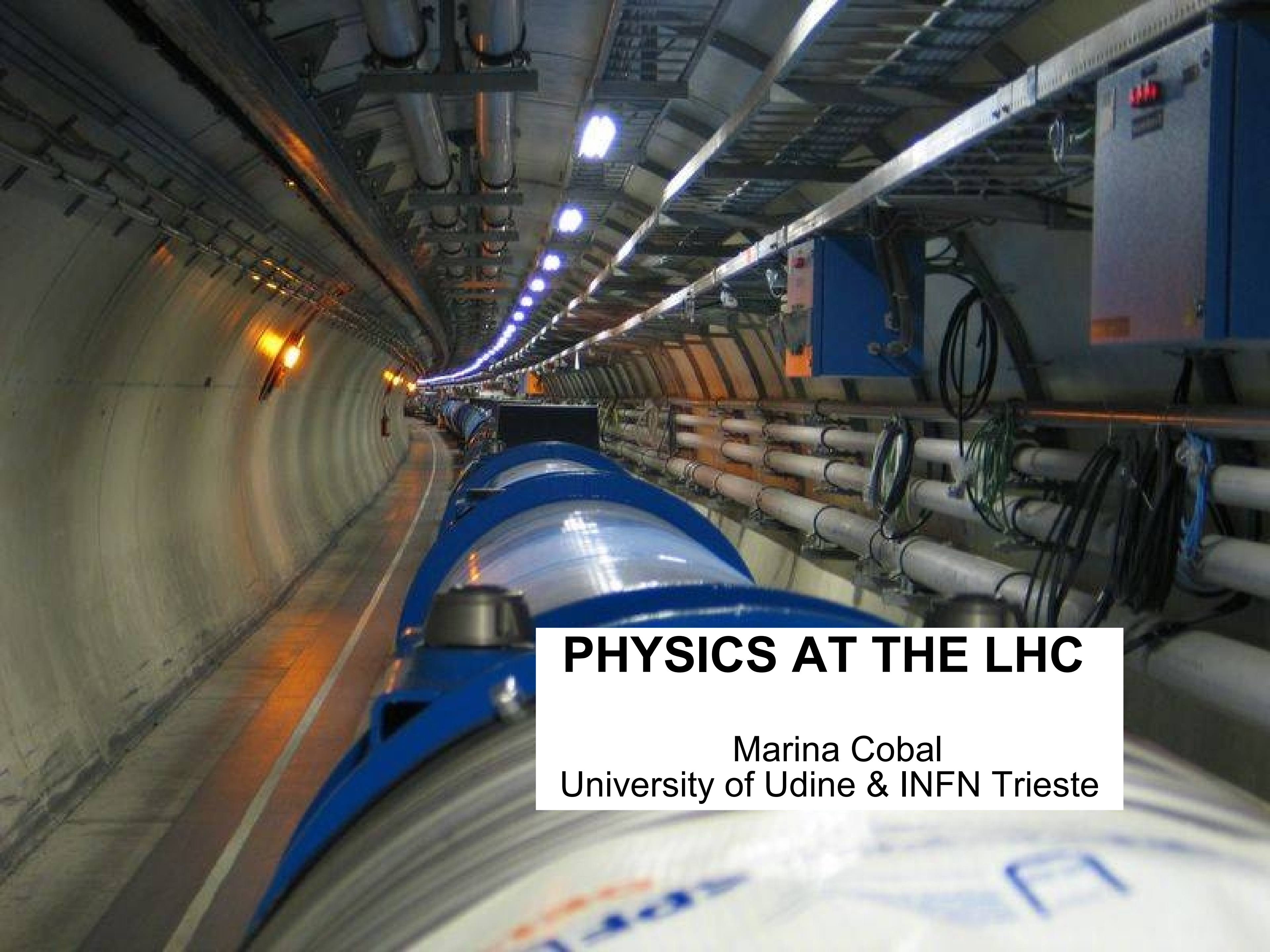
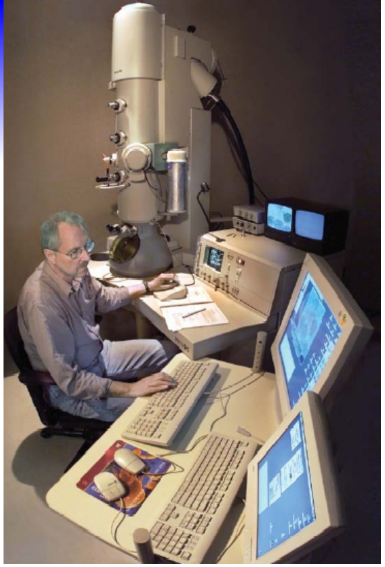


PHYSICS AT THE LHC

Marina Cobal
University of Udine & INFN Trieste

Microscopes in high energy physics



The ability of 'seeing' things depends on the incident light and the goodness of the eye. The smallest resolvable details have dimensions comparable with the incident light wavelength. Resolving power $\propto 1/\lambda$

In quantum mechanics every particle has an associated wavelength: $\lambda \propto 1/p$

$\Rightarrow$ high energy particles will allow to investigate at shorter distances

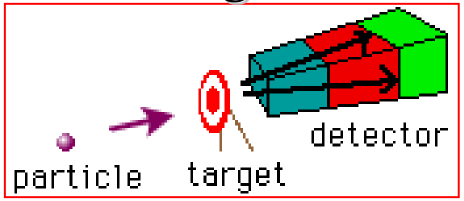
Object	Size	Energy of Radiation
Atom	10^{-10} m	0.00001 GeV (electrons)
Nucleus	10^{-14} m	0.01 GeV (alphas)
Nucleon	10^{-15}m	0.1 GeV (electrons)
Quarks	?	> 1 GeV (electrons?)

1 eV= energy of an electron accelerated from a potential of 1V

1 GeV= 1000000000 eV

1 GeV=0.016 g $(m/s)^2$

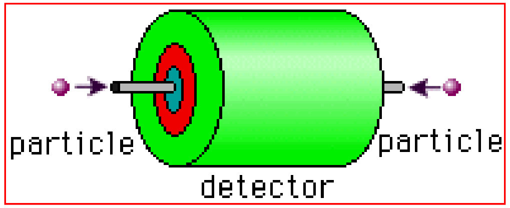
Fixed target



larger choice of particles and targets

energy is partly wasted

Colliders

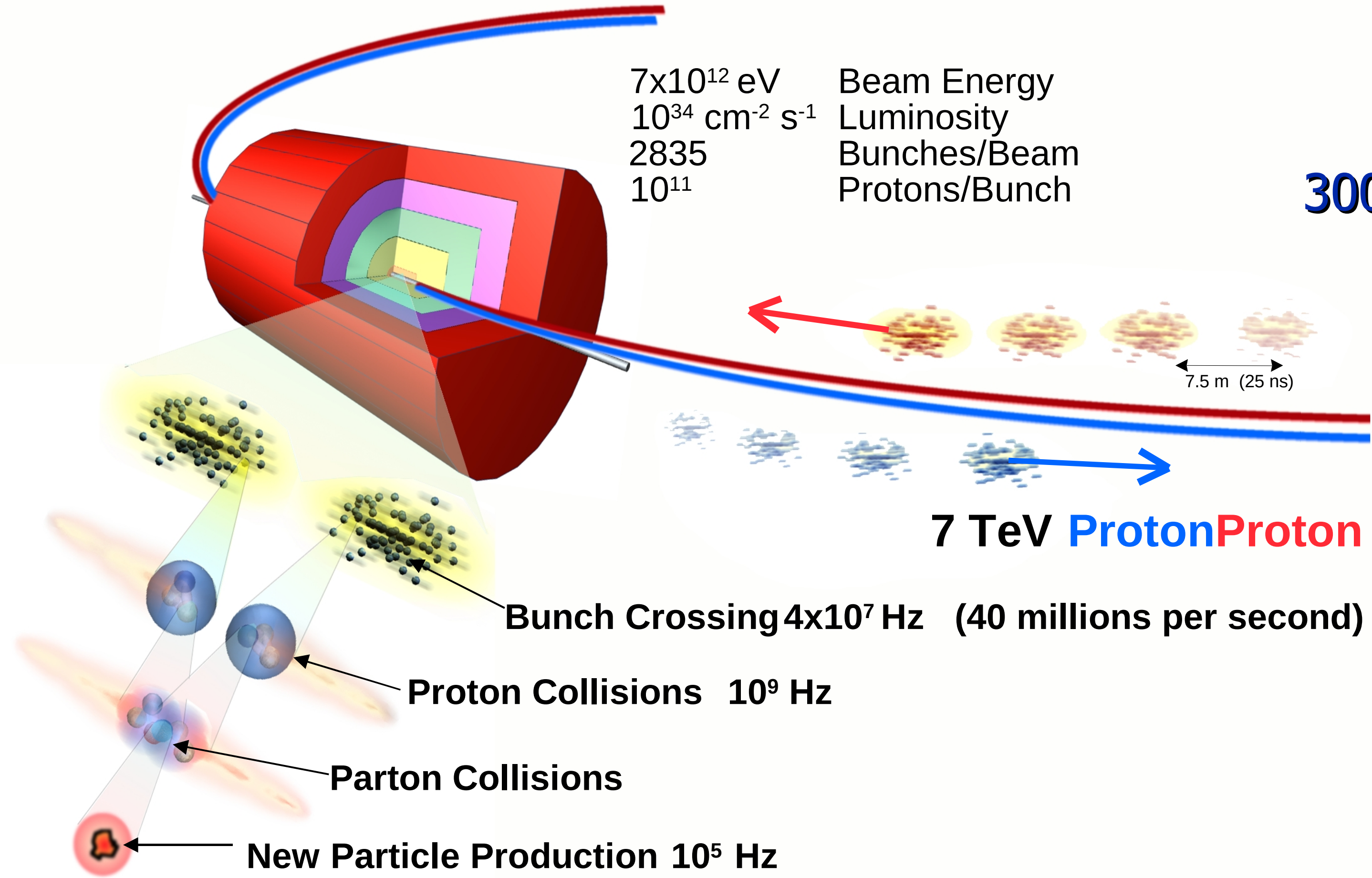


maximizes energy

limited choice of particles

(charged and stable $\Rightarrow$ ions, $e^{\pm}$, p)

Colliders: the case of the LHC

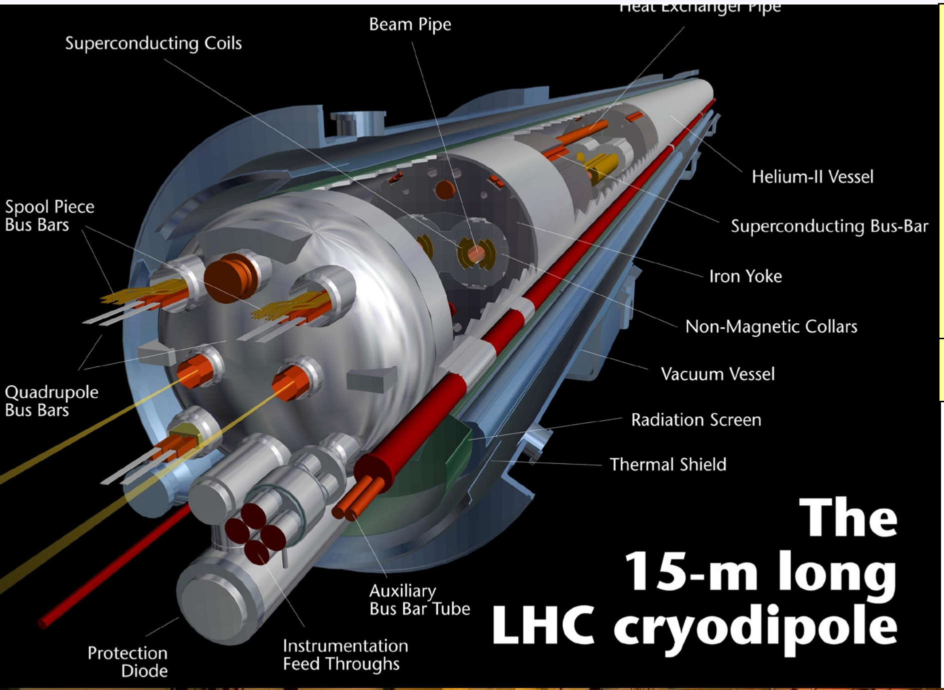


A beam has 300.000.000.000.000 protons !

