Hadron colliders: physics at the energy frontier

Paris Sphicas
CERN & University of Athens
Festkolloquium, zum 60. Geburtstag von Professor Dr. Thomas Müller
KIT, January 18, 2013

- **The Standard Model of Particle Physics**
- **The ISR**
  - **aka how to miss discoveries**
- **A matter-antimatter (p-pbar) collider, part I: SPS**
  - **The triumph of EWK theory (unification!)**
- **A proton-antiproton collider, part II: Tevatron**
  - **Top quark & EWK & B physics in hadron collisions**
- **The ultimate TeV machine: the LHC**
  - **A new boson with mass ~125 GeV!**
  - **It is the Higgs? What about new physics?**
- **Outlook**

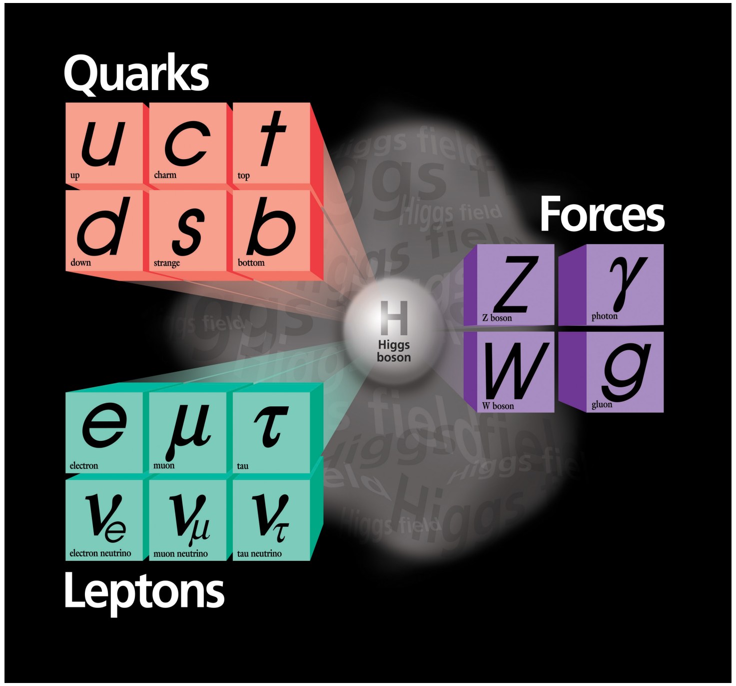
Standard Model of Particle Physics

Not even an introduction…

The "Standard Model"

Last 100 years: combination of **Quantum Mechanics and Special Theory of relativity** along with all new particles discovered has led to the **Standard Model of Particle Physics. With the new (final?) "Periodic Table" of fundamental elements**

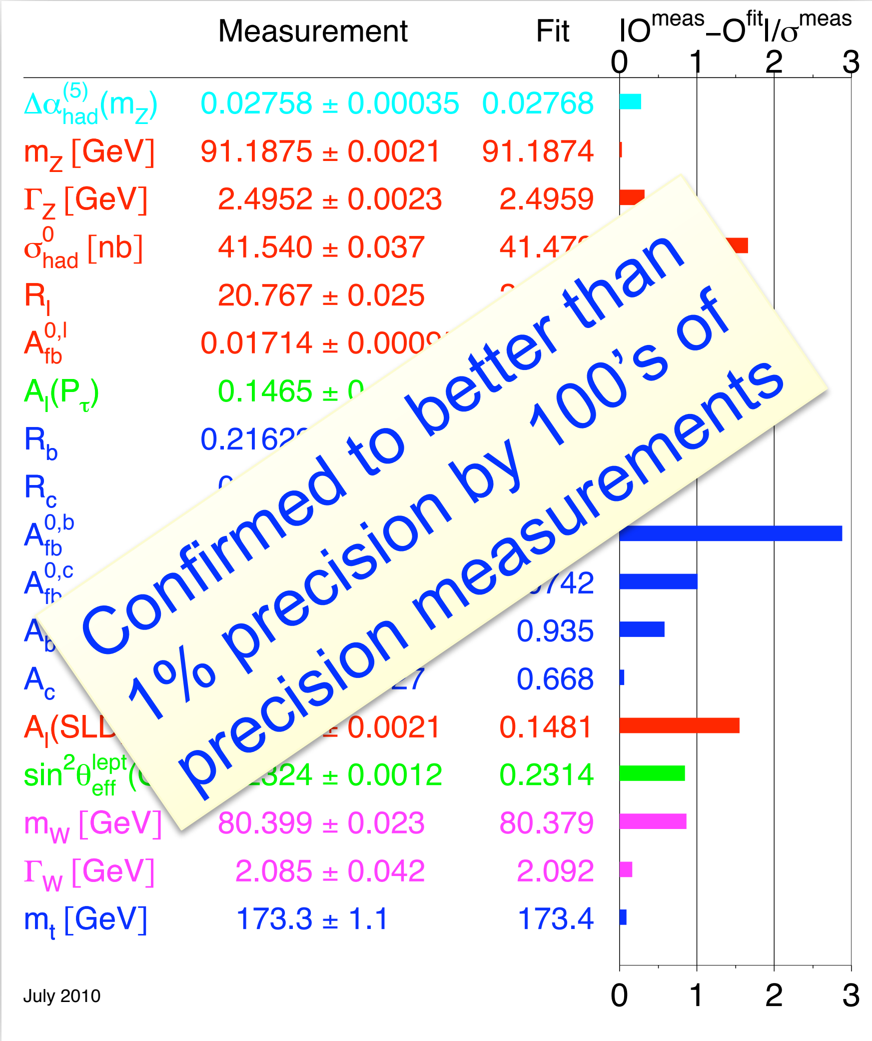
Matter particles

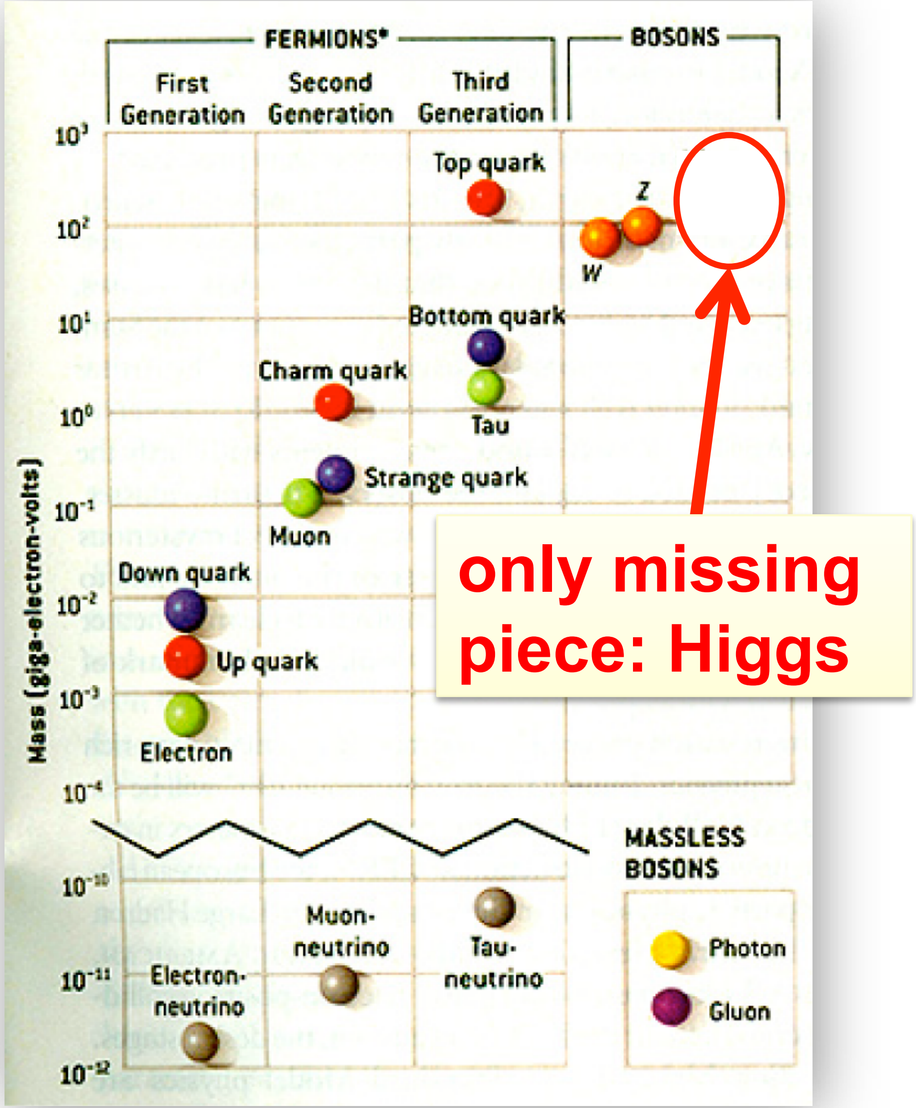


Force particles

The SM has been tested thousands of times, to excellent precision.
Of course, we need to verify its most basic mechanism, that of granting mass to particles, by establishing the Higgs boson.

The Standard Model

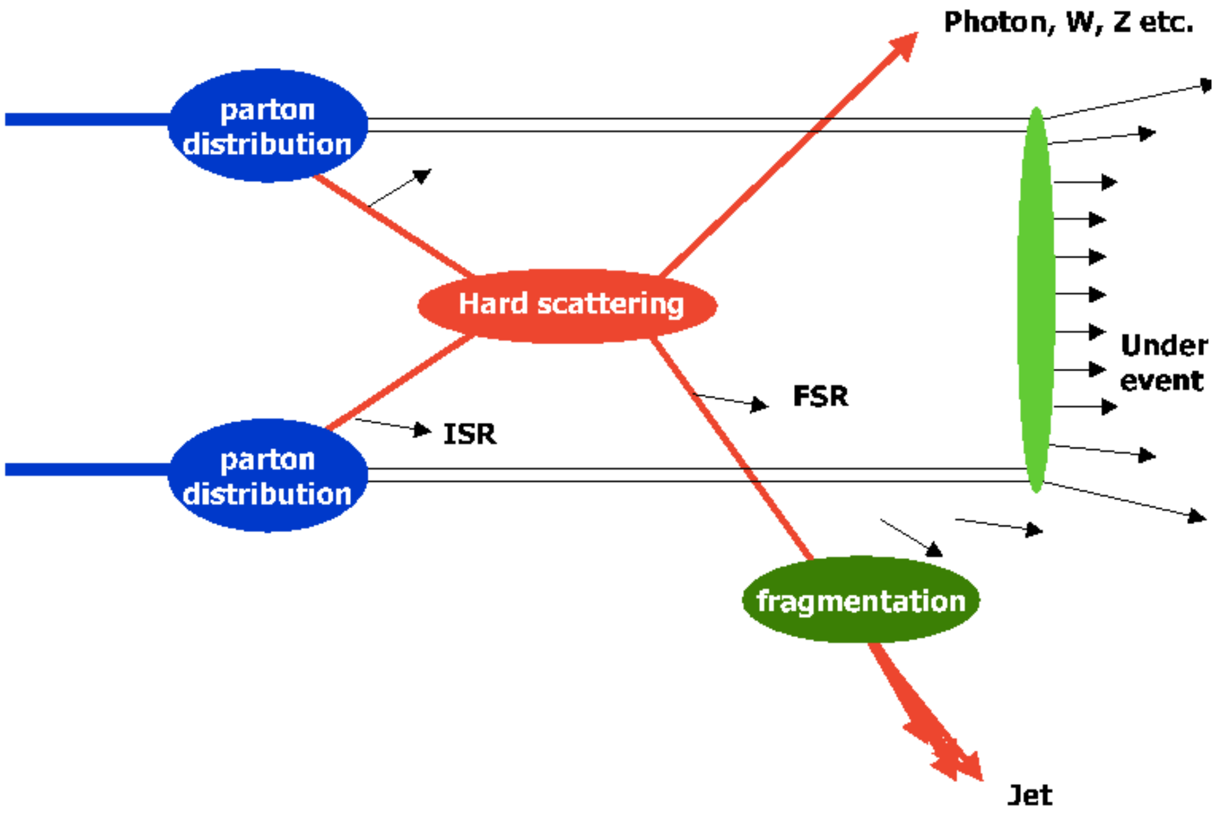




The beginning: AGS and ISR; Two + one lessons

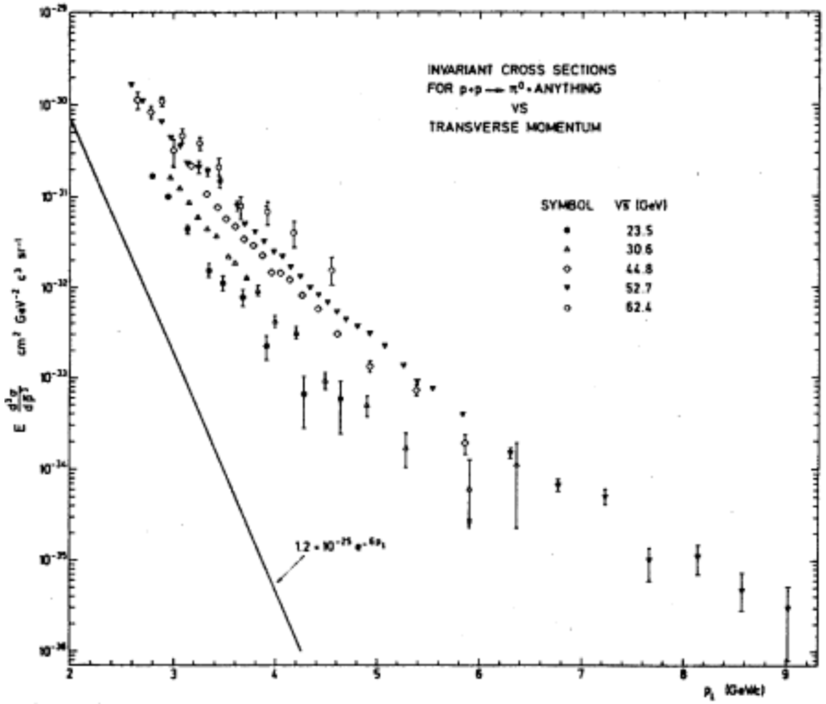
pp collisions :== parton-parton collisions

20-60 GeV pp collisions



Colliding watches

- **Late 60's:**
  - **Parton model: infant stage**
  - **Successful in spectroscopy + weak decays**
  - **Bjorken scaling + SLAC–MIT experiment**
  - **Question: is it applicable to hadron collisions?**



- **CCR: inclusive particle spectra → excess @ large P_T. Expected vs seen:**

$$E\frac{d^3\sigma}{dp^3} \approx A\frac{1}{P_T{}^8}\exp(-26x_T) \qquad E\frac{d^3\sigma}{dp^3} = \frac{1}{s^2}f(x_T,\cos\theta) = \frac{1}{P_T{}^4}g(x_T,\cos\theta)$$

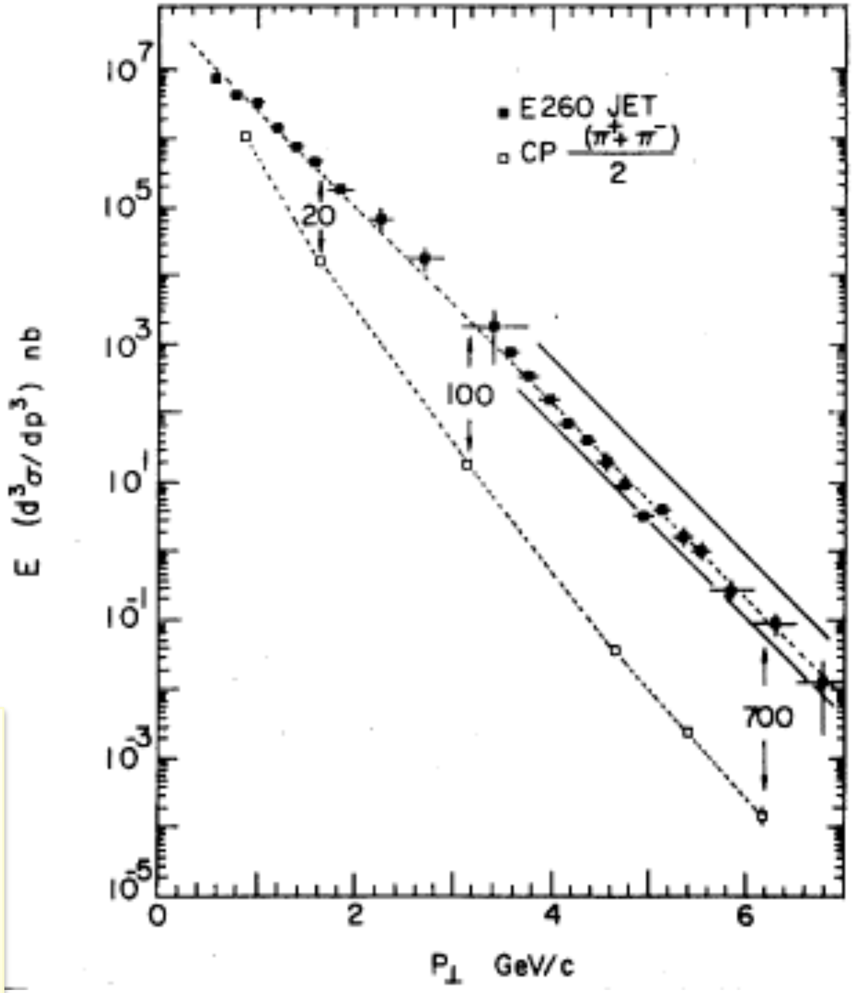
Jets were missing…

- **Killed by the trigger:**

ISR: triggering on single particles, not global E_T

1) Absence of CALO triggers (small E → bad CALO response)

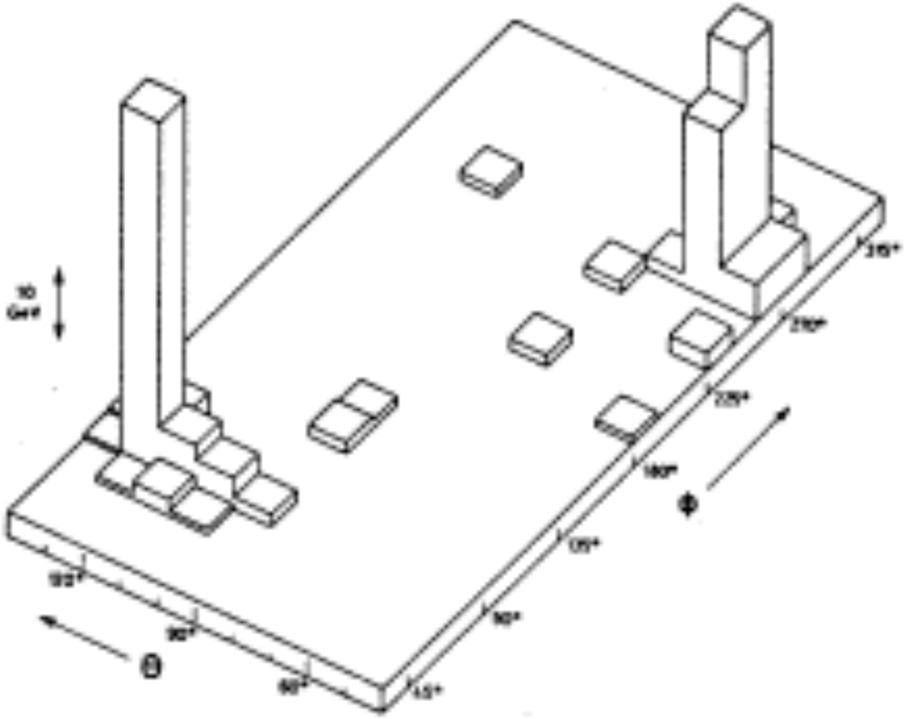
2) Jet spectrum: much steeper P_T spectrum than fragmentation → particle of given P_T most likely the leading particle of a soft jet...

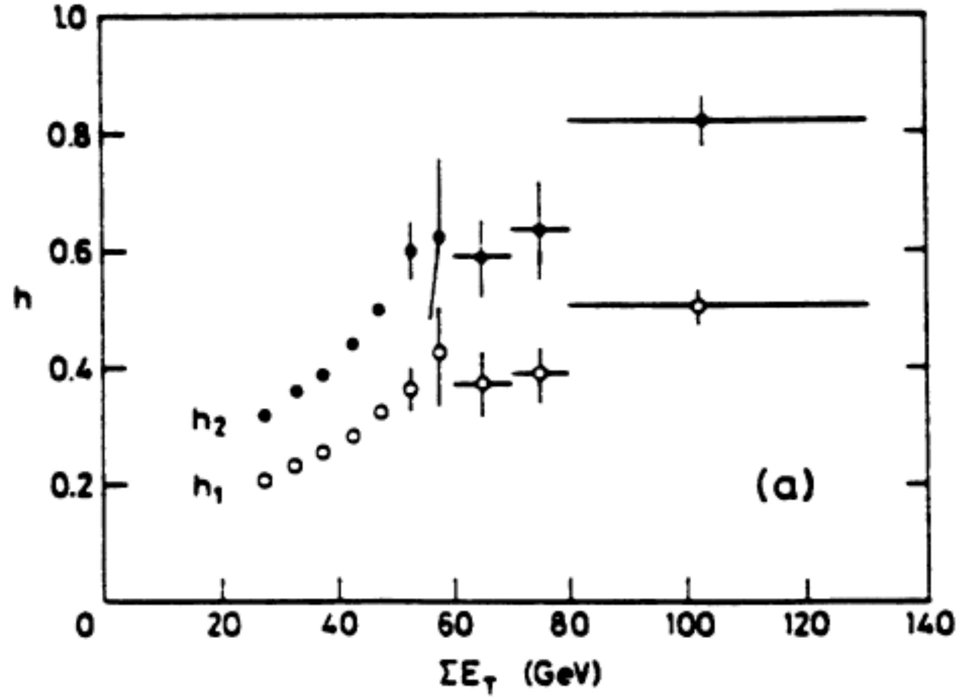


Lesson #1: triggering a risky and complicated activity; use inclusive triggers, e.g. based on the calorimeter!

The jets were there – only at the SPS…

- **UA2 experiment; "Paris conference" 1982**



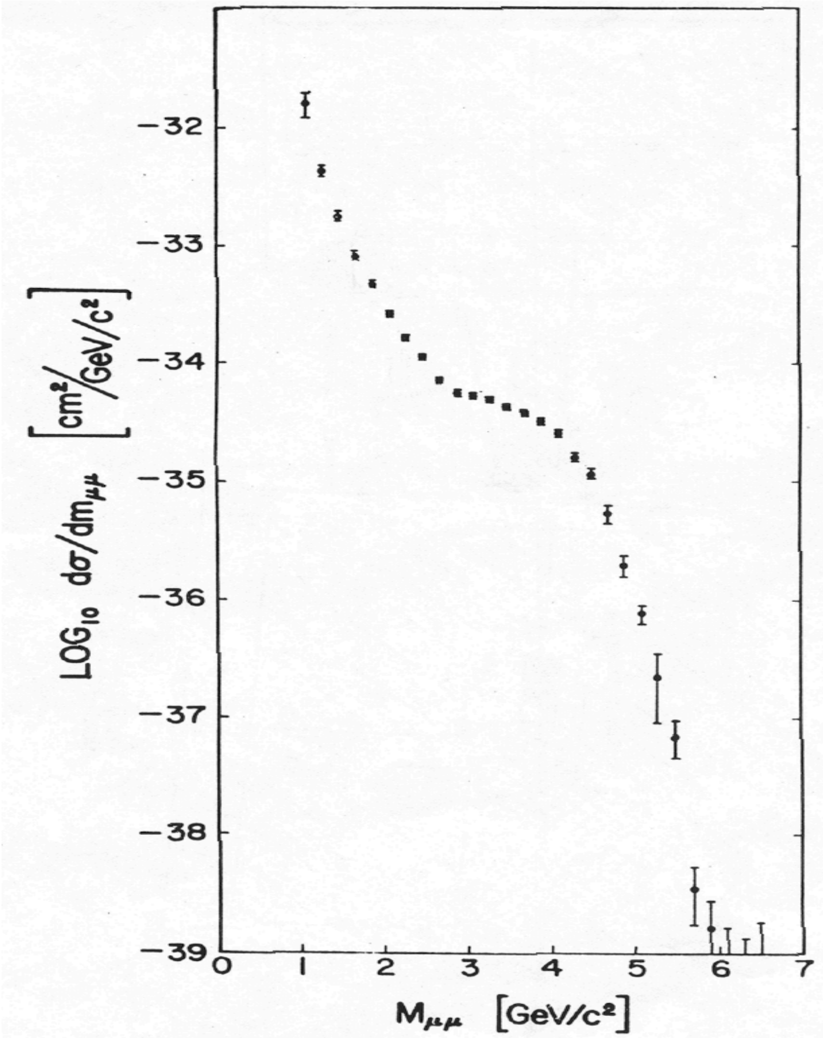


Discoveries missed: (well, AGS…) the J/ψ

- From Leon Lederman's autobiography at FNAL:
  - http://history.fnal.gov/autobiography.html

"In 1961 he worked under M. Schwartz and J. Steinberger on neutrinos. He was in charge of finding neutral currents. Schwartz was in charge of finding Lederman."

