Boston University, Oct. 3, 2006

Physics at the CERN Large Hadron Collider

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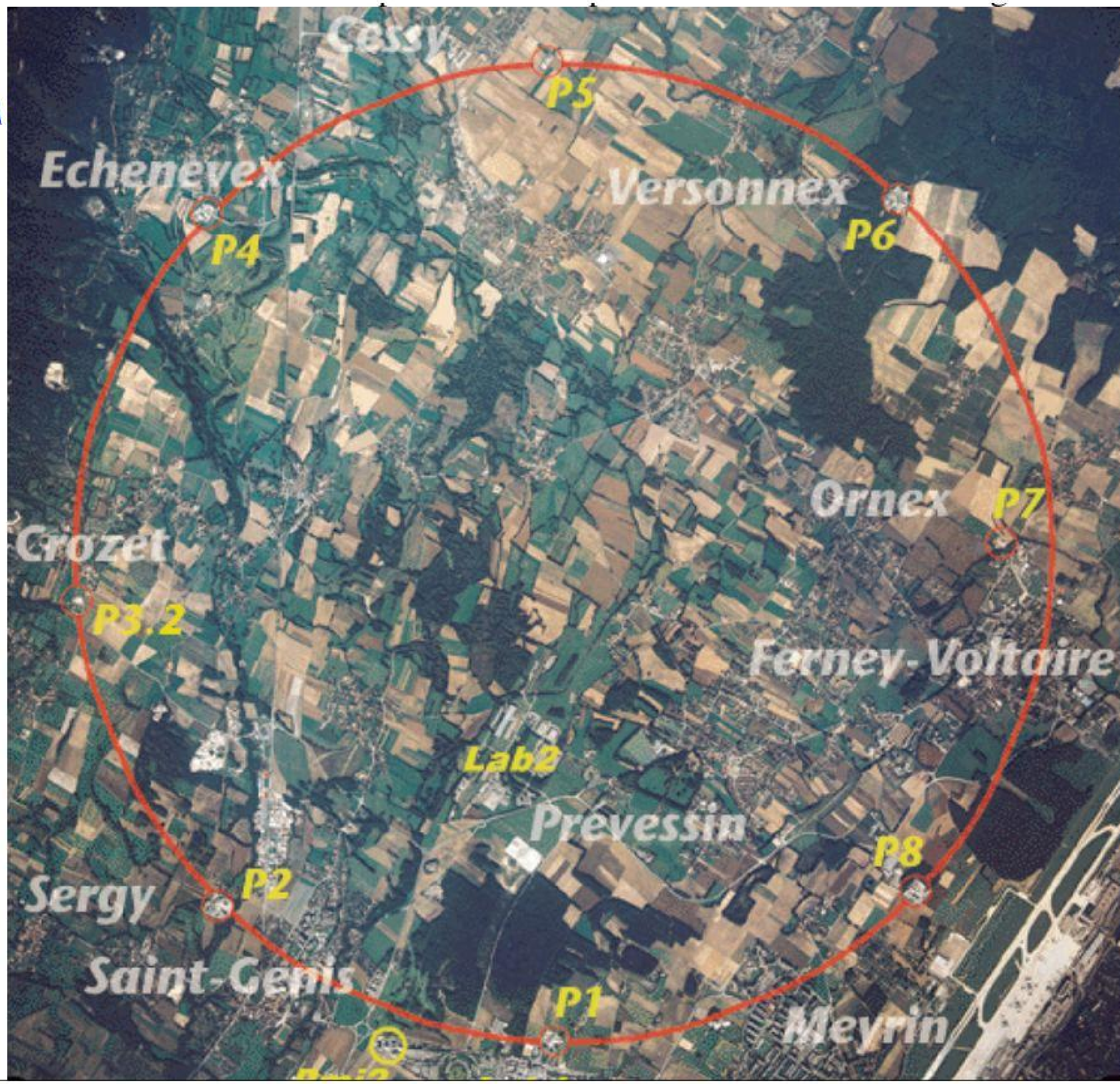
Conseil Européen pour la Recherche Nucléaire

Large Hadron (proton) Collider

$\overrightarrow{p}\ \overleftarrow{p}$



LHC Physics: The Wild East

The Good,

The Bad, AND

The Ugly.

TECHNICOLOR

Archives | ARTS & ENTERTAINMENT

Swiss Spaghetti Harvest

Originally featured on May 27, 2003

Enough with Jayson Blair, please. The Times has copped to it, Mr. Blair appears to be seriously troubled, and, in spite of the disgraced reporter's apparent crowing, it was a pathetic fraud, not exactly a brilliant hoax.

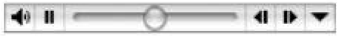
For that, you might look to the BBC, which pulled a hilarious bit of journalistic deception on April 1st, 1957. The august BBC ran a piece on a news program called Panorama, in which a highly-respected journalist, Richard Dimbleby, delivered with absolute seriousness a story about the **Swiss Spaghetti Harvest**. Spaghetti was relatively unknown at that time in the U.K. and viewers began calling the BBC asking how they could grow their own spaghetti tree. It is one of our favorite hoaxes of all time. So, for a laugh on a Tuesday morning, here's the transcript...

IL BUONO

The Z^0 Boson

"Every gun makes its own tune."

Man With No Name



Z^0 Discovery at CERN in UA1

$q\bar{q} \rightarrow Z^0 \rightarrow e^+e^-$ "two to two"

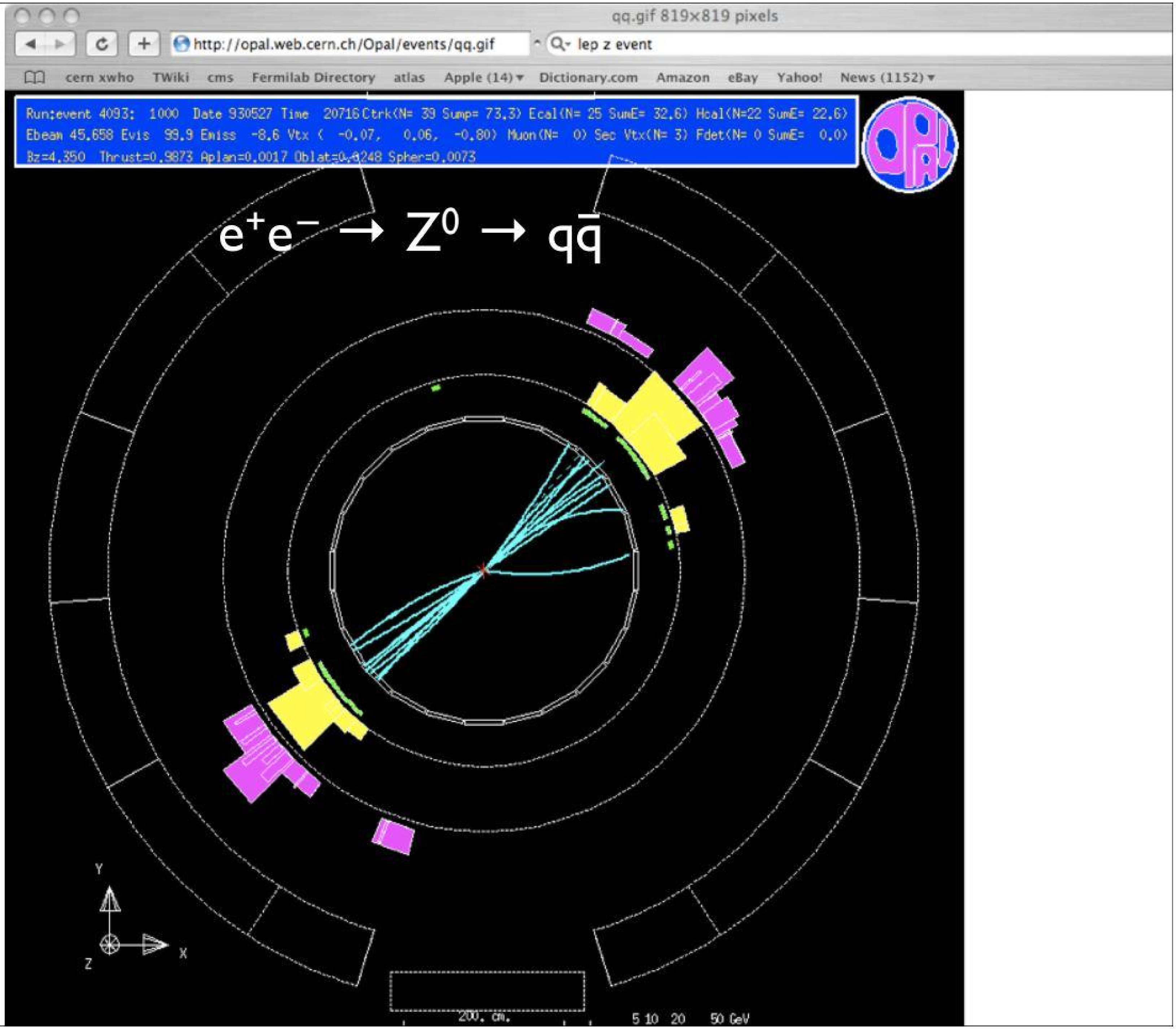
$$P = \frac{2ke^2\gamma^4 c}{3r^2}$$

radiated power from circular orbit

"It is apparent that as the velocity is increased there will come a point at which energy is radiated away just as rapidly as it is supplied by the accelerator. Thus, there exists a practical upper limit for the energy of electrons that can be achieved in a circular machine. This limit apparently is in the energy range 10-20 GeV."

Classical Electromagnetic Radiation

Marion and Heald (1980)



qq.gif 819×819 pixels
http://opal.web.cern.ch/Opal/events/qq.gif
lep z event
cern xwho TWiki cms Fermilab Directory atlas Apple (14) Dictionary.com Amazon eBay Yahoo! News (1152)
Run:event 4093: 1000 Date 930527 Time 20716 Ctrk(N= 39 Sump= 73.3) Ecal(N= 25 SumE= 32.6) Hcal(N=22 SumE= 22.6)
Ebeam 45.658 Evis 99.9 Emiss -8.6 Vtx (-0.07, 0.06, -0.80) Muon(N= 0) Sec Vtx(N= 3) Fdet(N= 0 SumE= 0.0)
Bz=4.350 Thrust=0.9873 Aplan=0.0017 Oblat=0.0248 Spher=0.0073
$e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}$
Y
Z
X
200. cm.
5 10 20 50 GeV

Large Electron Positron (LEP) Project

LEP was optimized for 85 GeV per beam, resulting in 27 km circumference after balancing costs of construction and operation

commisioned 1989, shut down end of 2000

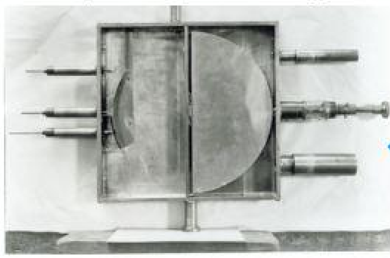
LEP machine radius = 1 TeV / tesla

U. Amaldi, "European Pro jects in High-Energy Physics," CERN-EP/81-149, invited talk given at the AIP Meeting on Particles and Fields, Santa Cruz, CA, 9-11 Sept. 1981, published in DPF 1981:0415 (QCD161:A6:1981).

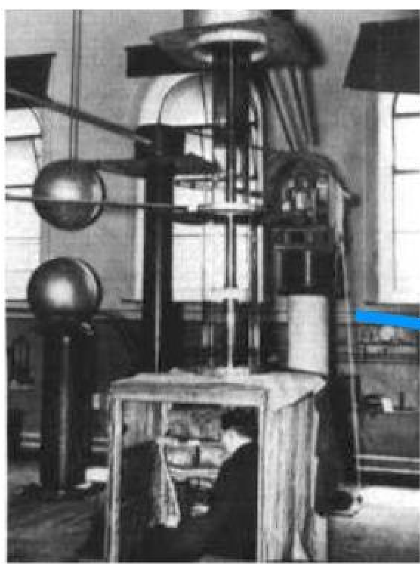
Livingston plot

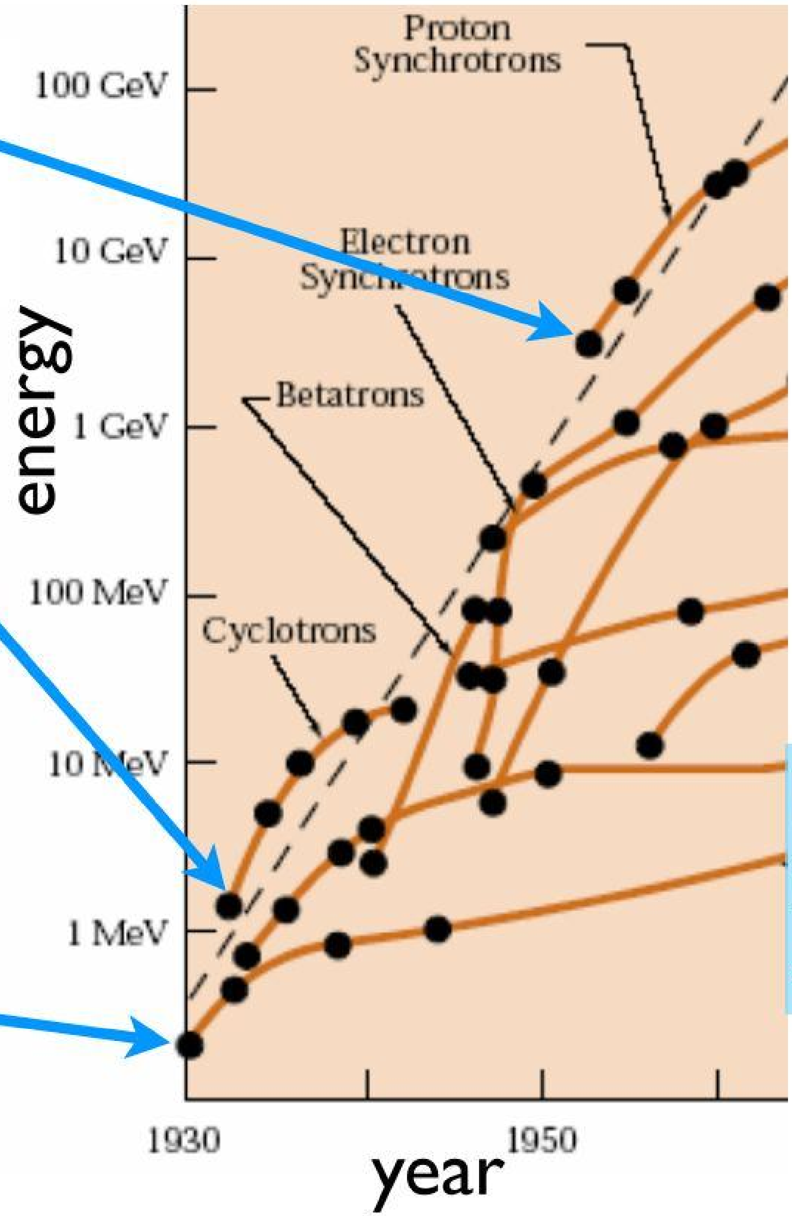
Brookhaven Cosmotron

Berkeley 11 inch Cyclotron



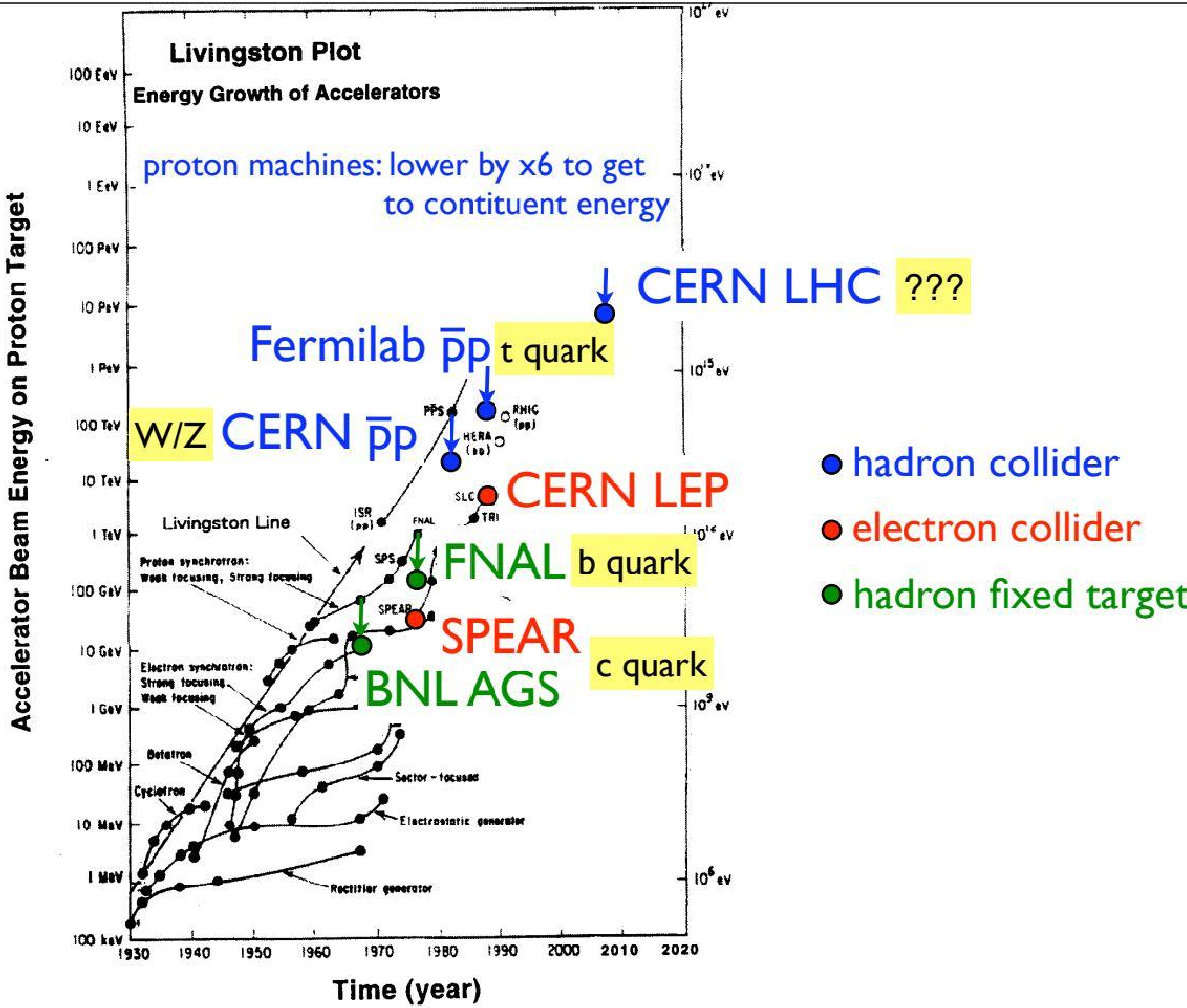
Cavendish Cockroft-Walton



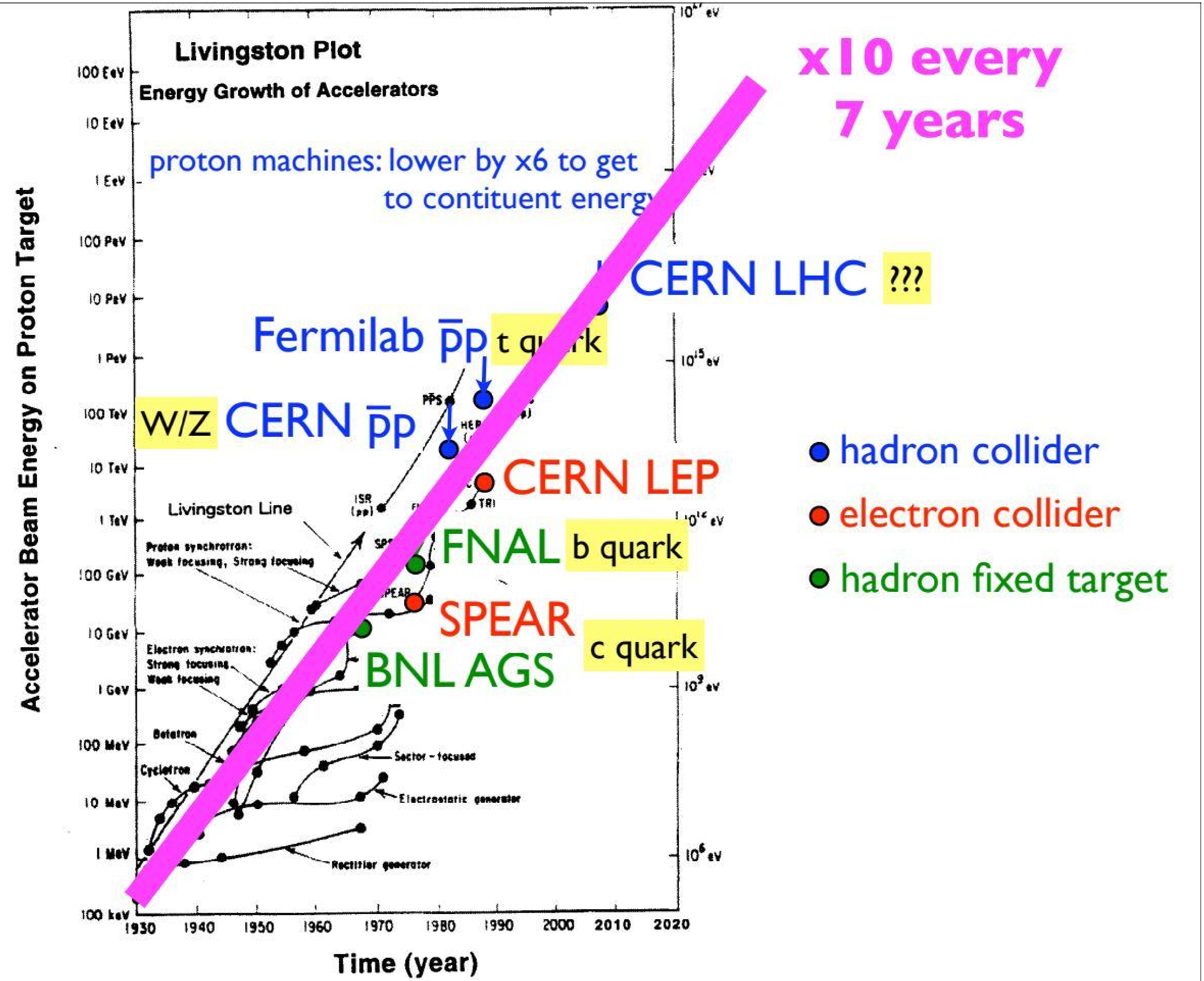


M. Stanley Livingston
(1905-1986)

Energy frontier increases x10 every 6 years

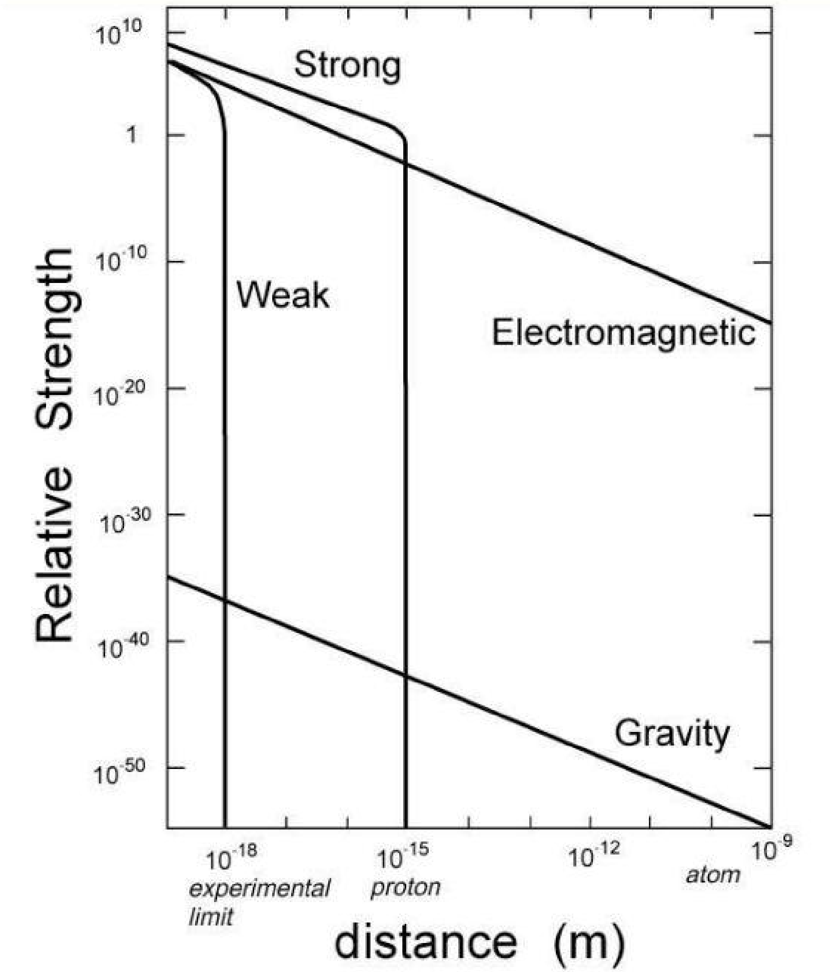


Livingston Plot
Energy Growth of Accelerators
proton machines: lower by x6 to get
to contituent energy
CERN LHC
???
Fermilab p̄p
t quark
W/Z
CERN p̄p
CERN LEP
FNAL
b quark
SPEAR
c quark
BNL AGS
hadron collider
electron collider
hadron fixed target
Livingston Line
Accelerator Beam Energy on Proton Target
Time (year)
100 EeV
10 EeV
1 EeV
100 PeV
10 PeV
1 PeV
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
100 keV
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
ISR (pp)
SPS
FNAL
SLC
TRI
RHIC (pp)
HERA (ep)
Proton synchrotron: Weak focusing, Strong focusing
Electron synchrotron: Strong focusing, Weak focusing
Betatron
Cyclotron
Sector - focused
Electrostatic generator
Rectifier generator



Livingston Plot
Energy Growth of Accelerators
proton machines: lower by x6 to get
to contituent energy
x10 every
7 years
CERN LHC ???
Fermilab $\bar{p}p$ t quark
W/Z CERN $\bar{p}p$
CERN LEP
FNAL b quark
SPEAR
c quark
BNL AGS
hadron collider
electron collider
hadron fixed target
Livingston Line
Proton synchrotron:
Weak focusing, Strong focusing
Electron synchrotron:
Strong focusing
Weak focusing
Betatron
Cyclotron
Sector - focused
Electrostatic generator
Rectifier generator
Accelerator Beam Energy on Proton Target
Time (year)

Large Hadron Collider: Why?

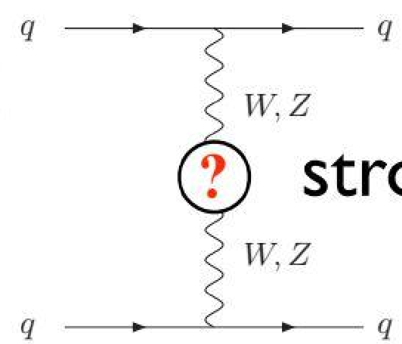


$$\alpha_W = \alpha\left(\frac{E}{m_W c^2}\right)^2$$

$$\alpha_W \approx 1 \quad \text{for} \quad E \approx 1 \text{ TeV}$$

Weak interaction probabilities increase without bound even though wavelengths are decreasing!

