8 lectures on accelerator physics

- Lectures can be found at
  - http://www.hep.lu.se/staff/christiansen/teaching/
- Lecture 1 and 2: Introduction
  - Why do we accelerate?
  - What are the important parameters for characterizing accelerators
- Lecture 3 and 4: Examples
  - Examples of accelerators
- Lecture 5 and 6: Advanced topics
  - Transverse motion, strong focusing, and LHC
- Lecture 7 and 8: Projects + presentations
  - Small group projects on free project

Project

- Idea: follow your own interest
  - 4 first lectures are designed to give you foundation to dig deeper
  - 4-5 groups and 8-10 minutes presentation
  - 1 lecture to prepare & 1 lecture to present
- Examples from autumn 2011 and spring 2012:
  - Opera neutrino results
  - Plasma wakefield acceleration
  - Cyclotrons
  - LHC overview & problems with superconducting magnets at LHC
  - History of accelerators
  - Medical isotope production
  - Hazards in accelerators

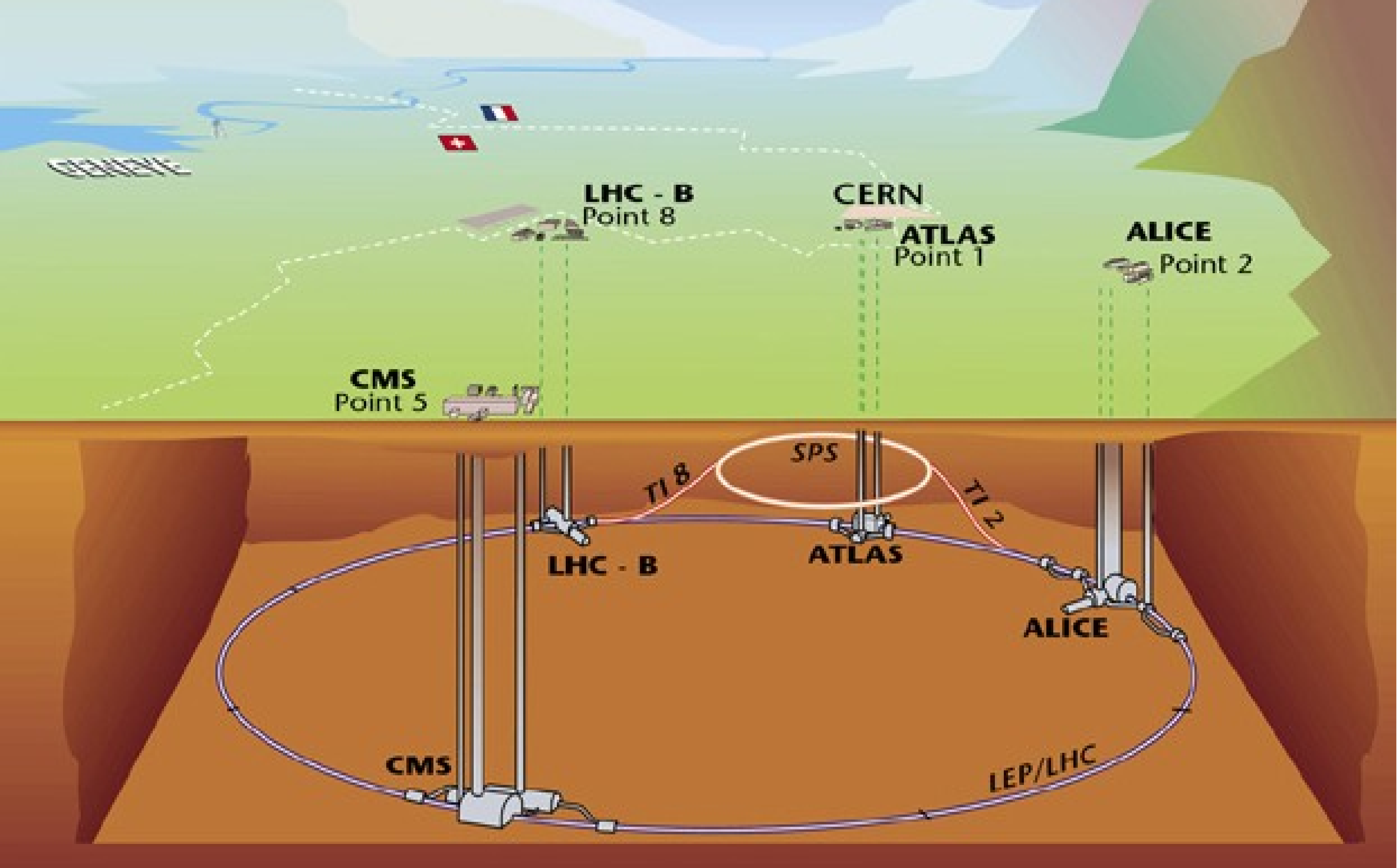
Plan

- This week
  - Thursday 8-10: lecture 1 and 2
  - Friday 10-12: lecture 3 and 4
- Next week
  - Monday 8-10: lecture 5 + group work on project
  - Tuesday 10-12: presentation + lecture 6
- If time: polarized protons at RHIC

Inspiration and slides

- “A BRIEF HISTORY AND REVIEW OF ACCELERATORS”, P.J. Bryant
- “Accelerator Physics”, S.Y.Lee, 2nd edition.
- Reviews of Accelerator Science and Technology Volume 1
- Lectures by Anders Oskarsson
- Lectures by Eric Torrence (University of Oregon)
- LHC lectures by Danillo Vranic

My main example will be LHC!



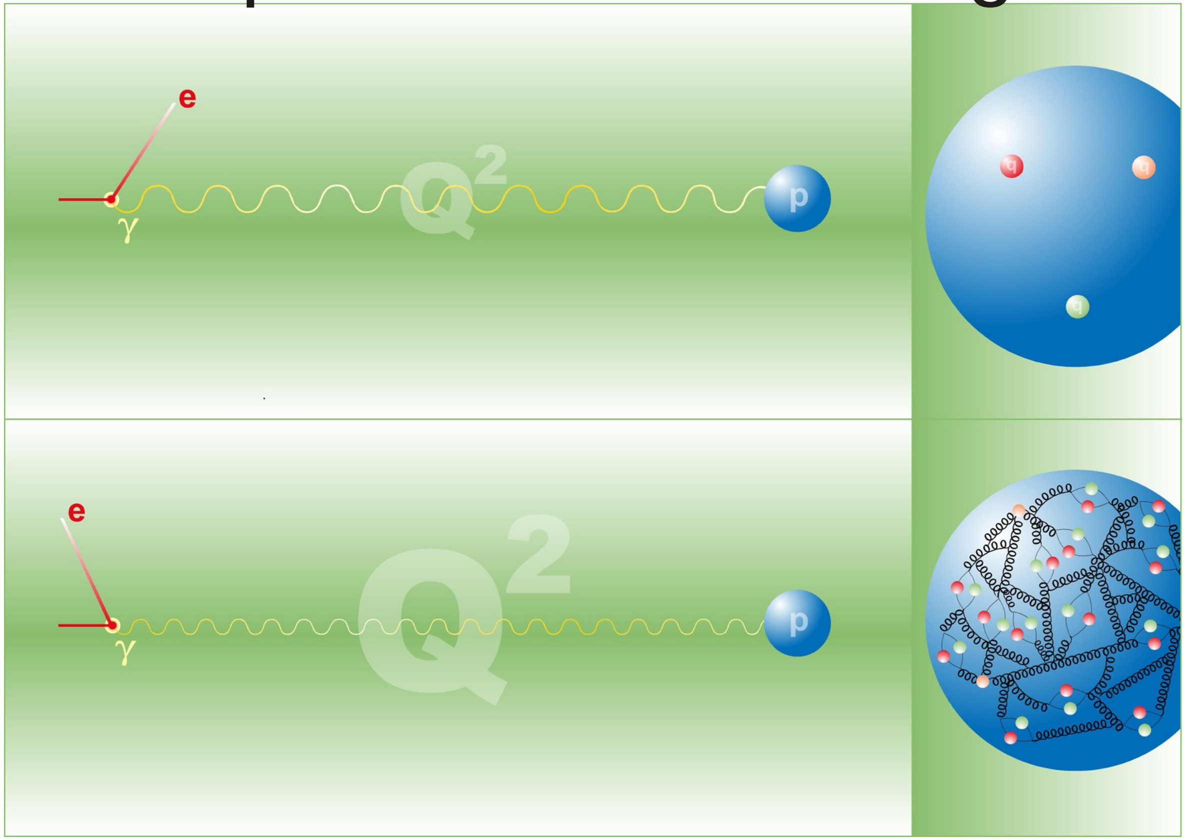
Think break

- Lecture 1 and 2: Introduction
  - Why do we accelerate?
  - What are the important parameters for characterizing accelerators

Why do we accelerate?

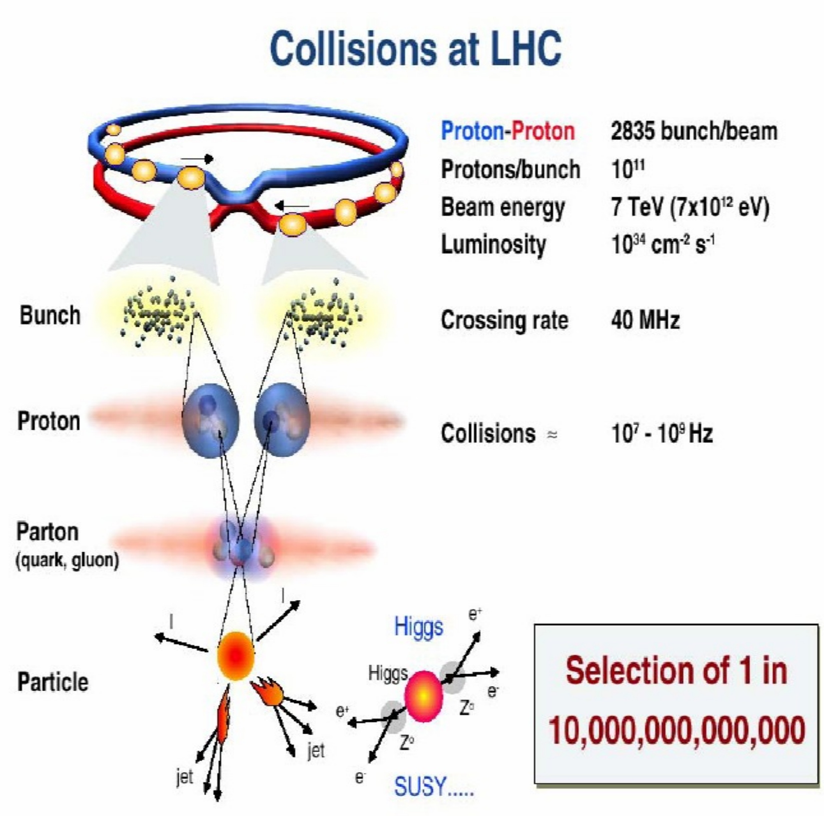
To probe the structure of e.g. protons

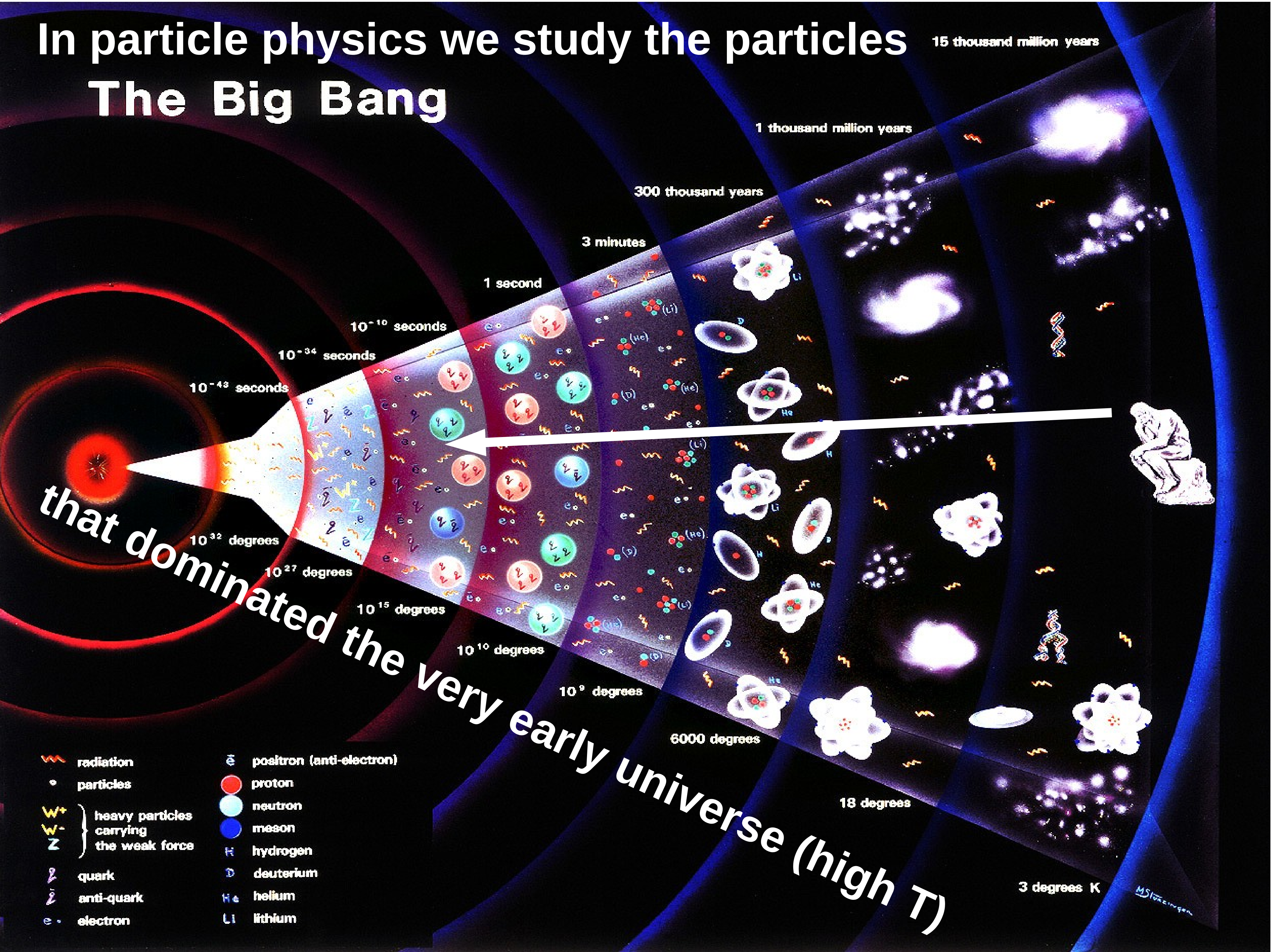
- The wavelength λ ~ hbar/E
  - Need big E to see small structures!
- Example: deep inelastic scattering



To create new particles

- Convert kinetic energy into mass ($E=mc^2$)
- Example:





In particle physics we study the particles
that dominated the very early universe (high T)
The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

What are the main characteristics of an accelerator

- Energy and Luminosity!
  - The rest of these 2 lectures will be about that!

