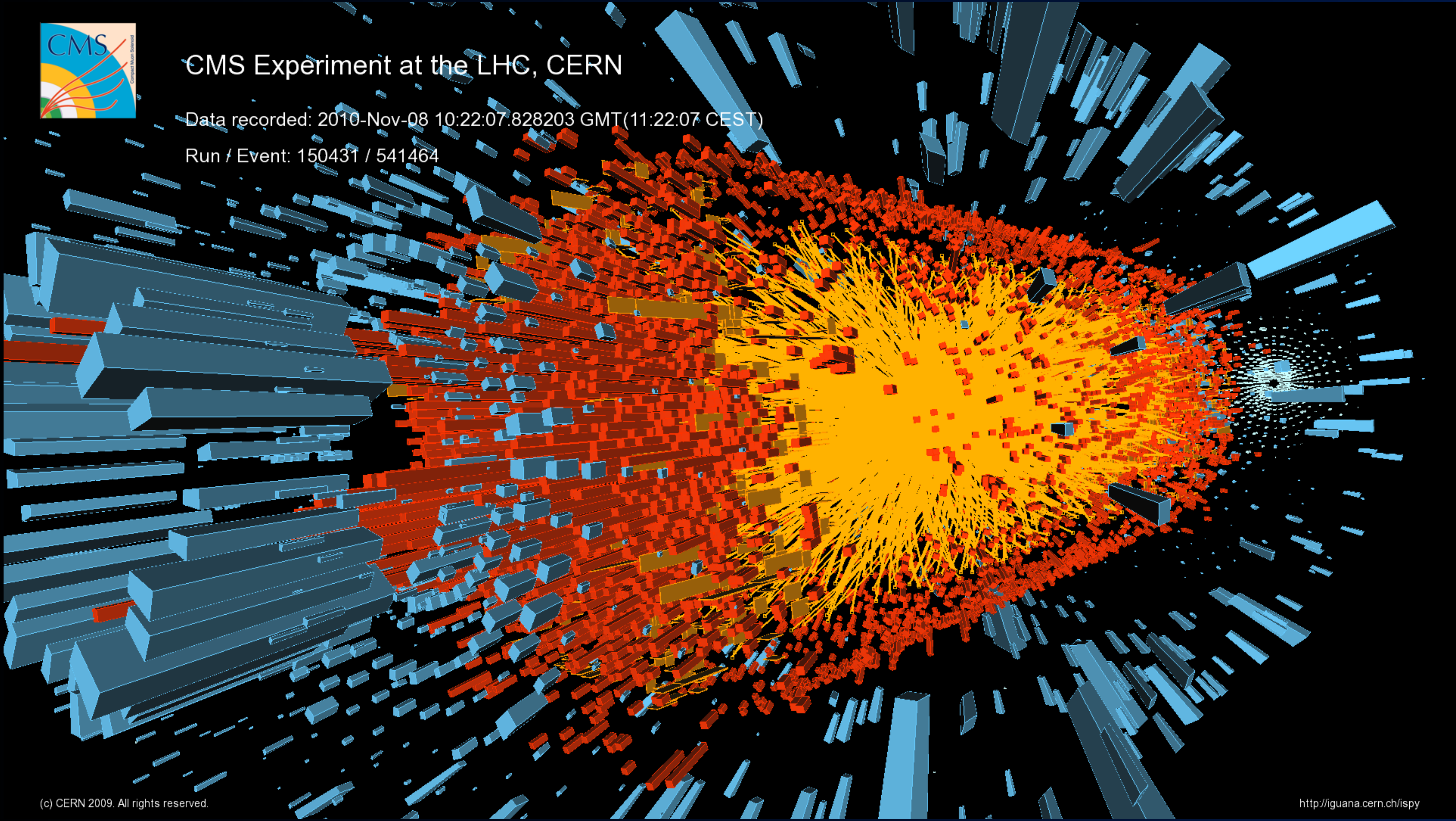
Stepping Stones to Discovery at CMS…



Steve Nahn – MIT/CMS Collaboration

Toronto HEP Seminar, April 4th , 2011

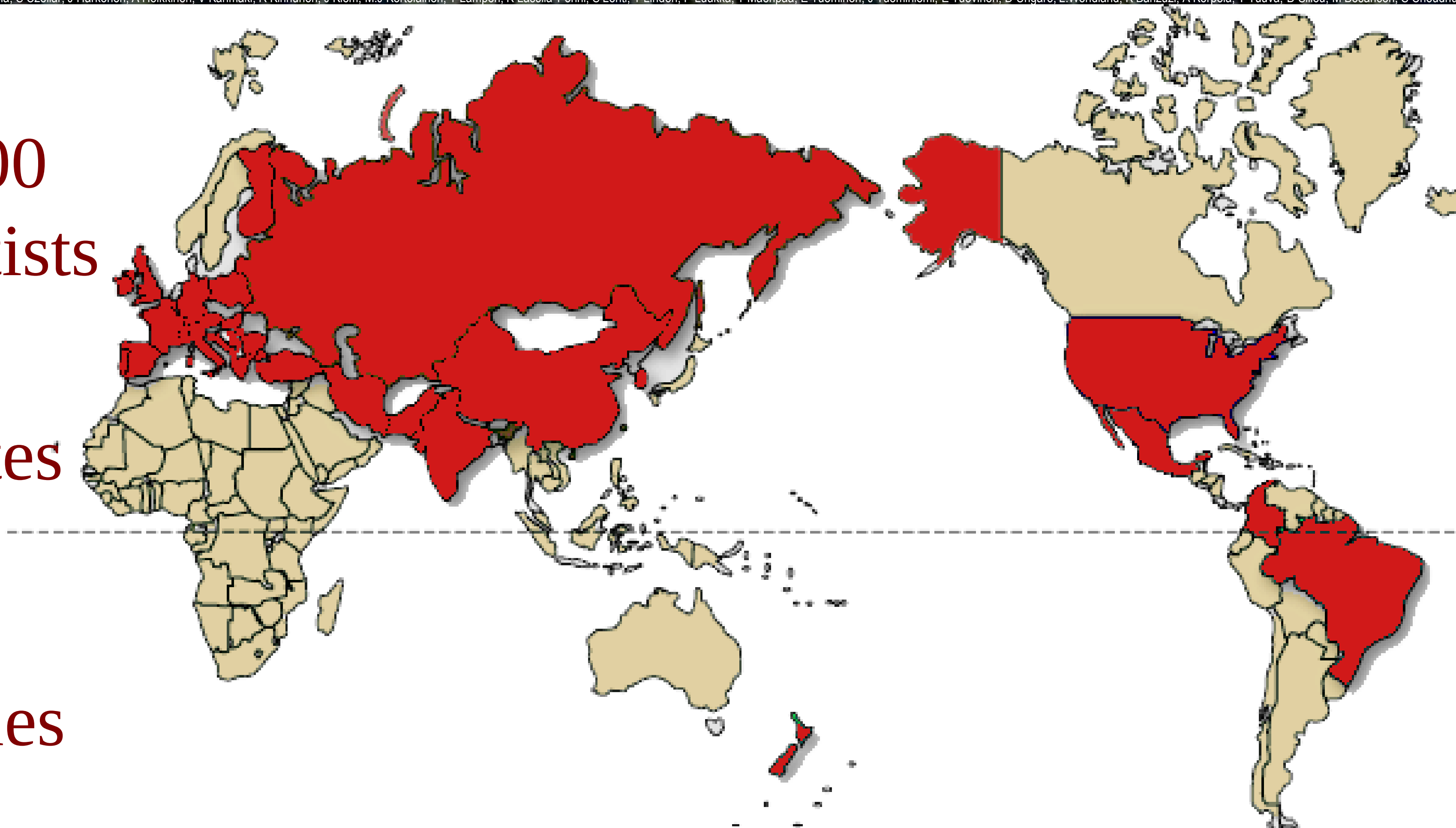
Who are you people?

V Khachatryan, A.M Sirunyan, A Tumasyan,W Adam, T Bergauer, M Dragicevic, J Ero, C Fabjan, M Friedl, R Fruhwirth, V.M Ghete, J Hammer, S Hansel, C Hartl, M Hoch, N Hormann, J Hrubec, M Jeitler, G Kasieczka, W Kiesenhofer, M Krammer, D Liko, I Mikulec, M Pernicka, H Rohringer, R Schofbeck, J Strauss, A Taurok, F Teischinger, P.Wagner, W.Waltenberger, G.Walzel, E.Widl, C.-E.Wulz, V Mossolov, N Shumeiko, J Suarez Gonzalez, L Benucci, K Cerny, E.A De Wolf, X Janssen, T Maes, L Mucibello, S Ochesanu, B Roland, R Rougny, M Selvaggi, H Van Haevermaet, P Van Mechelen, N Van Remortel, V Adler, S Beauceron, F Blekman, S Blyweert, J D'Hondt, O Devroede, R Gonzalez Suarez, A Kalogeropoulos, J Maes, M Maes, S Tavernier, W Van Doninck, P Van Mulders, G.P Van Onsem, I Villella, O Charaf, B Clerbaux, G De Lentdecker, V Dero, A.P.R Gay, G.H Hammad, T Hreus, P.E Marage, L Thomas, C Vander Velde, P Vanlaer, J.Wickens, S Costantini, M Grunewald, B Klein, A Marinov, J Mccartin, D Ryckbosch, F Thyssen, M Tytgat, L Vanelderen, P Verwilligen, S.Walsh, N Zaganidis, S Basegmez, G Bruno, J Caudron, L Ceard, J De Favereau De Jeneret, C Delaere, P Demin, D Favart, A Giammanco, G Gr´egoire, J Hollar, V Lemaitre, J Liao, O Militaru, S Ovyn, D Pagano, A Pin, K Piotrzkowski, N Schul, N Beliy, T Caebergs, E Daubie, G.A Alves, D De Jesus Damiao, M.E Pol, M.H.G Souza, W Carvalho, E.M Da Costa, C De Oliveira Martins, S Fonseca De Souza, L Mundim, H Nogima, V Oguri,W.L Prado Da Silva, A Santoro, S.M Silva Do Amaral, A Sznajder, F.A Dias, M.A.F Dias, T.R Fernandez Perez Tomei, E M Gregores, F Marinho, S.F Novaes, Sandra S Padula, N Darmenov, L Dimitrov, V Genchev, P Iaydjiev, S Piperov, M Rodozov, S Stoykova, G Sultanov, V Tcholakov, R Trayanov, I Vankov, M Dyulendarova, R Hadjiiska, V Kozhuharov, L Litov, E Marinova, M Mateev, B Pavlov, P Petkov, J.G Bian, G.M Chen, H.S Chen, C.H Jiang, D Liang, S Liang, J Wang, J Wang, X Wang, Z.Wang, M Xu, M Yang, J Zang, Z Zhang, Y Ban, S Guo, Y Guo,W Li, Y Mao, S.J Qian, H Teng, L Zhang, B Zhu, W Zou, A Cabrera, B Gomez Moreno, A.A Ocampo Rios, A.F Osorio Oliveros, J.C Sanabria, N Godinovic, D Lelas, K Lelas, R Plestina, D Polic, I Puljak, Z Antunovic, M Dzelalija, V Brigljevic, S Duric, K Kadija, S Morovic, A Attikis, M Galanti, J Mousa, C Nicolaou, F Ptochos, P.A Razis, H Rykaczewski, Y Assran, M.A Mahmoud, A Hektor, M Kadastik, K Kannike, M Muntel, M Raidal, L Rebane, V Azzolini, P Eerola, S Czellar, J Harkonen, A Heikkinen, V Karimaki, R Kinnunen, J Klem, M.J Kortelainen, T Lampen, K Lassila-Perini, S Lehti, T Linden, P Luukka, T Maenpaa, E Tuominen, J Tuominiemi, E Tuovinen, D Ungaro, L.Wendland, K Banzuzi, A Korpela, T Tuuva, D Sillou, M Besancon, S Choudhury, M Dejardin, D

2,500 scientists

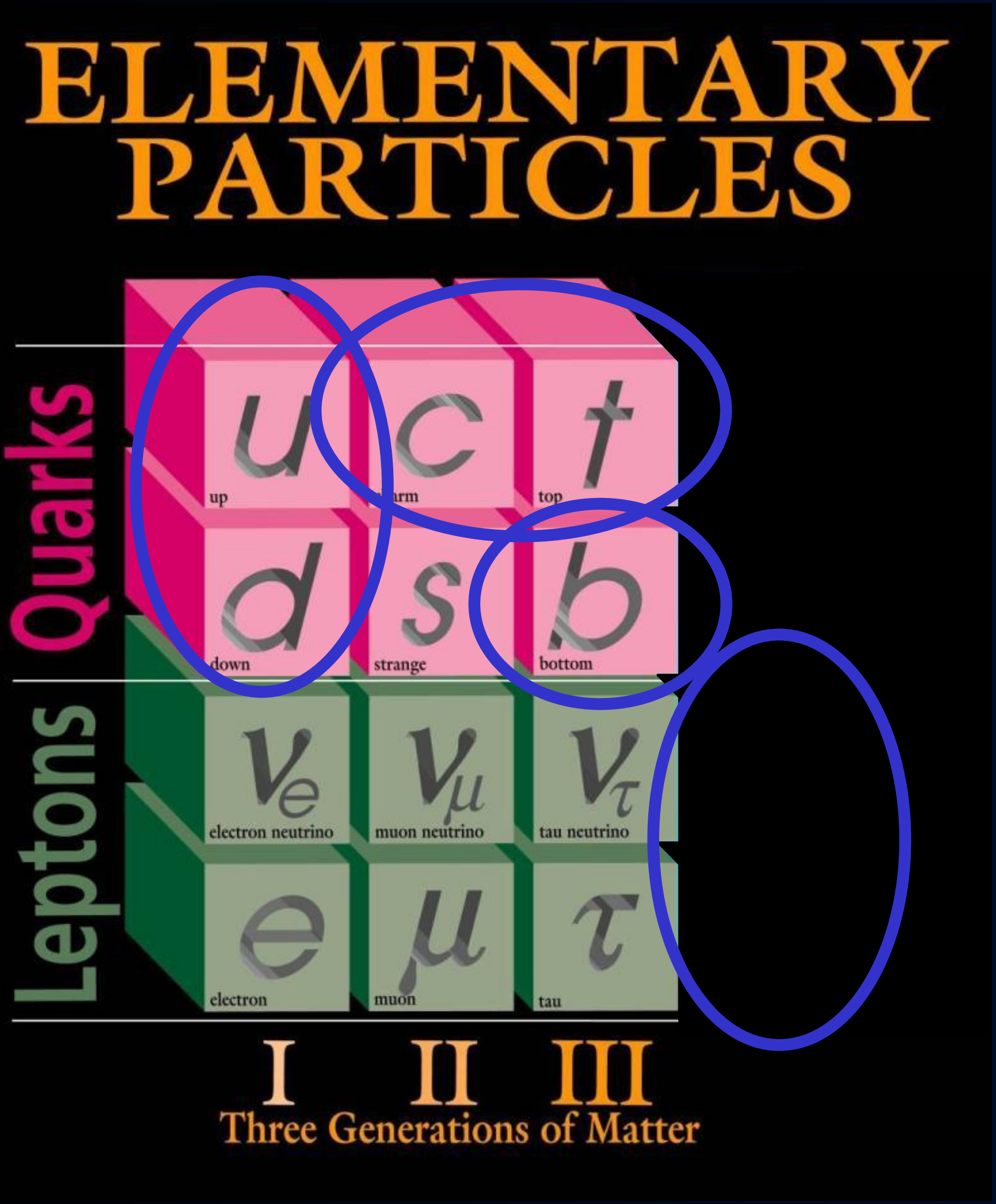
183 institutes

38 countries



L Apanasevich, Y Bai, V.E Bazterra, R.R Betts, J Callner, R Cavanaugh, C Dragoiu, E.J Garcia-Solis, L Gauthier, C.E Gerber, D.J Hofman, S Khalatyan, F Lacroix, M Malek, C O'Brien, C Silvestre, A Smoron, D Strom, N Varelas, U Akgun, E.A Albayrak, B Bilki, K Cankocak,W Clarida, F Duru, C.K Lae, E McCliment, J.-P Merlo, H Mermerkaya, A Mestvirishvili, A Moeller, J Nachtman, C.R Newsom, E Norbeck, J Olson, Y Onel, F Ozok, S Sen, J.Wetzel, T Yetkin, K Yi, B.A Barnett, B Blumenfeld, A Bonato, C Eskew, D Fehling, G Giurgiu, A.V Gritsan, Z.J Guo, G Hu, P Maksimovic, S Rappoccio, M Swartz, N.V Tran, A Whitbeck, P Baringer, A Bean, G Benelli, O Grachov, M Murray, D Noonan, V Radicci, S Sanders, J.S.Wood, V Zhukova, T Bolton, I Chakaberia, A Ivanov, M Makouski, Y Maravin, S Shrestha, I Svintradze, Z.Wan, J Gronberg, D Lange, D Wright, A Baden, M Boutemeur, S.C Eno, D Ferencek, J.A Gomez, N.J Hadley, R.G Kellogg, M Kirn, Y Lu, A.C Mignerey, K Rossato, P Rumerio, F Santanastasio, A Skuja, J Temple, M.B Tonjes, S.C Tonwar, E Twedt, B Alver, G Bauer, J Bendavid, W Busza, E Butz, I.A Cali, M Chan, V Dutta, P Everaerts, G Gomez Ceballos, M Goncharov, K.A Hahn, P Harris, Y Kim, M Klute, Y.-J Lee, W Li, C Loizides, P.D Luckey, T Ma, S Nahn, C Paus, D Ralph, C Roland, G Roland, M Rudolph, G.S.F Stephans, K Sumorok, K Sung, E.A Wenger, S Xie, M Yang, Y Yilmaz, A.S Yoon, M Zanetti, P Cole, S.I Cooper, P Cushman, B Dahmes, A De Benedetti, P.R Dudero, G Franzoni, J Haupt, K Klapoetke, Y Kubota, J Mans, V Rekovic, R Rusack, M Sasseville, A Singovsky, L.M Cremaldi, R Godang, R Kroeger, L Perera, R Rahmat, D.A Sanders, D Summers, K Bloom, S Bose, J Butt, D.R Claes, A Dominguez, M Eads, J Keller, T Kelly, I Kravchenko, J Lazo-Flores, C Lundstedt, H Malbouisson, S Malik, G.R Snow, U Baur, A Godshalk, I Iashvili, S Jain, A Kharchilava, A Kumar, S.P Shipkowski, K Smith, G Alverson, E Barberis, D Baumgartel, O Boeriu, M Chasco, S Reucroft, J Swain, D Wood, J Zhang, A Anastassov, A Kubik, N Odell, R.A Ofierzynski, B Pollack, A Pozdnyakov, M Schmitt, S Stoynev, M Velasco, S.Won, L Antonelli, D Berry, M Hildreth, C Jessop, D.J Karmgard, J Kolb, T Kolberg, K Lannon, W Luo, S Lynch, N Marinelli, D.M Morse, T Pearson, R Ruchti, J Slaunwhite, N Valls, J Warchol, M.Wayne, J Ziegler, B Bylsma, L.S Durkin, J Gu, C Hill, P Killewald, K Kotov, T.Y Ling, M Rodenburg, G.Williams, N Adam, E Berry, P Elmer, D Gerbaudo, V Halyo, P Hebda, A Hunt, J Jones, E Laird, D Lopes Pegna, D Marlow, T Medvedeva, M Mooney, J Olsen, P Piroue, X Quan, H Saka, D Stickland, C Tully, J.S.Werner, A Zuranski, J.G Acosta, X.T Huang, A Lopez, H Mendez, S Oliveros, J.E Ramirez Vargas, A Zatserklyaniy, E Alagoz, V.E Barnes, G Bolla, L Borrello, D Bortoletto, A Everett, A.F Garfinkel, Z Gecse, L Gutay, Z Hu, M Jones, O Koybasi, A.T Laasanen, N Leonardo, C Liu, V Maroussov, P Merkel, D.H Miller, N Neumeister, I Shipsey, D Silvers, A Svyatkovskiy, H.D Yoo, J Zablocki, Y Zheng, P Jindal, N Parashar, C Boulahouache, V Cuplov, K.M Ecklund, F.J.M Geurts, J.H Liu, B.P Padley, R Redjimi, J Roberts, J Zabel, B Betchart, A Bodek, Y.S Chung, R Covarelli, P de Barbaro, R Demina, Y Eshaq, H Flacher, A Garcia-Bellido, P Goldenzweig, Y Gotra, J Han, A Harel, D.C Miner, D Orbaker, G Petrillo, D Vishnevskiy, M Zielinski, A Bhatti, R Ciesielski, L Demortier, K Goulianos, G Lungu, C Mesropian, M Yan, O Atramentov, A Barker, D Duggan, Y Gershtein, R Gray, E Halkiadakis, D Hidas, D Hits, A Lath, S Panwalkar, R Patel, A Richards, K Rose, S Schnetzer, S Somalwar, R Stone, S Thomas, G Cerizza, M Hollingsworth, S Spanier, Z.C Yang, A York, J Asaadi, R Eusebi, J Gilmore, A Gurrola, T Kamon, V Khotilovich, R Montalvo, C.N Nguyen, I Osipenkov, J Pivarski, A Safonov, S Sengupta, A Tatarinov, D Toback, M.Weinberger, N Akchurin, C Bardak, J Damgov, C Jeong, K Kovitanggoon, S.W Lee, P Mane, Y Roh, A Sill, I Volobouev, R.Wigmans, E Yazgan, E Appelt, E Brownson, D Engh, C Florez, W Gabella, W Johns, P Kurt, C Maguire, A Melo, P Sheldon, J Velkovska, M.W Arenton, M Balazs, S Boutle, M Buehler, S Conetti, B Cox, B Francis, R Hirosky, A Ledovskoy, C Lin, C Neu, R Yohay, S Gollapinni, R Harr, P.E Karchin, P Lamichhane, M Mattson, C Milst`ene, A Sakharov ,M Anderson, M Bachtis, J.N Bellinger, D Carlsmith, S Dasu, J Efron, L Gray, K.S Grogg, M Grothe, R Hall-Wilton, M Herndon, P Klabbers, J Klukas, A Lanaro, C Lazaridis, J Leonard, R Loveless, A Mohapatra, D Reeder, I Ross, A Savin, W.H Smith, J Swanson, M Weinberg

