Introduction to Experimental HEP

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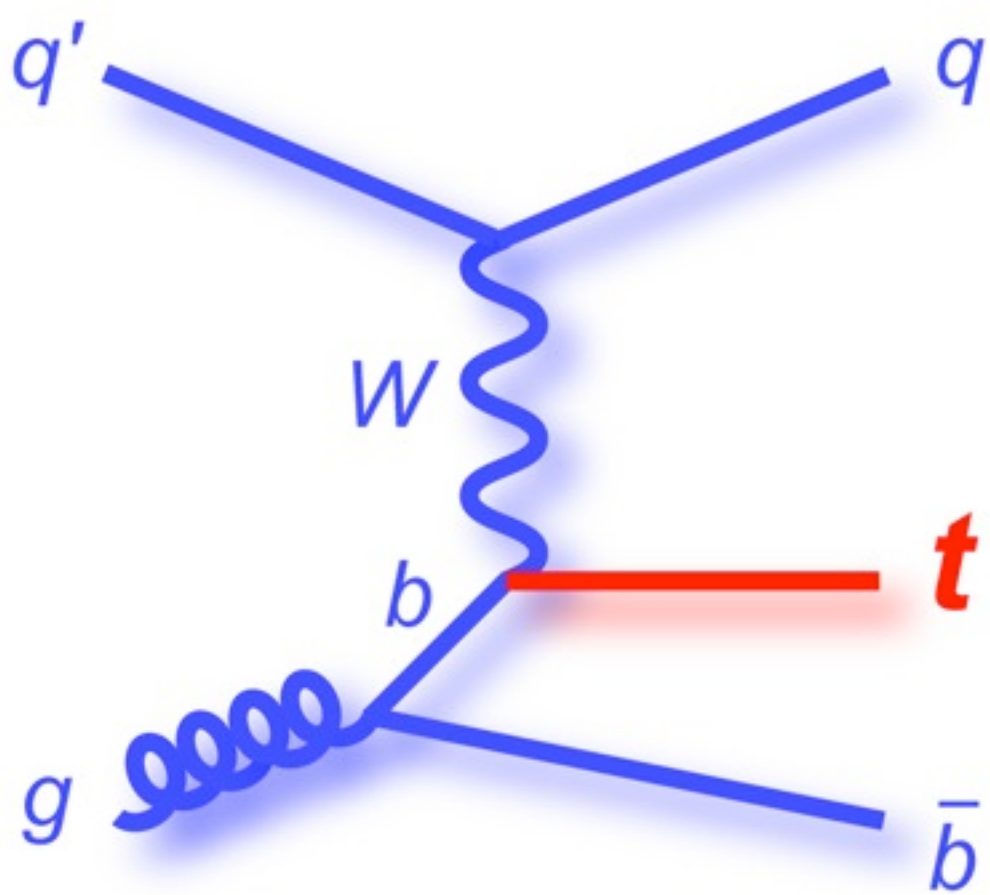
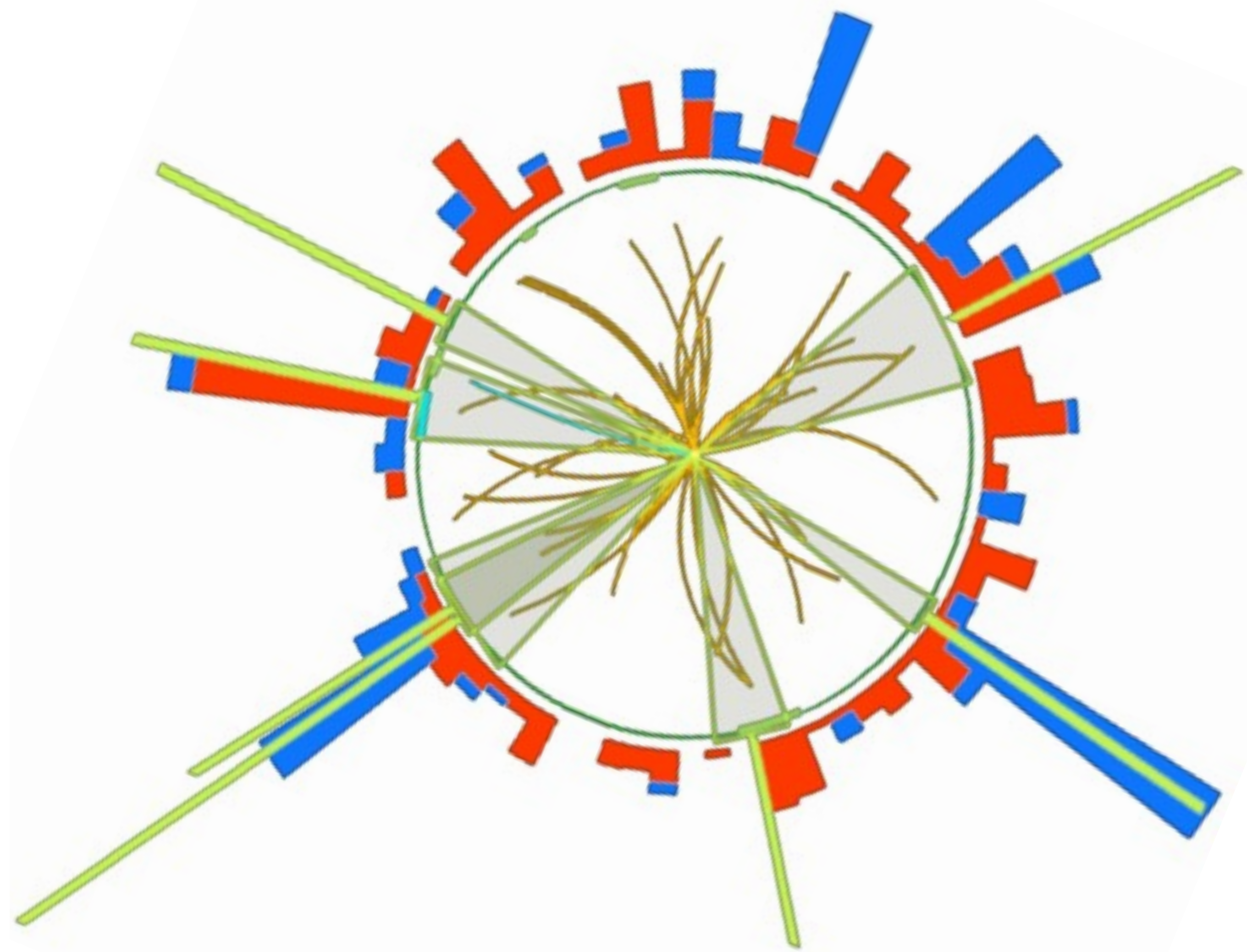




Overview

- Experimental HEP – what we do, and why
- Nuts, bolts, and big toys
- Where we stand today
- LHC programme – first major results
- The far future

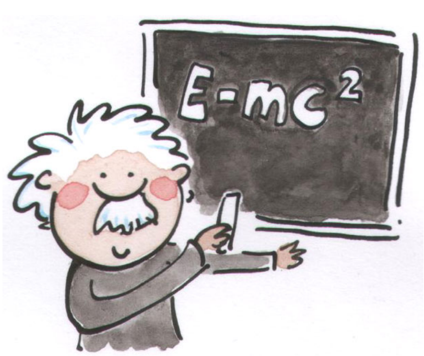
- You will not hear the complete story in two lectures!
- We will focus on energy frontier physics at colliders
  - Absolutely not the only game in town
  - Perhaps not even the most interesting one

- Please ask questions!

Theory and Experiment

- HEP theorists:
  - Think about Lagrangians
  - Particles = "field quanta"
  - (Can) work in small teams
  - Can rapidly play with new ideas
  - Admire elegance, simplicity (~ Dirac)
- But also…
  - Must invent new techniques
  - Interact with other fields
  - Get excited about new results

- HEP experimentalists:
  - Think about measurements
  - Particles = "tiny charged blobs"
  - (Must) work in huge teams
  - New ideas take years to test
  - Admire ingenuity, effectiveness (~ Rutherford)
- But also…
  - Must invent new technologies
  - Interact with other fields
  - Get excited about new results

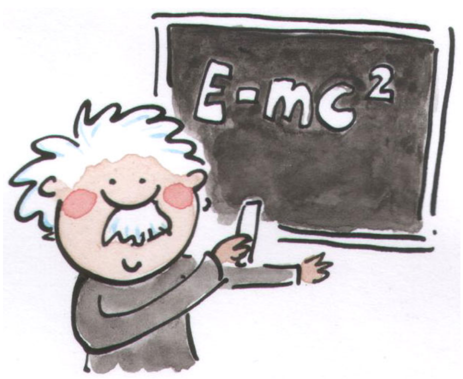


Real progress is only made when we work effectively together

Progress in HEP - The Ideal

Develop theoretical model with testable consequences

Devise experiment or observation to challenge model



Build and perform experiment

Scrap or further develop model

Unexpected results?

Progress in HEP - Reality Today

Ongoing pursuit of interesting / fashionable / promising problems

Form consensus on phenomena that might be observable (today)

Form consensus on next required large facility, carry out R&D

~ 5 - 10 years

Finance (G$), plan facility

~ 5 years

Collaborations propose and design experiments (cash limited)

~ 5 - 10 years

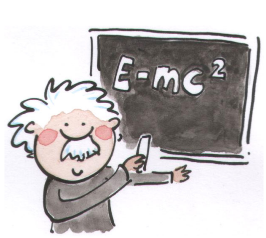
Perform experiments

~ 1 - 10 years

Discoveries / anti-discoveries (perhaps unexpected!)

Precision measurements of parameters

Scrap or further develop models



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Motherhood

- Particle physics is a complicated business
  - In theory and experiment: "All the easy experiments have been done"
  - Nobody understands the whole field or all the techniques
- You will meet 'experimentalists' who:
  - Know rather little about experiments
  - Know rather little about theory
  - All of the above
- Advice to the budding professional physicist:
  - Understand what can be measured, what *can't* be measured - and why
  - Understand where the key sources of uncertainty are
  - Learn the language of the experimentalists and use it
  - Provide the tools to allow your models to be used

- Here endeth the lesson

What Can We Measure?

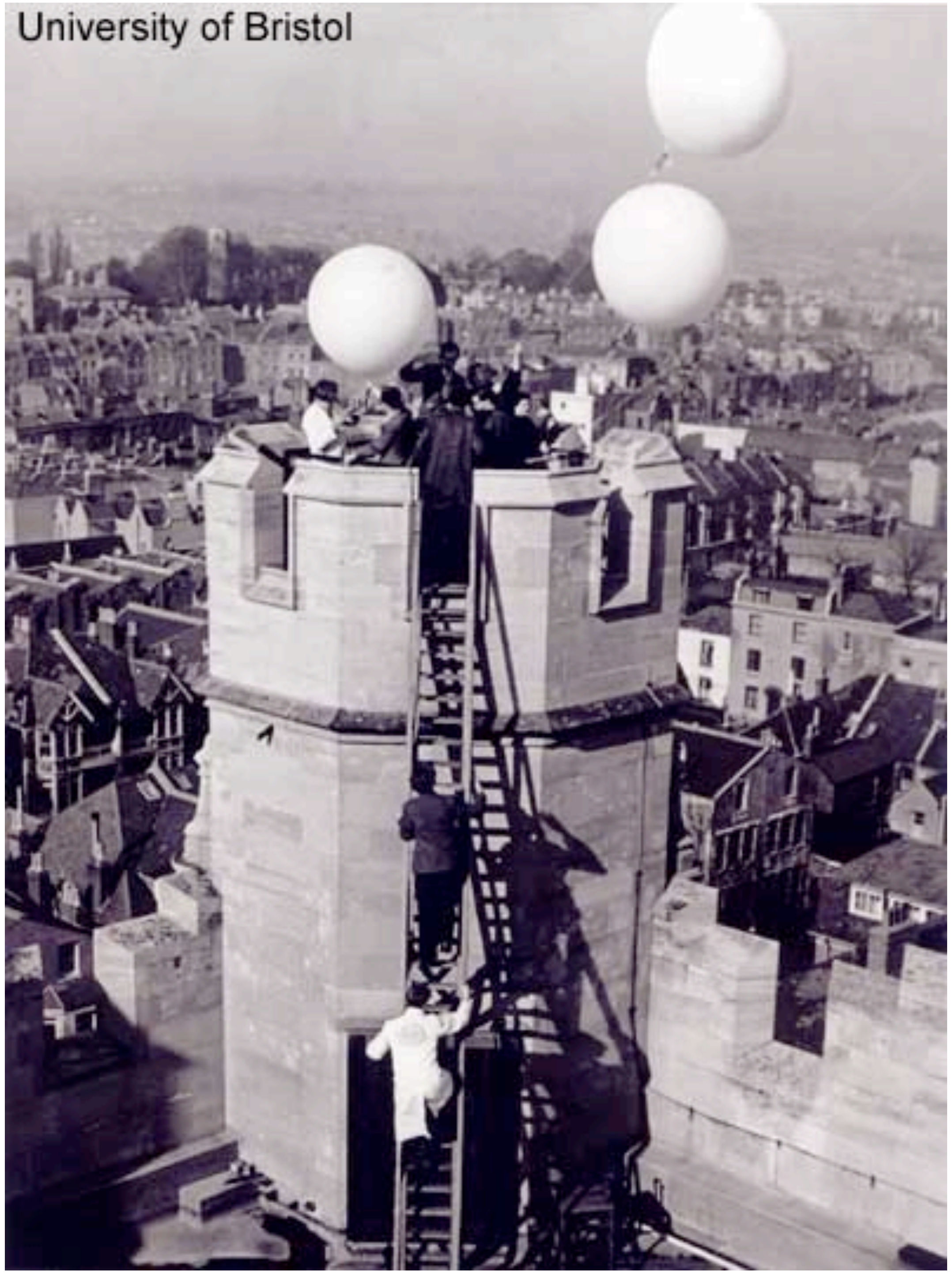
- Most often carry out statistical counting experiments
  - Where possible, prepare known initial state
  - Observe repeated collisions + try to measure the final state
  - Count rates of given final states -> cross sections
  - Examine distributions of parameters & compare with theory
- Static properties of bound states
  - Existence & mass
  - Quantum numbers (charges, J^{CP}) and couplings
  - Width / lifetime, branching ratios, mixing parameters
- Dynamic quantities
  - Cross sections as function of energy, momentum exchange, etc
- Often use ratios and derived quantities to cancel errors
  - Branching ratios, mixing angles, polarisations, decay parameters

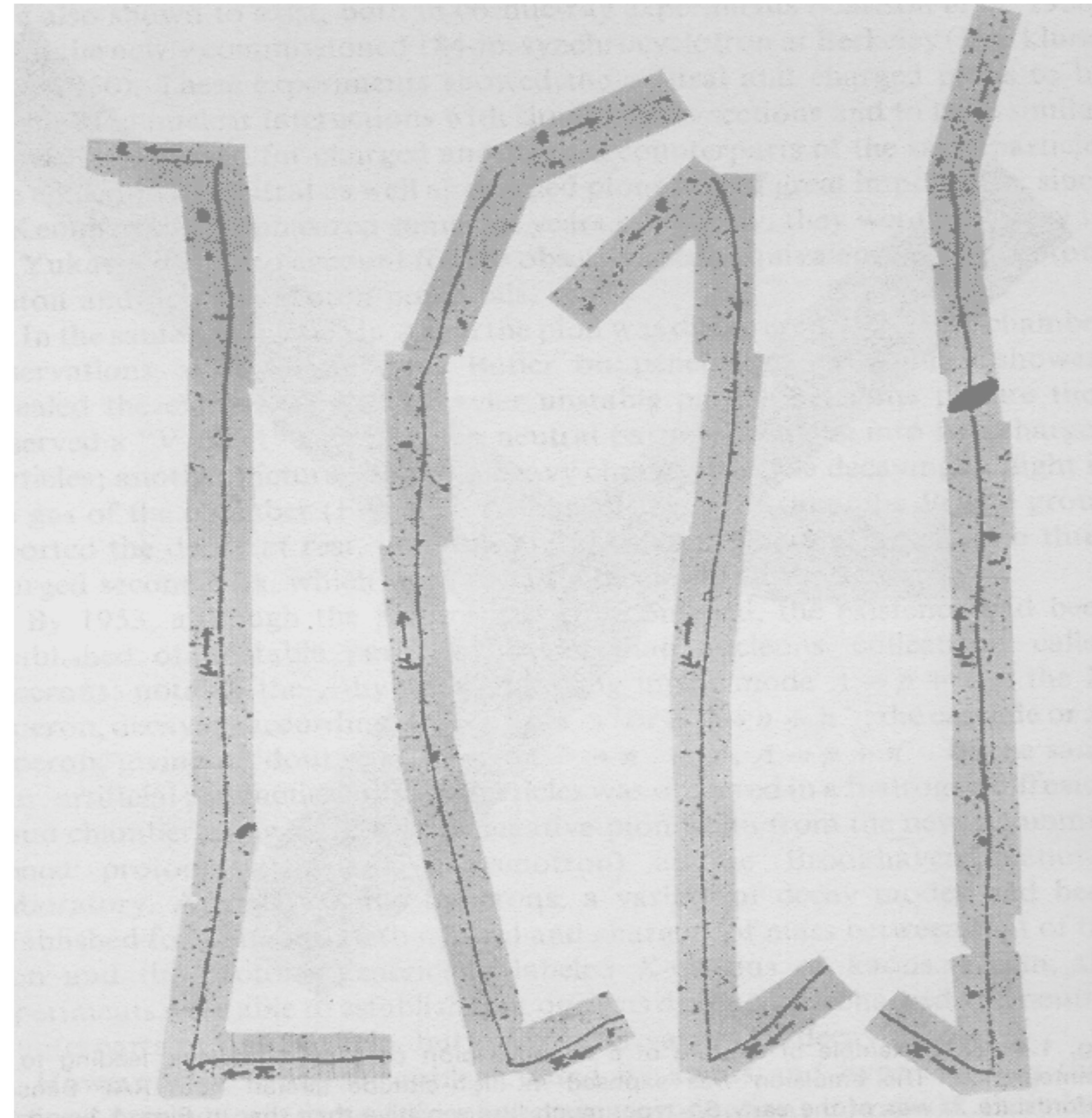
Doing Experiments: Initial State

- Decide on initial state
- Build detector
- Simulate performance
- Record collisions
- Reconstruct the events
- Isolate a signal
- Make measurements
- Compare with theory

- A source of high-energy particles is required
- Choices to make:
  - Identities of colliding particles
  - Energies: monochromatic / spread?
  - Colliding beams / fixed target?
  - Polarisation?
  - Particle flux?
- Realistically...
  - A free choice is not usually possible
  - Most experiments carried out at existing or new accelerator facility
  - Can also carry out 'observational experiments'

Natural Particle Sources

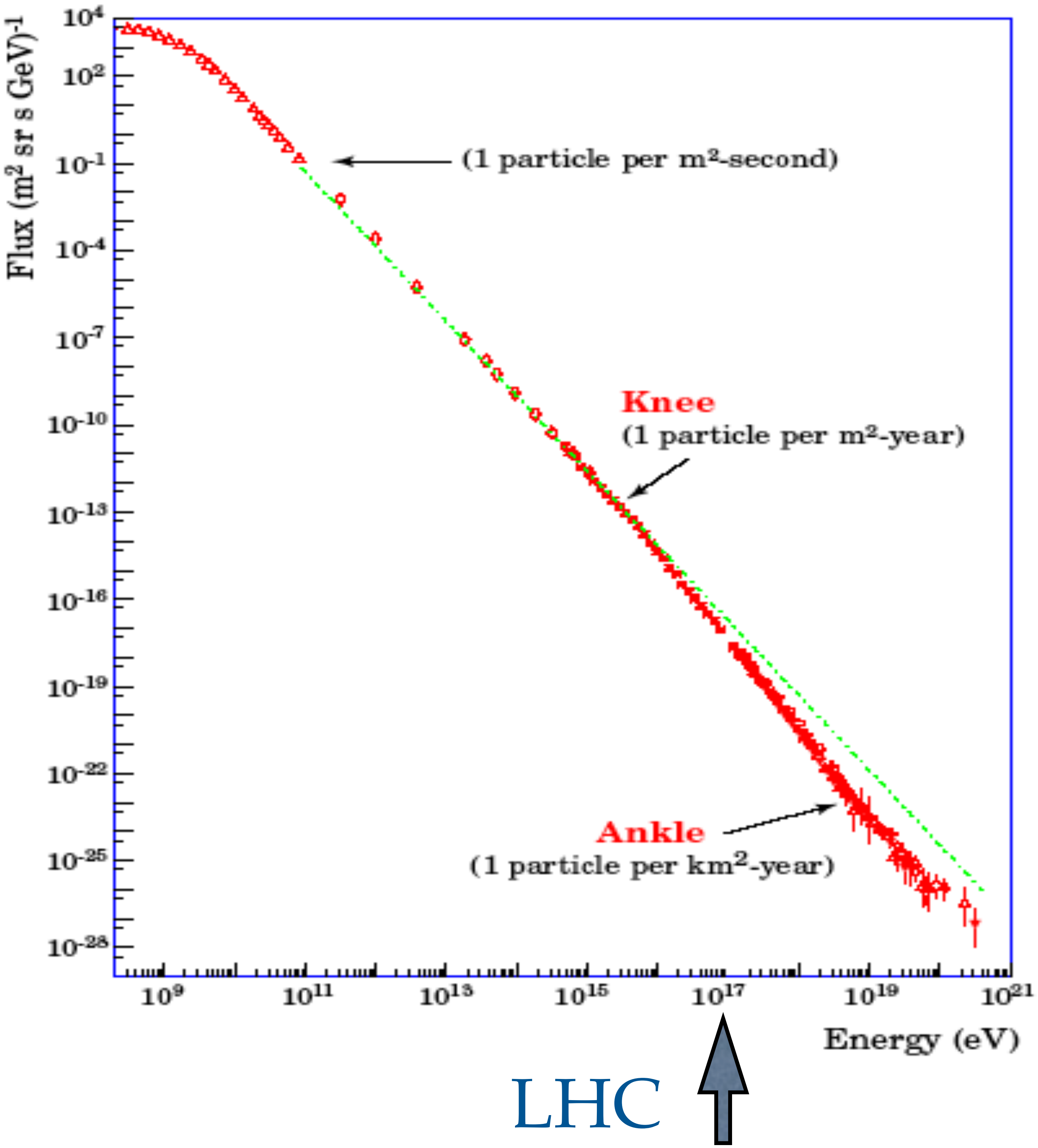




Emulsions containing the first evidence of pion scattering - Powell, Nobel Prize 1950

- Cosmic rays main source of high-energy flux until 1950s

Cosmic Ray Spectrum



- Spectrum extends to (very) high energies
  - Subject of ongoing study
- Flux is low
  - Cannot be used to study rare processes
  - Is an important background for many experiments
- Natural sources also important for:
  - Solar neutrino studies
  - Reactor neutrino studies
  - Direct DM searches – ?

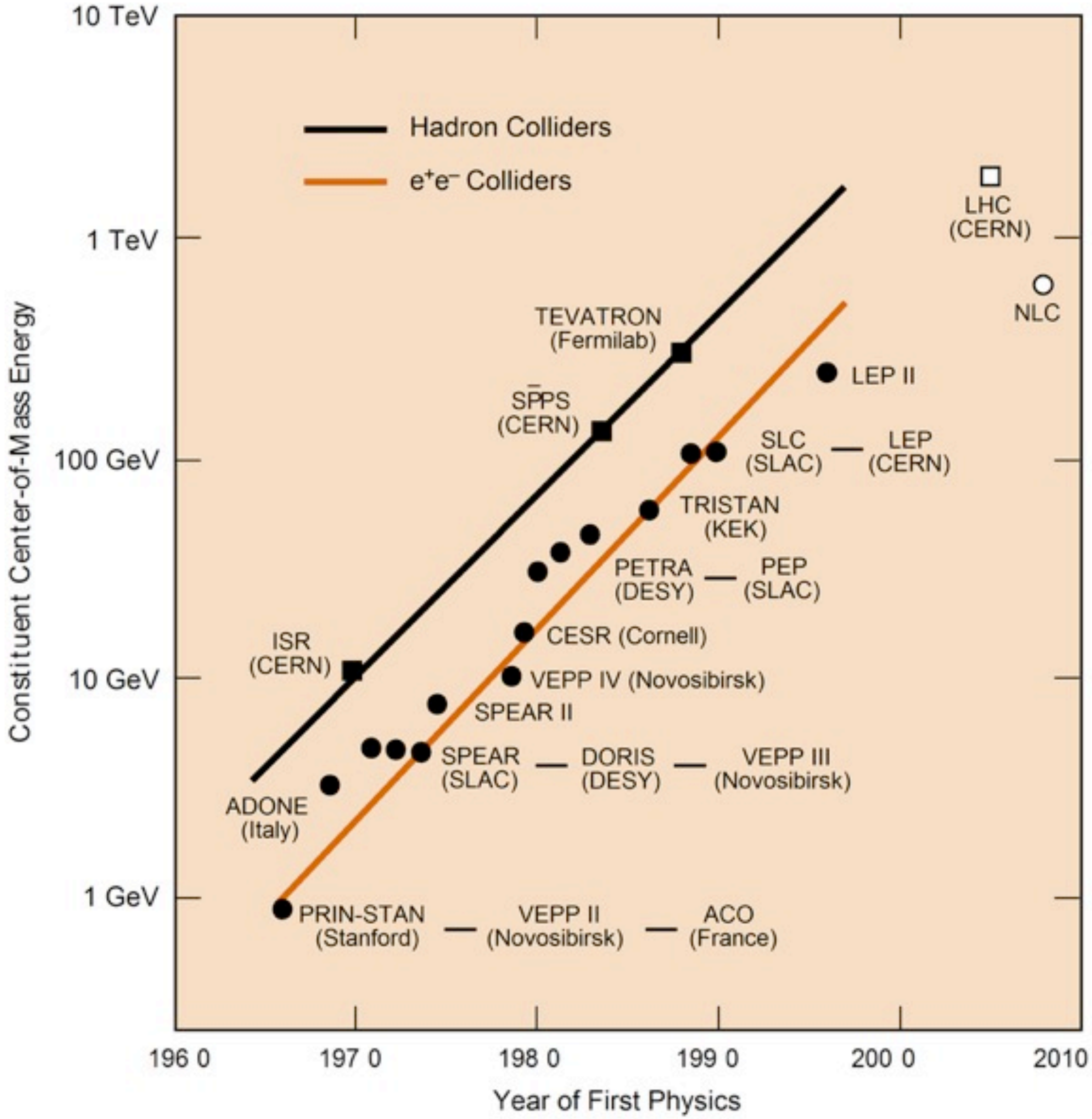
Particle Accelerators

- A ‘reliable’ and intense source of high-energy particles
  - Energies up to 3.5TeV per beam (record holder: LHC)
  - Colliding-beam luminosities up to $2.10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (record holder: KEKB)
- Accelerator modes:
  - Fixed-target: an accelerated beam on a stationary target
    - Very high effective luminosities, usefully boosted collision frame
  - Secondary beams (e.g. neutral and / or unstable beams)
  - Colliding beams, equal energies
    - Maximum centre-of-mass energy obtained
  - Colliding beams, asymmetric energies
- What particles can be used?
  - Today: stable particles only
  - p, pbar, e-, e+, heavy ions (stripped nuclei)
- Accelerator physics is a sizeable discipline in its own right

Accelerators: Operating Principles

- Basic idea:
  - Accelerate charged particles through a potential gradient
  - Use resonant oscillating fields in (superconducting) accelerating cavities
- Circular accelerators
  - Life is easier if we reuse the same gradient repeatedly
  - Synchrotrons use magnetic dipole field to achieve closed orbit (~circle)
  - Synchrotron radiation losses ~ m^{-4} – so no more circular e+e- machines
- Complexities
  - Beams will naturally diverge -> cooling and focusing necessary
  - Accelerators are the largest and most complex machines ever built
  - Practical + safety considerations -> often underground -> $$$
- Basic figures of merit for accelerators
  - Collision energy, luminosity
  - *Integrated luminosities* often quoted (e.g. 1/pb or 1/fb)

Progress in Accelerators



See PDG review for parameters of current machines:
http://pdg.lbl.gov/2010/reviews/rpp2010-rev-hep-collider-params.pdf

LEP / LHC @ CERN

e+e- collider, 89-00; LEP-1 ‘Z-factory’: M_Z, 600/pb , LEP-2: 200GeV, 2800/pb

LHC: pp collider, 7TeV -> 14TeV (2013 –), 3000/fb by 2030 [more later on LHC]

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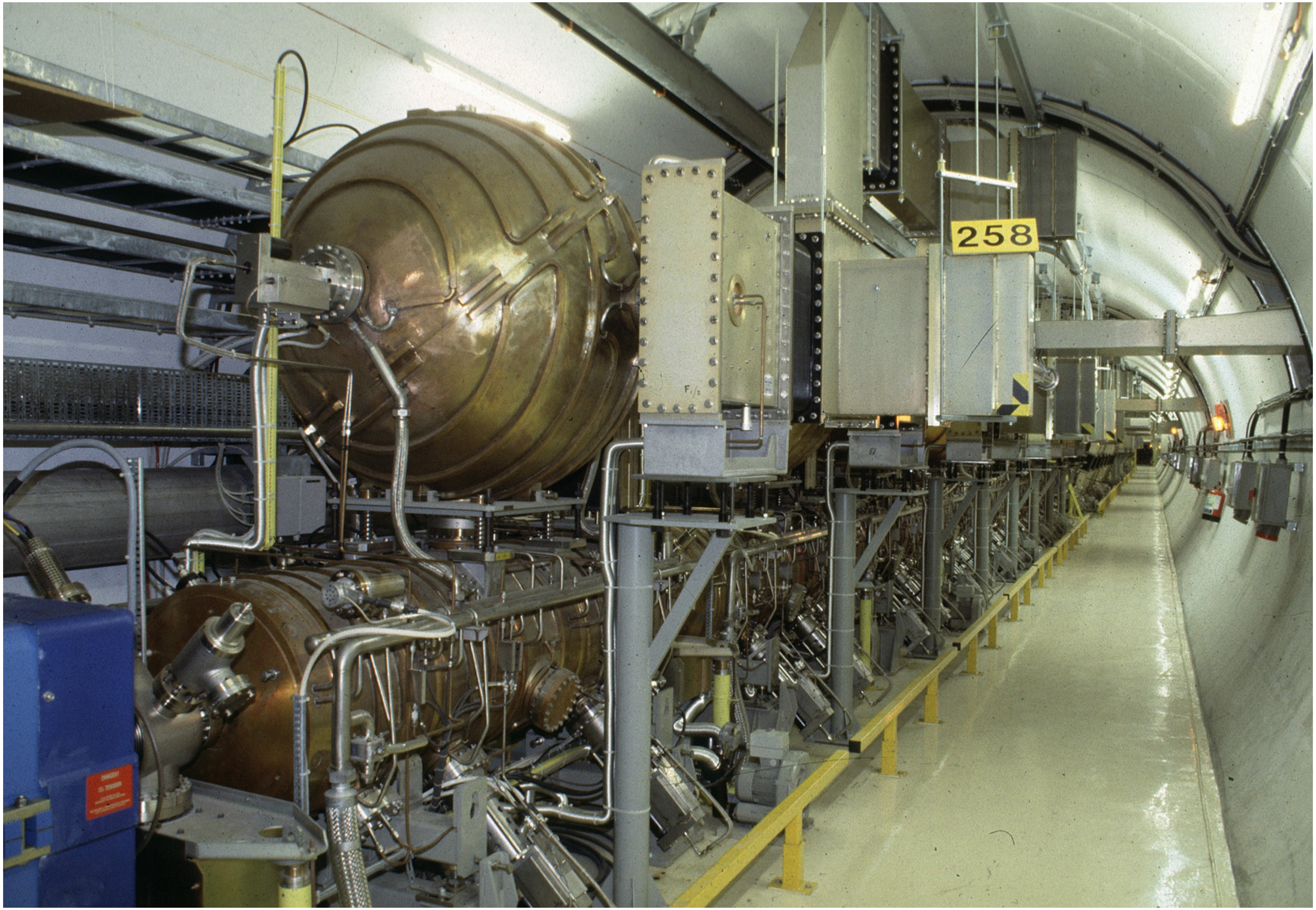
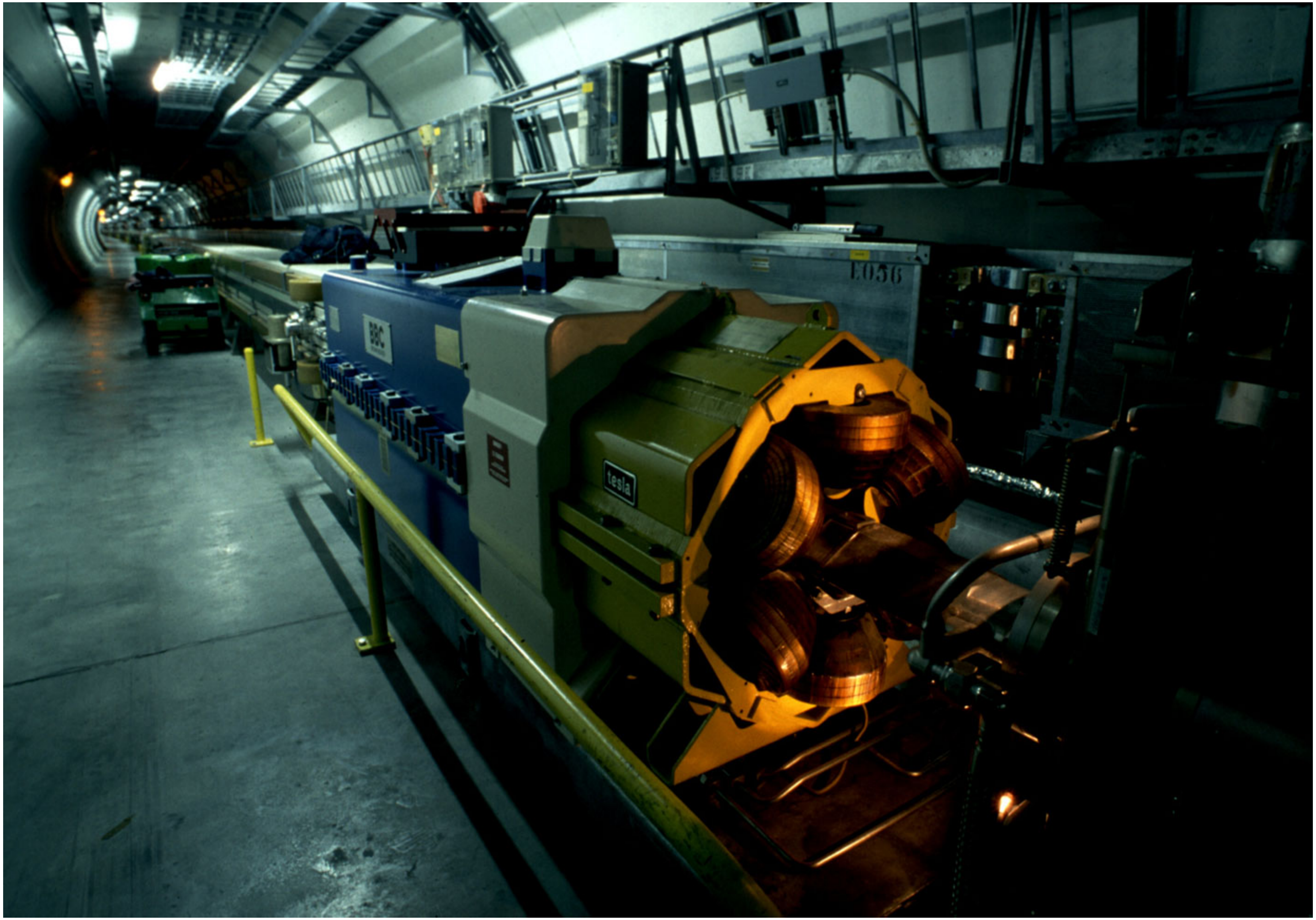
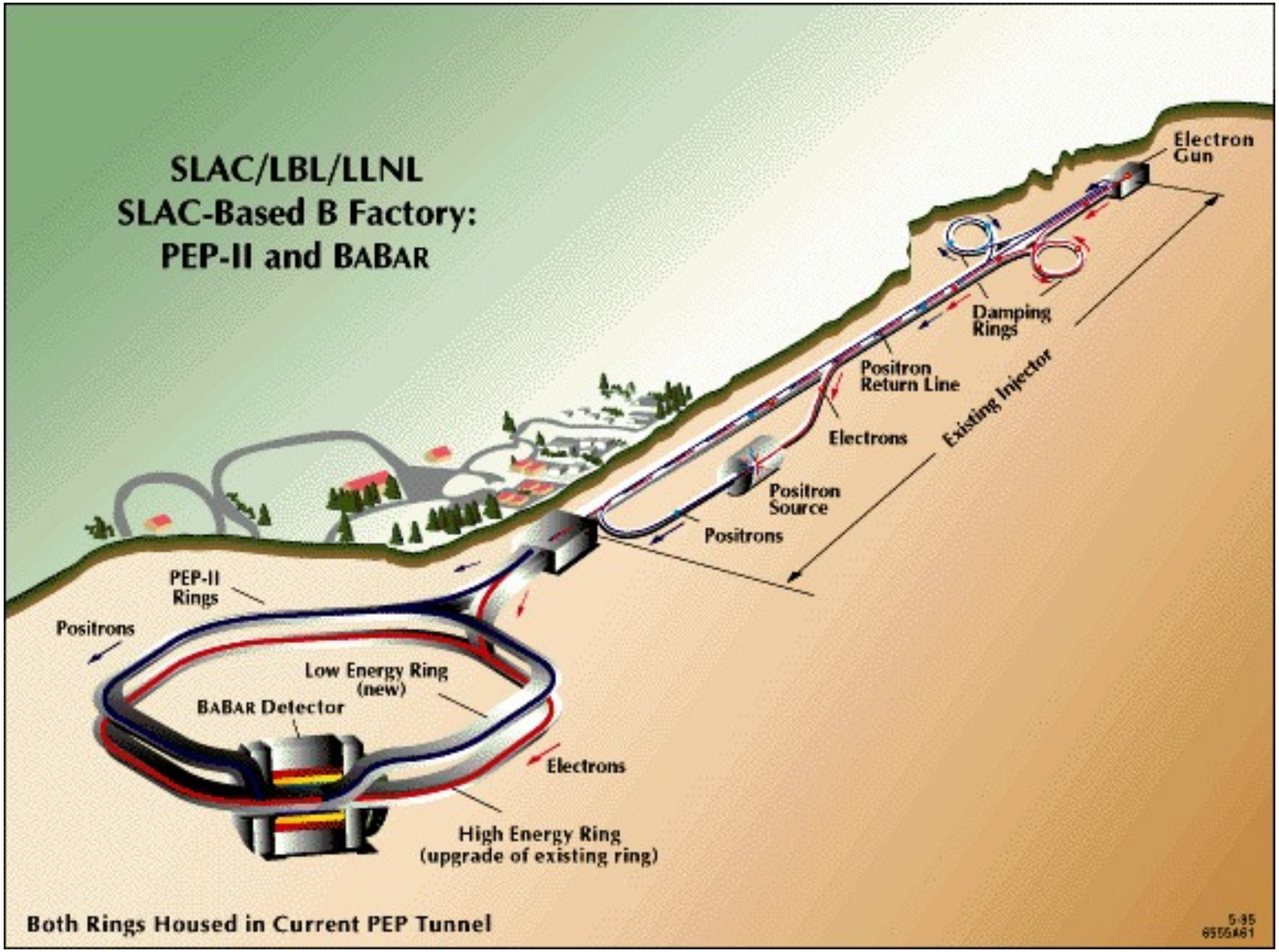
Inside LEP - Cavities



Inside LEP - Magnets



PEP-II @ SLAC



PEP-II: asymmetric e+e- b-factory (U_{4S} resonance), 240/fb. Used SLC infrastucture.

HERA @ DESY

HERA: asymmetric ep collider (unique), 800GeV p on 30GeV e+ (or e-).

Tevatron @ FNAL

Tevatron: p pbar collider, 1TeV, 240/pb (Run I), 2Tev, 7/fb (Run II, ongoing)

Doing Experiments: Detector

Decide on initial state

↓

Build detector

↓

Simulate performance

↓

Record collisions

↓

Reconstruct the events

↓

Isolate a signal

↓

Make measurements

↓

Compare with theory

- Experiment design / optimisation/ construction
  - Needs predictions (MC) of physics signatures & detector performance
- Which experiment to build?
  - General purpose detectors are flexible, but expensive
  - Specialised detectors are optimised for one set of channels / studies
  - (almost) always have more than one detector studying the same physics
- Cost, complexity, timescales
  - All now very large. LHC GPDS:
    - ~0.5GCHF, 80M channels, 20 years
  - New technologies in continuous devt.

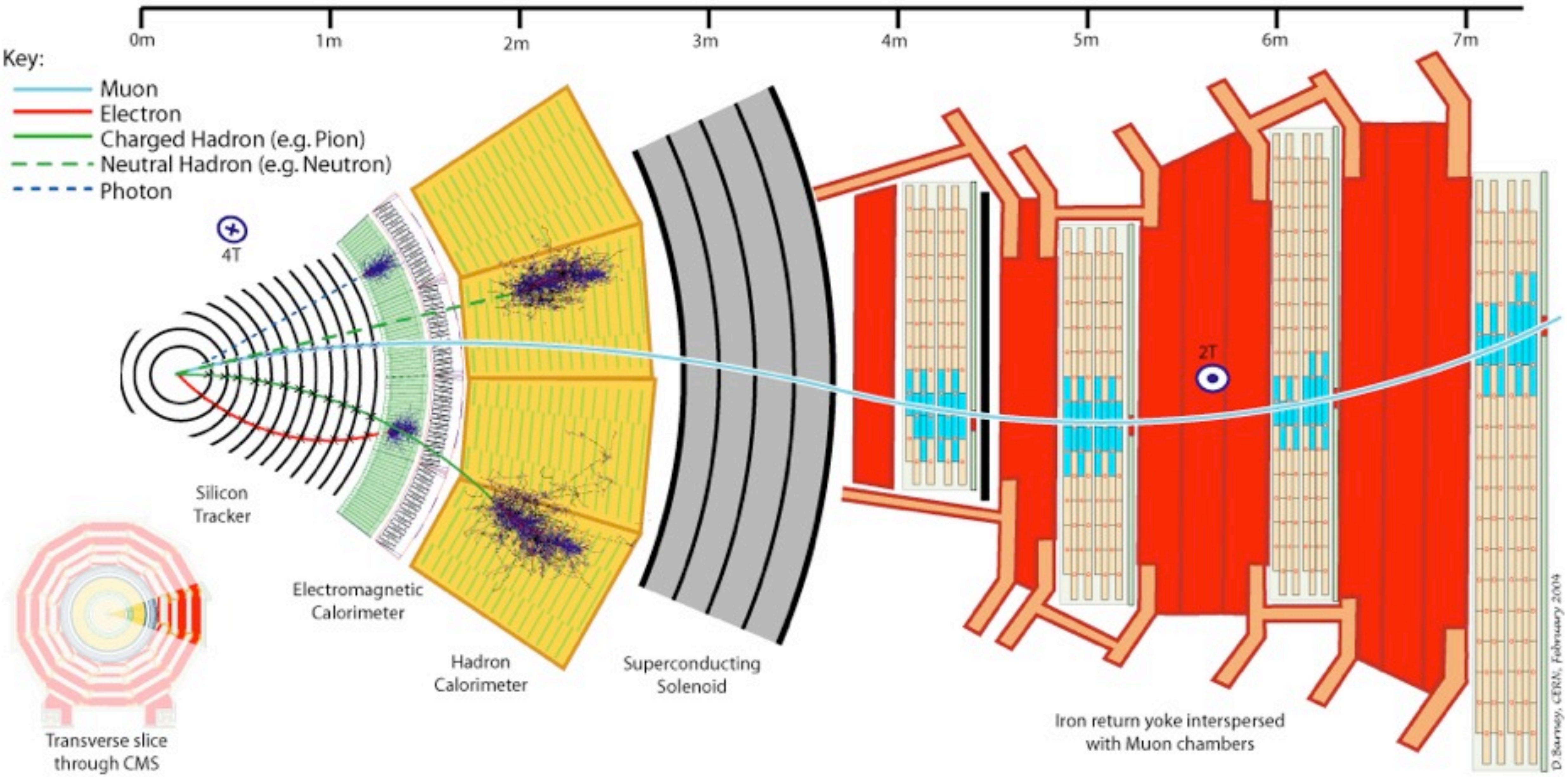
Basics of Particle Detection

- Charged particles
  - Ionization – basis of most techniques (gaseous, solid state detectors)
    - Liberated charge is amplified in a potential gradient and detected
    - Photographic emulsions still used…
  - Scintillation: excitation of a molecule or crystal lattice causes light emission
  - EM effects: Cherenkov / transition radiation
    - Interaction of particle with dielectric medium causes light emission
    - Uniquely, can be directly sensitive to particle *velocity*
- Neutral particles
  - Much more difficult - can detect only after interaction in material
  - Weakly interacting neutrals can be inferred by their absence…
- Radiochemical effects
  - Used (e.g.) for measurement of neutrino, WIMP fluxes
- Many other techniques exist, esp. in low background expts
  - e.g. bolometric measurements, superconducting detectors

Detector Subsystems

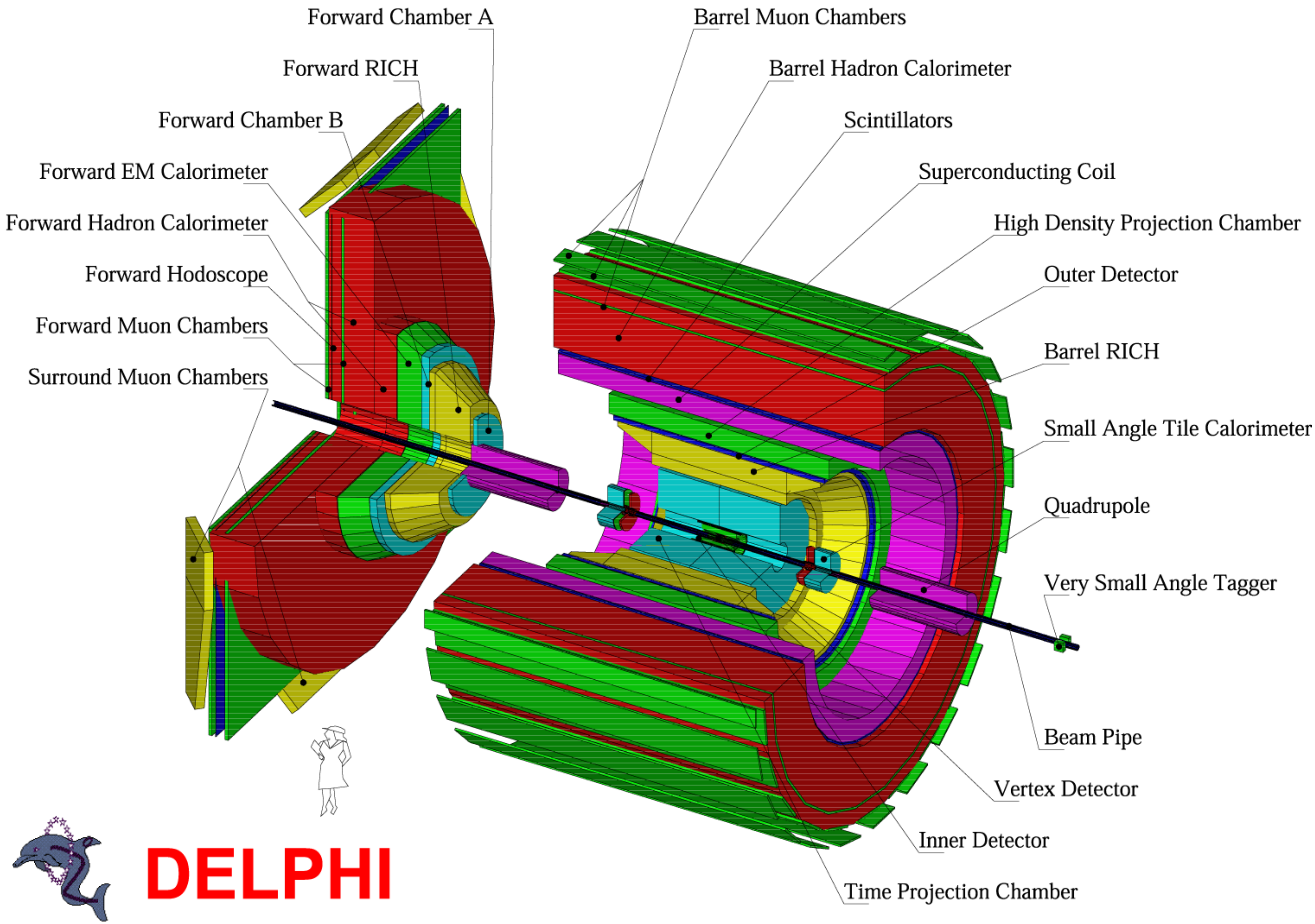
- Tracking system:
  - Measure trajectories of charged particles in a ~uniform magnetic field
  - Curvature measurement -> particle momentum
  - Position measurement -> vertex reconstruction
  - NB: Experimental magnets are large, expensive and dangerous
    - e.g CMS 4T solenoid, diameter 6m, temperature 5K, current 18kA, stored energy 2.3GJ
- Calorimeters
  - Heavy material causes particles to deposit entire energy in a small volume
  - Ionisation or light output proportional to total energy
  - Works for charged or neutral particles (incl. photons)
- Particle ID
  - Cherenkov / transition radiaton / time-of-flight detectors
  - Sensitive to velocity, and therefore mass (combine with momentum)
- Modern detectors use most or all of these techniques