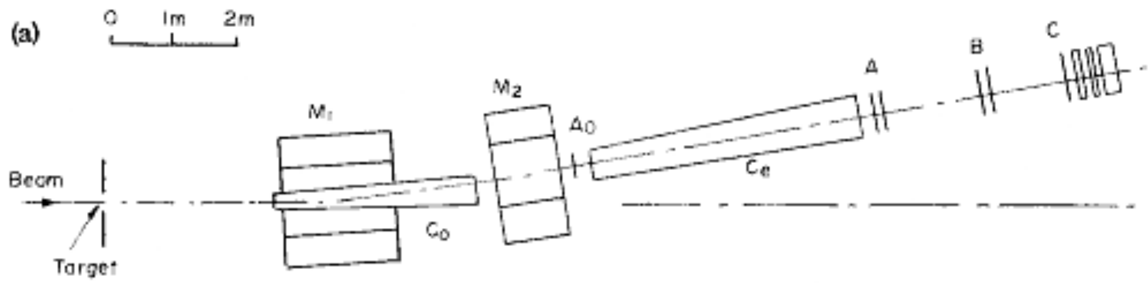
"In 1968 he invented the di-muon experiment and missed the J/Psi particle."



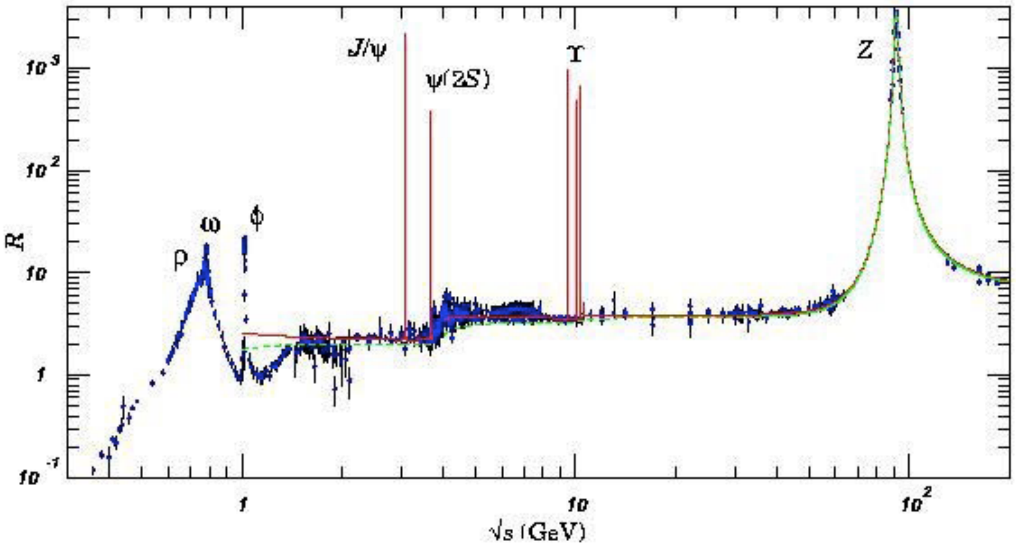
Lesson #2: resolution is so important!

Discoveries made: the J/ψ

- **Brookhaven AGS: p + Be → $e^+ e^-$ X**



- **SPEAR at SLAC:**



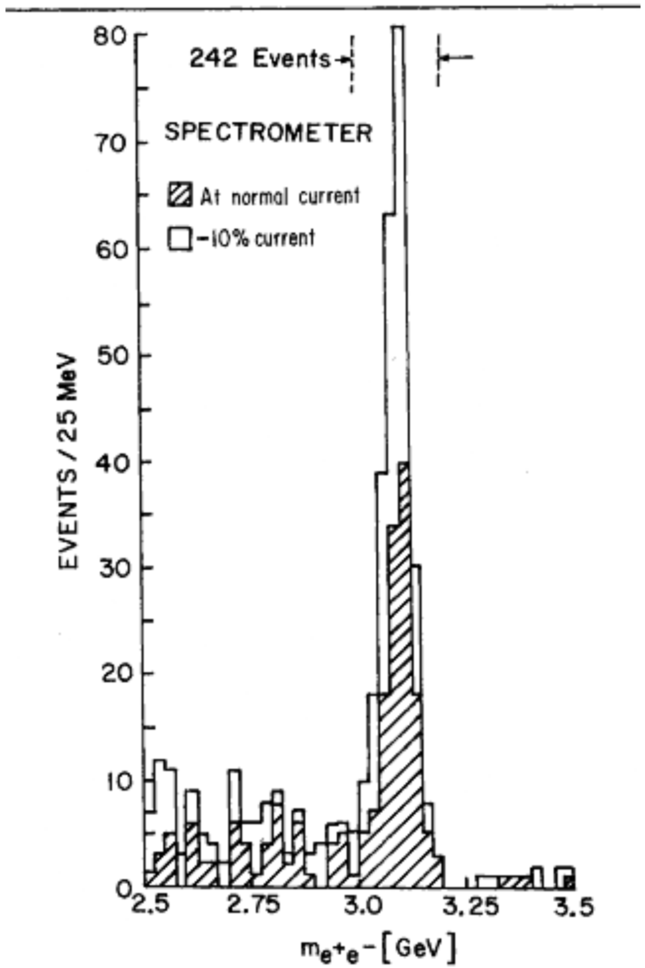


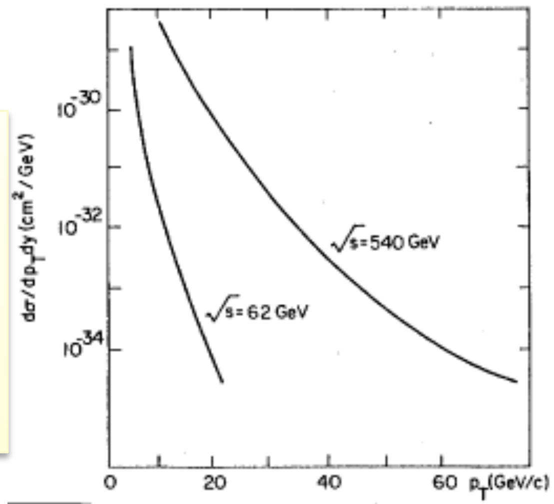
FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

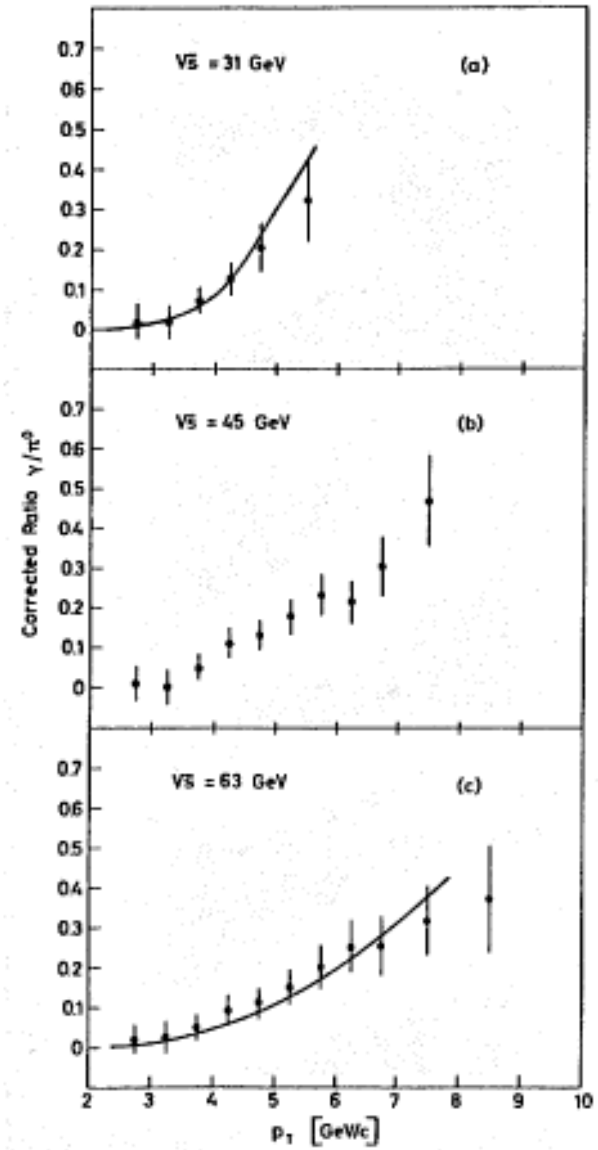
Evidence for the gluon (well...) SPS plans

- **Prompt photons seen:**
  - **ABCS: unambiguous rise of γ/π^0 ratio**
  - **Highly non-trivial (experimentally) exercise:**
    - **Huge background from decay photons...**
- **In QCD picture:**

  Quark+gluon → Quark + γ
- **Yet, so indirect…**

Meanwhile: SPS was in the works… Lesson #3: energy helps ☺

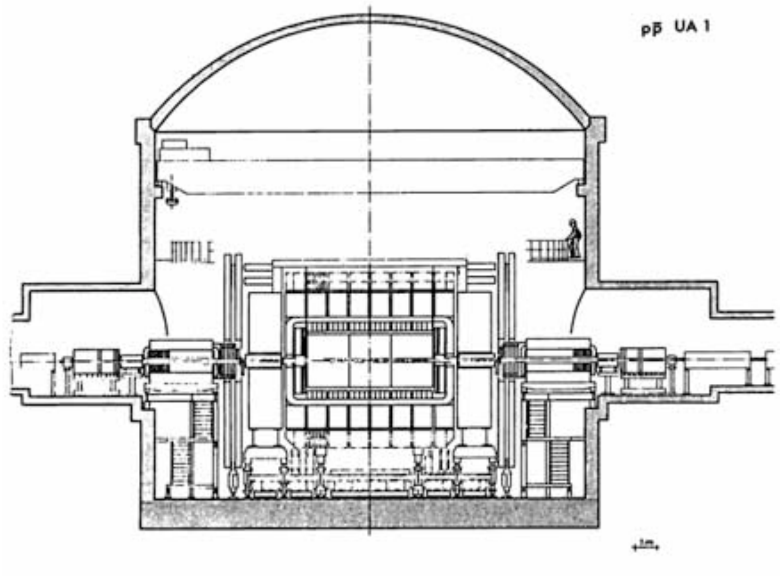


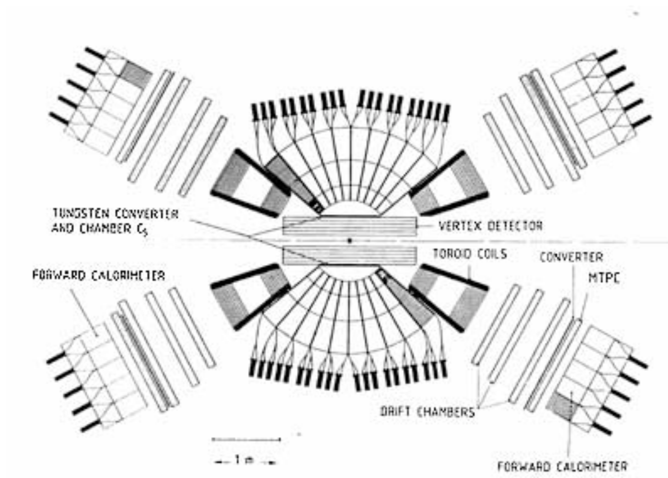


I met (professor) Thomas (Muller) on the UA1 experiment at the CERN SPS (sometime in the 80’s)

UA1 (and UA2)

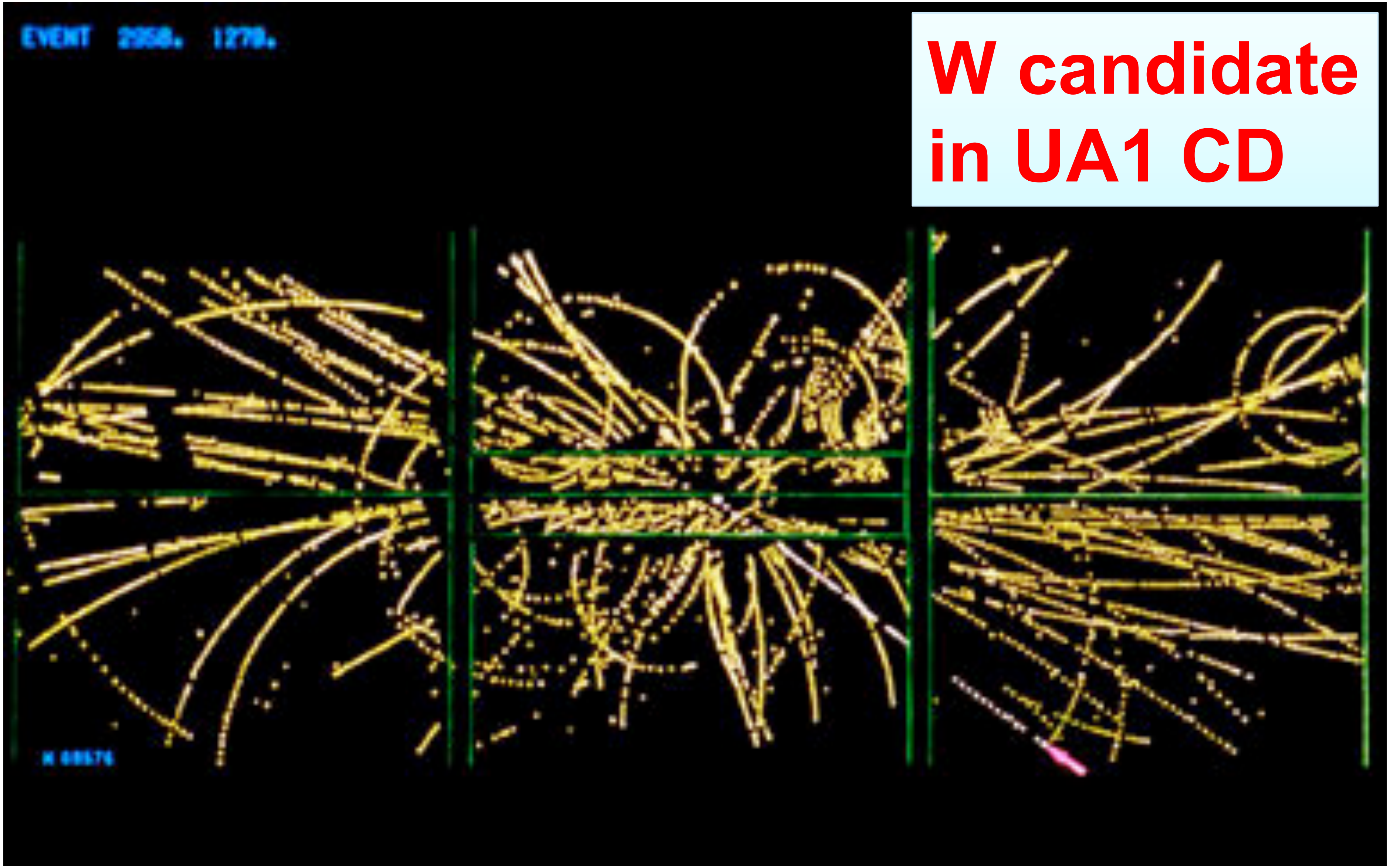
- **At the time, they were huge, very, very risky undertakings**
  - **To begin with, the collider had to bring in protons and ANTI-protons to collide (cross section for W/Z production in pp was too small)**
  - **Second, and above all, the result was predicted to be a MESS**
  - **Third, they had to draw from the lessons learned!**





A mess (or maybe not?)

W candidate in UA1 CD



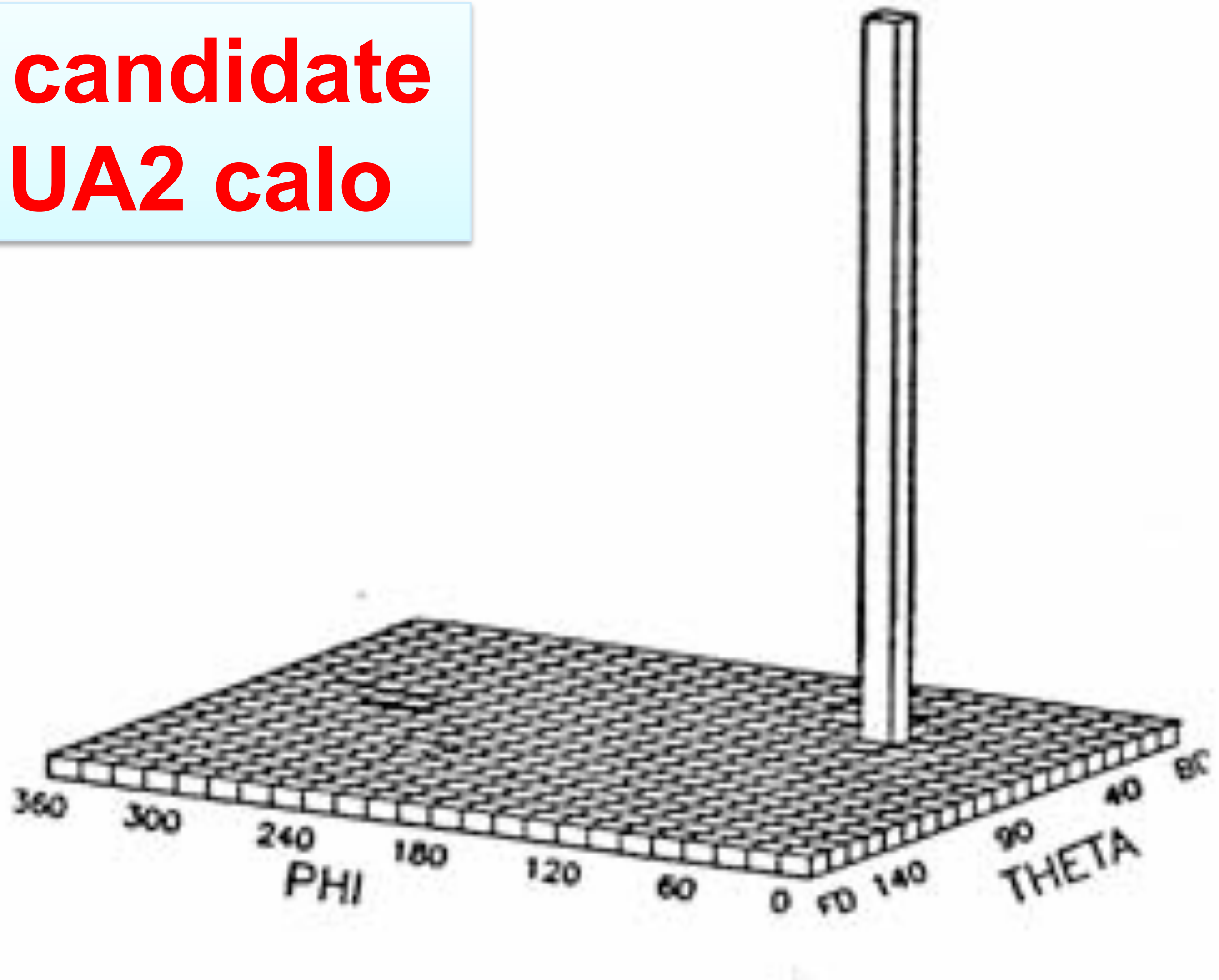
Hermeticity

Calorimeter (inclusive) trigger

Precision tracking

SPS legacy: "Intermediate Vector Bosons"

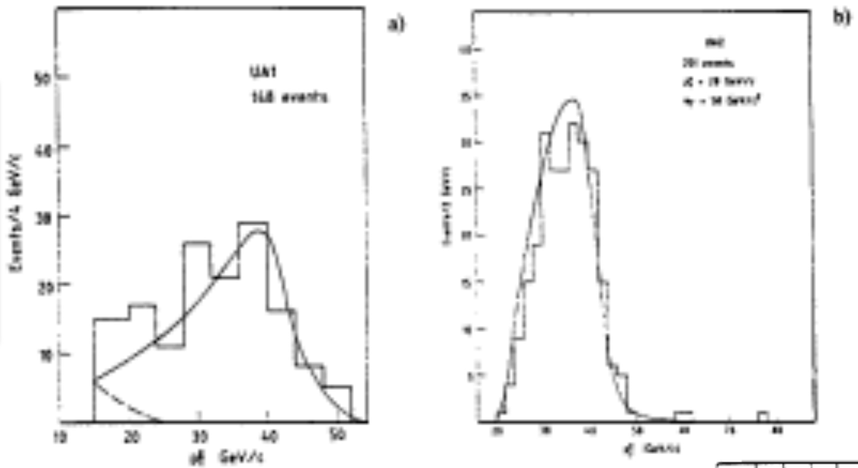
W candidate in UA2 calo

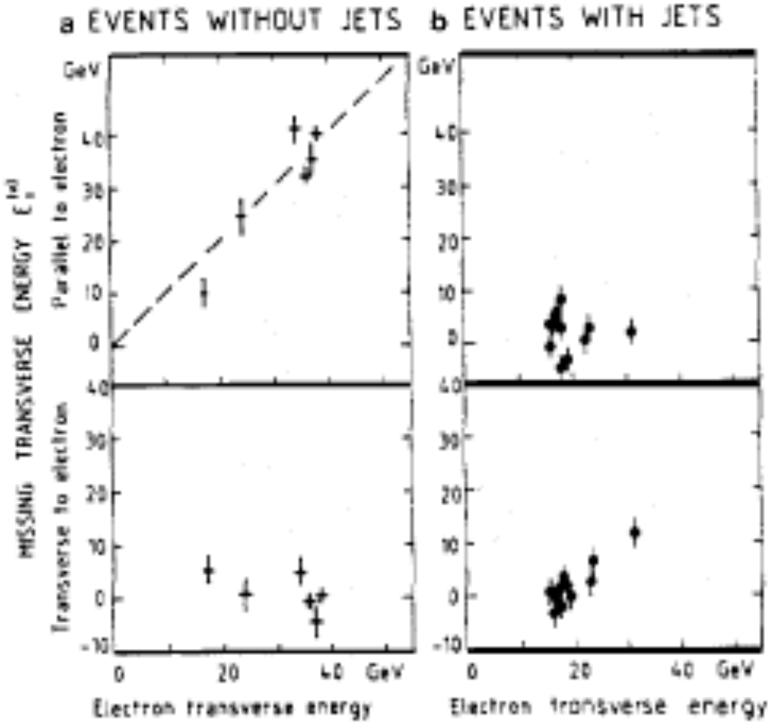


The rendez-vous with the W boson

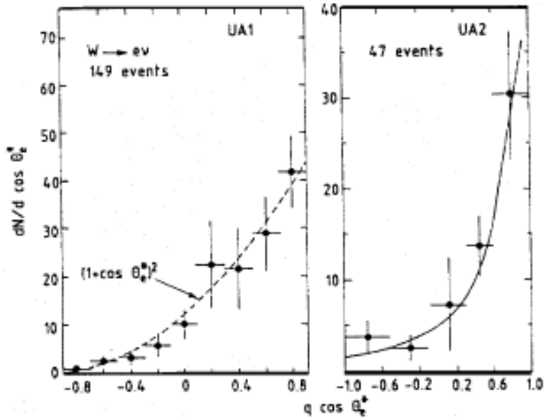
It was there, at the right time (number of events → rate → time of rendez-vous!)

at the right mass:



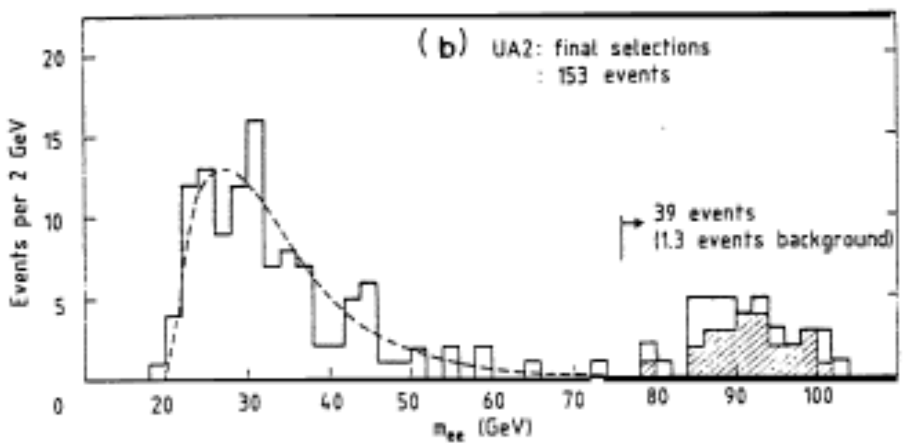


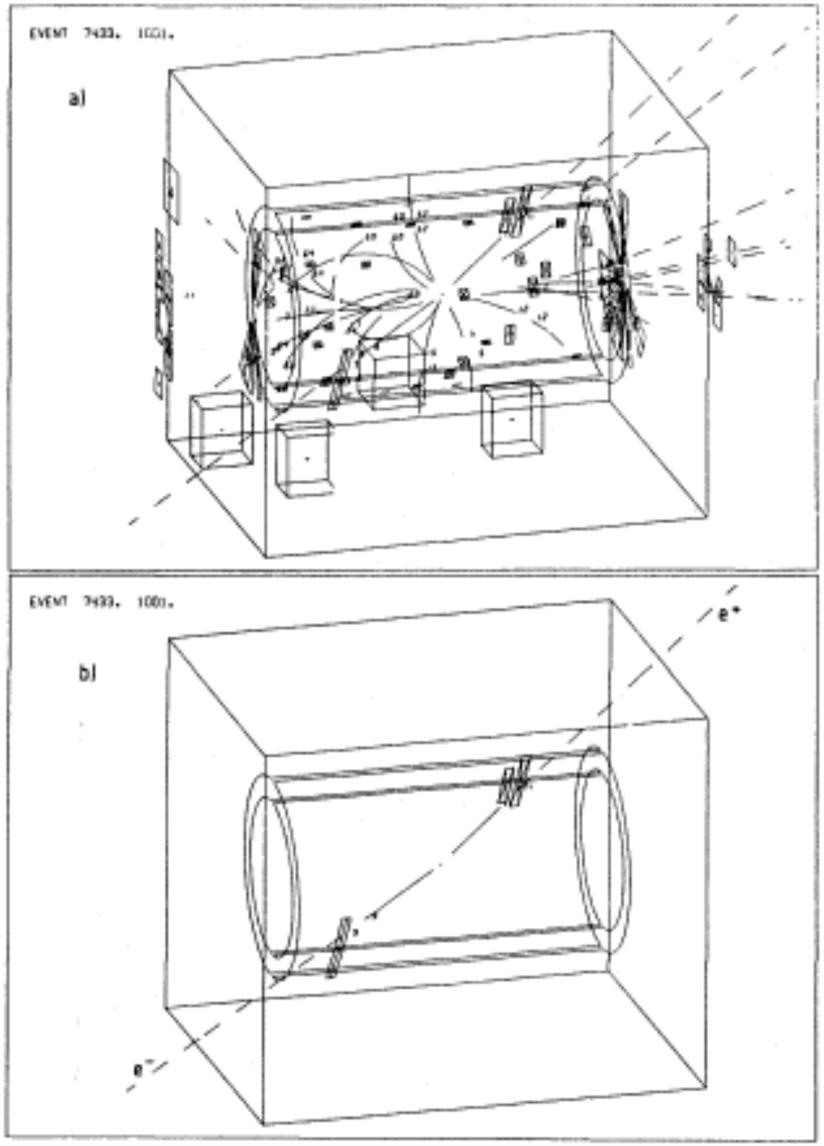
And with the correct spin…



The similarly punctual cousin: the Z boson

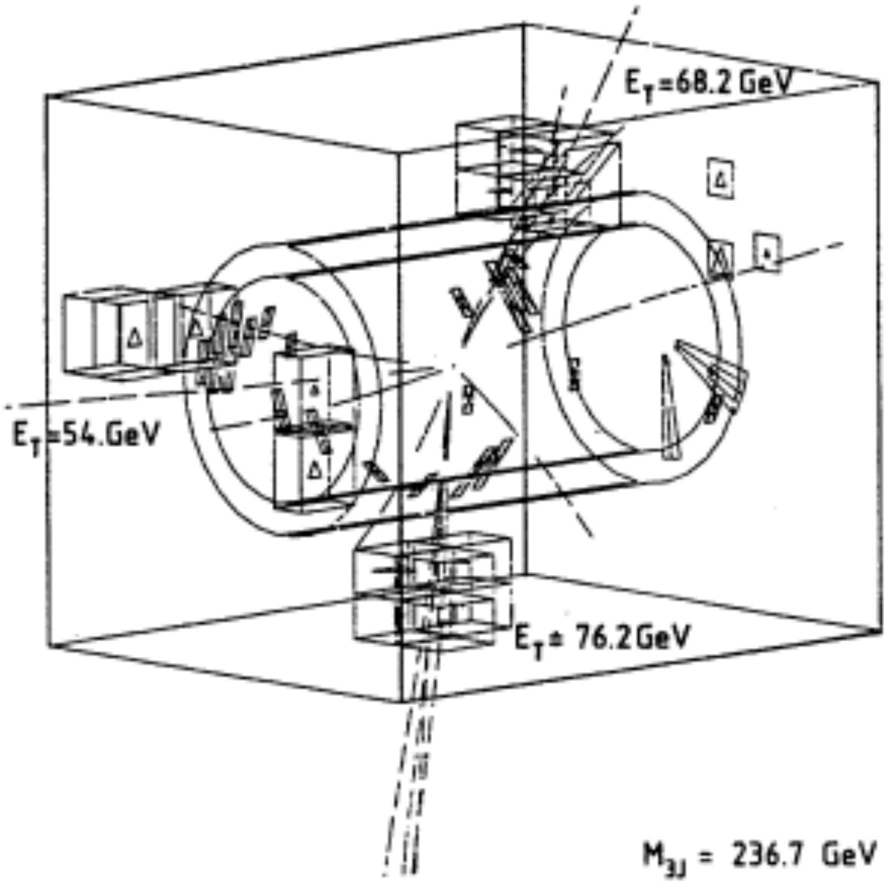
- **The Z boson was there as well**
  - **Also at the right time**
  - **At the right mass**

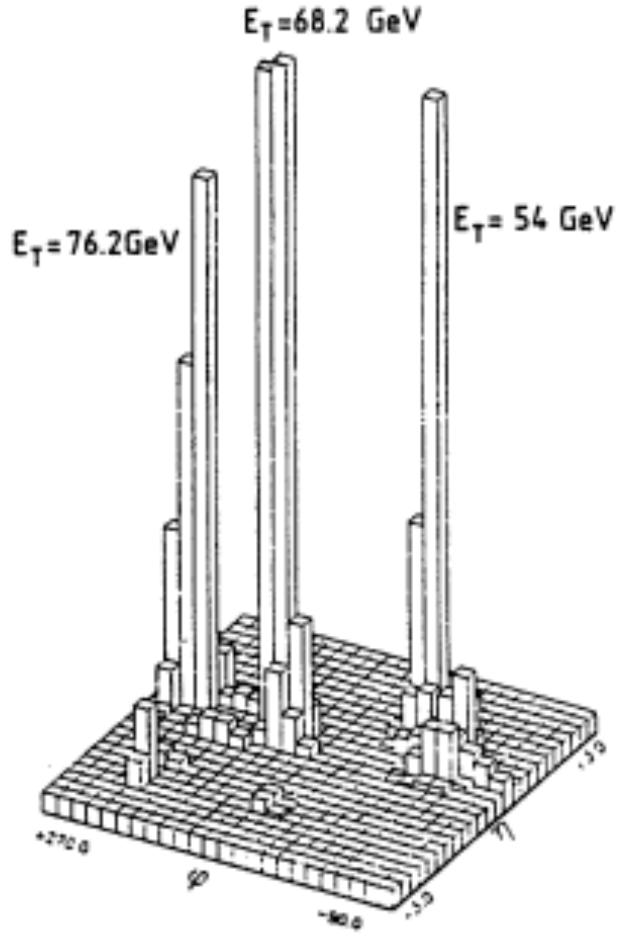




Jets in proton-antiproton collisions

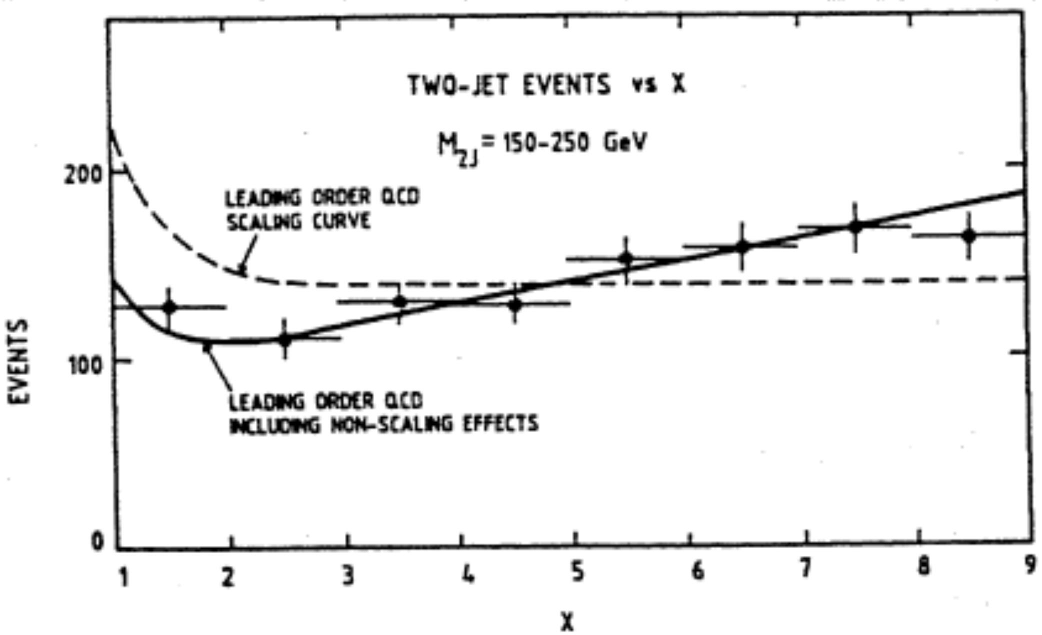
- **Even the gluon was still there – in three-jet events!**

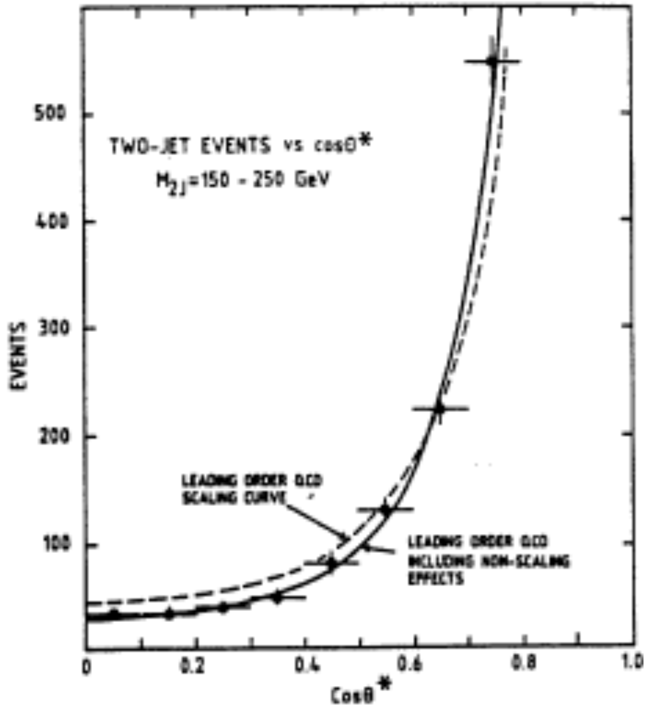




SPS legacy: strong interaction

Partons inside protons do scatter a la Rutherford!

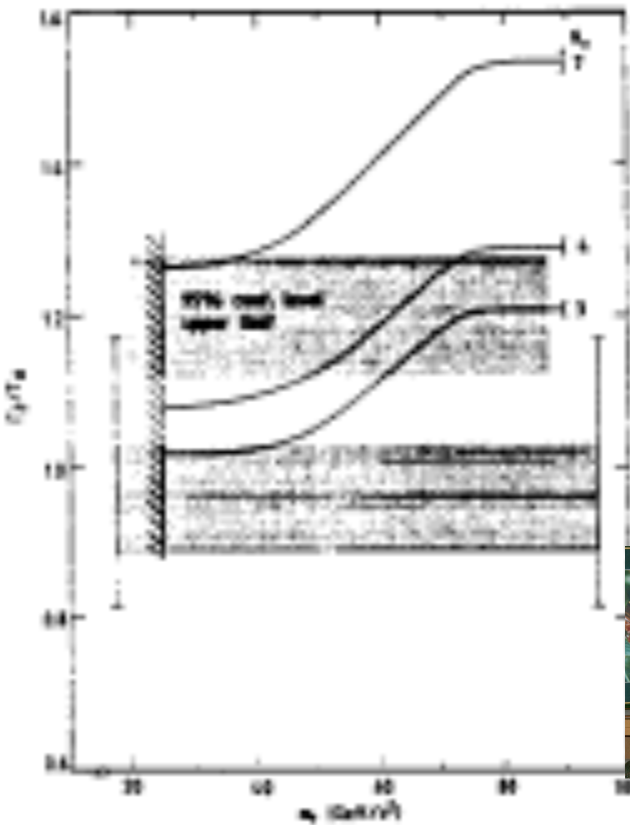




And the QCD "scaling violations" are, actually, visible – Q^2 dependence

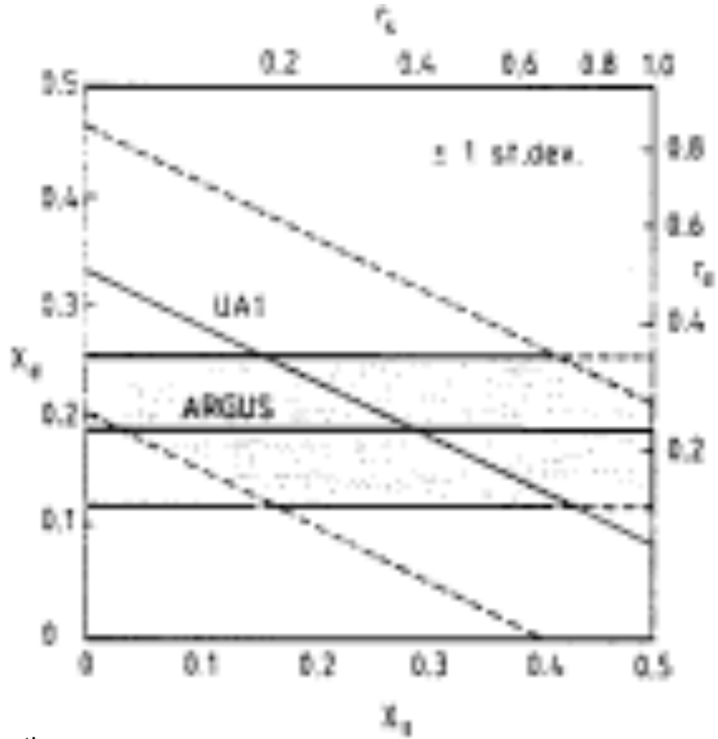
SPS: we learned a lot more as well

- **There are at most six neutrinos!**
  - From W width



[2] Production Properties of the Intermediate Vector Bosons W and Z at the CERN p anti-p Collider, Th. Muller, Fortschr. Phys.37:339, 1989.

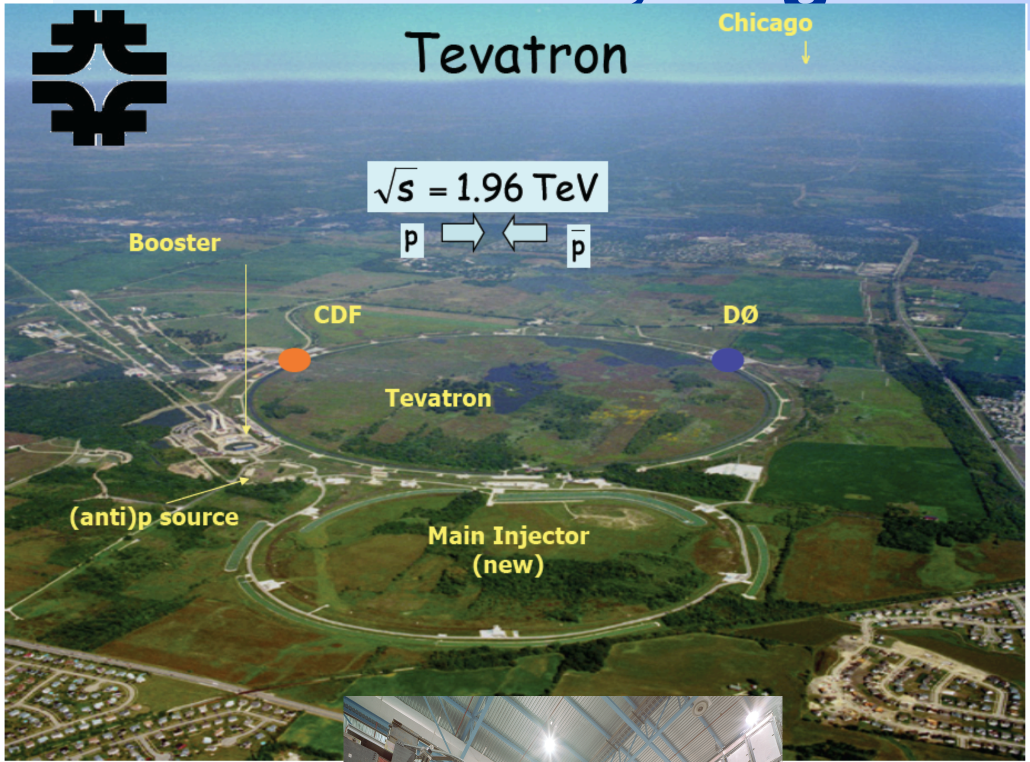
- **And B mesons mix a lot:**
  - Observation of $\mu^+\mu^+$ and $\mu^-\mu^-$ events:

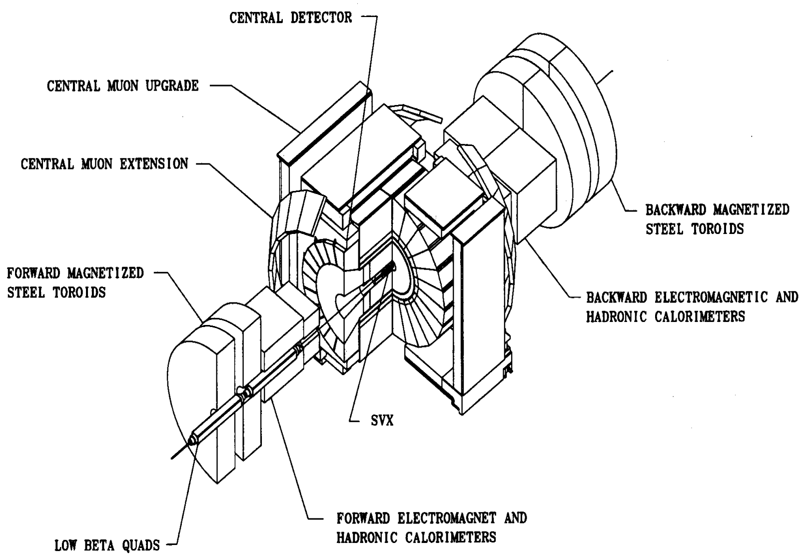


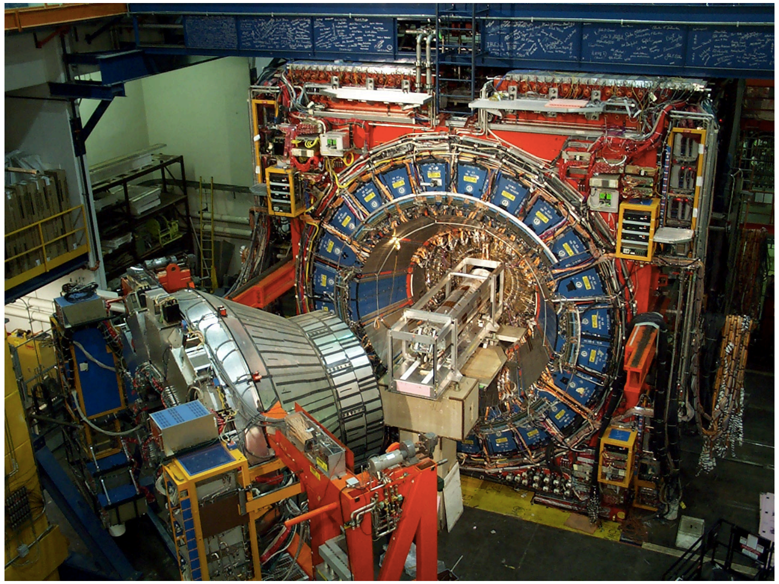
Passing the baton to Fermilab (end of the 80s)

aka “Go West my boy/girl, go west”

End of 80s, beginning of 90s: Tevatron

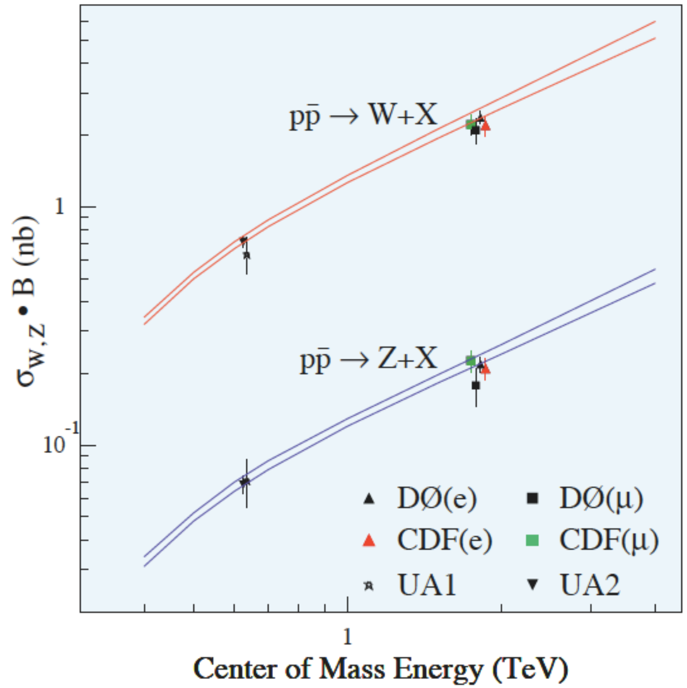


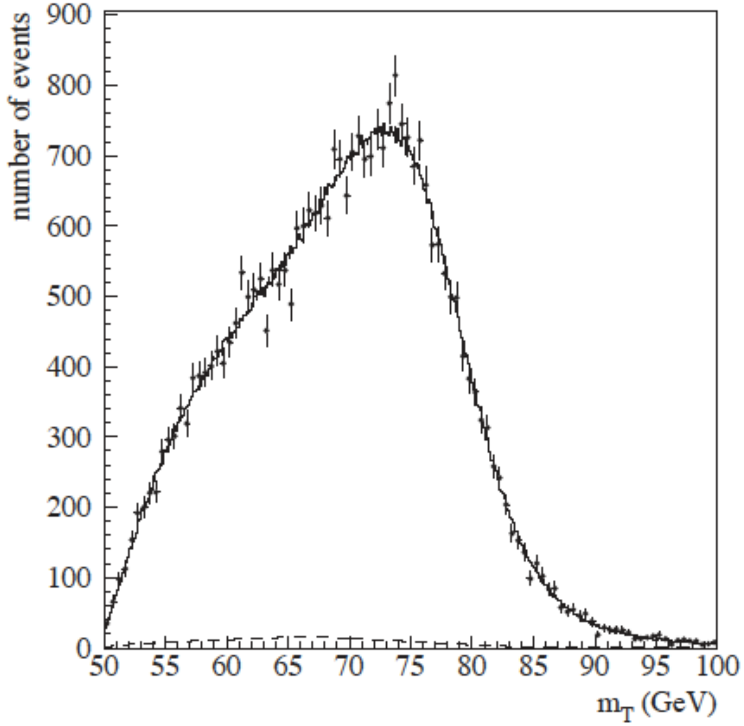




The Tevatron… W/Z physics, next-gen!