Warmup- the big picture…

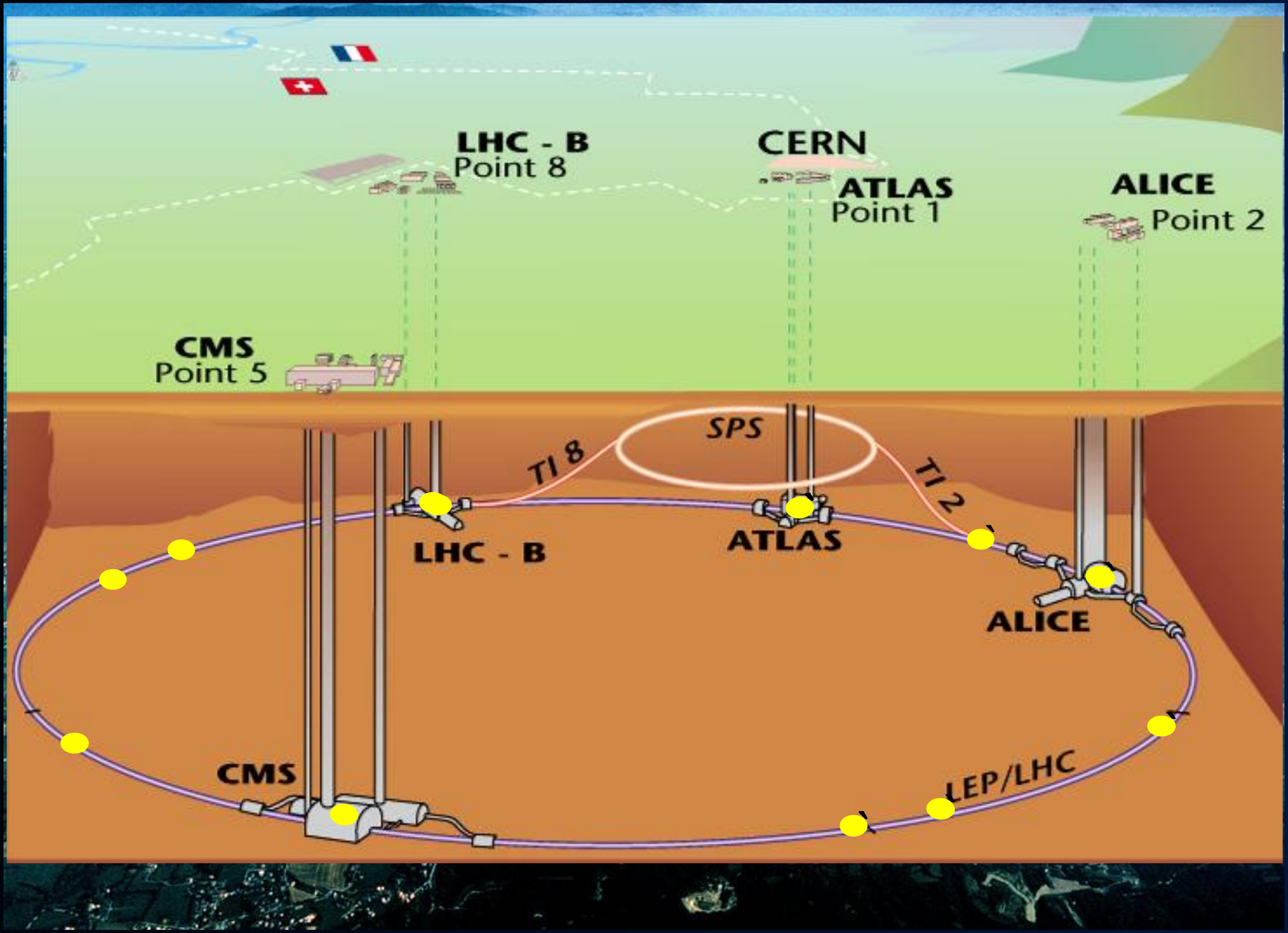


- **Some Findings using Accelerators**
  - **"Proton = 3 quarks"**
  - **"There are >3 quarks"**
  - **"We understand massive force carriers"**
  - **"Antiparticles not just Particles in mirror"**
- **Accelerators are useful**

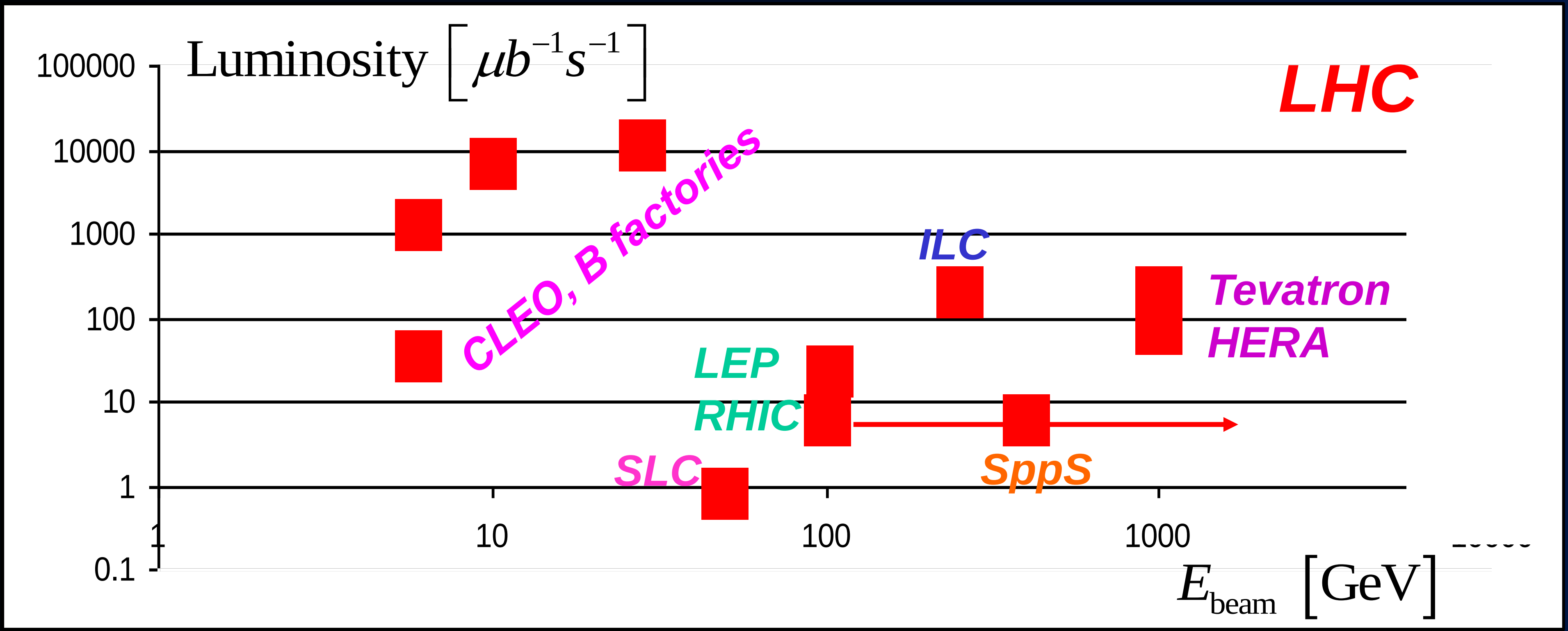
The Large Hadron Collider

Proton - Proton Collisions
Initially: 10^6 events/s, 7 TeV
Eventually: 10^9 events/s, 14 TeV

(Lead Ions
2.76 $\rightarrow$ 5.5
TeV/nucleon)

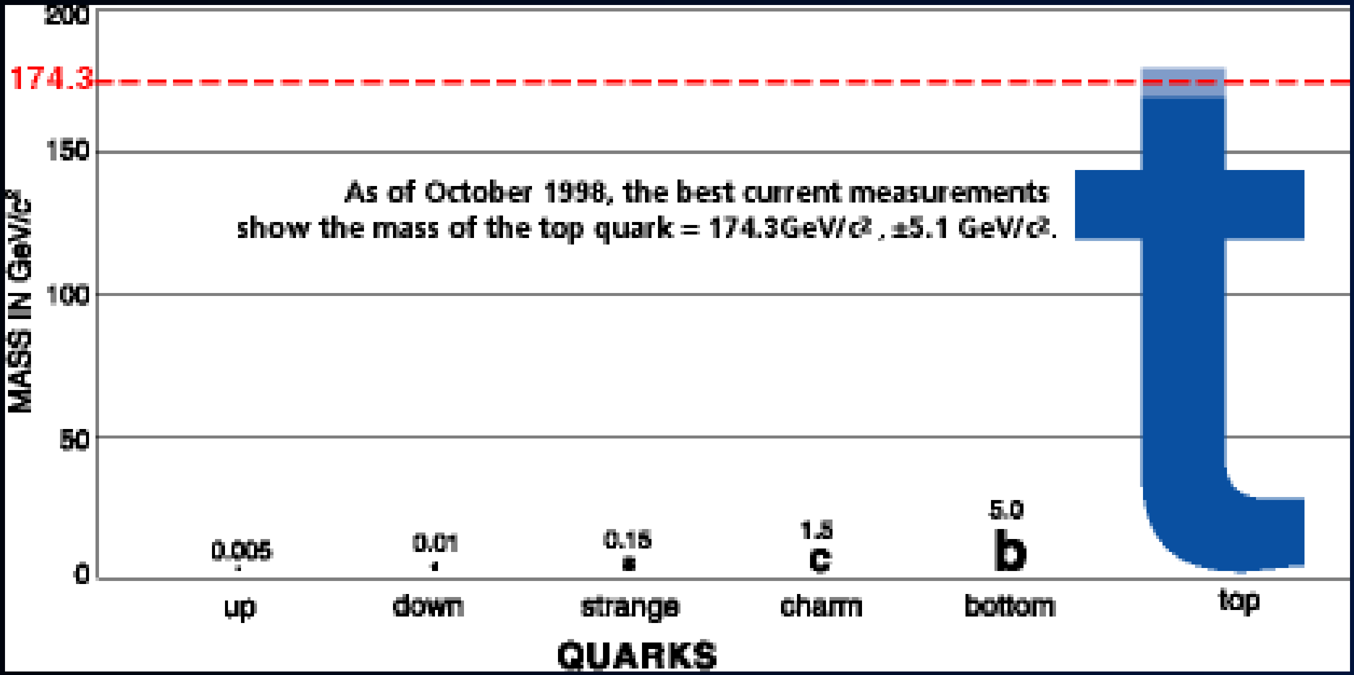


A BIG Step



- **LHC is the most important feature of the High Energy Physics landscape**

Hot topics: Where does Mass come from?

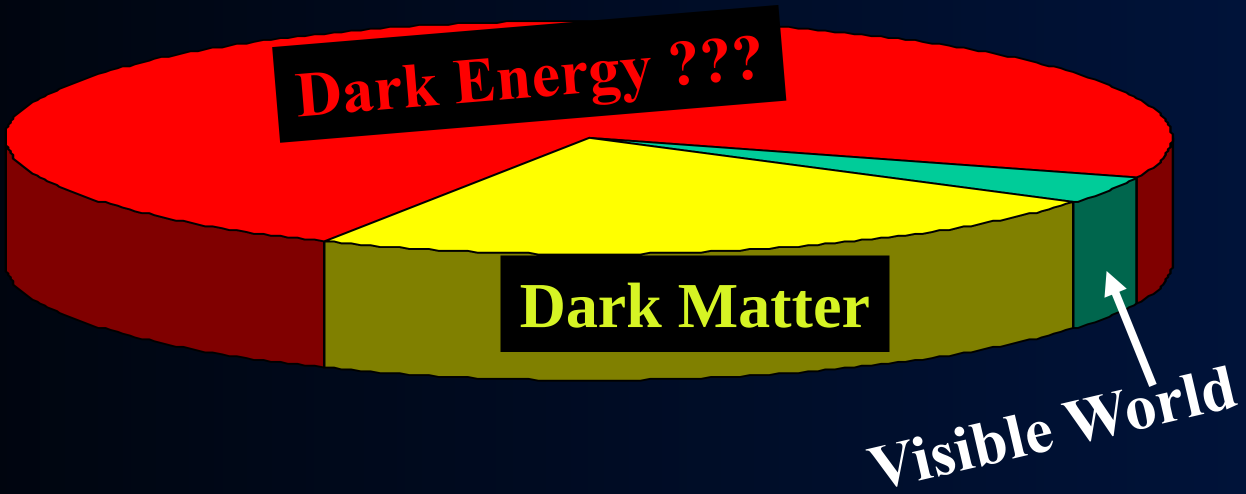


"Higgs Mechanism" = Economical way to have consistent theory with non-zero particle mass

$\Rightarrow$ New Particle between 114 and 1000 GeV

- **A Guarantee: WITHIN LHC REACH.**

Hot topics: Where is the rest of the Mass?

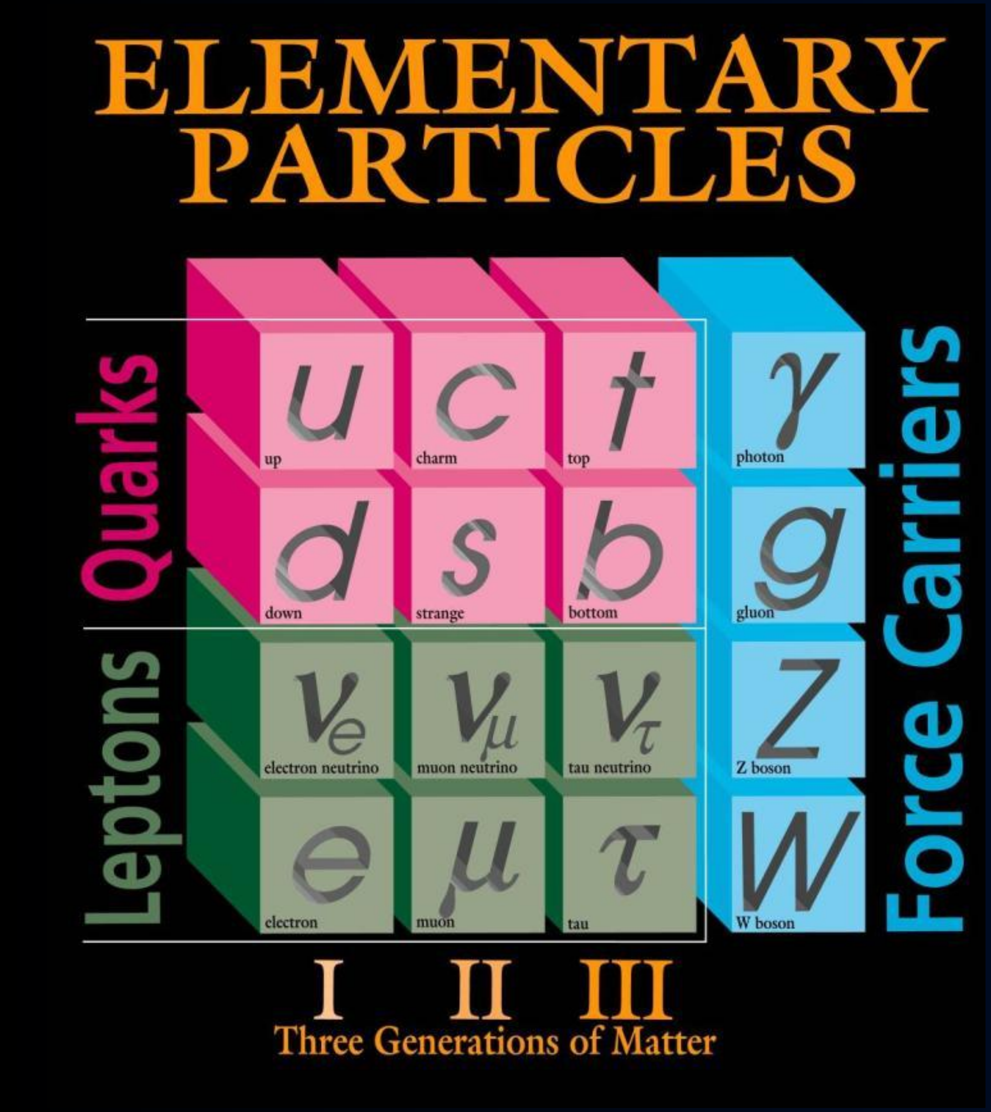


Next new particle ?=? Dark Matter

And unify the strong and electroweak forces
And cure further theoretical ailments
And …(save the economy?)

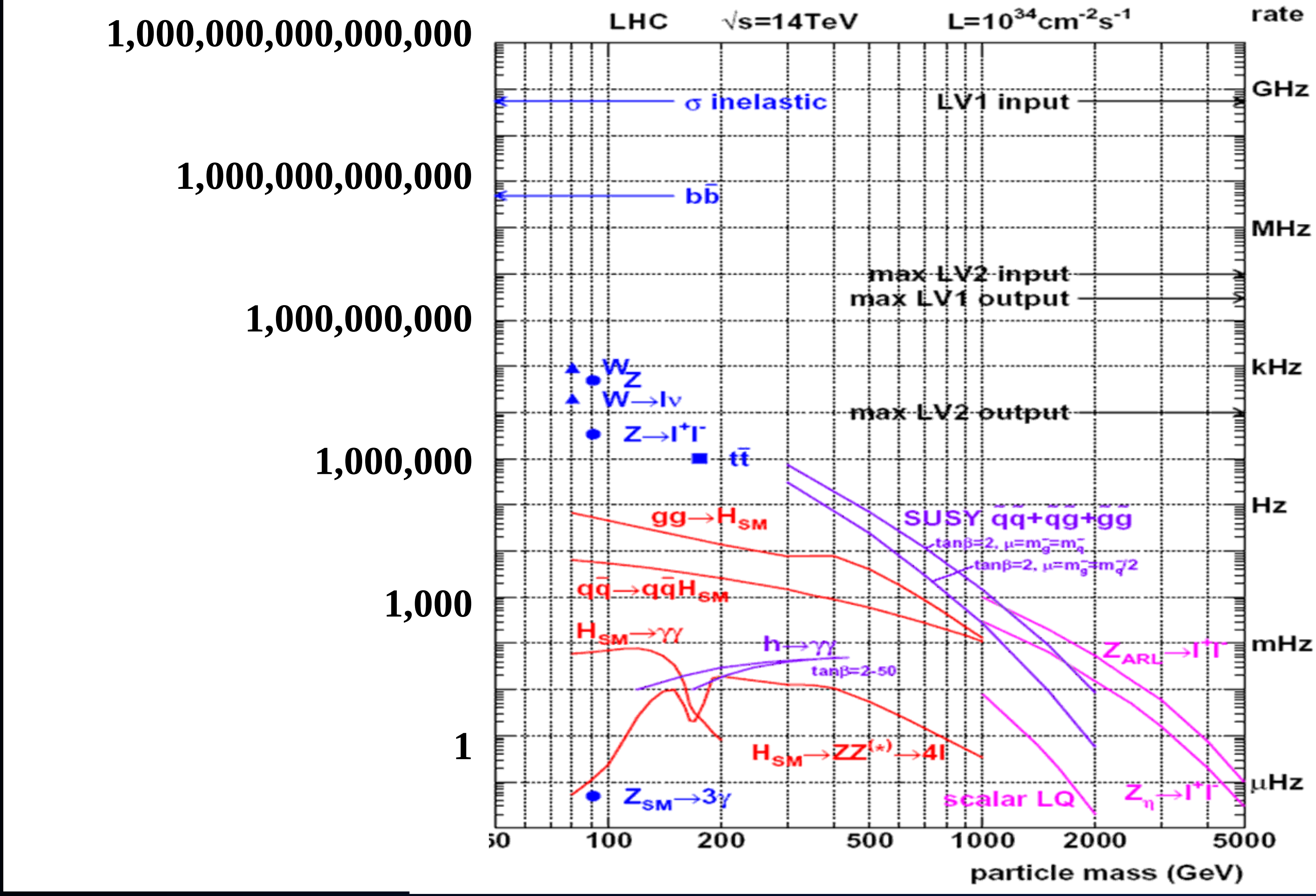
- **A Possibility: WITHIN LHC REACH?**

Hot Topics: Is this all there is?



