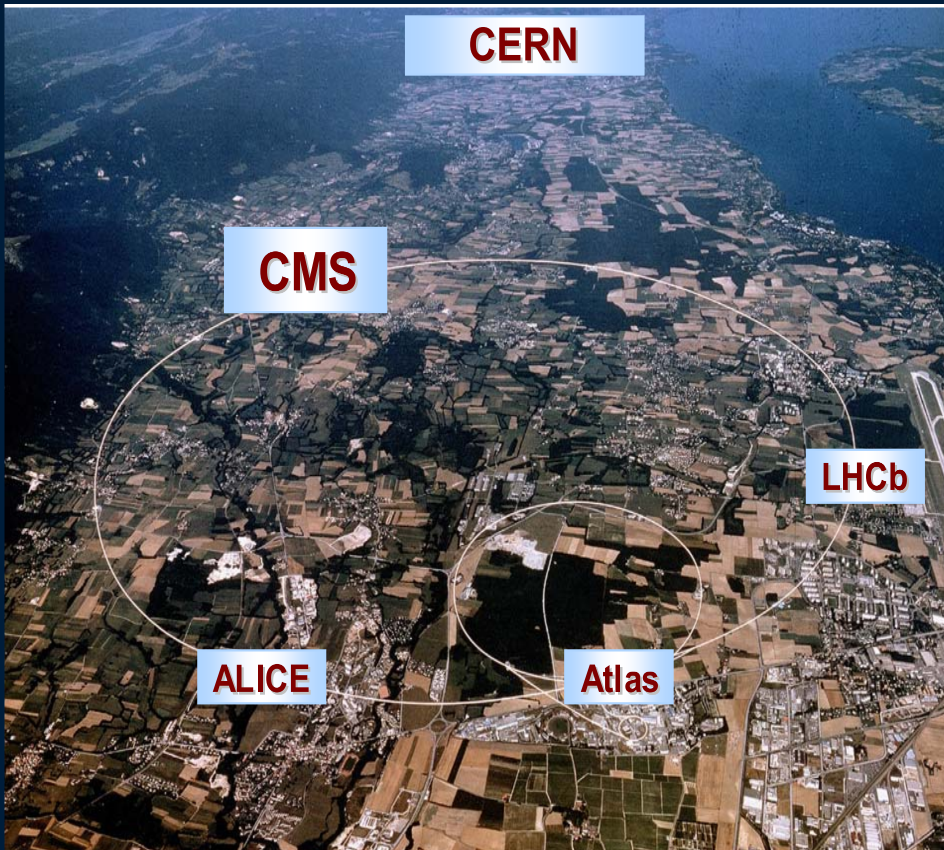
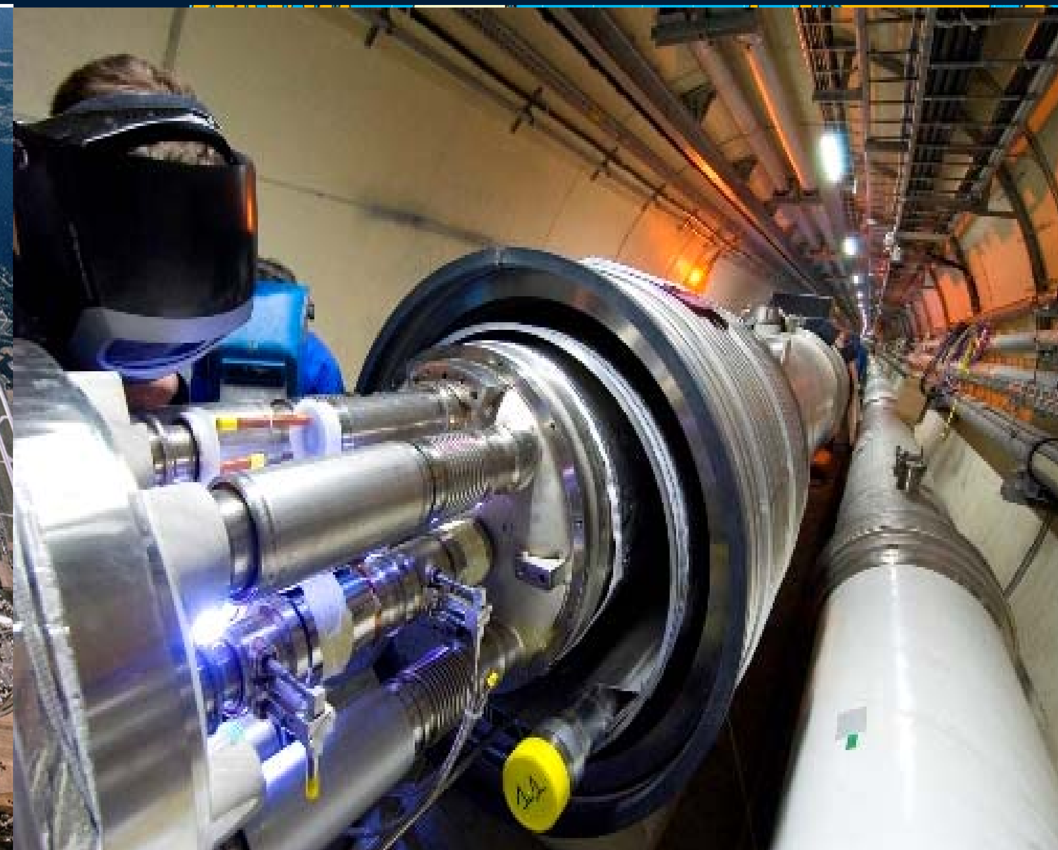
# Physics at the LHC: a New Window on Matter, Spacetime, and the Universe

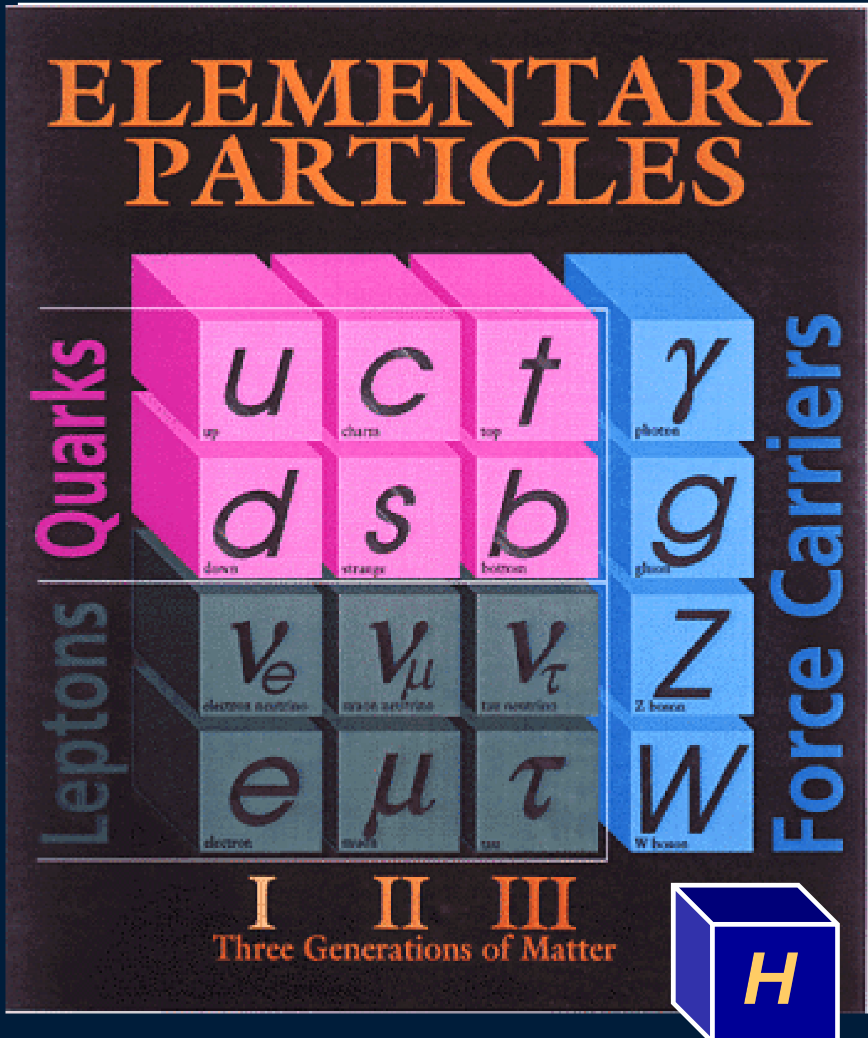


Harvey B Newman, Caltech

NCP Int'l Symposium on Contemporary Physics
Islamabad, March 28, 2007

# The Standard Model of Particle Physics: 3 Quark, 3 Lepton Families, 4 Forces




31 particle physicists have won Nobel prizes for making the experimental discoveries and theoretical breakthroughs that led to our present understanding

**The Higgs boson?**
**[It Generates Masses;**
**The Missing Link]**

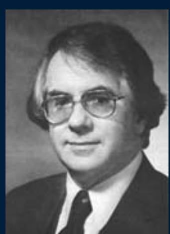
The theory describes the known forces and particles, with one very important exception:
***Gravity.***

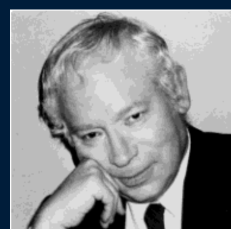
# Our present theory of particle physics: The Standard Model

**A grand achievement of the second half of the 20th Century**

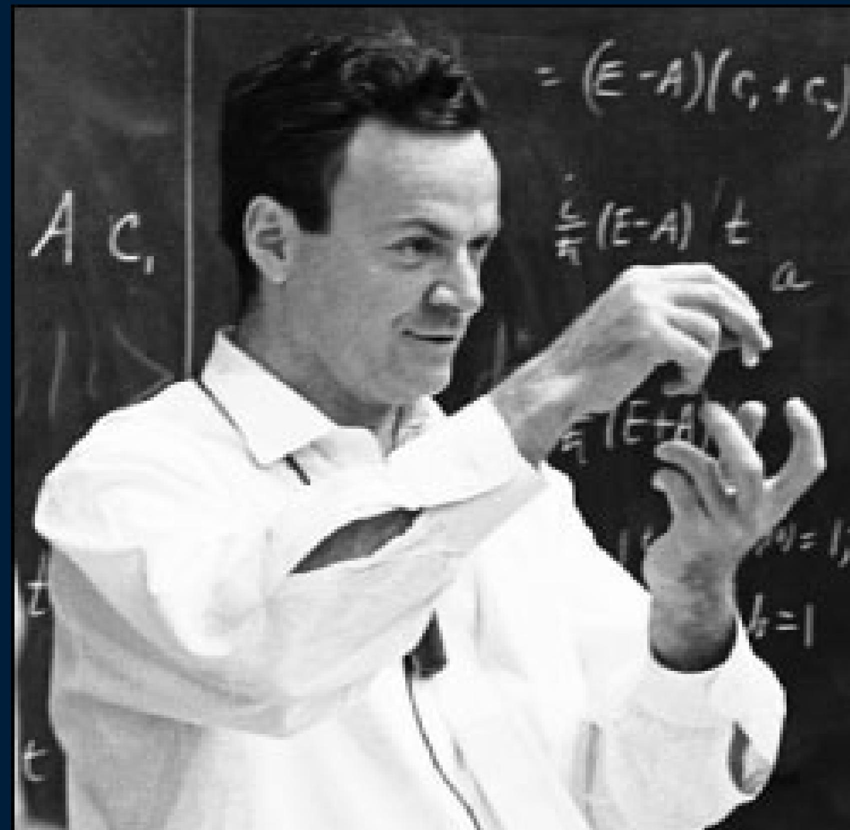
**Based on relativistic quantum field theories (QFT).**

- The first QFT was quantum electrodynamics
- Unified Electroweak



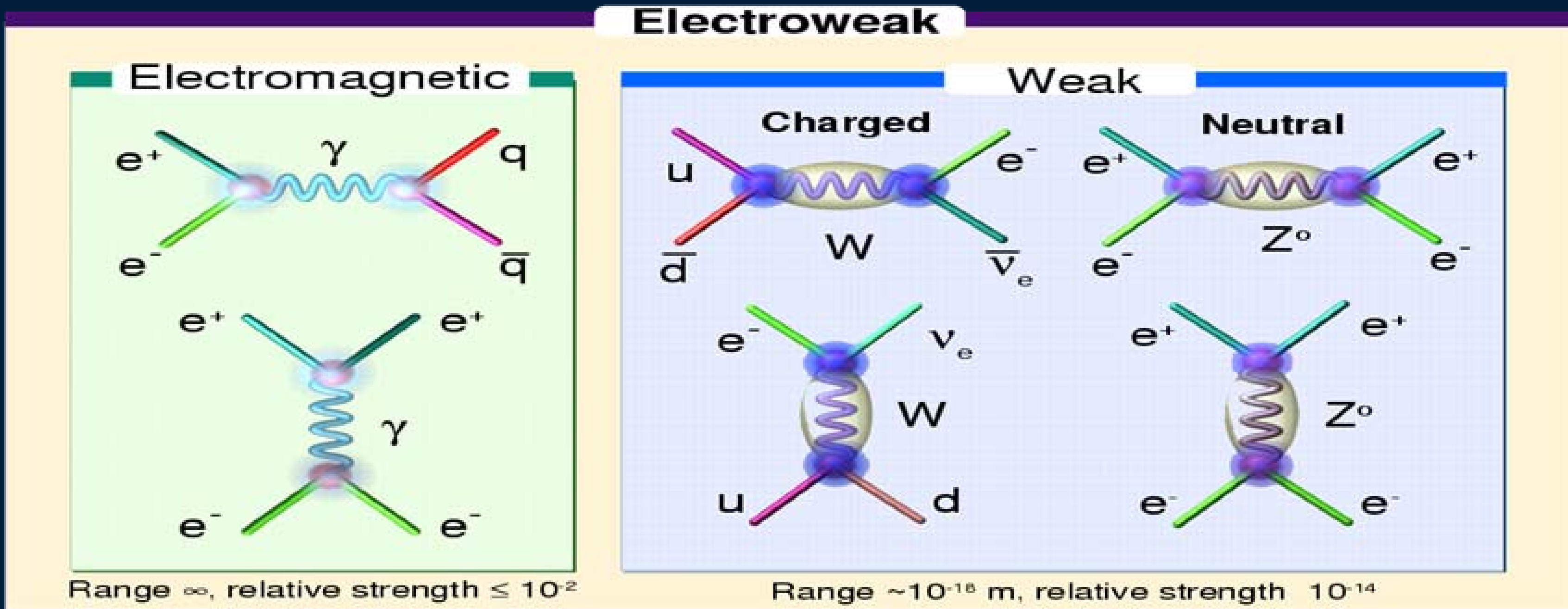


- QCD for the Strong Interaction; *Asymptotic Freedom*

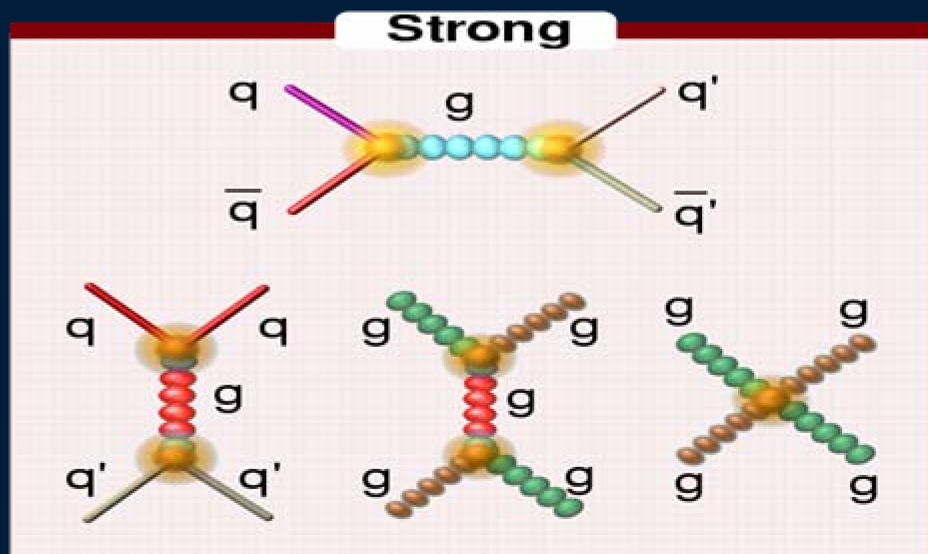


**Feynman ca. 1960 at Caltech**

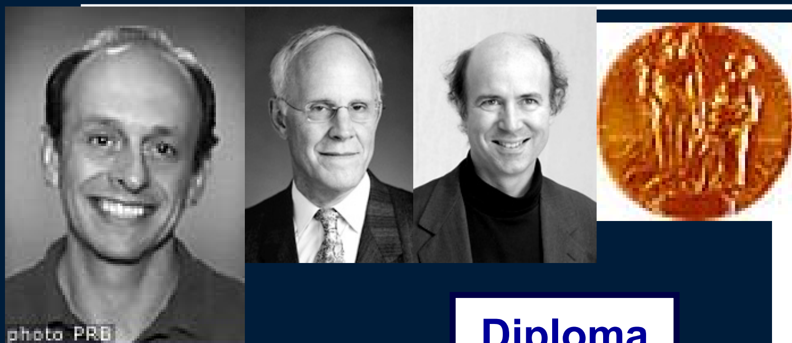
# Interactions: Coupling Forces to Matter




**Feynman Diagrams**

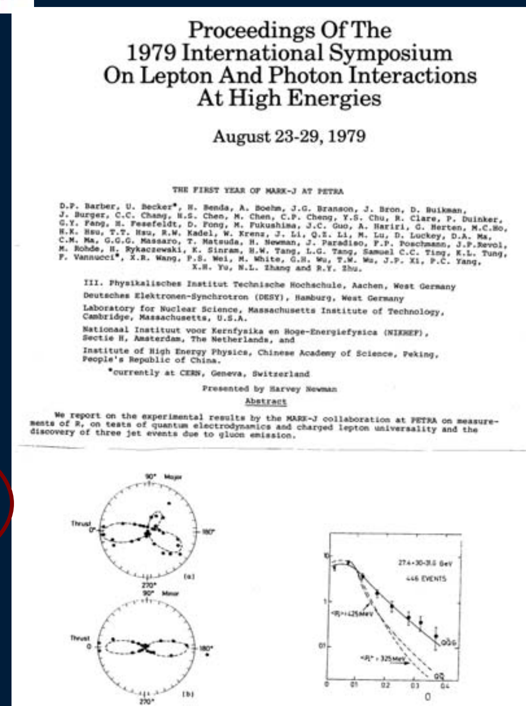


# Nobel Prize 2004, for Asymptotic Freedom (1973)




**Diploma**


**Discovery of Gluons**



Proceedings Of The
1979 International Symposium
On Lepton And Photon Interactions
At High Energies

August 23-29, 1979

THE FIRST YEAR OF MARK-J AT PETRA

D.P. Barber, U. Becker*, H. Benda, A. Boehm, J.G. Branson, J. Bron, D. Buikman, J. Burger, C.C. Chang, H.S. Chen, M. Chen, C.P. Cheng, Y.S. Chu, R. Clare, P. Duinker, G.Y. Fang, H. Fesefeldt, D. Fong, M. Fukushima, J.C. Guo, A. Hariri, G. Herten, M.C. Ho, H.K. Hsu, T.T. Hsu, R.W. Kadel, W. Krenz, J. Li, Q.Z. Li, M. Lu, D. Luckey, D.A. Ma, C.M. Ma, G.G.G. Massaro, T. Matsuda, H. Newman, J. Paradiso, F.P. Poschmann, J.P. Revol, M. Rohde, H. Rykaczewski, K. Sinram, H.W. Tang, L.G. Tang, Samuel C.C. Ting, K.L. Tung, F. Vannucci*, X.R. Wang, P.S. Wei, M. White, G.H. Wu, T.W. Wu, J.P. Xi, P.C. Yang, X.H. Yu, N.L. Zhang and R.Y. Zhu.

III. Physikalisches Institut Technische Hochschule, Aachen, West Germany
Deutsches Elektronen-Synchrotron (DESY), Hamburg, West Germany
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.
Nationaal Instituut voor Kernfysika en Hoge-Energiefysica (NIKHEF), Sectie H, Amsterdam, The Netherlands, and
Institute of High Energy Physics, Chinese Academy of Science, Peking, People's Republic of China.

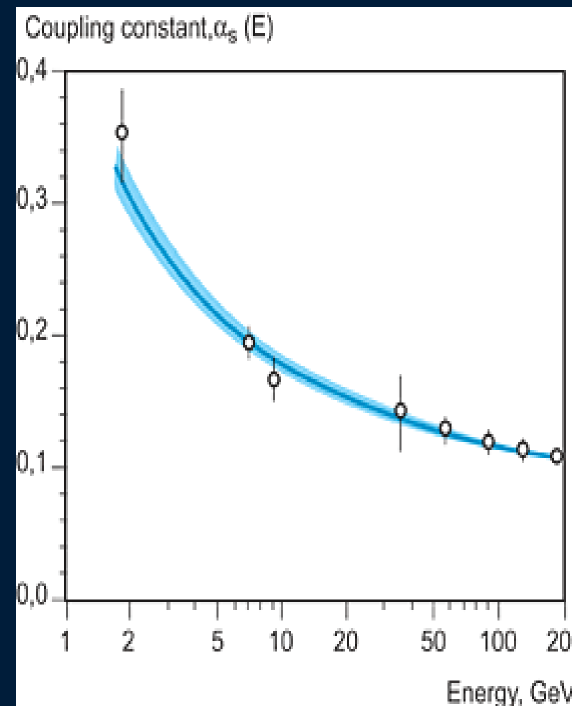
*currently at CERN, Geneva, Switzerland

Presented by Harvey Newman

Abstract

We report on the experimental results by the MARK-J collaboration at PETRA on measurements of R, on tests of quantum electrodynamics and charged lepton universality and the discovery of three jet events due to gluon emission.

**"Running" of $\alpha_s$**




**Color Screening of Quarks ➡ Possibility of Unification**

# Particles

## Leptons

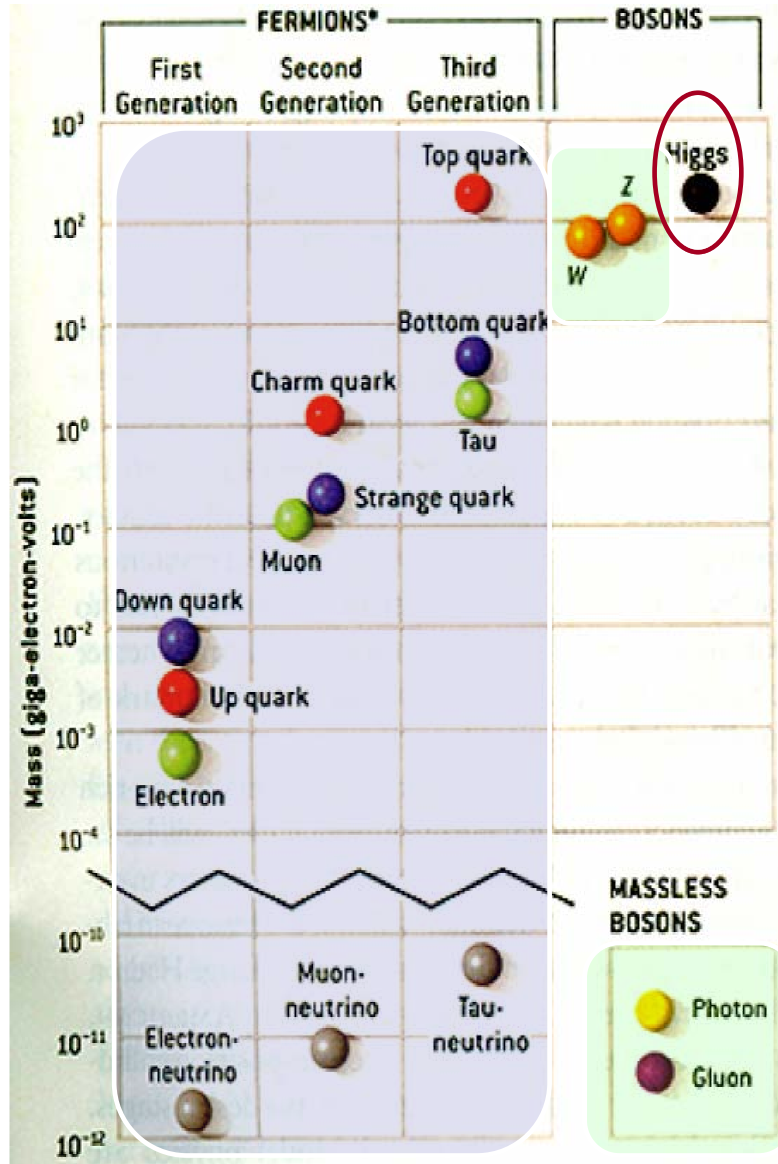
| | Electric Charge | | Electric Charge |
|---|---|---|---|
| Tau | -1 | Tau Neutrino | 0 |
| Muon | -1 | Muon Neutrino | 0 |
| Electron | -1 | Electron Neutrino | 0 |

**Gell-Mann, Zweig**

## Quarks

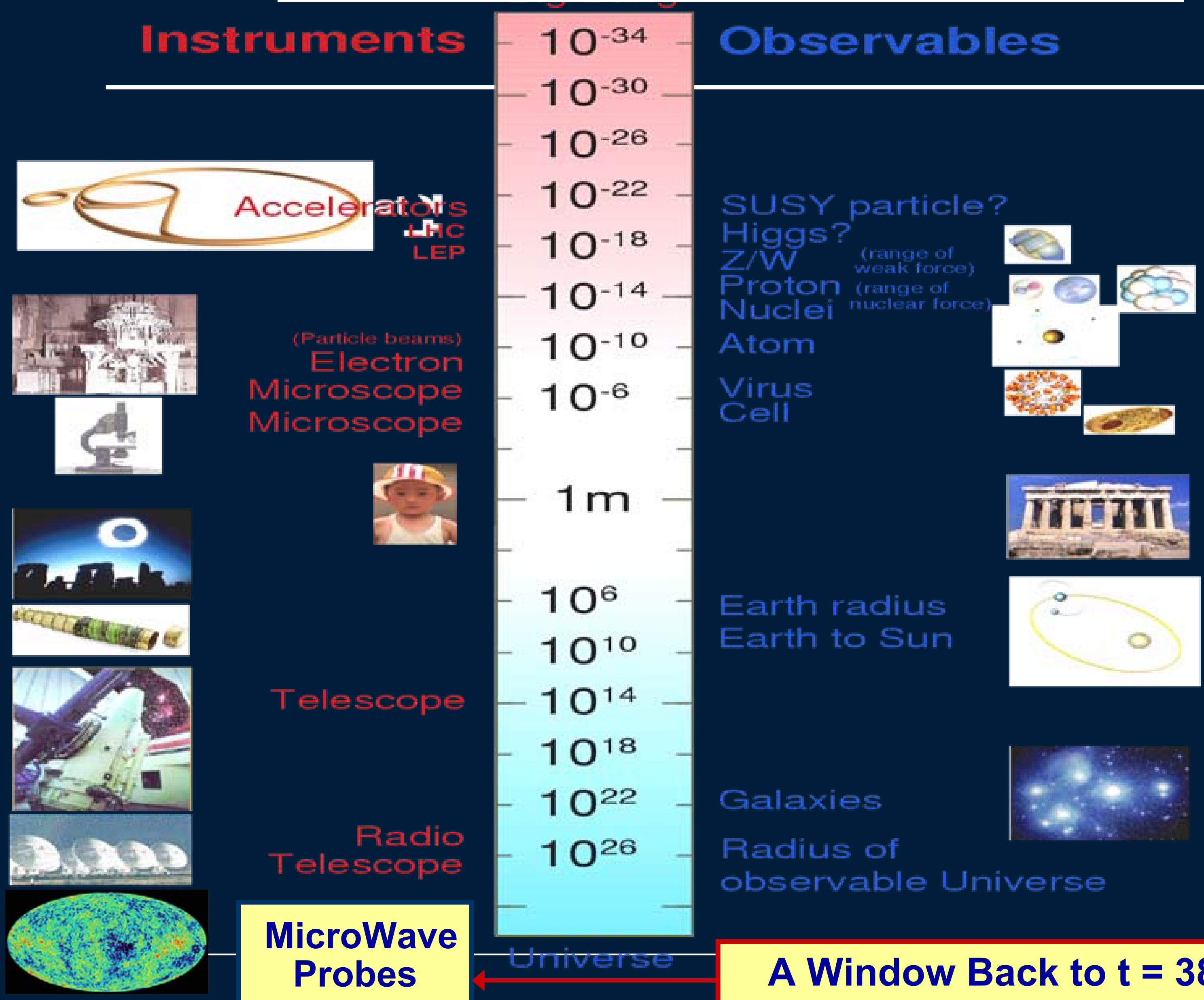
| | Electric Charge | | Electric Charge |
|---|---|---|---|
| Bottom | -1/3 | Top | 2/3 |
| Strange | -1/3 | Charm | 2/3 |
| Down | -1/3 | Up | 2/3 |

*each quark: R, B, G   3 colors*




**How Many Families (Generations) ? Mass Pattern ? Structure ?**

# Probing the Universe




A Window Back to t = 380,000 Years

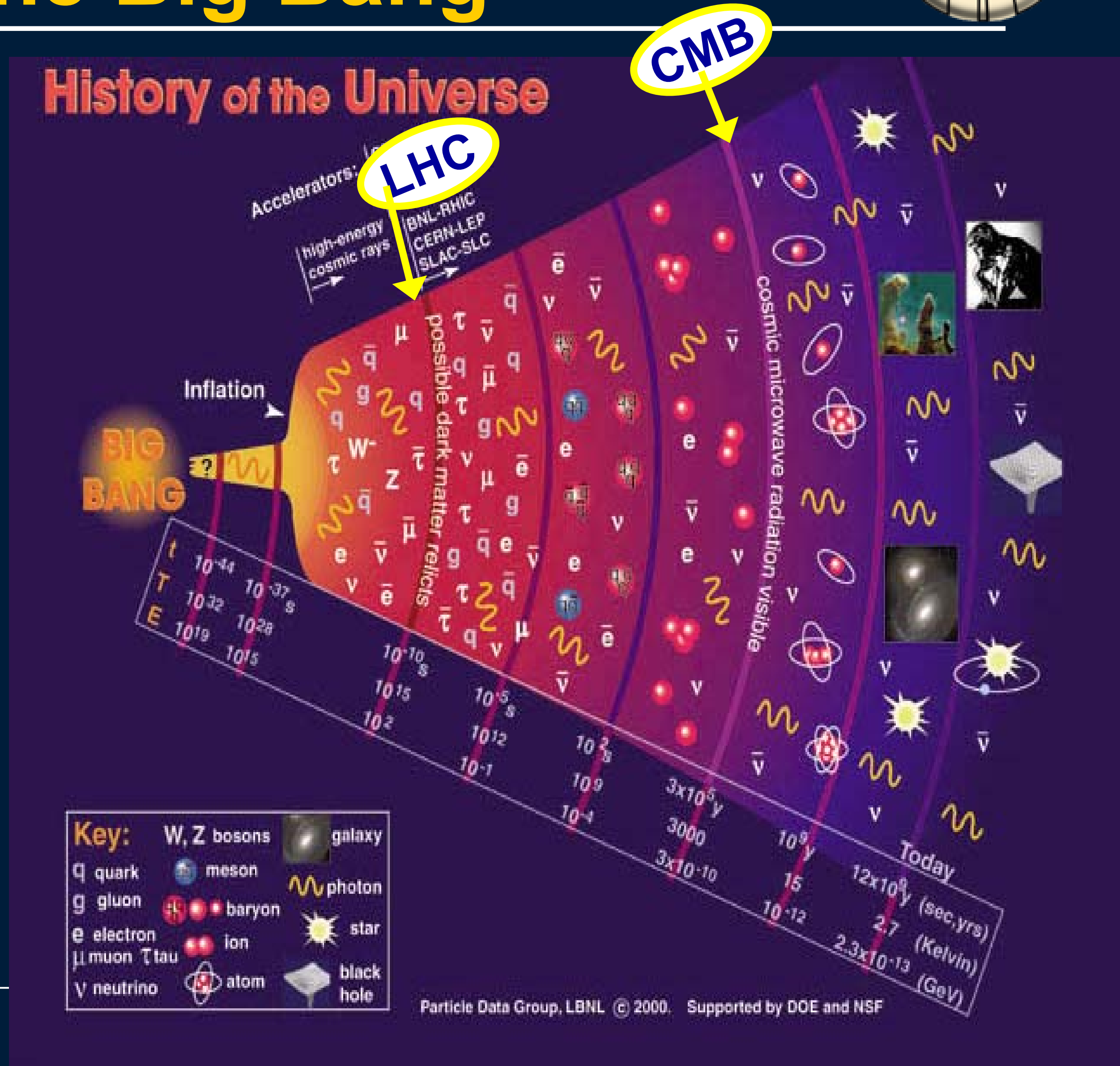
- → At All Distance Scales
- → With All the Means at Our Disposal:
- → With Probes of the Widest Range of Energies

