5 lectures on accelerator physics + 3 invited lectures

- 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 ESS (Mats Lindroos)
- This will be squeezed into 5 lectures!
- 3 invited lectures:
  - Mats Lindroos about ESS.
  - David McGinnis about RF instrumentation
  - John Weisend about cryotechnic for accelerators.

What are accelerators used for?

Inspiration

Discovery Science

- Particle and Nuclear Physics
- Materials science, chemistry, biology, …

Medicine

- Cancer therapy
- Medical radioisotopes

Accelerators and Beams

Energy and Environment

- accelerator-driven reactors (future)
- Inertial confinement fusion with heavy-ions (future)
- Flue-gas treatment

National Security

- Cargo screening
- Active interrogation
- Radiography

Industry

- Electron processing
- Sterilization
- Ion implantation

Accelerators by the Numbers

Inspiration

Application	Systems (thru 2008)
Ion Implantation	10,000
Electron beam modification	7,000
Electron and X-ray irradiators	2,000
Ion beam analysis and AMS	200
Radioisotope production	600
High energy x-ray inspection	750
Neutron generators	2000
Radiotherapy	8000
Hadrontherapy	25
Photon Sources (synchrotron radiation, …)	80
Nuclear and Particle Physics Research	110
Total	~30,000

The most well known category of accelerators – particle physics research accelerators – is one of the smallest in number. The technology for other types of accelerators was born from these machines.

Schedule

- Friday 8-10: lecture 1 and 2 (and part of 3)
- Monday 10-12: lecture 3 and 4 (and part of 5)
- Tuesday 8-9: lecture 5 and 6
- Tuesday 9-10: Mats Lindroos about ESS.
- Wednesday 10-11: David McGinnis about RF instrumentation
- Wednesday 11-12: John Weisend about cryotechnic for accelerators

Material: 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

Material: online resources for further information

- "Accelerators for pedestrians"
  - http://cds.cern.ch/record/1017689?ln=en
- "U.S. Particle Accelerator School"
  - http://uspas.fnal.gov/
    - See their lecture file catalogue

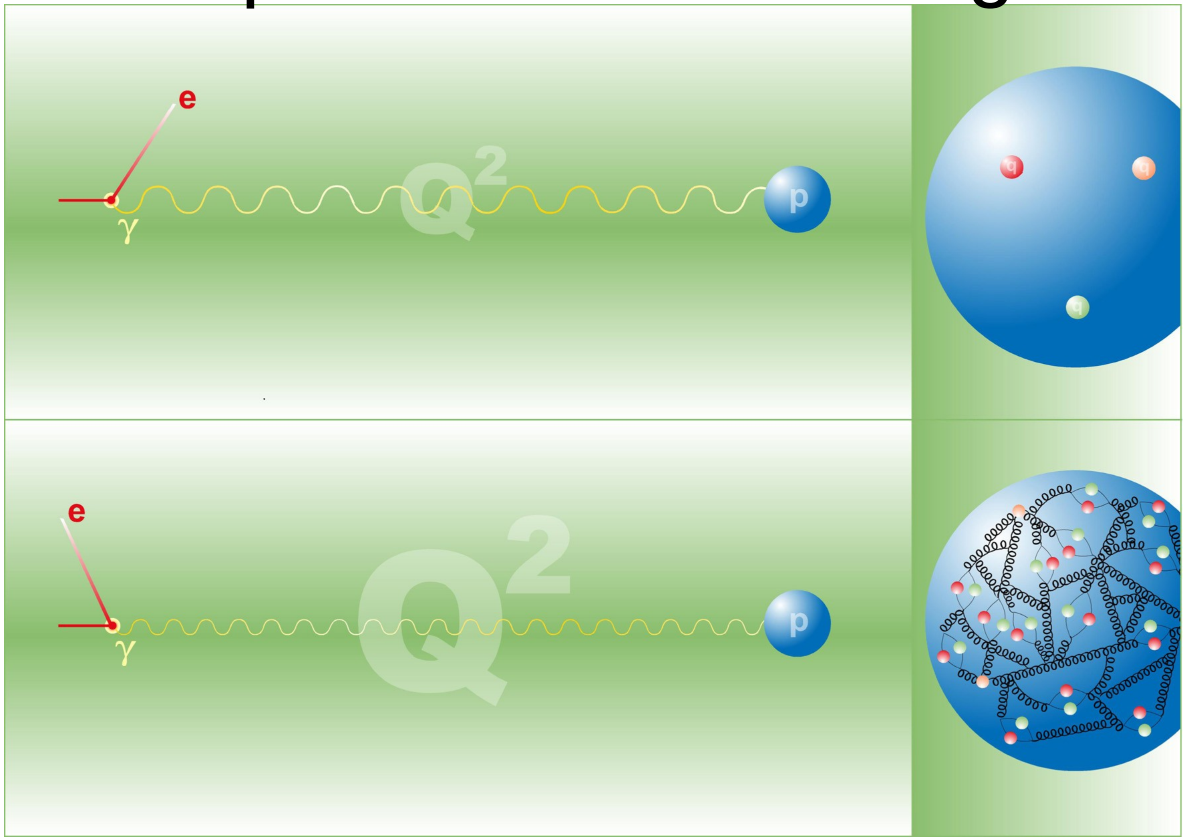
Think break

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

Why do we accelerate?

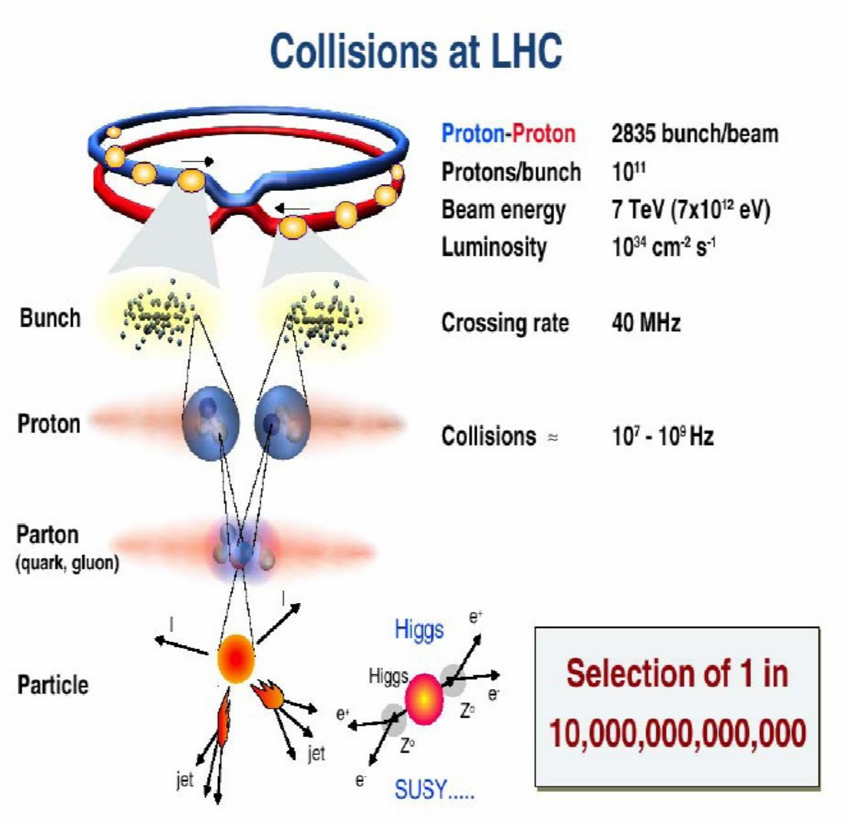
To probe the structure of e.g. protons

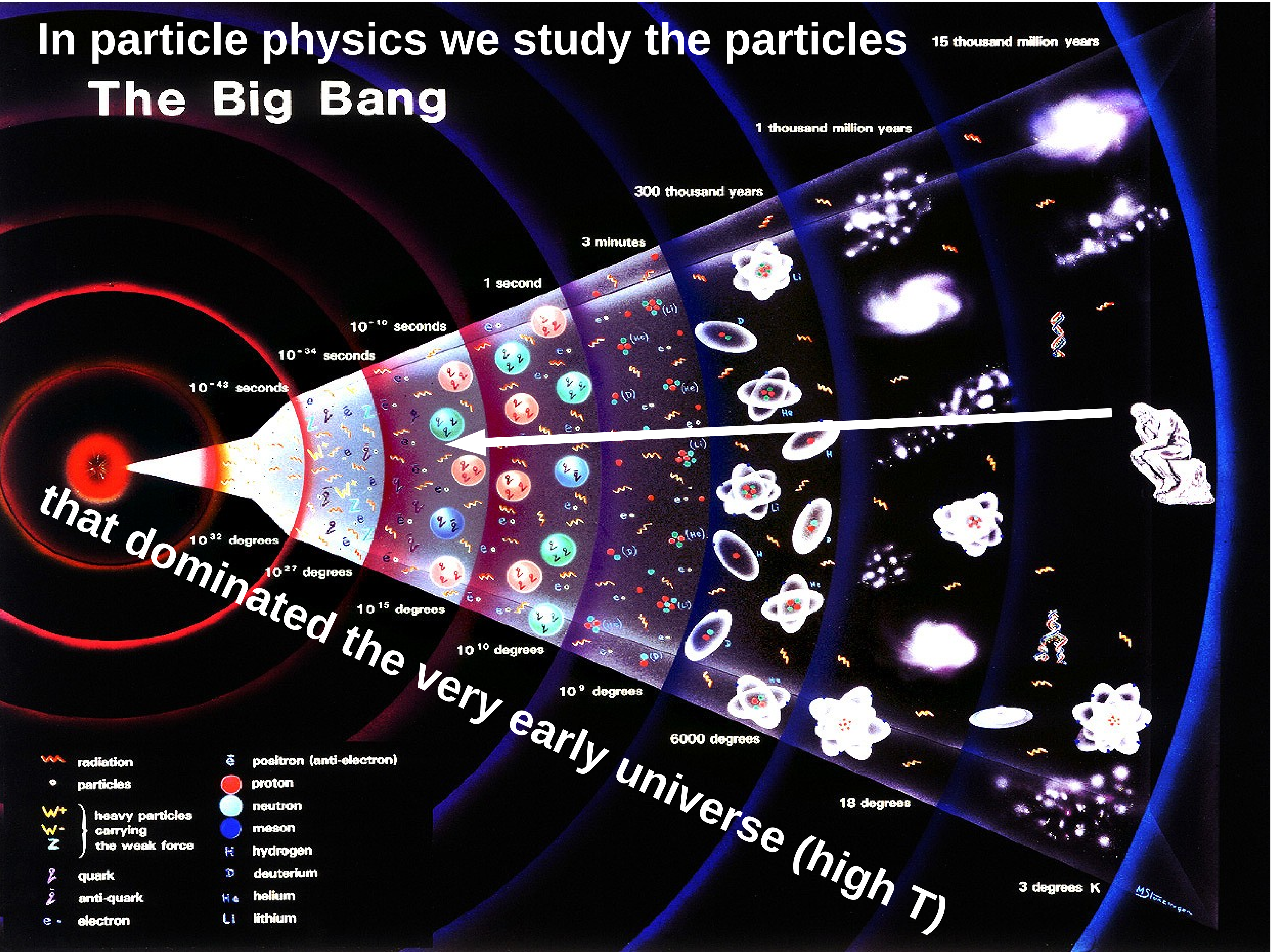
- The wavelength $\lambda \sim \frac{\hbar}{E}$
  - Need big E to see small structures!
- Example: deep inelastic scattering