- **Additional generations?**
- **Additional force carriers?**
- **Substructure?**
- **Fermions ⇔ Bosons**
- **A surprise? (I hope!)**

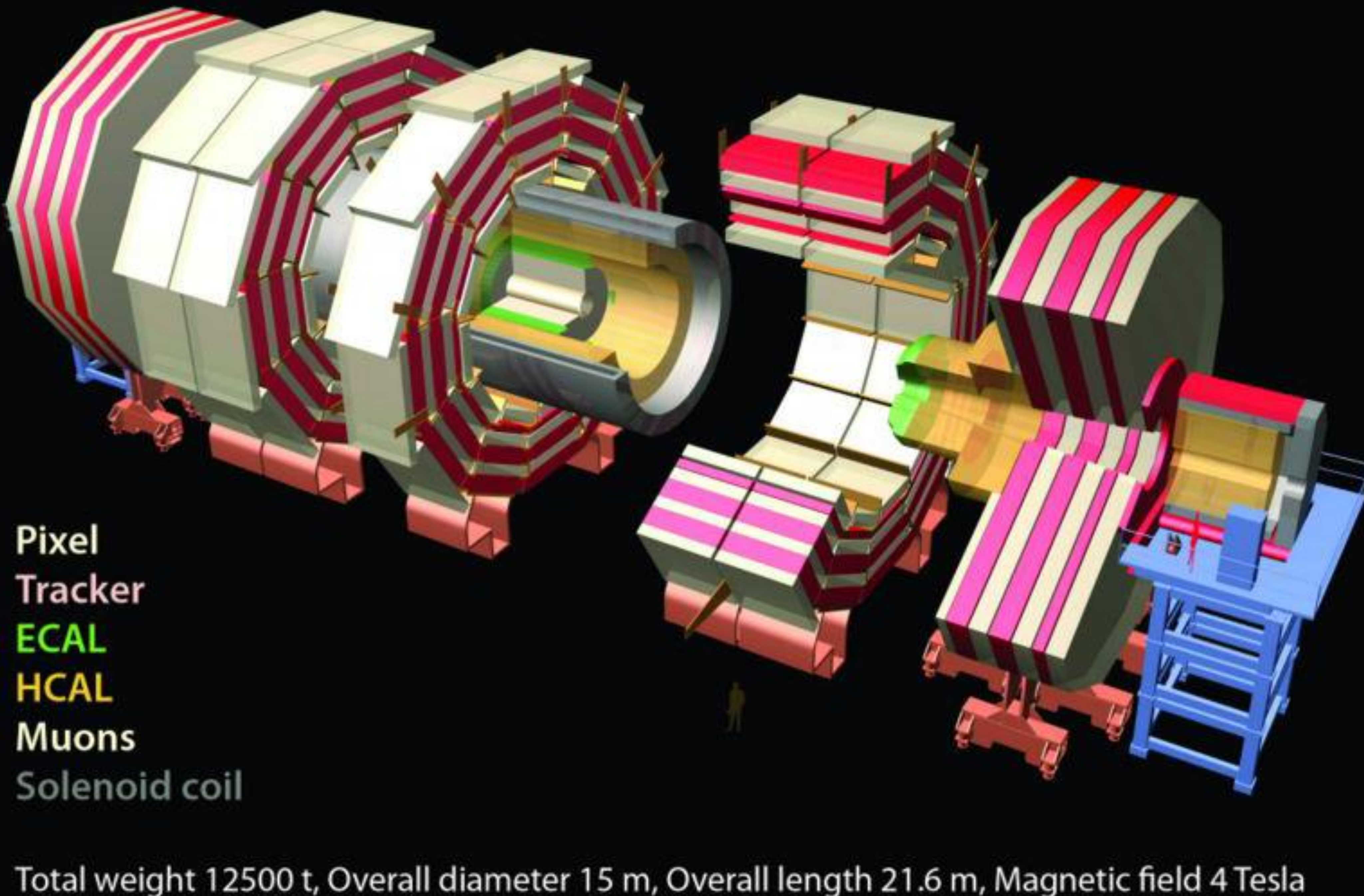
The needle in the haystack



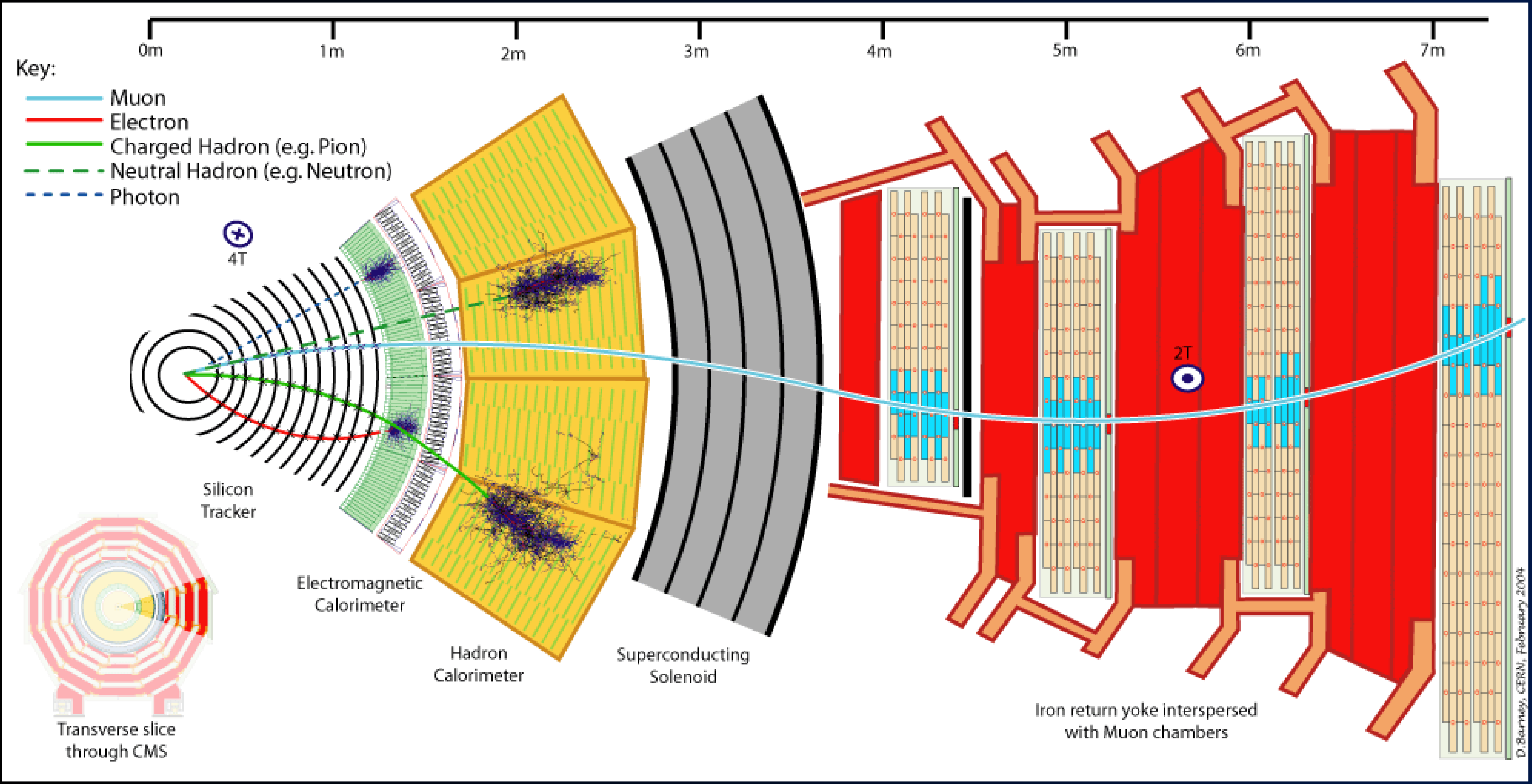
Need to step through the Standard Model to get to the 'New Stuff'

The detector

CMS in a nutshell



CMS Particle Detection Cribsheet



CMS Tracking Detector

- **All Silicon Tracker! 220 m^2 of Silicon!**
  - **Like a swimming pool covered in Silicon Wafers**

3D Pixels: 66 Mpix

3 barrel, 2x2 disks

2D Strips: 10 Mchan

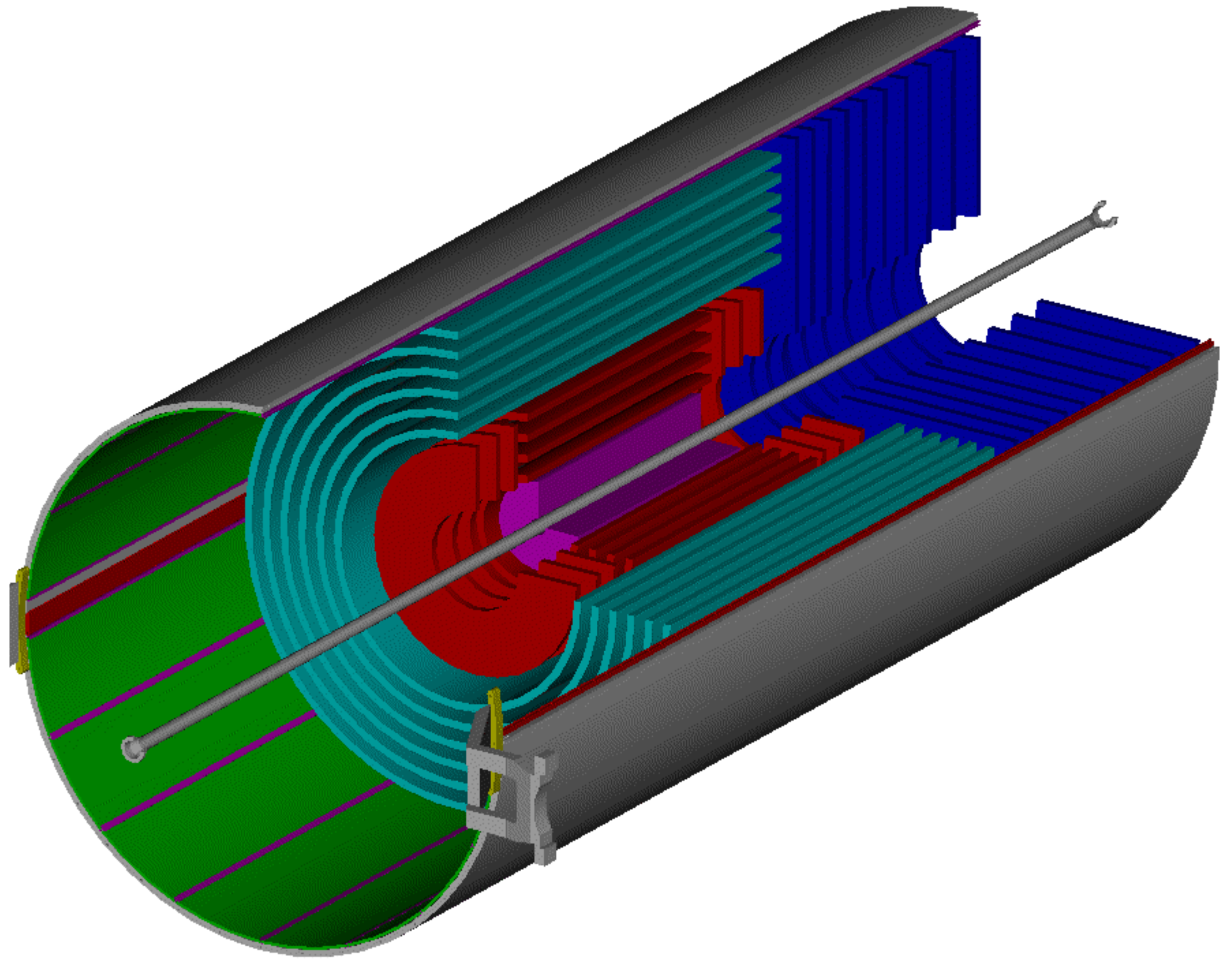
4 Inner, 6 Outer, barrel

2x 9 Endcap disks

$$|\eta| < 2.5, p_T > 300\, MeV$$

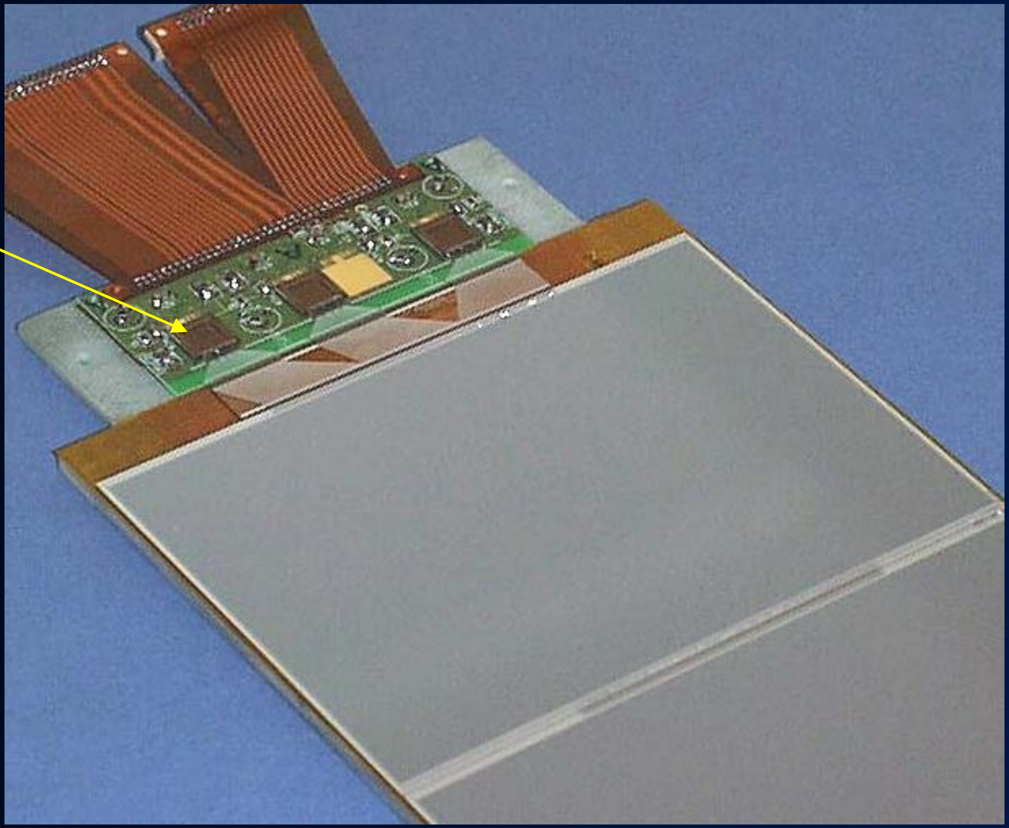
$$\left.\frac{\sigma_{p_T}}{p_T}\right|_{40\,GeV} \approx 1\%$$

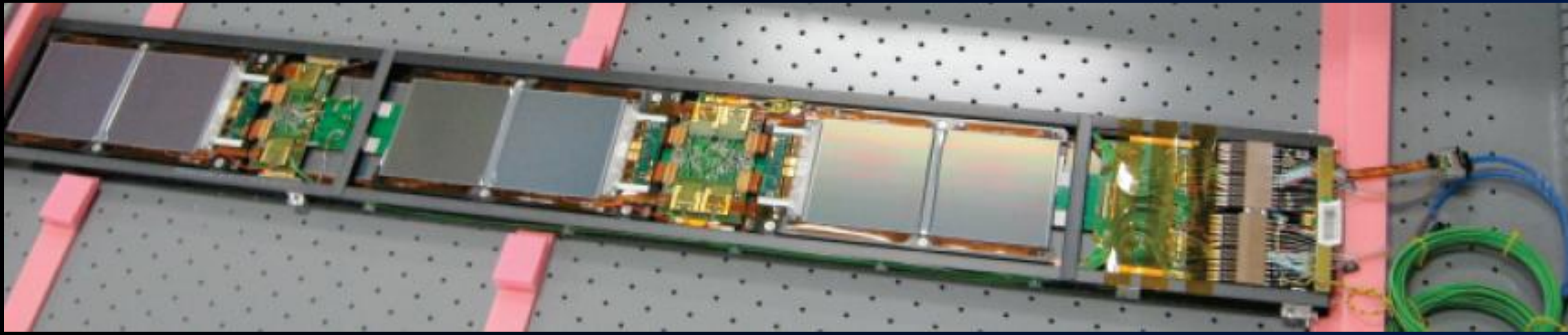
$$\sigma_{d0} \approx 15\,\mu m$$



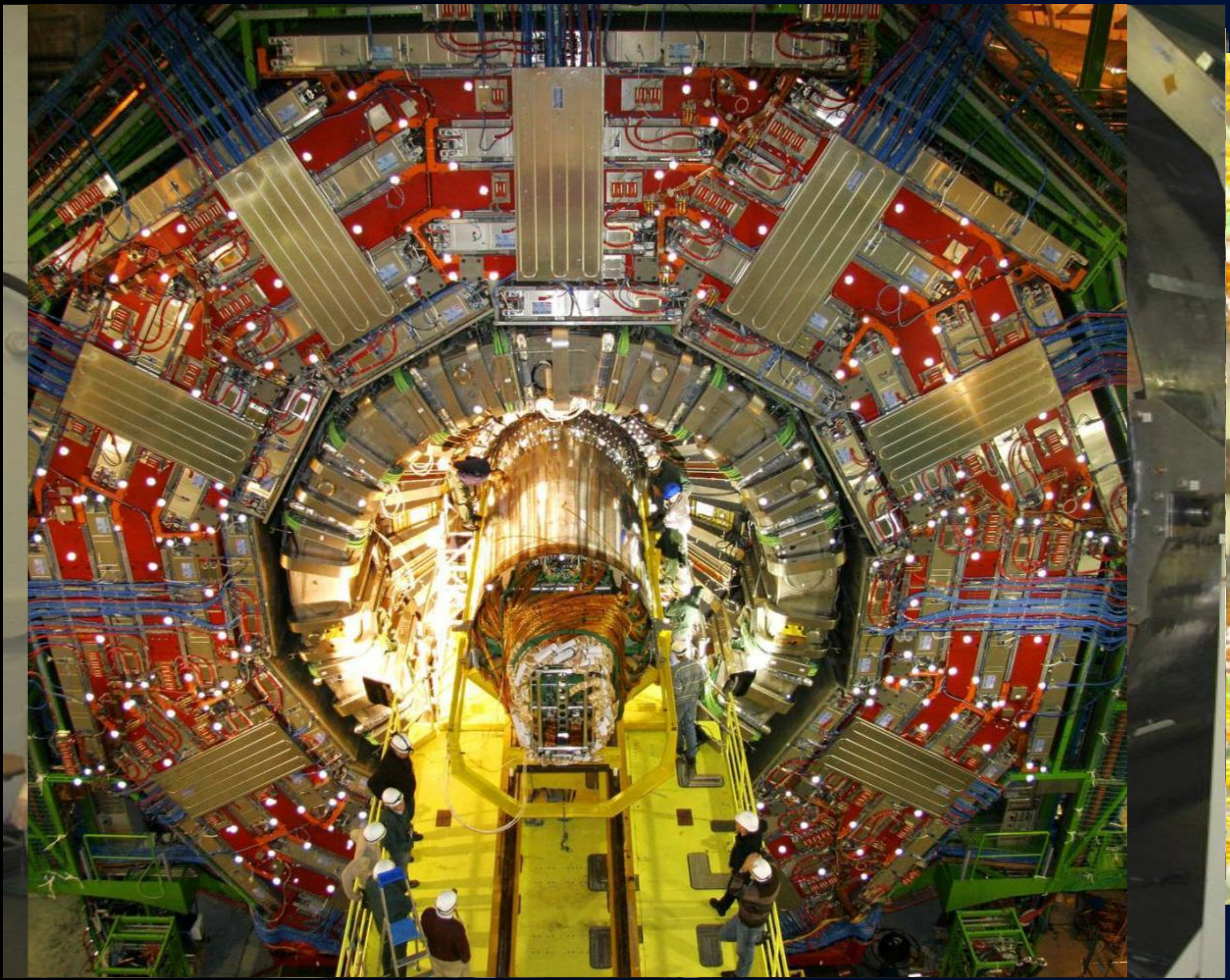
Some assembly required

- **On-board signal processing ASIC**
  - **Buffer high data rate**
- **Hybrid substrate**
  - **handle wafer i/o**
- **Carbon fiber frame**
  - **Integrated cooling**
  - **Fan in/out electronics**