How do W/Z interact at high energy?

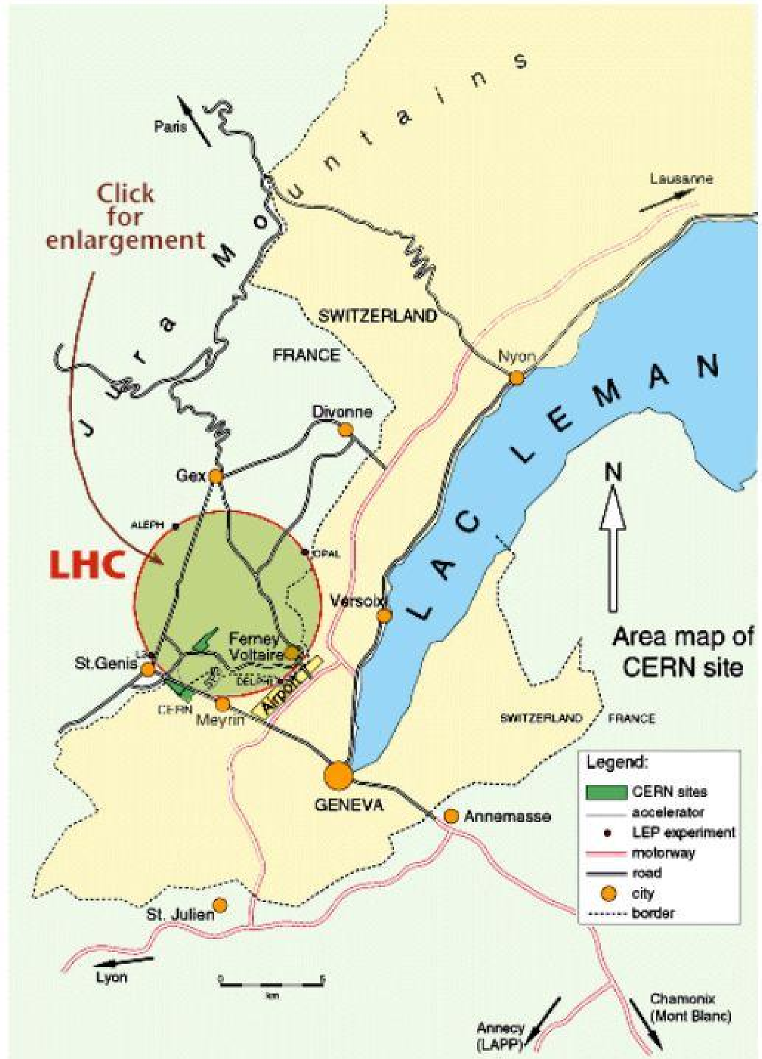


strong

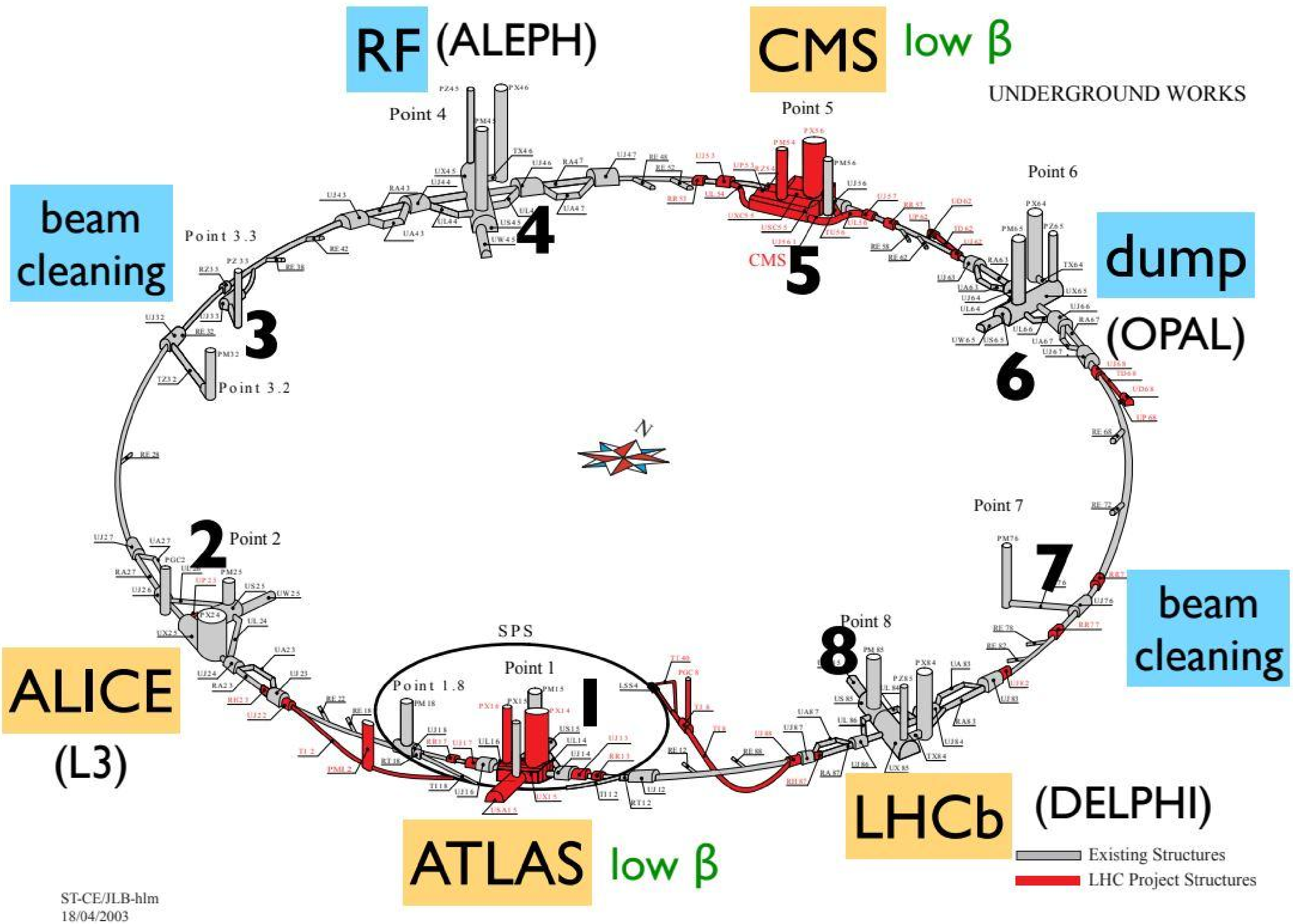
LHC Geographical Situation

electron machines: limited by synchrotron radiation

proton machines: limited by magnet technology



LHC Layout



RF (ALEPH)
CMS low β
UNDERGROUND WORKS
Point 4
Point 5
Point 6
beam cleaning
Point 3.3
4
CMS
5
dump
3
(OPAL)
Point 3.2
6
Point 7
2
Point 2
7
beam cleaning
SPS
Point 8
8
Point 1
Point 1.8
1
ALICE
(L3)
LHCb
(DELPHI)
ATLAS low β
Existing Structures
LHC Project Structures
ST-CE/JLB-hlm
18/04/2003

Basic Parameters of the LHC

circumference	26,659 m
dipole field	8.33 T
energy per beam	7 TeV
number of dipoles	1232
total number of magnets	9994
operating temperature	1.9 K
power consumption	120 MW
revolution frequency	11.2455 kHz
revolution period	88.9 μs
radio frequency (RF)	400.8 MHz
RF electric field	5.5 MV/m

0.5 amp proton currents!

Proton speed

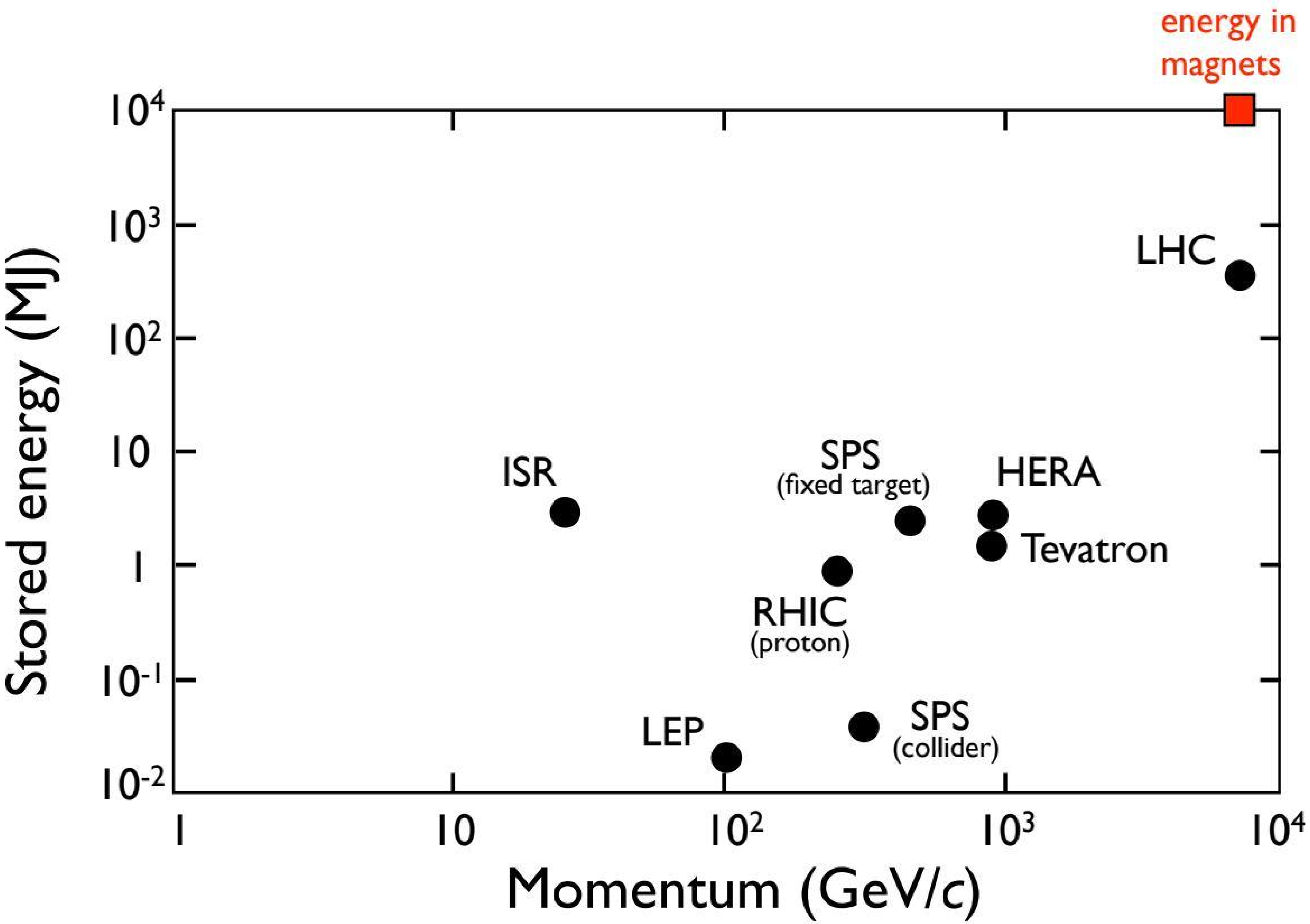
$$\gamma = \frac{1}{\sqrt{1-v^2/c^2}} = E/m$$

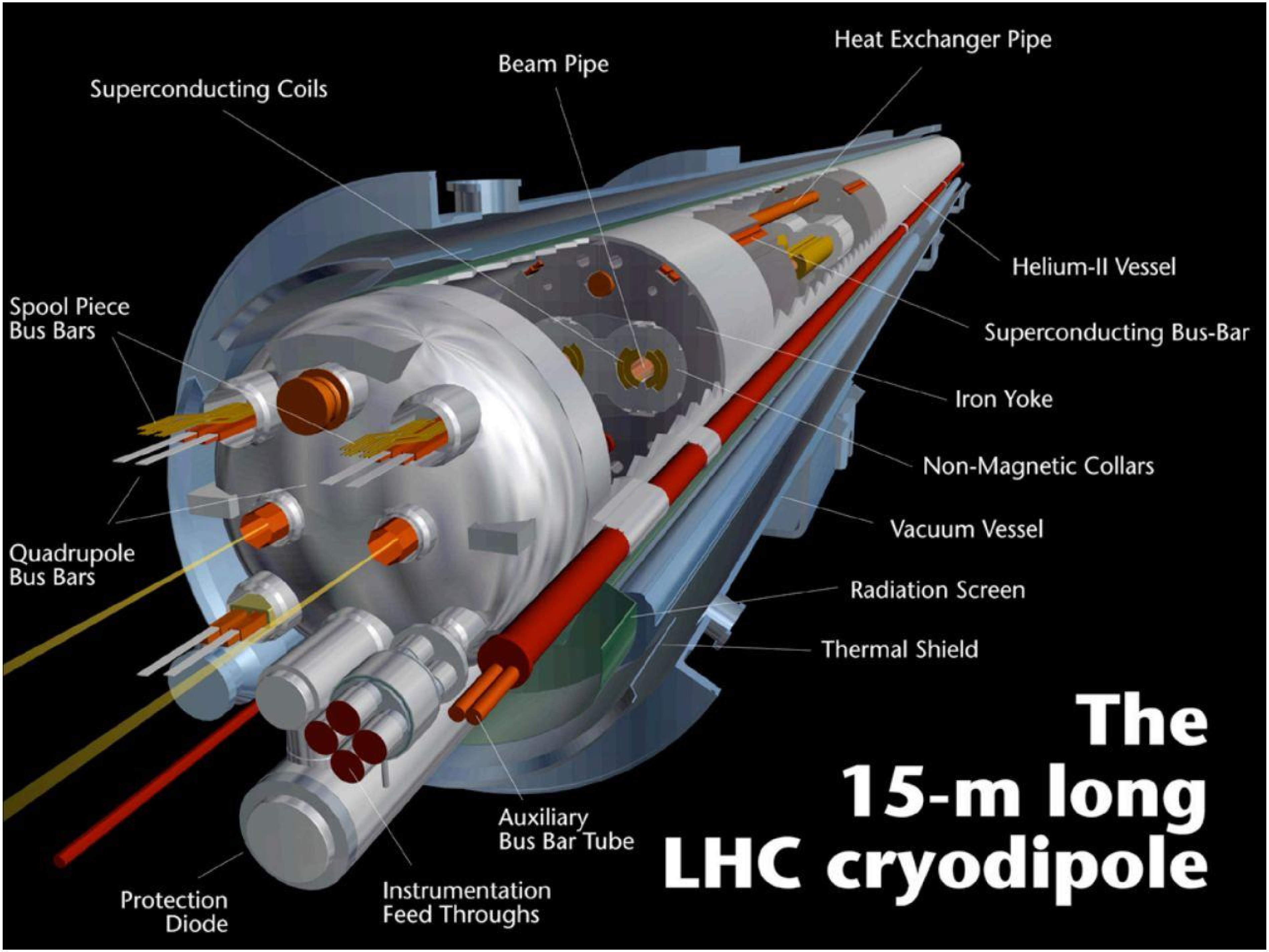
$$1 - v^2/c^2 = m^2/E^2$$

$$v = c\sqrt{1 - m^2/E^2}$$

$$v \approx c(1 - m^2/2E^2) = c - 2.7 \text{ m/s}$$

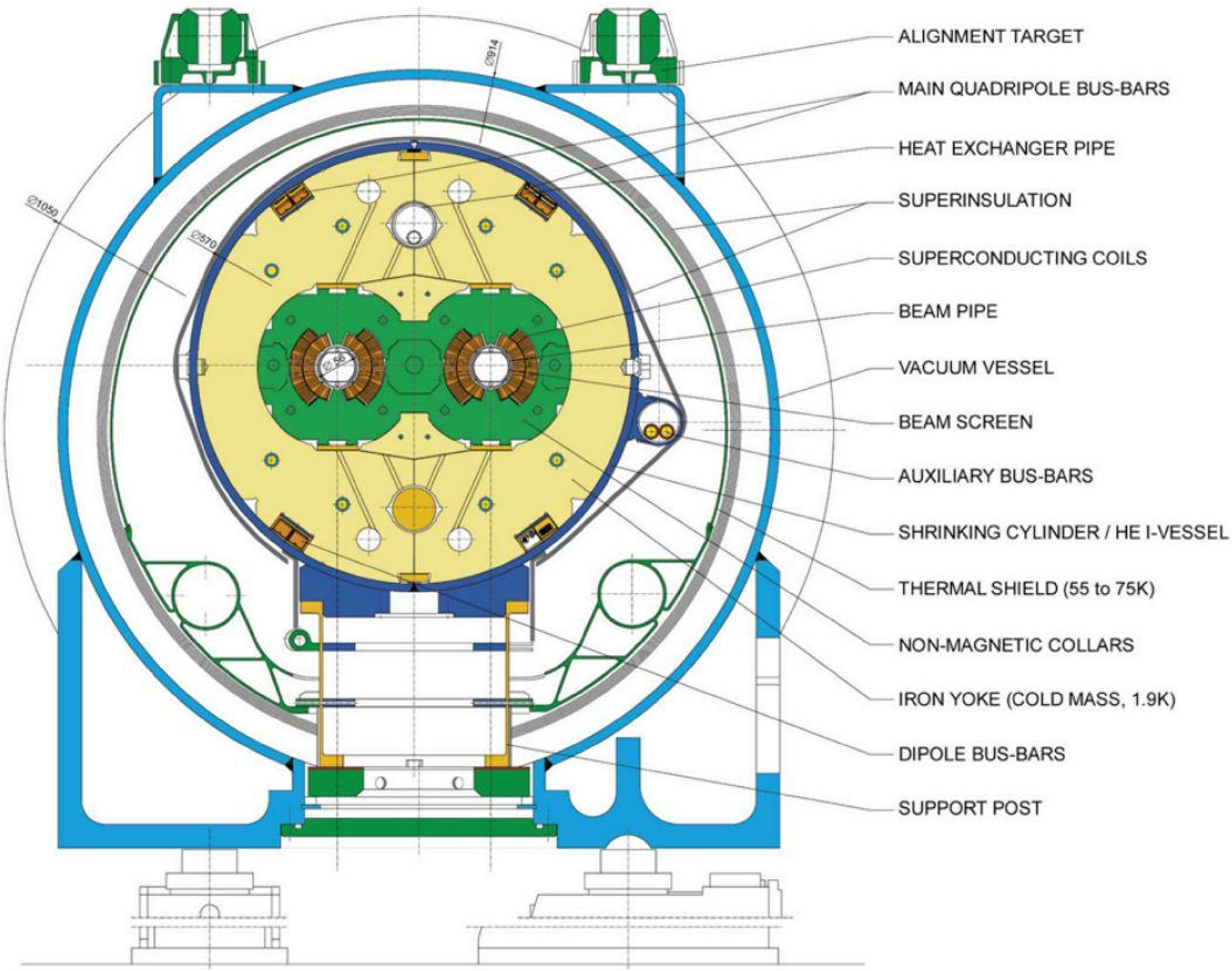
$$E_s = E_p n_b N_b = (7 \times 10^{12}\ \mathrm{eV})(1.6 \times 10^{-19}\ \mathrm{J/eV})(2808)(1.1 \times 10^{11}) = 350\ \mathrm{MJ}.$$




Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Quadrupole
Bus Bars
Vacuum Vessel
Radiation Screen
Thermal Shield
The
15-m long
LHC cryodipole
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs

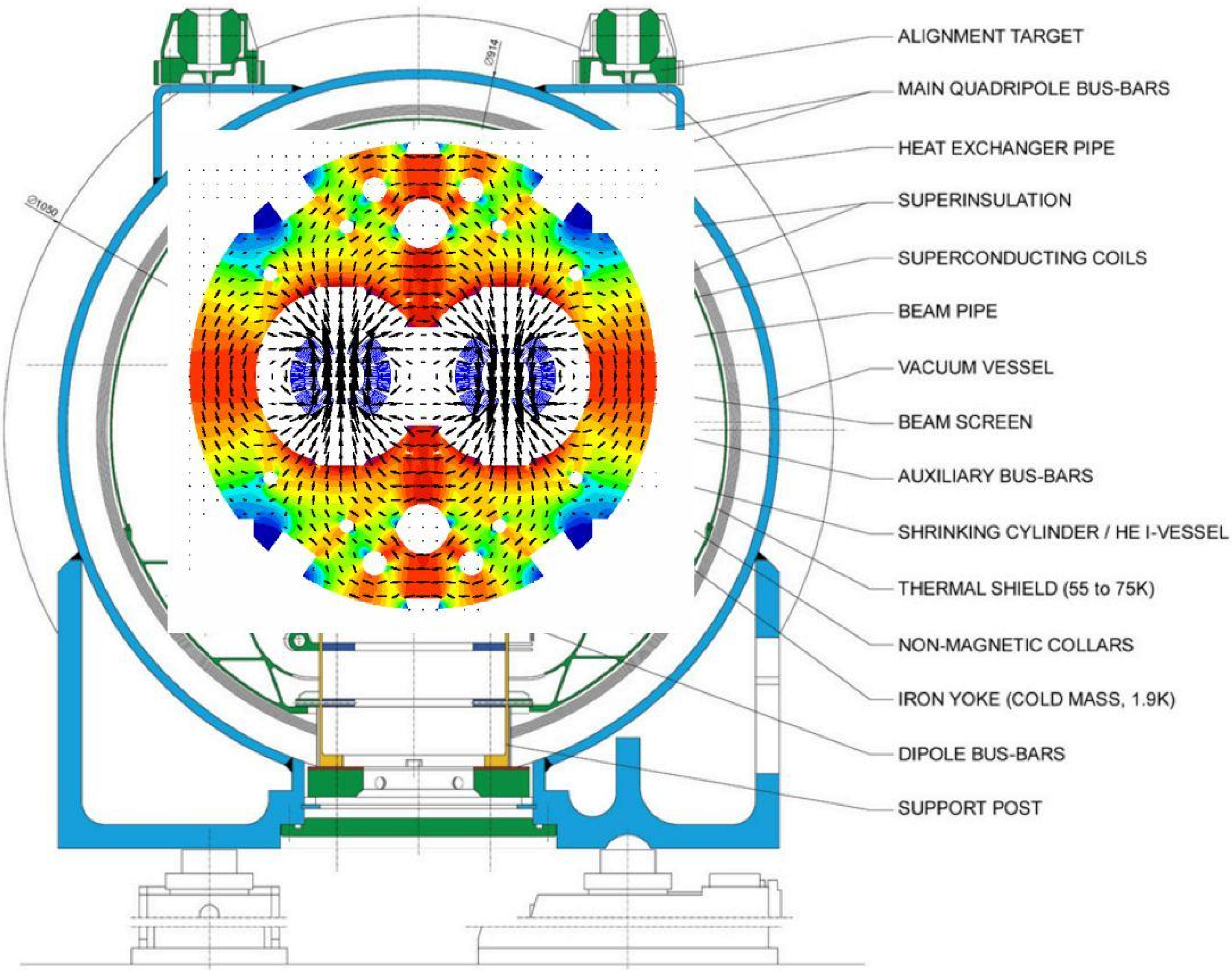
LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30 04 1999



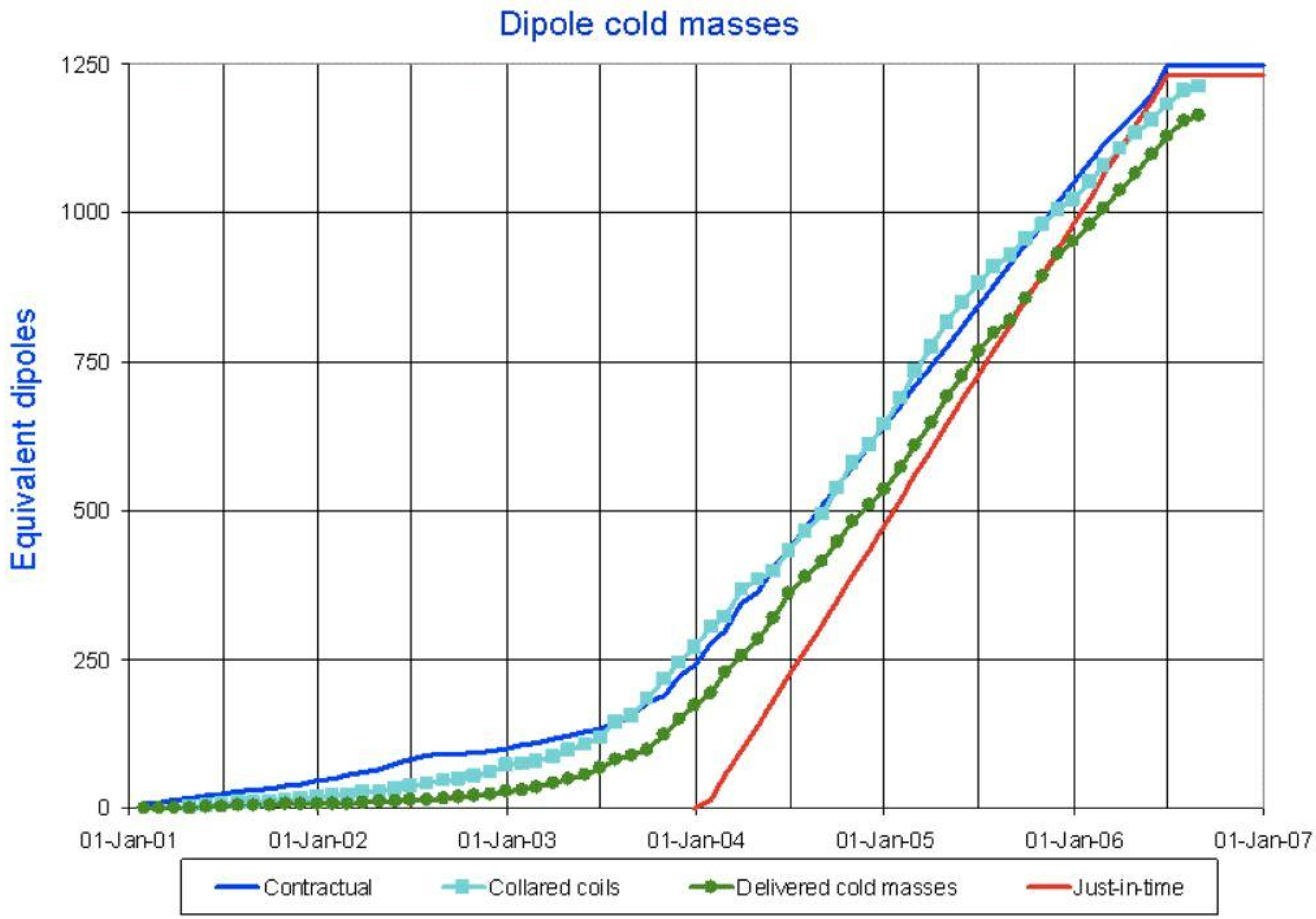
LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30 04 1999

