Physics at the Large Hadron Collider (LHC)

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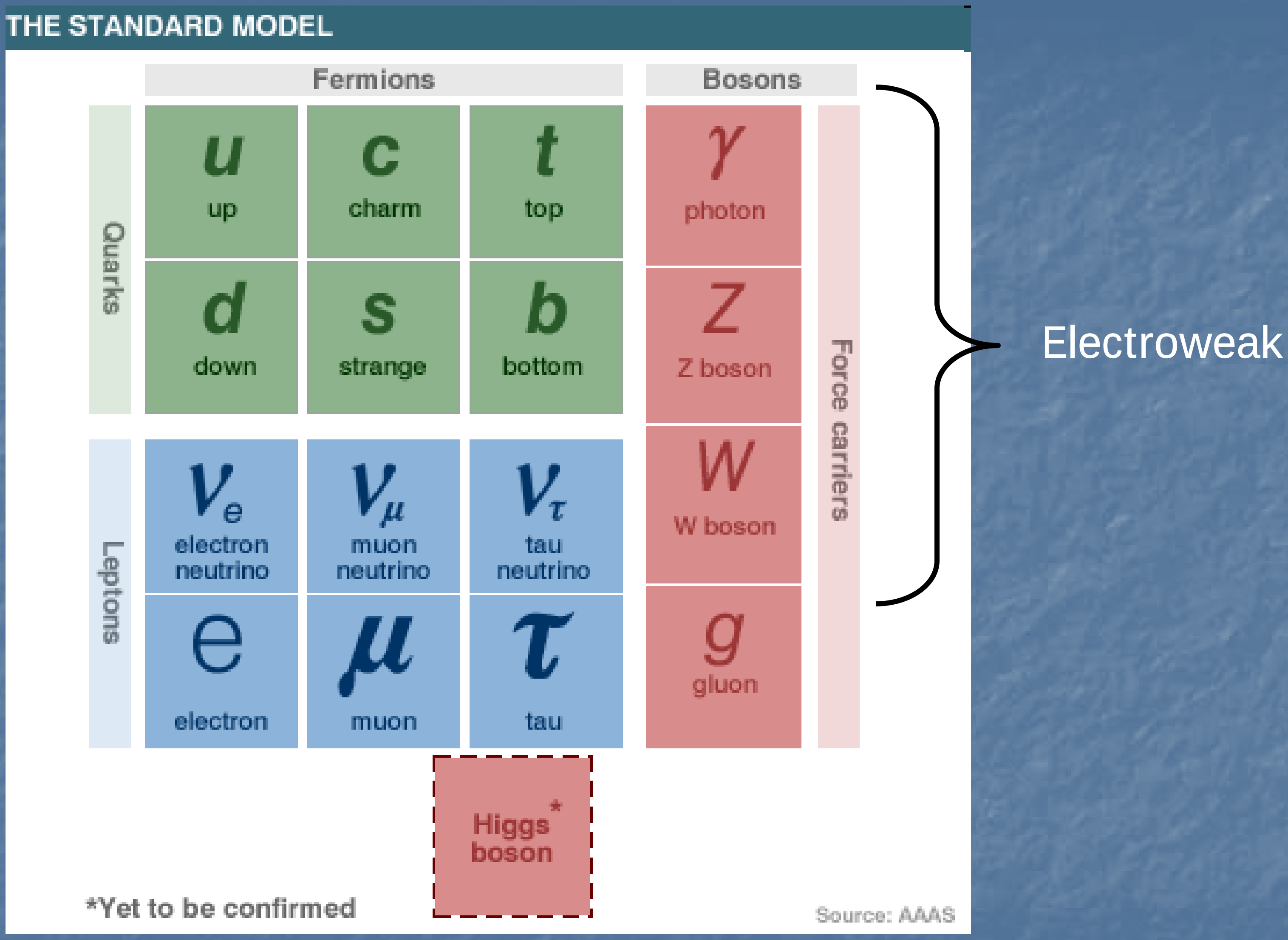
UC Santa Barbara
June 2, 2009

Outline

- What and Why?
- The LHC
- A detector (CMS), how we do physics at the LHC
- How to look for "New Physics"
- Status



THE STANDARD MODEL
Fermions
Bosons
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
e
electron
μ
muon
τ
tau
γ
photon
Z
Z boson
W
W boson
g
gluon
Force carriers
Higgs* boson
*Yet to be confirmed
Source: AAAS
Electroweak

- Standard Model (SM) works very well and has been tested to E~O(100 GeV)~10^{-18}m

- Several open questions
  - Why 3 generations
  - Why matter-antimatter asymmetry
  - Dark matter?
  - Dark energy?
  - How does the ElectroWeak interaction break into EM and Weak interaction at low energies (electroweak symmetry breaking)

ElectroWeak Symmetry Breaking

- Occurs at E ~ 1000 GeV (1 TeV)
- In the SM realized through interaction with Higgs field
- Results in a yet-to-be-discovered Higgs particle

- Do not know if the Higgs mechanism is the right answer
- But, if it is not the answer, something else must be operational at the TeV scale
- The LHC is the machine that will allow us to explore the TeV scale

- Find the Higgs (if it's there) and study its properties
- And/Or see if there is New Physics

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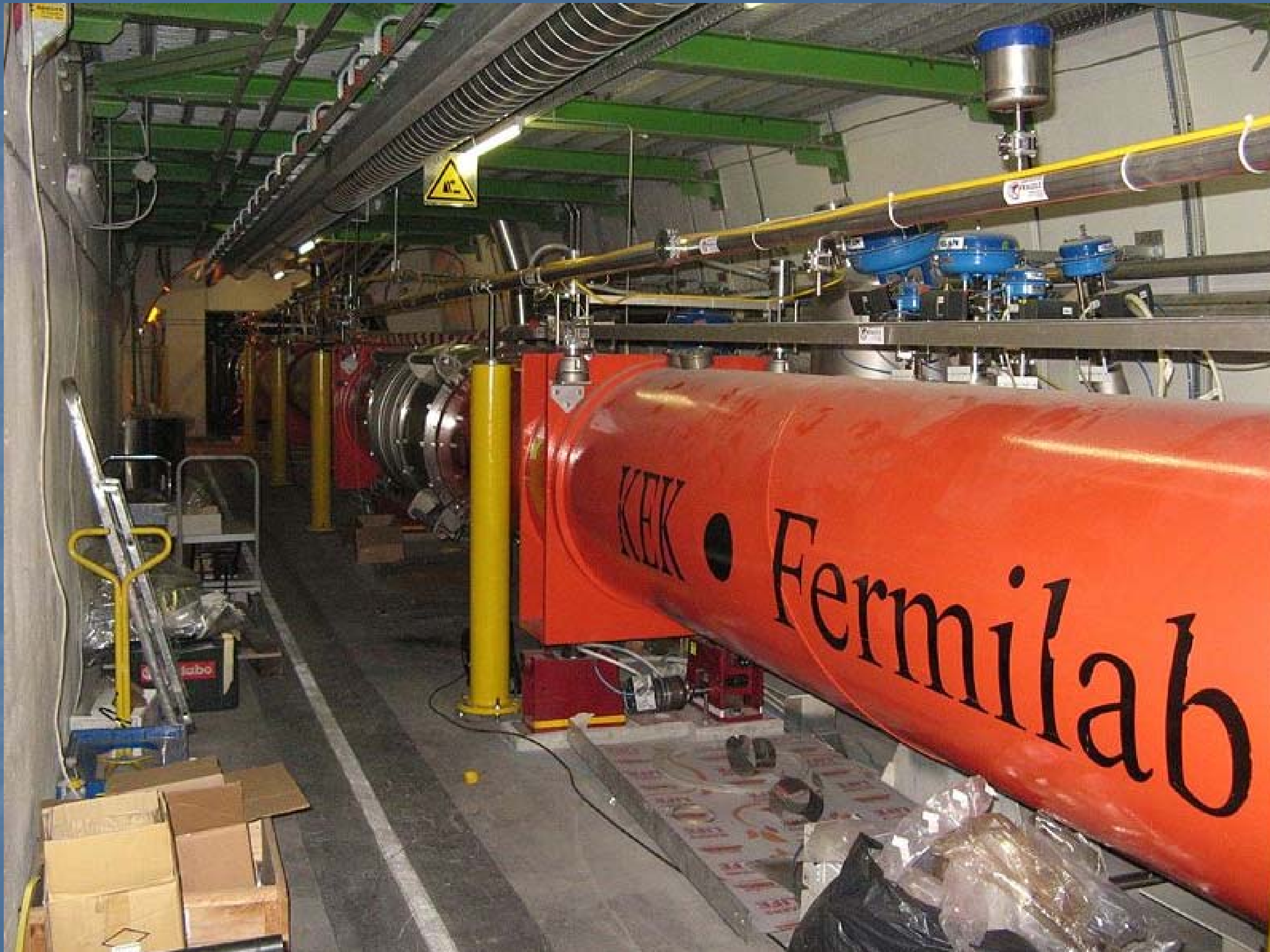
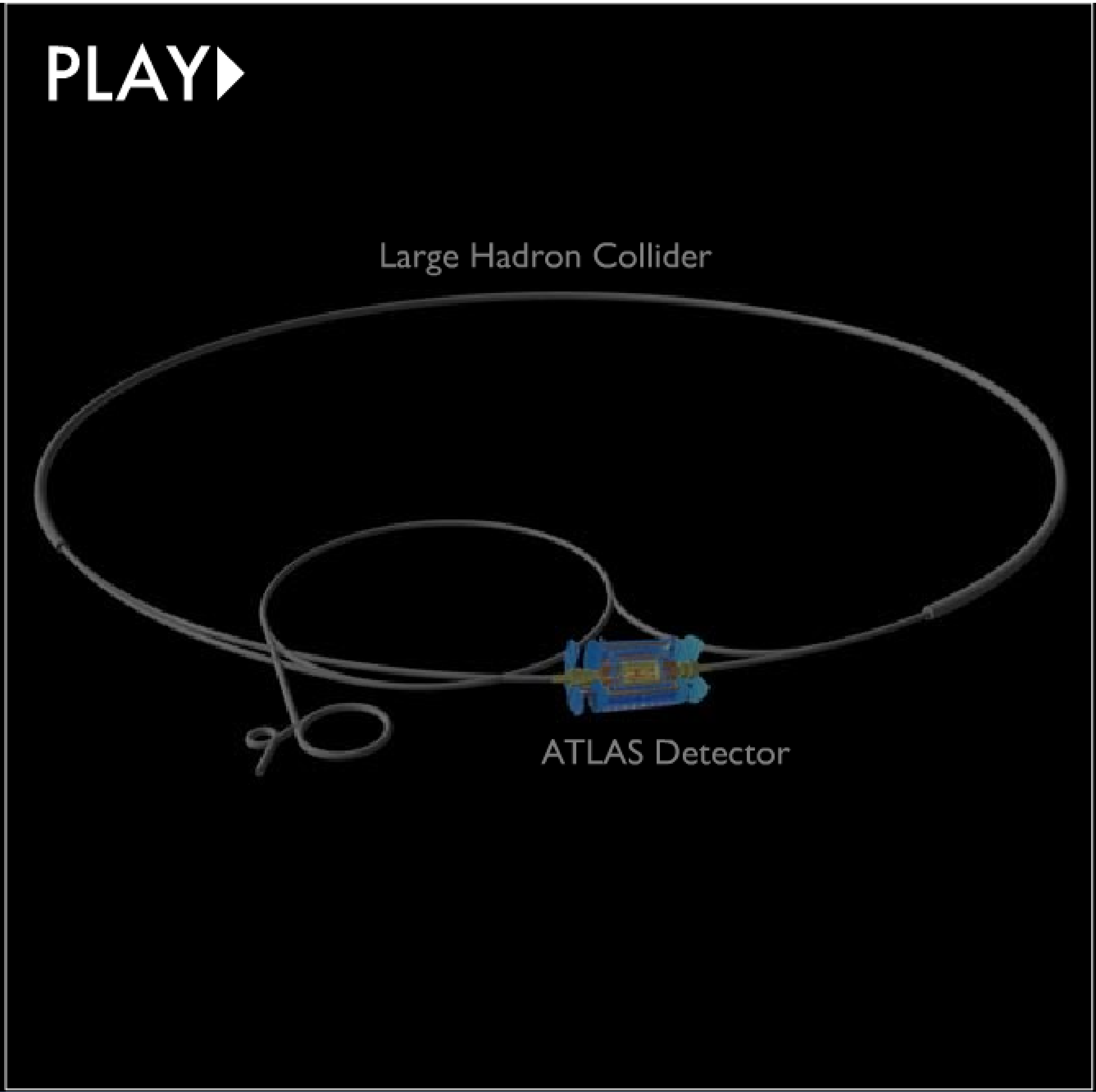
Large Hadron Collider (LHC)

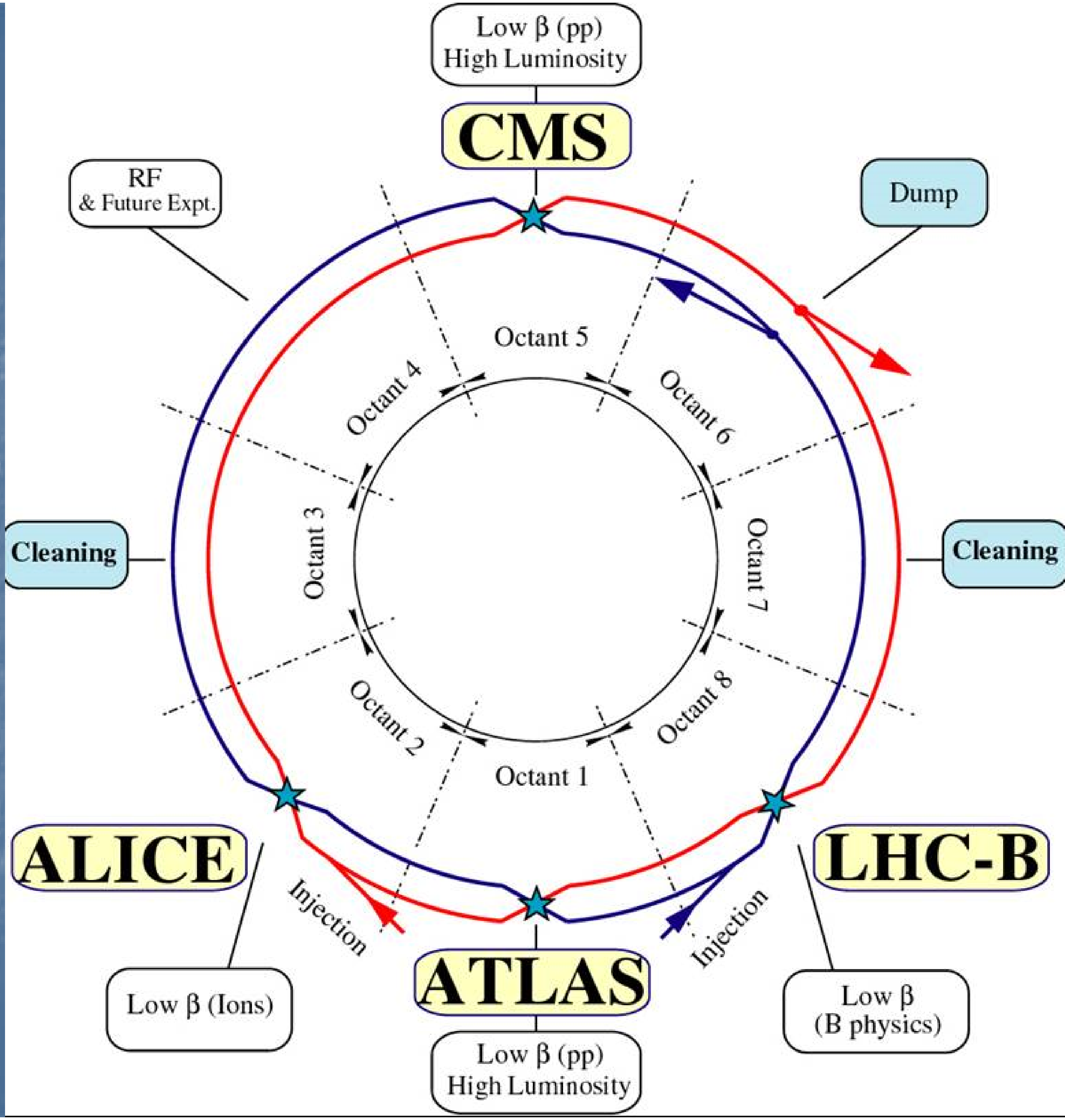
- A 14 TeV proton-proton collider
  - 1 TeV = 10^{12} eV
  - A factor of 7 more energy than the Fermilab Tevatron
- 27 Km long tunnel, 100 m below ground
- 9300 superconducting magnets (1232 dipoles)
  - 60 tons of liquid helium
  - 11,000 tons of liquid nitrogen
- Energy stored in magnets = 10 GJ

- Each of the 1232 dipoles....
  - is 15 m long
  - carries 11.8 kA of current
  - provides a field of 8.3 T
- There are 2808 "bunches" of protons in each beam
  - 10^{11} protons per bunch
  - 11,245 turn
- When brought into collision the transverse size of the bunches is of order 10 μm

Picture of the tunnel


KEK • Fermilab


PLAY
Large Hadron Collider
ATLAS Detector


Low β (pp)
High Luminosity
CMS
RF
& Future Expt.
Dump
Octant 5
Octant 4
Octant 6
Octant 3
Octant 7
Cleaning
Cleaning
Octant 2
Octant 8
Octant 1
ALICE
LHC-B
Injection
Injection
ATLAS
Low β (Ions)
Low β
(B physics)
Low β (pp)
High Luminosity