**An Increasingly Deep Connection Between HEP and Cosmology**

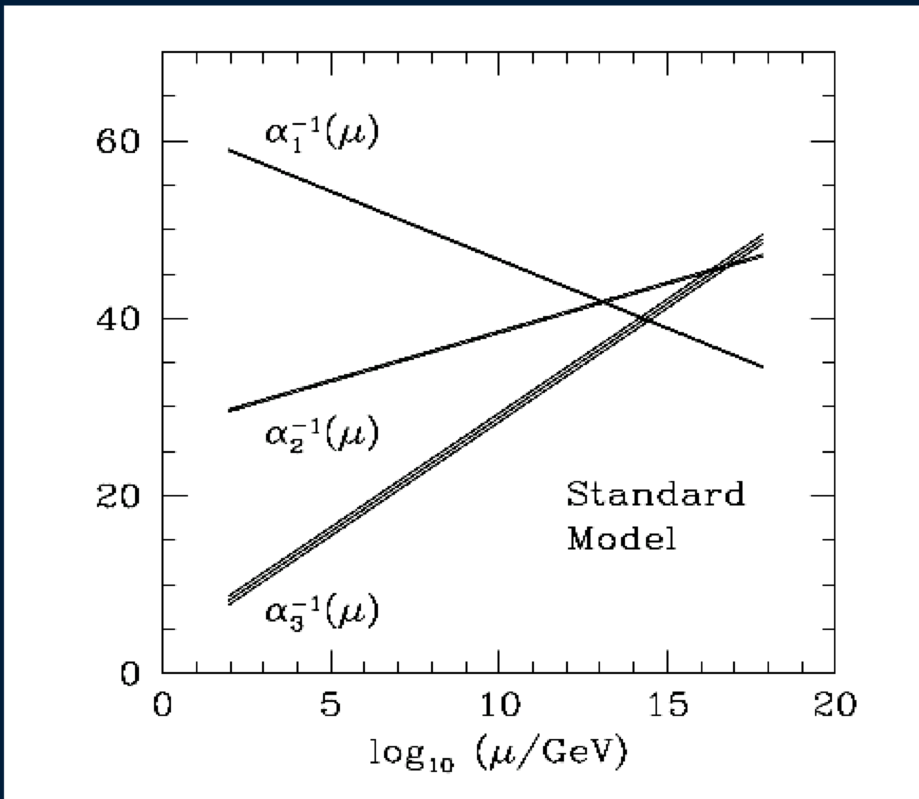
# The first particle physics experiment: The Big Bang

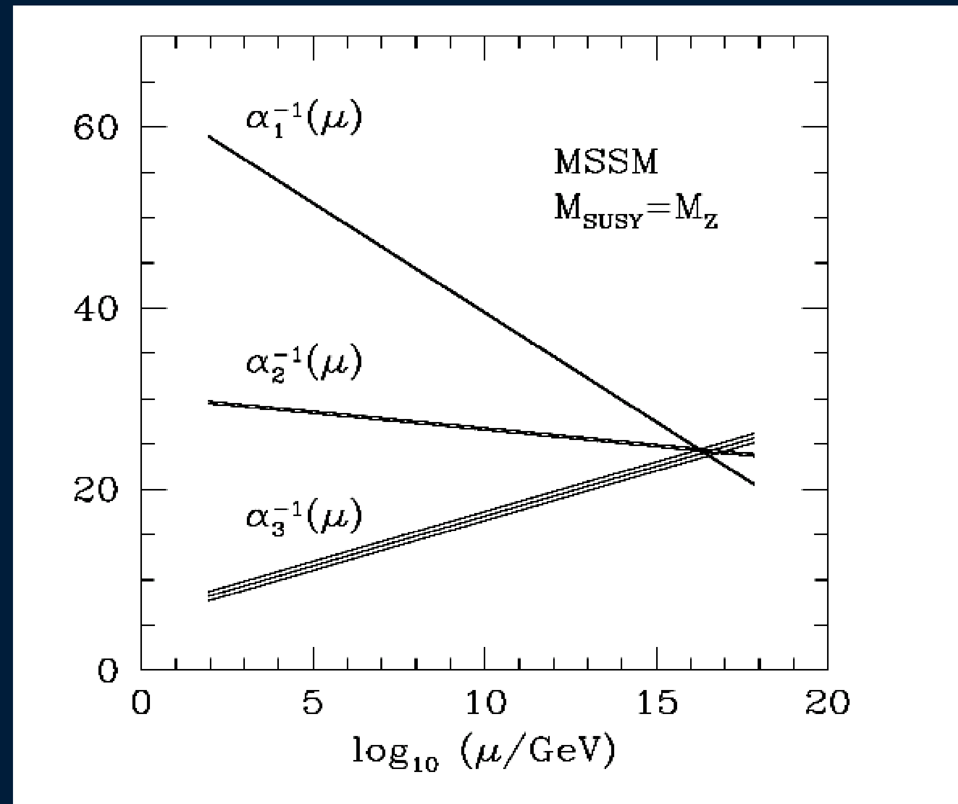
<u>A Brief History of Time</u>

- $10^{-43}$ secs; $10^{-37}$ secs
  - Gravity; Strong forces separate
- $10^{-35}$ secs
  - Inflation
- $10^{-10}$ seconds
  - Quark-AntiQuark Annihilation (CP Violation)
- 10 microseconds
  - Quarks form protons, neutrons
- 380,000 years (last scatter)
  - Nuclei capture electrons, form atoms; *universe transparent to light*
- 1.0 Gigayear
  - Galaxies begin to form
- 13.7 Gigayears: Today



# Supersymmetry and Grand Unification: Evolution of the Couplings

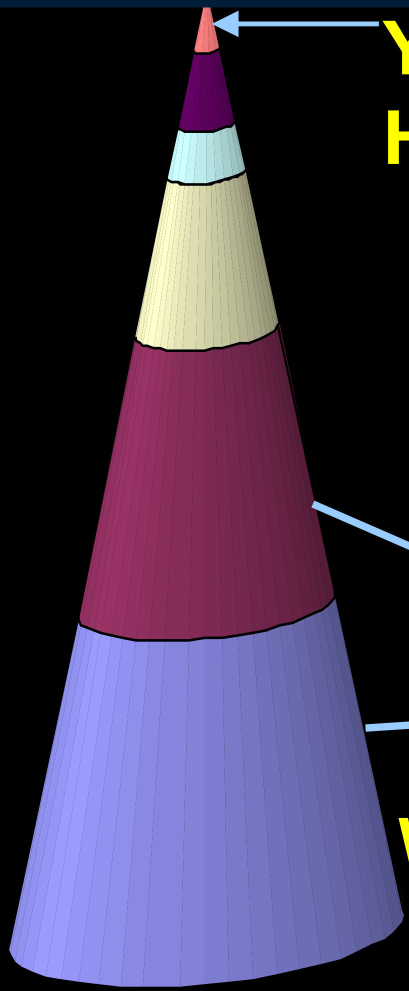


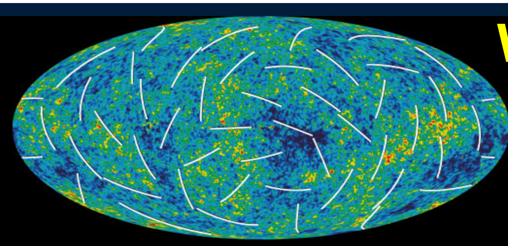

**Standard Model**

**With Supersymmetry (MSSM)**

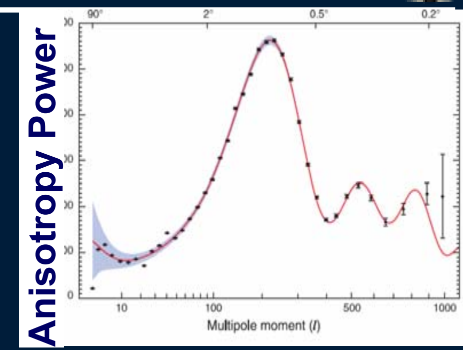
# "Beyond the Standard Model": HEP & Cosmology Understanding the Universe



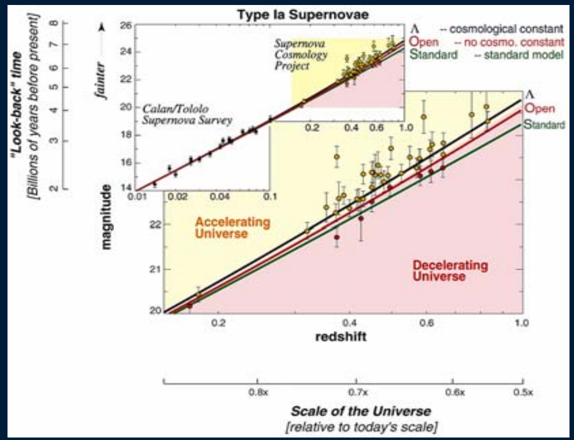
You Are Here.



WMAP




| | |
|---|---|
| Other elements | 0.03% |
| Neutrinos | 0.3% |
| Stars | 0.5% |
| Free H and He | 3% |
| Dark matter | 22% |
| Dark energy | 74% |



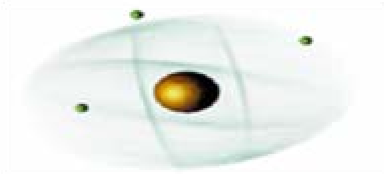

**We do not know what makes up 96% of the universe.**

***What is the Dark Energy Field ?***

# The Great Questions of *Particle Physics and Cosmology*

1. Where are the Higgs particles; What is the mysterious Higgs field ?
2. Where does the pattern of particle families and masses come from ?
3. Why do neutrinos and quark flavors oscillate ?
4. Is Nature Supersymmetric ? Is there Unification ? Why the hierarchy of scales ?
5. What is the nature of dark matter ?
6. Why is gravity so weak?
7. Why is any matter left in the universe?
8. Are there extra space-time dimensions?
9. What is the dark energy?

# Short history and new frontiers

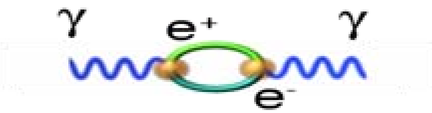


$\lambda = h / p$ — $T \approx t^{-1/2}$

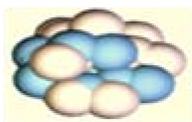
$10^{-10}$ m — $\leq 10$ eV — >300000 Y

**1900....1930s**
Quantum Mechanics
Atomic Physics

**X-Rays; Radioactive Sources; Cyclotrons; Cosmic Rays**




**1940-50**
Quantum Electro Dynamics



$10^{-15}$ m — MeV - GeV — ≈ 3 min

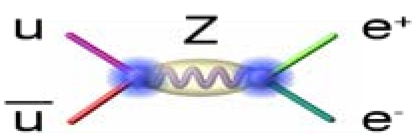
**Synchrotrons**

**1950-65**
Nuclei, Hadrons; Antiproton
Symmetries
Field theories

**Colliders**

$10^{-16}$ m — >> GeV — $\approx 10^{-6}$ sec

**1965-75**
Quarks; Color
Gauge theories




$10^{-18}$ m — ≈ 100 GeV — $\approx 10^{-10}$ sec

**SPS, p$\bar{p}$ 1970-83**
ElectroWeak Unification,
QCD: Asymptotic Freedom;
Discovery of Gluon, W, Z

**The Era of Colliders** ⬇

**LEP 1990**
3 families 6 Quarks; 6 Leptons

| | | | |
|---|---|---|---|
| 6 Leptons | $\nu_e$ e | $\nu_\mu$ μ | $\nu_\tau$ τ |
| 6 Quarks | u d | c s | t b |
| 3 "Colors" each quark | R | G | B |

**Tevatron 1994**
Top quark

**LHC 2007**

Origin of masses
The next step...
ν Masses & mixing

$10^{-19}$ m — $\approx 10^{3}$ GeV — $\approx 10^{-12}$ sec

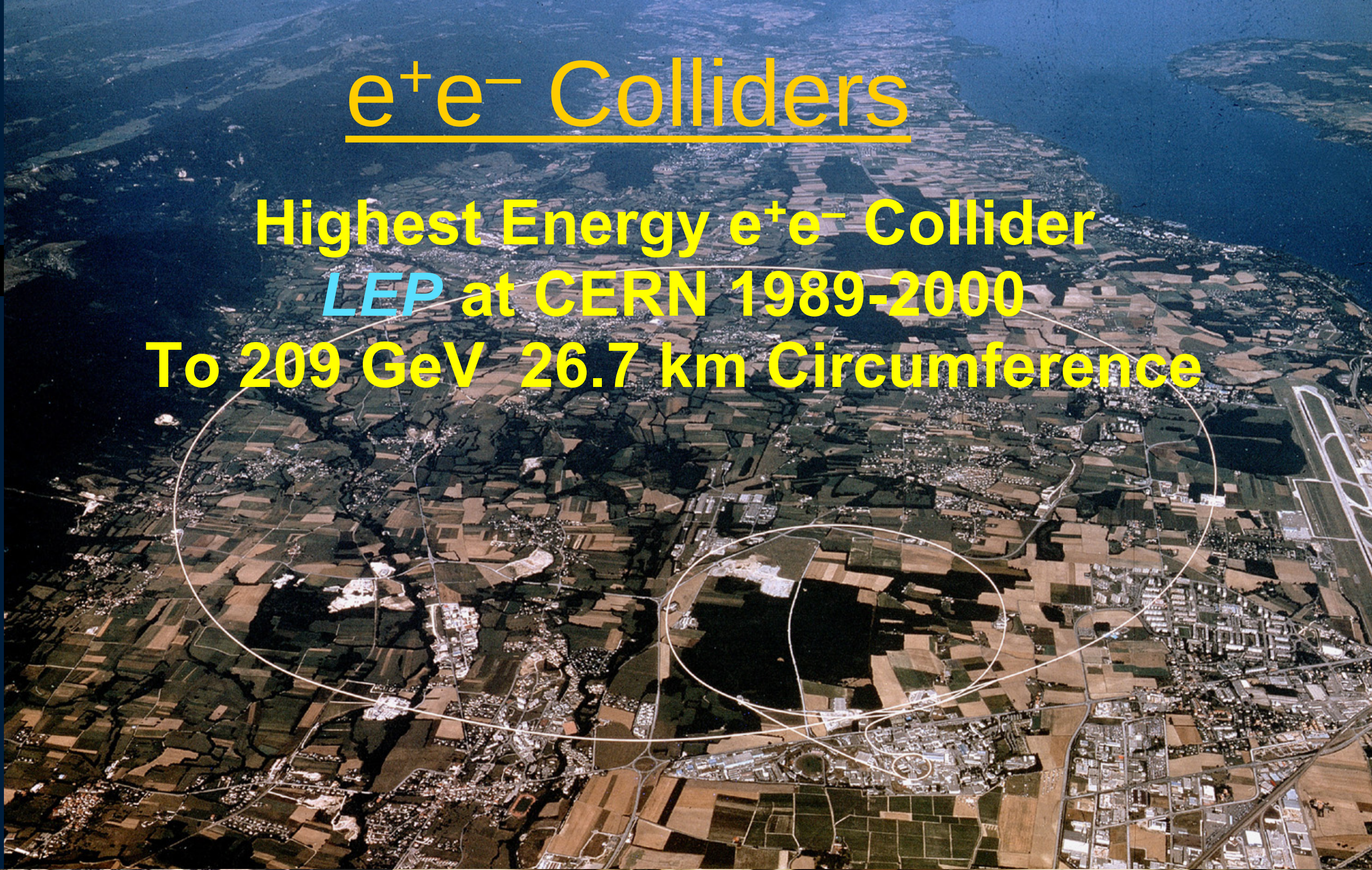
Higgs ? Supersymmetry ?
**Linear Collider; Future Accel.**
**Underground Labs**

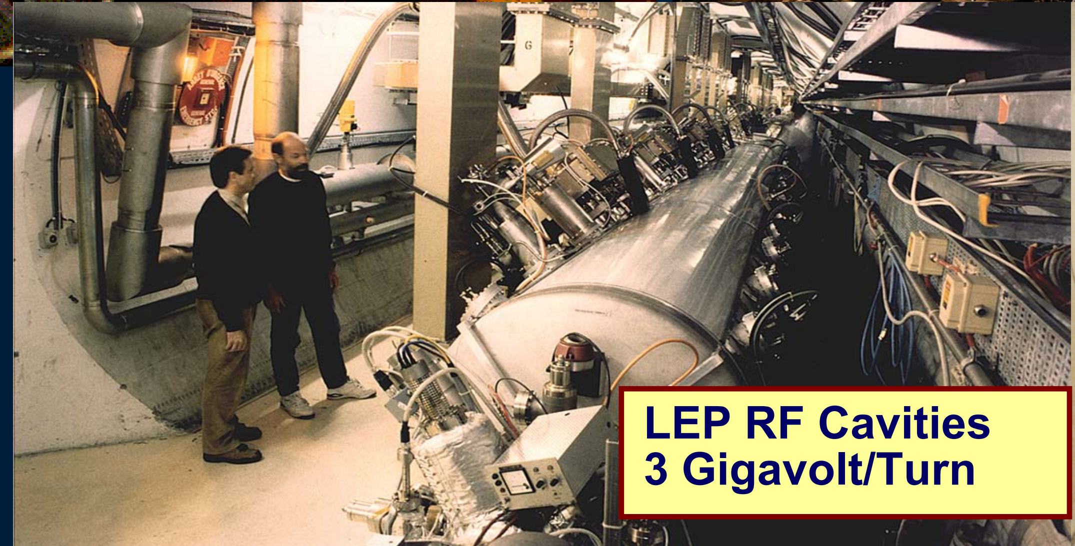
Proton Decay ?

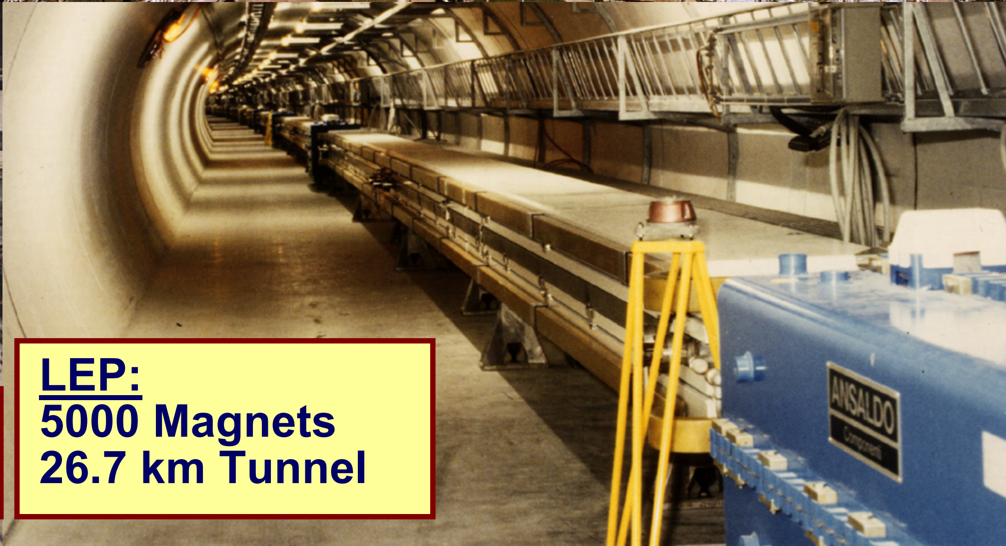
$10^{-32}$ m — $\approx 10^{16}$ GeV — $\approx 10^{-32}$ sec

GRAND Unified & String Theories ?

# $e^+e^-$ Colliders

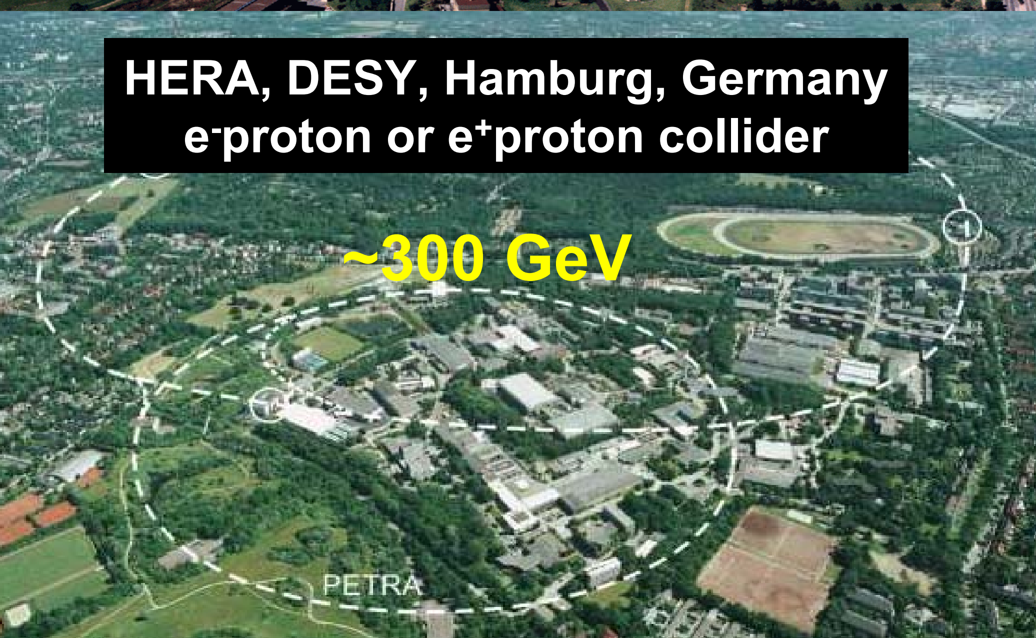



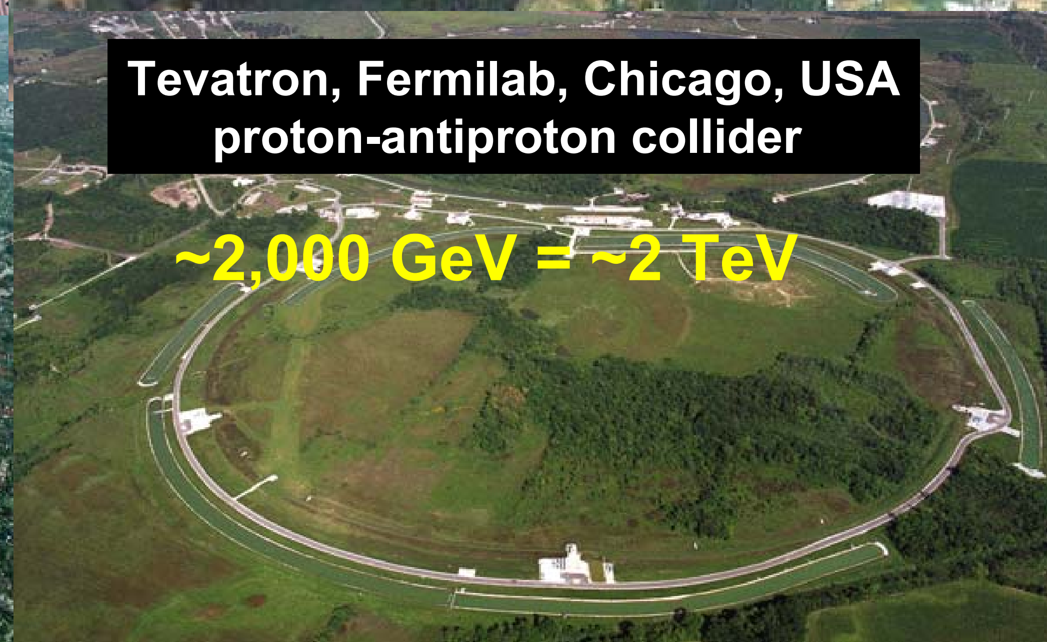



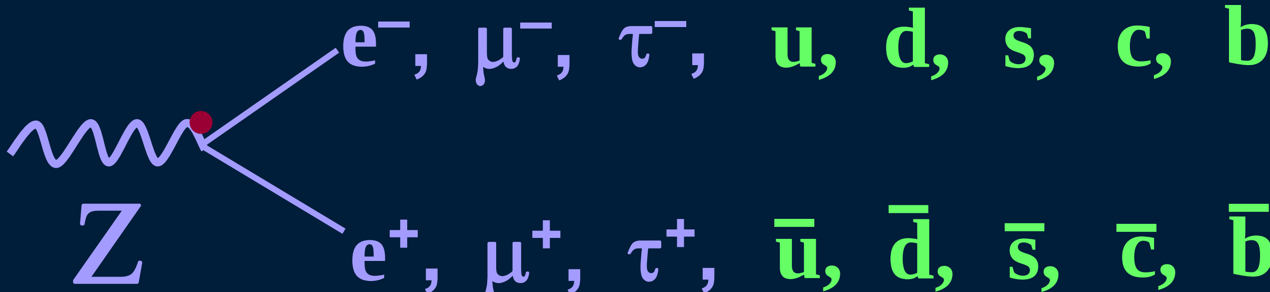
# Accelerators (output of Accelerator Science) are powerful tools for Particle Physics!



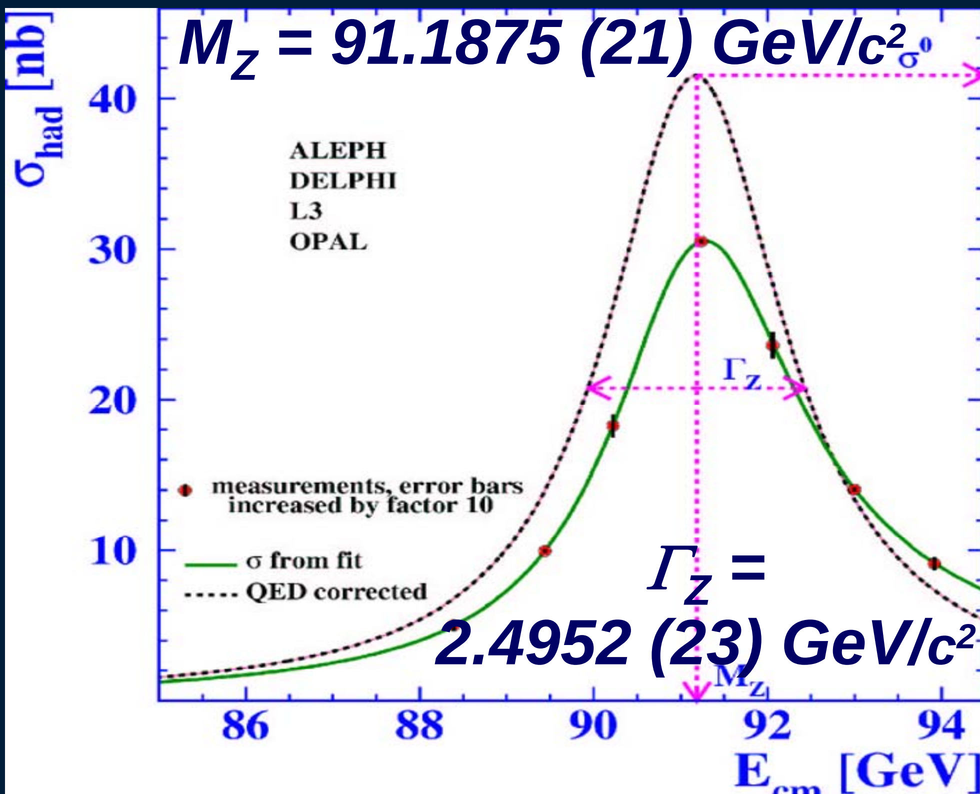


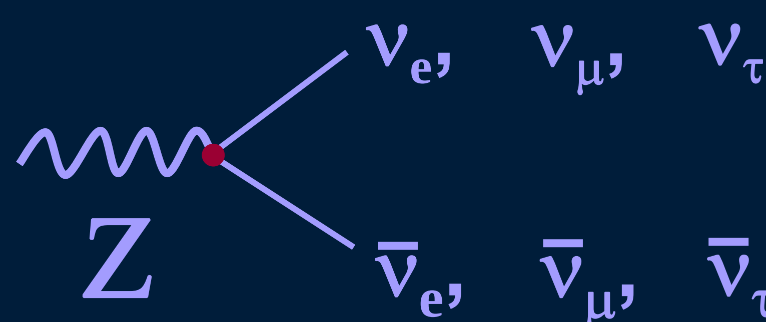



# LEP At the Z Resonance (15M Produced):
## Probing the Electroweak Field Precisely




**All Possible Forms of Matter that interact with the Electroweak Field (less than $M_Z/2$)**




$N_\nu$ = 2.9841 (83)

## *Global electroweak fit*

## To Z and W Boson Properties

# March 2007

$\alpha$

LEP Z lineshape and lepton $A_{FB}$

**Z mass to 2 X $10^{-5}$; Width to $10^{-4}$**
**Production Rate to $10^{-3}$;**
**Asymmetries to 1-3%**

LEP and SLD Z heavy flavour ⋆

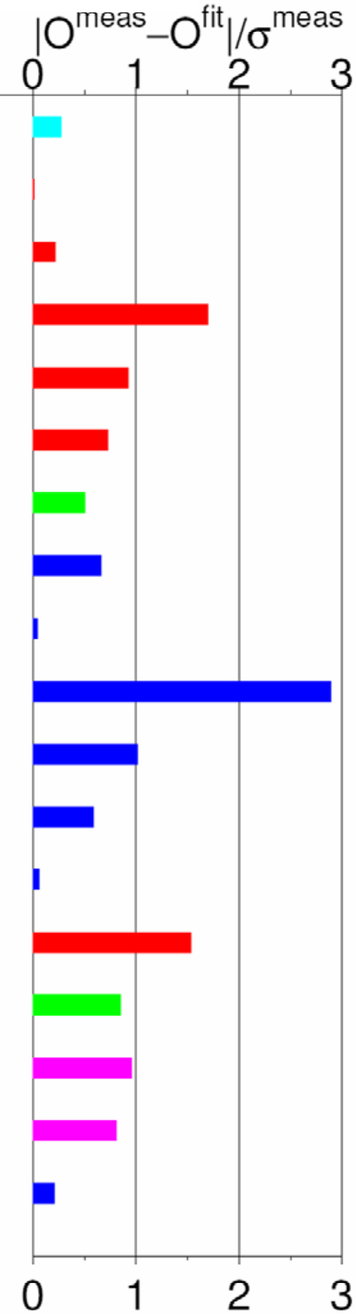
SLD $A_{LR}$

LEP hadronic $A_{FB}$ (inclusive)

**W Mass to 3 X $10^{-5}$; Width to 3%**

***Tevatron: Top Mass to 1%***

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02768 |
| ✸ $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1875 |
| ✸ $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4957 |
| ✸ $\sigma_{had}^{0}$ [nb] | 41.540 ± 0.037 | 41.477 |
| $R_l$ | 20.767 ± 0.025 | 20.744 |
| $A_{fb}^{0,l}$ | 0.01714 ± 0.00095 | 0.01645 |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1481 |
| $R_b$ | 0.21629 ± 0.00066 | 0.21586 |
| $R_c$ | 0.1721 ± 0.0030 | 0.1722 |
| $A_{fb}^{0,b}$ | 0.0992 ± 0.0016 | 0.1038 |
| $A_{fb}^{0,c}$ | 0.0707 ± 0.0035 | 0.0742 |
| $A_b$ | 0.923 ± 0.020 | 0.935 |
| $A_c$ | 0.670 ± 0.027 | 0.668 |
| $A_l$(SLD) | 0.1513 ± 0.0021 | 0.1481 |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 |
| ✸ $m_W$ [GeV] | 80.398 ± 0.025 | 80.374 |
| $\Gamma_W$ [GeV] | 2.140 ± 0.060 | 2.091 |
| ✸ $m_t$ [GeV] | 170.9 ± 1.8 | 171.3 |



