4th School on High Energy Physics,
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From the antiproton-proton collider and UA1 to the LHC and the CMS detector and some current physics results

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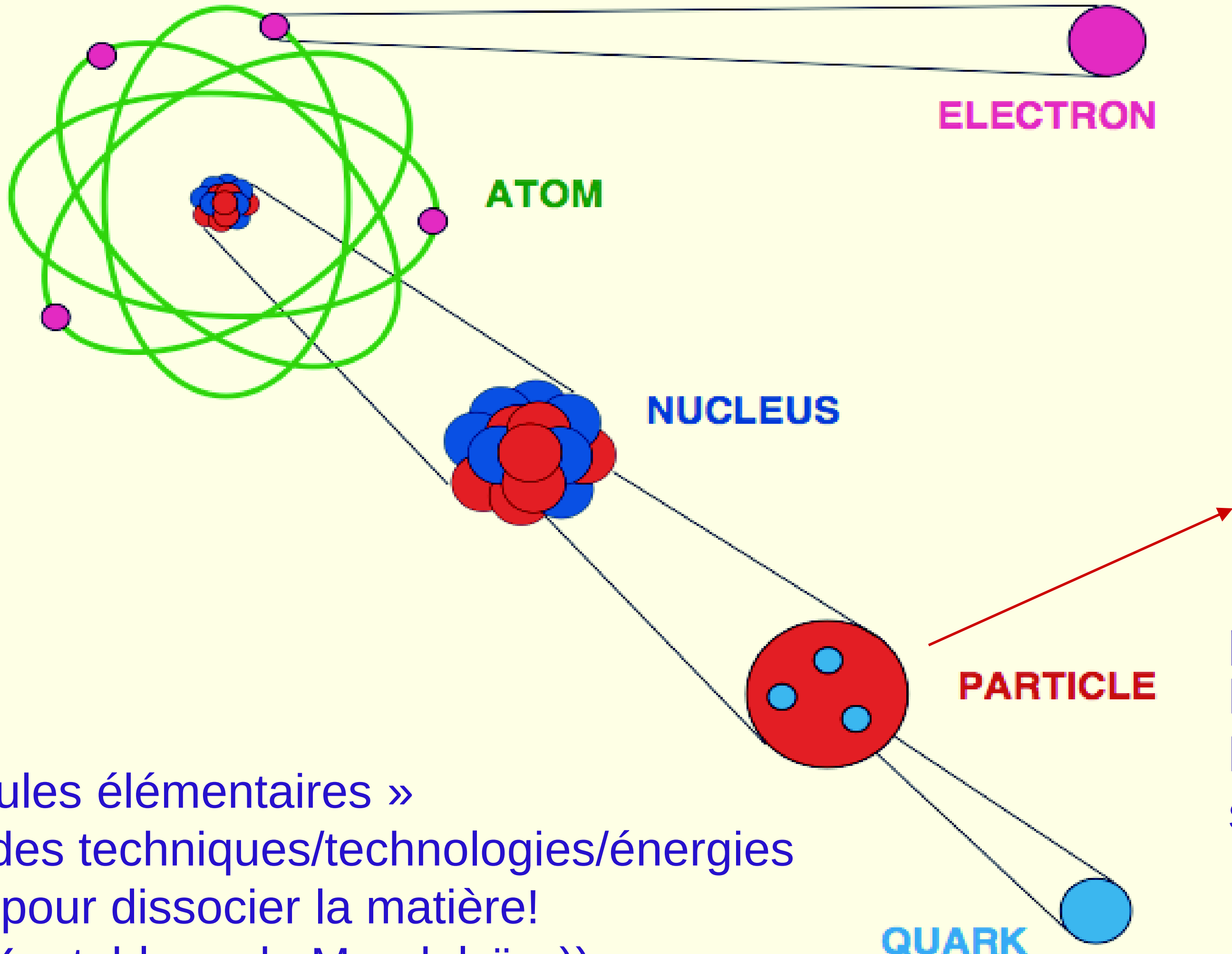
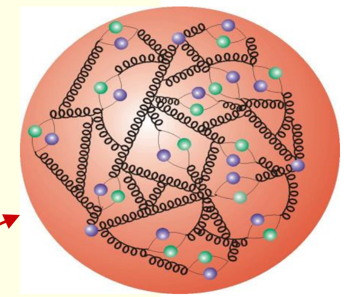
the antiproton-proton collider,
the UA1 detector and discovery of the W and Z,
the LHC and CMS detector, concept and performances
some results from the 2011/12 physics runs

What is Matter made of?





protons, neutrons, hadrons in general have a complex structure

Les « particules élémentaires » dépendent des techniques/technologies/énergies disponibles pour dissocier la matière!
Atomes (XIX - tableau de Mendeleïev)),
Noyaux - protons/neutrons, hadrons, leptons (XX)
Quarks, leptons…..(fin XX, début XXI)

Préons?
Strings/cordes?

Elementary particles: particles of matter, force carriers-mediators, and the Higgs boson

8 gluons

$m_g = 0$

the photon (γ)

$m_\gamma = 0$

W^+, W^-, Z

$m_{W,Z} = 80,90$ GeV

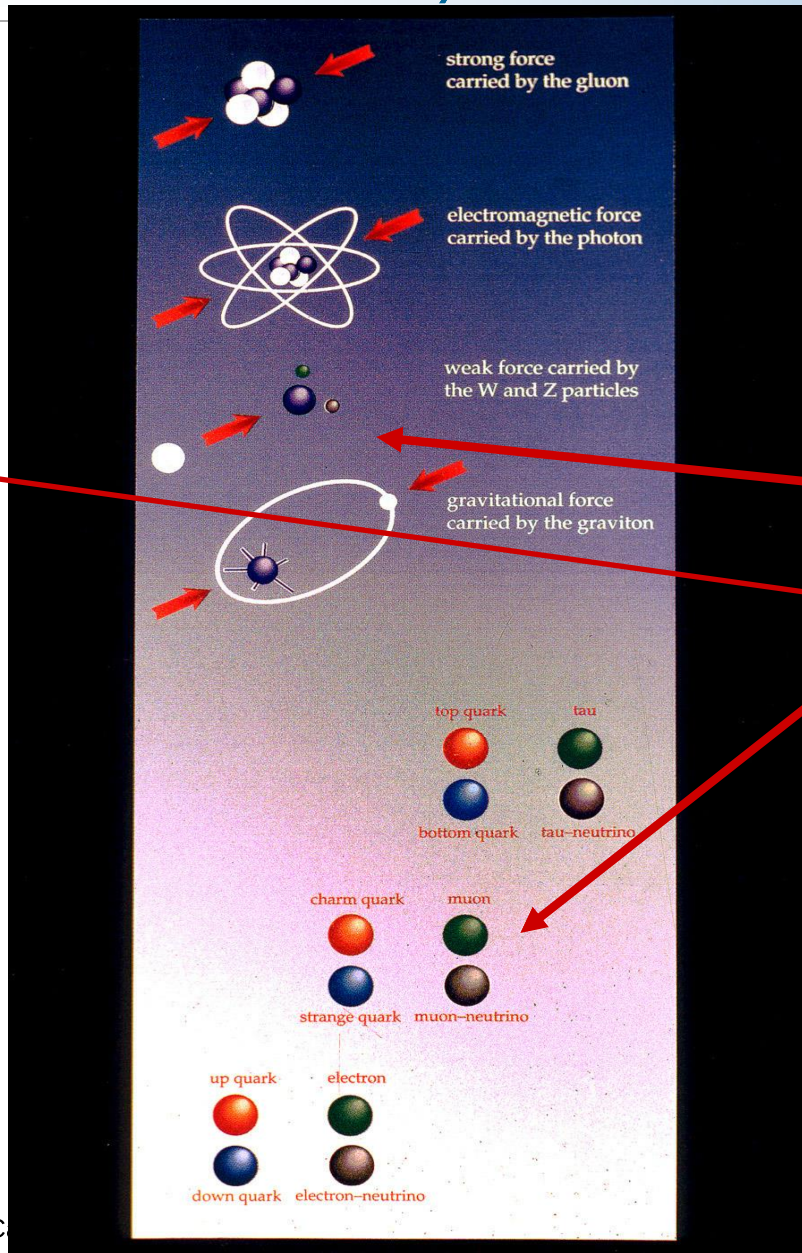
the graviton (hypothetical)

$m_G = 0$

3rd

2nd

1st generation



fundamental interactions

$R_{force} \sim 1/m_{mediator}$

+ Higgs (BEH) boson! responsible for the masses of the W,Z and of matter particles

particles of matter: quarks and leptons

30 years ago, discovery of the W and Z….

.

and how much progress since then!

Towards the Standard Model: electroweak unification

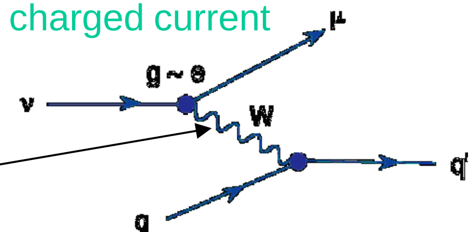
In 1965/67 S. Weinberg, A. Salam, J. Ward, S.L. Glashow… proposed a theory providing a unified description of electromagnetic and weak interactions in terms of a spontaneously broken local gauge symmetry SU(2) x U(1) - i.e. with a Higgs mechanism to give mass to the weak quanta;
the short range of weak interactions (< 10^{-15}cm) implied large masses for the W^+ and W^- force carriers (intermediate vector bosons) as $R_{force} \sim 1/M_{field\ quantum}$

- This unified scheme however implied the existence of four field quanta:

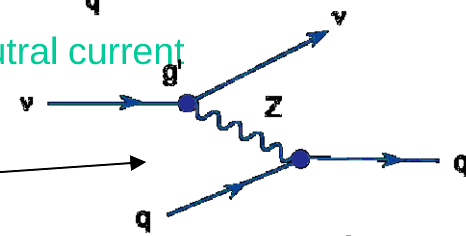
γ - which □□□□□□□□□□□□□□□□
□□□□□□□□□□□□□□□□□□□□□□,
W^+ and W^- - for charged weak interactions ("weak charged currents"),
Z^0 - a sort of "heavy photon" - implying the existence of "neutral current" weak interactions i.e. of a new type of weak interactions, unknown at that time!

- The theory had a single parameter, the weak mixing angle $\theta_{□}$,□□□□□□□ □□□□□□□□□□□□□their □□□□□□□□□ to fermions depending on this angle

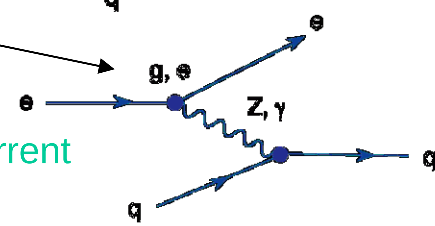
neutrino weak charged current Interactions:



neutrino weak neutral current Interactions:



electron weak neutral current interactions



Parity violation in atomic physics, or in DIS electron scattering

Electroweak unification (~ 1964 - 1971)

- From the SU(2): W_1, W_2, W_3 and U(1) B mass-less gauge vector fields through the mechanism of spontaneous symmetry breaking* you get the massive W^+, W^- and Z and the mass-less A (γ) □□□□d□ related by□

$$Z = W_3 \cos \theta_{□} - B \sin \theta_{□}$$
$$A = W_3 \sin \theta_{□} + B \cos \theta_{□}$$

* From the four scalars appearing in the theory 3 disappear into the W^+, W^-, Z masses, but a fourth massive scalar remains - the SM Higgs boson!

- The predicted W, Z masses:

$$m_W = [\pi\alpha/(\sqrt{2}\, G_F)]^{1/2}/\sin\theta_W = 37.4 \text{ GeV}/\sin\theta_W \qquad m_Z = m_W/\cos\theta_W$$

where α is the electromagnetic and G_F the Fermi constant

→ the expected W, Z masses were large for whatever $\theta_{□}$ thus escaping detection at the time the theory was formulated

- In 1971 G. ‘t Hooft and M. Veltman have shown that this electroweak theory was renormalizable

at this point this theory began to be taken seriously by theorists!

Towards the W, Z (period ~1970 - 1979)

- In 1973 discovery of neutral-current neutrino interactions at CERN (in Gargamelle): first experimental evidence in favour of the unified electro-weak theory!

  At this point experimentalists began to think seriously about this electroweak theory, although most of them were in "strong interaction physics", hunting resonances (filling the SU(3) multiplets - the "eight-fold way") - hadron spectroscopy being one of the two foundations of the quark model, the other being the "partons" seen in Deep Inelastic Scattering (e, SLAC)

- In 1970 the GIM mechanism was invented, the charm quark introduced and found in 1974 as J/ψ - the most "tangible" evidence for existence of quarks, then the Y system with b-quarks in ~1977;
  in 1973 QCD with its prediction of "asymptotic freedom" was introduced with SU(3) as the gauge symmetry - for the three colors of quarks (Nobels of 2004, Gross, Wilczek, Politzer), our present day SM was falling in place!

- parity violation in electron-nucleon scattering as expected from electro-weak theory was found at SLAC in 1978

- in 1979 Weinberg, Salam and Glashow got the Nobel Prize for the electro-weak unification and the prediction of the existence of the Z

➡ ……things were getting serious!

Expectations for W, Z (~1974 - 1980)

- First measurements of charged and neutral current neutrino interactions when interpreted in this unified electroweak scheme were giving:

$\sin^2\theta_w \sim 0.3 - 0.6$

implying:

$m_{W,Z} \sim 50 - 100$ GeV

Subsequent measurements were giving by 1980/81 $\sin^2\theta_w \approx 0.23$
and thus $m_W \approx 80$ GeV and $m_Z \approx 90$ GeV

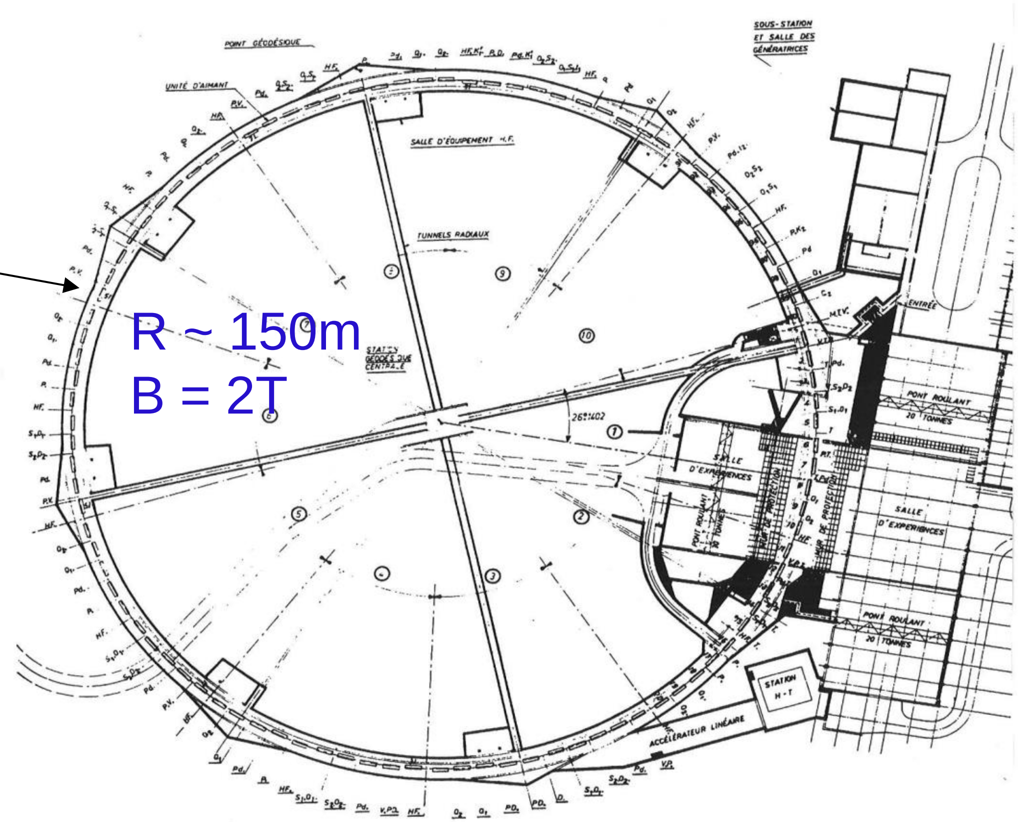
far too large masses to be produced by any existing accelerators, LEP was ~ ten years away, proton-proton collider ($\sqrt{s} \sim 200$ GeV) ISABELLE magnets could not be produced….

then came the suggestion of Rubbia, Mc Intyre, Cline to convert an existing proton synchrotron ($\sqrt{s} \sim 30$ GeV in a fixed target mode for the CERN SPS) into an antiproton-proton collider!

A proton synchrotron: the 27 GeV PS at CERN

Particle momentum
on a circular orbit:
p = ReB

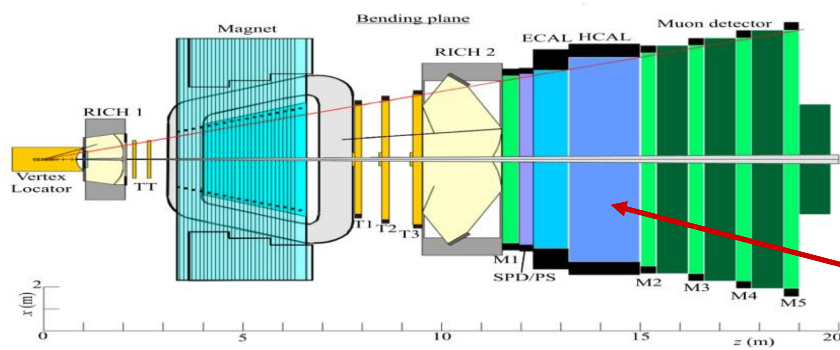
a similar 30 GeV proton synchrotron (AGS) in operation since 1960 at BNL



a typical fixed -target experimental set-up:

proton beam
from the CERN PS

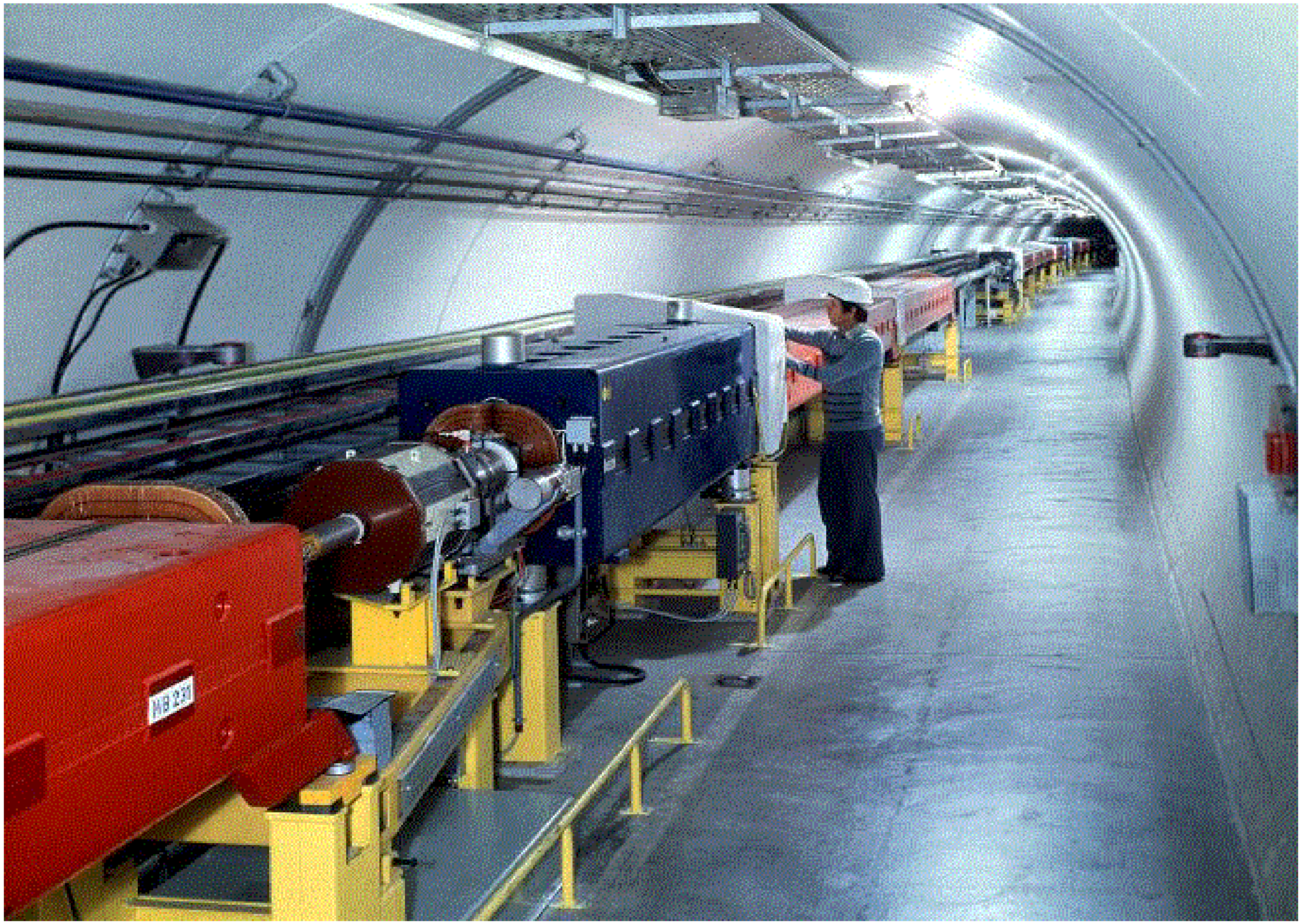
$\sim 10^{13}$ 26 GeV protons
every 2.4 s



a down-stream spectrometer:

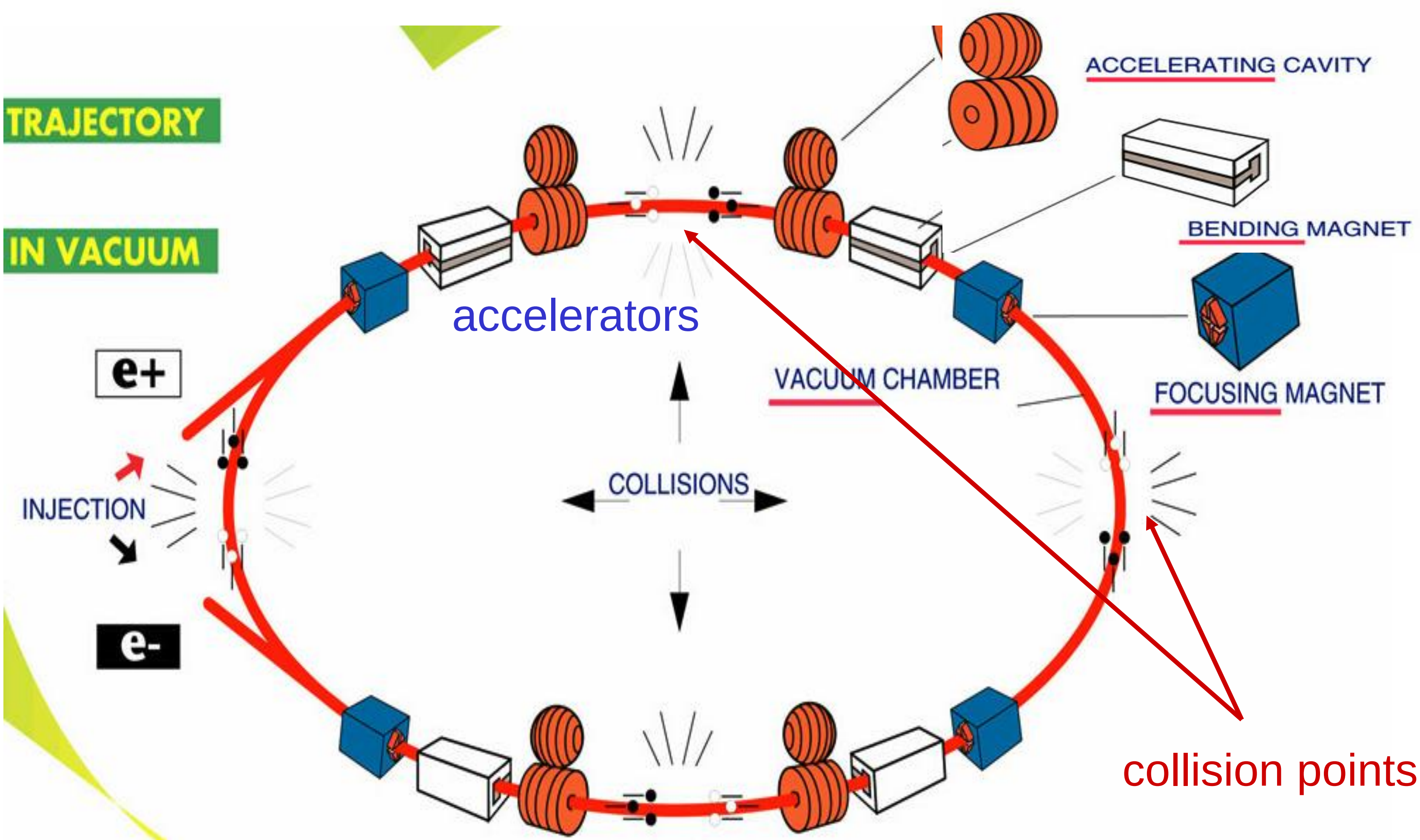
Existing CERN accelerators in the 70's, before W, Z discovery

- 26 GeV proton synchrotron (PS) in operation since 1959
- 450 GeV proton synchrotron (SPS) started operation in 1976



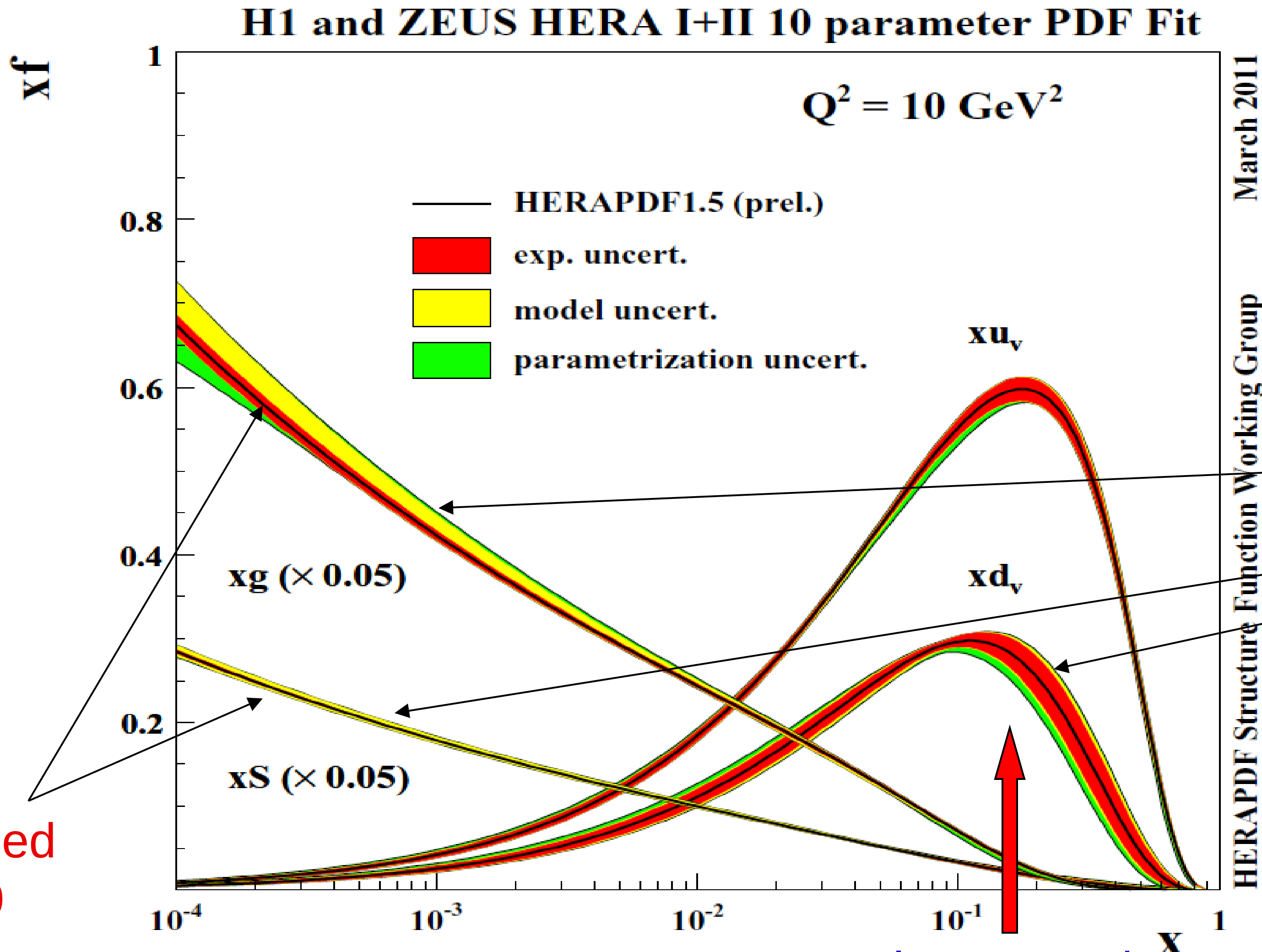
A view of the CERN SPS - a warm magnet synchrotron

Another concept: an accelerator - collider: basic elements



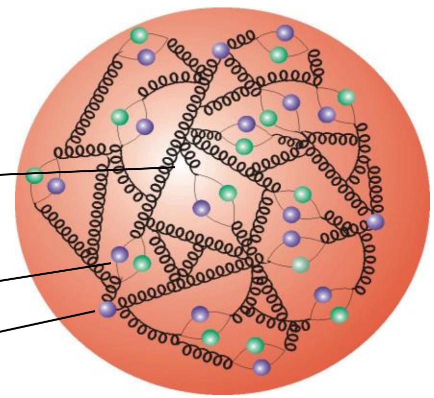
Colliders have been first developped for e^+e^- collisions, then for proton-antiproton and, with a somewhat different design, for proton-proton collisions

Structure functions –
as determined from HERA experiments
- needed when you collide protons/antiprotons



devided
by 20

Complex structure
of protons



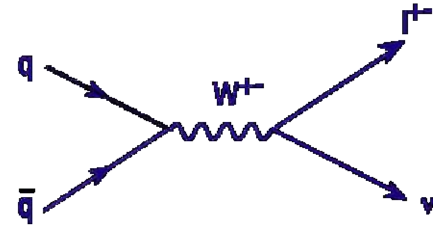
Valence quarks carry ~ 1/6
of proton's momentum

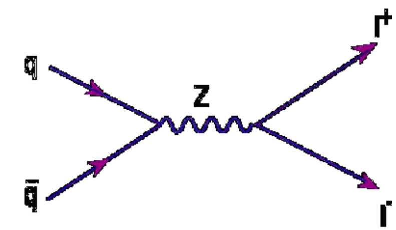
W, Z production, required collider center of mass energy and luminosity

Main W and Z production processes (DY) at a proton – antiproton collider:

$$u + \bar{d} \to W^+ \qquad \bar{u} + d \to W^-$$

$$u + \bar{u} \to Z \qquad d + \bar{d} \to Z$$





- Energy requirements:

proton (antiproton) momentum at high energies is carried by gluons (~ 50%) and valence quarks (antiquarks) (~ 50%) thus:

quark momentum ~ (1/6) proton momentum

➡ collider energy ≈ 6 x boson mass ≈ 500 – 600 GeV

- Luminosity requirements:

Inclusive cross-section for p + $\bar{p}$ → Z + anything at √s ~ 600 GeV: σ ≈ 1.6 nb

Branching ratio for Z → $e^+ e^-$ decay ≈ 3%

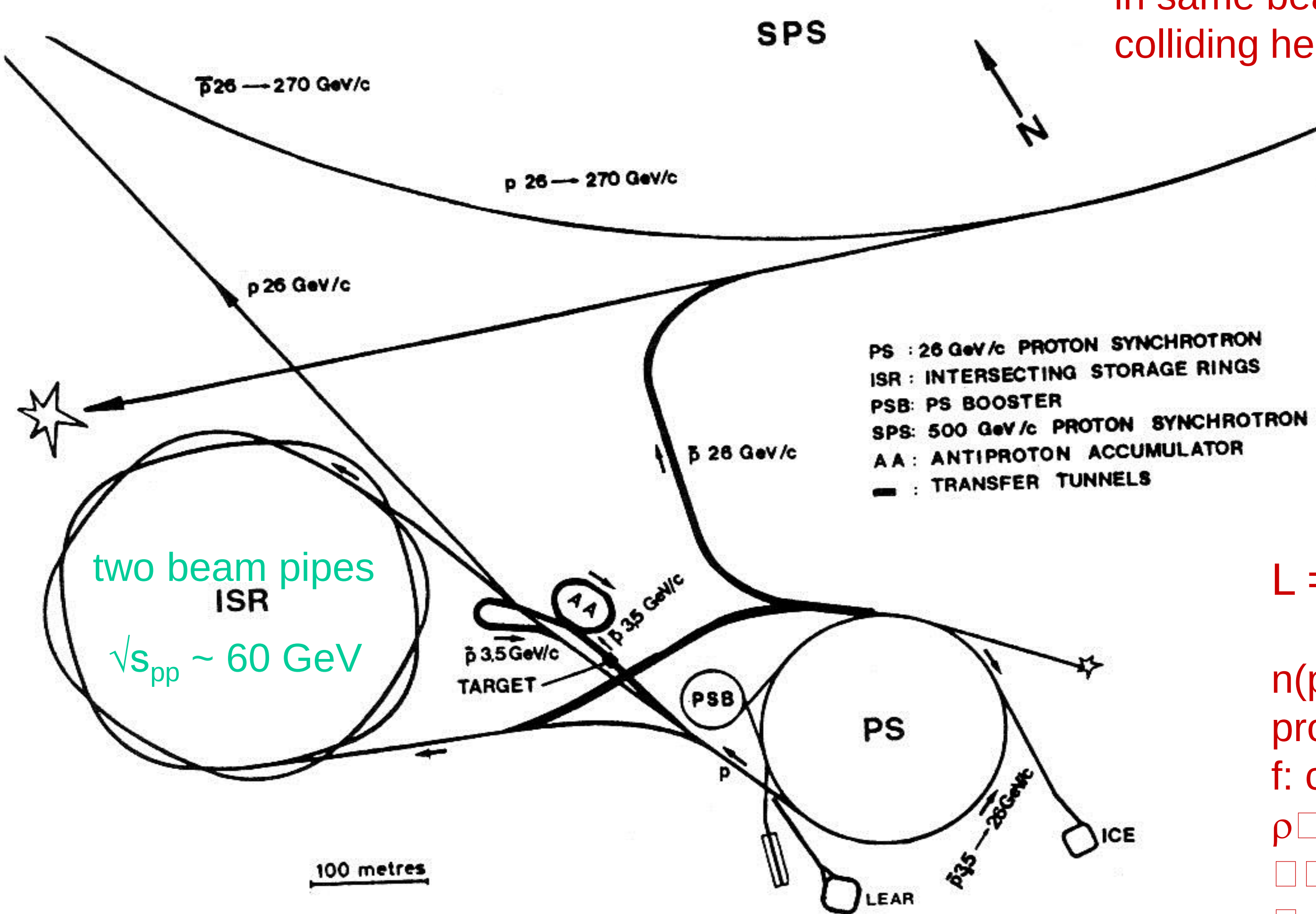
$$\sigma(\bar{p}p \to Z \to e^+e^-) \approx 50 \text{ pb} = 5 \times 10^{-35} \text{ cm}^2$$

Event rate = L σ [s^{-1}] (L ≡ luminosity)

requiring 1 event / day ➡ L ≈ 2.5 x 10^{29} cm^2 s^{-1} was needed

The CERN antiproton-proton collider complex

protons and antiprotons counter-rotating
in same beam pipe - as in an e+e- machine!
colliding head-on at √s ~ 500 - 600 GeV



two beam pipes

$\sqrt{s}_{pp}$ ~ 60 GeV

colliding head-on at √s ~ 500 - 600 GeV is equivalent to a fixed target experiment at ~ 150 TeV beam energy

Luminosity:

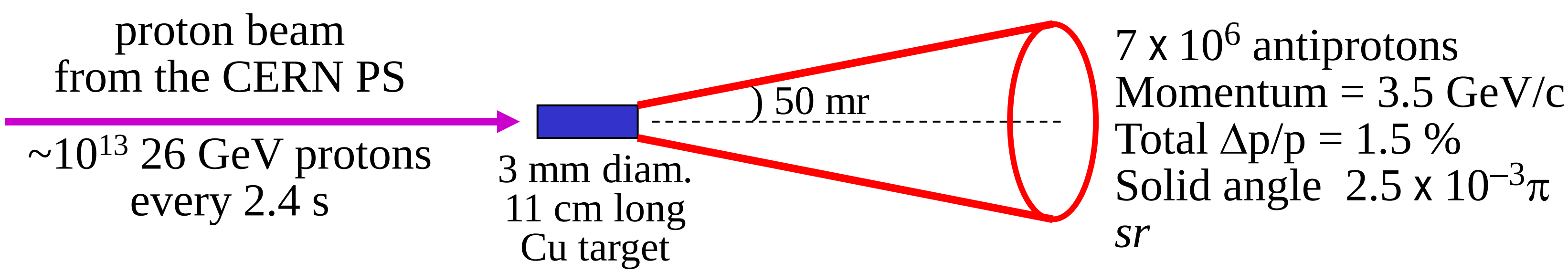
$L = n(p)n(\text{anti-}p)f/(4\pi\rho^2)$

n(p),n(anti-p): numbers of protons,antiprotons per bunch
f: circulation frequency
ρ□□□ ~ 100 μm

The transformation of the SPS into a collider at C. Rubbia's initiative was accomplished
by the summer of 1981 , in < ~ 2 years

p-pbar collider: need for cooling and operation

- Antiproton production rate : 1 antiproton (at 3.5 GeV) per 10^6 incident protons of 26 GeV on target, more precisely:

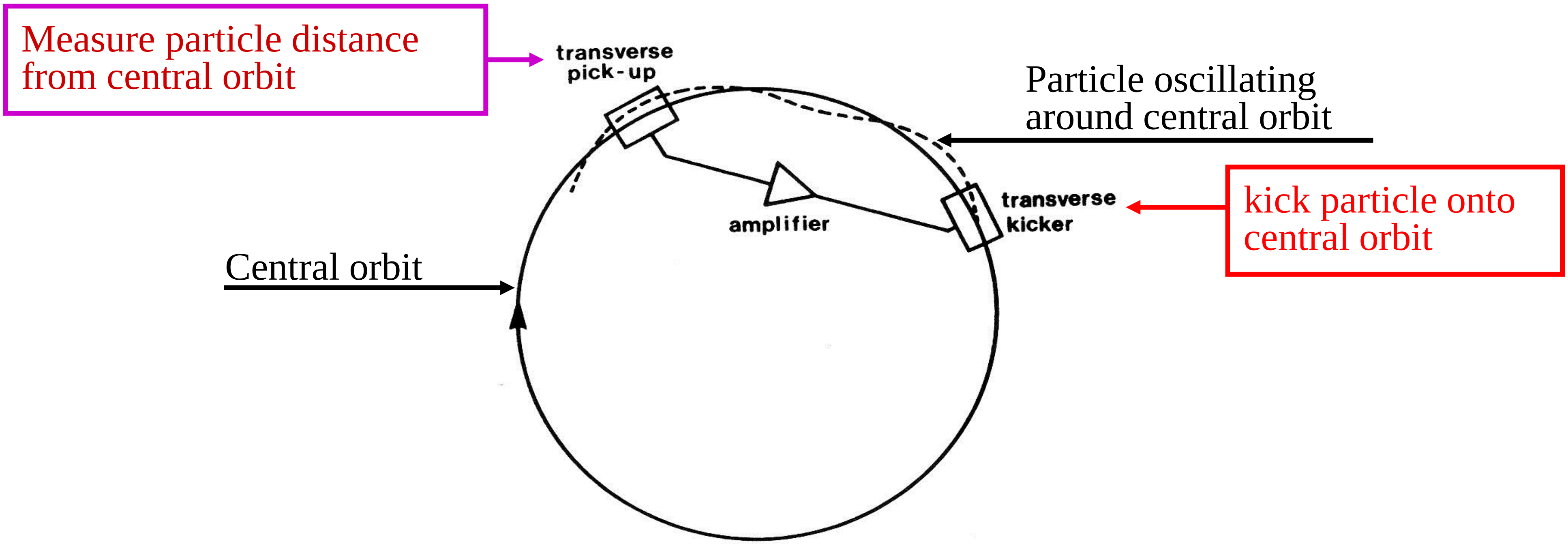


must increase the antiproton phase space density by >10^8 before sending them to the SPS! Here comes Van der Meer's "stochastic cooling"

- Collider operation: The antiprotons were stacked and stochastically cooled in the Antiproton-Accumulator (AA) at 3.5 GeV;
about 10^{11} cooled antiprotons were accumulated per day,
then reinjected in the PS, accelerated to 26 GeV and
injected in the SPS with counter-rotating protons and accelerated to 270 GeV and brought into collision at two points with center of mass energy $\sqrt{s}$ = 540 GeV (in 1984 increased to 630 GeV),
luminosity lifetime ~ one day

Stochastic cooling (Simon van der Meer)

Principle of operation: for ex. cooling in the horizontal plane:



In practice, the pick-up system measures the average distance from central orbit of a group of particles

Independent pick-up – kicker systems to cool:
- horizontal motion
- vertical motion
- longitudinal motion (decrease of $\Delta p/p$)

The CERN Antiproton Accumulator (AA)

3.5 GeV/c large-aperture ring for antiproton storage and cooling

CERN antiproton-proton collider, overview of runs 1981-90

Year	Collision Energy (GeV)		Peak luminosity ($cm^{-2} s^{-1}$)	Integrated luminosity (cm^{-2})	Int. Lumi per year (nb^{-1})	Hours realized	
1981	546	AA	$\sim 10^{27}$	2.0×10^{32}	0.2	140	jets
1982	546	AA	5×10^{28}	2.8×10^{34}	28	748	W discovery
1983	546	AA	1.7×10^{29}	1.5×10^{35}	153	889	Z discovery
1984-85	630	AA	3.9×10^{29}	1.0×10^{36}	1050	2420	B^0-$\overline{B^0}$ mixing
1987-90	630	AA+AC	$\sim 2 \times 10^{30}$	1.6×10^{37}	~16000	5140	

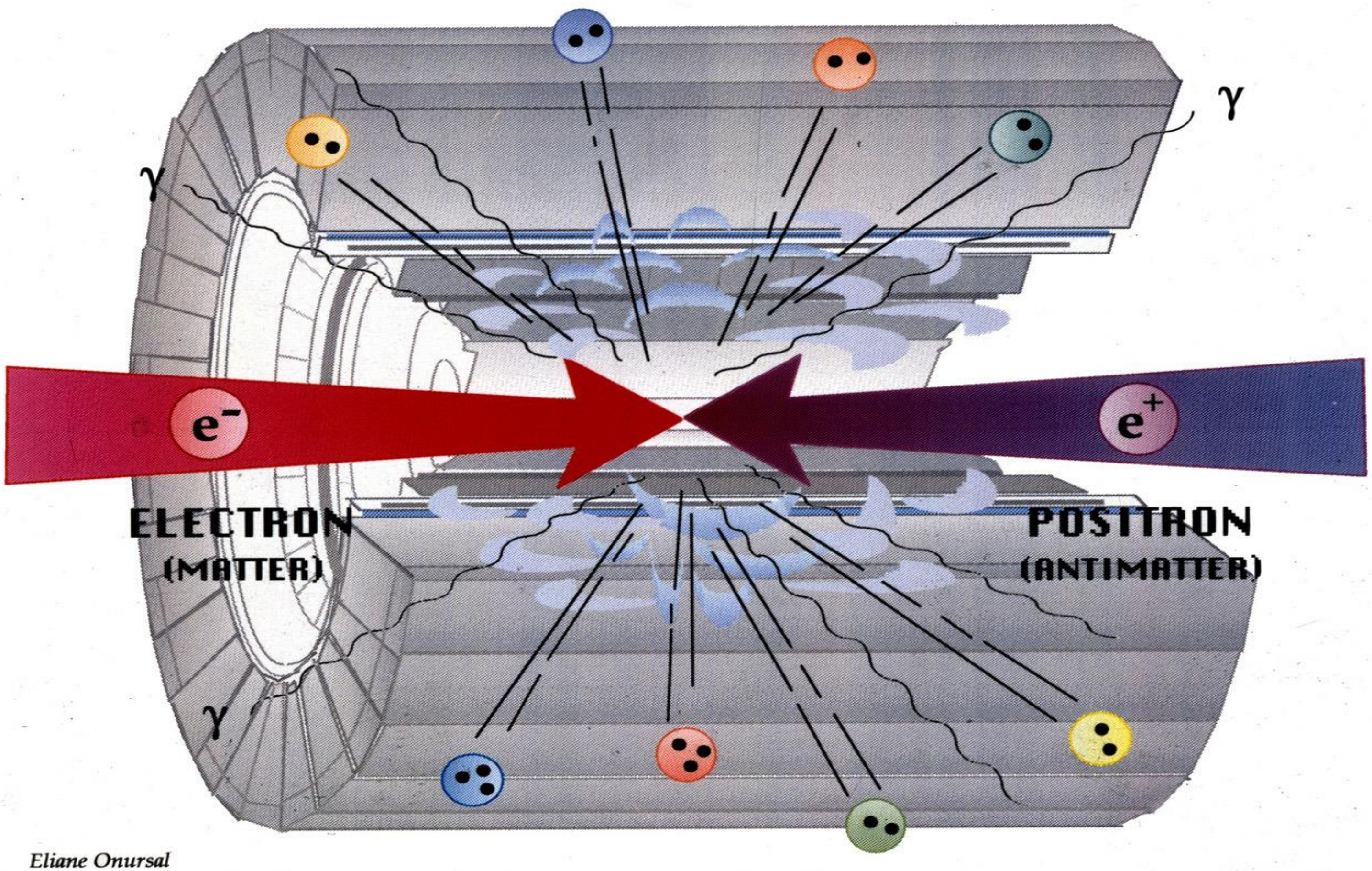
AA : Antiproton Accumulator

AA+AC : Antiproton Accumulator + Antiproton Collector

To summarize: Project approved in 1978,
First collisions in July 1981
Record luminosity 6 $\times 10^{30} cm^{-2} s^{-1}$ - in 1990
Collider stopped in 1991, due to Tevatron competition, start-up of LEP

What is a particle physics detector?
(configuration appropriate for a collider)

Beam from accelerator



Beam from accelerator

Beams can be with e^{+-}, protons anti-protons nuclei/ions….

The goal is to measure and identify all particles emerging from the interaction point

Le détecteur UA1 (Underground Area 1)

UA1 detector:

~10 x 6 x 6 m^3,

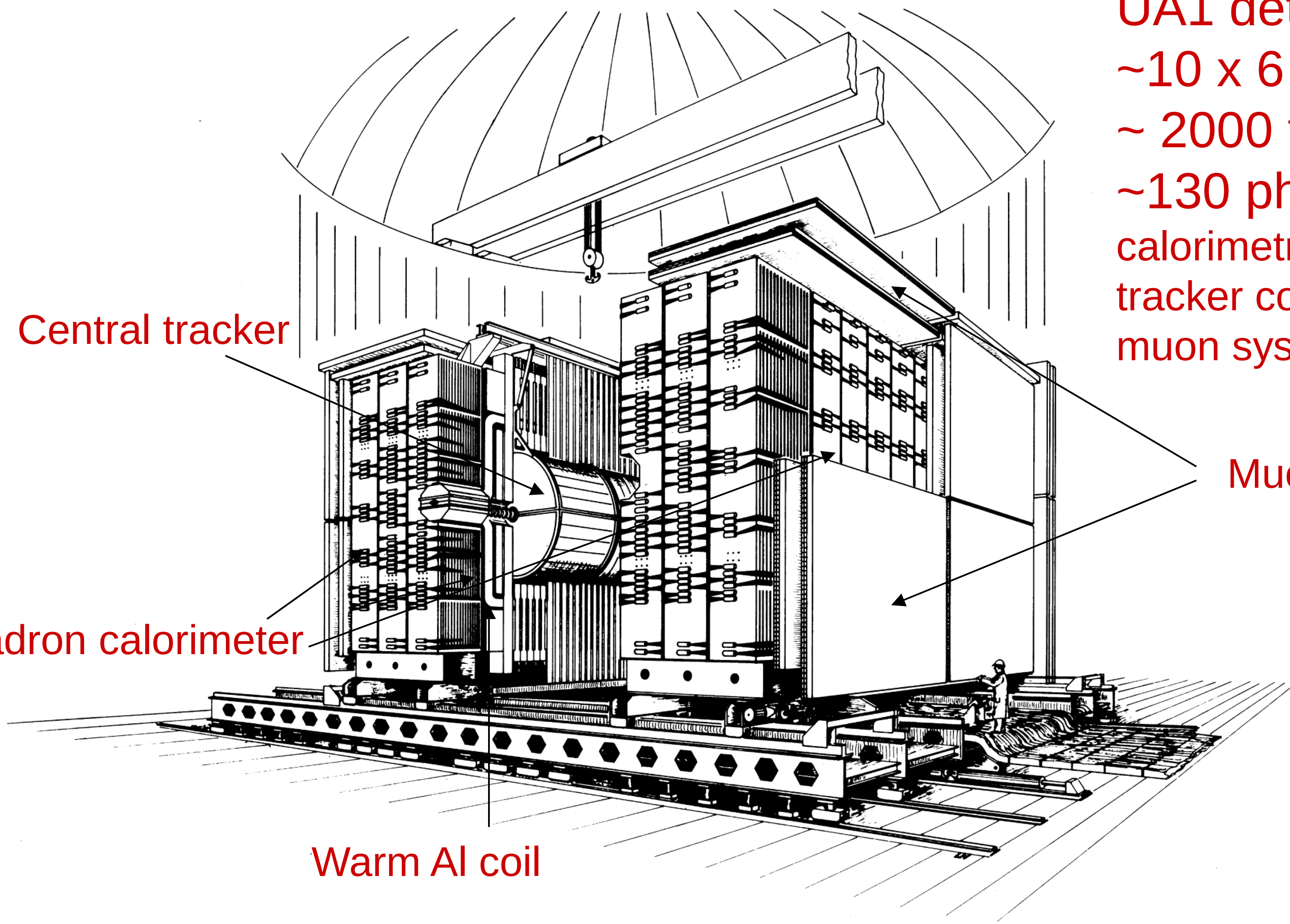
~ 2000 tons

~130 physicists

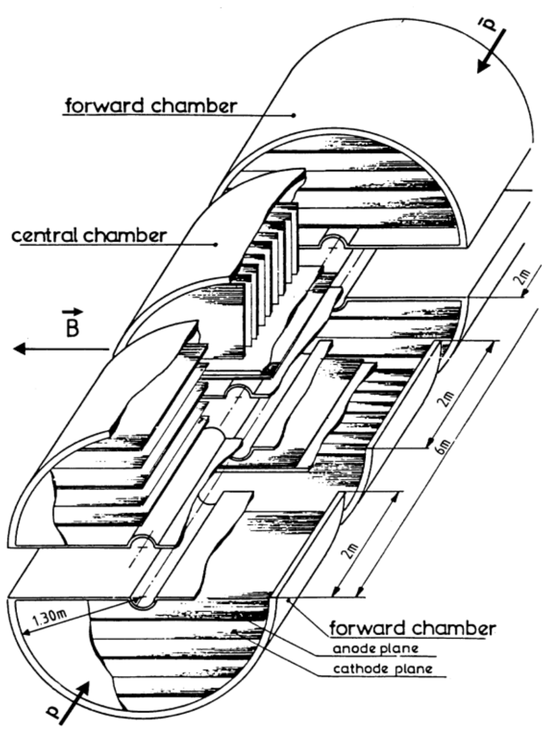
calorimetric coverage |η|< 5.0

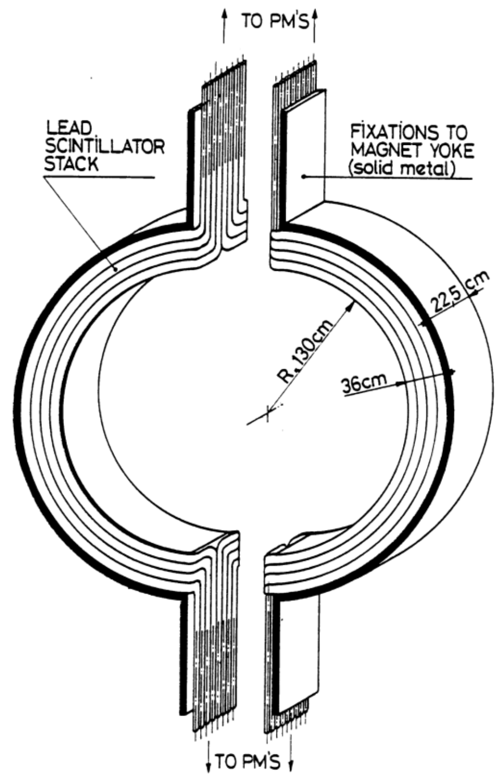
tracker coverage |η|< 3.0

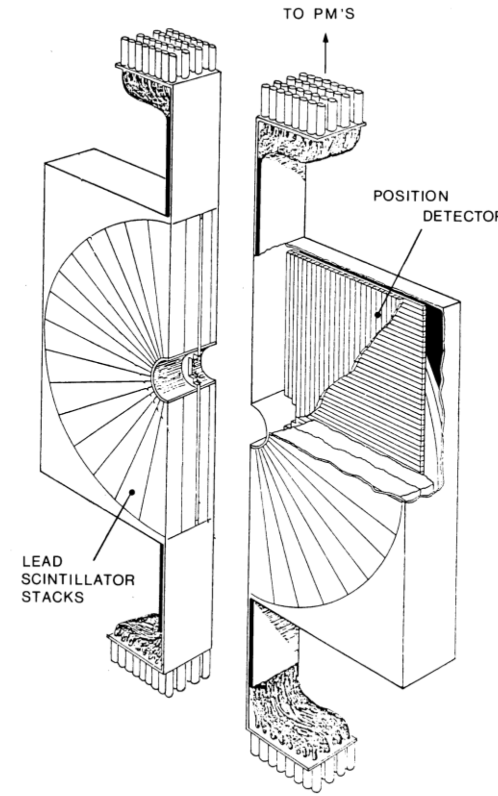
muon system coverage |η|< 2.3



The UA1 detector
key components: Electromagnetic Calorimeter and Tracker



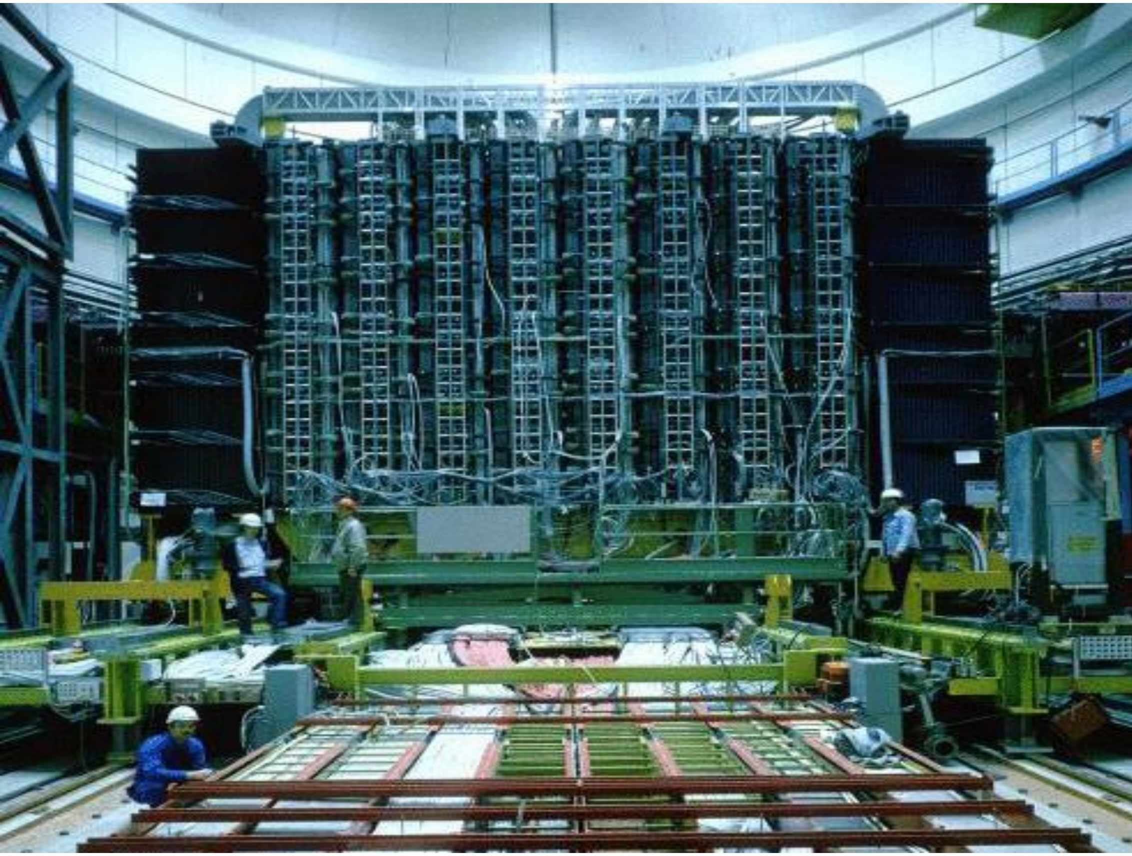




UA1 tracker: Imaging drift chamber, 6m long, 2.3m in diameter, 6176 sense wires, wires every cm,up to 180 hits per track,maximum drift distance 18cm i.e. 4μsec drift time,acceptance |η| < 3.0

ECAL (2x24 gondolas)
Scint.-Pb sandwich, 1.2mmPb/1.5mmSci
$\Delta\phi\Delta\eta = 180^o \times 0.14$; $27X_0$ deep, four segments in depth
+ 2x32 radial sectors in end-caps (bouchons)
ECAL acceptance: |η| < 3.0
Resolution for electrons/photons: $\Delta E/E \approx 14\%/\sqrt{E} + 3\%$(sust)

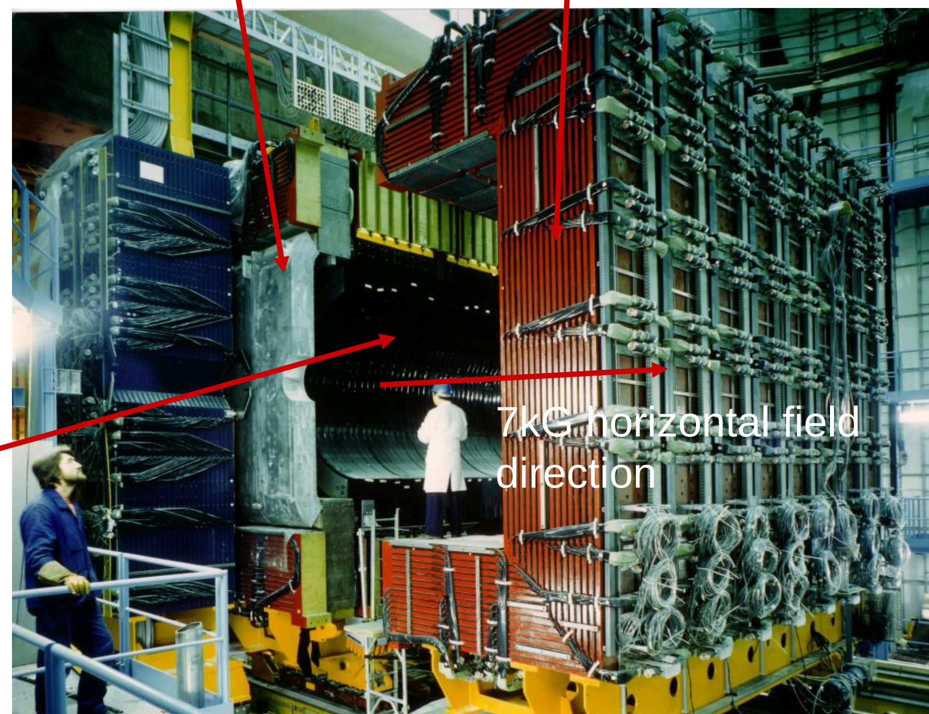
UA1 detector under construction (1979/81!!!)



UA1 detector: ~10 x 6 x 6 m^3,
~ 2000 tons ~130 physicists
calorimetric coverage $|\eta|< 5.0$
tracker coverage $|\eta|< 3.0$
muon system coverage $|\eta|< 2.3$

warm Al coil,
7kG horizontal field,

HCAL
5cm iron/1cmScint.
3.5 λ_{int} deep

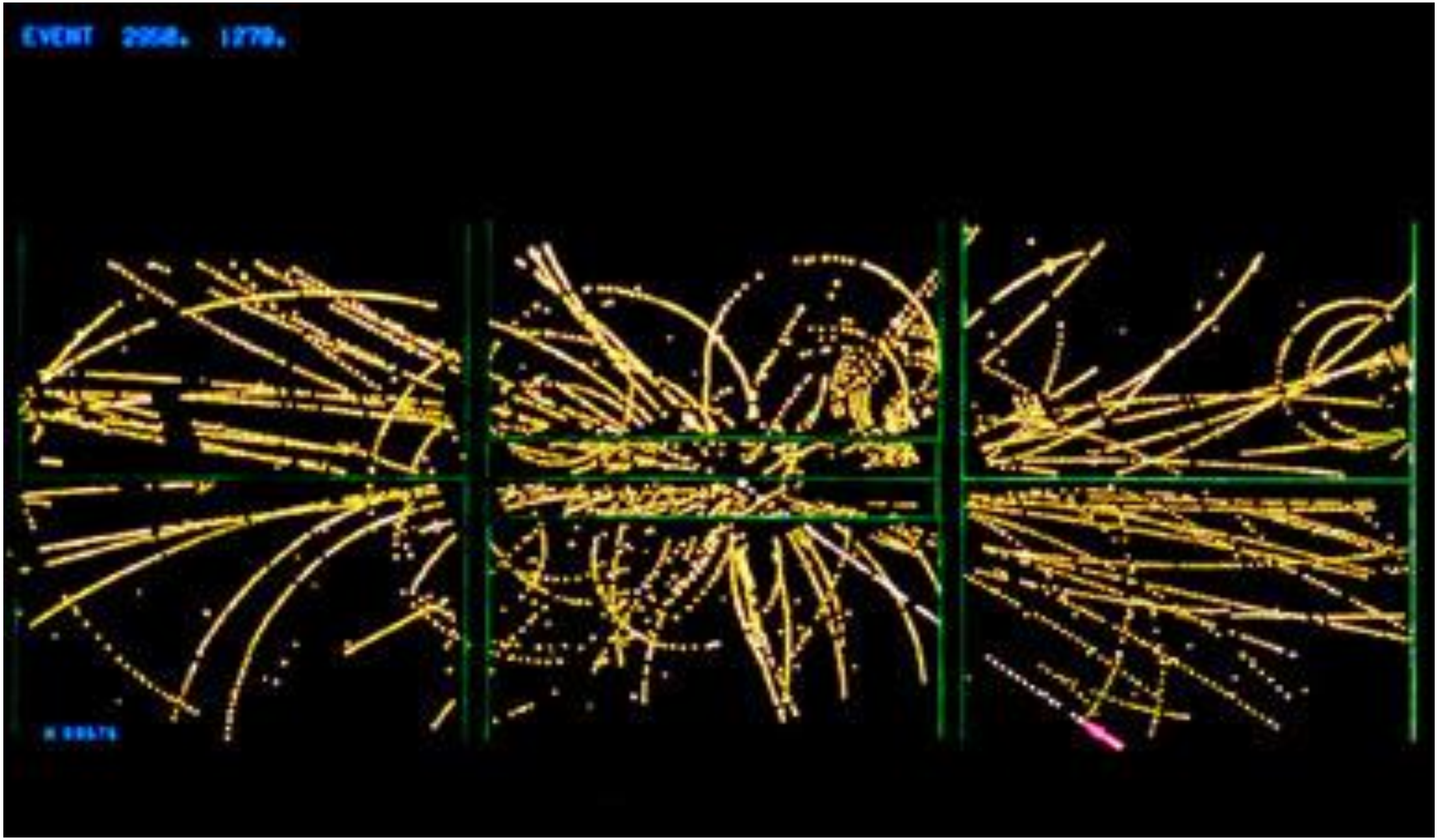


UA1 designed and built in < 3 years!!

