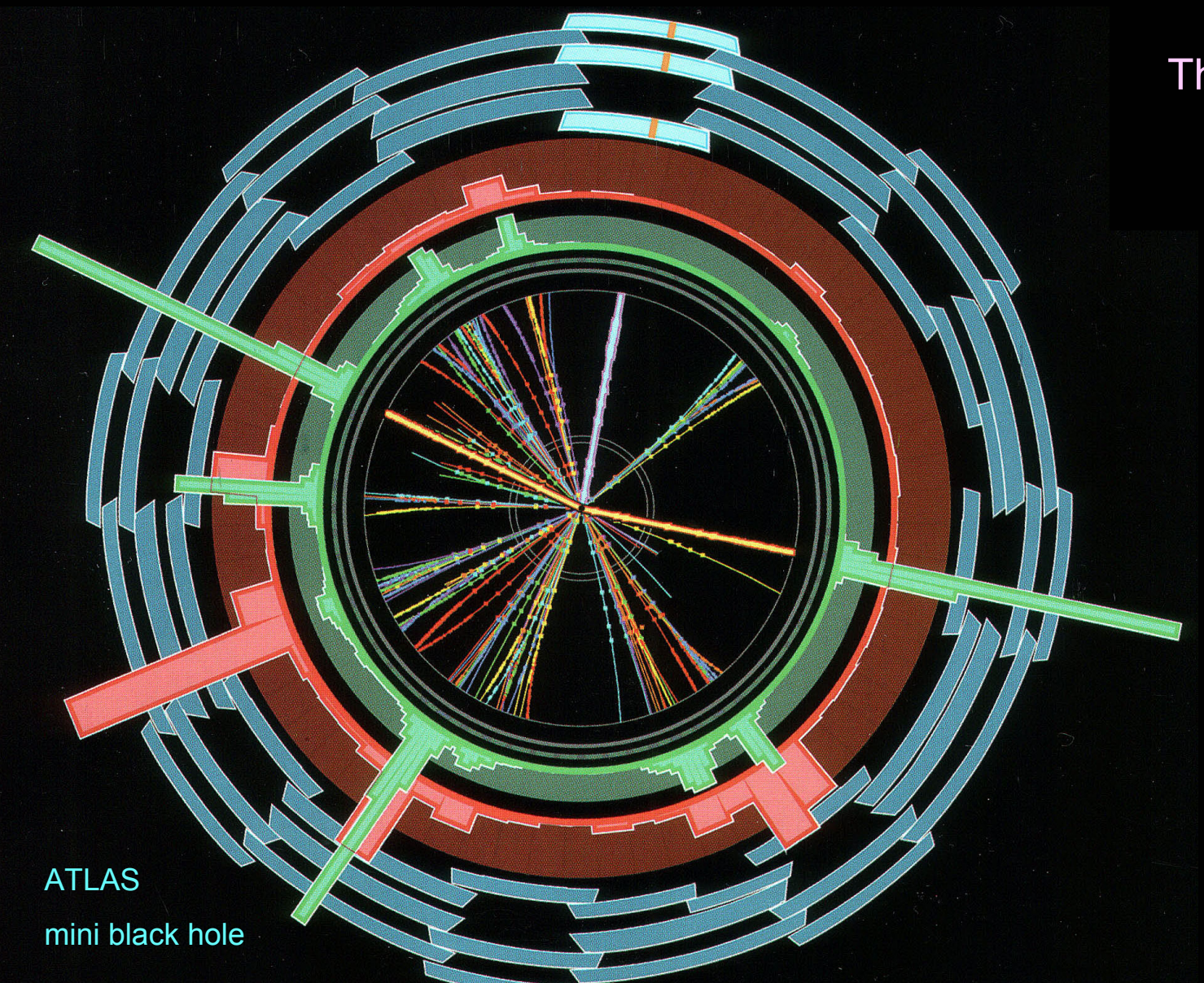
The „Large Hadron Collider“ **LHC**



ATLAS

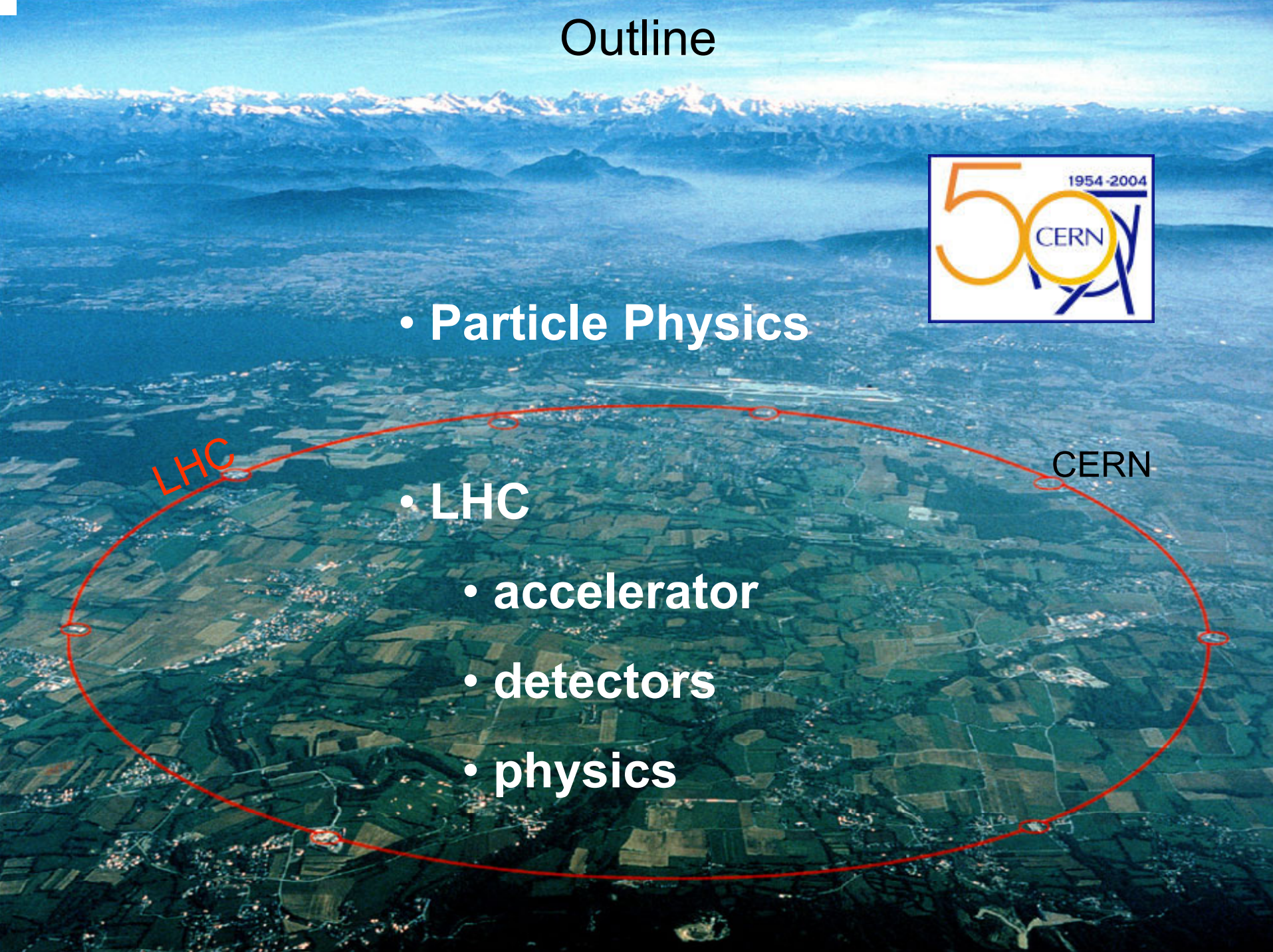
mini black hole

Thomas Hebbeker
RWTH Aachen

TU Dresden
11.05.2004

Outline

- Particle Physics
- LHC
  - accelerator
  - detectors
  - physics



CERN 1954-2004

Conseil Européen pour la Recherche Nucléaire

European Center for Particle Physics

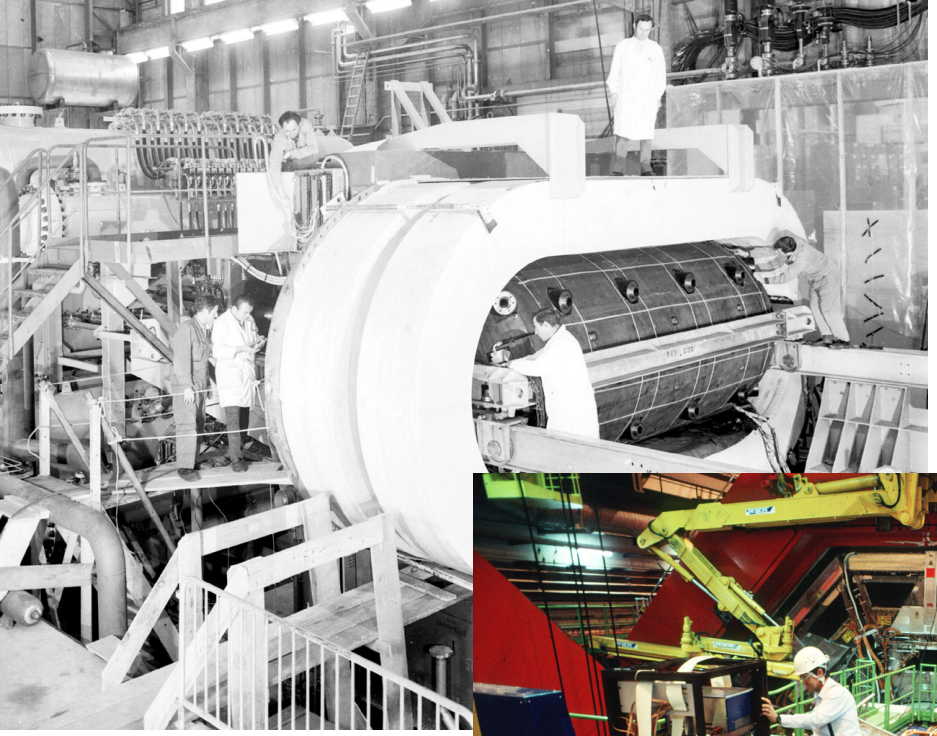
Sur le terrain du futur institut nucléaire

Sous la conduite de M. A. Picot, les membres du Conseil européen pour la recherche nucléaire se sont rendus hier à Meyrin pour reconnaître le terrain où s'élèvera le Centre nucléaire (voir en Dernière heure)

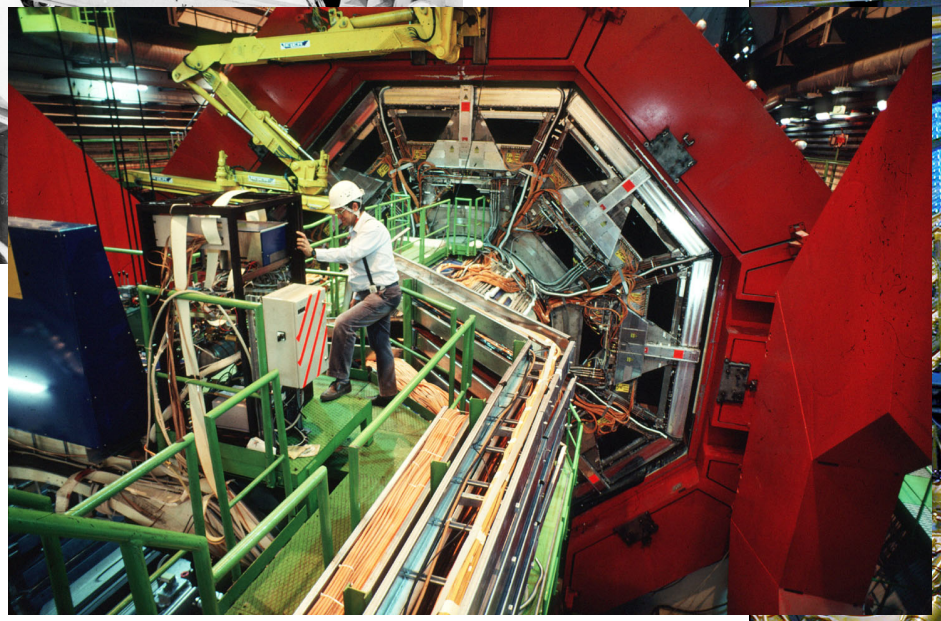
(Photo Freddy Bertrand, Genève)

La Suisse du 30 octobre 1953

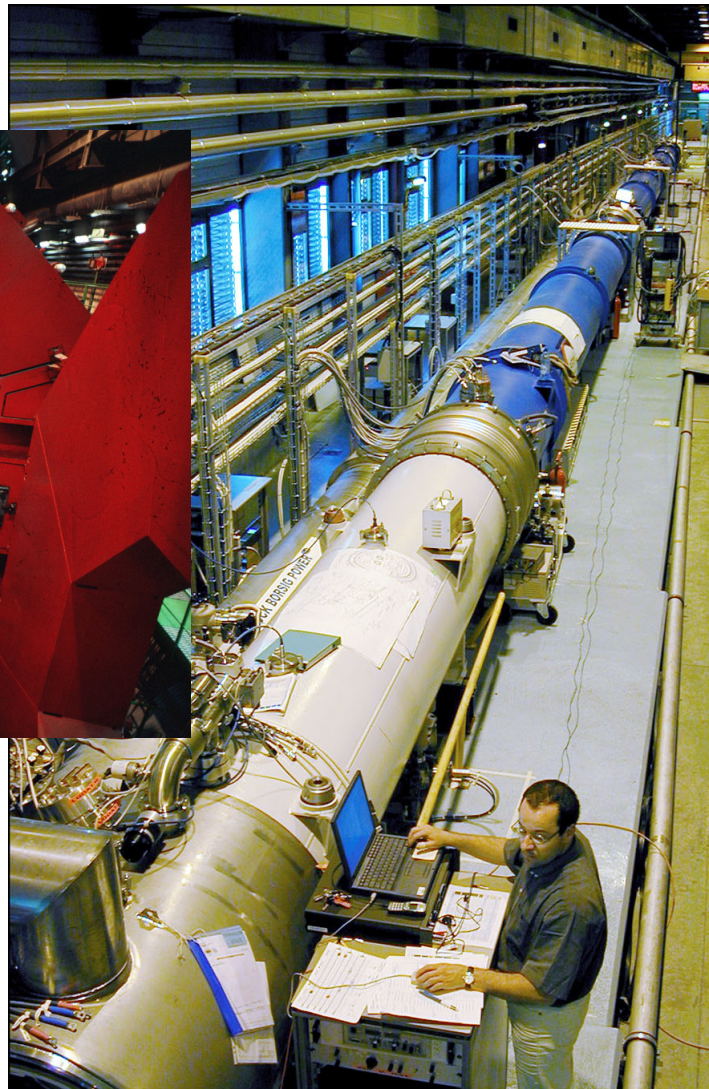
CERN 1954-2004



Gargamelle bubble chamber 1970



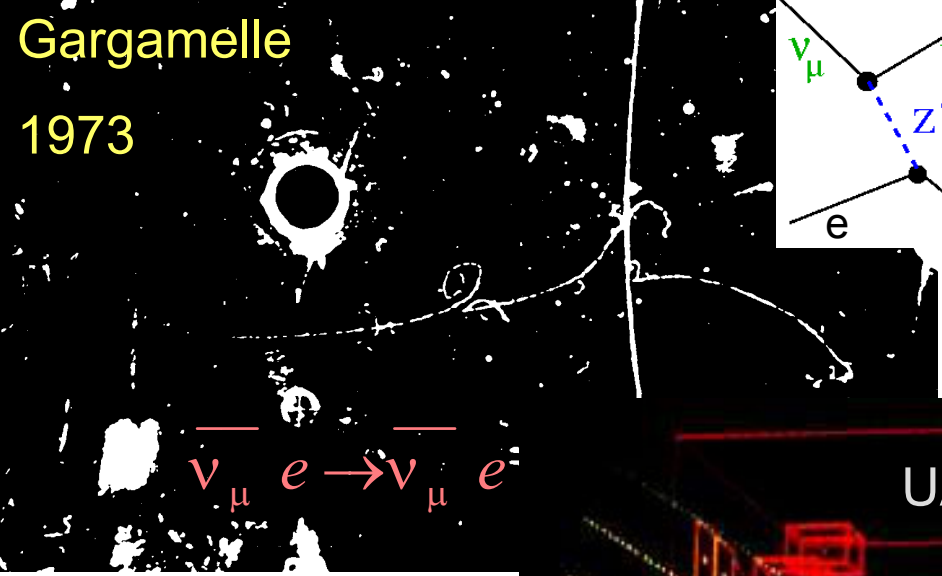
LEP detector L3 1991

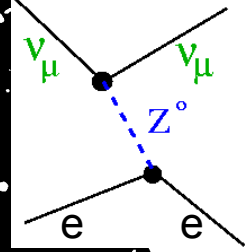


LHC dipole test 2001

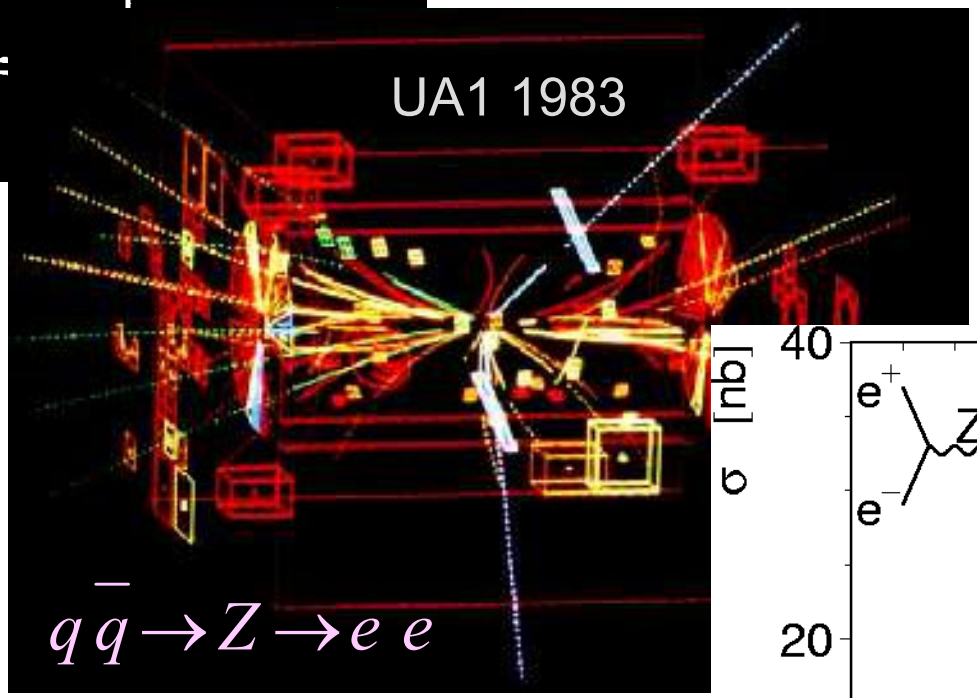
CERN 1954-2004

Z-Boson

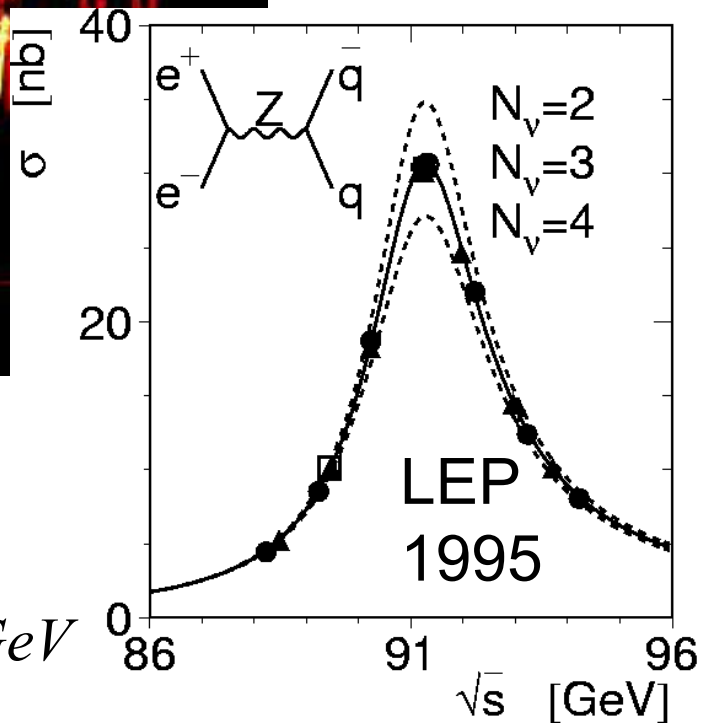




indirect evidence



direct production



precision measurements

$$m_Z = 91.1871 \pm 0.0021\,GeV$$

$$\hbar = c = 1$$

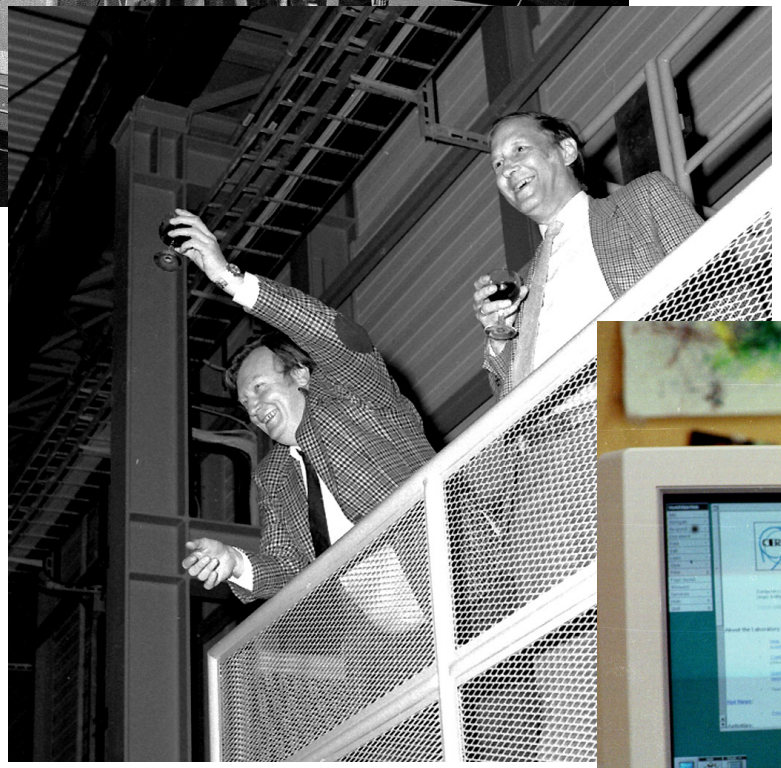
CERN 1954-2004

CERN 1954-2004

inauguration

ISR accelerator

1971



Carlo Rubbia und Simon van der Meer

Nobel prize 1984 (W, Z bosons)

