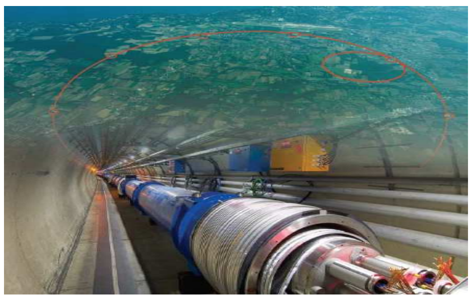
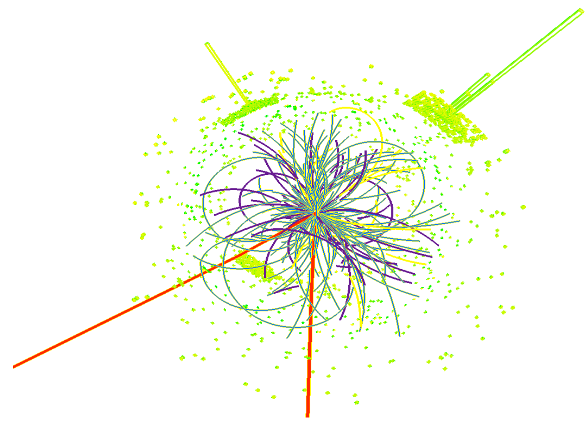
Physcis at the LHC: Recent Results



Lecture and Seminar
Humboldt-Universität zu Berlin
Graduate School Mass, Spectra, Symmetry
Summer Term 2012



Martin zur Nedden,
Humboldt-Universität zu Berlin
Sven-Olaf Moch,
DESY Zeuthen

Organization Issues

- **Lecture**
  - Dr. Martin zur Nedden, HU Berlin
    - nedden@mail.desy.de, Tel. 030 / 20 93 78 16
  - Dr. Sven-Olaf Moch, DESY Zeuthen
    - moch@mail.desy.de, Tel. 03akdjfd
  - FR, 9 – 13, every second week, NEW 14, 1'09
- **Seminar**
  - Important and integrated part of the lecture
  - Presentation of recent LHC (ATLAS) and theory papers by you
- **Information**
  - http://www-eep.physik.hu-berlin.de/teaching/lectures/ss2012/lhcphysik/
  - Book: QCD and Collider physics (R. Ellis et all)
  - ATLAS papers: Results from 2011 (on the web page)
  - Theory papers: review articles about Higgs and SUSY

Program

- **Introduction (27.04.)**
  - LHC and experiments
  - Hadron Colissions
- **Standard Model Physics (11.05.)**
  - Measurements of W and Z Bosons
- **Top physics (25.05.)**
  - Mass, cross sections, properties
  - Single top production
- **Standard Model Higgs Search (01.06.)**
  - Individual channels and their combination
- **Statistics and MSSM Higgs Search (08.06.)**
  - Neutral and charged MSSM Higgs
  - Statistical method for searches for new physics
- **Jets at LHC for searches for new physics (22.06.)**
  - di-Jets, jets with missing transverse energy, jets with high energetic leptons
- **Searches for Super Symmetry (06.07.)**
  - Searches with high energetic leptons, missing energy, jets and tauons

Topics for Student Talks

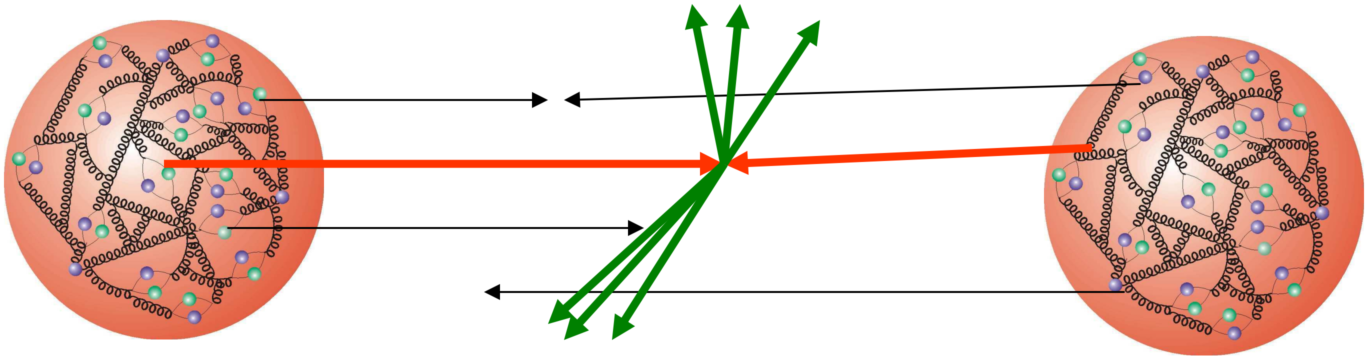
- **Experiment**
  - Standard Model Measurements (W+Z Bosons)
    - Mohamad (W/Z inclusive), Benedikt (W/Z with taus)
  - Top Physics (top properties, single top production)
    - Mohamad (single top), Peter (top pair)
  - Higgs Searches (Standard Model, all channels)
    - Carsten (Higgs inclusive cross sections), Rebekka (ATLAS measurements)
  - MSSM Higgs Searches (charged and neutral)
  - Statistical Methods for Searches (CLs Method)
    - Peter (Statistics), Geoffey (ATLAS Combination)
  - Jets for searches for new physics (di-jet, jet+MET, jet+high pT leptons)
    - Benedict (Jets)
  - Searches for super symmetry (with leptons, met, b-jets)
- **Theory**
  - LHC Higgs cross sections: inclusive observables
  - LHC Higgs corss sections: differential distributions
  - Beyond Standard Model searches
  - SUSY

Introduction Hadron Collides

- **Physics issues**
  - new energy frontier at the TeV scale
  - high energies and high luminosity
  - stable and charged particle
  - discovery machines: large region of energy to be covered (parton structure)
  - large cross sections for hard processes

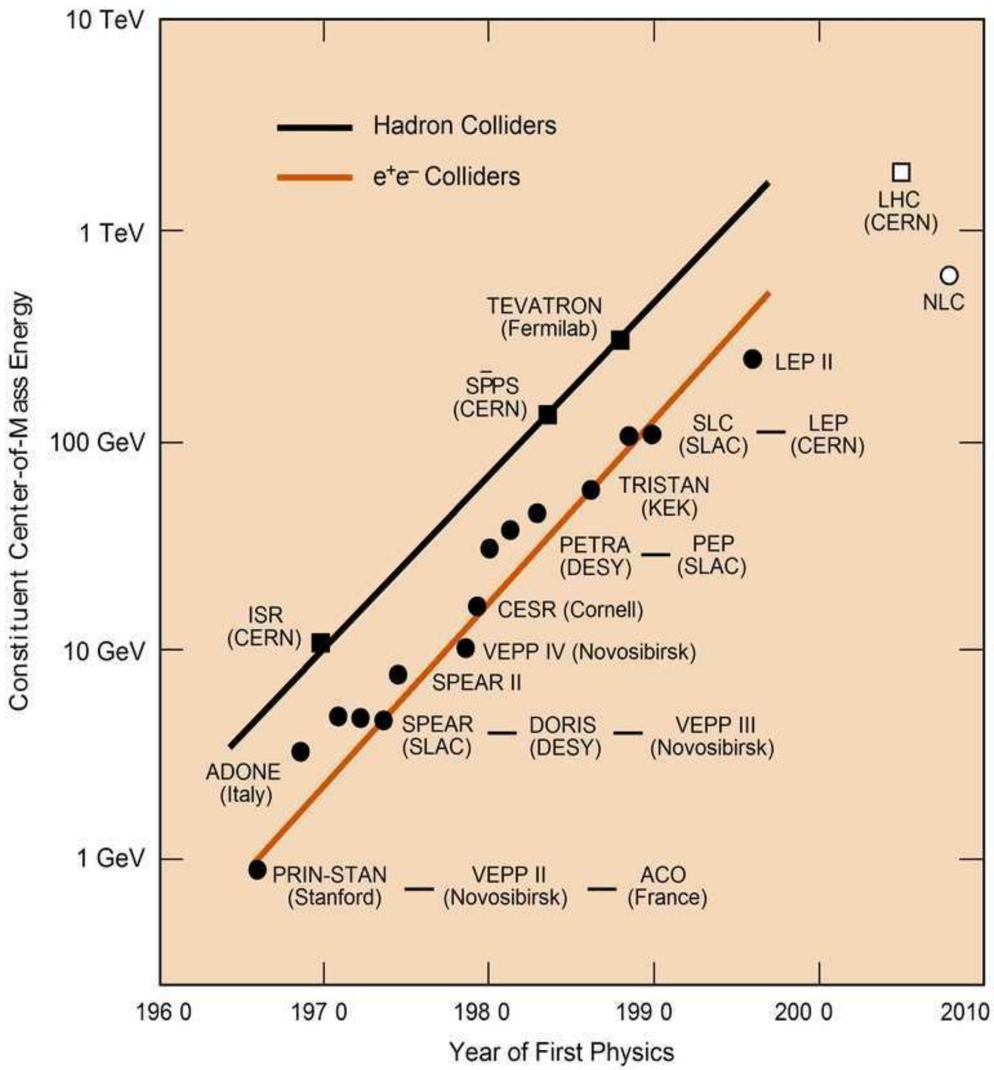
- **Technical issues**
  - low synchrotron radiation
  - large magnetic fields needed (up to 10 Tesla)
  - very dense and complex final state: good Trigger needed
  - very high radiation exposure of the detectors