The energy of a single LHC proton accelerated to 7 TeV corresponds to the kinetic energy of a flying mosquito

The energy of the LHC beam equals the kinetic energy of 100 tons trucks at a speed of 100 Km/h or of a Boeing 777 (50 tons) at takeoff (450 Km/h)

LHC magnets

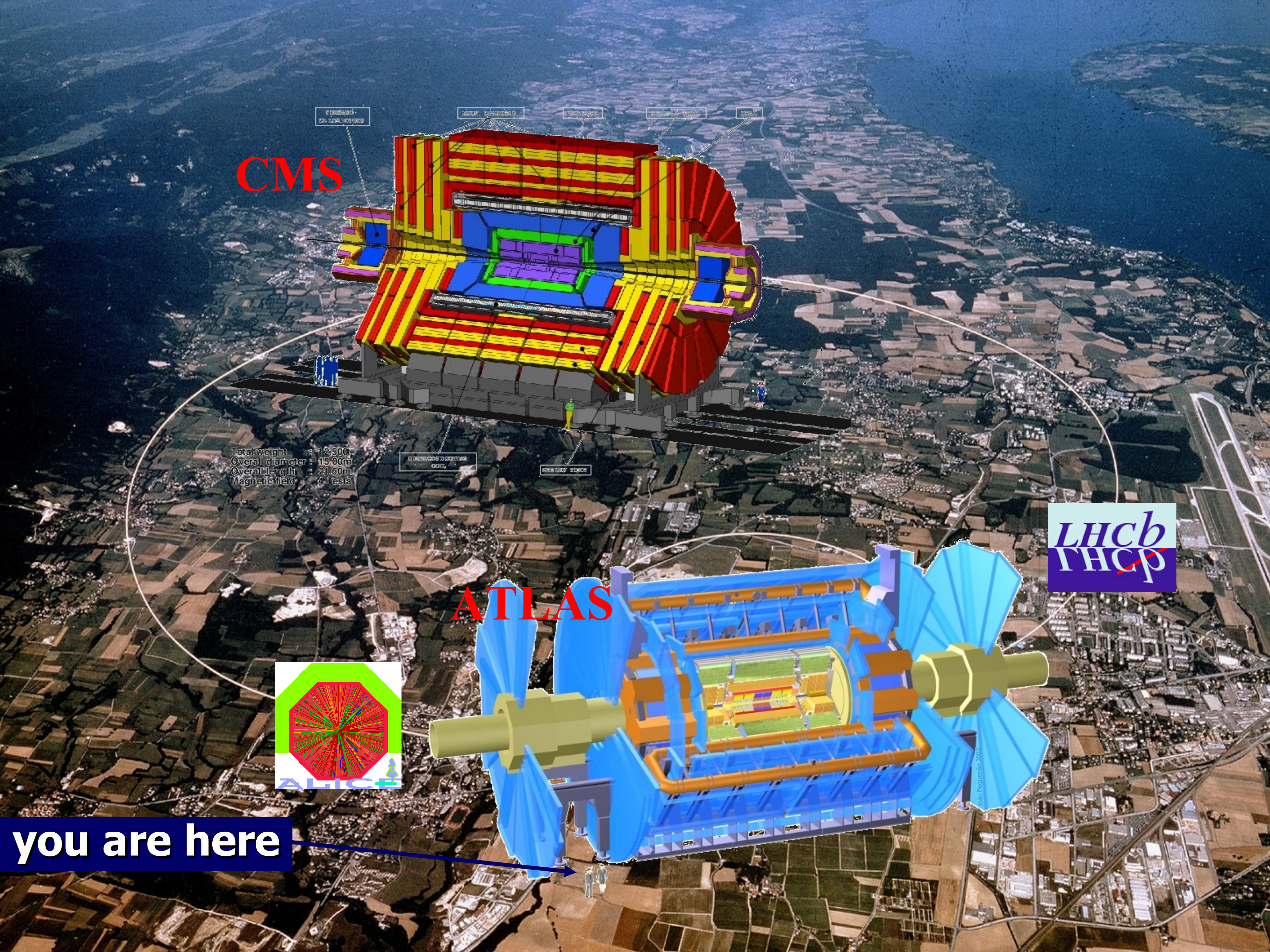


Dipoles	1232
Quadrupoles	400
Sextupoles	2464
Octupoles/decapoles	1568
Orbit correctors	642
Others	376
Total	~ 6700

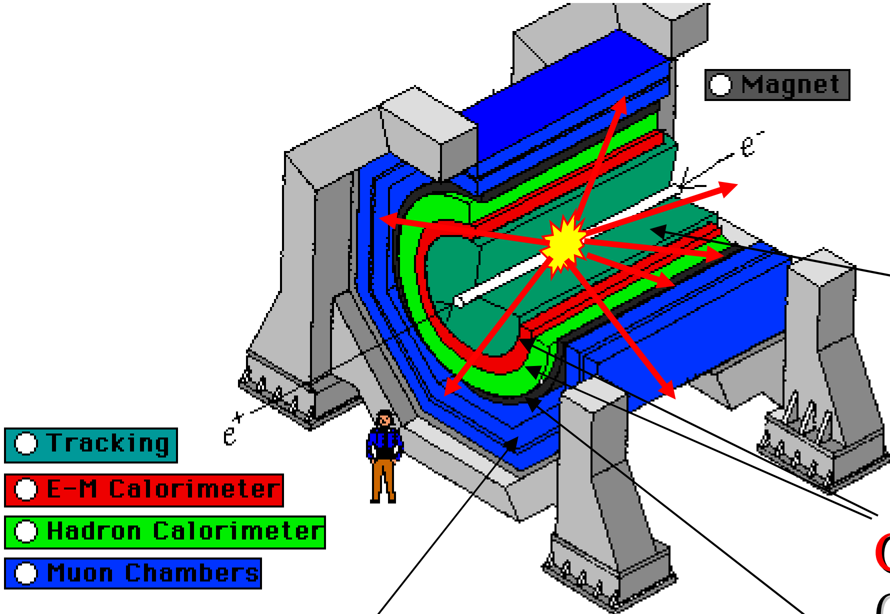
The LHC magnets are the most powerful mankind can build today on industrial scale.

They use superconductivity at 1.9^{o}K (-271^{o}C) in a bath of superfluid He.

Spin-off: research on superconductivity (cables, alloys).


CMS
Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla
ATLAS
LHCb
ALICE
you are here

Detectors on colliders



We want to measure:
direction, energy, momentum, electric charge, identity.

Tracking: measure trajectories of charged particles
(as lighter as possible)

Calorimeters: measure deposited energy
(dense, must stop particles)

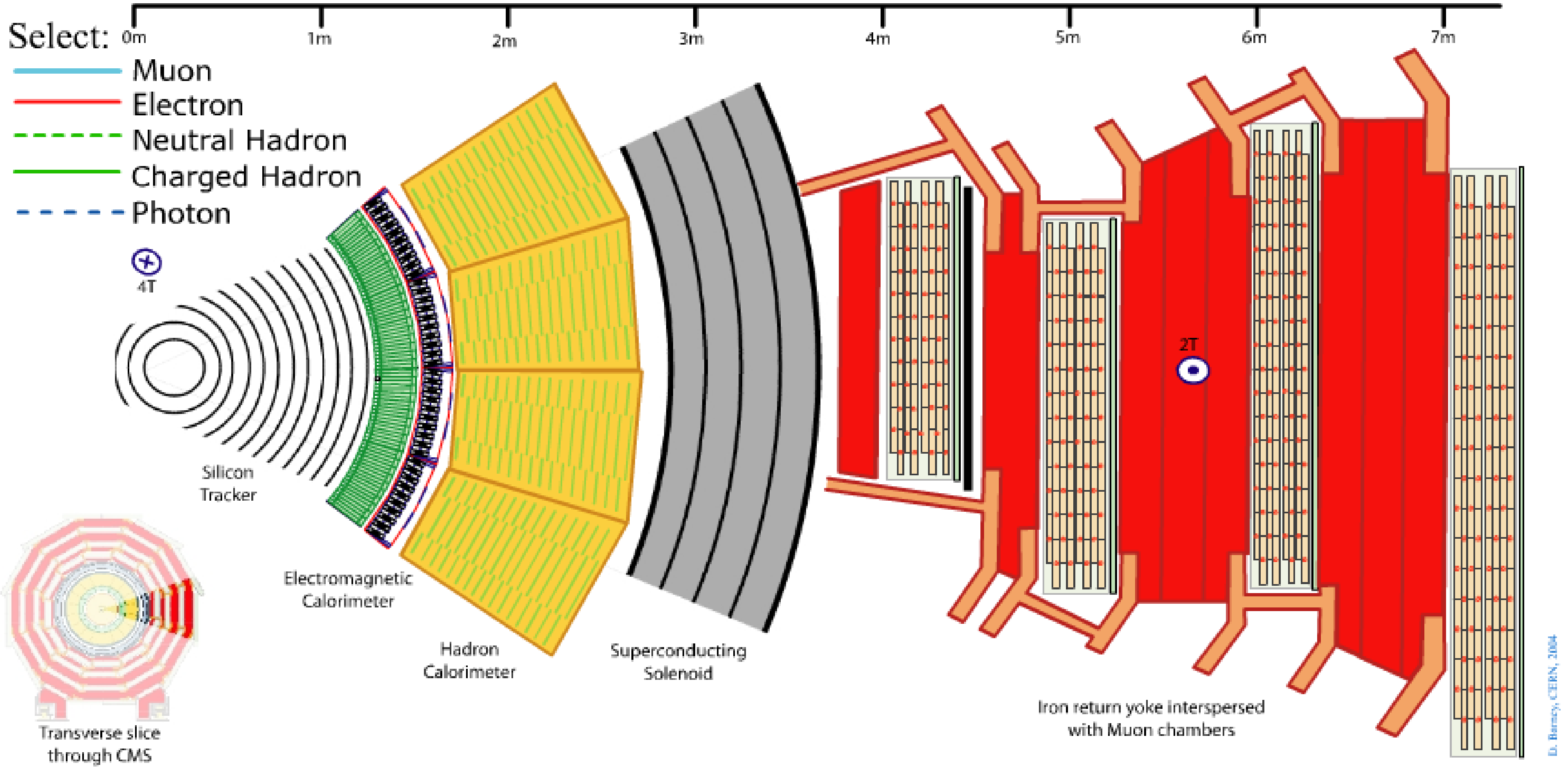
Muon chambers: measure charged particles not stopped by the other detectors
(only muons are known to do so)

Magnetic field to bend charged particles

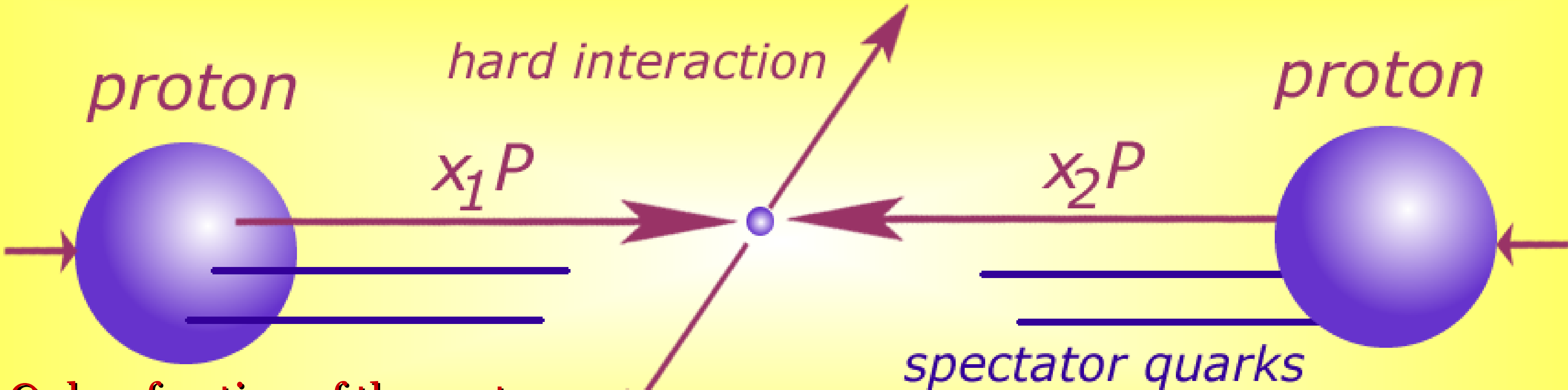
The detector must be able to take the 'picture' of the event before the next bunch crossing. This is very demanding at the LHC (25 ns).

Statistical distributions give information on average behaviour/properties.

Particle detection



Proton-proton collisions



Only a fraction of the proton energy will be available in the collision

$$\left.\begin{aligned} p_a &= x_a\, p_A \\ p_b &= x_b\, p_B \end{aligned}\right\} \quad \sqrt{\hat{s}} = \sqrt{x_a x_b s} \approx \underset{\text{if } x_a \approx x_b}{x} \sqrt{s}$$

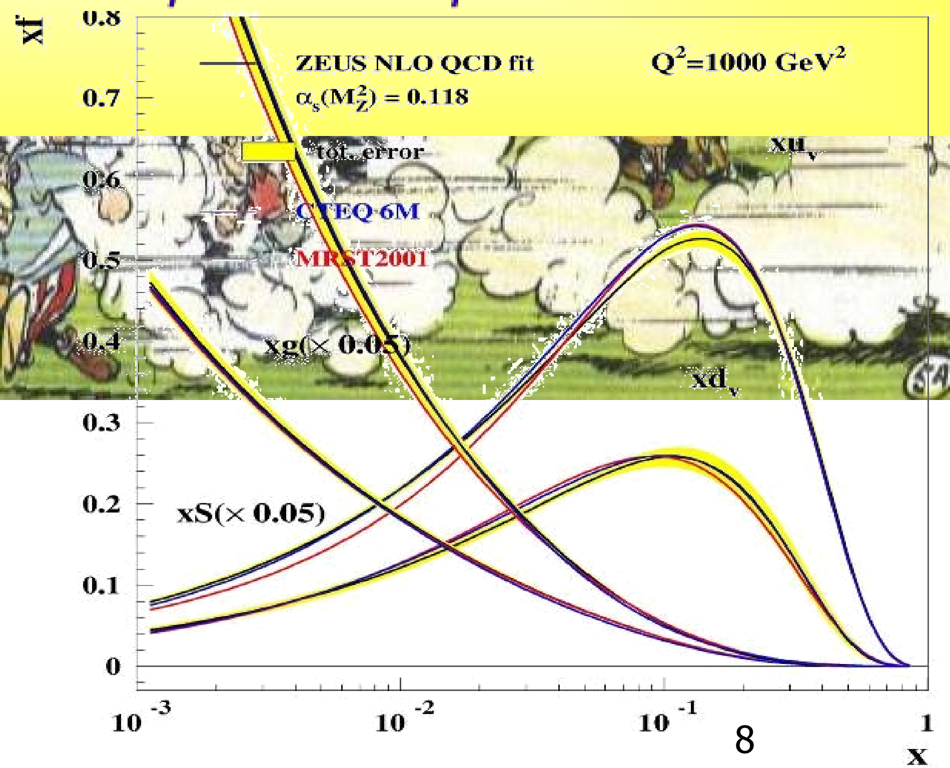
To produce a mass of:

100 GeV: $x \sim 0.007$

(dominated by gluons in the proton)

5000 GeV: $x \sim 0.36$

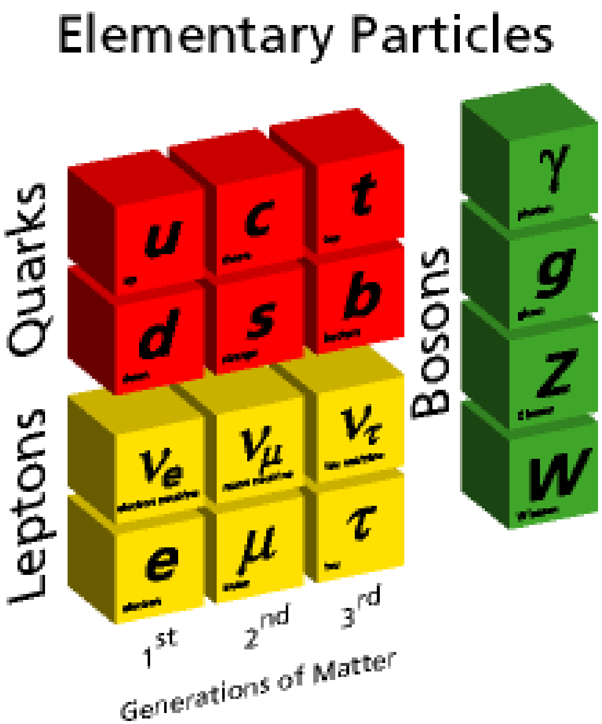
(dominated by quarks in the proton)



HEP: what do we know right now?