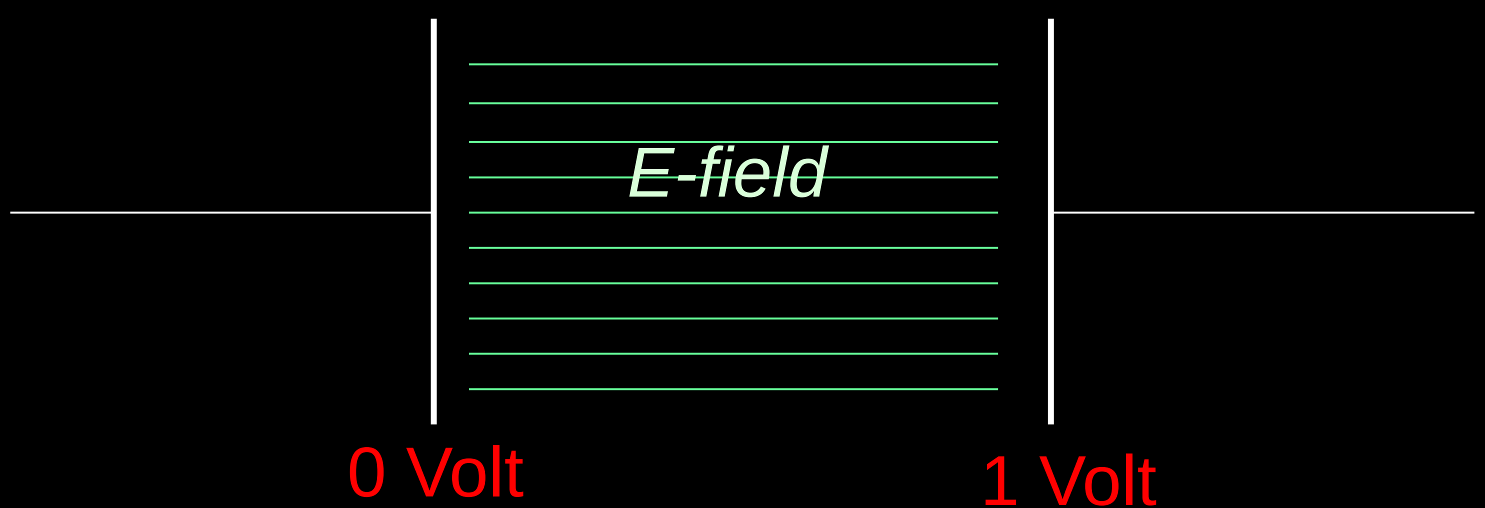
What is the relevant energy?

- We need to calculate the CM energy
- Two interesting limits
  - Fixed target (1 beam + stationary target)
  - Collider (beam-beam collisions)
- Make calculation!

Units of energy

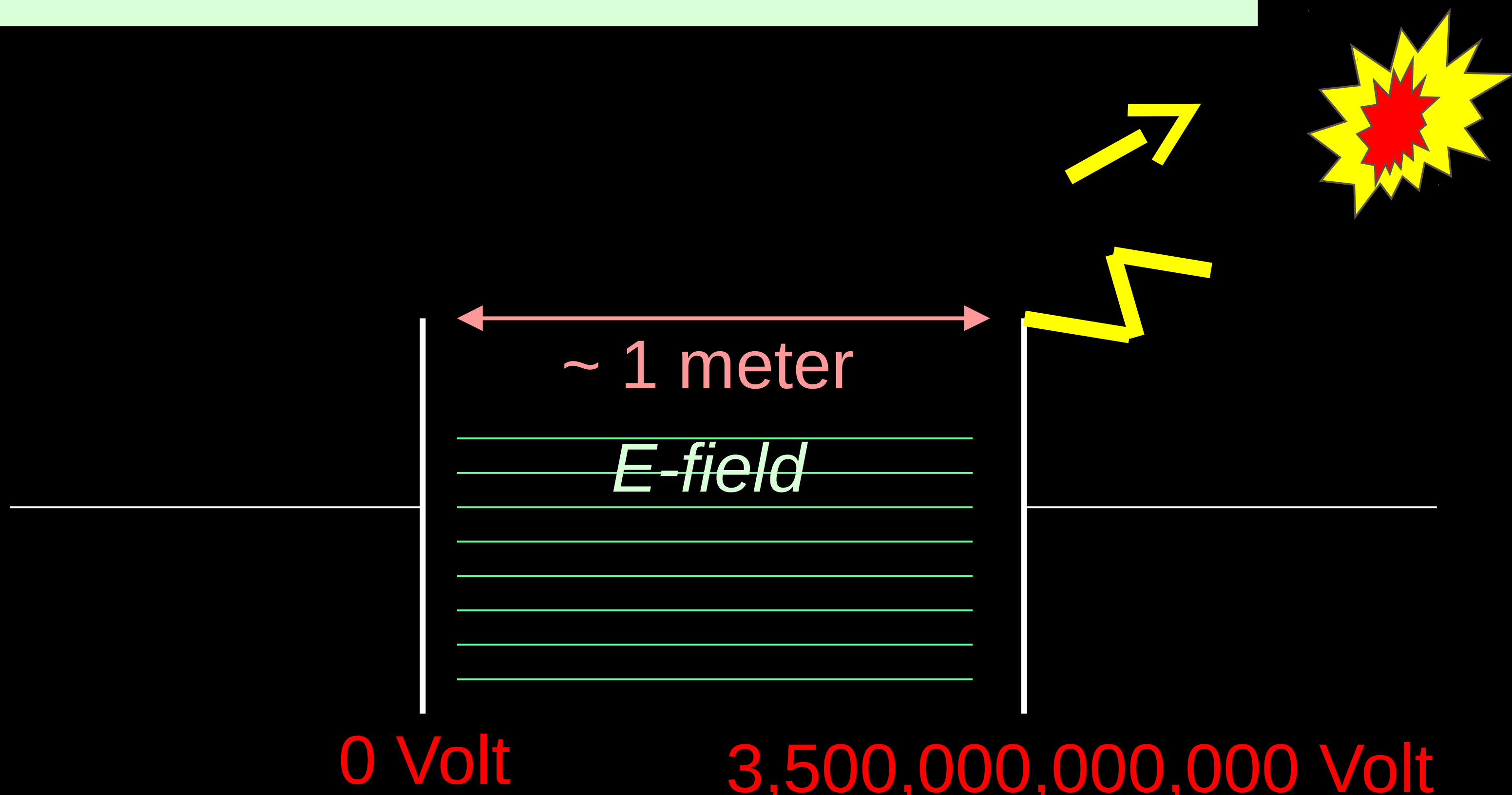
A charged particle with charge
+e gains an energy of 1eV (electronVolt)
when passing a voltage gap of 1Volt

1eV is $1.6*10^{-19}$ Joule

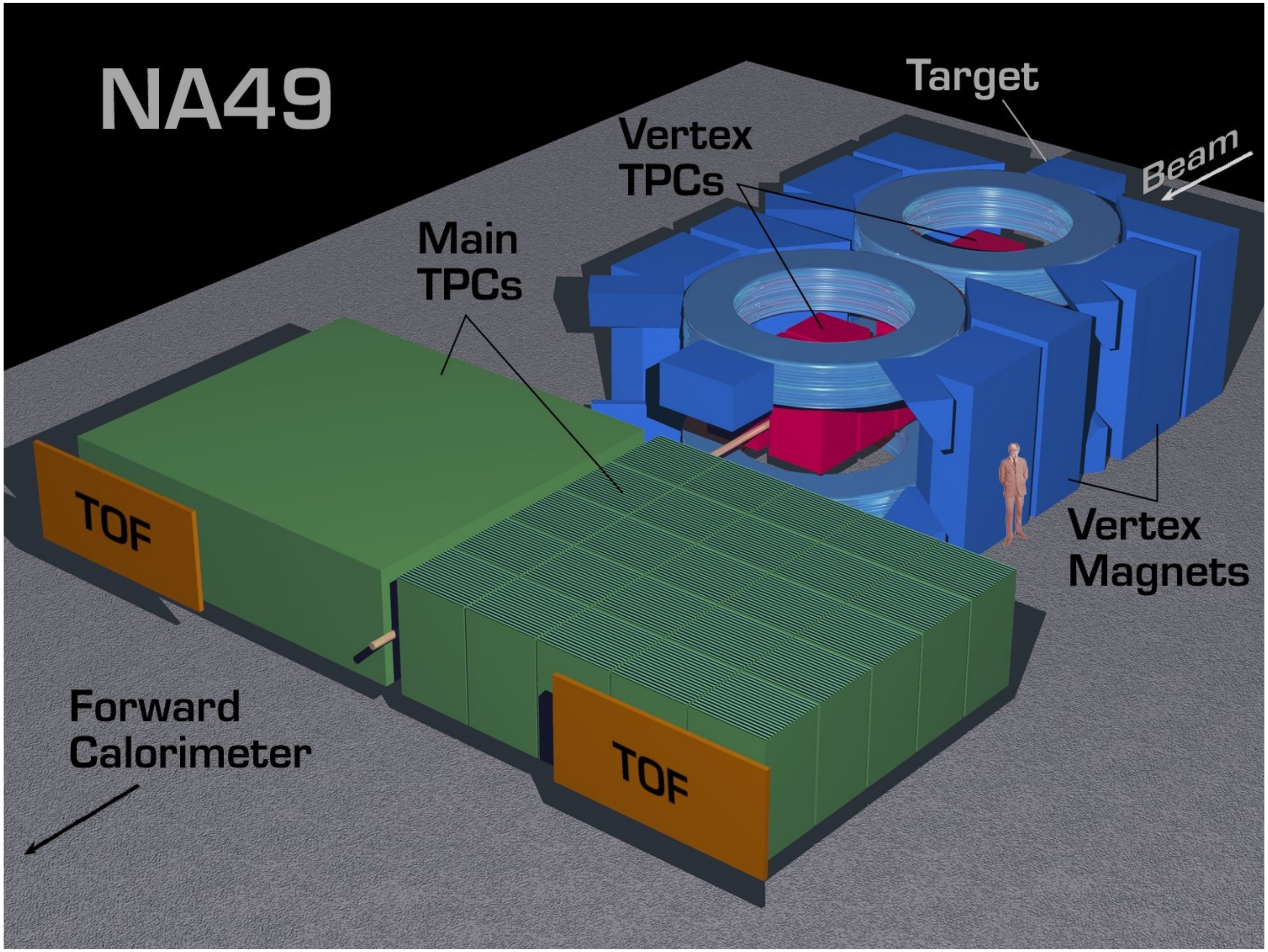


The “LHC” in 1m?
(√s = 7 TeV)

How to accelerate will be covered in lectures 3 and 4!