Putting It All Together



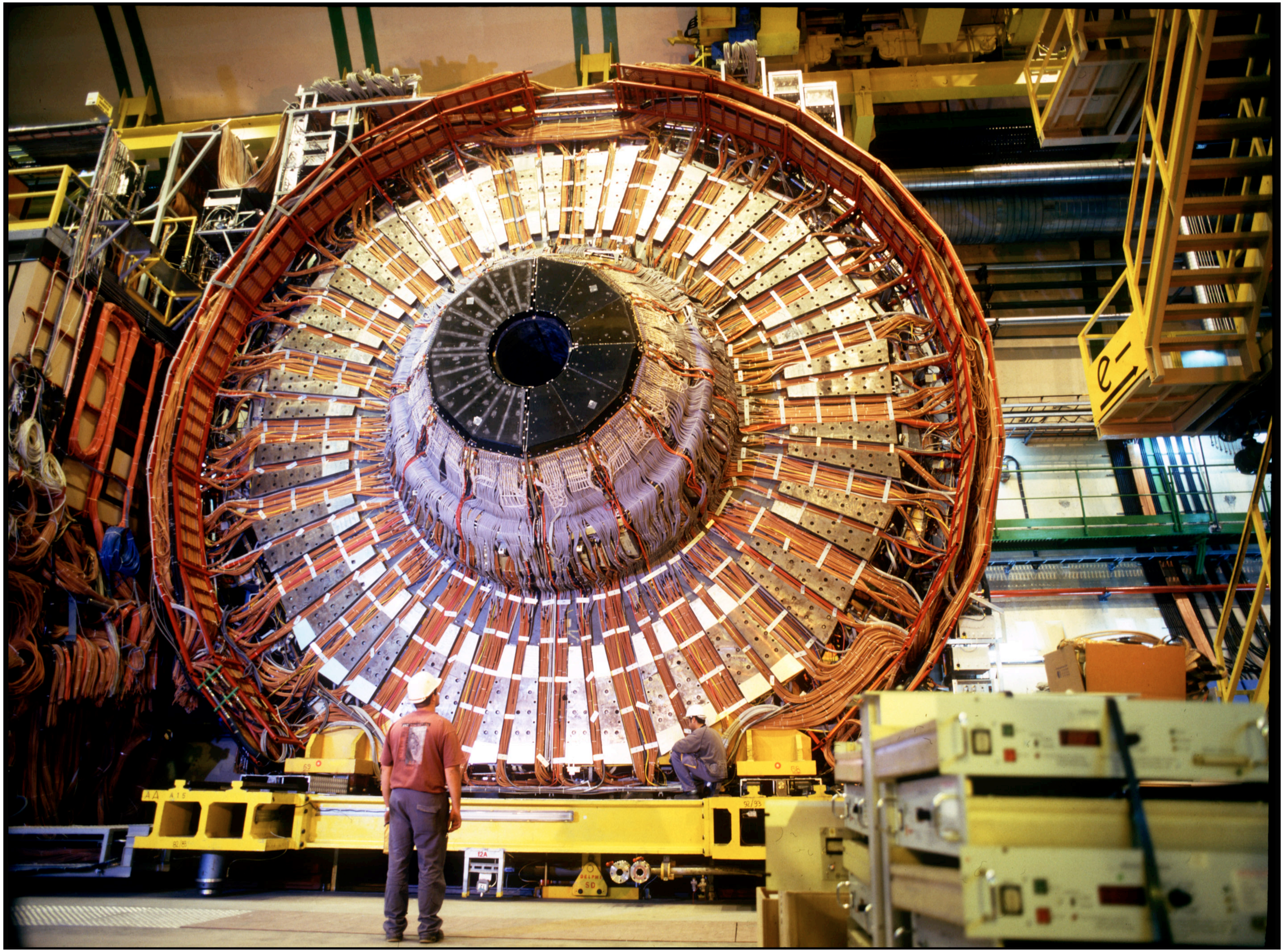
- CMS detector (GPD) layout (NB: no PID in CMS)
- Detector overall size scales with secondary particle energy

DELPHI (LEP)

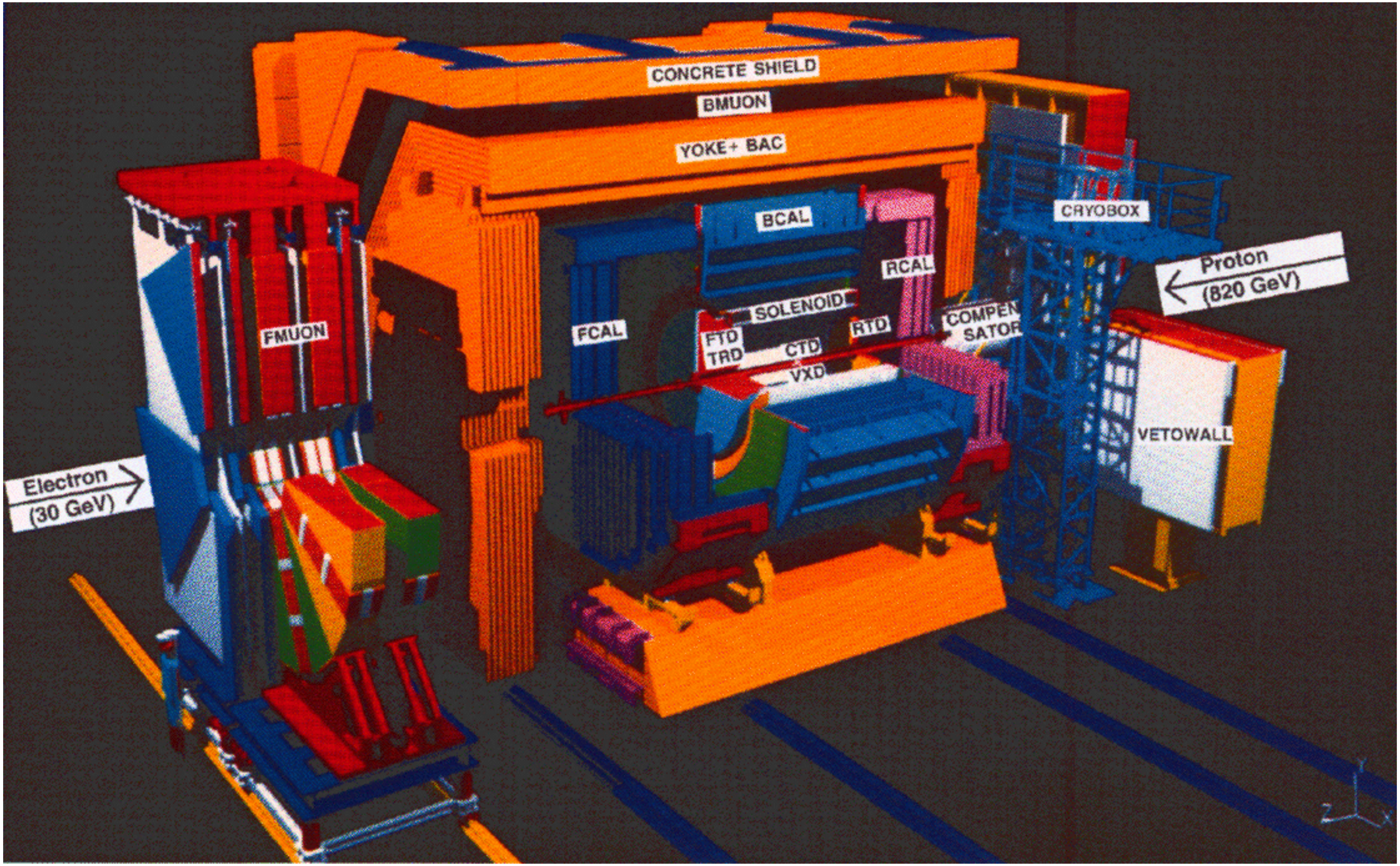


Forward Chamber A
Forward RICH
Forward Chamber B
Forward EM Calorimeter
Forward Hadron Calorimeter
Forward Hodoscope
Forward Muon Chambers
Surround Muon Chambers
Barrel Muon Chambers
Barrel Hadron Calorimeter
Scintillators
Superconducting Coil
High Density Projection Chamber
Outer Detector
Barrel RICH
Small Angle Tile Calorimeter
Quadrupole
Very Small Angle Tagger
Beam Pipe
Vertex Detector
Inner Detector
Time Projection Chamber
DELPHI

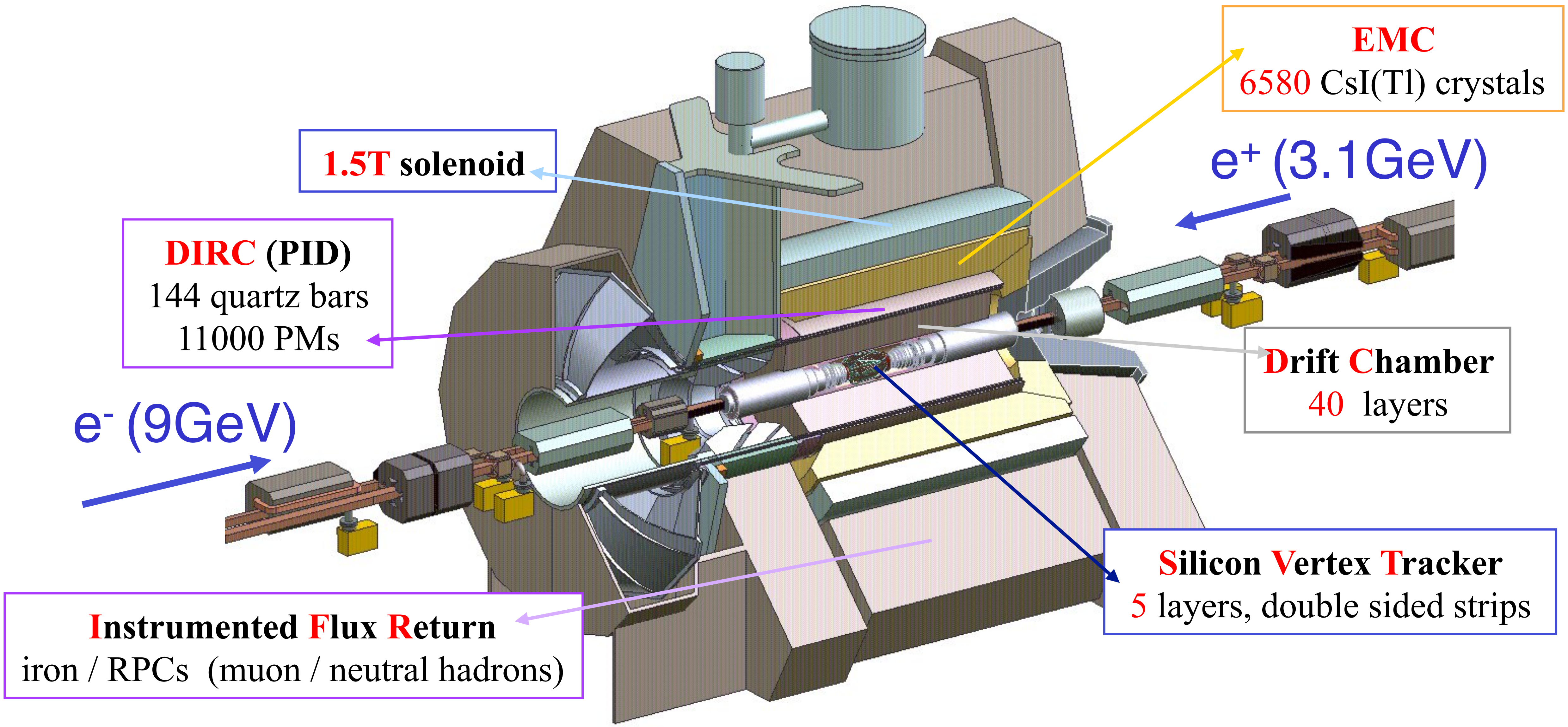
DELPHI (LEP)



ZEUS (HERA)

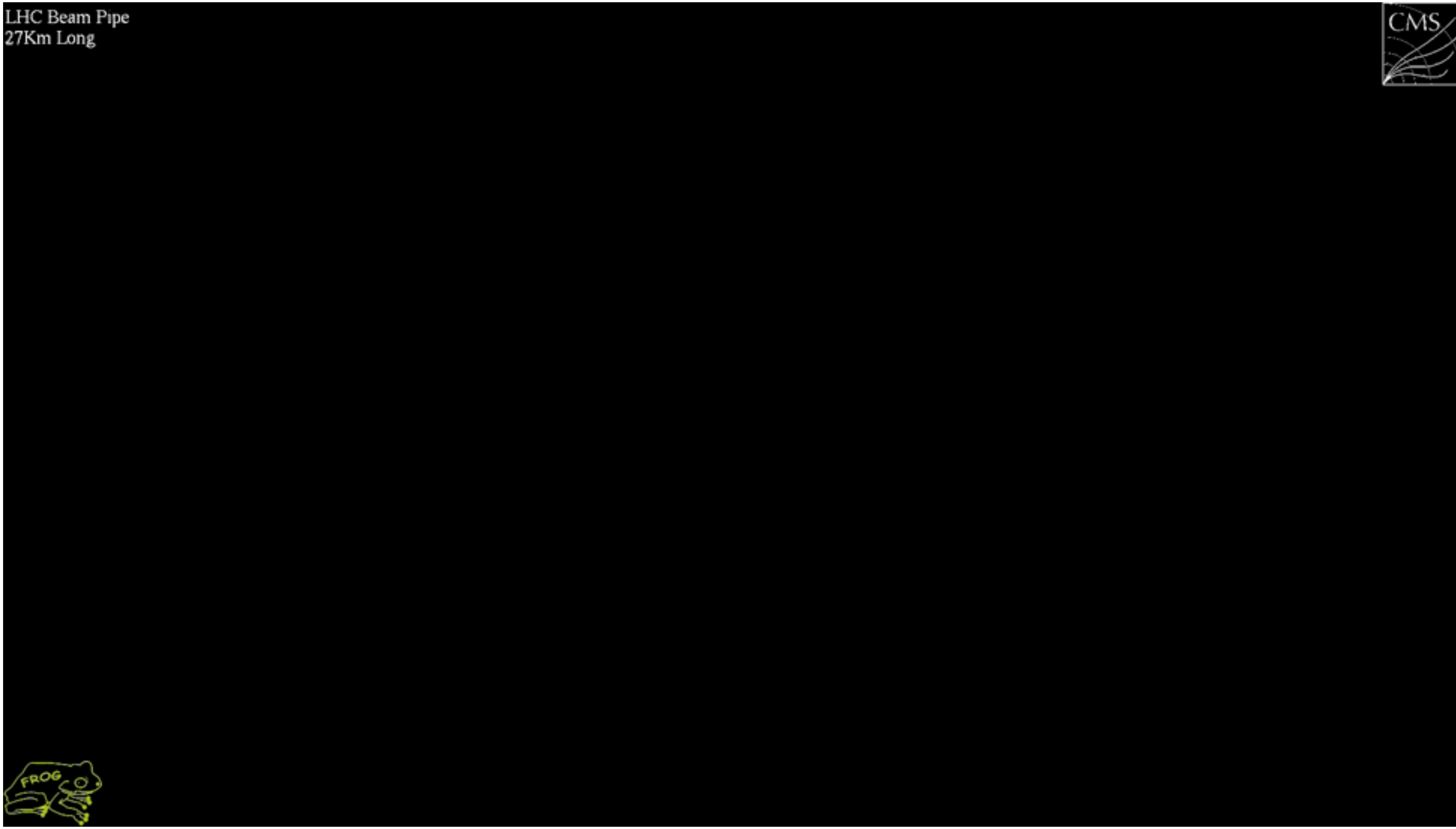

CONCRETE SHIELD
BMUON
YOKE+ BAC
BCAL
RCAL
SOLENOID
FMUON
FCAL
FTD
TRD
CTD
RTD
VXD
COMPEN
SATOR
CRYOBOX
Proton
(820 GeV)
VETOWALL
Electron
(30 GeV)

BaBar (PEP-II)

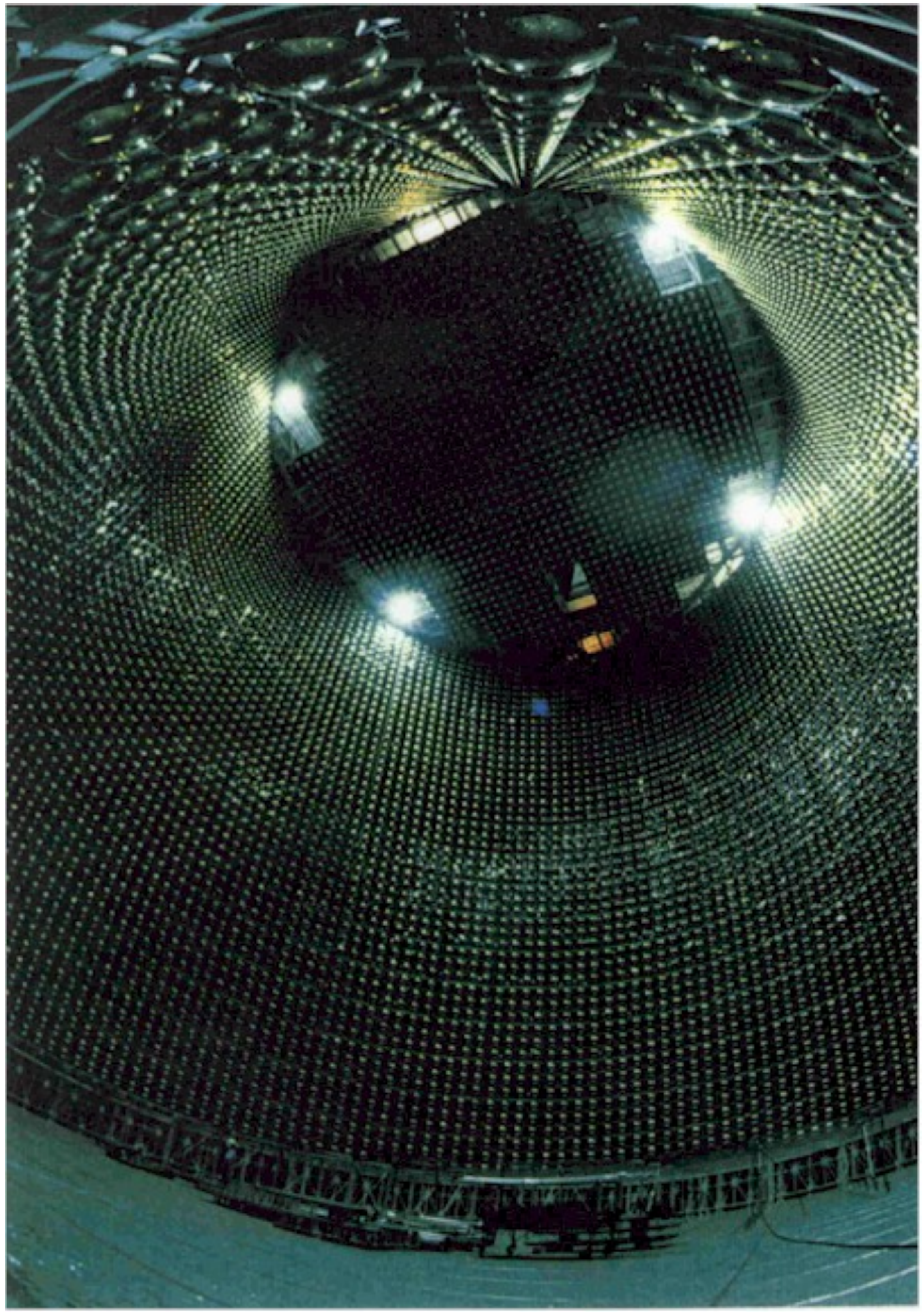


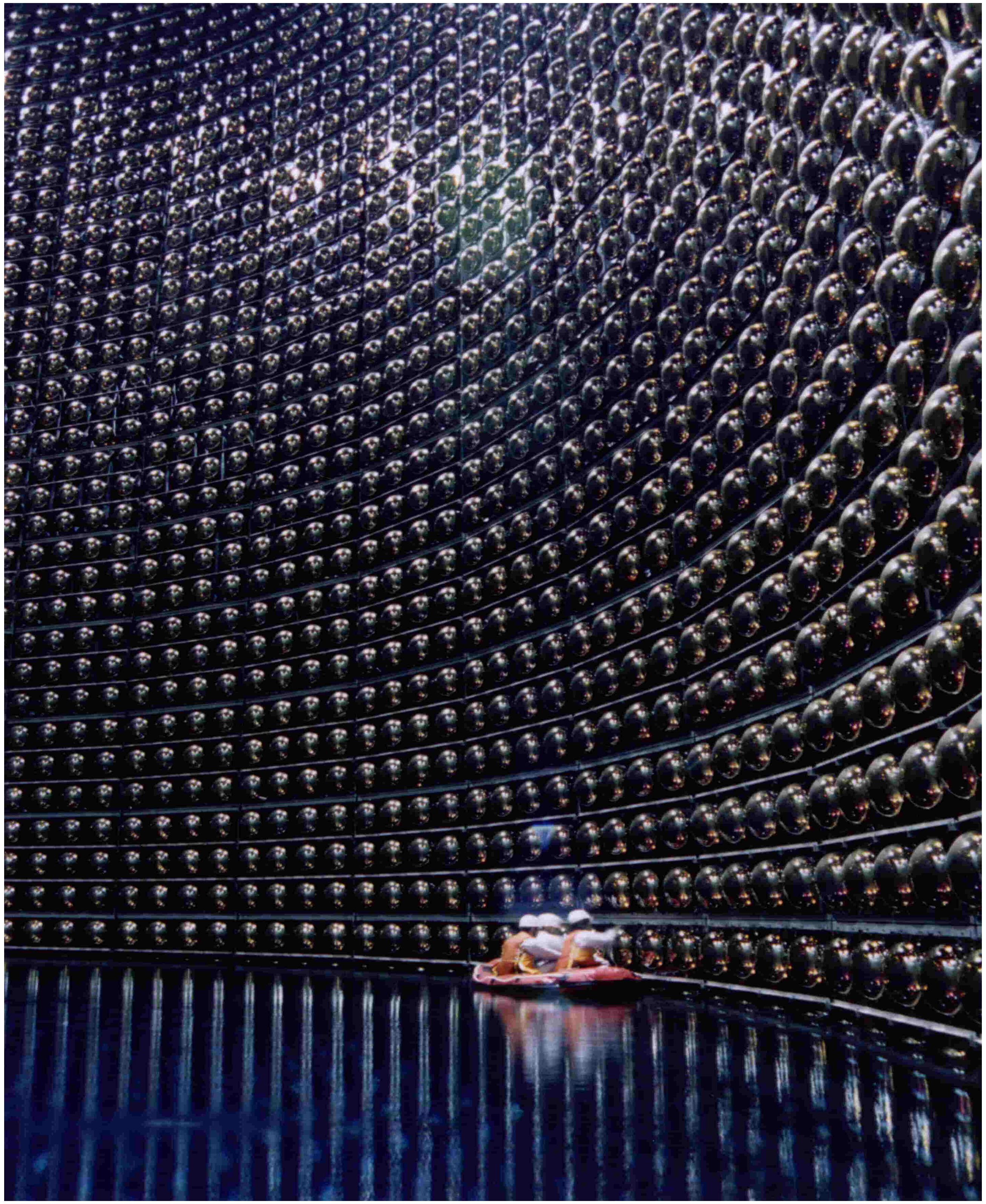
EMC
6580 CsI(Tl) crystals
1.5T solenoid
e+ (3.1GeV)
DIRC (PID)
144 quartz bars
11000 PMs
Drift Chamber
40 layers
e- (9GeV)
Silicon Vertex Tracker
5 layers, double sided strips
Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)

In Action

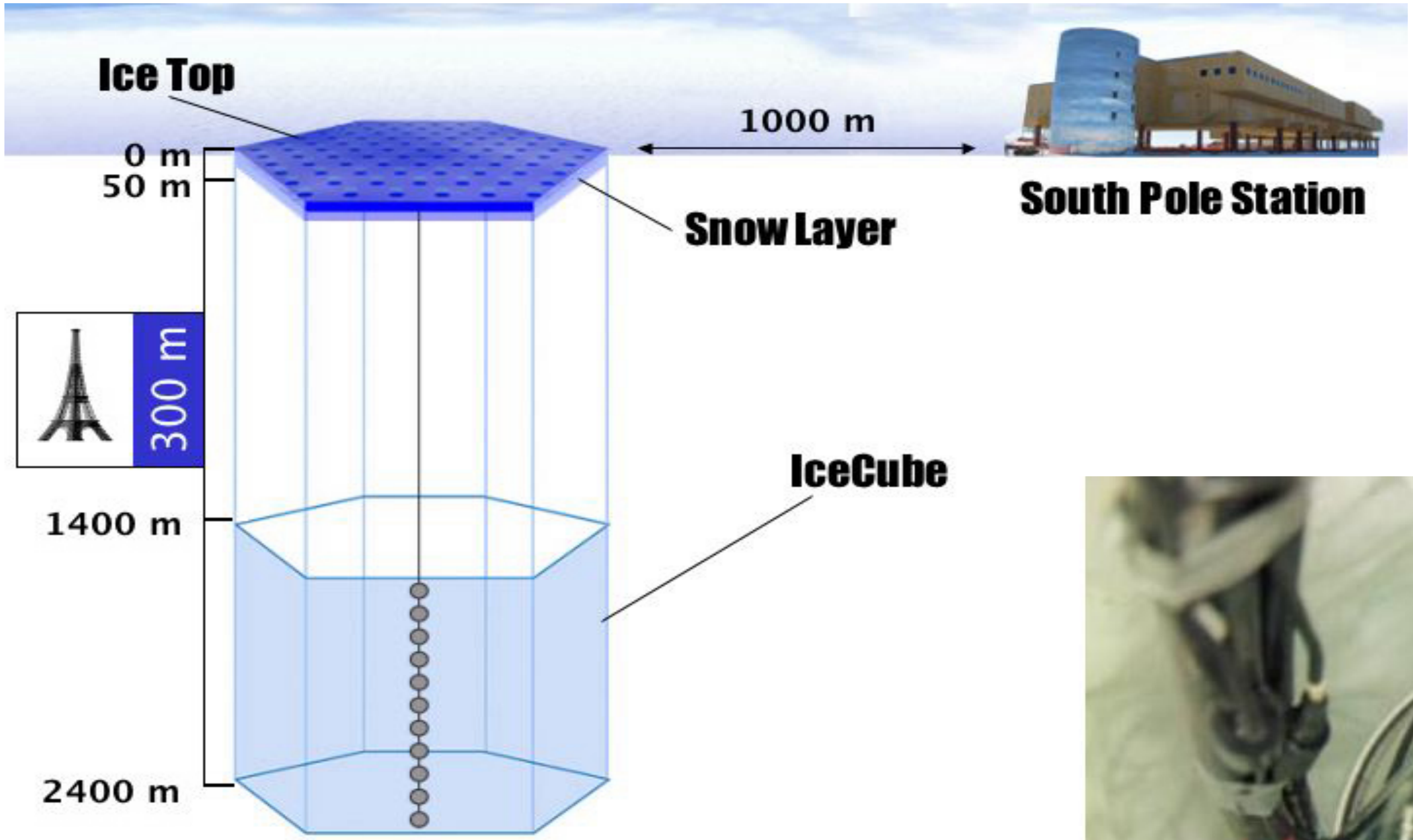


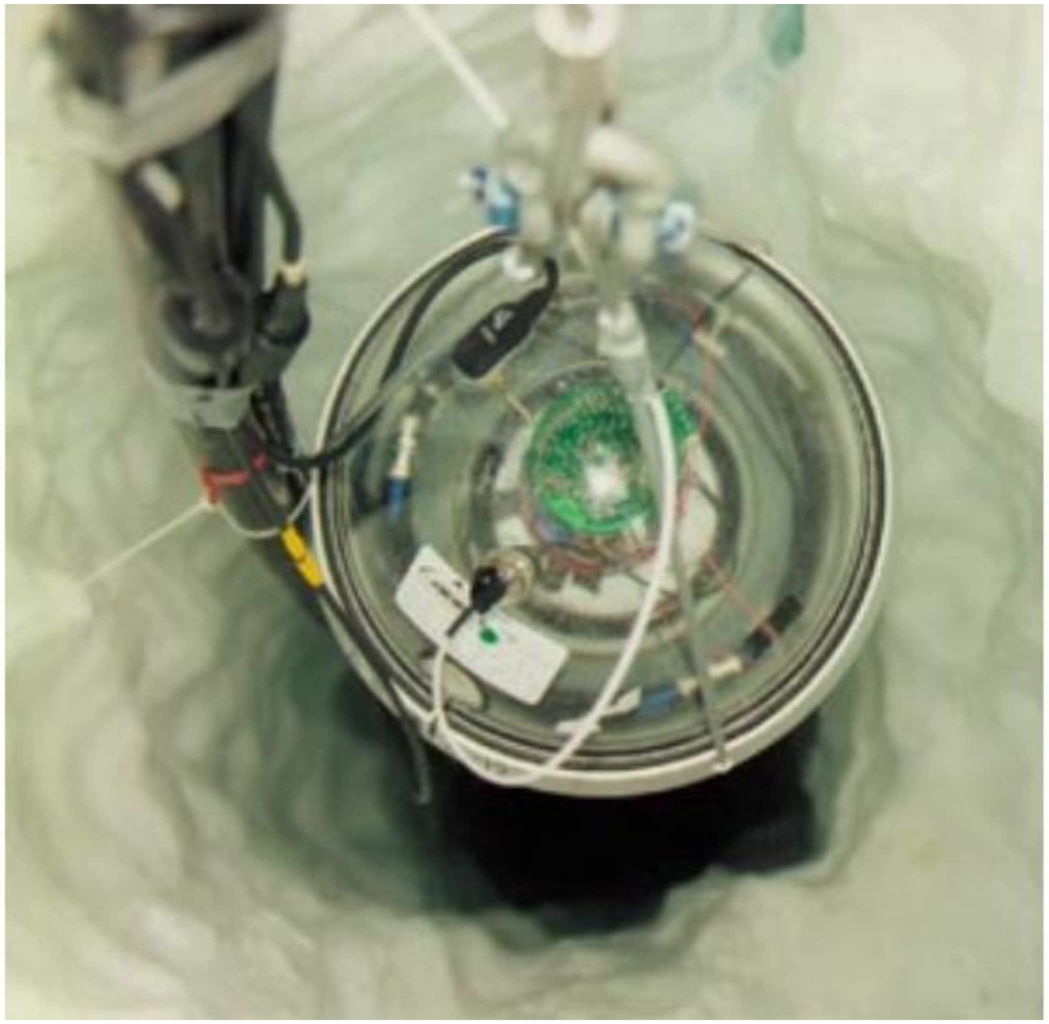
SuperKamiokande





IceCube

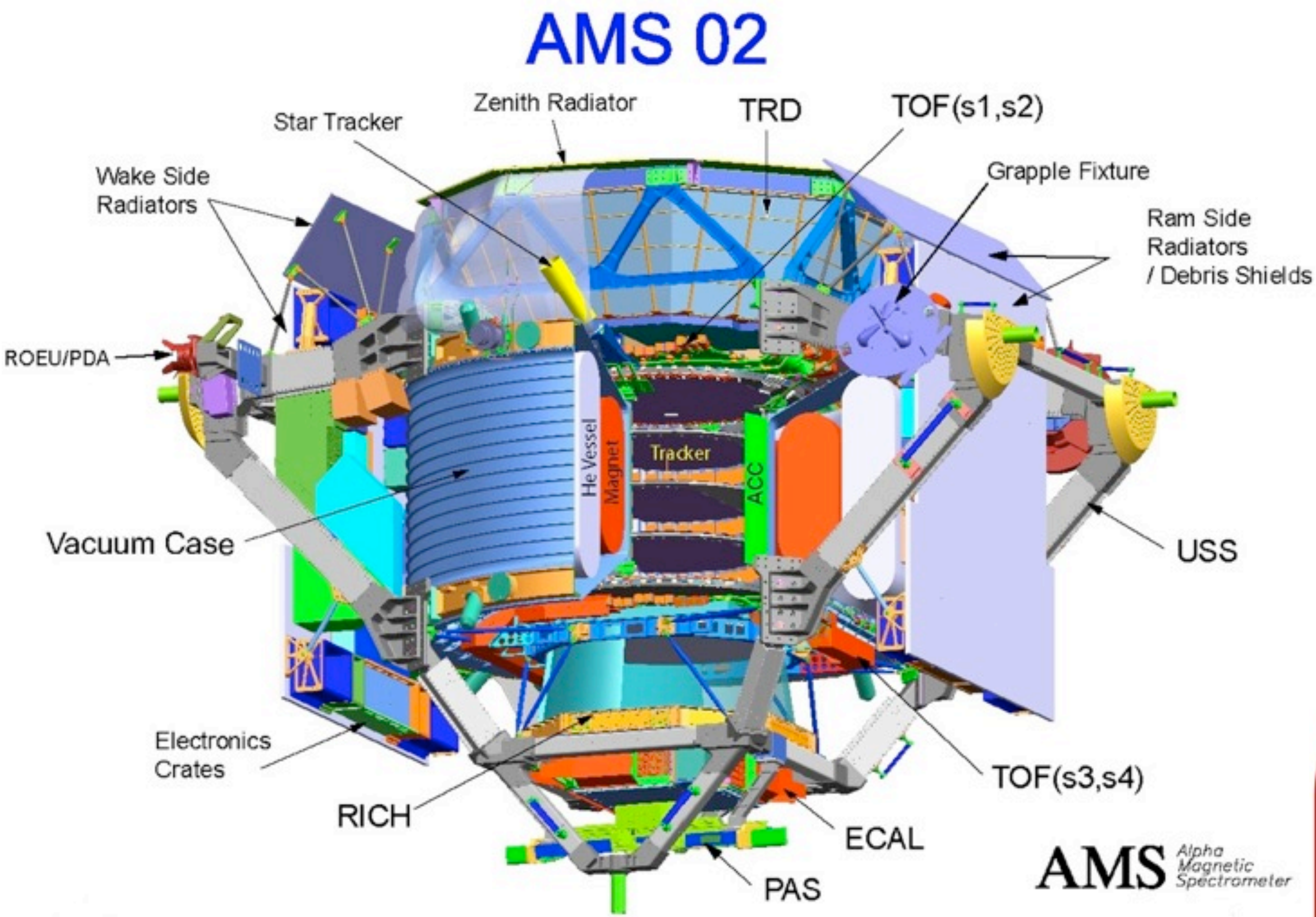

Ice Top
0 m
50 m
1000 m
South Pole Station
Snow Layer
300 m
IceCube
1400 m
2400 m



CAST

- "Light through a wall" experiment
- Uses spare LHC dipole to convert solar axions to photons

AMS


AMS 02
Zenith Radiator
Star Tracker
TRD
TOF(s1,s2)
Grapple Fixture
Wake Side Radiators
Ram Side Radiators / Debris Shields
ROEU/PDA
He Vessel
Magnet
Tracker
ACC
Vacuum Case
USS
Electronics Crates
TOF(s3,s4)
RICH
ECAL
PAS

Doing Experiments: Simulation

Decide on initial state

↓

Build detector

↓

Simulate performance

↓

Record collisions

↓

Reconstruct the events

↓

Isolate a signal

↓

Make measurements

↓

Compare with theory

- Monte Carlo simulation
  - Used for design and optimisation of detector, event selection, etc
  - Also used for unfolding of detector effects
    - Though data-driven methods are usually preferable
- Simulation software
  - De-factor standard simulation package is GEANT4
  - Experiments build software on this using accurate detector descriptions
  - Also have parameterised 'fast simulation' - useful for quick look at new ideas
    - GEANT sim for LHC takes ~minutes / evt

Doing Experiments: Data-Taking

Decide on initial state

↓

Build detector

↓

Simulate performance

↓

Record collisions

↓

Reconstruct the events

↓

Isolate a signal

↓

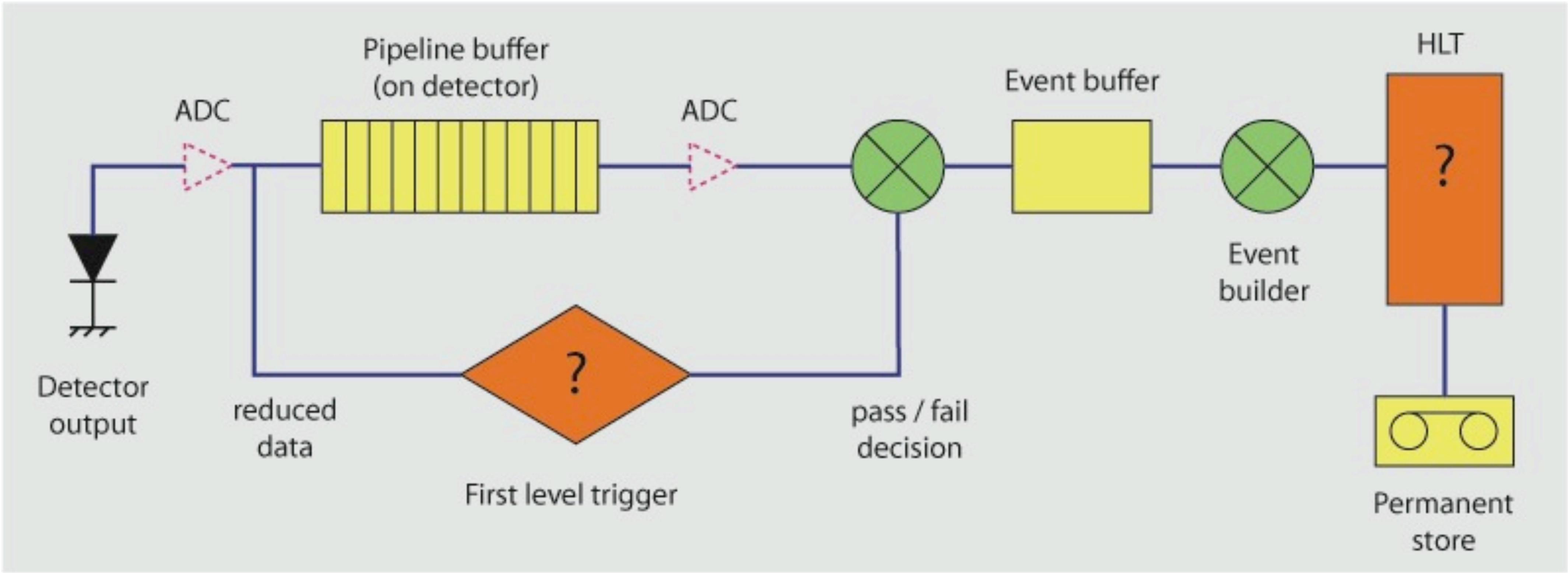
Make measurements

↓

Compare with theory

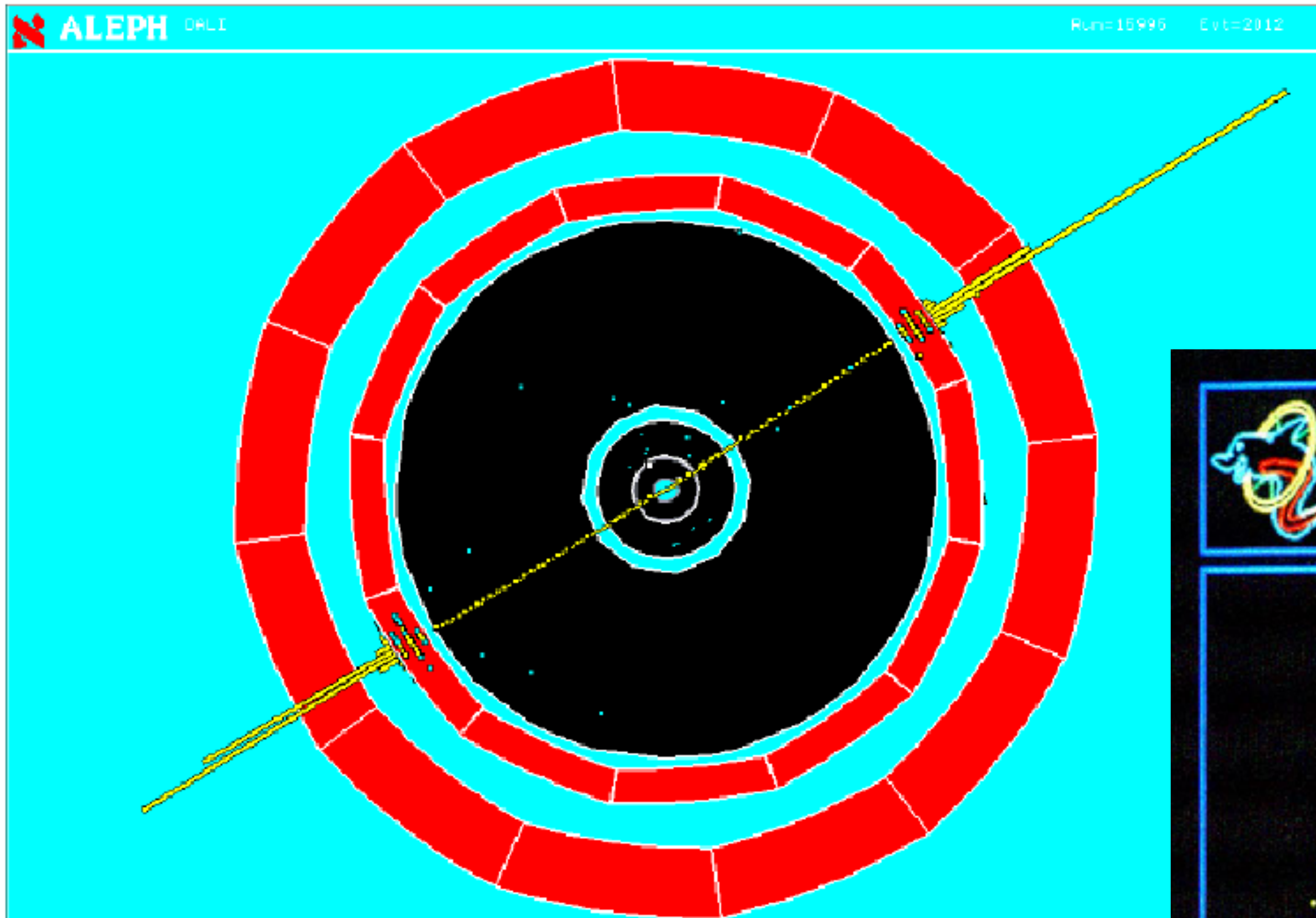
- Transmit, digitise, record and distribute signals from detectors
- DAQ is a major challenge
  - Significant fraction of detector cost
  - High performance, reliability essential
- Data rates
  - Can be extremely high
  - e.g. LHC: 2MB/evt * 40MHz crossing rate = 80TByte/s or 1YB/year
  - Online event selection is required
- Processing data
  - Extremely large processing & storage is required (distributed worldwide)
  - 'Bookkeeping' is a huge task

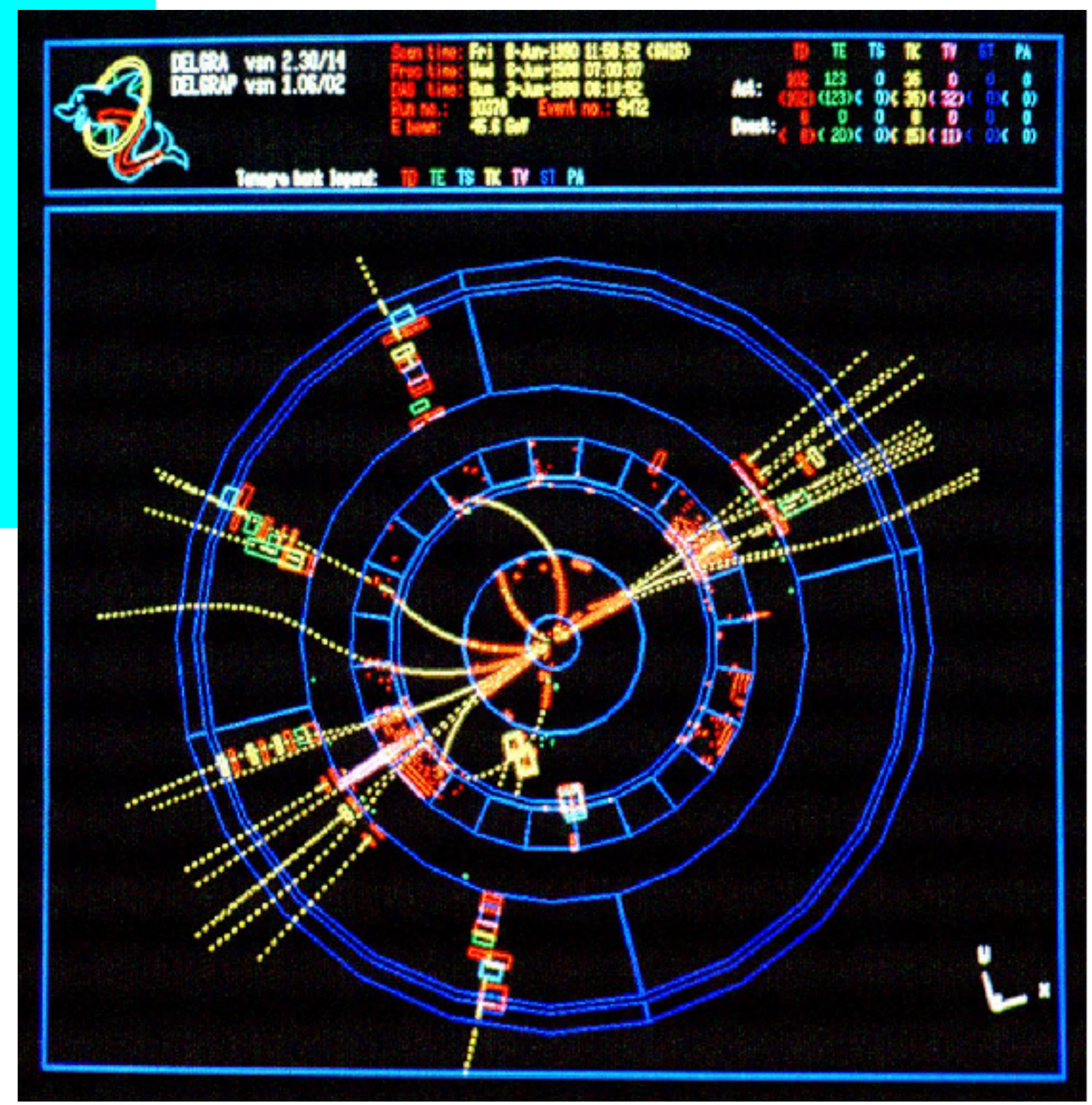
Online Event Selection



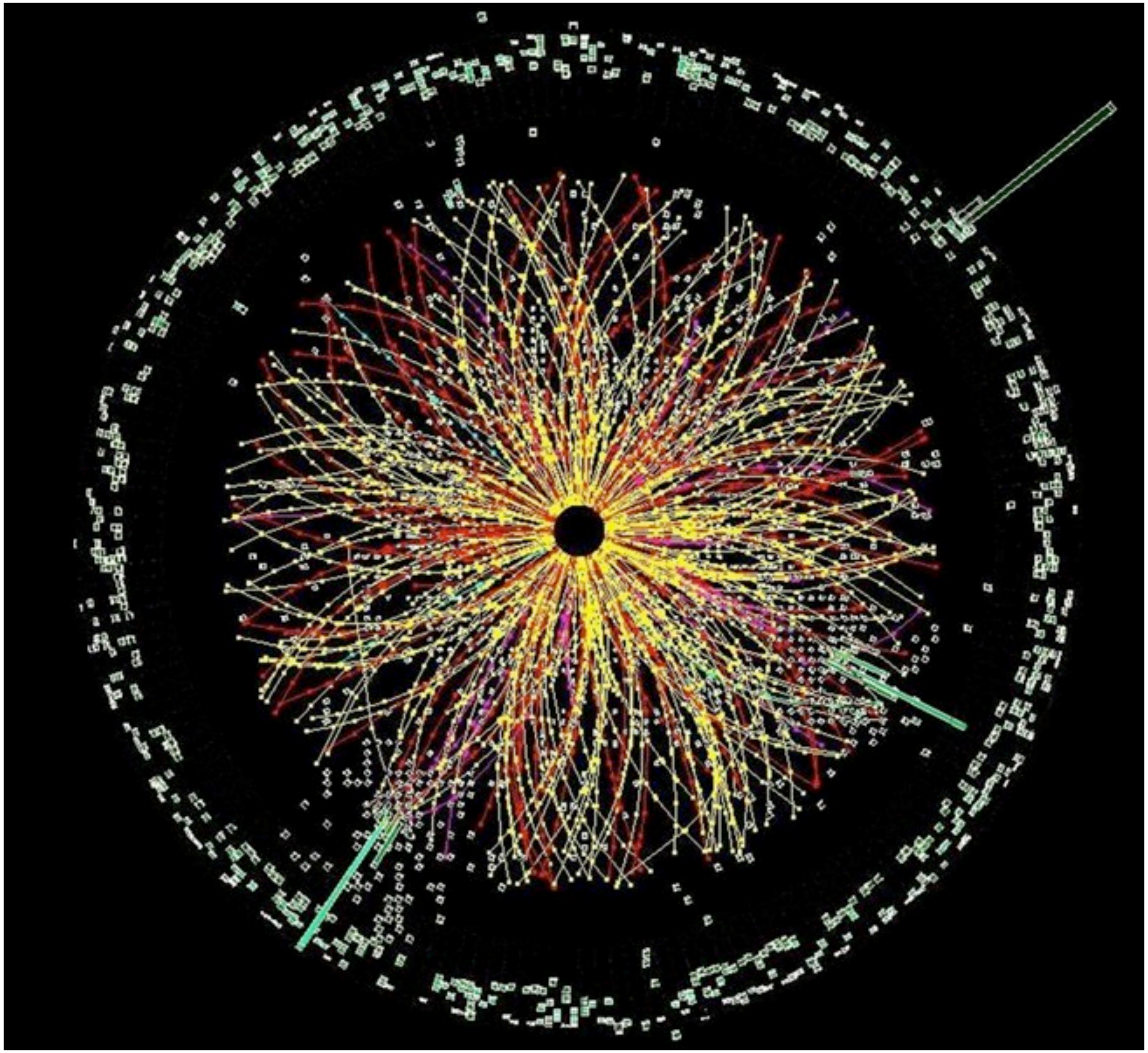
- Trigger system:
  - Must accept all events of interest while rejecting the boring ones
  - Must reduce rate of events to storage to acceptable levels
  - Online decision in fixed time (few μs) – events not accepted lost for ever
- Types of trigger
  - First level: usually custom high-speed electronics (digital or analogue)
  - Higher level: usually software on specialised or general purpose CPUs

