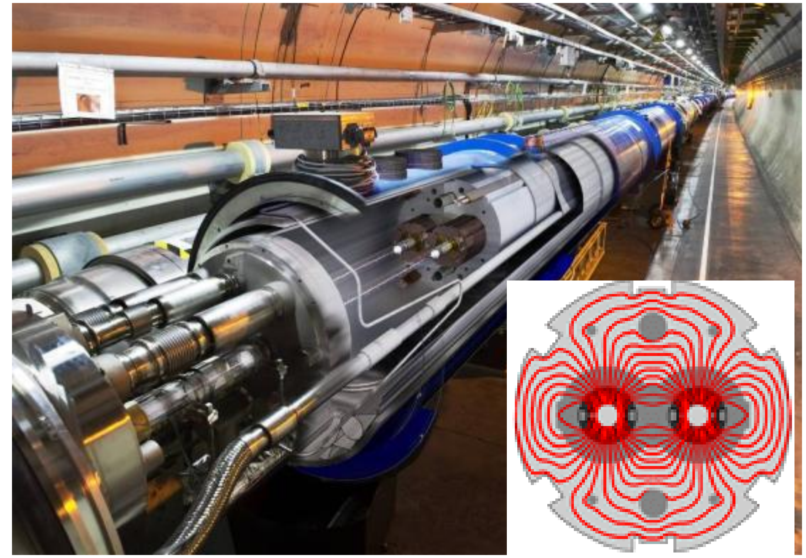
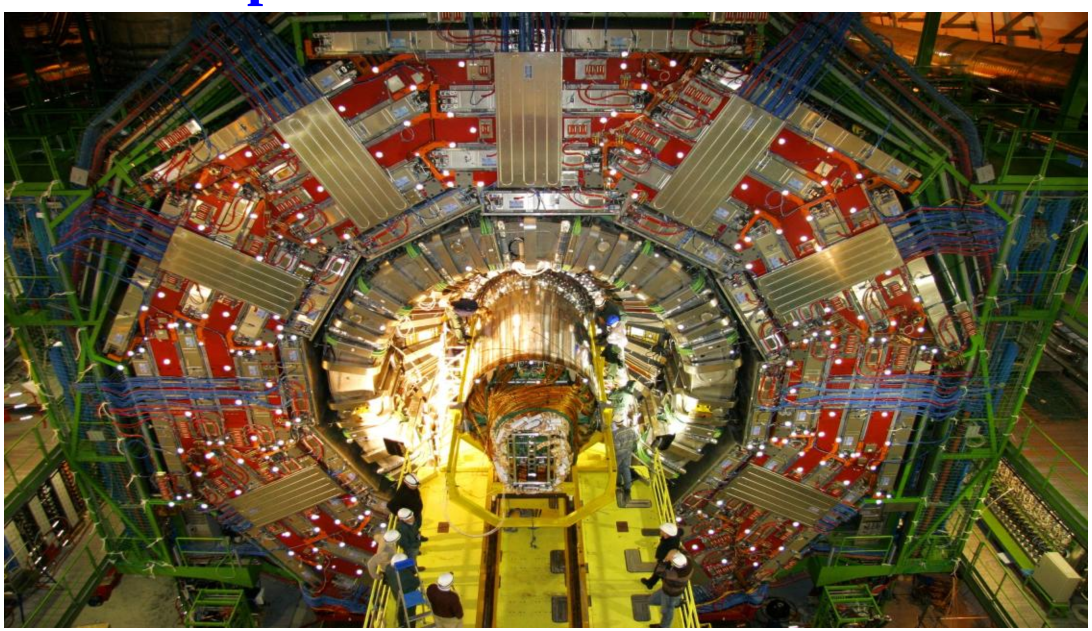
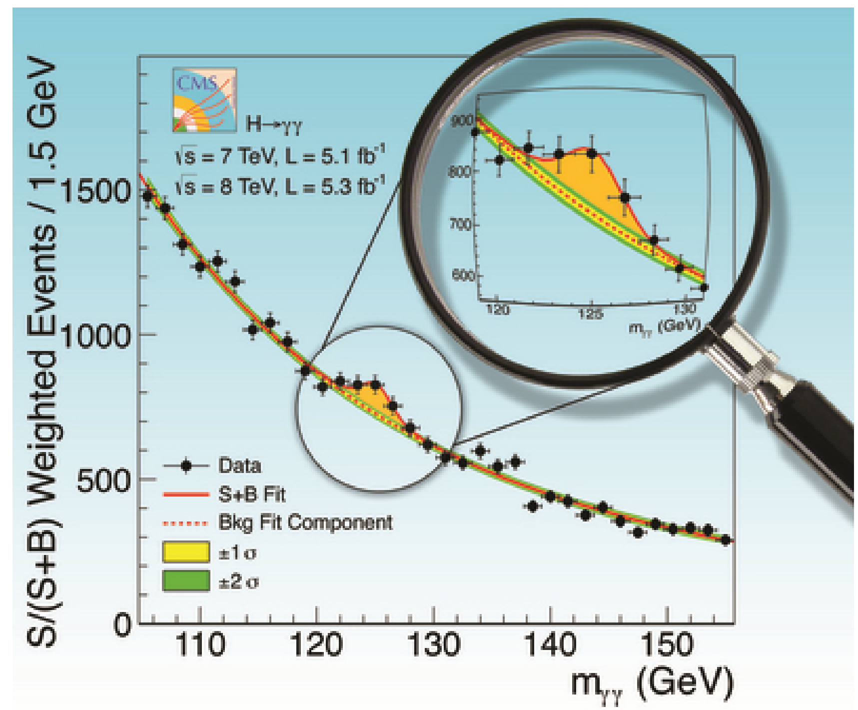
Experimental aspect of Higgs search

Gobinda Majumder, TIFR

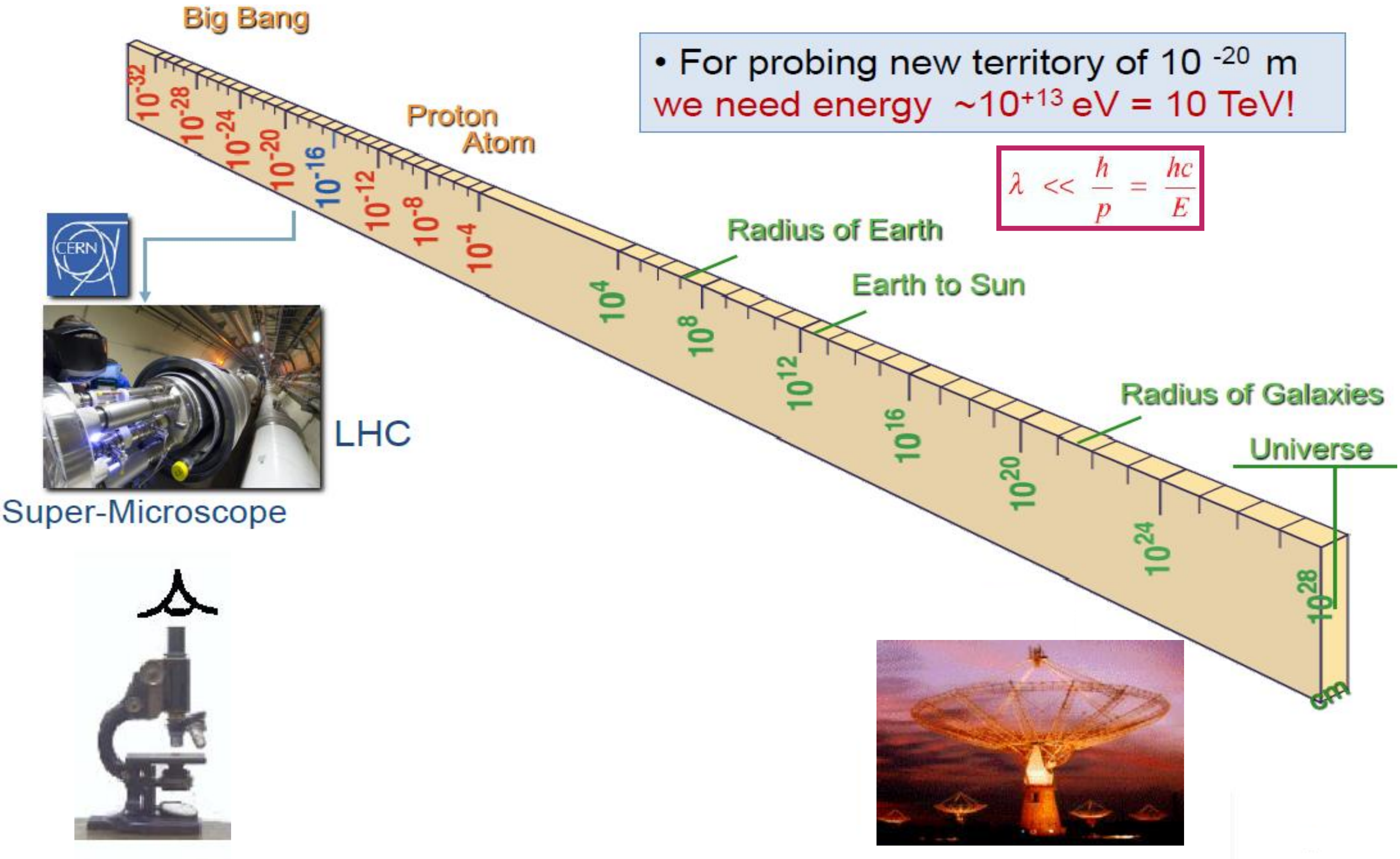


- **Introduction**
- **Development of accelerator**
- **CMS detector**
- **Higgs production and decay at LHC**
- **Expectation with the CMS detector**
- **CMS Search results**
- **Interpretation of observed distributions**





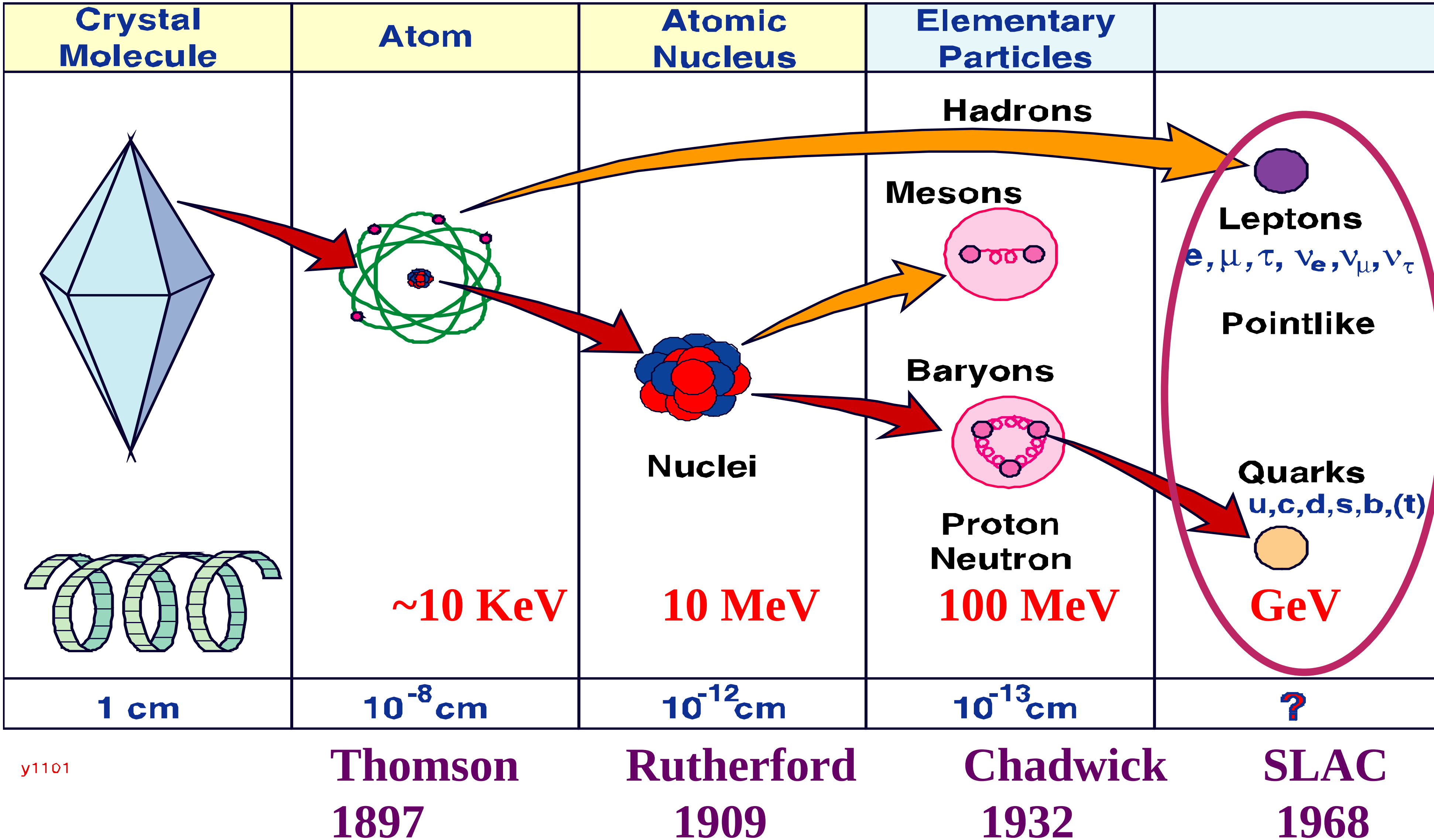
Scale of universe and LHC probe



- For probing new territory of 10^{-20} m we need energy $\sim 10^{+13}$ eV = 10 TeV!

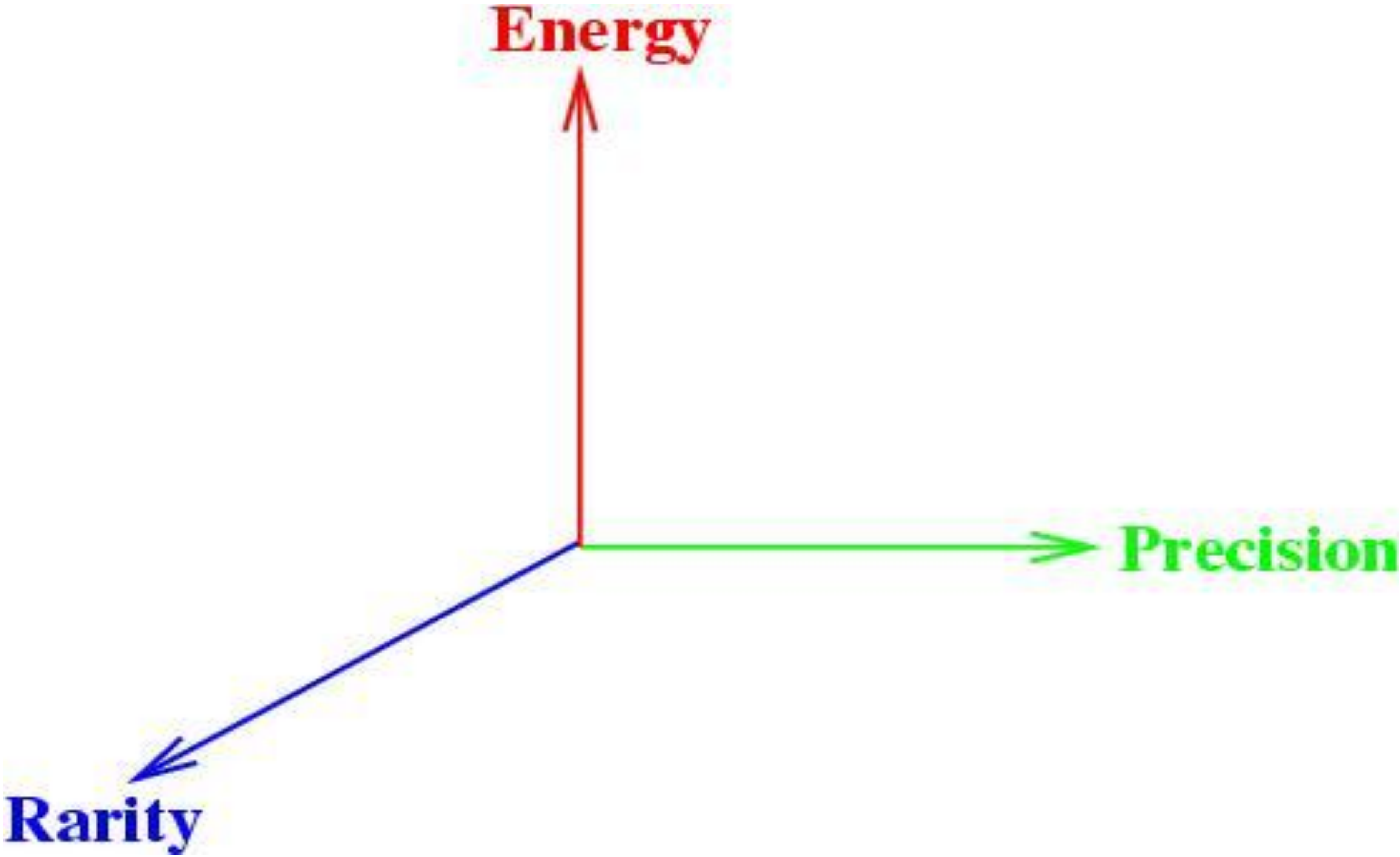
$$\lambda \ll \frac{h}{p} = \frac{hc}{E}$$

Constituent of matter



Probe smaller distance with higher energy ➔ Newer structure

Improvement of knowledge in particle physics



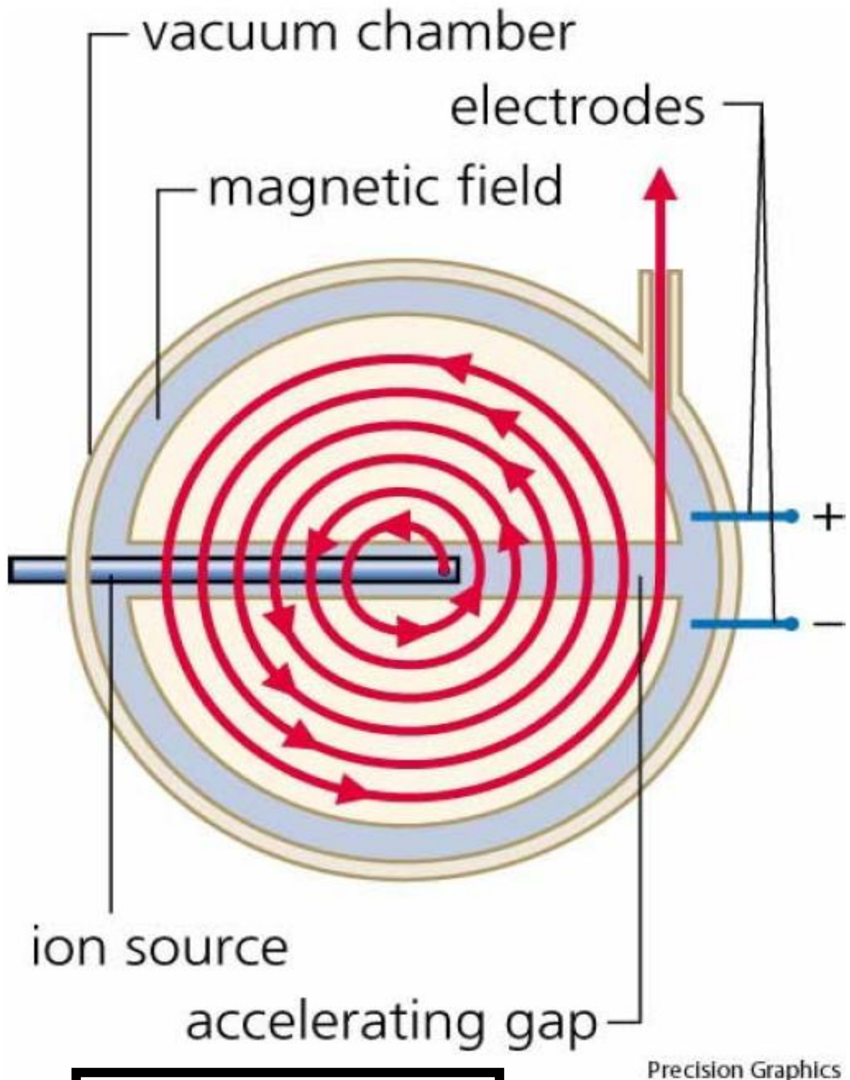
Energy Frontier/Principle of accelerator

We know only how to accelerate charged particles in a controlled way

→ Lorentz Force :

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

History of accelerators



$$q(\vec{v}\times\vec{B}) = mv^2/r$$
$$P_T = 0.3Br$$

Nobel, 1939, "for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements"

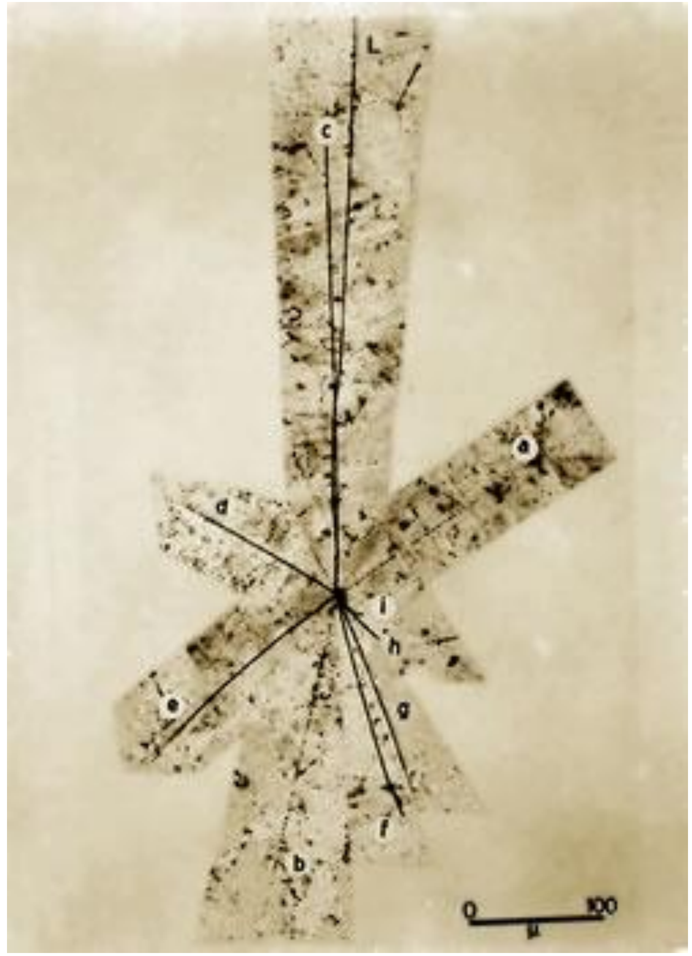
First Cyclotron built by E.O. Lawrence and his student M.S. Livingston

Diameter ~ 4.5" , E_p ~ 80 keV

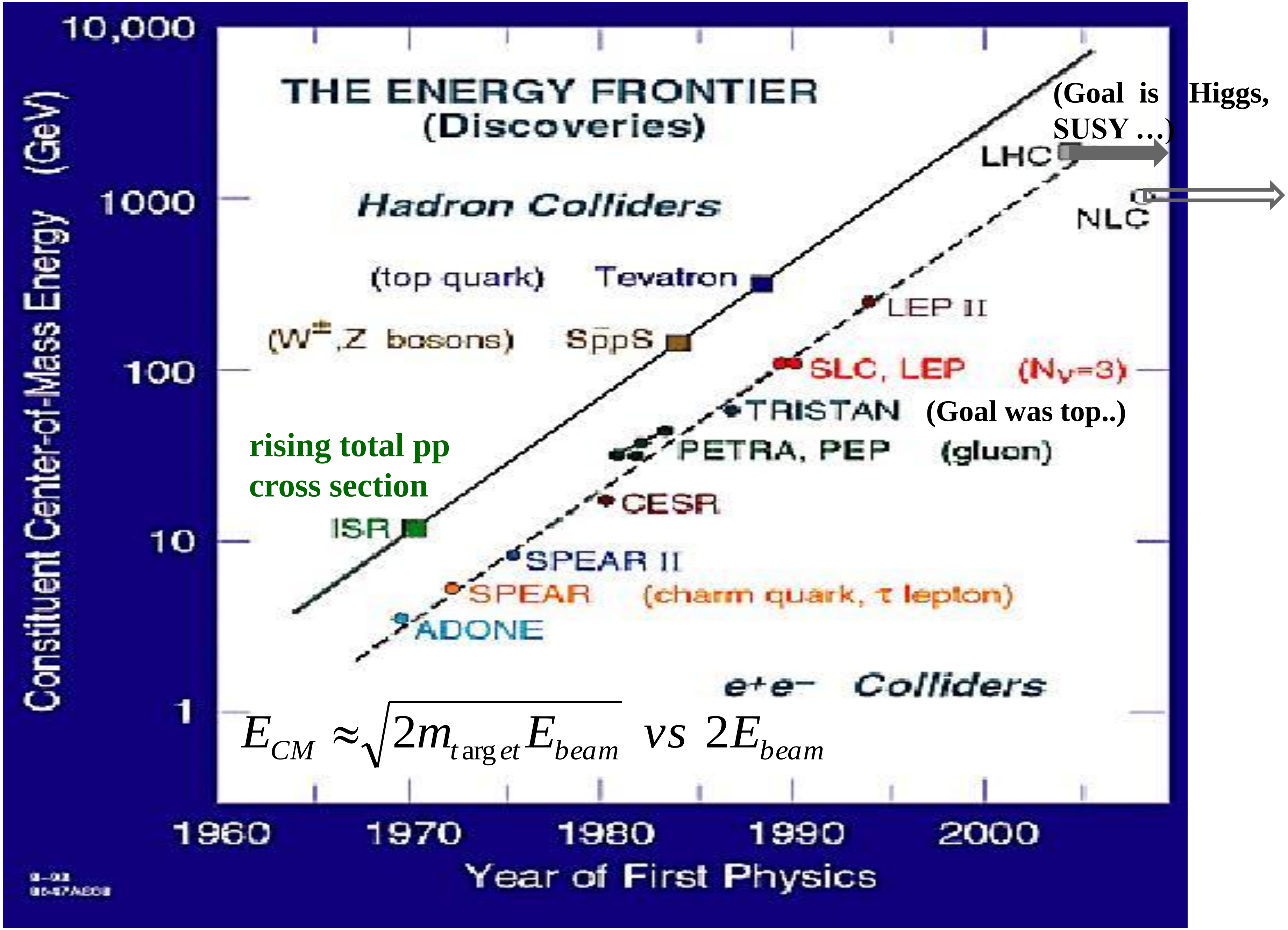
Discovery of antiproton

- **Dirac equation in 1928 and the discovery of Positron in 1932 predicted also an antiproton.**
- **But, to generate antiproton (conservation of baryon number, 1.19 GeV/c antiproton in spectrometer), need an accelerator, which can give about 6.5 GeV proton.**
- **1955 : Segre & Chamberlin used bevatron of 6.5GeV proton at LBNL : Used momentum and velocity (scintillator and Cherenkov) detector.**

One in 44000 particles produced in the interaction is antiproton



Emulsion chamber : 430 μm antiproton track, annihilate with proton and produce nine charge particle (pion)

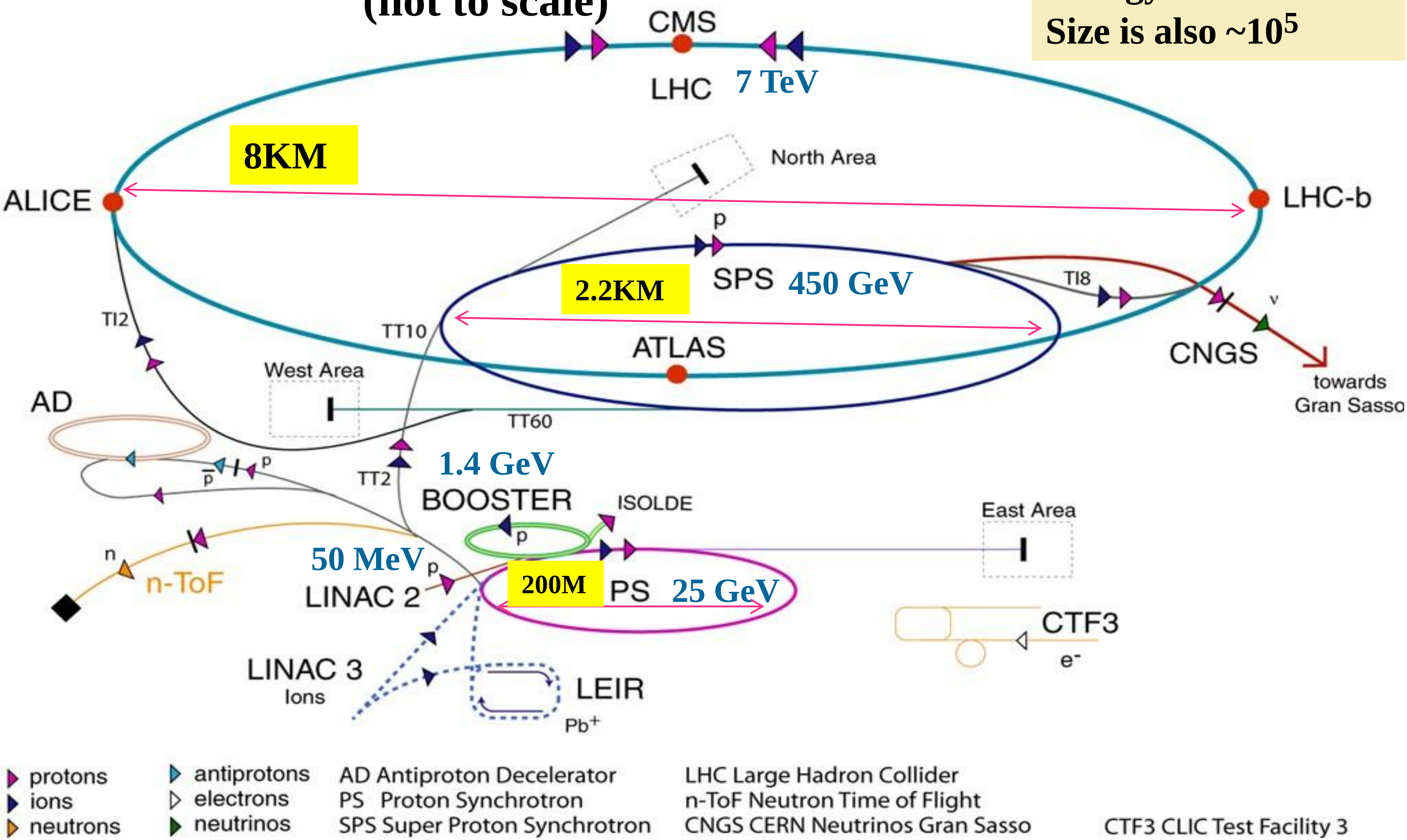


Initially increase of energy by ~10 fold in every ~12 year

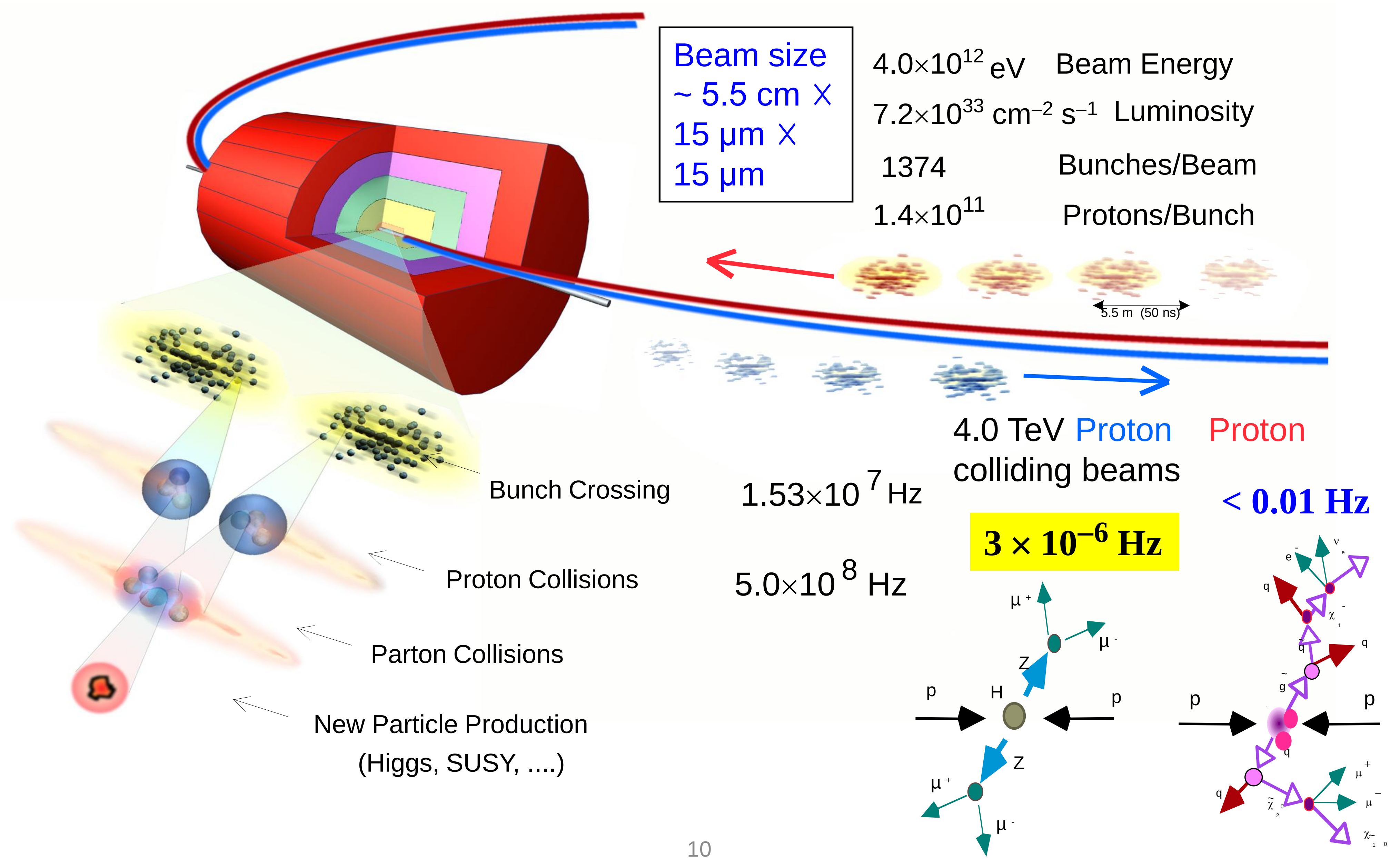
LHC Accelerator Layout

(not to scale)

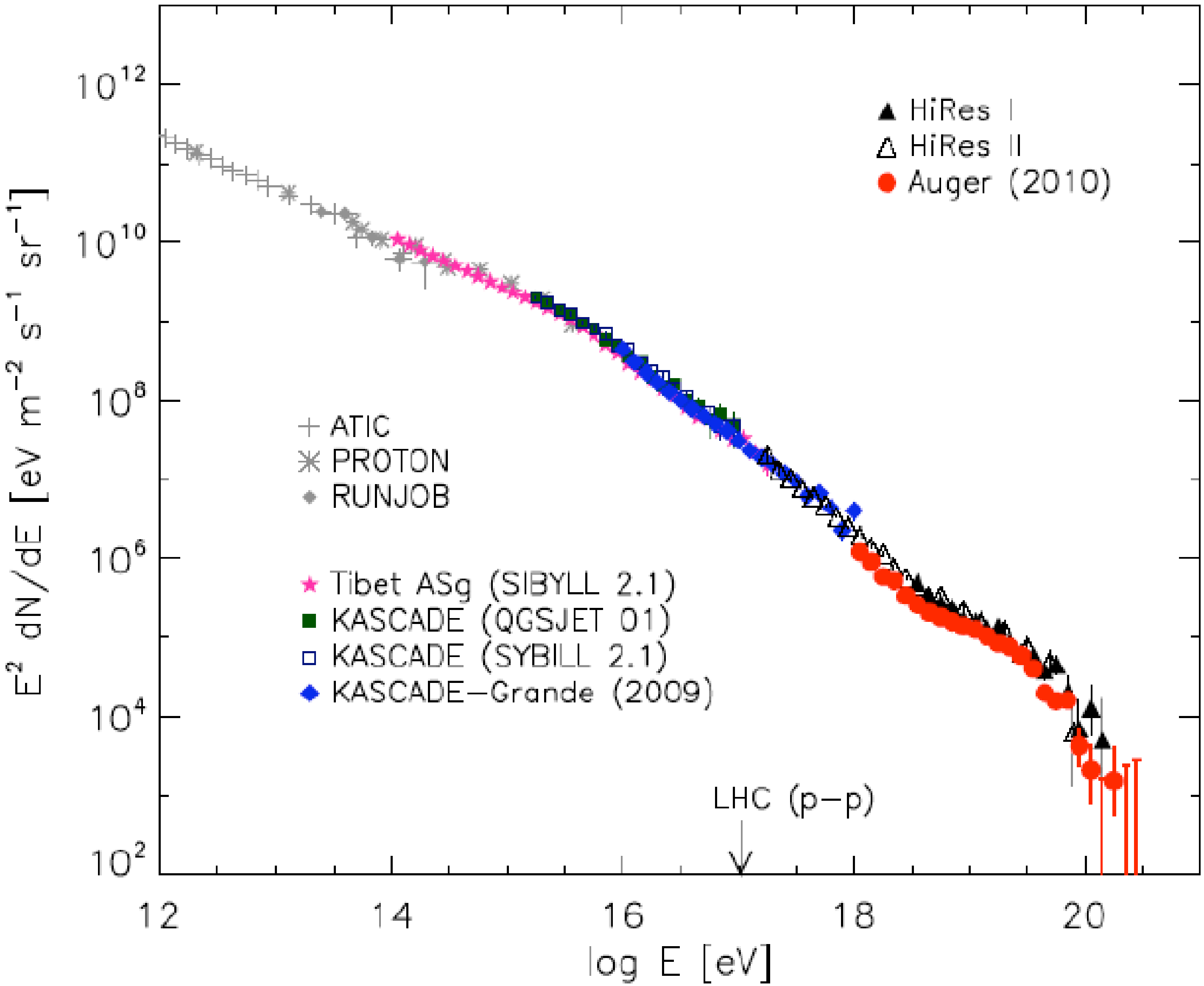
1939 → 2009
Energy ~10^5 times
Size is also ~10^5



Collisions at the Large Hadron Collider



Cosmic ray vs collider



for E_{beam}>>m_p

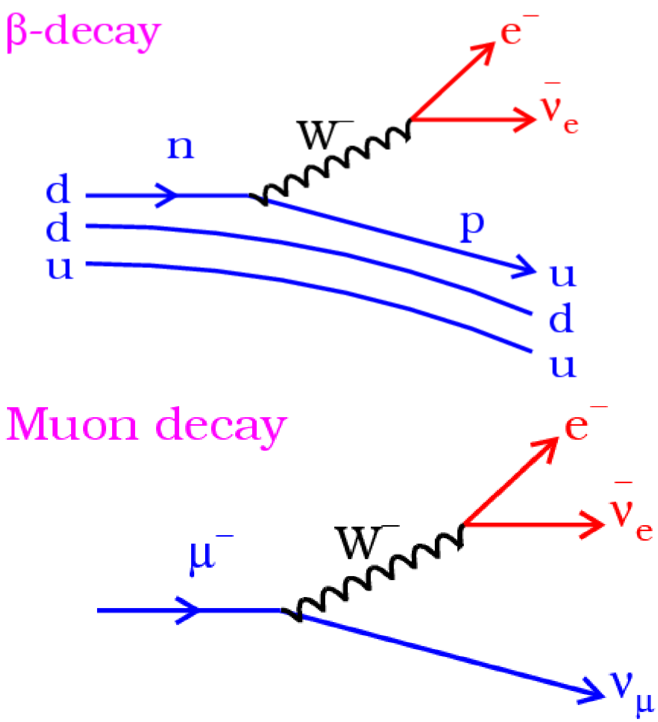
$$E_{CM} \approx \sqrt{2m_p E_{beam}}$$

Expect only 1000 events/year/km^2 with √S>14 TeV,

whereas in LHC, ~10^9 event/sec

Identification of collision processes and products

•Heavy particles are decay to low mass particles and only lighter particles are stable, which can be observed with instrument (detector) and reconstruct to identify collision processes

