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
  - LHC overview & problems with superconducting magnets at LHC
  - Medical isotope production
  - Hazards in accelerators

  + chapter “Applications of accelerators”
    - In the same book also chapter 1 (history) and chapter 14 (future) might be excellent inspiration

Plan

- This week
  - Friday 8-10: lecture 1 and 2
- Next week
  - Monday 10-12: lecture 3 and 4
  - Wednesday 10-11: lecture 5 and group work
- The following week
  - Tuesday 10-12: group presentations + lecture 6

Inspiration and slides

- “A BRIEF HISTORY AND REVIEW OF ACCELERATORS”, P.J. Bryant
- “AN INTRODUCTION TO PARTICLE ACCELERATORS”, E. Wilson
- “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

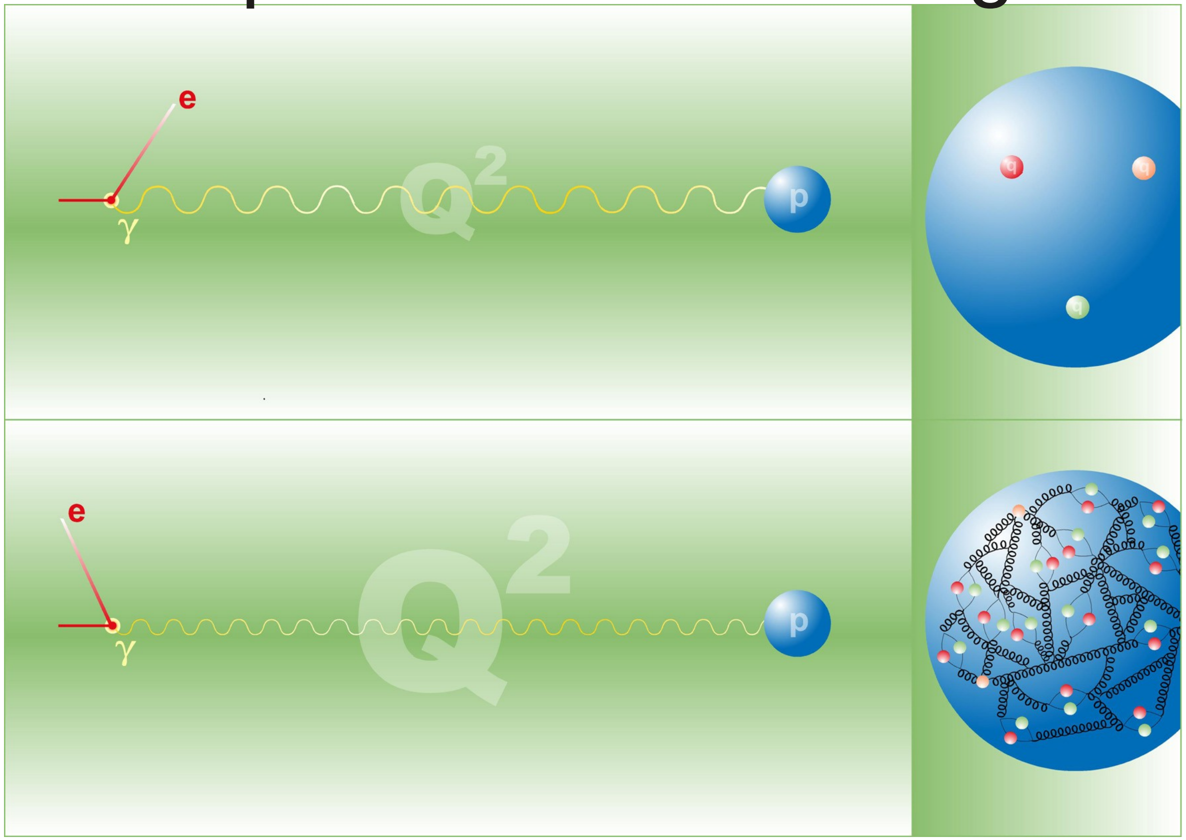
Think break

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

Why do we accelerate?

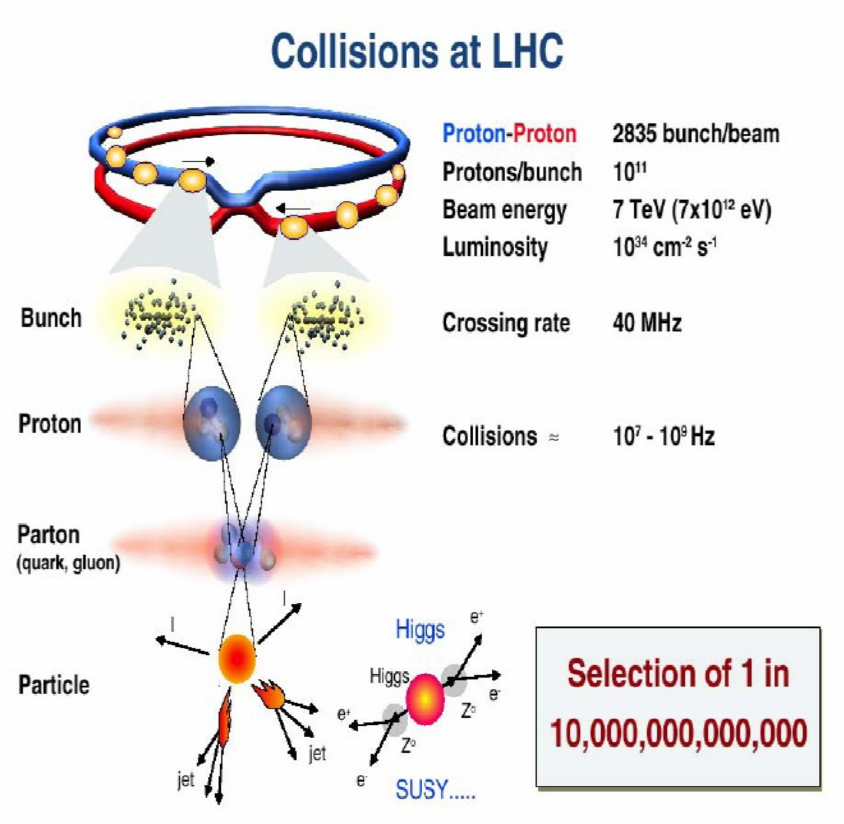
To probe the structure of e.g. protons

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

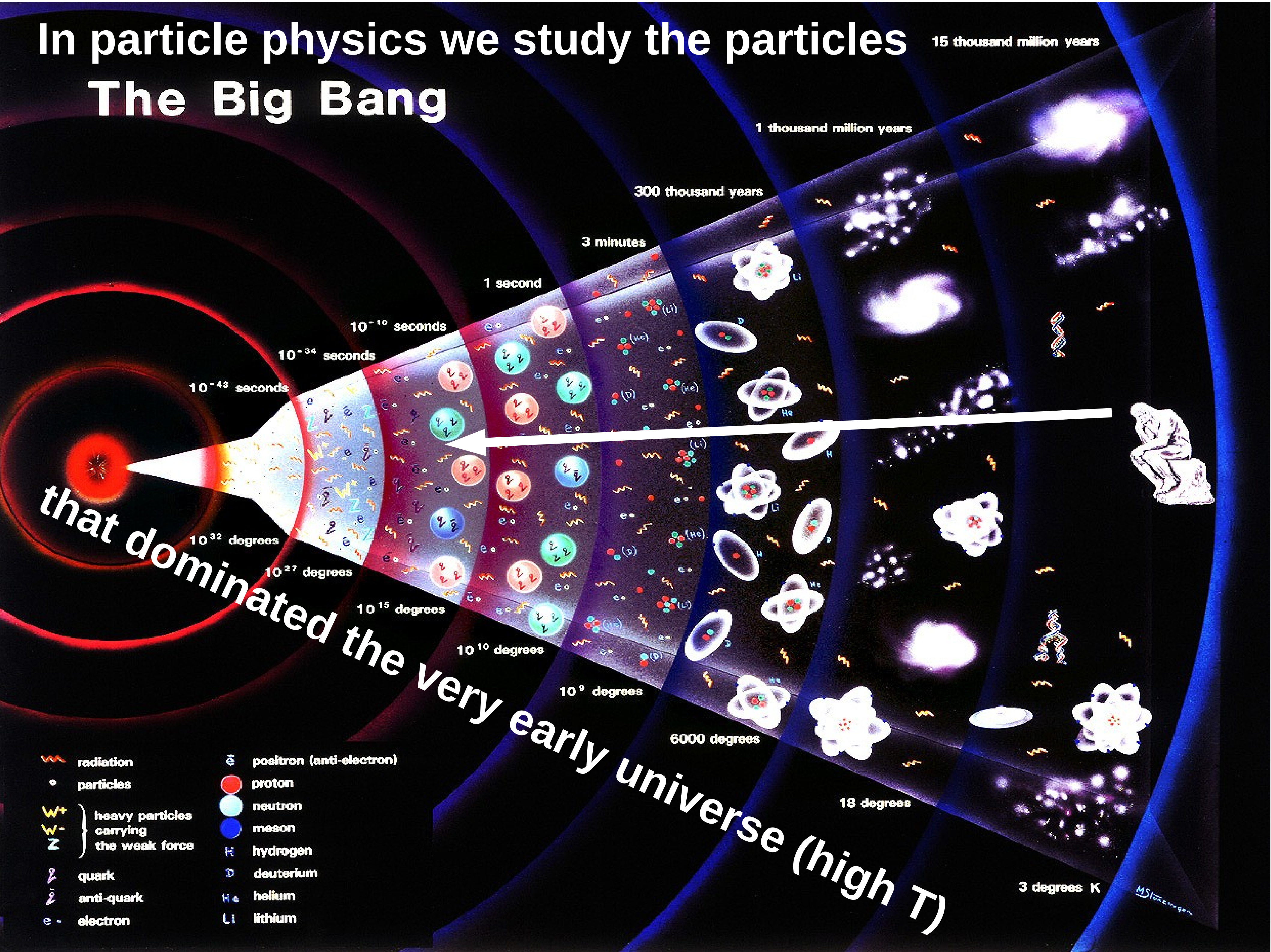


To create new particles

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



In particle physics we study the particles



that dominated the very early universe (high T)

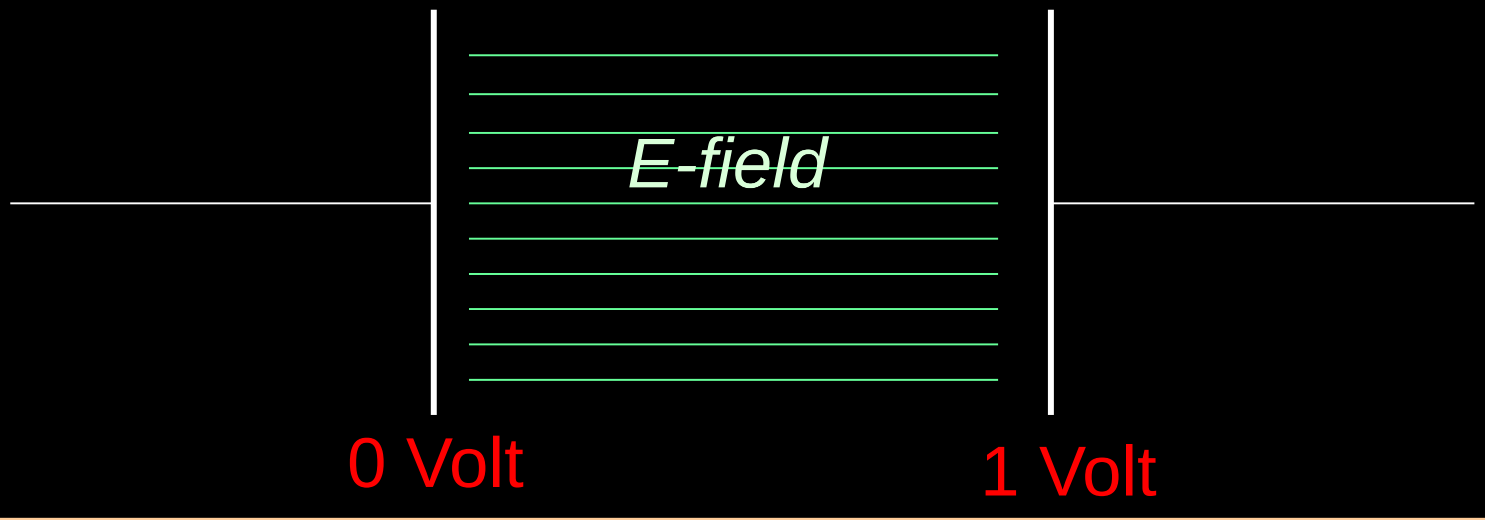
What are the main characteristics of an accelerator