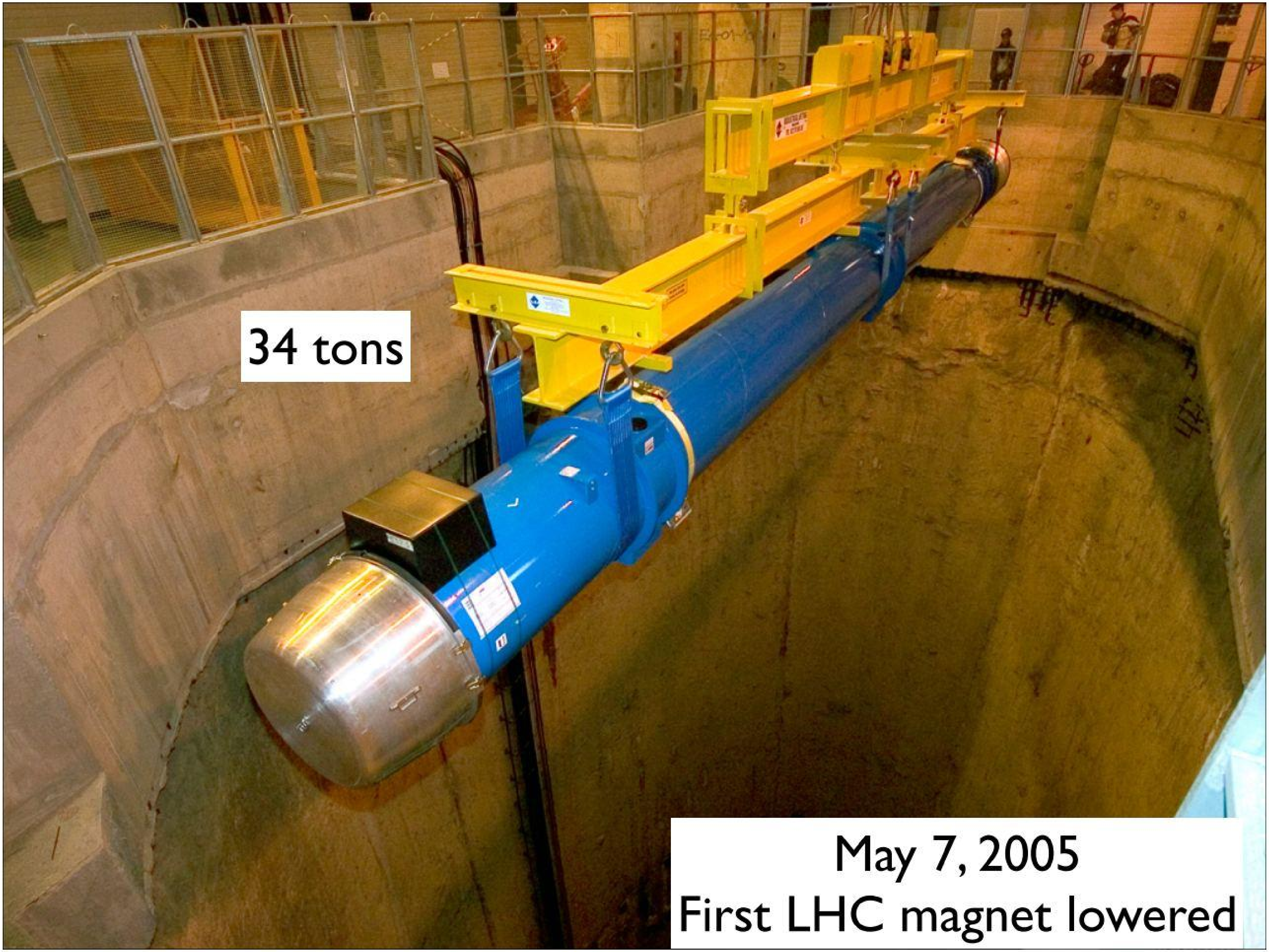


LHC Progress Dashboard

Accelerator Technology Department



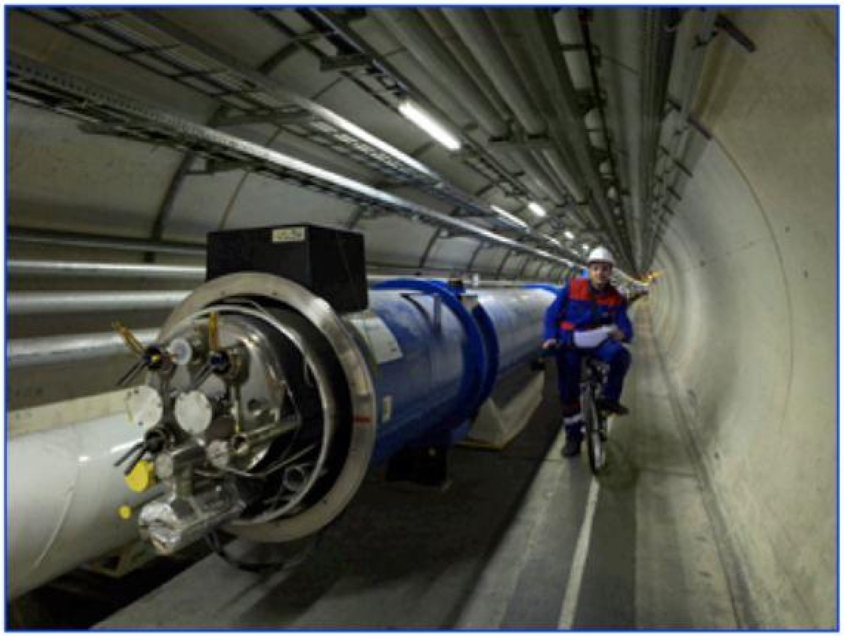
Magnet robot


34 tons
May 7, 2005
First LHC magnet lowered

July 12, 2006

The dipoles reach the half-way mark

With the positioning of the 616th magnet, installation of the LHC dipoles has reached the half-way mark.



Only half the dipoles remain to be installed! The 616th dipole out of a total of 1232 was installed at 3 a.m on Wednesday 12 July. Night and day, the tunnel is the setting for a never-ending series of carefully choreographed installation operations. At a rate of around twenty per week, there has been a steady underground flow of dipole magnets, each measuring 15 metres in length and weighing 34 tonnes. 'In order to recover the accumulated delays, installation is proceeding three times faster than planned', confides Claude Hauviller, who is supervising LHC installation. Four dipoles can be

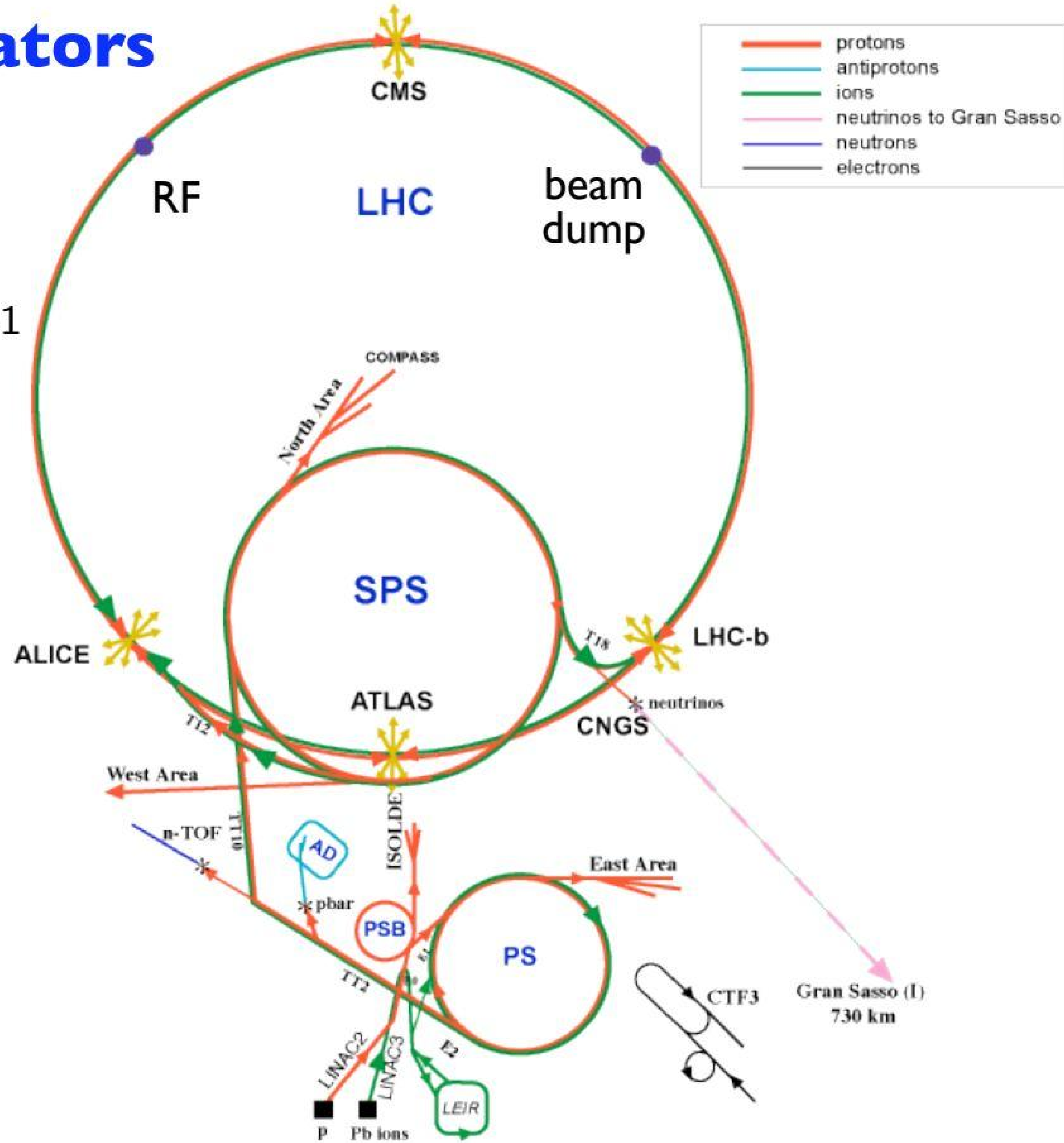

Superconducting RF

CERN Accelerators

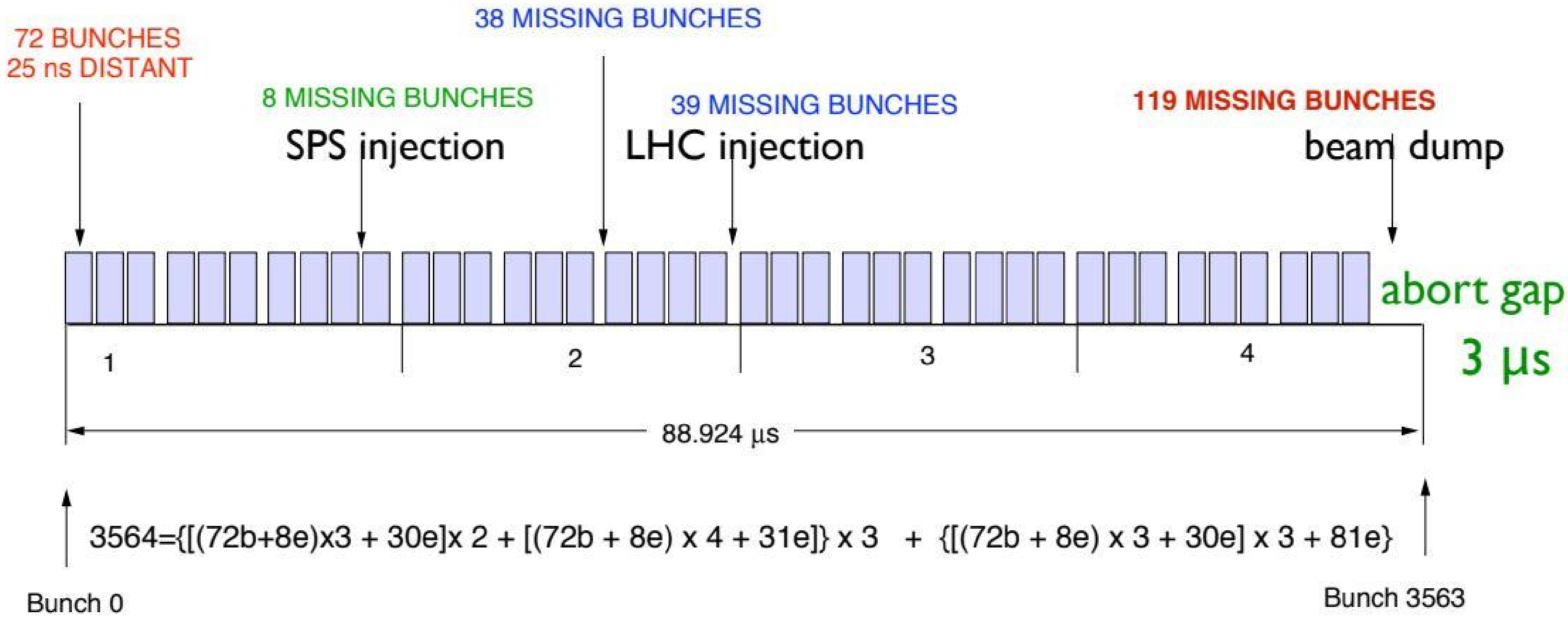
pp collisions:

$\sqrt{s} = 14$ TeV

$L = 10^{34}$ cm^{-2} s^{-1}



LHC Bunch Structure



Harmonic 84 = PS orbit is divided into 84 time slices or "buckets"

PS SPS LHC

$$(84)(11)\left(\frac{27}{7}\right) = 3564$$ # of buckets in LHC

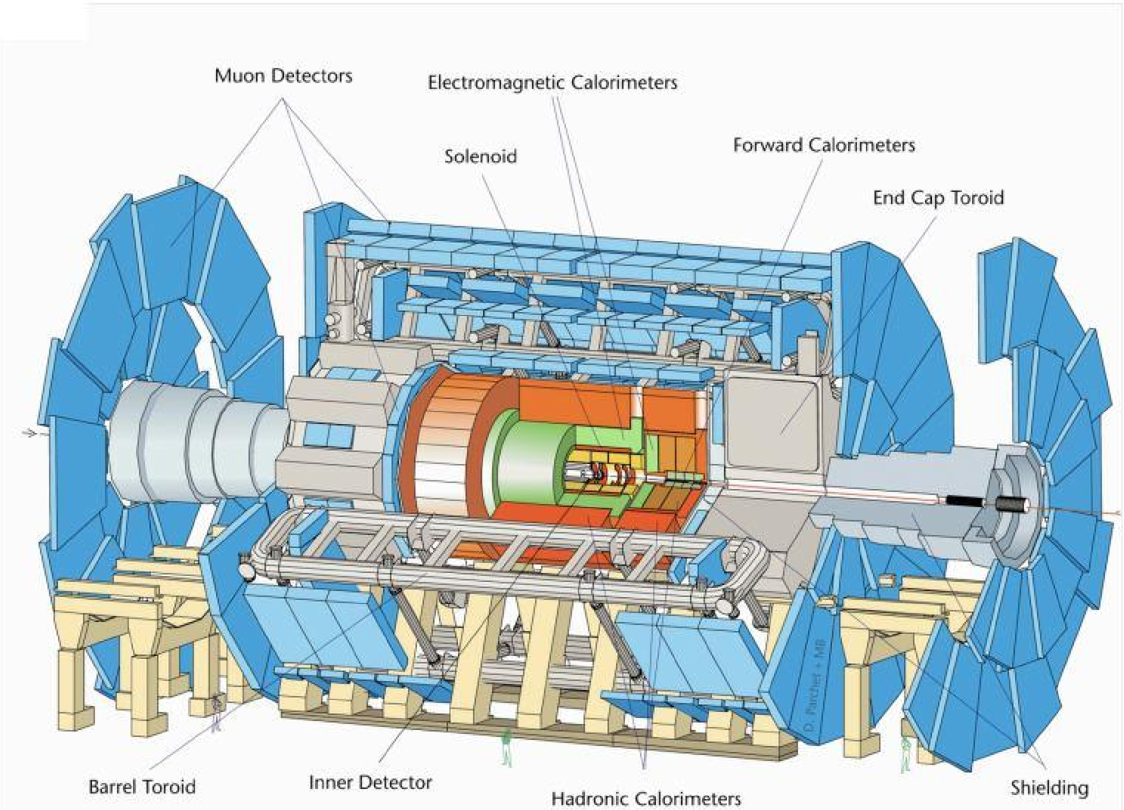
$$\frac{88924 \text{ ns}}{3564} = 24.95 \text{ ns}$$ bucket size in LHC

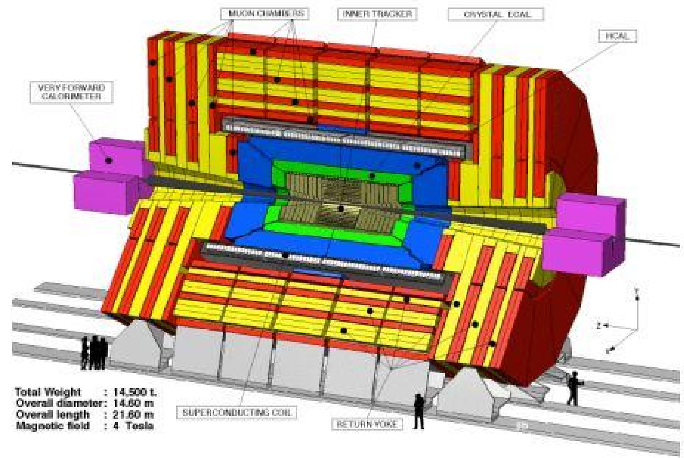
only 2808 buckets in known pattern have protons

40.079 MHz crossing frequency

Detectors: Overview

- muon detectors
- tracking in B field
- EM calorimetry
- hadron calorimetry



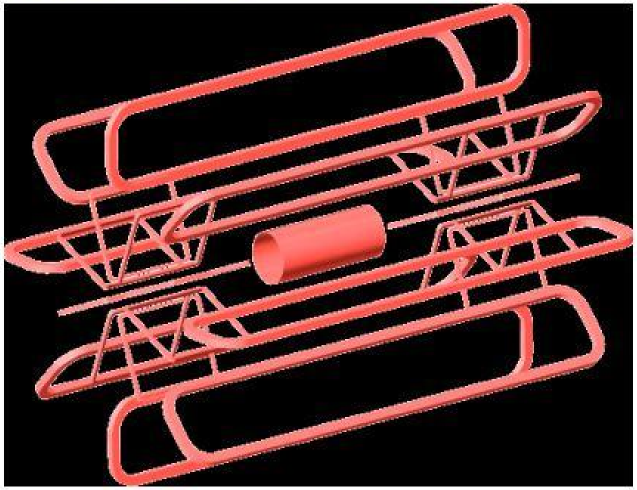


A Toroidal Large hadron collider AparatuS (ATLAS)
7 kTons 0.5 T toroid,
2 T solenoid, $(25\ \mathrm{m})^2 \times 46$ m
magnet=40% of $$,
good stand-alone muon res.

Compact Muon Solenoid (CMS) 14 kTons
4 T solenoid,
$(15\ \mathrm{m})^2 \times 22$ m
magnet=25% of $$,
high res.tracker & ECAL

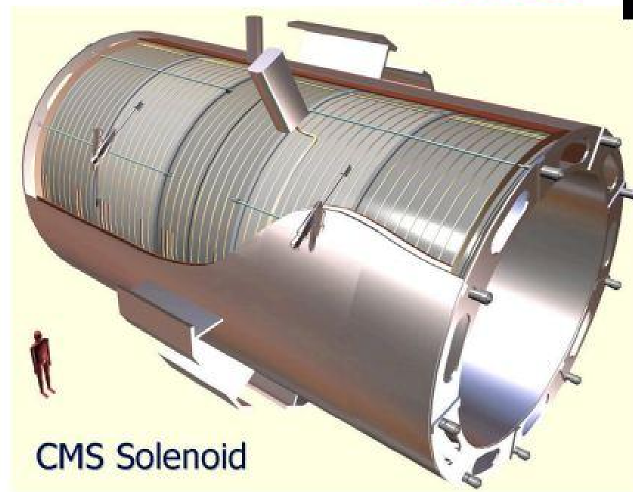
Magnet

ATLAS

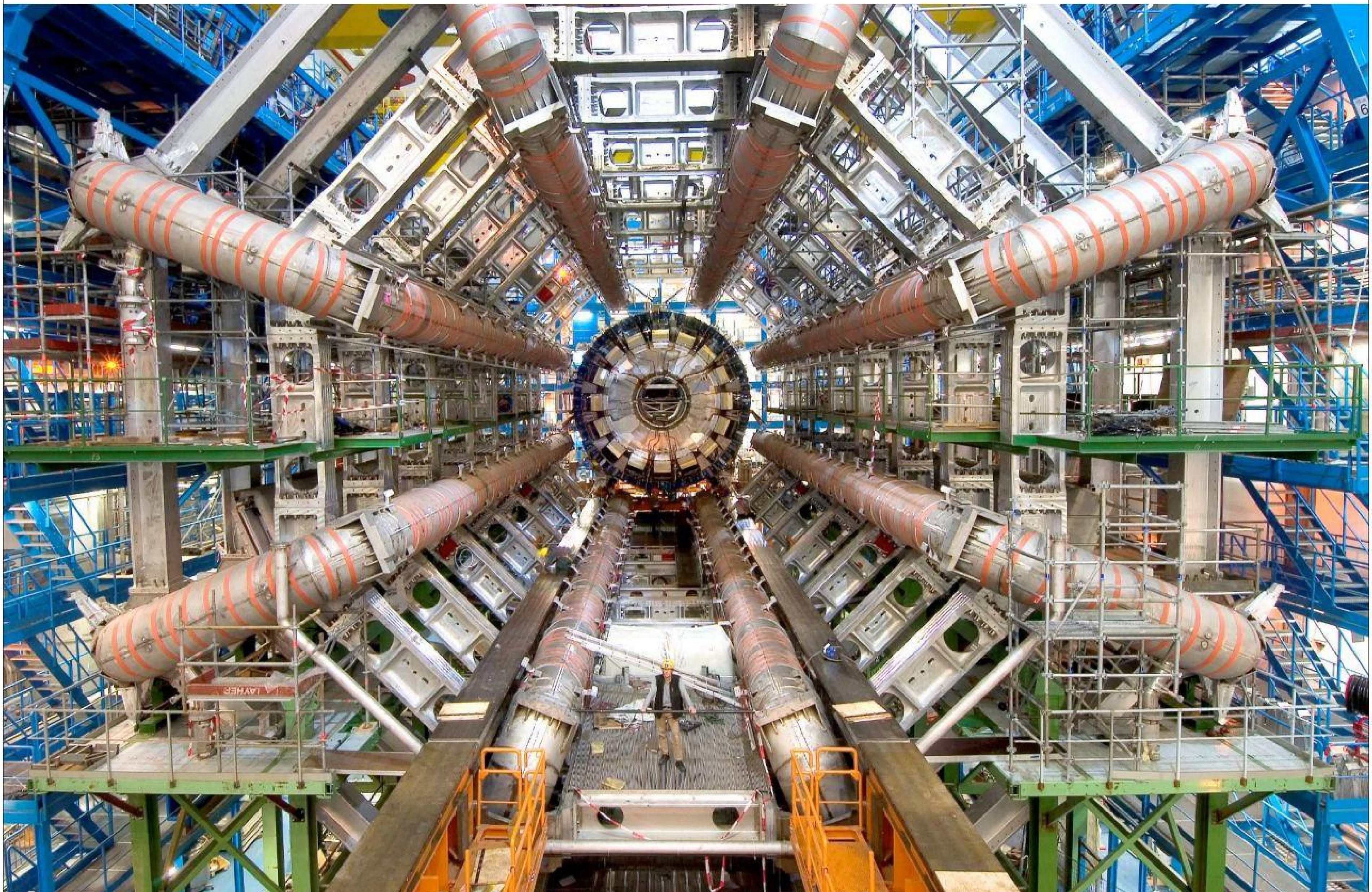


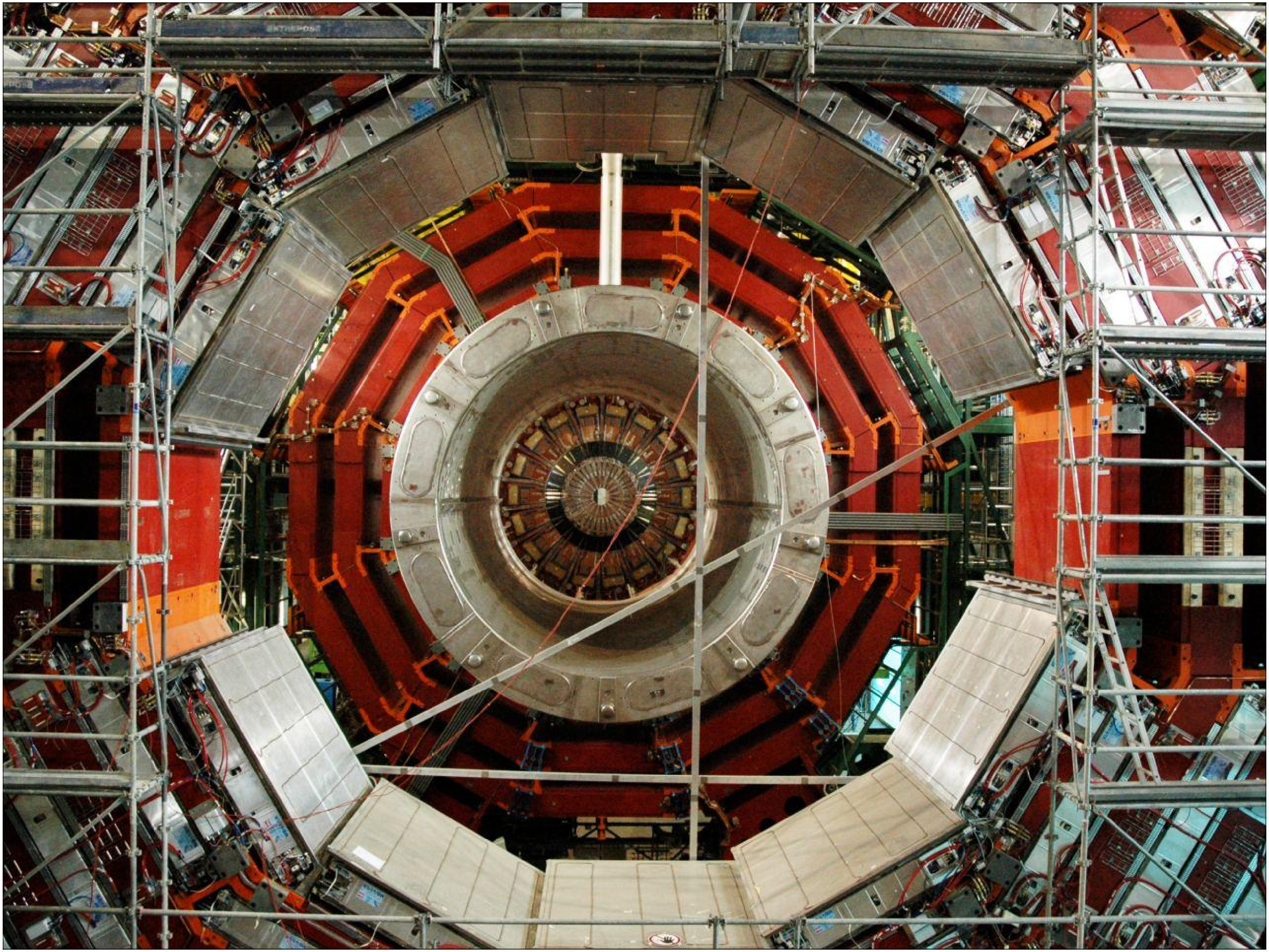
barrel toroids	length	25 m
	outer diameter	20.1 m
	peak field	4 T
	current	20.5 kA
endcap toroids	length	5 m
	outer diameter	10.7 m
	peak field	4 T
	current	20.5 kA
solenoid	length	5.3 m
	radius	1.2 m
	field	2 T
	current	7.6 kA
	stored energy (total)	1.6 GJ
	superconductor length	78 km