What We ‘See’ - LEP





What We 'See' - LHC



Simulated crossing at $L=10^{34}$

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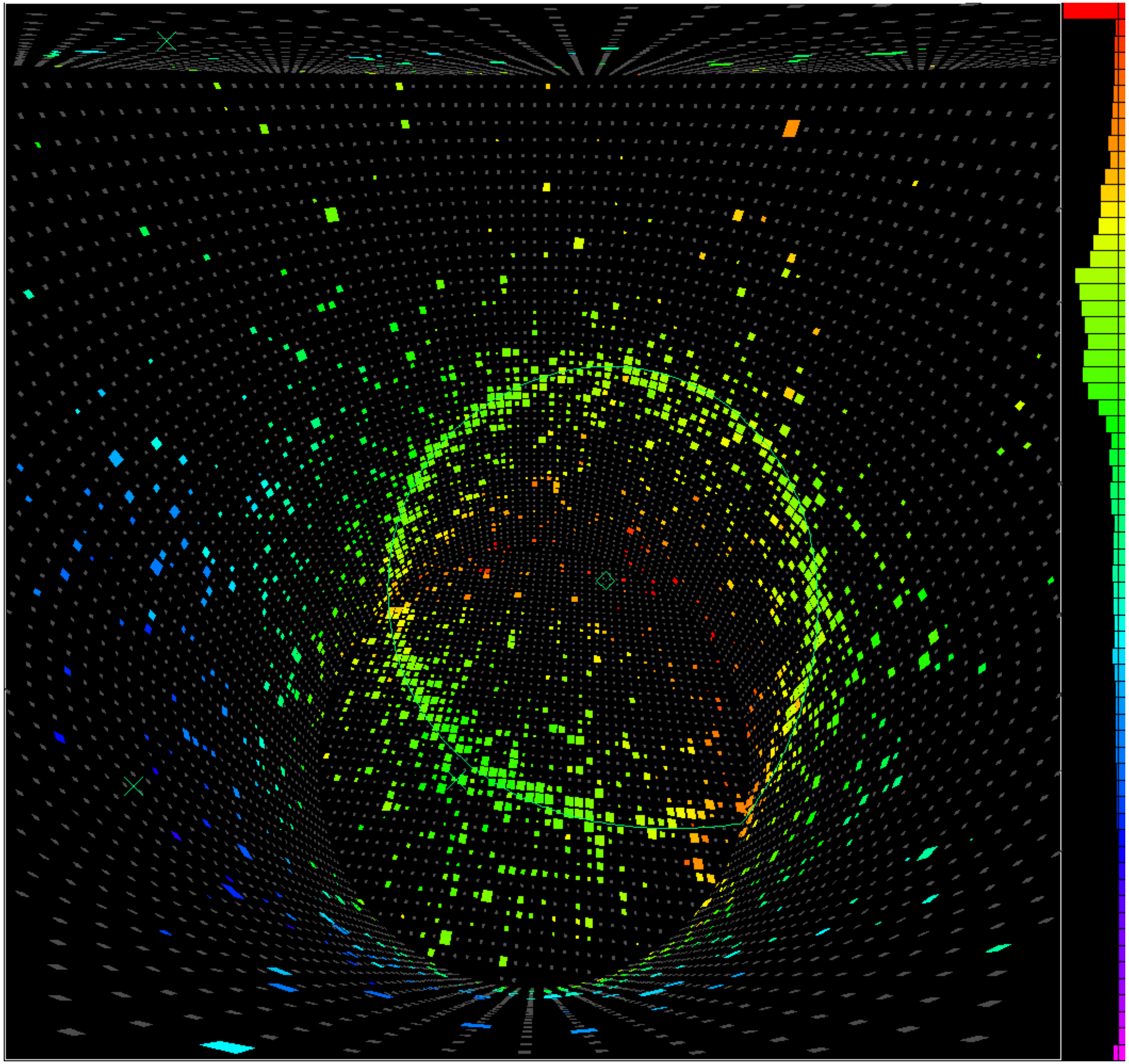
'What We See' - SuperK



Doing Experiments: Reconstruction

Decide on initial state

↓

Build detector

↓

Simulate performance

↓

Record collisions

↓

Reconstruct the events

↓

Isolate a signal

↓

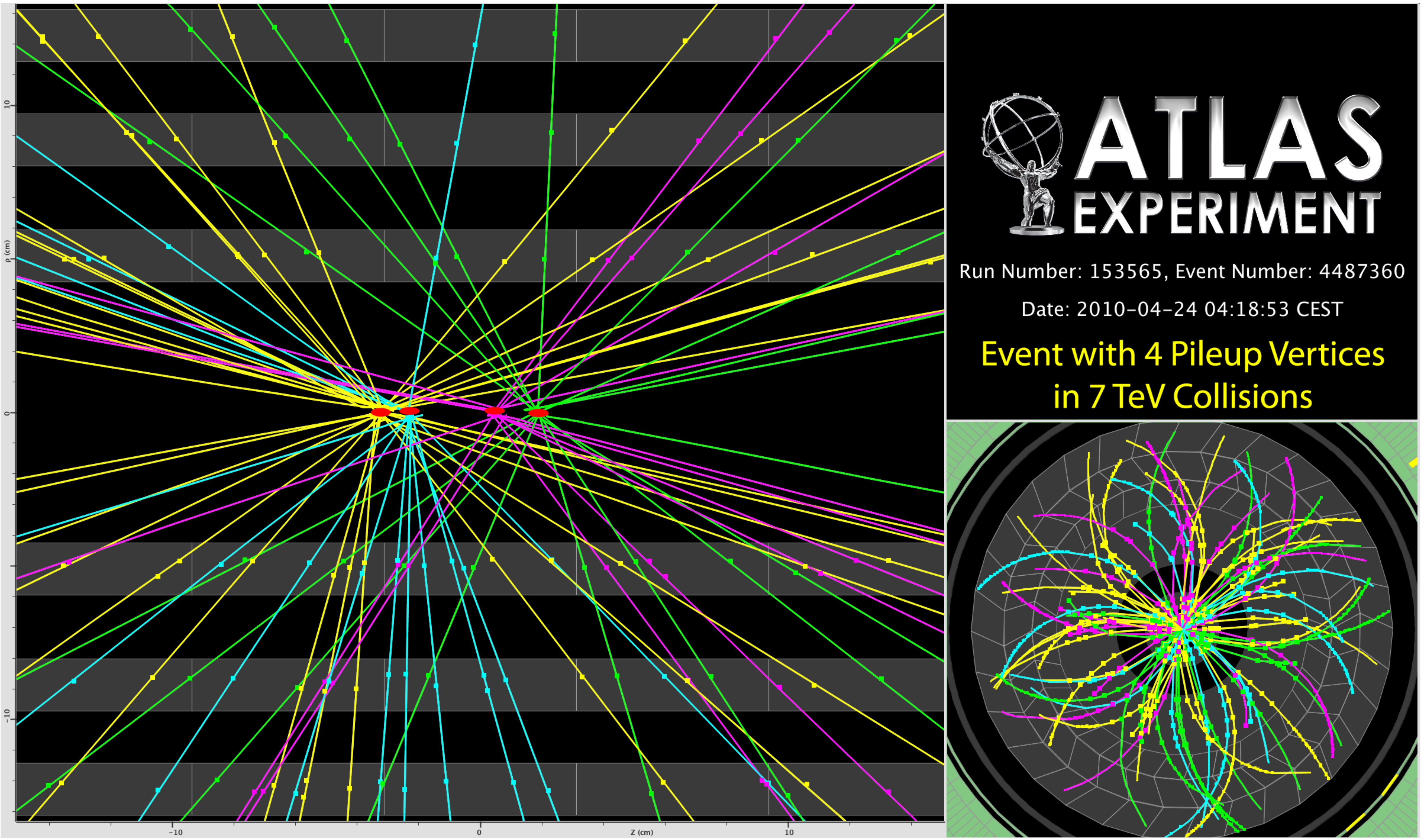
Make measurements

↓

Compare with theory

- Pattern recognition
  - Identify particle tracks / hits
  - Combine information statistically to provide information on each particle
- Event reconstruction
  - Identify primary vertex (collision pnt)
  - Find secondary vertices (particle decays in flight)
  - Try to identify decay topology (invariant masses, cascade decays, etc)
- Reconstruction software
  - Often several M lines of C++
  - Requires continuous tuning as conditions change in detector

Primary Vertex Reconstruction



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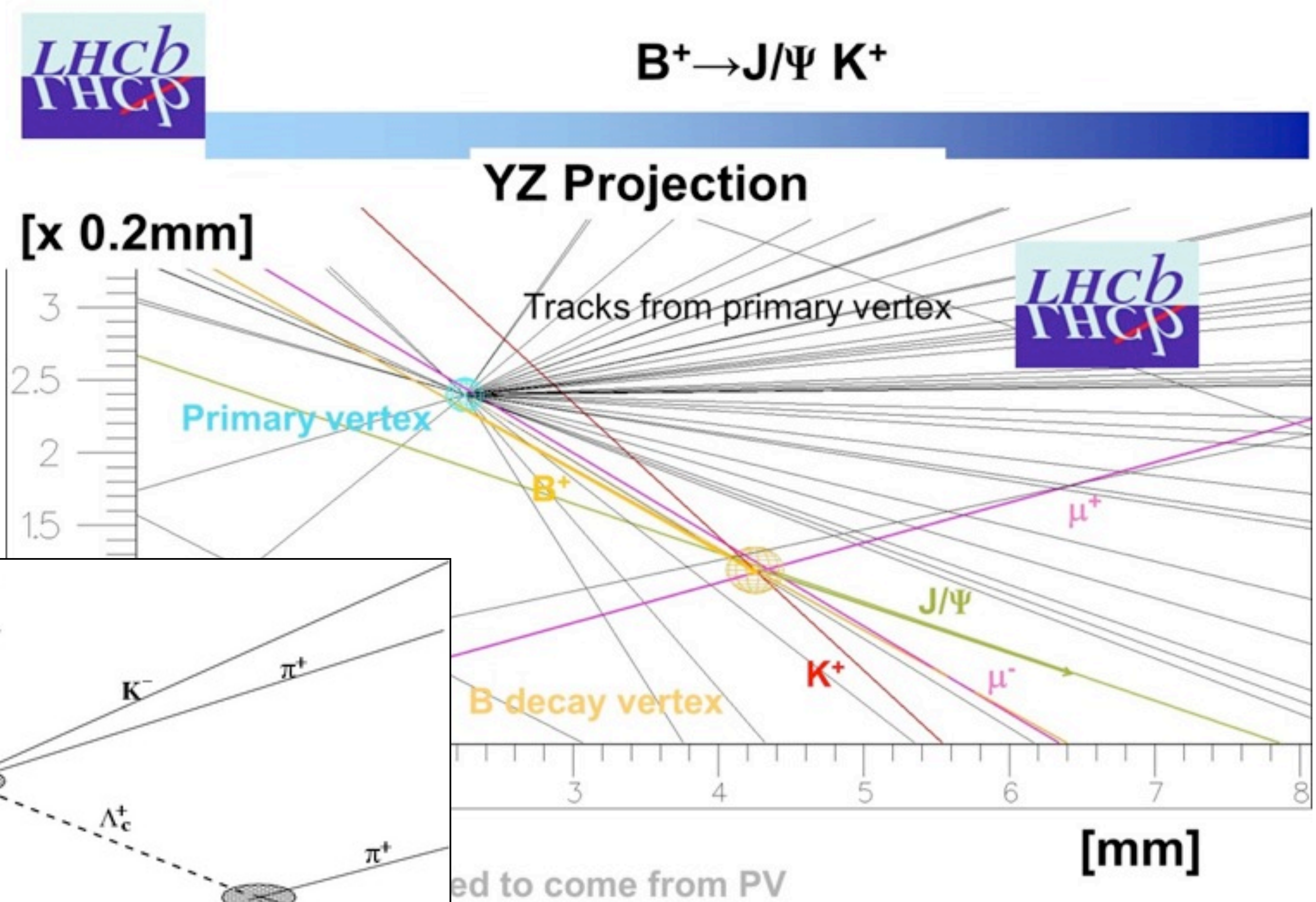
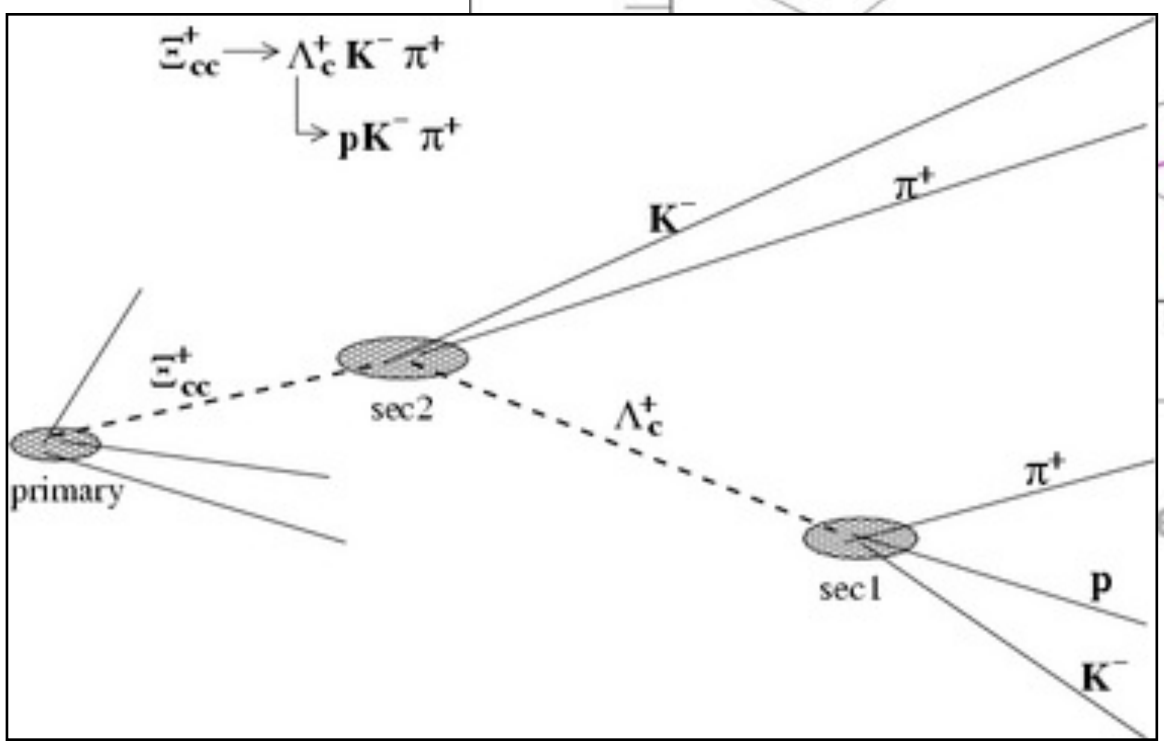
Secondary Vertex Reconstruction





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Doing Experiments: Find the Signal

Decide on initial state

↓

Build detector

↓

Simulate performance

↓

Record collisions

↓

Reconstruct the events

↓

Isolate a signal

↓

Make measurements

↓

Compare with theory

- 'Summarise' event
  - Form invariant mass combinations
  - Attempt to identify decay chain
  - Extract key kinematic parameters
- Isolate signal
  - 'Cut and count' traditional method
    - Make 'cuts' in multidimensional parameter space to enhance signal over background
  - More complex methods now used
    - Neural net, decision trees, etc
  - No signal is background free
    - Understanding background within the selection is of utmost importance
- Usually a long iterative process
  - What experimental PhD students spend their time doing...

Doing Experiments: Analysis

Decide on initial state

Build detector

Simulate performance

Record collisions

Reconstruct the events

Isolate a signal

Make measurements

Compare with theory

- At last!
  - Analyse distributions of whatever you are trying to measure...
  - Correct for background contamination
  - Write the paper.
- Never so simple
  - Is the result significant? How significant? Does it mean *anything*?
  - Need to carefully assess statistical and systematic errors
  - Complex multivariate statistics now commonplace in HEP.
- Usually turns out that...
  - The result is a statistical limit on observation of some event class

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Statistics: Advice for the Unwary

- Statistics in experimental HEP
  - An essential tool in producing information from the data
  - Typically not well understood
    - By most readers of experimental papers, and many writers
- A quiet revolution in the last ~15 years
  - Statistics now generally done 'properly' (by HEP standards)
    - A small industry of experts has grown up.
  - But... one still hears of '2-sigma exclusions' and '3-sigma observations'
- How to interpret experimental limits
  - Quite often, you simply can't without additional information
    - And certainly not from plots shown at conferences
    - Many assumptions are 'in the small print'
  - In particular, take great care when:
    - Comparing a result to the predictions of a model
    - Comparing or combining results from different experiments or runs (correlated errors, different assumptions, etc)

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Wise Comment

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"If your result needs a statistician, you should design a better experiment"

- Rutherford

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Wise Comment

"If your result needs a statistician, you should design a better experiment"

- Rutherford

"We haven't got the money, so we've got to think!"

- Rutherford

"Don't let me catch anyone talking about the Universe in my department"

- Rutherford

Comparison with Theory

Decide on initial state

↓

Build detector

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Make measurements

↓

Compare with theory

- Typical methodology
  - Use theoretical model to predict event yield of a given type
  - Requires assumptions about PDFs, etc, as well as hard collision model
  - Fold in detector resolutions, efficiencies
  - Estimate compatibility with data
- Event generators
  - The lingua franca between theory and experiment
  - If you want a model tested, make sure there is a generator implementation
  - A good knowledge of theory uncertainties will be required
    - In the limit of decent statistics

Your Mission

Should you choose to accept it

- Complete confirmation of the Standard Model
  - i.e. find the Higgs boson – or whatever else does the job
- Go beyond the standard model
  - Understand hierarchy problem, i.e. SUSY – or whatever else does the job
- Search for additional structure above 1TeV
  - Gauge extensions, 4th generation, compositeness, leptoquarks, etc
- Relate all of this to cosmology
  - Antimatter asym., CMWB, dark matter, dark energy, proton lifetime, etc
- It is unlikely to happen in this order
  - No plan survives contact with enemy

This slide will self-destruct in ten seconds

Constraining the Standard Model

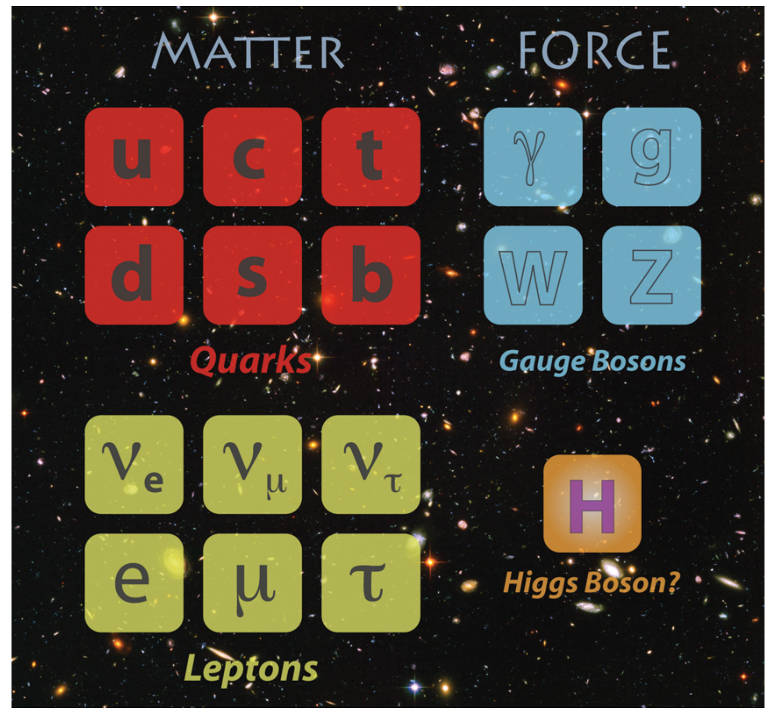
Higgs Searches?

(Still) closing in fast

Self-consistent within SM ✔

Electroweak fits

CKM



Cosmology

Lepton flavour sector

Blatant phenomena beyond SM ✘

Hints / speculations accumulate.
Here be dragons

Collider BSM searches

g-2, EDM, etc

DM searches

?

- Plus, a wealth of clear theoretical arguments for BSM physics
- For a full review, see proceedings of EPS2011, LP2011, etc

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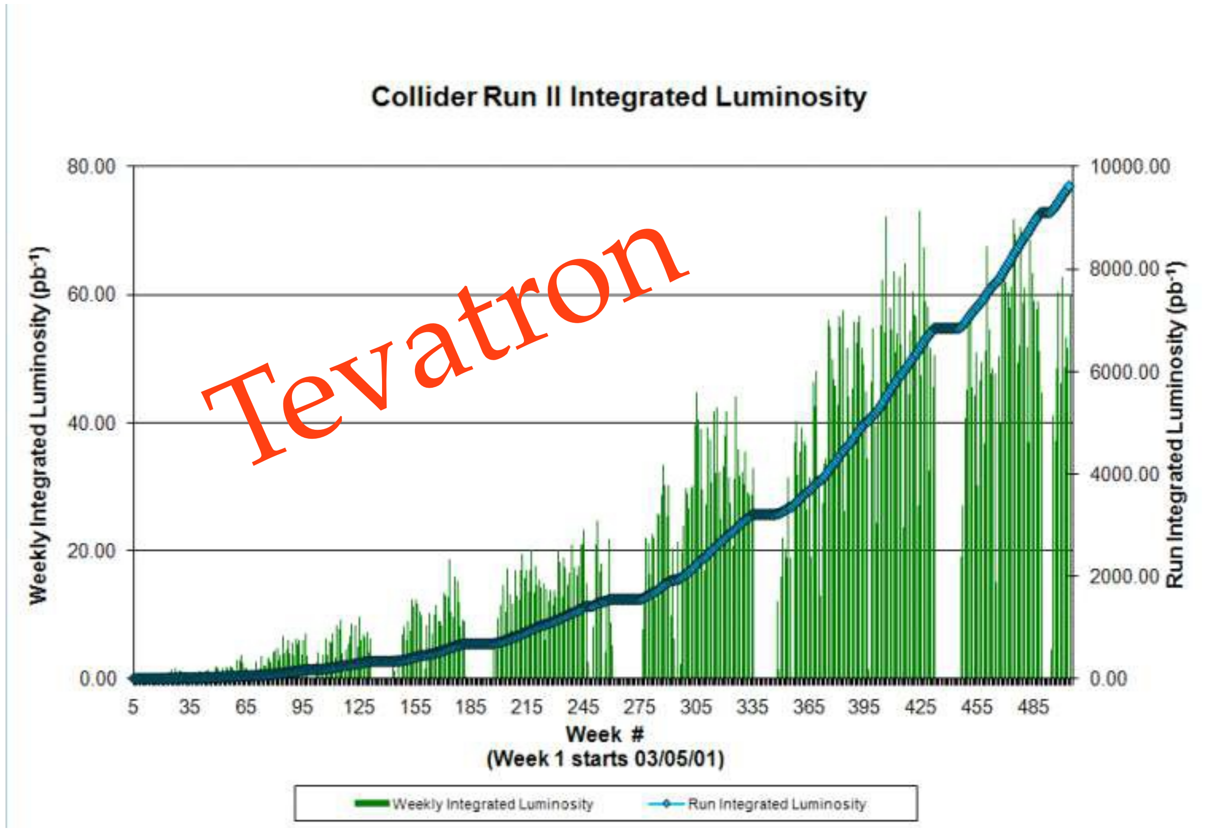
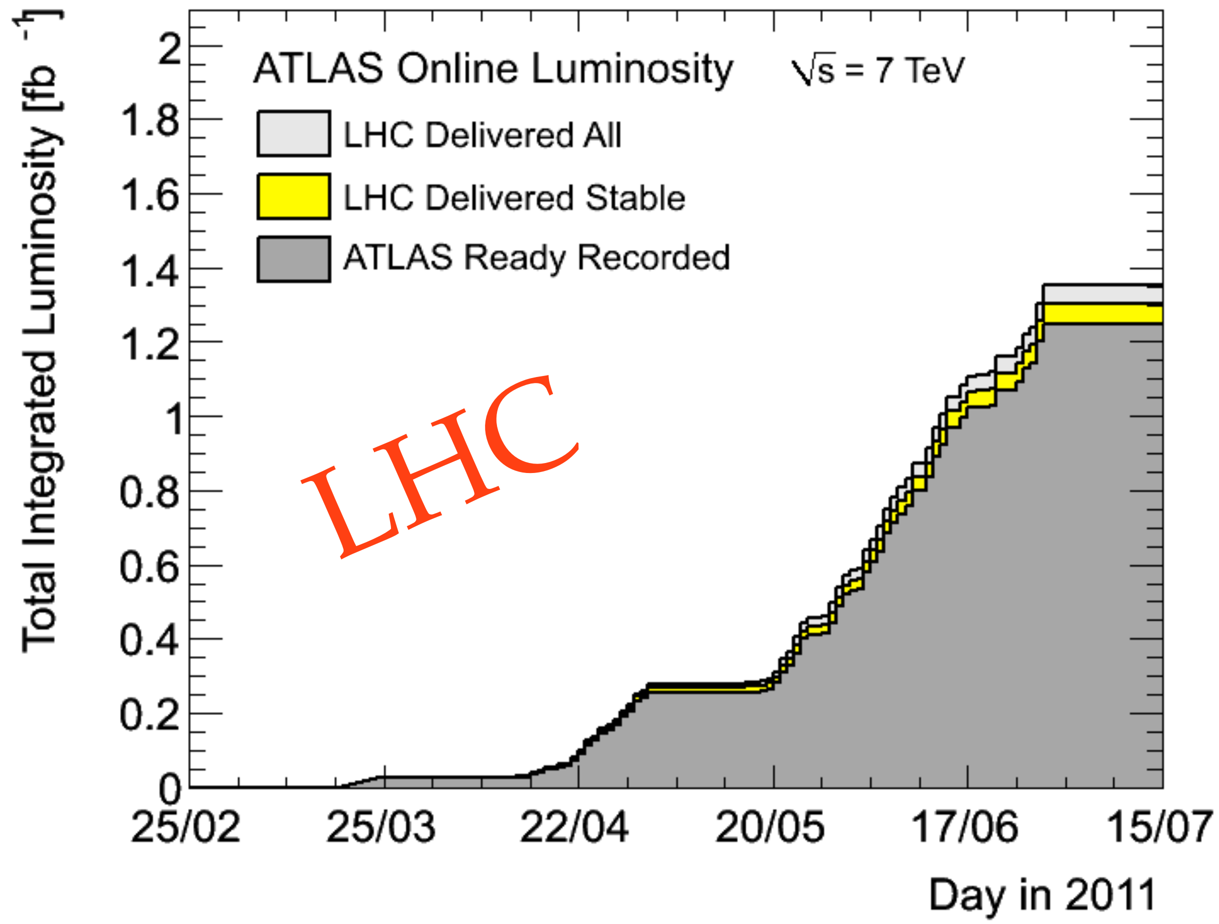
Tevatron vs LHC vs …





- Asymmetries accessible
- Cleaner environment
- Very well understood detectors

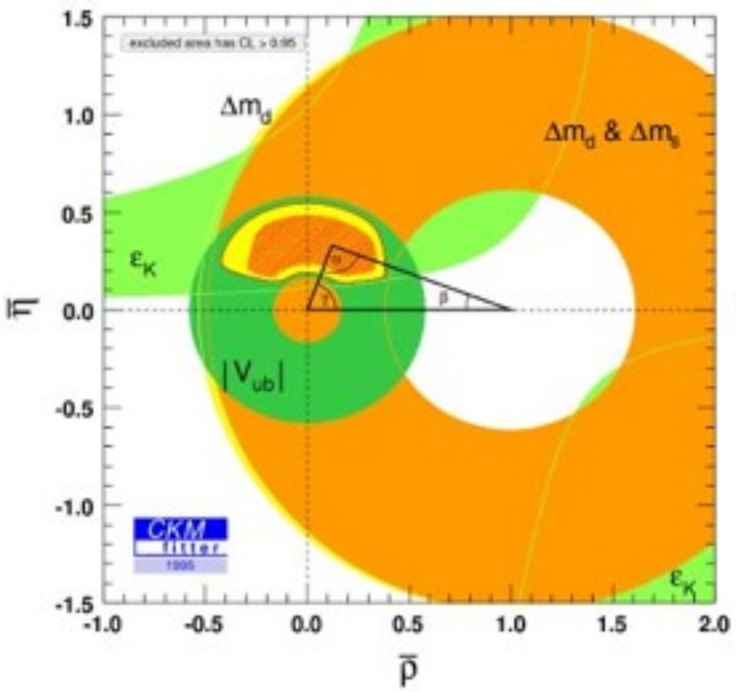
- Symmetric environment
- Increasingly dirty environment
- Higher energy – decisive advantage

- Many other complementary & competitive facilities
  - Non-accelerator searches; ‘intensity frontier’; neutrino beams, etc

Quark Flavour Sector

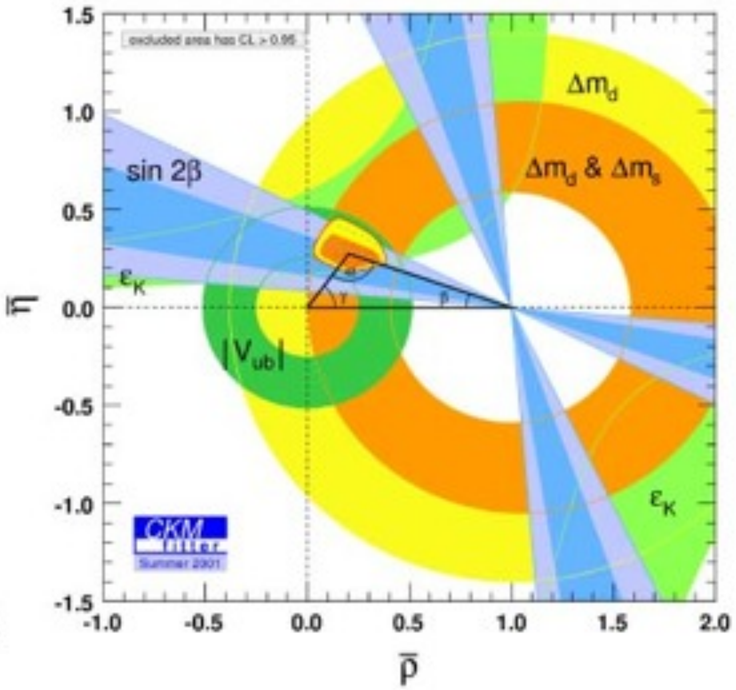
~1995

LEP, TeVatron (top), NA48, KTeV,…



S2001

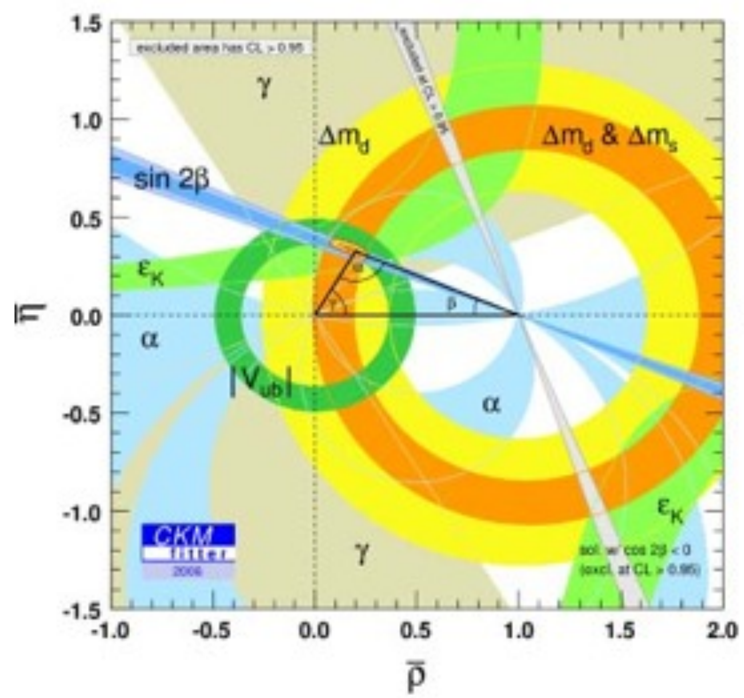
BaBar (SLAC), Belle (KEK), …



- Apparently a self-consistent picture of CPV in SM
- Note impact of LQCD in reducing theory uncertainty
- Results from LHC will have a further big impact
  - Particularly on γ

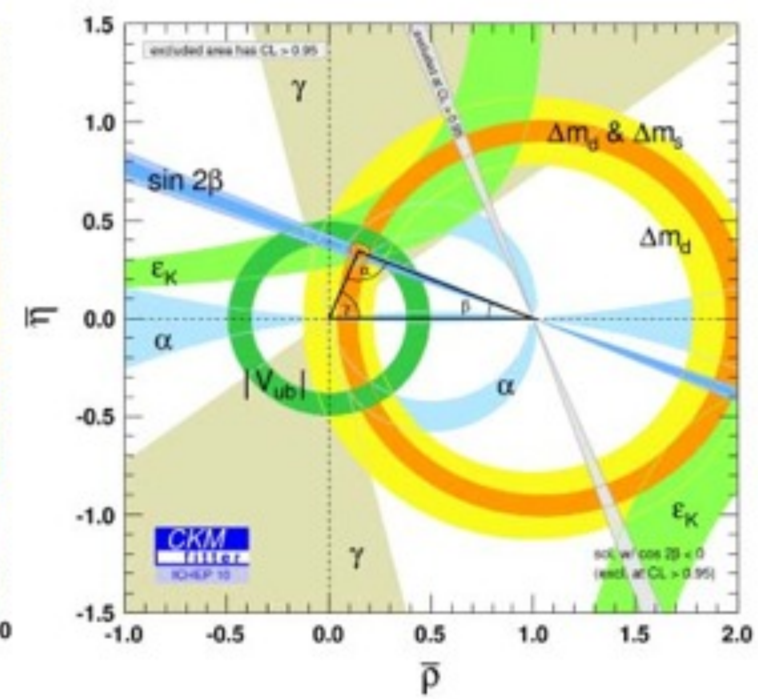
2006

BaBar, Belle and CDF/DØ (TeVatron Bs), …



2010

BaBar, Belle and LQCD, …



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Lepton Flavour Sector

Mixing angles

Atmospheric (SK) / Accelerators (K2K, Minos) — Reactors (CHOOZ) / Accelerators (JPARC) — Solar (SNO, SK) / Reactors (KamLAND)

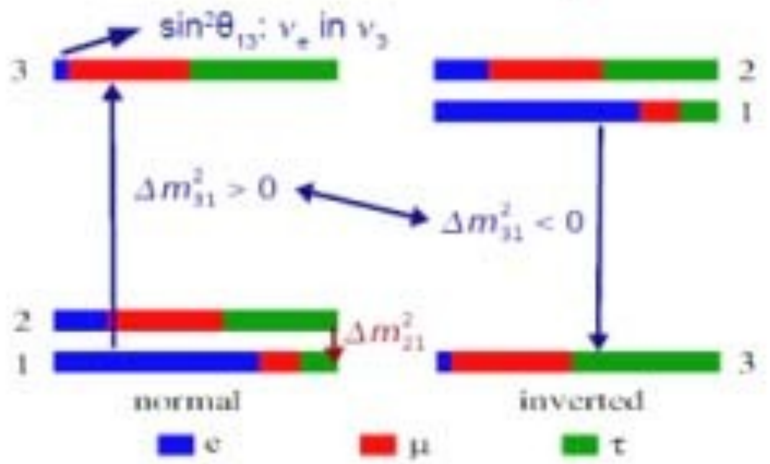
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \times \begin{pmatrix}\cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix} \times \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \times \begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha/2} & 0\\ 0 & 0 & e^{i\alpha/2+i\beta}\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\tan^2\theta_{23}=1.0 \quad 0.3$ — $\sin^2 2\theta_{13} < 0.16$ — $\tan^2\theta_{12}=0.47 \quad 0.05$

α,β : CP Majorana phase

δ_{CP}: CP Dirac phase

Mass hierachy



$\Delta m^2_{sol} = \Delta m^2_{12} = (7.58 \pm 0.21)\ 10^{-5}\ eV^2$

$\Delta m^2_{atm} = \Delta m^2_{31} = (2.2 \pm 0.2)\ 10^{-3}\ eV^2$

Absolute neutrino mass

Beta decay : $|m_\nu| = \Sigma\, |U_{ei}|\, m_i$ < 2.6 eV (90 % CL)

Double beta : $\langle m_{ee}\rangle = |\Sigma\, U^2_{ei}\, m_i|$ $< 0.3 - 0.7$ eV (95% CL)

Cosmology : $m_\nu = m_1 + m_2 + m_3$ $< 0.5 - 1$ eV (95 % CL)

Lepton Flavour Sector

Mixing angles

Atmospheric (SK)
Accelerators (K2K,Minos)

Reactors (CHOOZ)
Accelerators (JPARC)

Solar (SNO, SK)
Reactors (KamLAND)

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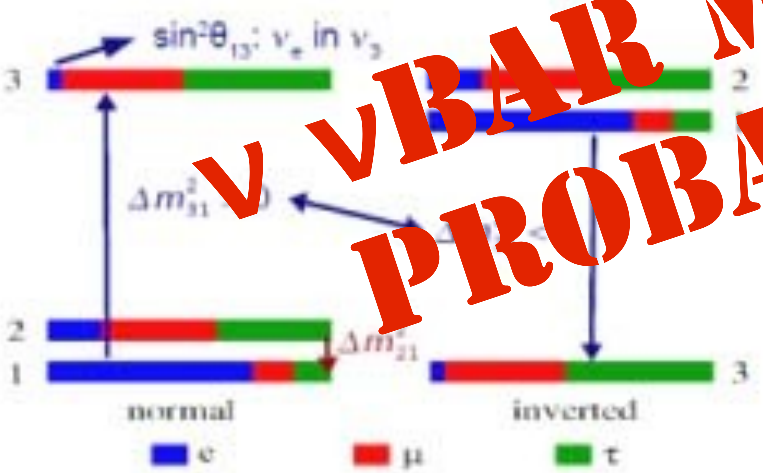
$\tan^2\theta_{23}=1.0$ 0.3 $\sin^2 2\theta_{13} < 0.16$ $\tan^2\theta_{12}=0.47$ 0.05

α, β: Majorana phase
δ_{CP}: CP Dirac phase

STOP PRESS:
ν νBAR MASS DIFFERENCE IS PROBABLY GONE – MINOS

Mass hierachy



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Cosmology : $m_\nu = m_1 + m_2 + m_3$ < 0.5 – 1 eV (95 % CL)

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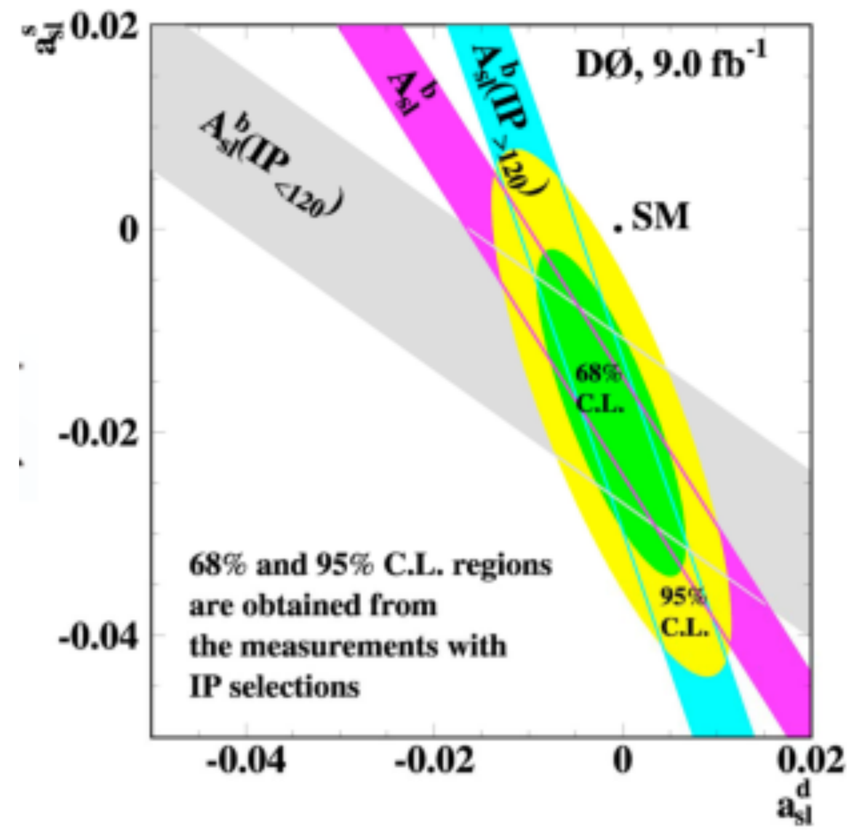
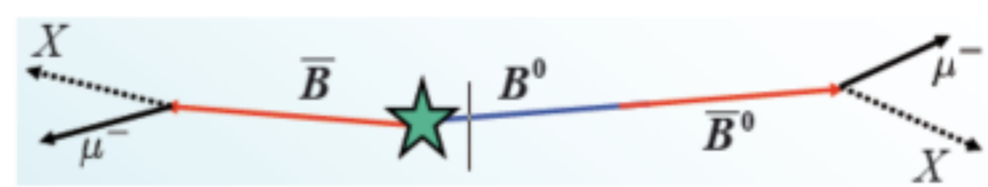
Tevatron New Physics Searches

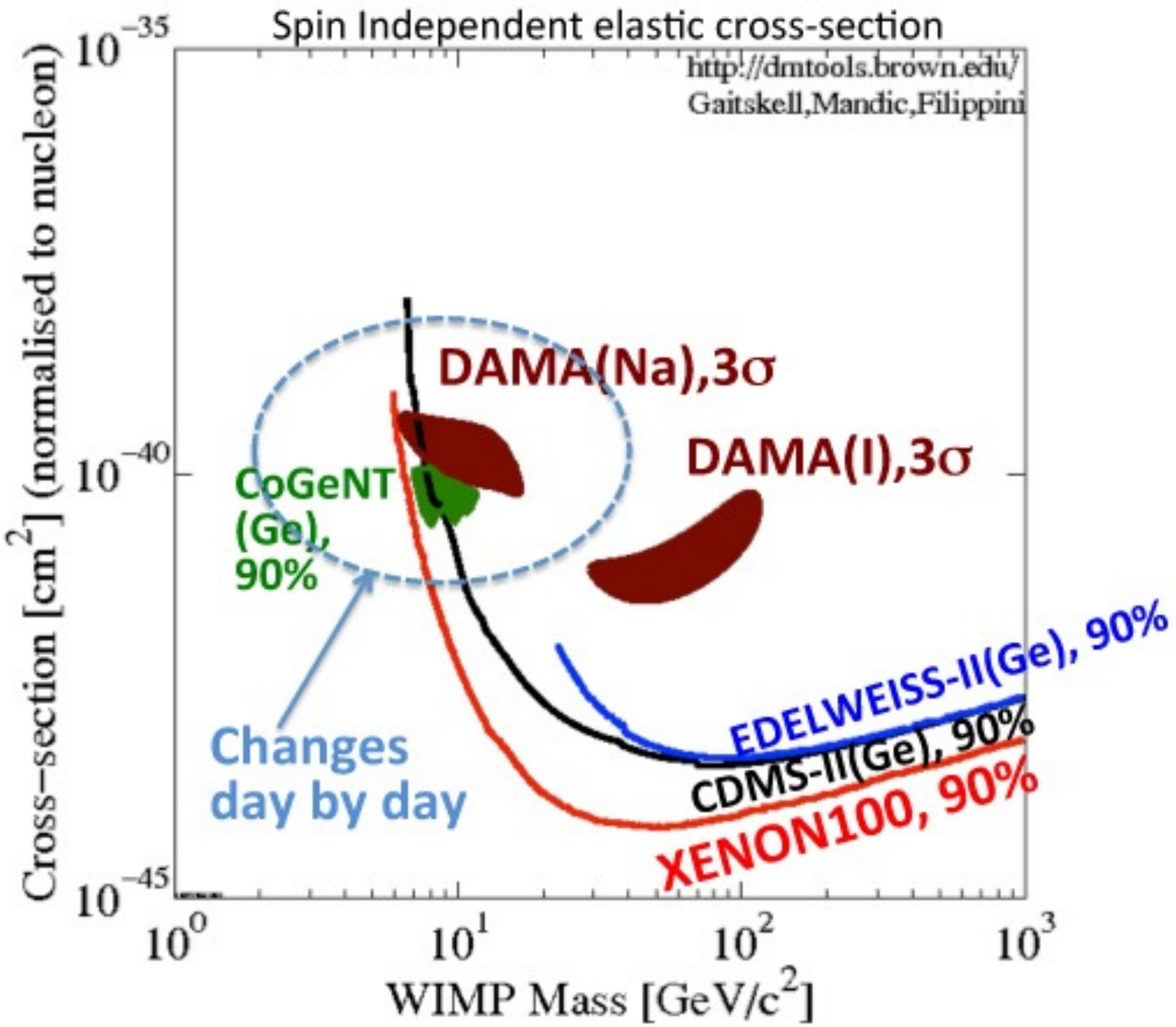
- No evidence for BSM physics in:
  - Structure / deviations in jet spectrum
  - Structure / deviations in dilepton / diphoton spectrum
  - tt resonances / anomalous top σ
  - 4th generation searches
  - Leptoquarks etc
  - Hidden valley and novel signatures
  - Many other studies
- Hints?
  - W+jets spectrum?
    - Looks to have gone away in cross-checks
  - Dimuon asymmetry (3.9σ from SM)?
  - t tbar FB asymmetry?
  - Bs -> mu mu?