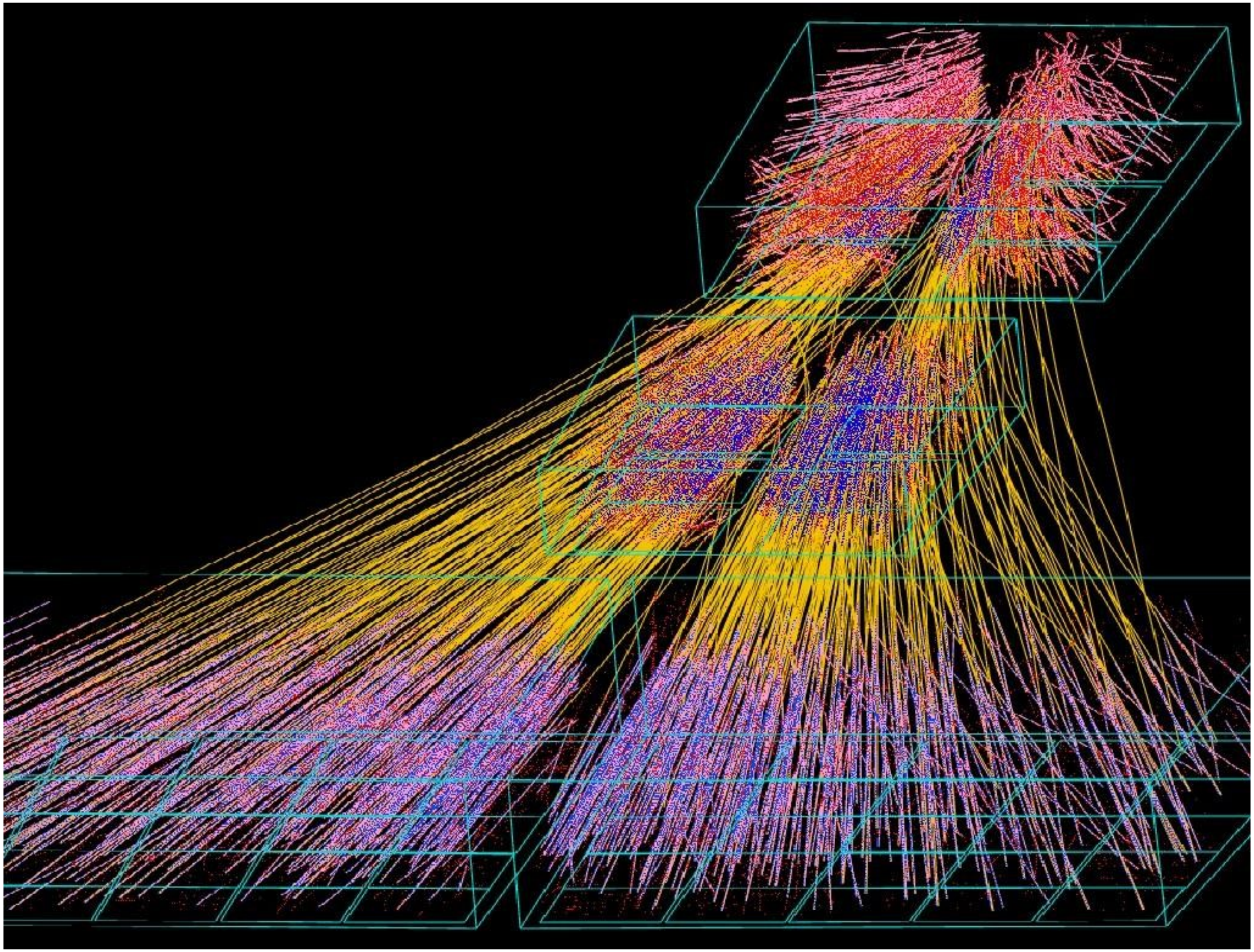
Example fixed target at CERN SPS



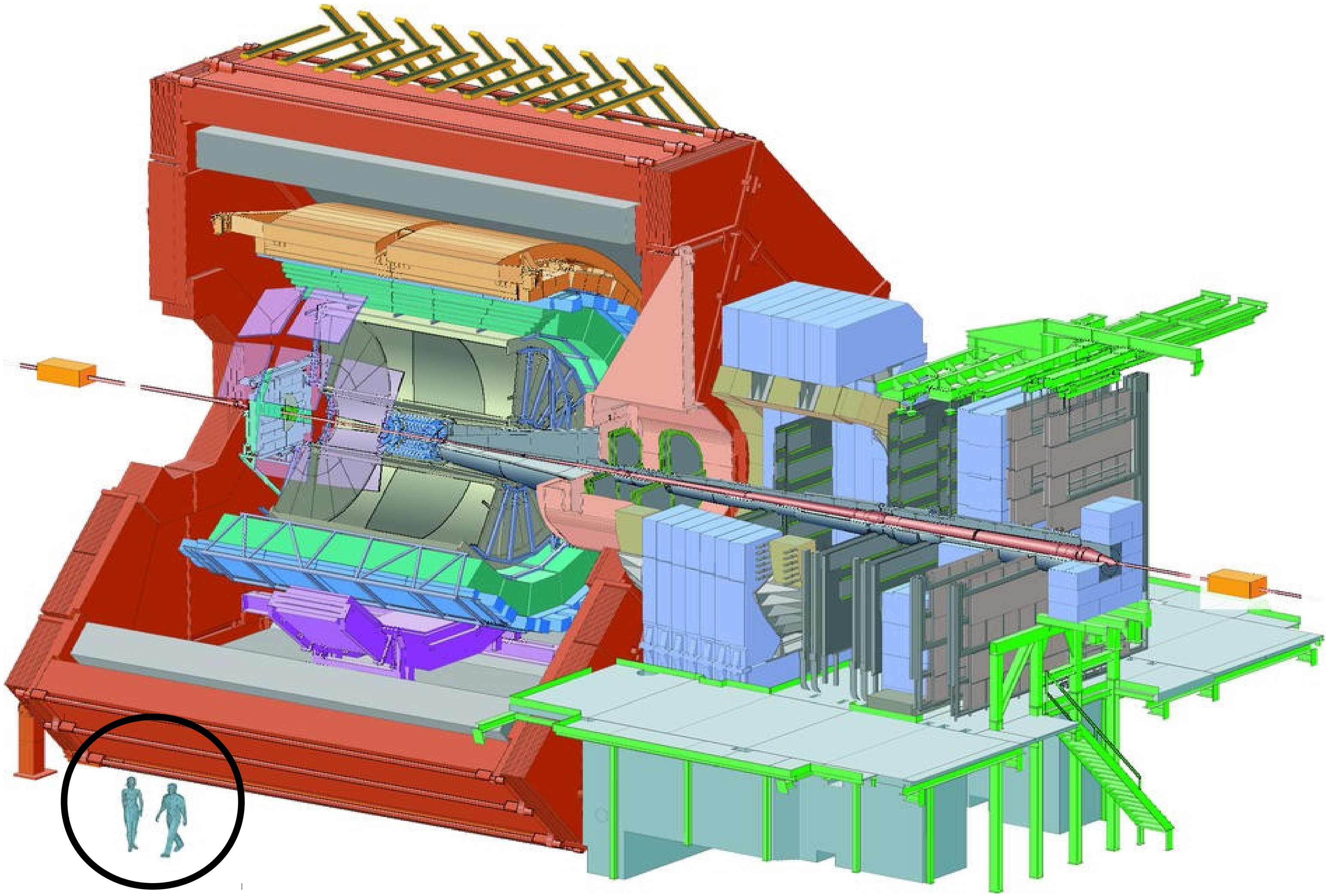
Pb at
160 A GeV

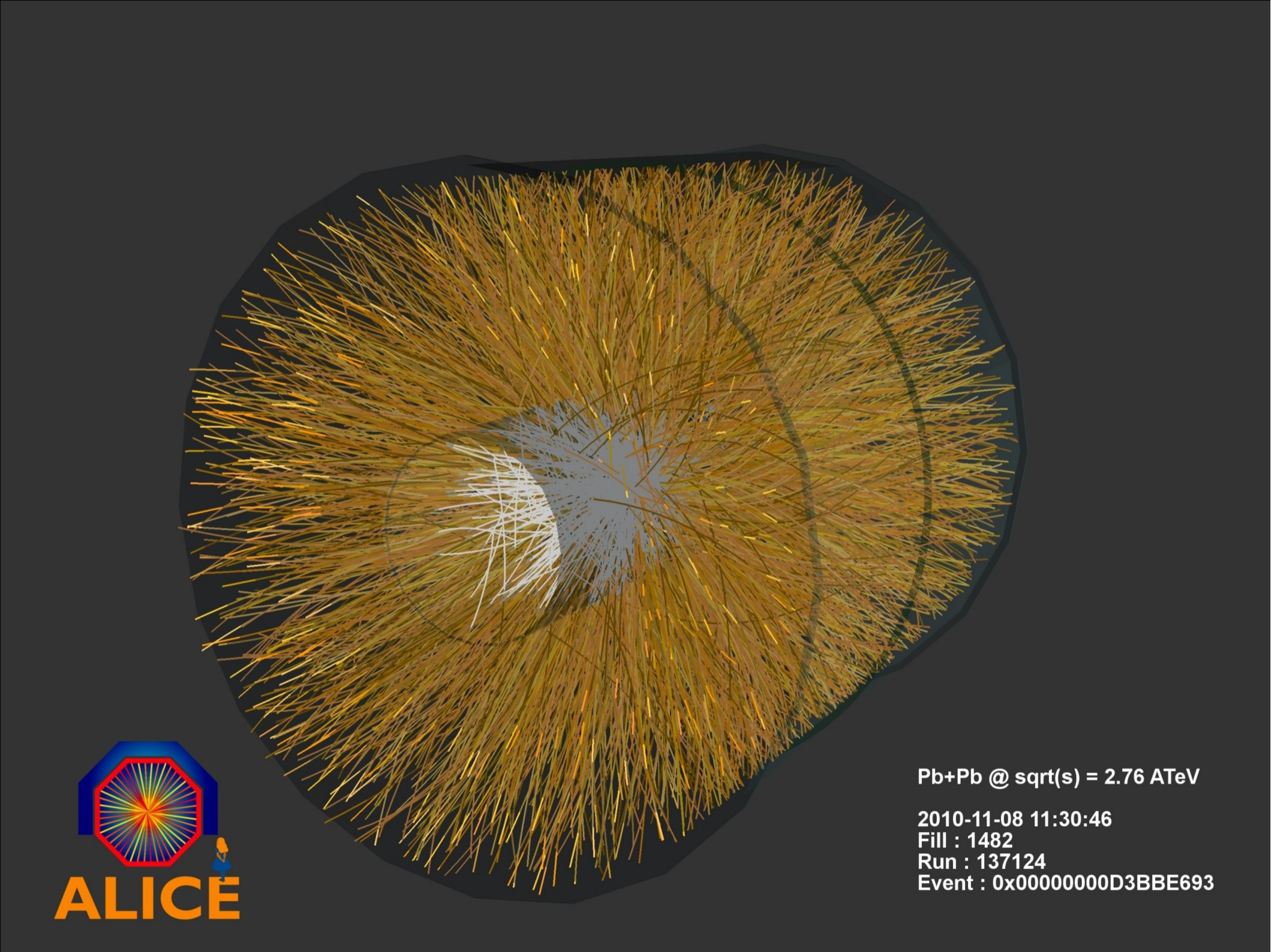
Reconstructed event

High p in lab system
Focused forward
in space
Very long exp. setup

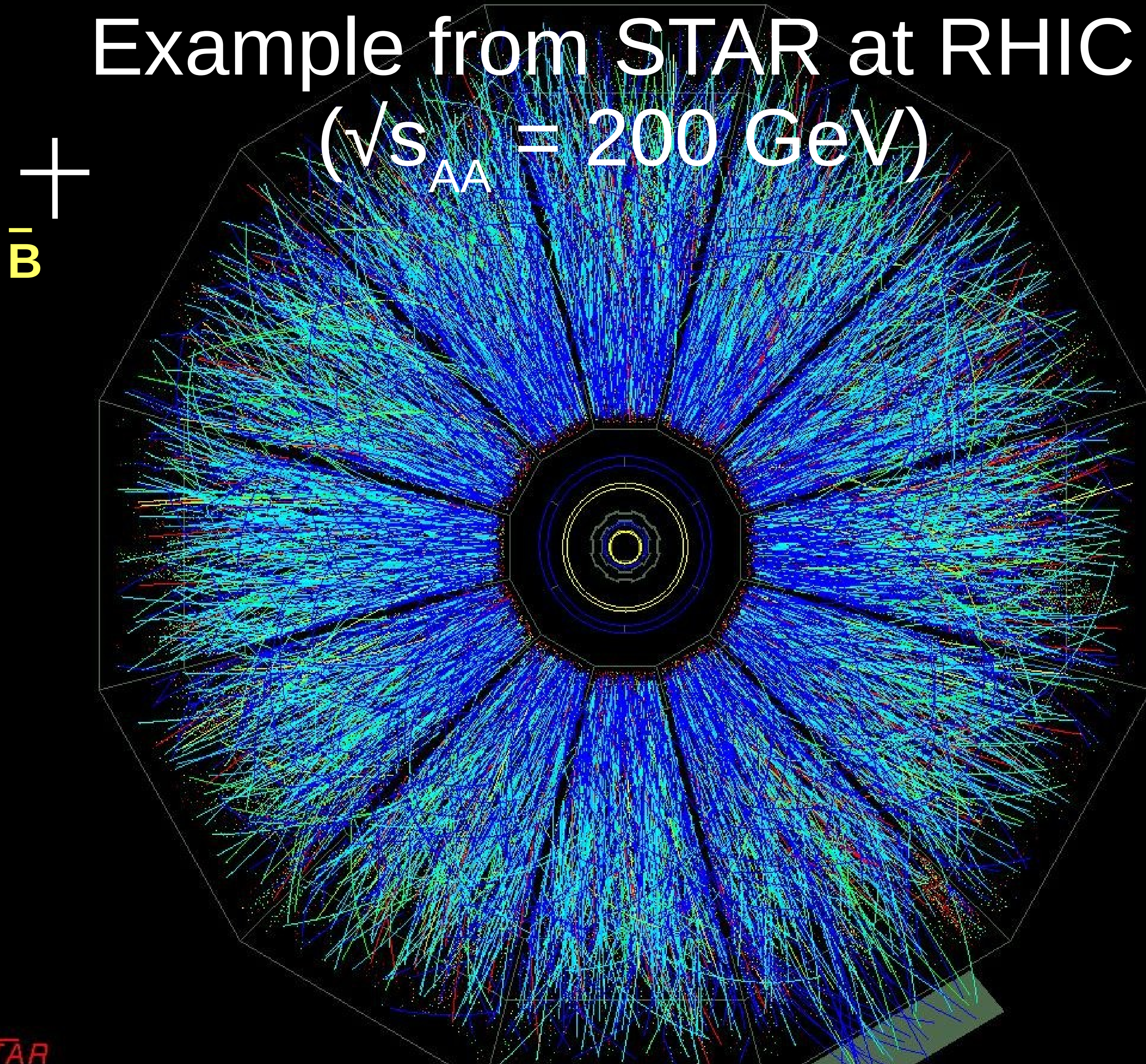


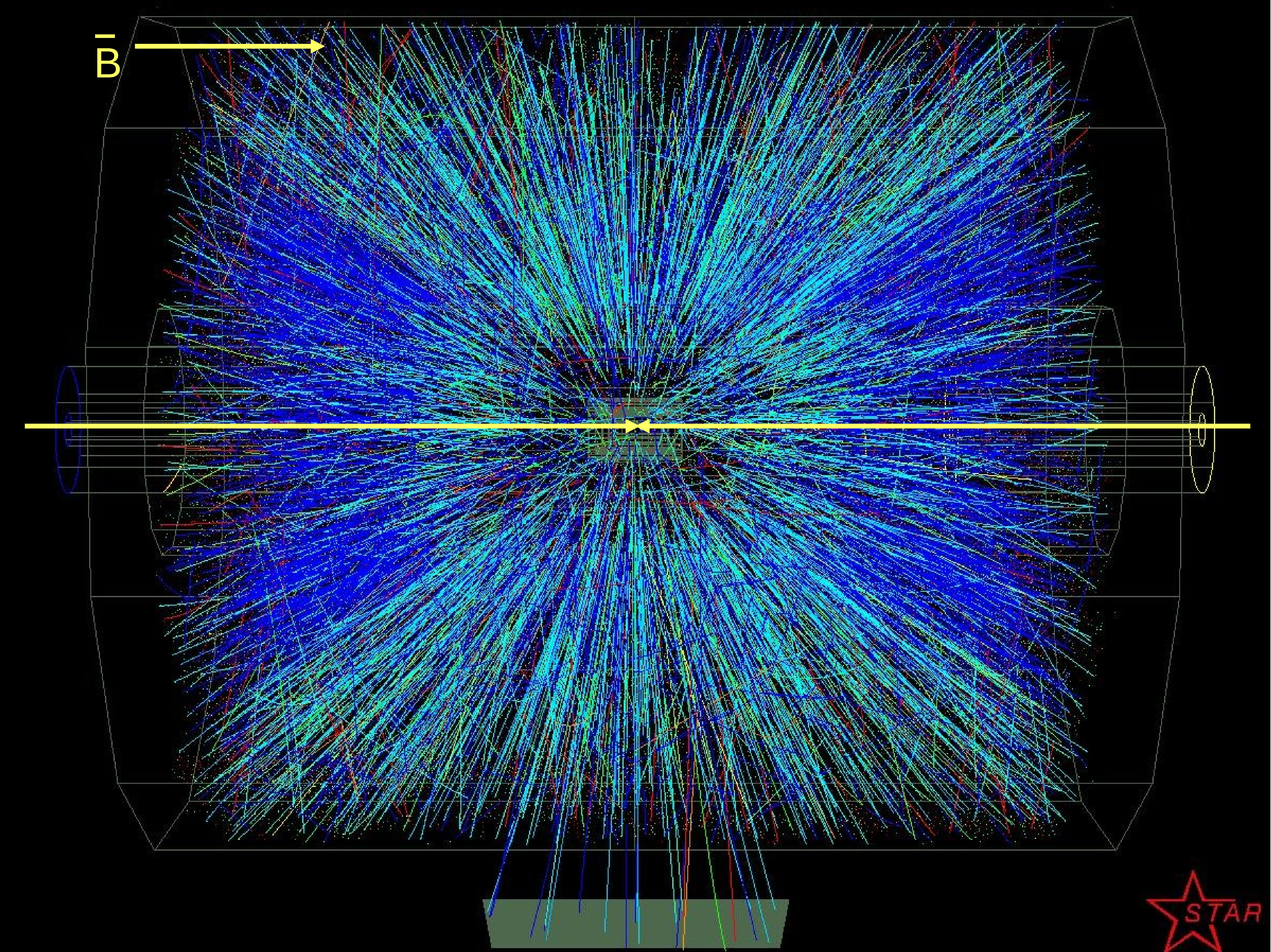
The ALICE experiment at LHC




Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
ALICE

Example from STAR at RHIC
($\sqrt{s_{AA}}$ = 200 GeV)

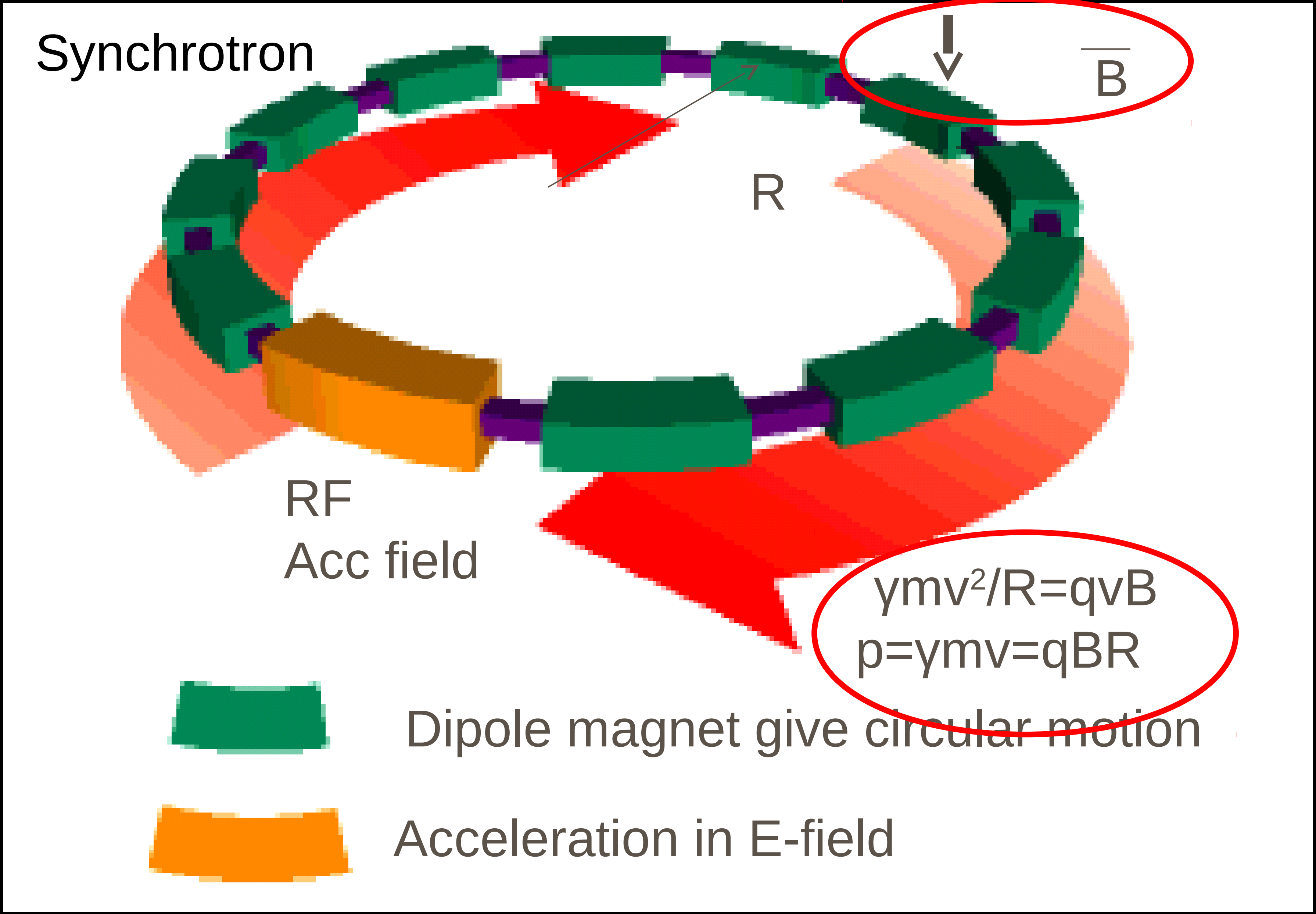



B̄

What limits the energy in a collider?

- Why can't the LHC run at, e.g., $\sqrt{s}$=20TeV?

The magnetic field! $p[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]$



BENDING