Tracker Evolution in Pictures



June 2005

Aug 2006

Oct 2006

Dec 2006

Feb 2007

March 21 2007
Tracker Done

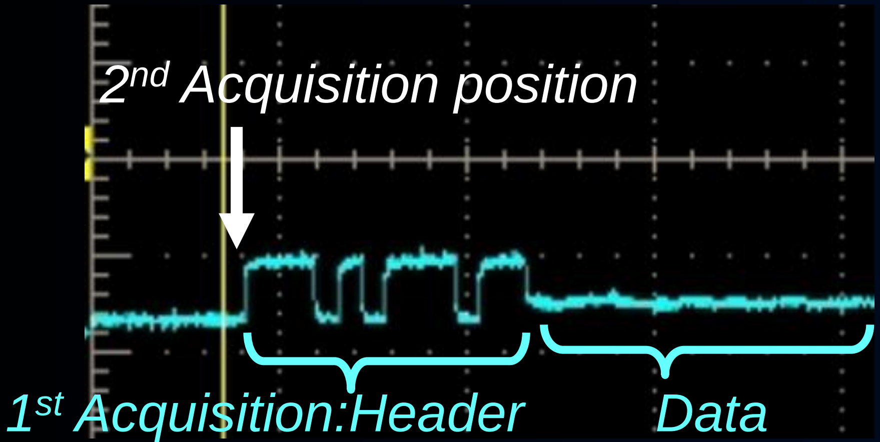
TIF Cosmics

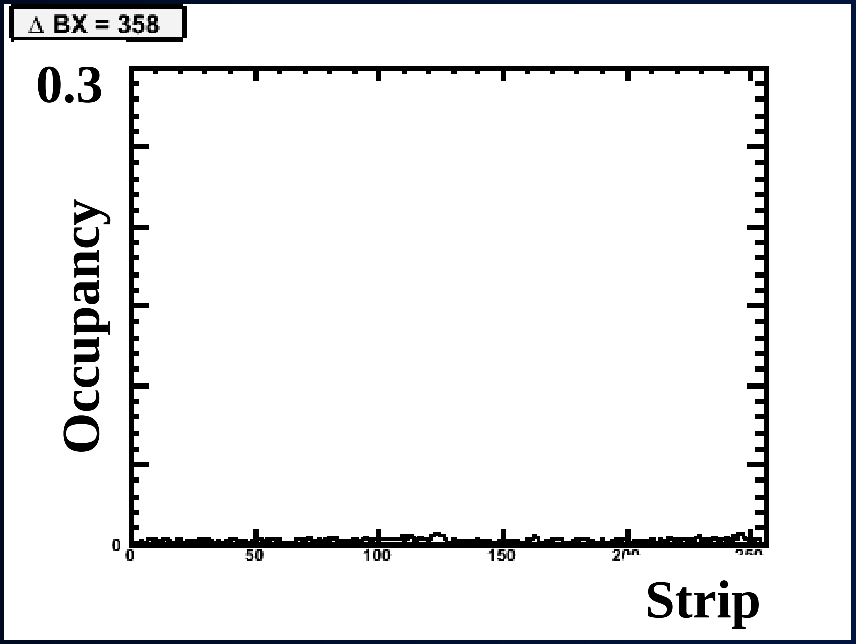
TK Packing
August 07

TK Delivery
Dec 07

Stepping Stone: Bump in the road

- **High Rate Testing**

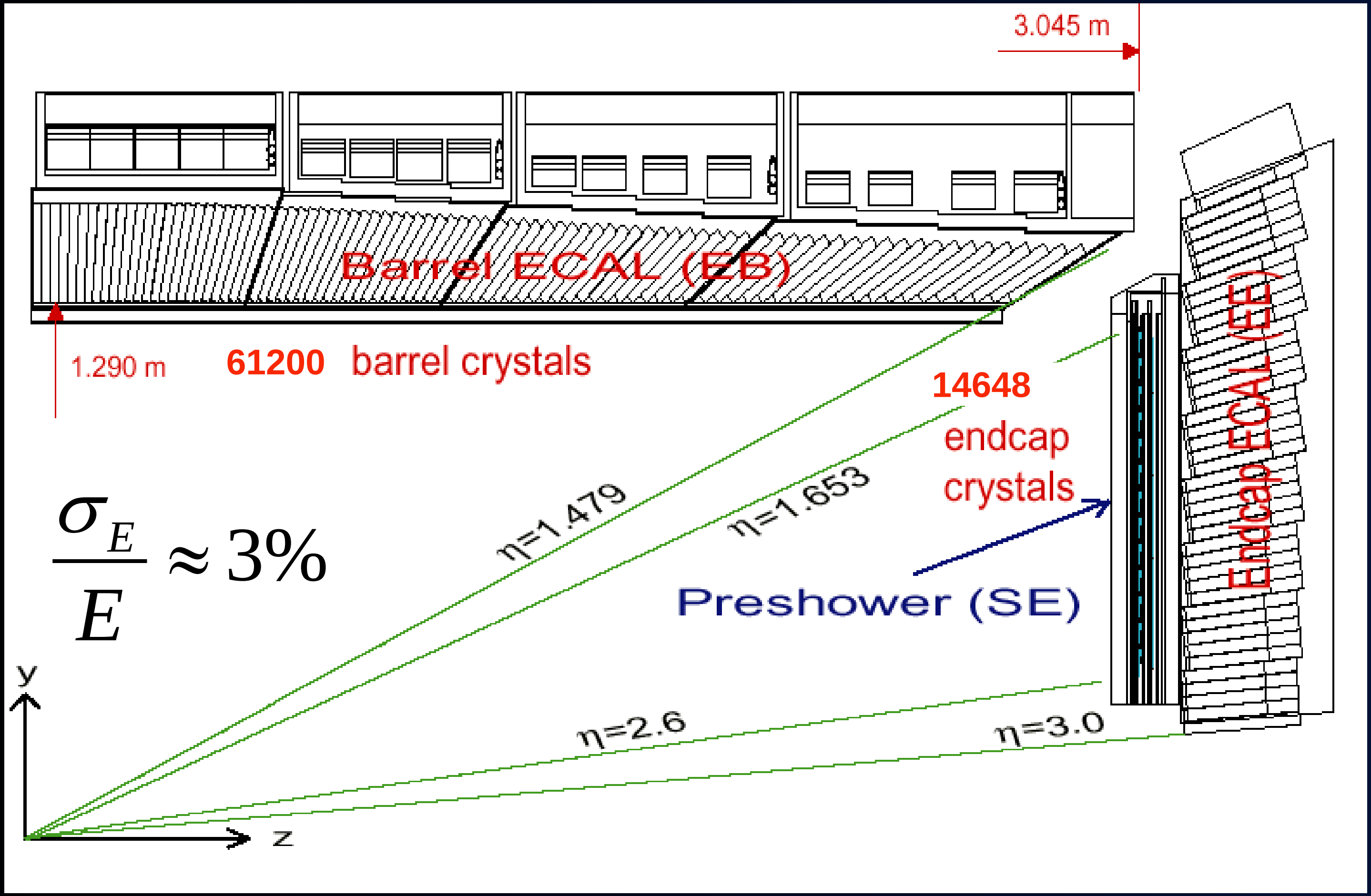




JINST 5 (2010) P07007

Electromagnetic Calorimeter

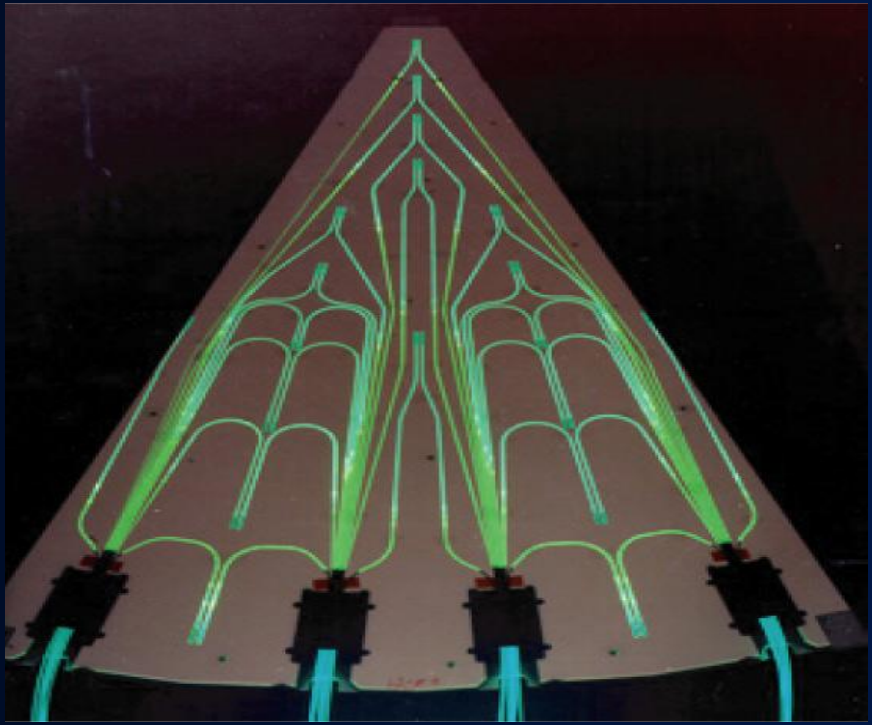
- **75 k PbW0_4 crystals, 2 x 2 x 23 cm, 3 lbs (1.4 kg)!**

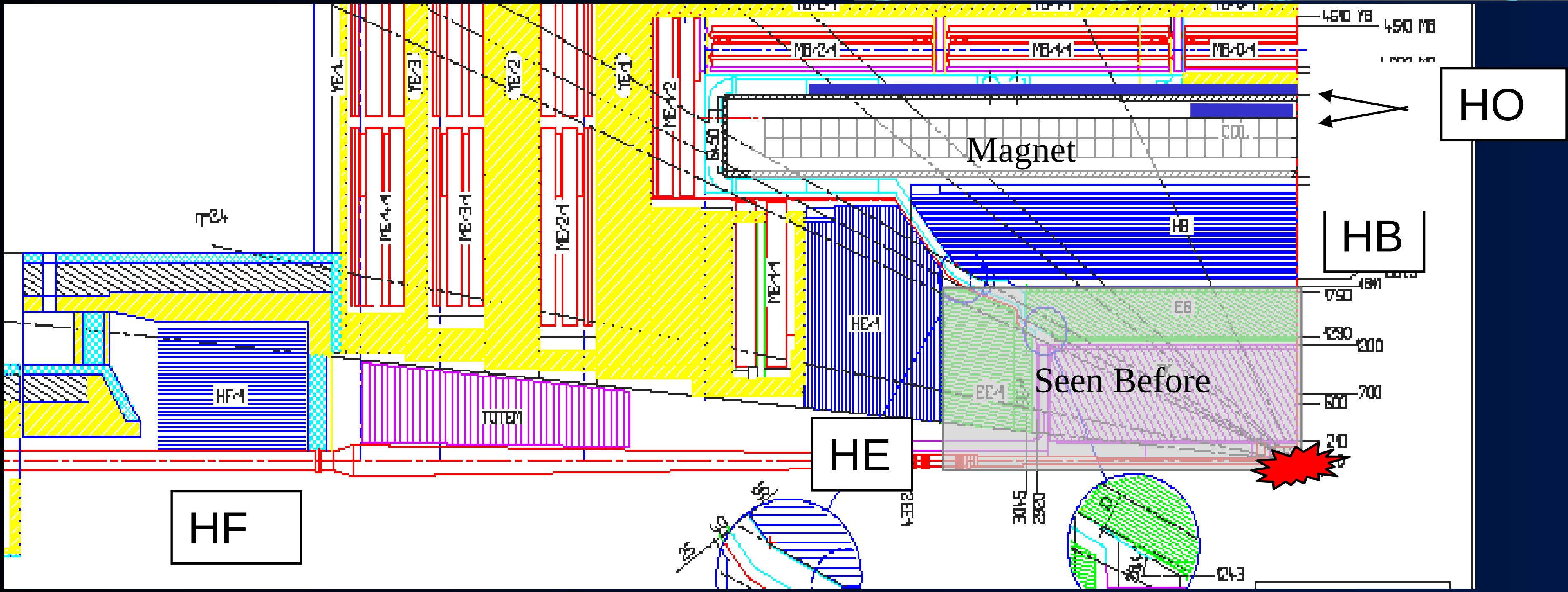


$$\frac{\sigma_E}{E} \approx 3\%$$

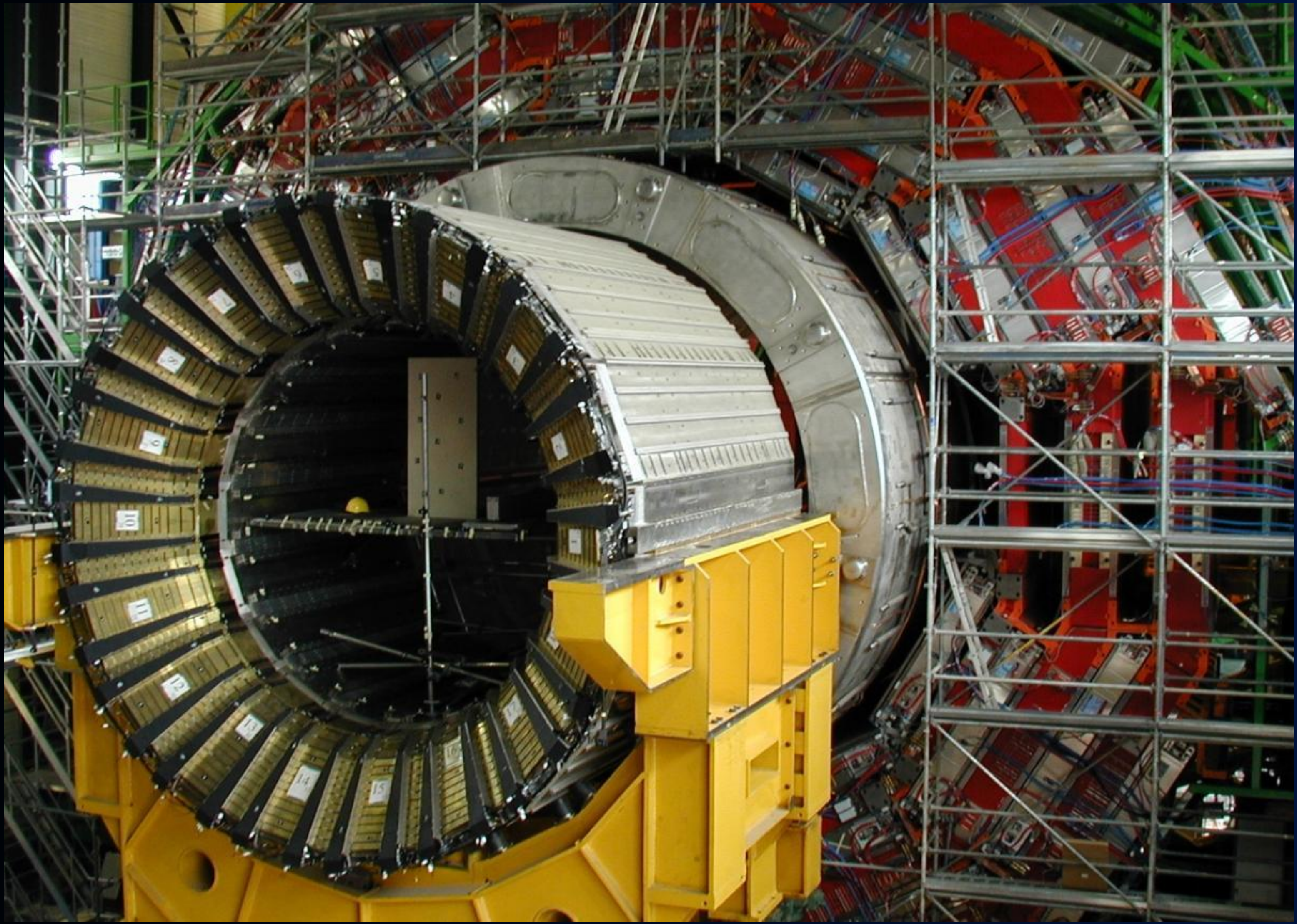
Hadron Calorimeter

- **Brass – Scintillator Sandwiches**
  - **WLS fibers read into Photodiodes**





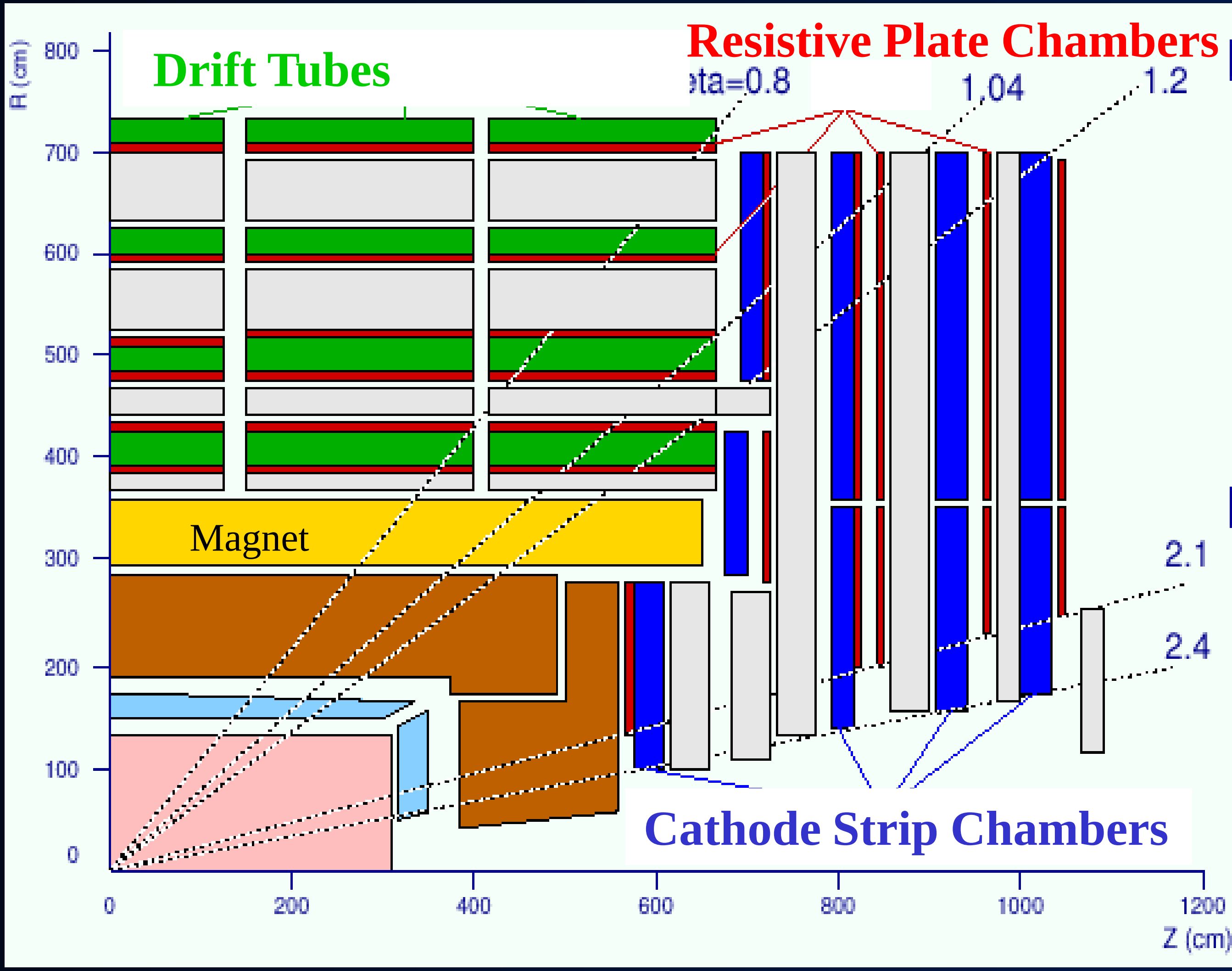
CMS Hadron Calorimeter



- **Brass recycled from Russian Cold War weaponry**

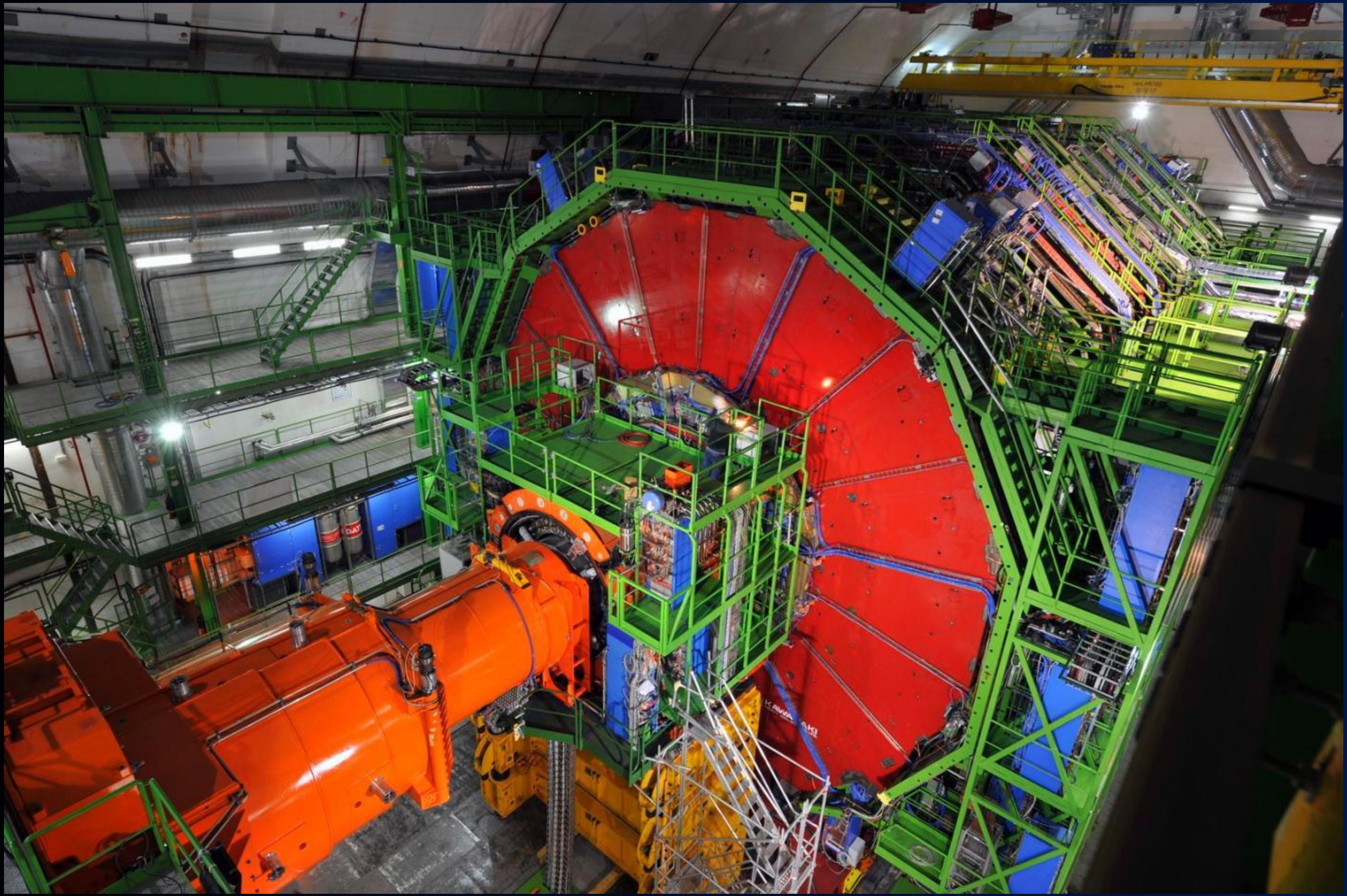
Muon Chambers

- **Immersed in Return Yoke**
- **25000 m^2 of detection planes**
- **~ 44 space points, expect 100 μm resolution**
- **Fast RPC trigger**