ECAL (2x24 gondolas) Scint.-Pb sandwich
1.2 mm Pb/1.5 mm Sci $\Delta\phi\Delta\eta$= 180^o x 0.14
27X_0 deep, four segments in depth + 2x32 radial
sectors in end-caps acceptance $|\eta| < 3.0$

W $\rightarrow$ eν candidate in UA1 tracker

No visible jet on the away side!



W candidate in UA1 tracker

The first major success: first observation of hadronic jets at the antiproton-proton collider - summer 1982

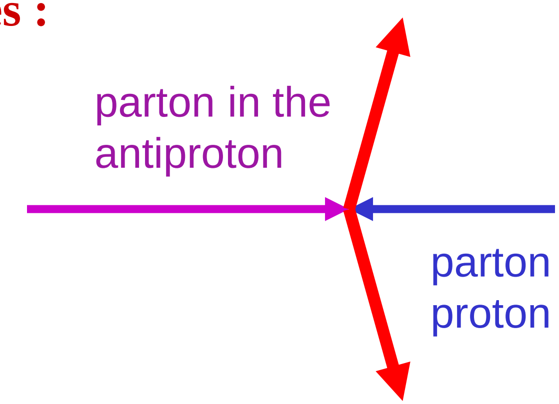
Not totally sure that jets would be seen in hadron collisions (NA35)

….

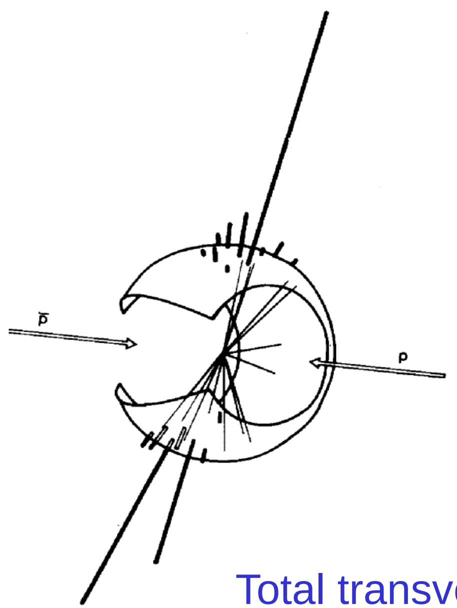
- but already seen in e+e- however!

Elementary processes :

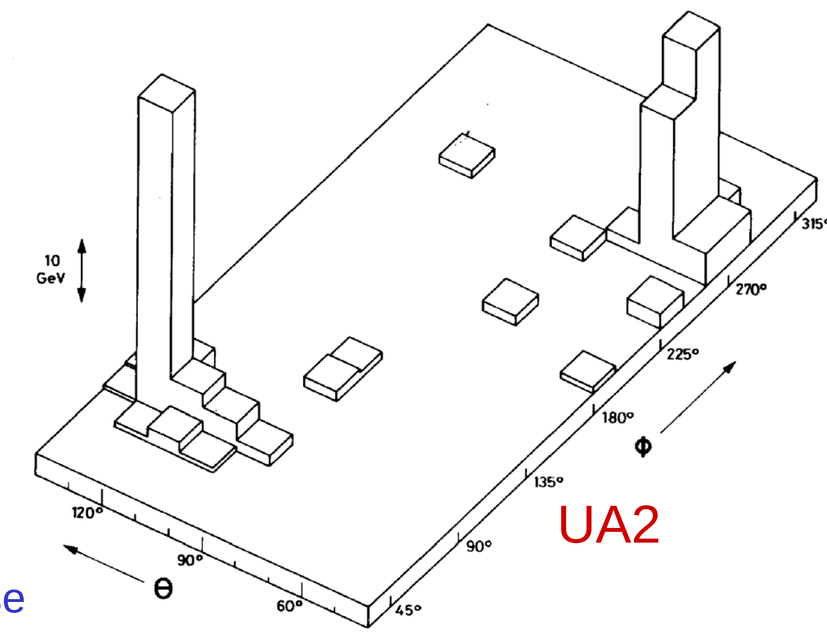
$$\bar q + q \to \bar q + q$$
$$\bar q + g \to \bar q + g$$
$$g + q \to g + q$$
$$g + g \to g + g$$
$$\bar q + q \to g + g$$
$$g + g \to \bar q + q$$



First evidence for jets in hadron colliders, December 1981 run, spectacular UA2 early jet event in calorimeters, Paris conf. summer 1982



Total transverse energy ~ 140 GeV



UA2

W search, missing-E_t method

Search for leptonic decays: $W^{+-} \rightarrow e^{+-} + \nu_e$ $\quad W^{+-} \rightarrow \mu^{+-} + \nu_\mu$

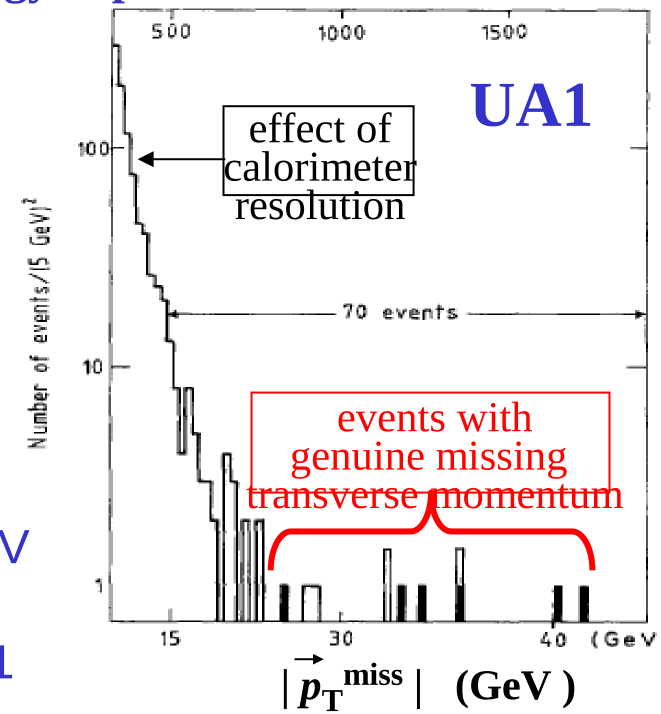
- Collider run of Nov./Dec. 1982, 18nb^{-1} of data collected, as $\sigma_W BR(W \rightarrow l\nu) \sim 0.5$nb → few W leptonic events expected! How to select them?
- The initial search/selection in UA1 went through the "missing E_t" road ("Saclay method"):

Missing transverse momentum ($\vec{p}_T^{\,miss}$):

- **Associate momentum vector $\vec{p}$ to each calorimeter cell with energy deposition > 0**
- **Direction of $\vec{p}$ from event vertex to cell centre**
- **$|\vec{p}|$ = energy deposited in cell**
- **Definition:**

$$\vec{p}_T^{\,miss} + \sum_{cells} \vec{p}_T = 0$$

just momentum conservation In the transverse plane! the neutrino taking away the missing momentum (when real)



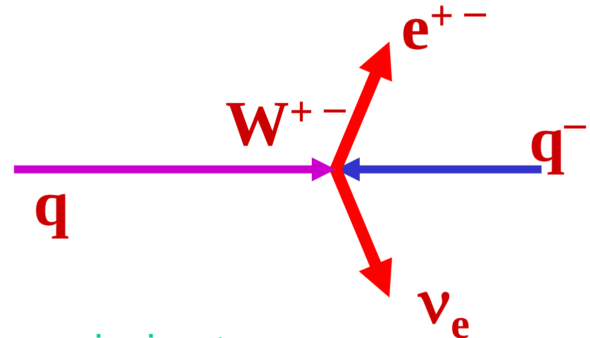
- In UA1 calorimetric coverage down to 0.2 degrees to beam i.e. acceptance $|\eta| < 5.0$, → resolution on missing-E_t ~ 6 GeV (in UA2 in was significantly worse ~ 20 GeV)

$\sigma(E_t^{missing}) = 0.65 \sqrt{\Sigma E_t}$ (in GeV) in UA1

W discovery, first W $\rightarrow e\nu$ events, run of 1982

Search for leptonic decays:

$W^{+-} \rightarrow e^{+-} + \nu_e$ $\quad$ $W^{+-} \rightarrow \mu^{+-} + \nu_\mu$



- UA1 W $\rightarrow e\nu$ initial selection cuts:

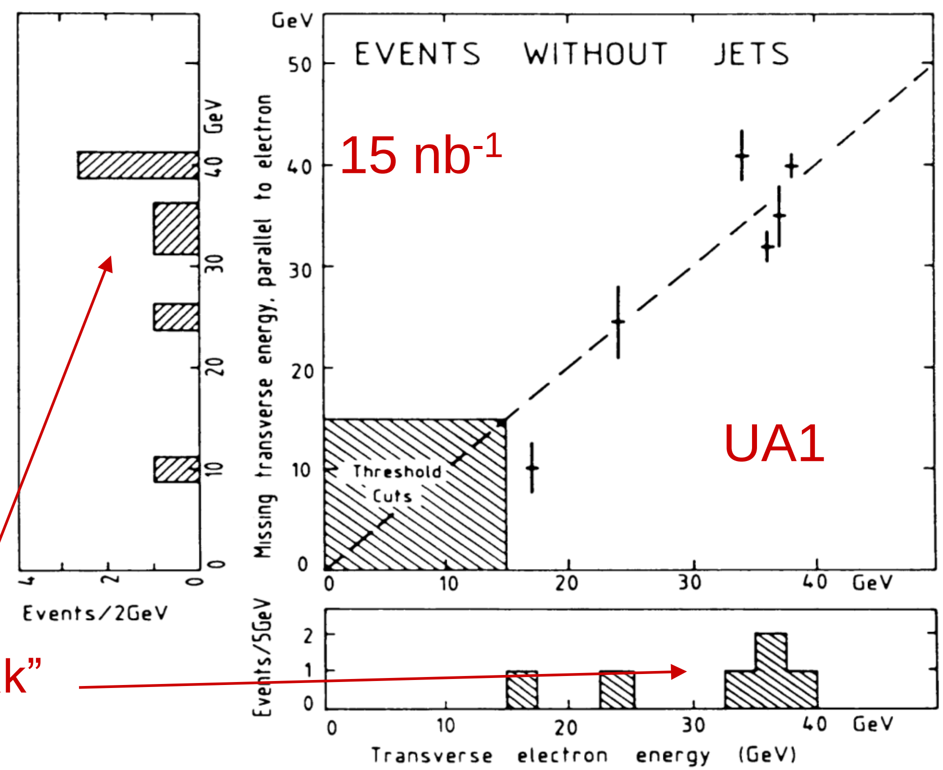
$E_t^{miss} > 15$ GeV (resolution in UA1 ~ 6 GeV),
$E_t^{ECAL} > 15$ GeV (cluster in 1 or 2 gondolas),
single hard track ($p_t > 7$ GeV) pointing to ECAL cluster,
no jet back-to back to e^{+-} candidate,

➡ 6 events selected (5 W$\rightarrow e\nu$ + 1 W$\rightarrow \tau\nu$)

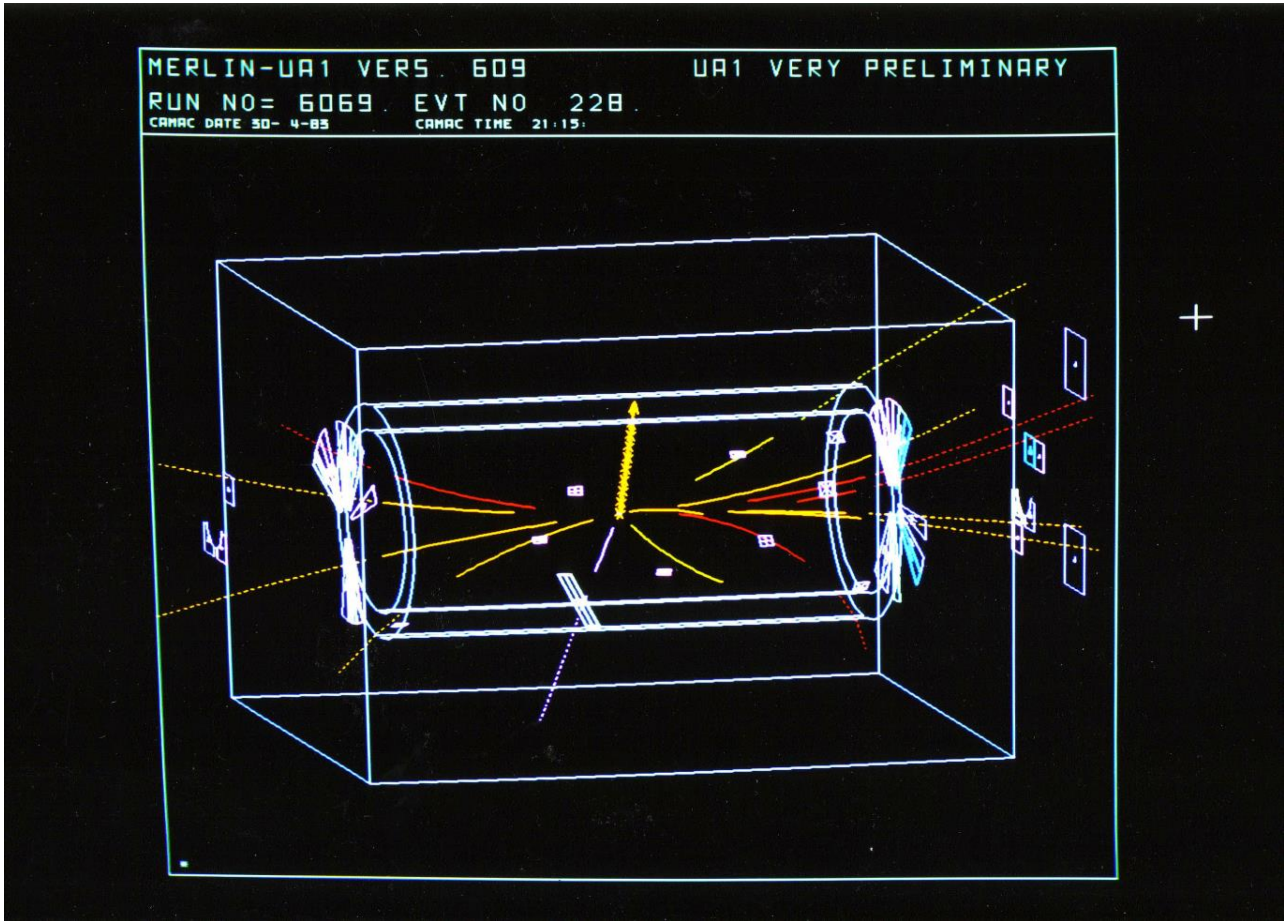
➡ $m_W = 81 \pm 5$ GeV (UA1)

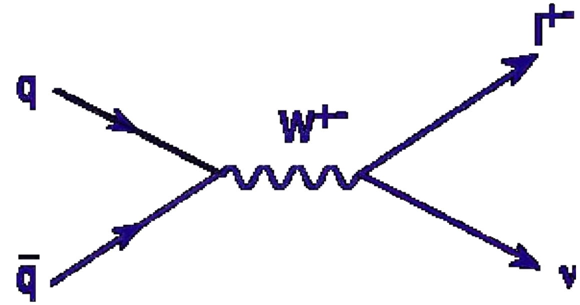
from first "Jacobian peak"

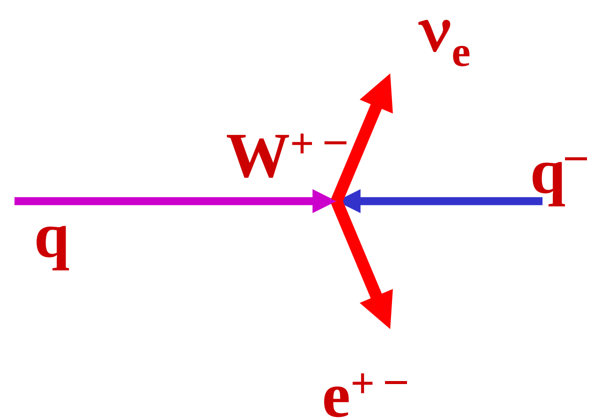
Correlation between missing transverse energy and e^{+-} transverse energy for the first W events



First W → eν events in UA1 (Jan.1983)





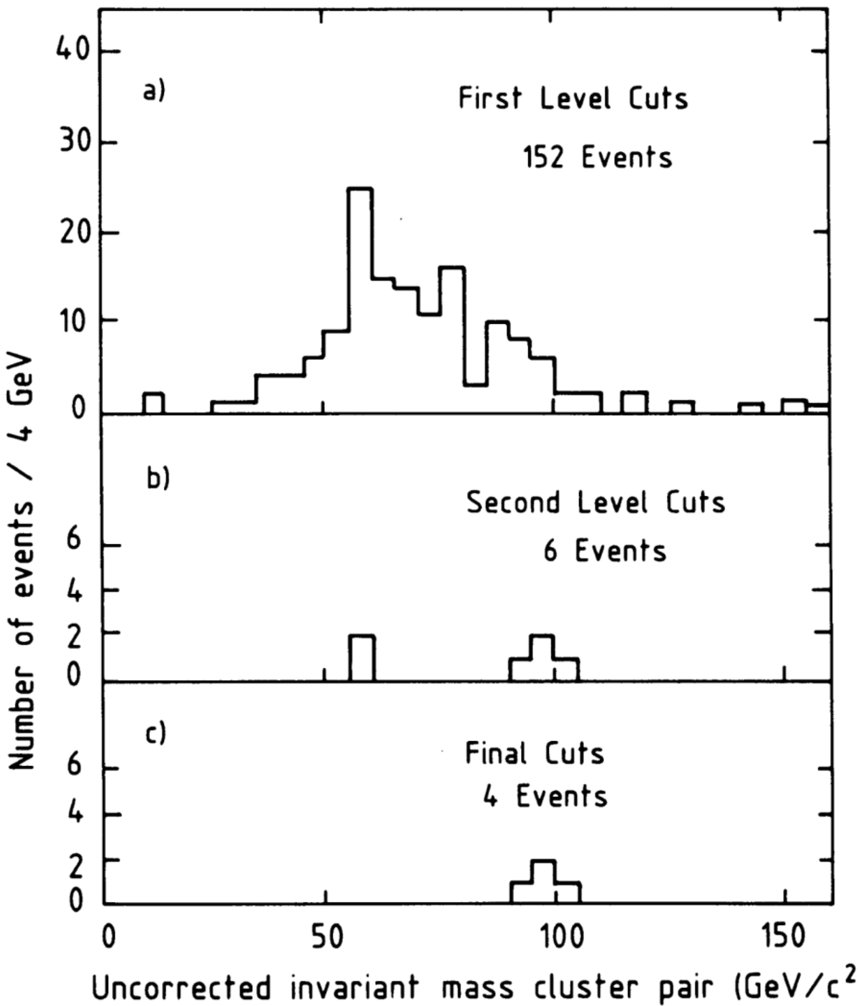


One of the very first W to eν events seen in UA1, as visible on the interactive graphic display (Megatek). There was a color coding for tracks and energy deposits in calorimetric cells. The high momentum electron track is pointing almost downwards towards a large energy deposit in a "gondola" (oblong white rectangle). The missing transverse energy vector is the heavy arrow pointing upwards.

Z discovery in UA1, run of 1983

- Collider run of April/May 83: peak luminosity 1.5 x 10^{29}, 3 on 3 bunches, 118 nb^{-1} of data

collected by UA1, as $\sigma_Z BR(Z \rightarrow ll) \sim 0.05nb$ $\rightarrow$ few leptonic Z events expected!
How to select them? "express" line in UA1 trigger/DAQ……..



Selection steps for the electron channel:

Two energy clusters (p_T > 25 GeV) in electromagnetic calorimeters; energy leakage in hadronic calorimeters consistent with electrons

Isolated track with p_T > 7 GeV pointing to at least one cluster and small HCAL deposition behind cluster

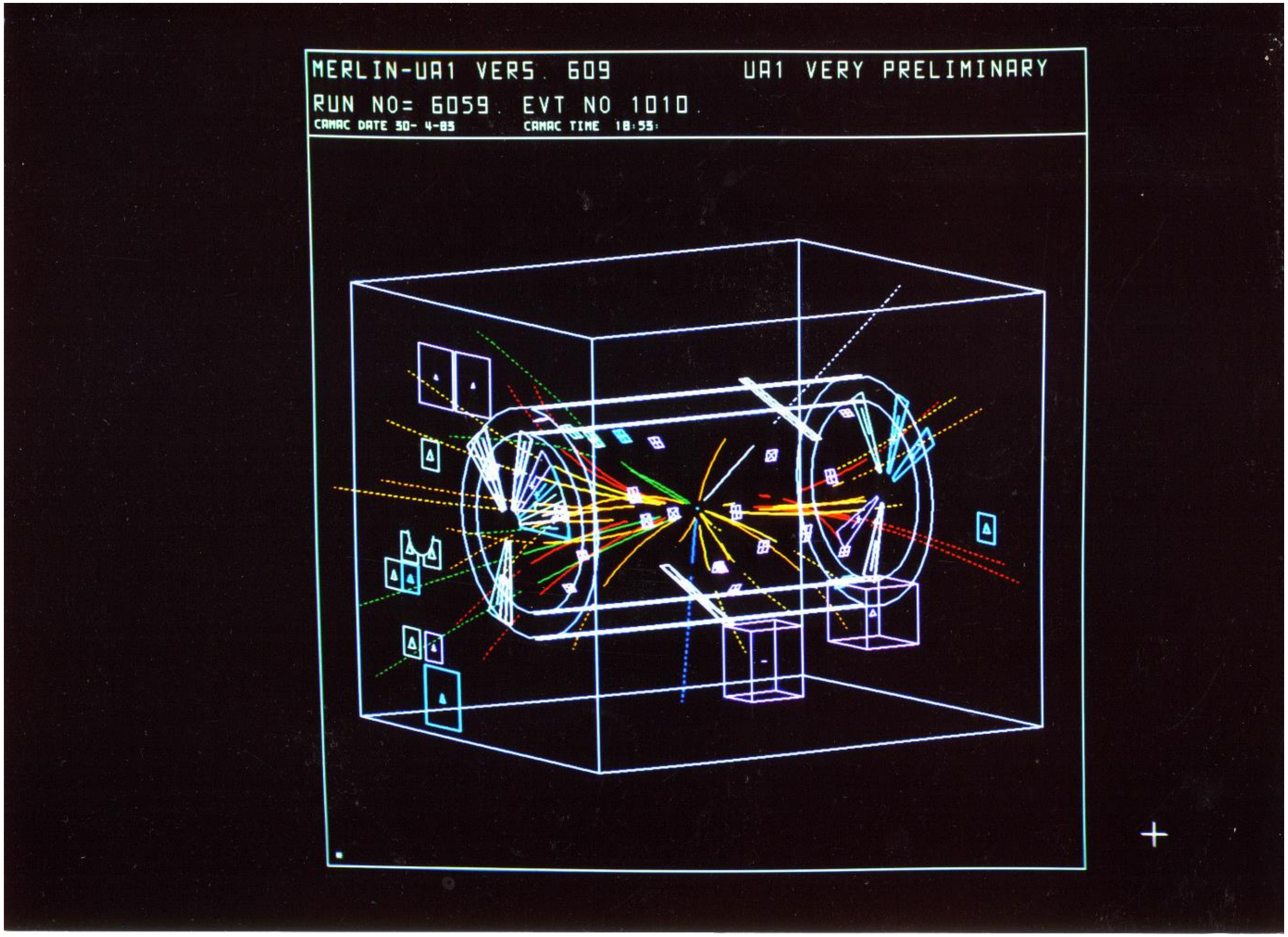
Isolated track with p_T > 7 GeV pointing to both clusters

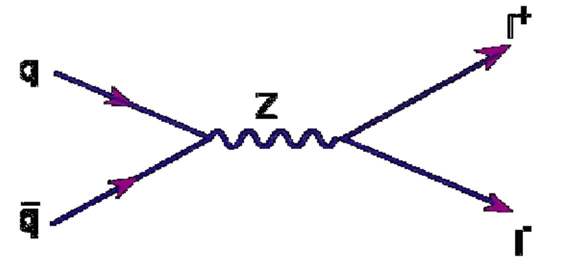
➡ 4 $Z \rightarrow e+e-$ events selected - with no visible background - with already 55nb^{-1}, published right away, during run, with 1 $Z \rightarrow \mu+\mu-$

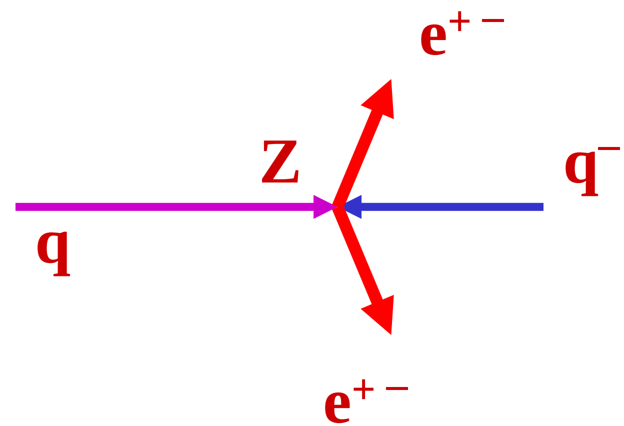
➡ $m_Z = 95.5 \pm 2.5 \pm (3.0)$ GeV (UA1)

$\sigma_Z BR(Z \rightarrow ll) = 41 \pm 21 (\pm 7)$ pb

First Z $\rightarrow$ e^+e^- events in UA1 (May 1983)





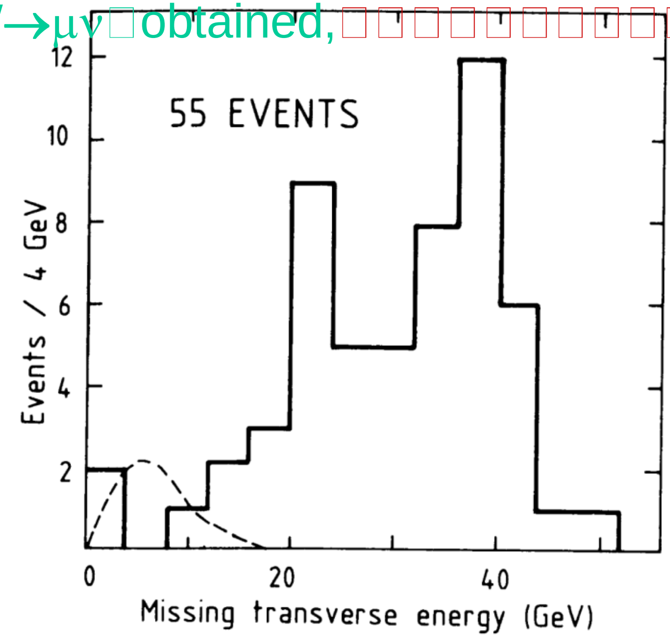


One of the first Z to e^+e^- events seen in UA1, as visible on the Megatek. The high momentum e^+ and e^- tracks are straight and pointing to large energy deposits in two "gondolas" in white. Smaller momentum tracks and energy deposits are also color coded.

$W \rightarrow e\nu$ events, UA1, run of 1983

- The collider run of April/May 83 allowed also a beautiful confirmation of the W signal!

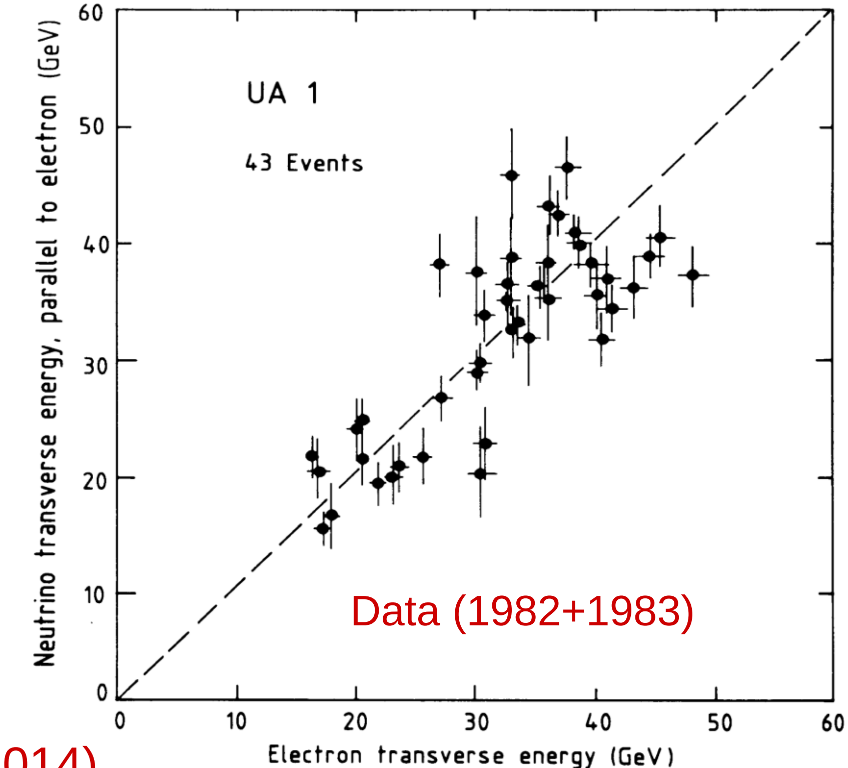
54 $W \rightarrow e\nu$ □□□□□□□□□□□□□, first
$W \rightarrow \mu\nu$ □obtained,□□!



Data (1982+1983)

clear Jacobian peak!

Correlation between missing transverse energy and e^{+-} transverse energy



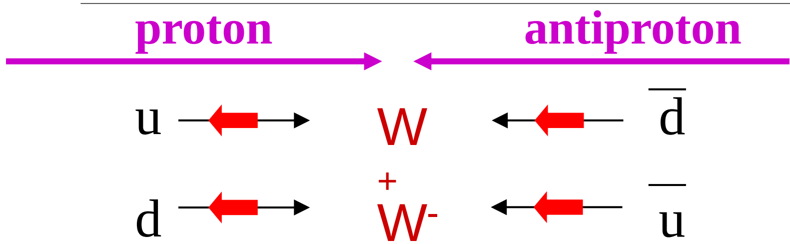
Data (1982+1983)

$m_W = 80.3 + 0.4 - 1.3$ (stat) $\pm$ (3.0 syst.) GeV
$\Gamma_W < 7$ GeV (90%CL) (UA1),

$\sin^2\theta_W = [(38.5 \text{ GeV})/m_W]^2 = 0.226 \pm 0.008 (\pm 0.014)$

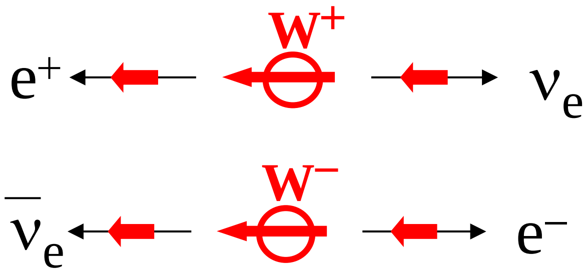
$\sigma_W BR(W \rightarrow e\nu) = 0.53 \pm 0.08 (\pm 0.09)$ nb to be compared to $\sigma_{th} = 0.4$ nb

W confirmation, V-A asymmetry in UA1, spring 1983



The almost complete $W^{\pm}$ polarization along antiproton direction was a consequence of V–A coupling - and of the collider cm energy ~ 500 - 600 GeV guarantying valence quark fusion into W (x_q, x_{anti-q} ~ m_W / $\sqrt{s}$ ~ 0.2), combined with V-A in decay results in leptonic ang. asymmetry!

In the W rest frame:



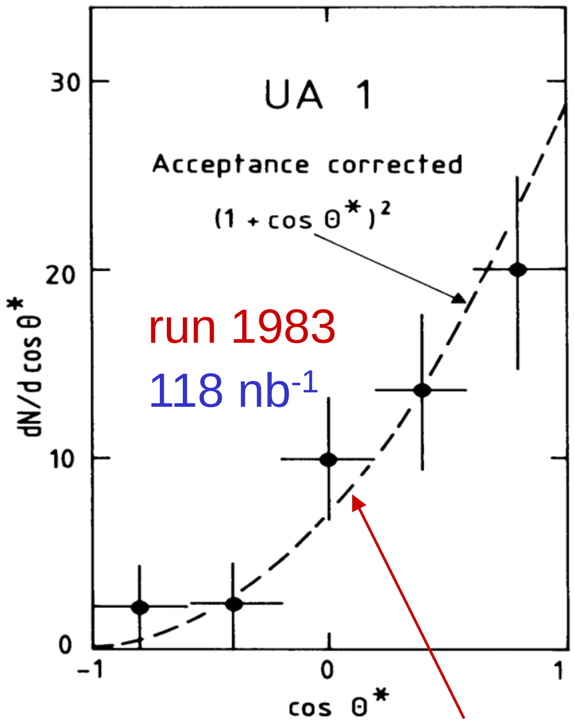
Electron (positron) angular distribution:

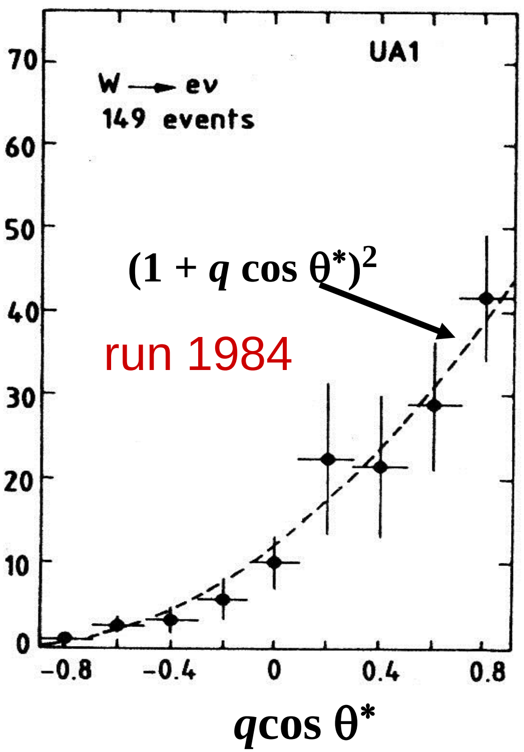
$$\frac{dn}{d\cos\theta^*} \propto \left(1+q\cos\theta^*\right)^2$$

q = +1 for positrons; q = -1 for electrons

θ^* = 0 along antiproton direction

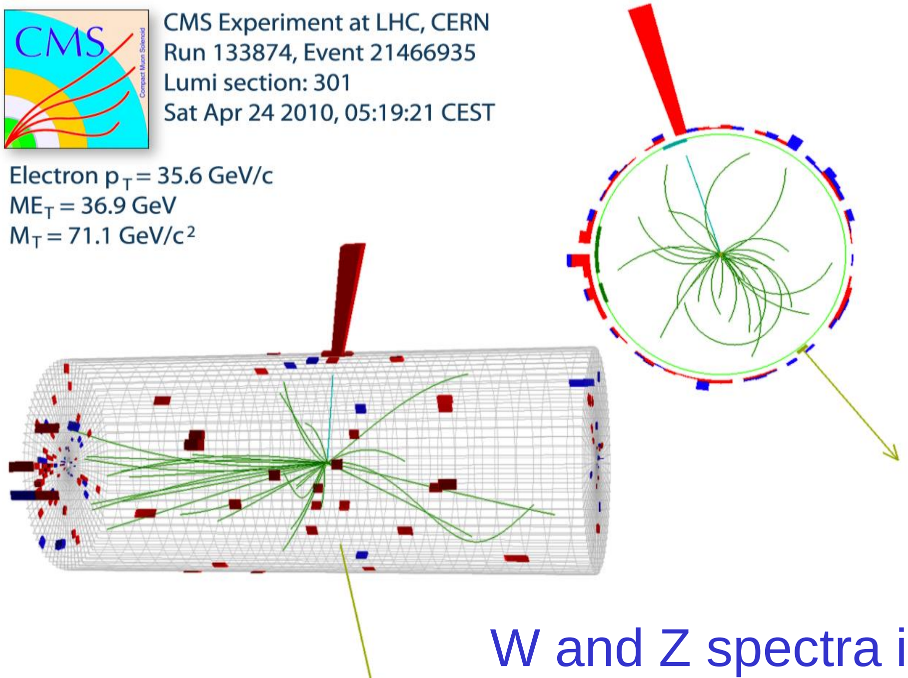
magnetic field of UA1 crucial for this!

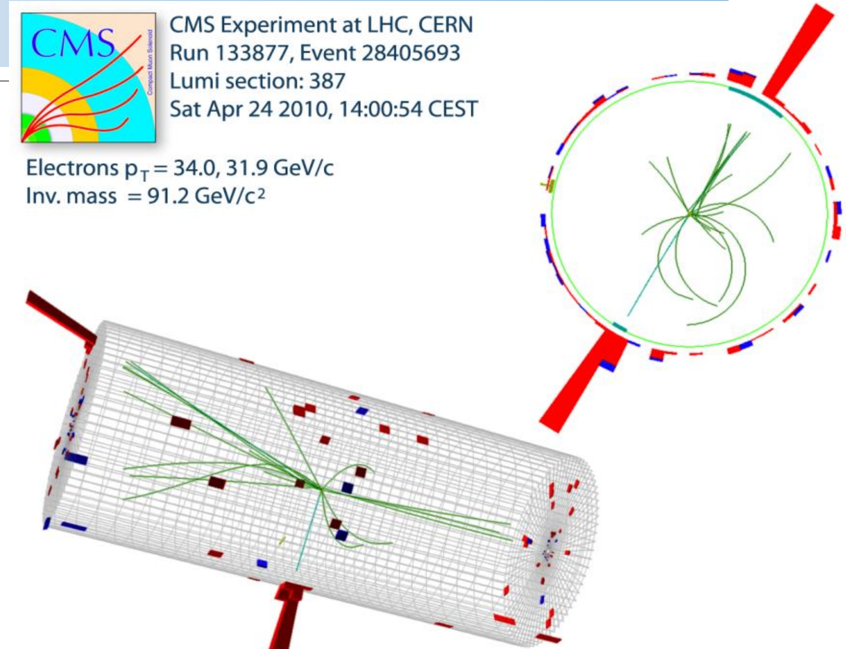




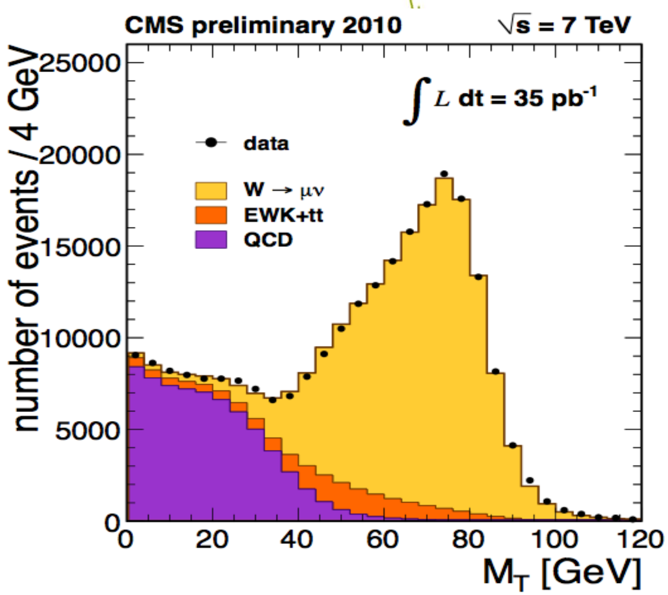
→ it is really THE W (spin =1, max. parity violation)!

First W → eν and Z → e⁺e⁻ events in CMS, April 2010

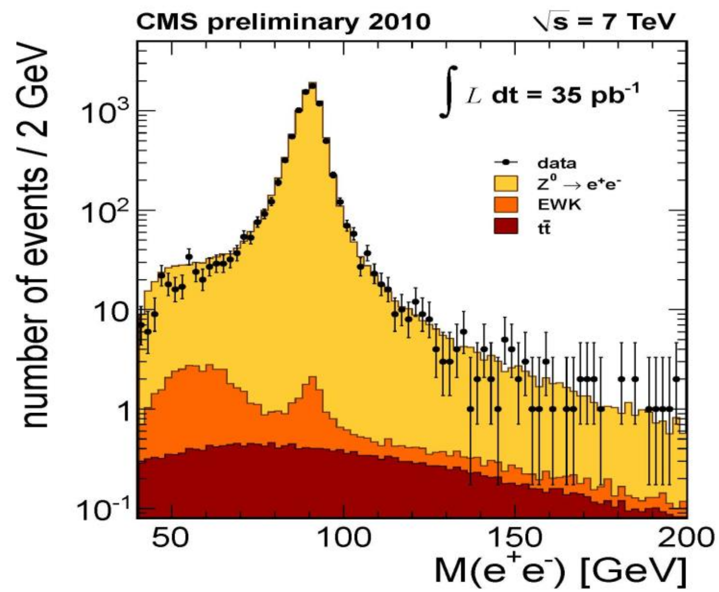




W and Z spectra in CMS, Nov. 2010



By end 2012 we had ~150.000.000 W and ~15.000.000 Z decaying leptonically



D

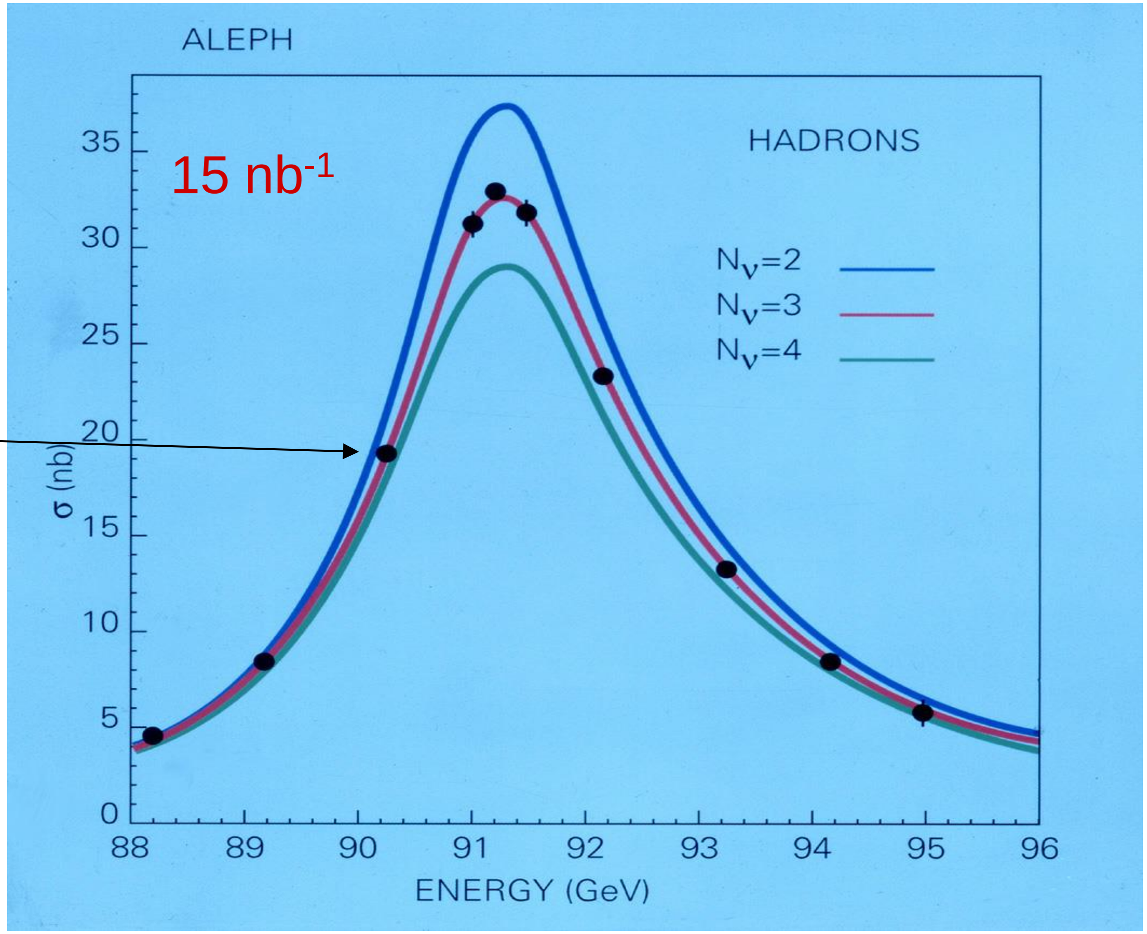
The Z at LEP (the Breit-Wigner shape) 1990/95 and counting the number of neutrino types

LEP: Large Electron Positron collider, operated from 1990 till 2000

UA1/2: $Z \rightarrow e^+e^-$

LEP: $e^+e^- \rightarrow Z$

LEP data on Z few years later!!



Altogether ~ 80 million Z's produced at LEP and ~ 17.000 W's

Tevatron has by now produced ~ 2 million W's decaying leptonically

➡ Three neutrino species! 15 nb^{-1}

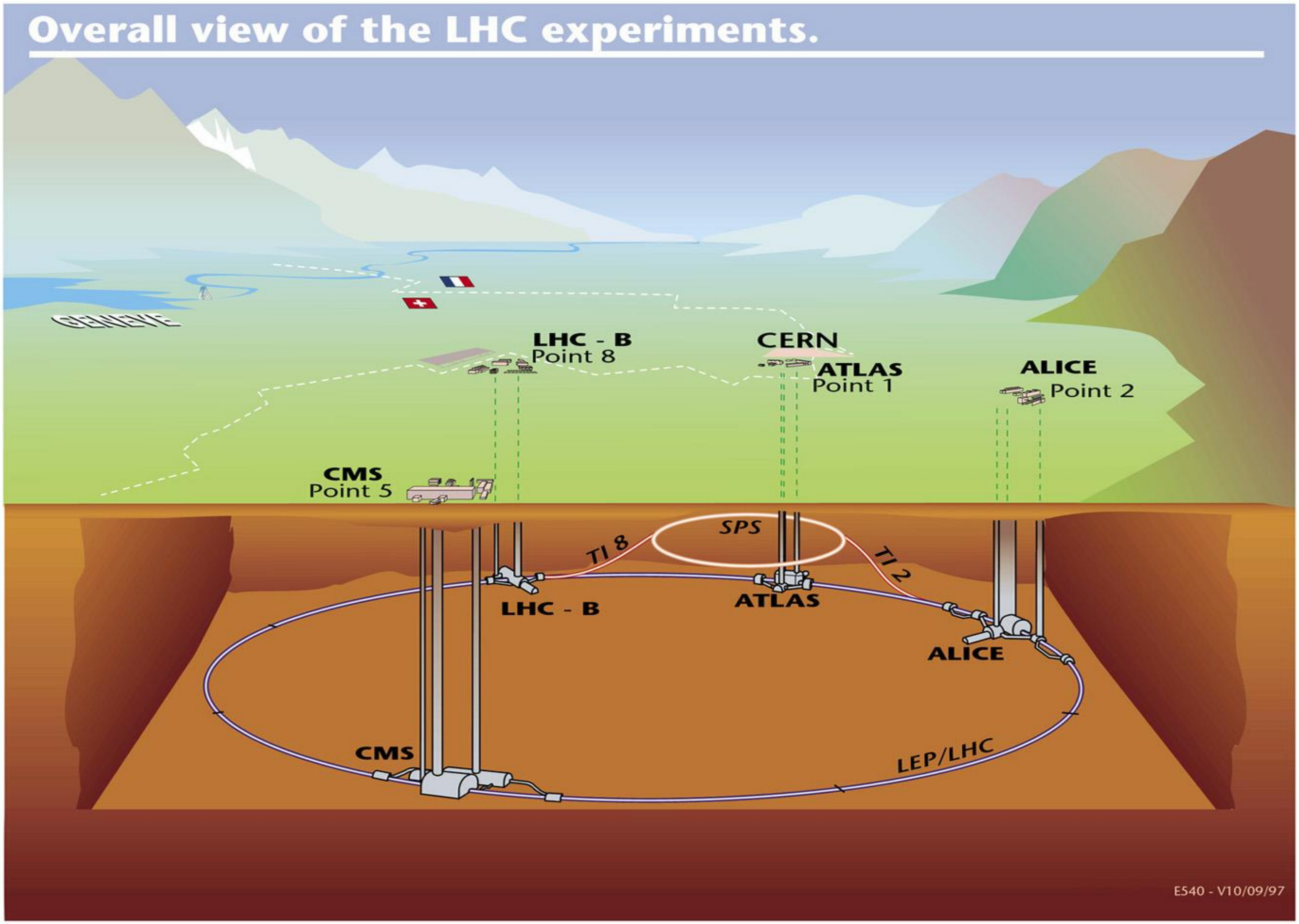
main LEP result: consolidation of the SM!!

The Large Hadron Collider (LHC) project and the CMS detector

The Large Hadron Collider (LHC) site - near Geneva

The project started in 1989….at the initiative of C. Rubbia (CERN-DG)
ECFA Conference in Aachen, October 1990 the real start-up

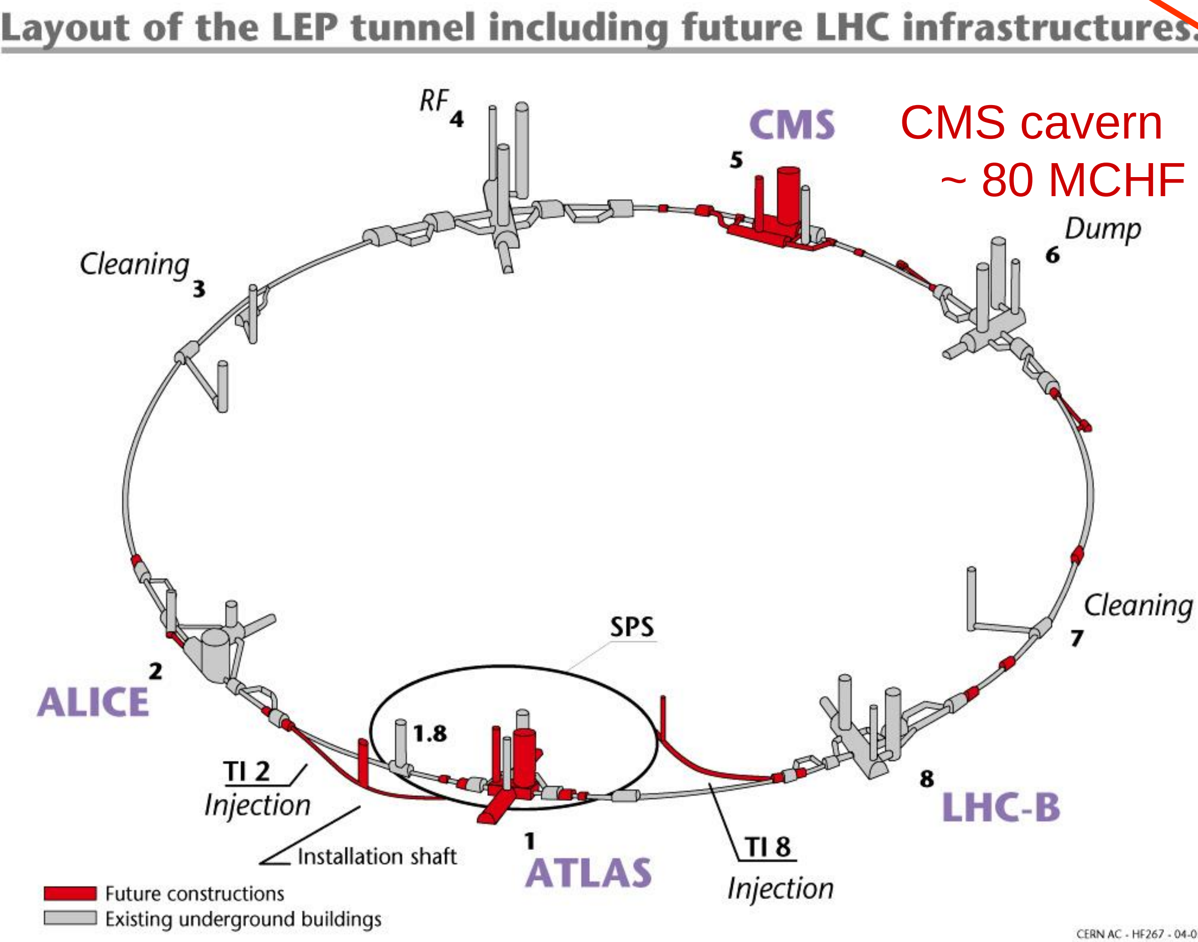
LHC and experiments

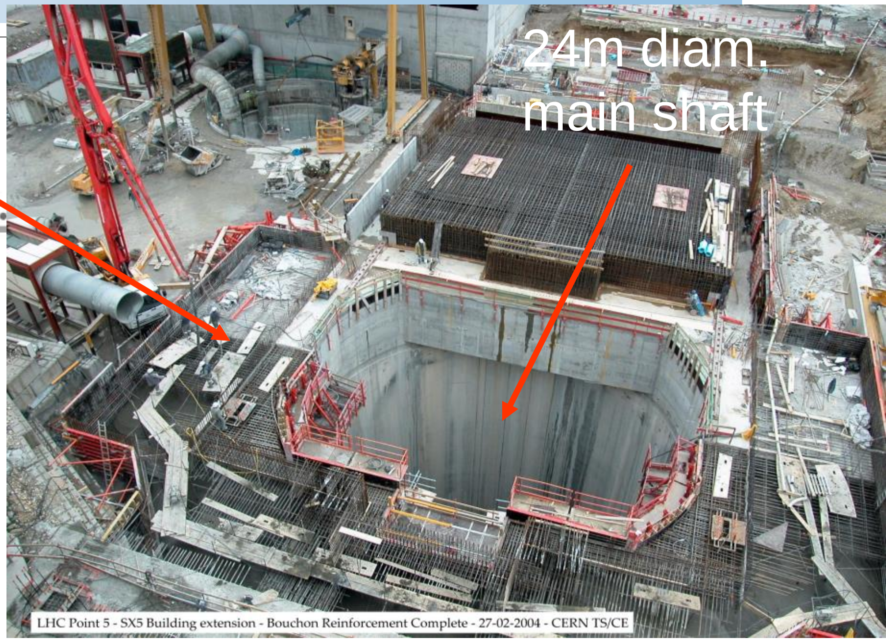


LHC infrastructures - a very major undertaking

Freeze-out of soil to
-70^{o}C before concreeting

CMS cavern
~ 80 MCHF

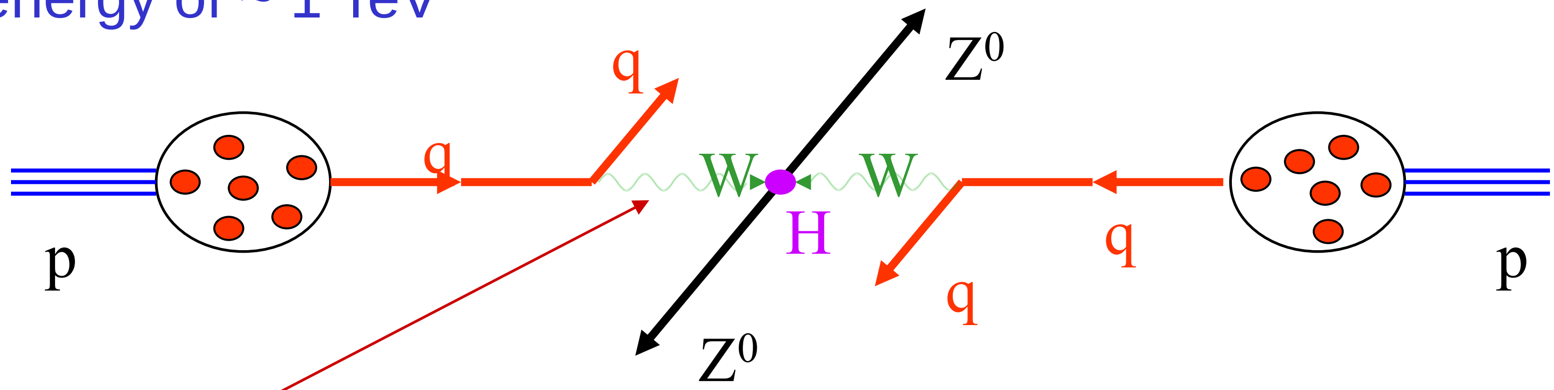




ATLAS cavern finished in May 2003
cost ~ 100 MCHF

The LHC: required energy and luminosity

- To solve ew symmetry breaking need to study W_L-W_L scattering at a centre of mass energy of ~ 1 TeV



E_W ~ 500 GeV

➡ E_{quark} ~ 1 TeV

➡ E_{proton} ~ 6 TeV ➡ required LHC energy: pp collisions at ~ 6 + 6 TeV

- Event Rate = Luminosity x Cross-section x Branching Ratio = L x σ x BR

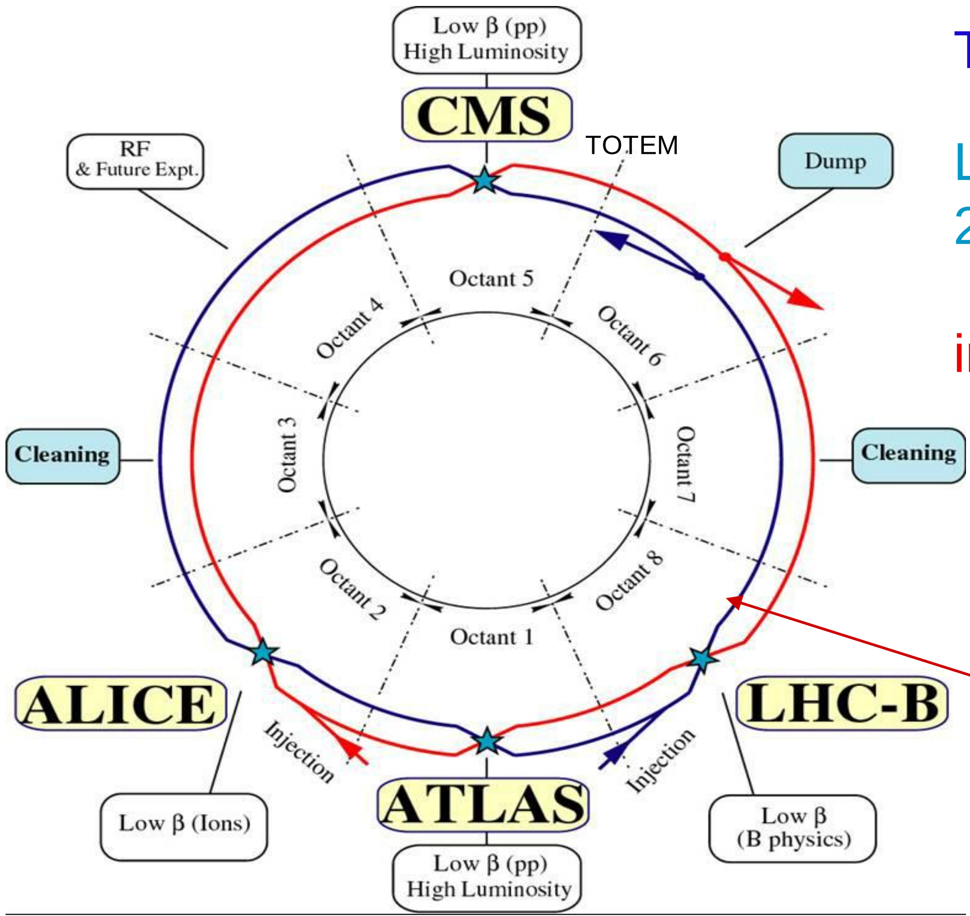
e.g. H(1TeV) → ZZ → 2e+2μ or 4e or 4μ

For 10 events/year = 10^{34}x10^{7}x10^{-37}x10^{-3} !! ➡ required L ~ 10^{34} cm^{-2} s^{-1}

Luminosity, measured in $cm^{-2}s^{-1}$, gives the number of proton-proton collisions taking place per sec. For L = $10^{34}cm^{-2}s^{-1}$ and σ(pp) ~ 100 mb ➡ rate = 10^{9}/sec

The Large Hadron Collider – few facts

~ 65% of the 27 km long circumference covered with 1232 2-in-1 superconducting dipoles of 14.3m length operated at 1.9 °K giving a field of B = 8.3T , 500 2-in-1 quadrupoles with 215T/m, altogether 1200 tons of superconducting cable and 40.000 tons of material at 1.9 °K superfluid He temperature!.



