LHC Searches

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Petnica Summer School
26th / 27th of July 2014

PART I

How did we end up building such a thing as the LHC?

- **Accelerators : why?**
- **Accelerators : What?**
- **The LHC**
    - CERN's accelerators complex
    - Technology challenges
    - Magnets
    - The LHC Story
    - Lumi and Pile-Up
- **Data Taking and Grid**
- **The Structure of an event**
- **Analysis of the data in detectors**
- **What is an Analysis?**

Accelerators : why?

- **Standard Model** : seen on your previous course, seems like a good theory but how to verify the existence of the predicted particles?

- **Accelerators** by accelerating and colliding the particles allows the creation of particles we couldn't observe otherwise because they decay too fast.

- High energy allows to create high mass particles

Most of them observed in the past : USA (Tevatron, SLAC), CERN (SPS + LEP).

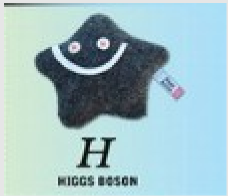
State of observation before LHC starts.

- What is left to be answered?

Accelerators : why?

To be answered :

• the Higgs prediction : (flashback before 2012) last particle predicted by the SM with the Higgs field, responsible for the mass of all particles.
But hasn't been observed yet : Does it exist? What are the properties?
Should we look for another mass explanation?



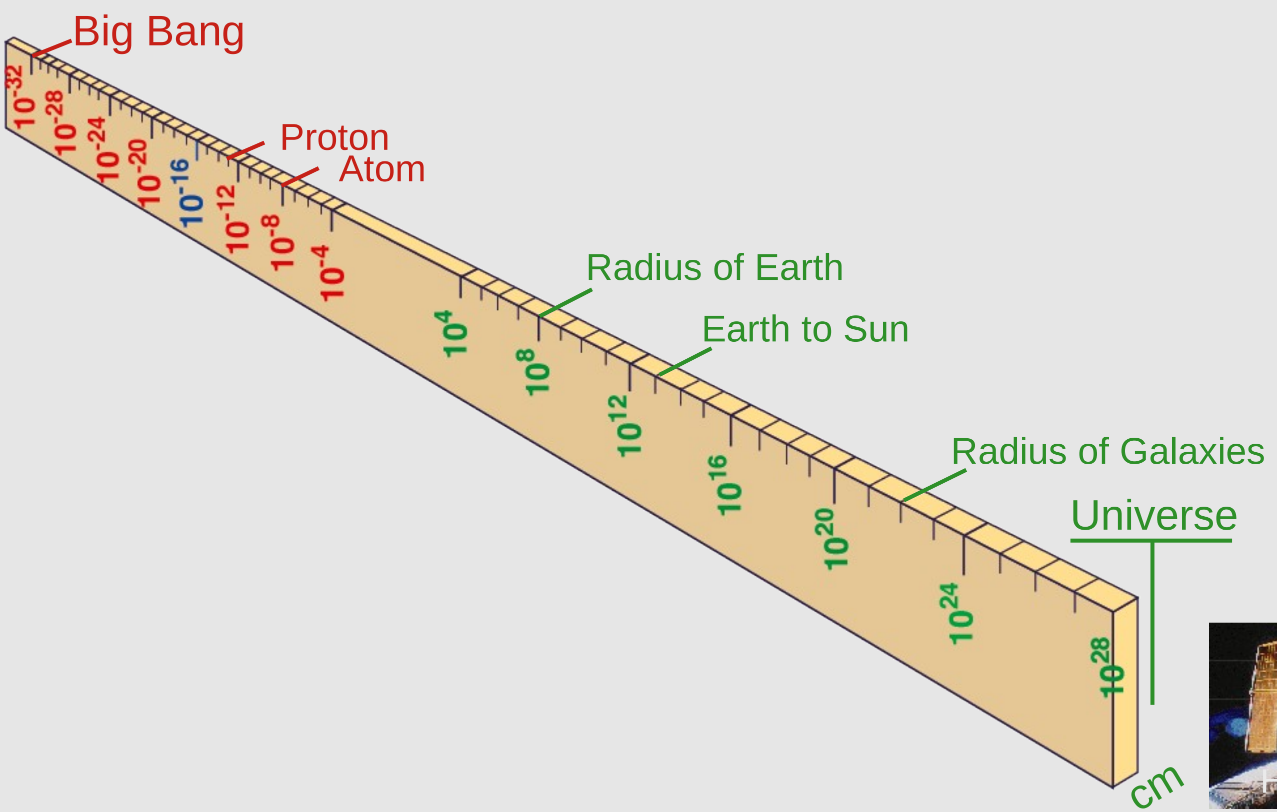
• Matter-antimatter : there should be in equal amount, but the matter dominates.
We have upper limit on amount of anti matter from gamma-rays and cosmic microwave background.

• dark matter : cosmo and astro observations showed that all visible matter ~ 4% of the Universe. Search for particle or explanation responsible for dark matter (23%, supersymmetric particles?) and dark energy (73%).

• force unification : how does gravity fit into the picture?
SM does not offer a unified description of all fundamental forces : gravity cannot be described like the 3 others. Supersymmetry (with massive partner for SM particles?)

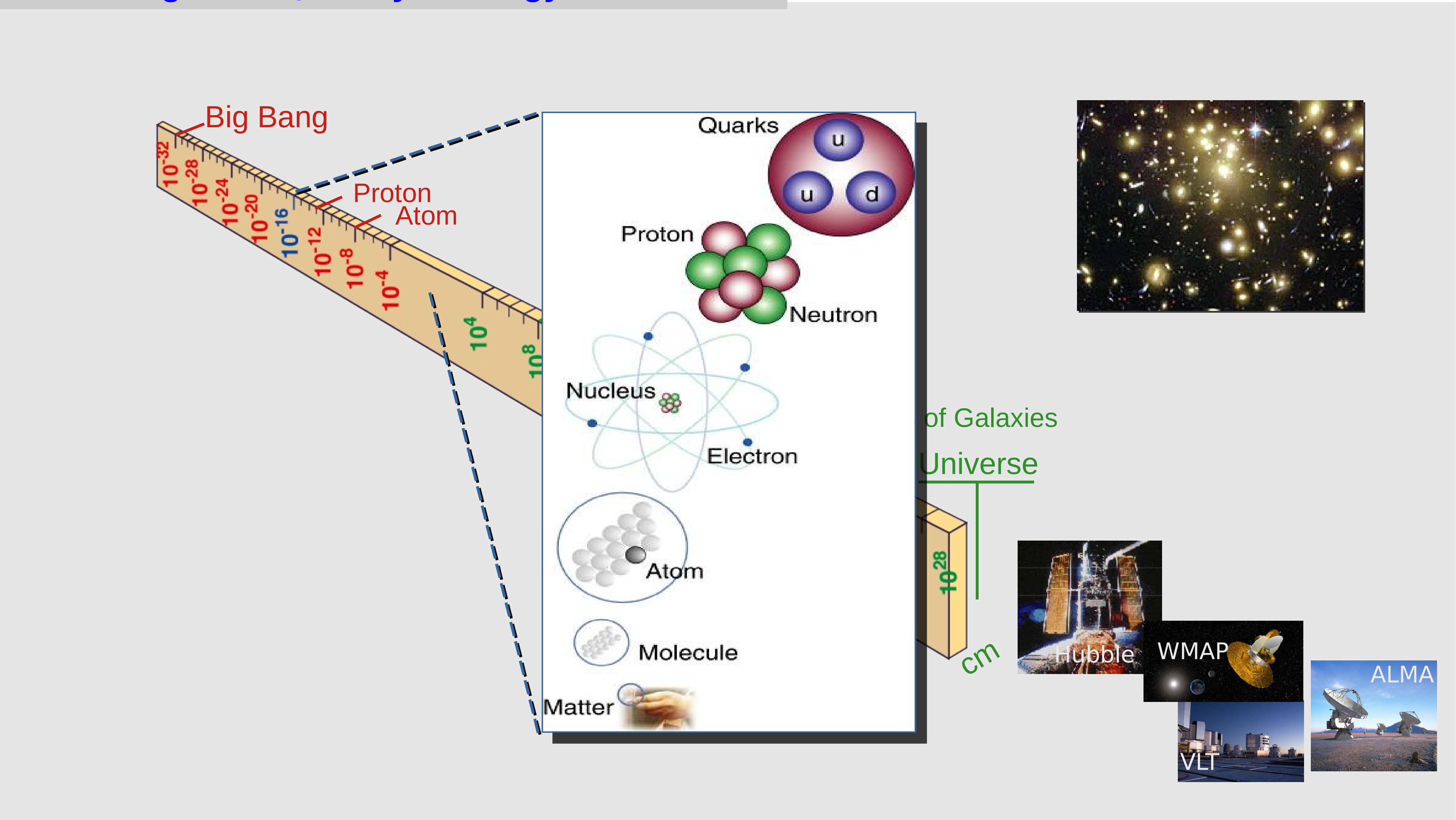
• Quark-Gluon plasma : a window to the early stage of our universe.
After the Big Bang, the Universe went through a stage where matter existed as a hot dense soup of elementary particles. Cooling → quarks trapped (confinement).
Can reproduce the QGP by colliding heavy ions. $T \sim 1M * T_{Sun}$

Broadest scale



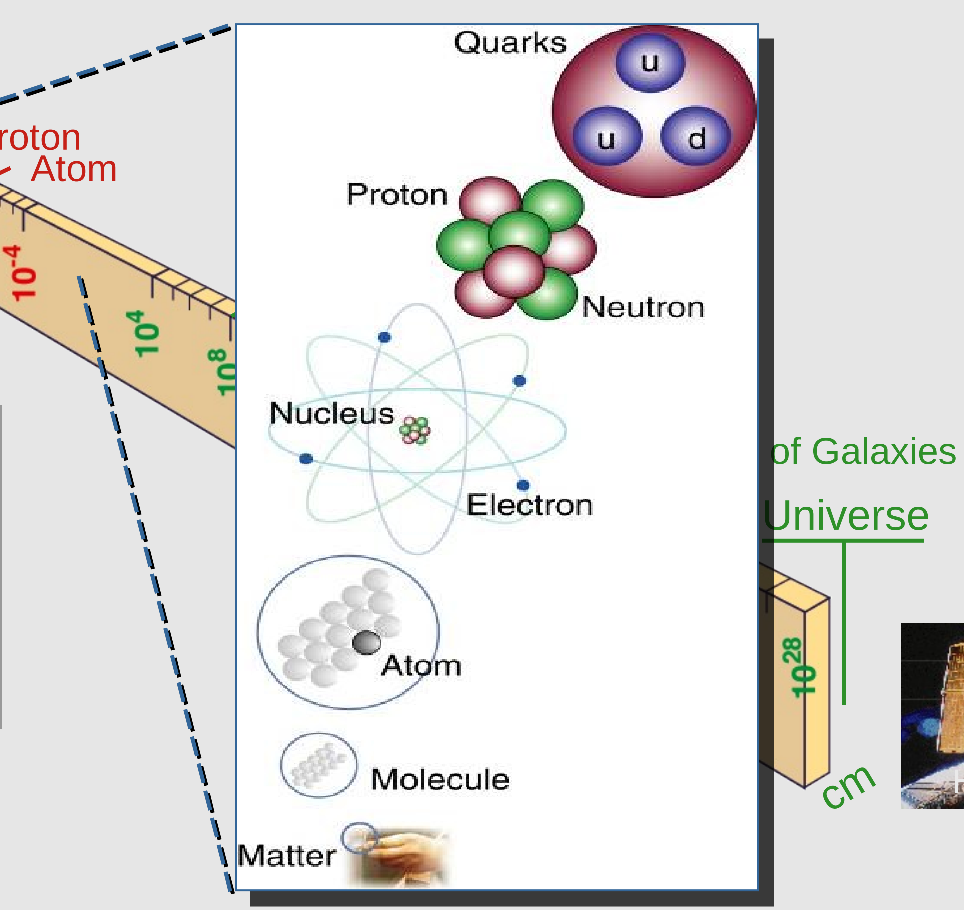
Accelerators : why?

Interesting = rare , heavy = energy



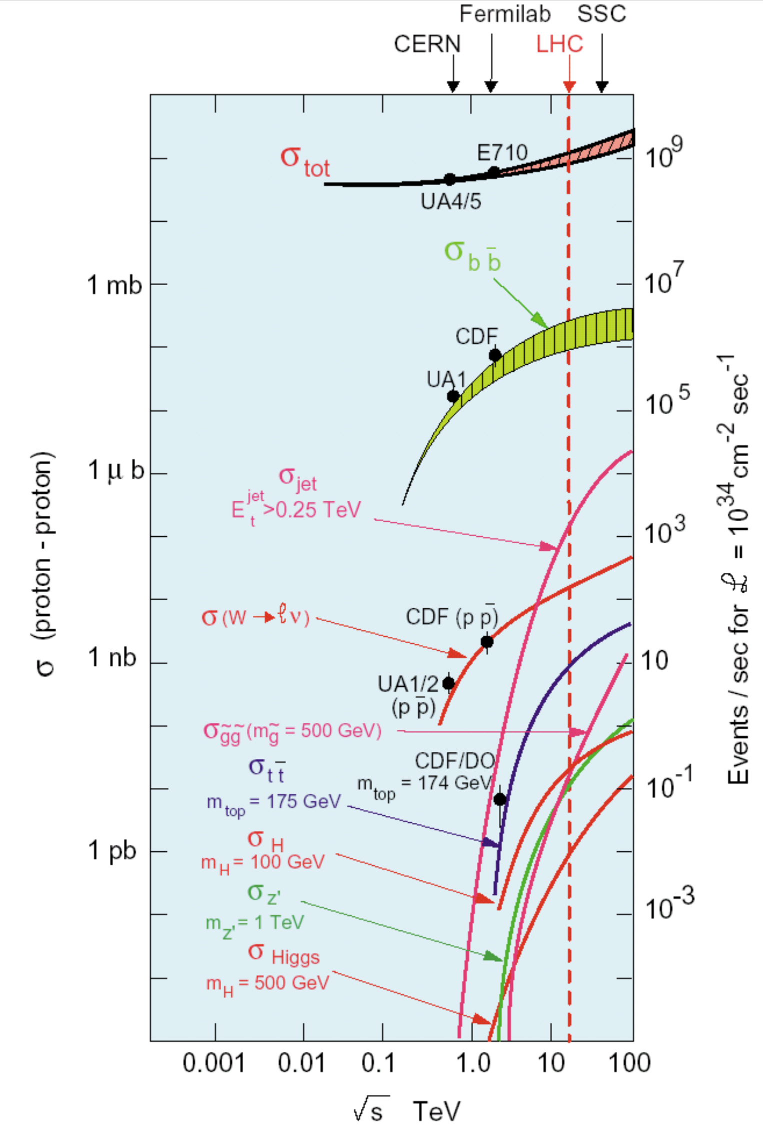
Broadest scale

Super-Microscope



Accelerators : why?

Interesting = rare , heavy = energy



- The interesting processes are rare = small cross section = small probability to happen.
- The cross sections of the production of those interesting events containing heavy particles increases dramatically with the energy at the center of the collision.

Types :

hadrons -> highest energy but initial state not precisely known due to proton being a composite particle from quarks and gluons

leptons -> for precision physics since initial state of collision known precisely. But energy not so high.

Accelerators : what?

Very first ones :

Electrostatic field do not change with time. Disadvantage = large electric field needed to accelerate particles to experimentally useful E.

Van de Graff
1931
2MeV

Cockcroft-Walton
1932

And later :

Oscillating : require fields that periodically change with the time.
→ acceleration to extreme high E

Linear Accelerators

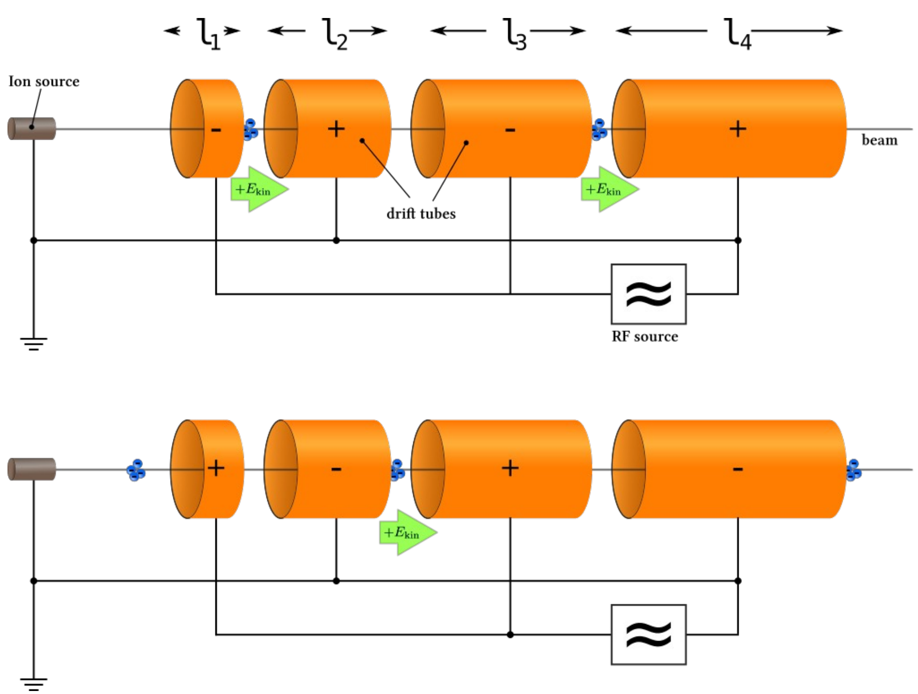
LINAC

Basic principles of LinAcs unchanged since Wilderoe (1920's)

• Alternative current (periodically reversed flow of electric charge) and series of drift tubes.

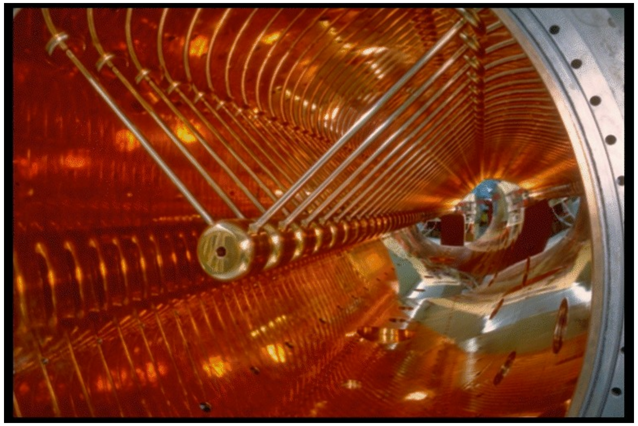
→ particle accelerated during a peak of voltage and hidden in drift tube during anti peak to avoid come back to starting point

• As particle get faster the drift tube need to get longer : length is one limiting factor for high energies



Largest LINAC at SLAC US : 3.2km, e^- and e^+ , 50 GeV

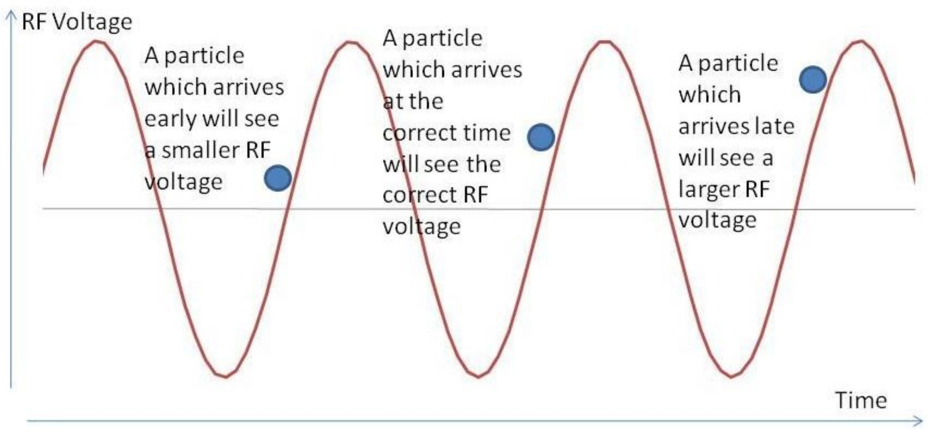
LINAC 4 being build at CERN



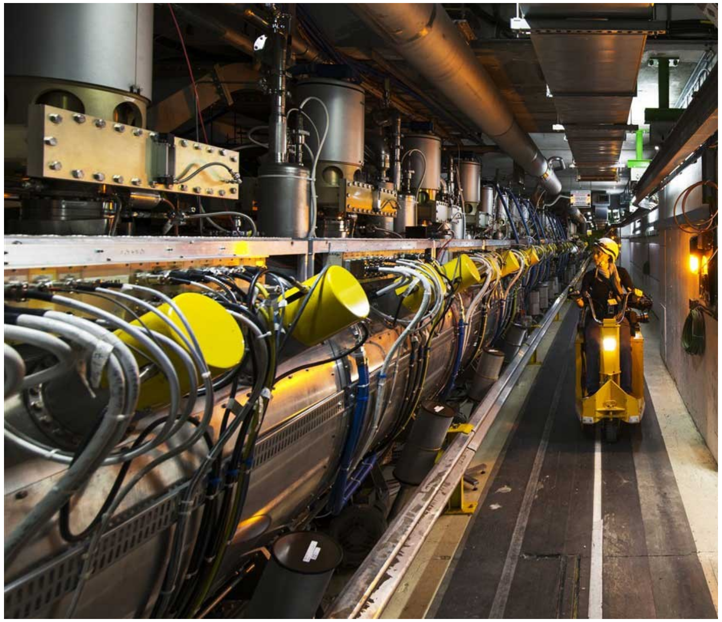
Need to synchronize between particle speed and electrical field.
Synchronous phase → creation of bunches of particles.

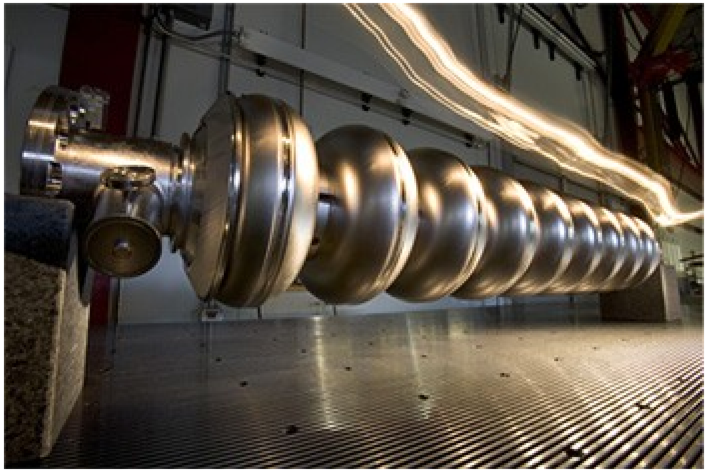
LINAC

As $v_{particle}$ ~ speed of light the switching rate of the electric fields becomes so high that they operate at radio frequencies and so resonant microwave cavities are used in higher energy machines instead of simple drift tubes.

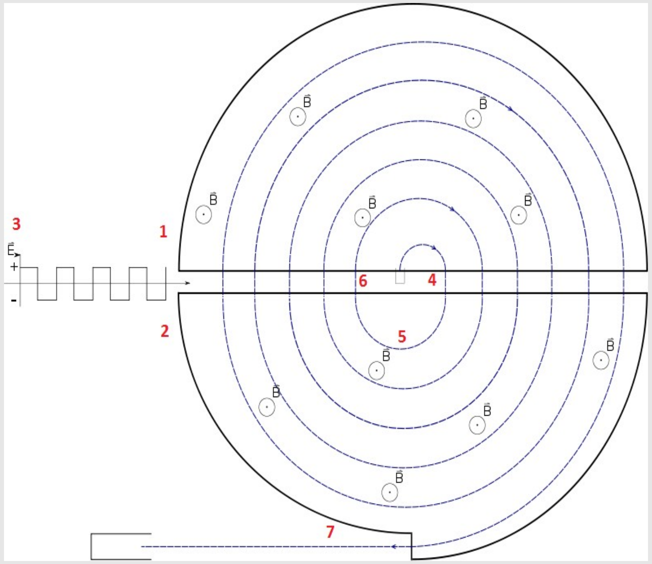


RF cavities at LHC





Cyclotron



First cyclotron: E.Lawrence in the 30's
2 D-shape electrodes alternatively charged by oscillator.

- Principle : magnetic field applied perpendicular to the plane of motion of an accelerated particle.
  → even more accelerated
- Constant magnetic field.
- Classical mechanics. 25 GeV max!

Improvement

Take into account the effects of relativity on mass of particles approaching the speed of light .

→ 1945, called Microtron.

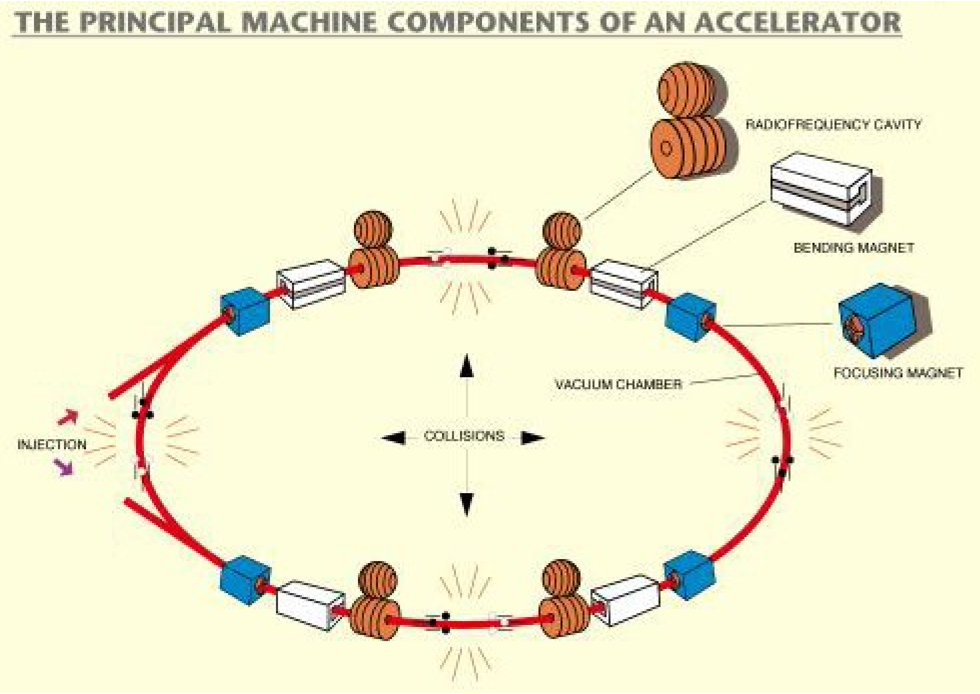
Synchrotron

Synchrotron

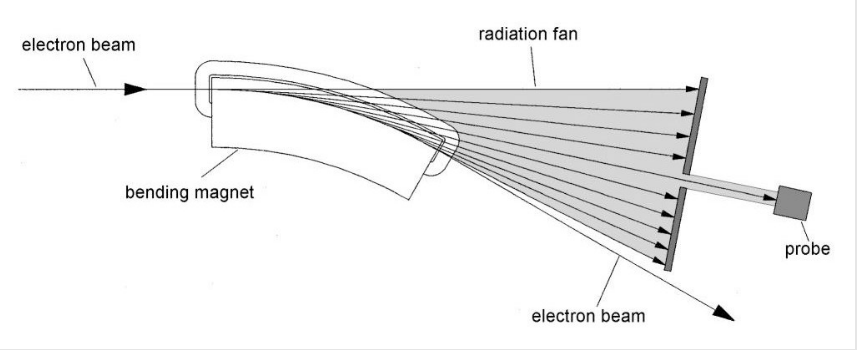
• Idea = keep the accelerated particles on a constant orbital radius.

• Synchronize the B with the energy of the accelerated particles.

• First in 1954. Many since!



Synchrotron radiation



• An electromagnetic radiation emitted by an accelerated particle with v ~c and a trajectory bended by a magnetic field.

• Synchrotron radiation :
energy loss ~ 1/mass^4

Synchrotron

Notation √s = blabla eV

Beam energies

1.) reminder of some relativistic formula

total energy $$E^2 = p^2c^2 + m_0{}^2c^4$$

$$\rightarrow \quad cp = \sqrt{E^2 - m_0^2c^4} = \sqrt{(\gamma m_0c^2)^2 - (m_0c^2)^2} = \sqrt{\gamma^2 - 1}\, m_0c^2$$

$$\rightarrow \quad cp = \gamma\beta * m_0c^2$$

Proton-antiproton collider
Tevatron (1980s-2010)

2.) energy balance of colliding particles

rest energy of a particle $$E_0{}^2 = (m_0c^2)^2 = E^2 - p^2c^2$$

in exactly the same way we define a center of mass energy of a system of particles:

$$E_{cm}^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i cp_i\right)^2$$

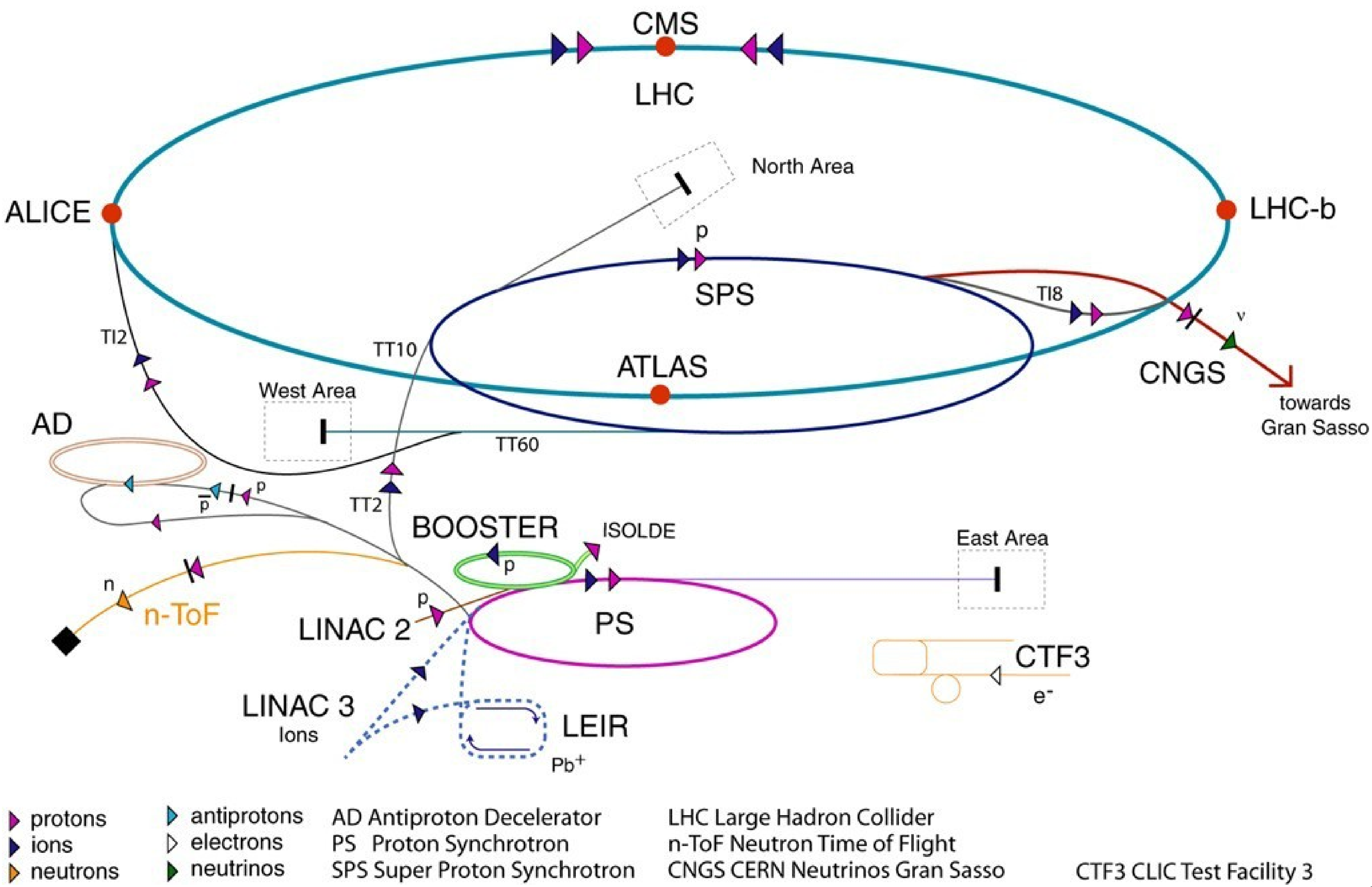
Proton-antiproton collider Tevatron (1980s-2010)

- Creates antiprotons by colliding protons on Ni Target
- Highest energy achieved with particle against anti-particle: 1.96 TeV
- But difficulties to produce and store them → Solution = proton against proton

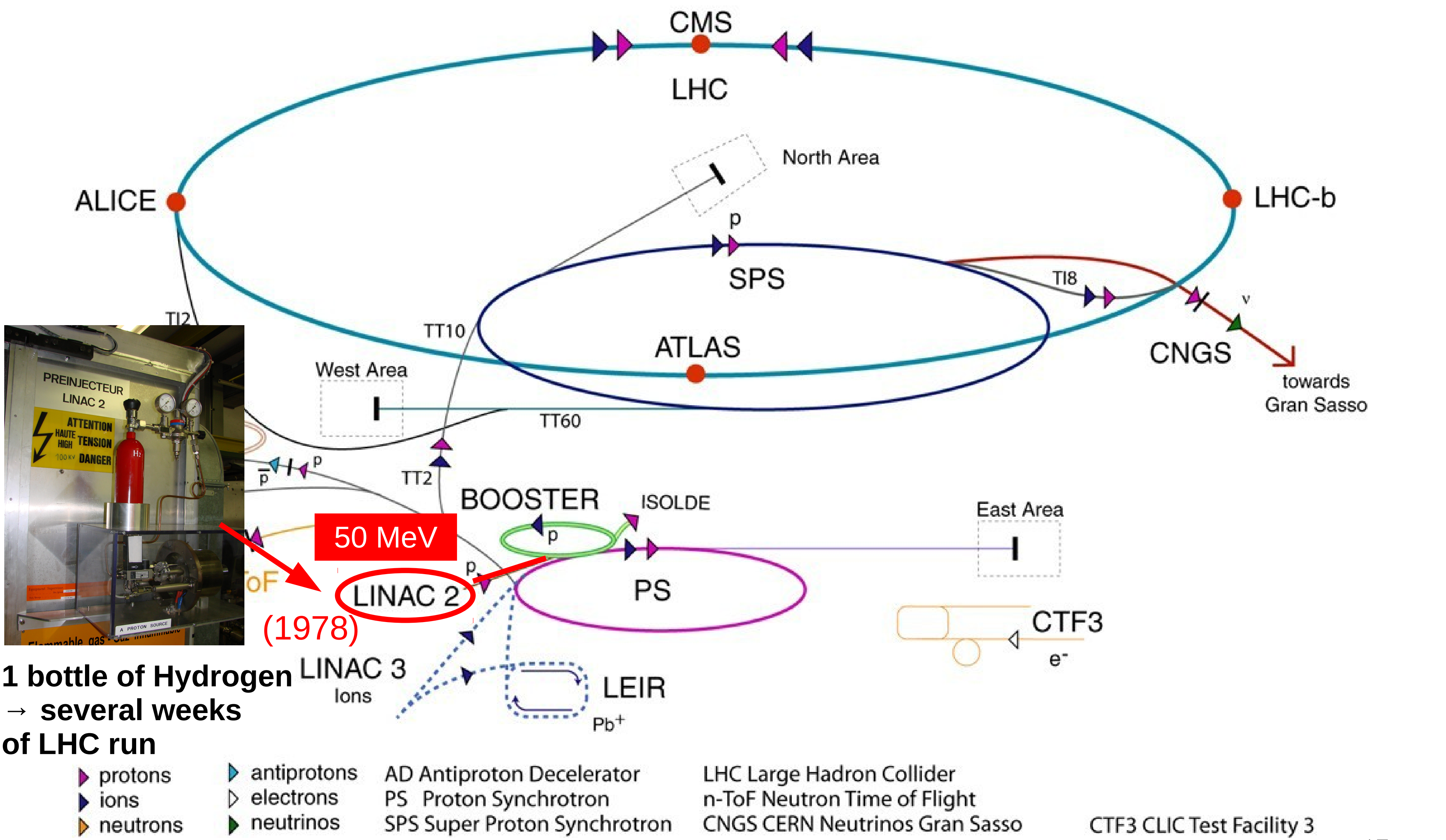
LHC

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

CERN's accelerators complex

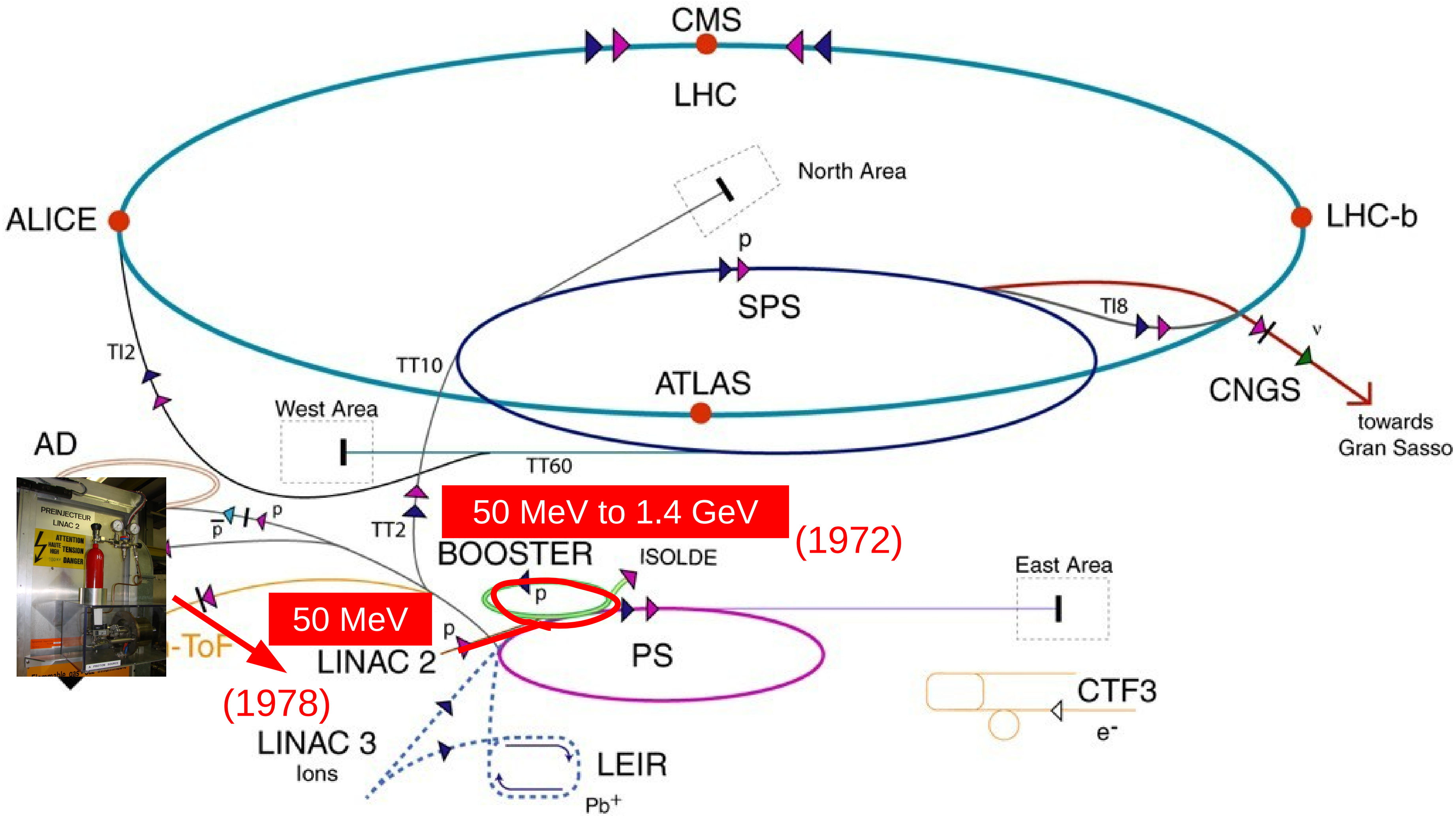


CERN's accelerators complex



1 bottle of Hydrogen → several weeks of LHC run

CERN's accelerators complex



protons
ions
neutrons

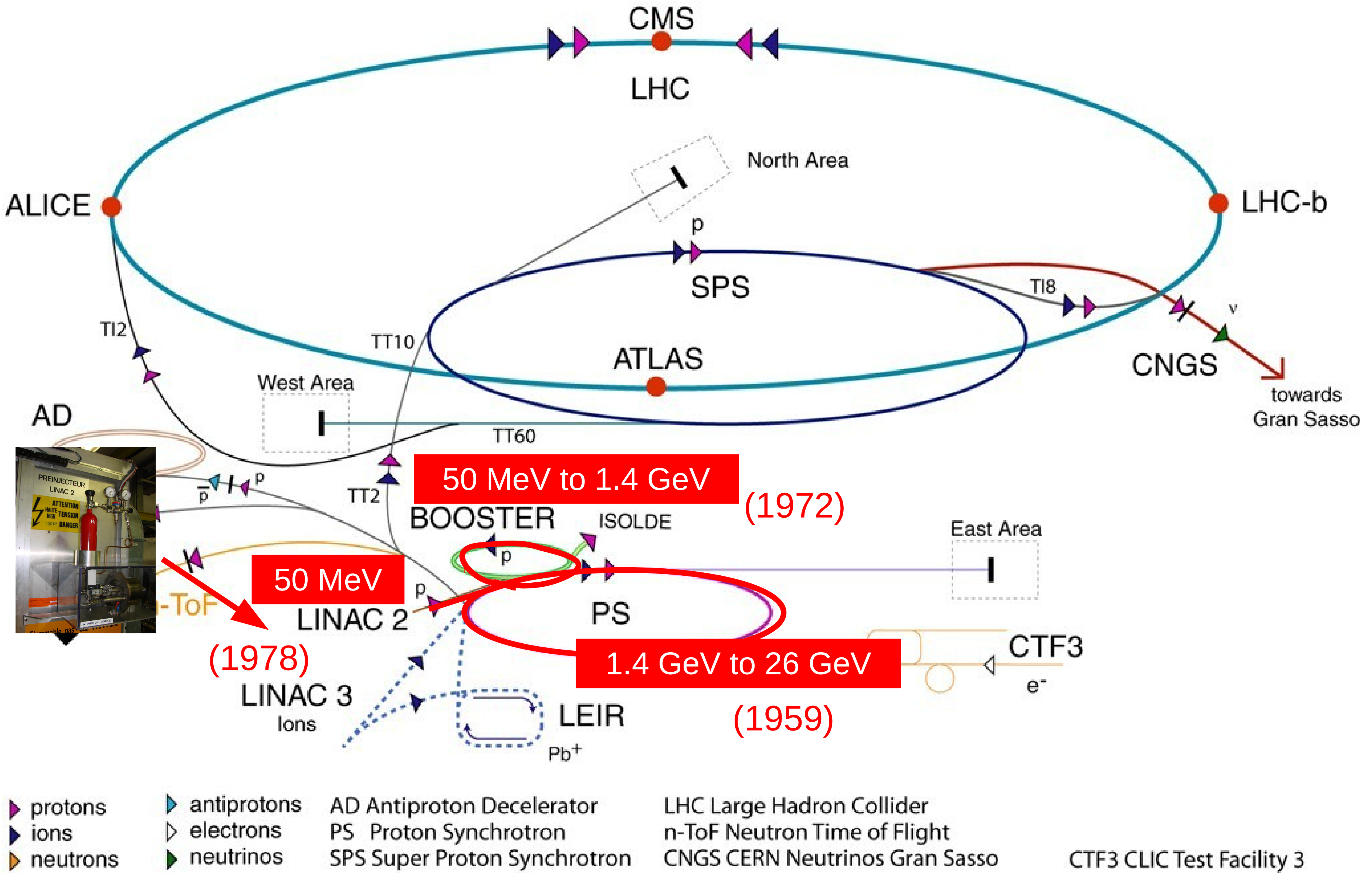
antiprotons
electrons
neutrinos

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

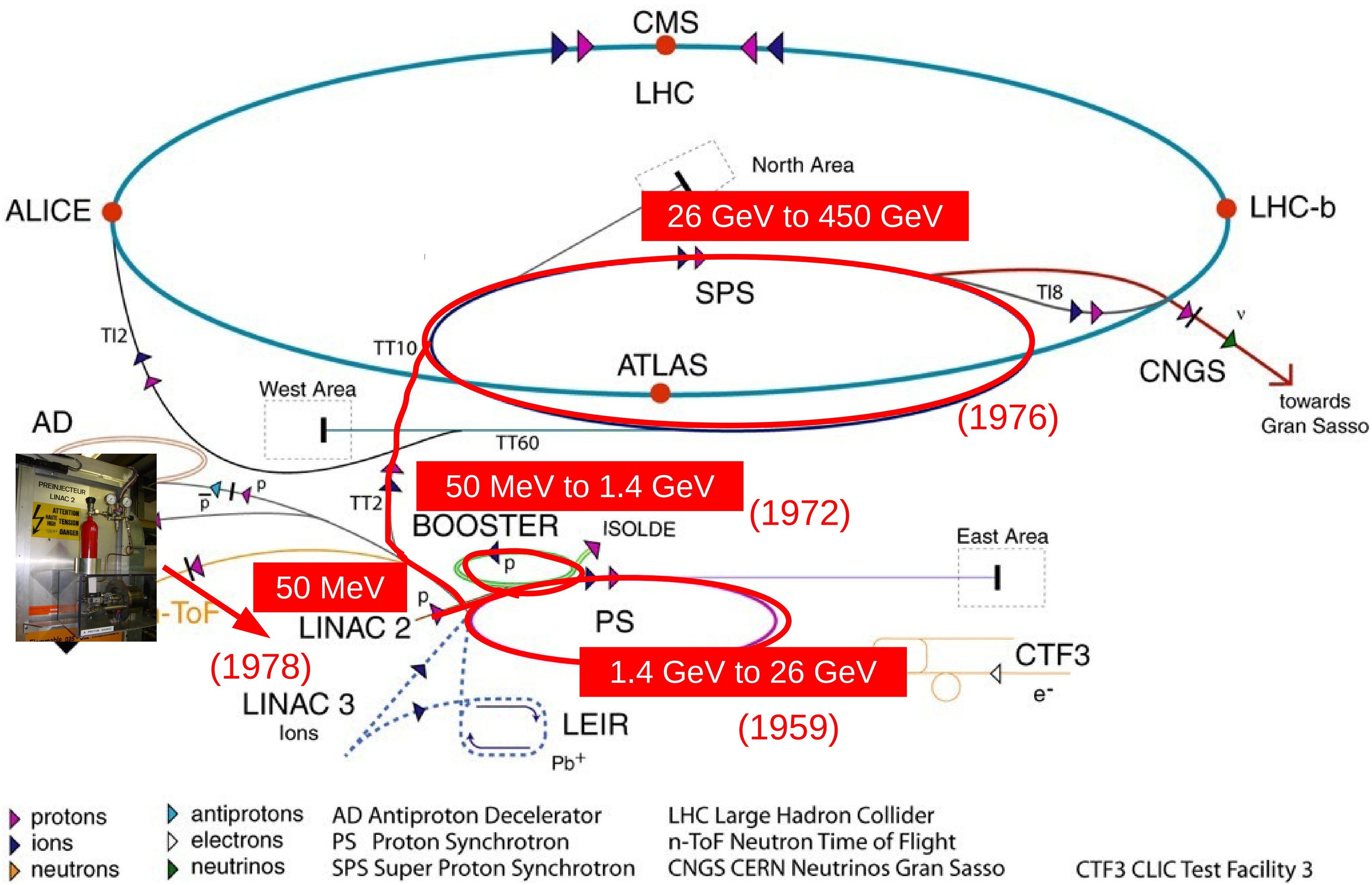
LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS CERN Neutrinos Gran Sasso