$$B \cdot \rho = p / e \qquad B \cdot \rho [Tm] = 0.299792458 \cdot p [GeV / c]$$

For a given radius maximum energy for proton synchrotron is limited by the maximal magnetic field.

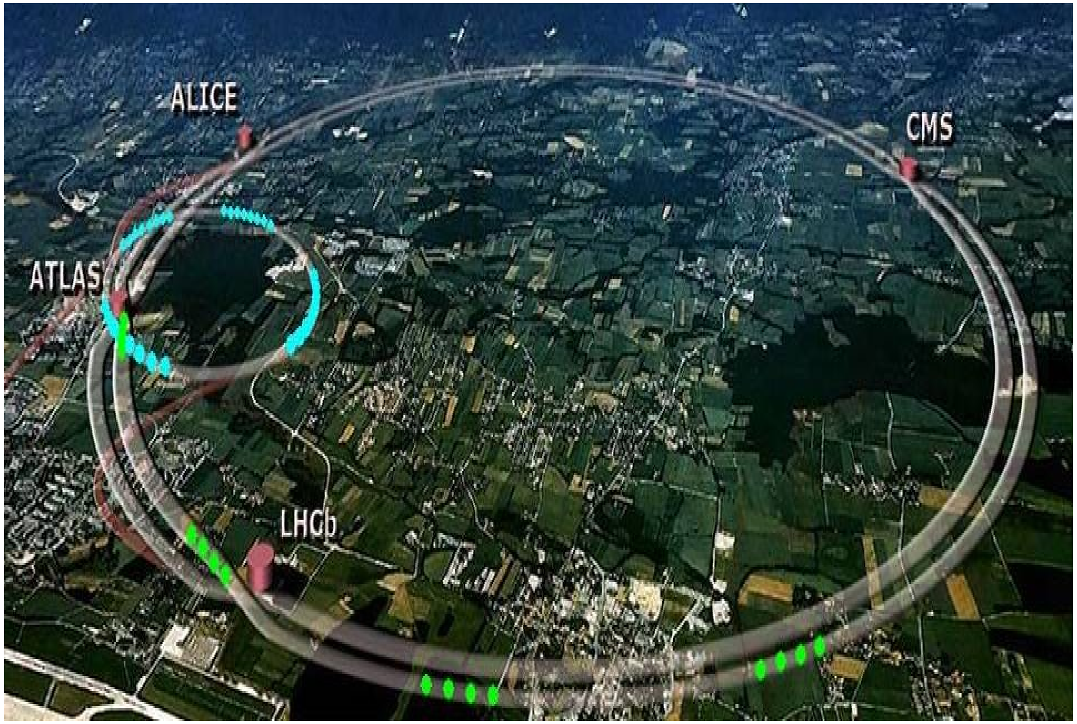
For LHC B_{max} =8.33T and bending radius 2803m we have

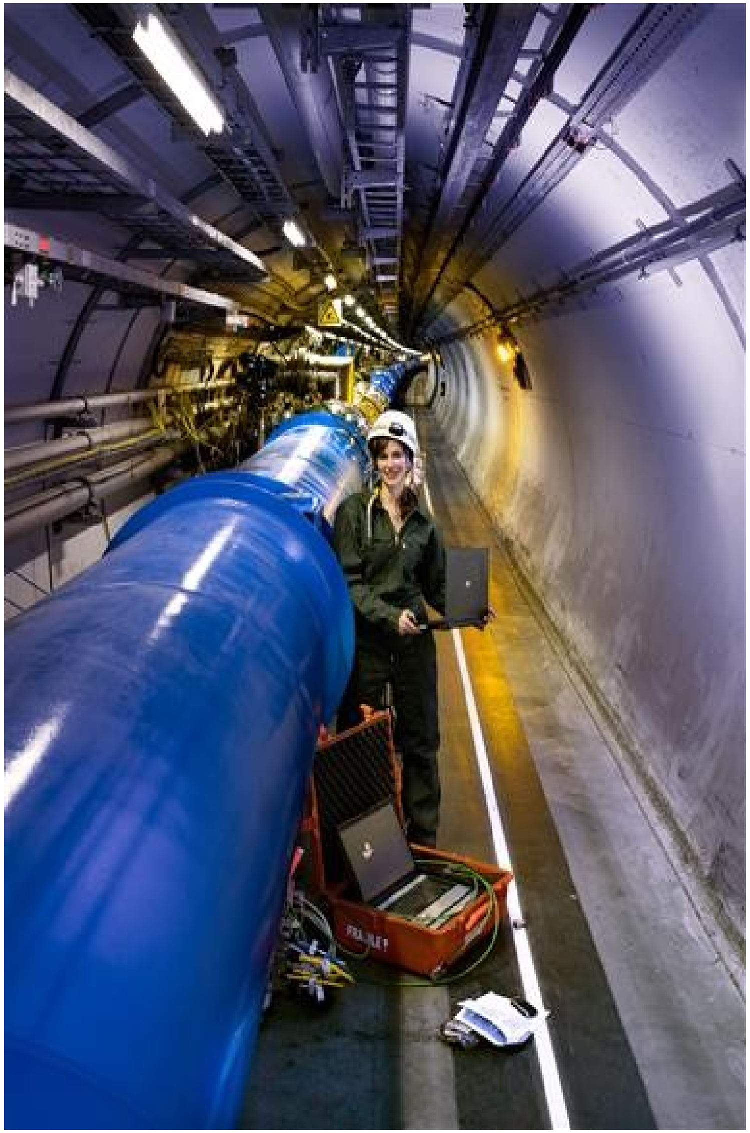
$$p = \frac{8.33 \cdot 2803}{0.3} = 7000 \, GeV / c$$

But LHC ring circumference is 26658.8832m and $R_{ave} = \frac{26658.8832}{2\pi} = 4242.9m$

We need room for focusing (SSS = short straight sections) and insertions.

Large Hadron Collider (LHC)





$$\sqrt{s} = 7 TeV (14 TeV, 2014)$$

$(vs\ 0.2\ TeV\ LEP)$

$(vs\ 1.8\ TeV\ Tevatron)$

Collides hadrons (protons and ions) instead of electrons.