Proton-Proton Interactions



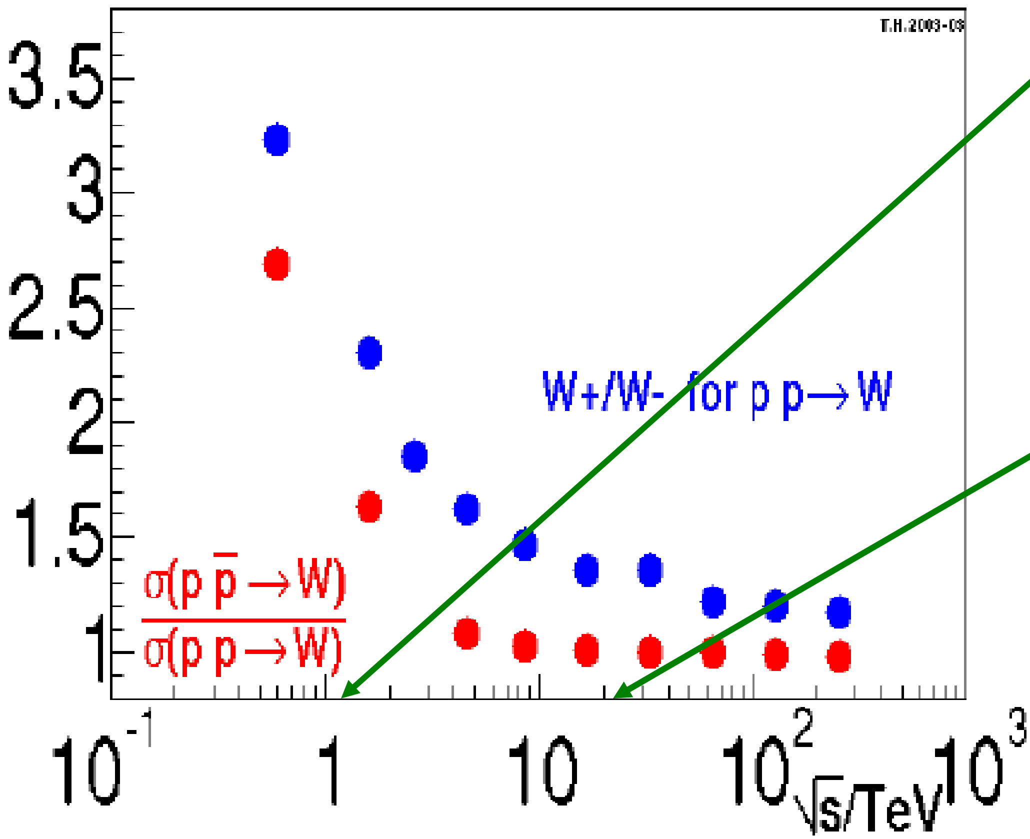
- **Complex and composed particles**
  - interaction energy at parton level unknown and dependent on proton structure: large energy region can be covered
  - Interaction energy << total proton energy
  - Complicated final state to be reconstructed from decay products
- **Strong Interaction**
  - large cross sections for strongly interacting particles
  - huge QCD background: effective Triggers on EW signals as high pT leptons or missing transverse energy

Energy Frontier Accelerators



- Last hadron collider:
  - TEVATRON, FNAL
  - 6 km circumference
  - CMS = 1.96 TeV
  - Stopped in 2011
- Last lepton collider:
  - LEP, CERN
  - 27 km circumference
  - CMS = 80 – 210 GeV
  - Stopped in 2000
- Next lepton collider:
  - Linear collider
  - Design not decided
  - CMS = 1 – 2 TeV (?)

Comparison Proton / Anti-Proton



low energy (TEVATRON):
Valence quarks dominating the hard interaction:

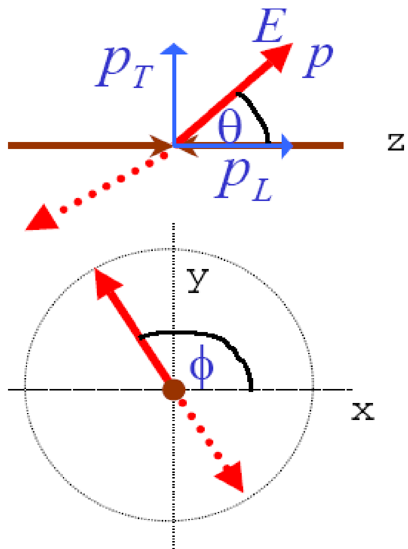
Proton / Antiproton > Proton Proton

high energy (LHC):
sea-quarks and gluons dominating the hard interaction

Proton / Antiproton = Proton Proton

Kinematic Variables

boost of the c.m.s. along the beam axis is **unkown**
Lorentz Invariant variables needed



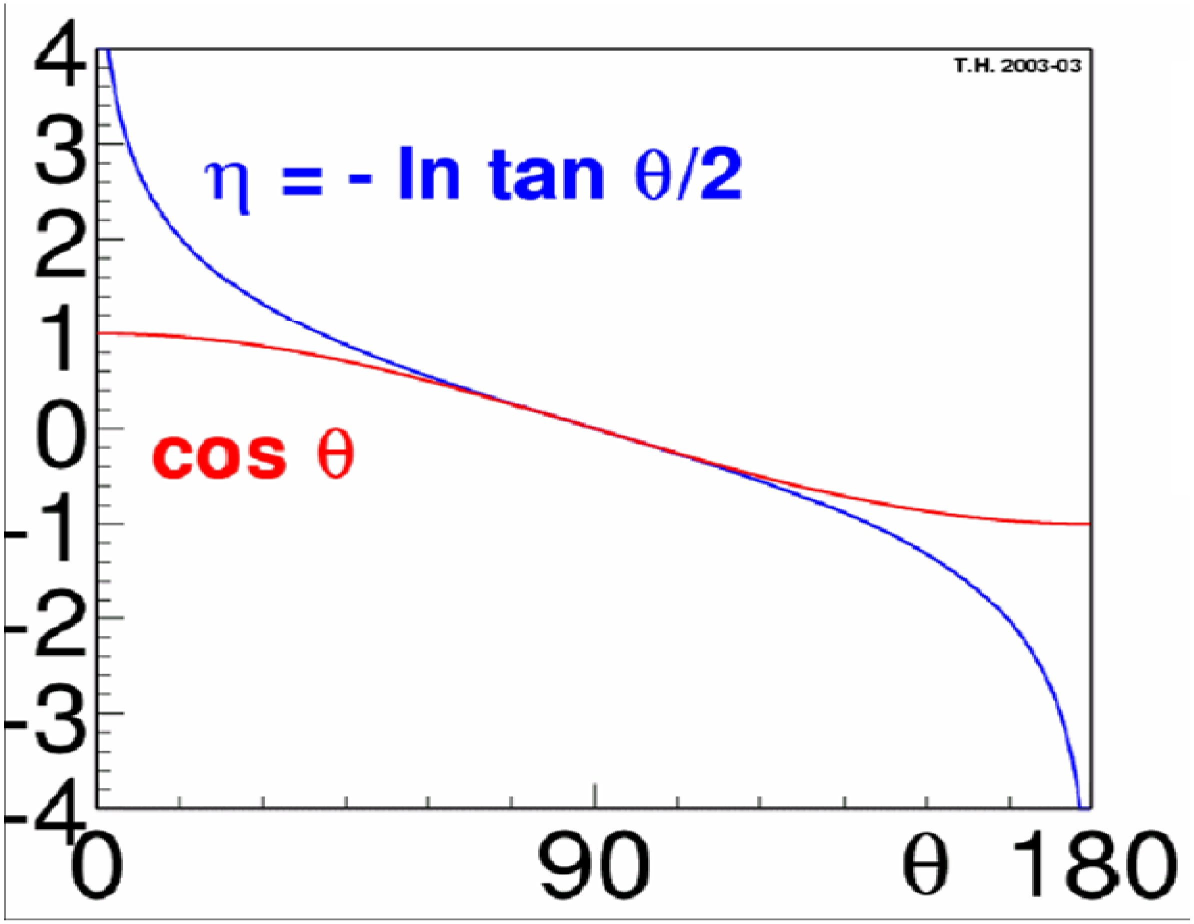
transverse momentum p_T (**LI**)
longitudinal momentum p_L
polar angle **θ**
energy **E**
momentum **p**
azimuthal angle **φ** (**LI**)

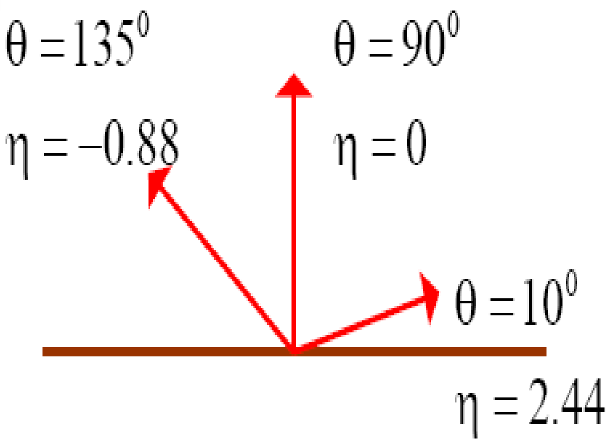
Lorentz **I**nvariant polar angle distribution rapidity **y**: $y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$

if (as usual..) $m << E, p_T$ pseudo – rapidity **η** $\eta = -\ln(\tan \frac{\vartheta}{2})$

Usually, the invariant variables $\Delta\eta = \eta_1 - \eta_2$ and $\Delta\varphi = \varphi_1 - \varphi_2$ are used

Rapididity and Pseudorapdidity





Distributions of rapidity and azimutal angle are correlated

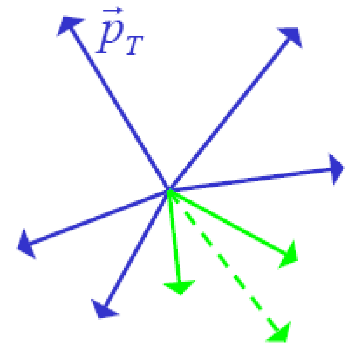
Missing Transverse Energy

- masses small: Energy = momentum
- transverse momentum measurable for all visible particles
- invisible particles:
  - small angles: escaping into beam pipe, but p_T small
  - neutral particles: neutrinos, neutralinos, gravitinos, ….

balanced momentum:

$\rightarrow$ **calculate missing transverse momentum/Energy**

$$\sum_{invis} \vec{p}_T = -\sum_{vis} \vec{p}_T \Rightarrow E_T^{mis} = \left| \sum_{invis} \vec{p}_T \right|$$



$$E_T^{miss} = \sqrt{(\Sigma_i E_i \sin \vartheta_i \cos \varphi_i)^2 + (\Sigma_i E_i \sin \vartheta_i \sin \varphi_i)^2}$$

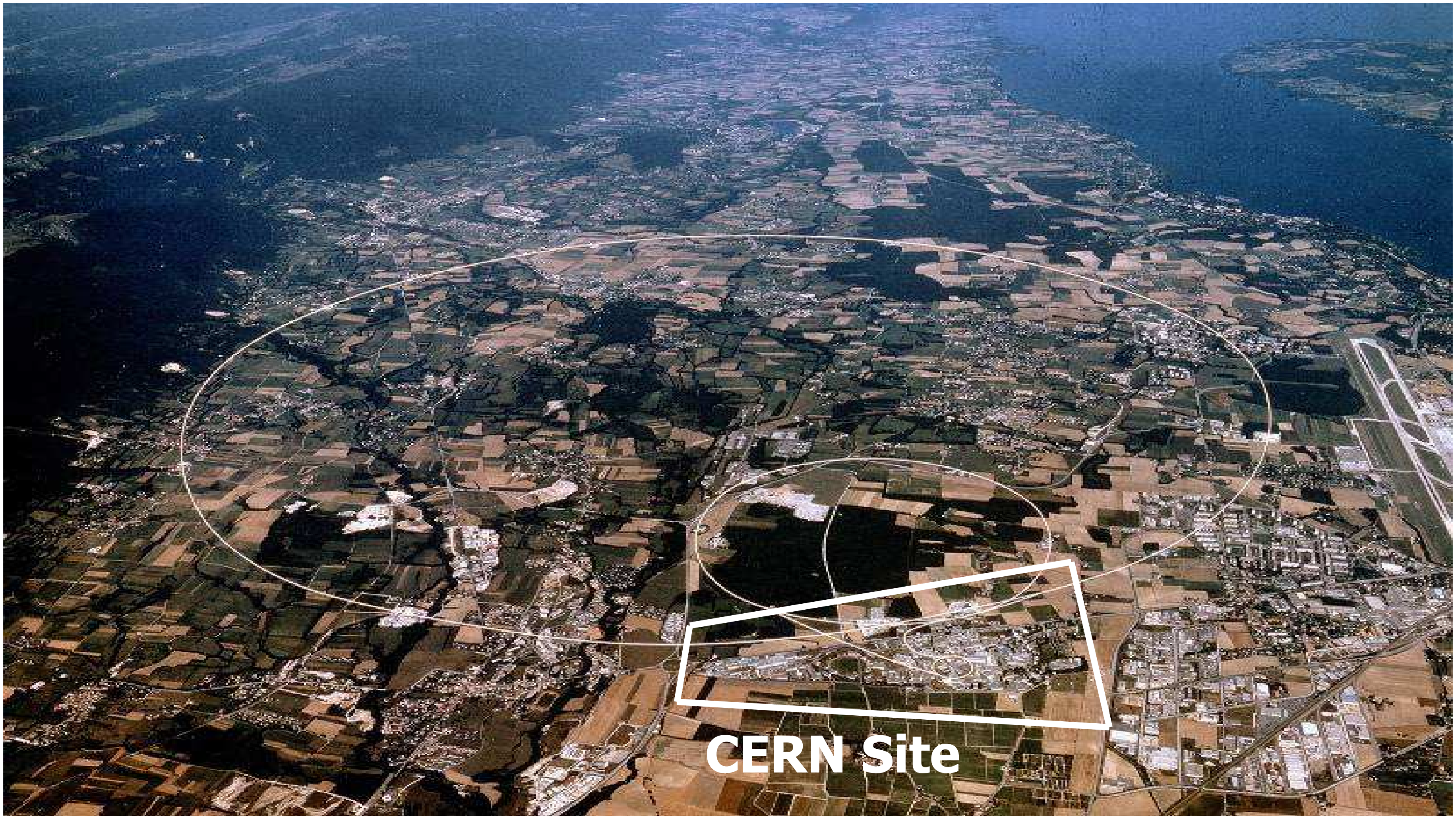
Example: W $\rightarrow$ μ ν

CERN

Conseil
Européen pour la
Recherche
Nucléair

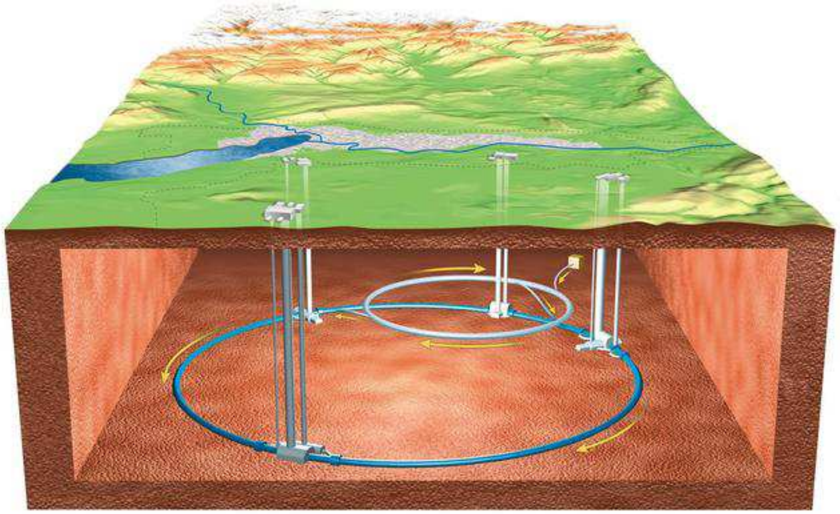
Place	Geneva (CH andF)
Member states	20 European nations
Budget per annum	~ 700 million Euro (20 % from Germany)
Collaborators on site	~ 3.400 (largest in world)
Total Scientists	~8.000 from 85 Nations

