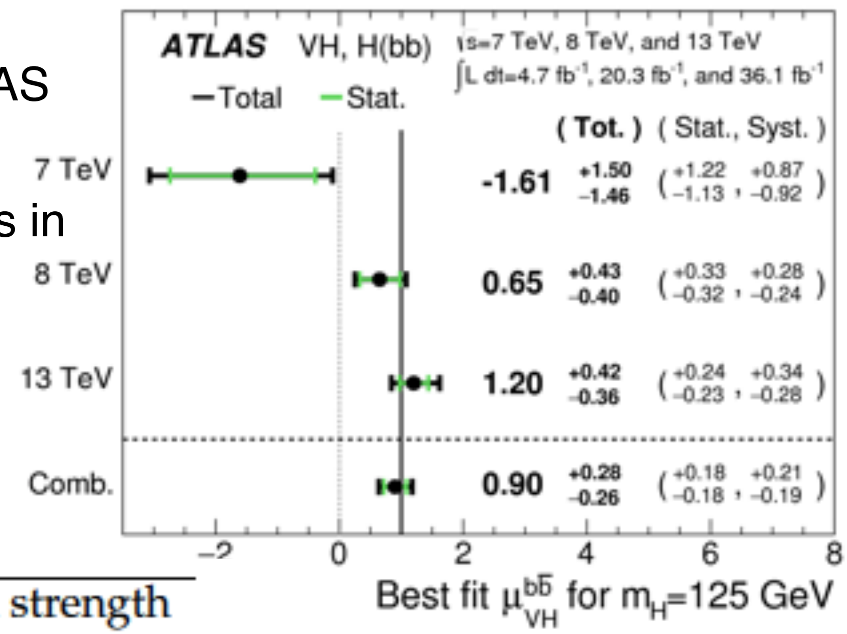
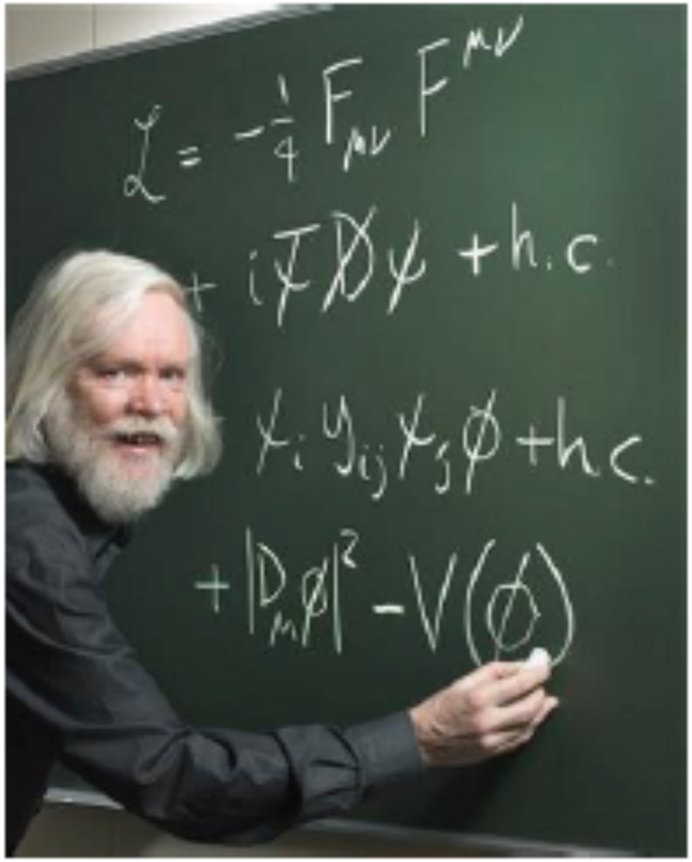


CMS

Data used	Significance expected	Significance observed	Signal strength observed
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
Combined	3.8	3.8	$1.06^{+0.31}_{-0.29}$

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 ?



1976

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)
CERN -- Geneva

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

A short historical digression

• Most of the techniques used for Higgs-boson discovery were developed in the 80s with studies for the SSC and for the ECFA La Thuile workshop (87-88):
comparison of LHC (20 TeV) vs SSC (40 TeV) vs CLIC (2-3 TeV).