To create new particles

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

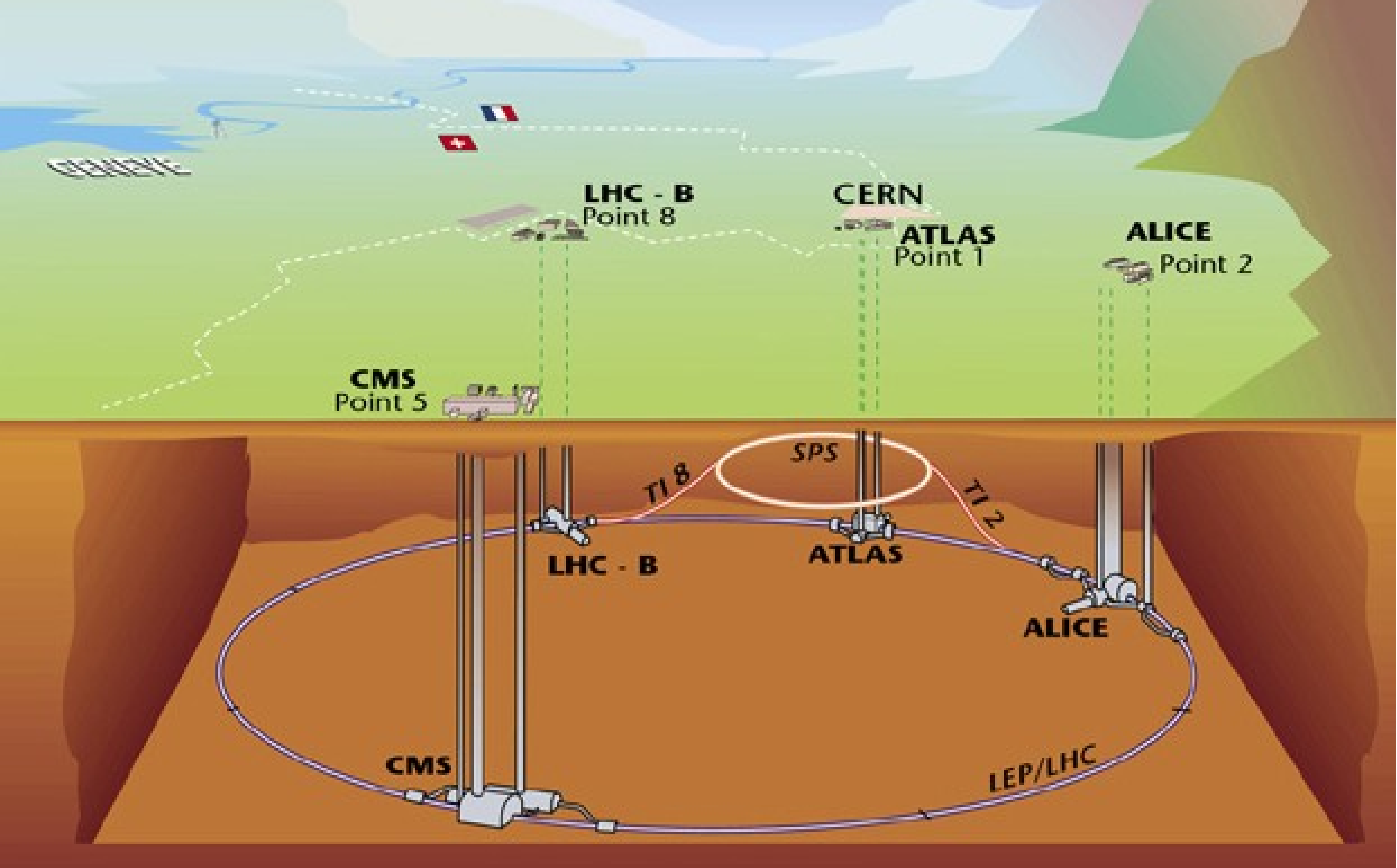



In particle physics we study the particles
that dominated the very early universe (high T)
The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees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

What are the main characteristics of an accelerator

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

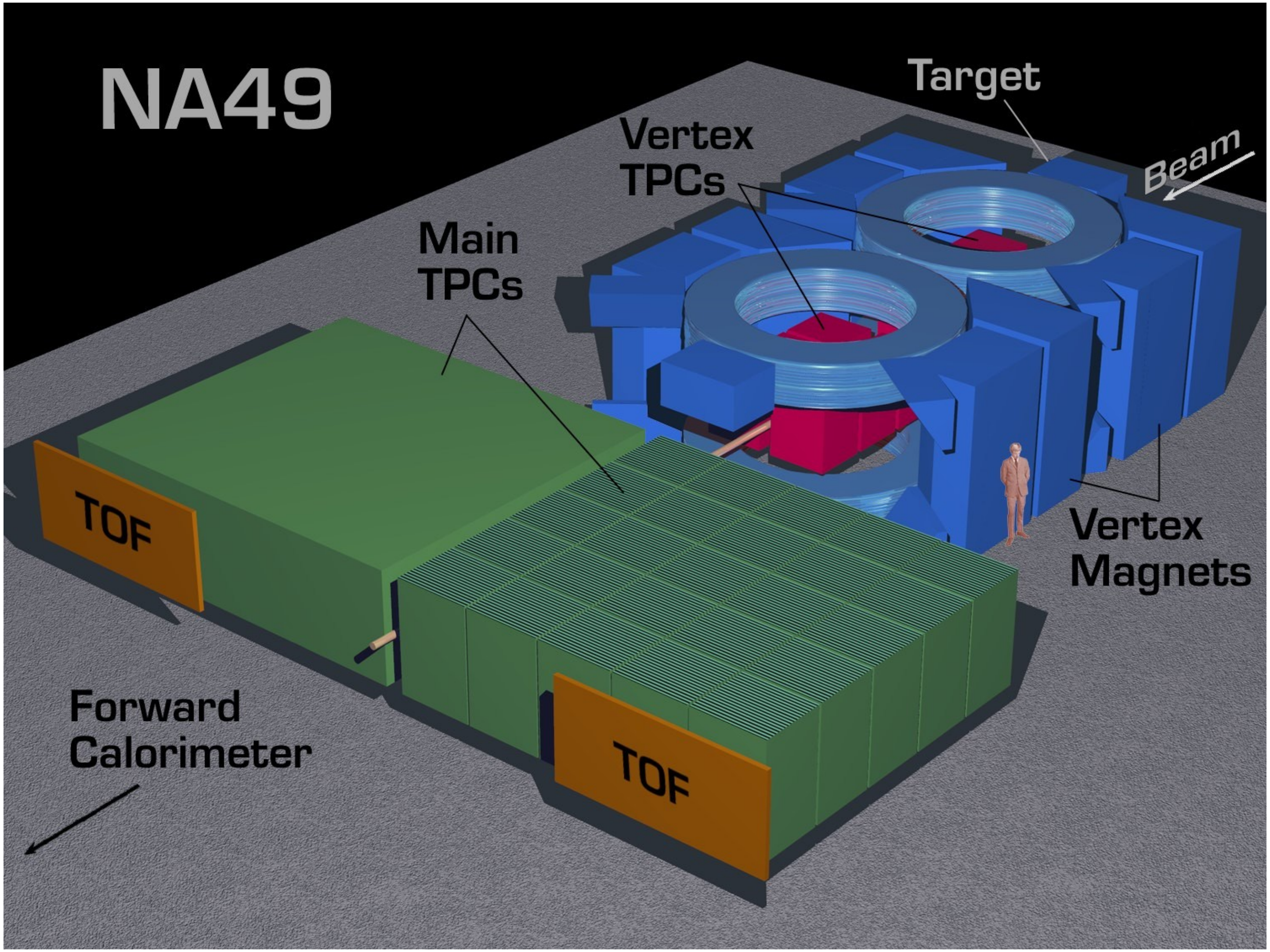
My main example will be LHC!