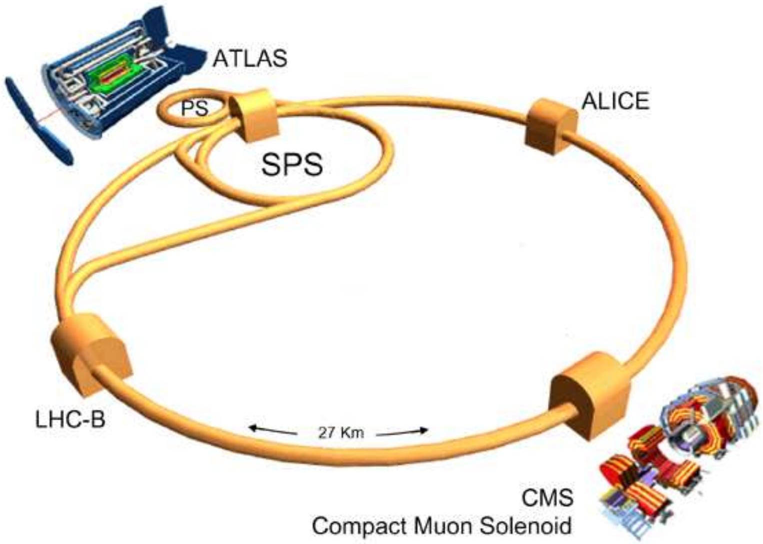
The CERN Site



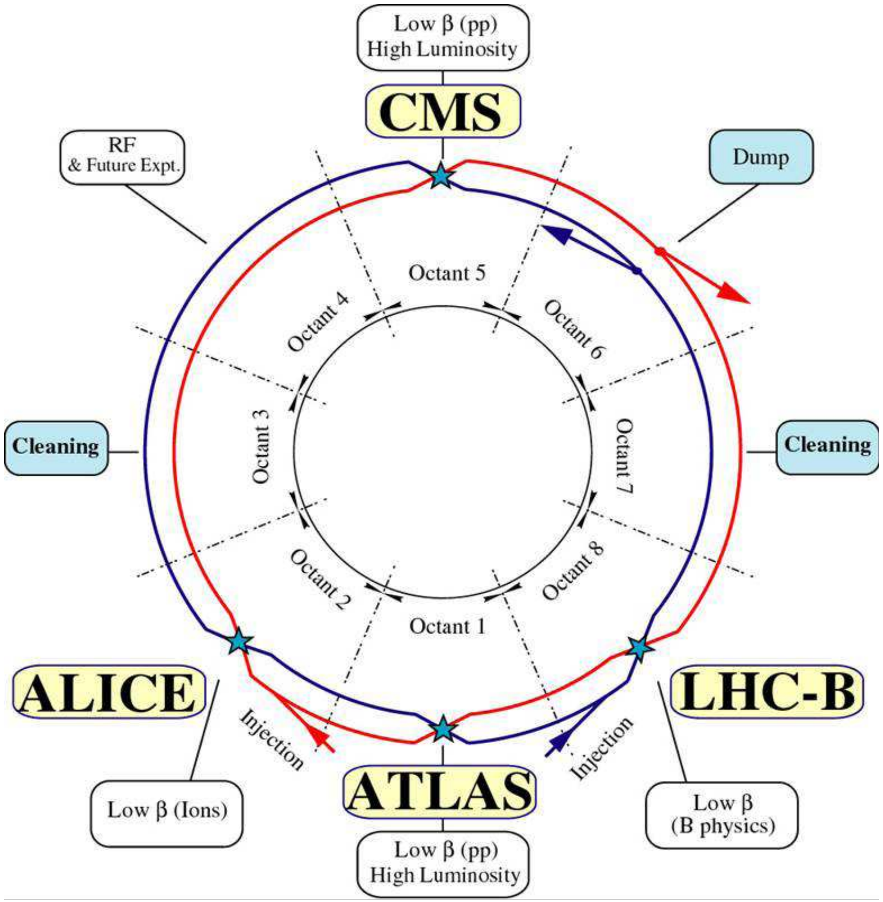
Accelerator LHC

Ring tunnel with 27 km circumference
50 – 175 m below floor





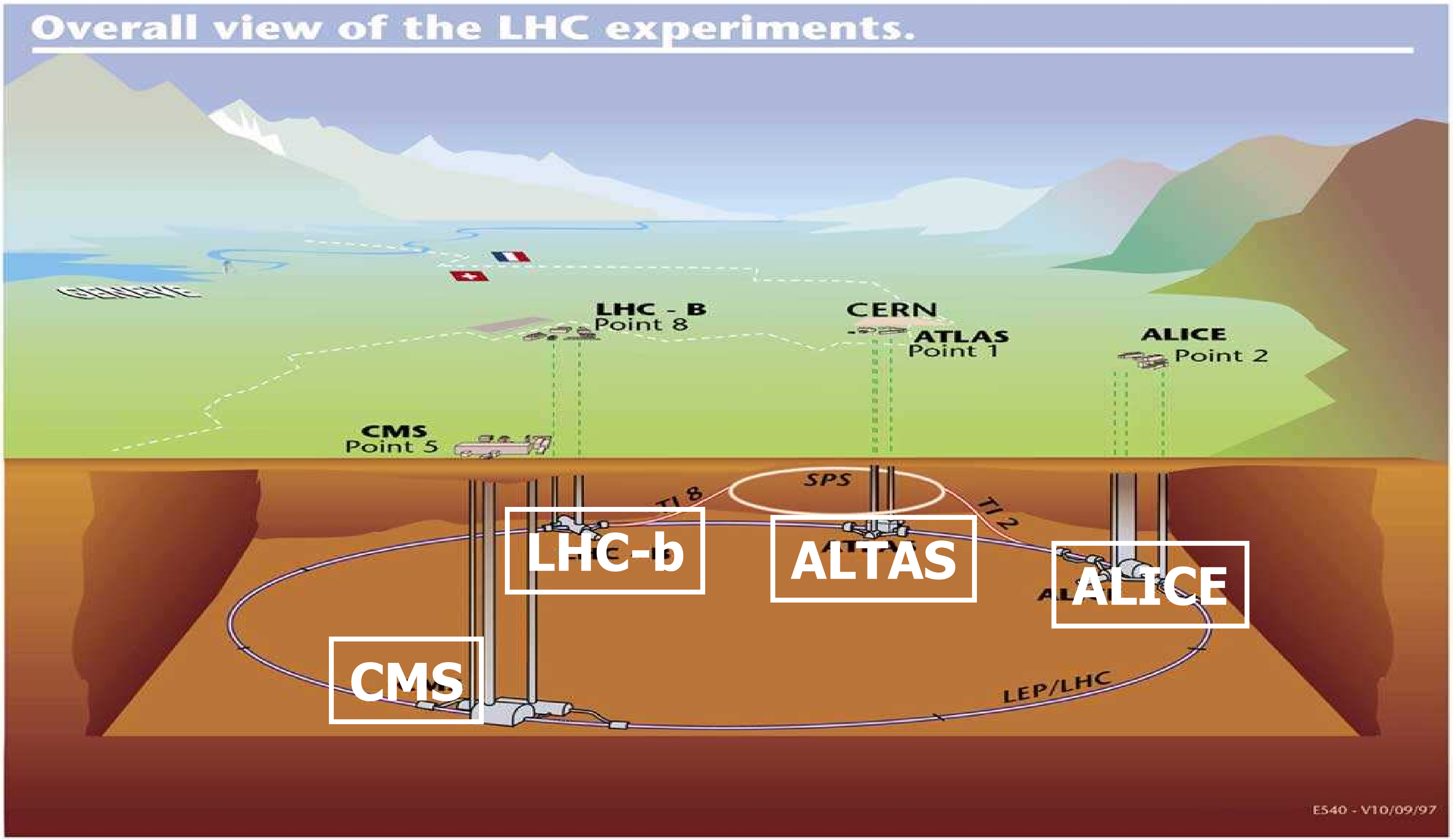
LHC: Technical Overview



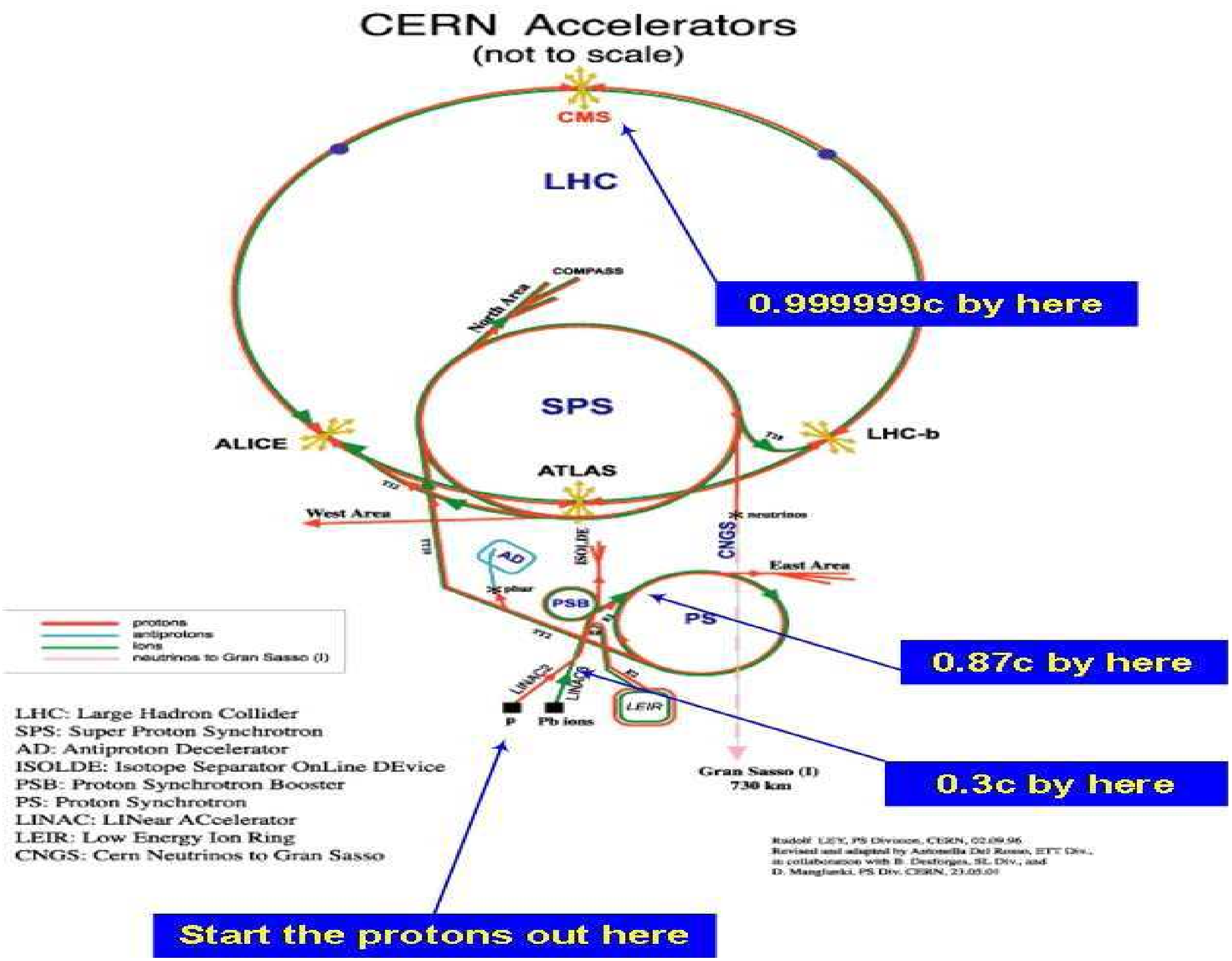
Most powerful accelerator in all parameters

type	Proton-Proton/ Pb-Pb Collider
circumfer.	26.7 km
Energy	7 TeV per beam
Luminosity	10^{34} cm^{-2}s^{-1}
Current	120 MWatt
planning	1984 – 1994
construction	1994 – 2008
duration	~ 25 years
costs	3 Bilions EURO
experiments	4 (6)