Tim Berners-Lee

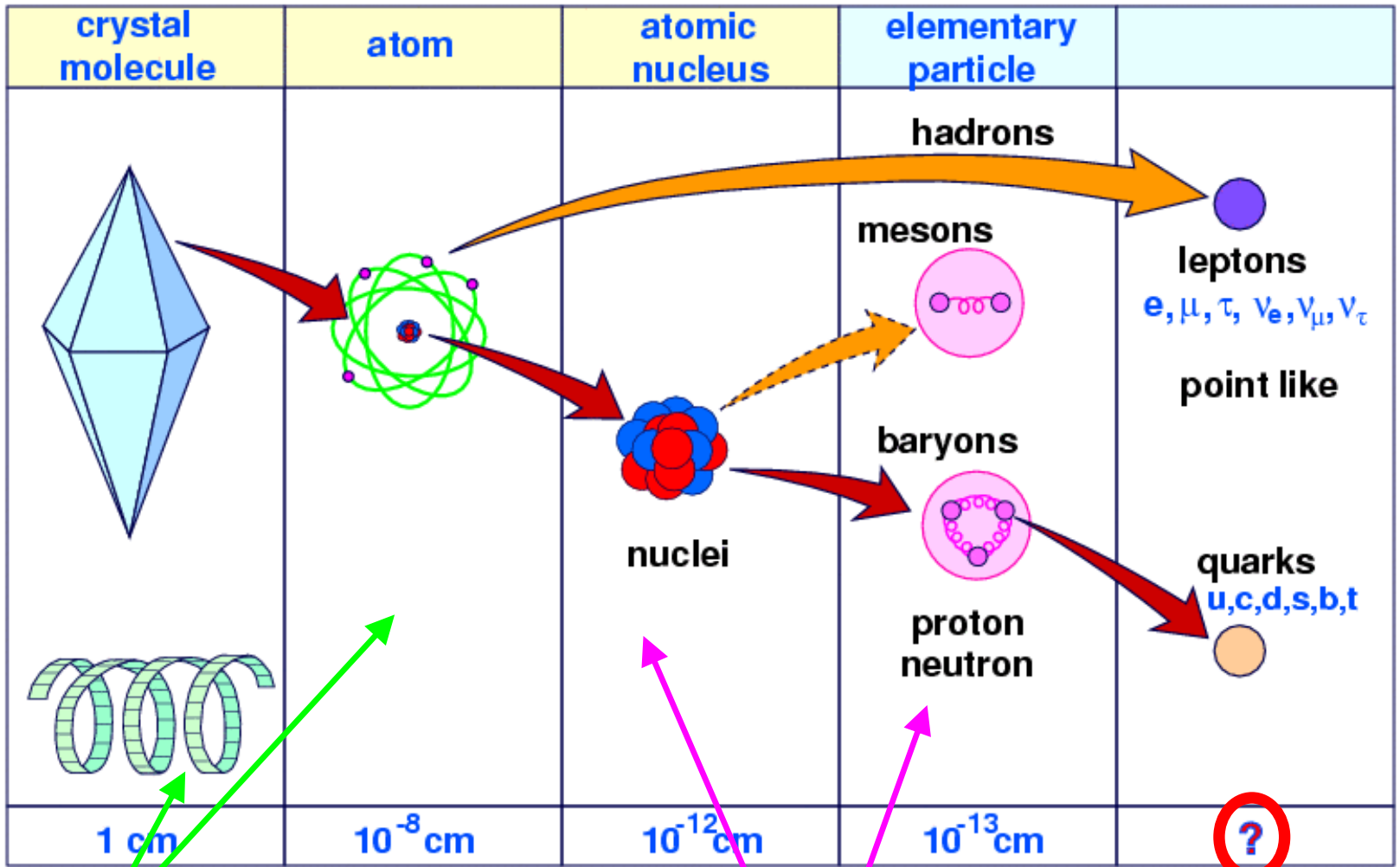
WWW 1991

Outline

- **Particle Physics**
  - **status**
  - **Higgs**
  - **supersymmetry**
  - **extra dimensions**

- **LHC**
  - **accelerator**
  - **detectors**
  - **physics**

The Structure of Matter



$= 1$ fm

$= 200$ MeV

$< 10^{-3}$ *fm*

$= 100$ *GeV*

electromagnetic interactions

strong interactions

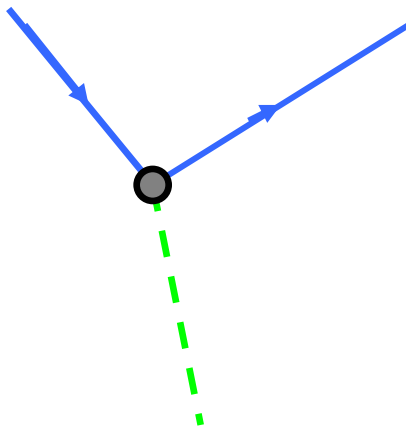
particle physics
= high energy physics

The Standard Model of Particle Physics

matter: spin ½ - fermions:

leptons: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$ $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

quarks: $\begin{pmatrix} u\,u\,u \\ d\,d\,d \end{pmatrix}$ $\begin{pmatrix} c\,c\,c \\ s\,s\,s \end{pmatrix}$ $\begin{pmatrix} t\,t\,t \\ b\,b\,b \end{pmatrix}$



interactions: spin 1 – gauge bosons:

electroweak:

photon	γ	massless
Z boson	Z	91 GeV
W boson	W^+ W^-	80 GeV

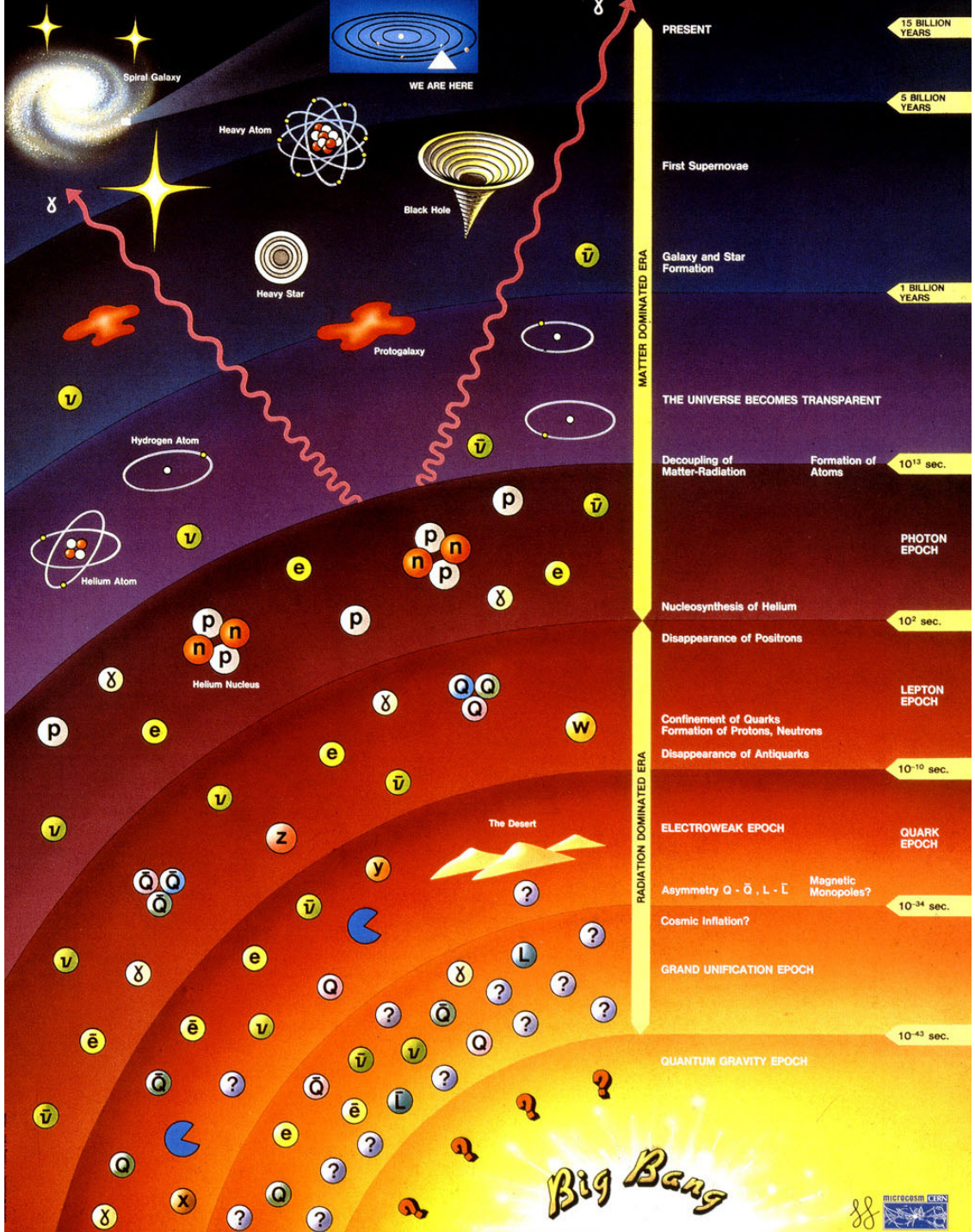
strong:

gluon	g	massless

+ Higgs

Experimental data = well described!

particle physics and cosmology



dark matter = neutralino ? (supersymmetry)

particle accelerators investigate processes 10^{-10} s after the Big Bang(100 GeV)

matter – antimatter asymmetry ?

The Higgs particle

Model of electroweak interactions:

- describes experiments very well
- predicts all fermion and boson masses

$$\left.\begin{array}{l}\\ \\ \end{array}\right\} \equiv 0 \quad + \text{Higgs}$$

Higgs model:

- particle masses allowed, W/Z mass ratio calculable

$$\frac{M_W}{M_Z} = \frac{80.451 \pm 0.033}{91.188 \pm 0.002} = 0.8823 \pm 0.0004 \quad \text{Measurement}$$

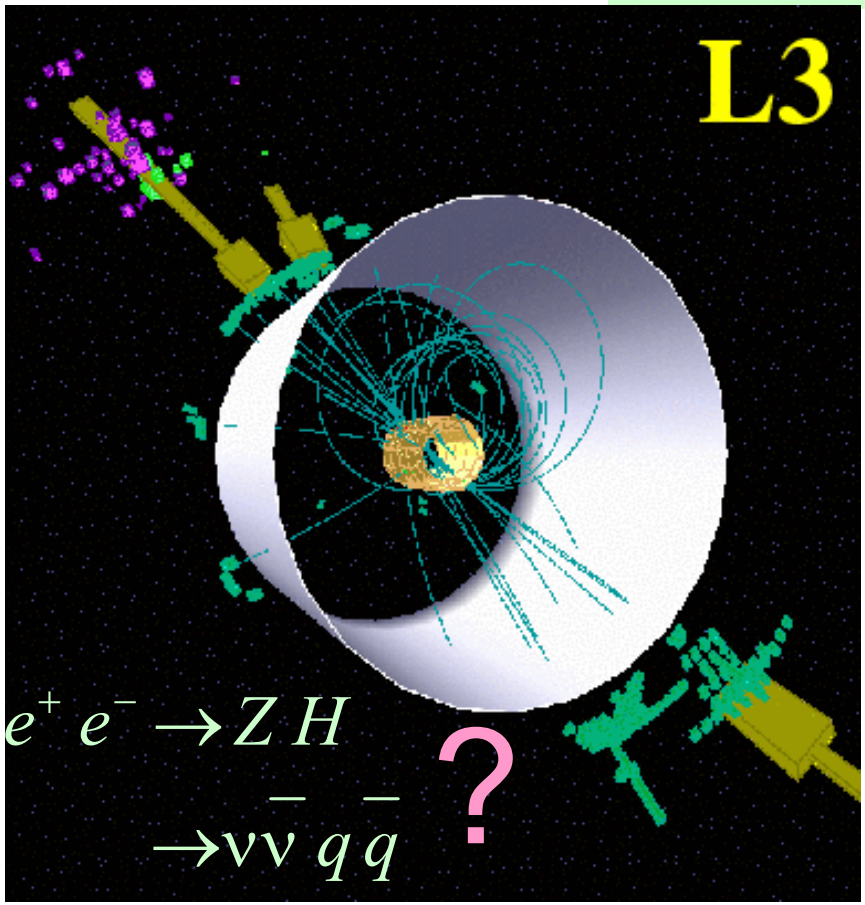
$$= 0.8812 \pm 0.0014 \quad \text{Calculation}$$

- new scalar particle, mass unknown

So far NOT discovered

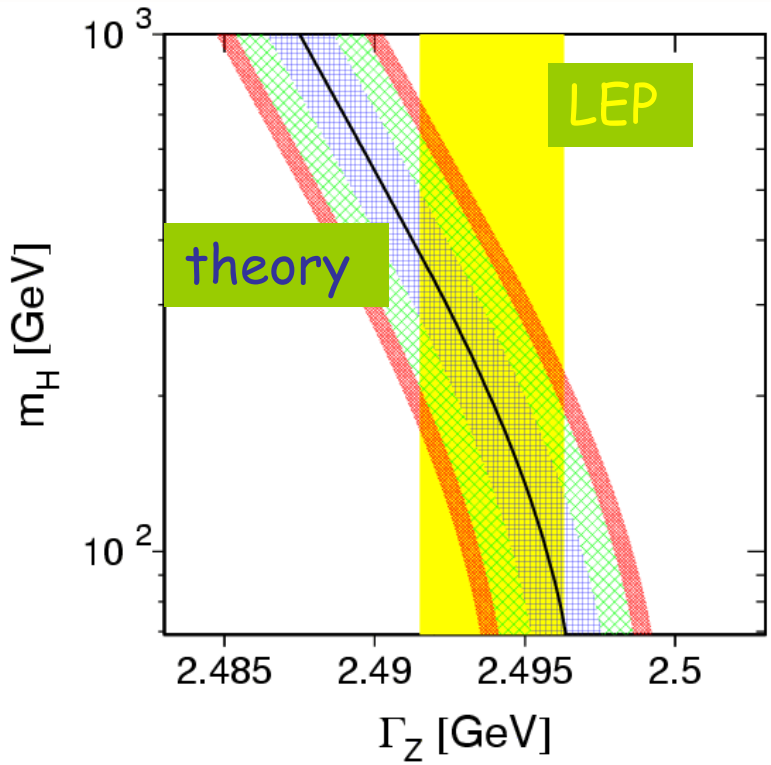
Higgs search at LEP e^+e^- accelerator

direct



$$m_H > 114\,GeV$$ (95%)

indirect



$$m_H < 219\,GeV$$ (95%)

Beyond the Standard Model

Fundamental questions:

Unification of forces ?

...

Why **3** fermion families ?

...

Relation fermions – bosons ?

...

Dark matter = ?

...

Gravity ? Why so weak ?

...

SUSY ?

extra dimensions ?

Supersymmetry

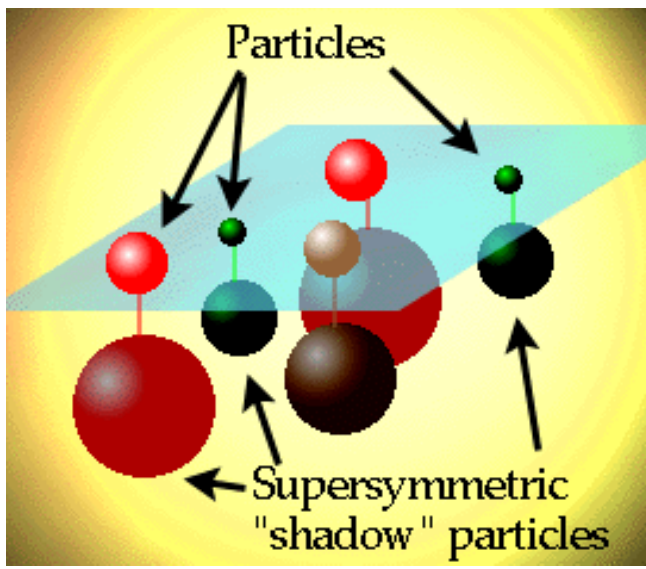
symmetry relating

bosons (forces) $\Longleftrightarrow$ fermions (matter)

$Q|\text{boson}\rangle = \text{fermion}$ $\qquad$ $Q|\text{fermion}\rangle = \text{boson}$

Prediction: each known particle has partner

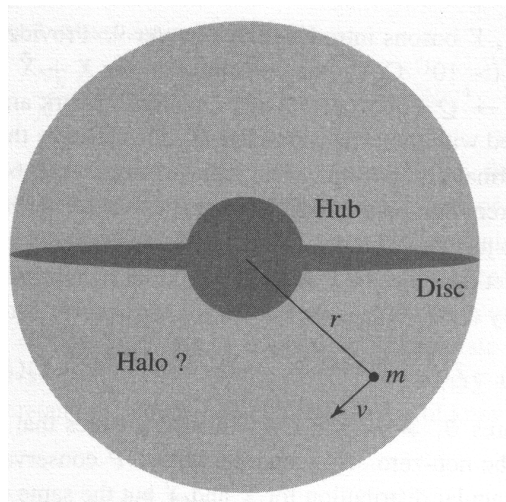
particle	spin	SUSY-partner	spin
e	1/2	$\tilde{e}$	0
q	1/2	$\tilde{q}$	0
γ	1	$\tilde{\chi}$	1/2



Expectation: m < TeV

Supersymmetry

- symmetry relating bosons (forces) $\Longleftrightarrow$ fermions (matter)
- grand unification of forces possible
- neutralino $\tilde{\chi}$ = stable
  = dark matter candidate
- ...



