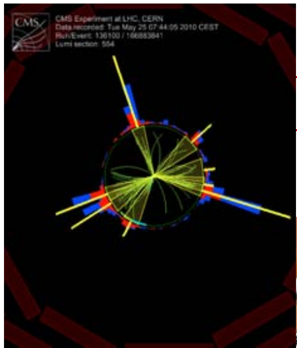
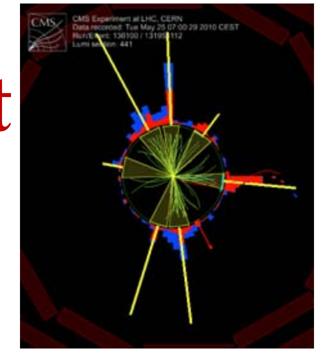
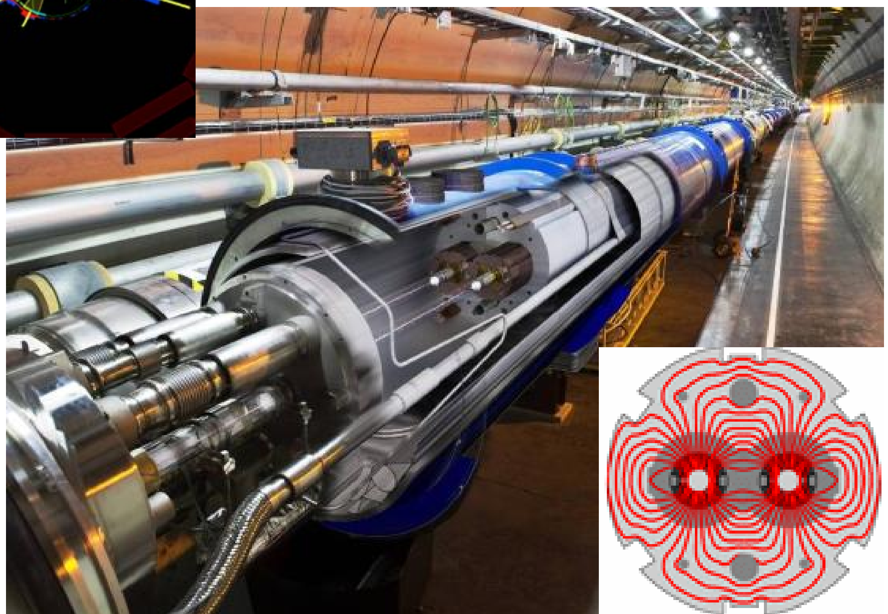


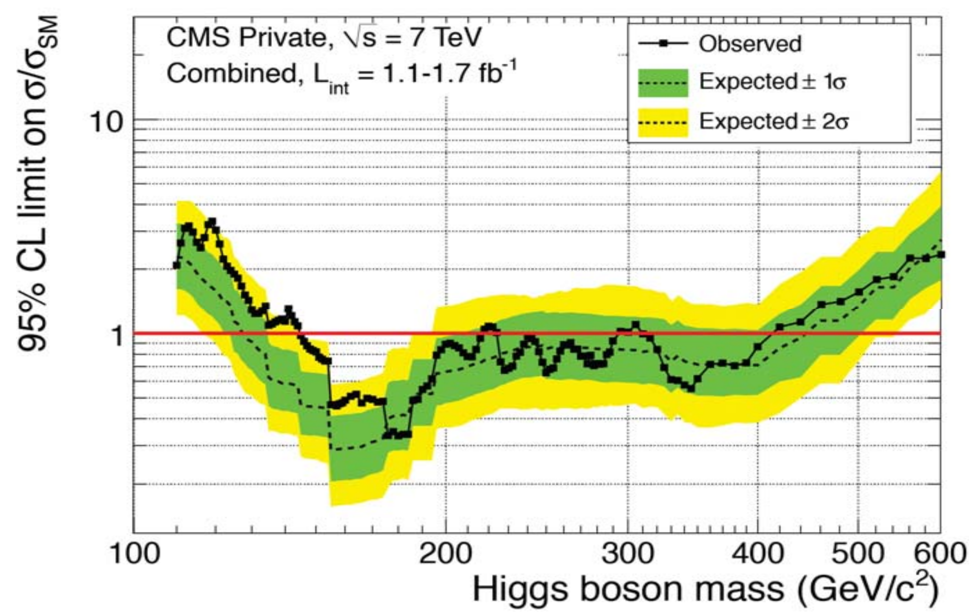
Physics Results from the CMS experiment



Gobinda Majumder, DHEP

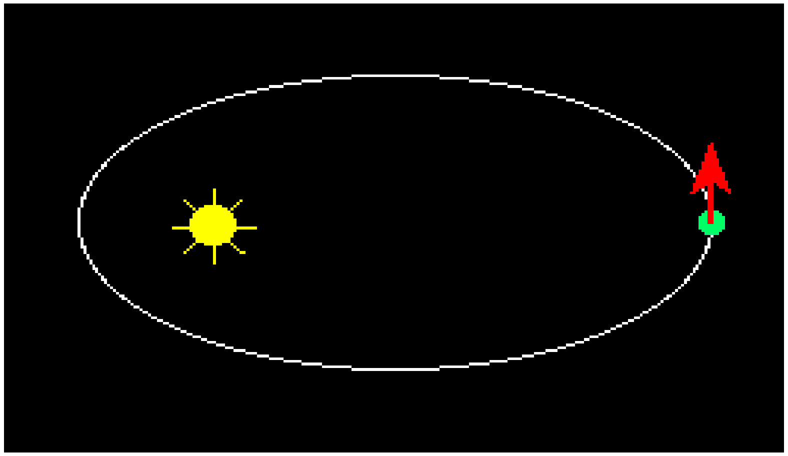


- **Introduction**
- **Development of Particle Physics**
- **Large Hadron Collider (LHC)**
- **CMS Experiment**
- **Standard Model Physics at LHC**
- **Search results**
- **Conclusion**



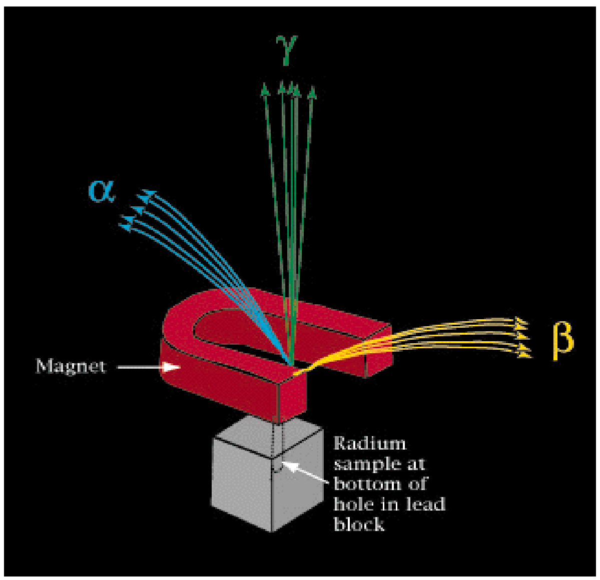
Nature of interations

Gravitational --solar system/galaxy

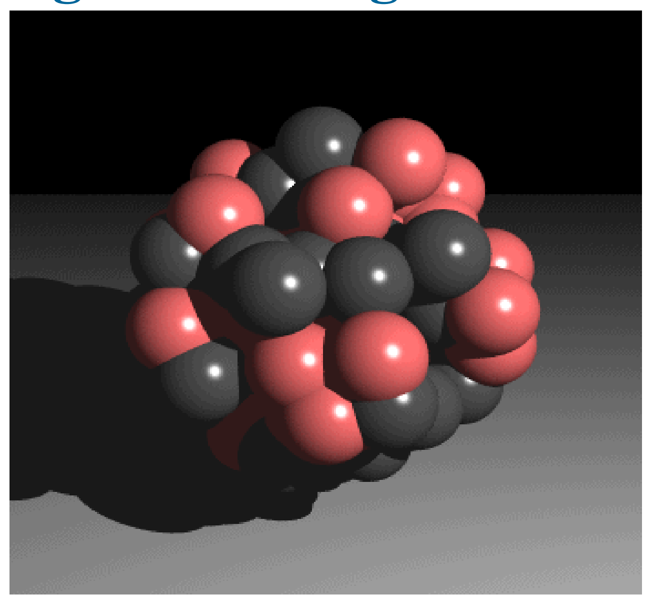


Electromagnetic --photon

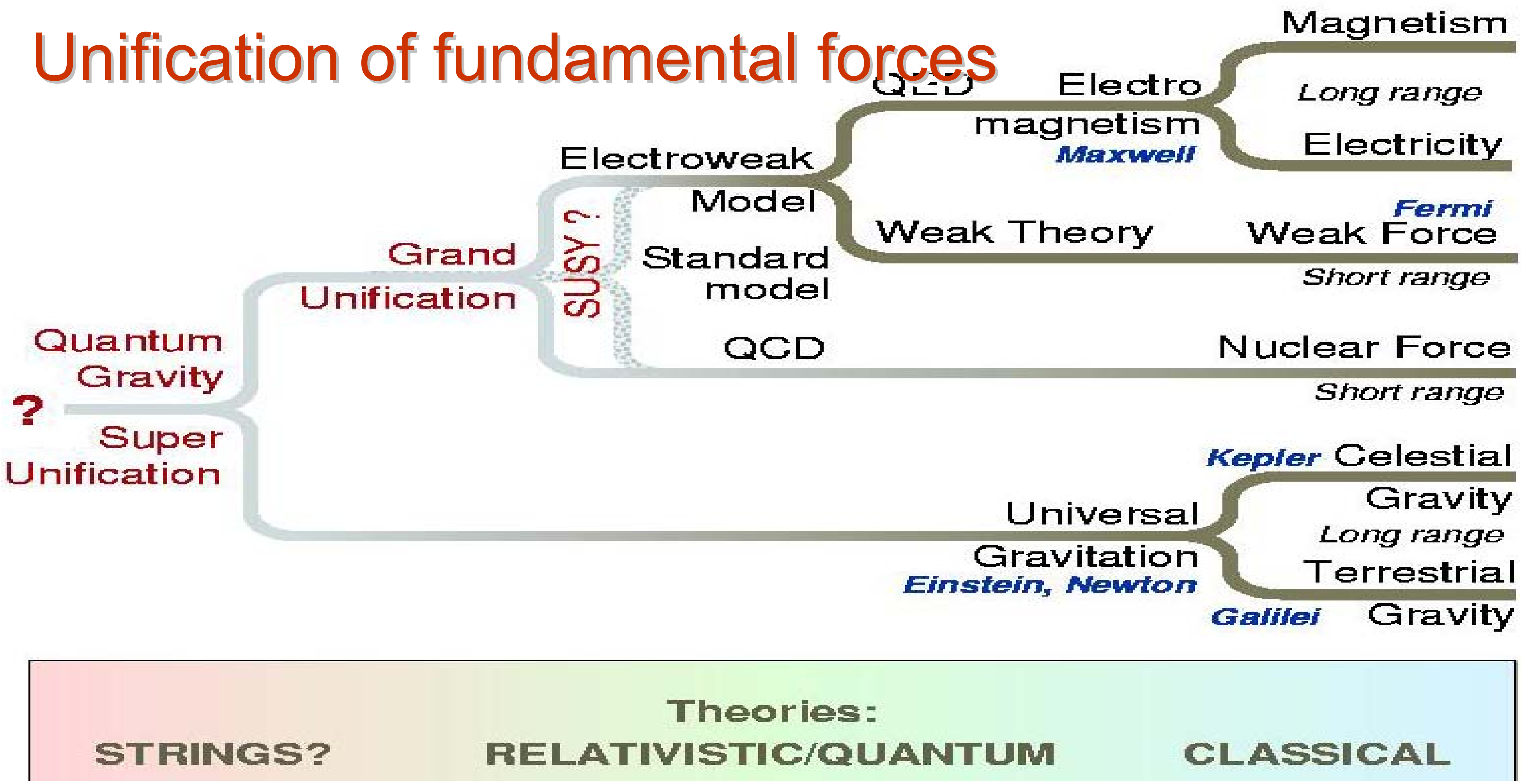
Weak --radioactivity



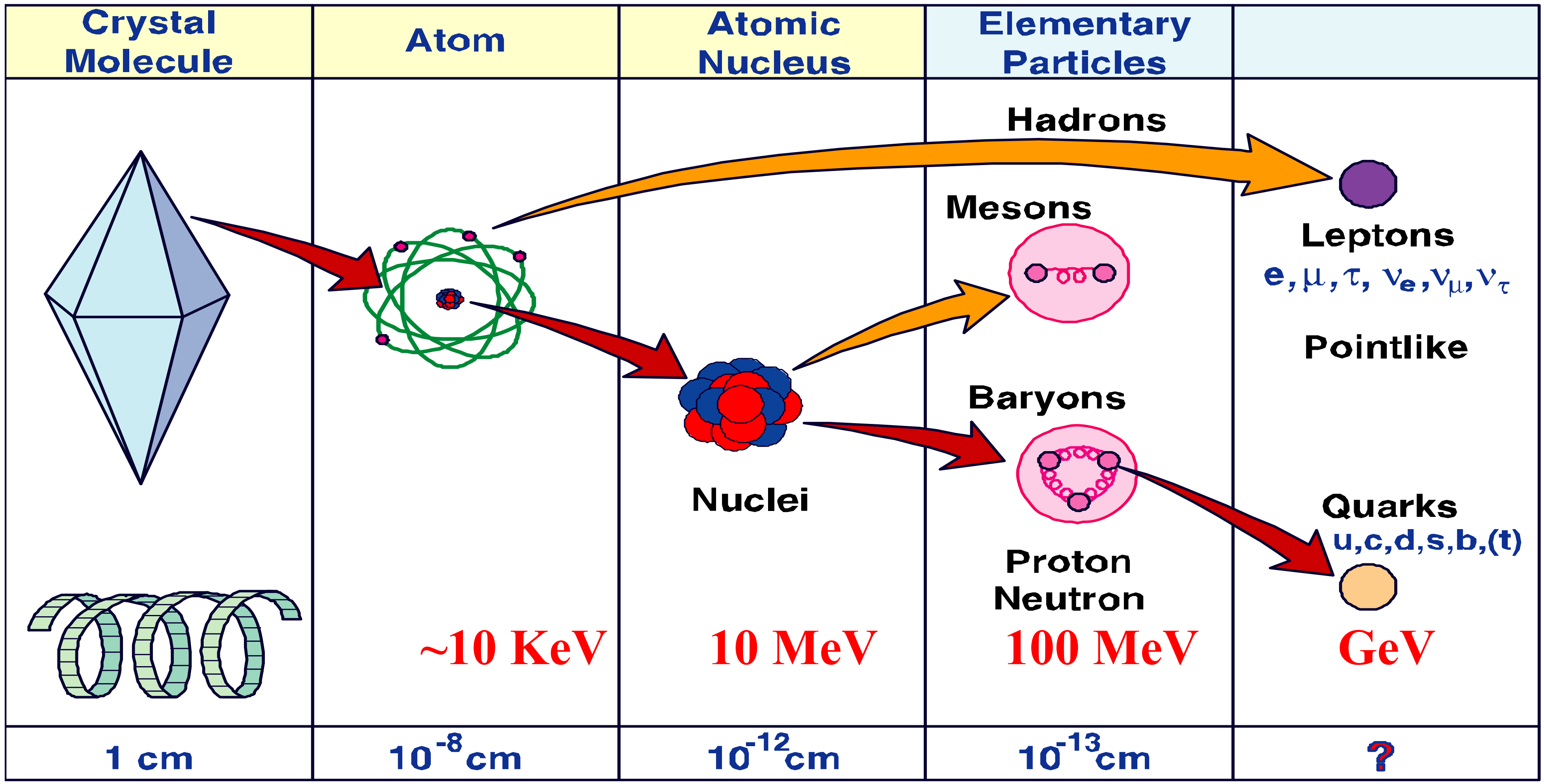
Strong --binding of nucleus



Unification of fundamental forces



Constituent of matter

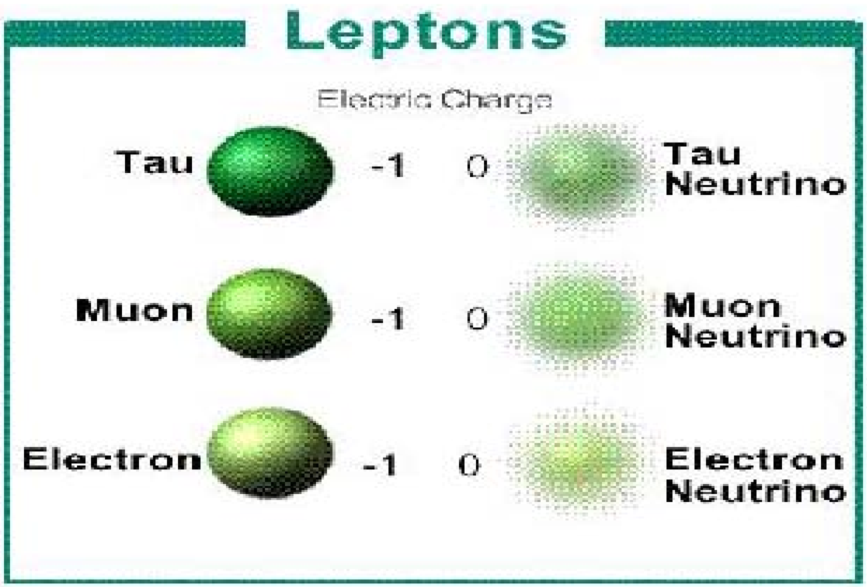


y1101

Thomson	Rutherford	Chadwick	SLAC
1897	1909	1932	1968

Probe smaller distance with higher energy ➔ Newer structure

Present Knowledge About Fundamental Particles

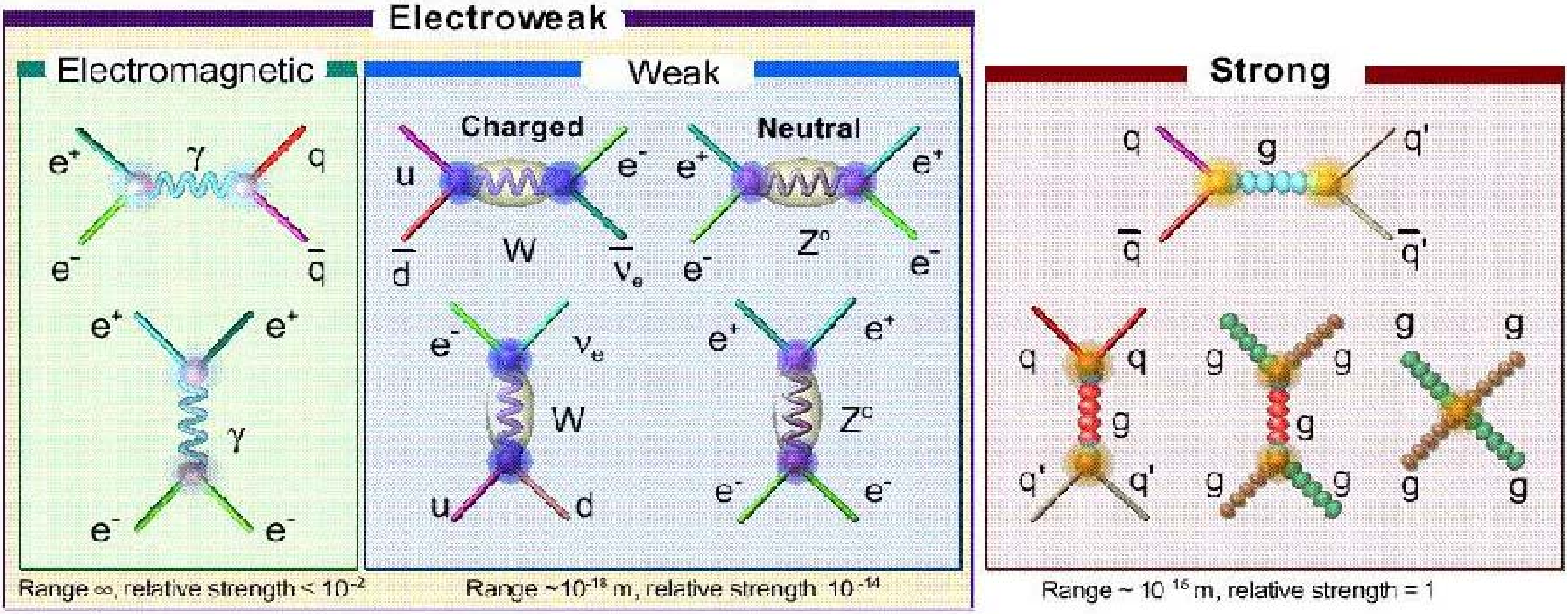


		Discovery
τ	$e^+e^- \longrightarrow e^\pm\mu^\mp \not{E}$	1975
ν_τ	$\nu_\tau \longrightarrow \tau + X$	2000
μ	Cosmic Ray	1937
ν_μ	ν-beam study	1962
e	Since ages	
ν_e	Reactor Expt	1957

u, d, s	Hadron Spectroscopy	early 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	$p\bar{p} \longrightarrow \ell^+\ell^-X$ $\ell^\pm$+Jet	1995

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

Fundamental Interactions



Interaction mediated by vector bosons

γ (photon) $W^{\pm}$(charged), Z(neutral) current g(gluon)

$p\bar{p} \rightarrow \ell^{\pm}\ \not{E}_T + X,\ \ell^{+}\ell^{-} + X$ $\qquad e^{+}e^{-} \rightarrow$ 3 Jets

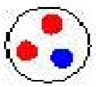
1983 early '80

All follows some symmetry operations

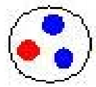
Composition of baryon and meson : Observed particles

Hadrons are composite particles made of quarks:

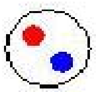
- Baryon : $\{qqq\}$
- Meson : $\{q\bar{q}\}$



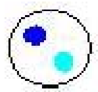
proton $= \{uud\}$



neutron $= \{udd\}$

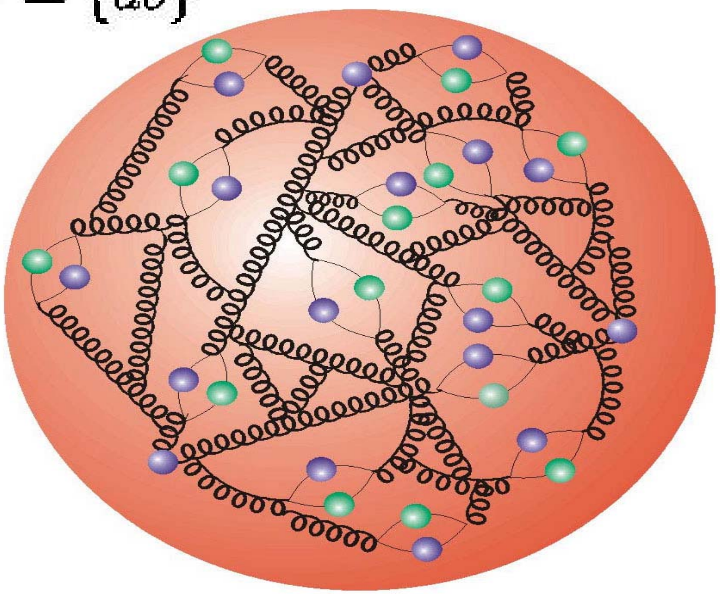


pion$= \pi^+ = \{u\bar{d}\}$

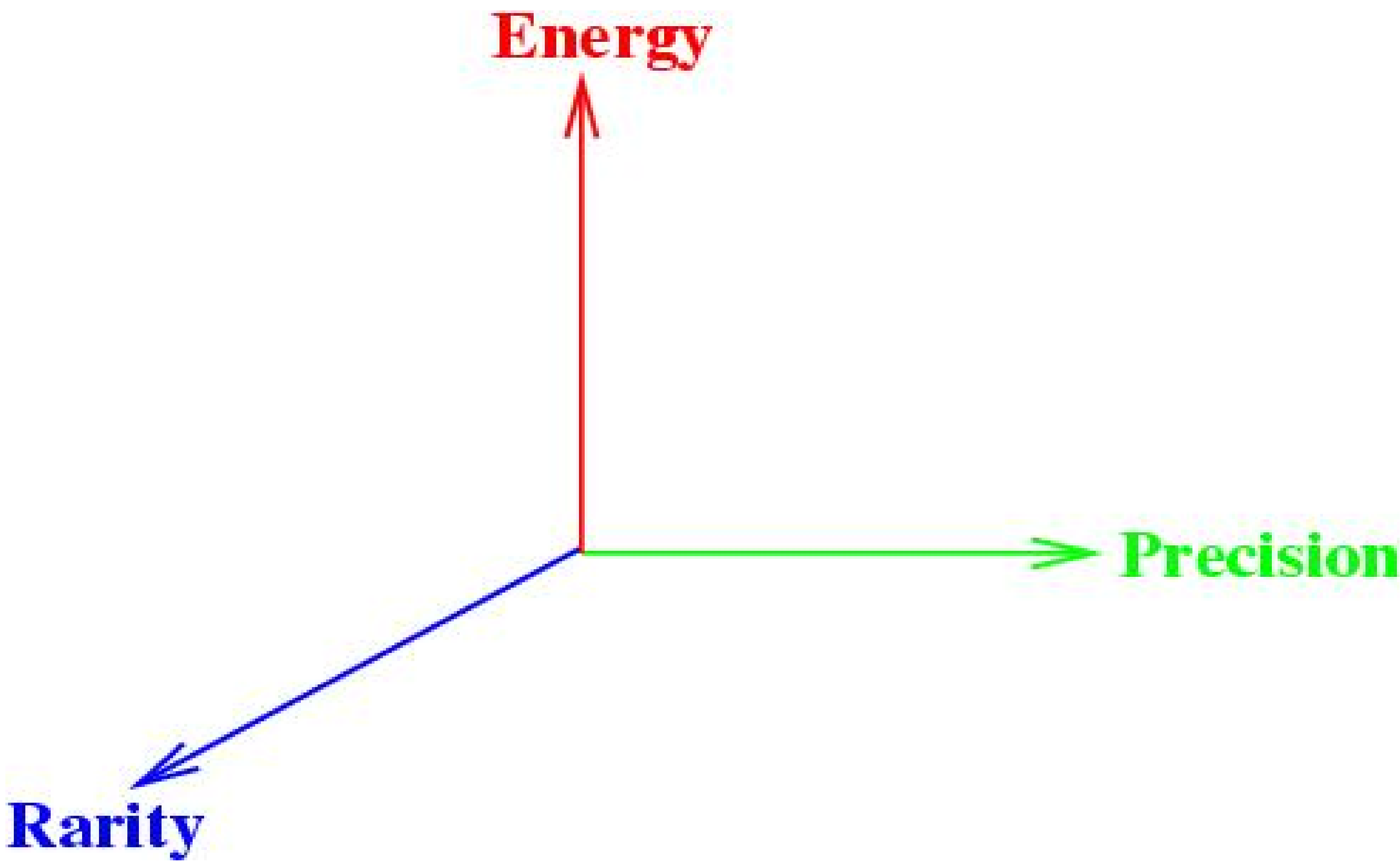


B meson $= B^0 = \{d\bar{b}\}$

Hadrons are not, in fact, simply made from three/two quarks .e.g., proton is actually made 3 "valence" quarks (uud) + a "sea" of gluons and short-lived quark-antiquark pairs



Knowledge of particle physics : Improvement

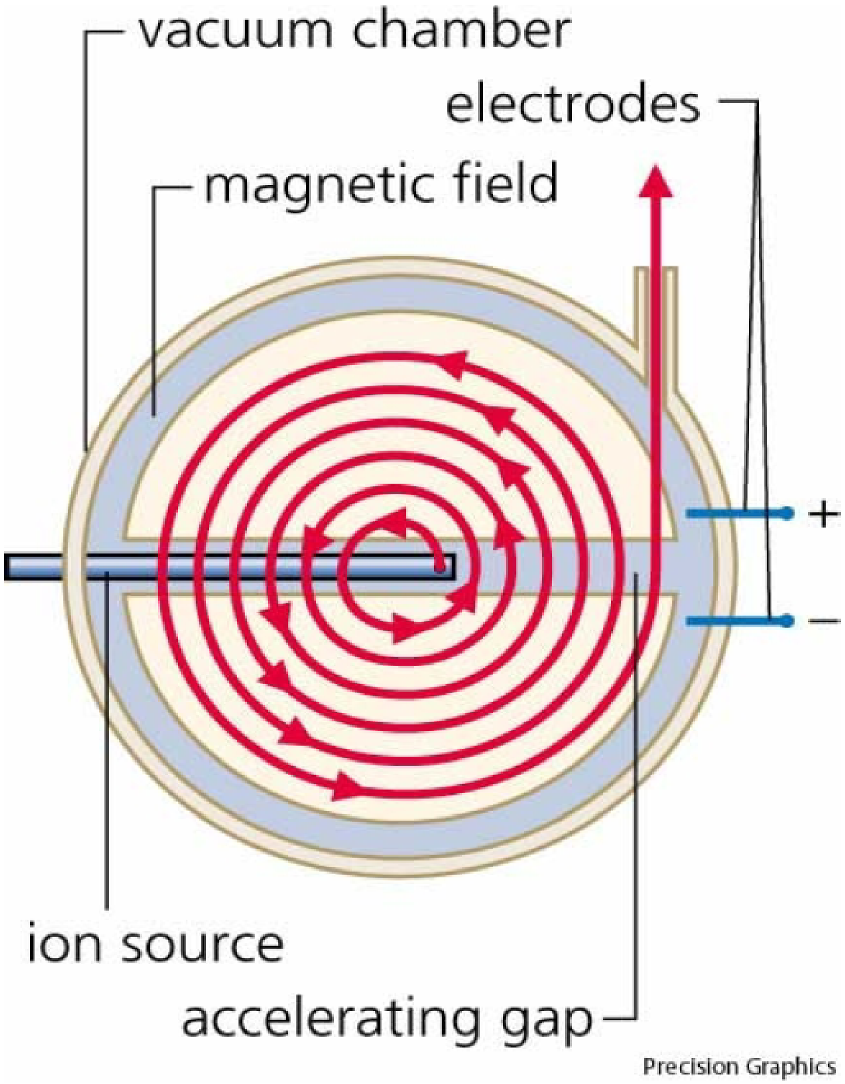


Energy Frontier

We know only how to accelerate charged particles in a controlled way
→ Lorentz Force :

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

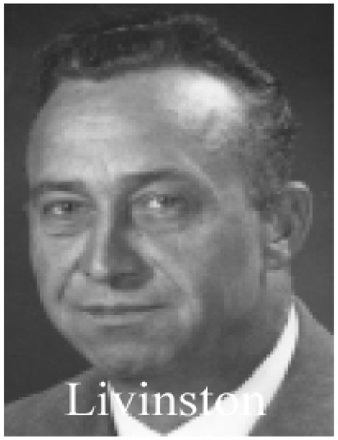
History of accelerators



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

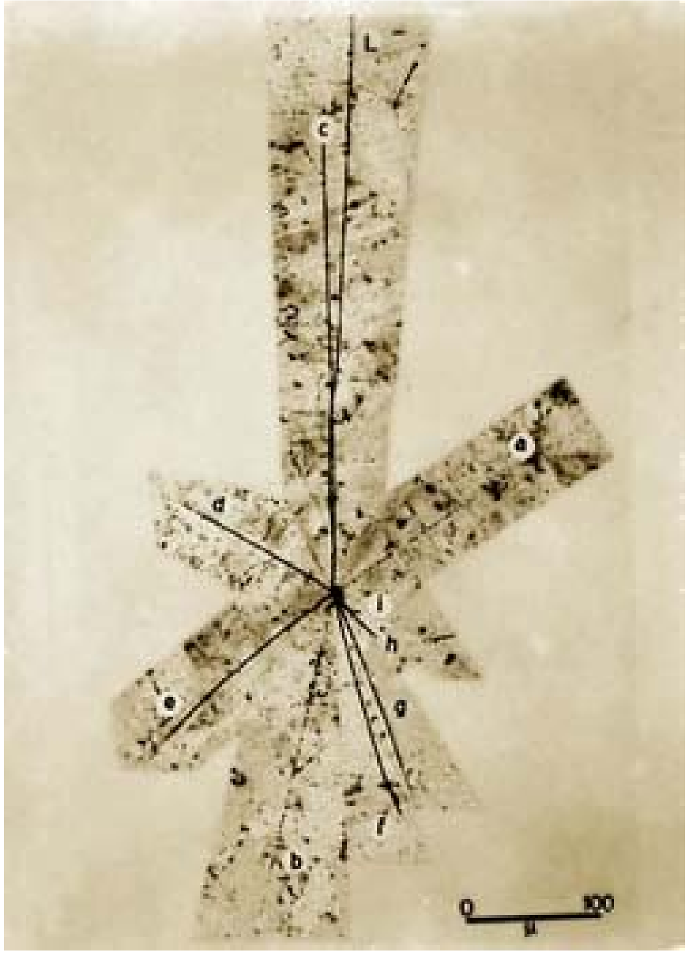
Diameter ~ 4.5" , E_p ~ 80 keV



Discovery of antiproton

- Dirac equation in 1928 and the discovery of Positron in 1932 (David Anderson, CalTech, using cloud chamber) predicted also an antiproton.
- But, to generate antiproton (conservation of baryon number, 1.19 GeV/c antiproton in spectrometer), need an accelarator, which can give about 6.5 GeV proton.
- 1955 : Segre & Chamberlin used bevatron of 6.5GeV proton at LBNL : Used momentum and velocity (scintialltor 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)

Types of Particle Collider

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

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

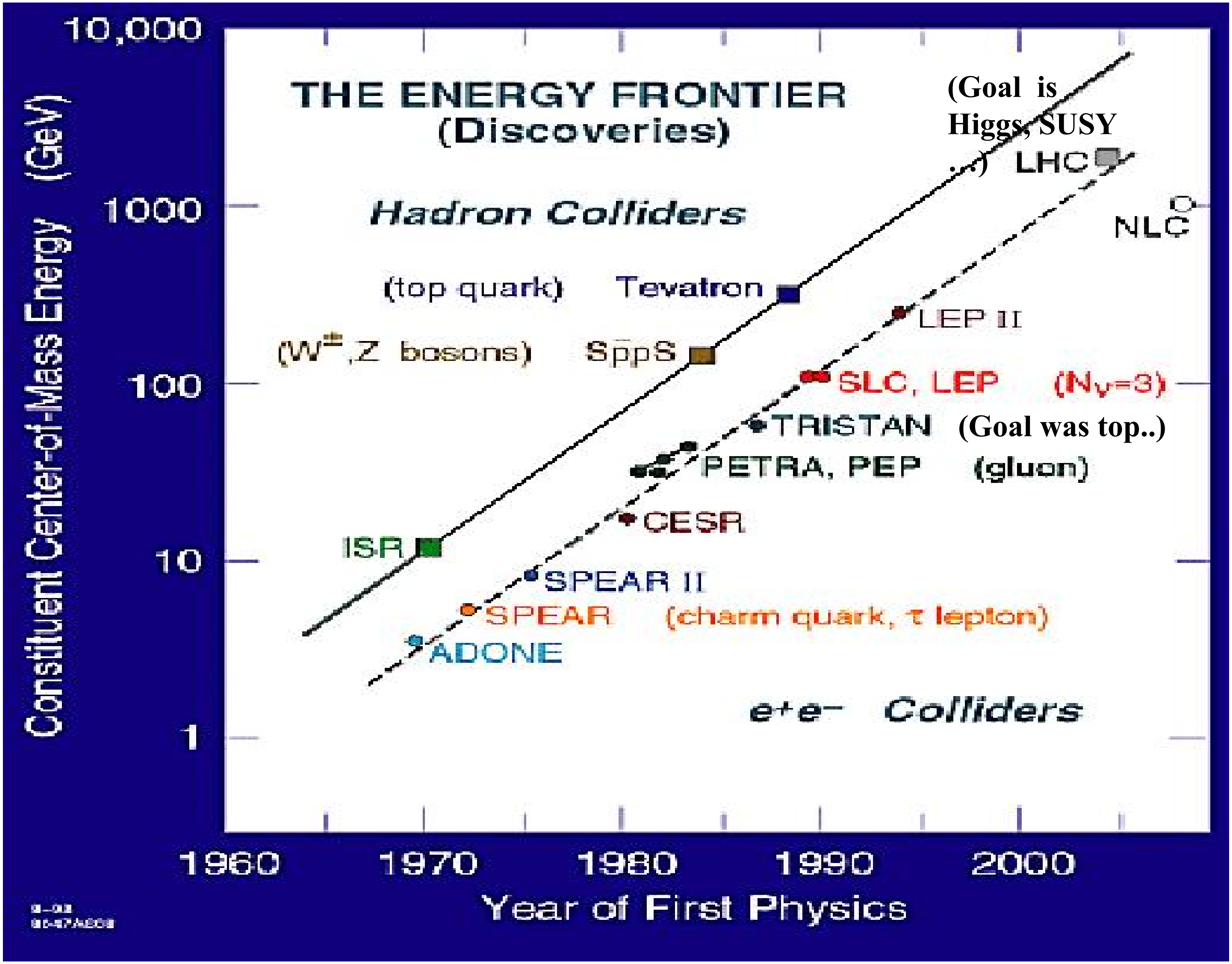
$E_{collision} = E_{e-} + E_{e+} = 2\ E_{beam}$