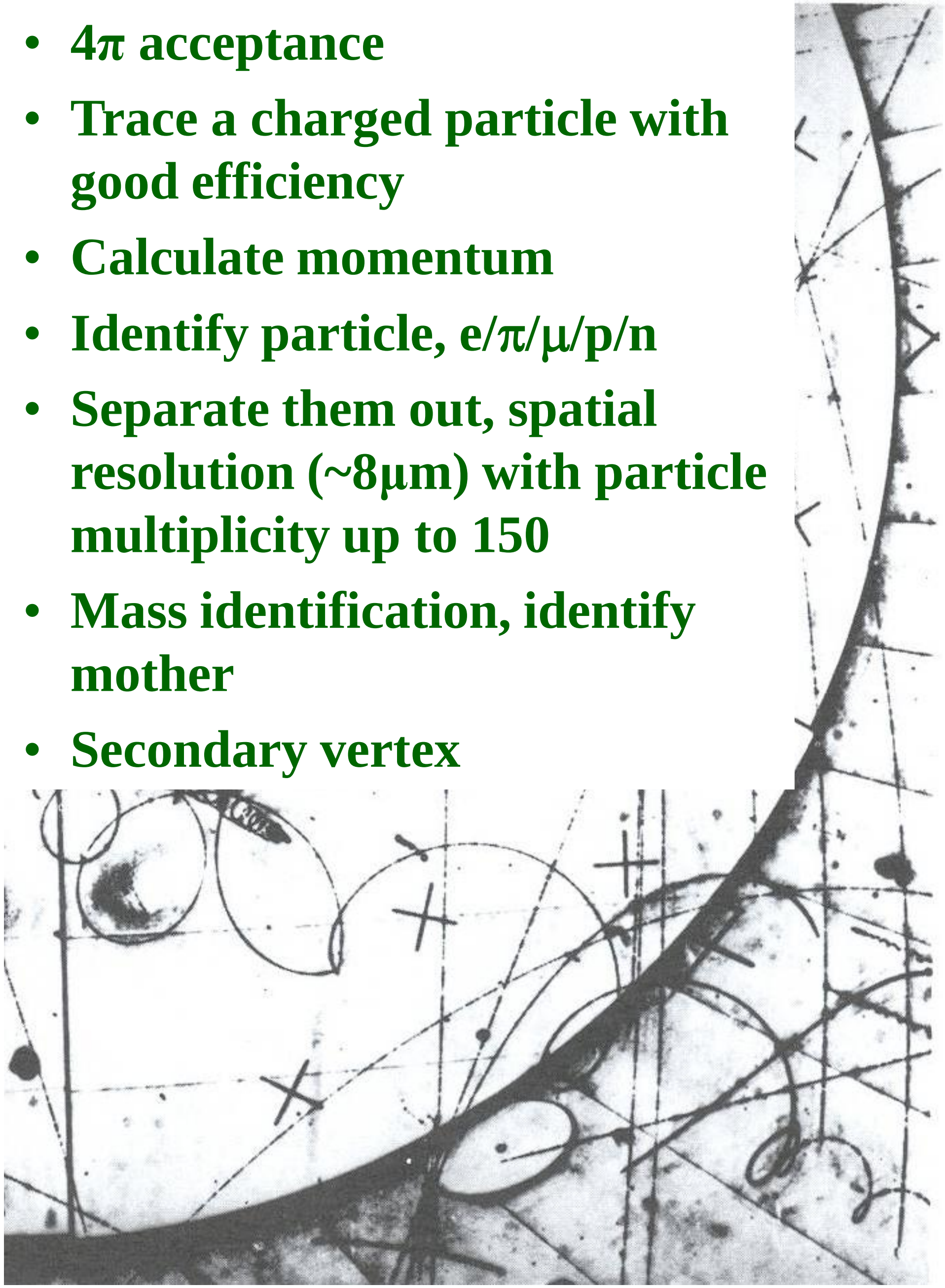


Particle	Mass	Lifetime
Proton	~1 GeV	$>10^{31} – 10^{33}$ year
^{60}Co		5.27 year
Neutron	~1 GeV	15 minute
Muon	106 MeV	2.2×10^{-6} sec
Σ^-	1197 MeV	1.5×10^{-10} sec
D0	1864 MeV	4.1×10^{-13} sec
$D^{*\pm}$	2010 MeV	7.0×10^{-21} sec
W/Z	80/91 GeV	$\sim 3 \times 10^{-25}$ sec
Higgs	125 GeV	1.65×10^{-22} sec

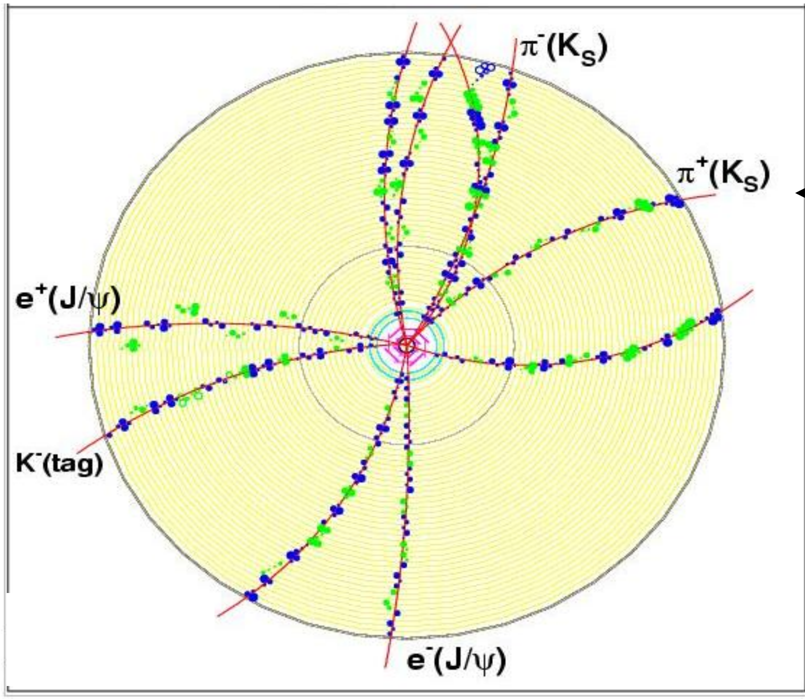
- Physical world is made up with only first generation
- Massive particles are available in laboratory
- As technology improves to go to higher and higher energies in laboratories, more and more massive particles are produced to study their properties

Golden period of particle physics

- 4π acceptance
- Trace a charged particle with good efficiency
- Calculate momentum
- Identify particle, e/π/μ/p/n
- Separate them out, spatial resolution (~8μm) with particle multiplicity up to 150
- Mass identification, identify mother
- Secondary vertex

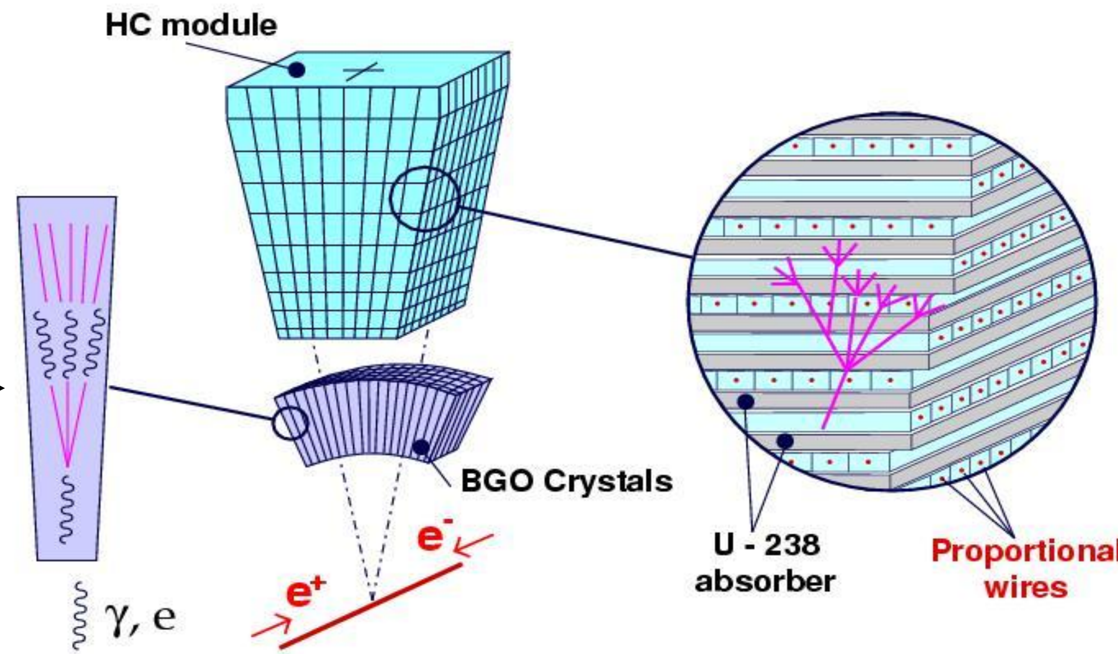


Building block of present day HEP detector



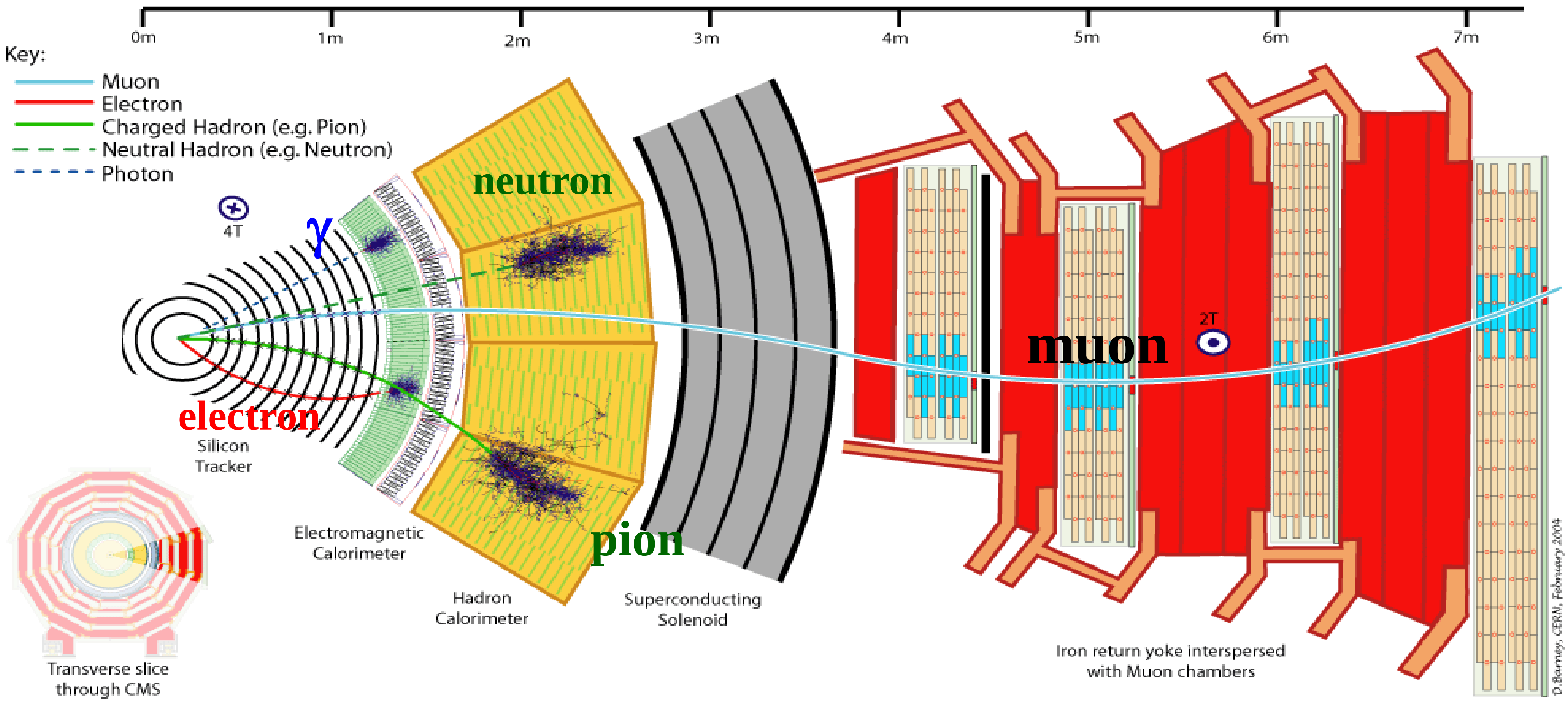
•Bending of charge particle in presence of magnetic field provides the information of momentum of charge particle $\vec{F} = q\ \vec{v} \times \vec{B}$

Calorimeter is mainly used for the measurement of energy of neutral particle

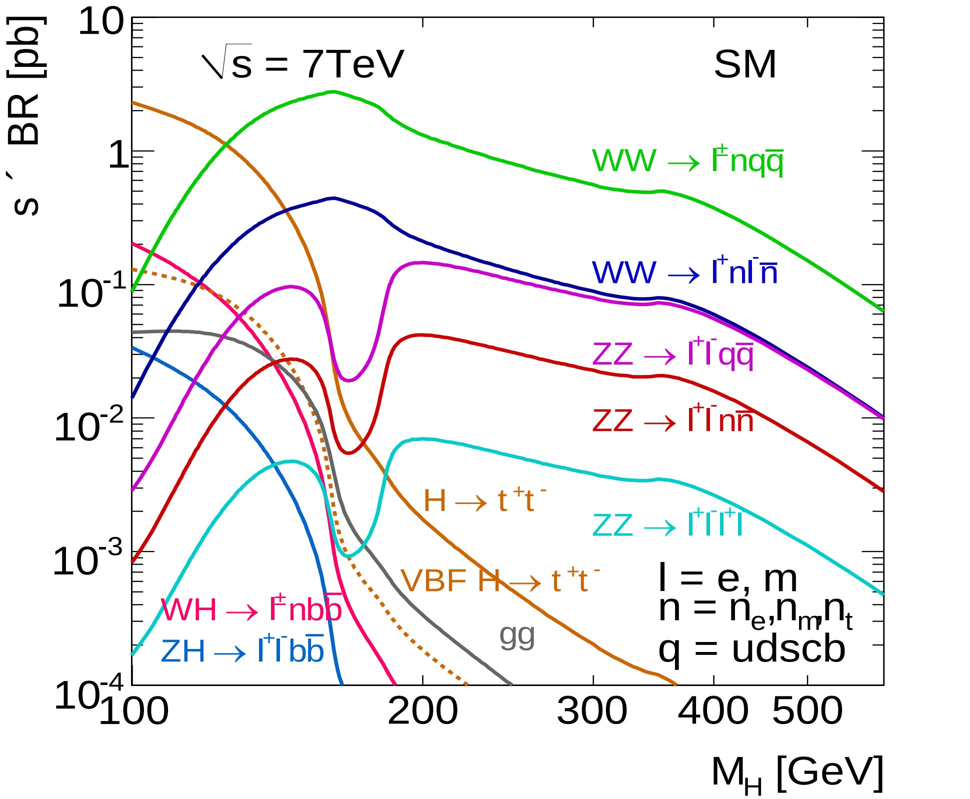


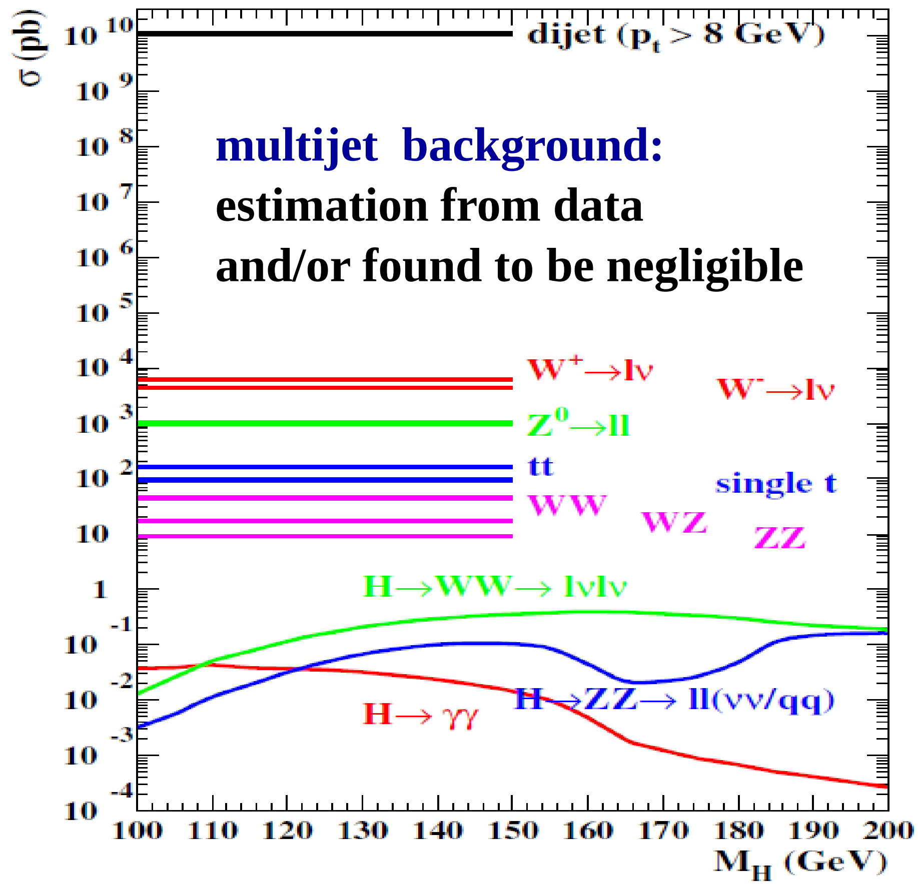
Basic concepts of HEP detector at collider

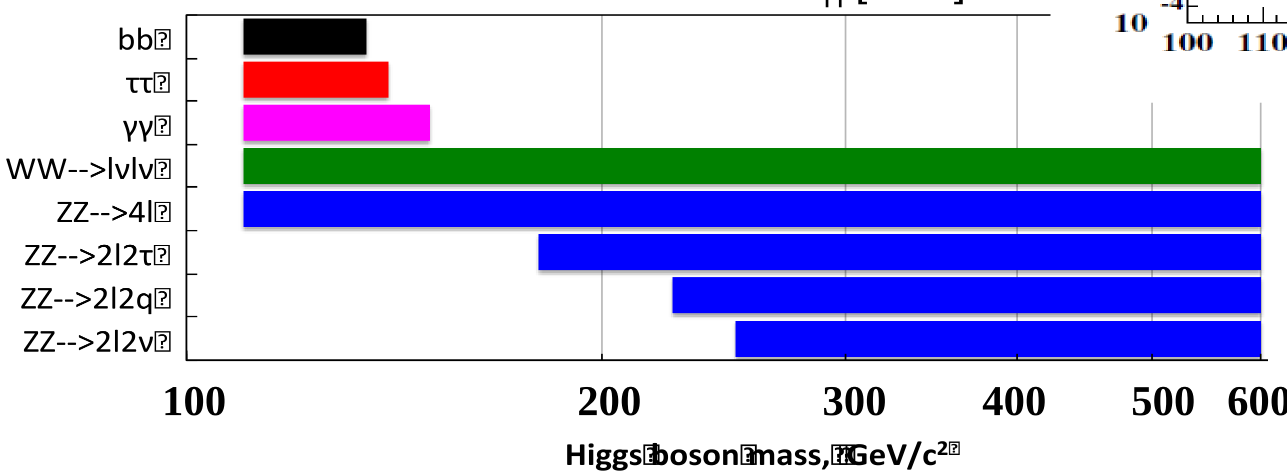
- Stable particles ($\tau \geq 10^{-8}$ sec) : $e^{\pm}$, γ, p, p-bar, $K^{\pm}$, $\pi^{\pm}$, K_L, n, n-bar, $\mu^{\pm}$, ν, ν-bar
- Design detector which can detect all these stable particles
- Layers of subdetectors to detect different particle in different detector layer
- Most interacting particles are detected in the innermost layer and less interacting one in the outermost



The Challenge: Tiny Signal-to-Background Ratio





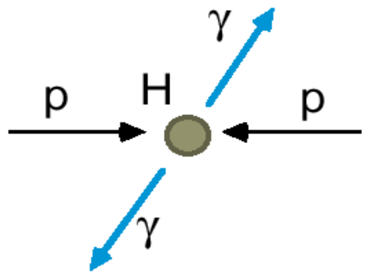


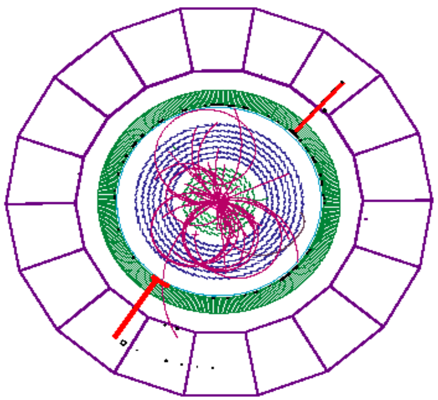
< 1 detectable Higgs boson per 10^{12} collisions

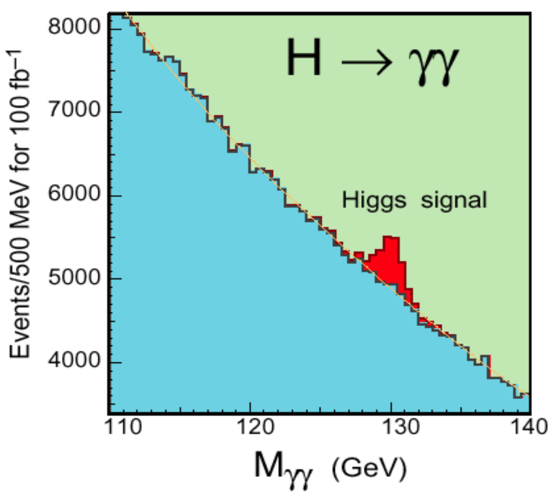
ggF, VBF, WH, ZH and t.tH production : 88%, 7%, 3%, 2% and 0.5%,

Higgs signal (will not see these figures any more)

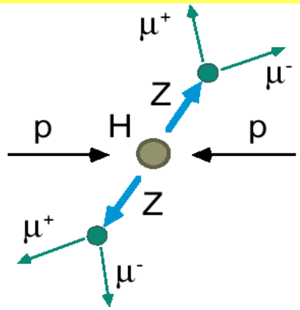
Low M_H < 140 GeV/c^2

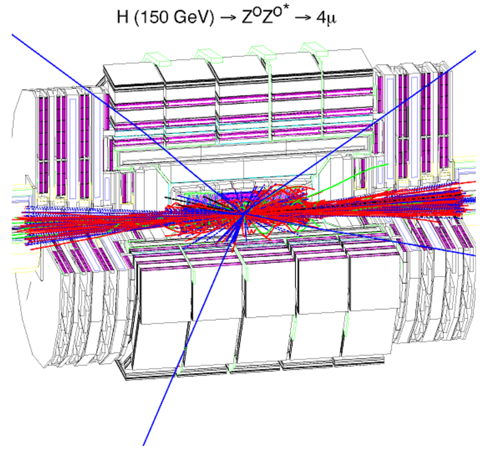


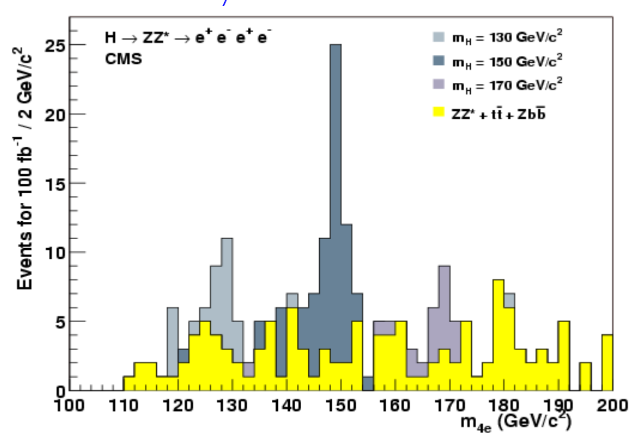




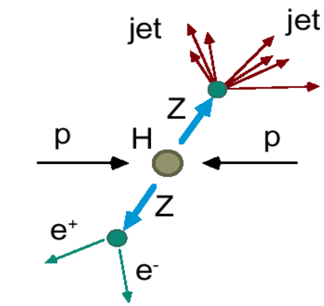
Medium 110<M_H<500 GeV/c^2

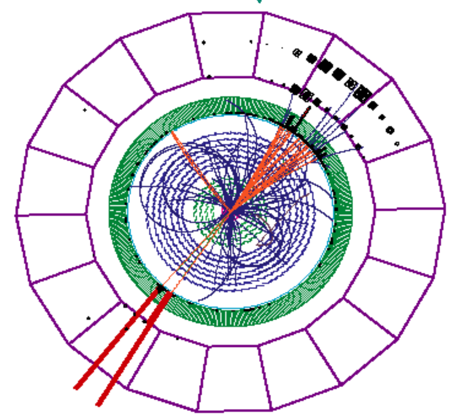


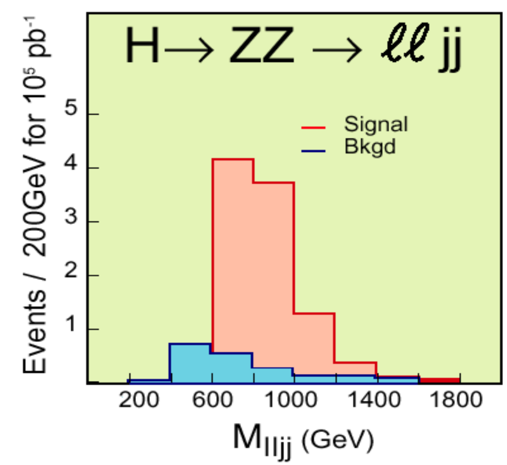




High M_H > ~300 GeV/c^2







The CMS Collaboration

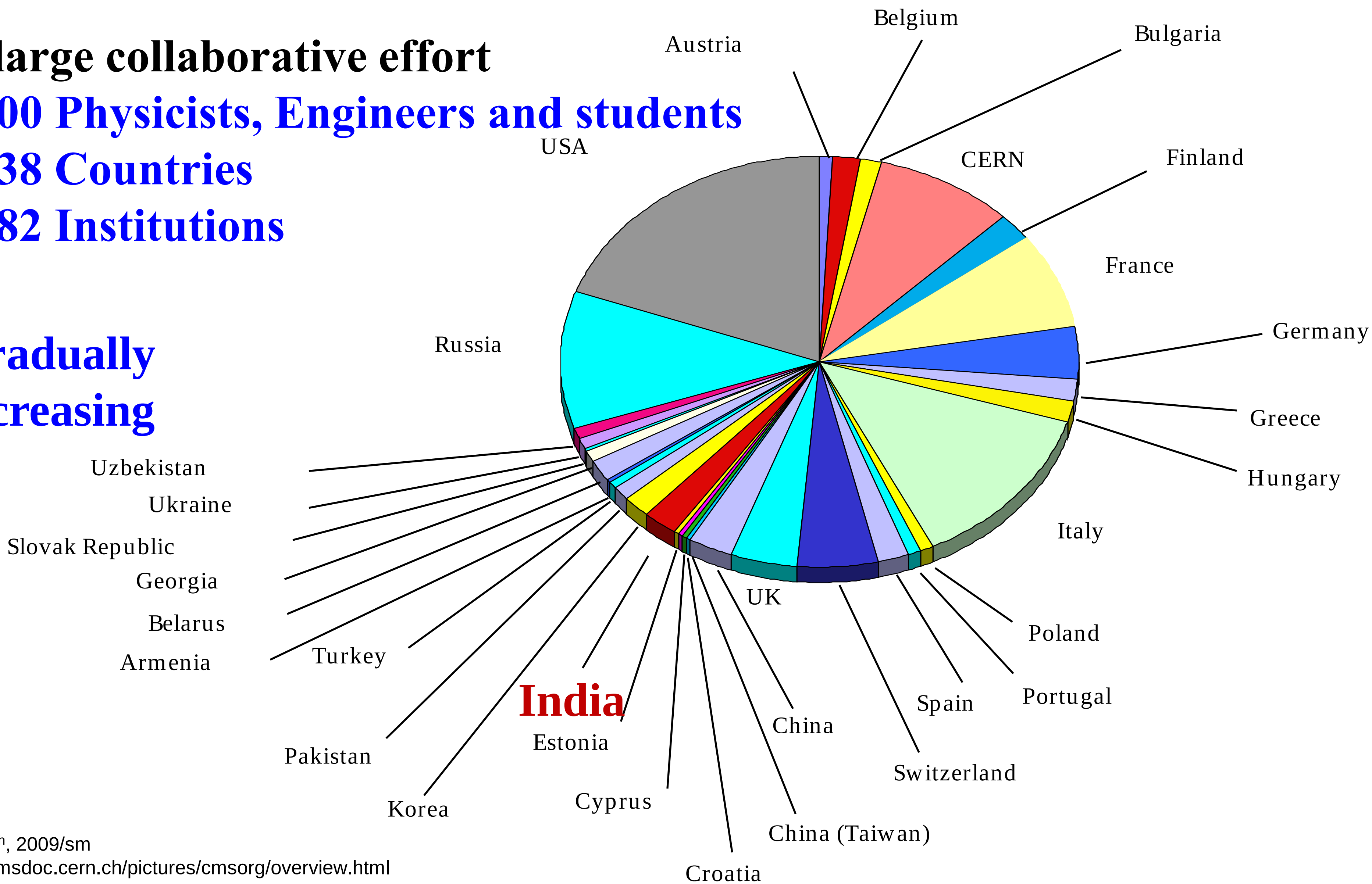
A large collaborative effort

3600 Physicists, Engineers and students

38 Countries

182 Institutions

Gradually increasing



Jan 29th, 2009/sm
http://cmsdoc.cern.ch/pictures/cmsorg/overview.html

Concept of a CMS detector during 1992

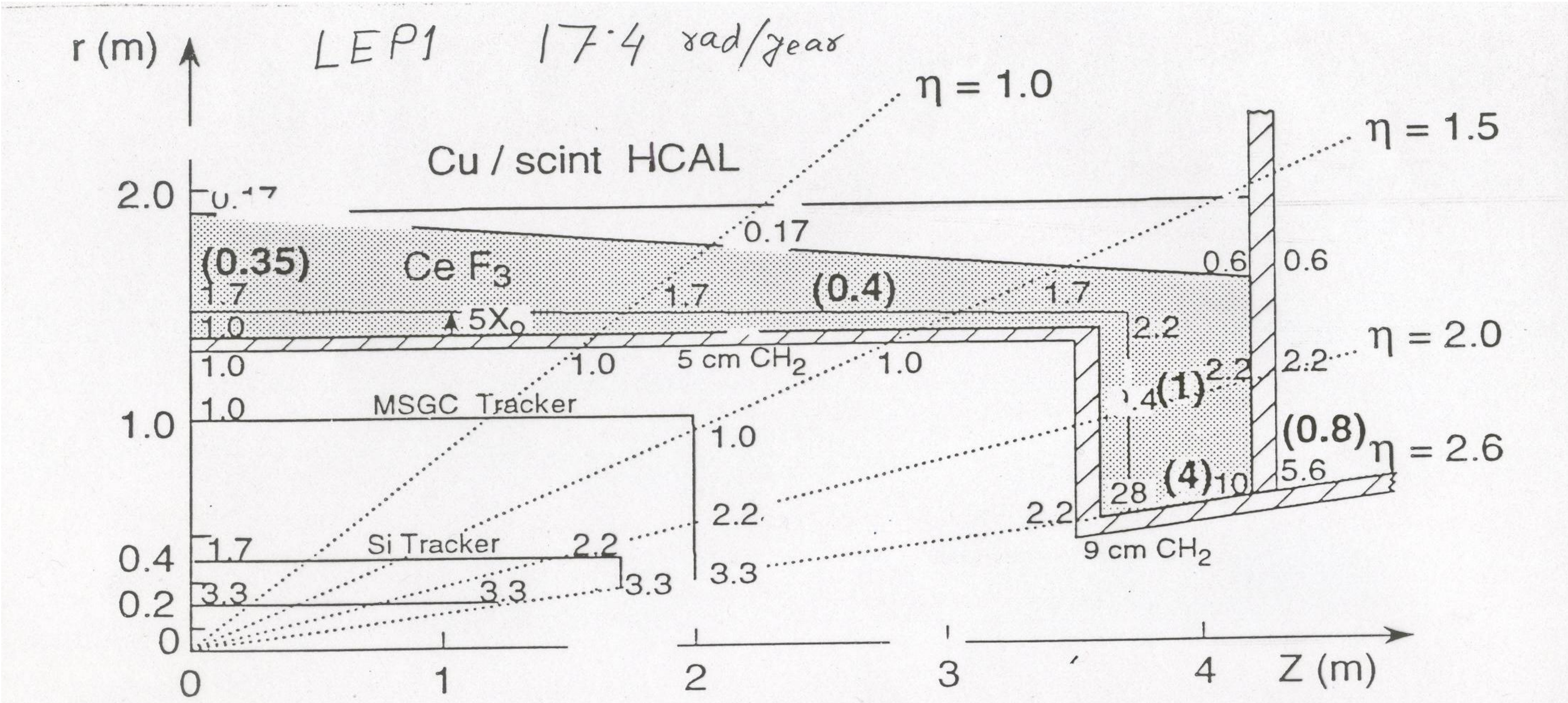


Fig. 1.4 : Neutron fluence and dose in CMS. The numbers in the figure are the fluence in units of 10^{13} n/cm^2. Numbers in bold are the dose in Mrads. These numbers are given for an integrated luminosity of L = 10^{42} cm^{-2}, corresponding to 10 years of running at design luminosity .

LHC
0·04 rad/s

γ-source
~56 rad/s

1·17 &
1·32 MeV } Co^{60}

CeF_3 ECAL instead of $PbWO_4$

MSGC tracker in place of Silicon strip

India and the CMS collaboration

- **Concepts of LHC and CMS came in mid 80s**
- **LHC approved in 1993**
- **In the same year TIFR/DU joins in the CMS experiment**
- **Initial activities at TIFR**
  - **Radiation hardness study of fast scintillator material**
  - **Simulation study for electromagnetic (EM) calorimeter detector design, granularity, material etc**
  - **Study of shashlik EM calorimeter**
  - **Optimisation of tracker detector material/geometry**
  - **……………………..**
- **Designing, building, commissioning, monitoring of the Outer Hadron Calorimeter and Silicon preshower for the CMS experiment (1996 --)**

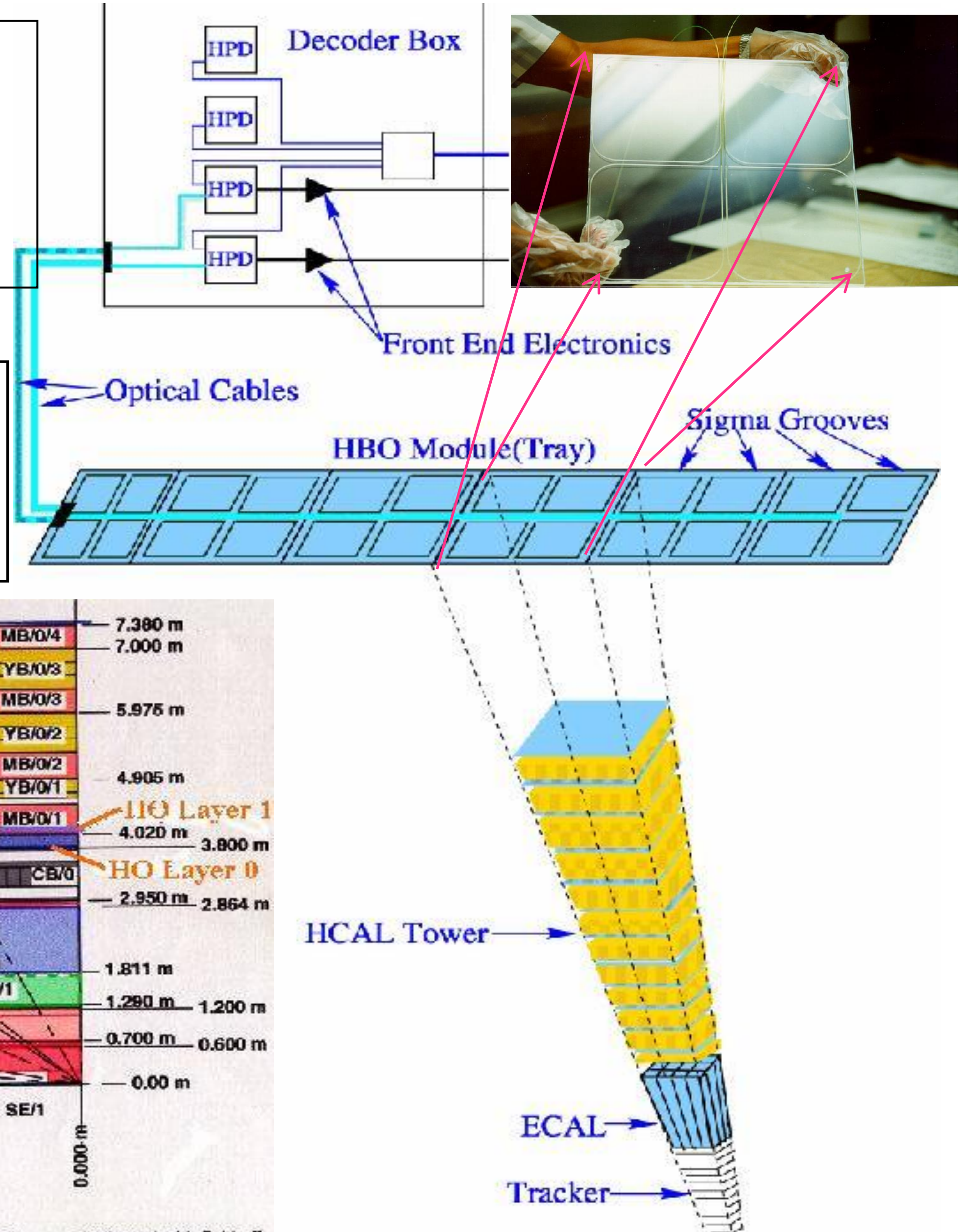
Study of physics potential in design phase and analysing data for physics publication along with the development of software, monitoring of detector performance, calibration ….