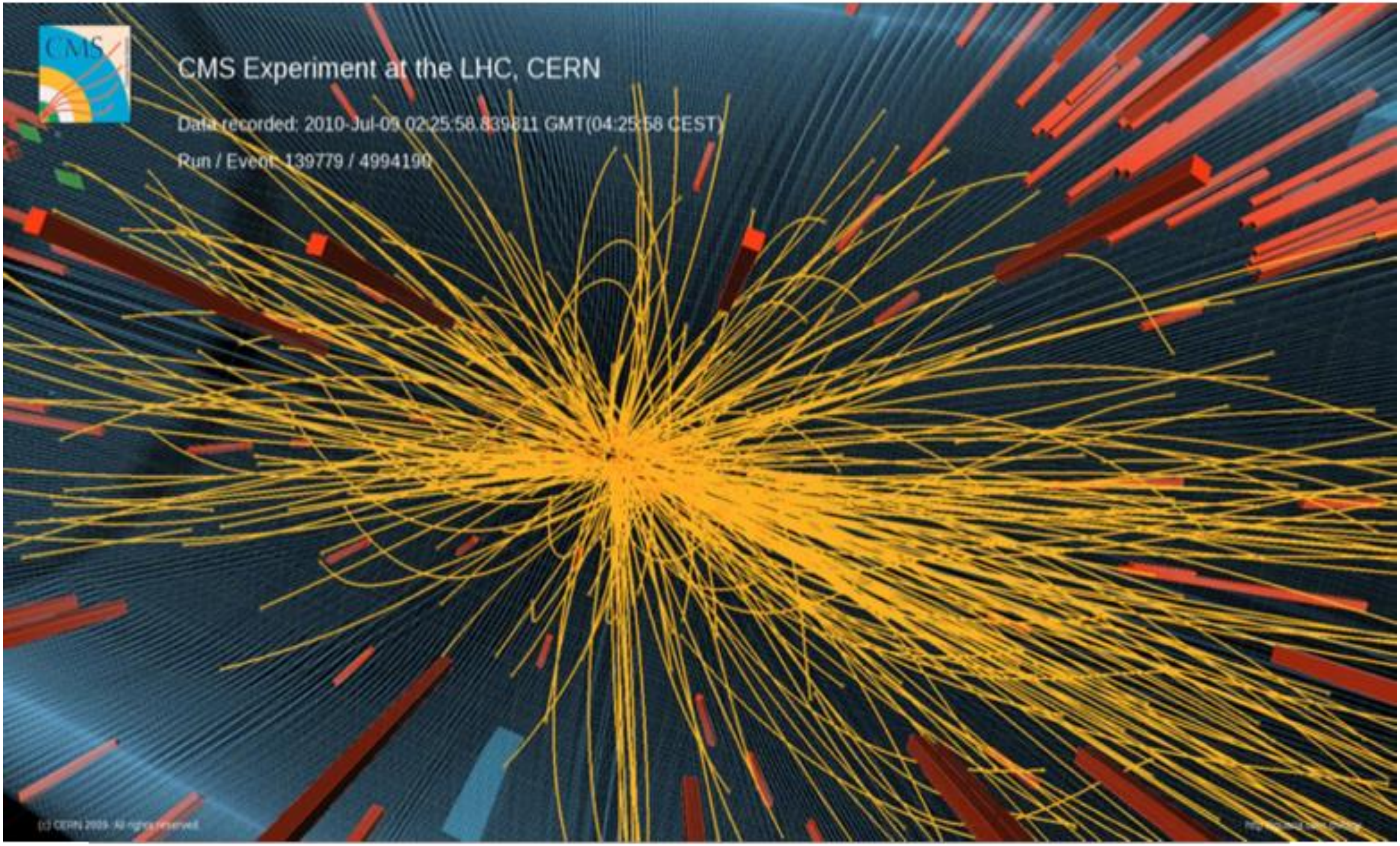
Tevatron p-p 2.000 GeV $3*10^{32}$ cm^{-2} s^{-1}

LHC(2012) pp 8.000 GeV $\sim 7*10^{33}$ cm^{-2} s^{-1}
2010/11 PbPb 2.800 $\sim 10^{26}$ cm^{-2} s^{-1}

in 2015: ~13.000 GeV $\sim 10^{34}$ cm^{-2} s^{-1}

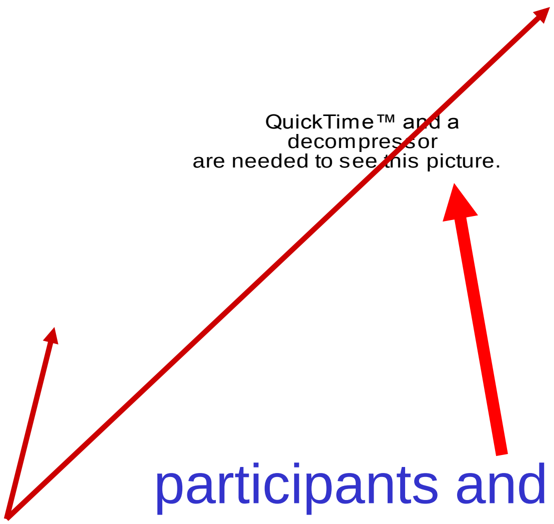
p = ReB

Typical proton-proton collision at the LHC
there is about a billion such collisions per second



Pb-Pb collisions at the LHC,

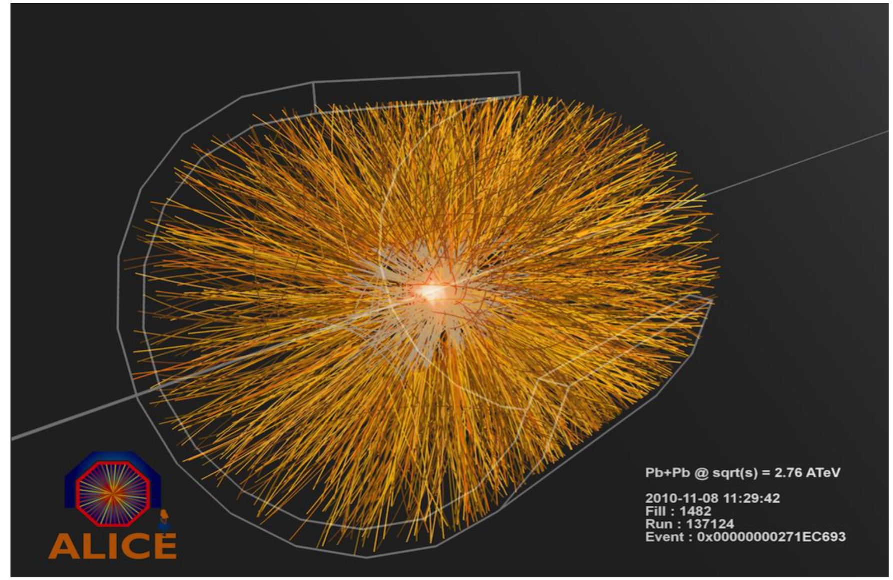
Nucleus-nucleus collision



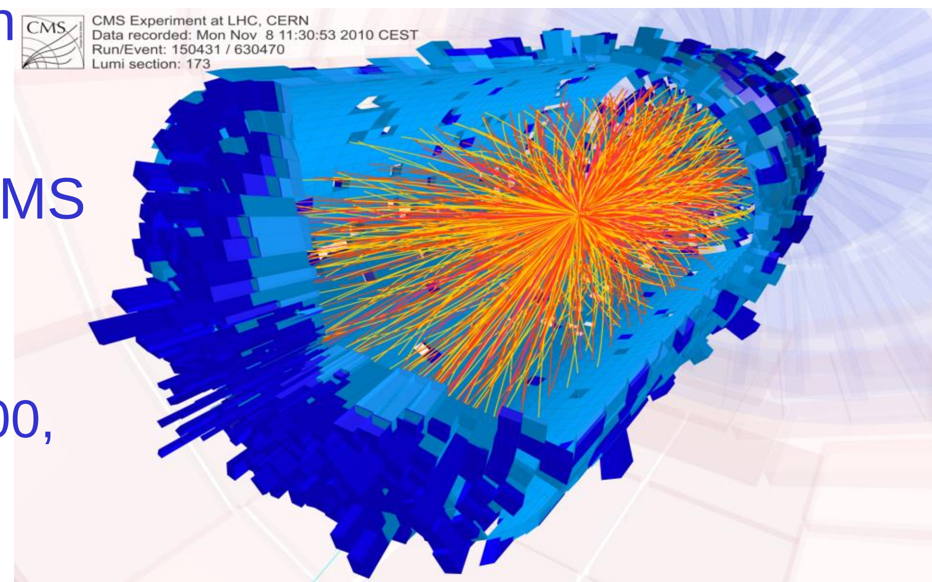
spectators

participants and QGP formation
what properties?

Pb-Pb collision in the ALICE TPC

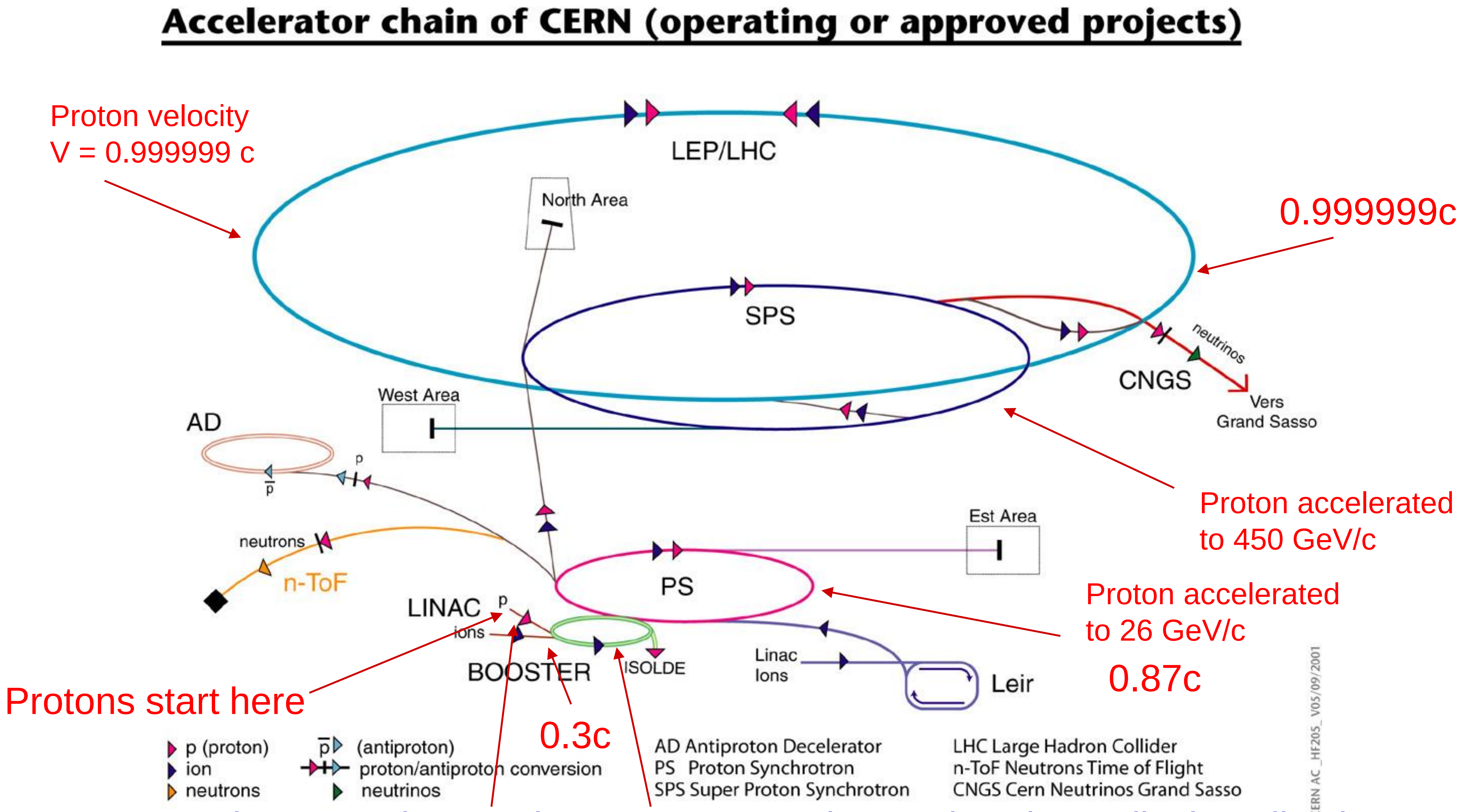


Pb-Pb collision in CMS



CMS tracker could sustain up to ~ 5000 particles per unit of rapidity!
It turned out that in reality there were ~1800, thus very successful HI program possible

CERN accelerator chain - injectors into the LHC



These are the accelerator types used nowadays in medical applications

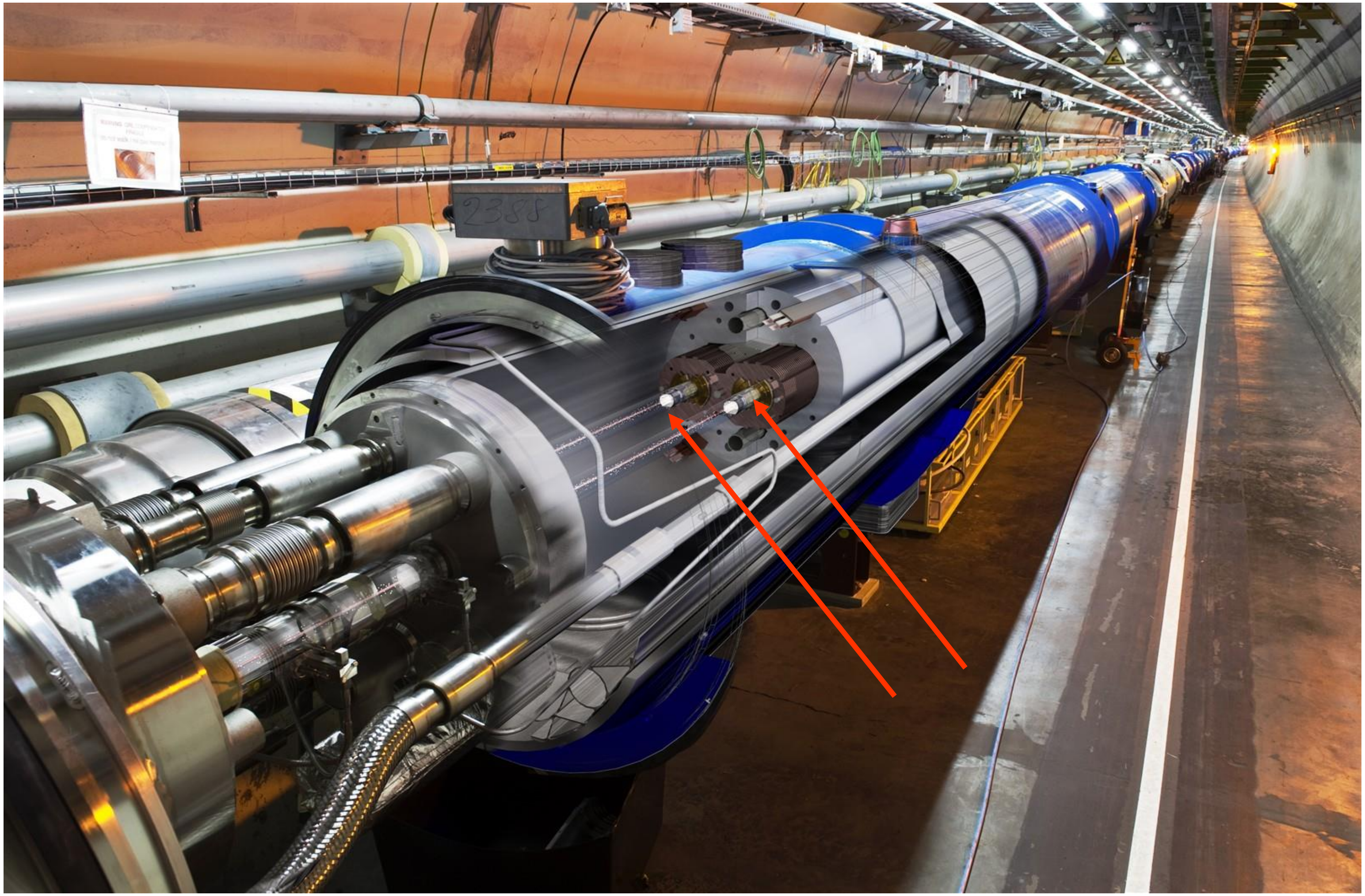
Intersecting Storage Rings -

a prototype of a hadron (pp) collider, CERN 1970's

QuickTime™ and a
decompressor
are needed to see this picture.

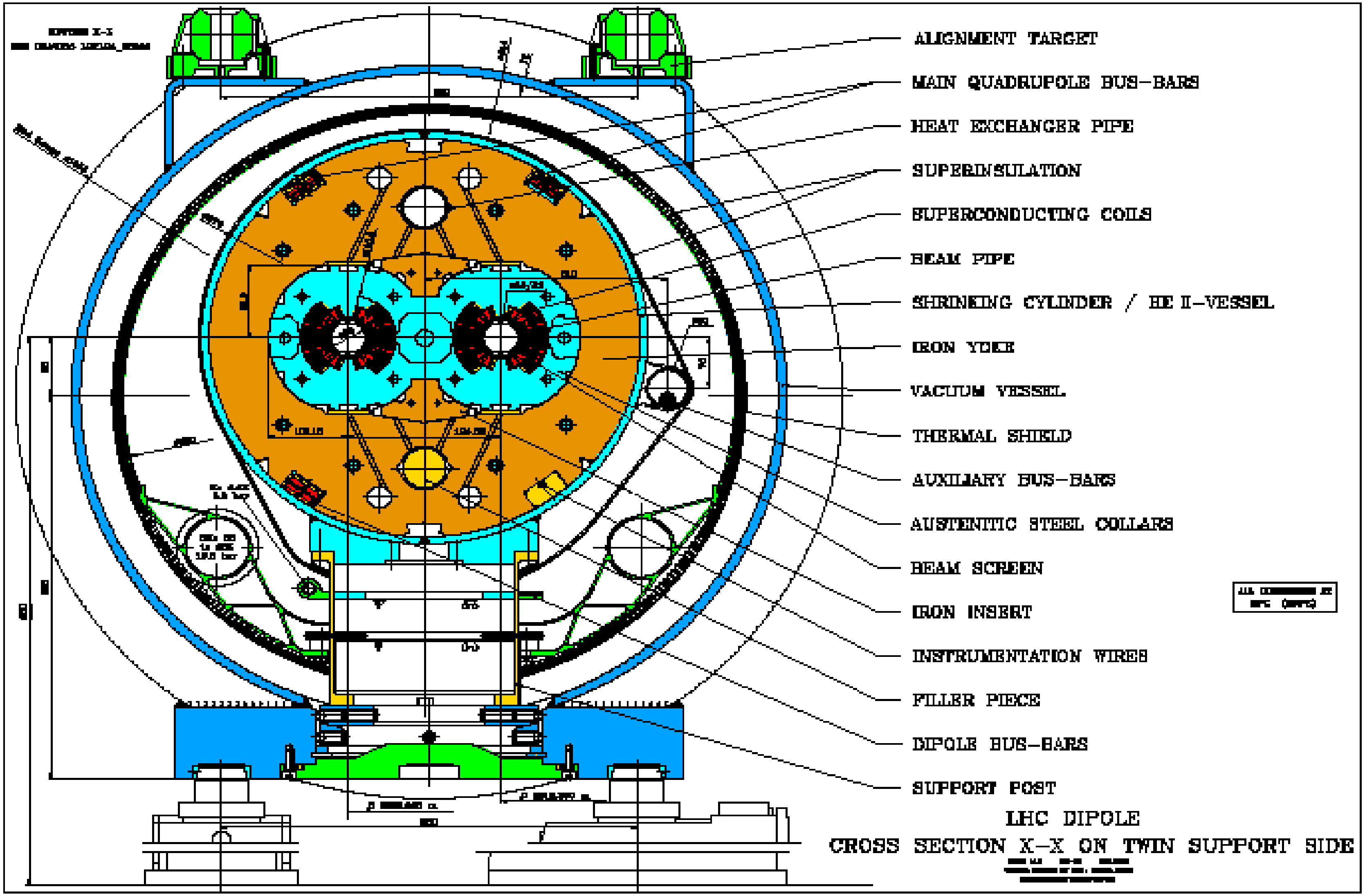
Two independent beams, pipes, sets of magnets etc……ISR. ISABELLE, SSC
were all constructed/conceived this way

LHC in the tunnel
- the "two-in-one" scheme



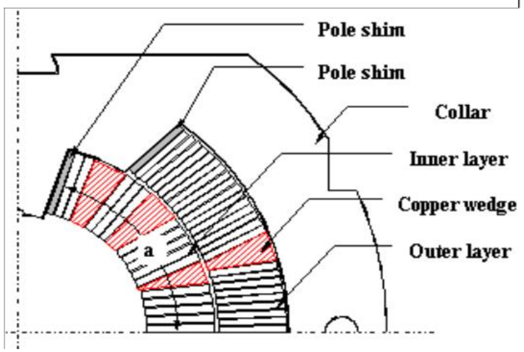
Magnets constructed between 2002 and 2007, by January 07 ~ 1200 dipoles and ~ 400 quads installed in the tunnel, they have to be aligned with 100μm precision

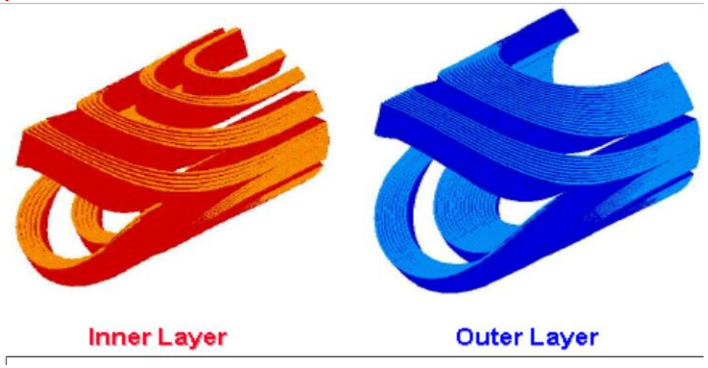
Cross section of an LHC dipole

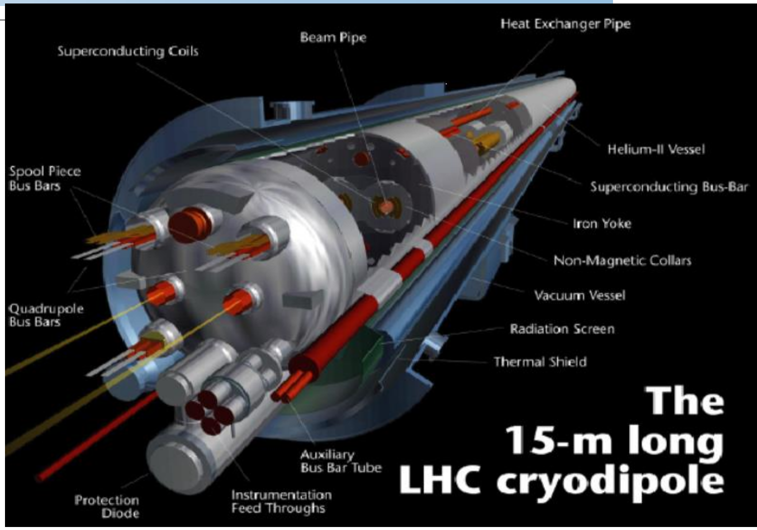


The key elements: LHC dipoles
coil structure for the two-in-one scheme
(suggested by R. Palmer in 1984)

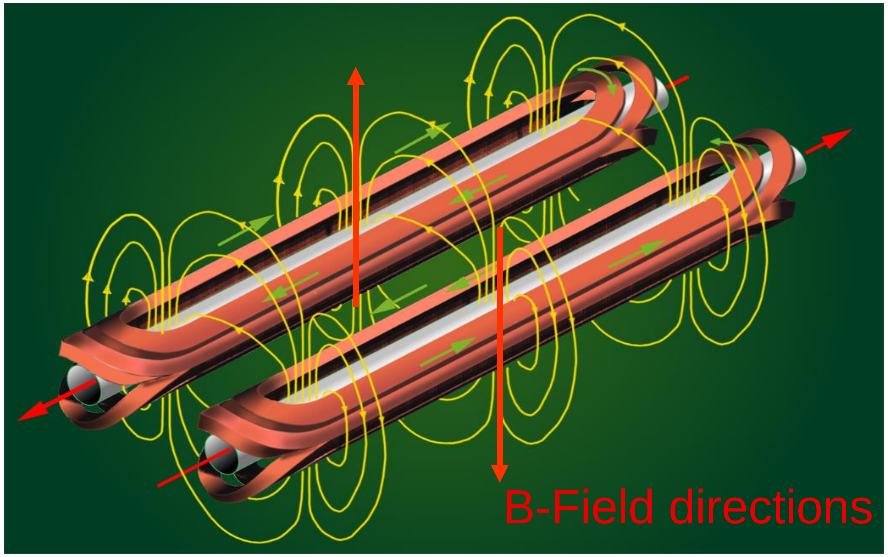
LHC dipole coil design, 6-block coil structure



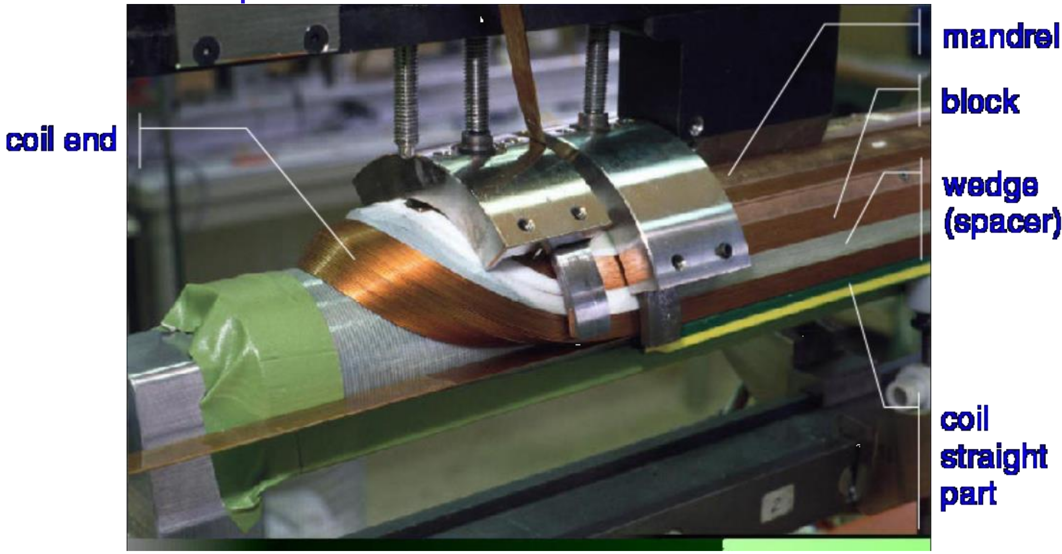




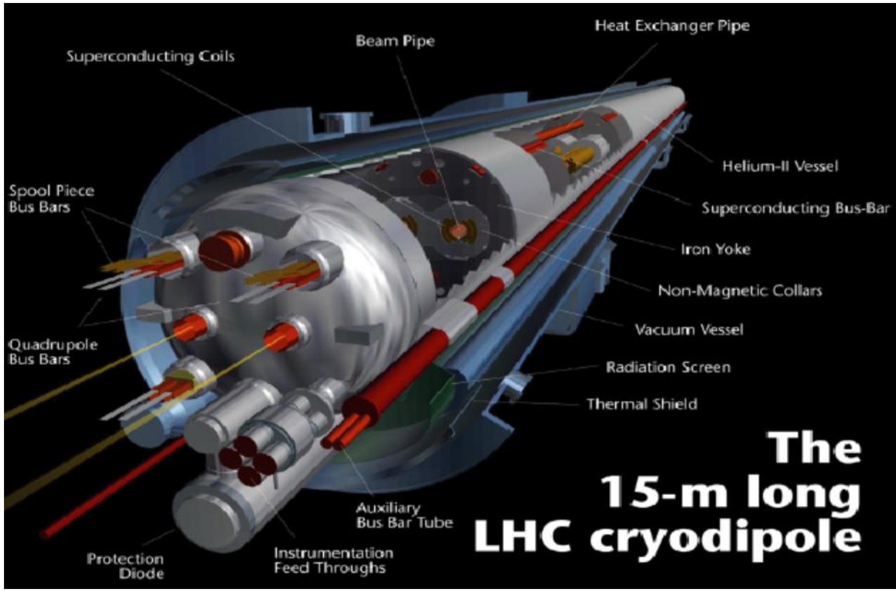
Field lines in the two-in-one dipole
(two beam-lines in a single magnetic enclosure)

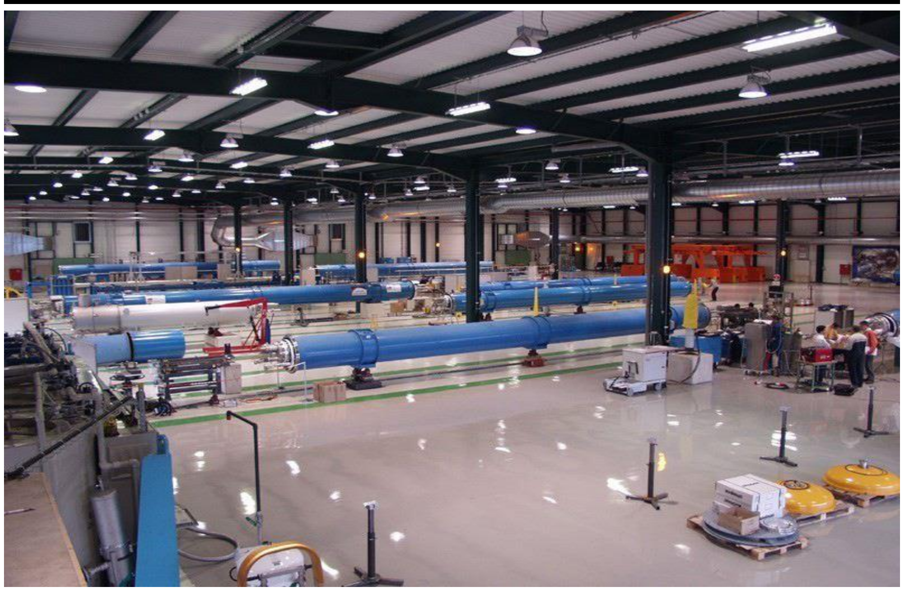


Most delicate is the coil end - this is where most of the quenches occur



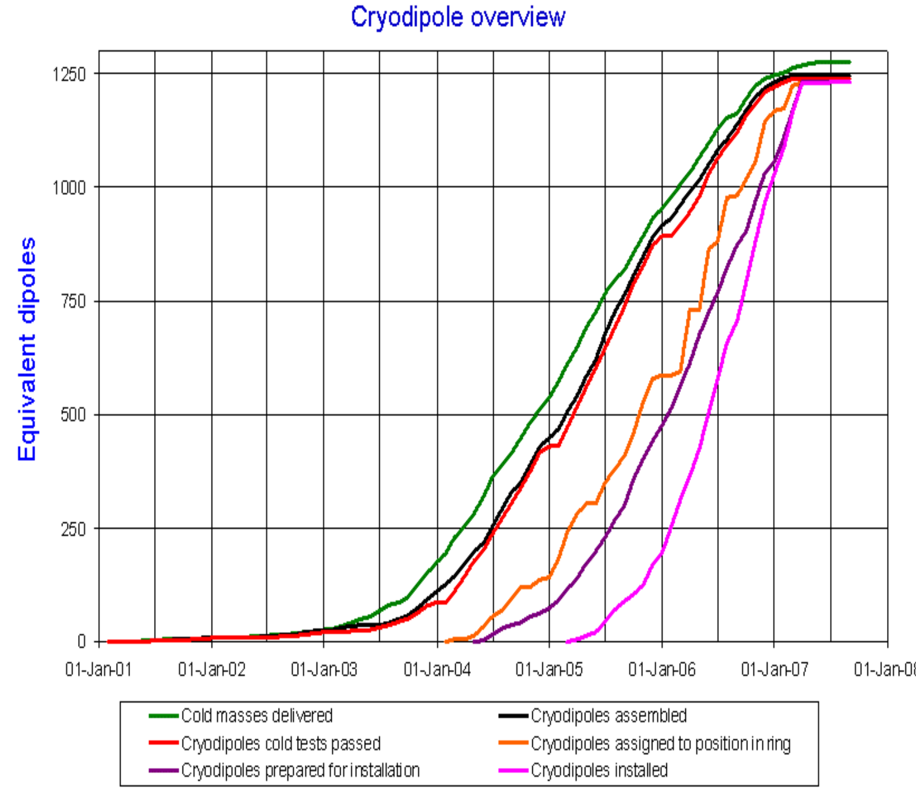
LHC dipoles production





LHC Progress Dashboard

Accelerator Technology Department



Updated 31 August 2007

Data provided by D. Tommasini AT-MCS, L. Bottura AT-MTM

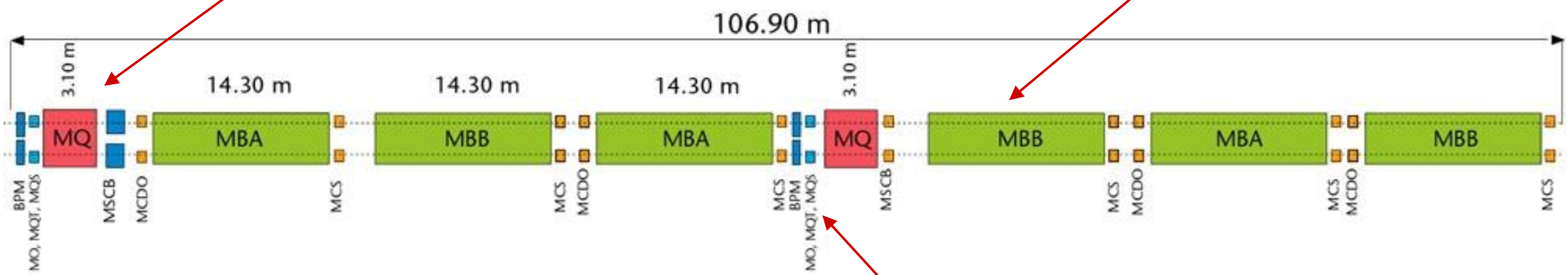
Hall at CERN for final assembly and testing of dipoles - 2005/2006

Layout of an LHC cell

Schematic layout of one LHC cell (23 periods per arc)

Focusing quadrupoles

Bending dipoles



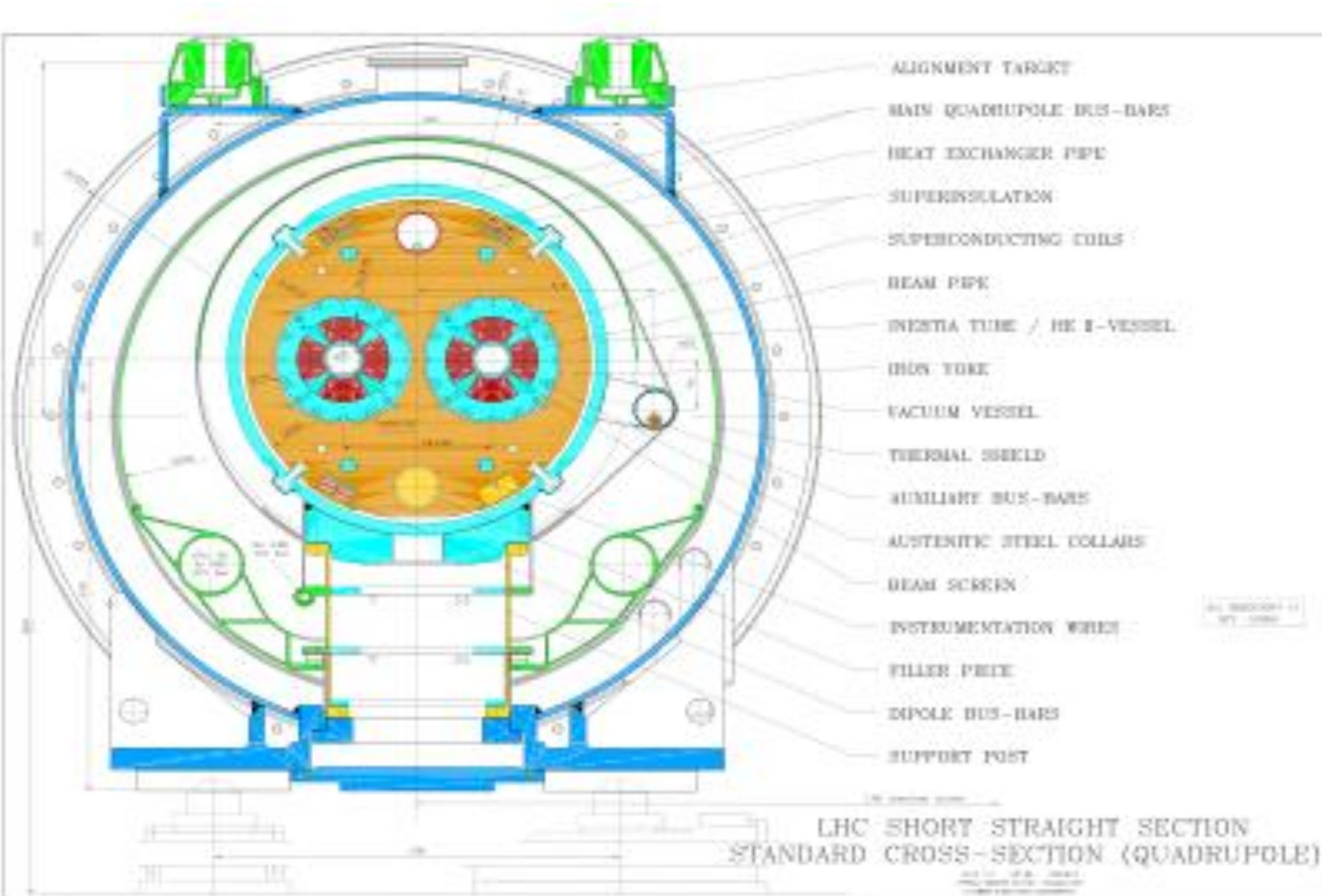
Corrector multipoles

MQ: Lattice Quadrupole
MO: Landau Octupole
MQT: Tuning Quadrupole
MQS: Skew Quadrupole
MSCB: Combined Lattice Sextupole (MS) or skew sextupole (MSS) and Orbit Corrector (MCB)
BPM: Beam position monitor
MBA: Dipole magnet Type A
MBB: Dipole magnet Type B
MCS: Local Sextupole corrector
MCDO: Local combined decapole and octupole corrector

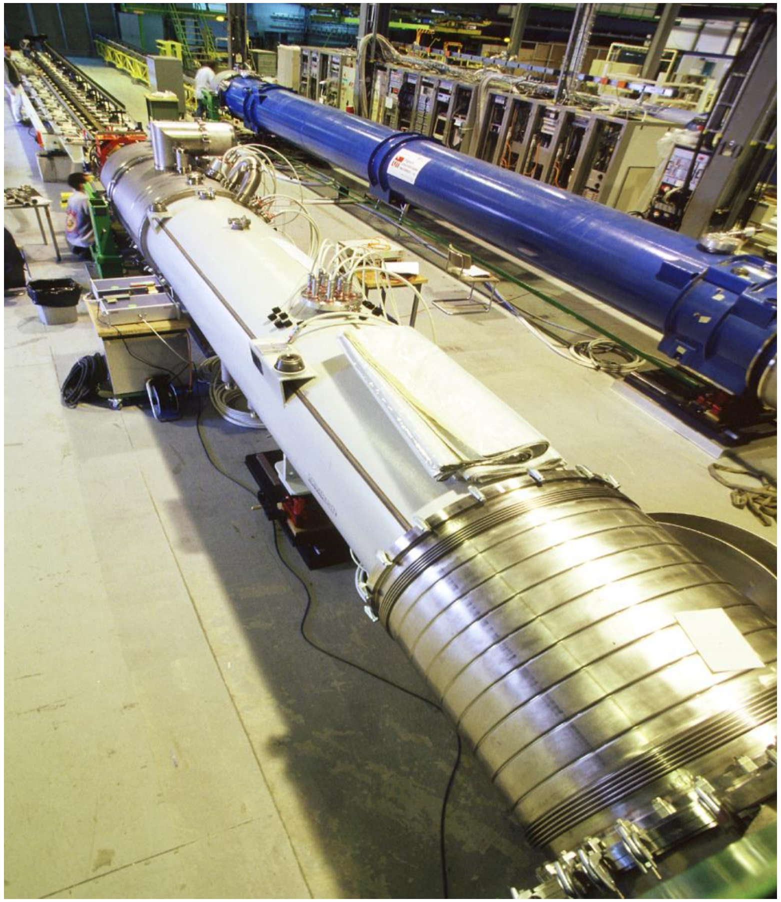
This sequence of magnets repeats itself on most of the 27 kms LHC circuference

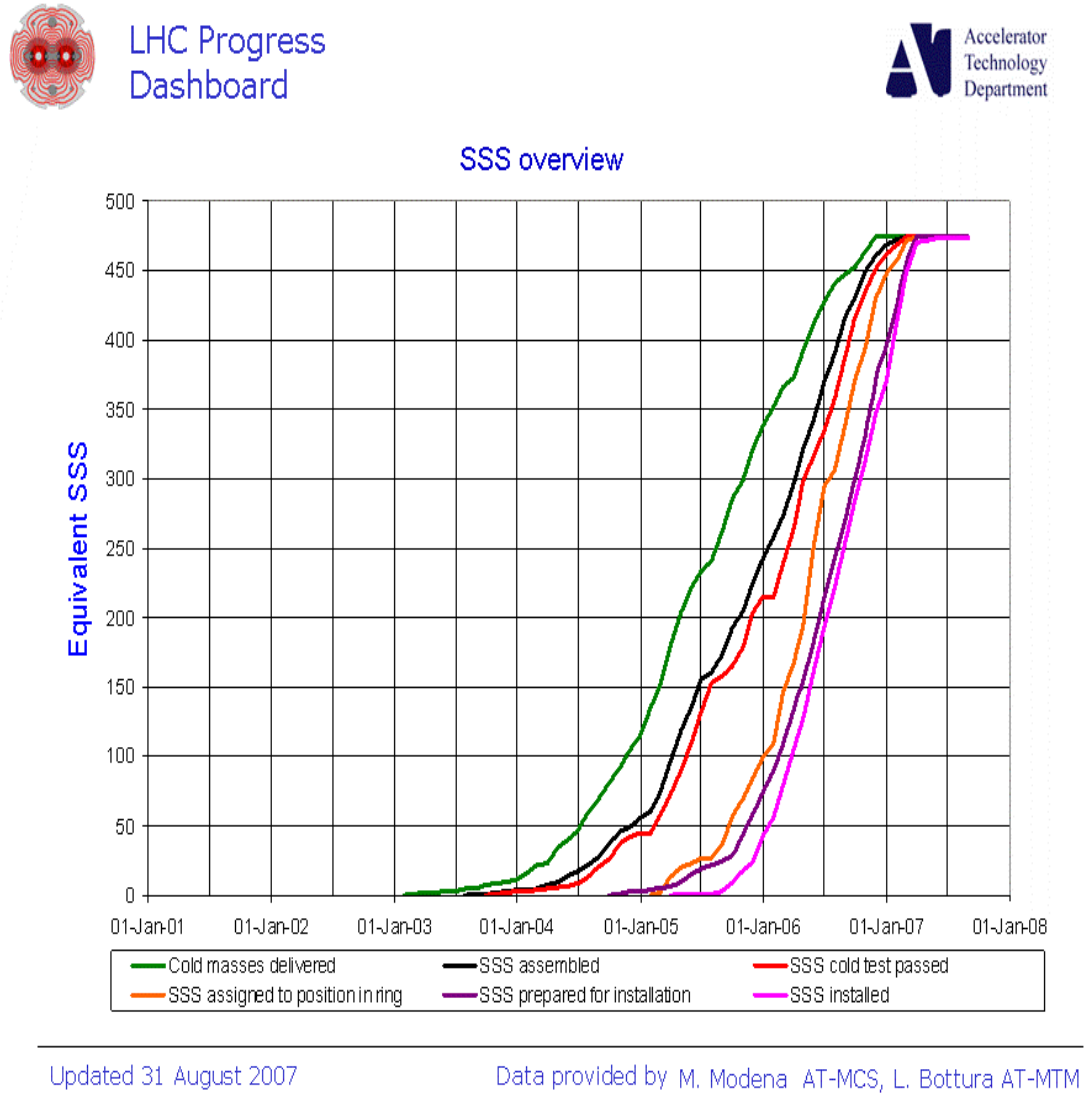
HF226 - v10/99

Quadrupoles - MQ X-sect (CEA-CERN)



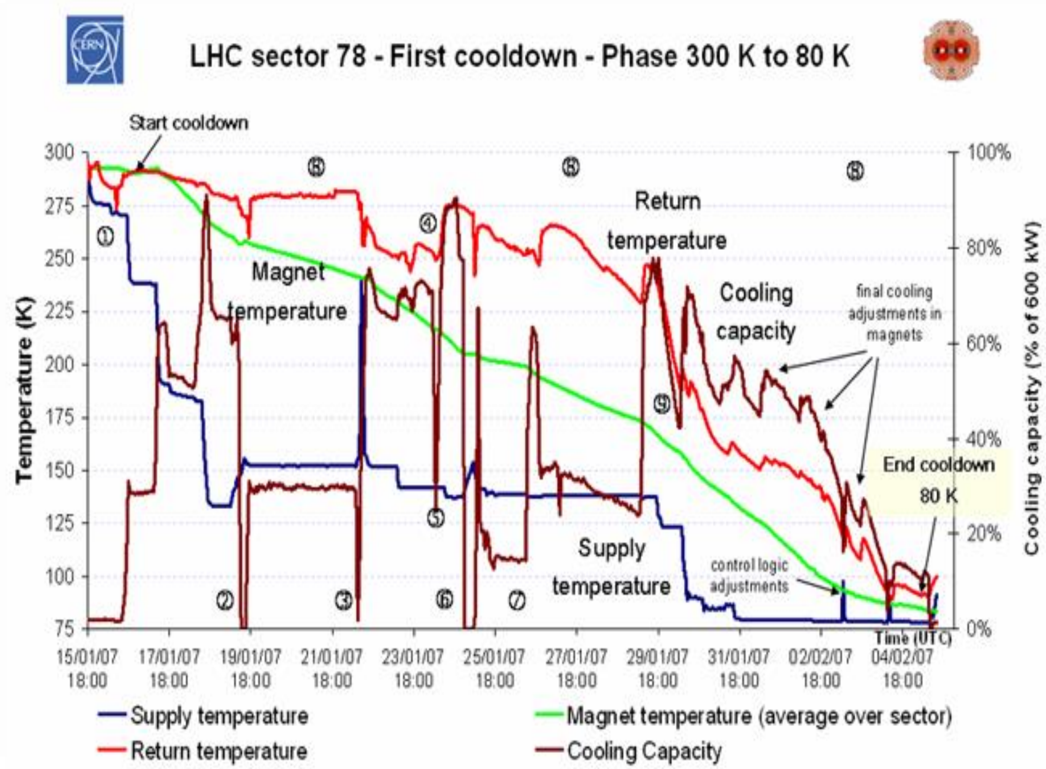
LHC quadrupoles, production



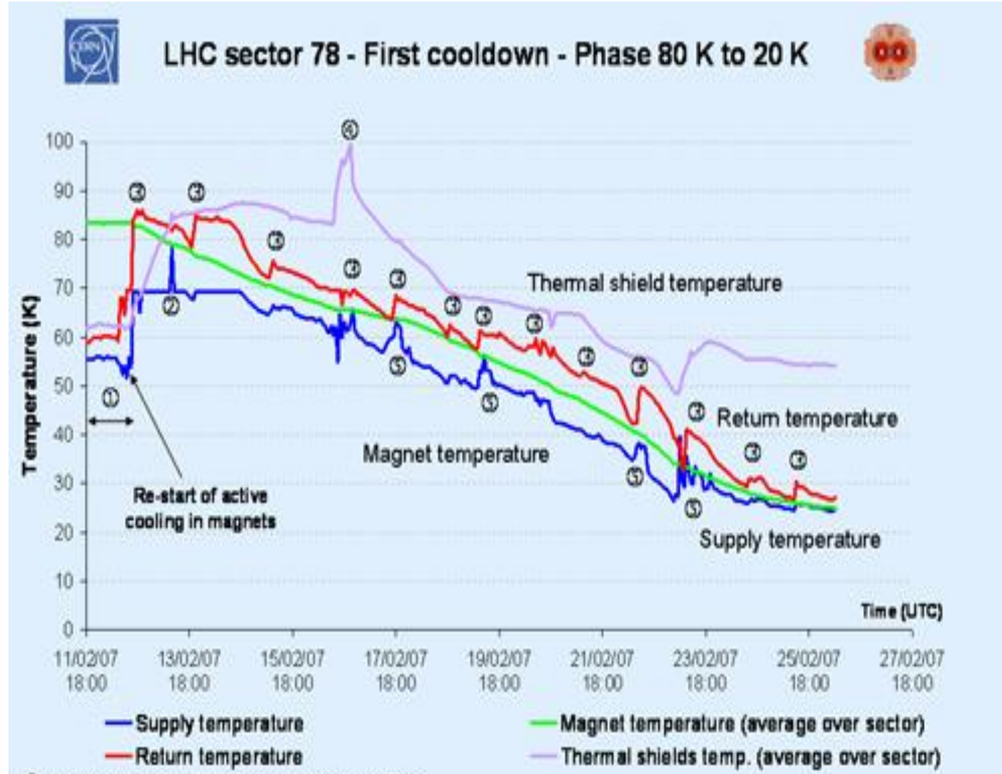


SSS:
6–12 m, 8 –19 tons
SC: Nb-Ti
Gradient Quad : 223 T/m

First LHC cooldown - sector 78, Jan.- Feb. 07

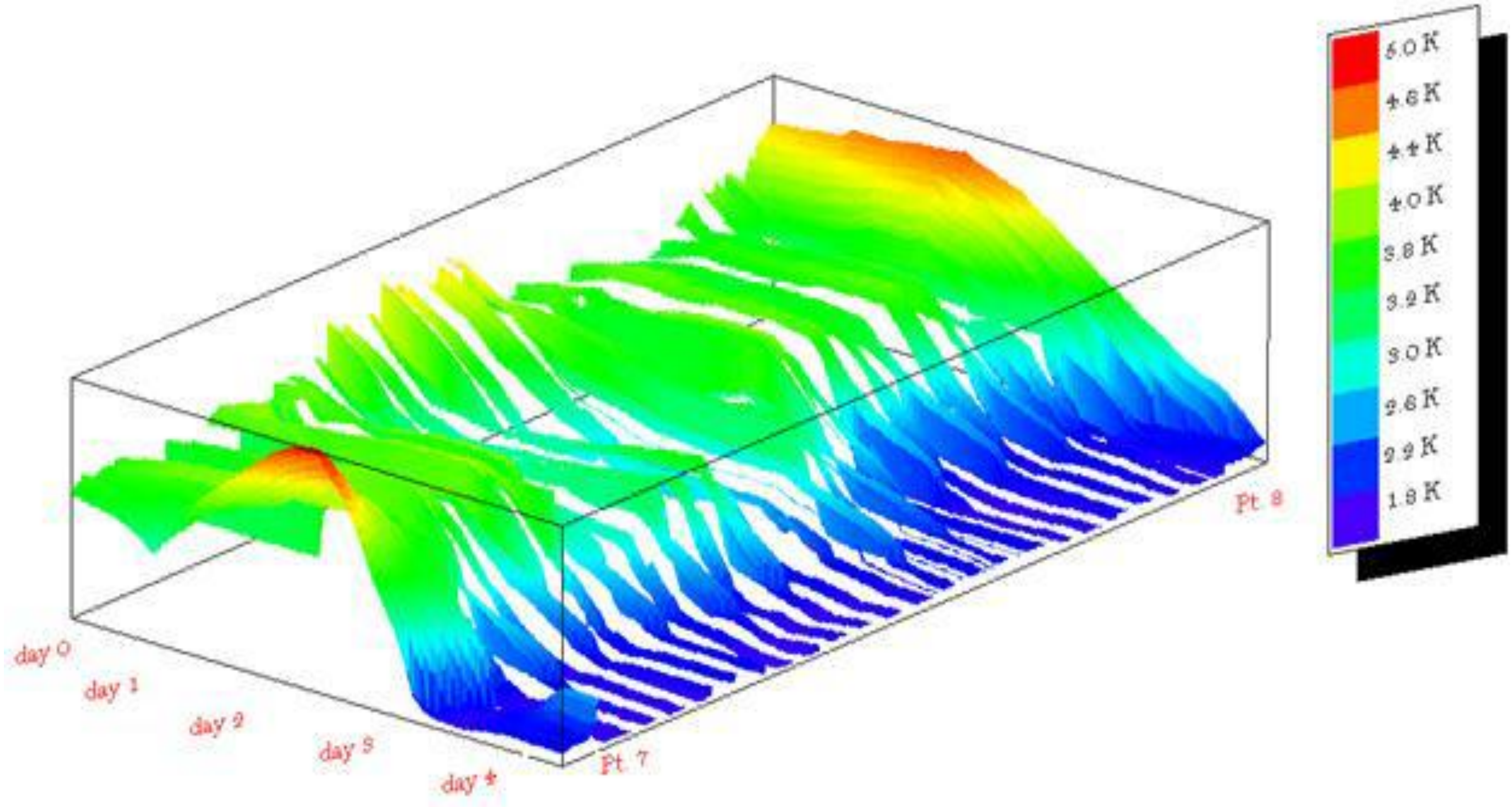


① Start cooldown tunnel without magnet
② Scheduled electrical stop & tunnel intervention
③ Control system stop for updates
④ Cooling adjustments in shields and magnets
⑤ Snow on roads for liquid nitrogen trucks
⑥ Unscheduled electrical stop & tunnel intervention
⑦ Reduced cooling capacity for magnet checking
⑧ Reduced cooling along week-end with only on-call activity
⑨ Random Emergency Stop in cryogenic surface building



① Magnet isolated for ELQA tests and consolidations
② Partial stop for leak reparation in level gauge connection
③ Cooling flow adjustments in magnets
④ Turbine filter exchange (Tu4)
⑤ Turbines or valves in 4.5 K refrigerator control tuning

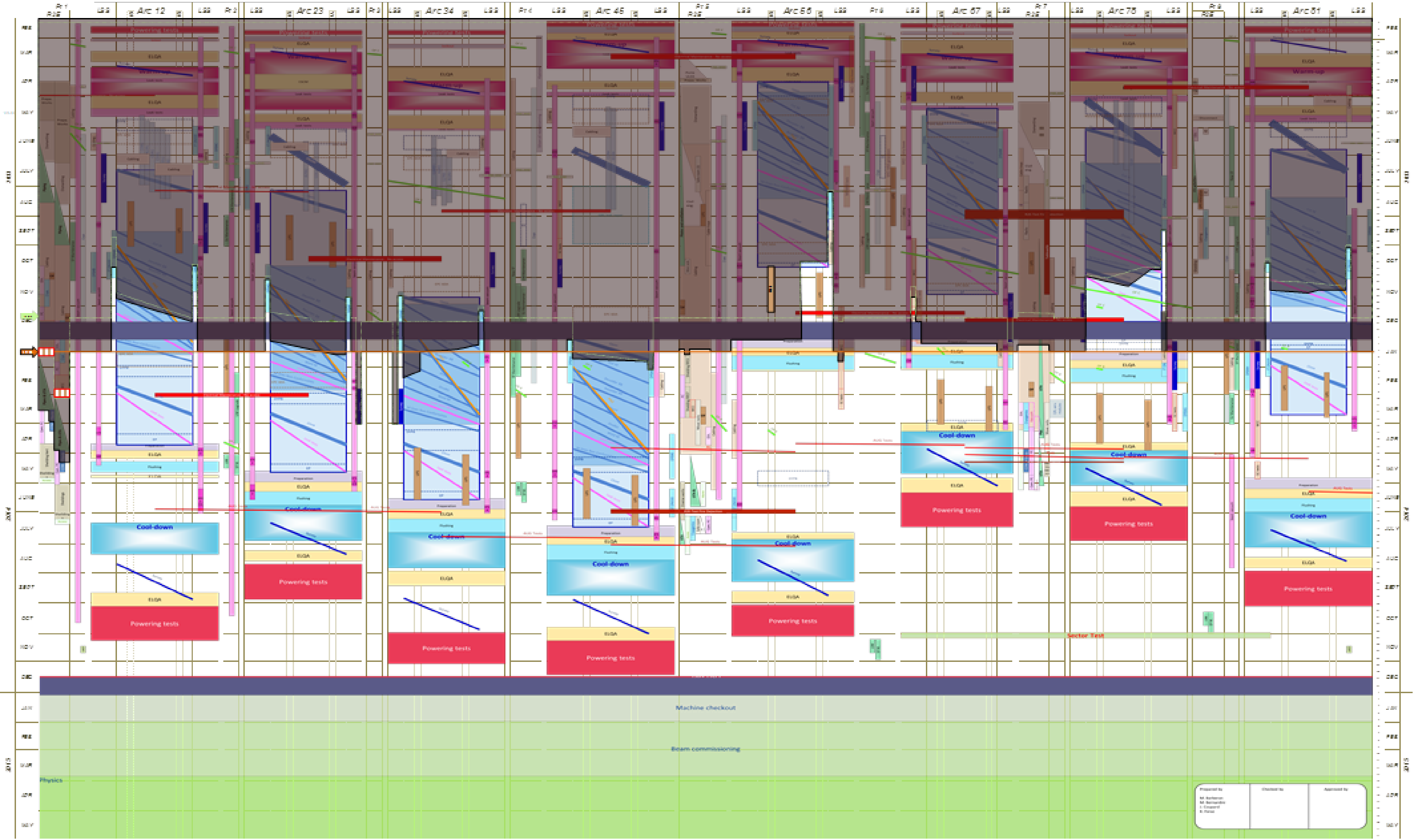
Sector 78 reached 1.9K April 10th 2007



The sector is 3.3 km long, consists of more than 300 dipoles and quadrupoles; cooling done in three phases, starting in January 07, first to 80K, then in March down to 4K and finally from mid-March down to super-fluid He temp at 1.9K reached in April.

Cooling with super-fluid ^{4}He is essential to LHC functioning at required luminosity

LHC: on schedule for beam in January 2015 - situation end-February 2014



A key property of a collider: Luminosity

Instantaneous luminosity L:

$$L = \frac{N^2 k_b f}{4\pi \sigma_x \sigma_y} F = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

measured in $cm^{-2}s^{-1}$, L is indicative of the number of proton-proton collisions taking place per sec.

N: number of protons per bunch
k_b: number of bunches per beam
f: circulation frequency
σ_x, σ_y: transverse sizes of beam at interaction point
F: crossing angle factor (~1)

Number of events: $N_{ev} = \sigma_{ev} \cdot L_{int}$ $\qquad L_{int} = \int L\,dt$

σ_{ev} cross-section for events of a specific type,

- L_{int} is the time integral over a run, or running period, of the instantaneous luminosity, it is indicative of the sensitivity of an experiment;
- unit for expressing integrated luminosity is inverse of a cross section $1/\sigma$, for example pb^{-1}, fb^{-1}

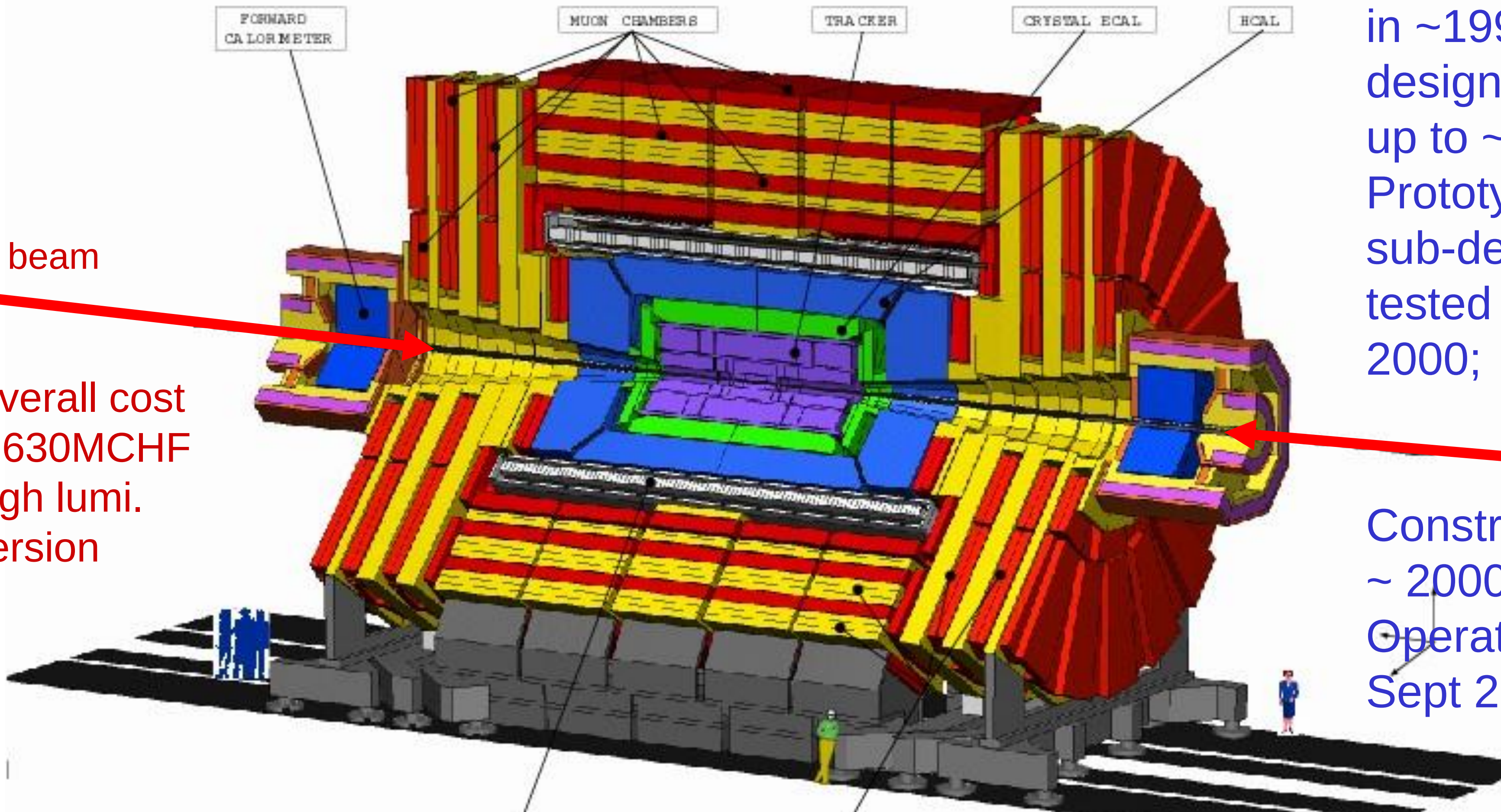
LHC performance in 2010, 2011, 2012

QuickTime™ and a
decompressor
are needed to see this picture.