- SUSY broken: no sparticle seen yet (mass limits ~50 GeV)
- > 100 new parameters $\Longrightarrow$ Minimal Model (MSSM, MSUGRA)

(Large) Extra Dimensions

Why is gravity so different from the other interactions ?

<u>mass scales:</u>

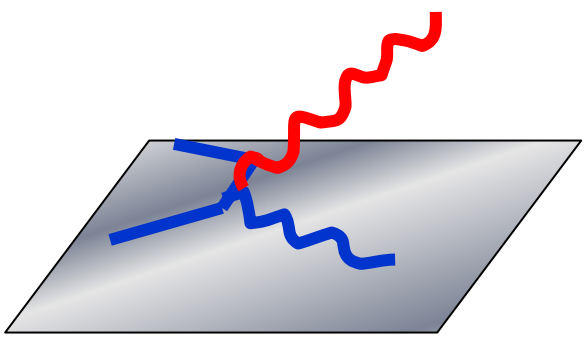
$$M_{ew} \sim \frac{1}{\sqrt{G_F}} \sim 10^2\, GeV \qquad l_{ew} \sim 10^{-18}\, m$$

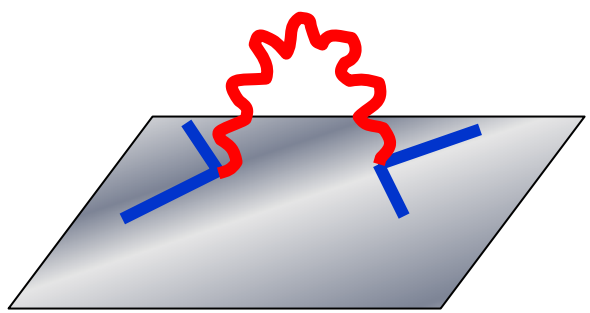
$$M_{Pl} \sim \frac{1}{\sqrt{G_N}} \sim 10^{19}\, GeV \qquad l_g \sim 10^{-35}\, m$$

Idea: only one fundamental scale M_S ~ 100-1000 GeV

gravity **appears** weak since gravitons propagate

in 4 + n dimensions („dilution")

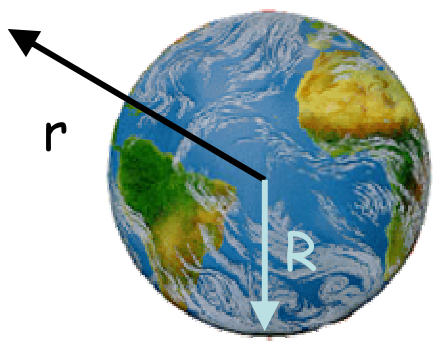




Arkani-Hamed, Dimopoulos, Dvali

Extra Dimensions: phenomenolgy

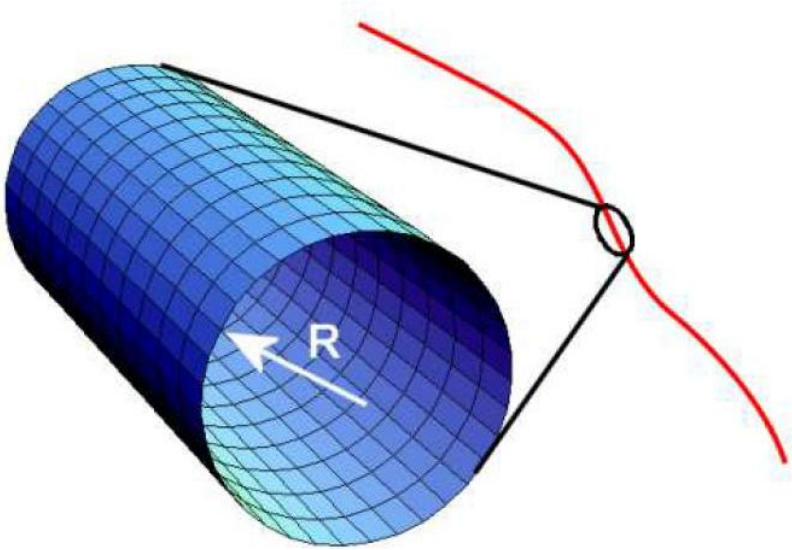
Gravity in classical mechanics:



$$F \sim \frac{M_E m}{R^3} r \qquad \text{inside}$$

$$F \sim \frac{M_E m}{r^2} \qquad \text{outside}$$

n curled-up extra dimensions of space with size R:

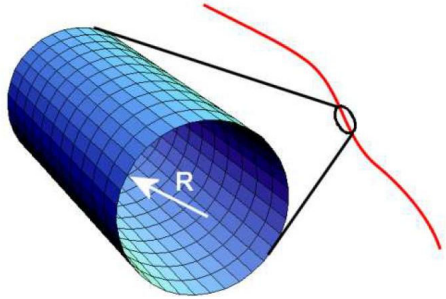


$$F \sim \frac{m_1 m_2}{r^{n+2}} \qquad \text{„inside"}$$

$$F \sim \frac{m_1 m_2}{r^2} \qquad \text{„outside"}$$

„outside":

$$F \sim \frac{1}{M_{Pl}^2} \frac{m_1 m_2}{r^2} \Rightarrow F \sim \frac{1}{M_S^{2+n}} \frac{1}{R^n} \frac{m_1 m_2}{r^2}$$



$$R = \frac{1}{2\sqrt{\pi} M_S} \left(\frac{M_{Pl}}{M_S} \right)^{2/n} \propto \begin{cases} 8 \times 10^{12} m, & n = 1 \\ 0.7\, mm, & n = 2 \\ 3\, nm, & n = 3 \\ 6 \times 10^{-12} m, & n = 4 \end{cases}$$

$M_s = 1 TeV$

- deviations from Newton/Einstein laws for r < R

  therefore n=1 and n=2 ruled out!

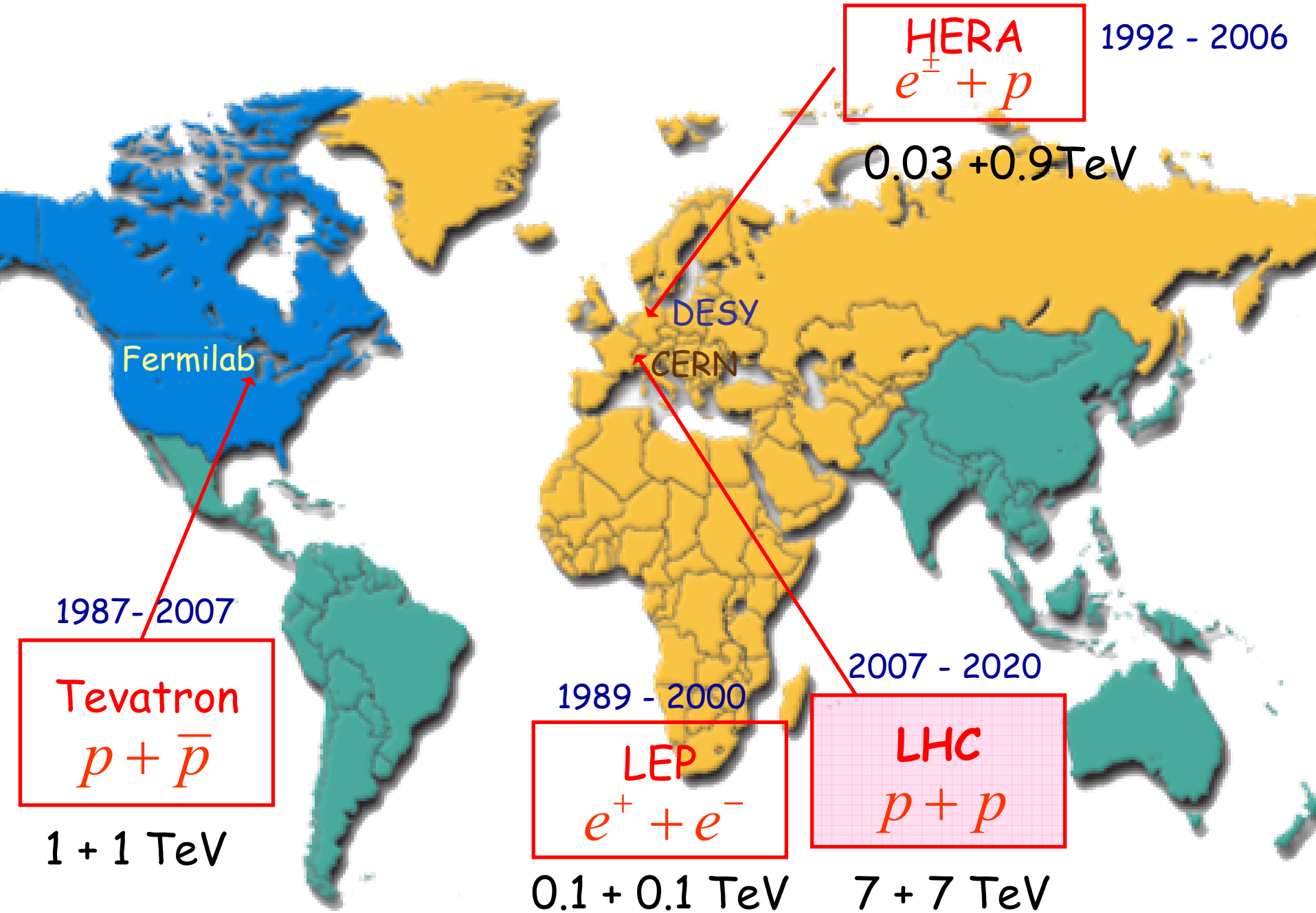
- gravitons G show up in high energy physics experiments as real or virtual particles } **pp colliders!**

Outline

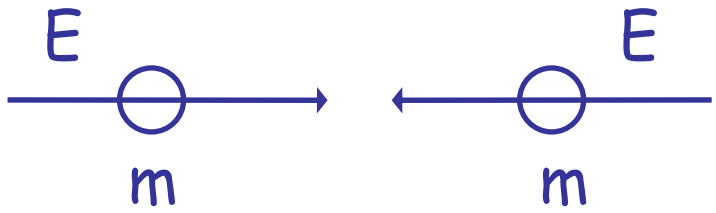
TeV experiments needed!

- Particle Physics
- LHC
  - accelerator
    - requirements
    - options
    - Large Hadron Collider
  - detectors
  - physics

High energy accelerator centers



New collider: Requirements



- **(parton) energy:**

center of mass energy $\sqrt{s} = 2E > m_{new}$

→ **Energy E > 1 TeV** (Higgs, SUSY)

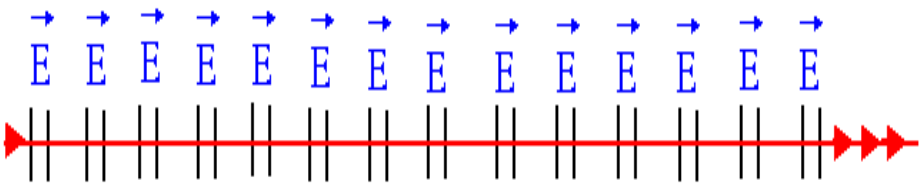
- **event rate:**

$$\dot{N} = \sigma \cdot L \quad > \mathbf{1/hour}$$

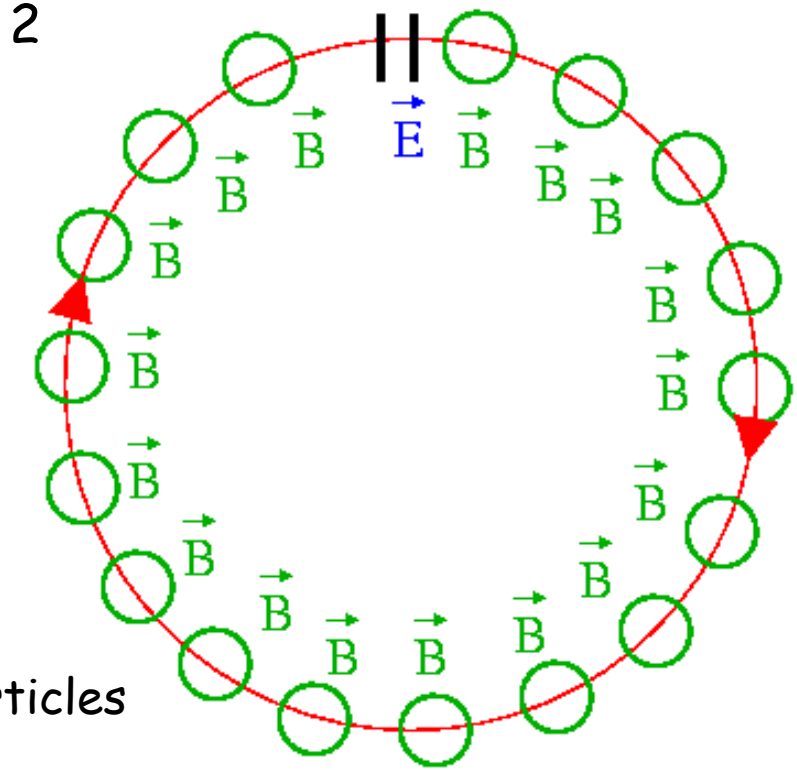
x 100 !

→ **Luminosity L large !** $\sim 10^{34} / cm^2 / s$

Accelerator options



x 2



- **linear:**

  + synchrotron radiation negligible

- **circular:**

  + „recycling"

  + particles + antiparticles

LHC: circular, hadrons

$$\Delta E_{sync} \sim \left(\frac{E}{m}\right)^4 \cdot \frac{1}{R}$$

$$R = 3\,km \cdot \frac{E/TeV}{B/T}$$

high energies (TeV) : accelerator several kilometers !

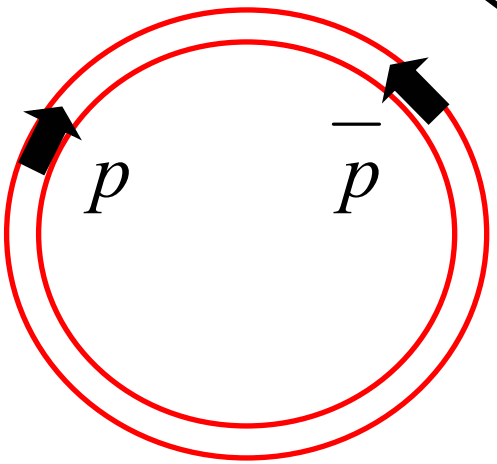
particles: e^+ e^- p $\bar{p}$ A

Proton or Antiproton ?

physics: similar!

$p\,\bar{p}$

one accelerator



antiproton production:

$$1\,\bar{p}\ \ per\ 3\cdot 10^{5}\ p$$

Tevatron: needs

$$1\cdot 10^{12}\ \bar{p}$$

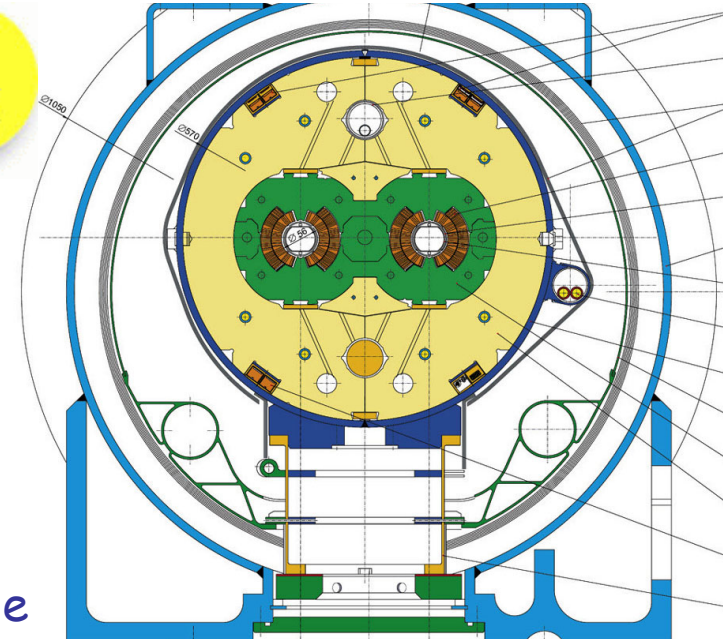
$p\,p$

two accelerators !

no antiprotons !

LHC: needs

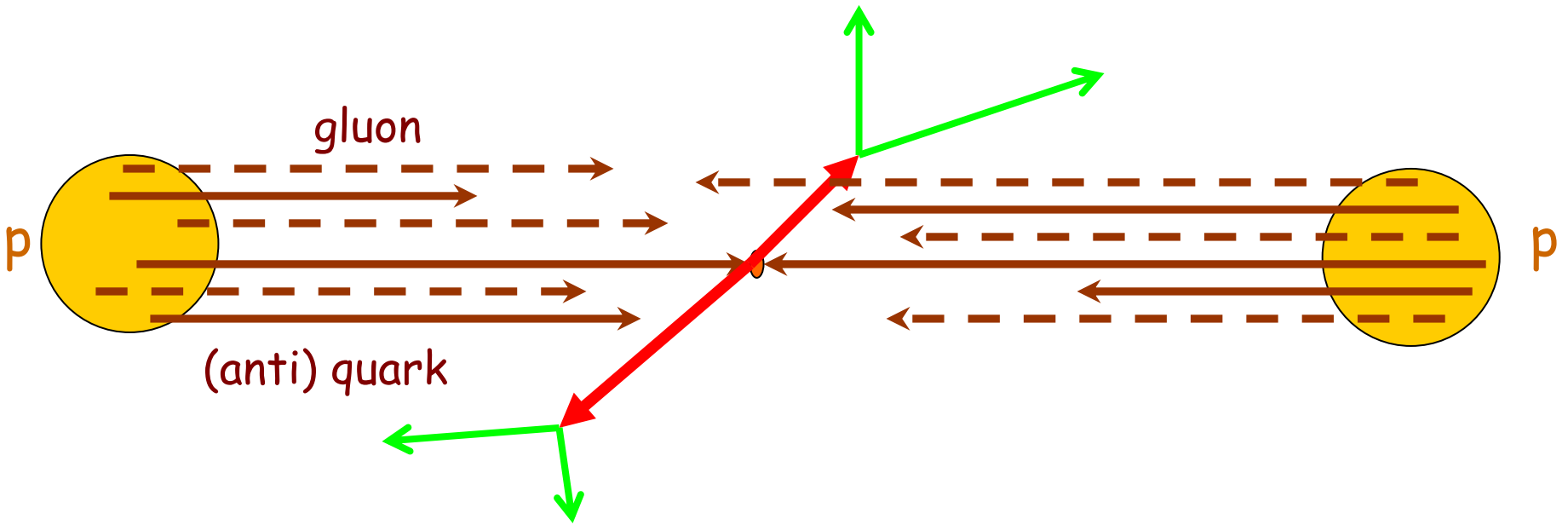
$$3\cdot 10^{14}\ p$$



LHC dipole

Center of Mass Energy $\sqrt{s}$

Required: $E_{parton} > 1TeV$



Rough estimate: $E_{parton} \approx \frac{1}{2} \bullet \frac{1}{3} \bullet E_{proton}$

$$E_{proton} \approx 6 \cdot 1TeV \rightarrow E_{proton} = 7\,TeV, \sqrt{s} = 14TeV$$