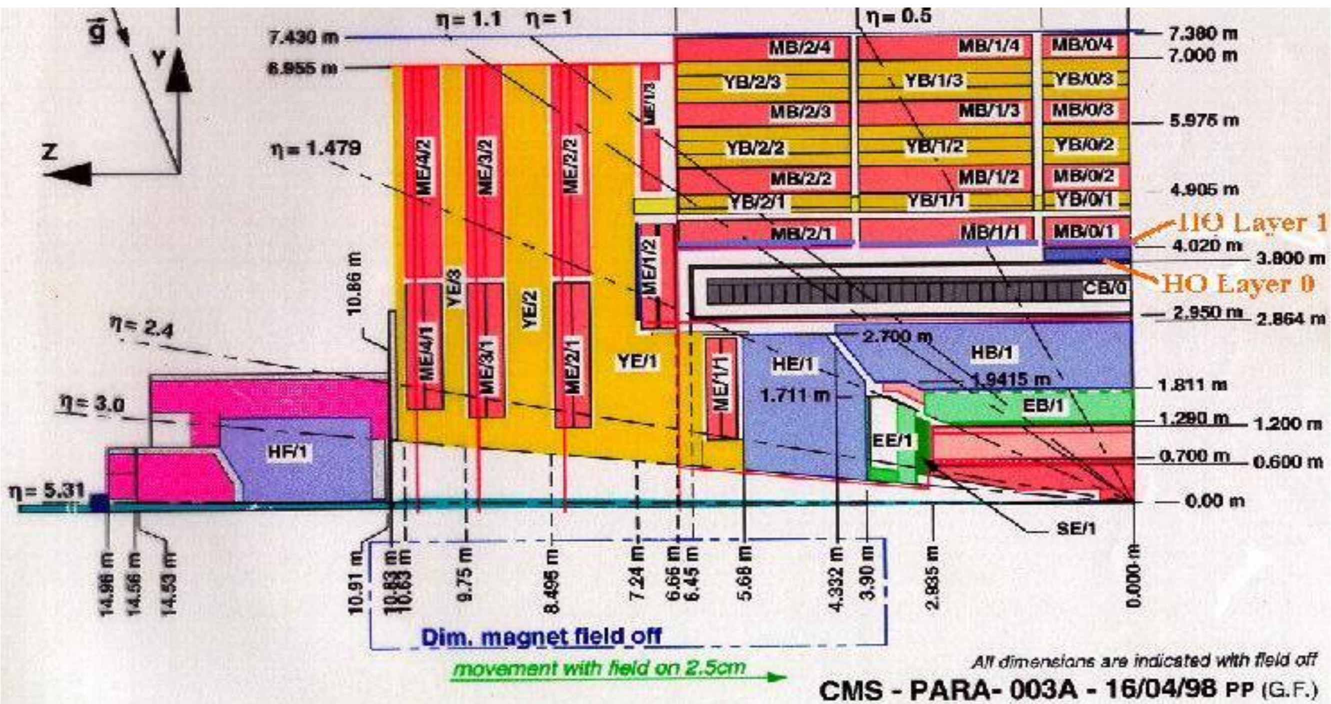
Indian contributions toward CMS detector

- TIFR, together with Panjab University constructed the outer hadron calorimeter
- HO covers central rapidity region |η|<1.3 occupied by the five muon rings to improve jet and MET resolution

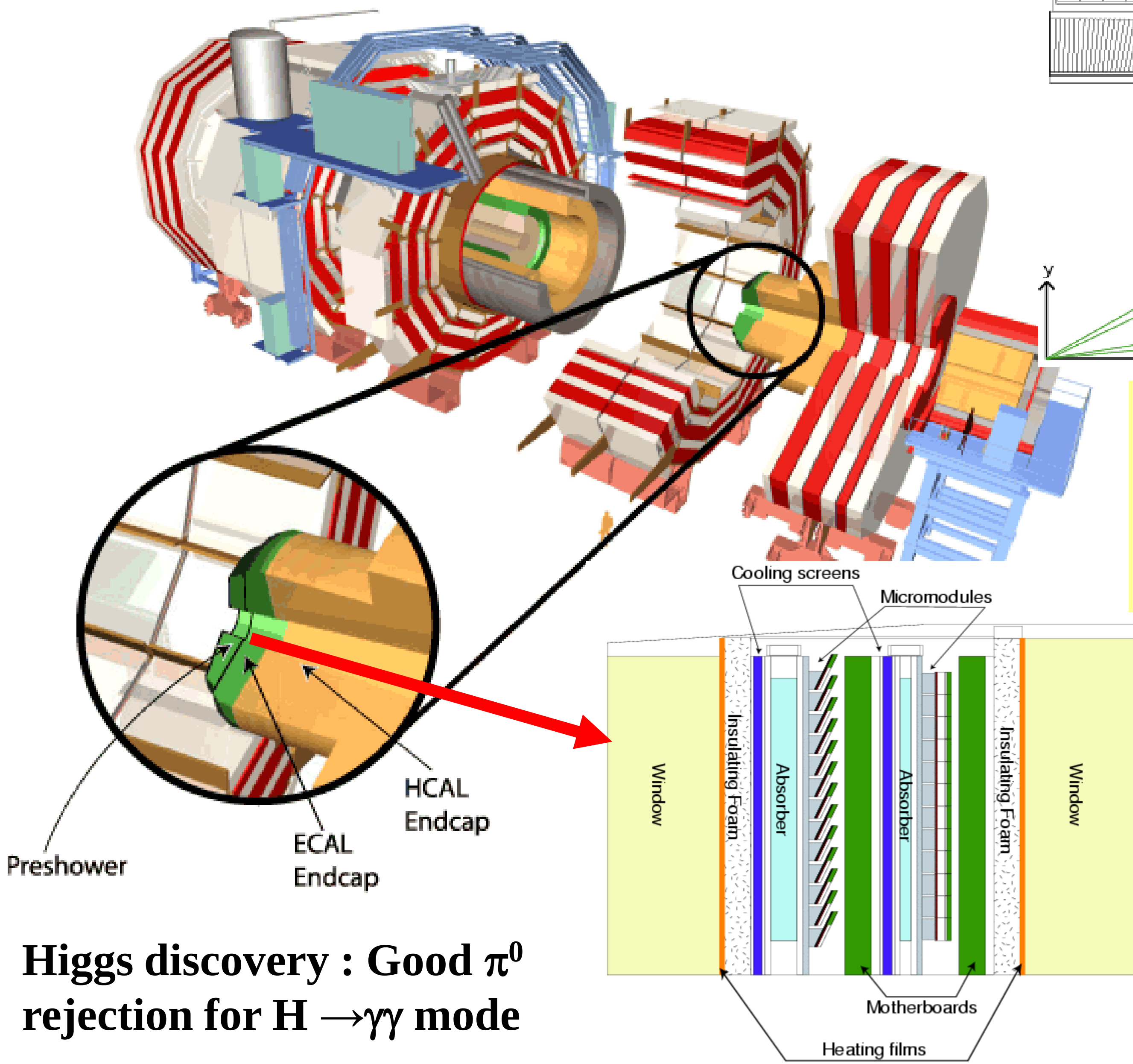
Pseudorapidity, $\eta = -\log_e(\tan(\theta/2))$

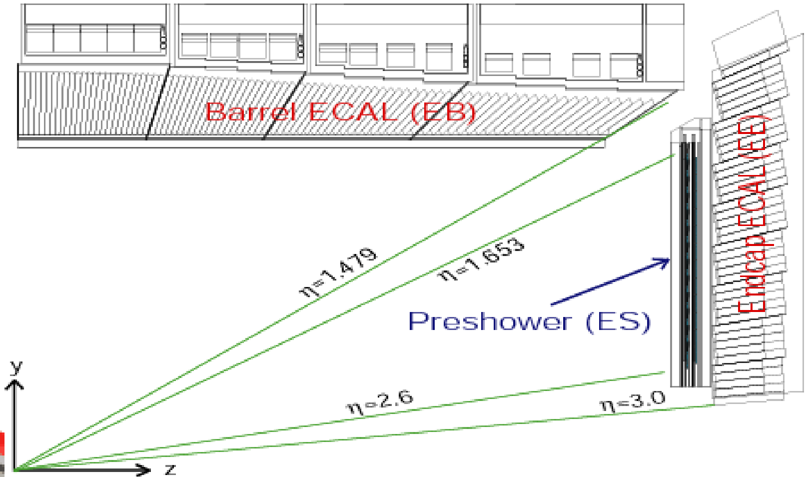
- Basic detector element maps tower granularity of 0.0873 × 0.0873 in η × Φ
- 432 trays are build from 2730 tiles





CMS Preshower Detector





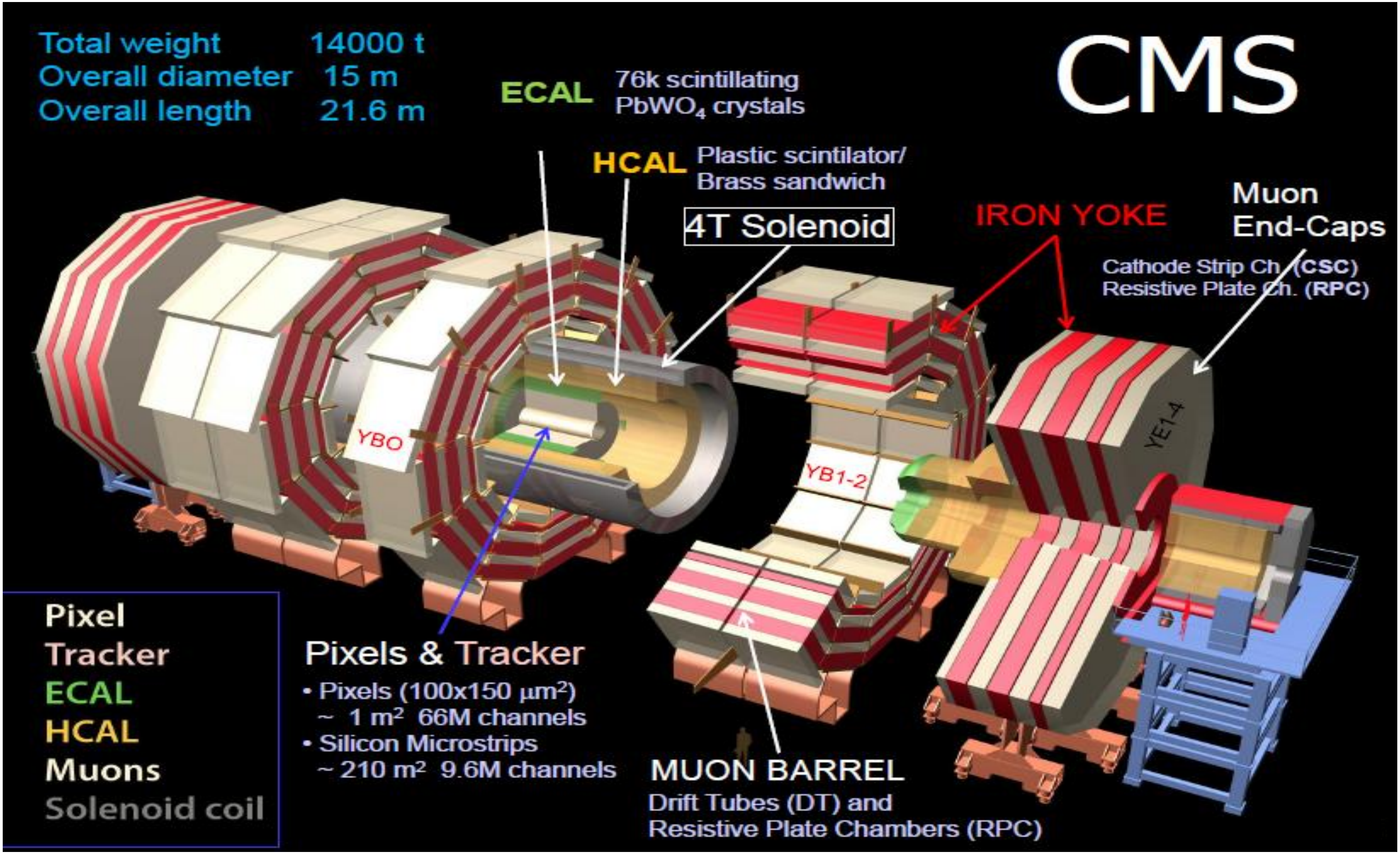
End caps of CMS detector have 4300 silicon strip detectors covering area of about 17 m^2

Under India-CMS collaboration, India has delivered more than 1000 detector modules for the CMS preshower

Higgs discovery : Good π^0 rejection for H $\rightarrow\gamma\gamma$ mode

First Silicon Strip Detector made in India

The CMS Detector



~77 million electronic channels readout in every 25ns

Mass resolution @ 125 GeV

Channel	CMS	ATLAS
γγ	3.72 (FWHM) 4.21 (FWHM)	4.15 4.15
ZZ→*llll*	1.6 (4μ) 2.1 (2μ2e) 2.7 (4e)	1.7 (4μ) 1.7/2.2 (2e2μ/2μ2e) 2.3(4e)
WW→*lνlν*	20%	
ττ	20%	13-20%
bb	8-9%	13%

The LHC Machine and Experiments

Luminosity

First phase

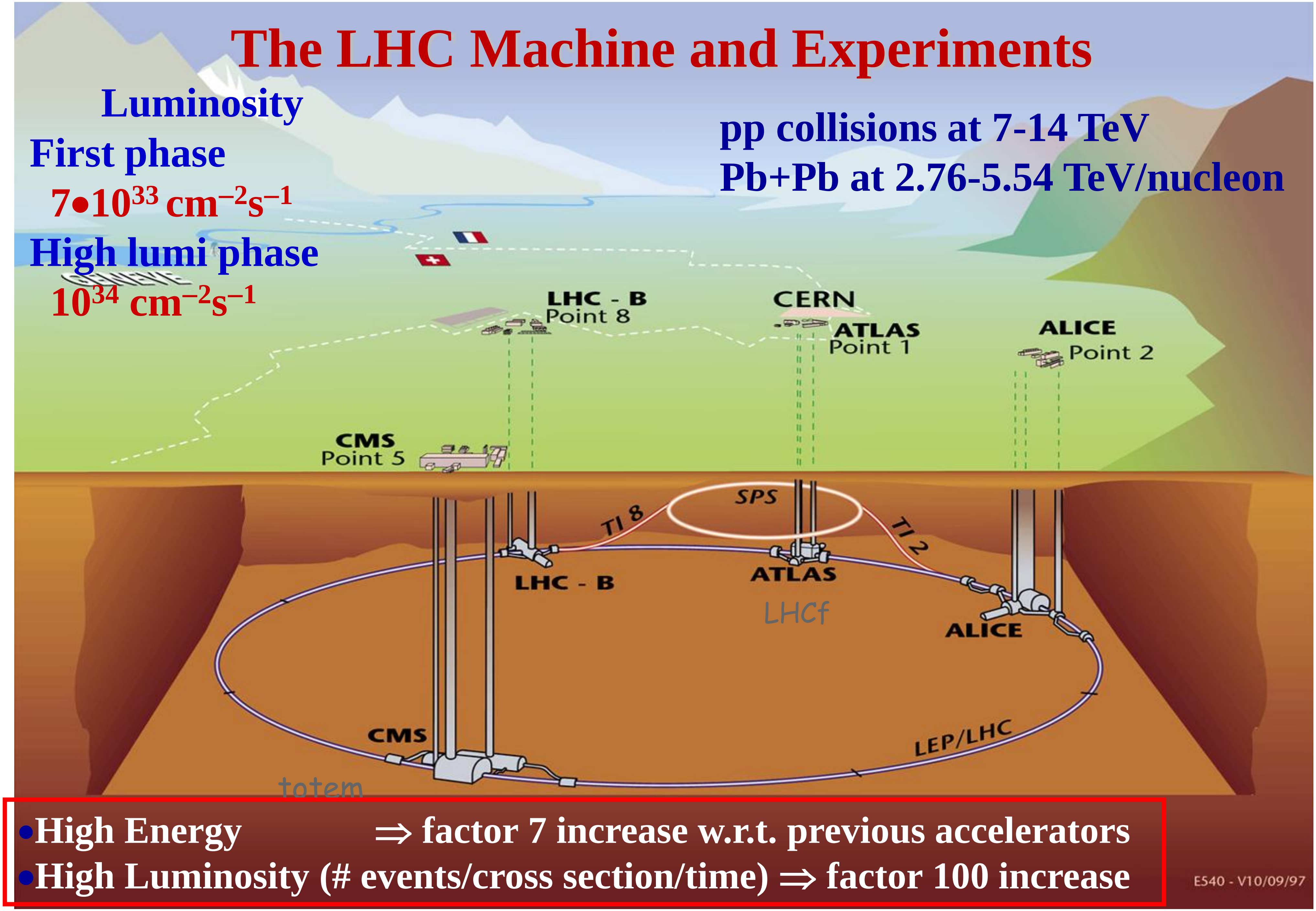
$7 \bullet 10^{33}$ $cm^{-2}s^{-1}$

High lumi phase

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

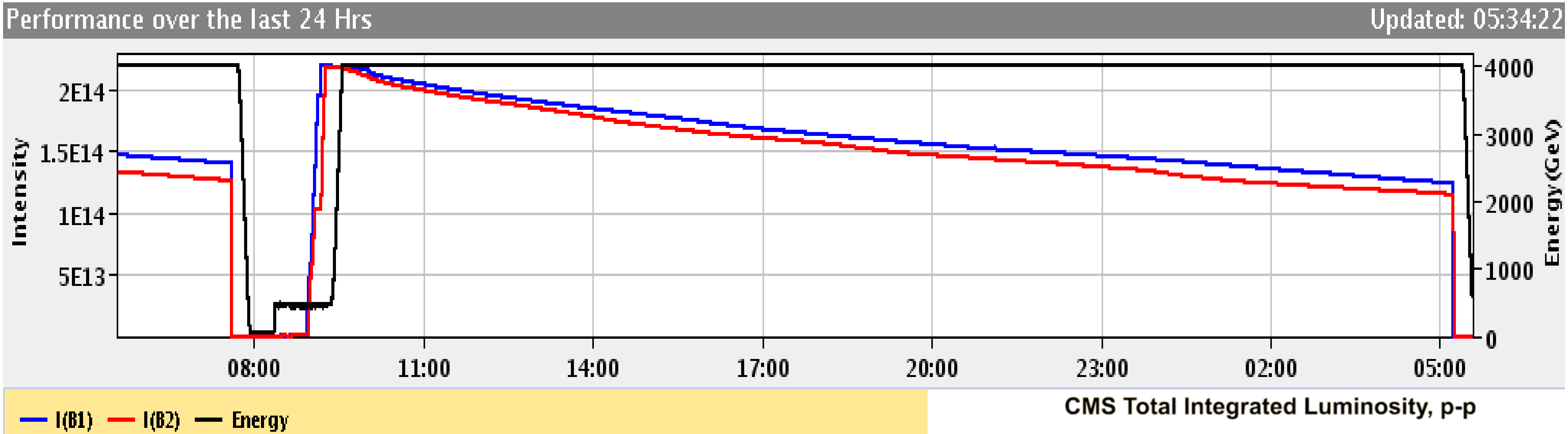
pp collisions at 7-14 TeV

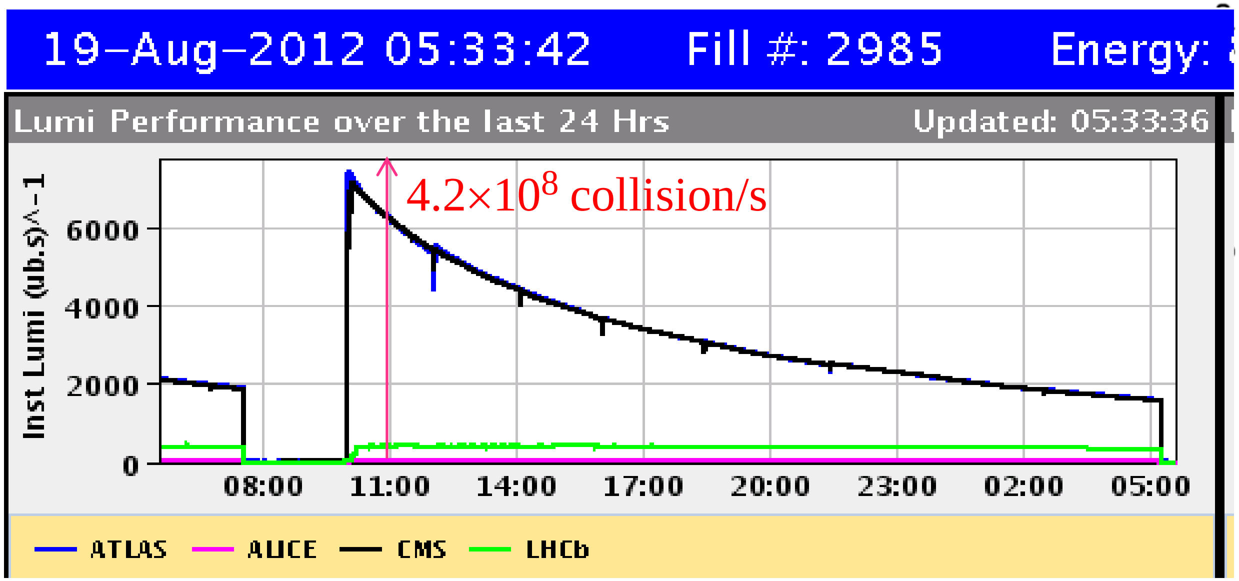
Pb+Pb at 2.76-5.54 TeV/nucleon

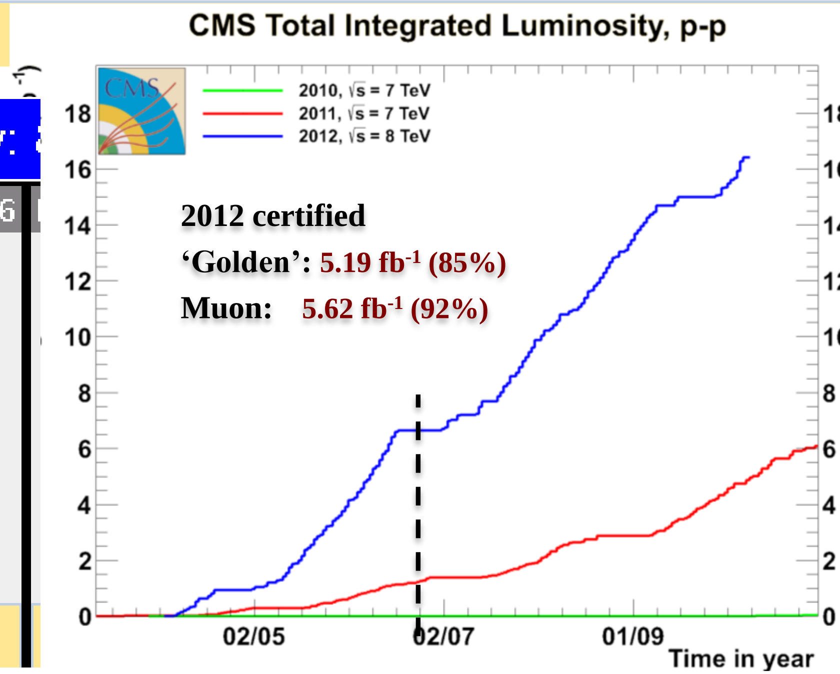


- **High Energy** ⇒ factor 7 increase w.r.t. previous accelerators
- **High Luminosity (# events/cross section/time) ⇒ factor 100 increase**

LHC performance: 2010-2011-2012



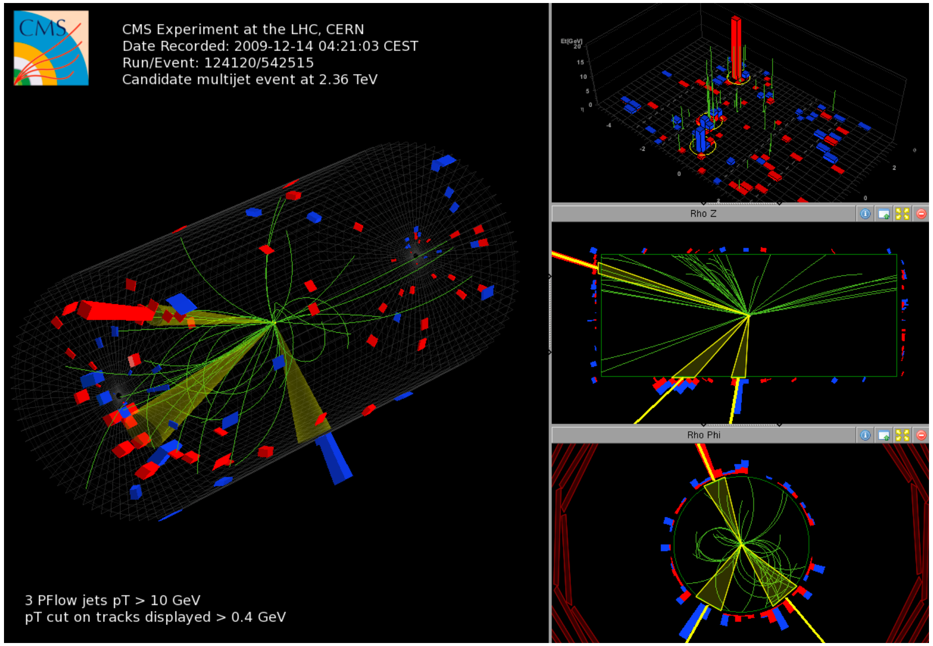


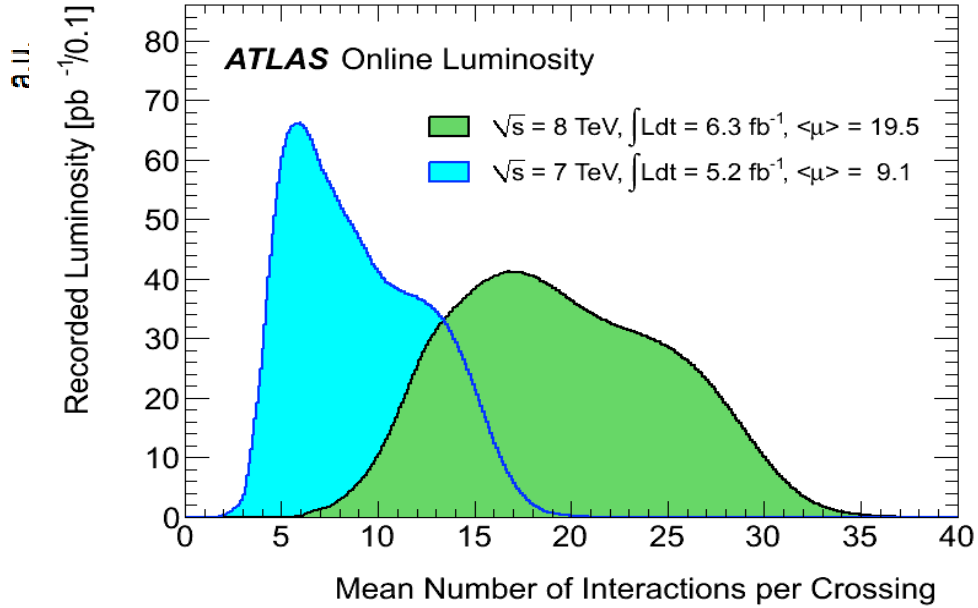


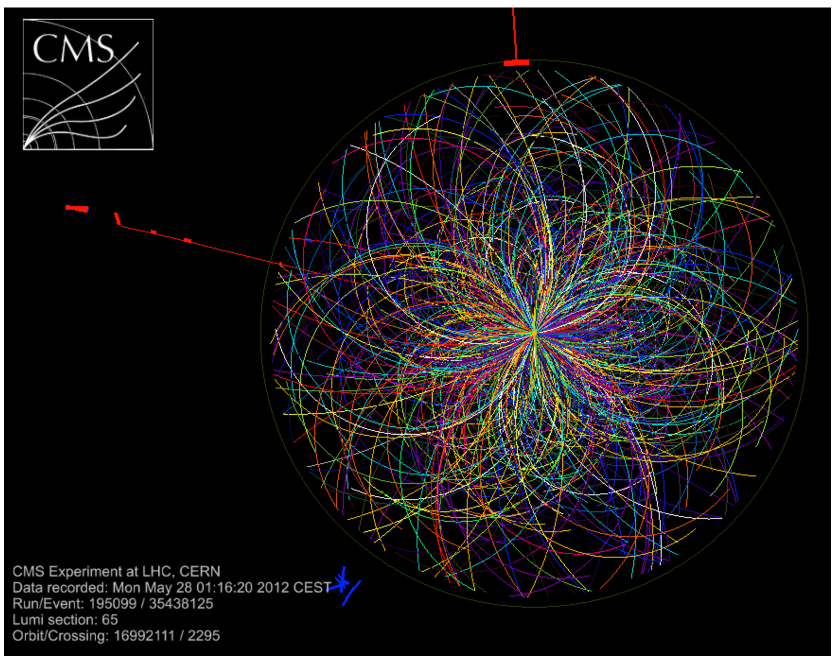
Maintains a constant luminosity @P8(LHCb) throughout the run

Total # of proton-proton collision : ~16×10^{14} (used ~7×10^{14})

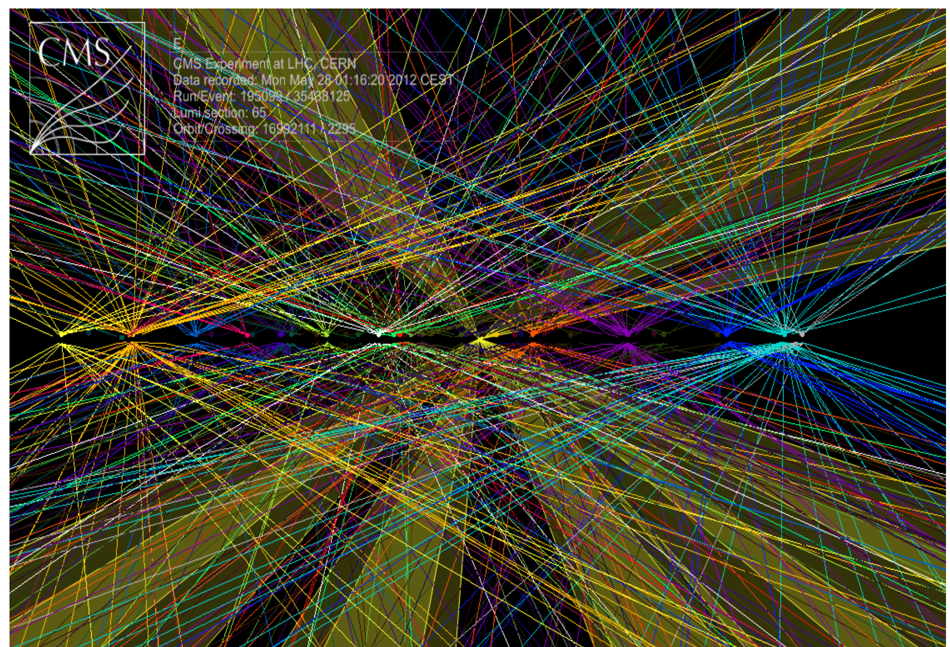
Proton proton collision - Pileup

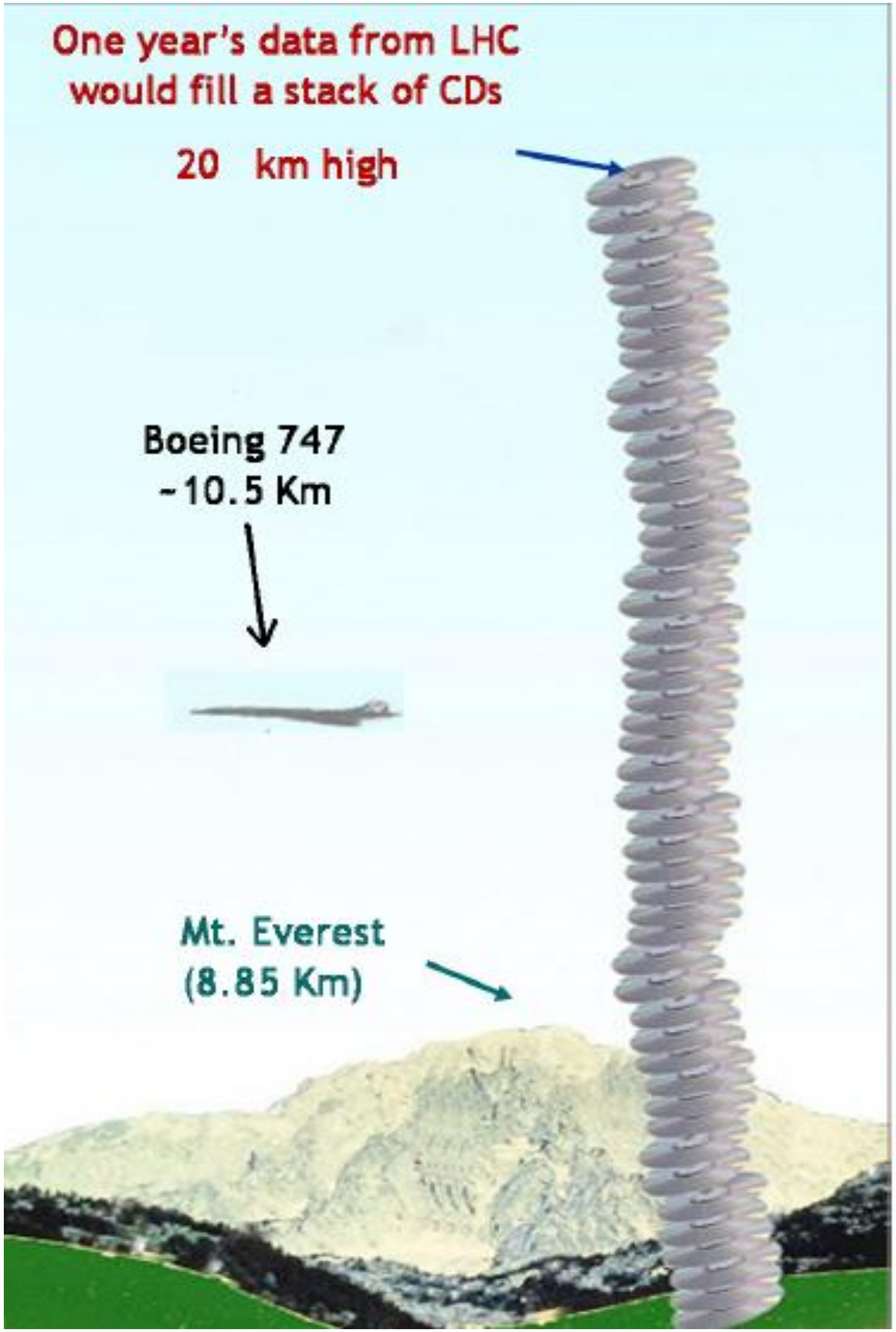






Upto 78 vertices





In hard numbers

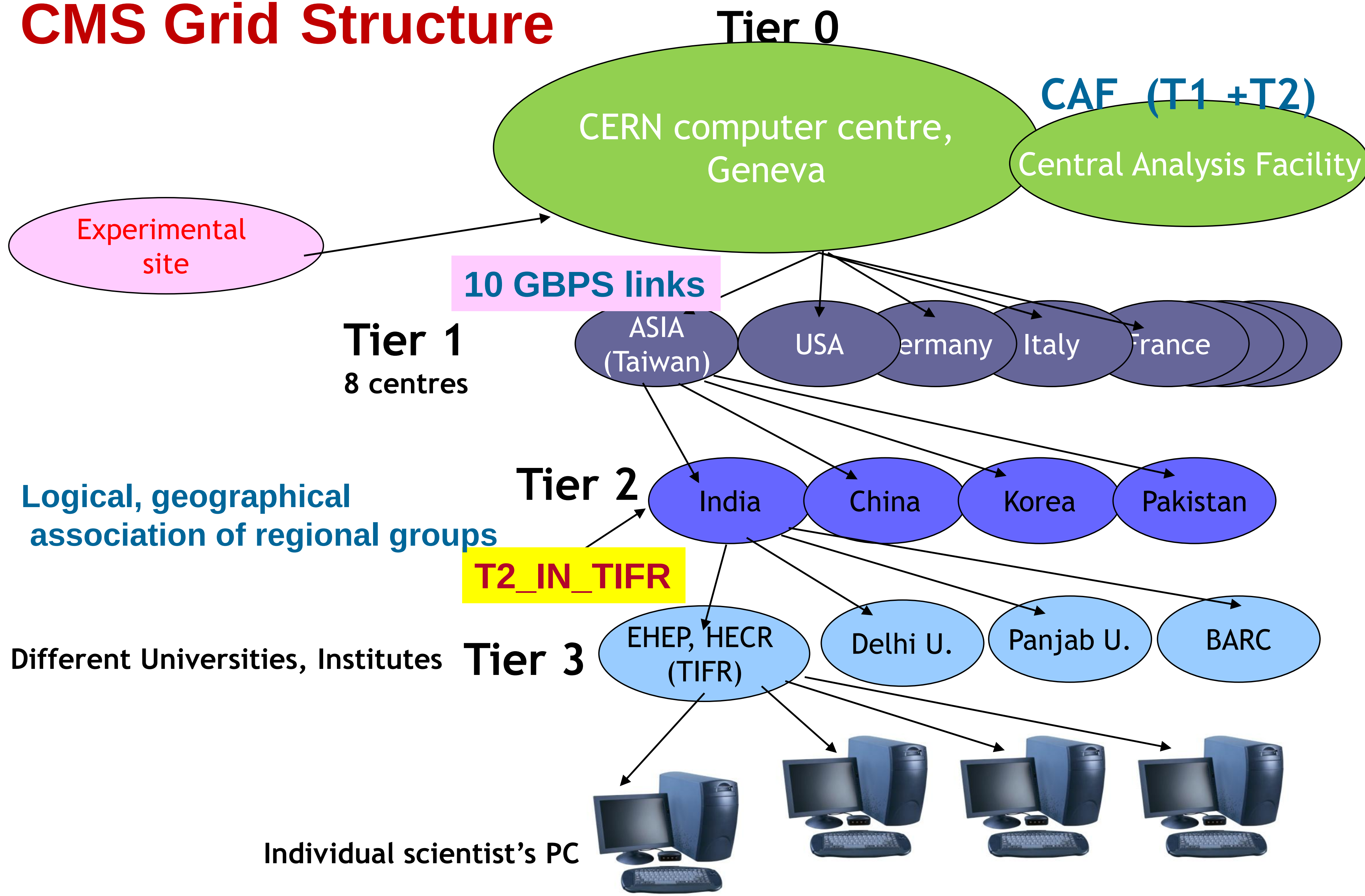
LHC collides 6-8 hundred million proton-on-proton per second for several years.

Only 1 in ~20 thousand collisions will have an important tale to tell, *but we do not know which one!*
➔ so we have to search through all of them!
➔ Huge task!

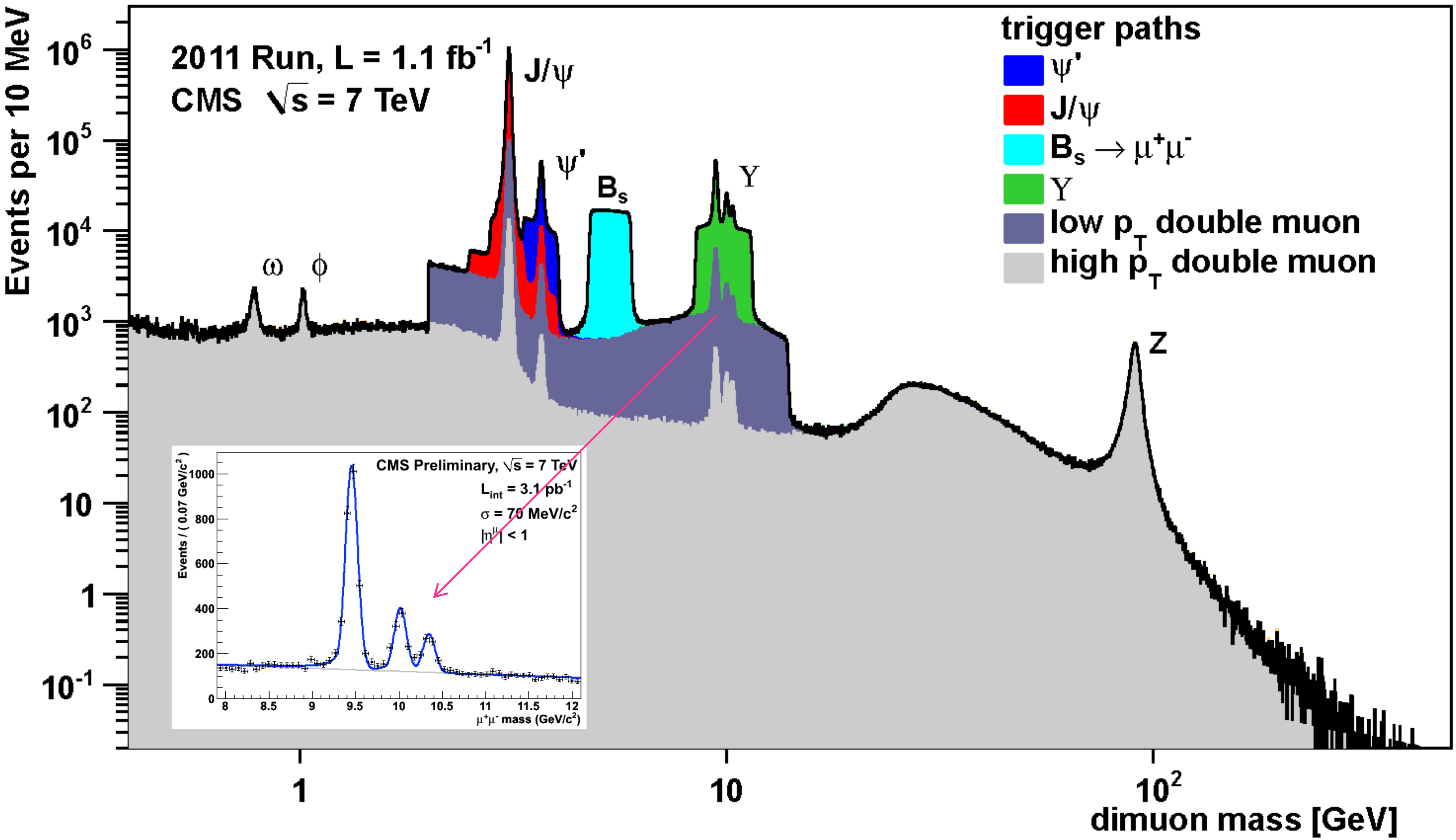
- 15 PBytes (10^{15} bytes) of data a year
- Analysis requires ~100,000 computers to get results in reasonable time.