# State of the Higgs: 2007

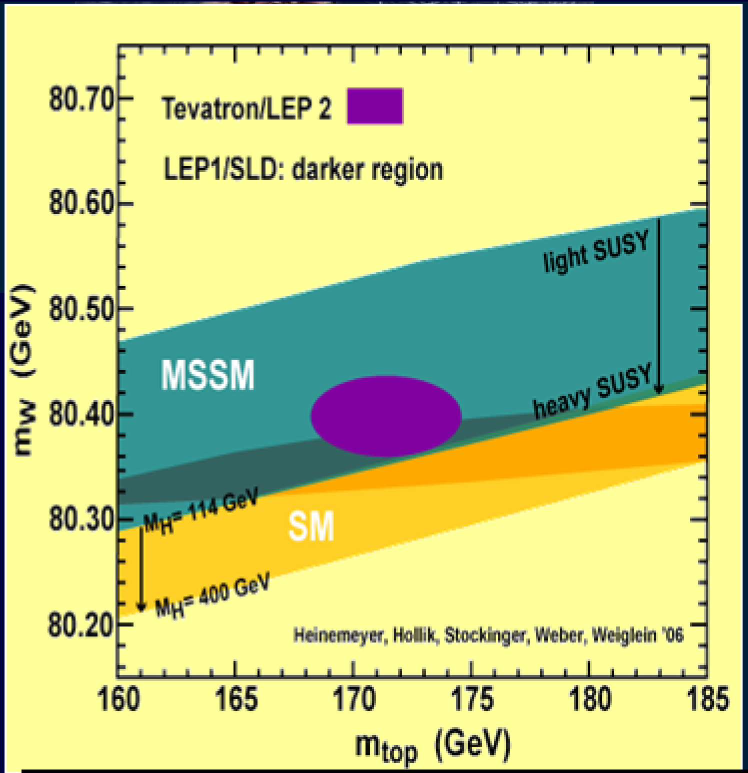
- Self-Interacting Effective Potential:

$$V(\varphi) = -\mu^2\varphi^2 + \lambda\varphi^4$$

- Spontaneous Symmetry Breaking

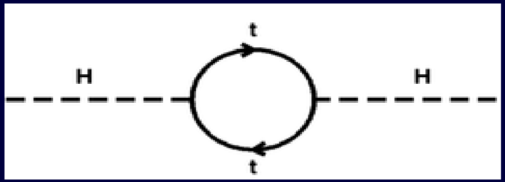
  - Elwk Vacuum at • VEV = 246 GeV $\langle\varphi\rangle = \frac{\mu}{\sqrt{2\lambda}}$
  - Gives W, Z, fermions their masses
  - Coupling to Fermions ~ $M_f$

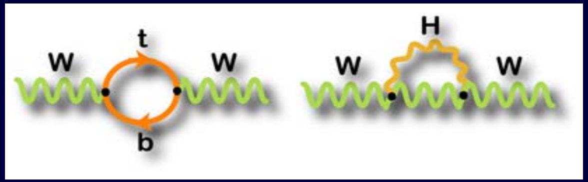
**Fit Higgs Mass Fit to Precise Elwk Data from LEP, SLC, Fermilab**




**Light SM Higgs ?**
**Heavy SUSY ?**

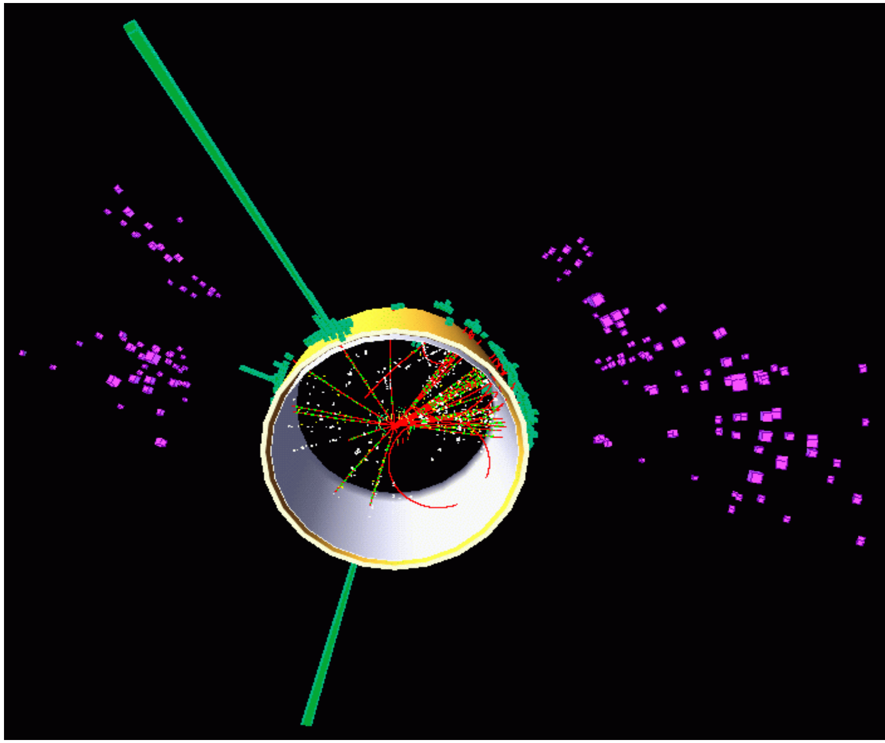
- Electroweak fit (w/ quantum corrections) to $m_H$ : depends on $m_W$, $m_{TOP}$

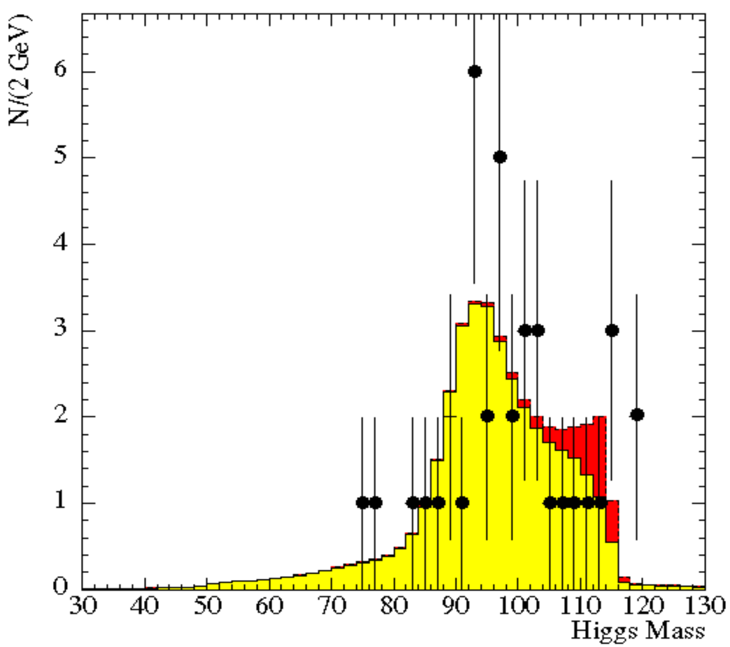


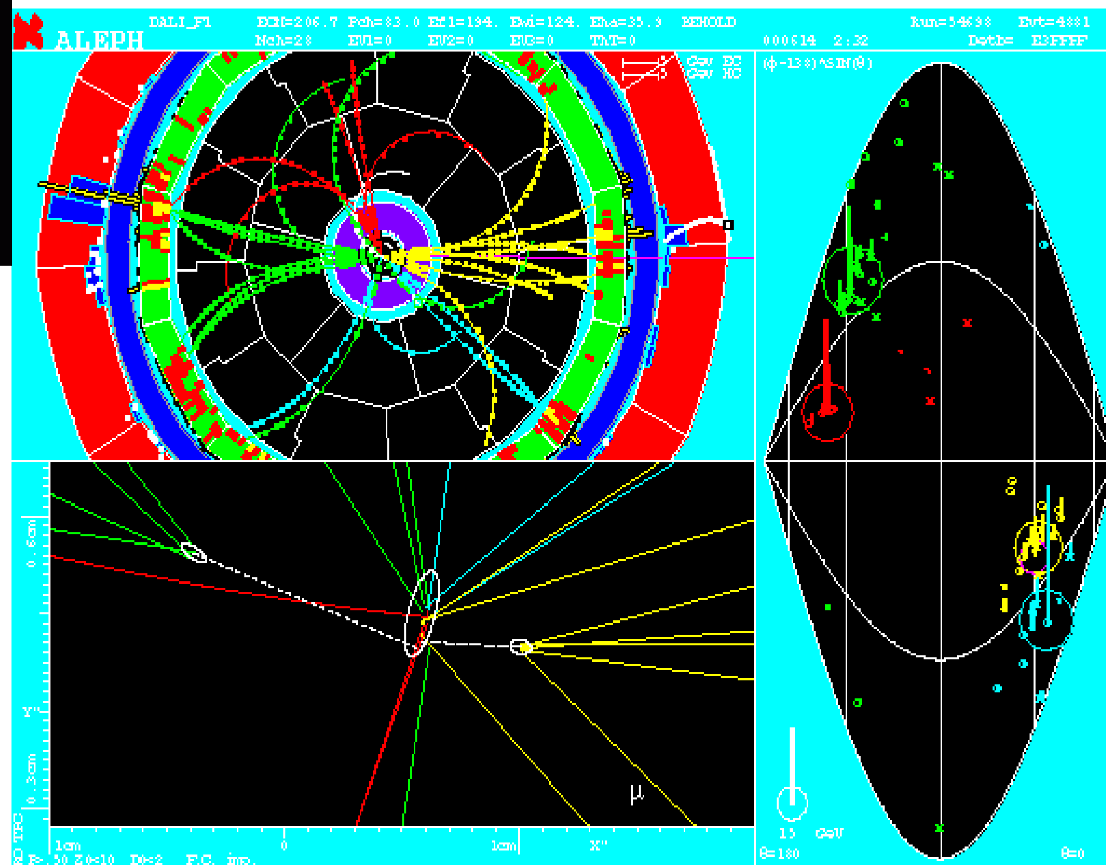




- Best-fit value (2007): $m_H = 76^{+34}_{-23}$ GeV
  using $m_{TOP}$ = 170.9 ± 1.8, $m_W$ = 80.396 ± .025 GeV
- Direct search limit: $m_H > 114.4$ GeV
- 95% CL upper limit: $m_H < 144$ GeV
  (182 GeV with direct limit)

# Evidence for the Higgs at LEP at $M_H \sim 115$ GeV
# Direct Search Limit $M_H > 114.4$ GeV





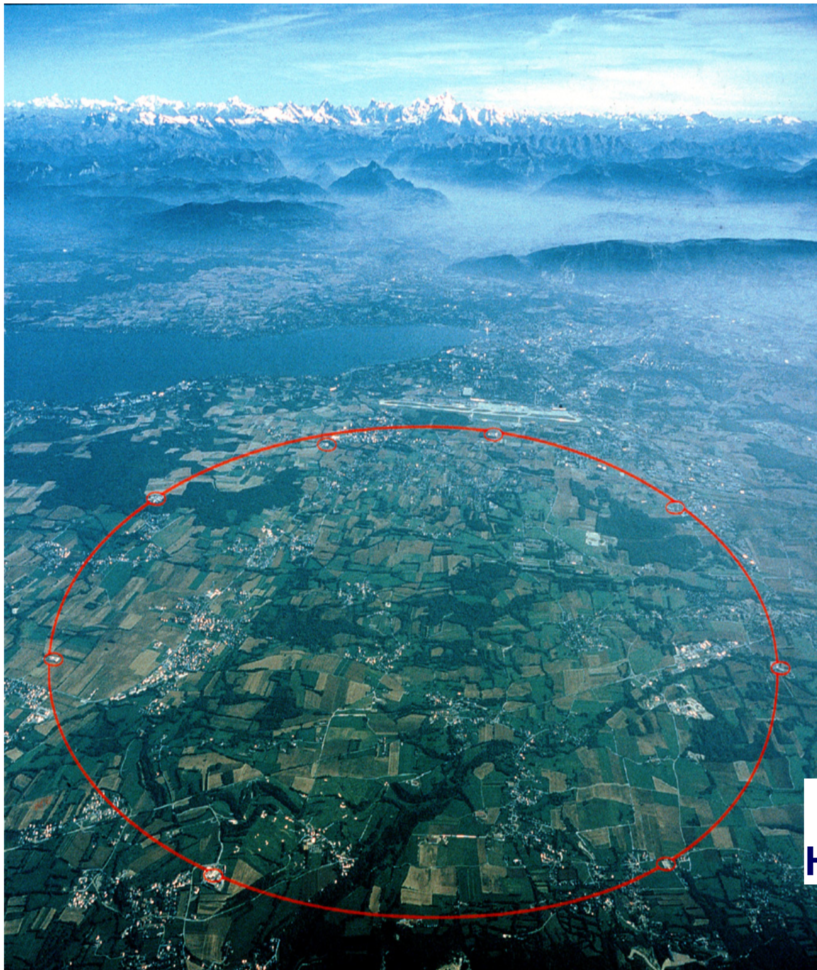



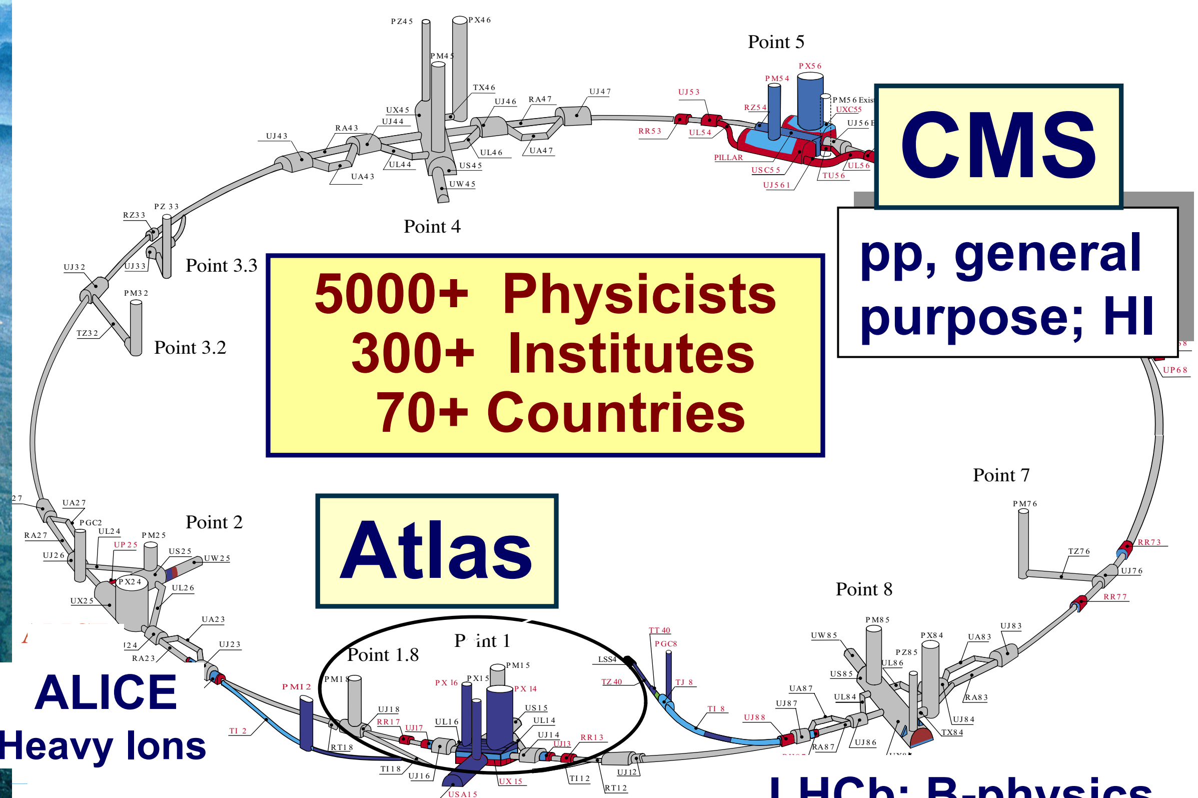
# LHC: Back to the Future In Geneva

**See http://www.interactions.org/LHC;**
**The LHC Guide: http://cdsweb.cern.ch/record/989631**

# Large Hadron Collider (LHC) at CERN, Geneva: 2007 Start

- pp $\sqrt{s}$ =14 TeV L=$10^{34}$ $cm^{-2}$ $s^{-1}$; Pb Ions
- 27 km Tunnel in Switzerland & France






**5000+ Physicists**
**300+ Institutes**
**70+ Countries**

**CMS**

pp, general purpose; HI

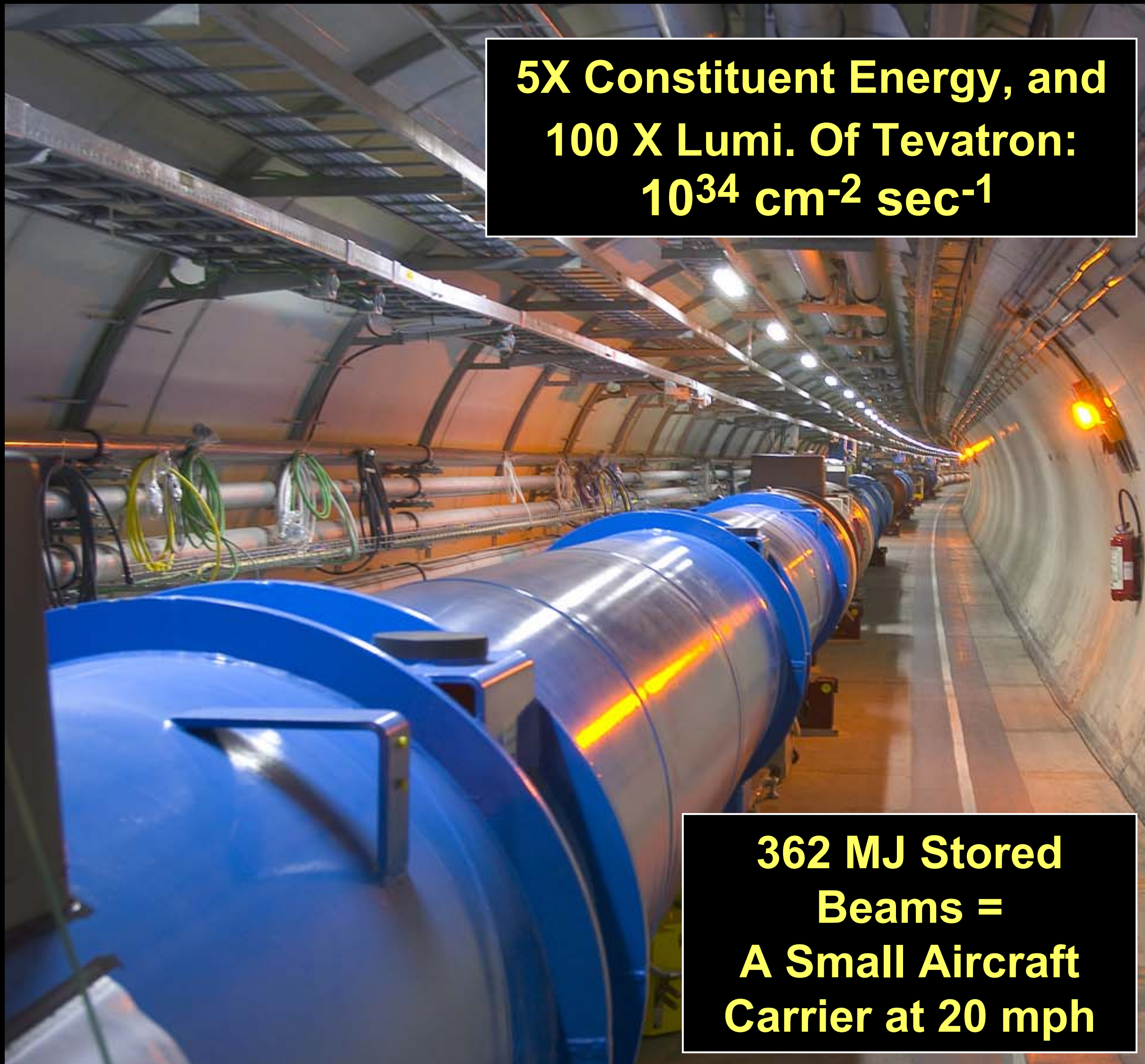
**Atlas**

**ALICE**
Heavy Ions

**LHCb: B-physics**

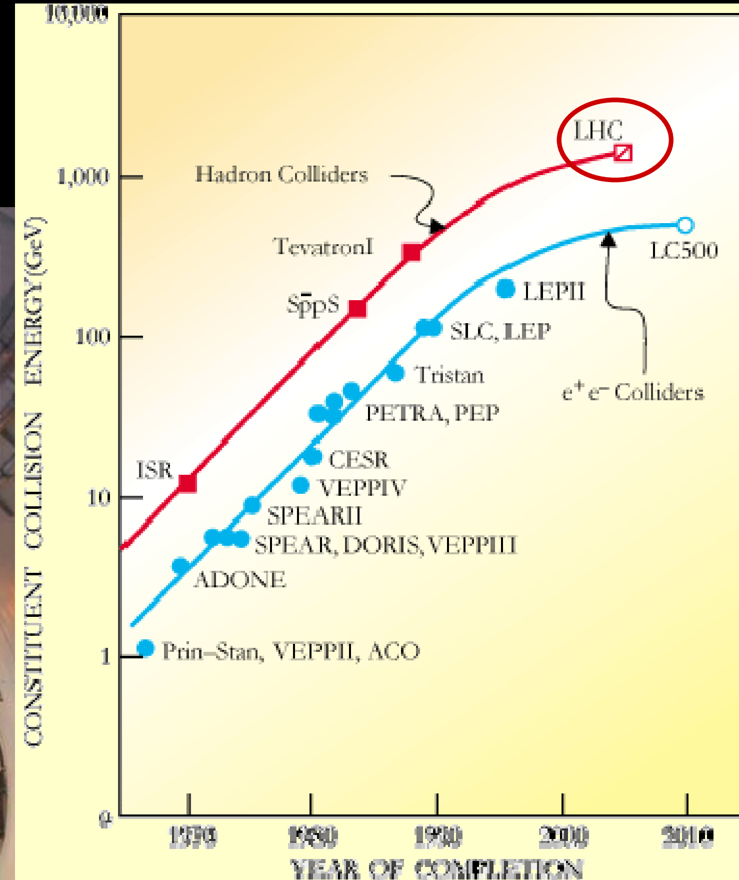
**Higgs, SUSY, Substructures, CP Violation, QG Plasma, …**
***Gravitons, Extra Dimensions … the Unexpected***

# *The LHC*



5X Constituent Energy, and 100 X Lumi. Of Tevatron: $10^{34}$ $cm^{-2}$ $sec^{-1}$

362 MJ Stored Beams = A Small Aircraft Carrier at 20 mph




9300 Supercond. Magnets: 1232 Dipoles (15m), 448 Main Quads, 6618 Correctors

Operating temperature: $1.9^{o}$ K

8.3 Tesla Field at 7 TeV

Stored Beam: 362 MJoules

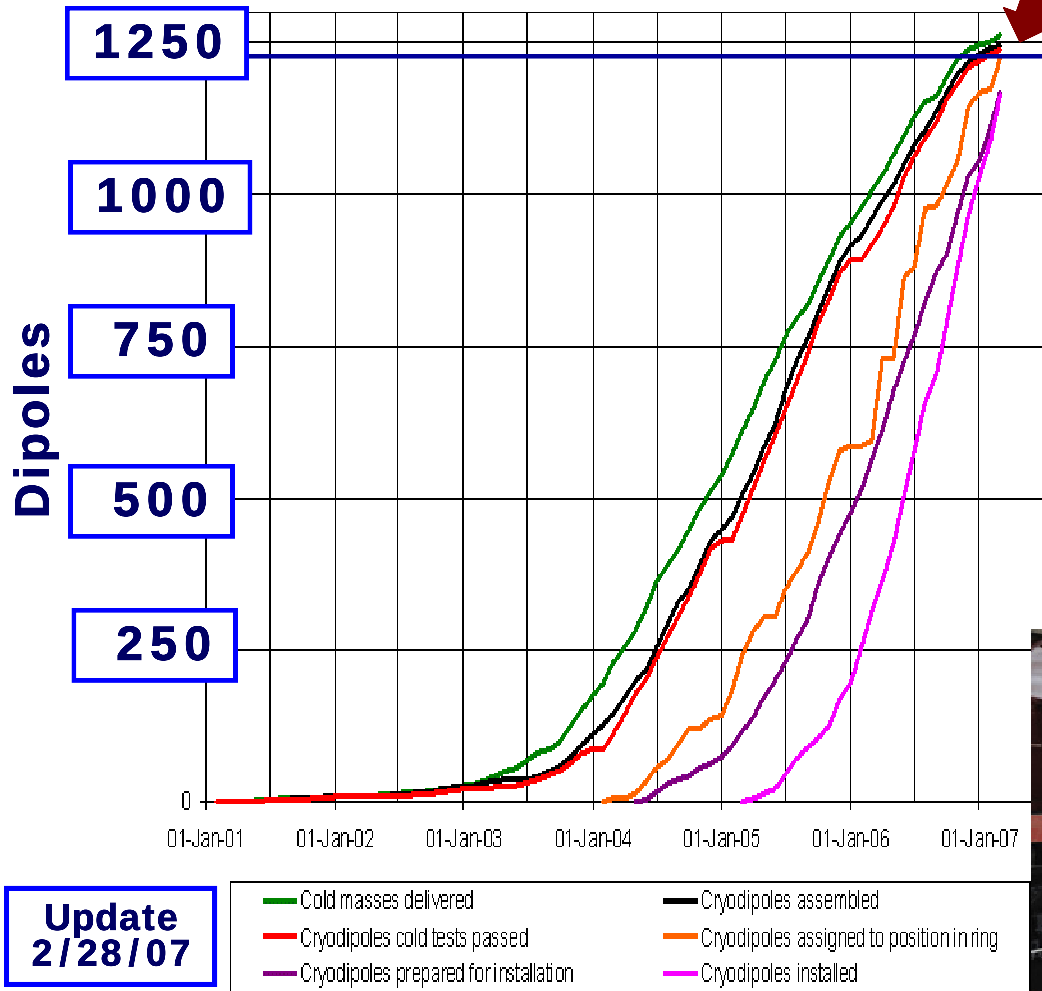
Slope of 26.7 km tunnel: 1.4%

# *The LHC Is Progressing:*

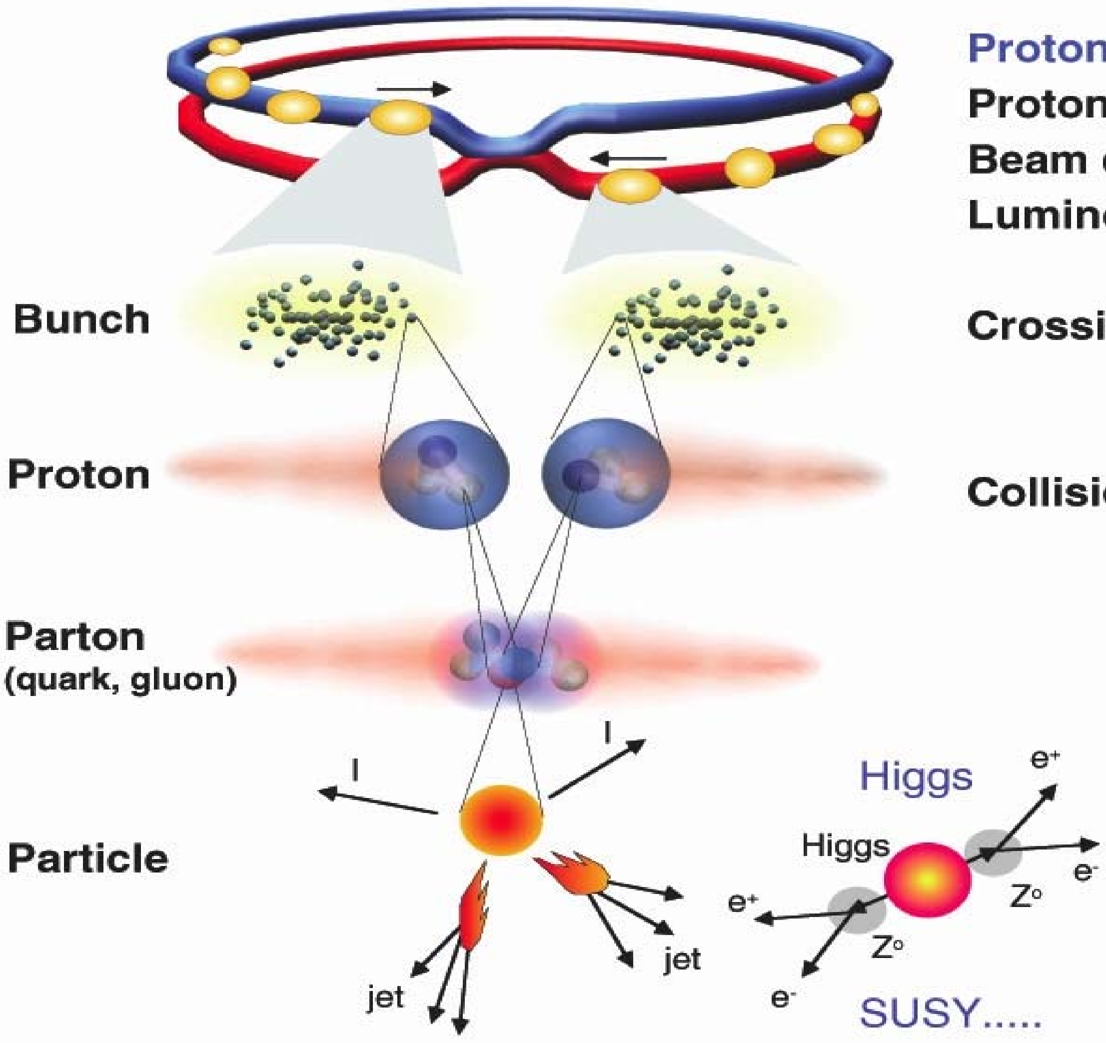
## Complete Magnet Installation *This Month*

## 1st Sector Cooled Down; 2 & 3 in April

### Cryodipoles (of 1232)




# LHC Collisions




| | |
|---|---|
| Proton-Proton | 2835 bunch/beam |
| Protons/bunch | $10^{11}$ |
| Beam energy | 7 TeV ($7 \times 10^{12}$ eV) |
| Luminosity | $10^{34}$ cm$^{-2}$ s$^{-1}$ |
| Crossing rate | 40 MHz |
| Collisions ≈ | $10^7$ - $10^9$ Hz |

**Selection of 1 in 10,000,000,000,000**

# LHC Startup: Fall 2007

Oct

450 GeV HWC

ACCESS TESTS

Operations testing

450 GeV HWC

Nov

Machine Checkout

(Access, Vacuum, Equipment Tests, Controls, Cycle (partial), Beam dump, Interlocks and INB)

Beam Commissioning at 450 GeV

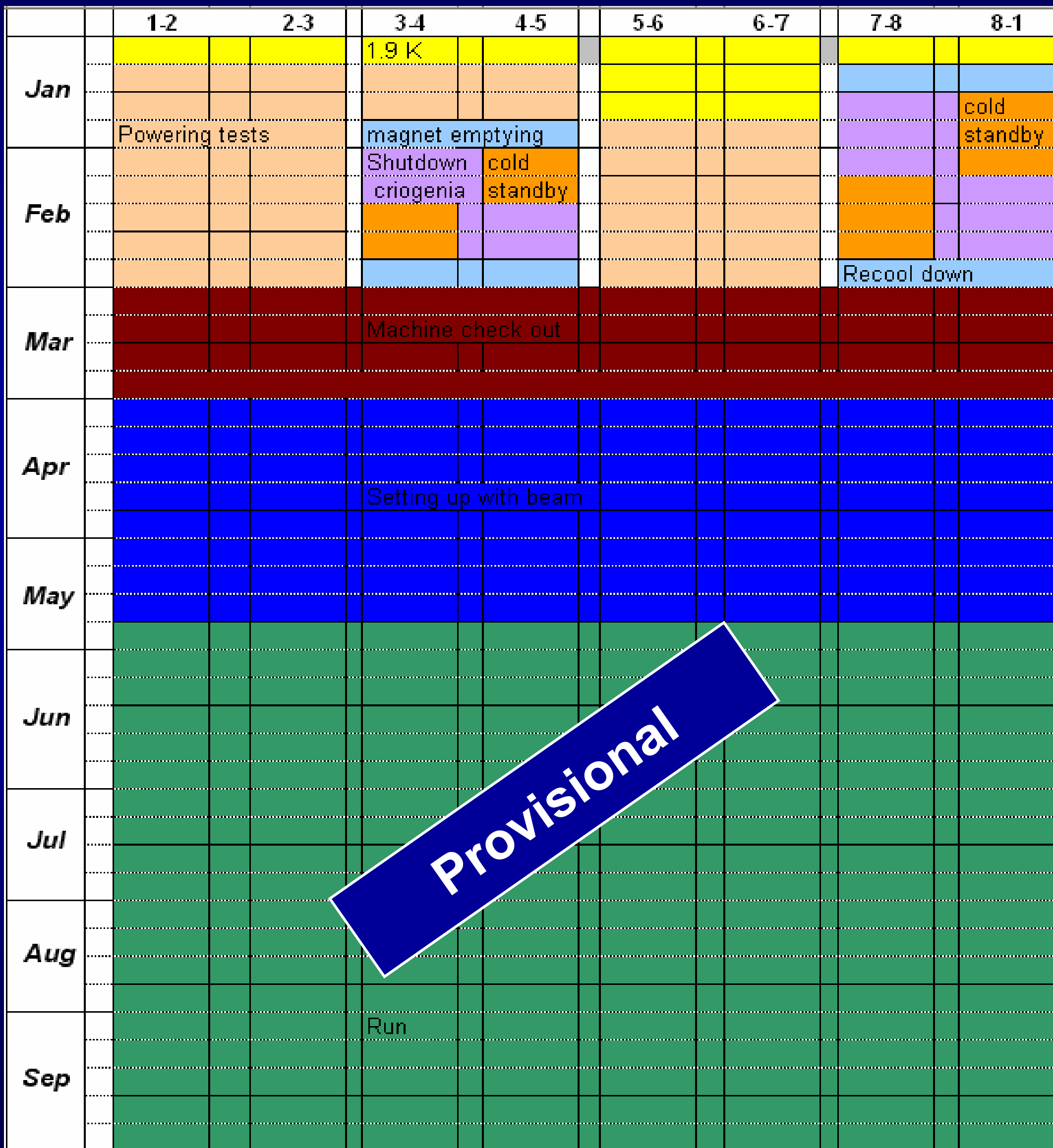
16 days beam time estimated

Dec

Calibration run (Collisions at 450GeV + ramp commissioning etc.)