The CMS detector

The CMS (Compact Muon Solenoid) detector

Physics requirements drive the design of the detector



beam

beam

Overall cost ~ 630MCHF high lumi. version

CMS designed in ~1991/92, design optimized up to ~1995; Prototypes for sub-detectors tested up to ~ 2000;

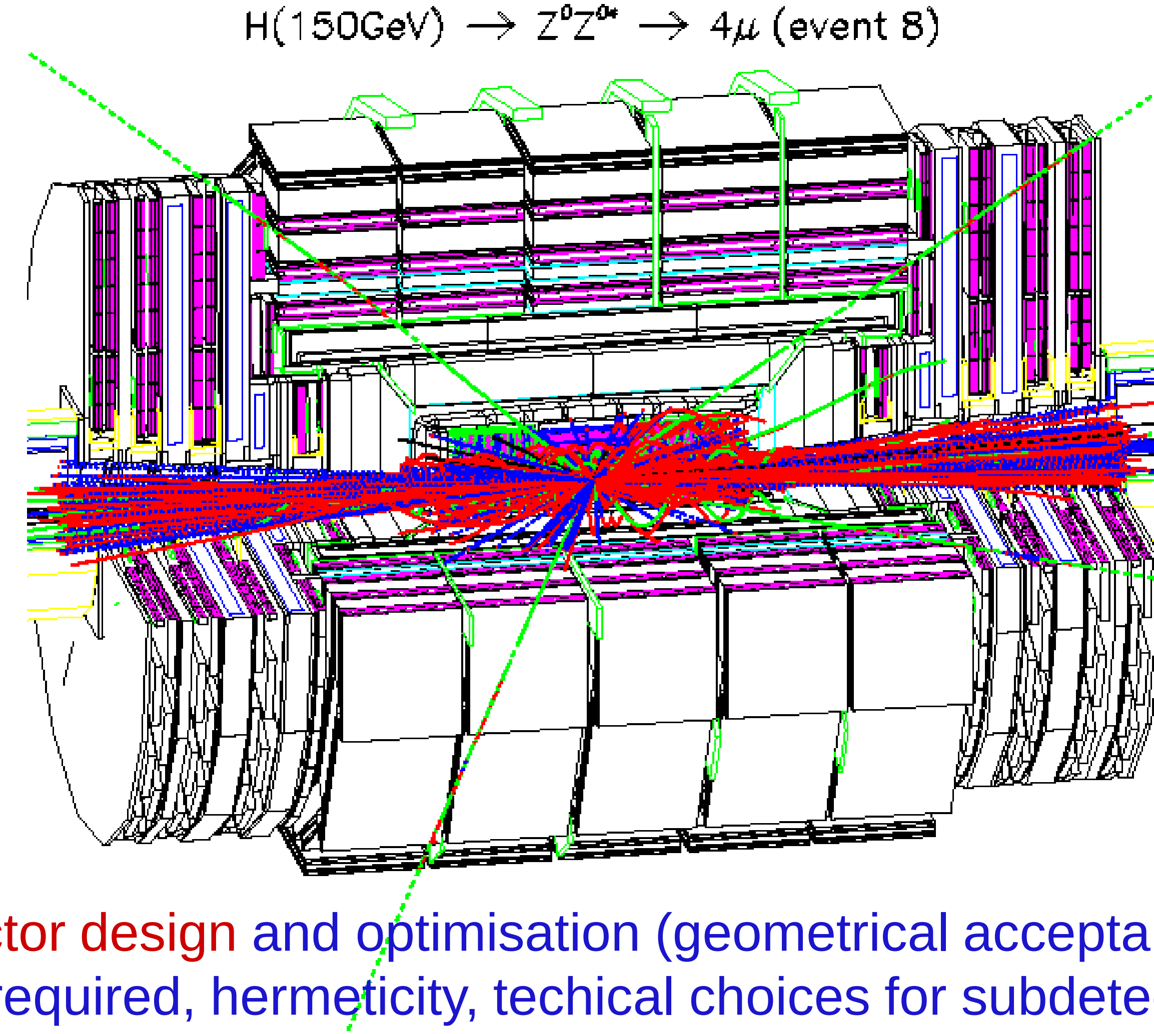
Construction from ~ 2000 till 2008 Operational in Sept 2008

Total weight	:	12,500t.
Overall diameter	:	15.00m
Overall length	:	21.60m
Magnetic field	:	4 Tesla

“Founding fathers”: S.Citollin, M. Della Negra, D. Denegri, K. Eggert, E. Radermacher, and T. Virdee

Determination of main CMS features, dimensions, geometrical acceptances, resolutions etc

Simulation of a Higgs event in CMS



During CMS design and optimisation cost effectiveness had to be always taken into account

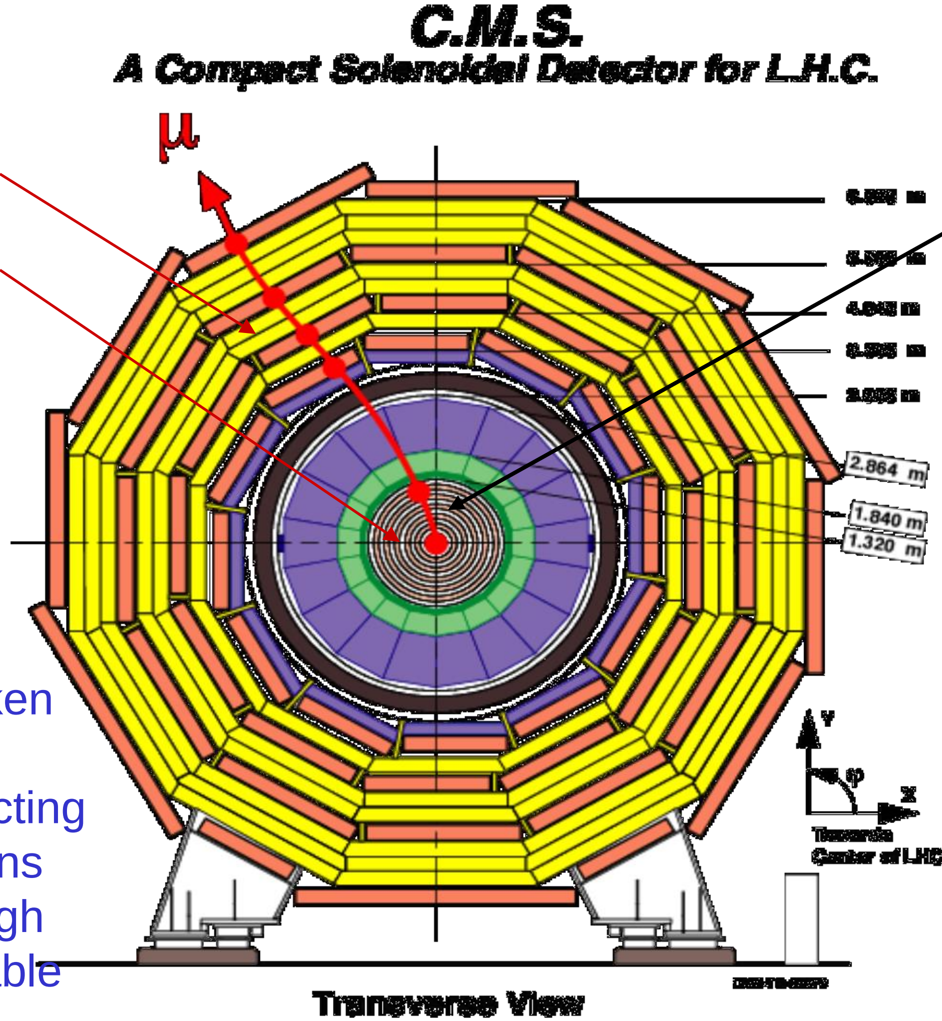
CMS detector design and optimisation (geometrical acceptance, energy- momentum resolution required, hermeticity, techical choices for subdetectors, DAQ) have been done with the Higgs search in mind, but also for top physics, SUSY, W', Z', BSM…..

CMS in transverse view - basic design

B ~ 2 Tesla

B = 4 Tesla

p = reB



Total bending power on a muon ~ 16Tm

In the design of CMS care was taken to have good efficiency for detecting ~4.5 - 5 GeV muons (penetration through calos,coil!) to be able to observe Y

momentum resolution from curvature:

$$\Delta p/p \sim \varepsilon\, p / (\sqrt{n}\; B\, l^2)$$

ε= resolution on point measurement

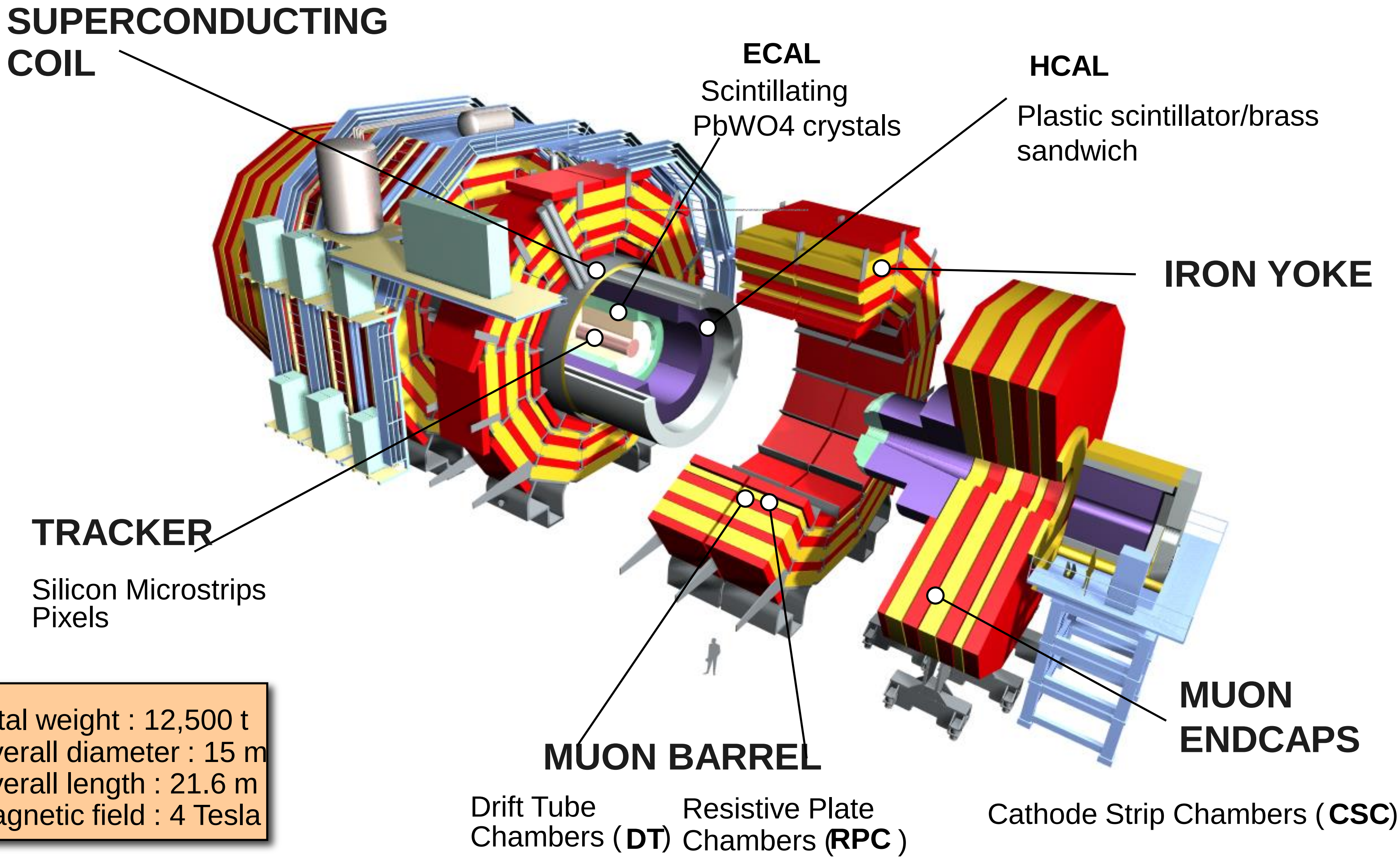
n = number of points measured per track

l = useful track length

B = magnetic field

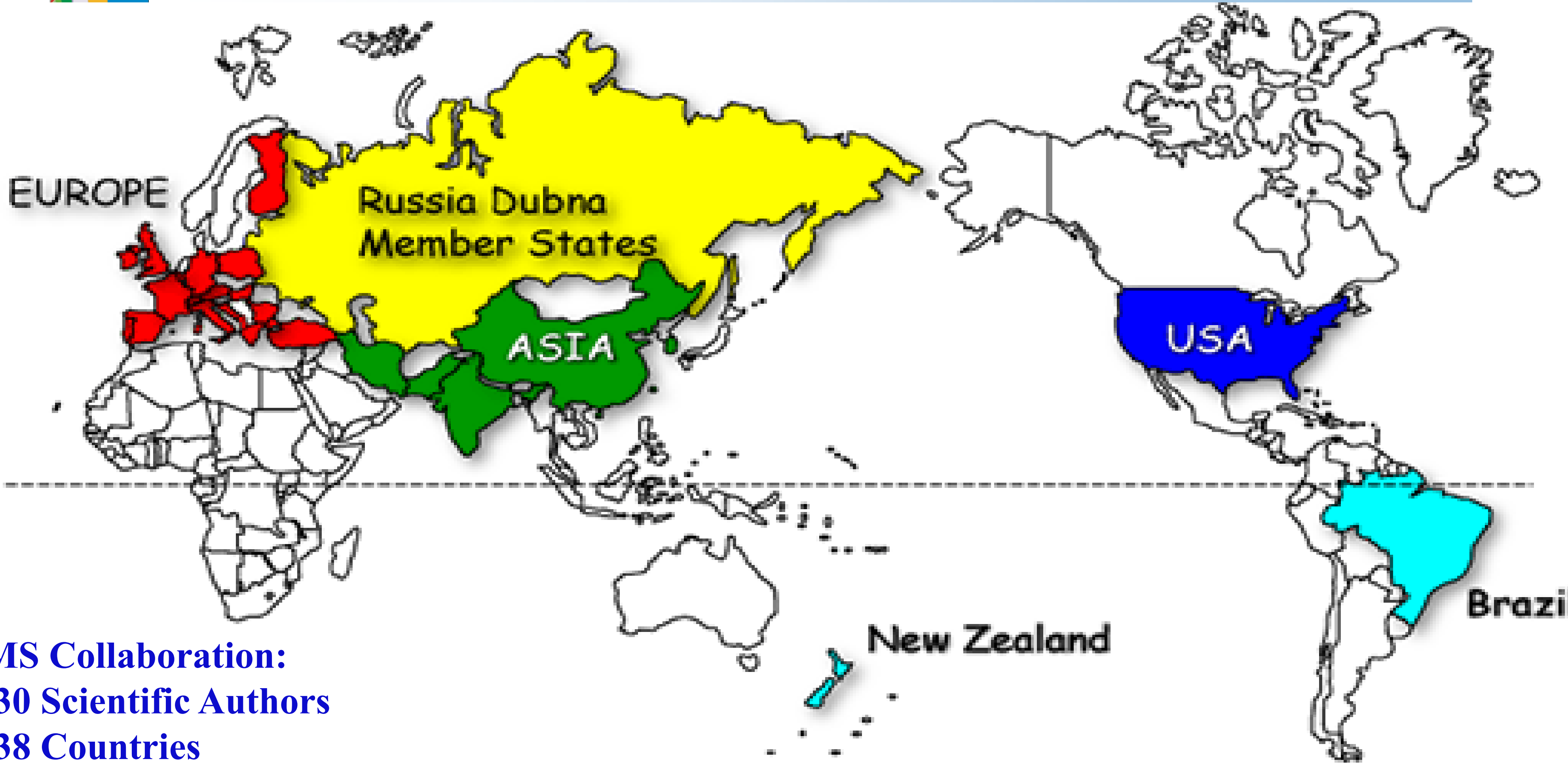
The goal is to identify and measure all particles produced at the interaction point

The CMS detector - a modular concept, major components



Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

CMS is a large international collaboration



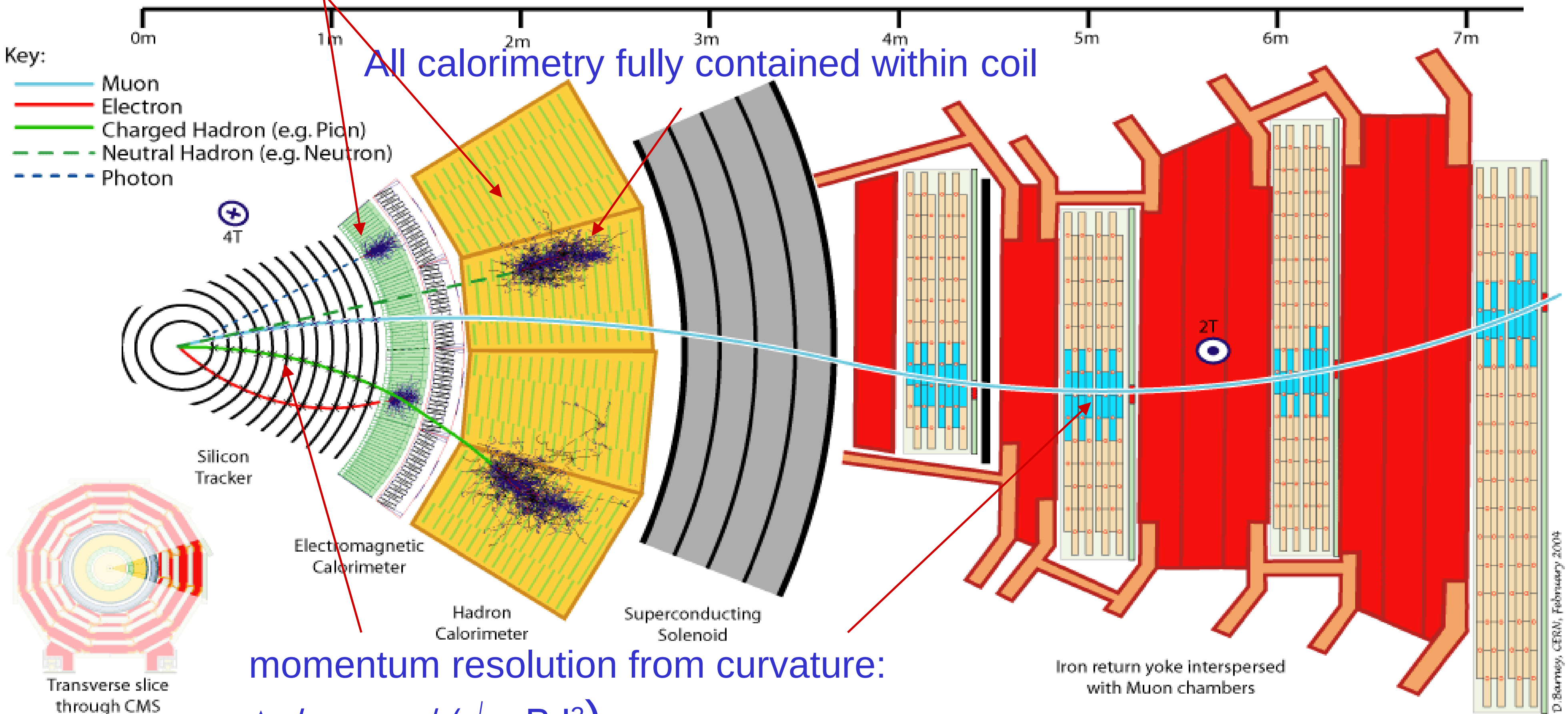
CMS Collaboration:
2030 Scientific Authors
38 Countries
182 Institutions

CMS is still growing: Serbia 2003, Mexico 2006, Columbia 2006, Lithuania 2007, Egypt in 2010 joined CMS, soon Malesia, Tunisia…..

Central region of CMS; detector functions

Tracking + Ecal + Hcal + Muons for $|\eta|<2.4$

$\Delta E/E \sim \sqrt{((a/\sqrt{E})^2 + (b/E)^2 + c^2)}$ generic resolution in calorimeters



All calorimetry fully contained within coil

momentum resolution from curvature:

$\Delta p/p \sim \varepsilon\, p / (\sqrt{n}\ B\, l^2)$

Redundancy and robustness in muon system

<u>Si TRACKER</u>

Silicon Microstrips and Pixels

<u>CALORIMETERS</u>

ECAL
Scintillating $PbWO_4$ crystals

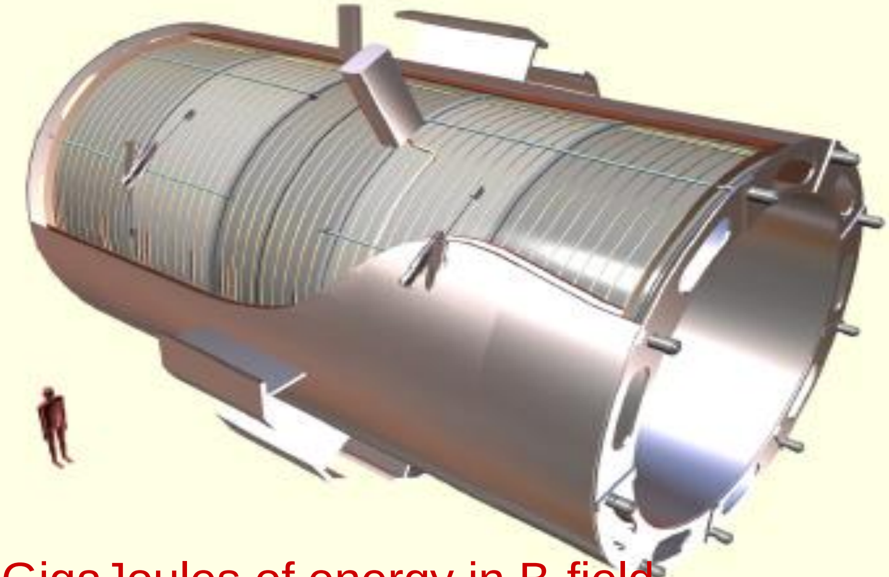
HCAL
Plastic scintillator/brass sandwich

<u>MUON BARREL</u>

Drift Tube Chambers (**DT**)

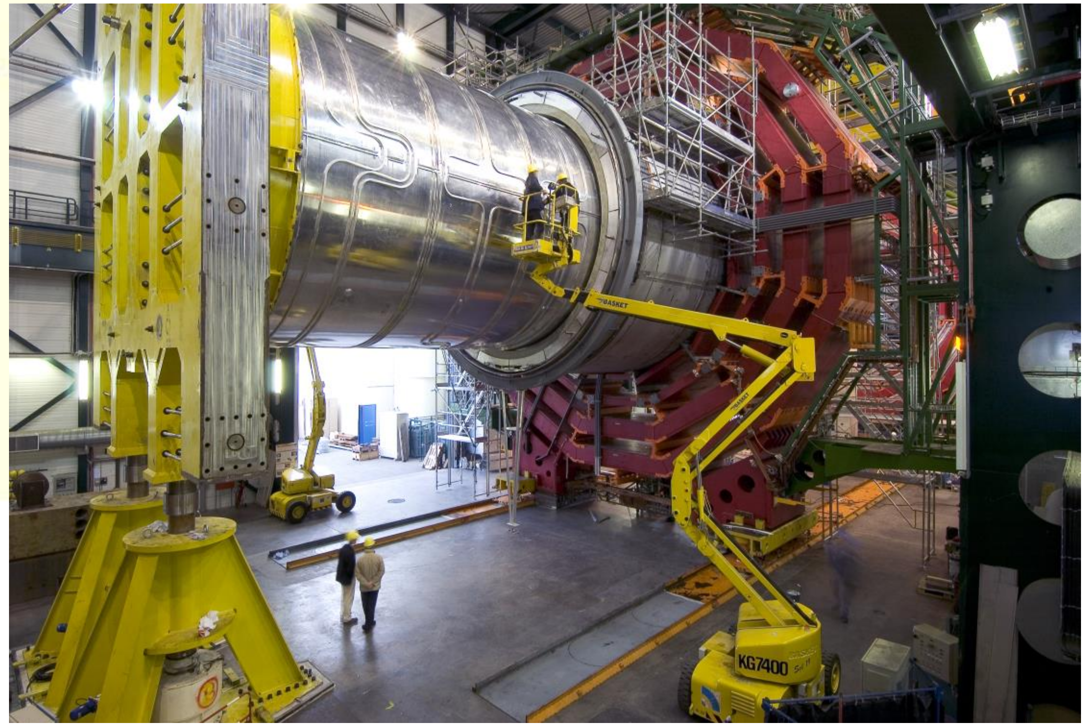
Resistive Plate Chambers (**RPC**)

The CMS solenoid - largest in the world - production/assembly cable and coil modules

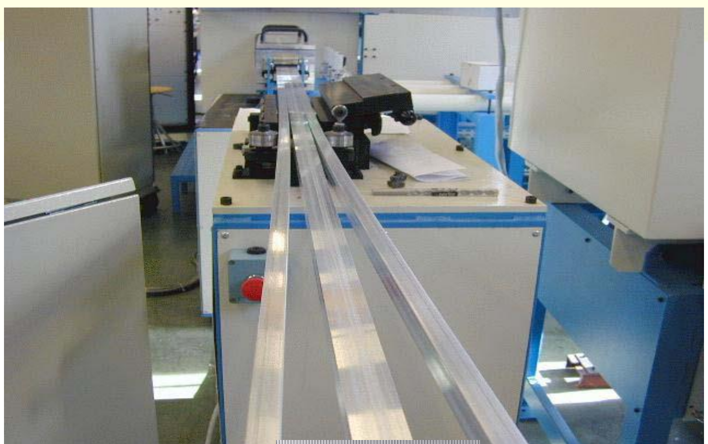


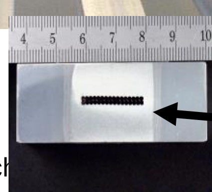
3 GigaJoules of energy in B-field

all 5 coil modules finished in 2004
assembly in CMS hall, Jan. 2005



Insertion of coil in vacuum
tank in September 05

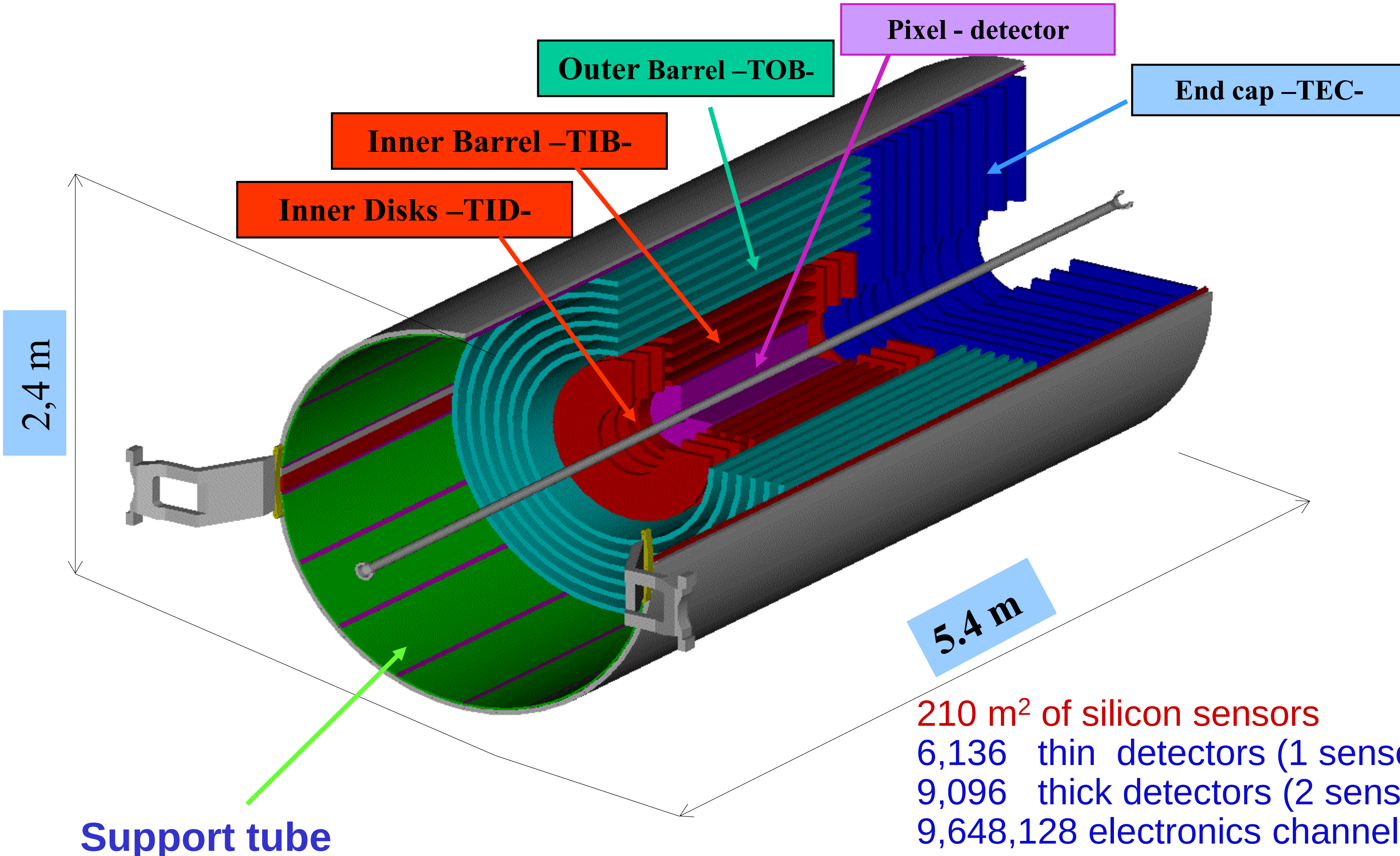




s.c cable: all 21 lengths (53 km) finished in 2003

Insert with superconductor

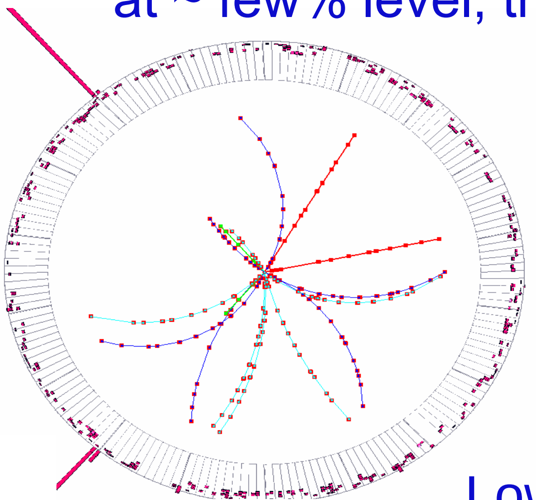
The all-Silicon CMS tracker

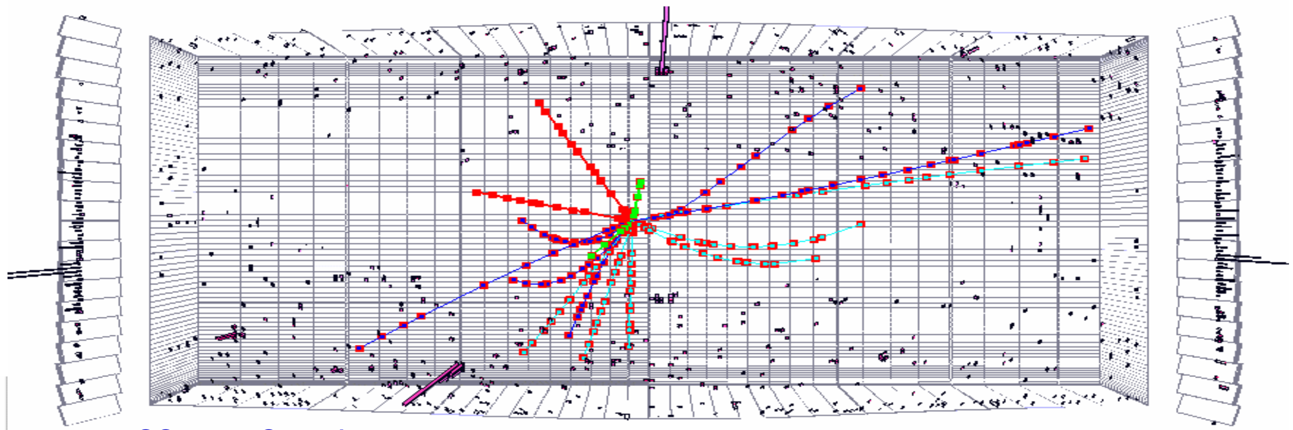


210 m^2 of silicon sensors
6,136 thin detectors (1 sensor)
9,096 thick detectors (2 sensors)
9,648,128 electronics channels
70 Million pixels

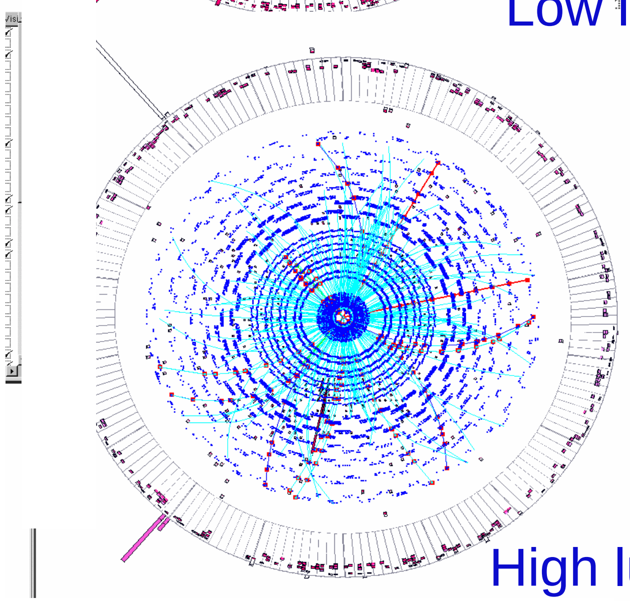
Need for granularity in a tracker at LHC - for pattern recognition

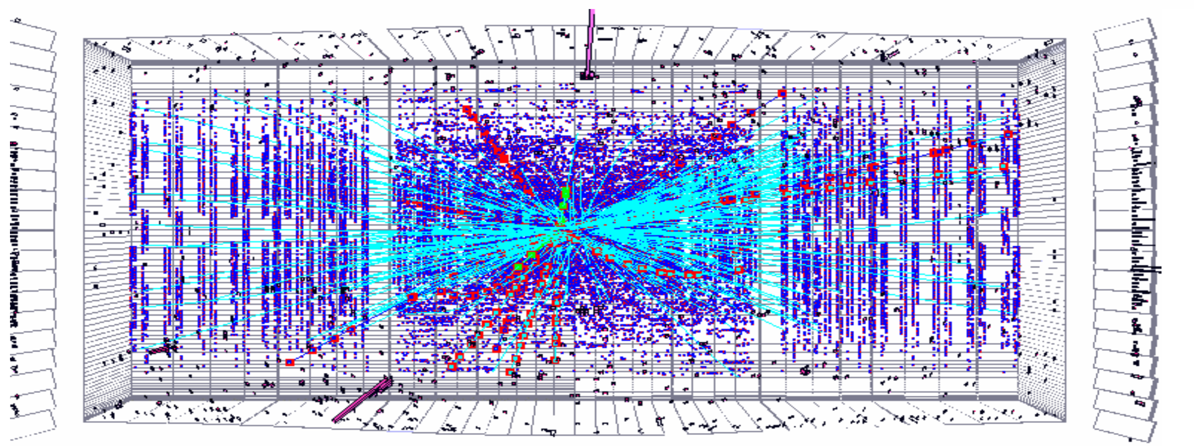
Good pattern recognition requires low occupancy of individual detectors, at ~ few% level, thus large number of small size detector channels, and fast….





Low lumi, $10^{32}cm^{-2}\ s^{-1}$





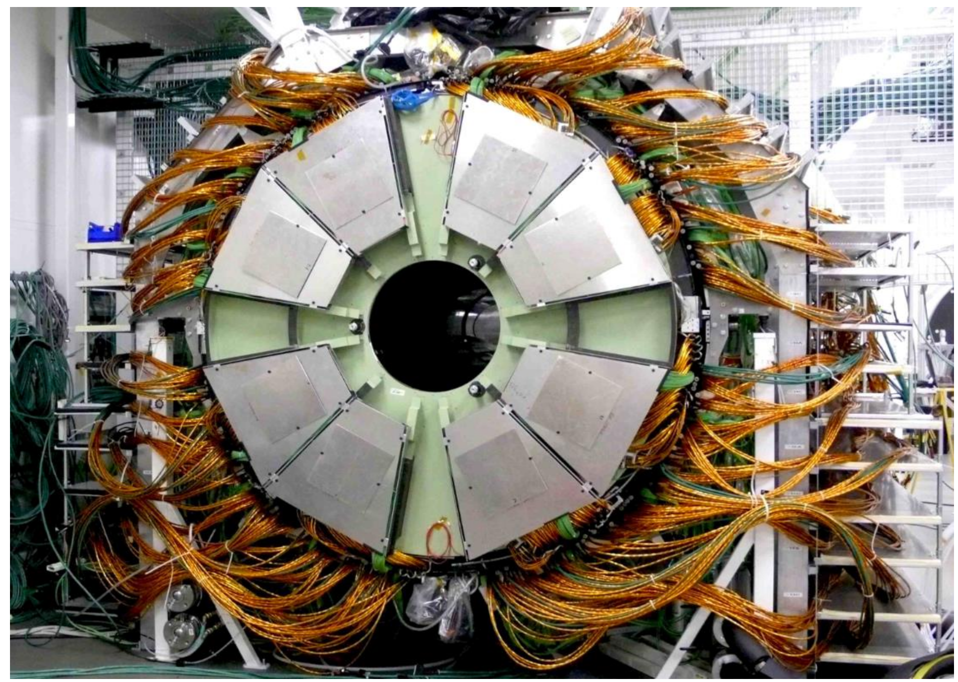
High lumi, $10^{34}cm^{-2}\ s^{-1}$ ← we MUST function in this regime!

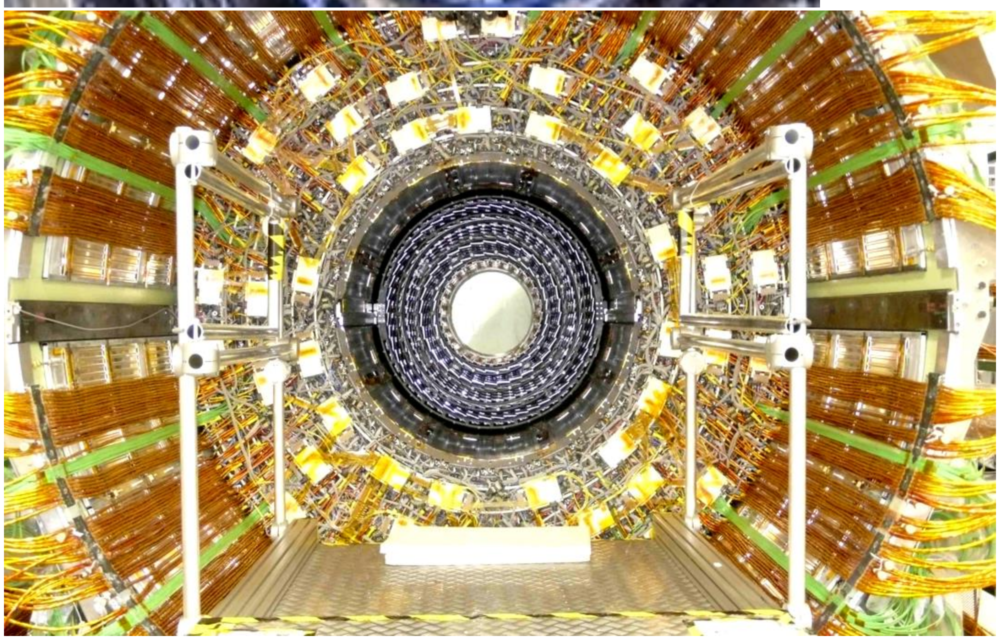
All-Silicon tracker of CMS - construction phases

TIB+ completed

Tracker of CMS:
10 million Si-microstrips
and 70 million Si-pixels

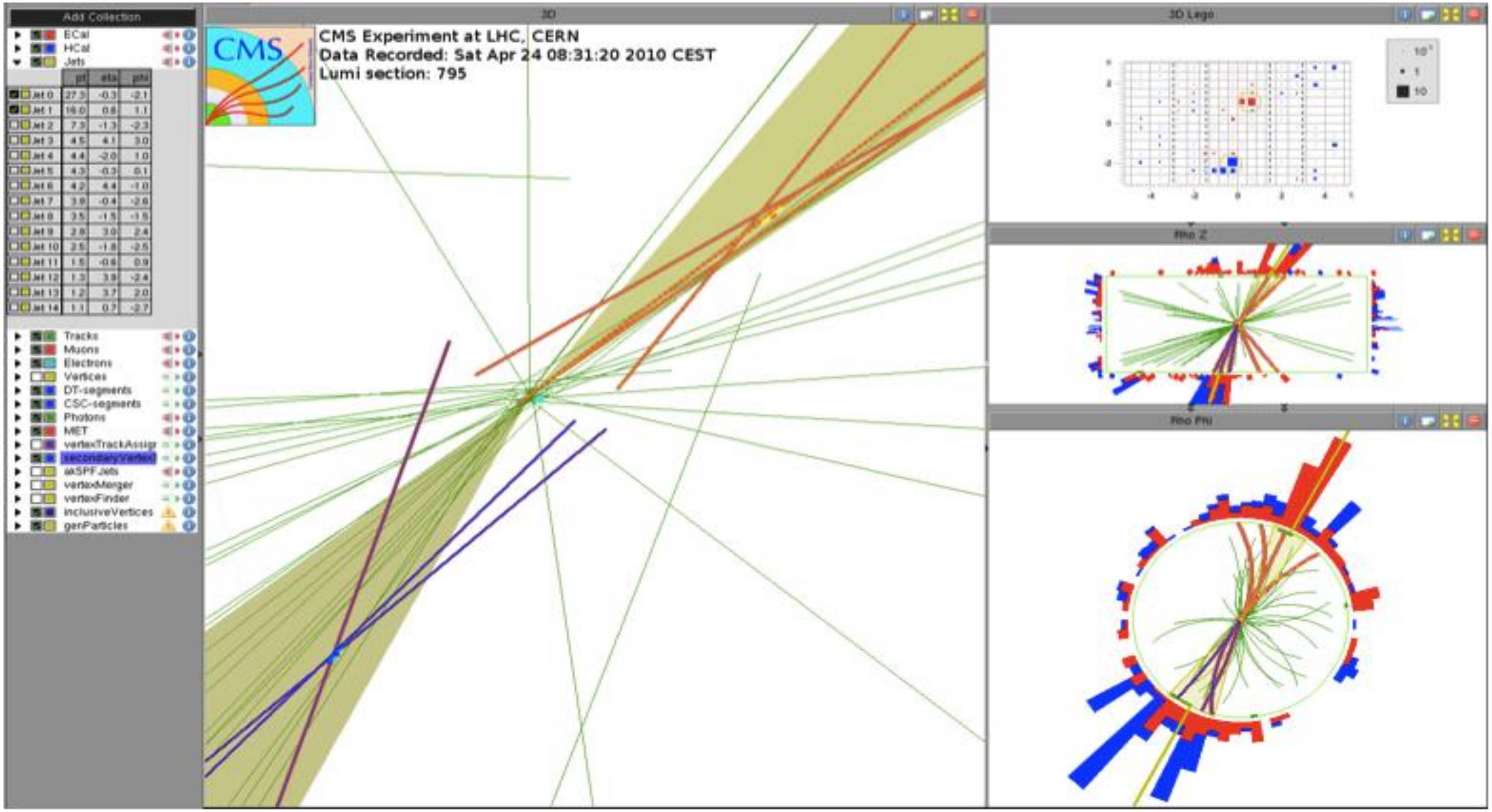
TEC inserted into TST





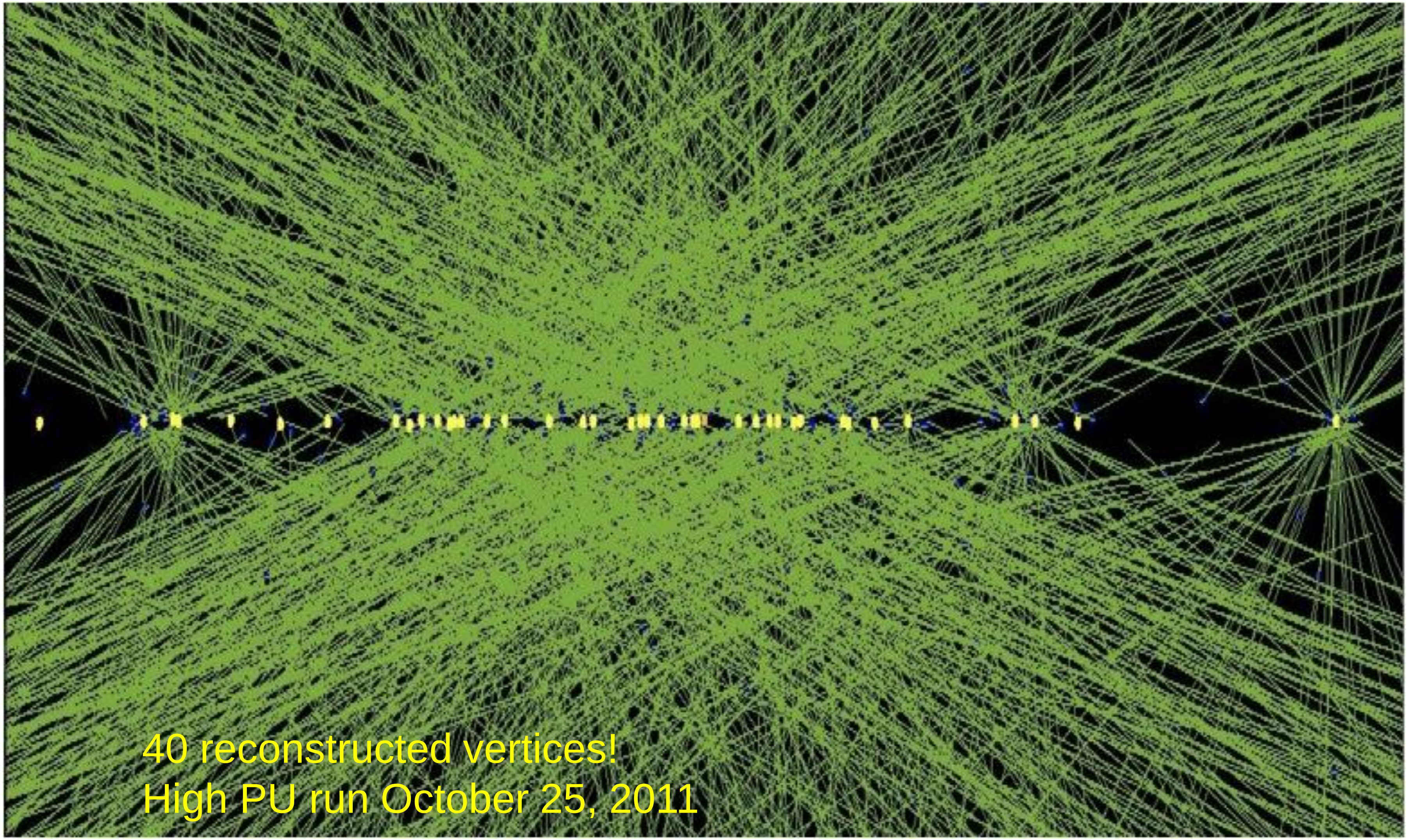
TIB+ inserted into TOB

Main task of tracker Si-pixels: reconstruction of secondary vertices, ex. b-jet reconstruction in CMS

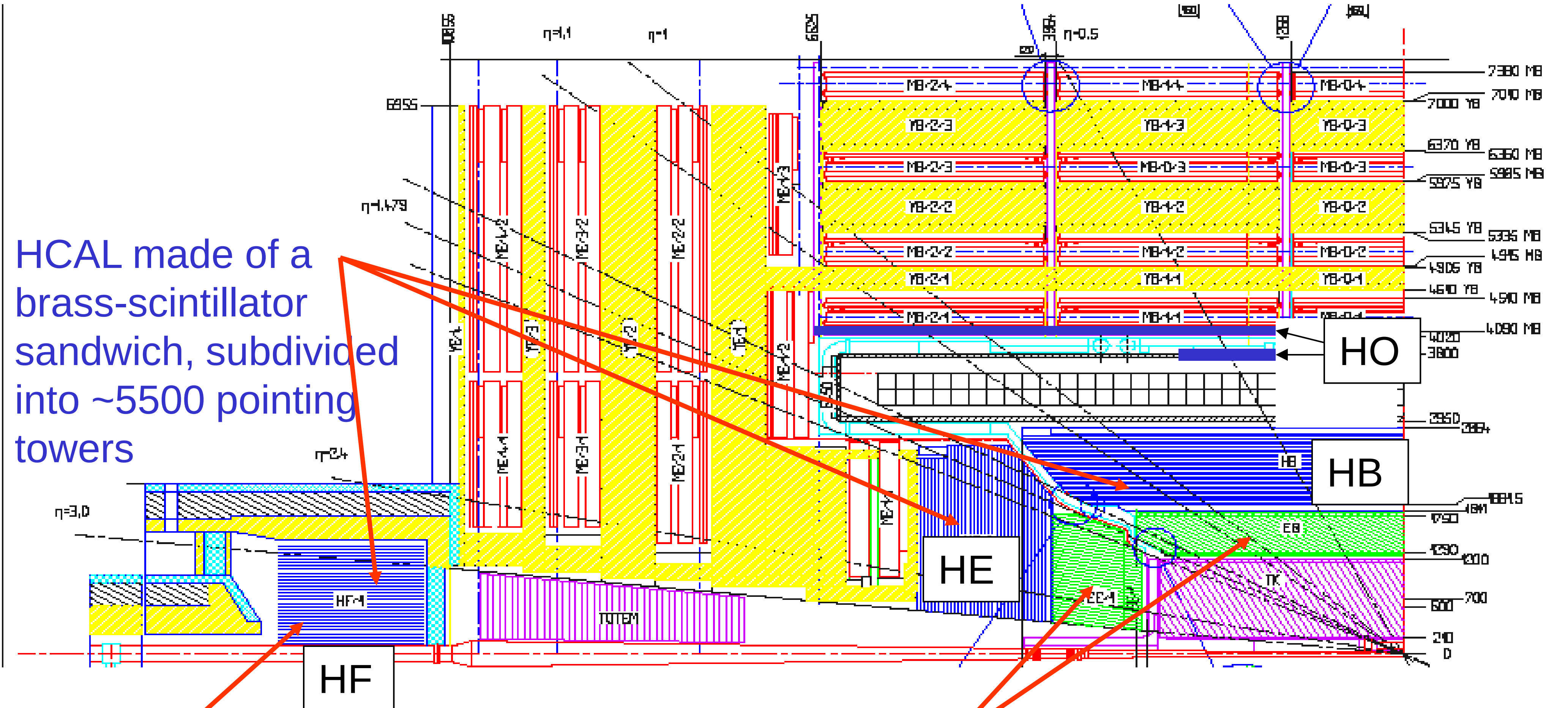


70 Million pixels, in three barrel layers at r = 4, 7 and 11cm, plus 2 x 3 end-cap planes; IP resolution ~ 20 μm asymptotically

LHC operation in 2012 : pile-up up to ~ 30 (50 nsec bunch crossing in 2012)



Calorimeters in CMS - ECAL for e/γ
HCAL essential for jets and E_t^{miss} measurements



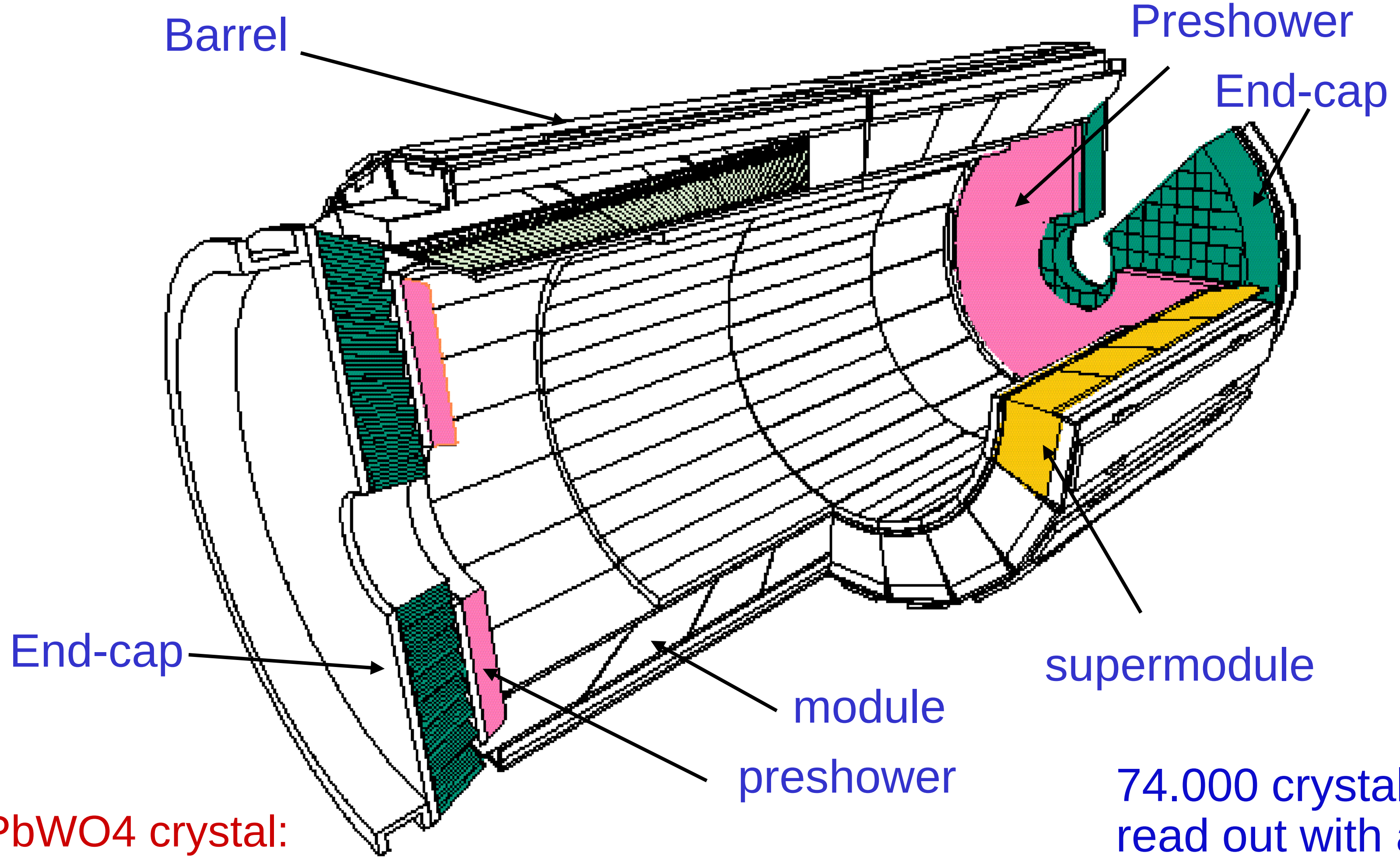
HCAL made of a brass-scintillator sandwich, subdivided into ~5500 pointing towers

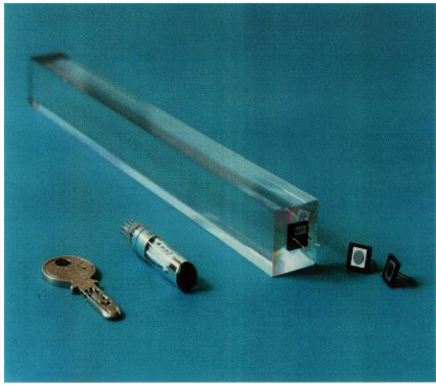
HF made of quartz fibers in Fe (Cerenkov calo)

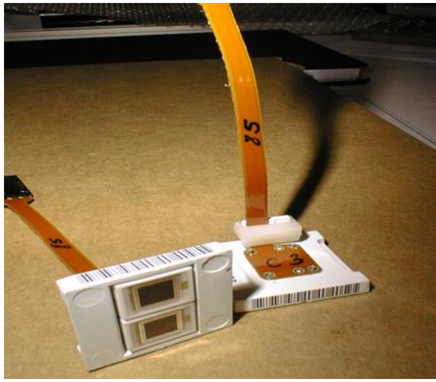
ECAL made of 76.000 pointing scintillating crystals

ECAL cost:~120 MCHF

Electromagnetic crystal ($PbWO_4$) calorimeter





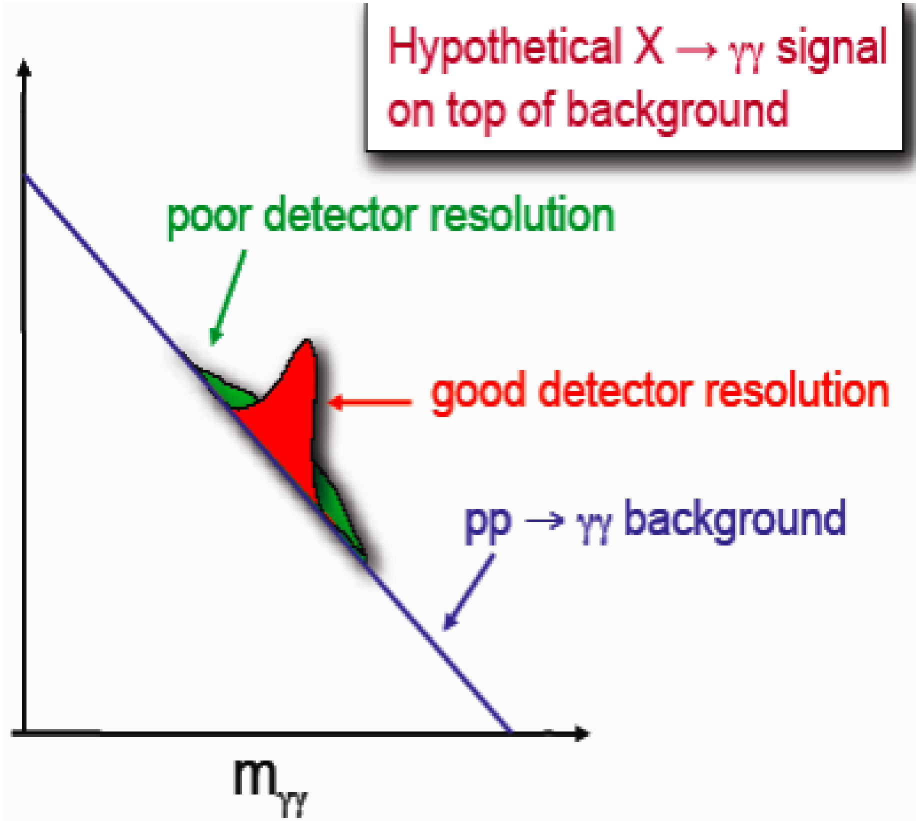


PbWO4 crystal:
Radiation length: 0.9 cm
Moliere radius: 2.3 cm
Scintilation time ~ 4nsec

Scintillating crystals produced in Russia and China 2000 - 2008

74.000 crystals altogether read out with avalanche photo diodes (Hamamatsu) in barrel and VPT's in the end-caps

Higgs decay to 2 photons influenced choice of ECAL in both ATLAS and CMS, aiming at ~1% resolution at ~100 GeV



$$M^2 = 2E_1E_2(1-\cos\theta)$$

$$dM/M \propto d\cos\theta/\cos\theta$$

$$dM/M \propto dE/E$$

QuickTime™ and a decompressor are needed to see this picture.

this is what we had in mind…..

γ_1= 86 GeV

QuickTime™ and a decompressor are needed to see this picture.