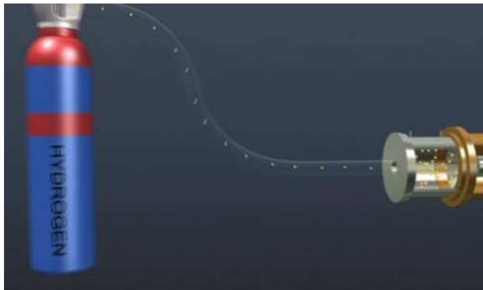
Experiments at LHC

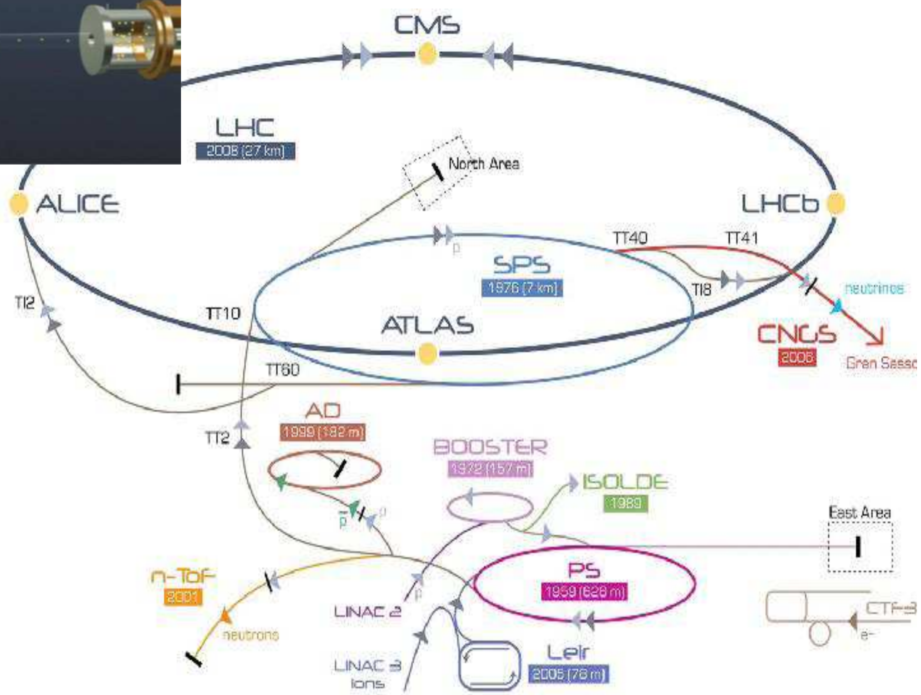


CERN Accelerators Complex



Proton source

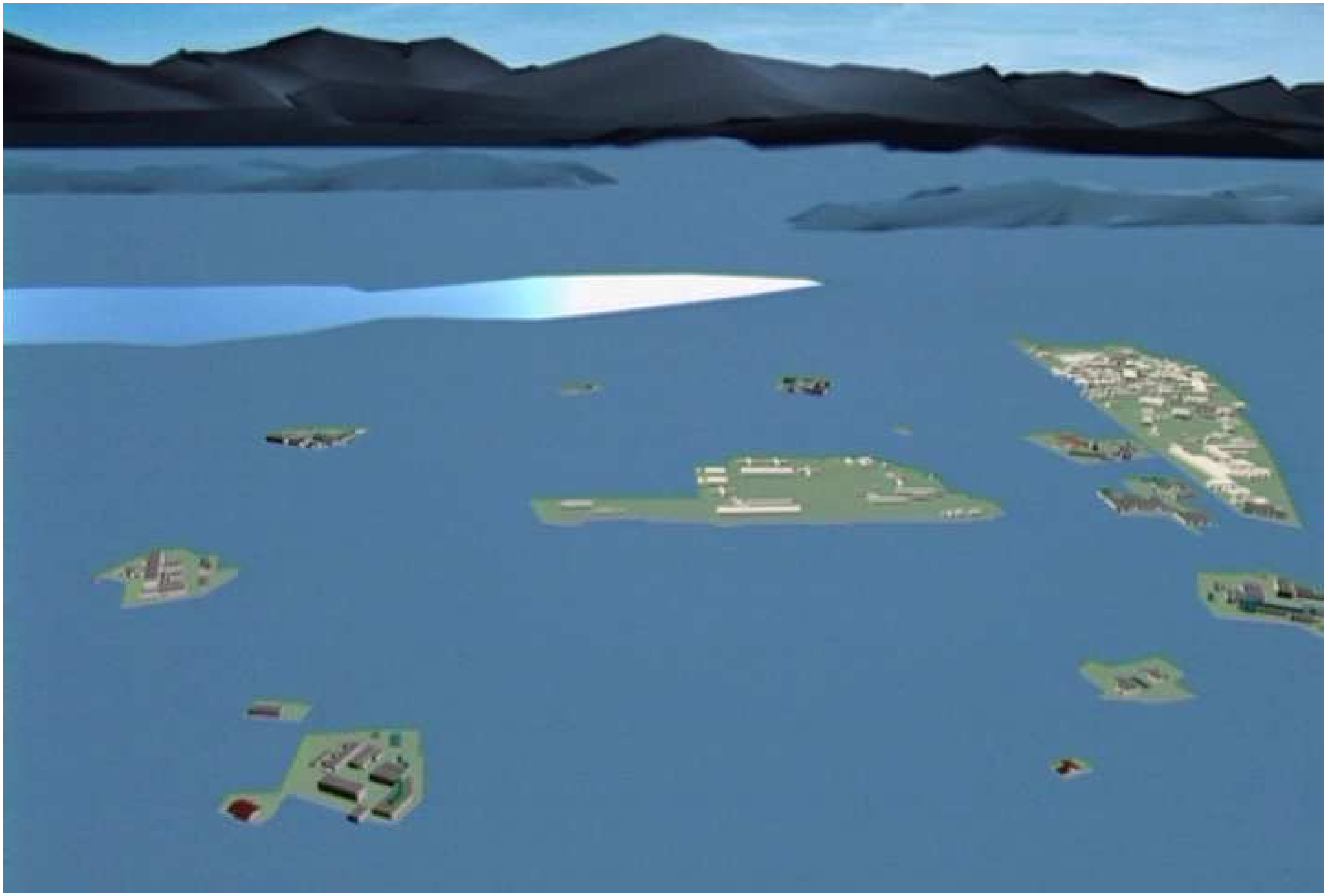




Acceleration chain:

1. Proton source (bottle), 2. LINAC2: 50 MeV,
3. PSB: 1.4 GeV, 4. PS: 28 GeV, 5. SPS: 400 GeV, 6. LHC: 3.5 TeV

LHC Complex

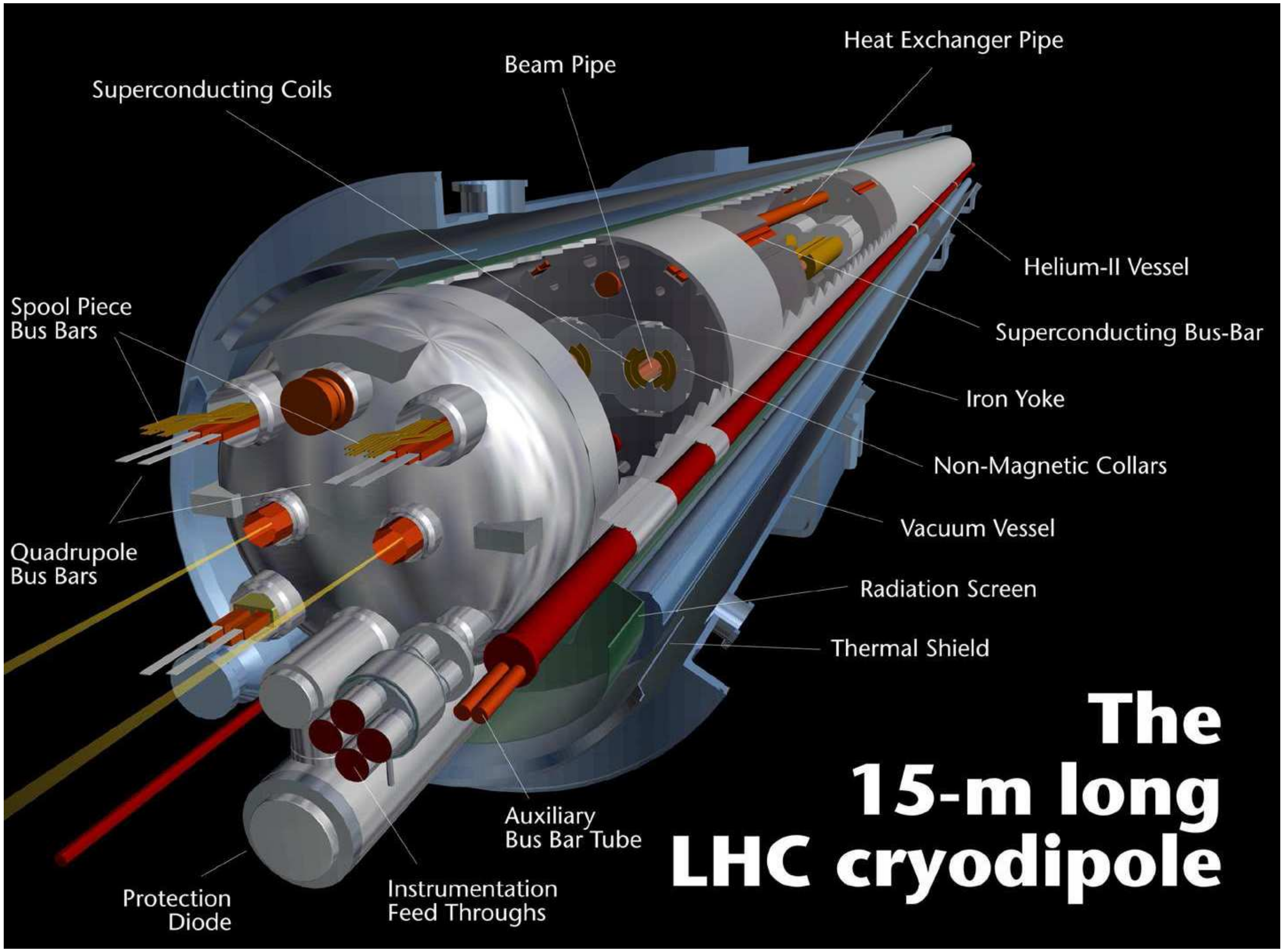


The LHC Beams

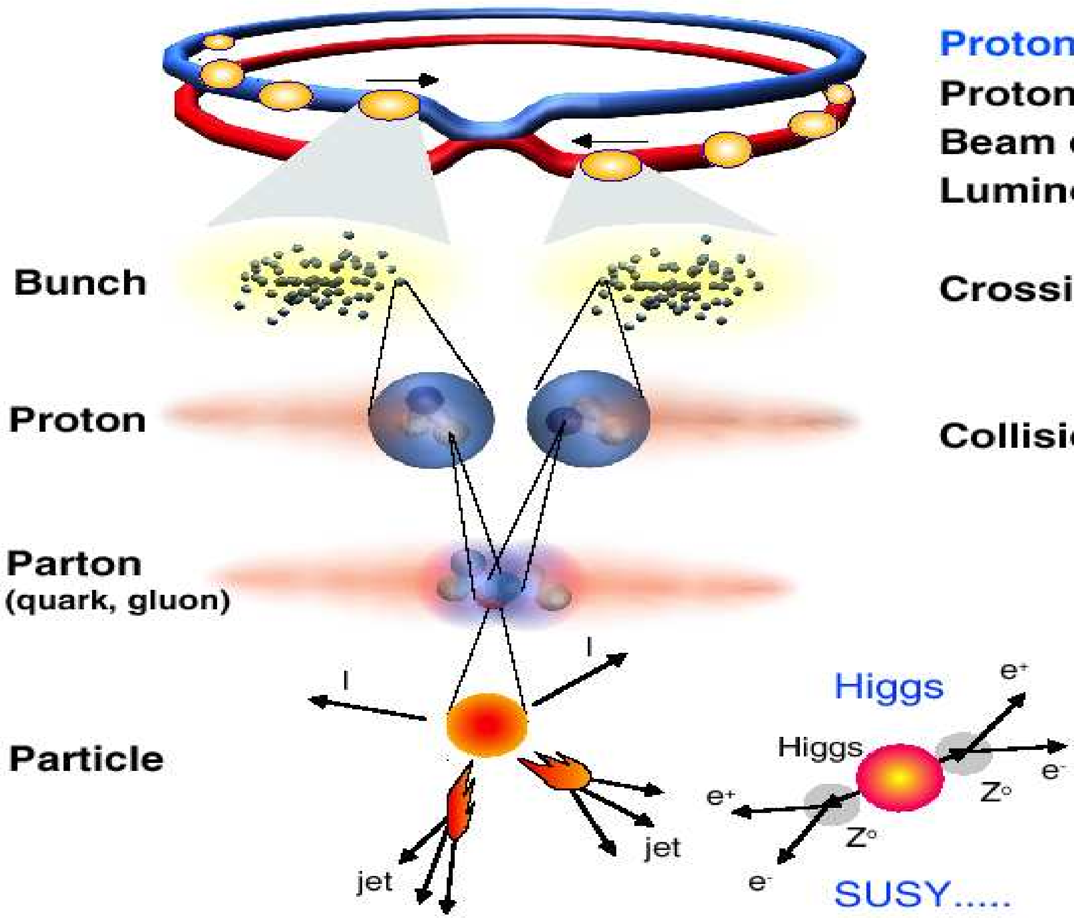
- **Beam parameters**
  - Ring length: 26658.883 m, 4 collision points, revolution frequency 11245 Hz, bunch spacing 25 ns (40 MHz)
  - Energy of each proton: 3.5 – 4 (7) TeV
  - 2808 bunches with 1.2×10^{11} protons
  - Beam at IAP: transverse 16 µm, longitudinal 7.55 cm
- **Stored energy in beam**
  - Proton (7 TeV): 1.2×10^{-6}J, bunch: 1.35×10^{5}J, beam: 3.78×10^{8}J
  - **LHC: 750 MJ**
    - two colliding ICEs at 150 km/h
    - 70 kg of TNT, can melt 10 t of copper

LHC Magnet System

9 Tesla magnets for design energy needed



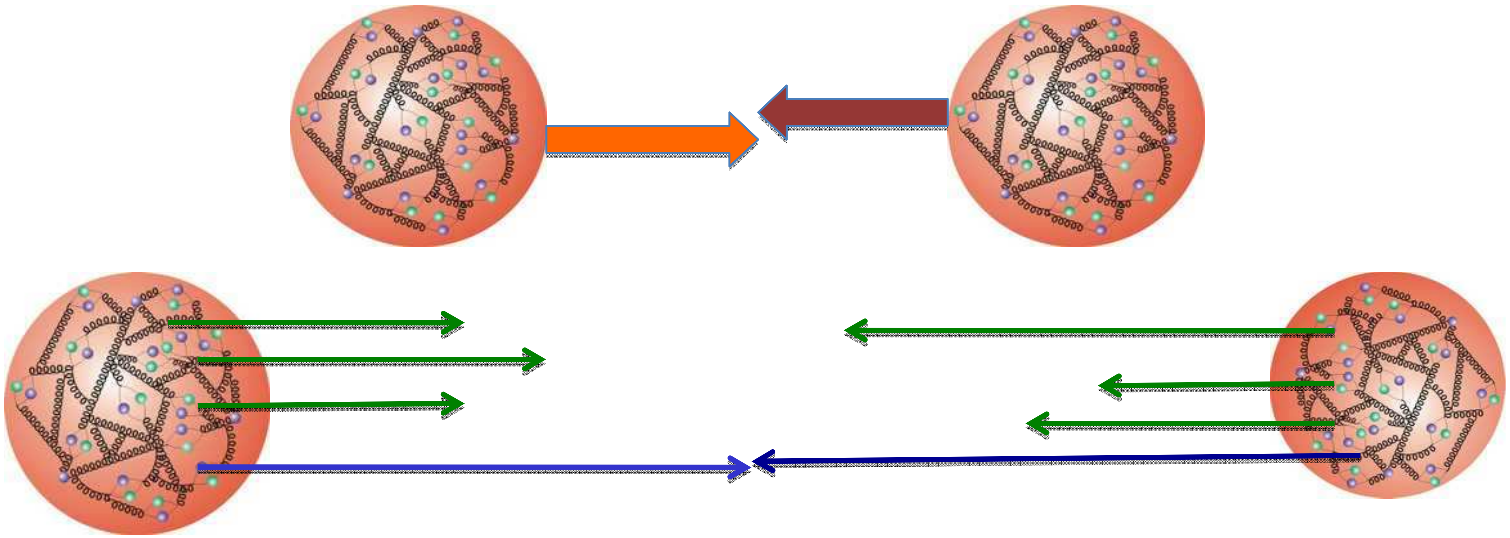
Particle Collissions at LHC



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

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

Proton Scattering

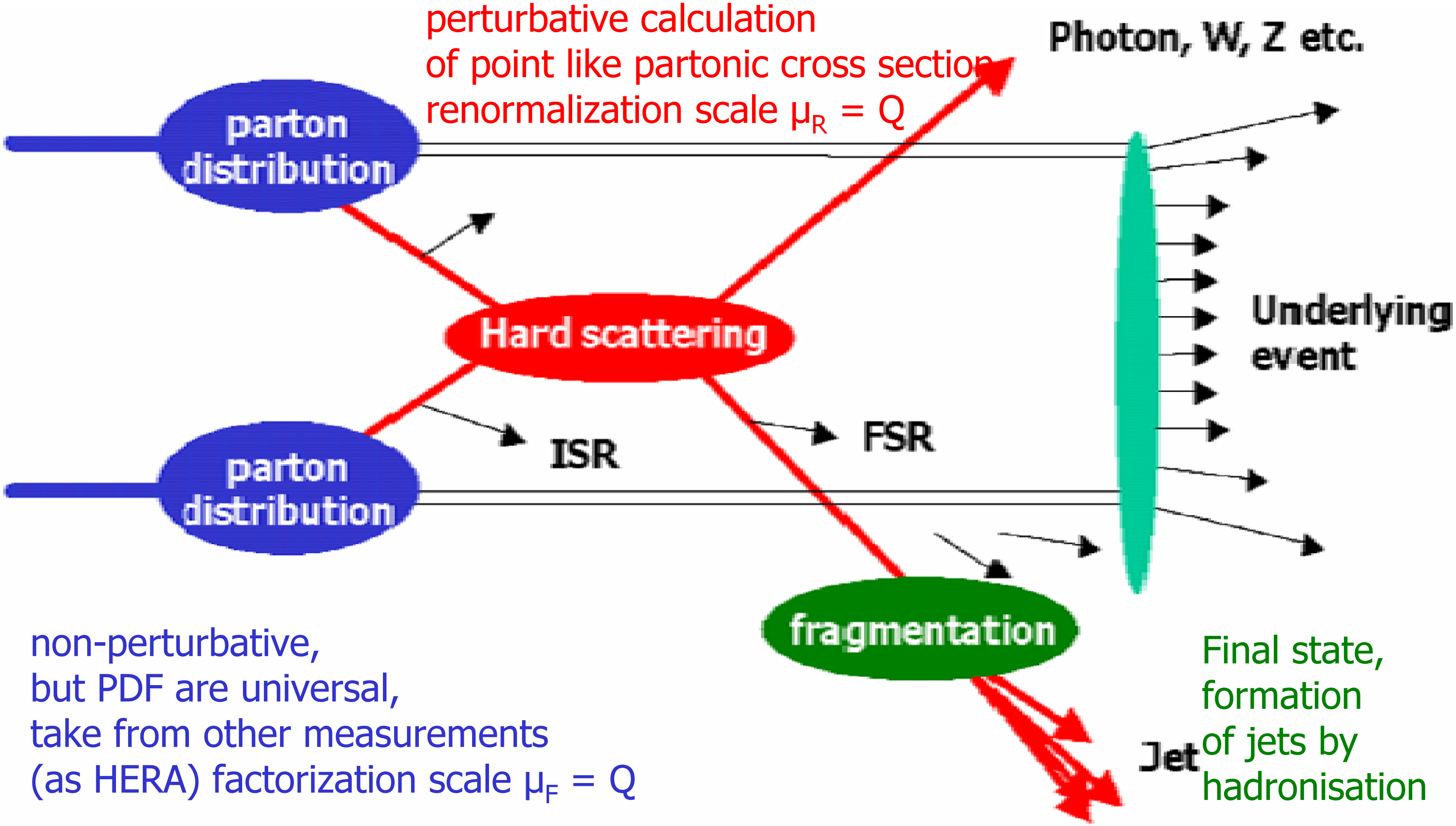


Proton scattering = scattering of quarks and gluons

$$\frac{d\sigma_{FS}(\sqrt{s},Q^2)}{dV} = \sum_{i,j} \int dx_i dx_j \, f_i(x_i,Q^2) \, f_j(x_j,Q^2) \frac{d\sigma_{FS}^{ij}(x_i,x_j,Q^2)}{dV}$$

Hadron Collisions

perturbative calculation
of point like partonic cross section
renormalization scale $\mu_R = Q$