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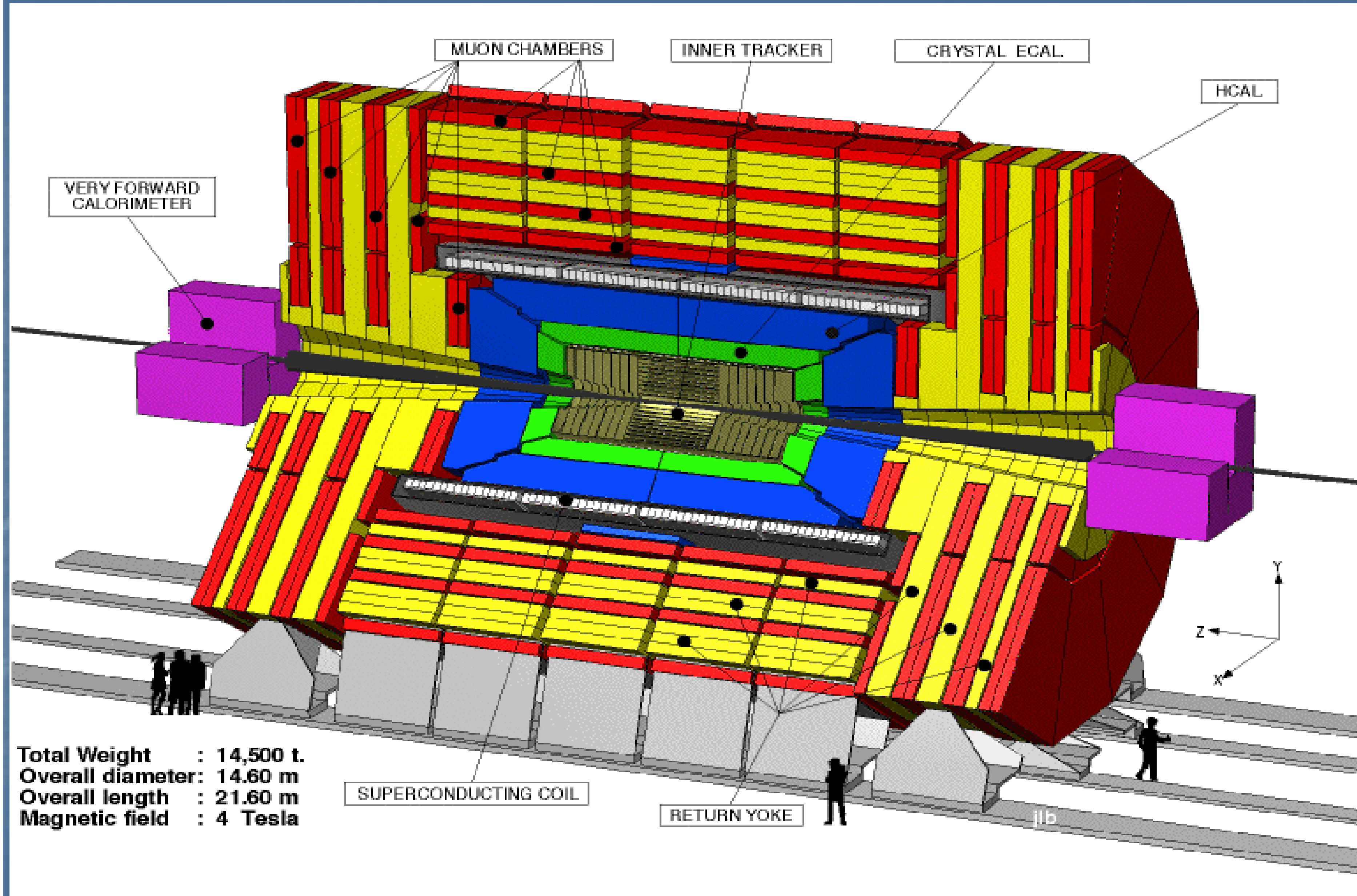
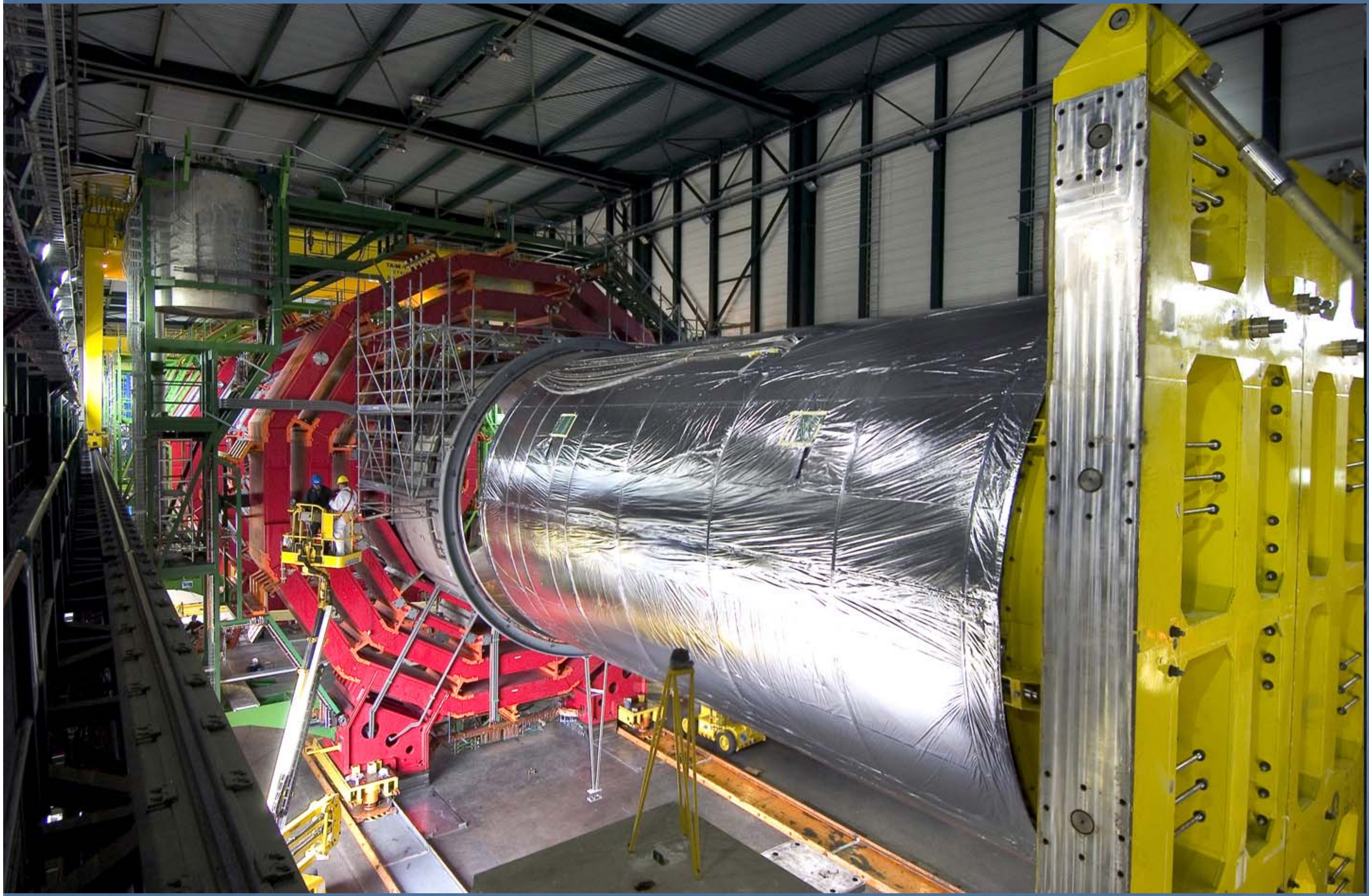
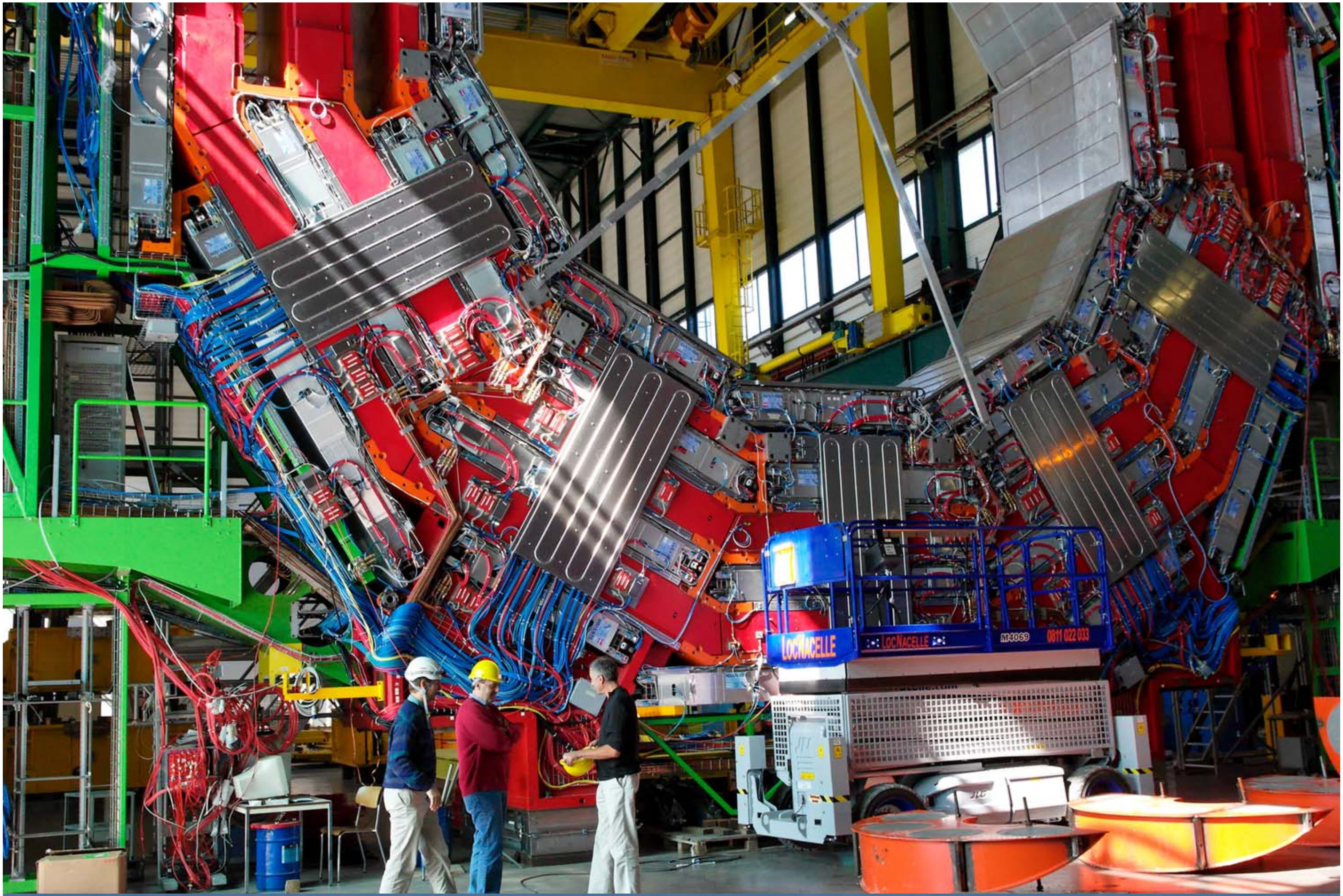

MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL.
HCAL
VERY FORWARD CALORIMETER
SUPERCONDUCTING COIL
RETURN YOKE
Y
Z
X
jlb
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

Coil insertion. 4T superconducting solenoid



Magnet is 12,000 tons. Stores enough energy to melt 18 tons of gold.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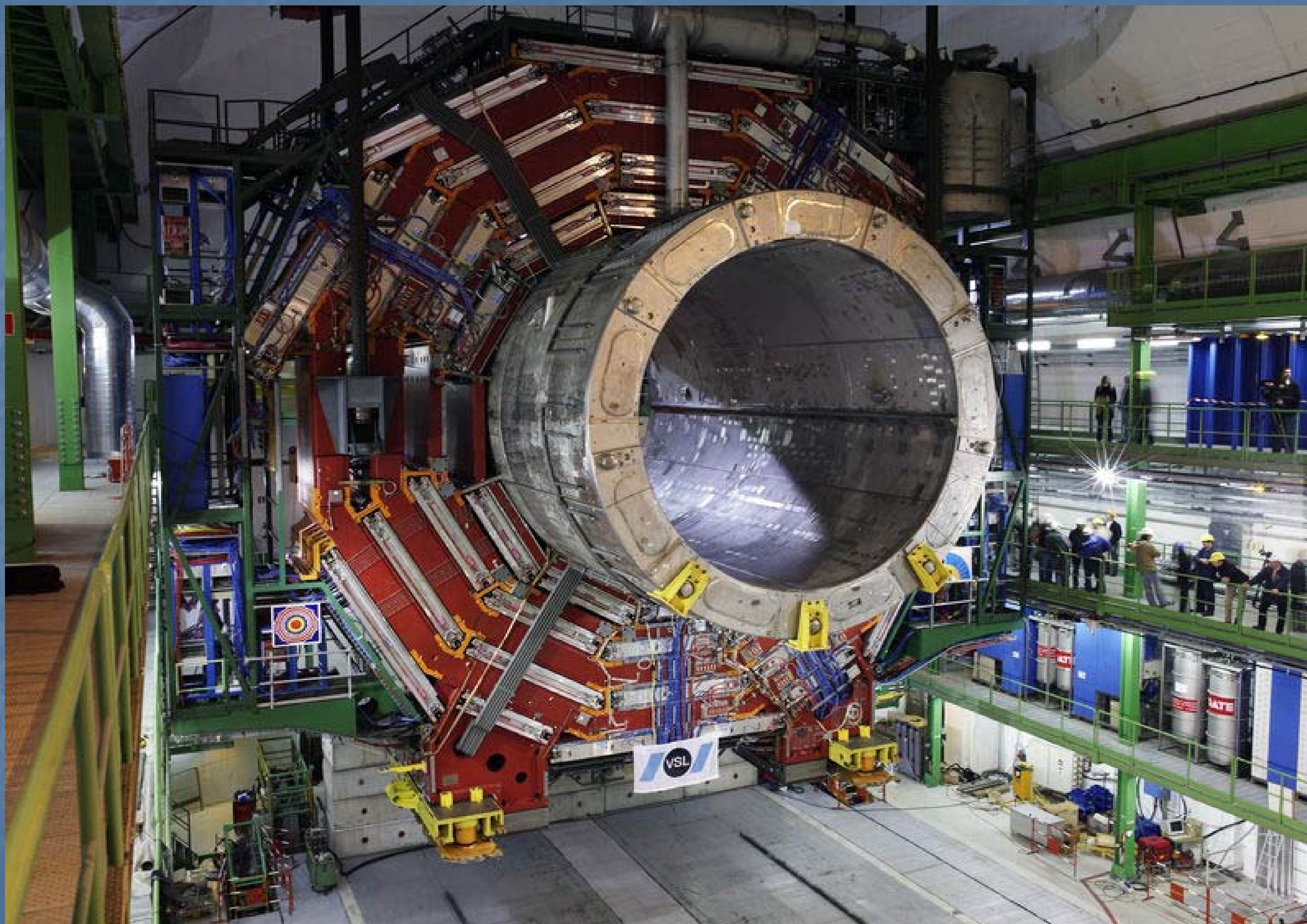
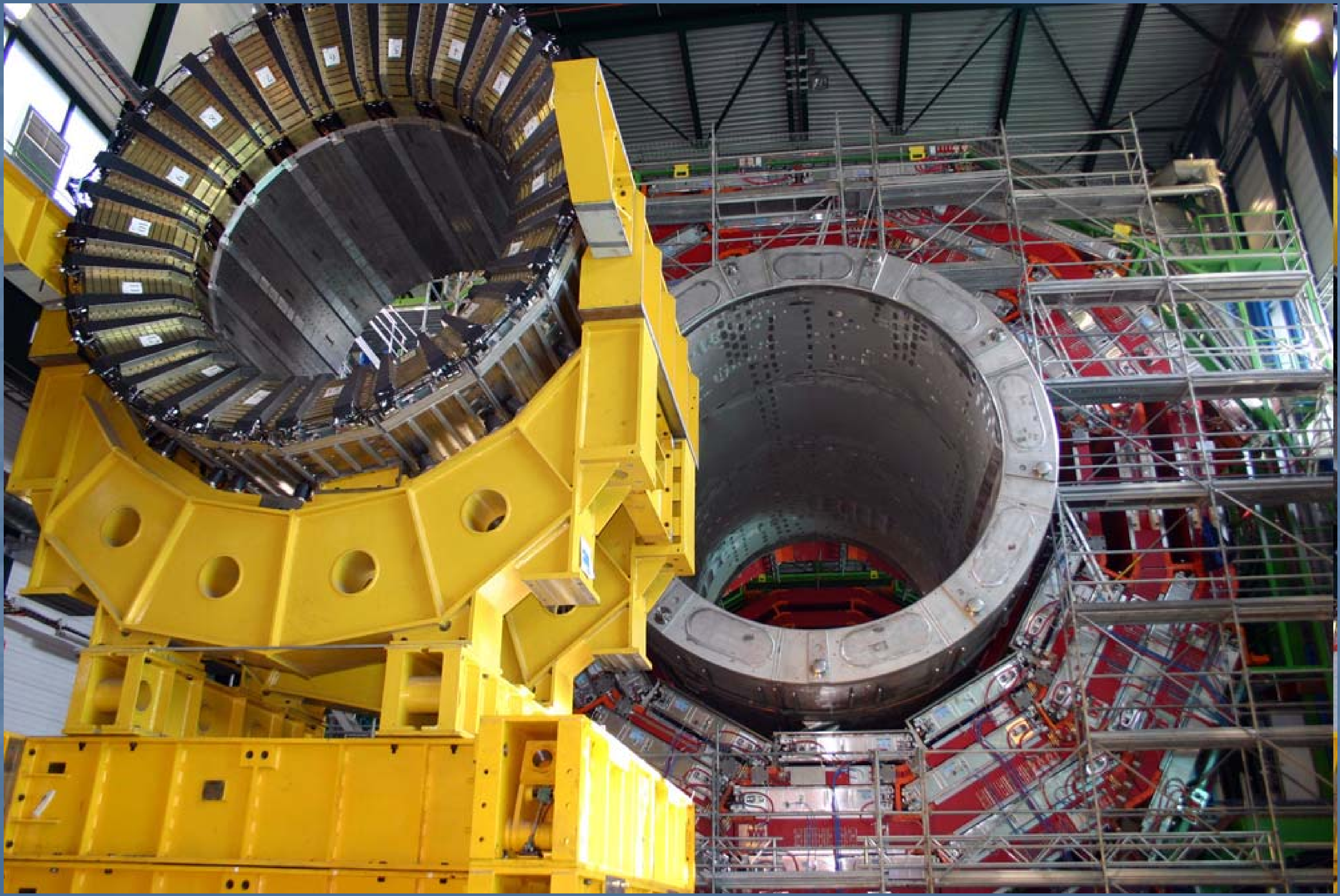
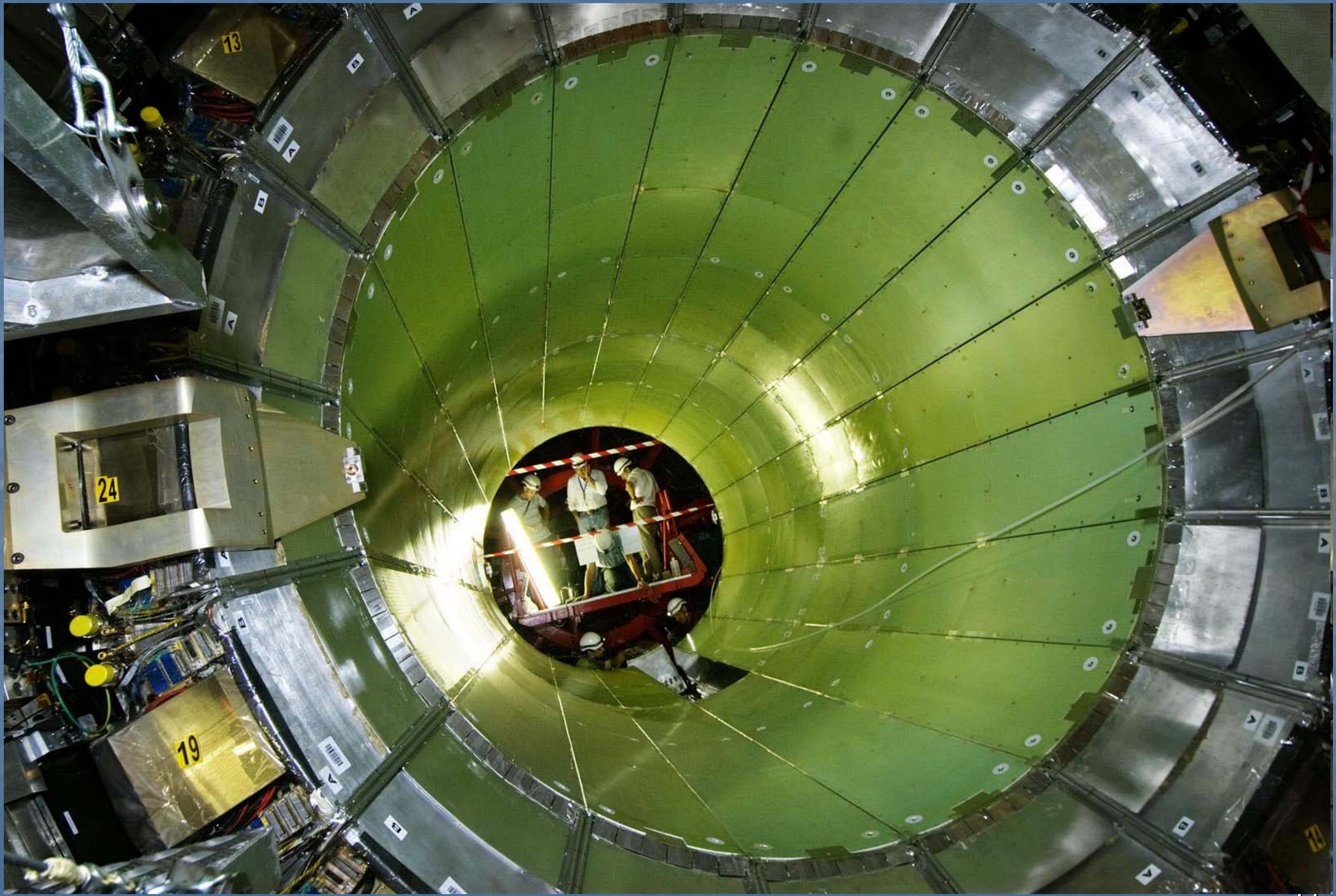
0811 022 033