Why protons?
Synchrotron Radiation

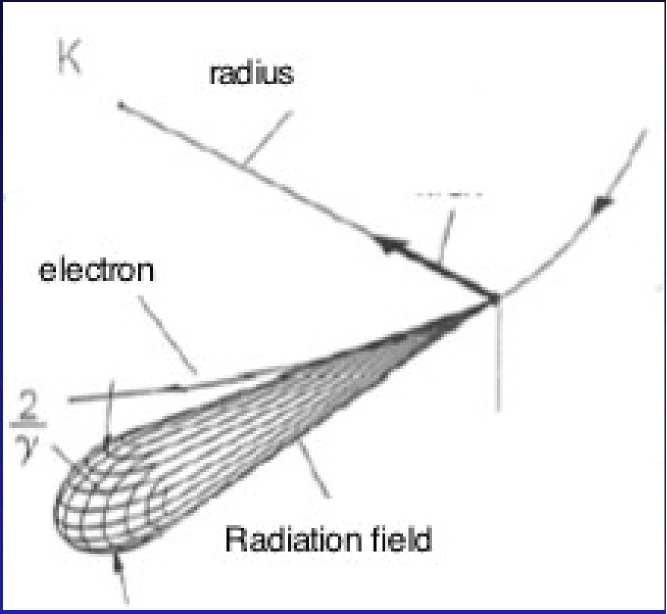
- Linear Acceleration

$$P_s = \frac{e^2 c}{6\pi\epsilon_0 (m_0 c^2)^2} \left(\frac{dE}{dx}\right)^2$$

10 MV/m -> 4 10^{-17} Watts

- Circular Acceleration

$$P_s = \frac{e^2 c}{6\pi\epsilon_0 (m_0 c^2)^2} \frac{E^4}{R^2}$$



Radius must grow quadratically with beam energy!

LEP Accelerator (CERN 1990-2000)

- 27 km circumference
- 4 detectors
- e^+e^- collisions
  - LEPI: 91 GeV
    - 125 MeV/turn
    - 120 Cu RF cavities
  - LEPII: < 208 GeV
    - **~3 GeV/turn**
    - 288 SC RF cavities

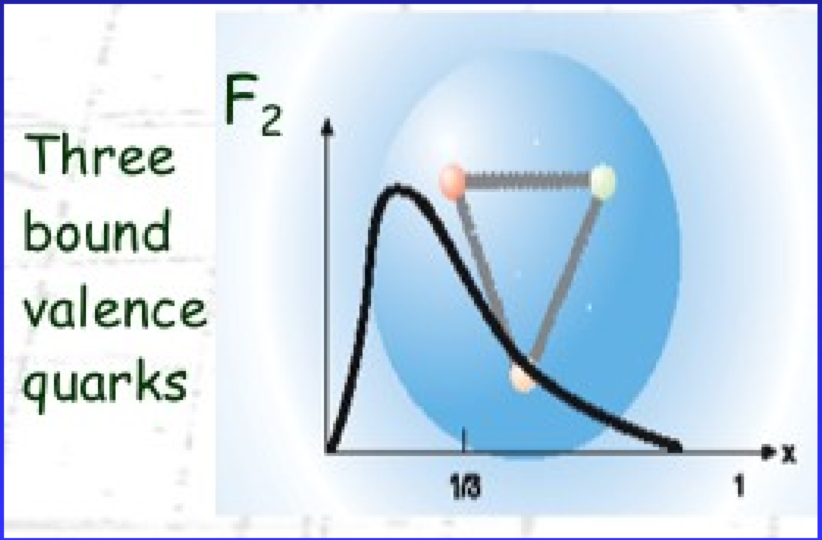
Protons vs. Electrons

$$P_s \propto \frac{E^4}{m_0^2 R^2}$$

- Can win by accelerating protons

$$\left(\frac{m_p}{m_e}\right)^2 = \left(\frac{938\text{MeV}}{0.511\text{MeV}}\right)^2 = 3.4 \times 10^6$$

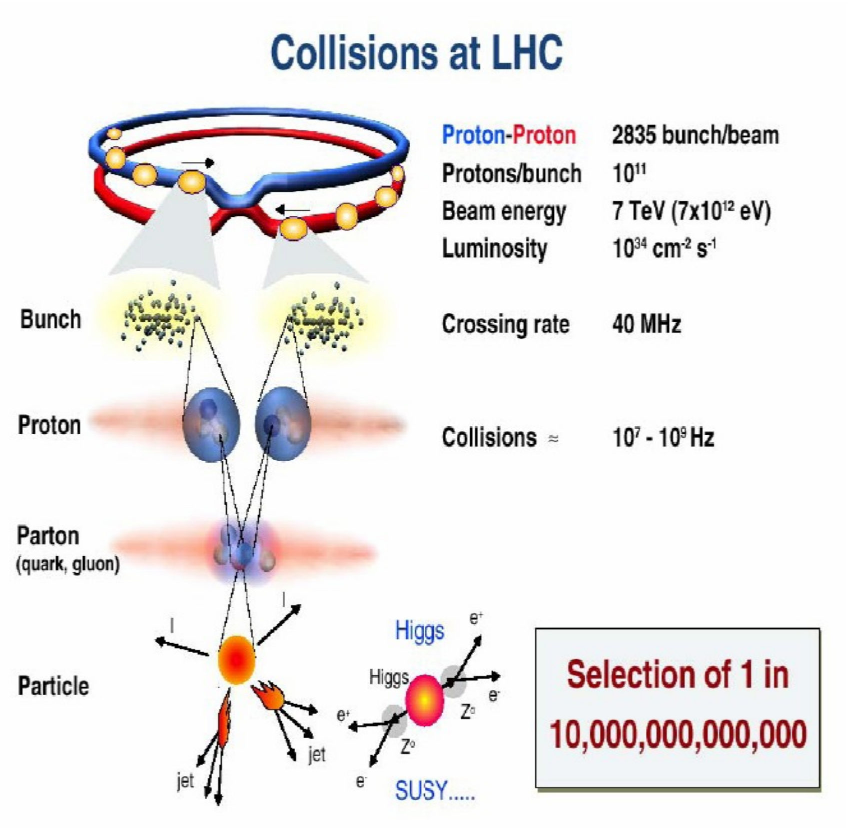
- But protons aren't fundamental



Only small fraction at highest energy
Don't know energy (or type) of colliding particles

LHC (and proton colliders in general) are discovery machines!

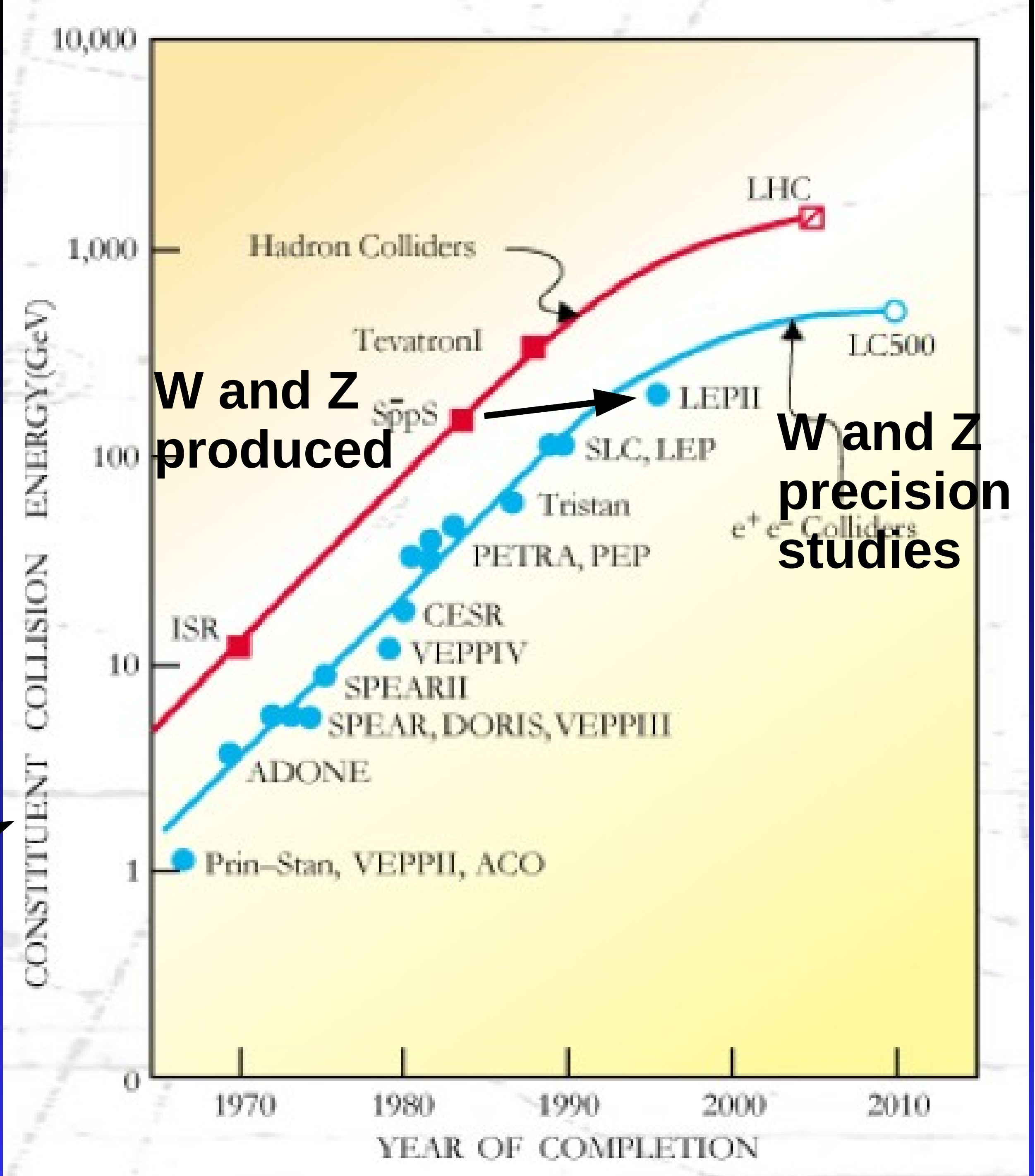
- We sacrifice the precise knowledge of the initial collision to reach unprecedented energies



History of accelerator energies

e^+e^- machines typically match hadron machines with x10 nominal energy

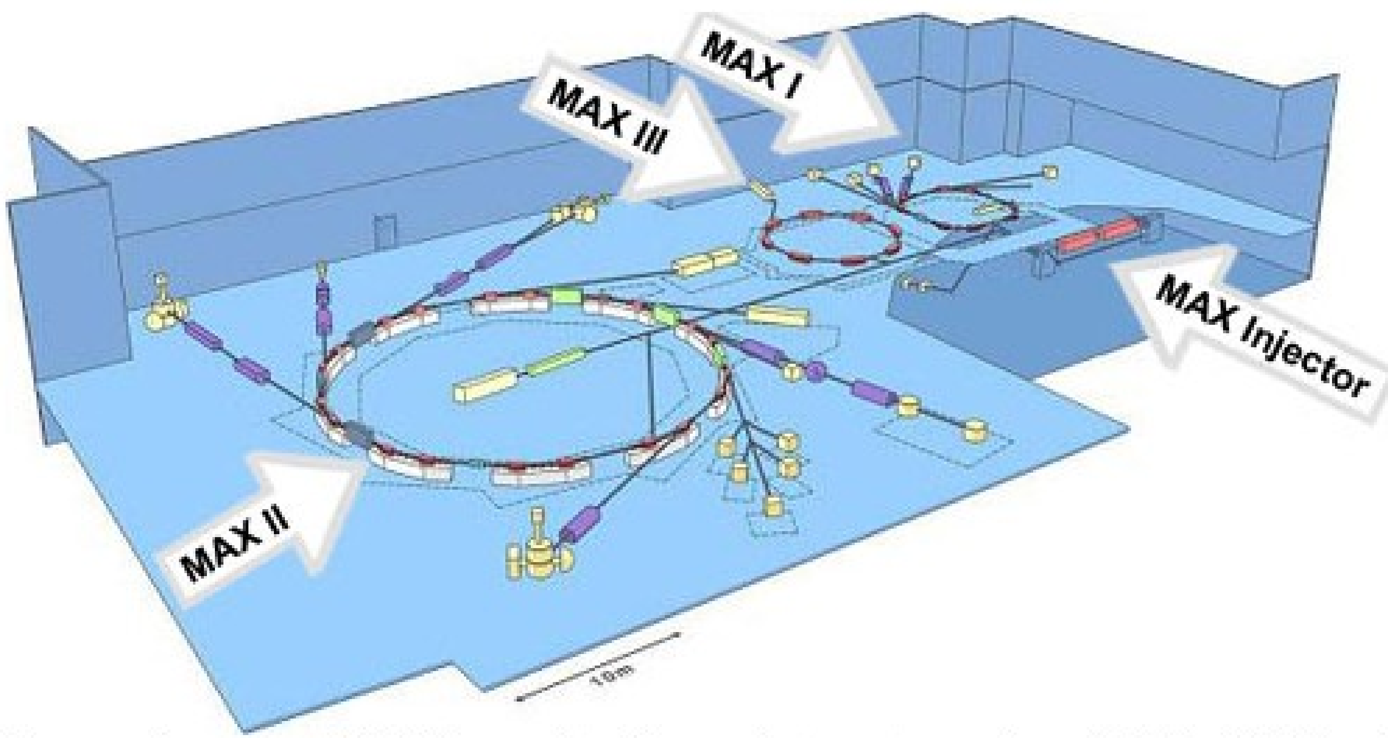
NB! Not CM energy for hadrons but some fraction (parton)



M. Tigner, Physics Today, January 2001

However – synchrotron light can itself be used for good physics

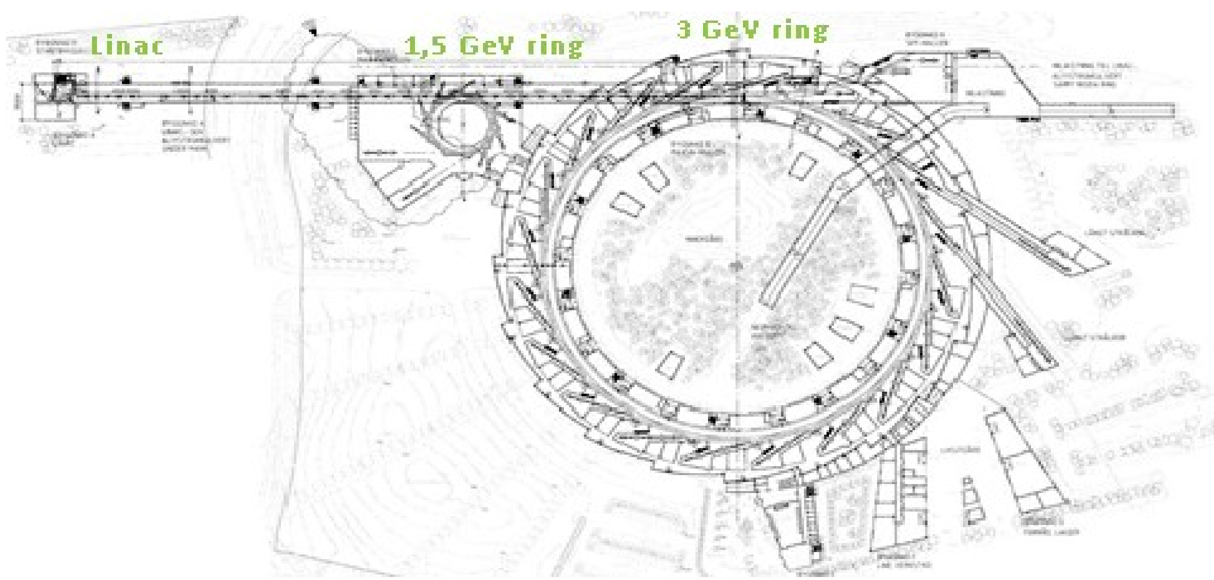
MAX-lab Accelerators



The accelerators at MAX-lab consist of three electron storage rings (MAX I, MAX II and MAX III) and one electron pre-accelerator (MAX injector). All three storage rings produce synchrotron light used for experiments and measurements in a wide range of disciplines and technologies. The MAX I ring is also used as an electrons source for experiments in nuclear physics.