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

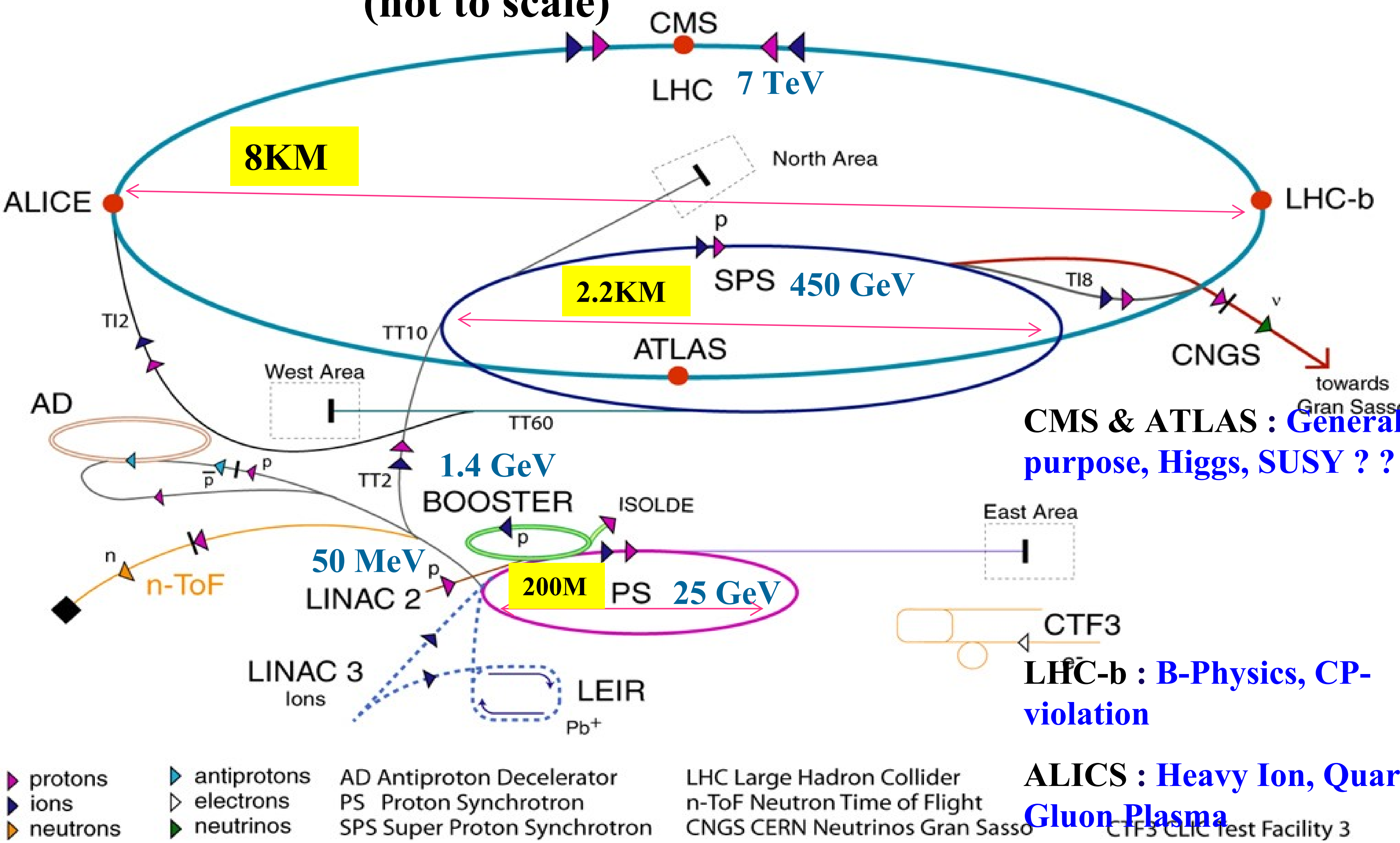
Combination of these two, electron+proton are also there, e.g. HERA



Increase of energy by ~10 fold in every ~12 year (faster for hadron collider)

LHC Accelerator Layout

(not to scale)

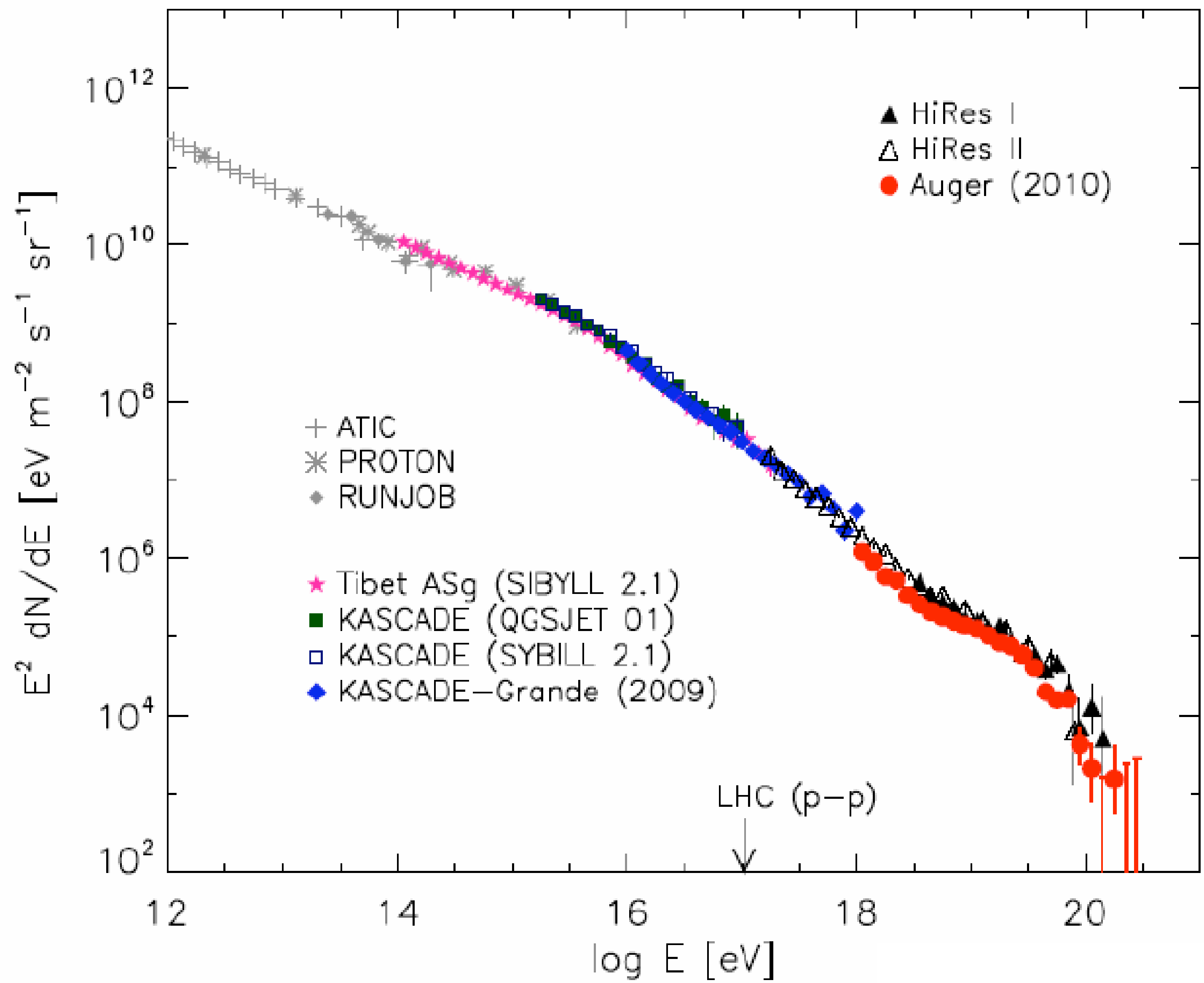


CMS & ATLAS : General purpose, Higgs, SUSY ? ?

LHC-b : B-Physics, CP-violation

ALICS : Heavy Ion, Quark Gluon Plasma

Cosmic ray vs collider



for $E_{beam} \gg m_p$

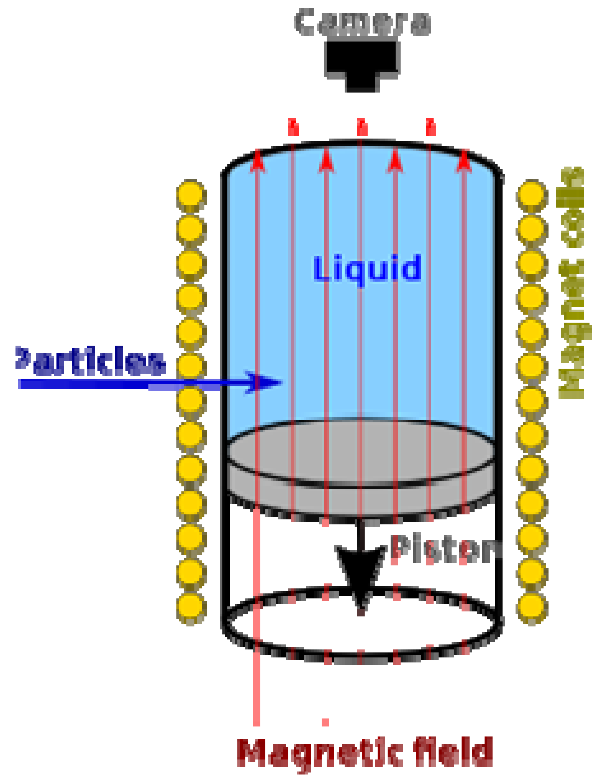
$$E_{CM} \approx \sqrt{2 m_p E_{beam}}$$

Expect only 1000 events/year/km^2 with $\sqrt{S}$>14 TeV,

whereas in LHC, 10^9 event/sec

Gargamelle Buble chamber : Discovery of neutral current

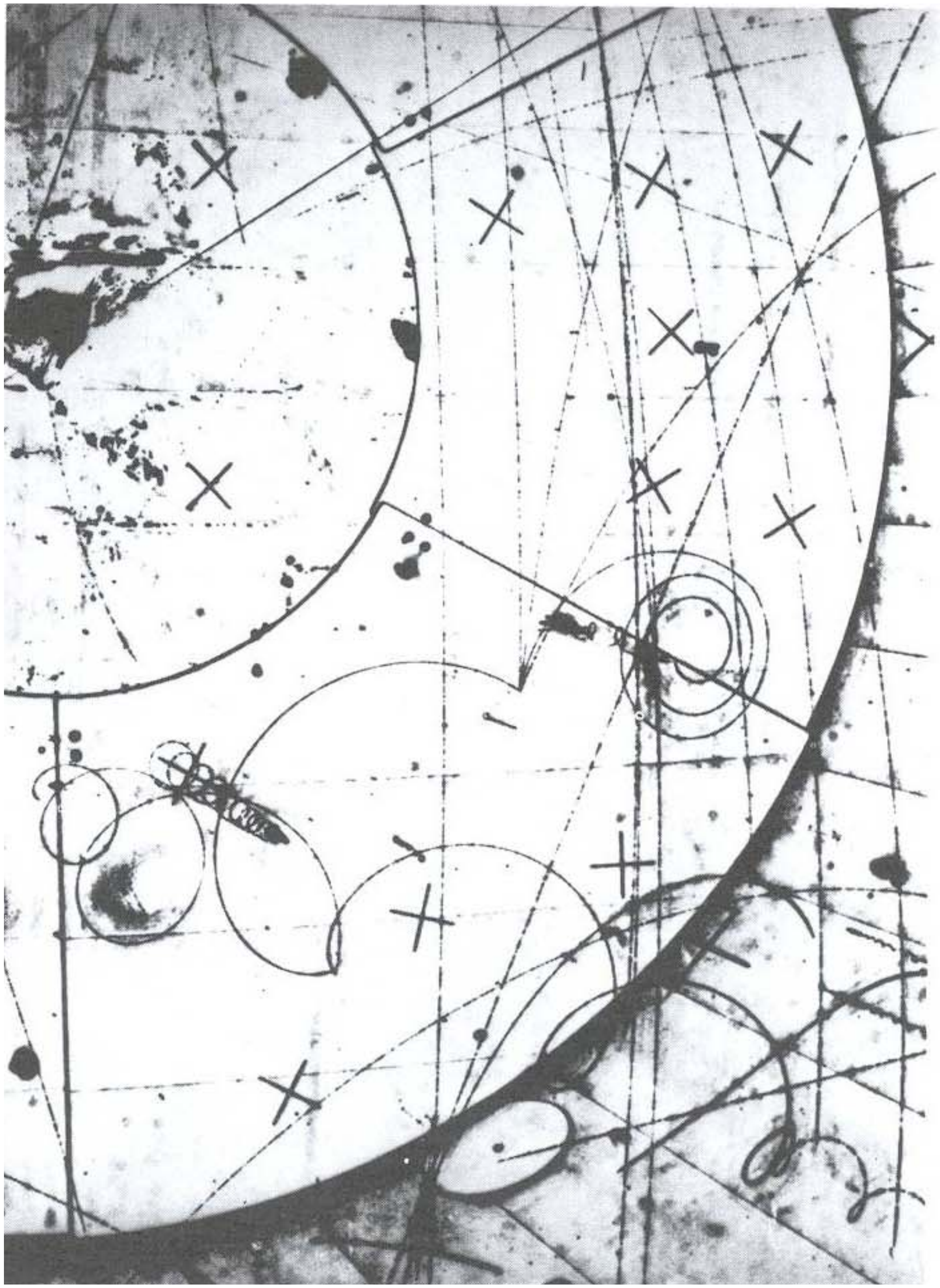
l=4.8m
d=2m
Wt=1000ton
18 ton liquid
freon (CF_3Br)

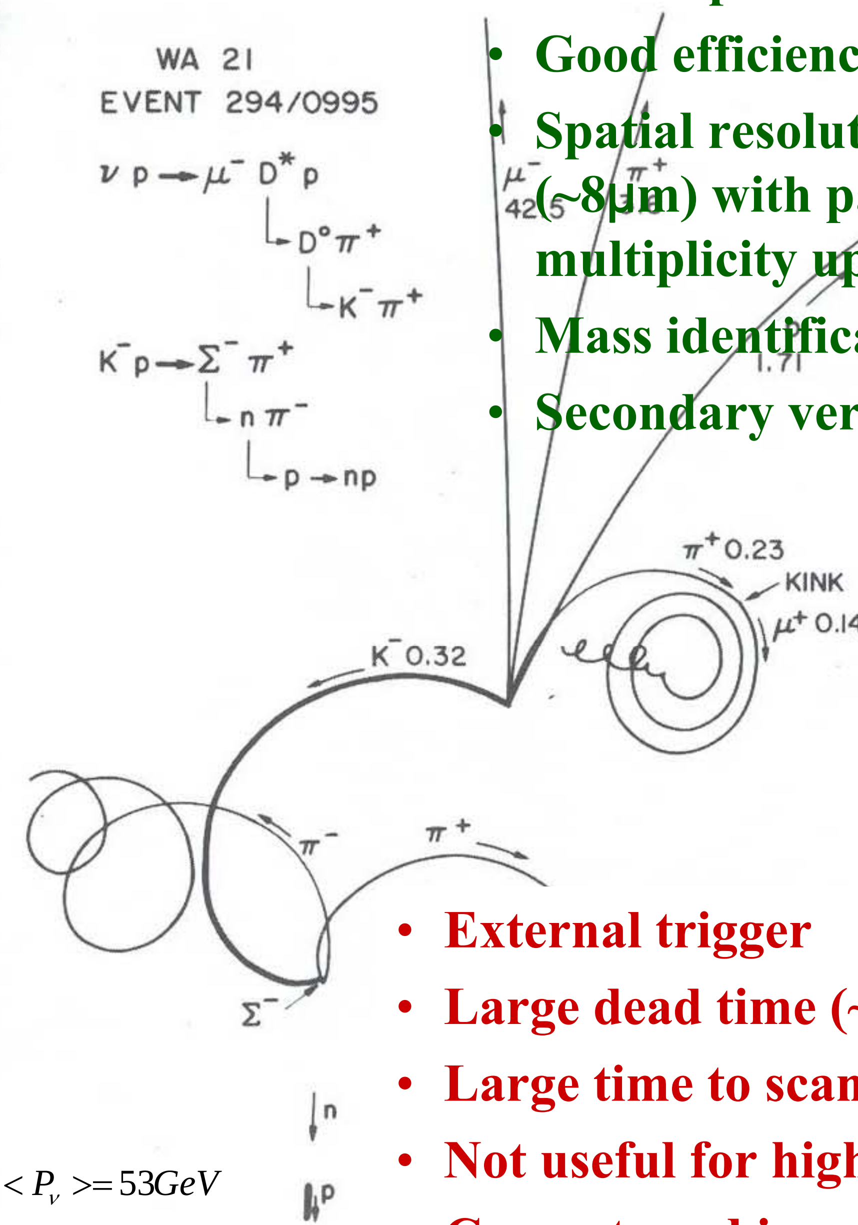


- A liquified gas like H2, D2, Ne, freon etc is kept in a pressure vessel below but close to its boiling point
- After the passage of ionising radiation, the volume of the chamber is expanded by the fast movement of a piston during about 1 μ s-1ms is such a was that the boiling temp is exceeded.
- Along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

An event in BEBC

- 4π acceptance
- Good efficiency
- Spatial resolution (~8μm) with particle multiplicity upto 150
- Mass identification
- Secondary vertex



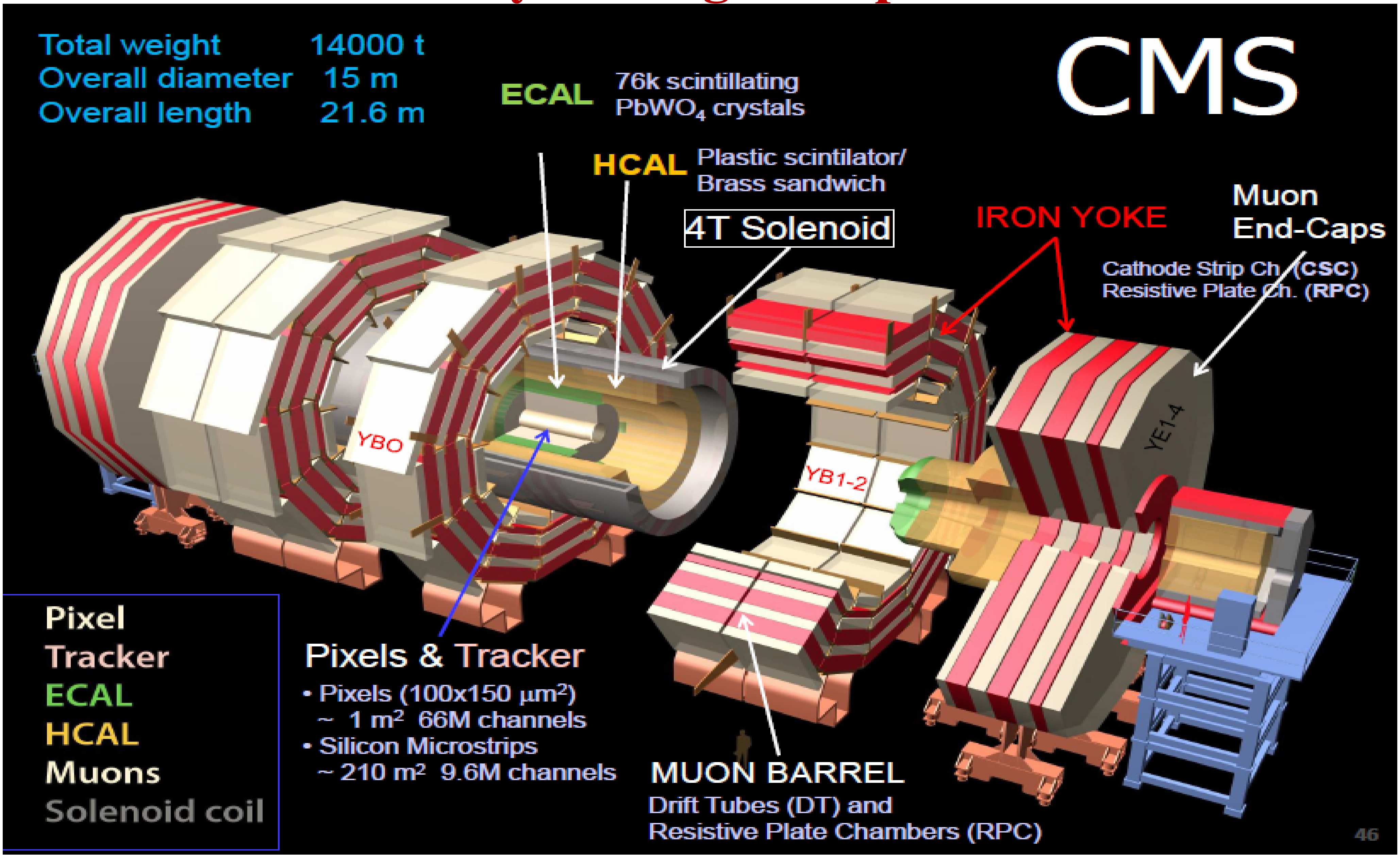


$< P_\nu >= 53 GeV$

$< P_{\bar{\nu}} >= 40 GeV$

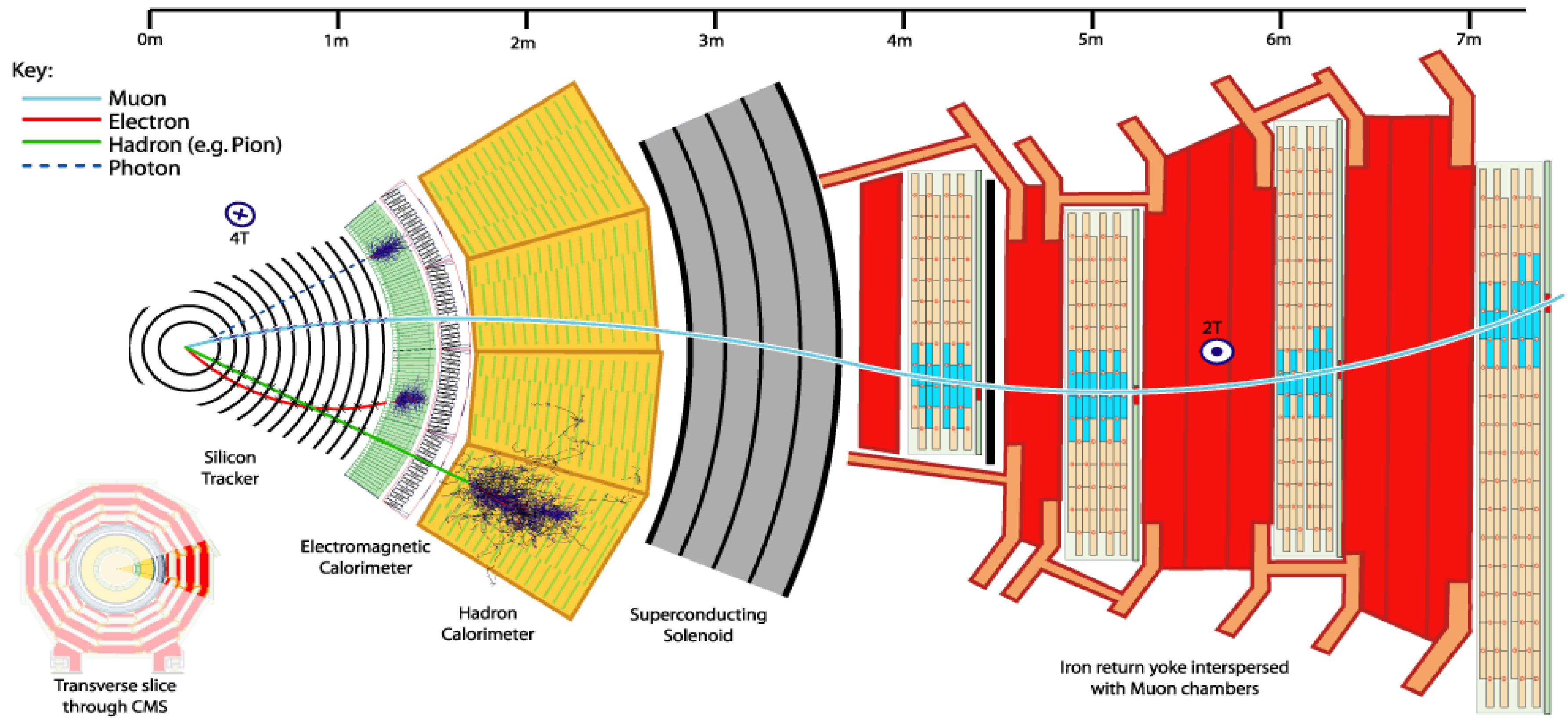
- External trigger
- Large dead time (~0.1sec)
- Large time to scan film
- Not useful for high P tacks
- Can not used in collider

Detector of today : a large complicated detector



~80 million electronic channels **Fifteen pieces assembled separately on surface**

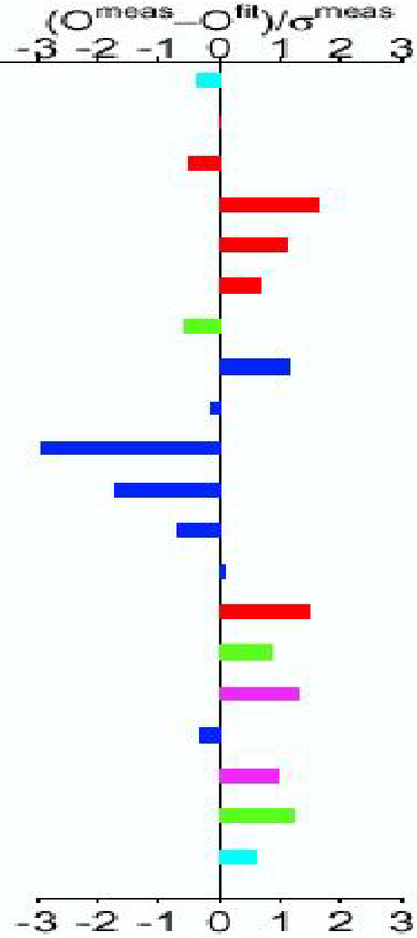
Detection of Fundamental Particles



SM Fundamental Particle	Appears As	$t \to W + b$	W + b
γ	γ (ECAL shower, no track)	$\nu_e \nu_\mu \nu_\tau$	Et missing in ECAL+HCAL
e	e (ECAL shower, with track)	$\tau \to l + \nu_\tau + \nu_l$	Et missing + charged lepton
μ	μ (ionization only)	$W \to l + \nu_l$	Et missing + charged lepton,
g	Jet in ECAL+ HCAL		Et~M/2
q = u, d, s	Jet in ECAL+HCAL	$Z \to l^+ + l^-$	charged lepton pair
q = c, b	Jet + Decay Vertex	$\to \nu_l + \nu_l$	Et missing in ECAL+HCAL

Precision measurements in LEP

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.35
m_Z [GeV]	91.1875 ± 0.0021	.03
Γ_Z [GeV]	2.4952 ± 0.0023	-.48
σ^0_{had} [nb]	41.540 ± 0.037	1.60
R_l	20.767 ± 0.025	1.11
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.69
$A_l(P_\tau)$	0.1465 ± 0.0033	-.54
R_b	0.21646 ± 0.00065	1.12
R_c	0.1719 ± 0.0031	-.12
$A^{0,b}_{fb}$	0.0990 ± 0.0017	-2.90
$A^{0,c}_{fb}$	0.0685 ± 0.0034	-1.71
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.47
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
$m_W^{(LEP)}$ [GeV]	80.450 ± 0.039	1.32
m_t [GeV]	174.3 ± 5.1	-.30
$m_W^{(TEV)}$ [GeV]	80.454 ± 0.060	.93
$\sin^2\theta_W(\nu N)$	0.2255 ± 0.0021	1.22
$Q_W(Cs)$	-72.50 ± 0.70	.56



The Standard Model is one of the most precisely tested theories in physics !

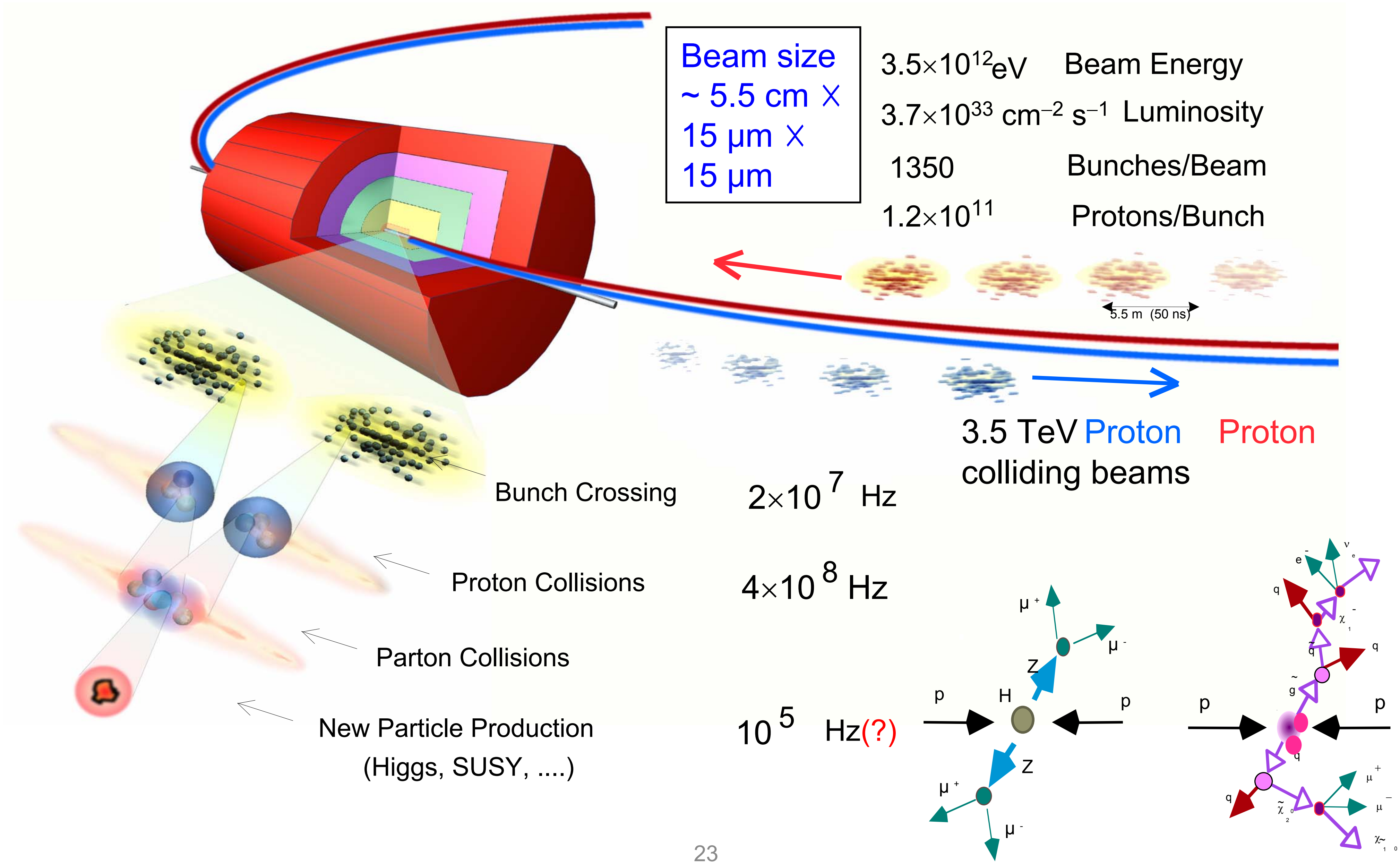
Why do we need a new accelerator ?

Unresolved Fundamental Questions in HEP

- **What is the origin of mass (Higgs mechanism) and how do we measure it ?**
- **Why are the known mass scales so different? $\Lambda_{QCD} \sim 0.2$ GeV << EW vev ~ 246 GeV << $M_{GUT} \sim 10^{16}$ GeV << $M_{PL} \sim 10^{19}$ GeV**
- **Why is the Universe made of matter? Does the answer lie in CP violation?**
- **What is "dark matter" made of ? Is a fundamental particle responsible for it ?**
- **Does a new form of matter exist at exceedingly high density and temperature ? Quark-gluon plasma ?**
- **Is there a new symmetry : SUSY ?**
- **Are the particles(quark/lepton) fundamental or do they possess structure ?**
- **How does gravity fit in with the strong, electromagnetic and weak forces?**


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.
CMS
LHCb
ALICE
LHC ring:
27 km circumference
ATLAS

Collisions at the Large Hadron Collider



Interesting facts about LHC

• LHC when running will consume as much power as a medium-sized European town

•LHC vacuum is 100 times more tenuous then the medium in which typical communications satellites move (10^{-8} torr)

• LHC magnetic fields of 8.4 Tesla are 100,000 times the Earth's

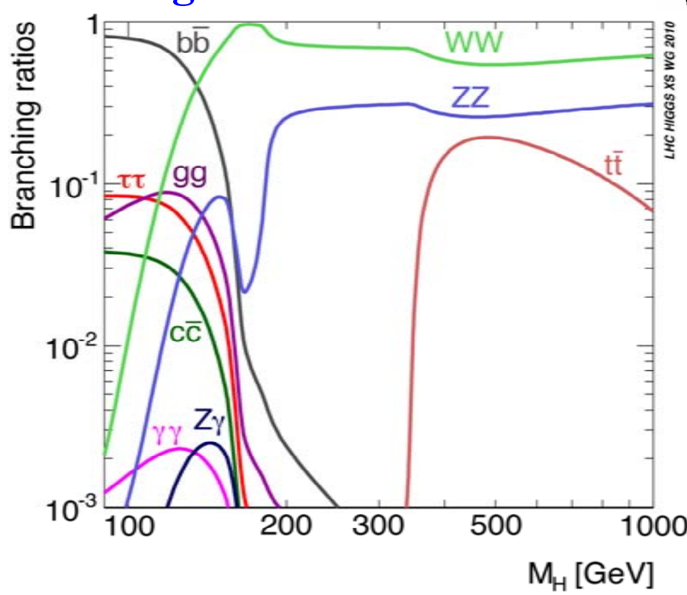
• LHC magnets will use 700,000 litres of liquid Helium and 12,000,000 litres of liquid Nitrogen

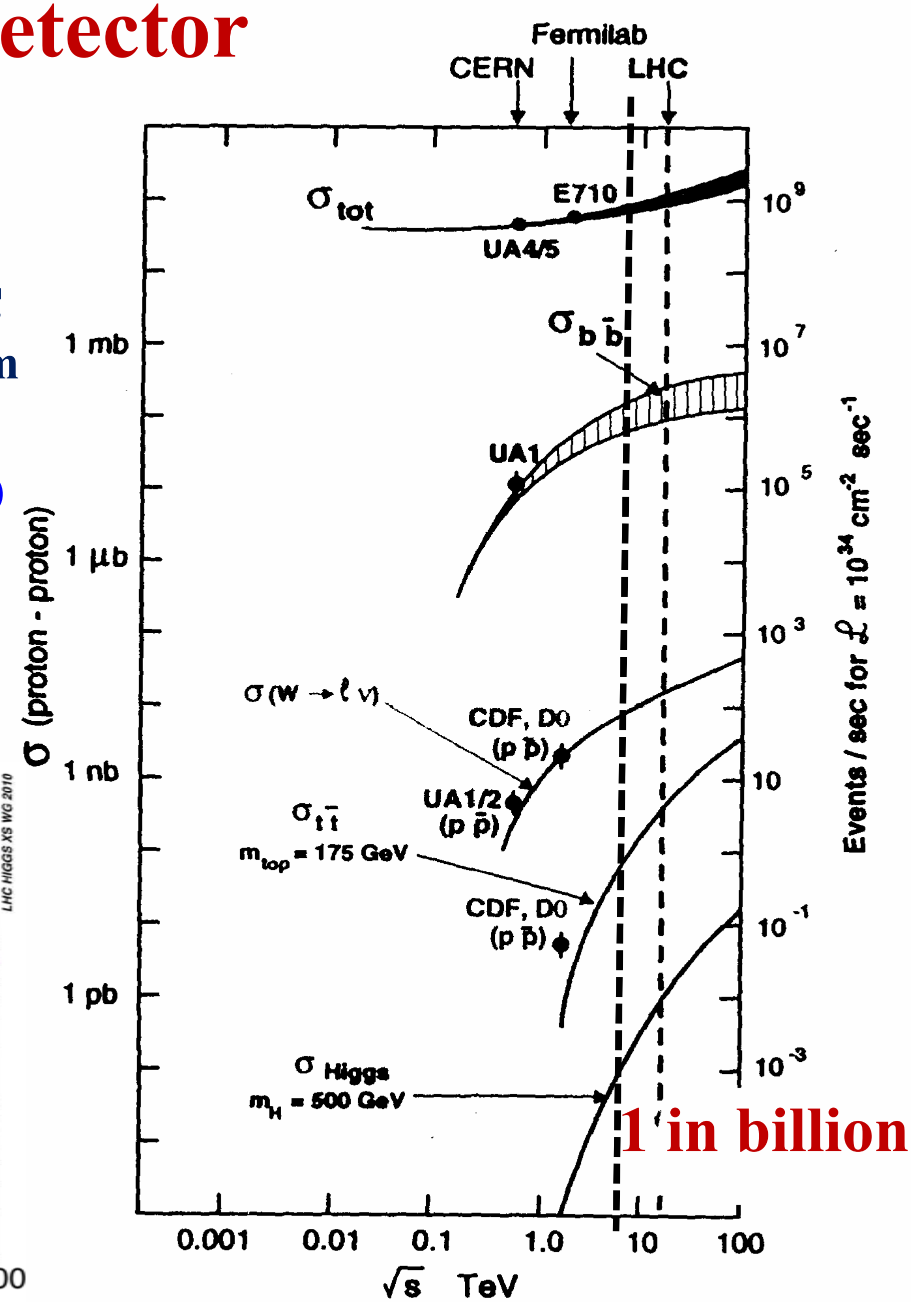
• LHC protons will have energies comparable to that of a flying mosquito, but total stored energy of magnet is ~10 GJ $\equiv$ Jumbo jet with 700km/h

• LHC data (~1petaByte/year) would eventually fill a stack of HD-DVDs 11 Km high (Mt. Everest is 8.8 Km high)

Physics goal and the CMS detector

- CMS is a "general purpose" detector – it was 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…..