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

Units of energy

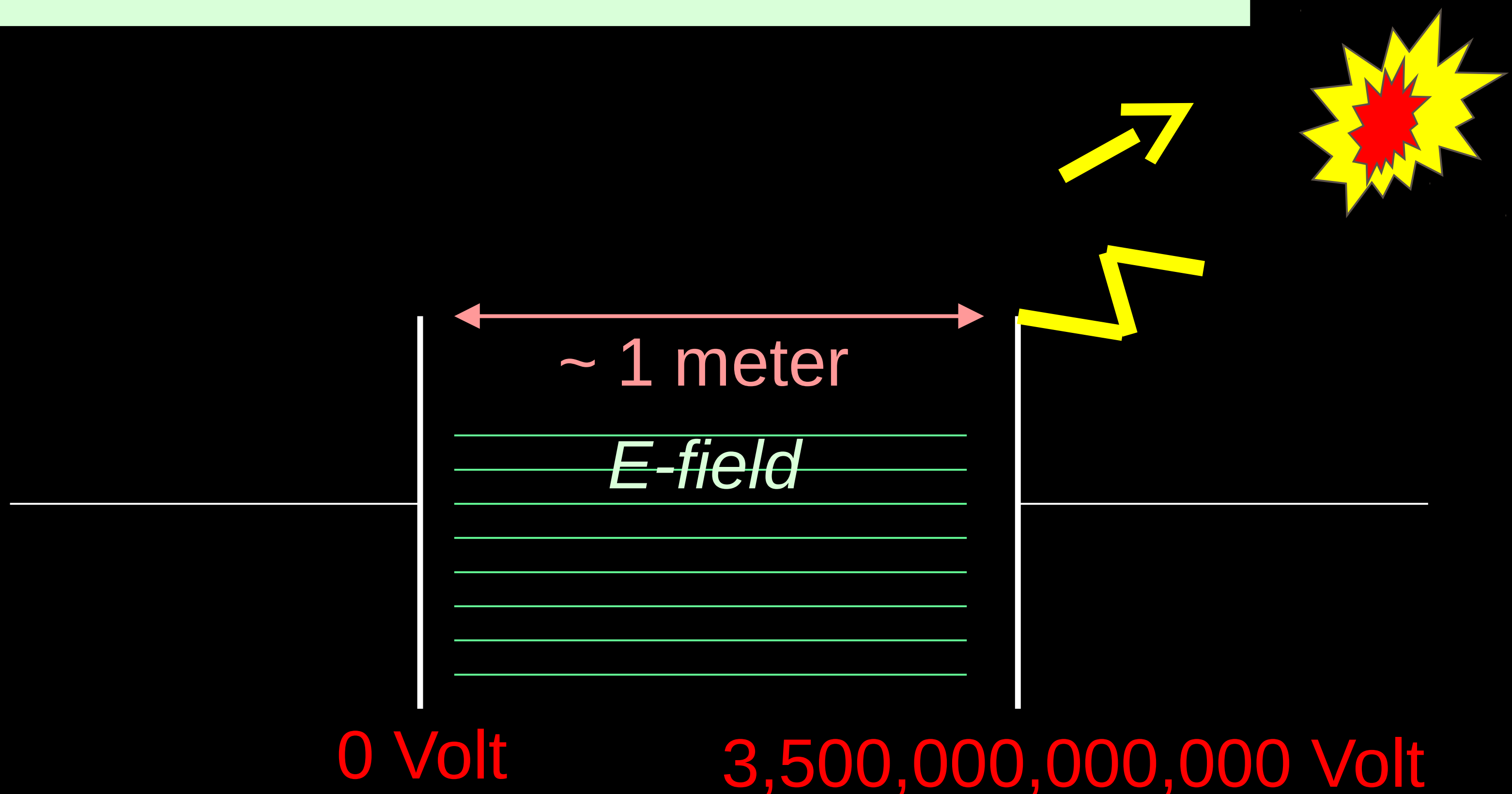
A charged particle with charge
+e gains an energy of 1eV (electronVolt)
when passing a voltage gap of 1Volt

1eV is 1.6×10^{-19} Joule

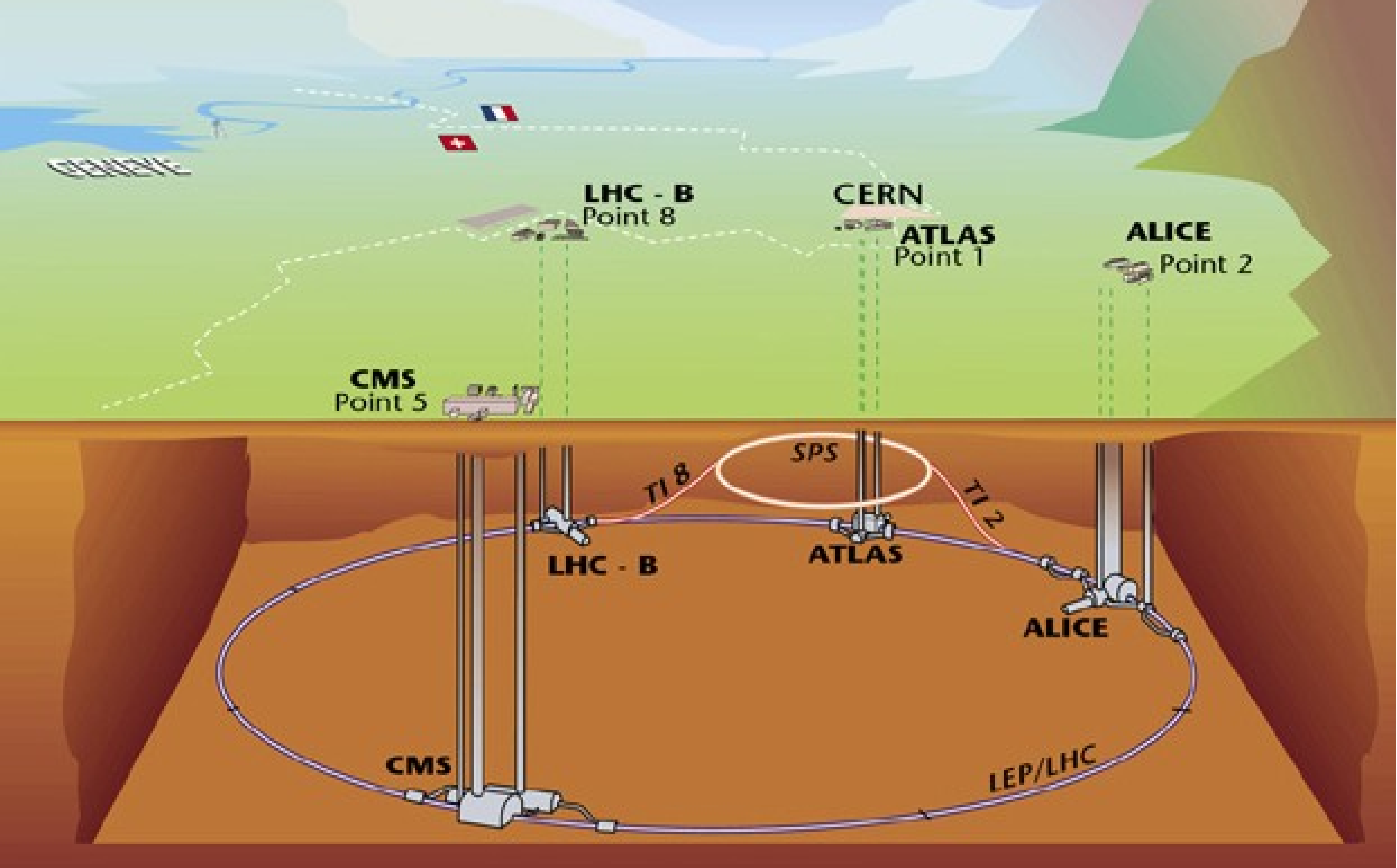


The “LHC” in 1m?
(√s = 7 TeV)

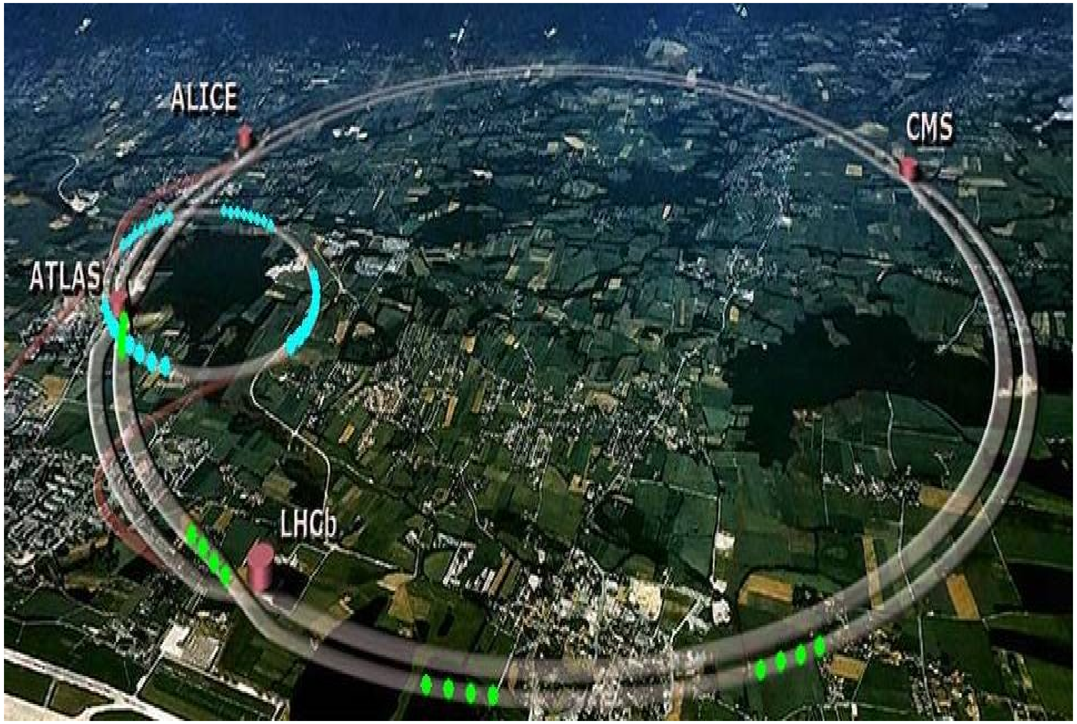
How to accelerate will be covered in lectures 3 and 4!



My main example will be LHC!

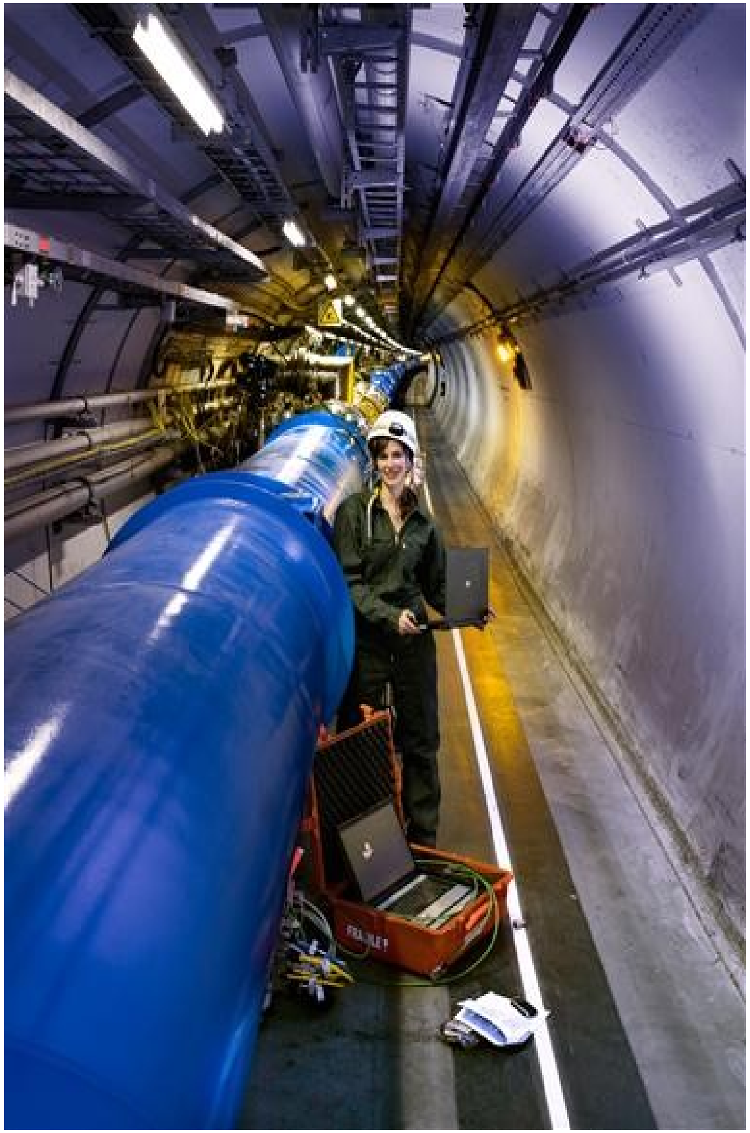


Large Hadron Collider (LHC)



$$\sqrt{s} = 7\text{TeV}\,(14\text{TeV}, 2014)$$
$$(vs\,0.2\,TeV\ LEP)$$
$$(vs\,1.8\,TeV\ Tevatron)$$