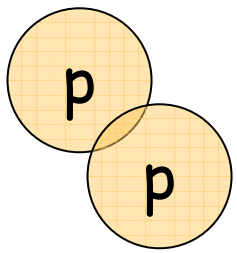
Cross Section and Luminosity

Required: $\dot{N} = \sigma \cdot L$ > 1/hour for signal events

strong

Total inelastic cross section

BACKGROUND

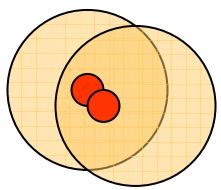


$$\sigma \approx 10\, fm^2 \approx 10^{-25}\, cm^2$$

electroweak

Pointlike cross section

SIGNAL



$$\sigma\,(Susy) \sim 10^{-37}\, cm^2$$

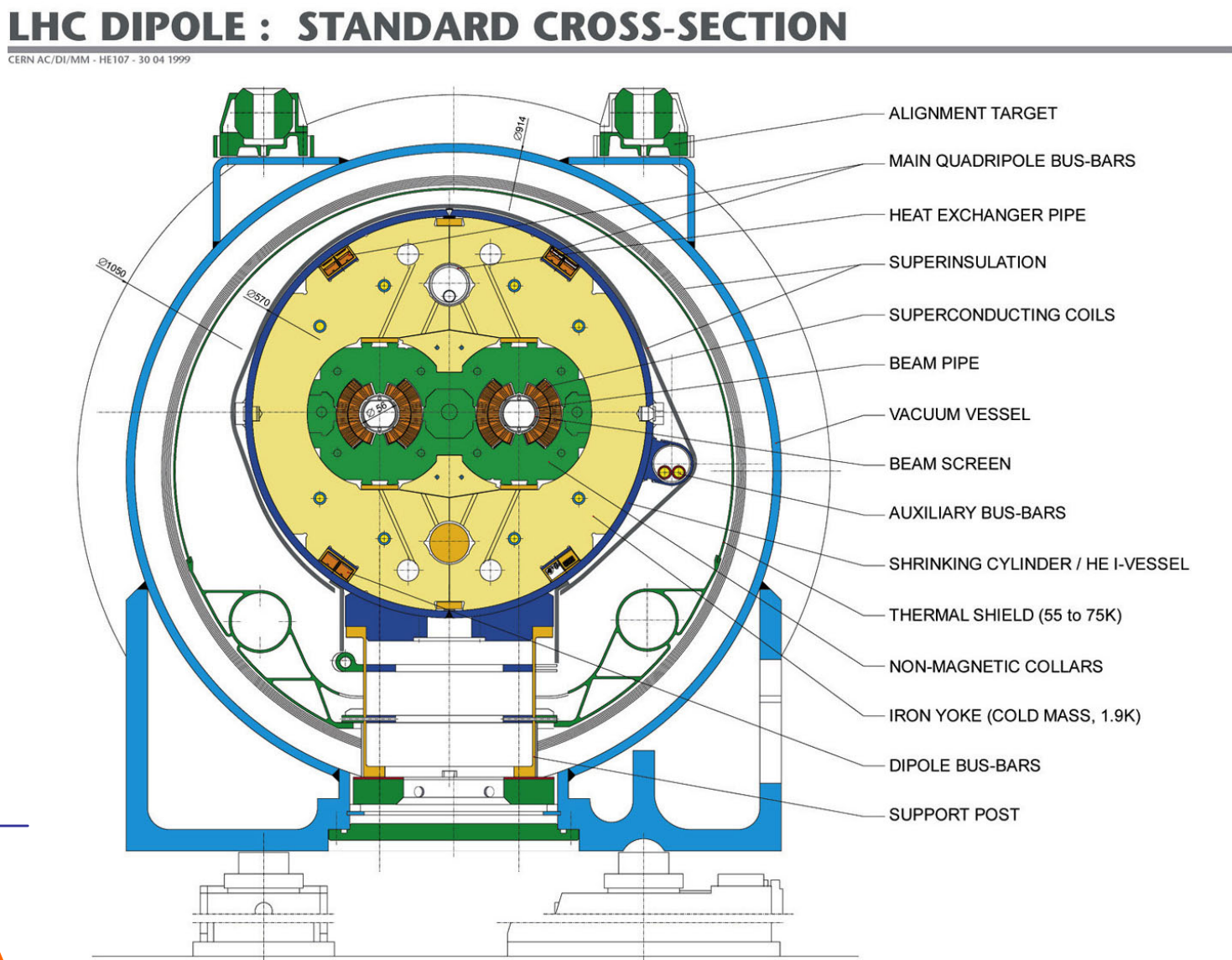
$$L = 10^{34} / cm^2 / s$$

100 particles /collision

huge background !

10^{11} particles /s

LHC superconducting magnets



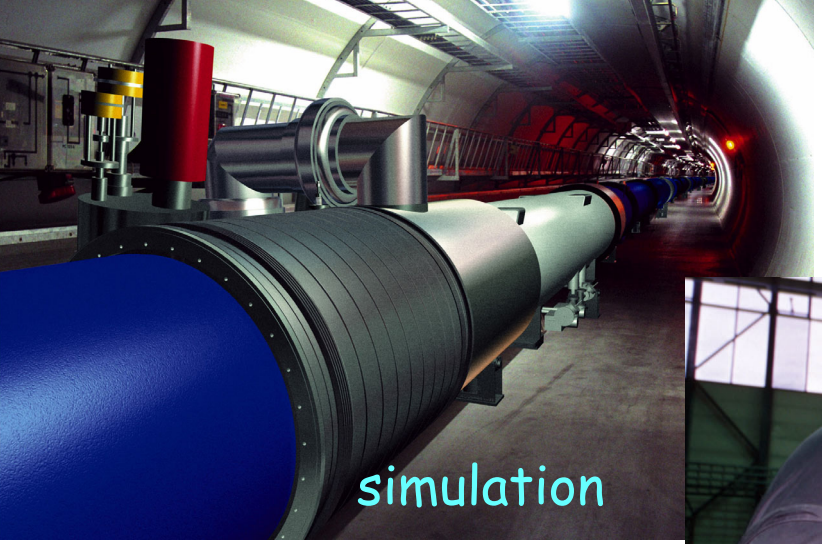
7 TeV

LEP tunnel R = 4km (70%)

$$R = 3\ \text{km} \cdot \frac{E\ /\ \text{TeV}}{B\ /\ T}$$

8.3 T 1.9 K NbTi 14.3 m 1232 x

LHC: from simulation to reality



April 2004: about 300 dipoles (out of 1232) delivered

LHC at CERN

27 km circumference

14 TeV (p p) B = 8 T

$L = 10^{34} / cm^2 / s$ $\dot{N} = 10^{11} / s$

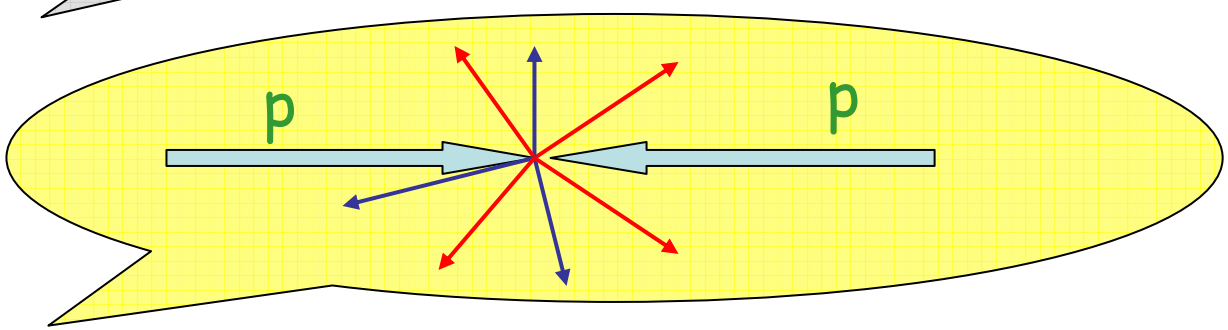
Large

p + p

A + A („heavy ions")

no antiparticles !

Hadron

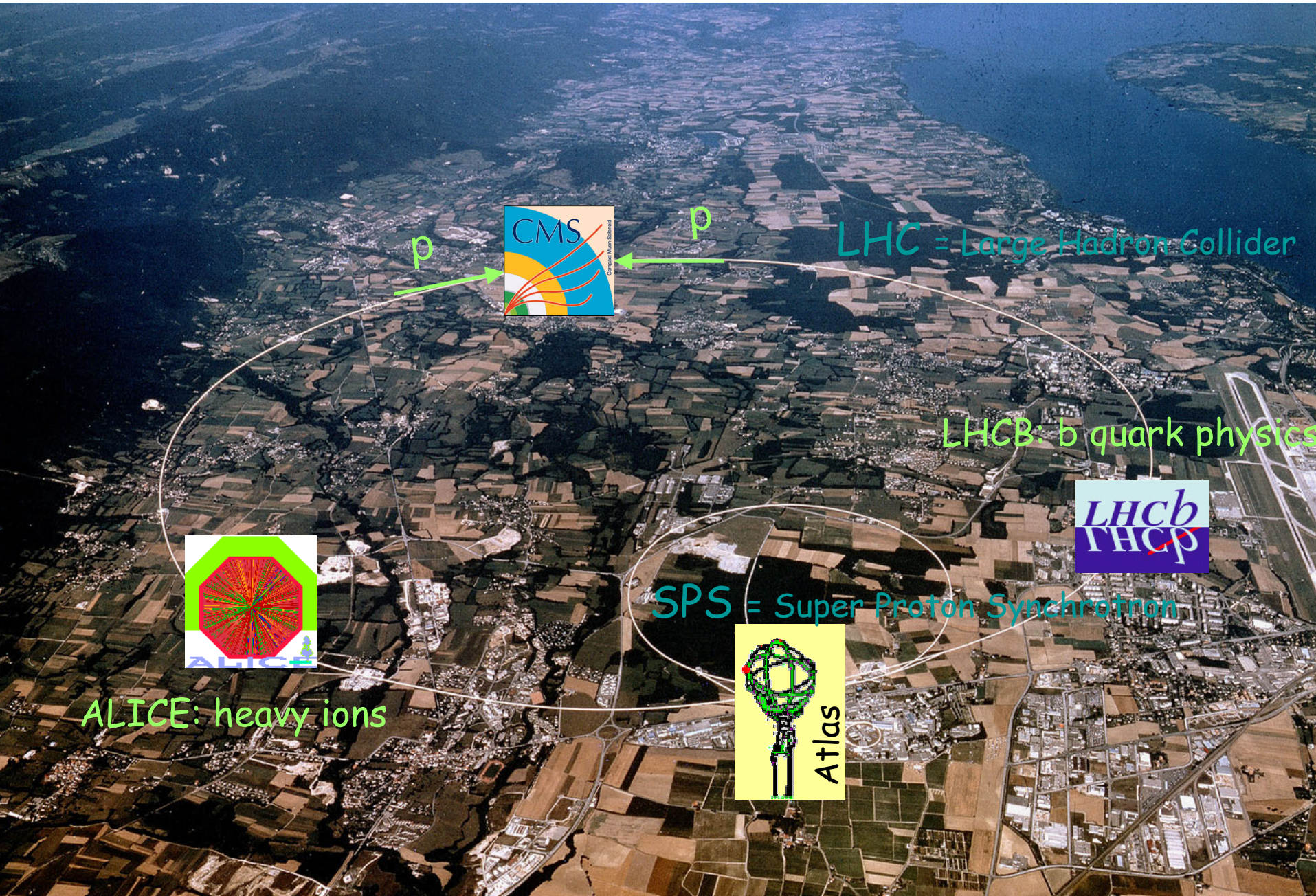


Collider

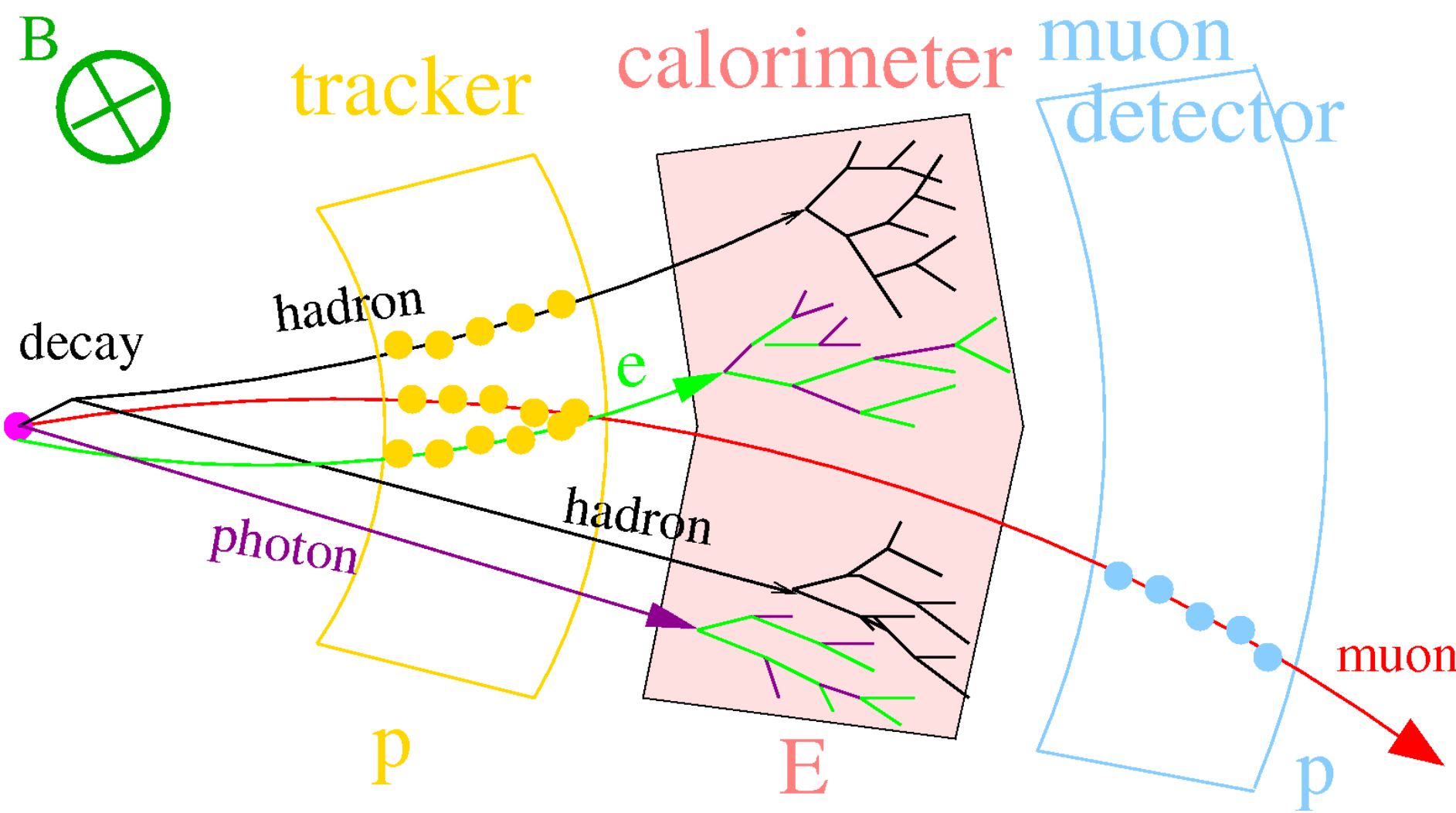
Outline

- Particle Physics
- LHC
  - accelerator
  - detectors
    - working principle
    - Atlas, CMS, ...
    - CMS
  - physics