- Standard Model: Relativistic quantum field theory (only known framework to formulate a theory consistent with QM and Special Relativity)
- Local internal (gauge) symmetries, governed by a SU(3)xSU(2)xU(1) algebra, leading to strong and EW interactions mediated by gluons, W/Z and photons
- Three families of quarks and leptons with a diverse mass spectrum:

10^{-8} GeV (ν) $\rightarrow$ 10^{2} GeV (top, W/Z)



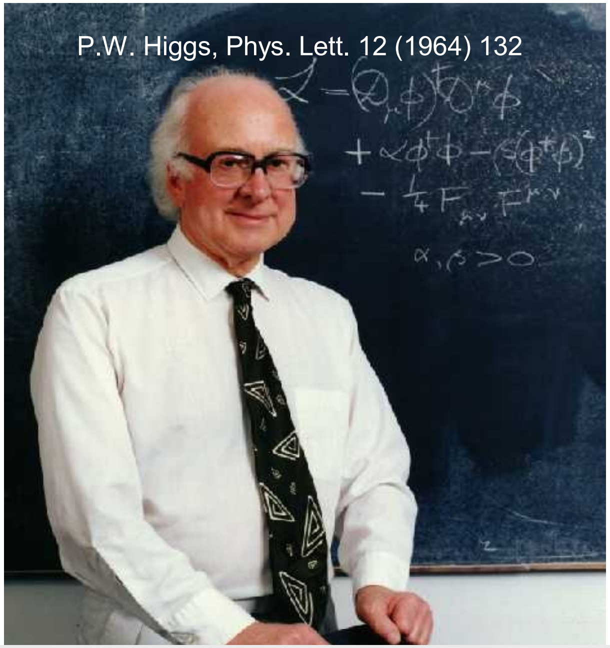
Overall extremely complete and succesfull description of known phenomena BUT….

Neutrino masses and inclusion of **gravity** in the SM require new physics at the scales ~10^{15} GeV and ~10^{19} GeV, respectively.

HEP: which issues are still open?

- Identify the **Higgs boson**, namely the particle responsible for the breaking of the SU(2)xSU(1) (EW) symmetry and for the **generation of the masses of SM particles**.
- Explore the nature of the Higgs boson, and establish the detailed dynamical mechanism with which the EW symmetry is broken.
  - Pure SM?
  - Supersymmetry
  - ExtraDimensions?
  - …

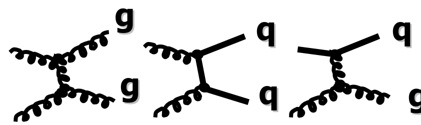
.. … don’t forget …
the Higgs is not yet discovered !



Only unambiguous example of observed Higgs

Standard Model processes

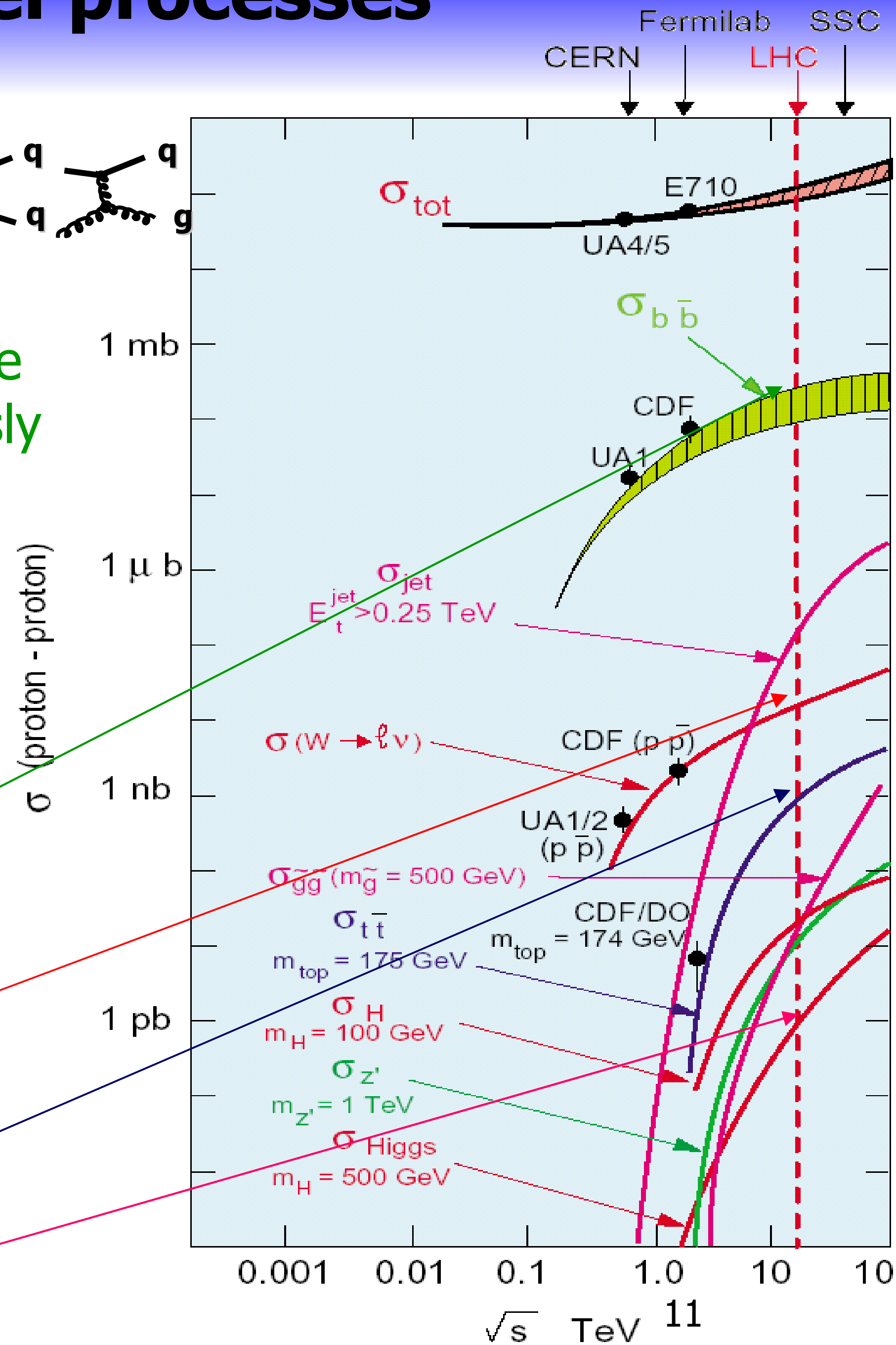
- In a hadronic environment jet production largely dominates



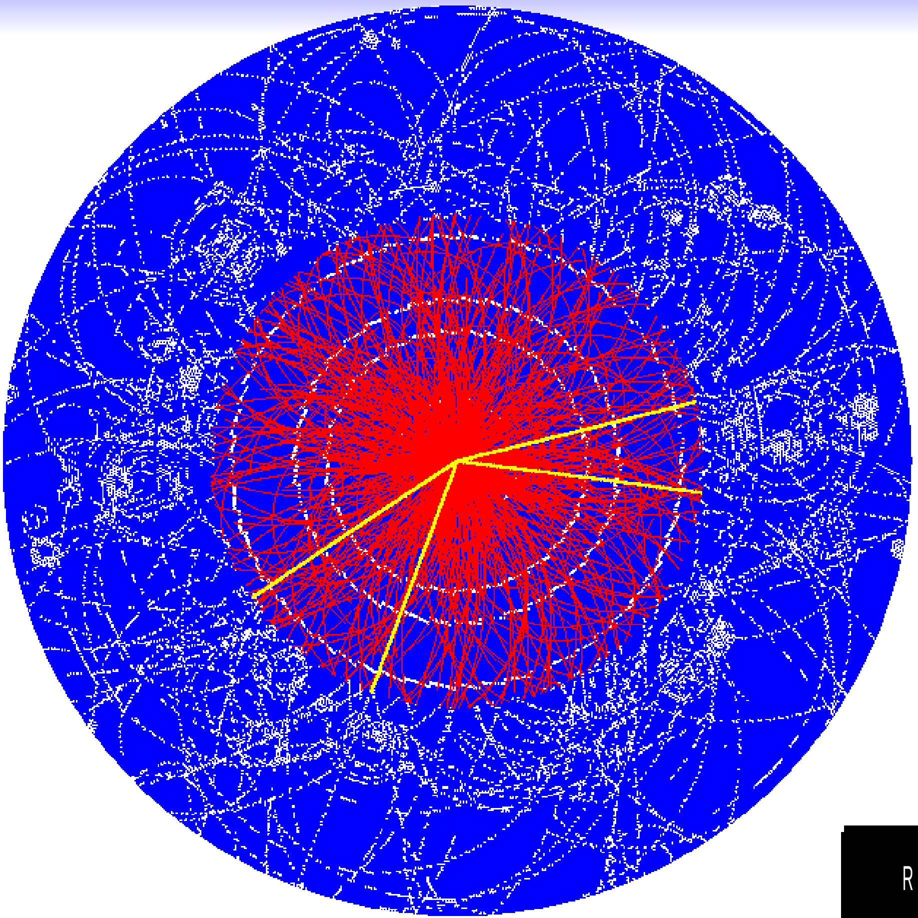
- Leptons (e, μ) are essential to trigger the events because easily and unambiguously identifiable

- There are (for instance) 10-11 order of magnitudes between the probability of producing a Higgs versus QCD (jets)

process	Evts/s	Evs/y
bb	10^6	10^{12}
$Z \to ee$	~3	10^7
$W \to e\nu$	~30	10^8
$WW \to e\nu X$	10^{-2}	6×10^3
tt	~2	10^7
H (700 GeV)	2×10^{-3}	10^4



Event reconstruction

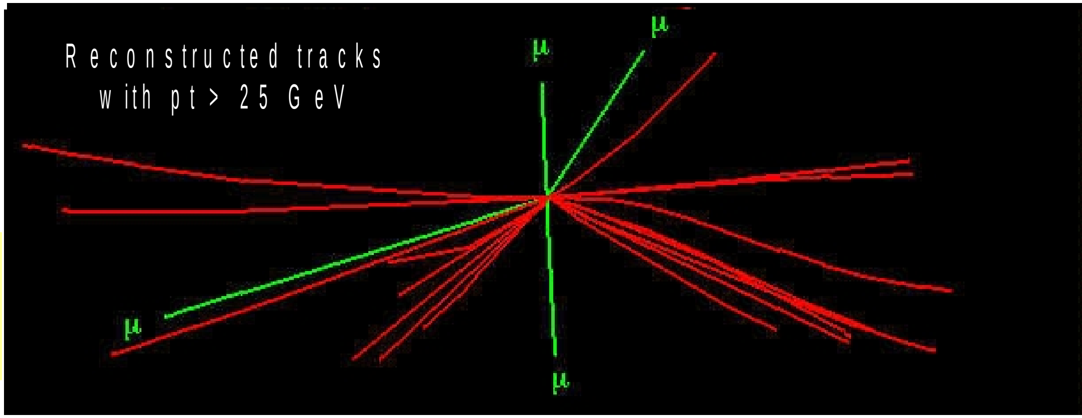


- Beams cross every 25 ns !
- Every beam crossing there are ~25 interactions of 'minimum-bias' (MB).
- A 'good' event (for instance $H \to ZZ \to \mu\mu\mu\mu$) is always accompanied by ~25 overlapping MB events.