• Many of the theoretical tools used at the time were only LO but they were nevertheless vital for the design of ATLAS and CMS
A few examples in a nutshell are given below and in next slide

• Vector boson fusion first proposed by Cahn et al., at that time for heavy Higgs-boson searches

• Fat jets to measure substructure properties (in reality top-quark mass) first proposed by GEM collaboration in their TDR

• And also, lack of tools to model complex SM backgrounds in an accurate way. History repeats itself at different moments in time, with the requirements for the tools having progressed basically as rapidly as the tools.

• And the LEPC wanted to understand the LHC potential for MSSM Higgs discovery

A short historical digression

• Most of the ... s
with studies f...
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• Many of th... e
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A few exampl...

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History repea... e
tools having p...

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Physics Division

Submitted for publication

PRODUCTION OF VERY MASSIVE HIGGS BOSONS

R.N. Cahn and S. Dawson

December 1983

• And the LEPC wanted to understand the LHC potential for MSSM Higgs discovery

A short historical digression

• Most of the techniques used for Higgs-boson discovery were developed in the 80s with studies for the SSC and for the ECFA La Thuile workshop (87-88): comparison of LHC (20 TeV) vs SSC (40 TeV) vs CLIC (2-3 TeV).

• Many of the theoretical tools used at the time were only LO but they were nevertheless vital for the design of ATLAS and CMS

A few examples in a nutshell are given below and in next slide

• Vector boson fusion first proposed by Cahn et al., at that time for heavy Higgs-boson searches

• Fat jets to measure substructure properties (in reality top-quark mass) first proposed by GEM collaboration in their TDR

• And also, lack of tools to model complex SM backgrounds in an accurate way. History repeats itself at different moments in time, with the requirements for the tools having progressed basically as rapidly as the tools.

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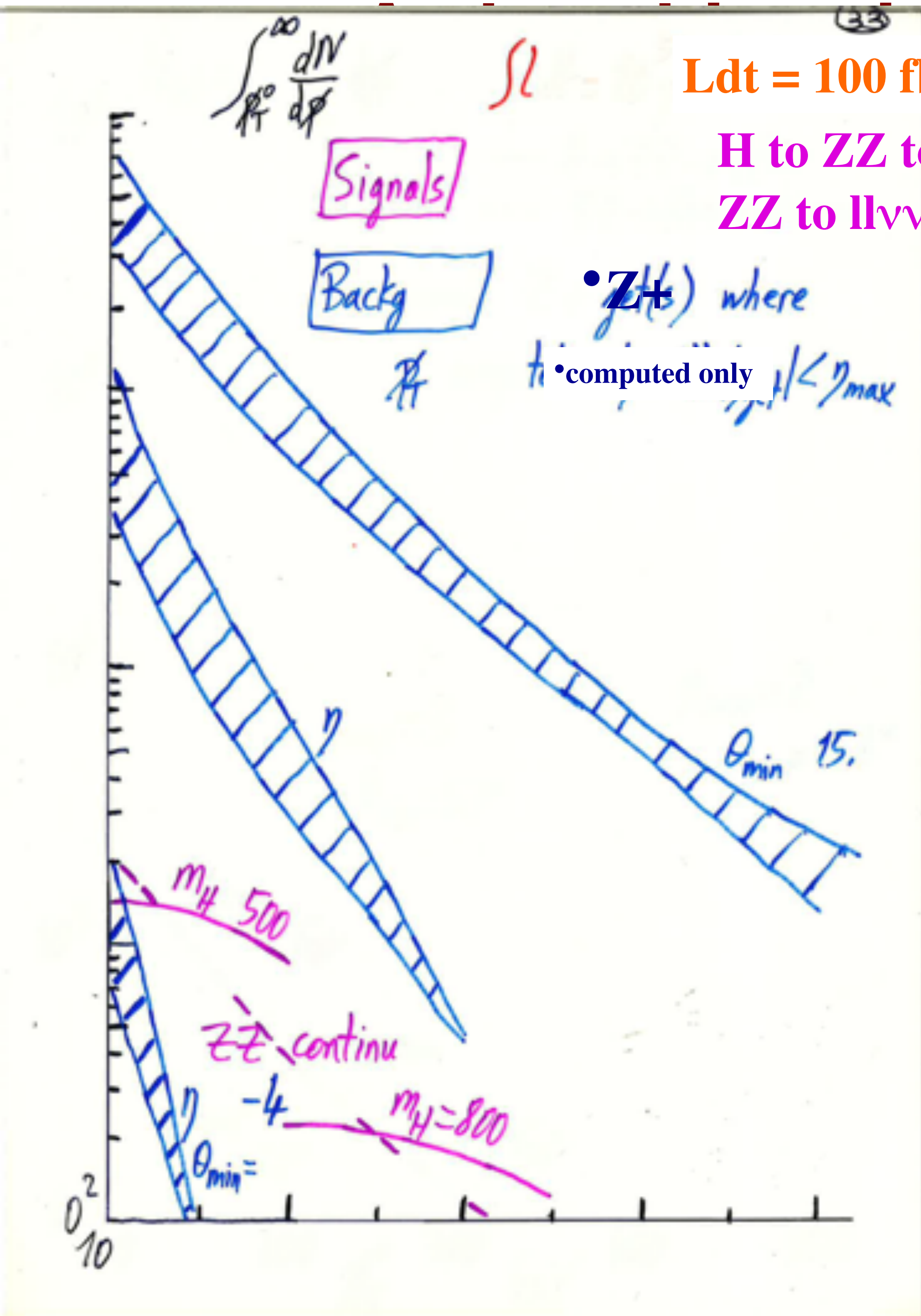