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



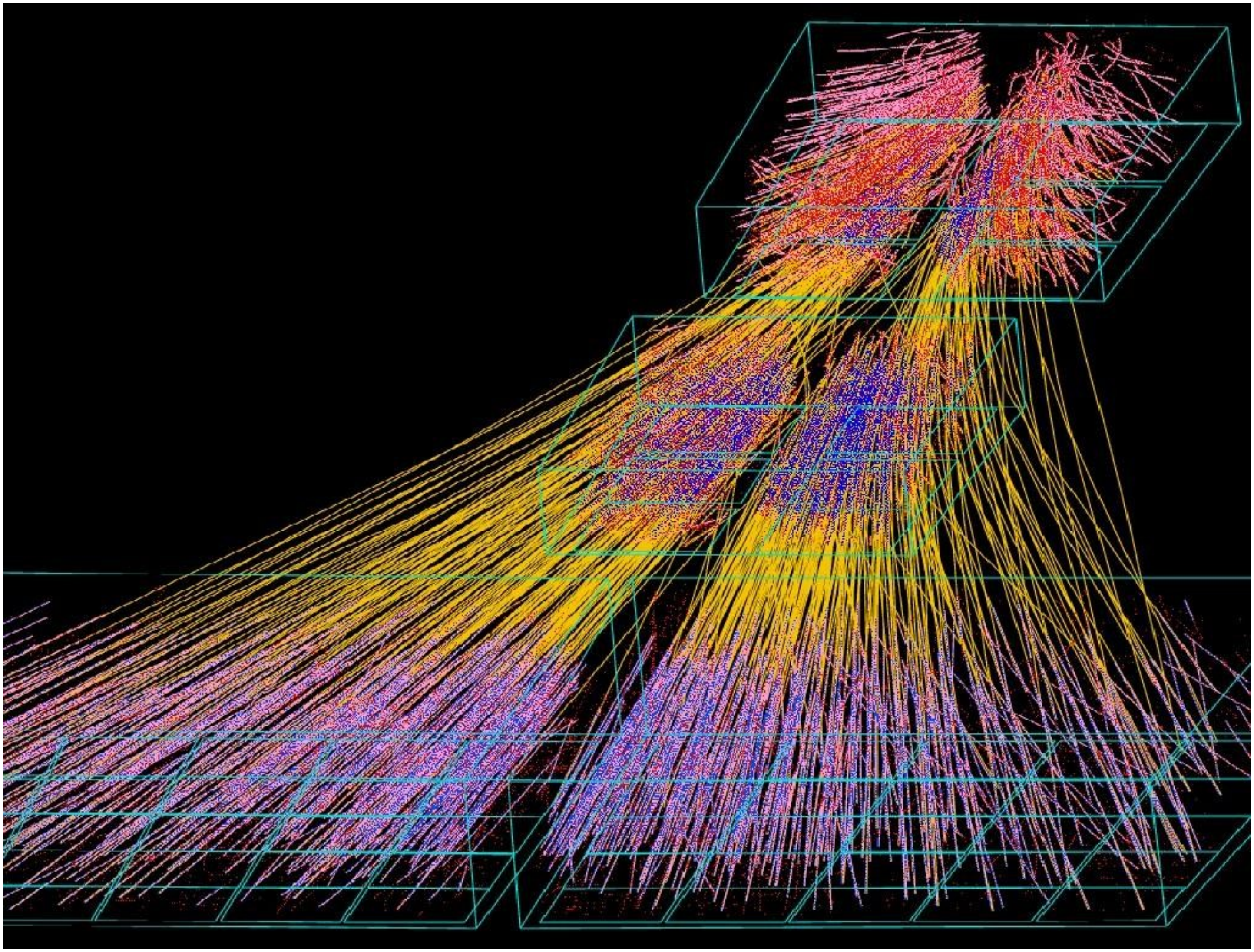
Pb at
160 A GeV
on Pb at
rest

Reconstructed event

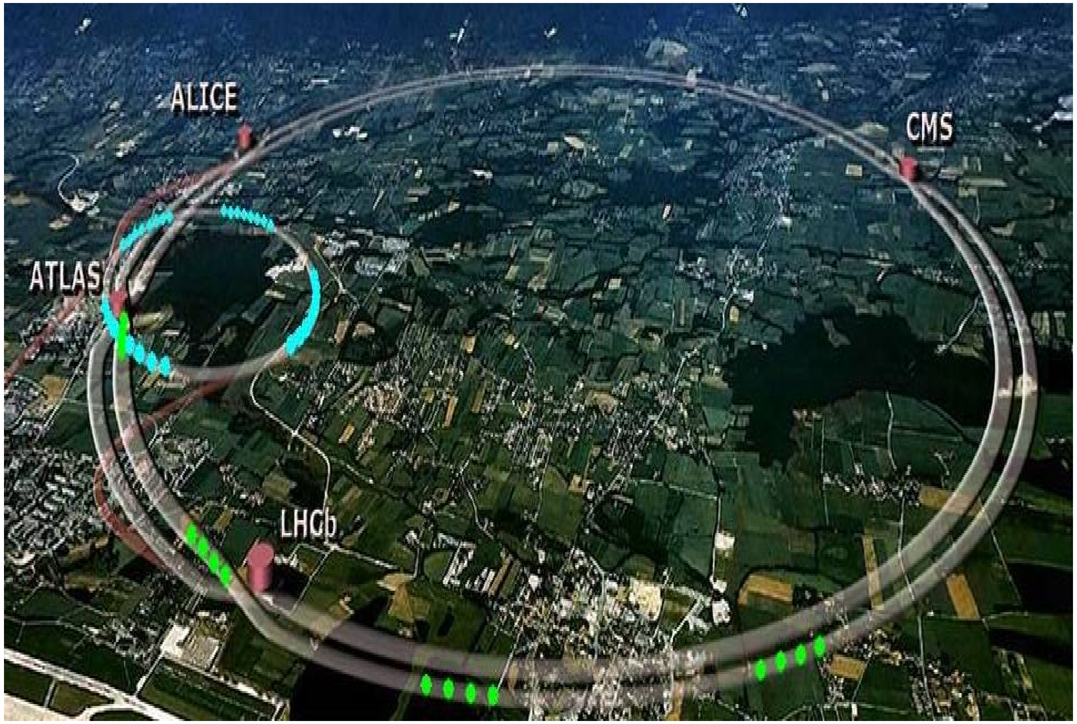
High momentum in laboratory system

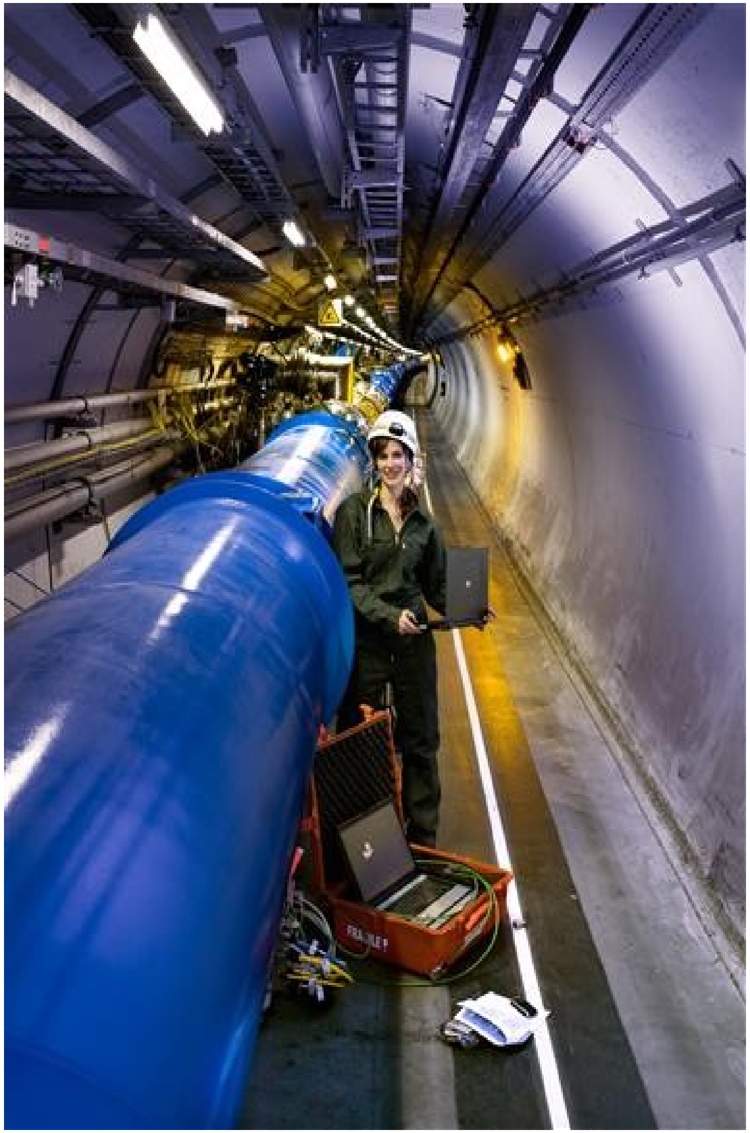
Particle production is focused forward in the direction of the Beam

Typically needs a long experimental setup



Large Hadron Collider (LHC)