CTF3 CLIC Test Facility 3

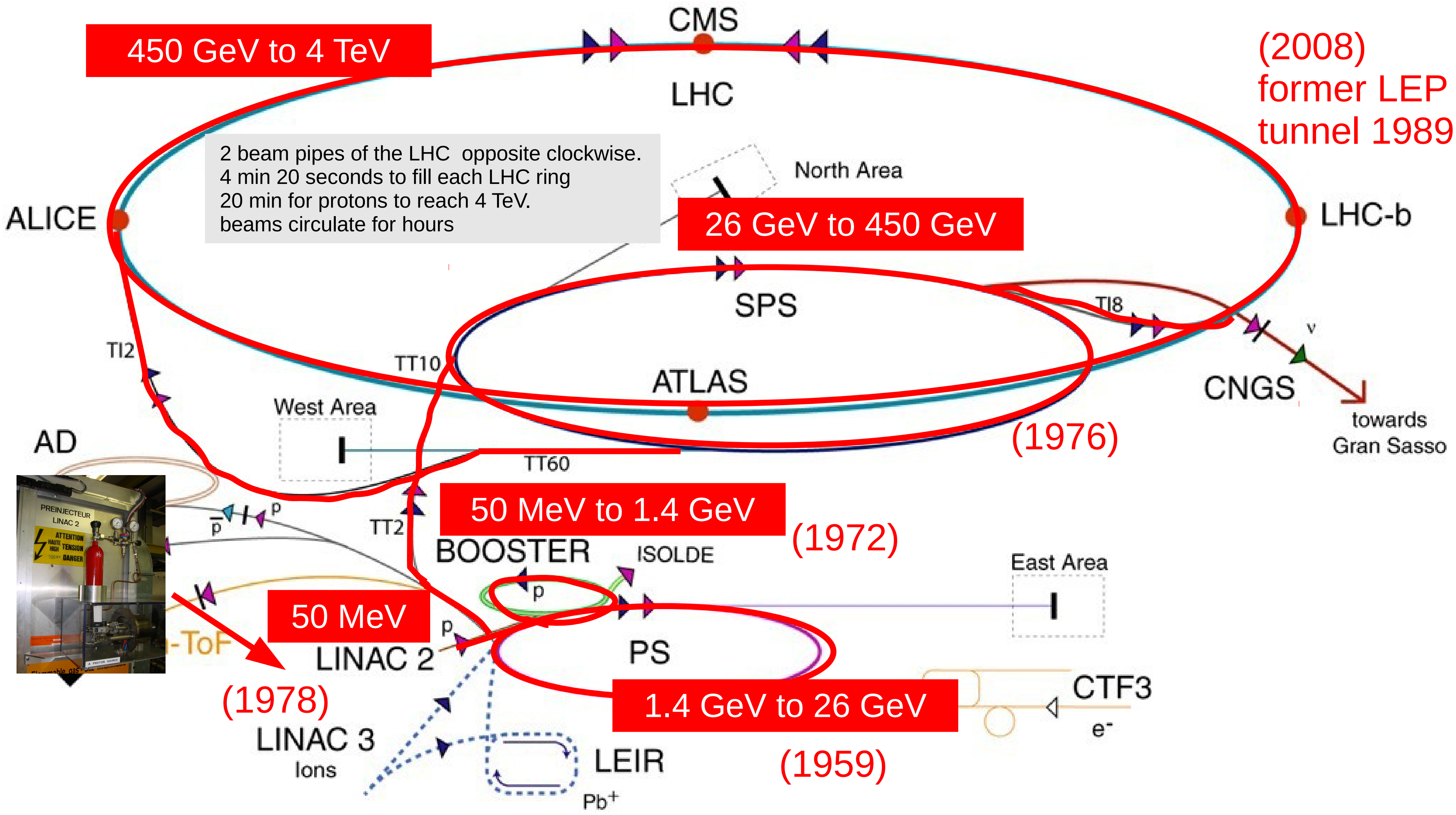
CERN's accelerators complex



CERN's accelerators complex

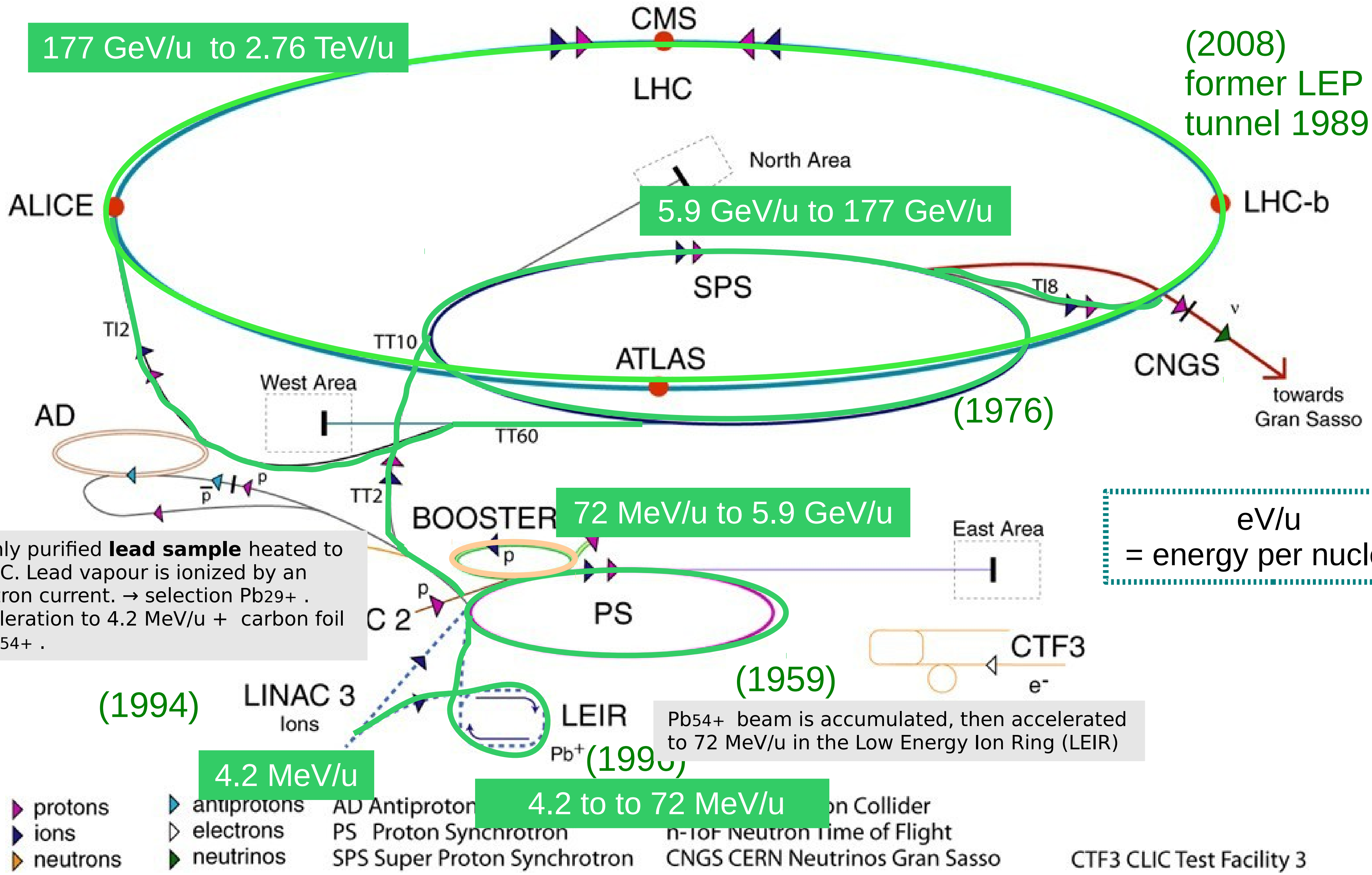


CERN's accelerators complex



protons	antiprotons	AD Antiproton Decelerator	LHC Large Hadron Collider	
ions	electrons	PS Proton Synchrotron	n-ToF Neutron Time of Flight	
neutrons	neutrinos	SPS Super Proton Synchrotron	CNGS CERN Neutrinos Gran Sasso	CTF3 CLIC Test Facility 3

Ions acceleration



Highly purified **lead sample** heated to 500°C. Lead vapour is ionized by an electron current. → selection Pb^{29+} . Acceleration to 4.2 MeV/u + carbon foil → Pb^{54+} .

Pb^{54+} beam is accumulated, then accelerated to 72 MeV/u in the Low Energy Ion Ring (LEIR)

eV/u
= energy per nucleon

Numbers!

Several thousand billion protons
99.9999991% of light speed
Orbit 27km ring
1 turn : 11 000 times/second
A billion collisions a second

The beam vacuum pressure : 10^{-13} atm, to avoid collisions with gas molecules : vacuum similar to interplanetary space:
pressure in the beam-pipes will be ten times lower than on the Moon

Beams squeezed to about 16 µm (a human hair is about 50 µm thick).

LHC 1.9 degrees above absolute zero = - 271 C
Outer space 2.7 degrees above zero = - 270 C

The total energy in each beam at maximum energy is about 350 MJ, which is about as energetic as a 400 tonnes train, like the French TGV, traveling at 150 km/h.
This is enough energy to melt around 500 kg of copper.

Technology challenge

Dipole magnets

To guide the accelerated protons :

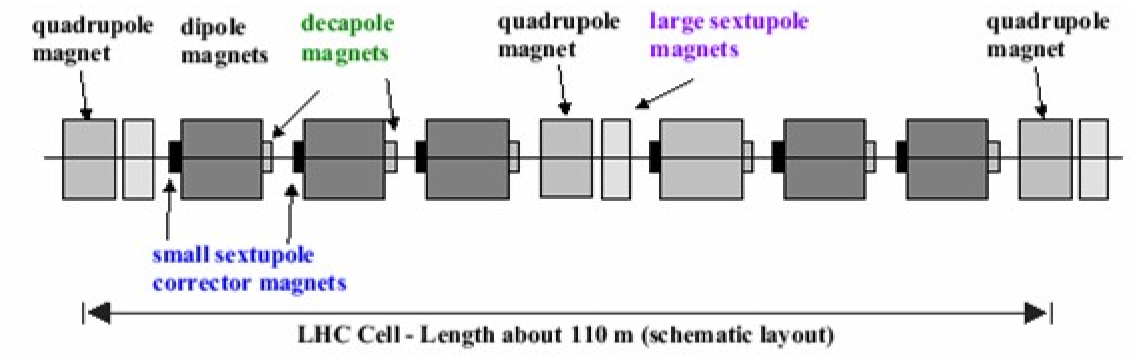
7000 GeV Proton storage ring
dipole magnets N = 1232
l = 15 m
q = +1 e
Example LHC:

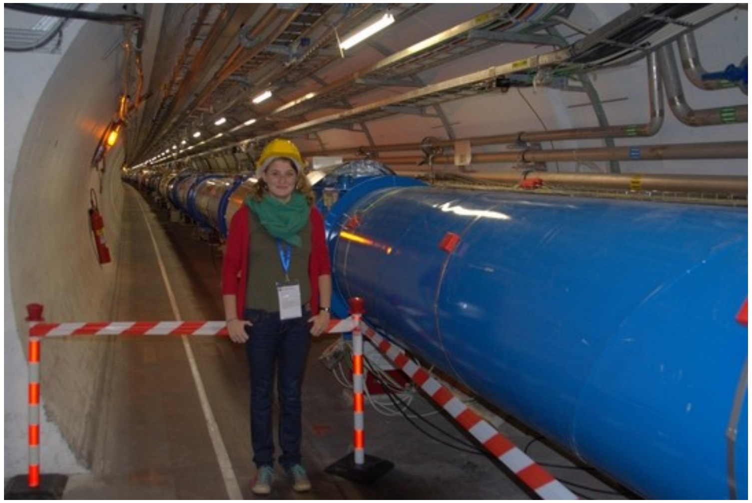
$$\int B\, dl \approx N\, l\, B = 2\pi\, p / e$$

$$B \approx \frac{2\pi \;\; 7000 \;\; 10^{9}\, eV}{1232 \;\; 15\, m \;\; 3\; 10^{8} \frac{m}{s} \;\; e} = 8.3\, Tesla$$

– more than 100,000 times more powerful than the Earth's magnetic field!

Designed for 14 TeV.





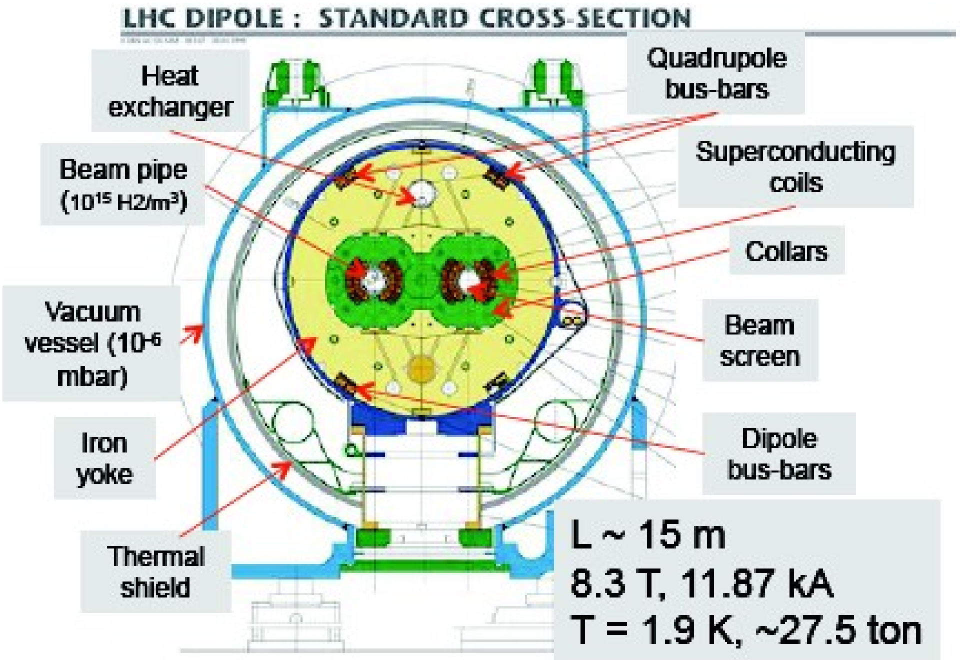
More on Magnets

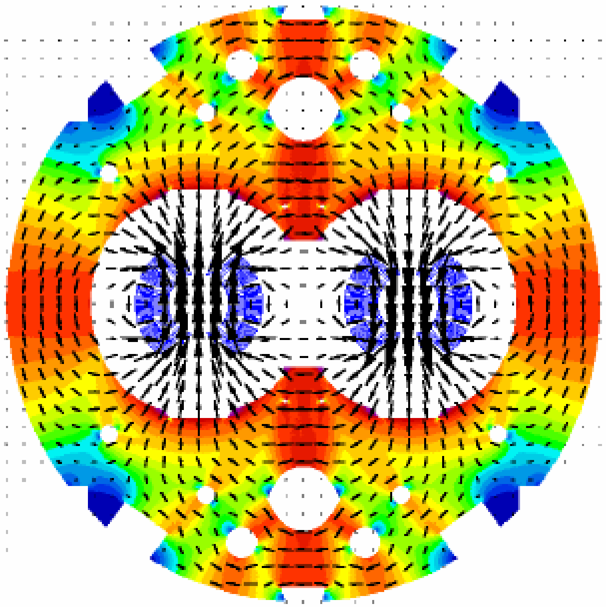
How do they do?

• LHC dipoles use niobium-titanium (NbTi) cables, which become superconducting below a temperature of 10 K (–263.2°C)
→ conduct electricity without resistance.

• LHC operate at 1.9 K

• Current of 11 850 A flows in the dipoles, to create the high magnetic field of 8.33 T



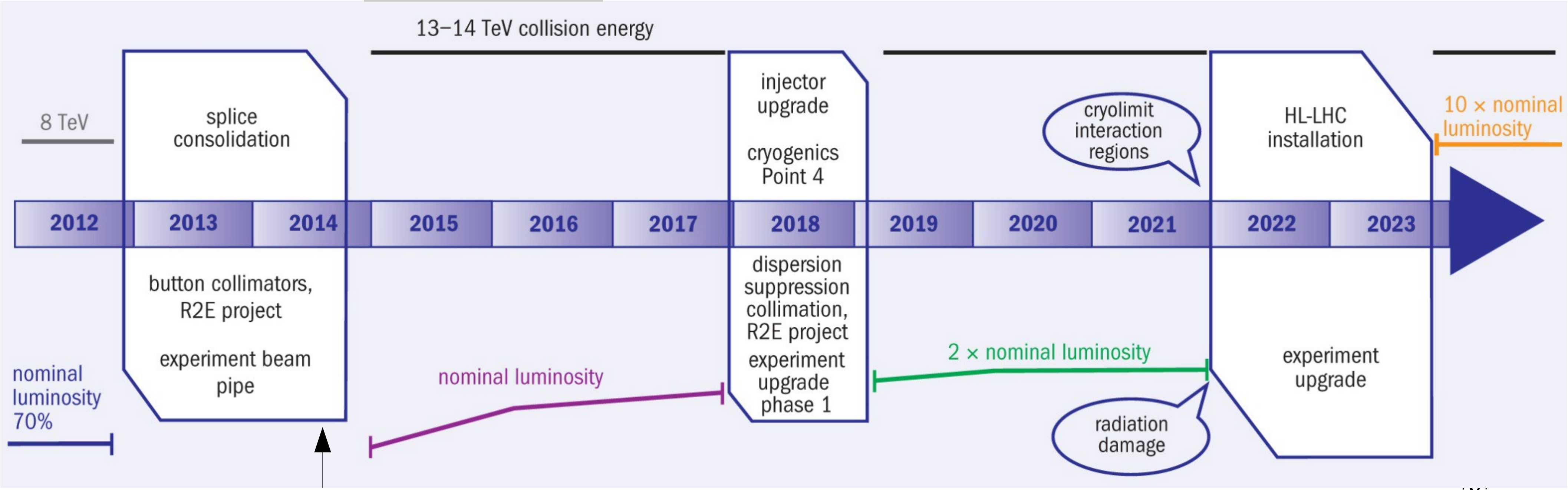


The LHC story

Past

10 September 2008 : first beam!
19 September 2008 : LHC accident , faulty electrical bus connection → release of He → damages
November 2009 : 1.18 TeV per beam
30 March 2010 : first collisions! at 7 TeV!
Ap 2010 – Nov 2011 : p-p coll. at 7TeV
Ap 2012 -Dec 2012 : p-p coll. at 8TeV
Nov 2011-Dec 2011 : Pb-Pb coll. at 2.76 TeV/u
Jan 2013- Feb 2013 : p-Pb coll. at 5.02 TeV/u

Future



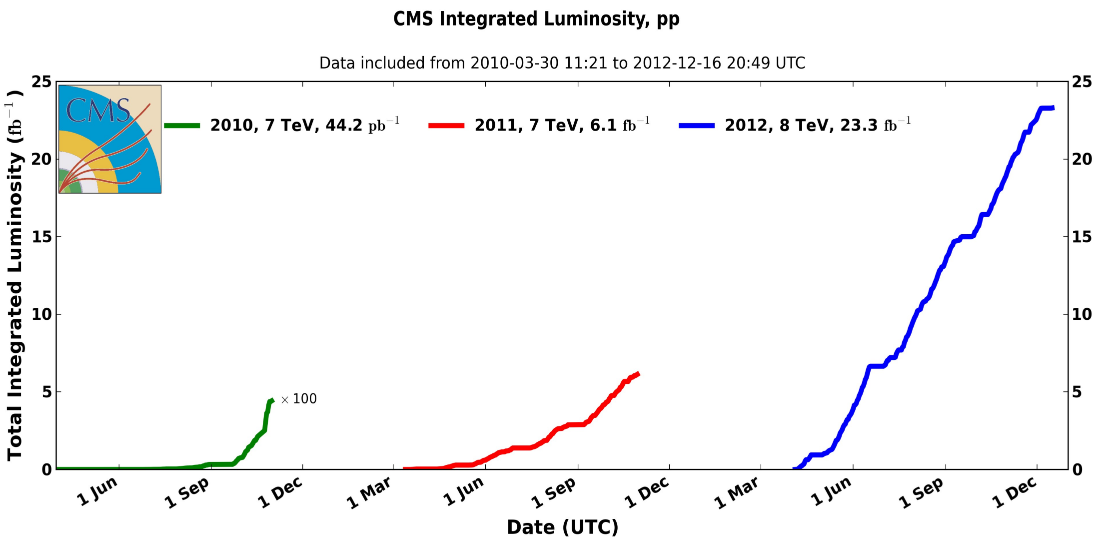
We are here : Long ShutDown

Luminosity

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^2}{4\pi\sigma_x\sigma_y}$$

revolving frequency: f_{rev}=11245.5/s
#bunches: n_{bunch}=2808
#protons / bunch: N_p= 1.15 x 10^{11}
Area of beams: $4\pi\sigma_x\sigma_y$~40 μm

Instantaneous versus time
Unit : $cm^{-2}\,s^{-1}$



Integrated versus time
cm^{-2} → barn

1 barn = 10^{-24} cm^{-2}

Luminosity

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} F = \frac{c}{4\pi} \frac{\gamma}{l} N_b^2 n_b \frac{1}{\varepsilon_n \beta^*} F$$

Accelerator features

Energy of the machine 7 TeV

Length of the machine 27 km

Beam intensity features

N_b Number of particles per bunch 1.15×10^{11}

n_b Number of bunches ~2808

Beam geometry features

ε_n Size of the beam from injectors: 3.75 mm mrad

β^* Squeeze of the beam in IP (LHC optics): 55 cm

F: geometry reduction factor: 0.84

Nominal luminosity: 10^{34} cm^{-2} s^{-1}

(considered very challenging in the 90's, pushed up to compete with SuperconductingSuperCollider)

Luminosity

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} F = \frac{c}{4\pi} \frac{\gamma}{l} N_b^2 n_b \frac{1}{\varepsilon_n \beta^*} F$$

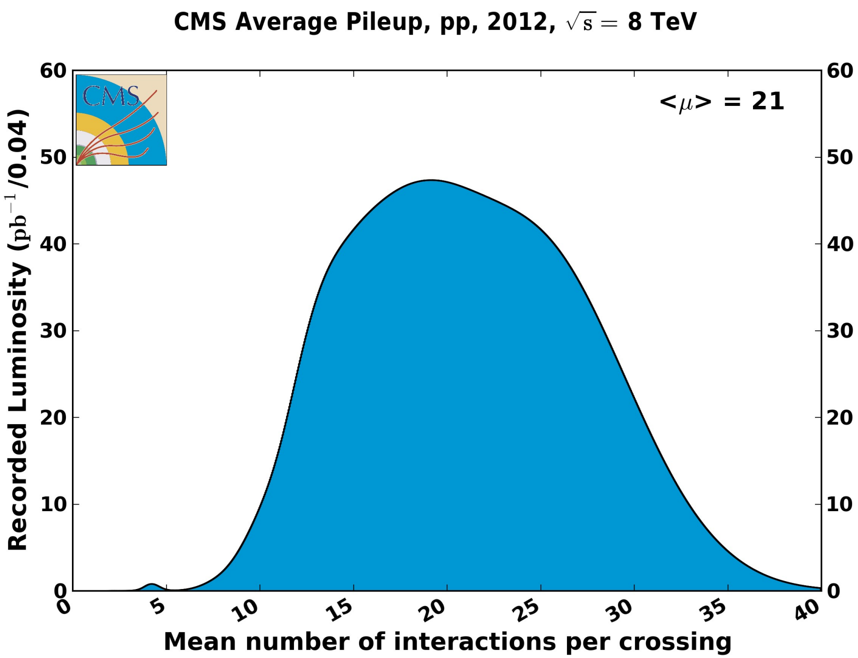
		Nominal	September 2012	Gain L	Ultimate	Gain L
N_b	(adim)	1.15E+11	1.55E+11	1.82	1.7E+11	2.2
ε_n	(m rad)	3.75E-06	2.5E-06	1.50	3.75E-06	1.0
n_b	(adim)	2808	1380	0.49	2808	1.0
β^*	(m)	0.55	0.60	0.92	0.55	1.0
E	(TeV)	7.0	4.0	0.57	7.0	1.0
L	($cm^{-2}\ s^{-1}$)	1.0E+34	7.0E+33	0.70	2.2E+34	2.2
Pile-up*	(adim)	25	36		55	

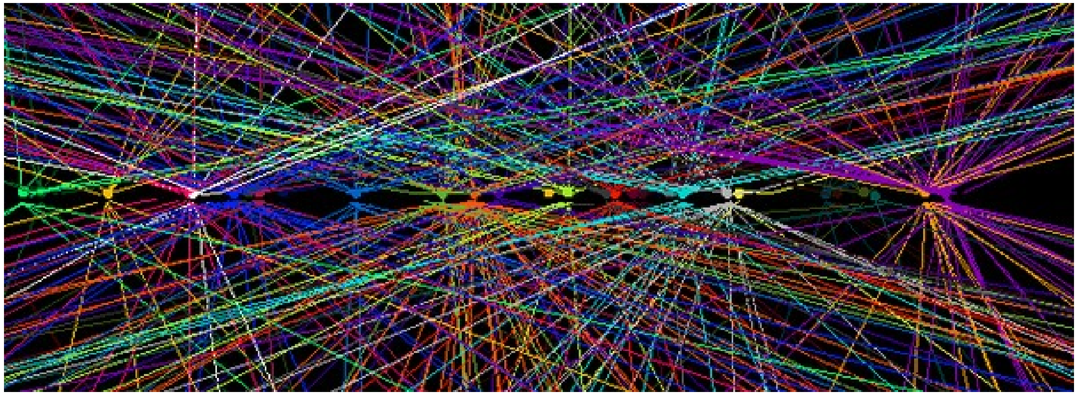
* 80 mbarn cross section assumed

Price to pay for luminosity!

Pile Up is the number of pp collisions in 1 bunch crossing.
Characterized by several primary vertices (hard process spot).

Facility	$\sqrt{s}$ [TeV]	σ_{inel} [mb]	L [10^{34} cm^{-2}s^{-1}]	τ_b [ns]	$< N_p >$	$< N_p > +2\sigma$
LHC (2012)	8	71.5	.75	50	27	38
LHC (nominal)	14	76	1	25	19	28
LHC (50 ns)	14	76	1	50	38	50

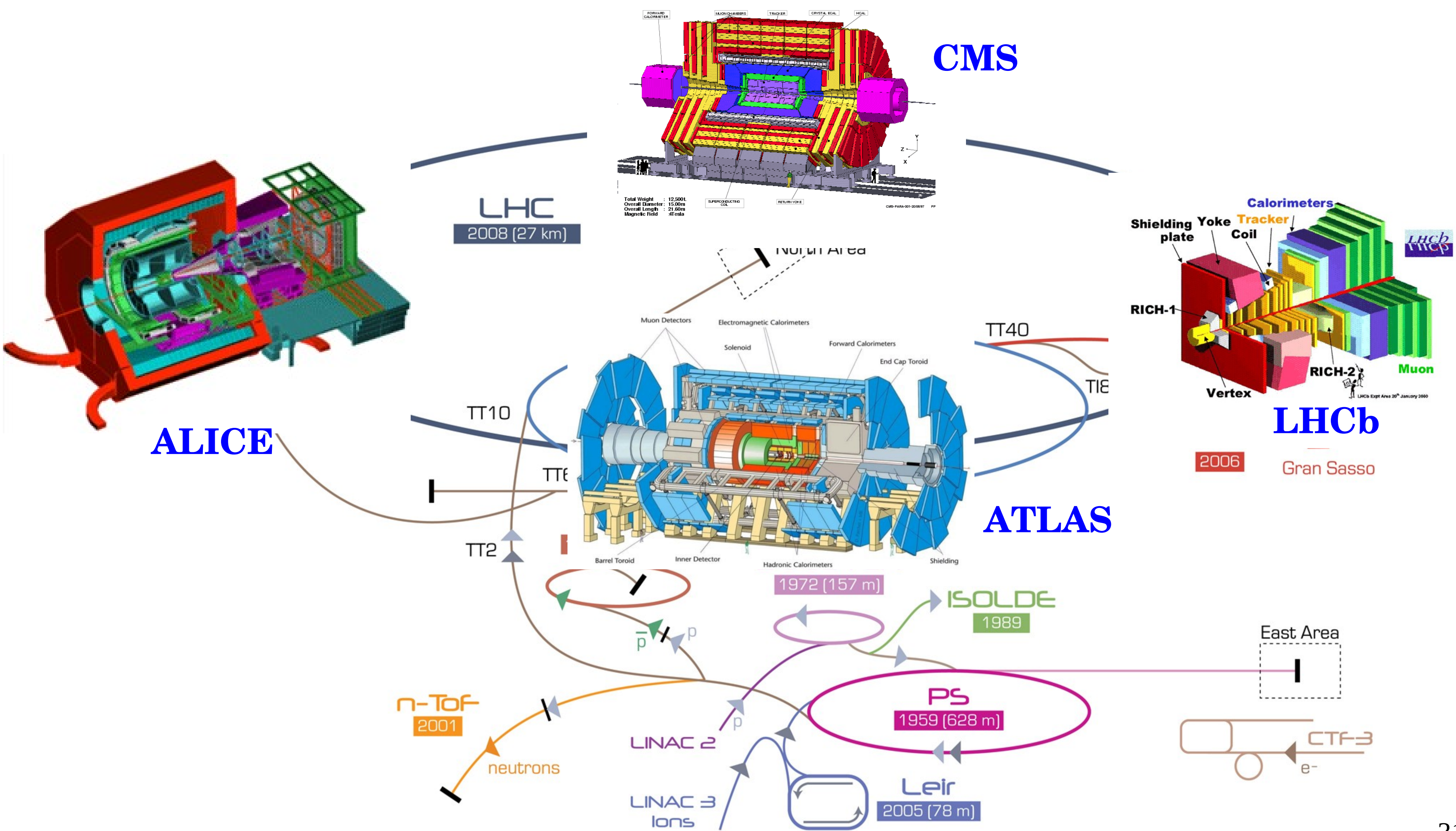




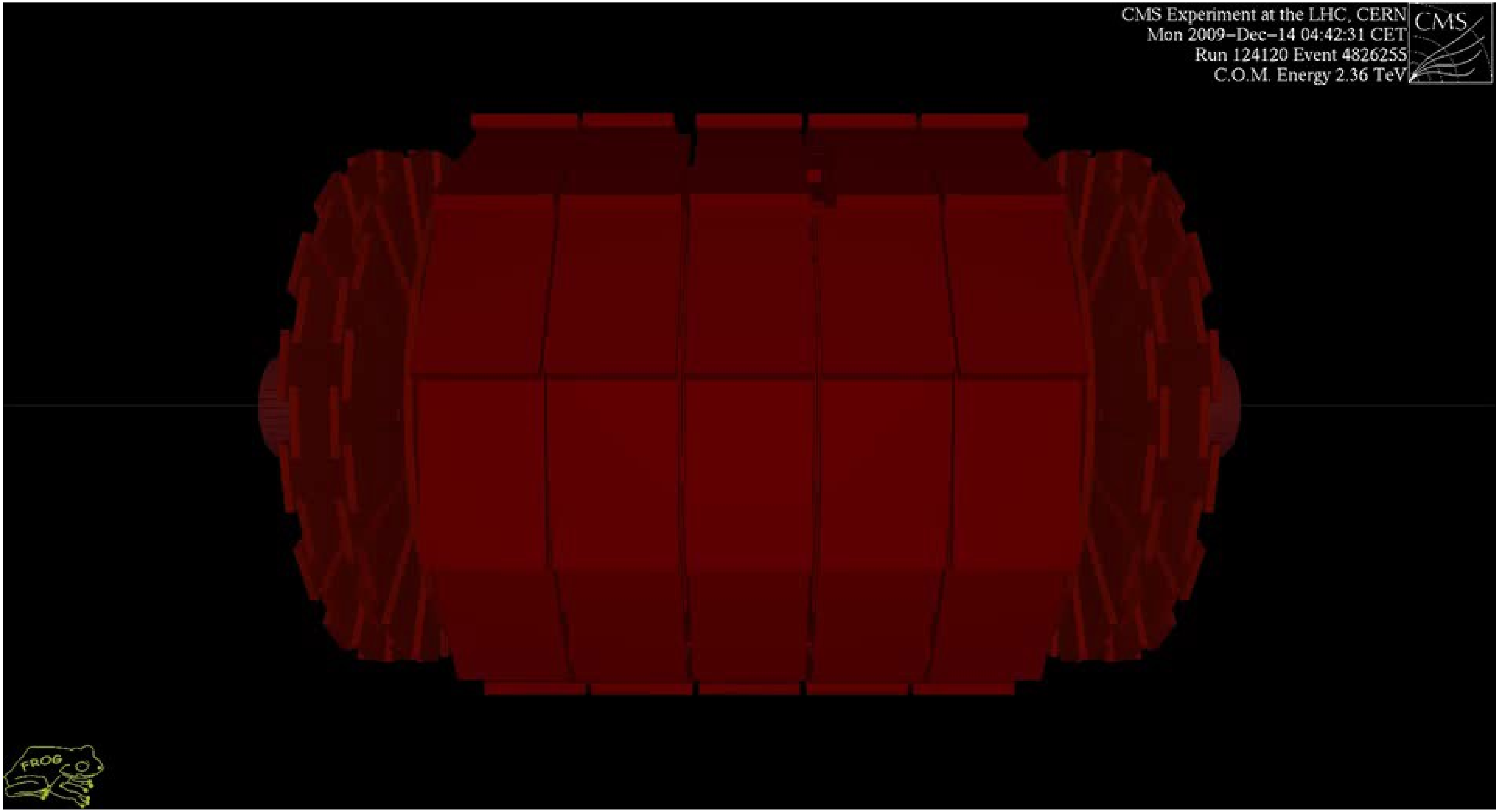
Event with 29 reconstructed vertices

Detectors

The Four Main experiments of the LHC



A collision in CMS



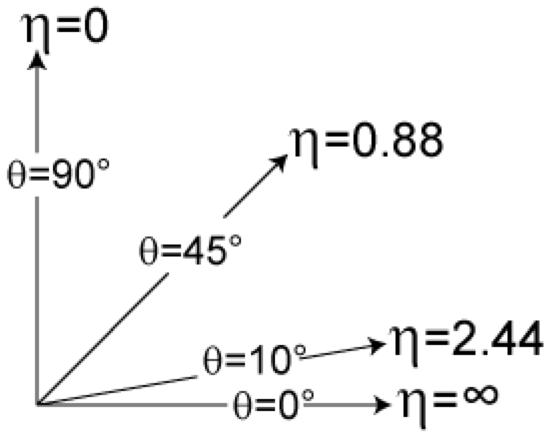
Coordinates

As a consequence of the collision kinematic, the visible pZ is not known.
Only the conservation of the transverse momentum pT can be used.

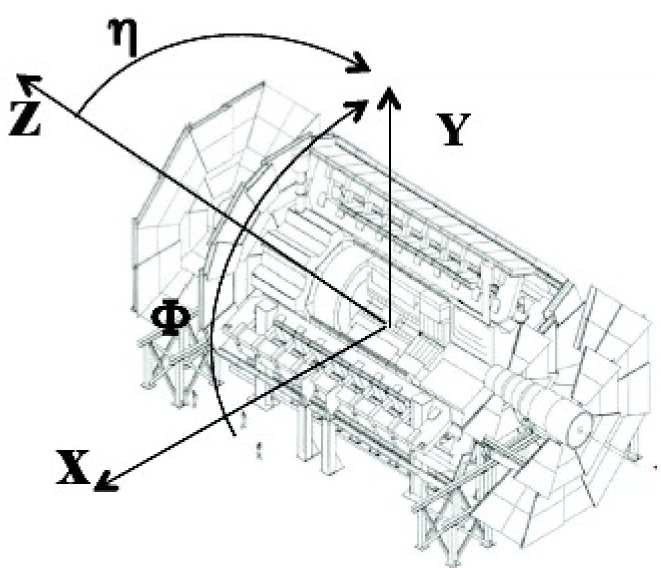
$$y = \frac{1}{2}\ln\frac{E+p_Z}{E-p_Z} \approx \eta = -\ln\left(\tan\frac{\vartheta}{2}\right)$$

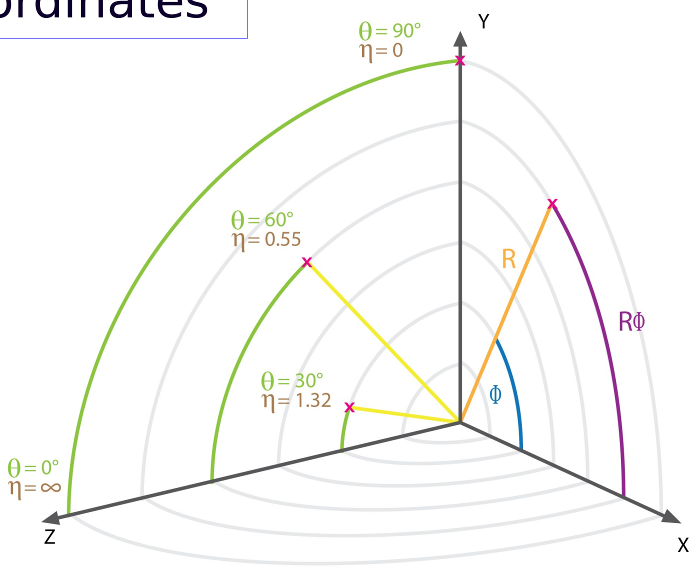
rapidity is Lorentz invariant

in massless approximation
pseudo rapidity ~ rapidity



Use relativistic cylindrical coordinates





Typical inputs of
4-vector:
pT, Φ, η, E

Data taking

The LHC computing GRID

• Number of collisions :
more than 500 Millions per second ~ 20 MHz

• The LHC experiments represent about 150 million sensors delivering
data 40 million times per second.