arXiv: 1106.6308



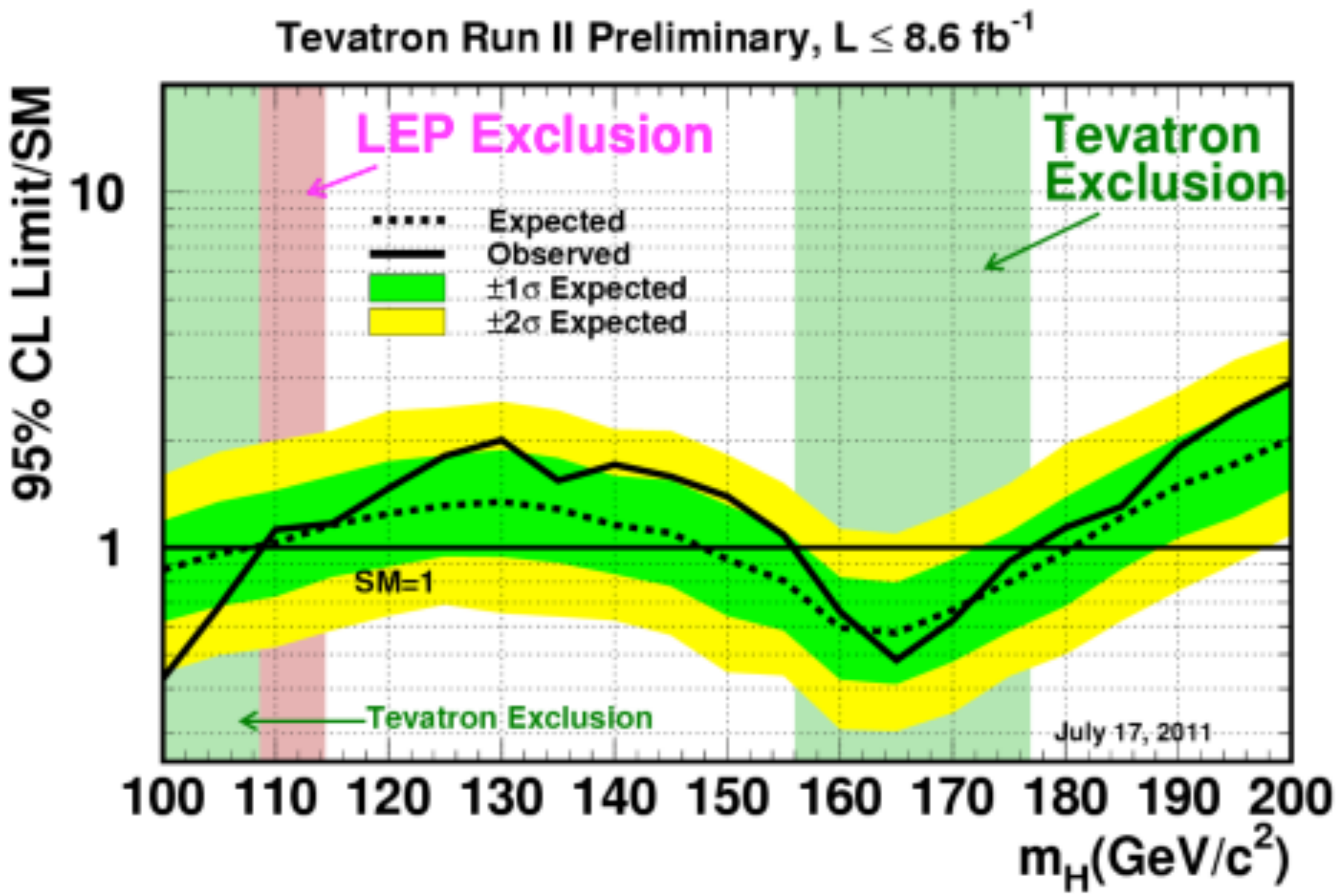


Direct DM Searches



- Substantial confusion & controversy over DM results
  - *Two* experiments observe annual modulation – interpretation challenging
  - More results and cross-checks urgently needed

Tevatron / LEP Higgs Limits



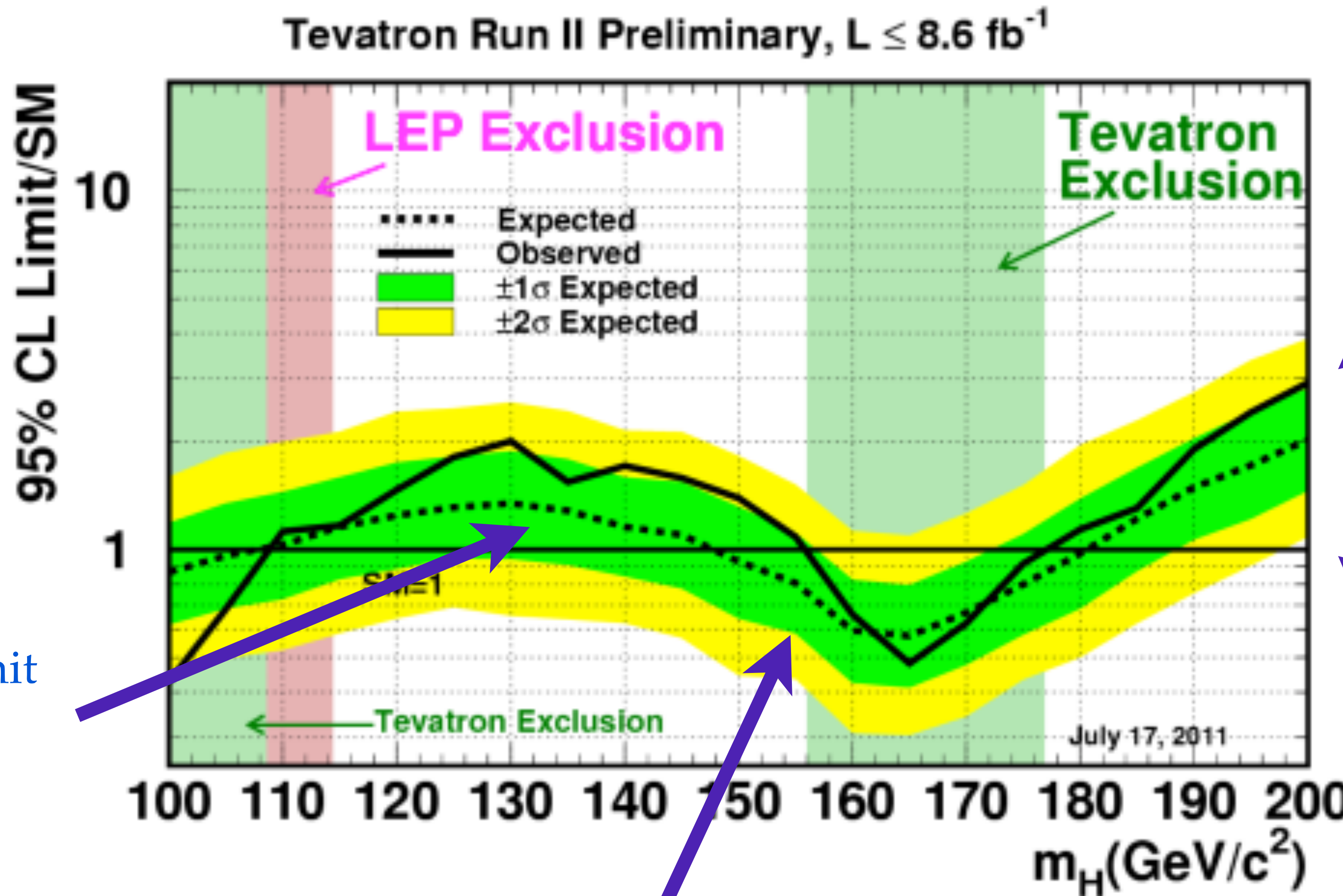
Observed Exclusion : 100-109 and 156-177 GeV/c^2

Expected Exclusion : 100-108 and 148-181 GeV/c^2

- Not taking into account various ‘ways out’
  - *Higgsless* models; *invisible* higgs; *buried* higgs; Higgs with *phobias*, etc etc

Limit Plots: Spotter's Guide

Upper x-section limit relative to SM



Observed limit from data

Standard Model prediction

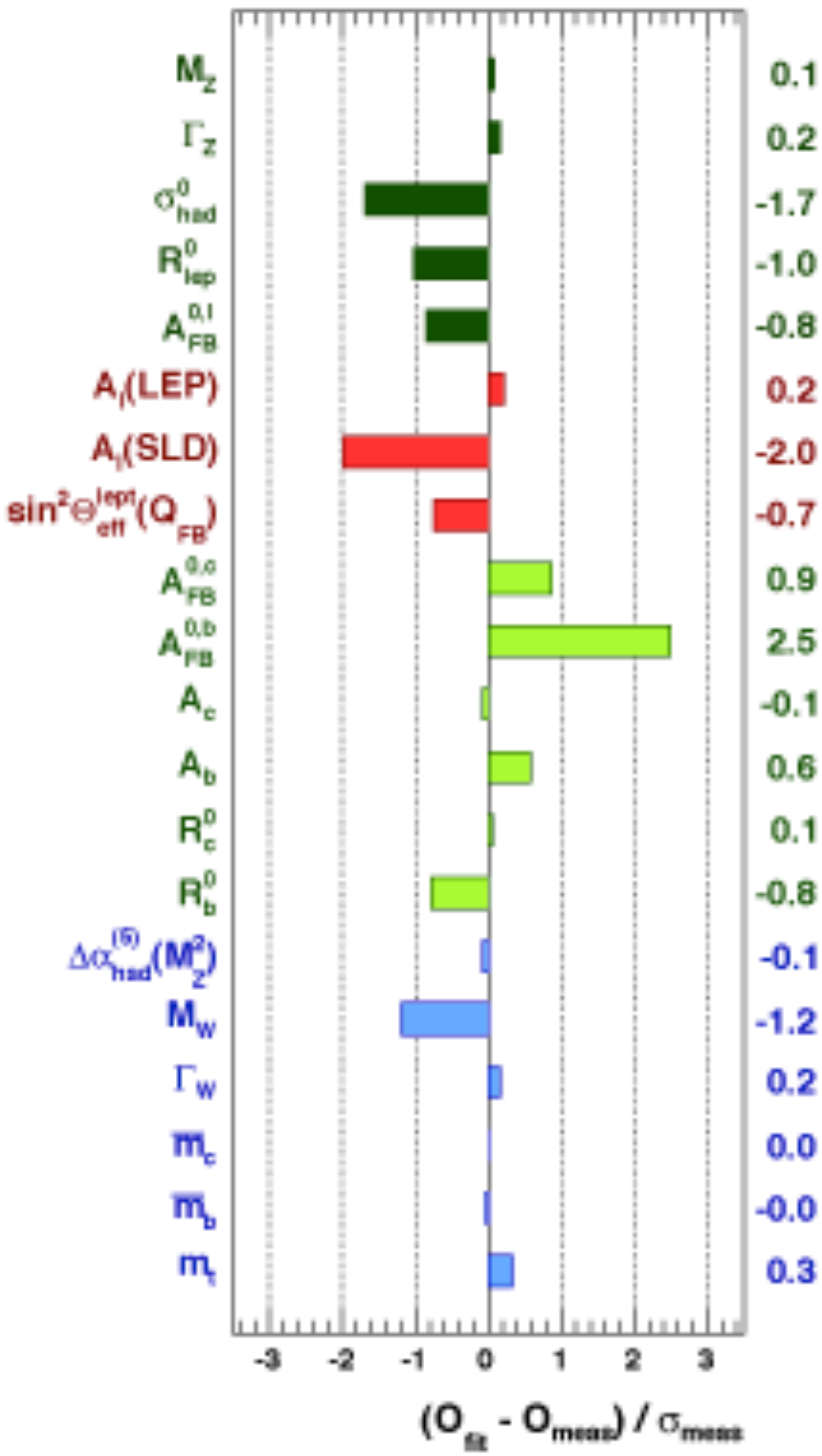
Median expected limit based on many background-only pseudoexperiments

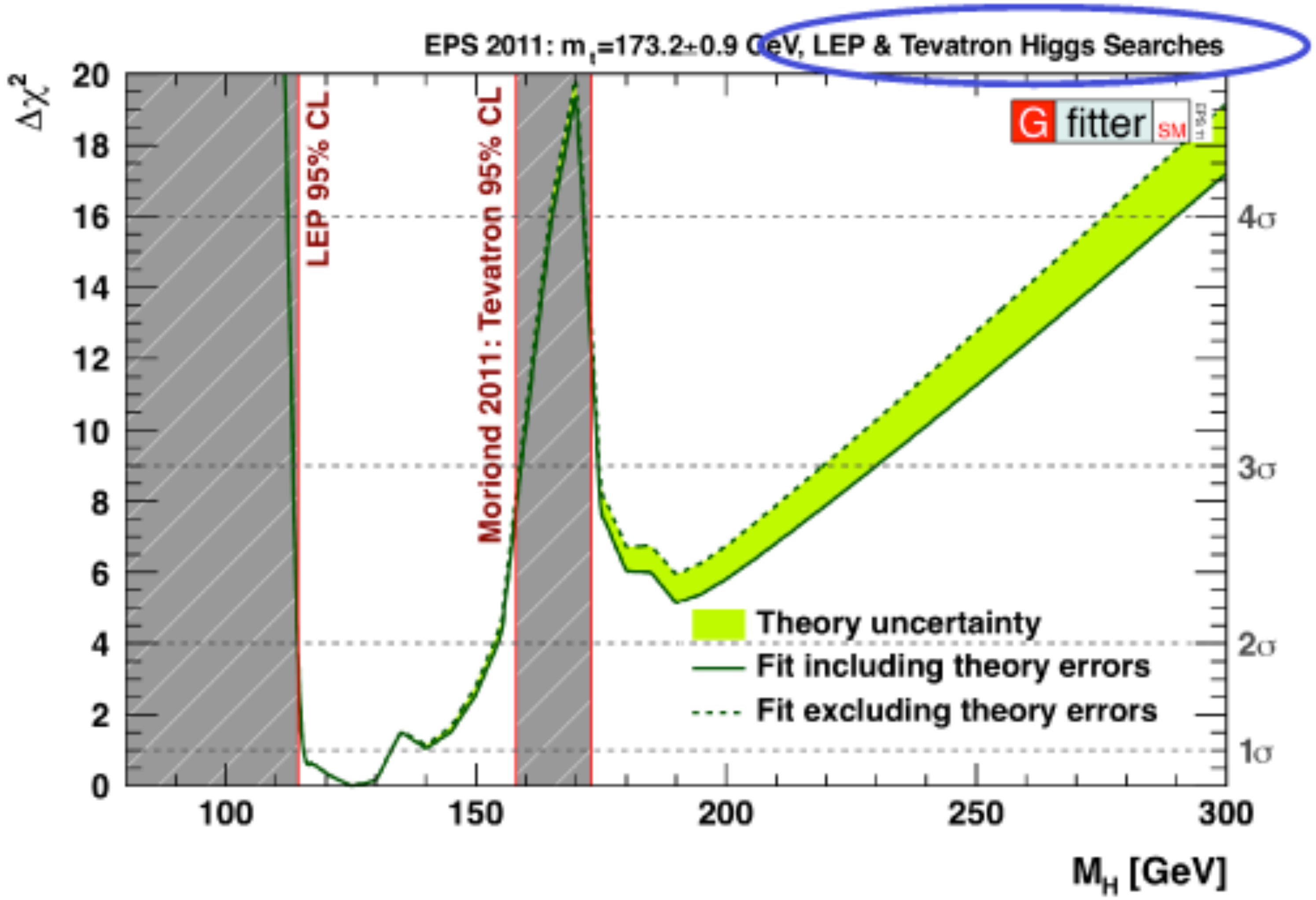
1σ (67%) and 2σ (95%) bands on expected limit

Limit calculated at many different mass hypotheses
- not independent!

- Statistics is important: remember, only O(10) events expected
  - Beware: expected limit band refers to *statistical* fluctuations only
  - These plots widely misinterpreted, esp. for searches (look elsewhere effect)

Electroweak Global Fits





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Whither the Standard Model?

Possibly more than a flesh wound

But Not Dead Yet

What Next?

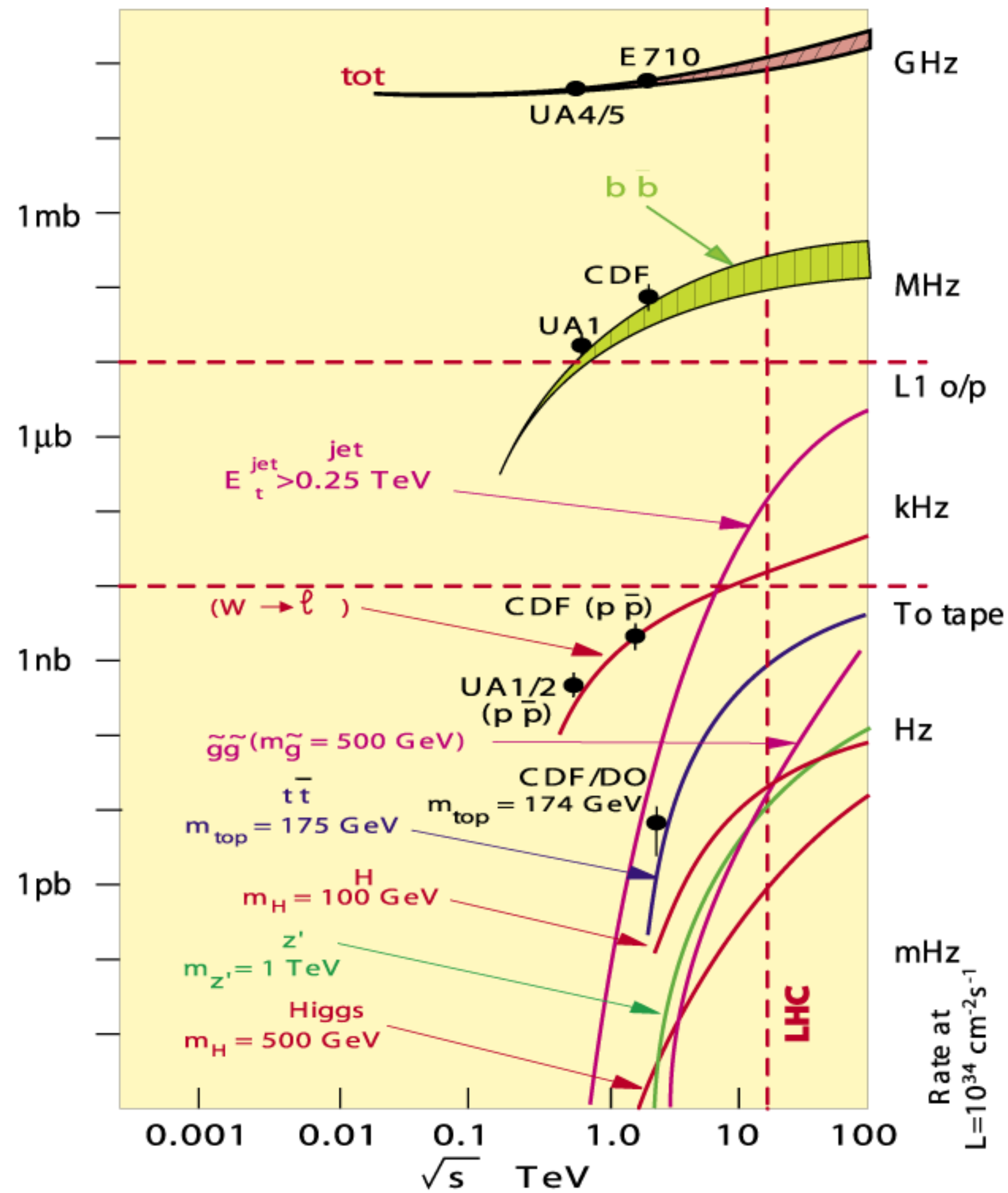
What Next?

What Next?

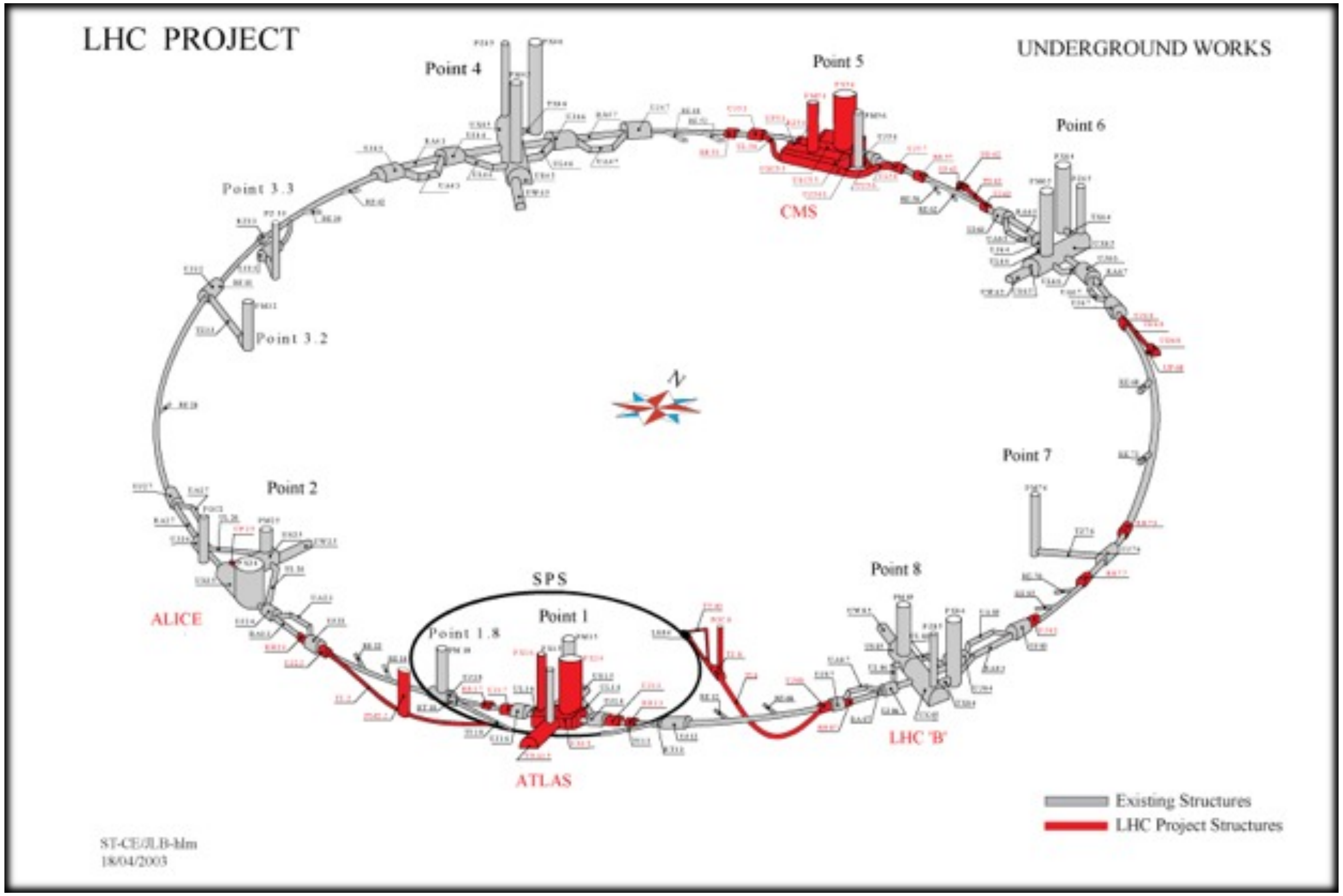
"We're going to need a bigger boat"

Welcome to the Energy Frontier

- Something interesting (probably) happens at ~1TeV
  - Build a collider with significant luminosity above sqrt(s)=1TeV
  - See what happens …
  - … be prepared for almost anything
- Looking for rare processes
  - Need very high luminosity
  - pp collider is the only choice
    - Better described as a g-g collider
- Experimental challenges
  - QCD – there's a lot of it about
  - Triggering and data handling
  - High energy final states
    - Strong B field, big detectors
  - Radiation dose & longevity

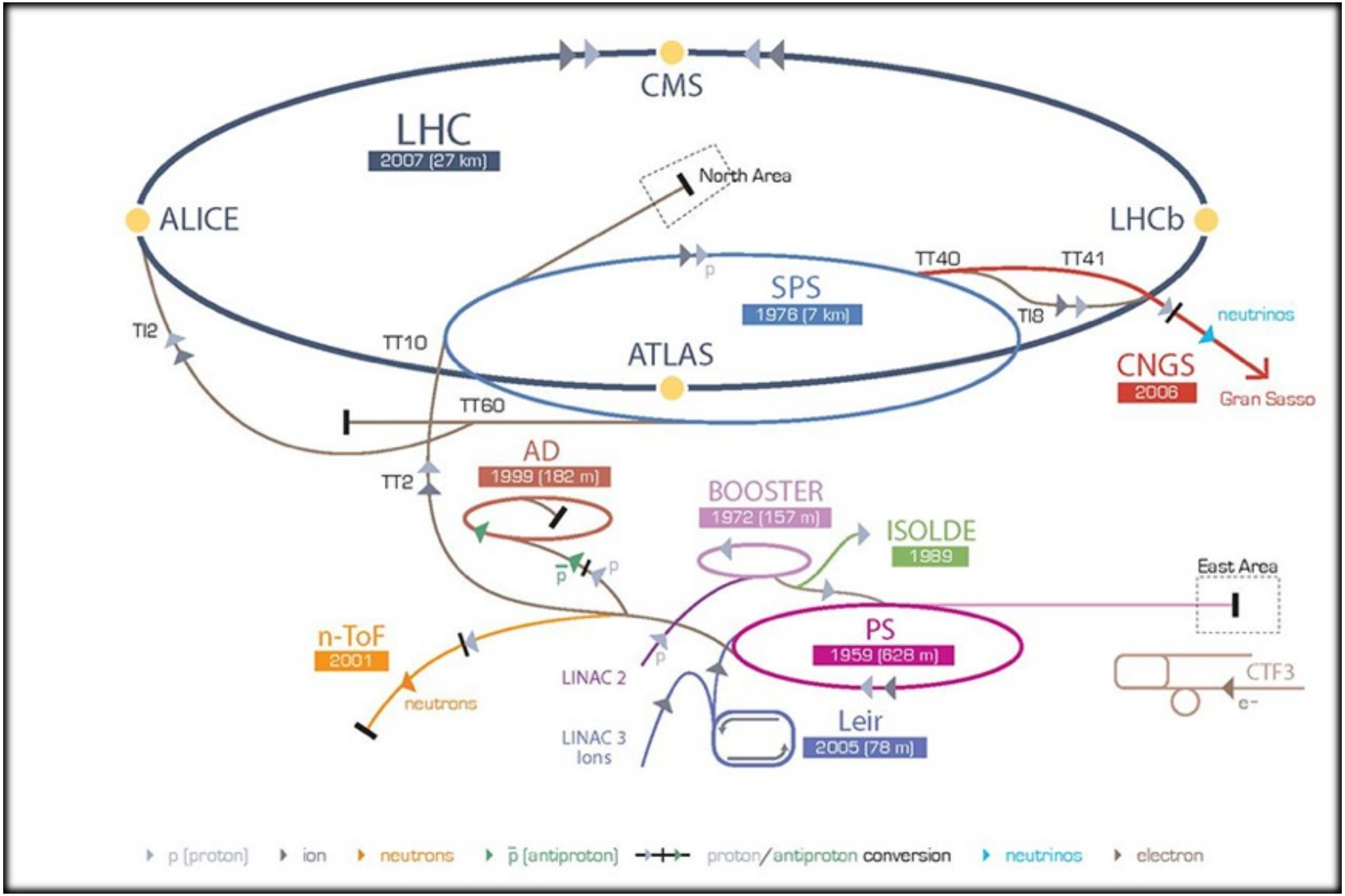


The Machine

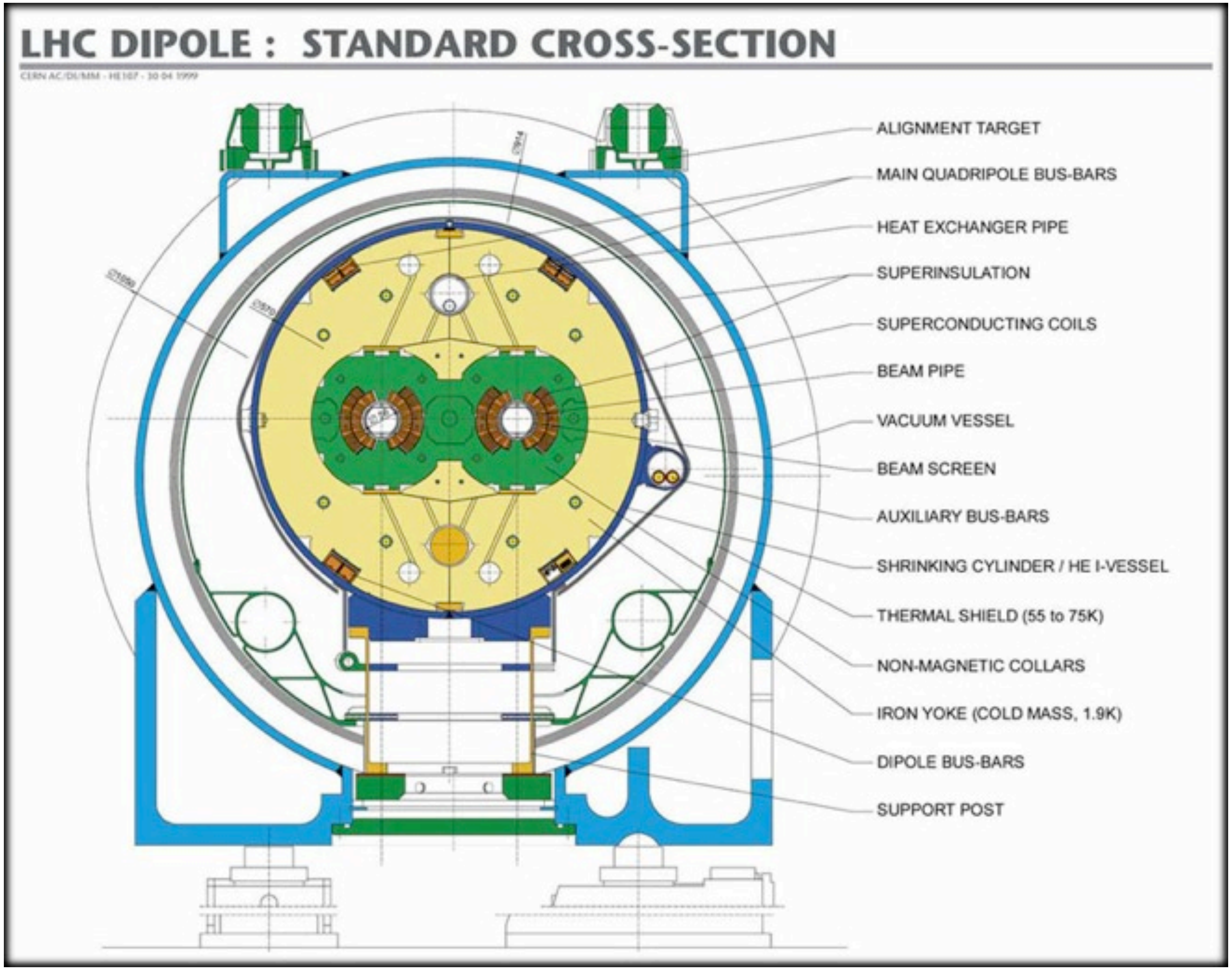


- Design parameters
  - Maximum possible energy in aleady-constructed LEP ring (7 + 7 TeV)
  - Highest possible luminosity within cost ($10^{34}cm^{-2}s^{-1}$, 100/fb/yr)
- Cost: ~2GCHF (same as LEP); ~12 years construction

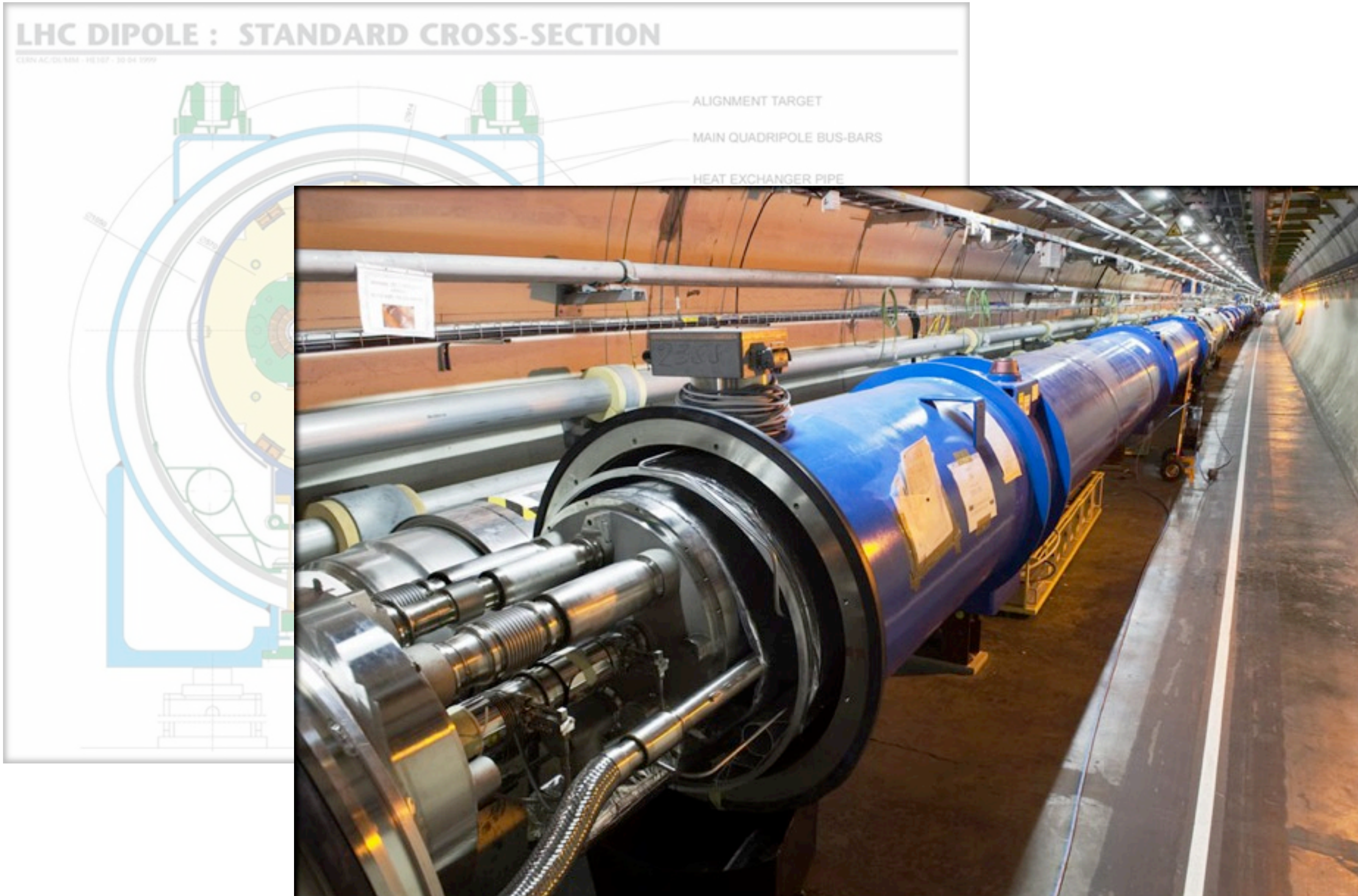
CERN Accelerator Complex



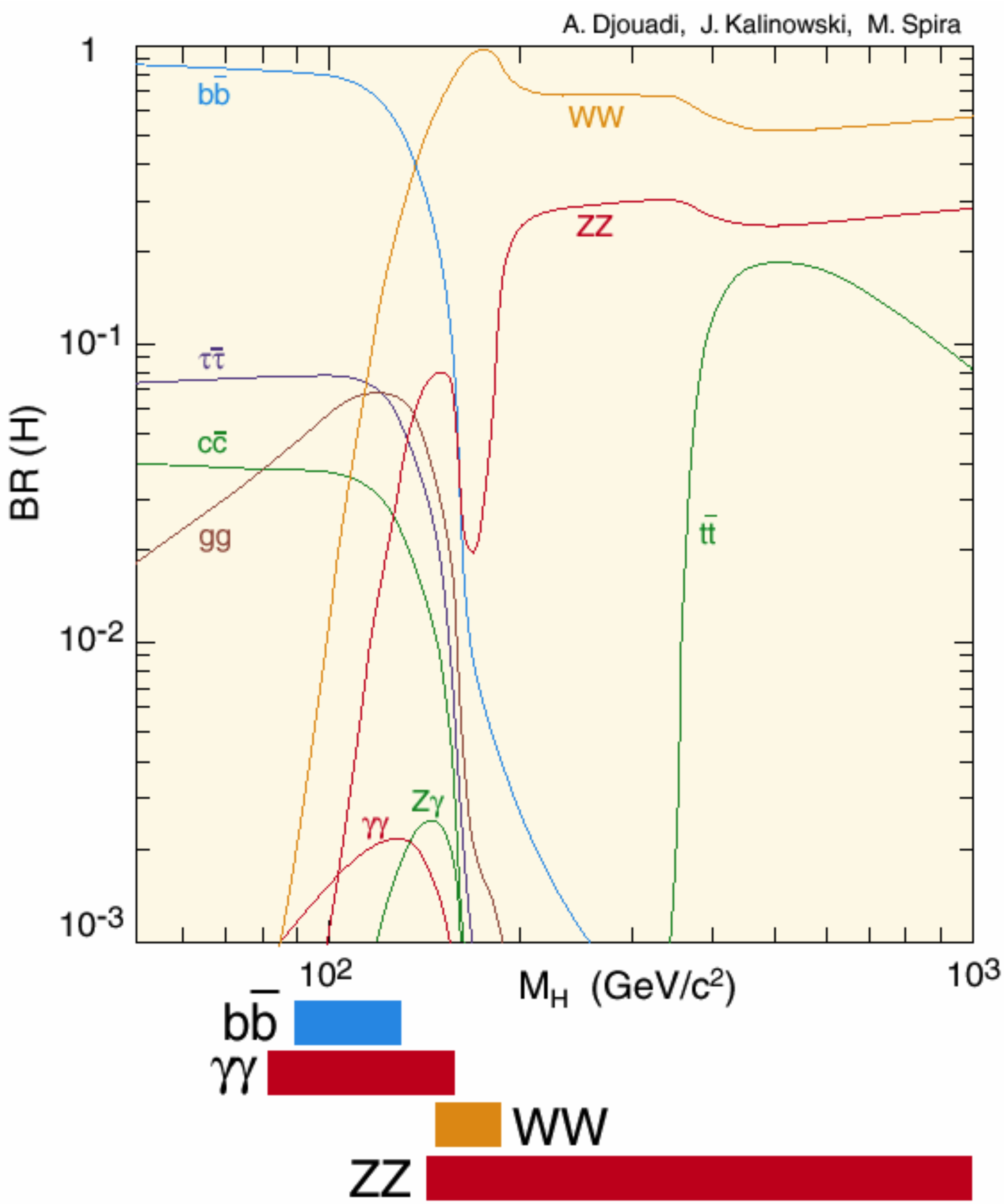
Superconducting Magnets



Superconducting Magnets



Designing the GPDs



- Design for most challenging case
  - e.g. light SM H -> γγ
  - Fortunate decision, it seems
- Points to note:
  - H -> bb is experimentally inaccessible at LHC
    - Modulo tricks with exclusive production?
    - Or is it?
  - H -> γγ has very low BR
    - And there are plenty of high pt photons from other sources
  - SM Higgs width at ~100GeV is narrow
    - This helps considerably

GPDs: Main Features

- Robust muon systems
  - Background estimates had large uncertainties in 1990s
  - If all else fails... nobody ever got fired for finding muons
  - Heavy shielding can cut down most sources of background
- Exceptional electromagnetic calorimetry (e, γ)
  - Motivated by narrowness of H -> $\gamma\gamma$ peak
  - Also helps with leptonic decays of heavy states
- High performance, highly redundant, tracking
  - Requires extremely strong magnetic field (4T / 2T for CMS / ATLAS)
  - Many layers of radiation-resistant silicon
  - Multi-layer pixel detectors for track finding with large occupancy
- Two GPDs at the LHC
  - Identical physics goals, different experimental strategies
  - So far, both appear to have comparable performance

ATLAS

Standalone muon spectrometer ($|\eta| < 2.7$), 3 layers gas based muon chambers,

muon trigger and muon momentum determination

- 46m length,
- 25m diameter,
- 7000t weight

- 3 level trigger,

Collision rate 40MHz,

LV1 accepts up to 75kHz,

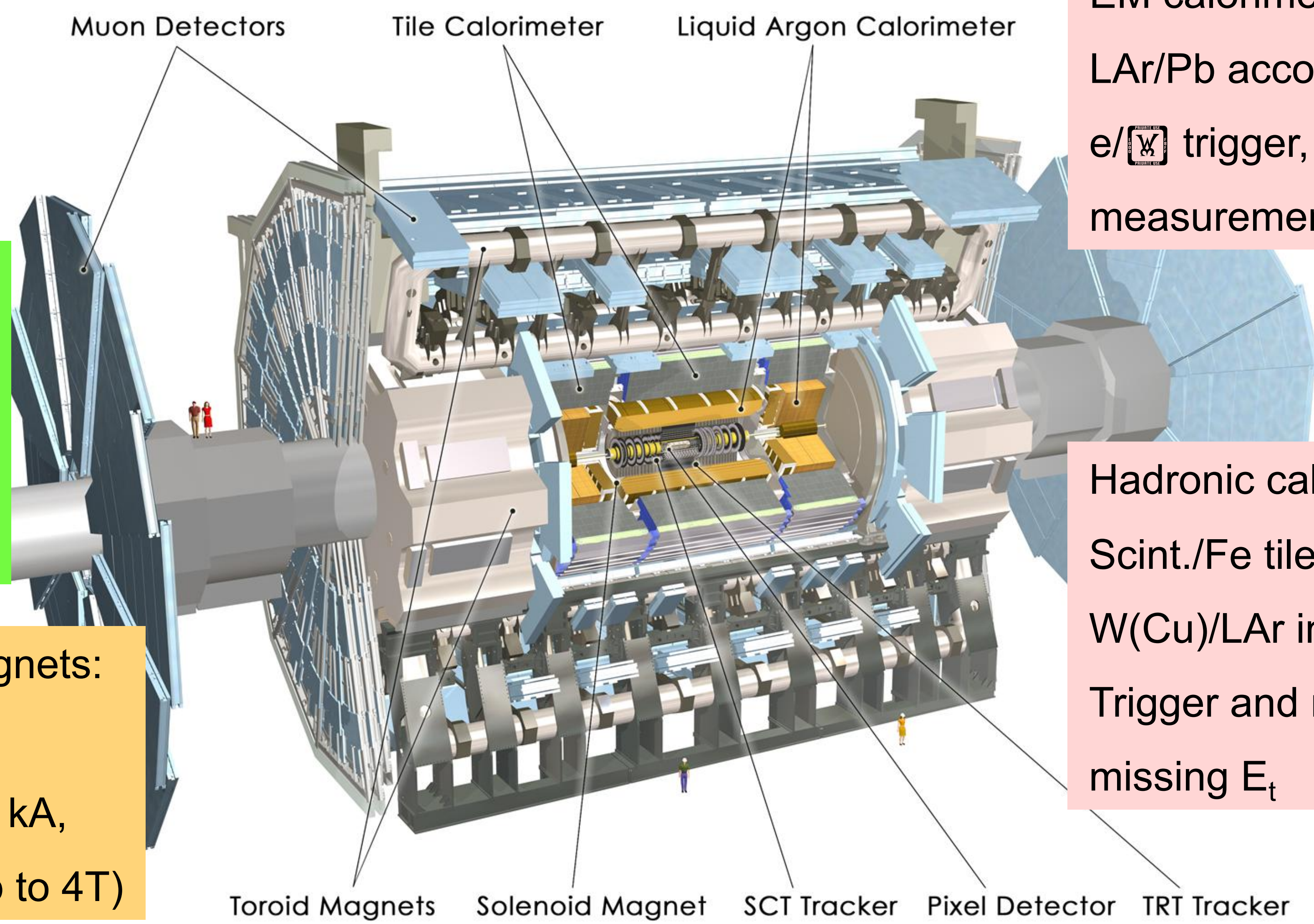
→ recorded ~300 Hz

Super-conducting magnets:

2T Solenoid (7.6kA) ,

3 Air Core Toroids (22 kA,

peak field strength up to 4T)



EM calorimeter:

LAr/Pb according structure

e/γ trigger, identification + measurement

Hadronic calorimeter:

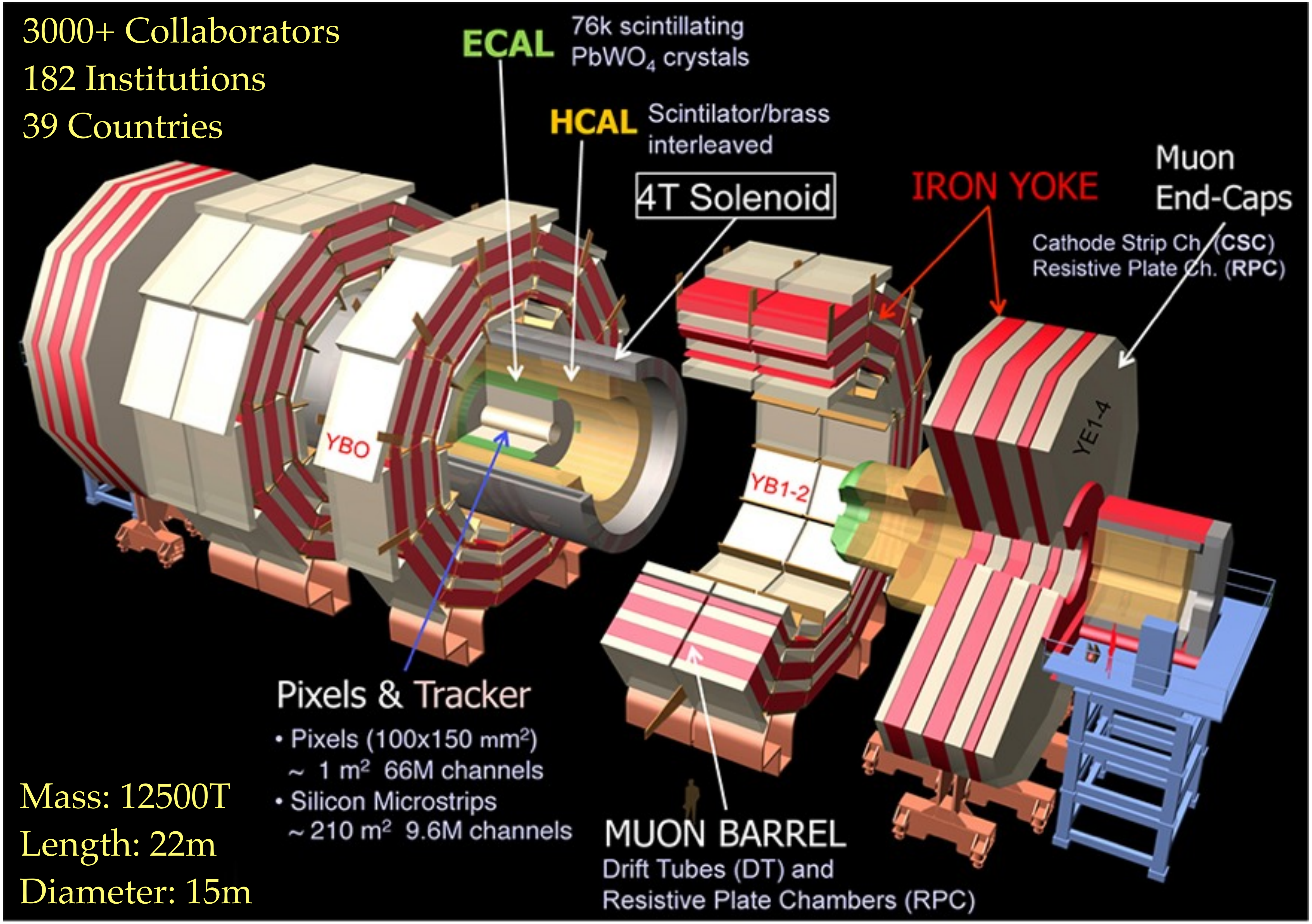
Scint./Fe tiles in the central,

W(Cu)/LAr in fwd region

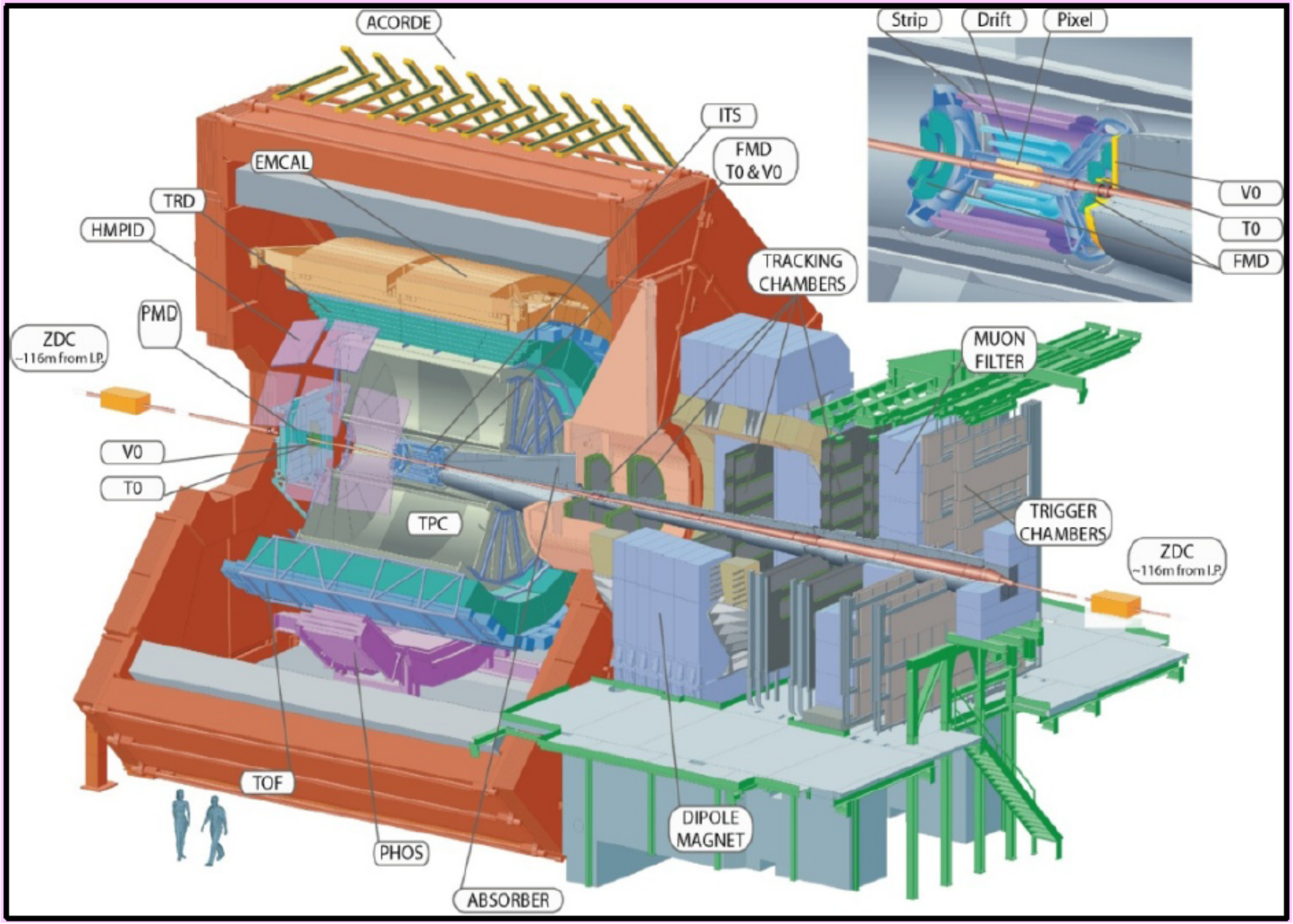
Trigger and measure jets + missing E_t

Inner Detector: ~10^8 Si Pixels, $6 \cdot 10^6$ Si Strips, Transition Radiation Tracker (TRT) – Xe-filled straw tubes interleafed with PP/PE foil for Cherenkov light: precise vertexing, tracking, e/γ separation