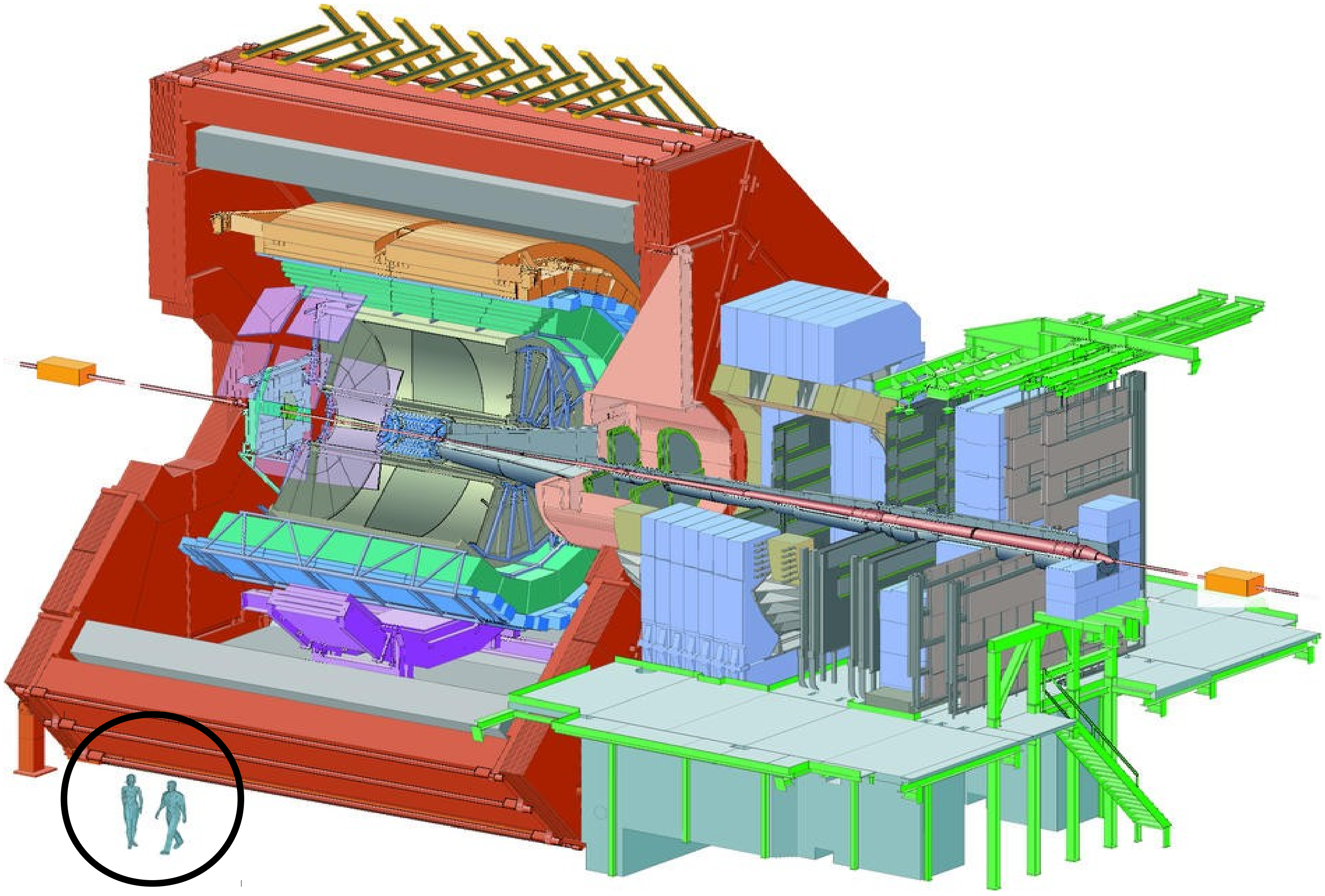


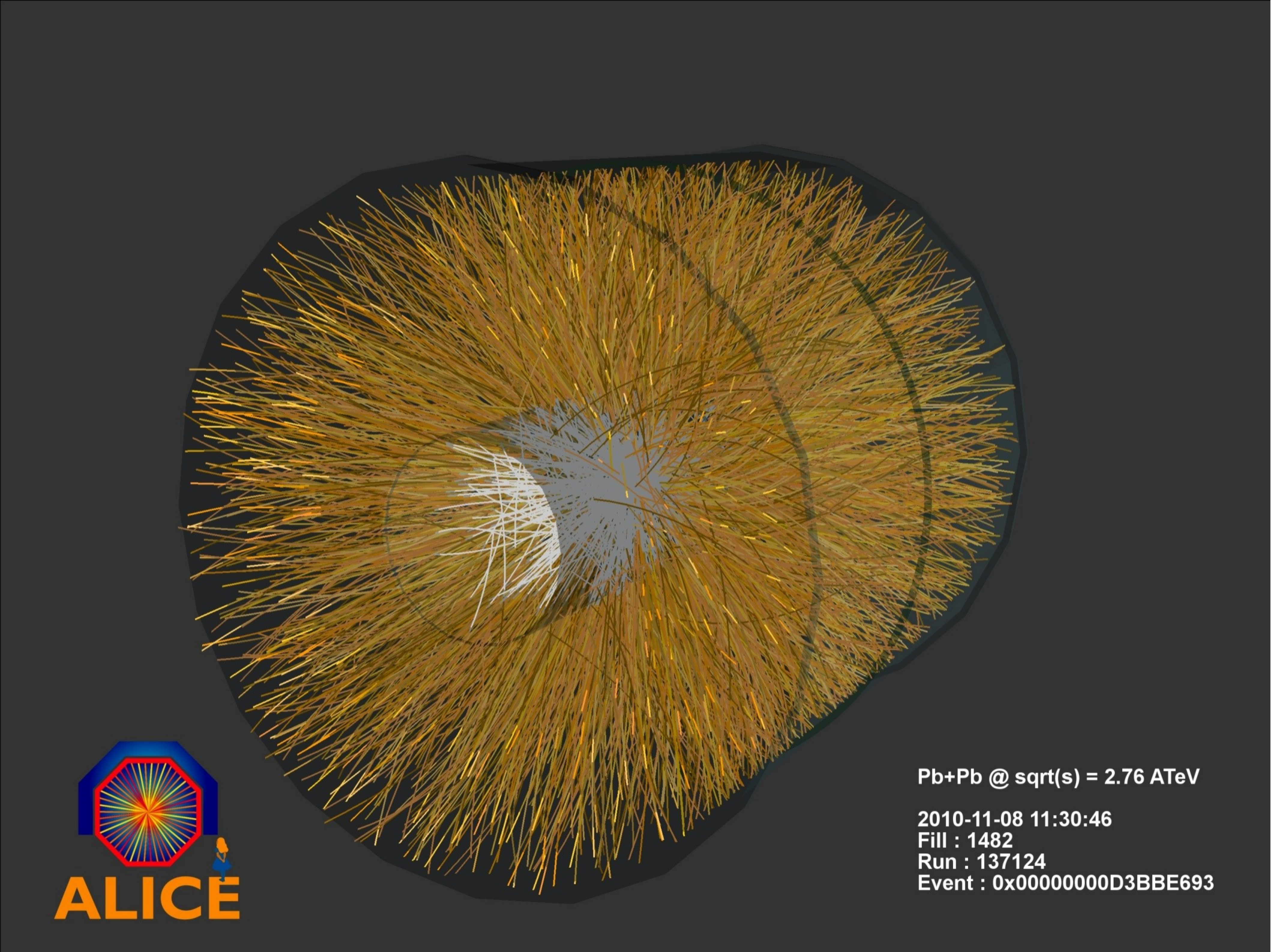


$$\sqrt{s} = 13 \text{TeV}$$
$$(vs\, 0.2\, TeV\ LEP)$$
$$(vs\, 1.8\, TeV\ Tevatron)$$

Collides hadrons (protons and ions) instead of electrons.