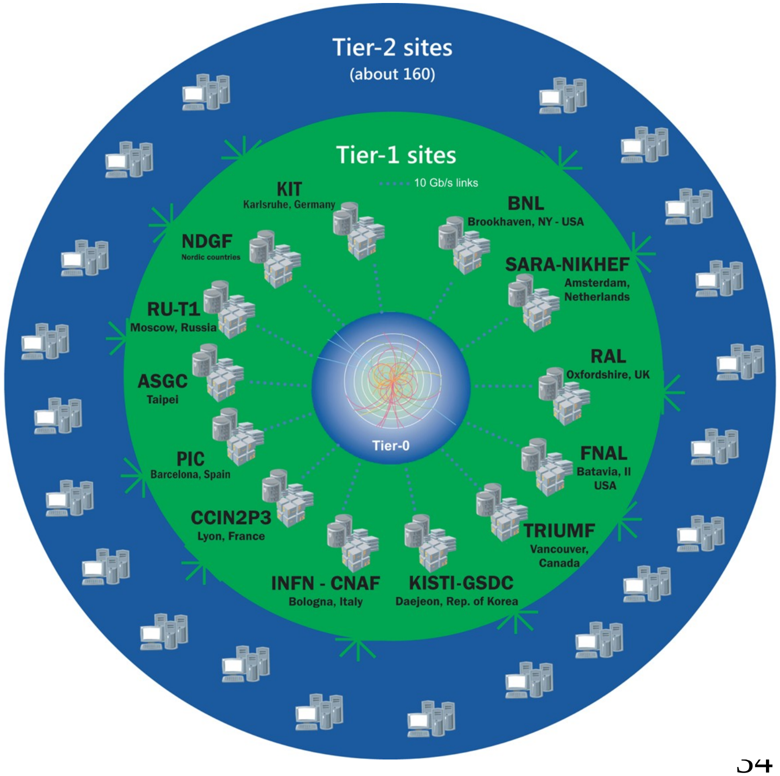
• After filtering there will be about
100 collisions of interest per second.

• The data flow from all four experiments will be about 700 MB/s ~15 PB per year
~ a stack of CDs about 20 km tall each year.

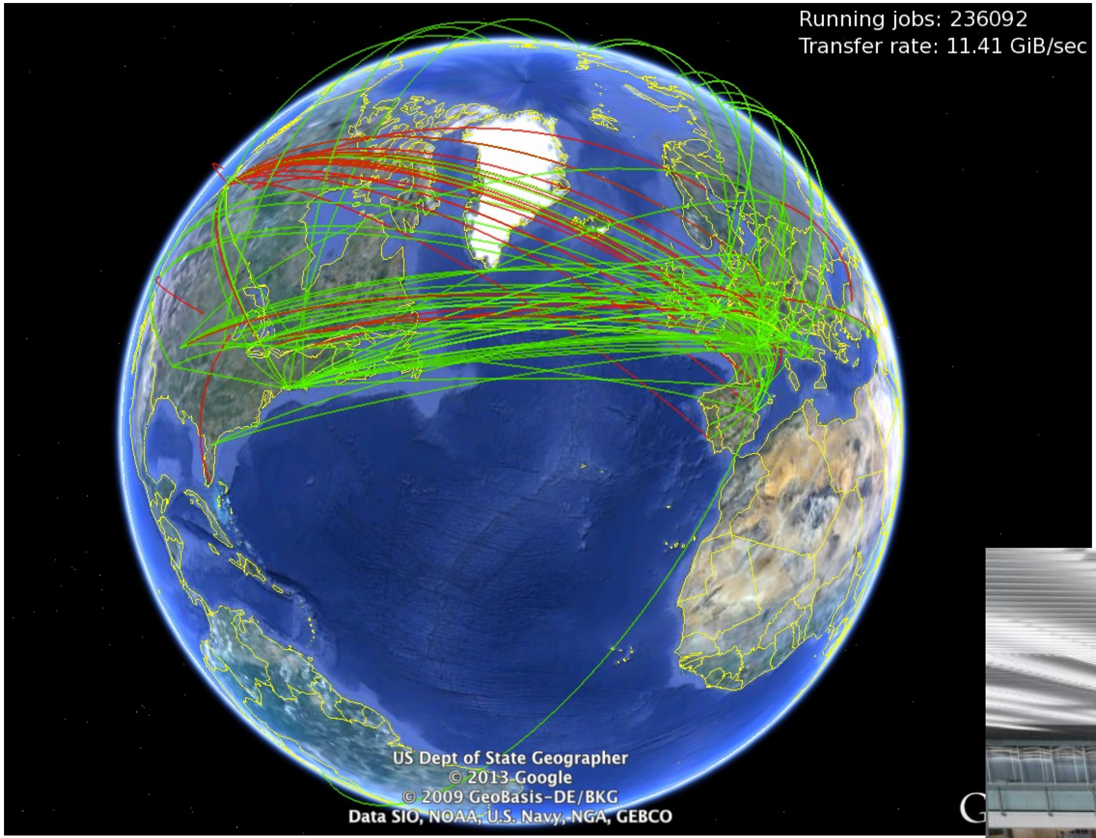
• Enormous amount of data will be accessed and analyzed by thousands of scientists
around the world.

• LHC Computing Grid built and maintain a data storage and analysis infrastructure for the entire high-energy physics community that will use the LHC.

<u>2 levels of Trigger</u> for each exp :
• Low level trigger 100 kHz in the cavern, 20 µs to decide → storage underground
• HLT 600 Hz, 100 ms to decide → storage on the ground → T0

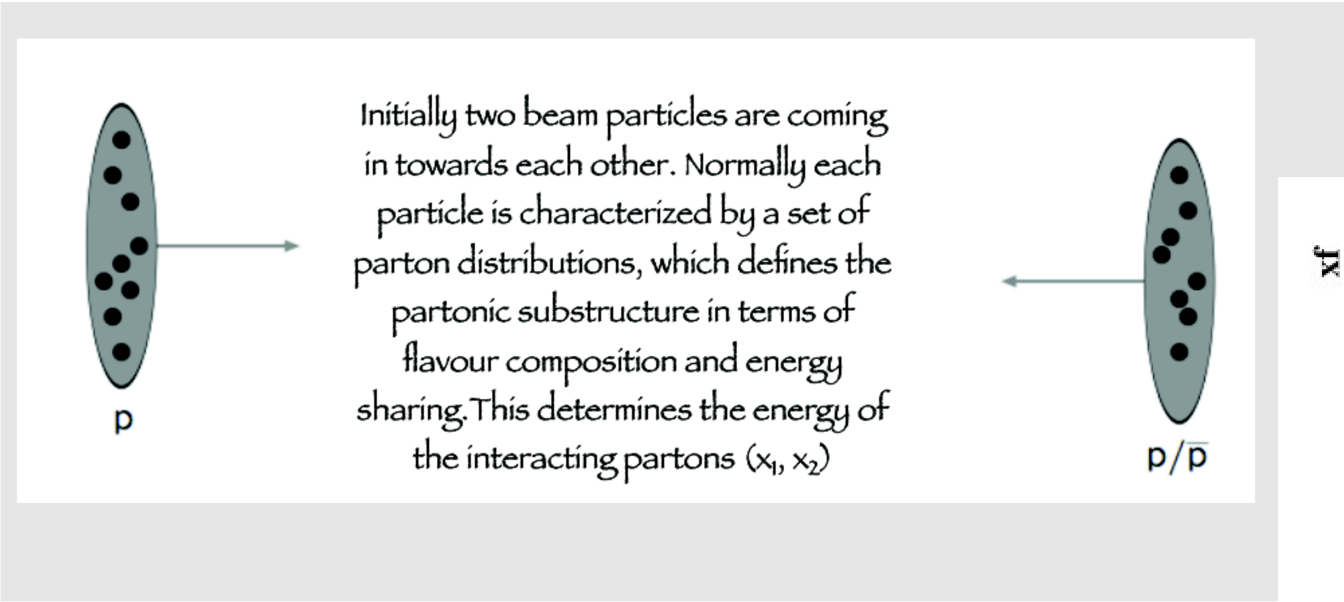


The Grid

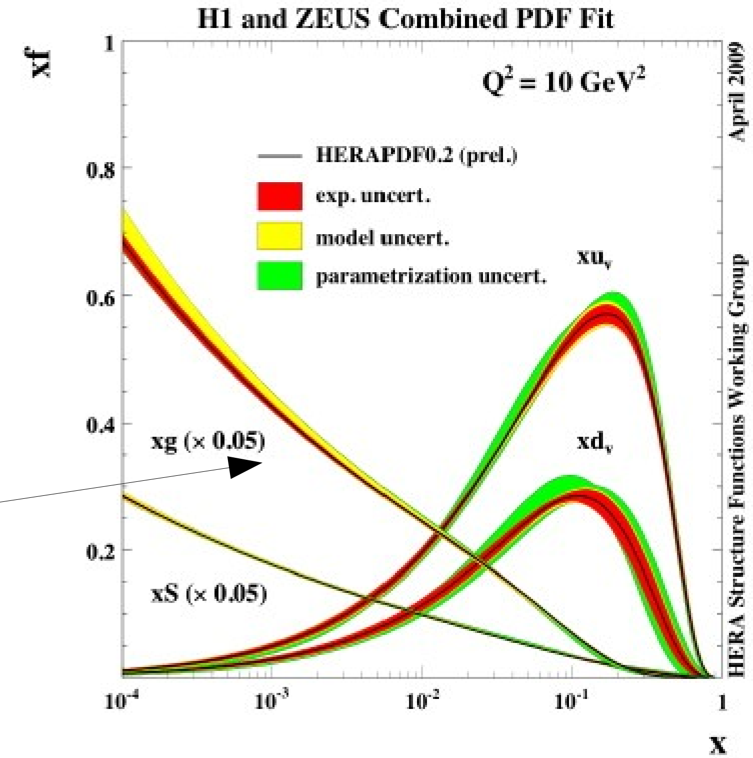


By 2012 data from over $3*10^{14}$ LHC proton-proton collisions had been analyzed. LHC collision data was being produced at approximately 25 petabytes per year, and the LHC Computing Grid had become the world's largest computing grid comprising over 170 computing facilities in a worldwide network across 36 countries

The structure of an event : pdfs



for most processes LHC is mainly a gg collider.



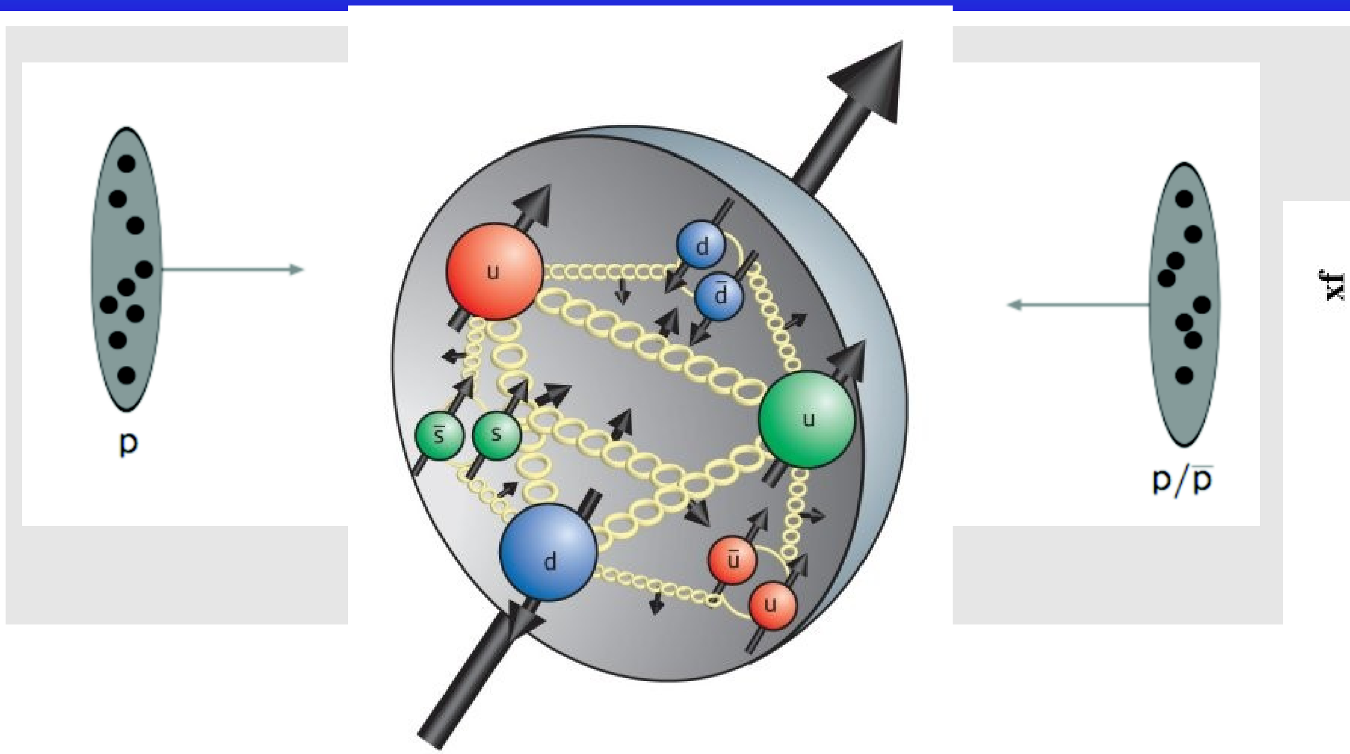
$$\sigma(p_1(P_1) + p_2(P_2) \to Y + X + \mathrm{Rest})$$

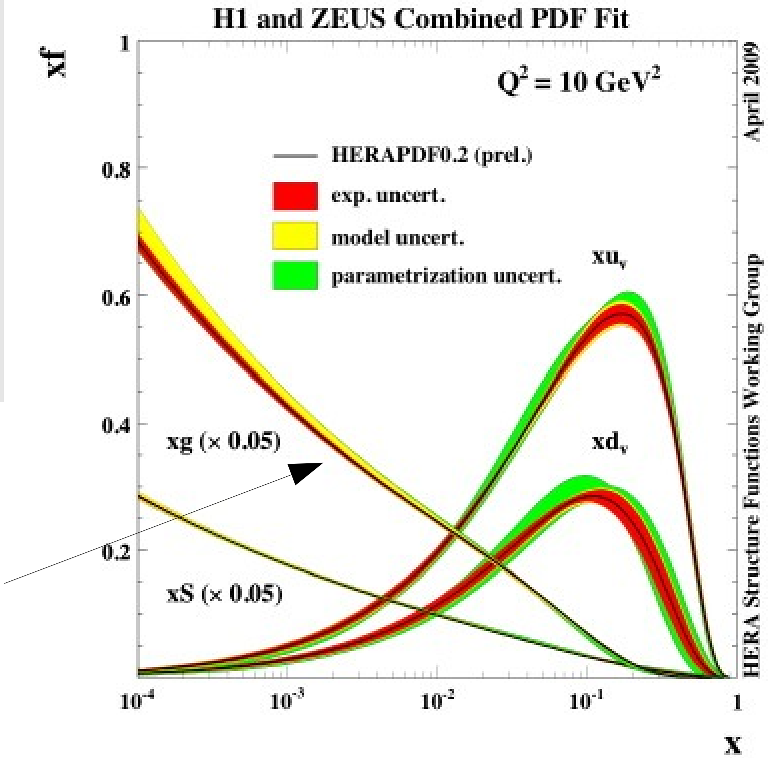
$$= \int_0^1 dx_1 \int_0^1 dx_2 \sum_f F_f(x_1) F_{\bar{f}}(x_2) \sigma(q_1(x_1 P) + q_2(x_2 P) \to Y + X + \mathrm{Rest})$$

Incoming beams :
parton density (measured)

Partonic cross section : phase space * matrix element

The structure of an event : pdfs





for most processes LHC is mainly a gg collider.

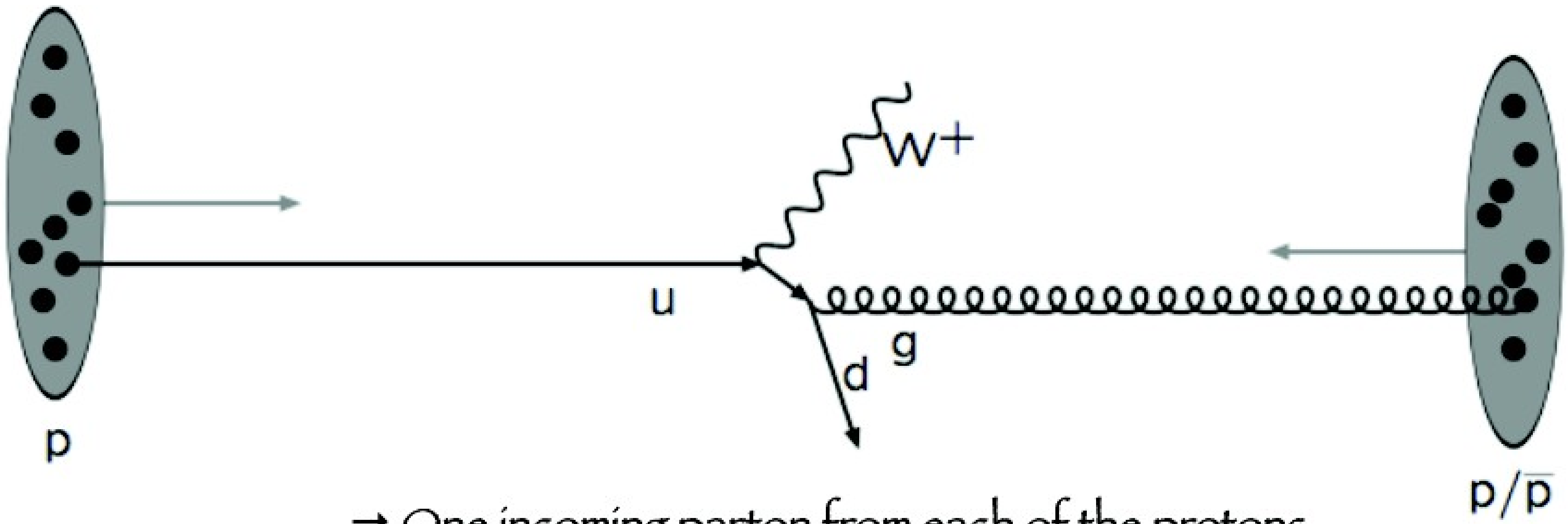
$$\sigma(p_1(P_1) + p_2(P_2) \to Y + X + \mathrm{Rest})$$

$$= \int_0^1 dx_1 \int_0^1 dx_2 \sum_f F_f(x_1) F_{\bar{f}}(x_2) \sigma(q_1(x_1 P) + q_2(x_2 P) \to Y + X + \mathrm{Rest})$$

Incoming beams :
parton density (measured)

Partonic cross section : phase space * matrix element

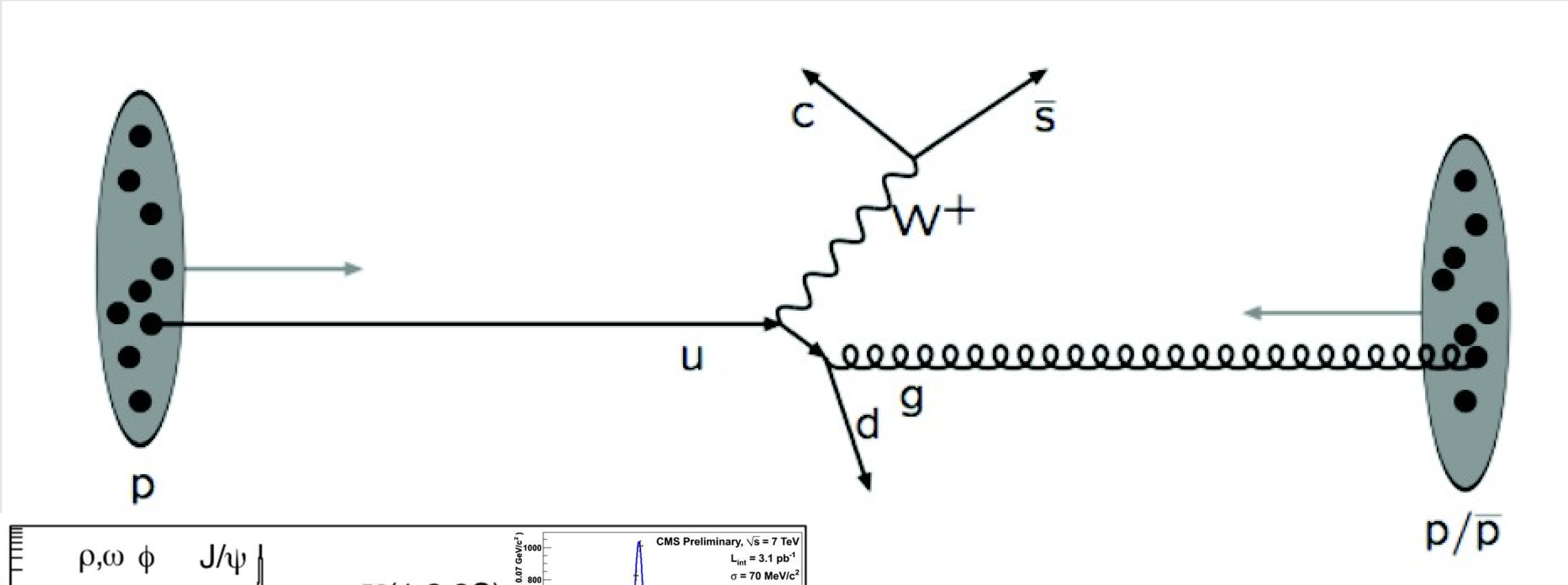
The structure of an event : hard process

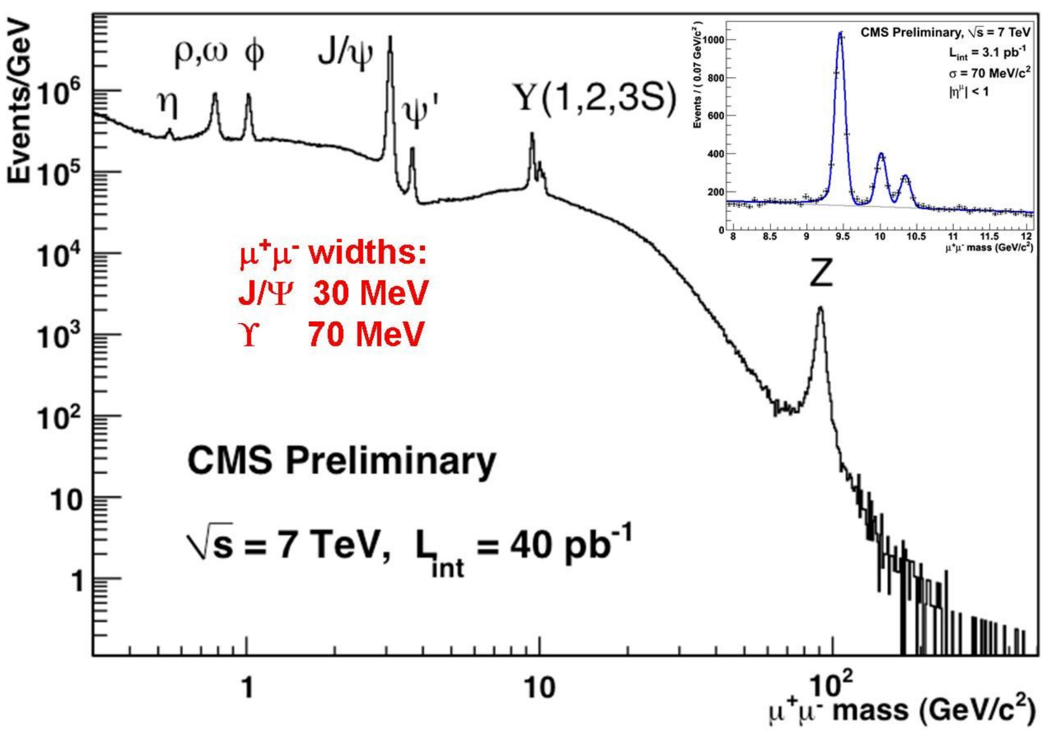


→ One incoming parton from each of the protons enters the hard process, where then a number of outgoing particles are produced. It is the nature of this process that determines the main characteristics of the event.

Hard subprocess described by Matrix Elements

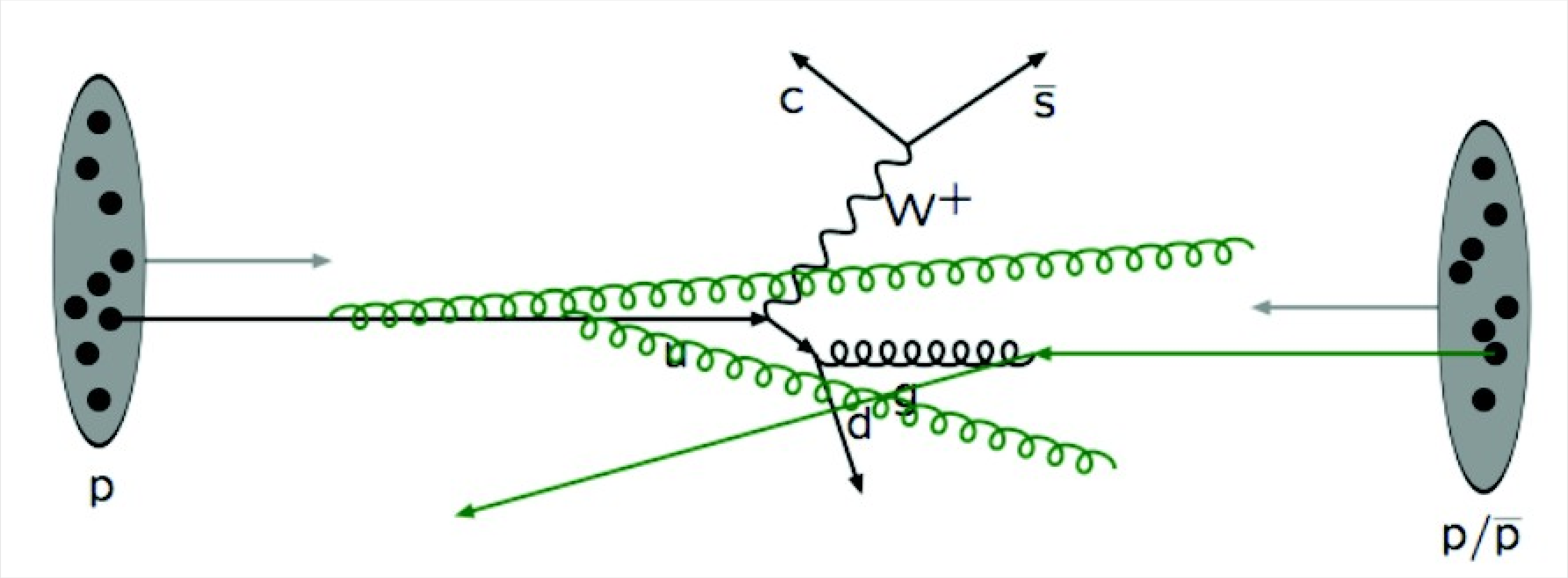
The structure of an event : resonance





The hard process may produce a set of short-lived resonances, like the $Z^0/W^{\pm}$ gauge bosons.

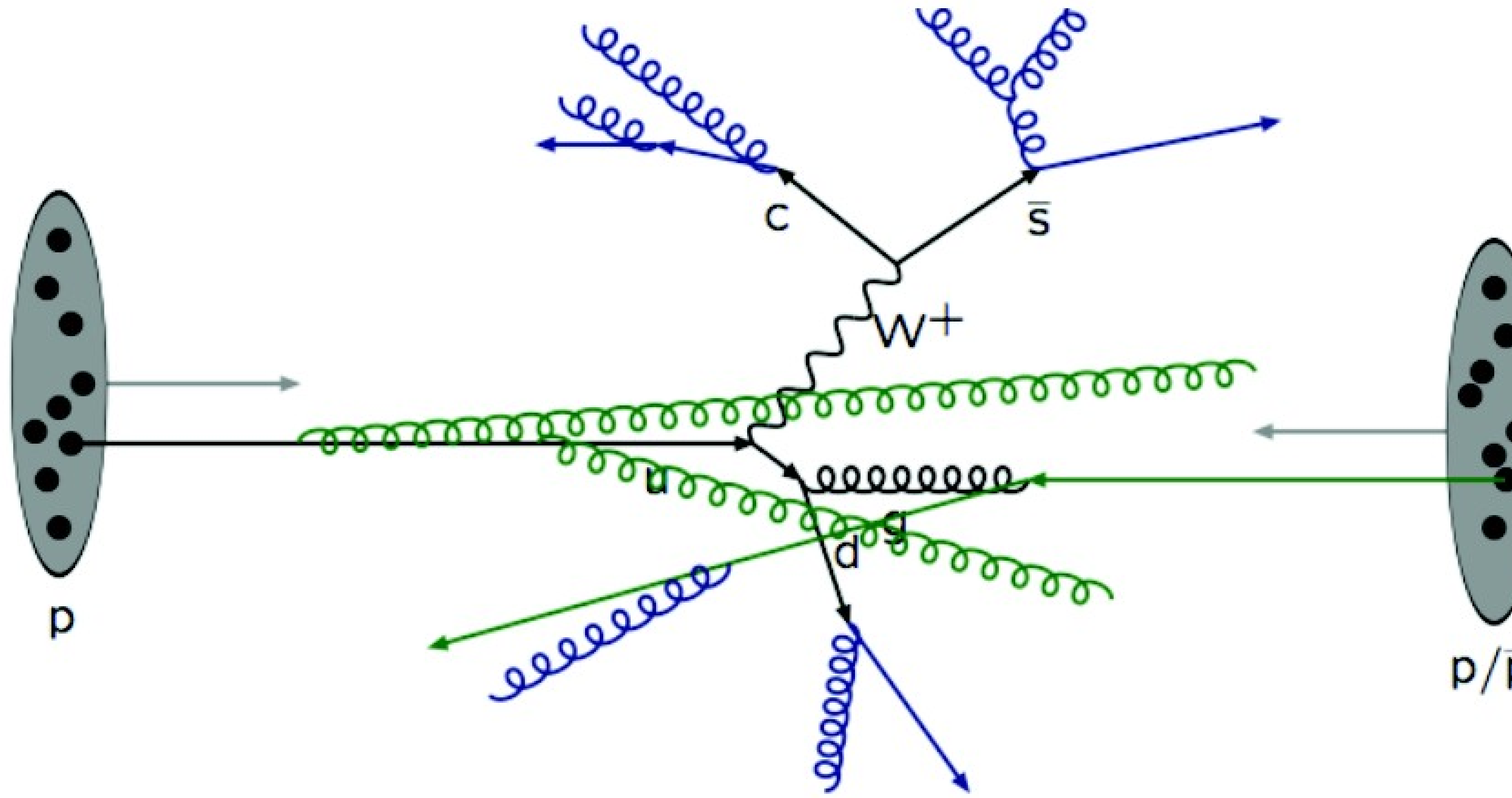
The structure of an event : ISR



One shower initiator parton from each beam may start off a sequence of branchings, such as $q \to qg$, which build up an initial-state shower.

Initial State Radiation

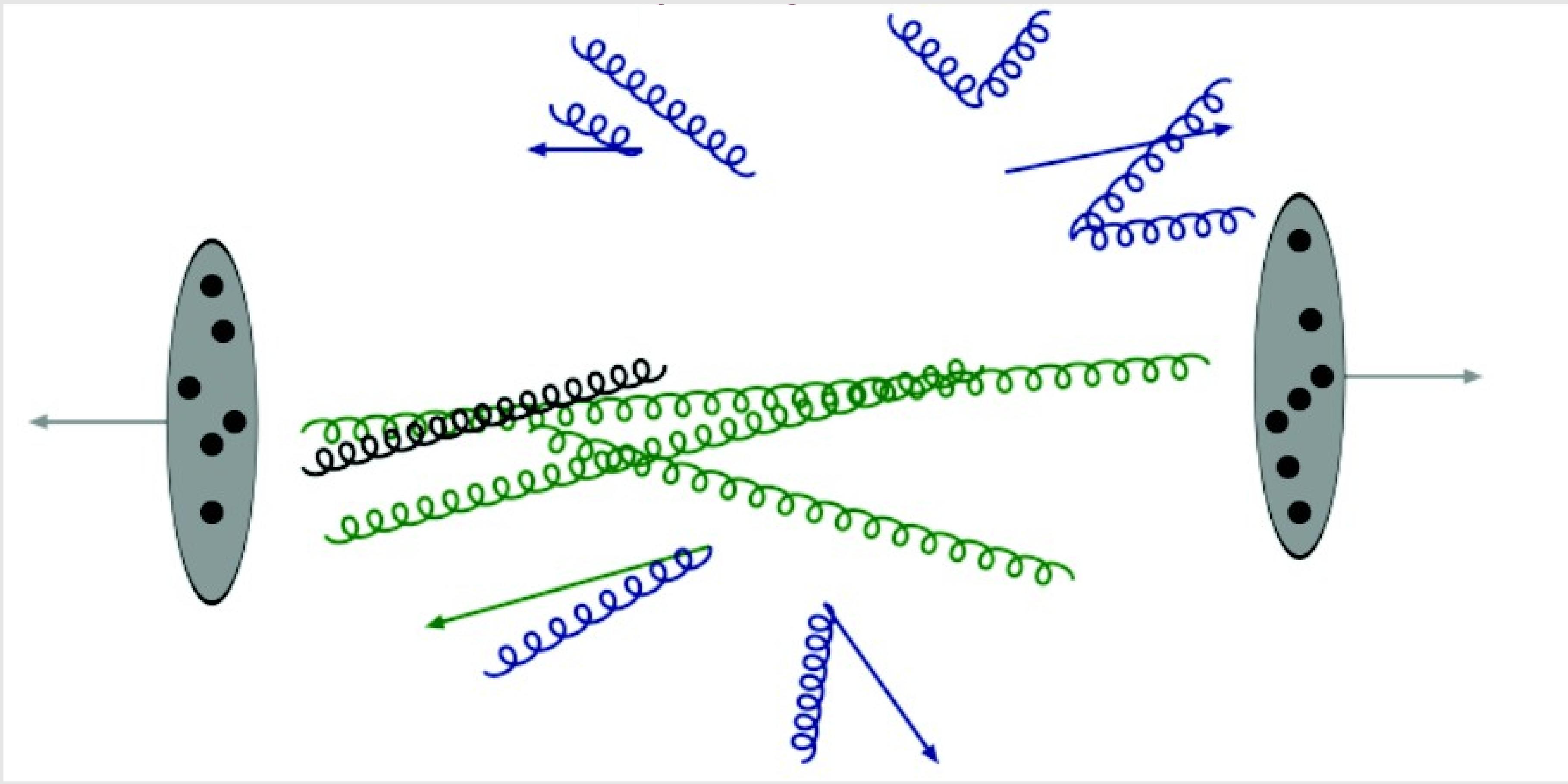
The structure of an event : FSR



The outgoing partons may branch, just like the incoming did, to build up final-state showers.

Final State radiations

An event : underlying event - minimum bias

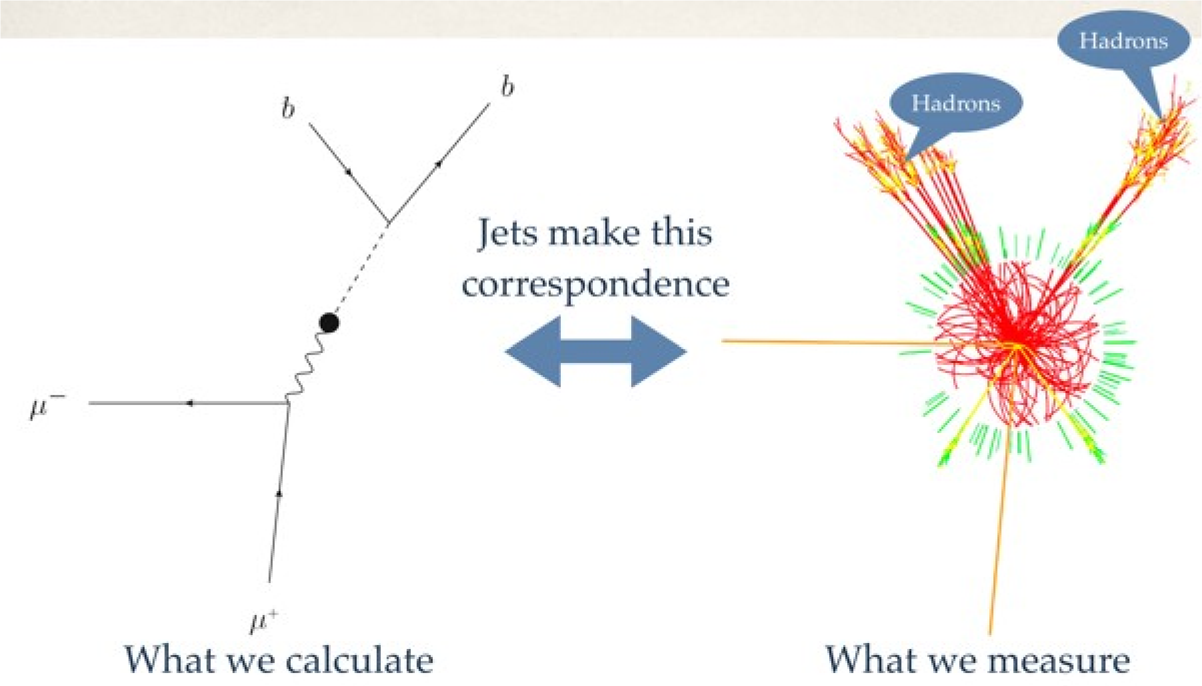


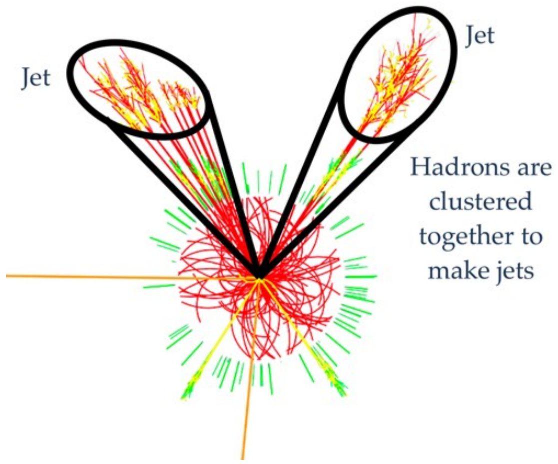
- Proton remnants (in most cases coloured!) interact: Underlying event, consist of low p_T objects.
- There are events without a hard collision (dependent on pT cutoff) , those are called **minimum bias**

An event : hadronization

Jets :

Quarks and gluon in the detector cannot be observed as free particles but as many Hadrons and in the detector as a jet of particle in a narrow cone.