# 2008: Brief Outlook

**Should look something like…**




Hardware commissioning to 7 TeV

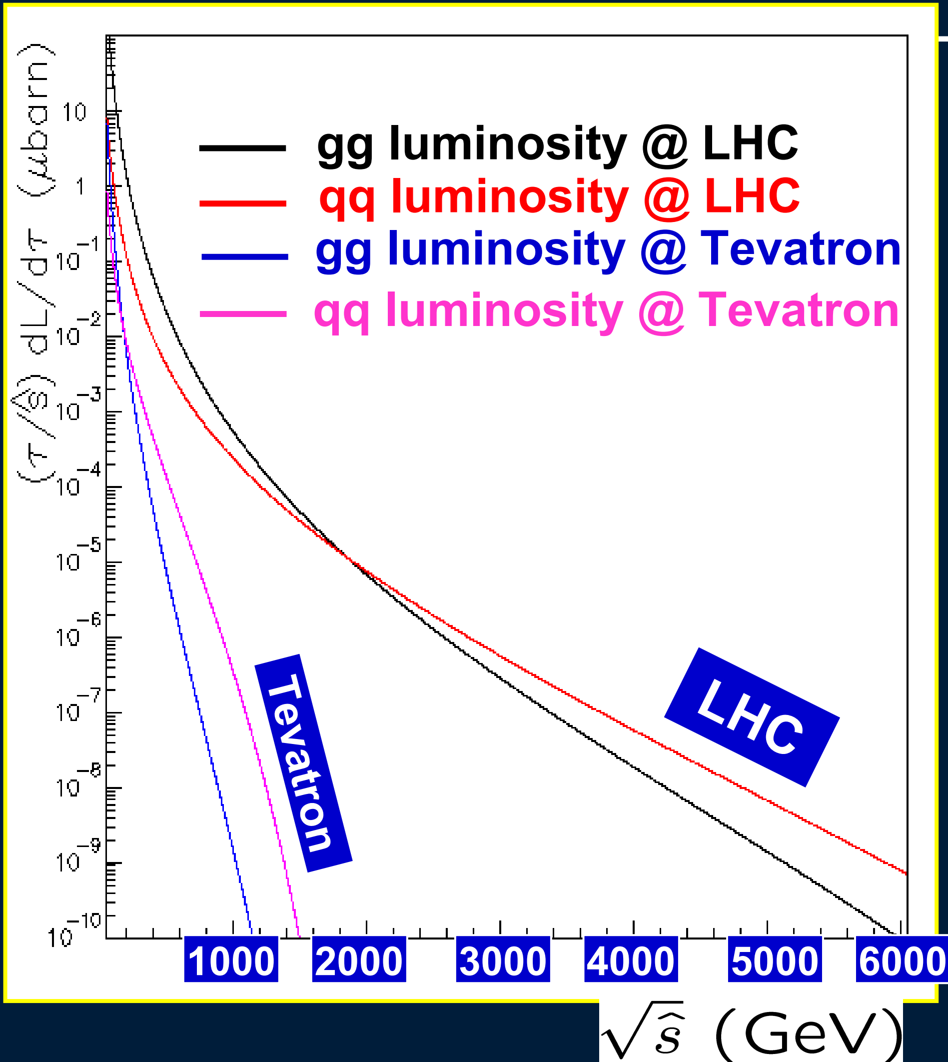
Machine Checkout
≈ 1 month

Commissioning with beam
≈ 2 months

Pilot Physics
≈ 1 month

Physics
Run: ~ 1 fb$^{-1}$

# Parton-Parton Luminosities: LHC Vs. Tevatron

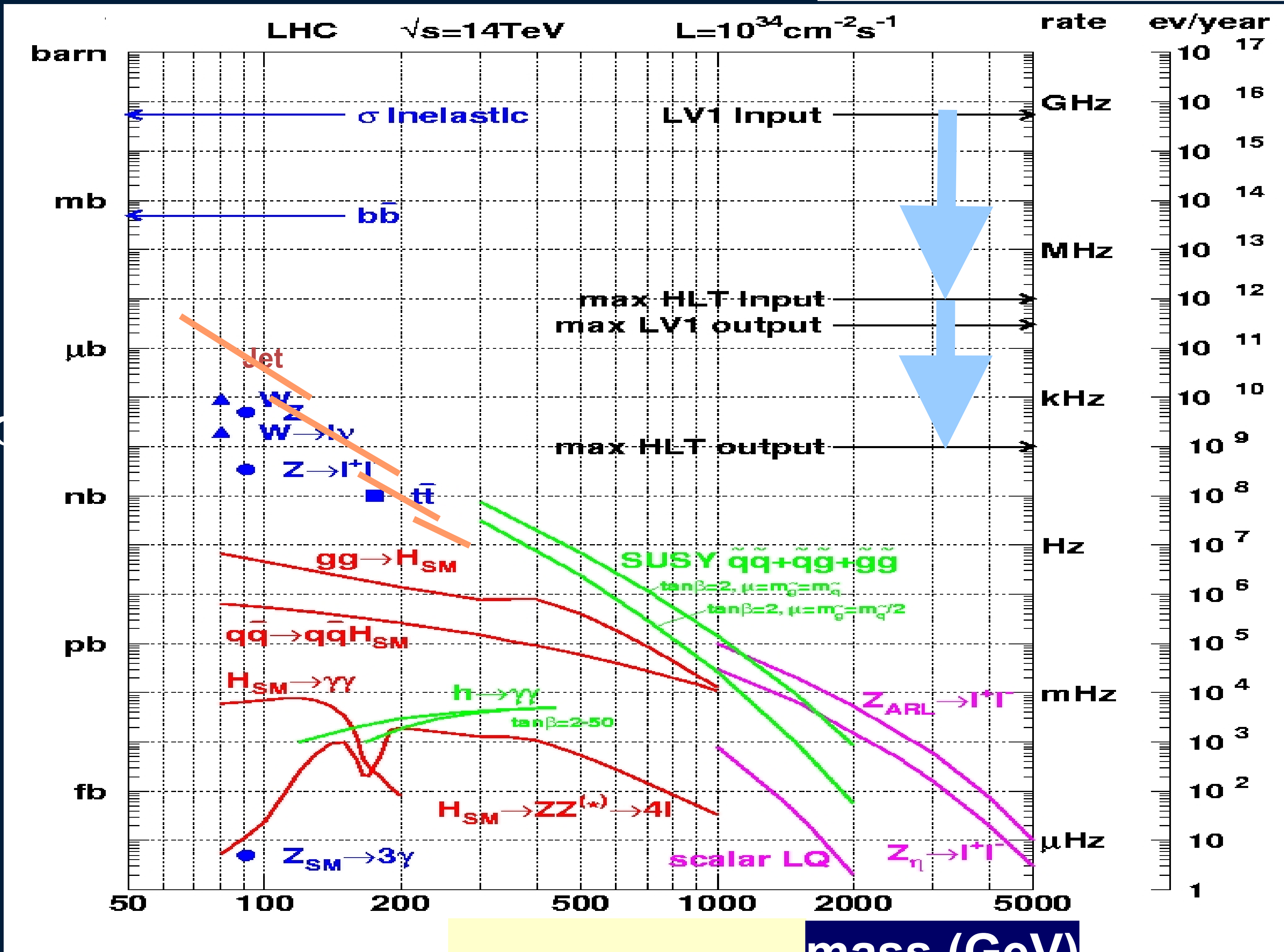



- The LHC is a Discovery Machine
- The first accelerator to probe deep into the Multi-TeV scale
- Many reasons to expect new TeV-scale physics

**Parton-Parton CM Energy**

# Huge LHC Rates/Yr

## At Design Luminosity (100X FNAL Tevatron)




*pp*

*W/Z^0*

**Top Quarks**

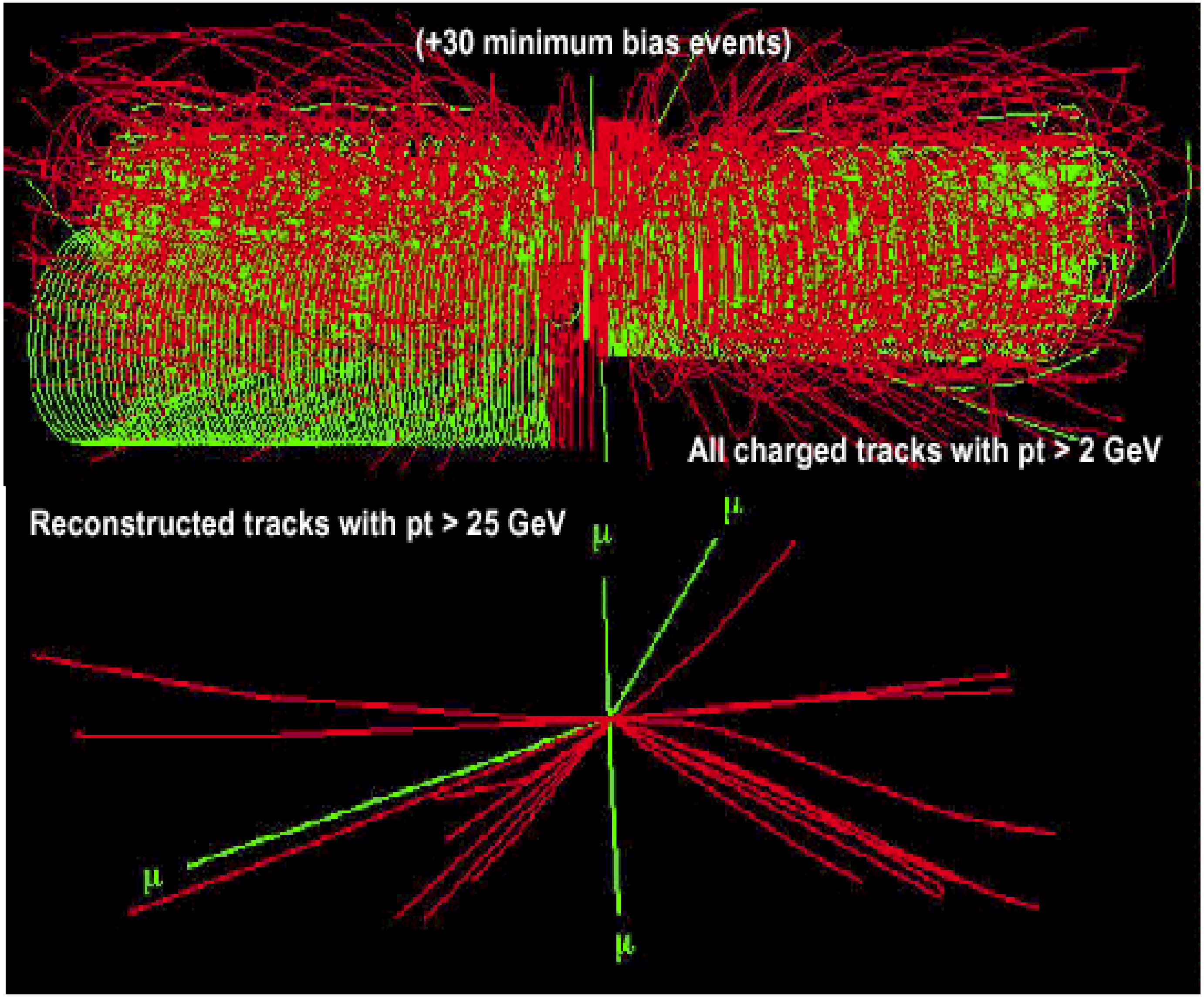
**TeV Jets**

**TeV Exotica**

***Higgs:10 -13***

**Last event**

# LHC: Many Petabytes/Yr of Complex Data




*A pp Bunch Crossing Every 25 nsec (40 MHz)*

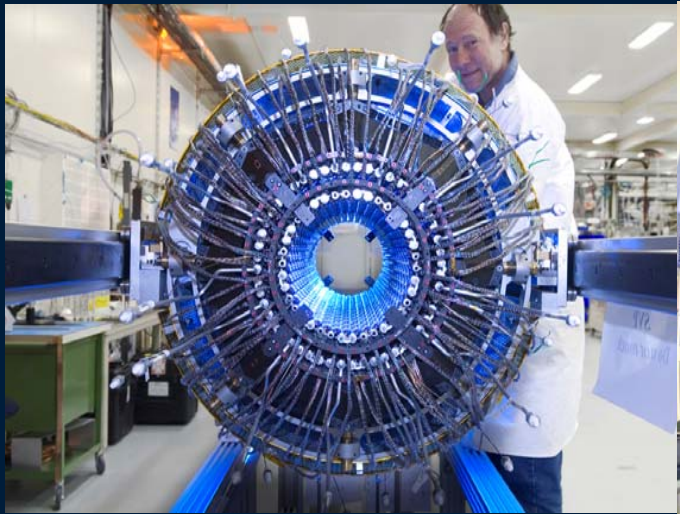
**At $10^{34}$ Luminosity**

**$10^9$ Interactions/s: ~20 pp Collisions Superimposed Per Crossing**

**Unprecedented Instruments, IT Challenges**

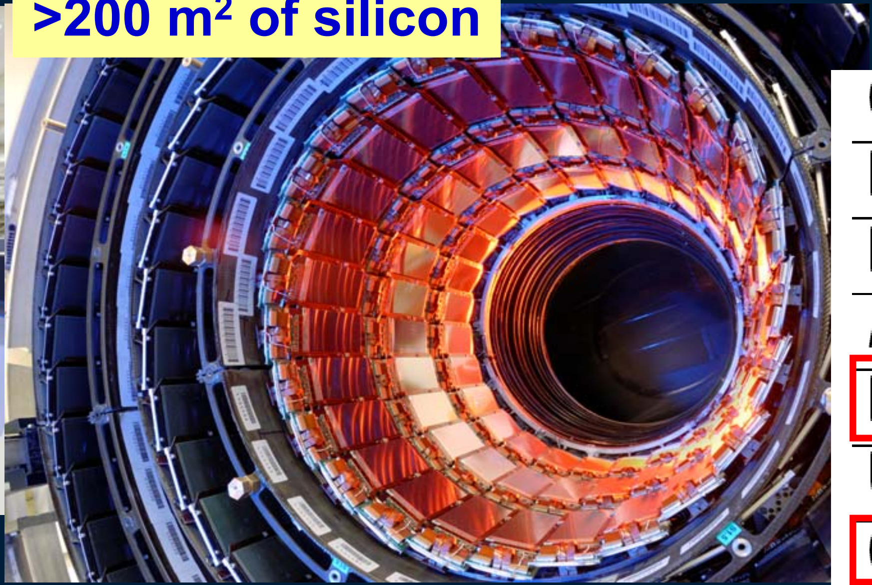
# LHC Detectors: Major Challenges

- CMS/ATLAS detectors have about **100 million read-out channels**
- Collisions in the detectors every **25 nanoseconds**
- ATLAS uses over **3000 km of cables in the experiment**
- The data volume acquired at the front-end in CMS is **~40 TBytes/sec much greater than the worldwide communication network traffic**
- **Data recorded** during the 10-20 years of LHC life **approx. = to all the words spoken by mankind since its appearance on earth**



ATLAS pixel detector

>200 $m^2$ of silicon

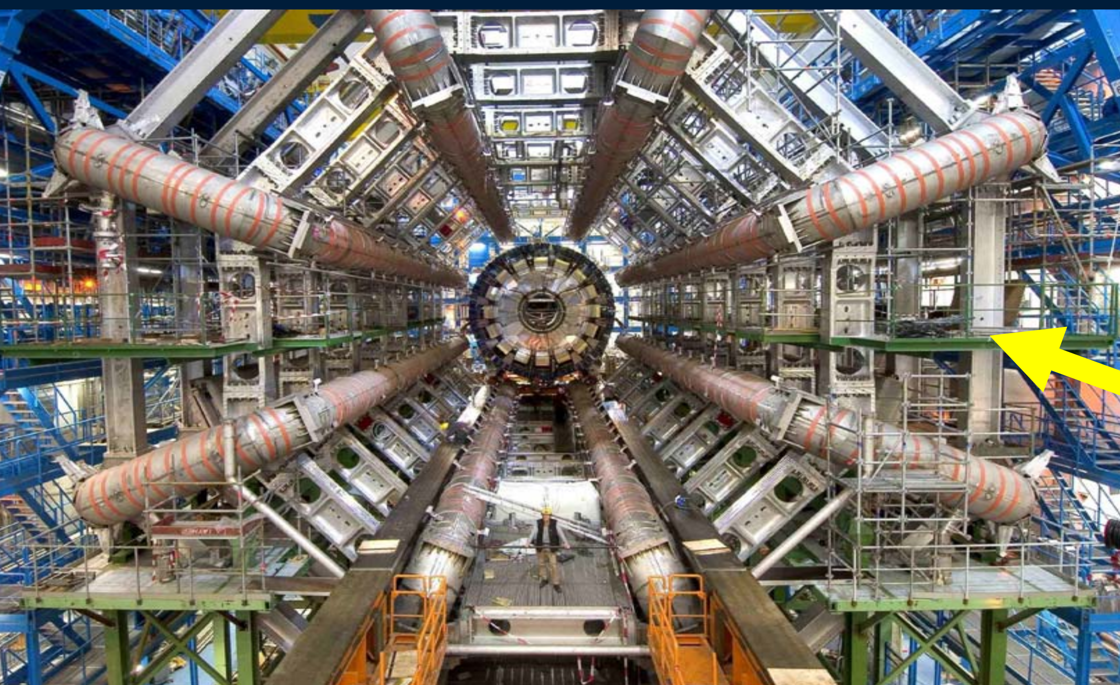


CMS silicon tracker

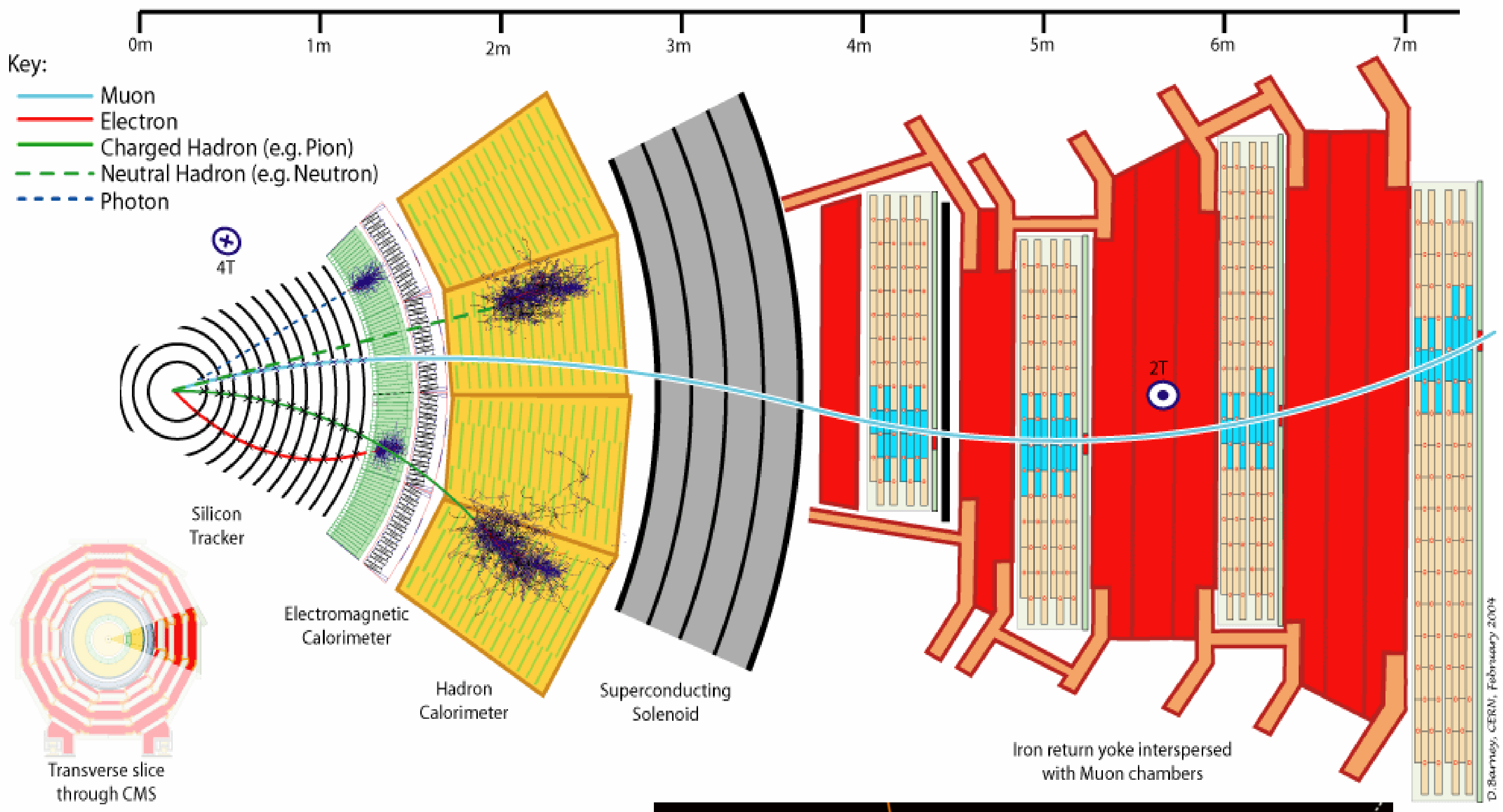
| Object | Weight (tons) |
| --- | --- |
| Boeing 747 [fully loaded] | 200 |
| Endeavor space shuttle | 368 |
| ATLAS | 7,000 |
| Eiffel Tower | 7,300 |
| USS John McCain | 8,300 |
| CMS | 12,500 |

# Status of ATLAS & CMS

CMS is modular (breaking with tradition). After successful testing of the 4-T (2.7 GJ) CMS magnet and some detector components, above ground, by measuring cosmic rays, CMS is being lowered at Point 5



ATLAS is being built in place at Point 1 - many sub-detectors, including the inner ones are already installed.

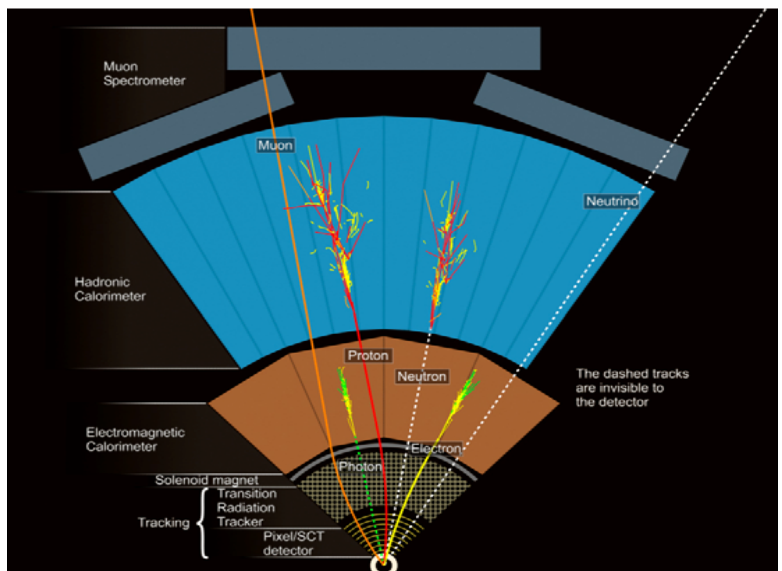


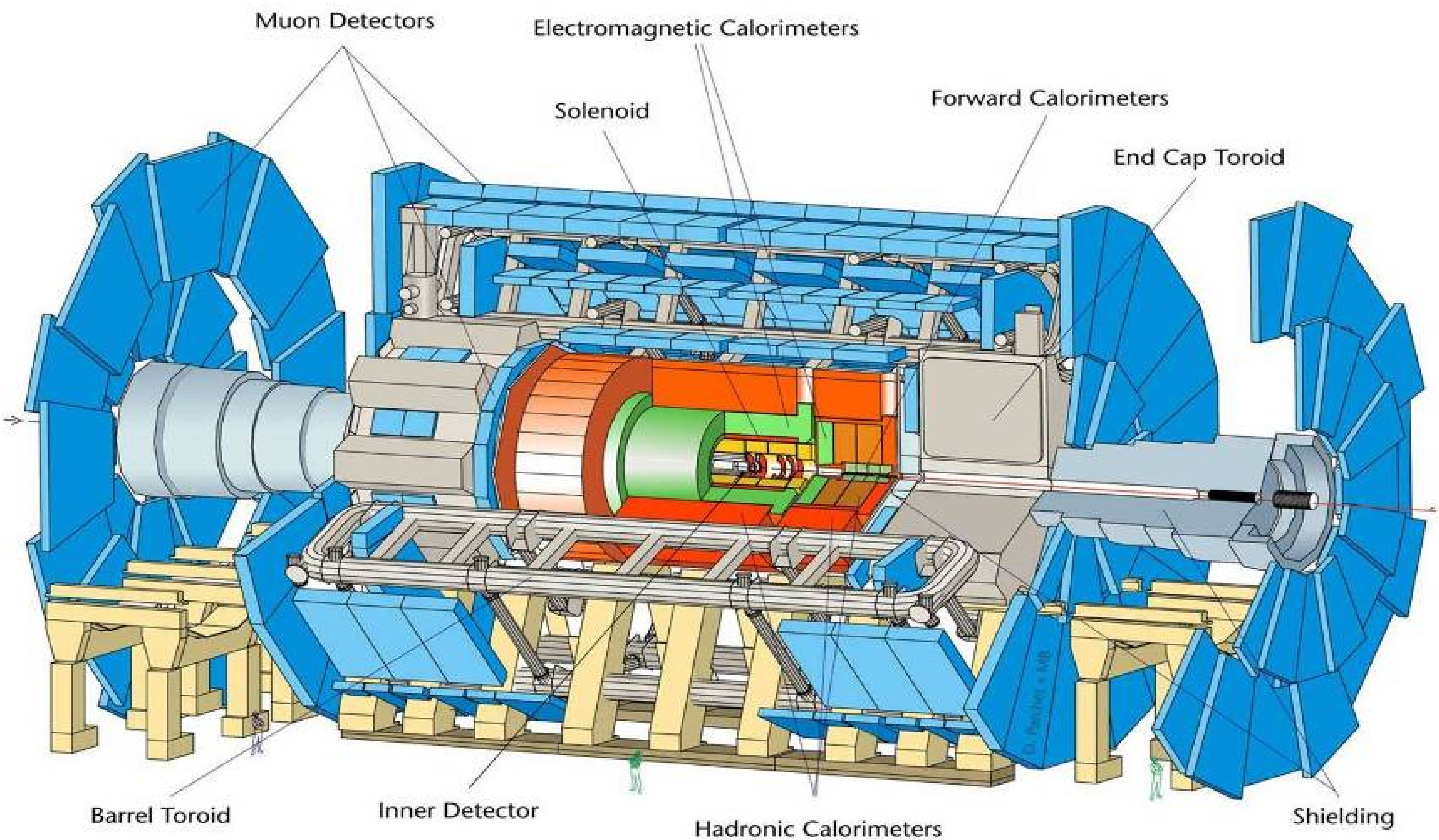

# CMS Slice

**CMS Design**

**High Field (4T)**
**Compact Tracker**
**Precise ECAL: inside Coil**
**Muons in & Out**

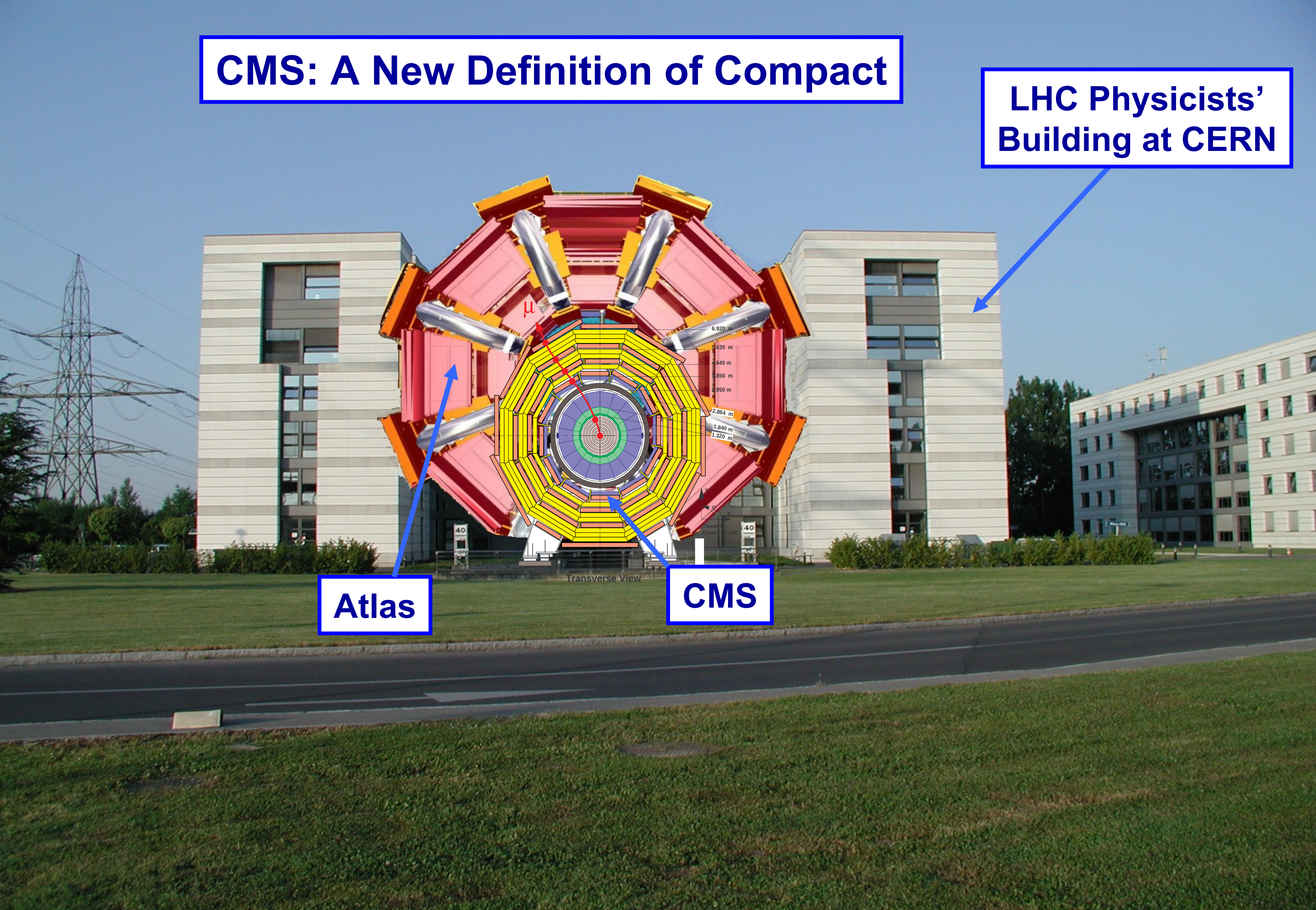
# ATLAS Slice (not to scale)