γ_2= 56 GeV

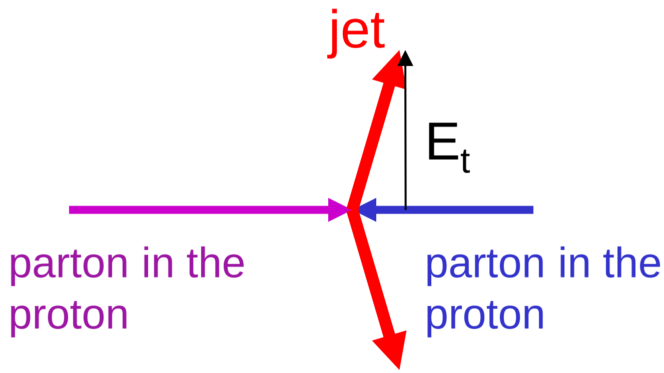
Higgs signal vs background S/B ~ 1/15, with ~1GeV ie ~1% mass resolution

Hadron Calorimeter: brass-scintillator sampling calorimeter - construction status in 2006

Half HCAL in CMS surface assembly hall

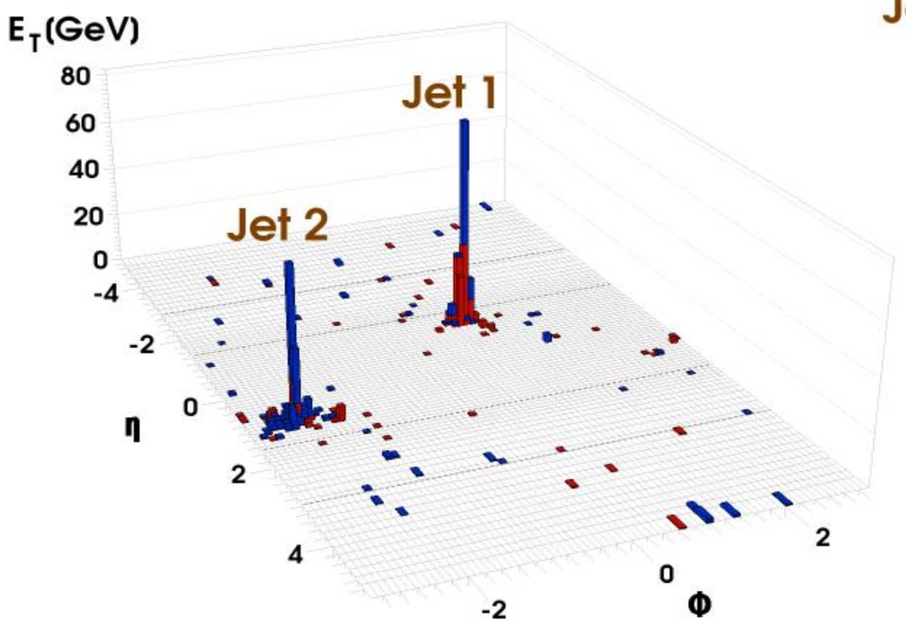
Observation of hard jets in CMS, June 2010

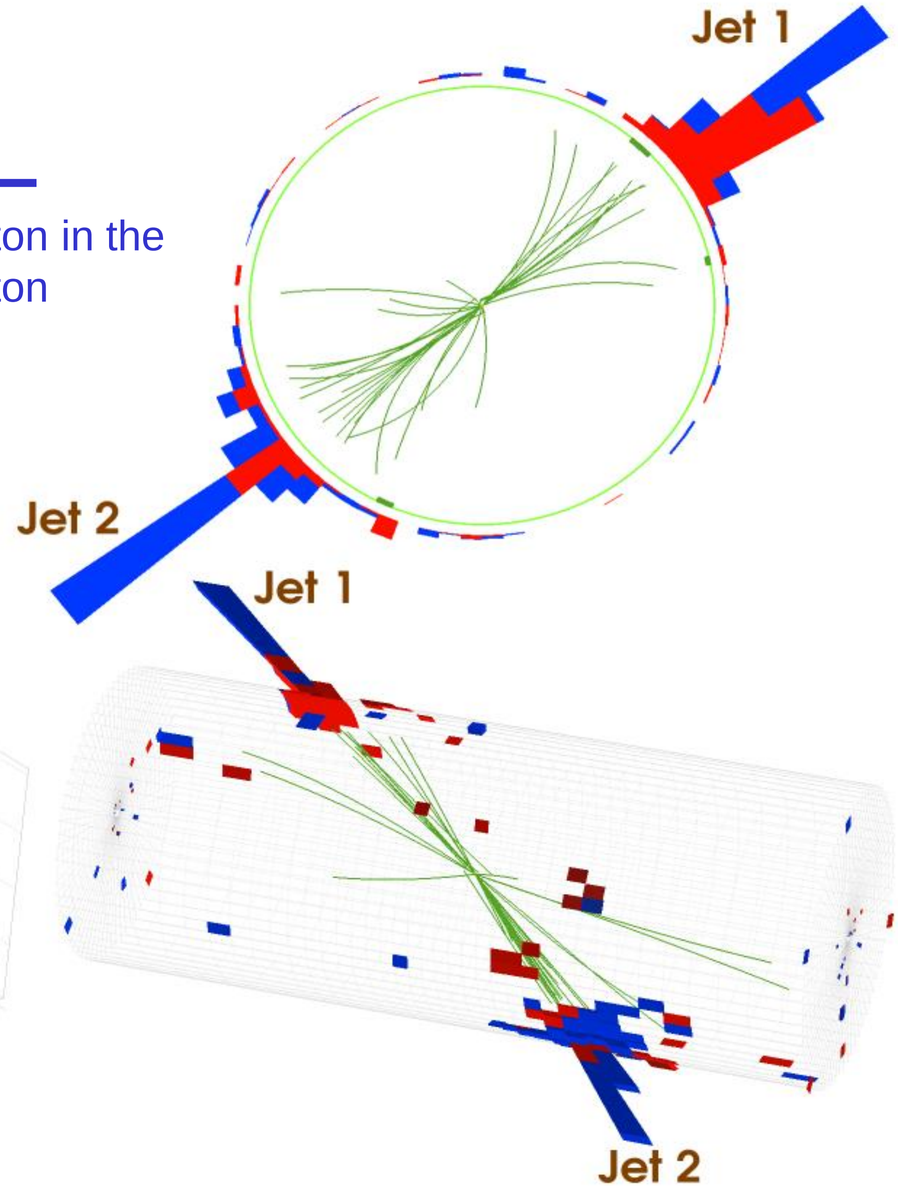
CMS Experiment at LHC, CERN
Run 133450 Event 16358963
Lumi section: 285
Sat Apr 17 2010, 12:25:05 CEST



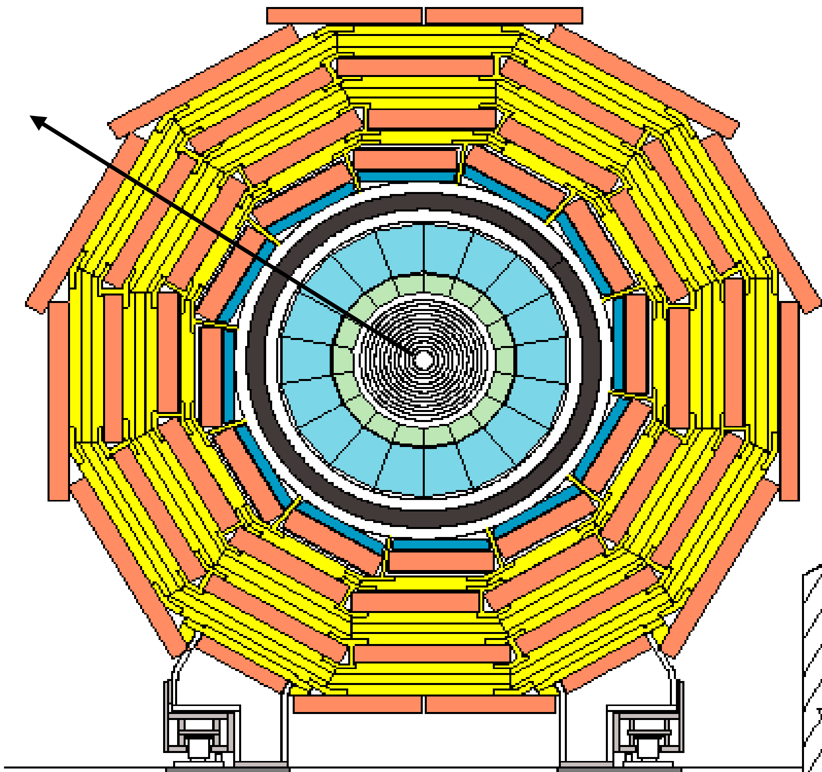
Jet1 p_T : 253 GeV
Jet2 p_T : 244 GeV

Dijet Mass : 764 GeV





Barrel muon system: drift tubes and RPC's

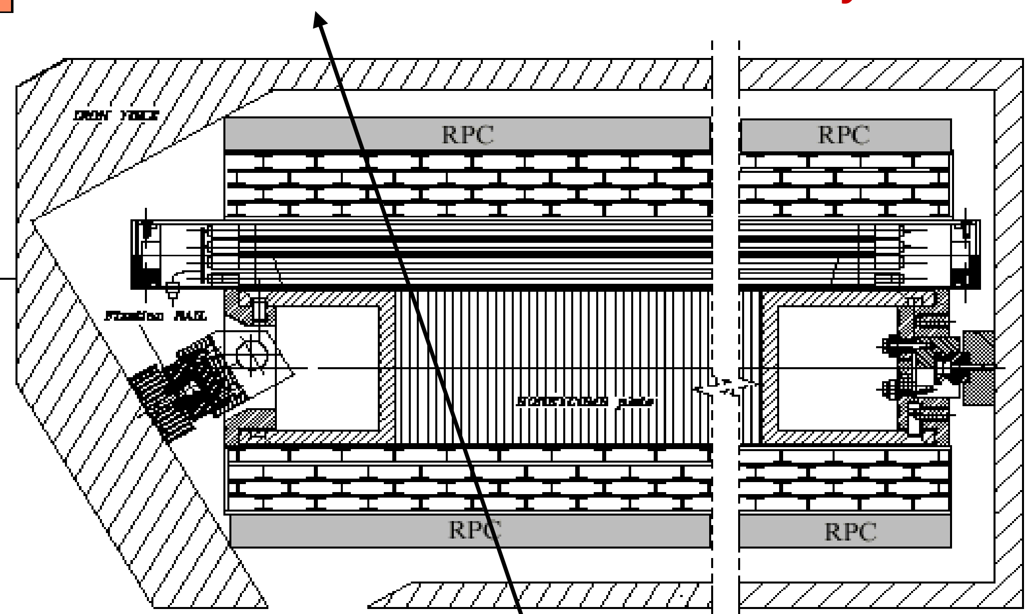


- MB1,2,3= 8 ϕ-layers
  + 4 θ-layers
- MB4= 8 ϕ-layers

- 250 chambers
- 192 000 channels

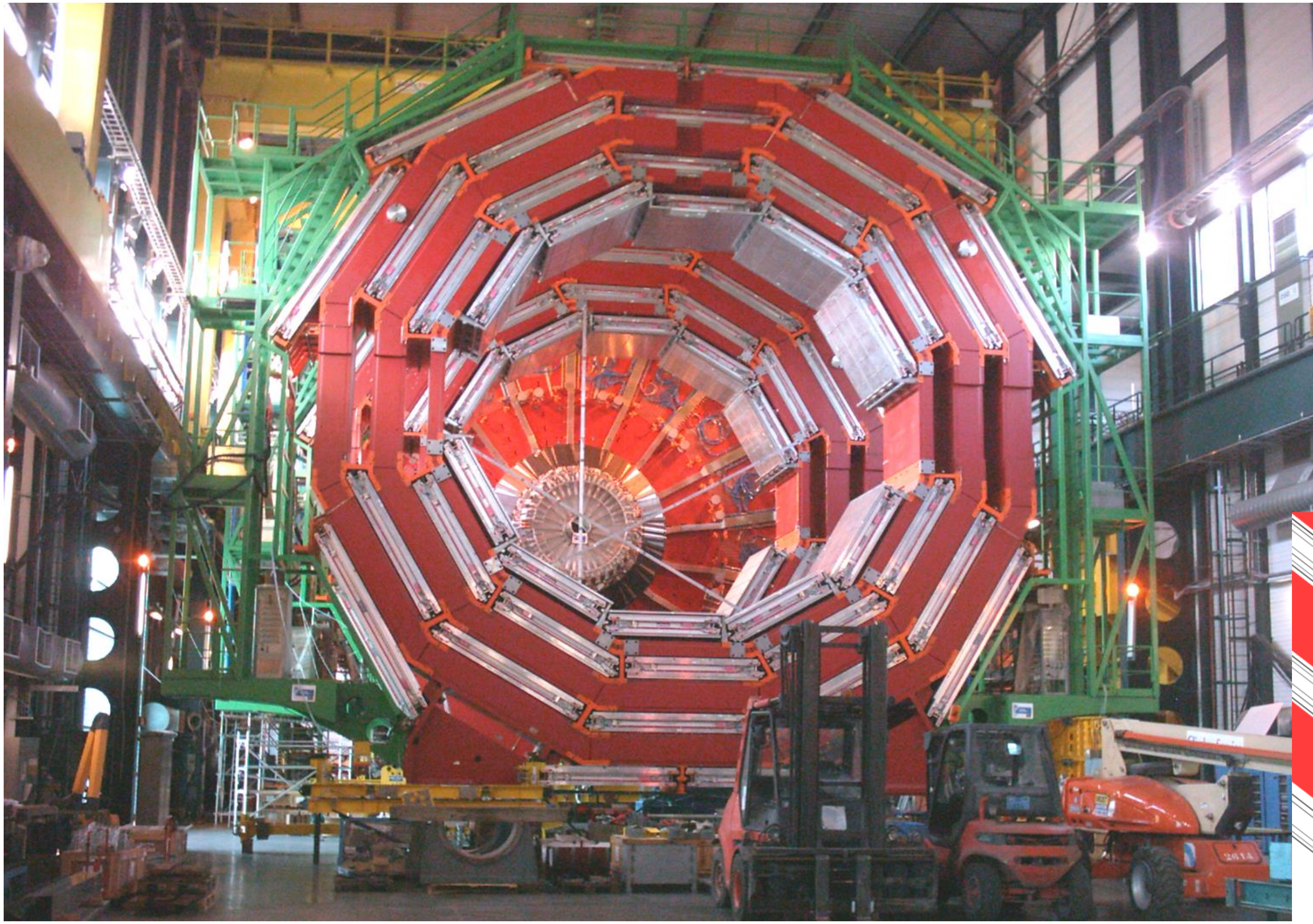
Spatial resolution needed per chamber ~ 100 μm and ~1mrad in track direction thus ~ 200 μm per layer is OK

- wire pitch = 4.2 cm
- max. drift time = 380 ns

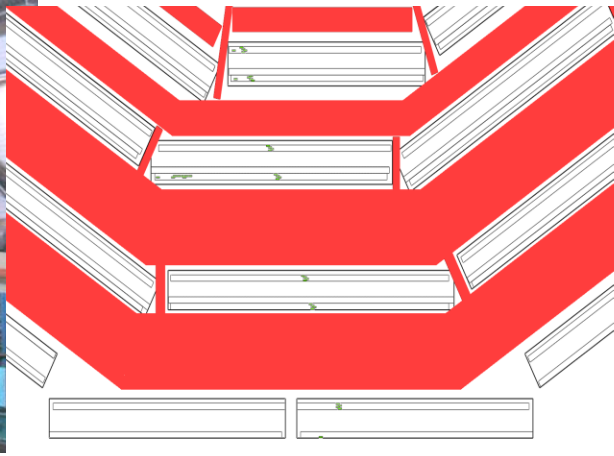


Crossing muon

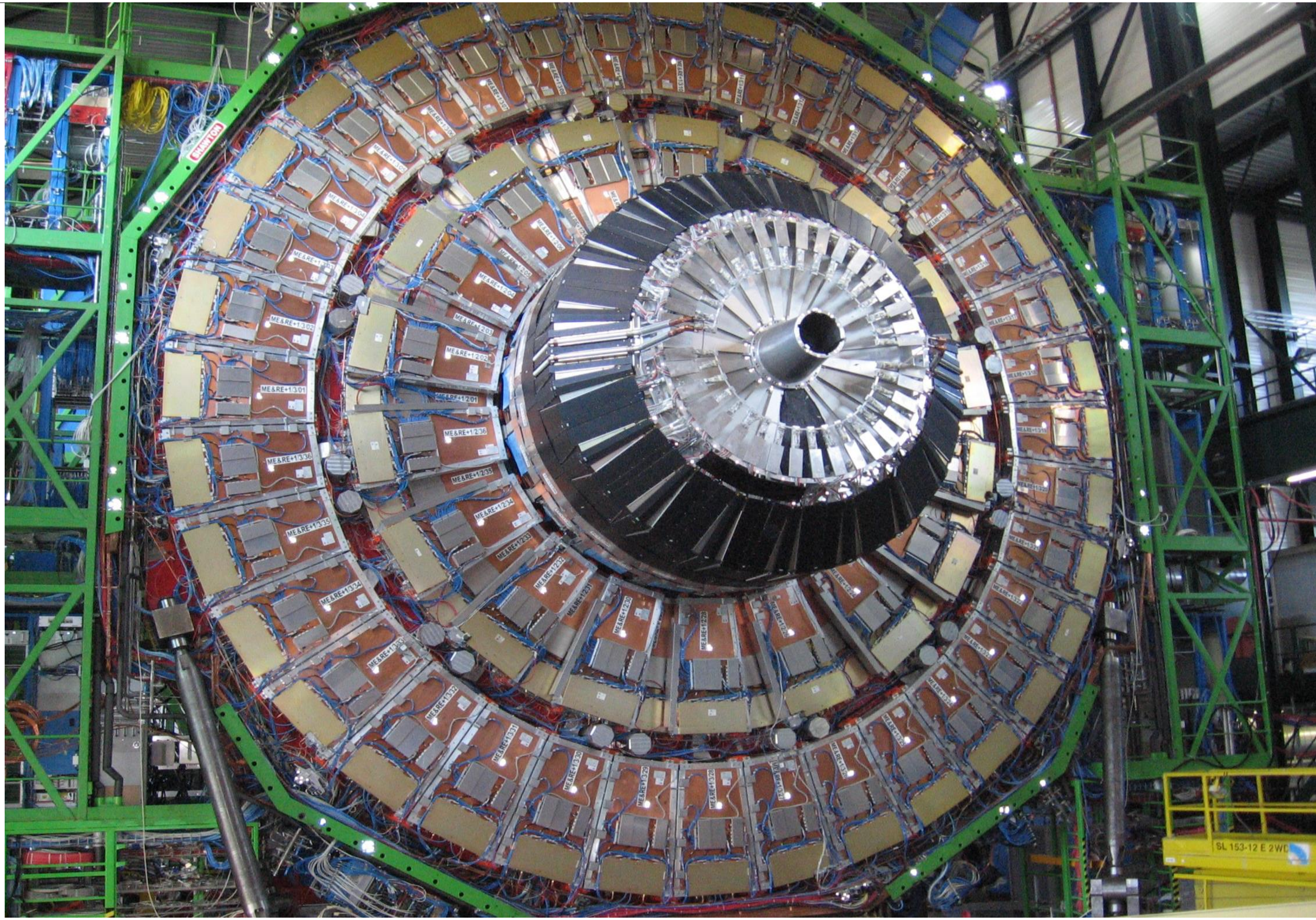
Barrel muon system: drift tubes
during construction and installation in 2005/06



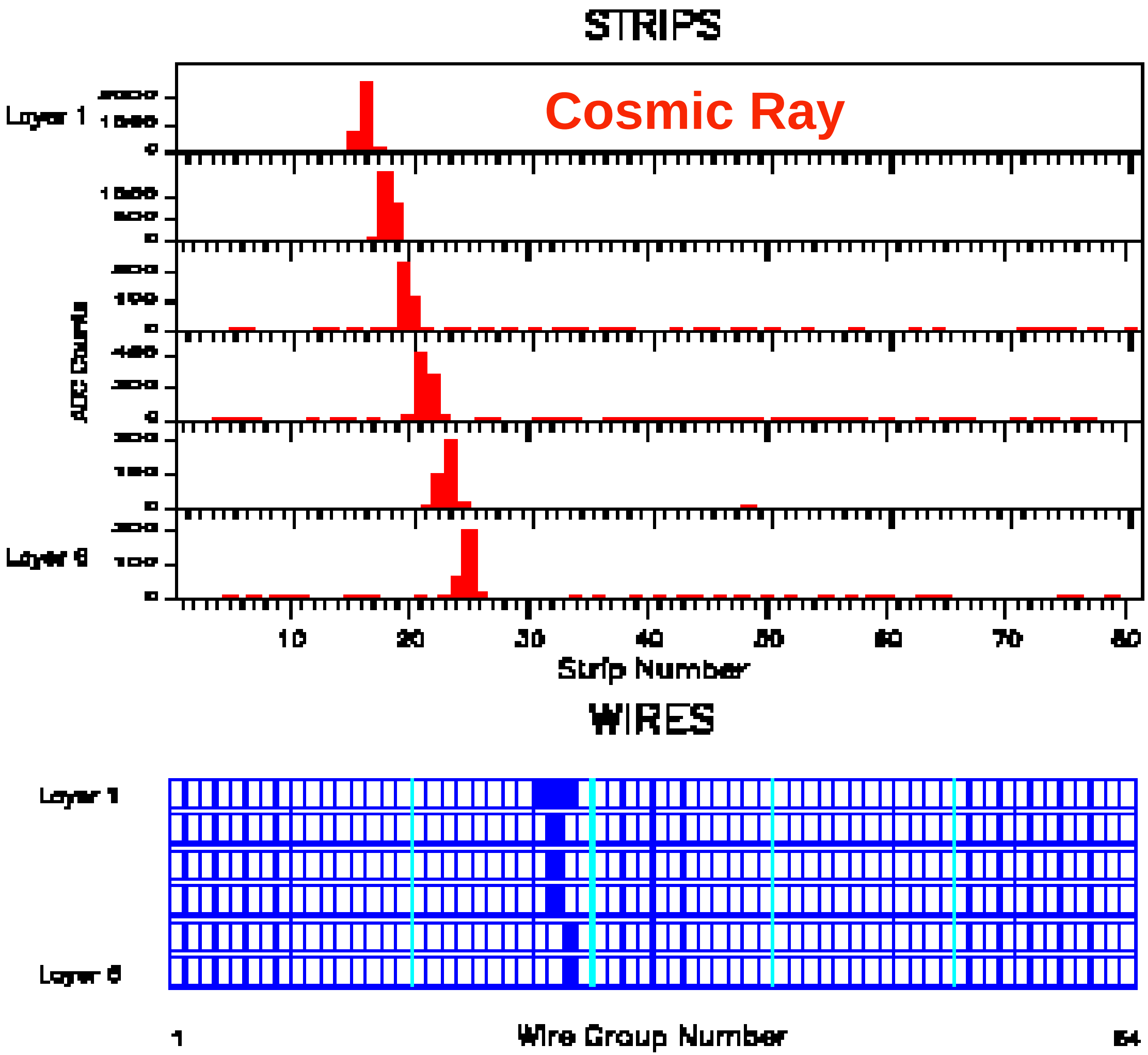
12 layers per chamber



Cathode Strip Chambers (CSC) and RPC's - status in Sept 2006



First real particles detected in CSCs in SX5 ! Cosmic ray run



CMS upgrades in LS1 - 2013/14
- situation end-February 2014

Muon coverage completion and consolidation

QuickTime™ and a
decompressor
are needed to see this picture.

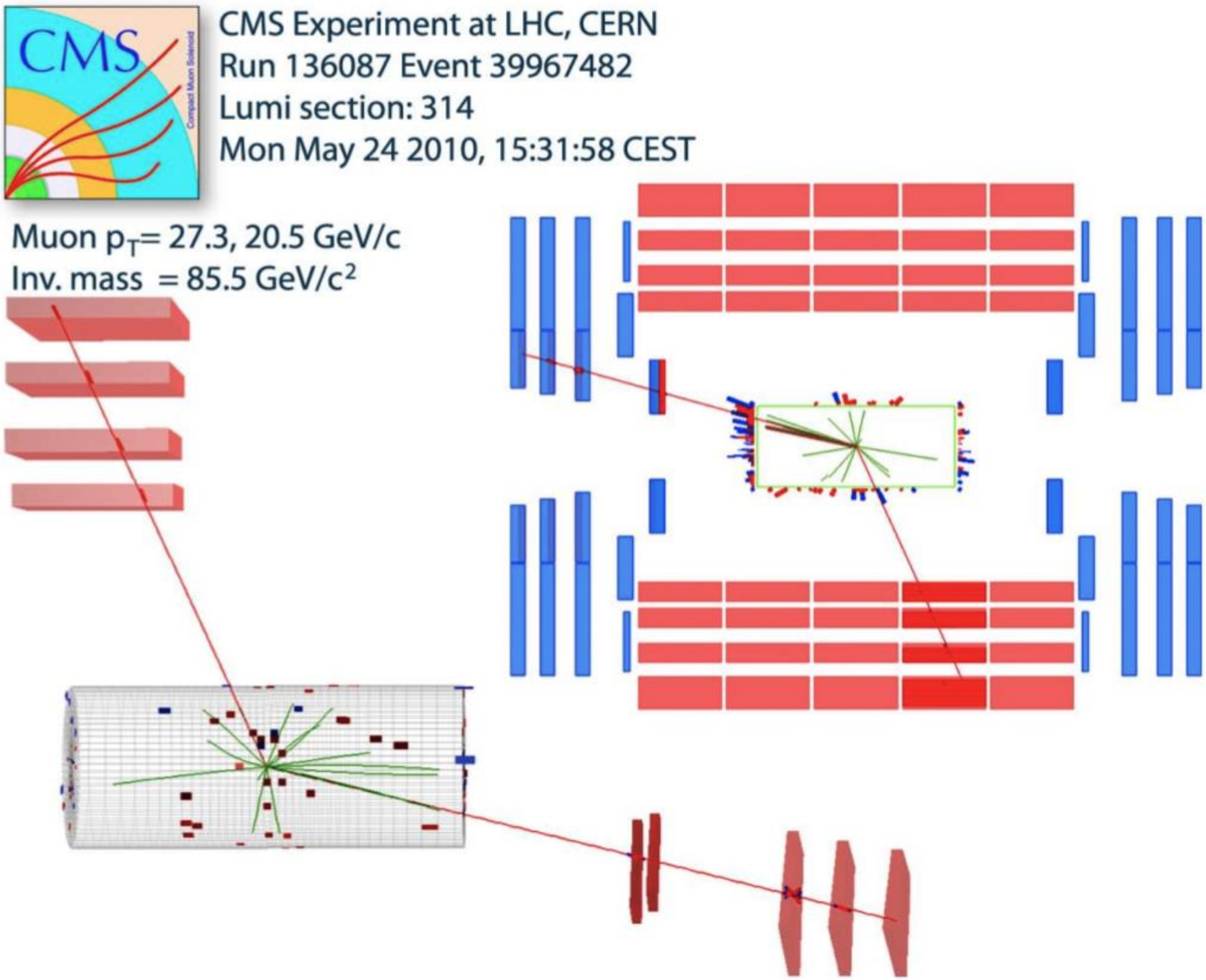
QuickTime™ and a
decompressor
are needed to see this picture.

ME4/2: + side DONE

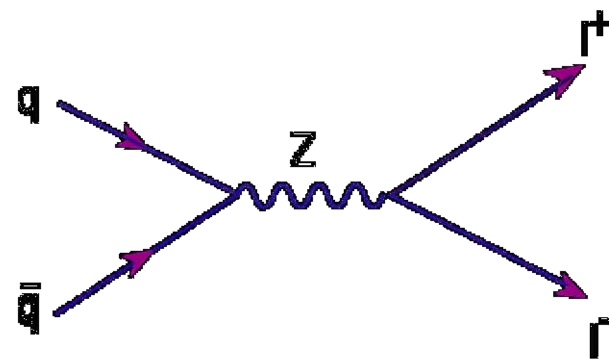
Team from Egypt takes part in this task

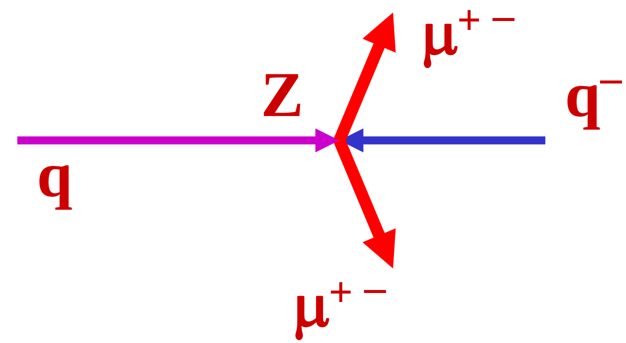
RE4 + side : DONE

First Z → $\mu^+\mu^-$ event in CMS, April 2010



$Z \rightarrow \mu^+ + \mu^-$

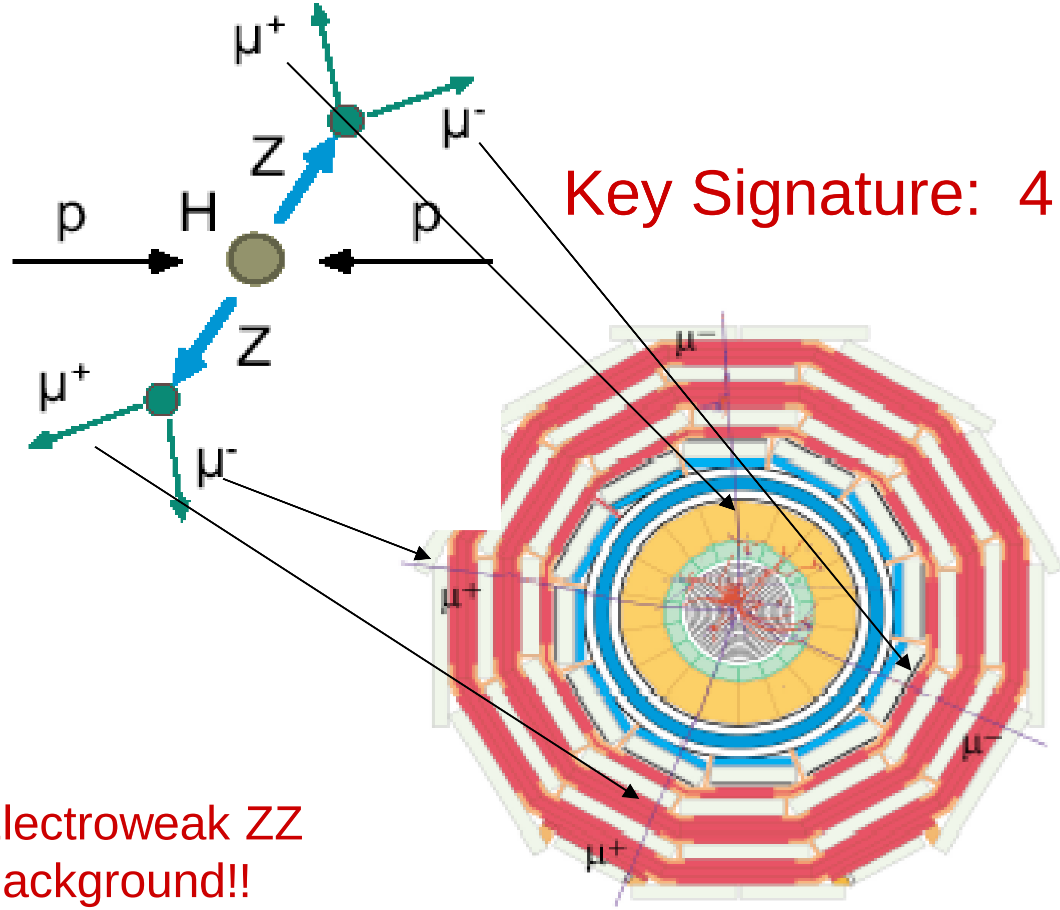




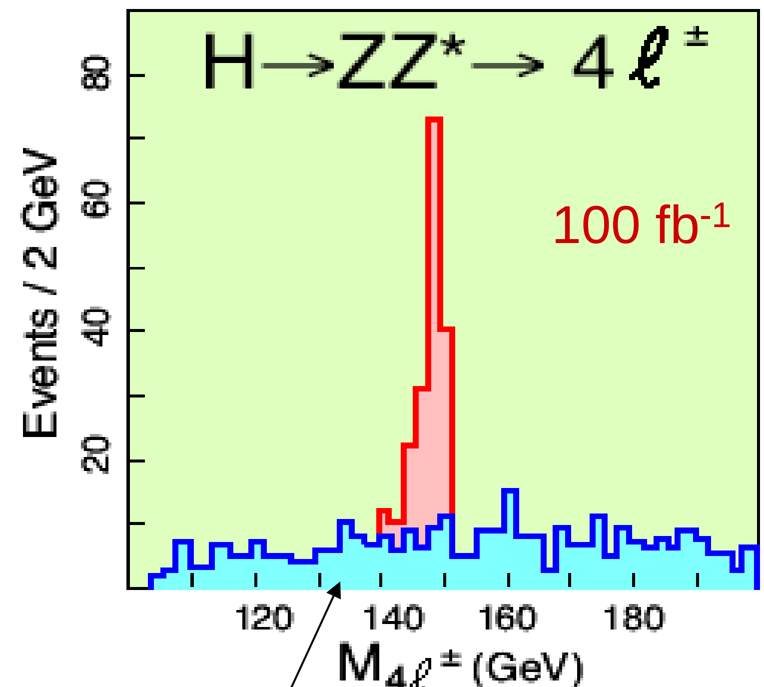
Production and detection of the Higgs in CMS - if m_H ~ 150 GeV ($H \longrightarrow ZZ/ZZ^* \longrightarrow$ 4 leptons)

- as expected in 1992/93!!

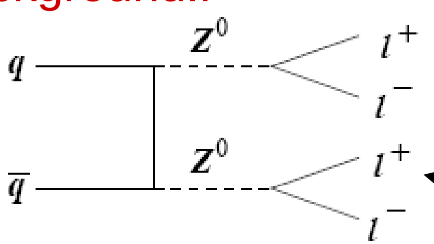
Key Signature: 4 muons/leptons



M_{Higgs} = 150 GeV



Electroweak ZZ Background!!



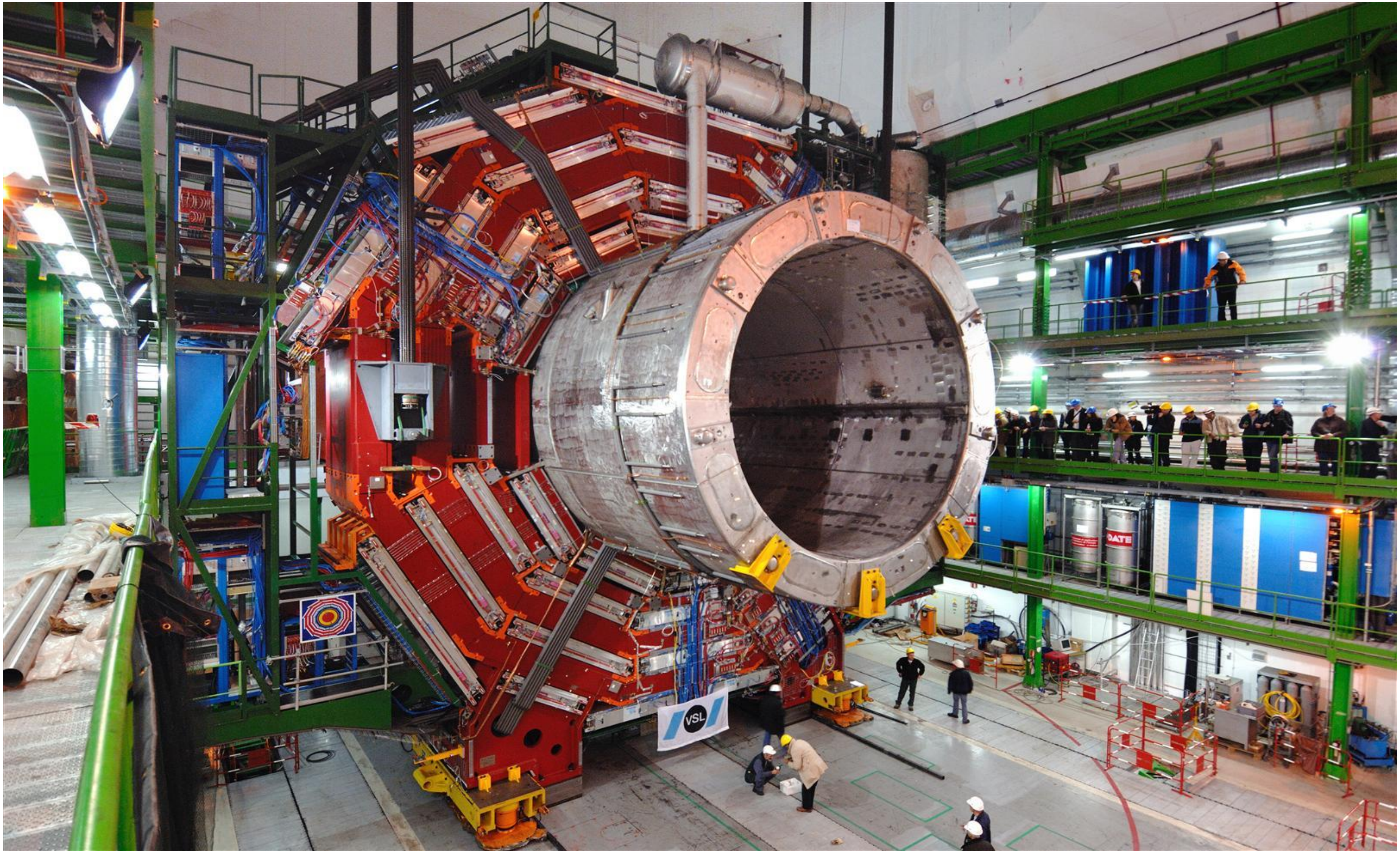
Electroweak ZZ background

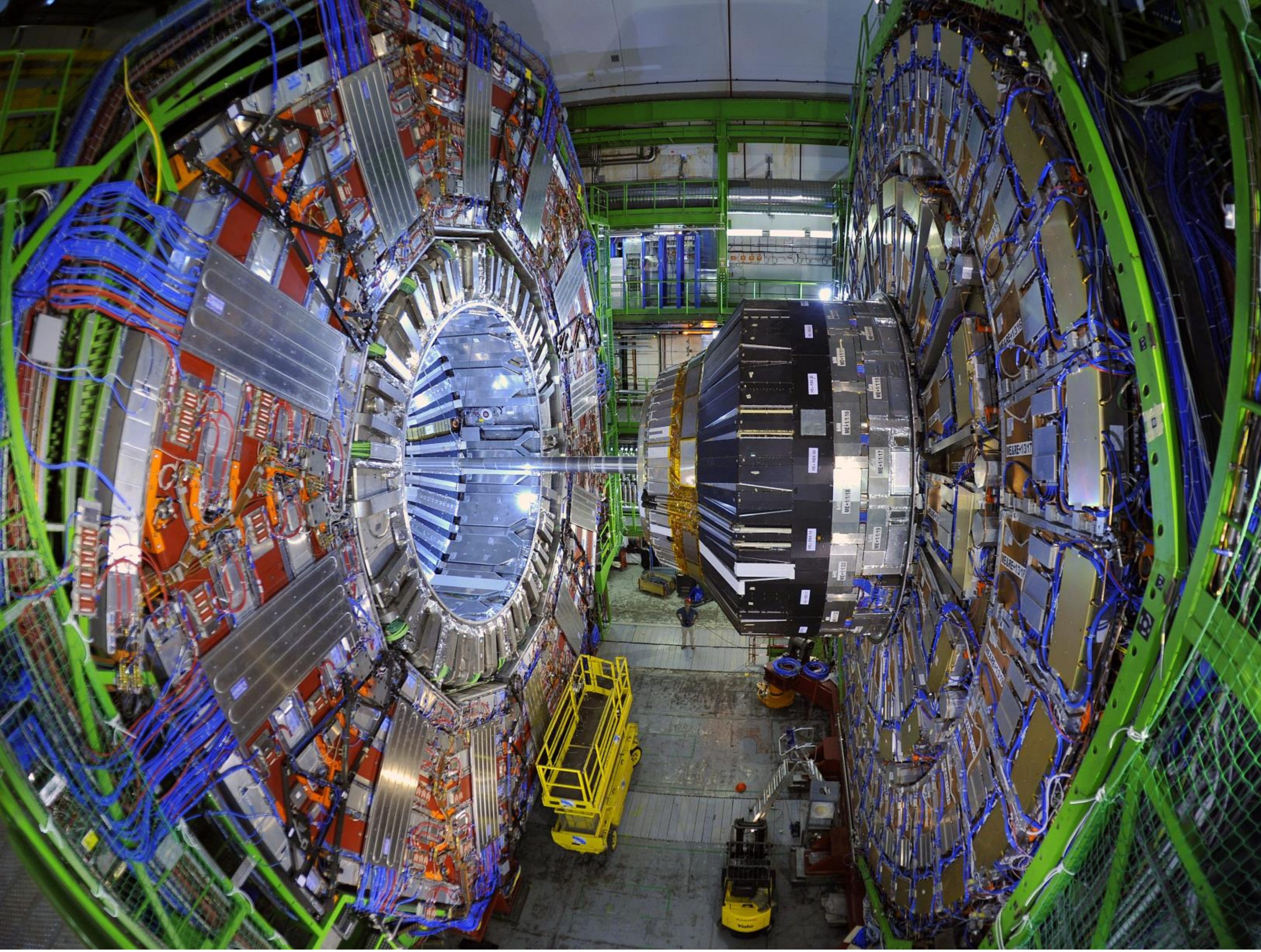
Higgs → 4 leptons, lepton pt spectra

QuickTime™ and a
decompressor
are needed to see this picture.

It is essential to go down to ~ 5-7 GeV,
In CMS we succeed with muons

YB0 in the CMS experimental cavern in Feb 2007



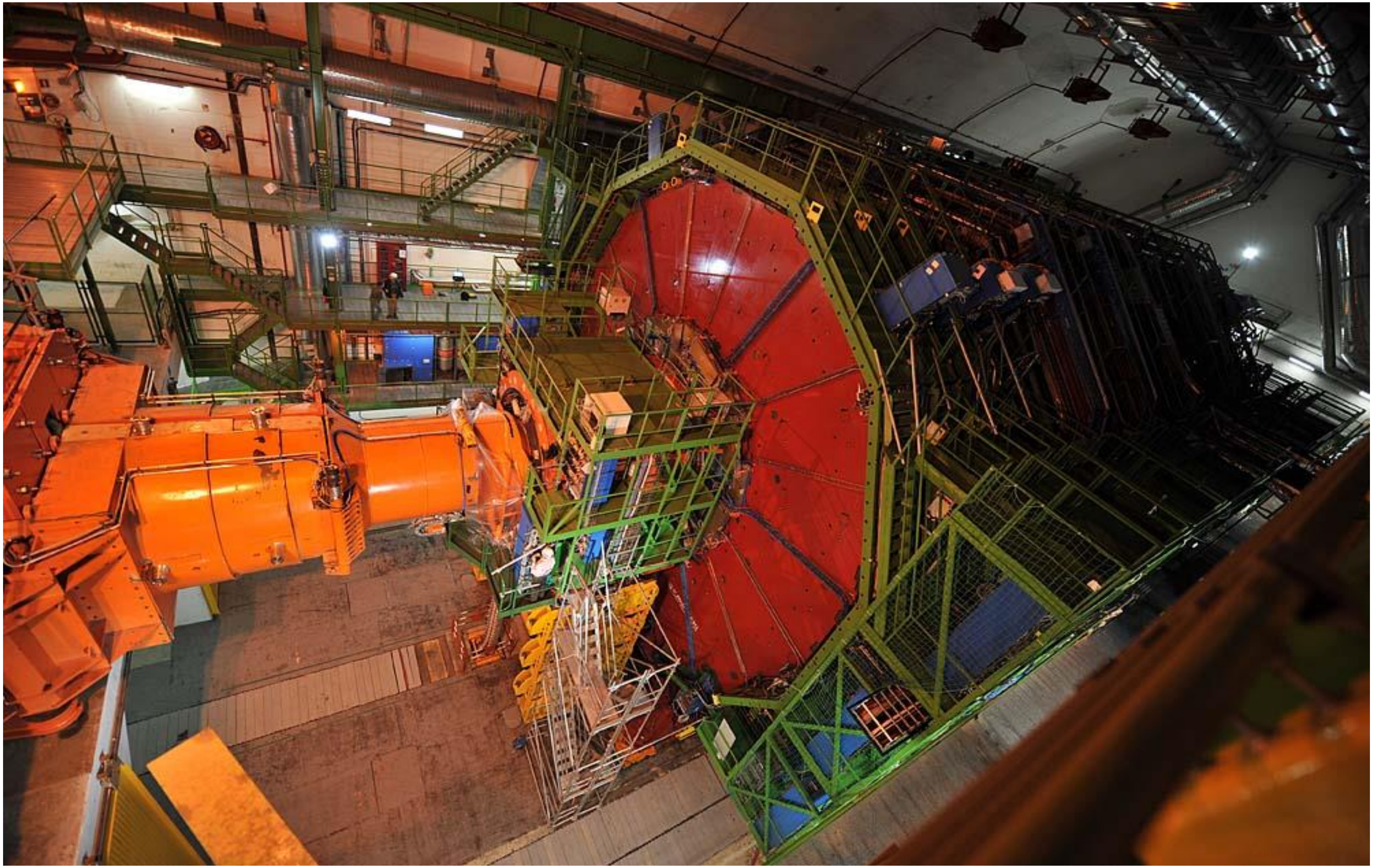


QuickTime™ and a
decompressor
are needed to see this picture.

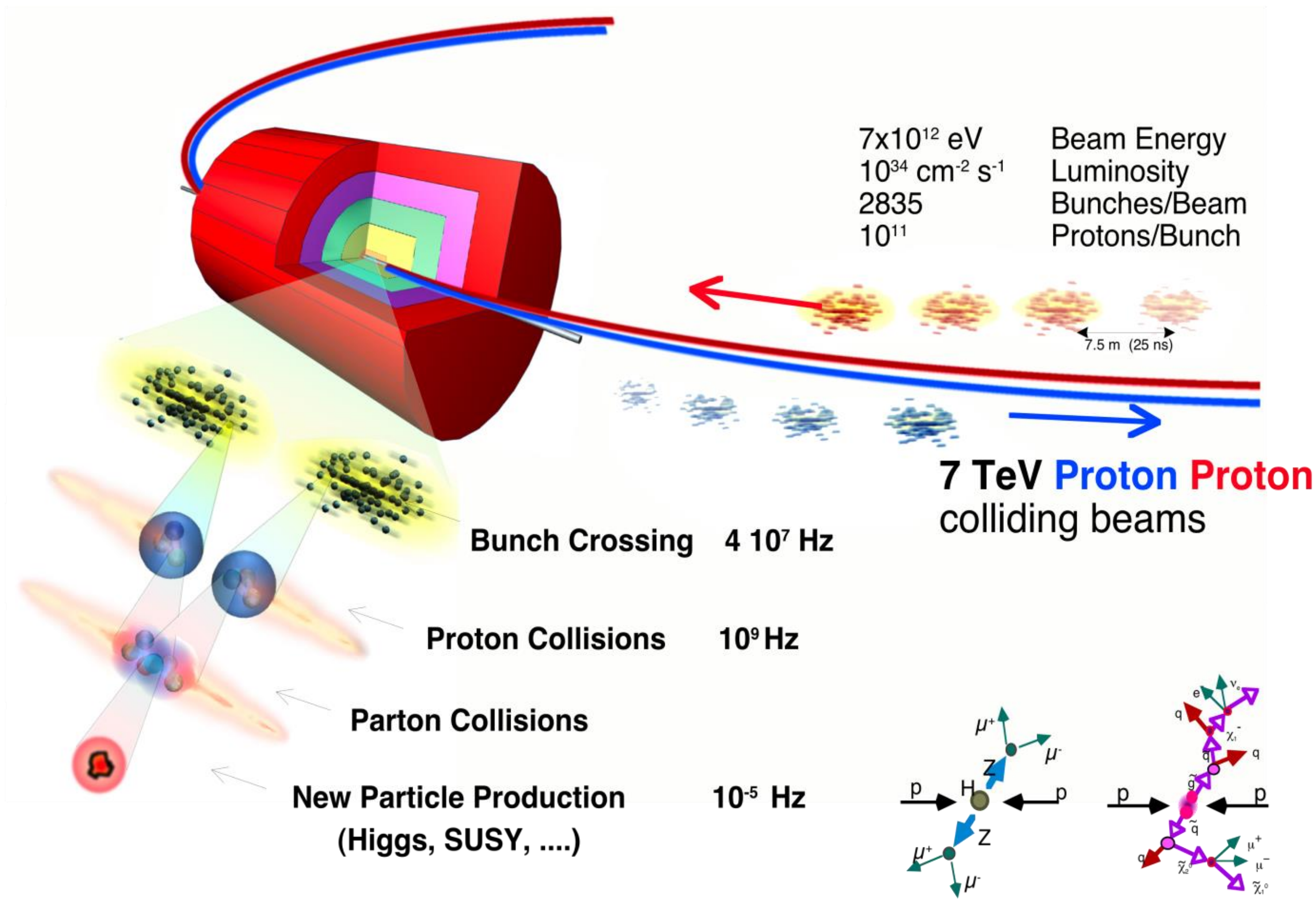
Installation of the beam pipe and initial closure of CMS
in summer 2008

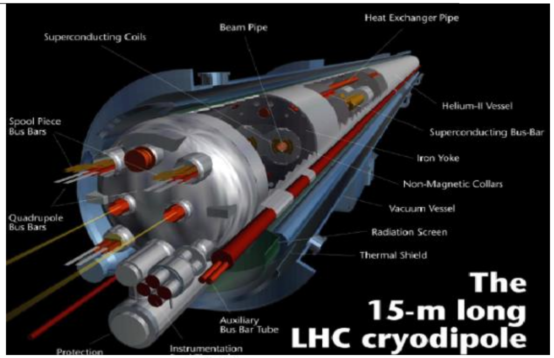
New Be beam pipe in 2013: finally OK

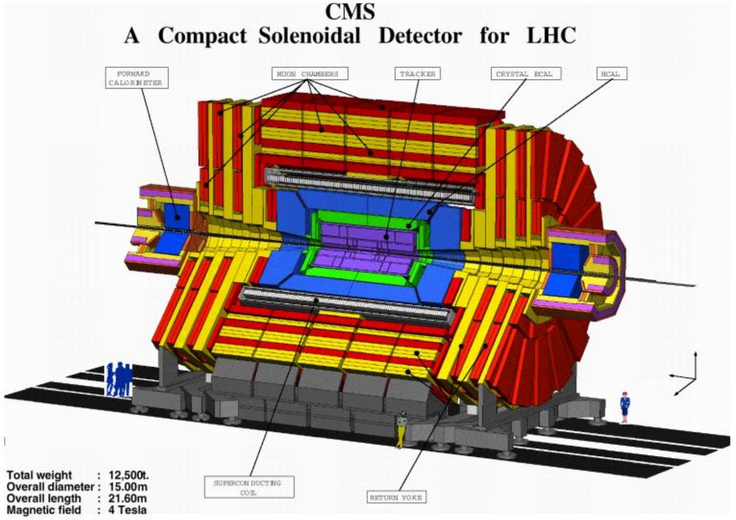
Final closure of CMS - September 2008 - ready for initial collisions



LHC operation mode and constraints on machine and experiments

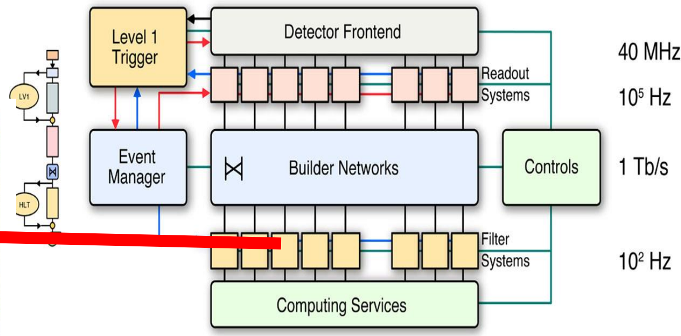






Selection of 1 event in 10,000,000,000,000

5000 processors

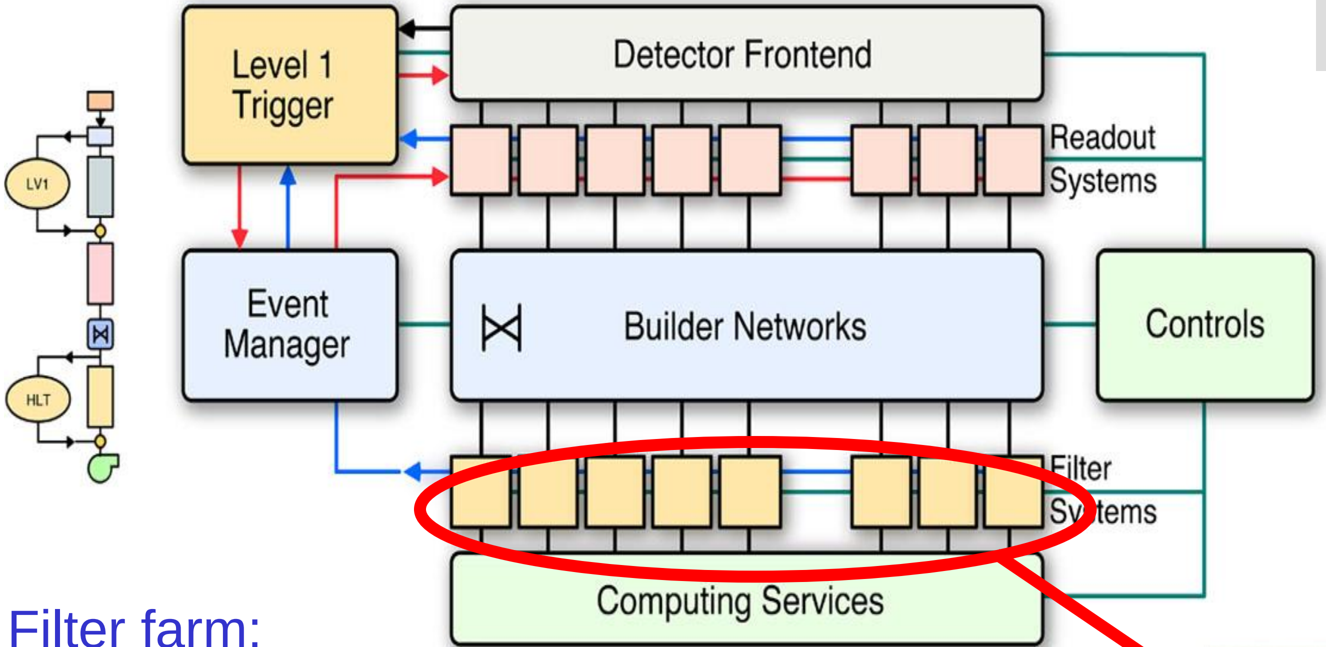


The trigger and data acquisition system of CMS

Example CMS:

Collision rate	**40 MHz**
Level-1 max. trigger rate	**100 kHz†**
Average event size	**≈ 1 Mbyte**

† 50 kHz at startup (DAQ staging)



40 MHz — From collider + detector

10^5 Hz — < 3μsec for L1 decision; L1 output

1 Tb/s

HLT takes ~ 40msec/event

10^2 Hz — Onto storage devices

Filter farm:

- approx. 5000 CPUs
- easily scaleable
- staged (lower lumi & saves money)
- uses offline software

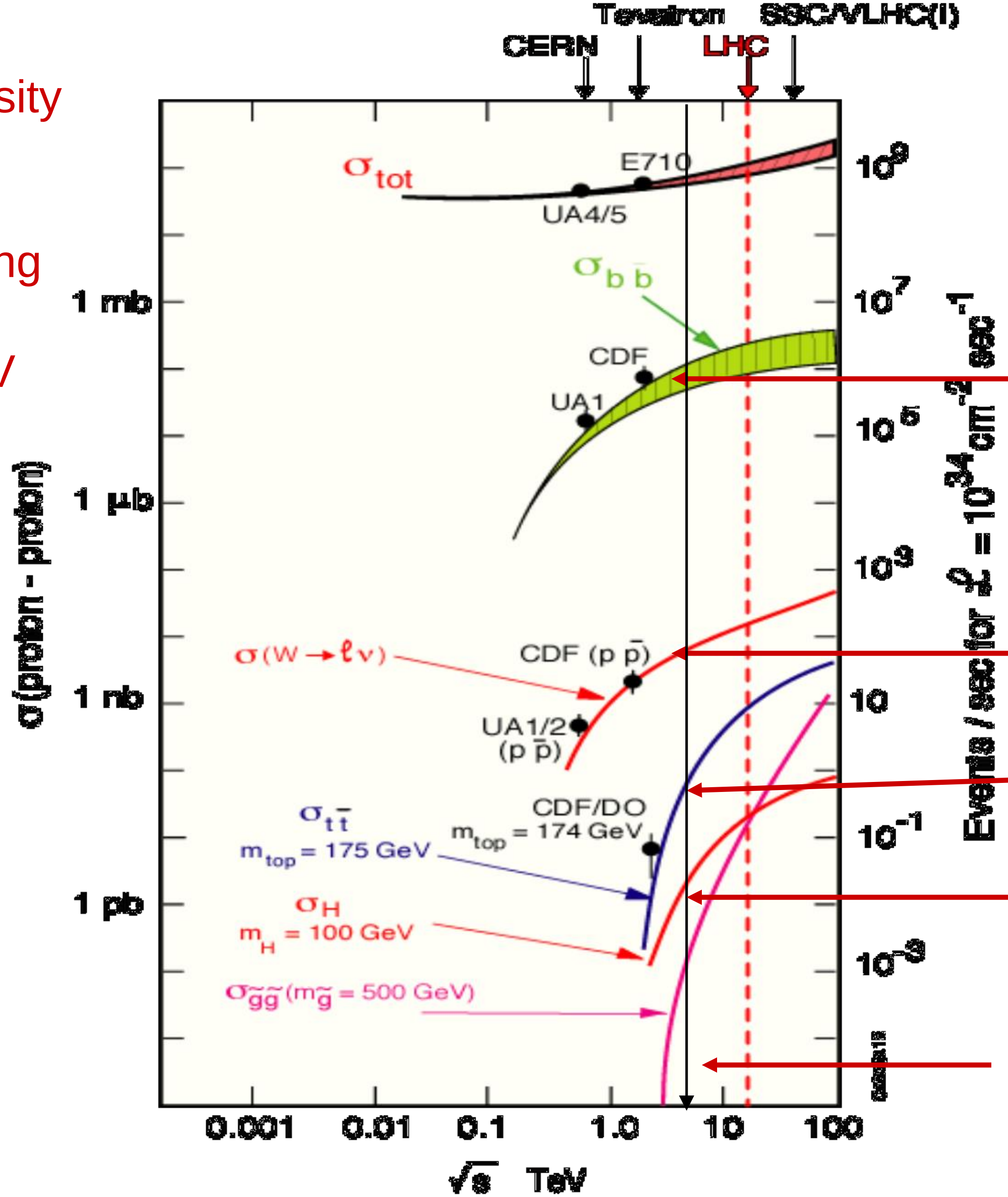
In May 2011 with L = $8x10^{32}$, L1 rate of 40 kHz, we measured 35% CPU usage. Need for constant upgrading

Some physics results and expectations

SM (jets, W/Z, top, B-phys), Higgs,

Cross sections and event rates at hadron colliders,
opening of channels with increasing luminosity

Increase in luminosity and consequent increase in LHC physics reach during the running in 2010/2011 at 7 TeV center of mass energy; in 2012 we ran at 8TeV. In 2015 expect ~13 TeV



Levels of sensitivity attained taking into account decay branching ratios);

Initial running, hadronic resonances

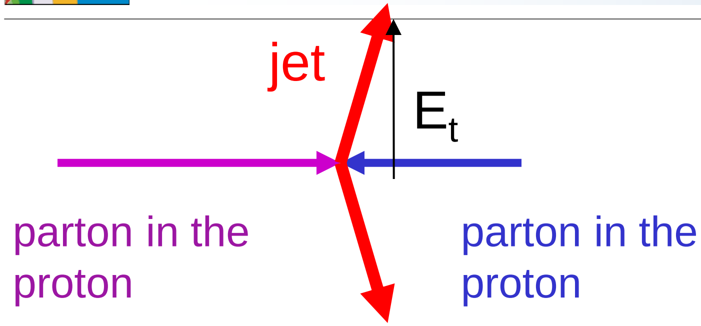
In April 2010, first W,Z events

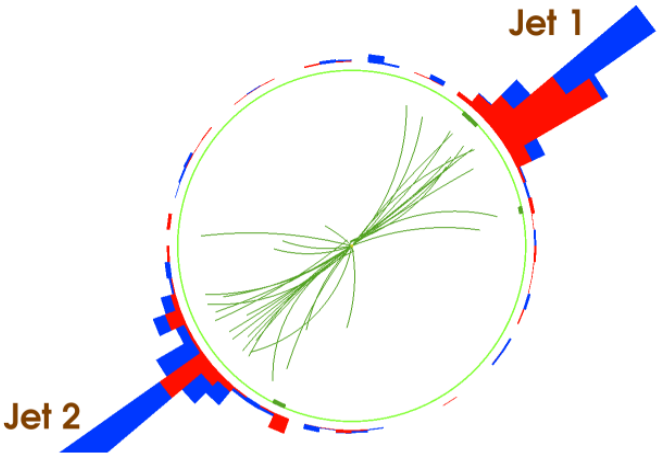
In July 2010, first tt events

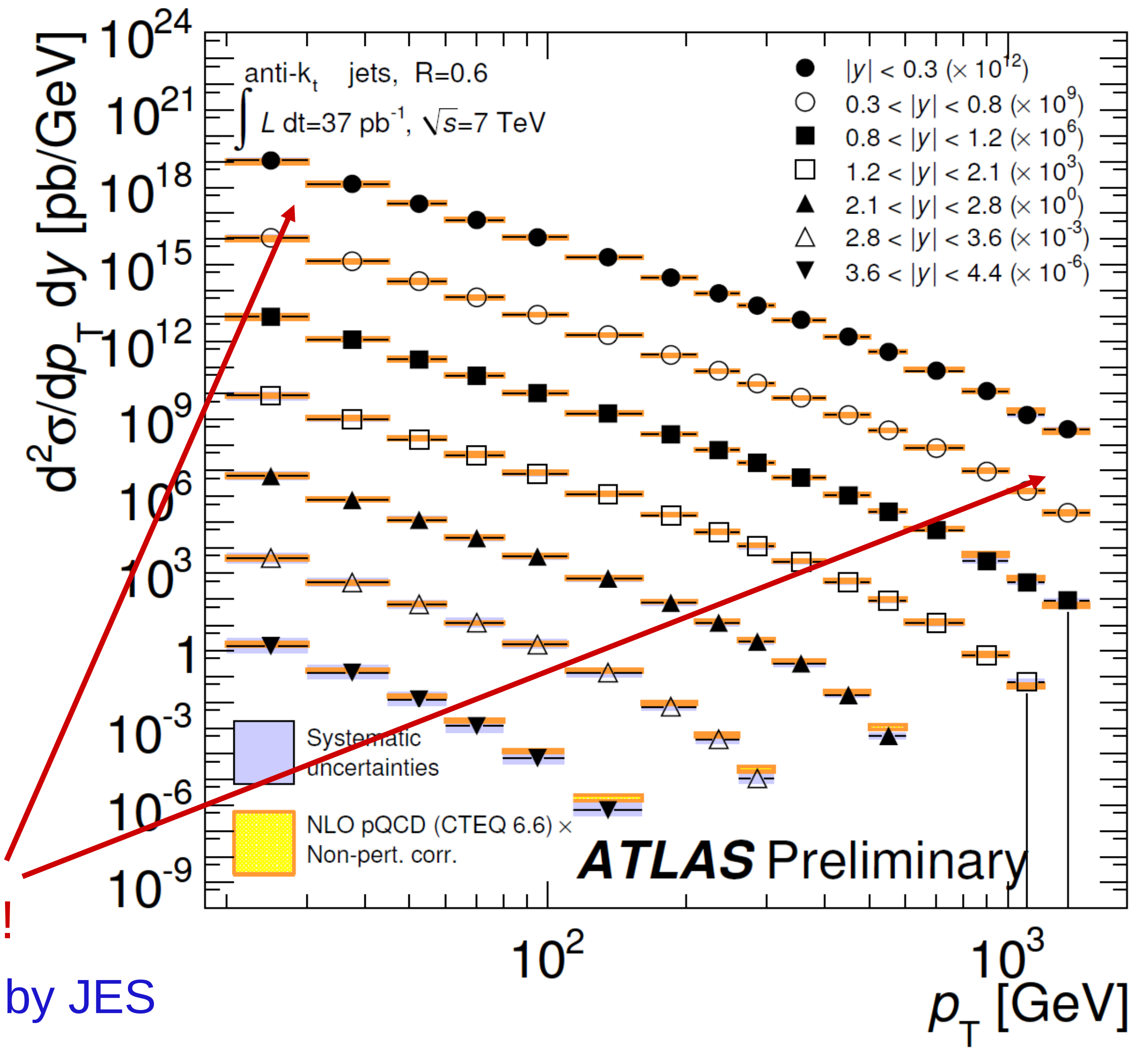
Expected level at end of 2011…. Higgs in July 2012

LHC running in 2010/11 at 7 TeV center of mass energy and at 8 Tev in 2012

Inclusive single jet double-differential cross section







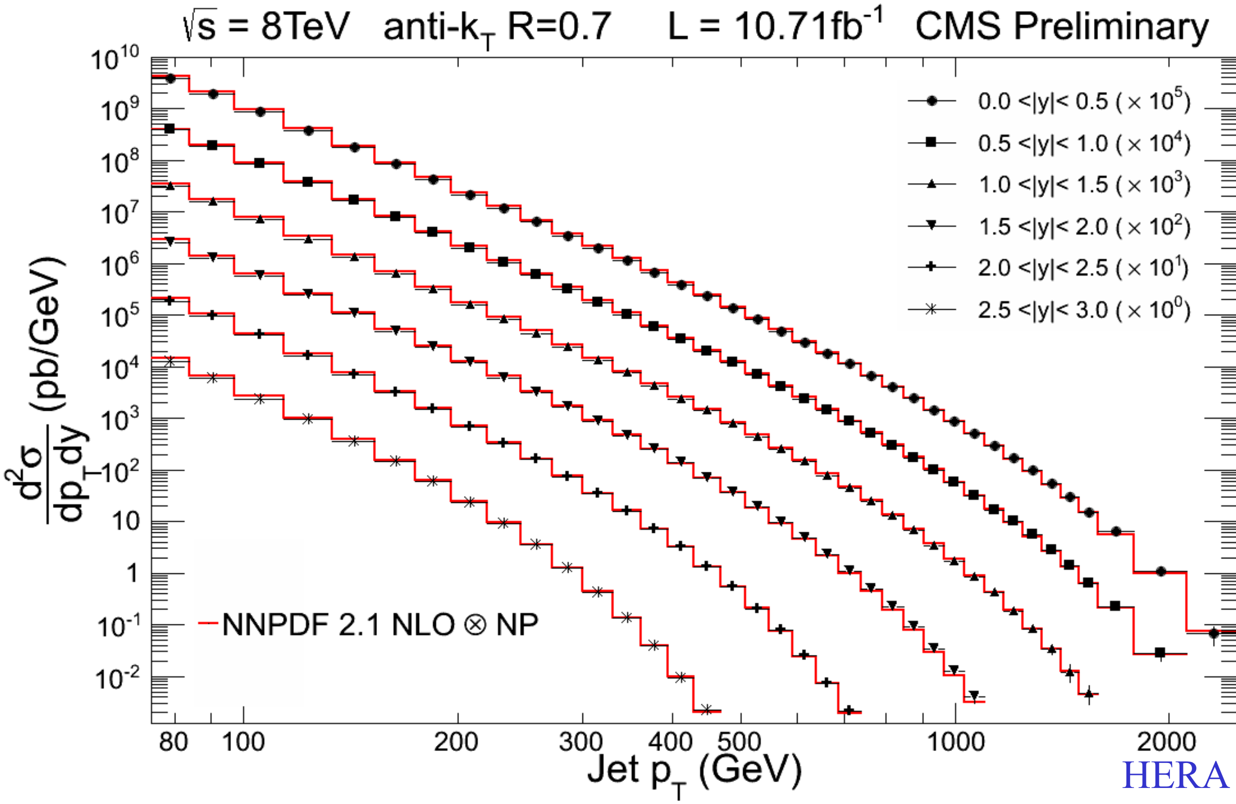
10-12 orders of variation in magnitude in cross section!!