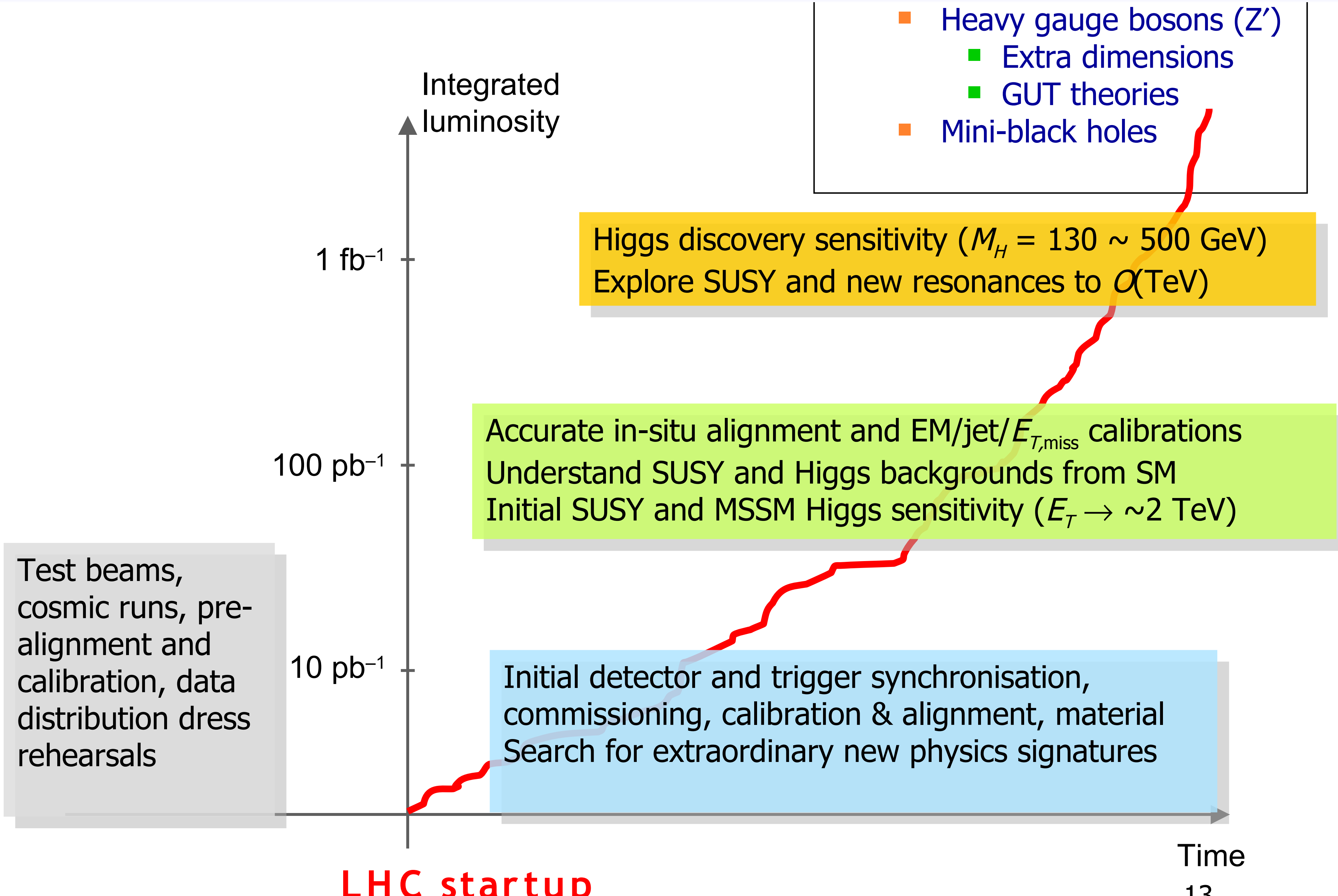
❖ thousands of particles every triggered event, mostly with low E

→ All this (not the Higgs event, though) repeats after every 25 ns !

Properties of particles are then determined on a statistical basis



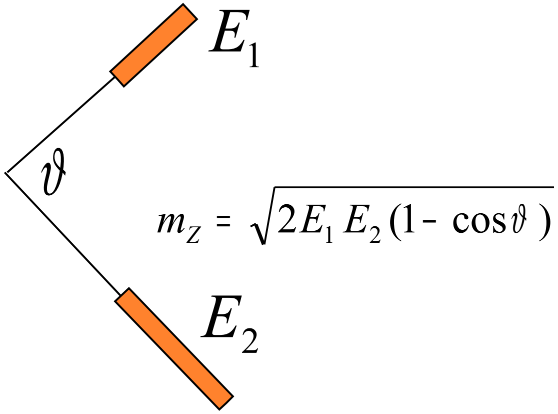
Physics potential at LHC



Early, standard, physics...

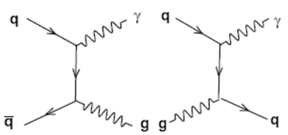
Commissioning with first physics

⇒ use known physics to understand the detectors at our best.

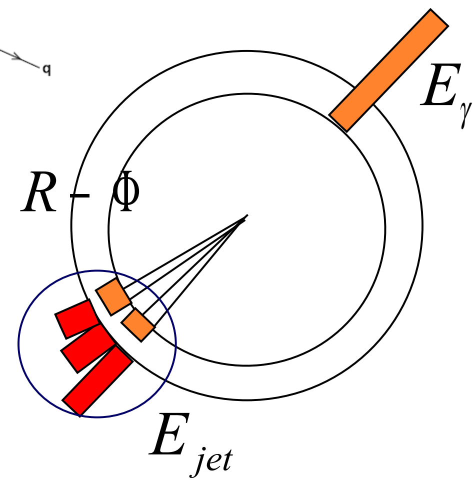


Most useful:

- $q\bar{q} \to Z \to e^+e^-$: use mass constraint to calibrate ECAL
- $q\bar{q} \to W \to e\nu$: compare E and p of electron
- $Z \to e^+e^-$, $\mu^+\mu^-$ can be used for further alignment
- M-B : use statistical balance in Φ for calorimetry calibration
- Z+jet, γ+jet : calibrate HCAL (jet energy) using kinematical balance in the R- Φ plane

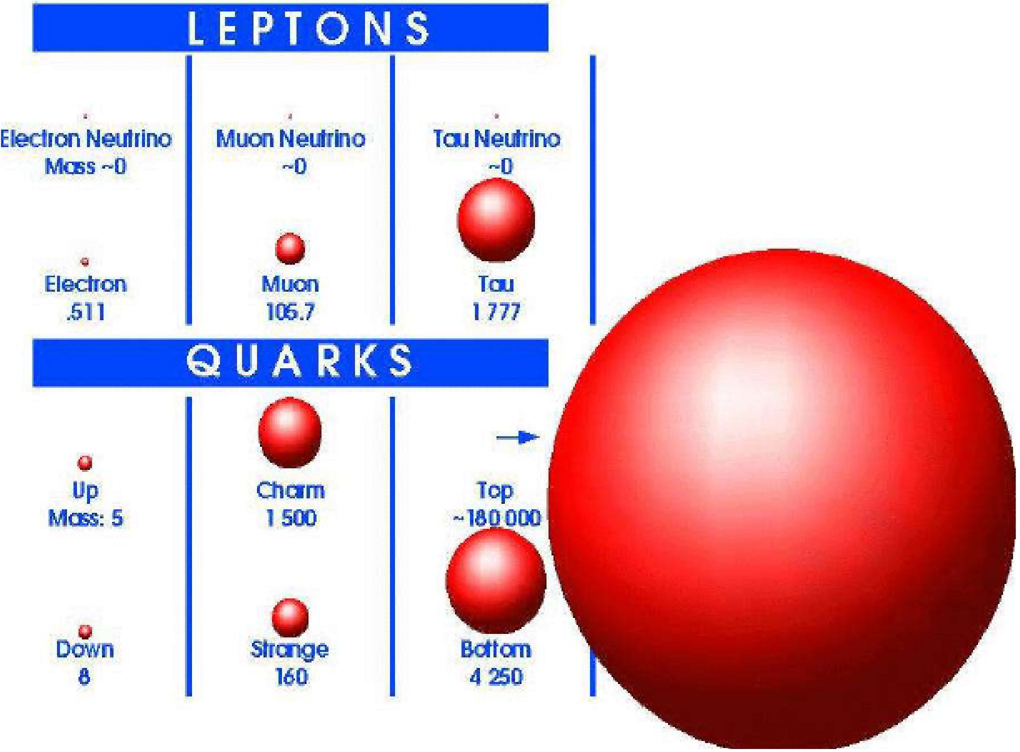


- $W \to$ jet-jet : use W mass constraint to calibrate the jet energies



- tt production deserves a special chapter:
  (only ~100 events produced so far in the world, LHC will use them also as a calibration tool)

Why is top production interesting?



Is it 'standard' physics?

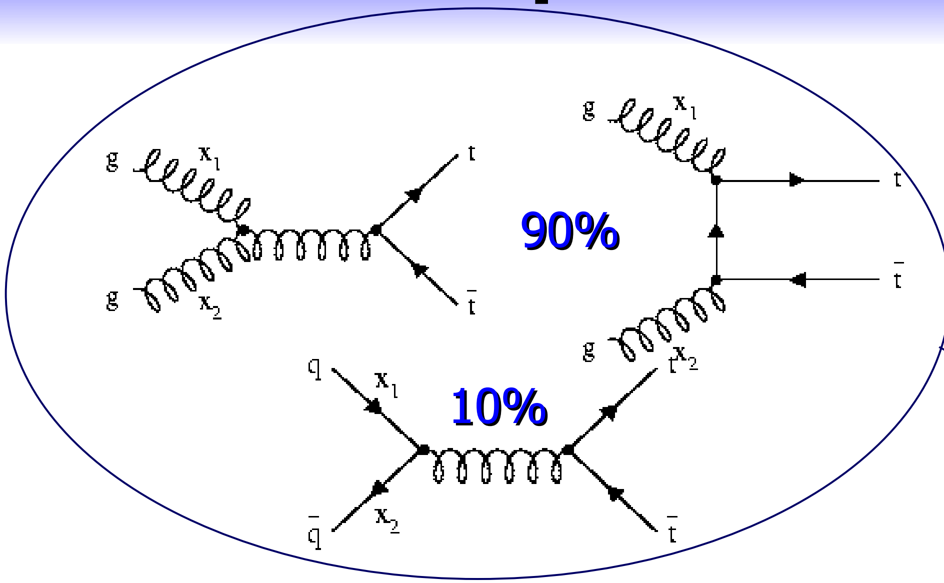
- The top turned ten years, but still so little known about it…
- Its large mass gives unique features for the investigation of EW symmetry breaking and physics beyond the SM (larger couplings with the Higgs boson) (can decay into heavier particles)
- Hope it will be the key for revealing new physics at the LHC.
- The top mass is now the key parameter to continue constraining the SM

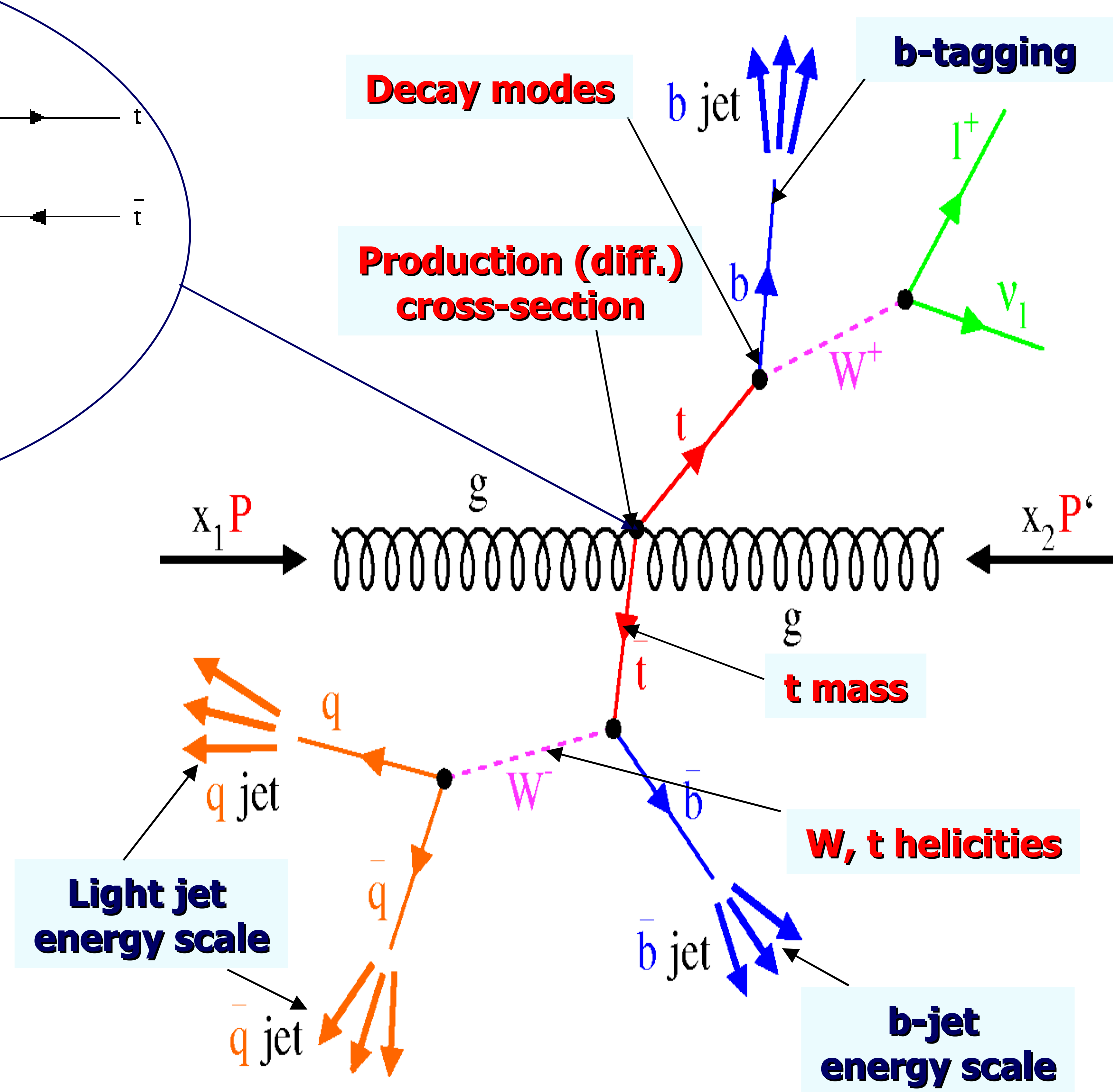
The LHC will be a top-factory

→ **2 tt events per second !**

→ **more than 10 million tt events expected per year: perfect place for precision physics**