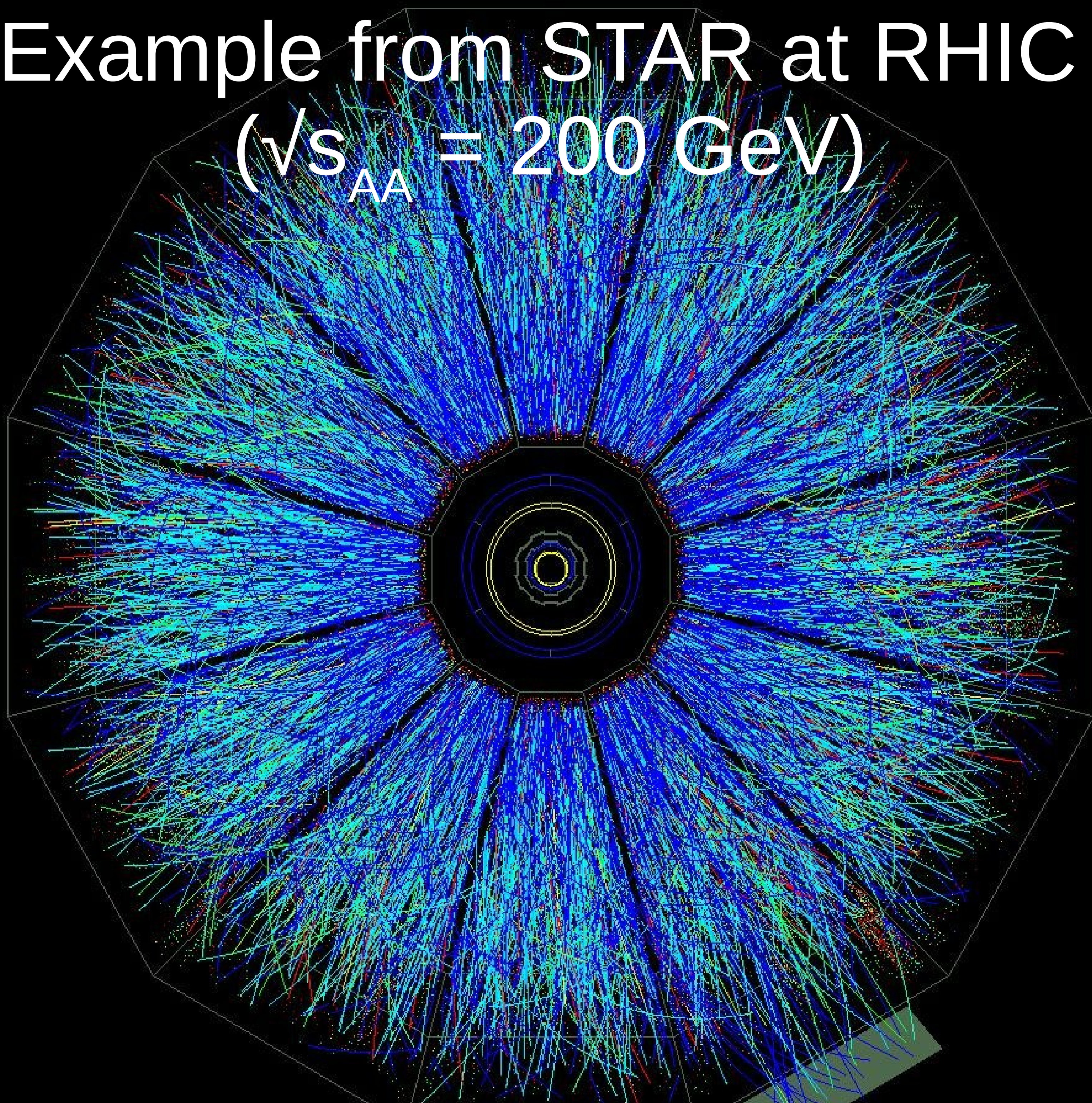
The ALICE experiment at LHC

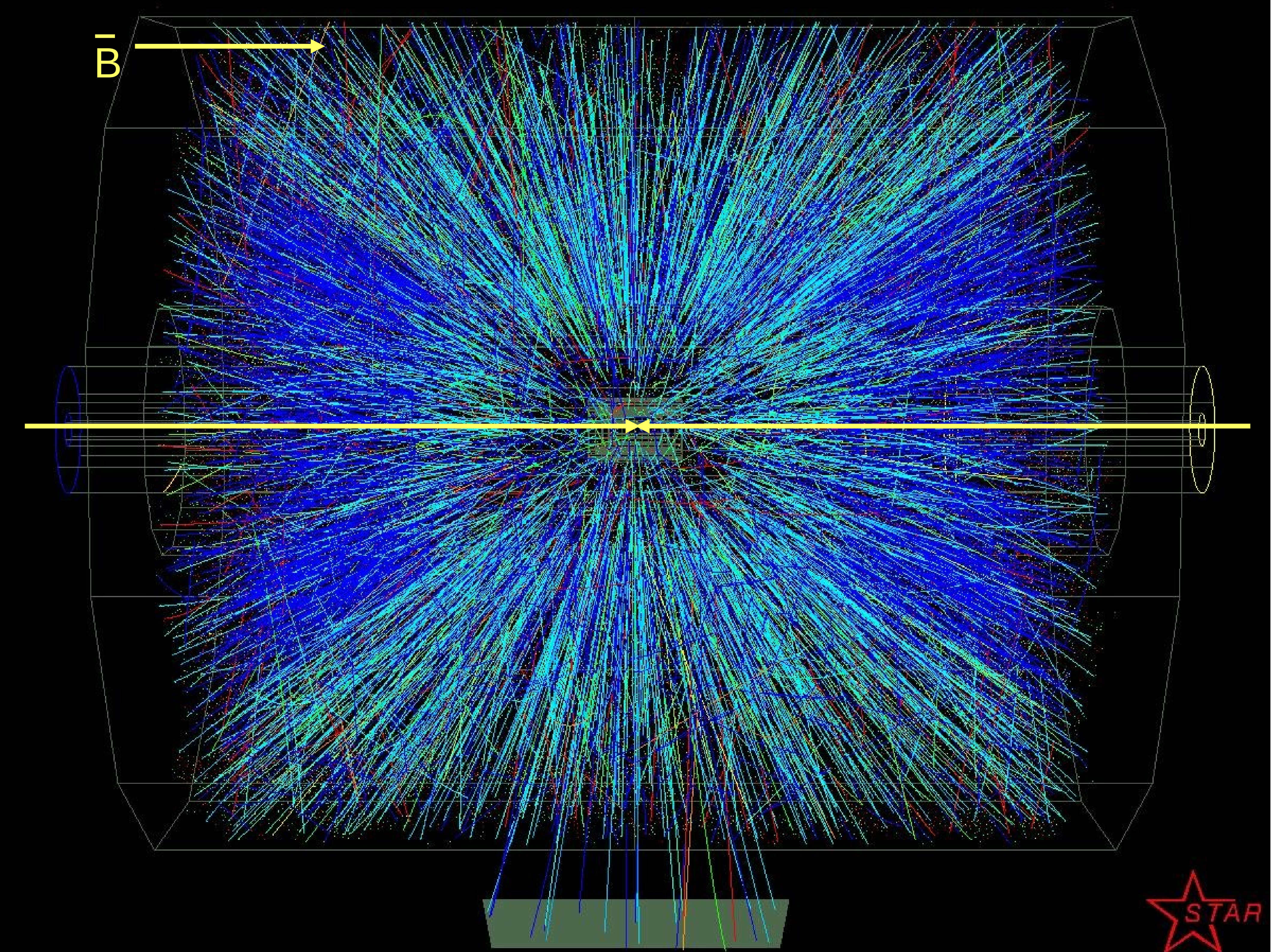



ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

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

$\bar{B}$





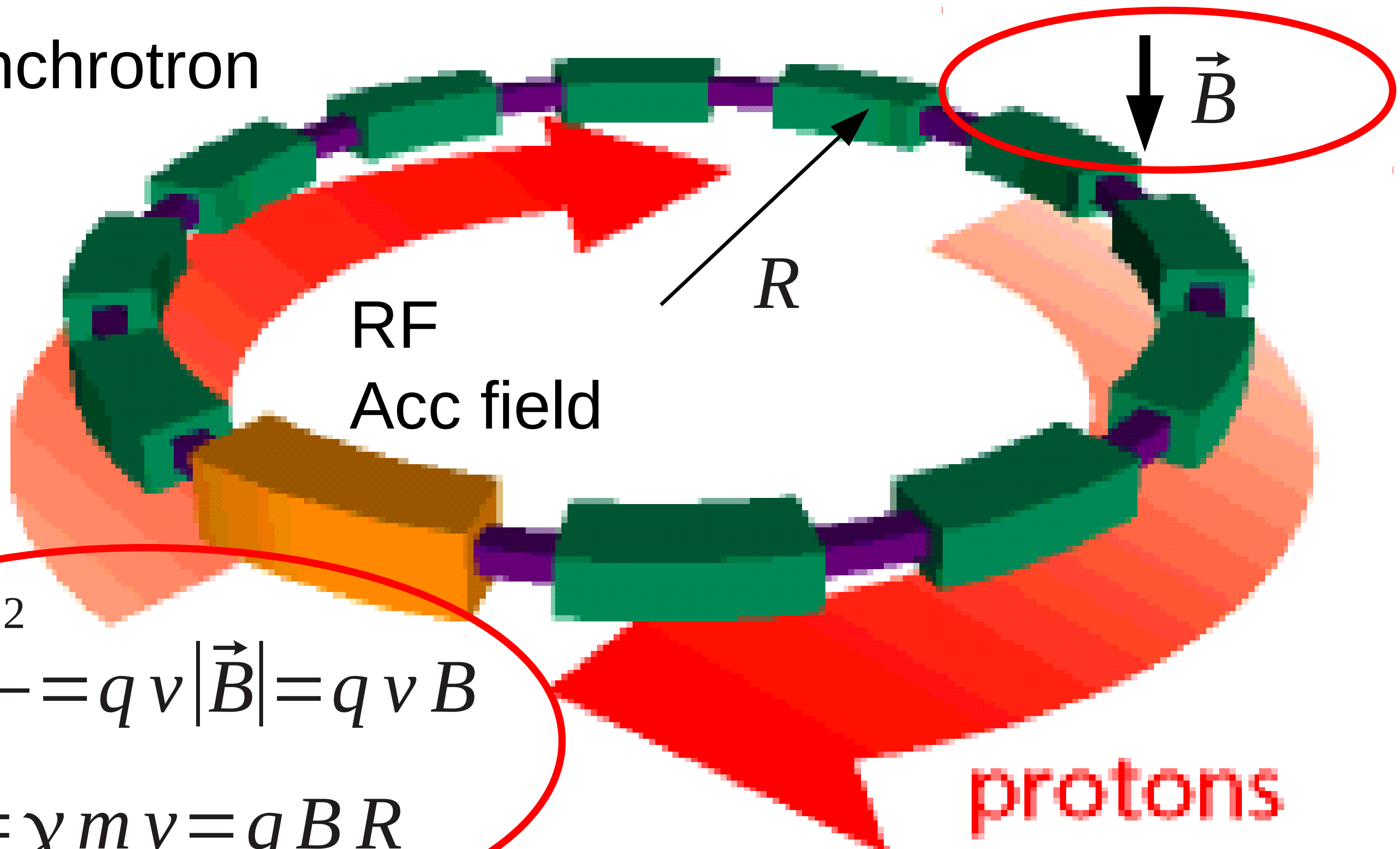
$\bar{B}$
STAR

What limits the energy in a collider?

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

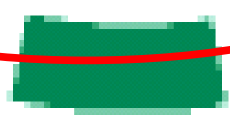
The magnetic field!

Synchrotron



$$\frac{\gamma m v^2}{R} = q v |\vec{B}| = q v B$$

$$p = \gamma m v = q B R$$



Dipole magnet give circular motion

Acceleration in E-field

Exercise

- Calculate the bending radius for LHC where maximum B = 8.33T and the maximum Ebeam = 7TeV using that

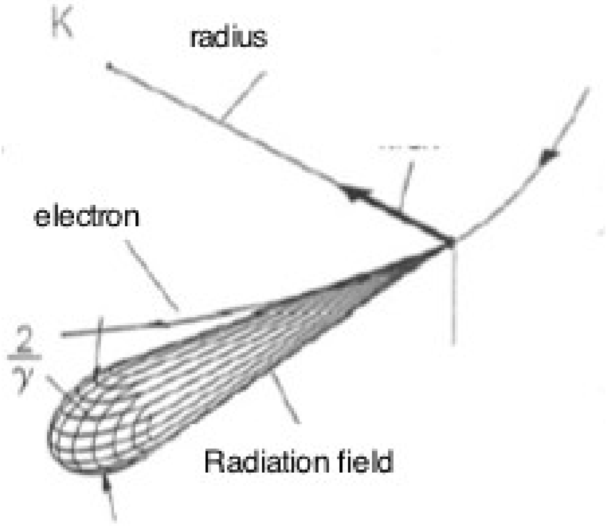
$$p[GeV/c] = 0.3 \cdot B[T] \cdot R[m]$$

- Compare the bending radius to the circumference of LHC which is 26.7 km

Why does LHC collide protons and not electrons?

Protons vs. Electrons: synchrotron radiation

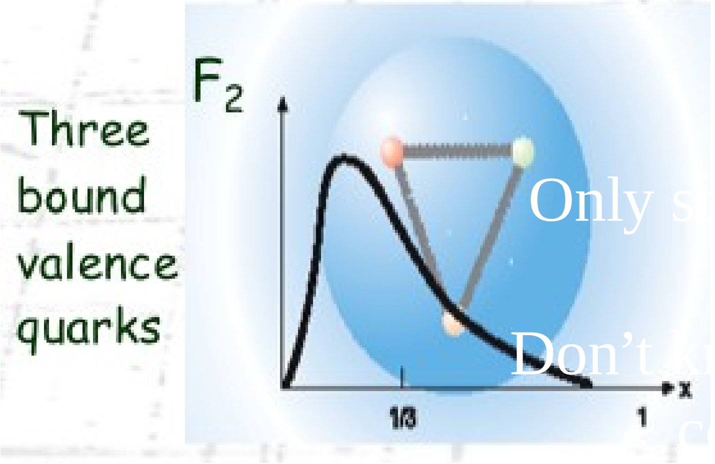
$$P_s \propto \frac{E^4}{m^2 R^2}$$



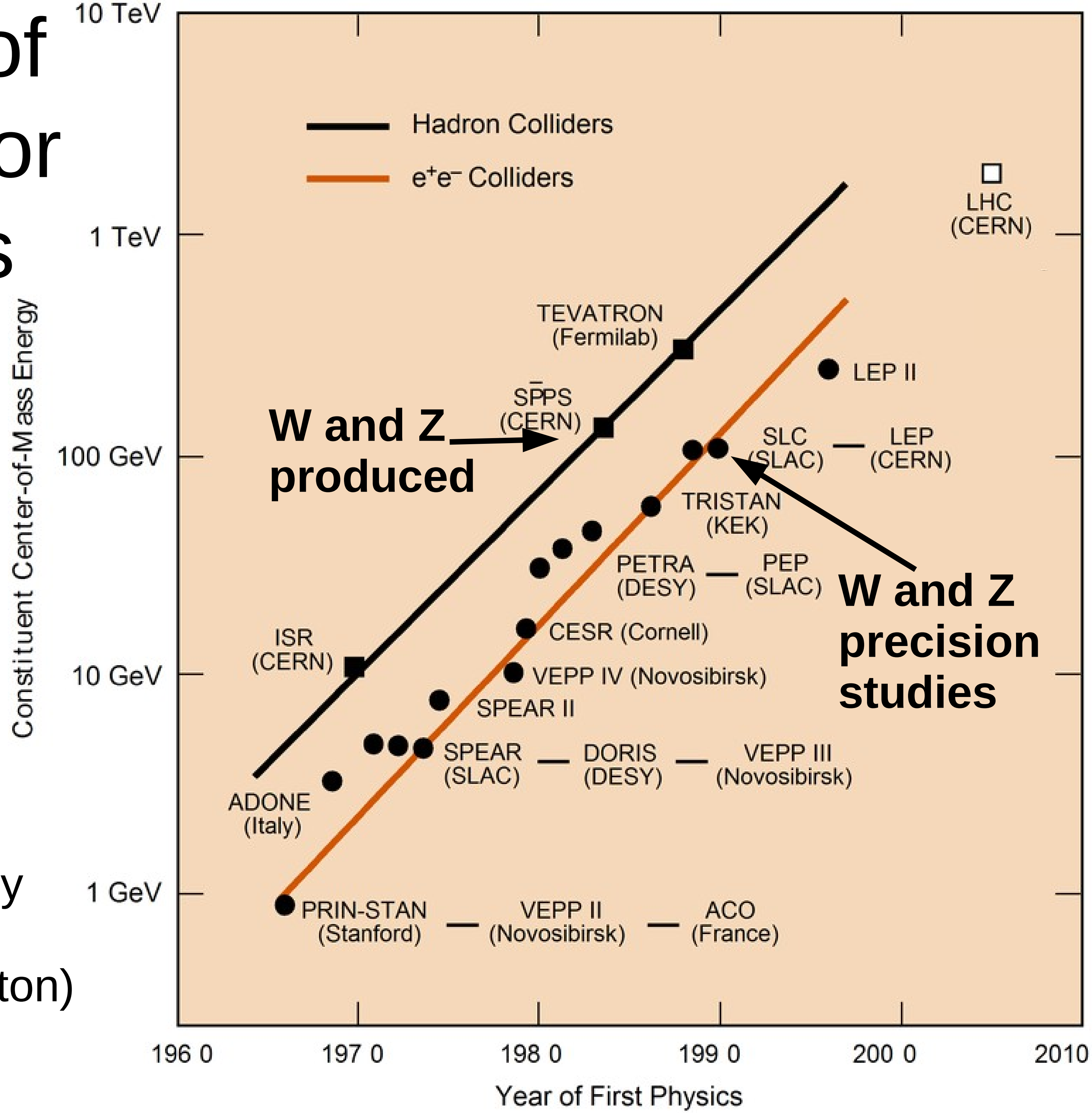
- Can win by accelerating protons

$$\left(\frac{m_p}{m_e}\right)^2 = \left(\frac{938\text{MeV}}{0.511\text{MeV}}\right)^2 = 3.4\times10^6$$