GRID computing is essential

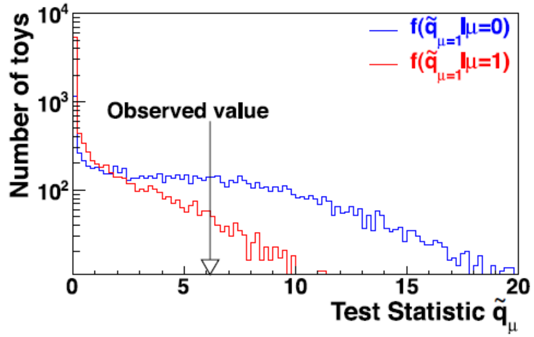
CMS Grid Structure



True concept of Compact *Muon* Solenoid



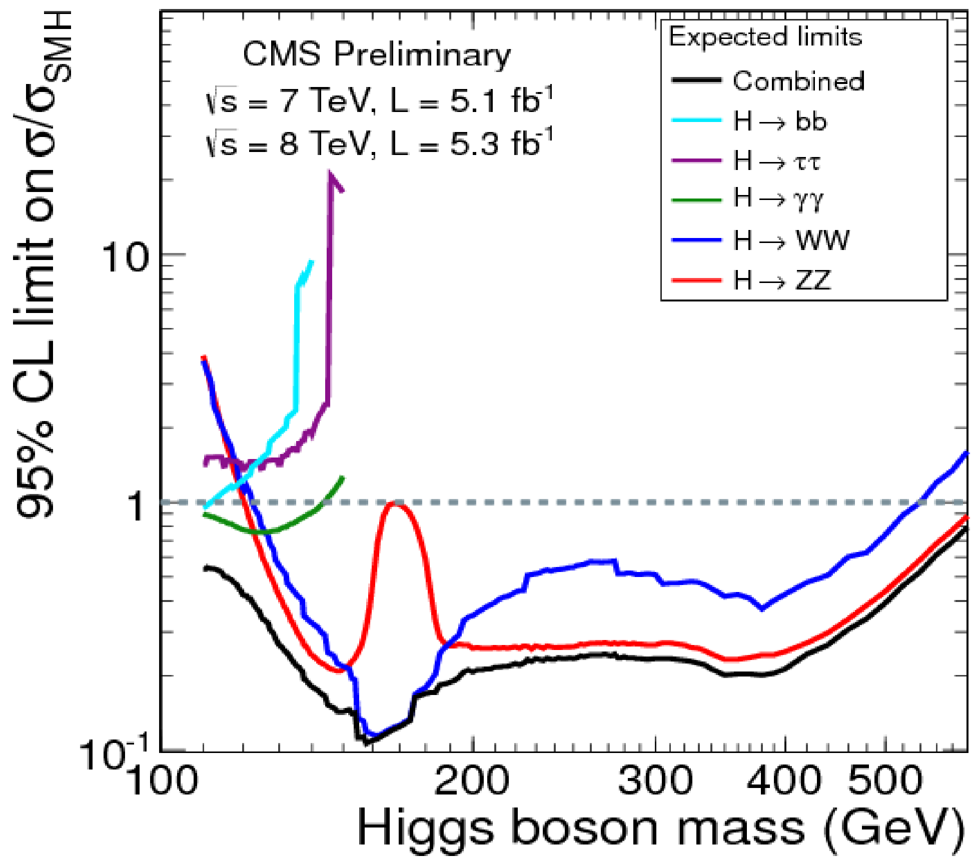
CMS Higgs search : In case of no Higgs signal

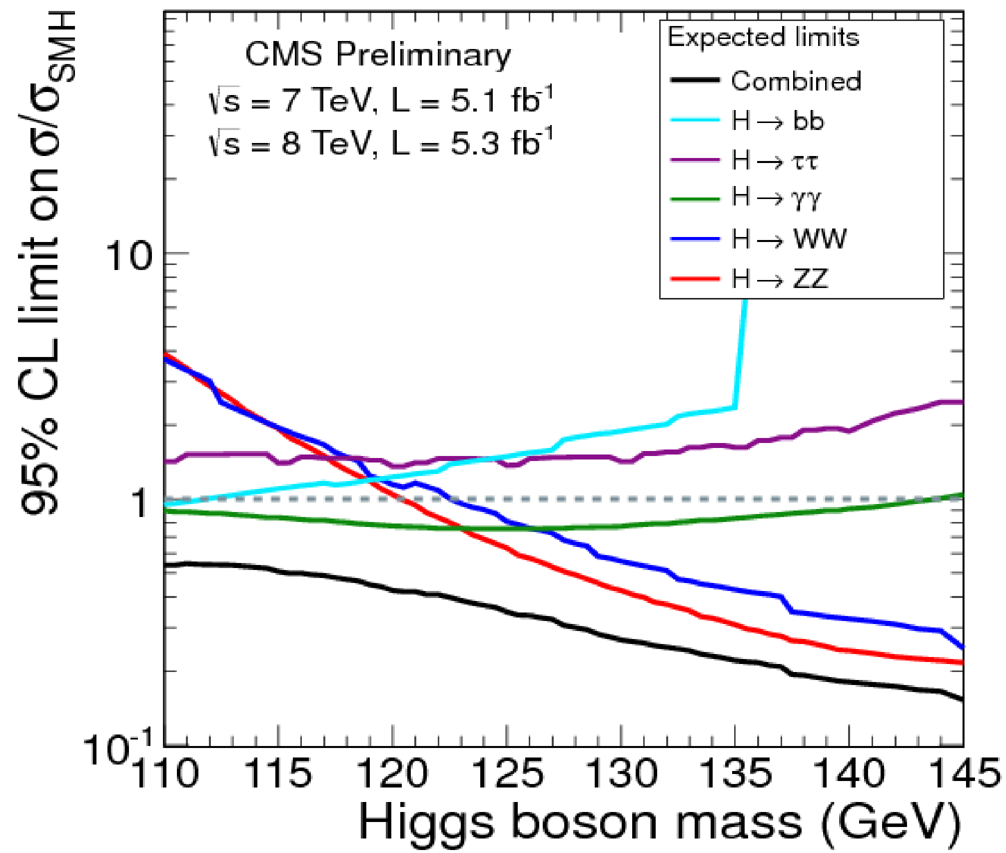


$N_{up} = f(N_{obs}, N_{b,}\ \theta)$

95% confidence limit on $\sigma_{up} = N_{up} / \int\mathcal{L}dt \times \beta \times \varepsilon$

σ_{up}/σ_{SMH}





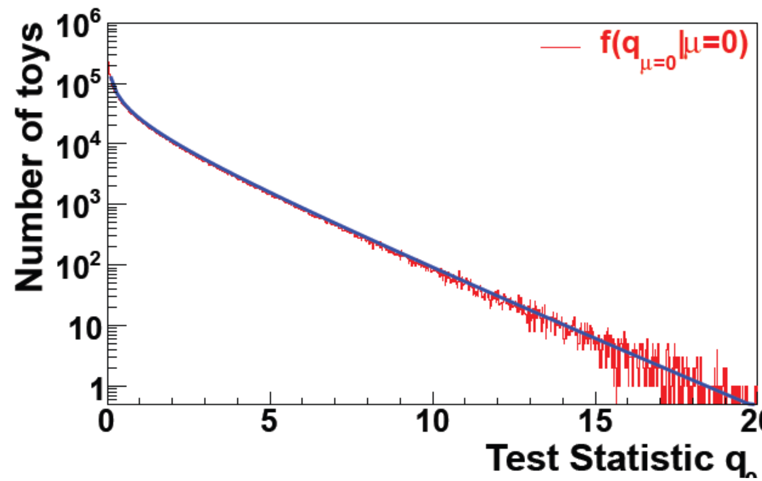
If there is no Higgs it can be excluded with existing CMS data

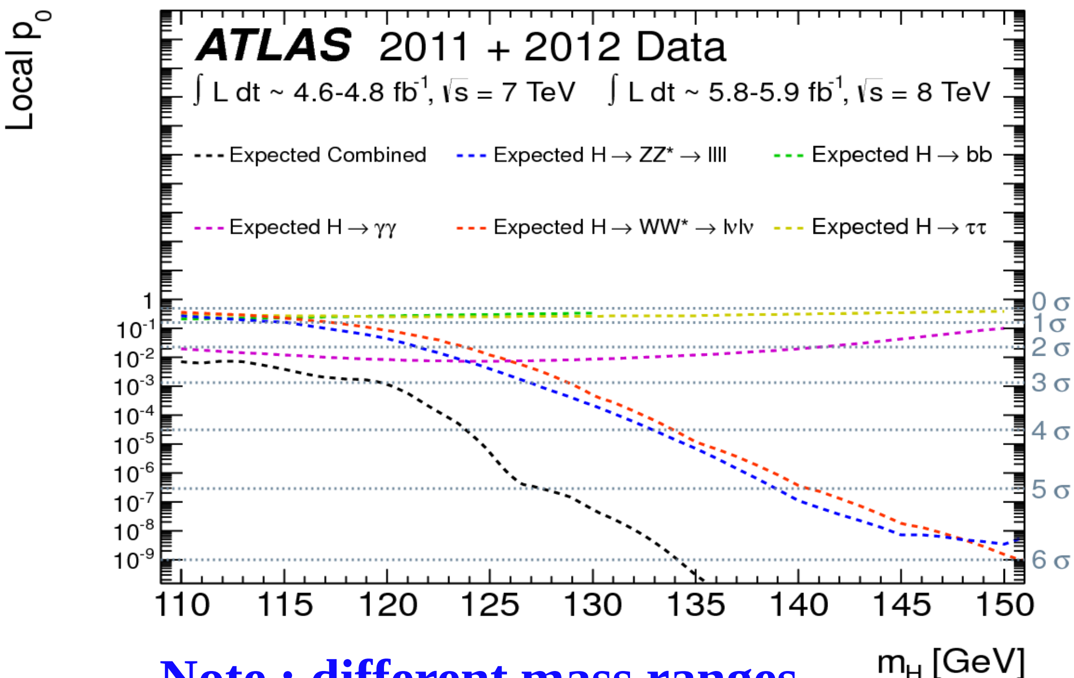
In case of signal, quantify an excess of events: Probability of background fluctuation

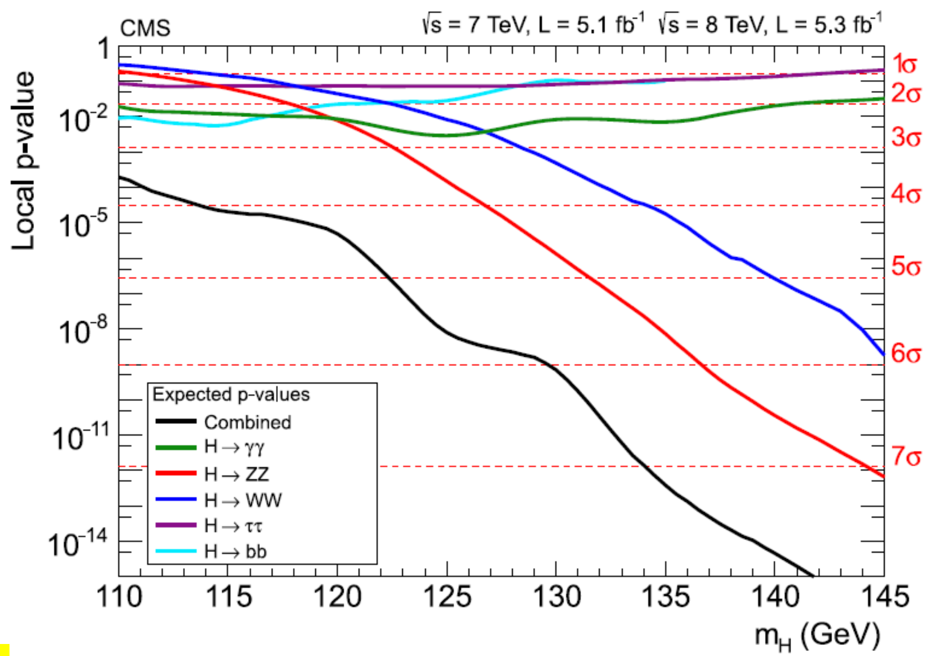
$$q_0 = -2\ln\frac{\ell(data\,|\,0,\hat{\hat{\theta}}_0)}{\ell(data\,|\,\hat{\mu},\hat{\theta})} \quad and \quad \hat{\mu}\geq 0$$

$$p_0 = P(q_0 \geq q_0^{obs})$$

$$P(\Delta\chi^2 = \chi_0^2 - \chi_{\mu_{obs}}^2 > 0)$$





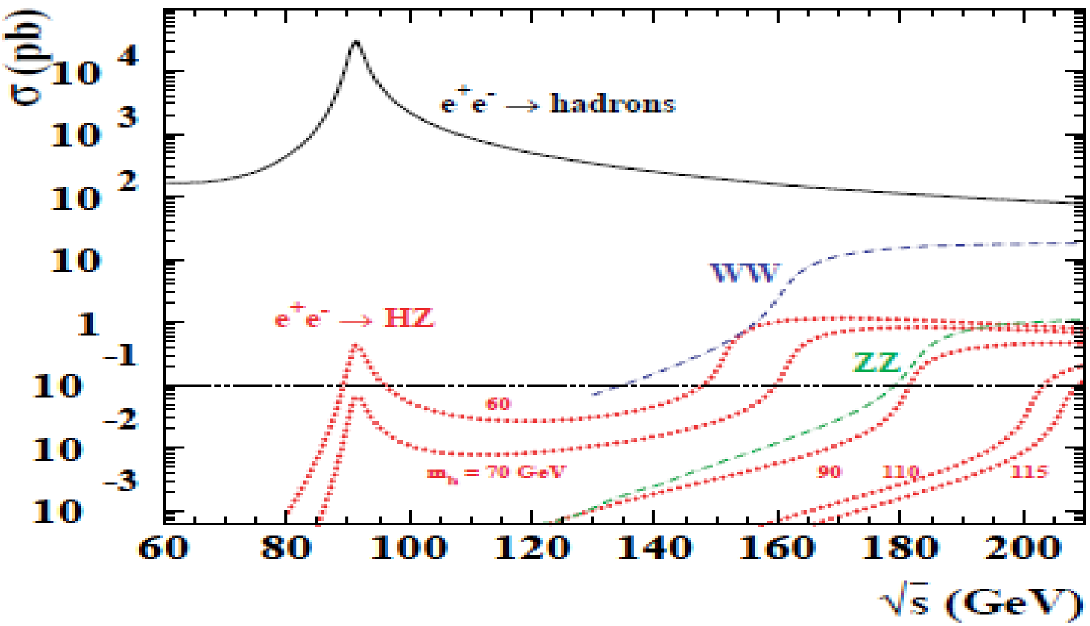


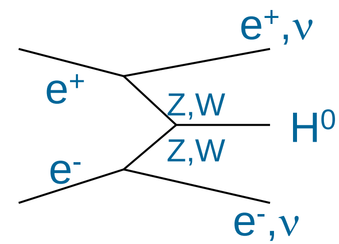
Note : different mass ranges

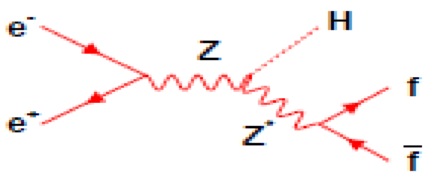
Higgs can not hide within this mass range

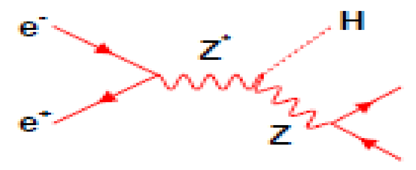
Higgs Search at LEP

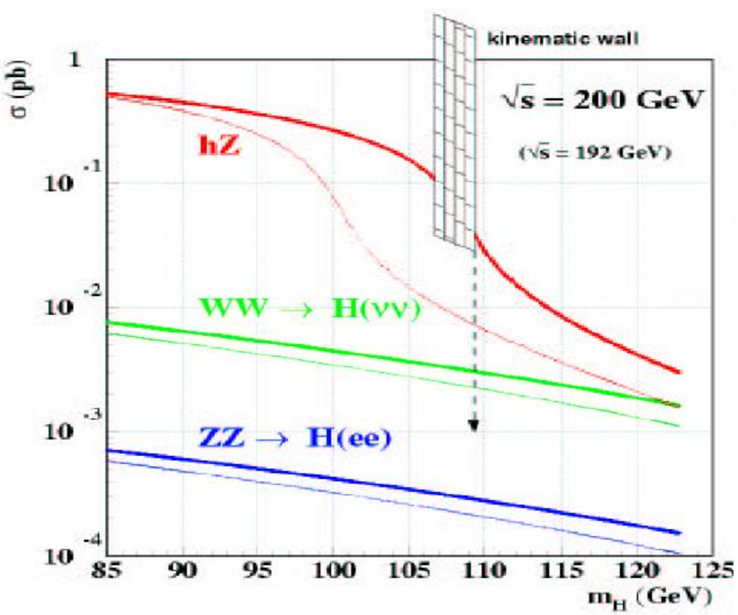
Higgs search at LEP

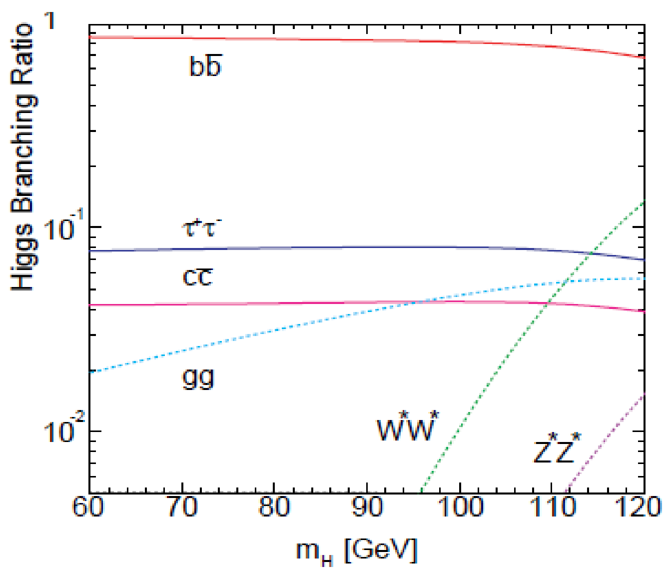






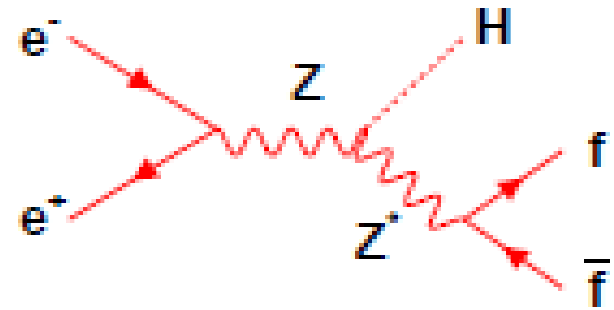






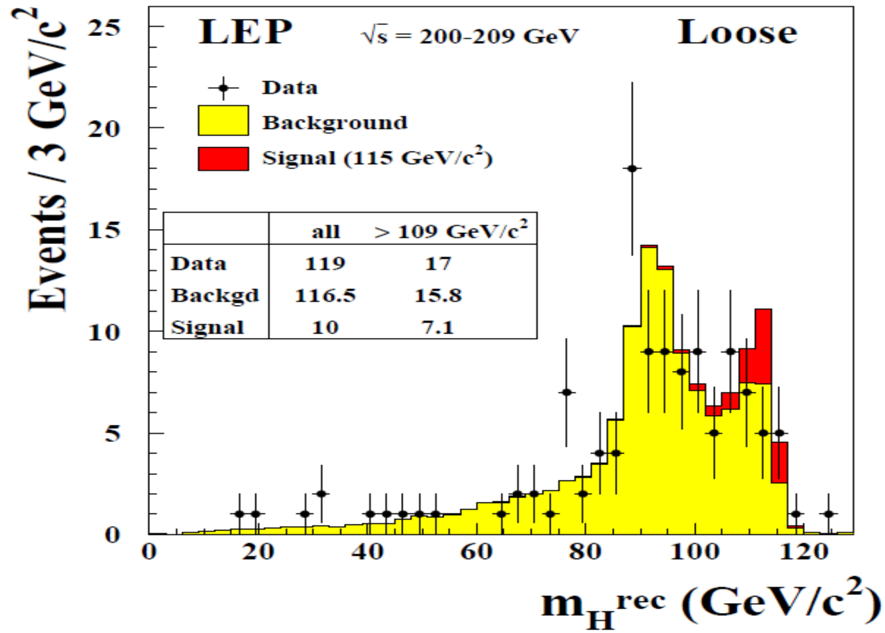
BR(%)	Higgs 115 GeV	Z boson
$q\bar{q}$		70
$b\bar{b}$	74	15
$c\bar{c}$	4	12
gg	6	0
$\ell^+\ell^-$		10
$\tau^+\tau^-$	7	3
$\nu\bar{\nu}$		20
W^*W^*	8	
Z^*Z^*	1	

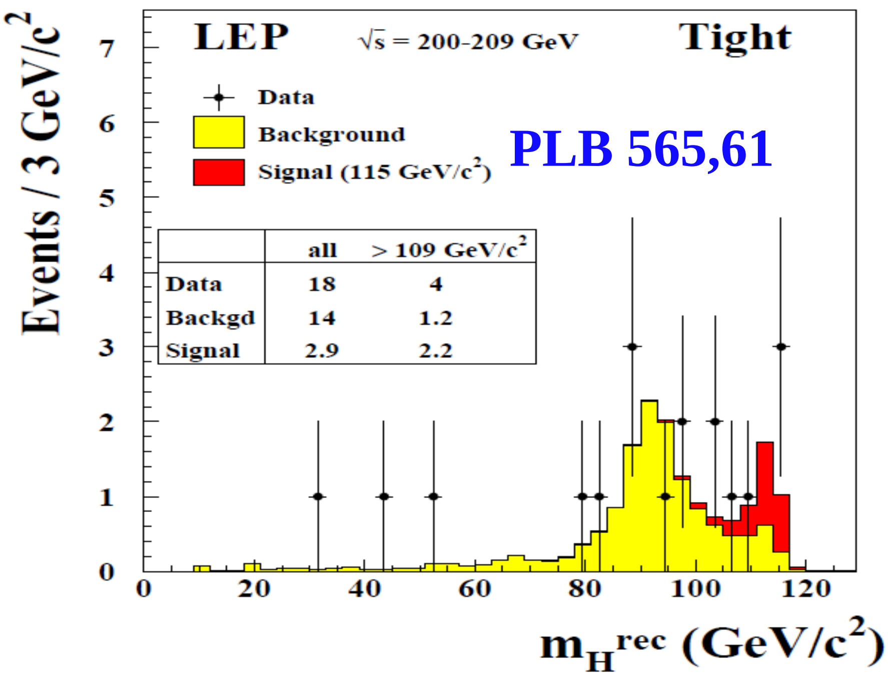
Early search in the domain m_H <20 GeV

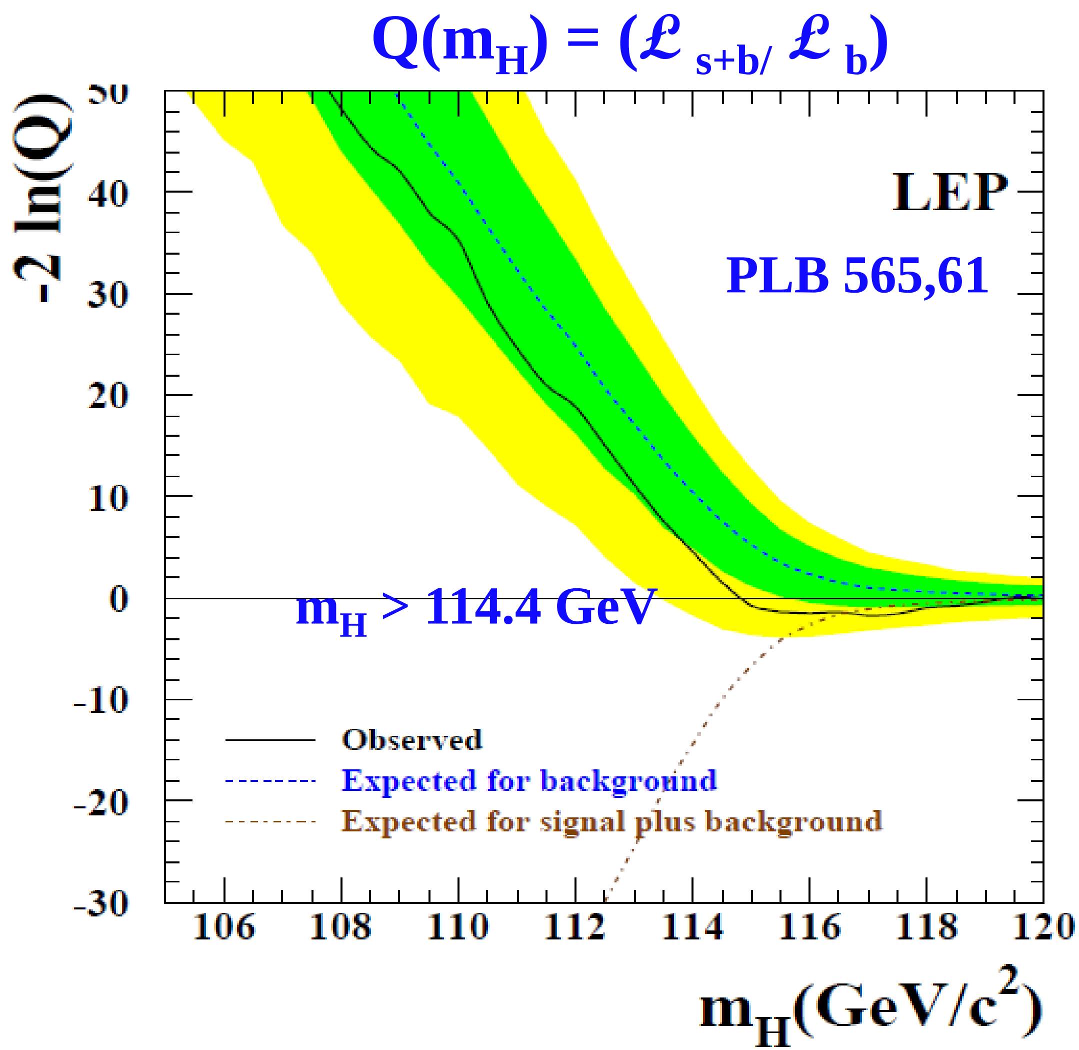


- Acoplaner lepton-pair. $m_H < 2m_e$, Higgs boson is long lived and thus escape detection
- Acoplaner pair : pair of charged particles from Higgs decay recoil against a $Z \rightarrow \nu\nu$
- Mono-jet topologies : Hadronic decays of the Higgs boson with an intermediate mass and with a more intricate fragmentation process, where a single jet recoils against a $Z^* \rightarrow \nu\nu$
- Last two has backgrounds from $e^+e^- \rightarrow \gamma^* Z$

Direct search results from LEP experiments

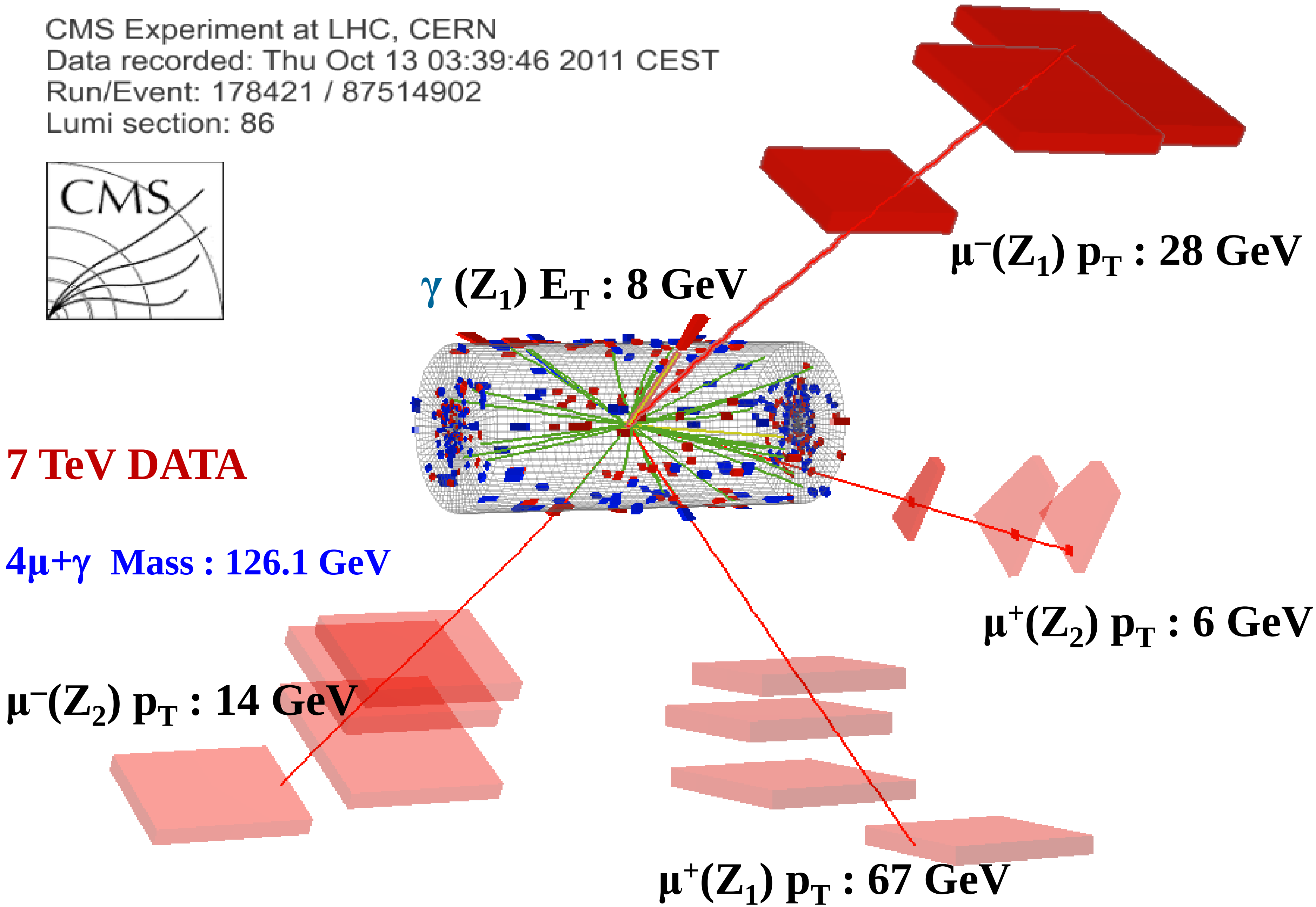






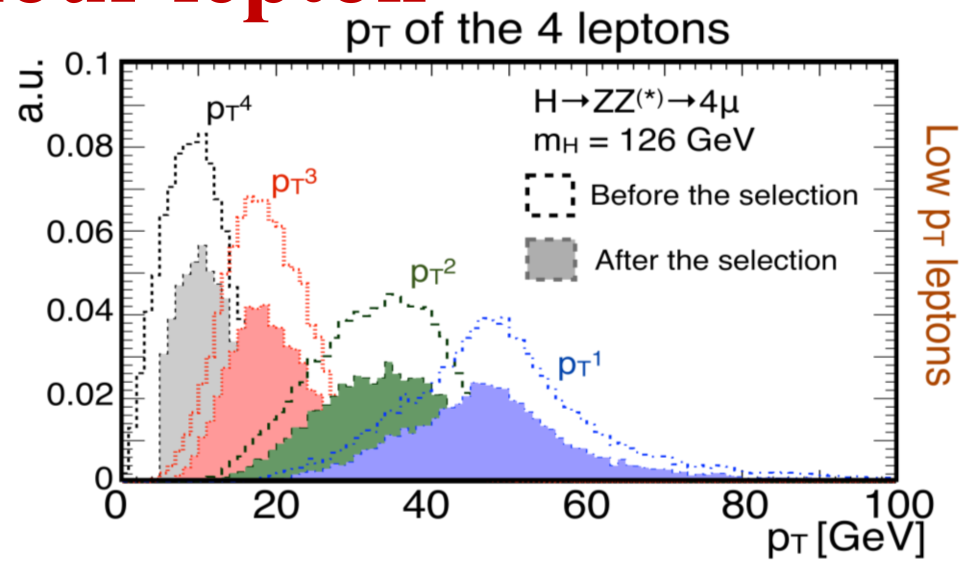
Higgs Search at LHC

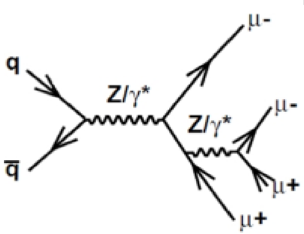
A candidate of H→ZZ* with FSR

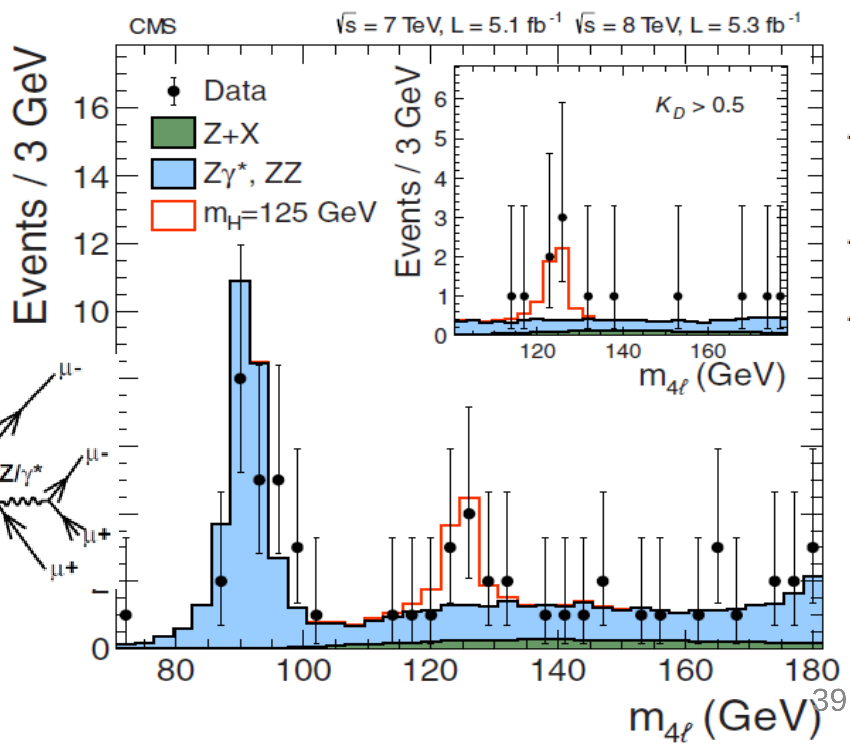


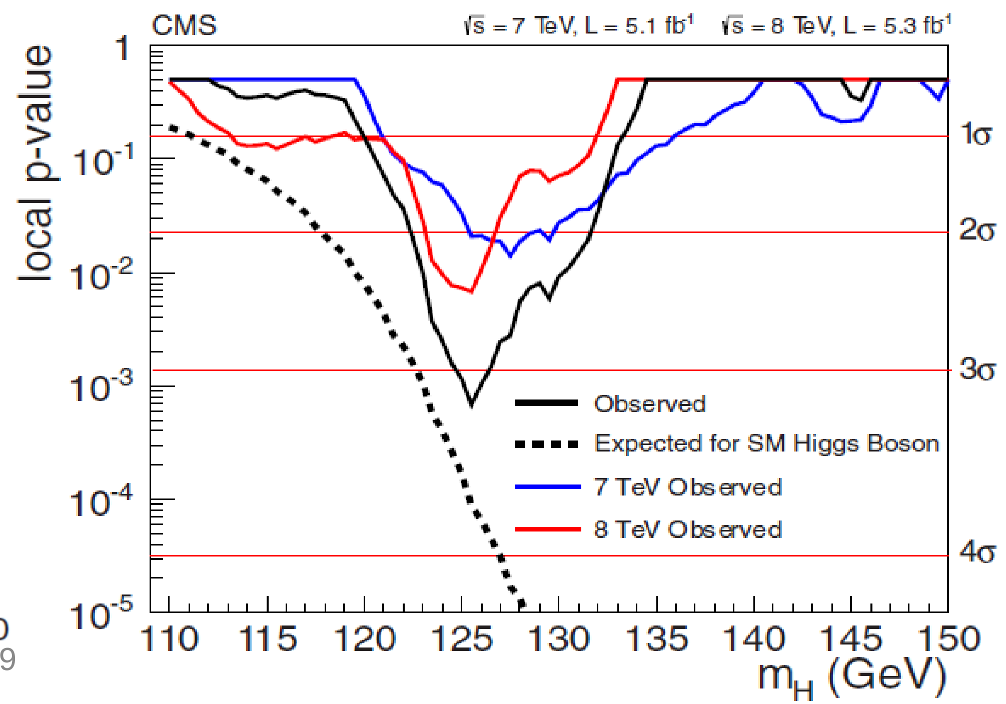
H→ZZ$^{(*)}$→four lepton

- **p_T >7/5 GeV and |η| < *2.5/2.4 for electron/muon .***
- ***40 <M_{ll}<120 & 12<M_{ll}<120)***
- **Lepton isolation within cone 0.3**
- **Include FSR, PT>2/4 GeV for ΔR<0.07/[0.07-0.5]**
- **Background : ZZ, Z+jet**







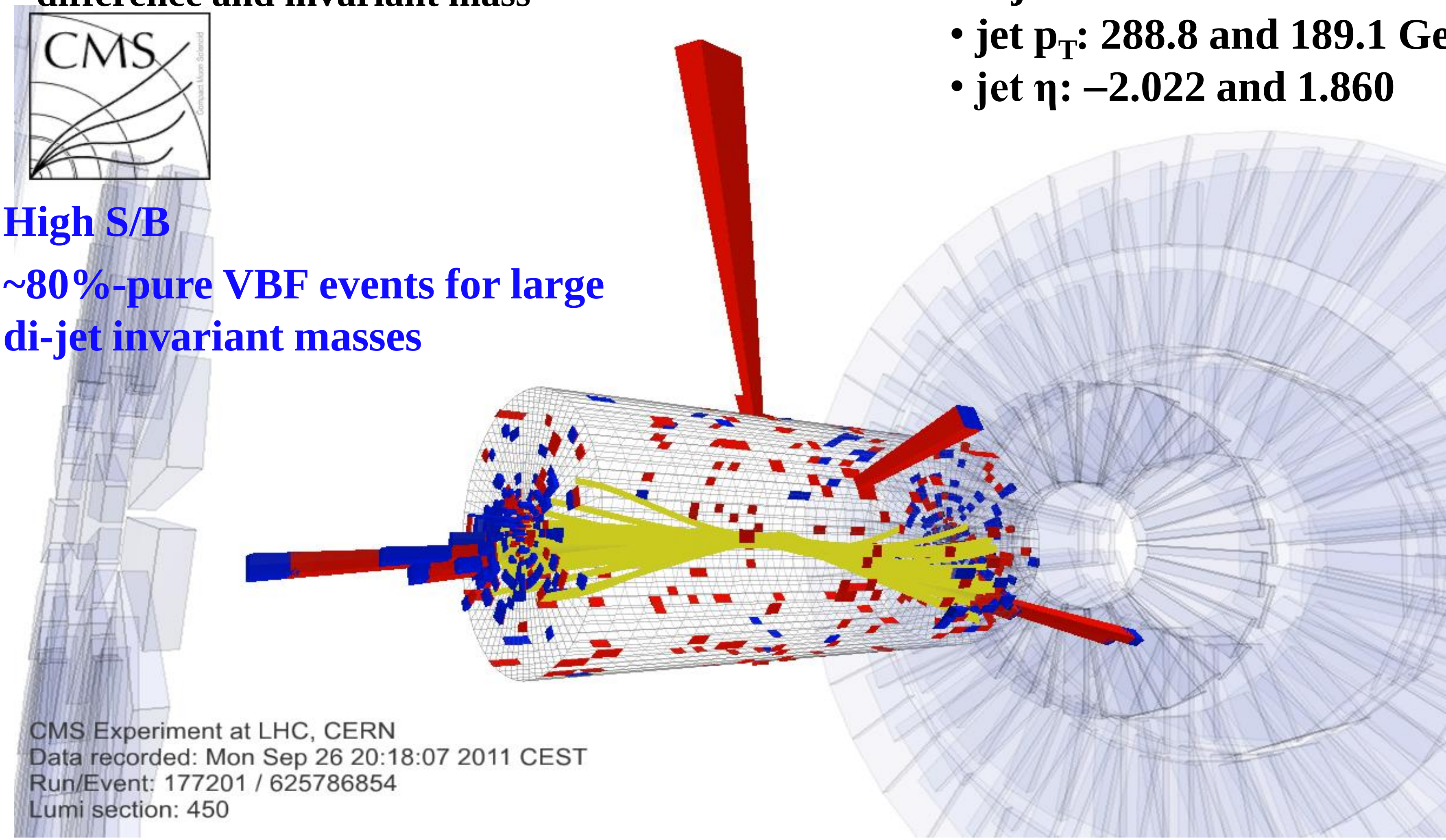


Di-jet Tagging $H \rightarrow \gamma\gamma$ candidate

- **Exclusive selection of di-photon events with VBF-like topology:**
  - **Two high pT jets with large pseudo-rapidity difference and invariant mass**
- **High S/B**
- **~80%-pure VBF events for large di-jet invariant masses**