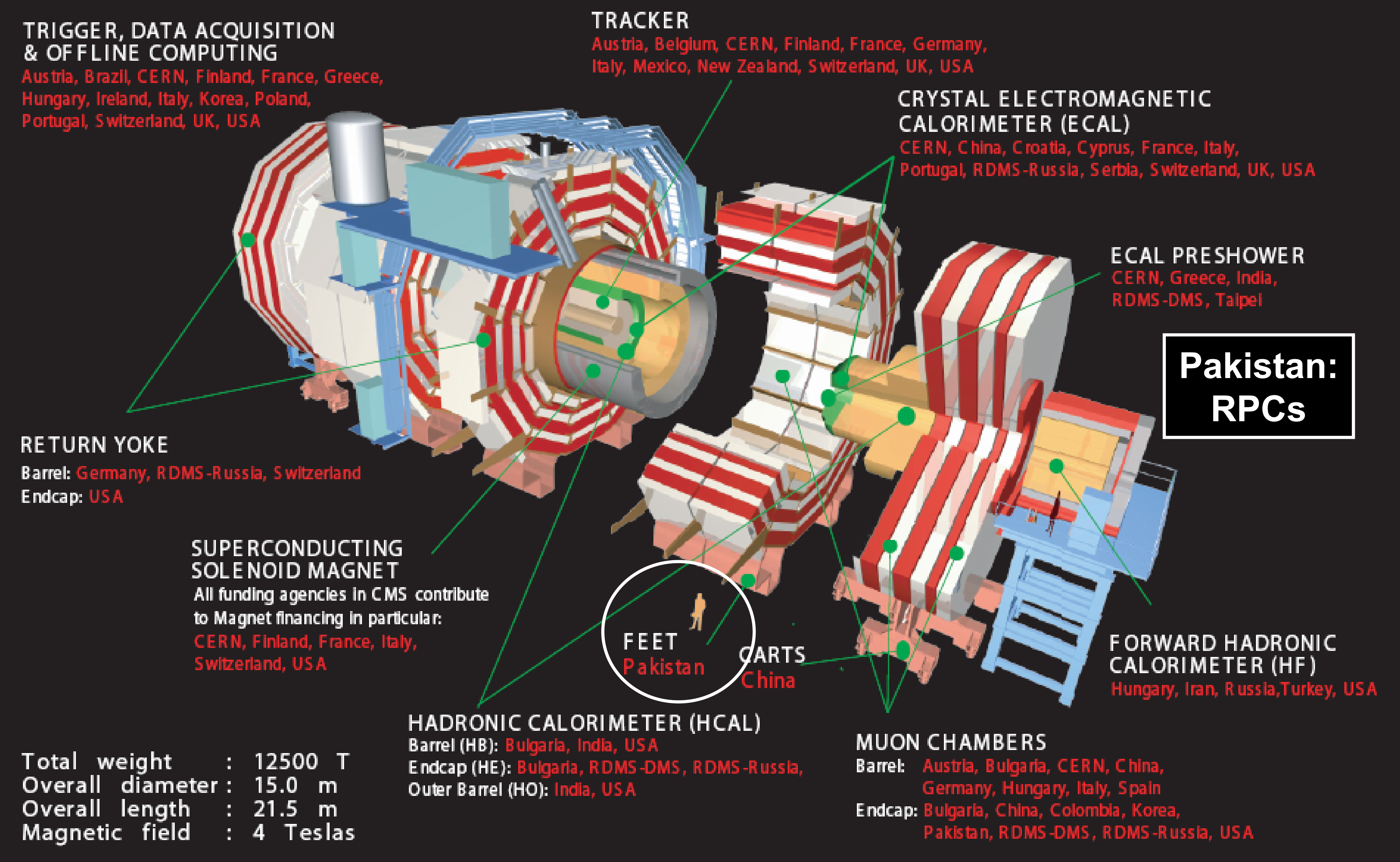



**Length = 55 m, Width = 32 m, Height = 35 m; But spatial precision ~ 100 μm**


Inside cryostat

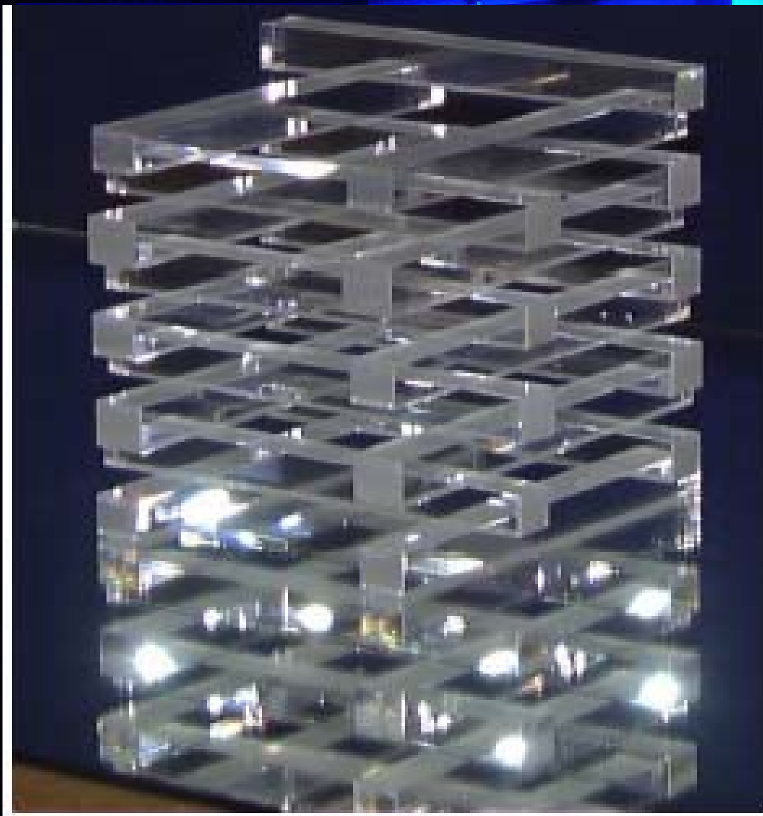

CMS: A New Definition of Compact
LHC Physicists' Building at CERN
μ
Transverse View
Atlas
CMS

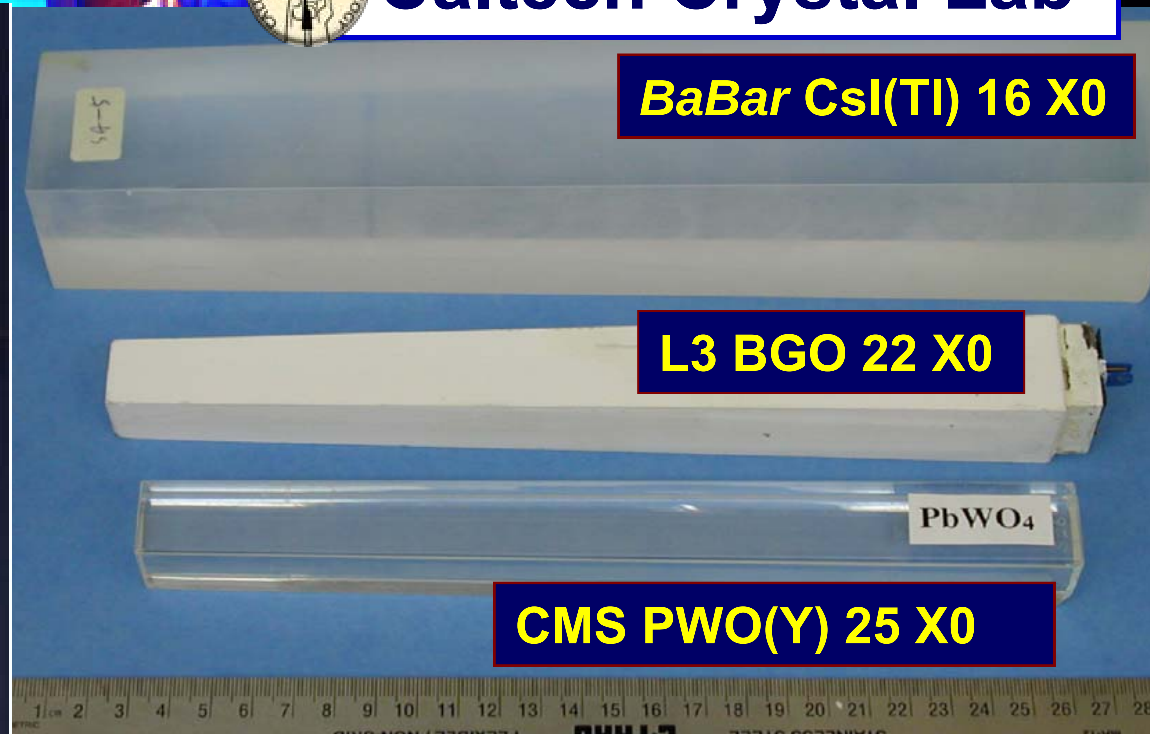
# CMS Collaboration



**> 62,000 Barrel Crystals in Hand: Endcap Production in Siberia and Shanghai Started**

## Caltech Crystal Lab



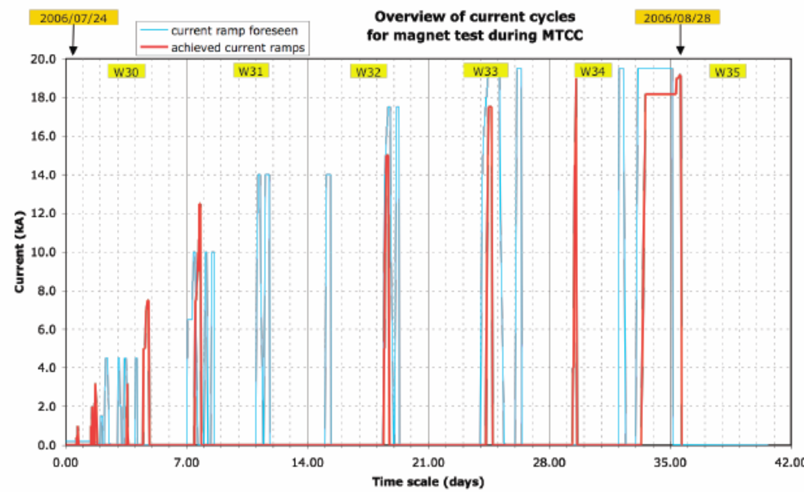



| Material | $PbWO_4$ | Pb | Fe |
|---|---|---|---|
| Density ($g/cm^3$) | 8.3 | 11.3 | 7.9 |
| $X_0$ (mm) | 8.9 | 5.6 | 17.6 |

# Magnet current cycles vs previsions (August)

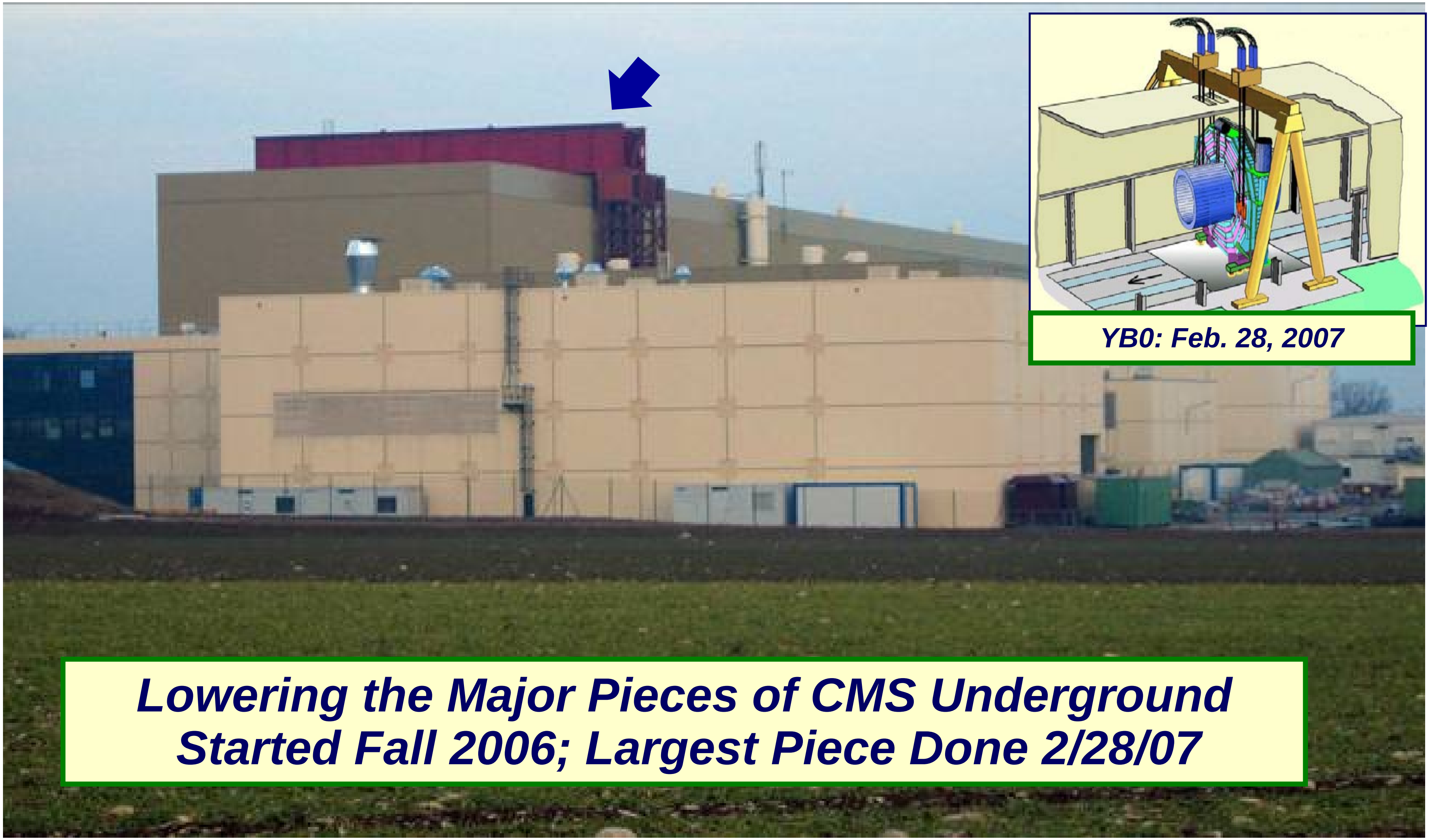
***Releasing He to Relieve Overpressure (> 18 Bars) After a Fast Quench***

| | |
|---|---|
| Magnetic length | 12.5 m |
| Free bore diameter | 6 m |
| Central B Field | 4 Tesla |
| Temperature | 4.2° K |
| Nominal current | 20 kA |
| Stored energy | 2.7 GJ |
| Magnetic Radial Pressure | 64 Atm. |



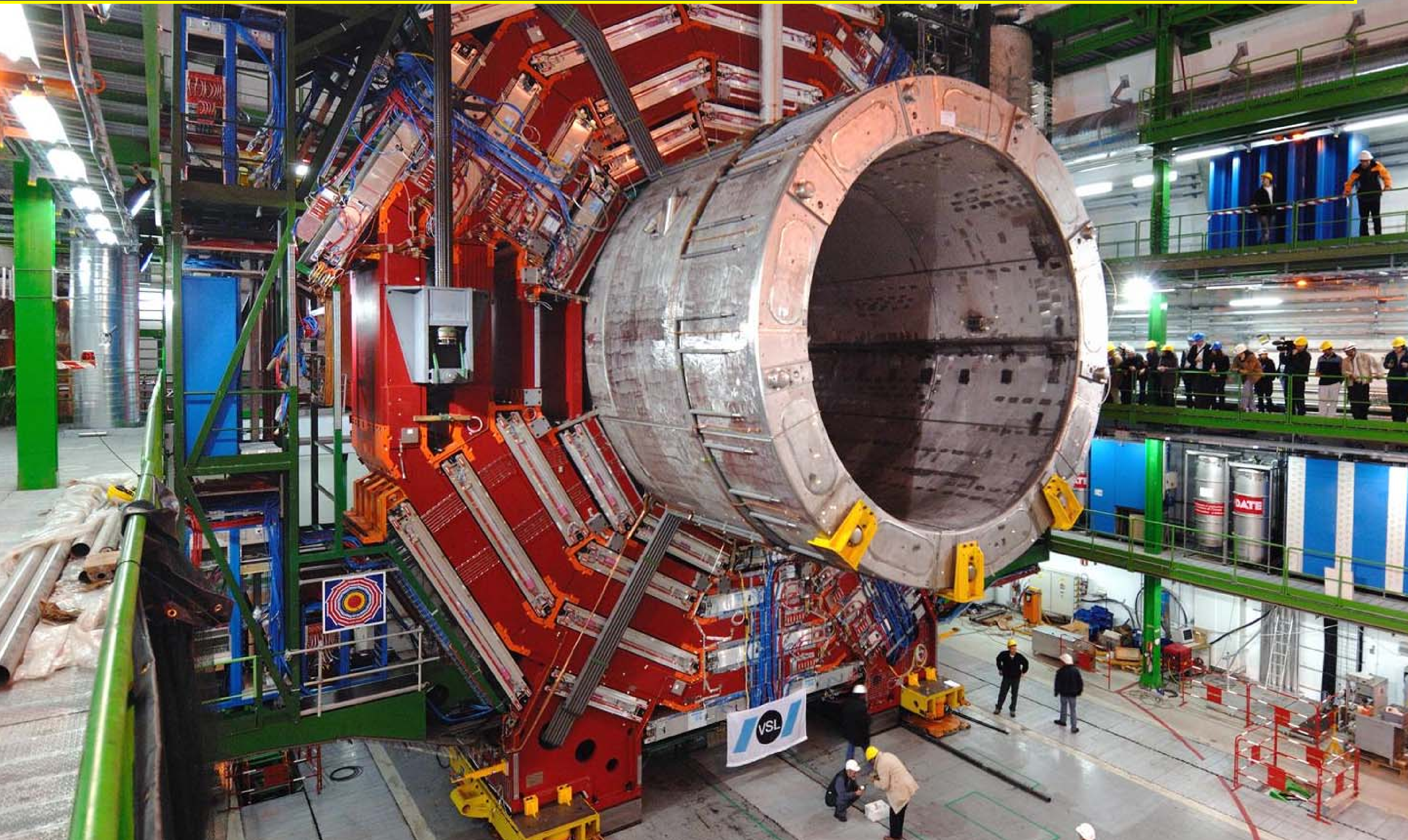

**Magnet Successfully Tested; Global Run with Cosmic Rays August 2006 !**

# *2500 Ton Gantry Crane Spanning the Surface Hall at Point 5 in France*

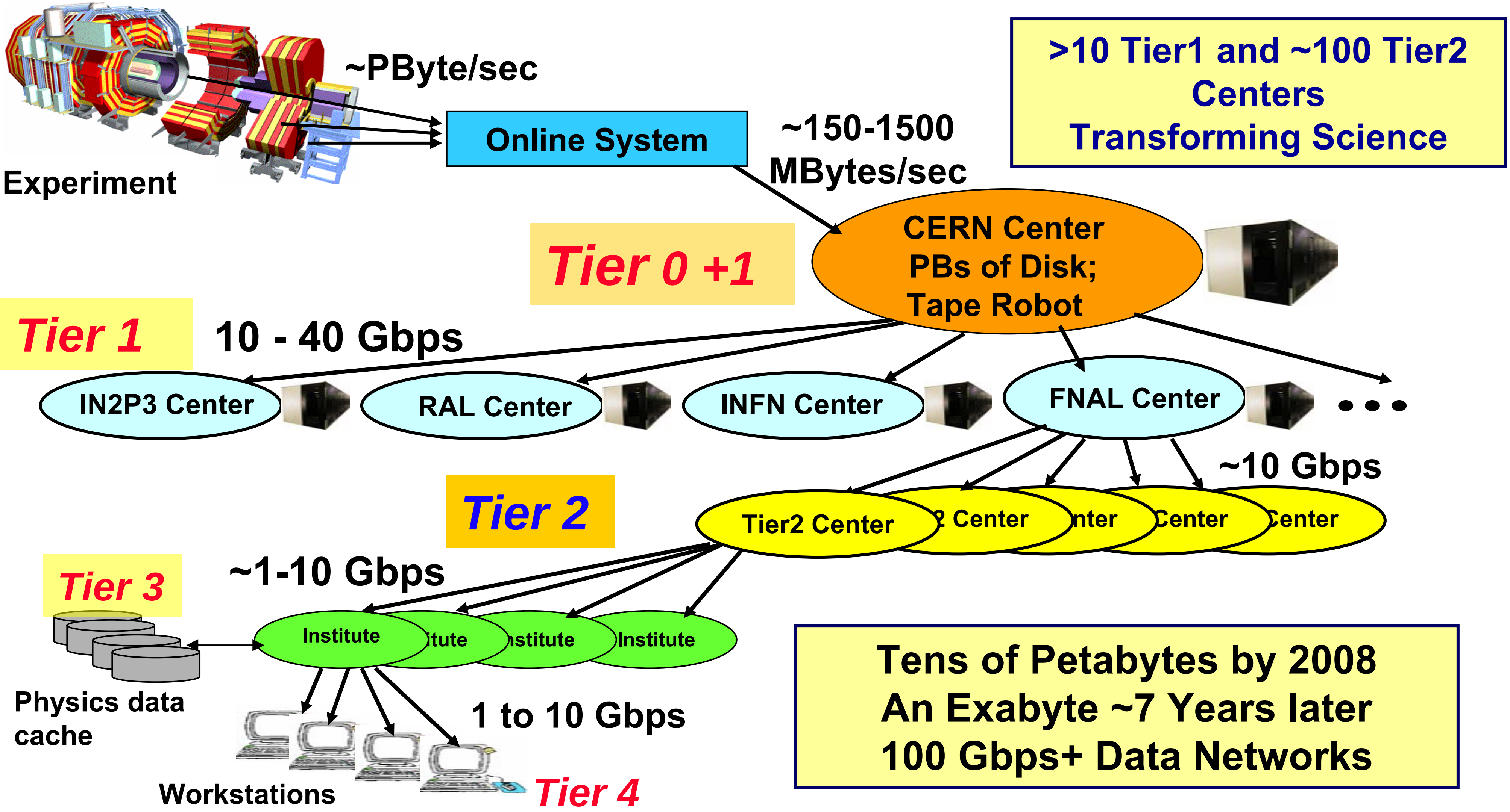

***YB0: Feb. 28, 2007***

***Lowering the Major Pieces of CMS Underground Started Fall 2006; Largest Piece Done 2/28/07***

**MOVIE** http://cmsinfo.cern.ch/outreach/cmseye/yb0_lowering.htm
**&** http://cmsinfo.cern.ch/outreach/CMSMedia/CMSMovies.html



# The LHC Data Grid Hierarchy: Developed at Caltech (1999)




**Emerging Vision: A Richly Structured, Global Dynamic System**

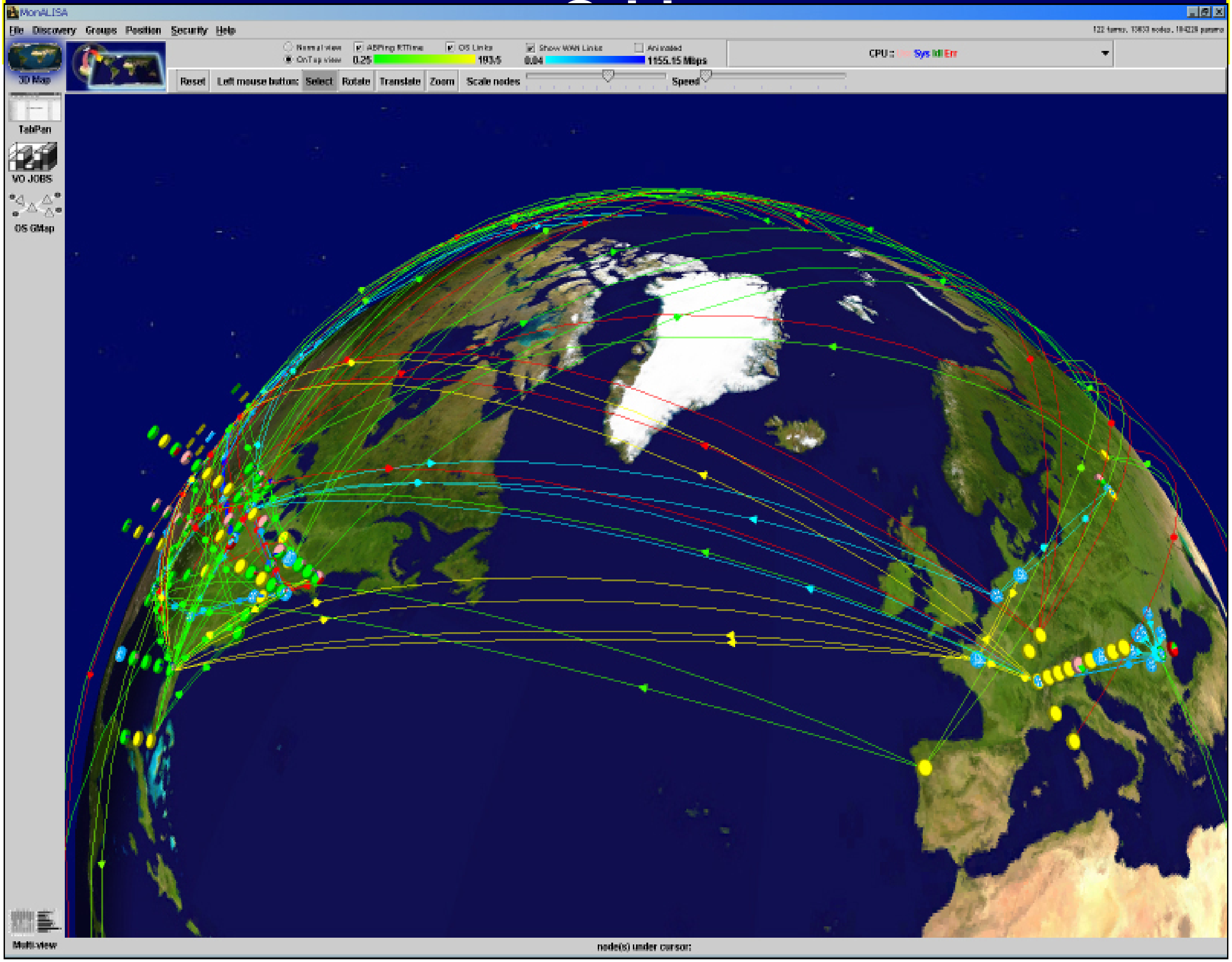
# Monitoring the Worldwide HEP Grid (MonALISA)

## MonALISA Today

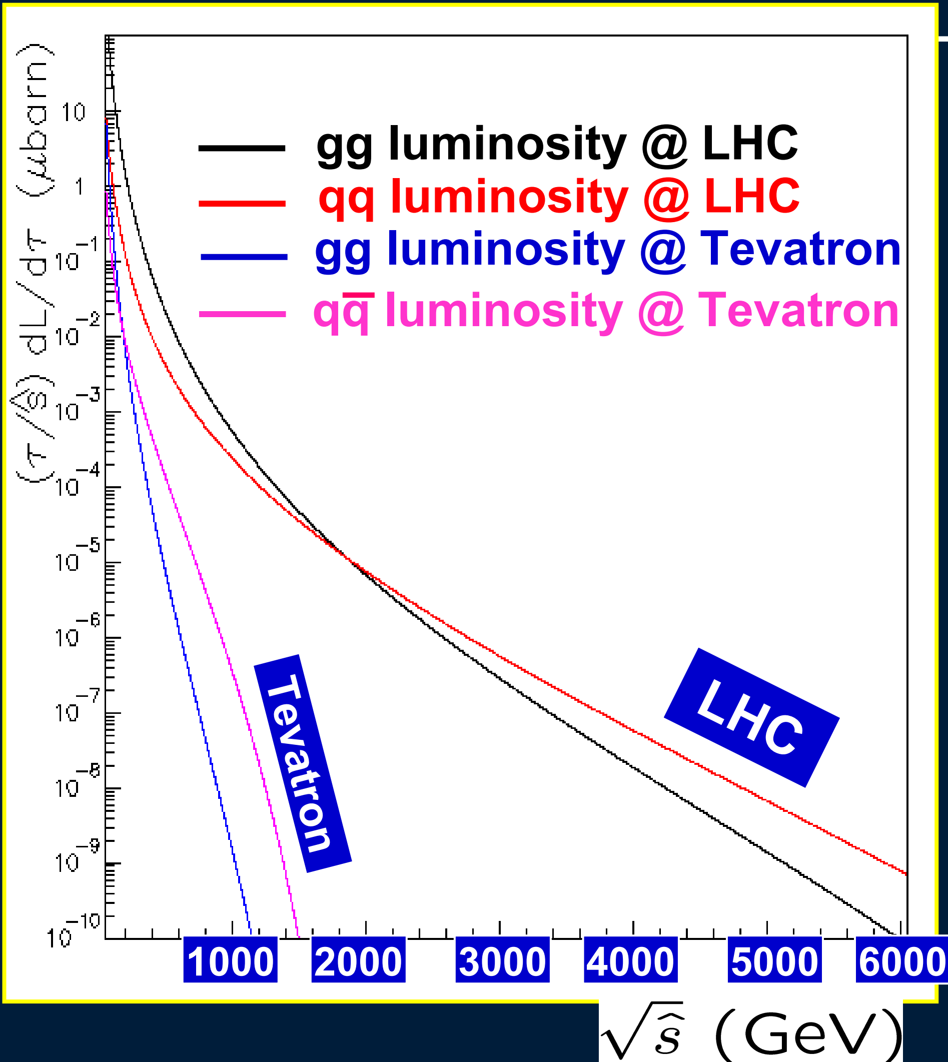
**Running 24 X 7 at 280 Sites**

- Monitoring
  - 40,000 computers
  - > 100 WAN Links
- Thousands of Grid jobs running concurrently
- Collecting > 750,000 parameters in near real-time
- Update rate of 25,000 parameter-updates per sec

## Monitoring the LCG and Open Science



# Parton-Parton Luminosities: LHC Vs. Tevatron



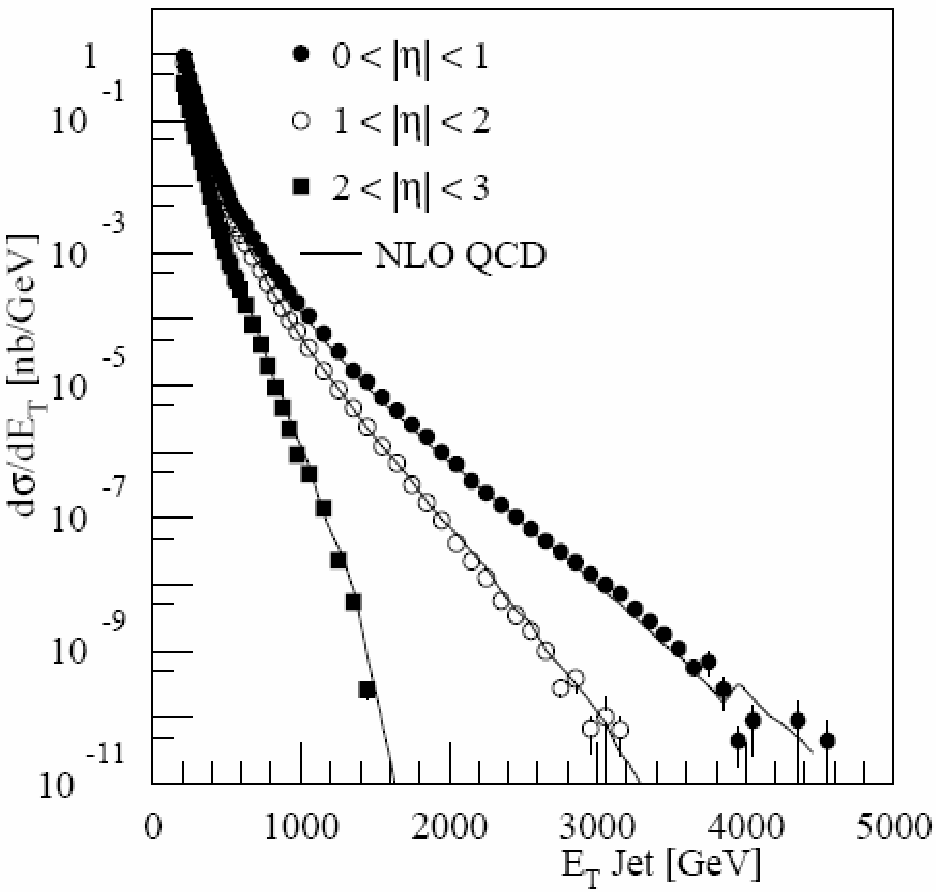

- The LHC is a **Discovery Machine**
- The first accelerator to probe deep into the Multi-TeV scale
- Many reasons to expect new TeV-scale physics

**Parton-Parton CM Energy**

# "Rediscovering the Standard Model"
# Search for Anomalies

**E.g. Jet Physics**

**Huge Jet Cross Sections:**
**E.g. for 1 $fb^{-1}$ ~ 10000 events with $E_T > 1$ TeV**
**100 events with $E_T > 2$ TeV**