CMS

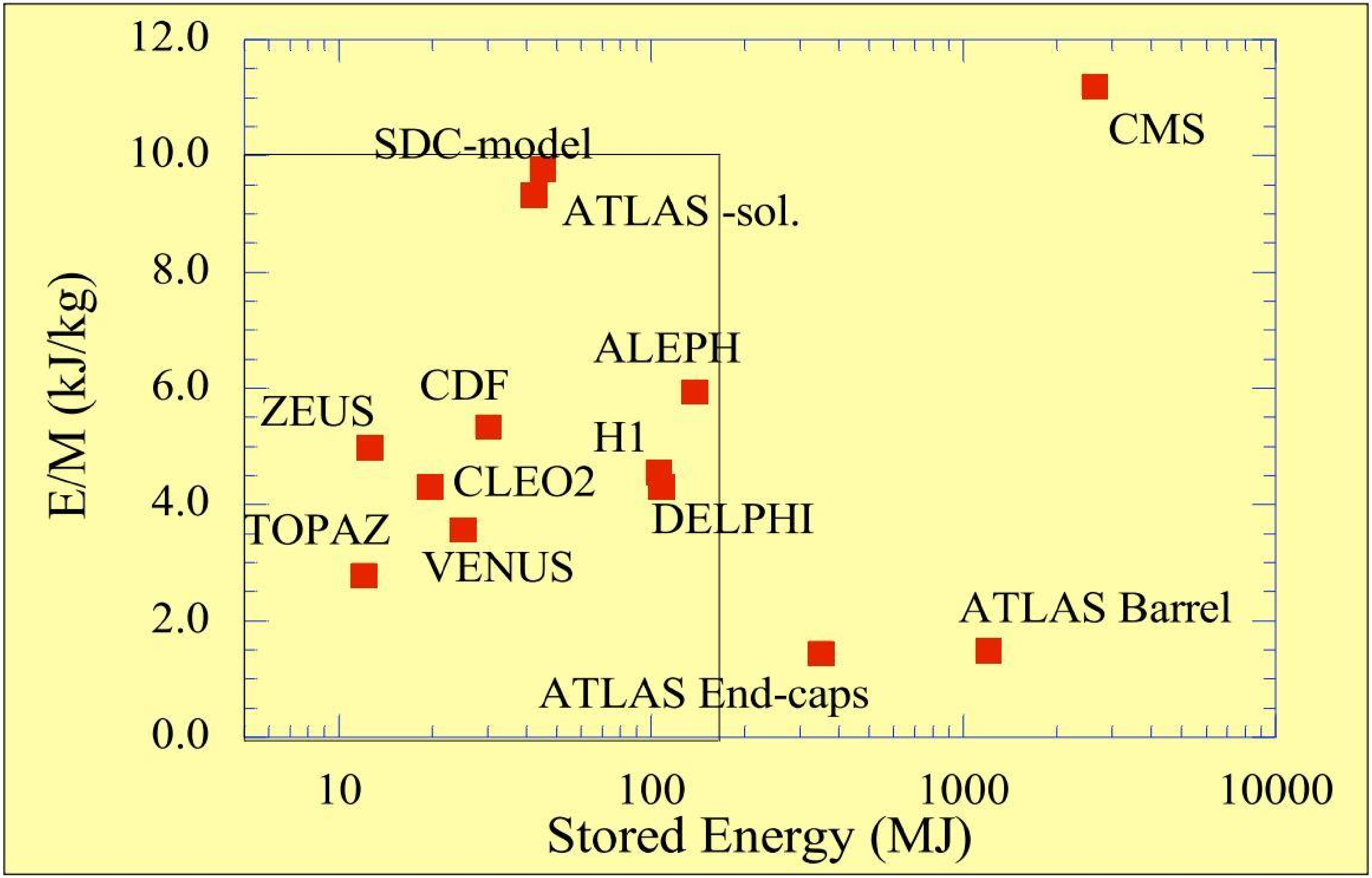


length	13 m
diameter	5.9 m
coil turns (4 layers)	2112
superconductor length	43 km
current	20 kA
field	4 T
length	13 m
inductance	12.6 H
stored energy	2.5 GJ

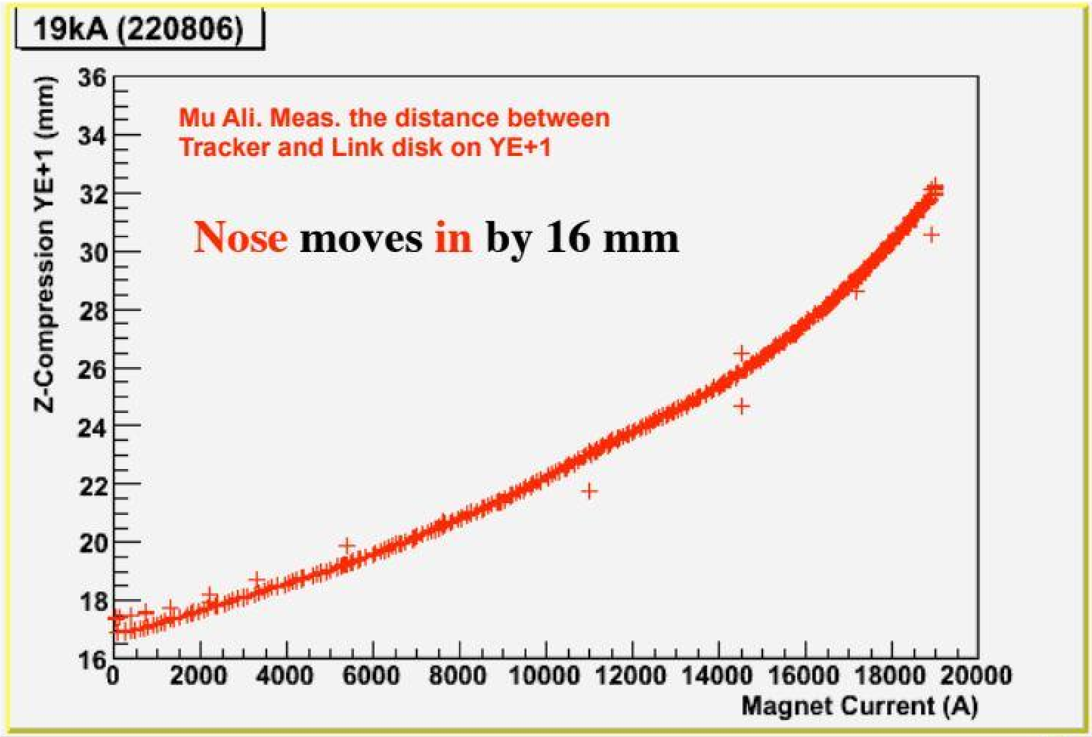


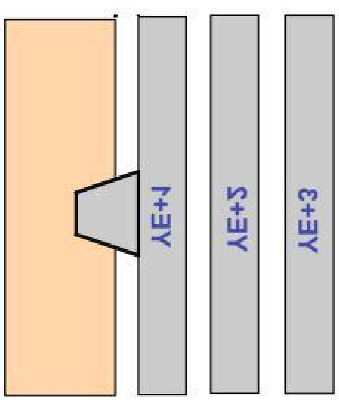


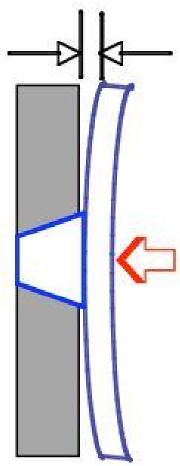
Specific Energy (kJ/kg of cold mass)



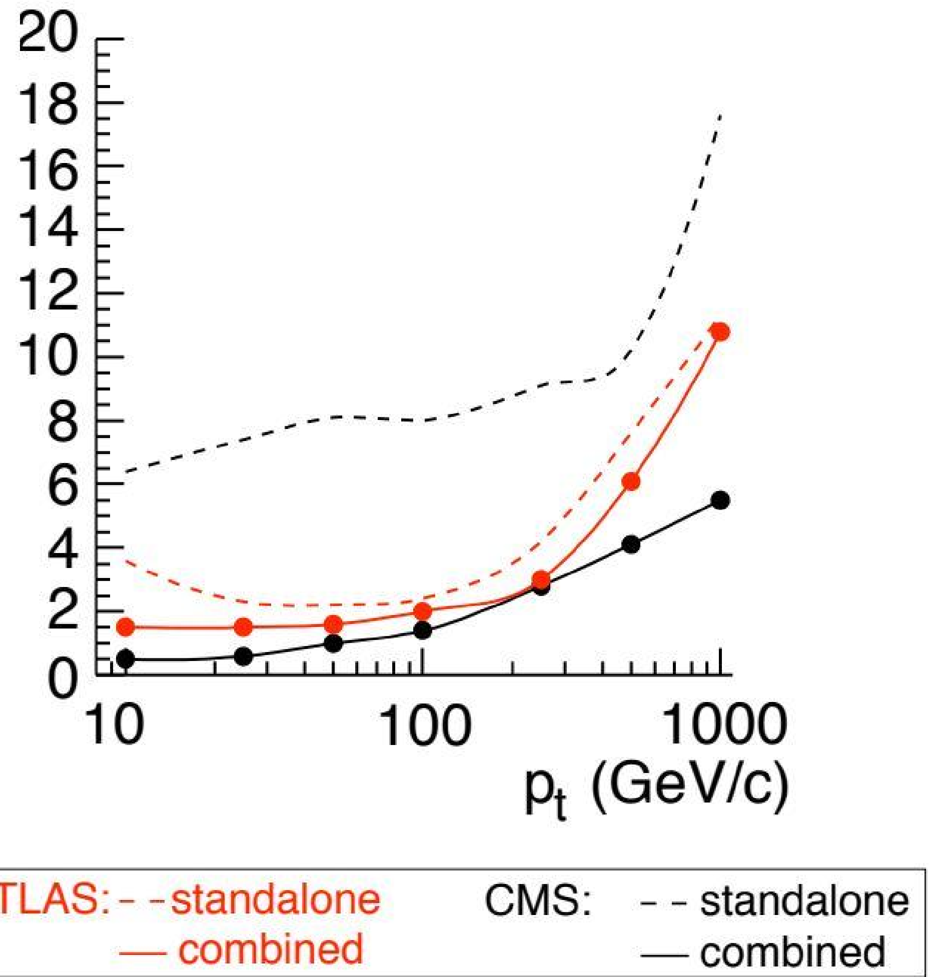
Dishing of YE-1





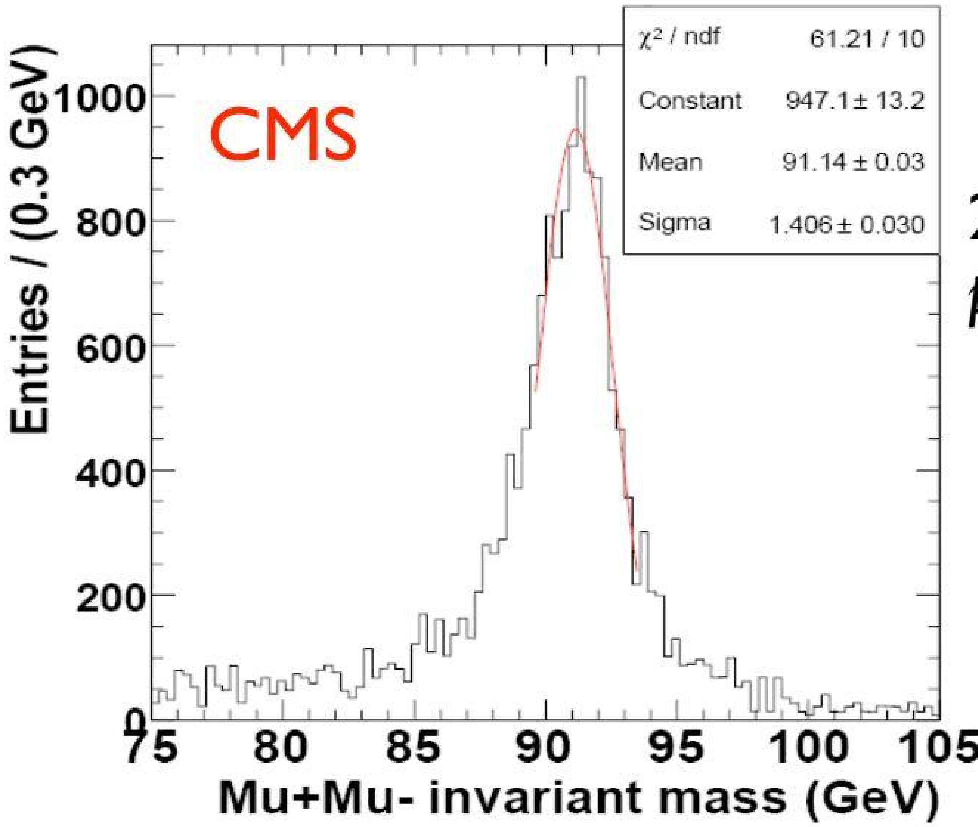


Muon Resolution



IL BUONO The Z^0 boson, continued

calibration, alignment, building blocks



2 isolated muons, p_T > 20 and 10 GeV

a few hours data at design lum.

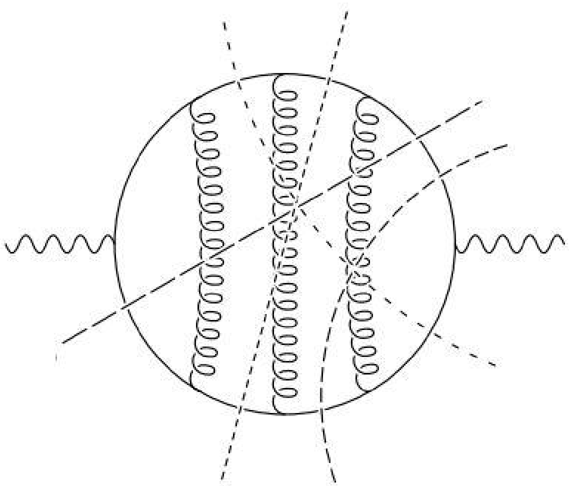
IL CATTIVO

QCD

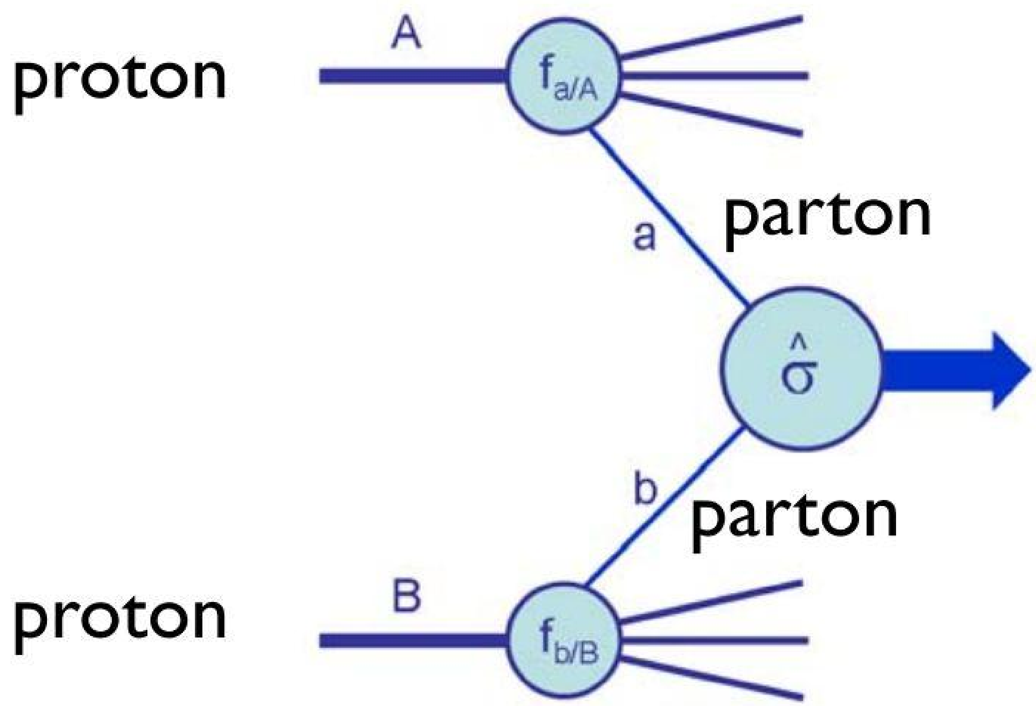
Quantum Chromodynamics

"I thought three was the perfect number."

Angel-Eyes



Generic LHC Collision

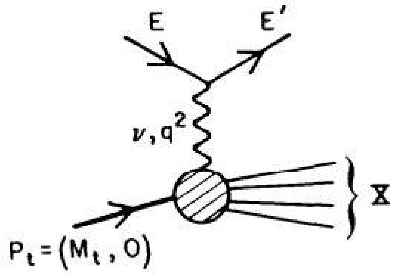


knowledge of the proton structure comes from decades of experimental work...

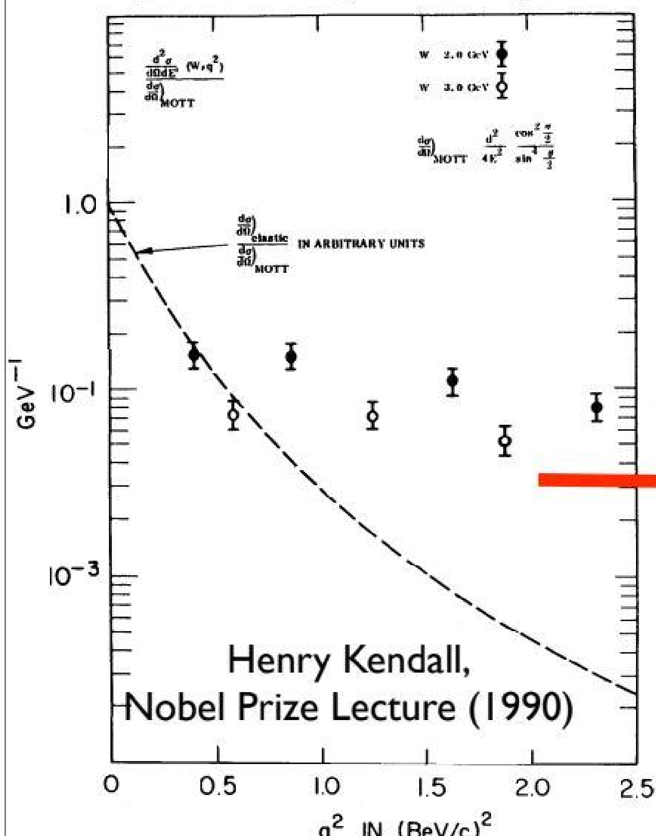
Stanford Linear Accelerator Center: End Station A

e+p → e+X

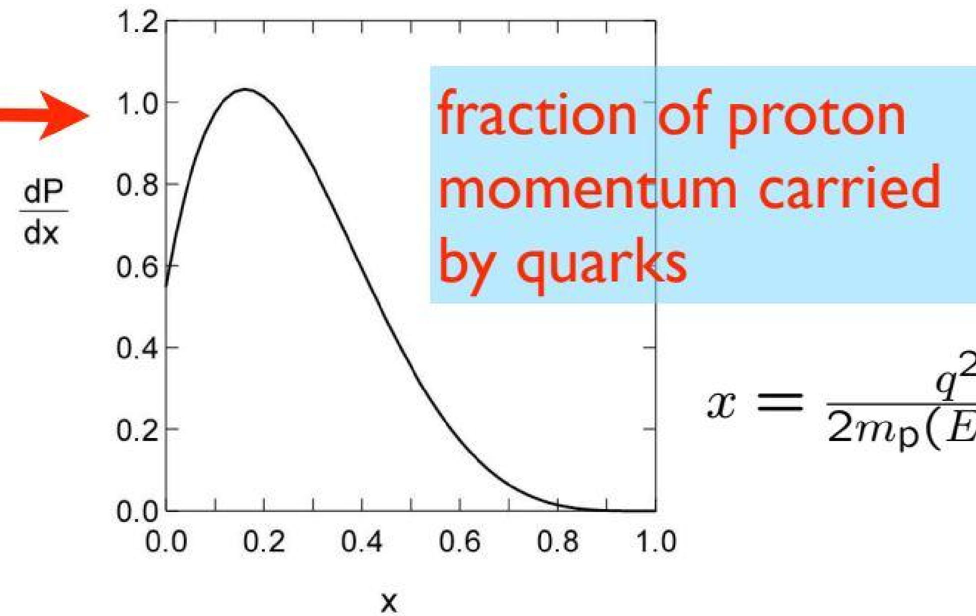
First evidence
for scaling (1968)



$$q^2 = 2EE'(1-\cos\theta)$$



These results were inconsistent with the current expectations of most physicists at the time.

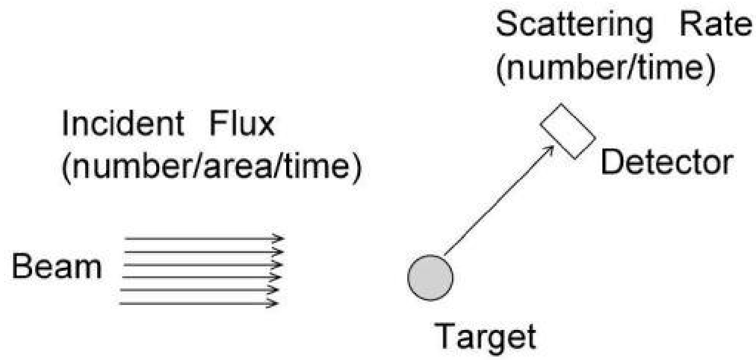


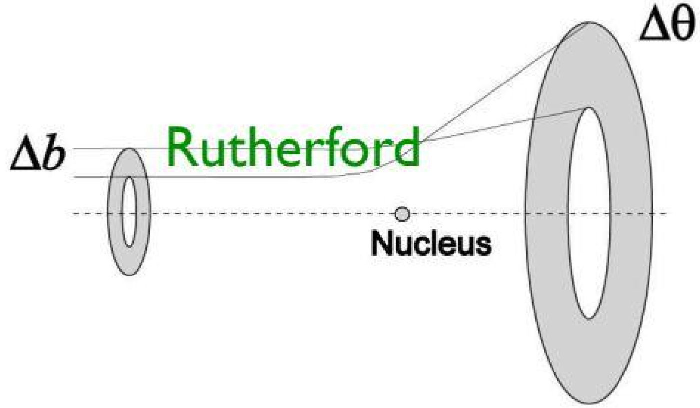
$$x = \frac{q^2}{2m_{\rm p}(E-E')}$$

Cross Section

$$\sigma = \frac{\text{transition rate}}{\text{incident flux}}$$

effective area of the target





often measured as differential, e.g. $d\sigma/d\theta$

unit: barn $\quad 1\ \text{b} = 10^{-28}\ \text{m}^2$

LHC Units

instantaneous pp design luminosity: $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$$1\ \mathrm{nb} = 10^{-33}\ \mathrm{cm}^{-2}$$

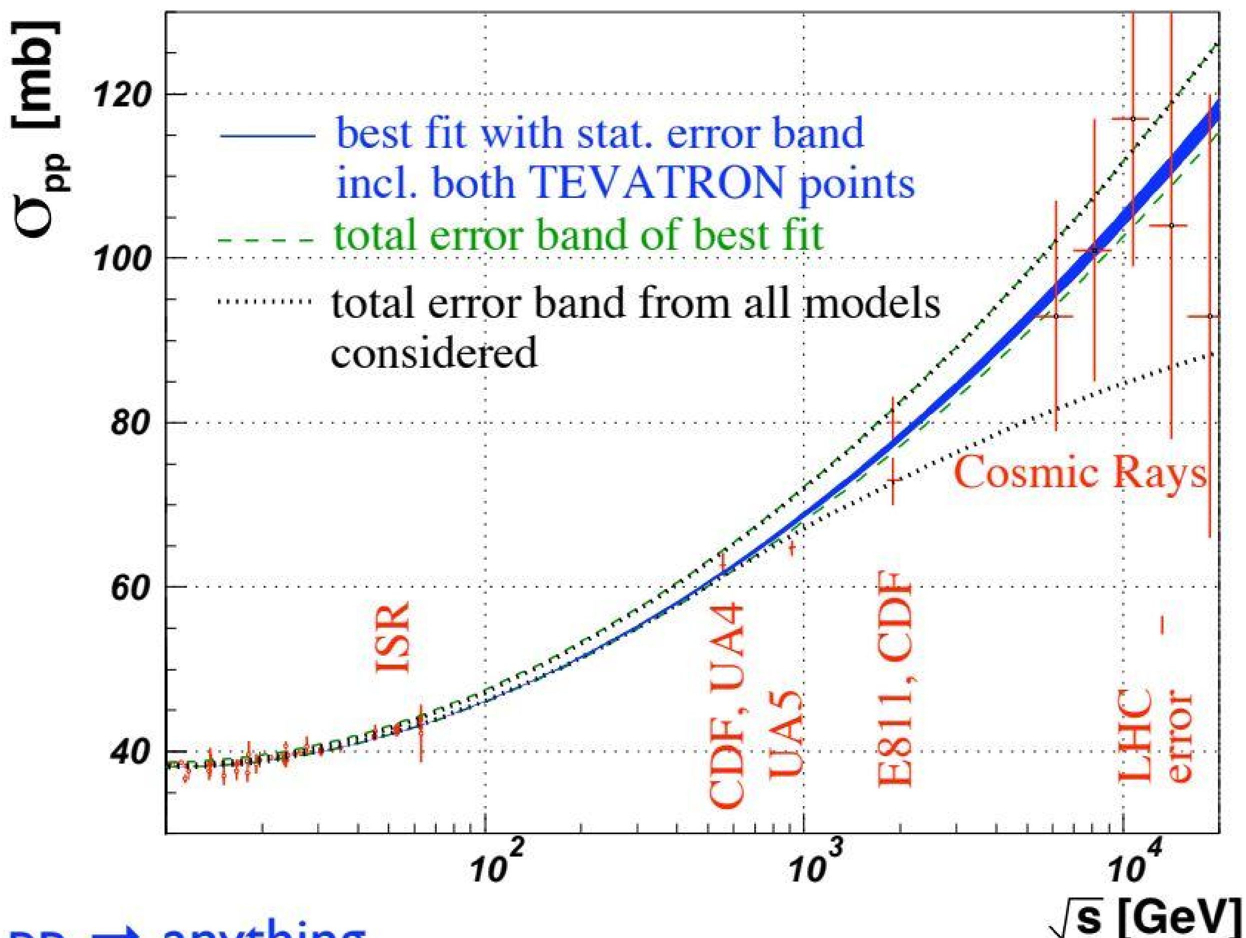
$$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} = 10\ \mathrm{nb}^{-1}\mathrm{s}^{-1}$$

A process with a cross section of 1 nb occurs 10 times per second.

pb → 1 per minute
fb → 1 per day

Predicting the total pp cross section at LHC

unit: barn $1\ \text{b} = 10^{-28}\ \text{m}^2$



100 mb

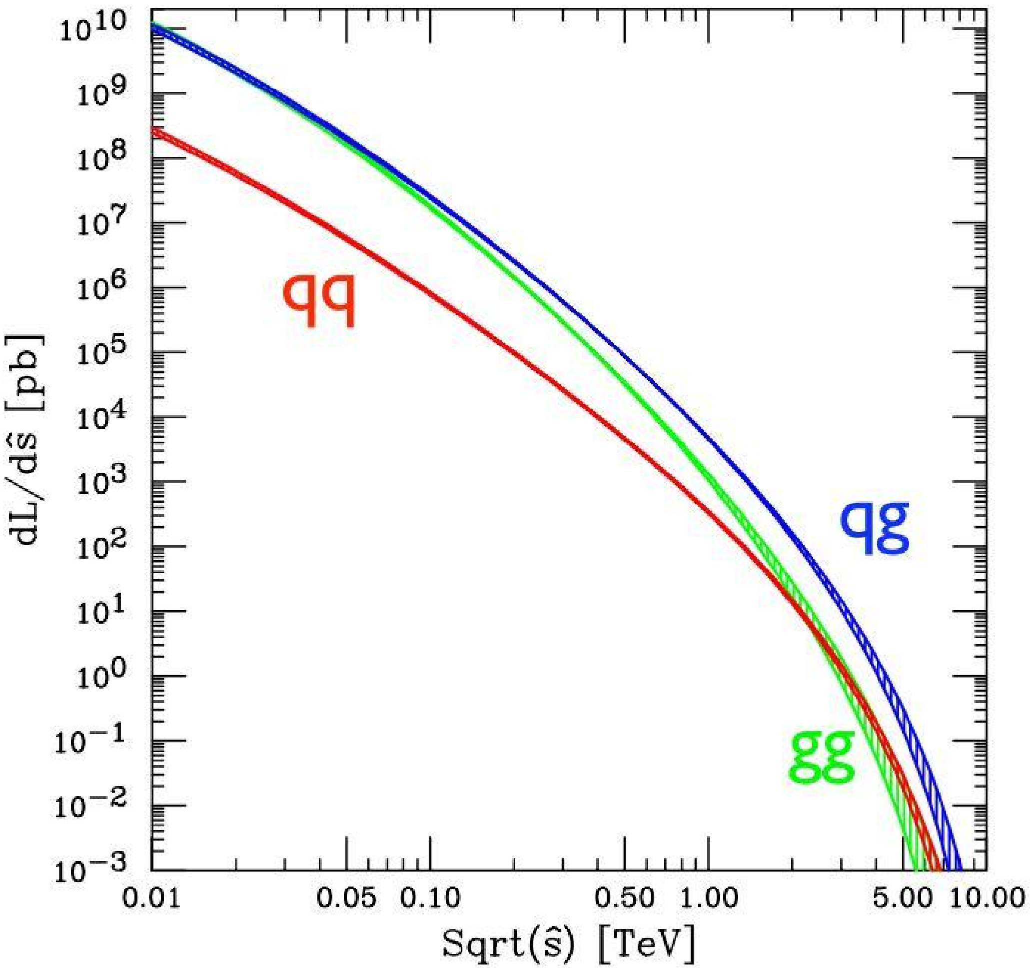
pp → anything
(by strong int.)