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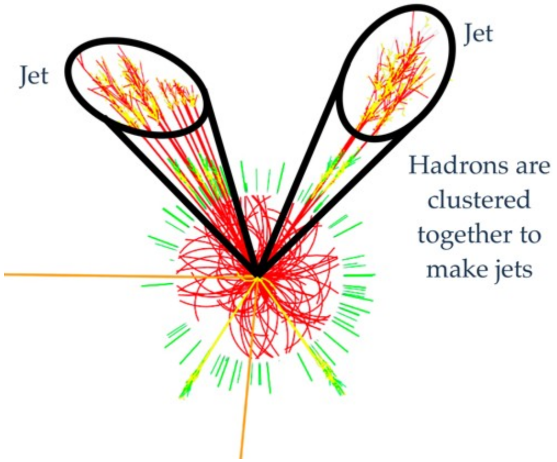
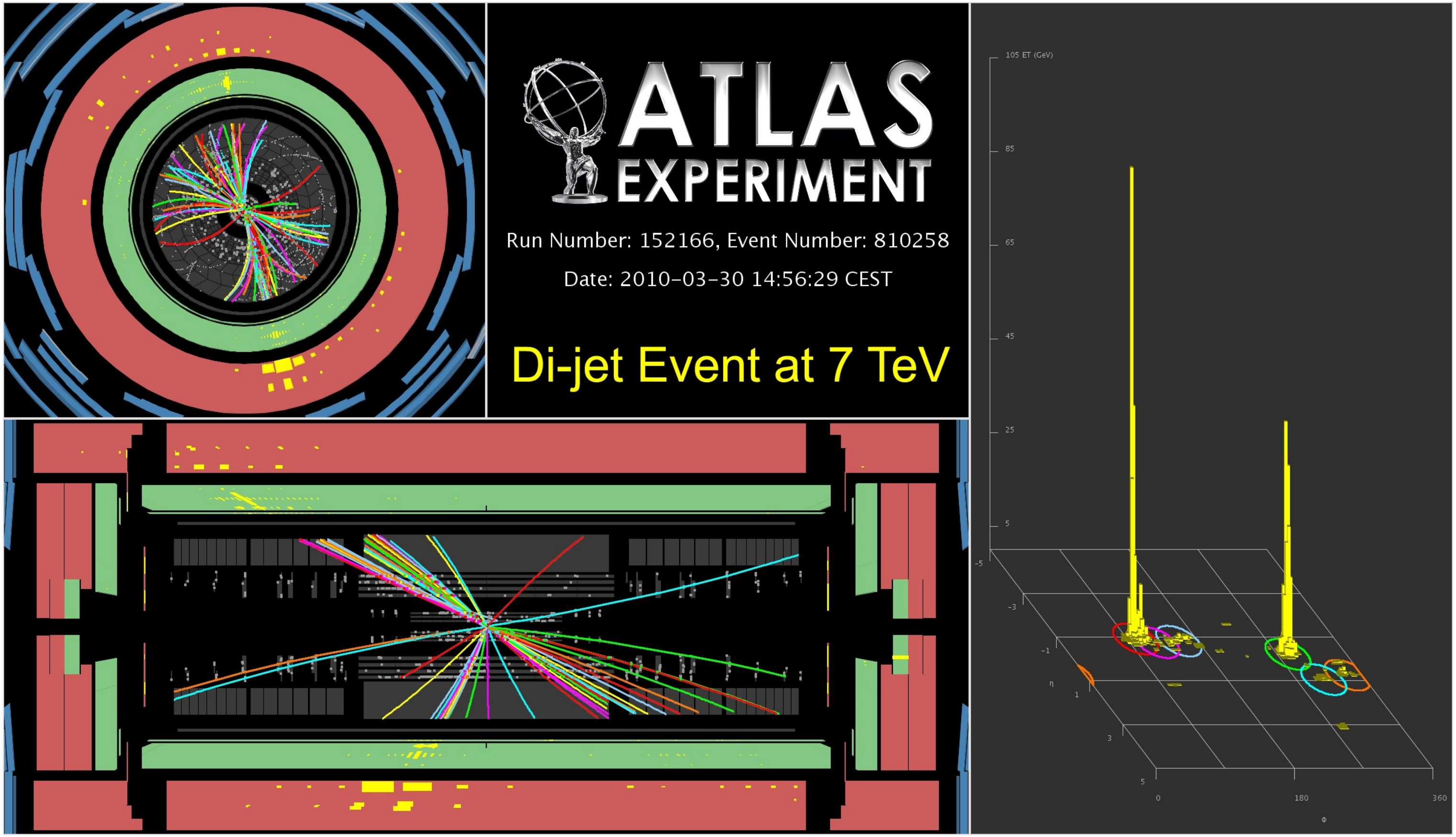




QCD and consequences

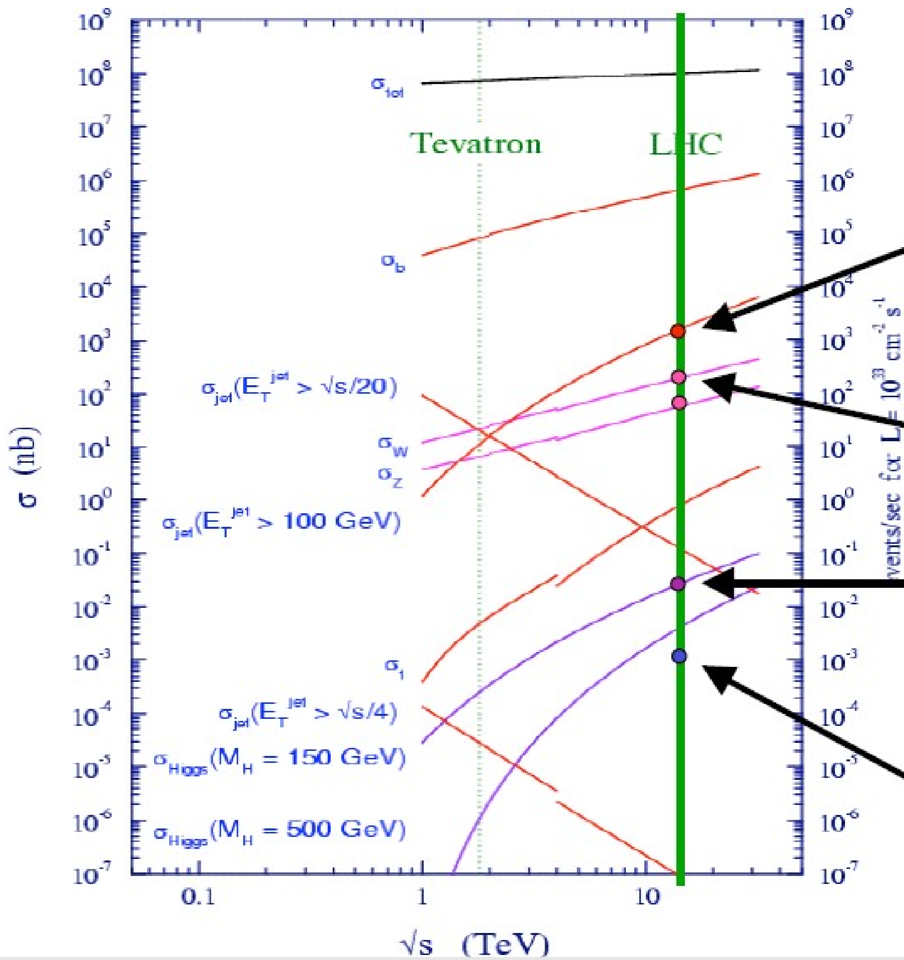
Enormous QCD background compared to what is interesting with jets :

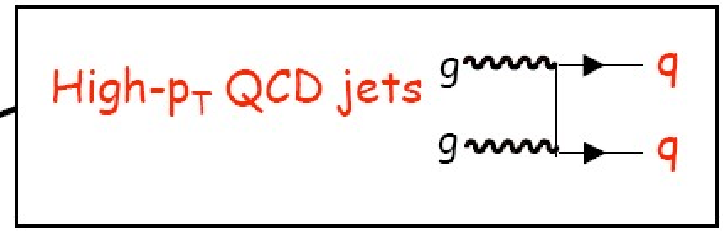
Represents a probability that an event will occur

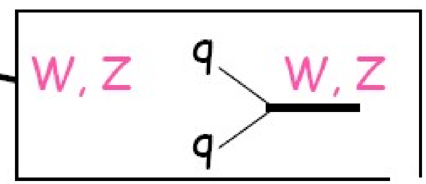
A cross section : σ = N/L

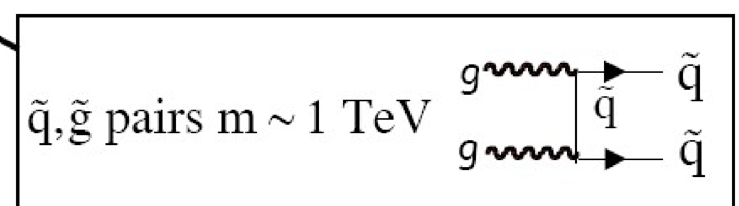
N is the number of events
L is the total integrated luminosity

Given a fixed luminosity, you expect :
X number of Z-boson events, Y number of tt events
Z number of Higgs events
All have different cross sections







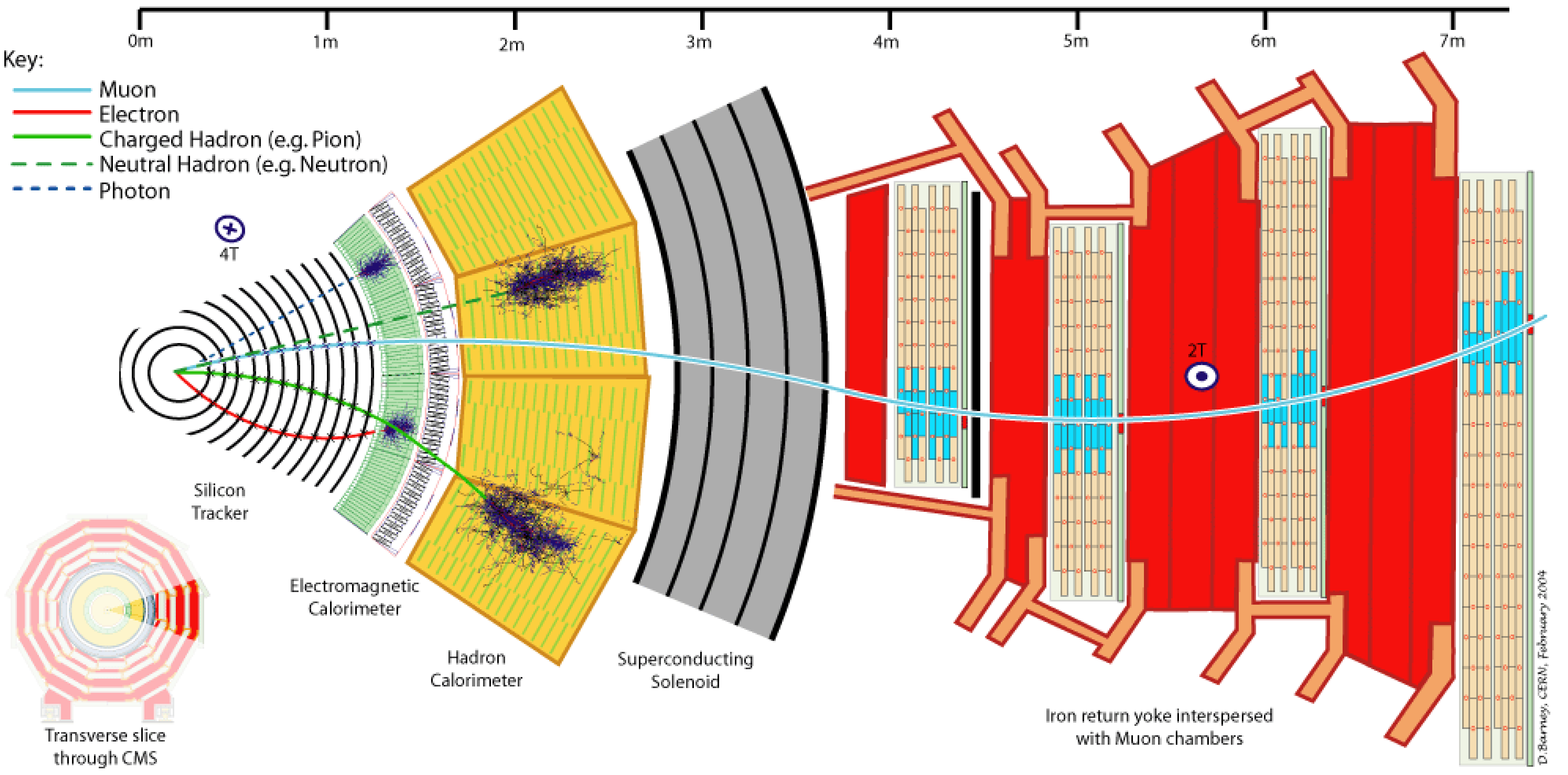


Light objects cannot be observed in fully hadronic state → need an isolated **lepton**

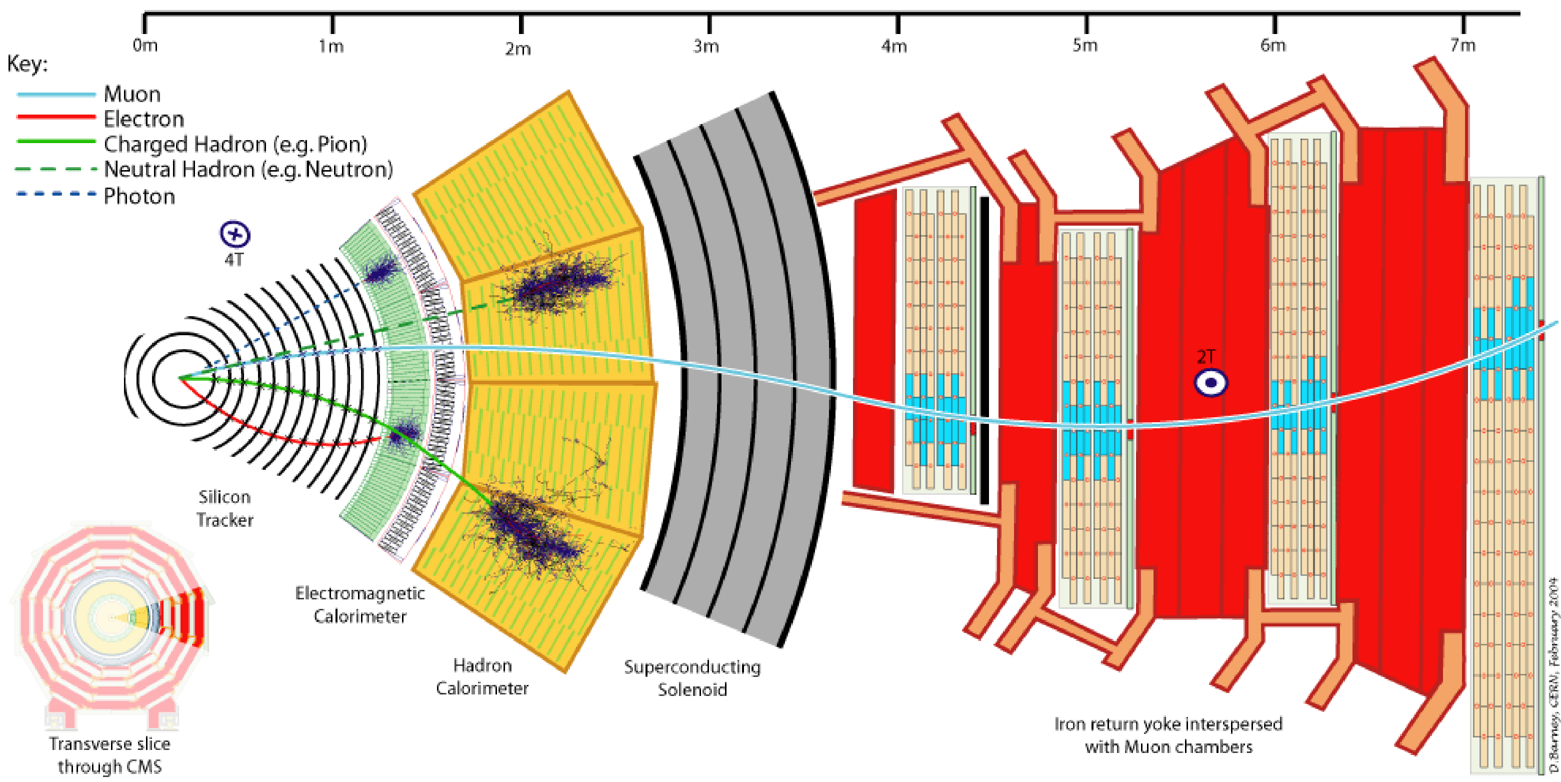
Analysis of the data

The Final State investigation

• We can only observe the final state of the particles in the detectors : e, μ, γ and hadrons
• We can only reconstruct those final state objects from theirs signatures/tracks left in the detectors



The Final State investigation



type	tracking	ECAL	HCAL	MUON
γ				
e				
μ				
Jet				
Et miss				

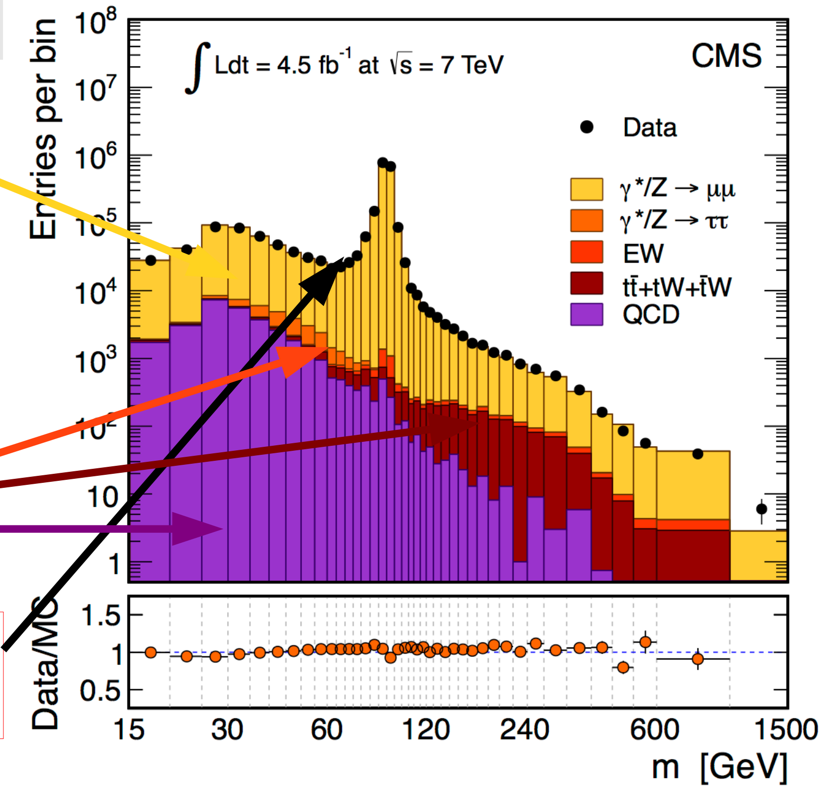
MET = the negative the vector sum of all the transverse components of observed energy.
It Indicates the presence of weakly interacting particles, usually neutrinos, but possibly new exotic objects that interact only weakly.

An analysis

Definition of Signal :

• The Signal is the process we want to observe = the final State we are looking for in the detector.
So selection of 2 μ in the data.
+ comparison to the simulation of Z→μμ process via MonteCarlo.

For example a Z decaying into 2 μ :



Definition of Background :

• All other processes that give the same final state or "mimic" the same final state :
since the objects (like muons here) are reconstructed from the detector info, there can be sometimes mis-reconstruction of the object.
• To evaluate the shape of those background we use **MC simulations** of those bck processes.

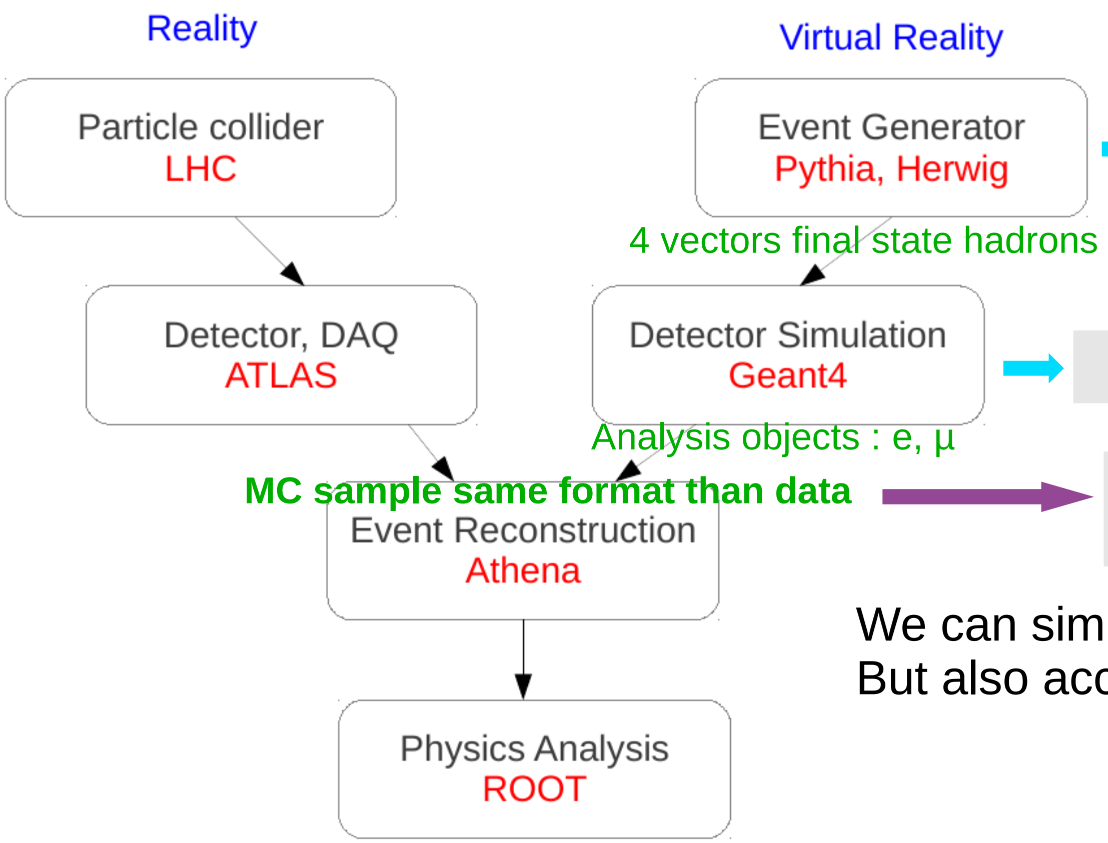
So the data selected <=> the signal + the background that couldn't be avoided to be selected at the same time.

Set up of cuts on the properties of the objects :

Cuts on object properties (pT, Φ, η, E , MET) are decided to keep max of signal while removing max of background.

Monte Carlo Simulation

Simulation of collisions between particles, used in all p.physics experiments :



MEM : hard process
Resonances (like Z-> ee)
Showering : ISR, FSR
Underlying events
Hadronisation of q and g

trigger, tracking, calorimeter sim

+ generated (truth info)
= Reco and Gen objects

We can simulate the events Standard Model like.
But also according to other non verified assumptions!

The cross section calculation may be:
Wrong, Incomplete, Inaccurate
The MC code with unknown bugs in it
Higher order corrections which have not been calculated
Cannot account for all detector effects

MC is not the truth !
What happened in the MC generator didn't happen at the LHC
The MC is our best guess
The MC only simulates specific physics processes
→ when possible comparison of the data with different type of generators

An analysis

Which quantities we are looking at :

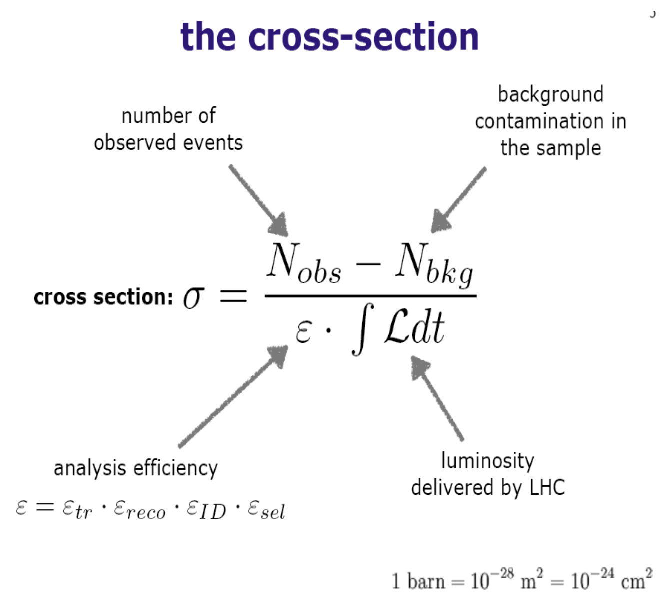
Standard Model Physics :

• check of well known quantities and comparison with the MC to get confidence in our measurement (mass of Z for eg)
• check of kinematics variables : pT of objects, combined mass of system (several jets together), MET, Number of jets in the event, angular distribution
• calculation of the cross sections

Searches :

• quantities where some deviation from the SM prediction is expected (thank you theorists) =
we look at the data and at the Standard Model MC simulation : can be a prove of new physics.
• Invariant mass for possible unknown resonances

See Higgs example!!

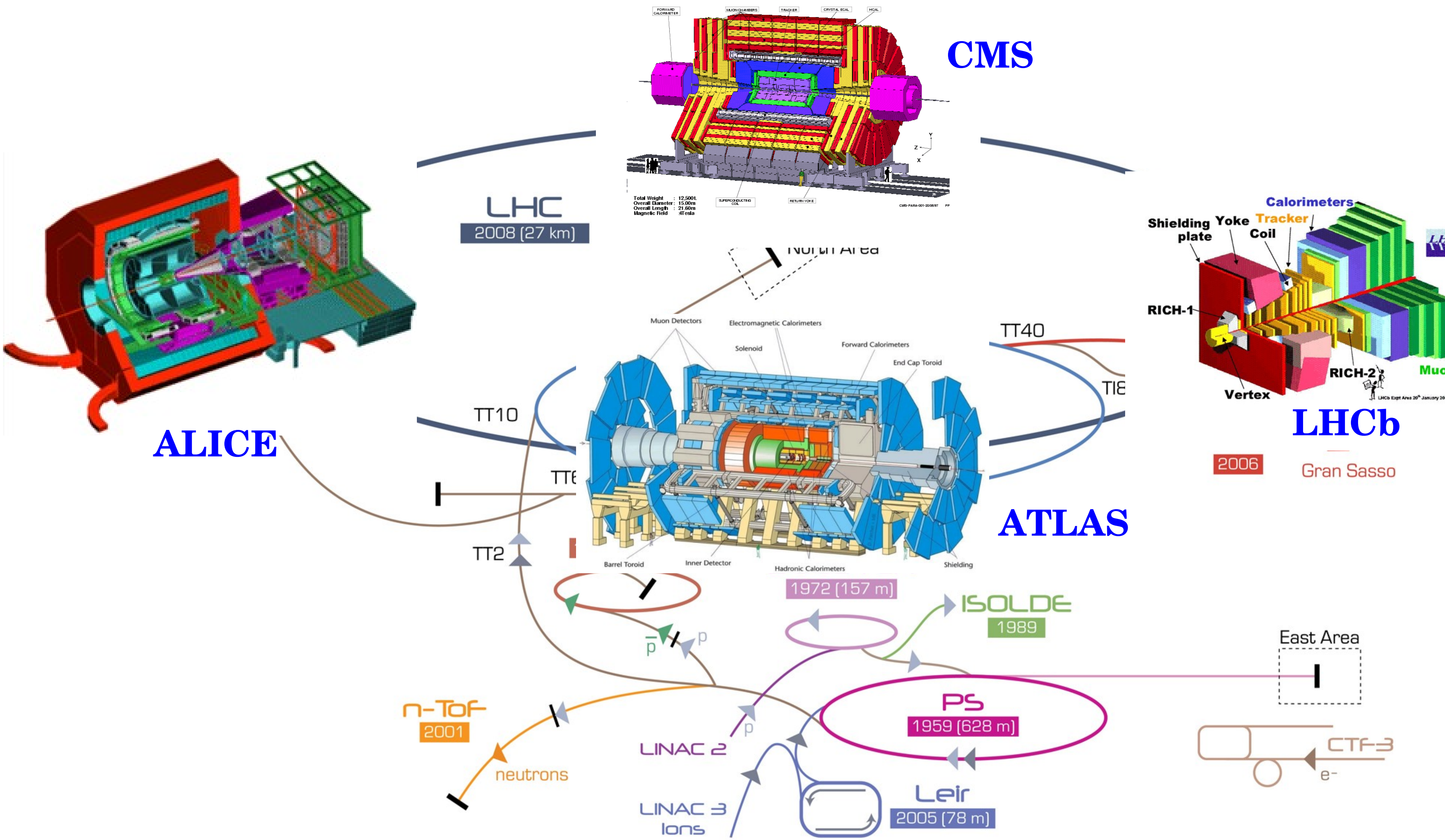


Errors :

Statistical, systematical
Efficiencies, purity ...

Detectors

The Four Main experiments of the LHC

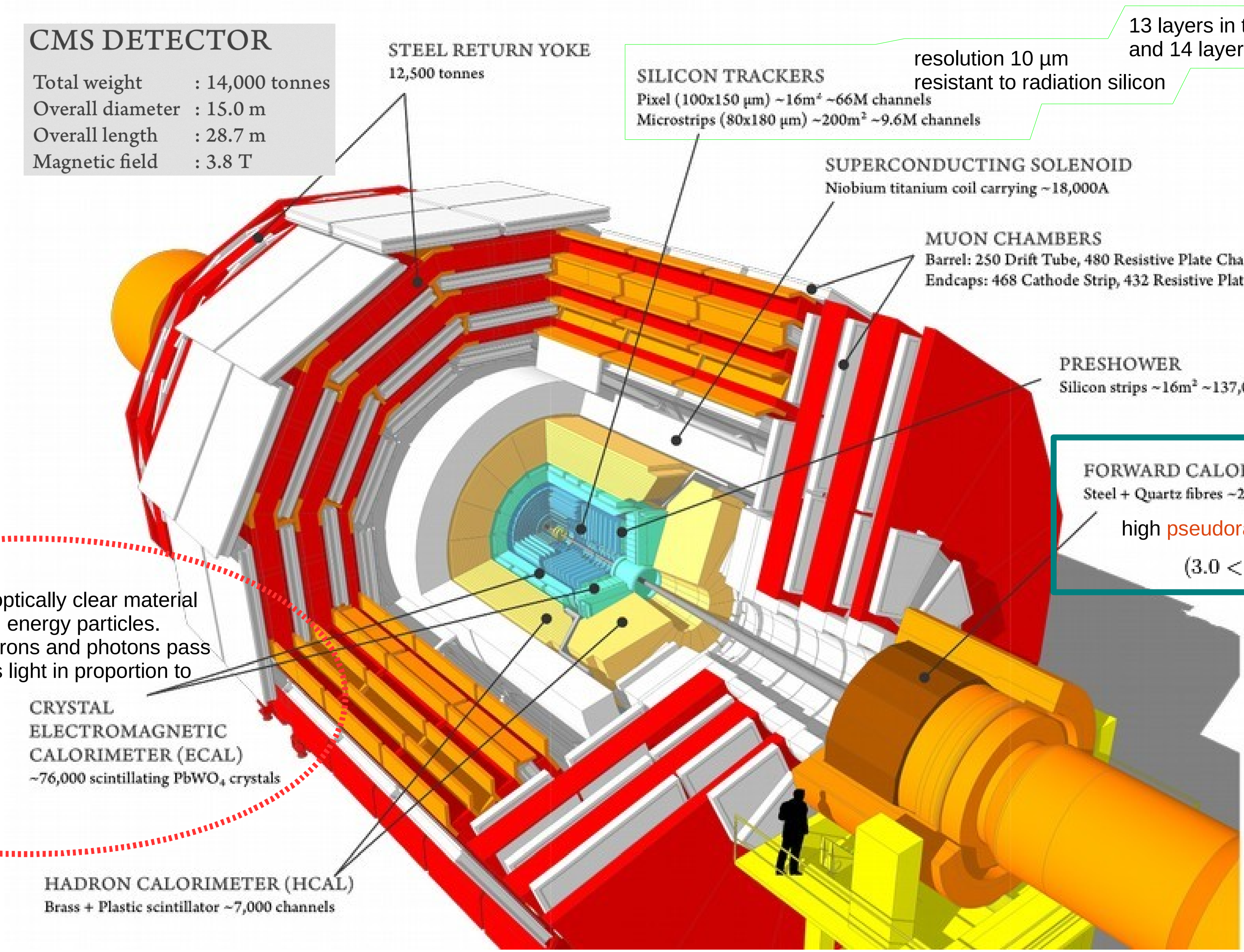


PART II

Let's see what people are really doing as Physics at the LHC.

- **CMS : Compact Muon Solenoid**
  - A SMP Analysis from head to toe : the Zbb analysis example
- **ATLAS : A Toroidal LHC ApparatuS**
  - Search and found for the Higgs into 4 leptons
- **The Higgs discovery**
- **Exotic and SUSY searches**
  - Exotic : the example of the Z' particle search
  - Status of Exotica and Susy (for experimentalists)
- **LHCb**
  - The $B_{S \rightarrow \mu\mu}$ result
- **ALICE**

CMS : Compact Muon Solenoid



13 layers in the central region and 14 layers in the endcaps

resolution 10 µm
resistant to radiation silicon

high pseudorapidity region

$(3.0 < |\eta| < 5.0)$

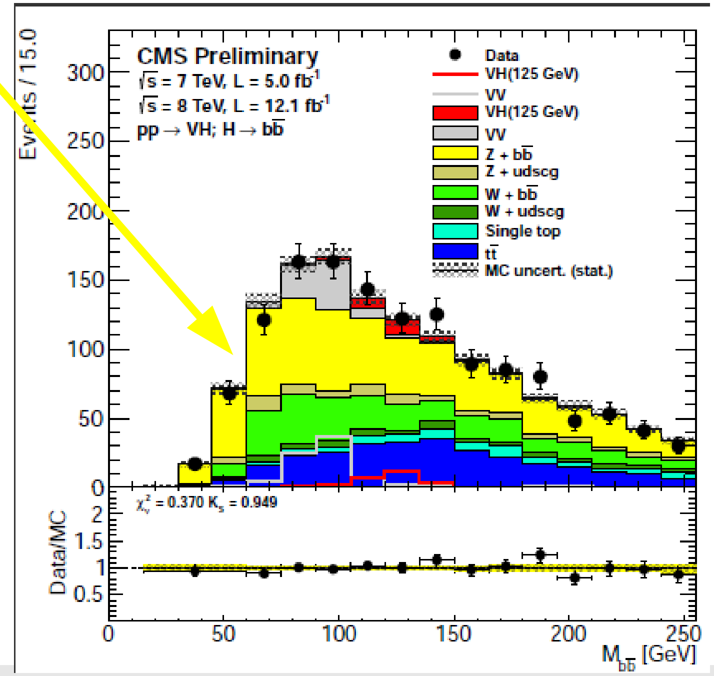
extremely dense but optically clear material ideal for stopping high energy particles. scintillates when electrons and photons pass through it → produces light in proportion to the particle's energy.

CMS + SMP analysis : Zbb

Motivations: why Zbb?

- Z+b-jets is background for many searches for undiscovered processes:

* **SM Scalar**:	Z(ll) H(bb)		
	H→Z(ll) Z(bb)		
* **BSM Scalar:**	H→Z(ll) A(bb)	*2HDM/Susy-like*	

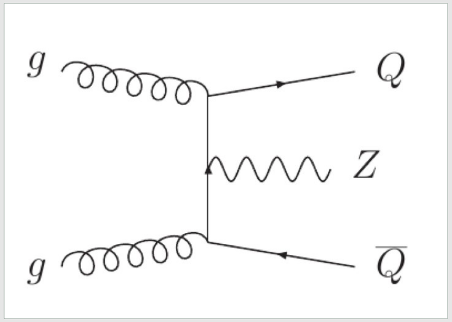


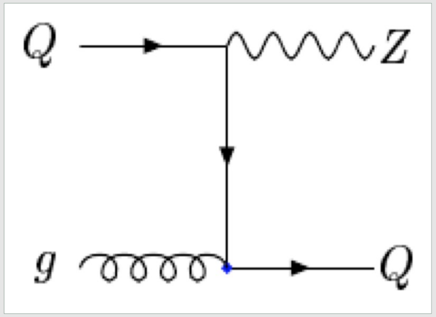
➔ Understand Z+b-jets process
Study kinematics

- Test of perturbative QCD ...or which way to compute reality is better

<u>4 flavor scheme</u>

Massive b
Full event description
MadGraph+aMC@NLO





<u>5 flavor scheme</u>

Splitting inside PDF
Massless b
MadGraph

➔ Study Z+bb production as function of number of b-jet , 1 or 2

Zbb Signal and backgrounds

Partial Luminosity 2011 : 2.1 fb^{-1} at 7 TeV
Also an analysis with full Lumi 2011 5.0 fb^{-1} but more complicated.

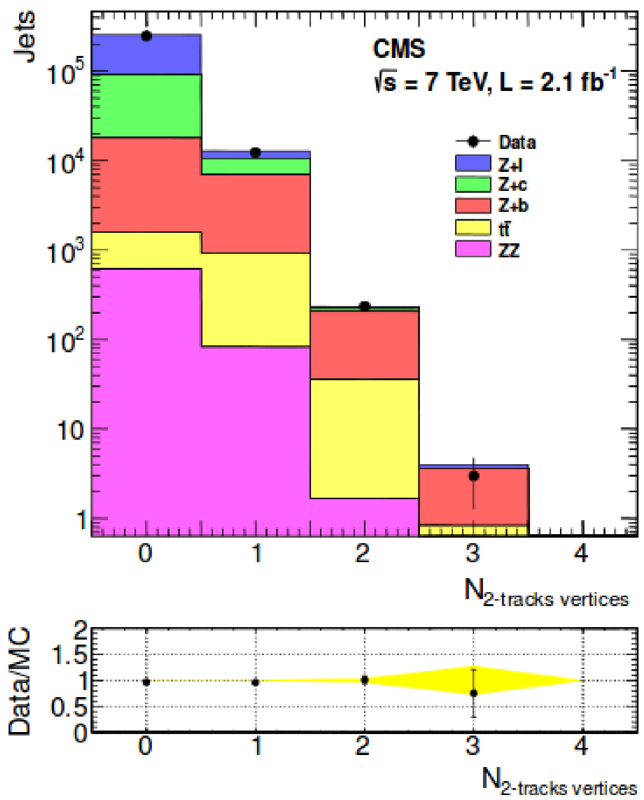
Signal:

Z + 1 b = one Z + exactly 1 b-jet (exclusive) = 1 step in the analysis
Z + 2 b = one Z + at least 2 b-jets (inclusive) = next step in the analysis

Phase space:

Z → l^+l^-
- l = μ/e, isolated
- pt > 20 GeV
- | η | < 2.4

b-tagged jets
- anti kT, ΔR = 0.5
- pt > 25 GeV
- | η | < 2.1



3 Backgrounds:

- **Z+c and Z+l** : because l and c can be confused with b!
- **$t\bar{t}$ → W(l,ν)b W(l,ν)b** same FS than signal + MET
- **ZZ → ll + bb**

Technically :data

This reconstruction has been done in several steps in T0 then checked by poor shifters, validated, moved to T1 → many people are involved in the collection and creation of one dataset.

CMS provides centrally sets of data for which all the events have been triggered by the same characteristic : we know that in any case we want 2 electrons or 2 muons → we are going to use the dataset triggered by DoubleEle trigger (with a certain energy so that they are nicely reconstruct), and DoubleMu.

In this dataset = for one event all the objects present have been reconstructed :
object electrons and muons with all their characteristics : pT, η, φ, E
jets reconstructed with different algorithms and all char.

First step = create a skim of this huuuuge dataset by putting some of your mandatory requirement in a code : here we want a Z so the combination of the 2 leptons must have an invariant mass around the nominal mass of the Z (90 Gev) → 60 and 120 GeV.
We can also here ask for one jet. And we can start to identify the **jets that can be b jets.**

→ Use the Grid to send your jobs on T2

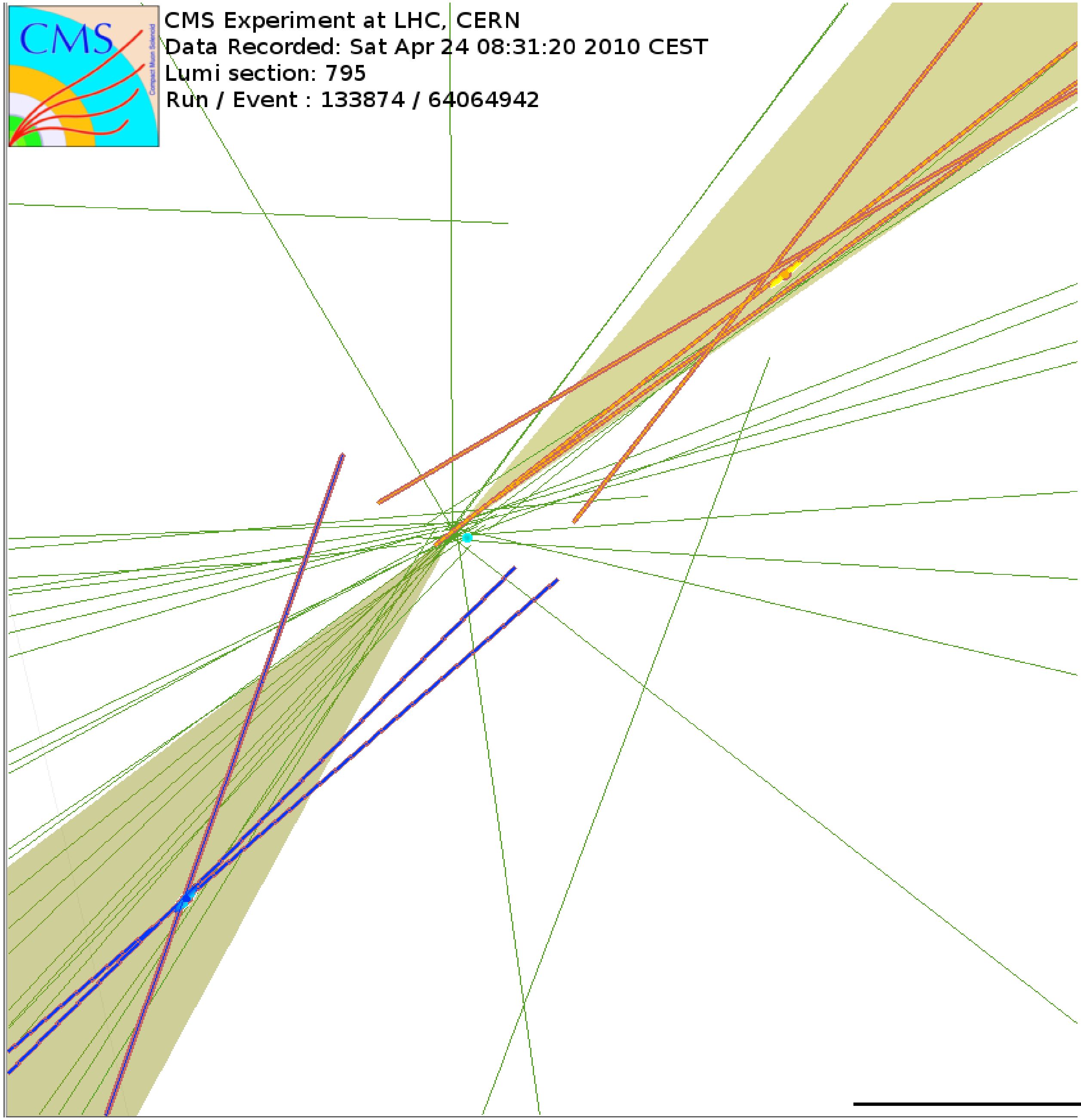
$$(Wc^2)^2 = \left(\sum E\right)^2 - \left\|\sum \mathbf{p}c\right\|^2$$

where

W is the invariant mass of the system of particles, equal to the mass of the decay particle.
$\sum E$ is the sum of the energies of the particles
$\sum \mathbf{p}$ is the vector sum of the momentum of the particles (includes both magnitude and direction of the momenta)

Rappel :
Invariant Mass

Zbb : b-tagging



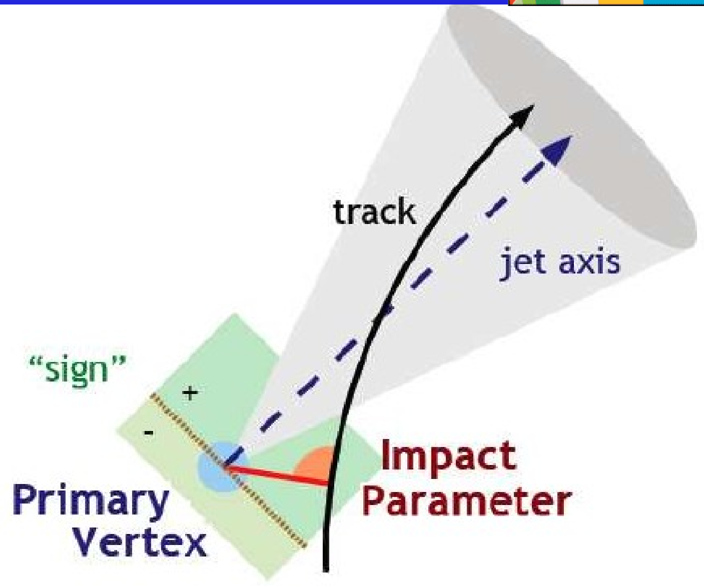
b bbar event

- B hadron longer time of flight
- Reconstruction of a second vertex with dedicated algorithm
  - -> Distance from primary vertex = d0
  - -> Mass
- Displaced tracks

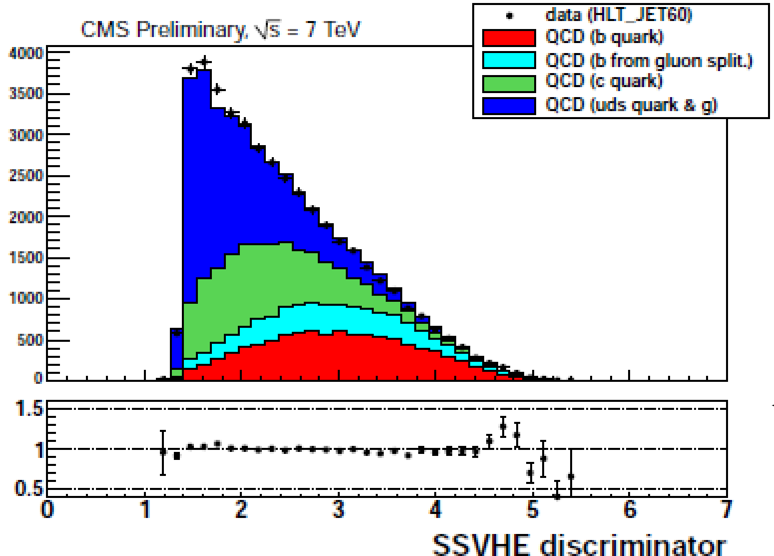
Zbb : b-tagging

- Track-counting (TC): tracks ordered by IP
  High-Eff (HE) = 2nd track,
  High-Pur (HP) = 3rd track.

- Simple Secondary Vertex (SSV): at least
  2 (High-Eff) or
  3 (High-Pur) tracks in vertex fit.



Working point	Requirement	Discriminant	Cut
SSVHEM	One secondary vertex with ≥ 2 tracks	$Log(1 + \frac{d_0}{\sigma_0})$	1.74
SSVHPT	One secondary vertex with ≥ 3 tracks		2.0



d0/σ0 = flight distance significance

Given by special b-tagging group

Technically : MC

Groups of people are obliged to run all those MC simulation (running during weeks or months)

CMS provides centrally MC simulation : remember those contain both Generated events and Reconstructed event (just like if they had passed through the detector).