The CMS Collaboration

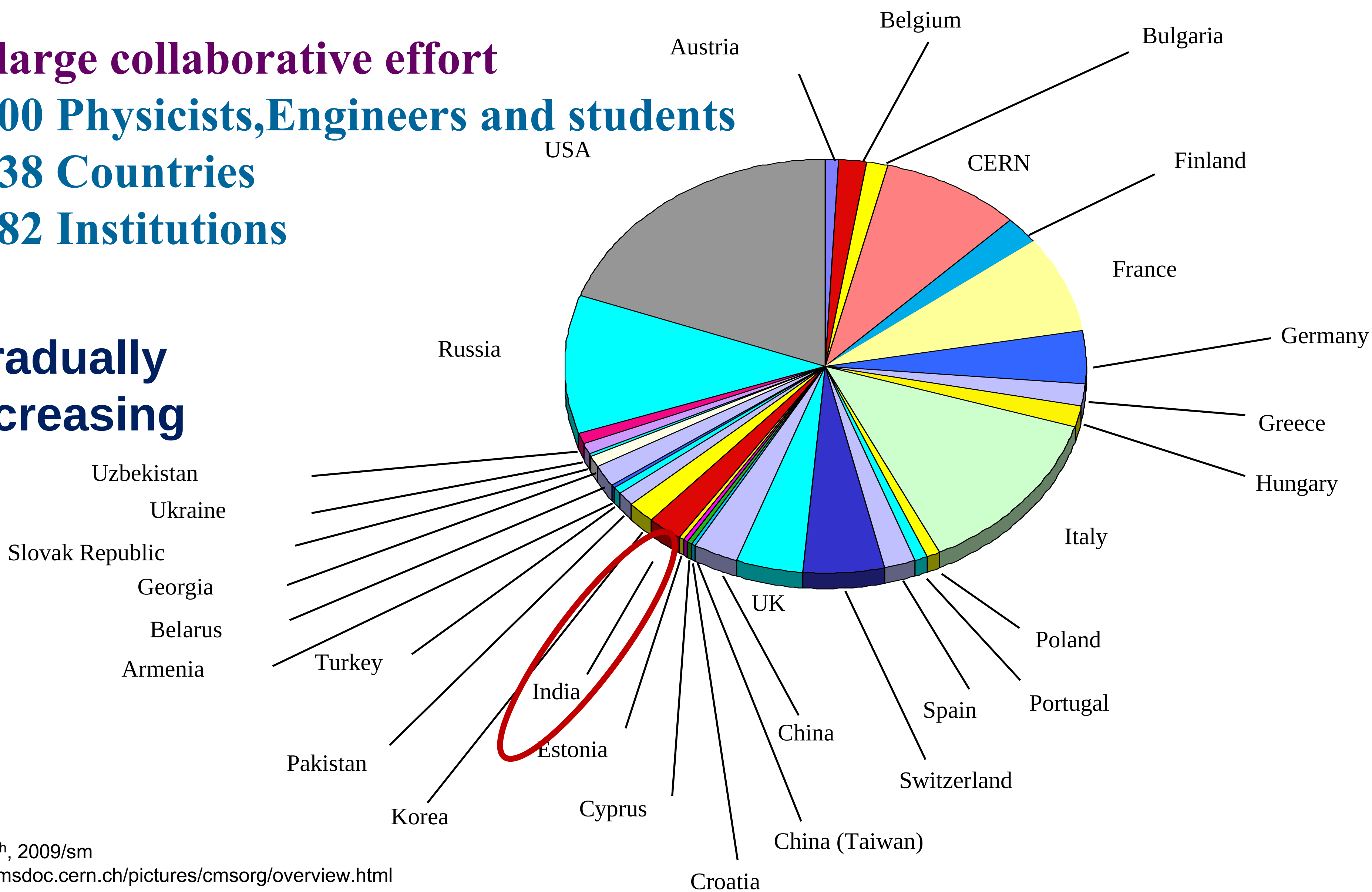
A large collaborative effort

3600 Physicists,Engineers and students

38 Countries

182 Institutions

Gradually increasing



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

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 ECAL detector design, granularity, material etc
  - Study of shashlik electromagnetic calorimeter
  - Optimisation of tracker detector material/geometry
  - ……………………..
  - …..
- Design and building of the Outer Hadron Calorimeter (Silicon preshower) for the CMS experiment (1996 --)
- Continue with MC simulation study from early 90's

Even before joining to the CMS collaboration, TIFR was associated with CCC to choose EM material for next generation experiments.

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 and R. Raghavan
Tata Institute of Fundamental Research, Bombay

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

Study of Light Collection as a Function of Shashlik Tile Size

S.R.Chendvankar, S.K.Gupta, A.Gurtu, M.Maity, G.Majumder, K.Mazumdar, T.Moulik

EHEP Group, Tata Institute of Fundamental Research, Colaba, Bombay 400 005, India

TIFR/EHEP/94-16
December 9, 1994

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

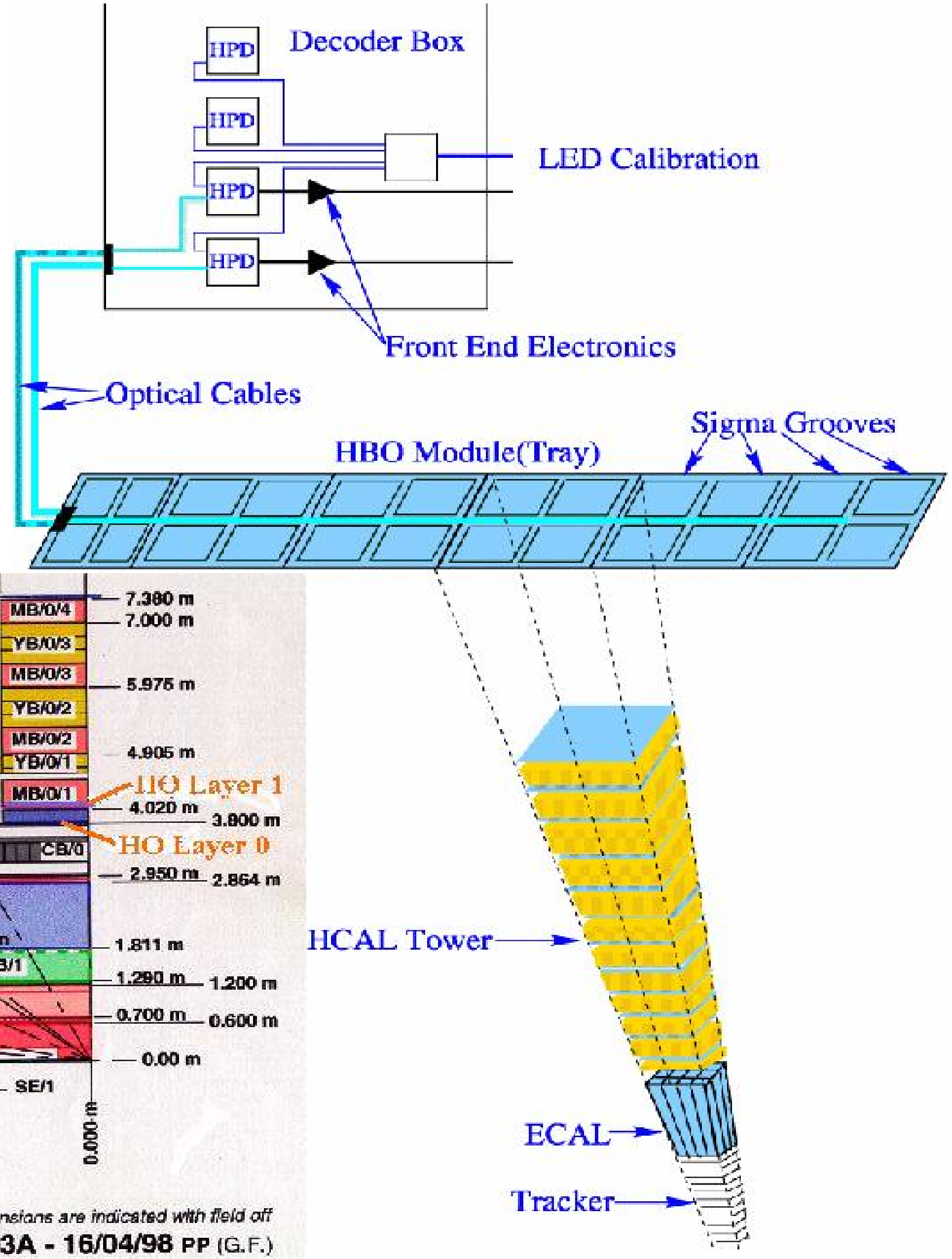
S. Banerjee, G. Majumder, K. Mazumdar, R. Raghavan
Tata Institute of Fundamental Research, Bombay

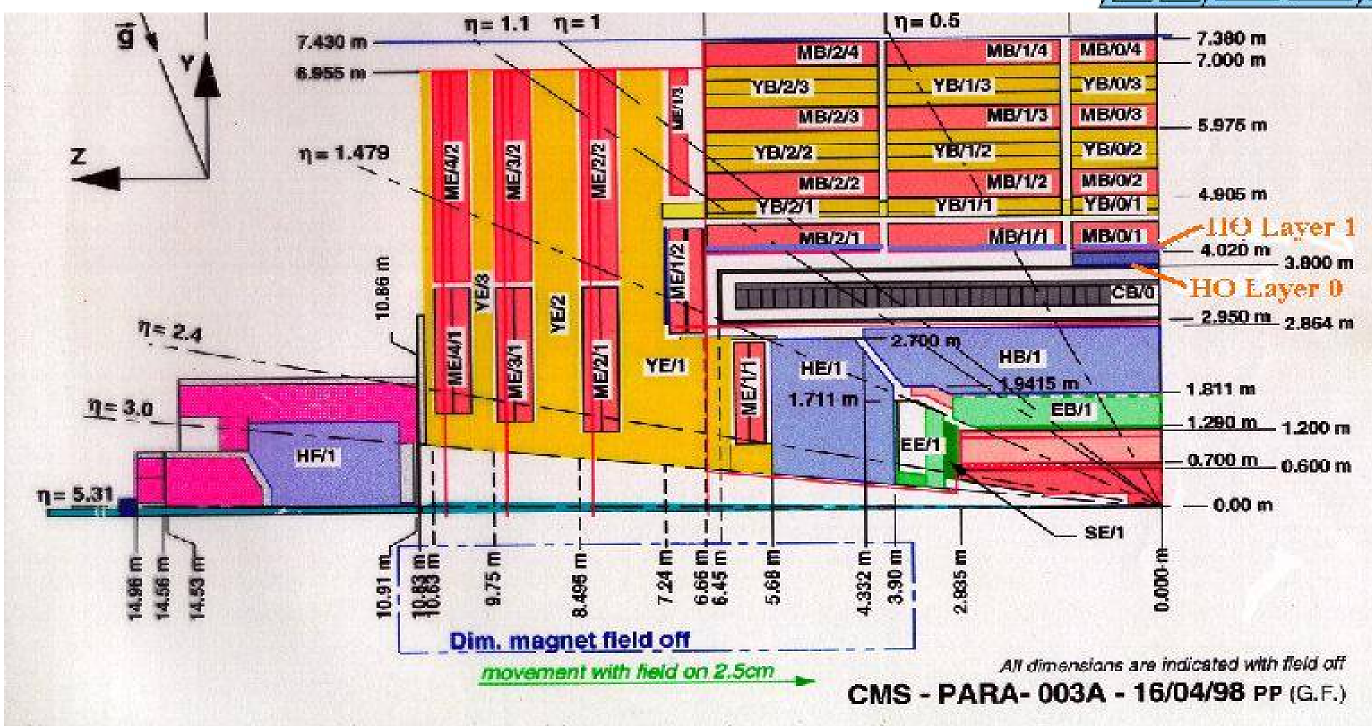
Indian contributions toward CMS detector

- **TIFR, together with Panjab University constructed the outer hadron calorimeter**
- **HO covers central rapidity region |η|<1.3 occupied by the five muon rings**

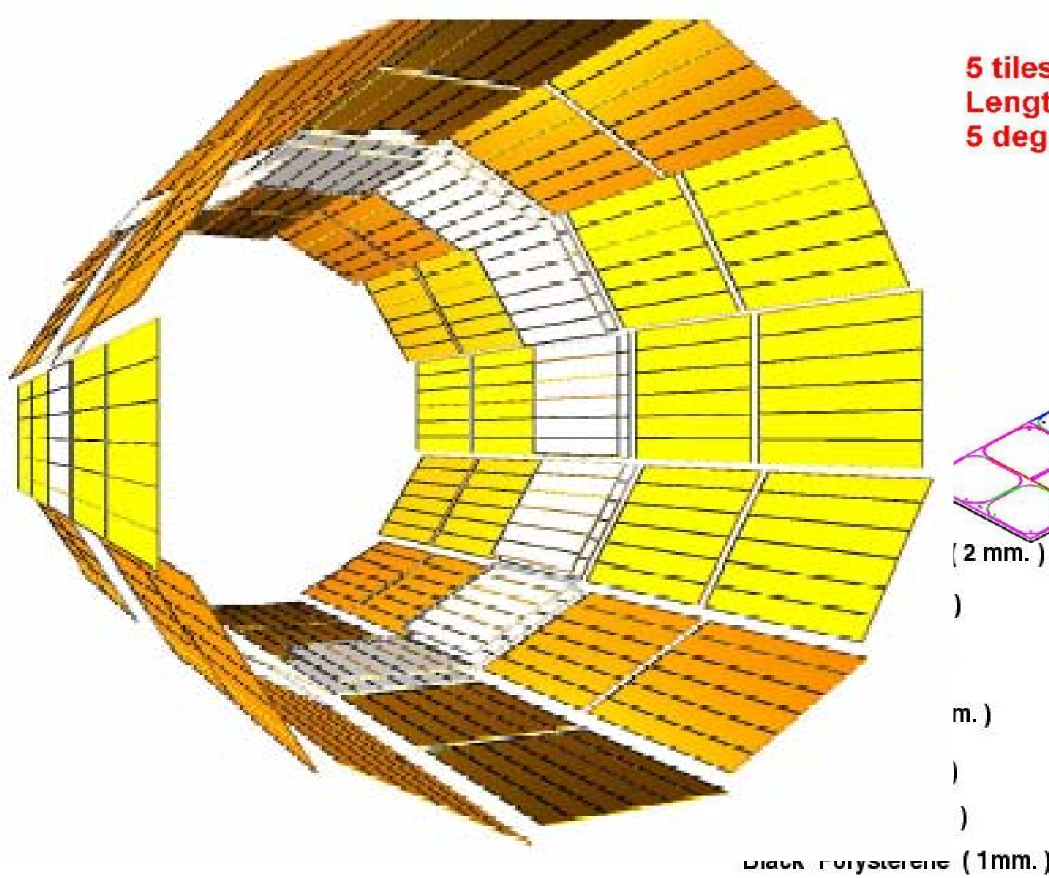
Pseudorapidity, $\eta = -\log_e(\tan(\theta/2))$

- **Basic detector element maps tower granularity of 0.0873 × 0.0873 in $\eta \times \Phi$**
- **432 trays are build from 2730 tiles**

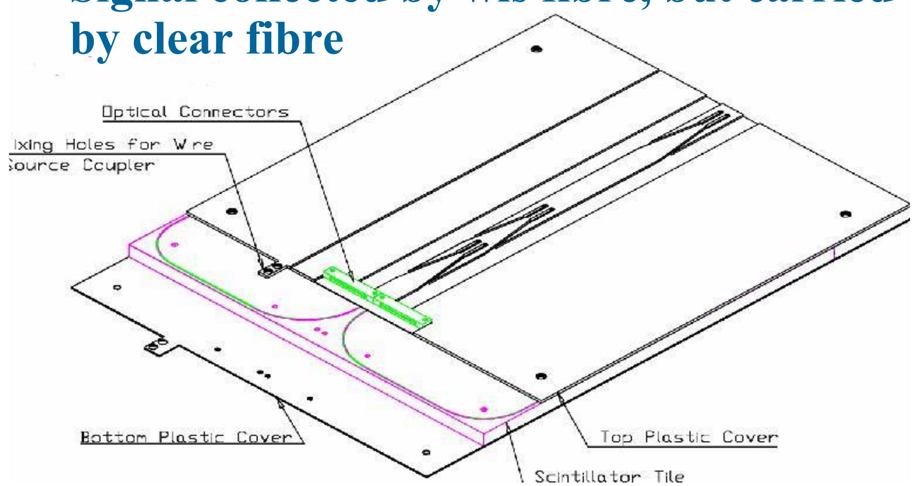


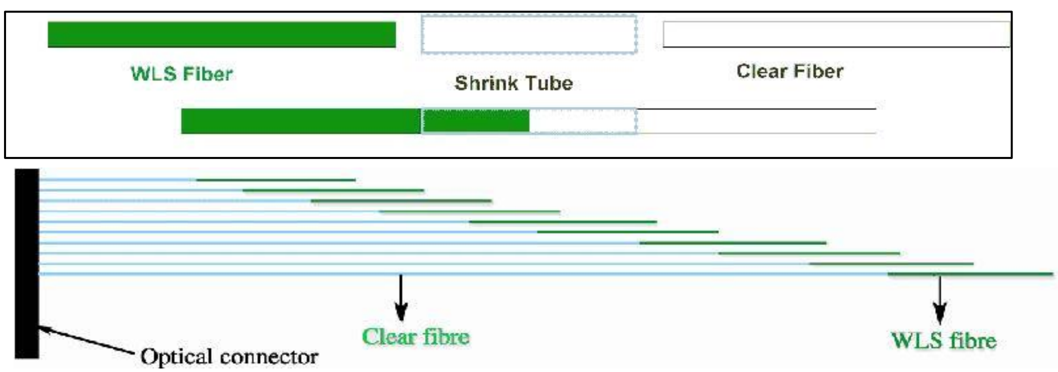


Construction of HO tiles



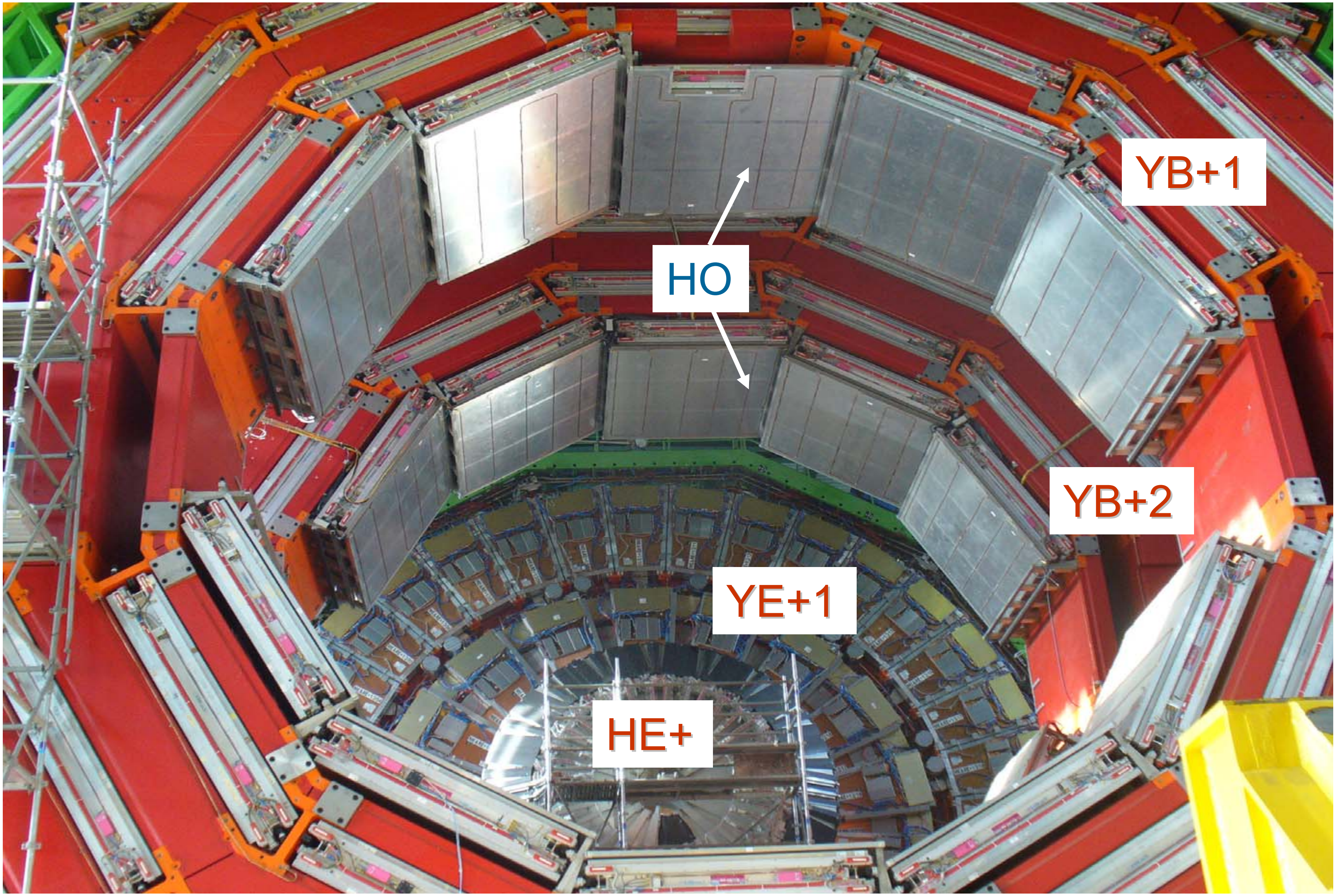
- **Optical fibres are grouped together as a pigtail and inserted into the grooves**
- **Signal collected by wls fibre, but carried by clear fibre**



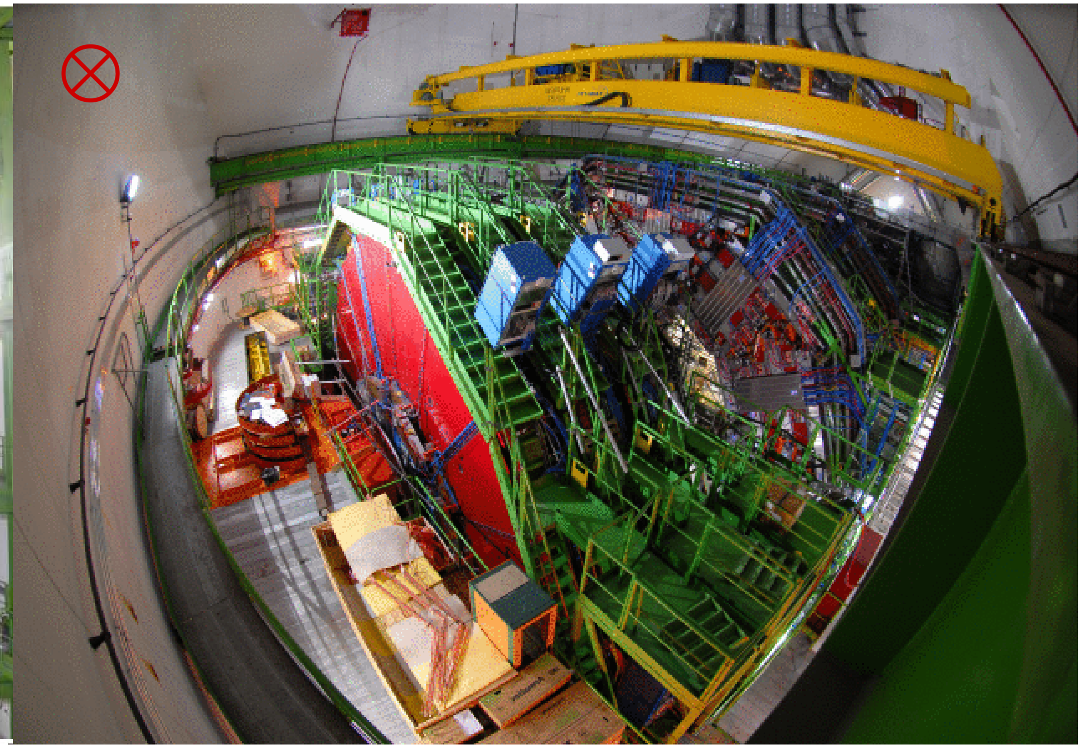


CMS status in 2005 : Surface hall

YB+1, YB+2, YE+1 and HE at surface hall



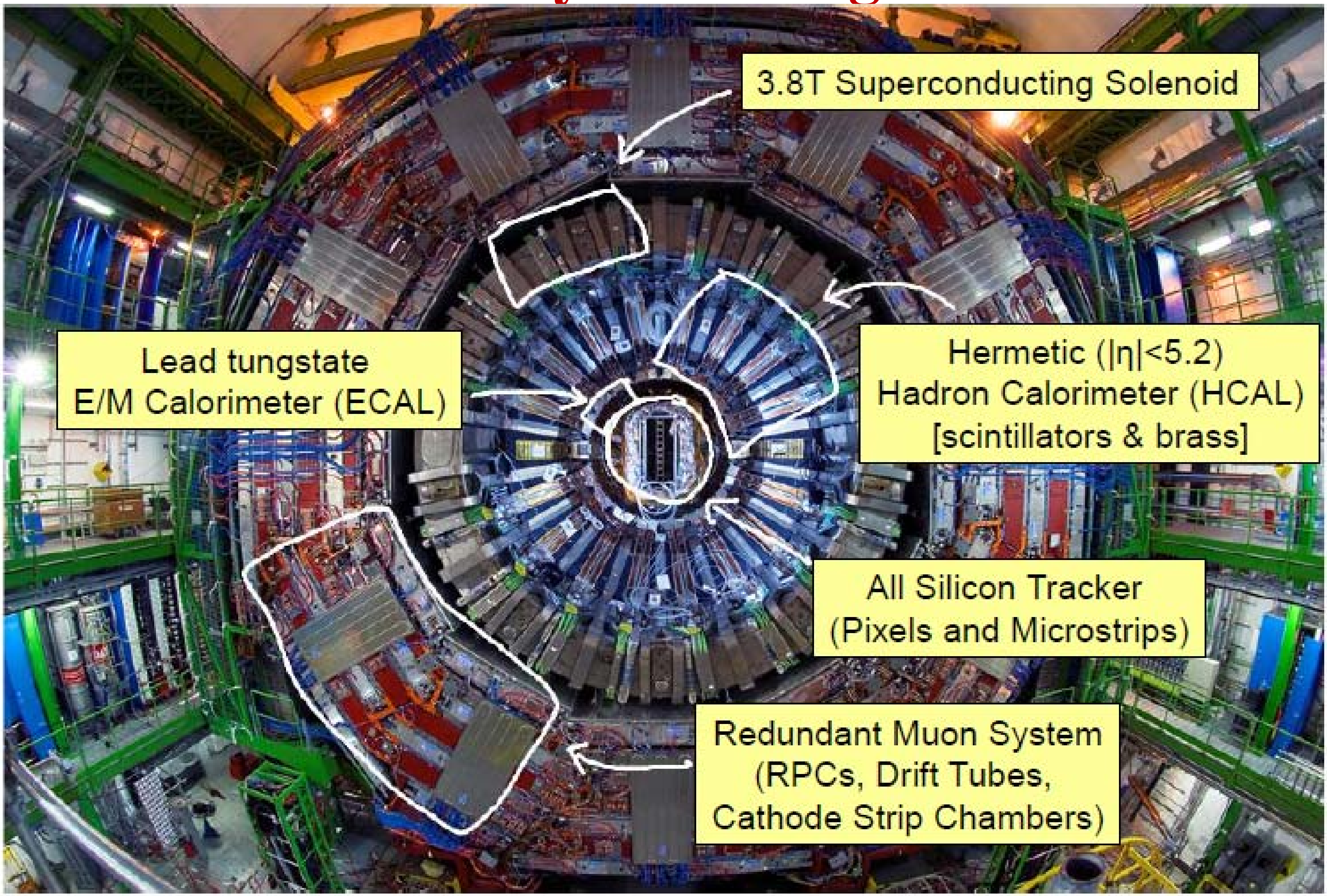
Assembly of the detector in CMS three years



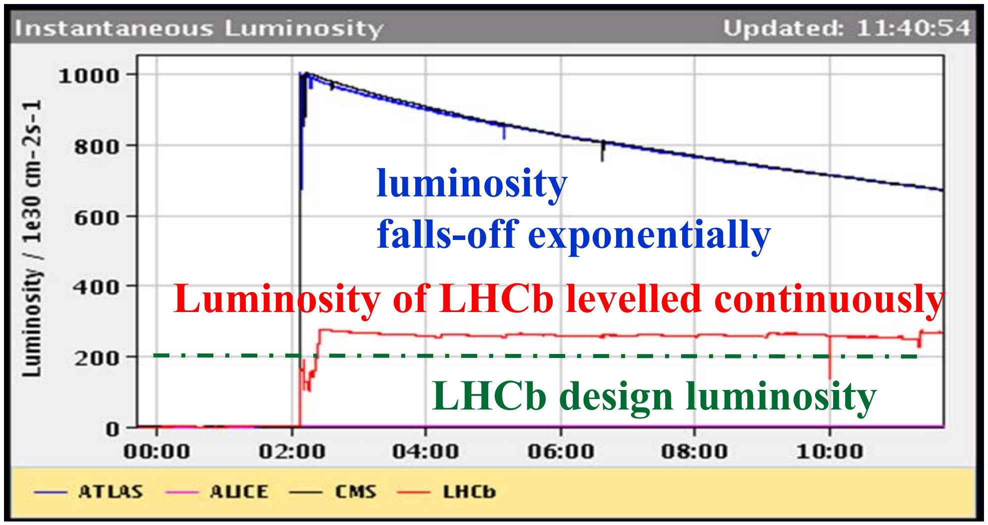
Status of ux5 hall, may 2006 → **Status of ux5 hall, September 2008**

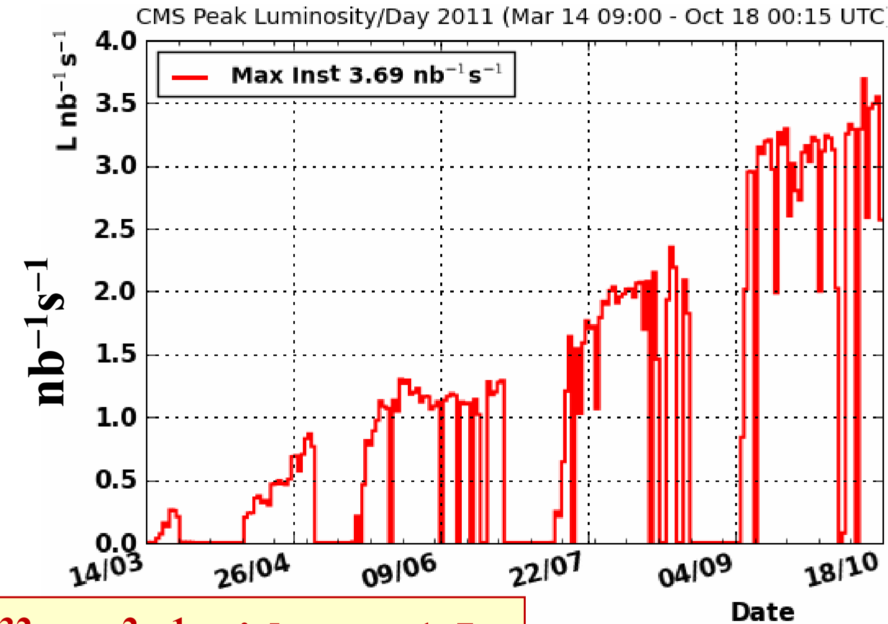
- **Following completion of Magnet Test and Cosmic Challenge (MTCC) in Nov-2006:**
- **we have started lowering of CMS heavy elements and**
- **Installation & Commissioning in underground hall (ux5) along with Surface area**
- **All these went in parallel**

Assembly in underground

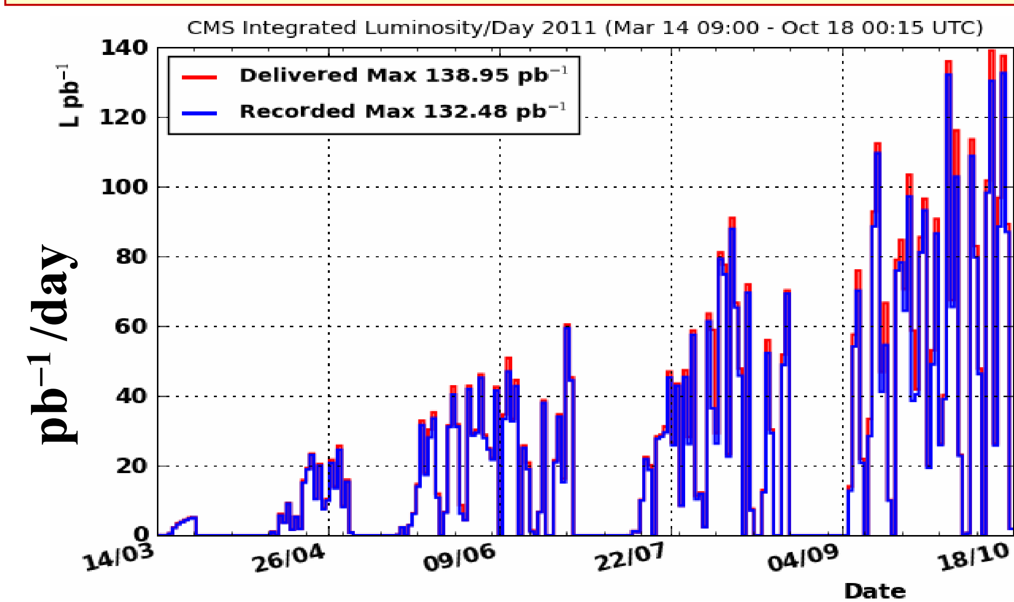


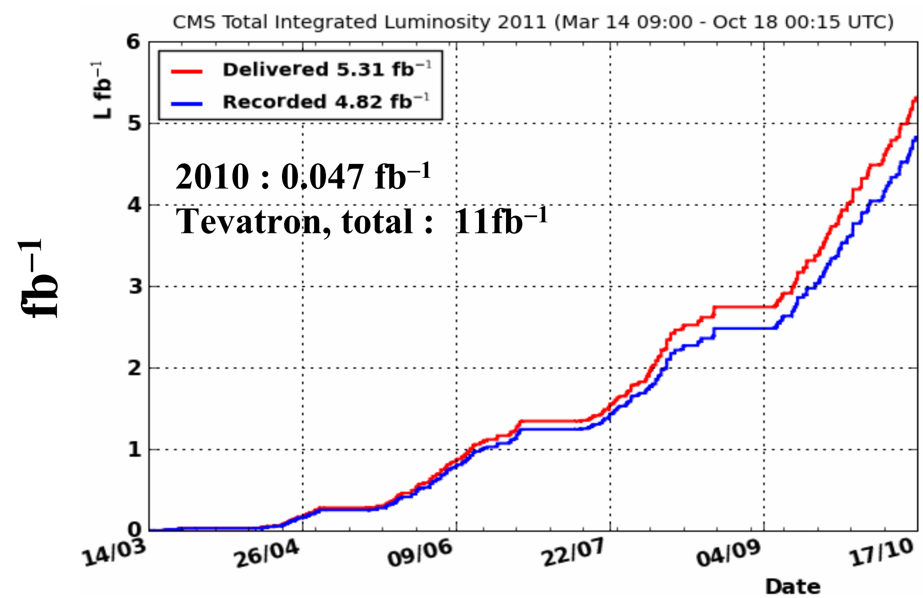
LHC Luminosity: Delivered & Recorded



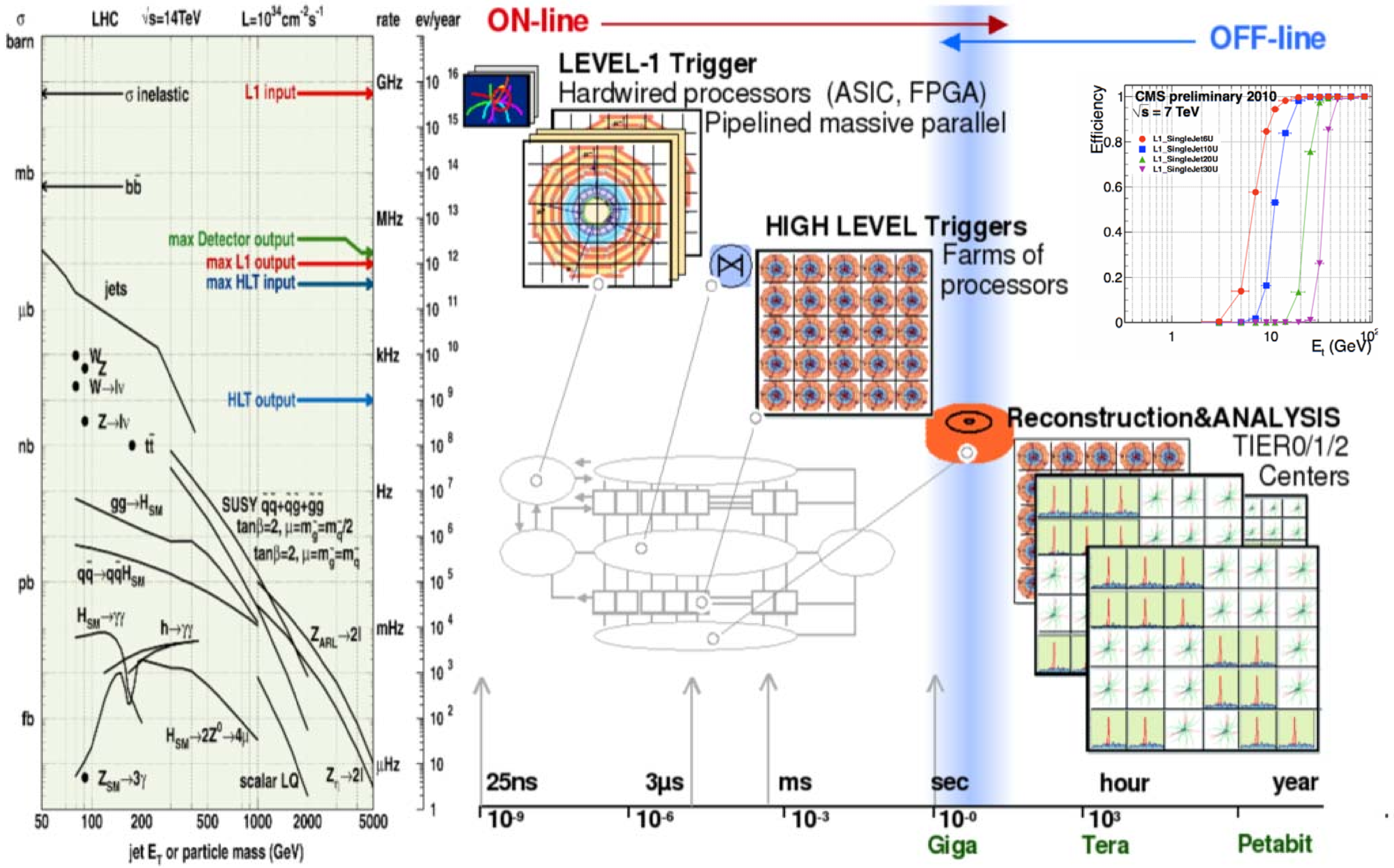


→ Since end of May running at constant $L \sim 3\cdot10^{32}$ cm^{-2}s^{-1} with $\mu \sim 1.5$