tt production at the LHC



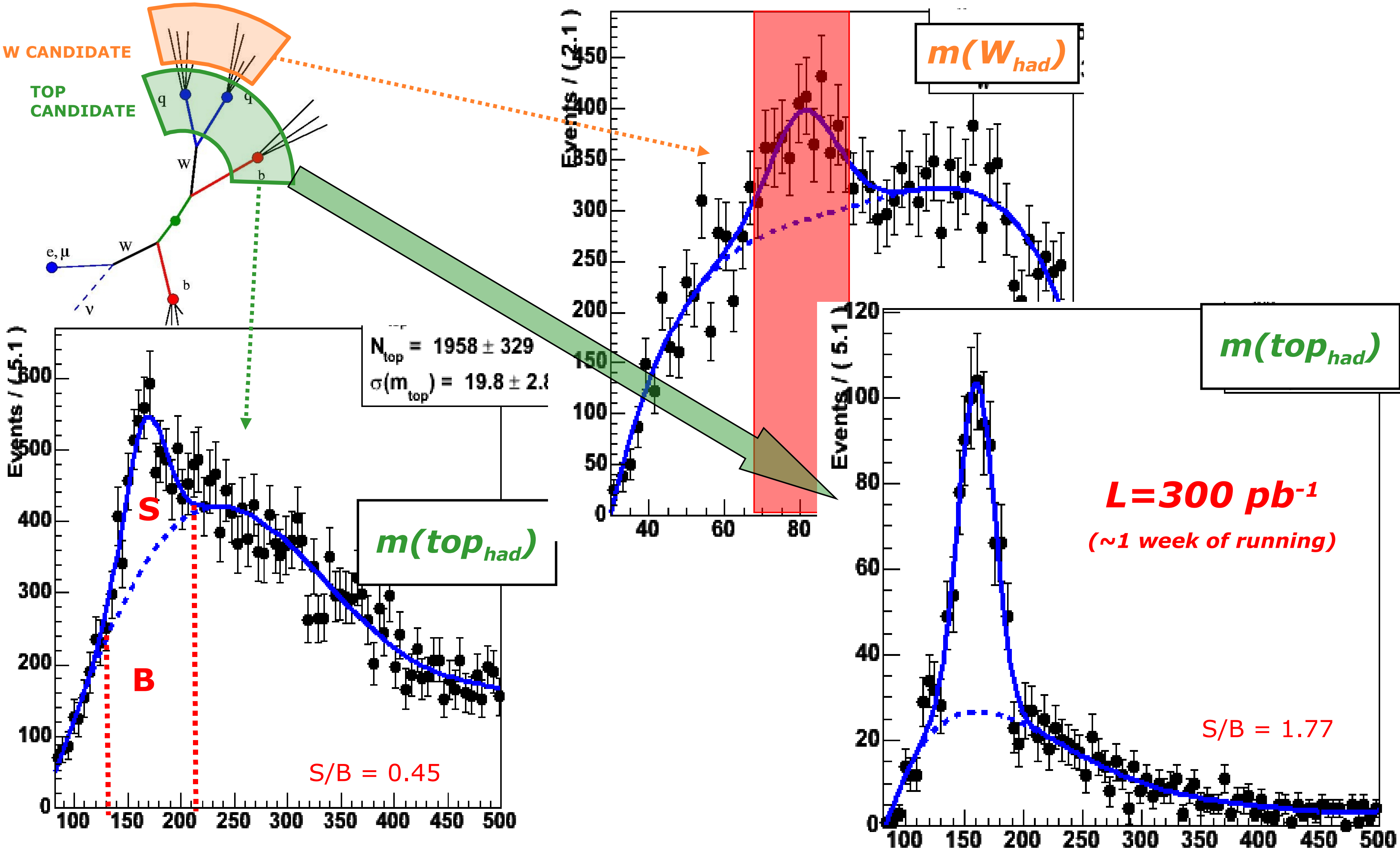


1. tt is an essential process for commissioning

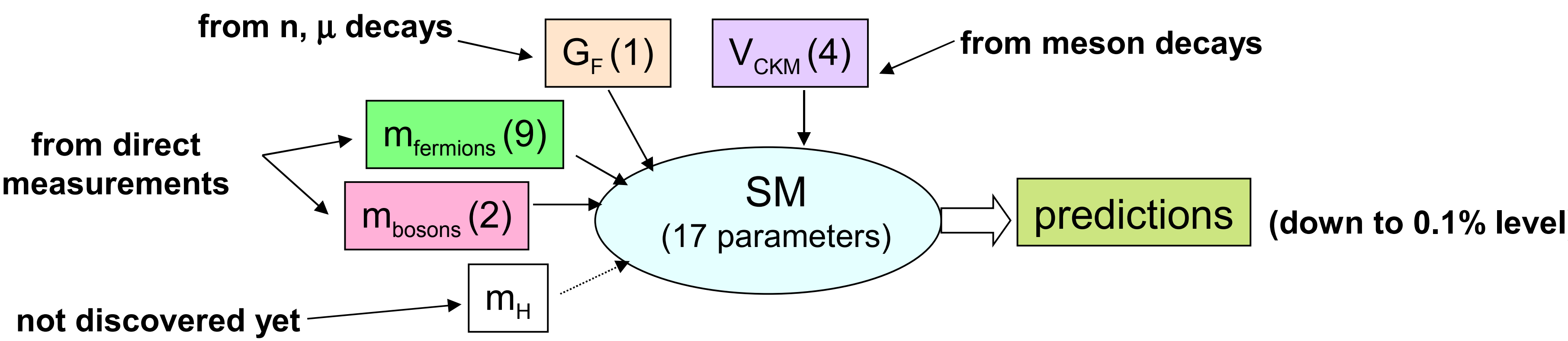
2. tt is a fundamental process for electroweak measurements

Finding tops

Can we see an early top signal even with limited detector performance?
Can we use this signal to commission detector and tools?



The Standard Model is all what we have so far



Parameters of the model are linked to each other via radiative corrections

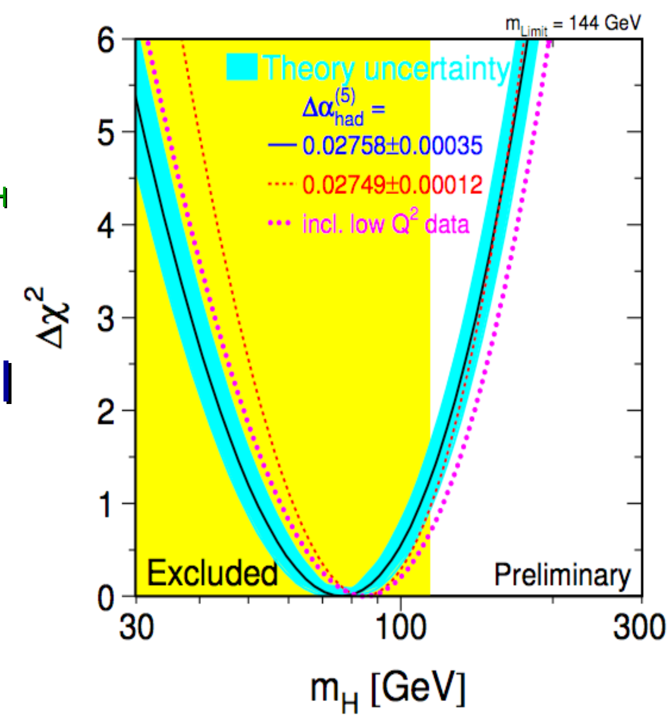
⇒ With precision measurements (interesting per se):
- one can get information on the missing parameter m_H
- one can test the validity of the SM

⇒ An improvement in the knowledge of the least known parameters (like mt !) is particularly useful

With present input: m_H<182 GeV/c² @95% CL

(m_H>114 GeV/c² [LEP])

But the Higgs boson has not been seen yet !



What after the Standard Model

- The origin of the masses

  Higgs boson? **New symmetries?**

  → Does the Higgs boson exist?
  → If not, what is the mechanism that gives masses?
  → Why do the fundamental particles have so different masses?

- Unification of forces and particles

  SUSY? **New constituents?**

  → Why matter (fermions) and force particles (bosons)?
  → Why 3 generations of fundamental particles?
  → Can forces be unified?

- Understanding the universe

  Extradimensions? **SUSY?**

  → Why is gravity 38 order of magnitude weaker than other forces?
  → What is the origin of dark matter?

Particles

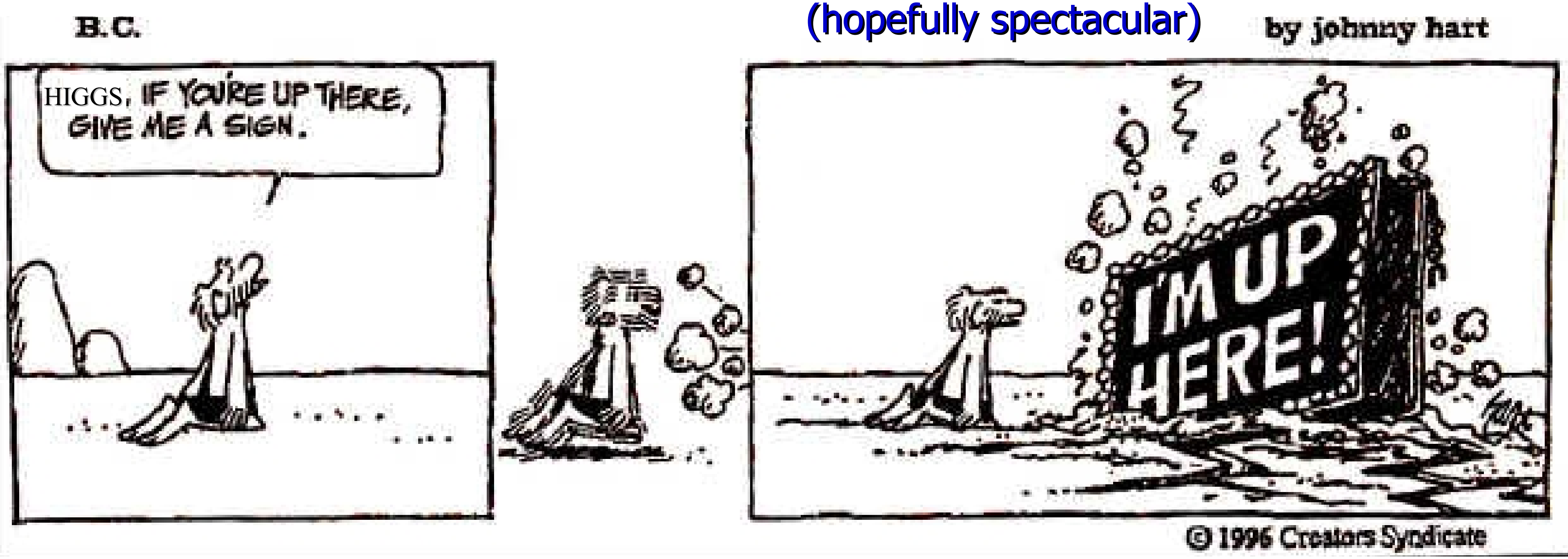
Cosmology

The LHC program is very ambitious.
We want to answer to many of those questions…

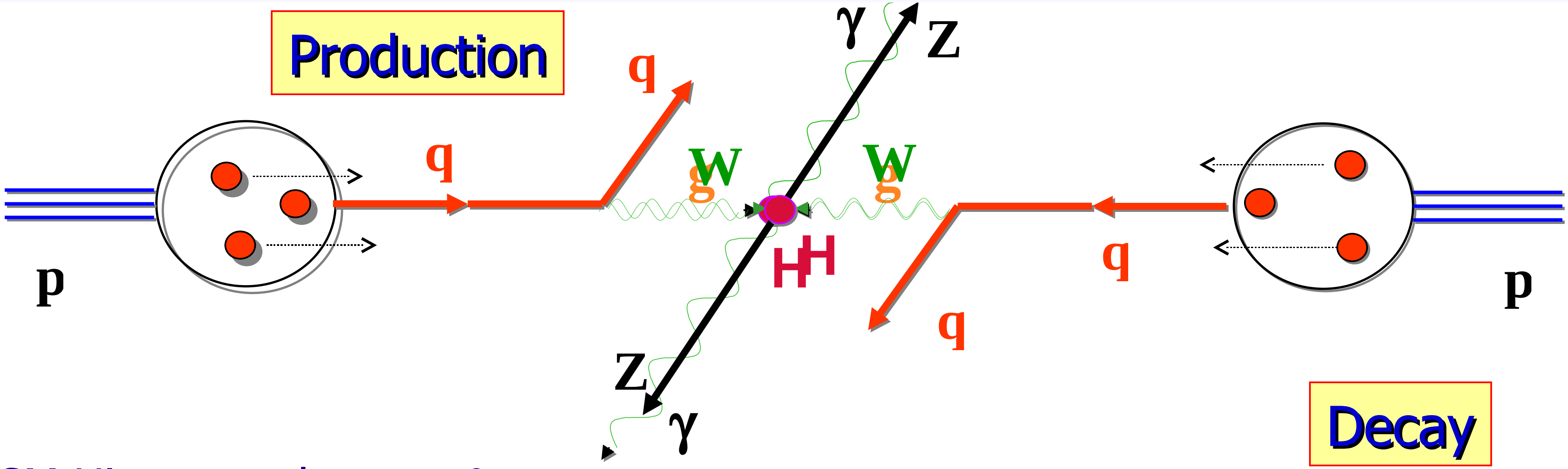
We might experience a revolution in our understanding of fundamental physics.