LHC + detectors

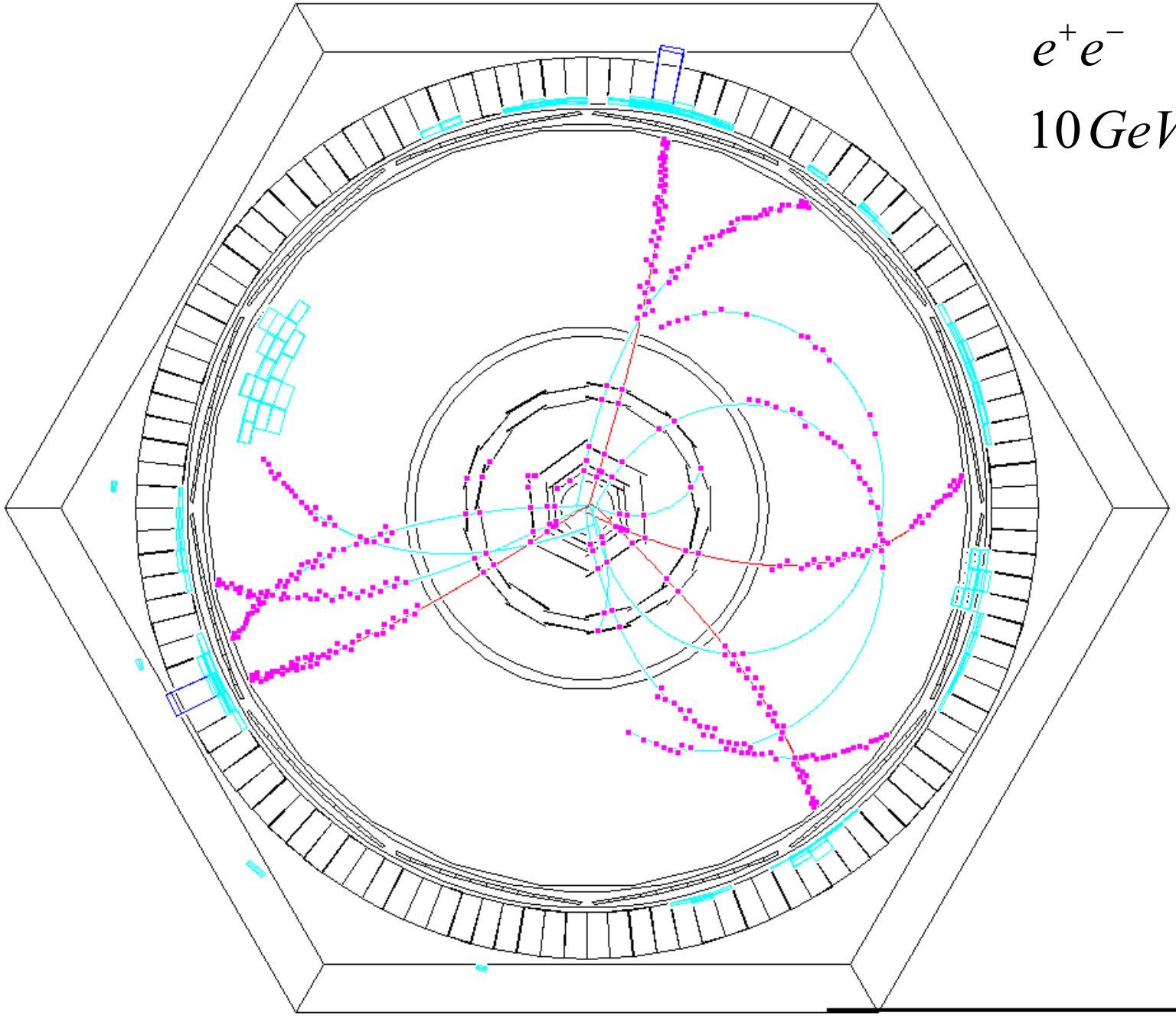


Particle detectors - principle

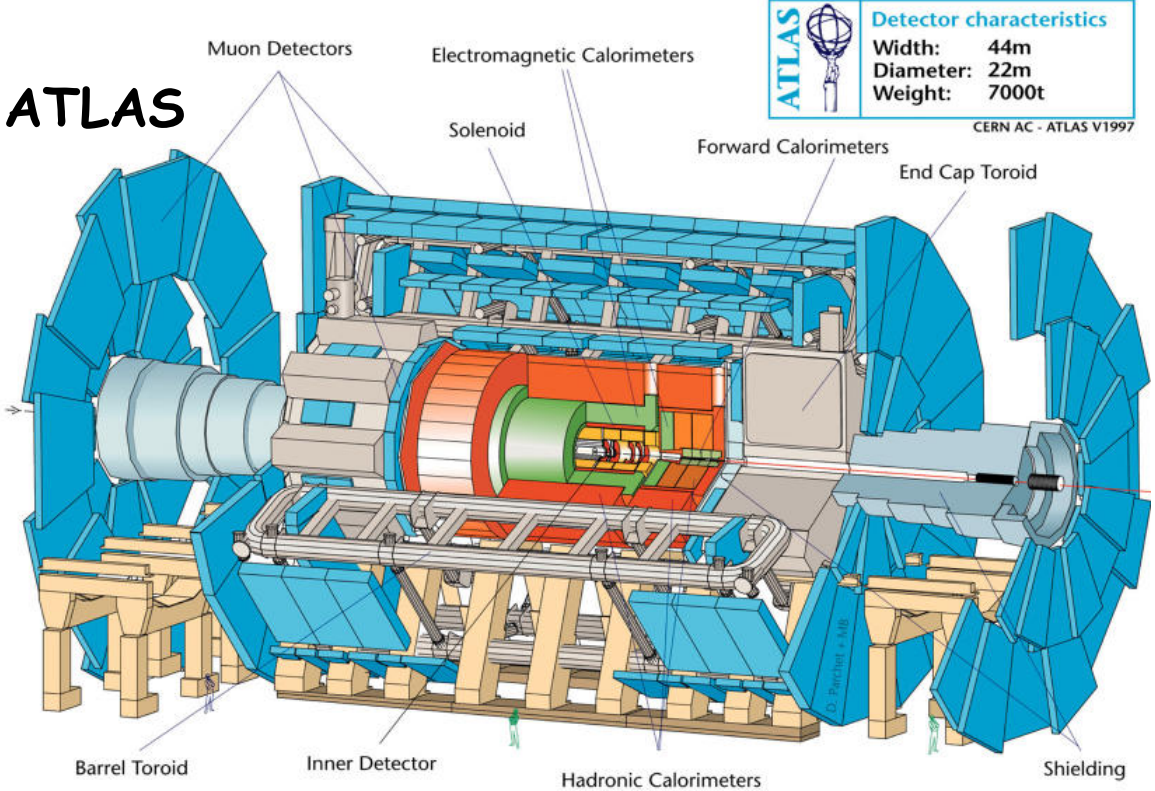


many particles are short-lived → identification via decay products

collision event in BABAR detector



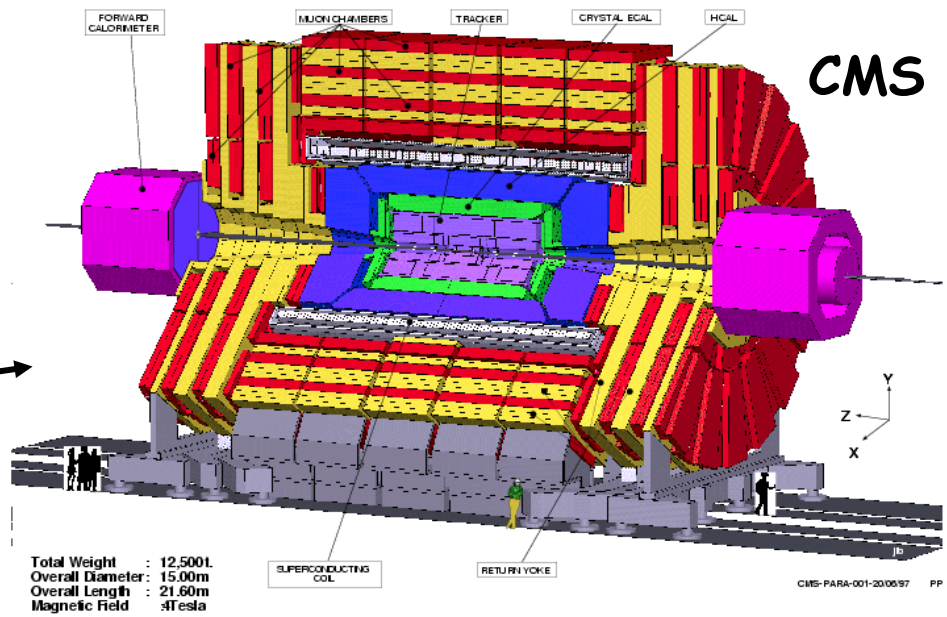
LHC general purpose detectors



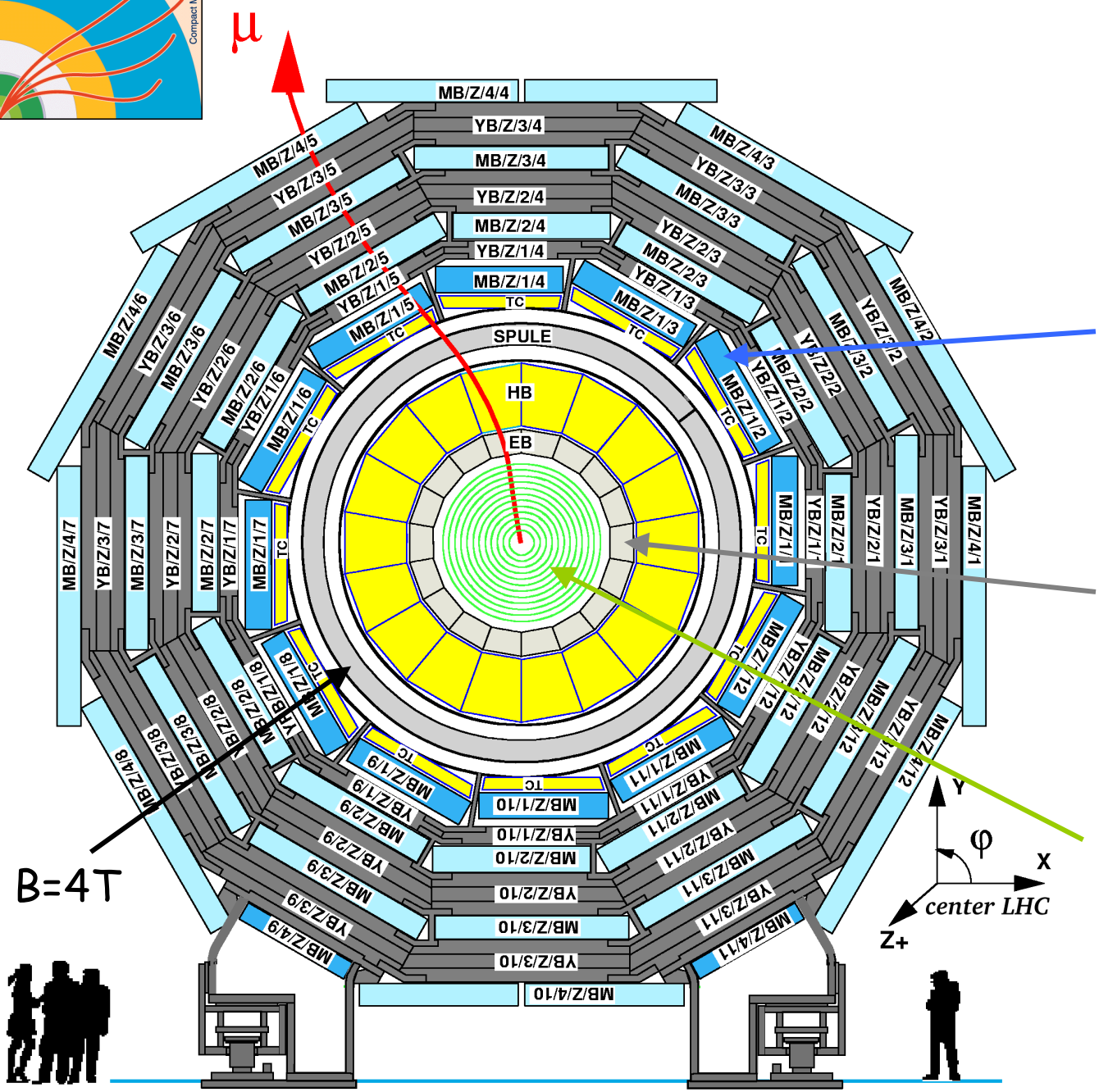
average mass density

0.3 g/ccm

3 g/ccm



CMS Detector



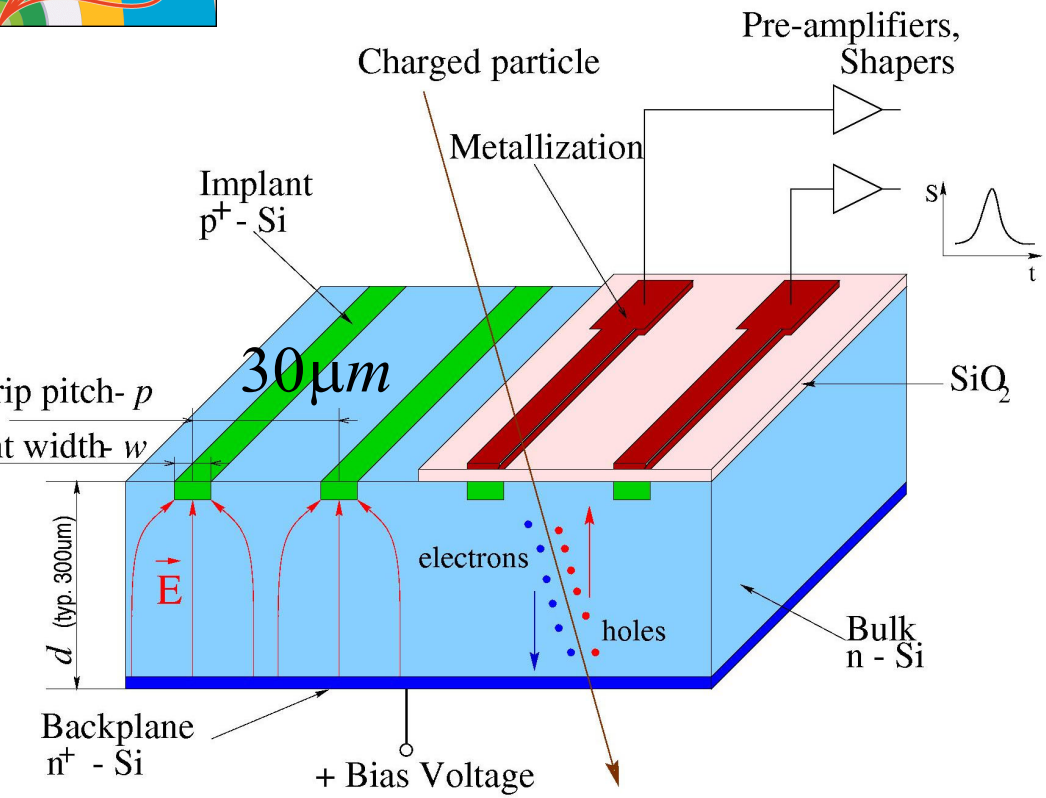
Muon detectors

electromagnetic calorimeter

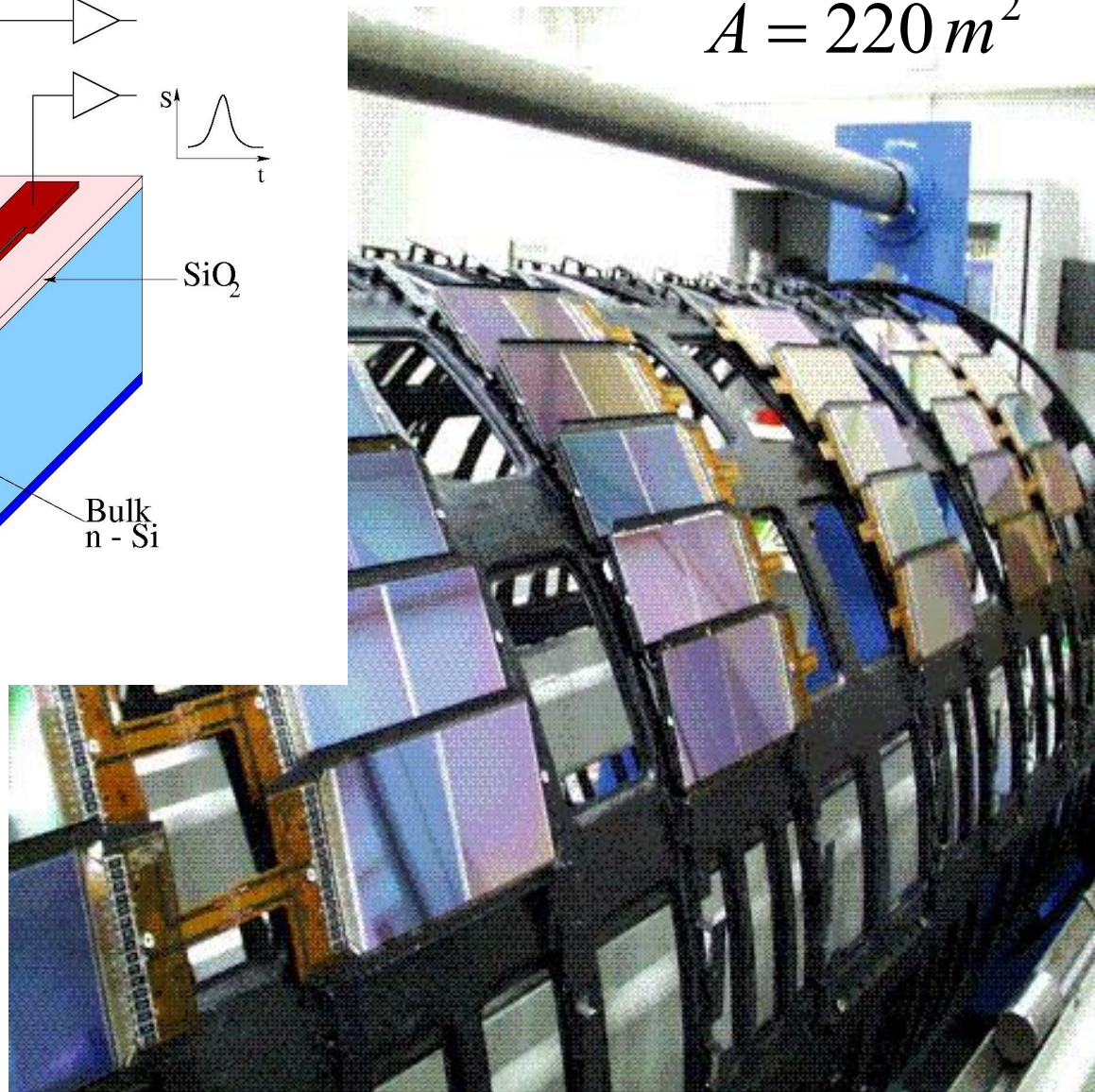
silicon track detector

Yoke: Installation of first wheel

CMS silicon tracker



$$A = 220\,m^2$$