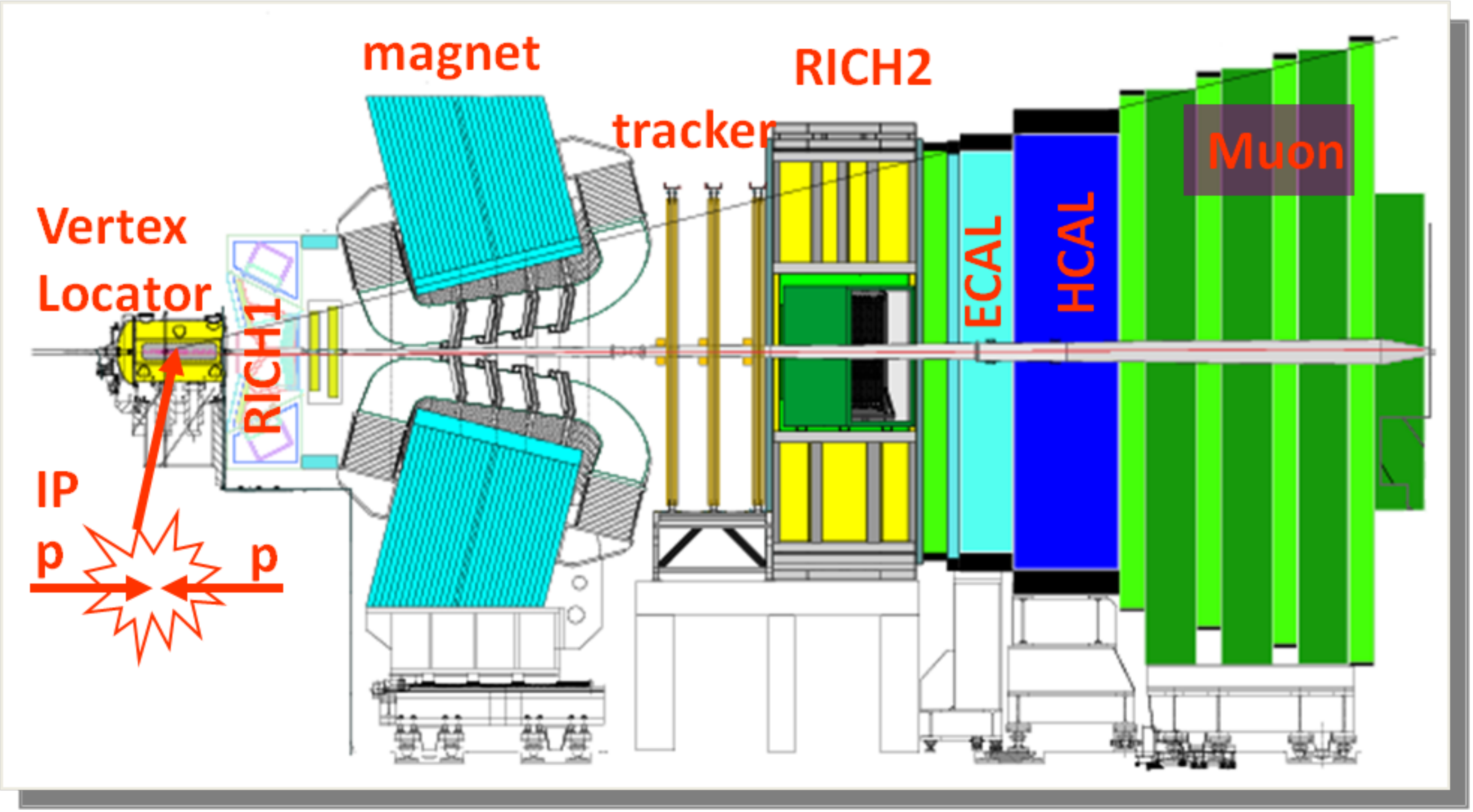
CMS


3000+ Collaborators
182 Institutions
39 Countries
ECAL
76k scintillating $PbWO_4$ crystals
HCAL
Scintilator/brass interleaved
4T Solenoid
IRON YOKE
Muon End-Caps
Cathode Strip Ch. (CSC)
Resistive Plate Ch. (RPC)
YBO
YB1-2
YE1-4
Pixels & Tracker
• Pixels (100x150 mm²)
~ 1 m² 66M channels
• Silicon Microstrips
~ 210 m² 9.6M channels
MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)
Mass: 12500T
Length: 22m
Diameter: 15m

ALICE (Heavy Ions)



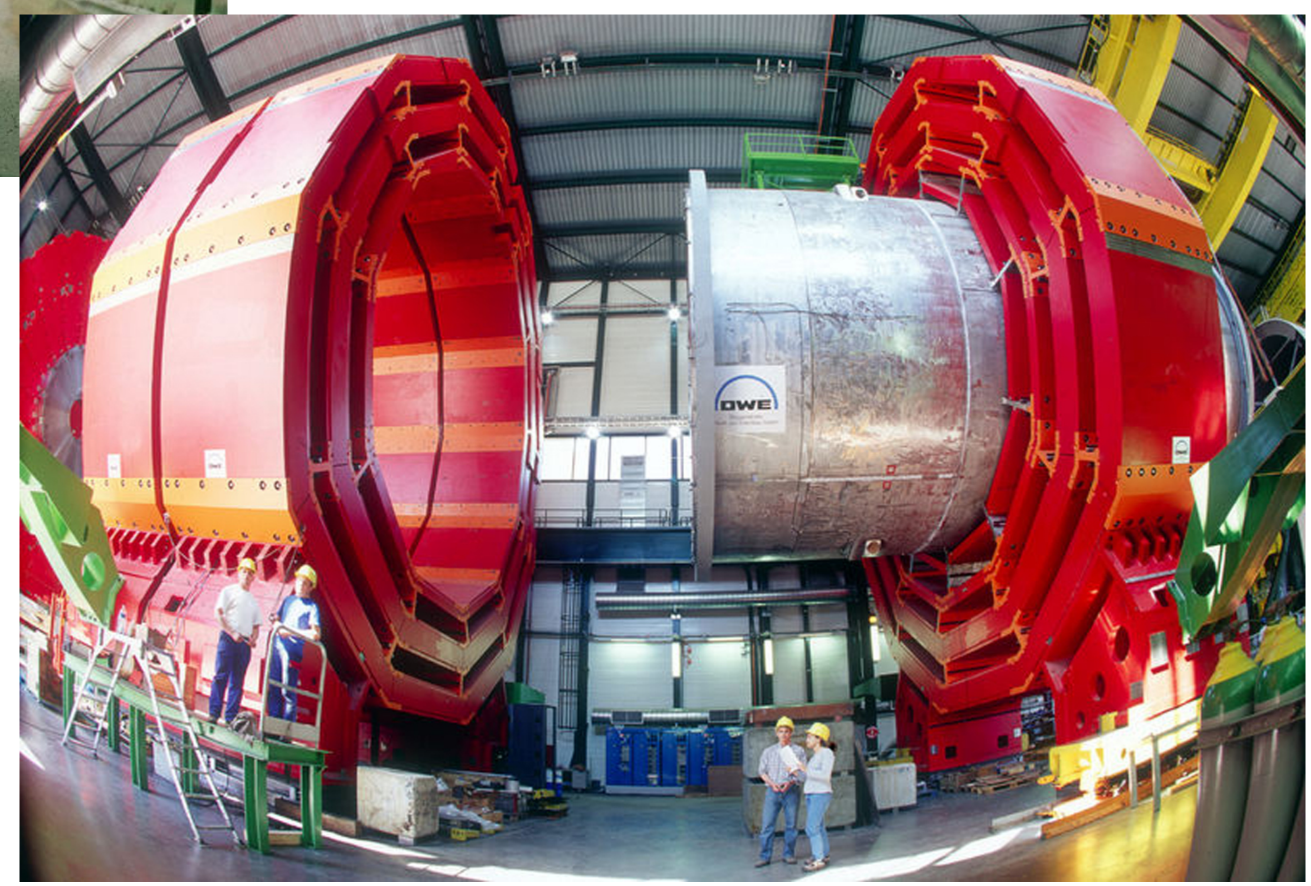
LHCb (b Physics)



Detectors: Magnets

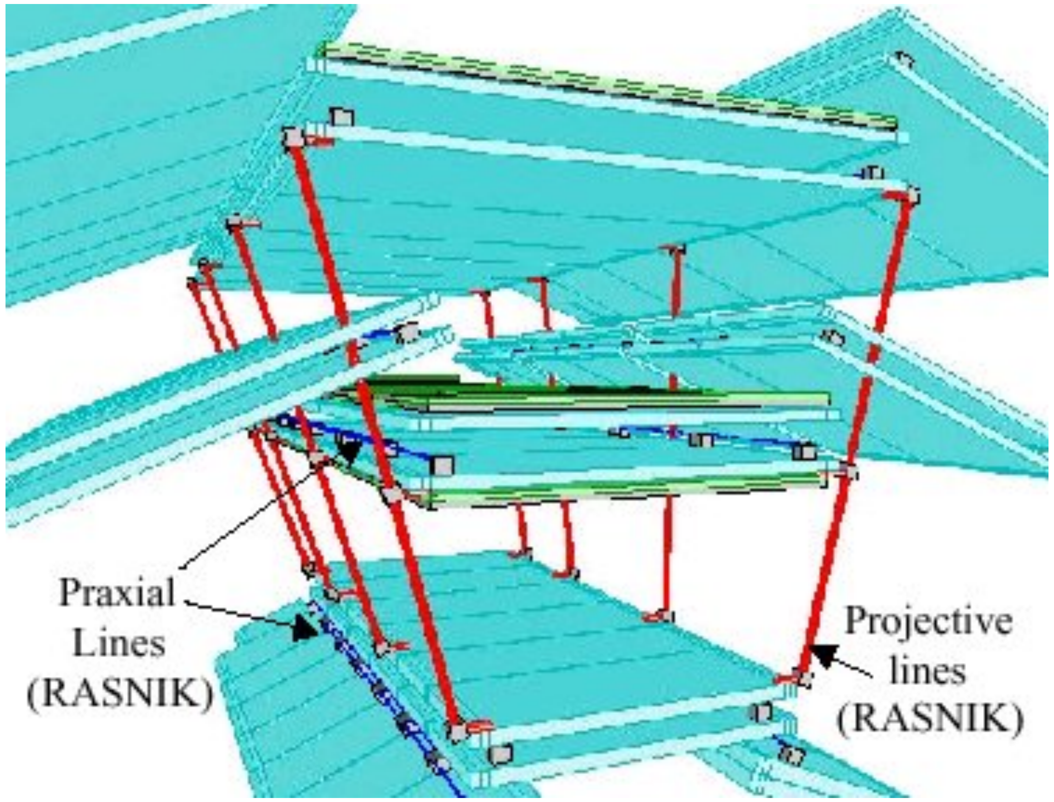
ATLAS toroid in transit

CMS yoke and solenoid vessel



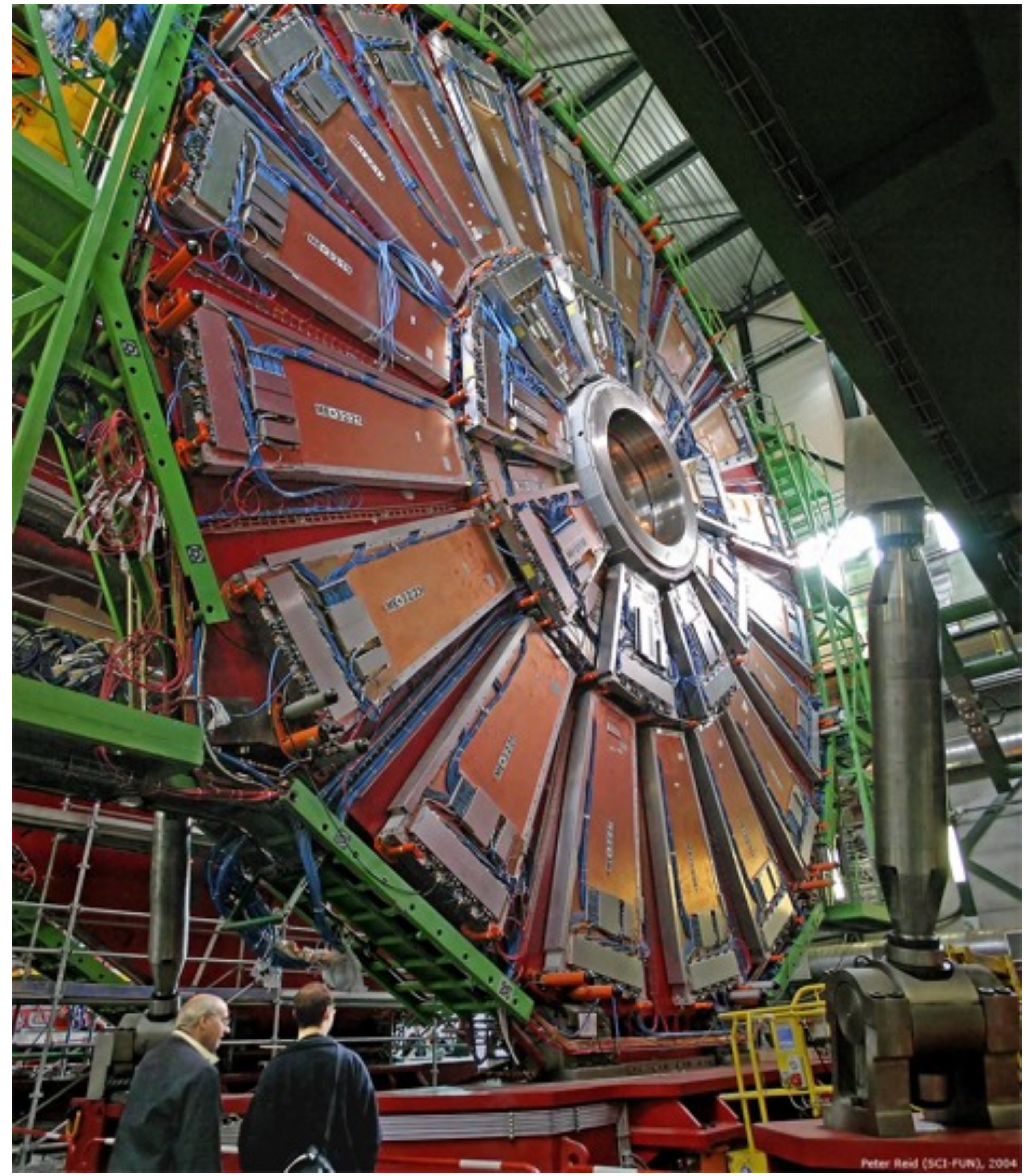
- Key challenges
  - Logistics and cost
  - Safety
  - Longevity

Detectors: Muons



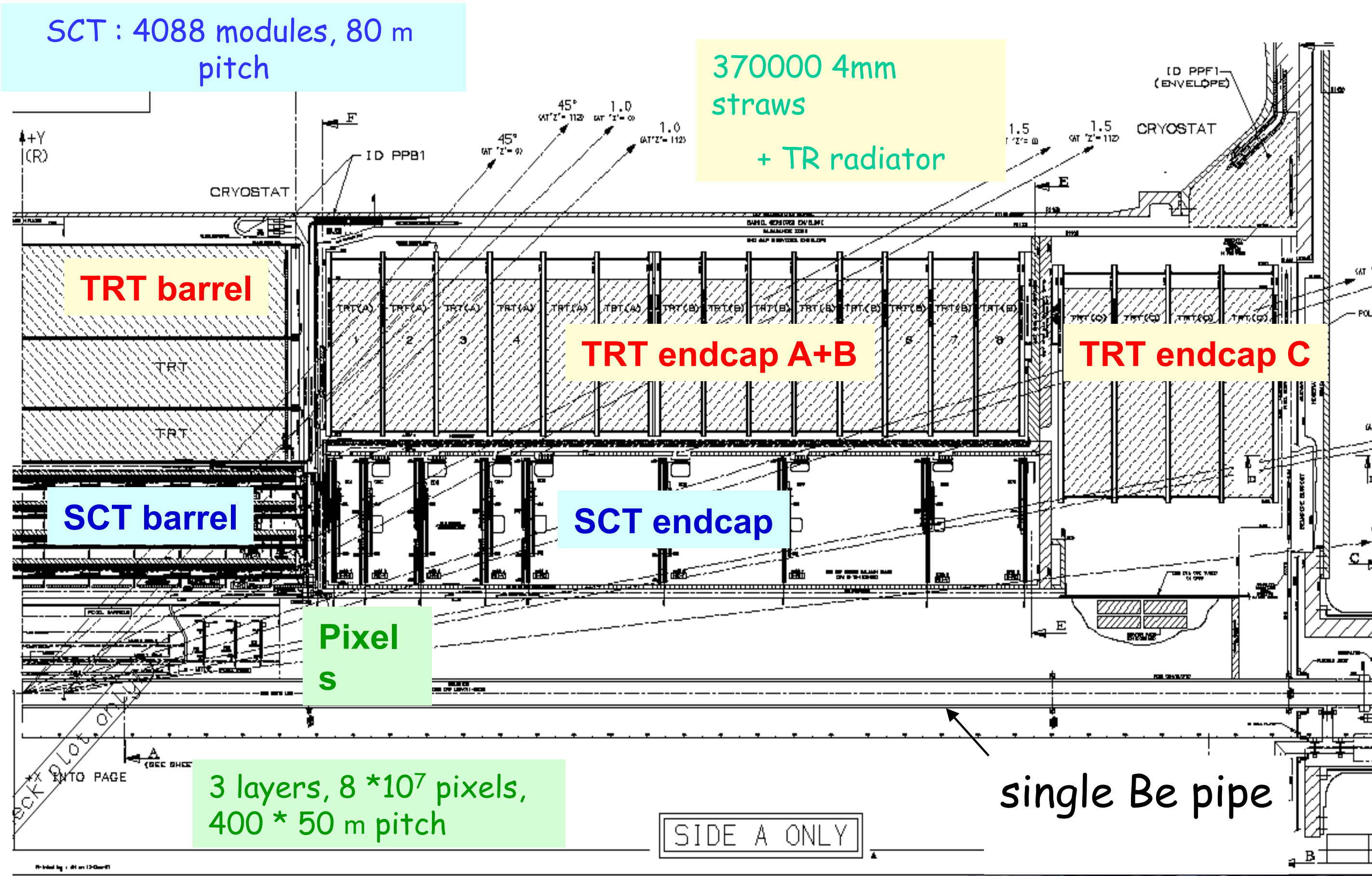
Optical alignment of muons / tracking

- Key challenges
  - Construction and scale
  - Alignment
  - Stable operation in aging



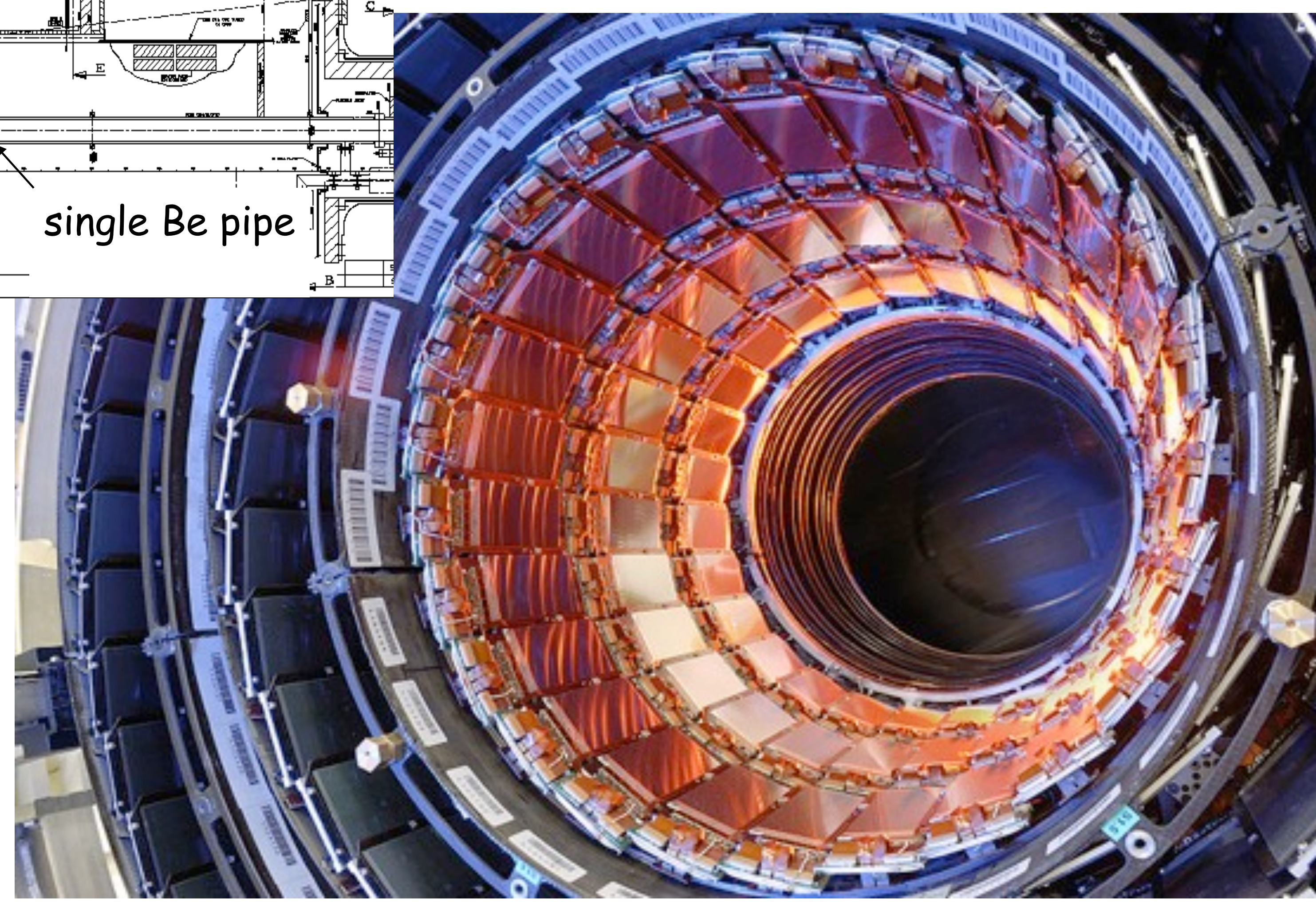
CMS endcap muon chambers

Detector Highlights: Tracking



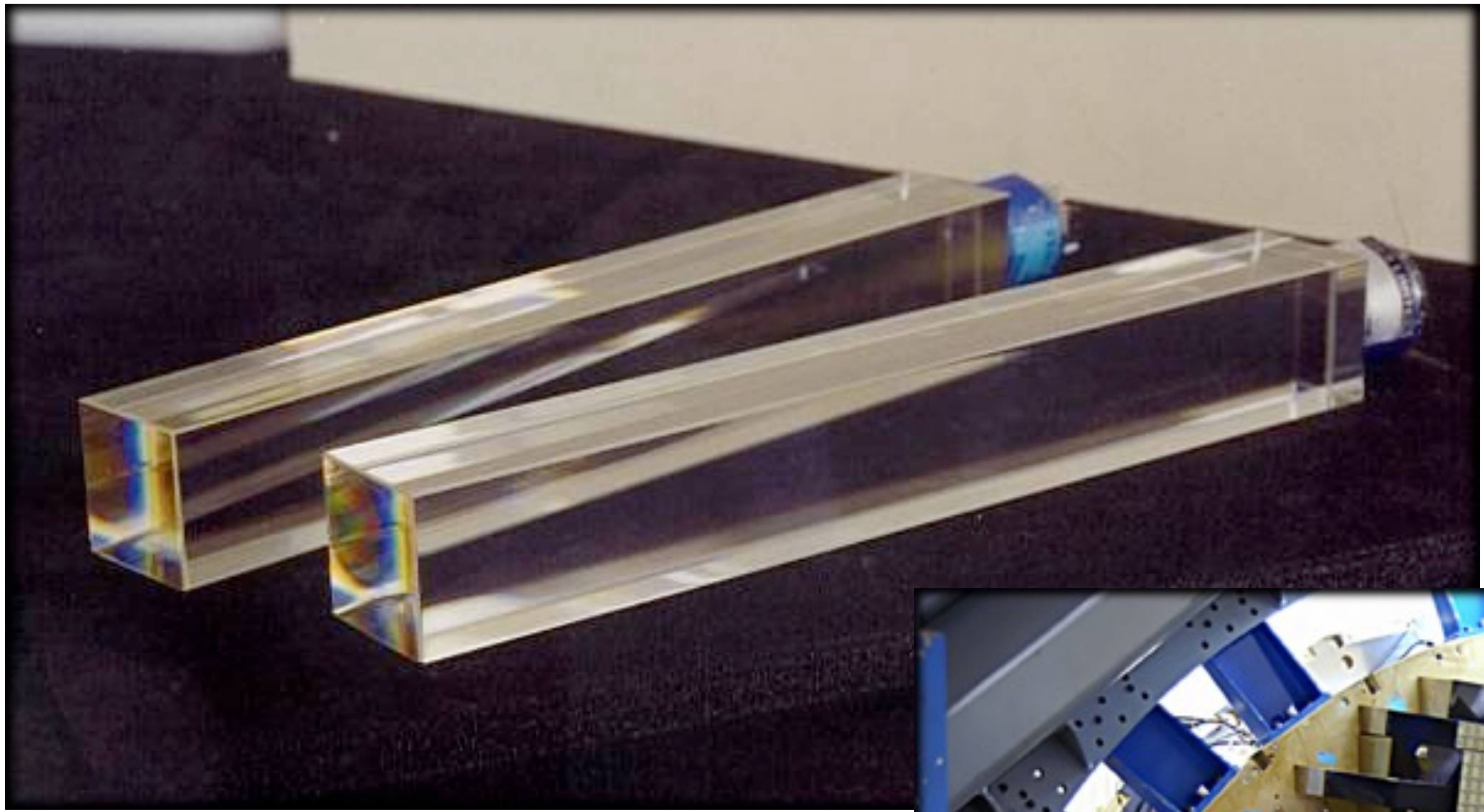
ATLAS Inner detector layout

CMS Tracker under construction



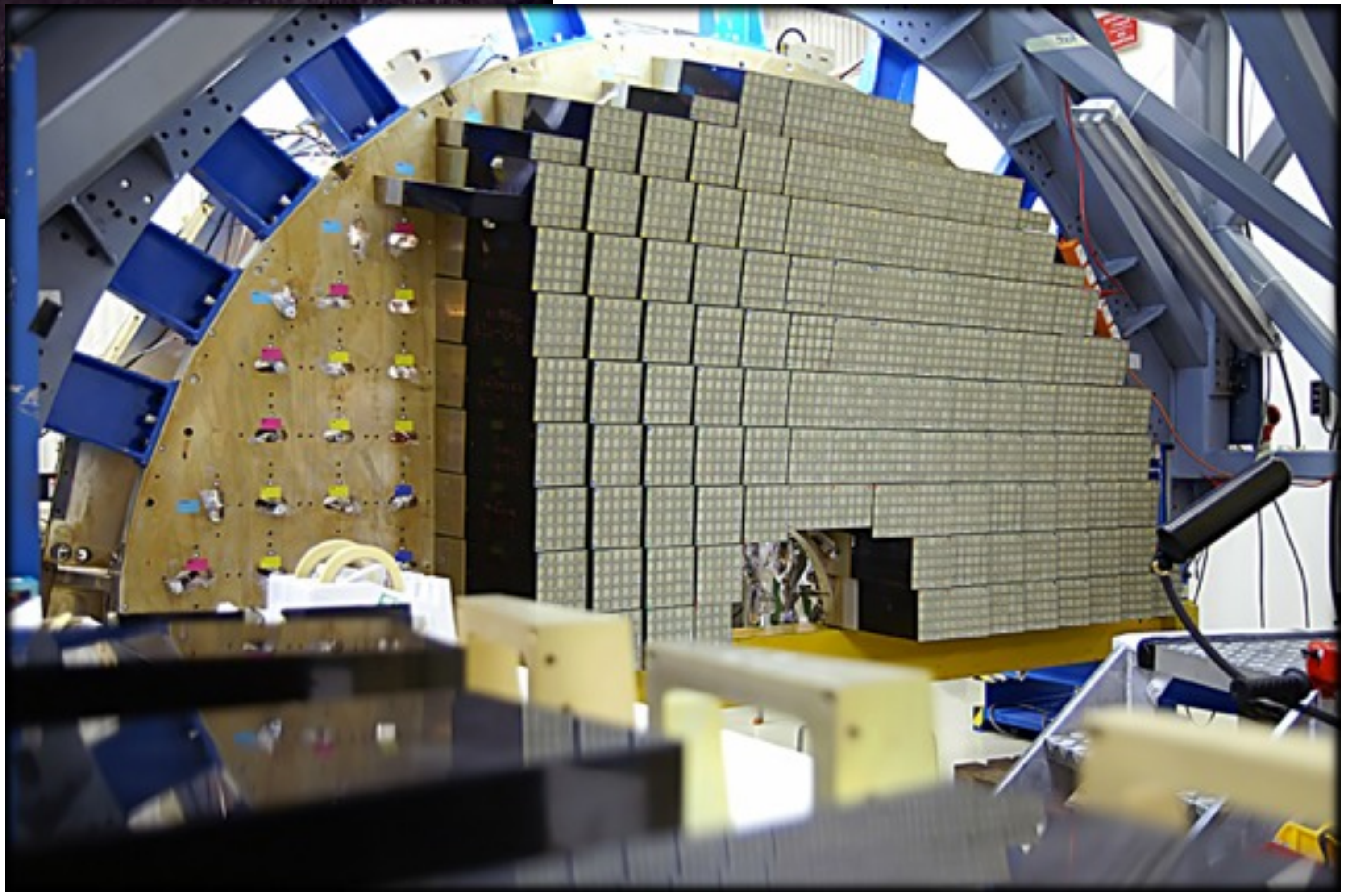
- Key challenges
  - Power, cooling, cabling
  - Alignment
  - Radiation tolerance
  - Beam safety

Detector Highlights: Calorimetry



CMS PbWO4 crystals: effectively, transparent metal (3kg each)

CMS endcap ECAL assembly by robot

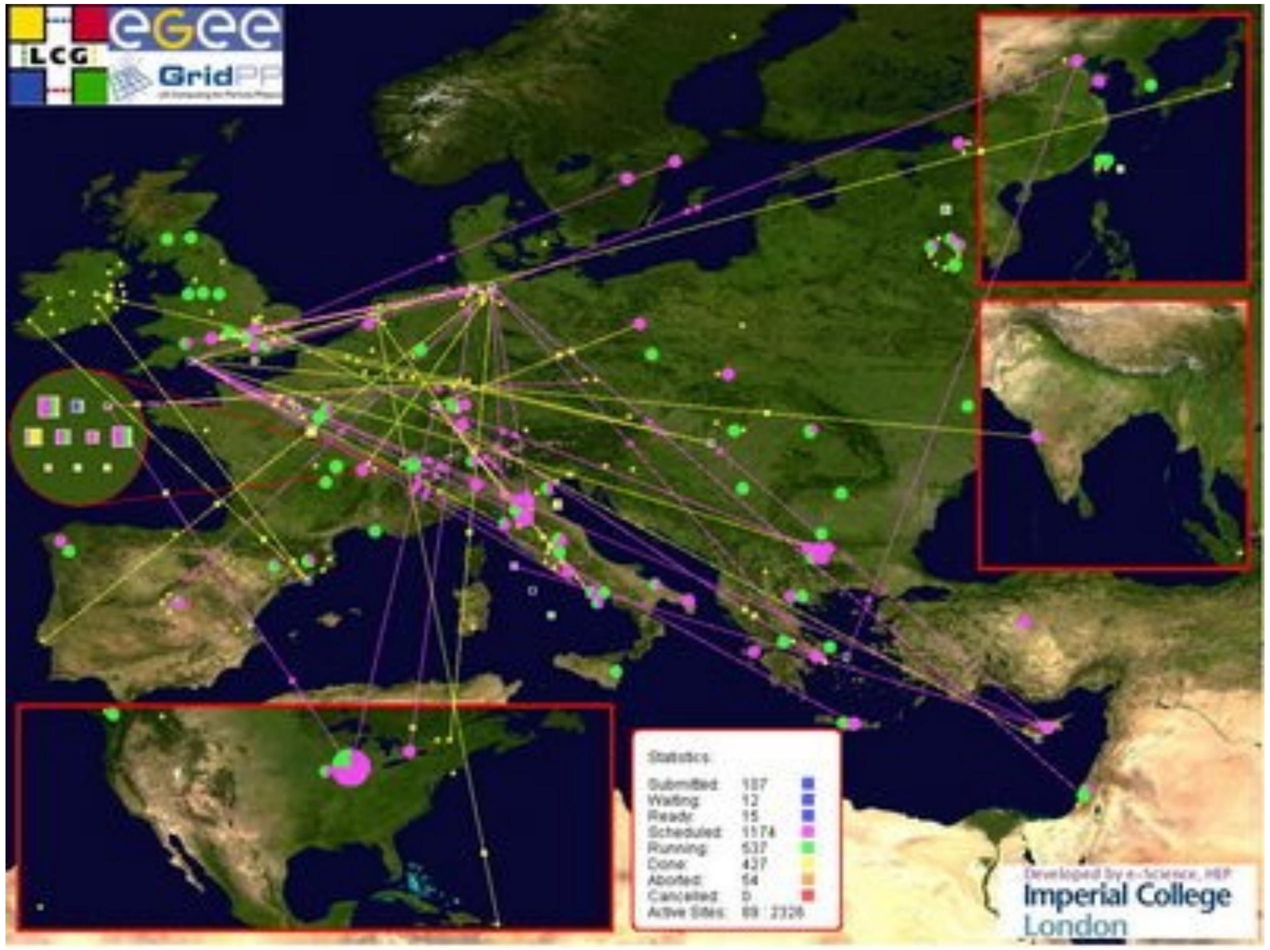


- Key challenges
  - Calibration (0.5% required)
  - Stability
  - Energy scale determination
  - Maintenance and disposal

Level-1 Trigger Strategy

- Driven by LHC physics conditions
  - Heavy decays against "soft" QCD b/g; intermediate W / Z; H-> γγ
  - -> Identify high-pt leptons* and photons (*including τ)
  - Low pt thresholds motivated by efficiency for W / Z / light Higgs
- Trigger combinations
  - >20GeV limit on single-lepton thresholds due to quark decay + π0 b/g
  - Can use lower thresholds for objects in combination (e.g. dileptons)
  - -> Find trigger objects locally, combine and cut only at last stage
- Large uncertainties in background (and perhaps signal)
  - Flexibility and control of rate are both vital
  - -> All trigger thresholds and conditions must be programmable
  - Trigger architecture is fixed, but this is a function of detector geometry
- Must have high and well-understood efficiency
  - -> Need to include overlapping and minbias triggers to measure ε

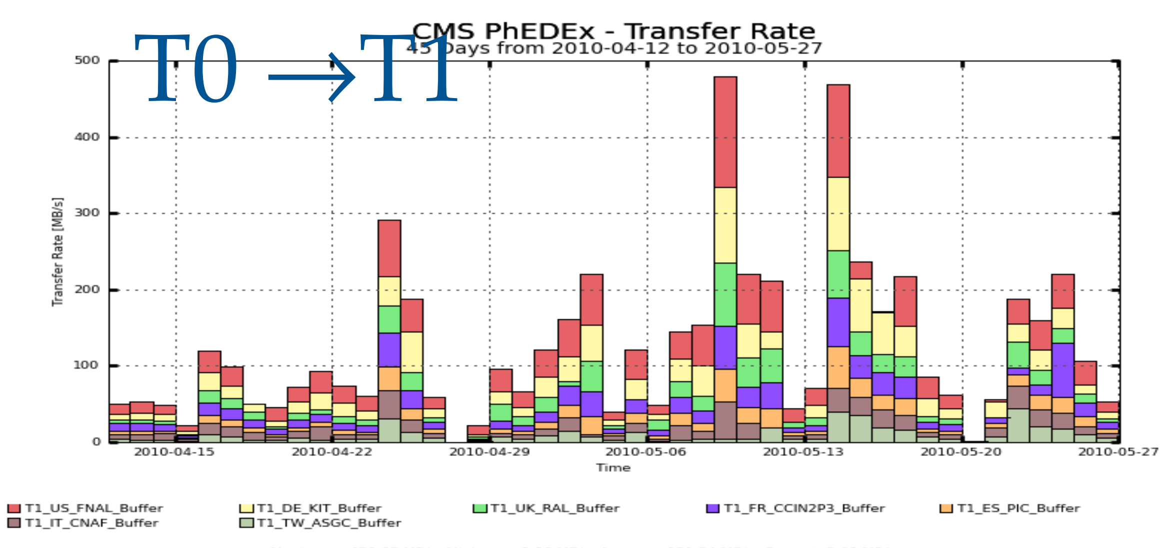
Data Handling



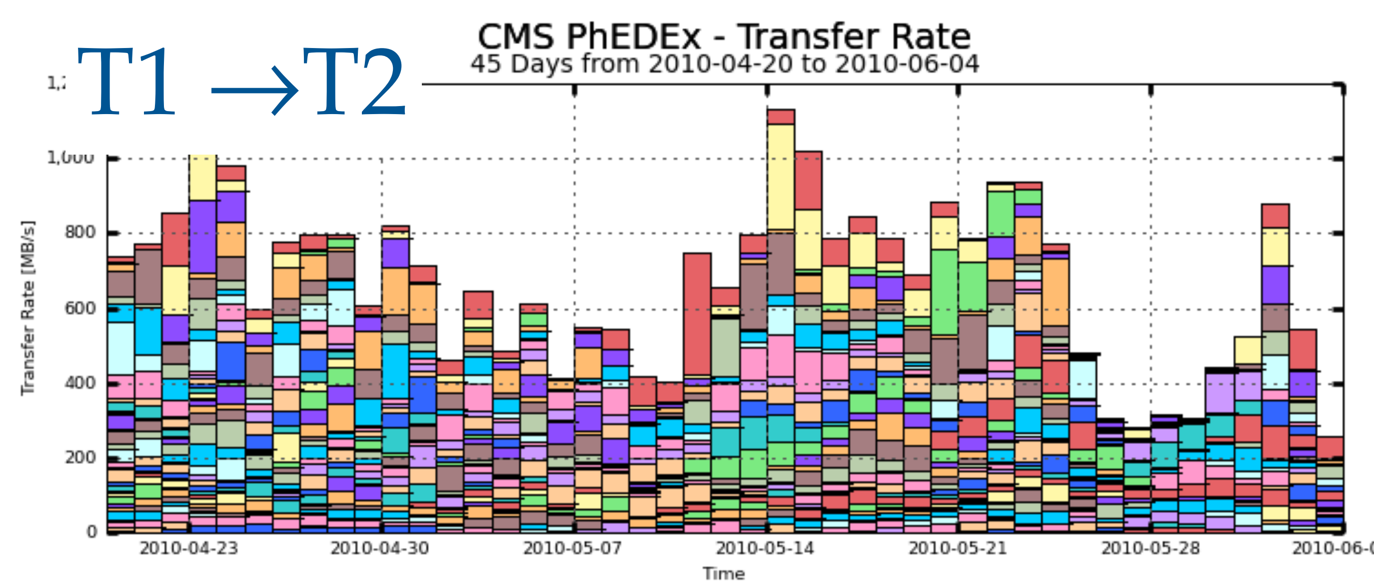
Data transfers worldwide

- Grid computing system
  - Built expressly for LHC data handling
  - World's largest distributed system
  - Dataflows > 400Gb/s partly on private optics
  - 100,000+ CPUs online

T0 →T1



T1 →T2



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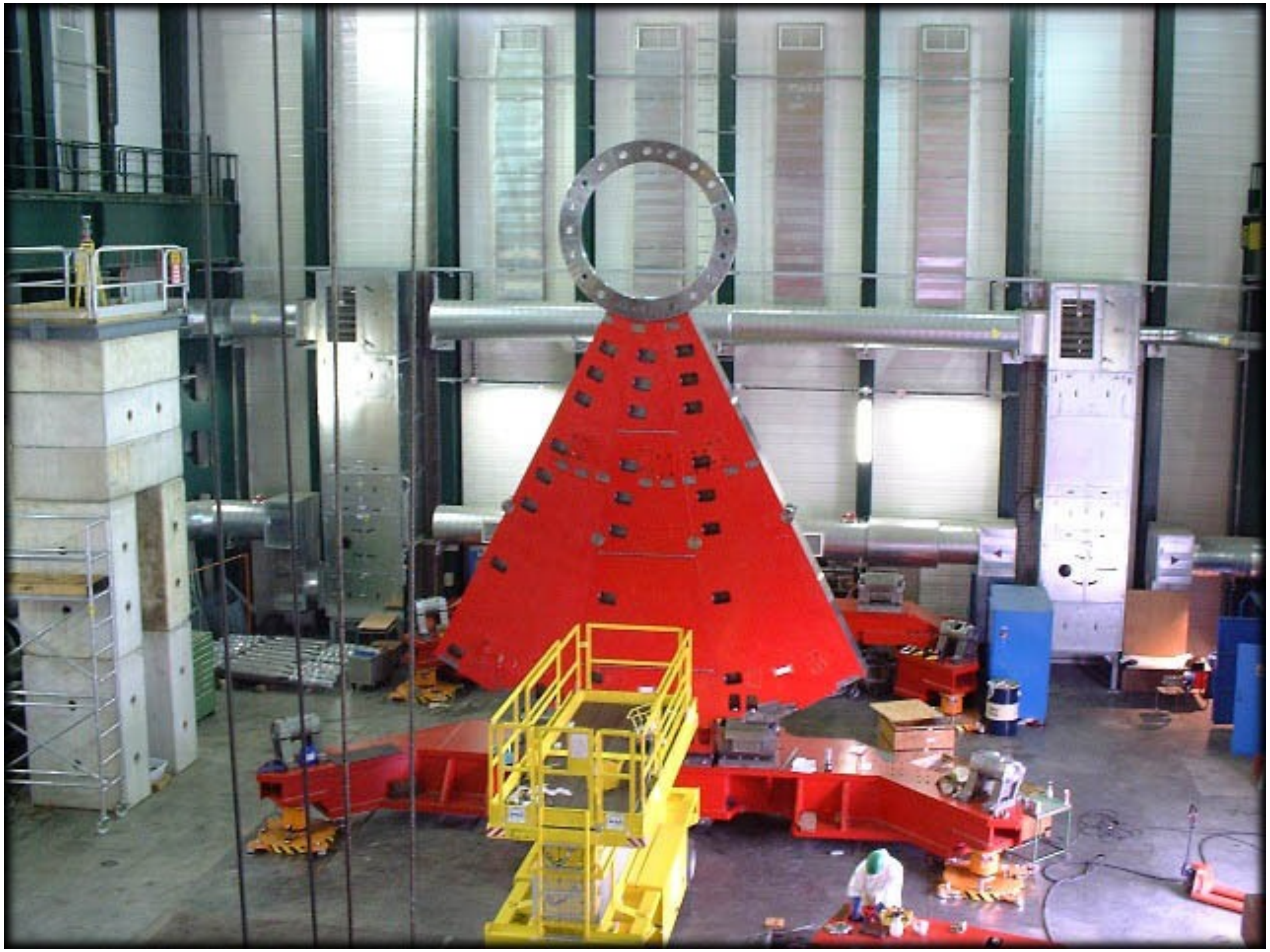
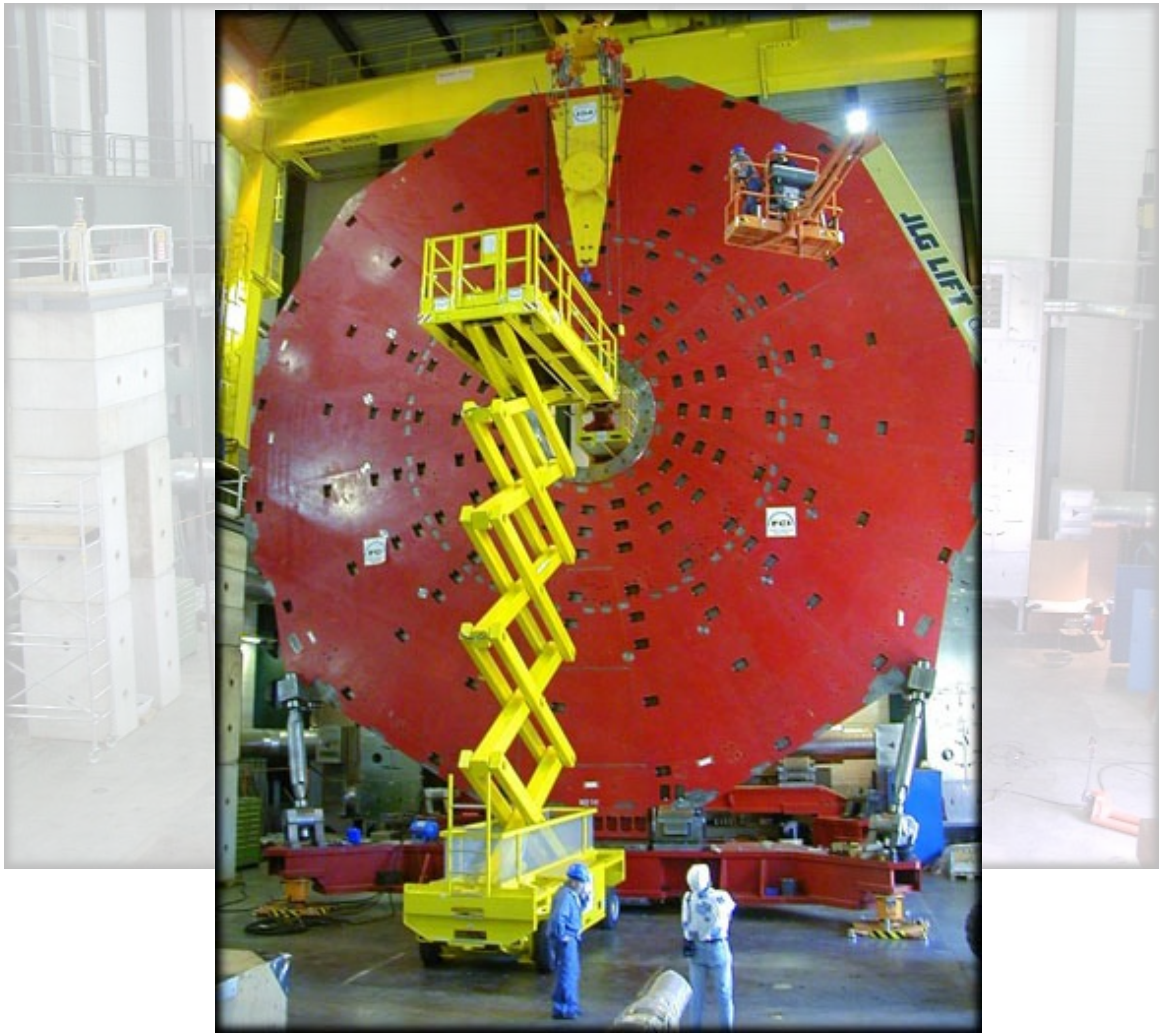
Construction of CMS