Signs of the Higgs boson

(hopefully spectacular)



Higgs production and decay



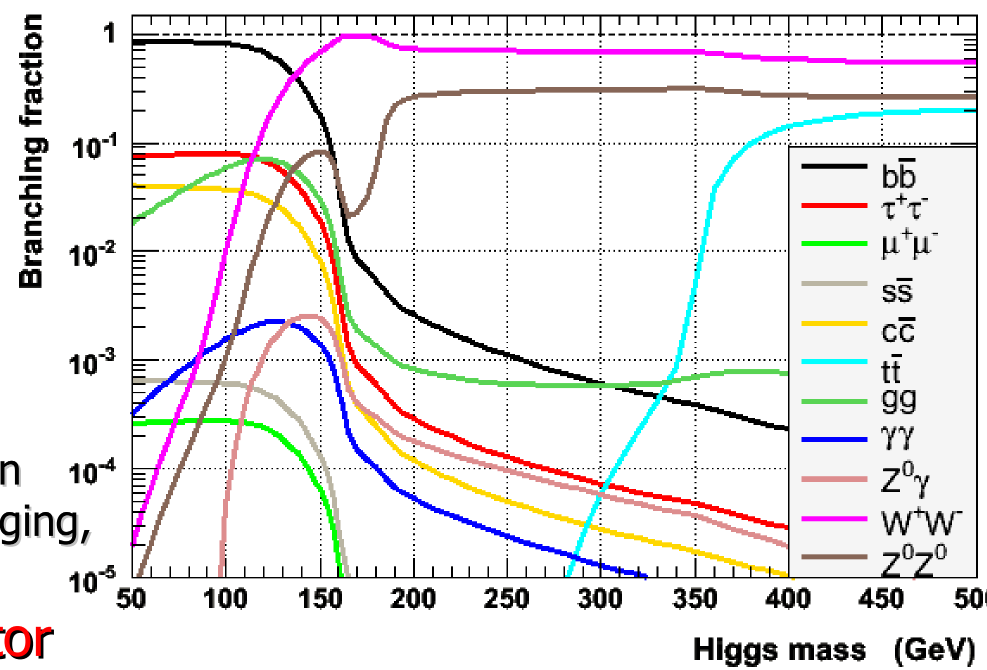
Decay

SM Higgs couples to m_f^2

✥ Decays into the heaviest fermion or boson

⇒ Final state depends on M_{higgs}

⇒ Ready to cover all possibilities

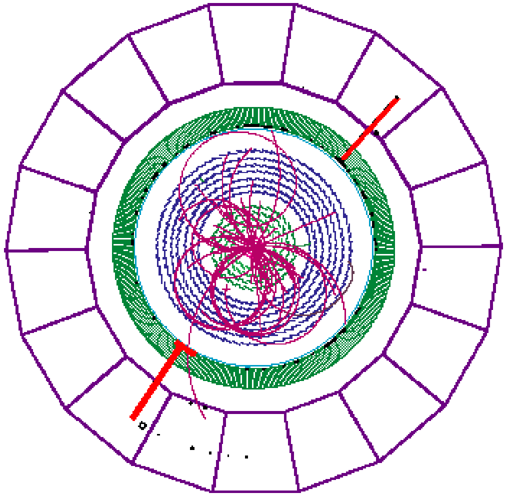


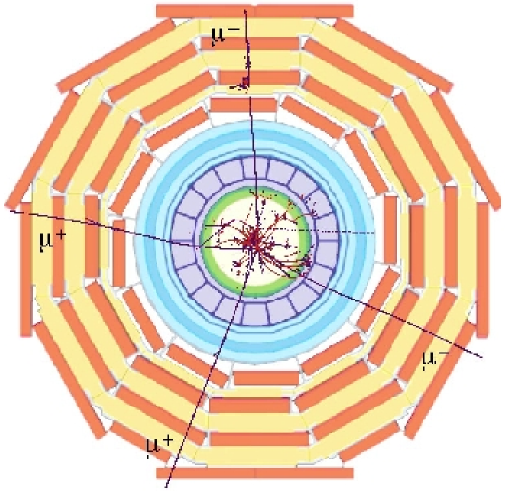
Needed ingredients:

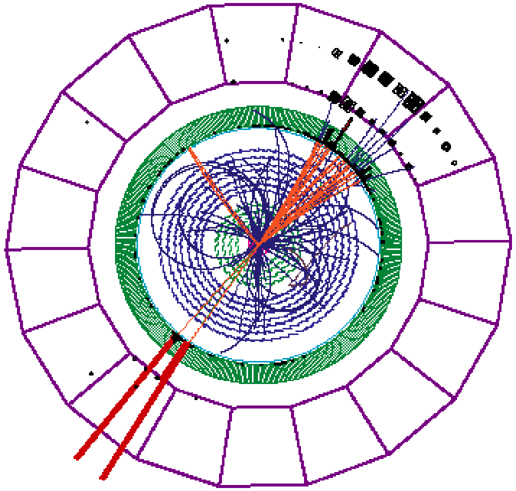
- charged lepton tagging (including τ), photon reconstruction, jet reconstruction and b tagging, missing E_T reconstruction

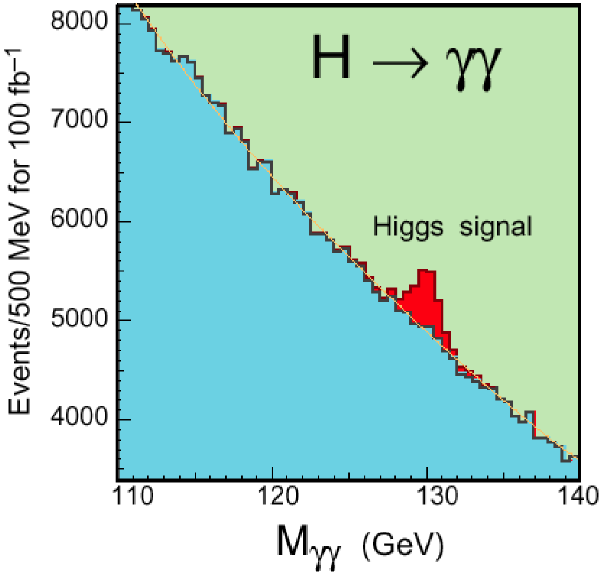
⇒ Need of a general purpose detector

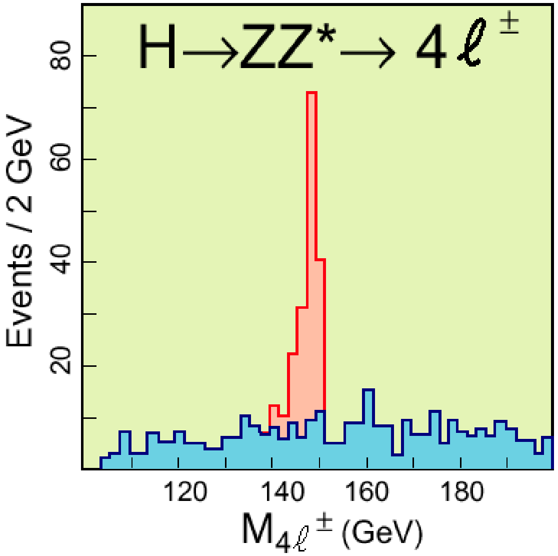
The Higgs in the detector

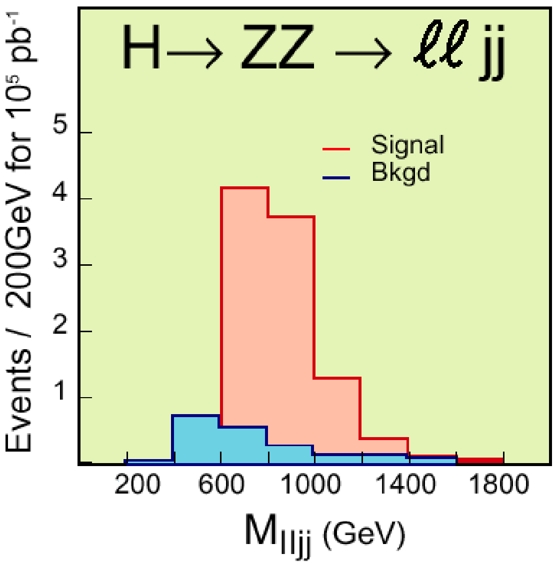










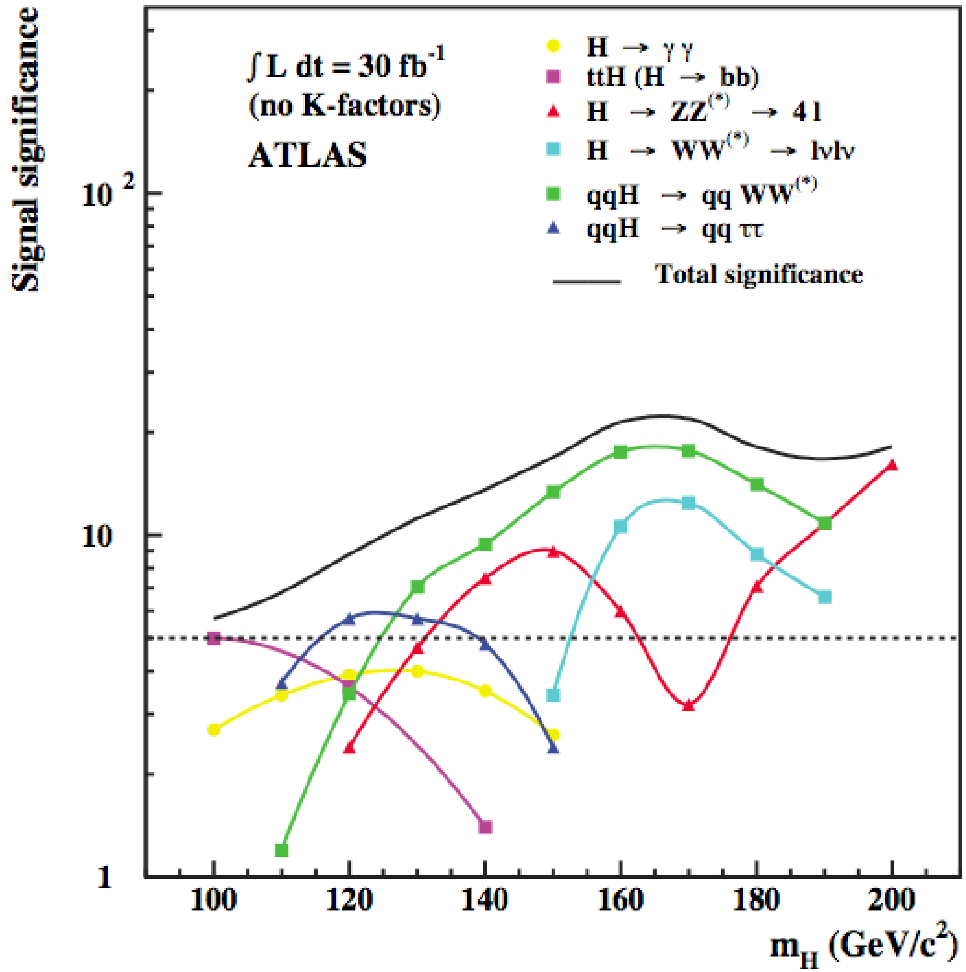


Higgs coverage

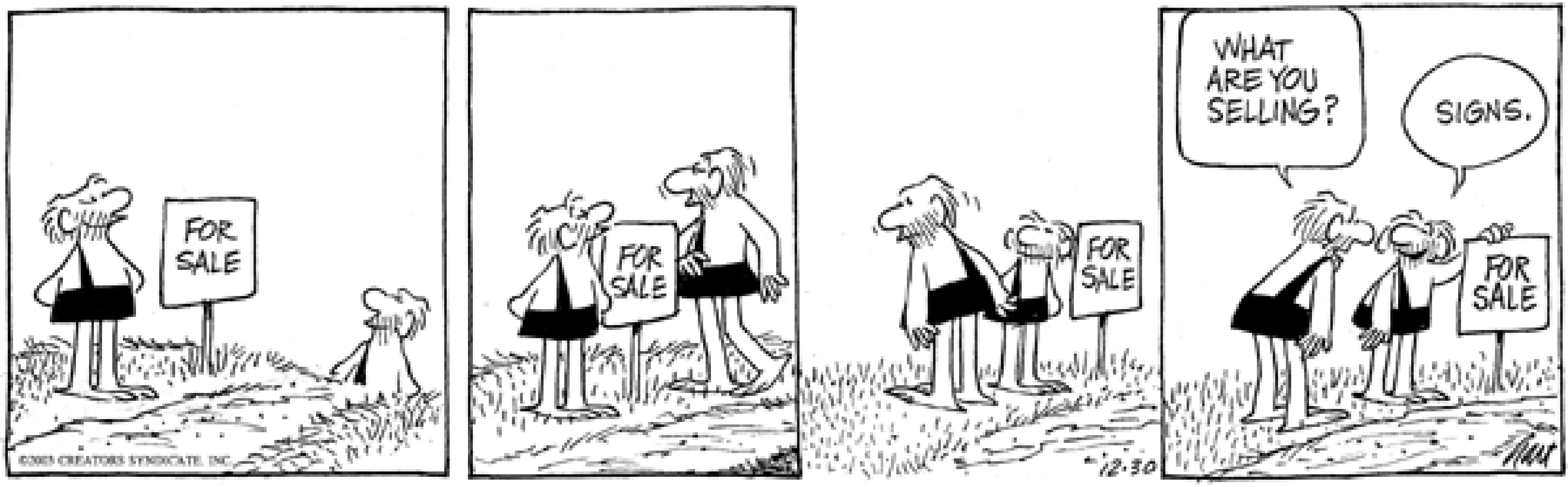
CMS/ATLAS can probe the entire set of allowed SM Higgs mass values
⇒ analyze all possible decays

Discovery happens early in the game (just 30/fb needed)
In several cases a few months at nominal luminosity are adequate for a proper 5σ observation

No holes in m_H coverage !