In this dataset = for one event all the objects present have been reconstructed :
object electrons and muons with all their characteristics : pT, η, φ, E
jets reconstructed with different algorithms and all char.

First step = run the exact same code than for data before to create a skim of this huuuuge dataset : you will end up with the same requirement on the Reco objects than for the data.

→ Use the Grid to send your jobs on T2

→ Use PhD students to send the jobs and babysit them :)

Remember :you have to do it for the signal and all the backgrounds :
We used here Z + jets for : the signal Zb
And 2 backgrounds : Z+l and Z + c

We used a ttbar sample for ttbar background.

And a ZZ sample for the ZZ background.

Technically : data and MC

When all your jobs are finished and nice :

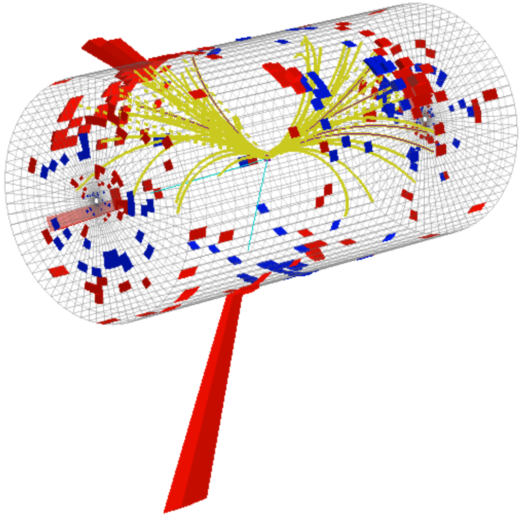
Step 2 = putting in place the analysis code with all the cuts and plot all the interesting variables!

$Z \rightarrow l^+l^-$
- 2 l = μ/e, isolated
- pt > 20 GeV
- $|\eta| < 2.4$
- 60 < mll < 120

1 or 2 b-tagged jets
- pt > 25 GeV
- $|\eta| < 2.1$
- From algo with HEfficiencies
- No overlap with leptons from the Z : dR > 0.5

10 CEST

Since we run now on the smaller skim : possible to do it on the university local server or Cern server.



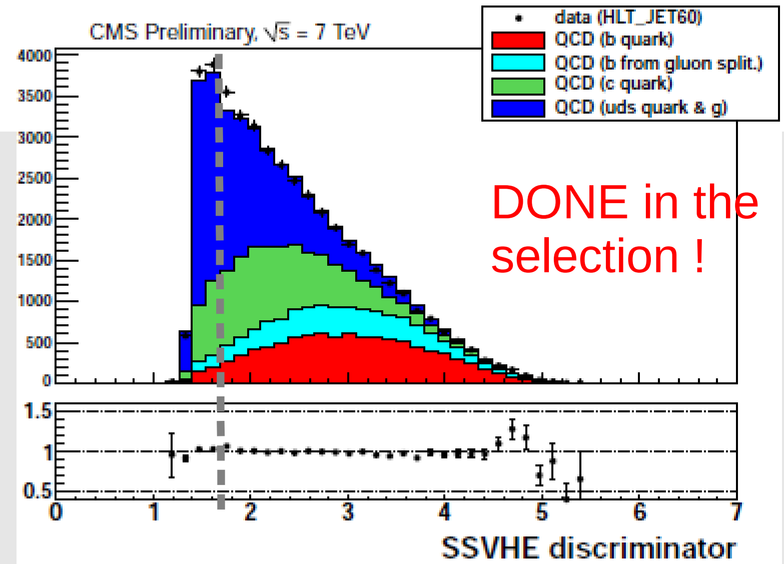
Superimpose the data and the all the different MC : signal and backgrounds.

Wait a second : did we get rid of all the background possible ? … mhum ...

Background: Z + light jets

Z+c, Z+udsg

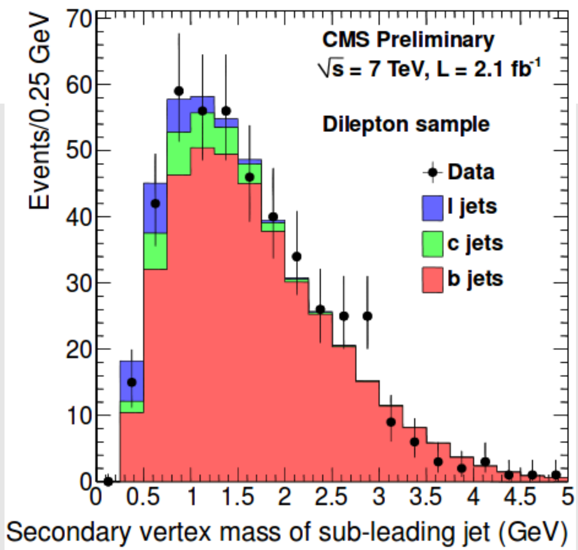
- **b-tagging: background reduction**
  - Detached secondary vertex
  - High efficiency selection: 55 %
  - 1% mistag



DONE in the selection !

- **background estimate**
  - Template fit to the Secondary Vertices Mass
    → b purity

We evaluate what we couldn't remove with templates of shapes.

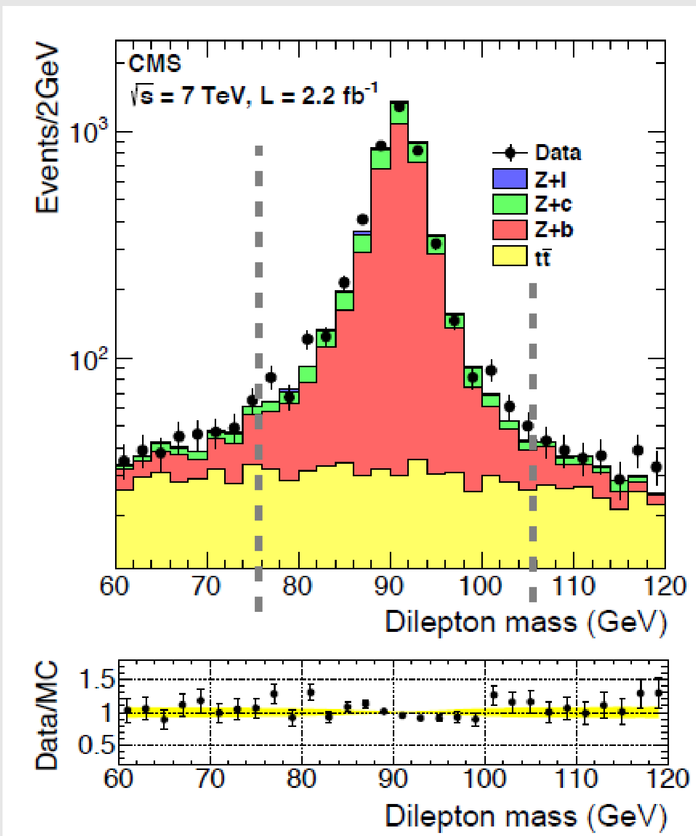


Background: ttbar

- **ttbar reduction:**

Z mass window

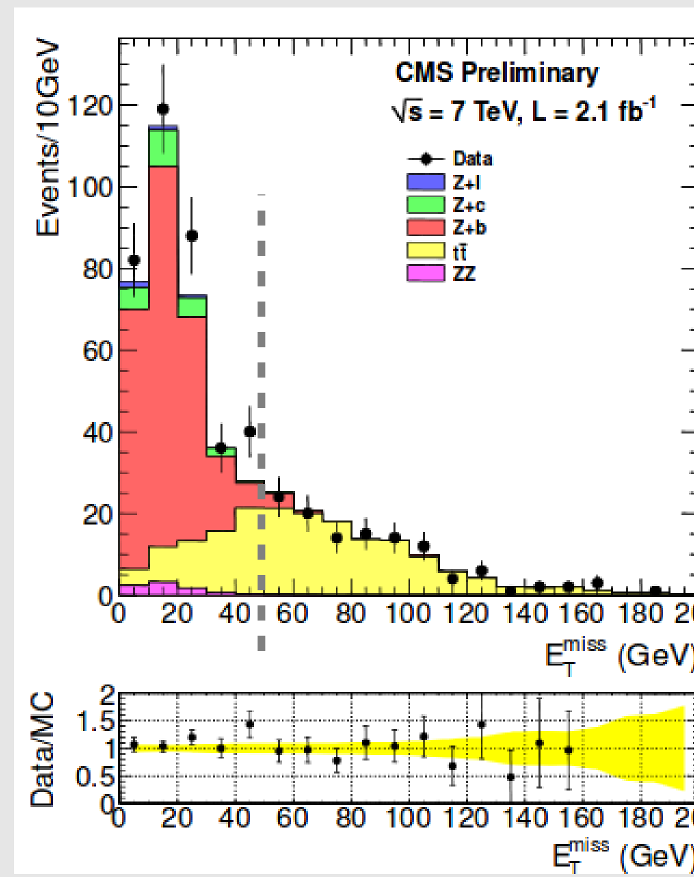
- 76 < m_{ll} < 106 (GeV)



Let's do this in the Selection !

MET criterium

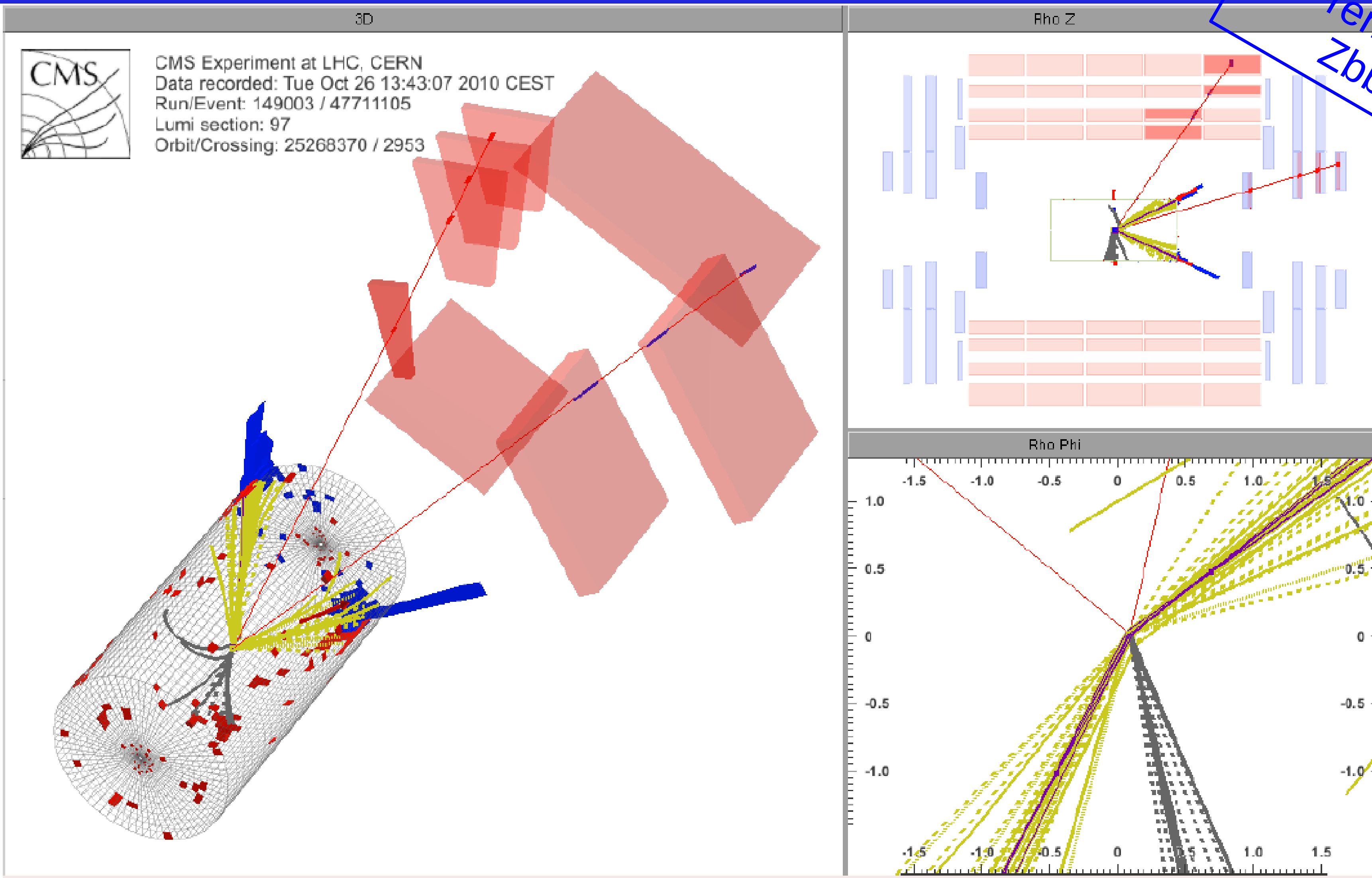
- MET < 50 GeV



Let's do this in the Selection !

- **ttbar estimate:** fit to m_{ll} from templates

And finally : an event!



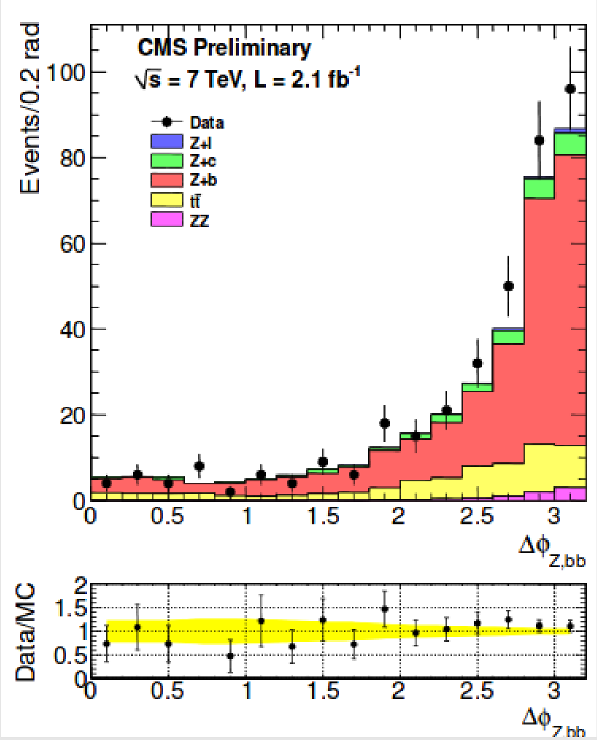
Premier candidat Zbb au LHC!

Object	p_T (GeV)
Muon 1	88.1
Muon 2	39.9
ME_T	34.3
Z	112
bb	103.3
Zbb	12.4

Run	149003	Event	47711105	Lumi Block	97
Object	p_T (GeV)	η	ϕ	SSVHE	SSVHP
jet 1	241	1.53	-2.06	3.17	3.17
jet 2	213	1.46	0.65	2.45	2.45
jet 3	40.2	-0.05	-1.34	-1	-1

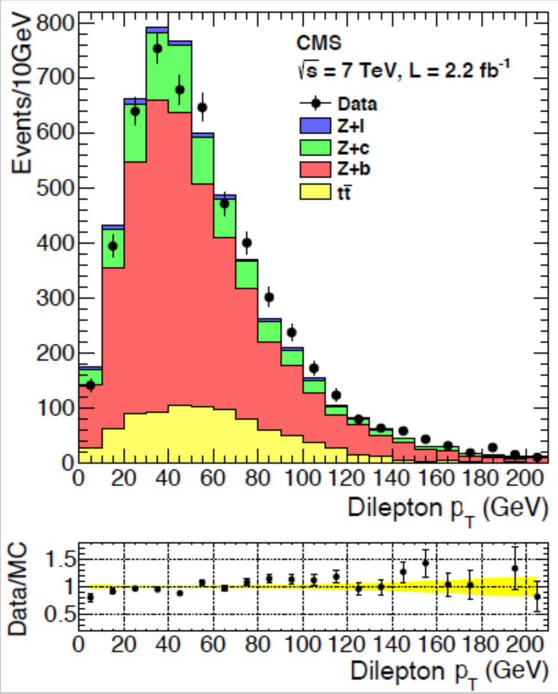
Object	Mass (GeV)
M_{ll} (GeV)	102.4
M_{bb} (GeV)	454.4
M_{Zbb} (GeV)	628

And finally : The plots!



Angular distributions :

- General reasonable agreement data/MC (MadGraph)
- MPI contribution reasonably modeled from low values of $\Delta\varphi_{Z,bb}$



Momentum distributions :

- Slightly harder spectrum for data than MC at LO
  → NLO to be considered

Calculation of a σ

We need to have access at the number of Signal events =
Number of data selected – number of background events we couldn't eliminate

We evaluated this :

Directly from MC survival events.

Background corrected signal yield (Z+1/2b)

$$N_{sig}^{Z+1/2b} = N_{rec}^{Z+1/2b} * (f_{bb} - f_{tt}) - N_{ZZ}$$

- f_{bb}: b-event purity
- f_{tt}: ttbar fraction
- N_{ZZ}: number of ZZ events

Unfolding, with expected efficiencies:

$$N_{gen}^{Z+1/2b} = \varepsilon_l * \varepsilon_b * \varepsilon_r * A_l * N_{sig}^{Z+1/2b}$$

- Correct for efficiencies using MC
  - Taking into account lepton/b-tag/PU data/MC scale factors
- Using matrix equations to take into account 2b→1b migrations

Still a lot of work to evaluate those corrections!

Unfolding and Results

Unfolding:

➔ # **reconstructed** b-jets → # **hadron-level** b-jets

$$\begin{pmatrix} \sigma(Z+1b) \\ \sigma(Z+2b) \end{pmatrix} = \frac{1}{\mathcal{L}} \times \mathrm{A}^{-1} \times \mathbf{E}_r^{-1} \times \mathbf{E}_l^{-1} \times \mathbf{E}_b^{-1} \times \begin{pmatrix} N_{sig}^{Z+1b} \\ N_{sig}^{Z+2b} \end{pmatrix}$$

Corrections for all efficiencies and acceptance

Cross sections:

- Results for ee and μμ channels compatible and combined in a single measurement

Cross sections at the particle level	
Multiplicity bin	Combination
$\sigma_{hadron}(Z+1b, Z \to ll)$(pb) $\sigma_{hadron}(Z+2b, Z \to ll)$(pb)	**3.41** ± 0.05 ± 0.27 ± 0.09 **0.37** ± 0.02 ± 0.07 ± 0.02
$\sigma_{hadron}(Z+b, Z \to ll)$(pb)	3.78 ± 0.05 ± 0.31 ± 0.11

Measurement: σ(Z(ll)+2b) = **0.37** ± 0.02 (stat.) ± 0.07 (syst.) ±0.02 (theory) pb

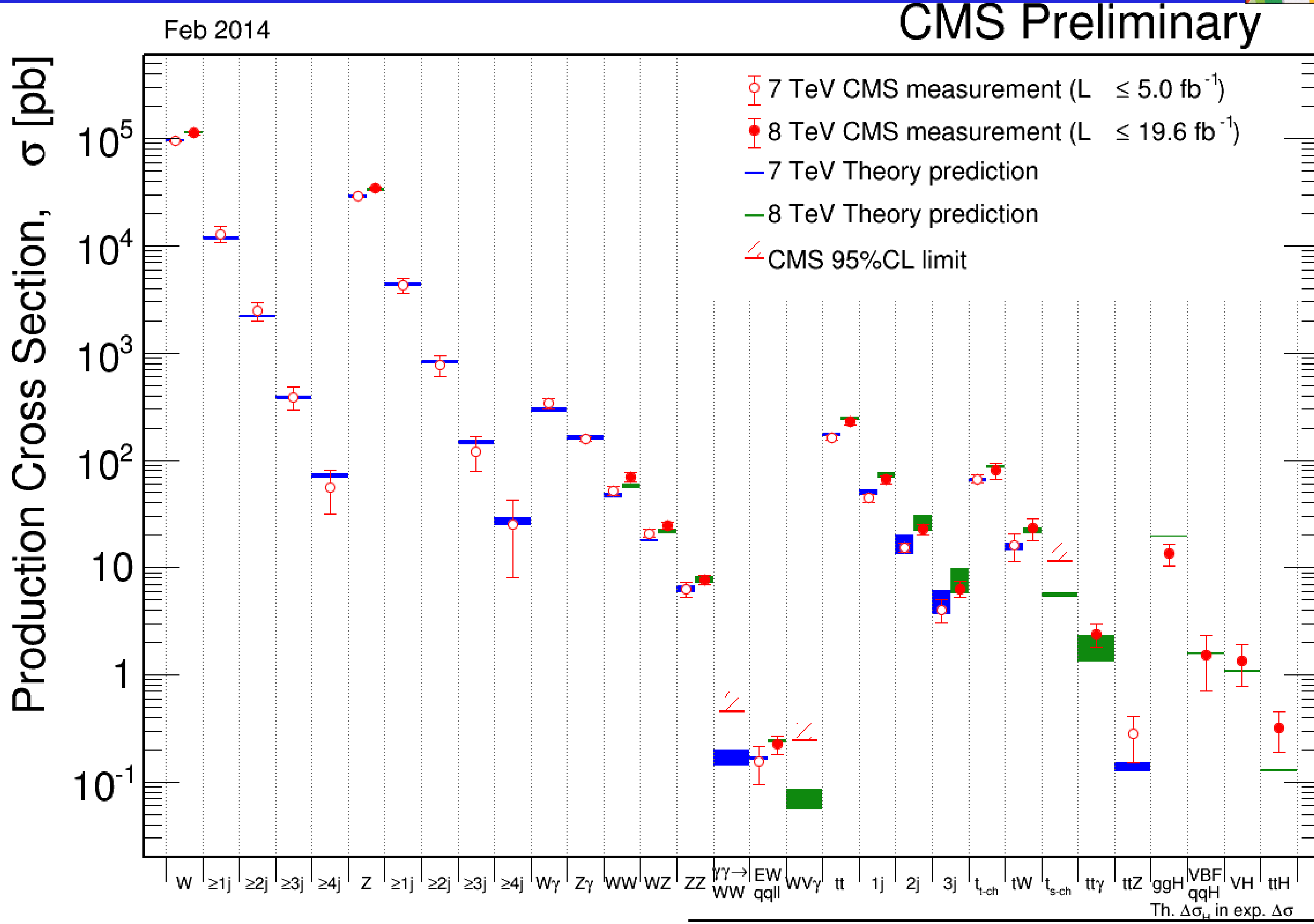
MadGraph expectation: σ(Z(ll)+2b) = **0.33** ± 0.01 (stat) pb

- Compatible with expectations from MadGraph 5 flavor corrected to NNLO

Systematic errors on the measurement

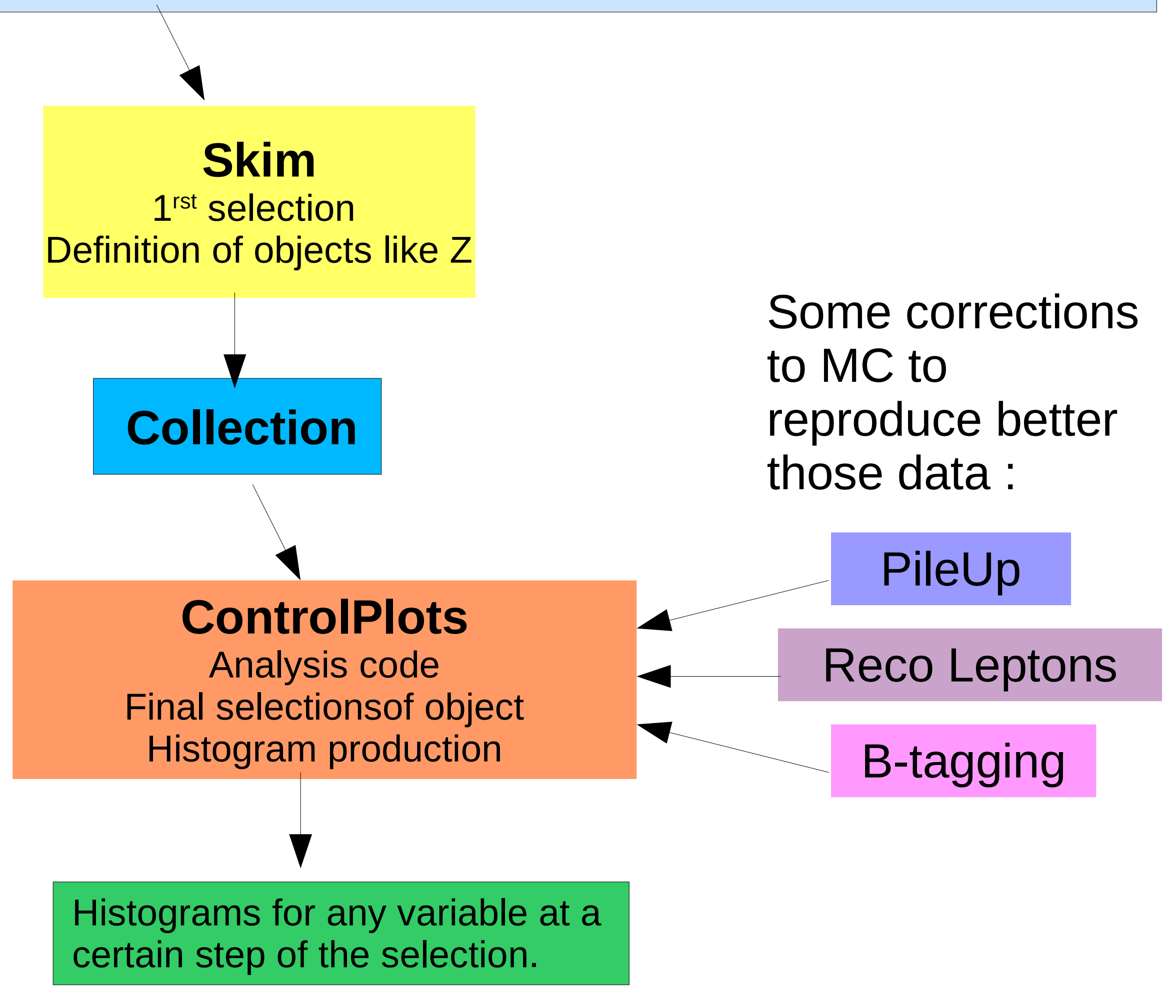
	Correlated sources	Fractional uncertainty (%)	
	b-tagging efficiency	10	
	b-jet purity	5.6 (ee+b)	4.6 ($\mu\mu$+b)
	$t\bar{t}$ contribution	2.9	
→	Jet energy scale	2.5	
	Luminosity	2.2	
→	Jet energy resolution	0.5	
± 0.6 interactions →	Pile-up	1.5 (ee+b)	0.5 ($\mu\mu$+b)
	Mistagging rate	0.04	
	Theory (via $\mathcal{A}_\ell$)	$^{+4.2}_{-6.5}$	
	Theory (via $\mathcal{C}_{\text{hadron}}$)	$^{+0.7}_{-6.9}$	
	Uncorrelated sources	**ee+b**	**$\mu\mu$+b**
	Trigger and dilepton selection	4	2
	$t\bar{t}$ contribution	1.9	2.2
	Experimental systematic	13.0	12.3
	Theoretical systematic	$^{+4.2}_{-9.5}$	$^{+4.2}_{-9.5}$
	Statistical	2.2	1.7

All the SMP results!



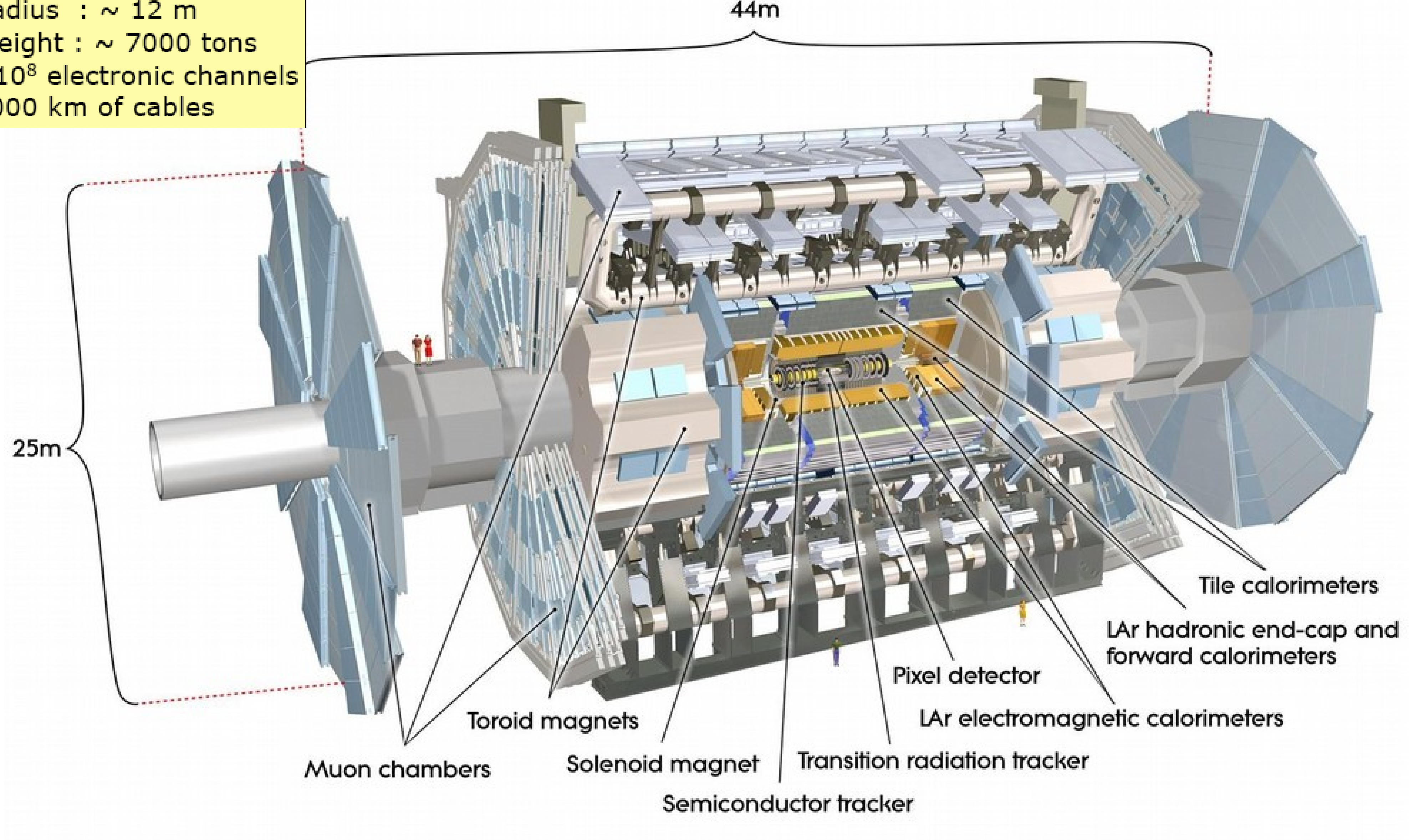
Analysis Chain Summary

- **Data** : dataset associated to a fixed lumi and a certain trigger (preselection on data)
- **MonteCarlo Simulation:** Signal and Background



ATLAS : A Toroidal LHC ApparatuS

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

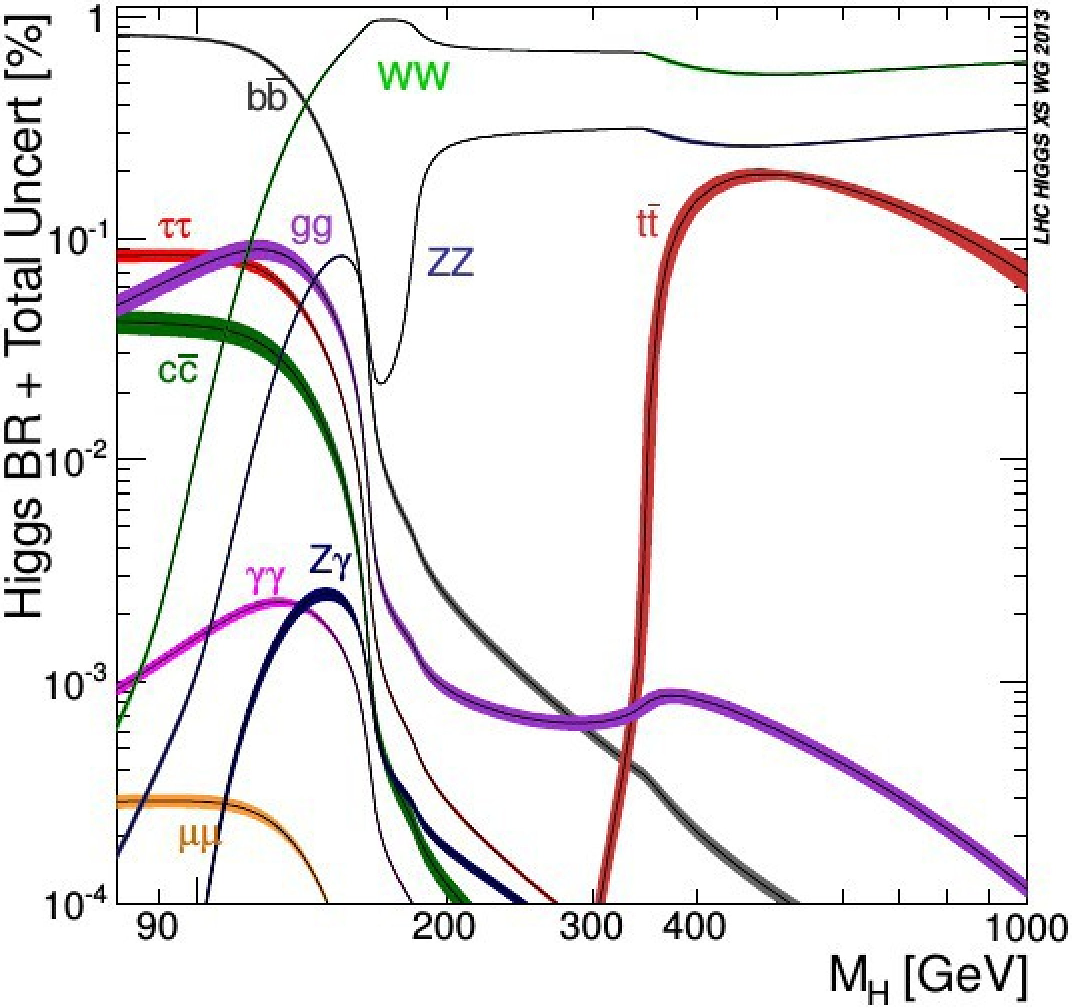


H → ZZ → 4leptons

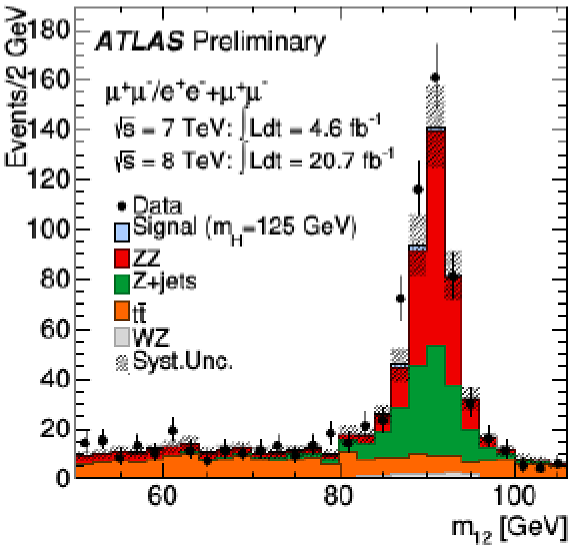
One of the most sensitive channels.

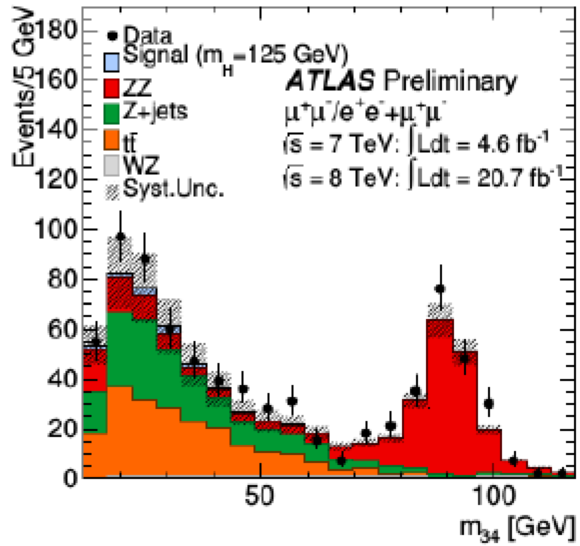
It provides a rather clean final state signature.

Final state fully reconstructed
Best mass resolution
Low BR fraction (at low mass)



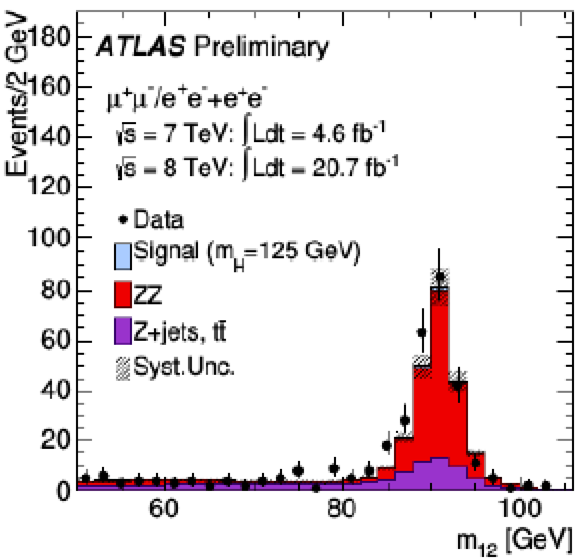
H-> ZZ-> 4 leptons

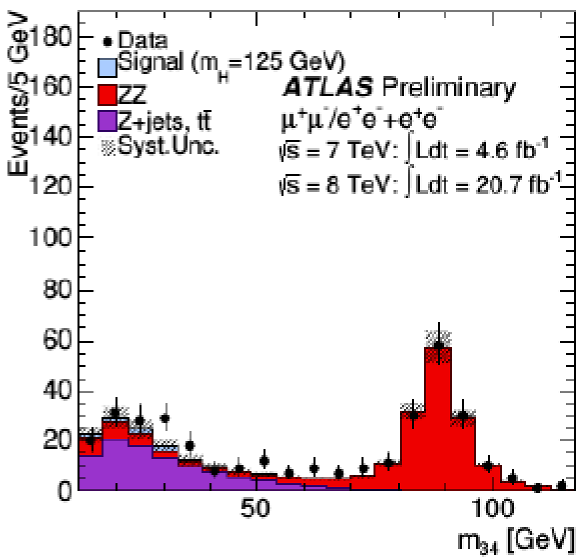




ll+μμ background

control region:
isolation and IP significance applied to the leading pair leptons only





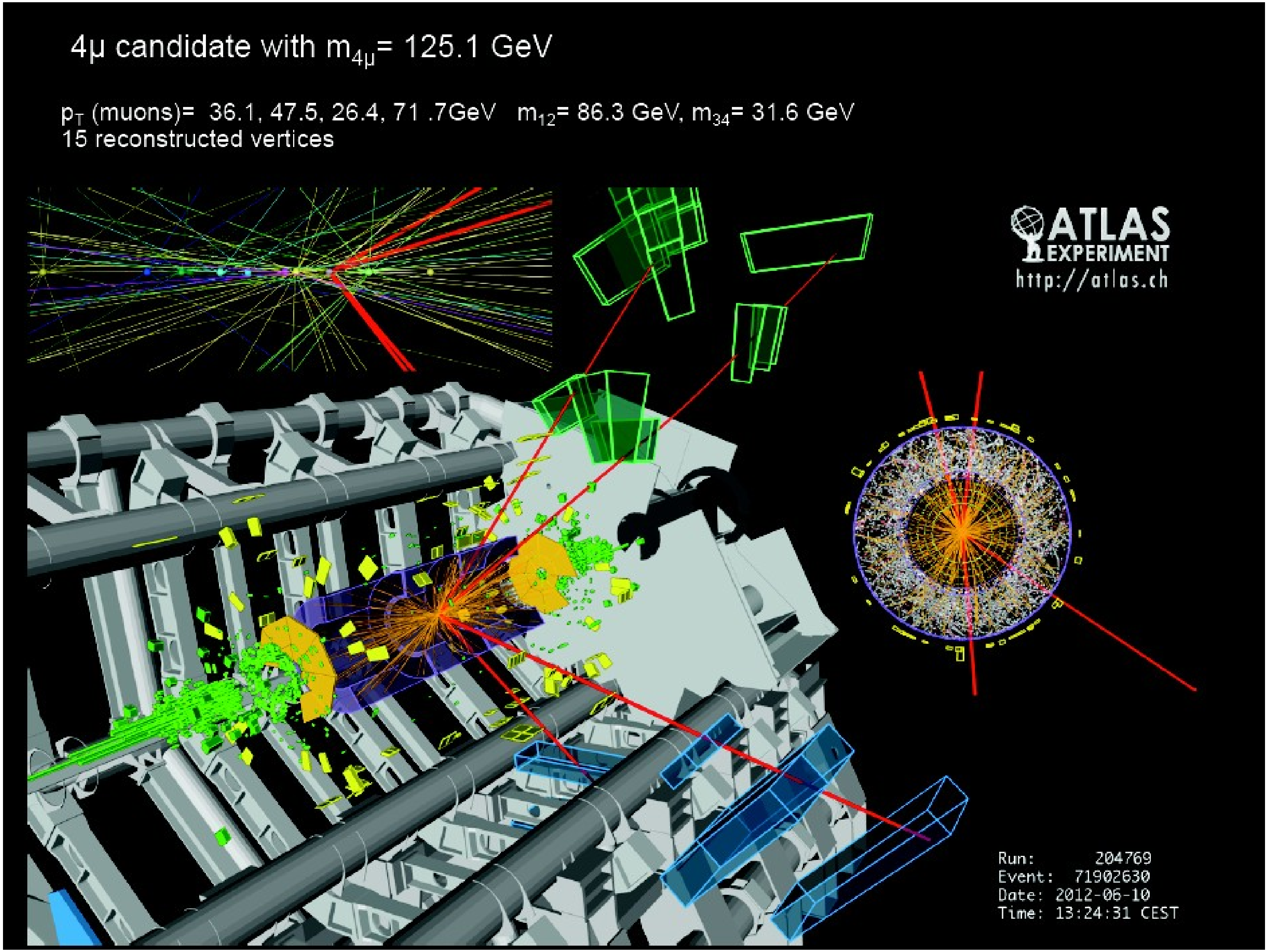
Good Agreement Data/MC

small signal contribution

ll+ee background

ATLAS Nikhef weekly - A. Salvucci

H → 4 leptons


4μ candidate with $m_{4\mu}$= 125.1 GeV
p_T (muons)= 36.1, 47.5, 26.4, 71 .7GeV m_{12}= 86.3 GeV, m_{34}= 31.6 GeV
15 reconstructed vertices
ATLAS EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

H-> ZZ-> 4 leptons

Animated gif which is making my computer die!