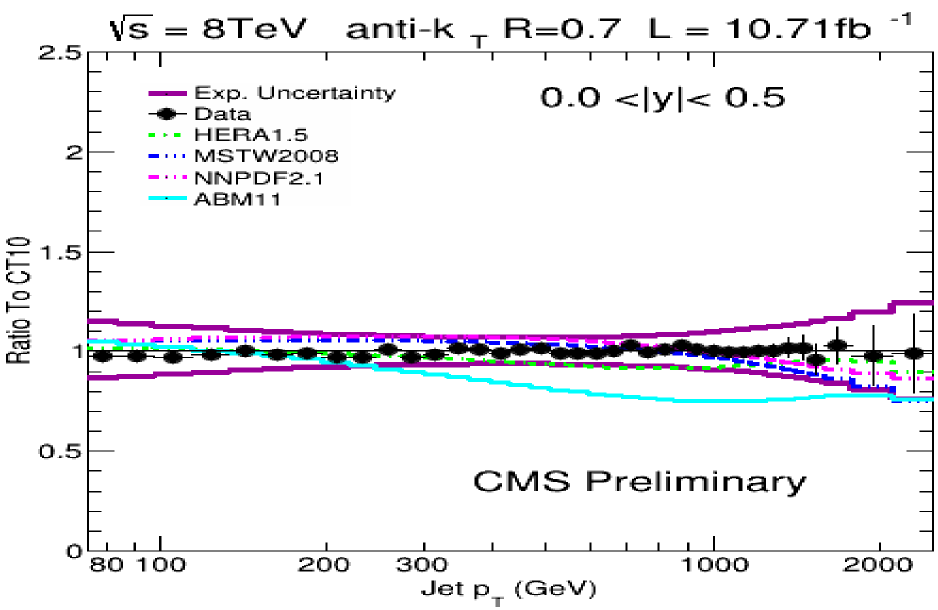
Total uncertainty 50-10% dominated by JES

Good agreement between data and NLO pQCD with various PDFs

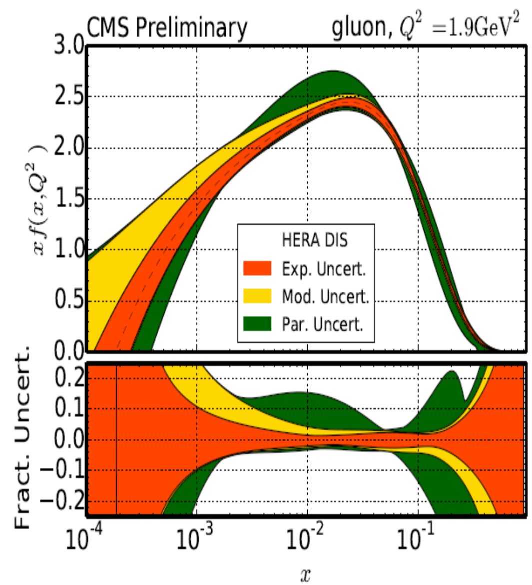
newest studies extend beyond jet-E_t of 2 TeV

Inclusive jets at 8 TeV, 2012 data

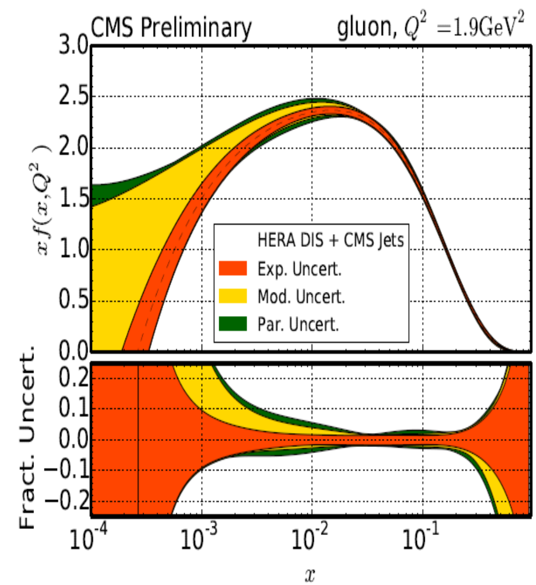




HERA DIS GLUON BEFORE CMS



GLUON AFTER CMS



3-jet to 2-jet cross section ratio and the strong coupling constant

QuickTime™ and a decompressor are needed to see this picture.

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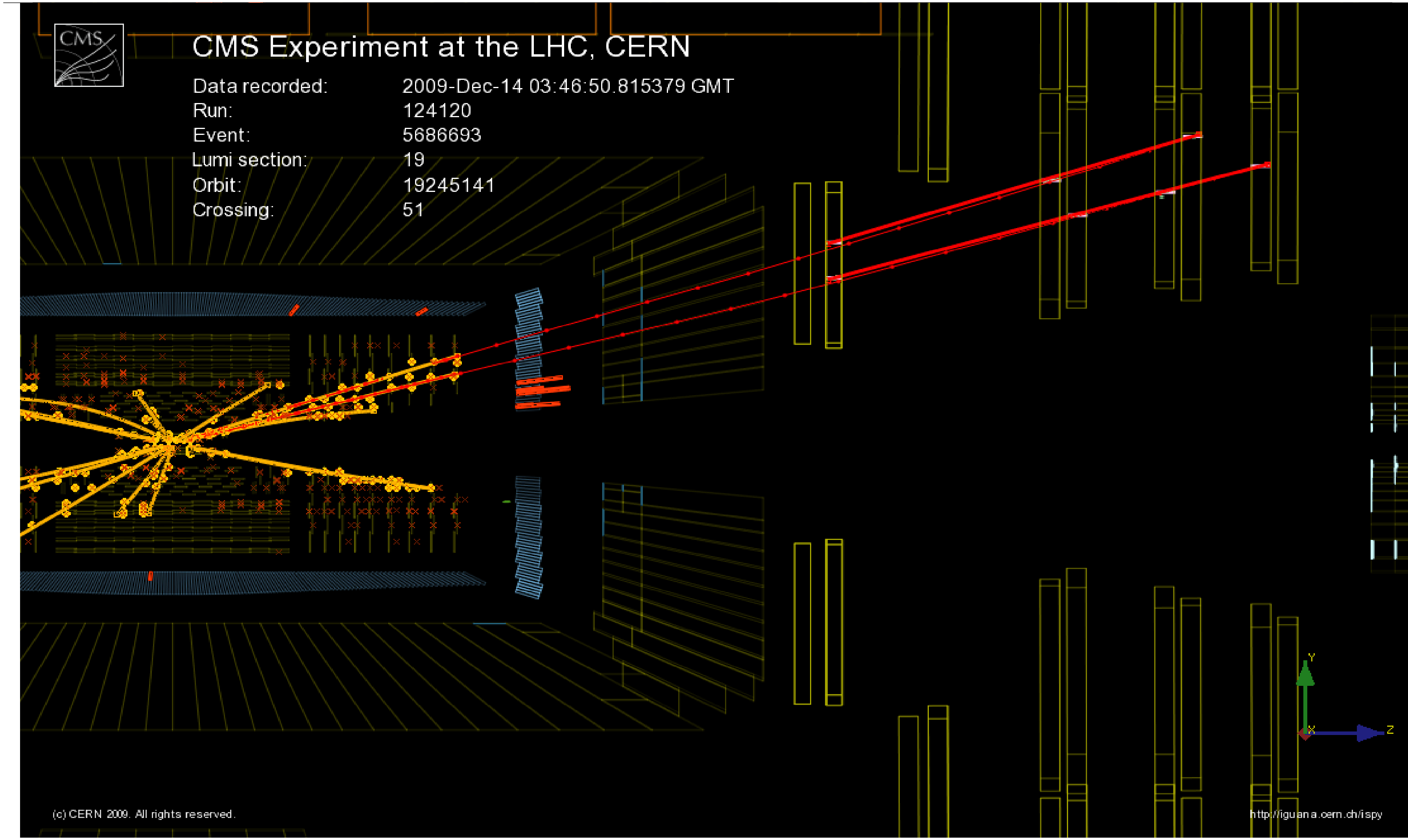
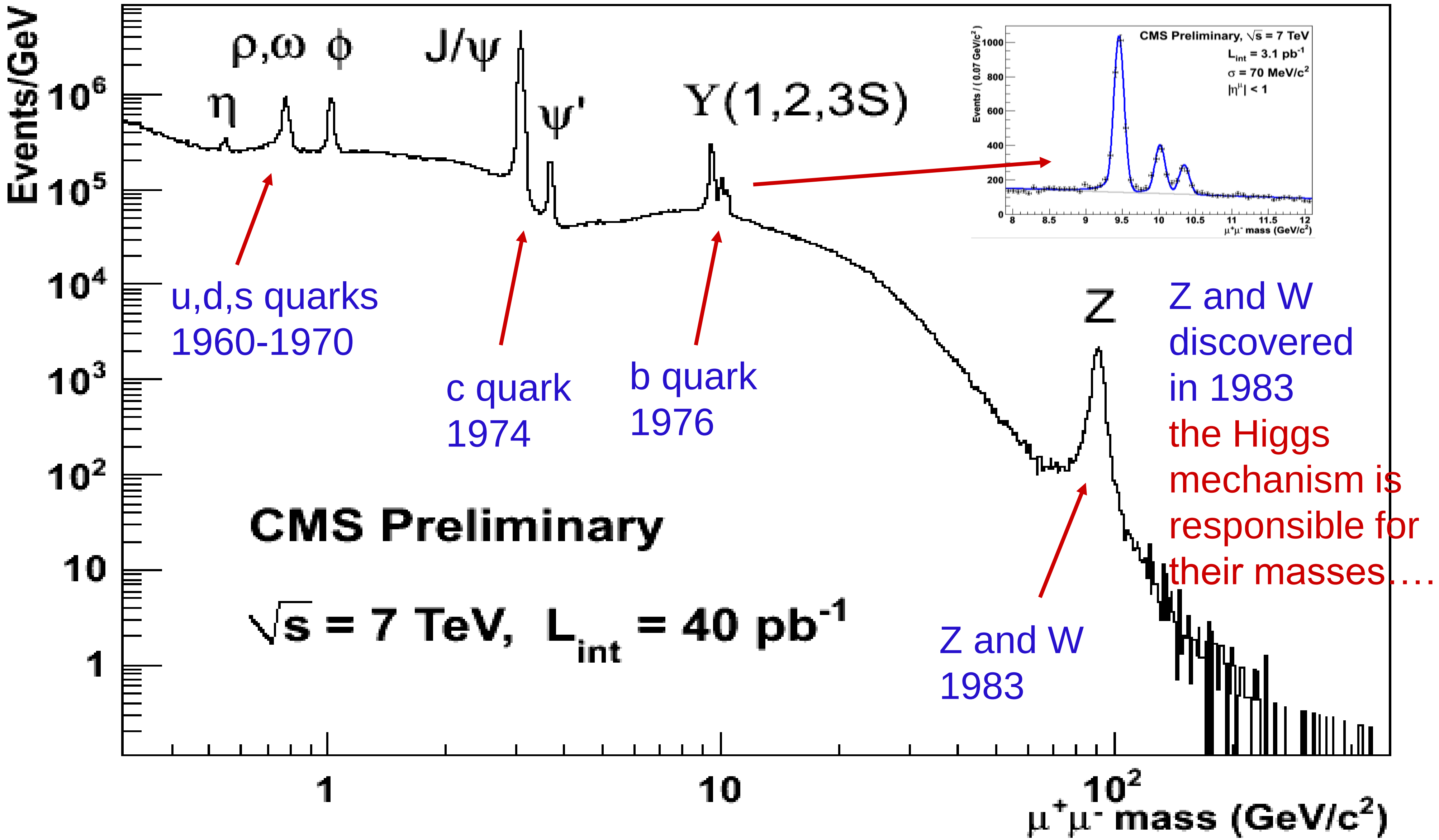
QuickTime™ and a decompressor are needed to see this picture.

A dimuon event in CMS



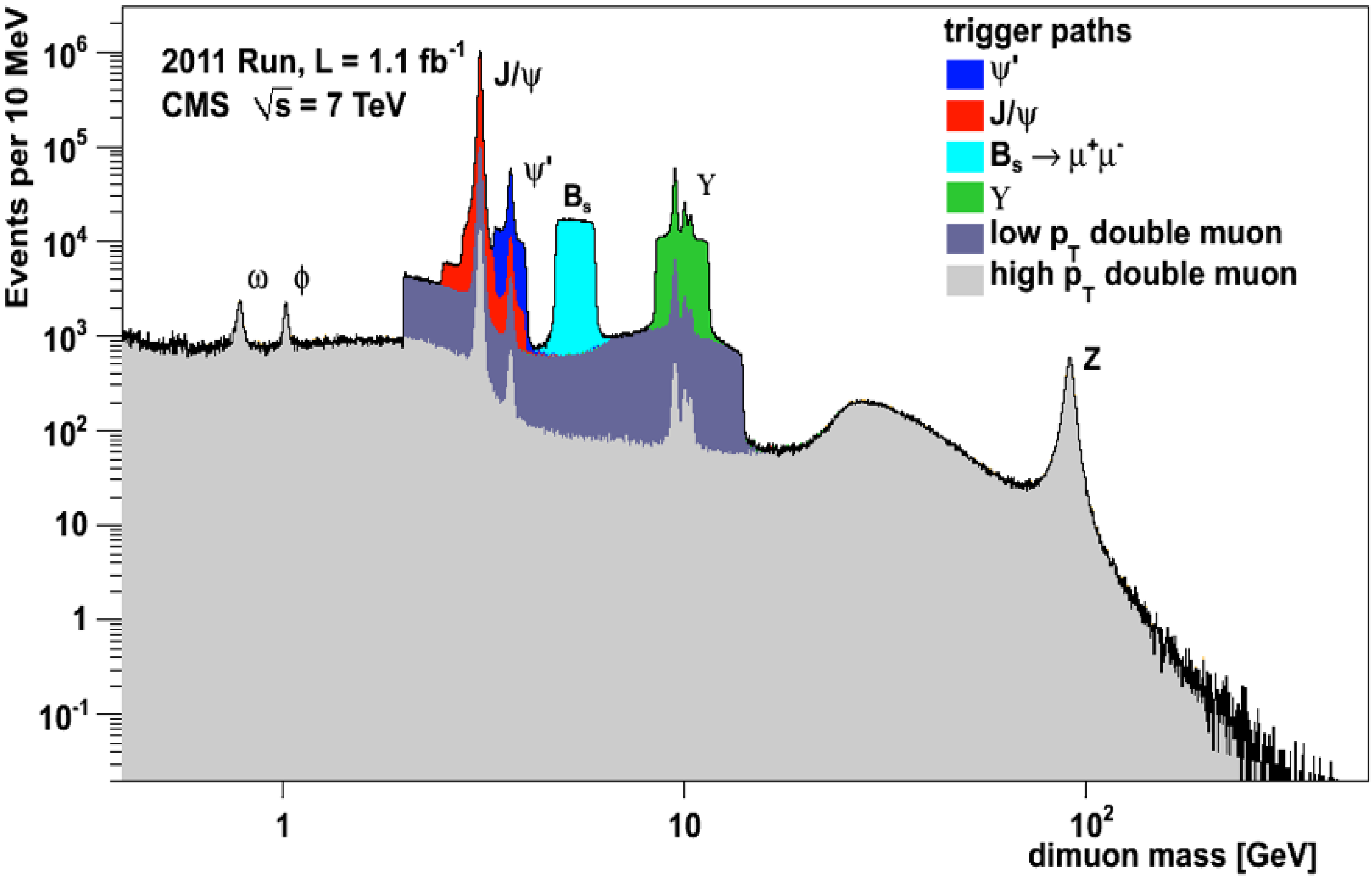
$p_T(\mu_1)$ = 3.6 GeV, $p_T(\mu_2)$ = 2.6 GeV, $m(\mu\mu)$= 3.03 GeV

Dimuon mass spectrum, CMS 7 TeV, full 2010 statistics



D

Di-muon spectrum in CMS, 2011 running



Dilepton spectra, Z'$\rightarrow$ l^+l^- searches in ATLAS and CMS, 2012 data, $\sqrt{s}$ = 8 TeV

QuickTime™ and a decompressor are needed to see this picture.

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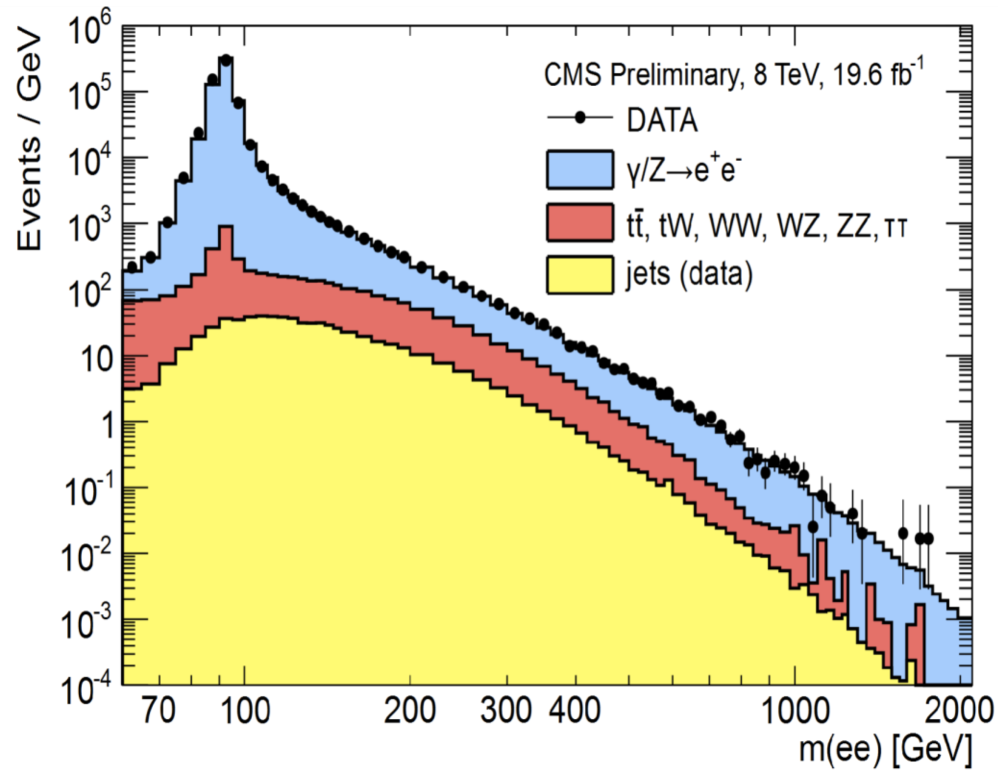


➡ M(Z'$_{SSM}$) > 2.8 TeV @ 95CL

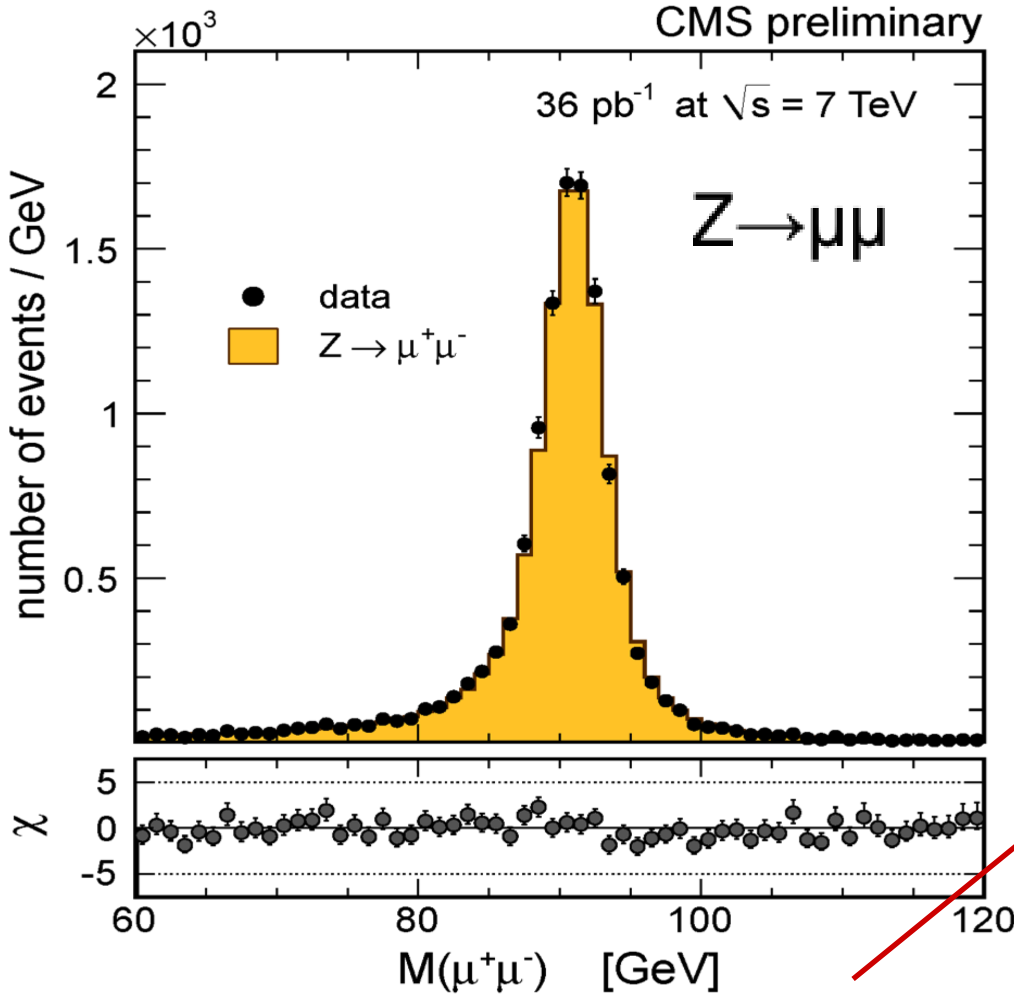
➡ similarly M(W'$_{SSM}$) > 2.8 TeV @ 95 CL

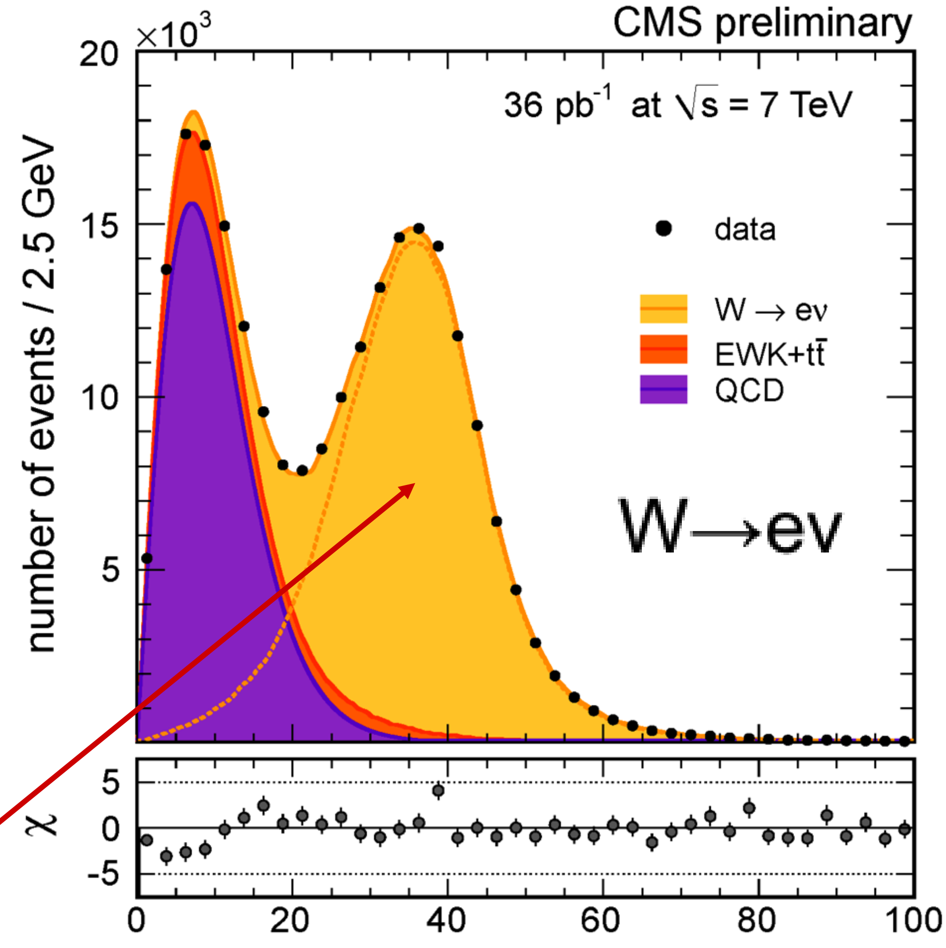
In 2015/16 these searches will be extended into the ~ 5 TeV range….
and beyond with the HL-LHC and HE-LHC!

Inclusive W, Z production, CMS, full 2010 statistics

(~ 23.000 Z and 250.000 W decaying leptonically in 2010)

(in 2011 we have ~35.000.000 W and ~4.000.000 Z decaying leptonically, and in 2012 four times as much)

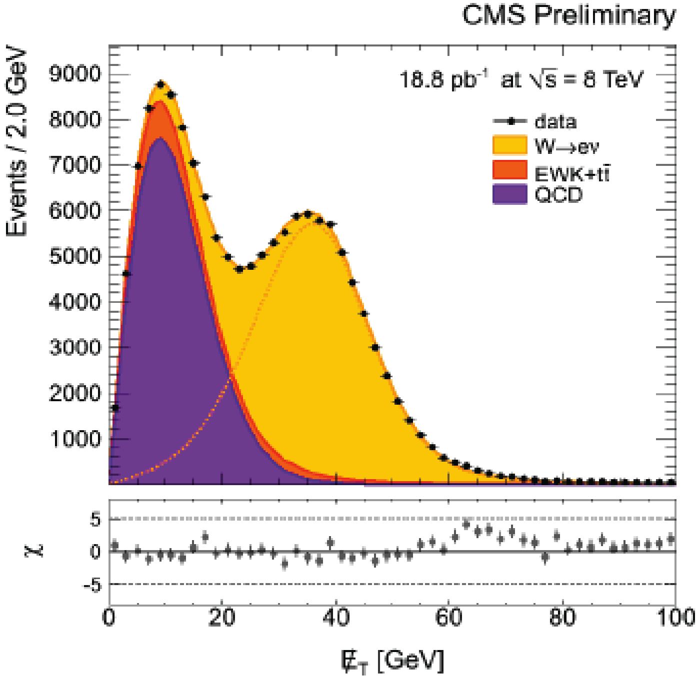




"Jacobian" peak

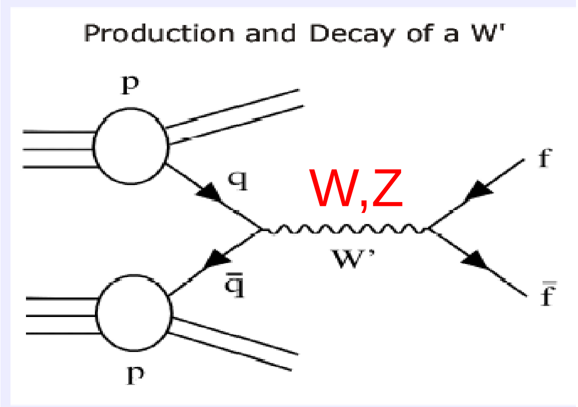
$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos\Delta\phi^{l,\nu}\right)}$$

W, Z production cross sections, testing QCD
from the CERN pp-bar collider to the Tevatron and the LHC



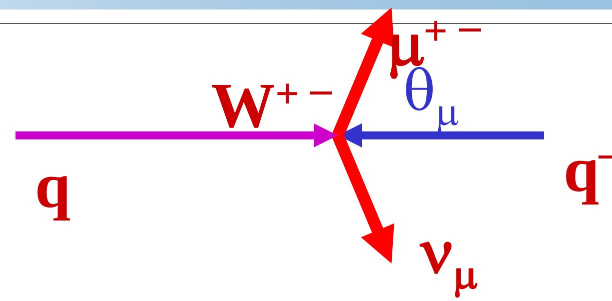
Use special low-pile-up runs with luminosity leveling ($18.8\ pb^{-1}$)

QuickTime™ and a decompressor are needed to see this picture.



W^{+-} charge asymmetry

$W^{+-} \rightarrow \mu^{+-} \nu$ charge asymmetry vs. η_μ



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decompressor
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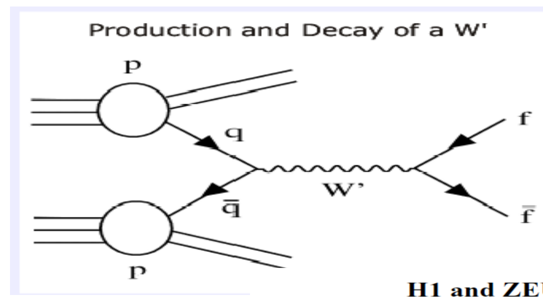
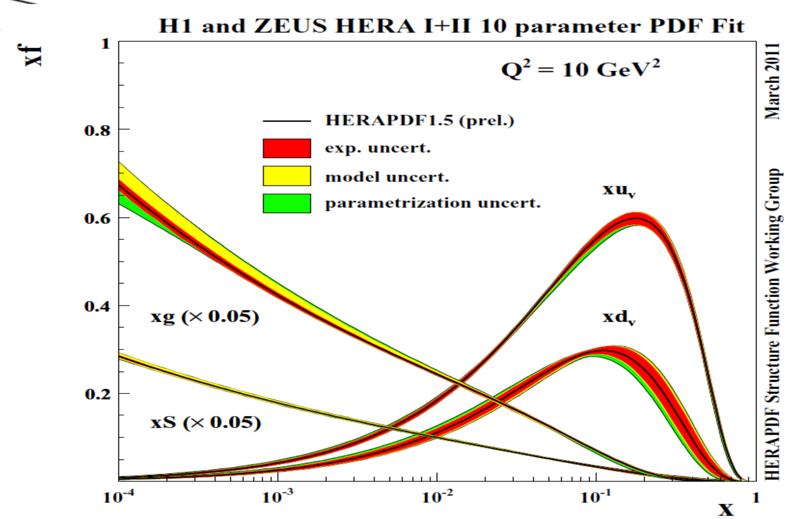
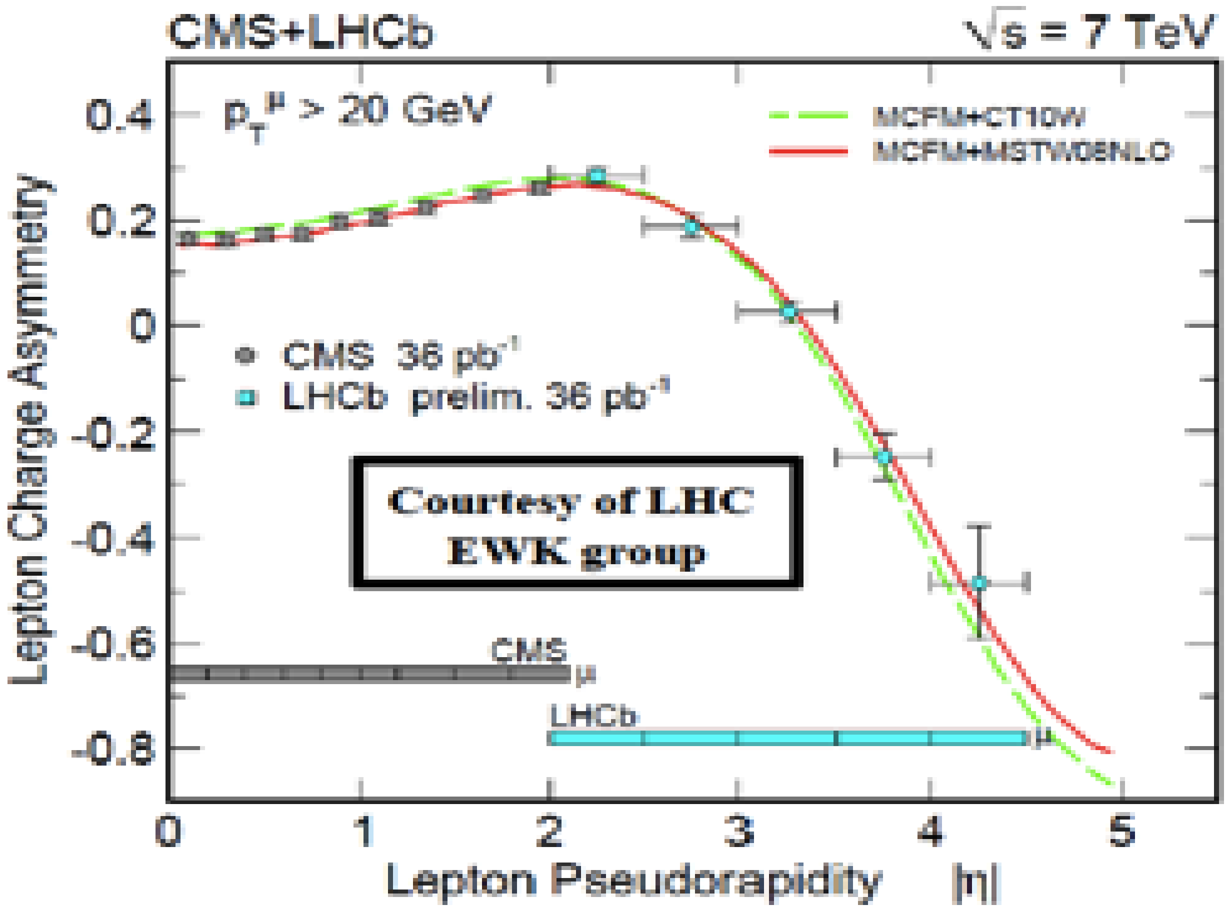




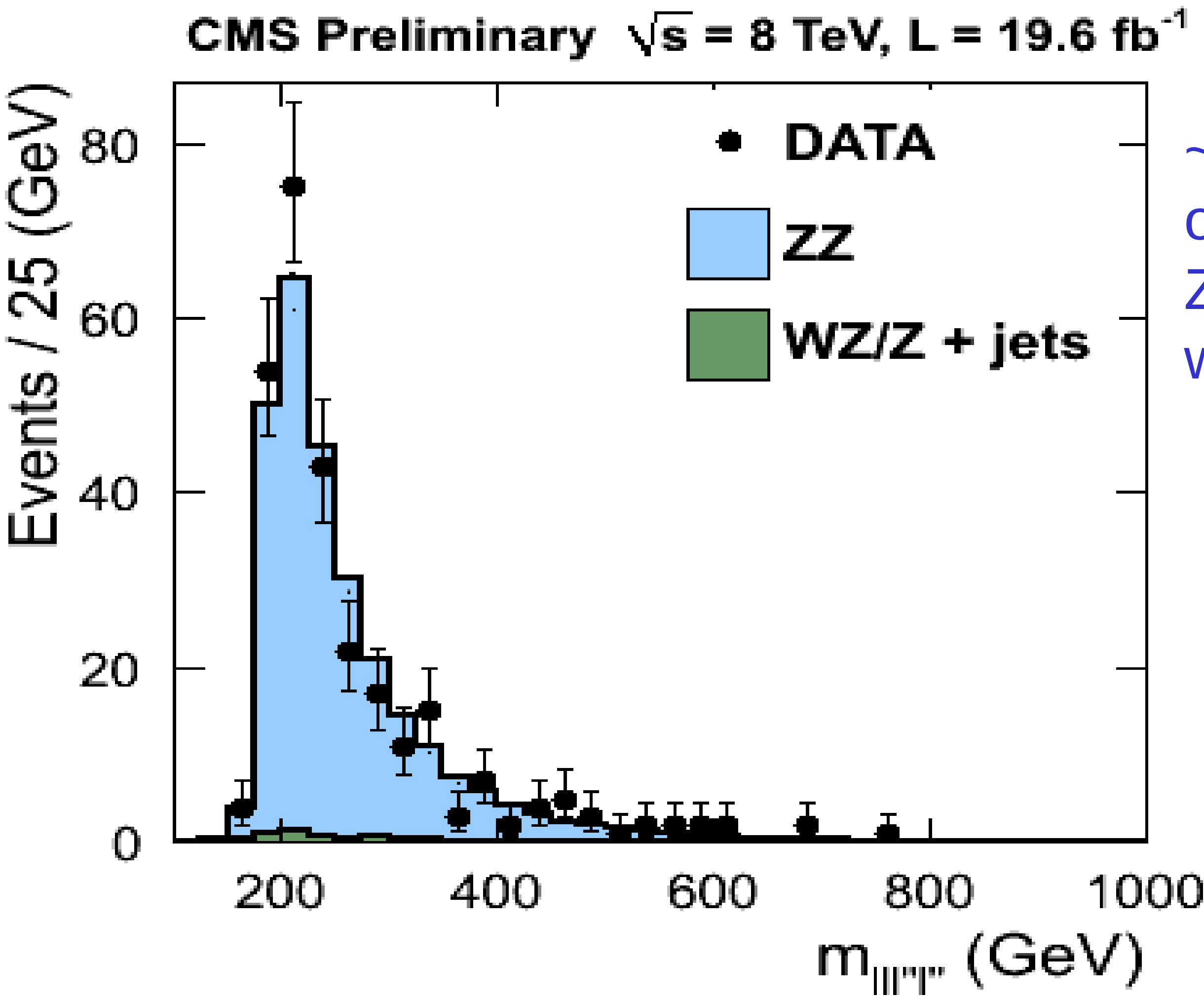
$$\eta_\mu = - \ln tg(\theta_\mu/2)$$

W production: charge asymmetry in forward region

$$A_W = \frac{d\sigma/d\eta(l^+) - d\sigma/d\eta(l^-)}{d\sigma/d\eta(l^+) + d\sigma/d\eta(l^-)}$$



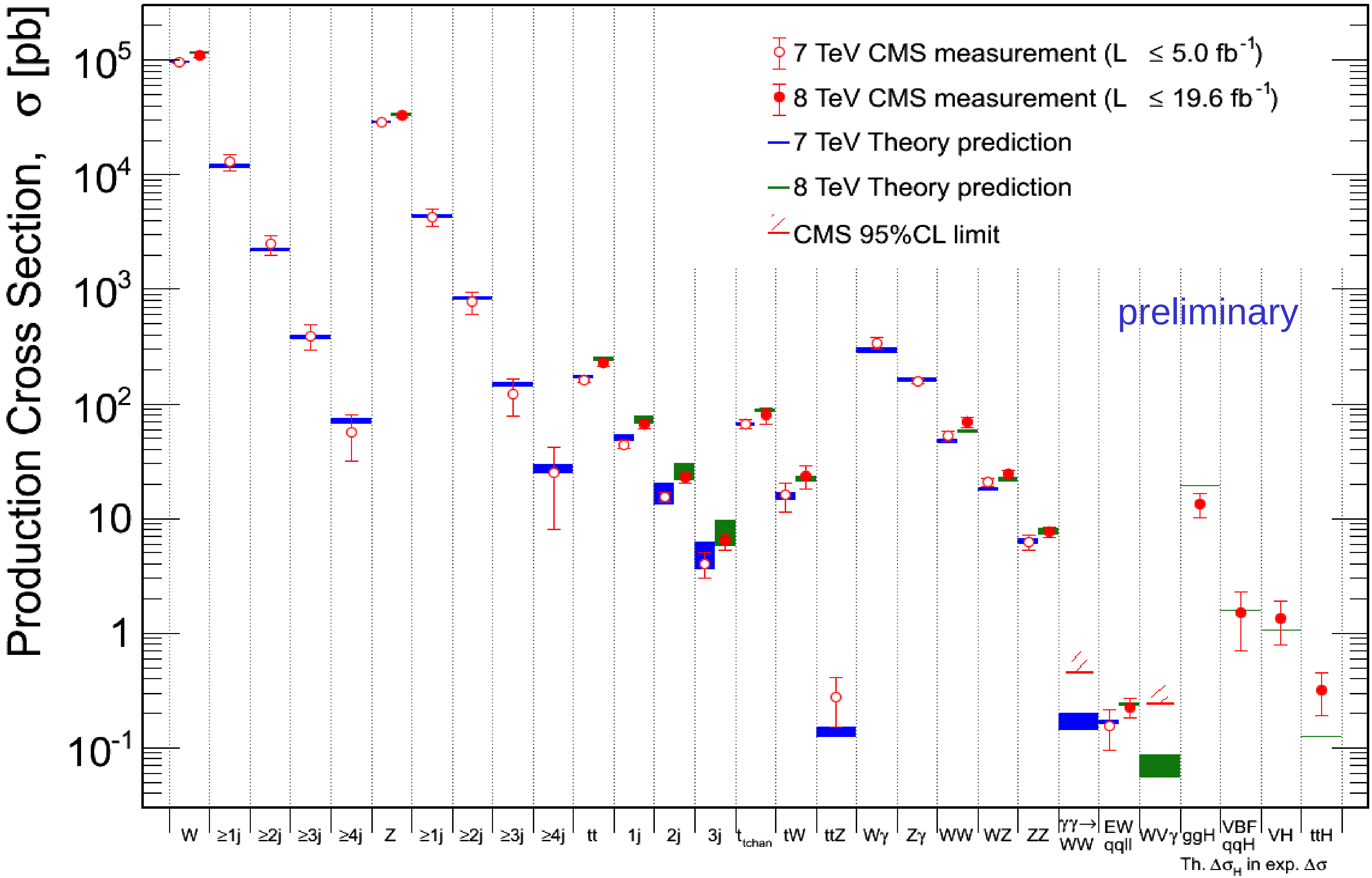
ZZ production at 8 TeV



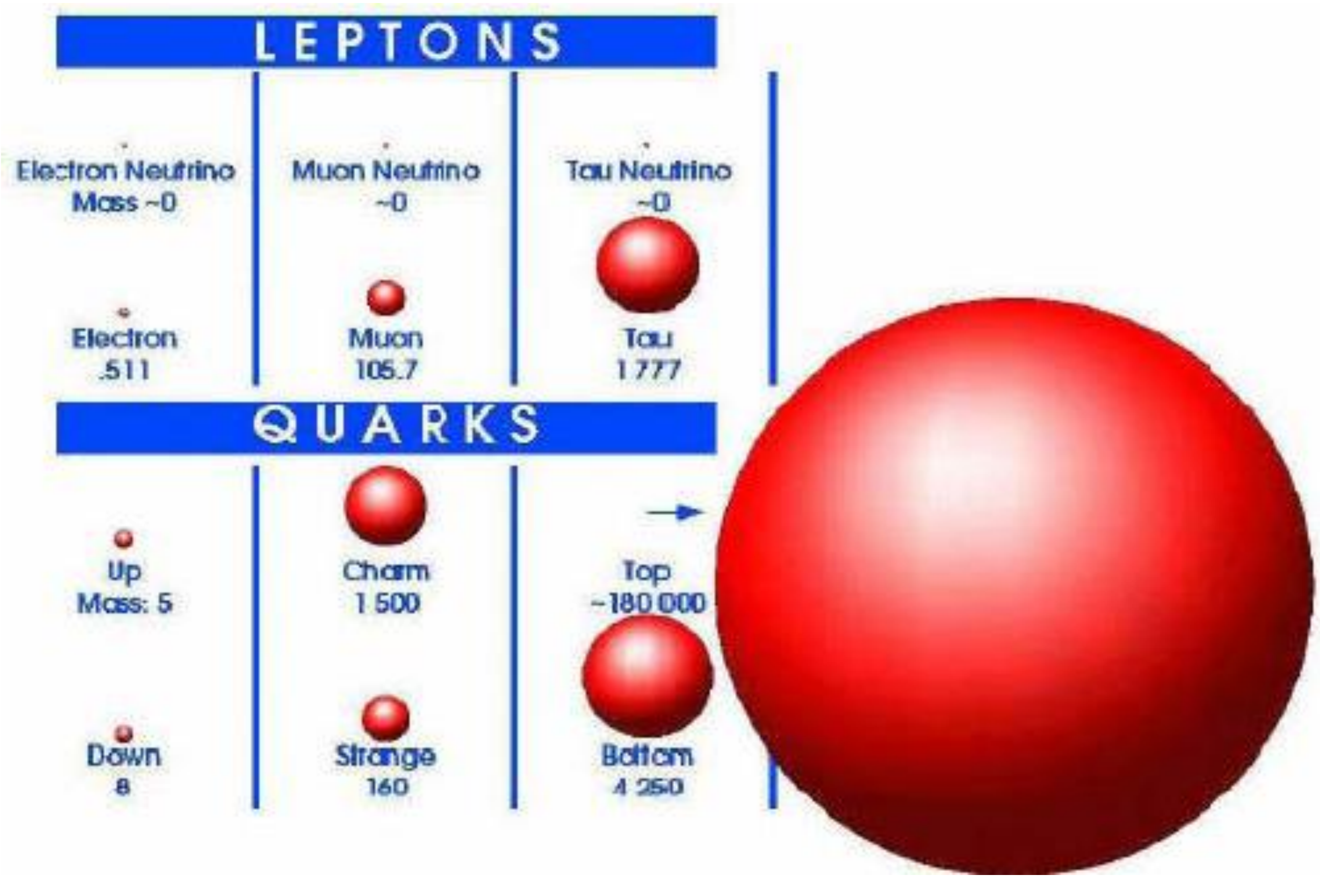
~300 ZZ to 4-lepton candidates observed at 8 TeV
Z and ZZ masses consistent with SM

World's strongest constraints on neutral anomalous TGCs (fZ ~ 3-5 10^{-3})

SM cross sections overview, CMS, end-2013

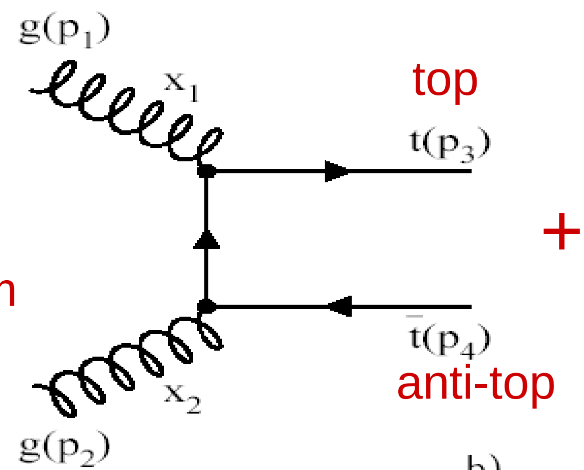


Study of the top quark: one of the main goals of the LHC

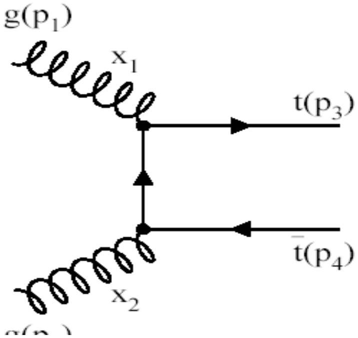


At nominal energy and luminosity LHC will produce about 1 top-antitop pair second!

Main top production mechanism at LHC

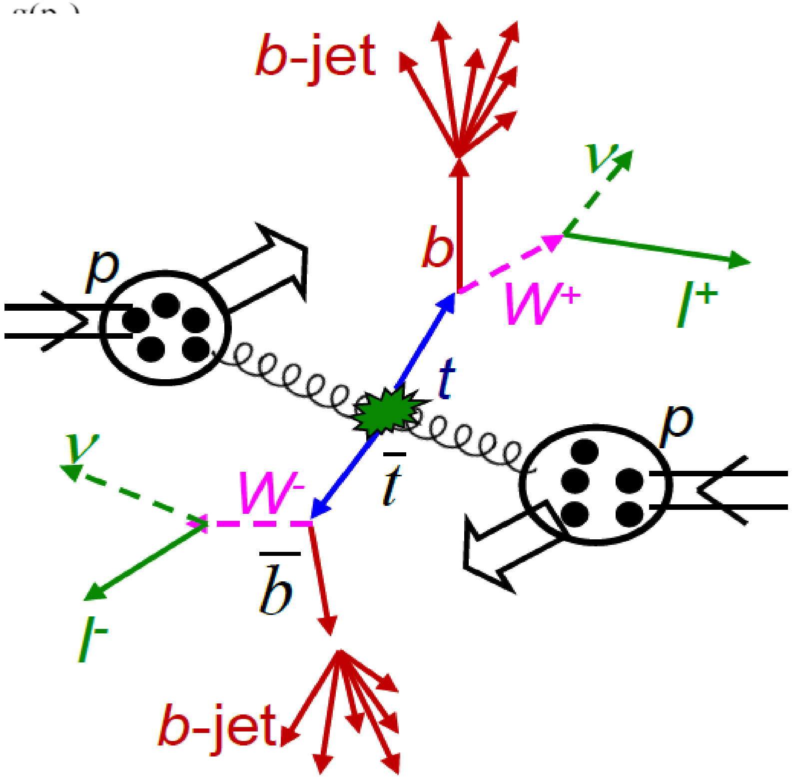


Top quark candidate in di-lepton mode, CMS



top

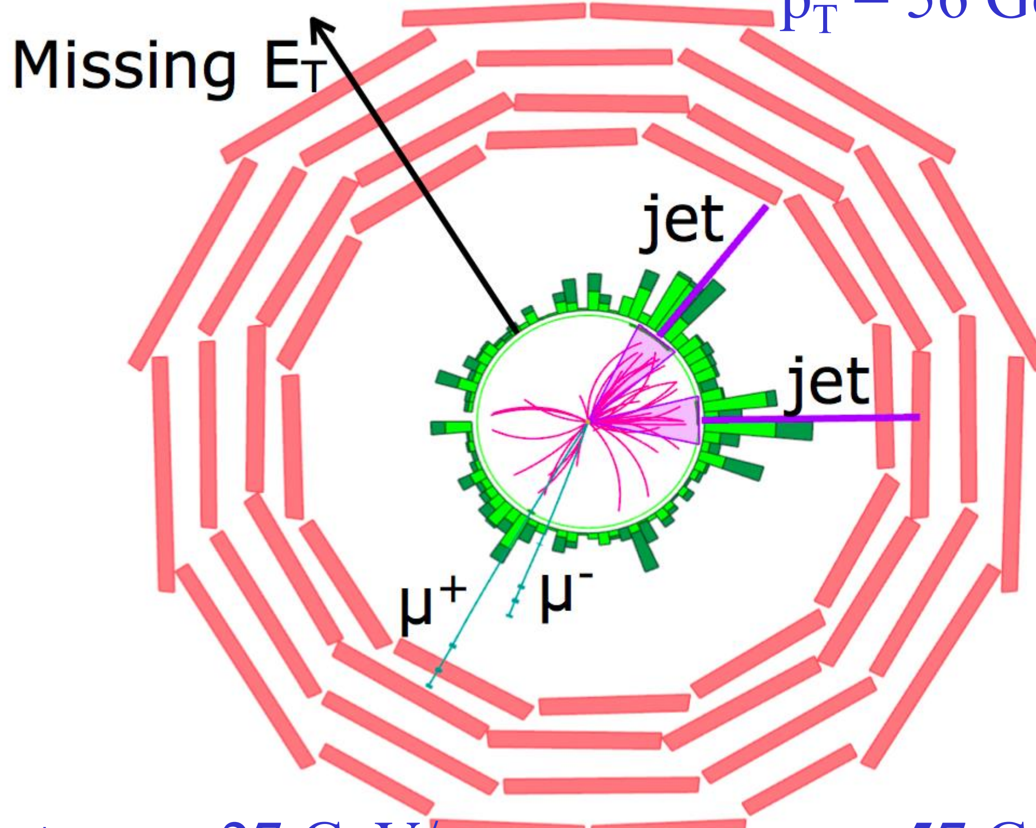
anti-top



MET = 57 GeV/c

p_T = 45 GeV/c

p_T = 56 GeV/c

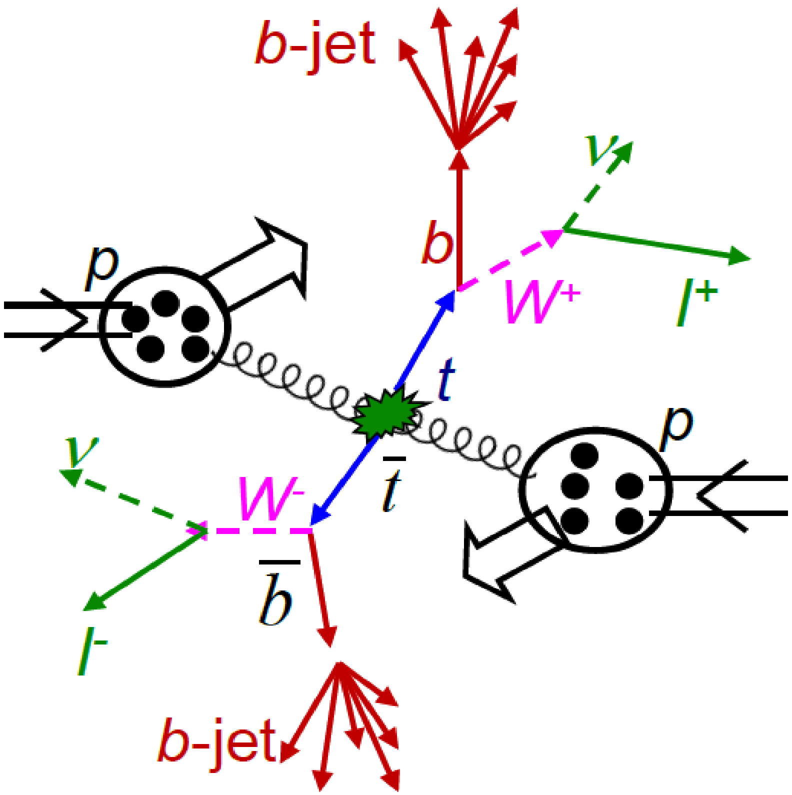


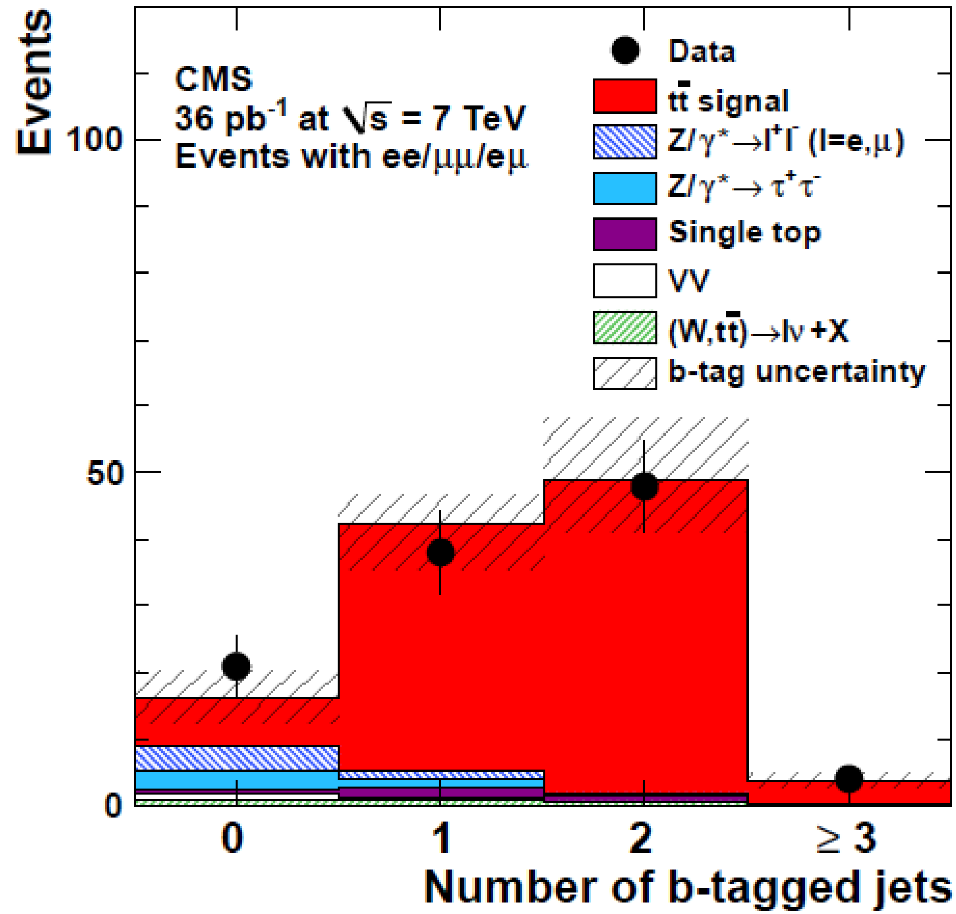
μ+ p_T = 27 GeV/c μ- p_T = 57 GeV/c

Top Di-Muon Candidate Event

m(μμ) = 26 GeV/c^2

Initial studies at LHC: top production and decay in the di-lepton channel, data of 2010

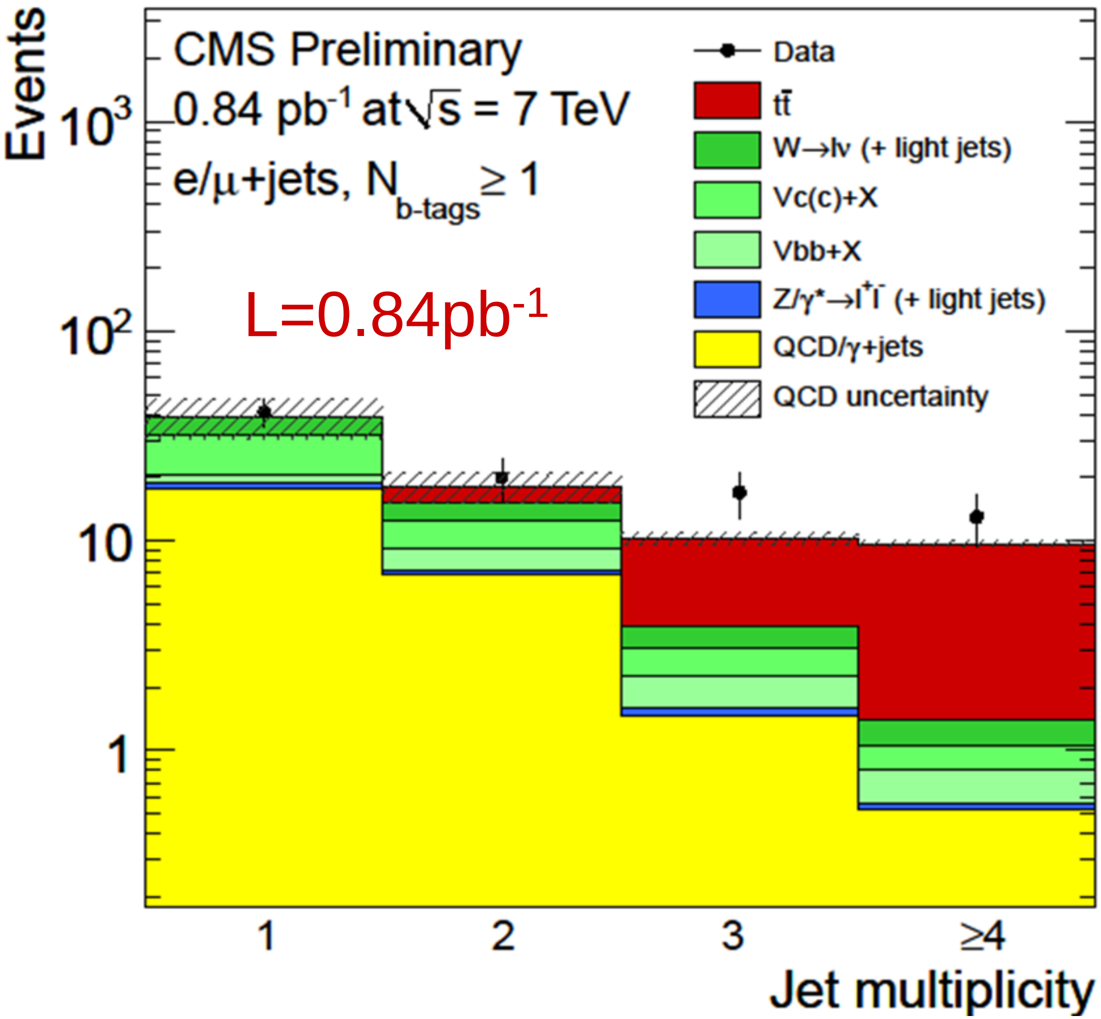


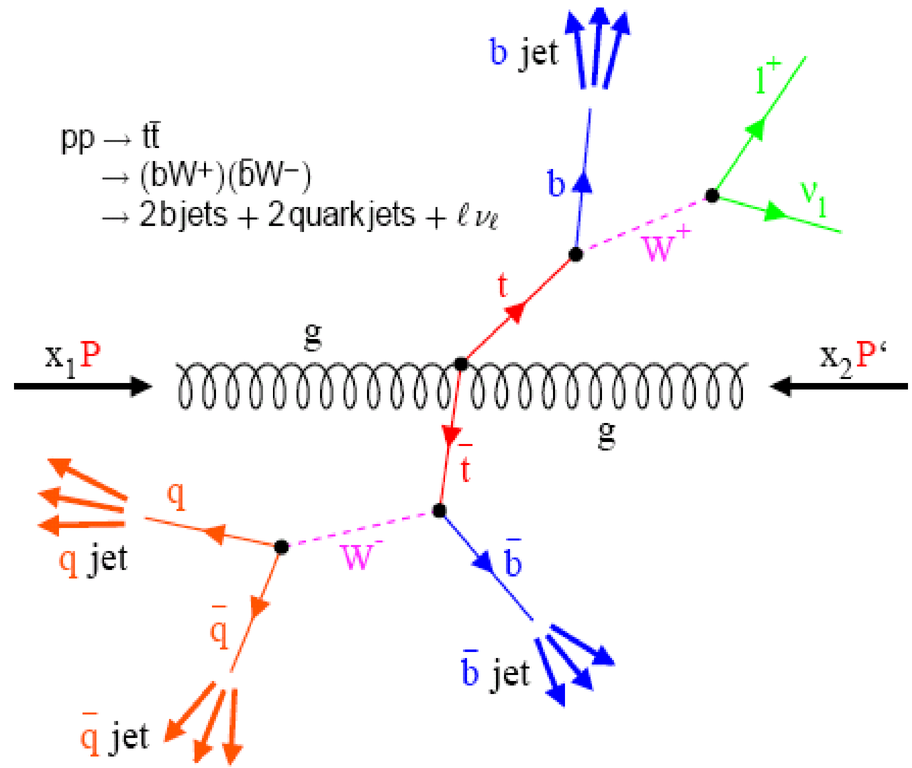


Very pure sample of top events!