- **Higher Energy: big difference in production cross section of massive particles + high luminosity : Huge samples**

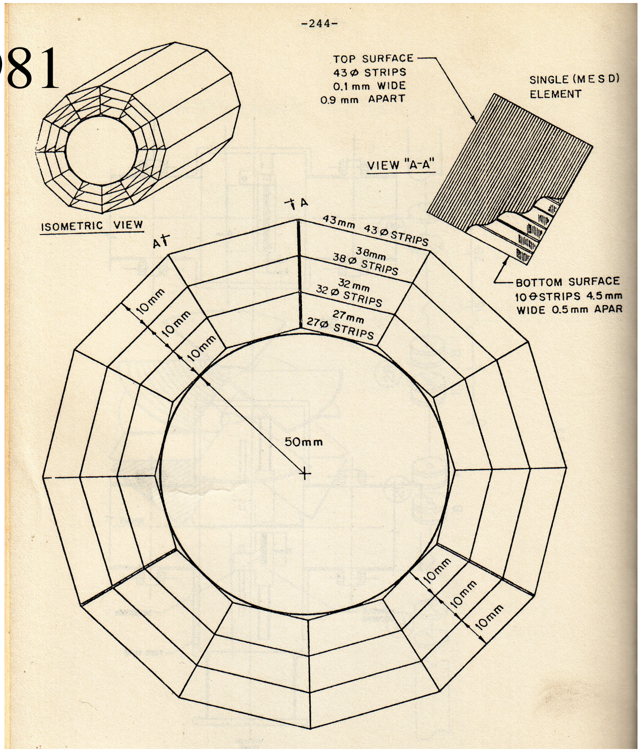


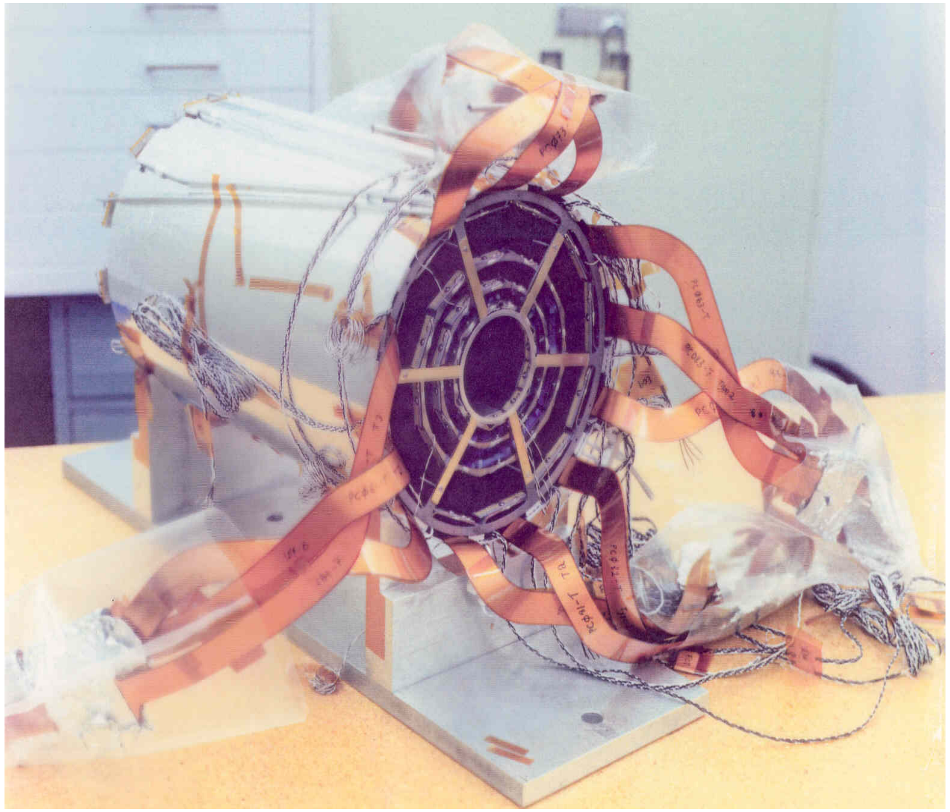


W boson transverse mass distribution from D0, circa 1997: 33,000 W candidates!

The true novelty: silicon vertex detector

1981

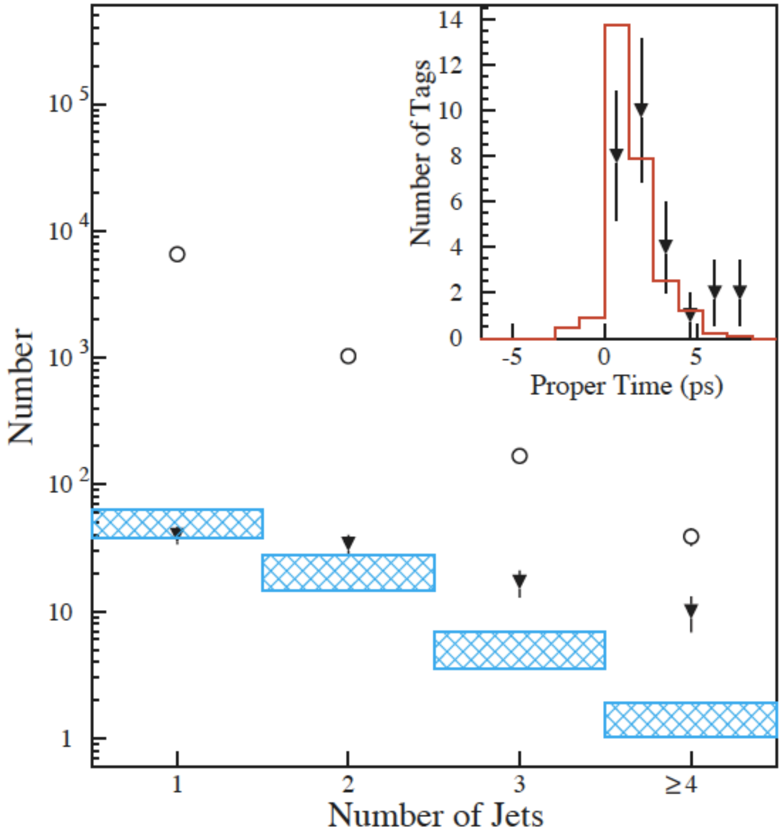


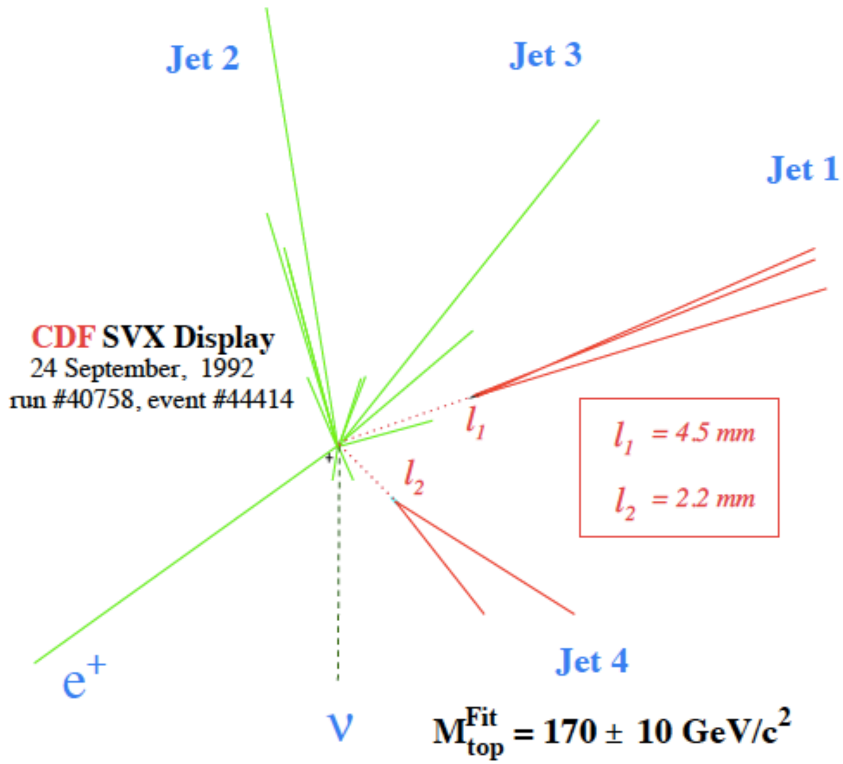


The SVX was the first silicon vertex detector and gave CDF a whole new physics capability

The Tevatron discovery: the top quark

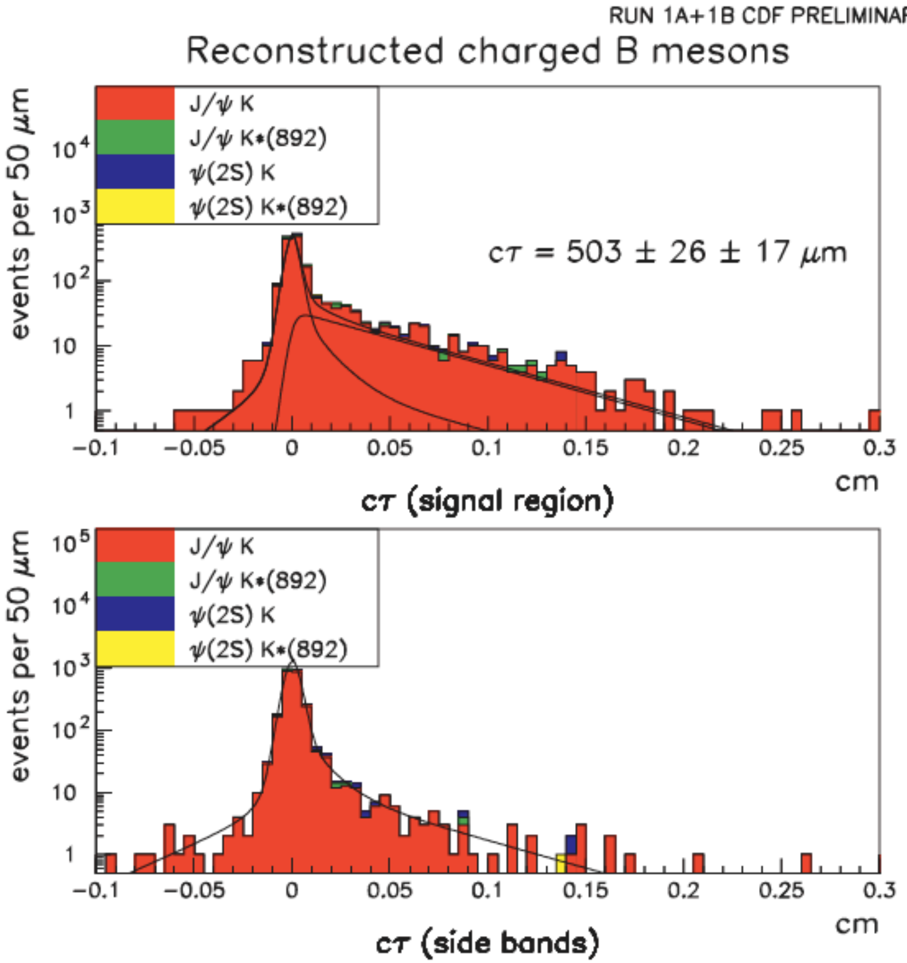
- **The crowning moment for the Tevatron experiments: the observation of the Top quark**
  - **The most complicated signature up to that point in time; leptons, jets, missing transverse energy, and b-tagging!**





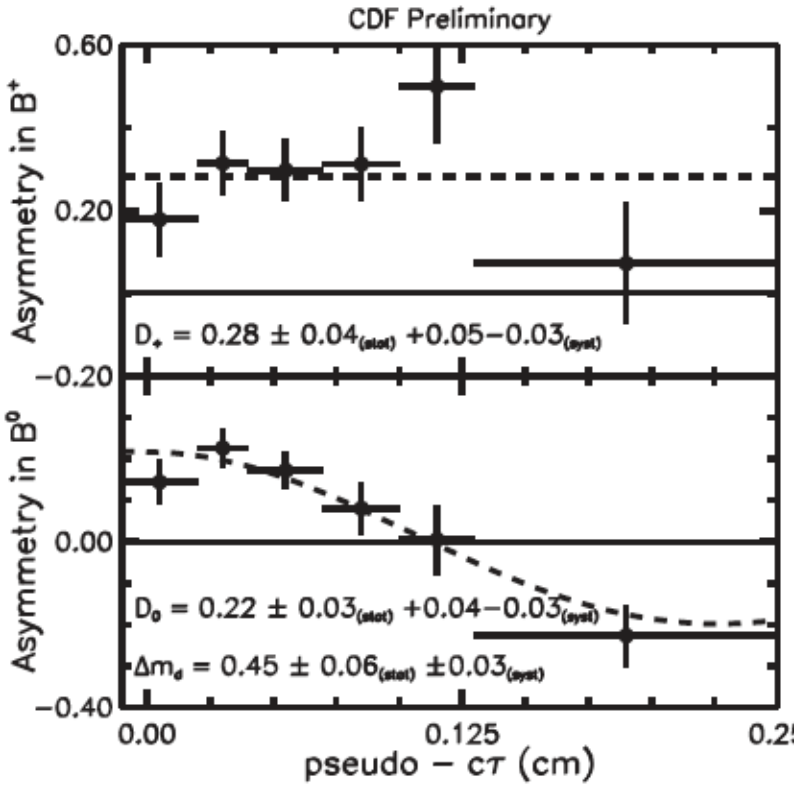
And then came the rich B physics program

- **Directly "see" B meson decay; also flavor-tag (B/B-bar)**



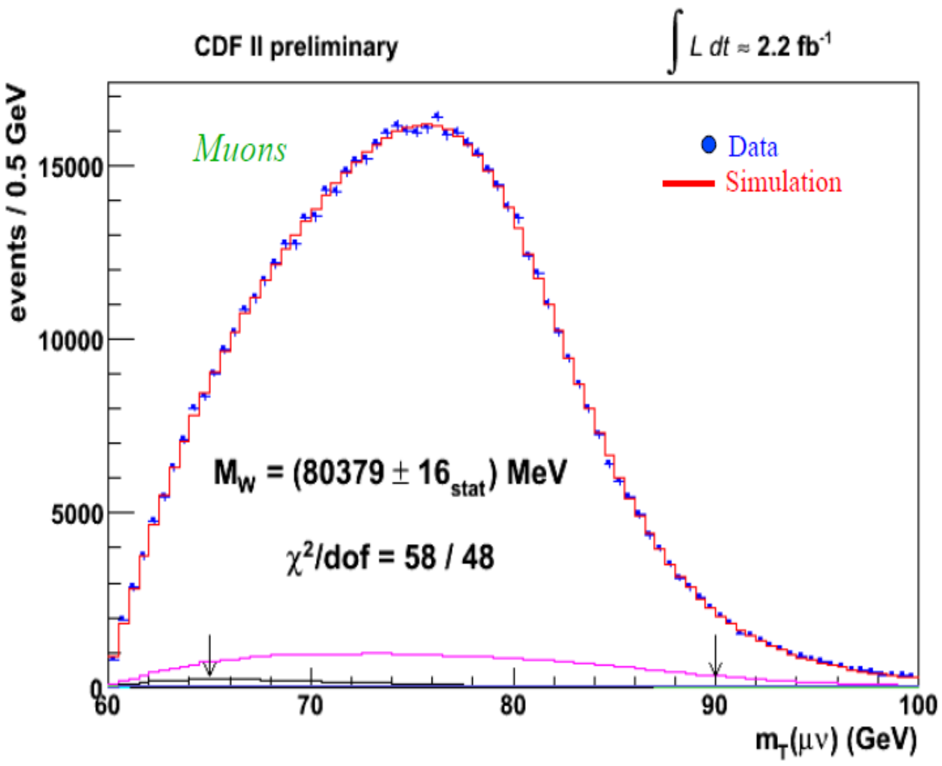
$B^+ \to J/\psi\, K^+$

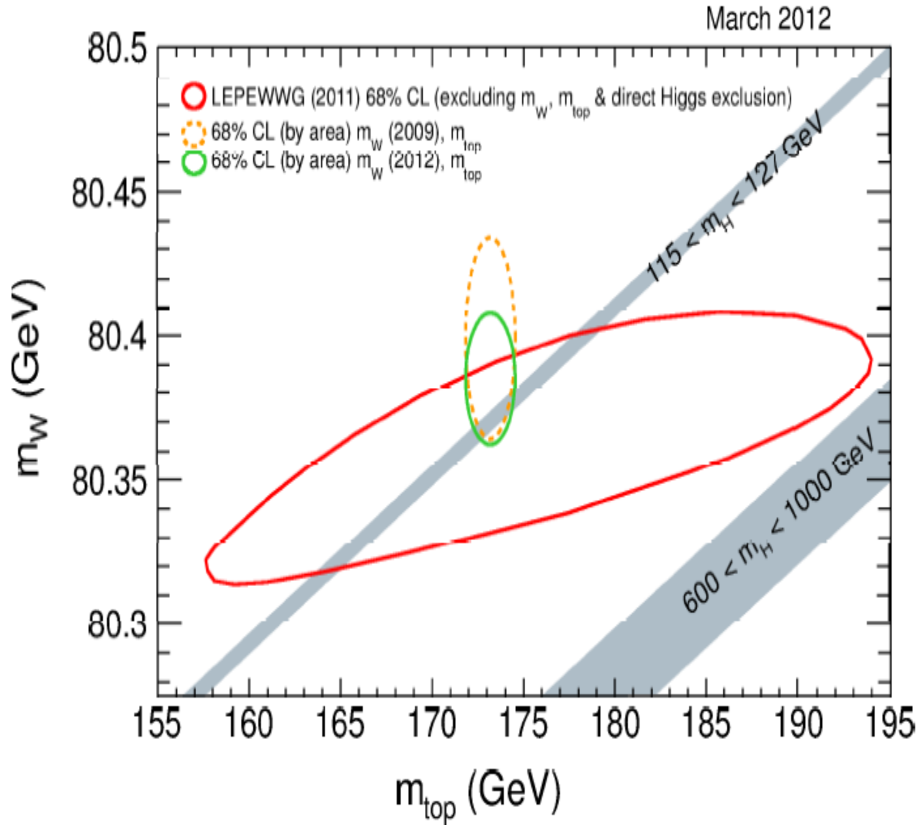
lepton+D; SST



The real surprise: precision on W mass

- **A measurement with a relative error of 0.24×10^{-3}**
  - **M_W = 80387 ± 19 MeV/c² (→ ± 12 (stat.) ± 15 (syst.))**



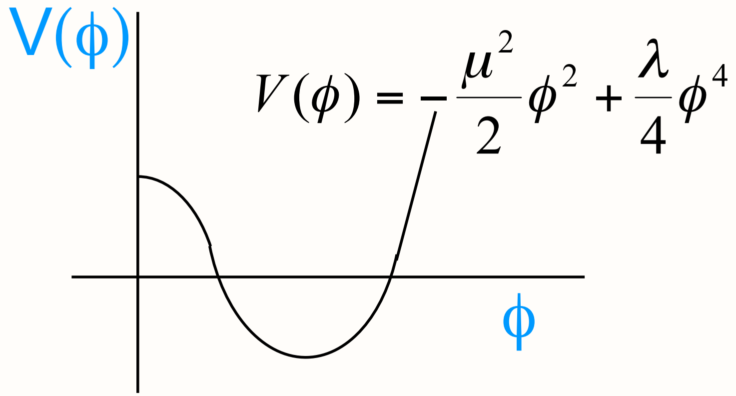


The Tevatron

The word “success” does not do justice
Yet… the Higgs Boson did not show up

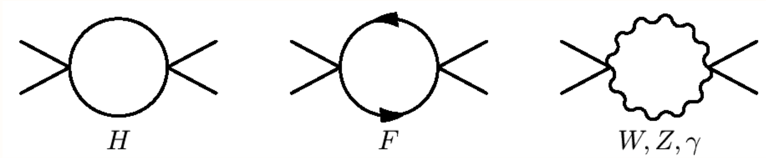
Known unknown: Higgs mass
Known once known unknown would be known:
Higgs decays

Scale of New Physics = $F(M_H)$



$$V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4$$

+



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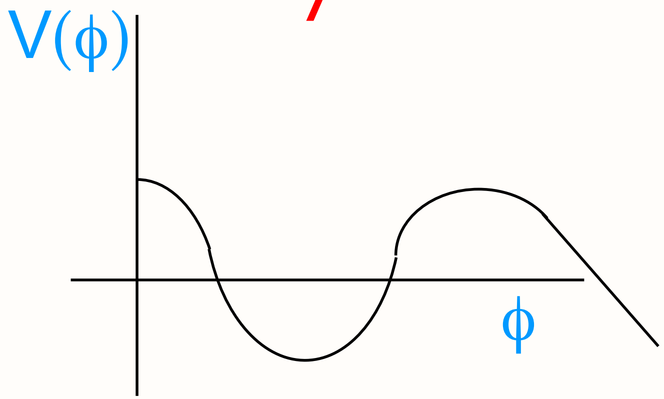
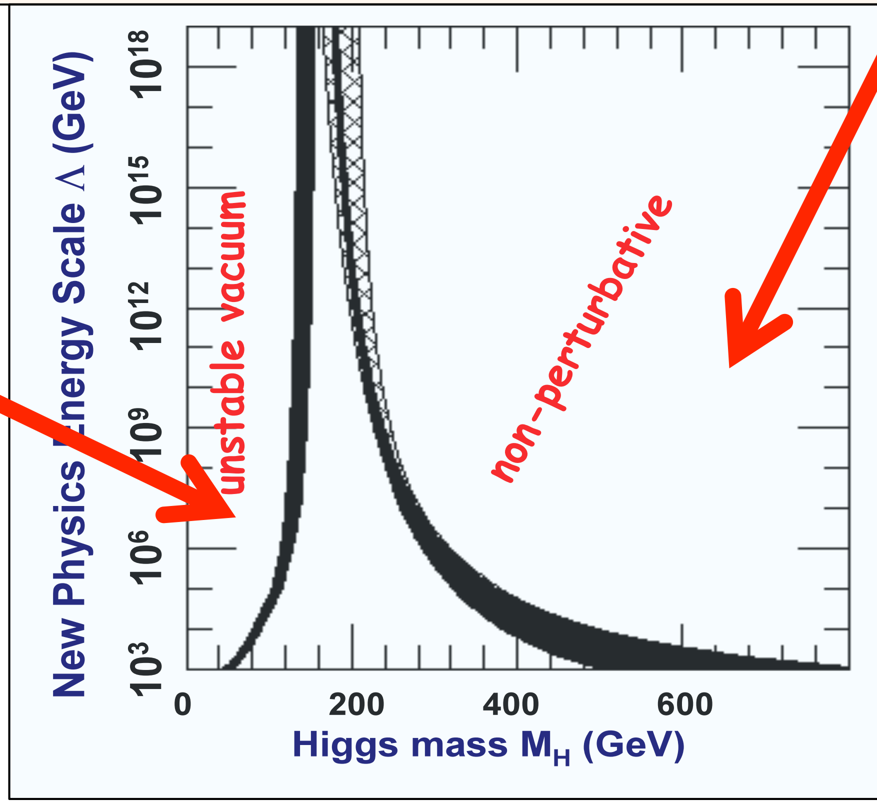


$$\lambda(Q^2) = \frac{\lambda(Q_0^2)}{1 - \lambda(Q_0^2)/16\pi^2 \log(Q^2/Q_0^2)}$$

$Q^2 \to \infty$, $\lambda \to \infty$!

$$\Lambda \leq M_H \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$



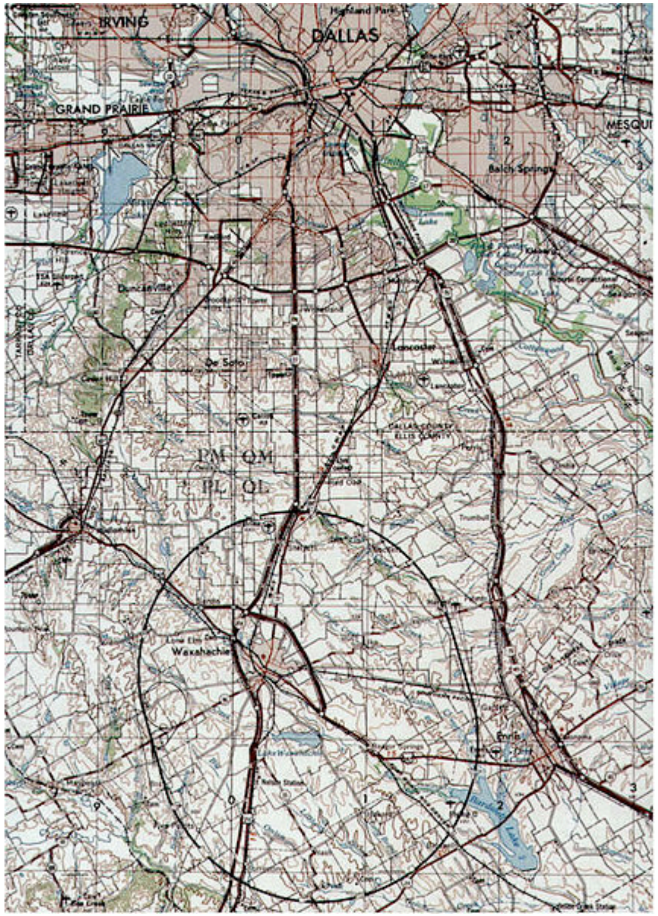
As far back as in early 90's, people realized a new machine would be needed

The Superconducting Supercollider (SSC)

aka "the HIGGSatron"

The machine what was not meant to be

- The dream of the 90s: “today’s physics at the Tevatron, tomorrow’s physics at the SSC”
- Provided much of the motivation for crossing the Atlantic in the early 90s
- SSC: a machine like no other
  - 87 km! 40 TeV! (Tevatron was 2 TeV!)