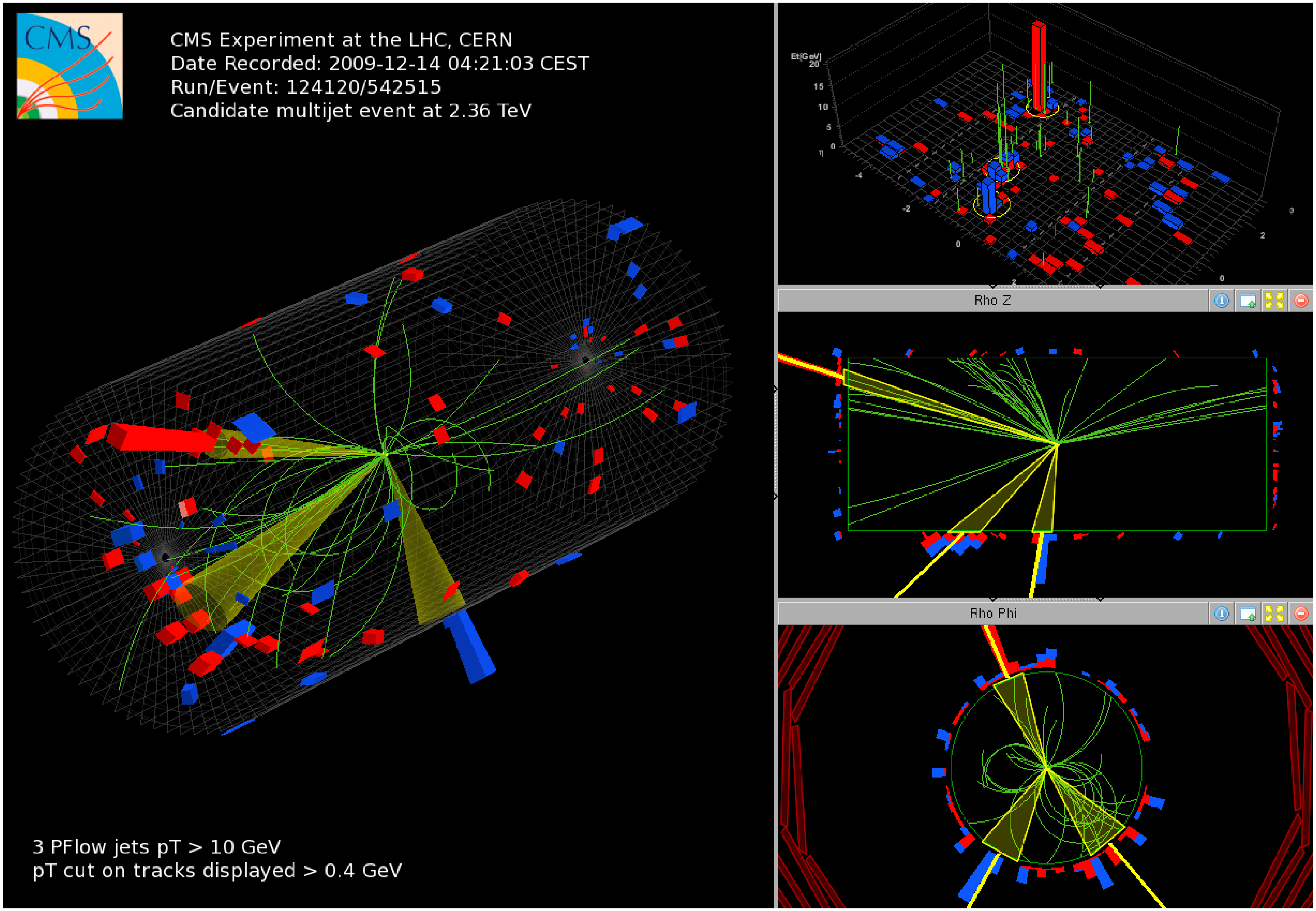


Trigger and DAQ: physics selection at CMS

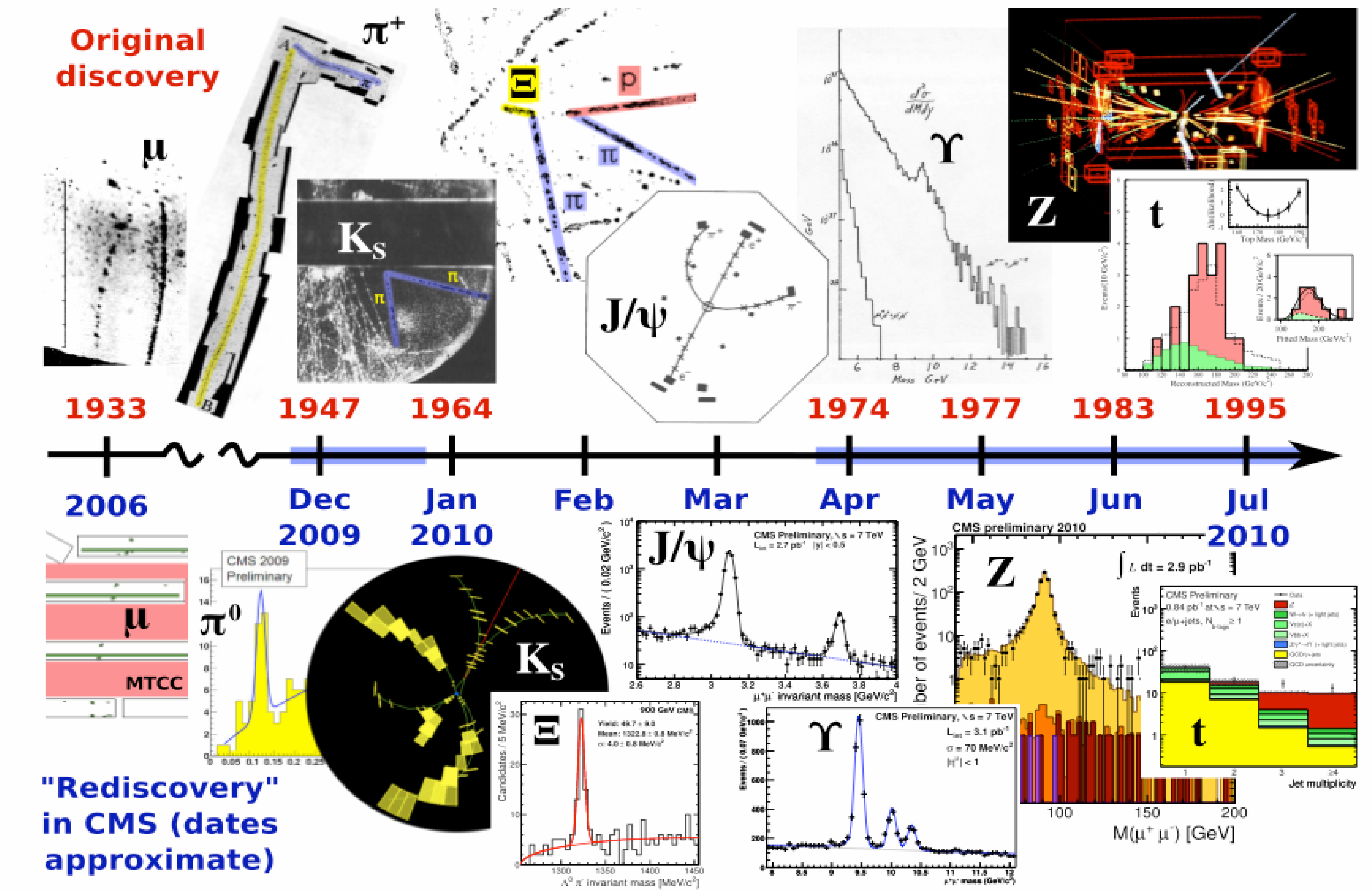


A typical minimum bias event

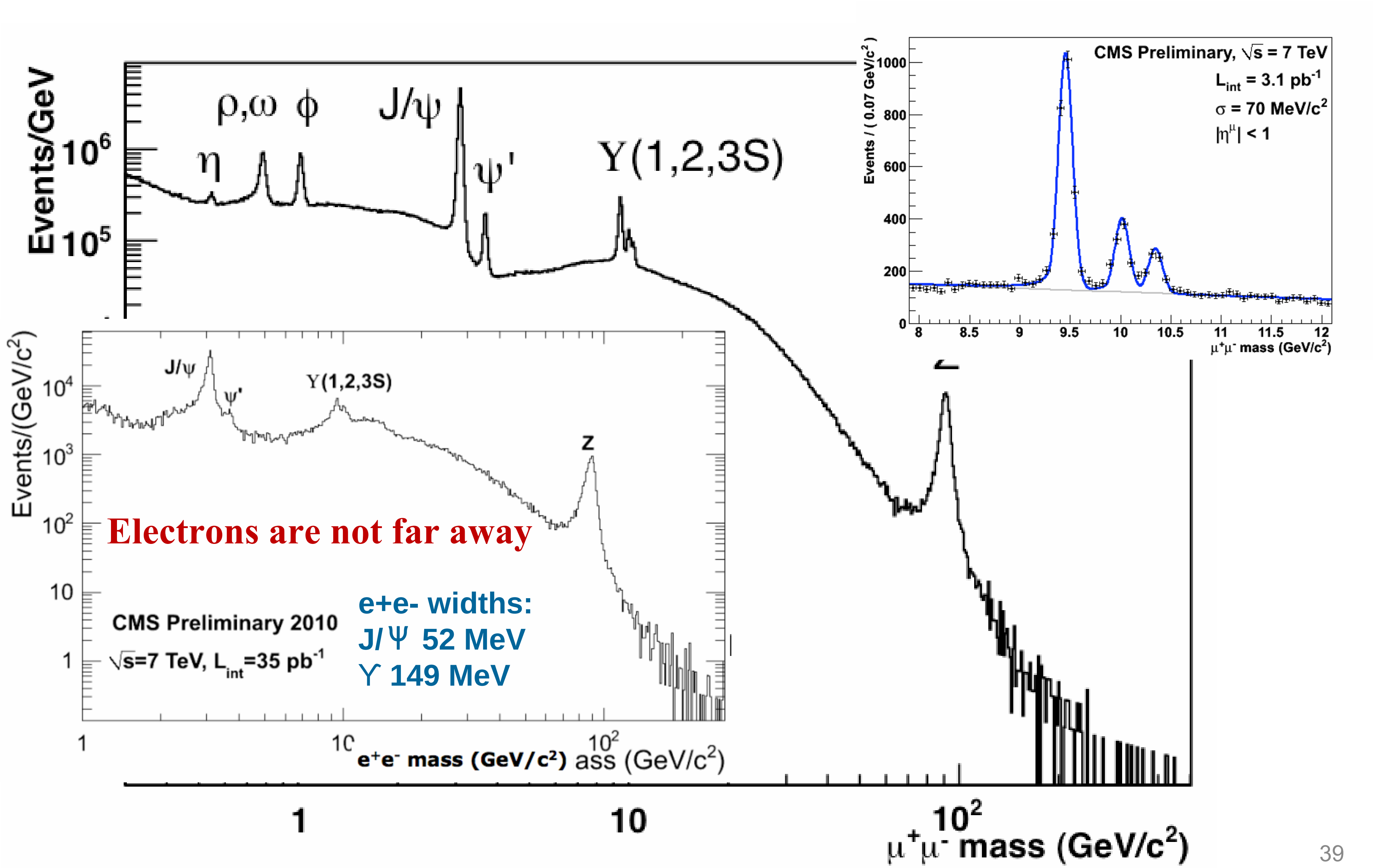
November/December 2009 first LHC collisions



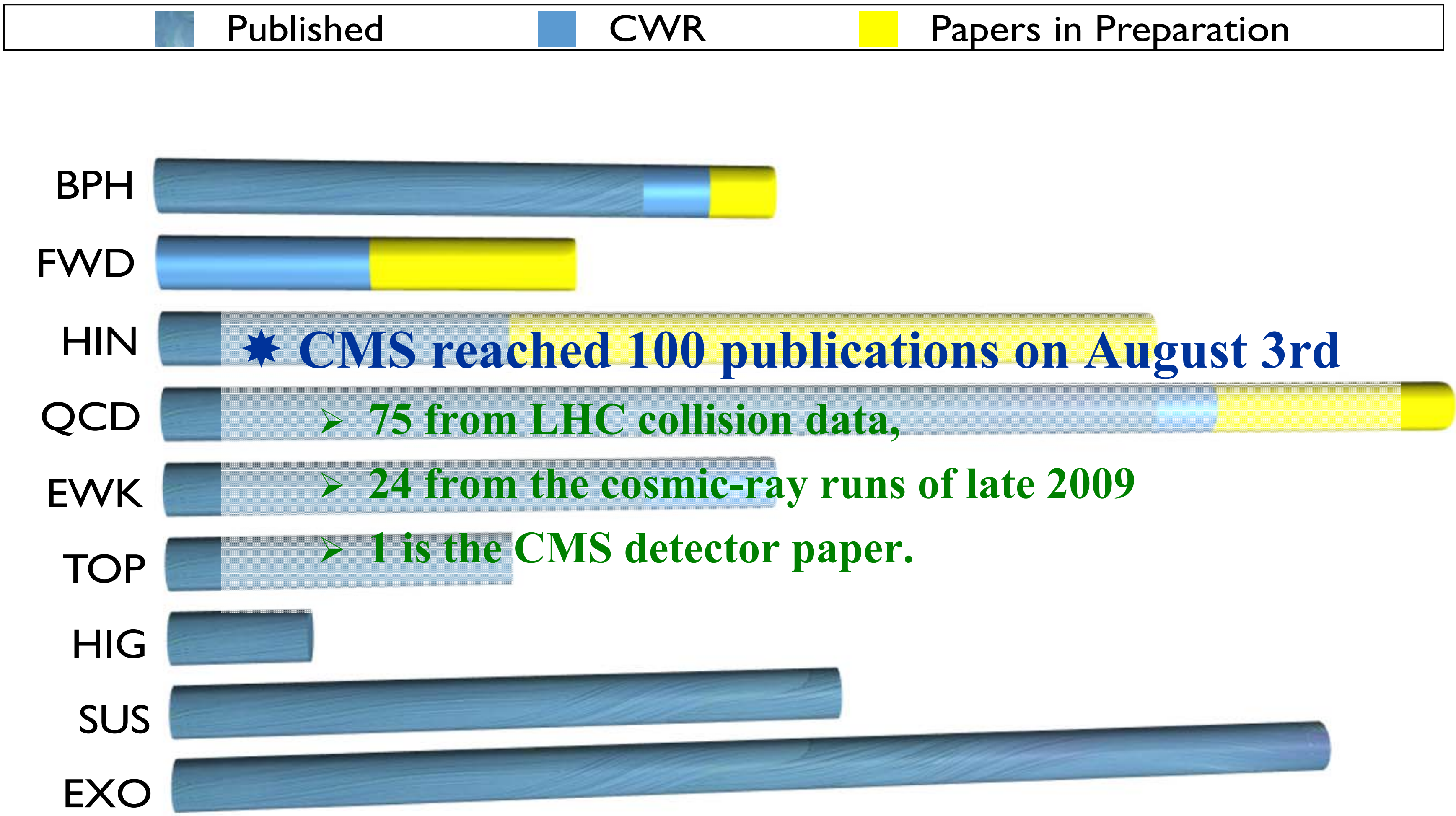
Re-discovering the Standard Model at 7TeV



True concept of Compact *Muon* Solenoid



Physics Analyses on 2010 Data



✸ **CMS reached 100 publications on August 3rd**

- 75 from LHC collision data,
- 24 from the cosmic-ray runs of late 2009
- 1 is the CMS detector paper.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Papers, and Physics Analysis Summaries (PAS): http://cdsweb.cern.ch/collection/CMS

Hadronic event shape variables : Comparison of Data with models of QCD multijet production

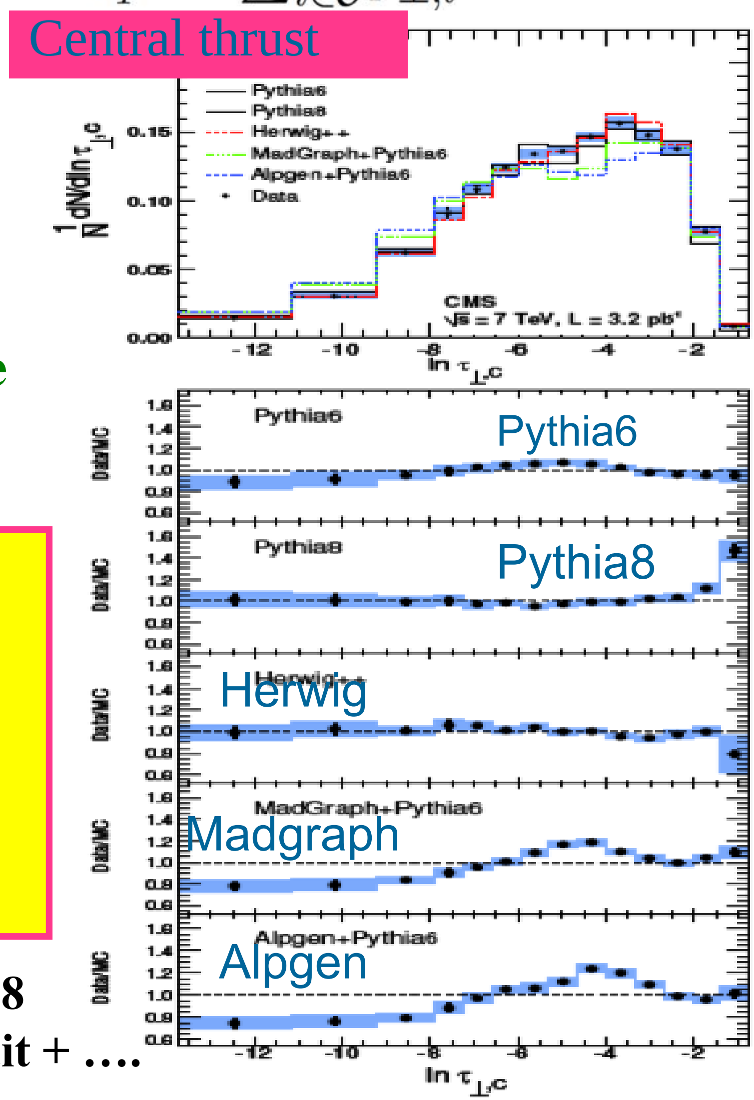
3.2pb^{-1} data

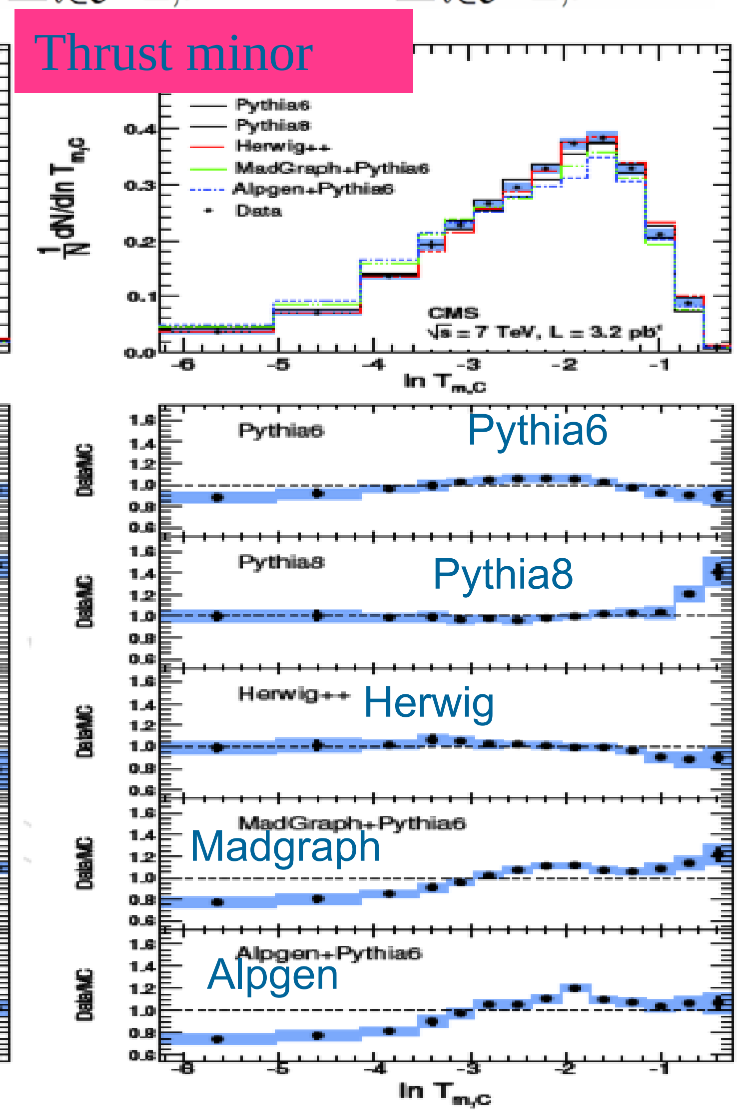
$$T_{\perp,C} \equiv \max_{\vec{n}_T} \frac{\sum_{i\in\mathcal{C}} |\vec{p}_{\perp,i}\cdot\vec{n}_T|}{\sum_{i\in\mathcal{C}} p_{\perp,i}} \qquad T_{m,\mathcal{C}} \equiv \frac{\sum_{i\in\mathcal{C}} |p_{x,i}|}{\sum_{i\in\mathcal{C}} p_{\perp,i}} = \frac{\sum_{i\in\mathcal{C}} |(\vec{p}\times\vec{n}_B)\times\vec{n}_{\mathrm{T},\mathcal{C}}|}{\sum_{i\in\mathcal{C}} p_{\perp,i}}$$

Event Shape variables can be used to distinguish different models of QCD multijet production

Possibility with large statistics: measurement of α s

Agree with Pythia6, Pythia8 and Herwig++ ,
Disagree with Madgraph and Alpgen



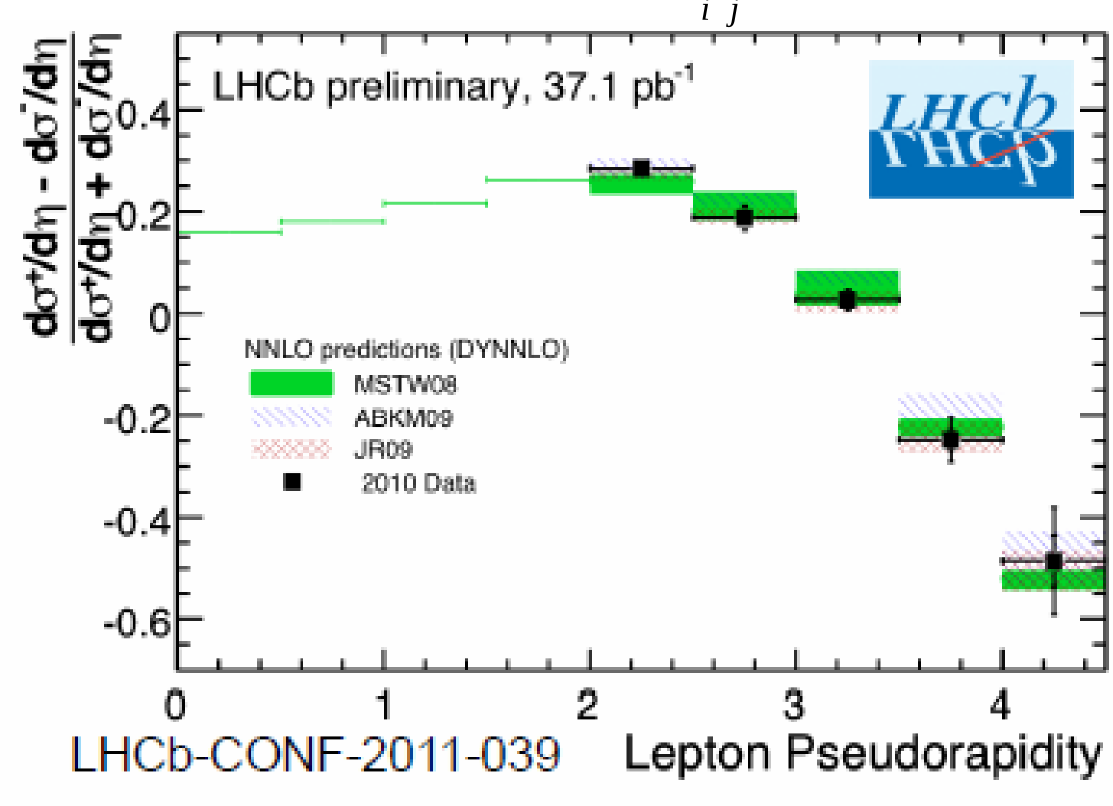


Phys. Lett. B699 (2011) 48
G. Majumder, M. Guchait + ….

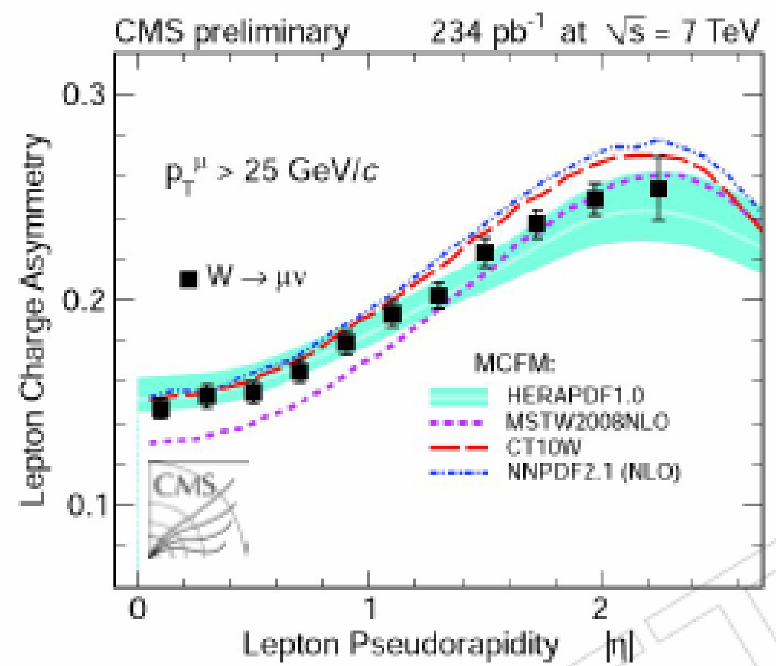
W Charge Asymmetry

- In pp collisions, more W^+ are expected than W^- (66/34) due to the excess of u-quark wrt to d-quark
- Asymmetry is a function of η since u quark carry higher fraction of proton momentum
- An asymmetry measurement could be used to explore the proton structure (PDF)

$$d\sigma_X = \sum_{i\,j} \int dx_1 dx_2\, f_i(x_1, Q^2)\, f_j(x_2, Q^2)\, d\hat{\sigma}_{i\,j \to X}$$

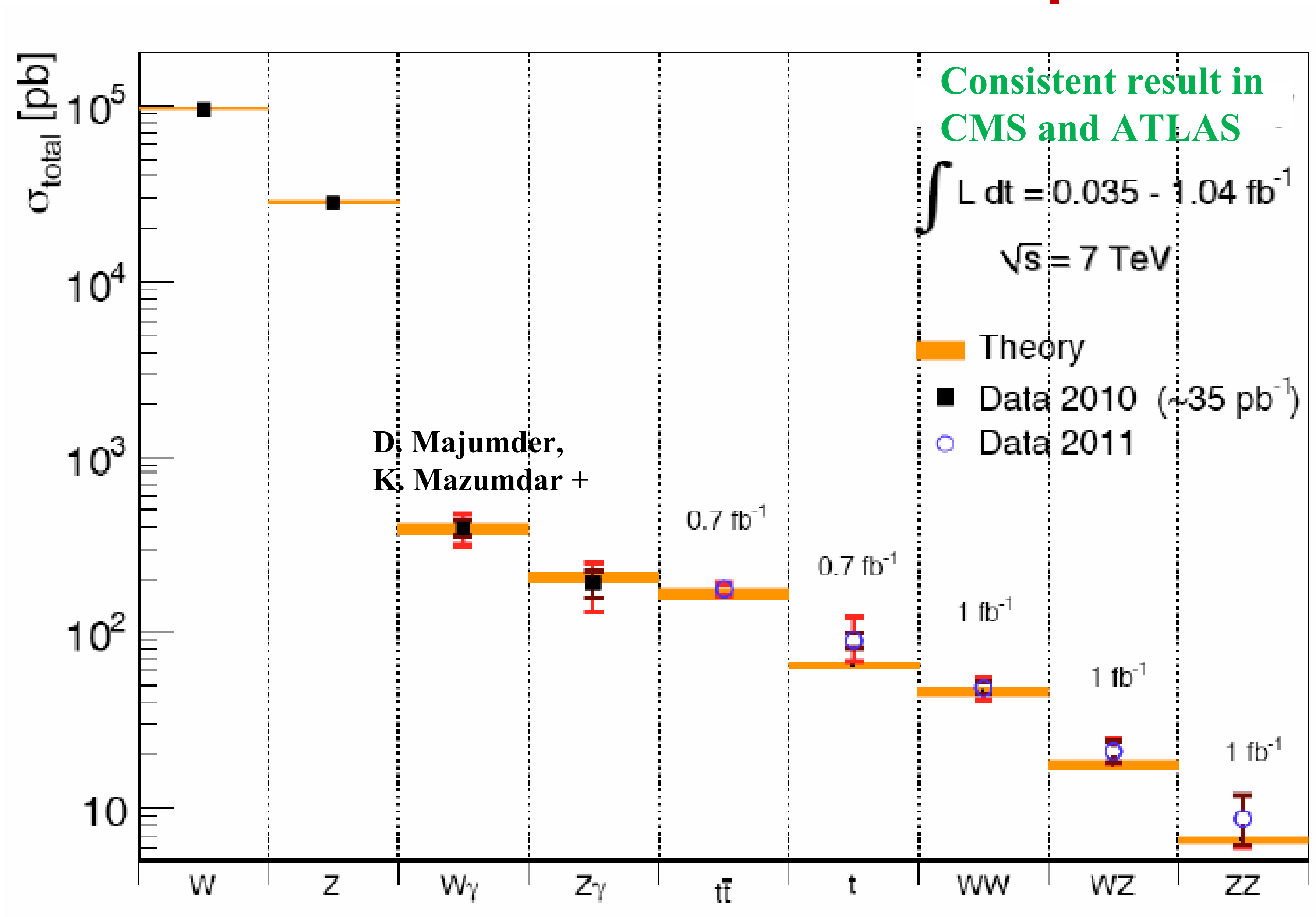


JHEP 04(2011) 050
G. Majumder , A. Saha + ..