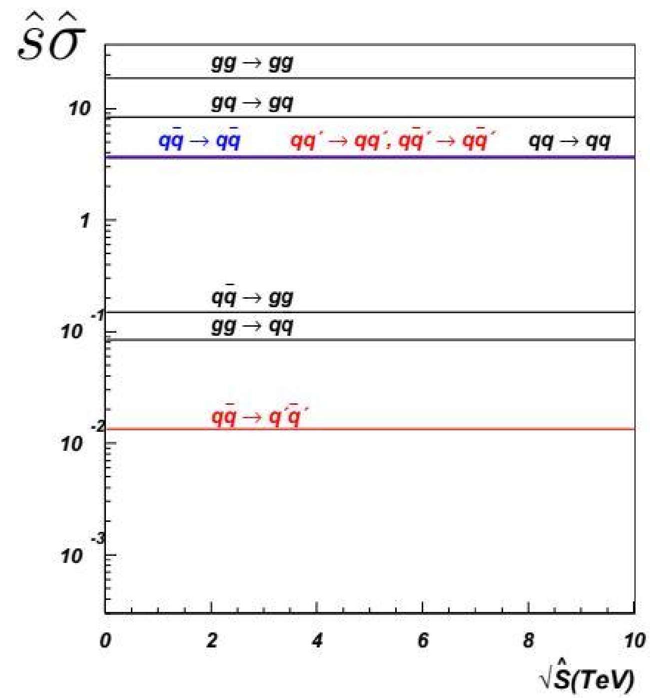
Rate = L σ = $(10\ \text{nb}^{-1}\text{s}^{-1})(10^8\ \text{nb}) = 10^9\ \text{s}^{-1}$

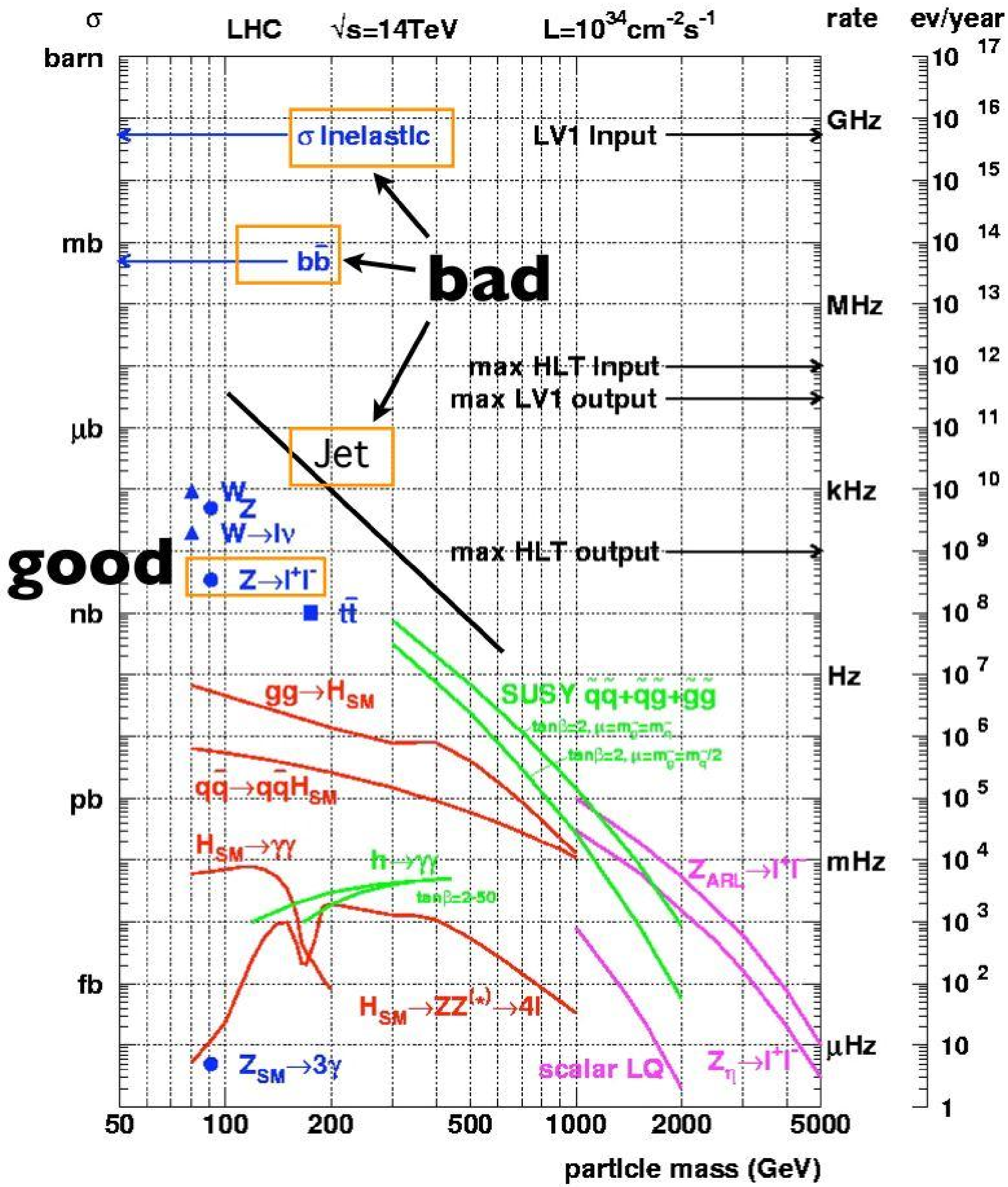
GHz

Differential Parton Luminosity

multiply by $\hat{s}\hat{\sigma}$ to estimate event cross section







Data Recording Rate

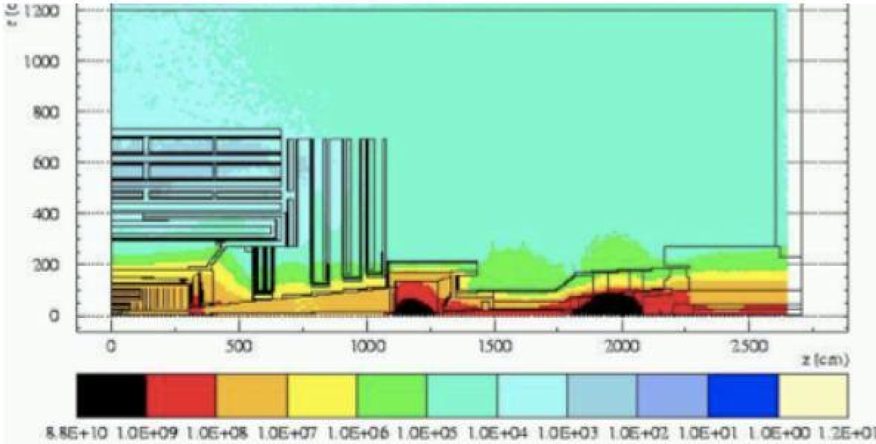
L1 hardware
leptons, jets, MET
→100 kHz

HLT software
→100-200 Hz

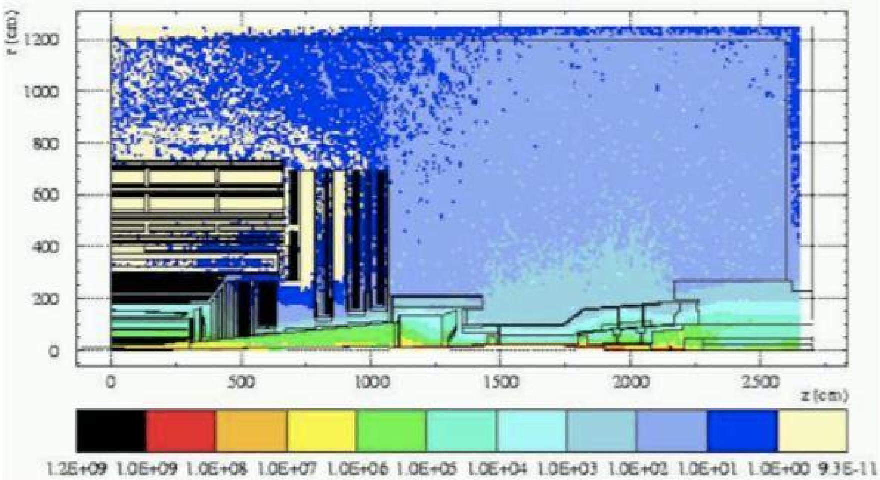
$(500\ s^{-1})(2\ \text{MByte}) =$ GByte/s

1 CD per second

10^{17} bits per year

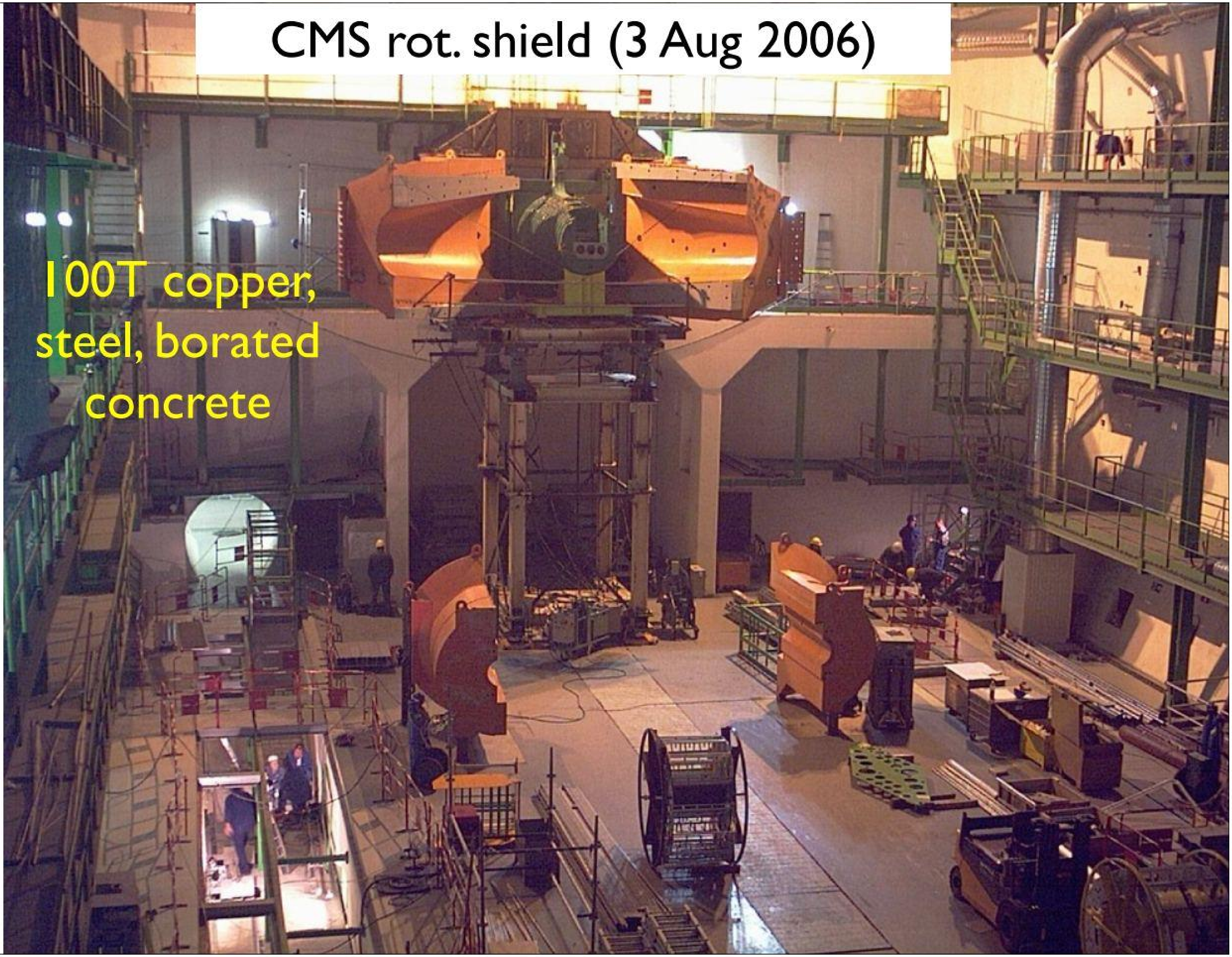


neutron flux

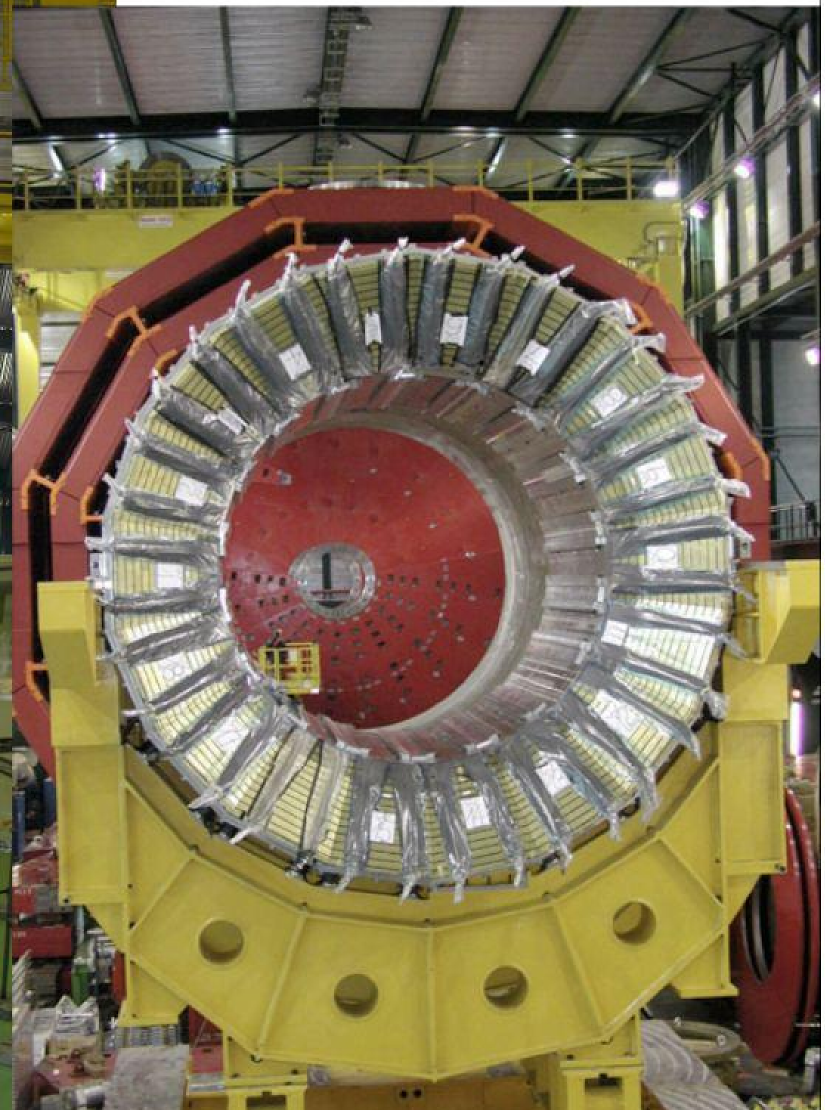


dose (Gy=J/kg absorbed)
2500 fb^{-1}

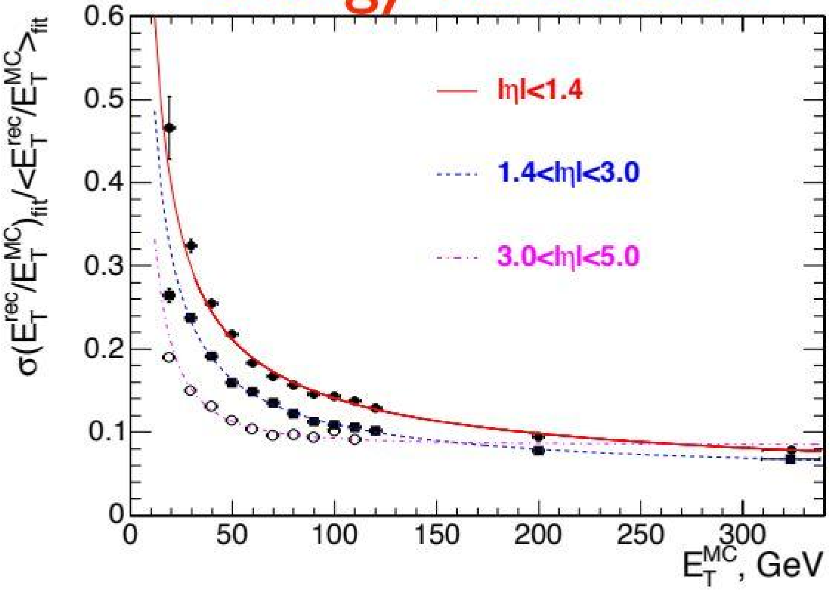
CMS rot. shield (3 Aug 2006)