CATO report

- **May 92:**

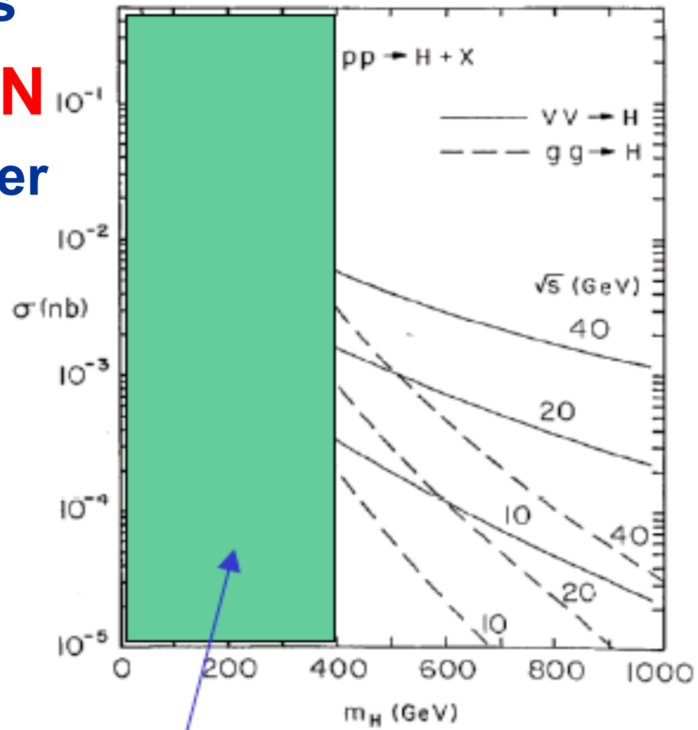
  "Congress soon will be deciding the fate of the Superconducting Super Collider—the $11 billion Department of Energy atom smasher.

  After five years of skyrocketing cost estimates and increasing skepticism about the scientific merit of the SSC, there is now growing support on Capital Hill for pulling the plug on what would be one of the most expensive science projects ever undertaken by the federal government.

  The administration, however, has been lobbying furiously to spare the SSC from the budget knife and even proposes a 30 percent increase in the project's budget…"

A machine for EWSB

- **Superconducting Supercollider (SSC) $\sqrt{s}$=40 TeV...**
  - **By now: would have had 3rd-gen results**
- **So: use existing LEP tunnel at CERN**
  - **Replace: e by p; increase bending power**
    - ➨ **Large Hadron Collider**

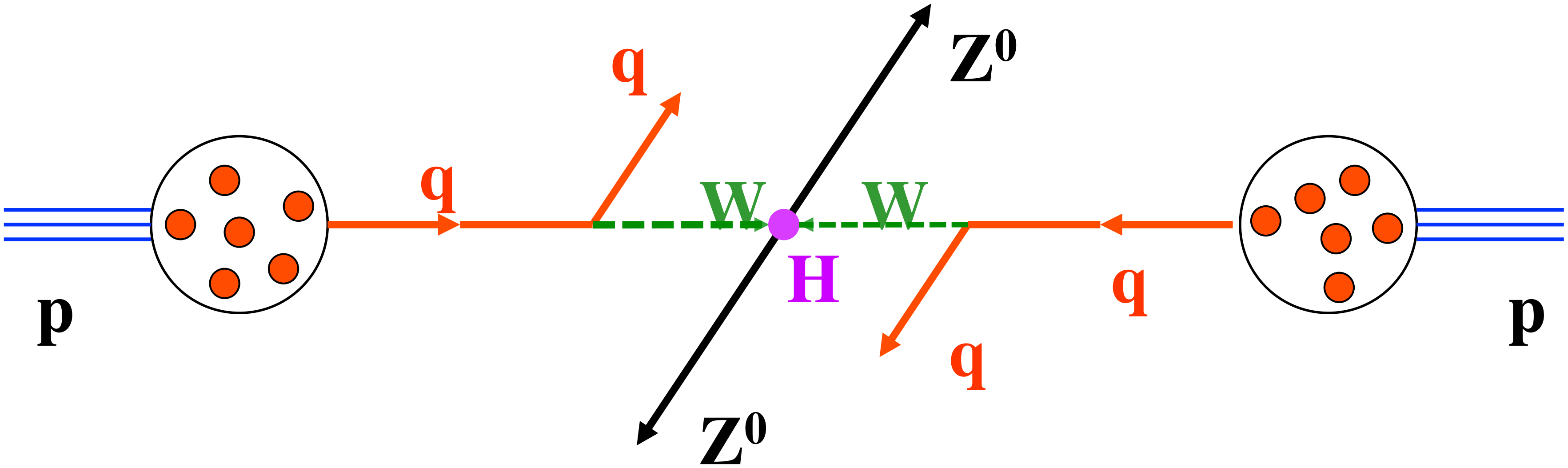


D.Dicus, S. Willenbrock

Phys.Rev.D32:1642,1985

Not true any more (M_T=175 GeV)

Higgs Production in pp Collisions



M_H ~ 1000 GeV

$E_W \geq 500$ GeV

$E_q \geq 1000$ GeV (1 TeV)

$E_p \geq 6000$ GeV (6 TeV)

→ **Proton Proton Collider with $E_p \geq$ 6-7 TeV**

pp collisions at 14 TeV at 10^{34} cm^{-2}s^{-1}

Interactions/x-ing:

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

$\sigma(pp)$ = 70 mb

→ $R_{interactions}$= 7×10^8 Hz

Time/BC, Δt = 25 ns

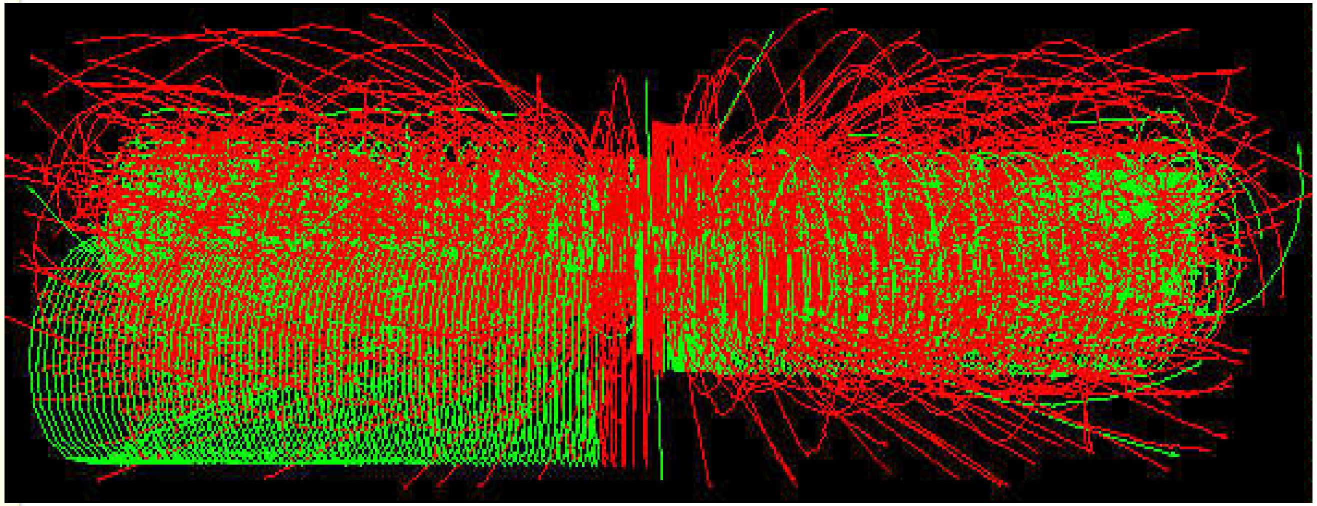
Interactions/BC=17.5

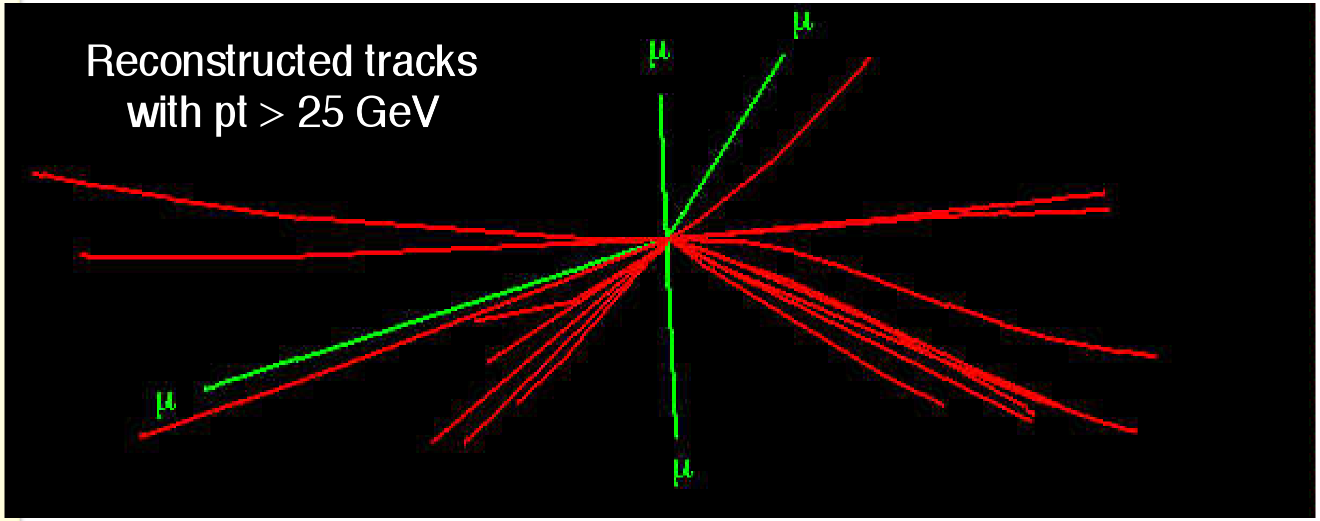
80% bunches full:
17.5x5/4 = 23

~ 20 min-bias events overlap!

Example: the cleanest ("golden") Higgs signature:

$H \rightarrow ZZ$, $Z \rightarrow \mu\mu$, $H \rightarrow 4\mu$:

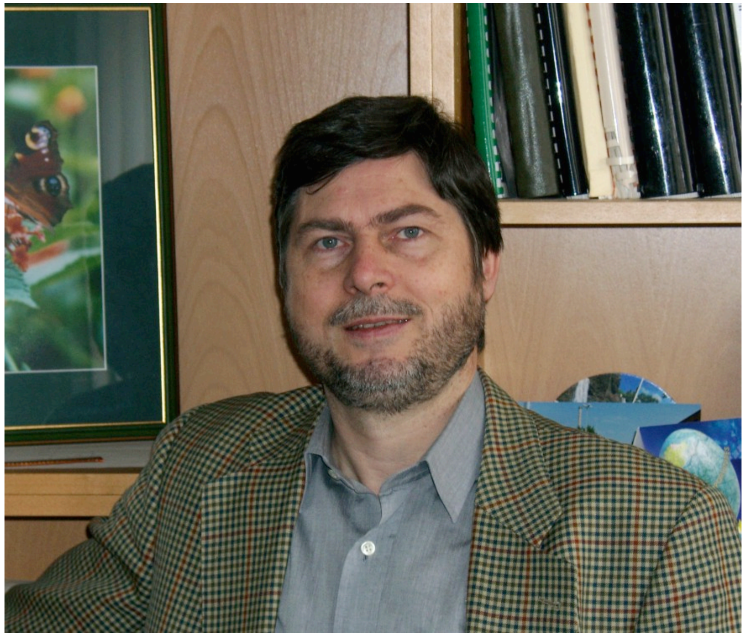




And this (not the H...) would repeat every 25 ns

US_CMS

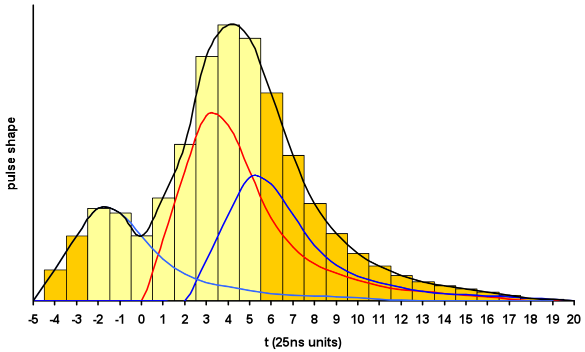
- **Feb 1994: a meeting of US institutions in Los Angeles**
  - **Right after the earthquake…**
- **Organized by UCLA**
  - **Professor Thomas Muller**
    - **(same as KIT's TM)**
  - **Pulling together lots of US institutions to listen to CMS management**
    - **ATLAS and CMS on a "US tour" at the time…**
- **And thus the seeds of "US_CMS" were planted…**



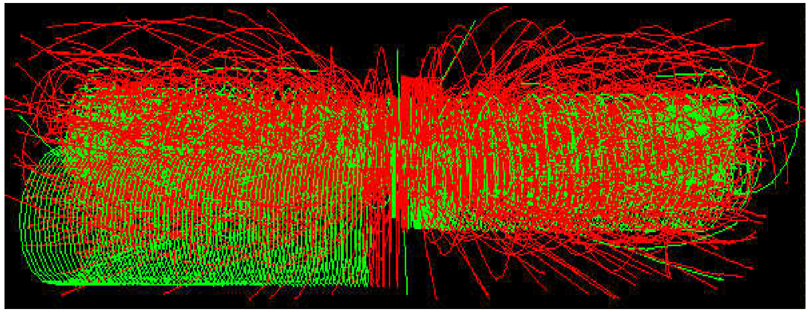
The LHC challenge

LHC challenges: detector design

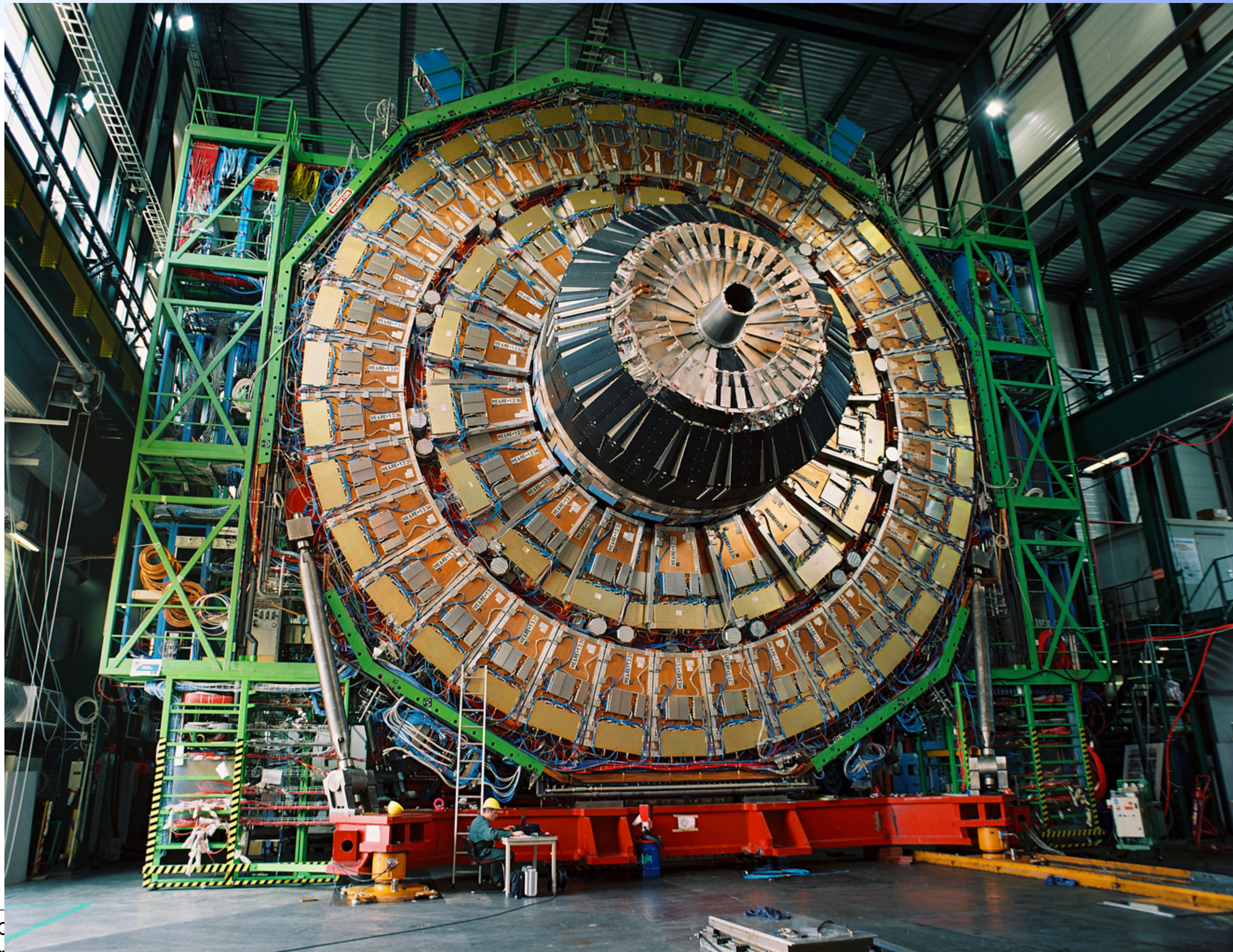
- **LHC detectors must have fast response**
  - Otherwise will integrate over many bunch crossings → large "pile-up"
  - Typical response time : 20-50 ns
    - → challenging readout electronics
- **LHC detectors must be highly granular**
  - Minimize probability that pile-up particles be in the same detector element as interesting object
    - → large number of electronic channels; high cost
- **LHC detectors must be radiation-resistant:**
  - high flux of particles from pp collisions → high radiation environment e.g. in forward calorimeters in 10 yrs of LHC:
    - up to 10^{17} n/cm^2 [10^7 Gy; 1 Gy = 1 Joule/Kg)



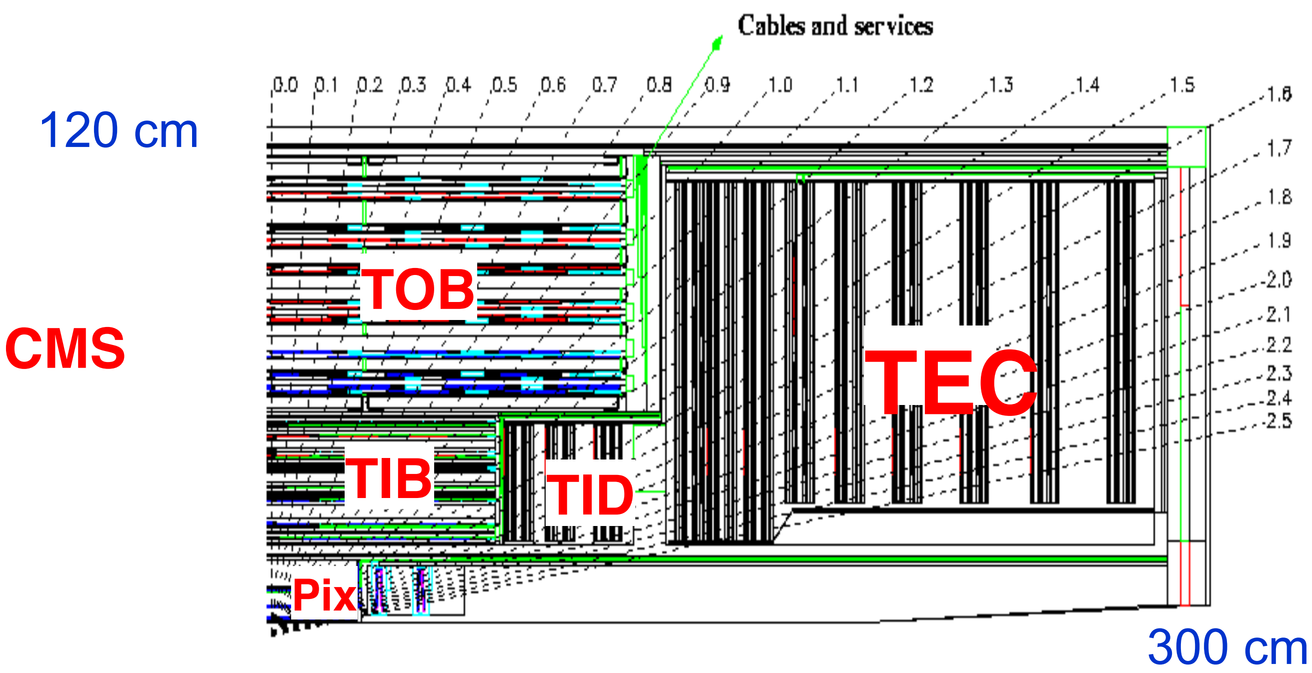
100 million channels per detector!



Endcap muons (Cathode Strip Chambers)



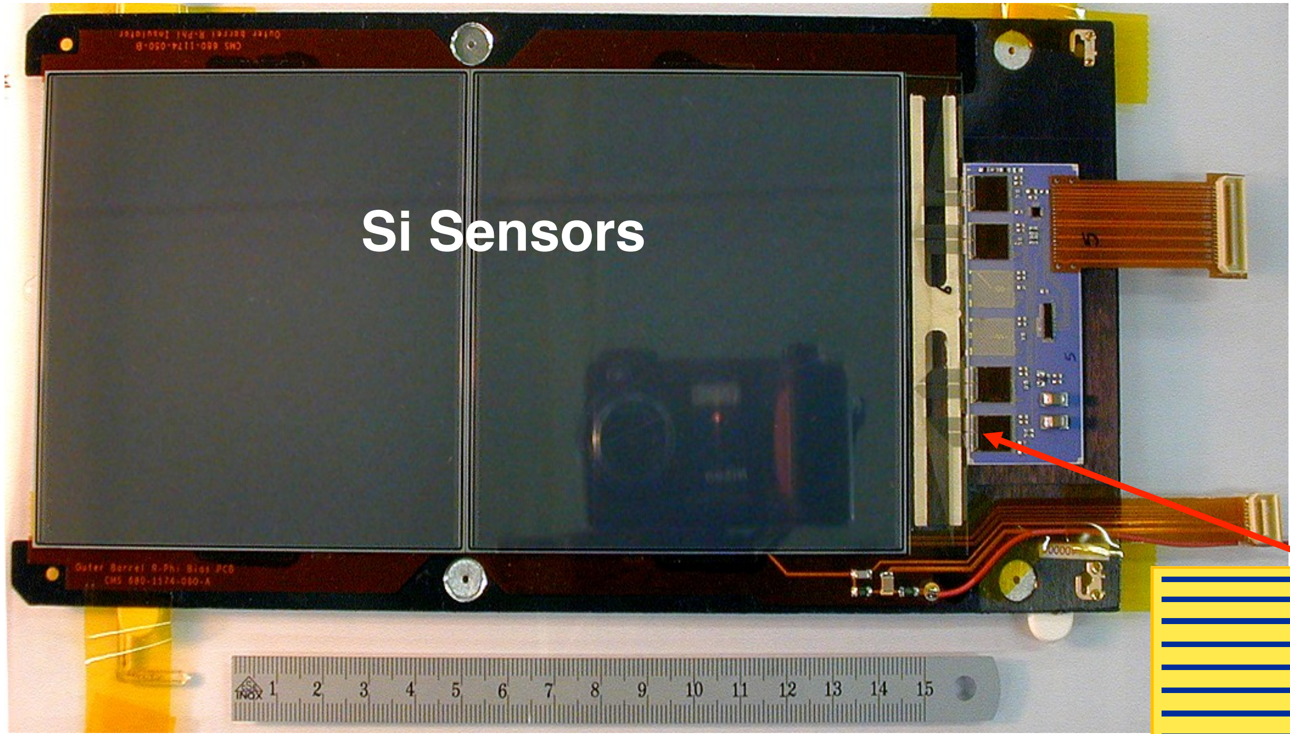
Layout of CMS Tracking



Si pixels surrounded by silicon strip detectors

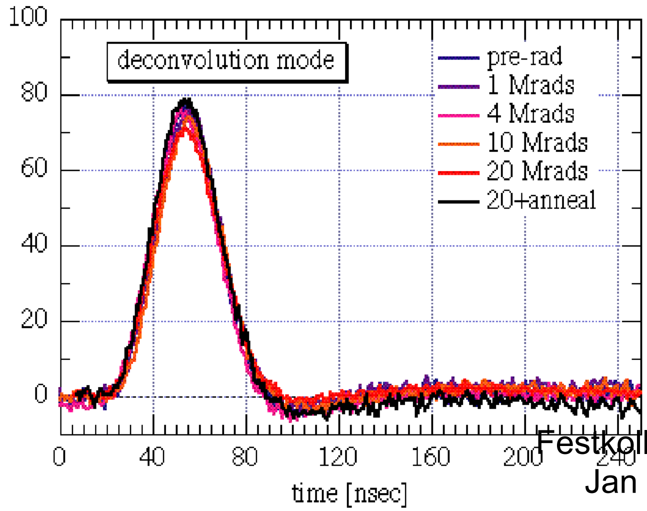
Pixels: ~ 1 m^2 of silicon sensors, 65 M pixels, 100x150 μm^2 , r = 4, 7, 11 cm
Si μstrips : 223 m^2 of silicon sensors, 10 M strips, 10 pts, r = 20 – 120 cm