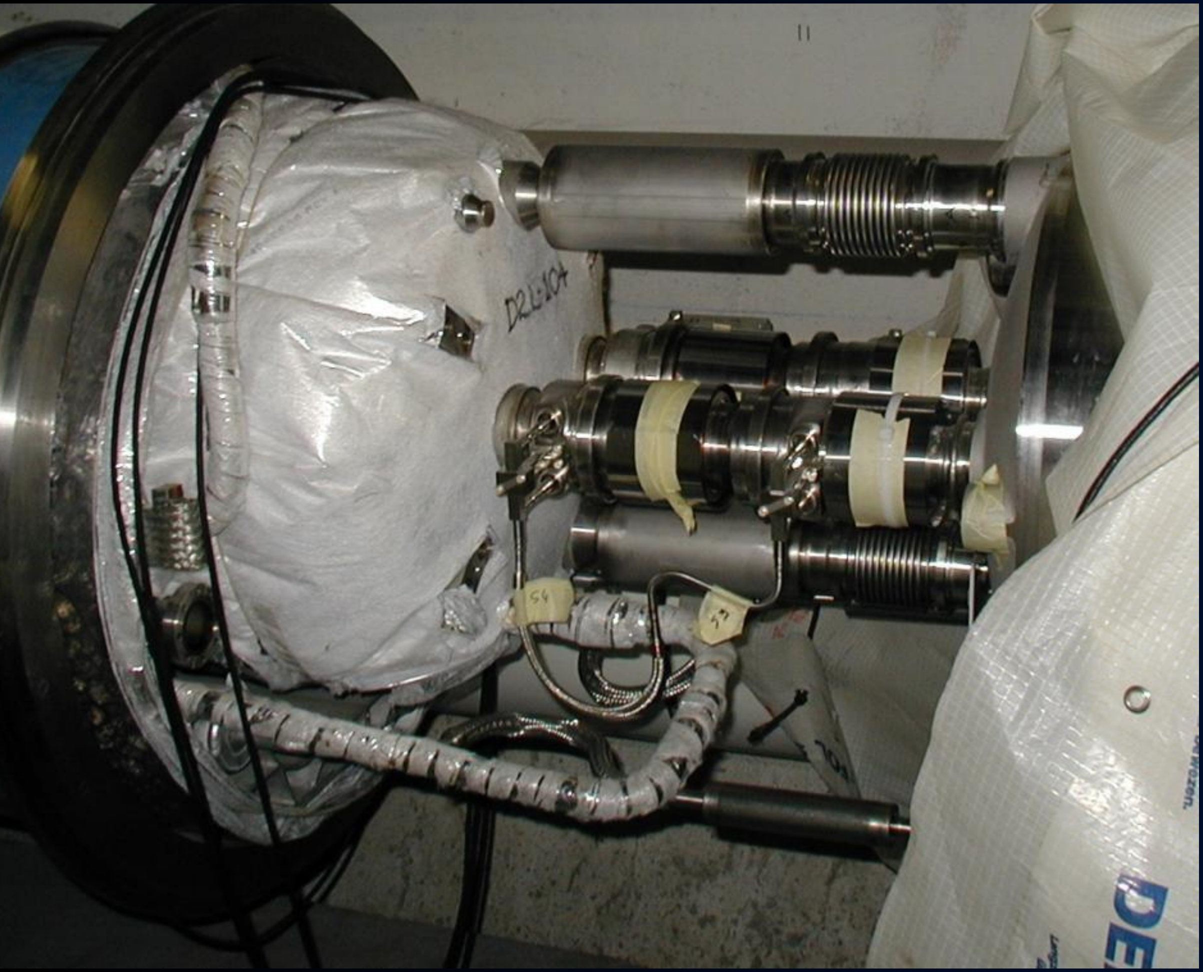
Just for scale…

All buttoned up



Another Stepping Stone…

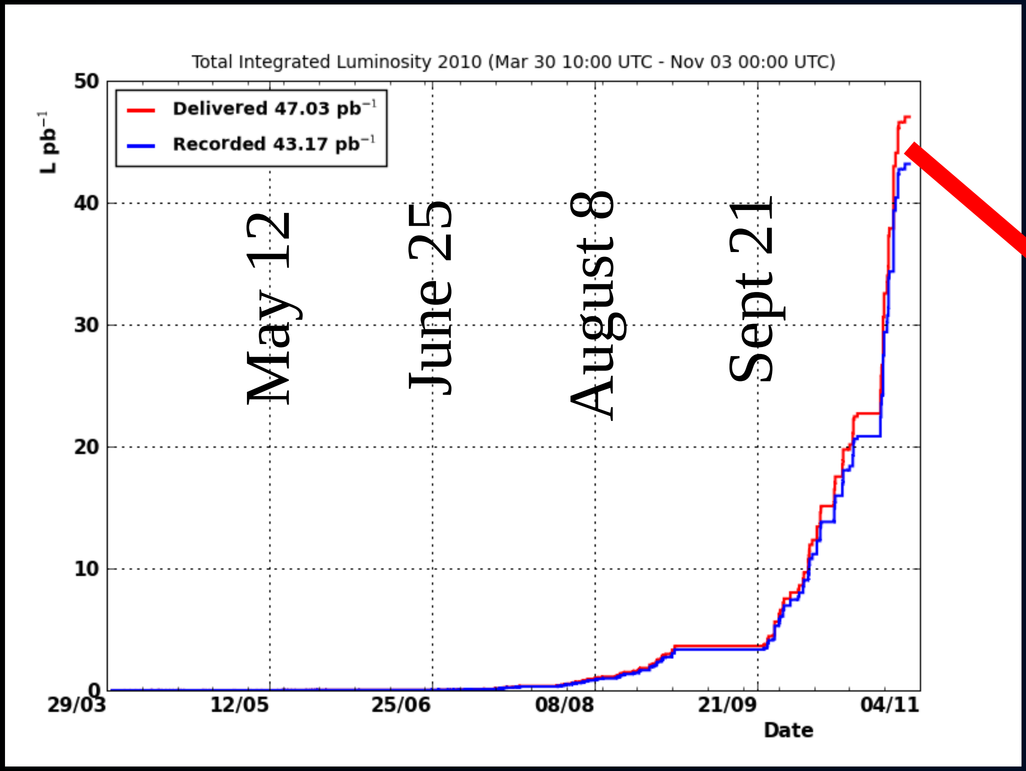
- **The accelerator has to work…**

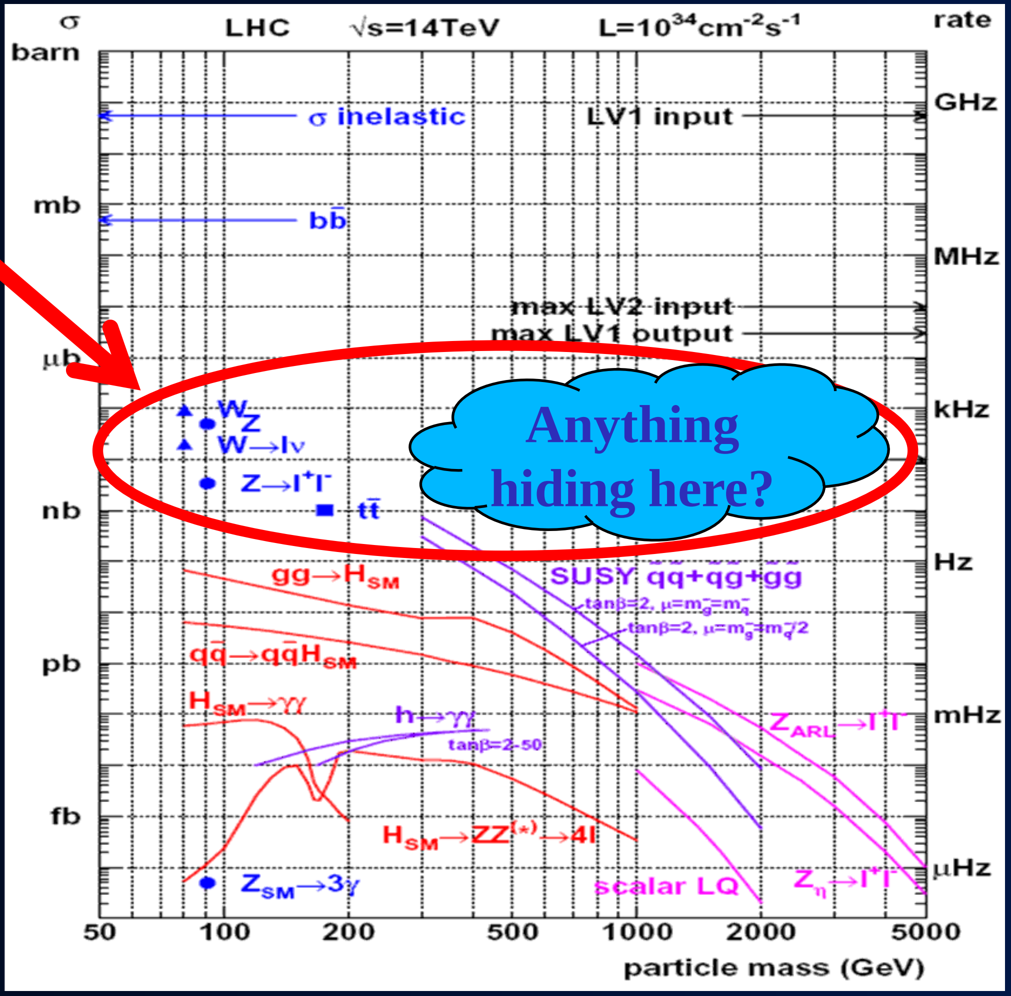


The 2010 run

After 2008 "trip", walk before you run

- **Cautious approach to increasing stored energy**





– **2011: ×20-100 more**

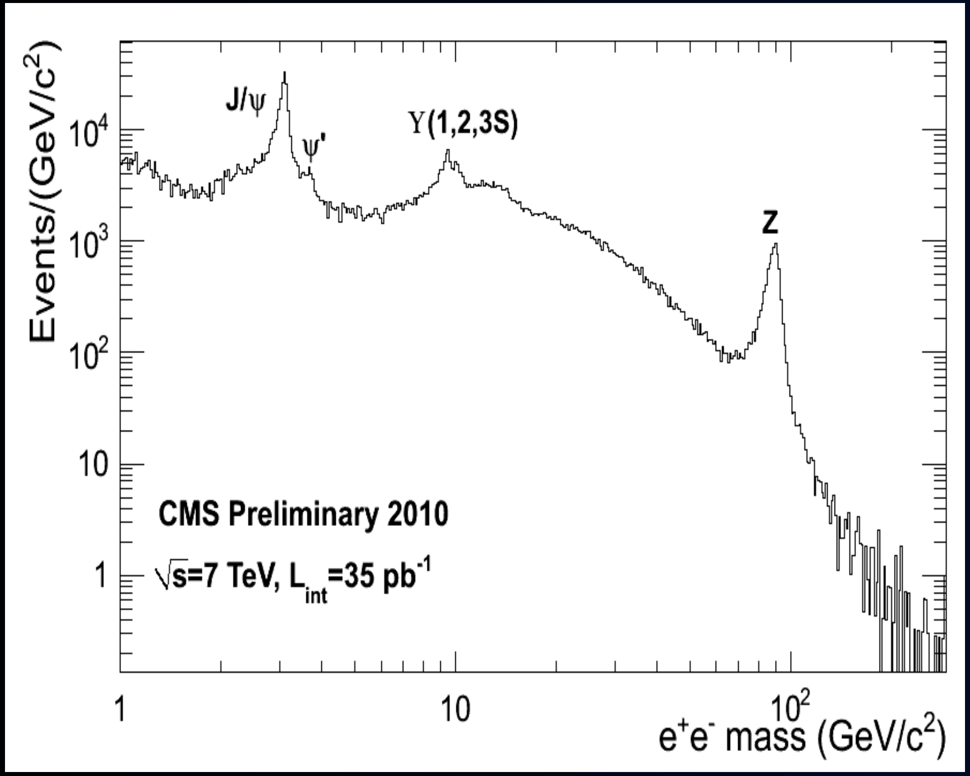
– **2012 Double again?**

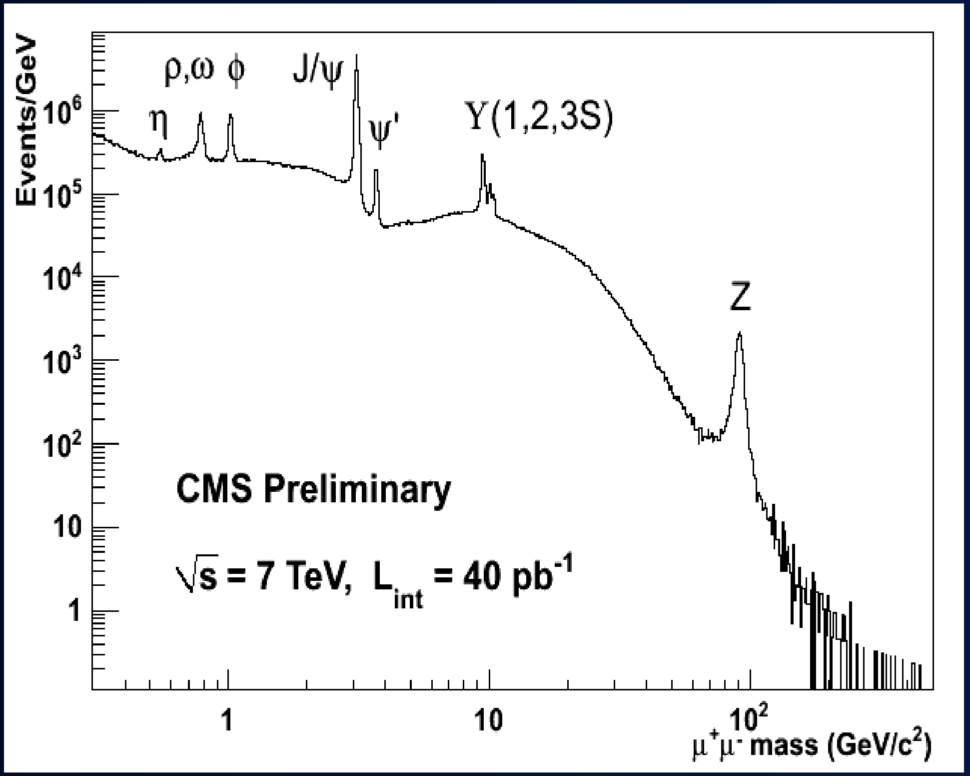
- **"Grain of salt" definitely applies**

Rediscovering the Standard Model

- **Known physics to benchmarks our performance**
  - **"Di-lepton" masses produce known particles**

electrons **muons**



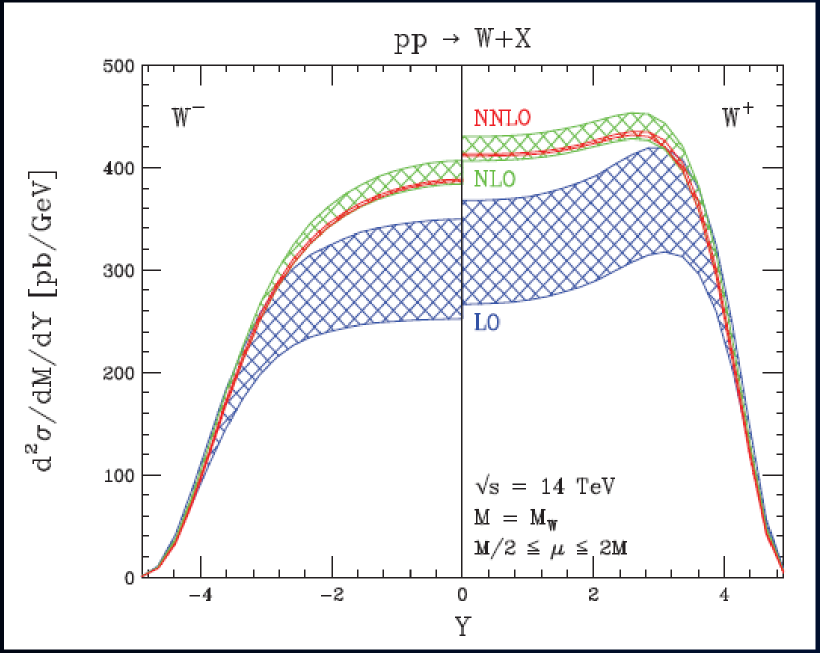


Stepping Stone: Electroweak Physics

- **First step in discovery is measuring a benchmark**

Inclusive Z and W cross sections in leptonic channels

- **New Energy point for SM measurement**



- **Understanding of Electrons, Muons, Missing Energy**
- **Future New Physics signatures or backgrounds**

Canonical Cross Section Measurement

$$\sigma(pp \to W/Z)\, Br(W/Z \to \ell\nu/\ell) = \frac{N_{\text{signal}}}{A\varepsilon \int \mathcal{L}dt}$$

Branching Ratios: From SM

 # Signal Events: Lepton Selection to reduce background, then fit for signal extraction

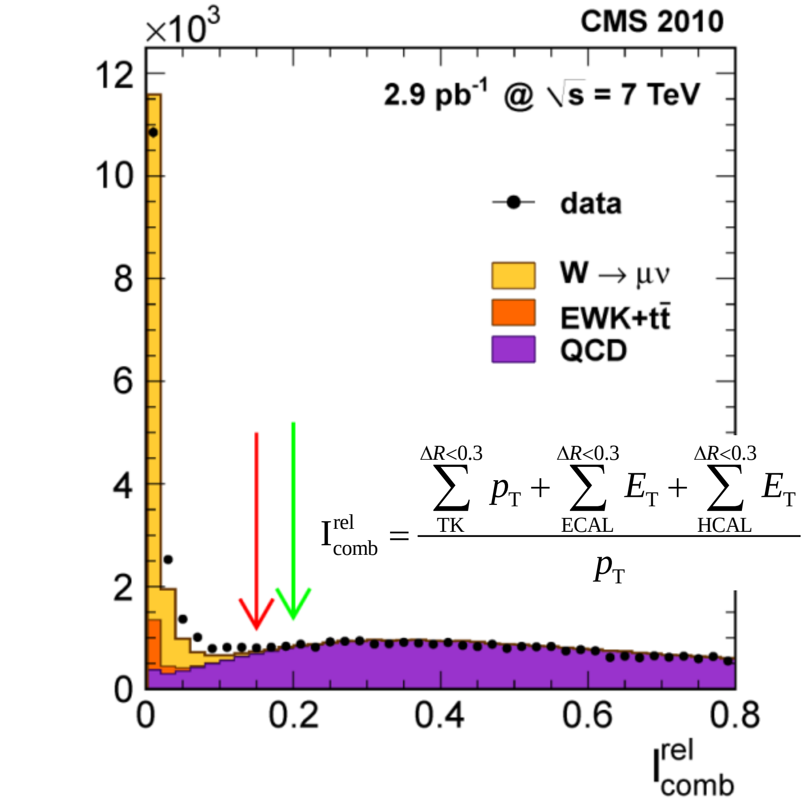
Acceptance: How much cross section measureable in CMS detector, from NLO simulation

Efficiency: Use NLO MC corrected by data driven scale factors via Z bosons "Tag and Probe"