- But protons aren't fundamental



History of accelerator energies

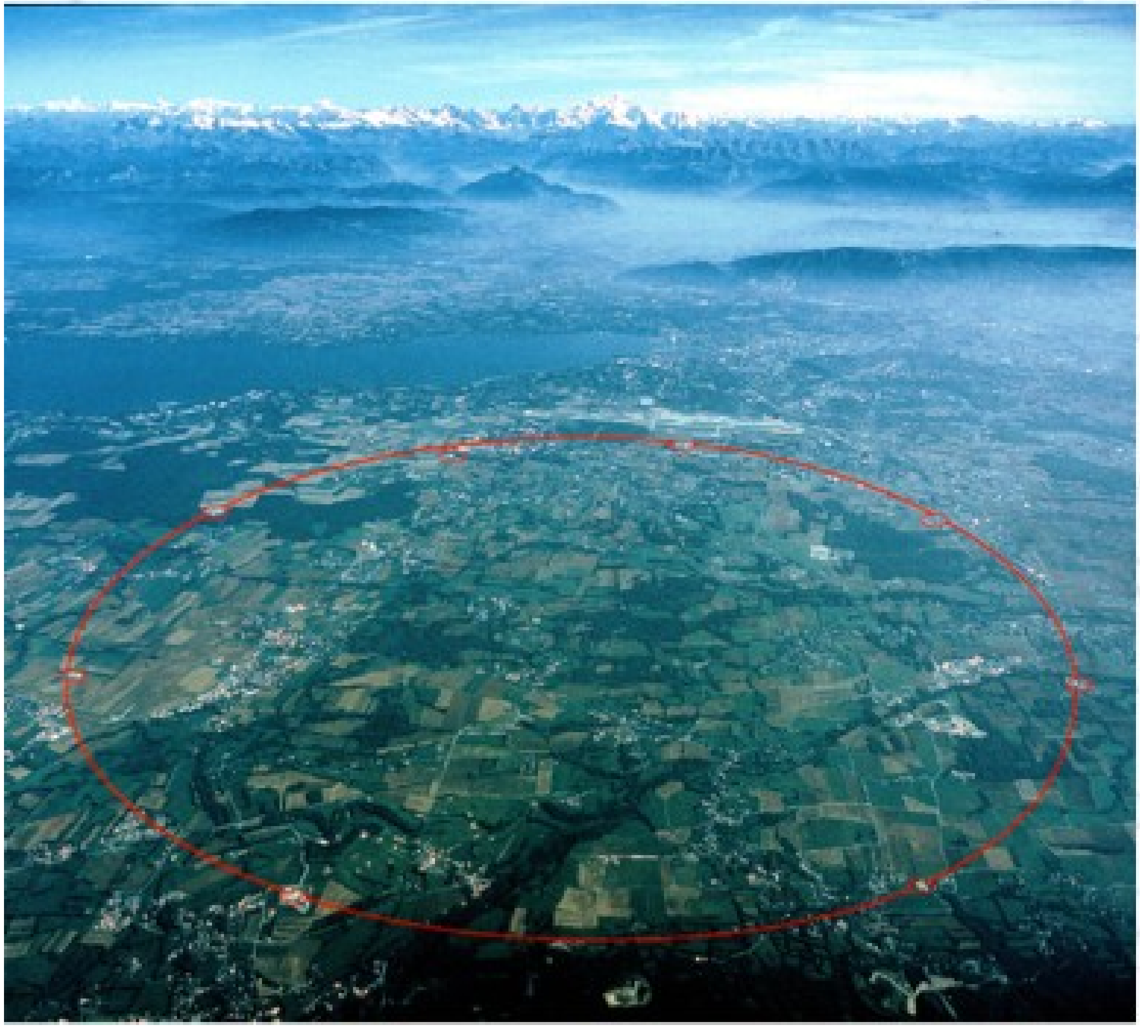


e^+e^- machines typically match hadron machines with 5x nominal energy

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

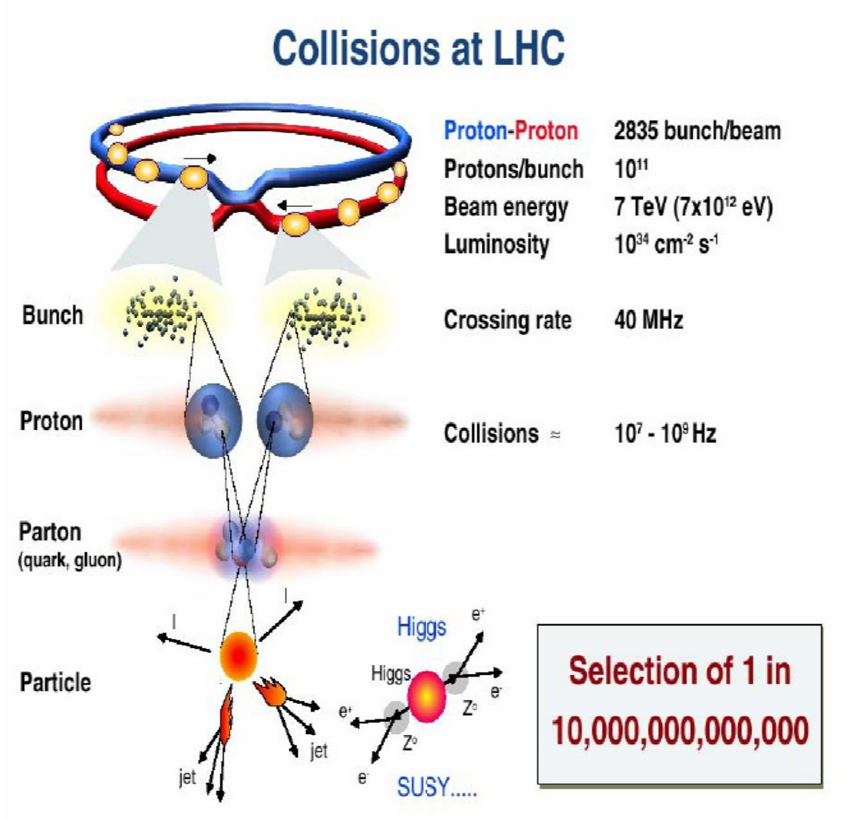
LEP Accelerator (CERN 1990-2000)

- 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



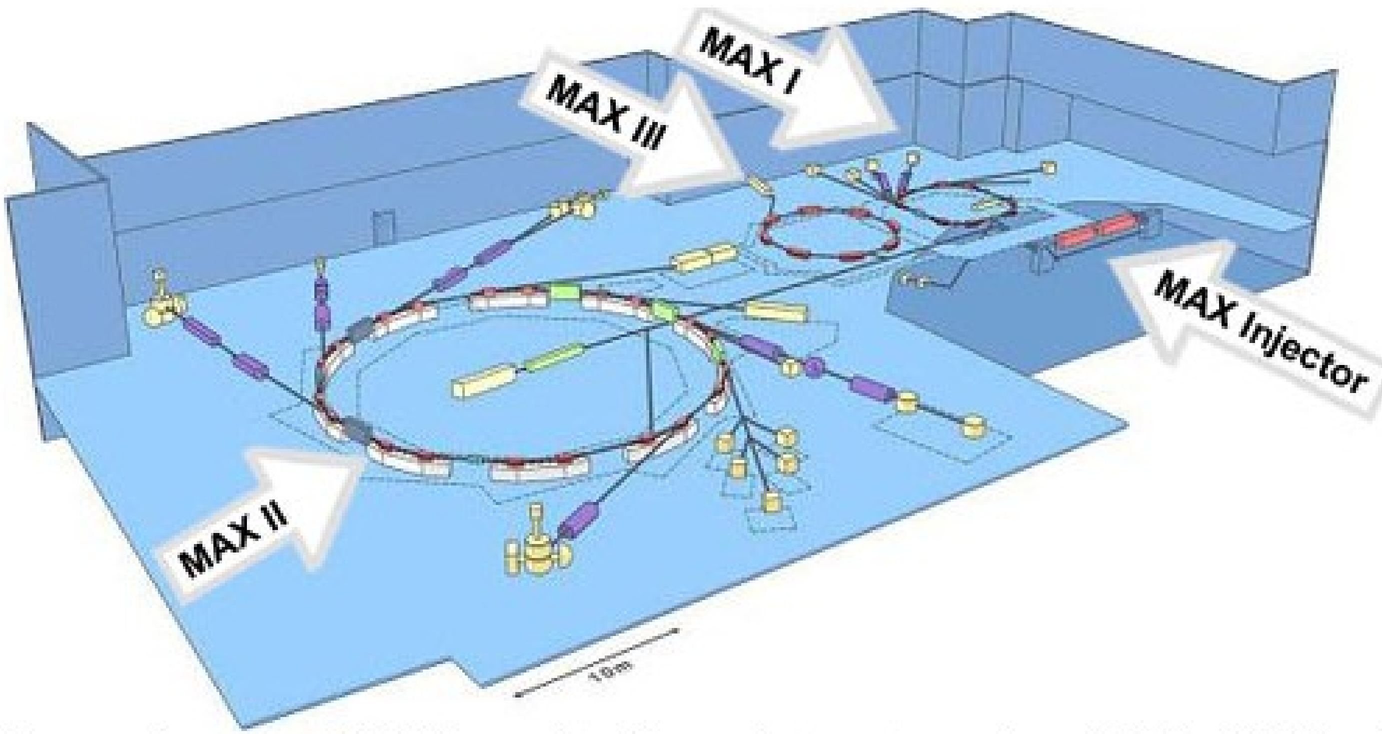
LHC (and proton colliders in general) are discovery machines!

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



However – synchrotron light can itself be used for good physics

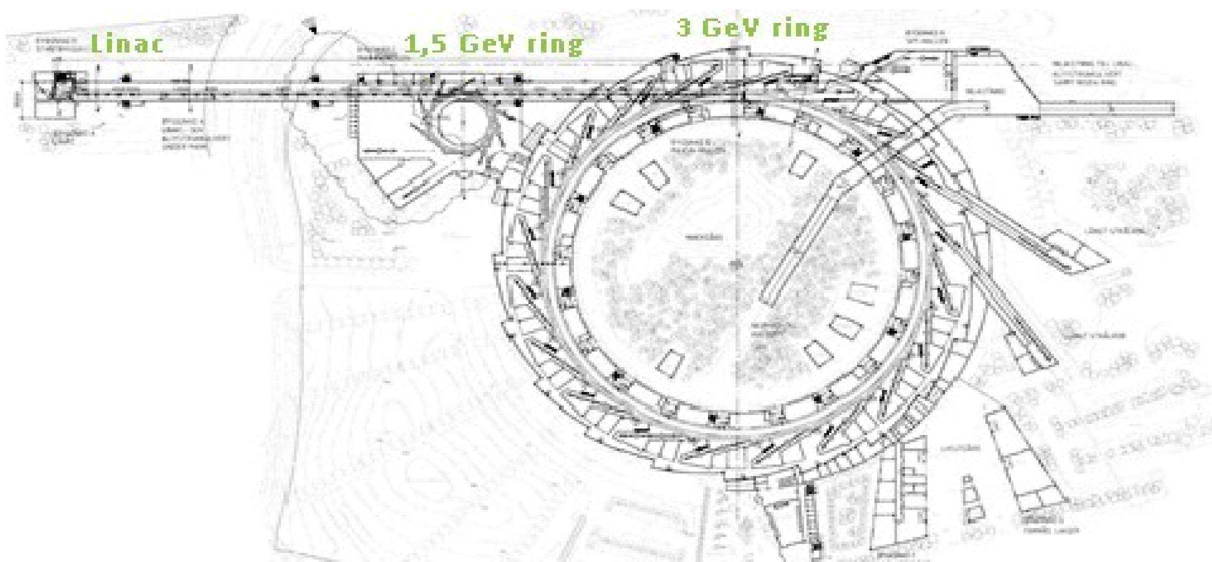
MAX-lab Accelerators



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!

The MAX IV Laboratory - our future light source



Final comment on synchrotron radiation

- Synchrotron radiation has also a positive effect in that it “corrects” for beam disturbances making electron beams easier to control

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

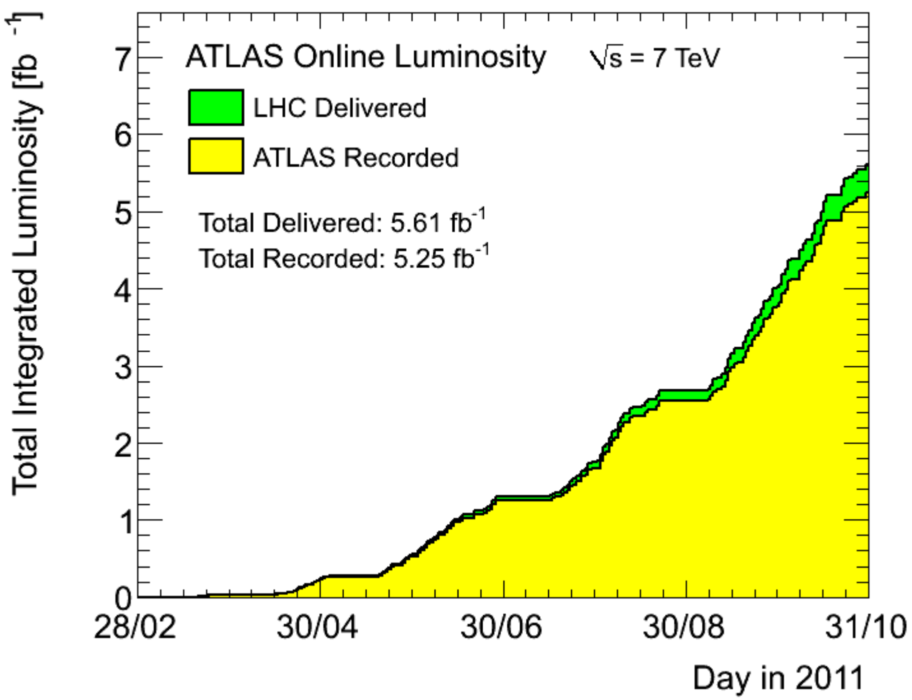
$$\mathcal{L} = \frac{1}{4\pi} \frac{f \cdot N_1 \cdot N_2}{\sigma_x \cdot \sigma_y}$$