Higgs discovery

Announcement the 4th of July 2012

For use in case of 5σ Higgs discovery

1. Check label for "Champagne". (Do not use "Cava") Remove protective cover.

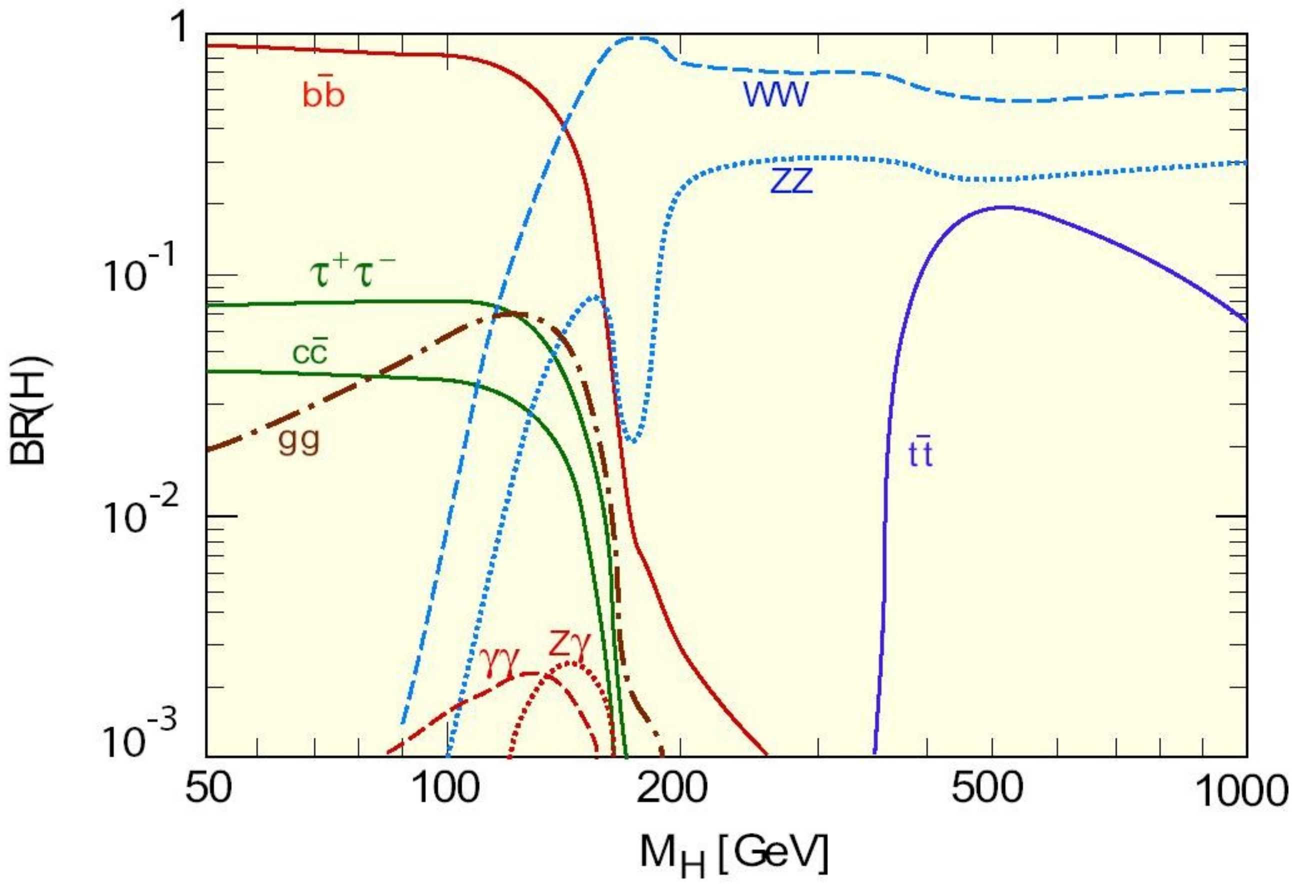
2. Gently twist cork to release fluid. (Aim away from face)

3. Apply fluid to Champagne flutes. Repeat until all flutes are filled.

More on Higgs discovery

How to observe the boson

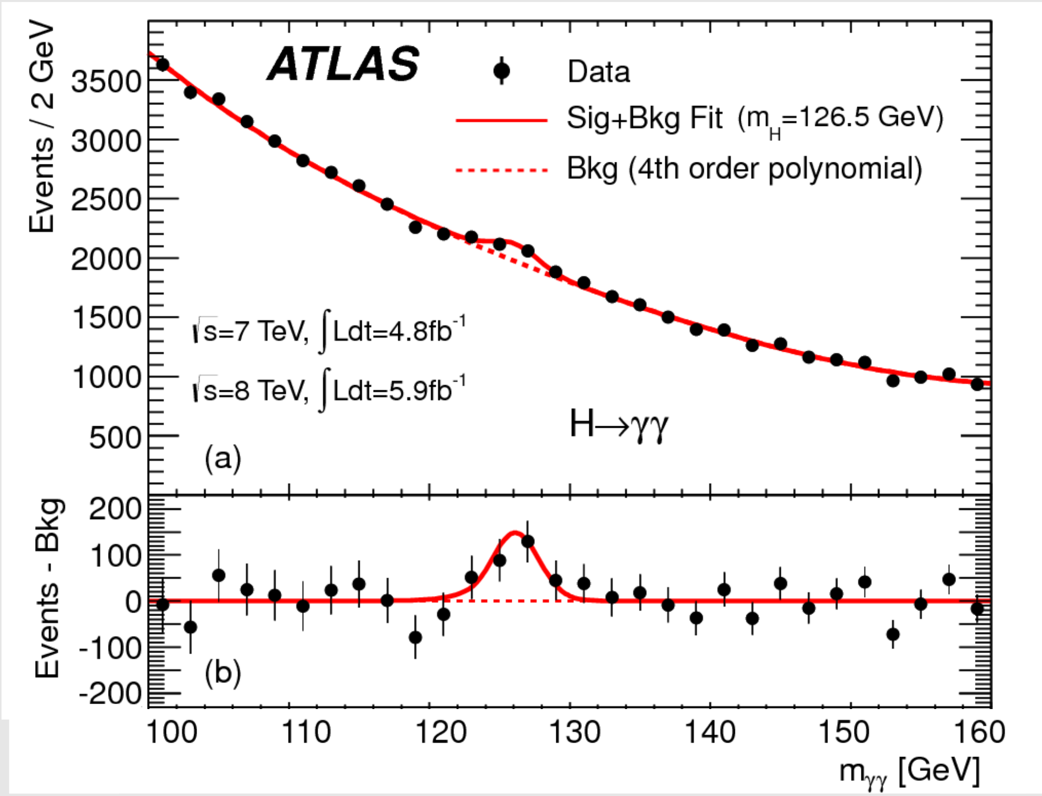
Observe the Higgs == observe a clear excess with respect to the expected background (predicted for a case with no Higgs)



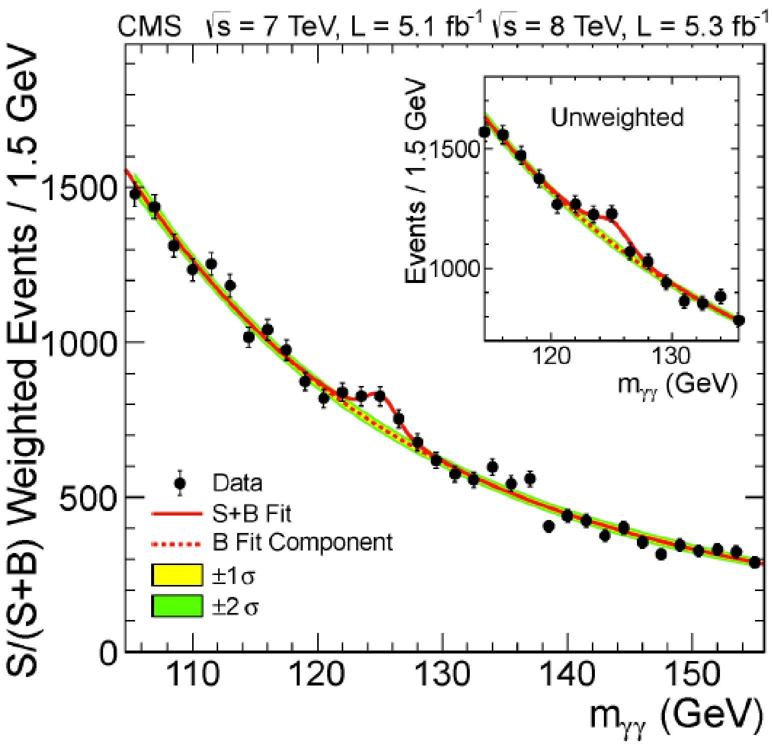
Several decay modes with different probabilities to happen in function of the mass it could have.

Higgs discovery

H-> γγ



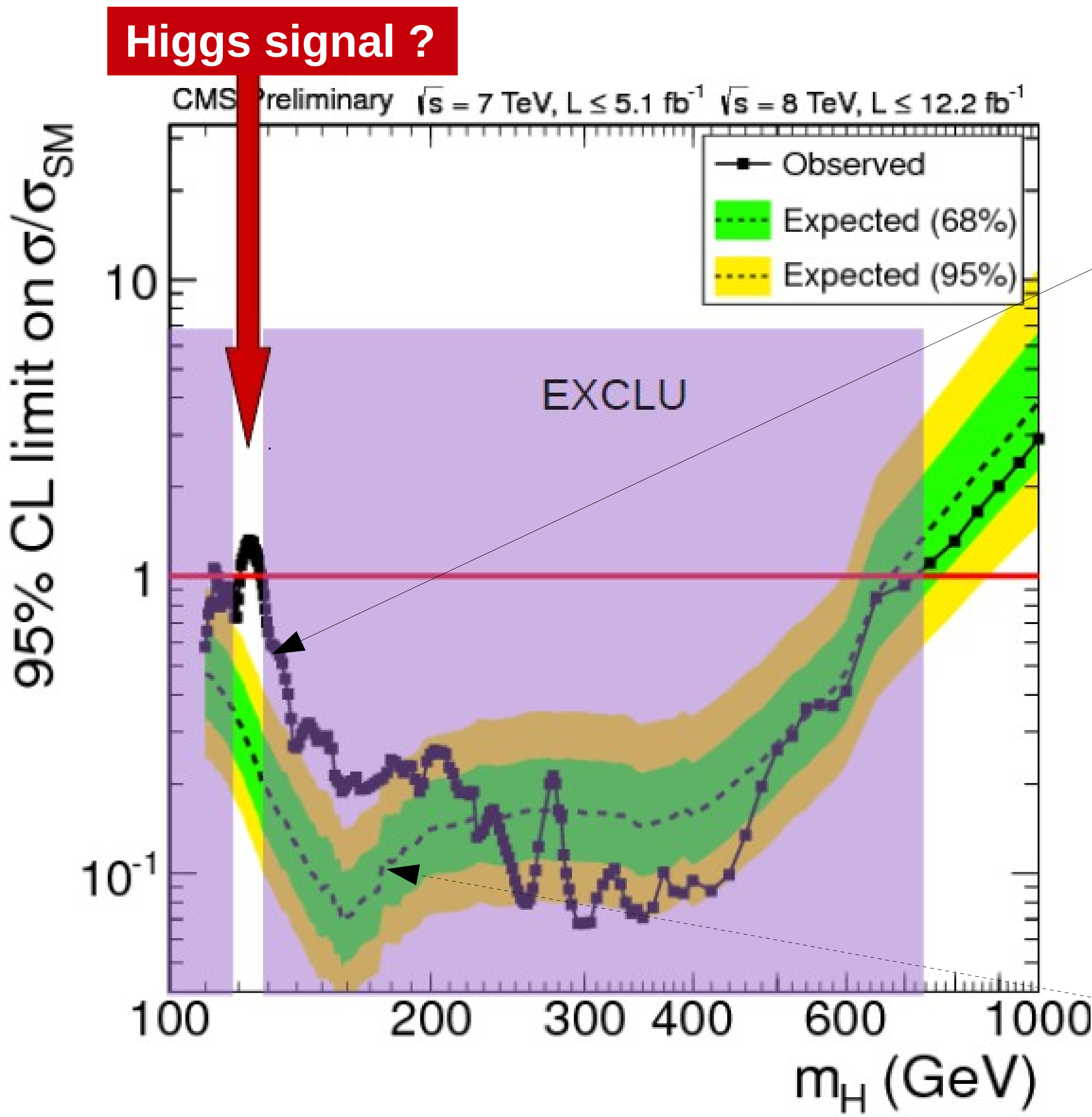
Deviation from background B.
B = all standard model processes that can lead to a γγ final state



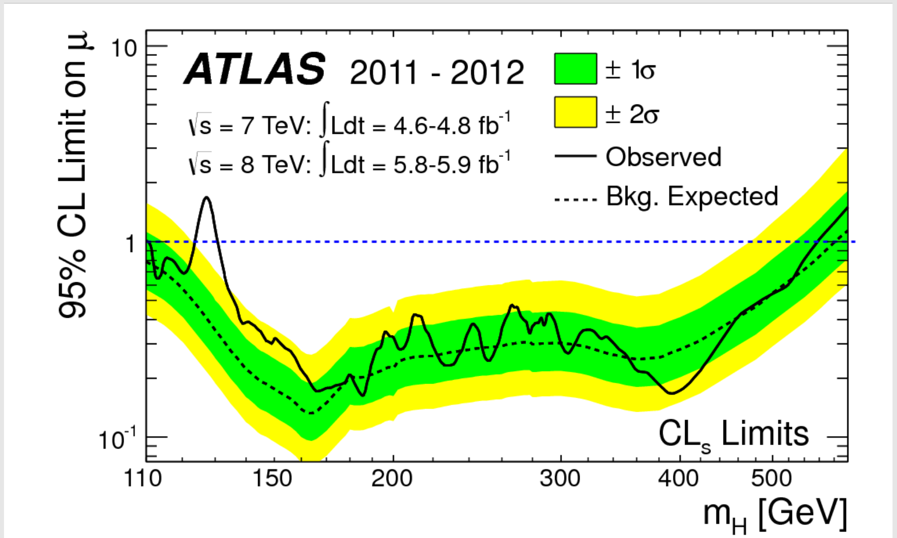
Higgs discovery

Exclusion of the possibilities : Brazilian plot

Ratio (μ) between the observed σ and the σ of the Standard Model with the hypothesis of a Higgs of mass x.



observed experimental limits for the production of a Higgs of each possible mass value

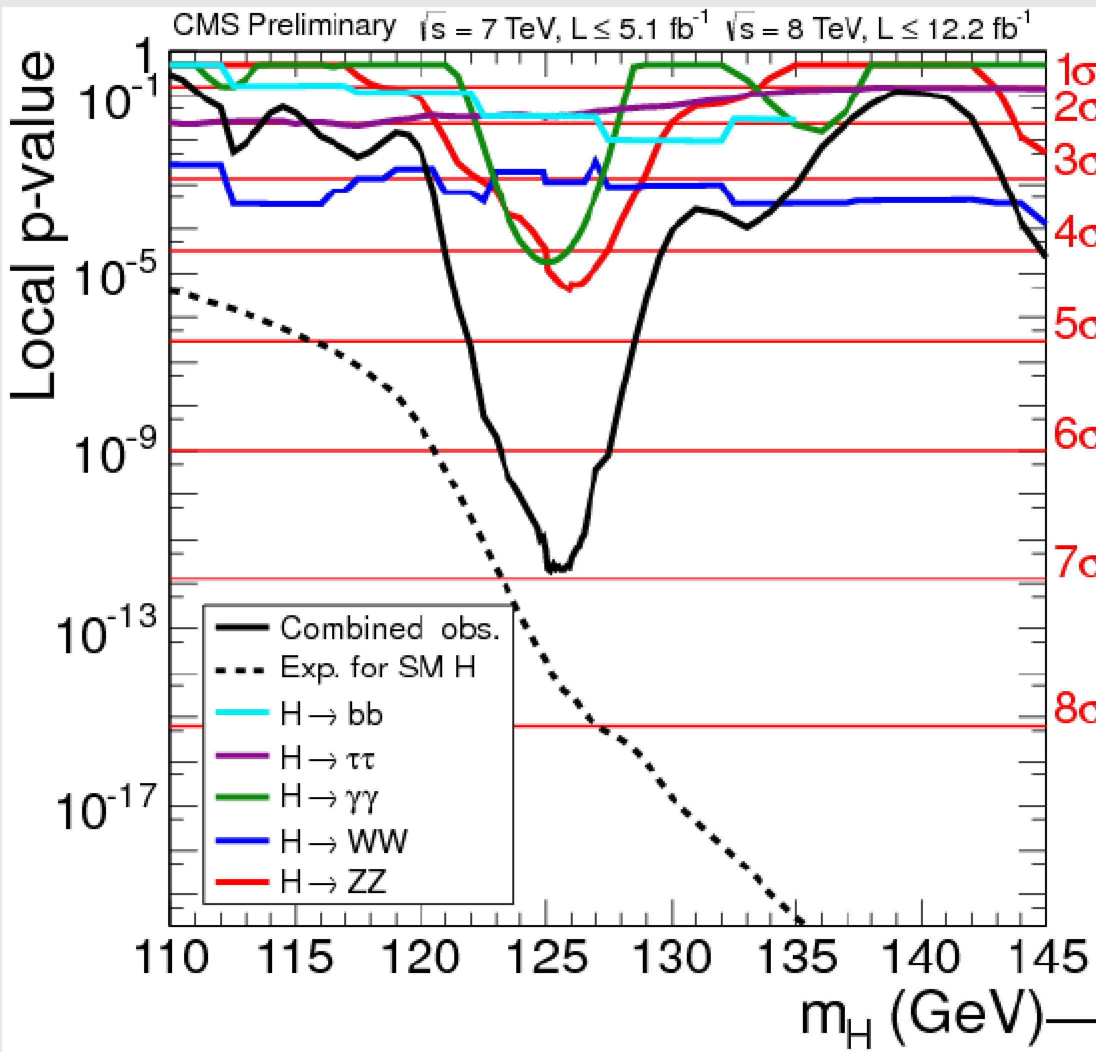


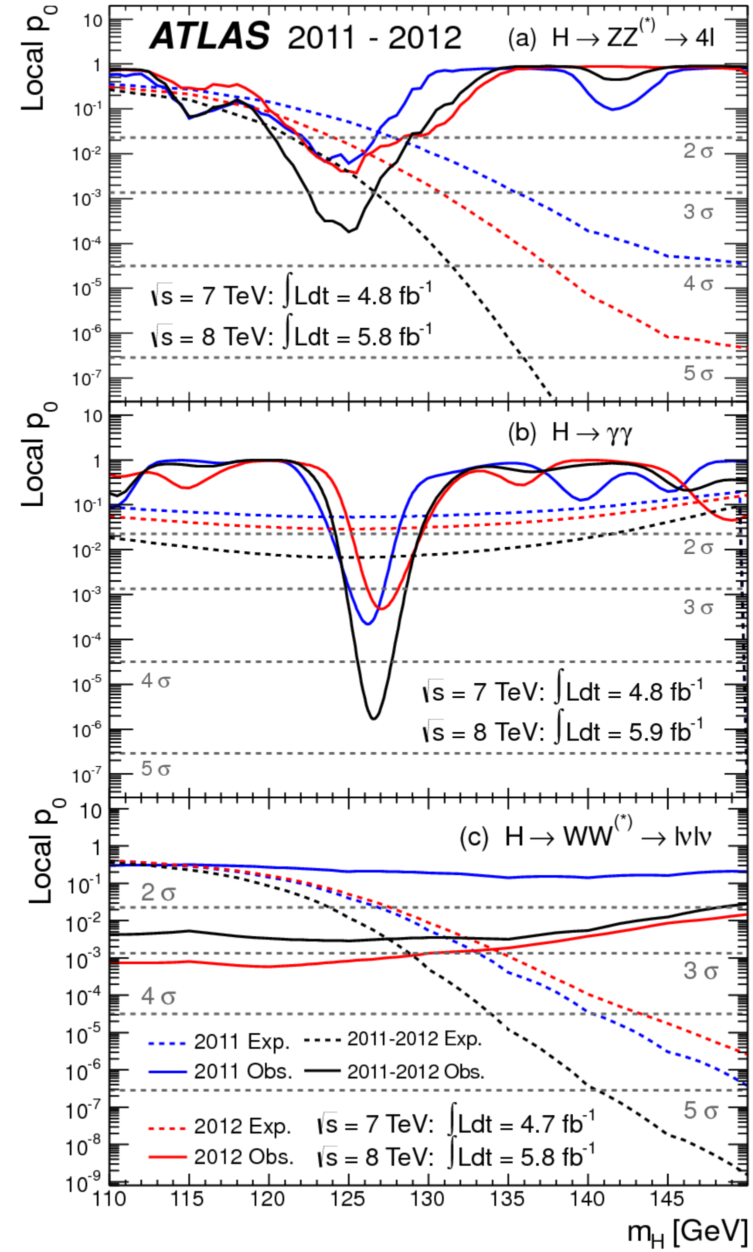
expected value from the SM in the hypothesis of no Higgs = only background

Higgs discovery

Probability : p-value plot

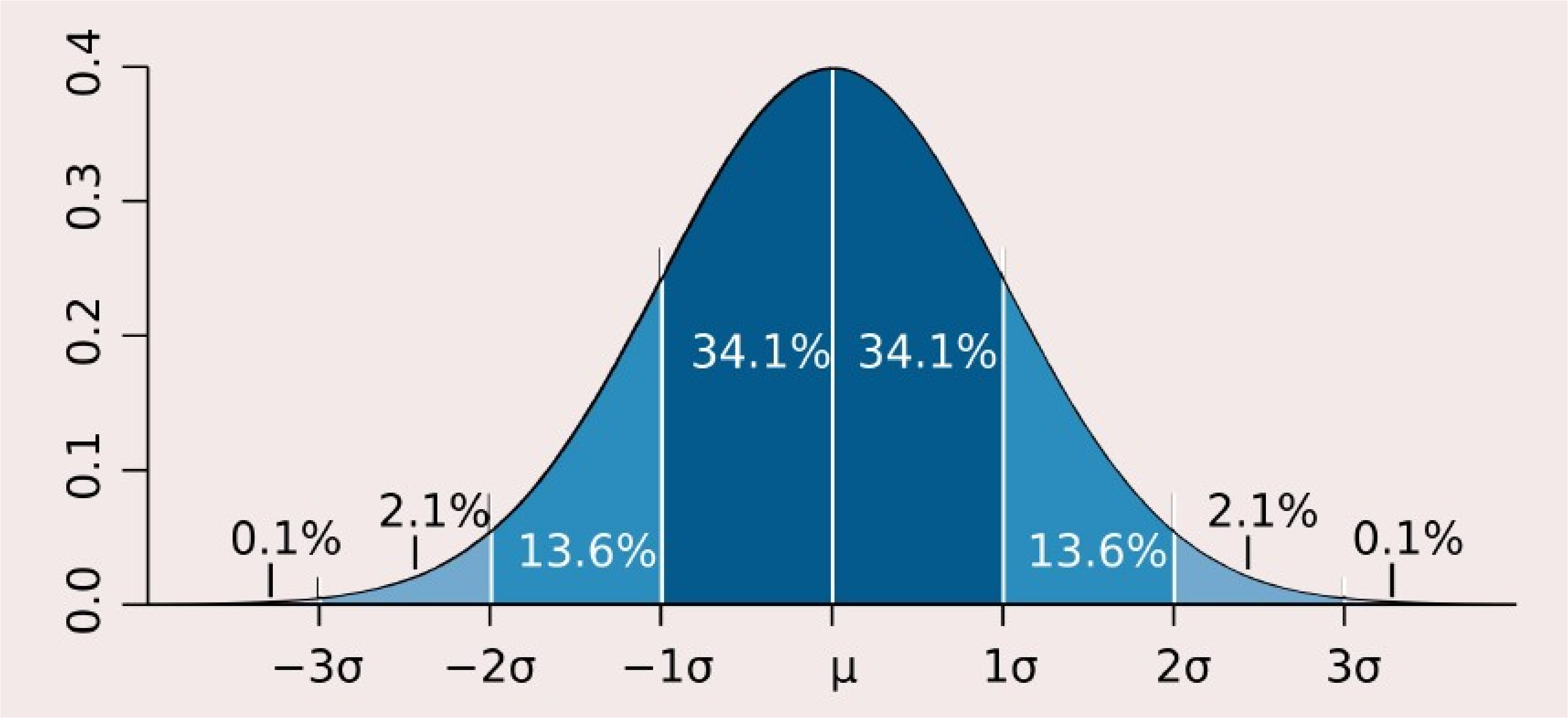
P-value =
probability of the null hypothesis (no Higgs of mass x).





Standard deviation

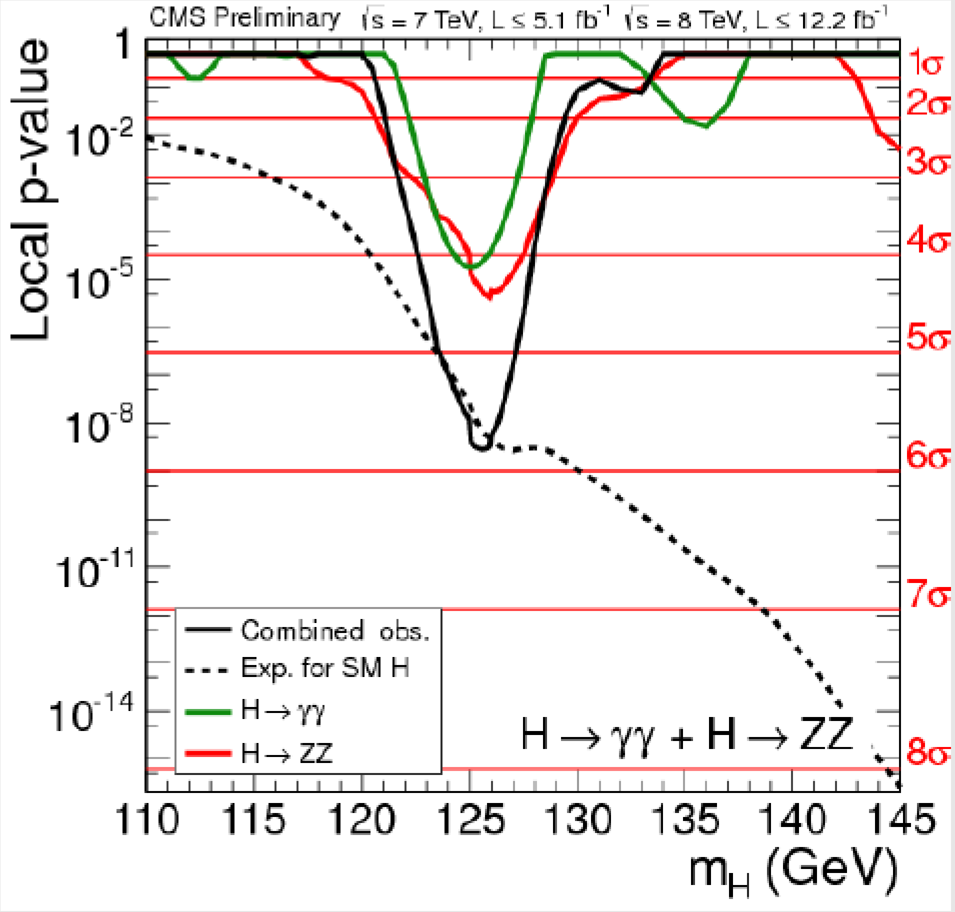
The number of standard deviation is a convention based on the Gaussian to express the small probabilities



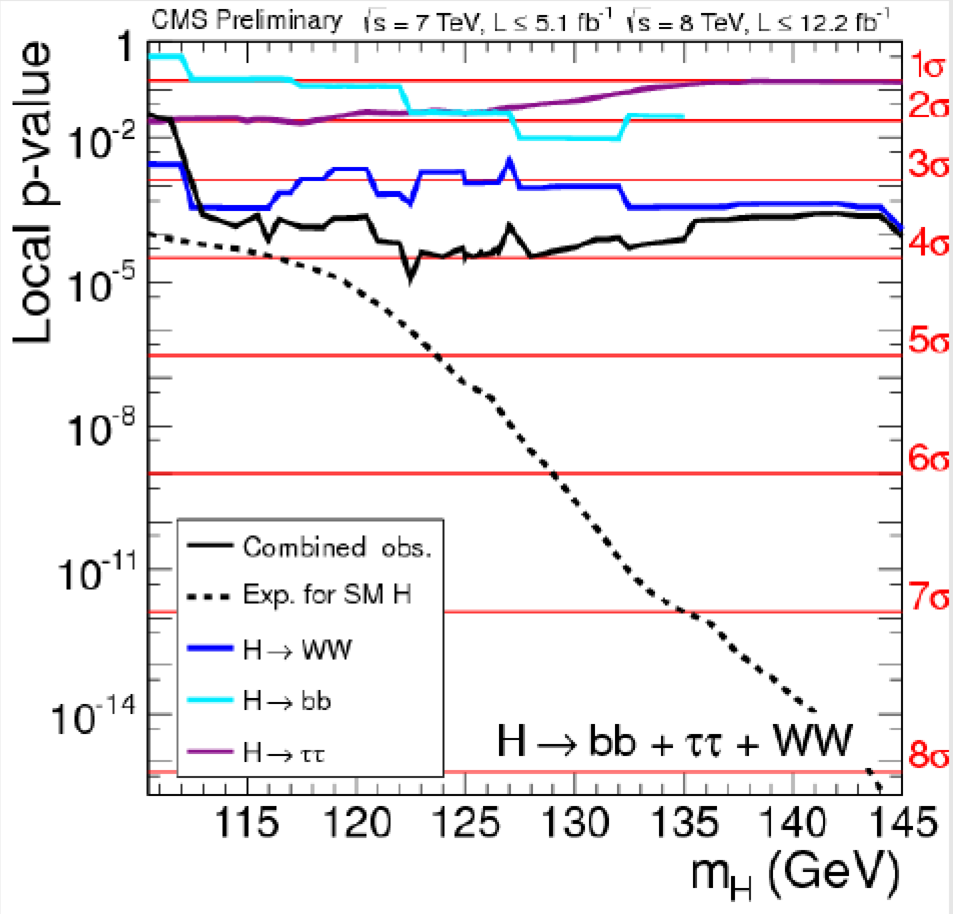
By convention/tradition we talk about evidence for 3σ et of discovery for 5σ.

Per channel

Discovery!

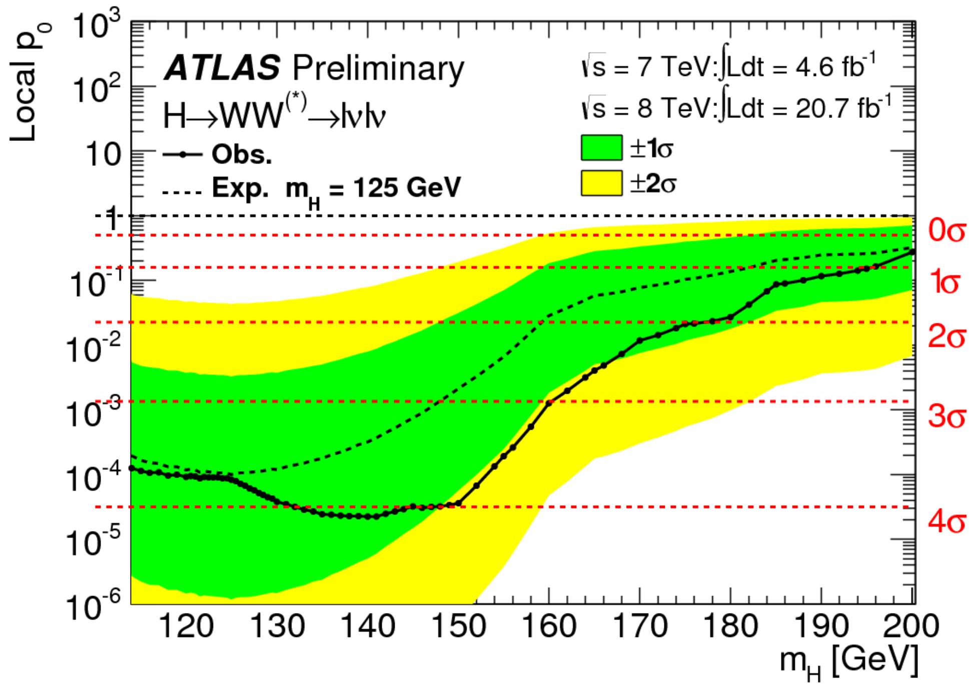


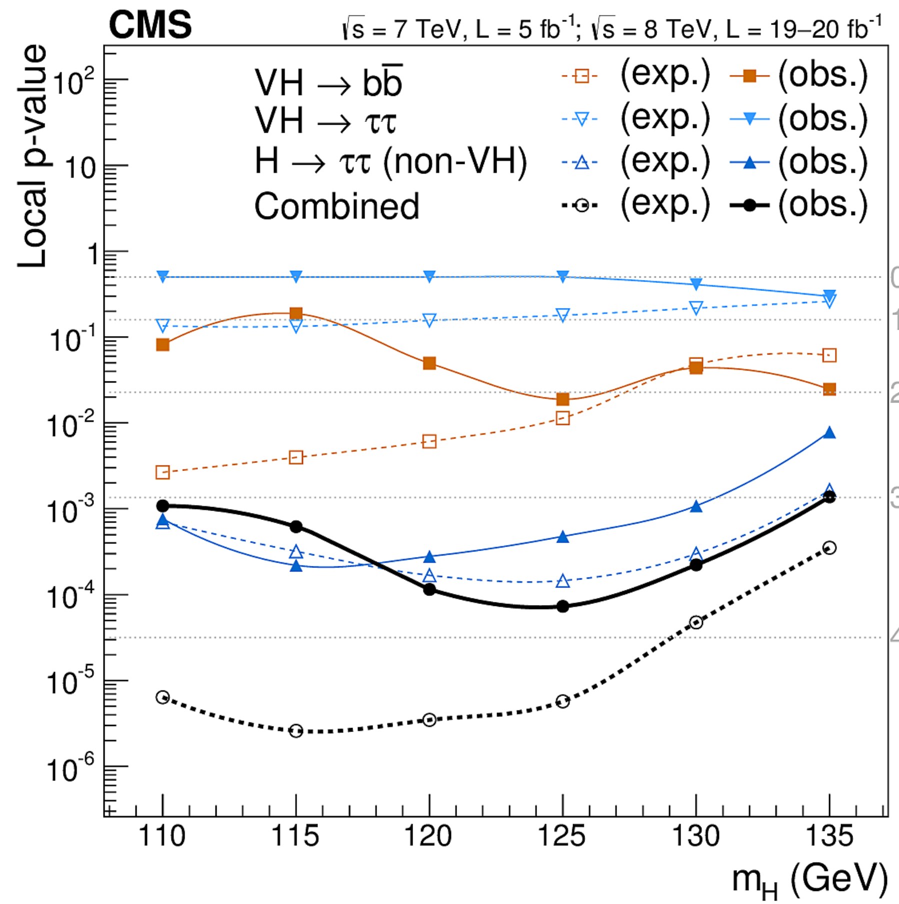
Evidences



Higgs discovery

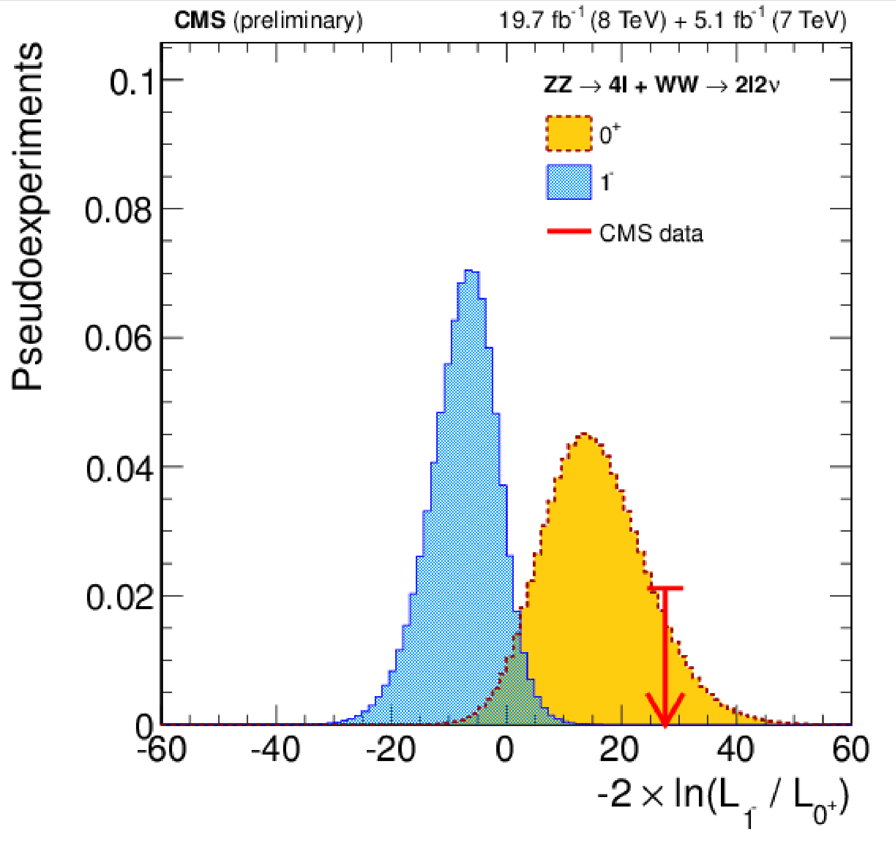
Latest H → WW and to fermions



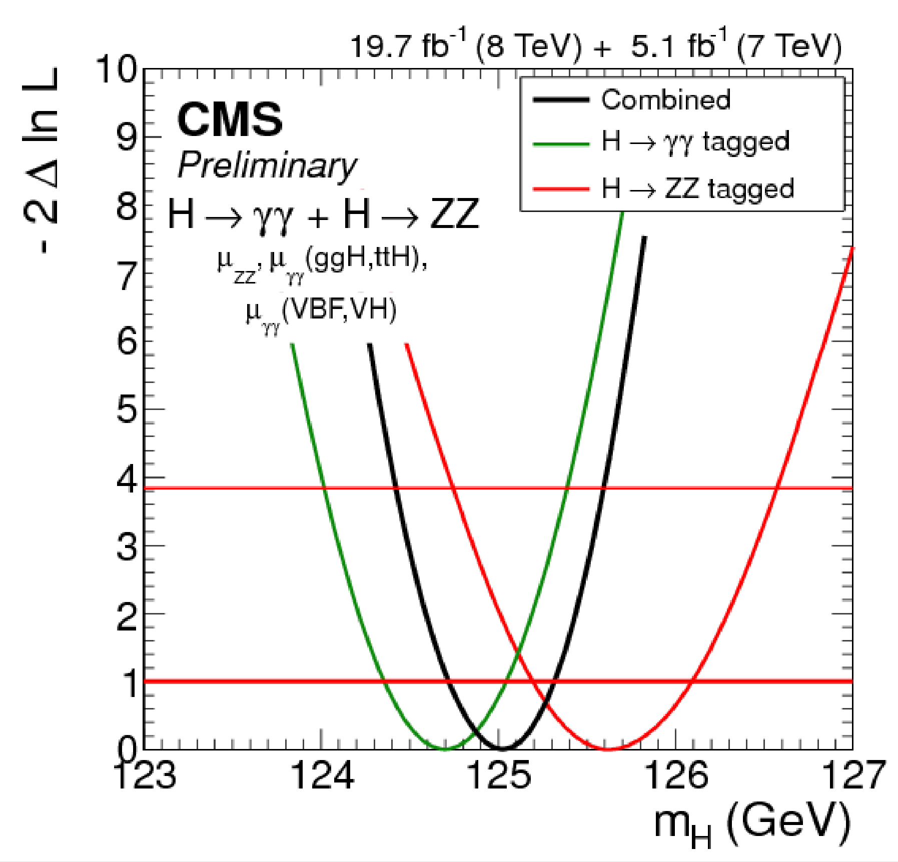


Higgs discovery

Property measurements :

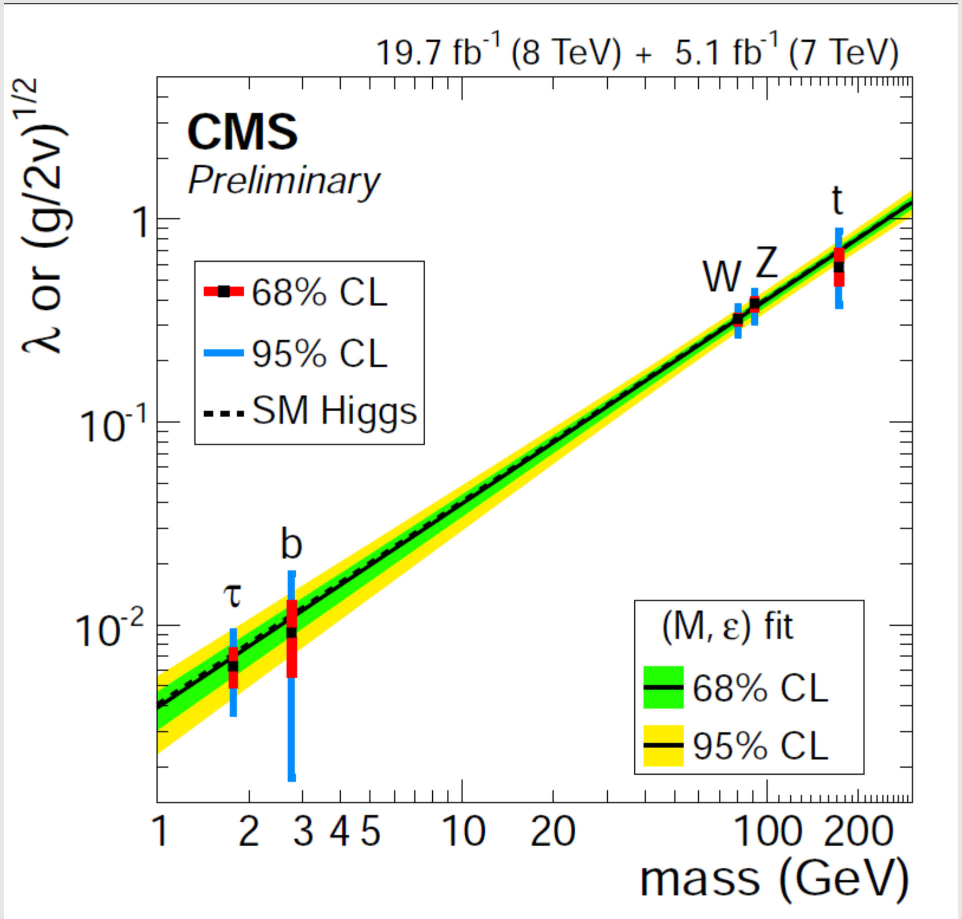


Spin 0 against spin 1 hypothesis

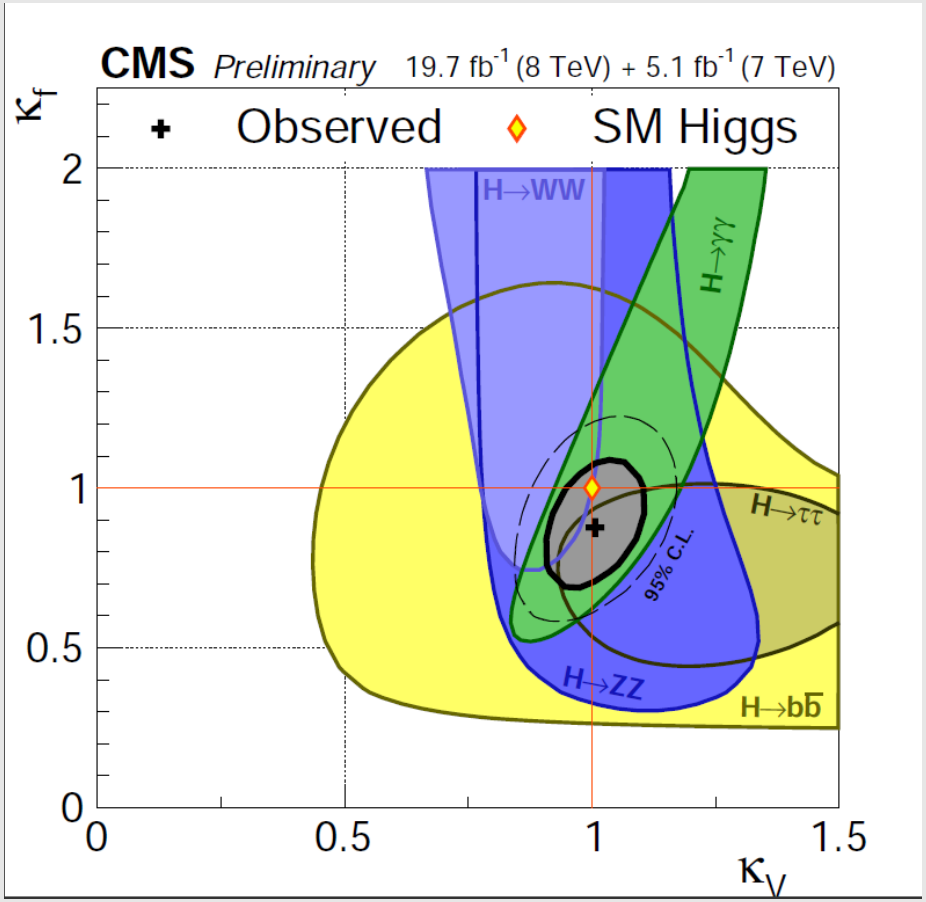


$$m_H = 125.03\,^{+0.26}_{-0.27}\,(stat)\,^{+0.13}_{-0.15}\,(syst) = 125.03\,^{+0.29}_{-0.31}\,(tot)\;GeV$$

Property measurements :



Coupling strength of Higgs as function of particle mass.