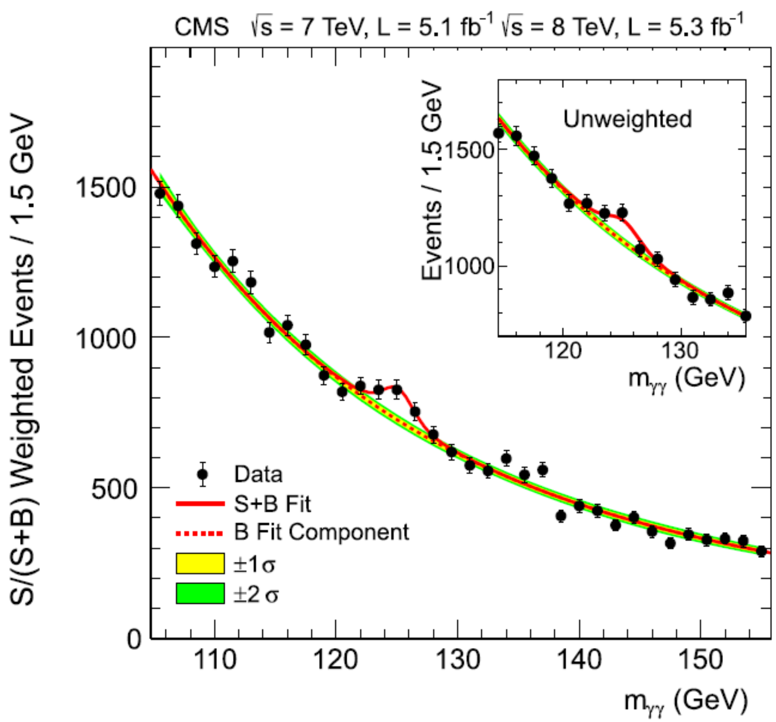
Di-jet event with:

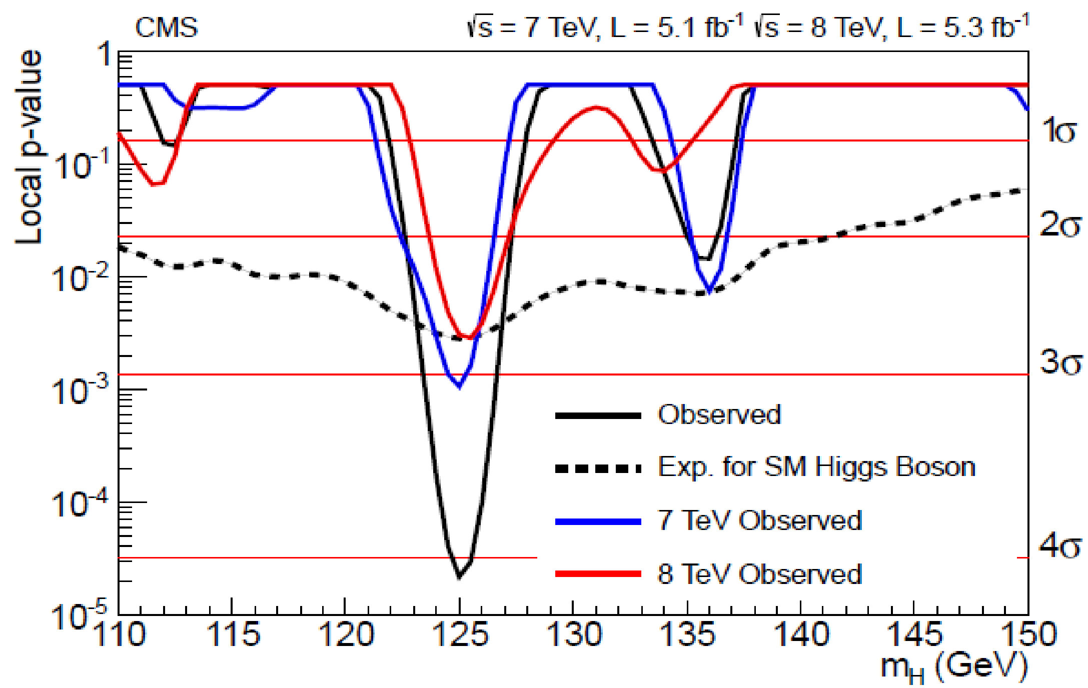
- **diphoton mass 121.9 GeV**
- **dijet mass 1460 GeV**
- **jet p_T: 288.8 and 189.1 GeV**
- **jet η: –2.022 and 1.860**



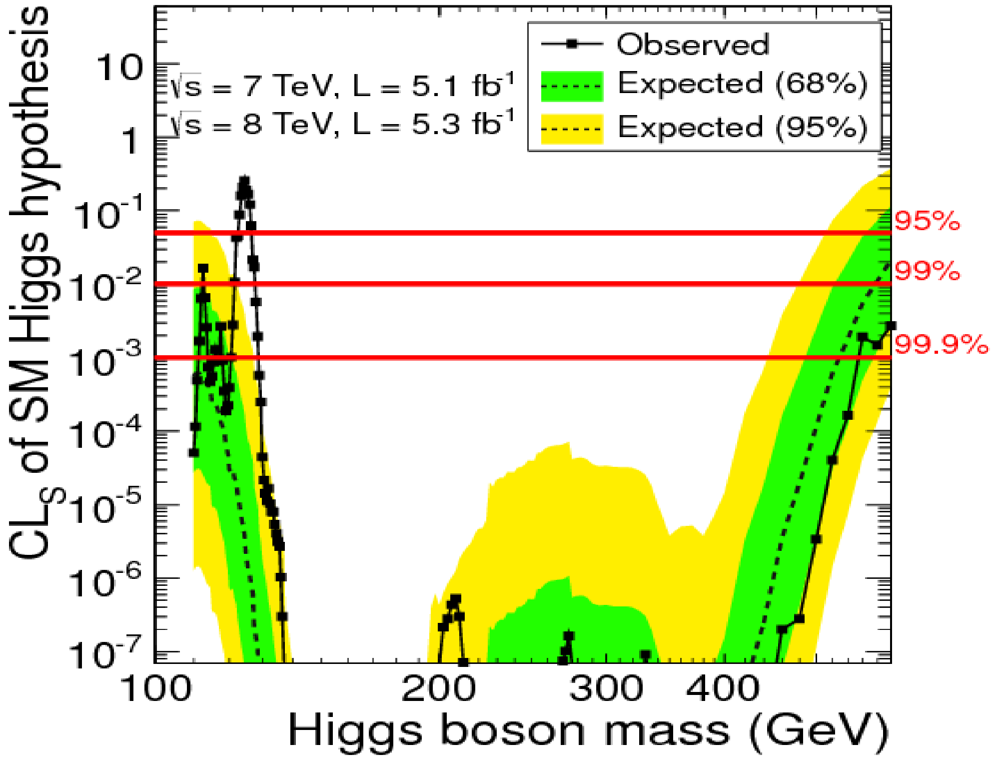
$H \rightarrow \gamma\gamma$

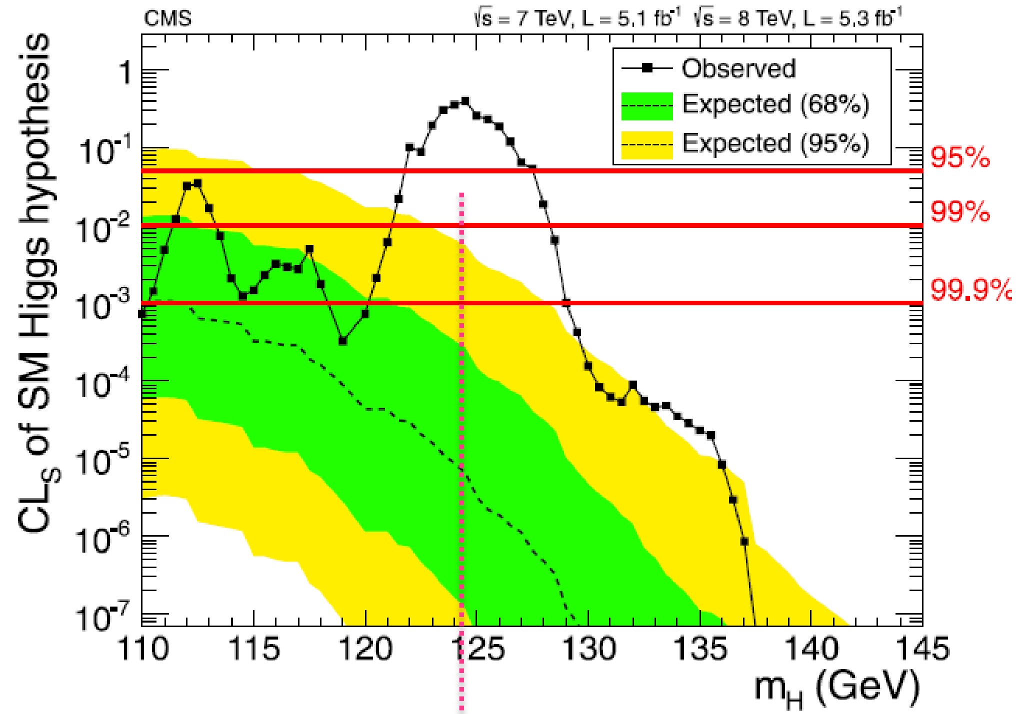
- $P_{T\gamma} > m_{\gamma\gamma}/3$ ($m_{\gamma\gamma}/4$) for leading (sub-leading photon), for VBF $P_{T\gamma} > m_{\gamma\gamma}/2$
- $|\eta_\gamma| < 2.5$ & $1.44 < |\eta_\gamma| < 1.57$
- Jet in VBF : Pt>30/20 GeV, $|\Delta\eta|>3.5$, $m_{jj}>350/250(500)$ for 7/8 TeV data, $|\Delta\eta_{[\gamma\gamma][jj]}| < 2.5$, $|\Delta\varphi_{[\gamma\gamma][jj]}|>2.6$
- BDT for photon identification
- Vertex : conversion tracks, $\sum P_T^2, \quad -\sum \vec{P}_T \cdot \frac{\vec{P}_T^{\gamma\gamma}}{|\vec{P}_T^{\gamma\gamma}|} \quad and \quad (\sum P_T - P_T^{\gamma\gamma})/(\sum P_T + P_T^{\gamma\gamma})$
- Background from nonresonant $\gamma\gamma$, γ+jet, QCD events





Compatibility of data with SM Higgs

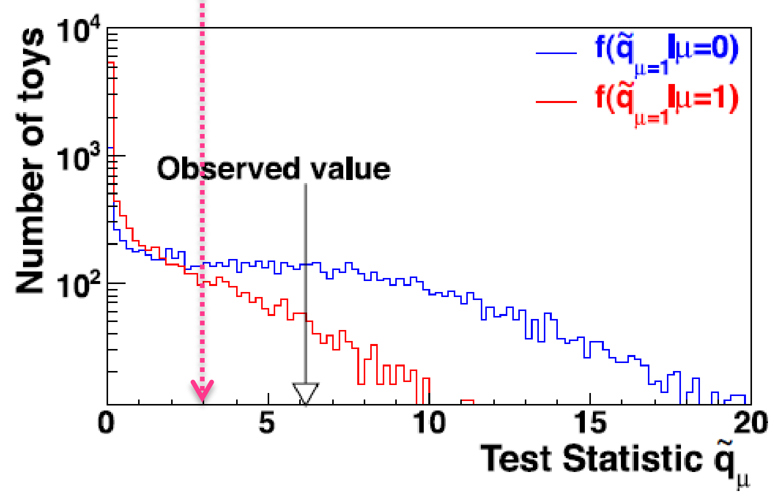




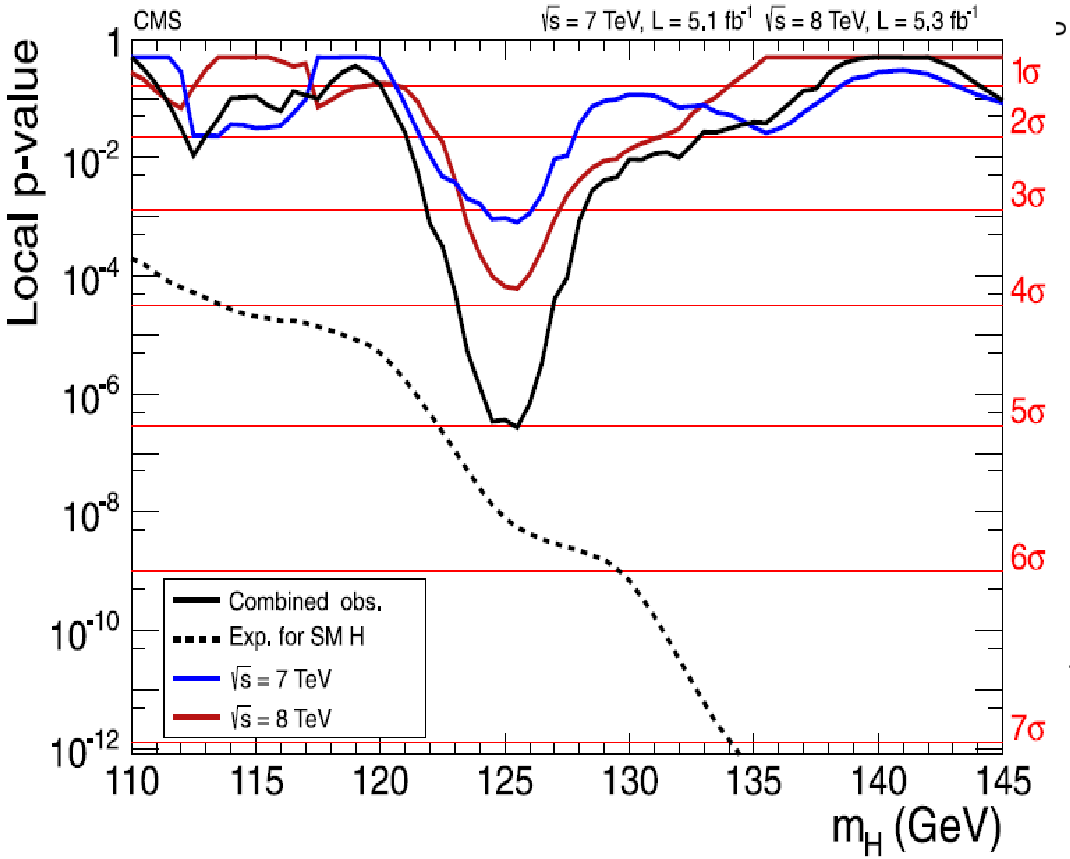
$$q_{\mu} = -2\ln\frac{\ell(data\,|\,\mu,\hat{\theta}_{\mu})}{\ell(data\,|\,\hat{\mu},\hat{\theta}\,)}, where\ \ 0 \le \hat{\mu} \le \mu$$

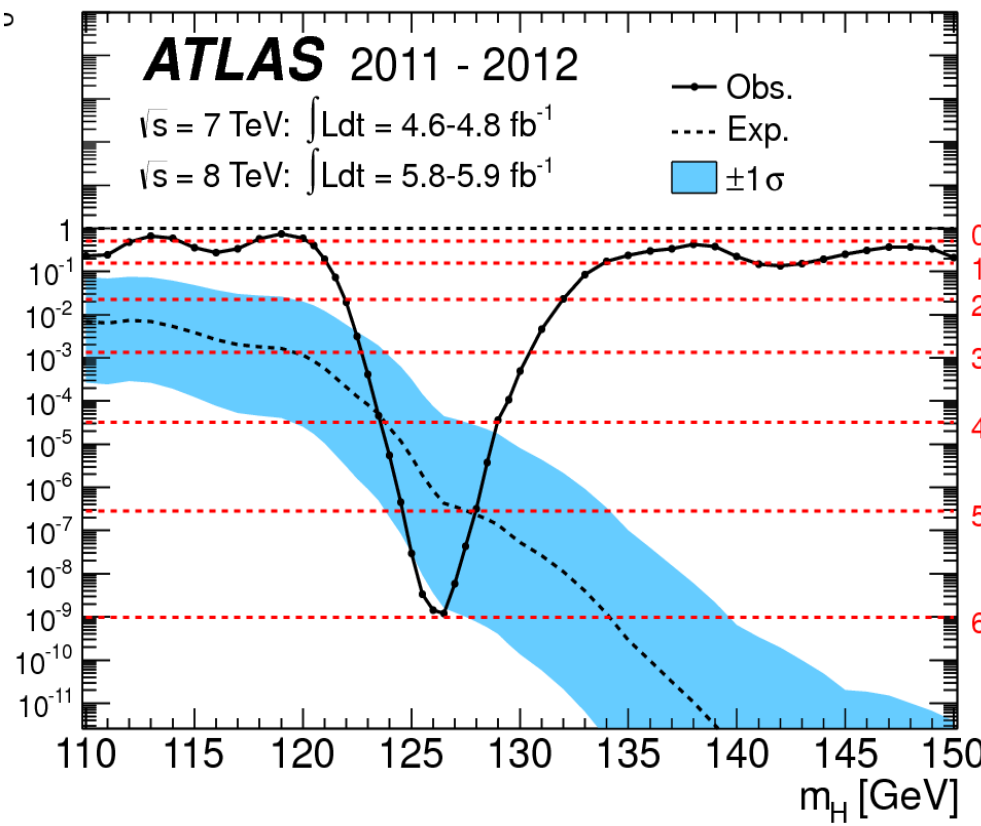
$$p_{\mu} = p(q_{\mu} \ge q_{\mu}^{obs}\,|\,\mu.s(\hat{\theta}_{\mu}^{obs}) + b(\hat{\theta}_{\mu}^{obs})) = \int_{q_{\mu}^{obs}}^{\infty} f(q_{\mu}\,|\,\mu,\theta_{\mu}^{obs})dq_{\mu}$$

$$p_{0} = p(q_{\mu} \ge q_{\mu}^{obs}\,|\,b(\hat{\theta}_{0}^{obs})) == \int_{q_{\mu}^{obs}}^{\infty} f(q_{\mu}\,|\,0,\theta_{0}^{obs})dq_{\mu}$$



Significance of the observed excess





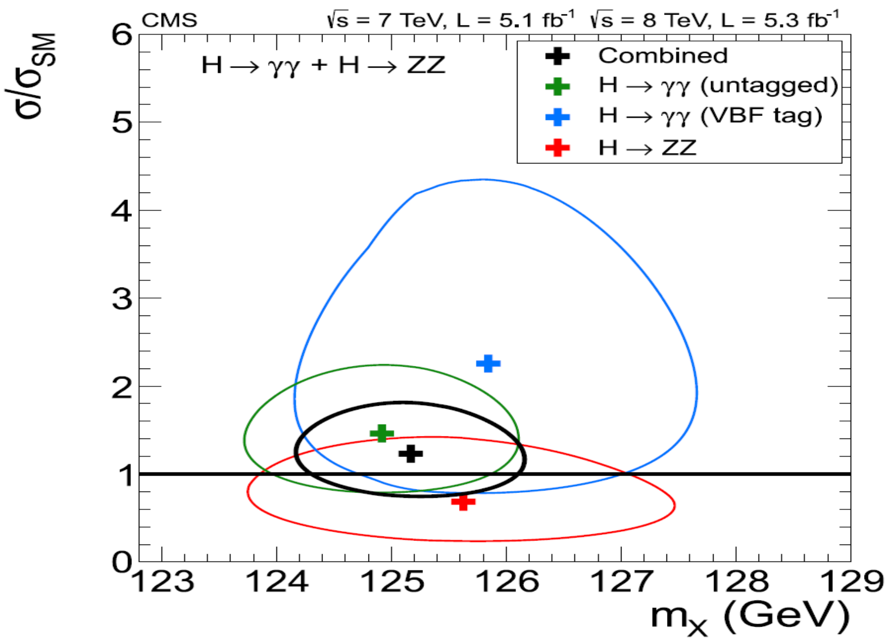
Note : Different mass ranges

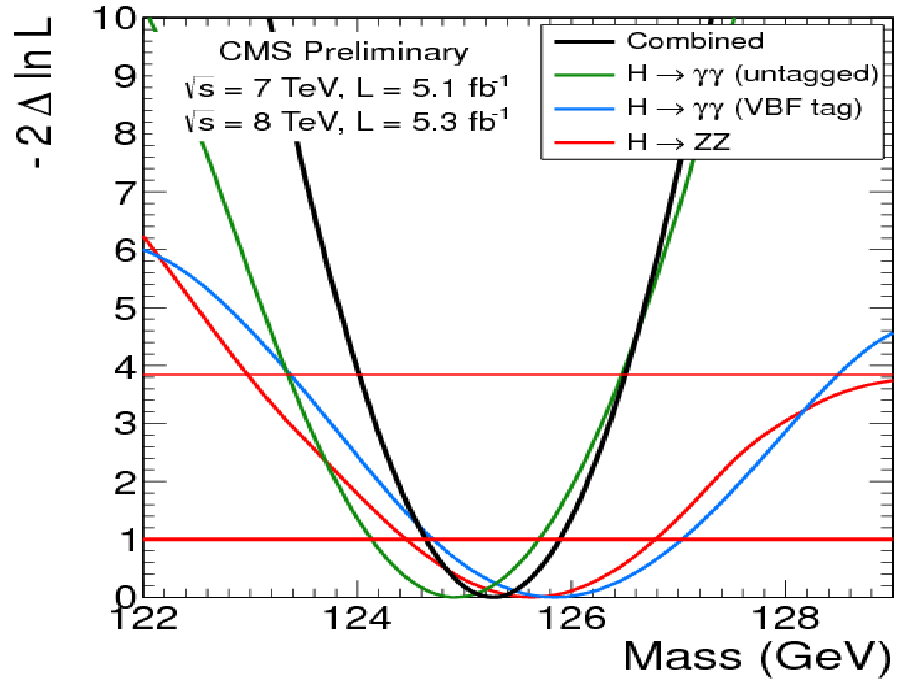
- **Observed significance in more (less) than the expected significance at m_H=125 (126) GeV in the ATLAS (CMS) expt.**

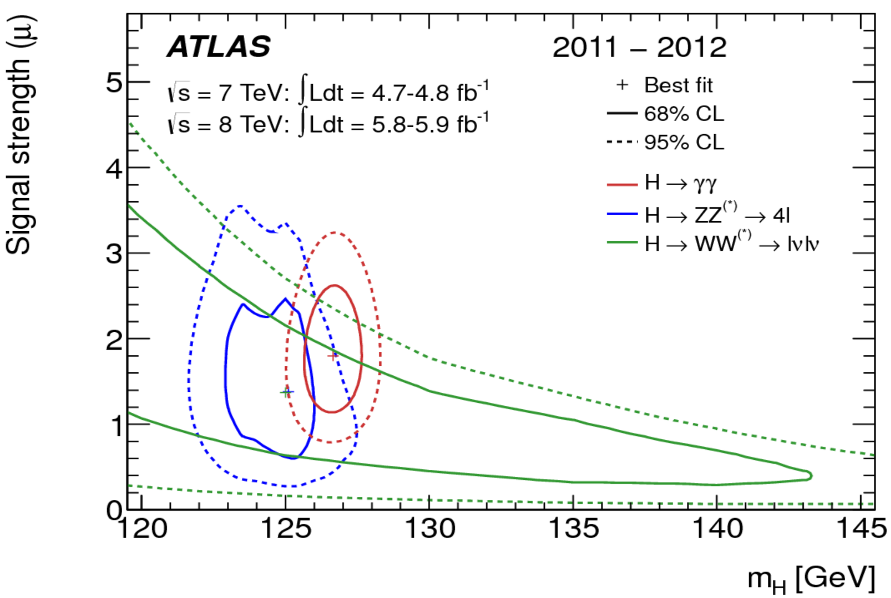
Significance of the observed excess (local p value) @ 125/126 GeV

Decay mode/ combination	Expected (σ)	Observed (σ)	ATLAS Exp (σ)	ATLAS Obs (σ)
γγ	2.8	4.1	2.5	4.5
ZZ	3.8	3.2	2.7	3.6
WW	2.4	1.6	2.3	2.8
ττ	1.4	0.0		
bb	1.9	0.7		
ττ + bb	2.4	0.5		
γγ + ZZ	4.7	5.0		
γγ + ZZ + WW	5.2	5.1	4.9	6.0(5.1)
γγ + ZZ + WW + ττ + bb	5.8	5.0(4.5)		

Mass of the observed boson

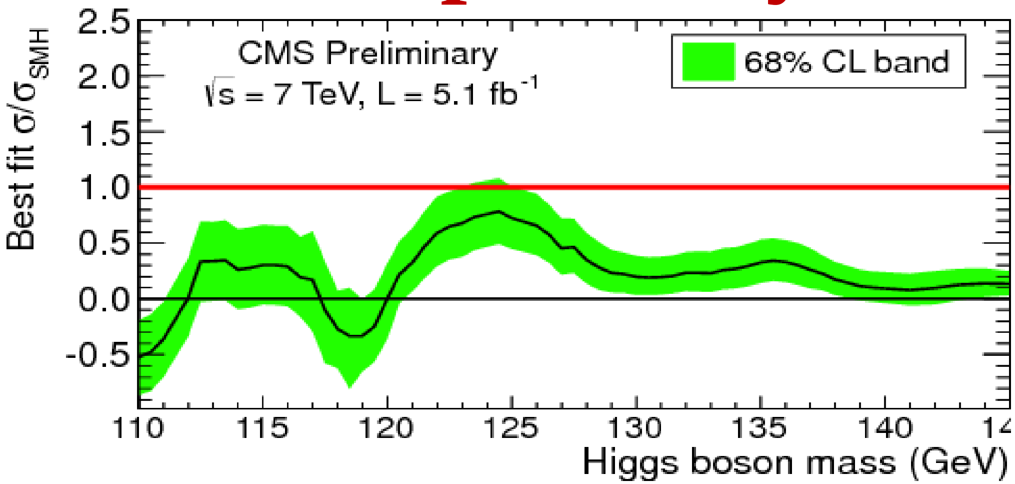


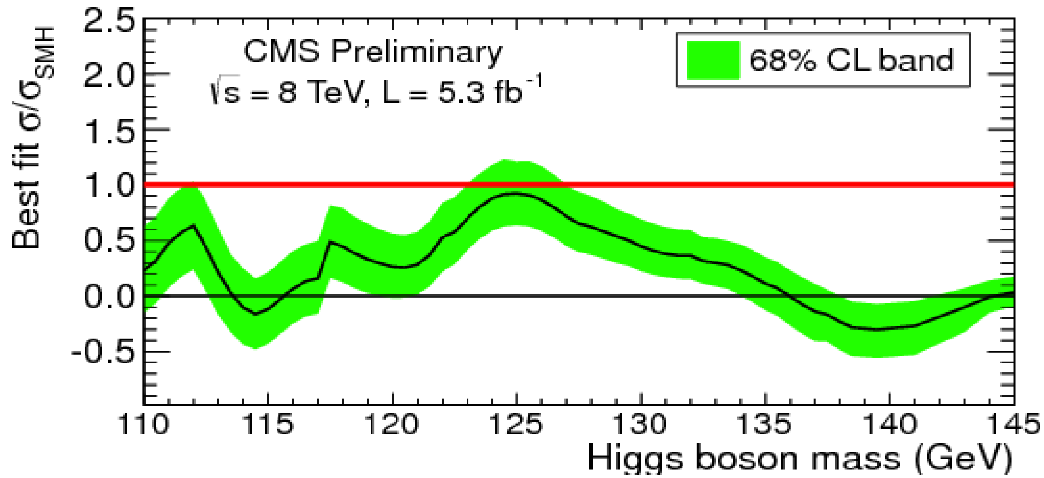


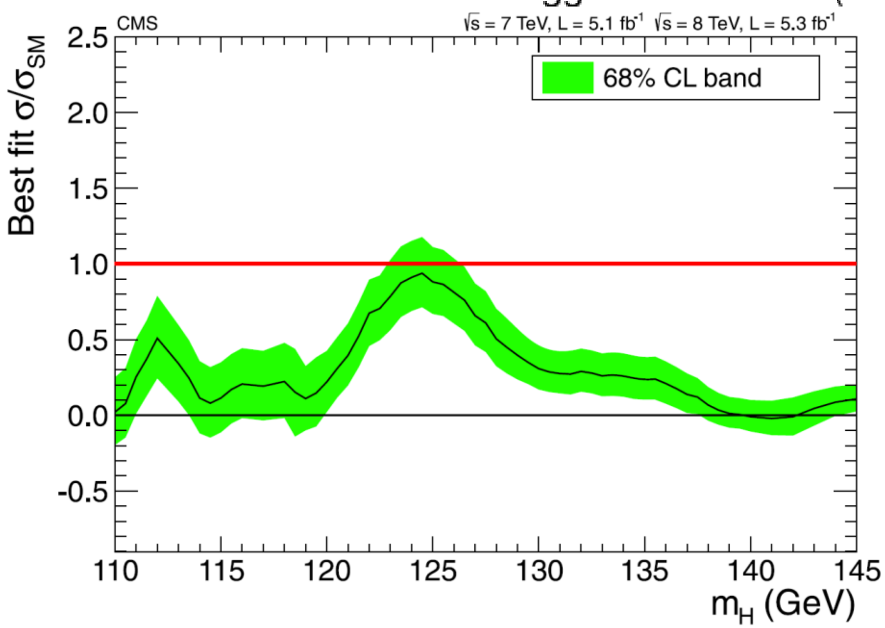


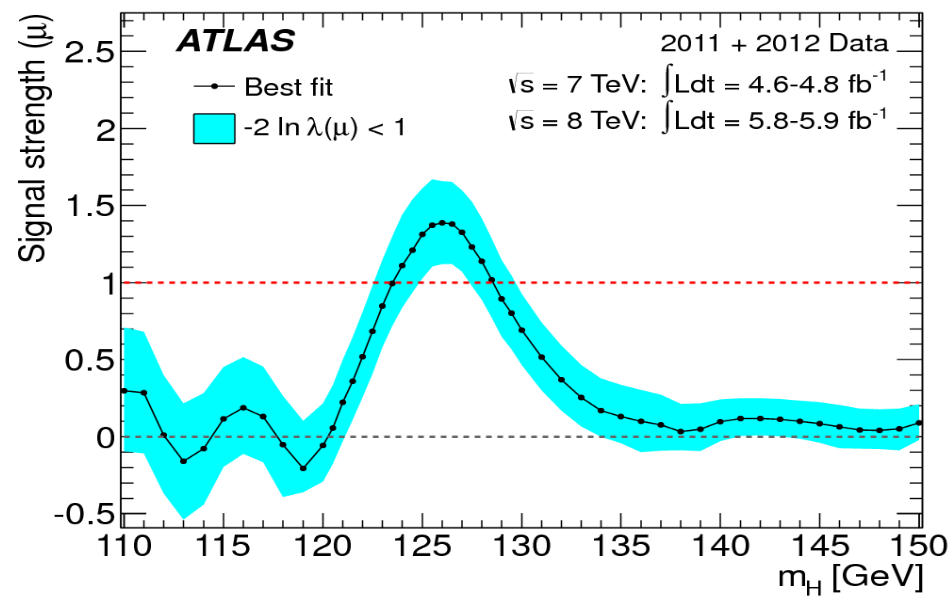
- **Imperfect simulation of electron and photon, extrapolate from m_Z to m_x~125 GeV (0.5%), lepton scale (0.5%)**
- **2D plots : Relative yield among three channels are from the SM**
- **$m_x = 125.3 \pm 0.4 \pm 0.5$ GeV** **(ATLAS : $126.0 \pm 0.4 \pm 0.4$ GeV)**

Compatibility with the SM Higgs boson



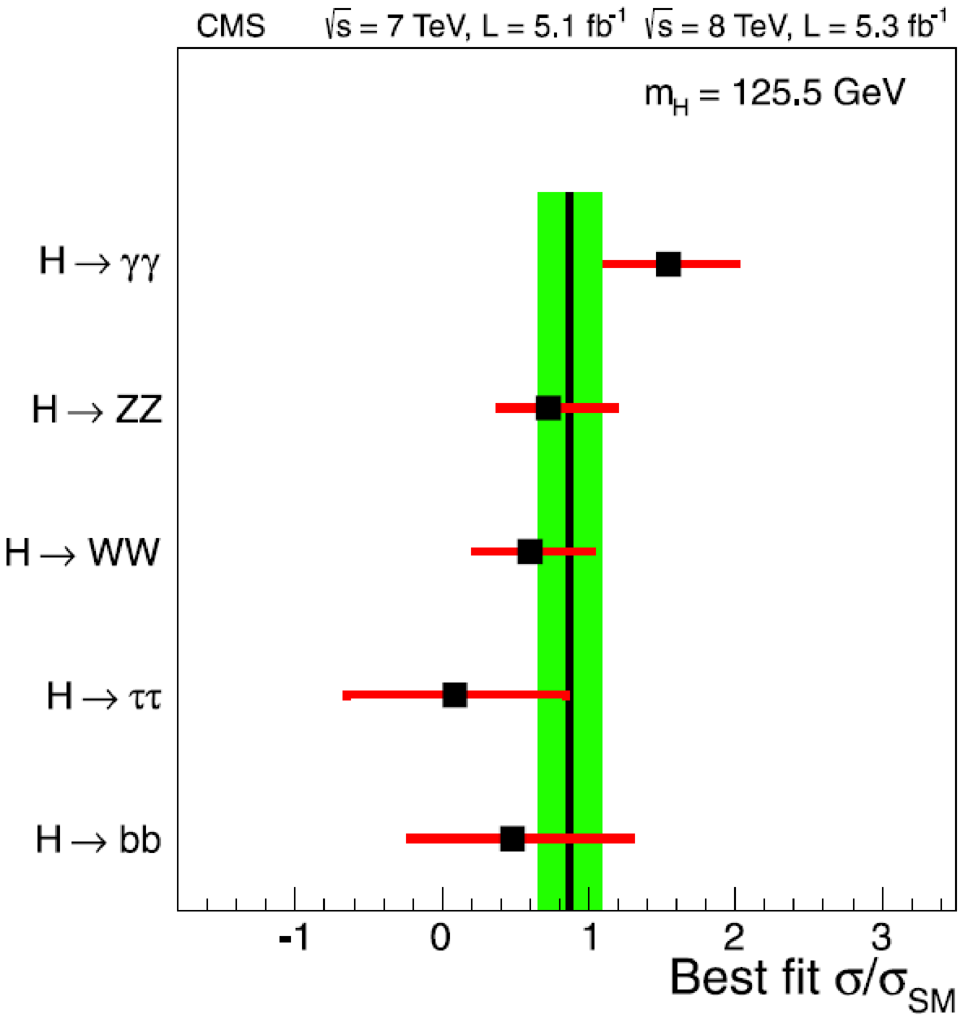


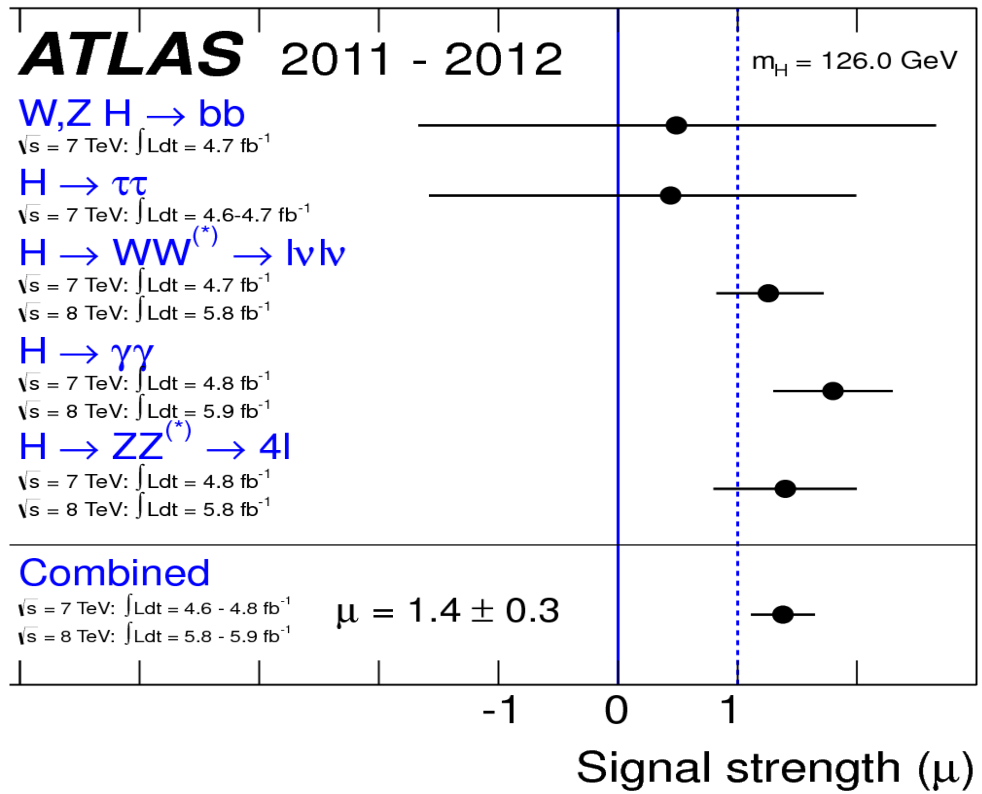




- **Best fit value for 7 TeV and 8 TeV data are consistent with each other**
- **Observed σ/σ_{SM} = 0.87±0.23 @ 125 GeV (ATLAS : 1.4 ± 0.3@126.0 GeV)**