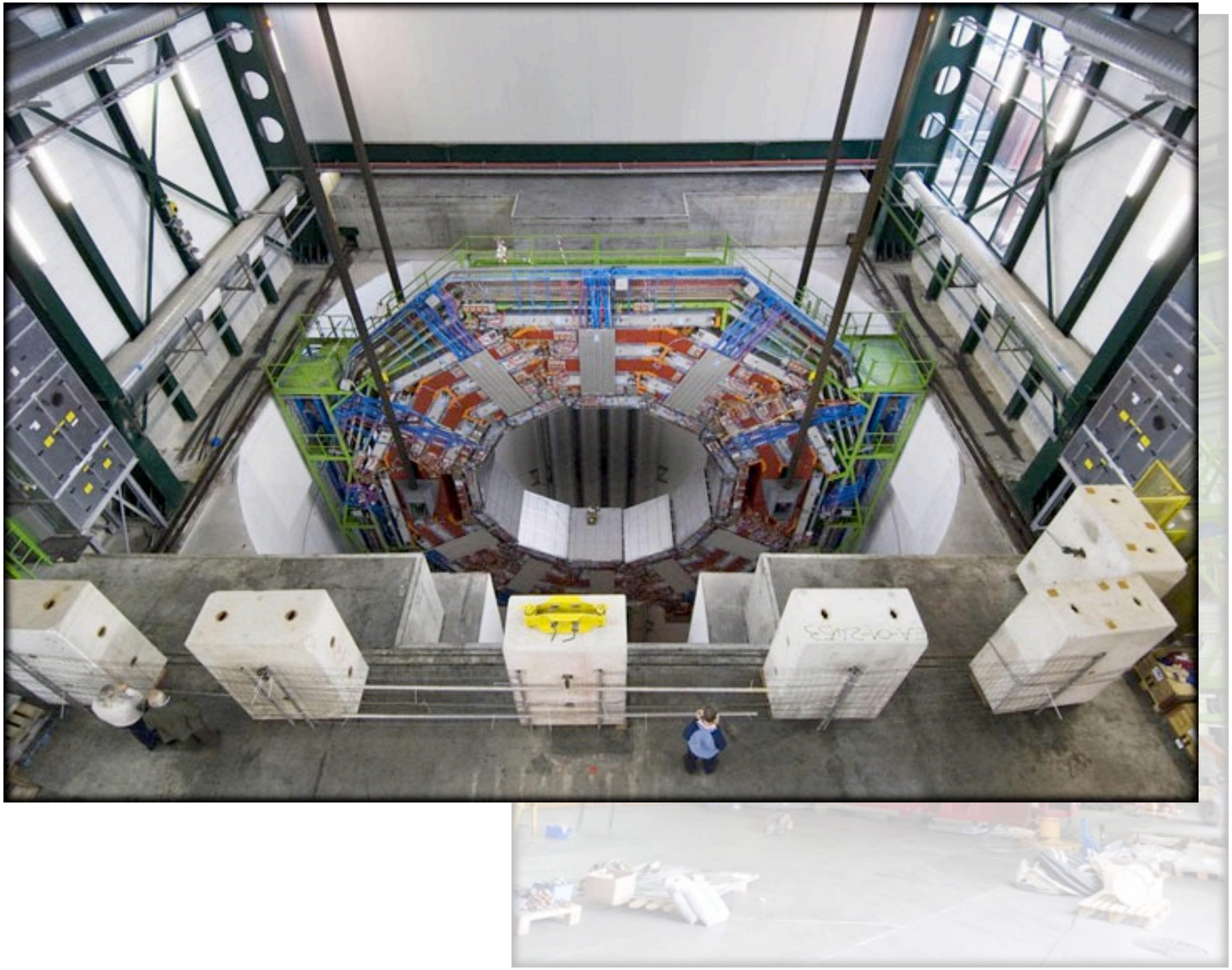
Construction of CMS



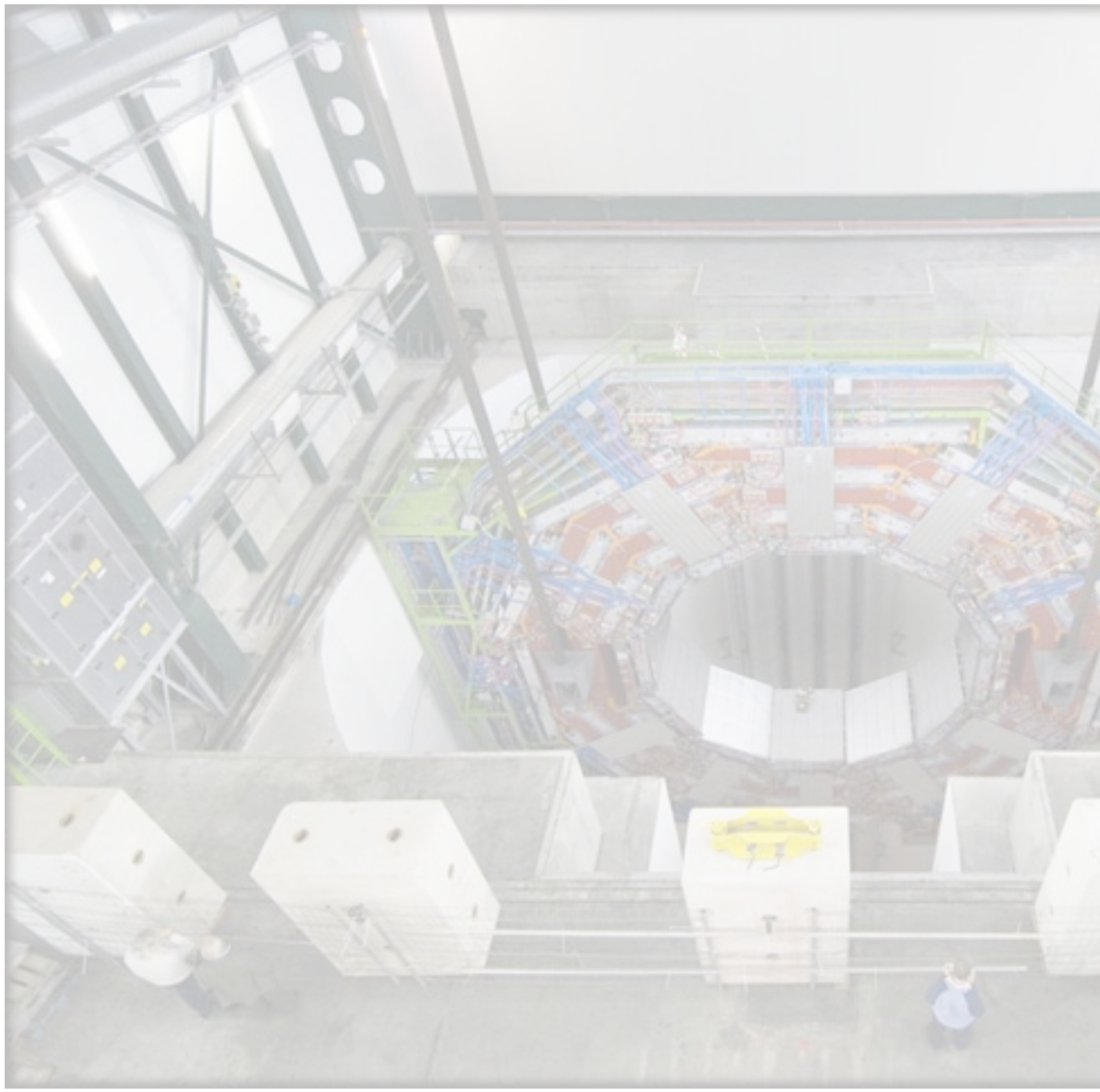
Construction of CMS

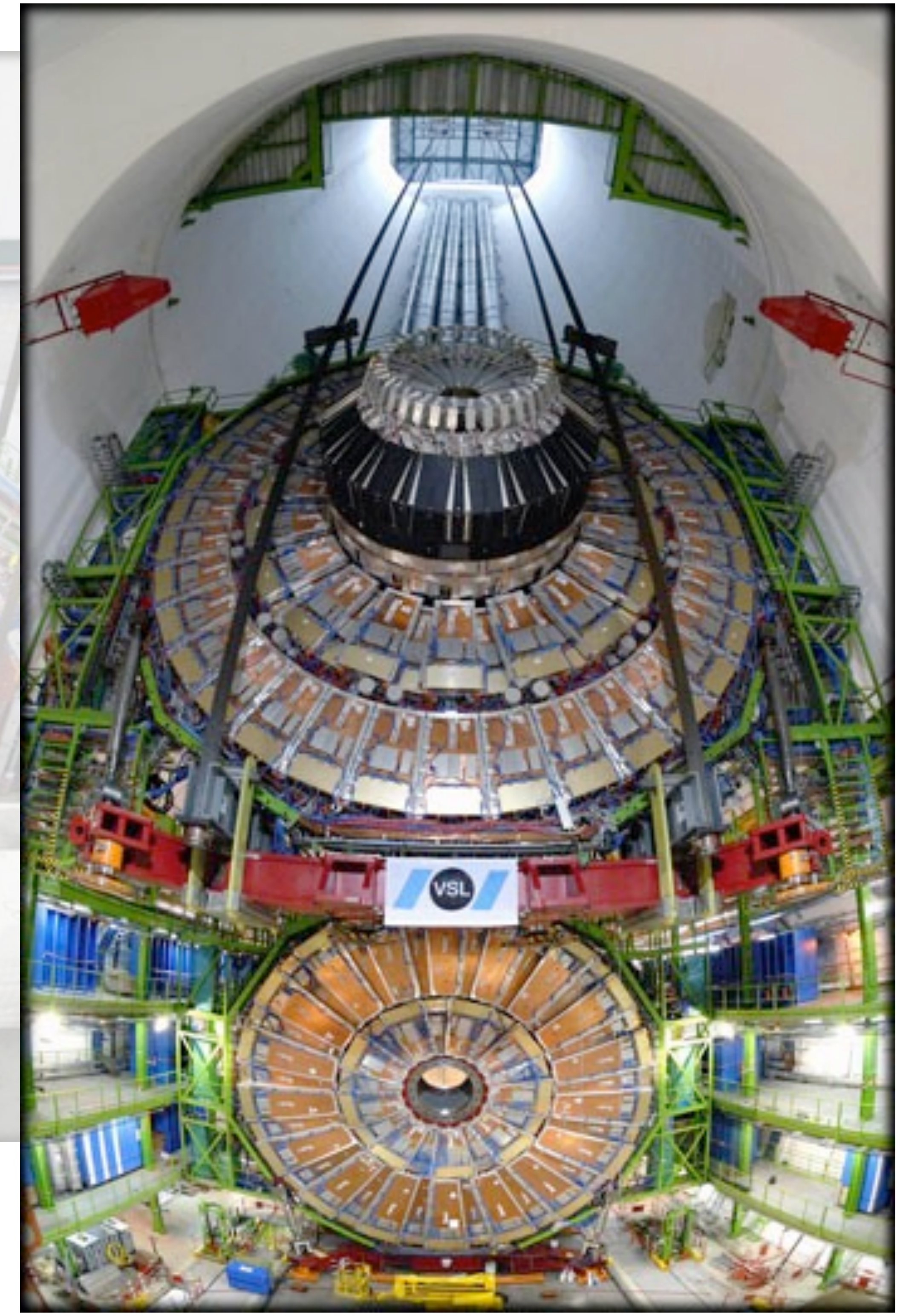
Construction of CMS

Construction of CMS



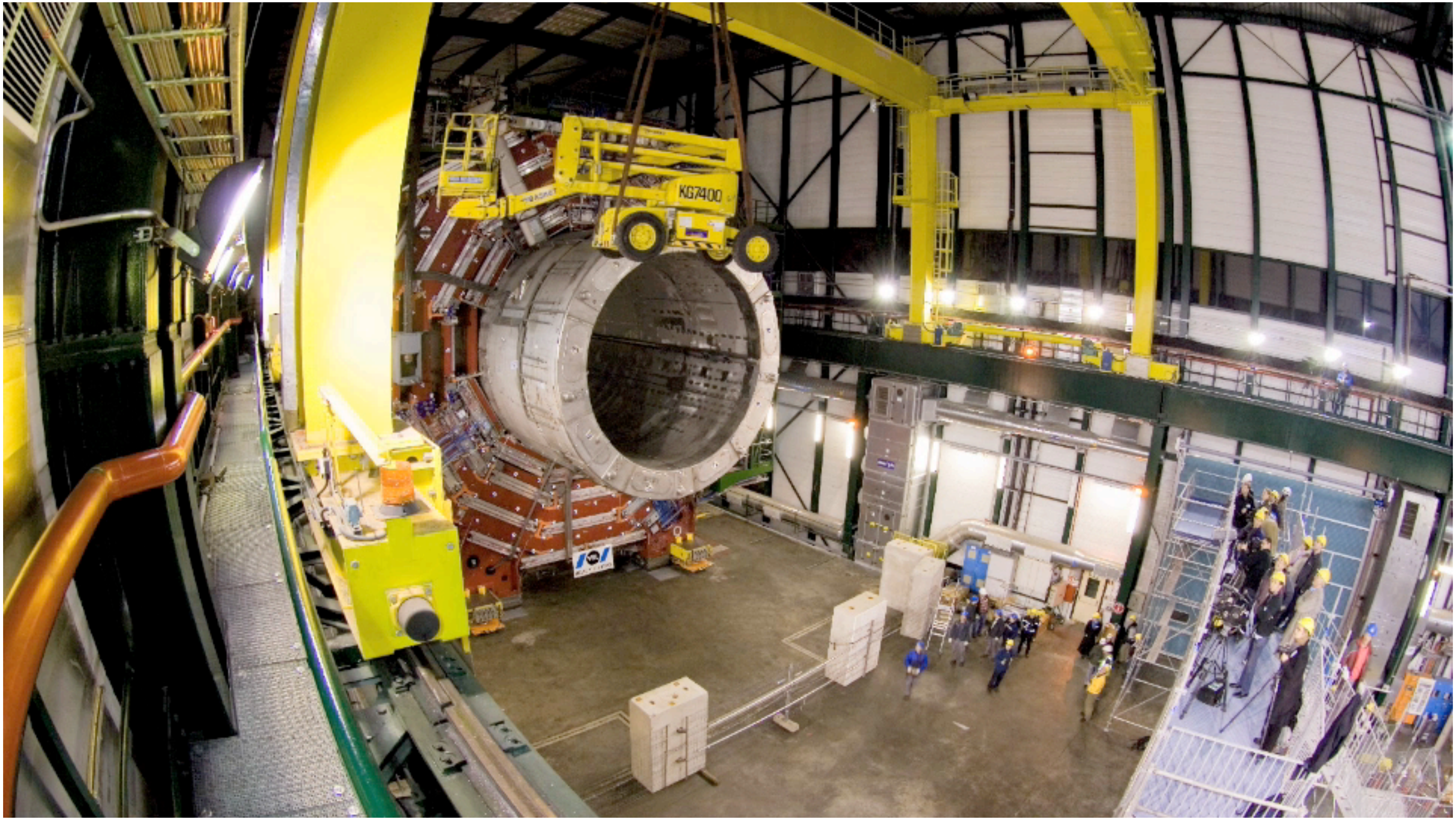
Construction of CMS



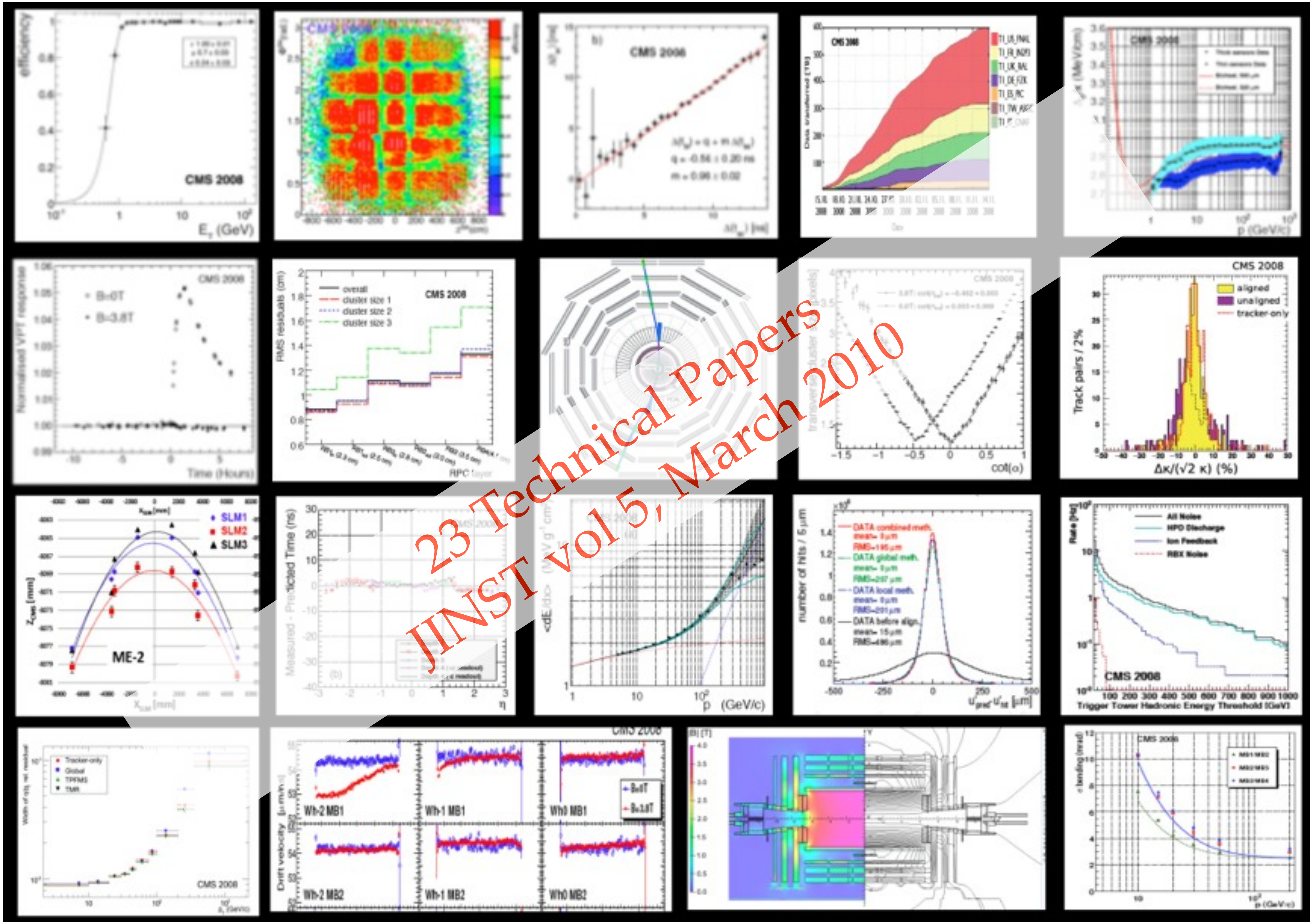


Going Underground

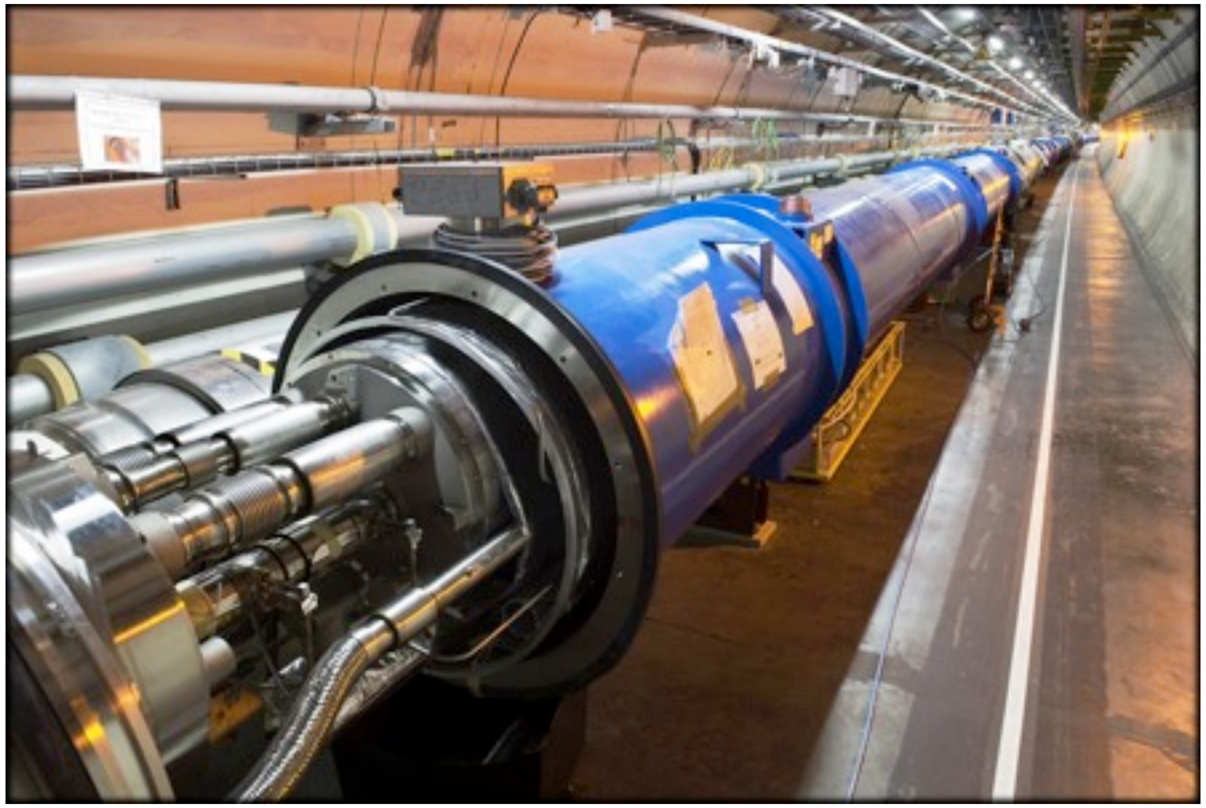
Going Underground

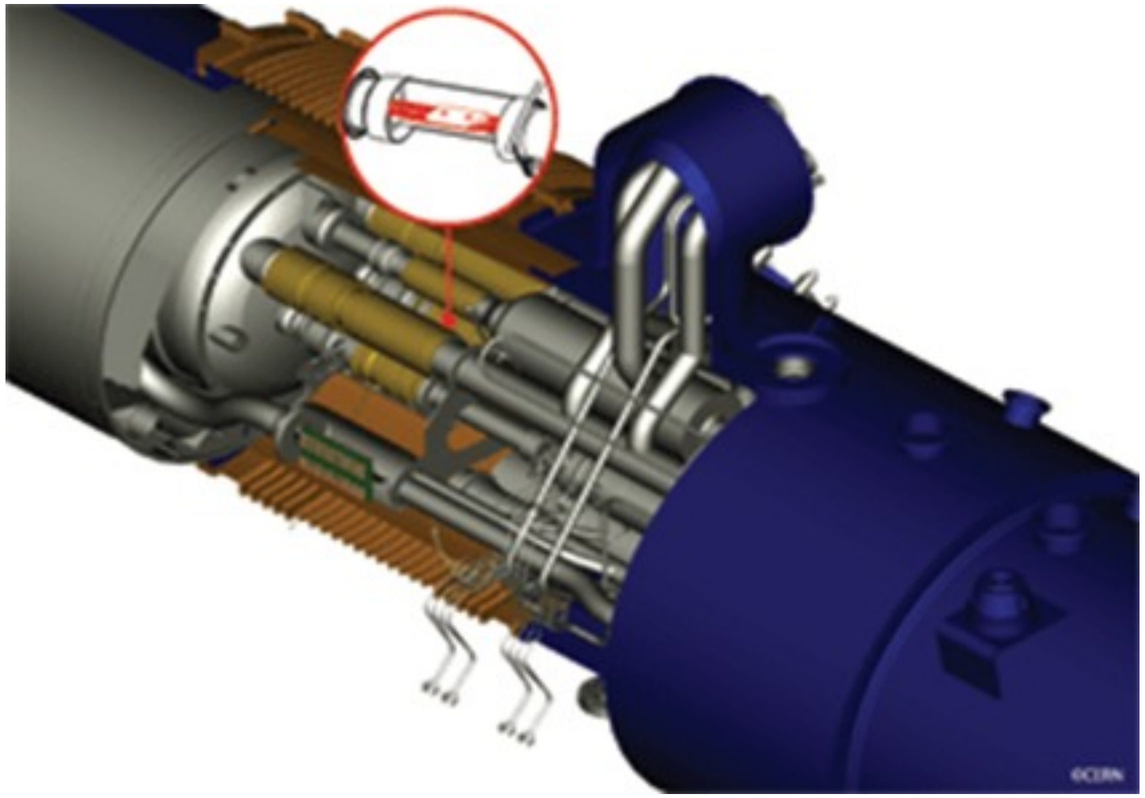


Before Collisions (~1950's Physics)



LHC Startup: Annus Horribilis





- LHC starts spectacularly on Sep 10th '08
  - LHC fail occurs on Sep 19th
  - Tiny imperfection in a soldered joint caused an electrical arc
  - Helium released, but safety systems prevented further damage
  - Remember, beam energies in 2011 > 100MJ (~1TW on a target)
- Fixing the machine is like a mission into space – 18 months

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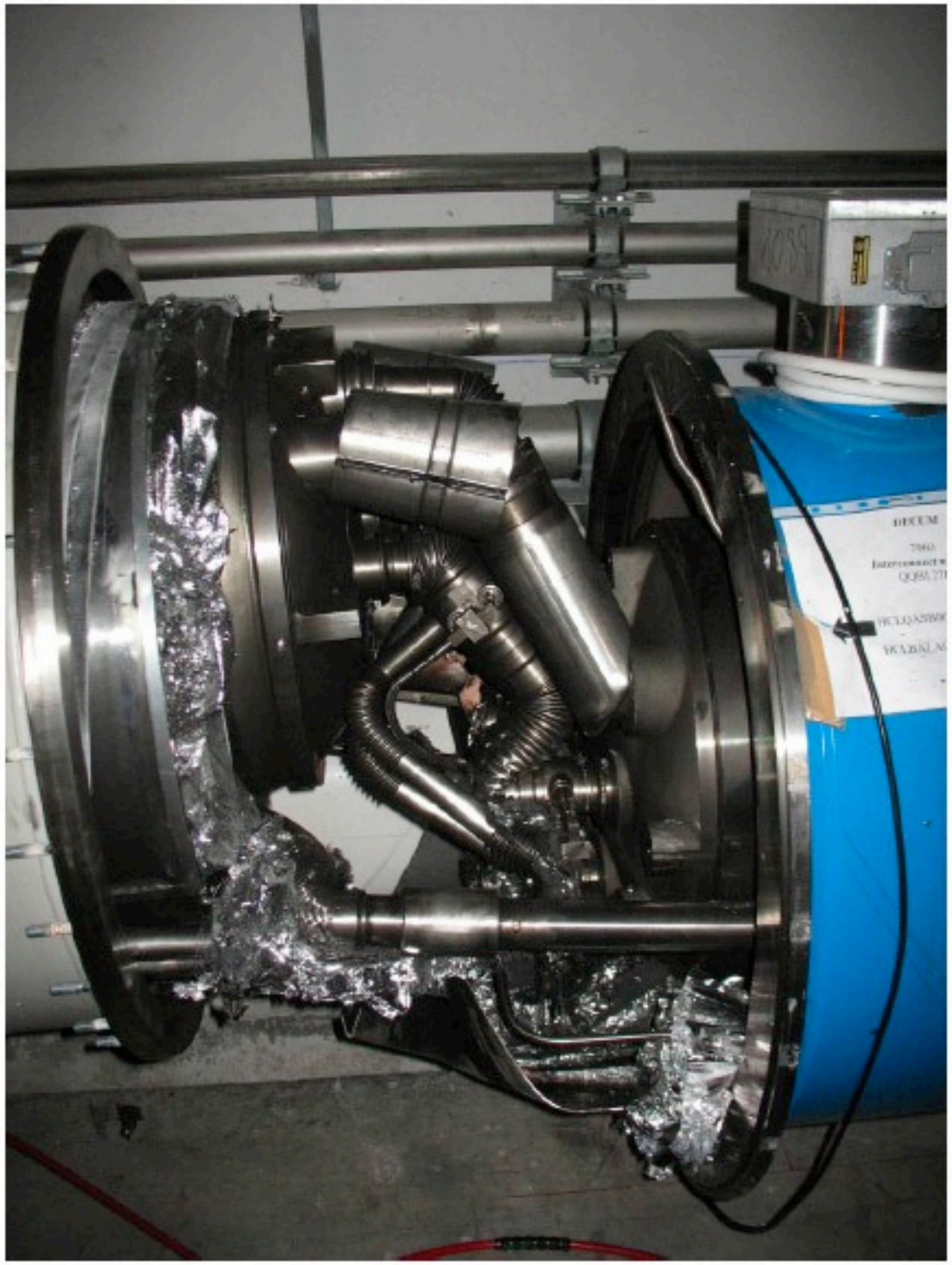
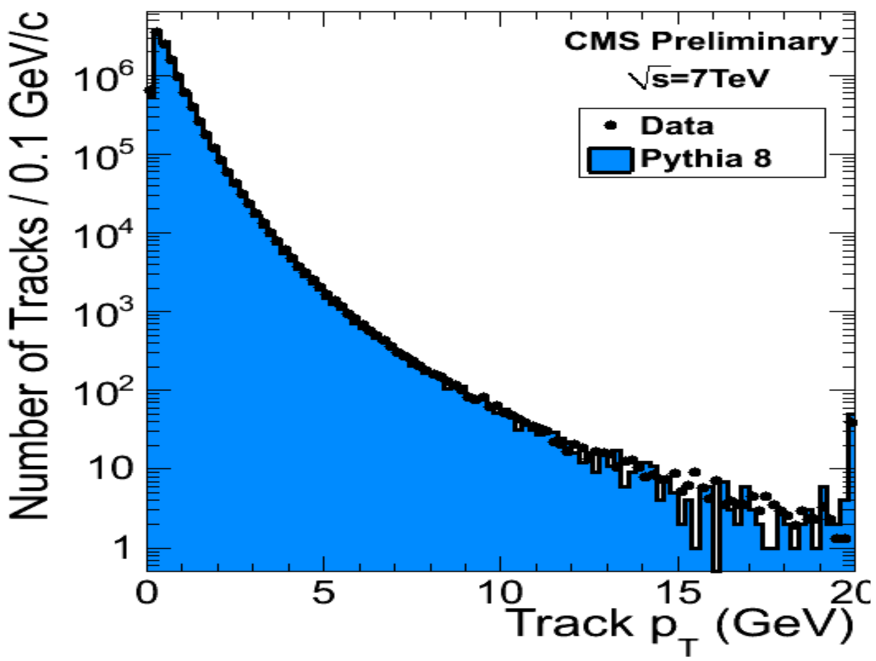
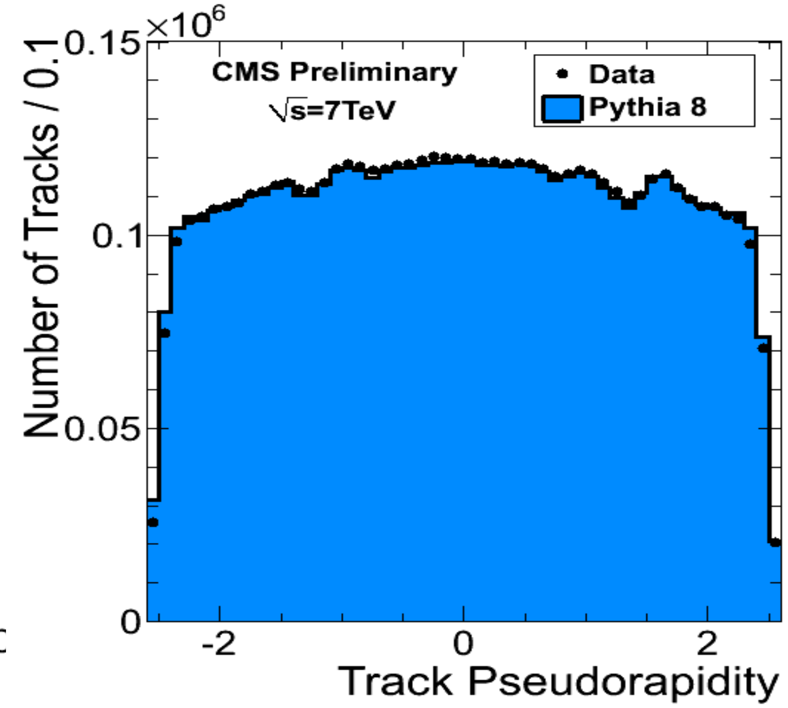
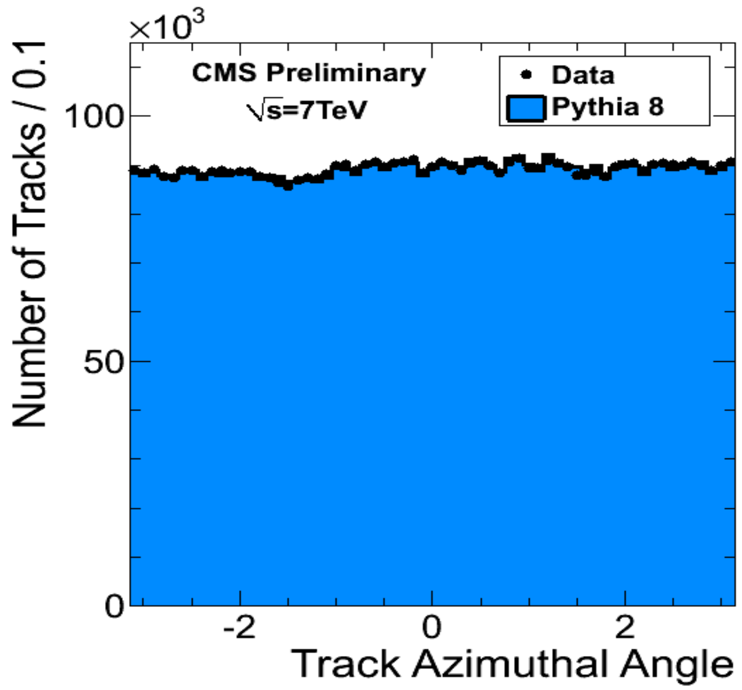
The Wrong Kind of Big Bang

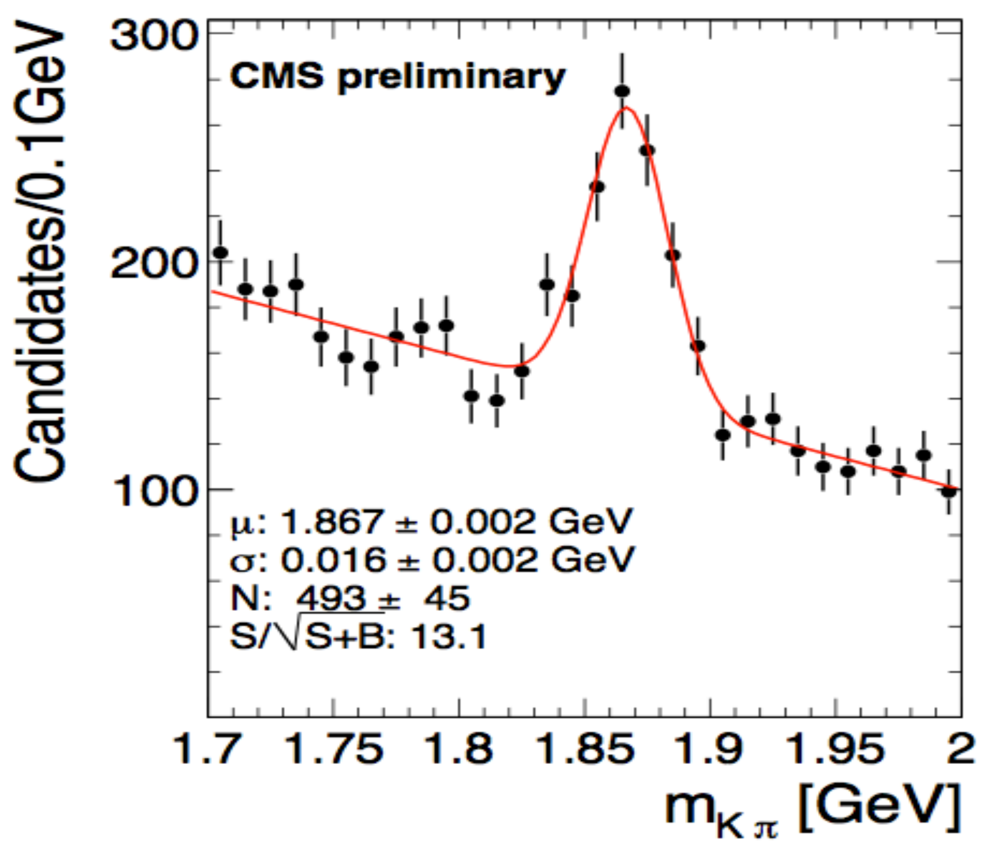


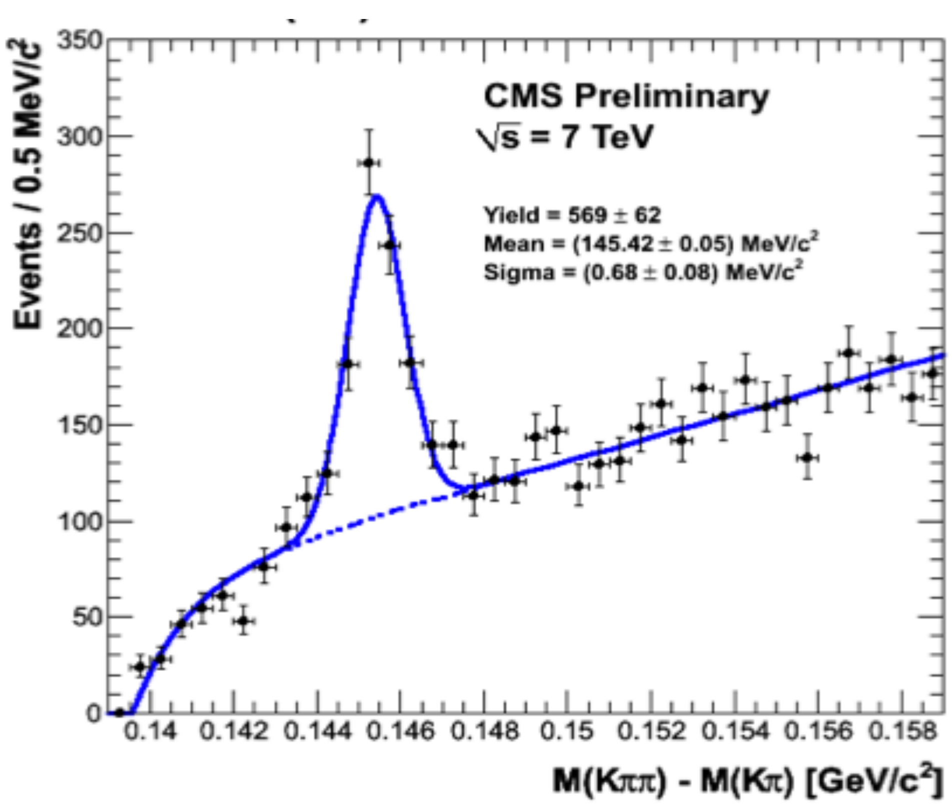
Understanding Detector: Tracking



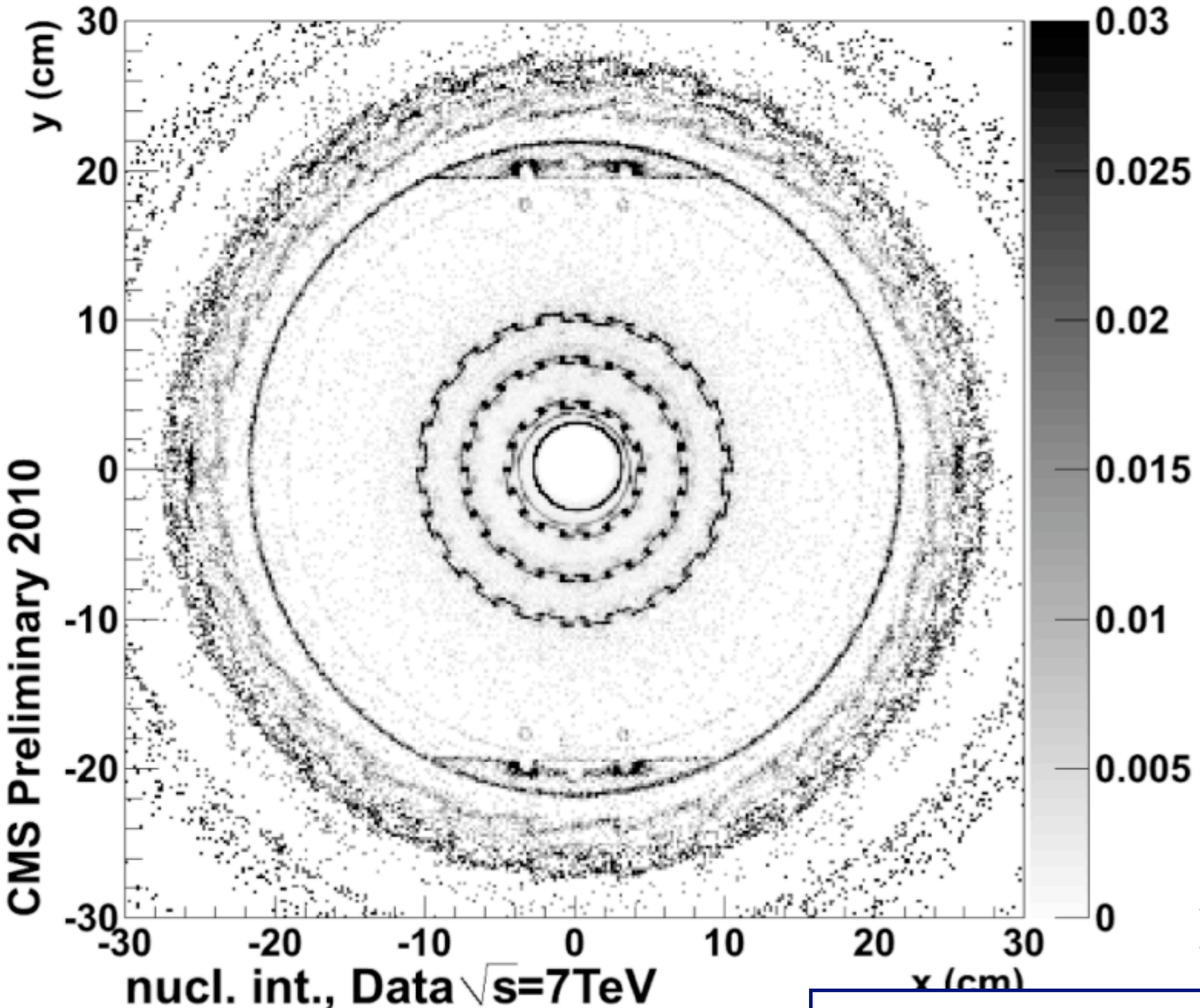






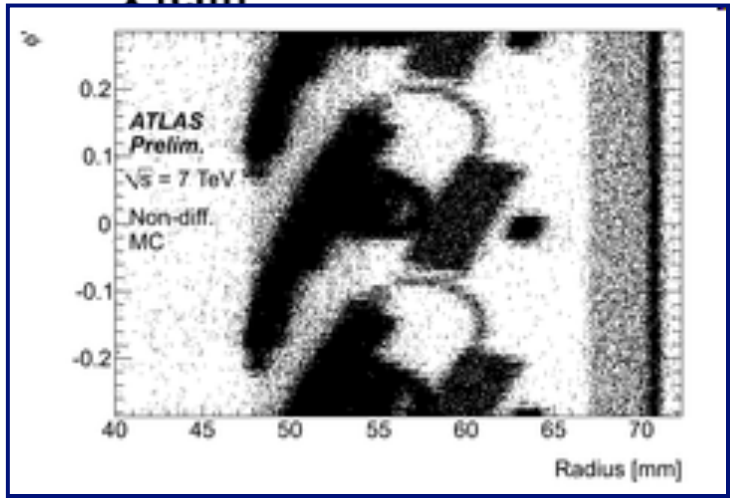


Understanding Detector: Material Plots

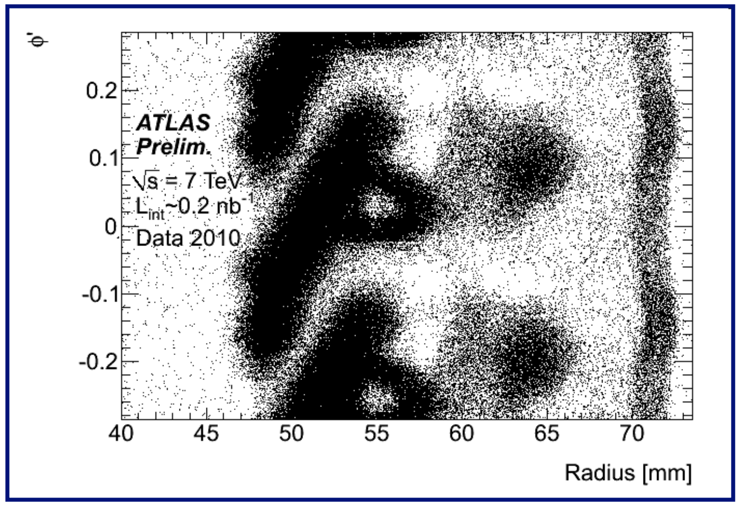


- Material distribution
  - Crucial test of detector MC accuracy
  - Essential in recovery of photon conversions
- Plot EM (γ) and hadronic interaction vertices