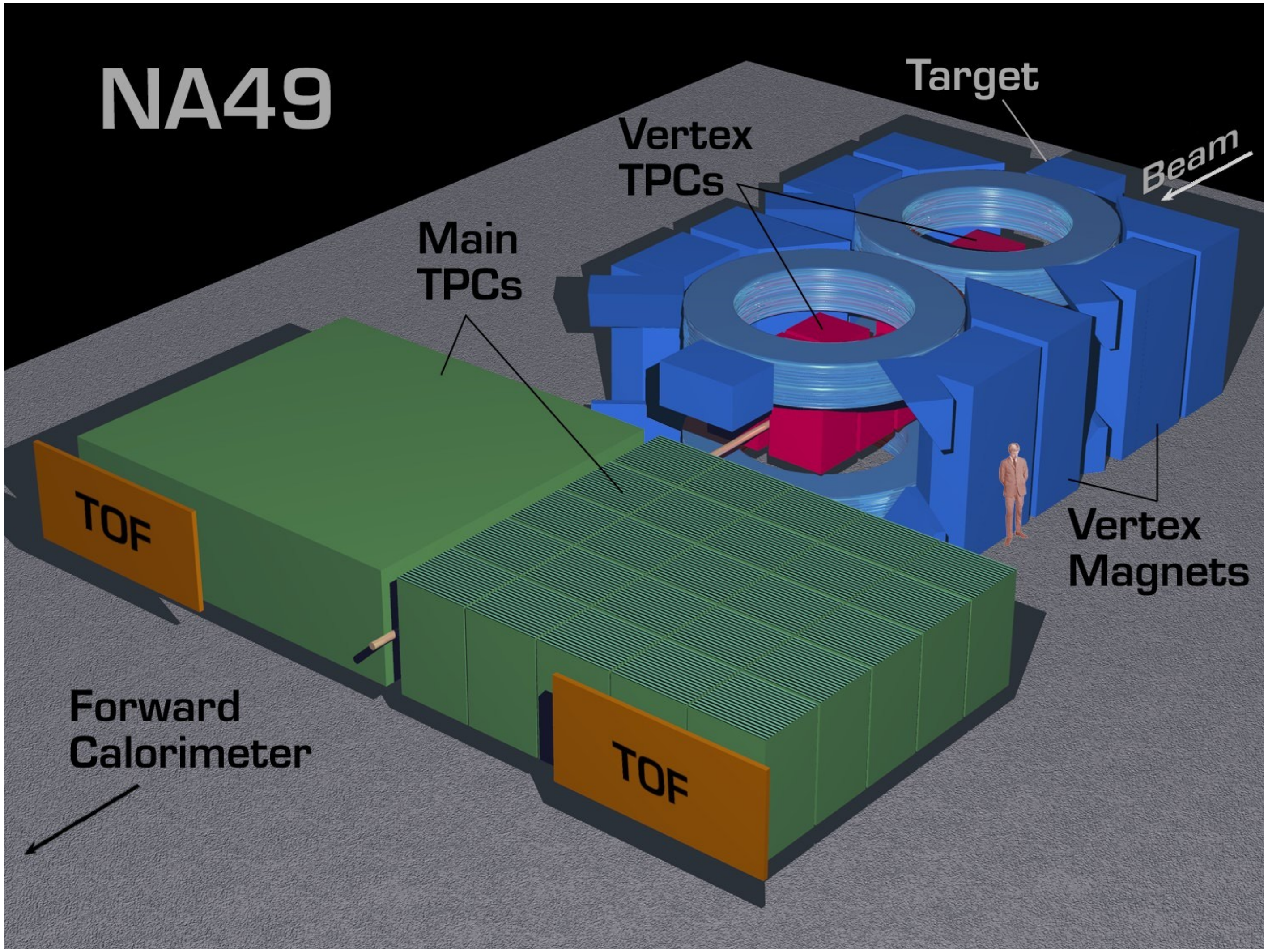
Collides hadrons (protons and ions) instead of electrons.



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!