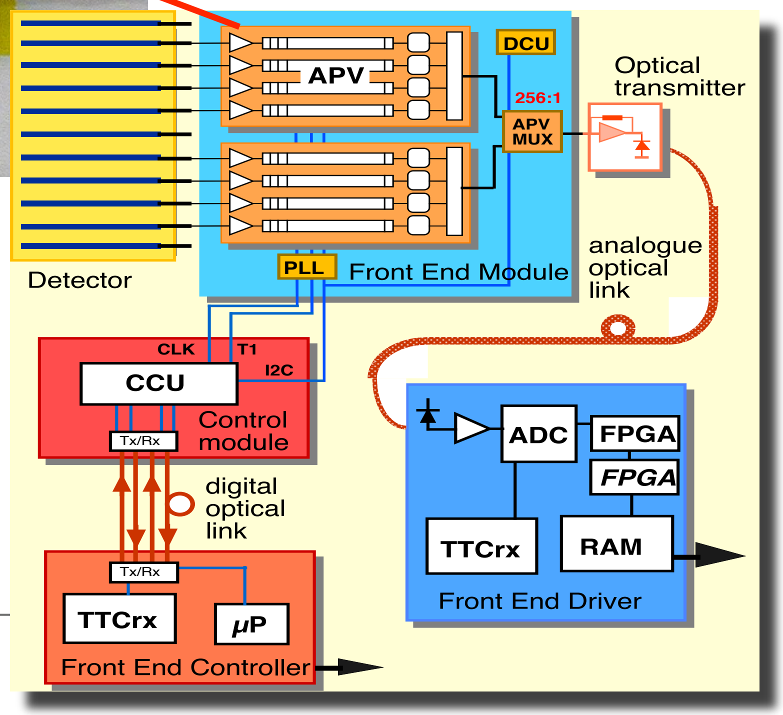
Si Modules and Electronics Chain



Ride on technology wave

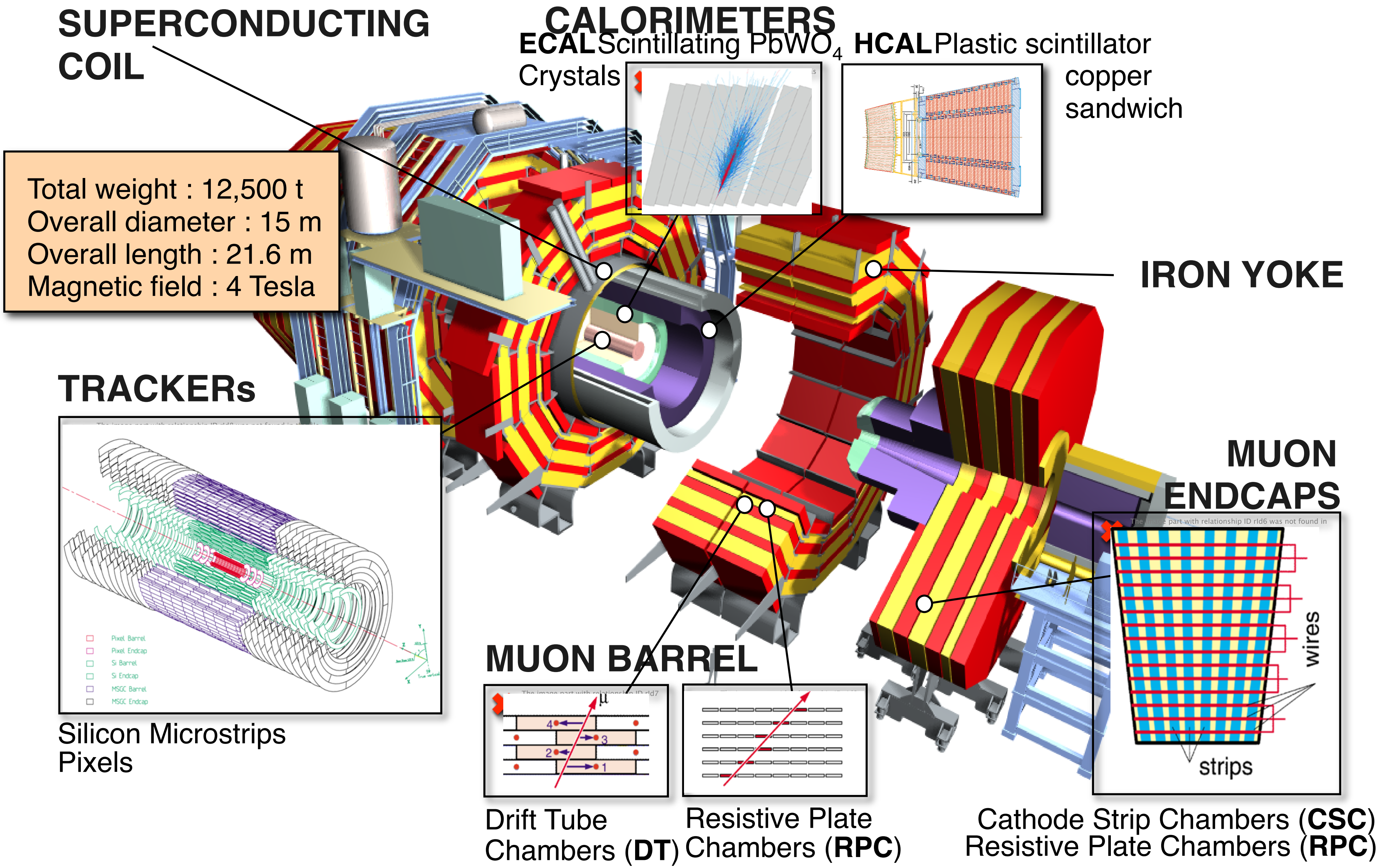
75k chips using 0.25μm technology





Si Tracker

The Compact Muon Solenoid (CMS)



Perspective: an LHC experiment

- **Analogy: 3D digital camera with 100 Mpix**
- **40 million pictures per sec (which correspond to the happenings during the first ~1/10 of a billionth of a second after the Big Bang)**
  - **Information: 10,000 encyclopedias per second**
- **First selection of photographs: 100,000 / sec**
  - **Each is up to ~ 1MB**
- **And gets analyzed on a process farm with ~ 5,000 CPU cores**
- **Every second, record [store permanently] the best 600 of these pictures**
- **~ 10 million GB/year (5 million DVDs/year)**

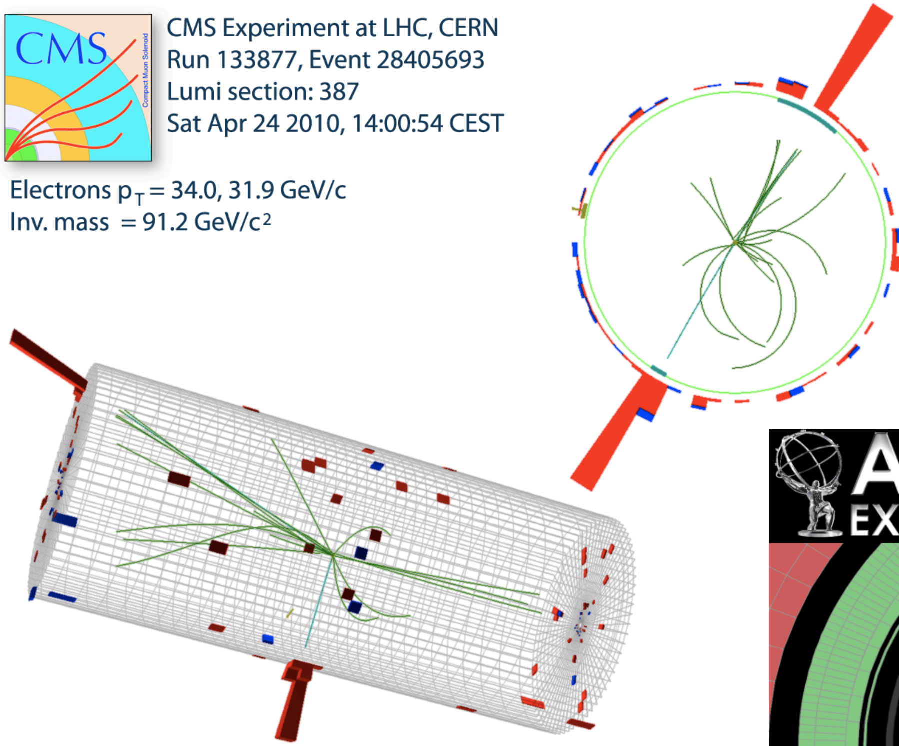
LHC($t_0+\Delta t=2.5$yrs):

Foundations established
a “tour de force” of SM measurements

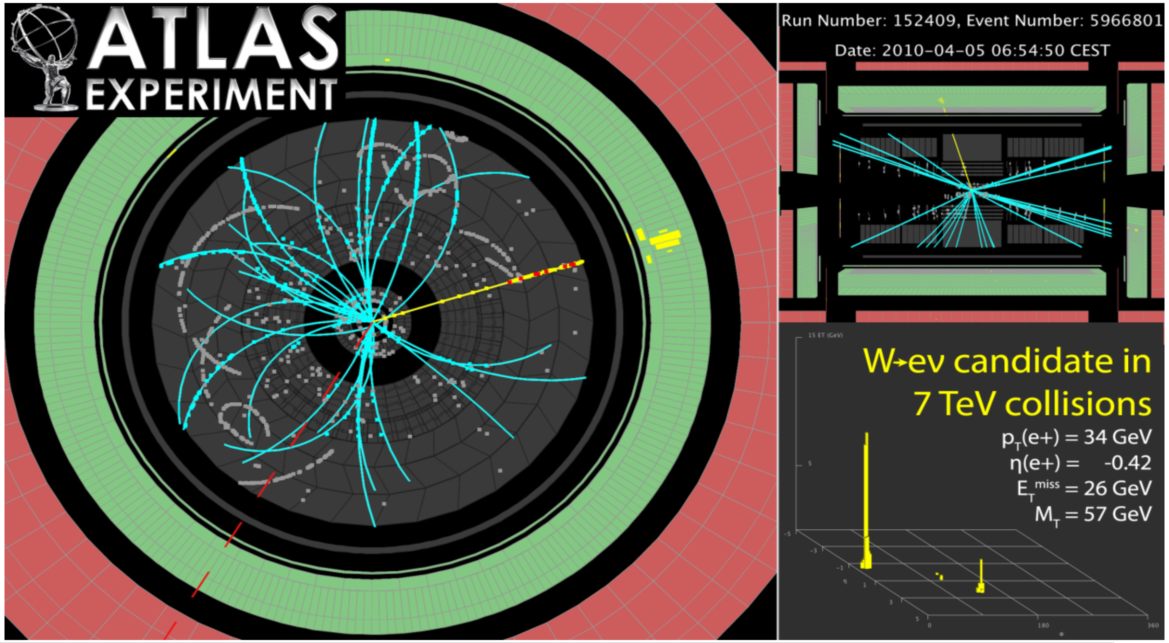
and, of course,
the hunt for the Higgs boson…

W/Z at 7 TeV: (still) clean & beautiful

Z → electron + positron

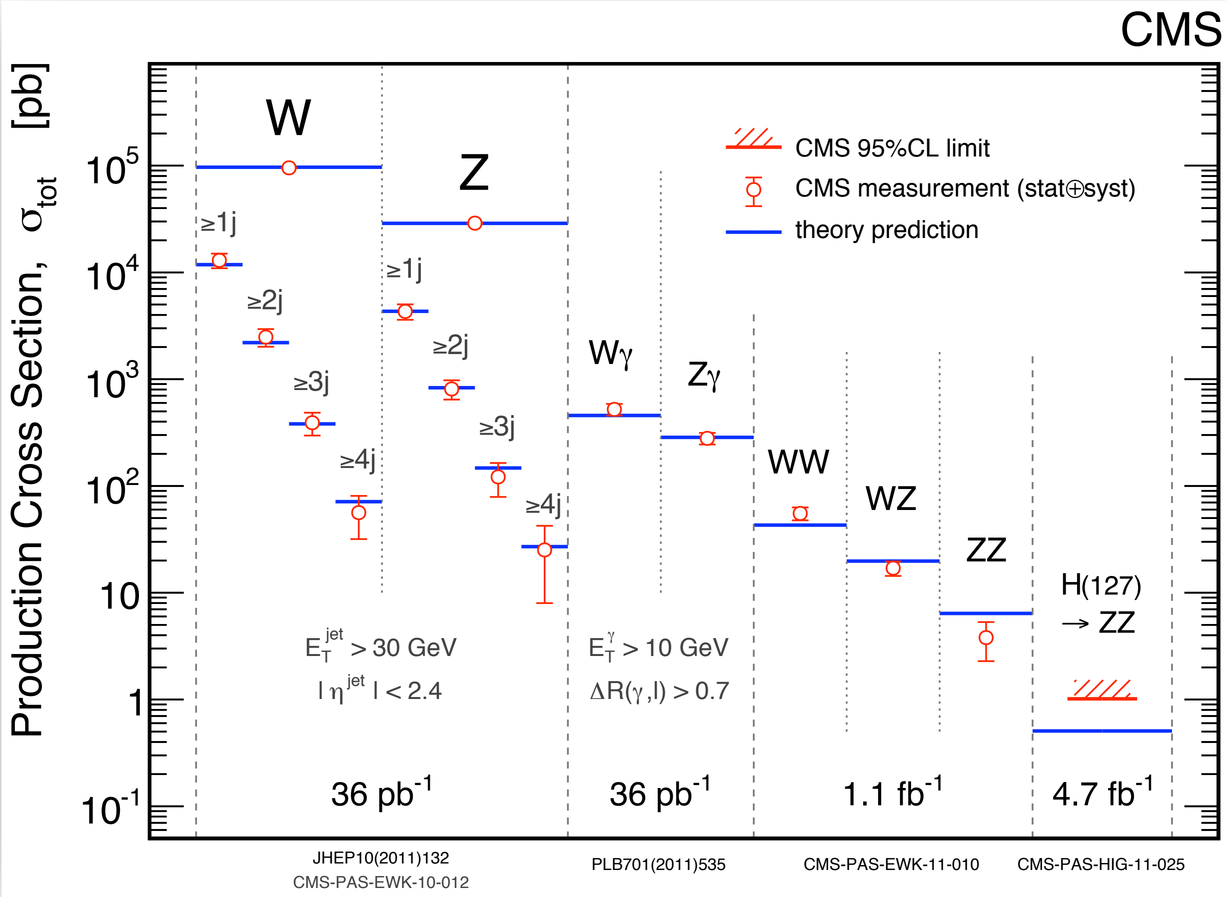


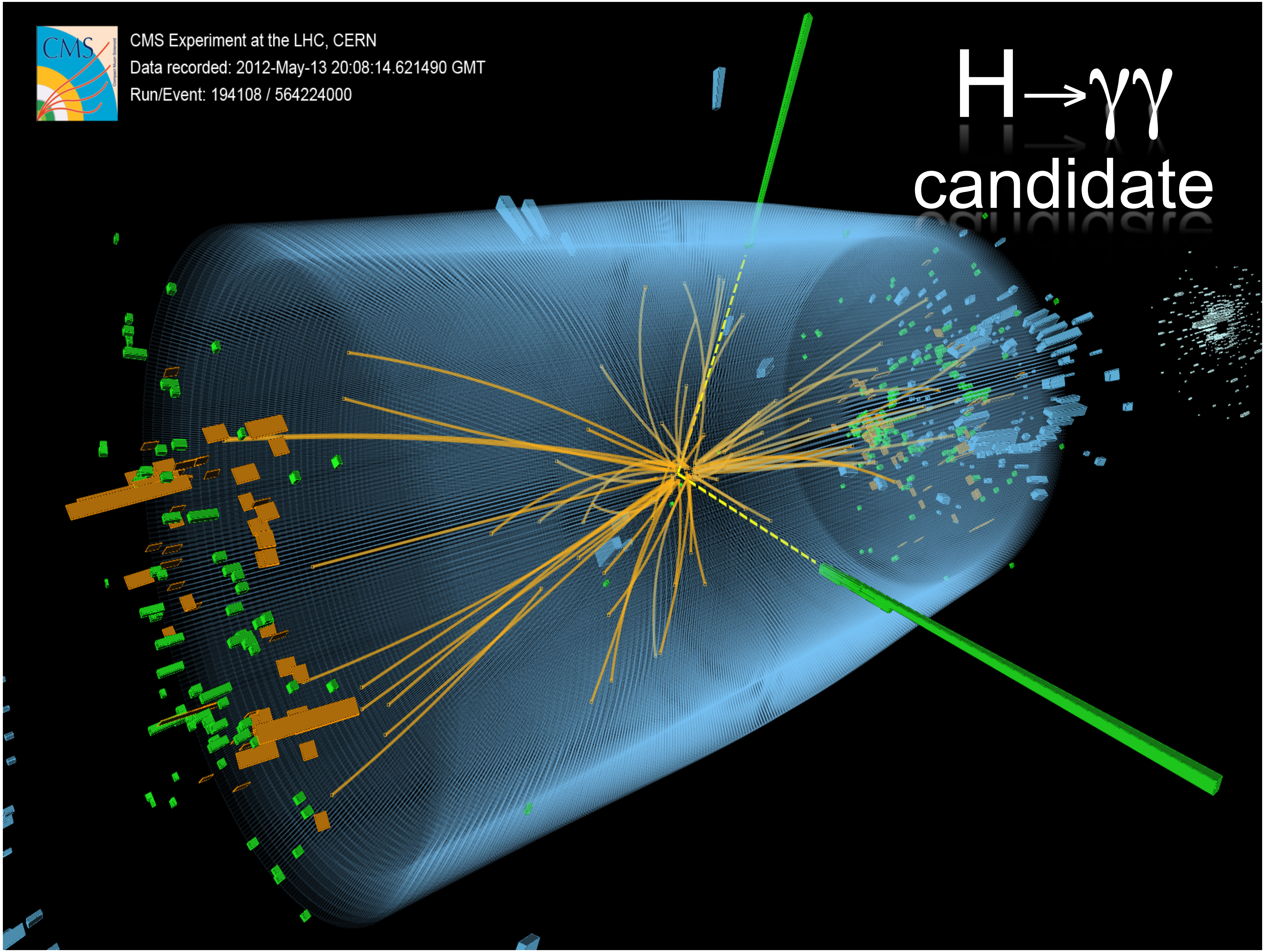
W → electron + neutrino



Standard model in pp collisions @ 7 TeV

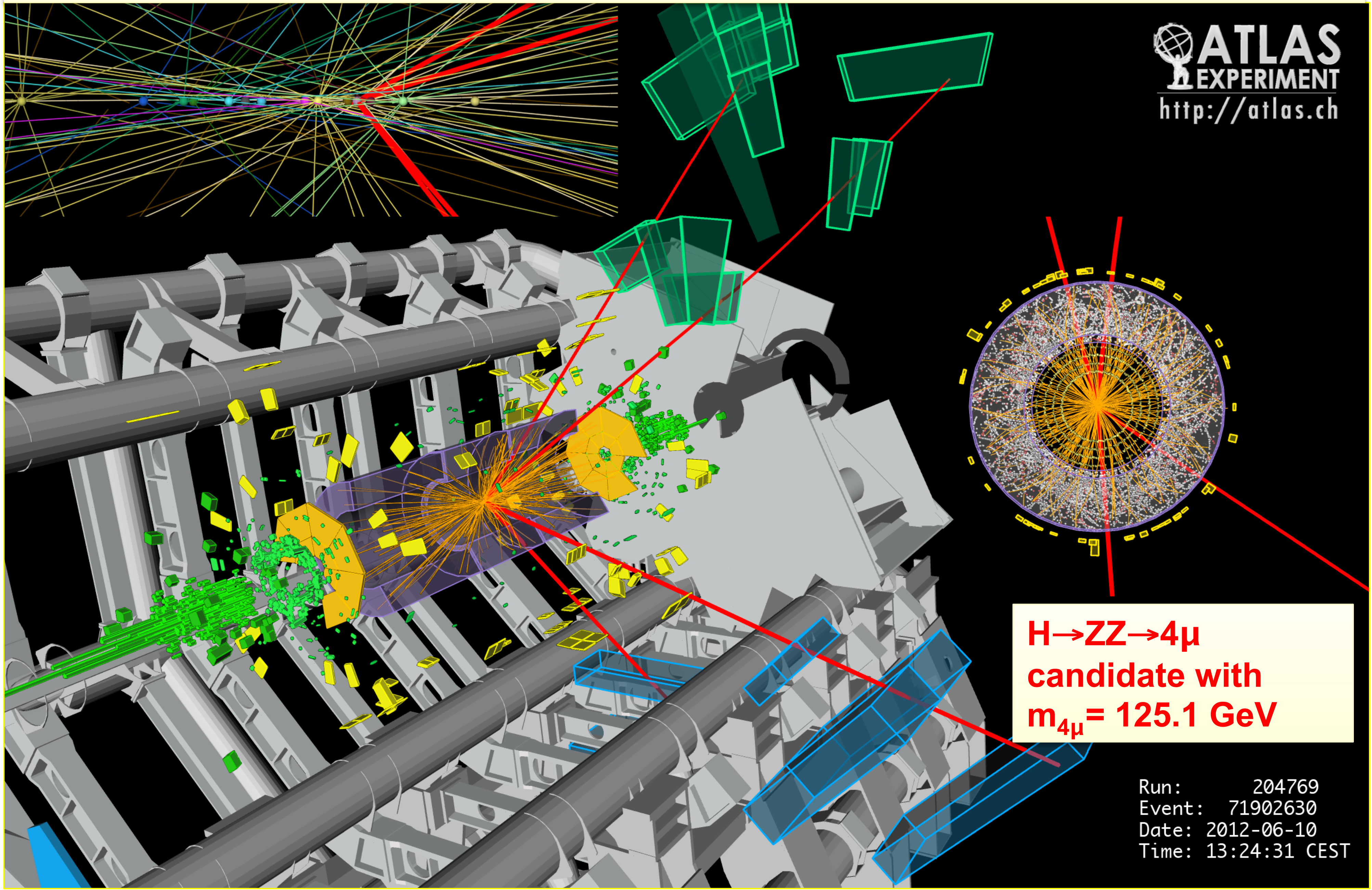
- **Understanding of SM processes at level of Tevatron experiments.**
  - **Let the search begin.**