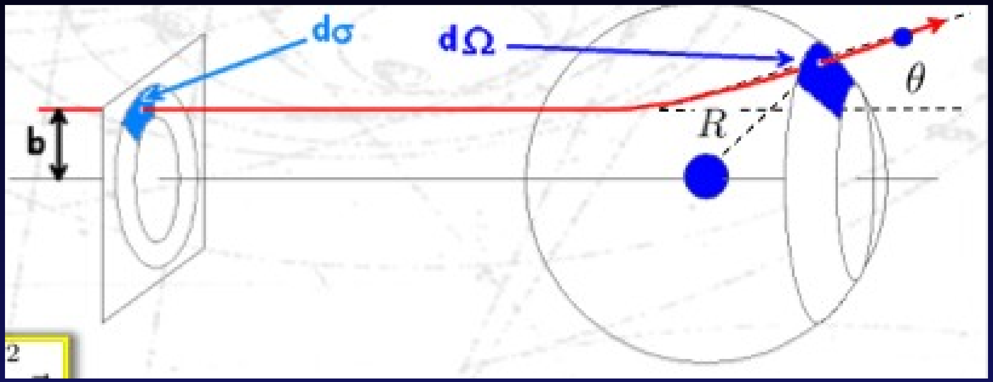
And maybe even good for your careers!

The MAX IV Laboratory - our future light source



Luminosity

Cross-section



- Area of target

  Hard Sphere - $\sigma = \pi r^2$

- Measured in barns = 10^{-28} m^2 = $100 fm^2$

  10 mbarn = 1 fm^2 - ~size of proton

- Cross-section depends upon process

$e^+e^- \to W^+W^-$ about 16 pb (others fb or less)

$e^+e^- \to e^+e^-$ technically infinite (E field)

Luminosity

- Intensity or brightness of an accelerator

$$N = \mathcal{L} \cdot \sigma$$

- Events Seen = Luminosity * cross-section

Rare processes (fb) need lots of luminosity (fb^{-1})

- In a storage ring

$$\mathcal{L} = \frac{1}{4\pi} \frac{f_u \cdot N_1 \cdot N_2}{\sigma_x \cdot \sigma_y}$$

Current

Spot size

More particles through a smaller area means more collisions

Collision rate

Collision rate is defined to be the number of 'events' per second, i.e. the number of collisions happening in the center of one of the experiments (depends on the cross section)

The collision rate can be increased if:

- There is more beam/bunch in the two rings (N_B,N_Y)
- There are more bunches colliding (k_b)
- The beam profiles, the size of the beam, at the interaction point, is small (σ_x,σ_y) -> β^*

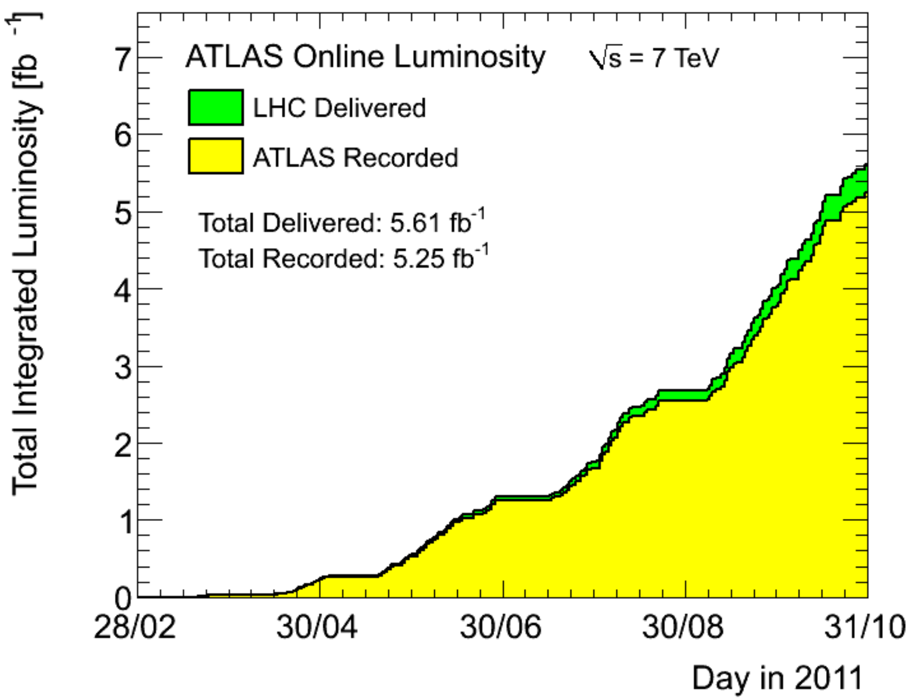
$$L = \frac{N_B N_Y}{4\pi\,\sigma_x \sigma_y} k_b f_{rev} \quad (\mathrm{cm}^{-2}\mathrm{s}^{-1})$$

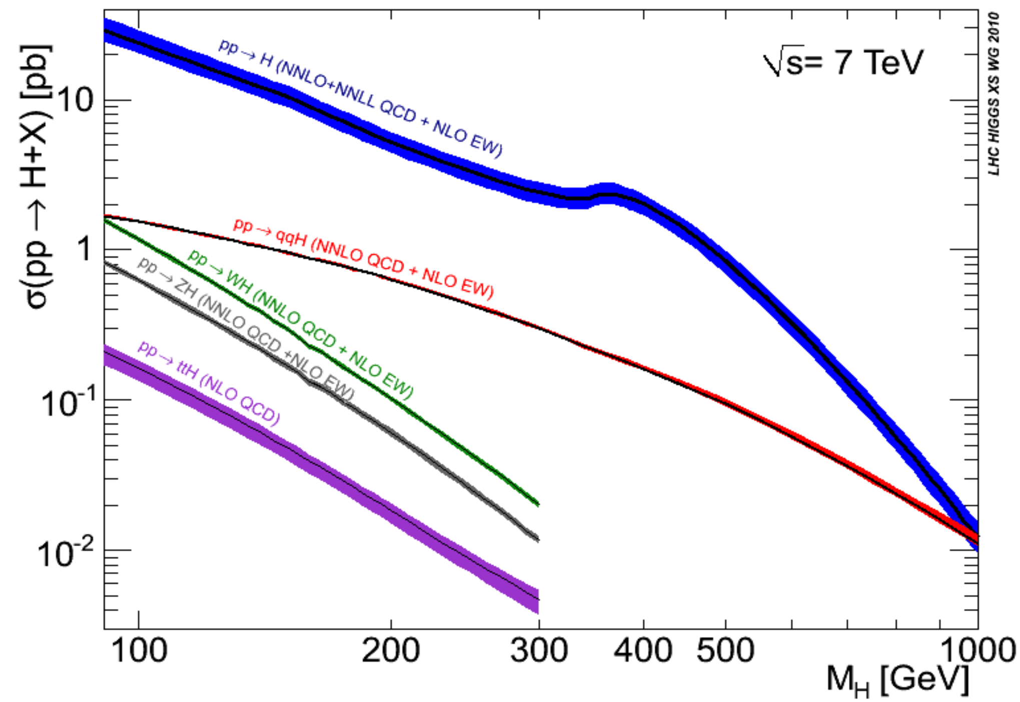
$R = L \cdot \sigma$

σ is the cross-section

R is the number of events per Second (corresponding to σ)

Higgs discovery at CERN
Status end of 2011



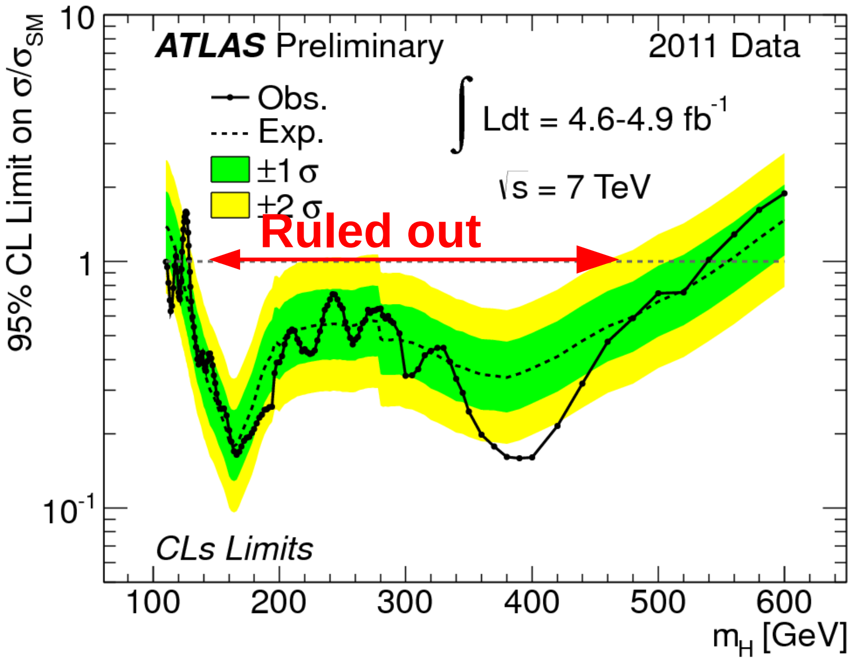


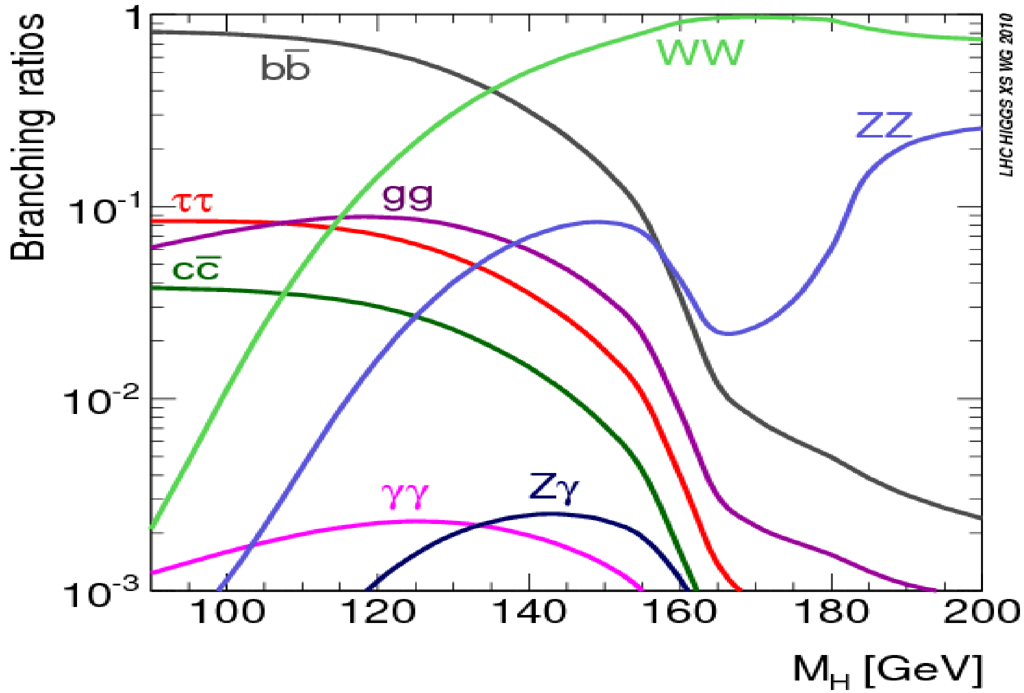
- What is the total # of produced Higgs's in the ATLAS experiment if m_H=130GeV?
- Answer: ~5fb^{-1}*10,000fb ~ 50,000!

Note that this corresponds to

- roughly
  - ~5,000,000,000,000mb^{-1}*~70 mb ~ 350,000,000,000,000 inelastic pp collisions in 2011!