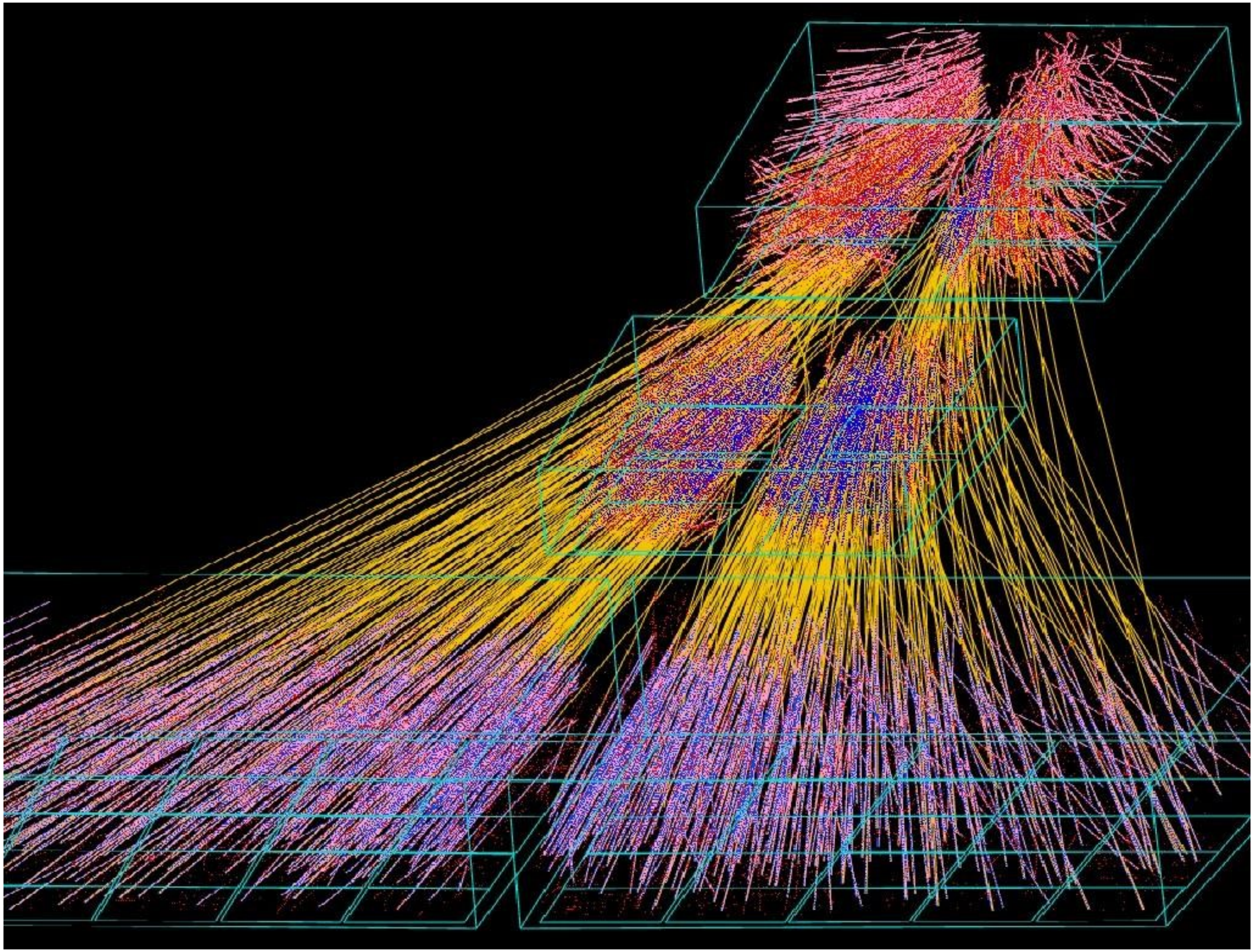
Example fixed target at CERN SPS



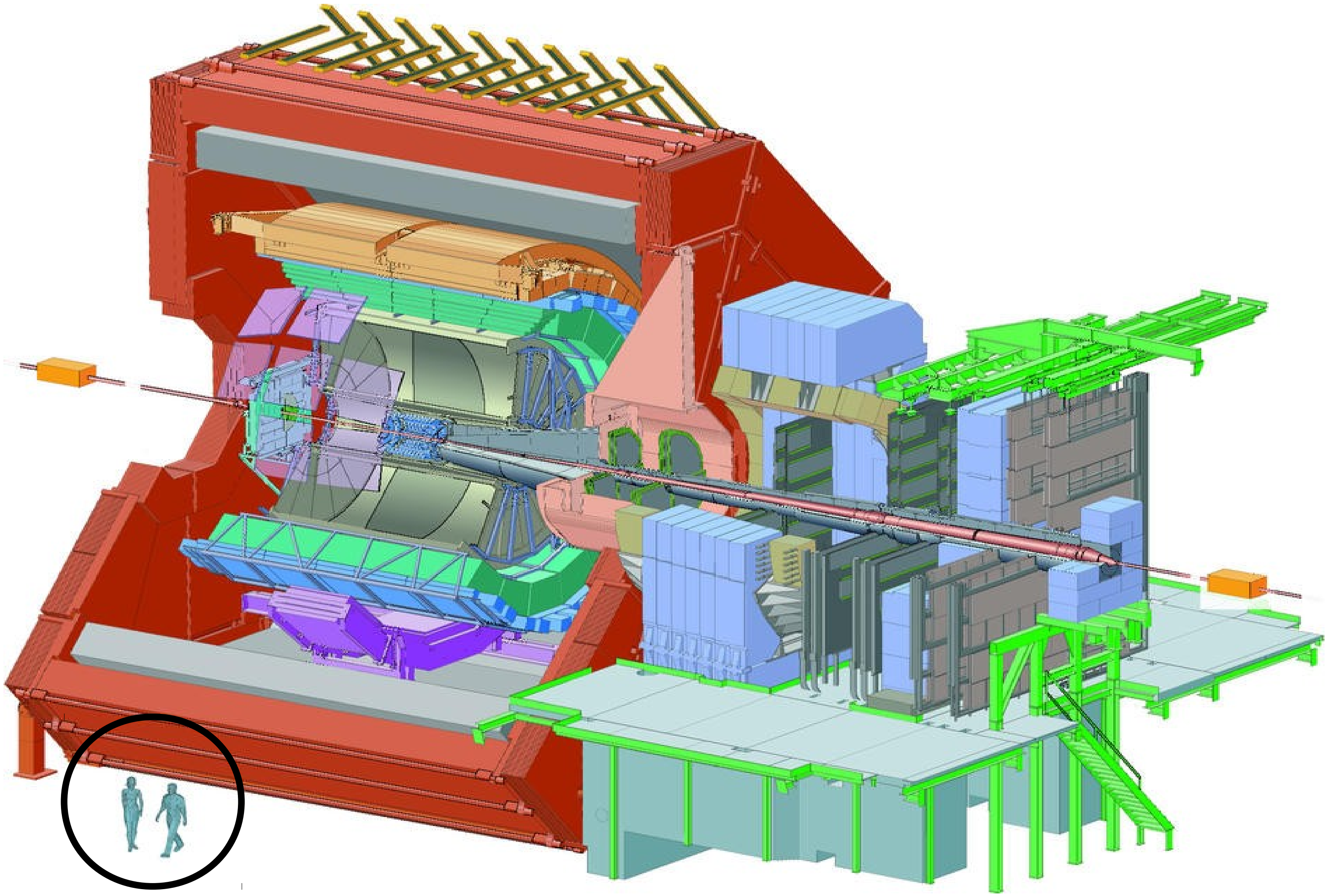
Pb at
160 A GeV

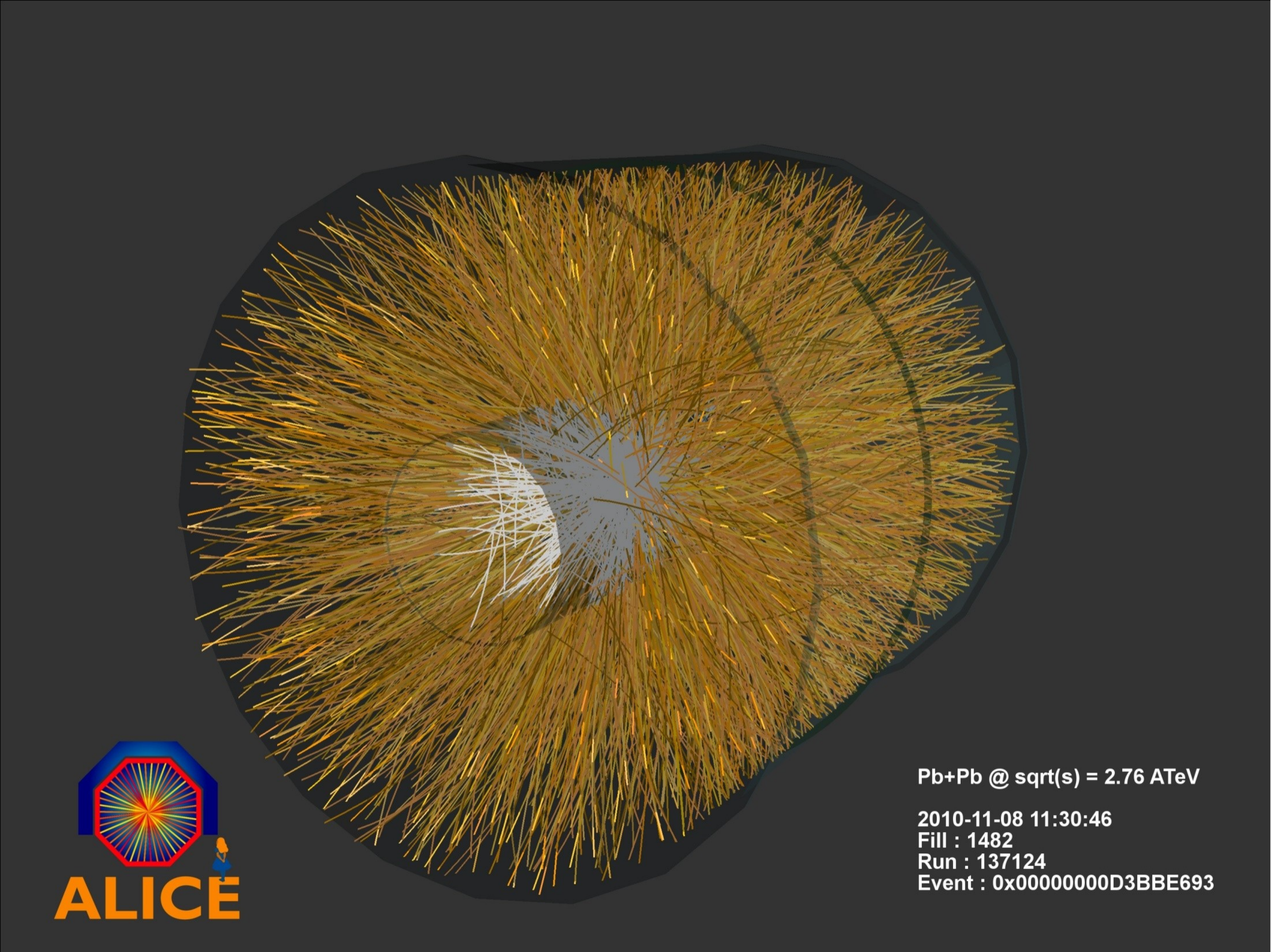
Reconstructed event

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



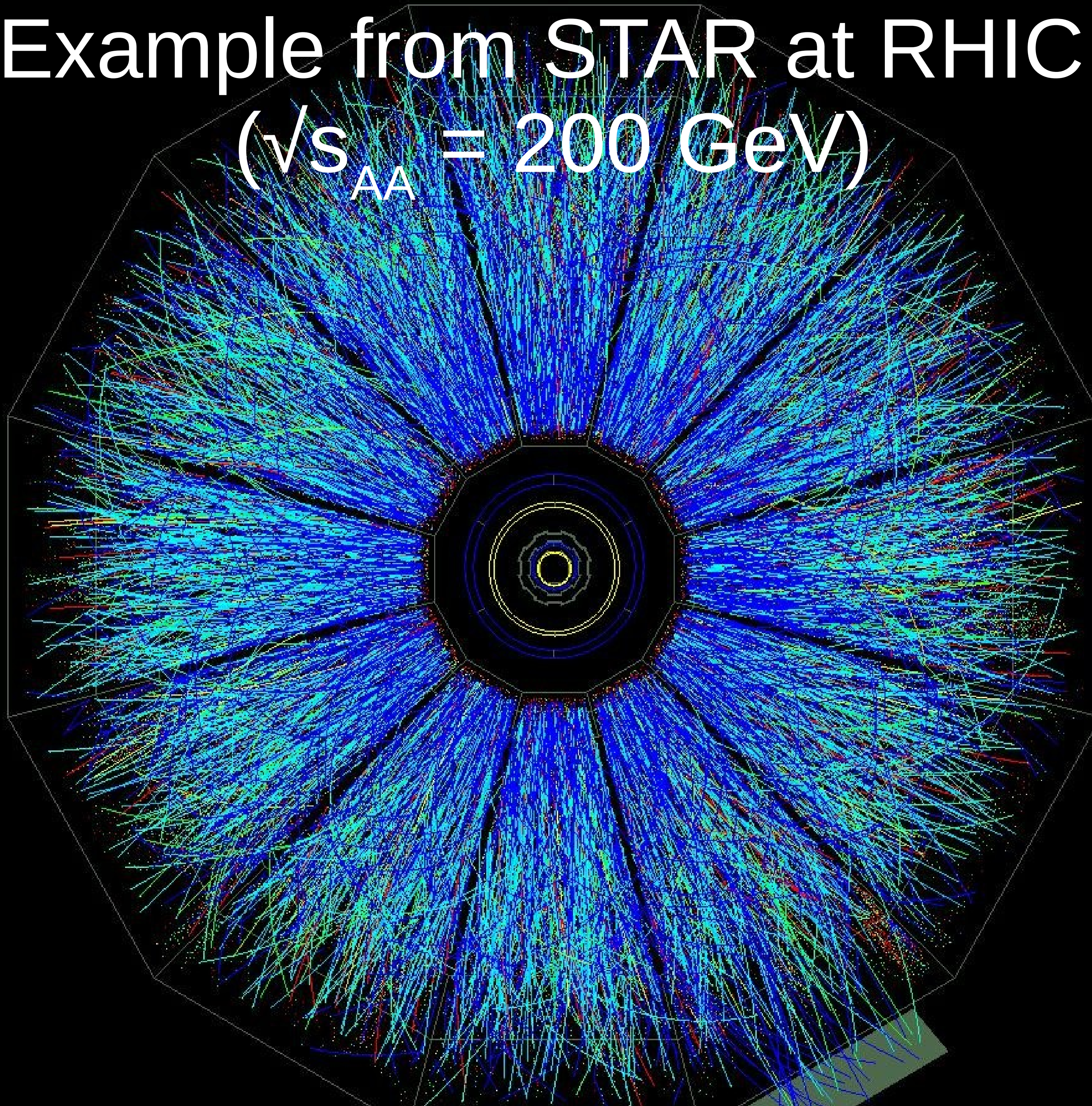
The ALICE experiment at LHC



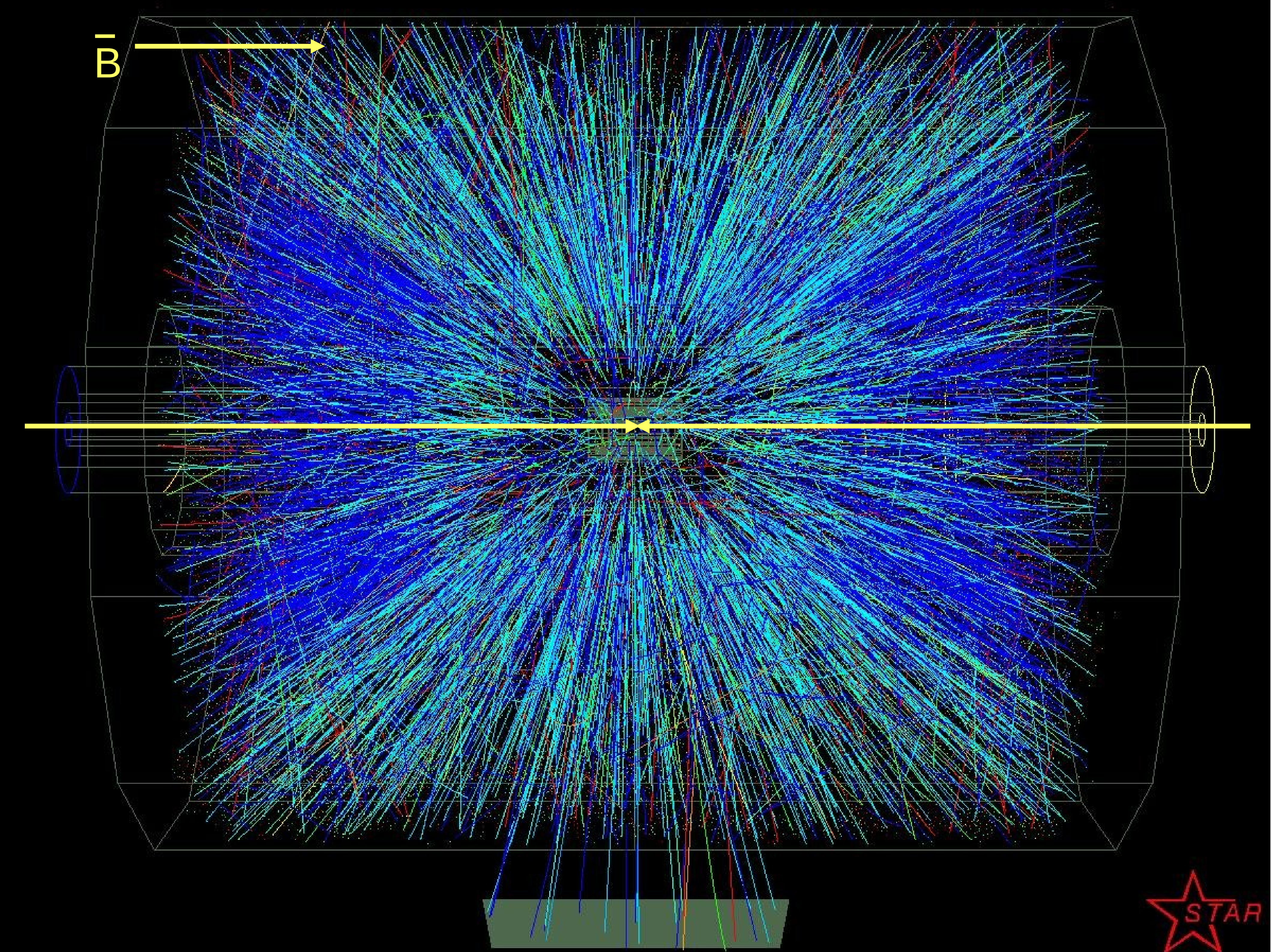

Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693
ALICE

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

$\bar{B}$



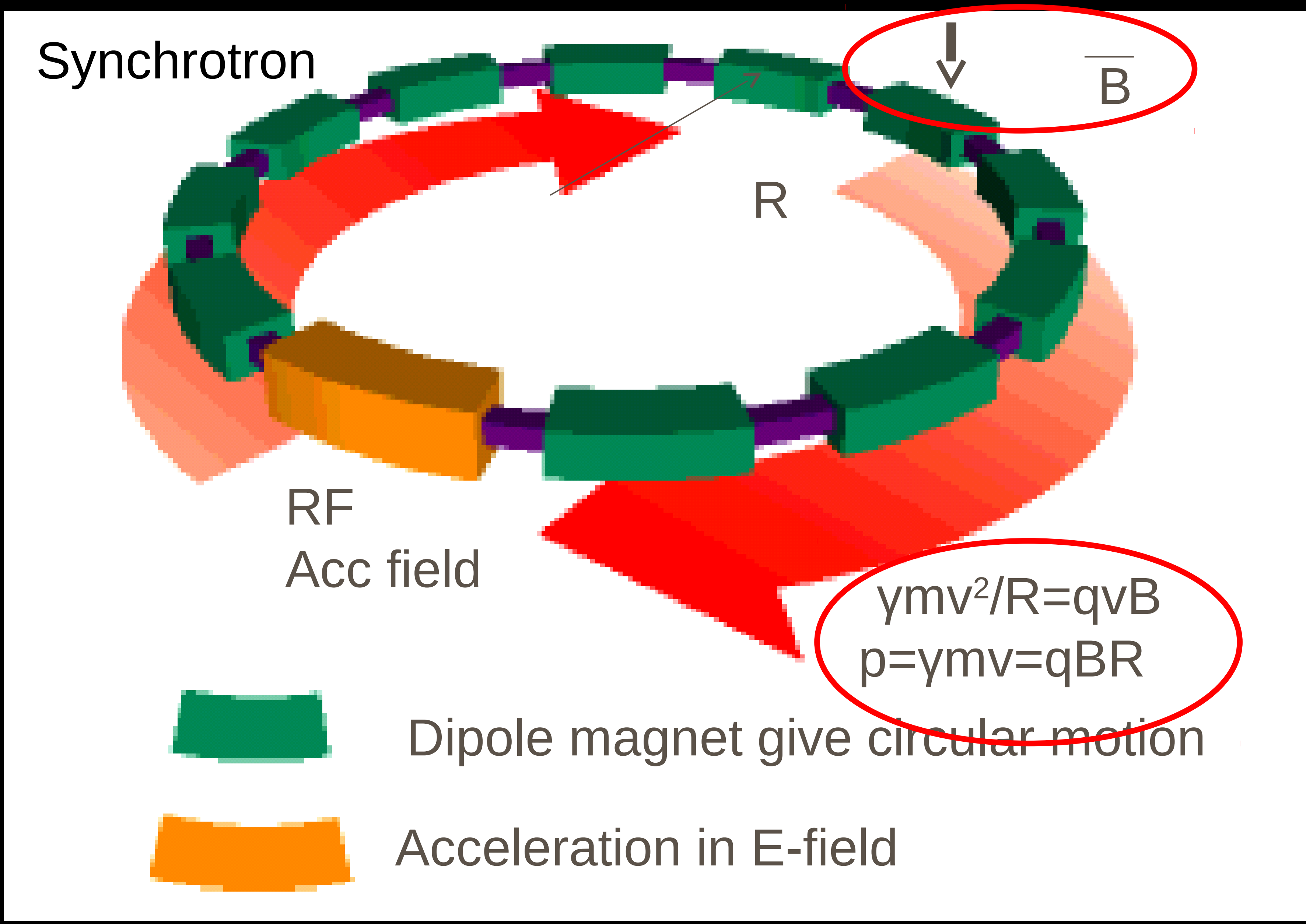
STAR


$\bar{B}$
STAR

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

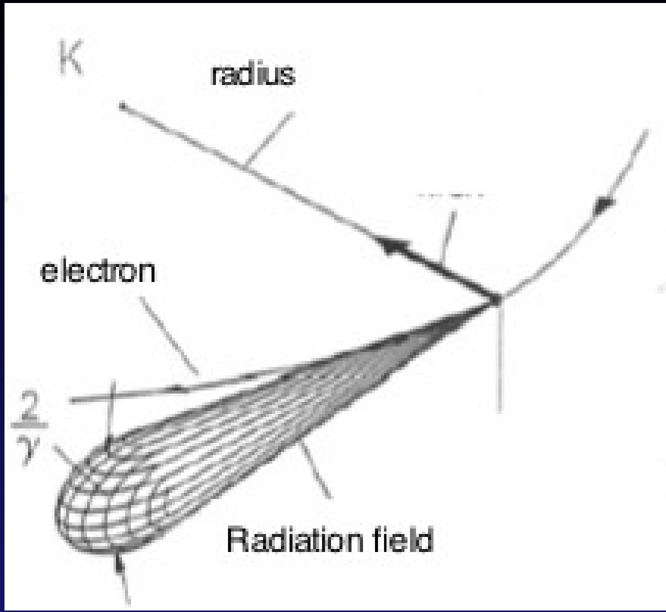
$$p = \frac{8.33 \cdot 2803}{0.3} = 7000\, GeV/c$$

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.