MC Sim



Data



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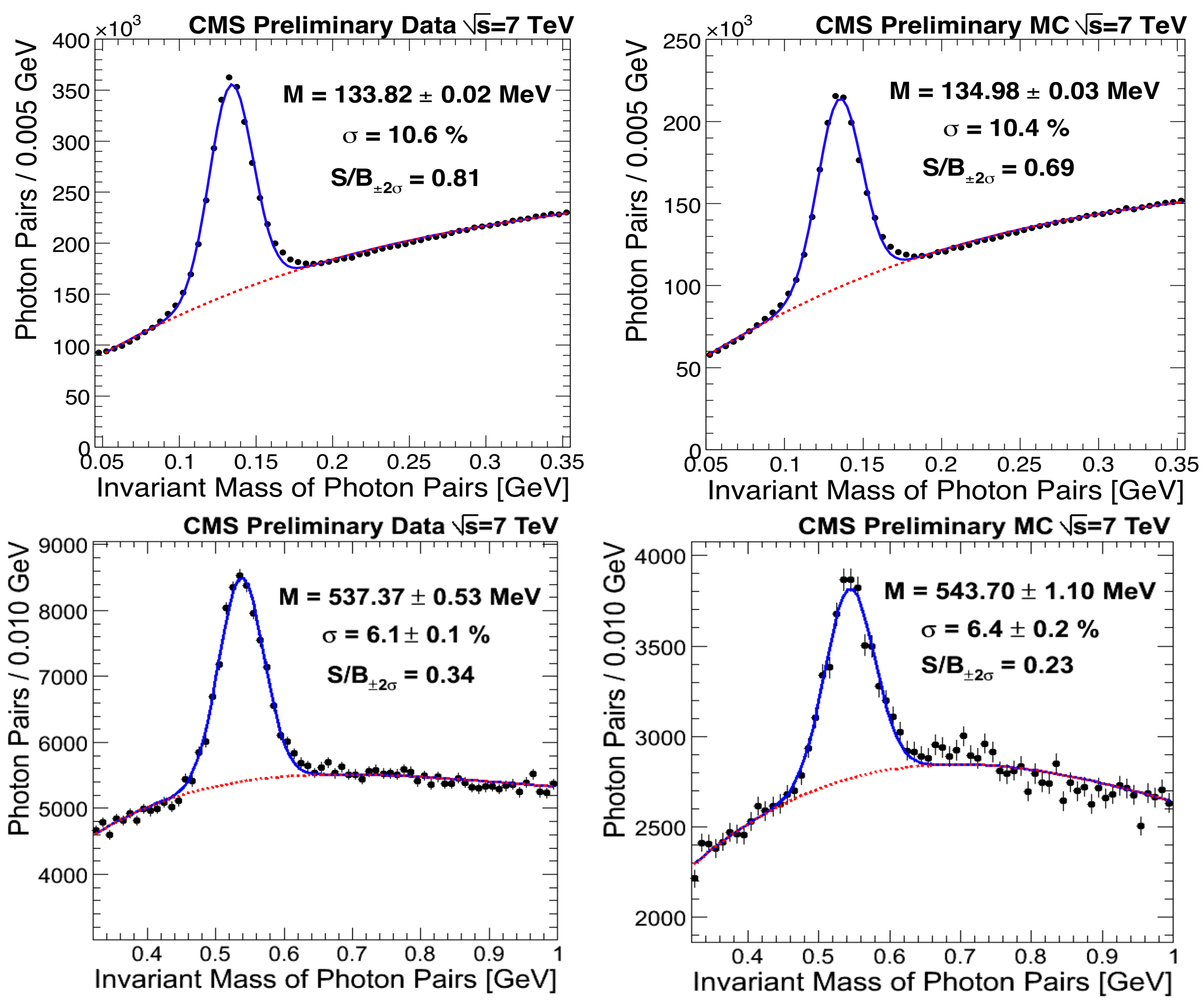
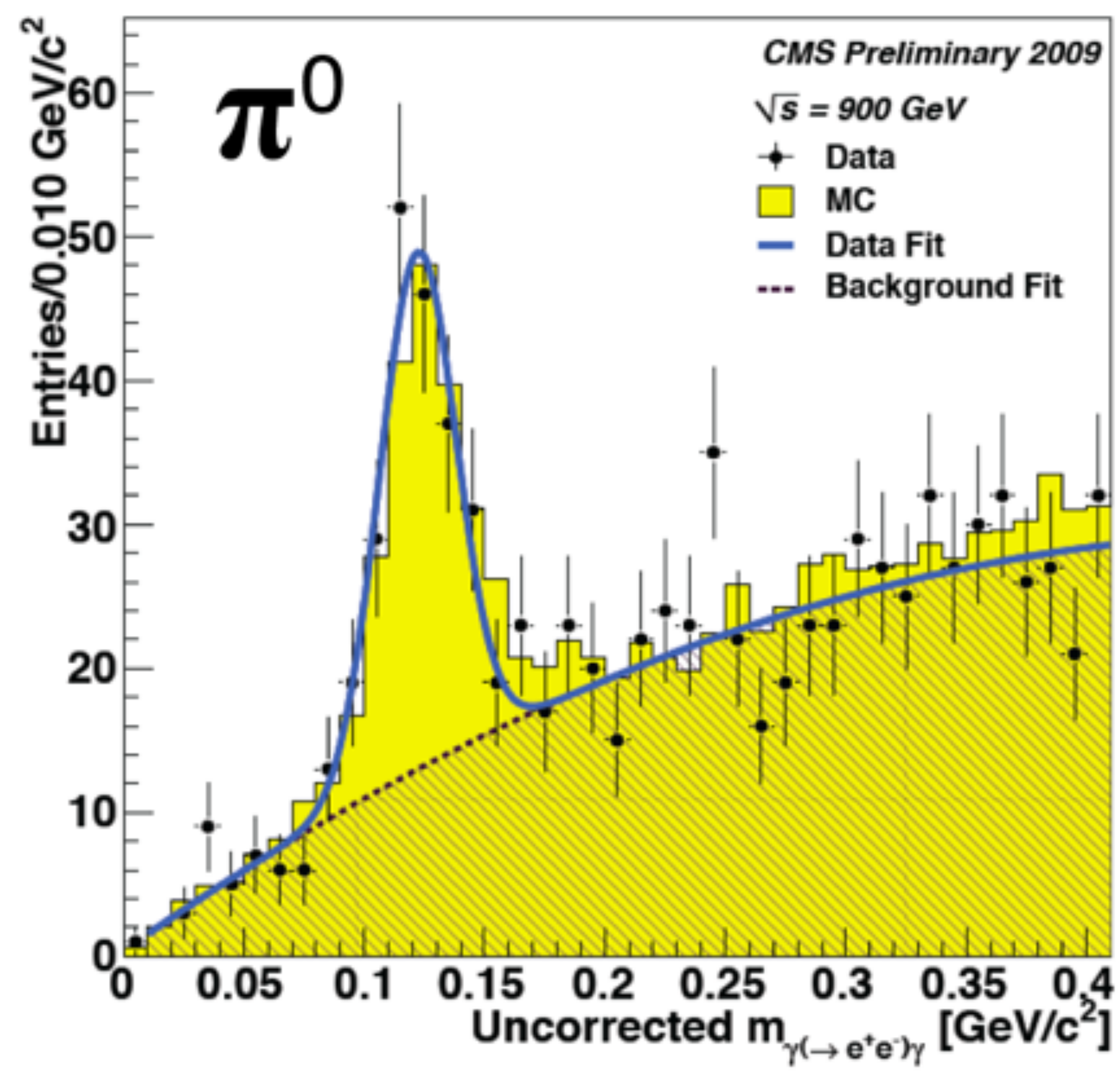
Understanding Detector: ECAL

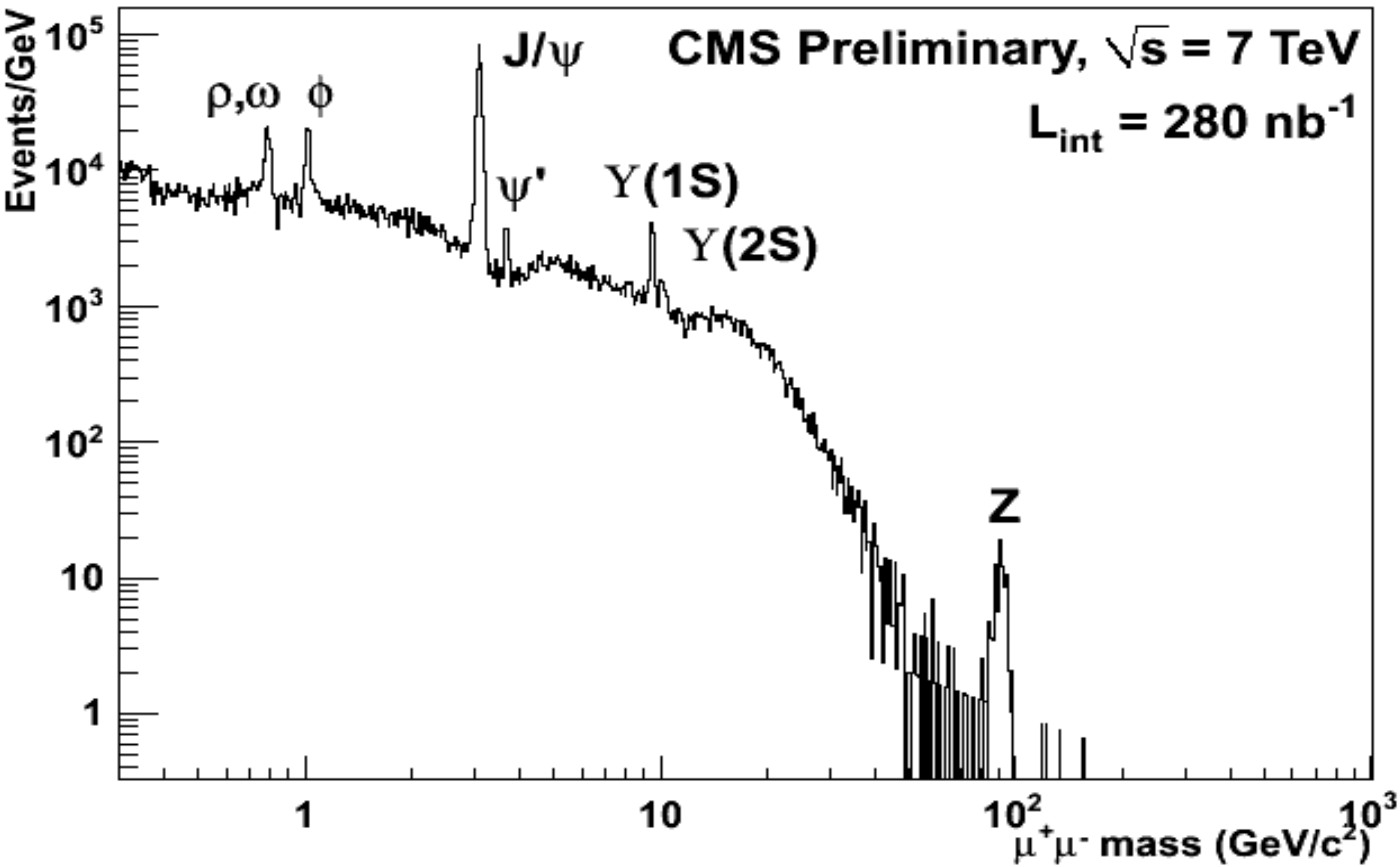


With one photon converted!

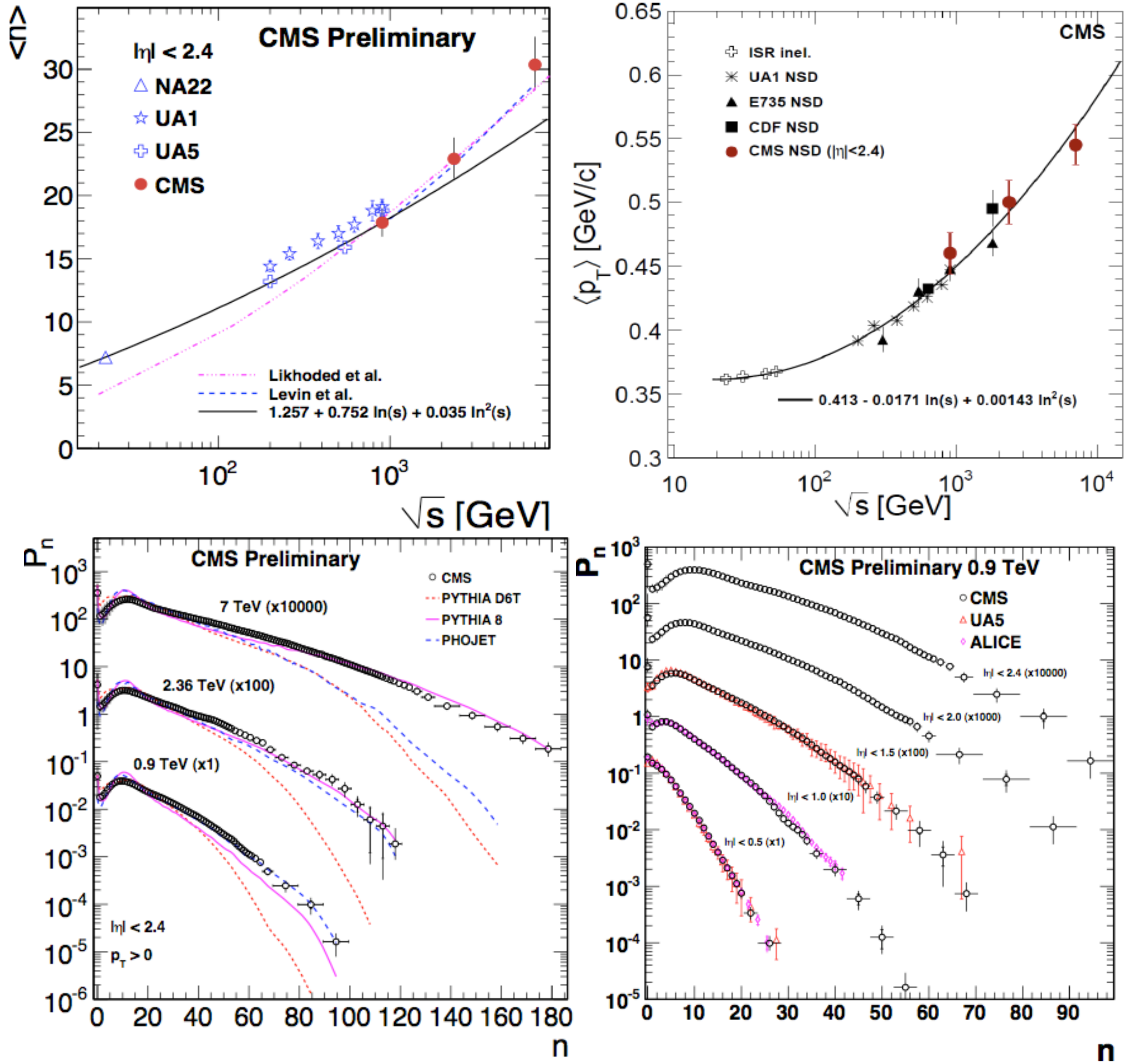


- Excellent agreement with MC
  - Calibration and energy scale are already good, and will improve

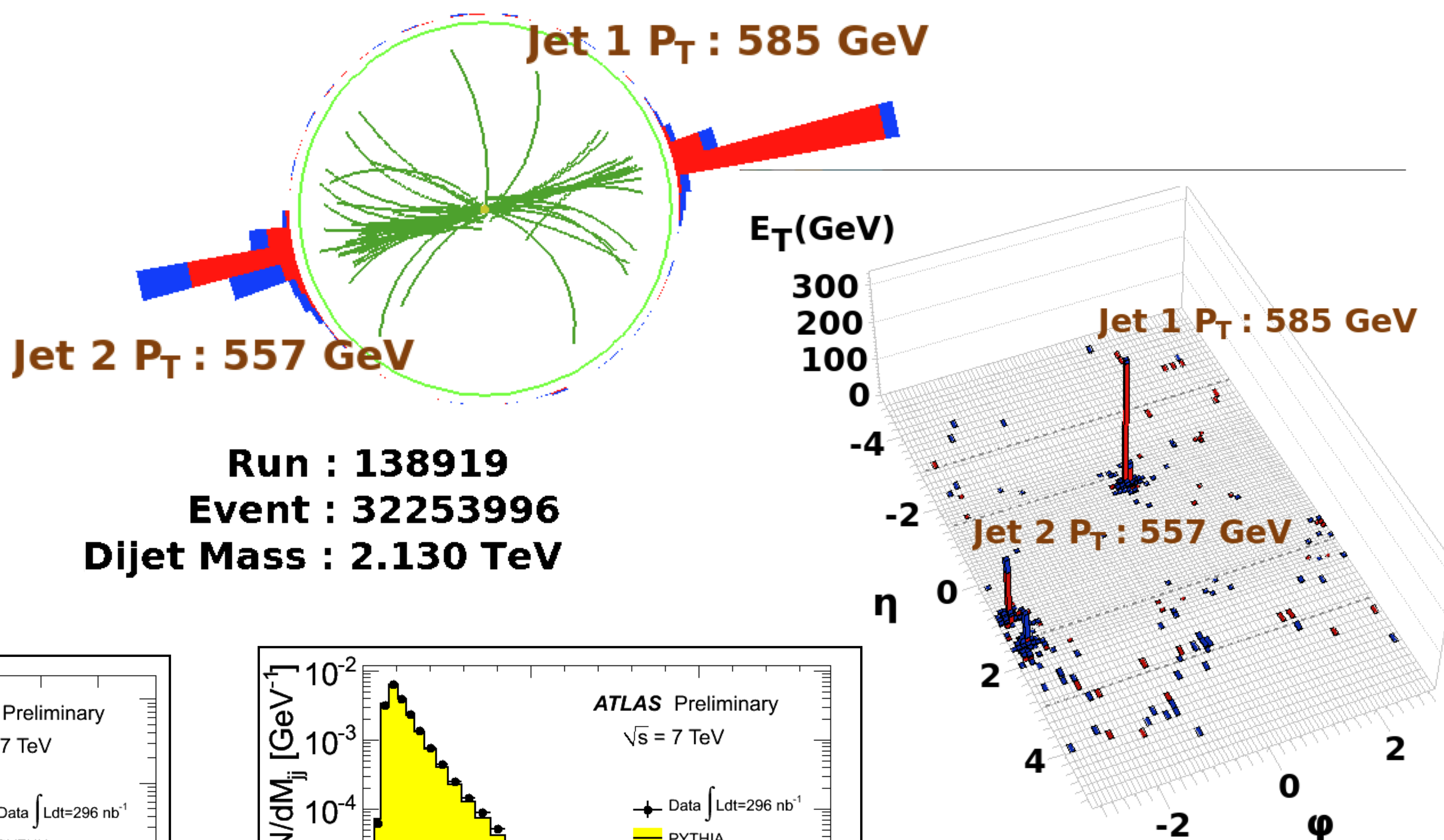
Understanding Detector: Muons

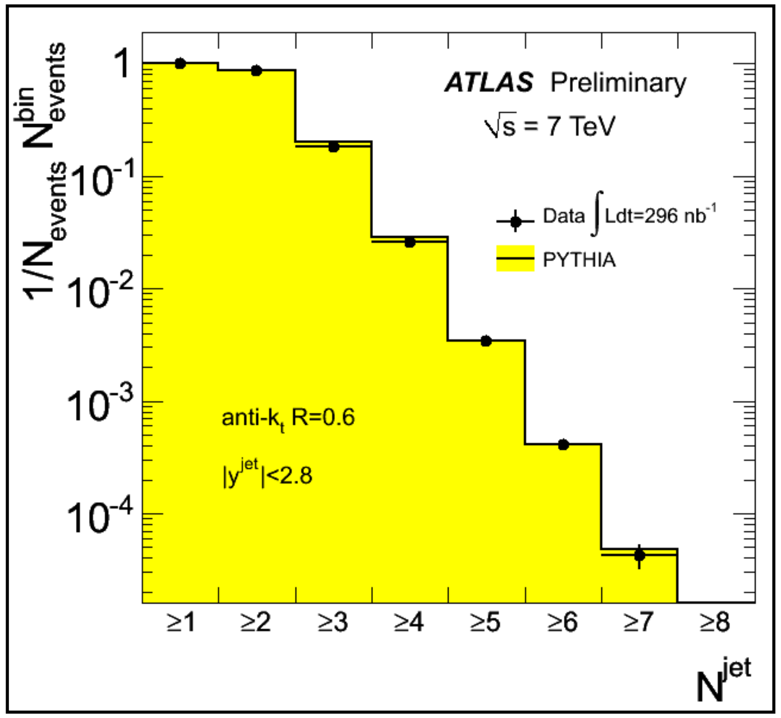


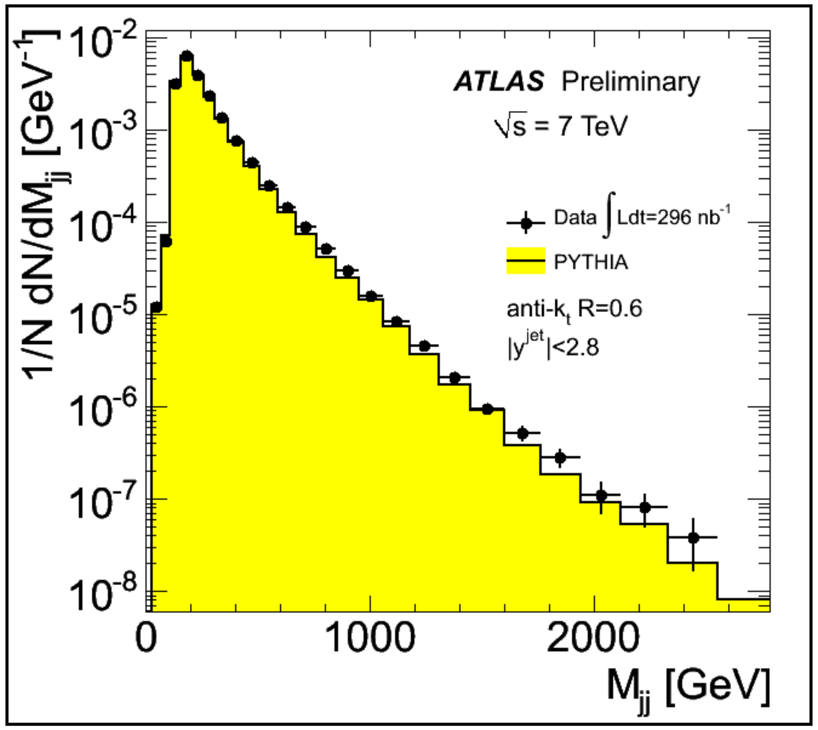
First Data: Minimum Bias (~1960's Physics)



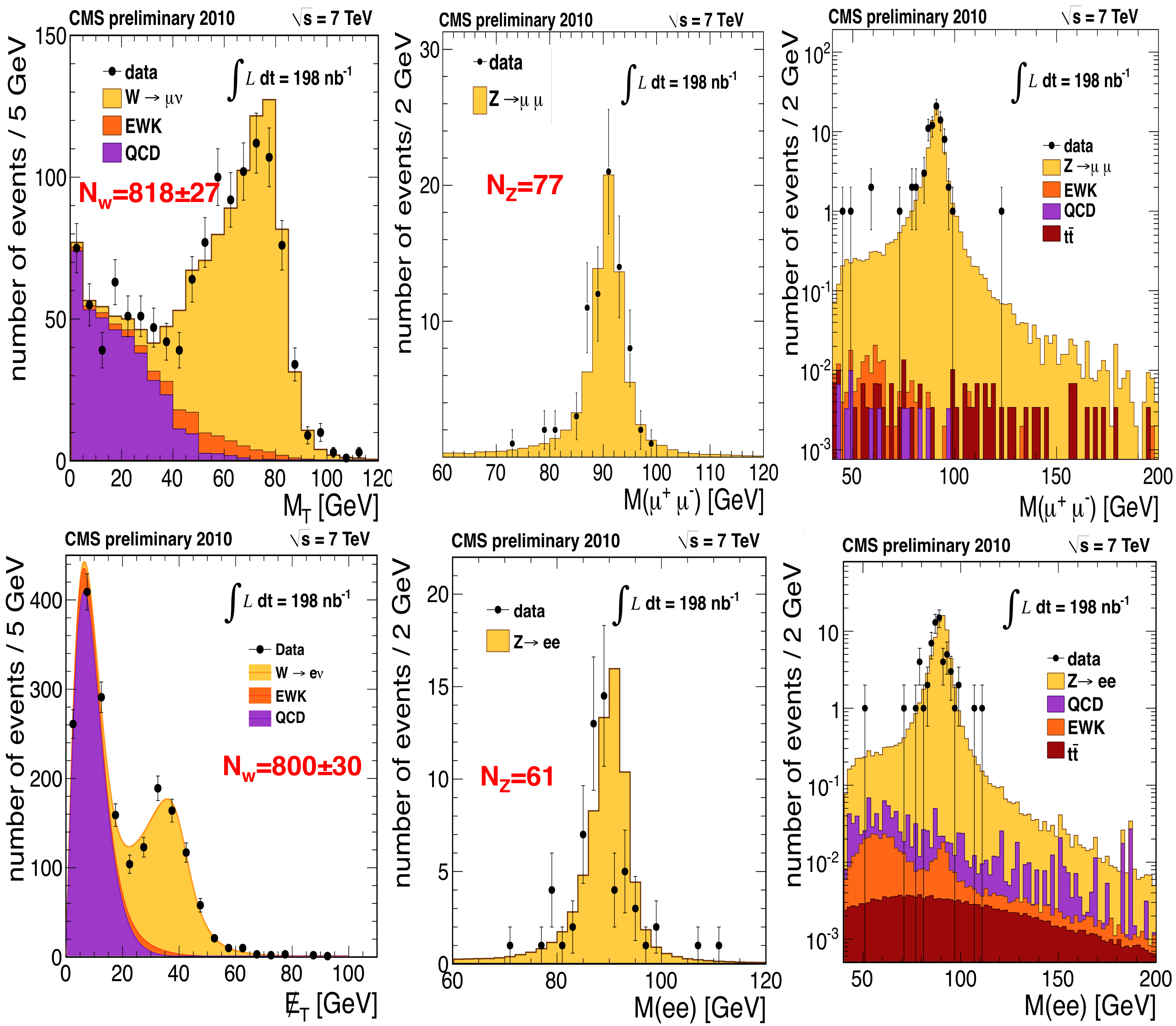
First Data: Jets (~1970's Physics)



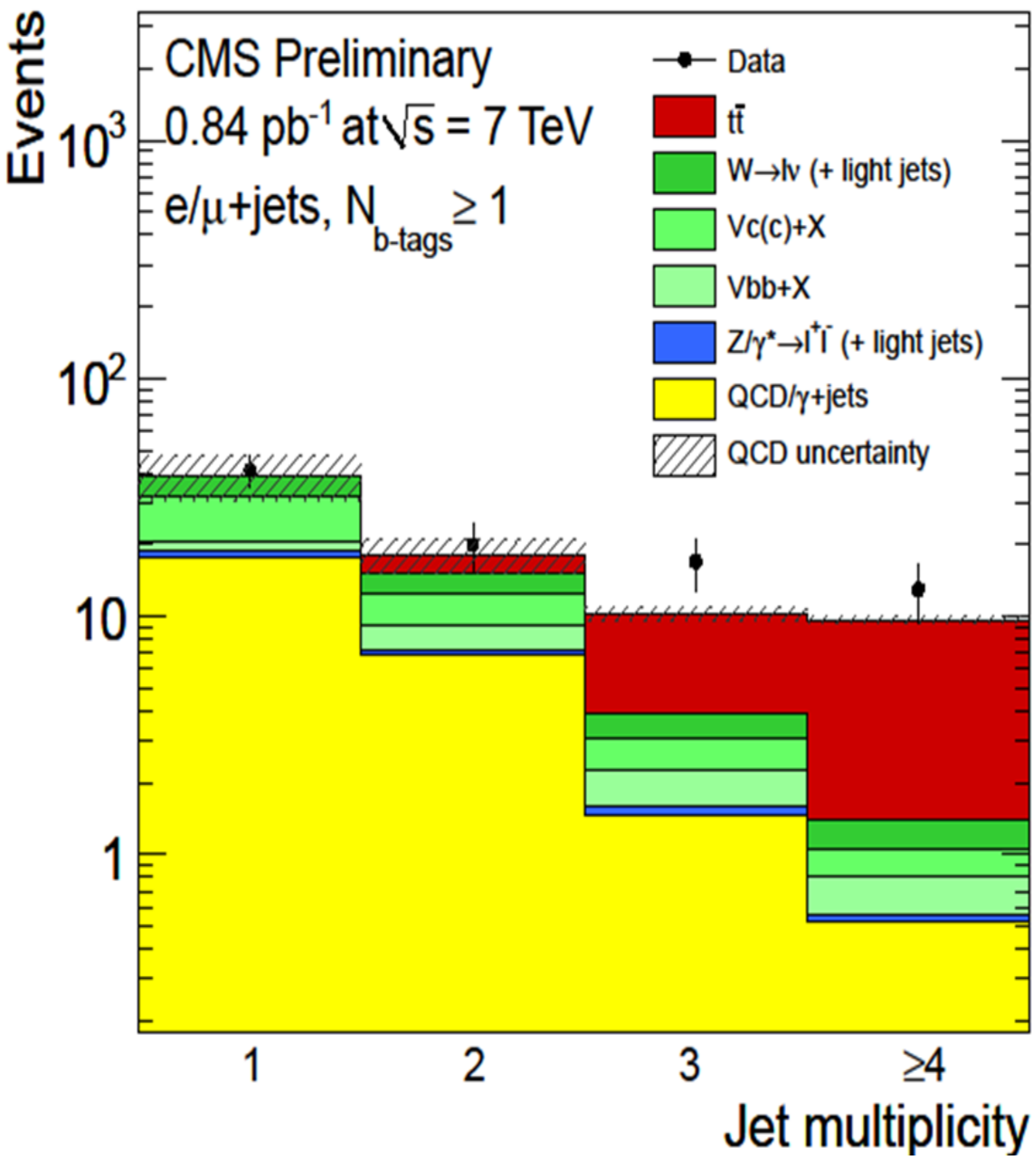


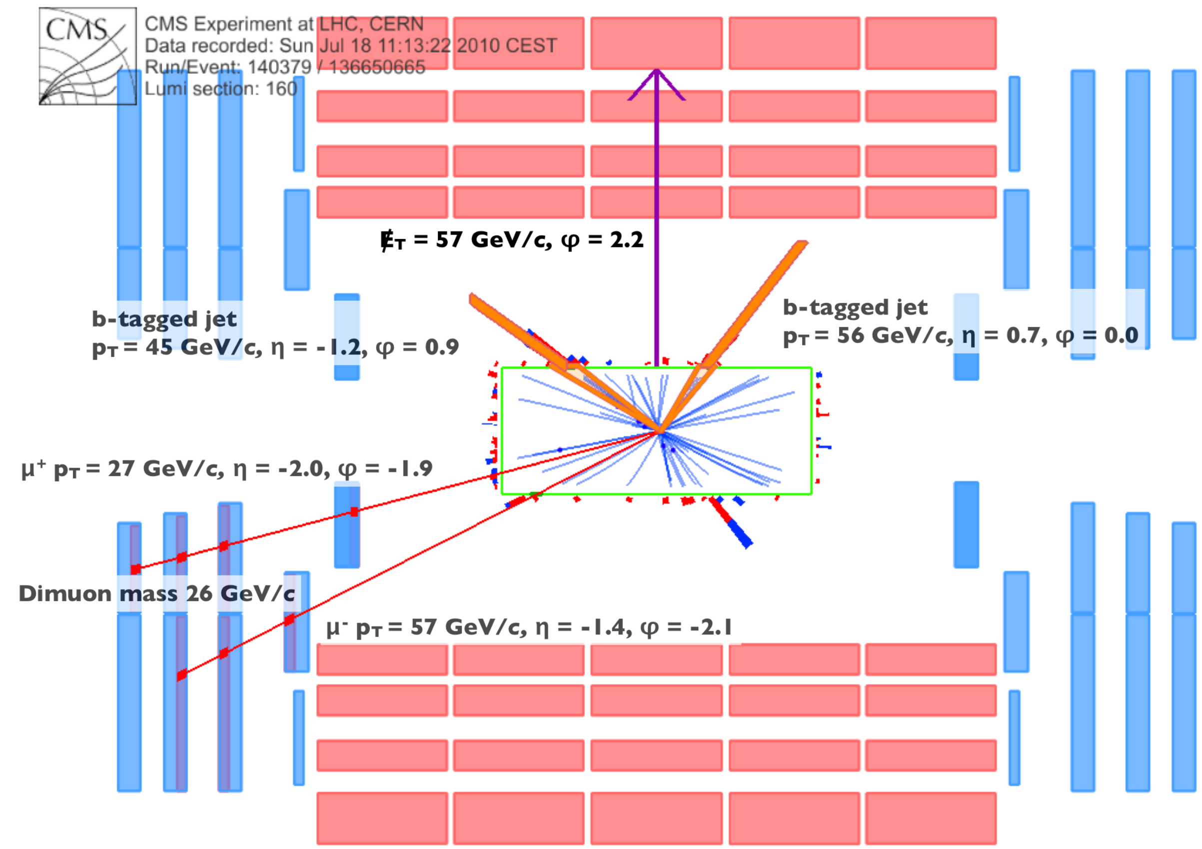


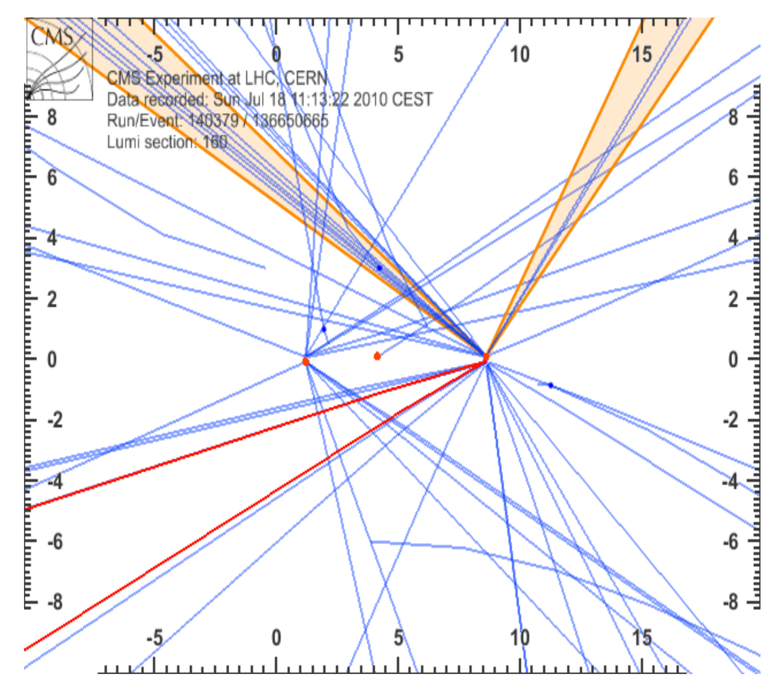
First Data: Electroweak (~1980's Physics)



First Data: Top (~1990's Physics)







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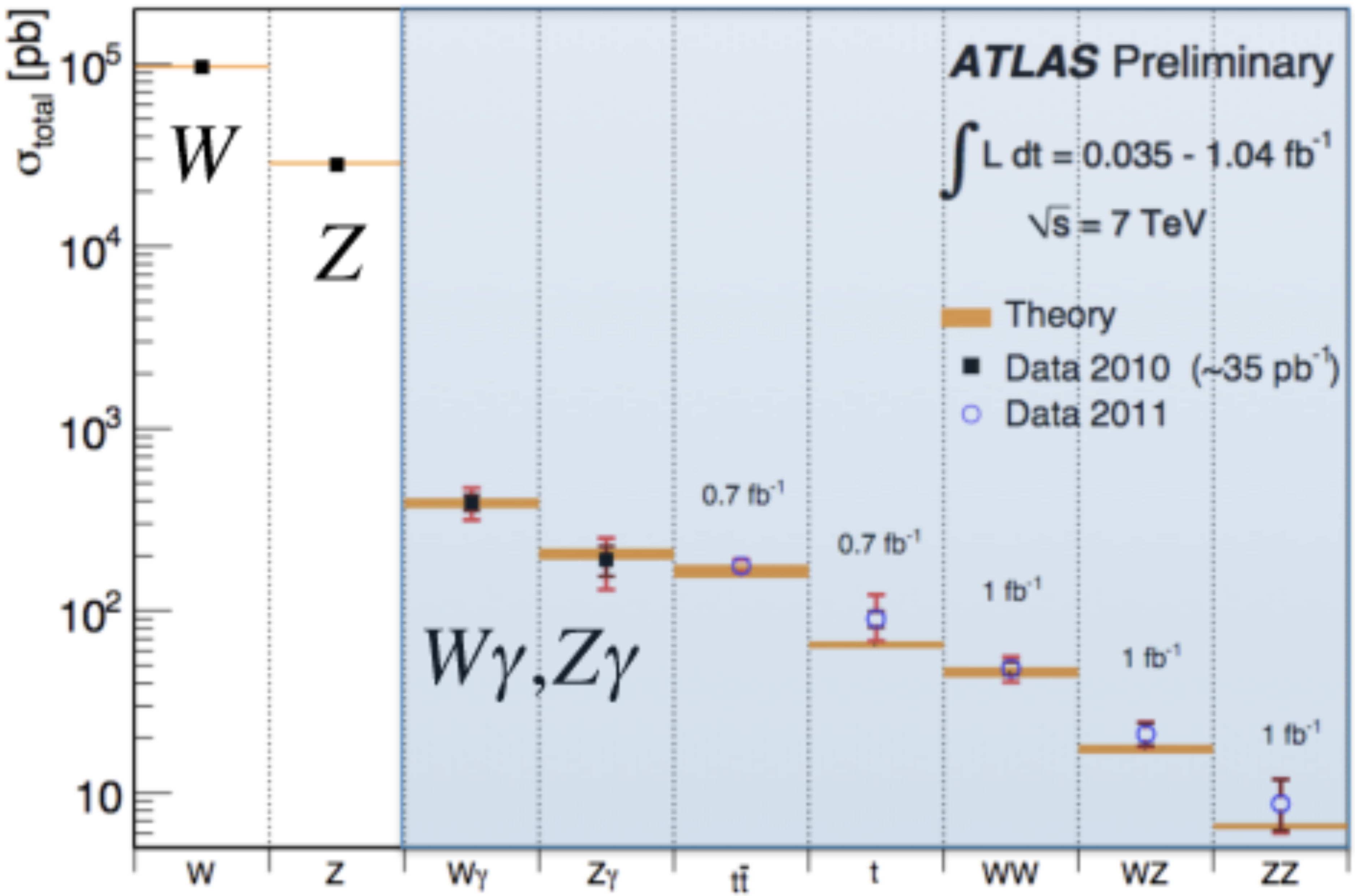
LHC Physics Programme

- Where we are today
  - Surprisingly well understood detectors and environment
  - Exponentially increasing luminosity
  - Huge number of channels to examine
- The emphasis
  - Increasingly detailed and precise SM measurements
  - Broad inclusive searches for a range of BSM phenomena
  - Few significant attempts at interpretation yet
- The challenges
  - The environment (esp pileup levels) is rapidly changing
    - And not for the better
  - Trigger conditions have rapidly evolved
    - Already, some interesting physics is ~inaccessible due to trigger constraints
  - Data handling – computing now becoming an issue
  - Organisation and prioritisation

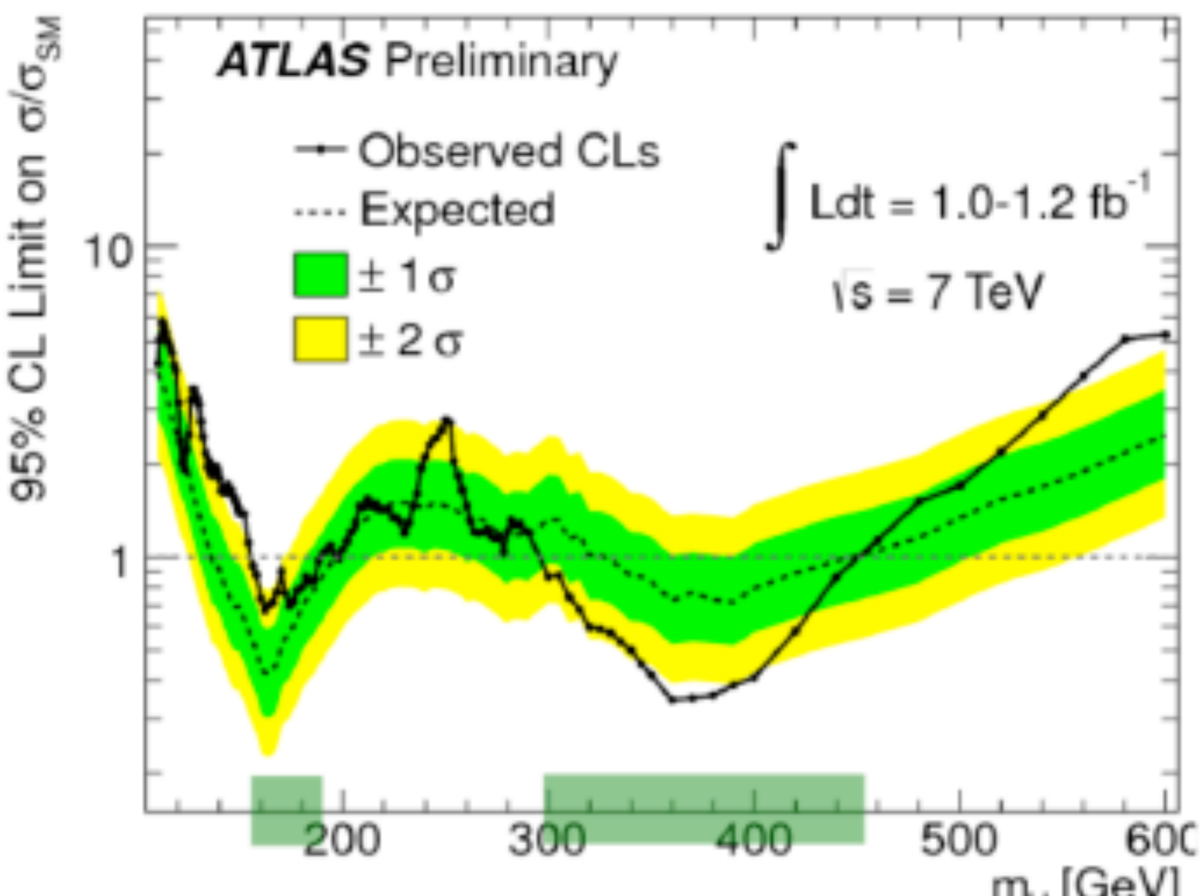
LHC Electroweak Measurements



~ SM Higgs

- Theory at NLO

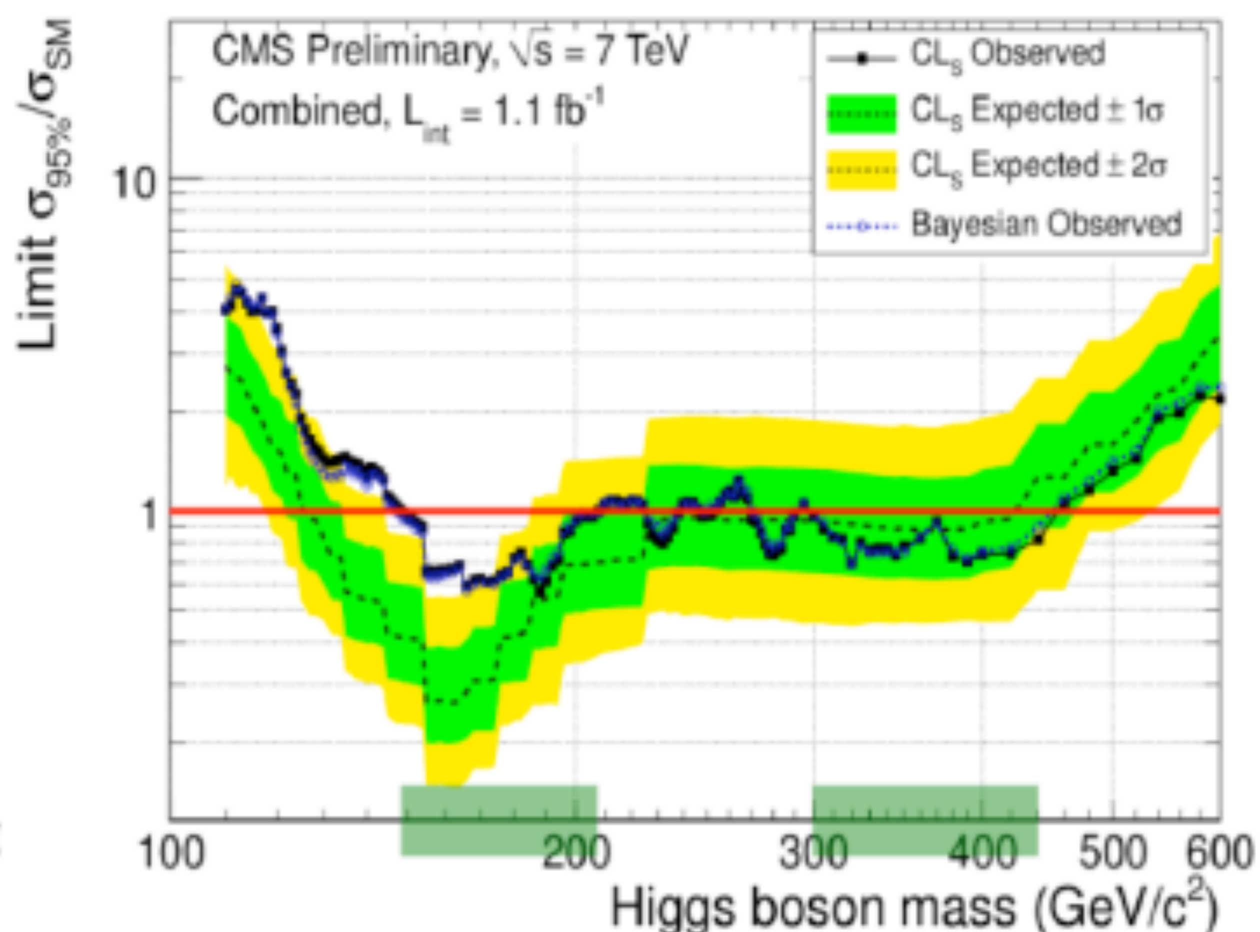
LHC Higgs Limits



SM Higgs excluded at 95% C.L.

$155 < M_H < 190$ GeV

$295 < M_H < 450$ GeV

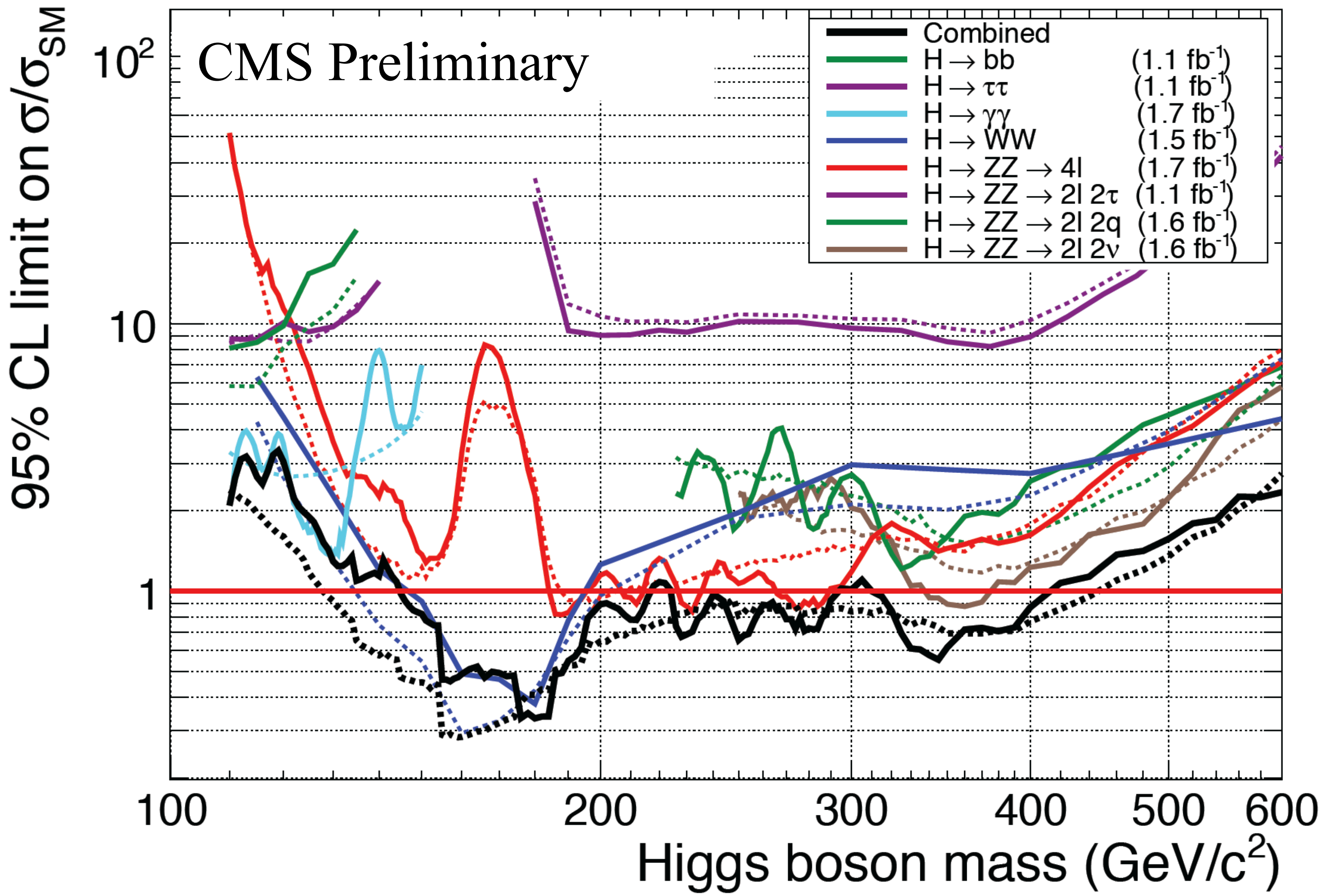


SM Higgs excluded at 95% C.L.