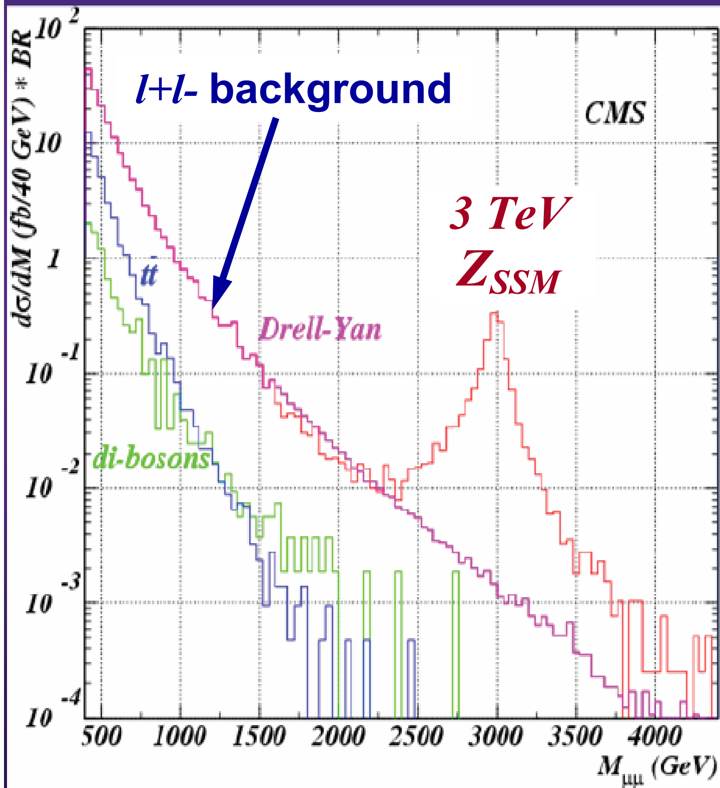

- **Proton Structure**
- **Jet shape**
- $\alpha_s$
- **New physics?**

- **Understanding QCD**
- **Then: precise measurements of W,Z, $t\bar{t}$, Drell-Yan production**
- **Then: W,Z+1 jet; W,Z+2 jets, etc.**
- ***Students from many universities will be at the forefront***

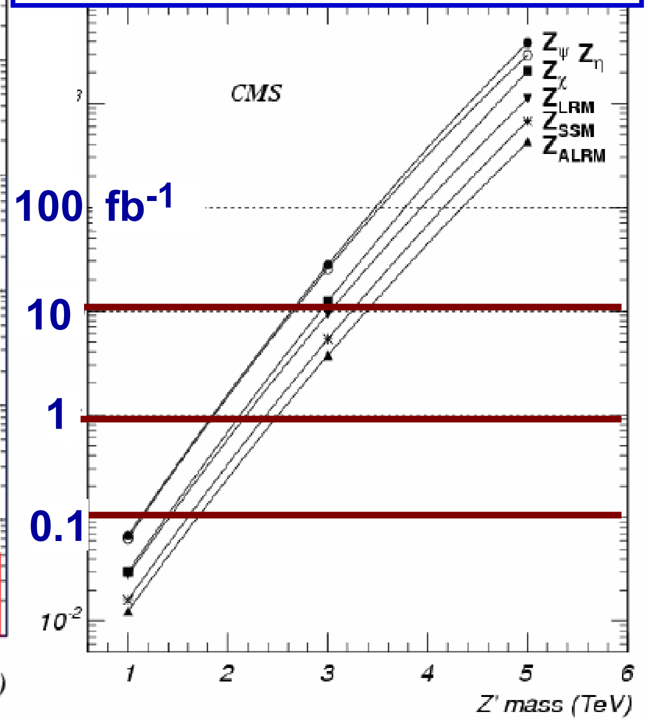
# Di-lepton Resonances Could Come Early

## $Z' \rightarrow ee/\mu\mu$: early golden search

- Search for high mass Z' resonance decaying to ee or $\mu\mu$
- Mass peak well separated from background




*$Z' \rightarrow \mu\mu$ $5\sigma$ Significance Curves*




**Physics Reach:**

0.1 $fb^{-1}$: ~1 – 1.5 TeV

1 $fb^{-1}$: ~1.8-2.5 TeV

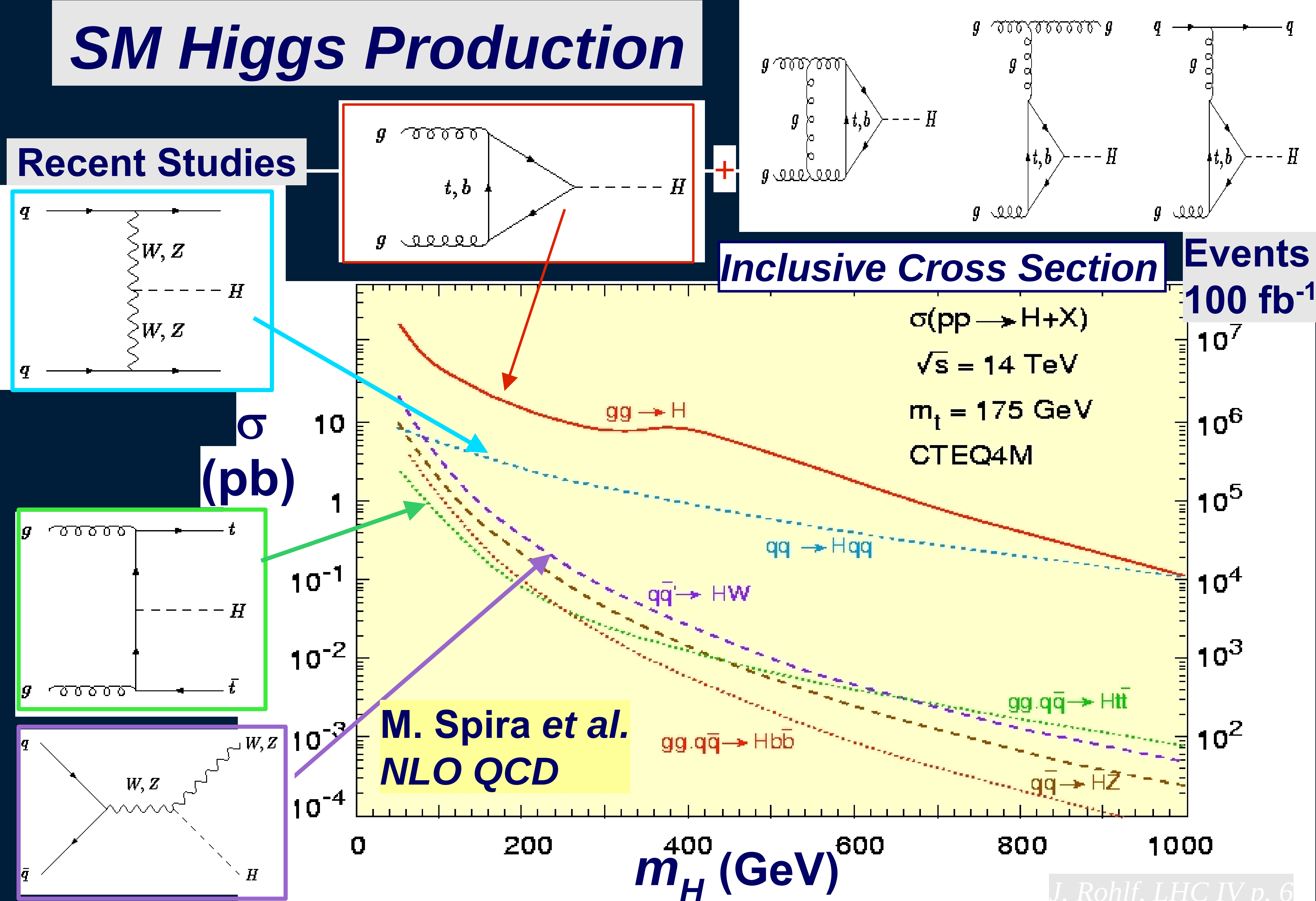
10 $fb^{-1}$: ~2.6-3.3 TeV

**Many Possible Models:**

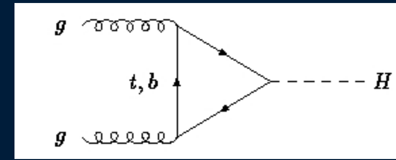
SSM, Extra U(1), E(6)…
KK, Extra Dimensions

➡ Distinguish spin-1 from spin-2 (Gravitons) using decay angular distributions

# SM Higgs Production



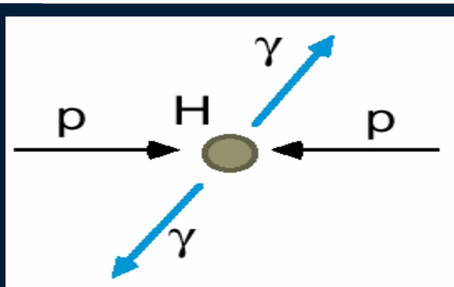
# Higgs Detection at CMS

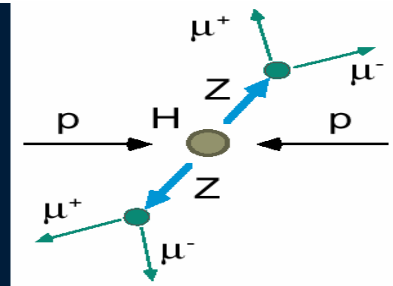


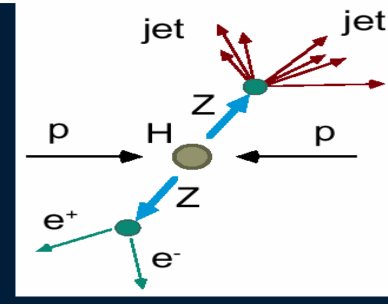

**Low $M_H$ < 150 GeV**

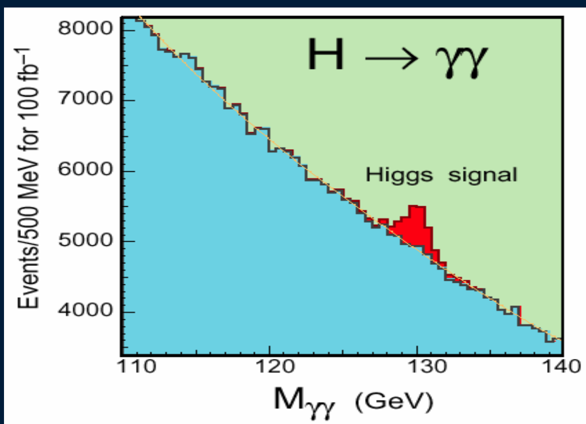
**Medium 130<$M_H$<500 GeV**

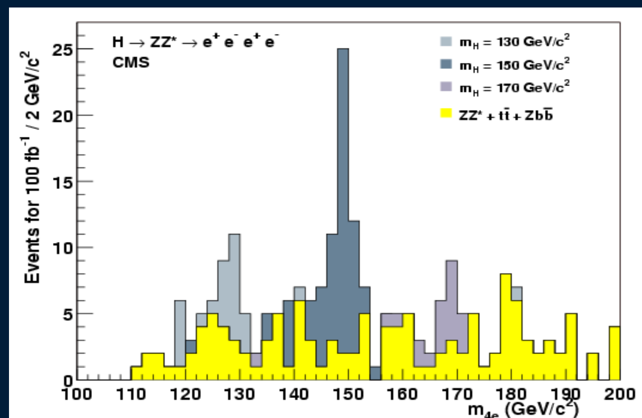
**High $M_H$ > ~500 GeV**

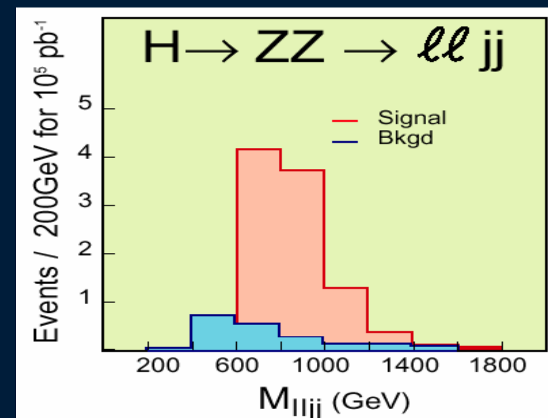


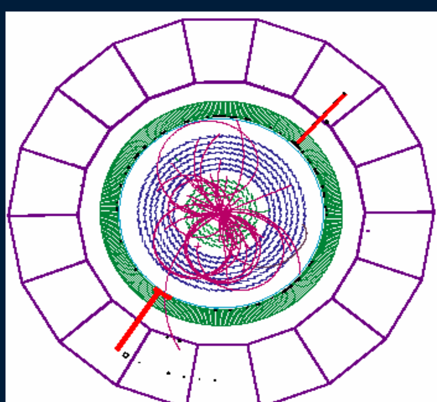



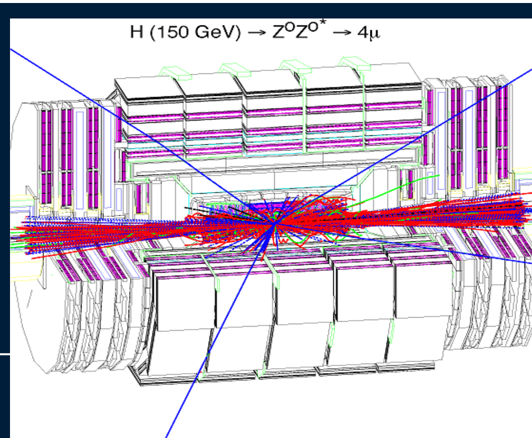



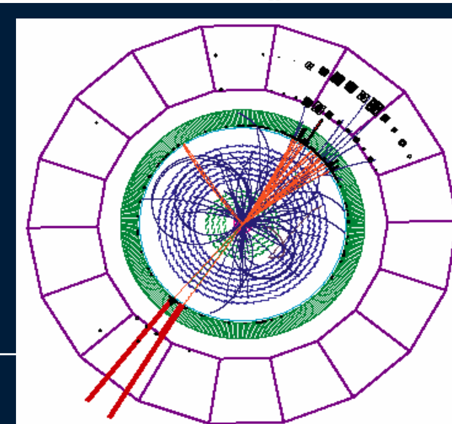





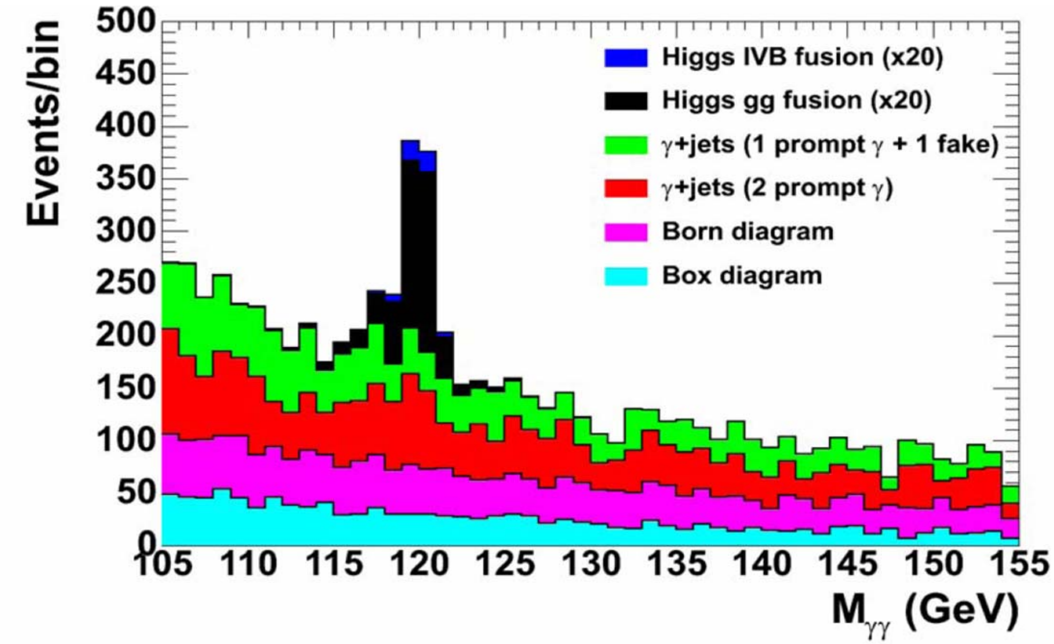



# Optimized H→ γγ Analysis (Categories) Fitting NN and Mass for Higgs and QCD

**Caltech + UCSD**

## Integrated luminosity for 5σ discovery

**Higgs Signal and Bkgds**

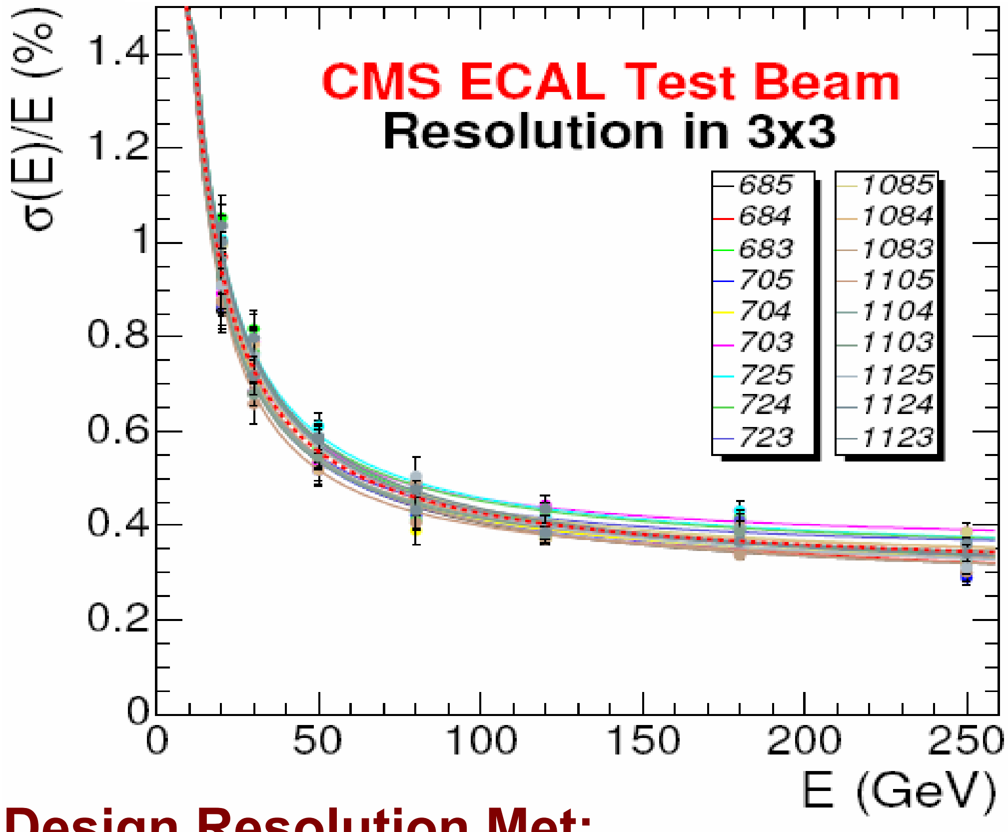


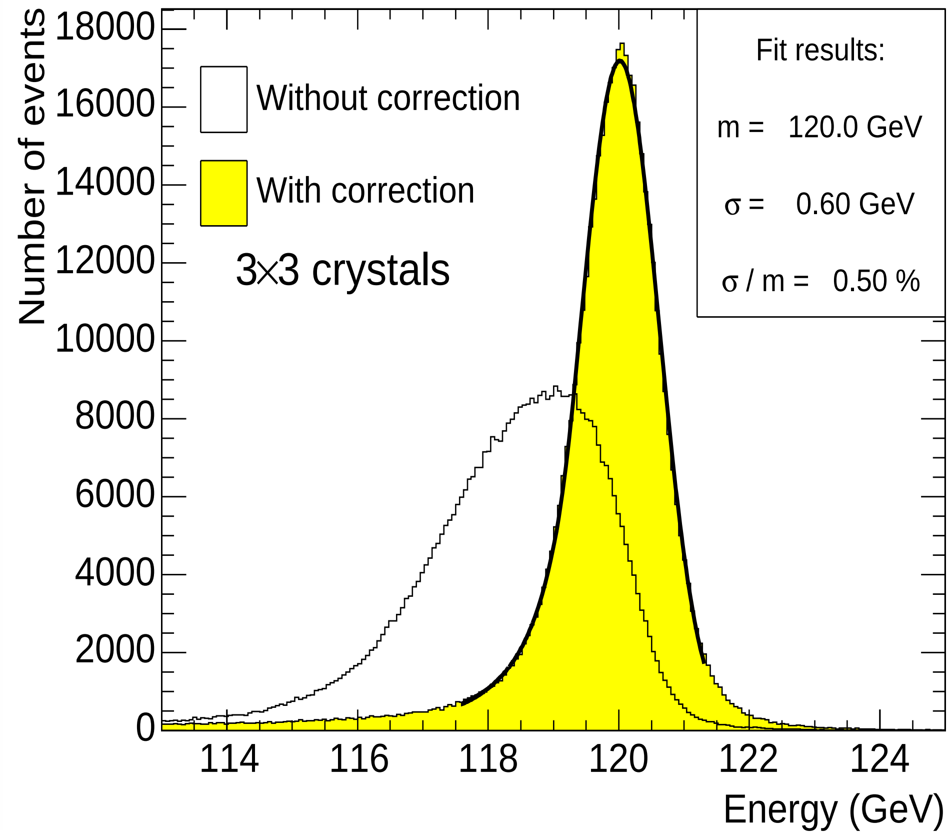

| $m_H$ GeV | L $fb^{-1}$ |
|---|---|
| 115 | 8.5 |
| 120 | 8 |
| 130 | 11 |
| 140 | 16 |
| 150 | ~30 |

- **Keys:** Clean Photon ID, 0.7% Mass Resolution, Precise Calibration
- **Next Steps:** Optimize Signal/Background Separation; Higher Order Calculations; Study ECAL Calibration Effects


S. Shevchenko, V. Litvin, R. Zhu, M. Dubinin (MSU), HN
+ *Y. Ma, V. Timciuc, J. Veverka, Y. Yang; T. Lee, A. Kumar*

# PbWO4 Crystals: Energy Resolution ! Precise Monitoring & Calibration

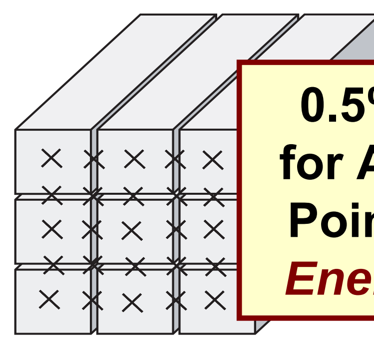



## Design Resolution Met:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.9\%}{\sqrt{E}}\right)^2 + \left(\frac{125(MeV)}{E}\right)^2 + (0.30\%)^2$$

**Caltech: Crystal R&D; Laser Monitoring System Monitor Stability 0.09% in Test Beam**



**0.5% Resol'n for Any Impact Point: *Precise Energy Profile***

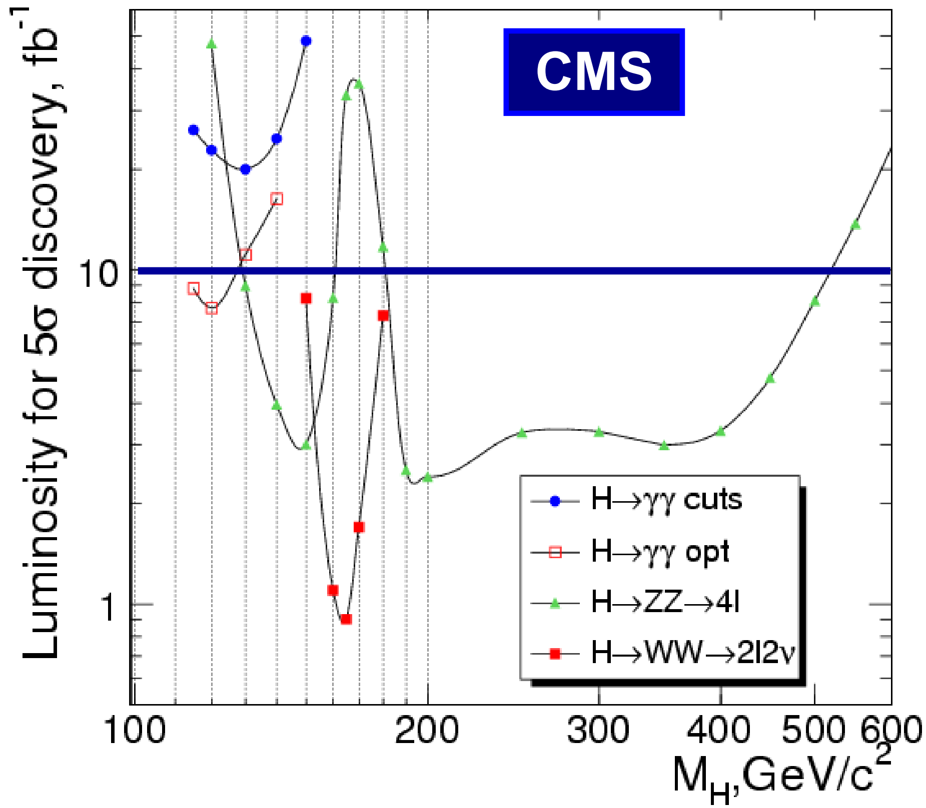
# Higgs Discovery Reach

## $M_H$ = 115 - 520 GeV covered with ~10 $fb^{-1}$

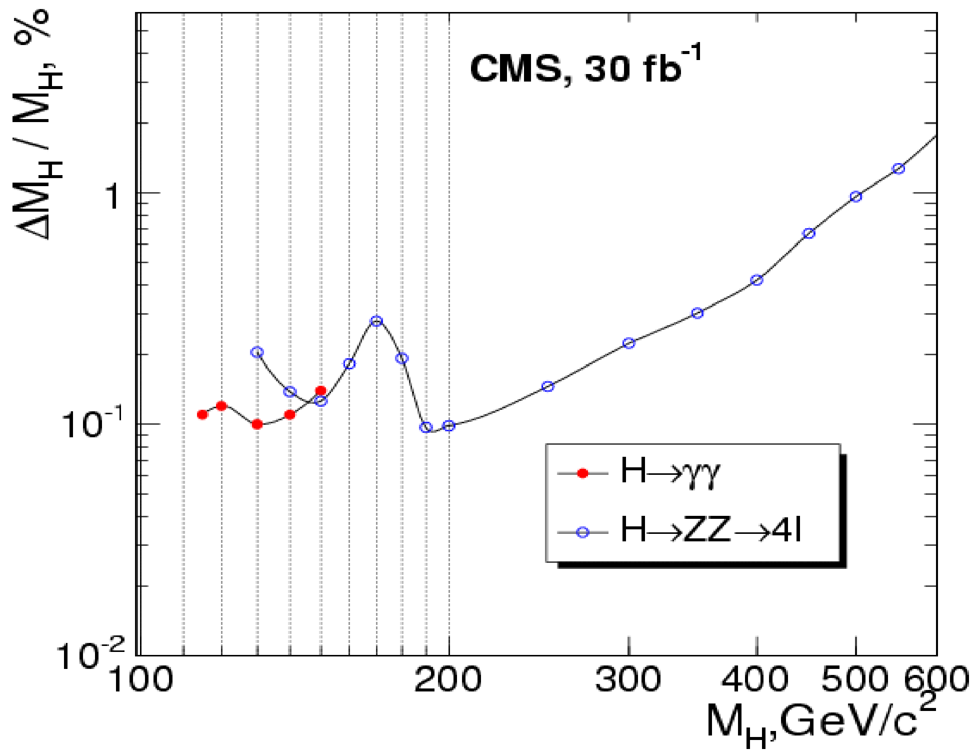
2007

**CMS: Higgs Discovery with 1 Year at 10% of Design Luminosity**

**By ~2010: Study if it is "the Higgs": Mass, J, total width, couplings, CP, …**




**Precise Mass With 30 fb-1**




***The Higgs, or Other New Physics Might Be Discovered Early***

# Supersymmetric Extension of Standard Model (SUSY)

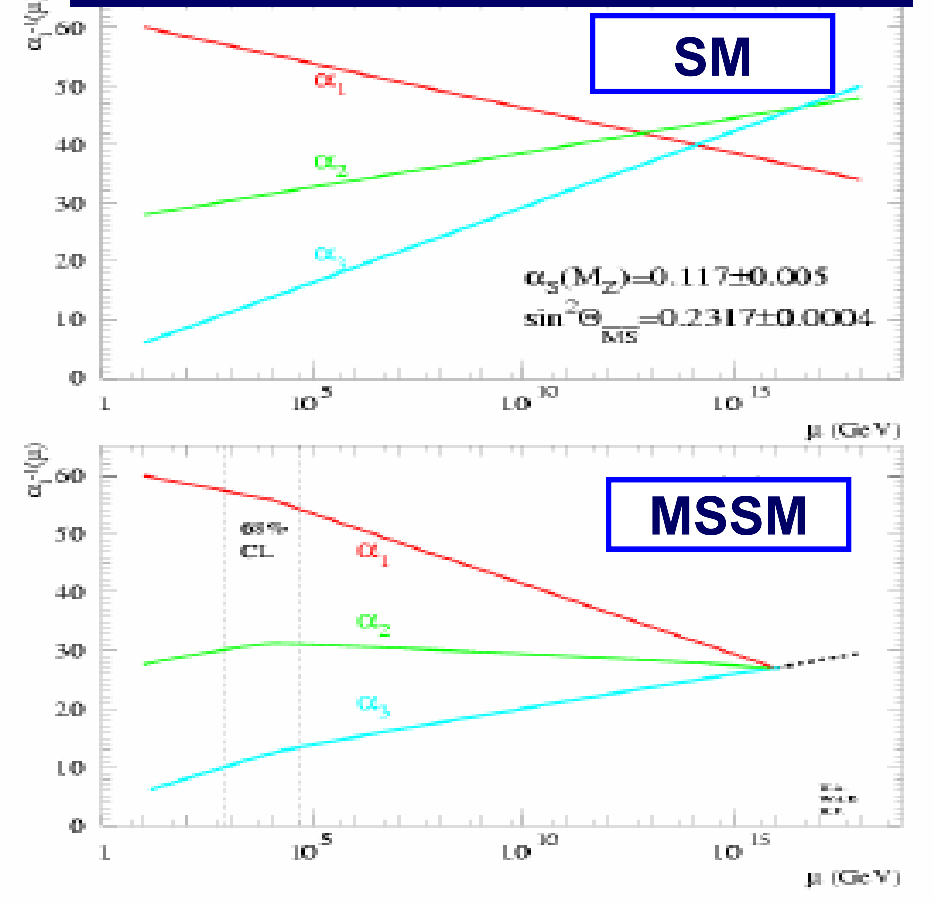
"SUSY is the only natural extension of the known space-time symmetries of particle physics"

SUSY transformations from
fermion → boson → fermion give spacetime translations; thus can connect quantum mechanics with General Relativity.