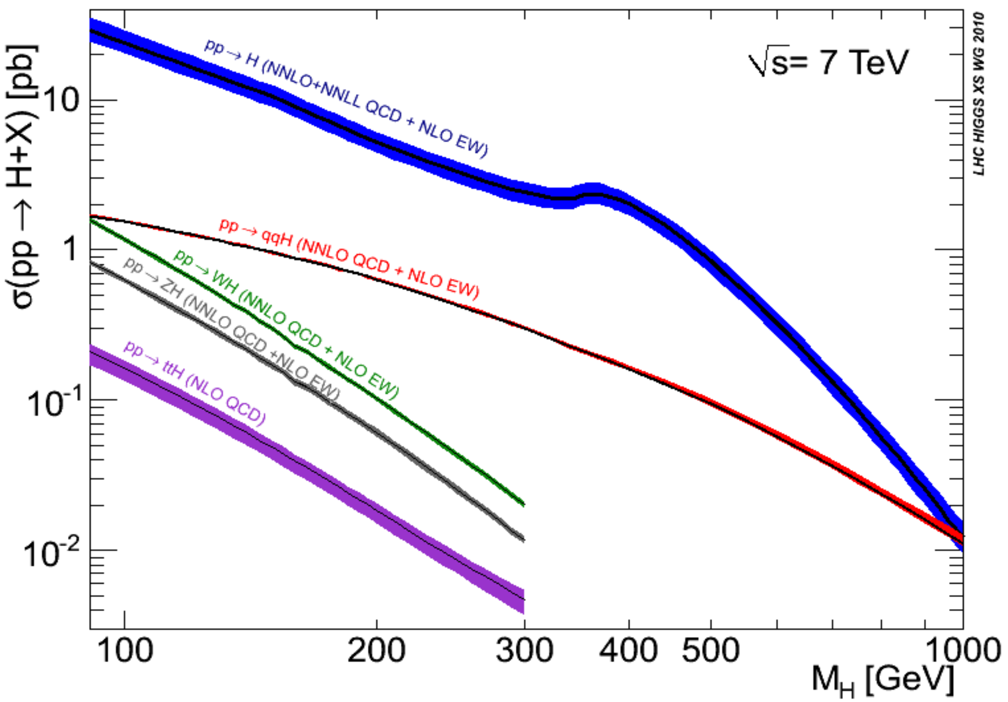
"Current"

"Spot size"

Where *f* 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



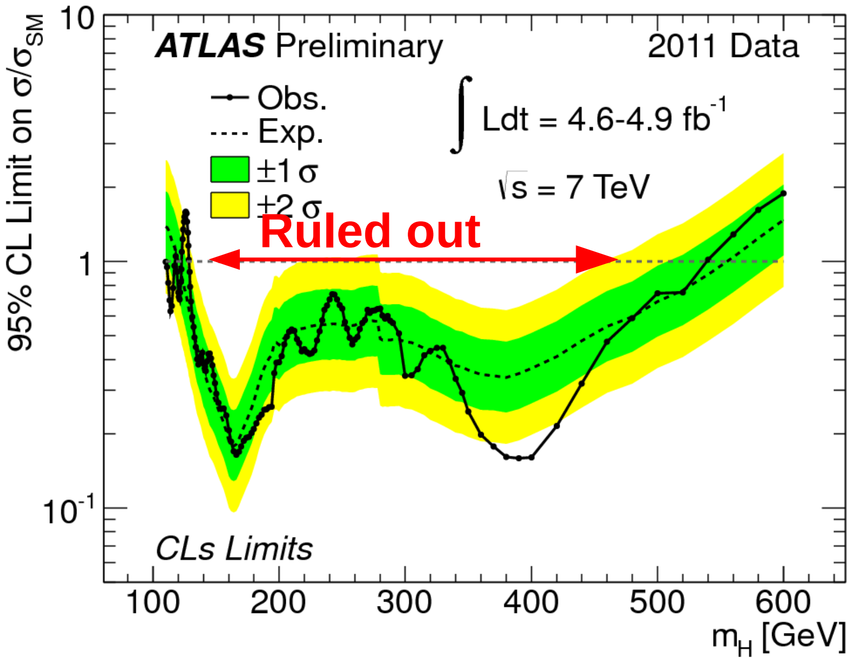


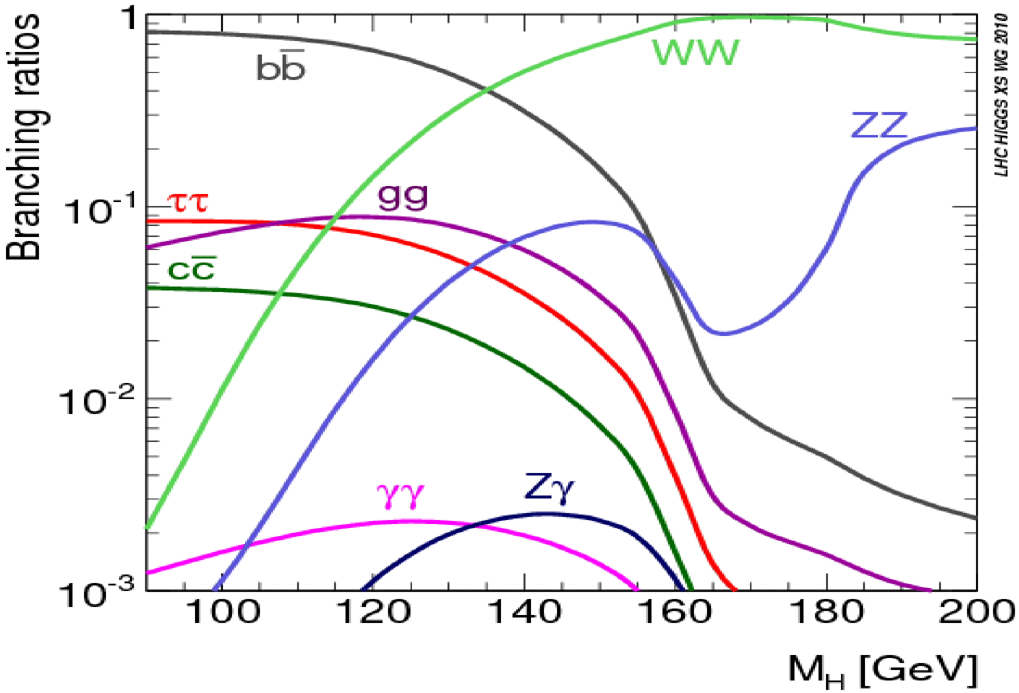
- What is the total # of produced Higgs's in the ATLAS experiment if m_H=130GeV?
- Answer: ~5fb^{-1}*10,000fb ~ 50,000!