Integrated Luminosity from dedicated measurement

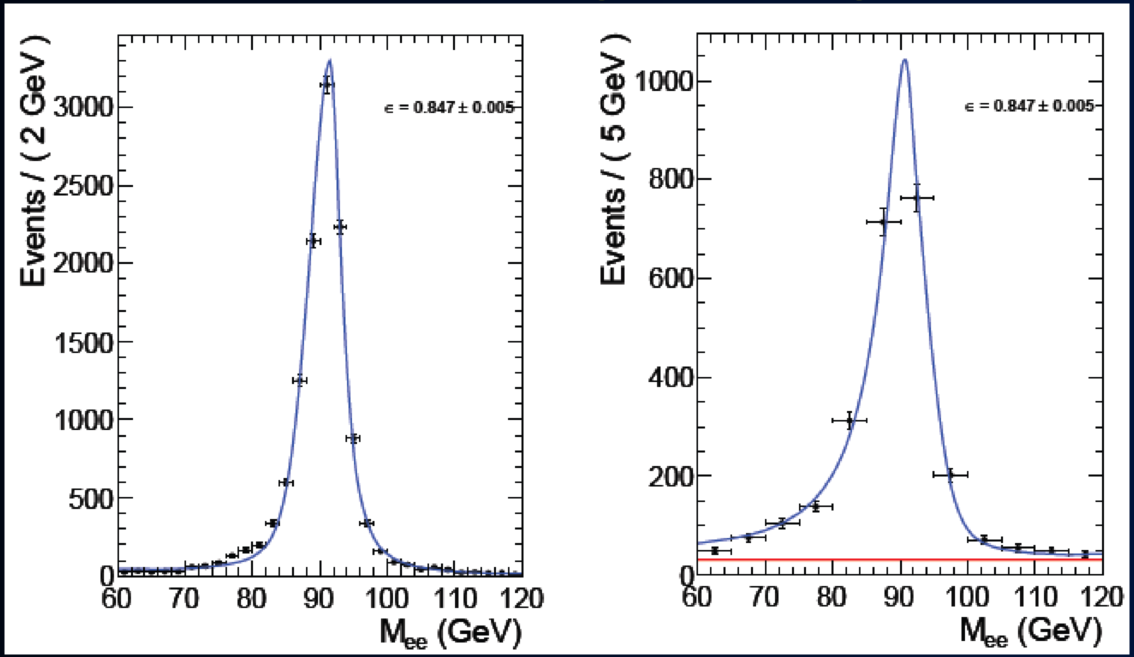
Leptons from W/Zs

- **Lepton ID crucial for all measurements**
  - **Single Lepton triggers – lowest unprescaled threshold**
    - **5-8 GeV *e*, 9-15 GeV μ**
- **Well identified p_T > 20 GeV isolated lepton**
  - **Compatible signals in all detectors**
    - **μ: track quality, TK+MU match**
    - ***e*: cluster shape, TK+ECAL match**
  - **Not QCD: Combined Isolation**
  - **Specific Background rejection**
    - **μ: d_0 cut for cosmics**
    - ***e*: conversion veto**



Bootstrapping from $Z \rightarrow \ell\ell$

- **Lepton Efficiency via "Tag and Probe"**
  - **"Tag" passes cuts, $|m_{\mathrm{TagProbe}}-m_Z| < 30$ GeV**
  - **Fit peak, count Probe failing/passing sample**

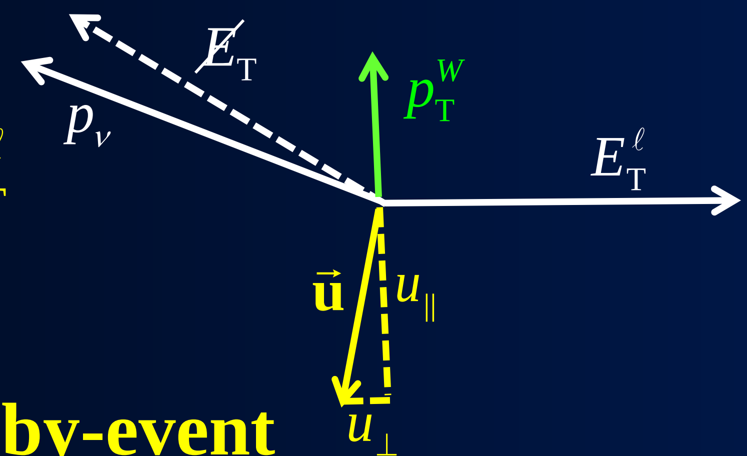


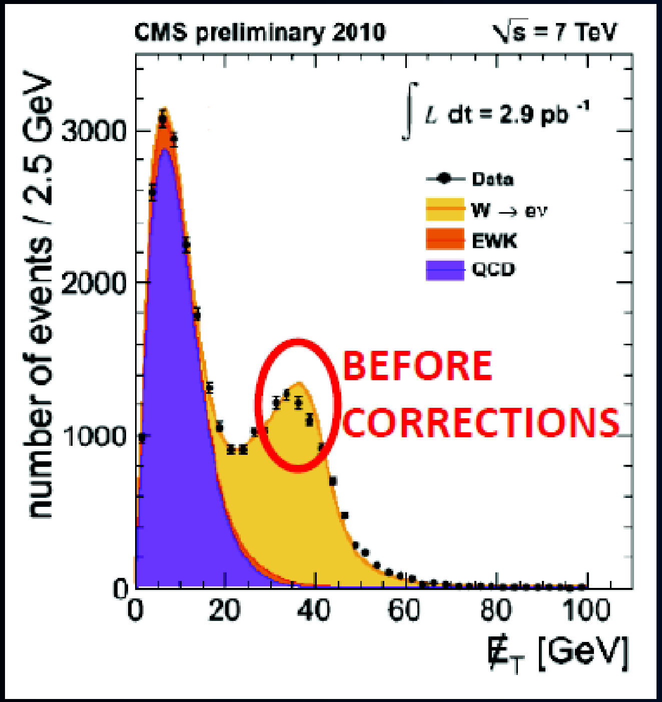
- **Lepton Energy scales via fit to *Z* mass peak**
  - **Calibrate vs. η via likelihood fits for scale, resolution**

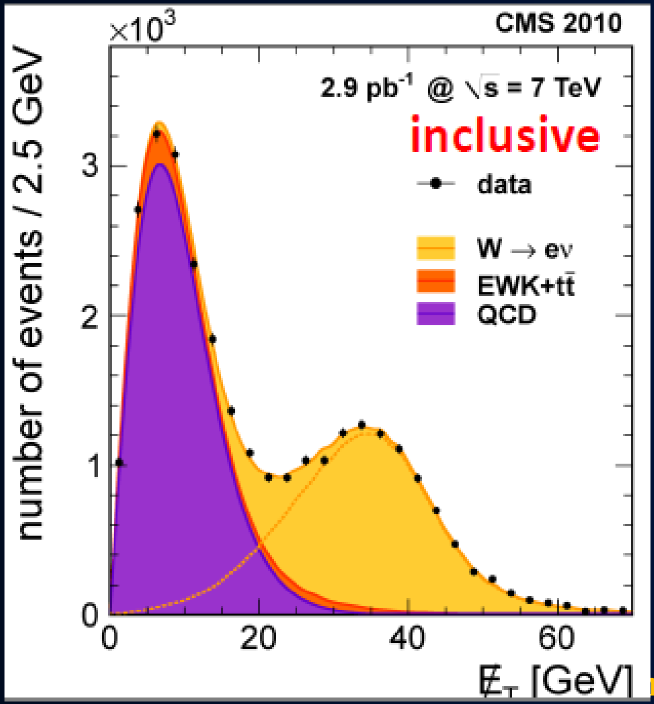
Missing Energy (MET) measurement

- **Basis of W signal extraction due to neutrino**
- **Uses Z recoil method**
  - **$Z\to\ell\ell$; reconstruct $\vec{\mathbf{u}} = \not{E}_{\mathrm{T}} - E_{\mathrm{T}}^{\ell}$**

    $u_{\parallel} \to \mathrm{scale}\left(p_{\mathrm{T}}^{Z}\right), u_{\perp} \to \mathrm{resolution}$
  - **Derive scale factors, apply event-by-event**







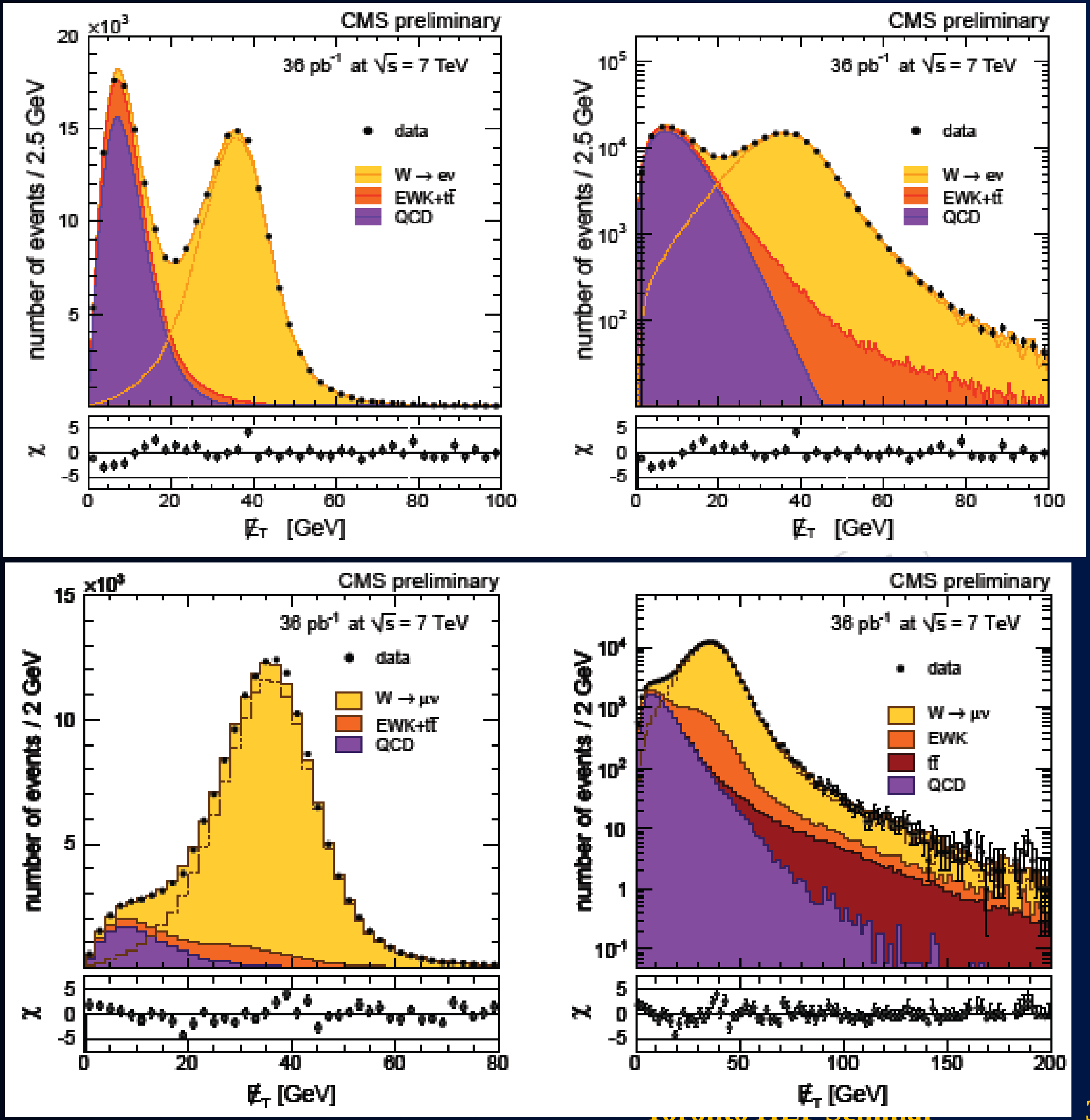
W Signal Extraction

- **Fit in MET**
  - ***e*: Analytic QCD shape**

136328 ± 386 ev.

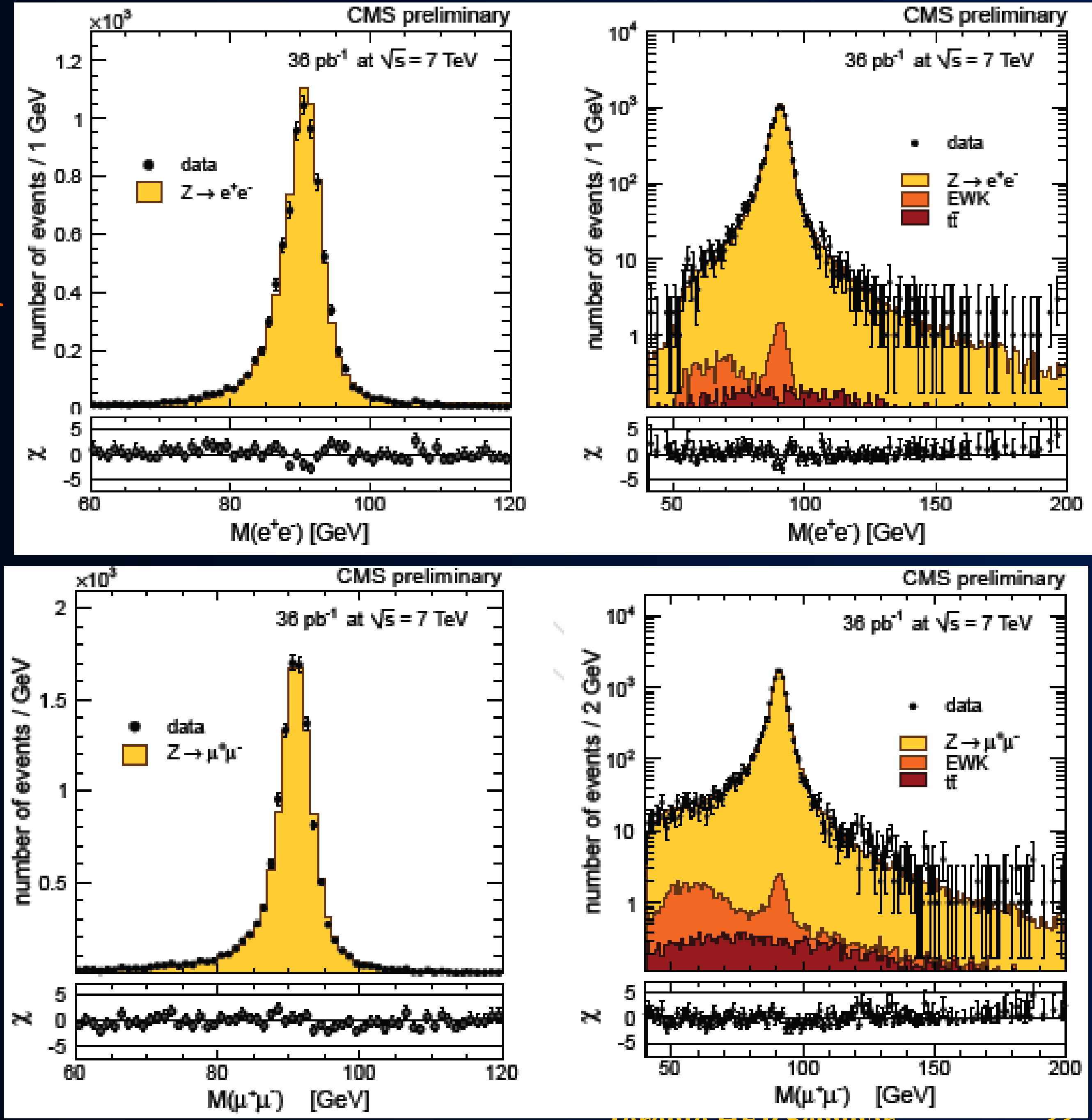
  - **μ: QCD from corrected non-isolation region**

114110 ± 384 ev.



Z signal extraction

- **No Background! can cut and count or fit for yield and efficiency**
  - ***e*: 8406 ± 92 ev.**
  - ***μ*: fit for σ and 5 efficiencies, no yield number**



Other ingredients

- **Luminosity: 36 pb^{-1}**
  - **independent measurement, known to 4%**
- **Acceptance:** $W \to e\nu \sim 0.49$, $\mu\nu \sim 0.46$, $Z \to ee \sim 0.39$, $\mu\mu \sim 0.40$
  - **Calculated at NNLO (FEWZ) with MSTW PDFs**
    - **systematics: PDF variation, FSR, resummation, scale variation, EWK corr.**
- **Systematics**

Source	$W \to e\nu$	$W \to \mu\nu$	$Z \to ee$	$Z \to \mu\mu$
Lepton ID/Reconstruction	**1.3**	0.9	1.8	---
Trigger pre-firing	---	0.5	---	0.5
Momentum scale/resolution	0.5	0.22	0.12	0.35
MET scale/resolution	0.3	0.2	---	---
Background subtraction/modeling	0.35	0.4	0.14	0.28
Experimental	1.5	1.1	1.8	0.7
Theoretical	0.9	1.1	1.7	2.0
Total	1.7	1.6	2.5	2.1