VSL

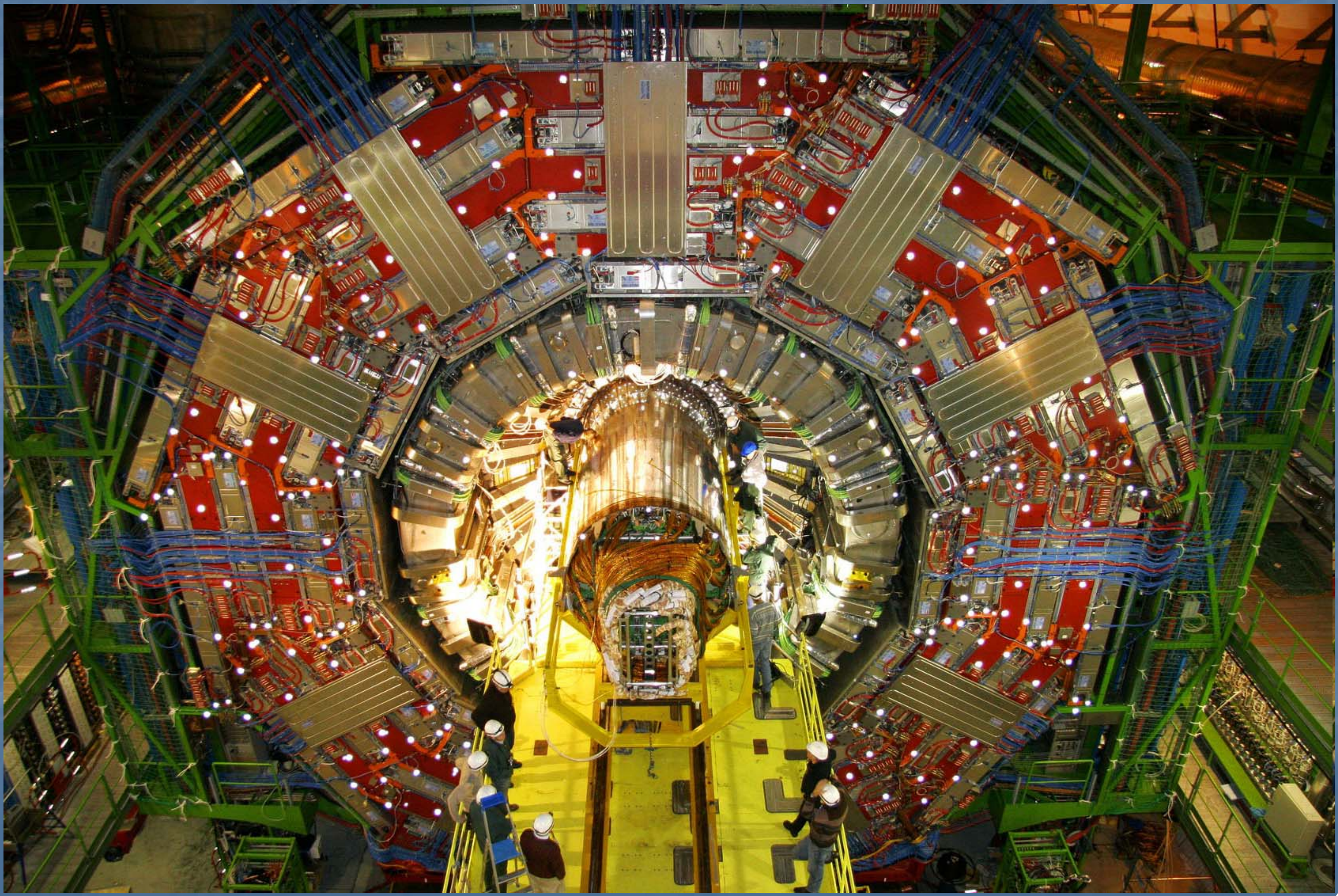
Insertion of HCAL



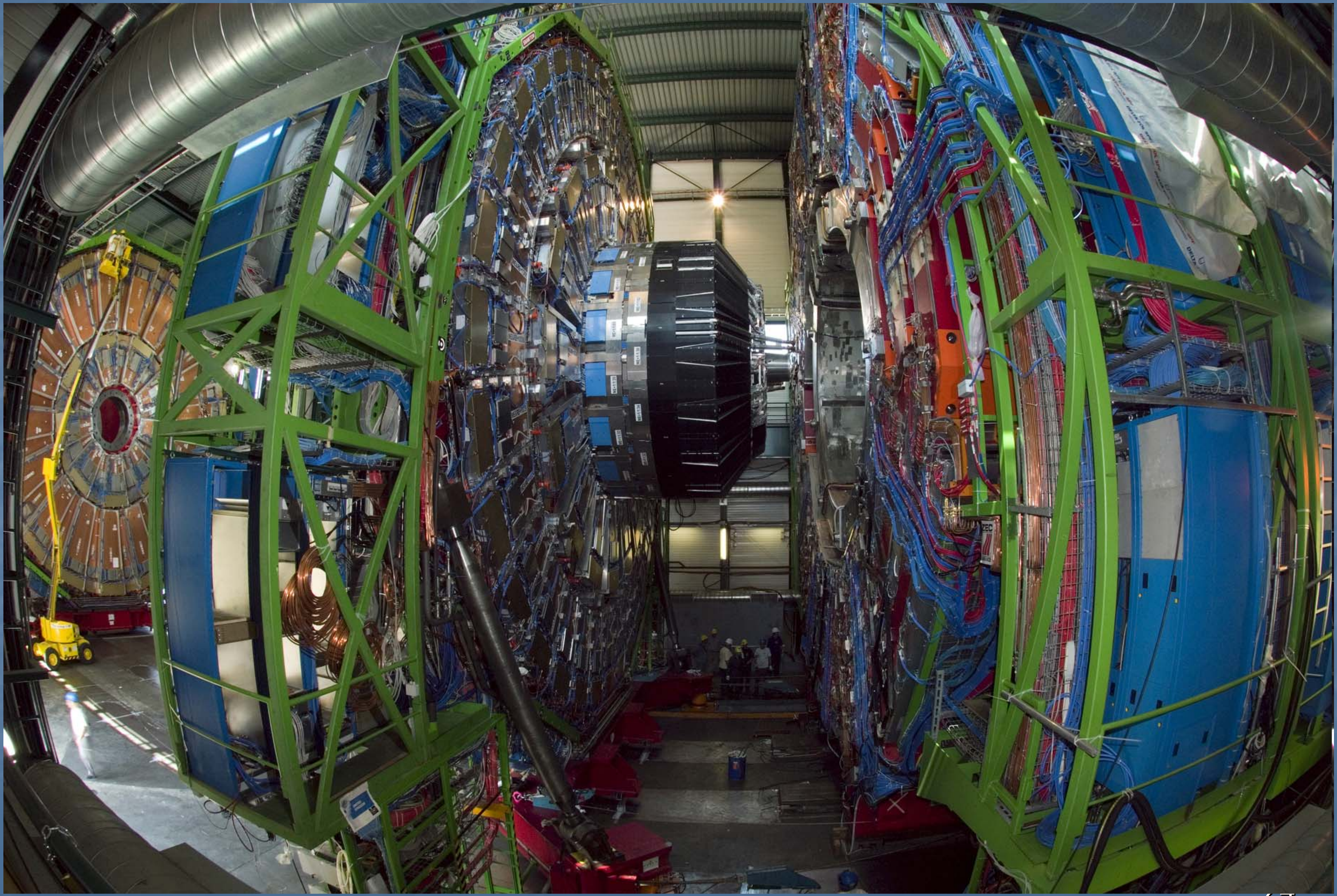
Insertion of ECAL super modules



Insertion of tracker

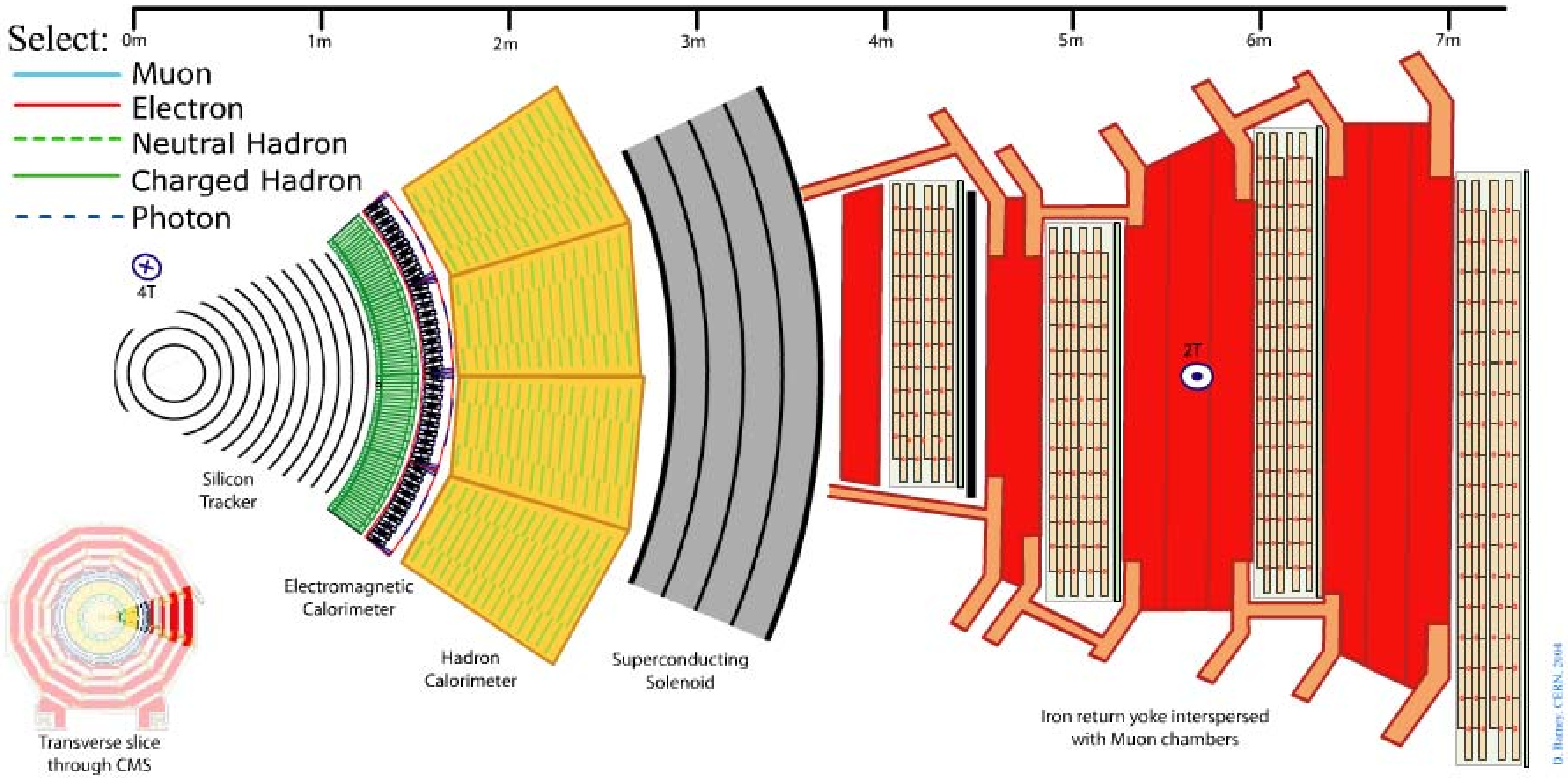


closing of detector for magnet test



What does the detector do?