Evidence for top in CMS from Lepton + jets final states, Sept. 2010 with ~1pb^{-1}

e/μ + jets final states

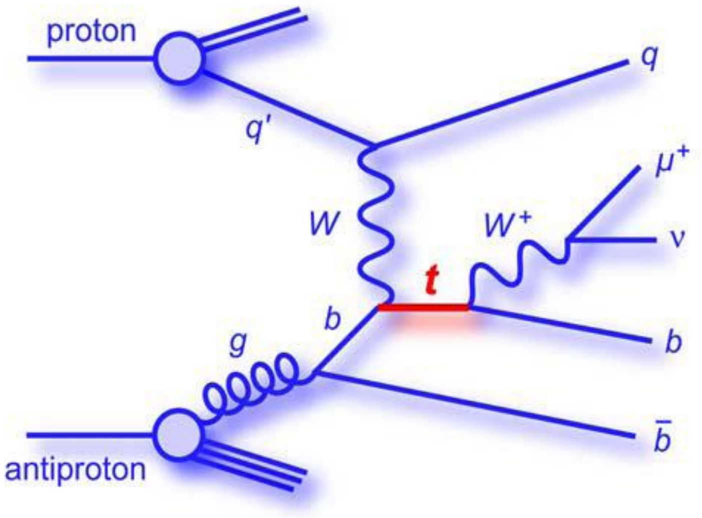


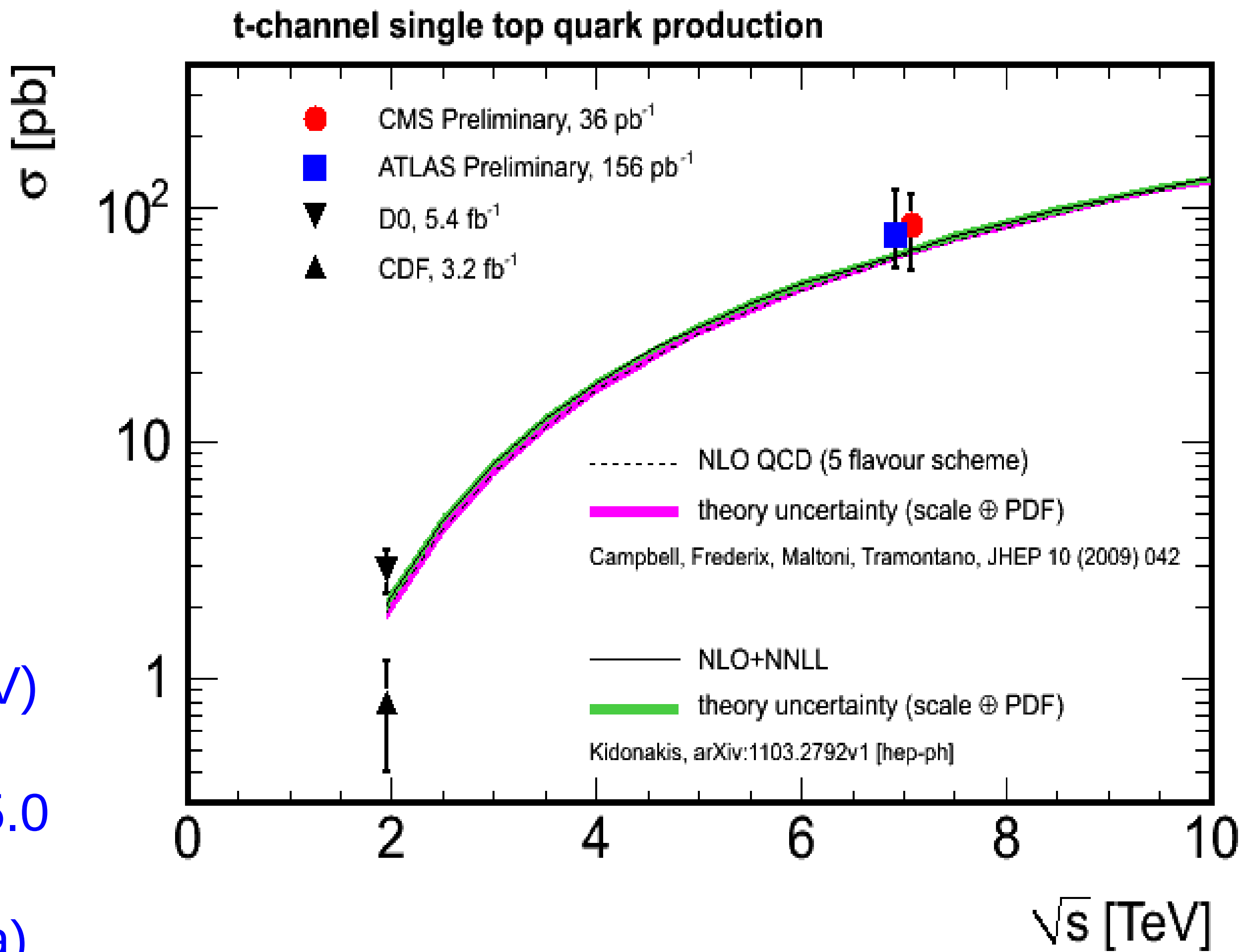


tt → bWbW → blνbqq

For N(jets) ≥3 we count 30 signal candidates over a predicted background of 5.3 events

Single top production, cross section, first observations, 2010 data only



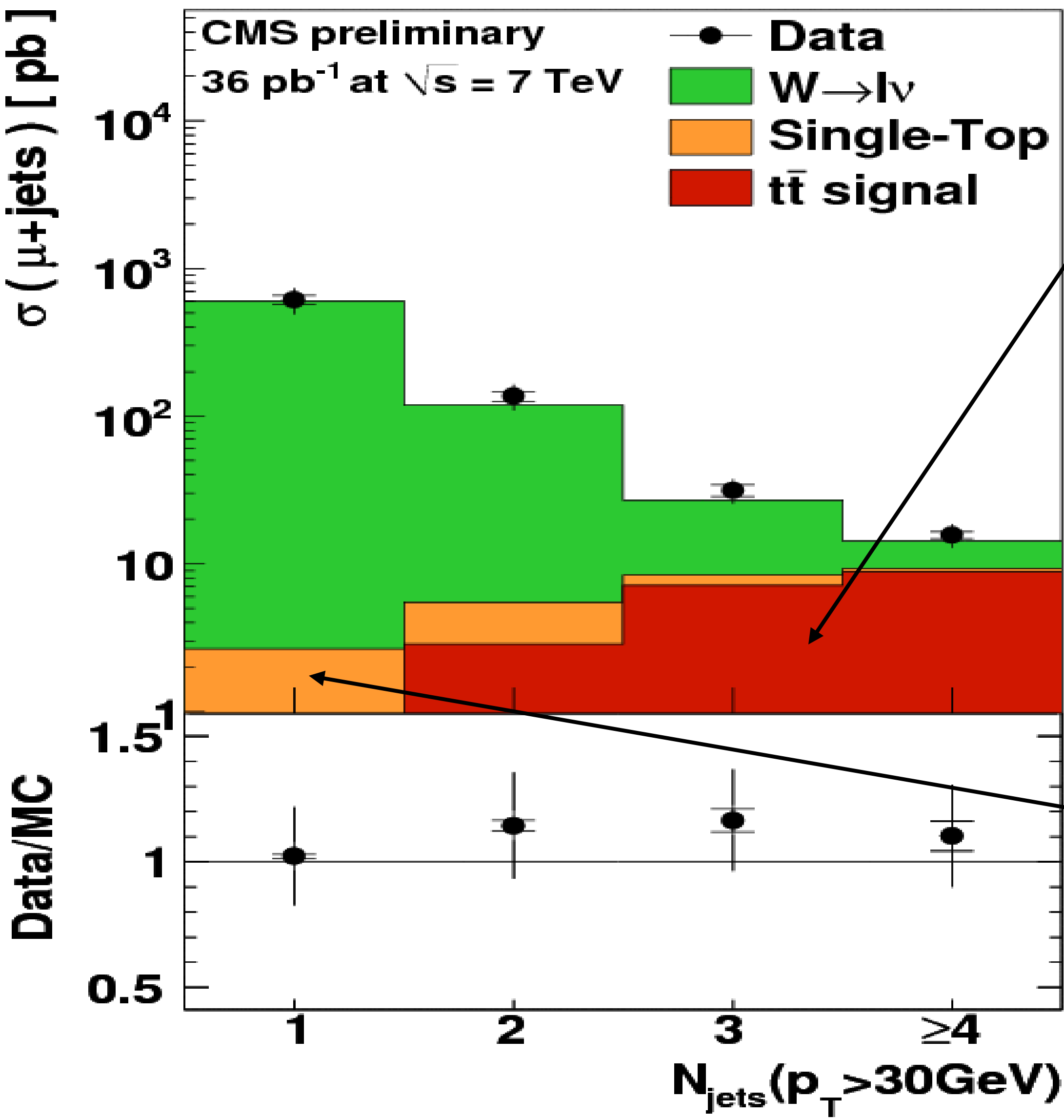


Selection of single top events
1 isolated electron (P_t > 30 GeV)
or muon (P_t > 20 GeV)
- 2 jets, E_t > 30 GeV, |eta|< 5.0
- One "tight" b-tag
- One "loose" b-veto (2D ana)

$$\sigma = 83.6 \pm 29.8(stat. + syst.) \pm 3.3(lumi.)\ \text{pb}$$

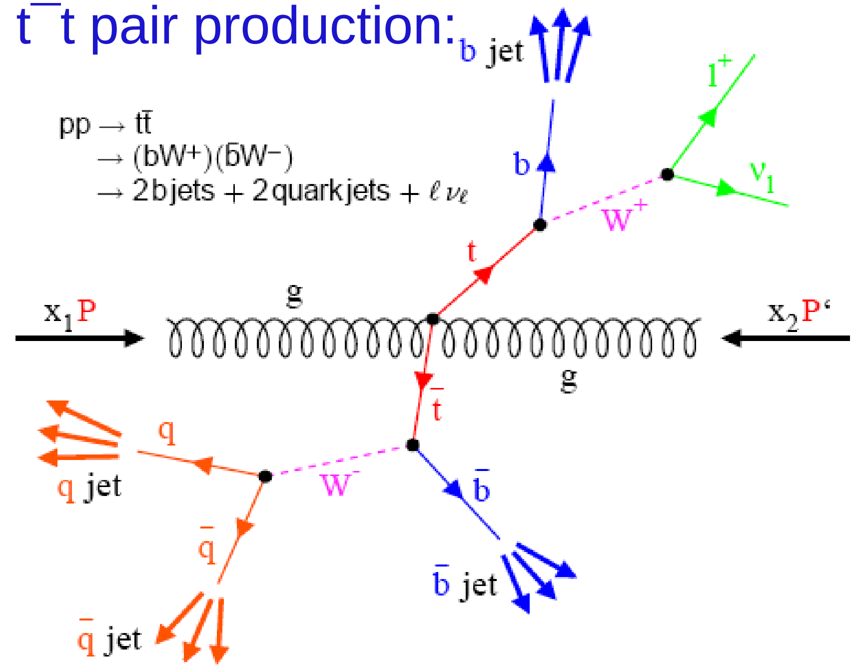
transv. W mass > 40(50) GeV

Top production in CMS in lepton + jets final states status March 2011, full 2010 statistics

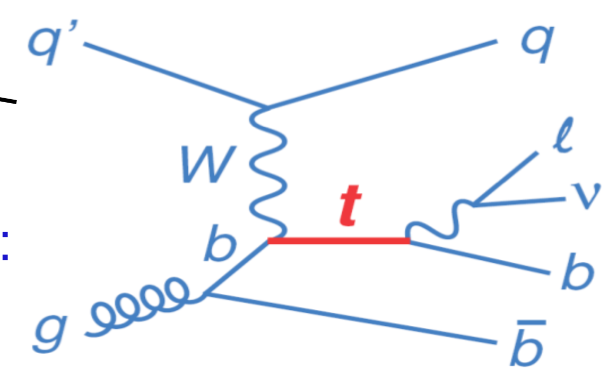


Lepton + jets, no b-tag (lepton hard and isolated)

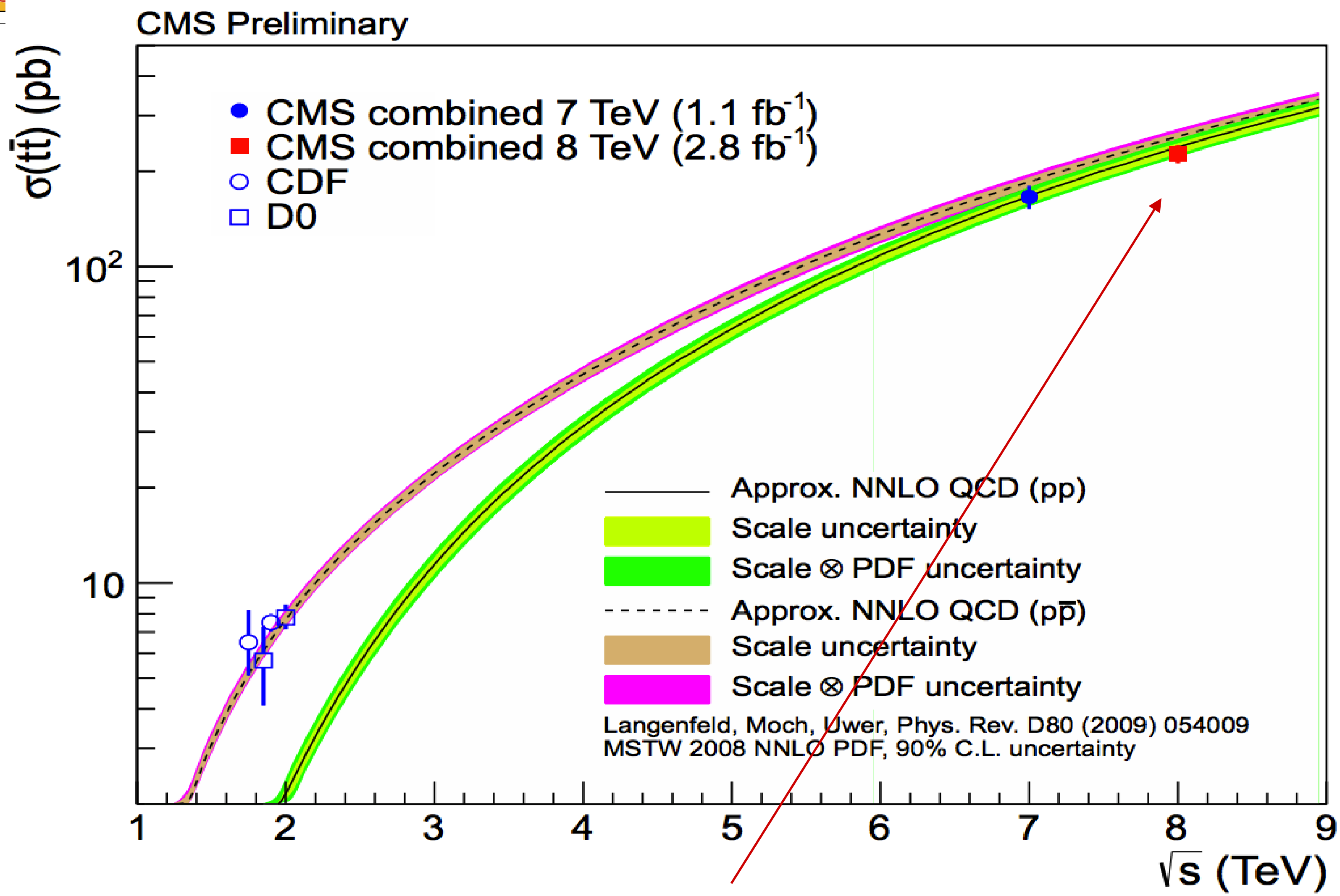
$t\bar{t}$ pair production:



single top production:



Top pair cross section, from Tevatron to LHC

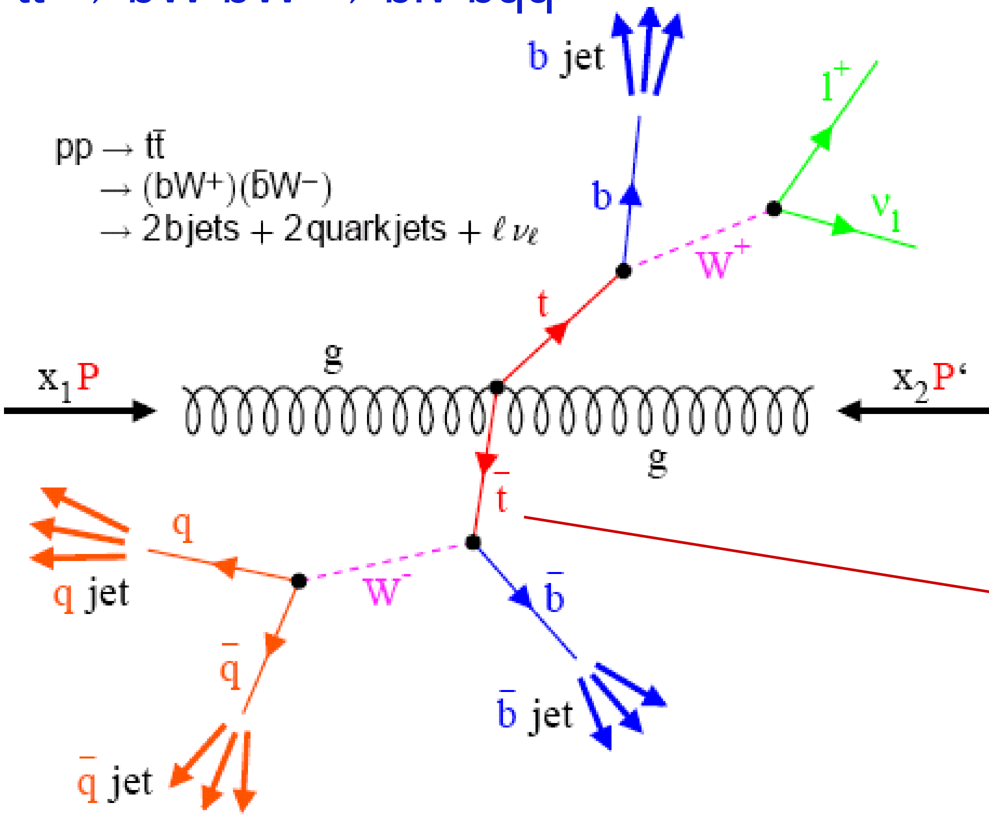


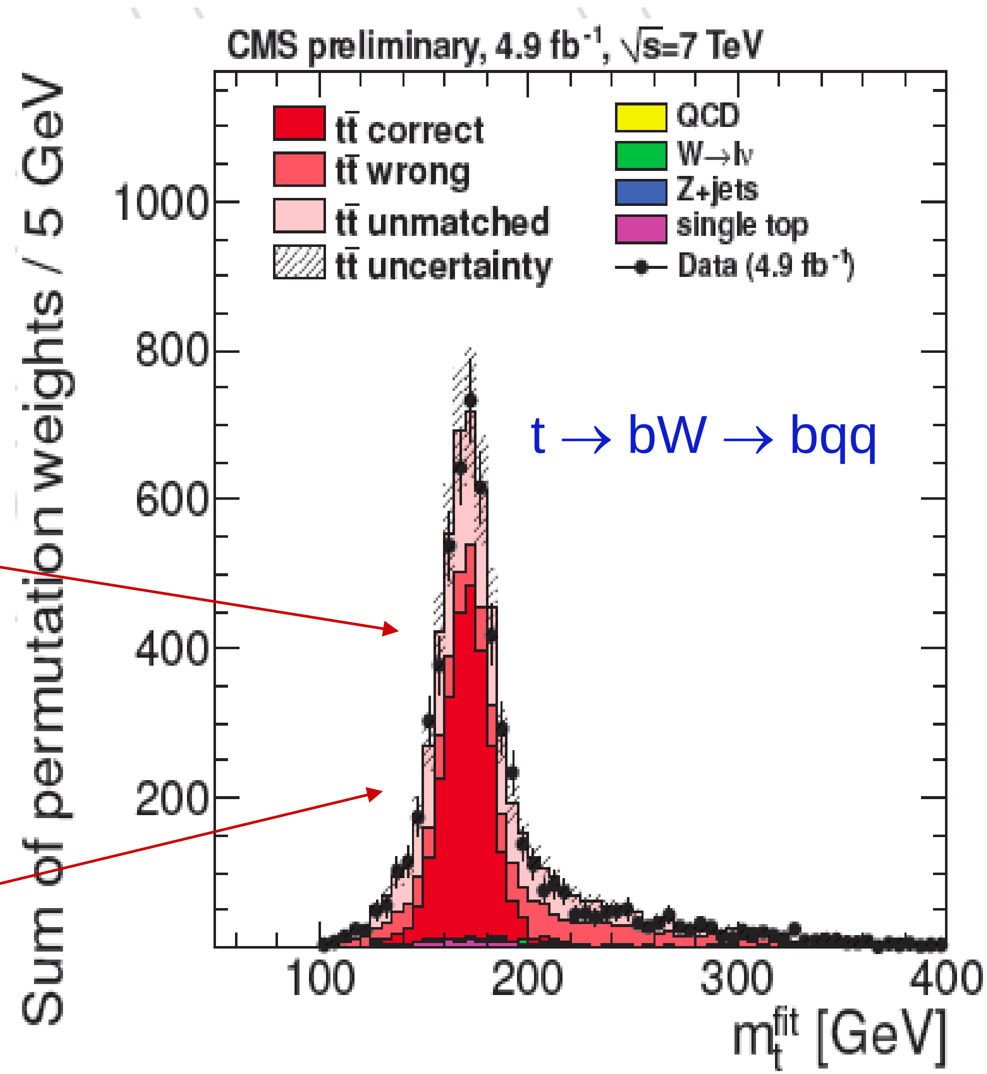
CMS at $\sqrt{s}$ = 8 TeV :

$\sigma(t\bar{t})$ = 227.8 ± 3.0 (stat) ± 10.5 (syst) ± 10.3 (lumi) pb

Top mass, in single lepton channel

tt → bW bW → blν bqq





CMS average : 172.6 ± 0.4 ± 1.2 GeV

Top from the Tevatron to the LHC, mass, an important issue….

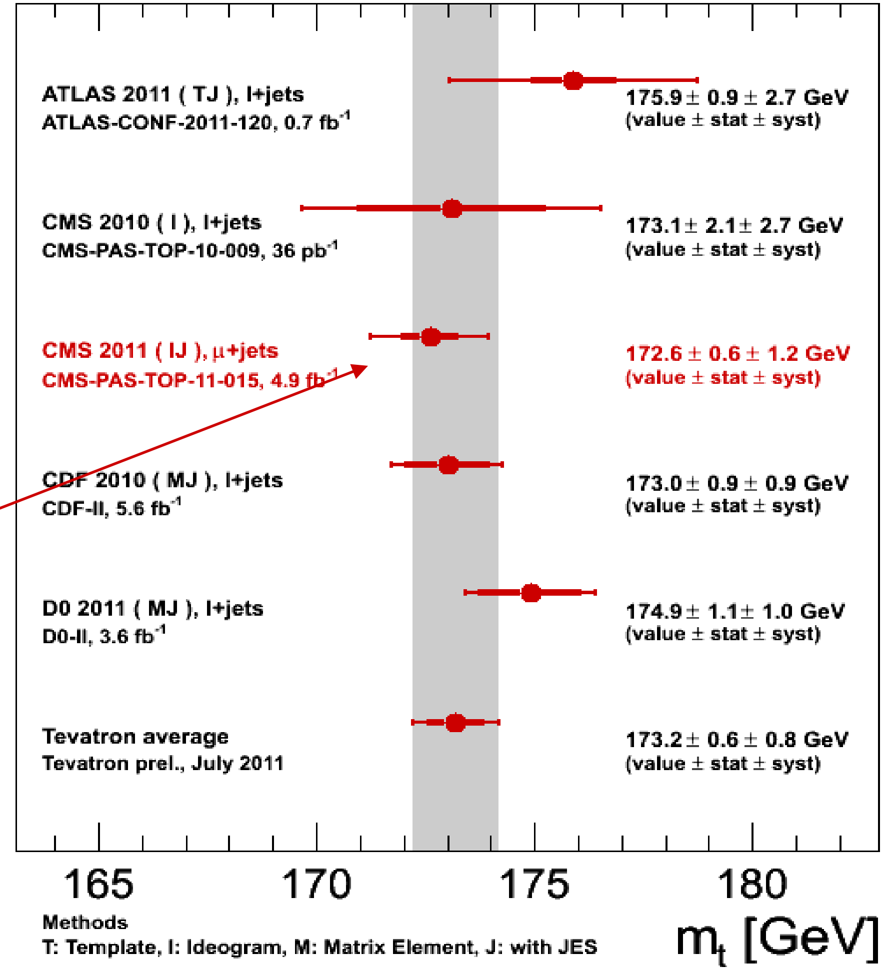
One-lepton final states:

$tt \rightarrow bW\ bW \rightarrow bl\nu\ bqq$

best for mass determination as full three-body mass can be reconstructed
Jet energy scale is the limiting factor,
Tevatron had long experience…..

The LHC cought-up with the Tevatron:

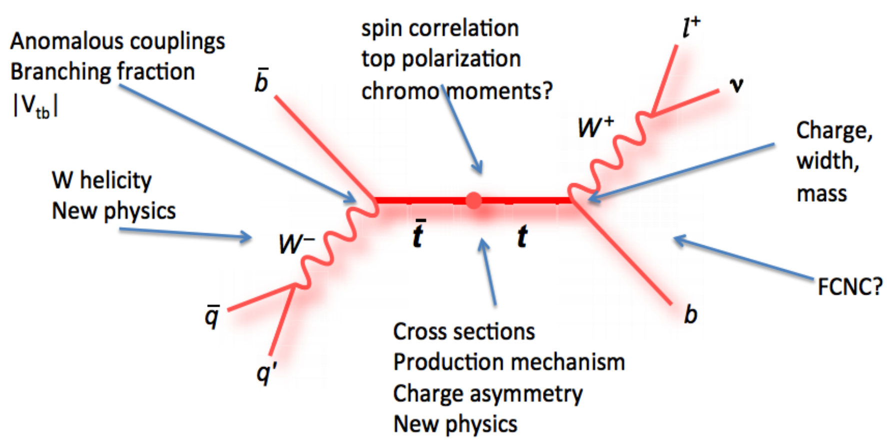
CMS average : 172.6 ± 0.4 ± 1.2 GeV
Tevatron average: 173.2 ± 0.6 ± 0.8 GeV

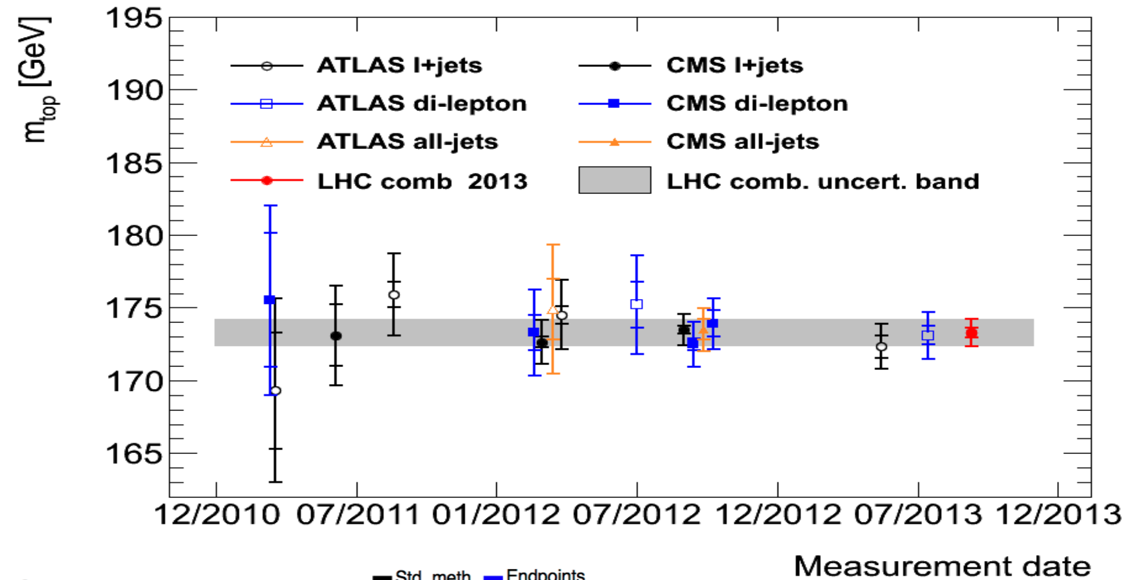


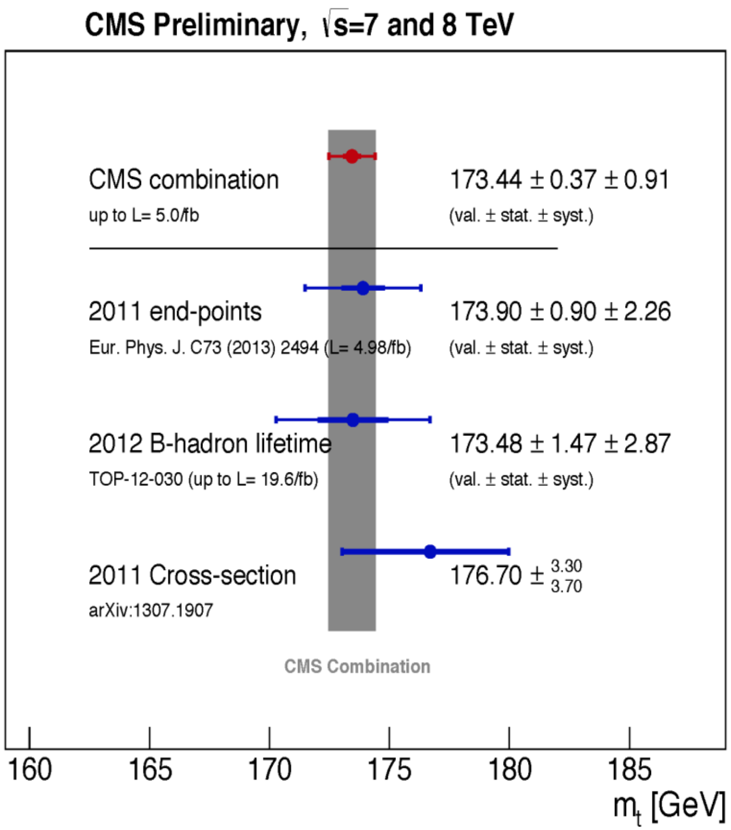
A significant improvement expected with the channel $tt \rightarrow bWbW \rightarrow bl\nu bqq$ with $b \rightarrow \psi + X$ with $\psi \rightarrow \mu^+\mu^-$ but this requires >~ 100 - 300 fb^{-1}

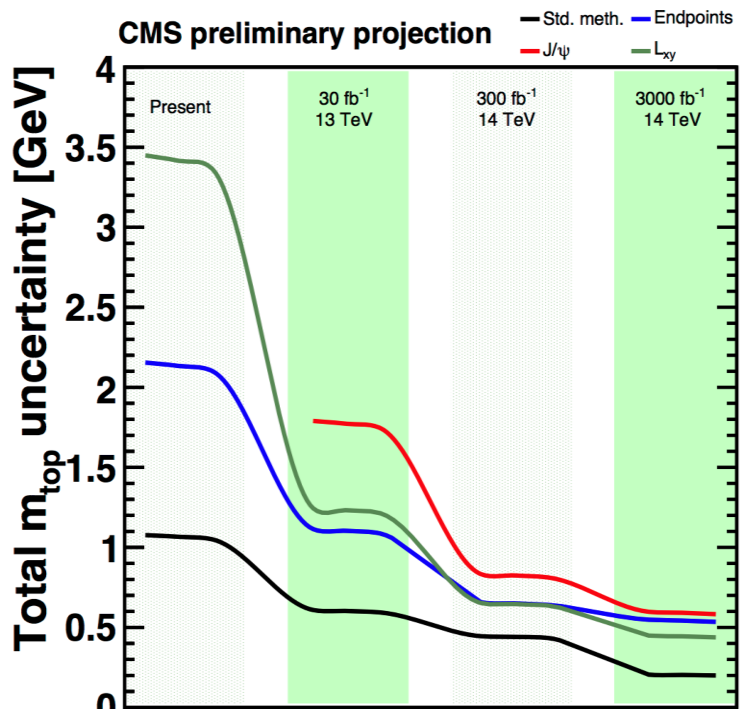
vacuum stability questions depend sensitively on Δm_{top} and Δm_H

Top properties, mass, 2013 and expectations





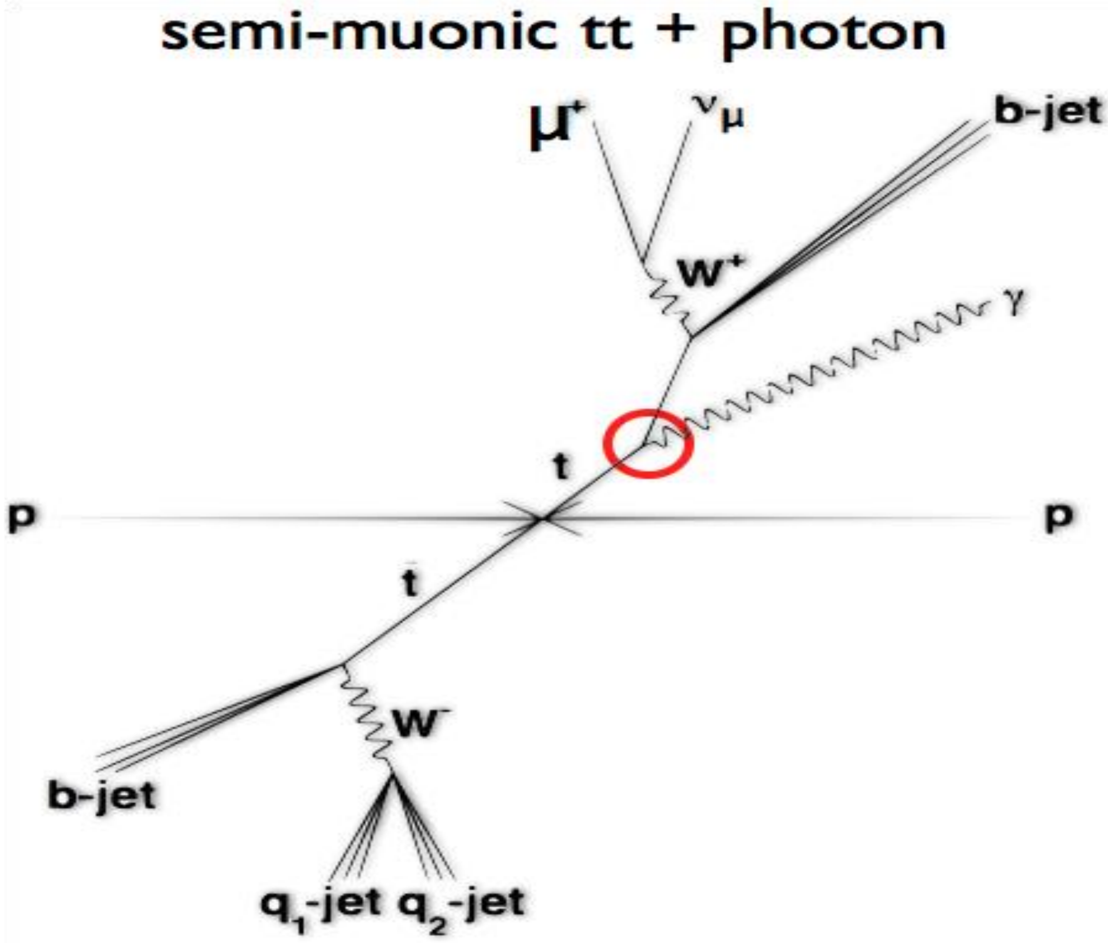




methods to reach 0.2 GeV Experimental precision for CMS alone (compared to 1 GeV now!)

Close to "ILC" projections (0.1GeV)

Top properties, charge, status in 2013



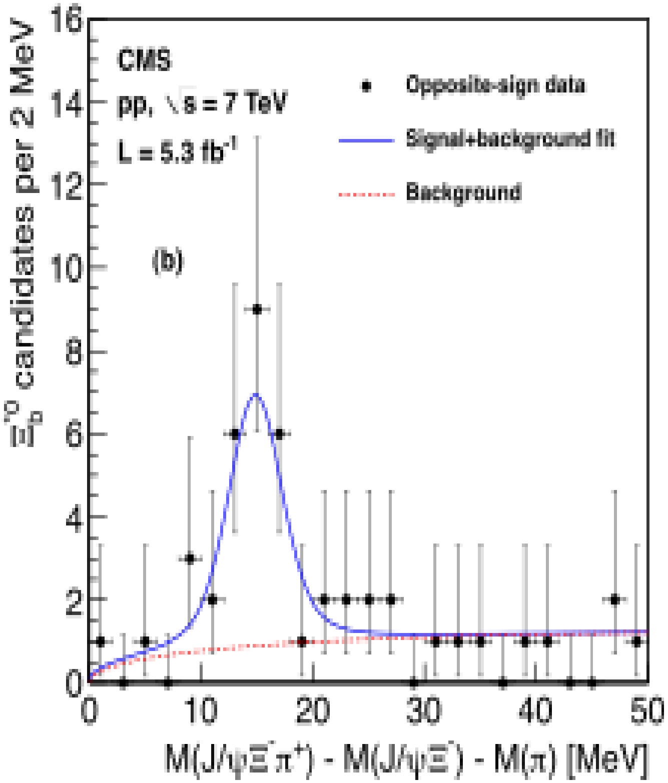
$t\bar{t}+\gamma$ $\Delta R(\gamma,\text{jet}) > 0.1$ and $p_T(\gamma) > 2\text{GeV}$

$\sigma(t\bar{t}+\gamma) = 2.4 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})$ pb

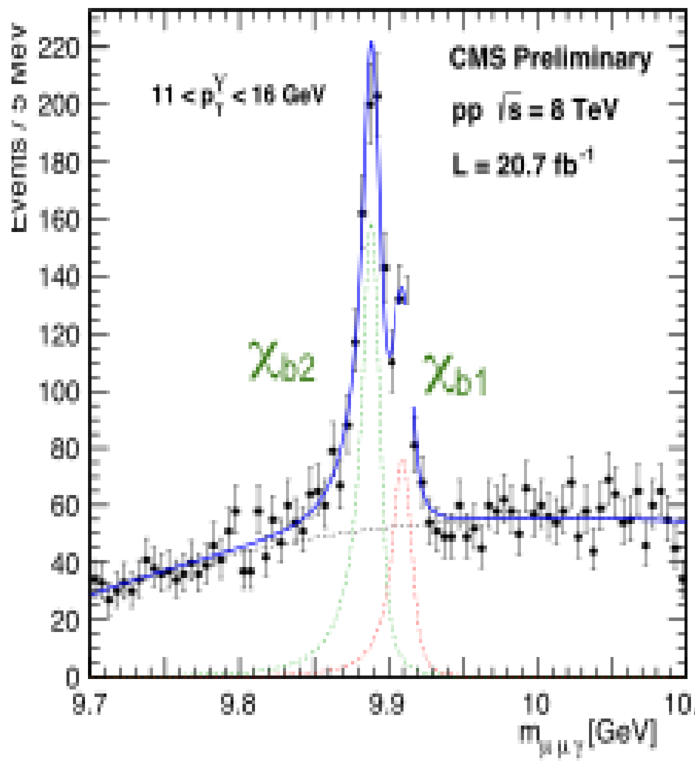
theory: 1.8 ± 0.5 pb

CMS successes in B and quarkonium physics

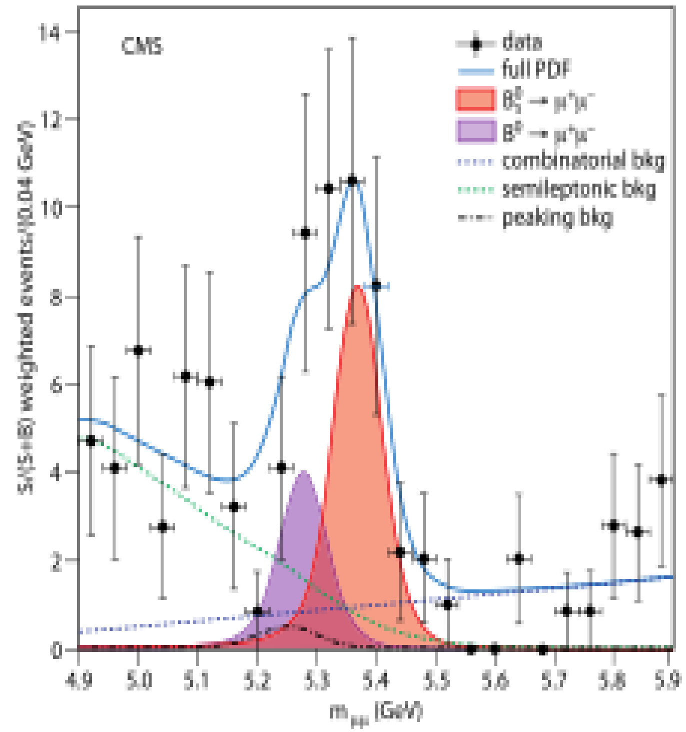
a new Ξ_b baryon



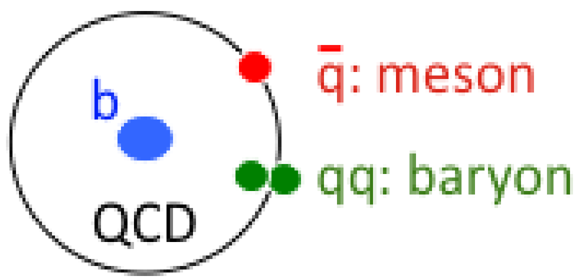
$\chi_b \rightarrow Y(1S) + \gamma$



$B_s \rightarrow \mu+\mu-$



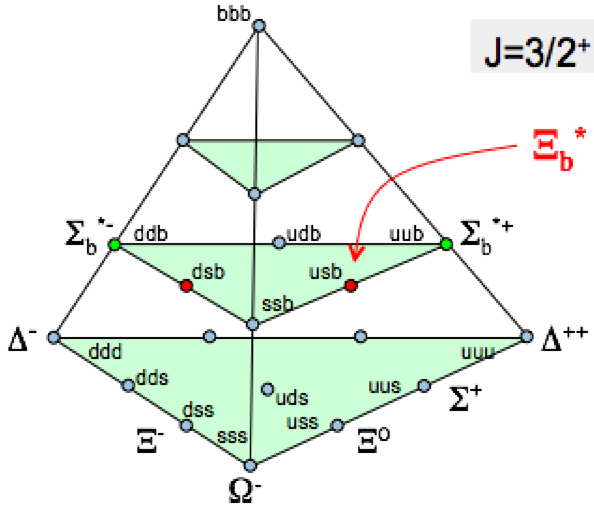
The *other* particle discovered by CMS



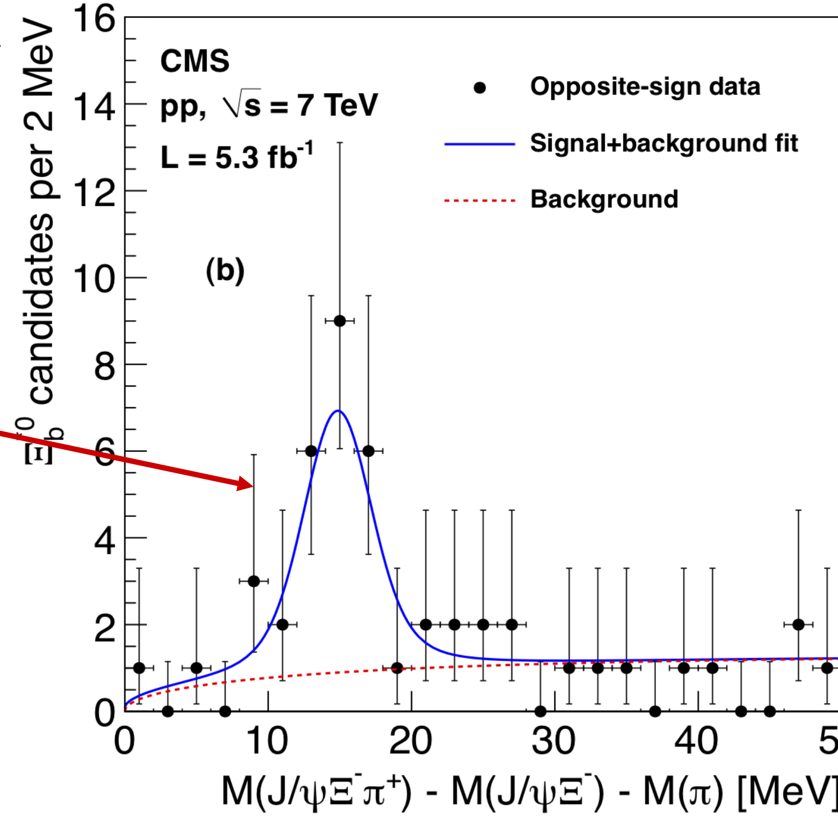
The Higgs is not the only new particle to be found at the LHC…..

SU4 20-plets

QuickTime™ and a
decompressor
are needed to see this picture.



Ξ^{*0}_b by CMS



Charm sector cousin:

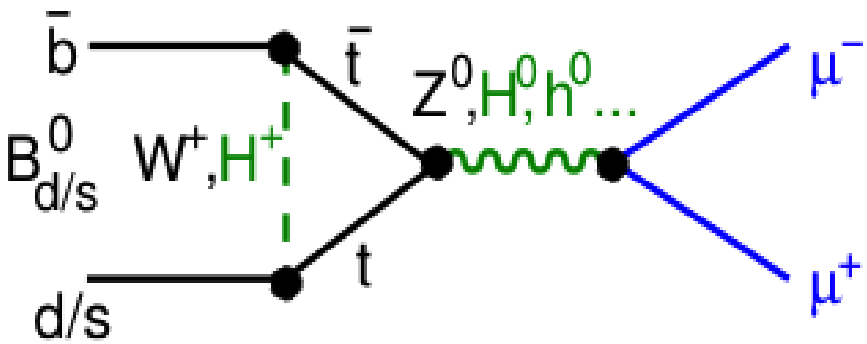
QuickTime™ and a
decompressor
are needed to see this picture.

$\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+ \rightarrow \Xi^- J/\psi\, \pi^+ \rightarrow \Lambda \pi^- \mu^+ \mu^- \pi^+ \rightarrow p^+ \pi^- \pi^- \mu^+ \mu^- \pi^+$

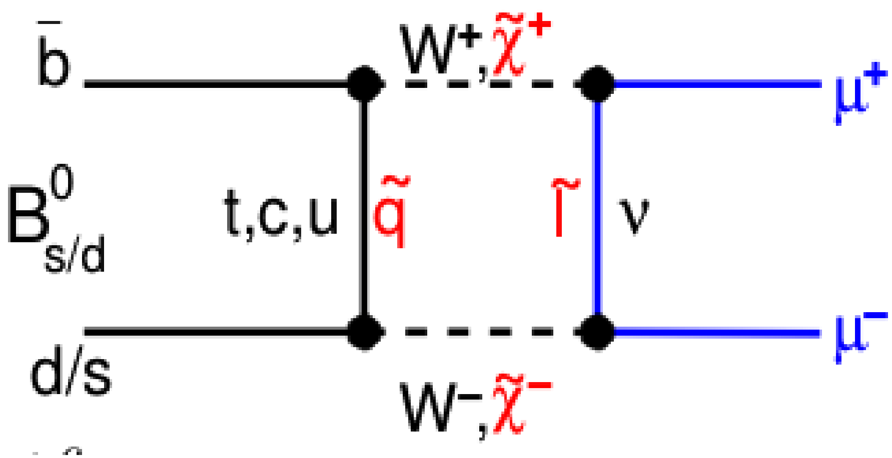
Expected $Q(\Xi_b^{*0}) = M(\Xi_b^{*0}) - M(\Xi_b^-) - M(\pi^+) \sim 11\text{-}29$ MeV

Search for rare decays $B^0_{d,s} \to \mu^+\mu^-$

Indirect search for new physics via rare decays, $B_s \to \mu^+\mu^-$

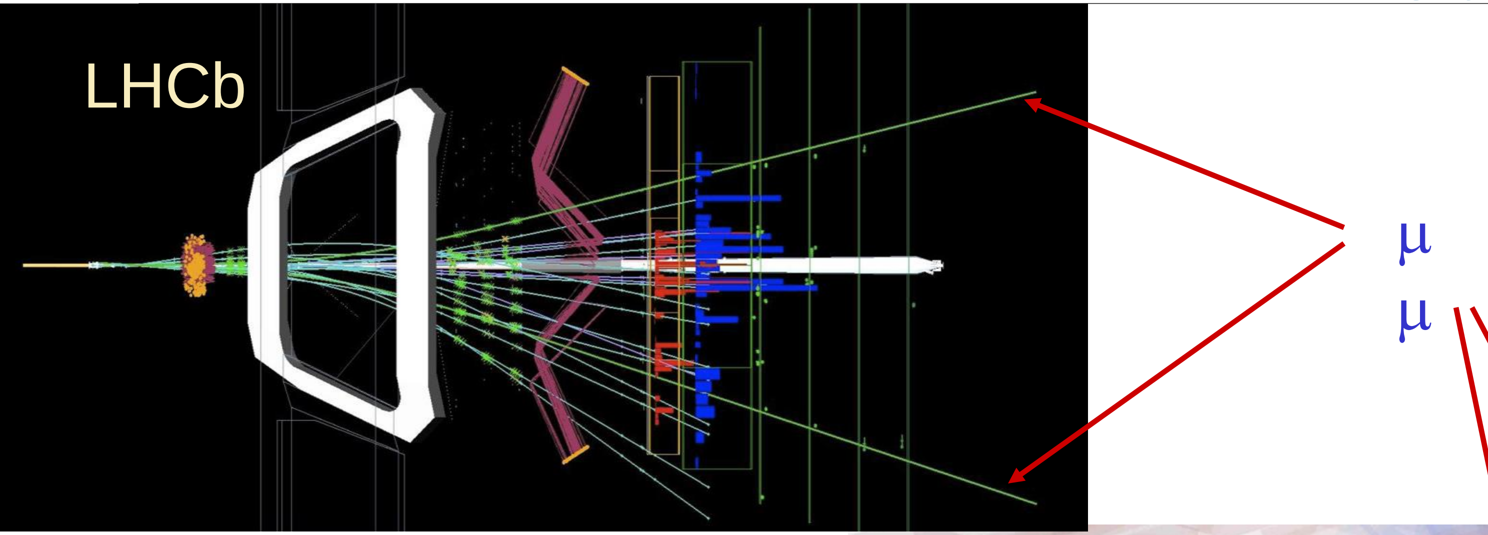


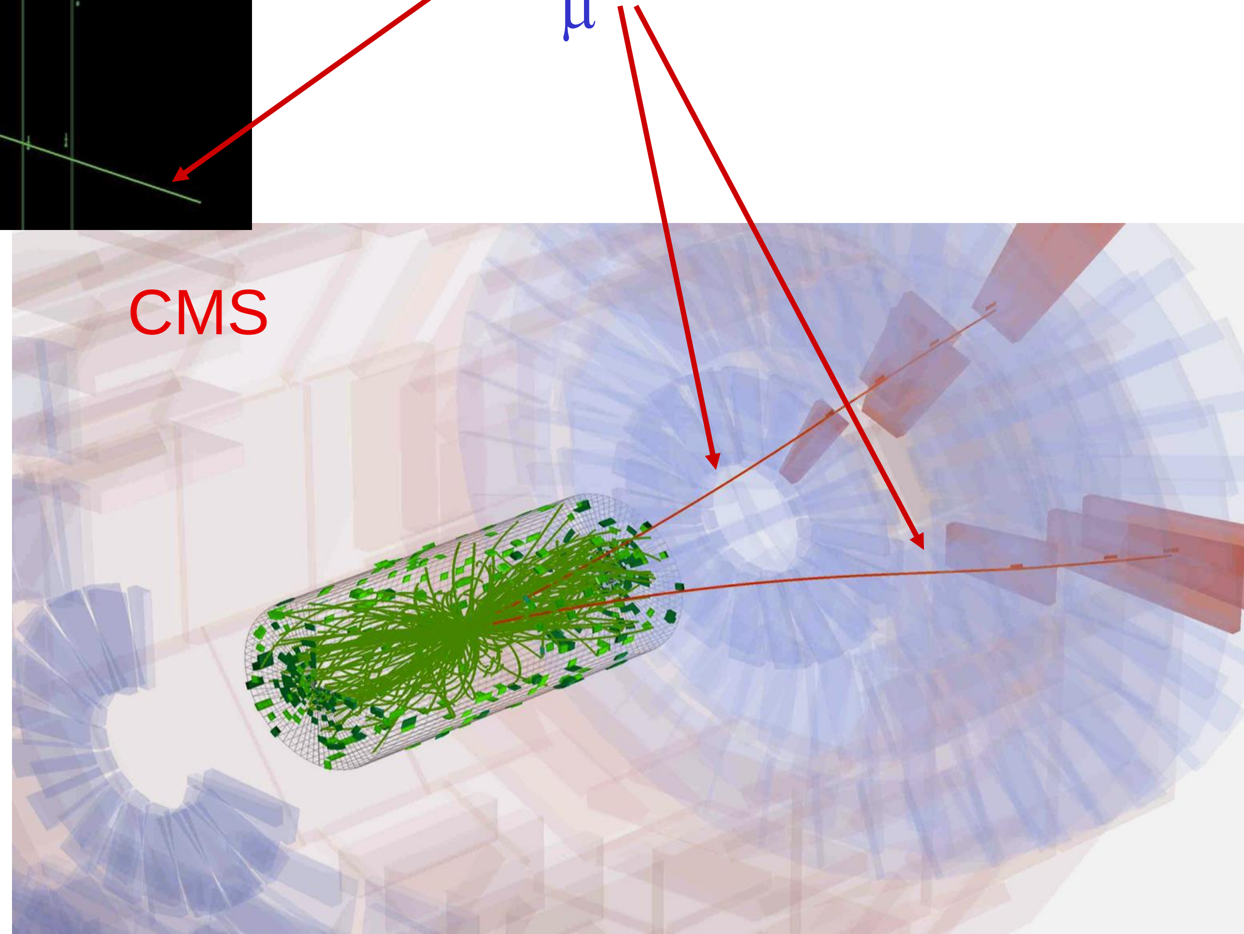
Search for rare modes, such as $B^0_{s,d} \to \mu\mu$ can reveal new physics present as virtual particles, in quantum corrections, before it could be produced kinematically as real particles



Decay	SM prediction
$B_s \to \mu^+\mu^-$	$(3.2\pm0.2)\times10^{-9}$
$B^0 \to \mu^+\mu^-$	$(1.0\pm0.1)\times10^{-10}$

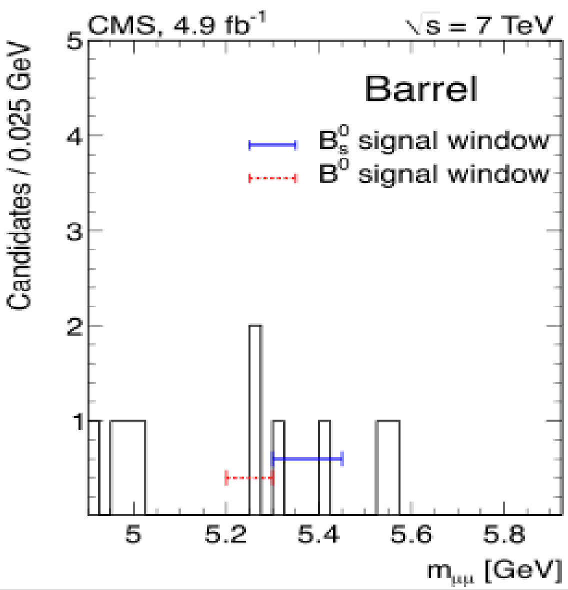
$B^0_{d,s} \rightarrow \mu^+\mu^-$ search, dimuon candidate in LHCb and CMS

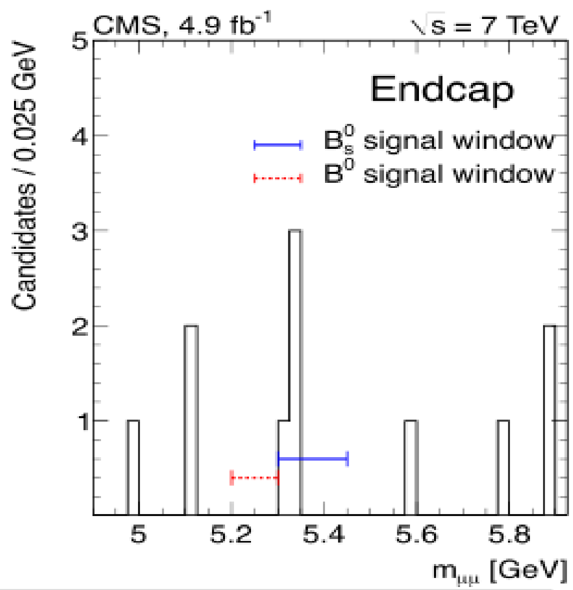


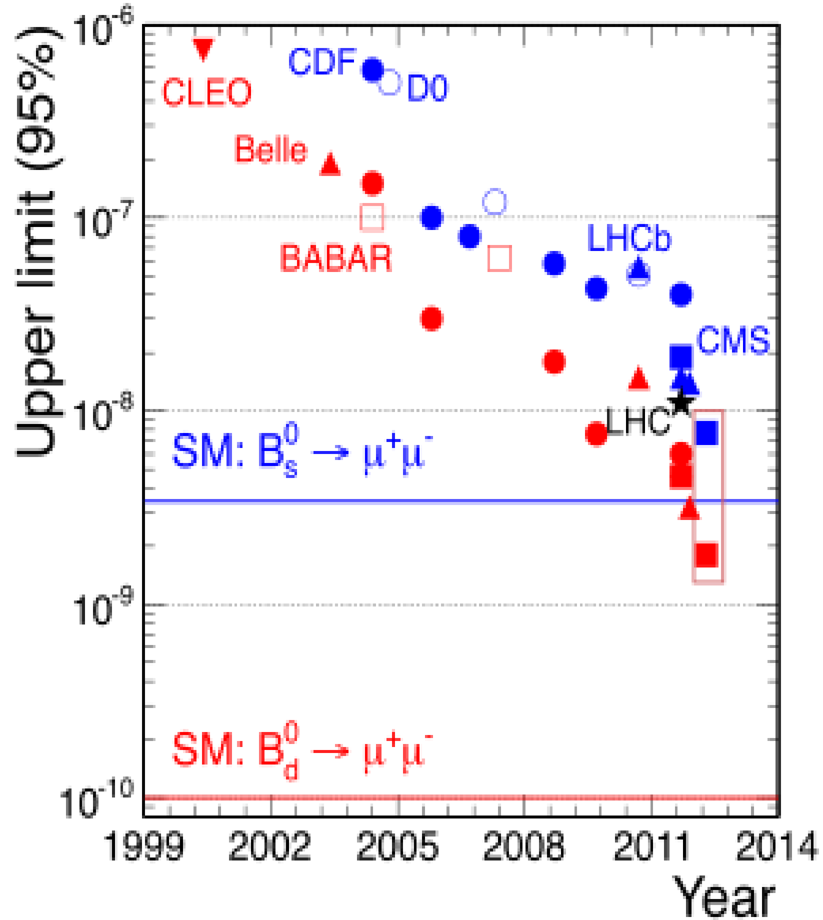


Search for rare decays $B^0_{d,s} \to \mu^+\mu^-$, full 2011 stat

Variable	$B^0 \to \mu^+\mu^-$ Barrel	$B^0_s \to \mu^+\mu^-$ Barrel	$B^0 \to \mu^+\mu^-$ Endcap	$B^0_s \to \mu^+\mu^-$ Endcap
Signal	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
Combinatorial bg	0.40 ± 0.34	0.59 ± 0.50	0.76 ± 0.35	1.14 ± 0.53
Peaking bg	0.33 ± 0.07	0.18 ± 0.06	0.15 ± 0.03	0.08 ± 0.02
Sum	0.97 ± 0.35	3.47 ± 0.65	1.01 ± 0.35	2.45 ± 0.56
Observed	2	2	0	4



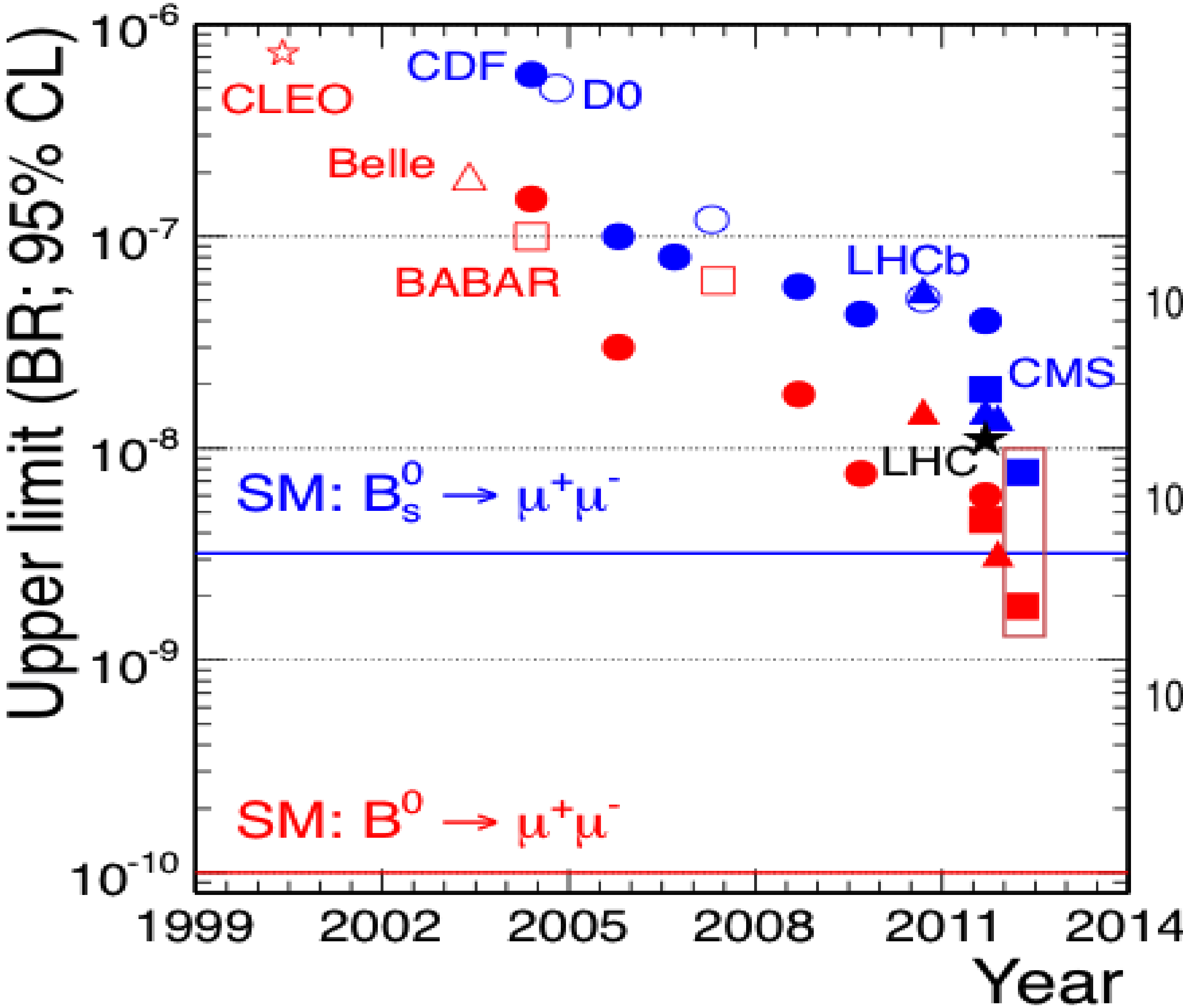




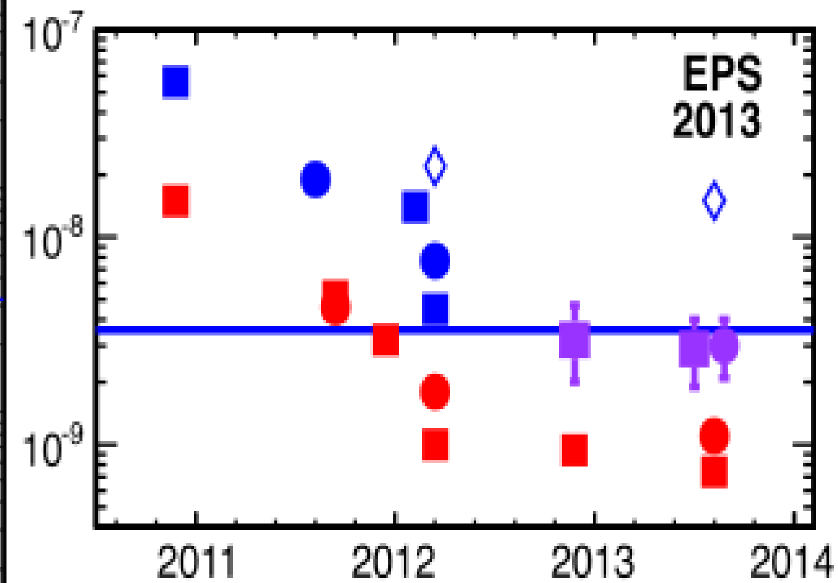
upper limit (95%CL)	observed	expected
$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	7.7×10^{-9}	8.4×10^{-9}
$\mathcal{B}(B^0 \to \mu^+\mu^-)$	1.8×10^{-9}	1.6×10^{-9}

World competition on $B^0_{d,s} \to \mu^+\mu^-$ final LHC success in 2013

CMS data of 2011, status March 2012 cut-based analysis



status in summer 2013



$B^0_s \to \mu^+ \mu^-$ - first observation in LHCb in March 2013, followed by CMS in July 2013

LHCb March 2013

QuickTime™ and a decompressor are needed to see this picture.

Signals observed in 2013 by both LHCb and CMS entirely compatible with the SM expectation for a BR of ~ 3.2 x10^{-9} (CMS: $3.0^{+1.0}_{-0.9}$ x 10^{-9} significance: ~4.8σ)

CMS July 2013

QuickTime™ and a decompressor are needed to see this picture.