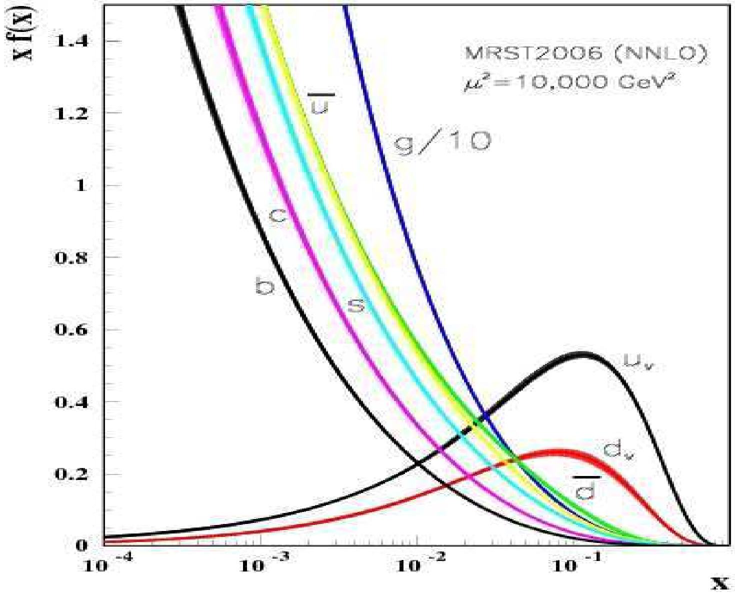
non-perturbative,
but PDF are universal,
take from other measurements
(as HERA) factorization scale $\mu_F = Q$

Final state,
formation
of jets by
hadronisation

Proton Interaction Cross section

wanted: **differential cross** section for a certain variable V at a certain Q^2

$$\frac{d\sigma_{FS}(\sqrt{s},Q^2)}{dV}$$



calculable**: partonic cross** section for two interacting partons i,j

$$\frac{d\sigma_{FS}^{ij}(x_i,x_j,Q^2)}{dV}$$

PartonDensityFunction known form other experiments:

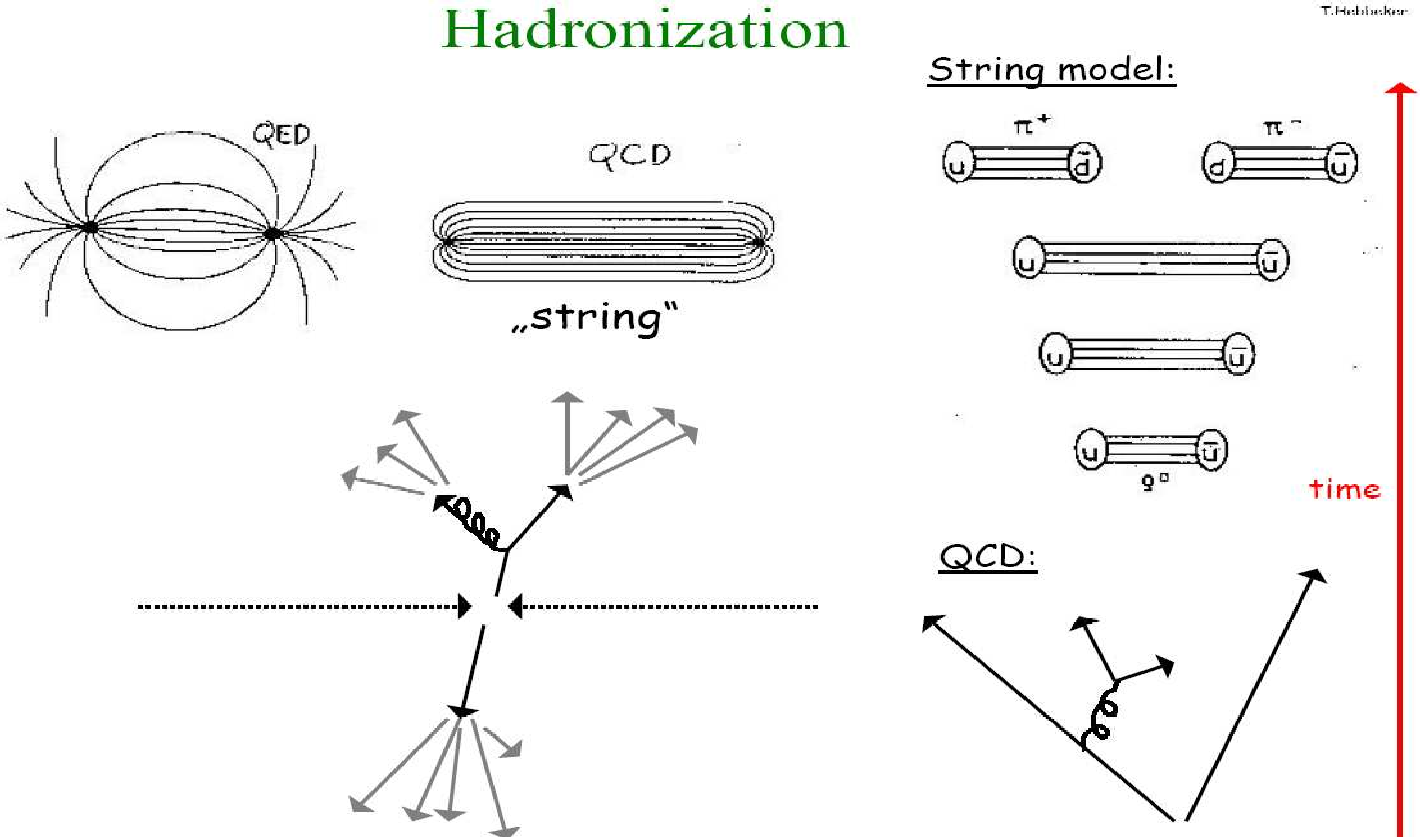
$$f_i(x_i,Q^2)$$

Factorisation!

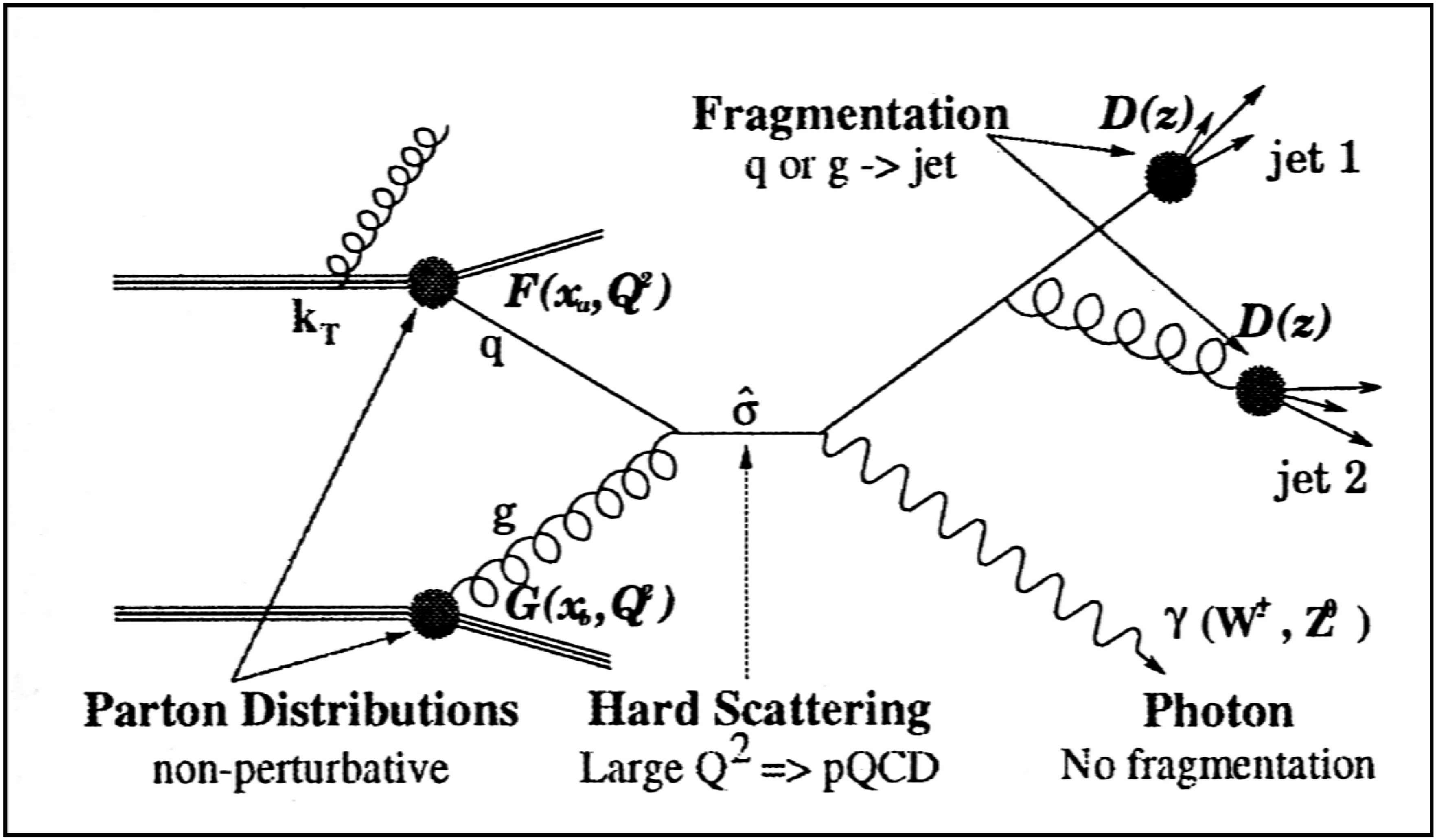
$$\frac{d\sigma_{FS}(\sqrt{s},Q^2)}{dV} = \sum_{i,j} \int dx_i dx_j\, f_i(x_i,Q^2)\, f_j(x_j,Q^2)\, \frac{d\sigma_{FS}^{ij}(x_i,x_j,Q^2)}{dV}$$