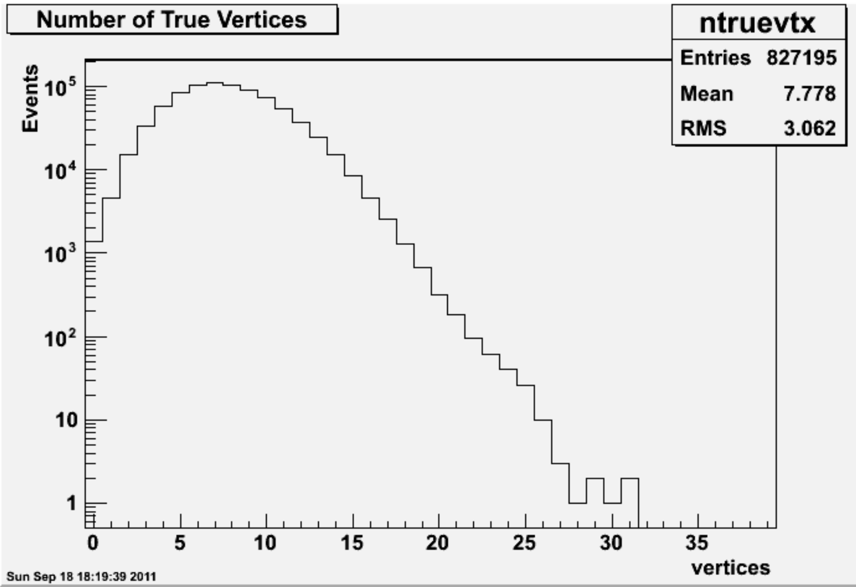


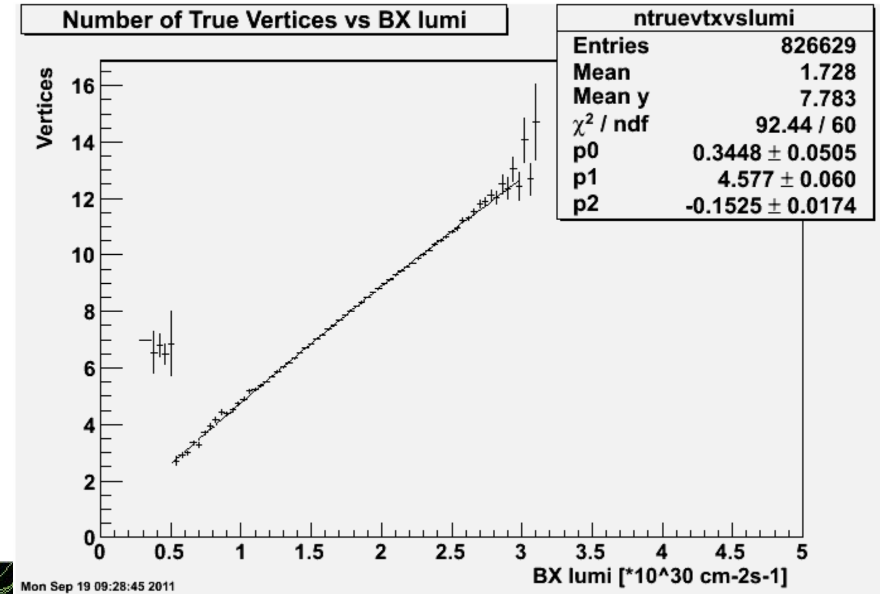
CMS-EWK-11-005

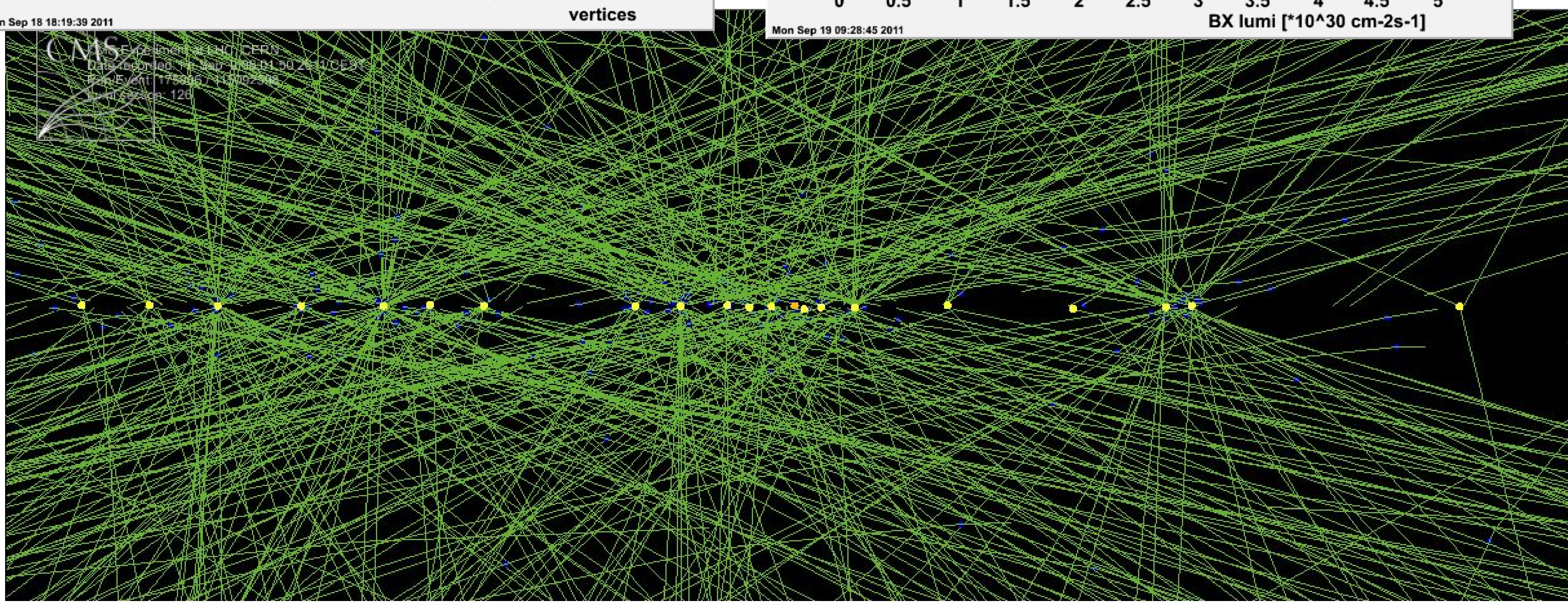
Precision measurement of EW processes



Increase of luminosity : Challenge of pileup







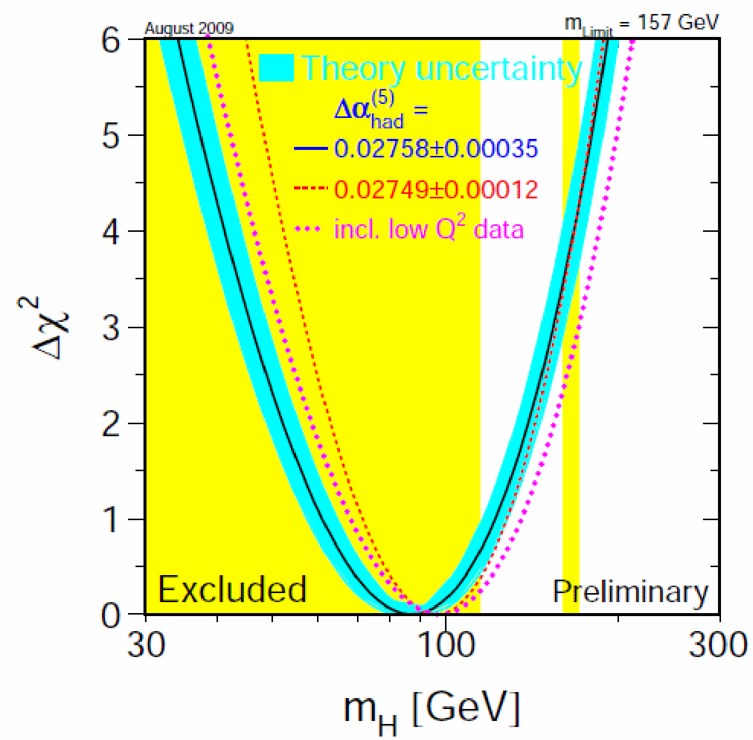
Status of Higgs search before LHC run

Experiment

Indirect constraints from precision EW data :

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

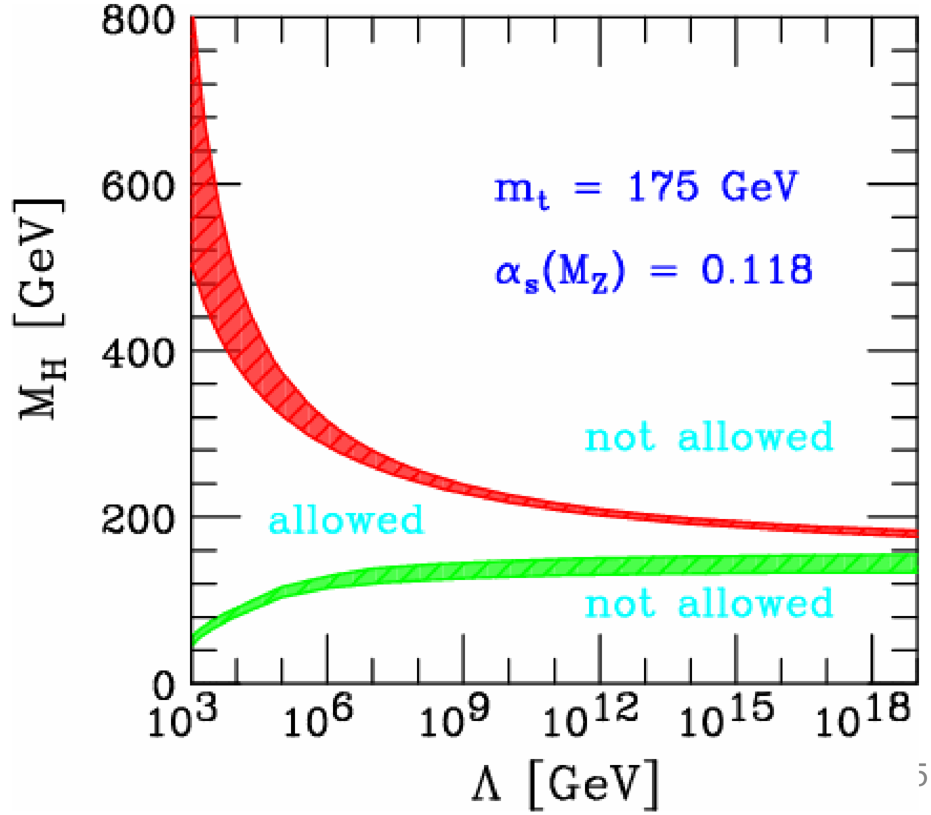
Direct limit from LEP:
Mh > 114.4 GeV



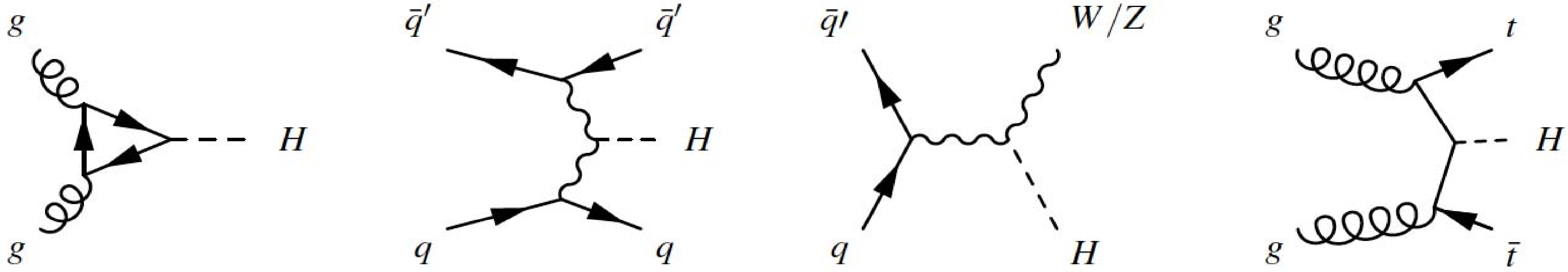
SM theory

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

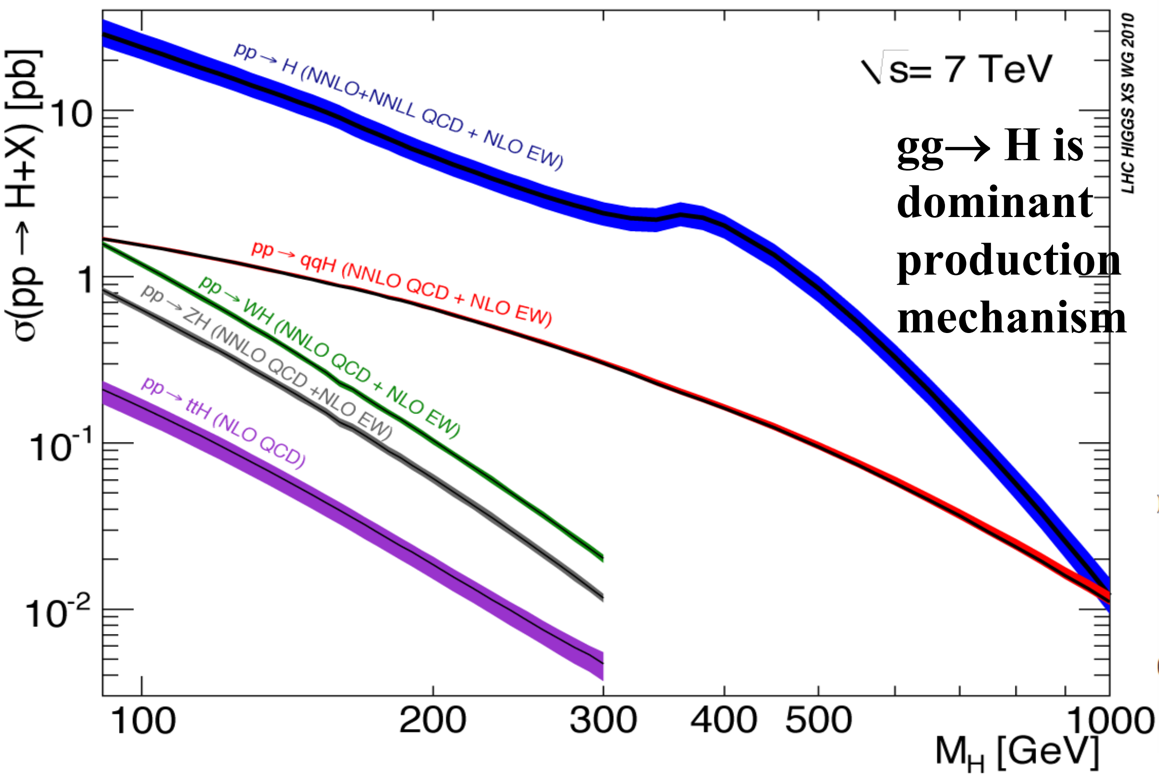
"triviality" :
Higgs self-coupling remains finite



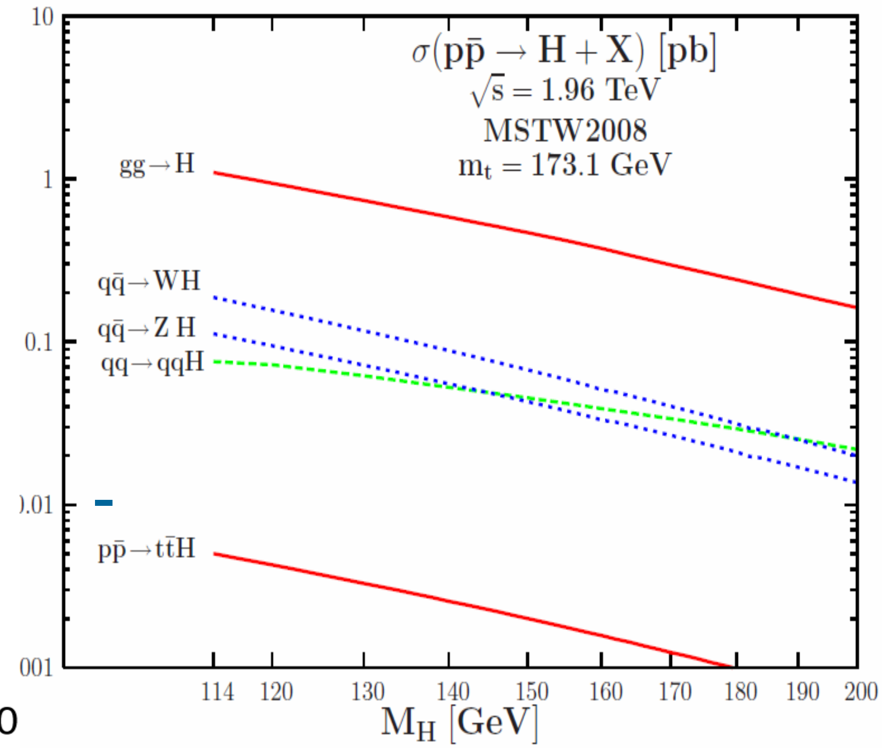
Higgs Production in 7 TeV pp Collsions



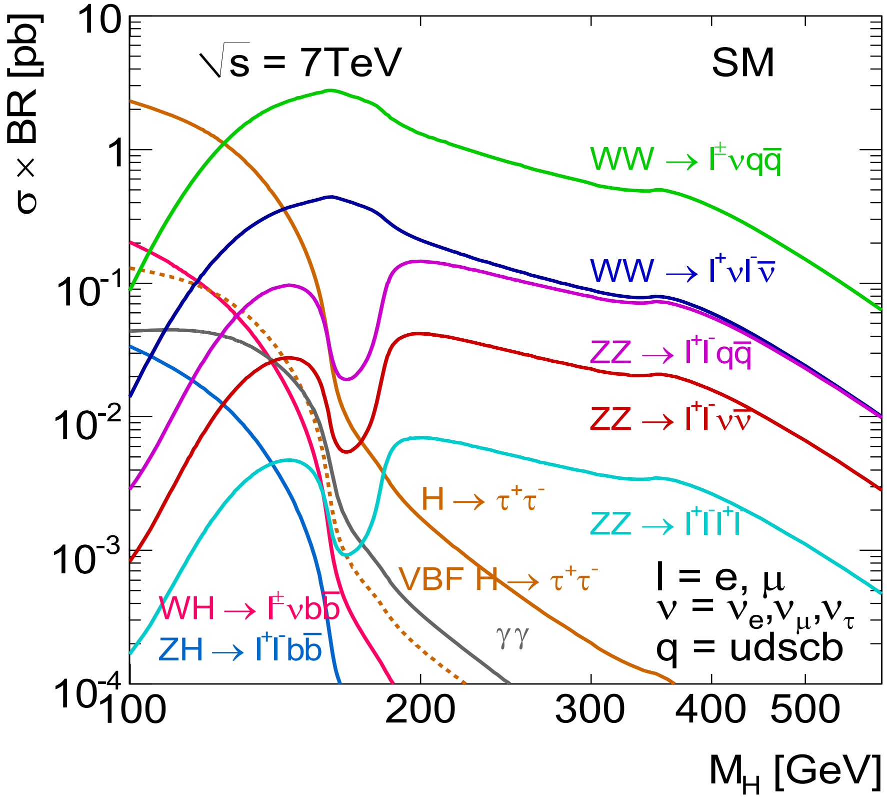
(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

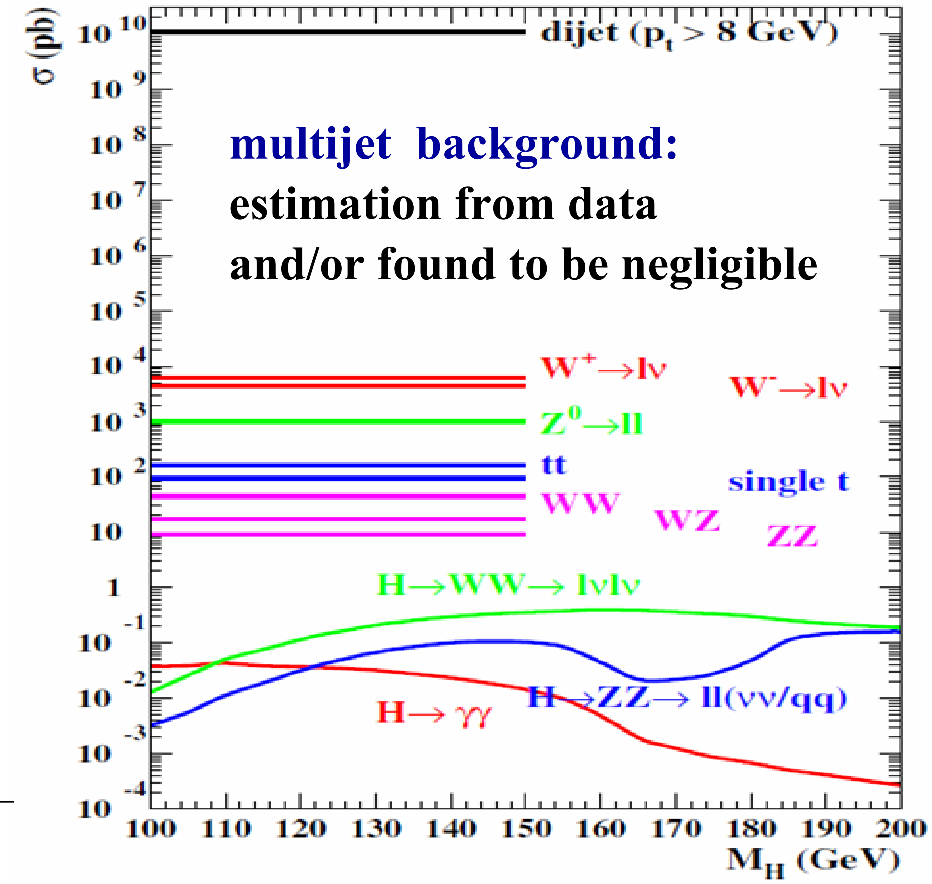


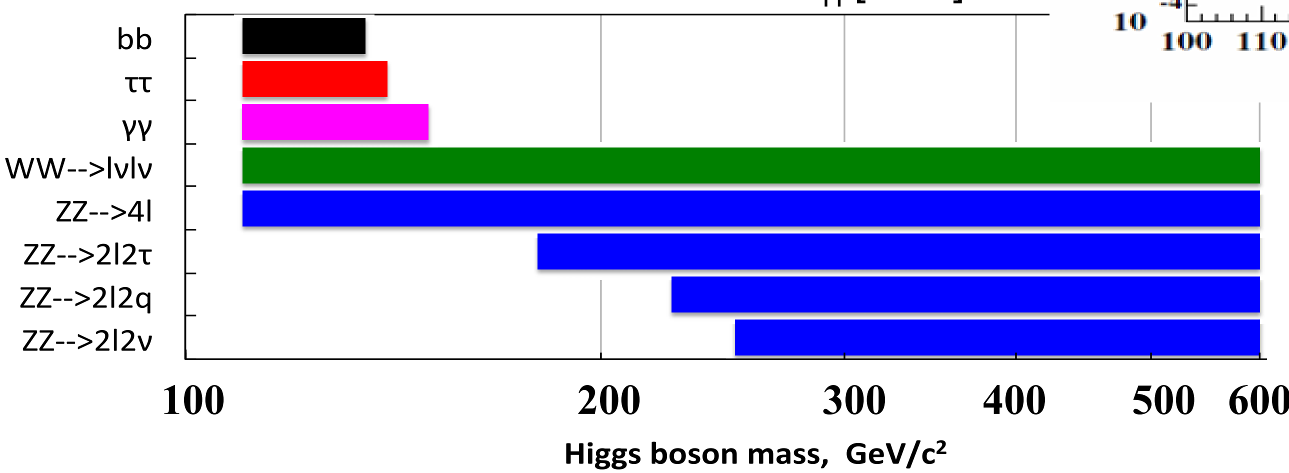
gg→ H is dominant production mechanism



The Challenge: Tiny Signal-to-Background Ratio



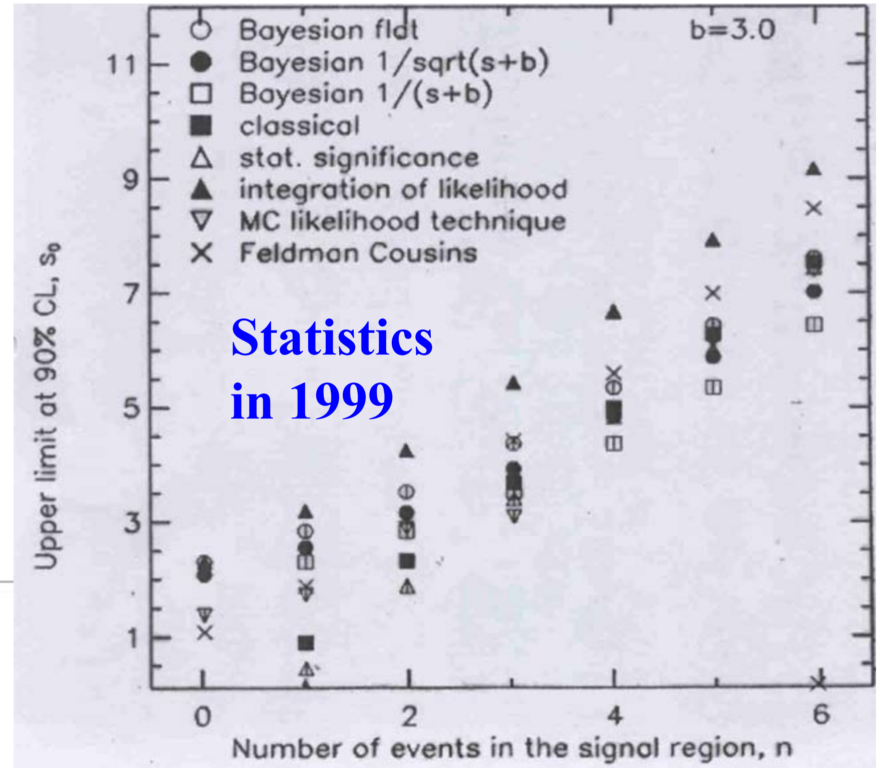




< 1 detectable Higgs boson per 10^{12} collisions

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

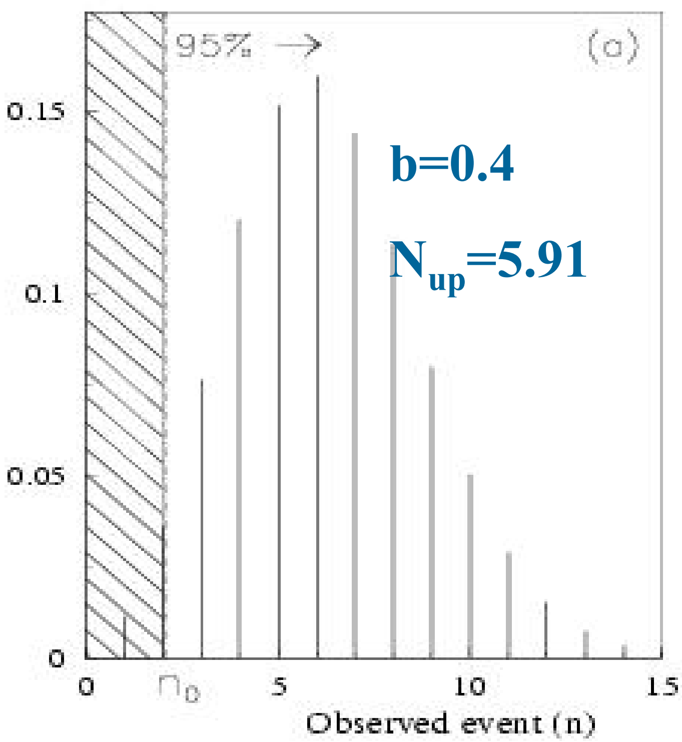
For Poisson distribution, counting a certain number of events, **n** : random repetition of the experiment with $\mu = N_{up}$ (N_{lo}) has probability (1-α) to observe more (less) than **n** events

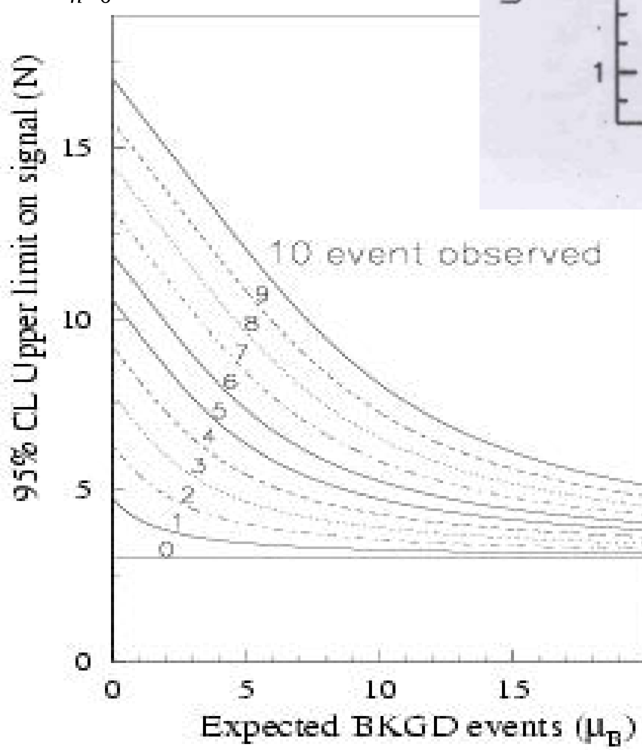


Simultaneously one can have lower and upper limit

In presence of background,

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





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 band
      - $N_{obs} = 6 \rightarrow N_{up} = 5.52$
      - $N_{obs} = 12 \rightarrow N_{up} = 10.74$
    - 2σ band
      - $N_{obs} = 3 \rightarrow N_{up} = 3.99$
      - $N_{obs} = 15 \rightarrow N_{up} = 14.15$

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

Take care of systematic error too

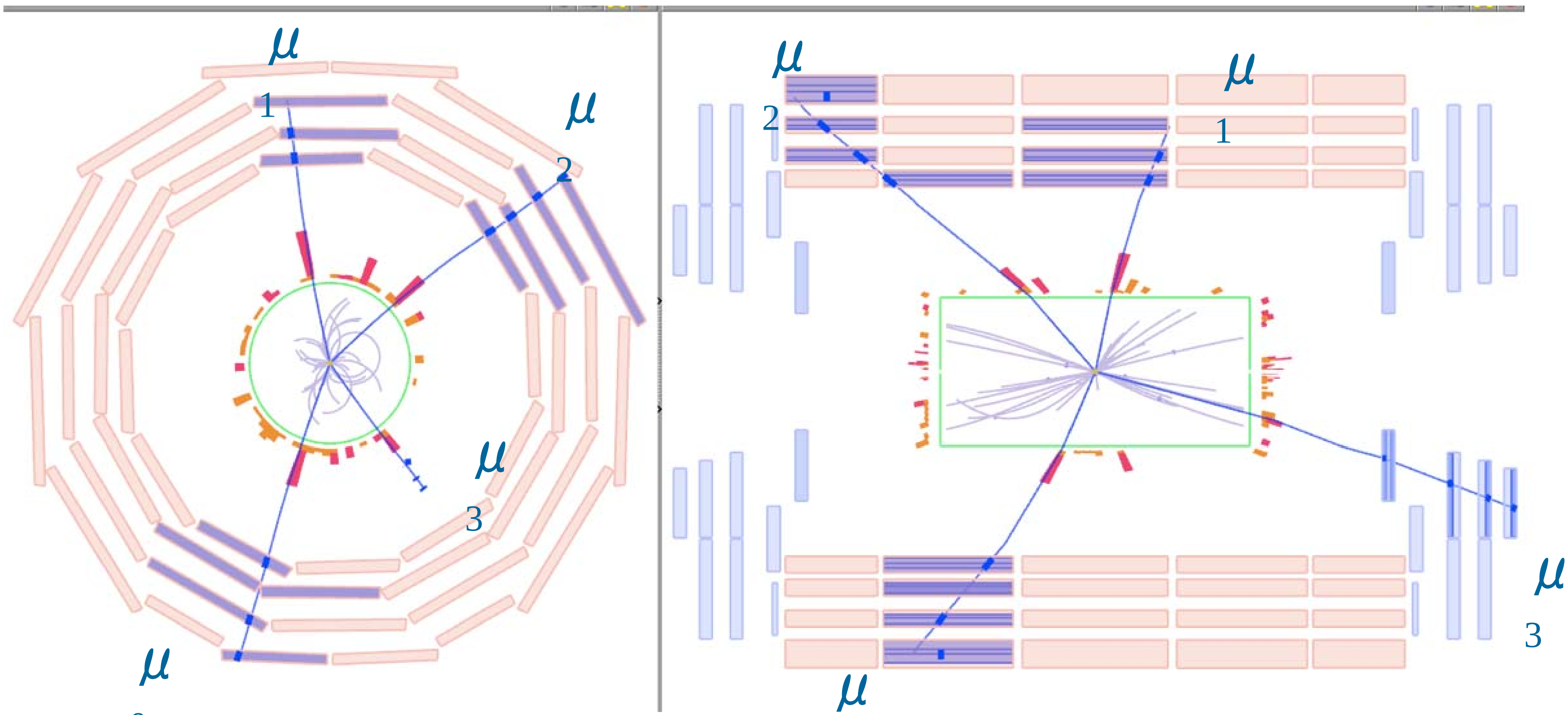
- Observe limit (data) :
  - Expected background, b=9, $N_{obs} = 13 \rightarrow N_{up} = 11.85$

- **CMS does not use this procedure, used**
  - Modified frequentist limits (CLs),
  - Bayesian limits with flat prior,

$$\int_0^{\mu_{95\%CL}} p(\mu \mid N_{obs})\, d\mu = 0.95$$

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

A beautiful ZZ event in 2010 data



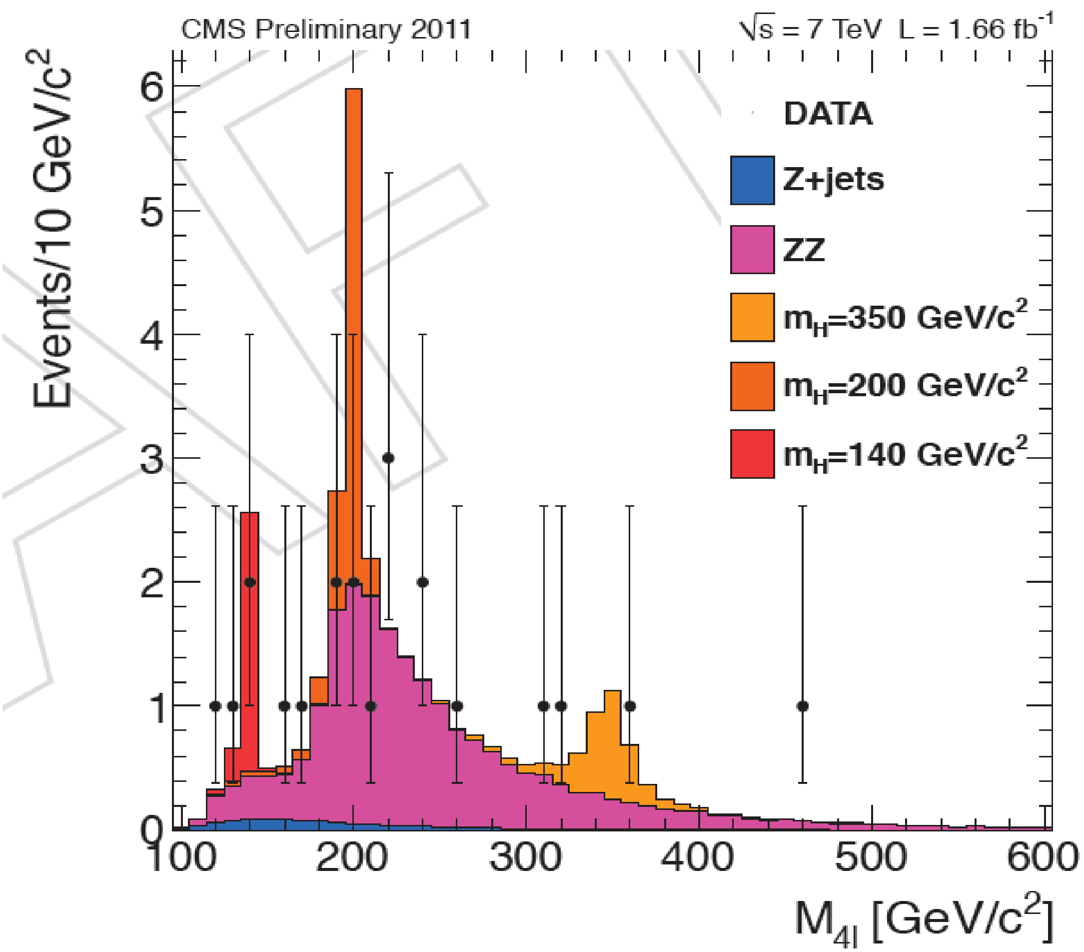
	Pt (GeV)	η	ϕ
μ_0	−48.14	−0.41	−1.9
μ_1	43.44	0.20	1.79
μ_2	25.88	−0.78	0.77
μ_3	−19.56	2.01	−0.98

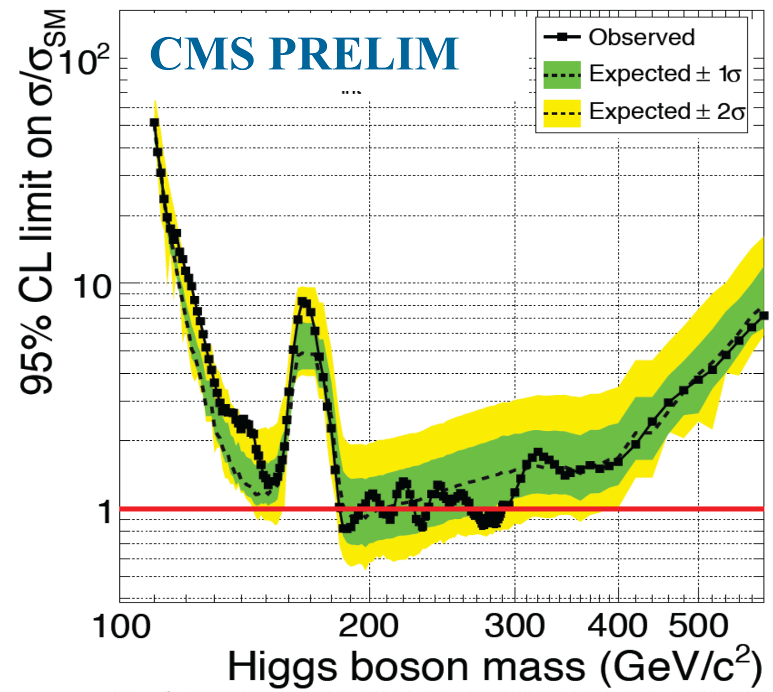
Invariant Masses

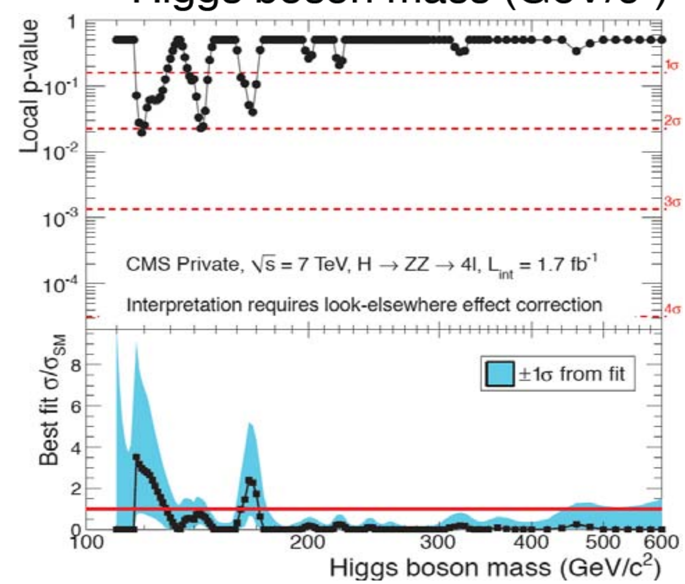
$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

Invariant Mass of 4μ: 201 GeV

H → ZZ → 4l : Observed Yields & Limits







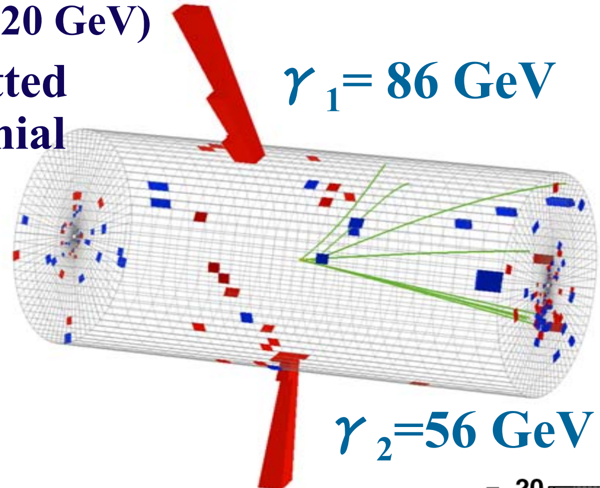
Resolution : 2.7/1.6/2.1 @ 150 GeV/c²
3.5/2.5/2.8 @ 190 GeV/c²

Three pairs of events at M_{4l} = 122, 142 & 165 GeV
Only M_{4l} =142 GeV consistent with SM Higgs expectation