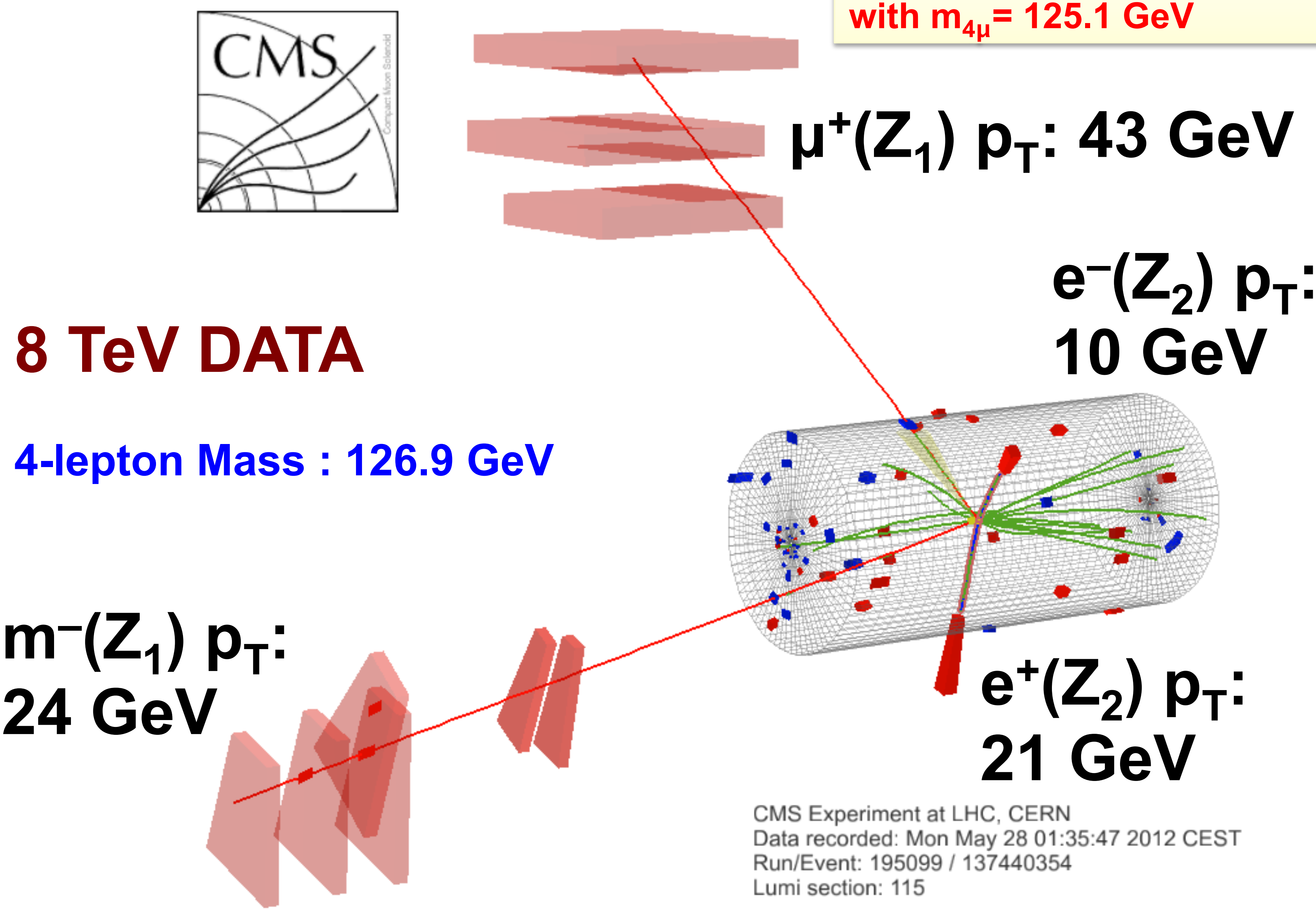

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H→γγ
candidate

$p_T(\mu)$= 36, 48, 26, 72 GeV; m_{12}= 86.3 GeV, m_{34}= 31.6 GeV

15 reconstructed vertices

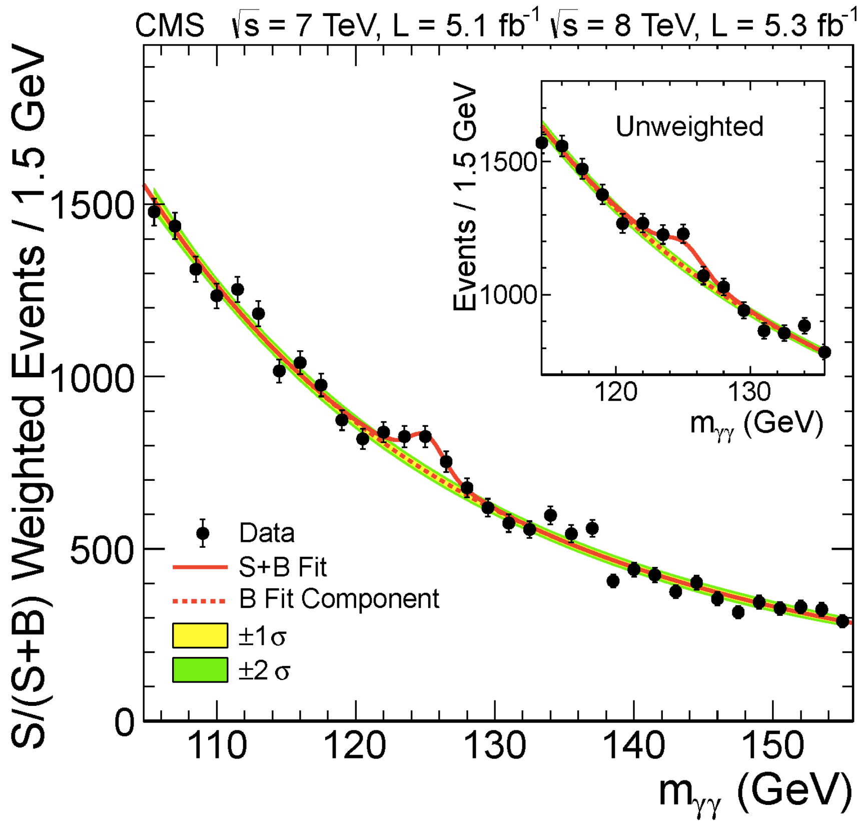


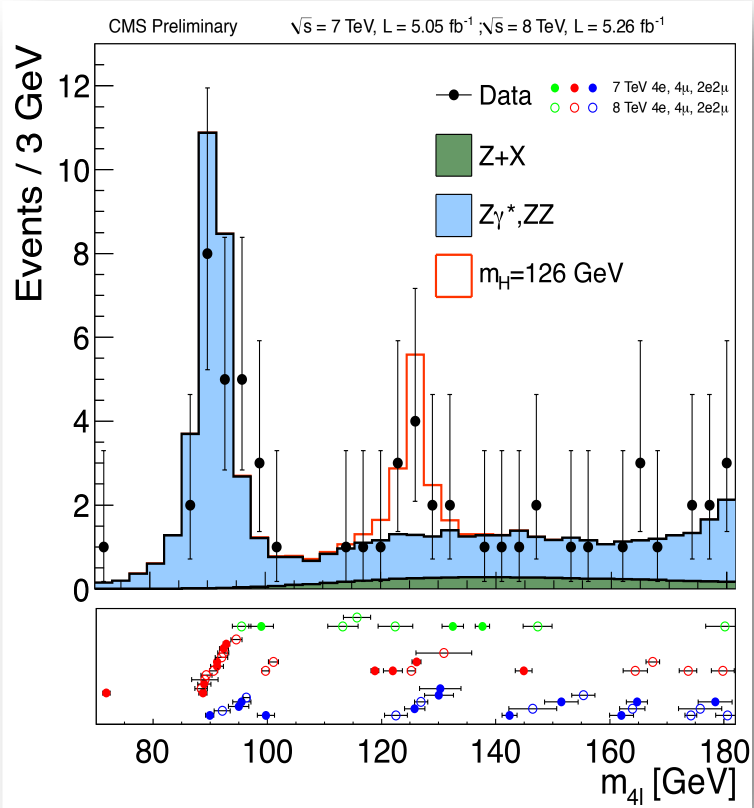
H→ZZ→μμee candidate with $m_{4\mu}$= 125.1 GeV



Mass peaks: H(?)→γγ & H(?)→ZZ→4leptons

Encode all relevant information on signal vs background discrimination (aside from $m_{\gamma\gamma}$ itself) into a single di-photon MVA output to first order independent of $m_{\gamma\gamma}$





And thus, on July 4th 2012,
"a new boson" was born.

it decays to two bosons
(two γ; two Z; two W)

It is not spin-1: it decays to two photons (Landau-Yang theorem)

It is either spin-0 or spin-2 (could also be higher spin, but this is really disfavored)

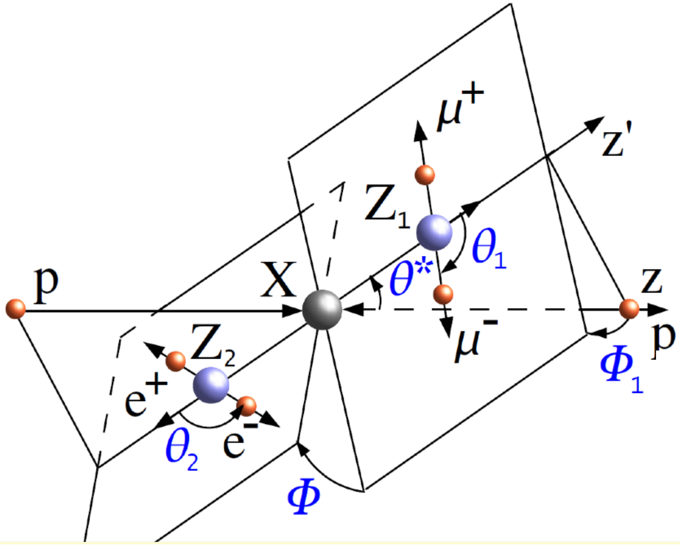
So, is it THE Higgs boson?

- **In general, when is a boson the SM Higgs?**
  - spin 0
  - neutral CP-even component of complex $SU(2)_L$ doublet with Y=1
  - couplings to SM fermions proportional to masses
- **The "new boson" can have many non-SM properties and still be the Higgs boson of electroweak symmetry breaking:**
  - CP mixture, mixture of two or more weak doublets!
  - Composite!
  - Nonstandard decay to gg or γγ from other colored/ charged exotic particles in loops

→ **Does it couple like a H-boson? (i.e. to mass?)**
  - Measure couplings to fermions and bosons, and see if they come out right

→ **What is its CP?**

H→ZZ→4leptons: angular analysis

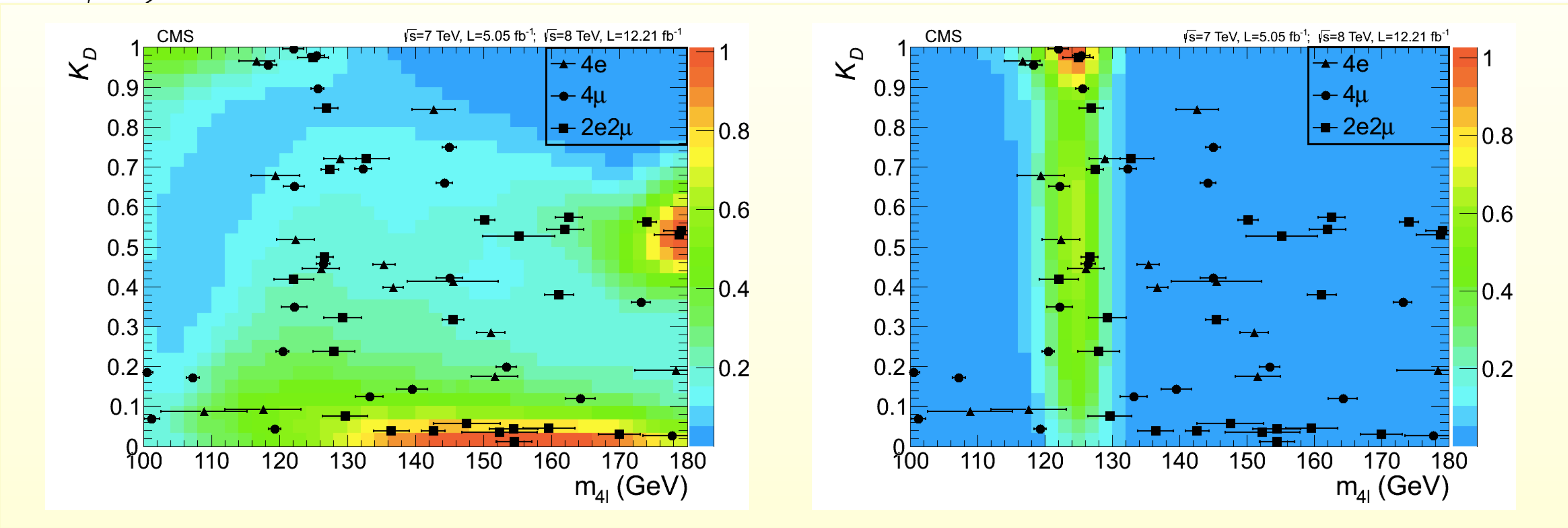


Matrix Element Likelihood Analysis:

uses kinematic inputs for signal to background discrimination

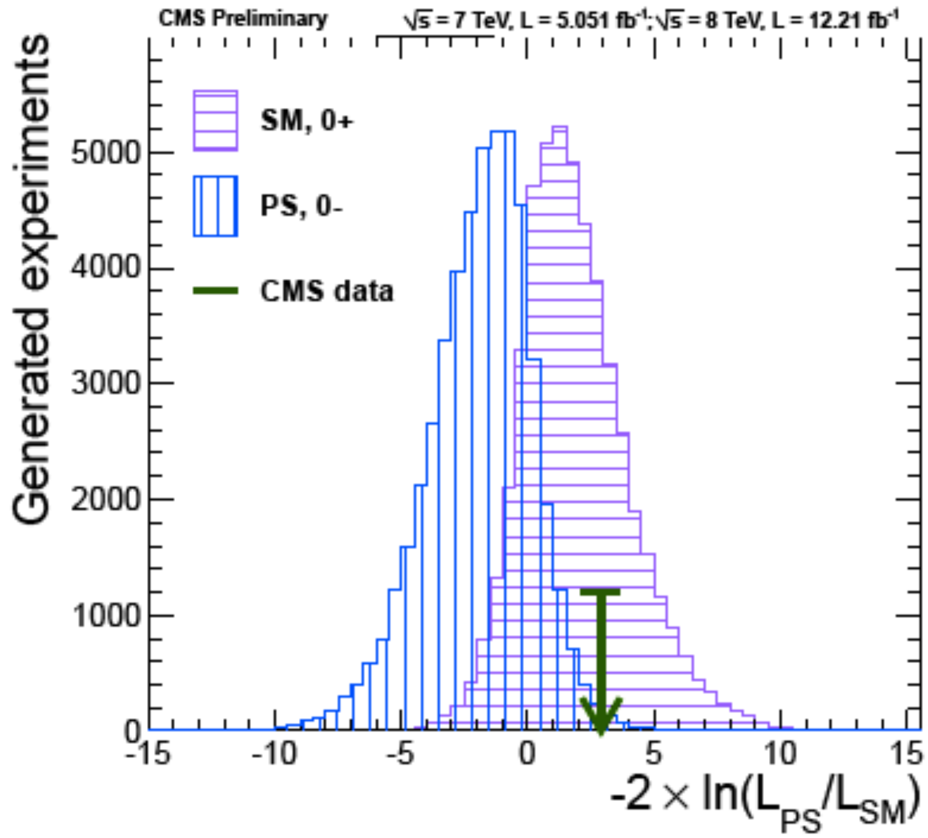
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})} \right]^{-1}$$



Scalar or pseudoscalar?

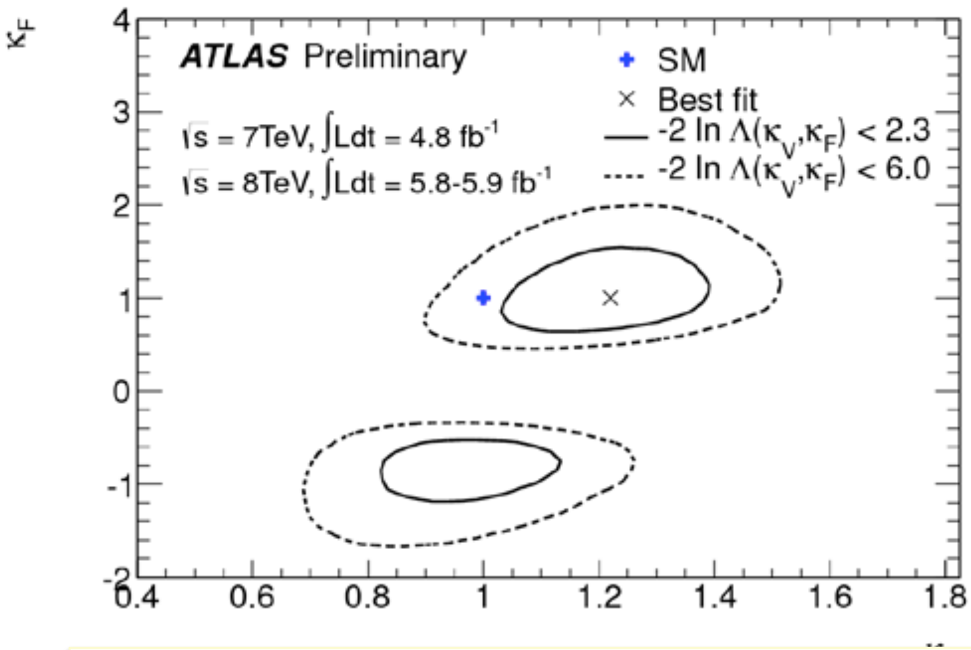
- **Test angular distributions under both the 0^+ and 0^- hypotheses:**
  - expected separation between 0^+ and 0^-: ~2 standard deviations
  - scalar (0^+): data consistent (0.6 standard deviations)
  - pseudo scalar (0^-): data different by 2.5 standard deviations

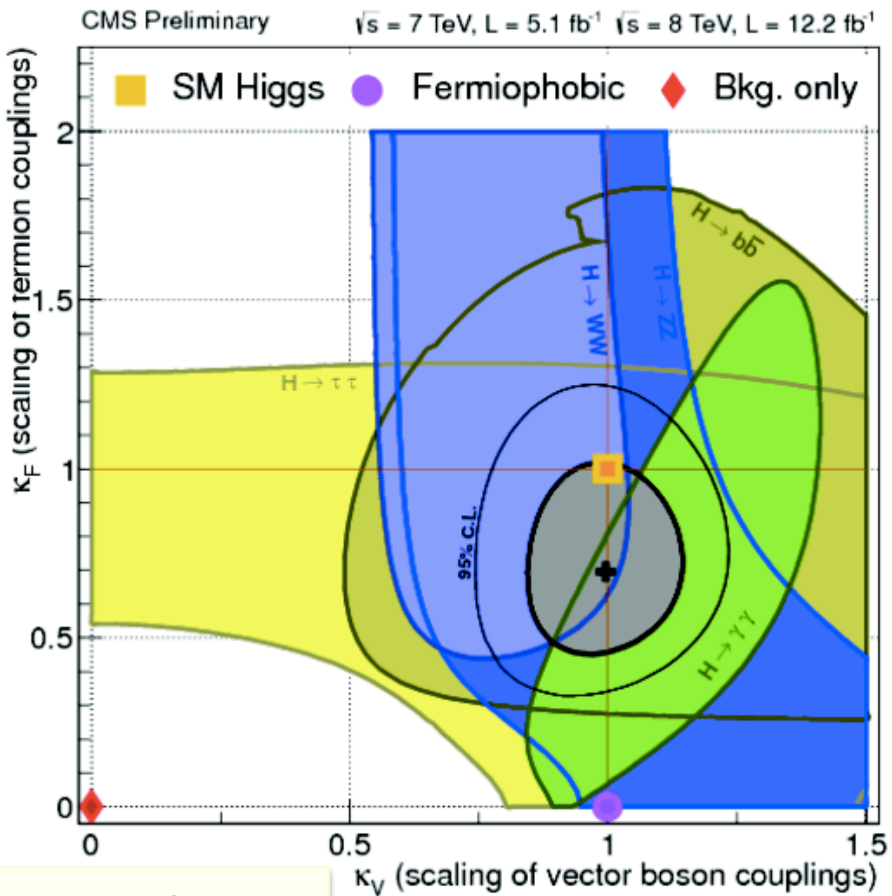


- **Excludes f-fbar bound state at >95%CL**

The latest on couplings

- **Fit κ_V vs κ_F Assume single coupling for all fermions (κ_F) and single coupling for vector bosons (κ_V)**





Sign from interference between top & W loops in $\gamma\gamma$ process

So is this it?

What about new physics?

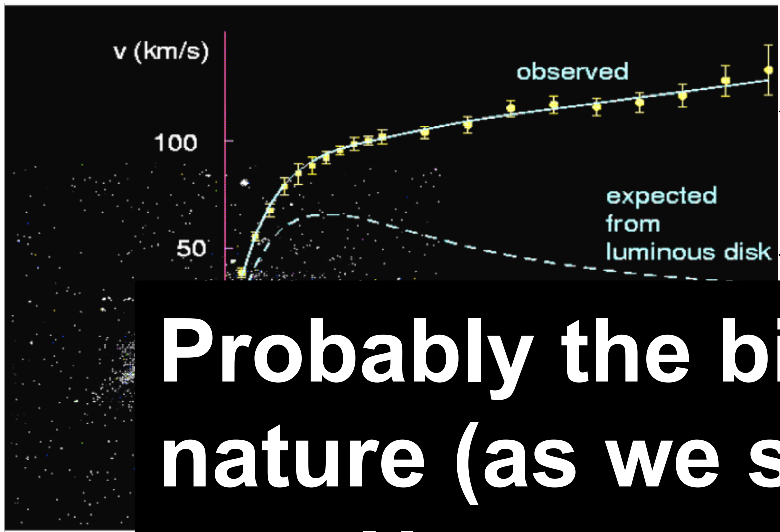
**In a world with a SM Higgs,
is there any room for new physics?**

Plenty of room for new physics

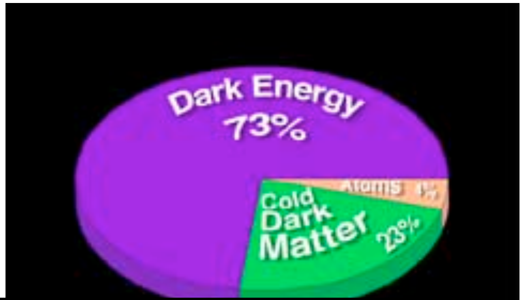
Some real and some virtual reasons to believe in new physics

Real reasons: dark matter & ν masses
Virtual reasons: naturalness

Real reason(s): dark matter

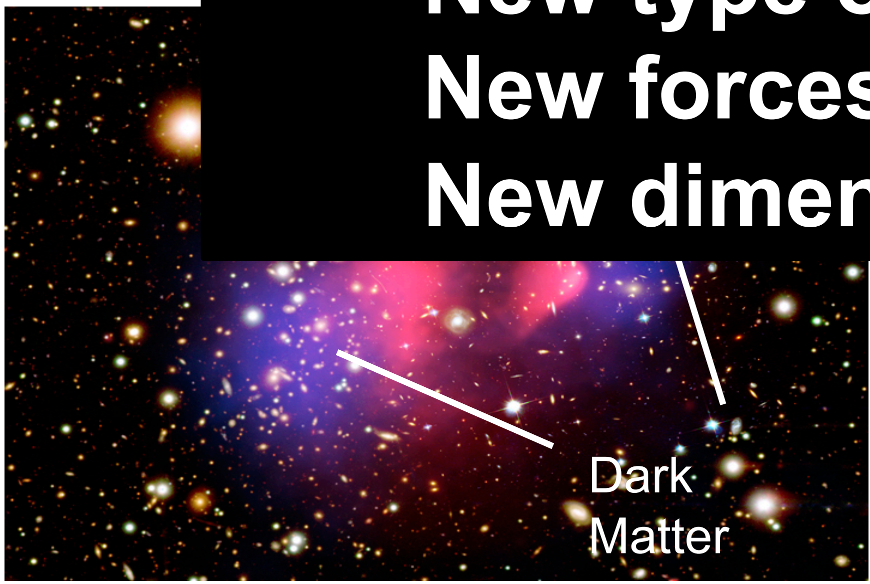


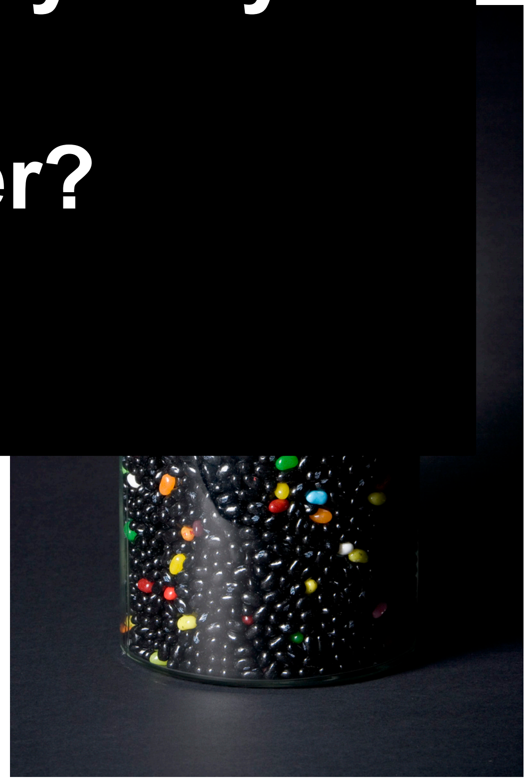
Dark (invisible) matter!