Signs of new physics



Supersymmetry

New symmetry between fermions (matter) and bosons (force).

For each particle p with spin s: SUSY partner $\tilde{p}$ with spin s-½

quarks	$\rightarrow$	squarks
leptons	$\rightarrow$	sleptons
$W^{\pm}$	$\rightarrow$	winos
$H^{\pm}$	$\rightarrow$	charged higgsino
γ	$\rightarrow$	photino
Z	$\rightarrow$	zino
h, H	$\rightarrow$	neutral higgsino
g	$\rightarrow$	gluino

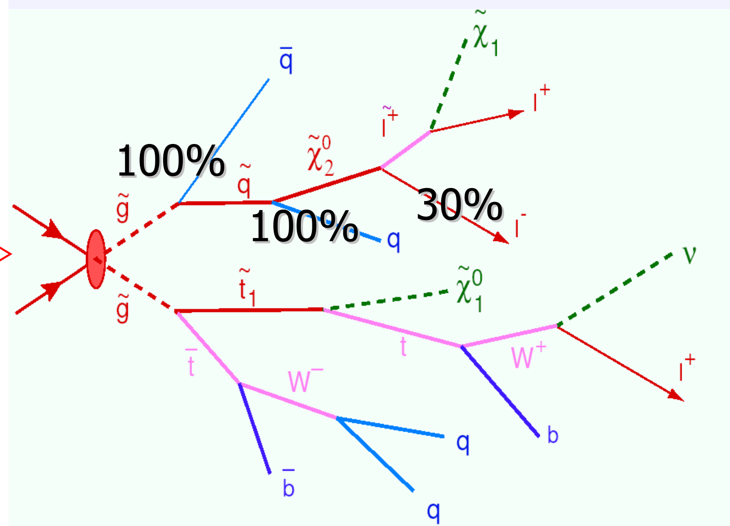
- Many additional parameters to describe the model
- The masses of SUSY particles are unknown, but the cross-sections are predicted to be big (~100 $\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ events/day at low luminosity for $m(\tilde{q}, \tilde{g}) \sim 1$ TeV)

  $\Rightarrow$ Fast discovery for the LHC
- The challenge is to measure the particle spectrum

In the decay chain the final products are fermions and the undetected LSP

$\Rightarrow$ Typically many jets + missing E_T

Spectacular signatures

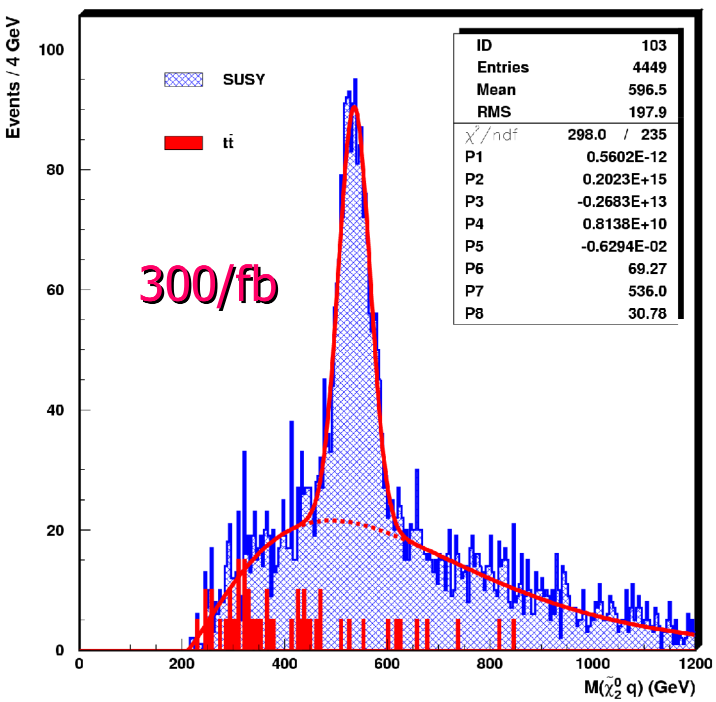


Supersymmetry reach

Spectacular evidence with full statistics
Different final states depending on the parameters and the model

$m \sim 1$ TeV , $\sigma \sim 1$ pb
$\rightarrow 10^4$ events/year at low L

$\Rightarrow$ Discovery possible up to sparticle masses of 3 TeV with 300/fb



Time period	Luminosity [$cm^{-2}s^{-1}$]	squark/gluino masses
1 month	10^{33}	~1.3 TeV
1 year	10^{33}	~1.8 TeV
1 year	10^{34}	~2.5 TeV
Ultimate	$\int = 300\ fb^{-1}$	~2.5–3 TeV
D0 & CDF	$\int = 0.3\ fb^{-1}$	$>_{(2\sigma)}$ 0.35 TeV

A good candidate for dark matter

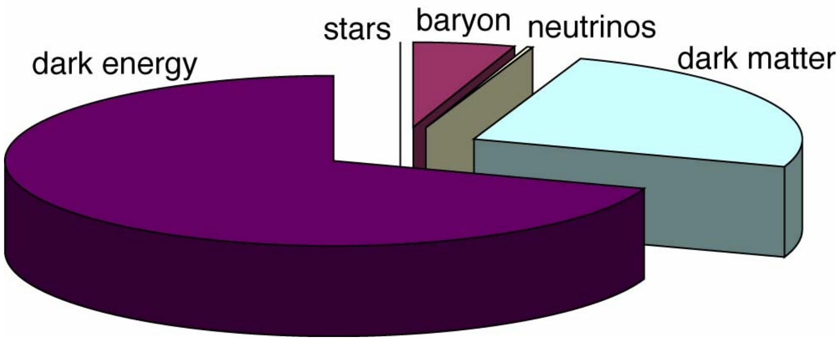
Stars and galaxies are moving too fast to just be subject to gravitational force of what is visible.

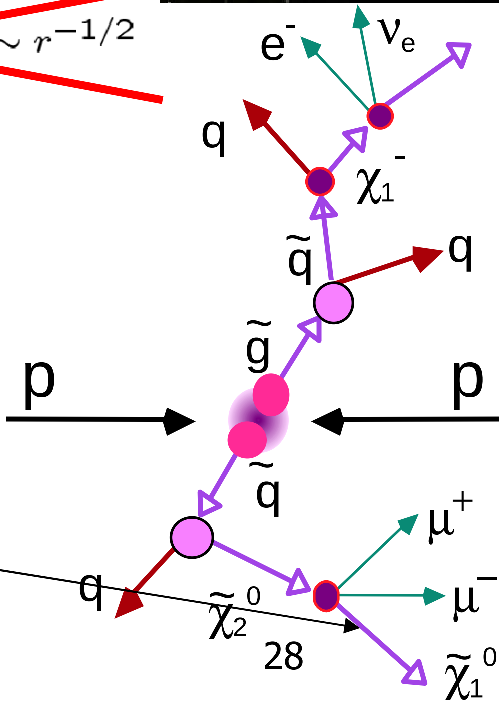
Example: rotational velocity of galaxies

Approximately just 5% of what we 'see' (meaning that can emit EM radiation) represents the mass of the universe.

⇒ Embarassing, isn't it?

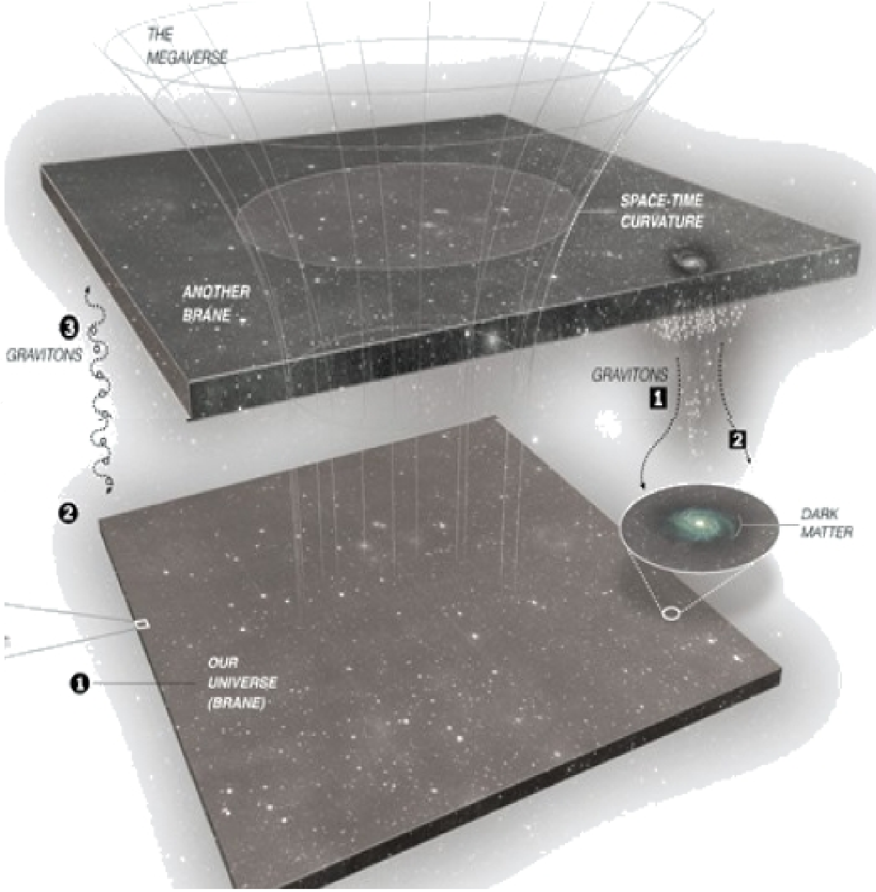
$$\cancel{\frac{Mv^2}{r} = \frac{GMM_{\mathrm{tot}}}{r^2} \Rightarrow v \sim r^{-1/2}}$$





SUSY could provide a good candidate for dark matter

Understanding gravity: extradimensions



Much theoretical interest in models with extra dimensions:

- All SM particles (us!) confined in a 4D world
- Only gravity 'sees' the other dimensions
- Gravity has the same strength than other forces, but is diluted in extra dimensions

⇒ Solves the so-called hierarchy problem

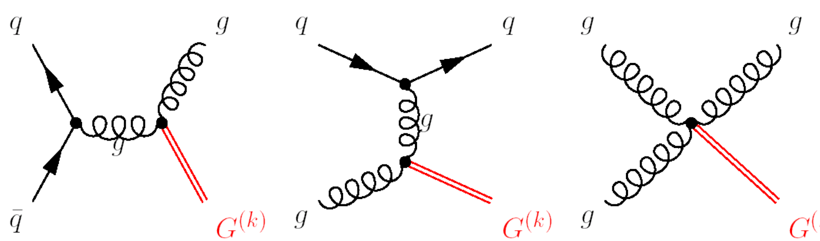
⇒ Gravitons can be coupled to ordinary particles, might be visible at the LHC

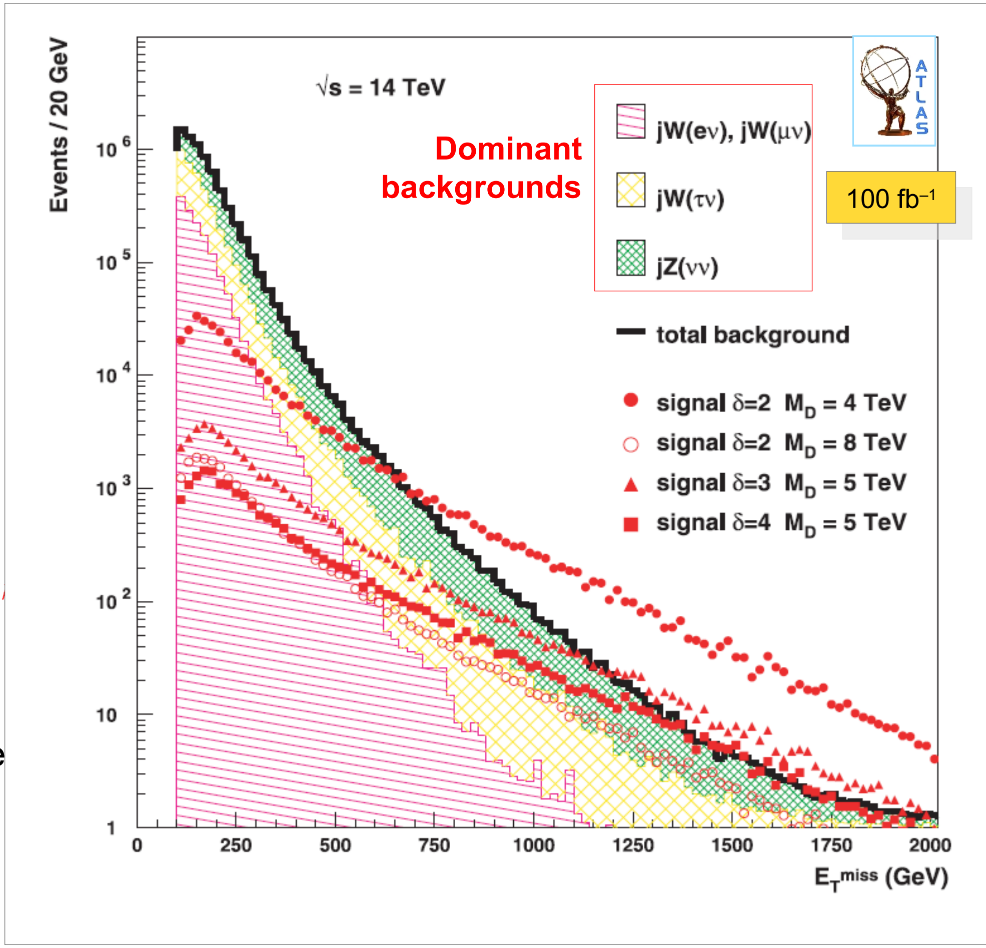
Gravitons at the LHC

Gravitons as final particles:

- they escape in extradimensions
- observed as missing energy
- signatures: jet + missing energy

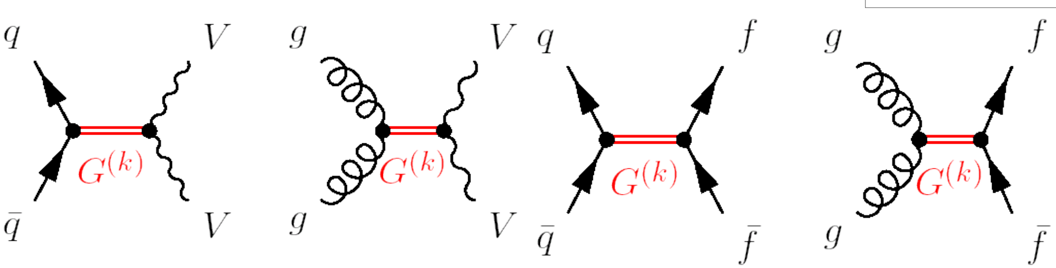
  γ + missing energy





Gravitons as virtual particles:

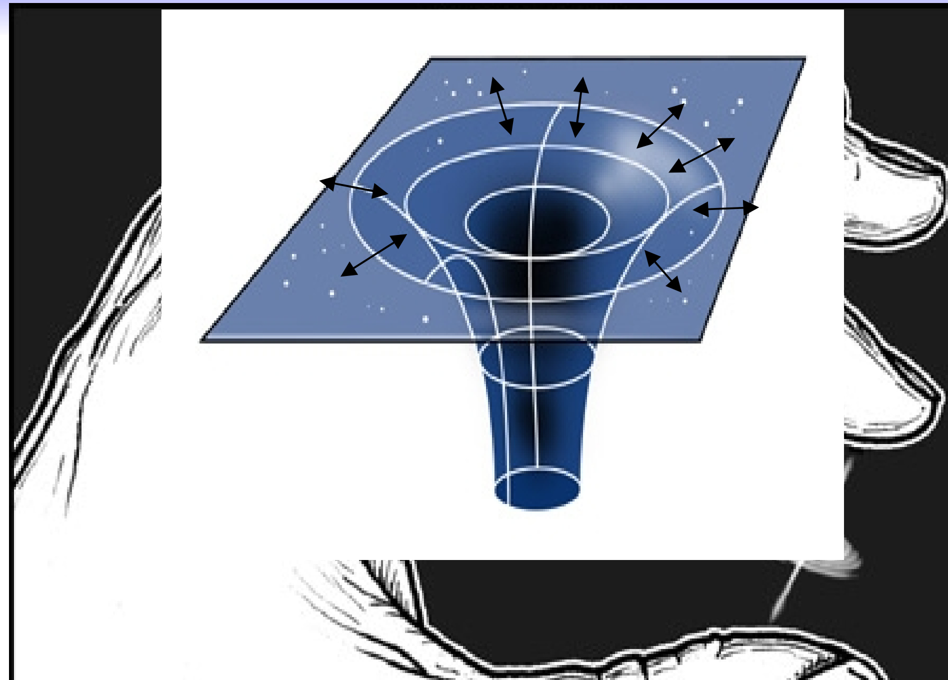
- extra production of standard particle
- observed as extra events
- possible presence of resonances



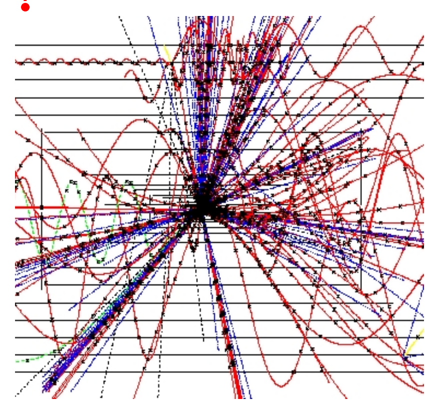
ADD

Black holes at the LHC

- Extra dimensions have very small radius and imply that gravity is much stronger at shorter distances
- Get more than ~TeV of energy into a small ‘enough’ region and a black hole forms spontaneously
- (impossible if only 4D)
- They decay instantaneously on the LHC time scales, and evaporate because of the Hawking radiation



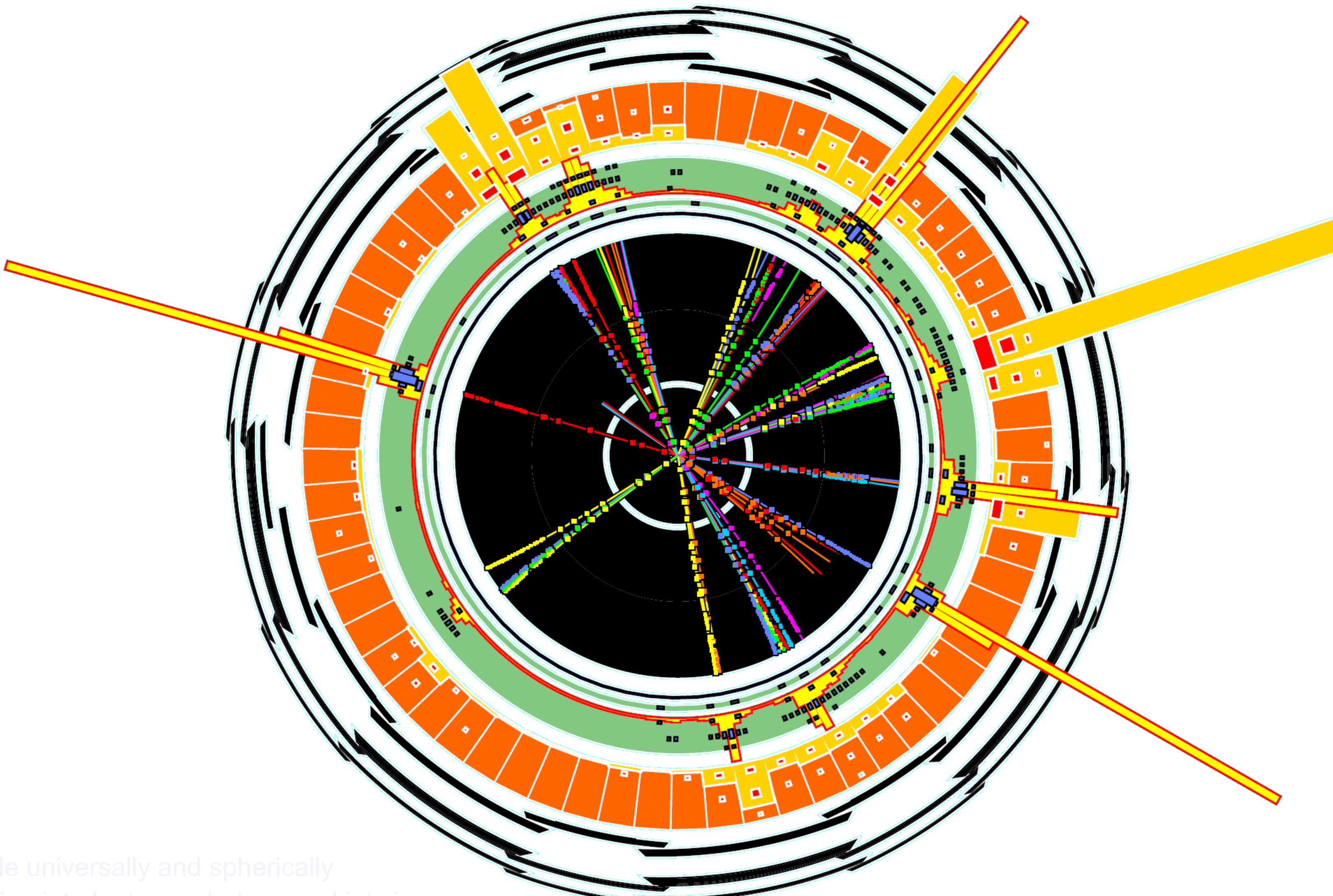
- Classically nothing escapes
- In Quantum Mechanics they radiate !



‘Normal’ BH:
mass: ~ m_{sun}
size: ~ Km
T: ~ 0.01 K
Lifetime: ~forever

‘Mini’ BH:
mass: ~ 1000 m_p
size: ~ 10^{-18} m
T: ~ 10^{16} K
Lifetime: 10^{-27} s

Black Holes at LHC



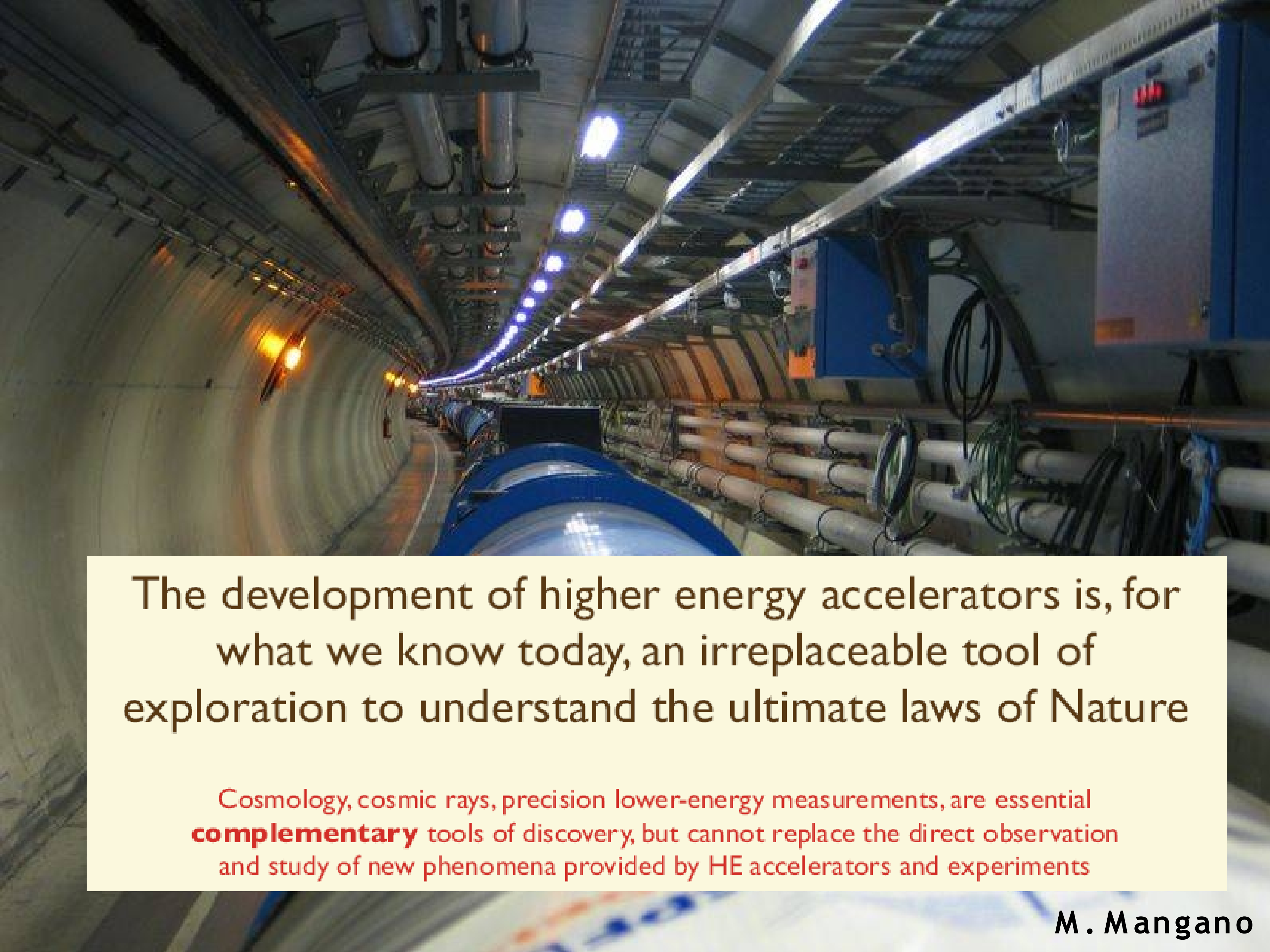
Black hole universally and spherically evaporating into leptons, photons and jets in ATLAS. Final state multiplicity increases with M_{BH}

(Personal) conclusions

- Too many things we do not know/understand.
- Any good high energy physicist cannot believe the SM is the end of the story.
- We are asking some of the most fundamental questions in modern physics.
  To answer, the needed tools are of incredible complexity.
- Still, one of the most exciting intellectual adventures of mankind

The LHC should help the next step in the understanding of fundamental aspects of the infinitely small and the infinitely large

After it, our view of (particle) physics could change forever



The development of higher energy accelerators is, for what we know today, an irreplaceable tool of exploration to understand the ultimate laws of Nature

Cosmology, cosmic rays, precision lower-energy measurements, are essential **complementary** tools of discovery, but cannot replace the direct observation and study of new phenomena provided by HE accelerators and experiments

M. Mangano