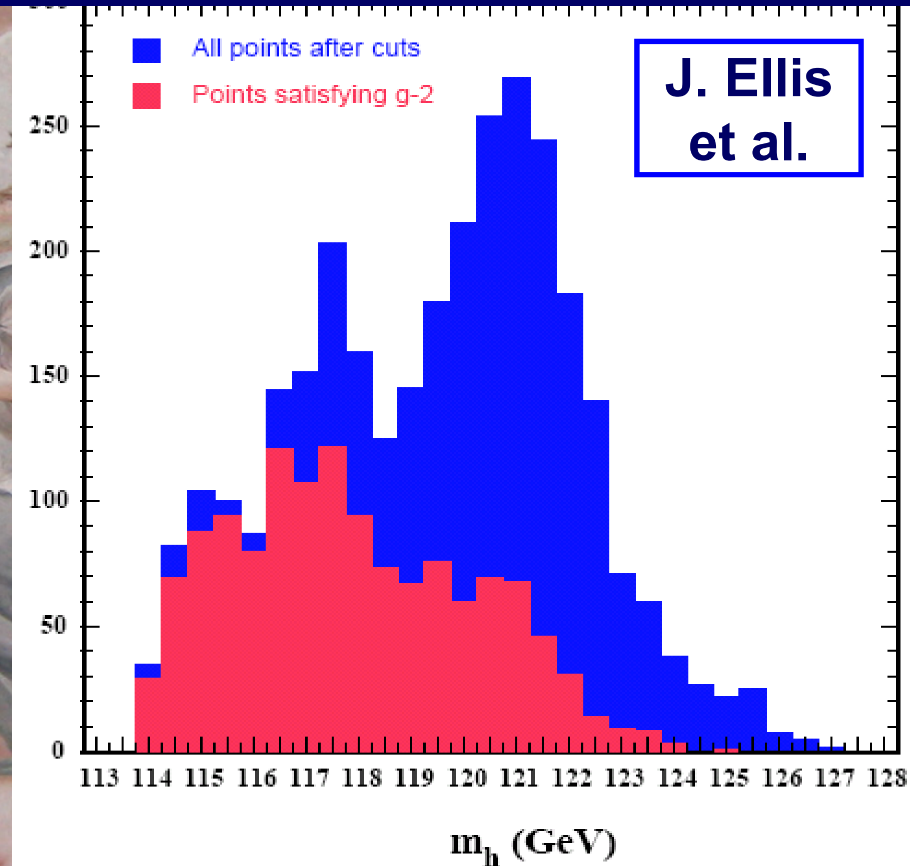
Supersymmetry is required by String Theory

# Reasons to Like SUSY

**Enables the gauge couplings to unify**

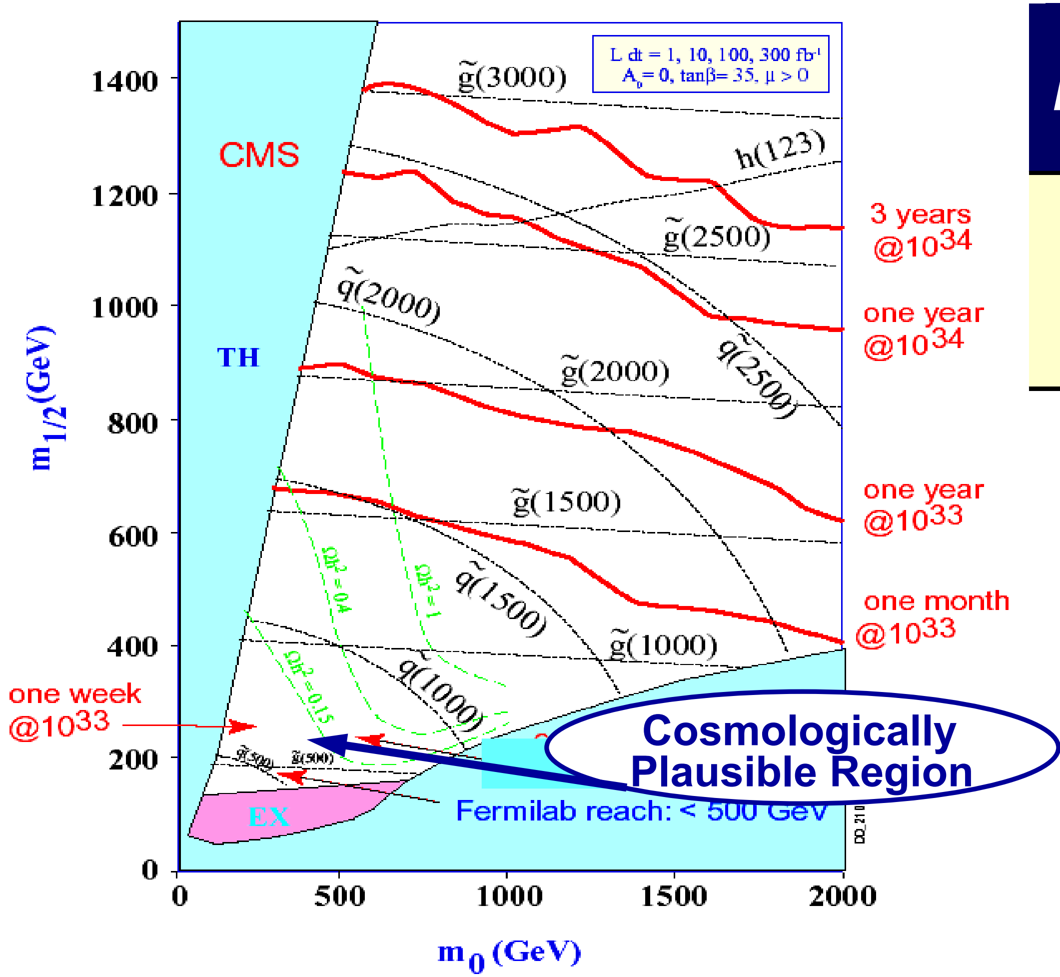



**✷LSP: weakly decaying, neutral: cold dark matter candidate**




**It predicts $m_H < 150$ GeV**

# CMS SUSY Reach: ($m_0$, $m_{1/2}$,…)
## Jets and Missing Energy



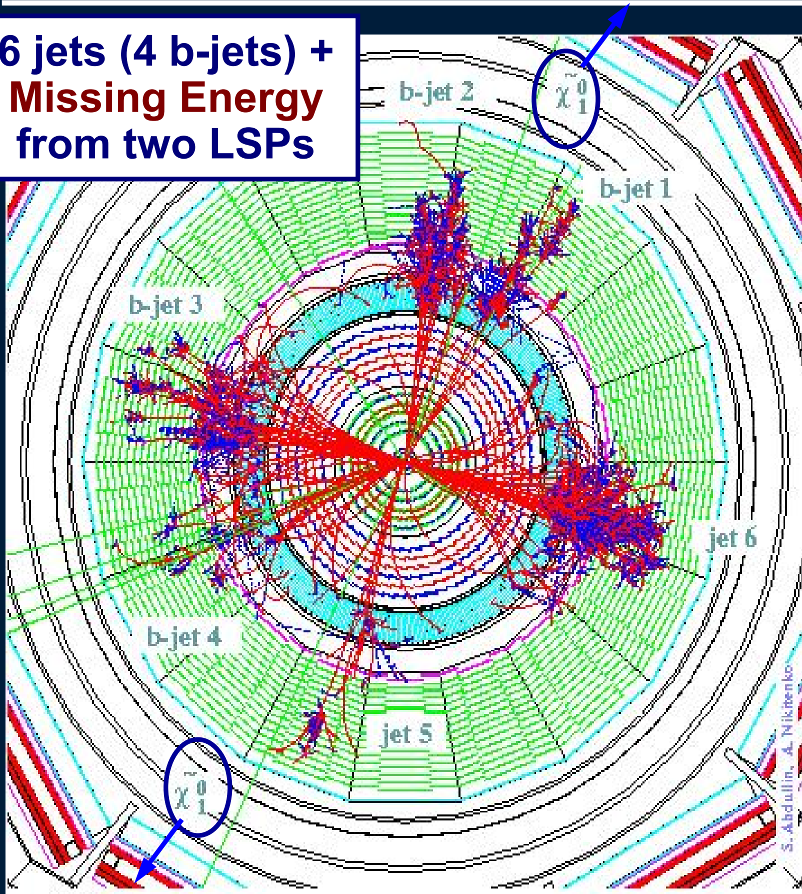

**WMAP: $\Omega_{CDM}h^2 = 0.127^{+0.007}_{-0.013}$**

| Mass(GeV) | σ (pb) | Events /month Low lum-high lum |
|---|---|---|
| 500 | 100 | $10^5$-$10^6$ |
| 1000 | 1 | $10^3$-$10^4$ |
| 2000 | 0.01 | $10^1$-$10^2$ |

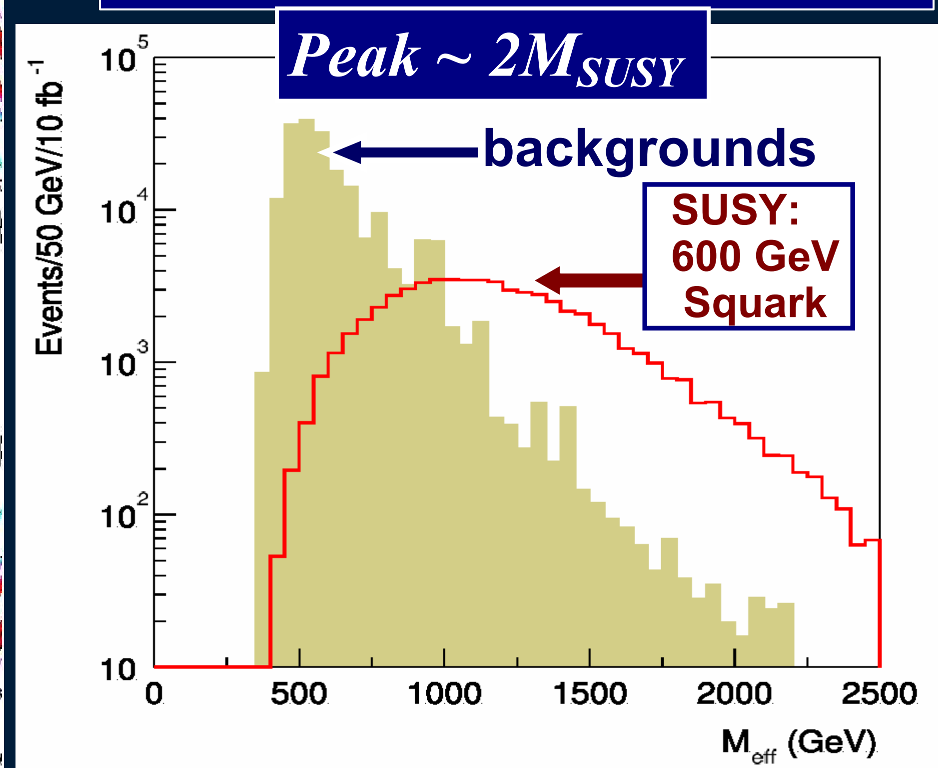
- **The cosmologically interesting region of SUSY space could be covered in the first months of LHC physics running (in 2008)**
- **The 1.5-2 TeV mass range for squarks q̃ and gluinos g̃ could be covered within one year at 10% of design luminosity**
- **Final mass Reach: 2.5-3 TeV**

# SUSY: Jets and Missing Energy

**6 jets (4 b-jets) +**
**Missing Energy**
**from two LSPs**

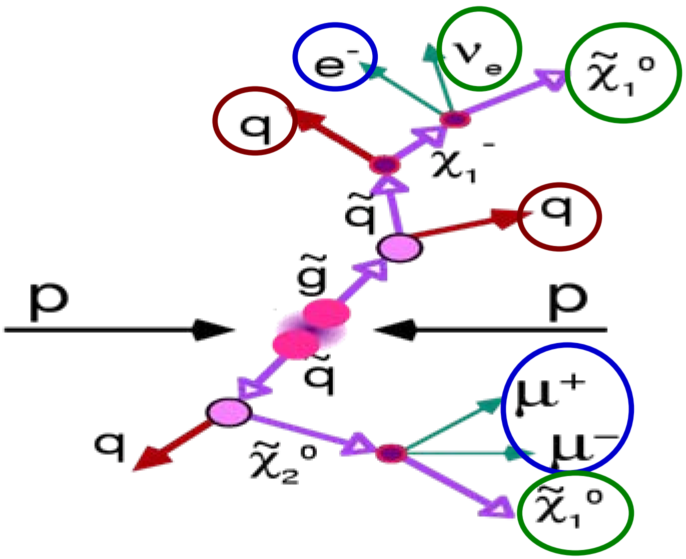



$$M_{eff} = P_T(\nu) + \sum P_T(\text{jets})$$

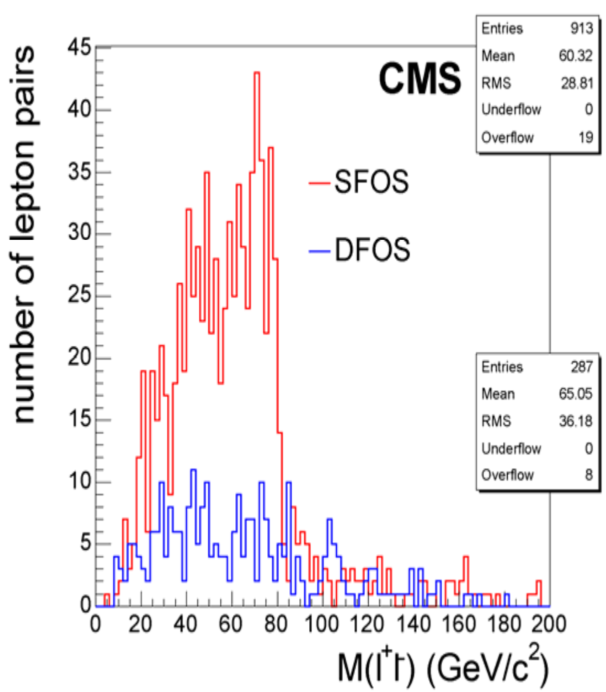


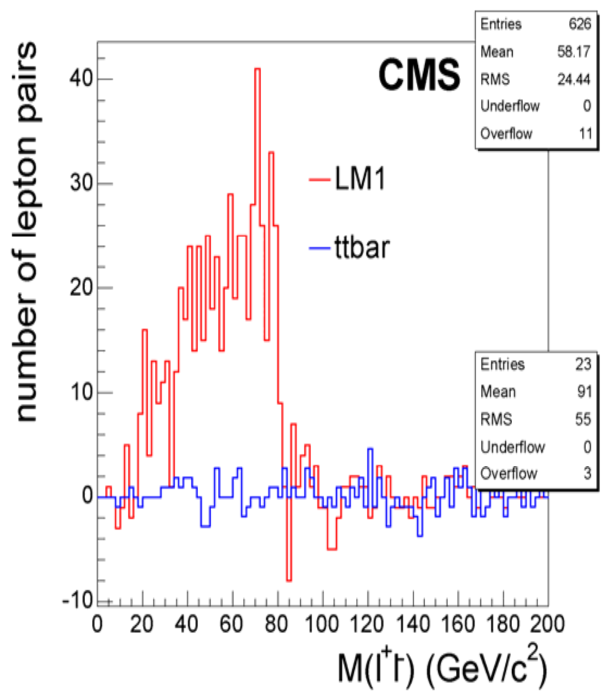

**Dramatic event signatures (LSP) and large cross sections mean we could discover SUSY quickly, if it exists.**

# Distinctive Signatures, Kinematic Spectra, and "Edges" Reveal the Mass Spectroscopy and Couplings




Production of sparticles may reveal itself though some spectacular kinematical spectra, with a pronounced "edge" in the $\ell^+\ell^-$ mass spectrum reflecting $\chi_2^o \rightarrow \ell^+\ell^-\chi_1^o$ production and decay.
An example of such a spectrum in inclusive $\ell^+\ell^- + E_t^{miss}$ and of a 3 $\ell^\pm$ production event are shown below



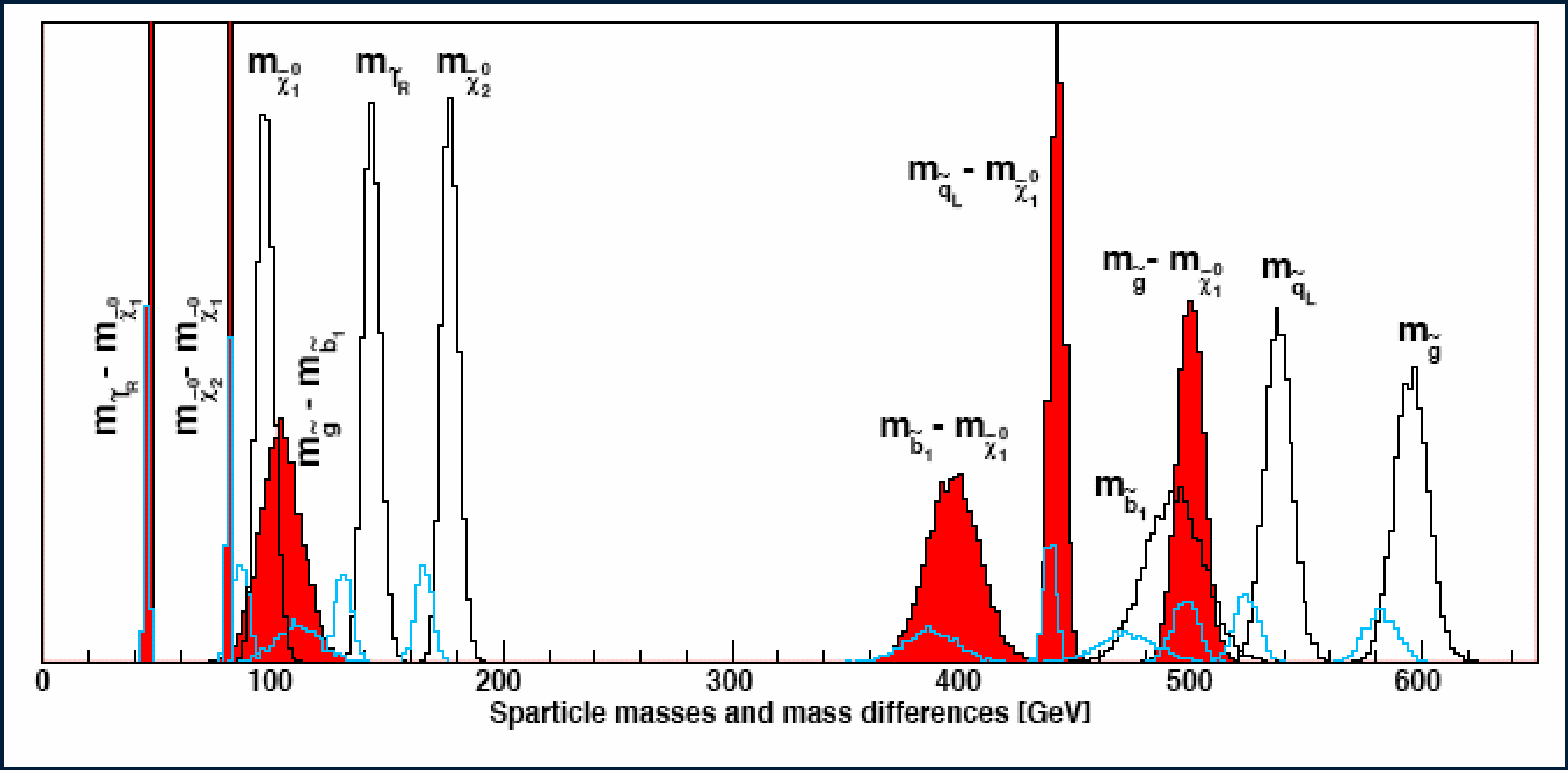




- **LM1 with 1 $fb^{-1}$ ( with uncertainty on alignment and energy scale):**

**$M_{ll}(max)$ = 80.0 ± 0.5 (stat) ± 1.0 GeV (sys.)**

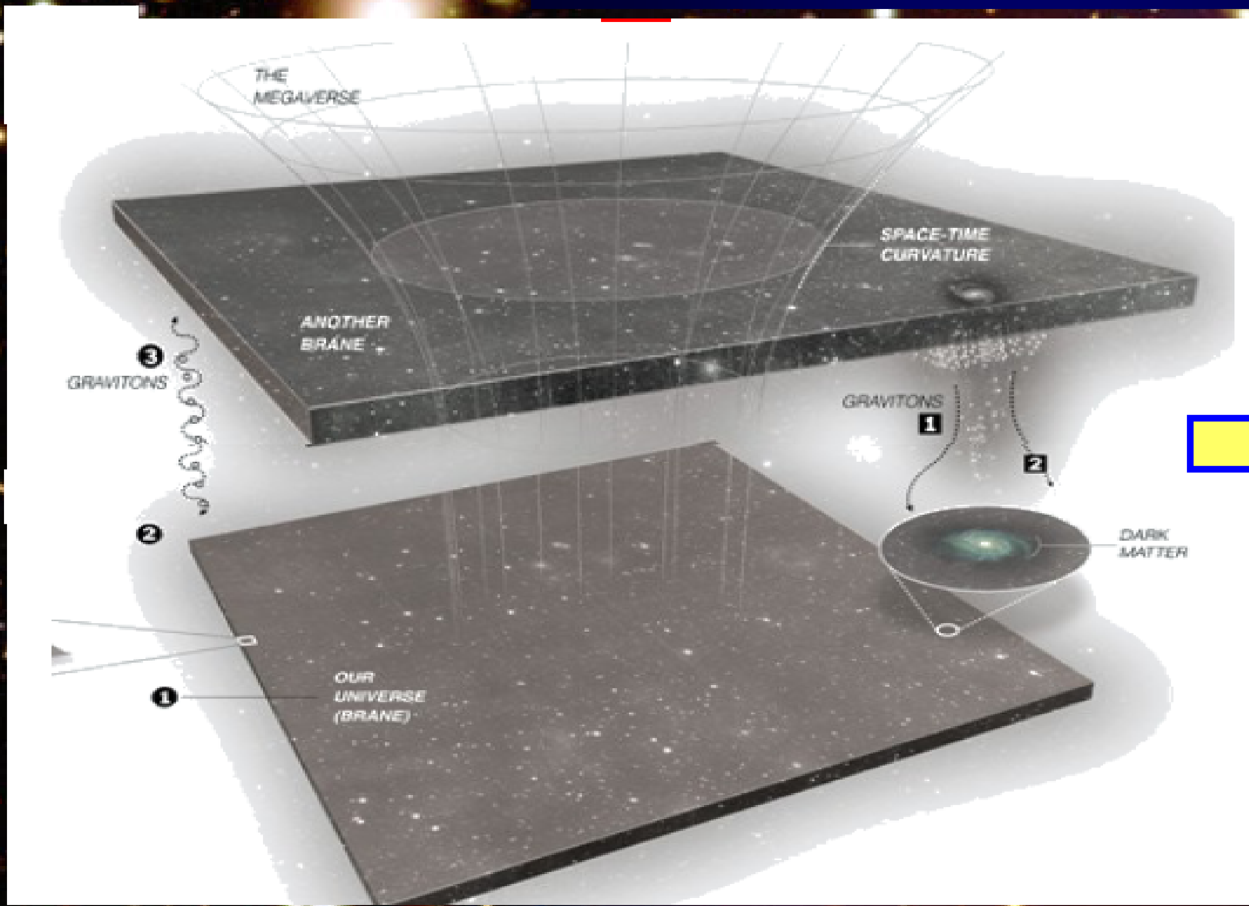
# A Possible Sparticle Spectroscopy (circa 2010)

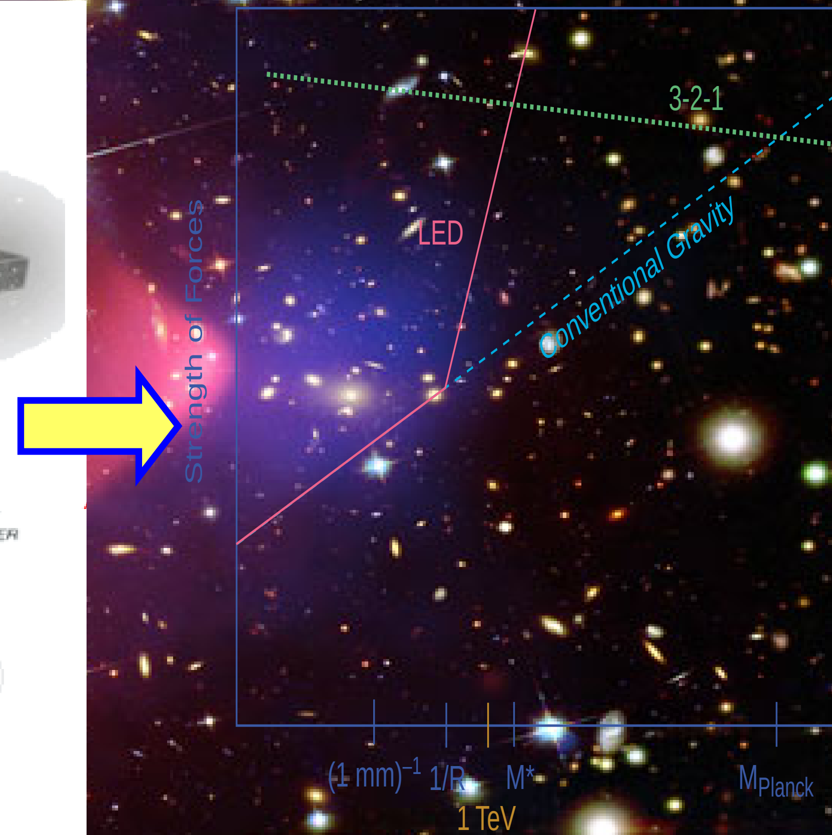
[J. High Energy Phys. 06 (2005) 015]



# Beyond the Higgs & SUSY

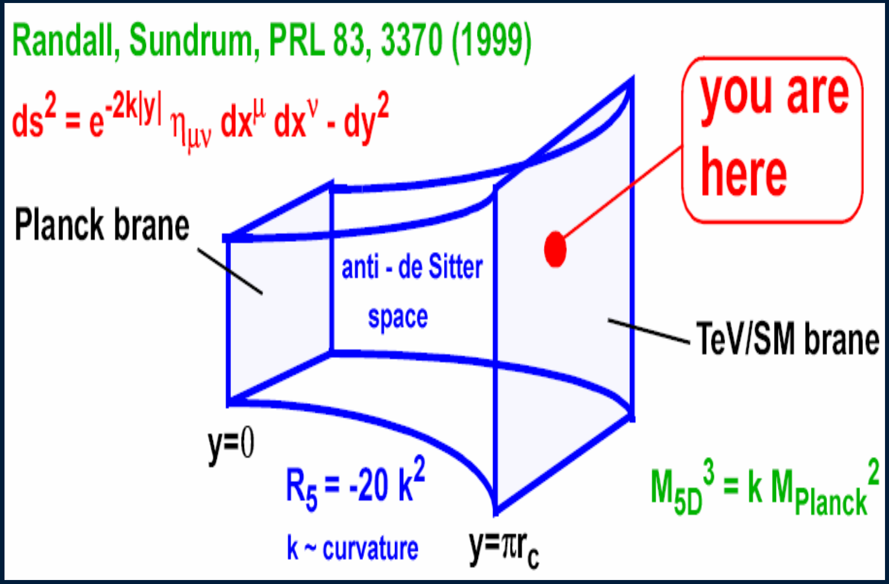
## Extra Space Dimensions

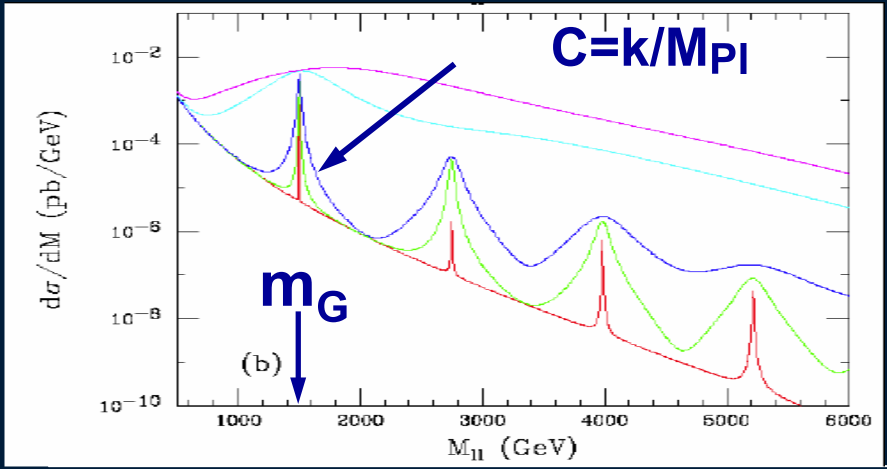



**Extra dimensions can bring the Planck Scale (10$^{19}$ GeV) into the Tera-Scale region (10$^{3}$ GeV)**

# Search for Randall –Sundrum Gravitons with Two Photon Decays



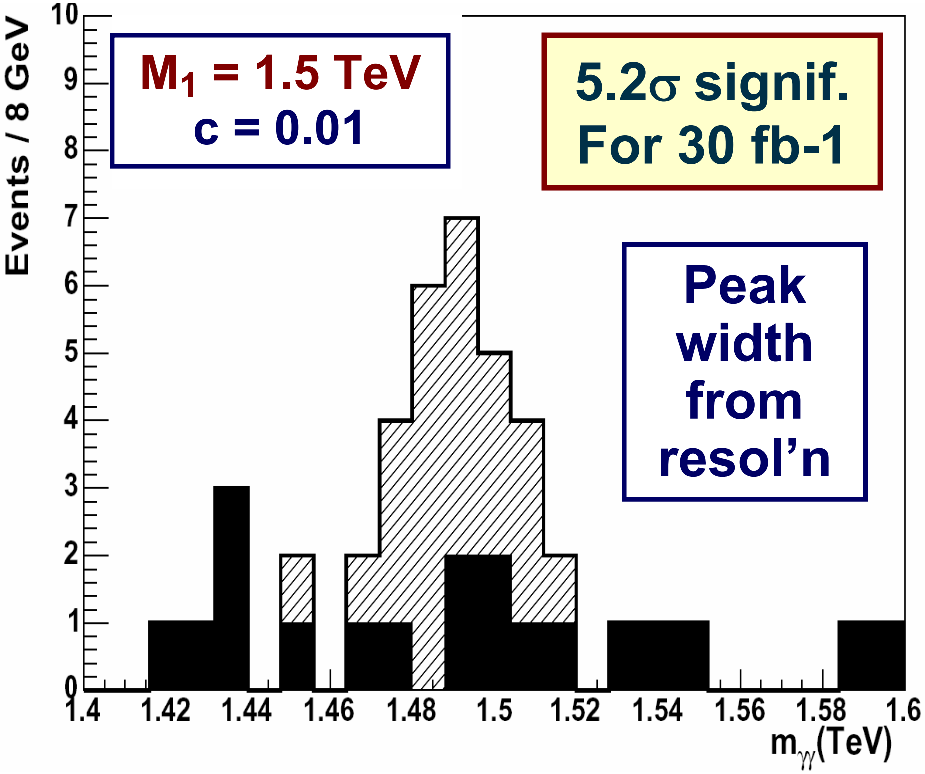



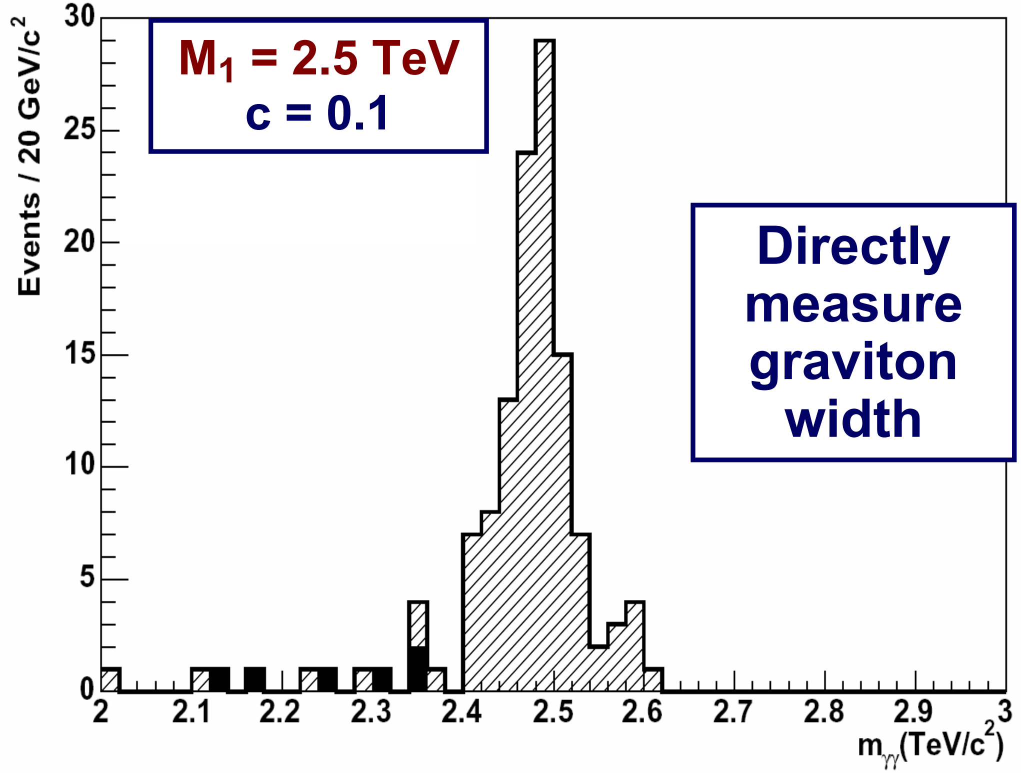

- Gravity scale = $M_{Planck}$ exp($-kr_c$) ~TeV; for $kr_c$ ~11-12, no hierarchy problem
- Graviton resonances $m_n = x_n k \exp(-kr_c)$, $J_1(x_n)=0$
- Two parameters control the properties of the RS model: mass of the graviton $m_G$ and the constant $c=k/M_{Planck}$ determining the graviton couplings and widths