$149 < M_H < 206$ GeV

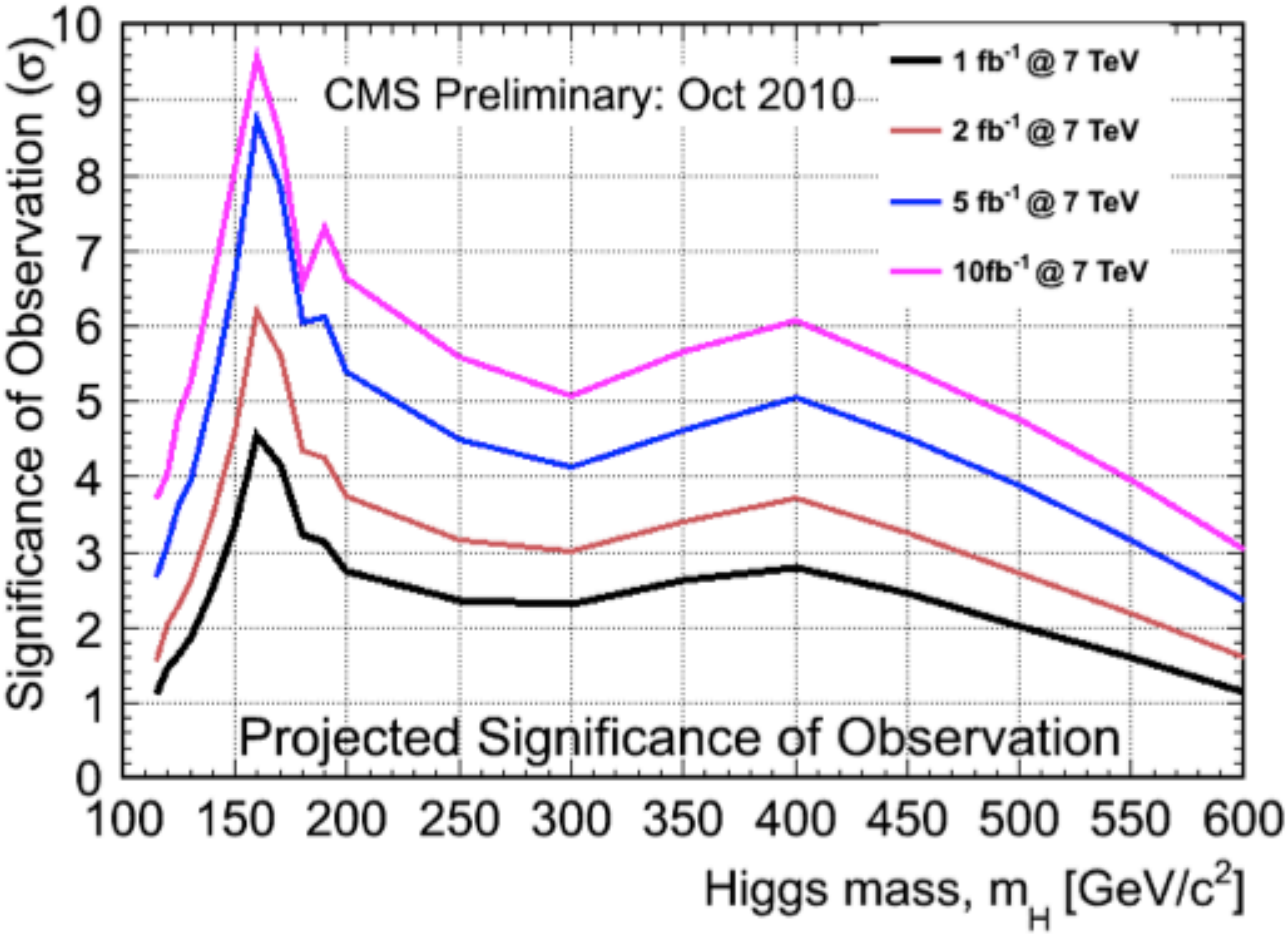
$300 < M_H < 440$ GeV

Higgs Combinations

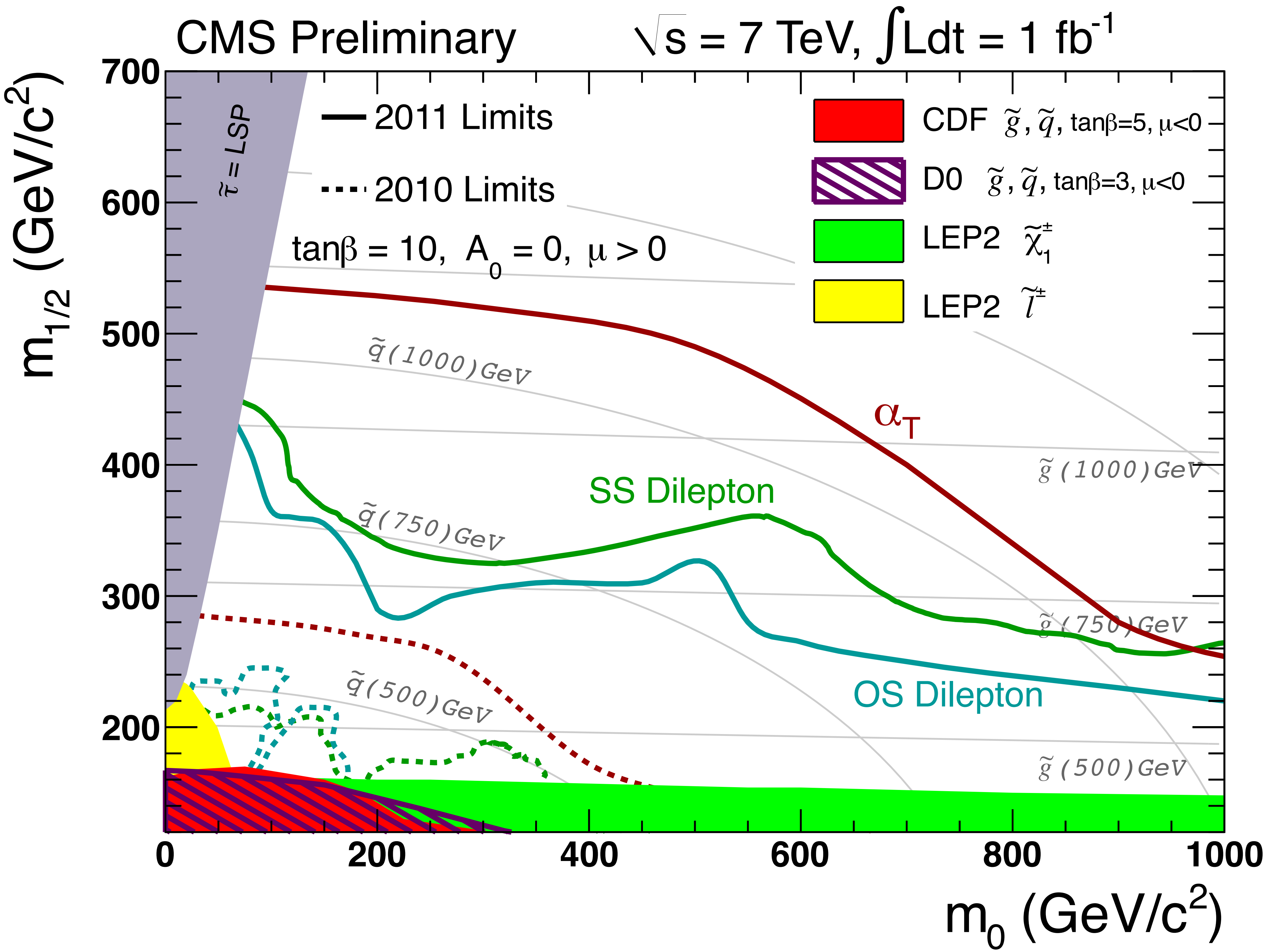


- A deep understanding of uncertainties and correlations required to form these combinations

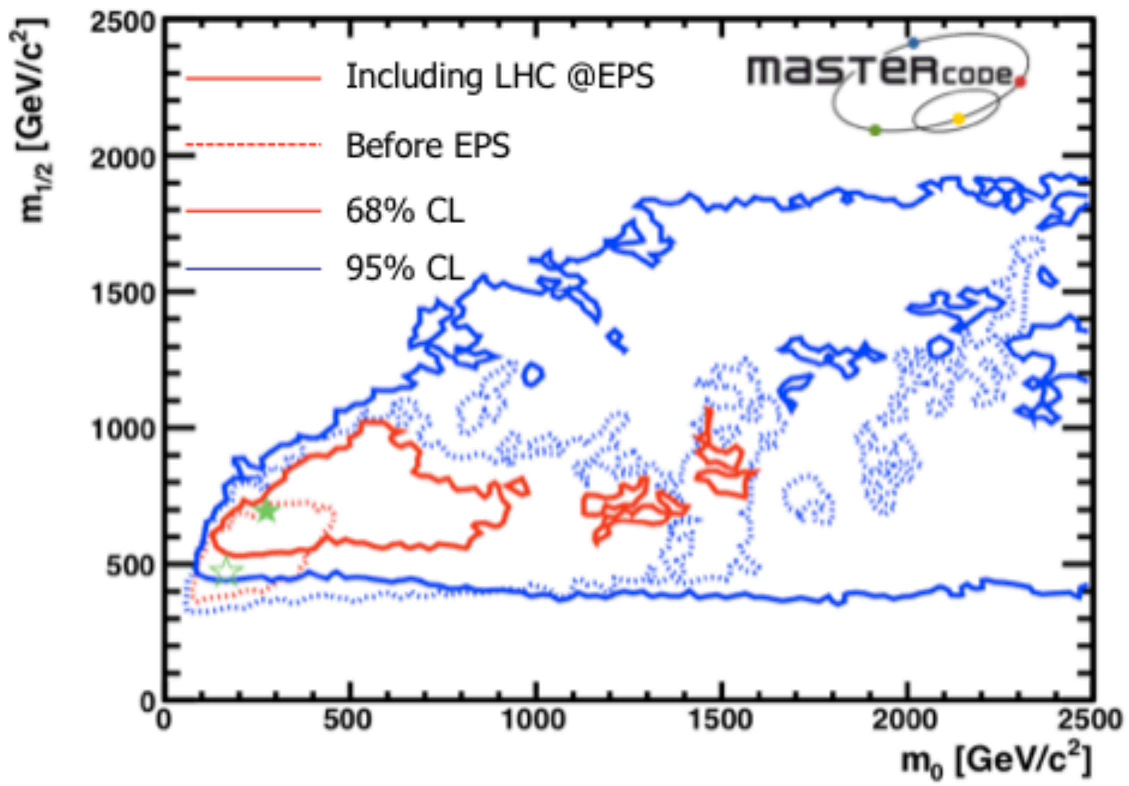
Higgs Outlook

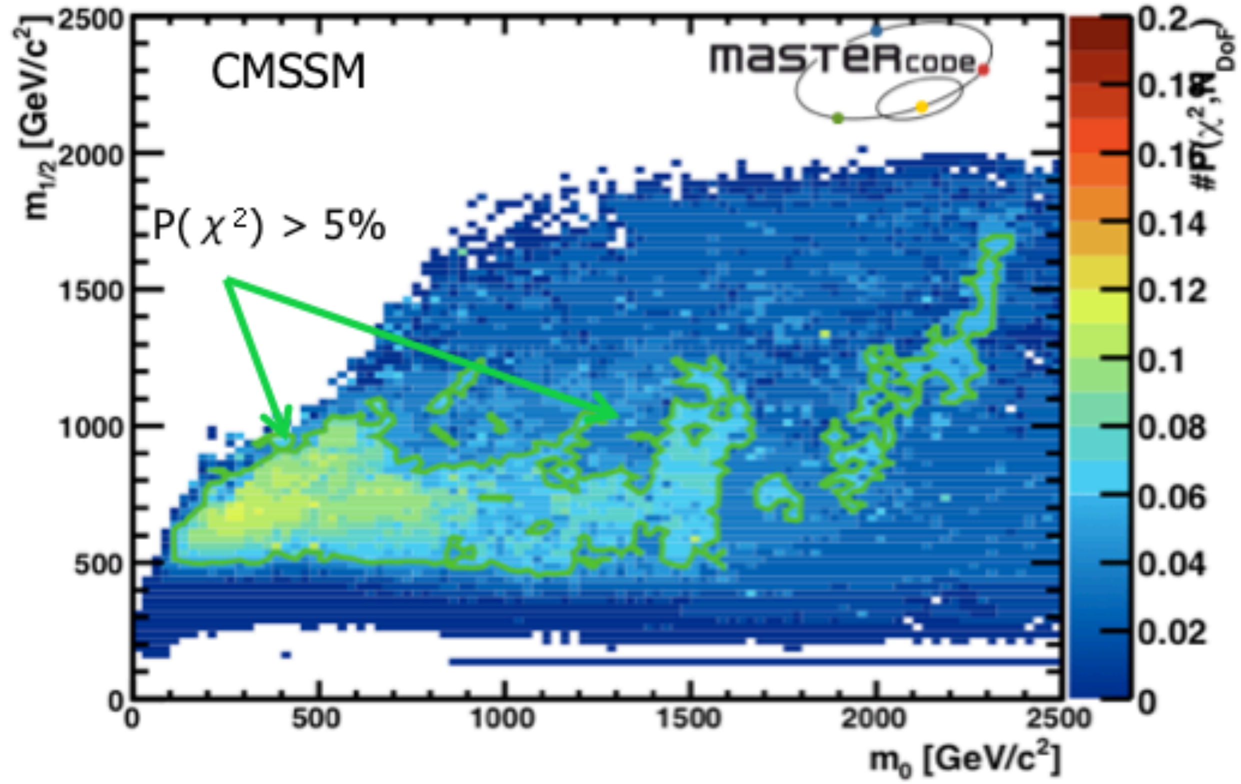


CMSSM Limits



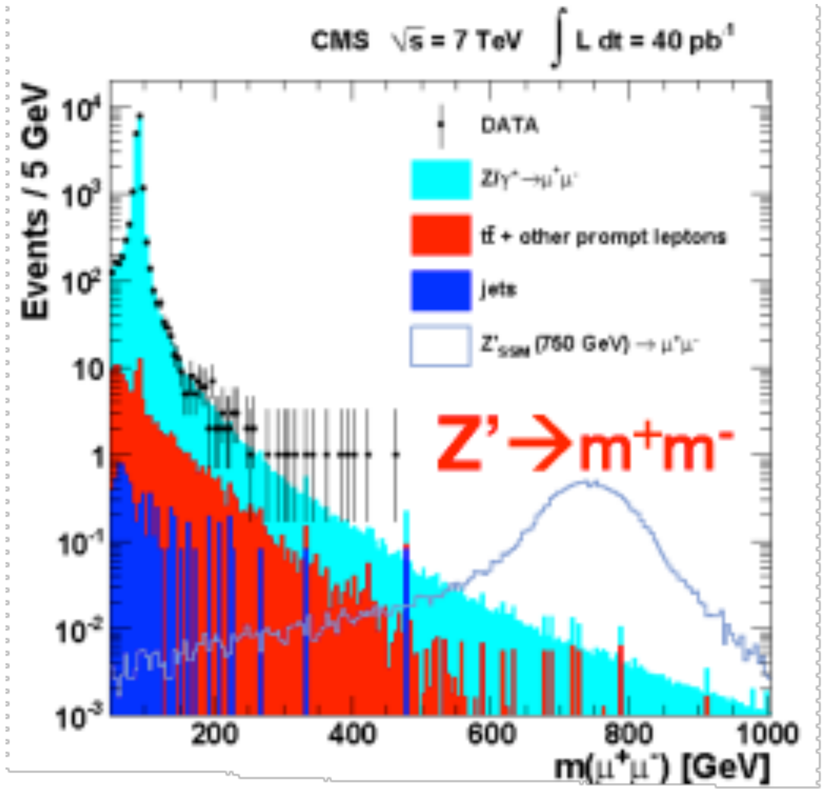
CMSSM Fits

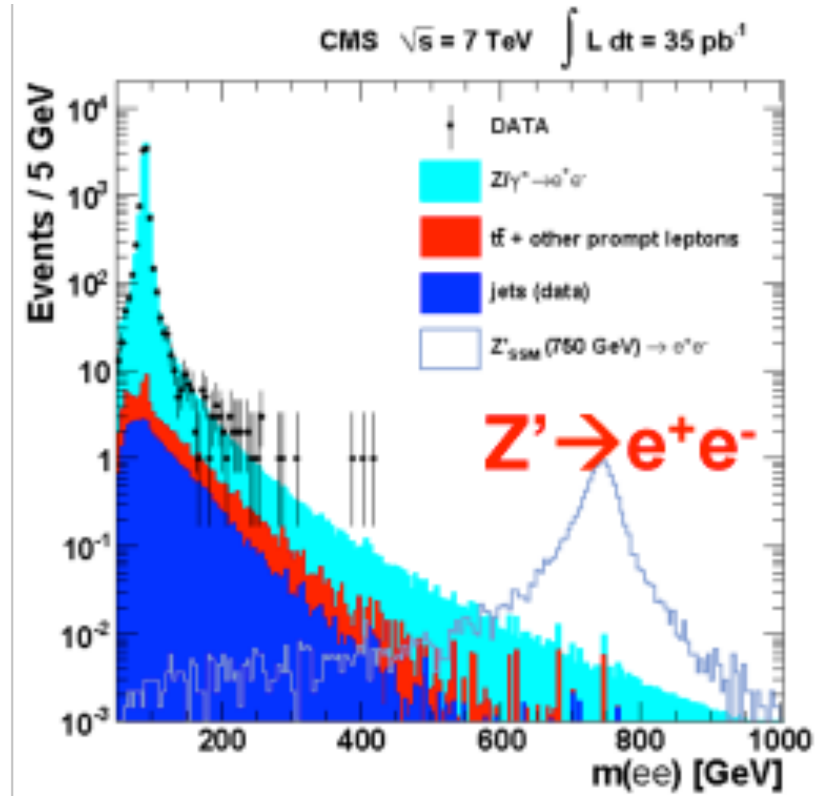


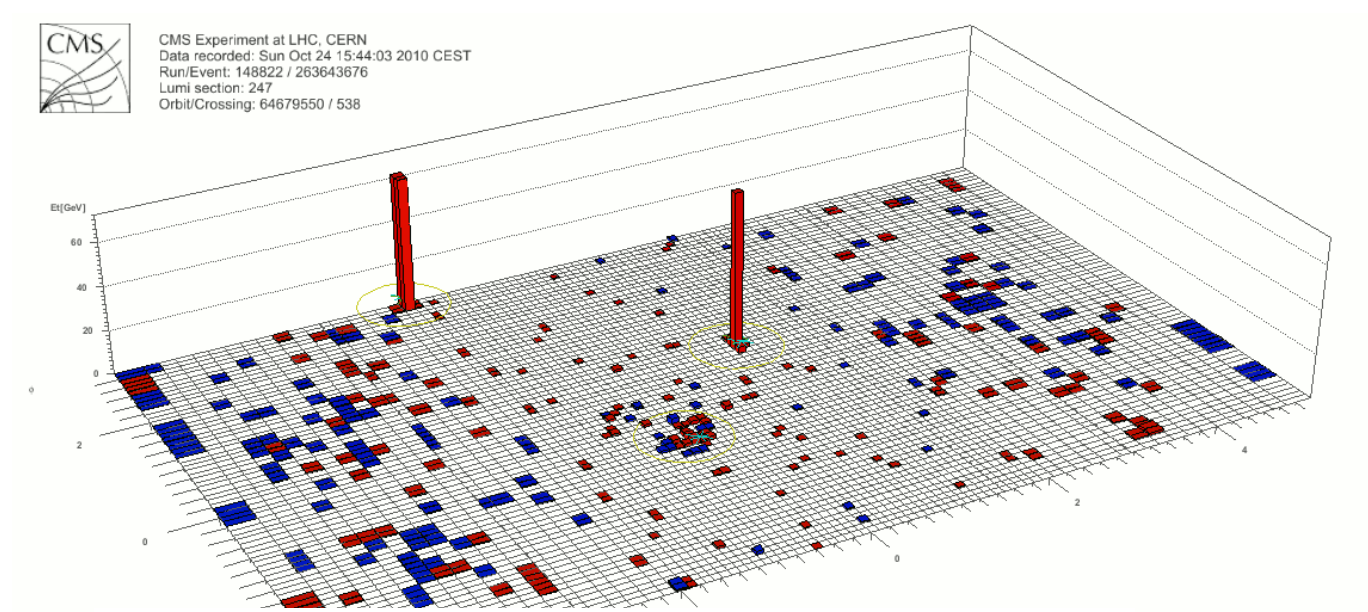


- Of course, plenty of theory space left yet
  - Constraints from other sources will be crucial here

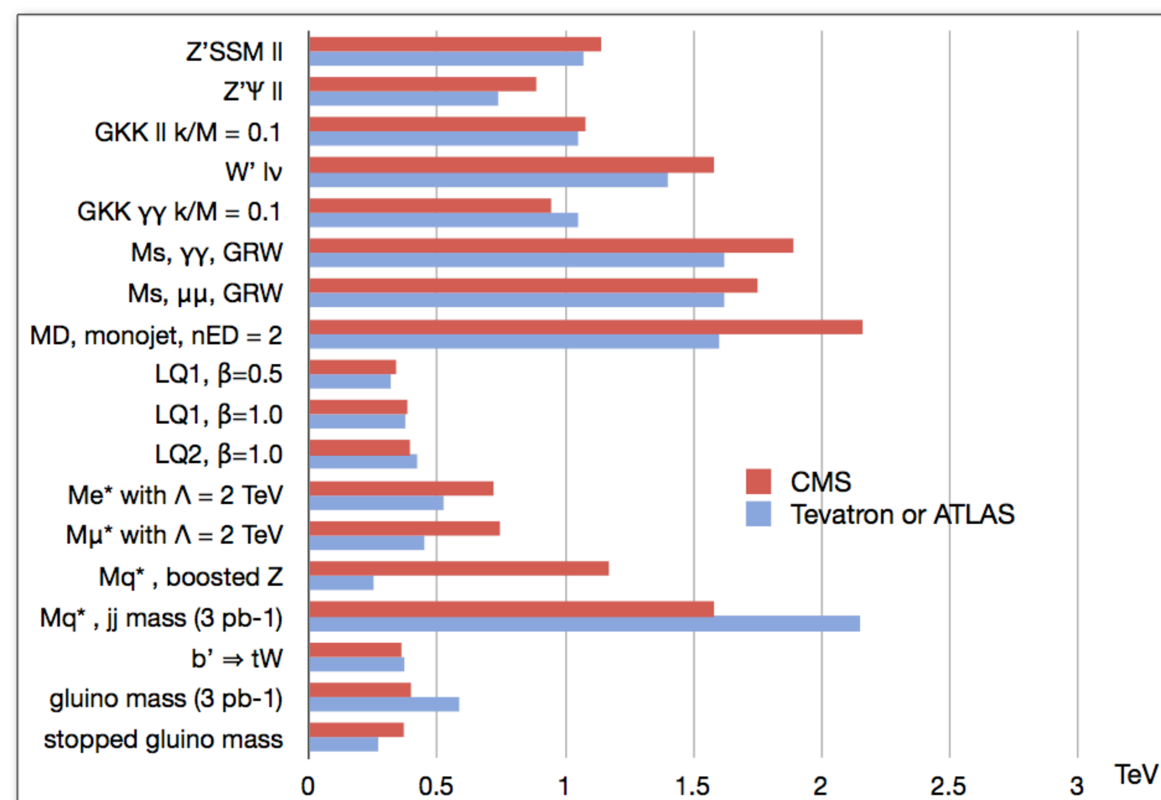
BSM - e.g. U(1) Extensions





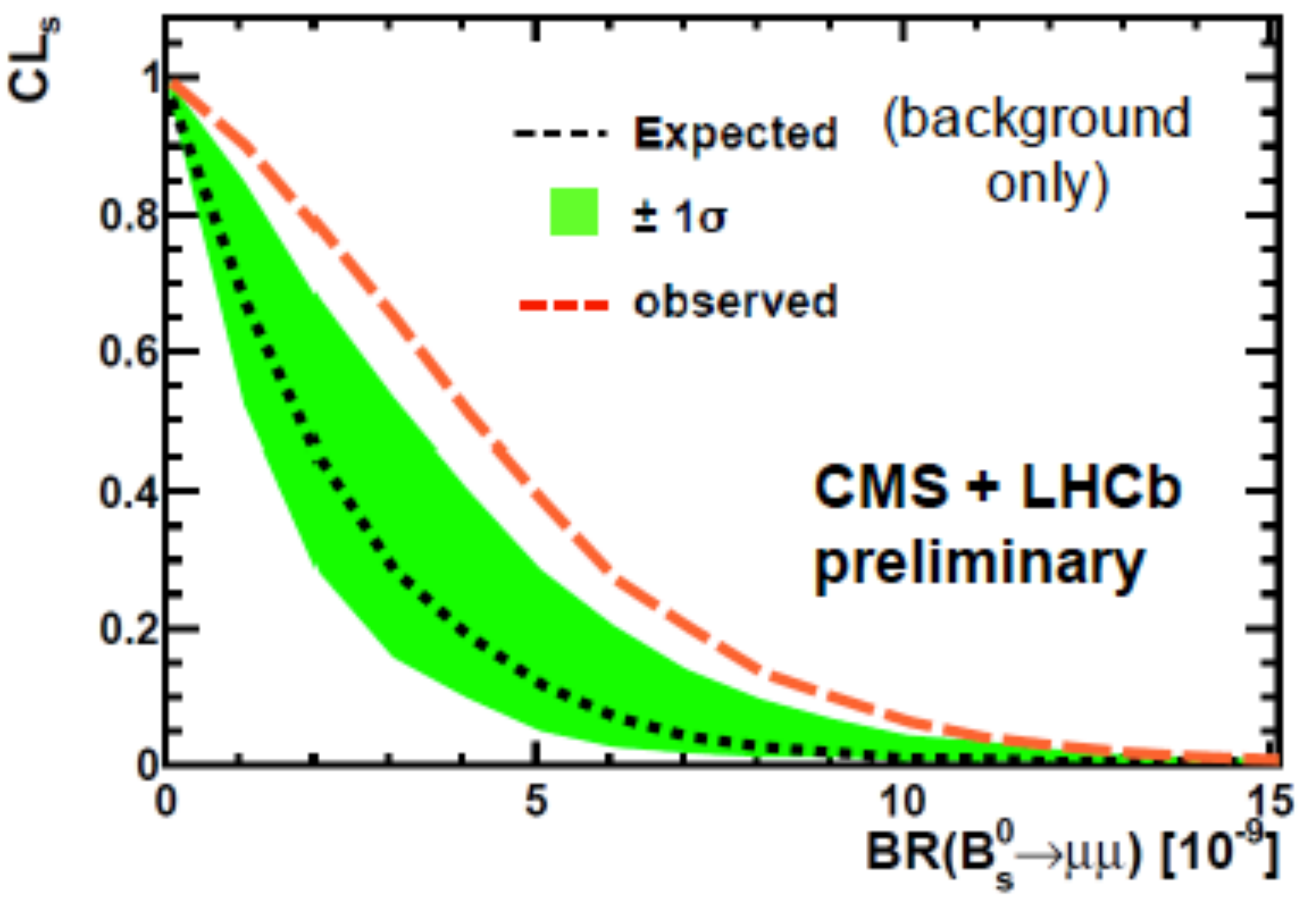


Very clean ~60+80GeV Et dielectron



Bs -> mu mu

A preliminary CMS-LHCb combination on BR($B_s \rightarrow \mu^+\mu^-$) has been performed, again using the CLs approach, & taking LHCb value of f_s/f_d as common input

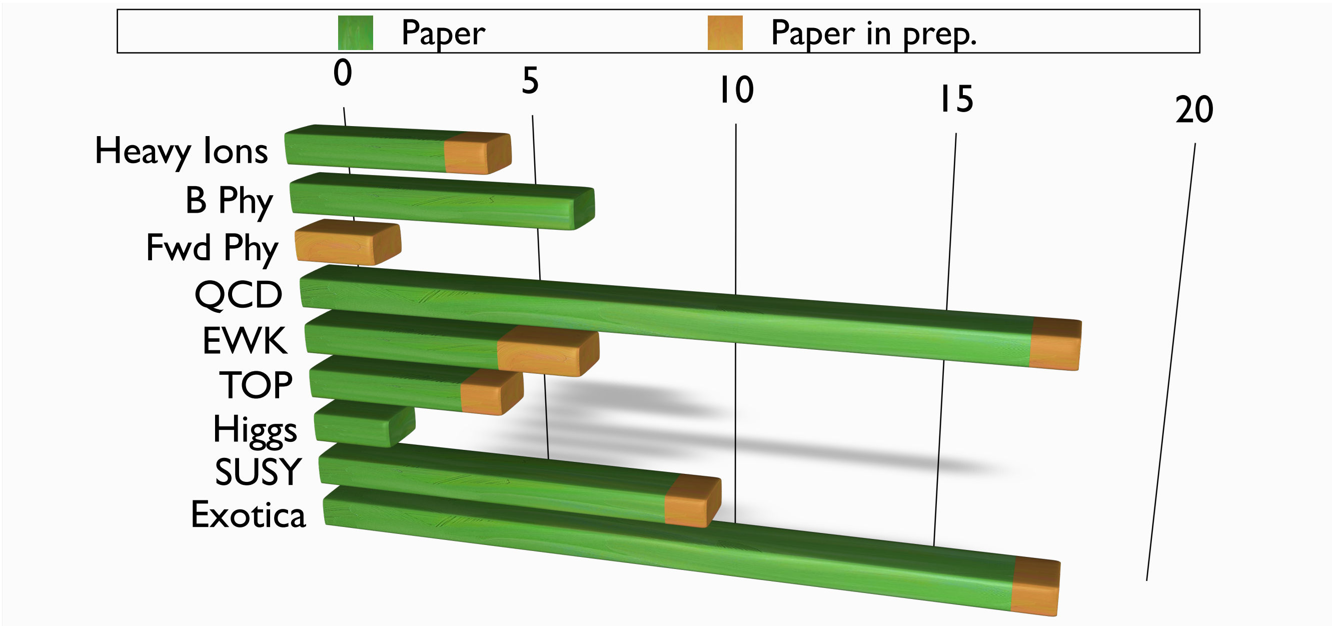


Observed limit at 95% (90%): $1.1\ (0.9) \times 10^{-9}$

This is 3.4 times the expected SM value

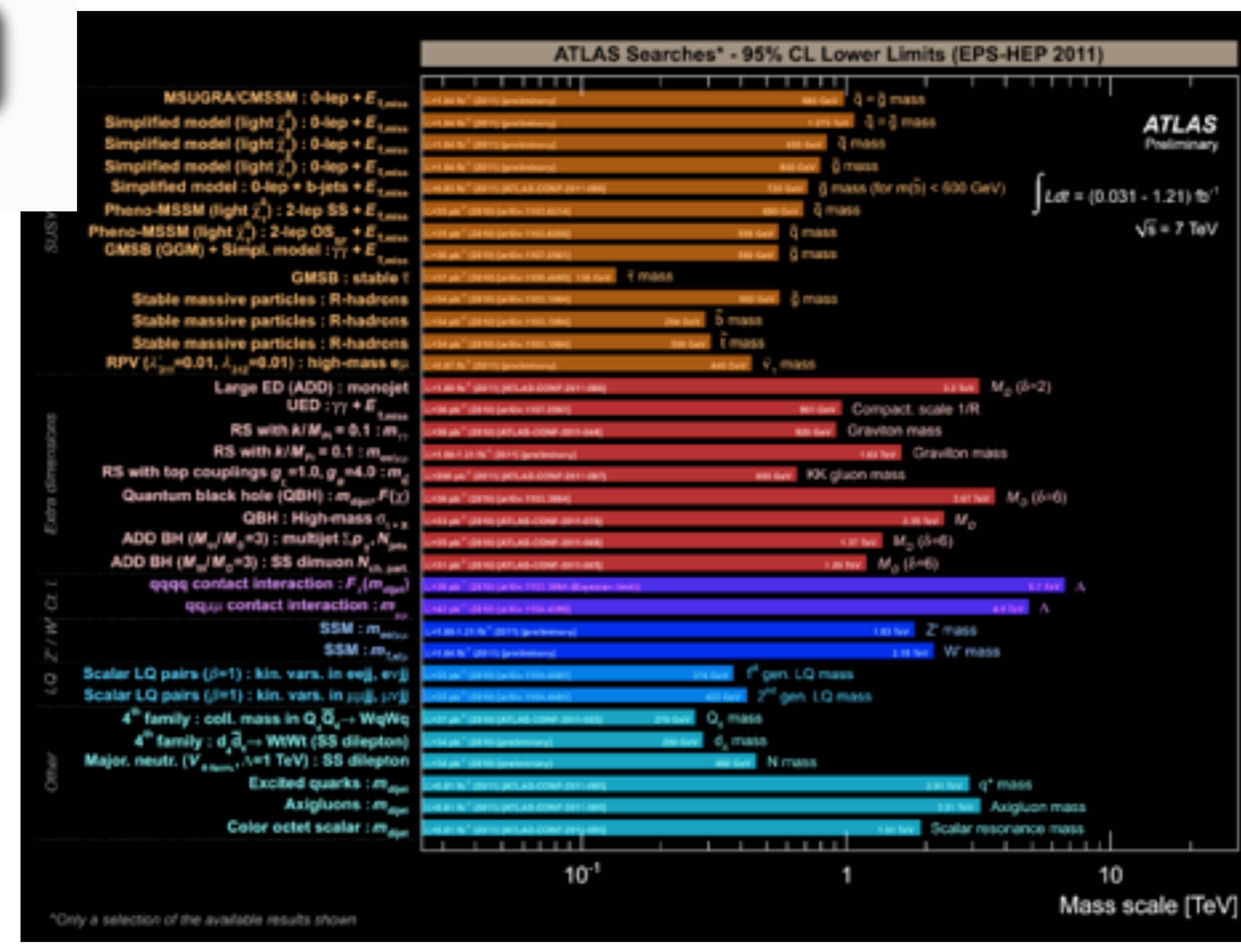
A BR of 1.8×10^{-8} has a CLs value of ~0.3%

No Time To Mention…



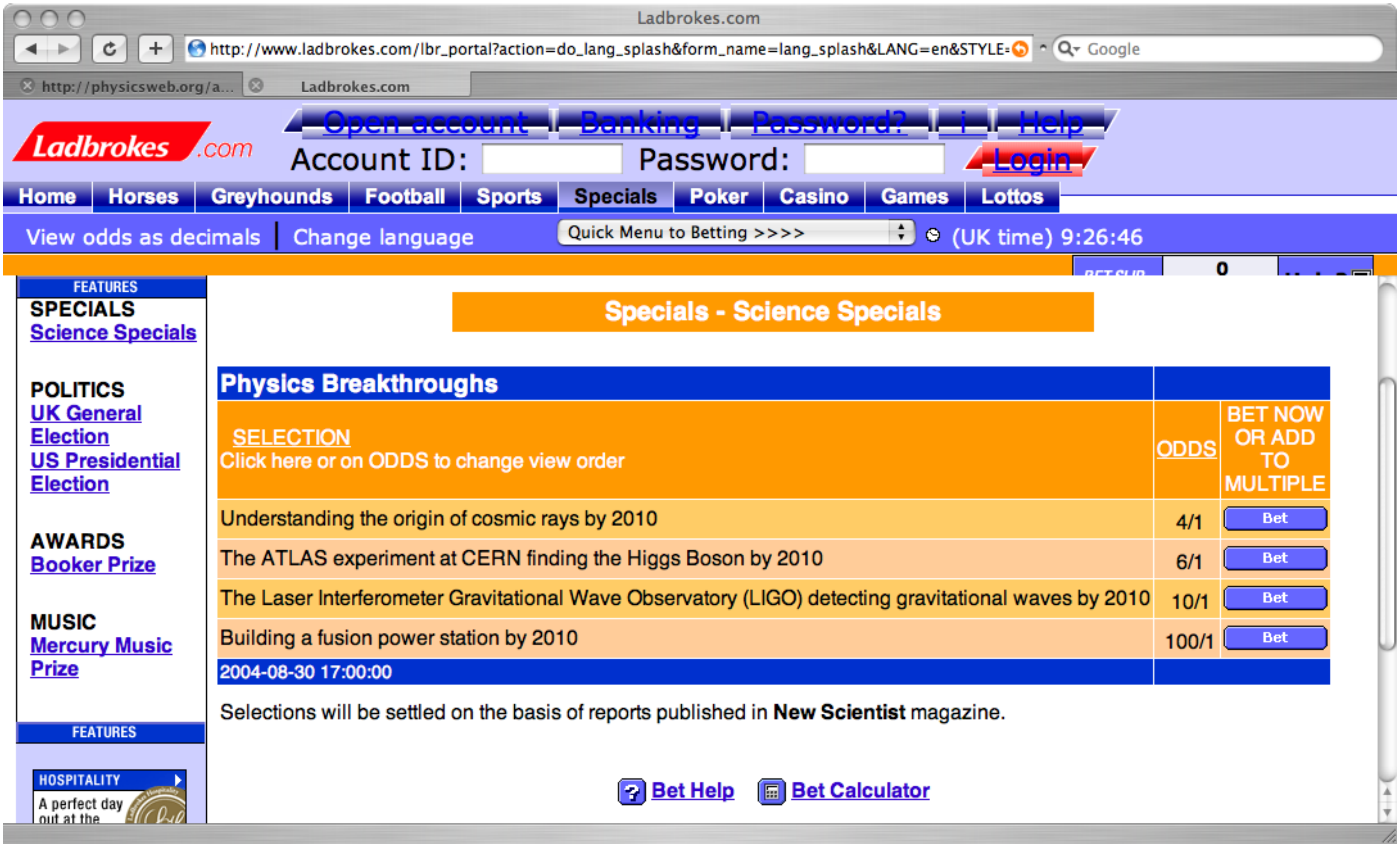
In total : **65** papers on physics analyses, submitted, accepted or published
9 papers close to submission

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



A Warning From History

- Shown at BUSSTEPP2004…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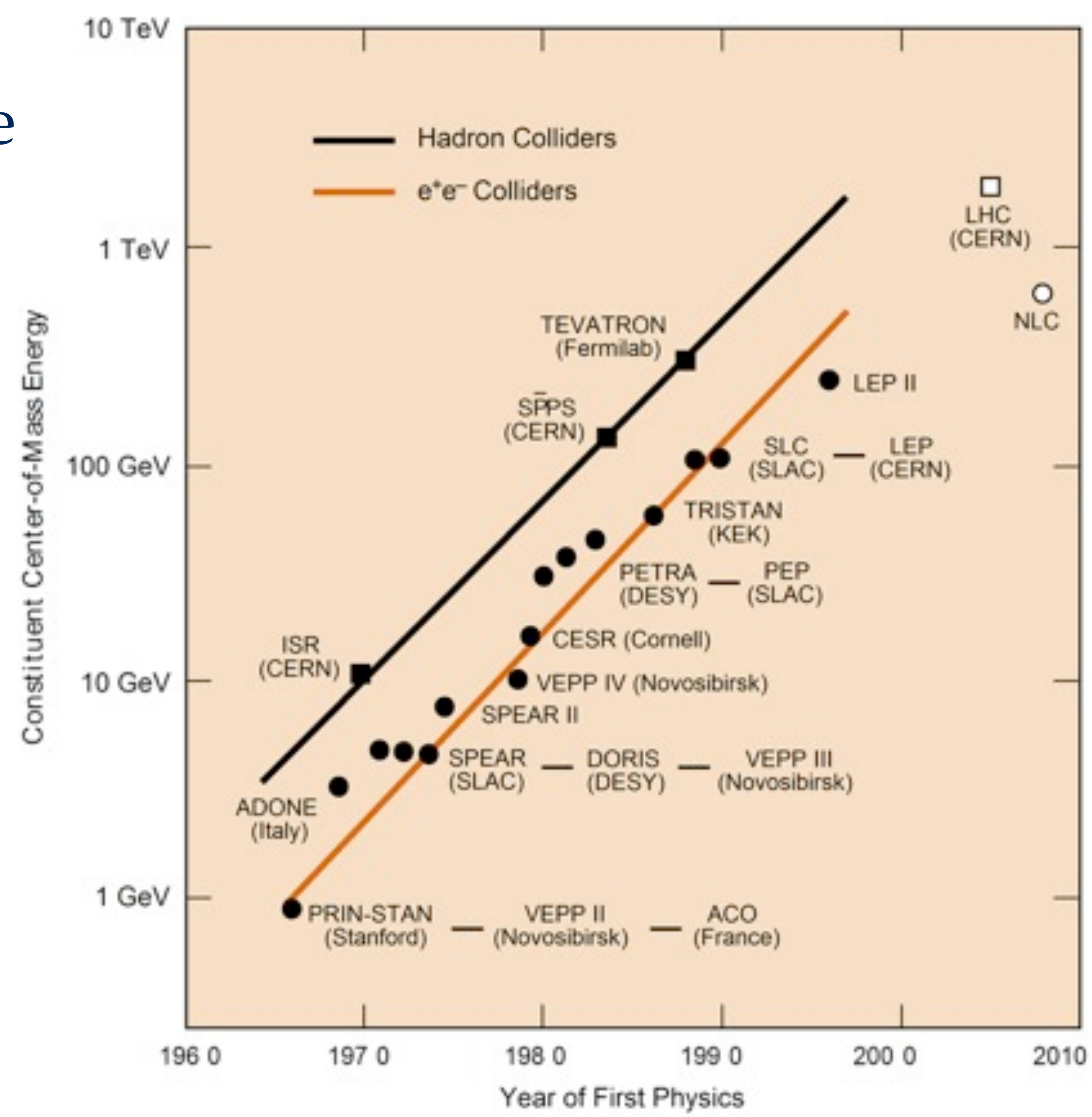
Building a fusion power station by 2010	100/1	Bet
2004-08-30 17:00:00		

Selections will be settled on the basis of reports published in **New Scientist** magazine.

Bet Help | Bet Calculator

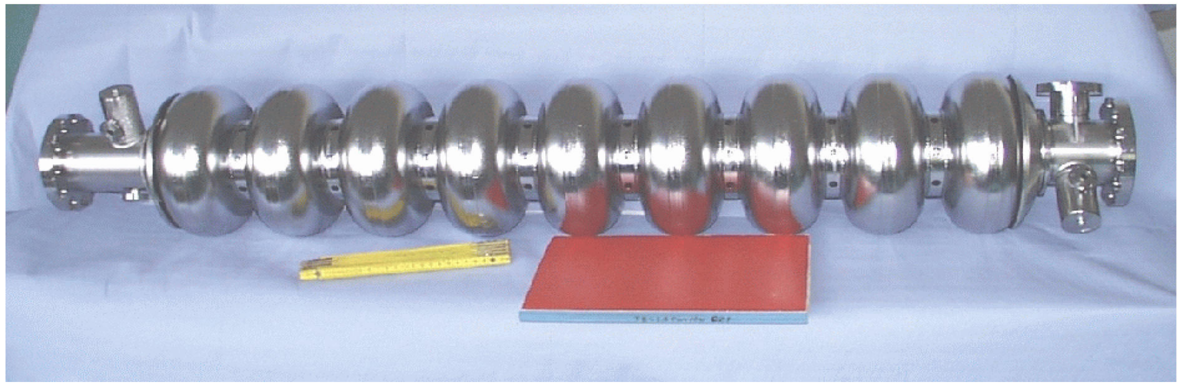
After the Champagne..?

- The LHC is a discovery machine
  - It may not be a measurement machine
  - Though one always finds a way...
- Exploring further
  - How do we exploit our new knowledge
  - e.g. measure Higgs couplings
  - e.g. measure SUSY spectrum
  - e.g. find a 2nd KK resonance
  - e.g. produce copious black holes

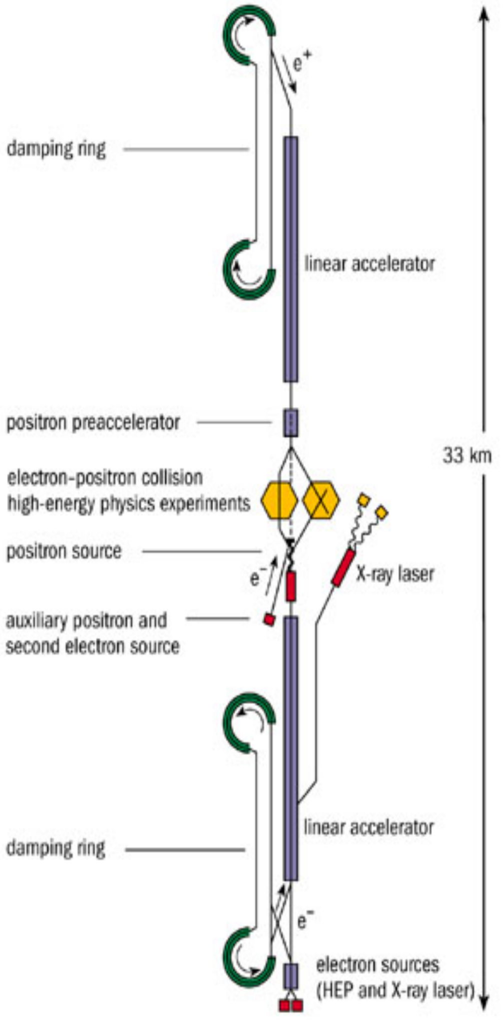


- The usual story applies
  - More events: HL-SLHC (10x luminosity)
  - More energy: HE-SLHC (3x energy)
  - More precision, cleaner environment: Next Linear Collider (e+e-)

Future prospects

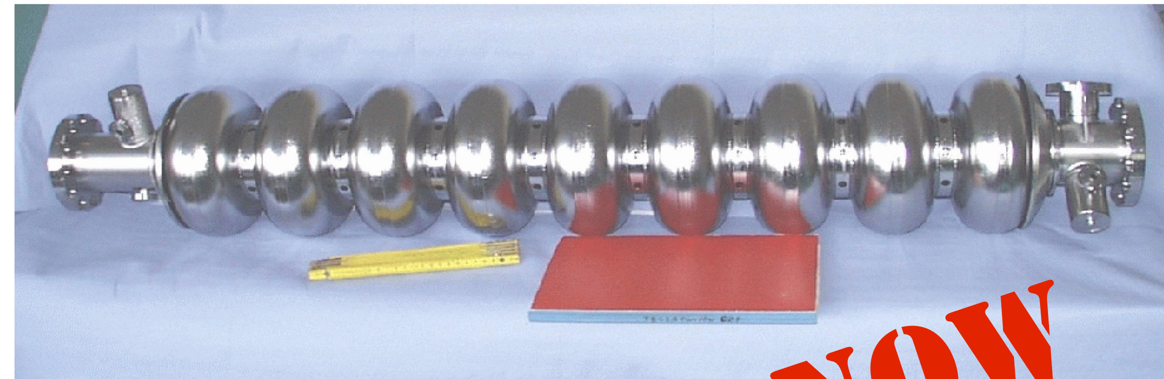


- Next Linear Collider
  - Avoid problems with synchrotron radiation with H/E electron beam
  - ~30km straight collider
  - ILC: superconducting cavity technology
  - CLIC: Two-beam acceleration (higher energy, tricky)
  - What energy? GigaZ / Higgs / SUSY scan?



- SuperLHC
  - Raise luminosity to $L=10^{35}$
  - This is going to be experimentally tough
    - As hard as the original LHC development
  - Work now under way on major GPD upgrades
- The far future? One can only speculate:
  - Neutrino superbeam? Mu-mu collider?
  - How can all of this be made affordable? How can we *downsize*?

Future prospects



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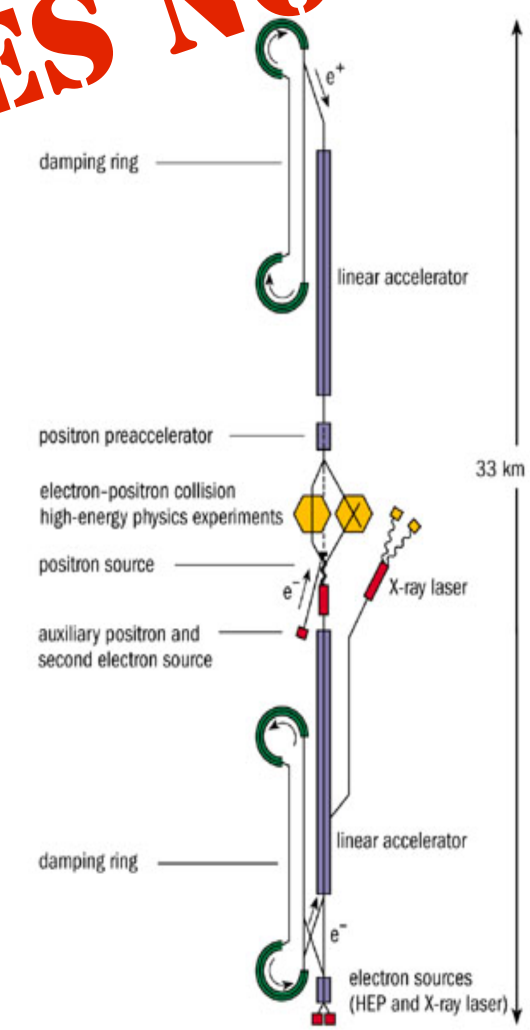

STOP PRESS:
HIGH LUMI (/AB) B FACTORIES NOW APPROVED

Final Thoughts

- Theory and experiment
  - We have been waiting a long time to test theoretical ideas
  - Probably has not been a healthy situation
- Now is a great time to be an experimentalist!
  - The next (last?) big energy frontier is being crossed
  - BUT - looks like no easy ride to new discoveries
    - 1/fb down, 2999/fb to go! Though LHC is by no means the only story
  - Lots of work and smart thinking required in the coming years
- Now is a great time to be a theorist!
  - Many beautiful ideas in circulation – which are correct? If any?
  - Something entirely unexpected could happen
  - Lots of work and smart thinking required in the coming years
- We must work together to exploit the new opportunities
  - The best of luck!