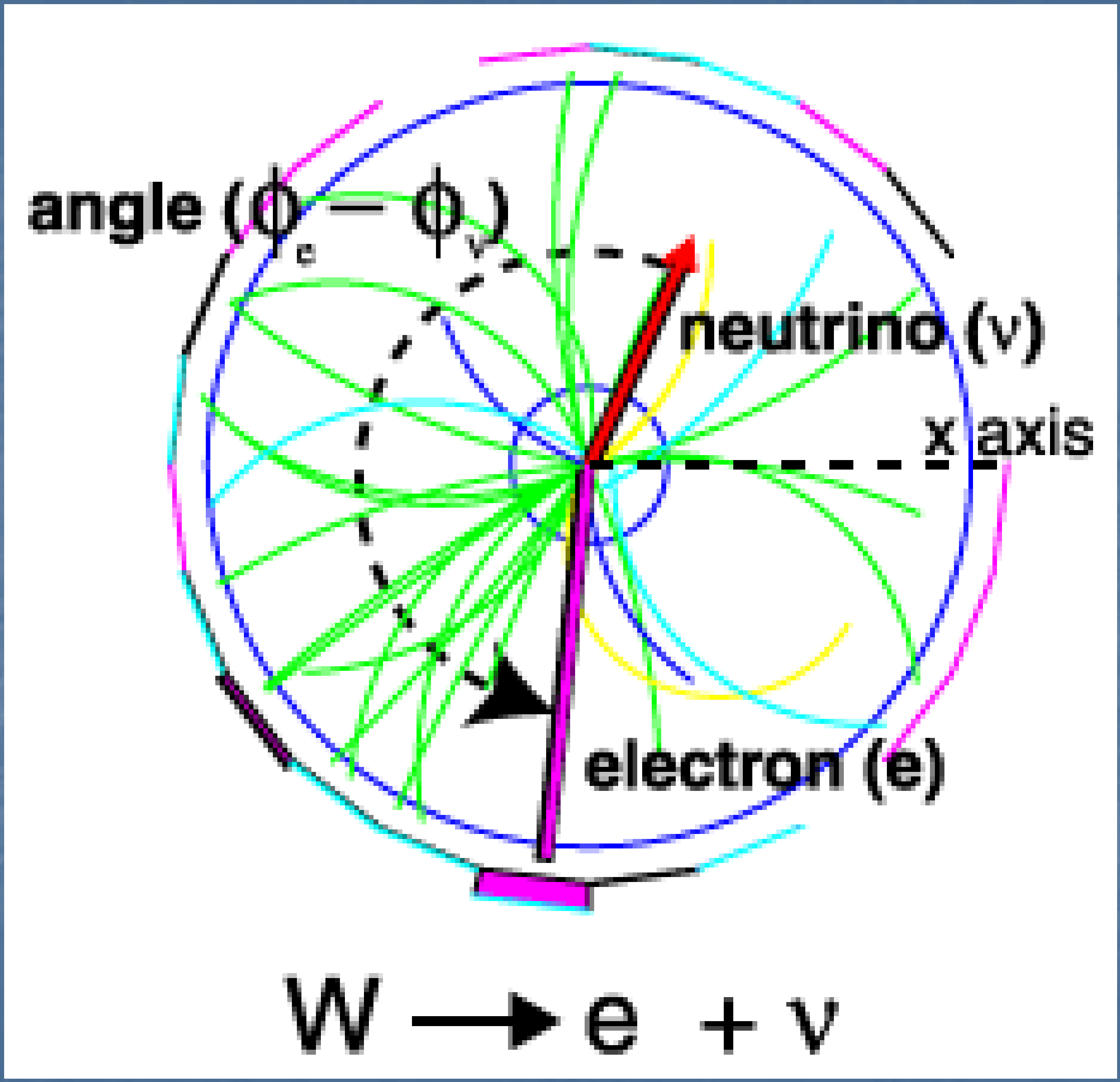
- The detector tries to measure the 4-momenta of all particles in a pp collisions
- 3-momenta of charged particles are inferred by reconstructing tracks as it bends in a 4T magnetic field
- For neutrals (γ, neutrons), energy is measured by size of "shower" in instrumented material (calorimeter)
- The interactions patterns of particles with the detector elements allows to "identify" the particle species
  - *e.g.*, electron vs muon vs proton



Select:
Muon
Electron
Neutral Hadron
Charged Hadron
Photon
0m
1m
2m
3m
4m
5m
6m
7m
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS

Neutrinos (or dark matter particles)

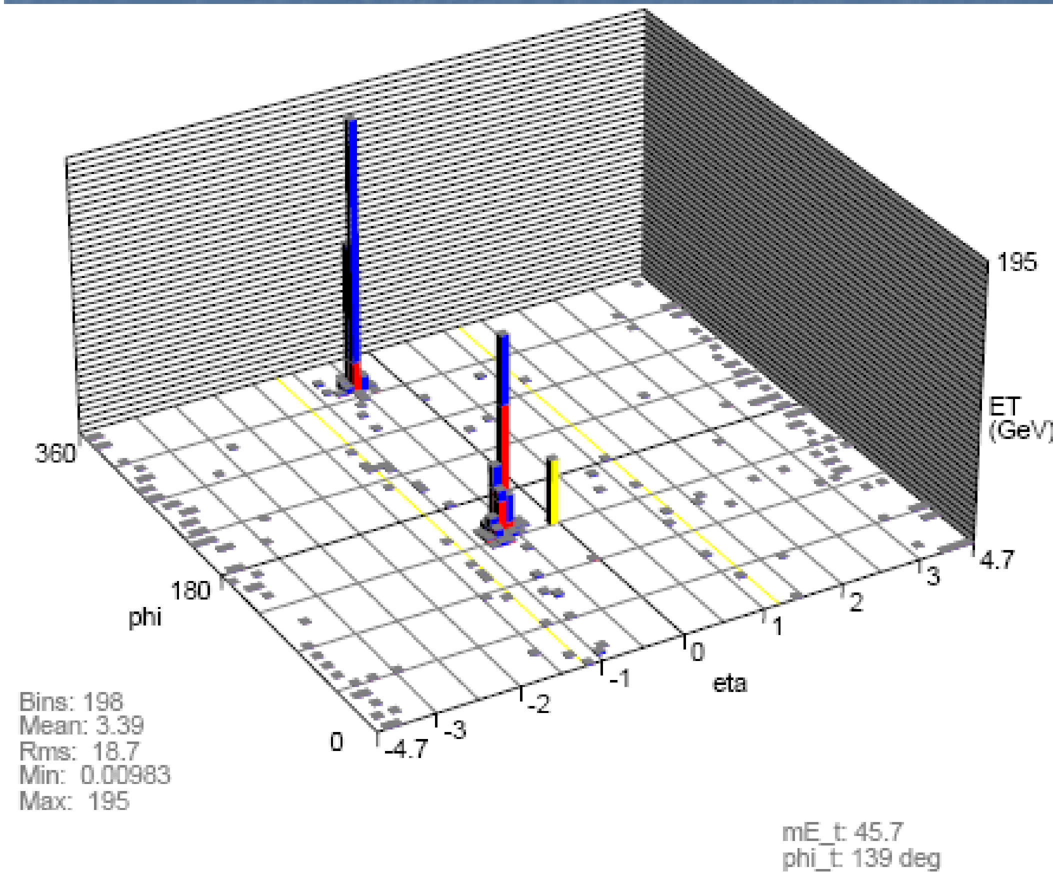
- They do not interact
- Their presence is inferred by conservation of momentum $\sum \vec{P}_\nu = -\sum \vec{P}_{\text{visible}}$
- In practice this can only be done in the plane transverse to the beam direction, since particles escaping down the beampipe are not measured
  - Missing Transverse Momentum, or Missing Transverse Energy

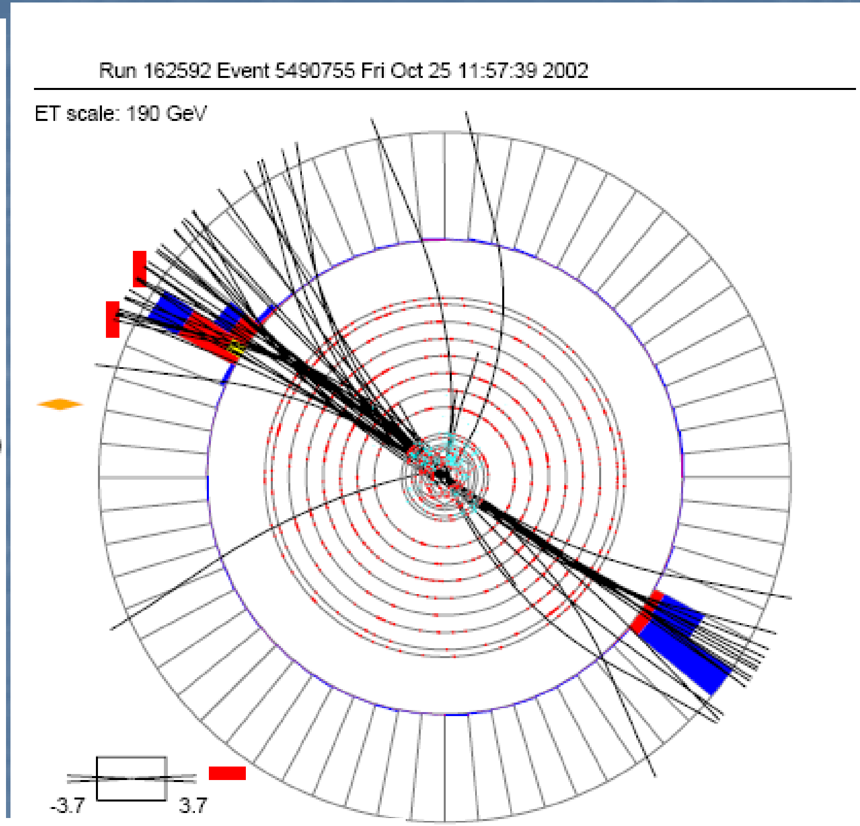

angle ($\phi_e - \phi_\nu$)
neutrino (ν)
x axis
electron (e)
W → e + ν

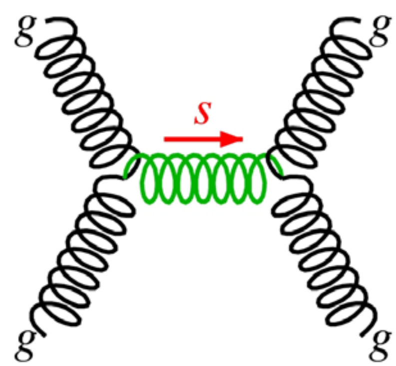
Gluons and quarks → jets

- They do not directly show up in the detector
- Quarks and antiquarks are pulled from the vacuum and bound states are formed (hadrons, eg, pions, protons, etc)
- If the original gluon or quark is energetic enough, the result is a spray of hadrons (jet) that preserves the direction and energy of the original gluon or quark (more or less)

A two jet event from D0 (di-jet)



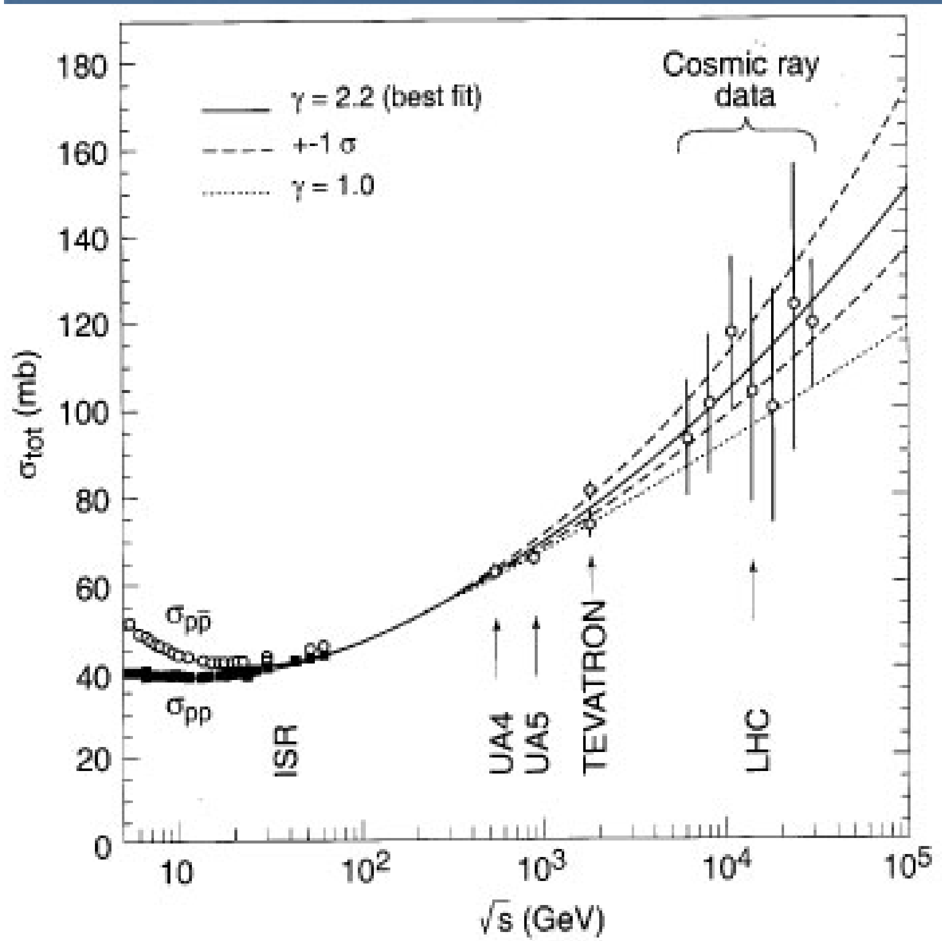


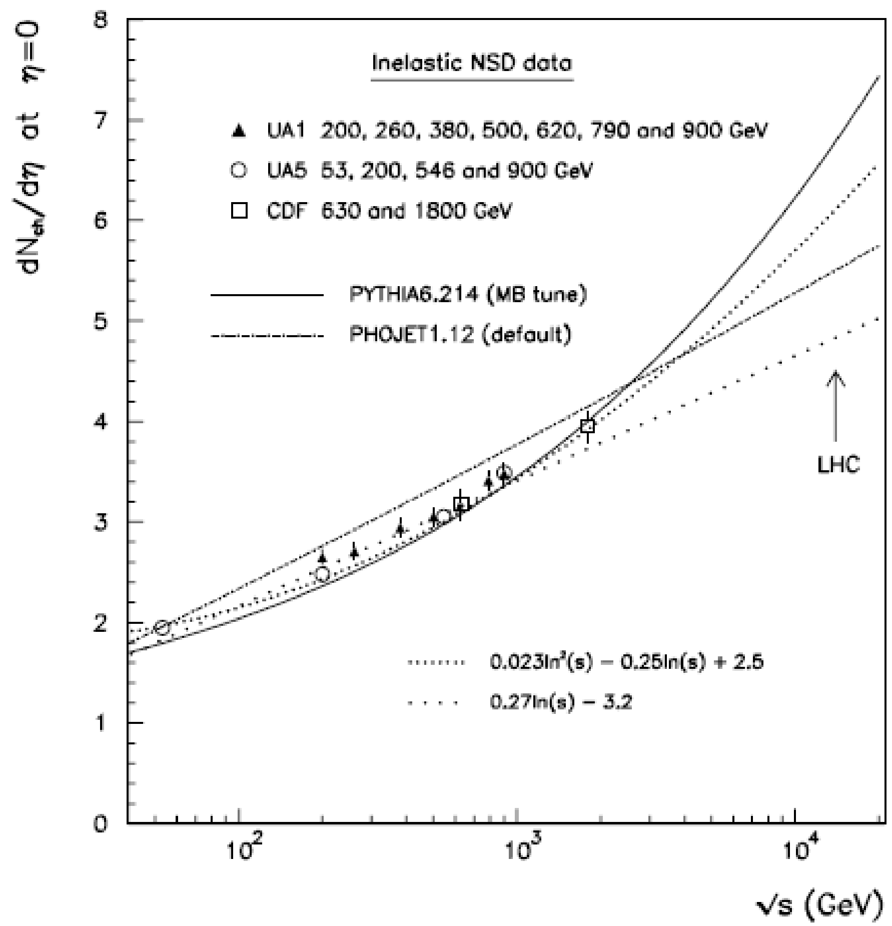


Two jets back-to-back in ϕ
Note: 45 GeV of MET

What happens when two protons collide?

- Most of the times: not very much
- The protons might break up with most daughter particles going down the beampipe. A few (~50-100) particles with small transverse momentum (P_T) show up in the detector



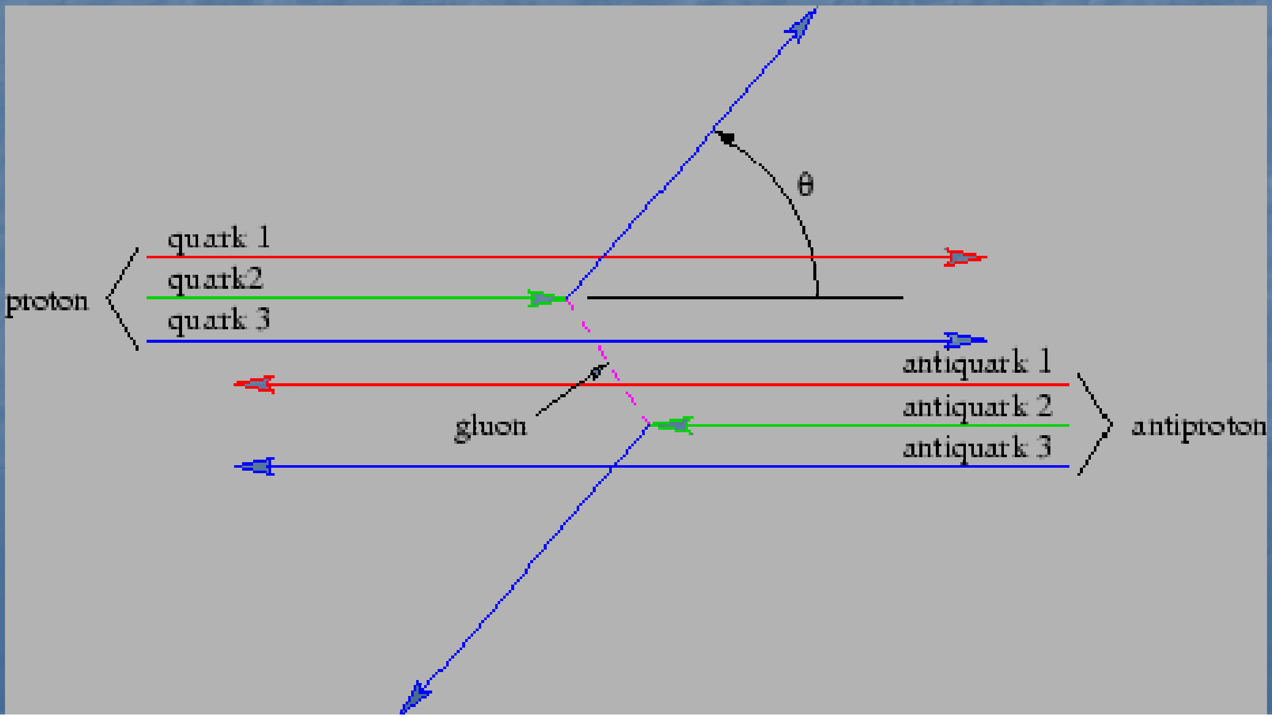


Physics 105B: Billiard ball scattering:

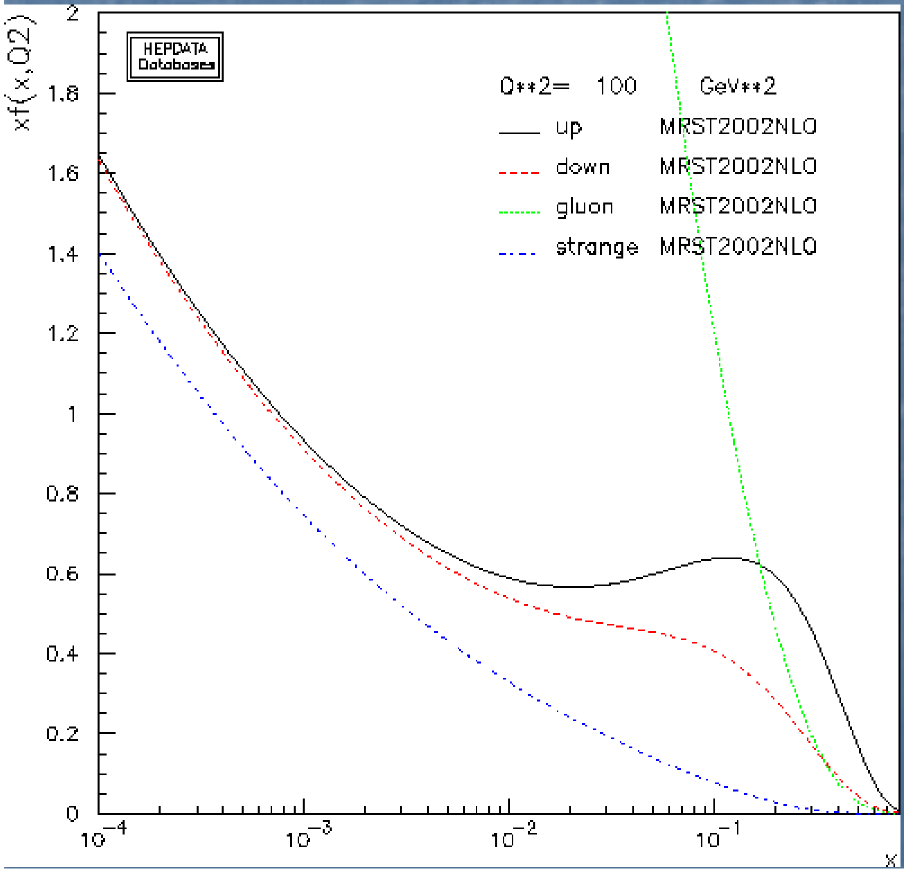
$\sigma=4\pi R^2$

$R_{proton} \sim 10^{-15}$ m → $\sigma(pp) \sim 10^{-29}$ m^2 = 100 mb

- The garden-variety collisions are not interesting (to most people)
- The interesting collisions are the "violent" collisions where a lot of transverse momentum is exchanged
- Here we can think of collisions between the components of the proton (quarks, antiquarks, and gluons, aka partons)

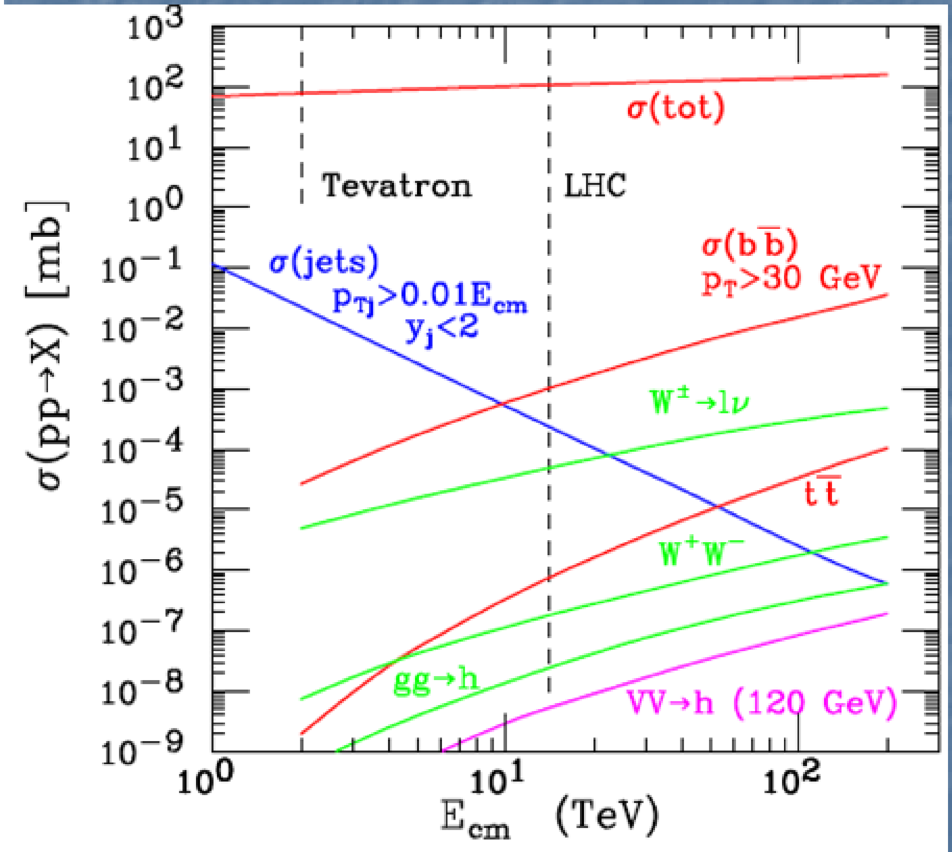


- Think of the LHC as a parton-parton collider
- Broadband collider. Partons in the proton can take any fraction of the proton momentum.
- In a probabilistic way, that we cannot calculate from first principles → measure it



- $f_i(x)$ = prob of parton i having momentum x^*P_{proton}
- Parton Distribution Function (pdf)
- Note that there are many many many gluons.
- LHC = gluon collider

Moving on to harder scatters



Note: TeV-scale SUSY, σ ~ 10^{-9}mb

- Jets have large cross-sections because they are strong processes, eg, gg→gg
- To look for "New Physics" require presence of γ or leptons (e, μ, τ) or missing energy
  - Backgronds are electro-weak processes
  - There are exceptions

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What Physics should I do at the LHC?

- To Higgs or not to Higgs?
  - Should I look for the Standard Model Higgs, or for "New Physics"?
- Interestingly enough all of us at UCSB have answered "not to Higgs"
- Remainder of the talk on searches for New Physics

3+1 Ingredients for New Physics Discoveries at the LHC

0. **Machine/detector:** *if they dont work, forget it*
1. **Trigger:** *if you did not trigger on it, it never happened*
2. **Backgrounds:** *It's the background, stupid*
   - Need to understand instrumental and Standard Model physics backgrounds
3. **Searches:** *If you look for something, you may not find it. But if you don't look, you will never find it*

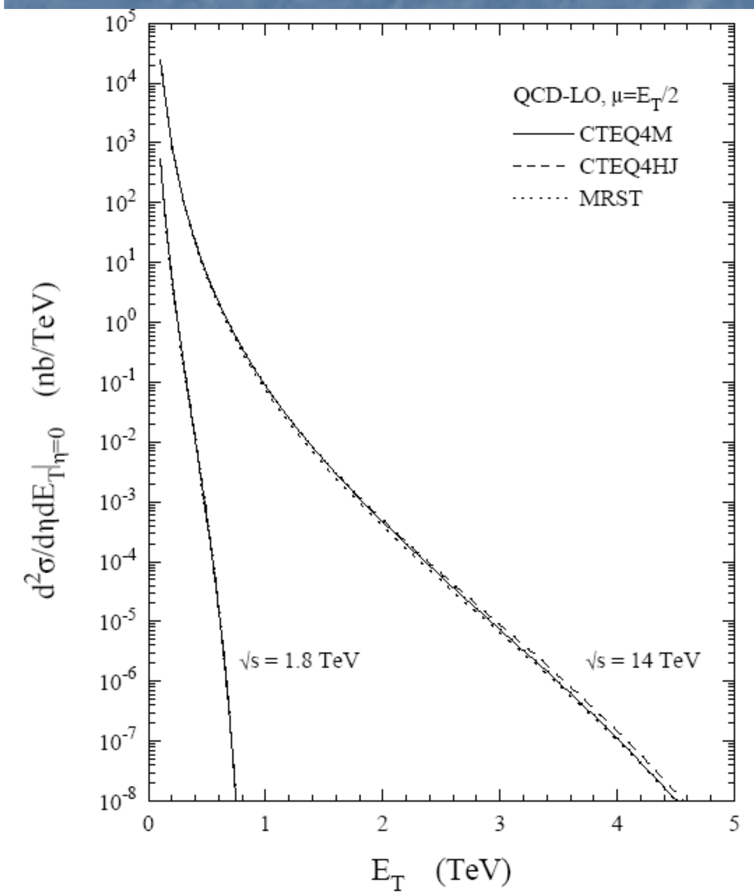
What is the "trigger"?

- $\sigma(pp) \sim 100$ mb
- Gives an "event rate" of order 100 MHz
- Each event is ~ 250 kb
- 250 kb x 100 MHz = 25 Tbytes/second

- Trigger is the system that selects the ~ 200 events/second that are saved for further study
- Most of the events are thrown away!!!!

Trigger (2)

- The decision on what to trigger on has enormous impact on the physics that we can do
- Trigger selects objects (e, μ, jets..) or combinations thereof
- All kinematical distributions fall steeply with P_T → trigger selects objects above a threshold



- It is always a compromise
- A balance between competing priorities
- A source of great debate in the collaboration
- If you, as a theorist have a great idea for NP…..
  1. Check that your events have been triggered on
  2. If not, try to convince people to devote bandwidth to your theory

And your argument better be good…

CMS "Trigger Menu"

Trigger	Threshold (GeV or GeV/c)	Rate (Hz)	Cumulative Rate (Hz)
Inclusive electron	29	33	33
Di-electrons	17	1	34
Inclusive photons	80	4	38
Di-photons	40, 25	5	43
Inclusive muon	19	25	68
Di-muons	7	4	72
Inclusive τ-jets	86	3	75
Di-τ-jets	59	1	76
1-jet * E_T^{miss}	180 * 123	5	81
1-jet OR 3-jets OR 4-jets	657, 247, 113	9	89
Electron * Jet	19 * 45	2	90
Inclusive b-jets	237	5	95
Calibration and other events (10%)		10	105
TOTAL			**105**

From the Technical Design Report. Obsolete. There are now close to 100 different triggers in the menu.....

New Physics discoveries @ LHC

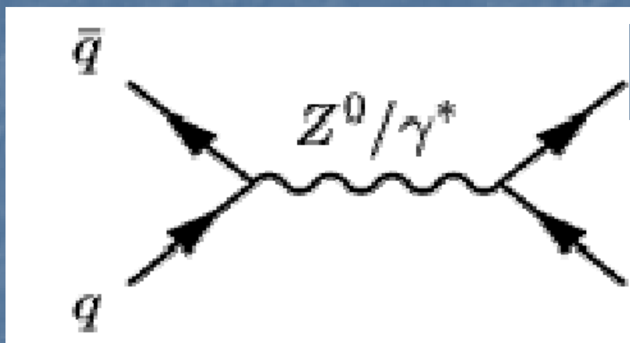
Broadly speaking, three types

1. ***Self Calibrating***
   - A signal that stands out, where you do not really need to understand the background very well
2. ***Counting experiments***
   - The number of observed events of some type is >> than the SM prediction
3. ***Distributions***
   - The distribution of some kinematical quantity is inconsistent with the SM prediction

Self Calibrating Signals (SCS)

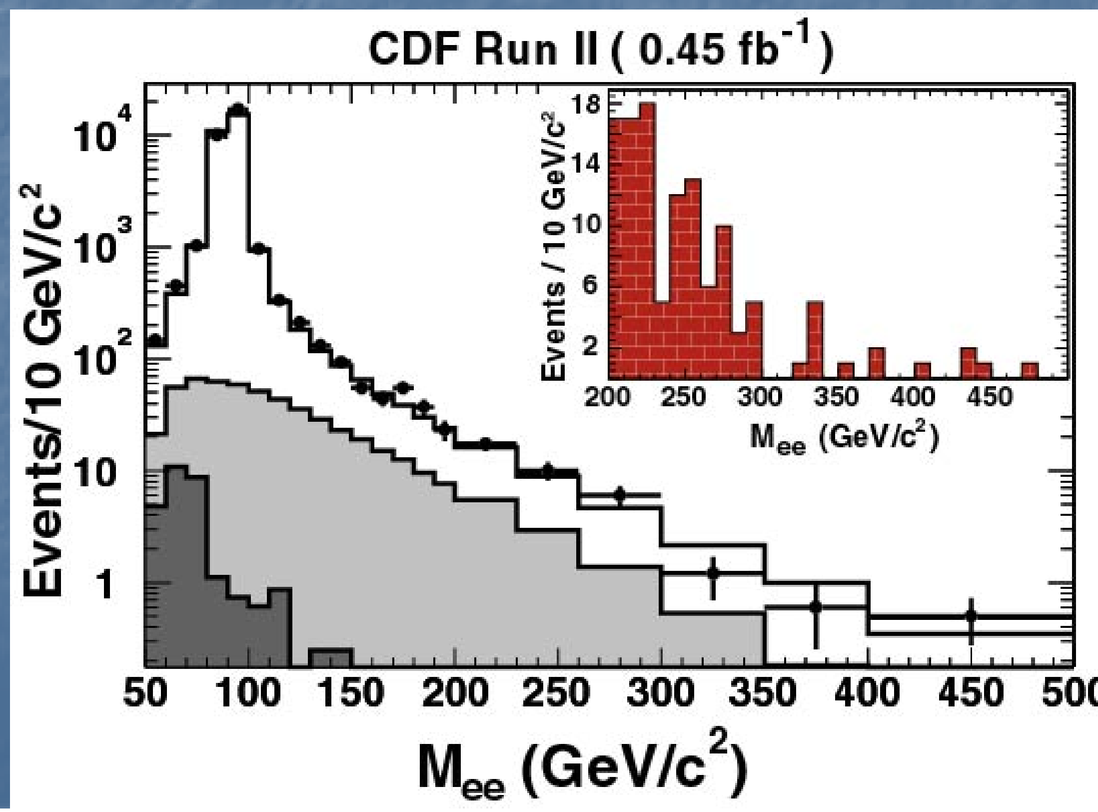
- A NP signal that obviously stands out
  - where you do not need to know the SM BG very precisely
- For example:
  - A mass peak
    - X→AB, measure the 4-momenta of A & B, then, $(P_A+P_B)^2=M_X^2$
  - A <u>huge</u> distortion to some kinematical distribution