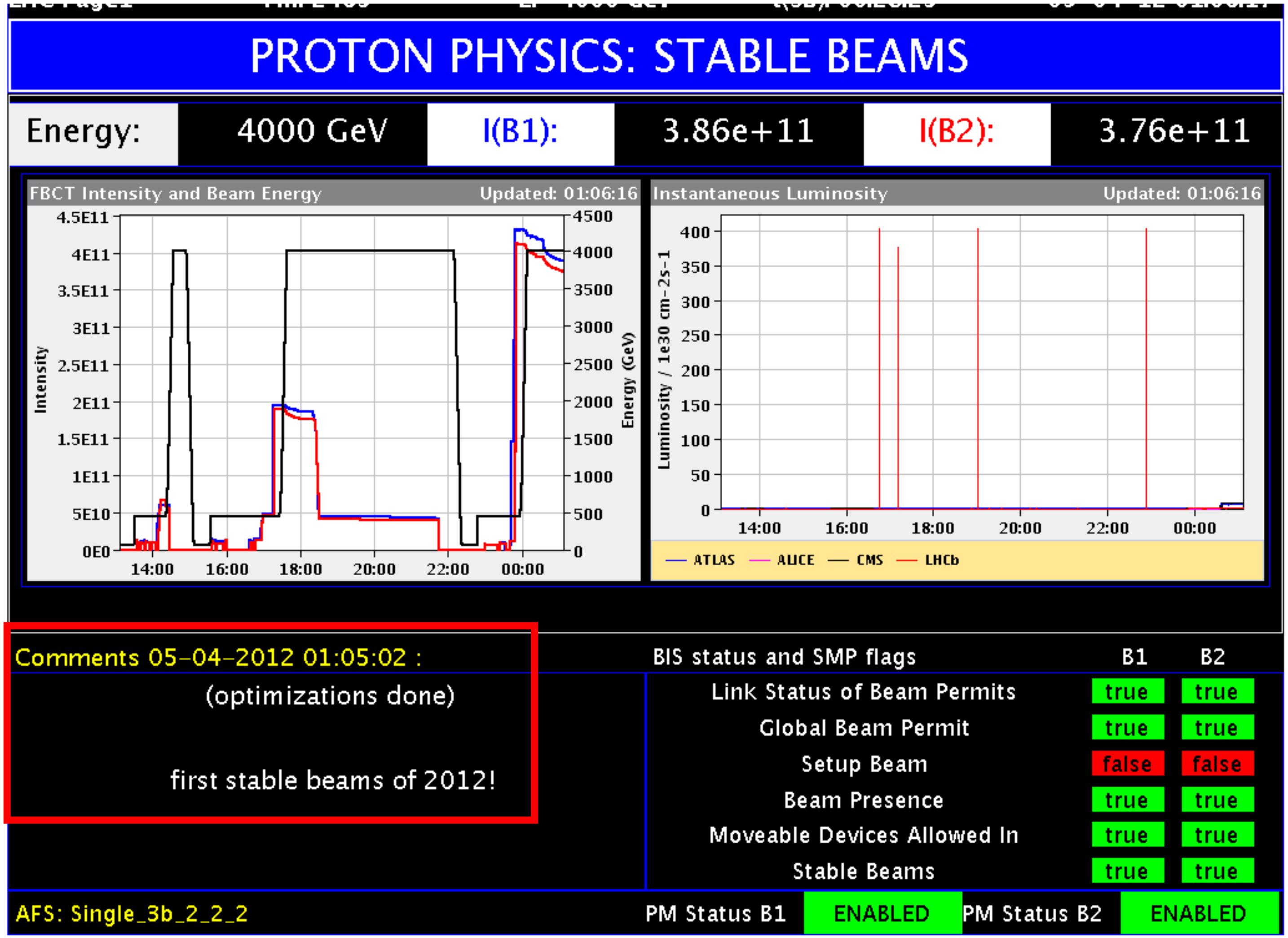
Higgs mass window
End of 2011





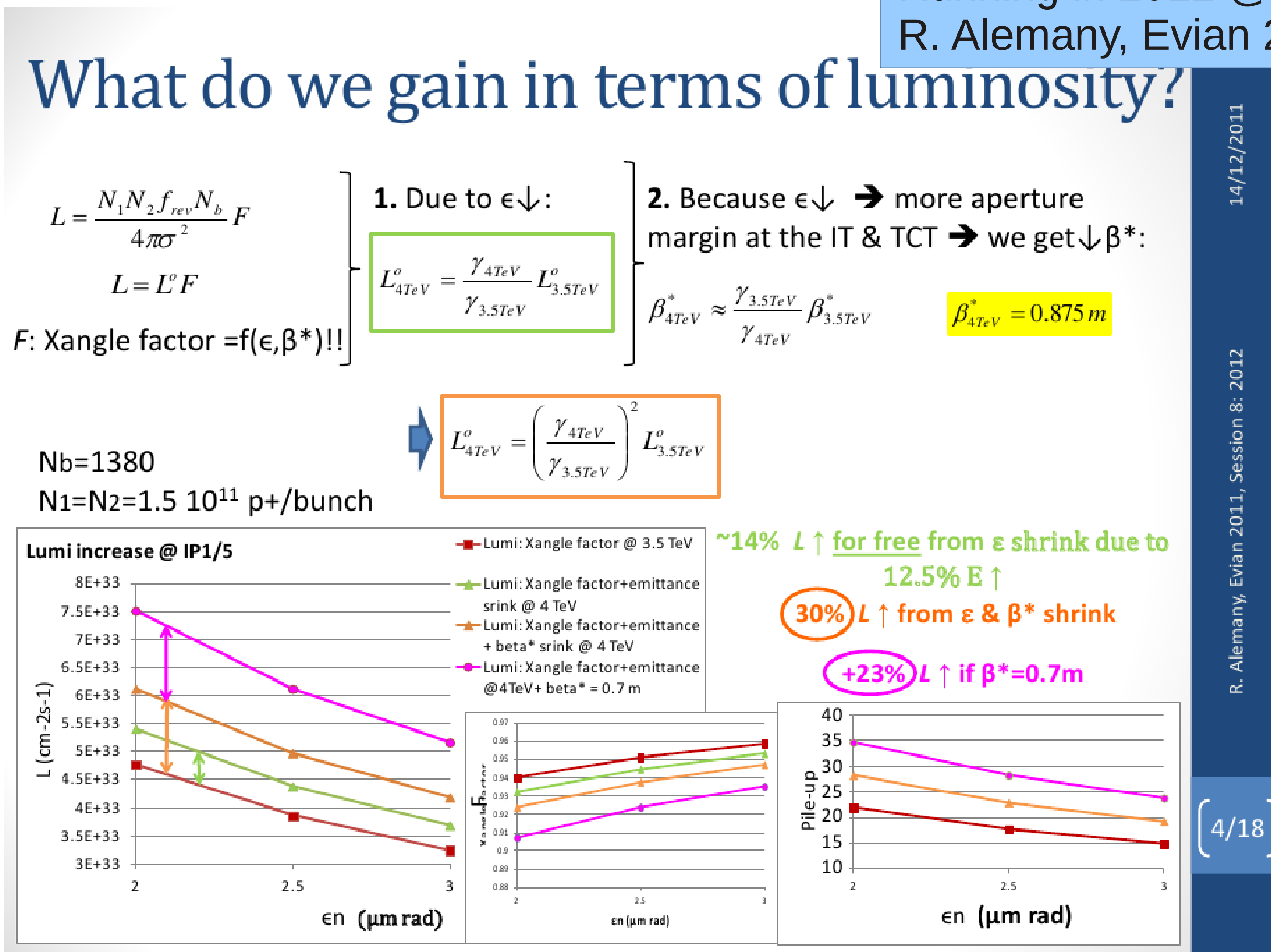
- Why is the limit not better at low mH where the cross section is larger?
- Answer: m_H too low for direct decay to 2W or 2Z = cleanest signatures!

Why LHC is running at 8 TeV in 2012 (1/3)



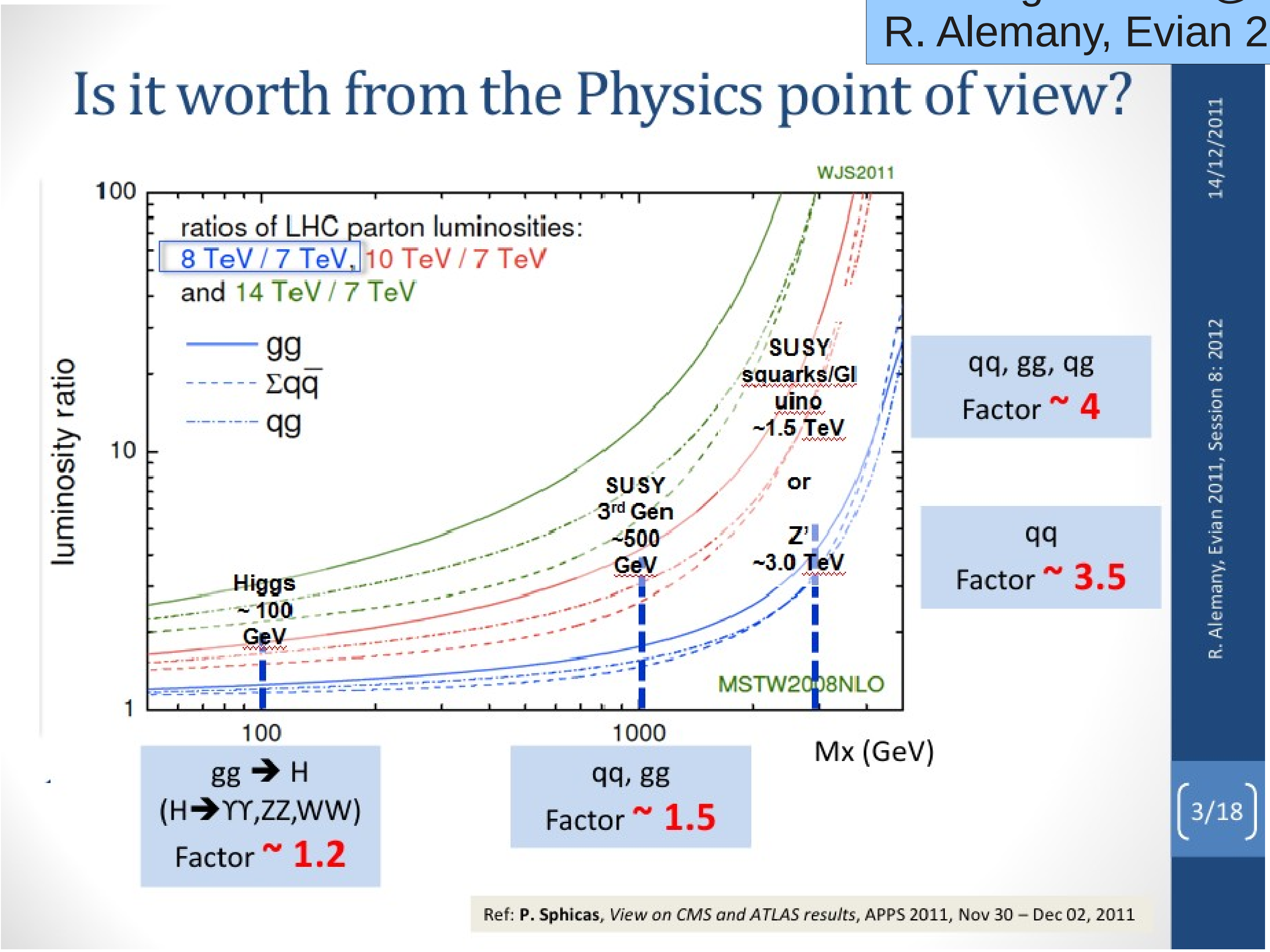
Why LHC is running at 8 TeV in 2012 (2/3) – Luminosity

Running in 2012 @ 4 TeV/beam
R. Alemany, Evian 2011.



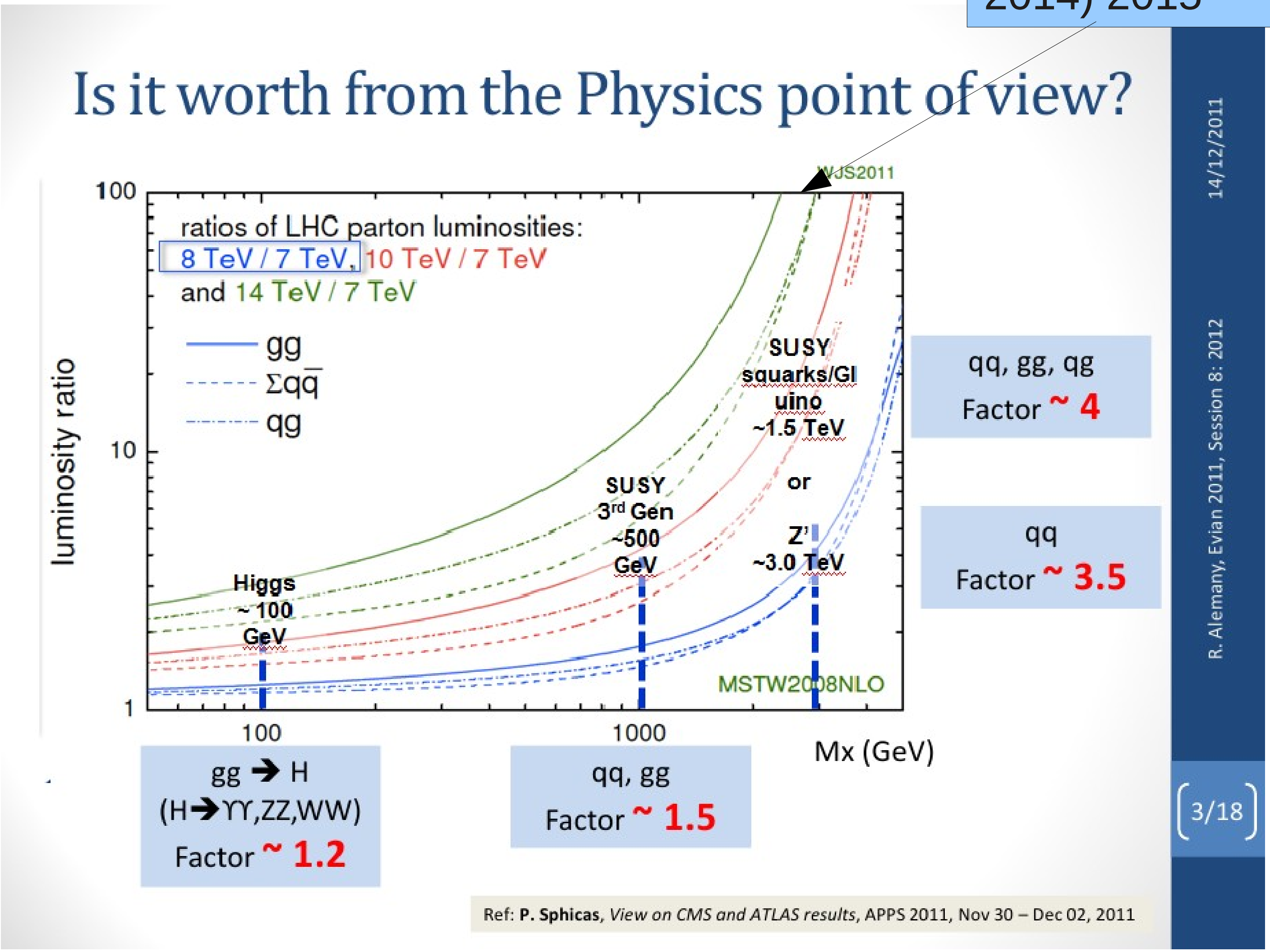
Why LHC is running at 8 TeV in 2012 (3/3) – Cross section

Running in 2012 @ 4 TeV/beam
R. Alemany, Evian 2011.