Compatibility with the SM Higgs boson @ 125 GeV





- **Need more data to reduce the error on individual measurements**

Conclusion

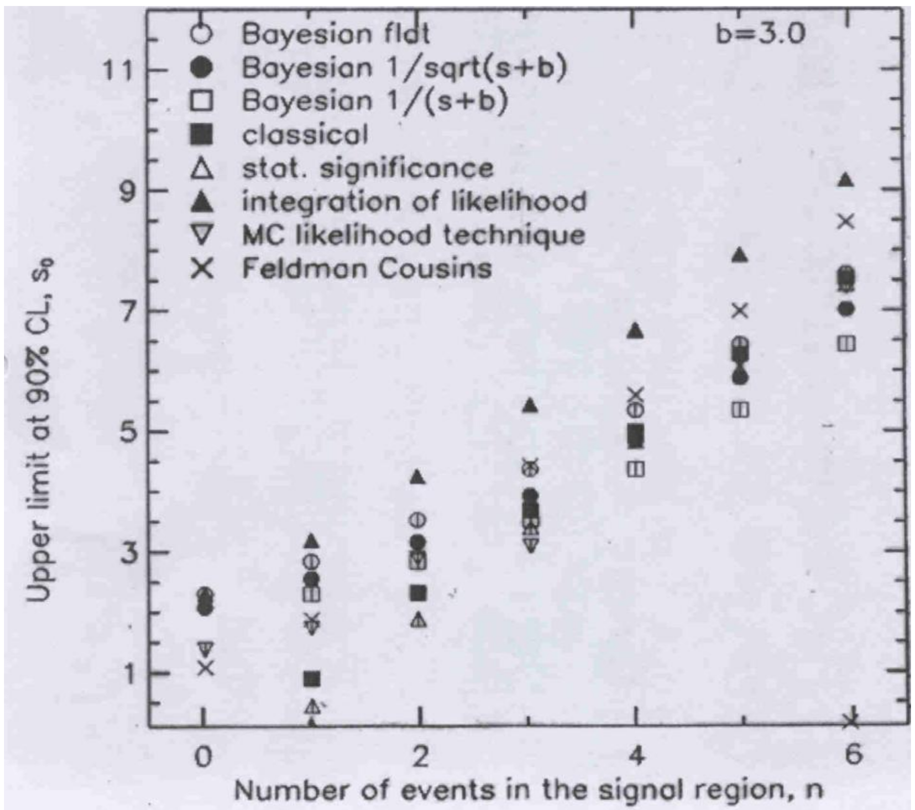
- **Direct constraints from LEP, m_H > 114.4 GeV**
- **The CMS/ATLAS collaboration has looked for the SM Higgs boson with pp collision data at $\sqrt{s}$ = 7 and 8 TeV with luminosity ~5.1 fb^{-1} and ~5.3fb^{-1} respectively.**
- **Reported search results on five decay modes : γγ, ZZ, WW, ττ and bb channels.**
- **Observe a significance excess for CMS in two high resolution channels with local-p value 5.0σ, whereas expected local significance of signal was 5.8σ, whereas for ATLAS, those are 6.0σ and 4.9σ**
- **Mass of the excess signal, m_x = 125.3 ± 0.4 ± 0.5 GeV (ATLAS : 126.0 ± 0.4 ± 0.4 GeV)**
- **γ γ channel disfavour spin-1 hypothesis**
- **With more data in 2012, both CMS and ATLAS collaborations will study properties of this signal.**

Limits for low statistics (counting expt with/without background)

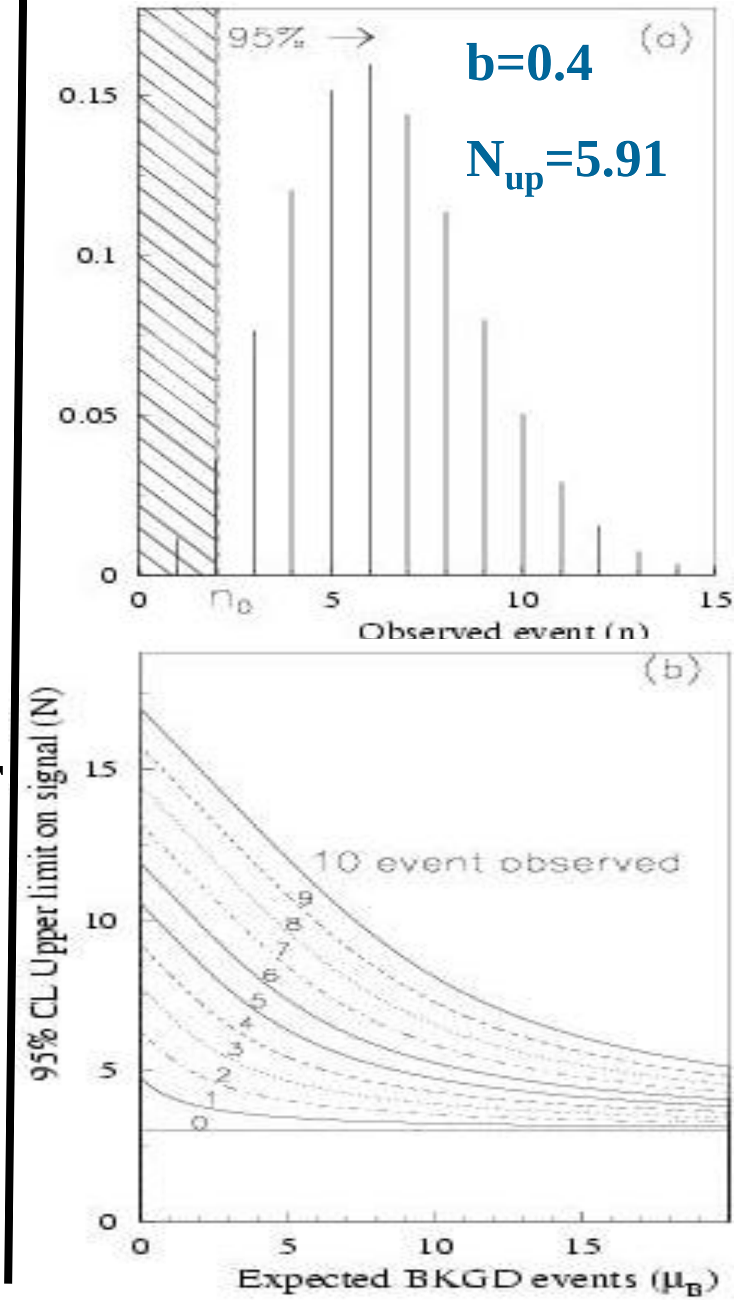
For Poisson distribution, counting a certain number of events, n : random repetition of the experiment with $\mu = N_{up}$ (N_{lo}) has probability $(1-\alpha)$ to observe more (less) than n events

In presence of background,

$$\alpha = \frac{\sum_{n=0}^{N_{obs}} \exp\left(-(N_{up}+b)\right)\frac{(N_{up}+b)^n}{n!}}{\sum_{n=0}^{N_{obs}} \exp(-b)\frac{b^n}{n!}}$$

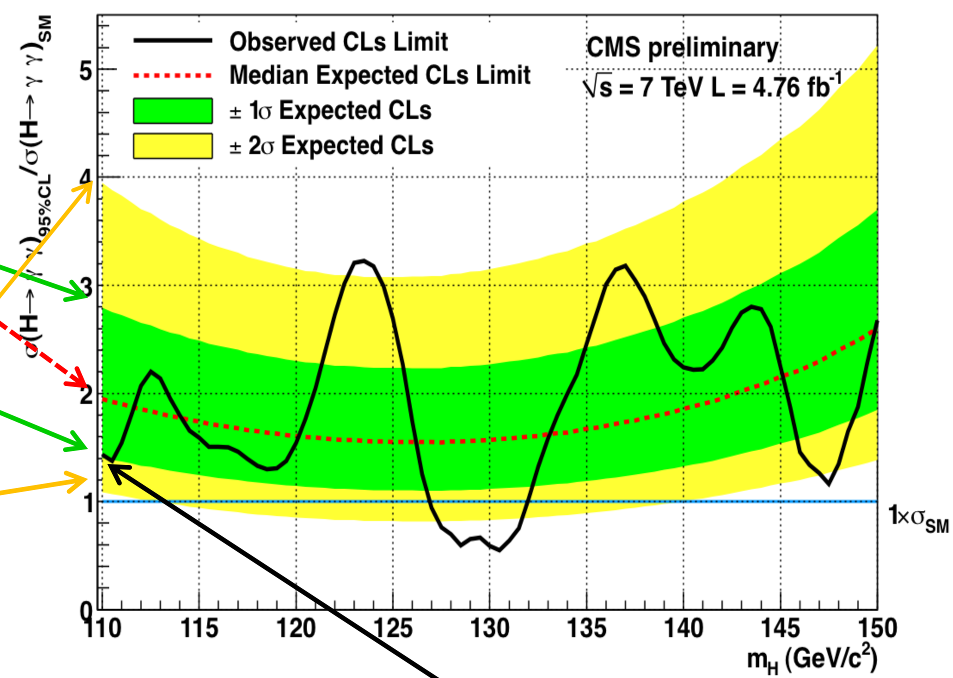


Small number is always a tricky problem. There is no thumb rule for this.



Limit calculation (qualitative argument)

- MC prediction on limit : assume null signal, S=0 and expected background, b=9
  - $N_{obs} = 9 \rightarrow N_{up} = 7.77$
    - 1σ range
      - $N_{obs} = 12 \rightarrow N_{up} = 10.74$
      - $N_{obs} = 6 \rightarrow N_{up} = 5.52$
    - 2σ range
      - $N_{obs} = 15 \rightarrow N_{up} = 14.15$
      - $N_{obs} = 3 \rightarrow N_{up} = 3.99$



- Observe limit (data) :
  - Expected background, b=9, $N_{obs} = 13 \rightarrow N_{up} = 11.85$

95% confidence limit on $\sigma_{up} = N_{up} / \int \mathcal{L}dt \times \beta \times \varepsilon$

- **CMS/ATLAS does not use this procedure, used**
  - Modified frequentist limits (CLs)

Modified frequentist (CLs) method for limit

$p_i(\bar{\theta}_i \mid \theta_i)$ **The probability of measuring θ_i-bar, given the true value θ_i**

$$\ell(data \mid \mu, \theta) = Poisson(data \mid \mu \cdot s(\theta) + b(\theta)) \cdot \prod_i p(\bar{\theta}_i \mid \theta_i)$$

$$Poisson(data \mid \mu s + b) = \prod_j \frac{(\mu . s_j + b_j)^{n_j}}{n_j!} e^{-\mu . s_j - b_j}$$

$$for \;\; an \;\; unbinned \;\; likelihood \;\; over \;\; k \;\; events: k^{-1} \prod_j (\mu S f_s(x_j) + B f_b(x_j)).e^{-(\mu S + B)}$$

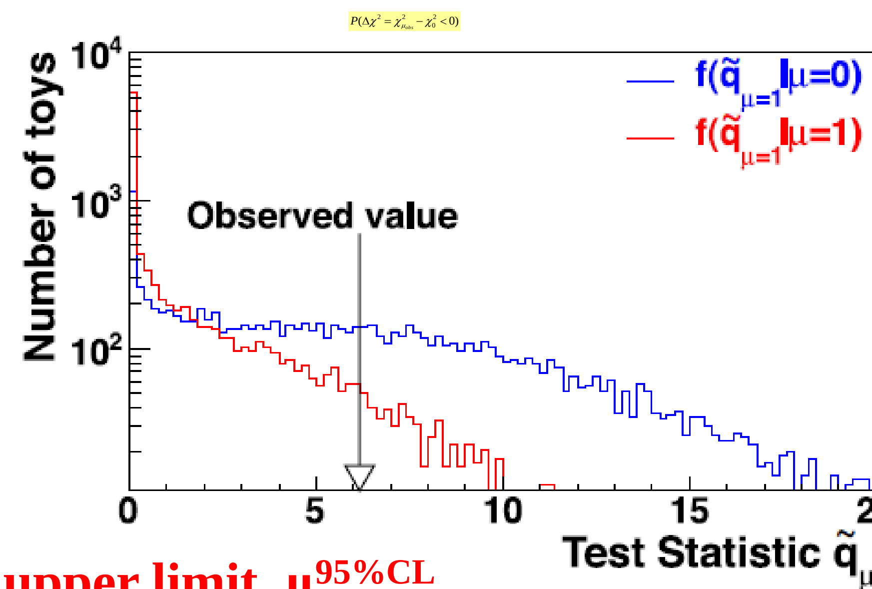
$$\text{Profile likelihood ratio}, \; q_\mu = -2 \ln \frac{\ell(data \mid \mu, \hat{\theta}_\mu)}{\ell(data \mid \hat{\mu}, \hat{\theta})}, where \;\; 0 \le \hat{\mu} \le \mu$$

$$p_\mu = p(q_\mu \ge q_\mu^{obs} \mid \mu.s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs})) = \int_{q_\mu^{obs}}^{\infty} f(q_\mu \mid \mu, \theta_\mu^{obs}) dq_\mu$$

$$p_0 = p(q_\mu \ge q_\mu^{obs} \mid b(\hat{\theta}_0^{obs})) == \int_{q_\mu^{obs}}^{\infty} f(q_\mu \mid 0, \theta_0^{obs}) dq_\mu$$

Number of nuisance parameters were 156 to 222 in last publication (Depending on mass)

$$CLs(\mu) = \frac{p_\mu}{p_0}$$



For μ=1 and $CL_S \le \alpha$ ⇒ The SM Higgs boson is excluded with (1–α) CL_S confidence level (C.L.)

Adjust μ until reach CL_S =0.05 to quote 95% CL upper limit, $\mu^{95\%CL}$

The predictable future: LHC Time-line

2009 — **Start of LHC**

Run 1: 7 and 8 TeV centre of mass energy, lu... ramping up to few 10^{33} cm^{-2} s^{-1}, few fb^{-1} d...

2013/14 — **LHC shut-down to prepare machi... nominal luminosity**

Run 2: Ramp up lu... ...0 to 100 fb^{-1}

2018 — **Injector a... ...imate luminosity**

Run 3: Ra... ...nominal, reaching ~100 fb^{-1} / year a... ...ured fb^{-1}

~2022 — **Phase-II: High-... ...ty LHC. New focussing magnets and CRAB cavities fo... ...ery high luminosity with levelling**

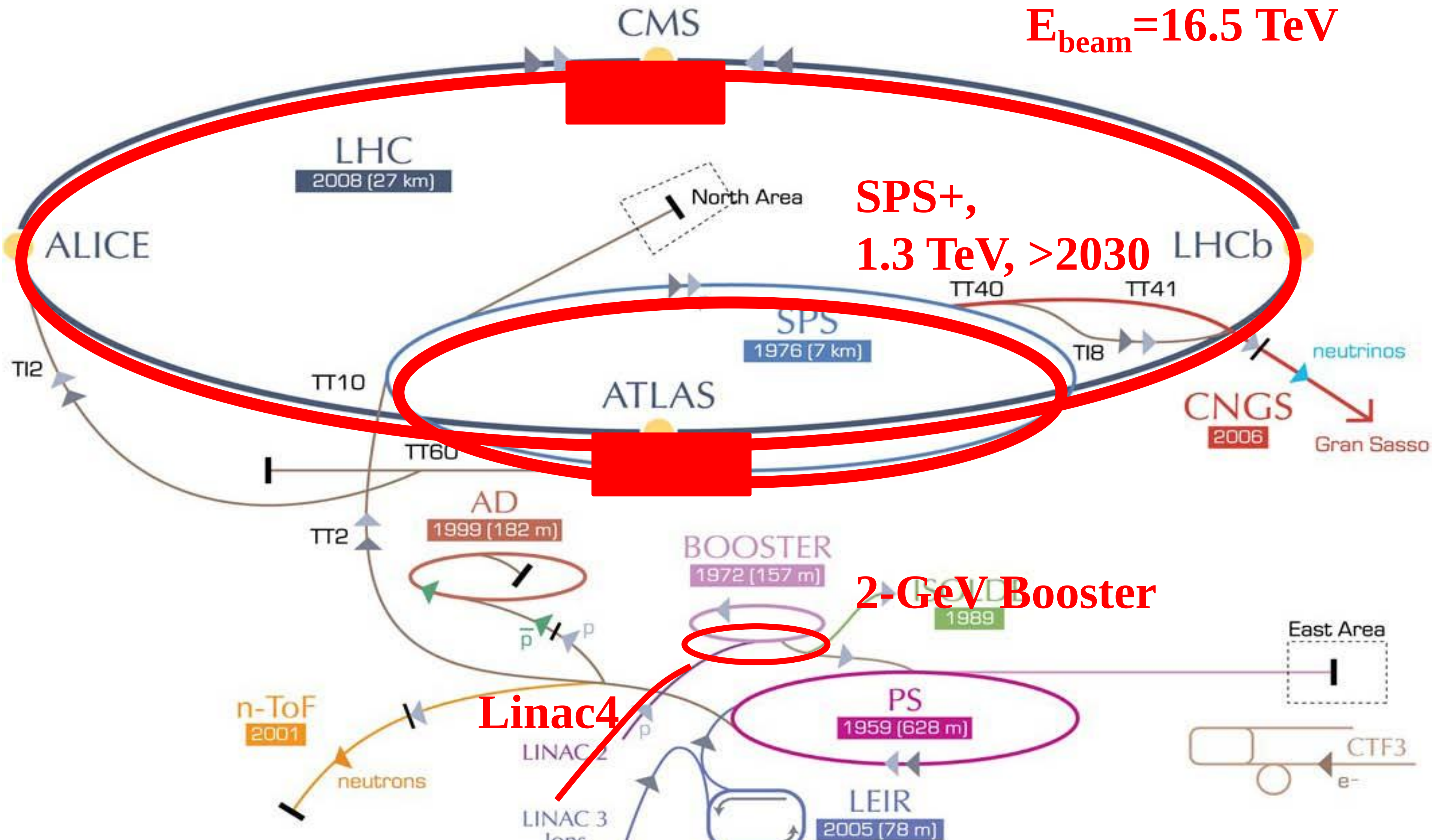
Run 4: Collect data until > 3000 fb^{-1}

2030

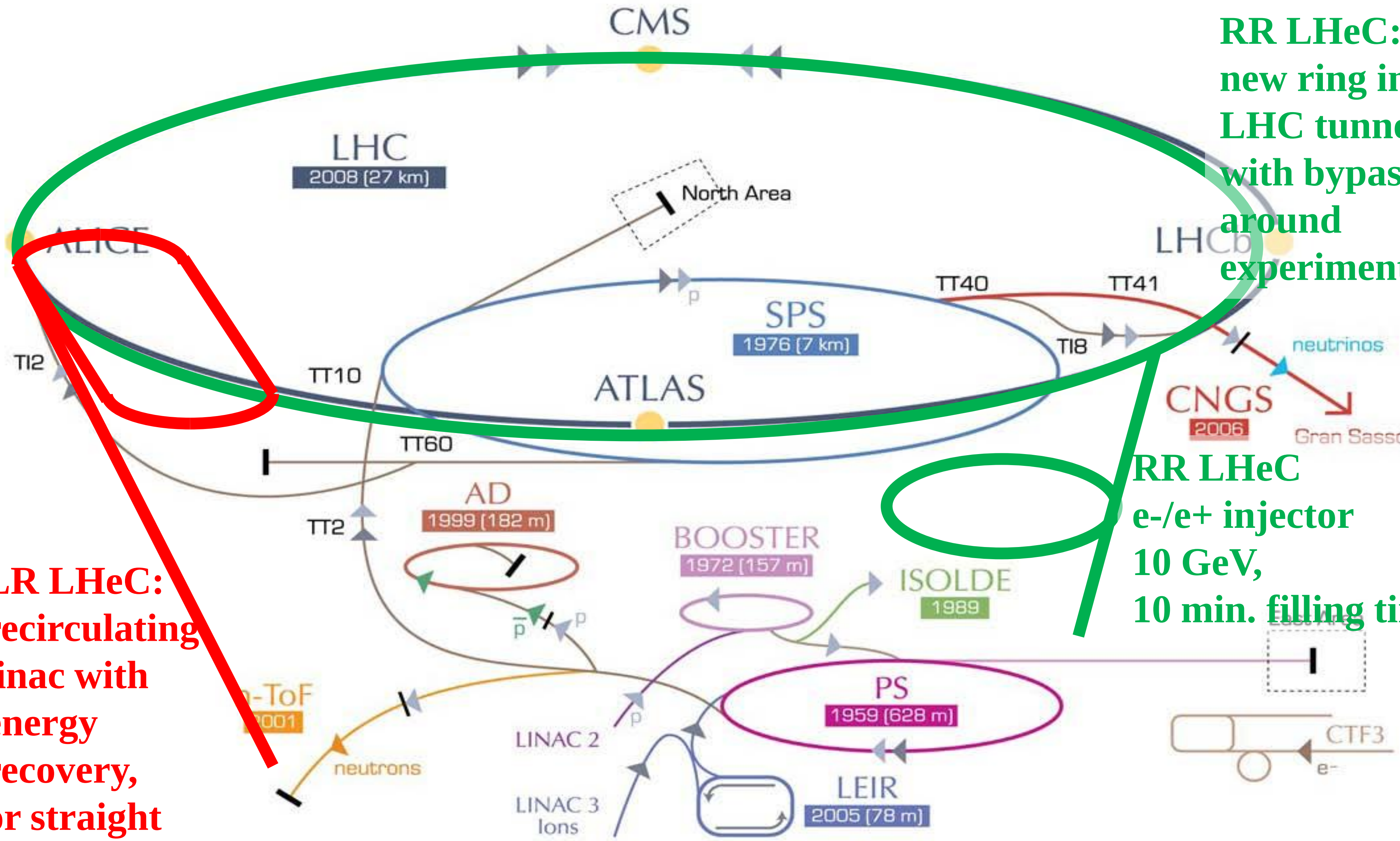
Study of the properties of the Higgs Boson
or
other ew symmetry breaking mechanism
and
Physics beyond the Standard Model

HE-LHC – LHC modifications

HE-LHC >2030
E_{beam}=16.5 TeV



LHeC options: RR and LR

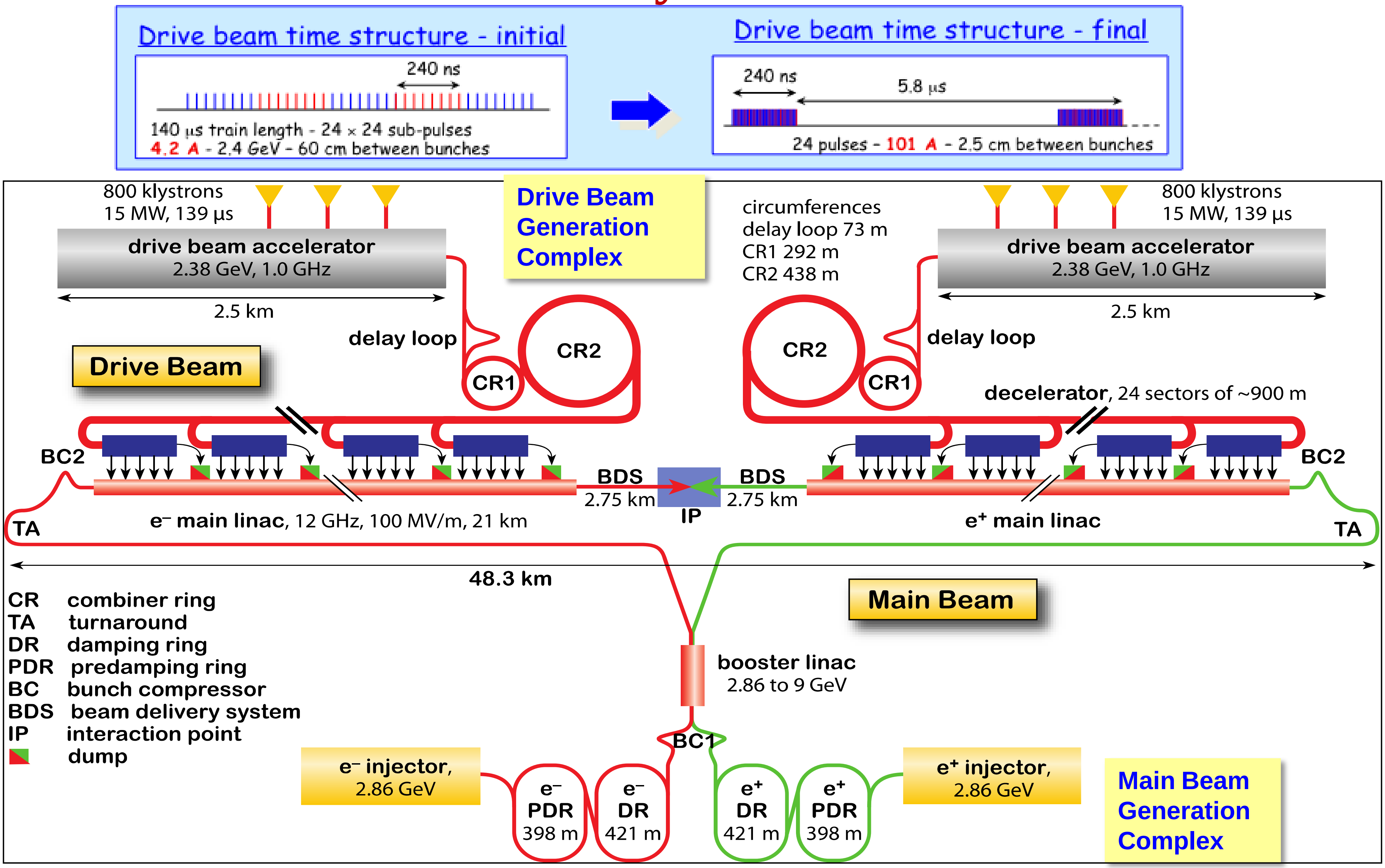


RR LHeC: new ring in LHC tunnel, with bypasses around experiments

RR LHeC e-/e+ injector 10 GeV, 10 min. filling time

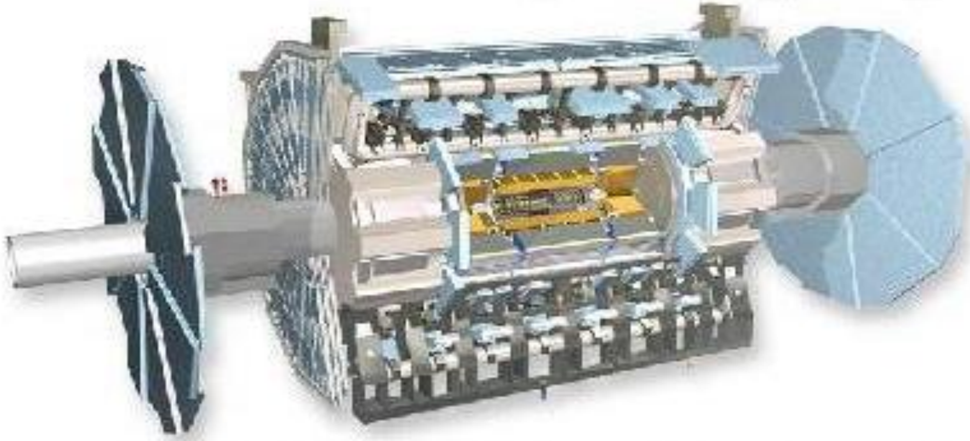
LR LHeC: recirculating linac with energy recovery, or straight linac

CLIC Layout at 3 TeV



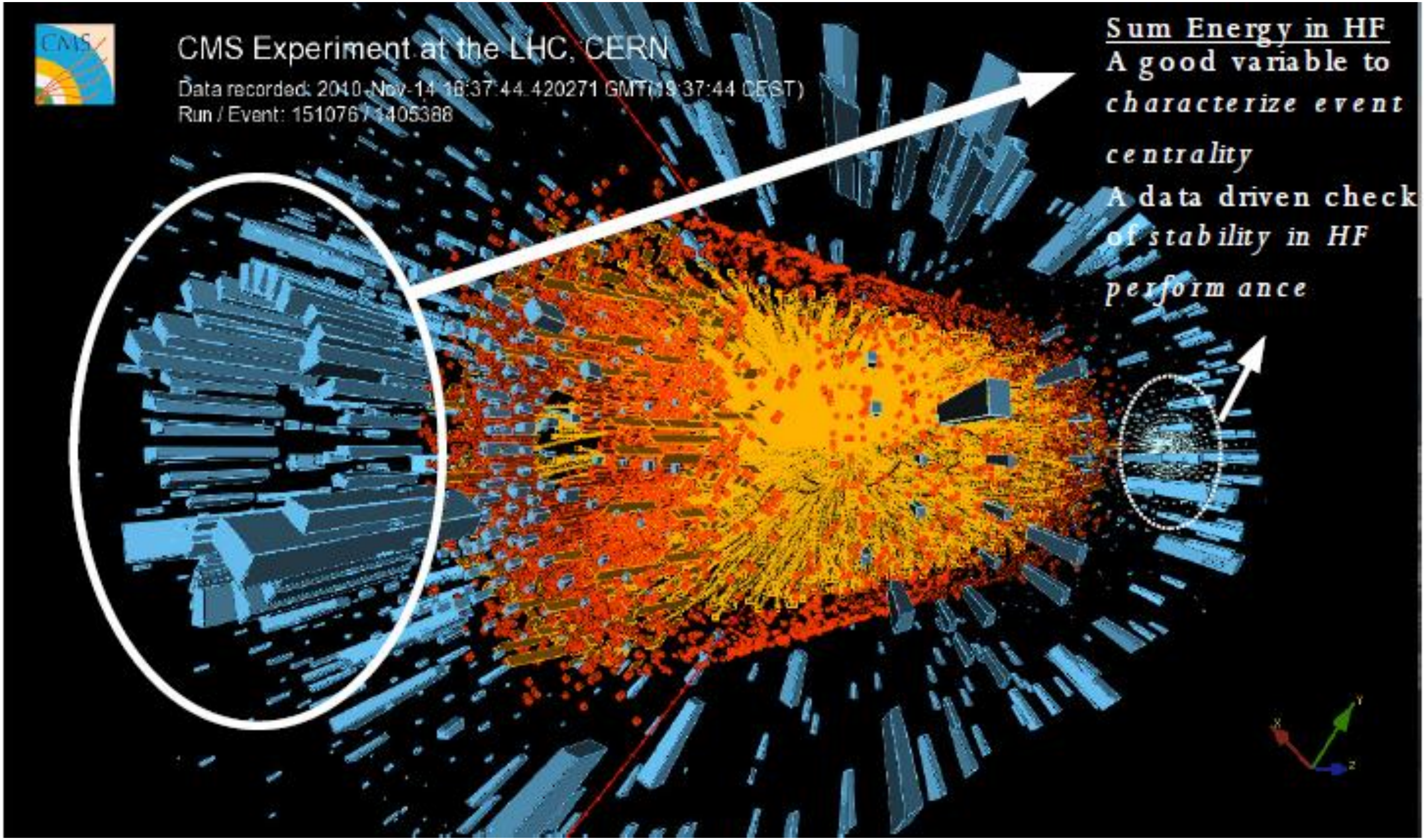
ATLAS and CMS Detectors

B field: 2.6 T (Solenoid), 4 T (Toroid) | 3.8 T (Solenoid)



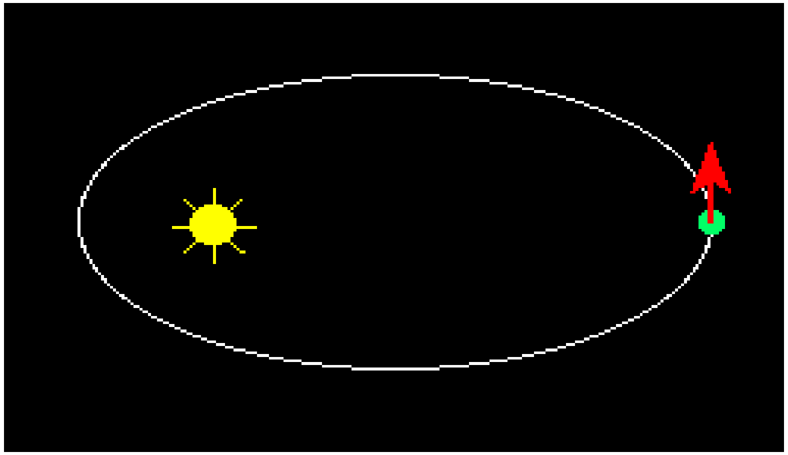
		ATLAS	CMS
Inner tracker:	$\|\eta\|$ coverage	2.5	2.5
	$\sigma(p_T)/p_T$ at p_T=100 GeV	3.8%	1.5%
EM calorimeter:	$\|\eta\|$ coverage	3.2	3.0
	$\sigma(E)/E$	$9\%/\sqrt{E} + 0.5\%$	$3\%/\sqrt{E} + 0.25\%$
HAD calorimeter:	$\|\eta\|$ coverage	4.9	5.2
	$\sigma(E)/E$ (EM+HAD combined)	$70\%/\sqrt{E} + 3.3\%$	$70\%/\sqrt{E} + 8\%$
Muon system:	$\|\eta\|$ coverage	2.7	2.4
	$\sigma(p_T)/p_T$ at p_T=1 TeV	7%	5%

Pb+Pb interation



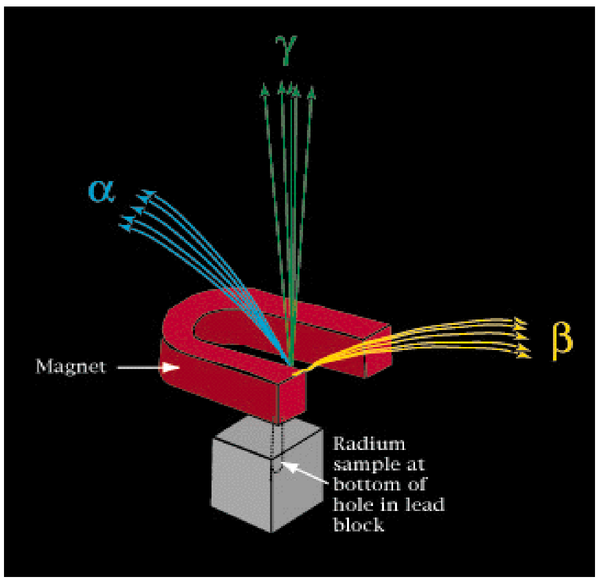
Nature of interactions

Gravitational --solar system/galaxy

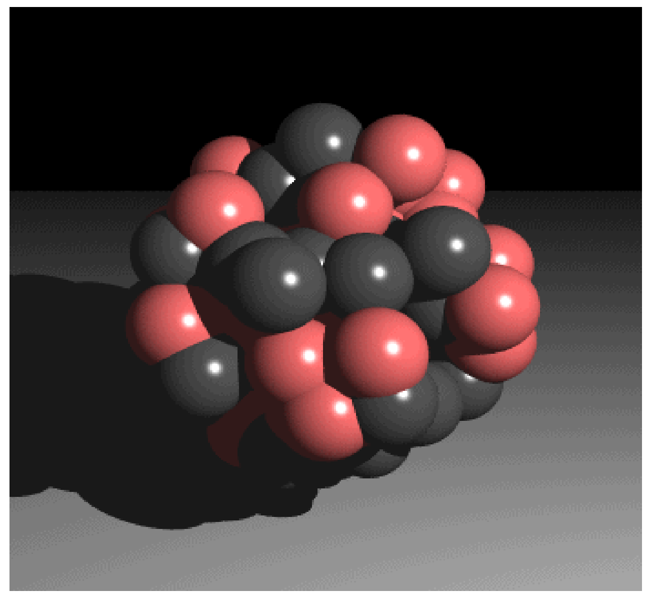


Electromagnetic --photon

Weak --radioactivity



Strong --binding of nucleus



Electromagnetic interactions : Maxwell's Equations

James Clerk Maxwell

1831-1879

$\nabla \bullet D = 4\pi\rho$	Inverse square law
$\nabla \bullet B = 0$	No magnetic charges
$c\nabla \times E = \partial B / \partial t$	Electromagnetic induction
$c\nabla \times H = - \partial D / \partial t + 4\pi J$	Ampere's circuital law + charge conservation

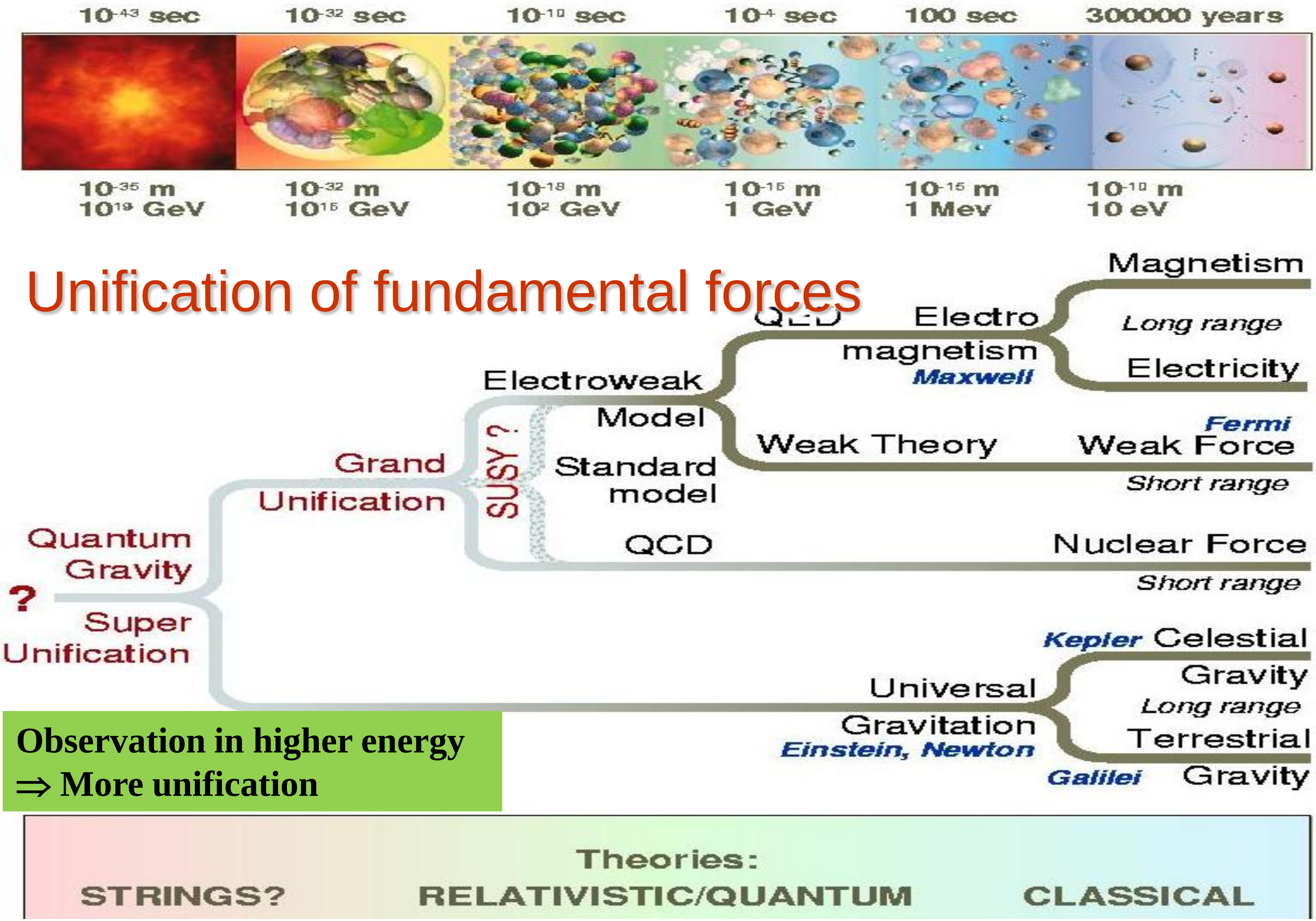
Unified Theory of Electricity and Magnetism

$$c\, \partial_\mu F^{\mu\nu} = 4\pi J^\nu$$

$$\partial^\mu F^{\nu\lambda} + \partial^\nu F^{\lambda\mu} + \partial^\lambda F^{\mu\nu} = 0$$