…….thus no signs (yet) from this type of study of physics beyond the SM,
next episode will be the search for B^0_d in 2015/16

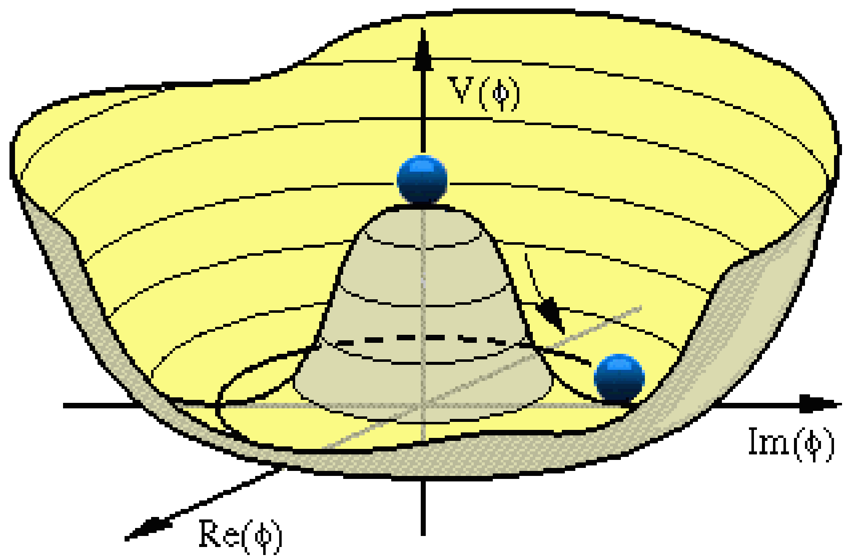
the Higgs…..

Path to the Higgs somewhat complex….
Higgs potential,

Unified electroweak theory:

- Introduce a local gauge invariance a la isotopic spin SU2 add a U1 this gives 4 vector fields with zero mass gauge bosons – infinite range – two charged, two neutral (W_1,W_2,W_3,B)
- Bring the "Higgs mechanism" with 4 scalar fields (Goldstone-Nambu), 3 are absorbed and provide masses (and longitudinal components) to W^+,W^- and Z^0, whilst photon remains mass-less (W,G,W,S model)
- One scalar field survives – "the Higgs" and should be looked for!

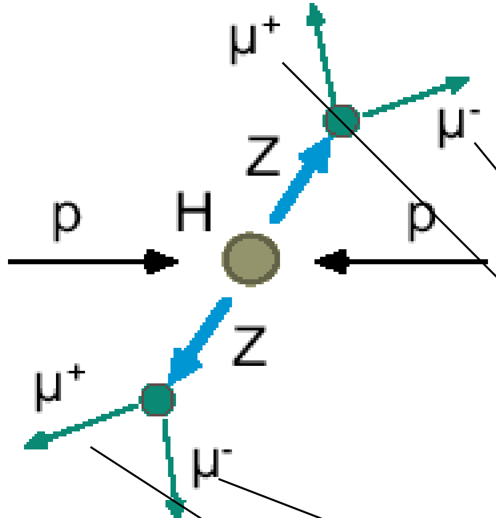
The lowest energy state of the theory - vacuum - has a non-zero value for the (scalar) Higgs field!

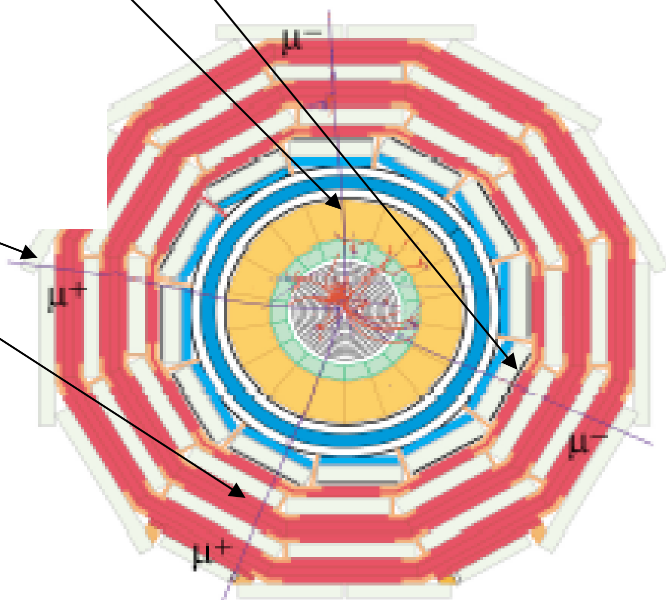


Production and detection of the Higgs in CMS - if $m_H \sim 150$ GeV ($H \longrightarrow ZZ/ZZ^* \longrightarrow 4$ leptons)

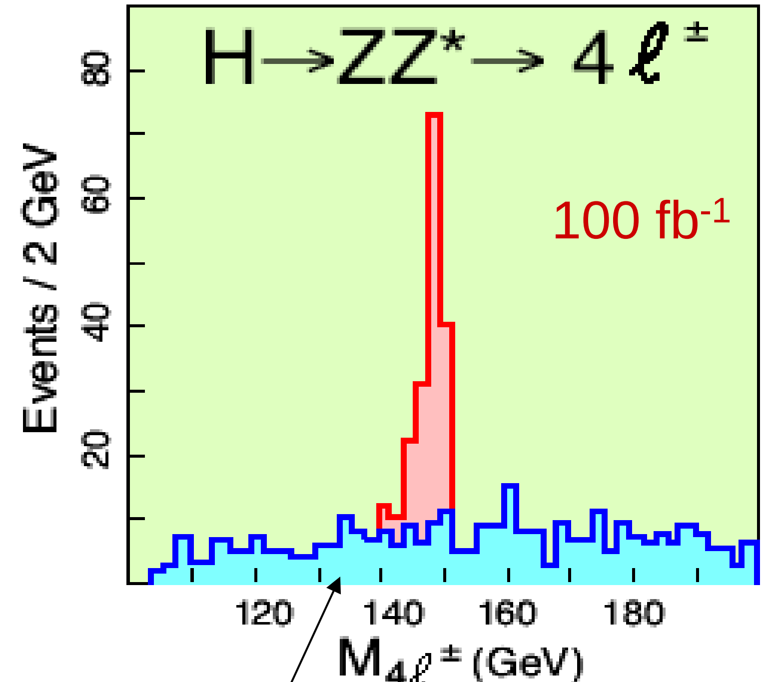
- as expected in 1992/93!!

Key Signature: 4 muons/leptons

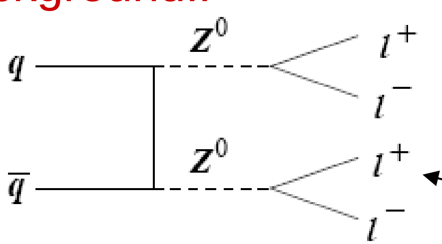




M_{Higgs} = 150 GeV

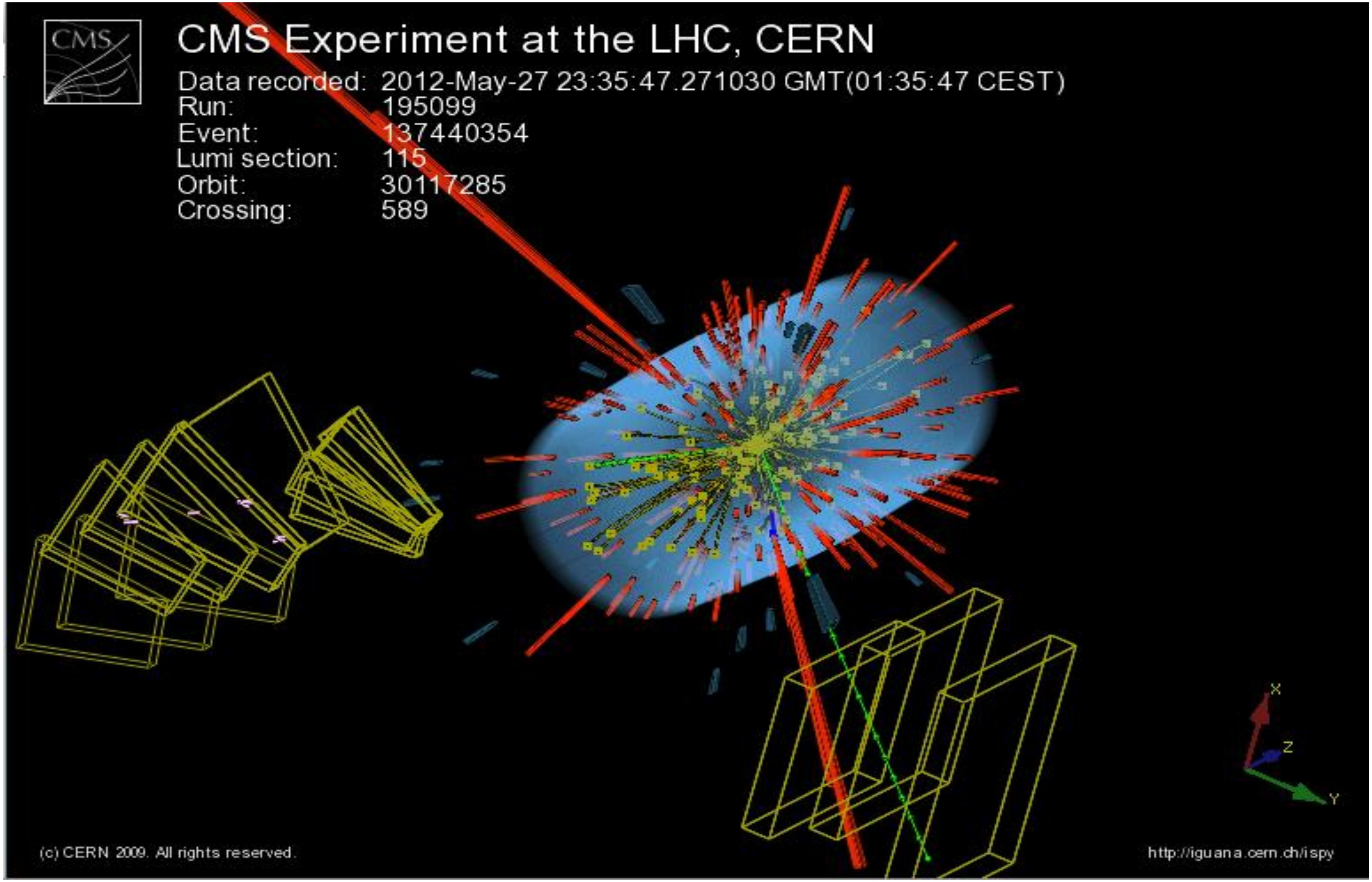


Electroweak ZZ Background!!

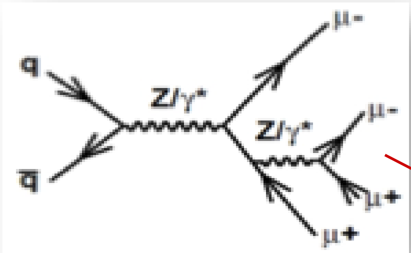


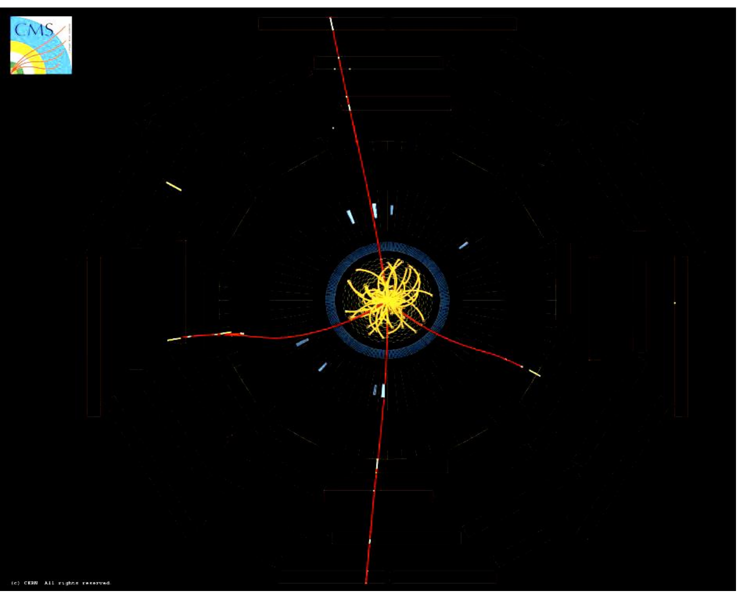
Electroweak ZZ background

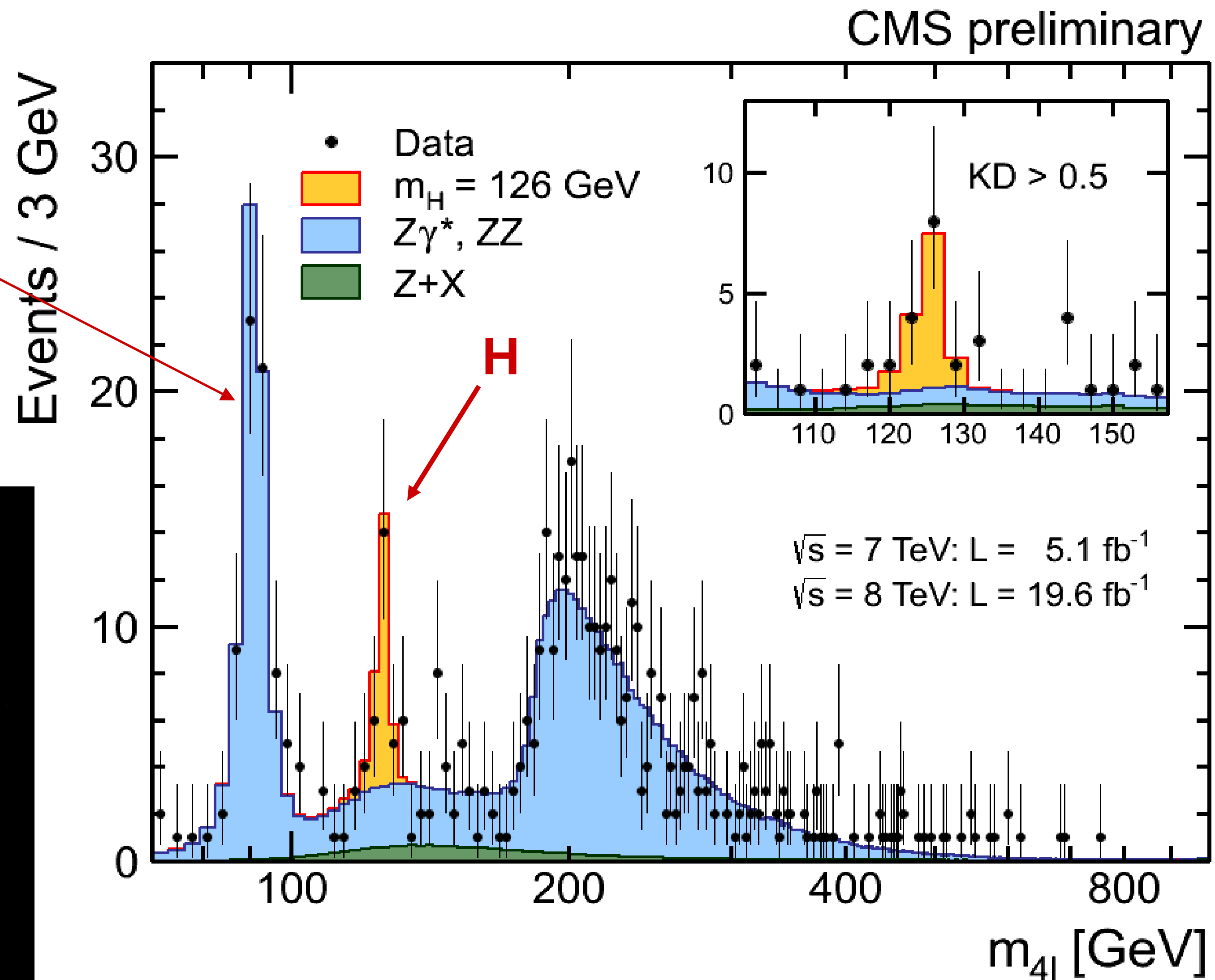
$H \rightarrow ZZ \rightarrow ee\mu\mu$ candidate event in CMS, $\sqrt{s}$ = 8 TeV, data of June 2012



Higgs → 4 leptons, CMS, full statistics, Feb. 2013, full mass range



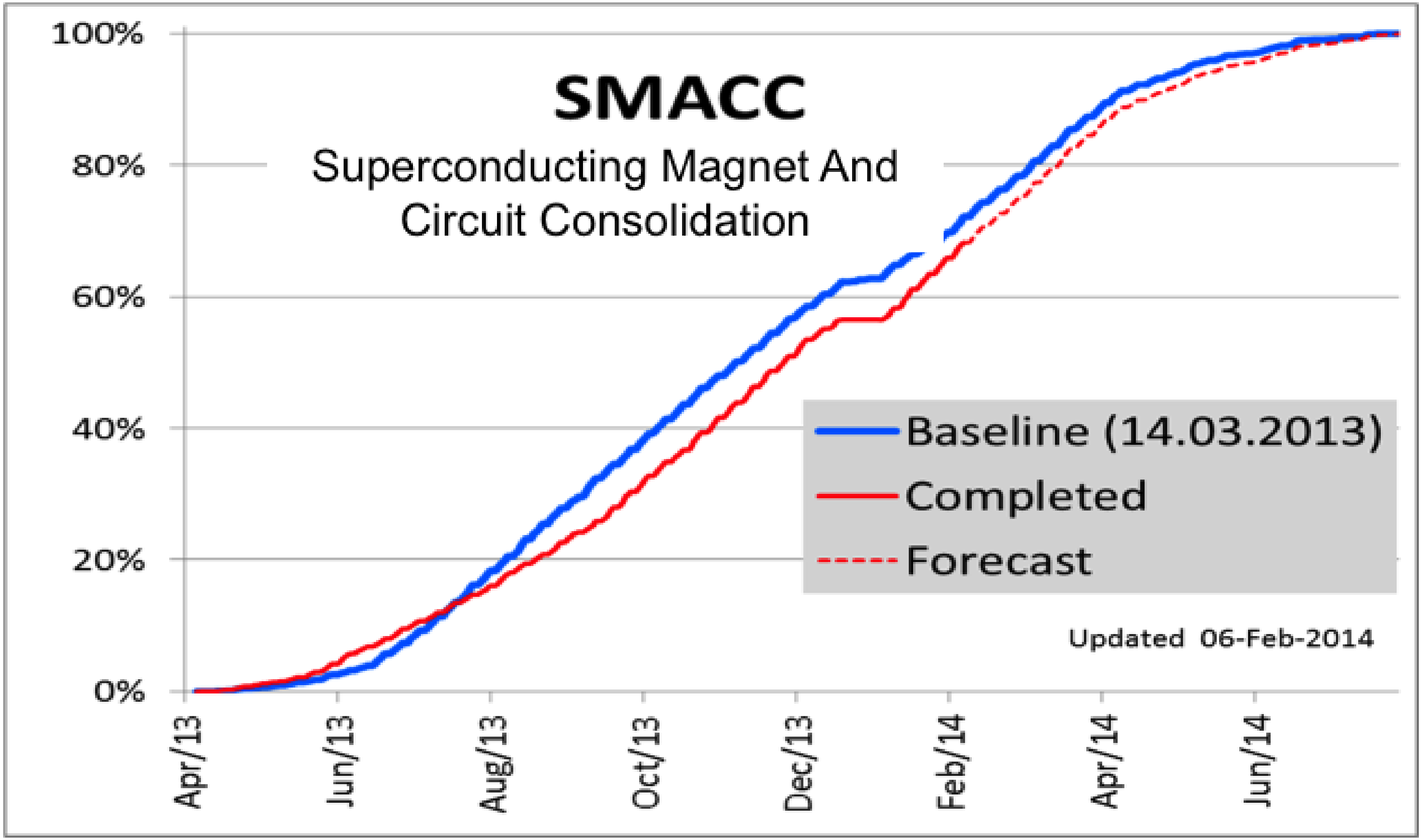




Title

QuickTime™ and a
decompressor
are needed to see this picture.

LHC consolidation activities, 2014 situation end-February 2014



CMS: Pixels and HCAL, upgrades in 2013 - 1016

- New Pixels Design
  – 4 barrel layers and
  3 endcap disks at each end.
  smaller inner radius
  –– Reduced mass

QuickTime™ and a
decompressor
are needed to see this picture.

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decompressor
are needed to see this picture.

- Installation date
  – Ready by late-2016,

QuickTime™ and a
decompressor
are needed to see this picture.

- New HCAL Design
  – HF new PMT
  – Replace HPDs with SiPMs in HB and HE
  - longitudinal segmentation

- Installation date
  - HF full PMT in LS1
  - HBHE slice after LS1
  - HB and HE in LS2

QuickTime™ and a
decompressor
are needed to see this picture.

CMS phase-2 upgrades

Muon system
- GEM Glass RPCs
- Extended η coverage
- New DT minicrates

Tracker
- Higher granularity
- Less material
- Better pT resolution
- Extended η coverage
- Track trigger at L1

Trigger/DAQ
- New FE and RO
- L1 up to 1 MHz
- HLT up to 10 KHz
- Tracking at L1

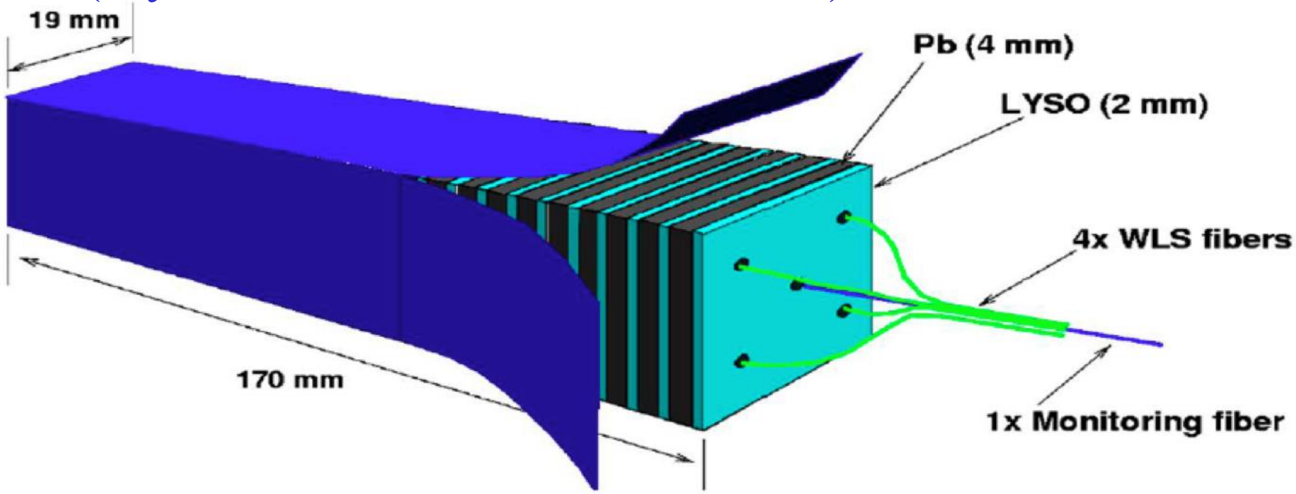
QuickTime™ and a
decompressor
are needed to see this picture.

Replace Endcap
Calorimeters

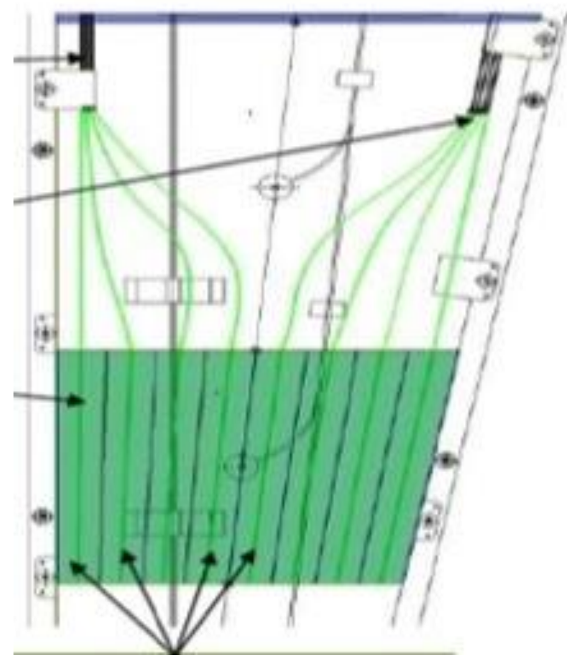
CMS upgrade: calorimeters; two approaches

Keep present towers geometry, but use more radiation tolerant technology:

EE towers e.g. in Shashlik design
(crystal scintillator: LYSO, CeF)

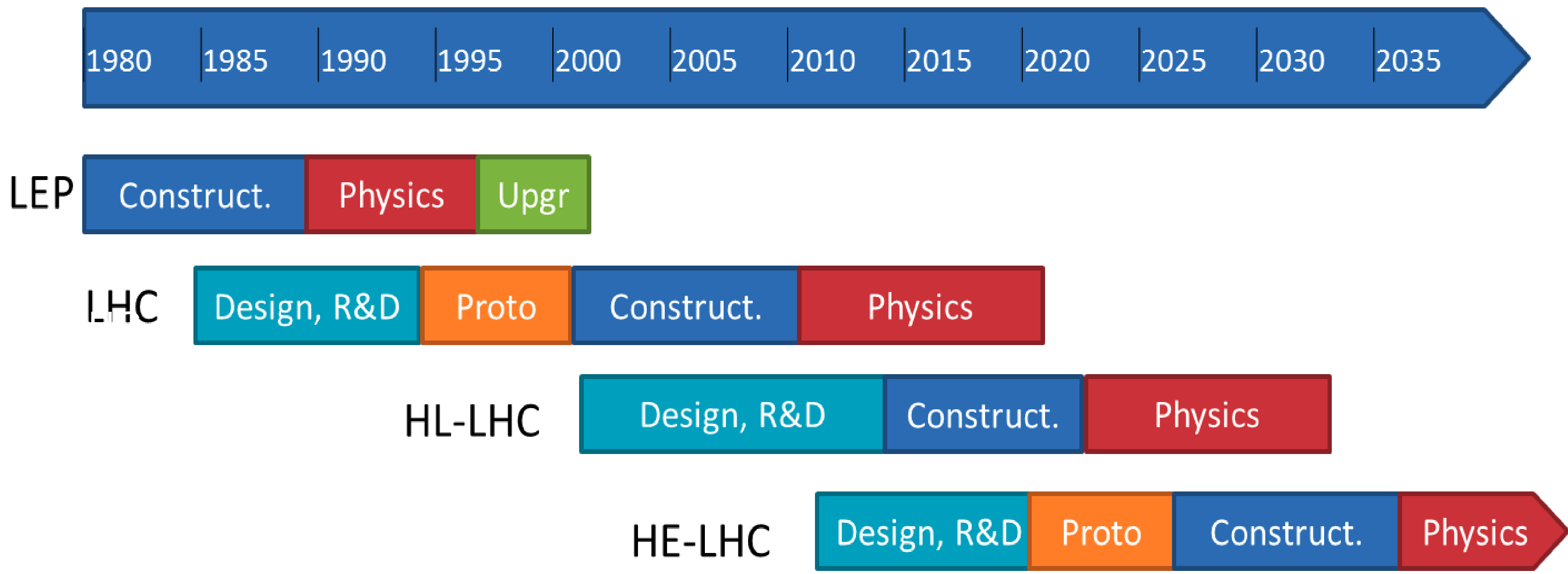


Rebuild HE with more fibers

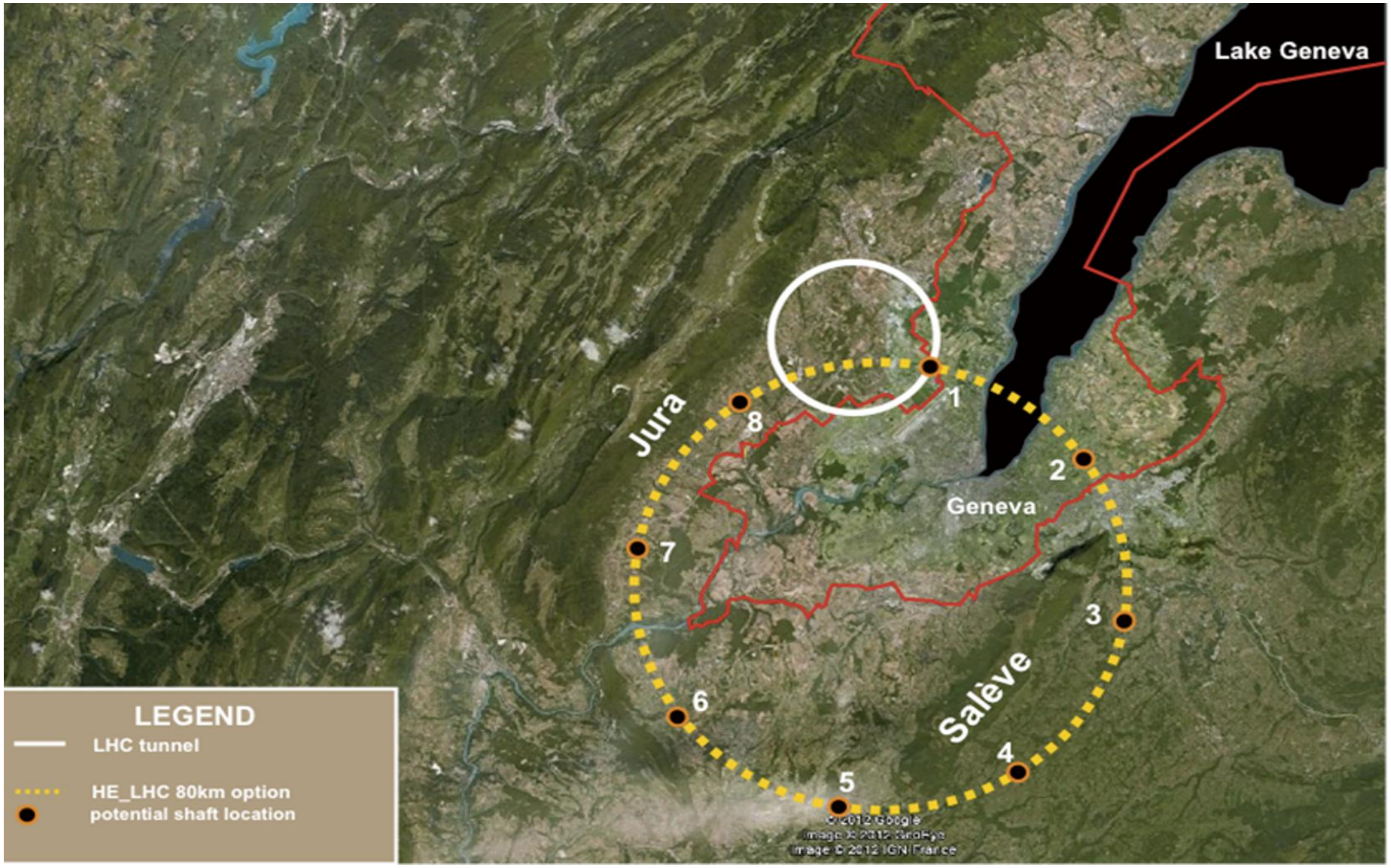


Alternative geometry/concepts
Potentially improved performance and/or lower cost
i) Dual fiber read--out: scintillation & Cerenkov (DROC)
– alla DREAM/RD52
ii) Particle Flow Calorimeter (PFCAL)
– following work of CALICE

Long-term exploitation of the LEP/LHC complex



T-LEP - a potential longer-term future for CERN and the FCC project with ee, eh, hh collisions



~ 90 km circumference tunnel with a E_{cm}~ 350 GeV e^+e^- collider capable of producing ~ 80000 Higgs bosons/year; tunnel reusable for a hadron collider at ~100 TeV proton-proton cm energy, e-proton and heavy ion collisions too.

Conclusions

The LHC is an incredible technological and scientific endeavor - on a world-wide scale

The LHC has started operation in November of 2009; in March 2010 started operating at 7 TeV center of mass energy; between March and November 2010 the luminosity has increased by a factor ~ 100000; the restart in March 2011 was very successful, running at 7 TeV center of mass energy and gainning another factor of ~10 in luminosity approaching 3.5 x 10^{33} cm^{-2} s^{-1}; in March 2012 LHC restarted at 8 TeV and a gain of another factor ~ 2 in luminosity was achieved;

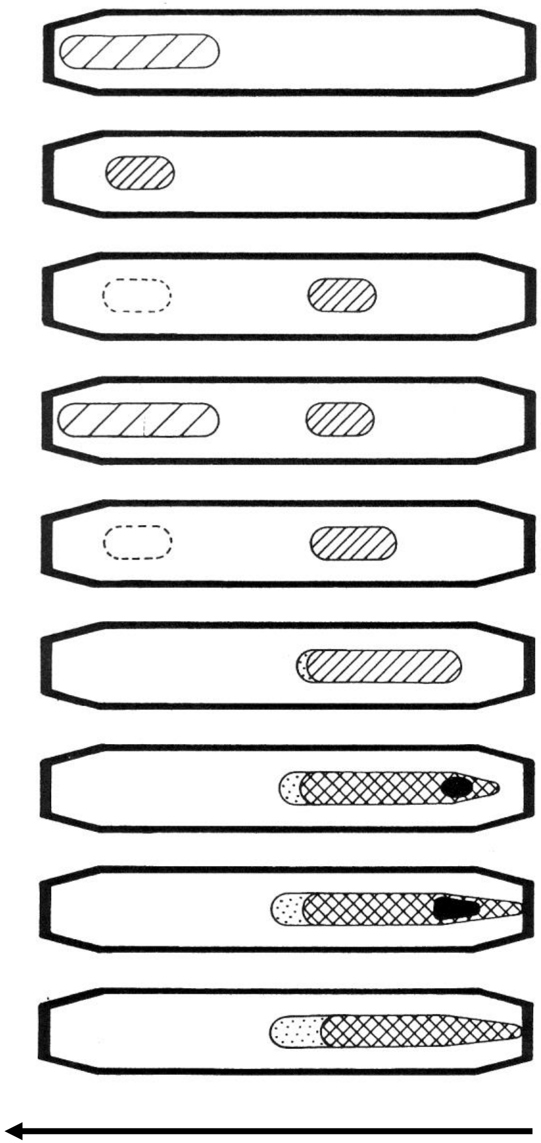
The four major experiments ATLAS, CMS, ALICE and LHCb have taken in 2011 and 2012 high quality data operating extremely successfully, with very high efficiencies. The main goal of the LHC, observing the Higgs boson at a mass of 125 GeV was realized in 2012

The year 2015 will be very exciting, the LHC will go to ~13 TeV and feed the world particle physics community for the next ~ 15 years

SPARES

Antiproton Accumulator - operation

AA vacuum chamber



The first pulse of 7 x 10^6 $\bar{p}$ has been injected

Precooling reduces momentum spread

First pulse is moved to the stack region where cooling continues

Injection of 2^{nd} $\bar{p}$ pulse 2.4 s later

After precooling 2^{nd} pulse is also stacked

After 15 pulses the stack contains 10^8 $\bar{p}$

After one hour a dense core has formed inside the stack

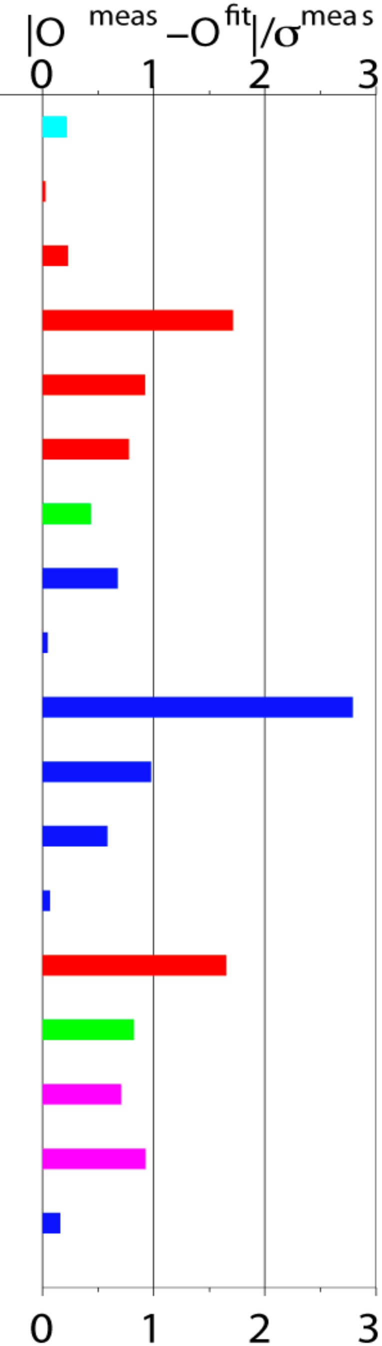
After one day the core contains enough $\bar{p}$'s for transfer to the SPS

The remaining $\bar{p}$'s are used for next day accumulation

SM fits at LEP

+ SLC and Tevatron

	Measurement		Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758	± 0.00035	0.02766
m_Z [GeV]	91.1875	± 0.0021	91.1874
Γ_Z [GeV]	2.4952	± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540	± 0.037	41.477
R_l	20.767	± 0.025	20.744
$A_{fb}^{0,l}$	0.01714	± 0.00095	0.01640
$A_l(P_\tau)$	0.1465	± 0.0032	0.1479
R_b	0.21629	± 0.00066	0.21585
R_c	0.1721	± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992	± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707	± 0.0035	0.0741
A_b	0.923	± 0.020	0.935
A_c	0.670	± 0.027	0.668
A_l(SLD)	0.1513	± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324	± 0.0012	0.2314
m_W [GeV]	80.392	± 0.029	80.371
Γ_W [GeV]	2.147	± 0.060	2.091
m_t [GeV]	171.4	± 2.1	171.7



Summer, 2006

LHC experiments are really international endeavors! CMS for example:

Flux return yoke
Germany,Russia,Chekia,Japan

Hadron calorimeter
USA,Russia,Ukraina,Turkey,Iran, India,Hungary

Solenoid magnet
France,Italy,Switzerland,Finland, Croatia,UK,Japan,CERN

Tracking system
Germany,Italy,France,Belgium,USA Finland,Switzerland,CERN…..

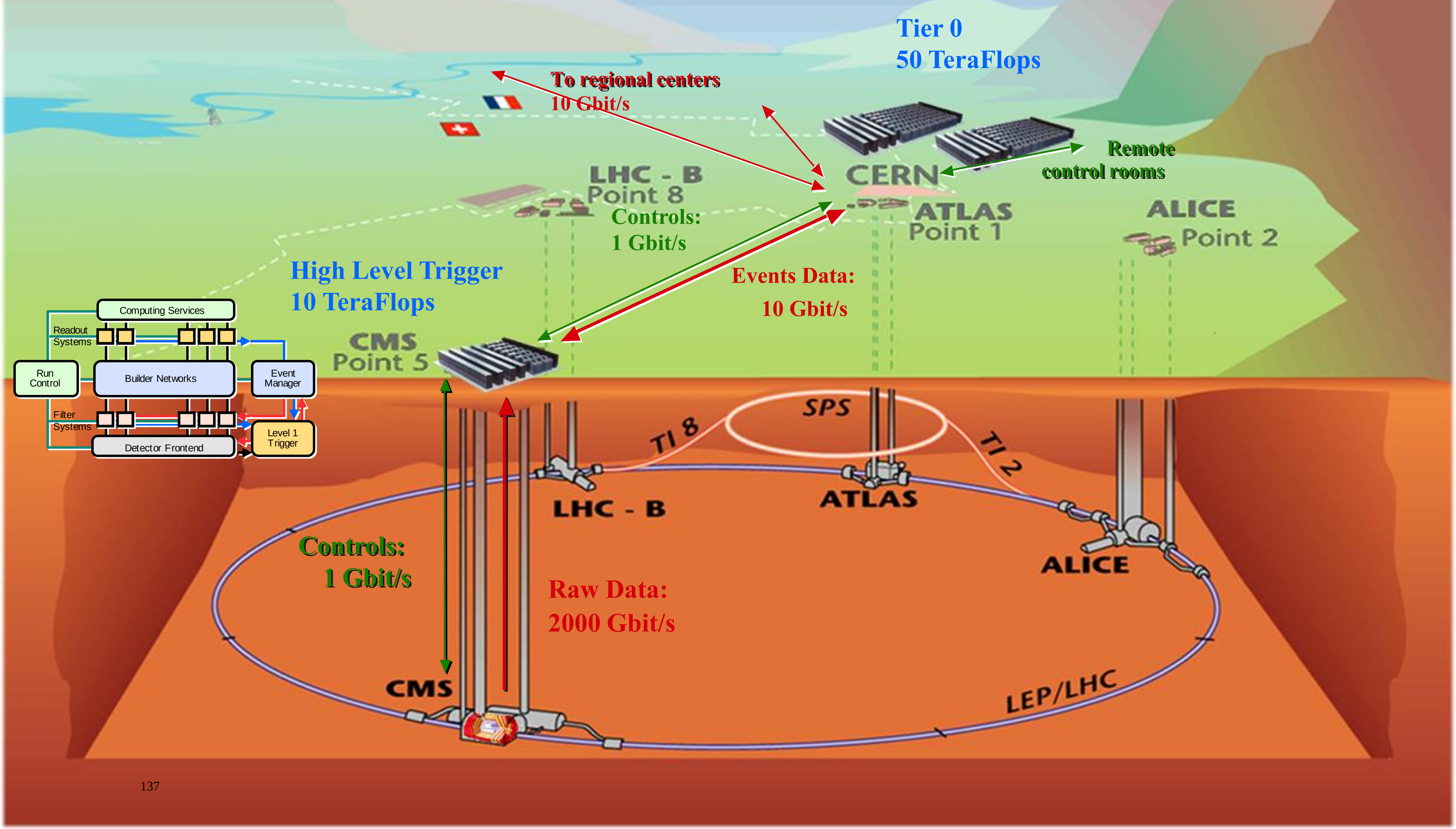
Electromagnetic calorimeter
Russia,China, France,Italy,Japan, UK,Switzerland,Greece,Taiwan

Muon system
Italy,Germany,Spain,USA,Russia, Egypt, Bulgaria,Korea,Pakistan,CERN

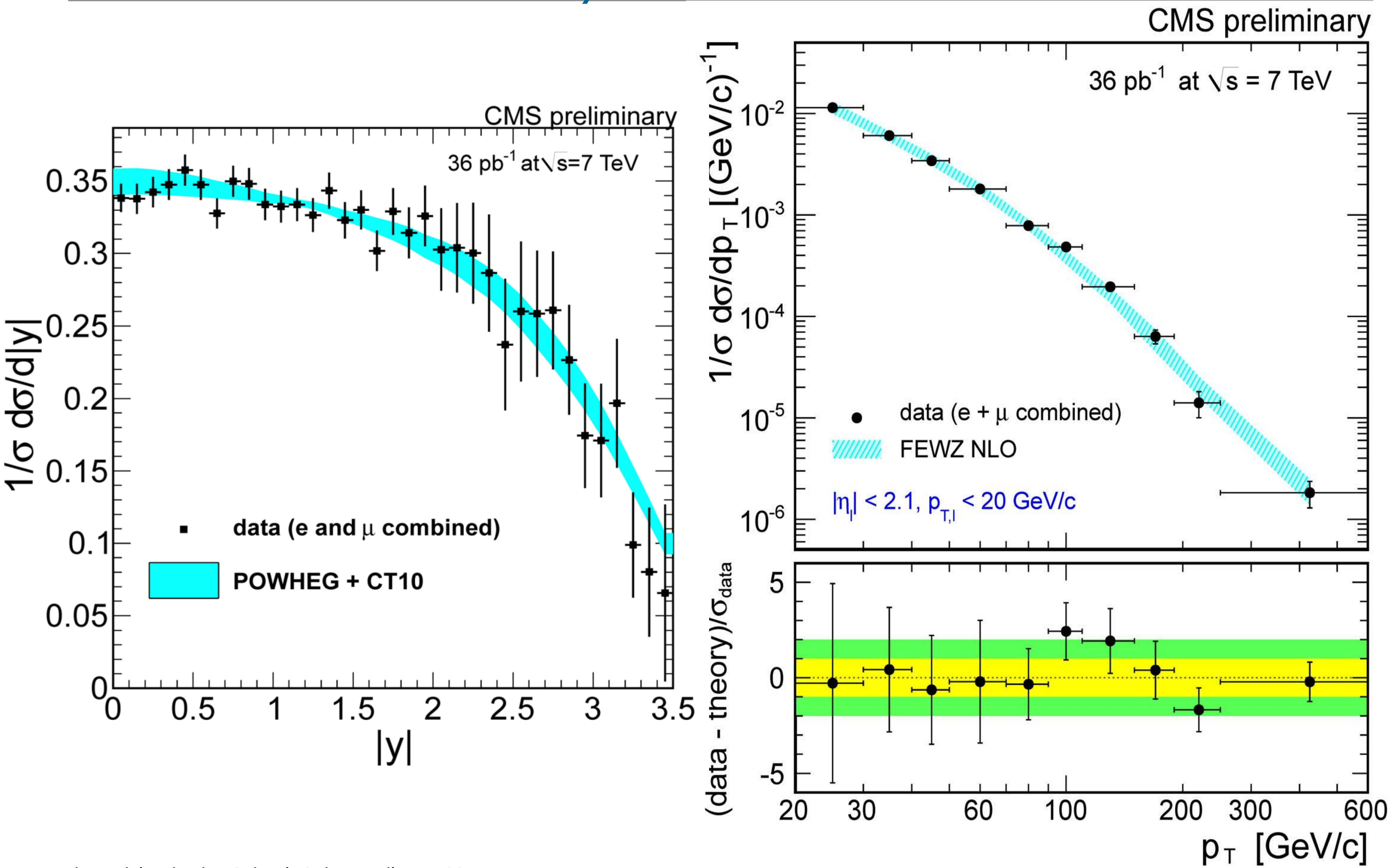
Support system
China,Pakistan,USA

CMS data flow and on(off) line computing

typical event size ~2Mbytes, ~400 events per second kept and stored for analysis

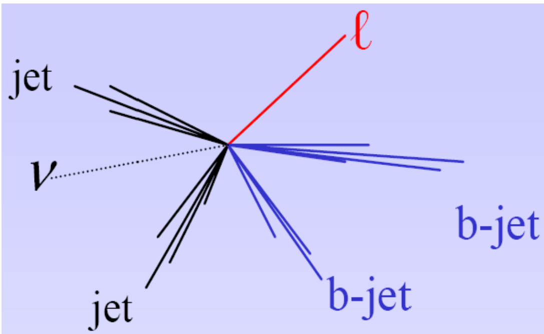


Z production, Z rapidity and p_t distributions, CMS, full 2010 statistics



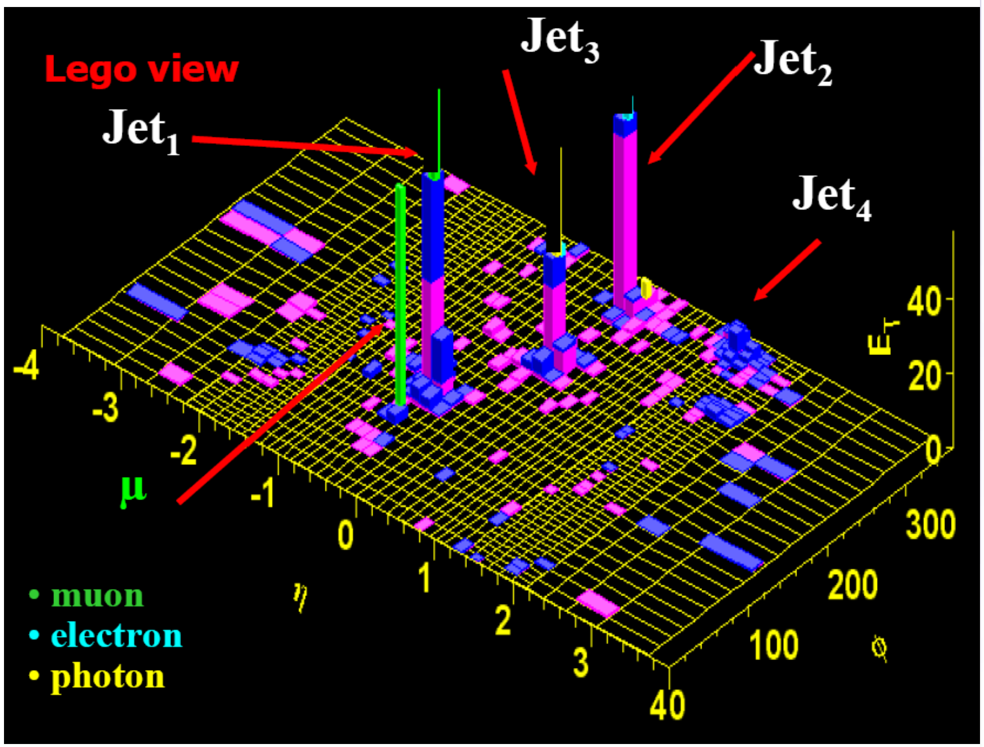
Top production at the Tevatron

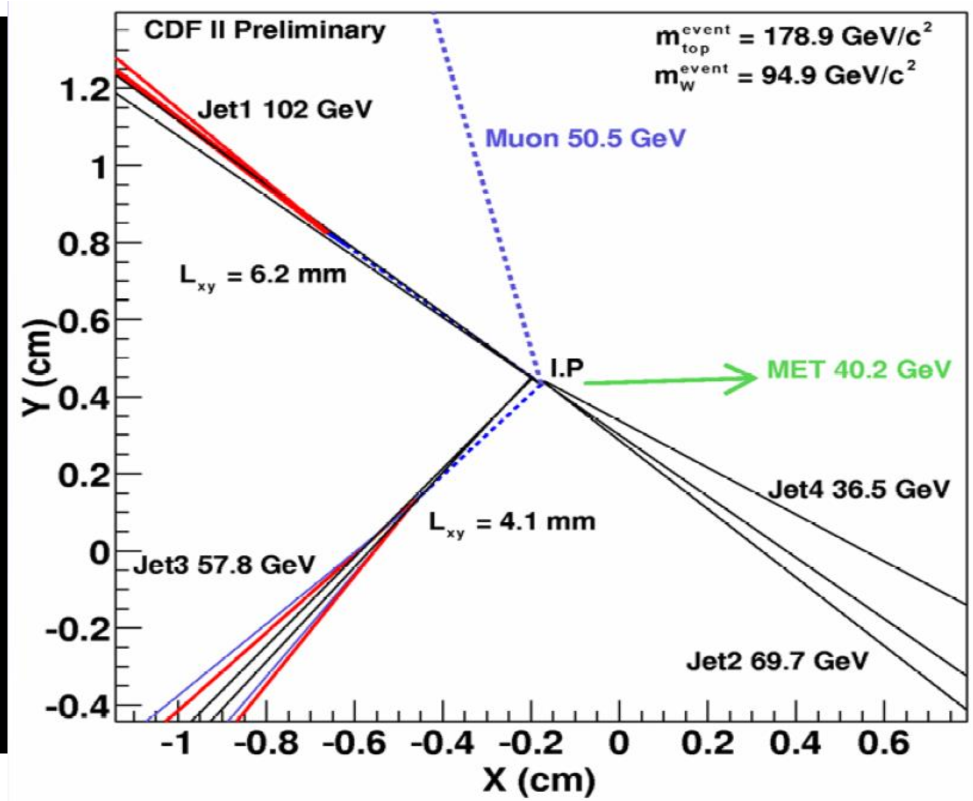
ttbar production cross sections: ≈ 6 pb (Tevatron), ≈ 800 pb (LHC)



1 muon
1 neutrino (missing E_T)
2 light quark jets
2 b-quark jets
tagged by displaced vertices

From Tevatron to LHC cross section increases by a factor ~130!!



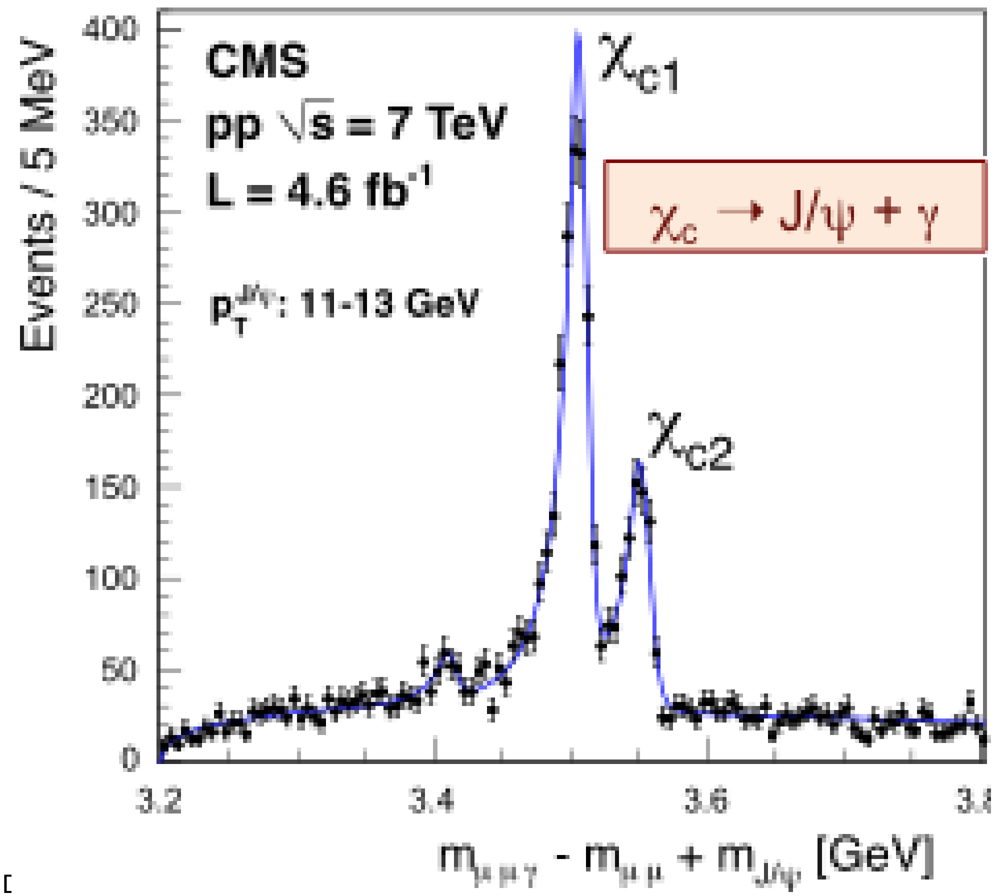


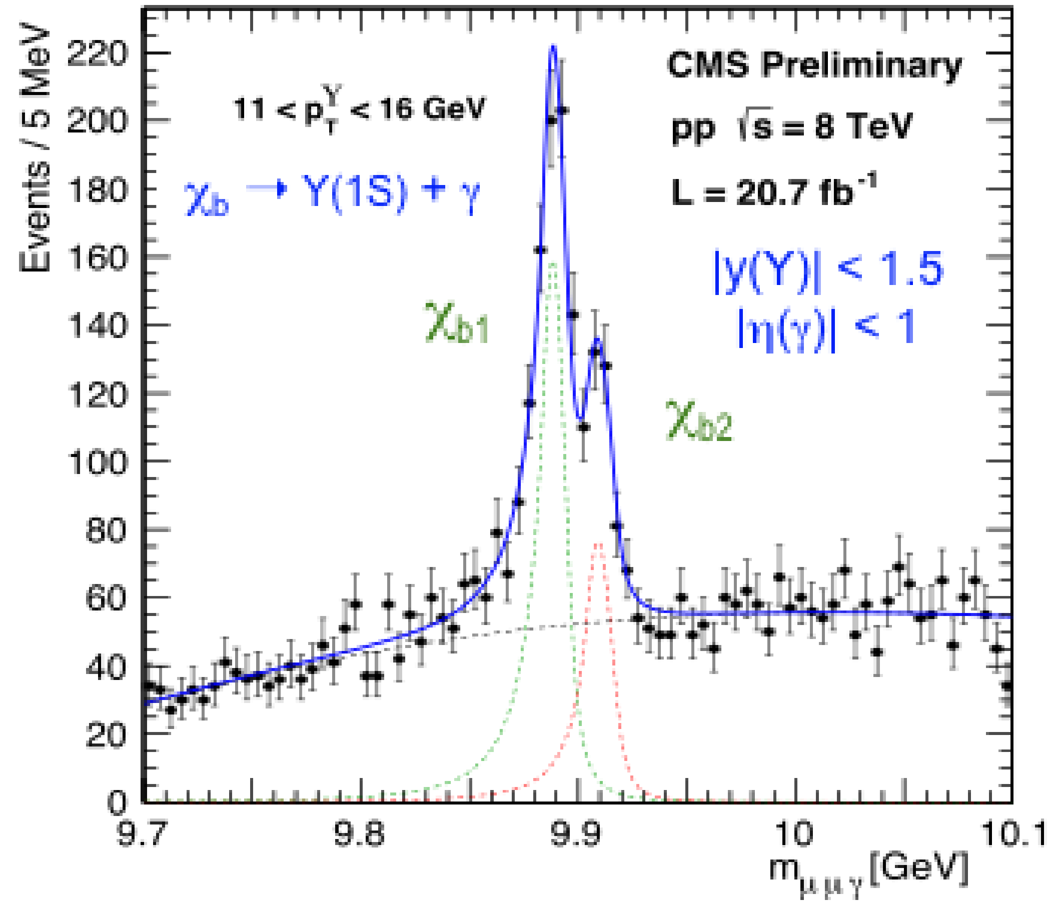
χ_{b2} / χ_{b1} cross-section ratio at 8 TeV

The χb2(1P) / χb1(1P) cross-section ratio has been measured for the first time in a hadron collider

Systematic uncertainties are dominated by the fit to the mass distribution

Mass resolution of 5 MeV resolves the two peaks, separated by only 19 MeV





Path to the Higgs is complex….Higgs potential

The B-E-H mechanism generates particle masses preserving the SU(2)xU(1) gauge invariance of the interactions/fields, by making the vacuum non-symmetric.

In the SM, a doublet of scalar fields $\phi = (\phi^+, \phi^0)$ is introduced, with $< 0| \phi^0|0 >$ not 0 (nonzero vacuum expectation value v, ie the lowest energy state of the theory - vacuum - has a non-zero value for the (scalar) Higgs field! Of the 4 degrees of freedom introduced with ϕ, 3 generate the masses of W^+, W^- and Z, the fourth remains as the scalar Higgs boson! Same field ϕ generates fermion masses.

$L_S = D_\mu \phi^\dagger D^\mu \phi - \mu^2 (\phi^\dagger \phi) - \lambda(\phi^\dagger \phi)^2$ v

$m_W = gv/2$ $\quad m_Z = m_W/\cos\vartheta_W$ v

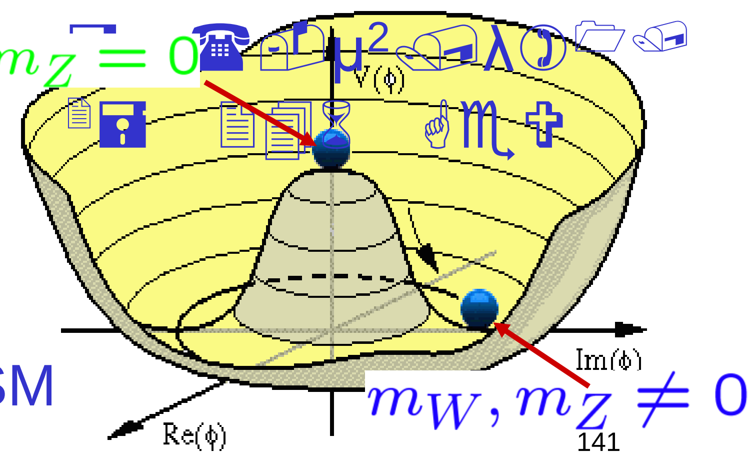
a scalar particle: $J^{PC} = 0^{++}$ (CP-even)

Higgs couplings ∝ particle masses:

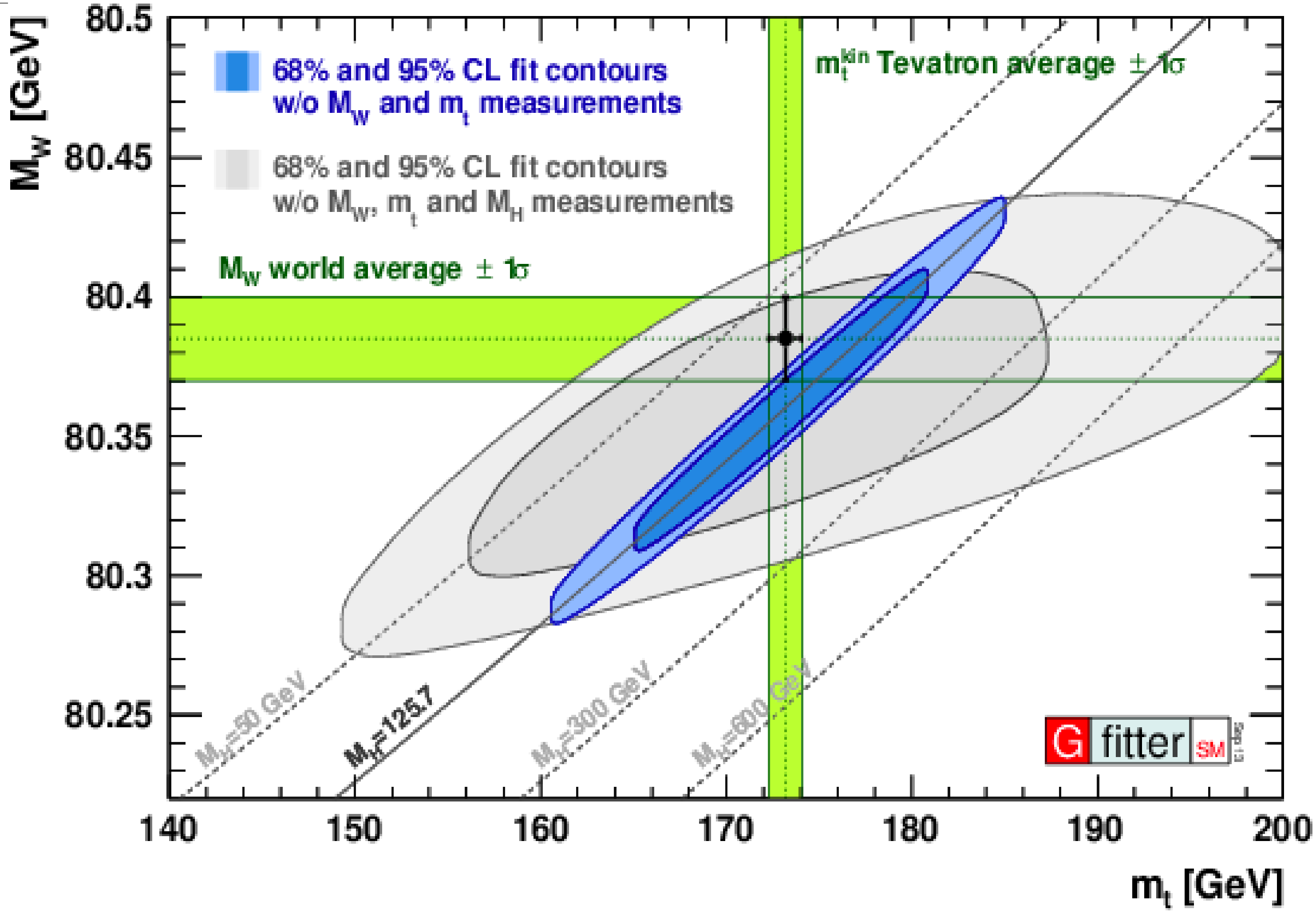
$g_{HVV} = 2m_V^2/v \quad g_{Hff} = m_f/v \quad g_{HHH} = 3m_H^2/v$

masses and self couplings from v

m_H (or λ) - the last unknown parameter of the SM



Compatibility with SM



SM-like Higgs discovery at ~125.7 GeV is compatible with global EWK data at 1.3 sigma. Global p-value of all data is 18%