Drell-Yan



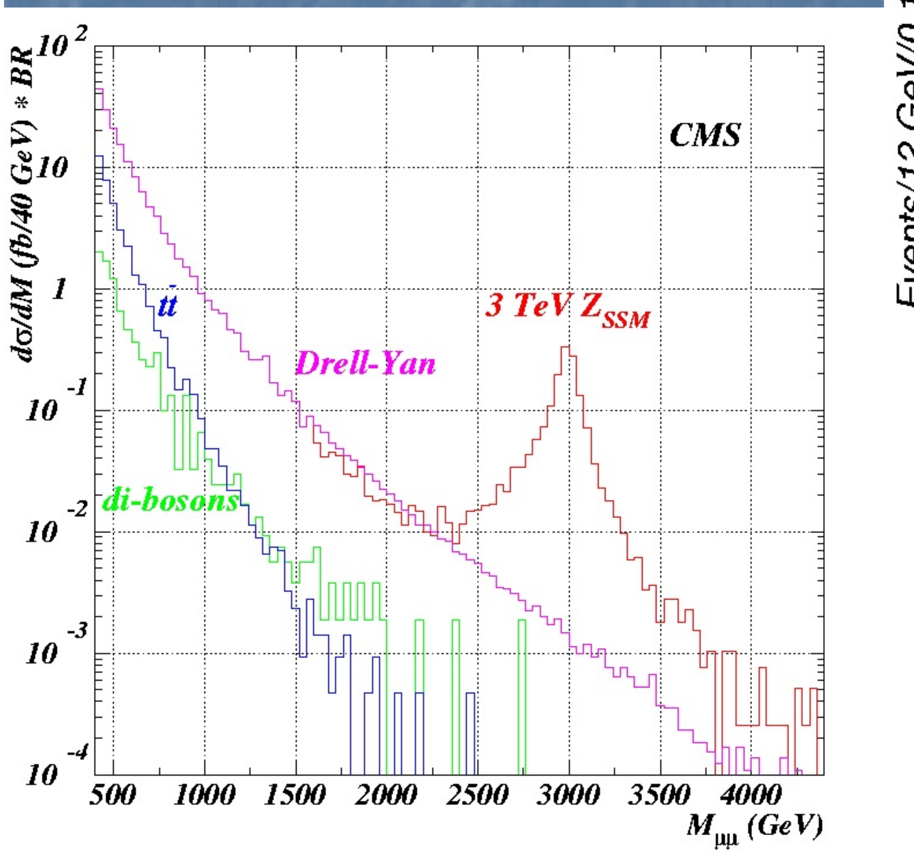
e^- or μ^-

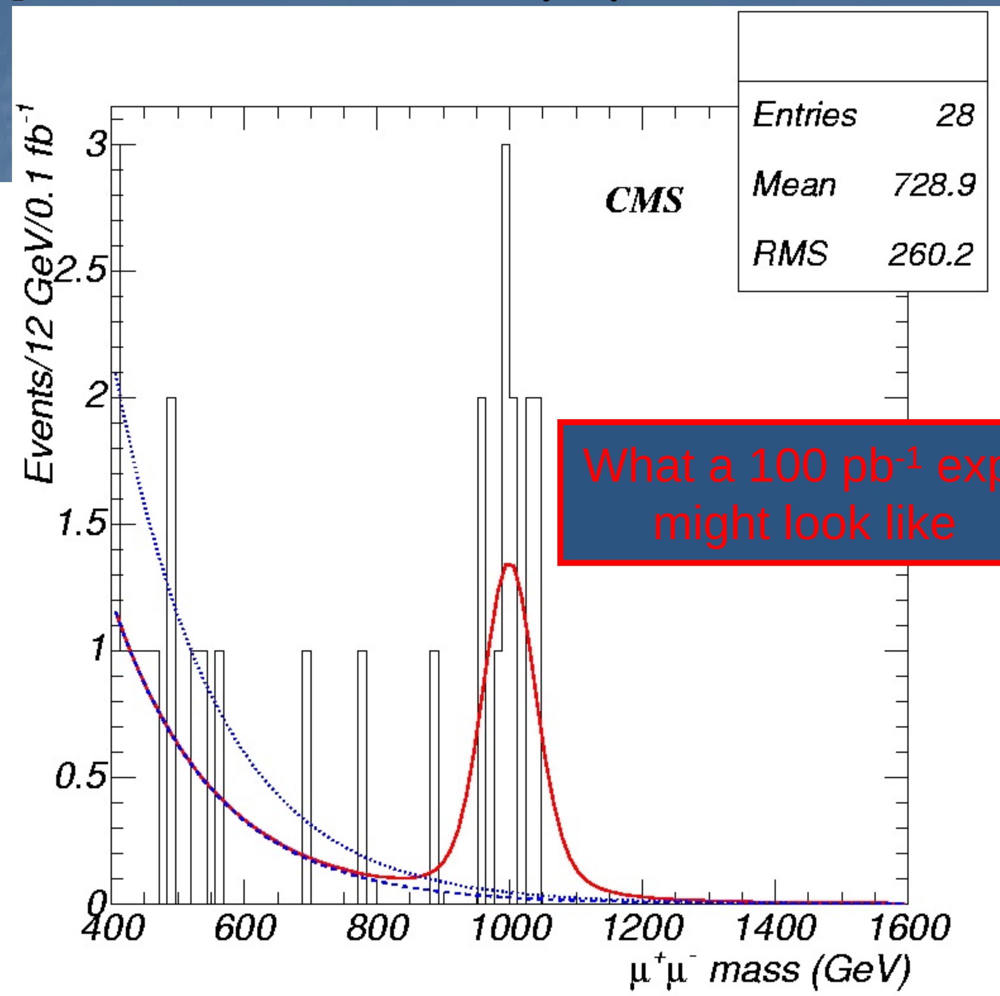
e^+ or μ^+



- SM Drell-Yan
- Di-jet background
- WW background

SCS example: Z' → μμ

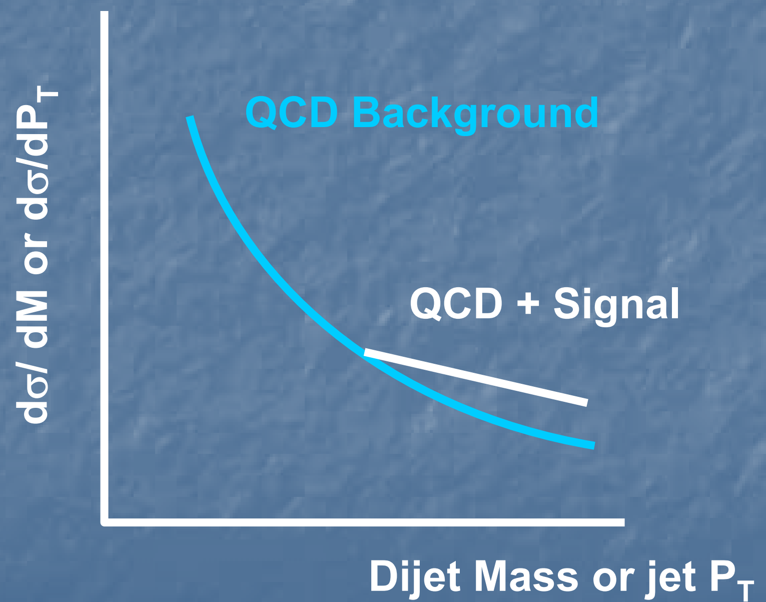


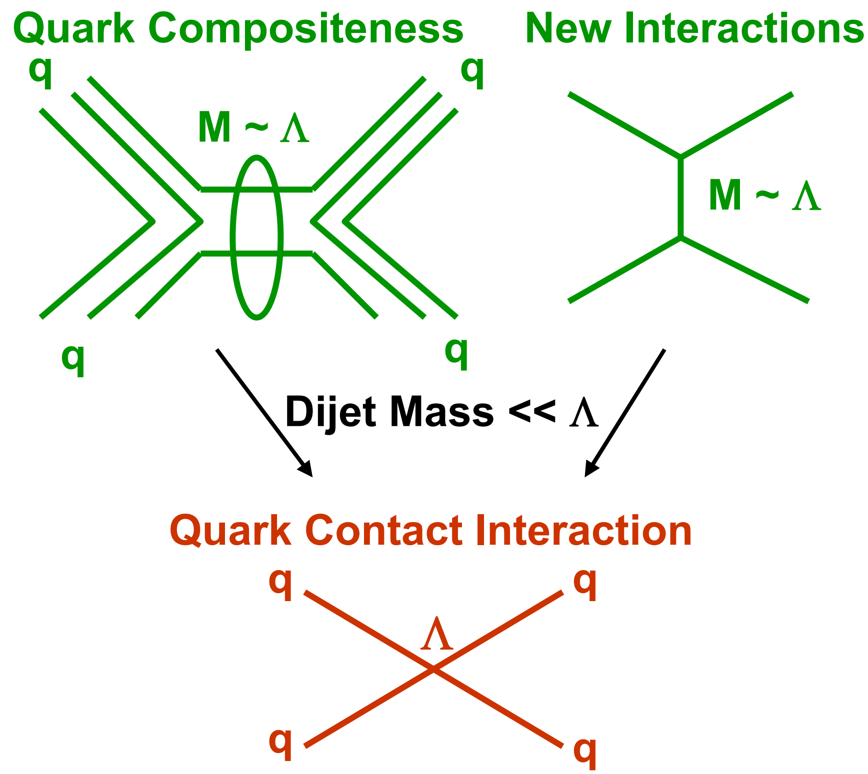


What a 100 pb^{-1} expt might look like

Another SCS example: di-jet mass distribution

- Distorts angular distributions
- More scatters at high angles
  - More jets at high P_T
  - More di-jets at high mass

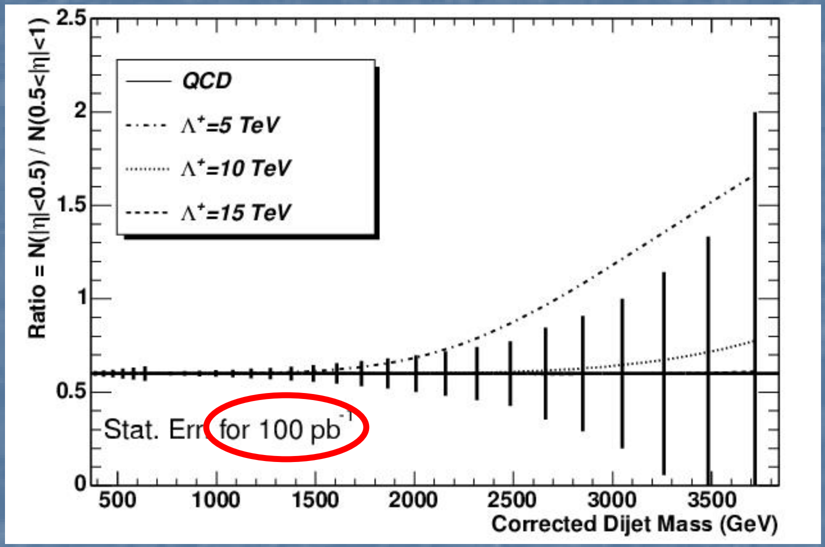


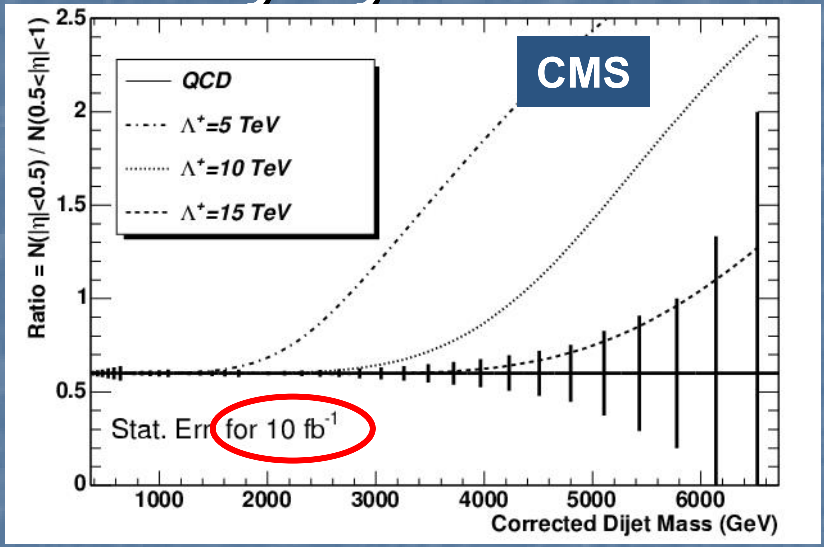


If the "edge" is low enough, this could be a relatively easy discovery (*Self-calibrating* variety)

Di-jet mass distribution distortion

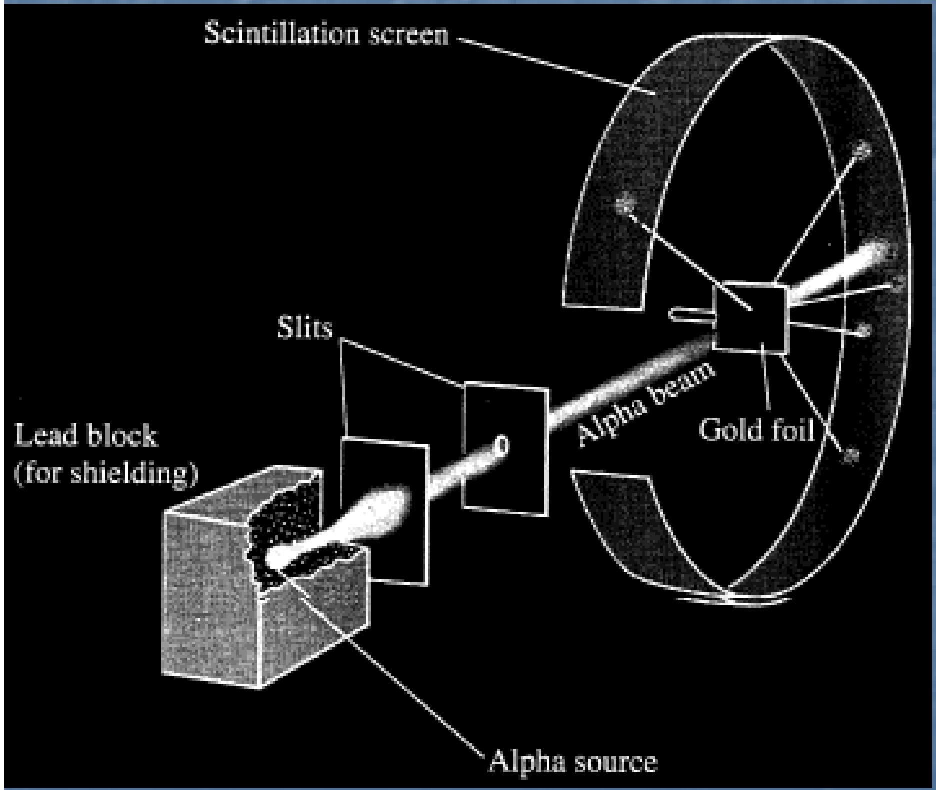
- Ratio of events at high-low η is a sensitive variable that eliminates many syst

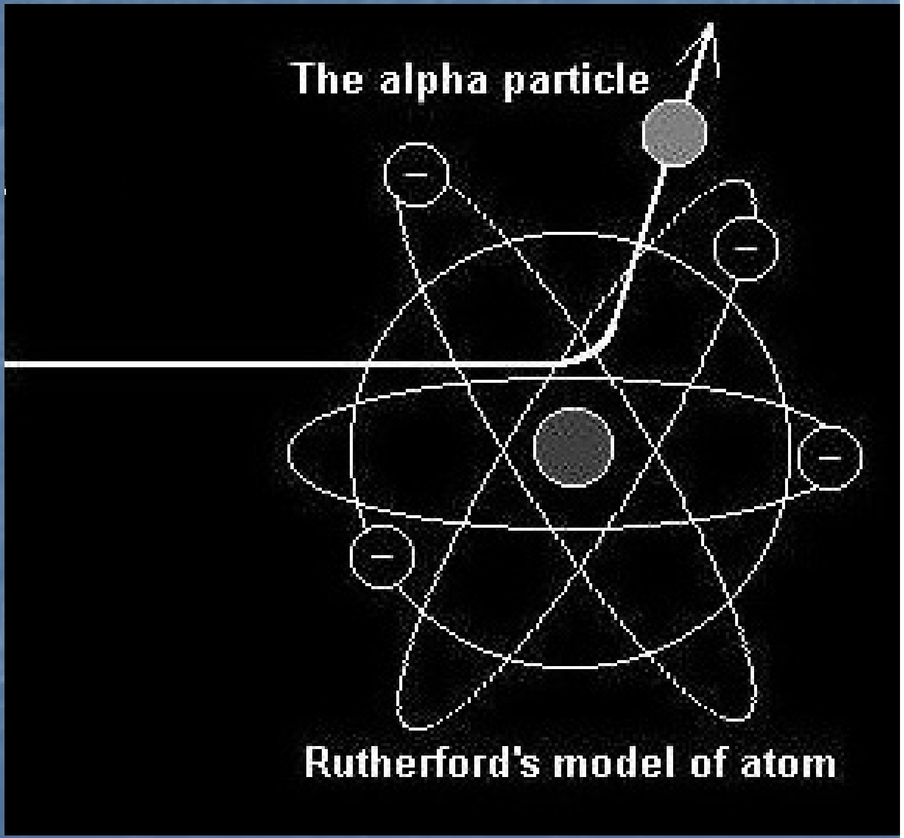




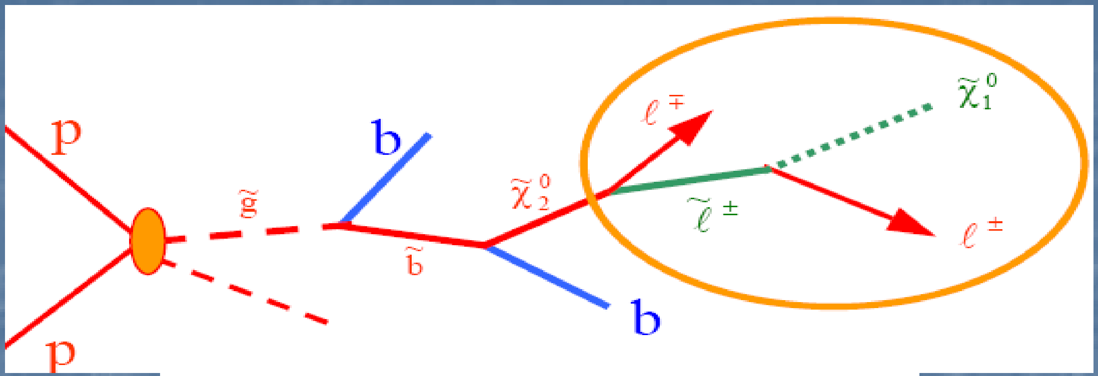
Left-Handed Quark Contact Interaction	Λ^+ for 100 pb^{-1} (TeV)	Λ^+ for 1 fb^{-1} (TeV)	Λ^+ for 10 fb^{-1} (TeV)
95% CL Exclusion	**6.2**	**10.4**	**14.8**
5σ Discovery	**4.7**	**7.8**	**12.0**

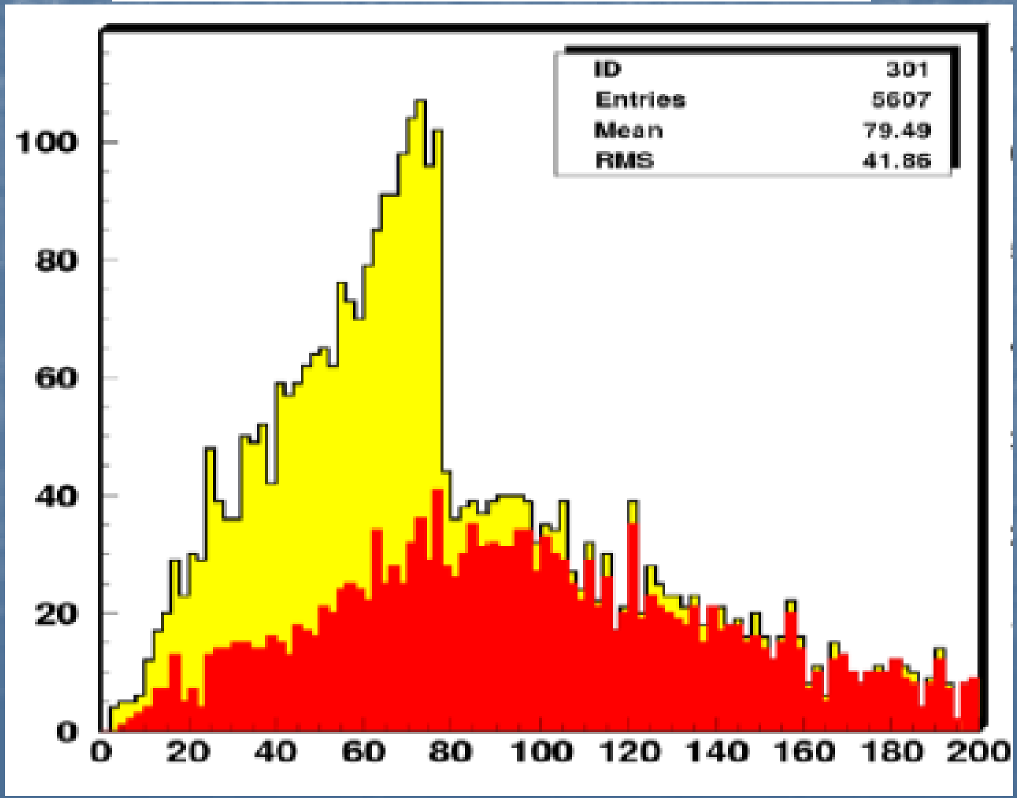
What was just described is like Rutherford Scattering, but with quarks!