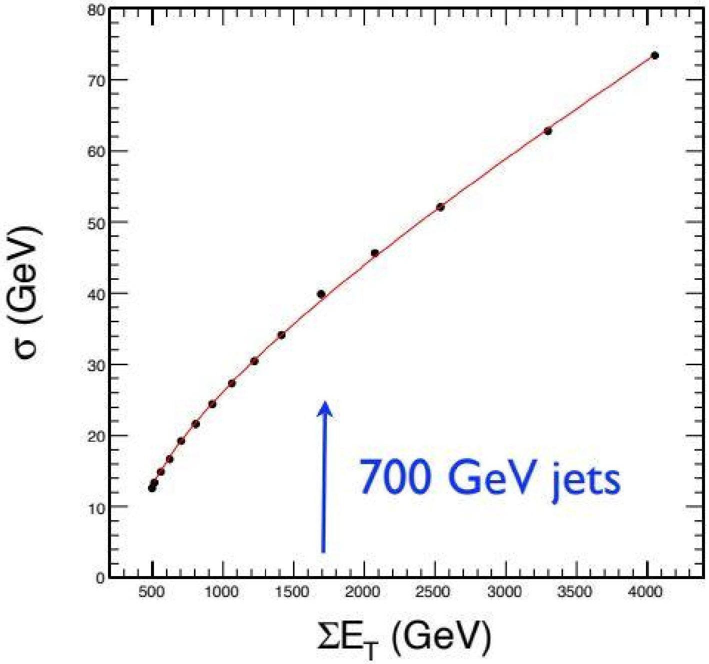
HCAL



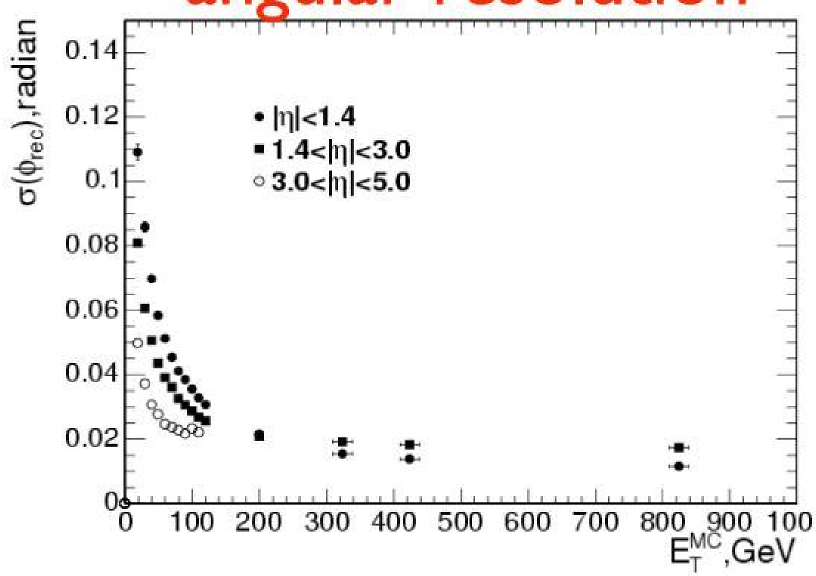
energy resolution



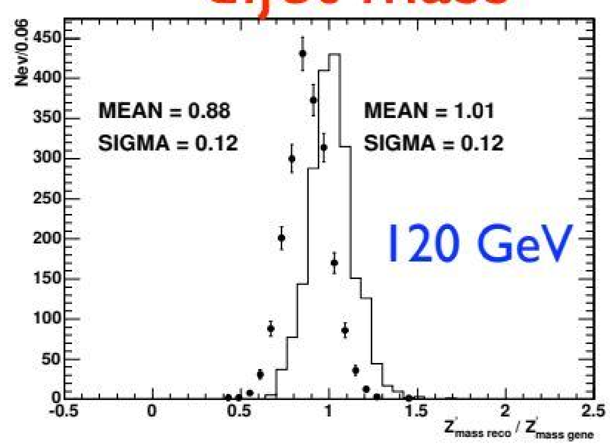
E_T^{miss} resolution



angular resolution



dijet mass

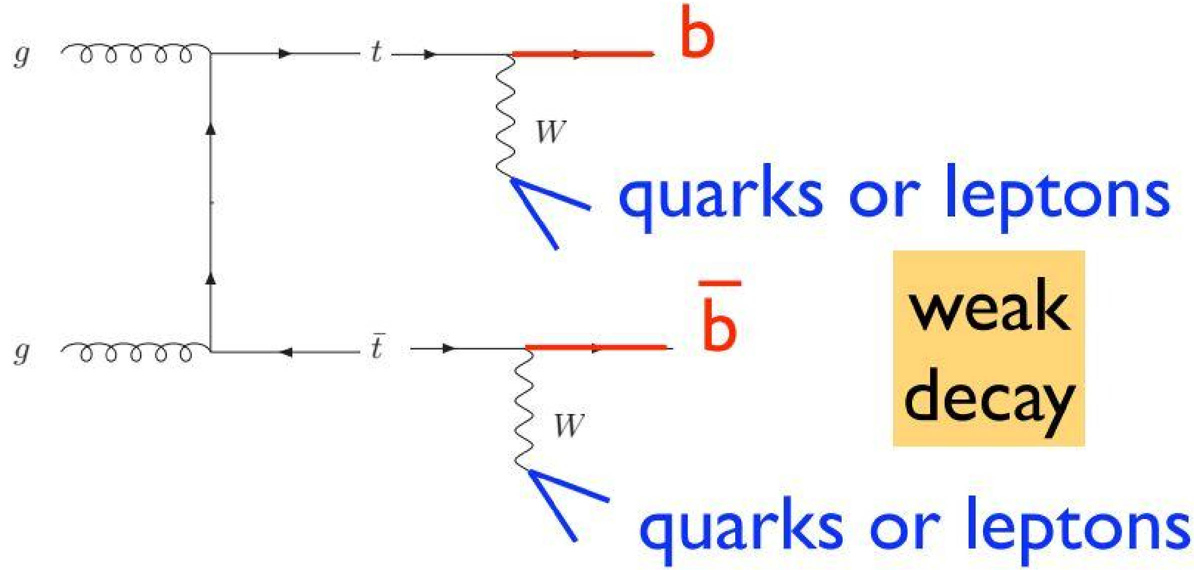


IL BRUTTO

The top quark

“One bastard goes in, another one comes out.”
Tuco

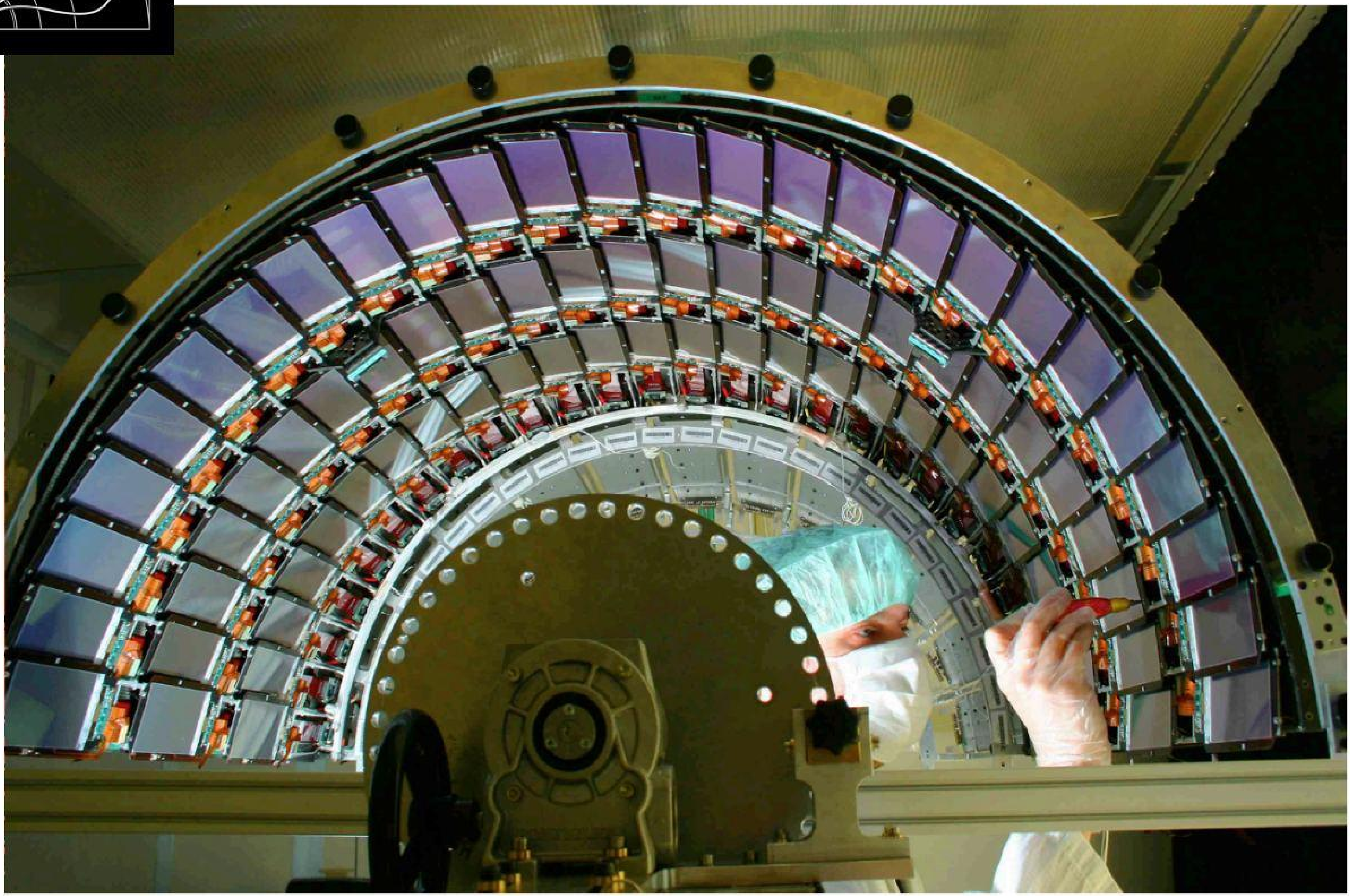
strong production



weak decay

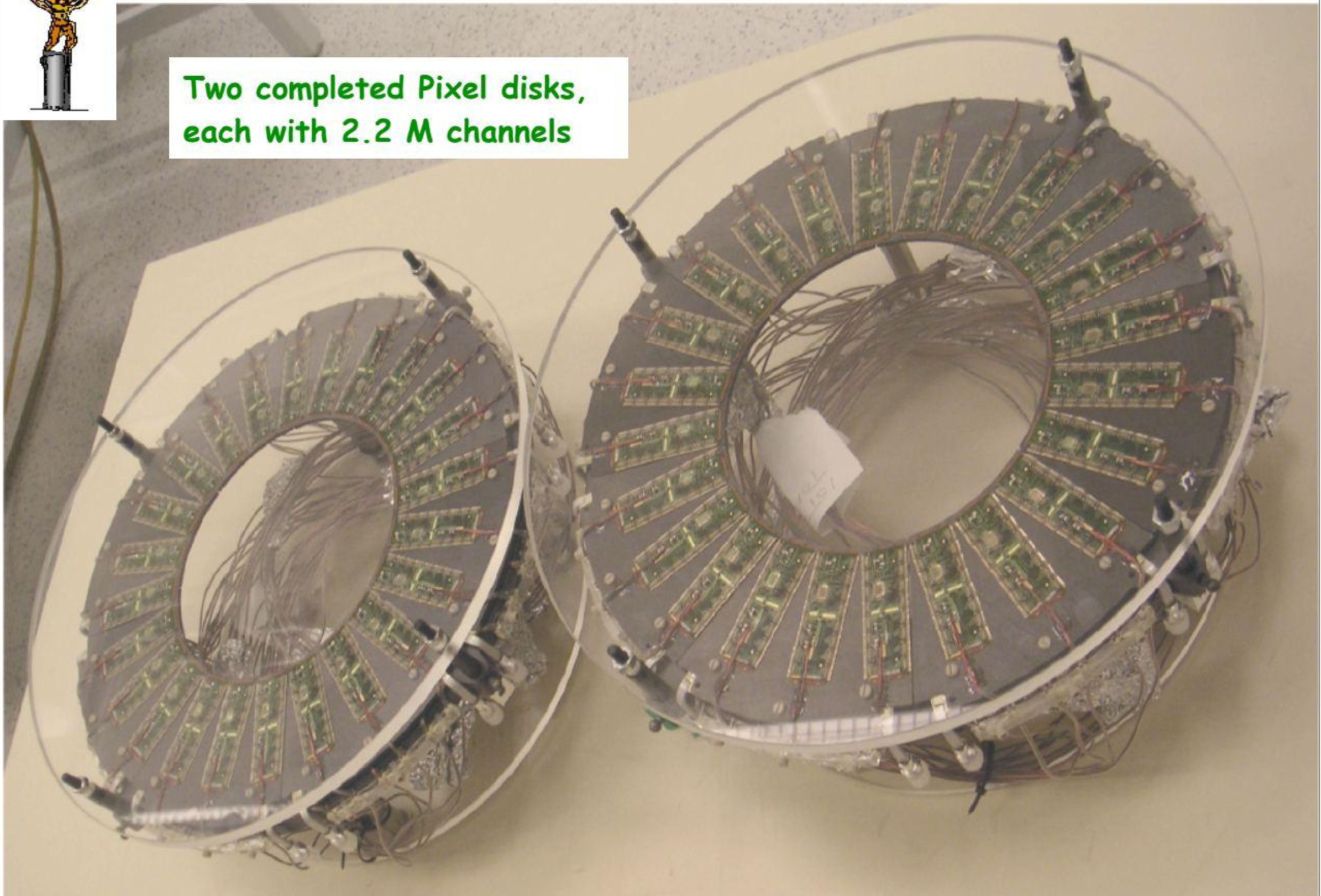
10 Hz of serious background!

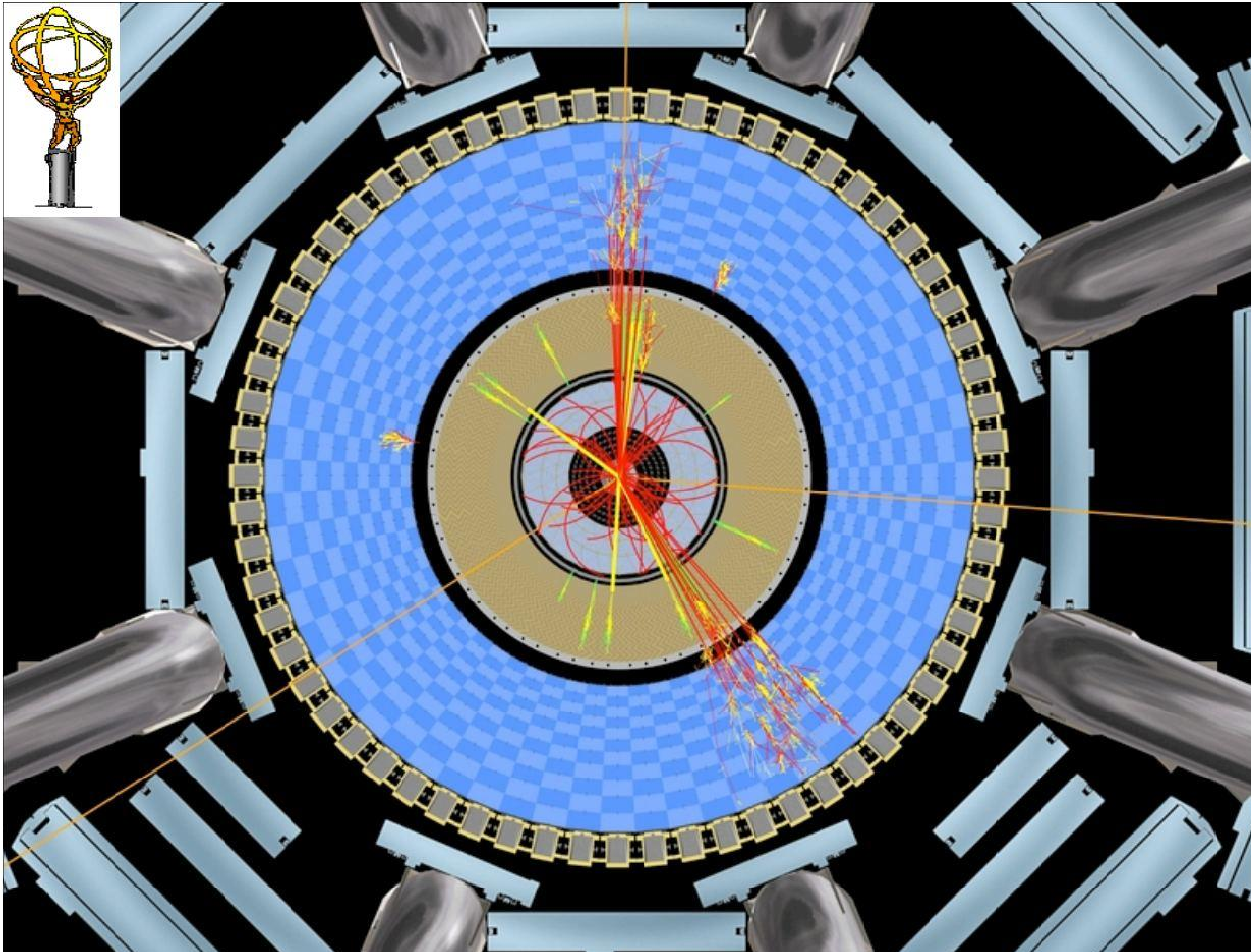
Silicon Tracker



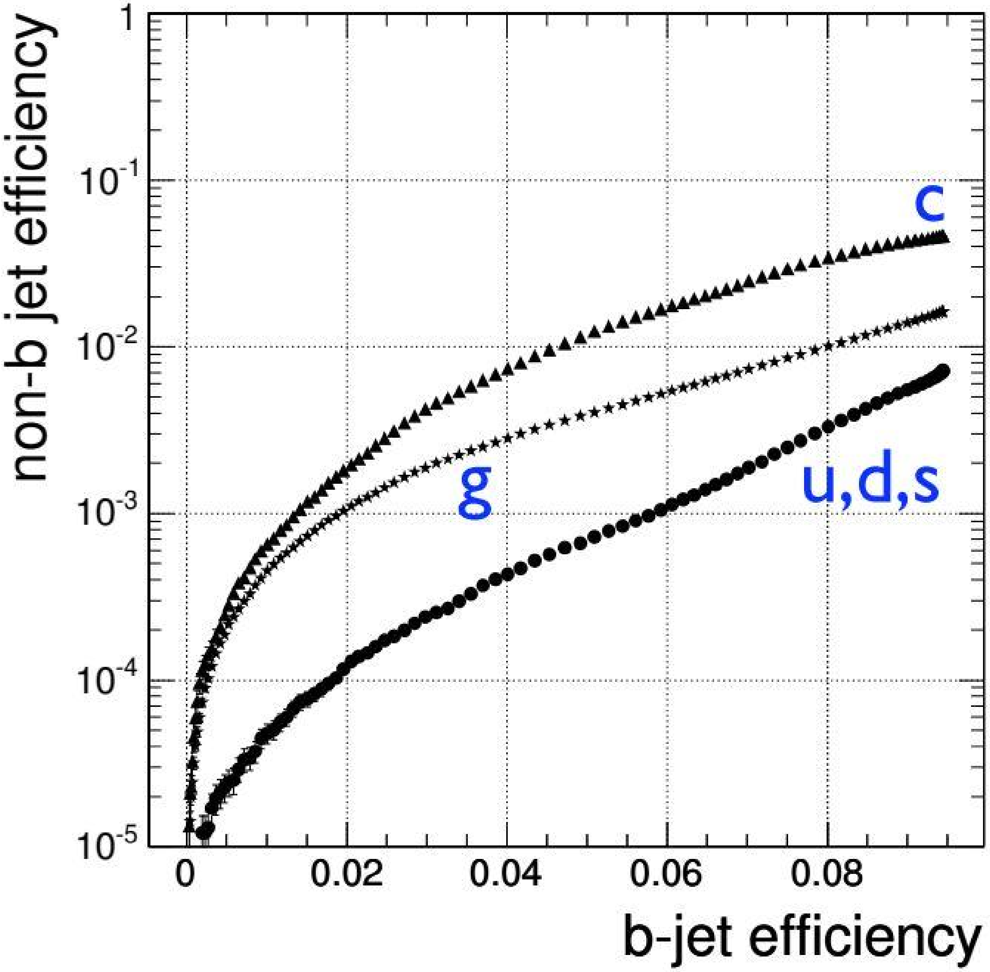
ATLAS Pixels

Two completed Pixel disks,
each with 2.2 M channels



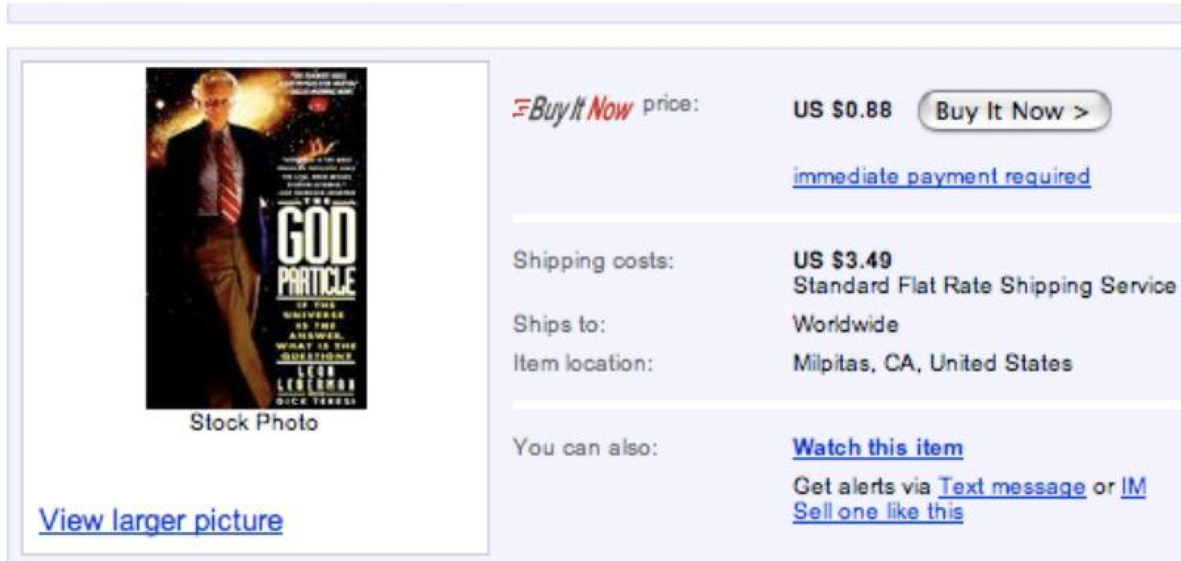


Tagging the b jets

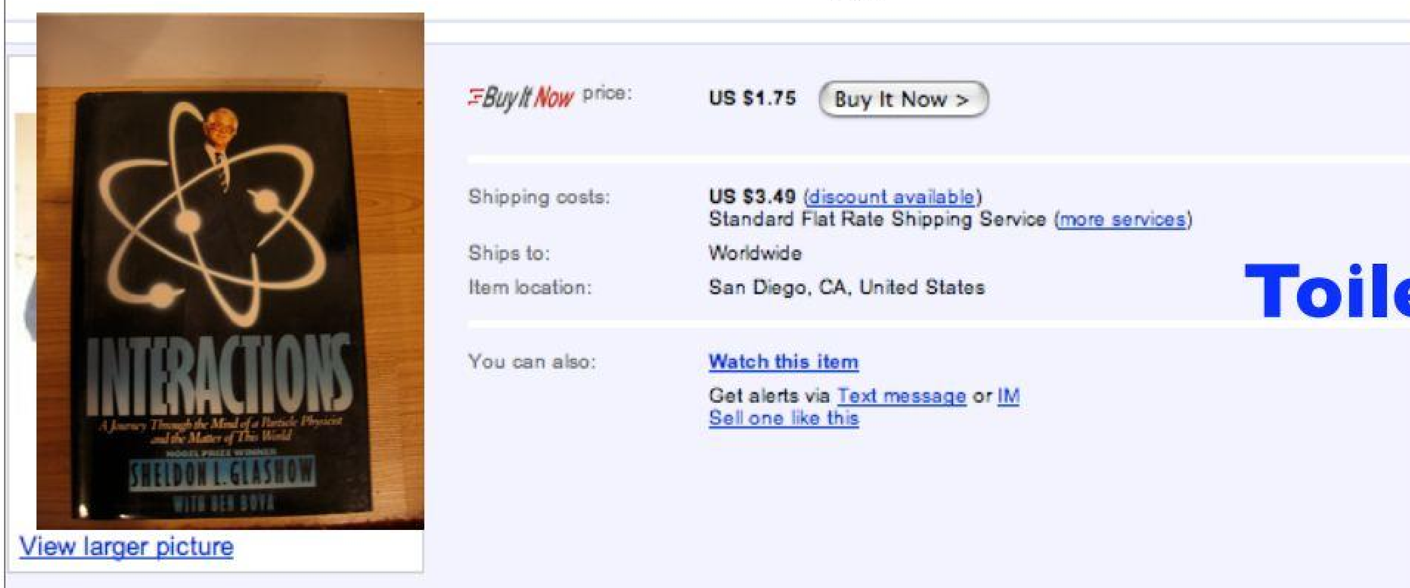


The Higgs Boson

God Particle



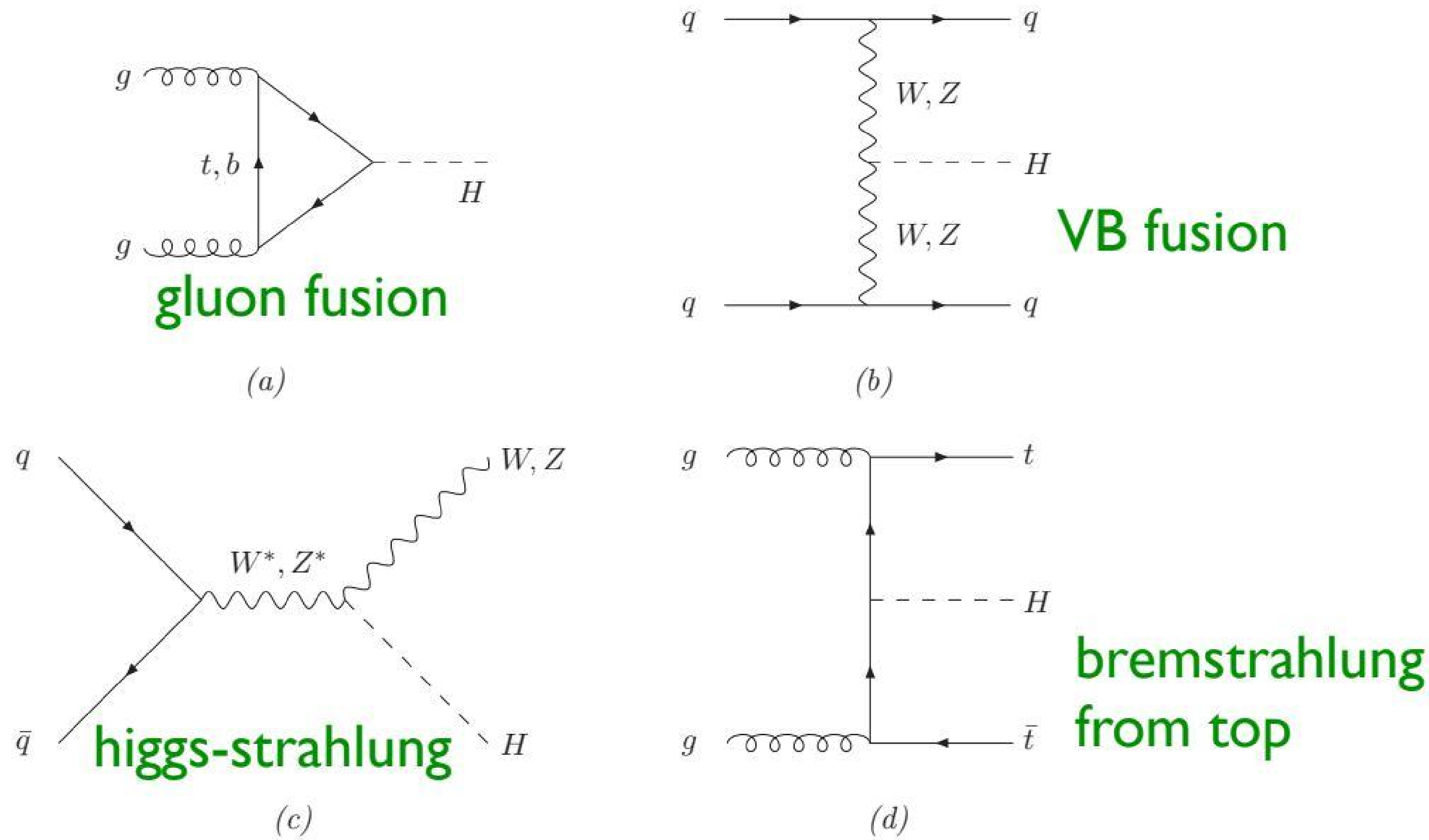
or



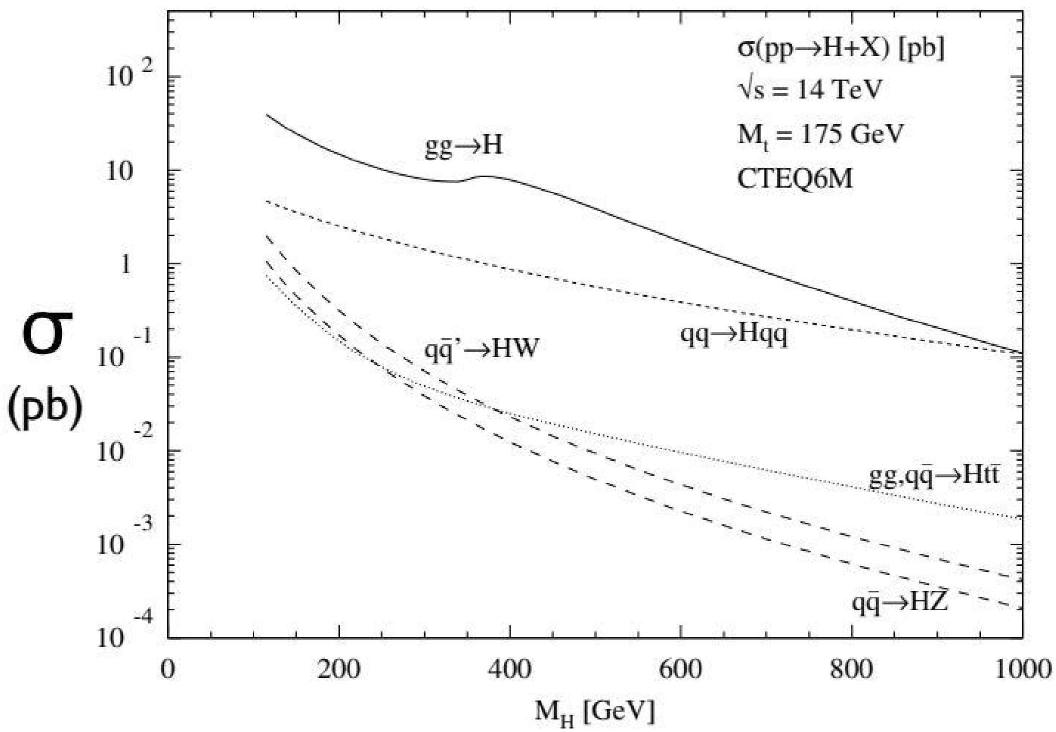
Toilet Bowl ?

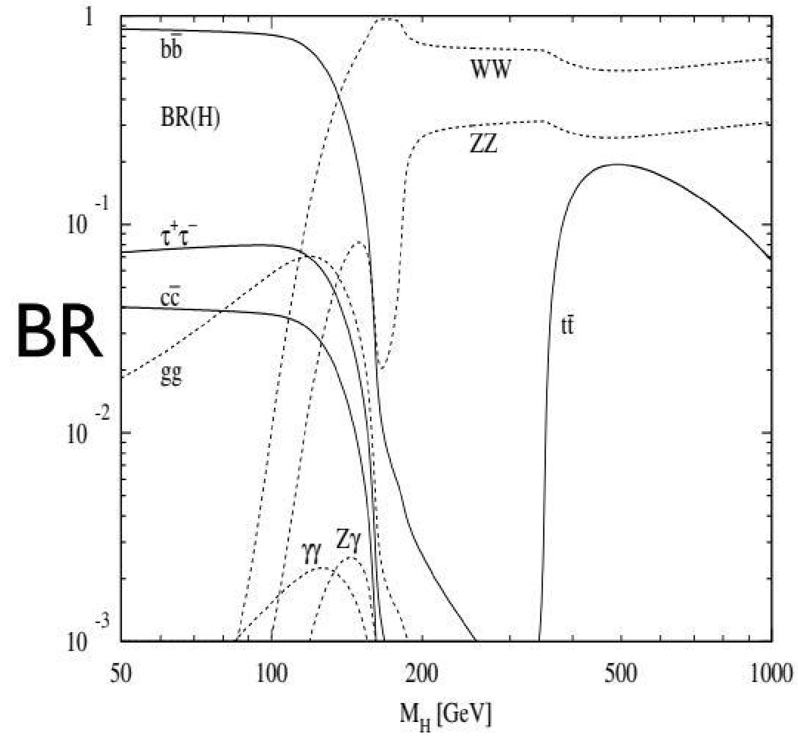
yes.