Why does LHC collide protons and not electrons?

Protons vs. Electrons

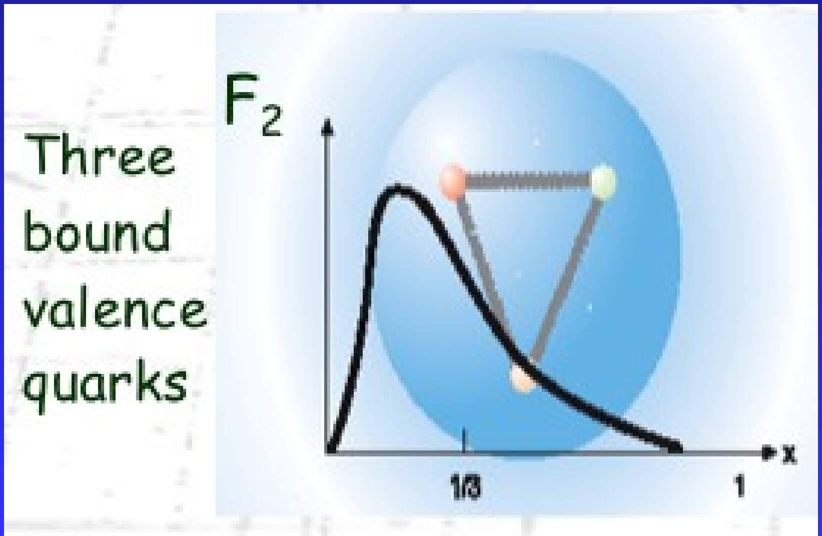


$$P_s \propto \frac{E^4}{m_0^2 R^2}$$

- Can win by accelerating protons

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

- But protons aren't fundamental



Only small fraction at highest energy

Don't know energy (or type) of colliding particles

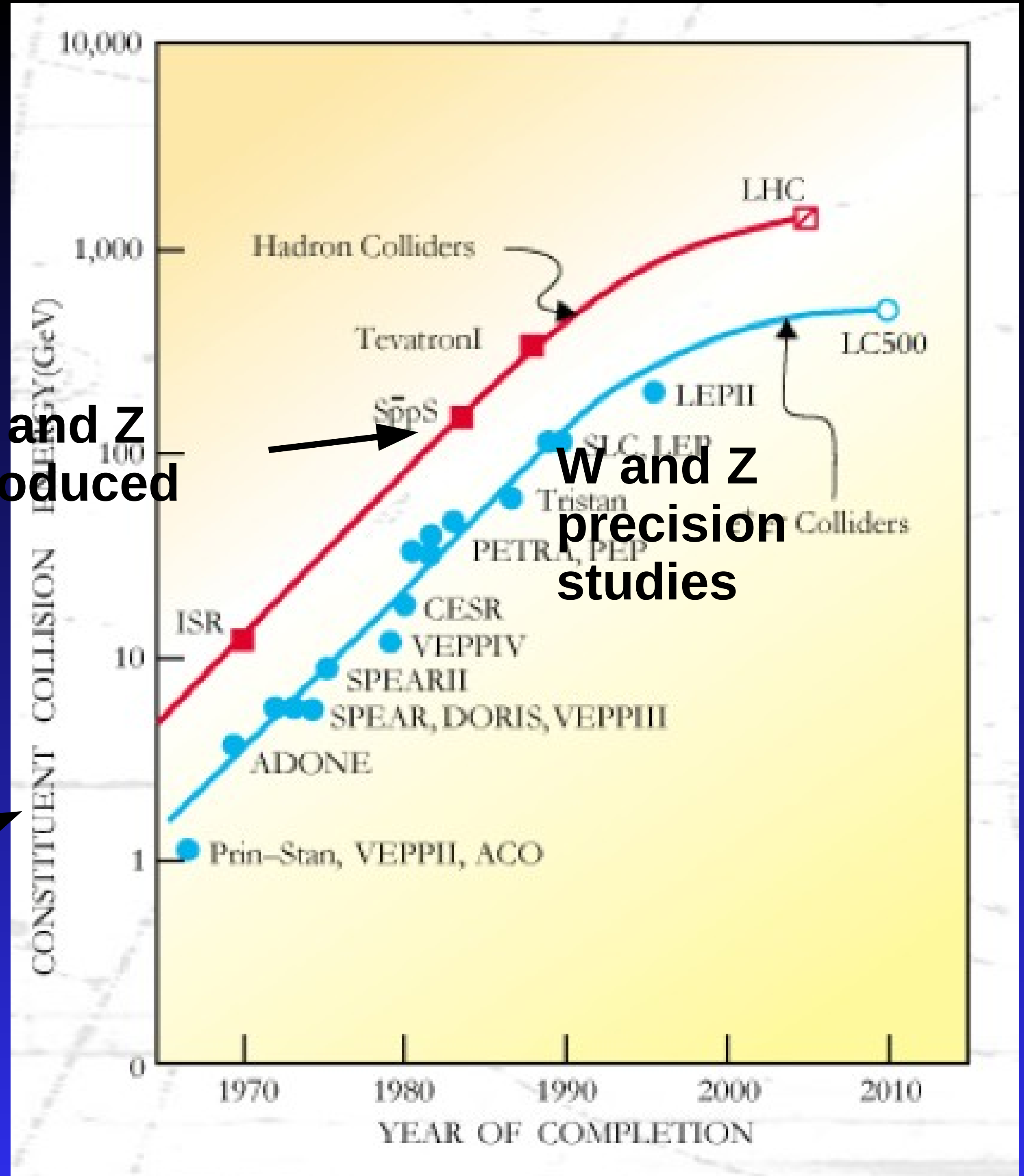
History of accelerator energies

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

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

W and Z produced

W and Z precision studies



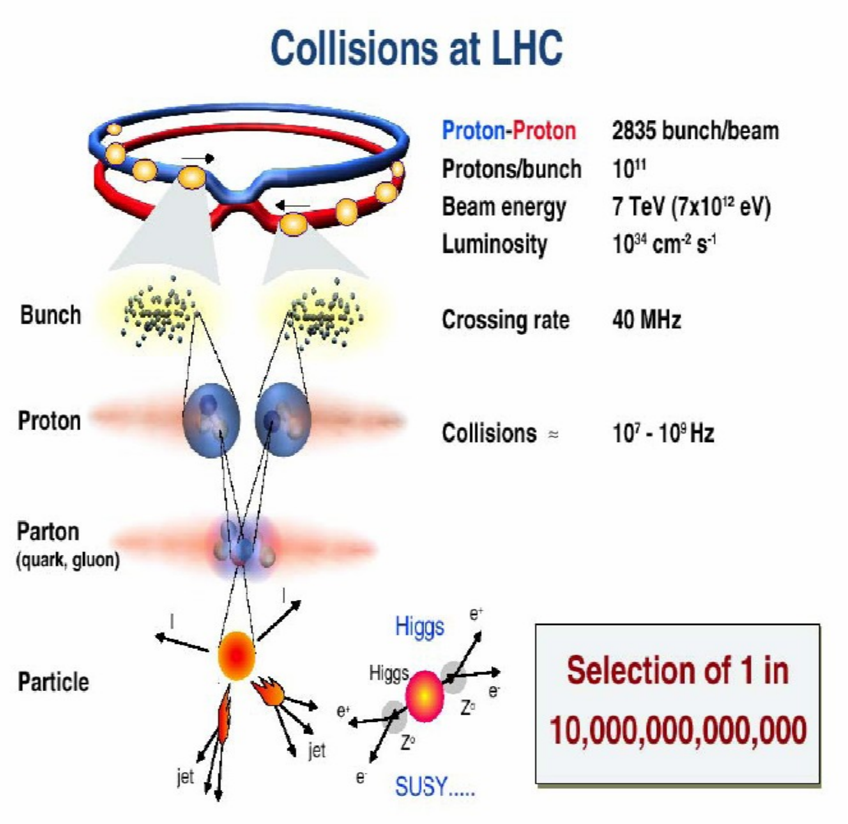
M. Tigner, Physics Today, January 2001

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

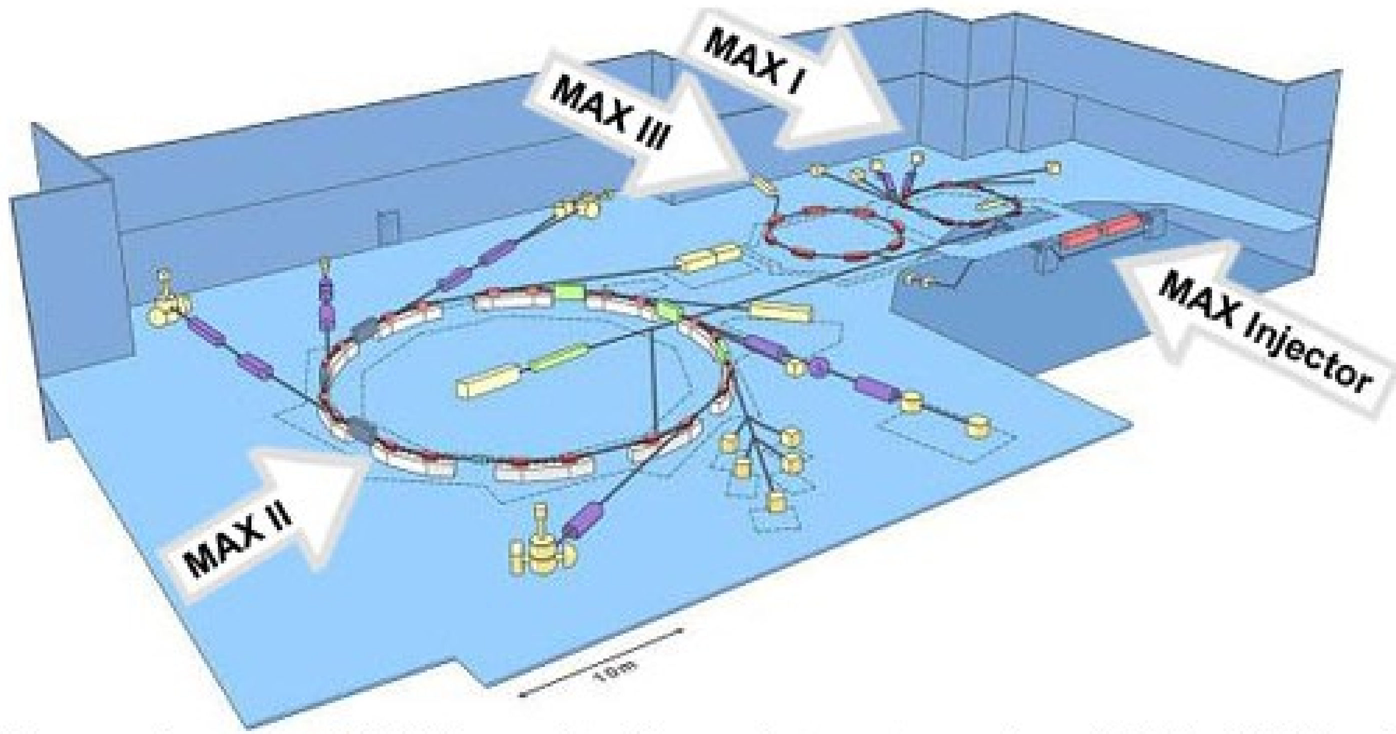
LHC (and proton colliders in general) are discovery machines!