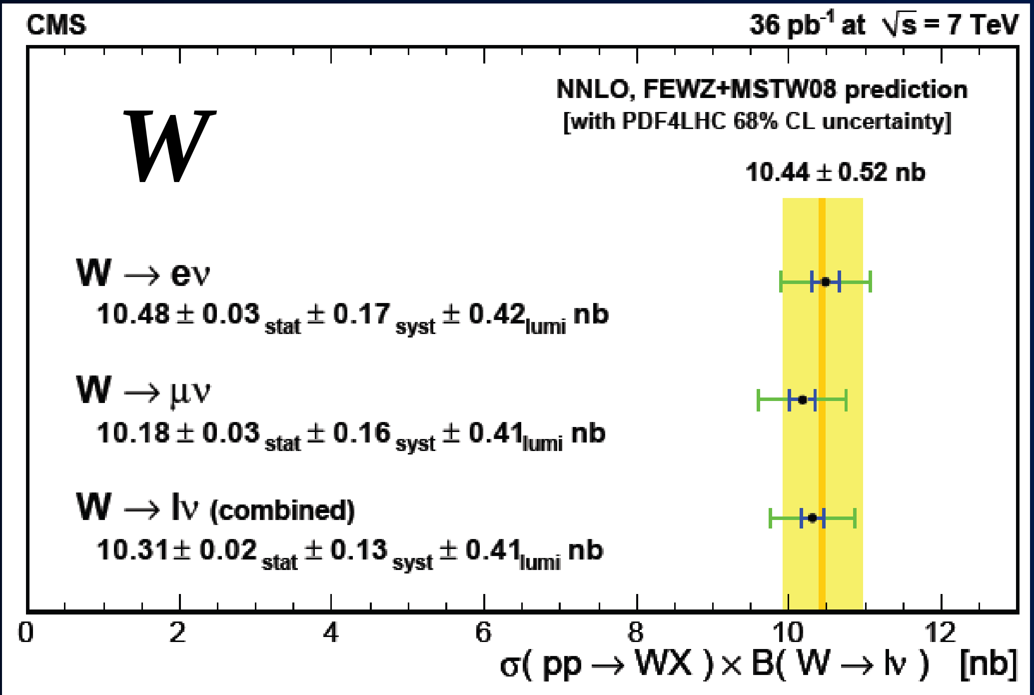
Z vs. W

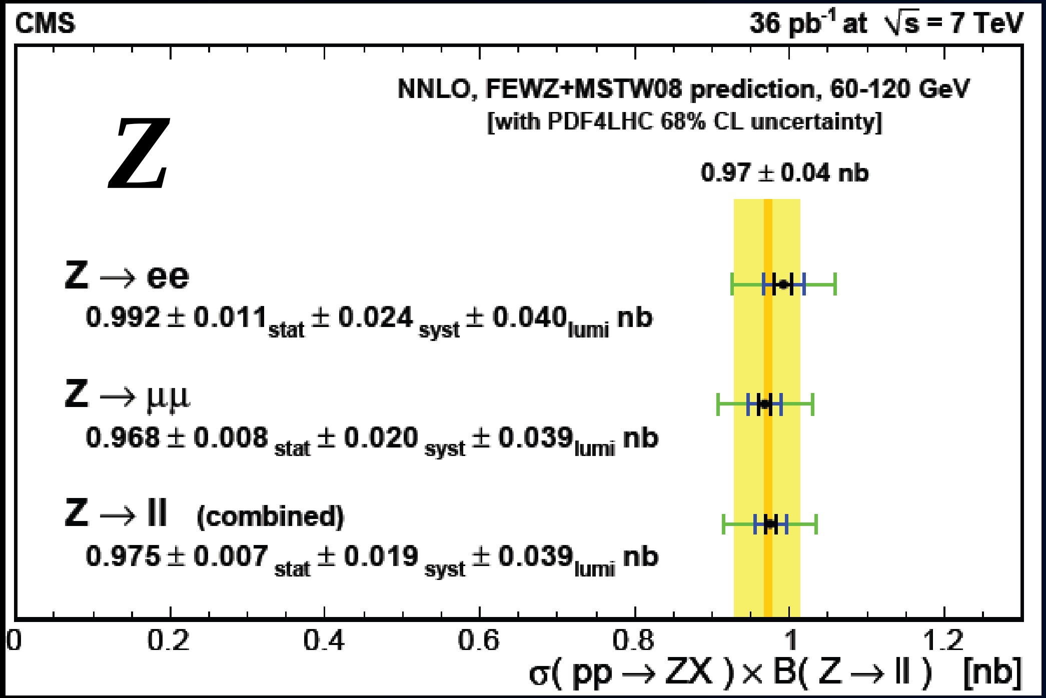
Theory

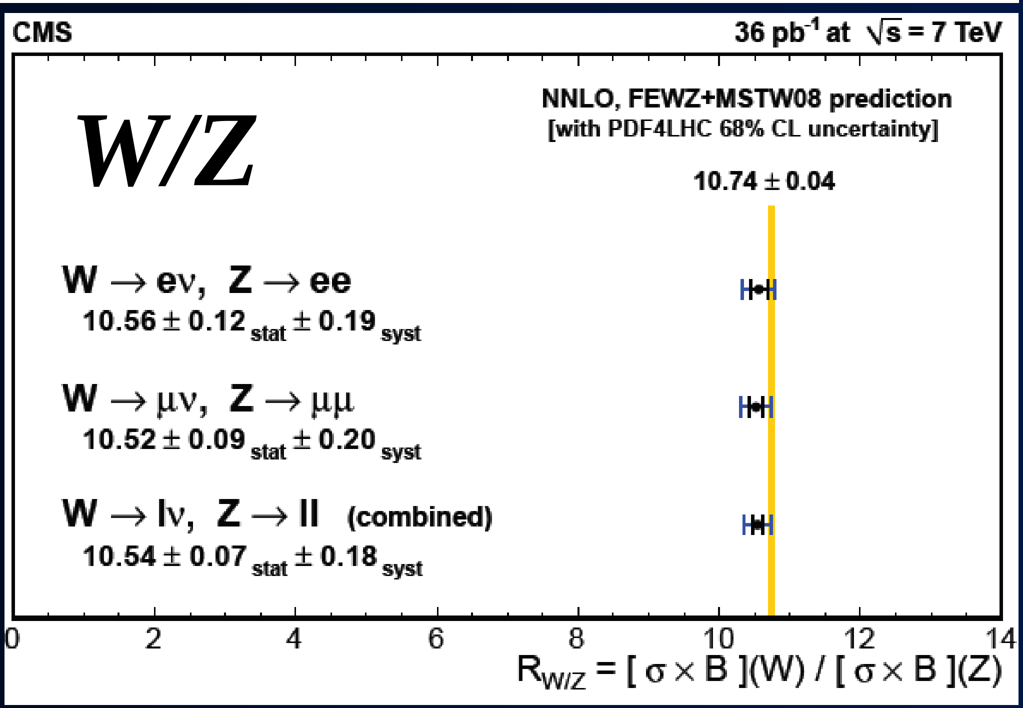
Statistics

+Systematics

+Luminosity

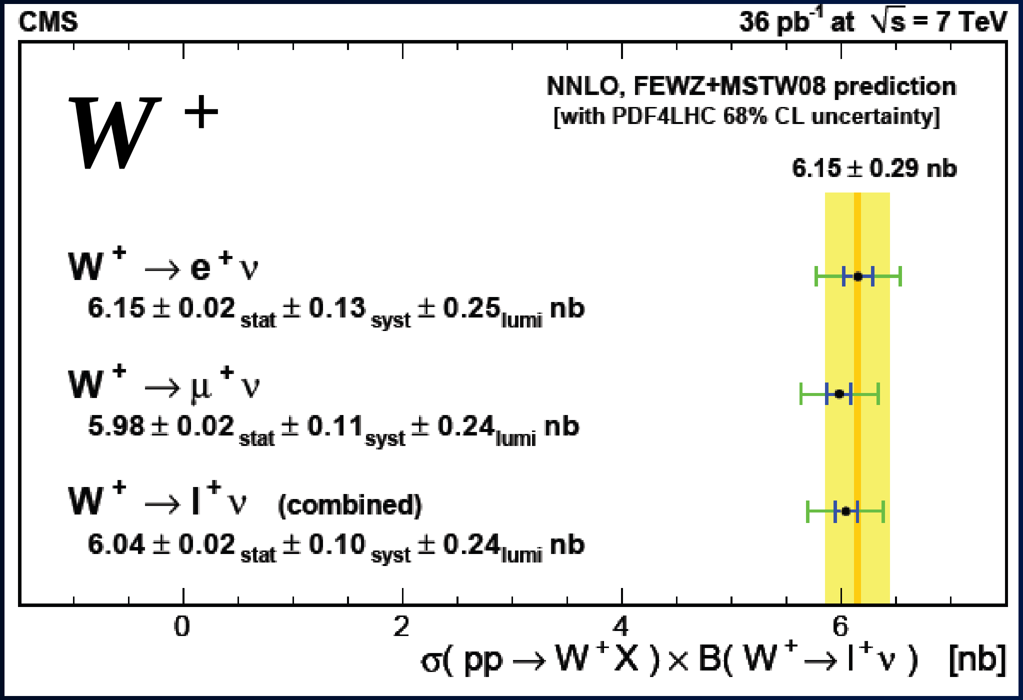


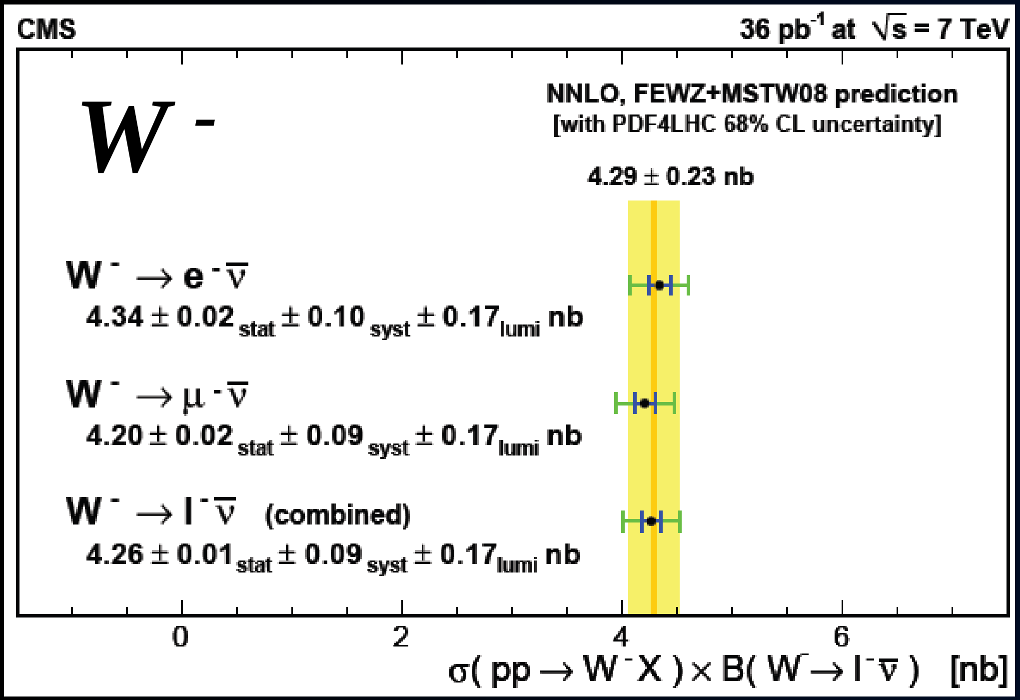


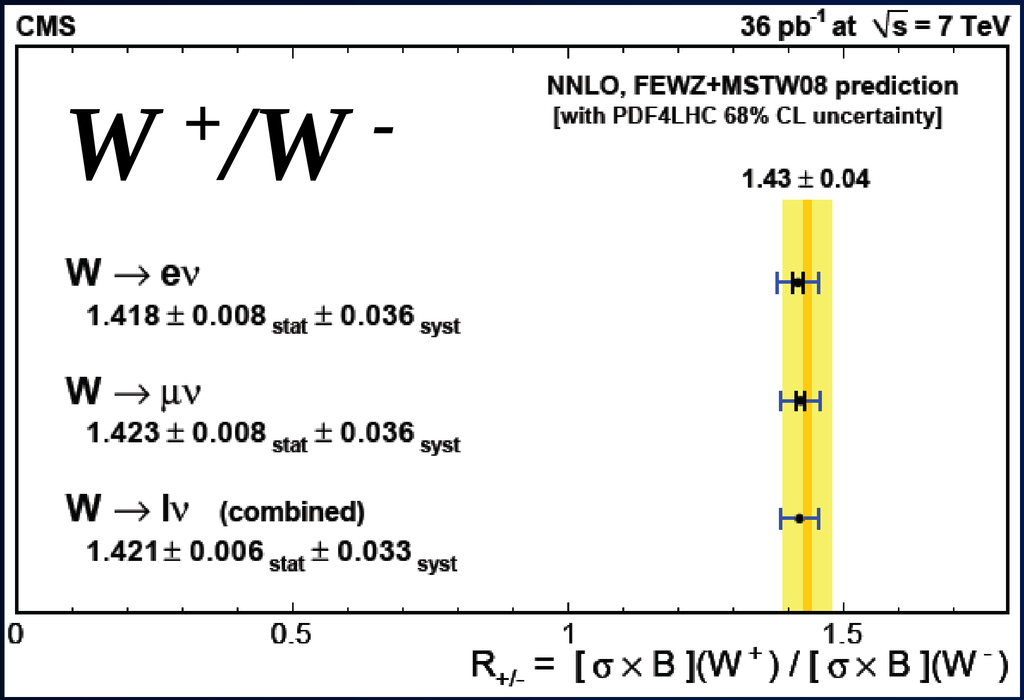


W^+ vs W^-

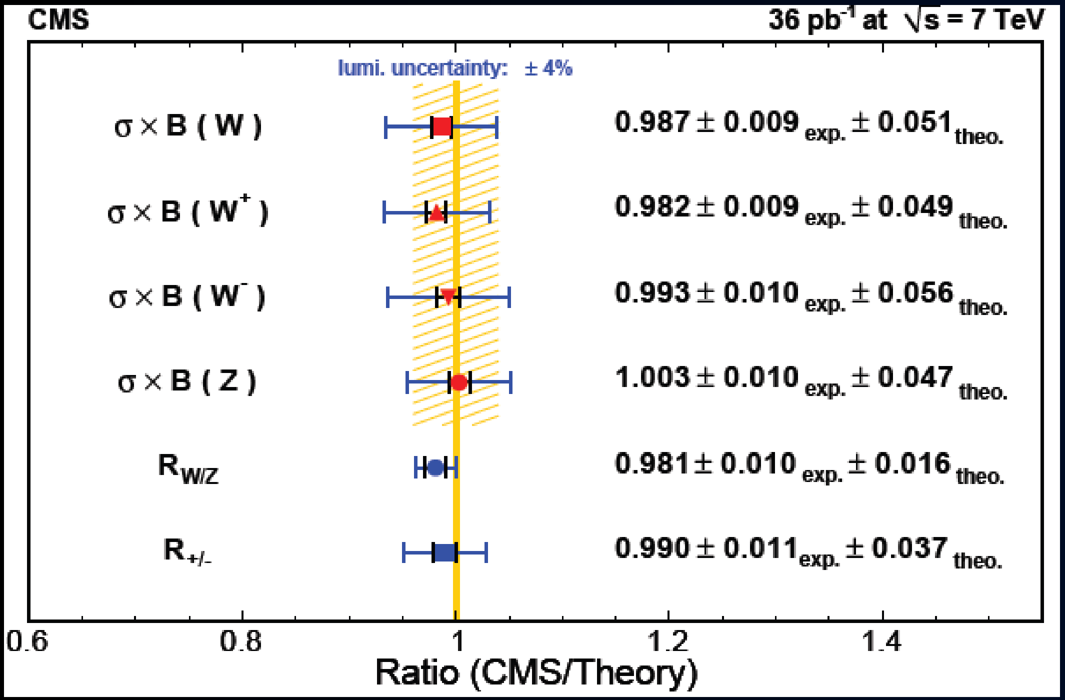
- **Efficiencies, acceptance, yields, systematics all determined independently**
  - **Sensitive to PDFs**

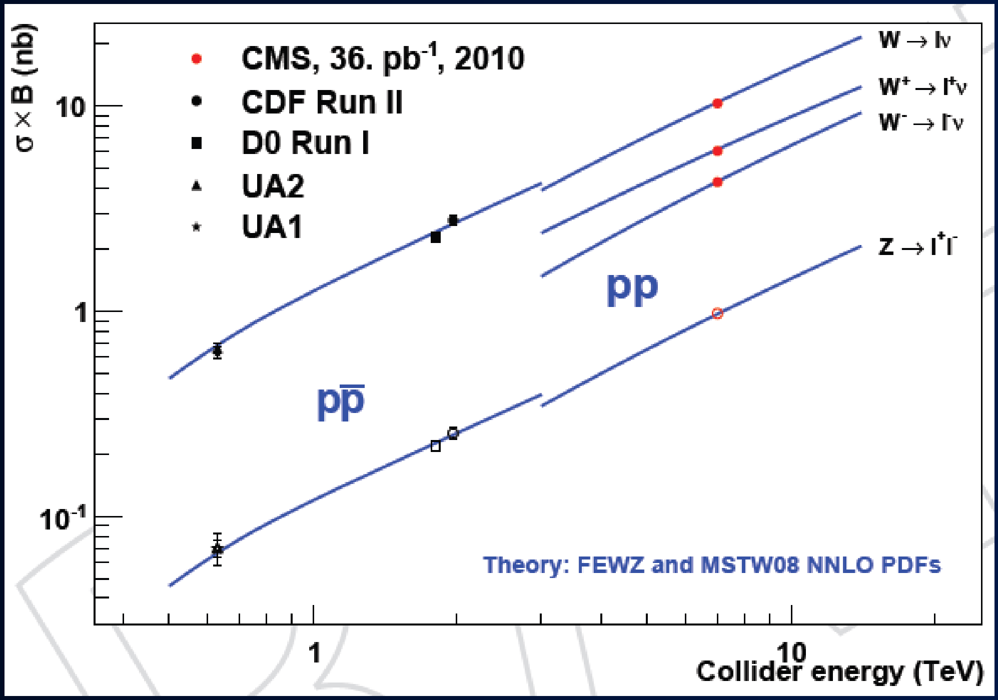






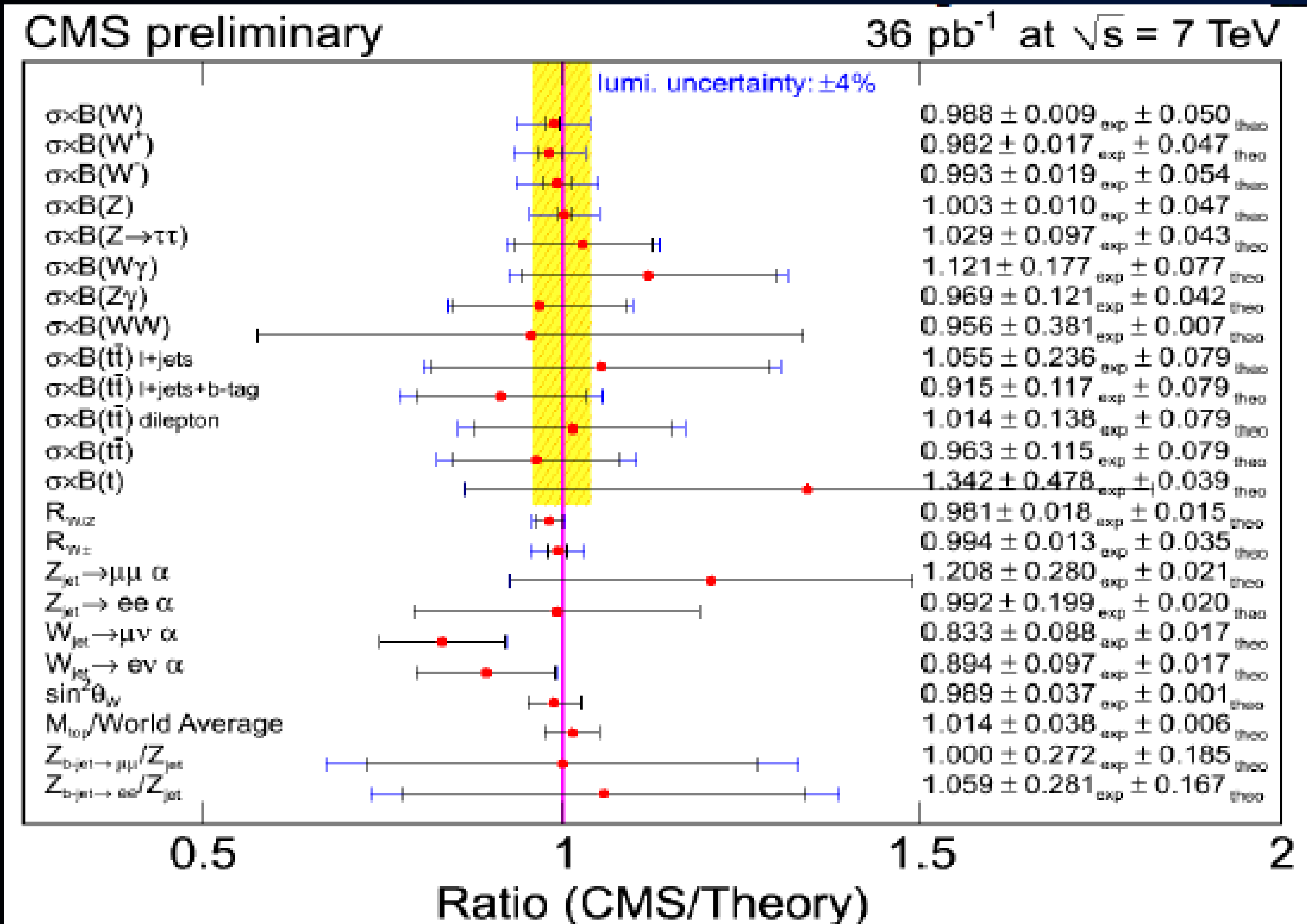
Experiment vs. Theory





- **Inclusive cross sections on the money**
  - **Confident in understanding of leptons and MET**
  - **Starts to constrain theory…**
  - **Can move in many directions from here…**

EWK as seen by CMS, Moriond 2011



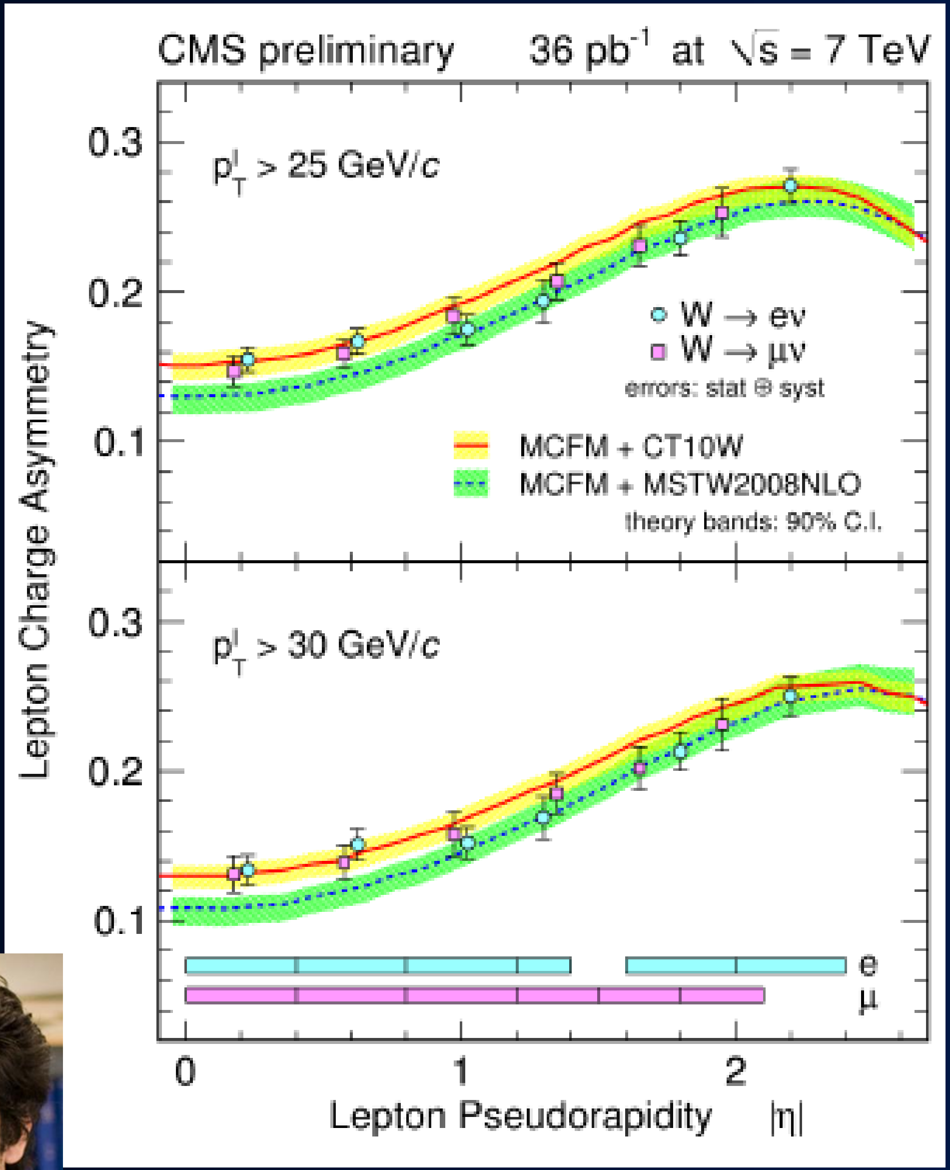
CMS Public Analysis Summaries, most on way to publication

Look at differential distributions

- **Lepton Charge Asymmetry vs η**
  - **Enhanced sensitivity to sea quark PDFs**

$$A(\eta)=\frac{\frac{d\sigma}{d\eta}\left(W^+\to\ell^+\nu\right)-\frac{d\sigma}{d\eta}\left(W^-\to\ell^-\nu\right)}{\frac{d\sigma}{d\eta}\left(W^+\to\ell^+\nu\right)+\frac{d\sigma}{d\eta}\left(W^-\to\ell^-\nu\right)}$$