$H \rightarrow \gamma\gamma$, 1.7 fb^{-1}

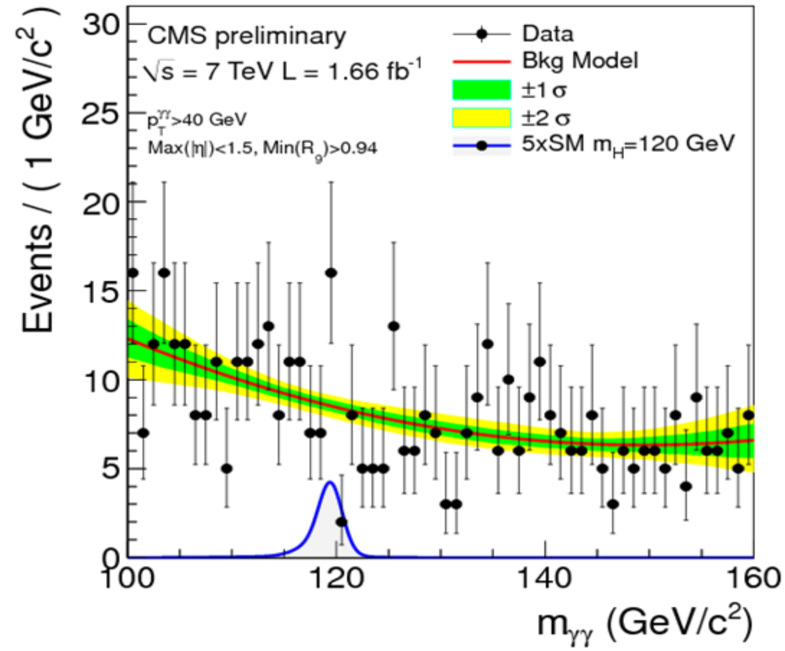
PAS HIG-11-021

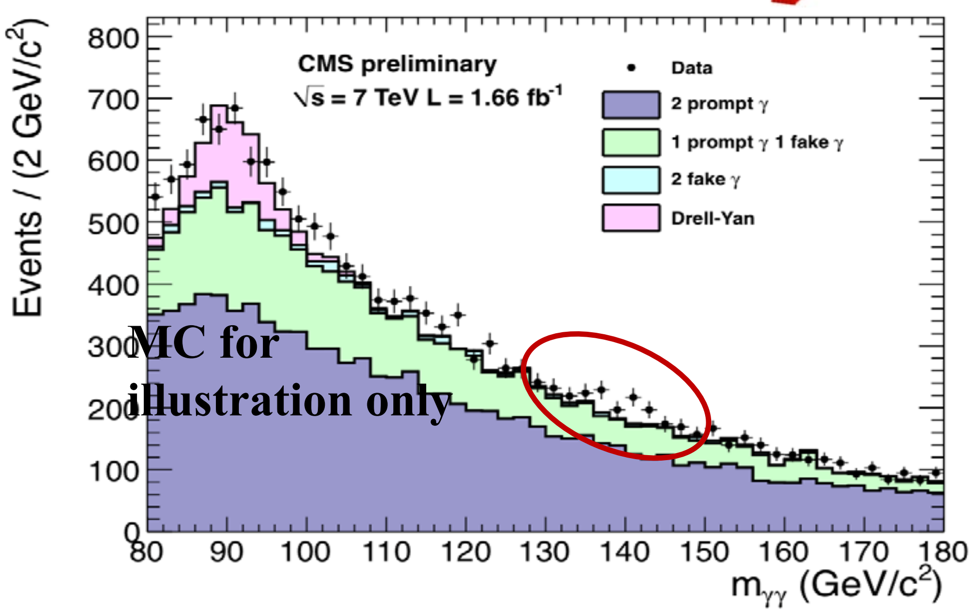
- Two isolated γ's with P_T>40, 30 GeV
- Data divided into 8 categories depending on resolution and $p_T(H)$ σ_{eff}(mass) varies from 1.4 to 3.6 GeV (@m_H=120 GeV)
- Background shape fitted by 2nd order polynomial in each category
- Signal energy resolution extracted from Z→ee data



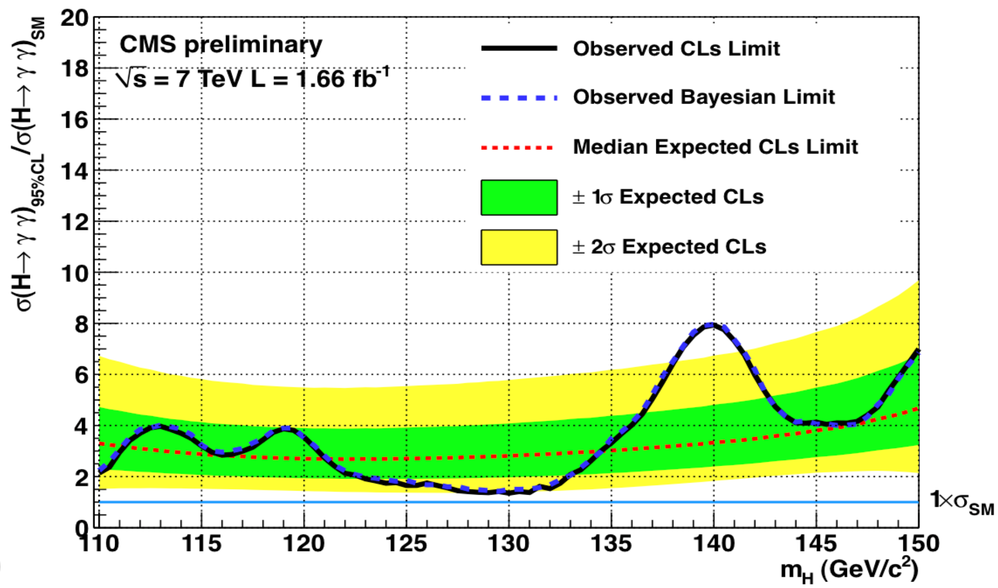
γ_1= 86 GeV

γ_2=56 GeV



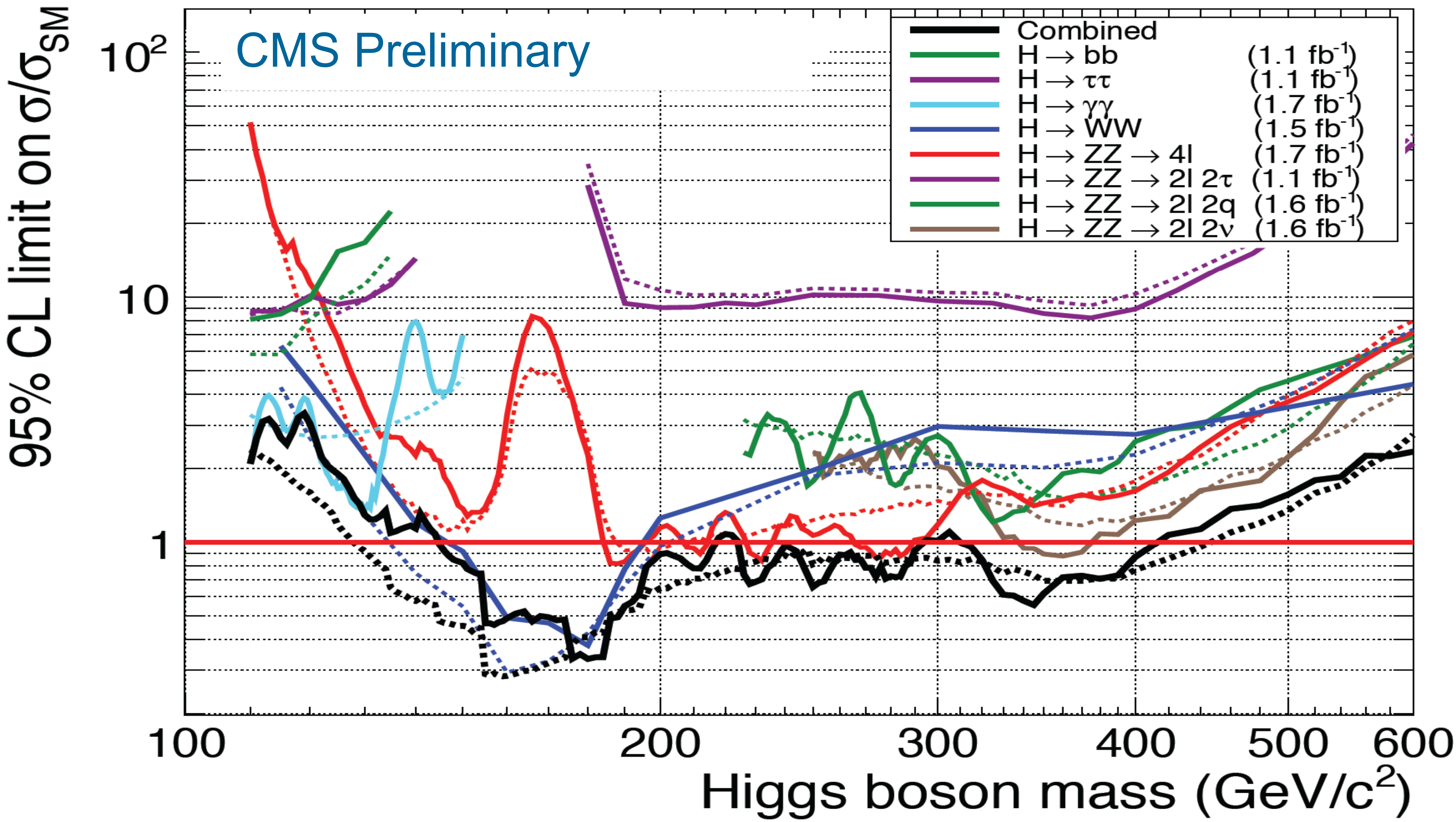


MC for illustration only

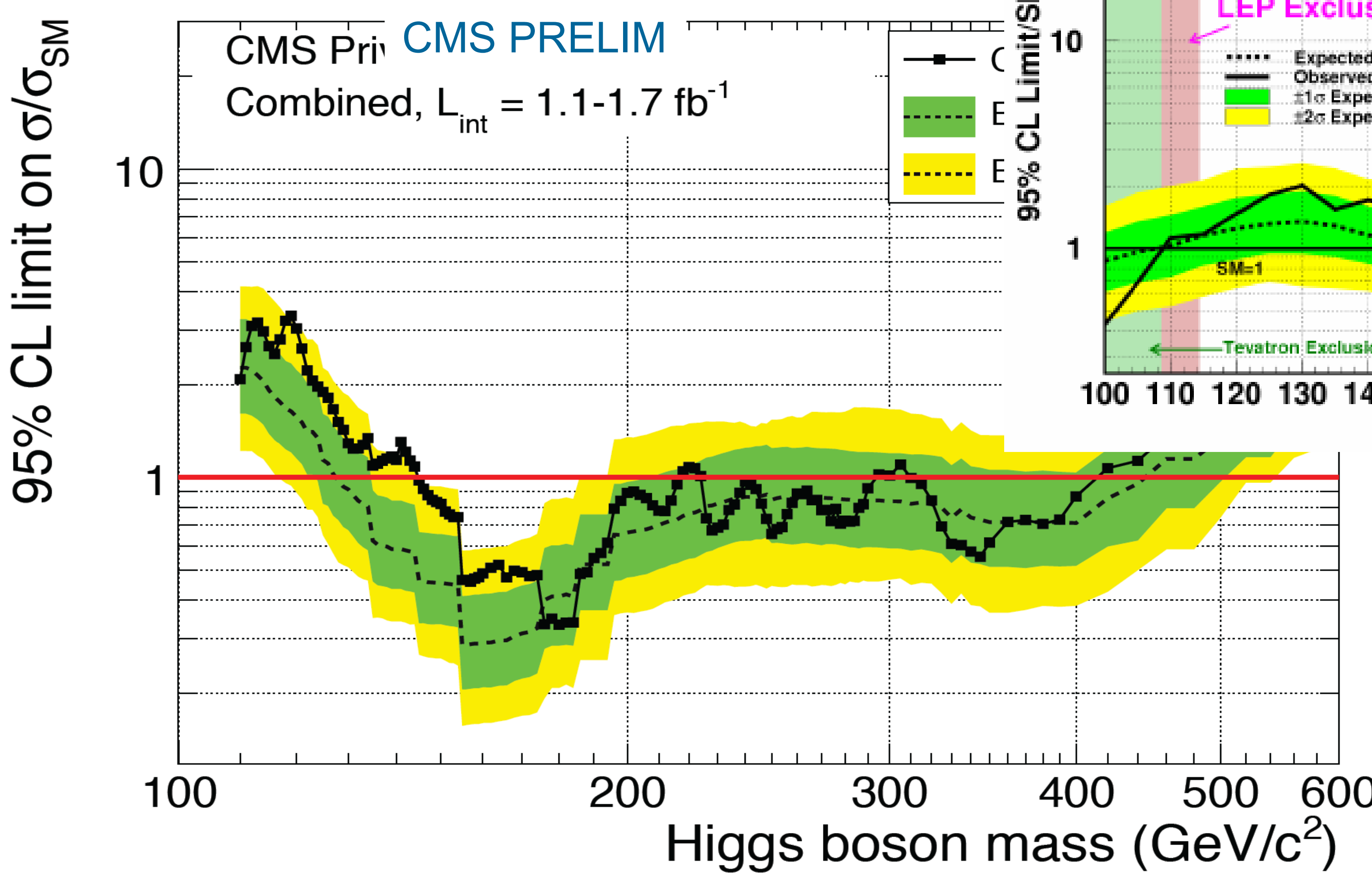


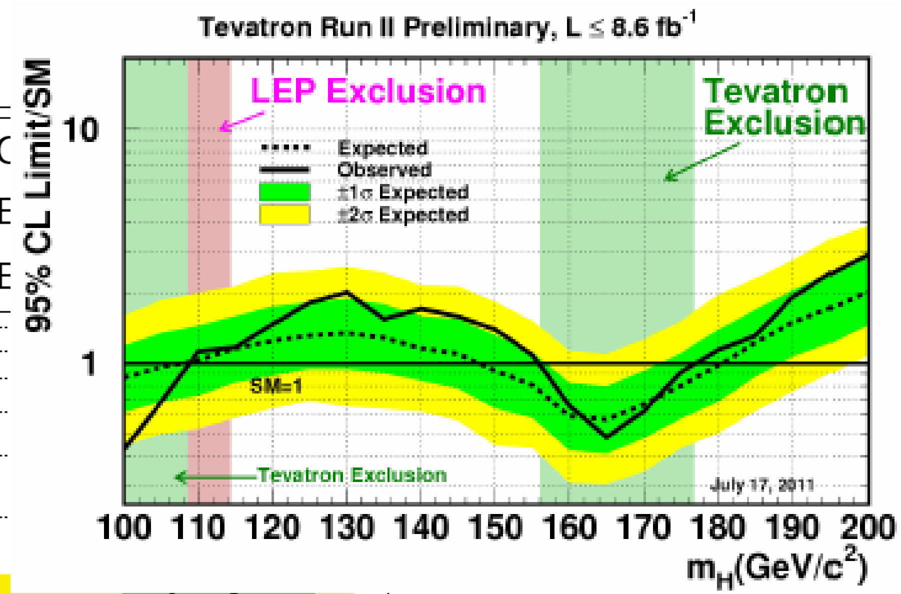
Summary Of Higgs Searches : Expected & Observed

Solid line = Observed limit ; Dashed line = Median Expected



SM Higgs Search Combination





Projection with 30fb^{-1} data

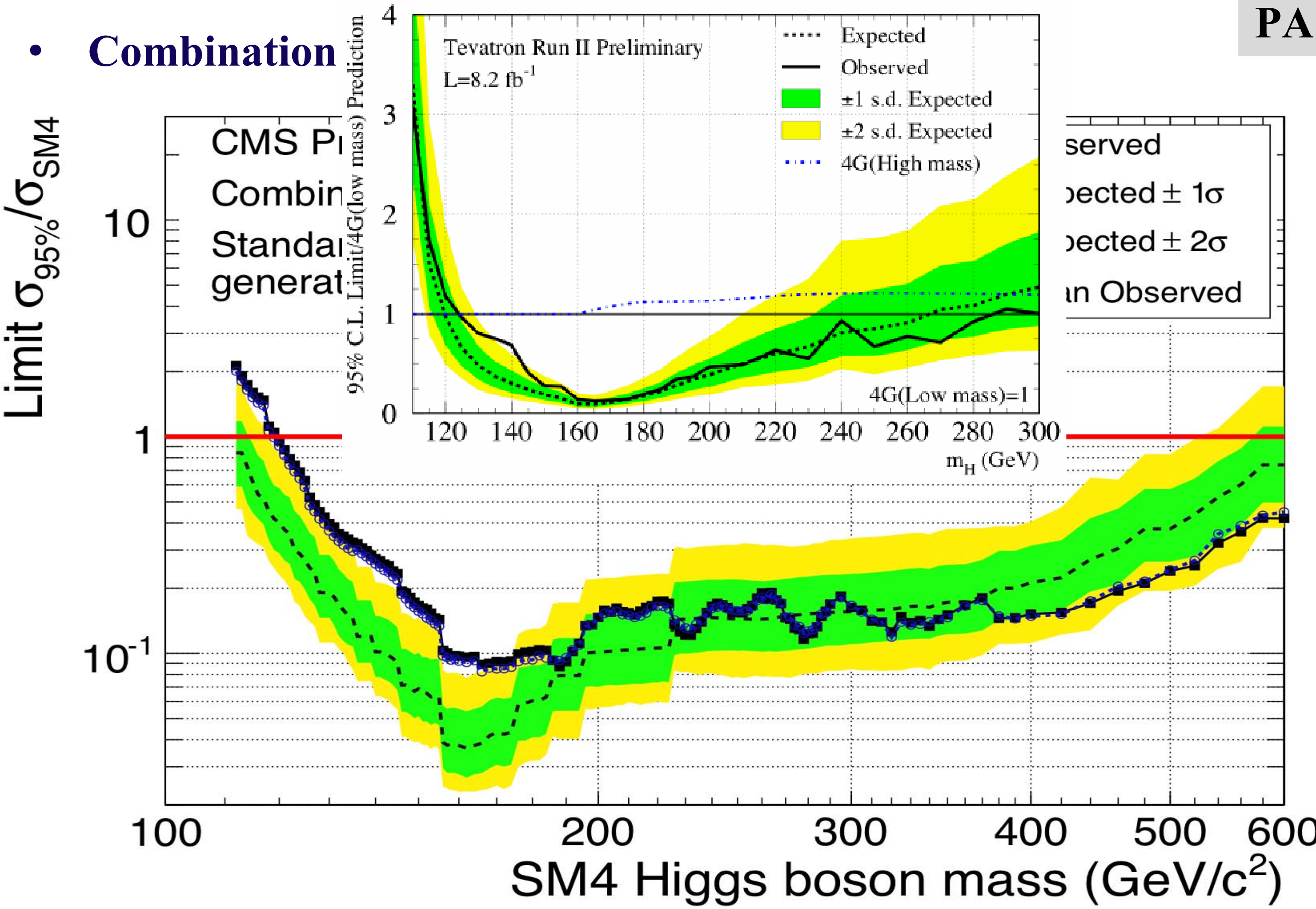
<550 GeV (99.9%)
<600 GeV (99%)

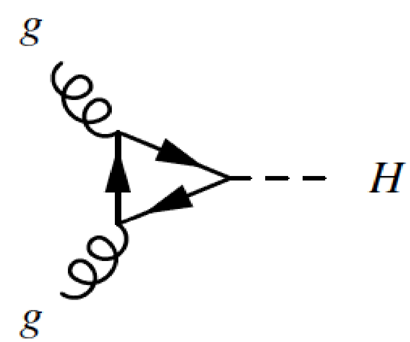
Expected exclusion mass range: 130 – 440 GeV
Observed exclusion mass range: 145-216, 226-288, 310-400 GeV

Higgs with 4 Fermion Generations, 1.1 fb^{-1}

PAS HIG-11-011

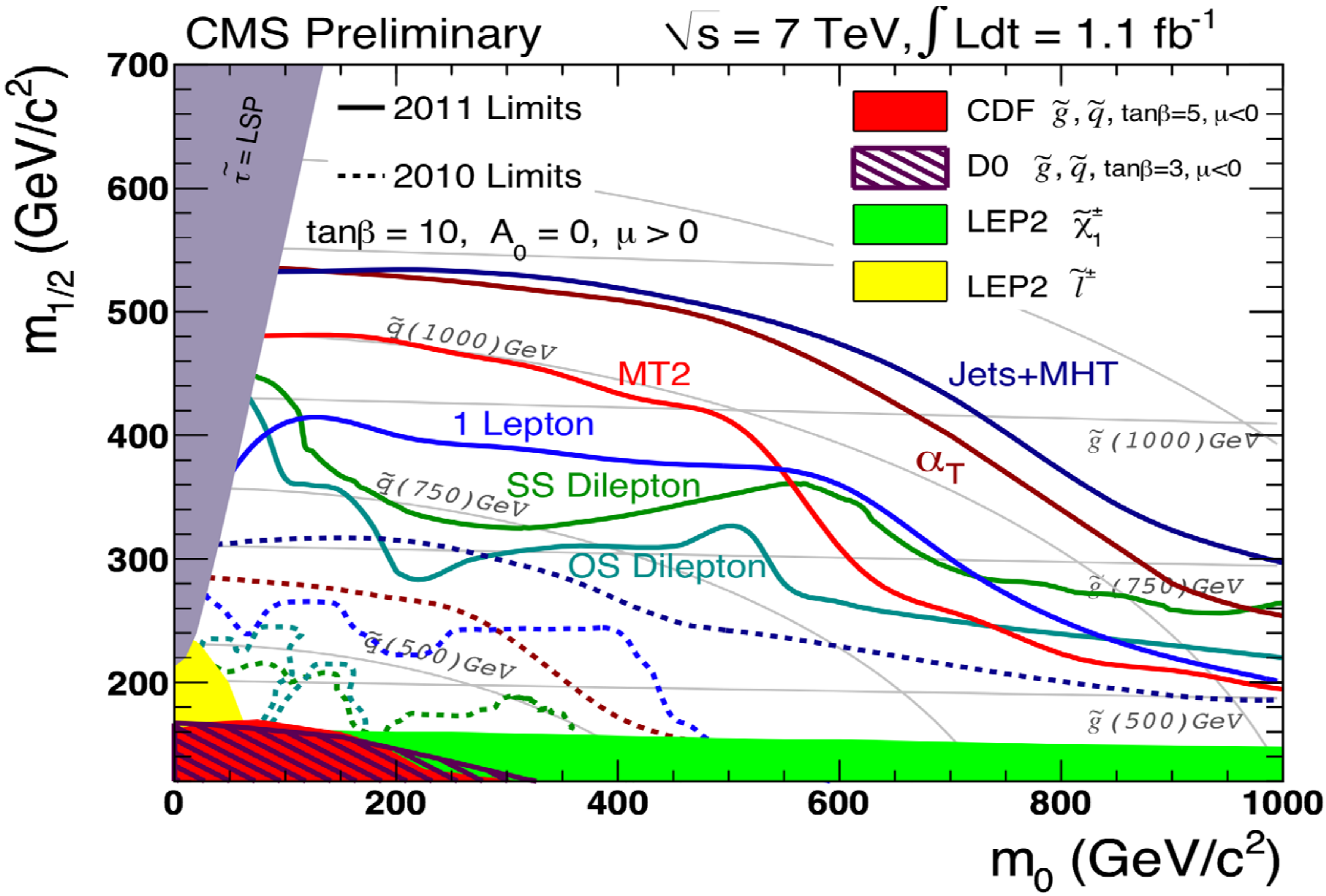
- **Combination**





- **Heavy 4th fermion generation coupling to SM Higgs disfavoured over m_H=120 - 600 GeV @ 95% CL**

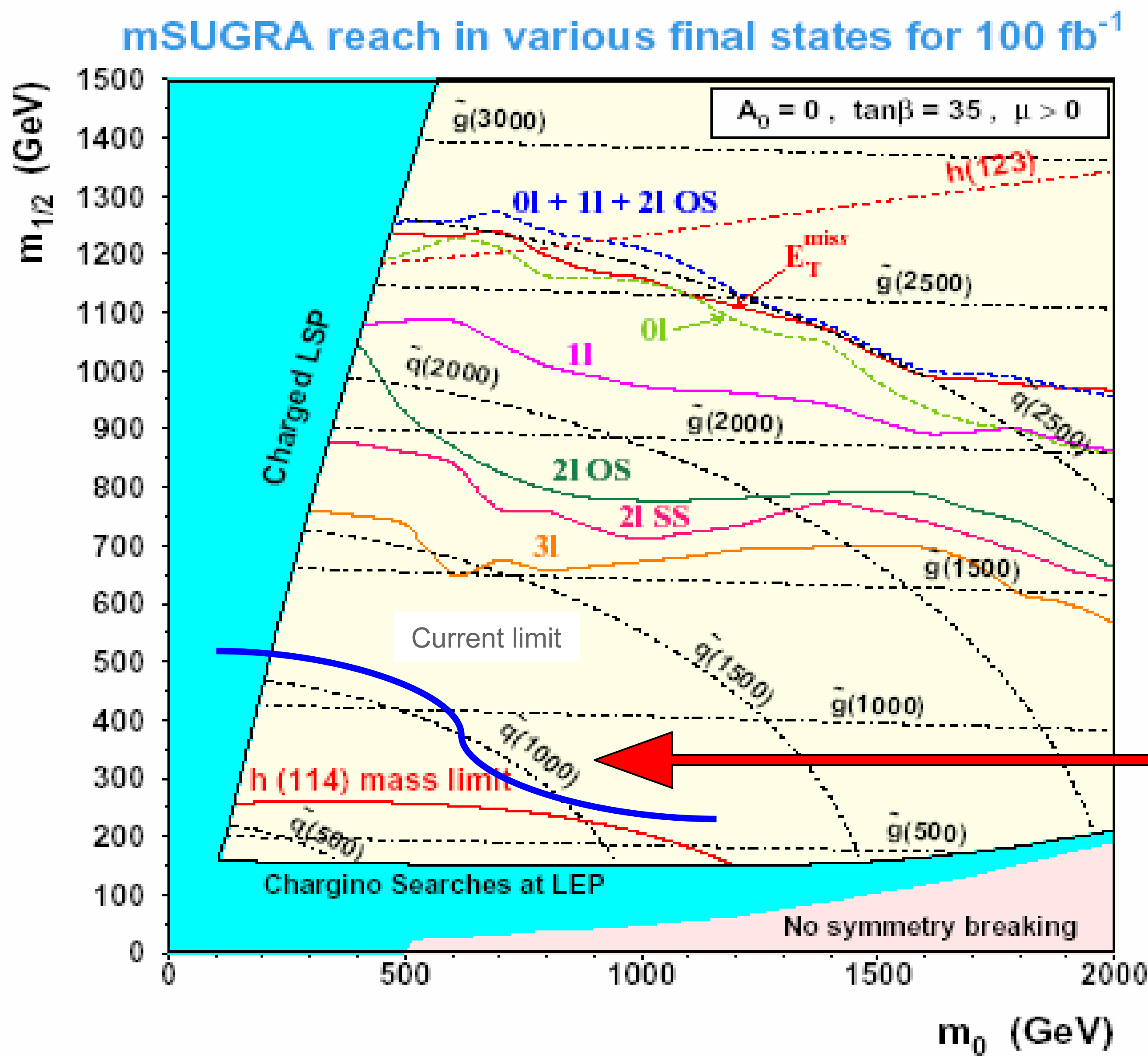
SUperSYmmetry: CMSSM exclusion summary

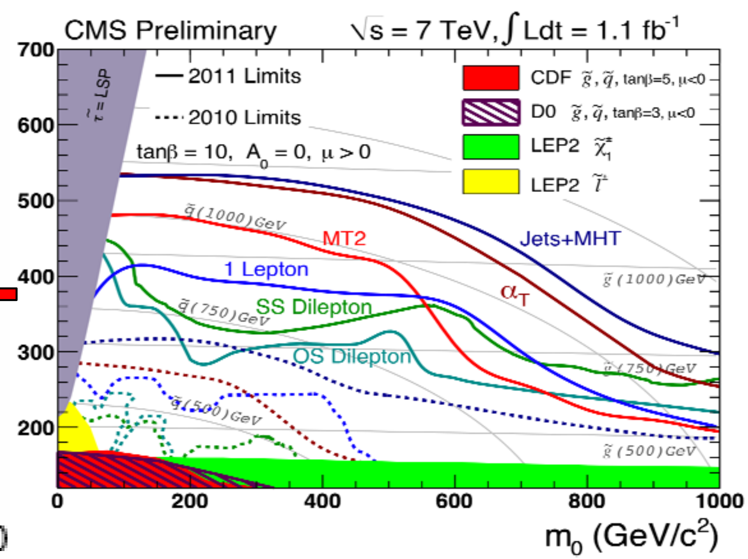


Mass limits has gone up in few times the Tevatron/LEP limit

Expected SUSY search limit

Where we need to go: **LHC @ 14 TeV, reach for 100 fb^{-1}**





Summary of CMS searches

	Lower Limit (95% C.L.)
SUSY ($m_{\tilde{q}} = m_{\tilde{g}}$)	1 TeV
Gauge bosons (SSM)	2 TeV
Excited quark	3 TeV

Conclusion

- After initial failure in 2008, LHC is operating much better than our anticipation.
  - Instantaneous luminosity went beyond 3.7 nb^{-1}
  - Total luminosity >5.3 fb^{-1}
- LHC has provided sufficient data to test detector performance.
- Performance of the CMS detector is also excellent, even beyond the expectation.
- With 1/3-1/4 of the 2011 data taken at CMS is able to perform a comprehensive set of Standard Model measurements at 7 TeV.
- Yet to find Higgs and/or new physics.

Grid computing is an integral part of an HEP experiment.
TIFR Tier2 is one of the T2 with largest storage space.

Modified frequentist (CLs) and Bayesian Limits

$$\rho(\theta \mid \bar{\theta}) = p(\bar{\theta} \mid \theta) \cdot \pi_\theta(\theta)$$

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

$$\text{Pr}\,ofile\ \ likelihood\ \ ratio,\ \ q_\mu = -2\ln \frac{\ell(data \mid \mu, \hat{\theta}_\mu)}{\ell(data \mid \hat{\mu}, \hat{\theta}_\mu)}$$

$$p_\mu = p(q_\mu \geq q_\mu^{obs} \mid \mu_S(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs}))$$

$$p_0 = p(q_\mu \geq q_\mu^{obs} \mid b(\hat{\theta}_\mu^{obs}))$$

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

$$p(\mu \mid data) = \frac{1}{C} \int_\theta p(data \mid \mu_S(\theta) + b(\theta)) \rho_\theta(\theta) \pi_\mu(\mu) d\theta$$

$$\int_0^{\mu 95\% CL} p(\mu \mid data) d\mu = 0.95$$

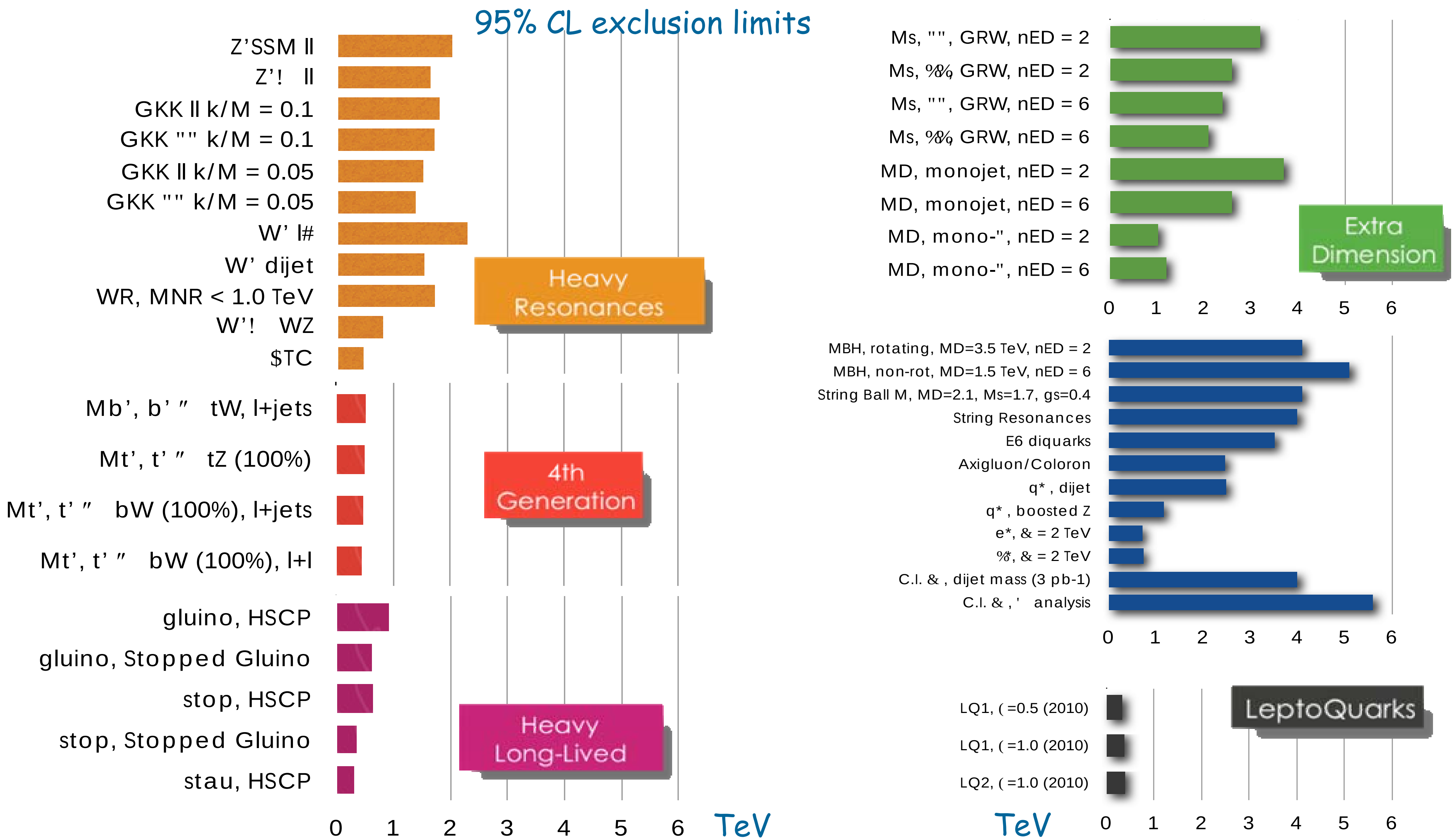
HO and improvement of Jet/MET

- **HO Task Force was formed in April 2011: G. Majumder + …..**
- **HO was designed to improve MET, but at 7 TeV and low luminosity, effect of HO was not significant.**
- **With larger lumisity, effect of HO is clearly visible**
  - **Identification of noise in ECAL/HCAL**
  - **Improvement of dijet balance and MET**

	Stats w/o HO	Stats with HO	Fit RMS with HO	Fit RMS w/o HO	STAT RMS with HO	STAT RMS w/o HO
HO(σ>2 & ΔR<0.3)>0	9985	9985	27.2	27.6	28.7	28.8
HO(σ>2 & ΔR<0.3)>1	3690	3690	27.3	27.5	28.3	28.6
HO(σ>2 & ΔR<0.3)>3	1757	1757	27.2	27.3	28.3	28.8
HO(σ>2 & ΔR<0.3)>5	1149	1149	25.3	27.3	27.6	28.3
HO(σ>2 & ΔR<0.3)>10	579	579	26.4	27.9	27.1	28.0
HO(σ>2 & ΔR<0.3)>20	223	223	27.3	28.6	27.2	28.6

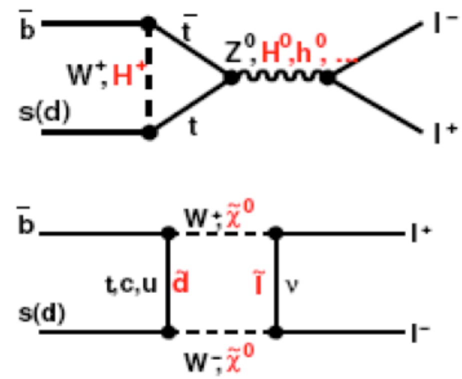
Already seen 3-4% improvement in Jet energy measurement, expected better Jet/MET performance with proper calibration