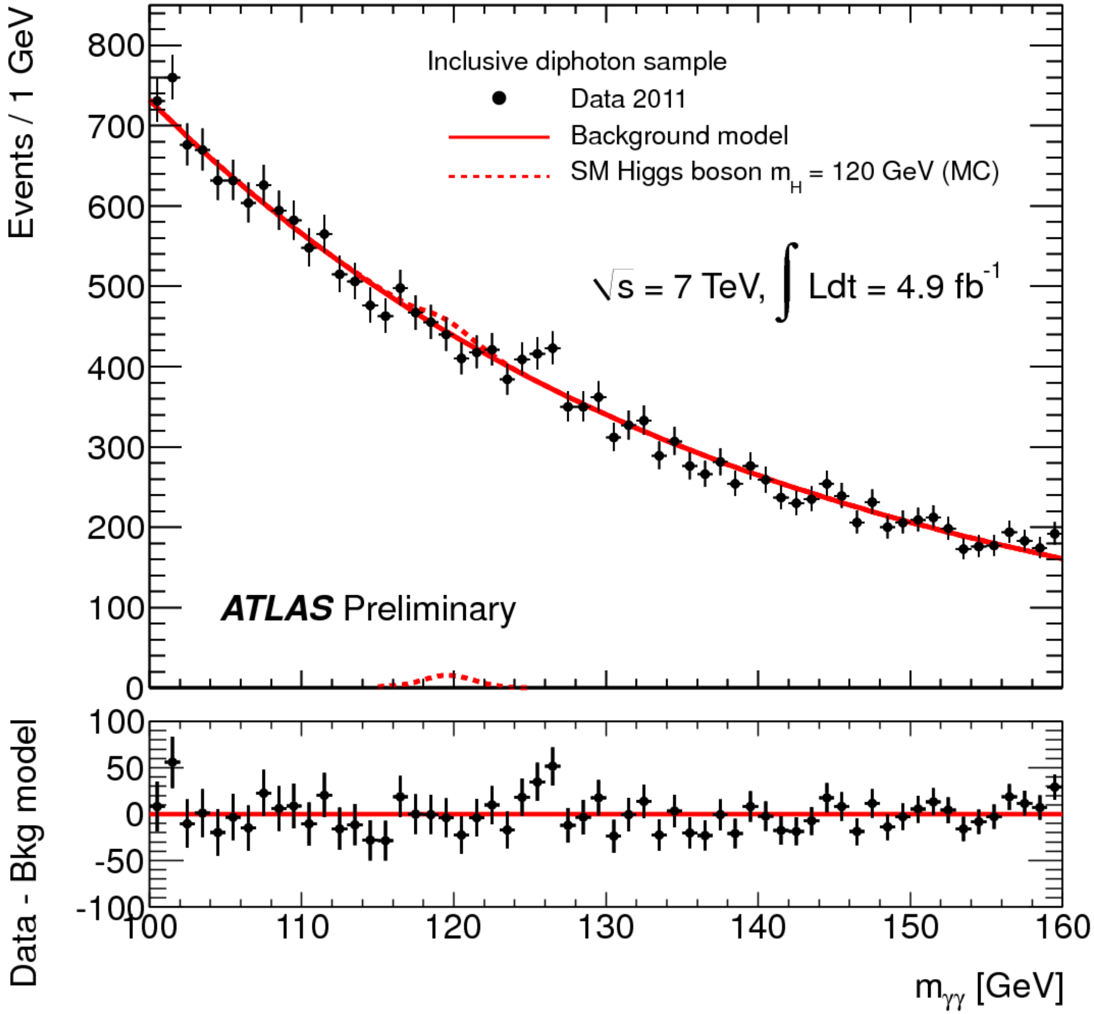


Also interesting for you!

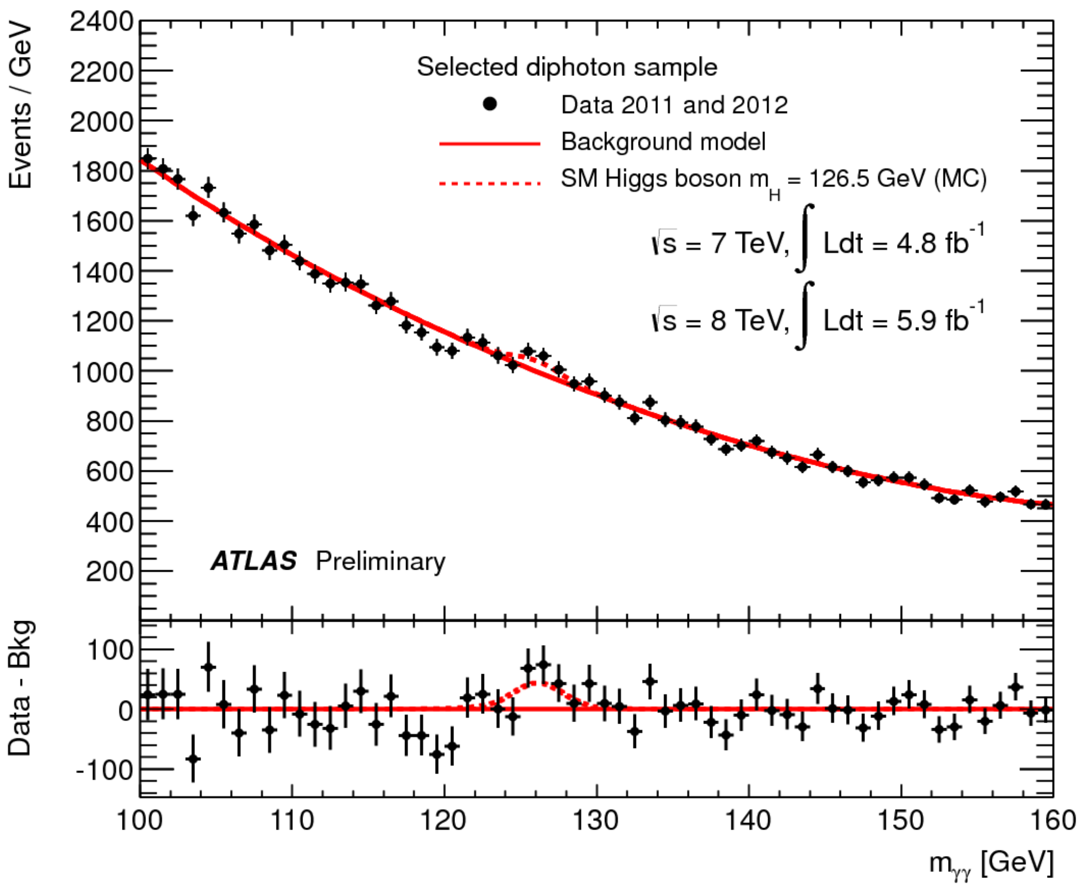
Start up (end of 2014) 2015



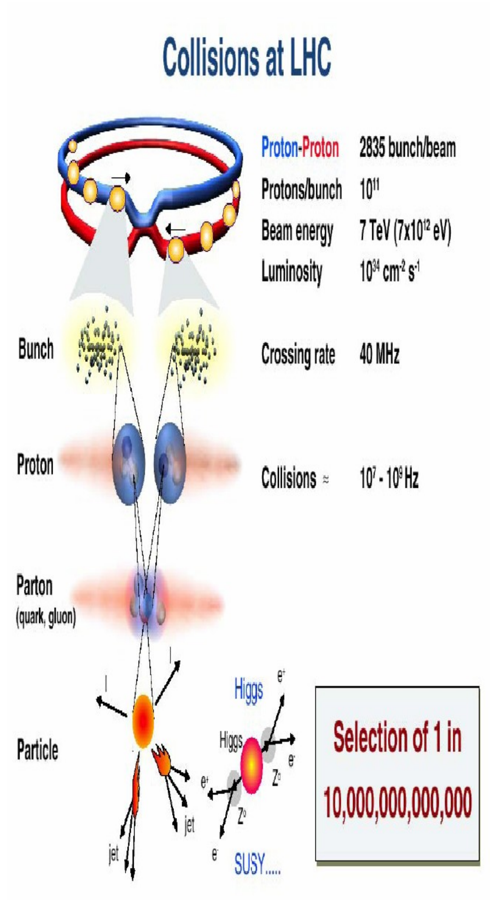
Best Higgs signature: H → 2γ
2011 pre-discovery

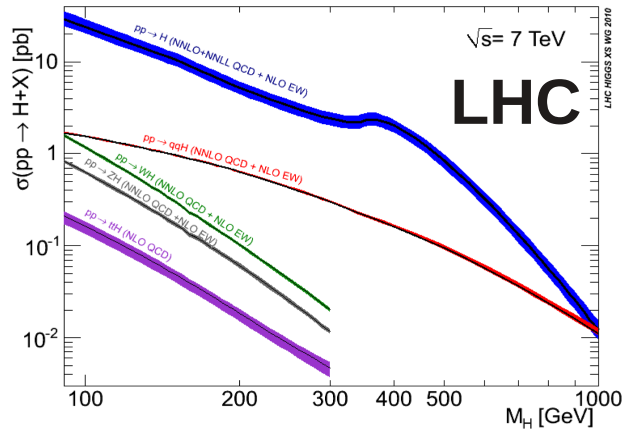


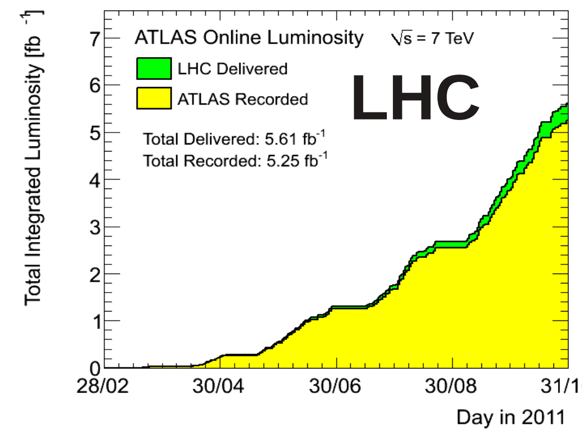
Best Higgs signature: H → 2γ
2012 discovery

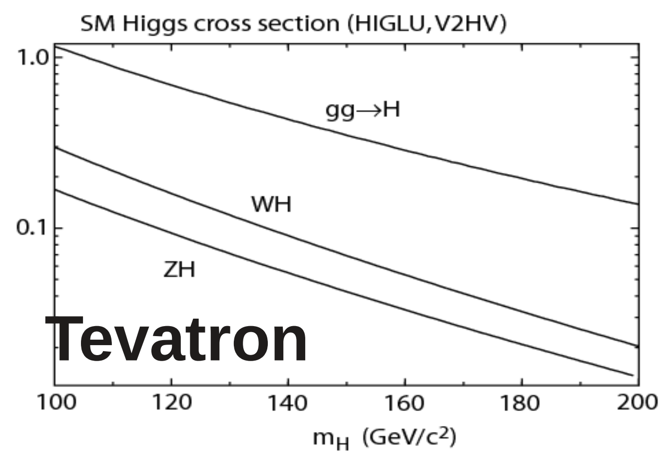


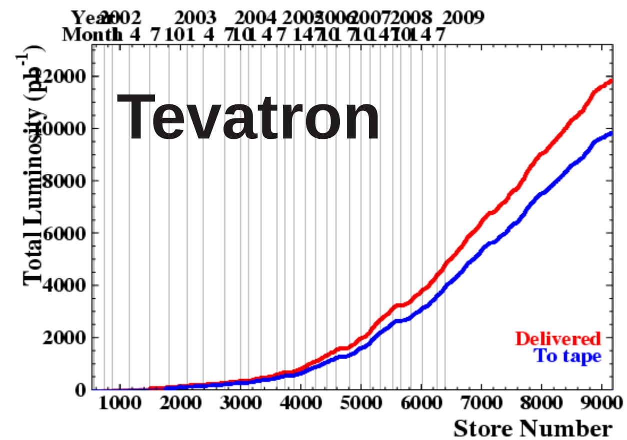
Summary
Main ingredients in LHC success











- Energy → 10 times higher cross section than Tevatron and integrated luminosity already ½ at end of 2011!
- For 2012 the goal is 25 fb^{-1} = 2.5 * integrated Tevatron!