$$\Delta x = 10\,\mu m$$

momentum resolution

2% at 100 GeV

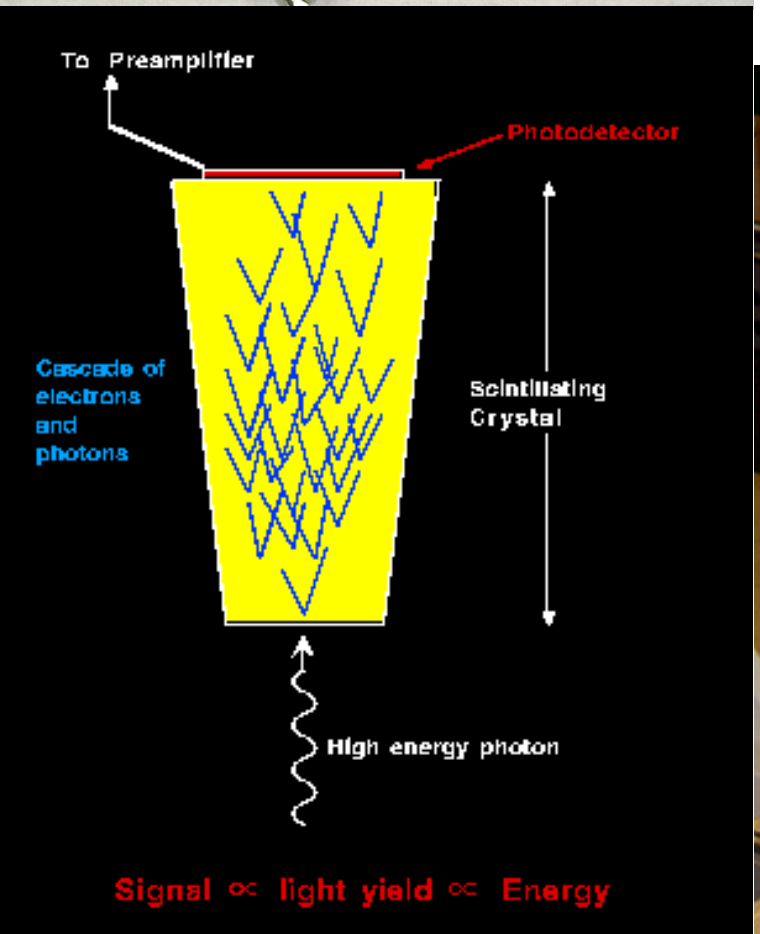
CMS electromagnetic calorimeter

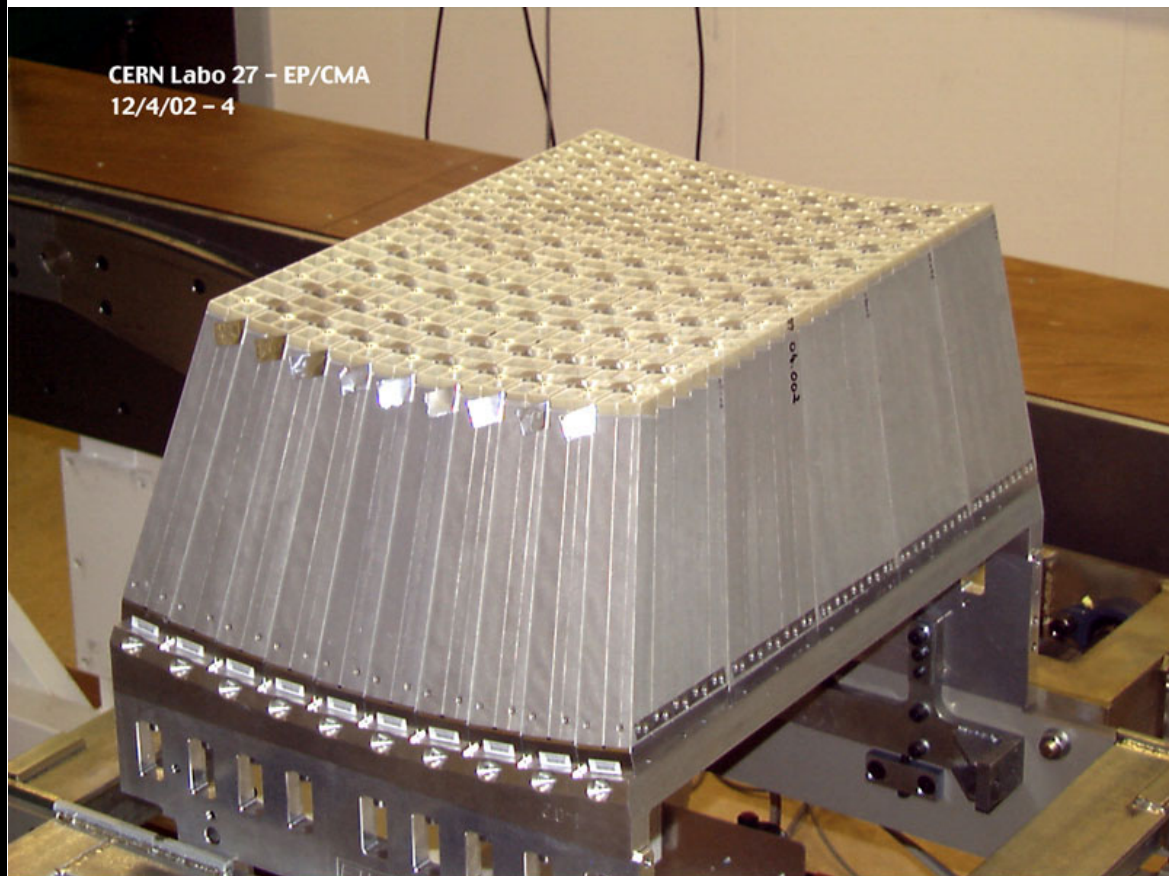
$PbWO_4$

X 100000

energy resolution

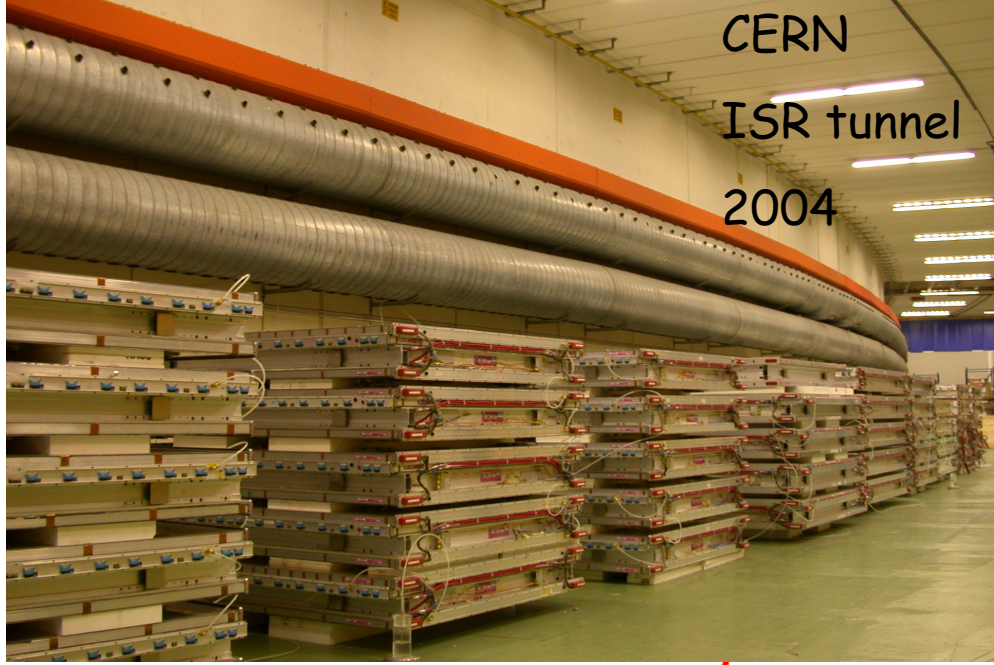
1% at 100 GeV

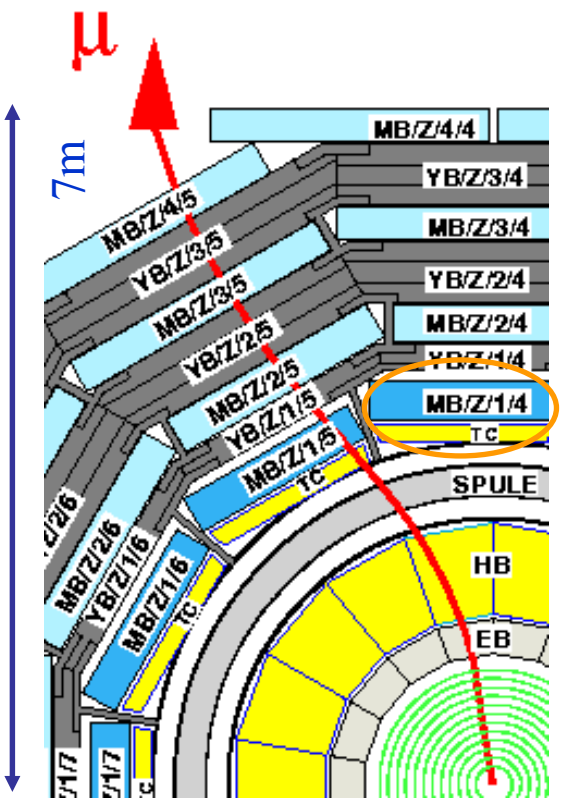


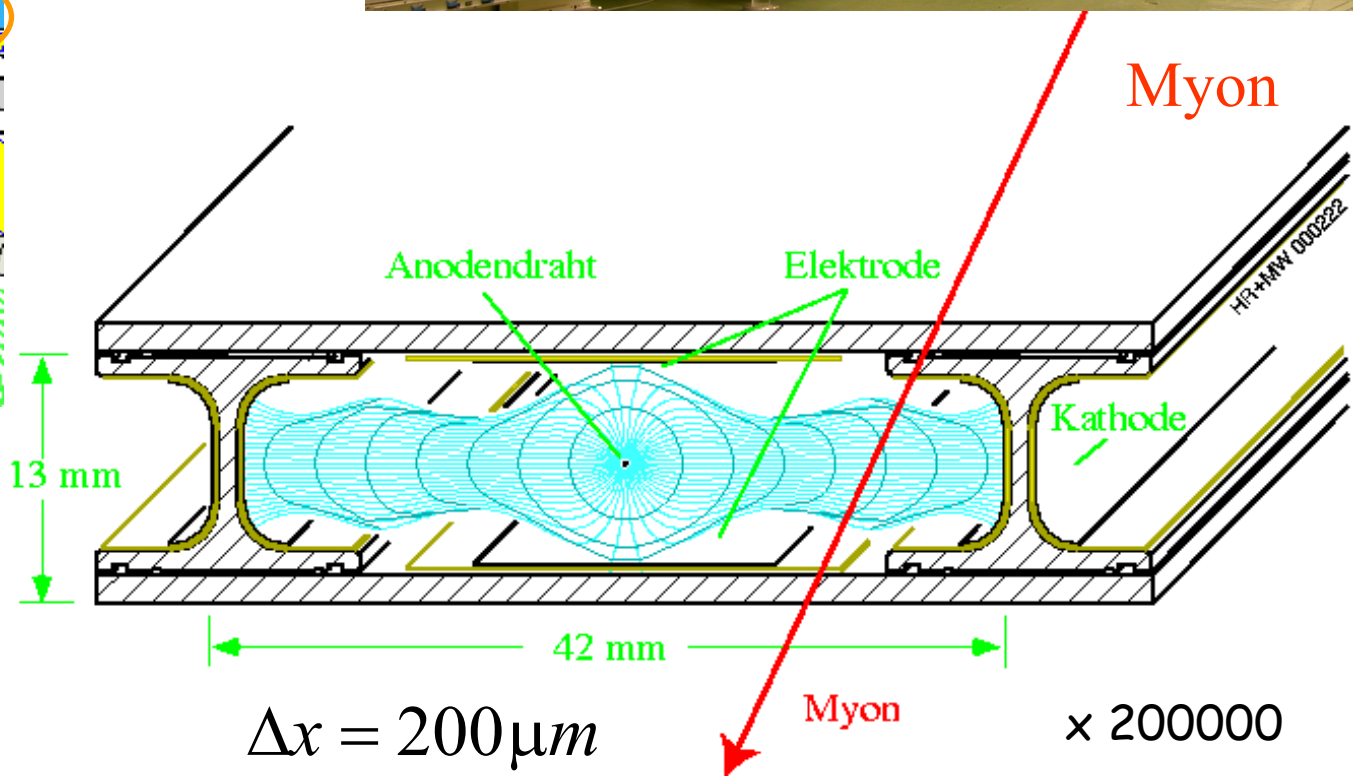


CMS muon system

$$A = 18000\, m^2$$







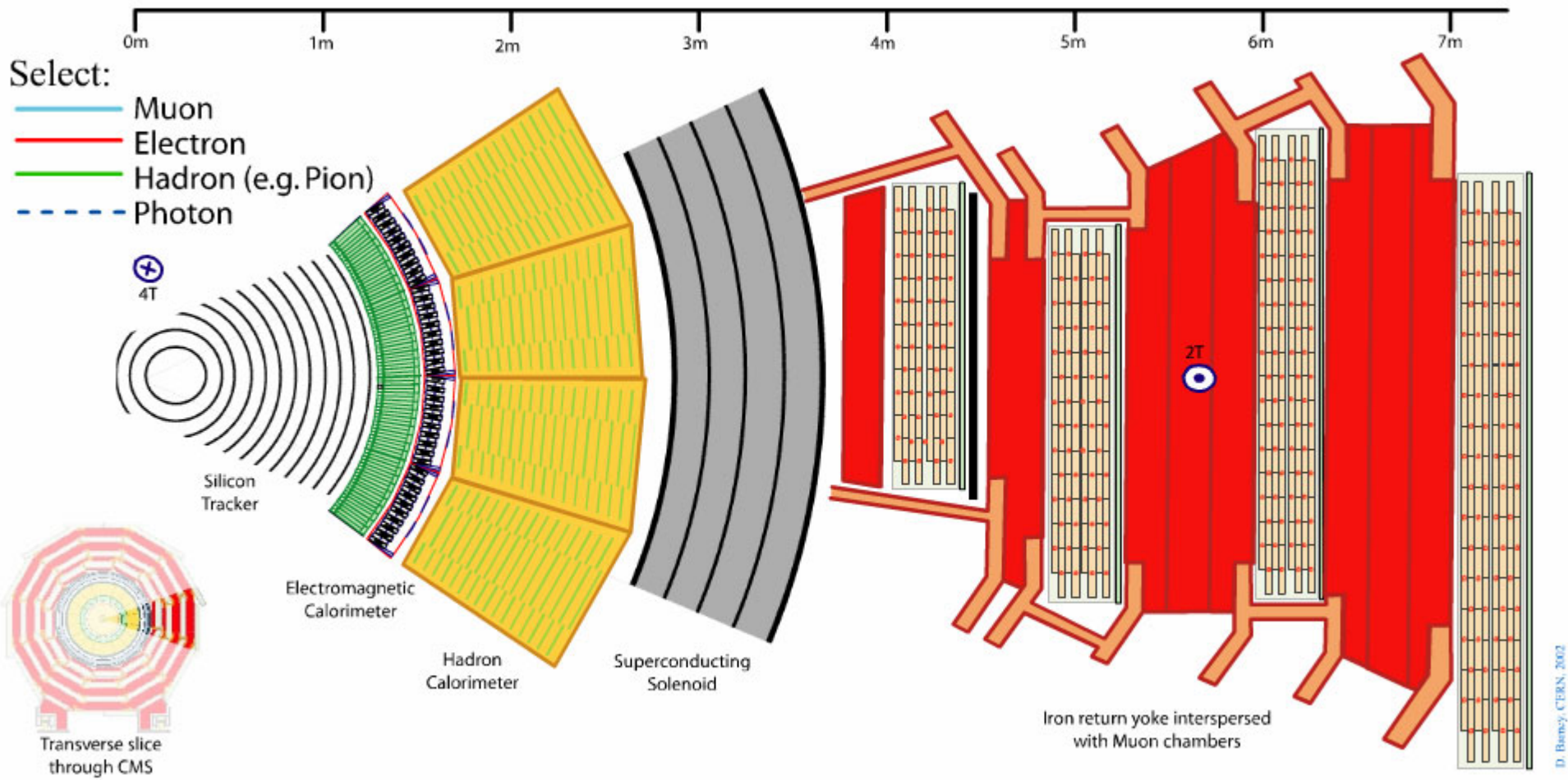
momentum resolution

9% at 100 GeV

$$\Delta x = 200\,\mu m$$

x 200000

CMS detector: simulation

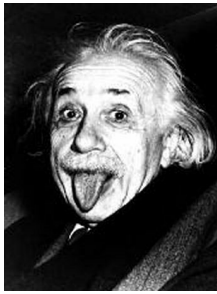


Radiation and data rate (per detector)