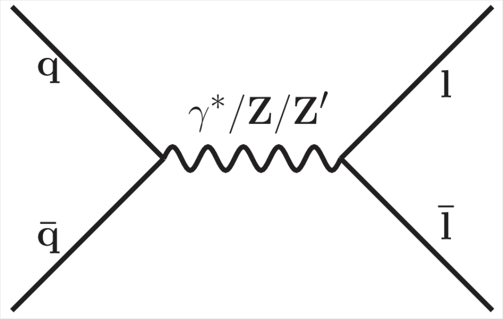


Combination for coupling to fermions and bosons

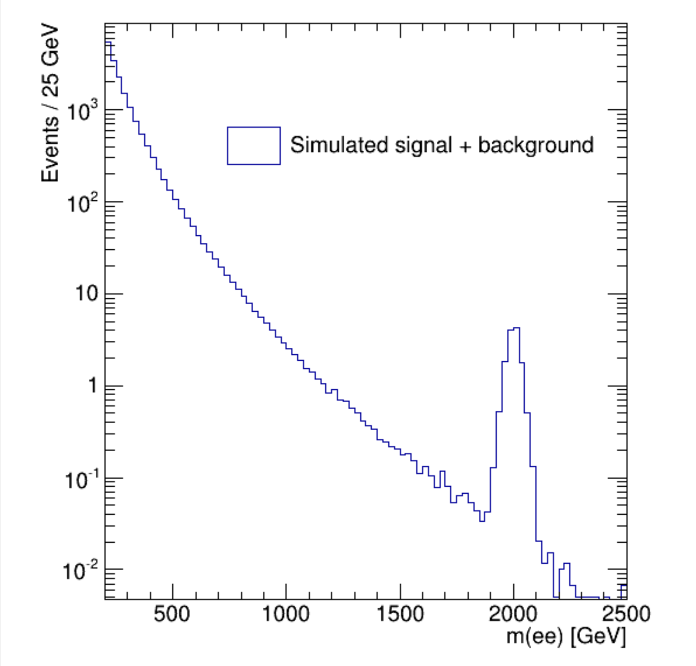
CMS + exotic search (and not found!)

Z' → 2leptons

- Many theories predict heavy resonances.
  - Extra dimensions
    heavy Z's (spin 1)
    heavy gravitons (spin 2)
  - Grand unified theories



A search for such resonances with leptons provides a clean access.
Best performance with electrons and muons. Decaying taus are more difficult to handle.
Leptons have high momentum and care is necessary for the selection

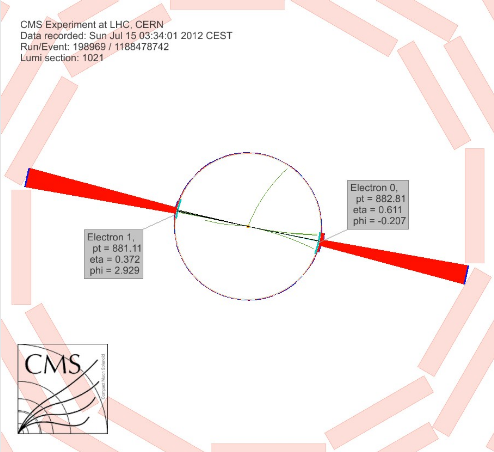


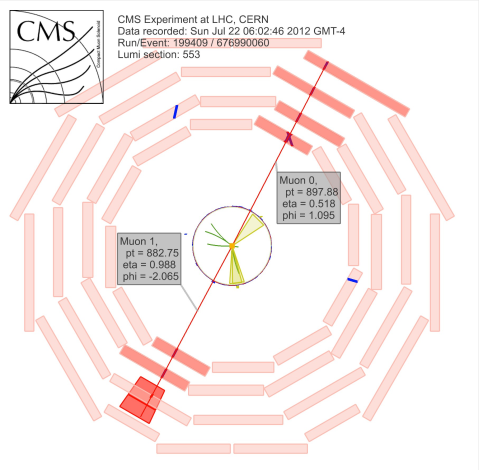
Search for a narrow resonance (Detector resolution much wider than natural width of the resonance) on steeply falling SM background

CMS + exotic search (and not found!)

Z' → 2leptons

Electron selection:
Two electrons candidates with high energy deposit in the ECAL and associated track.
No other energy deposits around the electron candidate (ECAL isolation).
No other tracks in a cone around the electron candidate (Tracker isolation).



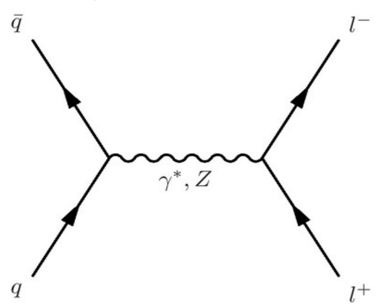


Muon selection:
Two opposite charge muon candidate tracks reconstructed in the inner tracker and the muon chambers.
No other tracks in a cone around the muon candidate (Tracker isolation).
Both tracks must be close to the same vertex (Cosmic muon rejection).

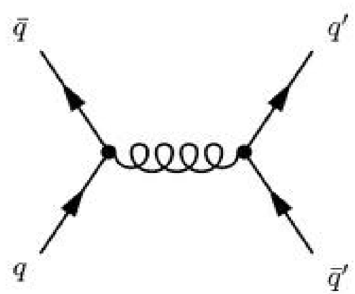
Z' → ll

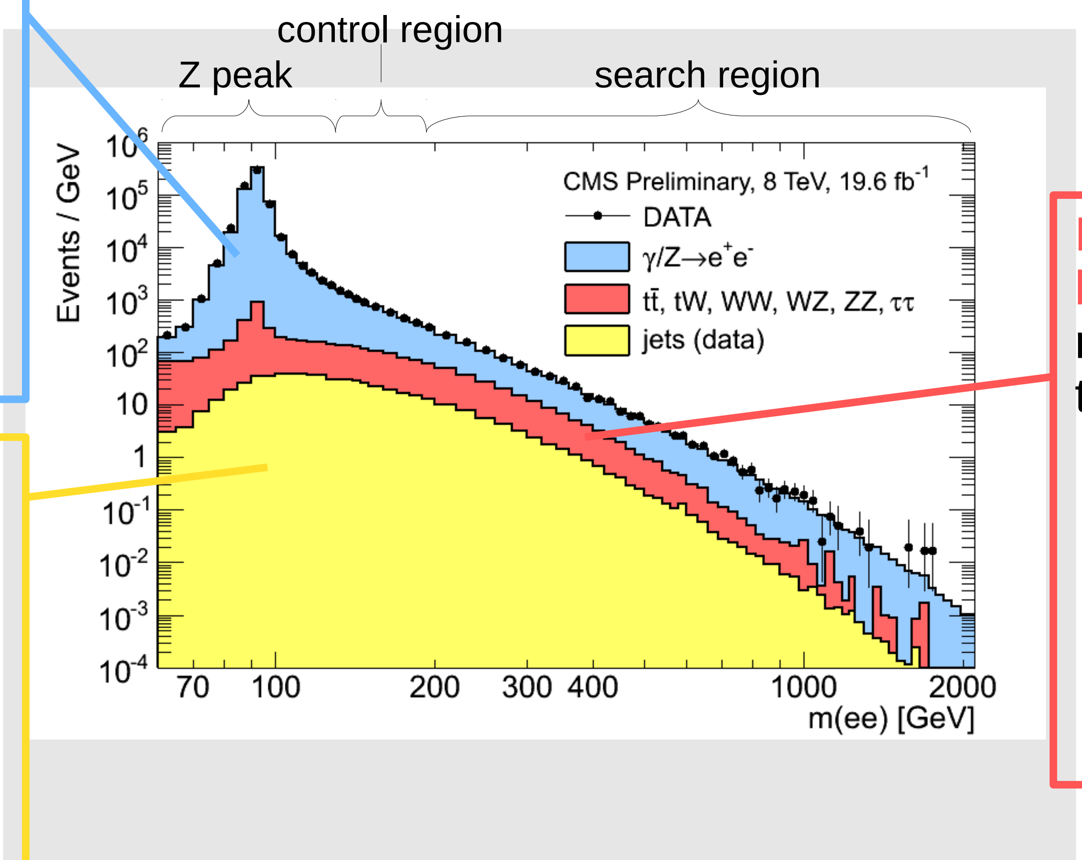
Result Invariant Mass :

Drell-Yan process
Irreducible background

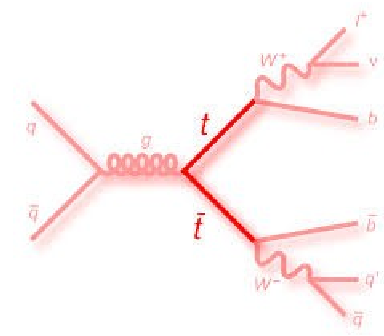


Jet background
Jets misreconstructed as electrons or muons





Reducible backgrounds with real dileptons.
tt̄, WW, WZ, ...



Good agreement between data and SM background prediction. -> No new physics found (yet).

Z' → ll

Exclusion plots :

In absence of a significant excess over the SM we set limits on the cross section of new physics processes.

- Spin 1 and spin 2 resonances have different kinematics -> different acceptance in the detector -> Different limit plots necessary

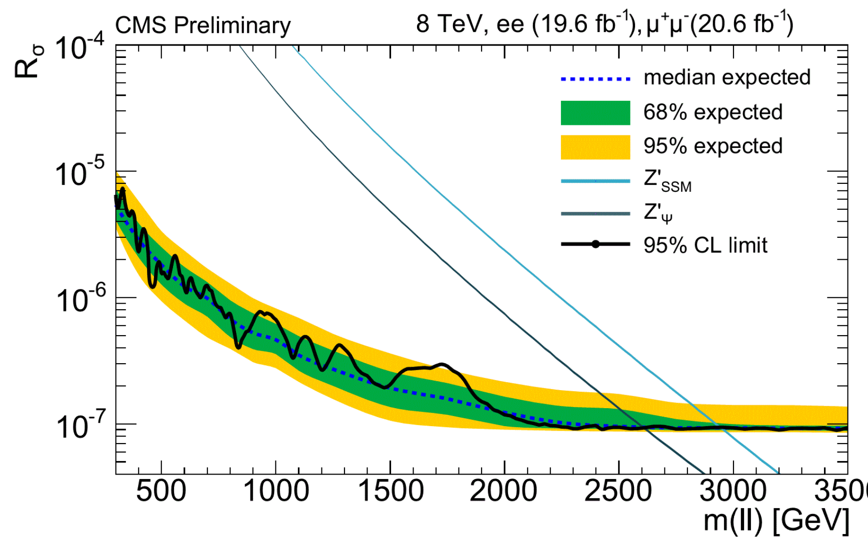
- Limit curve below the theory line -> theory excluded at > 95% confidence level

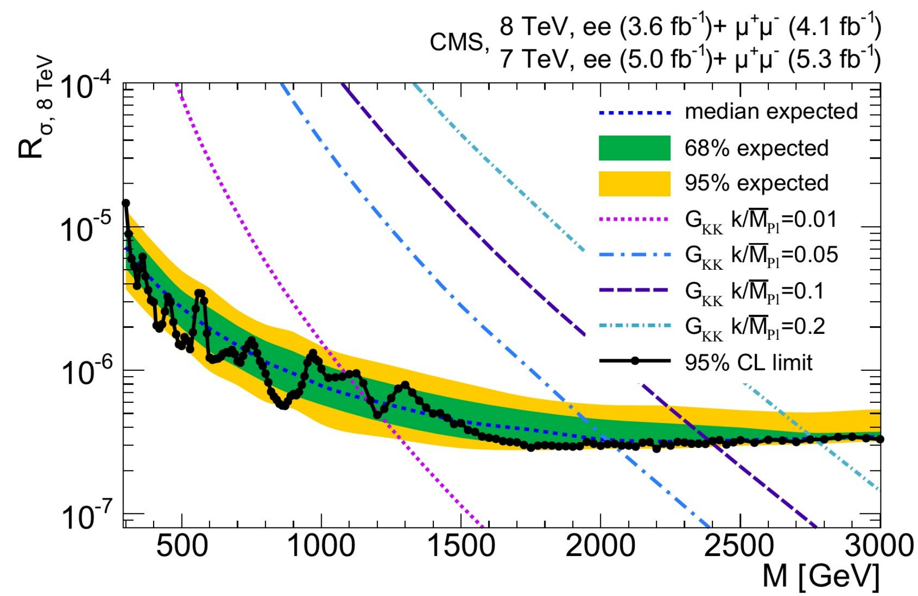
- Intersection between limit curve and theory curve give the mass up to which the theory is excluded at 95% CL

In the spin 1 case:

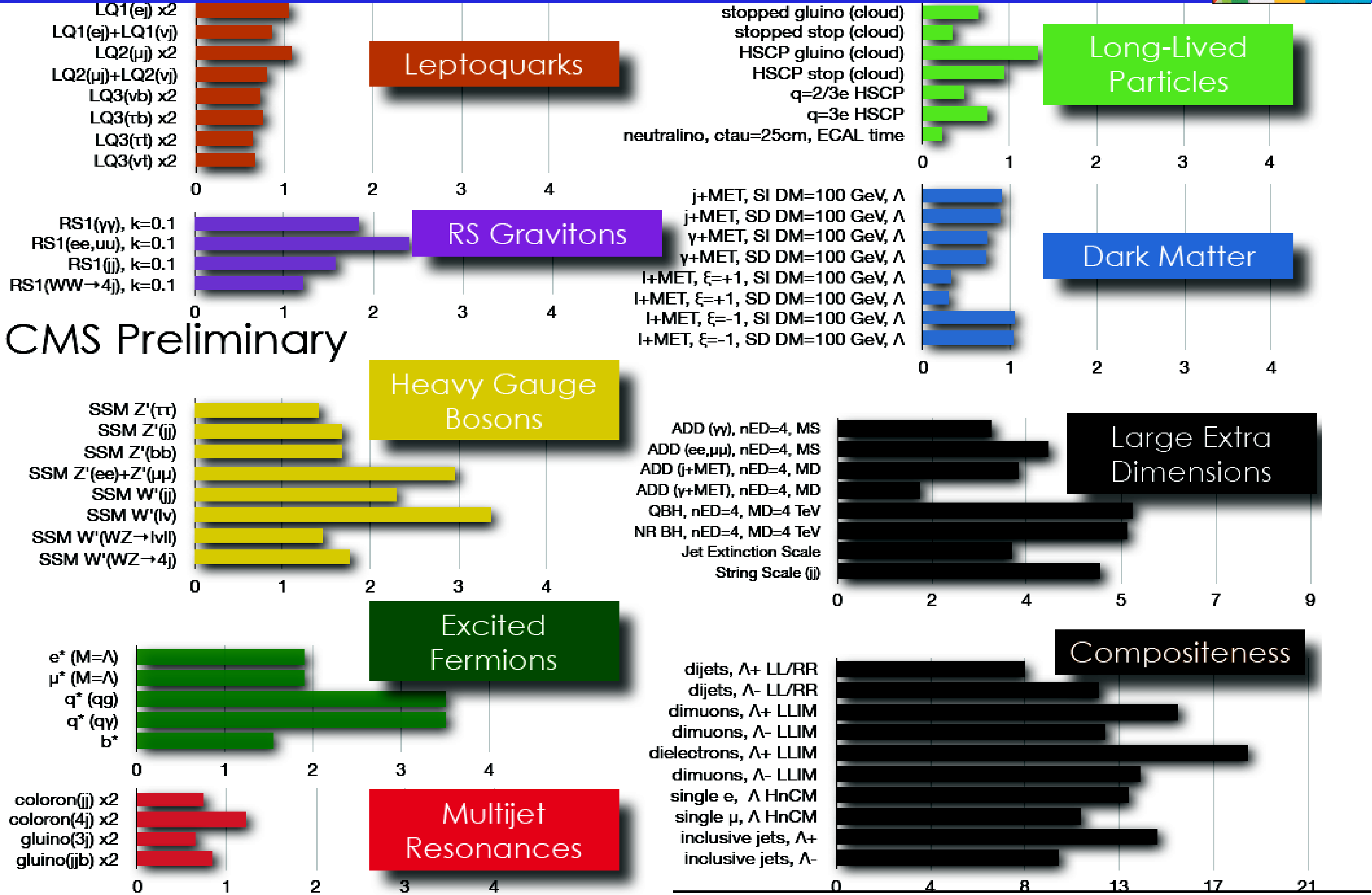
Z'_{SSM} excluded up to 2.96 TeV

Z'_{ψ} excluded up to 2.6 TeV

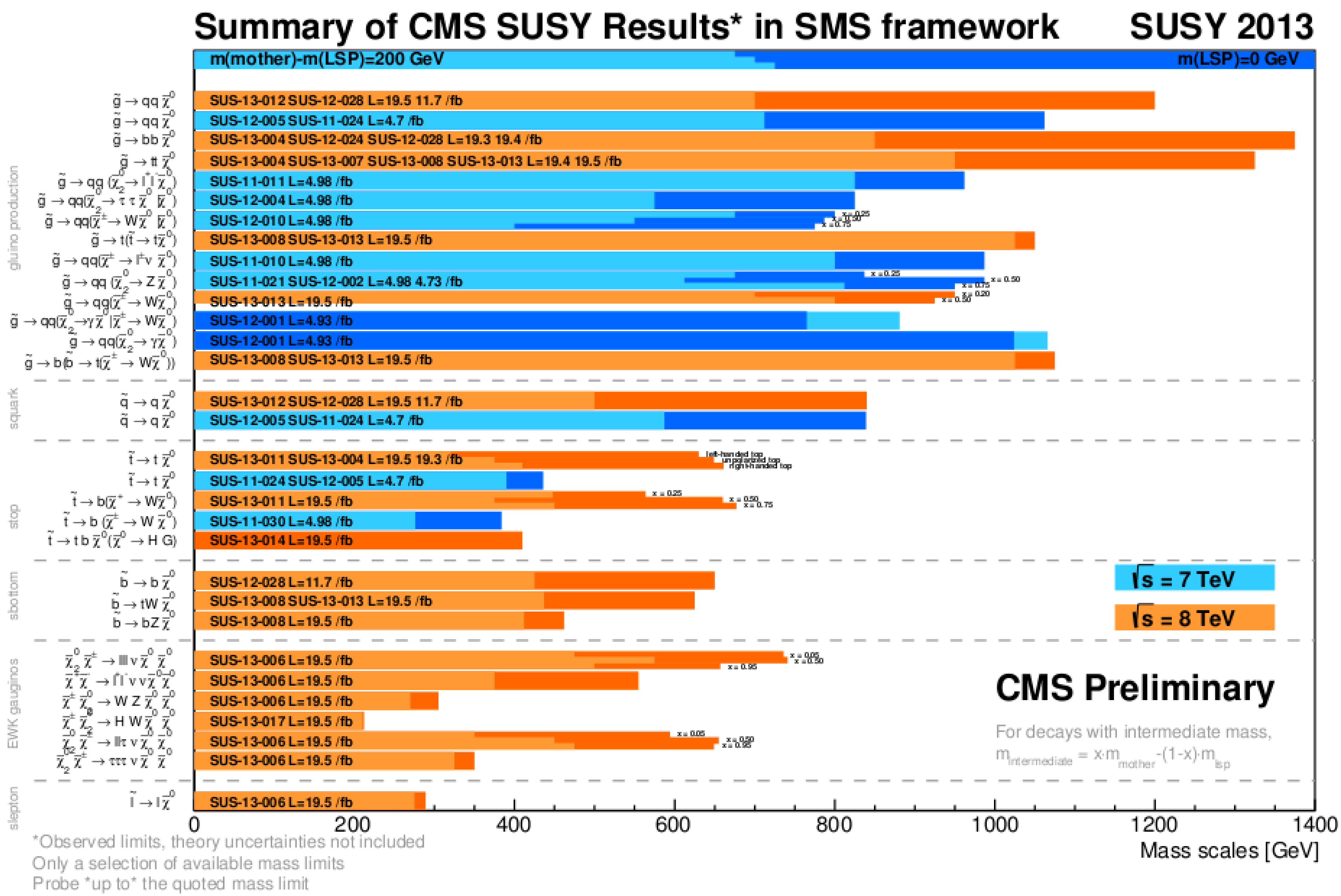




Exotica status



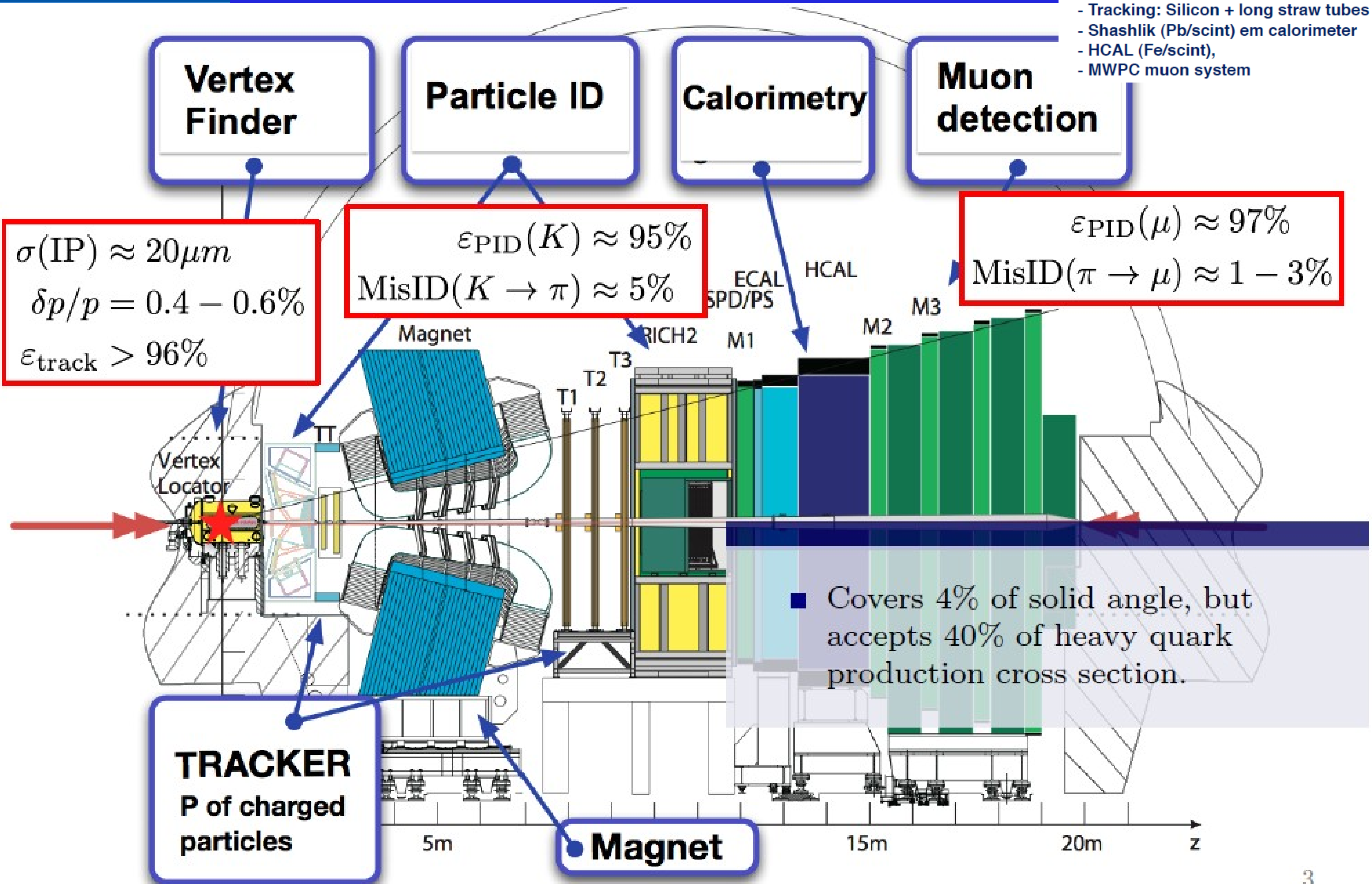
SUSY state


Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
squark
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
stop
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
SUS-13-014 L=19.5 /fb
sbottom
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
EWK gauginos
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
slepton
SUS-13-006 L=19.5 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother - (1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

LHCb

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

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

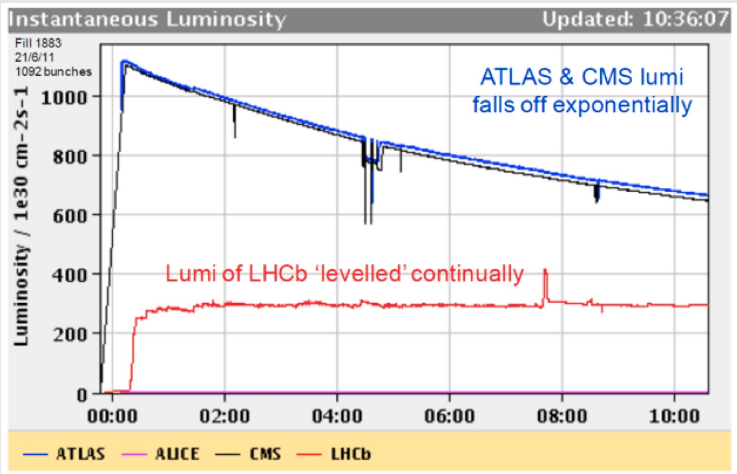


- Covers 4% of solid angle, but accepts 40% of heavy quark production cross section.

3

LHCb

Luminosity levelling



- LHCb designed to run at lower luminosity than ATLAS/CMS.
- LHCb tracking/PID is sensitive to pile-up.

→ LHC pp beams are displaced to reduce instantaneous luminosity - stable running conditions.

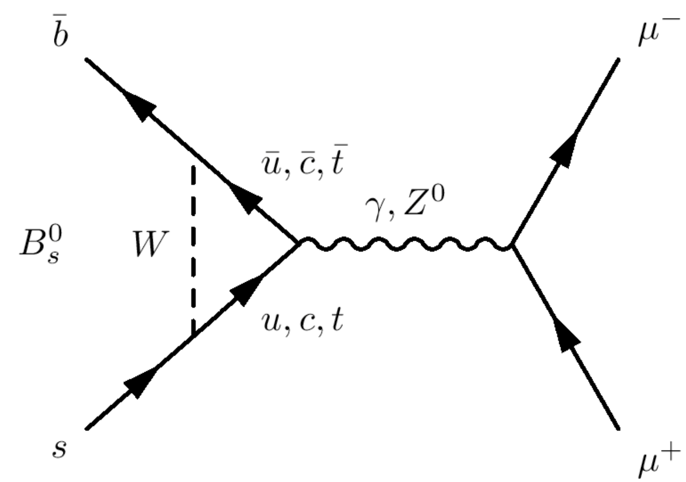
L 2011 : 2.7* $10^{32}cm^{-2}s^{-1}$

L 2012 : 4.0* $10^{32}cm^{-2}s^{-1}$

Searching for new physics

INDIRECT search : if it's not a W but a heavier (unknown) particle in the virtual quantum loop Branching Ratio $B_s \to \mu\mu$ will be different than the one expected from the standard model :

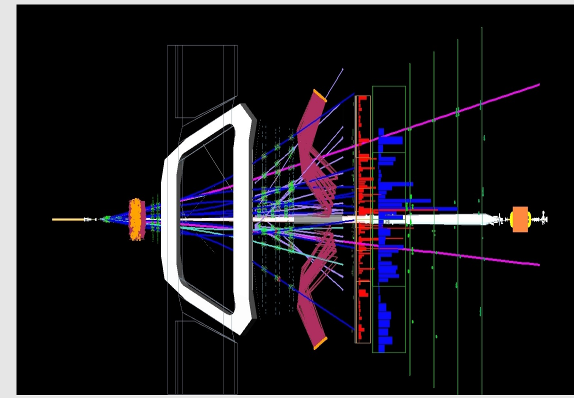
- $\mathcal{B}(B_s^0 \to \mu\mu) = (3.35 \pm 0.28) \times 10^{-9}$
- $\mathcal{B}(B^0 \to \mu\mu) = (1.07 \pm 0.10) \times 10^{-10}$



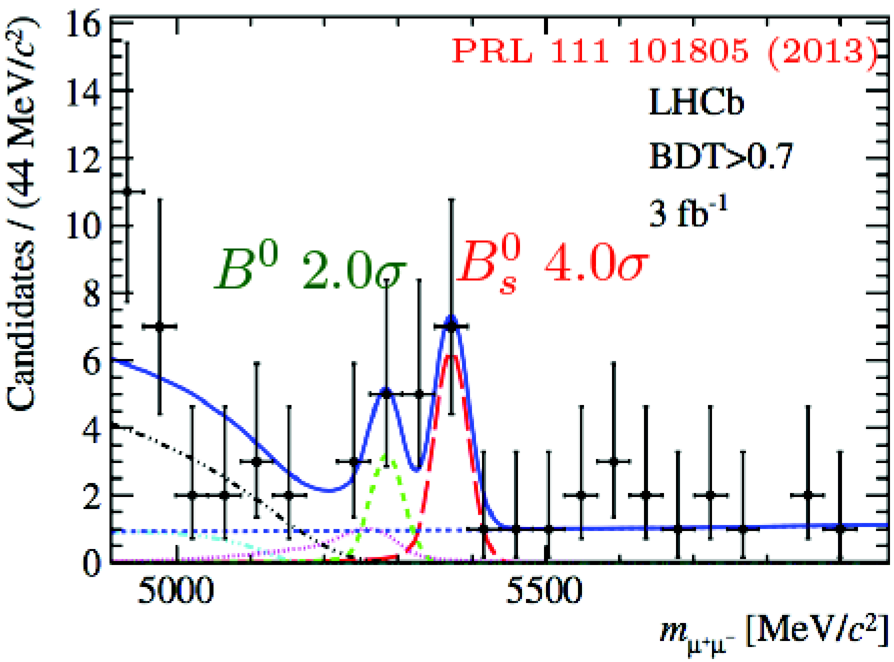
$B_s \to \mu\mu$

First evidence of $B_s \to \mu\mu$:

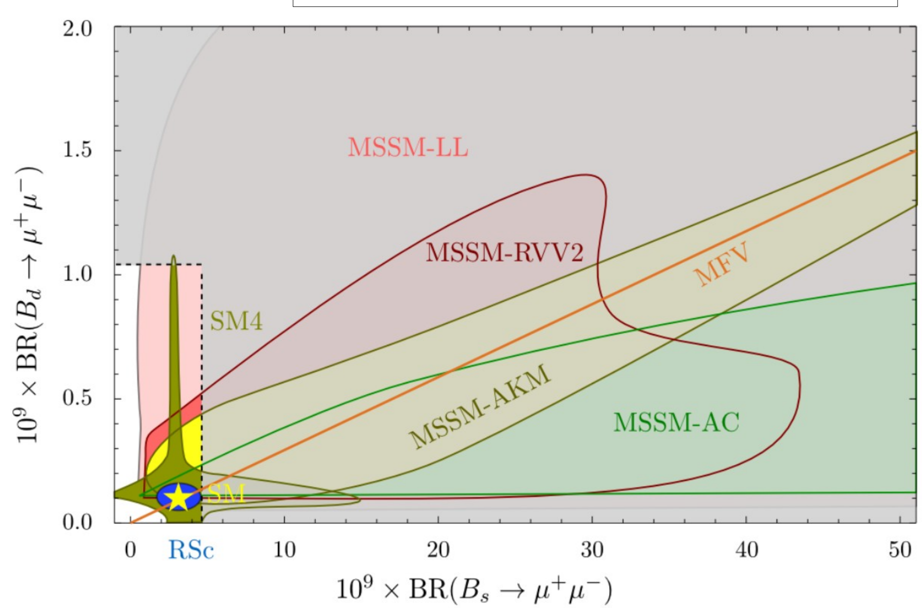
	$\mathcal{B}(B_s^0 \to \mu\mu) \times 10^{-9}$	$\mathcal{B}(B^0 \to \mu\mu) \times 10^{-9}$
LHCb	$2.9^{+1.1+0.3}_{-1.0-0.1}$	$3.7^{+2.4+0.6}_{-2.1-0.4}$
CMS	$3.0^{+1.0}_{-0.9}$	$3.5^{+2.1}_{-1.8}$
Combined	2.9 ± 0.7	$3.6^{+1.6}_{-1.4}$



Compatible with the SM predictions.

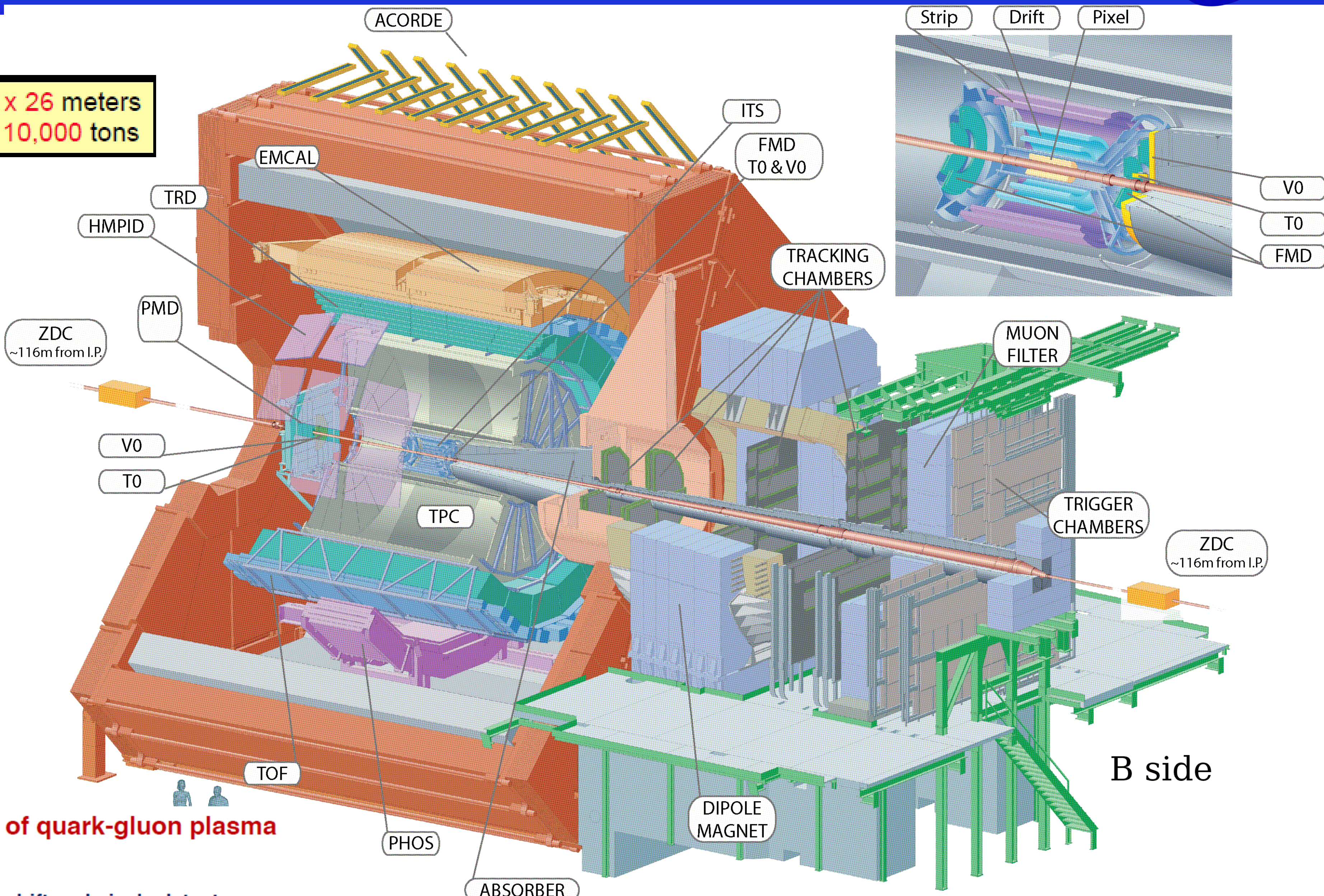


Implication to New Physics Model



ALICE

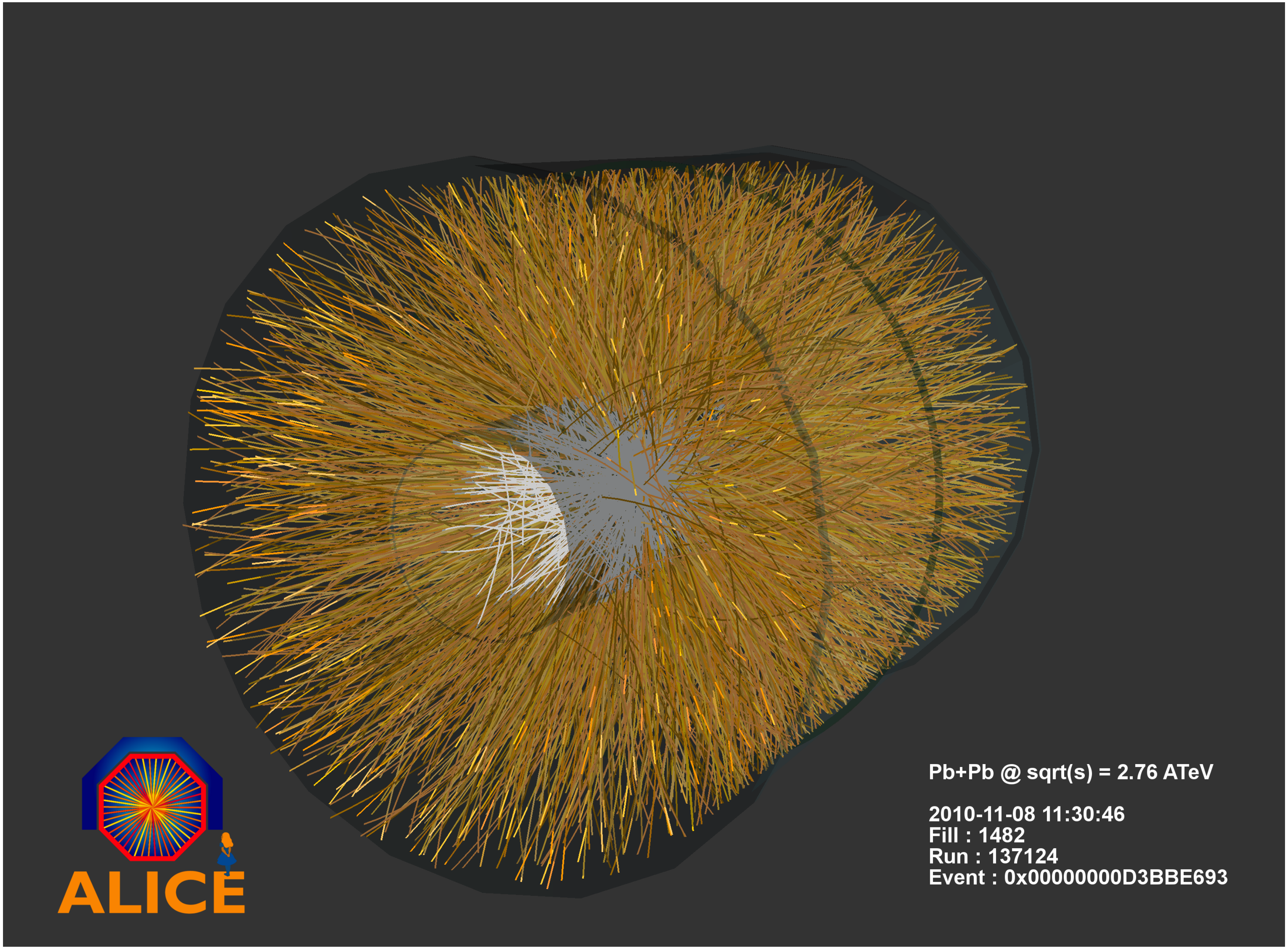
Size: 16 x 26 meters
Weight: 10,000 tons