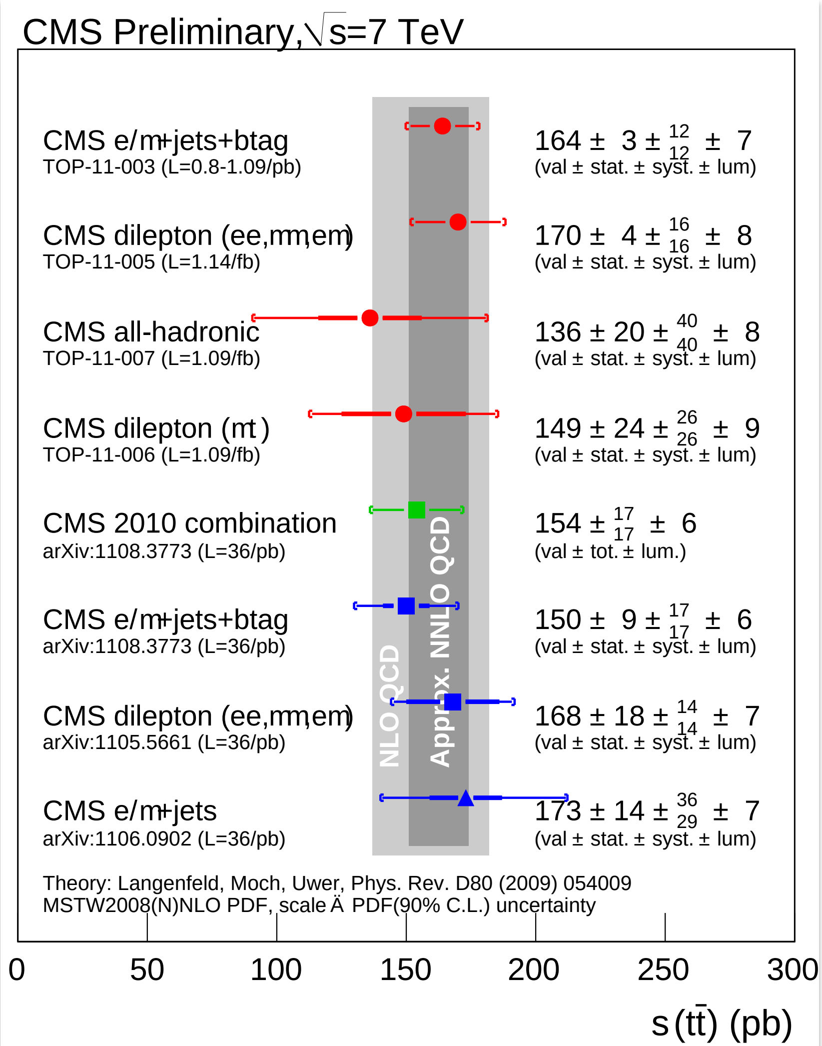
The road to unification

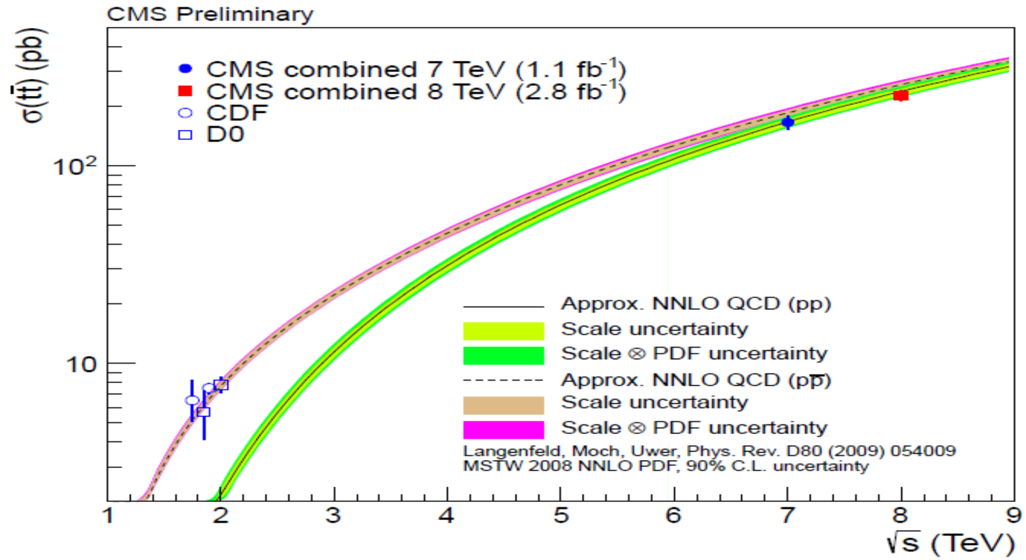
Unification of fundamental forces

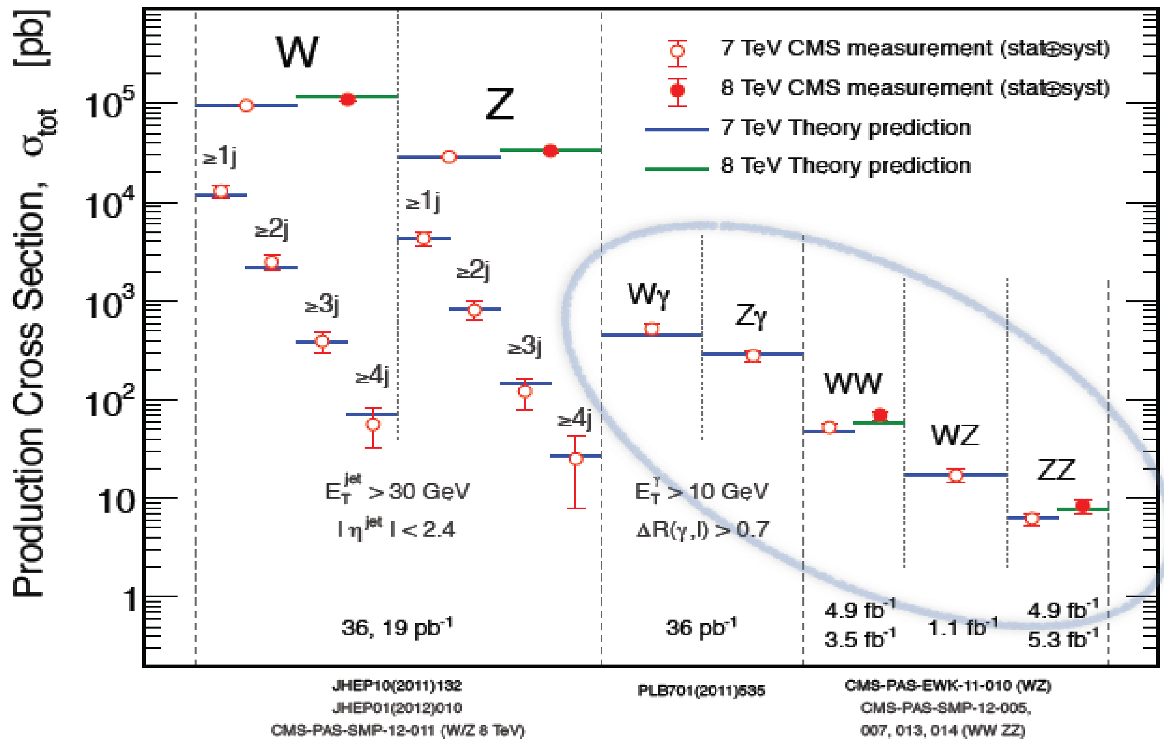


Observation in higher energy
⇒ More unification

Standard model processes at √s=7 and 8 TeV







- **Good agreement**
- **Lots of data,**
  - **confident to look on Higgs**

Common uncertainties in Higgs searches

- Integrated luminosity : 2 (4)% in 7 (8) TeV data
- Trigger efficiency of electron/photon/muon
- Electron/photon energy scale
- Muon energy scale
- Jet Energy Scale
- Theoretical uncertainty on production rate and braching fraction
  - QCD scale (μ_F,μ_R) : +7-8% for gg, 1% for WH/ZH, +4-9% for ttH
  - Branching fraction 5%
  - PDF : 8 (4)% for gluon (quark) initiated processes
  - Jet associated channels : upto 25%
  - Interference of Higgs signal with other SM processes, <0.3%

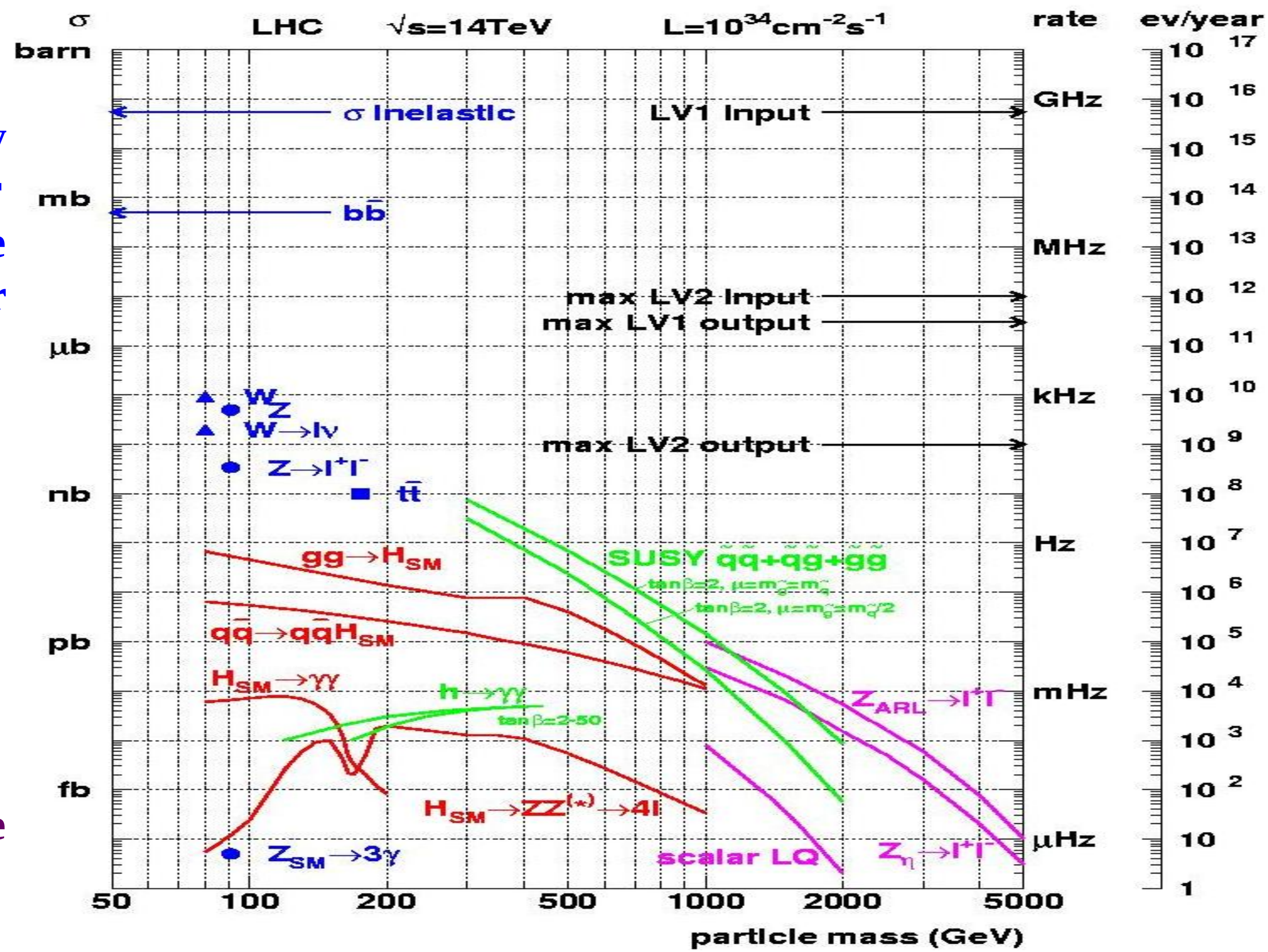
Physics goal at LHC and design of detectors

- CMS and ATLAS are "general purpose" detectors – those were designed to be able to detect anything!
- We believe that the Higgs boson, and/or Supersymmetric (SUSY) particles exist, and the LHC will provide collisions energetic enough to create them

But we cannot see Higgs/SUSY particles directly as they either decay to lighter (stable) particles or cannot be seen with any known detector

We have designed our detector to look for the stable particles and signs of "invisible" particles…..

Interesting physics processes are 10^{-10} - 10^{-9} times smaller than inelastic pp interaction rate ➜ Searching for a needle in a hay stack

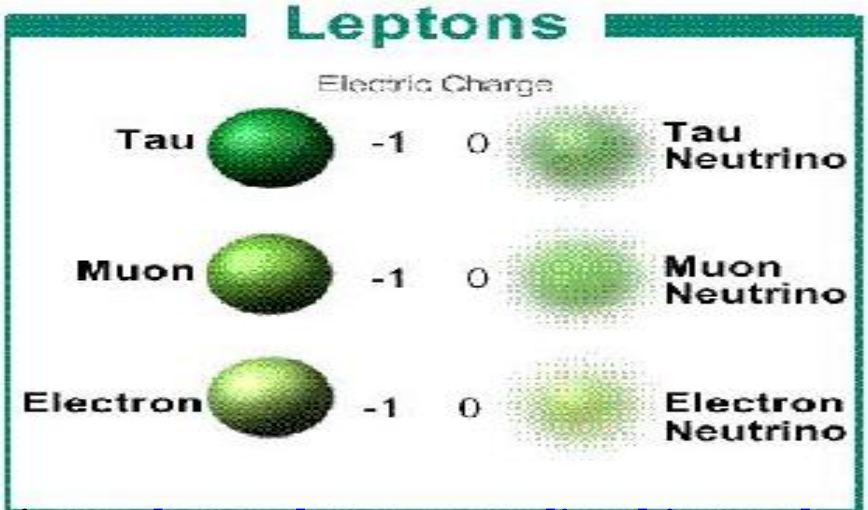


Present Knowledge About Fundamental Particles

3rd

2nd

1st



	Discovery	
τ	$e^+e^- \longrightarrow e^{\pm}\mu^{\mp}\ \not{E}$	1975
ν_τ	$\nu_\tau \longrightarrow \tau + X$	2000
μ	Cosmic Ray	1937
ν_μ	ν-beam study	1962
e	Since ages	
ν_e	Reactor Expt	1957

Generation : Theory does not predict this number

3rd

2nd

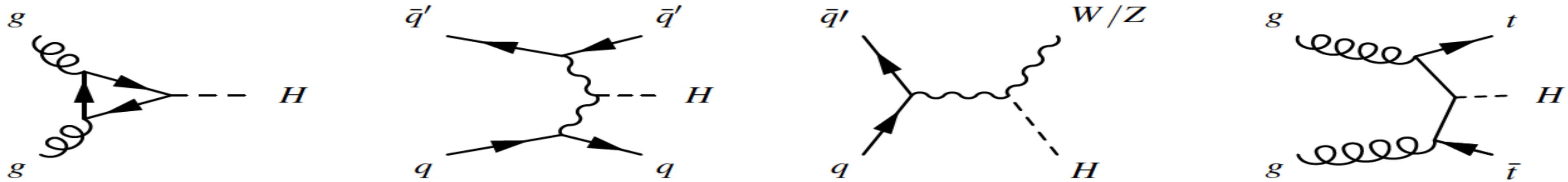
1st

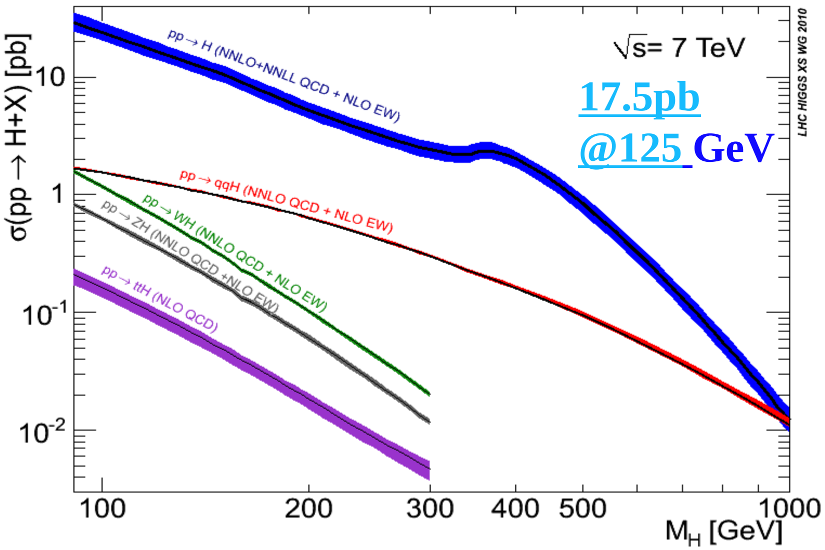
u, d, s	Hadron	early
	Spectroscopy	60's
Charm	p Be $\longrightarrow c^+c^-X$	
	$c^+c^- \longrightarrow X(f\bar{f})$	1974
Beauty	pPt $\longrightarrow \mu^+\mu^-X$	1977
Top	$p\bar{p} \longrightarrow \ell^+\ell^-X$	1995
	$\ell^{\pm}$+Jet	

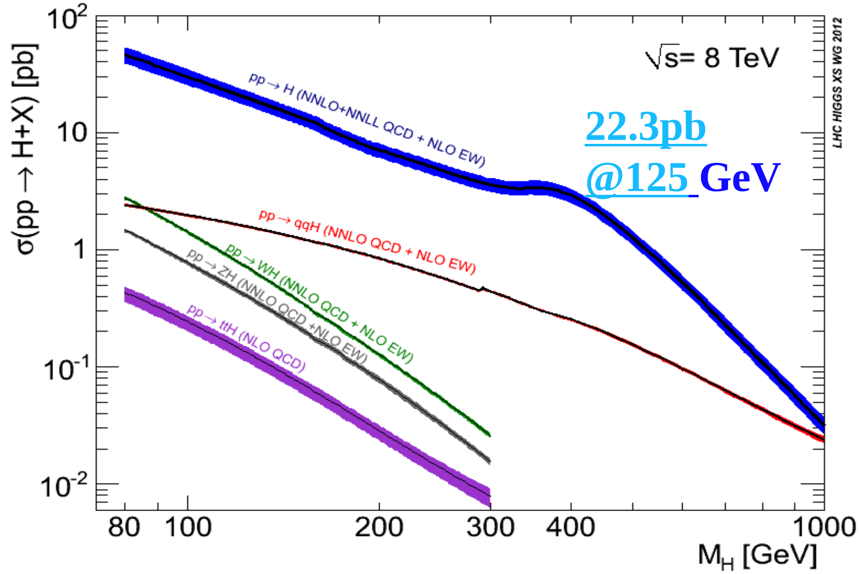
Late discovery : High mass or low interaction rate (rare process)

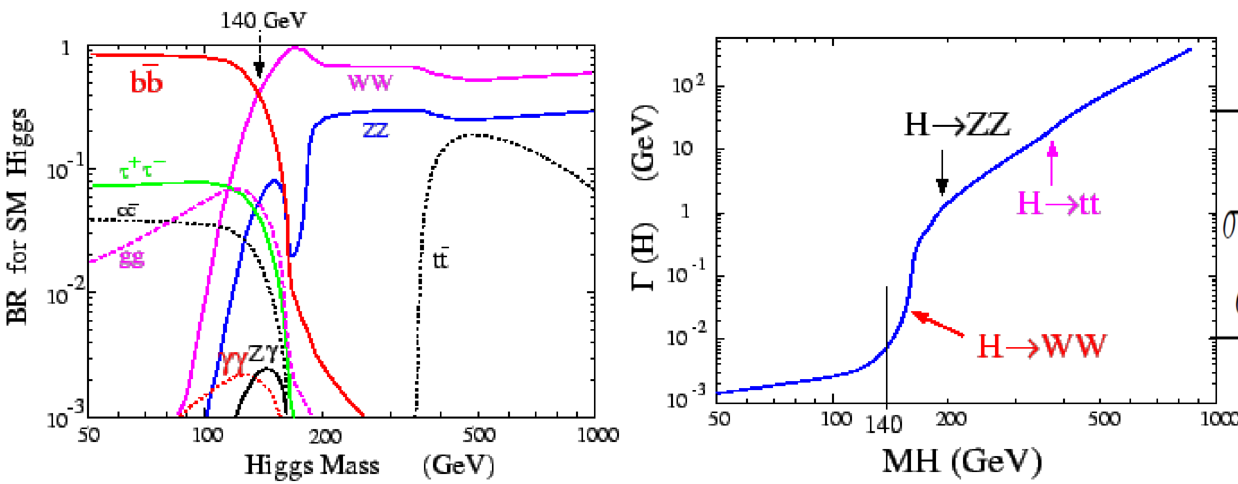
- **Heavy particles (unstable) decay to low mass particles**
- **Stable particles ($\tau \geq 10^{-8}$ sec) are detected in the instrument**

Higgs production cross section







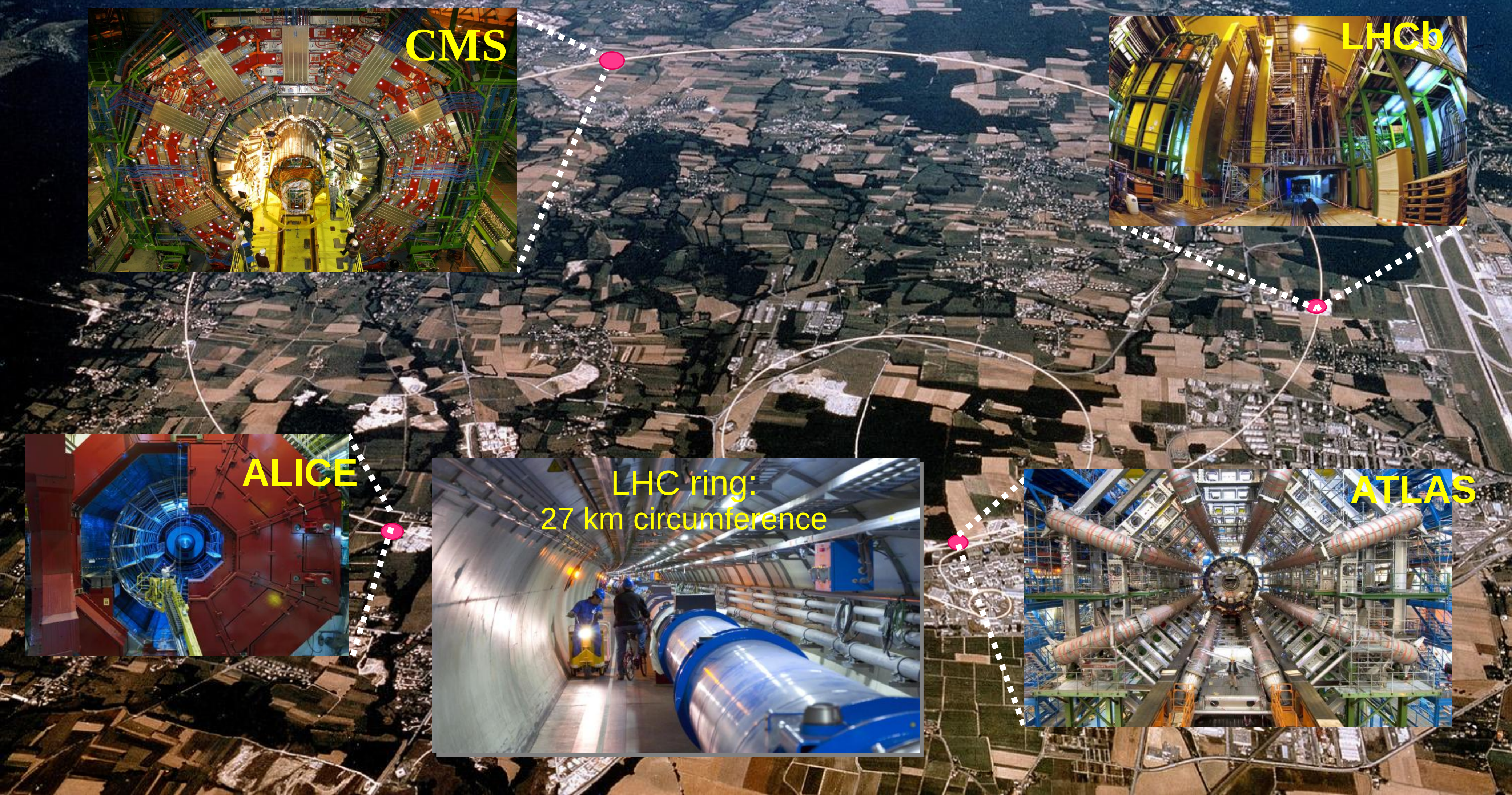


	Tevatron	8 TeV LHC
σ_{ggH} - gluon fusion	0.95 pb	19.52 pb
σ_{VH} - associated production	0.21 pb	1.09 pb
σ_{VBF} -vector boson fusion	0.07 pb	1.56 pb

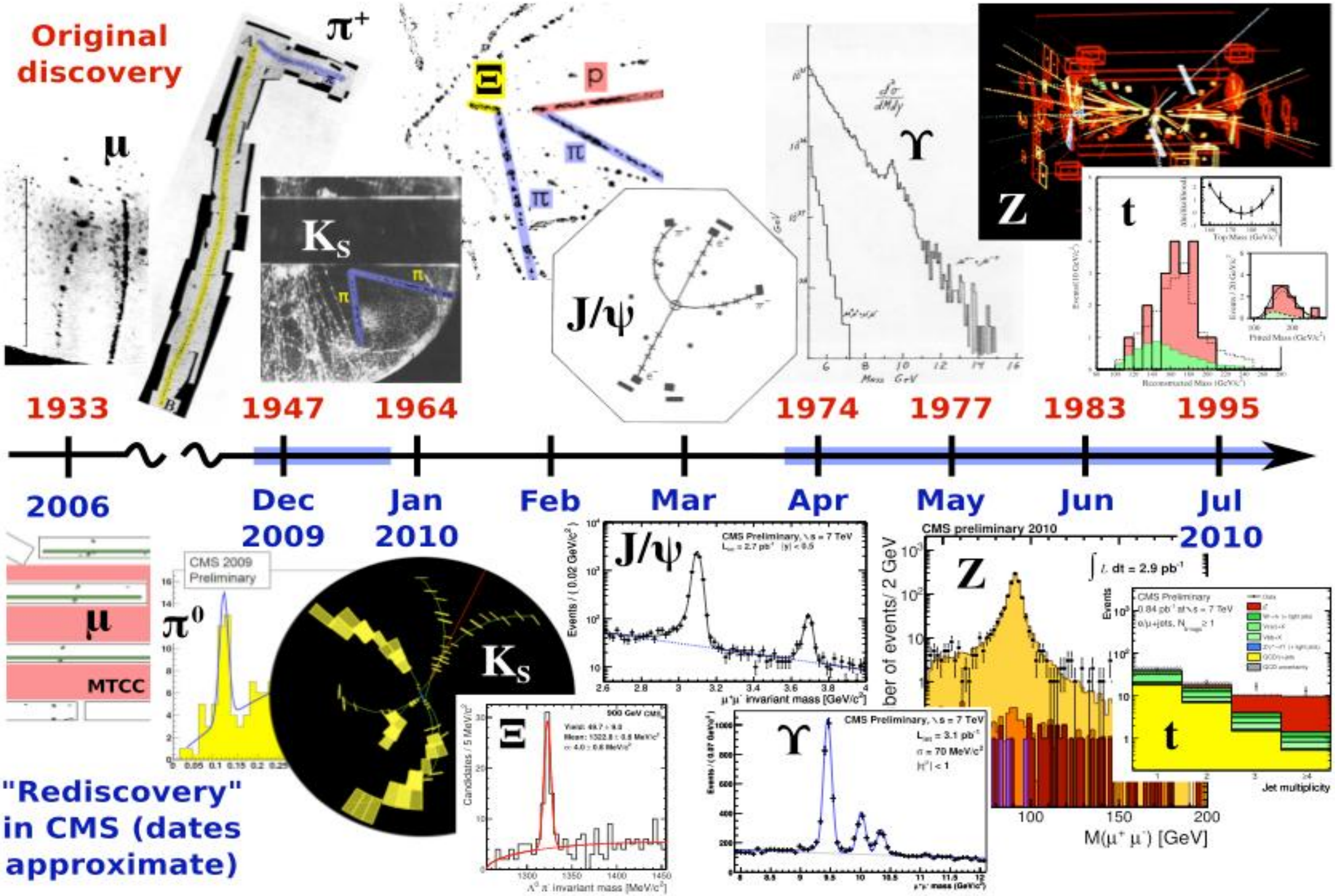
$m_H = 125\ \mathrm{GeV}/c^2$

We are entering a New Era in Fundamental Science

The Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is a turning point in particle physics.



Re-discovering the Standard Model at 7TeV



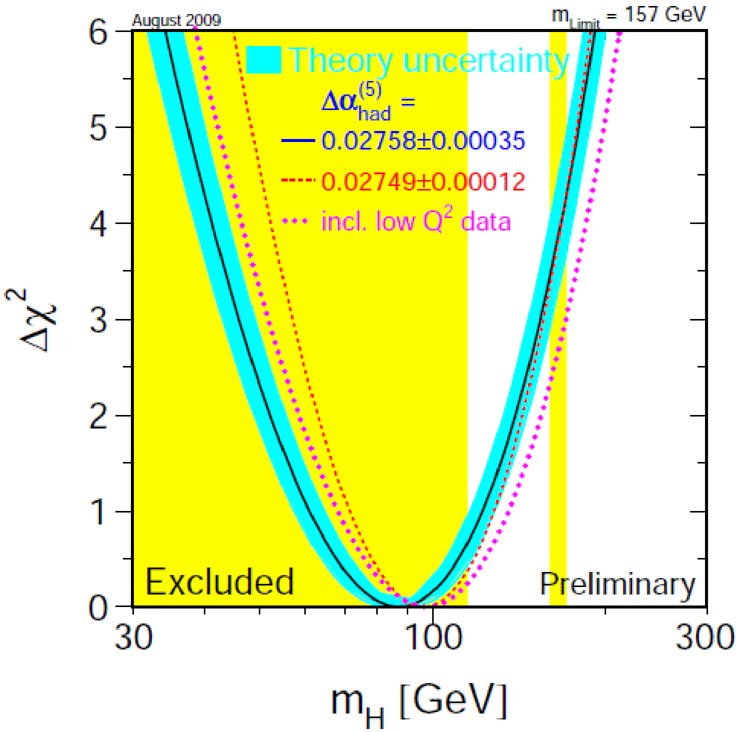
Status of Higgs search before LHC run

Experiment

Indirect constraints from precision EW data :

M_H< 260 GeV(2004)
M_H< 186 GeV(2005)
M_H< 166 GeV(2006)
M_H< 154 GeV(2008)
M_H < 157 GeV(2009)

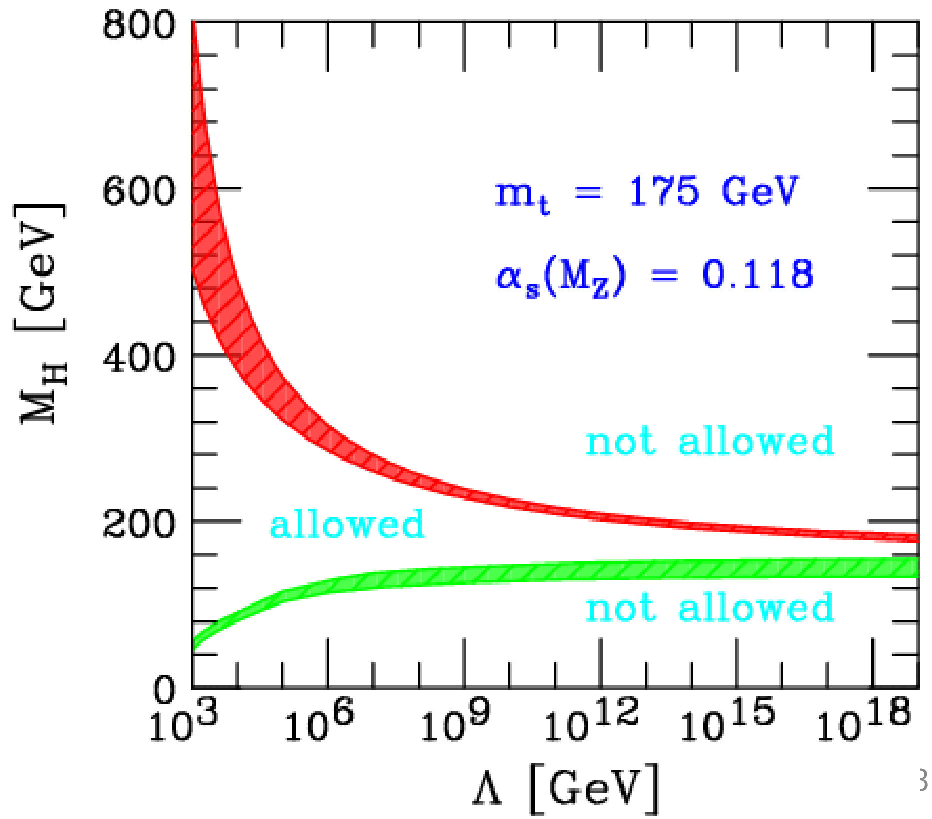
Direct limit from LEP:
M_H > 114.4 GeV



SM theory

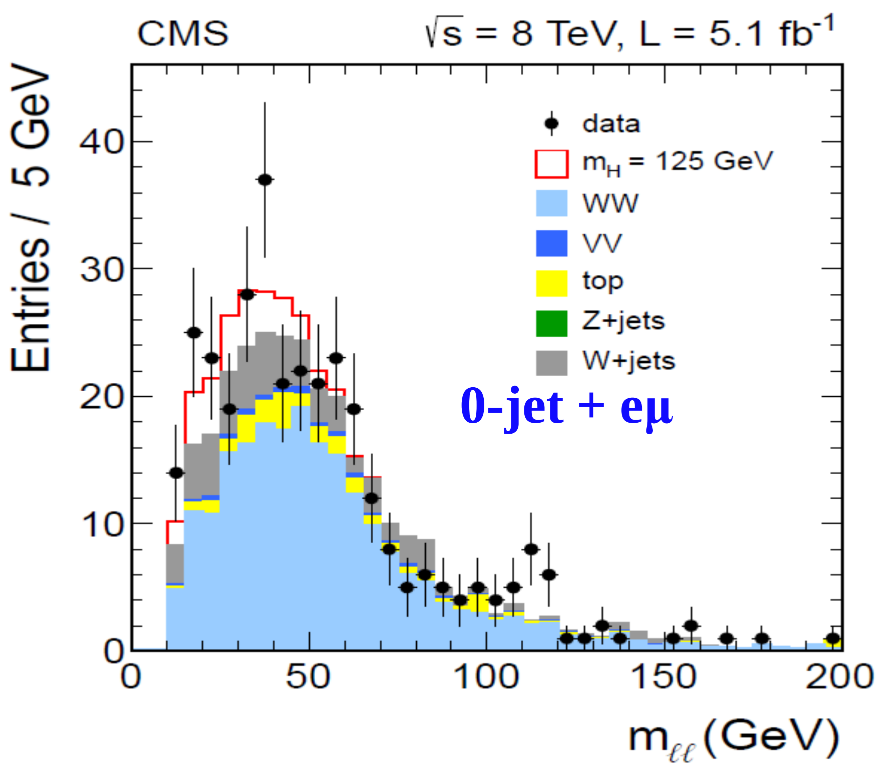
The triviality (upper) bound and vacuum stability (lower) bound as function of the cut-off scale Λ

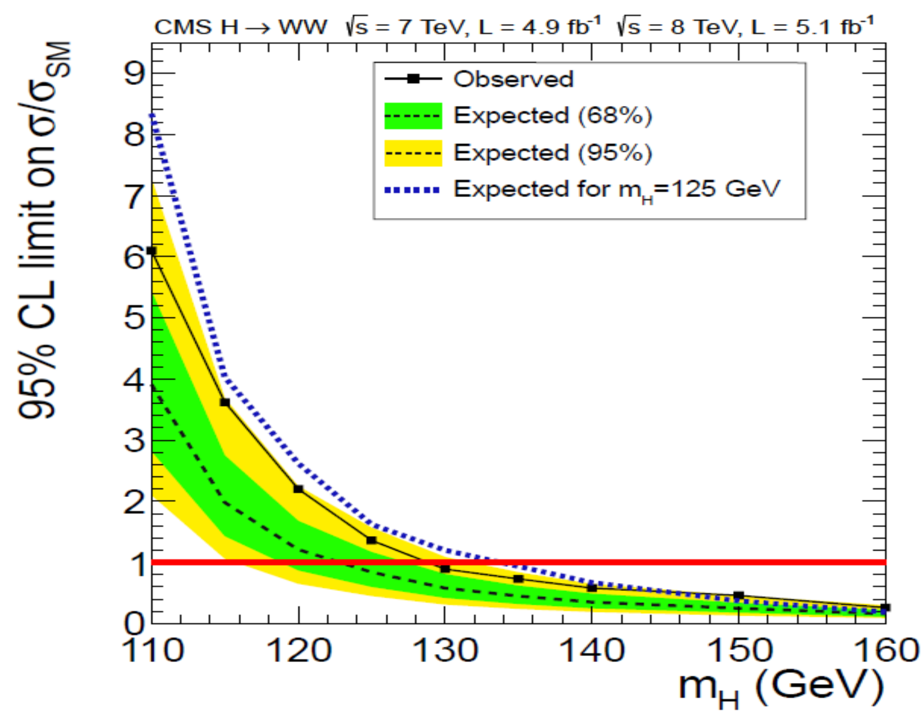
"triviality" :
Higgs self-coupling remains finite



$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

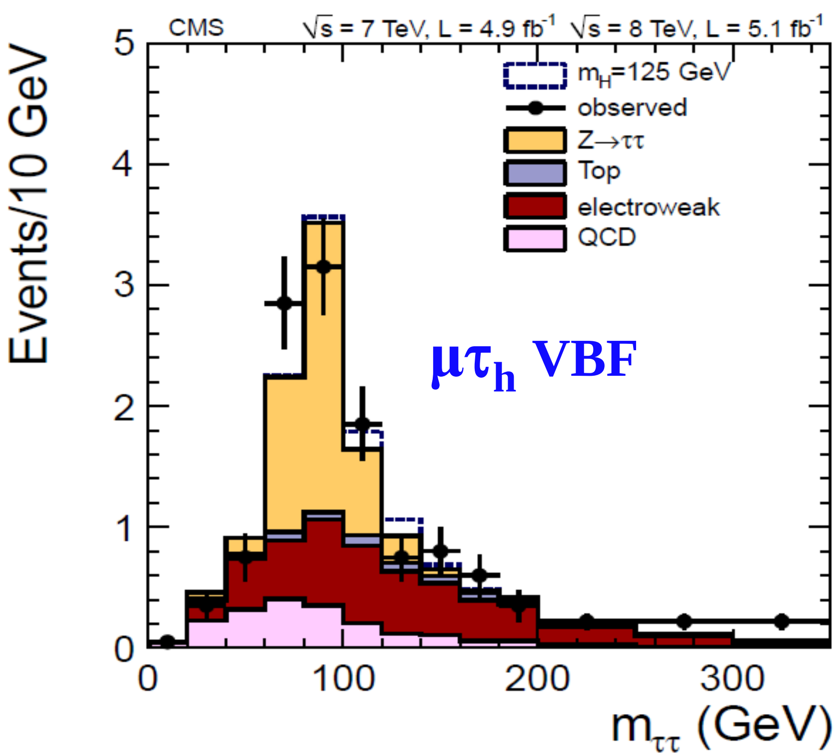
- P_T>20(10) GeV
- Separate selection for o-jet, 1-jet and 2-jet categories
  - Same is true for ee/μμ and eμ channel
- M_{ll} >12 GeV and | M_{ll} – M_Z|>15 GeV
- $E^{miss}_{T,rel}$ ($E^{miss}_T \times Sin(min(\Delta\varphi,\pi/2))$) > 25 GeV, for opposite/same flavour Δφ=angle between E_T^{miss} and nearest lepton
- Dominant background is tt-bar and DY, also WZ, ZZ and Wγ