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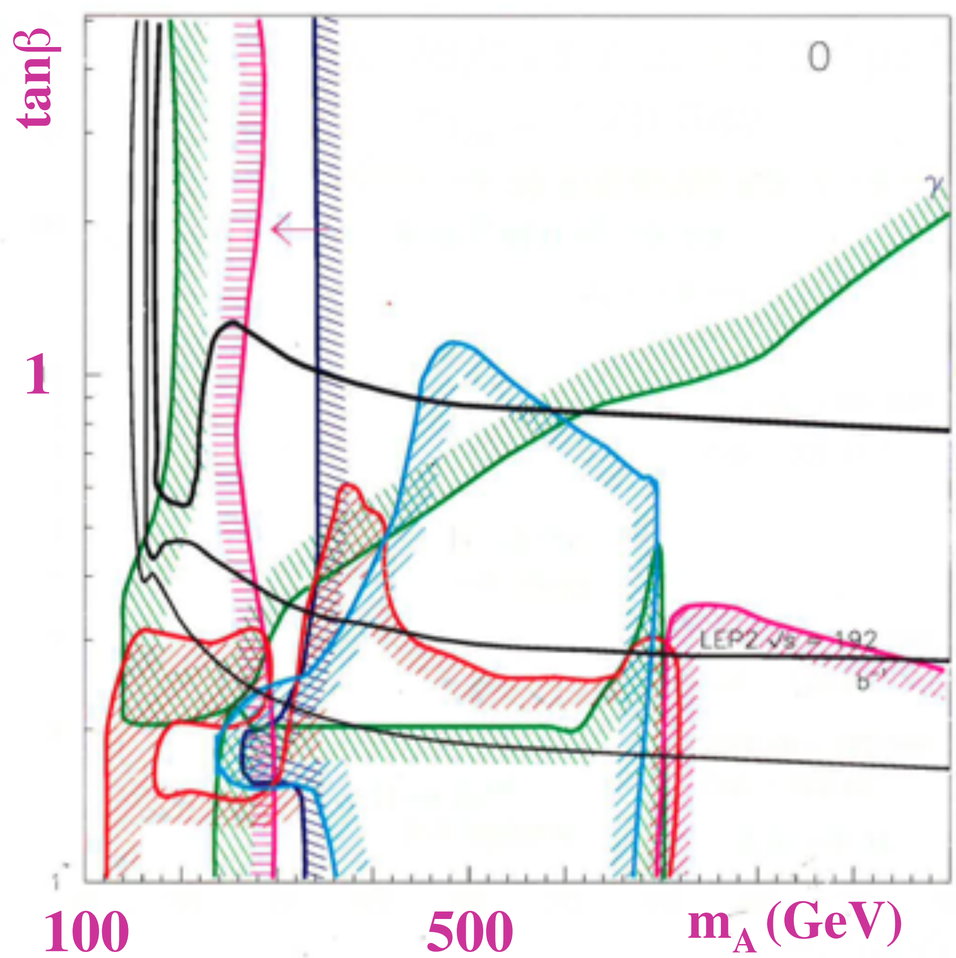
MSSM Higgs sector at LHC
(discovery curves)
for m_{top} = 175 GeV



A short historical digression

Importance of theory (QCD): not only NNLO cross-sections, but more importantly NNLO differential calculations