Standard Model Higgs Production



Higgs Cross section and Branching Ratio





uncertainties:
gg 10-20% (NNLO)
qqH 5% (NLO)
WH, ZH 5% (NNLO)
ttH 10-20% (NLO)

BR known to few % (NLO)

Event Selection: $H \rightarrow e^+e^-\mu^+\mu^-$

m_H = 140 GeV

	Signal	$t\bar{t}$	$Zb\bar{b}$	$ZZ^\star/\gamma^\star$
Production cross-section (NLO)	33.6×10^3	840×10^3	555×10^3	28.9×10^3
$\sigma\times$BR(4 lepton final state)	11.6	-	-	367.5
Pre-selection: $\sigma\times\text{BR}\times\epsilon$	3.29±0.04	743±2	390±1	37.0±0.4
Level-1 trigger	3.24±0.04	707±2	360±1	36.3±0.4
High Level trigger	2.91±0.03	282±1	237±1	32.5±0.4
$e^+e^-\mu^+\mu^-$ reconstructed	2.23±0.03	130±1	141±1	24.1±0.3
Vertex and impact parameter cuts	2.01±0.03	18.9±0.3	18.4±0.2	21.5±0.3
Isolation cuts	1.83±0.03	1.34±0.07	5.8±0.1	20.0±0.3
Lepton p_T cuts	1.61±0.03	0.40±0.04	0.56±0.03	17.6±0.3
Z mass window cuts	1.35±0.02	0.20±0.03	0.23±0.02	13.8±0.3
Higgs mass window cuts	1.17±0.02	0.02±0.01	0.025±0.007	0.15±0.03
Expected events for $\int\mathcal{L} = 10\ \text{fb}^{-1}$	11.7±0.2	0.2±0.1	0.25±0.07	1.5±0.3

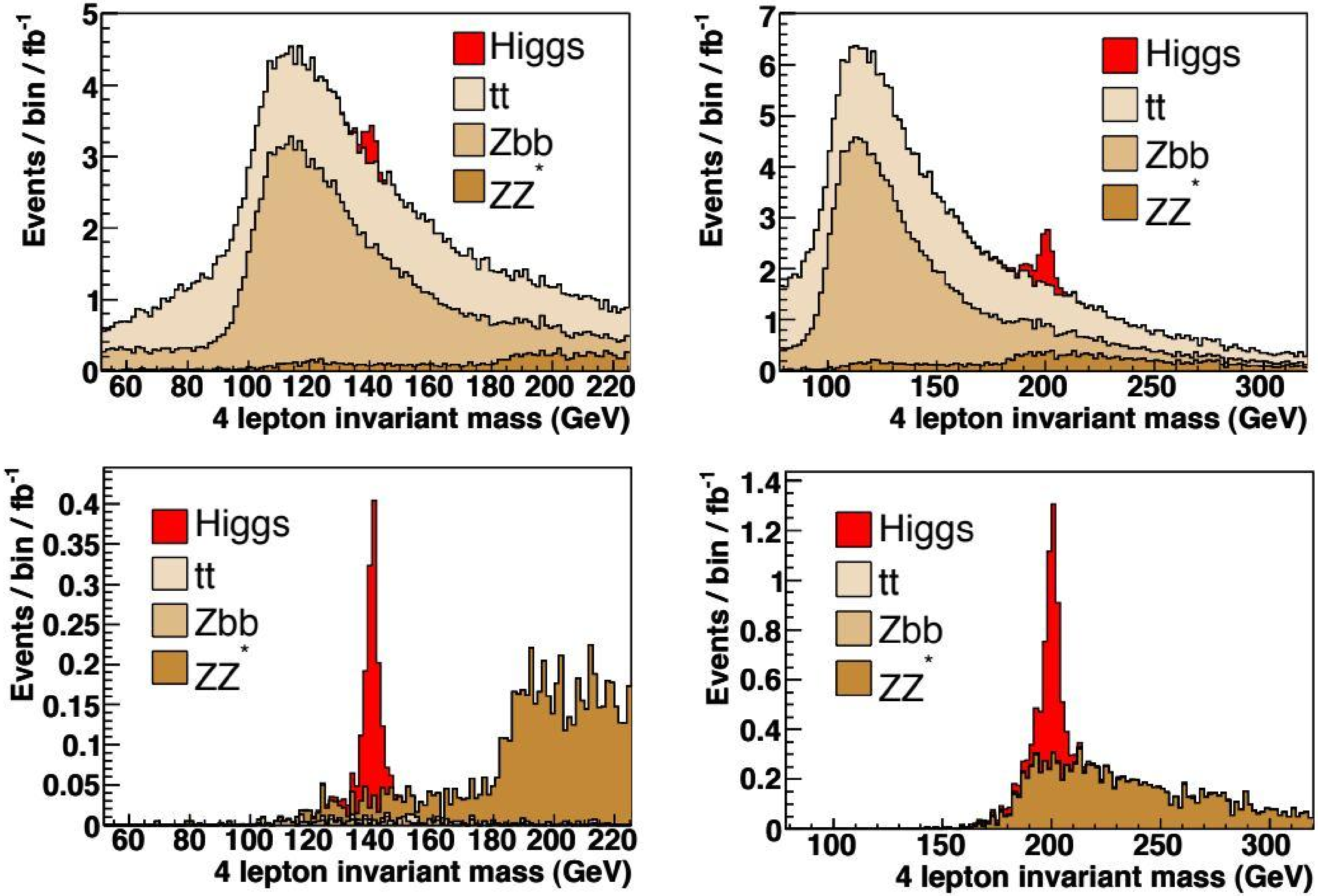
m_H = 200 GeV

	Signal	$t\bar{t}$	$Zb\bar{b}$	$ZZ^\star/\gamma^\star$
Production cross-section (NLO)	17.9×10^3	840×10^3	555×10^3	28.9×10^3
$\sigma\times$BR(4 lepton final state)	23.8	-	-	367.5
Pre-selection: $\sigma\times\text{BR}\times\epsilon$	7.39±0.09	743±2	390±1	37.0±0.4
Level-1 trigger	7.36±0.09	707±2	360±1	36.3±0.4
High Level trigger	6.82±0.08	282±1	237±1	32.5±0.4
$e^+e^-\mu^+\mu^-$ reconstructed	5.51±0.07	130±1	141±1	24.1±0.3
Vertex and impact parameter cuts	5.03±0.07	18.9±0.3	18.4±0.2	21.5±0.3
Isolation cuts	4.92±0.07	5.1±0.1	12.3±0.2	21.3±0.3
Lepton p_T cuts	4.78±0.07	1.93±0.09	1.78±0.06	18.7±0.3
Z mass window cuts	4.45±0.07	0.15±0.03	0.12±0.02	14.4±0.3
Higgs mass window cuts	3.64±0.06	0.006±0.005	0.006±0.003	1.61±0.09
Expected events for $\int\mathcal{L} = 10\ \text{fb}^{-1}$	36.4±0.6	0.06±0.05	0.06±0.03	16.1±0.9

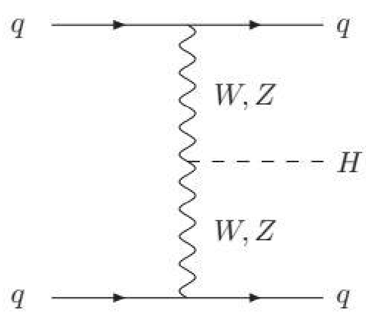
m_H = 140 GeV m_H = 200 GeV

before selection

after selection

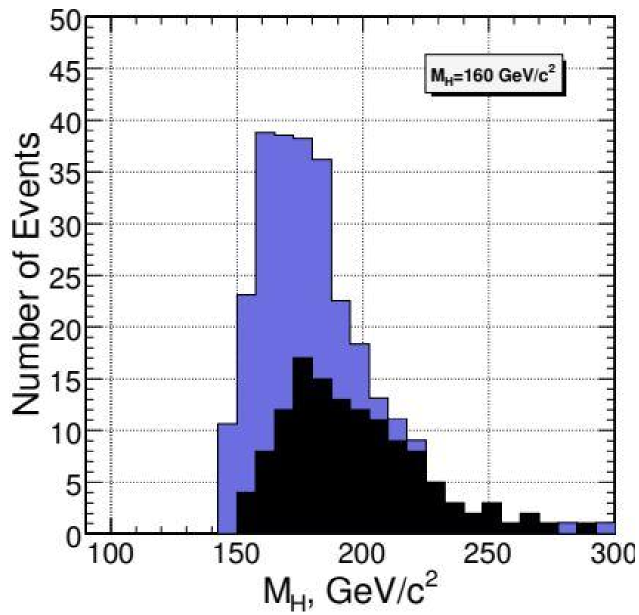


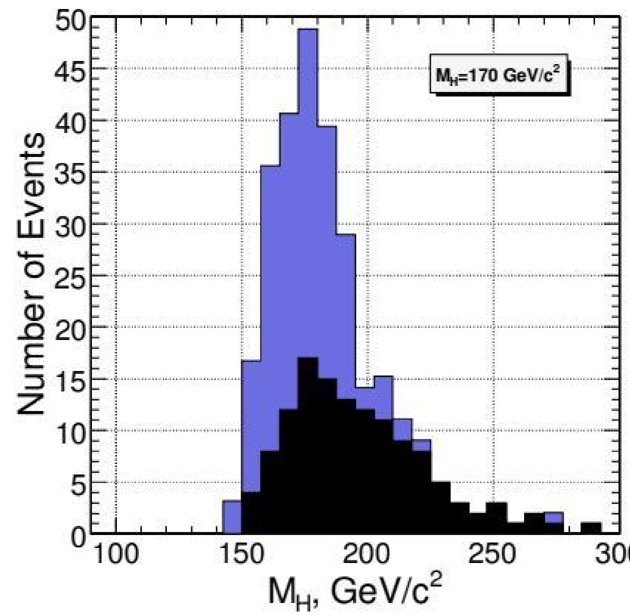
Vector Boson Fusion



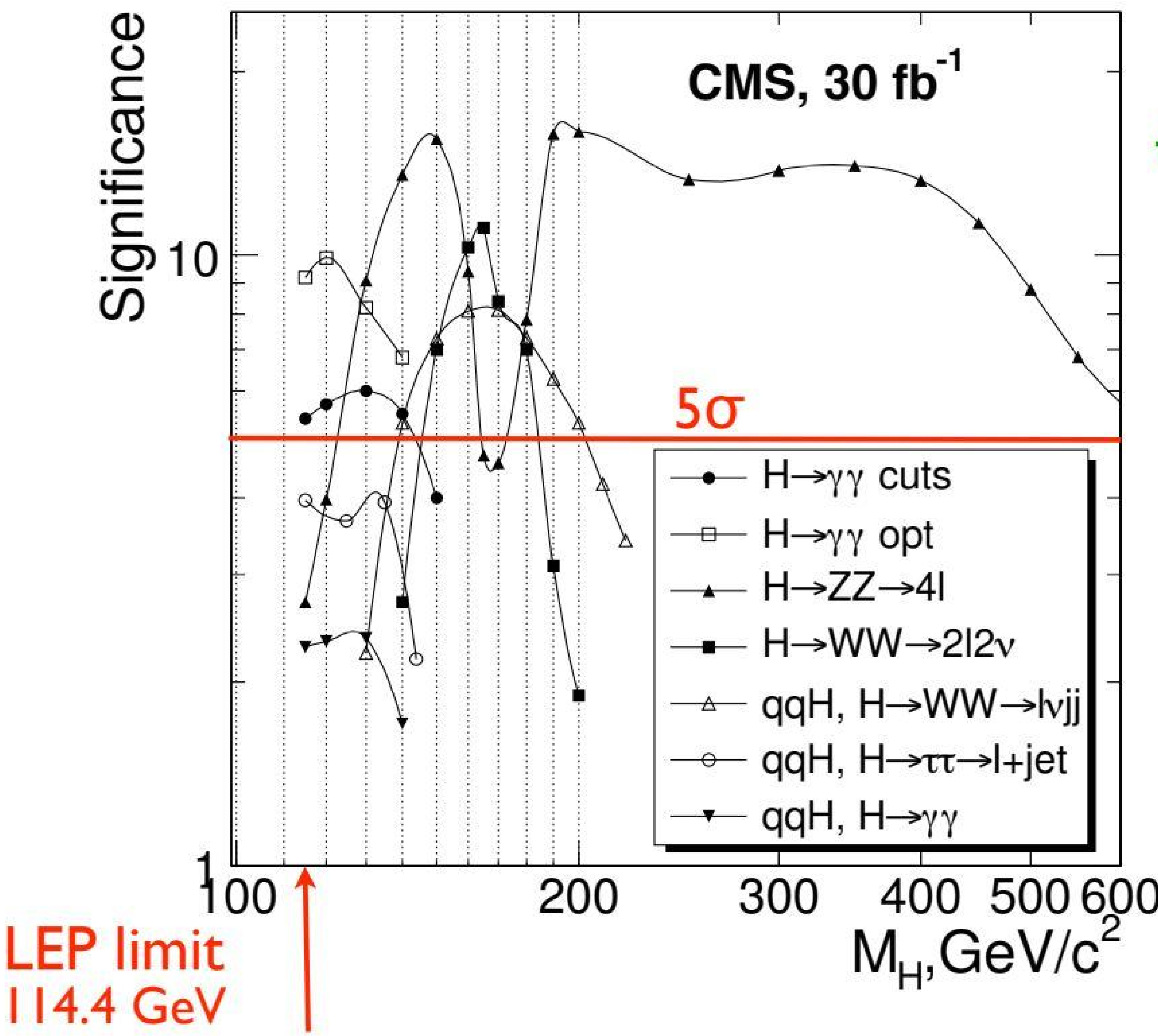
$H \to WW \to l\nu jj$

Selection	Configuration
Lepton selection	calorimeter-based e/μ isolation $30 < p_T < 120\,GeV/c$ $\Delta R_{\ell,j} > 0.5$
Jet selection	$N_{jet} \geq 4$ jets with $E_T > 25\,GeV$ $E_T^{miss} > 30\,GeV$
Forward jet tagging	$E_T > 30\,GeV$ $\eta_1 \cdot \eta_2 < 0$ $\|\eta_1 - \eta_2\| > 3.8$ $m_{jj} > 800\,GeV/c^2$
Hadronic-W	$\Delta m_W < 25\,GeV/c^2$ ($m_H \geq 160\,GeV/c^2$) $30 < m_W < 90\,GeV/c^2$ ($m_H < 160\,GeV/c^2$) select di-jet with the least Δm_W
Leptonic-W	using lepton and E_T^{miss} select Leptonic-W candidates of smaller $\Delta R(\mathrm{Leptonic-W, Hadronic-W})$





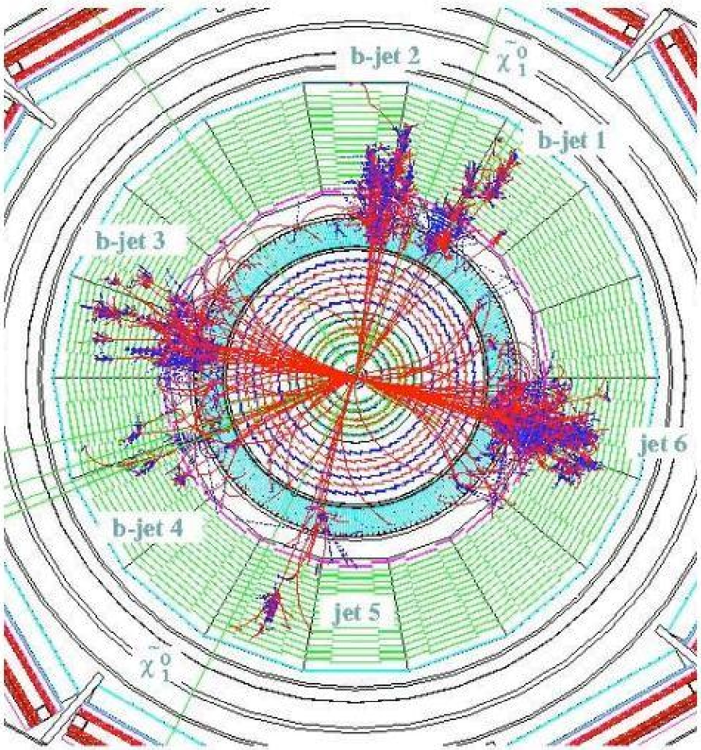
Summary: Standard Higgs Reach

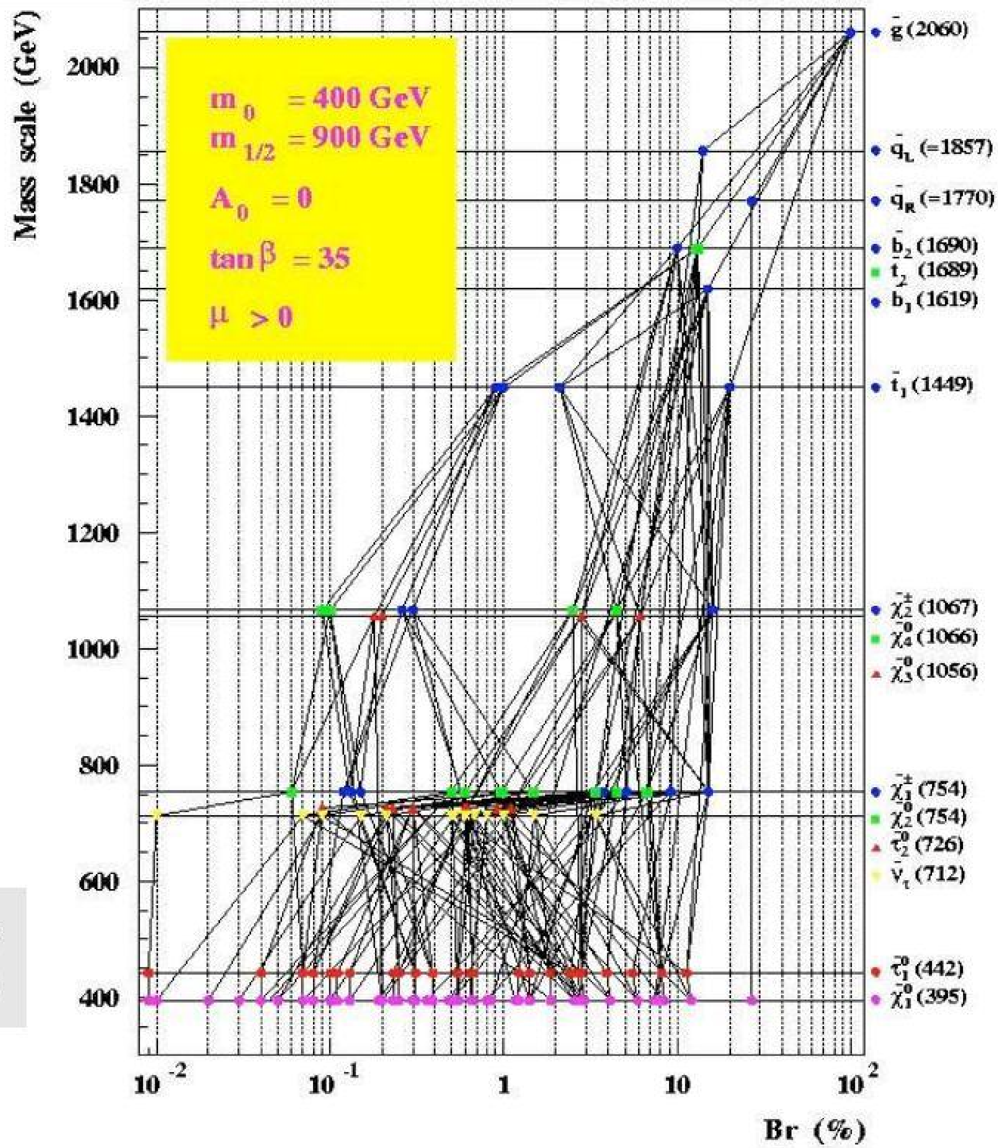


full simulations
(2006)

SUSY: Sparticle Search

Supersymmetry





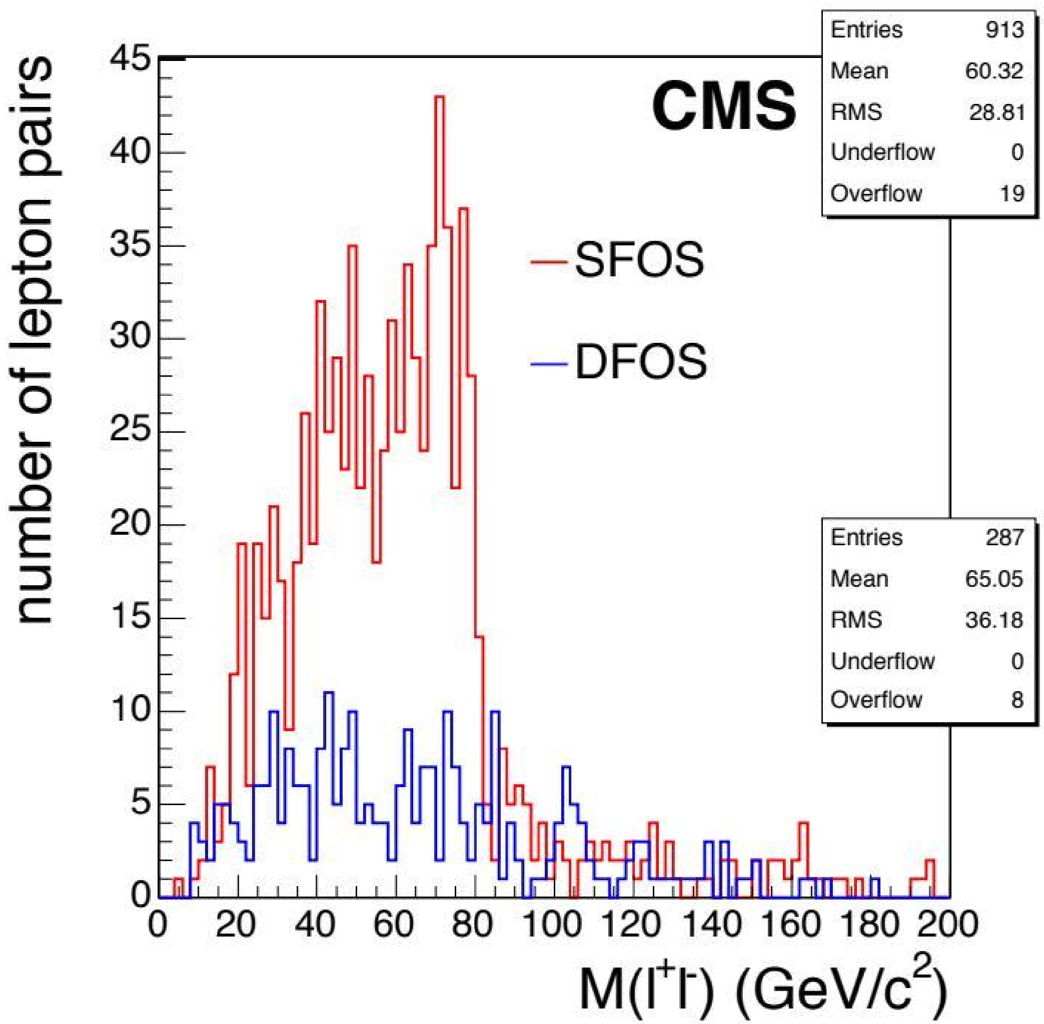
Distinctive signature of leptons, jets, missing E_T for some events

Supersymmetry: Dilepton Selection

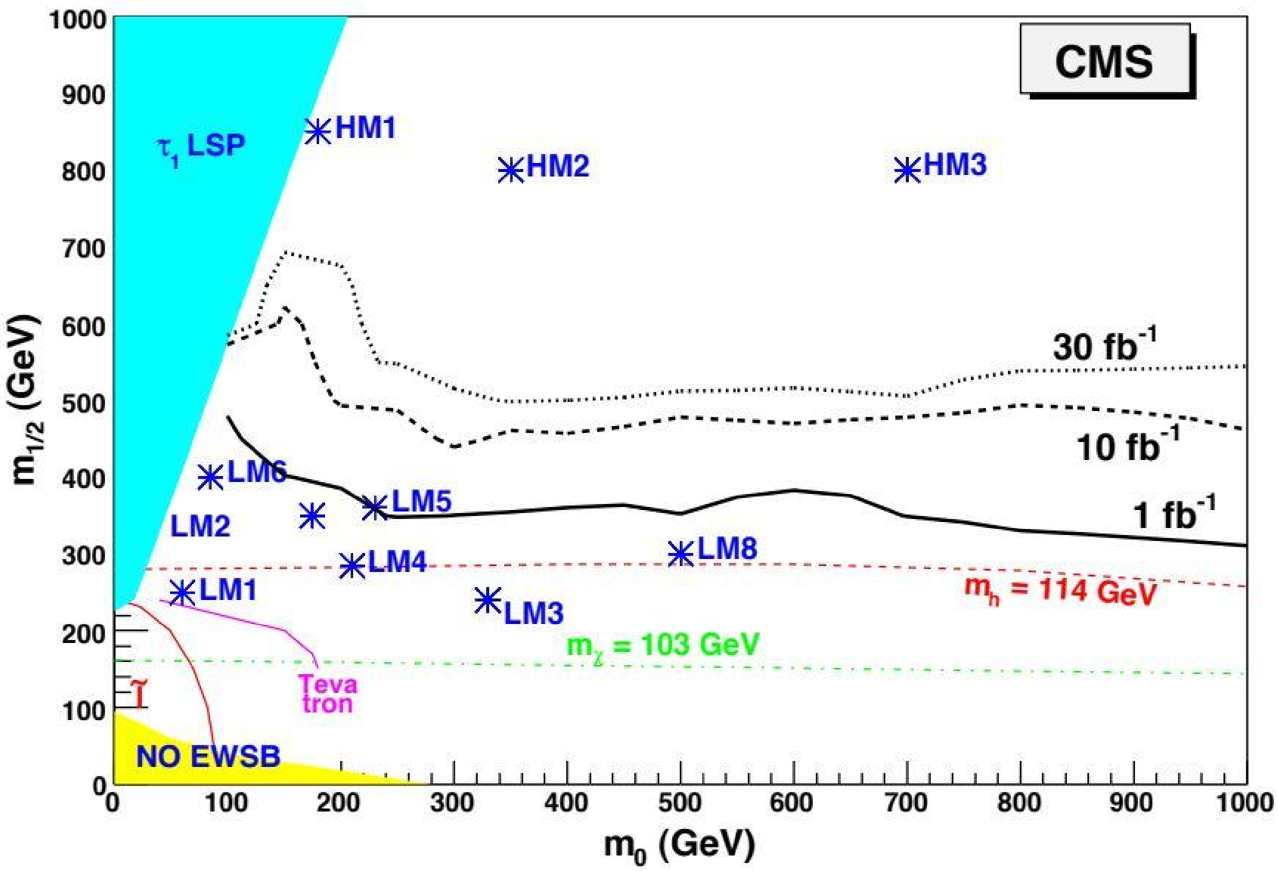
$$\tilde{\chi}_2^0 \quad \longrightarrow \quad l^+ l^- \tilde{\chi}_1^0$$