40 MHz bunch collision rate

10^{11} particles /s

2000 physicists



10^{5} *Gy / year*

500 GBit/s DAQ

100 events / s à 1 Mbyte

10000 PCs

Outline

- Particle Physics
- LHC
  - accelerator
  - detectors
  - physics

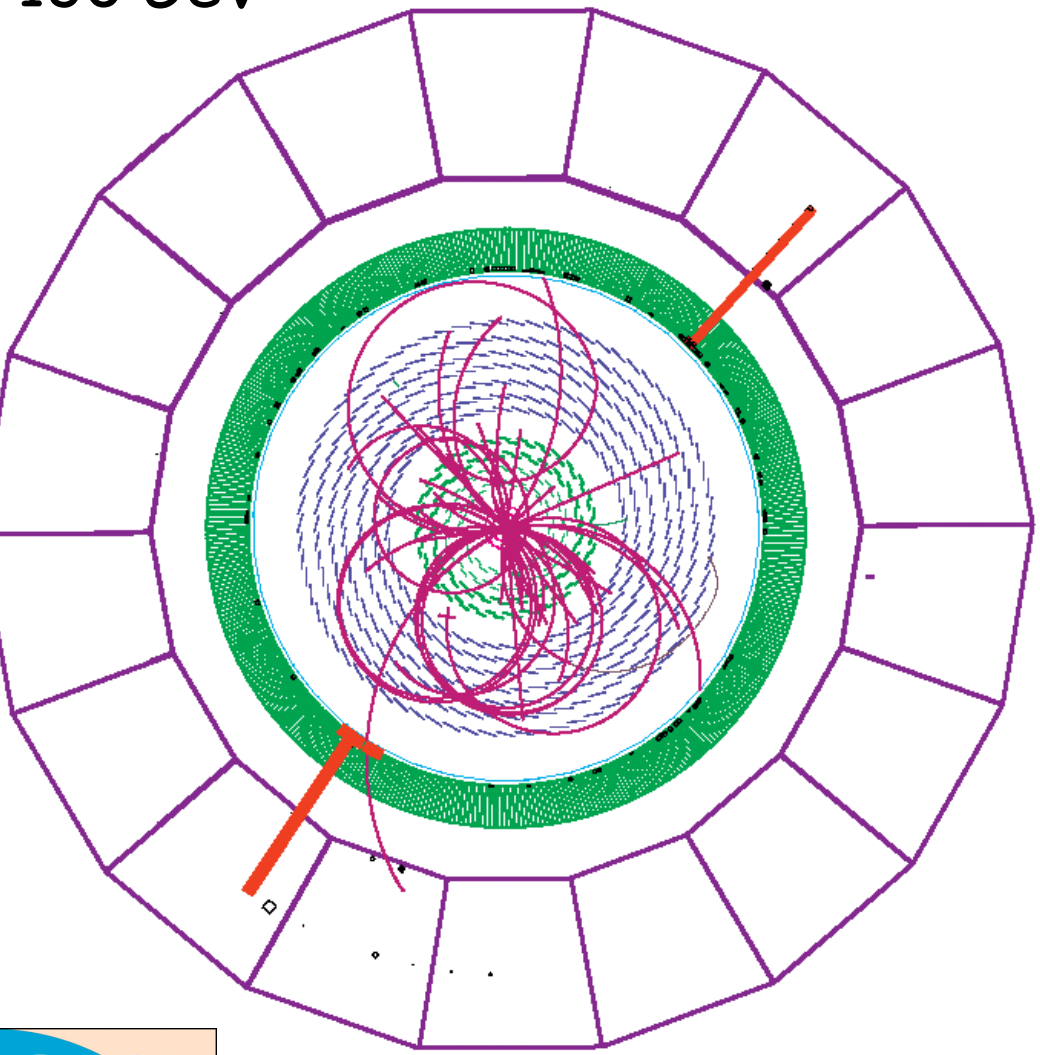
    Higgs

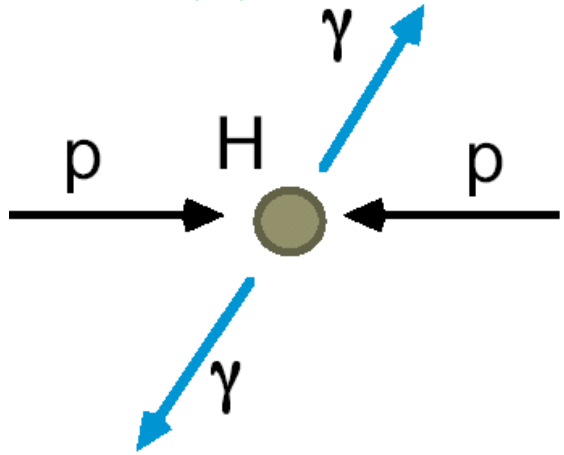
    extra dimensions

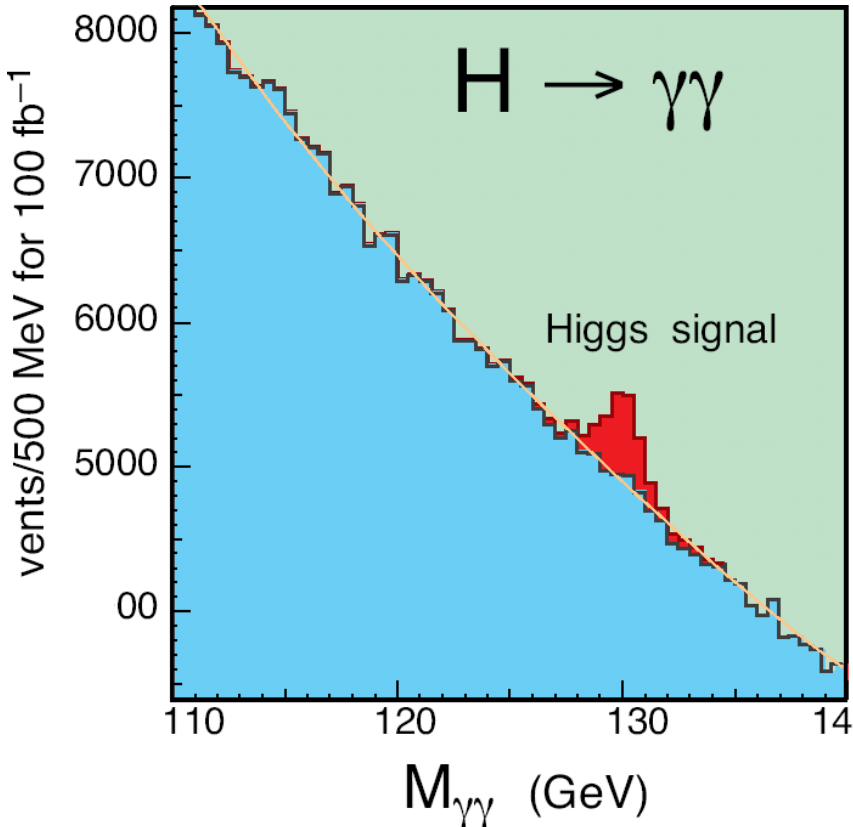
    mini black holes

Higgs (m = 110-150 GeV) $\rightarrow \gamma\gamma$

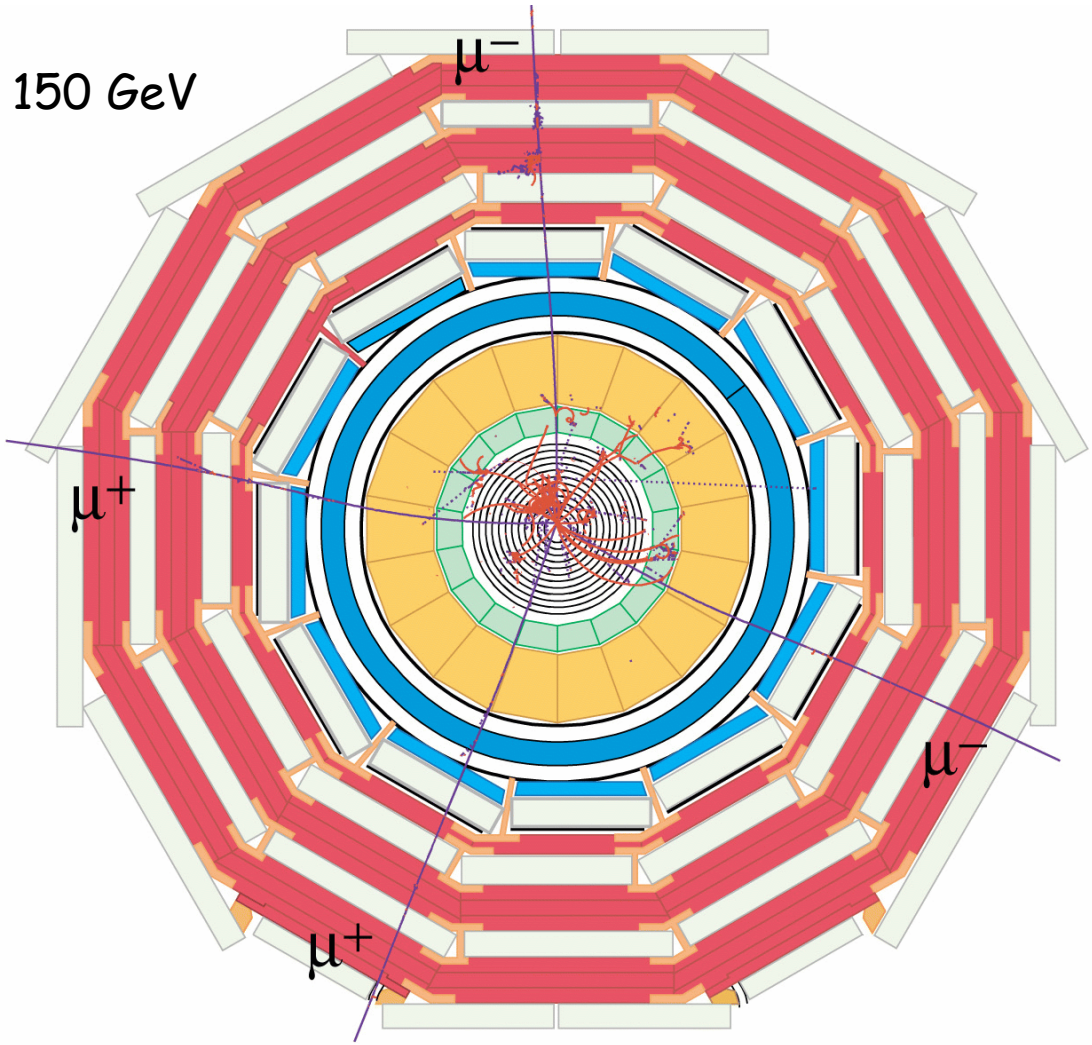
130 GeV

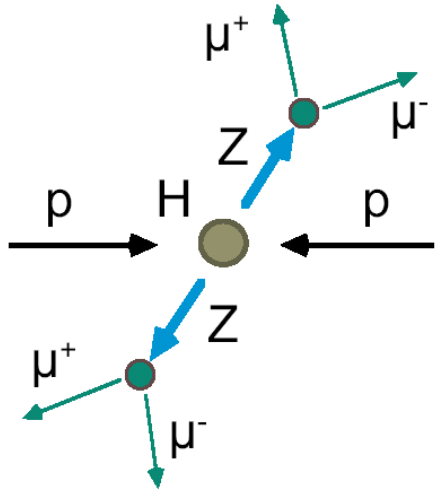


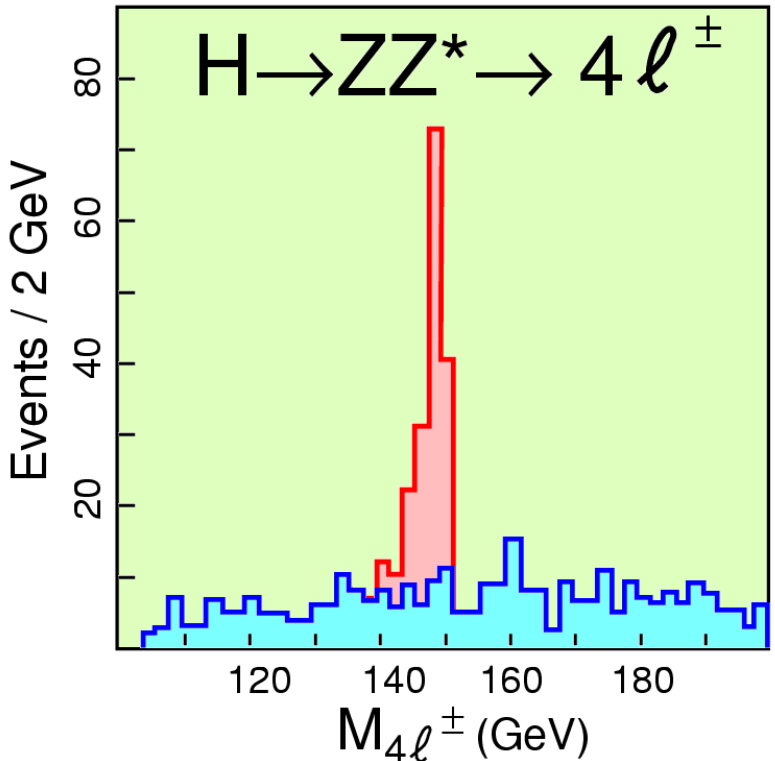




Higgs (130-700 GeV) $\rightarrow Z\,Z$

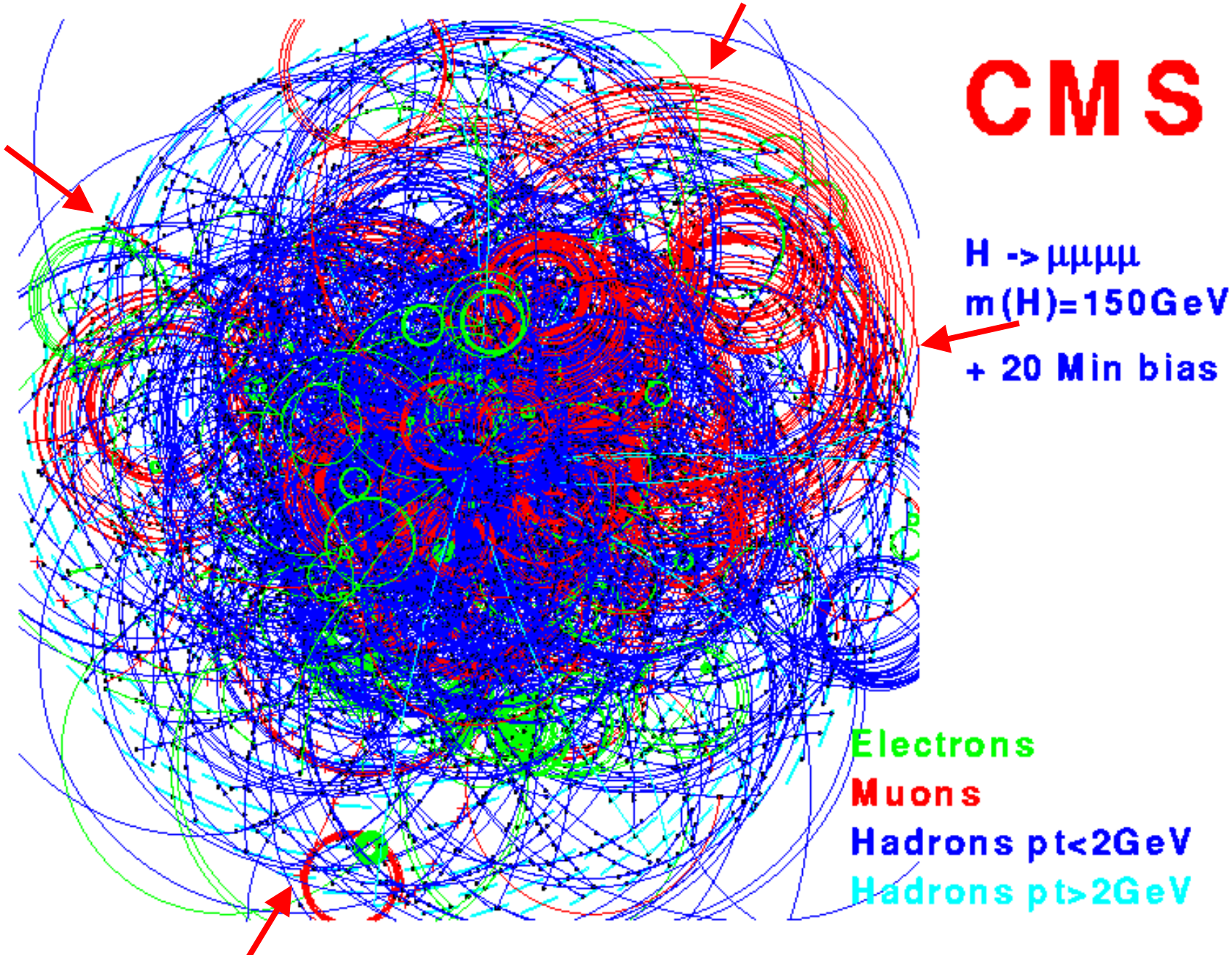






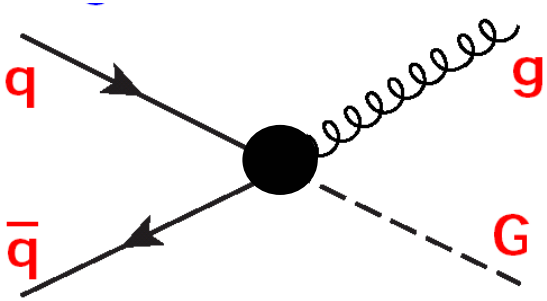
EXPERIMENTUM CRUCIS

Higgs event in CMS tracker (simulation)

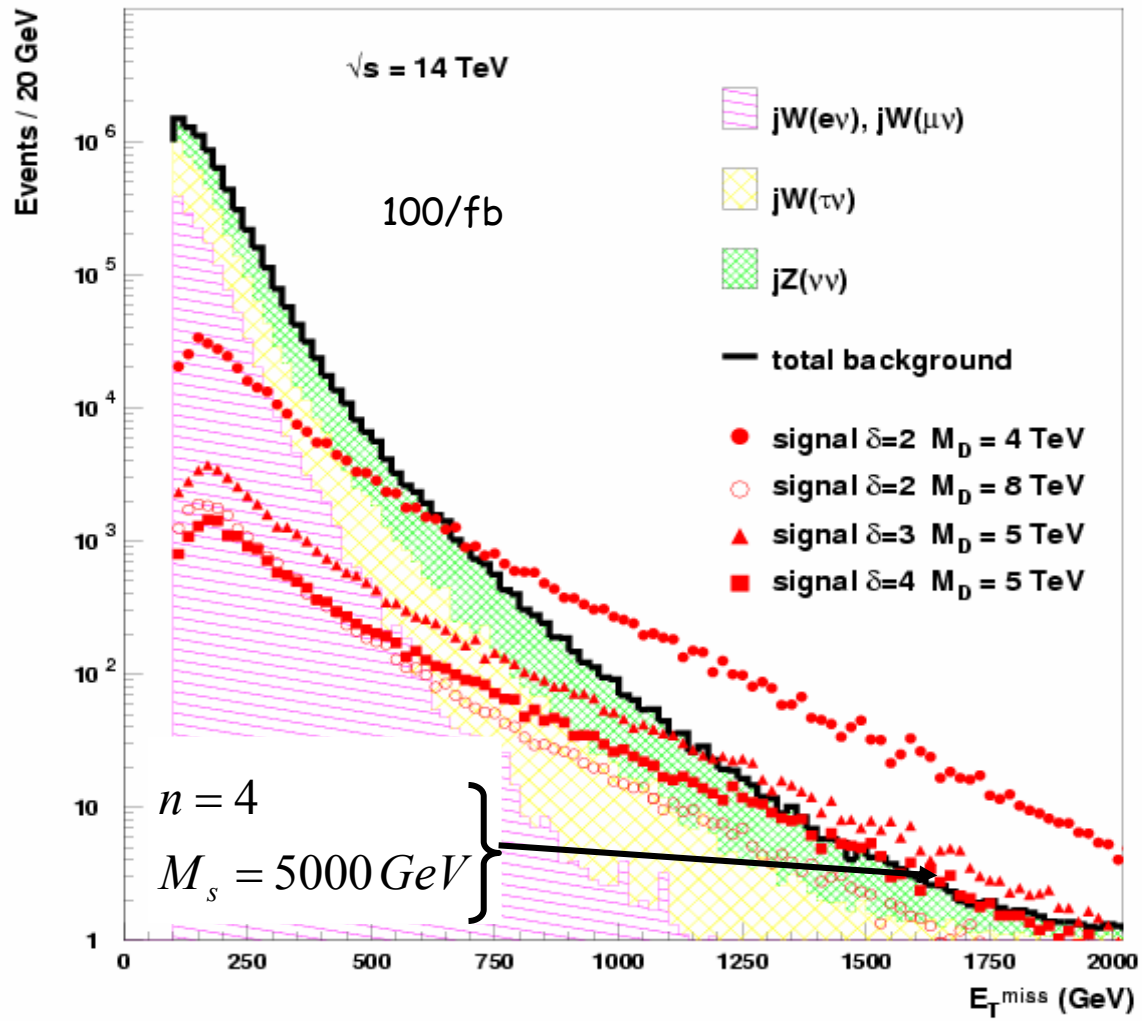


Extra dimensions

Real Graviton Emission in p p



G = missing energy



Interesting parameter space accessible!

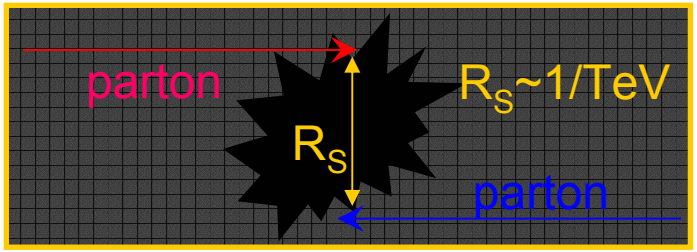
missing energy = escaping graviton

Mini Black Holes ?

predicted in large extra dimension models

production: mass 1 – 10 TeV,

cross section large (~ R_S^2 ~ 10^{-34} cm^2)
~ 1 event / s

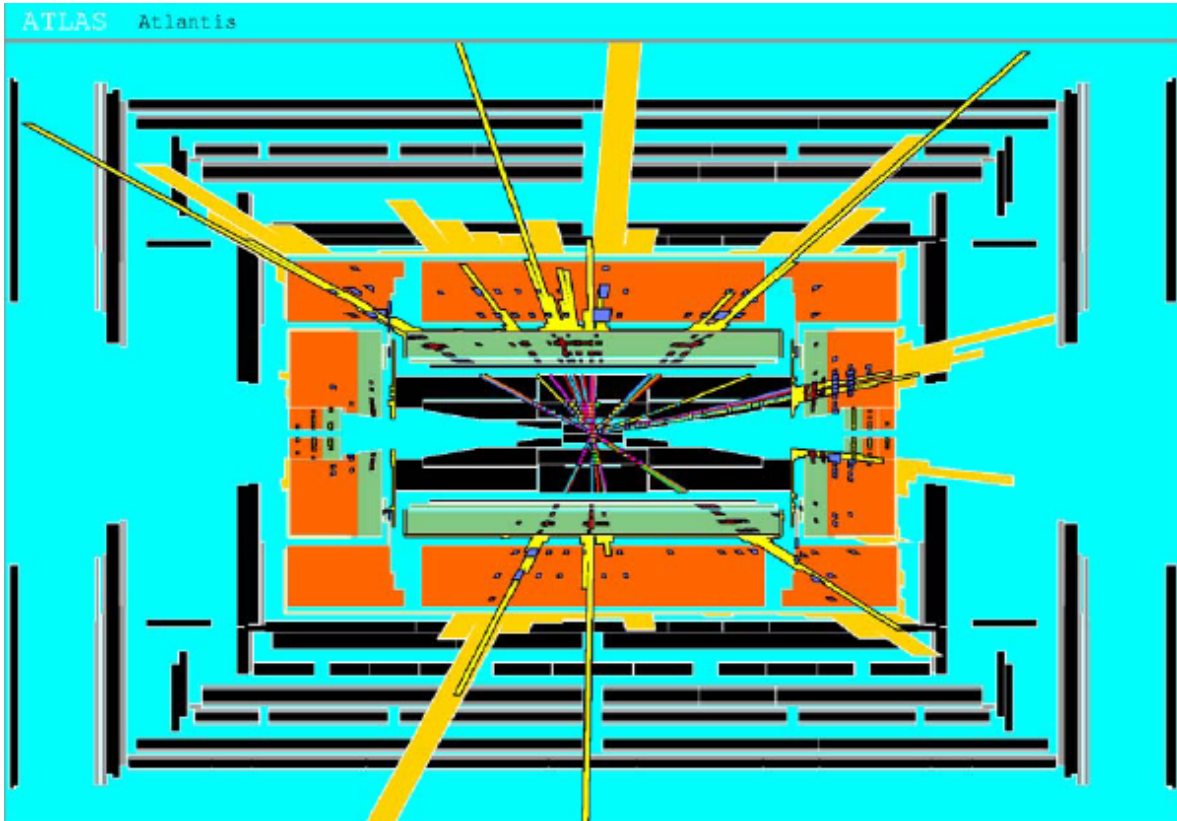


decay:

Hawking radiation

All SM d.o.f.

Multiplicity up to 30

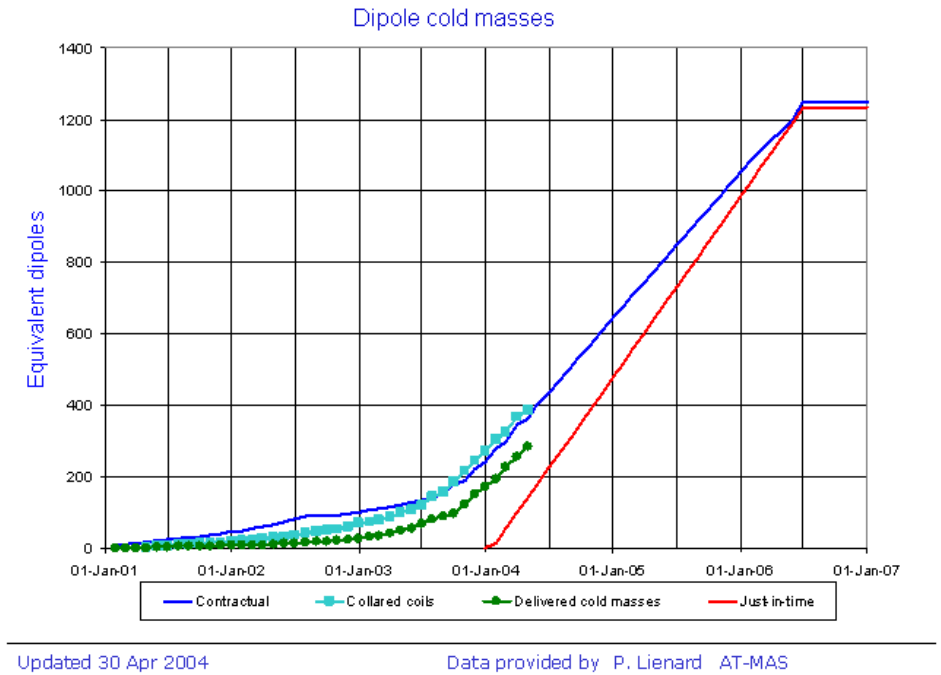


Decay also into higgs!

LHC: Status / Outlook

LHC Progress Dashboard

Accelerator Technology Department



2004

- accelerator parts:

  ~ 25% built

- detector components

  ~ 35% built

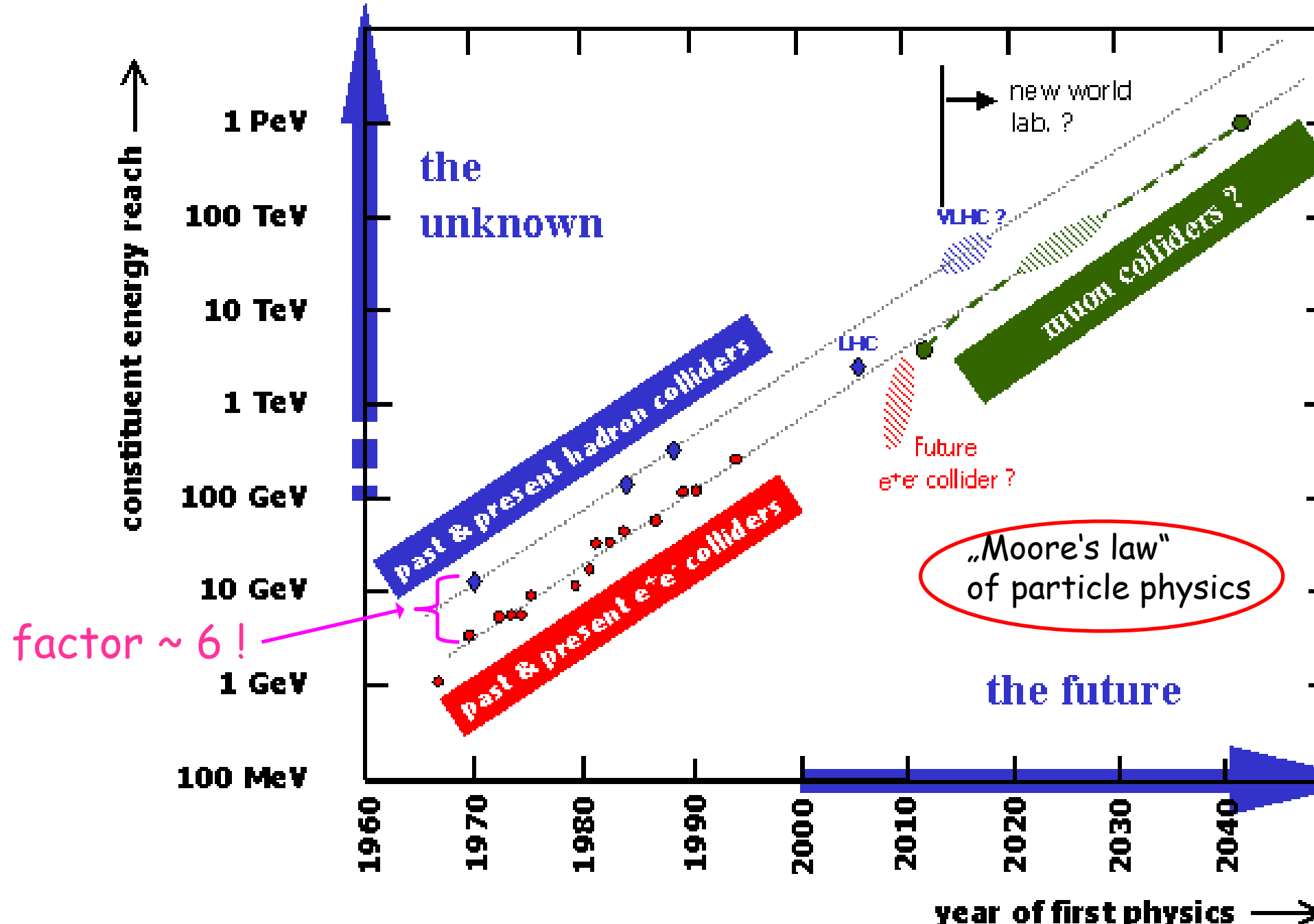
2007 ? first (colliding) beams

2008 ? Susy discovery ?