Search for Beyond Standard model

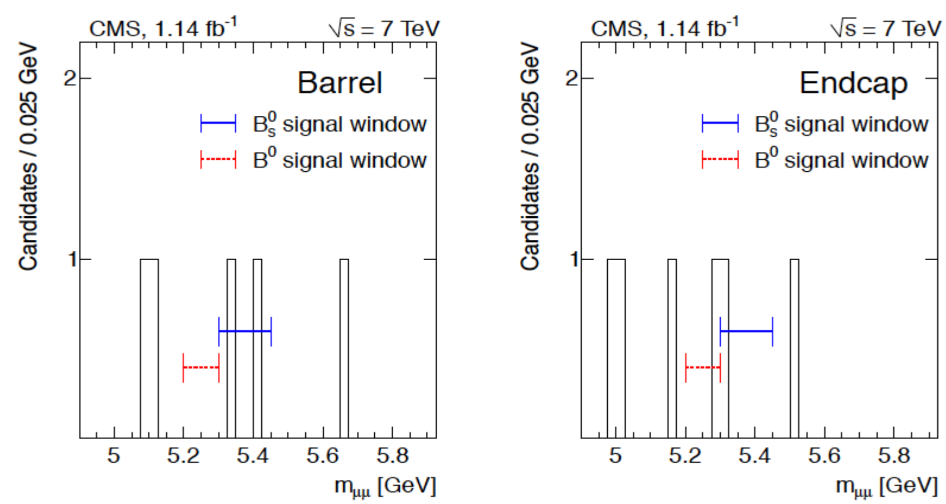


Search for $B_{s(d)} \rightarrow \mu\mu$, 1.1 fb^{-1}

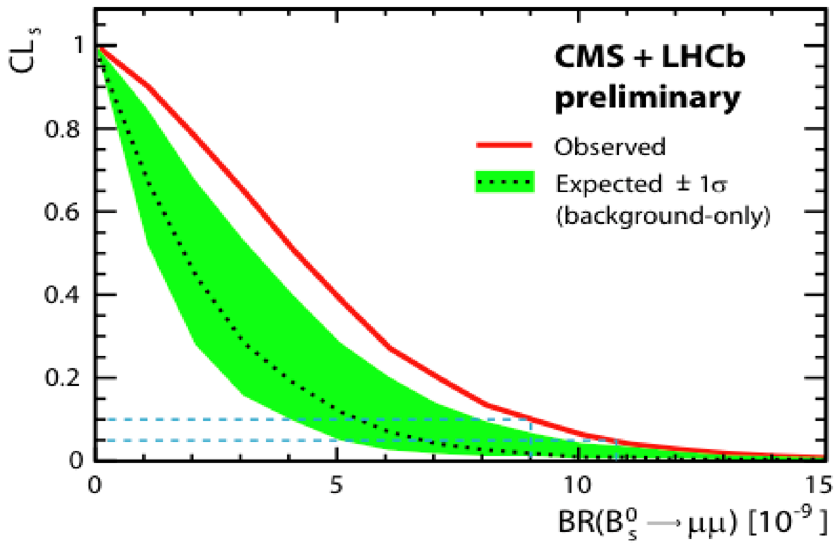
arXiv 1107.5834
accepted by PRL

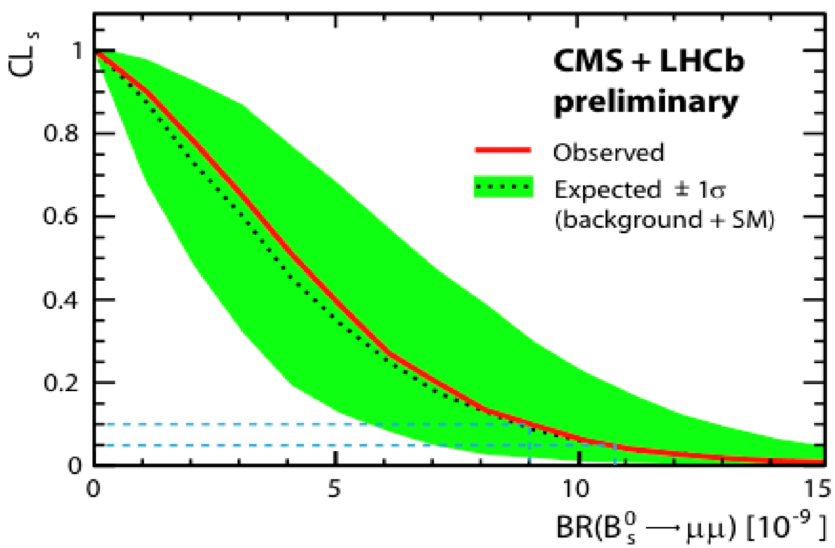


- **Decays are highly suppressed in the SM**
  - **BR($B_s \rightarrow \mu\mu$): $(3.2\pm0.2)\times10^{-9}$, $B_d \rightarrow \mu\mu$: $(1.0\pm0.1)\times10^{-10}$**
- **Indirect sensitivity to new physics**
  - **MSSM: BR $\propto (\tan\beta)^6$**
- **Blind analysis**
  - **$B^+ \rightarrow J/\psi\, K^+$ used for normalization**
  - **$B^0 \rightarrow J/\psi\, \phi$ used as control regions for efficiencies**
- **Events observed in the unblinded windows are consistent with bkg. plus SM expectations.**
- **CMS BR Limits at 95% CL**
  - **$B_s \rightarrow \mu^+\mu^- < 1.9\times10^{-8}$**
  - **$B_d \rightarrow \mu^+\mu^- < 4.6\times10^{-9}$**



CMS + LHCb Combination $B_s \rightarrow \mu\mu$





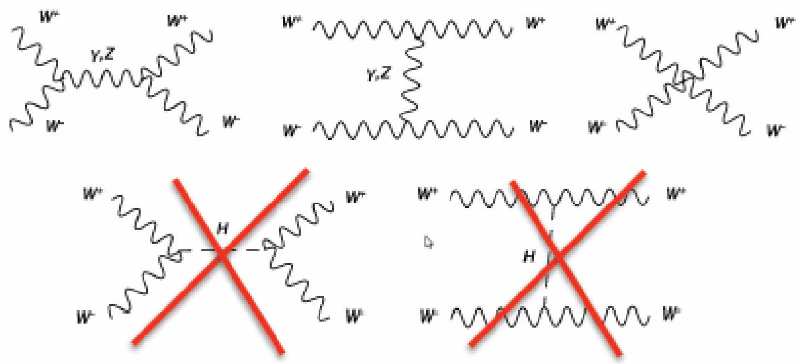
- **CMS BR Limit**
  - $B_s \rightarrow \mu^+\mu^- < 1.9\times10^{-8}$
- **LHCb BR limit**
  - $B_s \rightarrow \mu^+\mu^- < 1.5\times10^{-8}$
- **Combination of LHCb+CMS:**
  - $B_s \rightarrow \mu^+\mu^- < 1.08\times10^{-8}$

- **The value of CLs is in good agreement with background + SM**

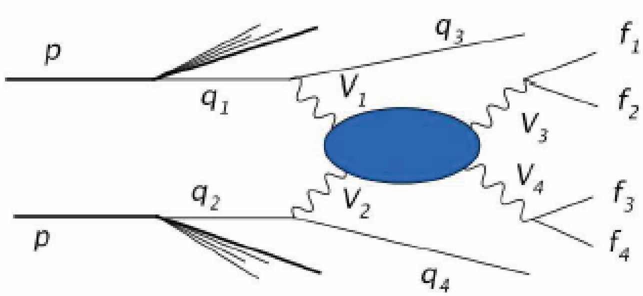
LHCb-CONF-2011-047
CMS PAS BPH-11-019

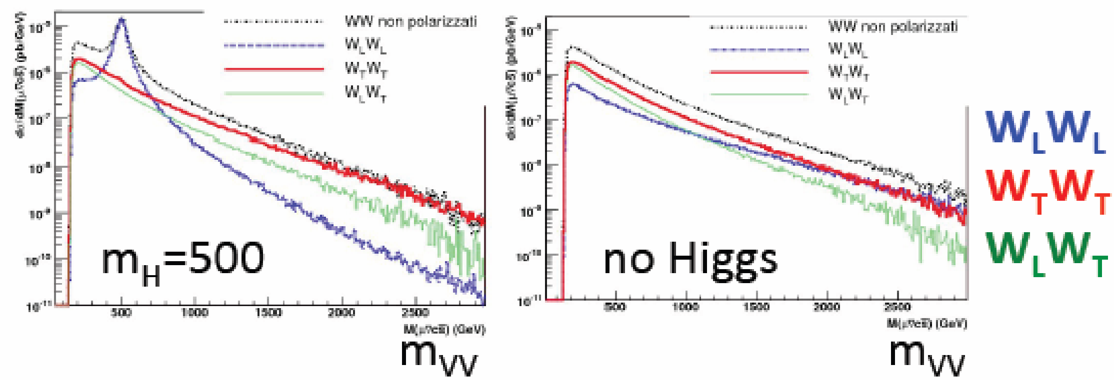
Giving up SM like Higgs ?

Without Higgs below 1 TeV, we expect WW scattering starting to diverge at high sqrt($\hat{s}$).



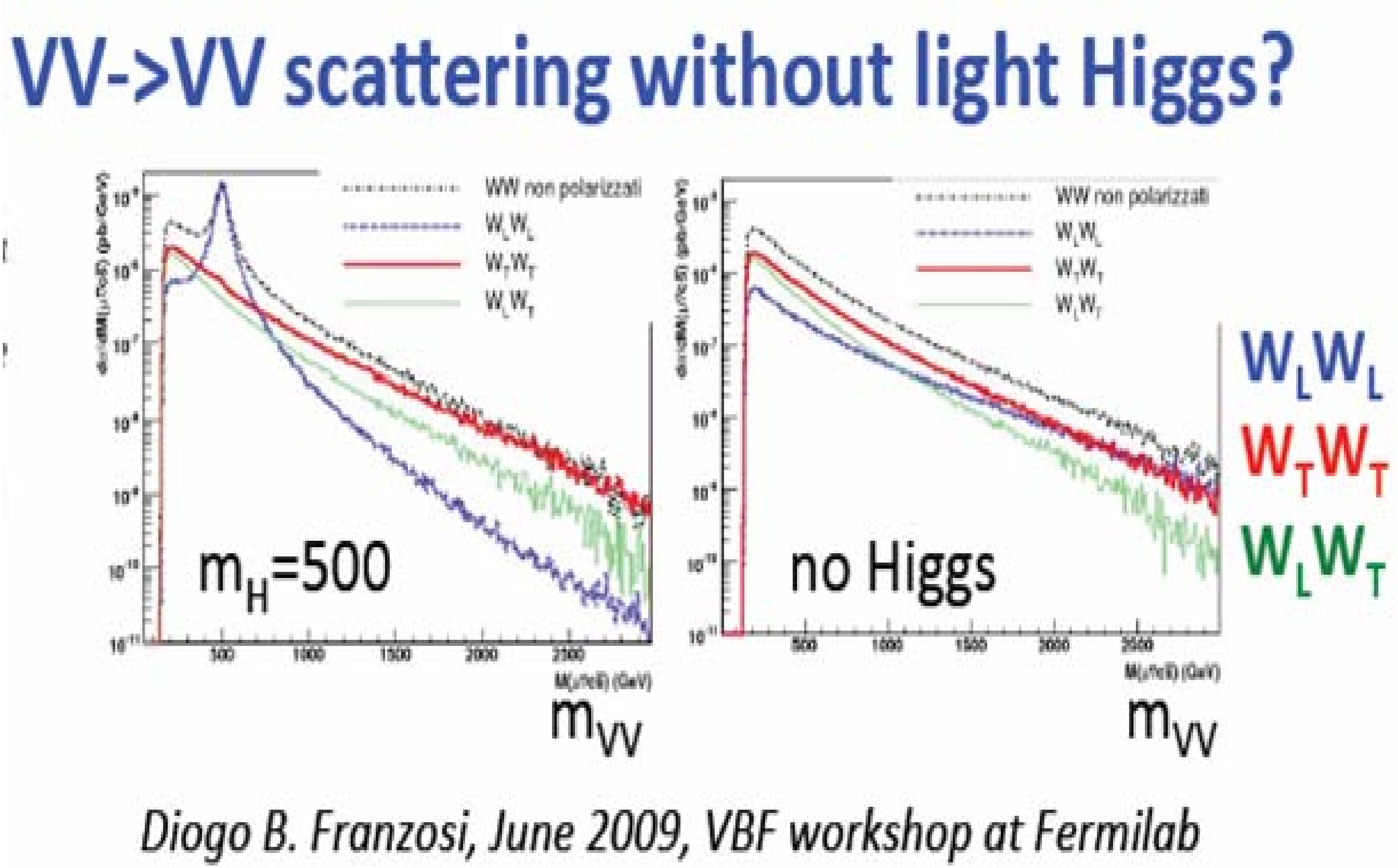
Can we see anomalous VV->VV scattering without light Higgs?





Diogo B. Franzosi, June 2009, VBF workshop at Fermilab

Giving up SM like Higgs ?



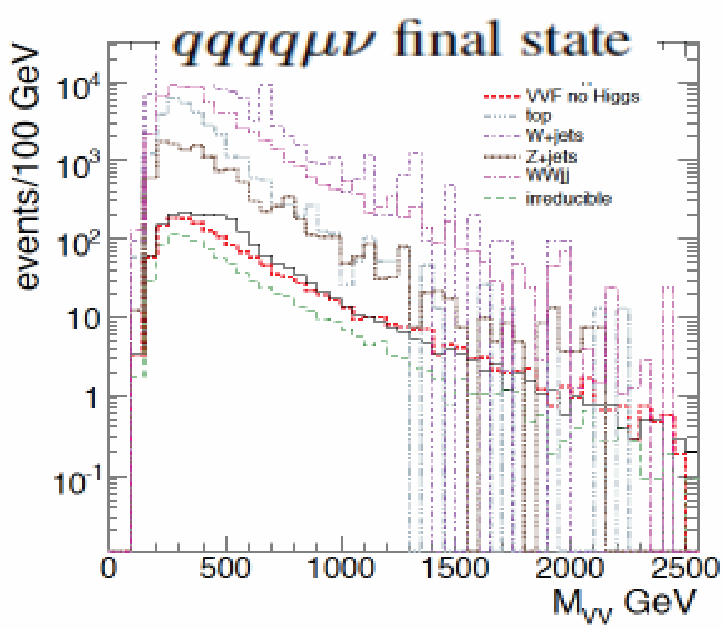
Can we see anomalies in VV→VV without Higgs ?

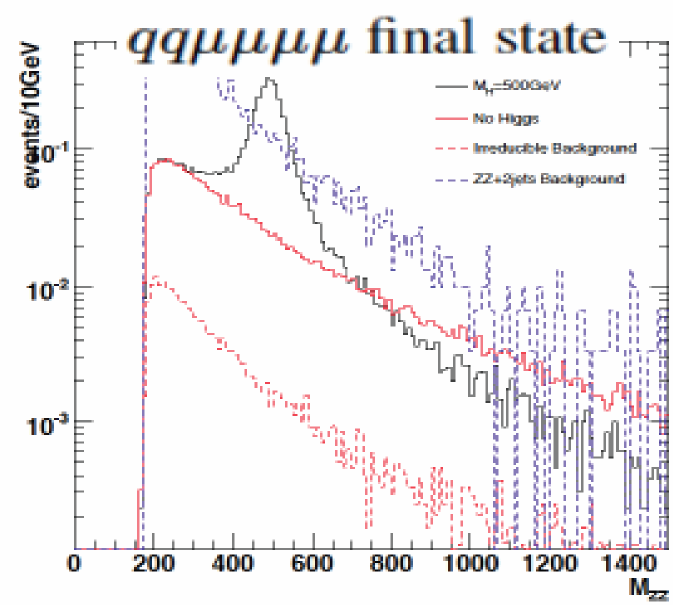
final state	VV->VV events **without** Higgs $\left(\int_{1TeV}^{+\infty} NdM\right)_{noHiggs}$	VV->VV events **with** Higgs $\left(\int_{1TeV}^{+\infty} NdM\right)_{m(H)500}$	$\frac{\left(\int_{1TeV}^{+\infty} NdM\right)_{noHiggs}}{\left(\int_{1TeV}^{+\infty} NdM\right)_{m(H)500}}$	backgrounds $\left(\int_{1TeV}^{+\infty} NdM\right)_{backgr}$
$qqqq\mu\nu$	31	23	1.35	973
$qqqqe\nu$	26	19	1.34	185
$qqqq\mu\mu$	5	2.7	1.85	355
$qqqqee$	6.4	4.4	1.45	140
$qq\mu\mu\mu\mu$	0.16	0.061	2.6	0.30
$qqeeee$	0.2	0.07	2.86	0.25
$qq\mu\mu\mu\nu$	2.66	1.9	1.4	2.3
$qq\mu^{\pm}\nu\mu^{\pm}\nu$	6.9	4.3	1.6	651.2

Feasibility study for 14TeV and 60

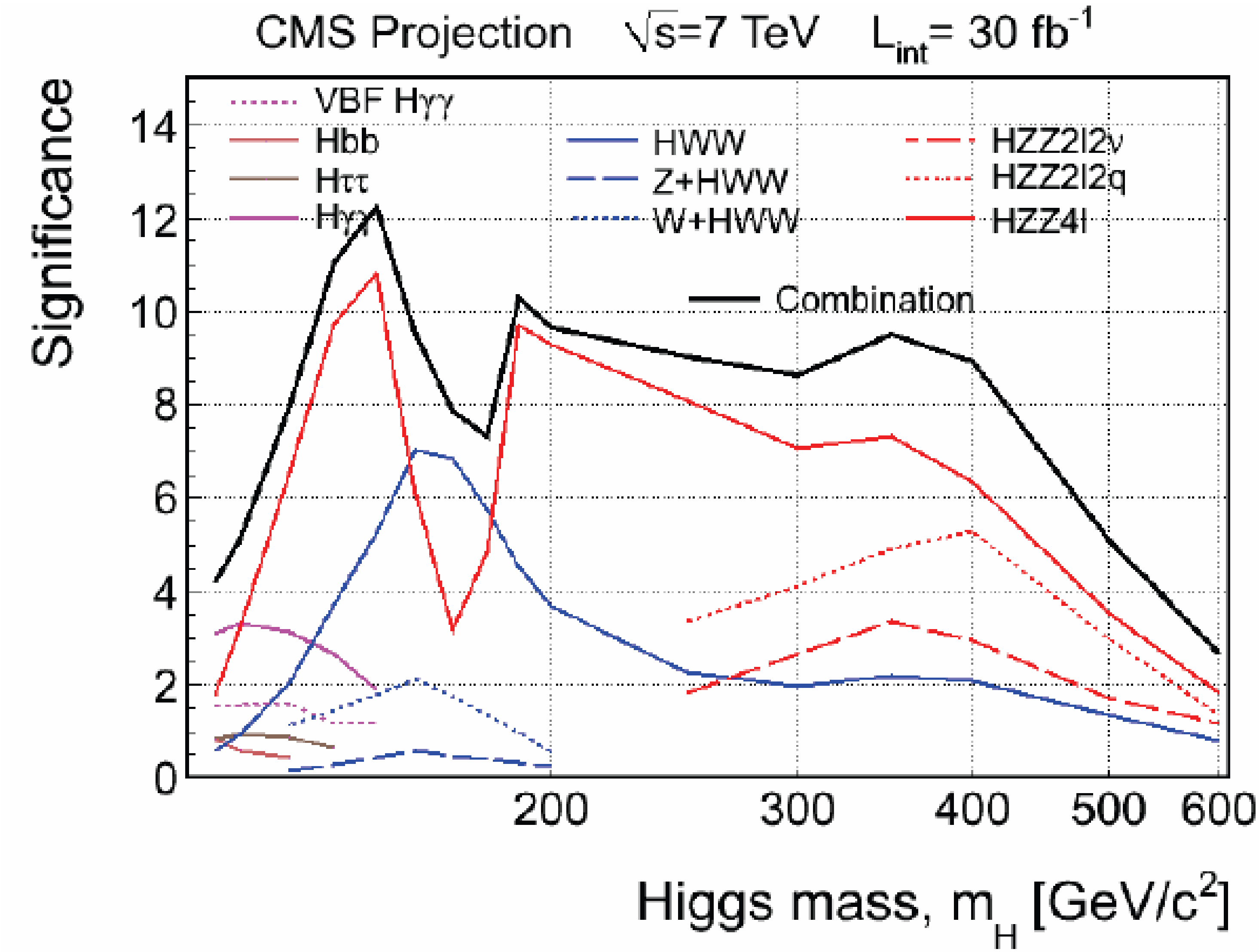
Divide all number by 5 for 7 TeV

Not next year, if ever



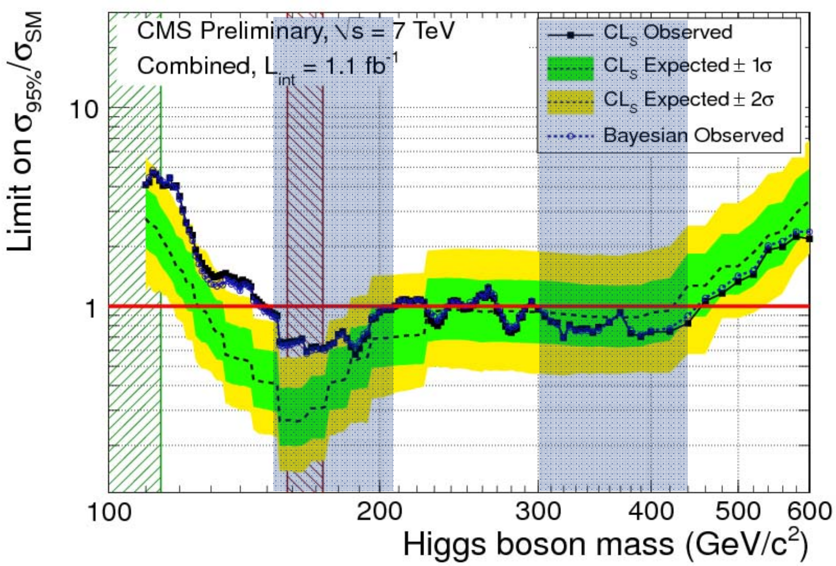


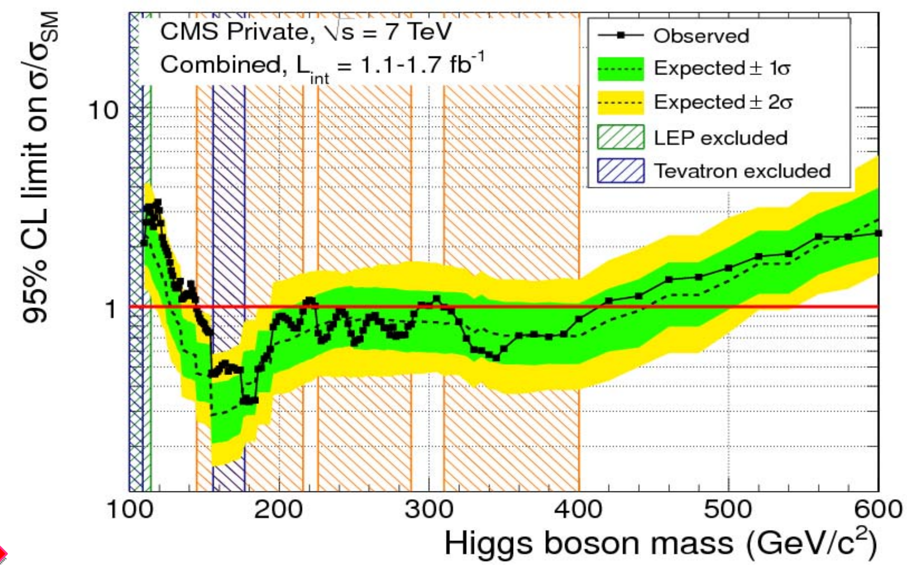
Discovery of Higgs with 30fb^{-1}

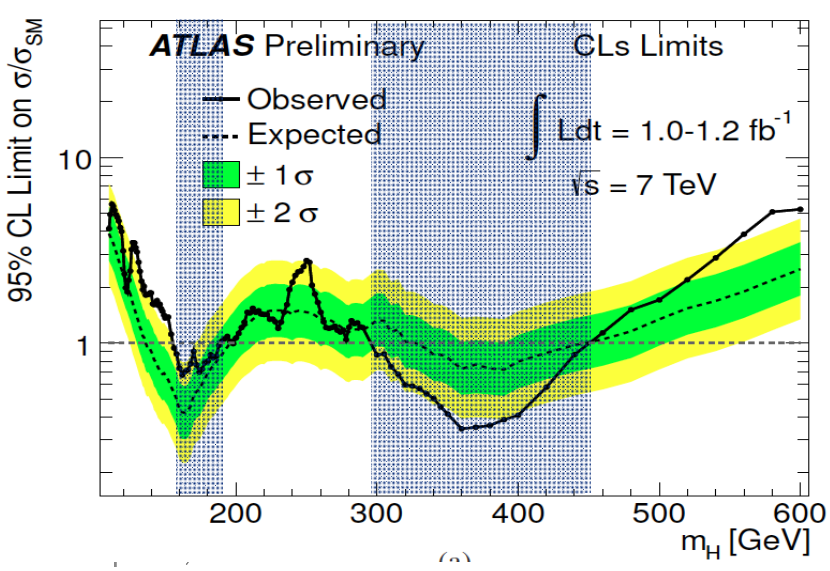


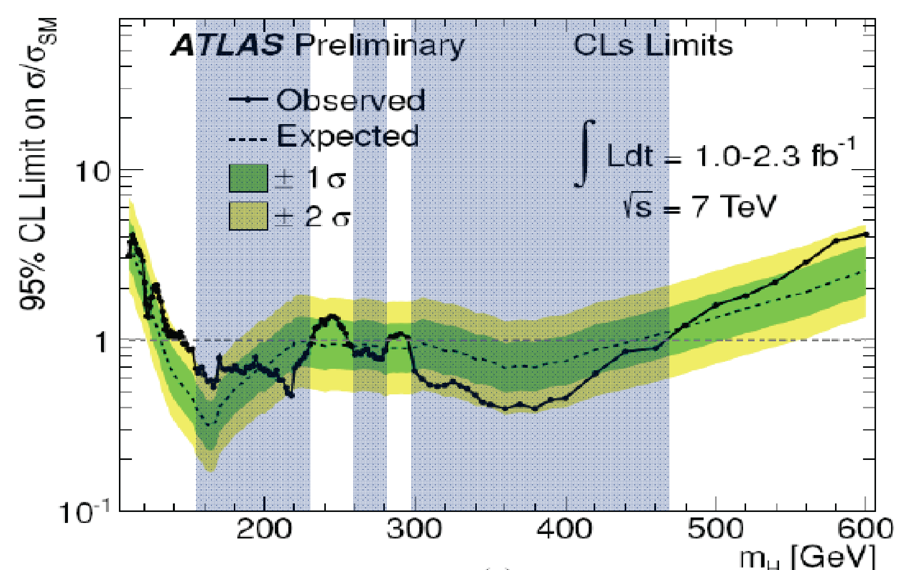
If SM Higgs boson is there, we will able discover it with 30fb^{-1}

EPS -> LP side by side



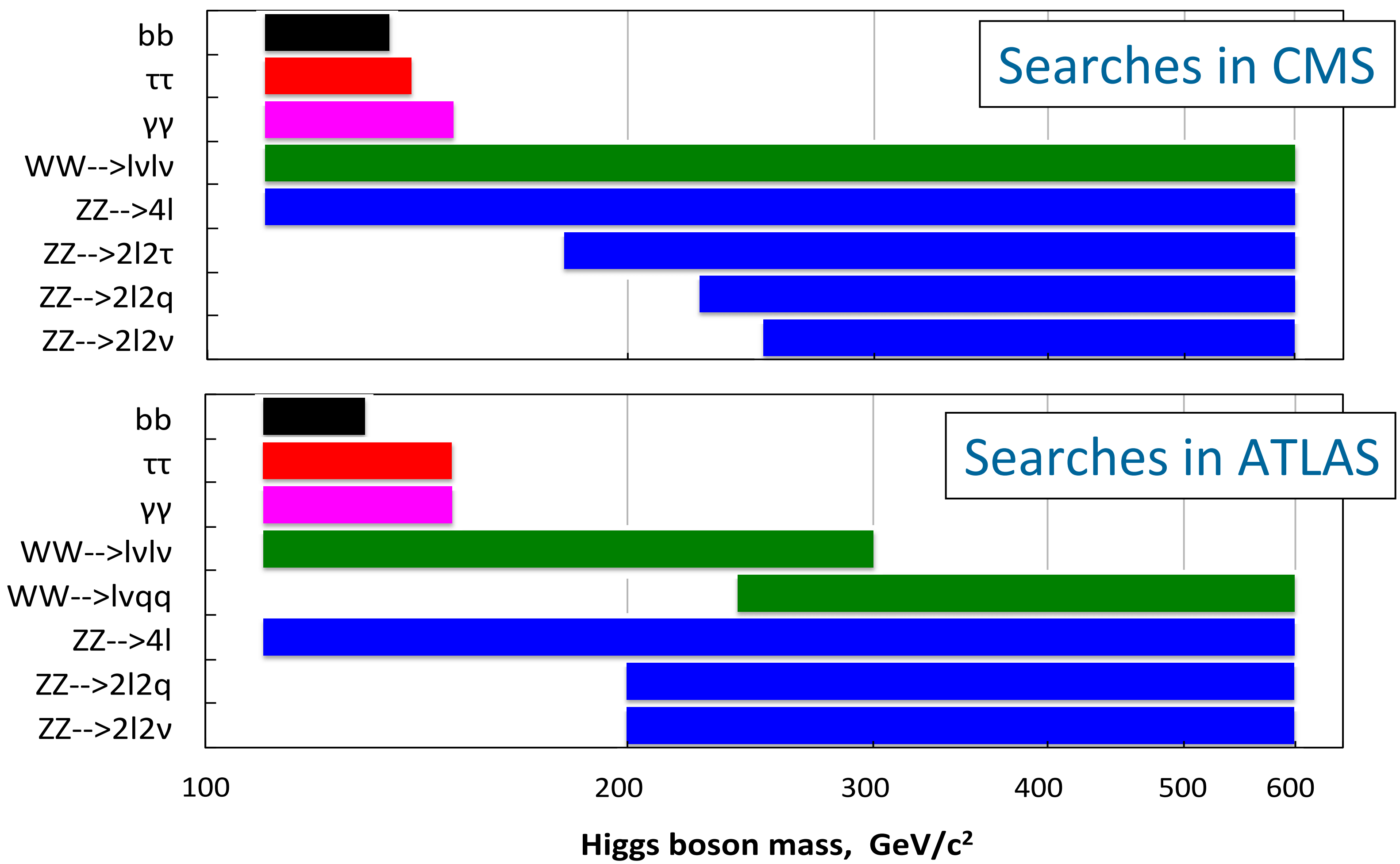






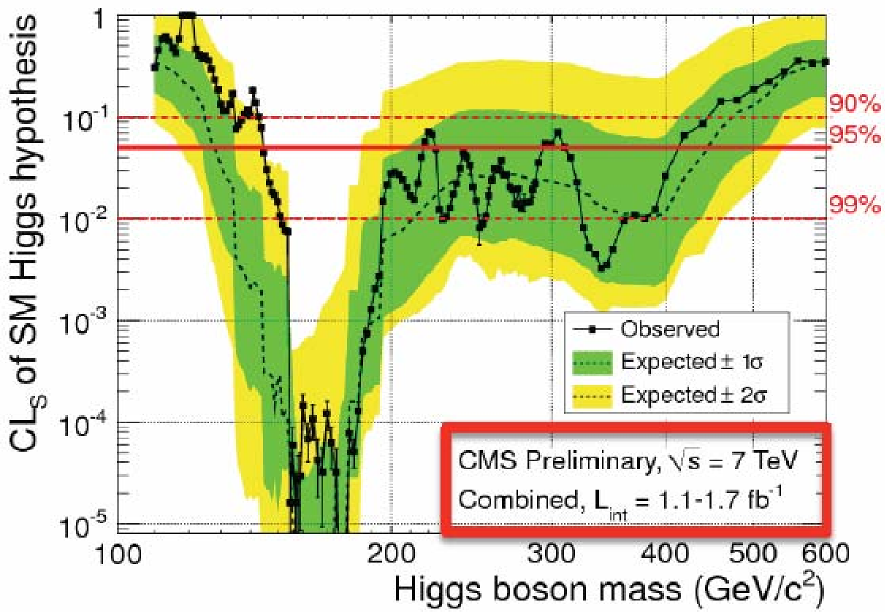
LHC-Higgs Combination Group

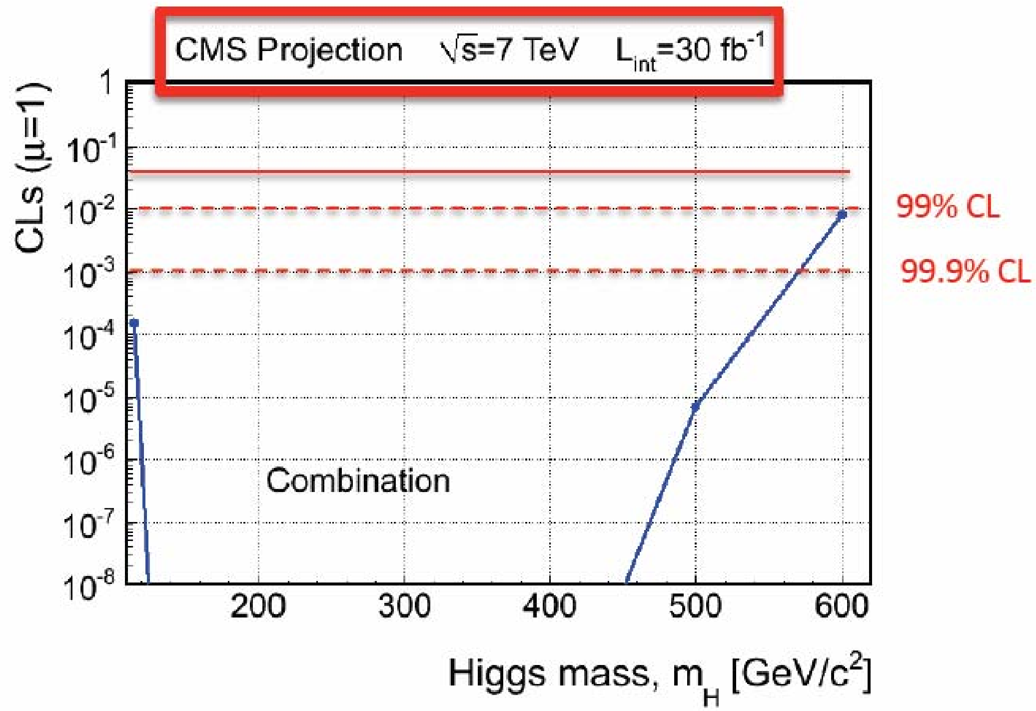
Channels in the combination



Expected Higgs search limit

- "SM Higgs boson is no more" has very serious implications and will require more than 95% CL
- Need 99% and even more than 99.9% CL

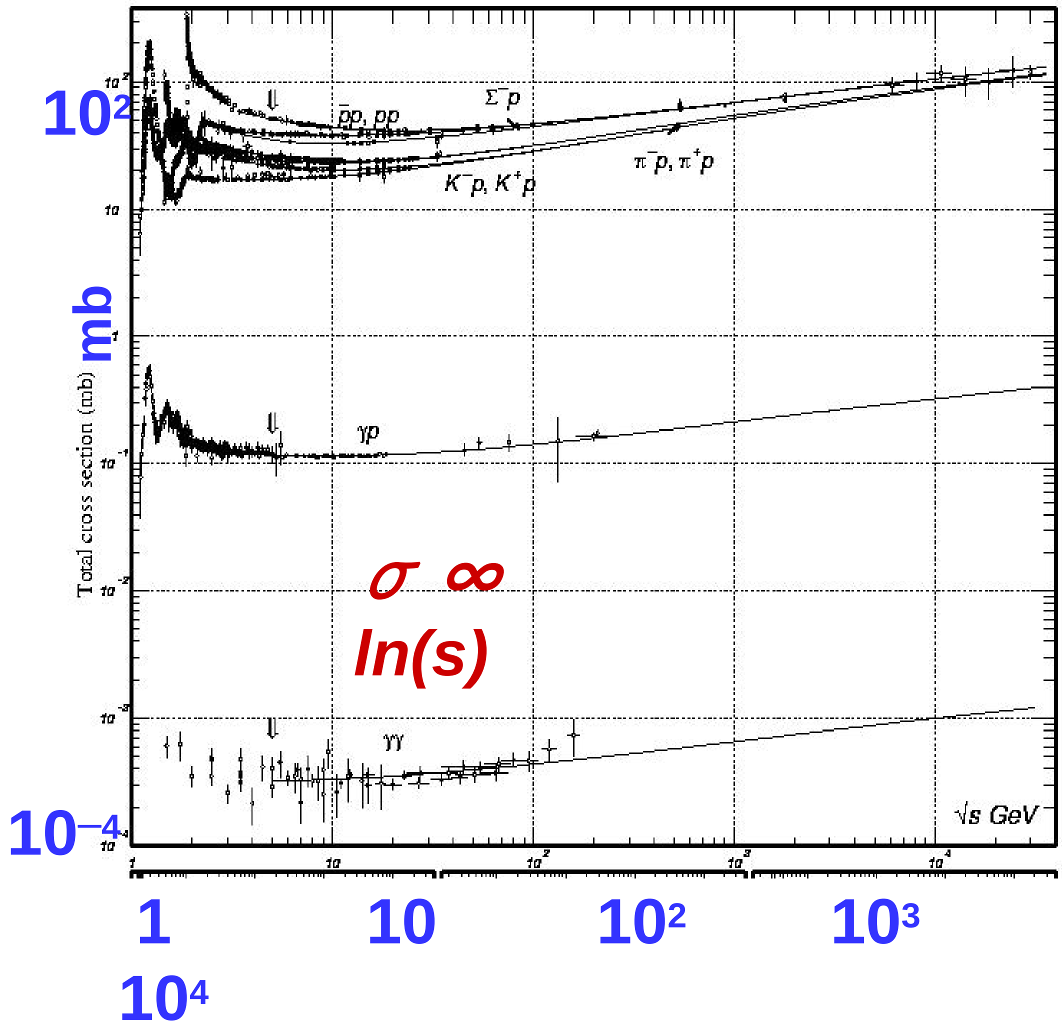


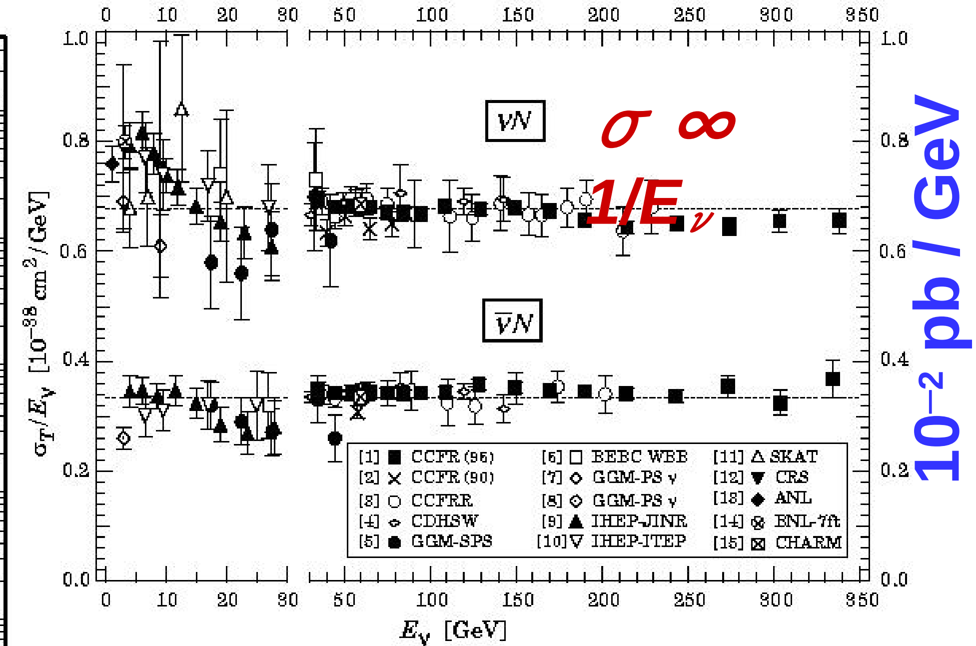


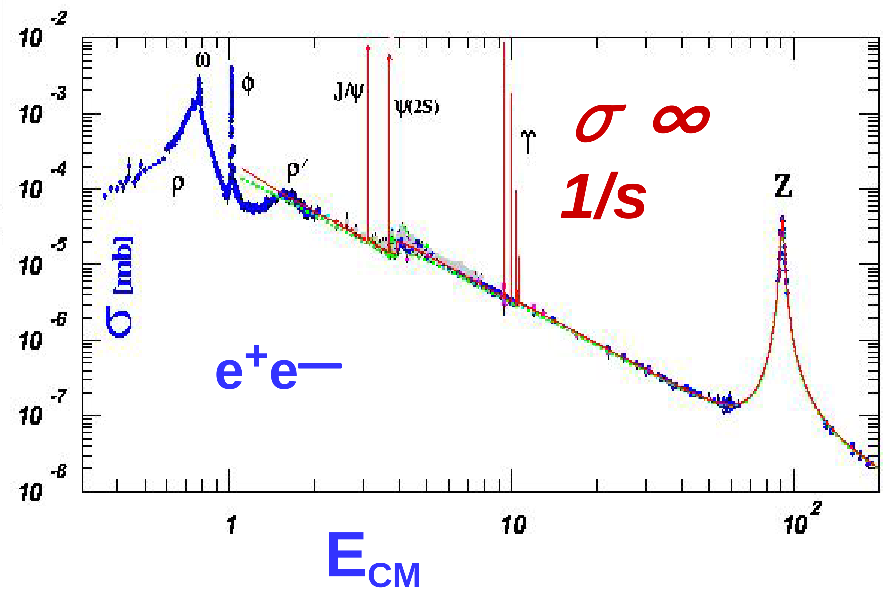
With 30fb^{-1} data, expect

- 99% exclusion in the mass range < 600 GeV
- 99.9% exclusion in the mass range <550 GeV