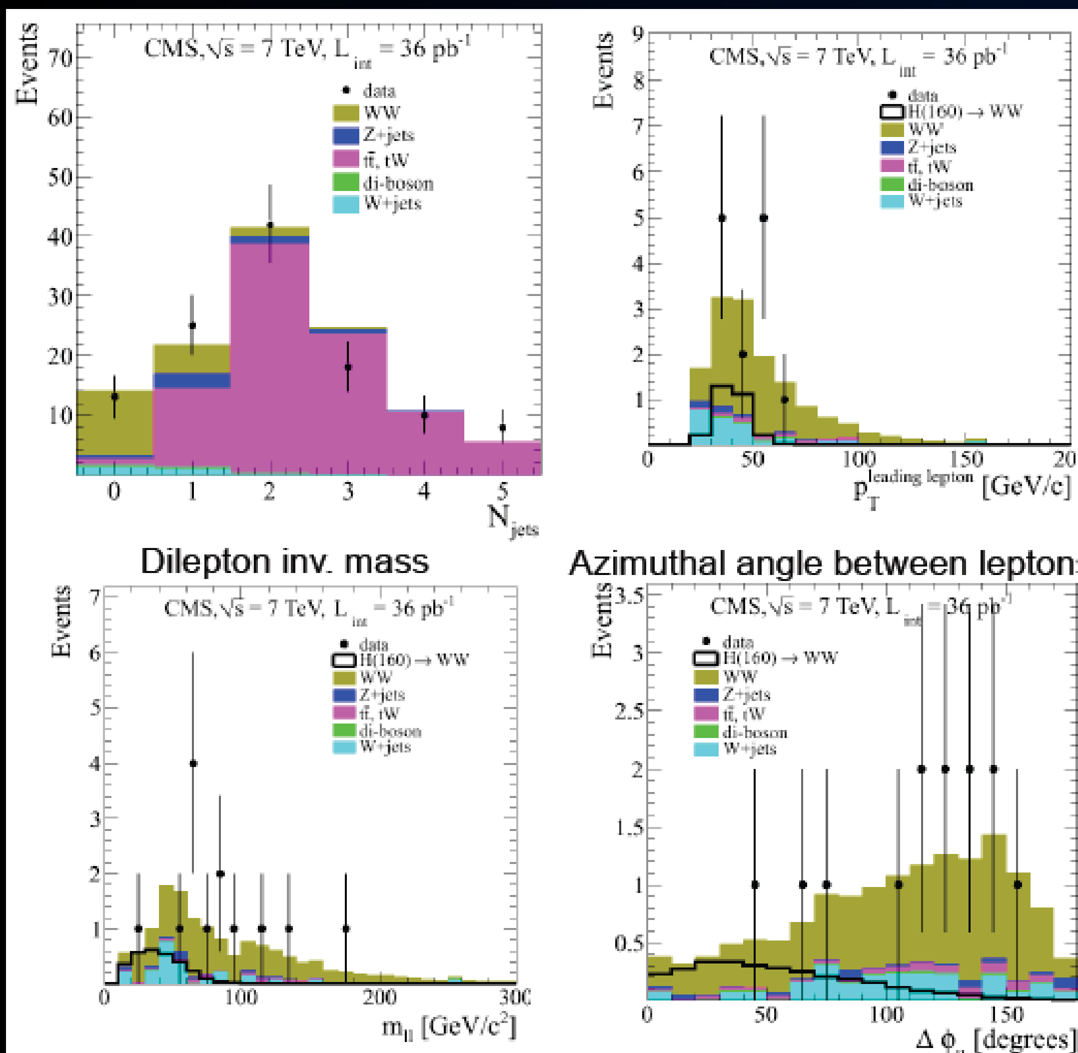
- **Charge misid crucial**
  - ***e*: < 0.5%**
  - ***μ*: < 10^{-4}**

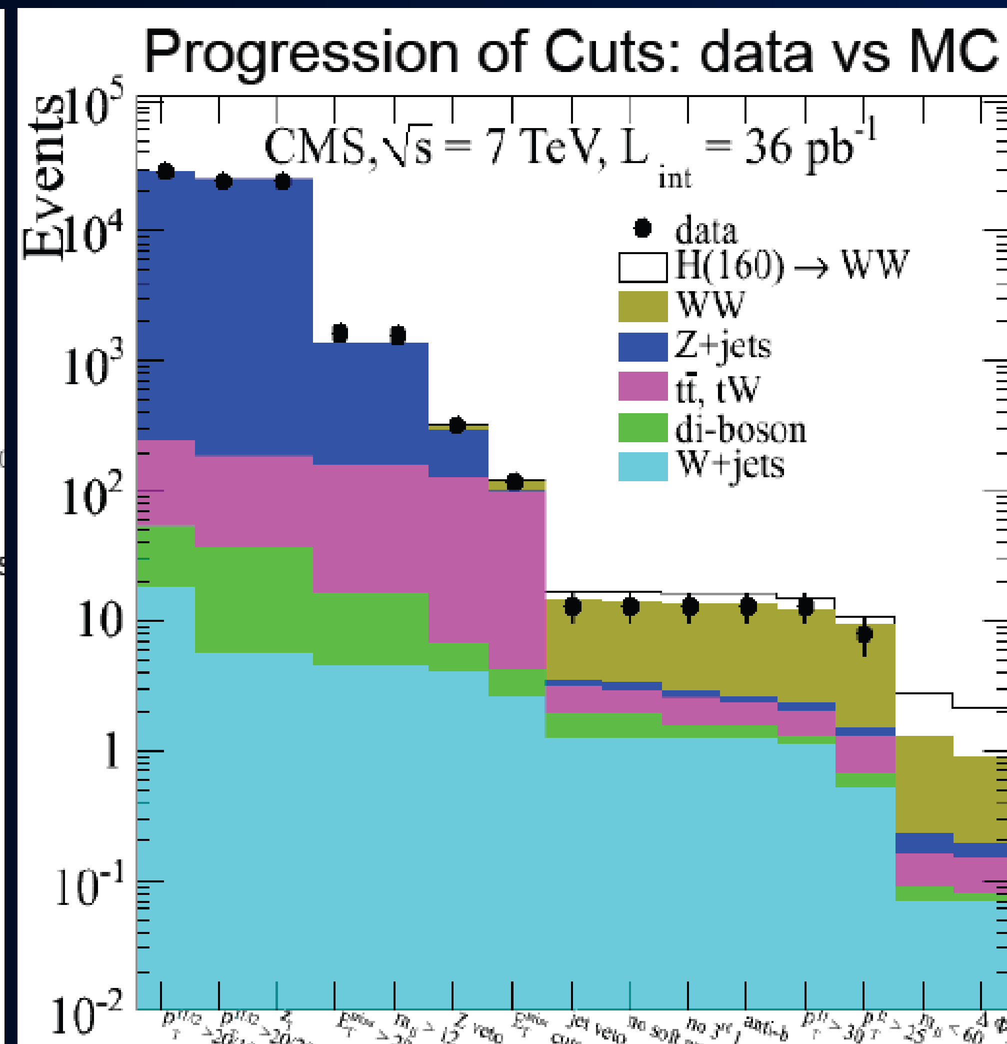


If one boson is good, two are better…

$$\sigma\left(pp \to WW \to \ell\nu\ell\nu\right) = 41.1 \pm 15.3 \pm 5.8 \pm 4.5(\mathcal{L})\,\mathrm{pb}$$

based on 13 events ion cut based analysis, 36 pb^{-1}

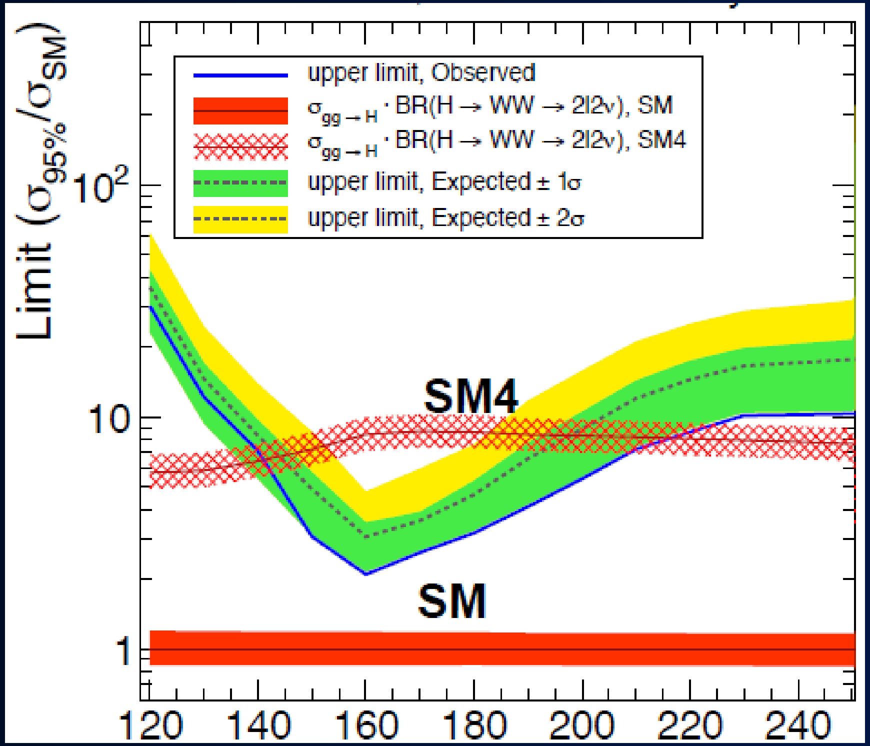




in terms of Higgs hunt

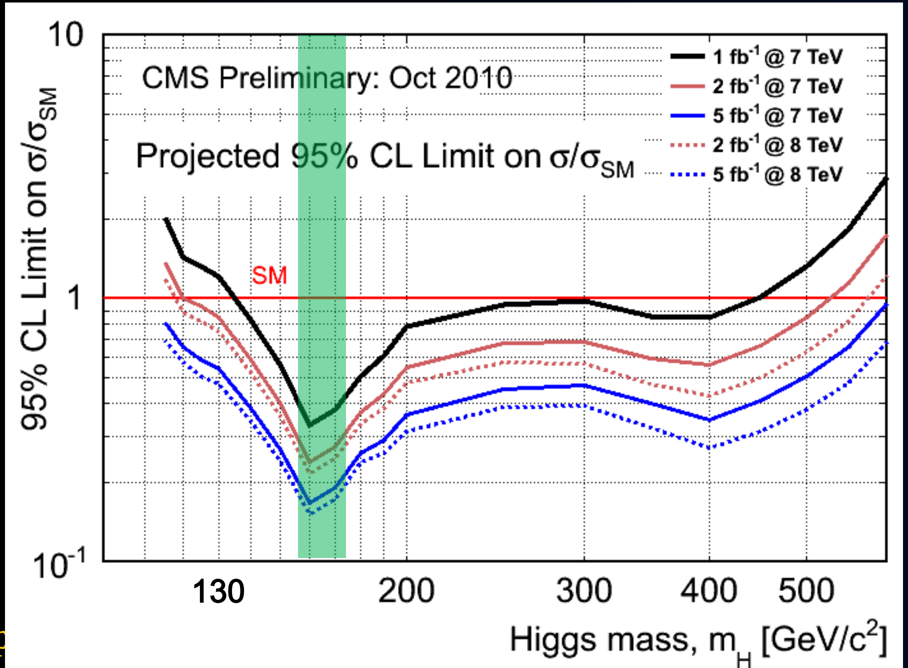
- **95% CL for $m_H = 160$**
  - **expected: 3×SM**
  - **observed 2.1×SM**
  - **4th Gen. Model SM Higgs:**

    $m_H \notin [144,207]$

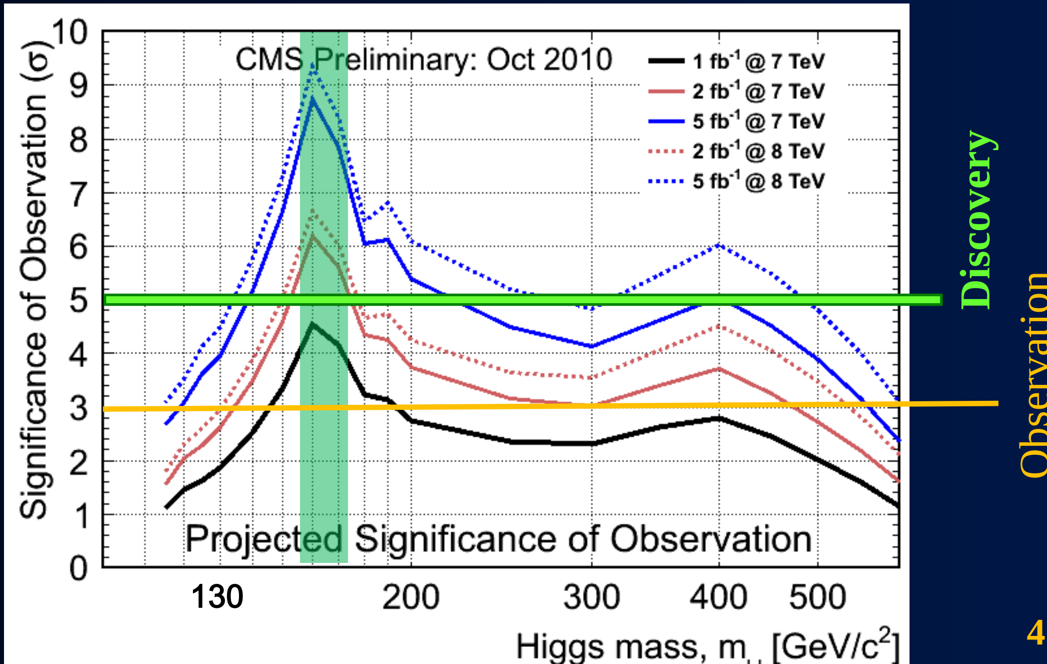


- ***Conservative* projections:**

exclusion



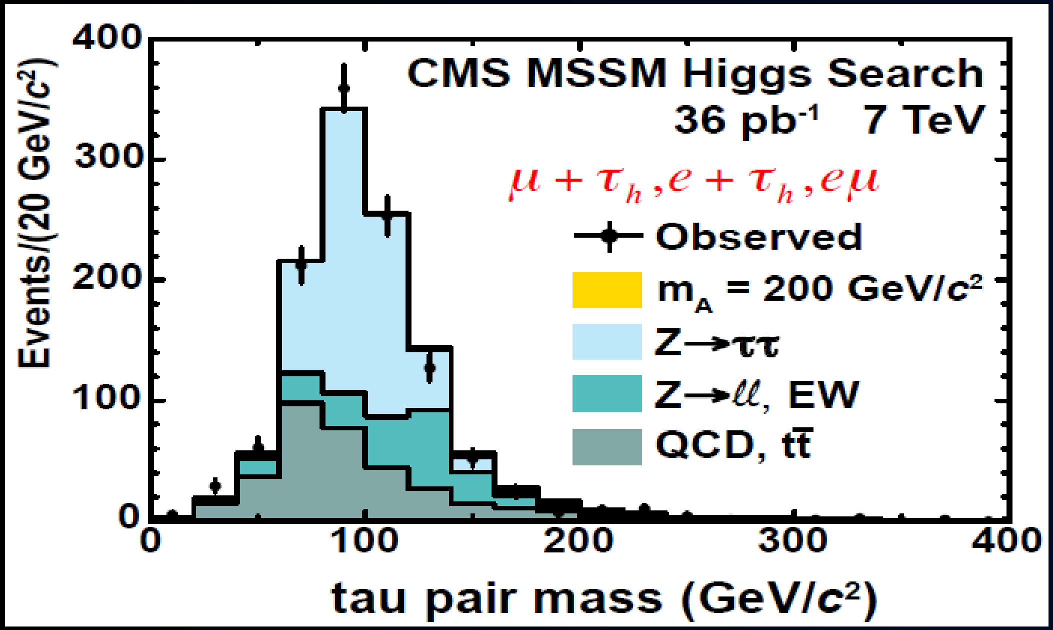
discovery

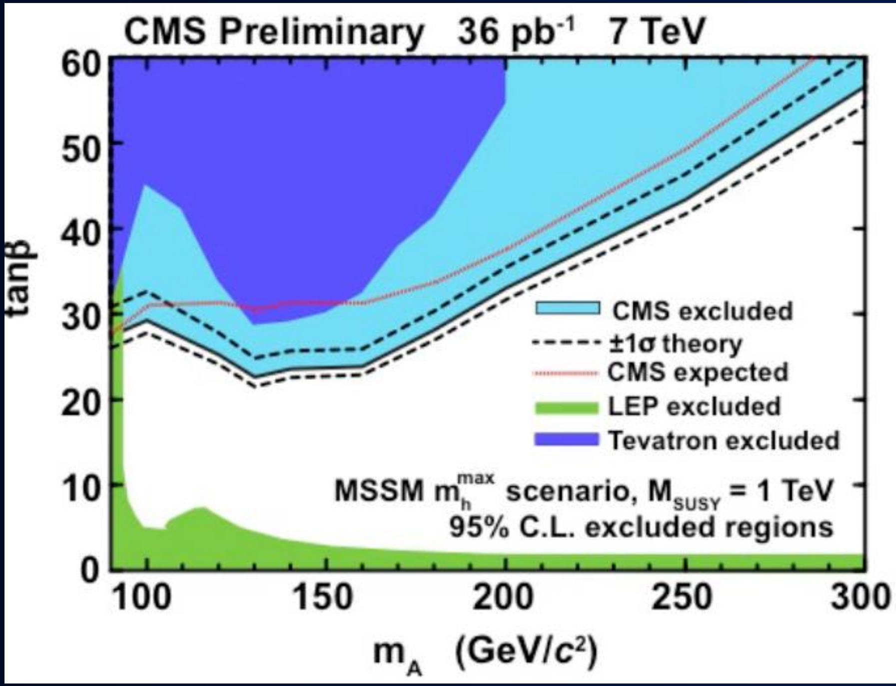


Taus decay to leptons too

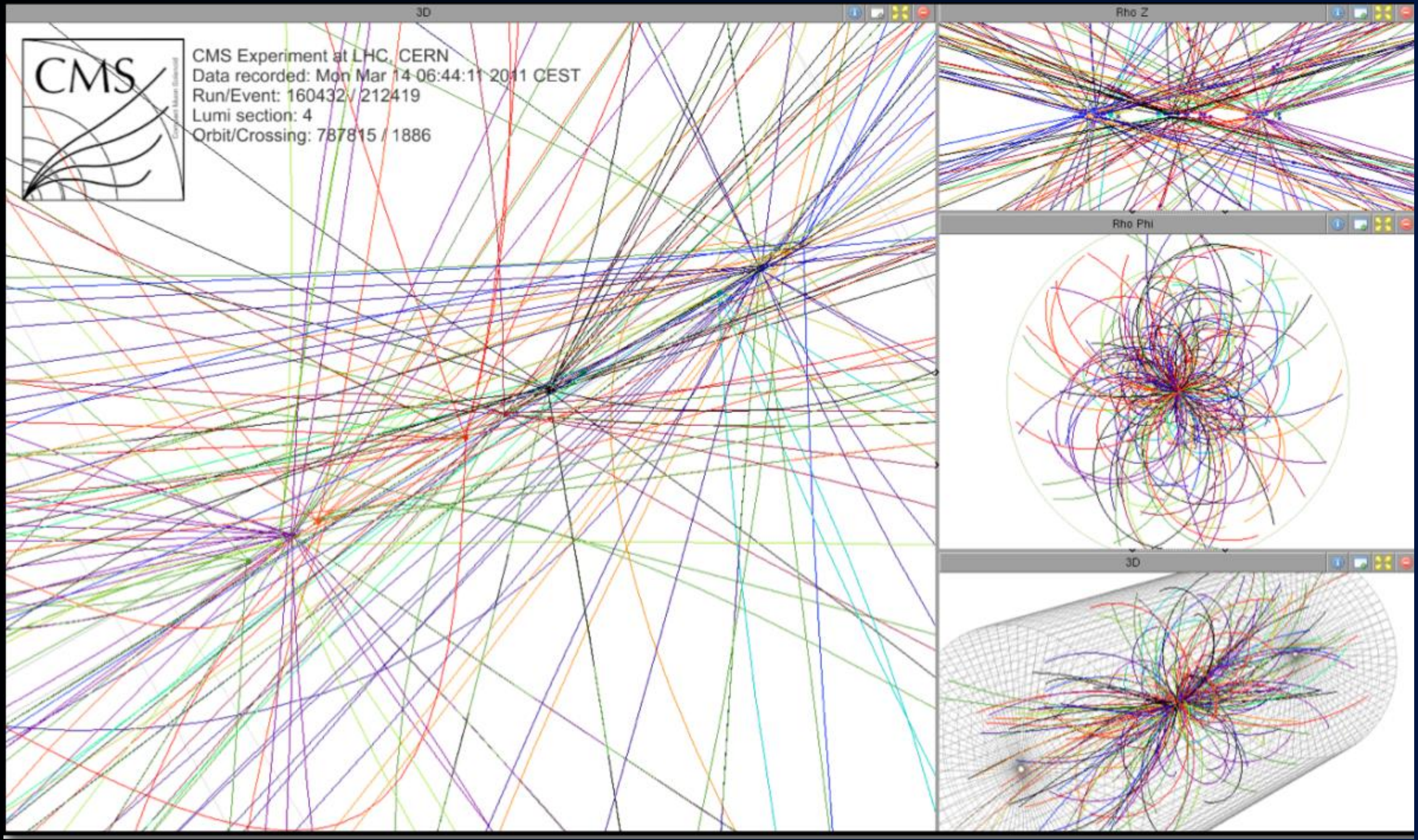
$$\sigma\left(pp \to ZX\right) \times Br\left(Z \to \tau\tau\right) = 1.00 \pm 0.05 \pm 0.08 \pm 0.04\left(\mathcal{L}\right)\text{nb}$$

- **Bootstrapping tau id on knowledge of leptons**
- **Many of the same techniques apply**
  - **Close up new territory in SUSY space**





but…



at least 7 vertices in here…maybe some more stones…

Well, we shall see…

- LHC is a fertile field to find something new
  - And hopefully unexpected!
- The complex experiments are harvesting the data
  - 2010 rediscovered the Standard Model
    - we're confident we could confidently have something to say
  - Scratching the surface of new physics – off to the races!
- Just need to turn up the Luminosity
  - and cope with the consequences

stay tuned