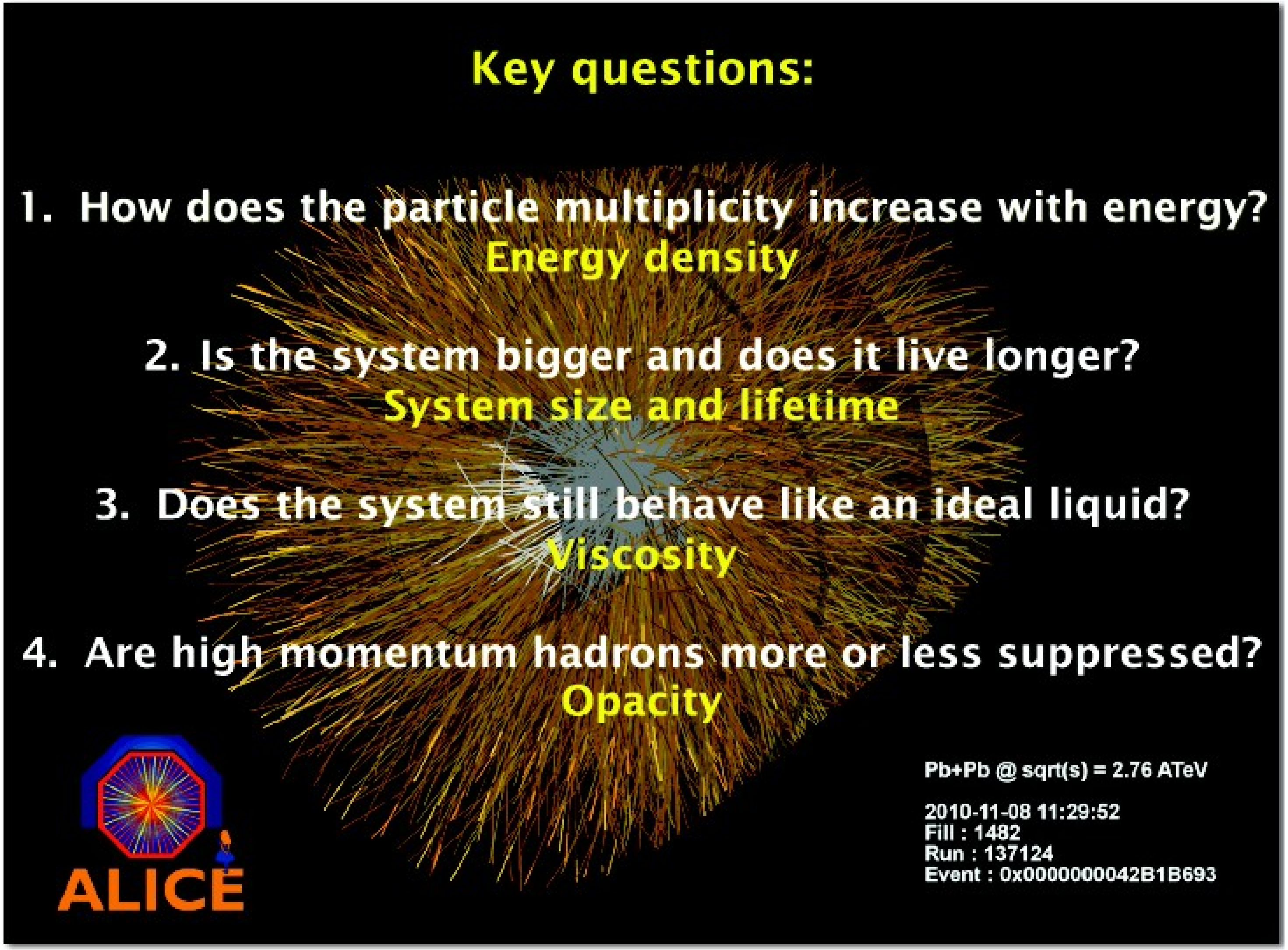


ALICE: study of quark-gluon plasma

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

ALICE Physics



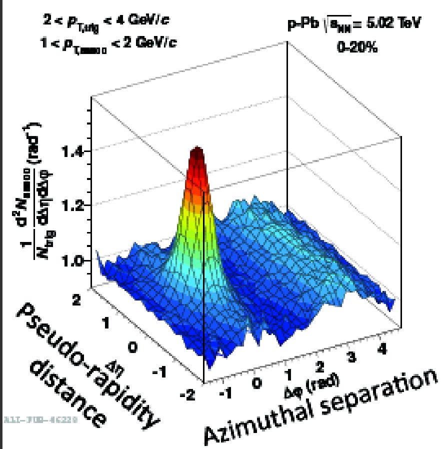

Key questions:
1. How does the particle multiplicity increase with energy?
Energy density
2. Is the system bigger and does it live longer?
System size and lifetime
3. Does the system still behave like an ideal liquid?
Viscosity
4. Are high momentum hadrons more or less suppressed?
Opacity
ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:29:52
Fill : 1482
Run : 137124
Event : 0x0000000042B1B693

Two-particle correlations in p-Pb

ALICE: arXiv:1212.2001

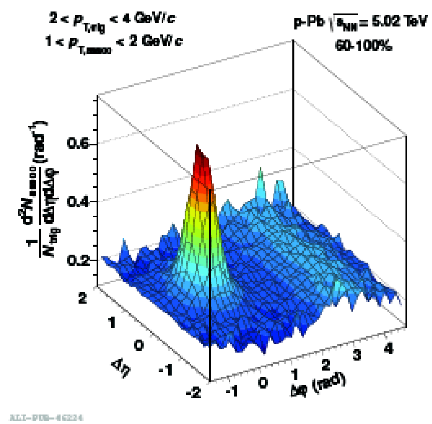
L. Milano Fri 15:20

The method: from the high-multiplicity yield subtract the jet yield in low-multiplicity events (no ridge)



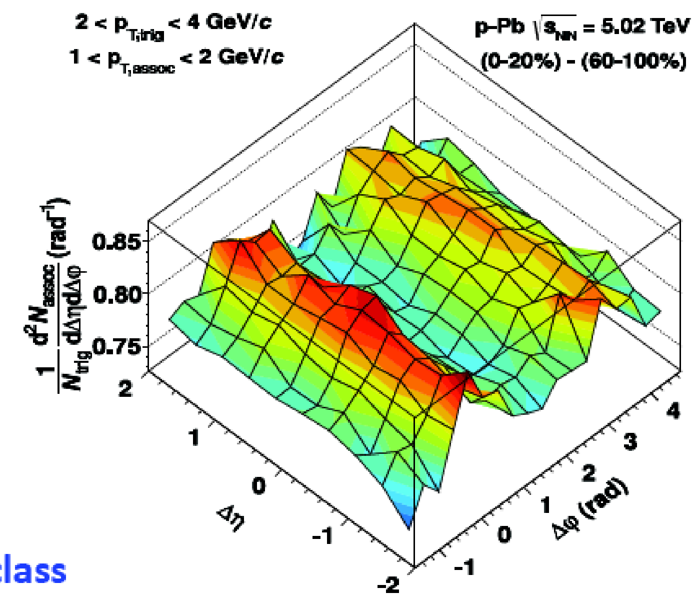
High multiplicity event class

<dN$_{ch}$/dη> ~ 35



Low multiplicity event class

<dN$_{ch}$/dη> ~ 7



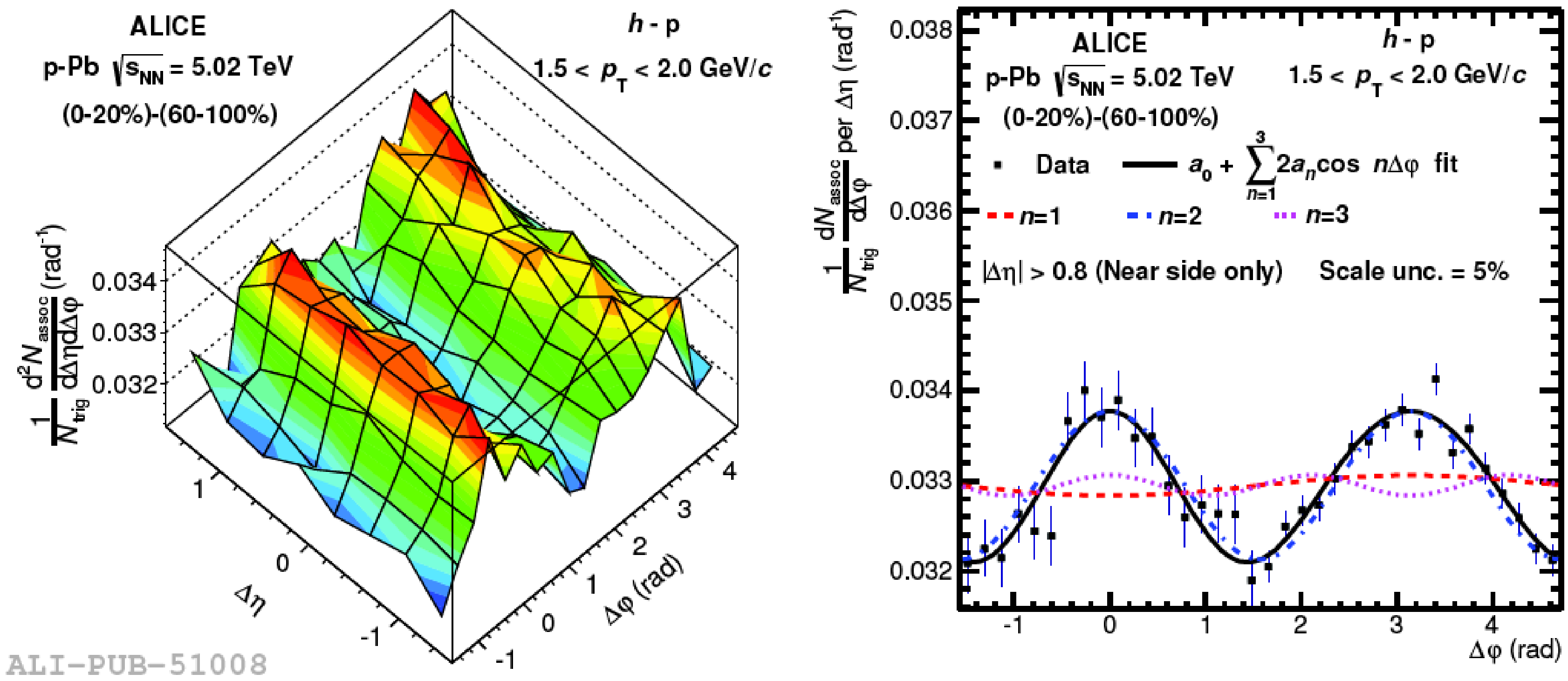
Remaining correlation: two twin long range structures

Analysis in multiplicity classes defined by the total charge in VZERO detector (away from the central region)

SQM 2013, M. Ploskon

Twin ridge structure in p-Pb with identified particles

Shown here: hadron-proton correlation (high-low mult. percentile subtracted)



L. Milano Fri 15:20

Jet peak excluded: Δη < 0.8

SQM 2013, M. Ploskon

Other experiments at CERN

Many !!!!!!

Using the LHC :

- Totem forward to CMS
- LHCf forward to Atlas
- AD : from PS beam :Antiproton Decelerator : studying antimatter, first anti H atom!
- Gran Sasso (Italy) : using the neutrinos from SPS (and sometimes see them faster than speed of light)

Give a break to LHC :

- ISOLDE
- Cloud, NA48, CAST, COMPASS ….

What is TOTEM?

TOTEM will measure the effective size or 'cross-section' of the proton at LHC. To do this TOTEM must be able to detect particles produced very close to the LHC beams. It will include detectors housed in specially designed vacuum chambers called 'Roman pots', which are connected to the beam pipes in the LHC. Eight Roman pots will be placed in pairs at four locations near the collision point of the CMS experiment. TOTEM has more than 70 members from 10 institutes in 7 countries (May 2007).

Size	440 m long, 5 m high and 5 m wide
Weight	20 tonnes
Design	roman pot and GEM detectors and cathode strip chambers
Material cost	6.5 MCHF
Location	Cessy, France (near CMS)

For more information visit: http://totem.web.cern.ch/Totem/

What is LHCf?

LHCf is a small experiment that will measure particles produced very close to the direction of the beams in the proton-proton collisions at the LHC. The motivation is to test models used to estimate the primary energy of the ultra high-energy cosmic rays. It will have detectors 140 m from the ATLAS collision point. The collaboration has 21 members from 10 institutes in 6 countries (May 2007).

Size	two detectors, each measures 30 cm long, 10 cm high, 10 cm wide
Weight	40 kg each
Location	Meyrin, Switzerland (near ATLAS).

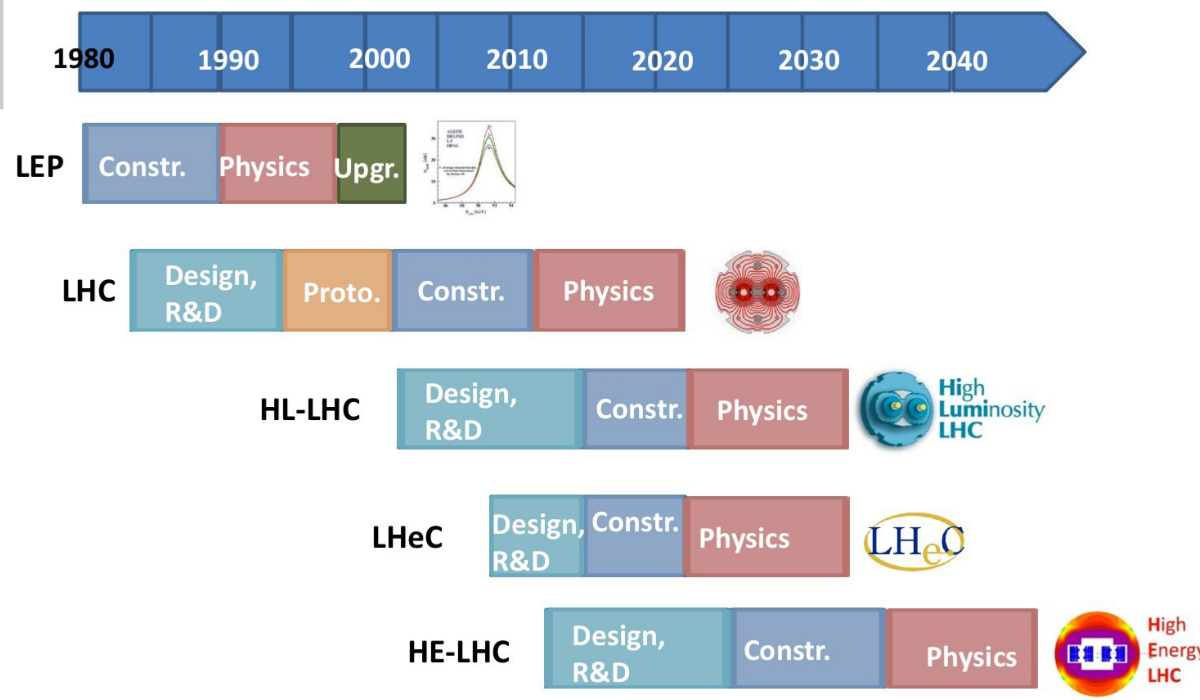
Conclusion

- **LHC has fulfilled his contract of discovery machine :**

A new scalar particle very SM-Higgs-boson-like has been discovered!

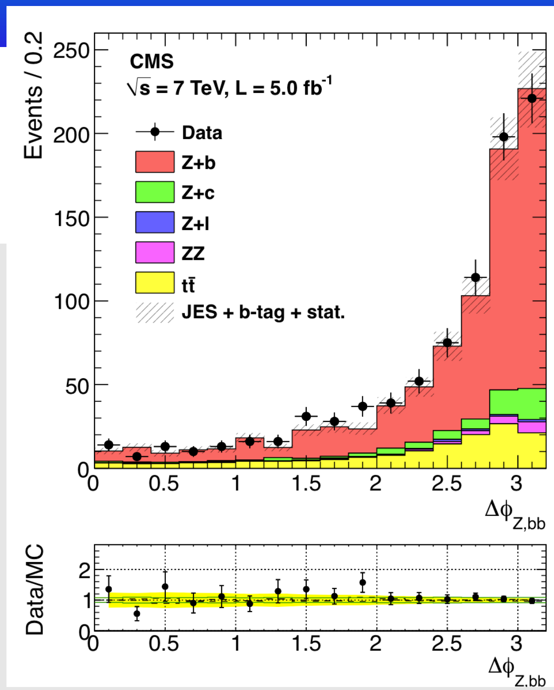
- **But for the moment nothing that haven't been predicted by SM : Where is the New Physics?**

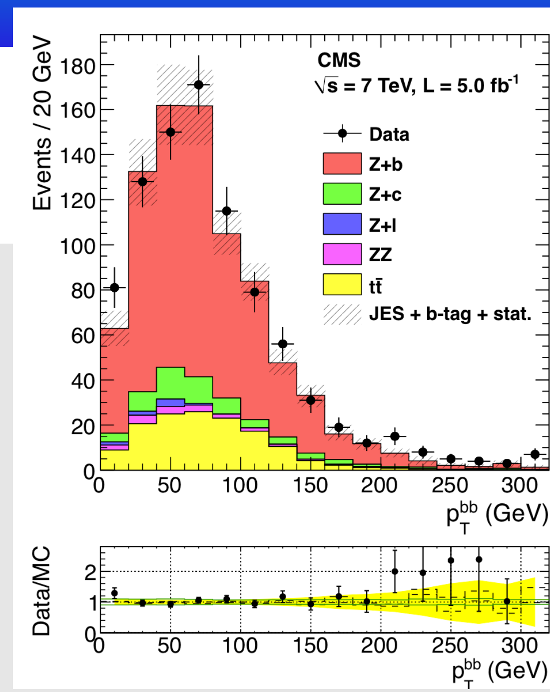
- **All physicists are waiting for the restart of the LHC in 2015 to keep on looking!**

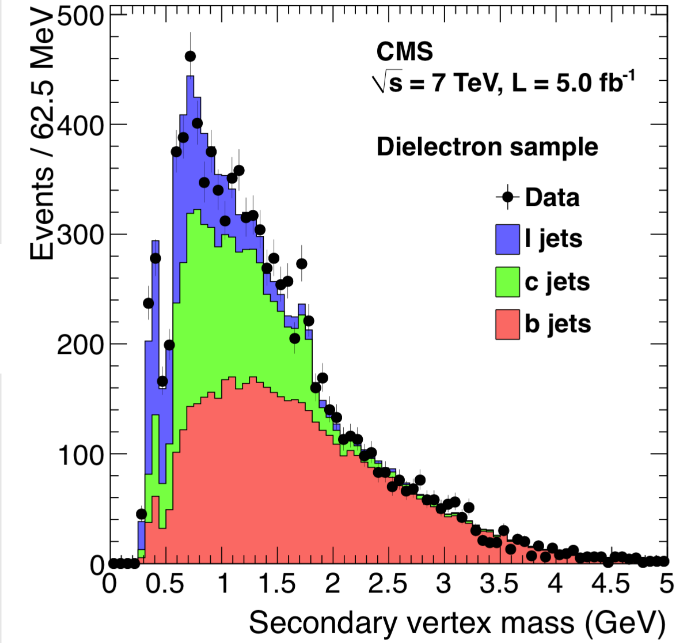


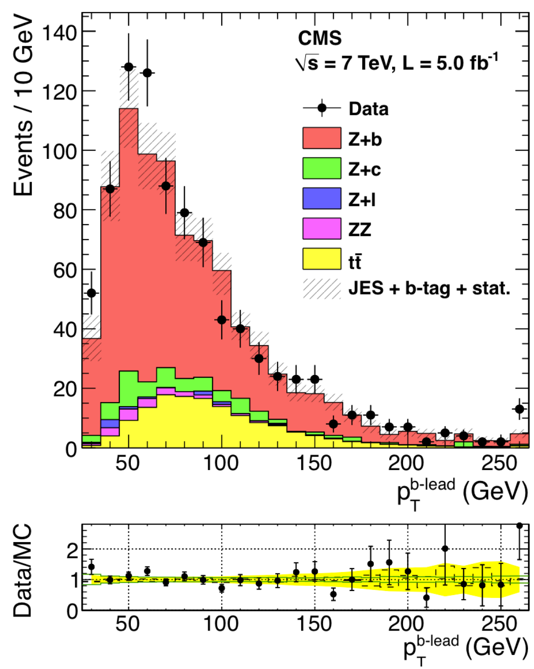
Back-up

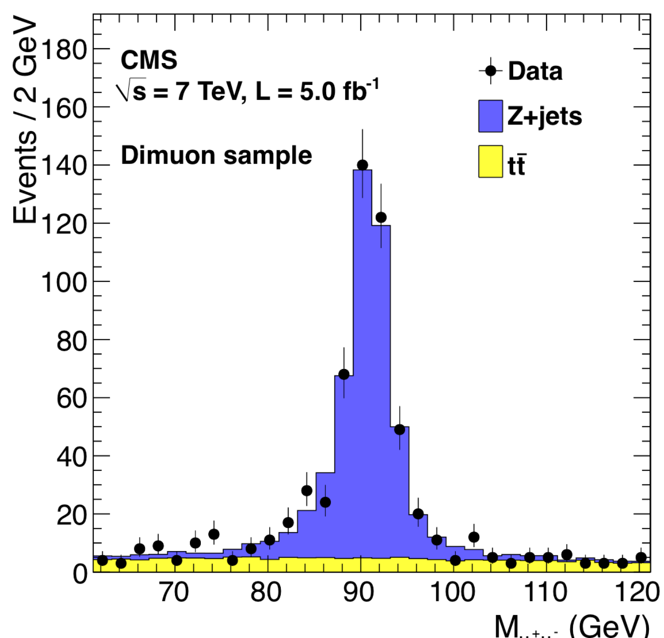
Z + b


CMS
√s = 7 TeV, L = 5.0 fb-1
Data
Z+b
Z+c
Z+l
ZZ
tt̄
JES + b-tag + stat.
Events / 0.2
Δφ Z,bb
Data/MC


CMS
√s = 7 TeV, L = 5.0 fb-1
Data
Z+b
Z+c
Z+l
ZZ
tt̄
JES + b-tag + stat.
Events / 20 GeV
p_T^bb (GeV)
Data/MC


CMS
√s = 7 TeV, L = 5.0 fb-1
Dielectron sample
Data
l jets
c jets
b jets
Events / 62.5 MeV
Secondary vertex mass (GeV)


CMS
√s = 7 TeV, L = 5.0 fb-1
Data
Z+b
Z+c
Z+l
ZZ
tt̄
JES + b-tag + stat.
Events / 10 GeV
p_T^b-lead (GeV)
Data/MC


CMS
√s = 7 TeV, L = 5.0 fb-1
Dimuon sample
Data
Z+jets
tt̄
Events / 2 GeV
M μ+μ- (GeV)

Theory

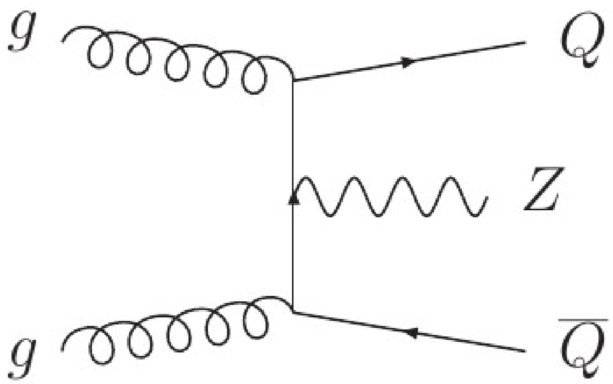
Calculations currently derived in 2 ways:

4-flavour scheme

Dittmaier, Kramer, Spira, Dawson, Jackson, Reina, Wackeroth

Explicit gluon splitting -> divergences if massless b.

massive b, g -> bb , 1 or 2 b observed

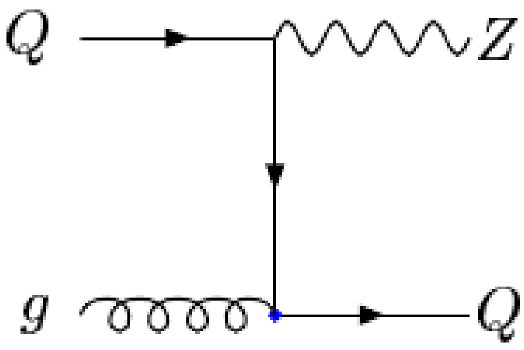


5-flavour scheme

Campbell, Ellis, Maltoni, Willenbrock

g -> bb inside b-PDF -> all orders = no divergences.

in calculations, b is massless.
second b added during parton shower and hadronisation by Pythia



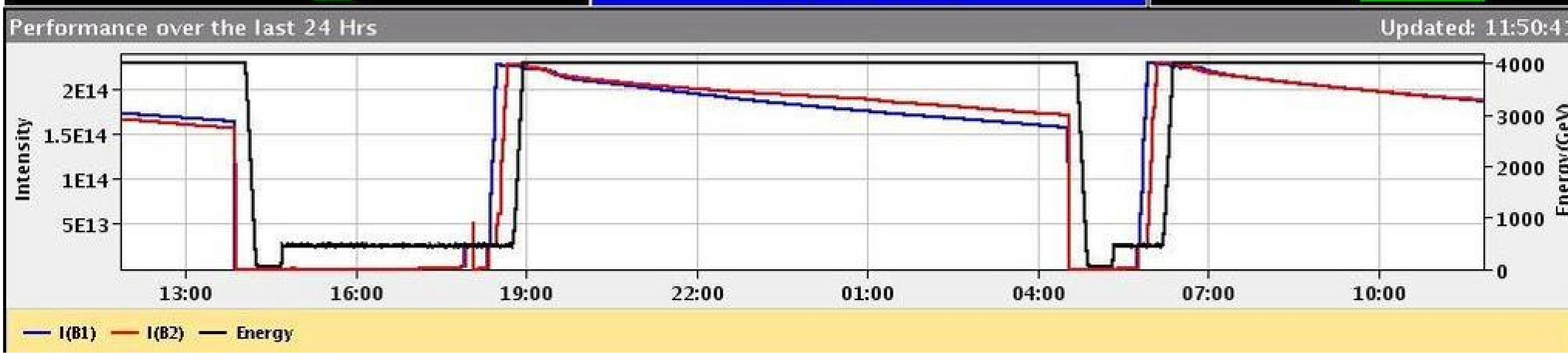
Should agree at NLO

LHC Run

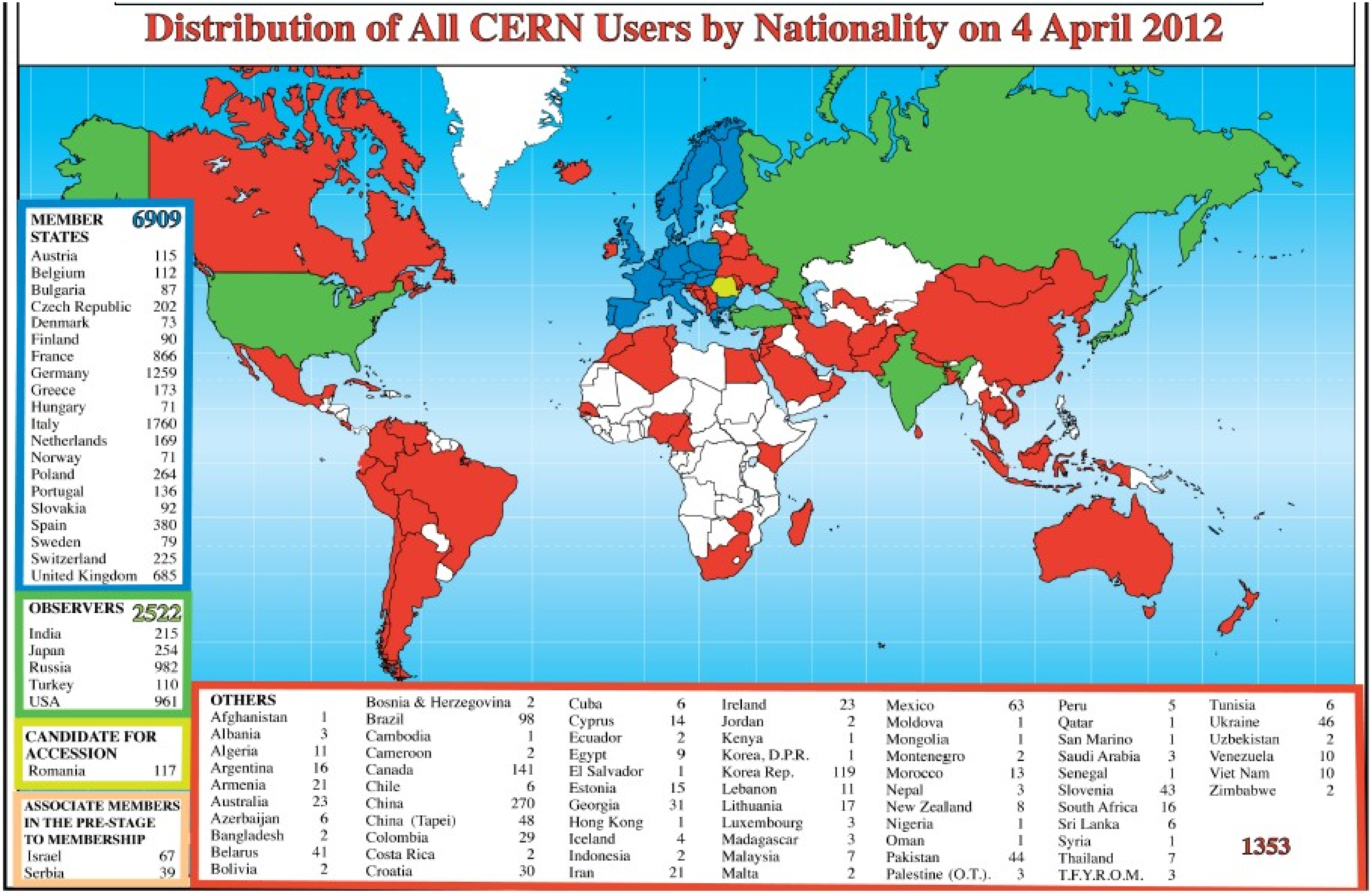
15-Nov-2012 11:50:45 | Fill #: 3288 | Energy: 4000 GeV | I(B1): 1.87e+14 | I(B2): 1.88e+14

	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	THANKS!!
Instantaneous Lumi [(ub.s)^-1]	3993.7	2.511	4080.1	395.9
BRAN Luminosity [(ub.s)^-1]	4083.7	1.632	4078.3	210.5
Fill Luminosity (nb)^-1	87568.7	61.0	89584.7	6829.4
BKGD 1	0.422	0.589	2.586	0.892
BKGD 2	83.489	177.284	3.361	4.286
BKGD 3	1.517	5.974	15.079	1.312

LHCb VELO Position IN Gap: -0.0 mm | STABLE BEAMS | TOTEM: STANDBY



Global Science



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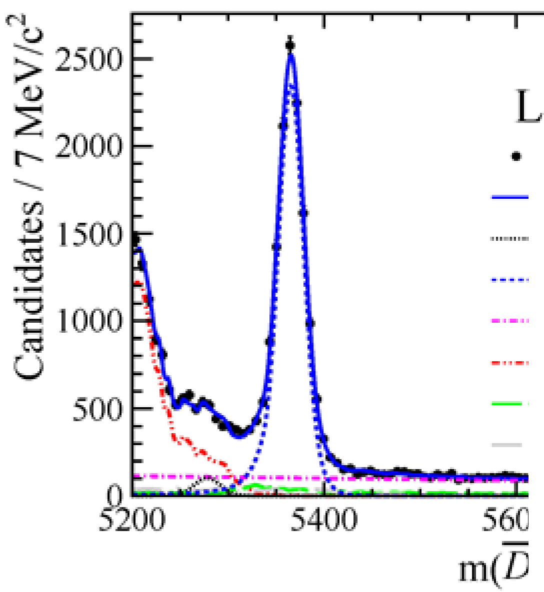
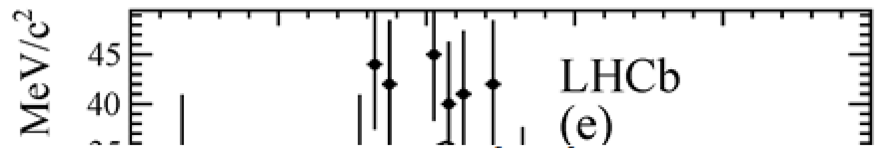
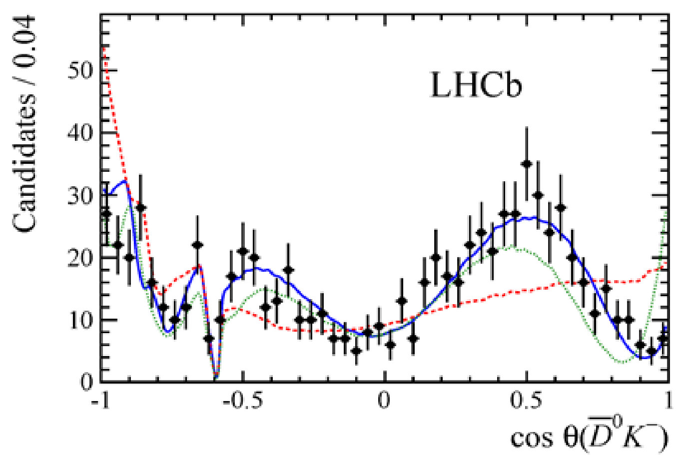
LHCb Other results

15 July 2014: First observation of a heavy flavored spin-3 particle

Today at the 15th International Conference on B-Physics at Frontier Machines at the University of Edinburgh, Beauty 2014, the LHCb collaboration has presented the results of a study of strange beauty meson B^0_s decay into an anti-charm meson $\overline{D}^0$, a K^- meson and a π^+ meson ($B^0_s \rightarrow \overline{D}^0 K^- \pi^+$). Previous results indicated the existence of a strange-charm $D^*_{sJ}(2860)^-$ particle in the $\overline{D}^0 K^-$ invariant mass spectrum, and the study of the $B^0_s \rightarrow \overline{D}^0 K^- \pi^+$ decay allows one to study this structure and measure its properties. Today's LHCb observation shows with 10σ significance that, in fact, this excess seen in the $\overline{D}^0 K^-$ mass spectrum is composed of two particles with different spins, spin-1 and spin-3. This is the first observation of a heavy flavored spin-3 particle, and the first time that any spin-3 particle has been seen to be produced in B decays.







The $B^0_s \rightarrow \overline{D}^0 K^- \pi^+$ decay is clearly identified as seen in the left image above. The right image above shows the enhancement at the 2.85 GeV/c^2 mass in the $\overline{D}^0 K^-$ invariant mass spectrum divided into two components as measured by LHCb physicists. The wider one corresponds to the spin-1 particle contribution and the narrow one represents the spin-3 contribution. The non-peaking distributions show contributions from other resonances that peak far from the 2.85 Gev/c^2 $\overline{D}^0 K^-$ mass region.

The left image shows to experts that the data $\overline{D}^0 K^-$ angular distribution (black points) is very well described by the presence of both spin-1 and spin-3 particles (solid blue curve). The models with only either a spin-1 (red curve) or a spin-3 (green one) particle are not supported by data.

click the images for higher resolution

The $D^*_{sJ}(2860)^-$ particles are composed of an anti-charm quark $\bar{c}$ and a strange quark s. The quark-anti-quark pair is bound by strong interactions and can form different quantum states with different values of spin and angular momentum in analogy to the different quantum states of ordinary atoms. The presence of the spin-3 contribution gives a clear signature that both particles are members of the so called 1D family having two units of angular momentum between the quark and the antiquark. This discovery demonstrates that the spectroscopy of the 1D families of heavy flavoured mesons can be studied experimentally. Further insights can be expected with similar analysis of B decays at LHCb and the LHCb upgrade.

LHCb Other results

14 November 2011: CP violation in charm decays.

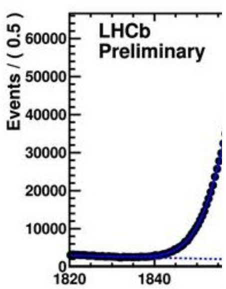
[ΔA_{CP} = (-0.82 ± 0.21 ± 0.11)%]

The LHCb Collaboration has presented today at the Hadron Collider Particle Symposium in Paris possible first evidence for CP violation, the difference between behaviour of matter (particles) and antimatter (antiparticles), in charm decays. The study of CP violation in both charm and beauty particle decays is central to the LHCb physics programme. In the Standard Model CP violation is expected to be very small in the charm sector, whereas new physics effects could generate enhancements.

In this new analysis the LHCb physicists have used data collected in the first half of the 2011 run to study the differences in decay rates of neutral D meson particles composed of a charm quark c bound with an up antiquark ($\bar{u}$) and D meson antiparticles ($\bar{D}$) composed of a charm antiquark ($\bar{c}$) bound with an up quark (u). The decays of D^{*+} mesons into D mesons and π^+, and D^{*-} mesons into $\bar{D}$ mesons and π^- were used to select the D and $\bar{D}$ mesons. In the next step of the analysis the difference (asymmetry A_{CP}) between the decay rates of D and $\bar{D}$ mesons into K^+K^- pairs as well as into $\pi^+\pi^-$ pairs was measured. By determining the *difference*, ΔA_{CP}, in CP asymmetries for the K+K- and $\pi^+\pi^-$ decays, the analysis strongly suppresses possible measurement biases which could arise through effects related to particle production, selection etc. The following preliminary result is obtained:

ΔA_{CP} = (-0.82 ± 0.21 (stat.) ± 0.11 (sys.))% [3.5 sigma significance for experts]

A very interesting period now i
theoretical work will be require
physics explanation is requirec

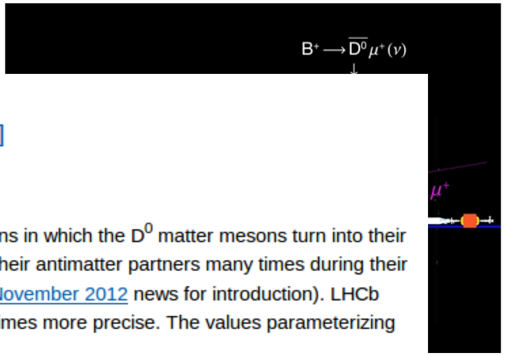


12 March 2013: Improved search for CP violation in charm decays.

[ΔA_{CP} = (−0.34 ± 0.15 ± 0.10)%, pion tagged]
[ΔA_{CP} = (+0.49 ± 0.30 ± 0.14)%, muon tagged]

The LHCb Collaboration presented today at the Rencontres de Moriond QCD, La Thuile, Italy, results of an improved search for the difference between properties of matter and antimatter, CP violation, in charm decays, see 14 November 2011 news for introduction. The difference (Δ) of CP asymmetry (A_{CP}) between the decay rates of D (matter) and $\bar{D}$ (antimatter) mesons into K^+K^- pairs and into $\pi^+\pi^-$ pairs was measured. The results presented today profited from three improvements to the previous analysis: the full 1.0 fb^{-1} data sample collected in 2011 was used instead of 0.6 fb^{-1}, the analysis technique was improved and also in addition another independent method was used to select matter D and antimatter $\bar{D}$ particle decays.

In the Standard Model CP violation was expected to be very small in the charm sector, whereas new physics effects could generate enhancements. Therefore the 14 November 2011 announcement by the LHCb Collaboration of 3.5σ evidence of CP violation in charm sector, ΔA_{CP} = (-0.82 ± 0.21 ± 0.11)%, triggered intensive theoretical activity with conclusions that some special Standard Model effects could generate CP violation effects even as big as about 1%. This interesting LHCb result was later confirmed by the CDF and Belle collaborations. The new improved LHCb result presented today, ΔA_{CP} = (−0.34 ± 0.15 ± 0.10)%, is more precise thanks to the larger data sample and several improvements resulting in better background suppression by a factor of 2.5. The central value is, however, closer to zero than in the previous measurement, which it supersedes.



In the measurement presented above the D (matter) and $\bar{D}$ (antimatter) mesons were selected using the D^* meson decays, $D^{*+(-)} \to \pi^{+(-)}D(\bar{D})$, which means that the presence of π^+ in the decay identified matter D meson production while π^- accompanied antimatter $\bar{D}$ production. LHCb physicists presented today also results of a second independent analysis in which the D and $\bar{D}$ mesons were selected using so called semileptonic beauty B decays, for example $B^{+(-)} \to \mu^{+(-)}\nu\bar{D}(D)$. In the second analysis, the positive charge of μ^+ identified the $\bar{D}$ meson, while the negative one, μ^-, the D production. The image at the left hand side shows a selected event. A zoom around the pp interaction point shows a B^+ meson decay point located at the distance of 17 mm from the pp collision point and the $\bar{D}$ meson decay place still 9 mm further away. The second analysis also measures a value that is consistent with zero: ΔA_{CP} = (+0.49 ± 0.30 ± 0.14)%. A combination of the two LHCb results gives ΔA_{CP} = (-0.15 ± 0.16)%.

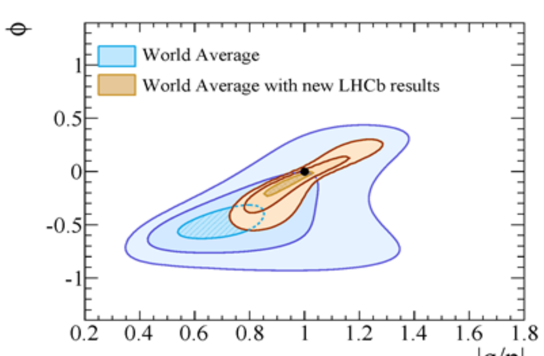
[$x'^2 = (5.5 \pm 4.9)\times10^{-5}$; $y' = (4.8 \pm 1.0)\times10^{-3}$]
[$A_\Gamma(KK) = (-0.35 \pm 0.62 \pm 0.12)\times10^{-3}$ $A_\Gamma(\pi\pi) = (0.33 \pm 1.06 \pm 0.14)\times10^{-3}$]

The LHCb Collaboration has reported recently new important results on charm physics.

(1) Ten months ago, the LHCb Collaboration presented the first observation of the D^0-$\bar{D}^0$ oscillations in which the D^0 matter mesons turn into their antimatter partners. Contrary to the B^0-$\bar{B}^0$ and B^0_s-$\bar{B}^0_s$ oscillations in which the mesons turn into their antimatter partners many times during their lifetime, the D^0-$\bar{D}^0$ oscillations are very slow, over one hundred times the average lifetime (see 7 November 2012 news for introduction). LHCb has now updated this result using the full 2011 and 2012 data set of 3 fb^{-1}. The new result is 2.5 times more precise. The values parameterizing the oscillations, the so-called mixing parameters y' and x'^2, are shown above.

By now, CP violation, differences in the behaviour of matter and antimatter, has been observed in all oscillating neutral-meson (K^0, B^0, B^0_s) systems apart from the charm system. First evidence for charm CP violation (see 14 November 2011 news) has not been unambiguously confirmed to date (see 12 March 2013 news). The D^0 mesons are the only mesons containing up-type quarks which undergo matter anti-matter oscillations (called also mixing) and therefore provide unique access to effects from physics beyond the Standard Model.

As part of the new analysis, LHCb has investigated whether there is a CP violating contribution to the oscillations, in contrast to the Standard Model expectation. This is done by investigating whether the oscillation parameters for mesons produced as D^0 and $\bar{D}^0$ differ. Studying the D^0 and $\bar{D}^0$ decays separately shows no evidence for CP violation and provides the most stringent bounds on the parameters (A_D and |q/p| for experts) describing this violation from a single experiment.



(2) LHCb physicists measured the asymmetry A_Γ of the inverse of effective lifetimes in decays of D^0 and $\bar{D}^0$ mesons to the K^-K^+ and $\pi^-\pi^+$ final states. The measured values of the parameter A_Γ shown above represent the world's best measurements of this quantity, and are the first searches for CP violation in charm oscillations with sensitivity better than 10^{-3}. They do not indicate CP violation, and show no difference in A_Γ between the two final states.

The results of other experiments combined by the Heavy Flavor Averaging Group indicated a hint for possible non-zero values of the CP violation parameters (|q/p| and φ for experts). Both LHCb results presented above do not support this indication as seen in the image. The size of the contour with the new LHCb results is about a factor of two smaller in each of |q/p| and φ. They provide very stringent limits on the underlying parameters, thus