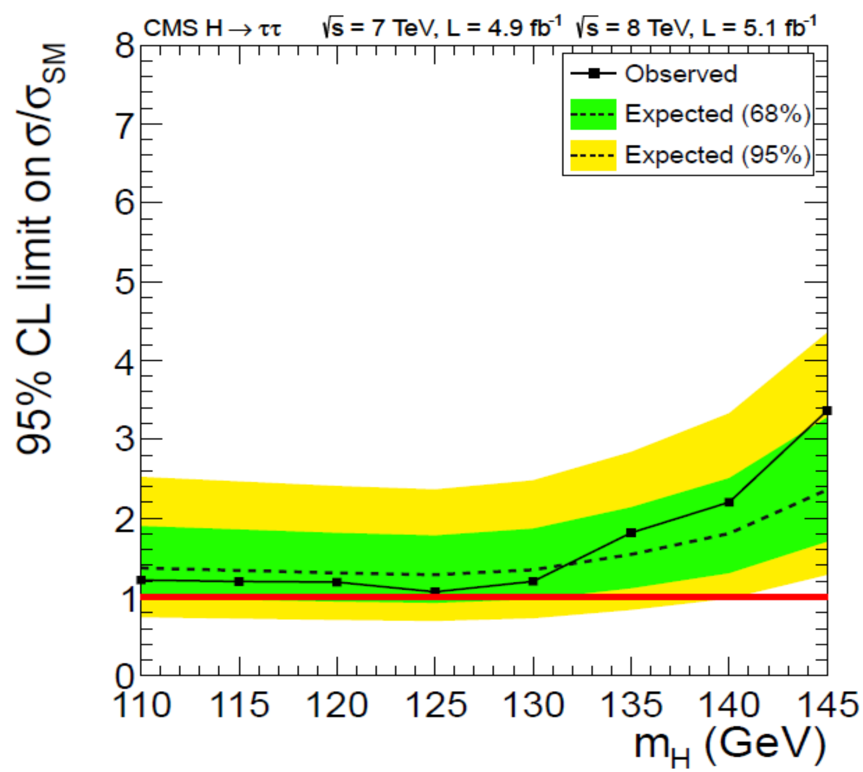




$H \rightarrow \tau\tau$

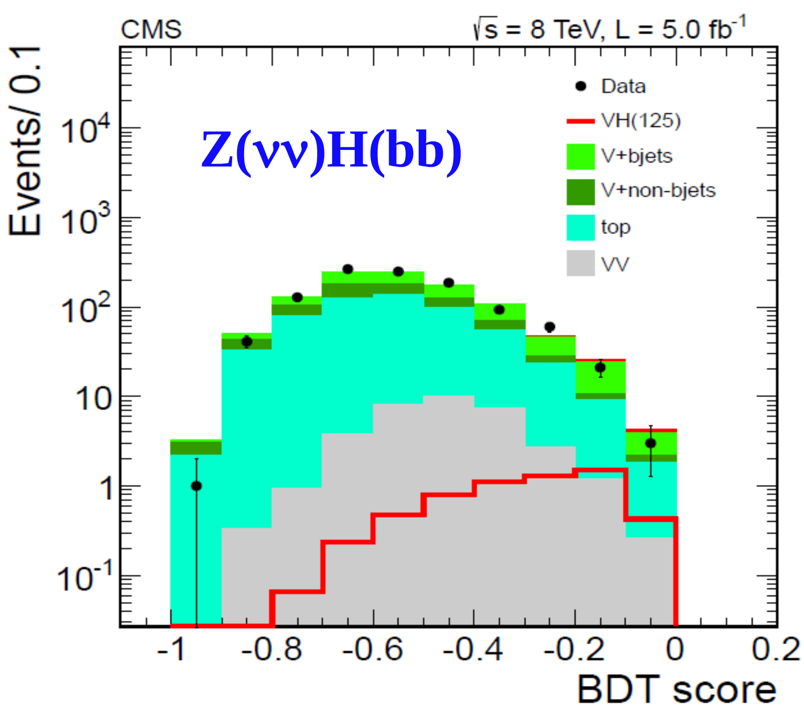
- $e\mu$, $\mu\mu$, $e\tau_h$, $\mu\tau_h$
- Also according to # of jets (P_T>30 GeV)
- Leading P_T >40 GeV for hadronic tau and >35(30) for $e\mu/\mu\mu$ channel
- $m_{\tau\tau}$: reconstruction using missing E_T projection along lepton direction
- Backgrounds : $Z\rightarrow\tau\tau/\mu\mu$, QCD, W+jets, Z+jet, tt-bar, Diboson
- M_T of lepton and missing E_T <40 GeV (remove W+jet events)

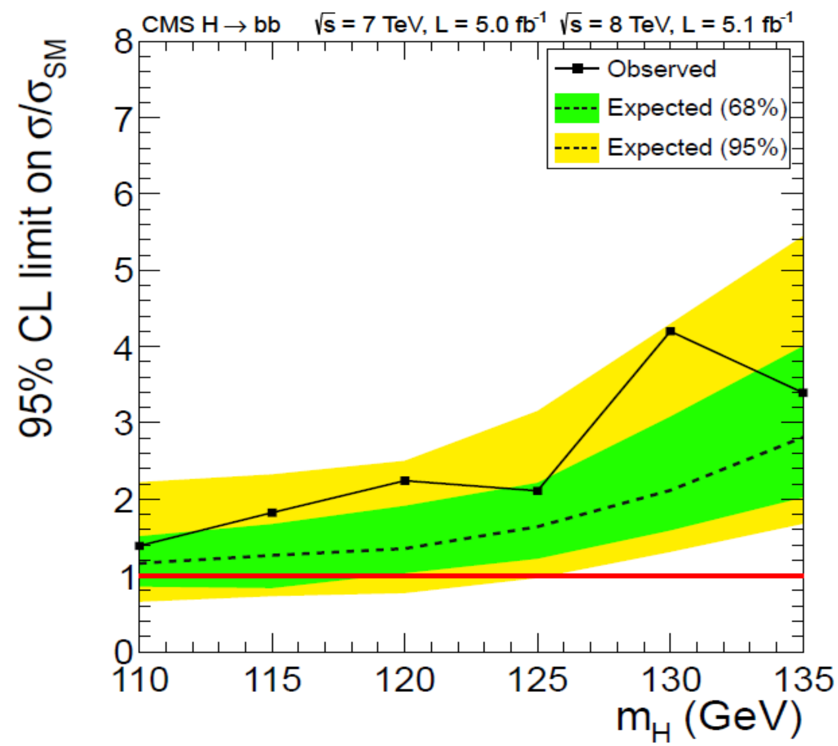




VH→*ll*/*l*ν/νν bb

- Due to large background and trigger criteria, it is looked with an association with W or Z
- P_T(V) :[50-100] GeV range with Z (*ll*)
- P_T(V) >170 GeV with W(*l*ν)
- 120 < P_T(V) < 160 GeV with Z(νν)
- BDT trained at discrete mass points
- Backgrounds : QCD, W/Z+jets, tt-bar, Single top, Diboson





Types of Particle Collider

Begins with fix target (one beam), for $E_{beam} >> m_{pro}$, $E_{CM} \approx \sqrt{2 m_{pro} E_{beam}}$

Proton-Proton Collider (e.g., LHC)

Discovery machine

$$E_{proton1} = E_{d1} + E_{u1} + E_{u2} + E_{gluons1}$$

$$E_{proton2} = E_{d2} + E_{u3} + E_{u4} + E_{gluons2}$$

Collision could be between quarks

or gluons, so

$$0 < E_{collision} < (E_{proton1} + E_{proton2})$$

i.e., with a single beam energy you can "search" for particles of unknown mass!

Limited by the strength of bending magnet

Electron-Positron Collider (e.g., LEP)

Mainly for precision study

Electrons are elementary particles, so

$$E_{collision} = E_{e-} + E_{e+} = 2\,E_{beam}$$

e.g., in LEP, $E_{collision} \sim 91$ GeV $= m_Z$

i.e., can tune beam energy so that you always produce a desired particle!

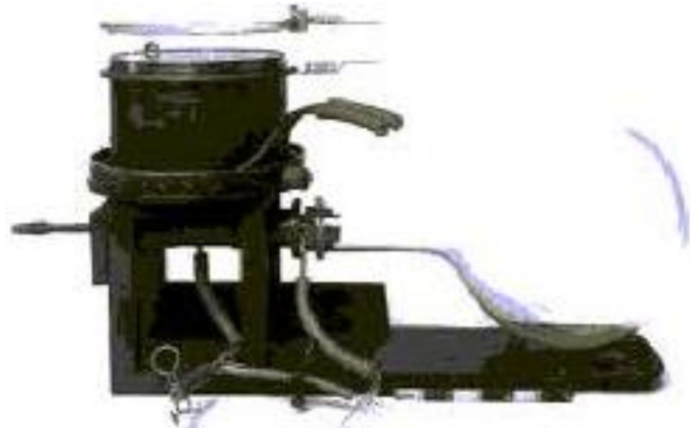
Limited by synchrotron radiation loss

Combination of these two, electron+proton are also there, e.g. HERA

Precision and rarity

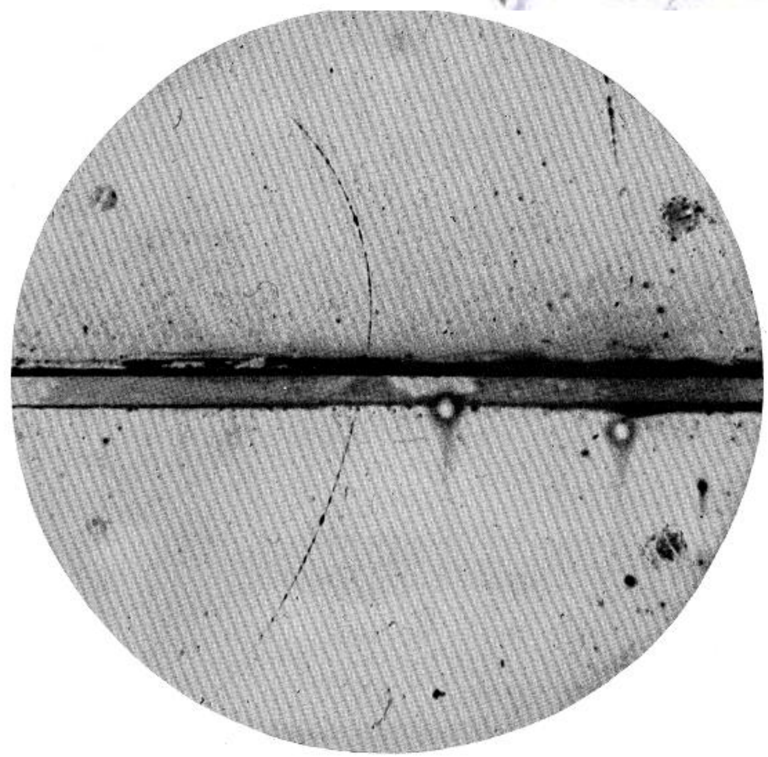
Wilson Cloud chamber : Ions act as nuclei for the condensation of supersaturated water vapour

Wilson's original cloud chamber, 1911



Discovery of positron in 1932 :

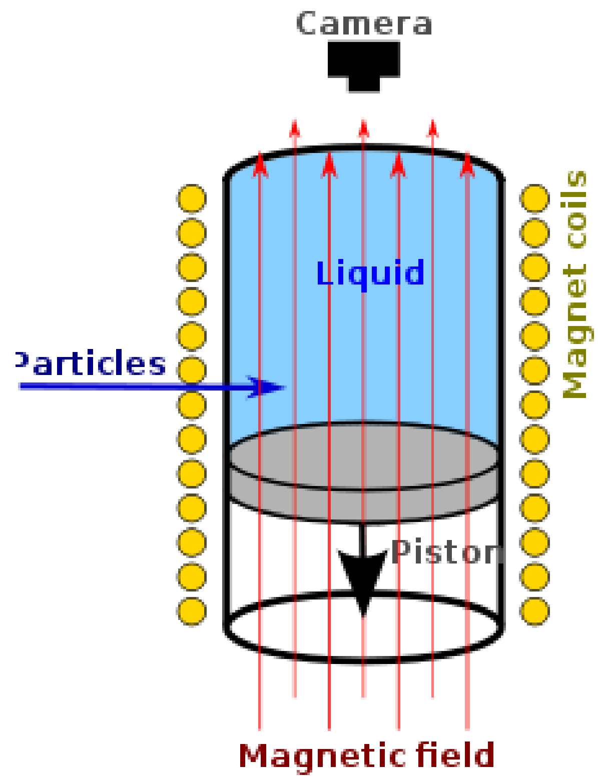
63 MeV positron passed 6mm lead from bottom and emerging as a 25MeV positron



Not possible to study interaction of particles, Position resolution : 500µm, ….

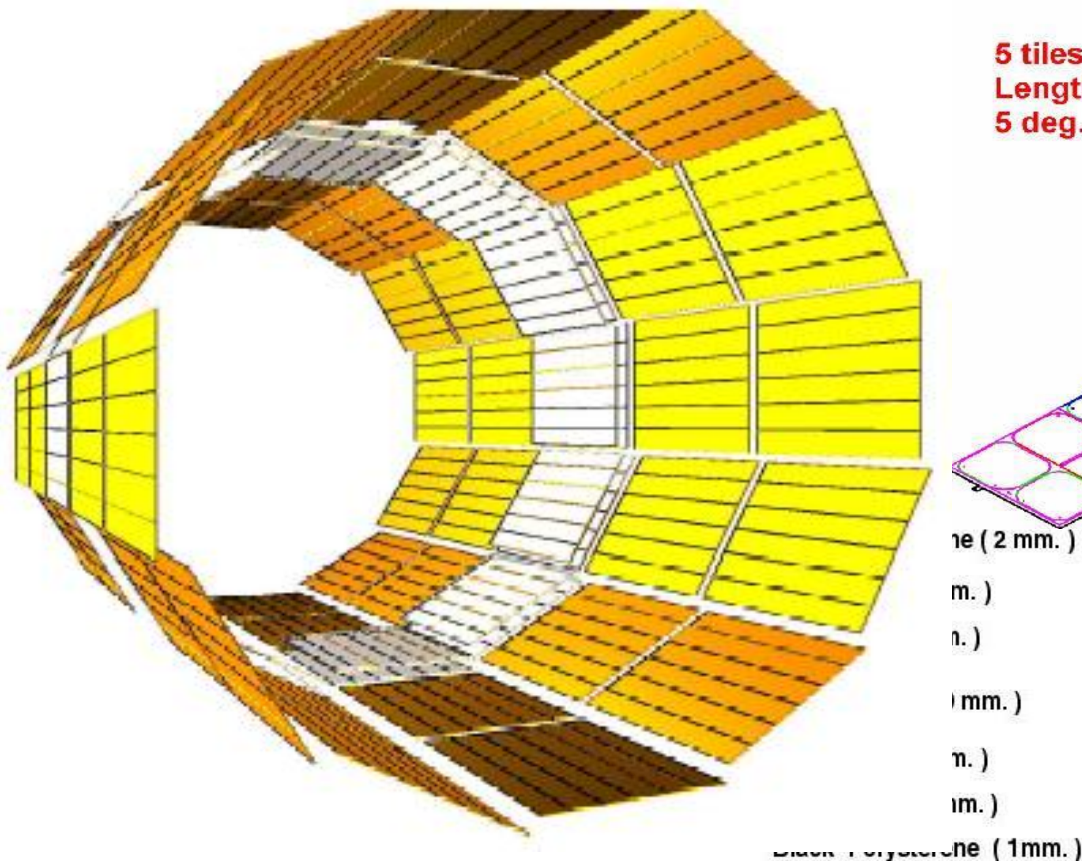
Gargamelle Bubble chamber : Discovery of neutral current in 1973

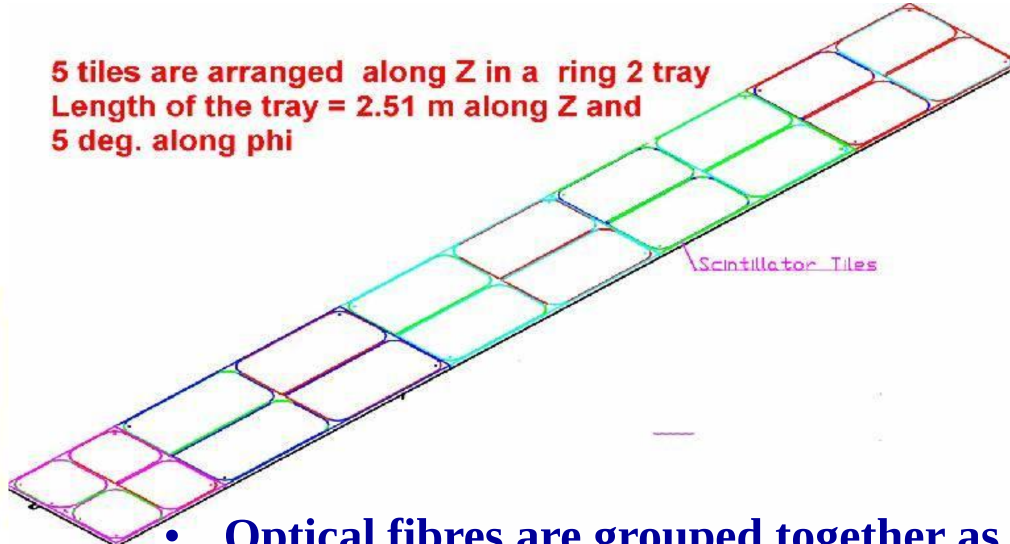
l=4.8m
d=2m
Wt=1000ton
18 ton liquid
freon (CF_3Br)



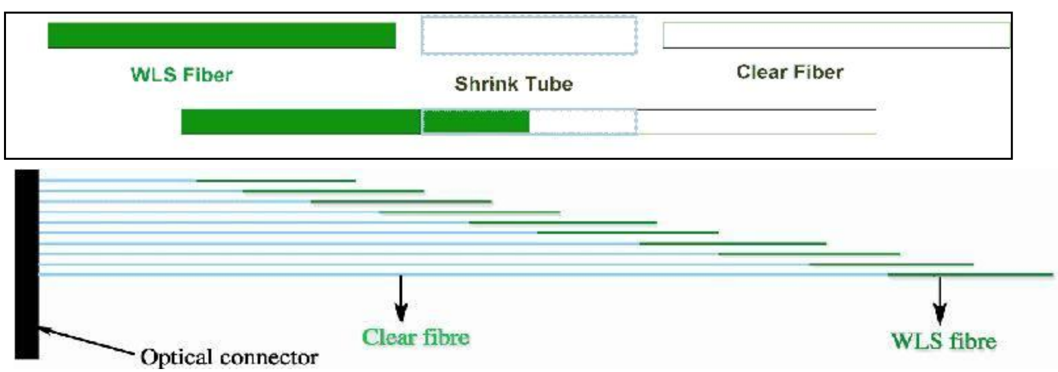
- A liquefied gas like H2, D2, Ne, freon etc is kept in a pressure vessel below but close to its boiling point
- After the passage of ionising radiation, the volume of the chamber is expanded by the fast movement of a piston during about 1µs-1ms is such a was that the boiling temp is exceeded.
- Along the ionising tracks gas bubbles are formed in the liquid, due to the heat developed by the recombination of ions.

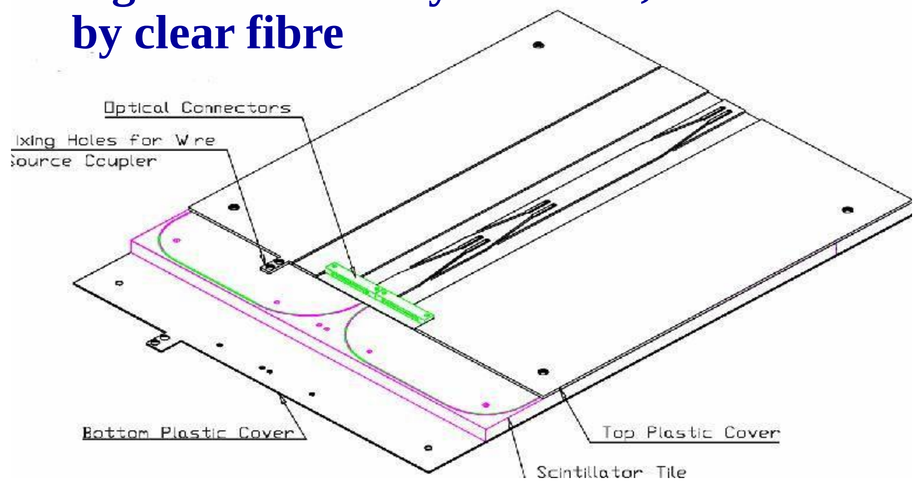
Construction of HO tiles





- Optical fibres are grouped together as a pigtail and inserted into the grooves
- Signal collected by wls fibre, but carried by clear fibre



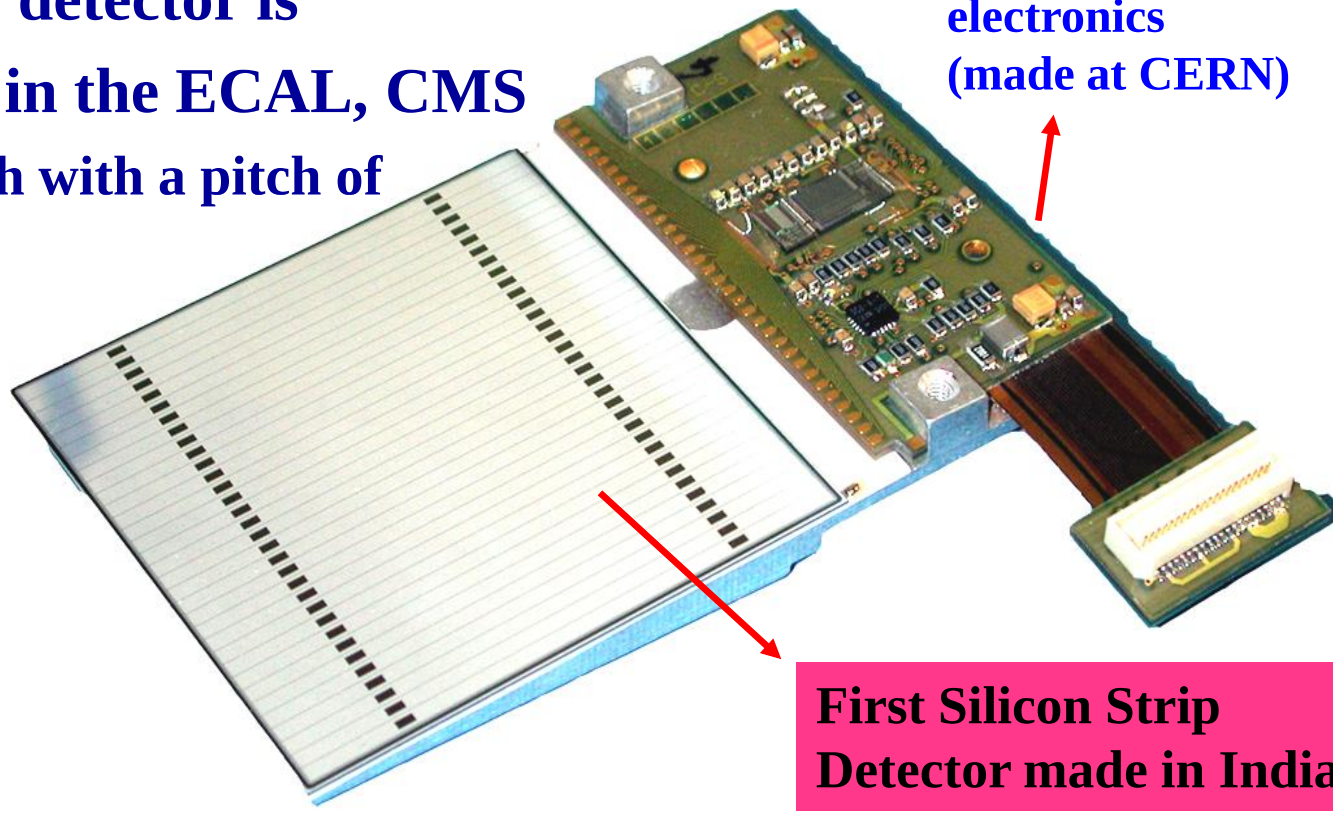


The Preshower Silicon Detector

Preshower silicon strip detector is used for π^0/γ rejection in the ECAL, CMS

- **Strips of 1.80 mm width with a pitch of 1.9 mm**
- **Area - 63mm x 63mm**

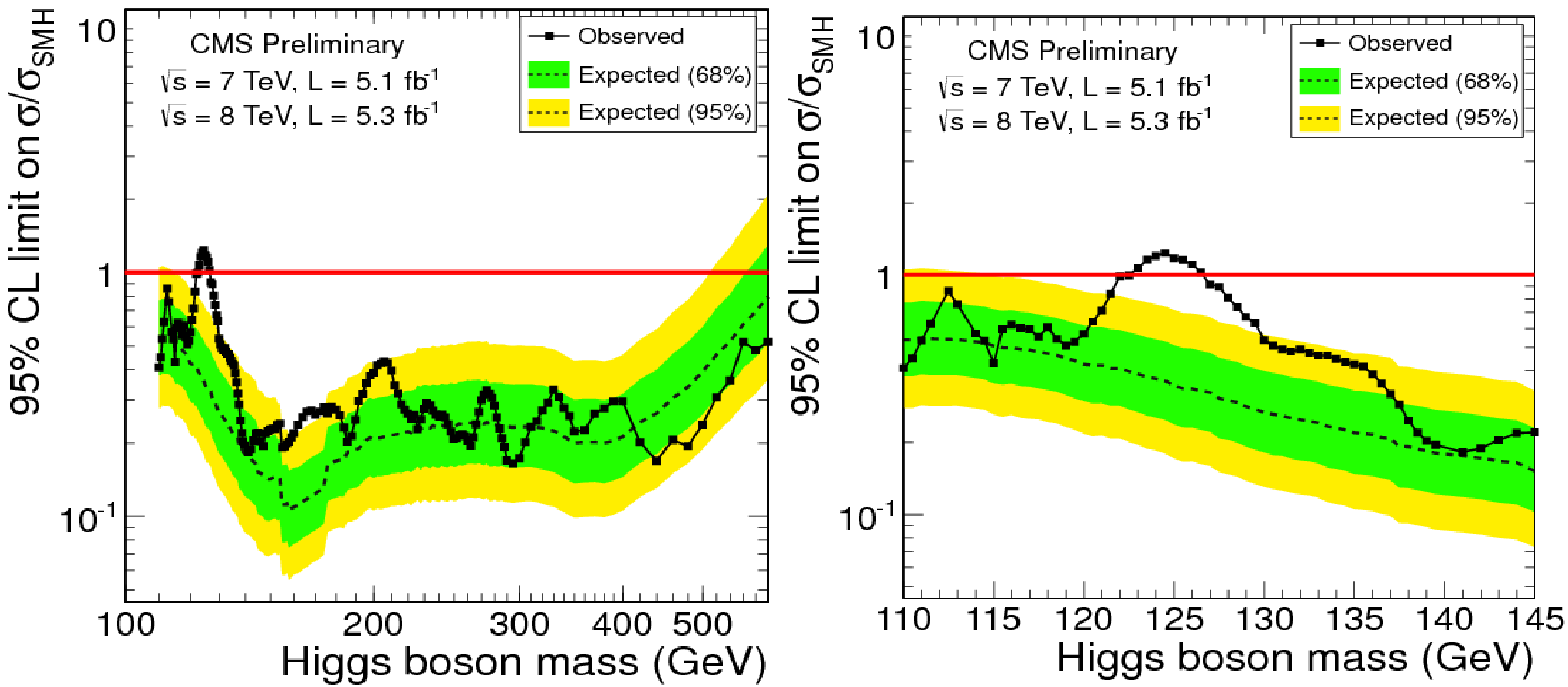
Rad-hard front end electronics (made at CERN)



First Silicon Strip Detector made in India

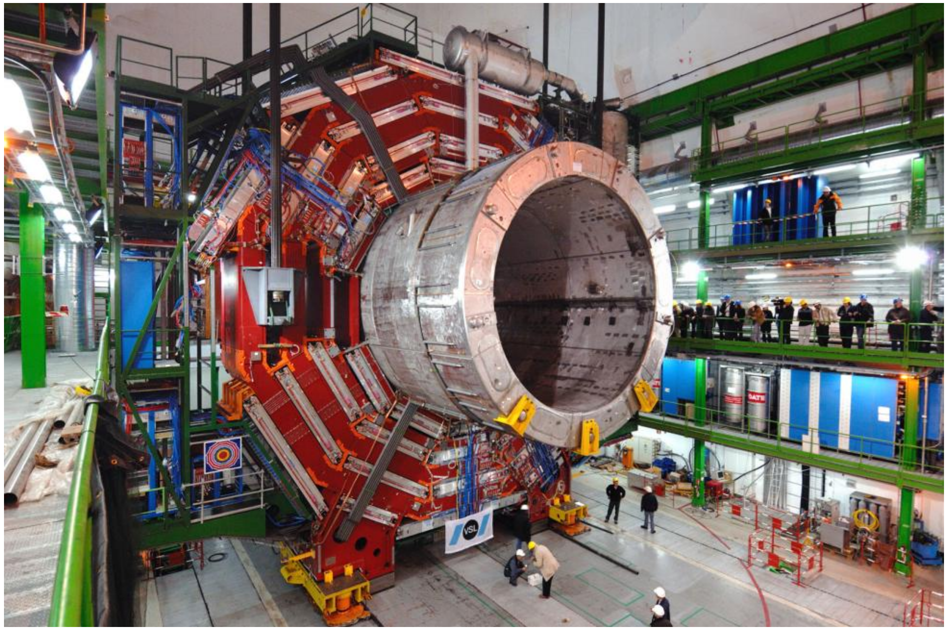
Detector specifications are very stringent as they are to be operated in a high radiation background of neutrons ($2x10^{14}$ /cm^2) & gamma (10Mrad) for a long period of ten years

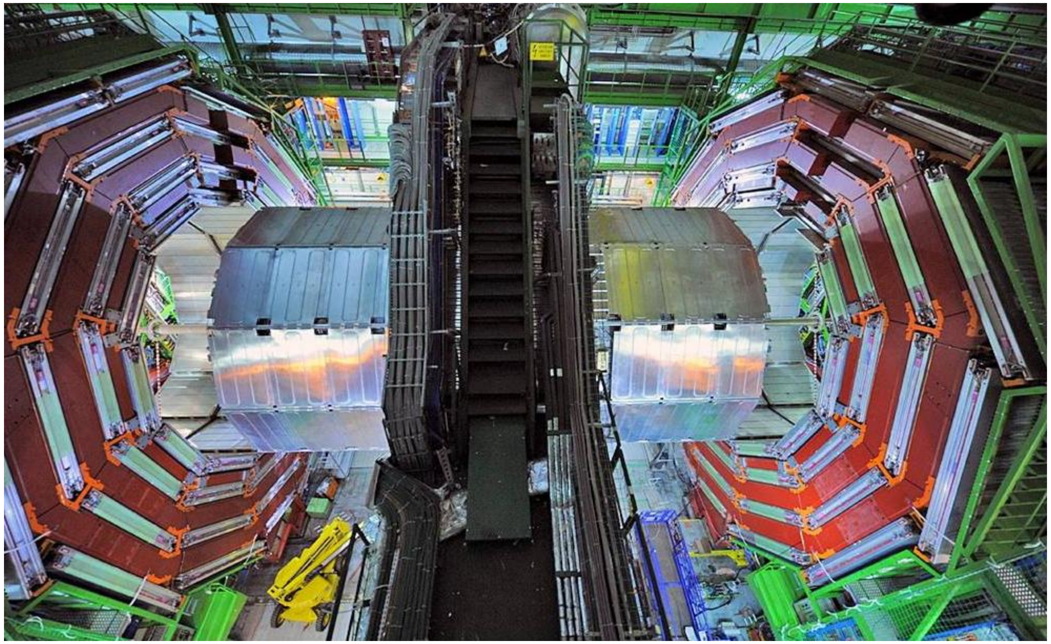
CMS results on Exclusion limit

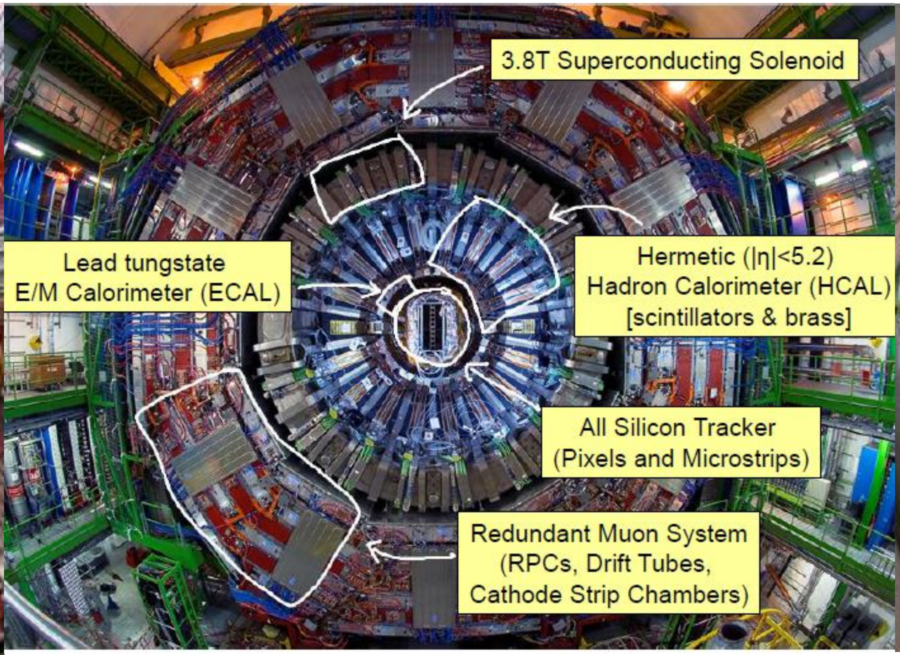


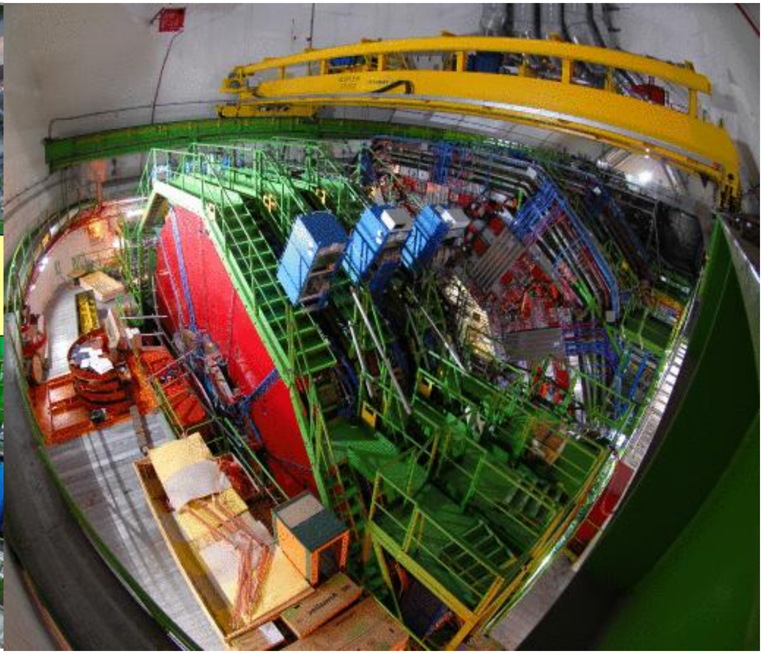
- **With 95% CL Higgs is excluded from 110 - 121.5 GeV and 128 - 600 GeV**
- **In the range 121.5 < m_H < 128 GeV, observe upper limit is much higher than expected limit ⇒ Extra events from the physics beyond the SM background (excluding Higgs)**

Fifteen pieces assembled individually

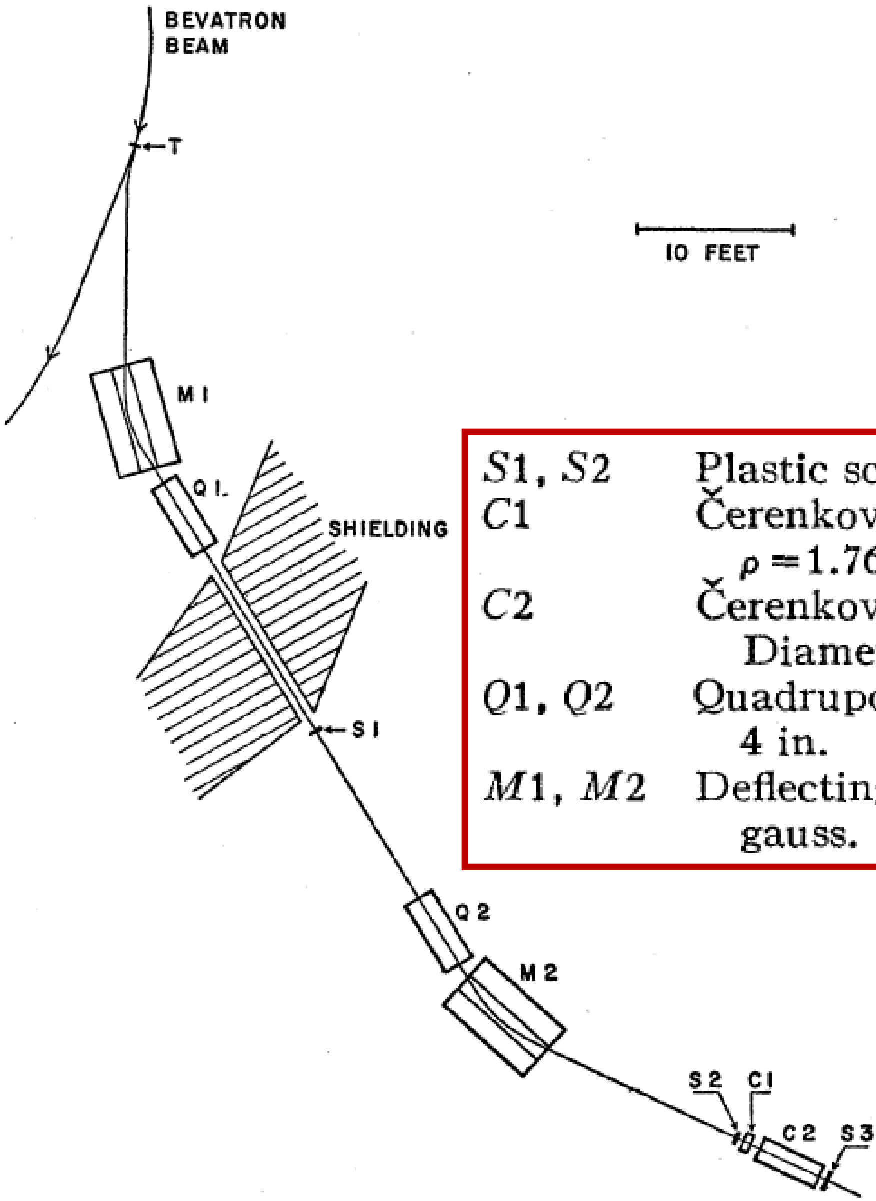








Aparatus used to detect antiproton



- **Proton-mass particles of momentum 1.19GeV/c incident on S2 have v/c=β=0.78 and has momentum resolution within 2%**
- **Threshold vel, β>0.79 for C1**
- **<β>=0.765 in C2, which counts particles in narrow velocity interval 0.75<β<0.78.**

$S1$, $S2$	Plastic scintillator counters 2.25 in. diameter by 0.62 in. thick.
$C1$	Čerenkov counter of fluorochemical 0–75, ($C_8F_{16}O$); $\mu_D=1.276$; $\rho=1.76$ g cm^{-3}. Diameter 3 in.; thickness 2 in.
$C2$	Čerenkov counter of fused quartz: $\mu_D=1.458$; $\rho=2.2$ g cm^{-3}. Diameter 2.38 in.; length 2.5 in.
$Q1$, $Q2$	Quadrupole focusing magnets: Focal length 119 in.; aperture 4 in.
$M1$, $M2$	Deflecting magnets 60 in. long. Aperture 12 in. by 4 in. $B\cong 13\,700$ gauss.

Early studies for the choice of CMS detector materials and designs

TIFR/EHEP/94-12
CMS TN/94 - 238
August 31, 1994

Radiation Hardness Study of CeF_3, $PbWO_4$ Crystals and Heavy Glass to MeV Neutrons [1)]

S. Banerjee, S. Mangla, G. Mazumdar
Tata Institute of Fundamental Rese

TIFR-EHEP/94-13
CMS-TN/94-240
September 8, 1994

Study of Light Collection as a Function of Shashlik Tile Size

rtu, M.Maity, G.Majumder,
.Moulik

Fundamental Research,
0 005, India

TIFR–EHEP/94–15
CMS–TN/94–291
December 6, 1994

Neutral Pion Rejection and Position Resolution for Gammas as a Function of Granularity for a $PbWO_4$ Crystal Calorimeter

S. Banerjee, R. Raghavan
Tata Institute of Fundamental Research, Bombay

Radiation Hardness Study of Plastic Scintillator Tiles to MeV Neutrons and Photons

S.Banerjee, G.Majumder and R.Raghavan
Tata Institute of Fundamental Research, Bombay

TIFR–EHEP/94–17
CMS–TN/94–292
December 21, 1994

Neutral Pion Rejection, Position and Angular Resolution for Gammas as a Function of Granularity for a CeF_3 Crystal Calorimeter

S. Banerjee, G. Majumder, K. Mazumdar, R. Raghavan
Tata Institute of Fundamental Research, Bombay