2009 ? Higgs discovery ?

appendix

The Livingston Plot: Past, Present & Future(?)



How to design a TeV particle collider ?

$$m_{particle} \geq \sqrt{s}$$

$$\Delta x \sim \frac{0.0002\, fm}{\sqrt{s}\,/\,TeV}$$

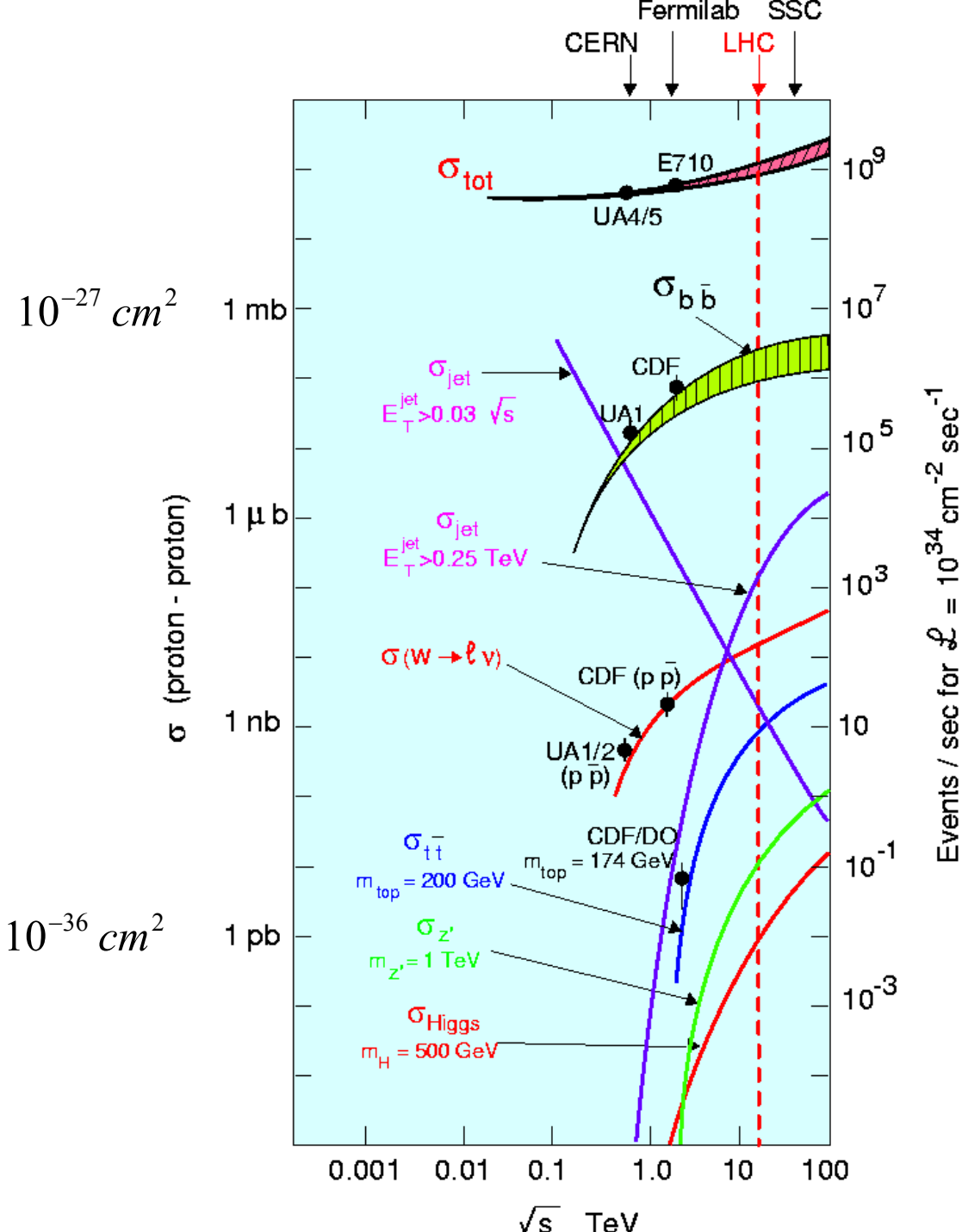
$$\sigma < \frac{\alpha^2}{s} \cdot f(m_{particle})$$

$$\sigma < \frac{0.087\, pb}{s\,/\,TeV^2}$$

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

$$R = 3\, km \cdot \frac{E\,/\,TeV}{B\,/\,T}$$

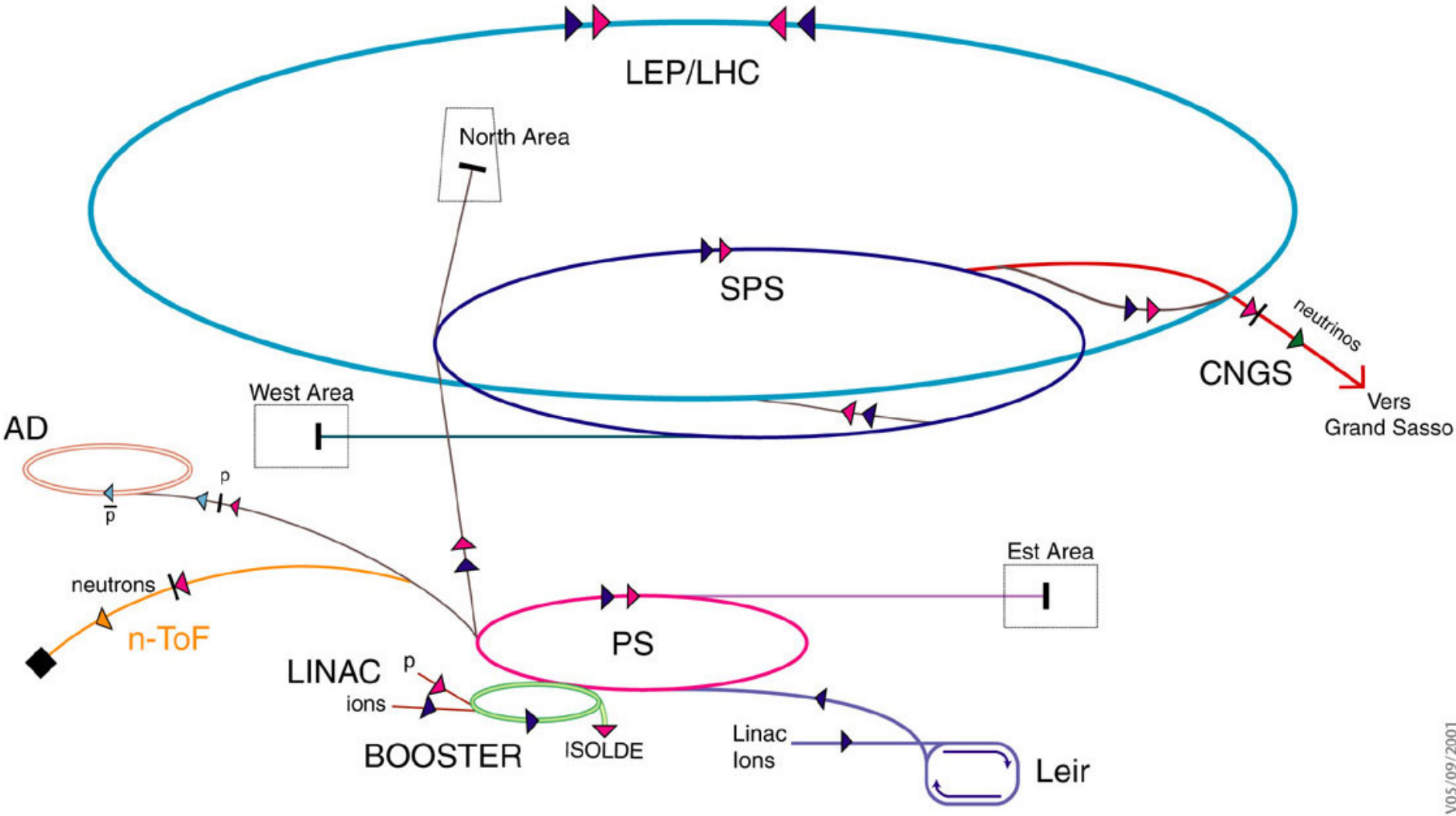
Cross Sections at Hadron Colliders



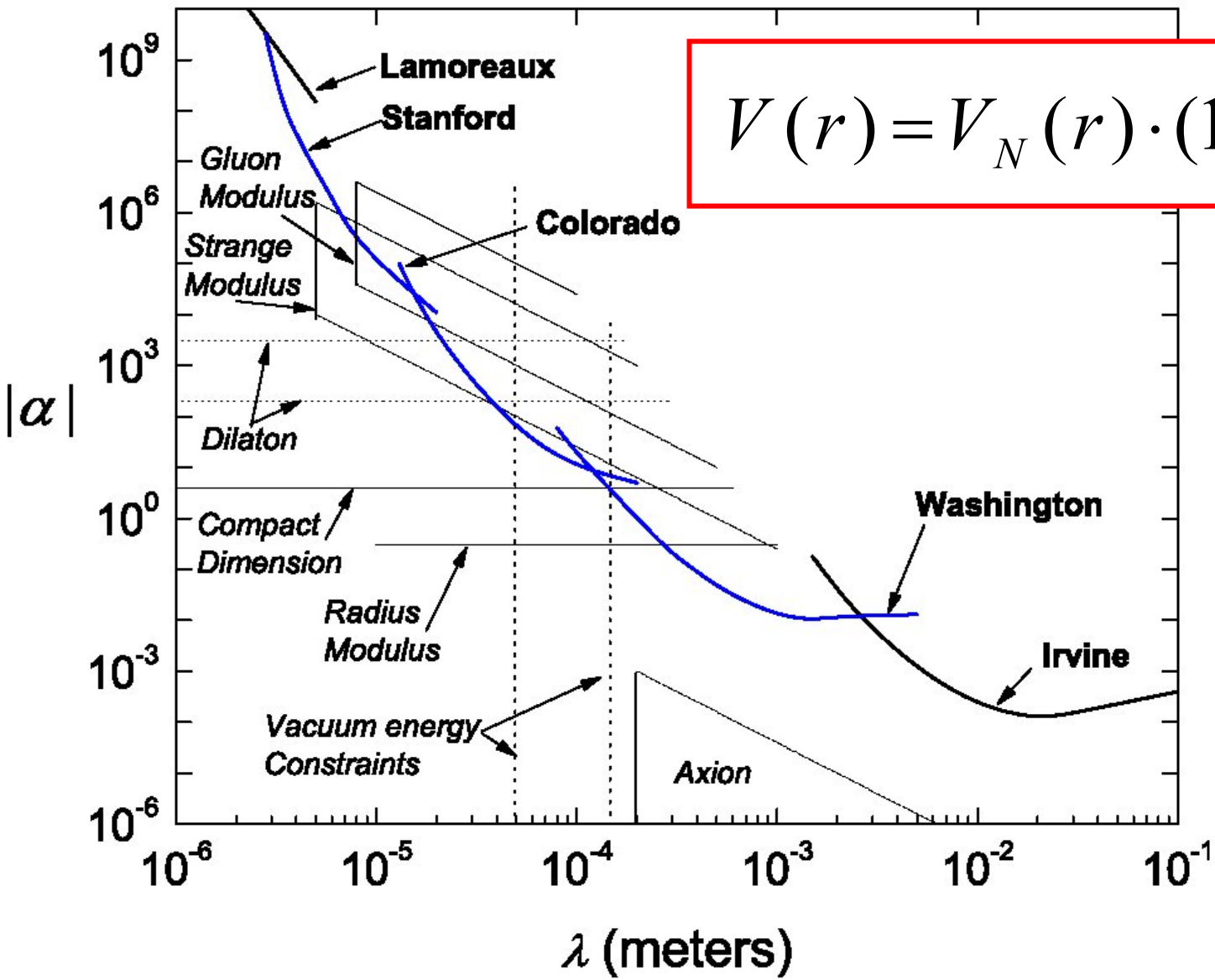
signal/background

$\sim 10^{-12}$

CERN accelerator complex



Gravity at small distances – experimental constraints

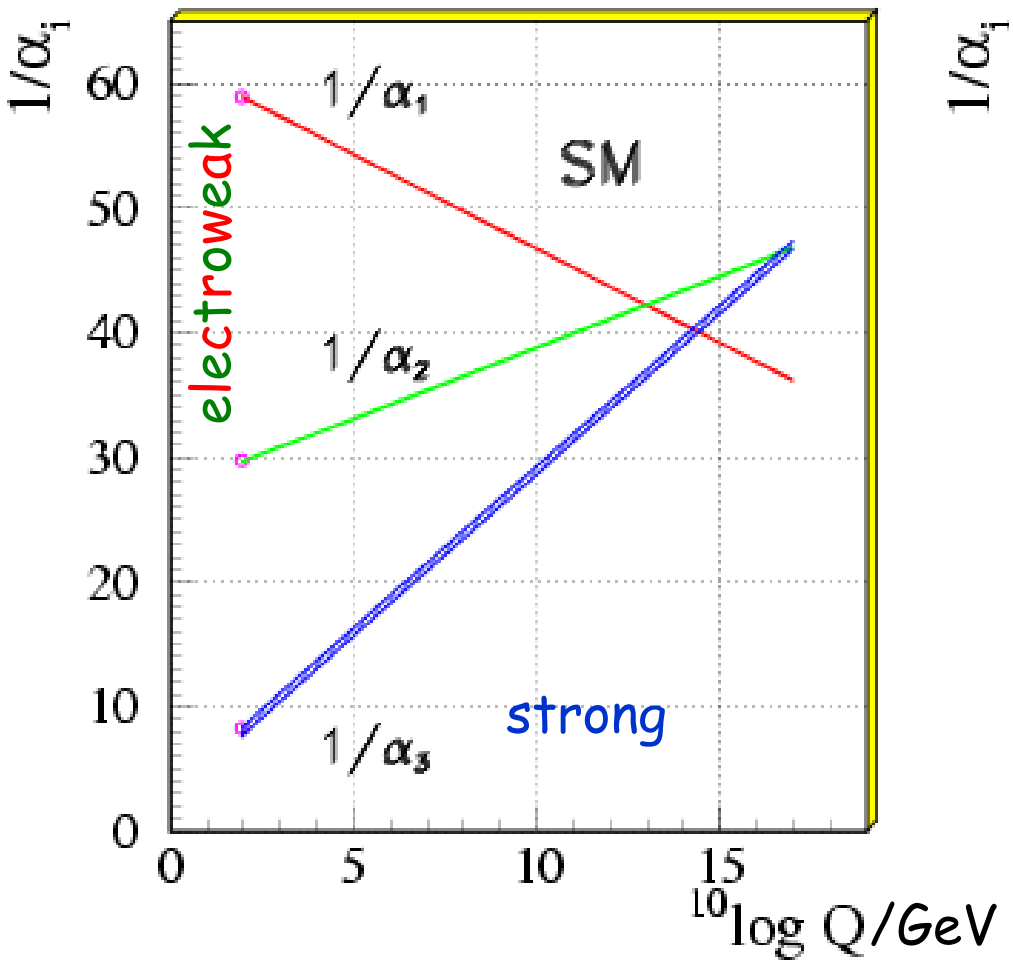


$$V(r) = V_N(r) \cdot (1 + \alpha\, e^{-r/\lambda})$$

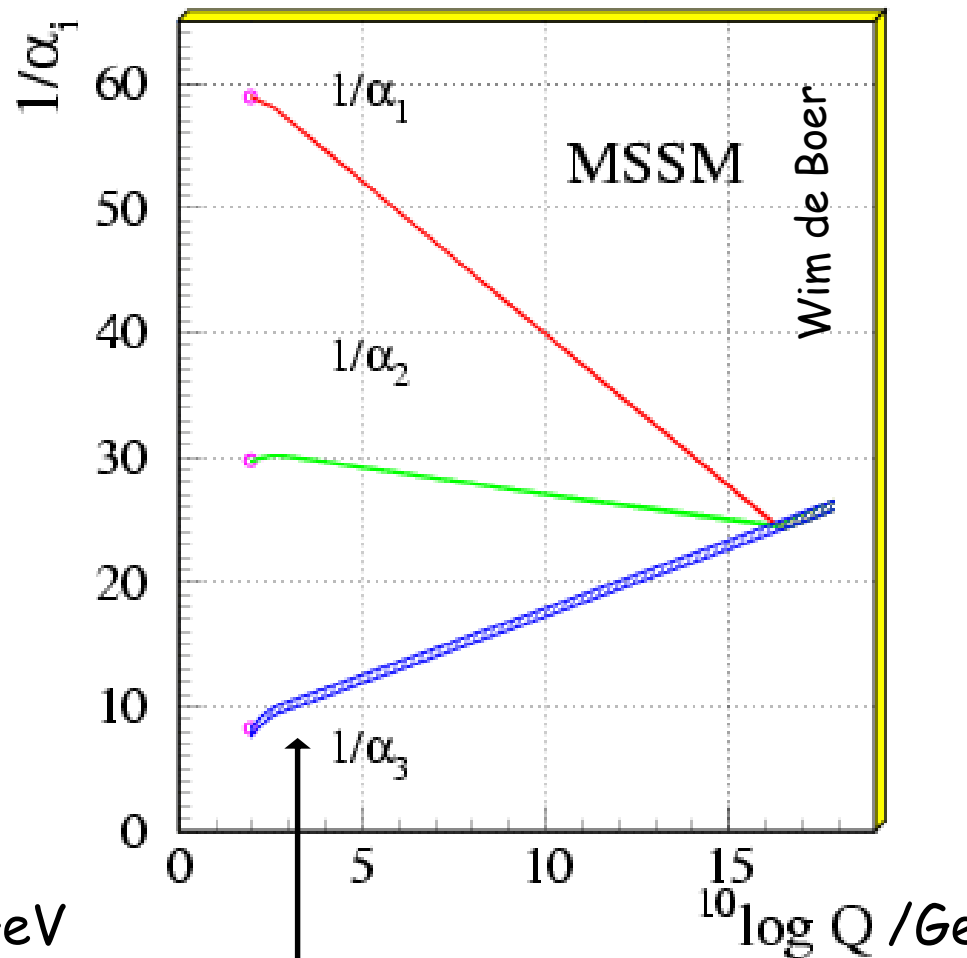
?

Grand Unification of forces ?

Standard Model



Supersymmetry



SUSY mass scale ~ TeV

timing

- Cern 10‘
- Physics 15‘
- accelerator 10‘
- Detectors 10‘
- LHC physics 10‘