SCS: Edges





$M(l^+l^-)$

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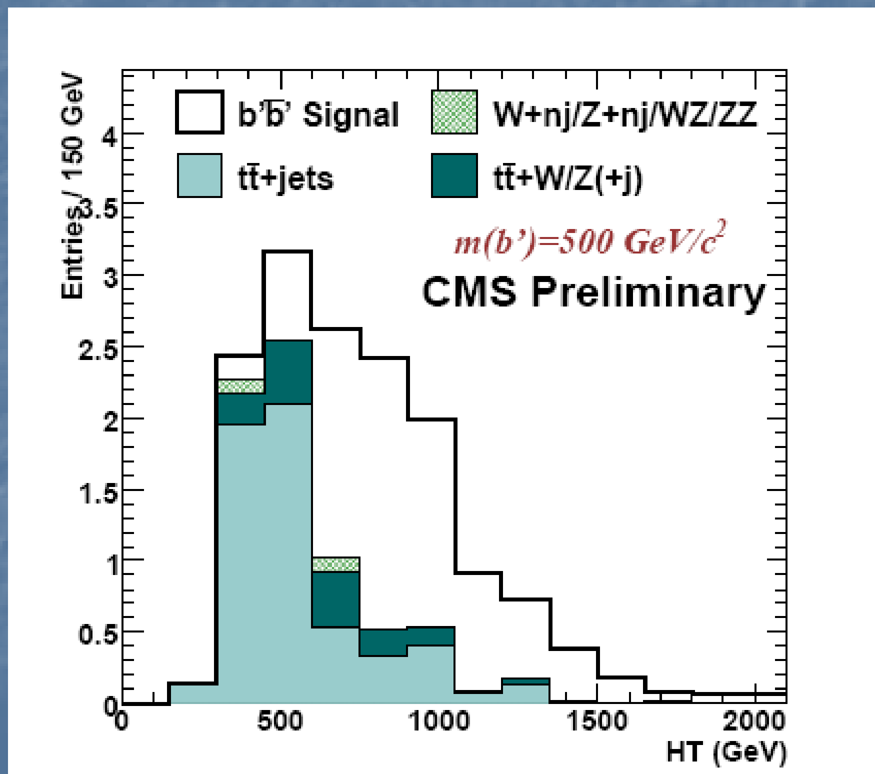
Less dramatic signals

- Not all NP signals are as dramatic as a mass peak
- Particularly for signal with dark matter particles, eg, SUSY
  - Because dark matter particles are not detected, only inferred from Missing Transverse Energy
  - And most often you have two per events

$$\vec{P}_T(\text{Dark1}) + \vec{P}_T(\text{Dark2}) = -\sum \vec{P}_T(\text{visible})$$

- Signal can be
  - "number of events passing selection" > SM expectation
  - "kinematical distributions" inconsistent with SM

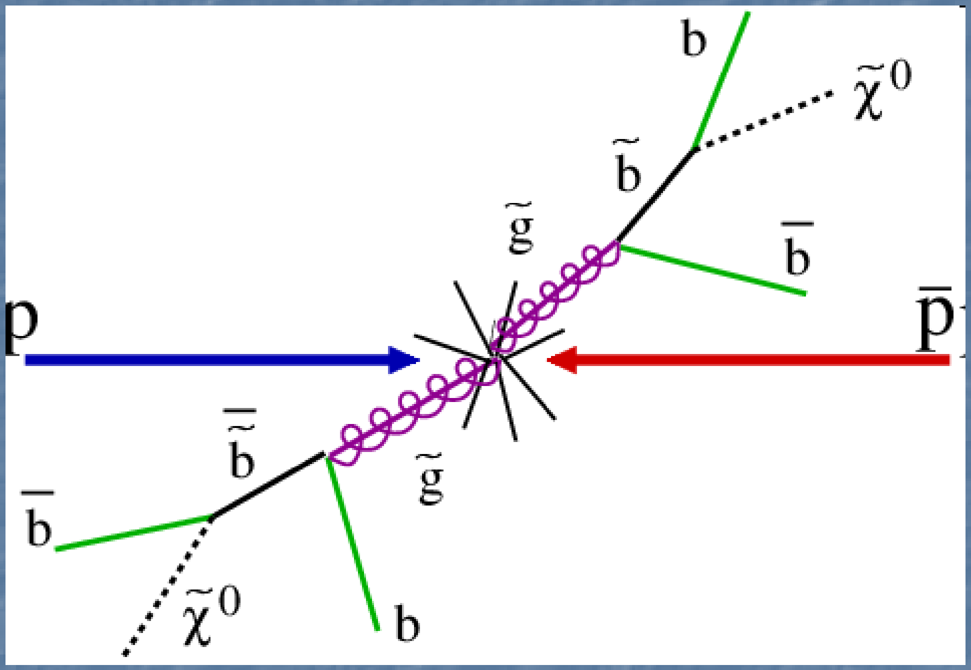


Example: pp → b'–' → tW ŏW. HT=sum of P_T of all objects

- Understanding the SM background is key
- This is were most of the work goes
- Difficult because background is usually an "unlikely" SM event
  - In the tail of distributions
- Methods that try to estimate the background from the data itself using clever tricks are the most robust

Example

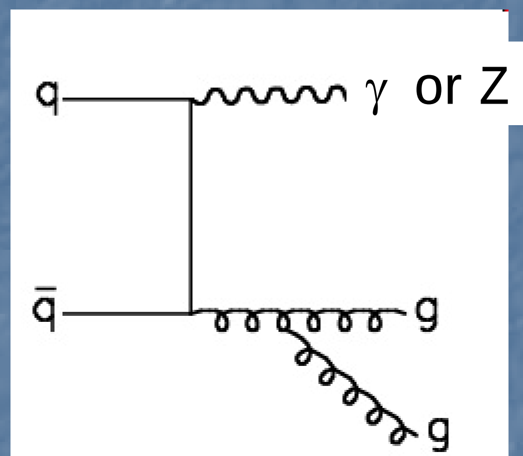
- pp → jets + MET is a generic signature of SUSY



- pp → Z + jets, with Z → νν gives similar signature
- Crucial to have an estimate of it
- **<u>But SM theory is uncertain to factors O(2) or more</u>**

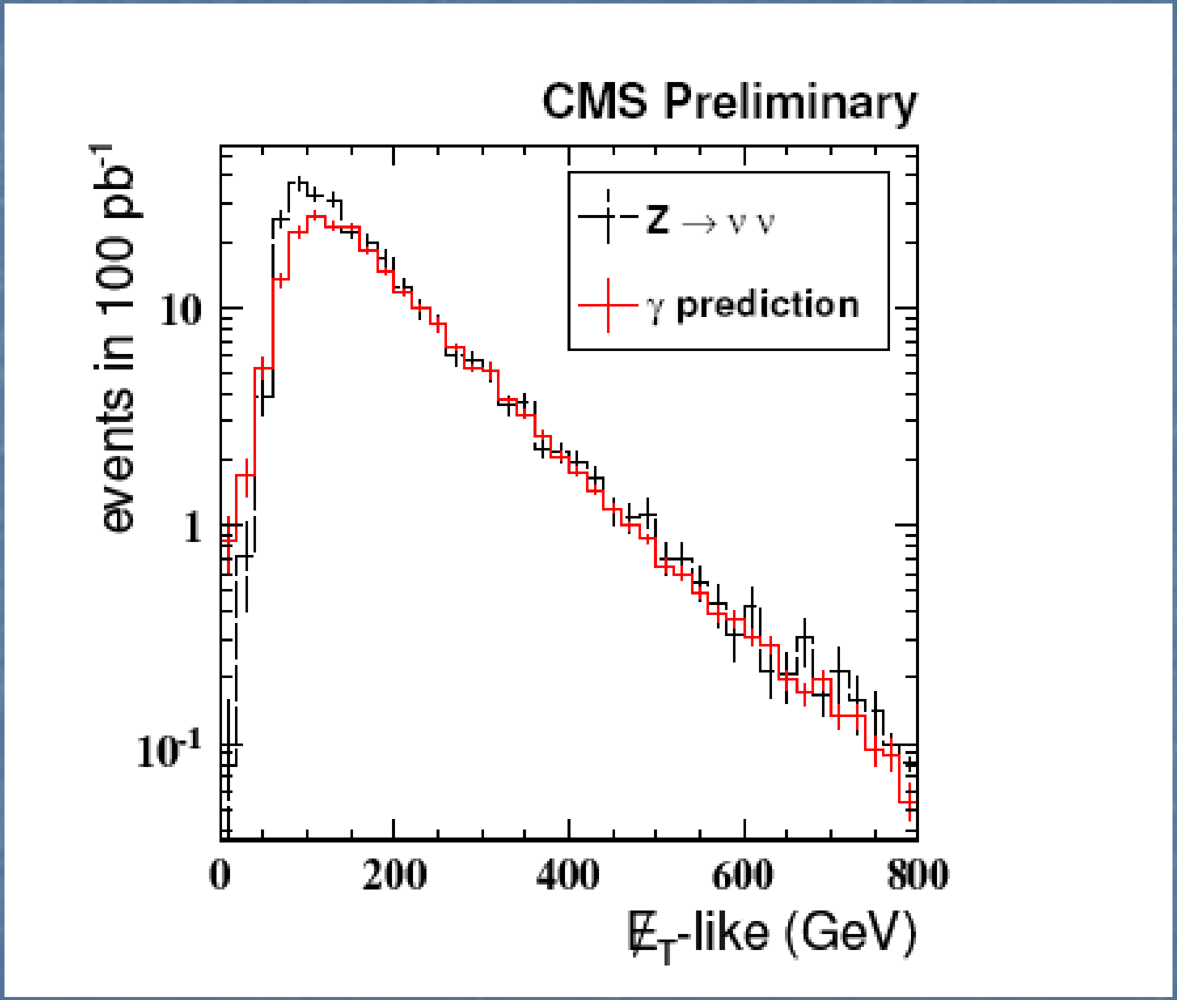
Clever *data driven* idea

- pp → Z + jets and pp → γ + jets have similar production properties



- Use pp → γ + jets **data**, delete γ from the event, apply some well understood corrections, predict pp → Z($\nu\nu$) + jets

Test this idea on simulated data



(J. Incandela et al)

- Important to come up with clever tricks
- Lots of work to validate theoretical tools when clever tricks do not quite work

4 Conclusions

Advanced MC tools for the description of the SM, and for the isolation of possible new physics at the LHC, are becoming mature. Validation and tuning efforts are underway at the Tevatron, and show that a solid level of understanding of even the most complex manifestations of the SM are well under control. The extrapolation of these tools to the energy regime of the LHC is expected to be reliable, at least in the domain of expected discoveries, where the energies of individual objects (leptons, jets, missing energy) are of order 100 GeV and more. However, the consequences of interpreting possible discrepancies as new physics are too important for us to blindly rely on our faith in the goodness of the available tools. An extensive and coherent campaign of MC testing, validation and tuning at the LHC will therefore be required. Its precise definition will probably happen only once the data are available, and the first comparisons will give us an idea of how far off we are and which areas require closer scrutiny.

M. Mangano, **Int.J.Mod.Phys.A23:3833-3848,2008**

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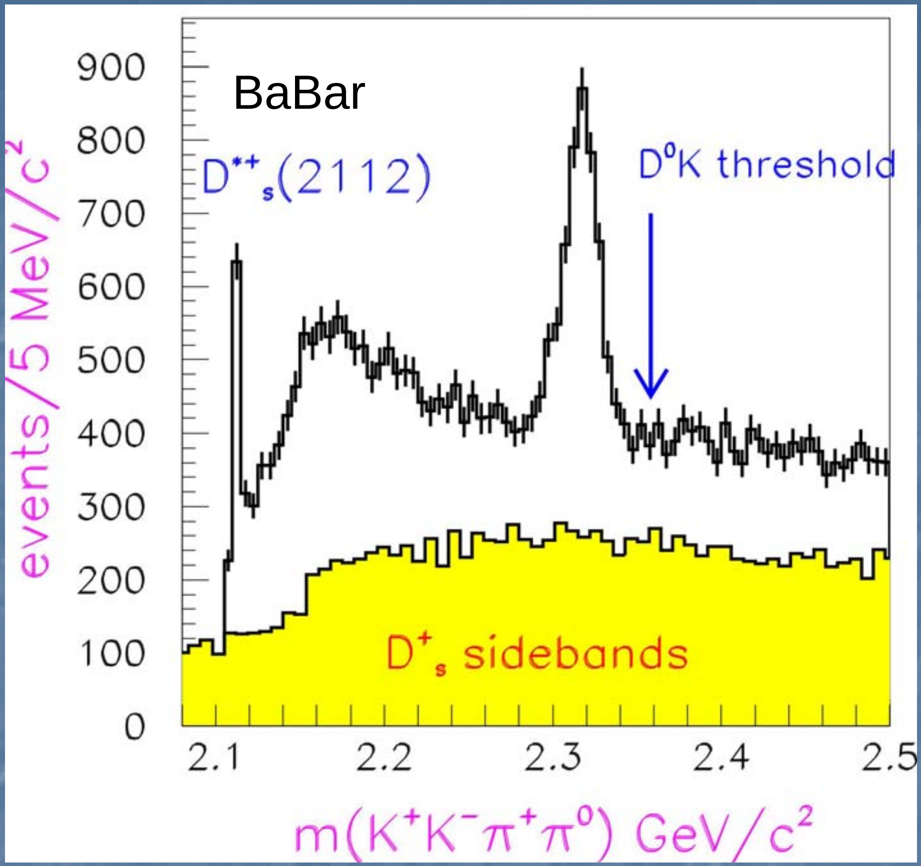
Model dependent vs. model independent searches

- Can search for generic NP signatures
  - e.g., the e + γ + MET
- Or, for very specific, complicated signatures
  - e.g., $pp \rightarrow TT$, $T \rightarrow tZ$ $T \rightarrow bW$, $t \rightarrow e\nu b$ $Z \rightarrow \mu\mu$, $W \rightarrow \mu\nu$
- Because we do not know what the NP is, generic searches are very powerful
- But in a generic search worry about missing complicated signature that nobody thought about......



Palano (Bari)
$D_{sJ}(2317) \rightarrow D_S\ \pi^0$
PRL90 242001 (2003)

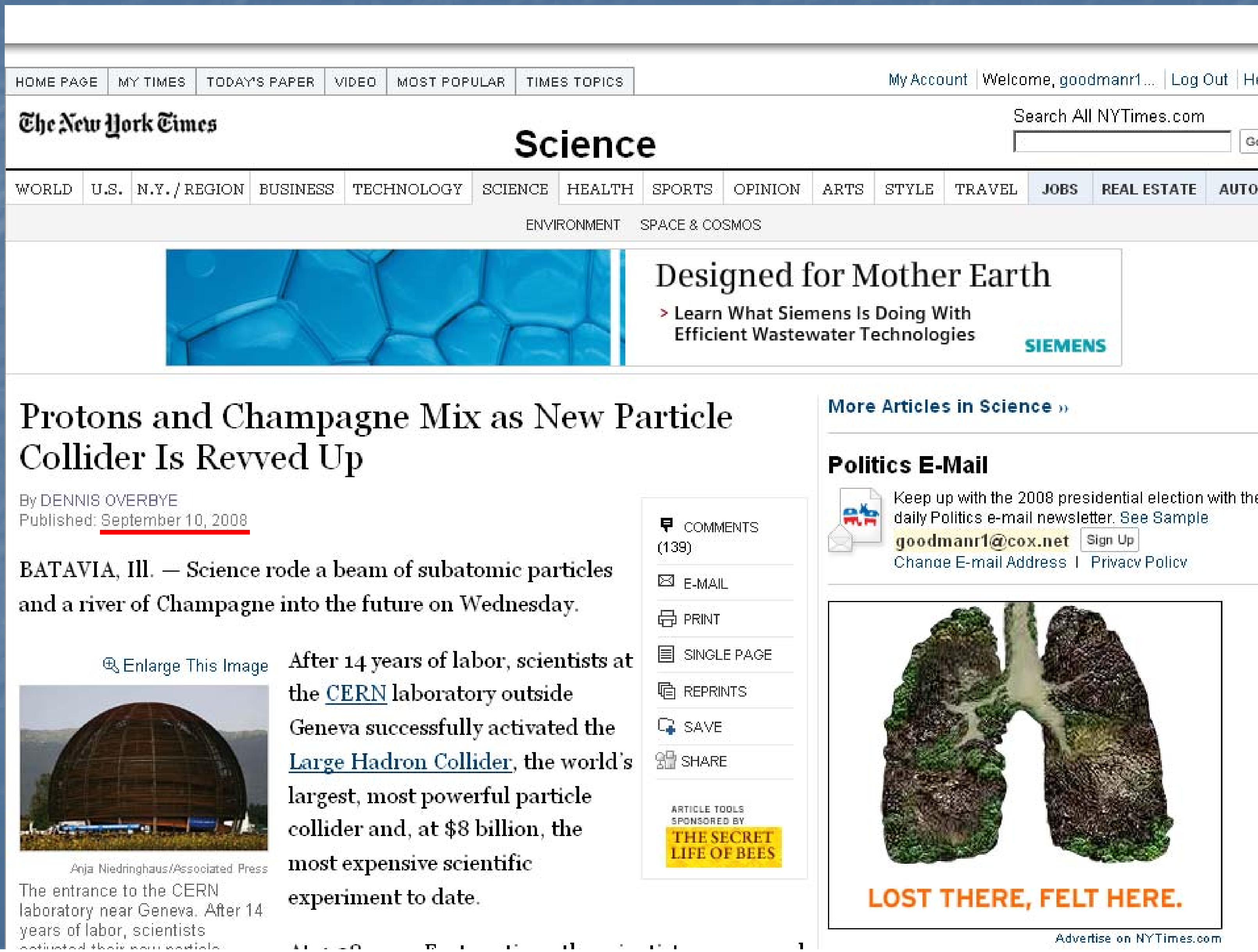
cŌ meson. Was expected to have mass ~ 2.5 GeV, decay strongly to DK, and therefore have broad width
So: noone bothered to look!

This huge signal had been in various data sets for many years!!