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



However – synchrotron light can itself be used for good physics

MAX-lab Accelerators

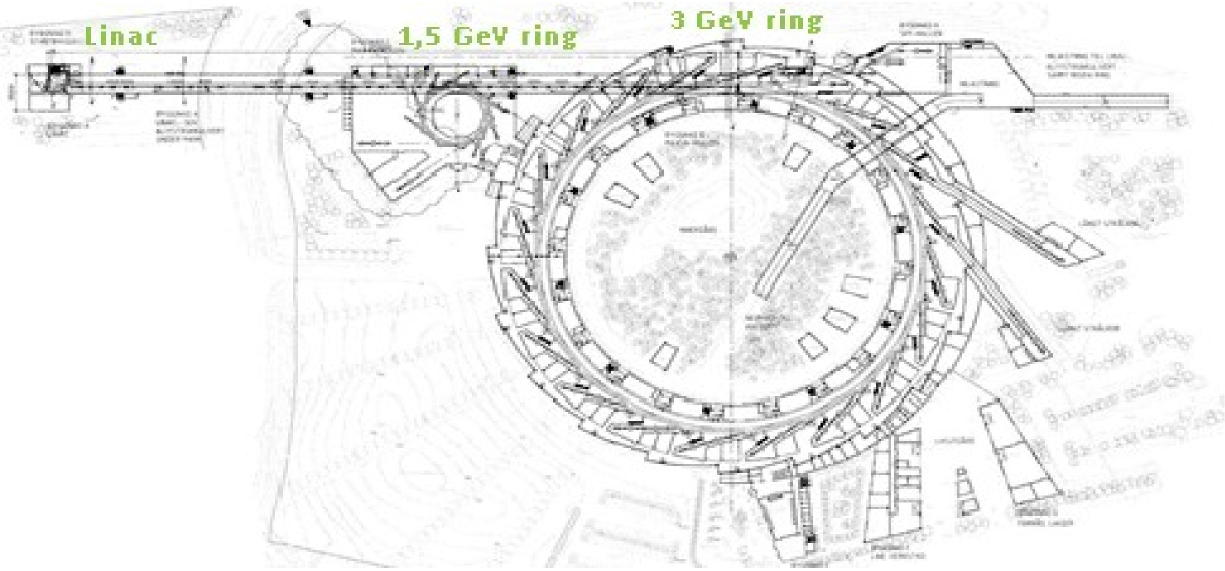


The accelerators at MAX-lab consist of three electron storage rings (MAX I, MAX II and MAX III) and one electron pre-accelerator (MAX injector). All three storage rings produce synchrotron light used for experiments and measurements in a wide range of disciplines and technologies. The MAX I ring is also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

And maybe even good for your careers!

MAX IV

The MAX IV Laboratory - our future light source



Luminosity and collisions rates

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

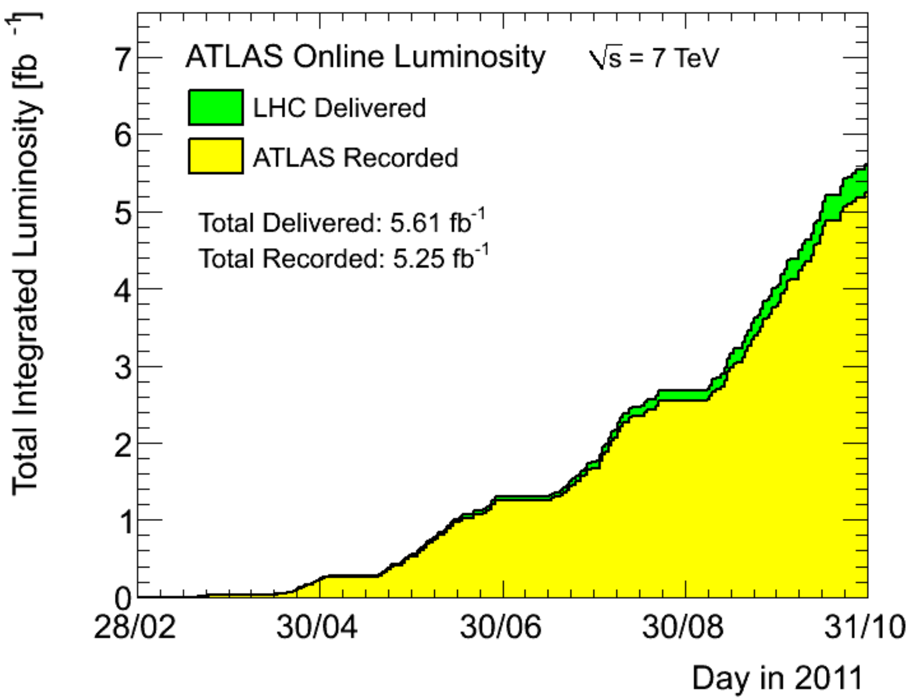
$$\mathcal{L} = \frac{1}{4\pi} \frac{f_u \cdot N_1 \cdot N_2}{\sigma_x \cdot \sigma_y}$$

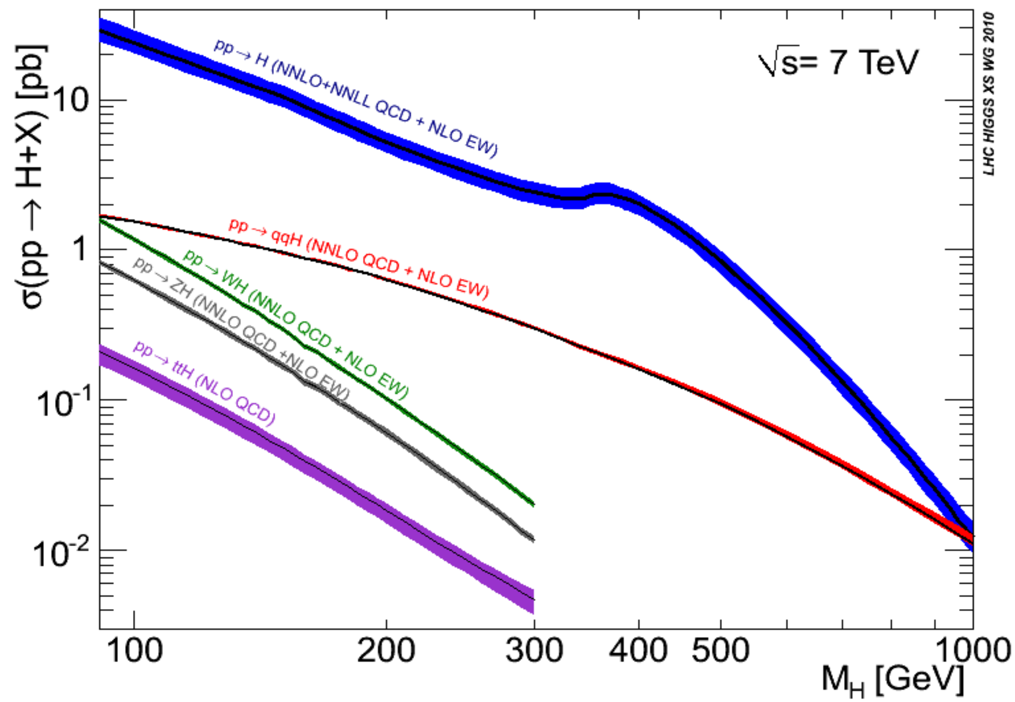
Current

Spot size

Where fu is the revelation frequency multiplied by # of colliding bunches
More particles through a smaller area means more collisions

Higgs discovery at CERN
Status end of 2011



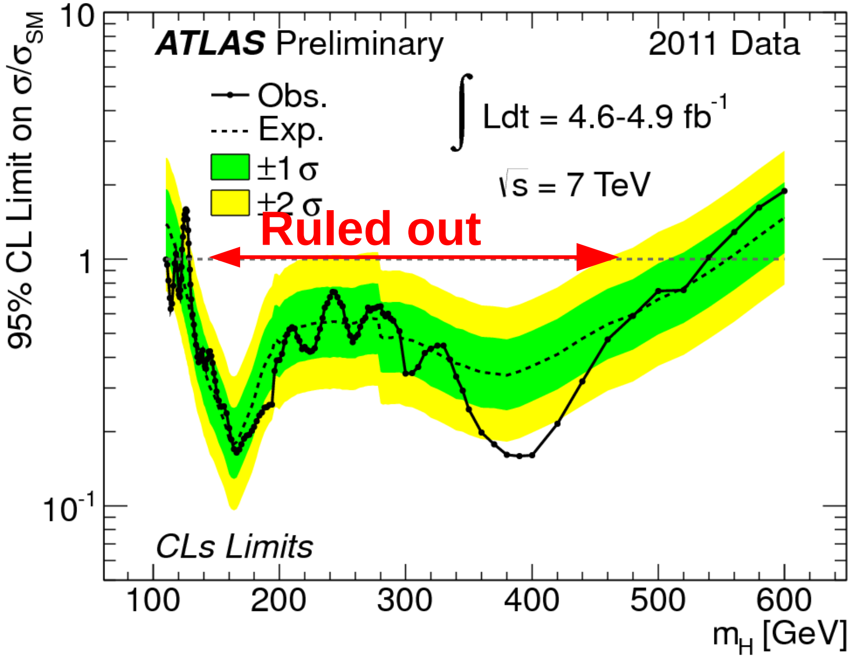


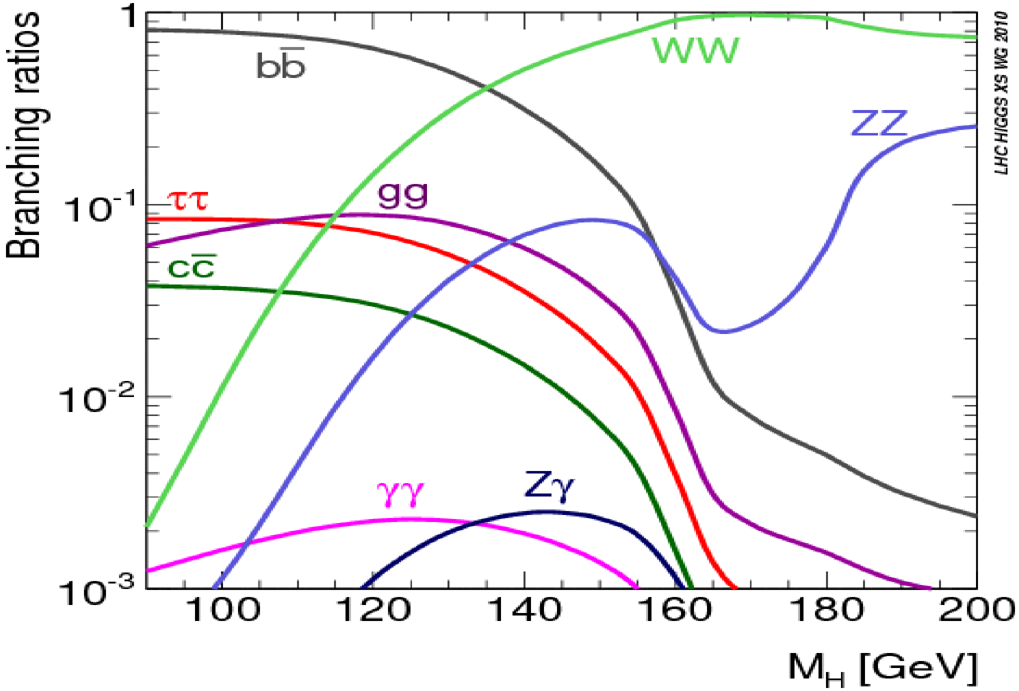
- What is the total # of produced Higgs's in the ATLAS experiment if m_H=130GeV?
- Answer: ~5fb^{-1}*10,000fb ~ 50,000!