Probably the biggest mystery in nature (as we speak)

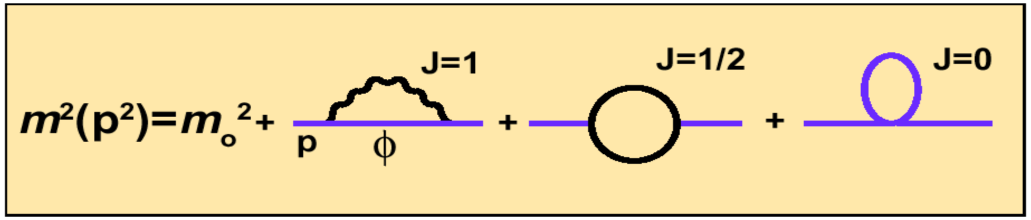
- **New type of matter?**
- **New forces?**
- **New dimensions?**





Virtual reasons: Higgs mass

- **Foremost: how can the mass of the Higgs boson be anything "small"?**
  - **It should "resist" itself (since it couples to mass, it should couple to itself as well); Its mass should be almost infinite:**



  - **Quadratic divergence in the Higgs mass**

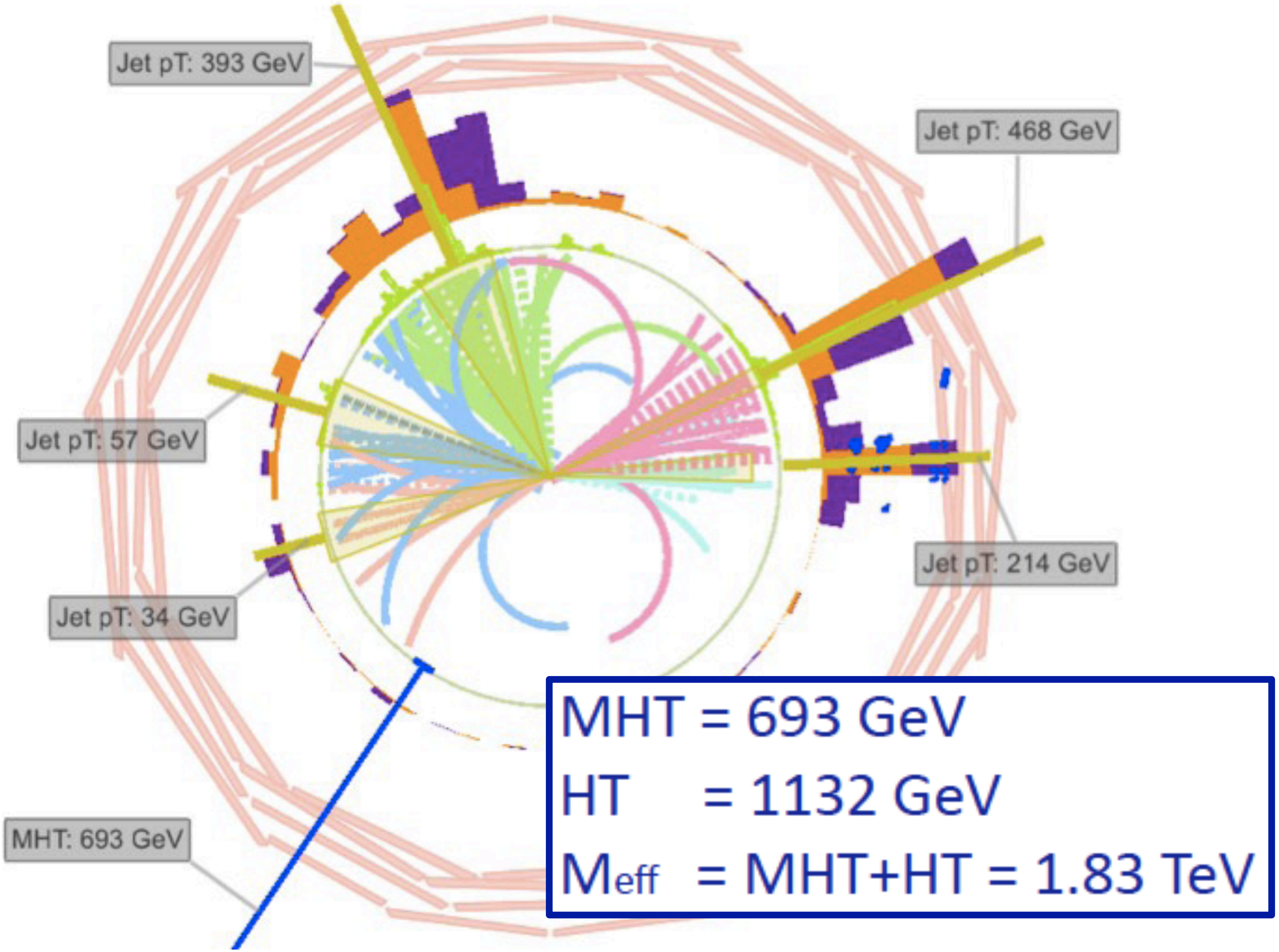
$$m^2(p^2) = m^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2$$

  - **Why is the Higgs mass so low? What is the mechanism?**
  - **Strong dependence of Physics(Λ_{EWK}) on Physics(Λ_{PL})**
    - **It's like saying that to describe the Hydrogen atom one needs to know about the quarks inside the proton (not true!)**
    - **Implies extreme fine-tuning (ETF) of parameters**

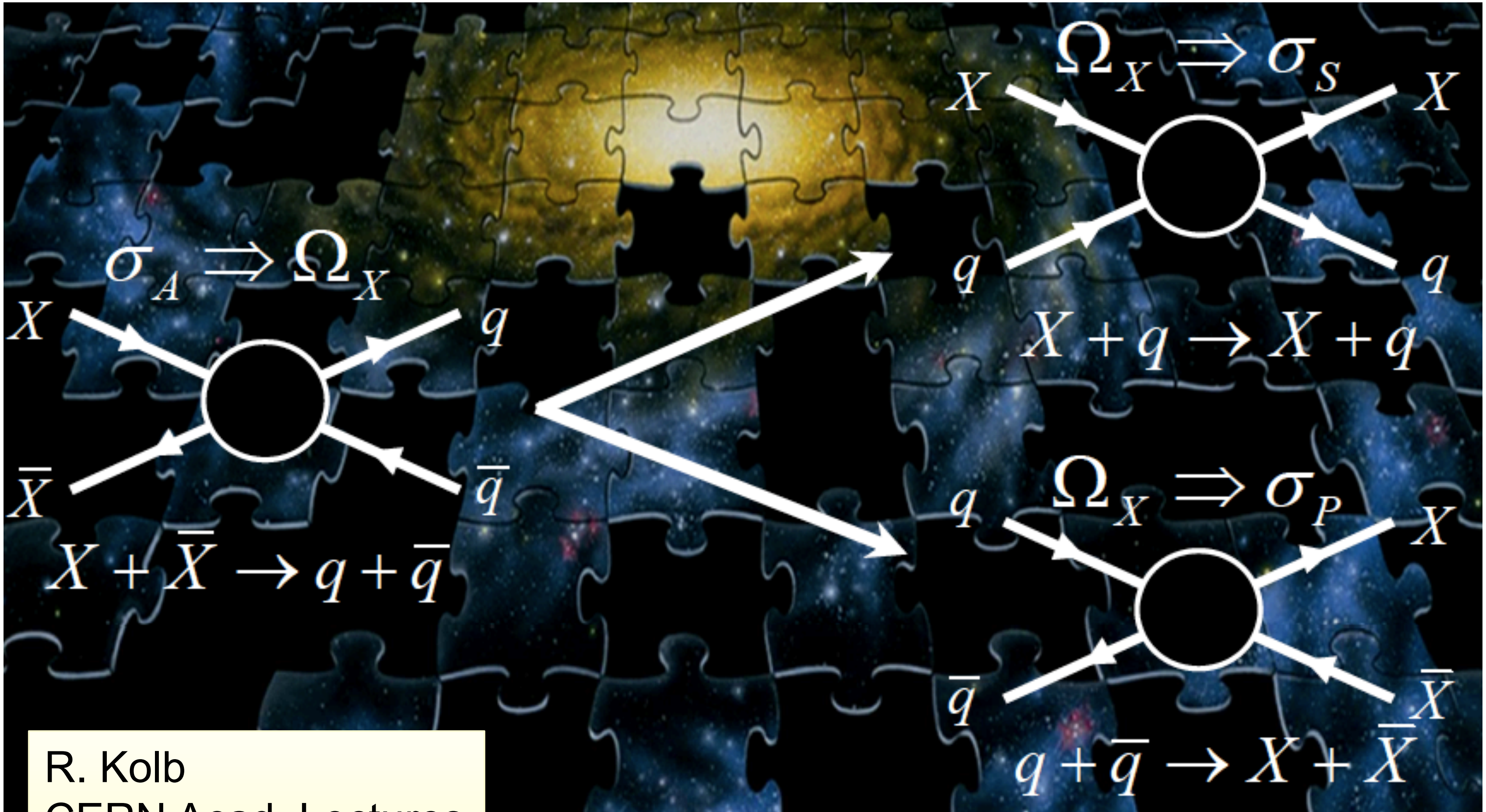
Bringing gravity into the game…

- If cut off at Λ_{PL}, why $m_W \ll M_{Pl}$? Or, why is gravity ($G \sim 1/M_{Pl}$) so very very weak?
  - And by the way, the mighty SM ignores gravity (too weak)
- Interestingly, beyond the Higgs, the biggest problems come from gravity-related measurements:
  - Dark matter, Dark Energy, and a non-matter-dominated universe
- Where is all this vacuum energy?
  - We would expect a tremendous energy density, >Googol (10^{100}) times larger than observed! ("Cosmological constant too small")
  - Size of the universe if the Higgs, as we expect it was there (ALONE): a football (soccer) ball)

SUSY? What it could look [looks?] like



Search for dark matter (and friends)

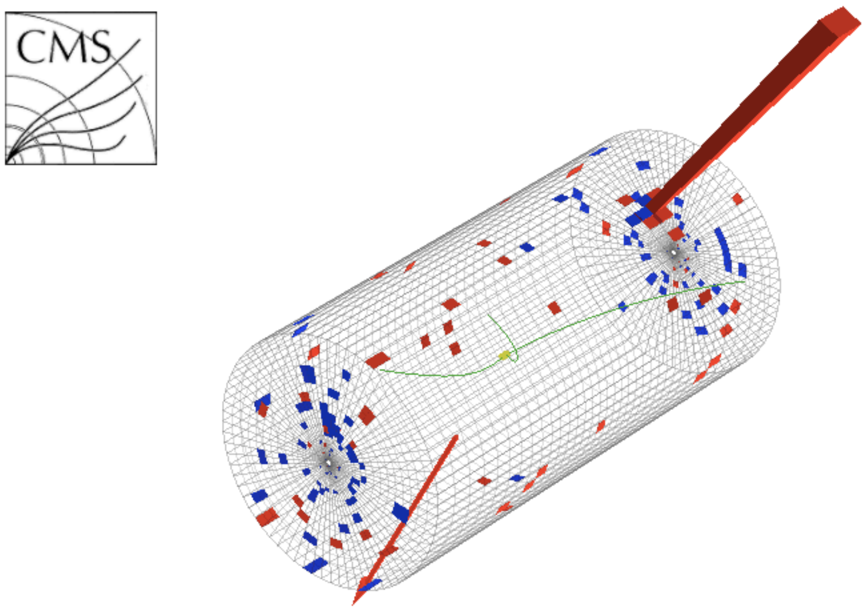


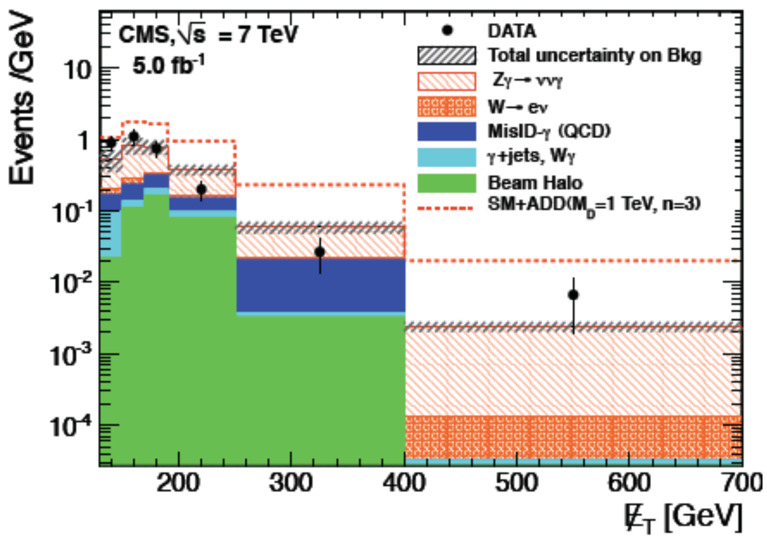
R. Kolb
CERN Acad. Lectures

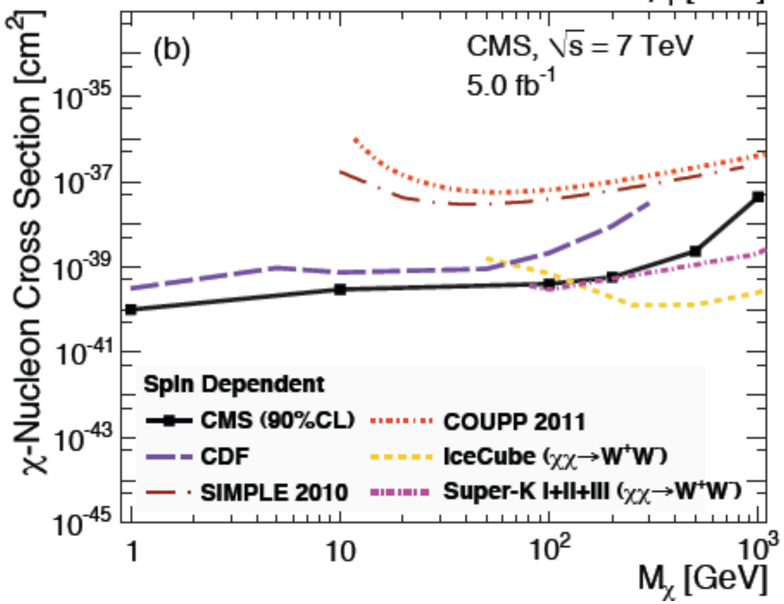
Search for dark matter: photon+MET

γ+MET signature from:

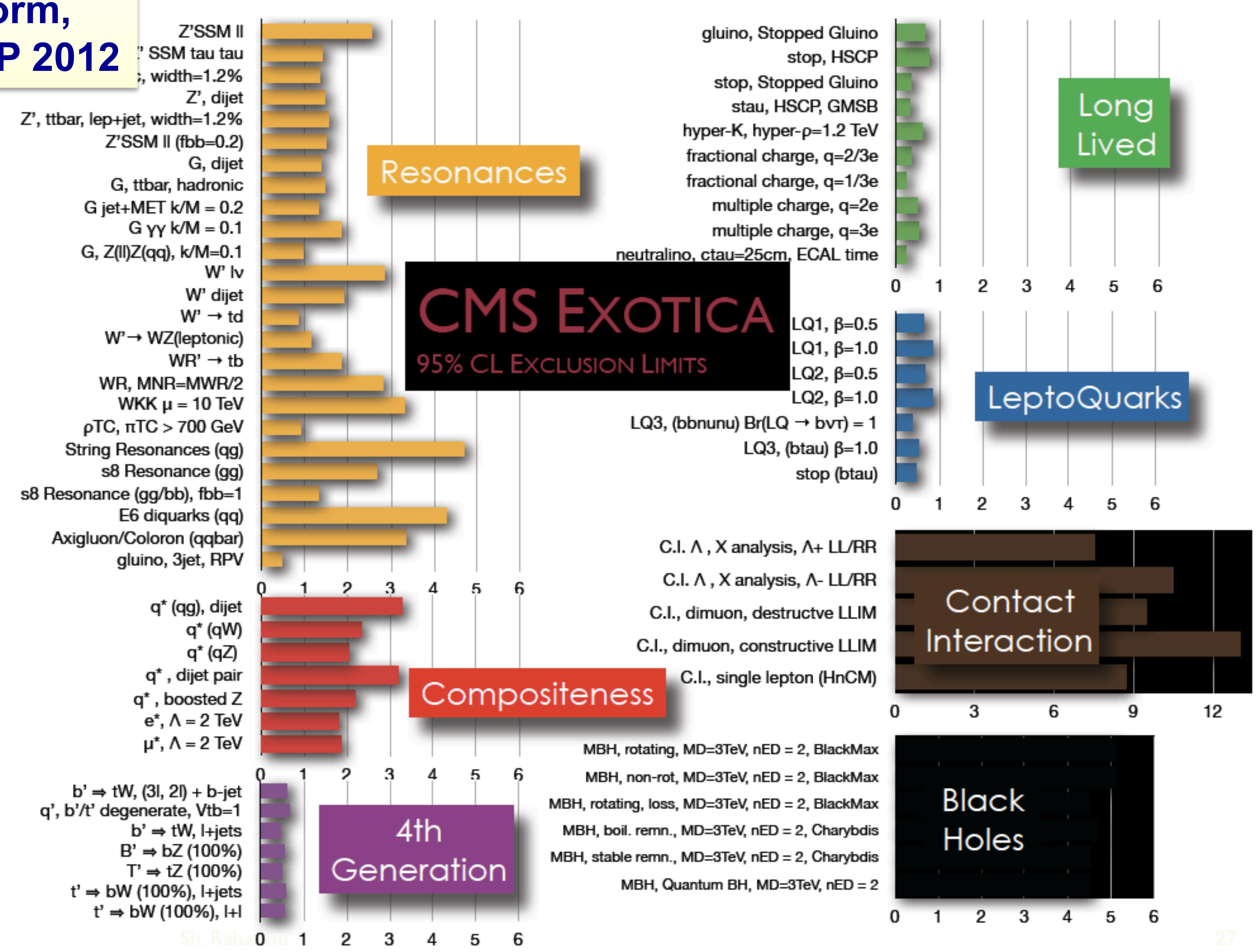
- Extra dimensions $q\bar{q} \rightarrow \gamma G$
- Dark matter $q\bar{q} \rightarrow \gamma\chi\bar{\chi}$







S. Worm, ICHEP 2012

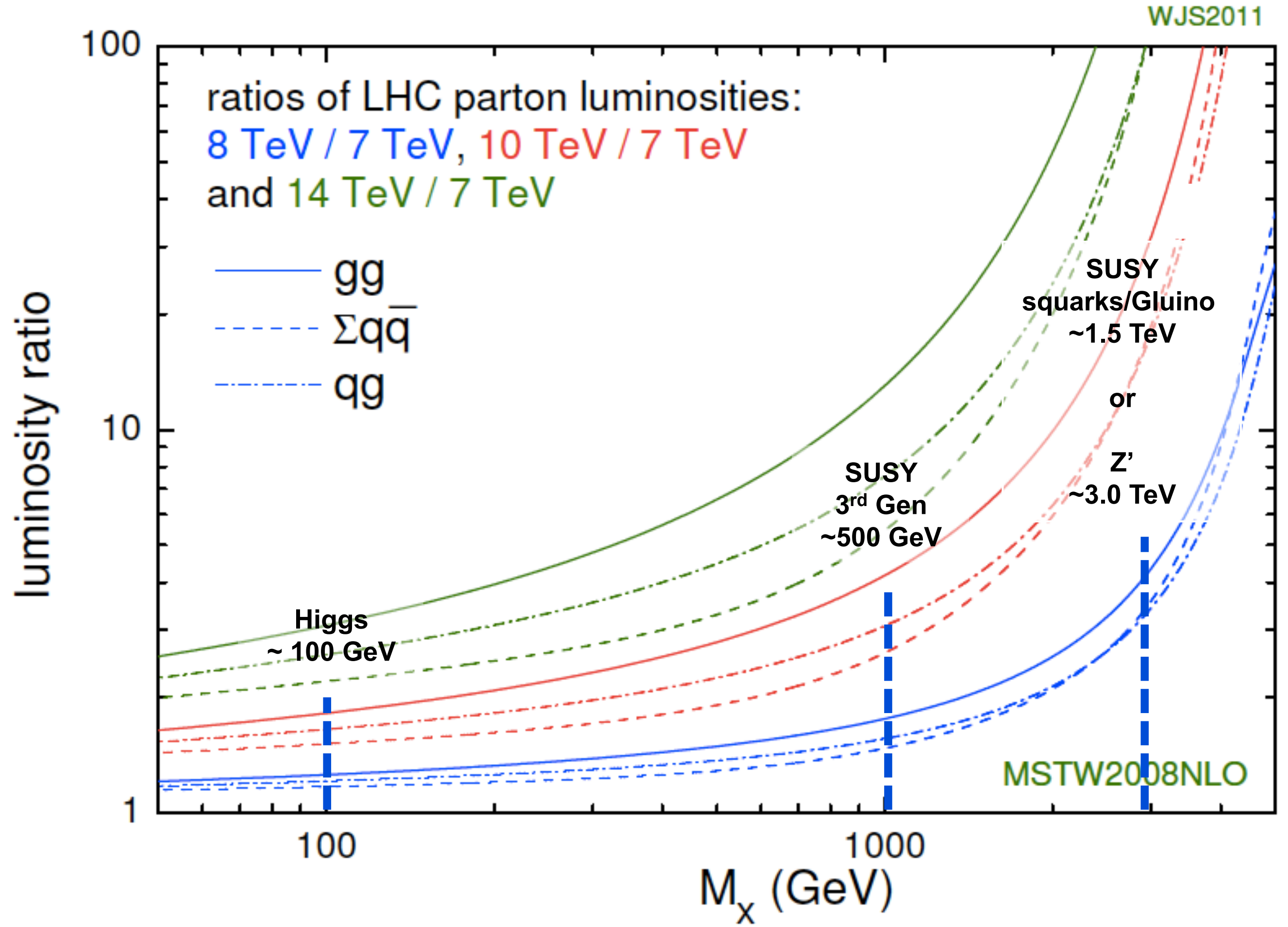


S. Worm, ICHEP 2012

Outlook
(LHC at 13-14 TeV &
at very high luminosity)
&
Summary

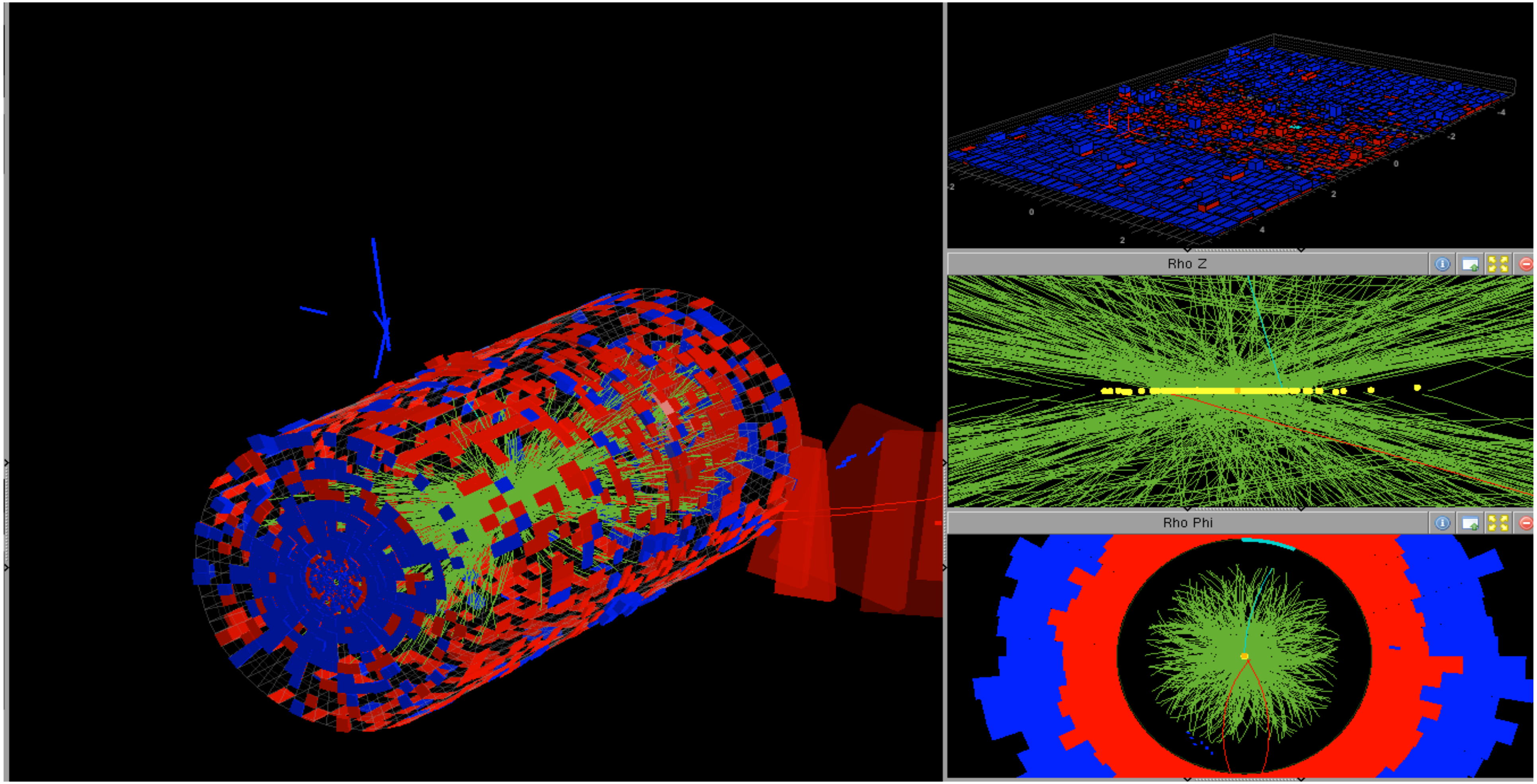
LHC running in at higher energy

- **Enhances physics reach in two ways:**
  - **Higher cross sections for new physics over full mass range**



Going beyond design conditions

CMS event with 78 reconstructed vertices and 2 muons…



Summary

- **Over the past 40 years experiments at hadron colliders have pushed the energy frontier**
  - Including pBe collisions, we got three new quarks (c, b, t) two gauge bosons (W, Z) and a new boson (H?). The latter may well be a particle like no other!
- **The biggest, greatest HEP instrument thus far: the LHC and its experiments**
  - A huge, painstaking design, construction and commissioning effort that lasted 20 years
  - Result: beautiful physics-producing engines!
- **A new boson with mass 125-126 GeV has been found**
  - We are beginning to probe its properties
    - IFF it is spin 0, it is not a pseudoscalar!
- **Even if this turns out to be the very Higgs boson of the Standard Model, there are huge reasons to believe that new physics is within reach;**
  - a gigantic amount of work on searches for SUSY, extra dimensions, etc…; Null so far, but, the best has yet to come!

Prof. Thomas Muller

is *only* 60 years young!