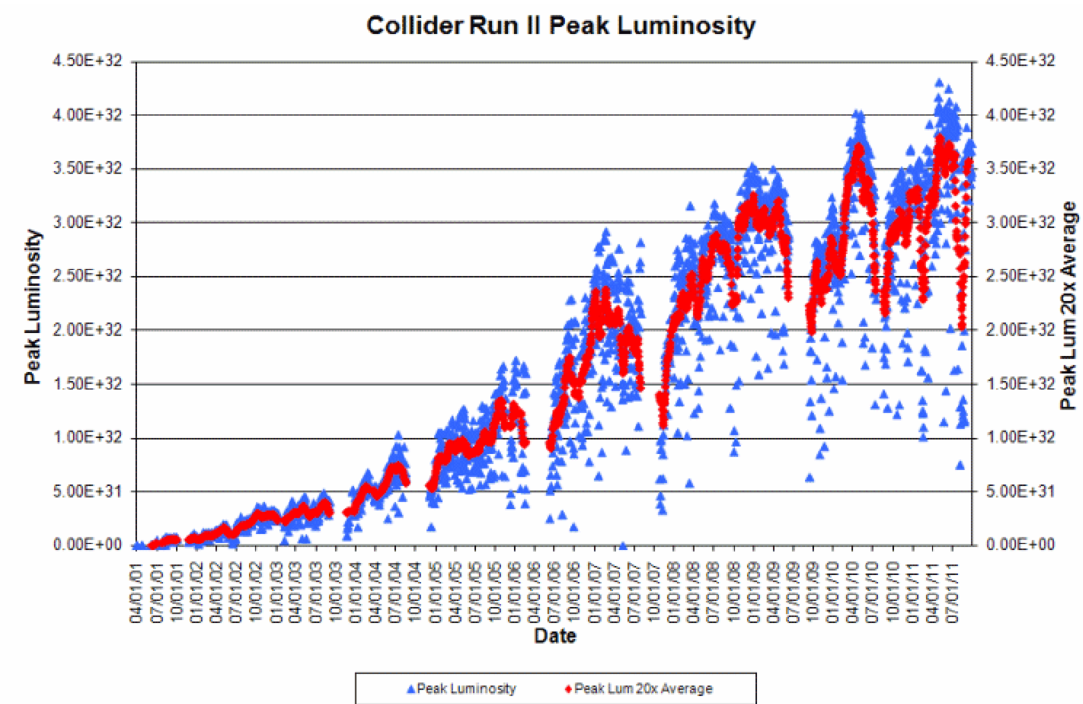
Interaction cross sections







Tevatron luminosity record

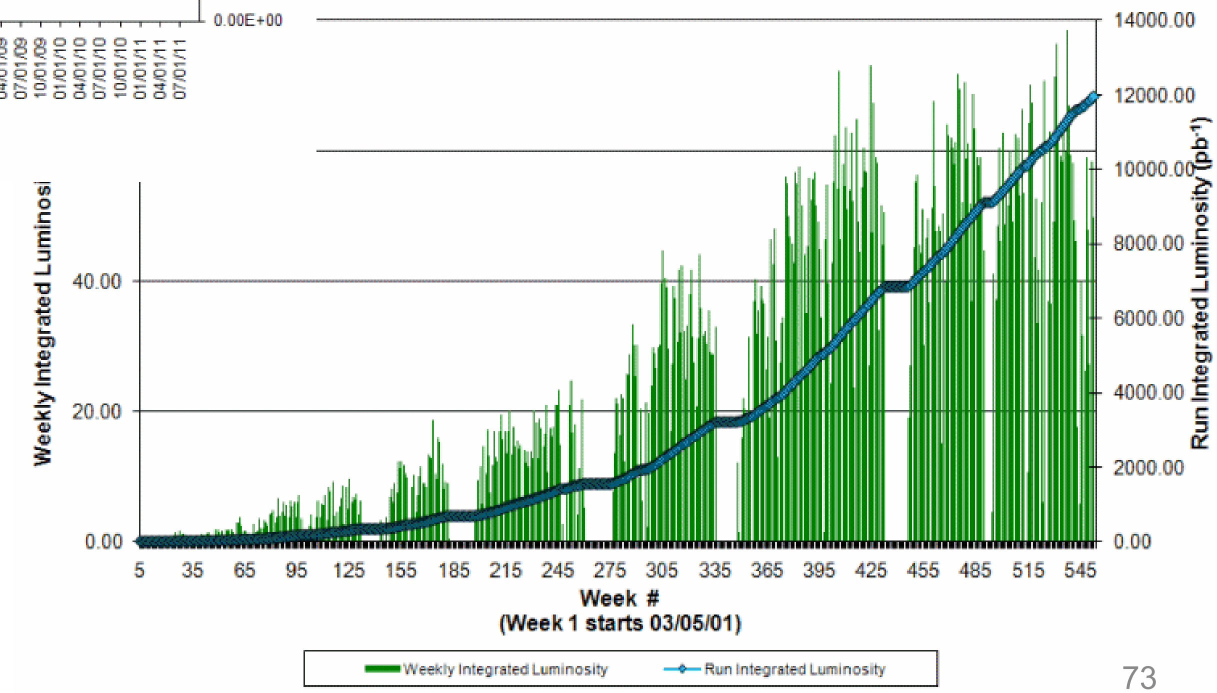


SPPS : peak $2.4\times10^{30}\mathrm{cm}^{-1}\ \mathrm{s}^{-1}$ (same as ISR)

Dicovery of W : $20\mathrm{nb}^{-1}$ data

Discovery of Z : $55\mathrm{nb}^{-1}$ data

$\int \mathcal{L}dt = 13.2\mathrm{pb}^{-1}$ (1988 - 1990@630GeV)

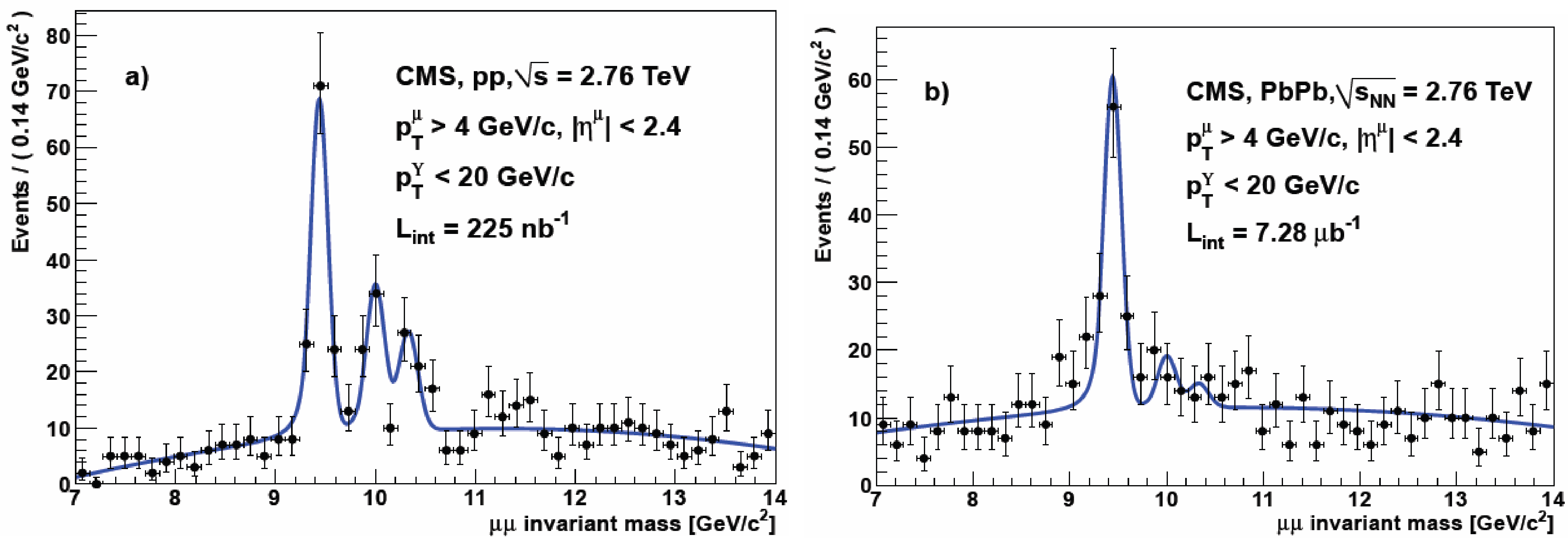


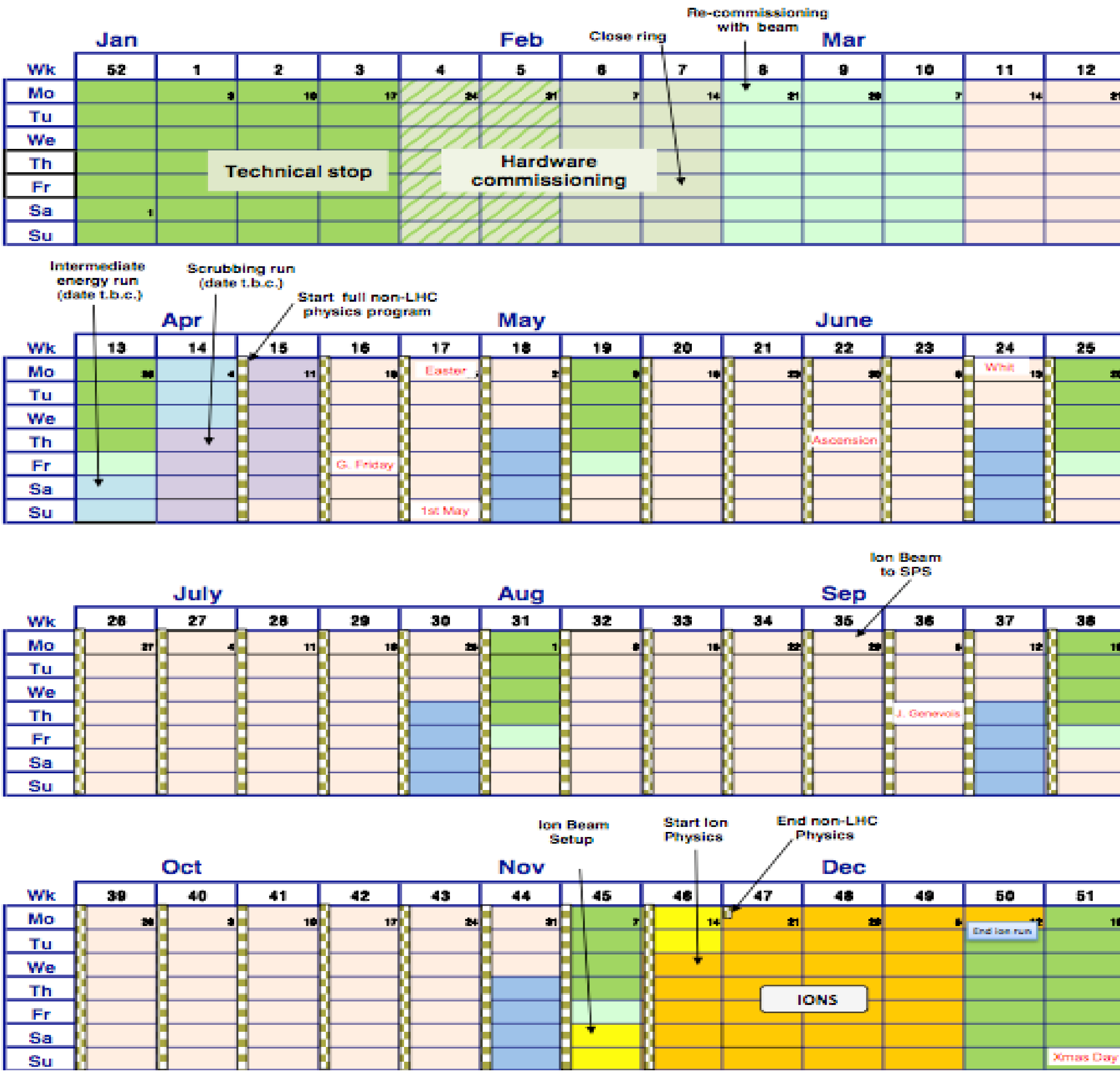
Different component of the CMS detector

- ~66 Million silicon pixel channels,
- ~10 Million Silicon microstrip channels,
- ~75000 $PbWO_4$ crystals,
- 137000 Silicon preshower
- ~15k Hadron CALorimeter channels,
- 250 Drift Chamber chambers (170k wires),
- 450 Cathode Strip Chamber chambers (~200k wires) ,
- ~ 500 Barrel Resistive Plate Chambers and
- ~ 400 endcap Resistive Plate Chambers,
- muon and calorimeter trigger system,
- 40000 Hz Data Aquisition system
- (~ 10000 CPU cores),
- Grid Computing (~ 50 000 cores),
- offline (> 2 Million lines of source code).

QGP

$[\Upsilon(2S+3S)/\Upsilon(1S)]_{PbPb}/[\Upsilon(2S+3S)/\Upsilon(1S)]_{pp}$ =
0.31 +0.19 –0.15 (stat) ± 0.03 (syst)





2011

- Beam back around 21st Feb.
- 2 weeks re-commissioning with beam (at least)
- 4 day Technical Stop (TS) every 6 weeks (Σ 6 TS)
- Count 1 day to recover from TS (optimistic)
- 2 days machine development every 2 weeks or so
- 4 days ions set-up
- 4 weeks ion run
- End of run – 12th December

~200 days proton physics

Very Long Term Objectives: Higher Energy LHC : 2030-33

Preliminary HE-LHC : **parameters with large error bars**

	nominal LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40-45
#bunches / beam	2808	1404
bunch population [10^{11}]	1.15	1.29
initial transverse normalized emittance [μm]	3.75	3.75 (x), 1.84 (y)
number of IPs contributing to tune shift	3	2
maximum total beam-beam tune shift	0.01	0.01
IP beta function [m]	0.55	1.0 (x), 0.43 (y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})
stored beam energy [MJ]	362	479
SR power per ring [kW]	3.6	62.3
longitudinal SR emittance damping time [h]	12.9	0.98
events per crossing	19	76
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0
beam lifetime [h]	46	13
integrated luminosity over 10 h [fb^{-1}]	0.3	0.5

Electroweak symmetry breaking

To generate particle masses in an SU(2)×U(1) gauge invariant way:
introduce a doublet of scalar fields $\Phi = \binom{\Phi^+}{\Phi^0}$ with $\langle 0|\Phi^0|0\rangle \neq 0$

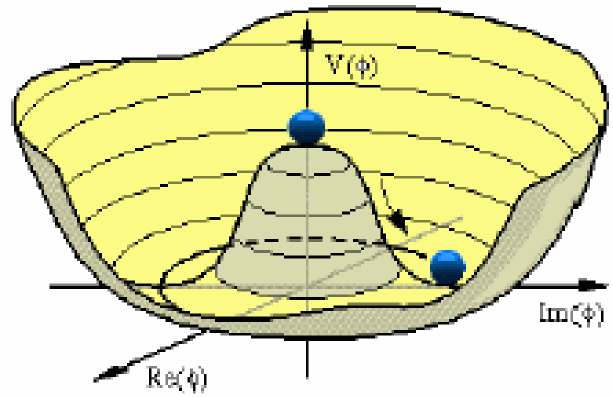
$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$

$v = (-\mu^2/\lambda)^{1/2} = 246$ GeV

$\Rightarrow$ three d.o.f. for $M_{W^\pm}$ and M_Z

For fermion masses, use <u>same</u> Φ:

$\mathcal{L}_{Yuk} = -f_e (\bar{e}, \bar{\nu})_L \Phi e_R + \ldots$

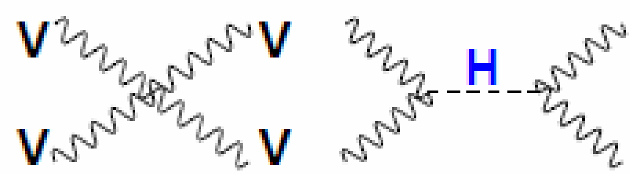


Residual dof corresponds to spin–0 H particle.

- The scalar Higgs boson: $J^{PC} = 0^{++}$ quantum numbers.
- Masses and self–couplings from V : $M_H^2 = 2\lambda v^2, g_{H^3} = 3\frac{M_H^2}{v}, \ldots$
- Higgs couplings $\propto$ particle masses: $g_{Hff} = \frac{m_f}{v}, g_{HVV} = 2\frac{M_V^2}{v}$

The Higgs unitarizes the theory:

without Higgs: $|A_0(VV \to VV)| \propto E^2/v^2$

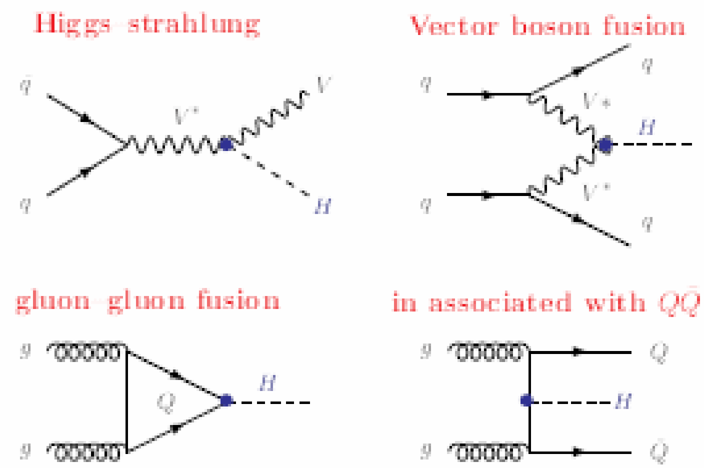


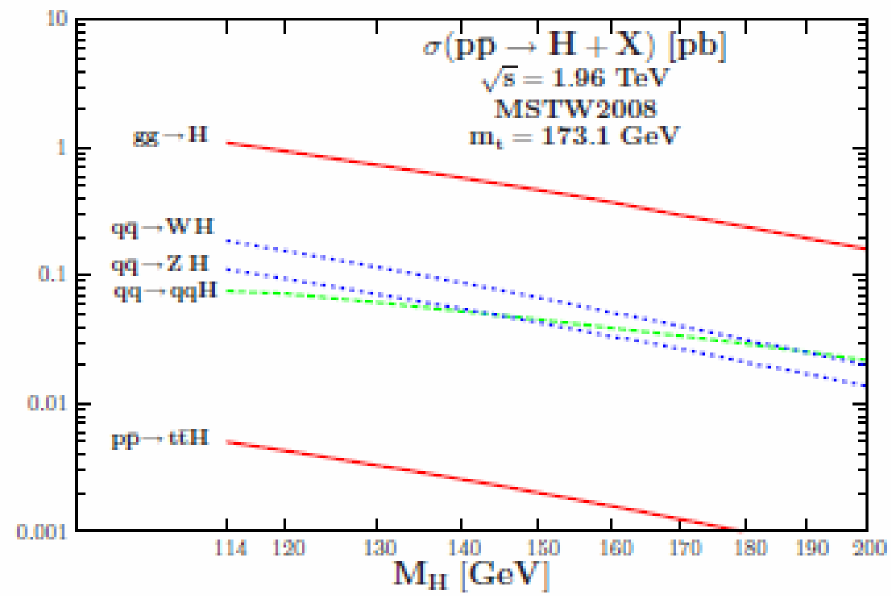
including H with couplings as predicted:

$|A_0| \propto M_H^2/v^2 \Rightarrow$ the theory is unitary but needs $M_H \lesssim 700$ GeV...

Higgs at LHC

Main Higgs production channels





Large production cross sections

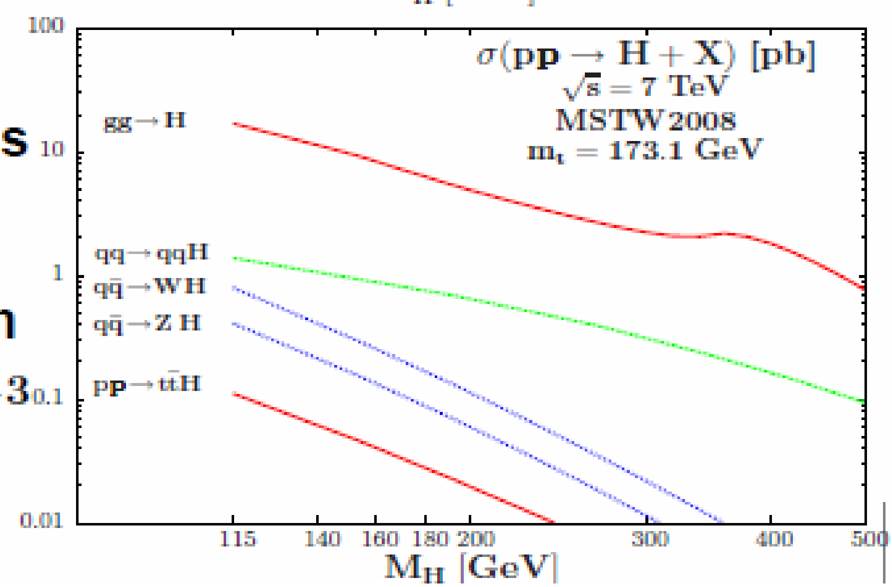
with gg$\longrightarrow$ H by far dominant process

1 $\mathrm{fb}^{-1} \Rightarrow \mathcal{O}(10^4)$ events@lHC

$\Rightarrow \mathcal{O}(10^3)$ events @Tevatron

but eg BR(H$\longrightarrow \gamma\gamma, ZZ \longrightarrow 4\ell) \approx 10^{-3}$

... a small # of events at the end...

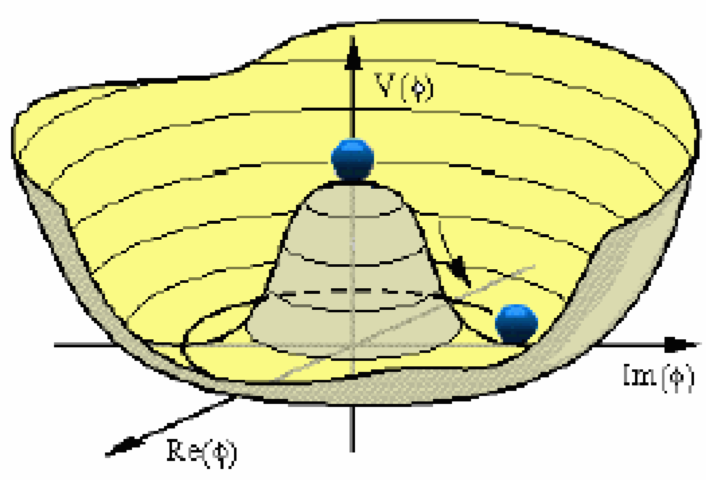


Electroweak symmetry breaking

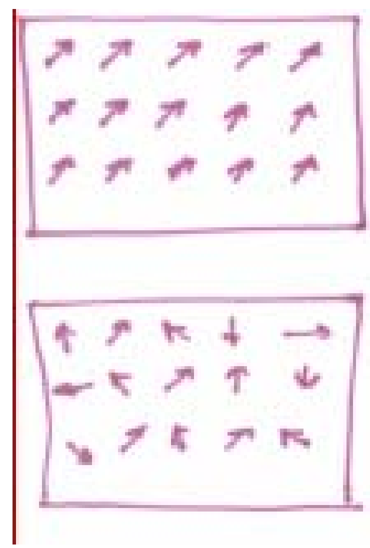
- **Question : How to provide masses to W and Z, while preserving the symmetry**
- **Answer : We only need to preserve the symmetry of the interactions, not the whole theory. The Lagrangian of the theory is invariant under the symmetry, but the ground state is not.**

- **Most famous example is the ferromagnet, whose Lagrangian is invariant under rotation, but the magnetisation is not**

- **Anderson-Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism**



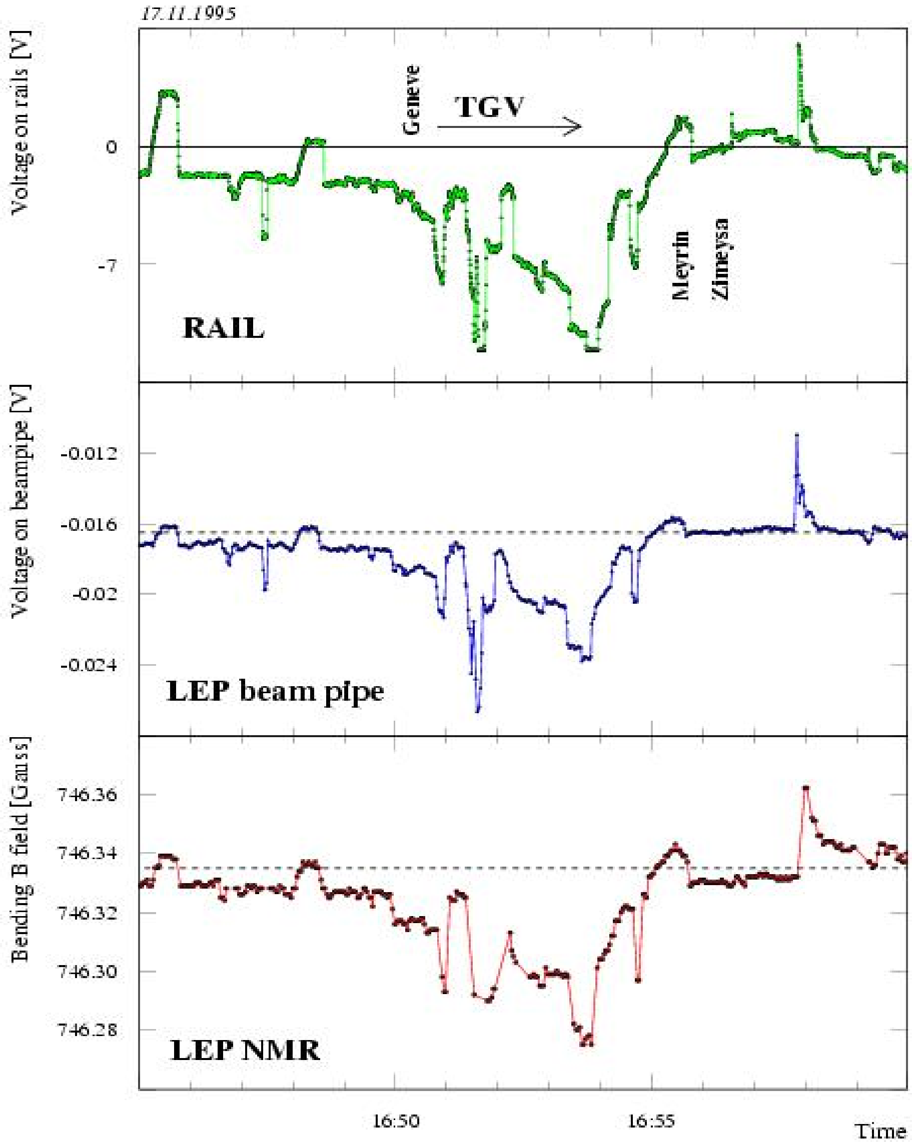
At low energy or ground stat the potential is still symmetric, but not the position of the ball. At higher energy the shape of the potential is different ⇒phase transition

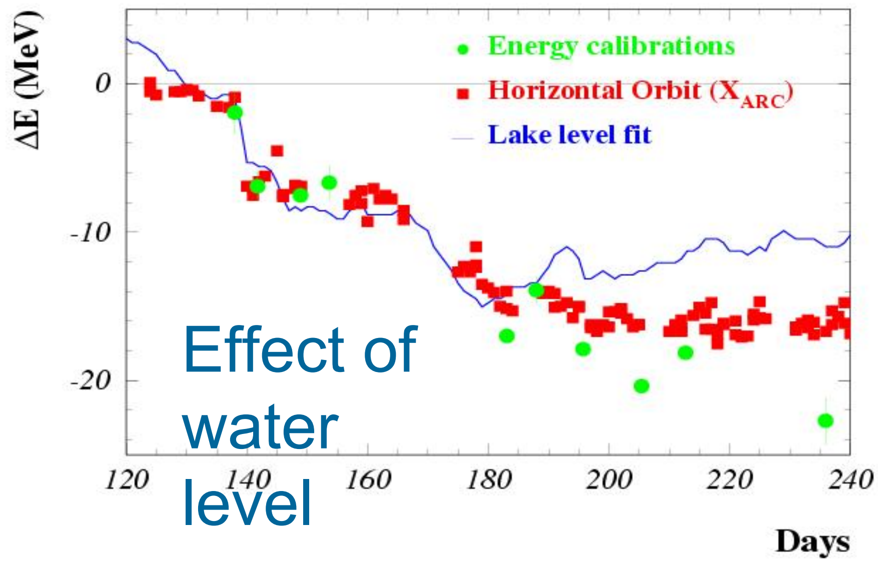


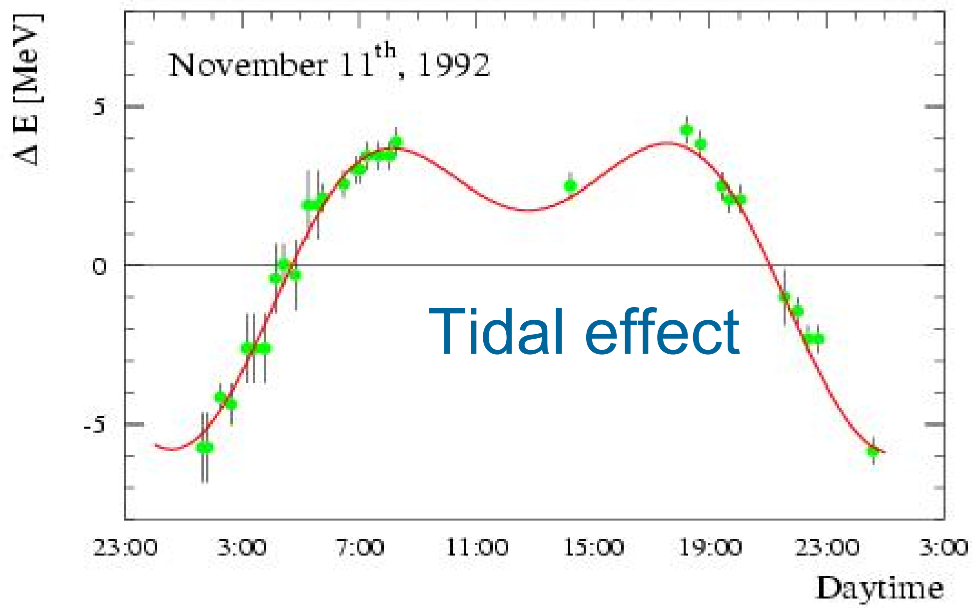
Below Curie point

Above Curie point

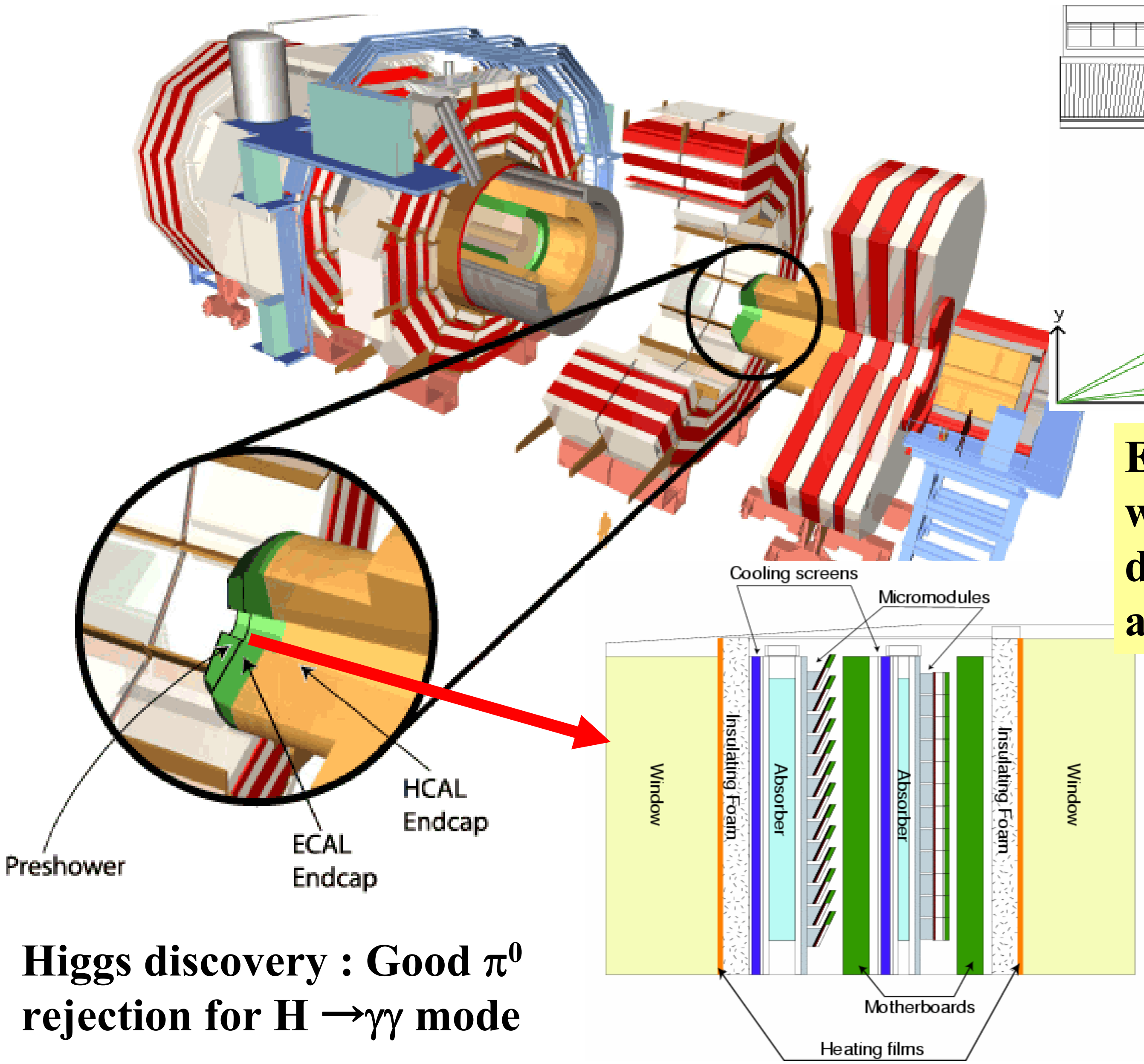
The same tunnel was used in LEP, noticed effect TGV, tide. water level at lake

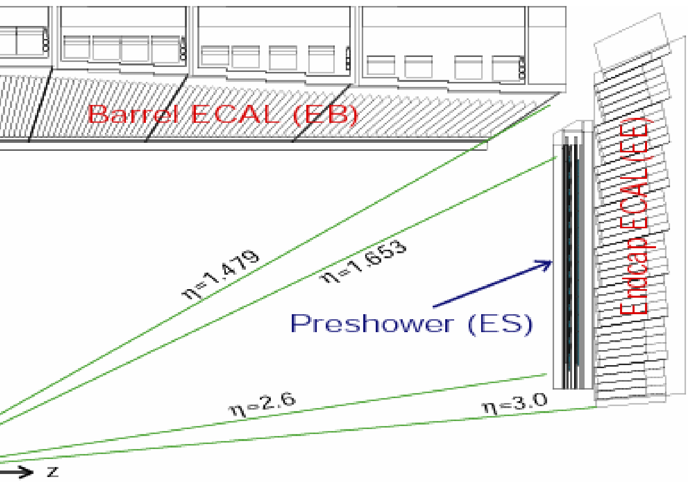






CMS Preshower Detector





End caps of CMS detector will 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