Note that this corresponds to

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

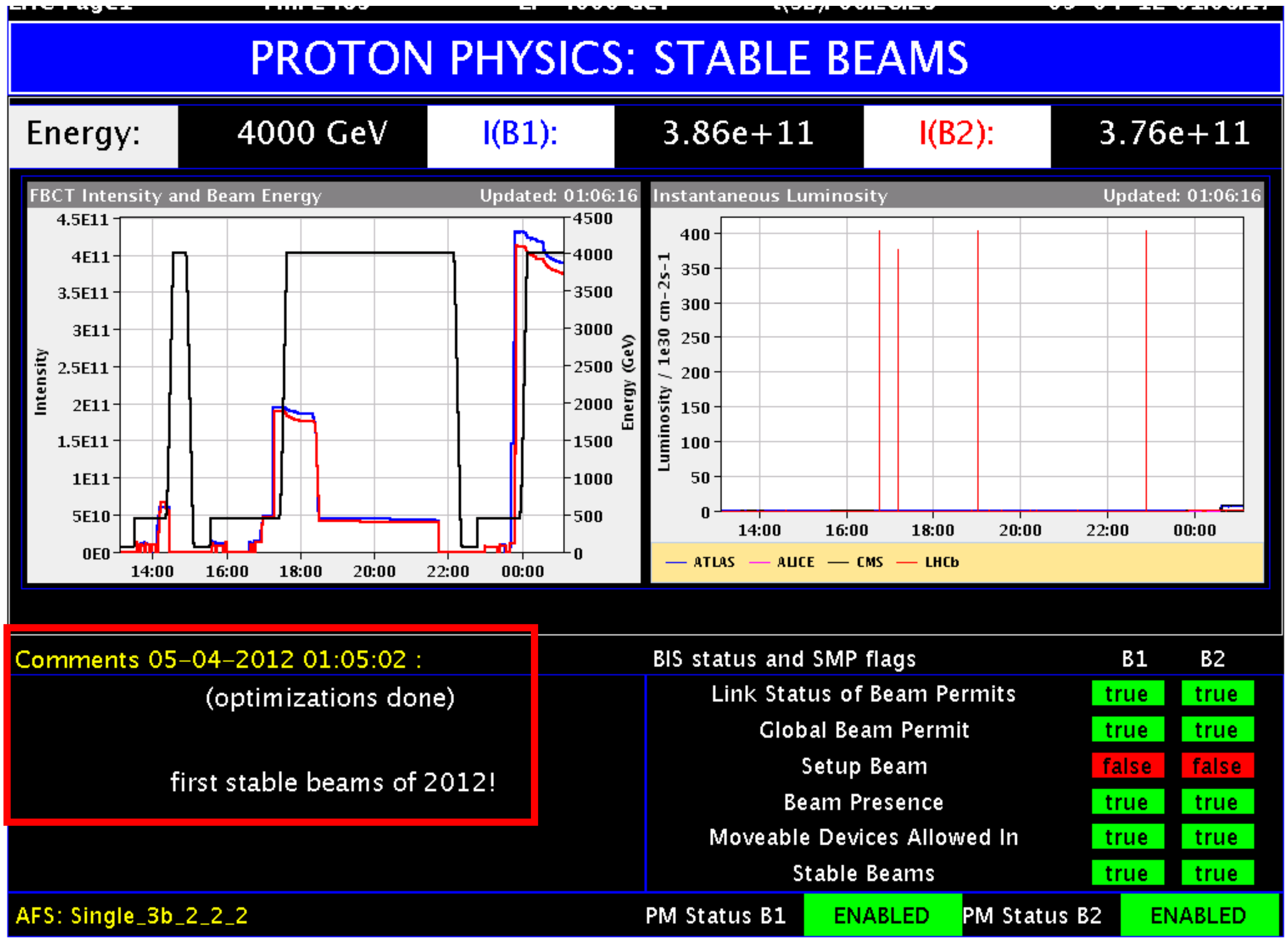
Higgs mass window
End of 2011





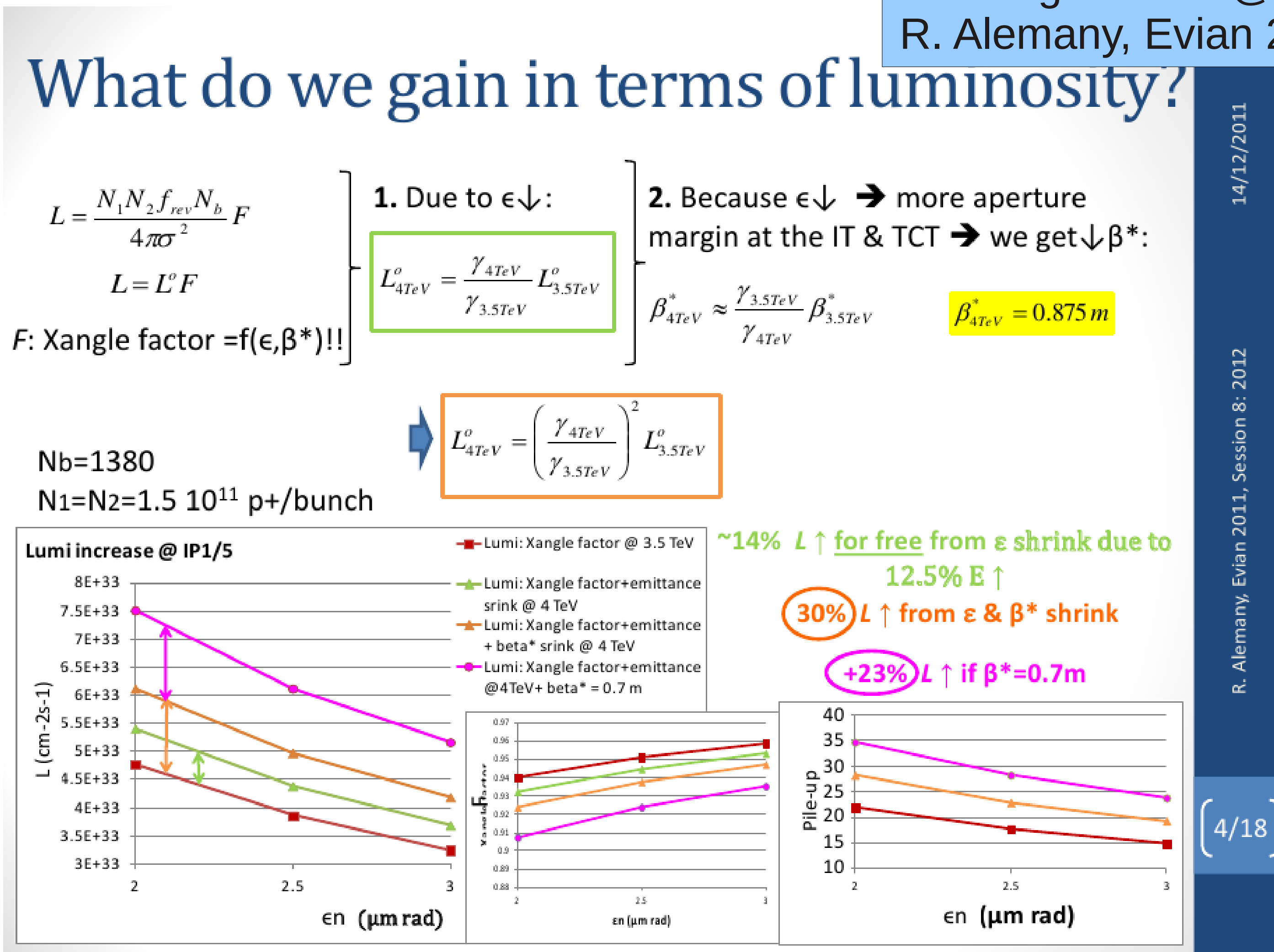
- Why is the limit not better at low mH where the cross section is larger?
- Answer: m_H too low for direct decay to 2W or 2Z = cleanest signatures!

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



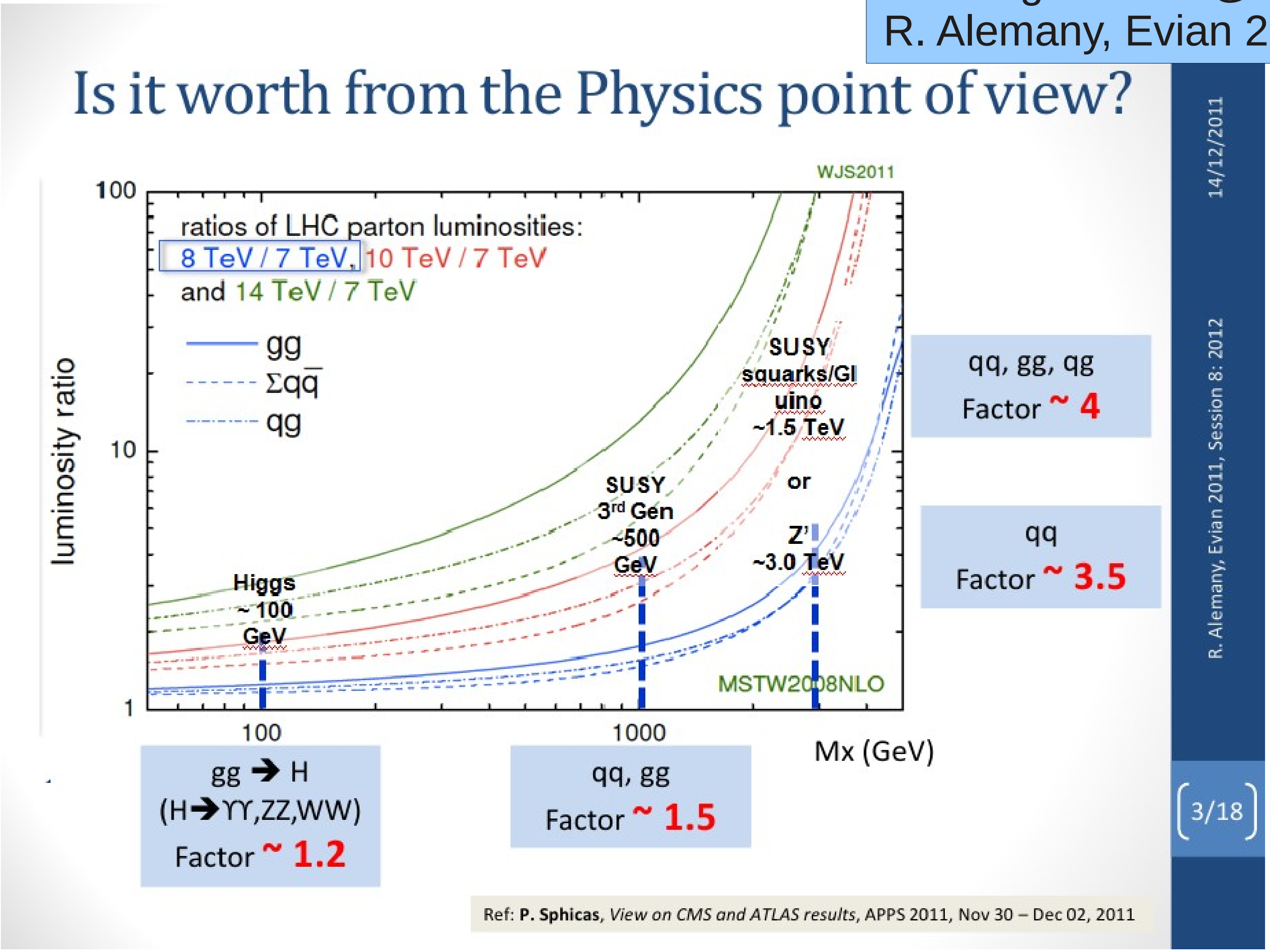
Why LHC was running at 8 TeV in 2012 (2/3) – Luminosity

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



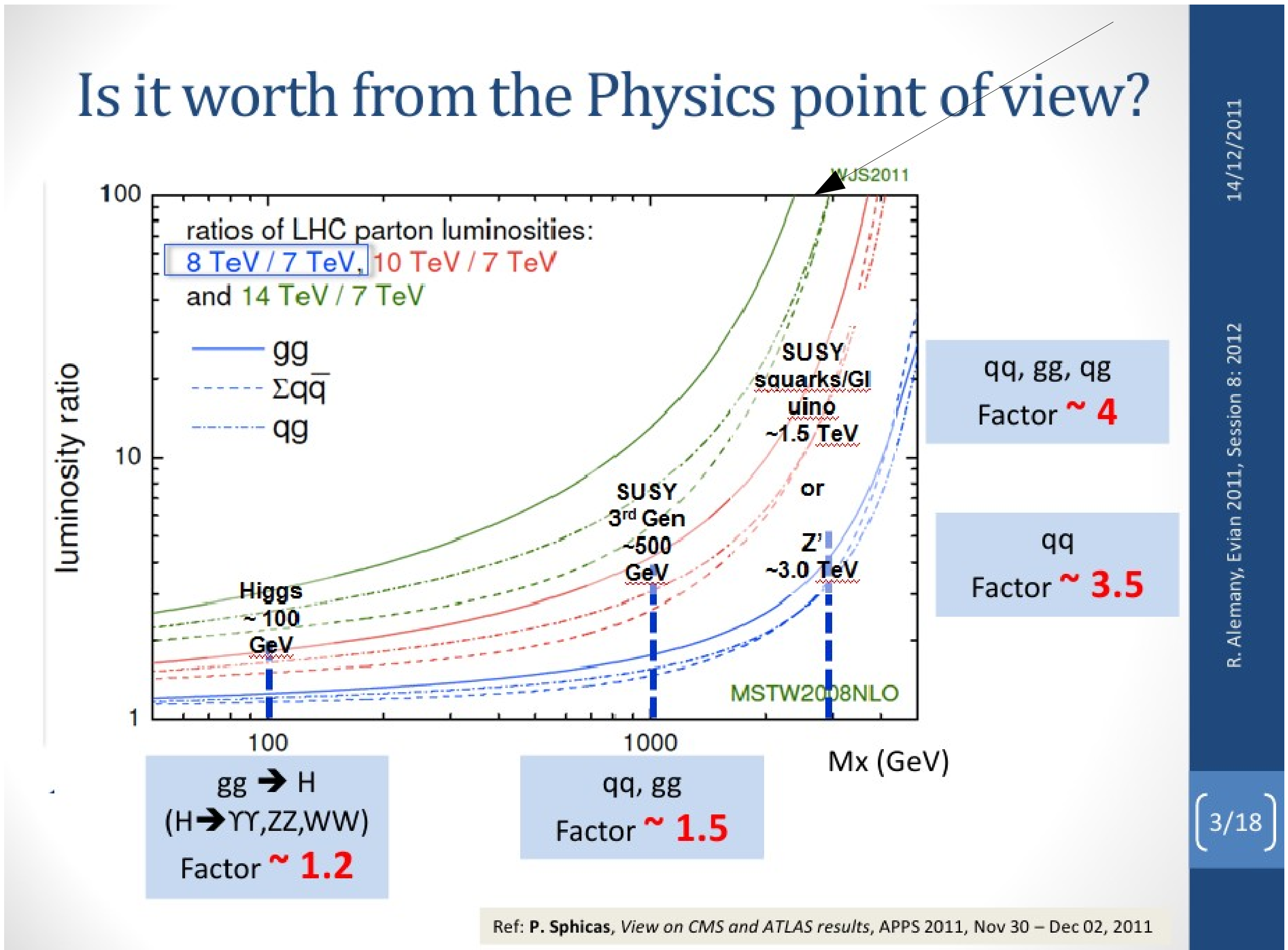
Why LHC was running at 8 TeV in 2012 (3/3) – Cross section