Note that this corresponds to

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

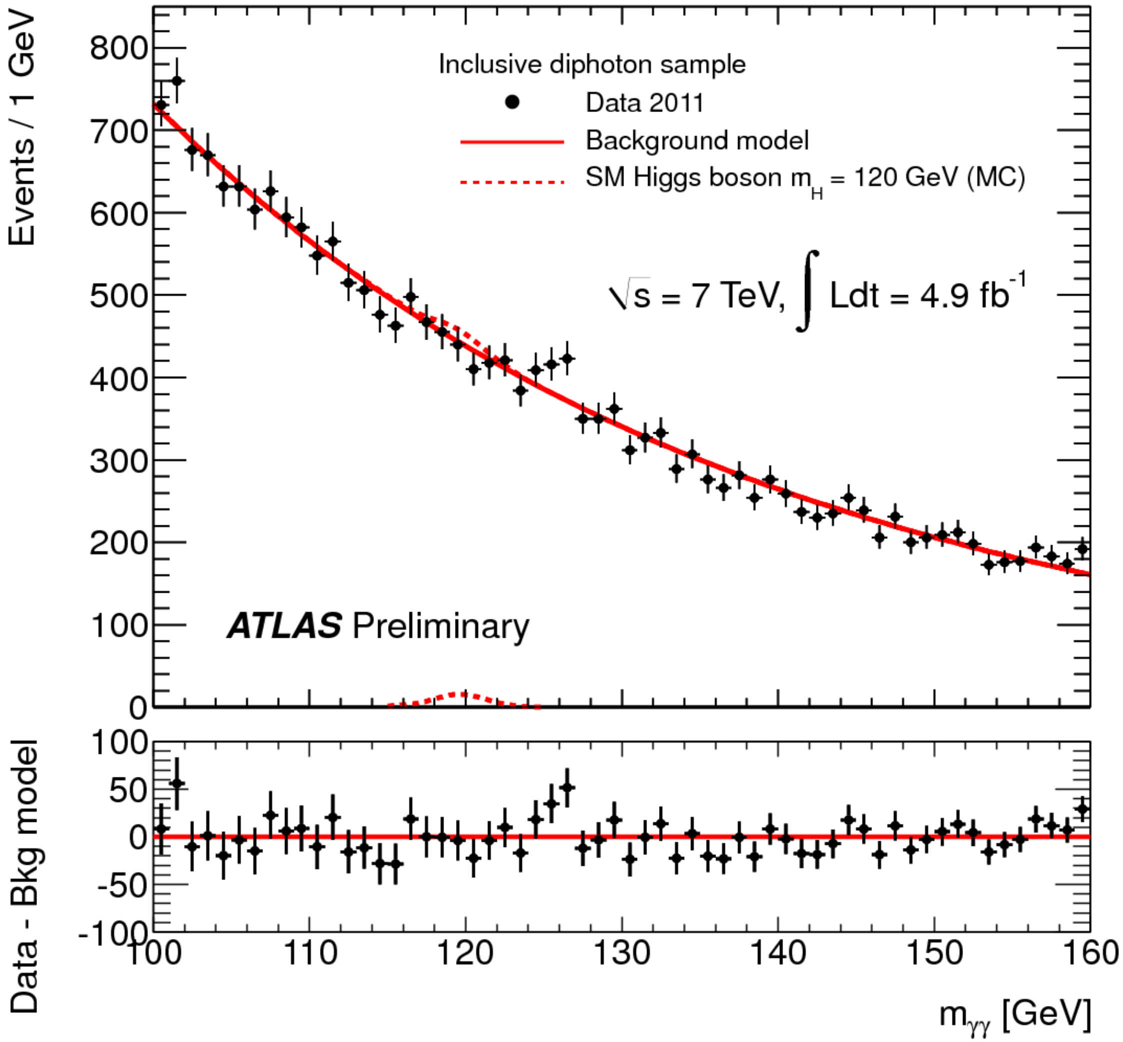
Higgs mass window
End of 2011



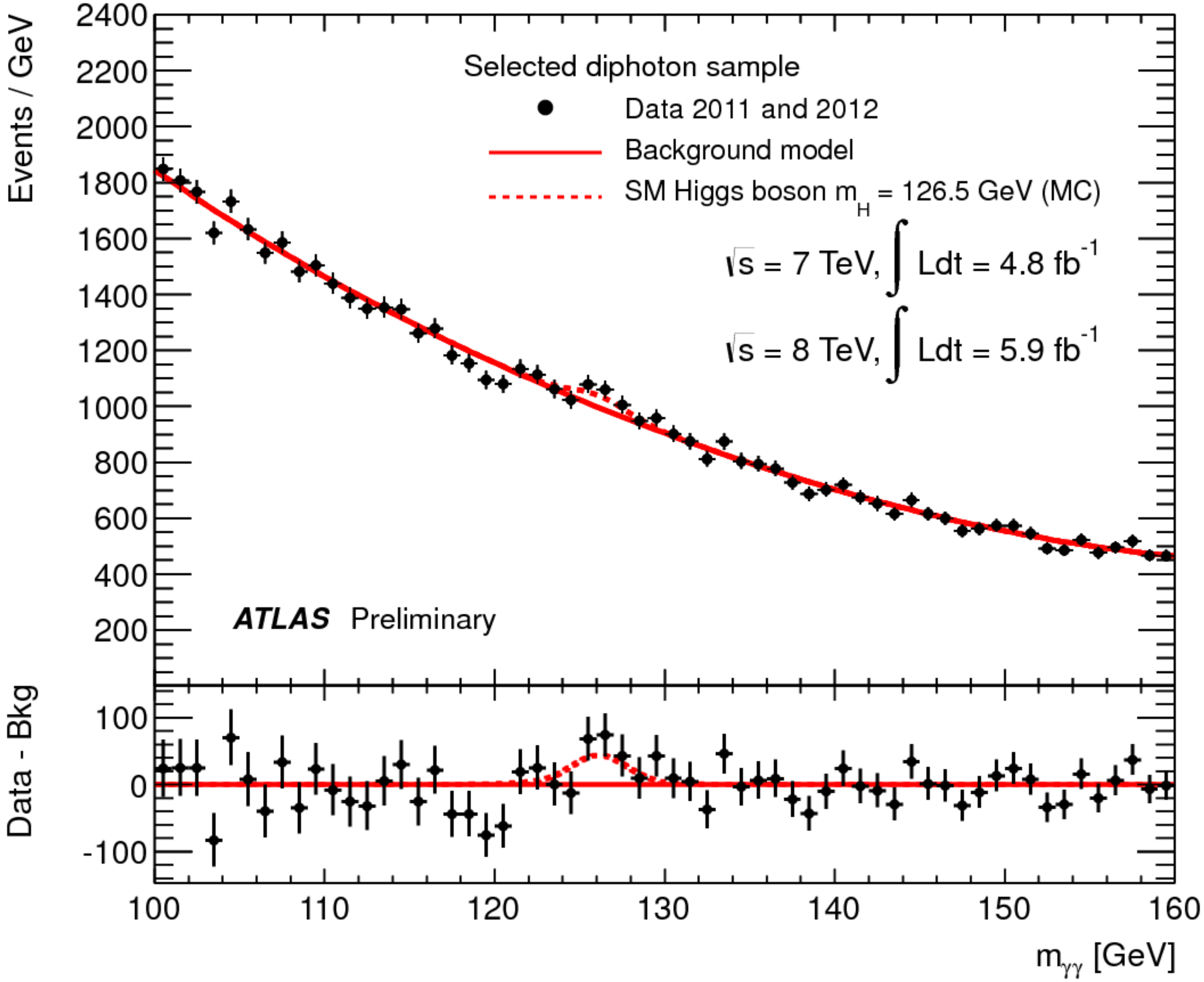


- Why is the limit not better at low mH where the cross section is larger?
- Answer: m_H too low for direct decay to 2W or 2Z = cleanest signatures!

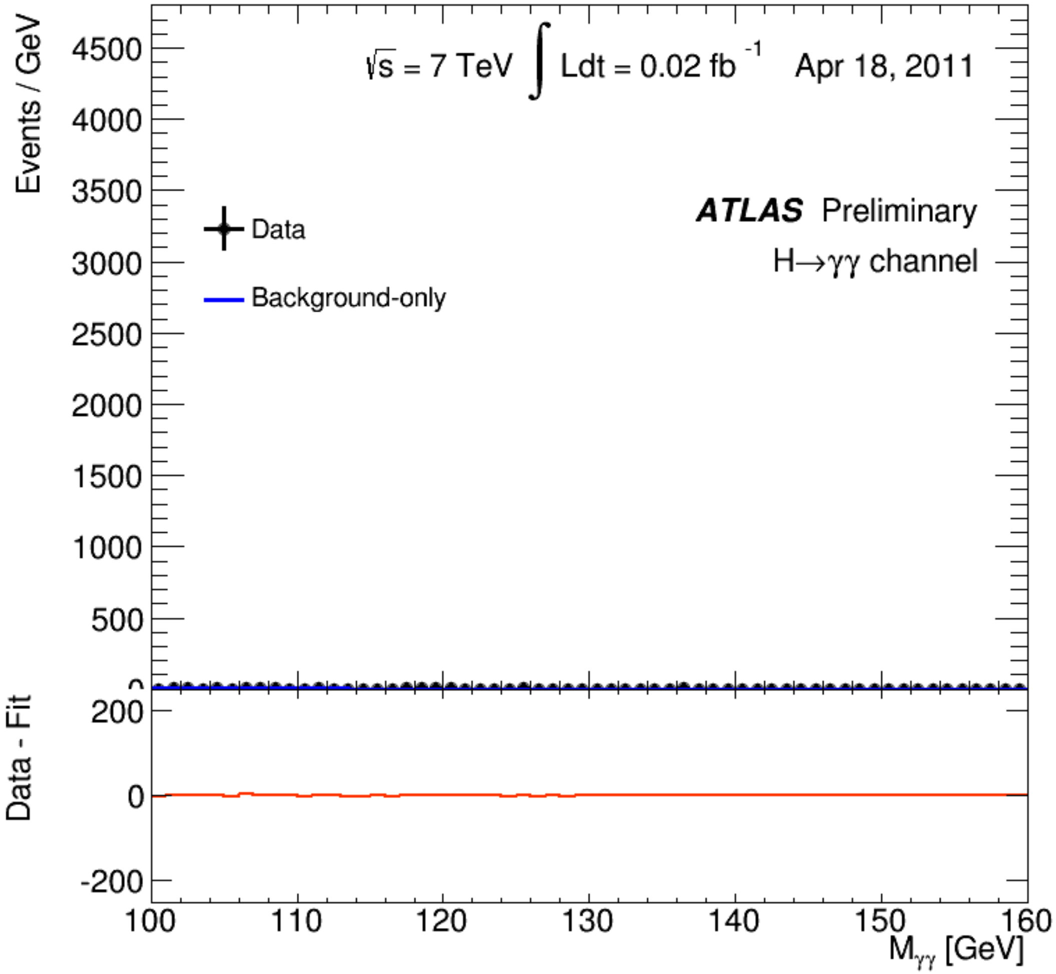
Best Higgs signature: H→2γ
2011 pre-discovery



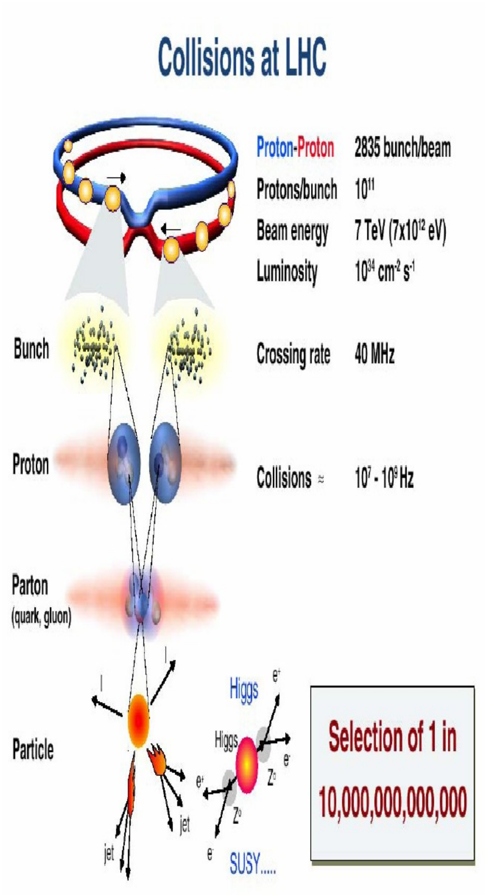
Best Higgs signature: H→2γ 2012 discovery

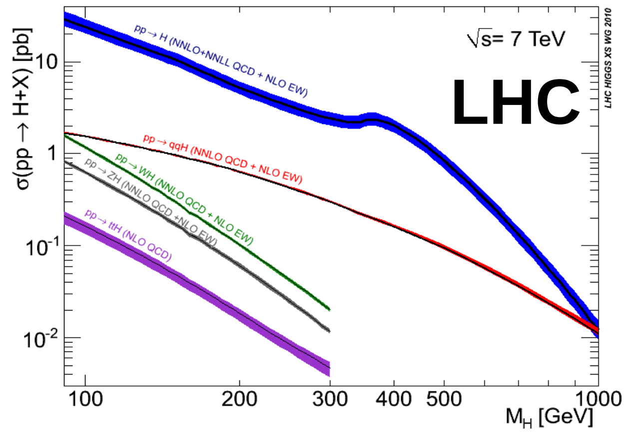


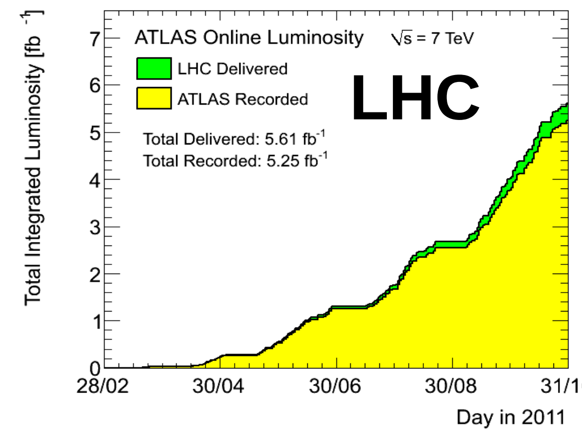
H→2γ evolution during run 1

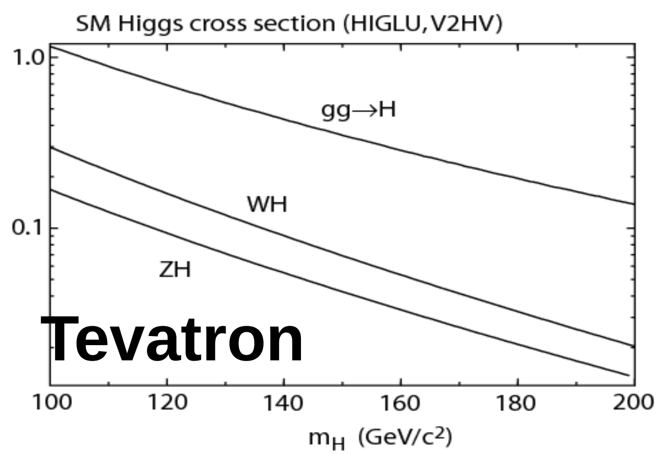


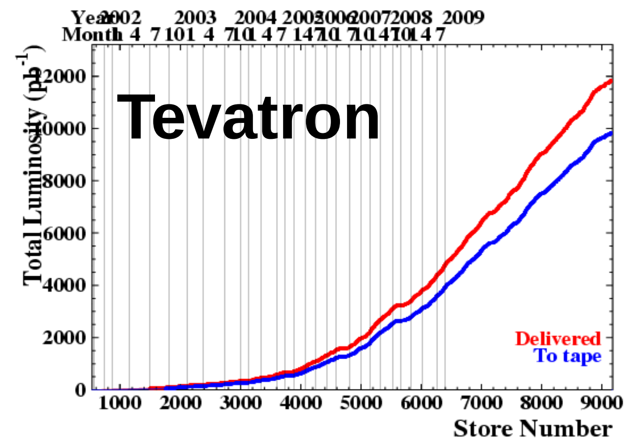
Summary
Main ingredients in LHC success











- 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!