Process	σ (pb)	Ev. analysed	ε	N$_{ev}$ in 1 fb^{-1}
SUSY (LM1)	52	478k	0.016	853
$t\bar{t}$	830	913k	$1.9 \cdot 10^{-4}$	155
$WW+$ jets	188	197k	$1.4 \cdot 10^{-4}$	26
$Z+$ jets	$5 \cdot 10^3$	606k	$4.8 \cdot 10^{-6}$	24
DY$\rightarrow 2\mu$	$3.97 \cdot 10^3$	916k	$< 1.1 \cdot 10^{-6}$	< 4
DY$\rightarrow 2\tau$	$3.97 \cdot 10^3$	514k	$1.1 \cdot 10^{-6}$	4.5
$Zbb \rightarrow llbb \, (l = \ e, \ \mu, \ \tau)$ P$^T_{hat} > 60\,\mathrm{GeV}/c$	57.4	621k	$8.4 \cdot 10^{-5}$	4.83
$t\bar{t}b\bar{b}$	3.3	50k	$9.8 \cdot 10^{-4}$	3.2
$ZZ+$ jets	11	37k	$2.4 \cdot 10^{-4}$	2.7
$W+$ jets	$1.5 \cdot 10^5$	1765k	$6.7 \cdot 10^{-9}$	1

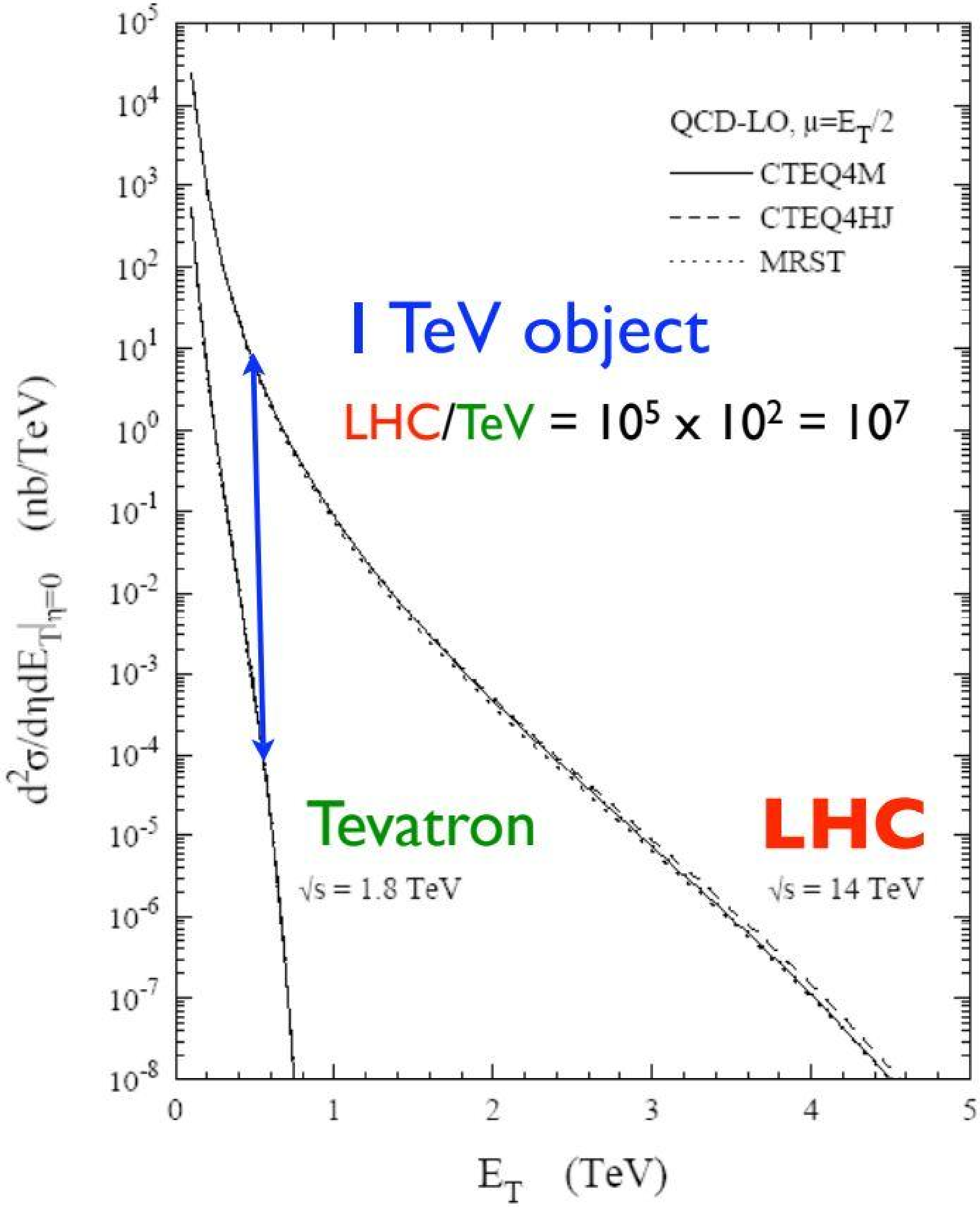
Dilepton Edge



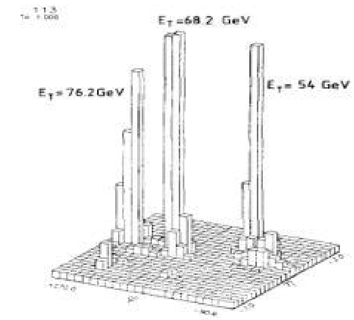
5σ Reach with Inclusive Dileptons



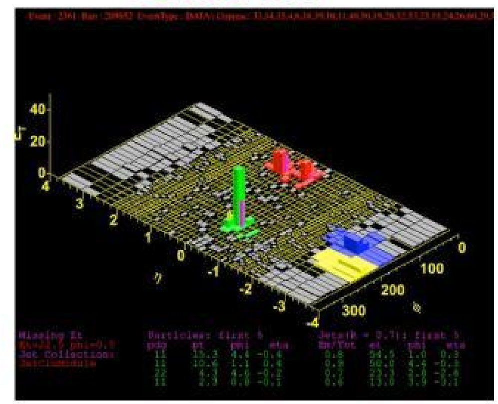
Jet Cross Section

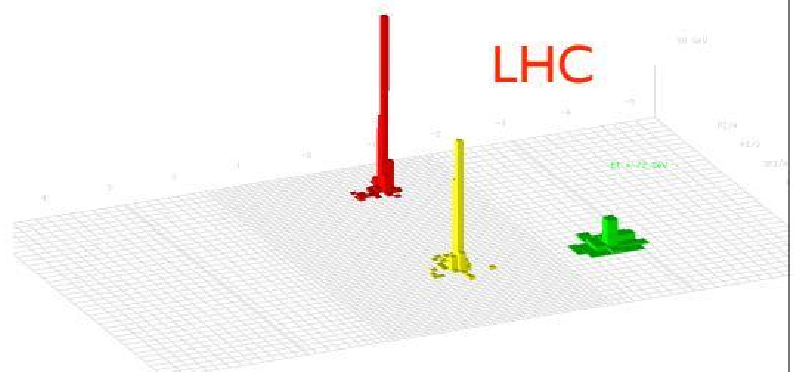


CERN SPS



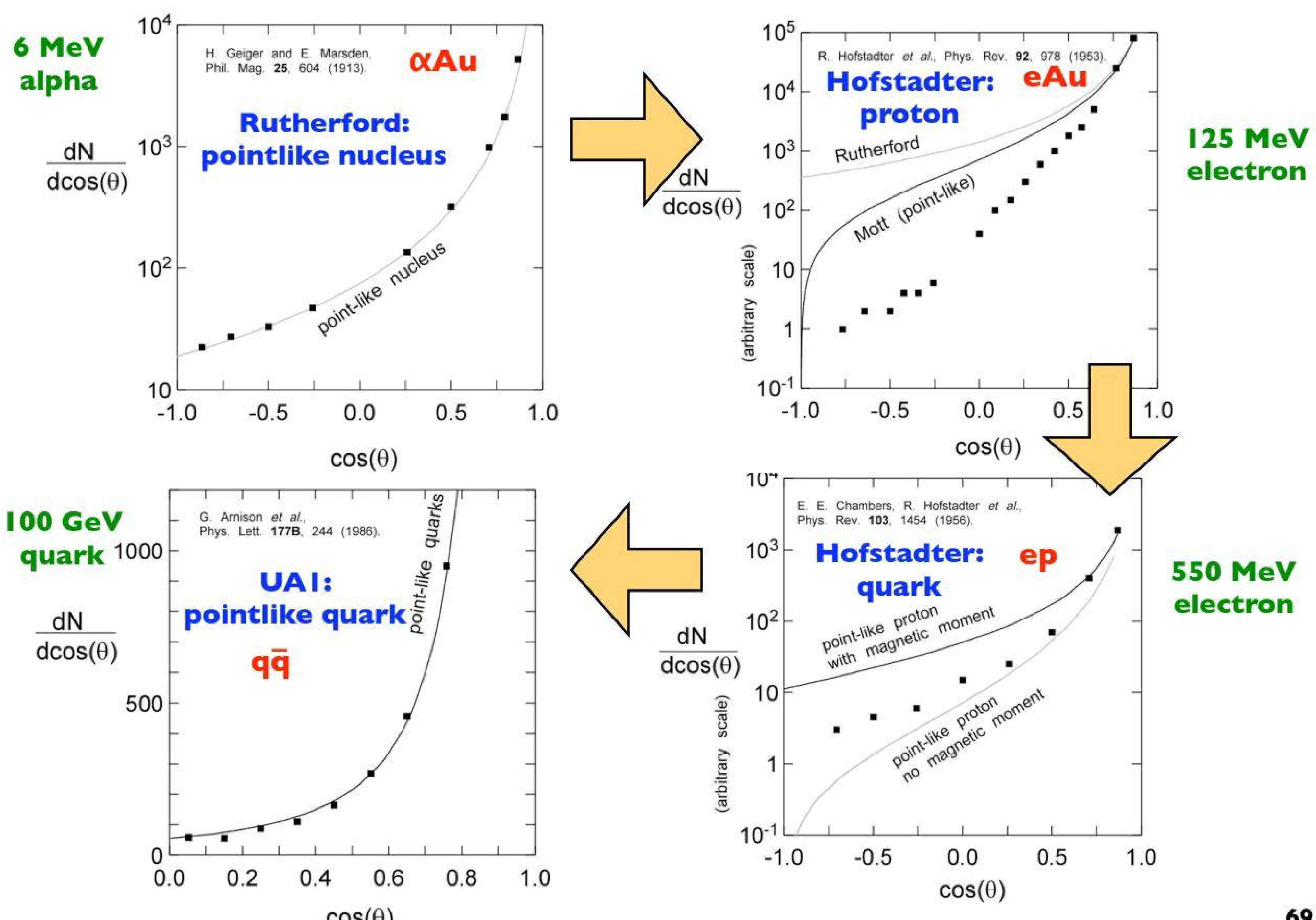
Tevatron

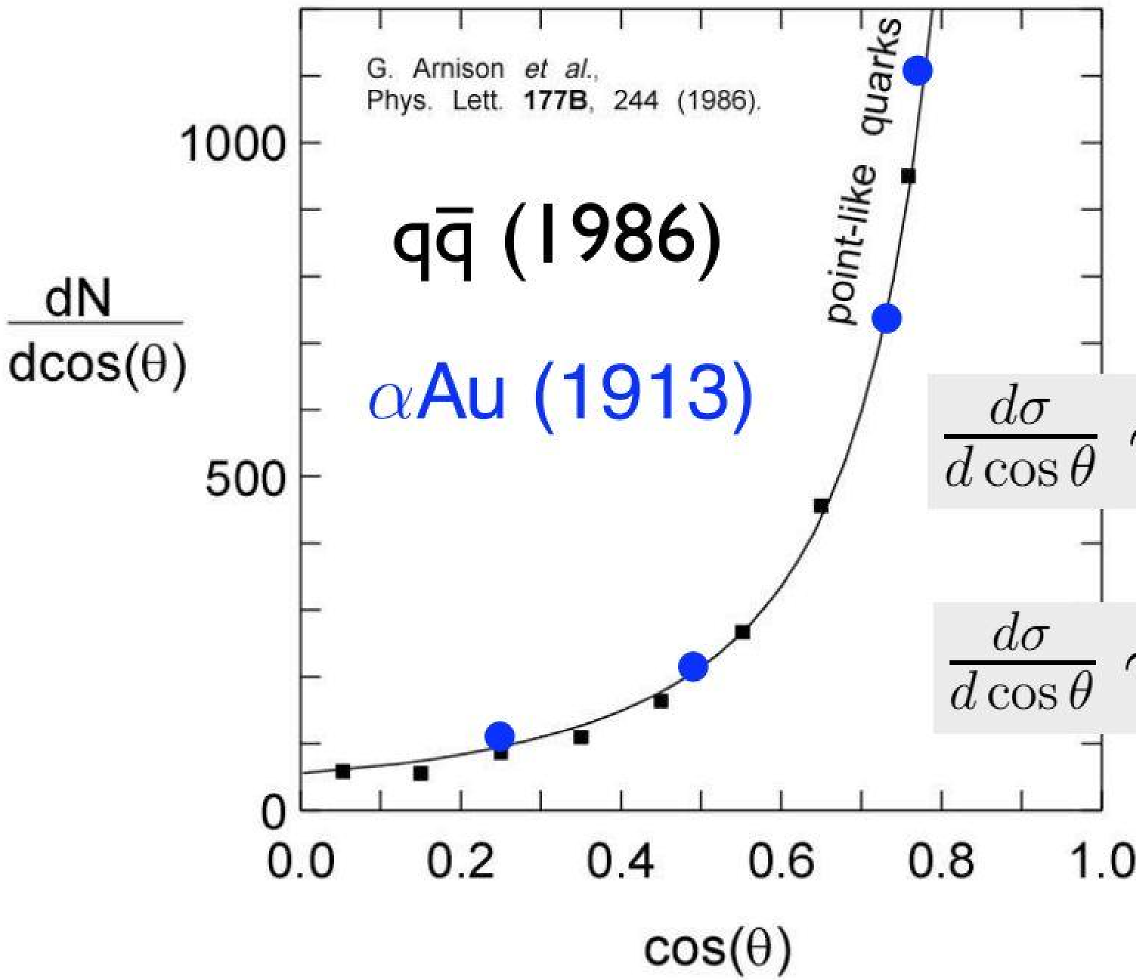




History of compositeness

J. Rohlf: Modern Physics from α to Z^0





Electromagnetism

$$\frac{d\sigma}{d\cos\theta} \sim \alpha^2\left(\frac{\hbar c}{E_{\mathrm{k}}}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

QCD

$$\frac{d\sigma}{d\cos\theta} \sim \alpha_s^2\left(\frac{\hbar c}{E_{\mathrm{CM}}}\right)^2 \frac{1}{(1-\cos\theta)^2}$$

LHC Timeline

1982 high energy (100 GeV) jets observed at CERN,
world interests shifts from an electron linear collider to a proton synchrotron collider

1983 W and Z discovered at CERN, SSC formally initiated (40 TeV, 10^{32} $cm^{-2}s^{-1}$), ISABELLE cancelled!

1989 LEP commisioned

1993 SSC cancelled!

1994 CERN Council approves LHC

2000 LEP shut down to allow LHC construction

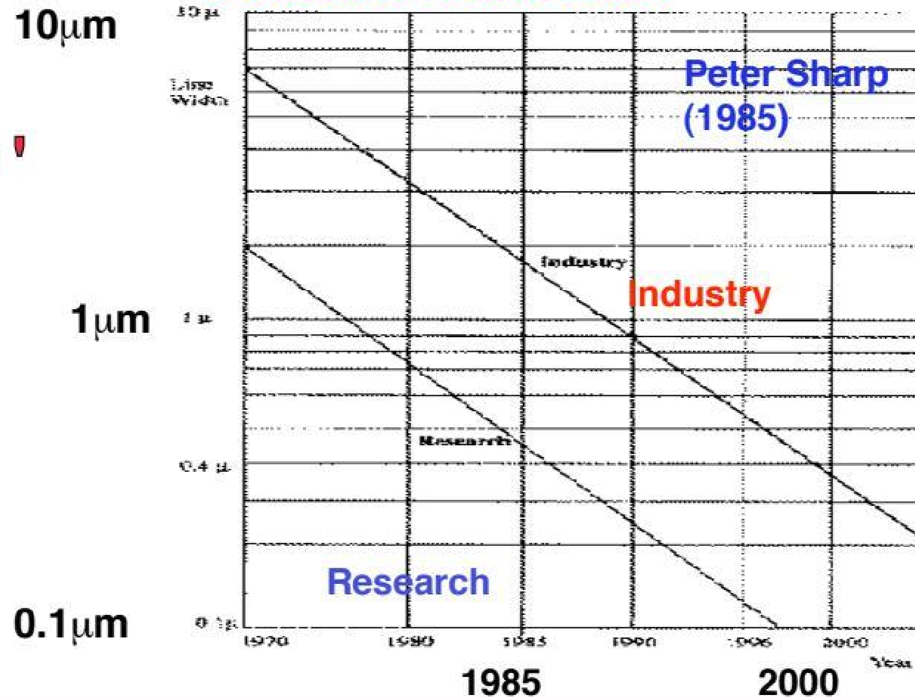
2007 First collisions in LHC expected

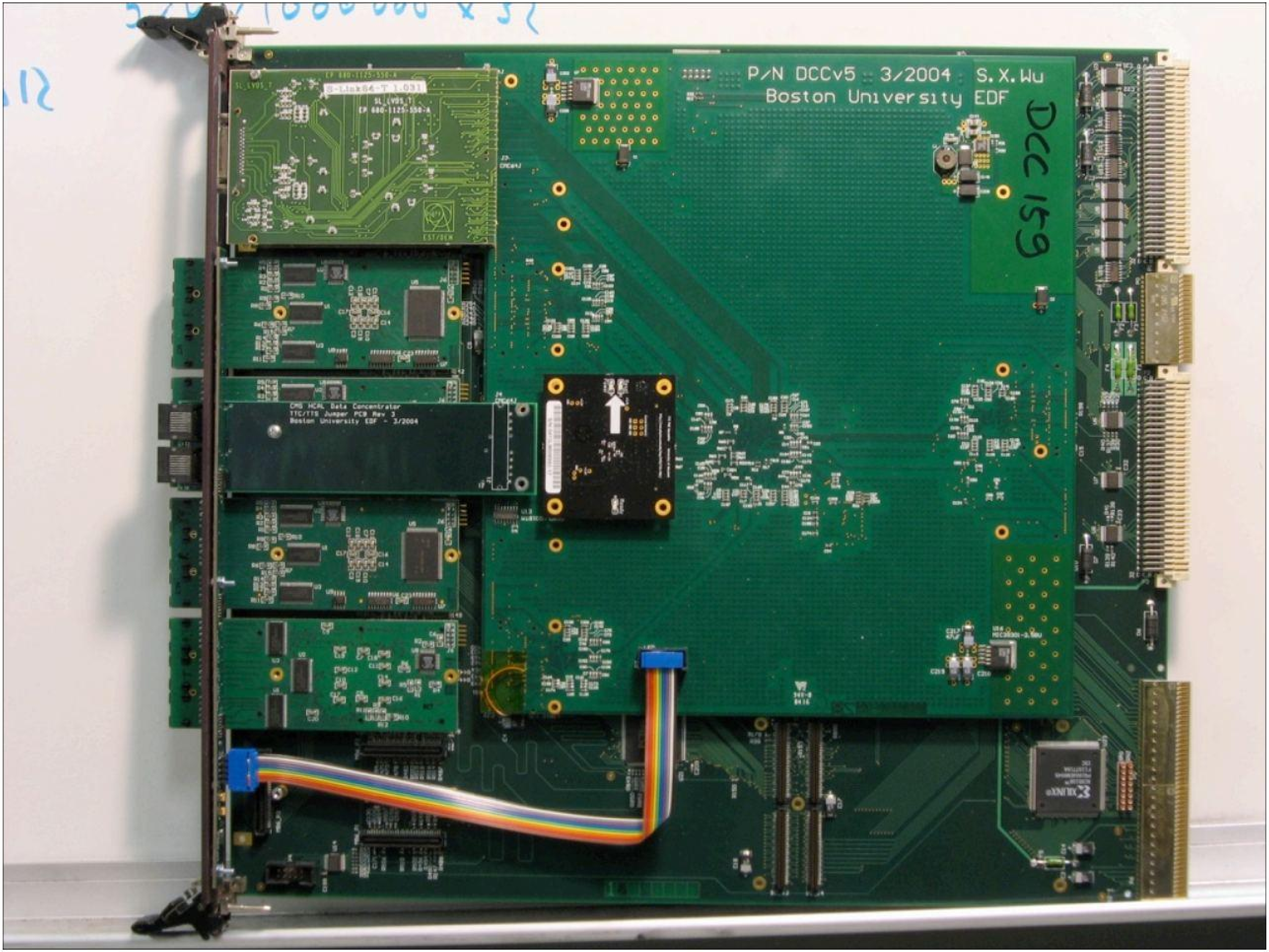
What has been Learnt from the last 15 Years ?

' Moores Law '

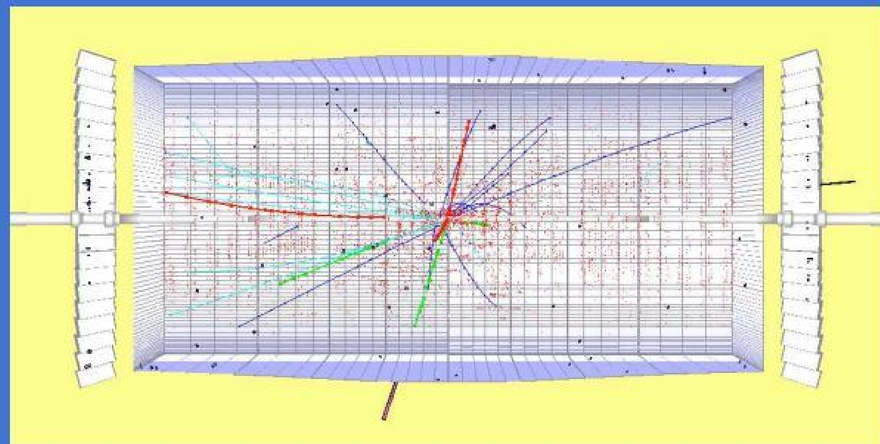
A plot made in 1985

Evolution of Line Width

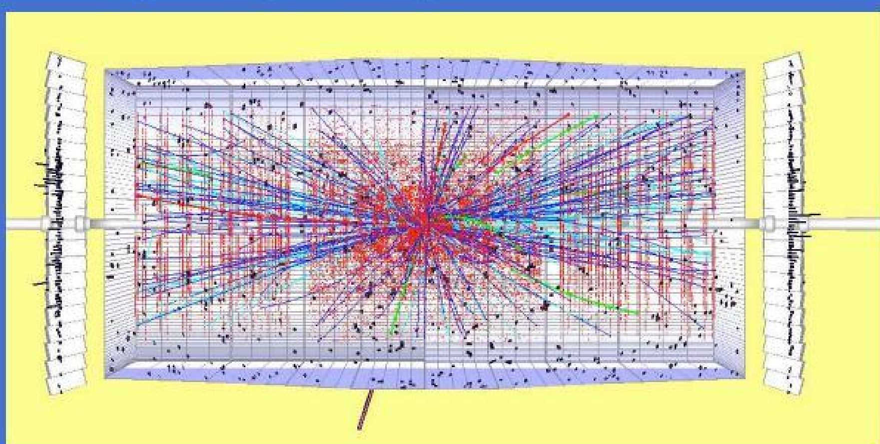



P/N DCCv5 3/2004 S.X.Wu
Boston University EDF
DCC 159
CMS HCAL Data Concentrator
TTC/TTS Jumper PCB Rev 3
Boston University EDF - 3/2004

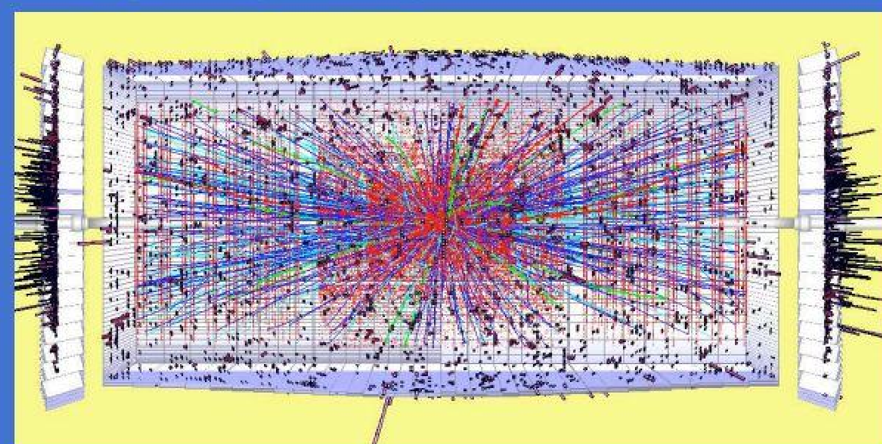
$10^{33}\ \mathrm{cm^{-2}s^{-1}}$



$10^{34}\ \mathrm{cm^{-2}s^{-1}}$

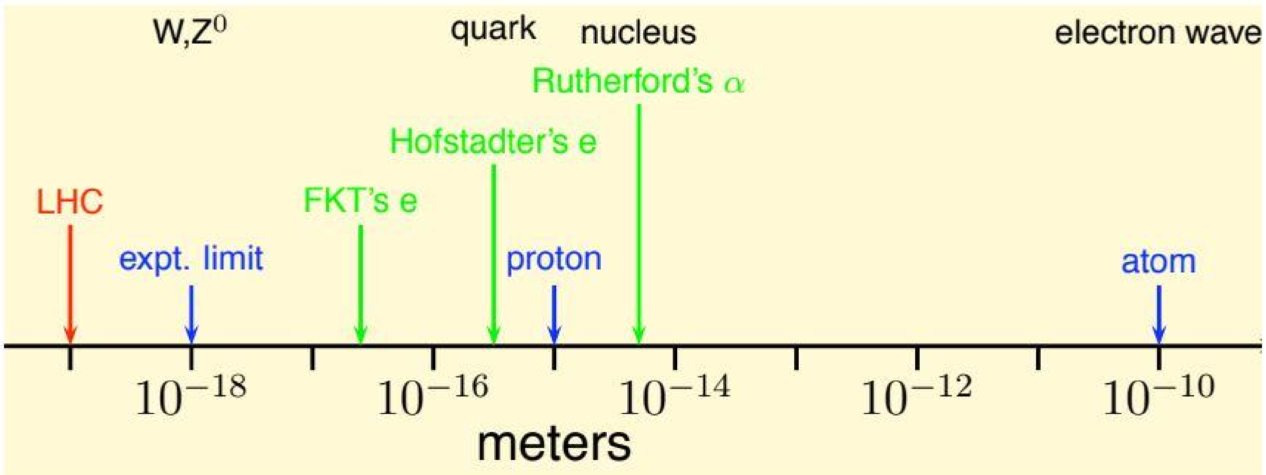


$10^{35}\ \mathrm{cm^{-2}s^{-1}}$



Summary

$$d \sim \frac{\hbar}{p} \simeq \frac{0.2 \text{ GeV}\cdot\text{fm}}{2 \text{ TeV}} = 10^{-19} \text{ m}$$



The LHC is going to take us down to a distance scale of 10^{-19} m. We expect to settle once and for all the existence (or not) of the higgs boson. Most of all, we hope to see something nobody has thought of yet.