# *Extra Dimensions and Search for Randall –Sundrum Gravitons:* G → $\gamma\gamma$

**Caltech + Saclay**

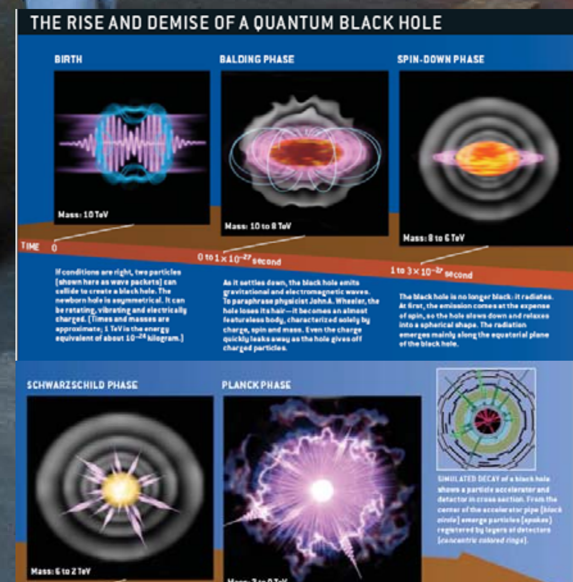
- **Graviton resonances**
  $M_n = (x_n/x_0)\, M_0$;  $J_1(x_n)=0$



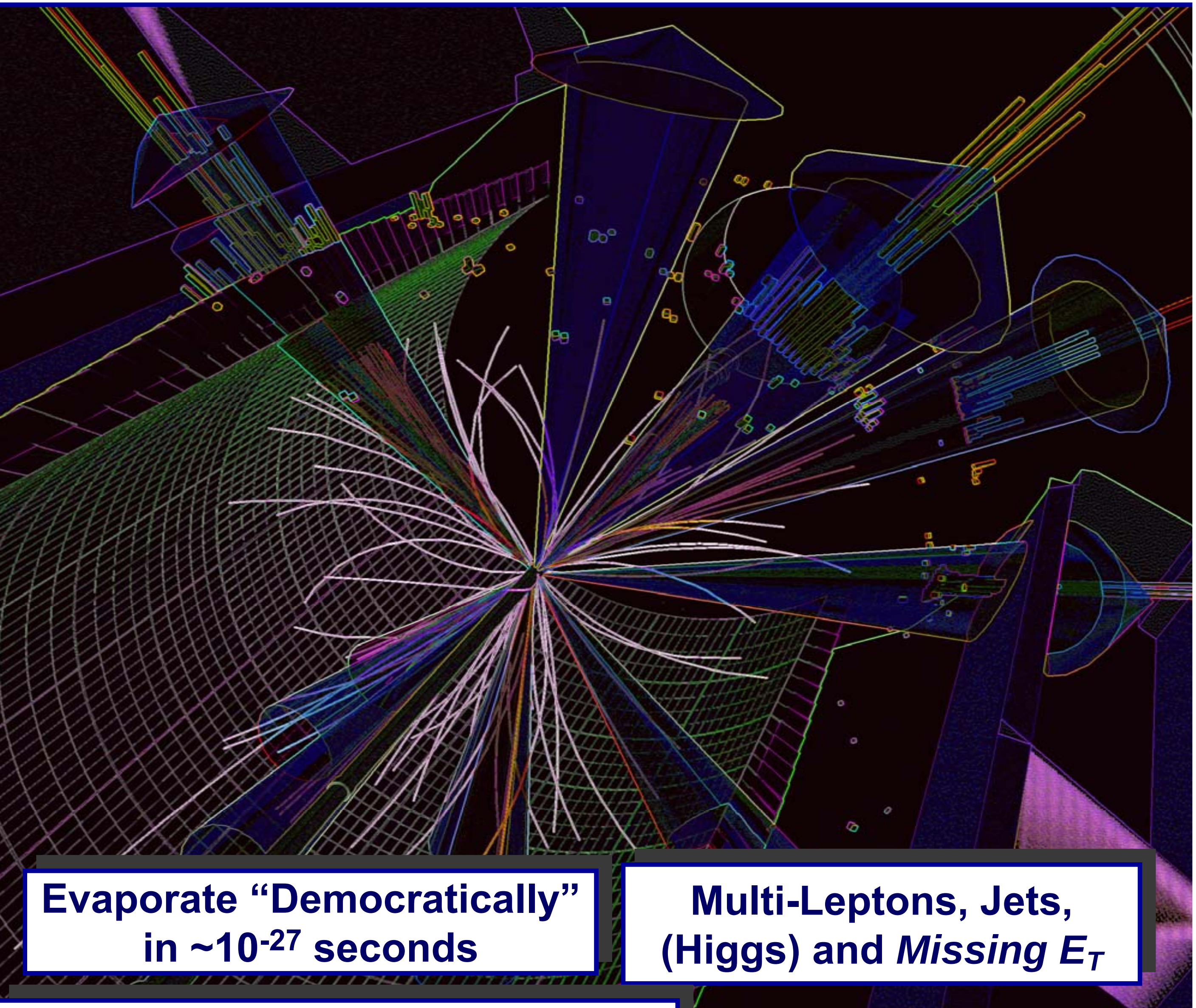




**10 $fb^{-1}$: $M_G$ > 3.14 TeV for c=0.1; $M_G$ > 1.32 TeV for c=0.01**
**30 $fb^{-1}$: $M_G$ > 3.54 TeV for c=0.1; $M_G$ > 1.59 TeV for c=0.01**

# Black Hole Hunters at the LHC…



# Making Black Holes: $M_{BH} > M_*$(Gravity) (Saved by Hawking Radiation)



Evaporate "Democratically" in ~$10^{-27}$ seconds

Multi-Leptons, Jets, (Higgs) and *Missing* $E_T$

Hewett, Lillie, Rizzo, PRL 95, 261603 (2005)

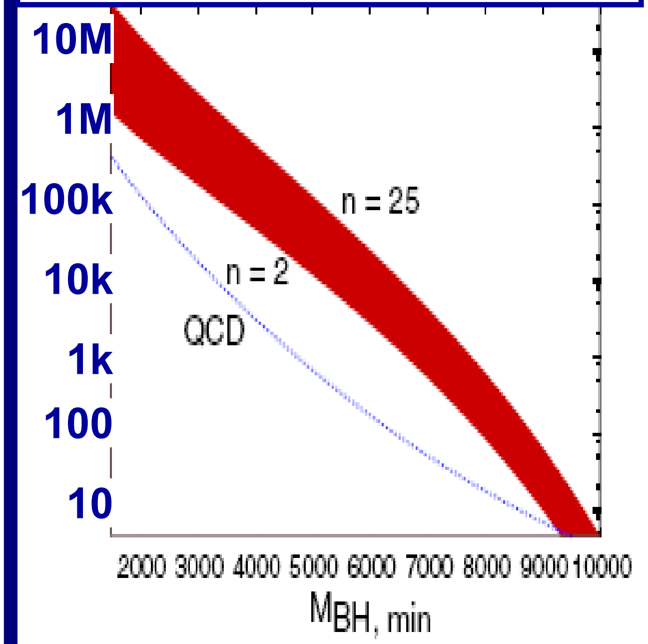
**Black Holes may be copiously produced:**

**scale of $\sigma = \pi R_s^2$ ~1-100pb**

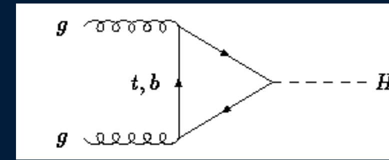
**~Number of extra dim. $n$ for large $n$**

**➡ $n$ can be determined: especially if $n$ > 6-7**

**BH Events per year at Low Lumi**



# Modifications to the Properties of the Higgs Boson



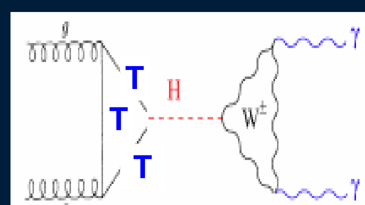

## Manohar and Wise, Phys. Lett. B636 (2006) 107-113

### Motivation

- "Minimal" solution to the Hierarchy Puzzle, through new physics at $\Lambda \sim 1$ TeV

### LHC: Promising Scenario

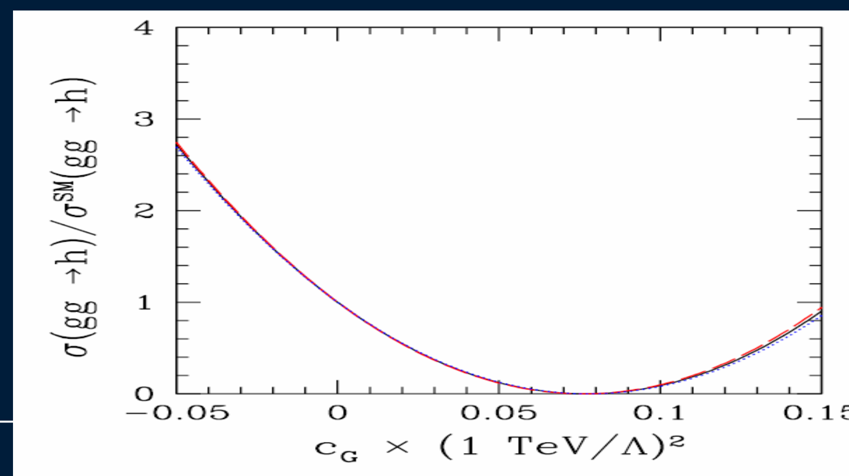
- Higgs production through "gluon fusion" ($gg \rightarrow h$) could be enhanced, relatively sensitive to new physics
  - $gg \rightarrow h$ already at one loop: a higher order process in perturbation theory
  - $WW \rightarrow h$, $ZZ \rightarrow h$ etc. affected less
  - New Top-like mesons also could appear




### A New Effective Theory

$$\delta\mathcal{L} = -\frac{c_G g_3^2 v^2}{4\Lambda^2} G^A_{\mu\nu} G^{A\mu\nu} - \frac{c_G g_3^2 v h}{2\Lambda^2} G^A_{\mu\nu} G^{A\mu\nu} - \frac{c_G g_3^2 h^2}{4\Lambda^2} G^A_{\mu\nu} G^{A\mu\nu} \ldots$$

- New "dimension 6" operators that couple the gluon & higgs fields
- $0.01 < C_G < 0.1$ from Tevatron data and neutron dipole moment
- Higgs gg fusion rate could be several times, or much less than in the SM



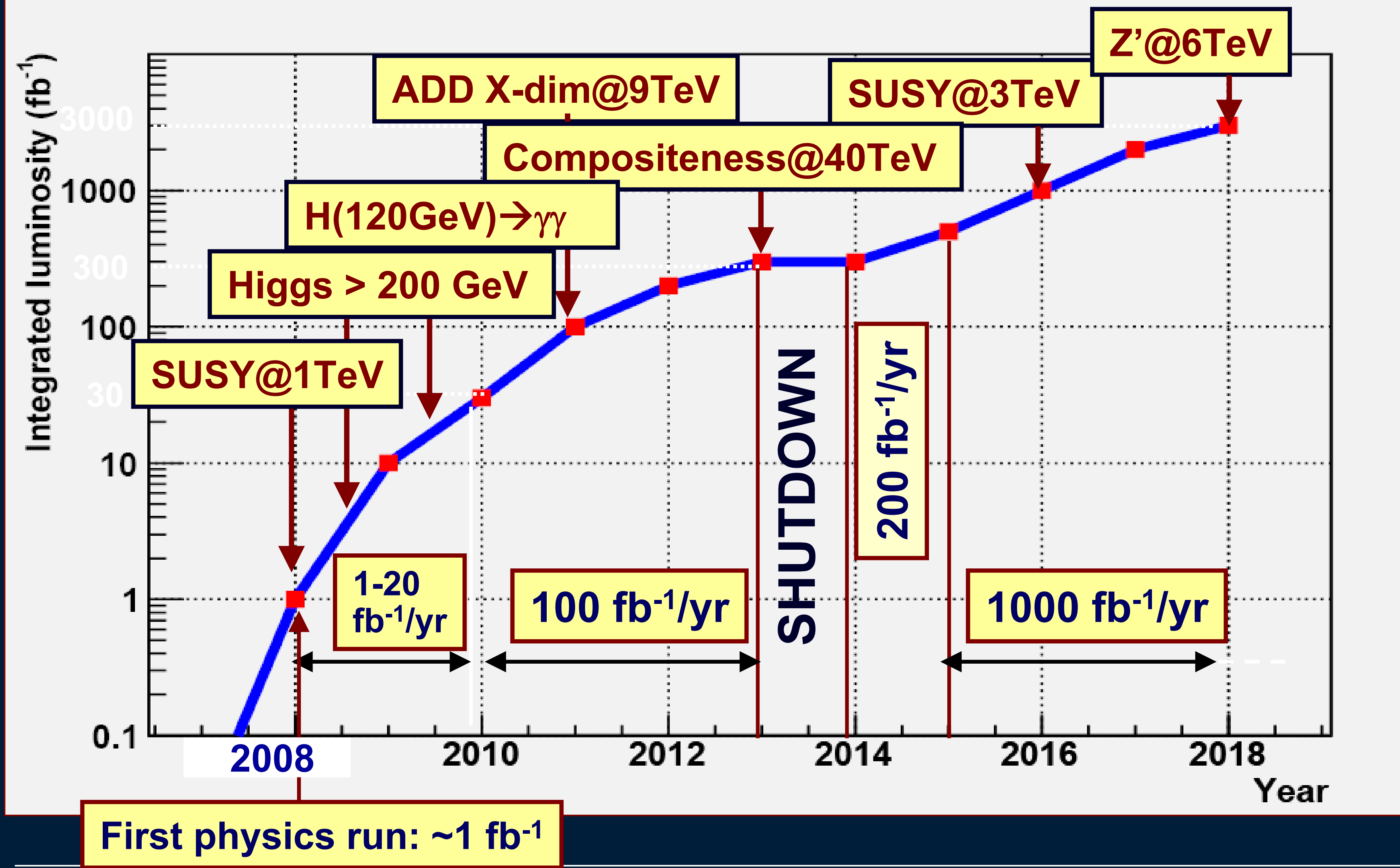
# Summary: A New Window on the Universe; A Long Road Ahead

- LHC first collisions in 2007, at 450 GeV low luminosity:
  - Commissioning of LHC & detectors: *triggers, alignment, calibration* Watch out for large signal new phenomena…
- First physics run in 2008: expect of O(1) $fb^{-1}$. "Rediscover" the SM
  - Low mass SUSY reach extended far beyond Tevatron's
  - Open new windows: for extra dimension searches, black holes, new force carriers, substructures
- Physics run in 2009: expect ~5-10 $fb^{-1}$.
  - SM Higgs mass range largely covered !
  - Much of high mass SUSY covered !
  - Multi-TeV reach for more and more New Physics scenarios
- Design luminosity by ~2010-11: 100 $fb^{-1}$ per yr
- A steep learning curve for the next 3 years

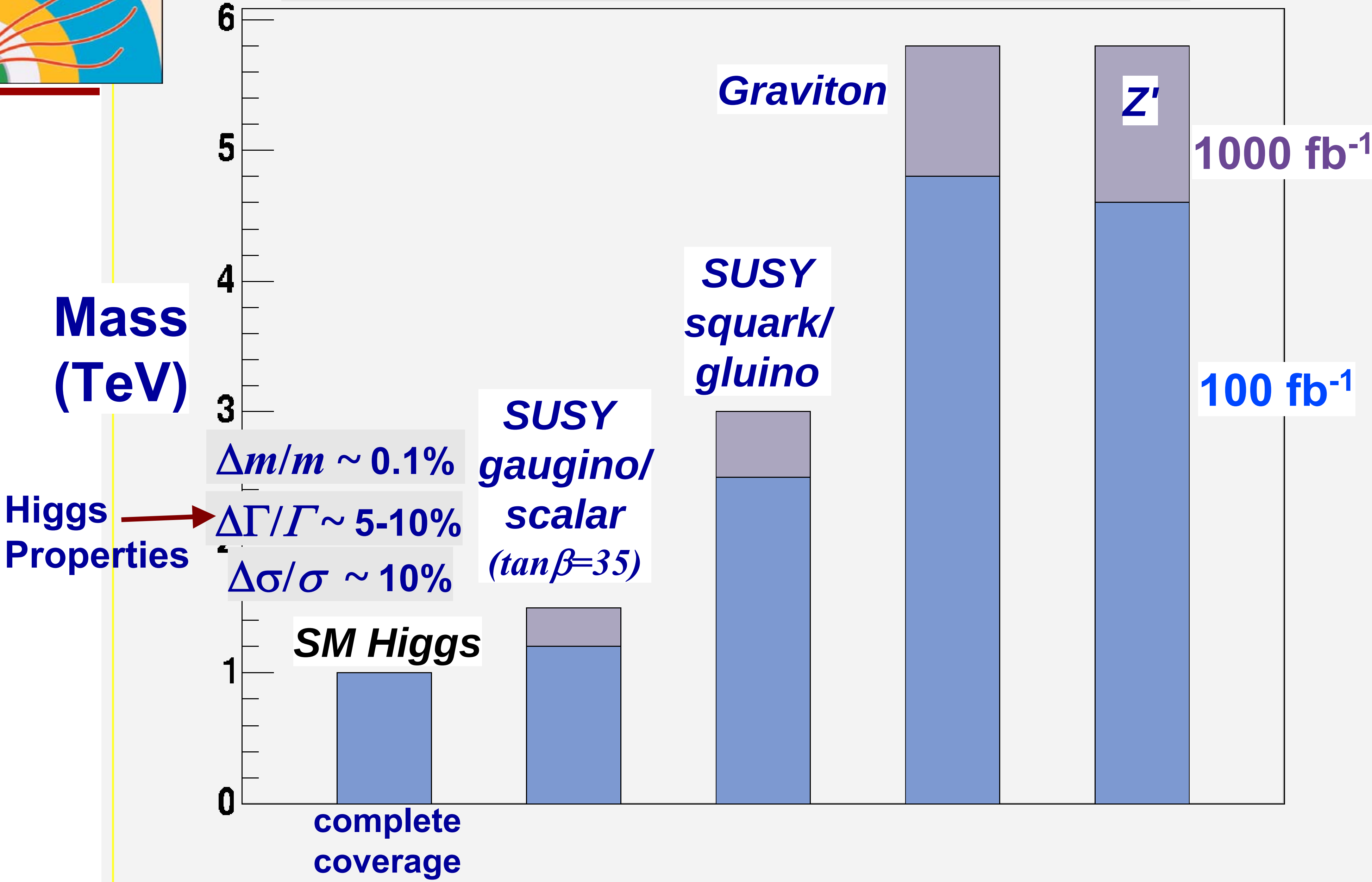
$\Rightarrow$ It will be Very Rewarding

# LHC Luminosity and Physics Profile

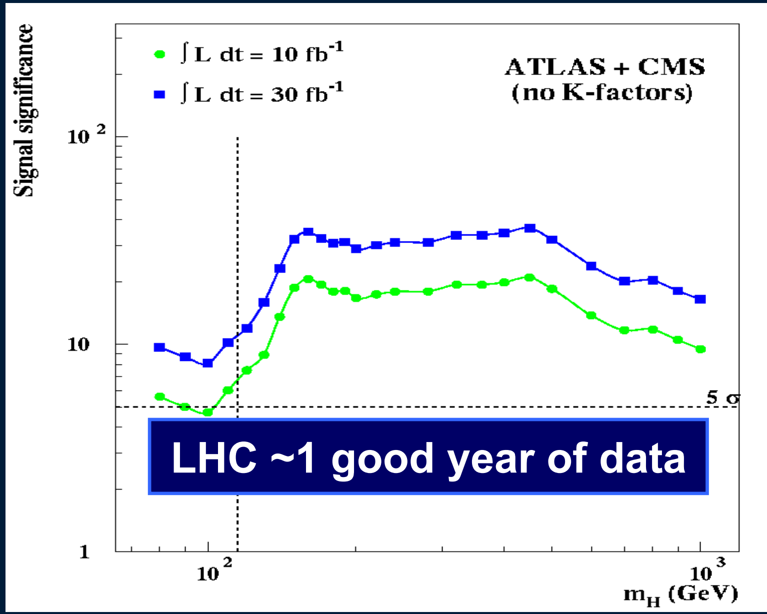
$L = 10^{33}$ $L = 10^{34}$ Super-LHC: $L = 10^{35}$



# CMS Mass Reach: Summary



# The SM Higgs at the LHC and SLHC




- **First step**
  - ✸ Discover a new Higgs-like particle at the LHC, or exclude its existence
- **Second step**
  - ✸ Measure properties of the new particle **to prove it is the Standard Model Higgs**
    - Mass
    - Width
    - Cross sections x branching ratios
    - Ratios of couplings to particles (~$m_{particle}$)
    - Decays with low Branching ratios (e.g $H \rightarrow \mu\mu$)
    - Measure CP and spin quantum numbers (scalar particle ?)
    - *Measure the Higgs self-coupling ($H \rightarrow HH$): to test the theory, and reconstruct the Higgs potential*

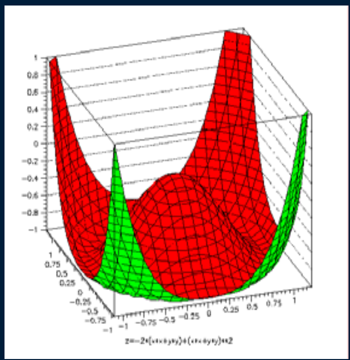
**SLHC added value**

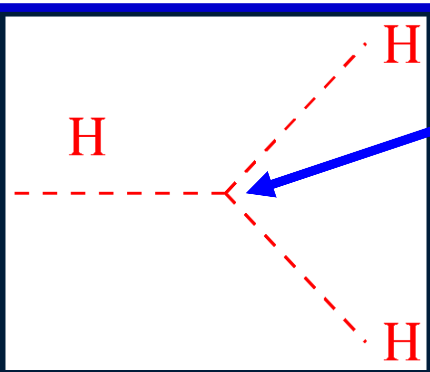
**Only then we can be sure it's the Higgs particle we are looking for**

# Higgs Self Coupling (CMS):

## Once Higgs is found, try to reconstruct the Higgs potential

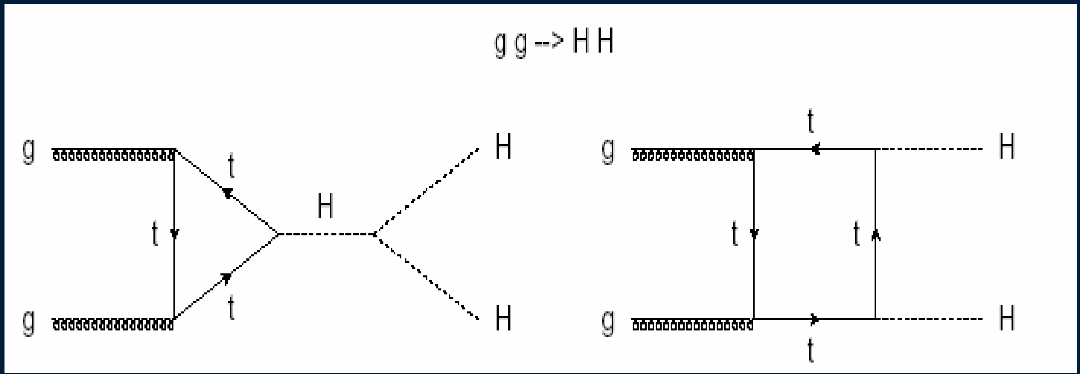
$$V(\Phi) = -\lambda v^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$






$\sim \lambda v$

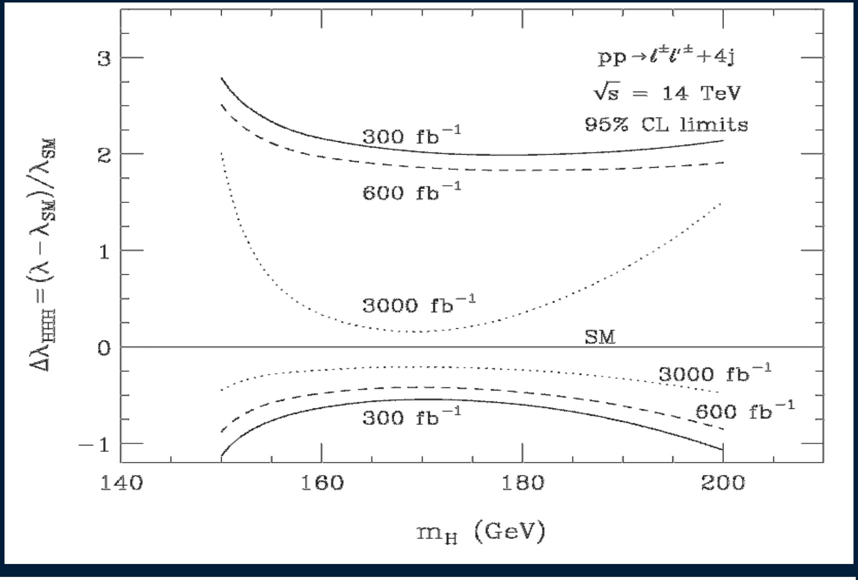
$m_H^2 = 2\,\lambda v^2$




$HH \rightarrow W^+ W^- W^+ W^- \rightarrow l^\pm \nu\ l^\pm \nu\ +\ 4$ Jets

**Baur, Plehn, Rainwater**

**Limits achievable at 95% CL for $\Delta\lambda=(\lambda-\lambda_{SM})/\lambda_{SM}$**

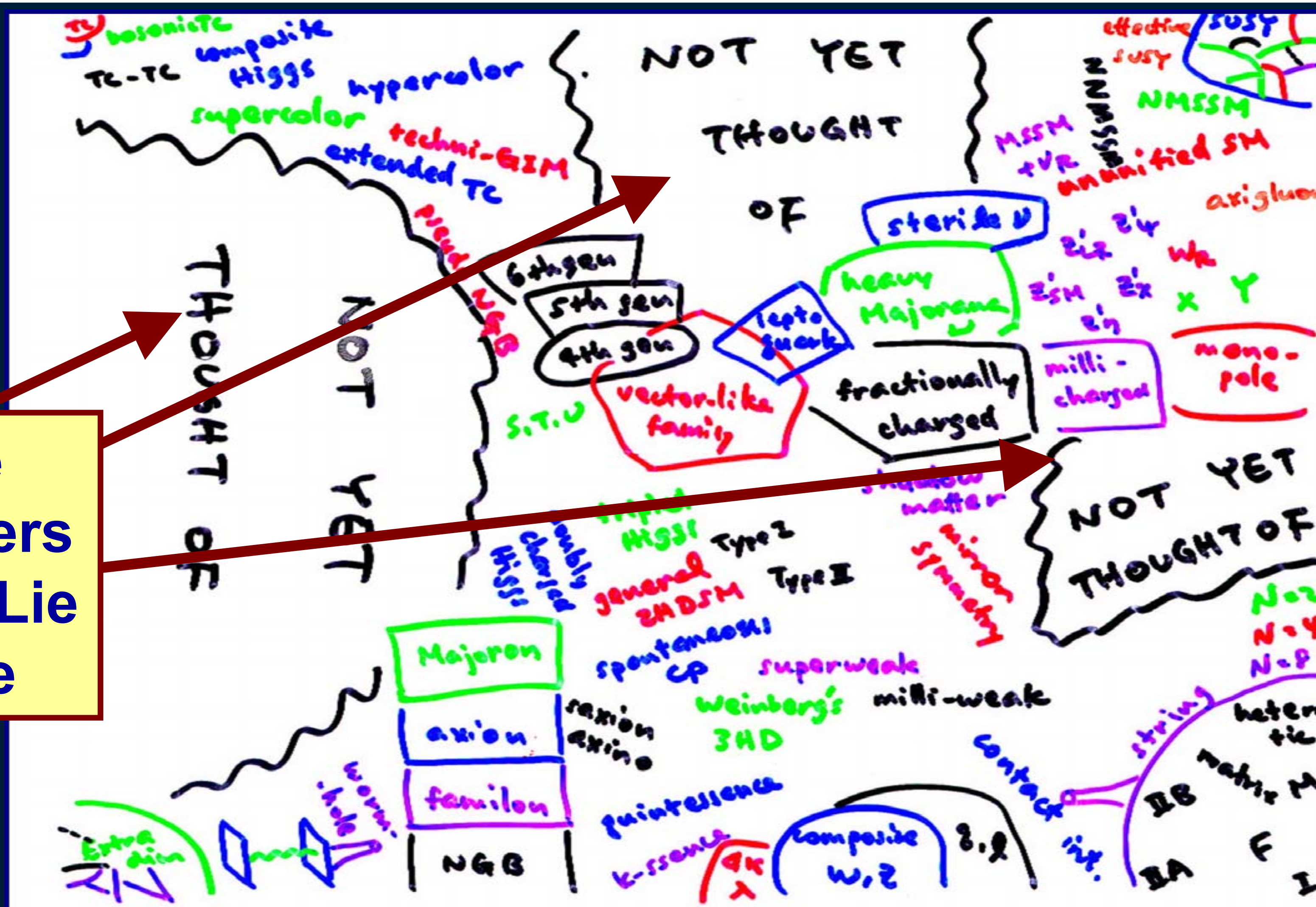



**LHC: $\lambda$= 0 can be excluded at 95% CL**

**SLHC: $\lambda$ can be determined to 20-30% (95% CL)**

# There are many ideas.

## But as we enter a new energy scale…

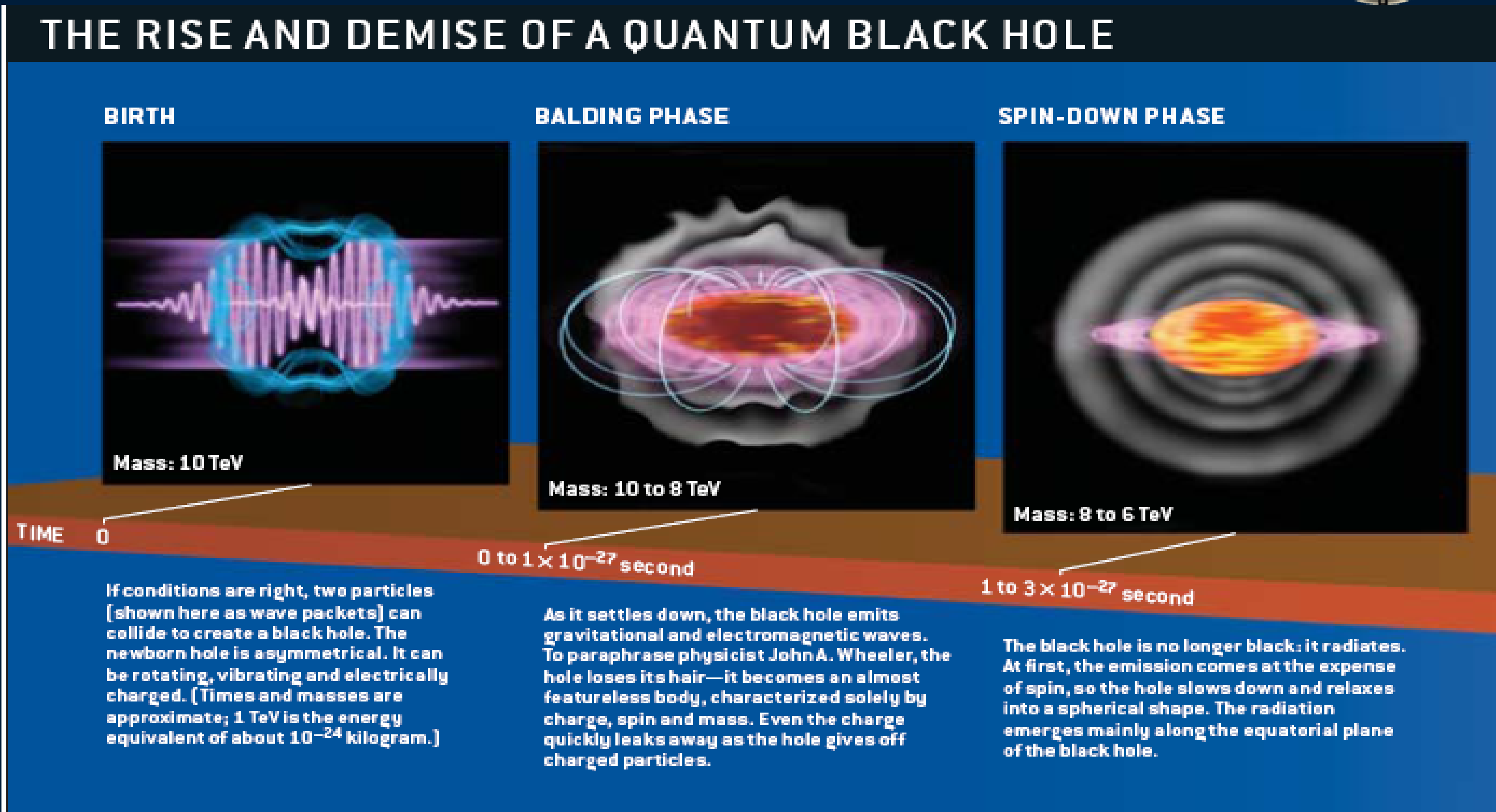



**The Answers Often Lie Here**

# It may take another generation of physicists to figure out Dark Energy

# Extra Slides Follow

# Black Hole Production and Evolution at the LHC…



# Black Hole Rundown and Wink-Out