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

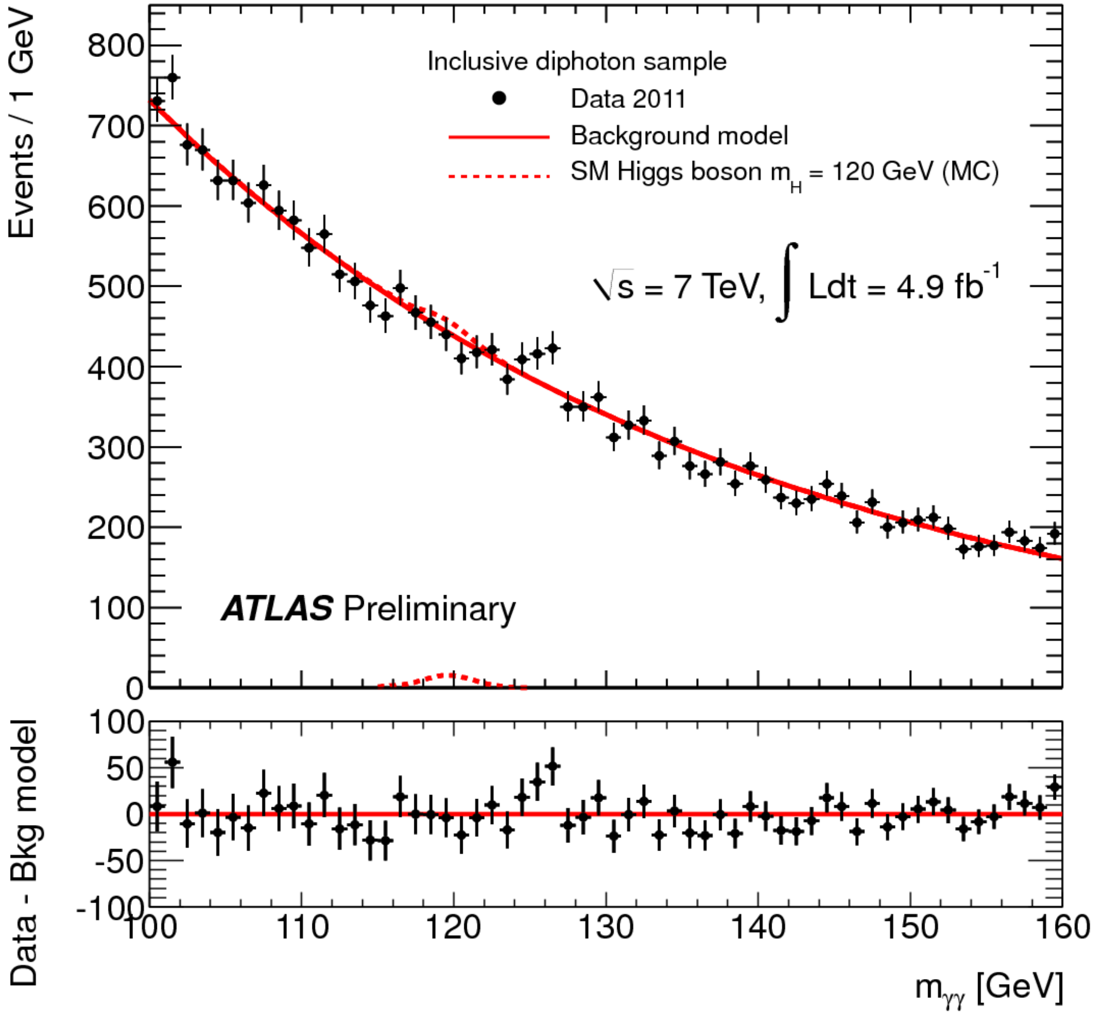


Also interesting for you!

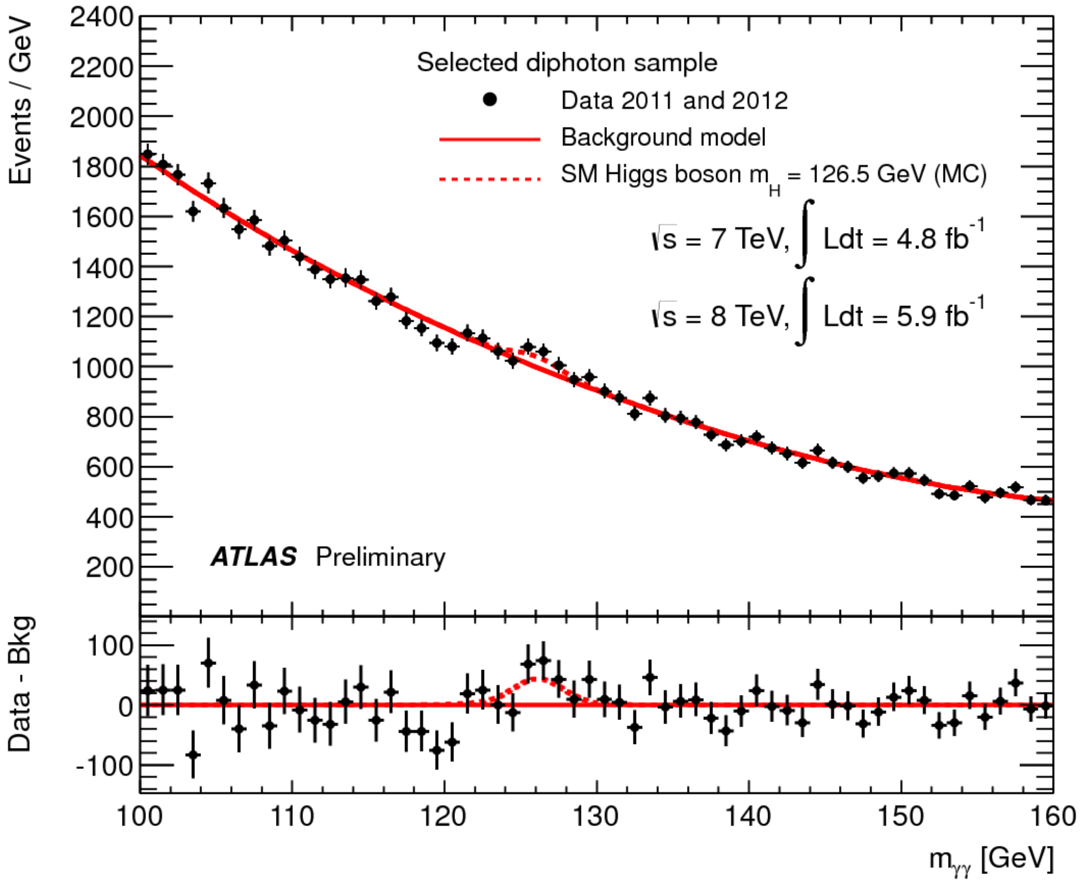
Start up 2015



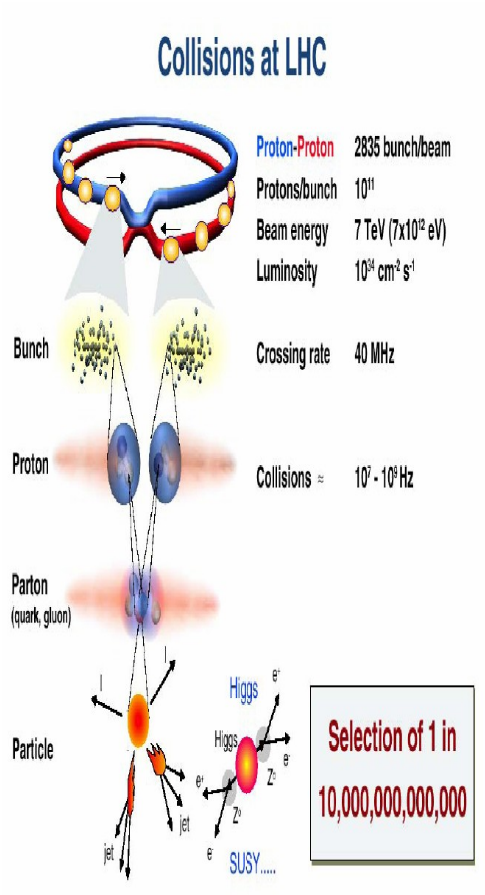
Best Higgs signature: H→2γ 2011 pre-discovery

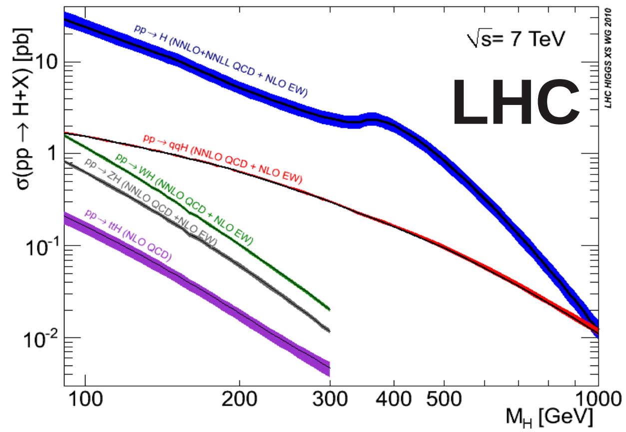


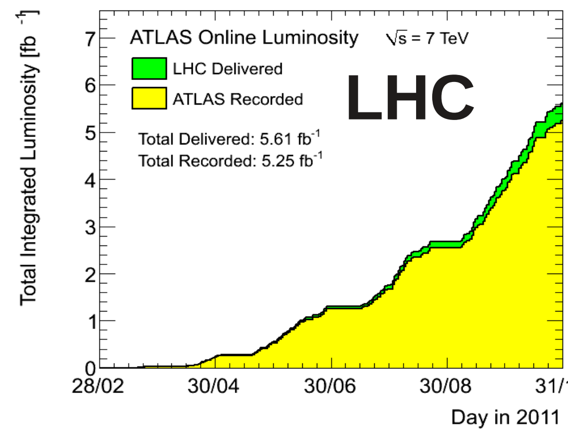
Best Higgs signature: H→2γ 2012 discovery

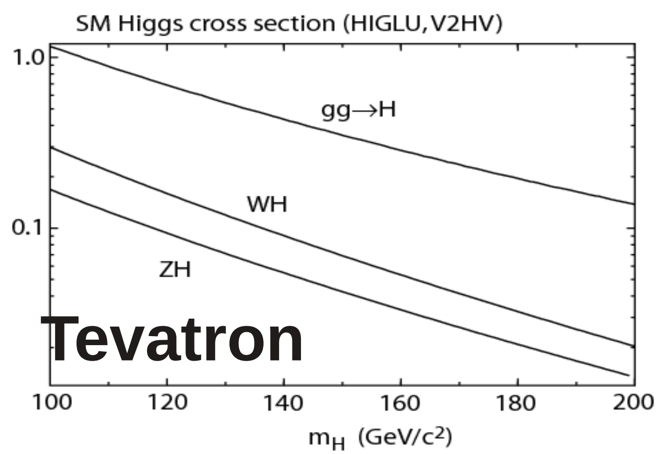


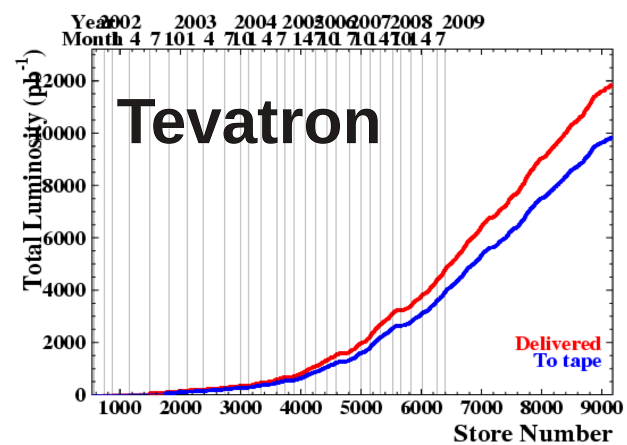
Summary
Main ingredients in LHC success











- Energy → 10 times higher cross section than Tevatron and integrated luminosity already ½ at end of 2011!
- In 2012 LHC collected 20 fb^{-1} ~ 2 * integrated Tevatron!