Outline

- What and Why?
- The LHC
- A detector (CMS), how we do physics at the LHC
- How to look for "New Physics"
- Status

Where are we now



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Protons and Champagne Mix as New Particle Collider Is Revved Up

By DENNIS OVERBYE
Published: September 10, 2008

BATAVIA, Ill. — Science rode a beam of subatomic particles and a river of Champagne into the future on Wednesday.

Enlarge This Image

Anja Niedringhaus/Associated Press

The entrance to the CERN laboratory near Geneva. After 14 years of labor, scientists

After 14 years of labor, scientists at the CERN laboratory outside Geneva successfully activated the Large Hadron Collider, the world's largest, most powerful particle collider and, at $8 billion, the most expensive scientific experiment to date.

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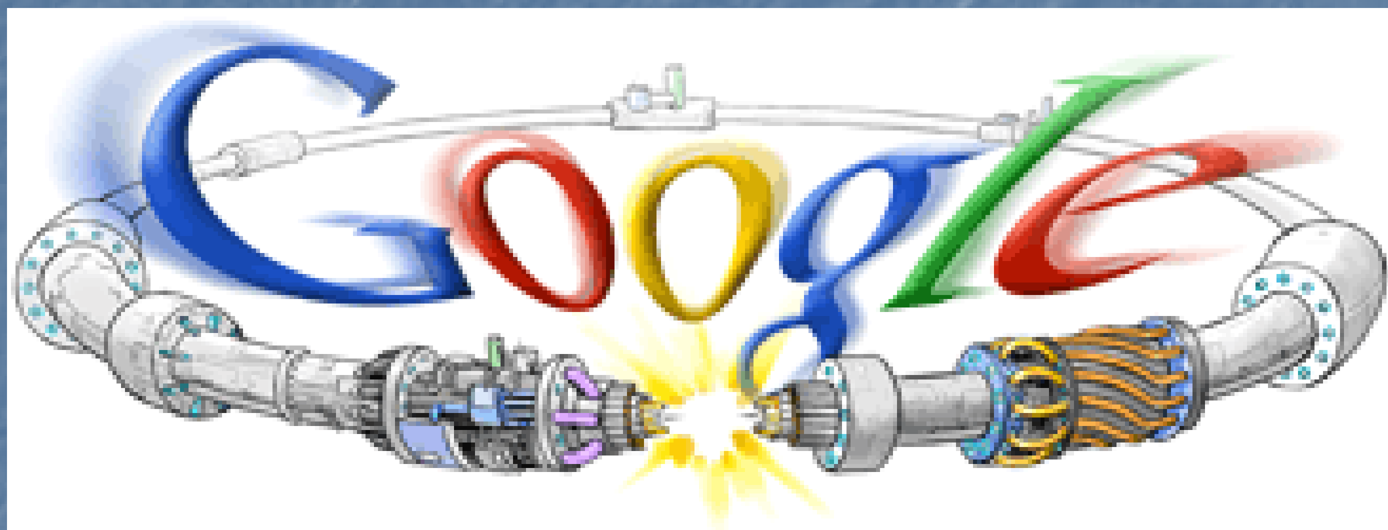
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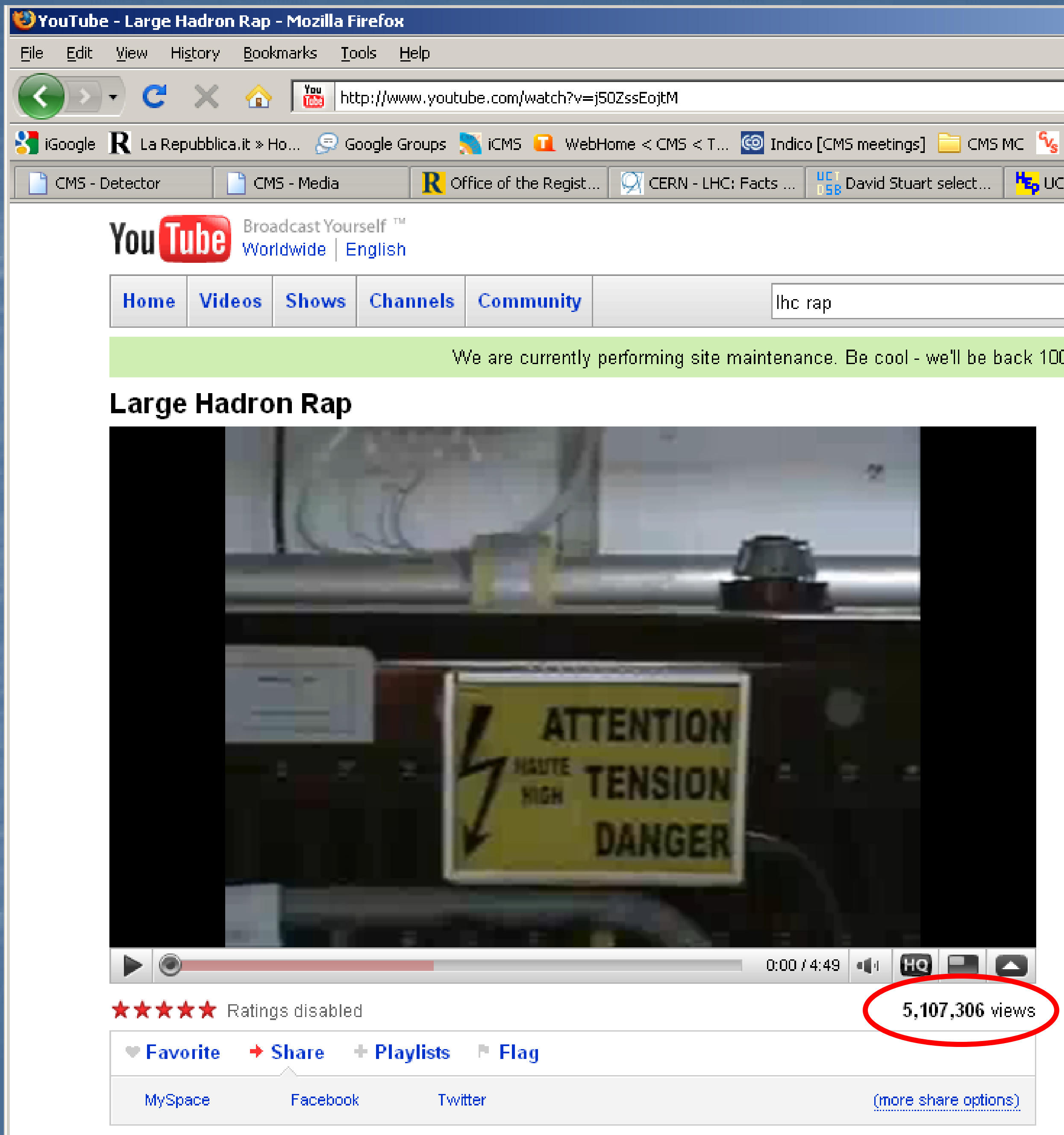
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We are currently performing site maintenance. Be cool - we'll be back 100
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The Top 10 Everything of 2008

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Top 10 Scientific Discoveries

1. Large Hadron Collider

By JEFFREY KLUGER

Good news! The Large Hadron Collider (LHC) — the massive particle accelerator straddling the Swiss-French border — didn't destroy the world! The bad news: The contraption didn't really work either. In

Good news! The Large Hadron Collider (LHC) — the massive particle accelerator straddling the Swiss-French border — didn't destroy the world! The bad news: The contraption didn't really work either. In September, the 17-mile collider was switched on for the first time, putting to rest the febrile webchatter that the machine would create an artificial black hole capable of swallowing the planet or at least a sizeable piece of Europe — a bad day no matter what. No lucid observer ever thought that would really happen, but what they did expect was

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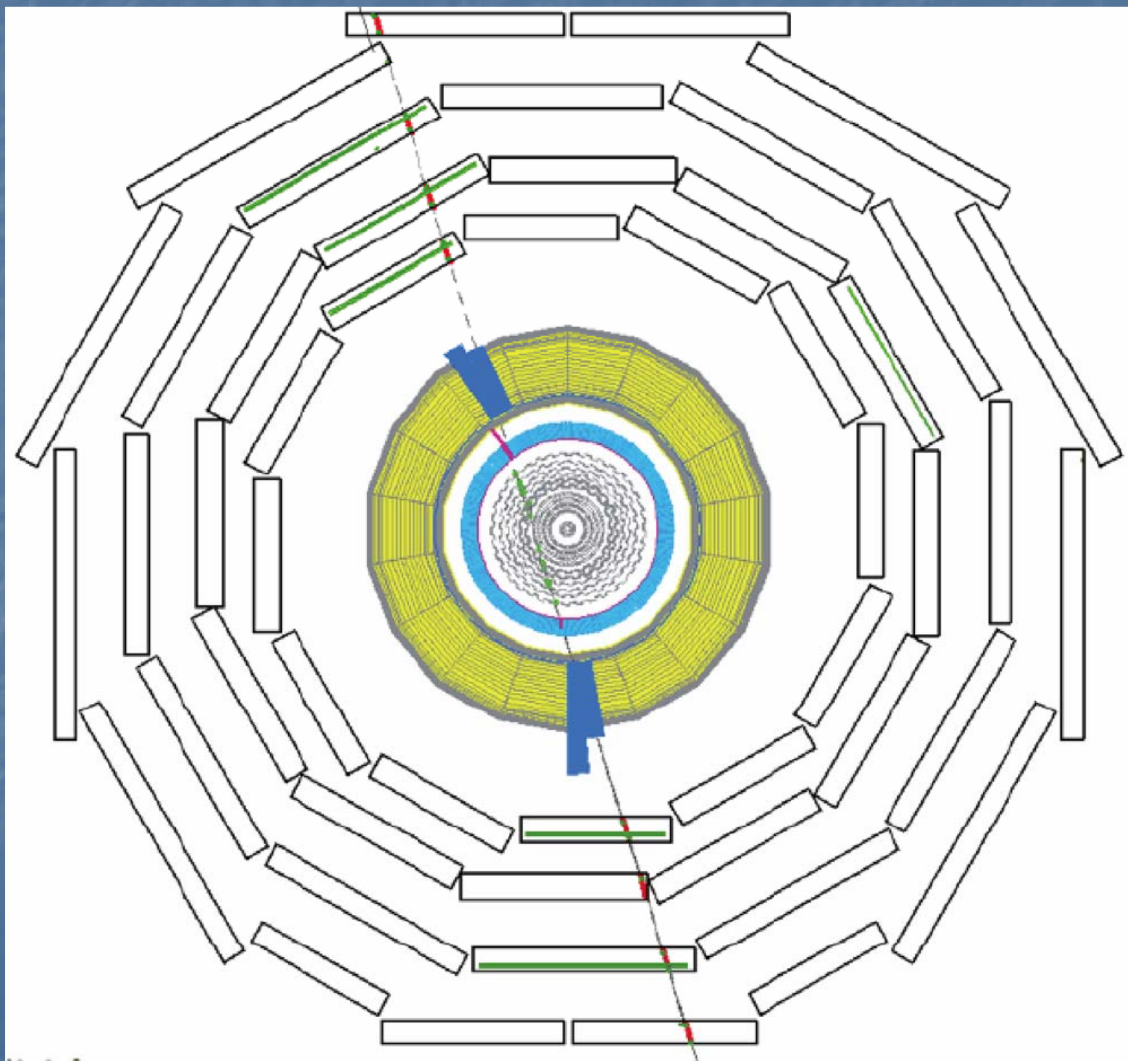
The Top 10

Current Schedule

- After extensive repairs the machine is scheduled to come on line this Fall
- Energy of 10 TeV (design is 14)
- Low intensity to commission
- First results in 2010

In the meantime the experiments are getting ready for data.
Using cosmic rays to debug detector, align components, etc



Conclusions

- The LHC era is (finally) about to begin
- We are looking forward to finding out what nature has in store for us

The End

Interim Summary Report on the analysis of the 19th September 2008 incident at the LHC

Incident during powering

The magnet circuits in the seven other sectors of the LHC had been fully commissioned to their nominal currents (corresponding to beam energy of 5.5 TeV) before the first beam injection on 10 September 2008. For the main dipole circuit, this meant a powering in stages up to a current of 9.3 kA. The dipole circuit of sector 3-4, the last one to be commissioned, had only been powered to 7 kA prior to 10 September 2008. After the successful injection and circulation of the first beams at 0.45 TeV, commissioning of this sector up to the 5.5 TeV beam energy level was resumed as planned and according to established procedures.

On 19 September 2008 morning, the current was being ramped up to 9.3 kA in the main dipole circuit at the nominal rate of 10 A/s, when at a value of 8.7 kA, a resistive zone developed in the electrical bus in the region between dipole C24 and quadrupole Q24. The first evidence was the appearance of a voltage of 300 mV detected in the circuit above the noise level: the time was 11:18:36 CEST. No resistive voltage appeared on the dipoles of the circuit, individually equipped with quench detectors with a detection sensitivity of 100 mV each, so that the quench of any magnet can be excluded as initial event. After 0.39 s, the resistive voltage had grown to 1 V and the power converter, unable to maintain the current ramp, tripped off at 0.46 s (slow discharge mode). The current started to decrease in the circuit and at 0.86 s, the energy discharge switch opened, inserting dump resistors in the circuit to produce a fast power abort. In this sequence of events, the quench detection, power converter and energy discharge systems behaved as expected.

Sequence of events and consequences

Within the first second, an electrical arc developed and punctured the helium enclosure, leading to release of helium into the insulation vacuum of the cryostat.

The spring-loaded relief discs on the vacuum enclosure opened when the pressure exceeded atmospheric, thus relieving the helium to the tunnel. They were however unable to contain the pressure rise below the nominal 0.15 MPa absolute in the vacuum enclosures of subsector 23-25, thus resulting in large pressure forces acting on the vacuum barriers separating neighboring subsectors, which most probably damaged them. These forces displaced dipoles in the subsectors affected from their cold internal supports, and knocked the Short Straight Section cryostats housing the quadrupoles and vacuum barriers from their external support jacks at positions Q23, Q27 and Q31, in some locations breaking their anchors in the concrete floor of the tunnel. The displacement of the Short Straight Section cryostats also damaged the “jumper” connections to the cryogenic distribution line, but without rupture of the transverse vacuum barriers equipping these jumper connections, so that the insulation vacuum in the cryogenic line did not degrade.

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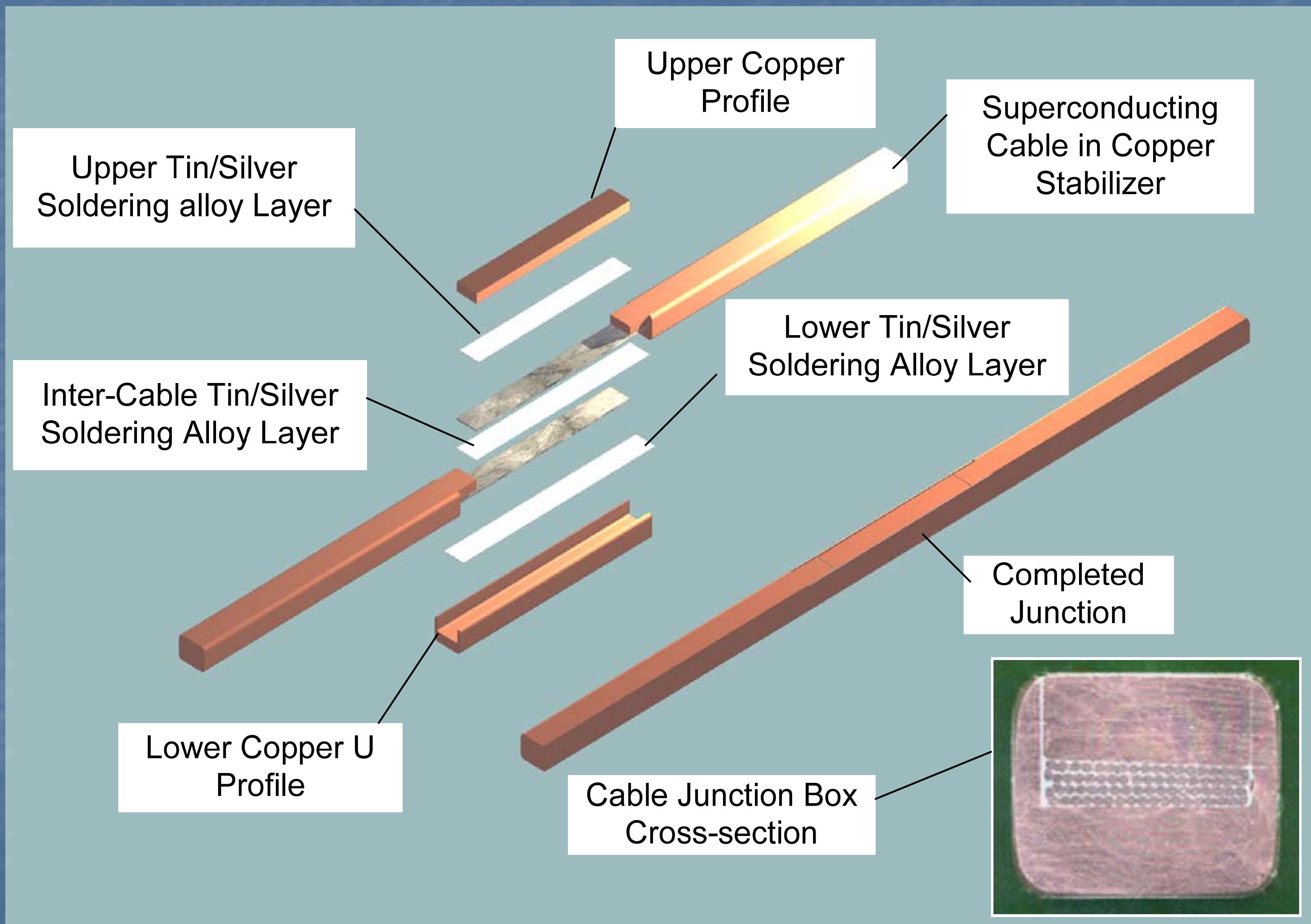
Busbar splice



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