Fragmentation Processes

Hadronization

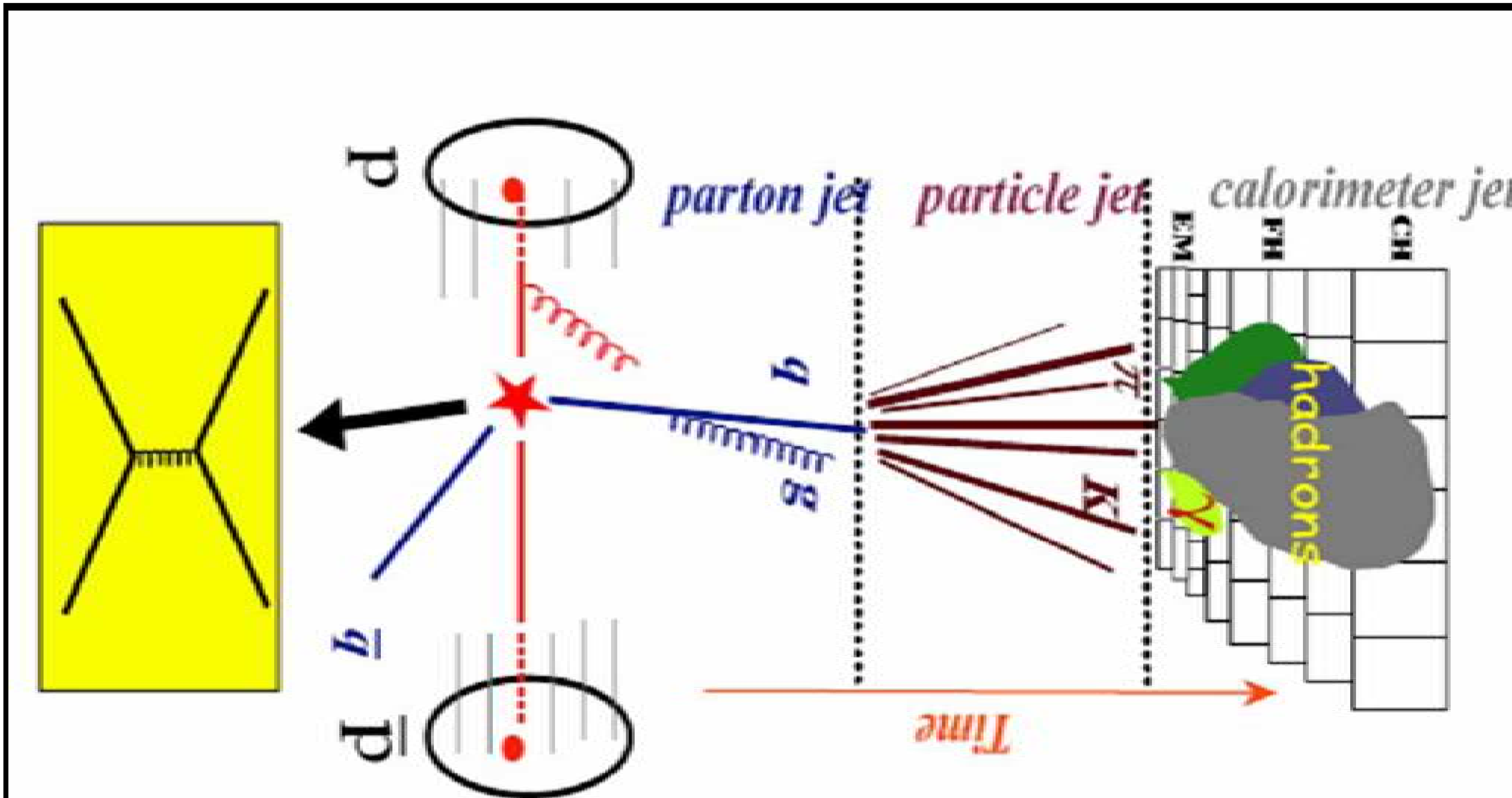


From Parton Density to Fragmentation

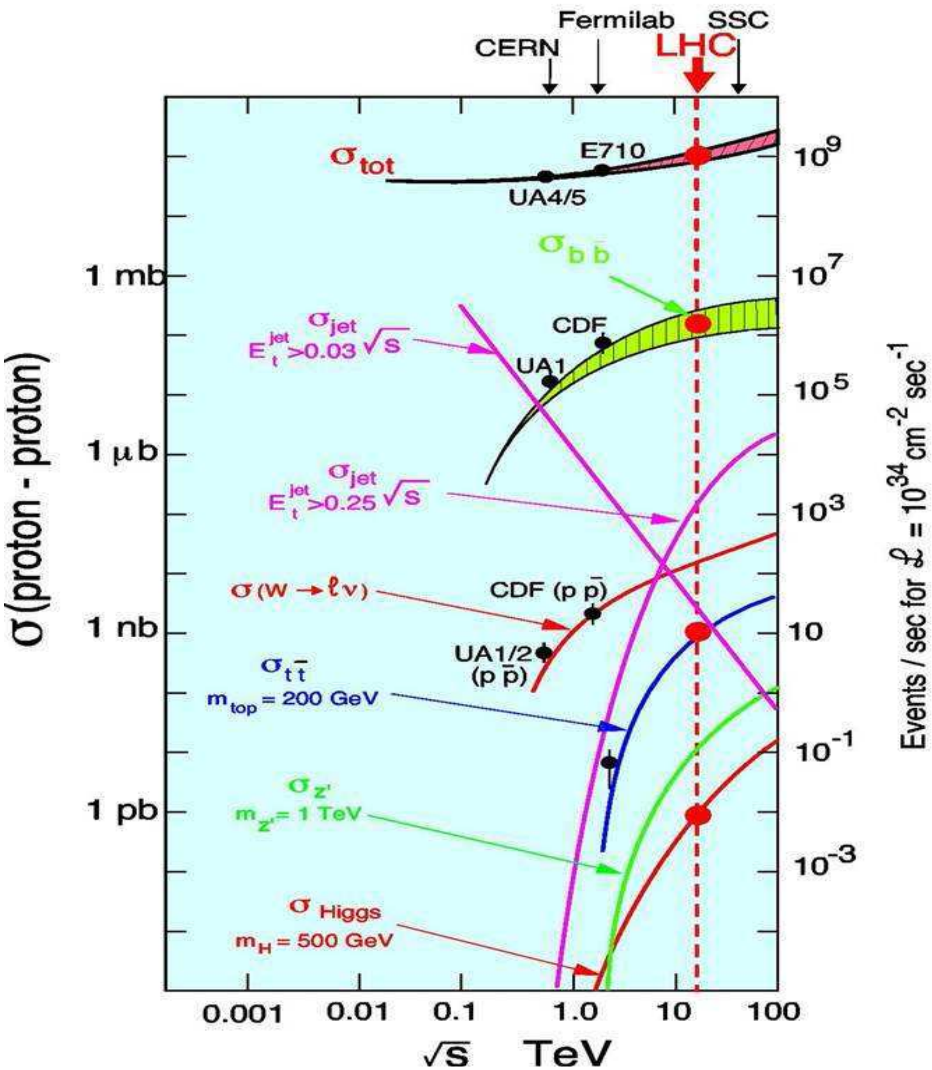


Formation of a Jet

from parton interaction to energy measurement in the calorimeter



Cross sections at the LHC



- **Huge signal cross sections**
  - ~ 150 W -> e ν / s
  - ~ 15 Z -> ee / s
  - ~ 8 ttbar / s
- **Background huge**
  - 10^9 inelastic pp interactions per second (minimum bias)
  - ~ 25 IA / bunch crossing
  - Thousands of jets events / s
- **Sophisticated triggering**
  - High p_T leptons
  - Missing E_T
  - Multiplicities (leptons and jets)
  - topologies

Luminosity

Luminosity defined as: $$\frac{dN}{dt} = L \cdot \sigma$$

determined by bunch size, revolution frequency and beam current

$$L = f_c N_b \frac{N_1 N_2}{4\pi \sigma_x \sigma_y}$$

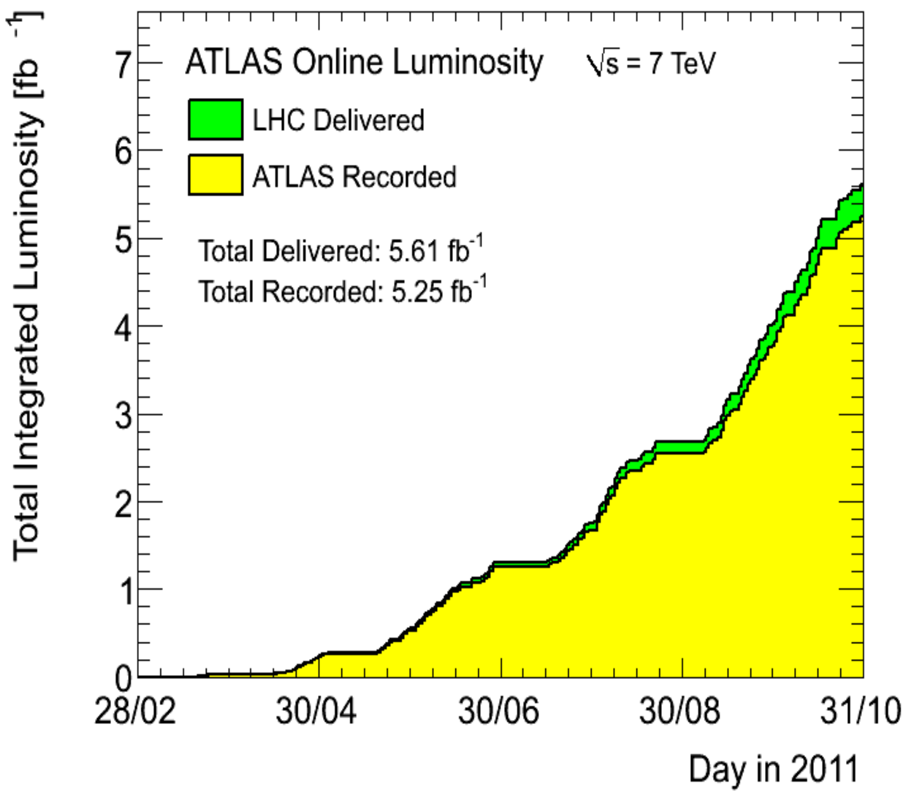
High luminosity: high beam current and small beam size

LHC Values:

$$\sigma_x \approx \sigma_y \approx 15\mu m, N_1 \approx N_2 \approx 10^{11}, f_c \approx 12000/s, N_b \approx 2800$$

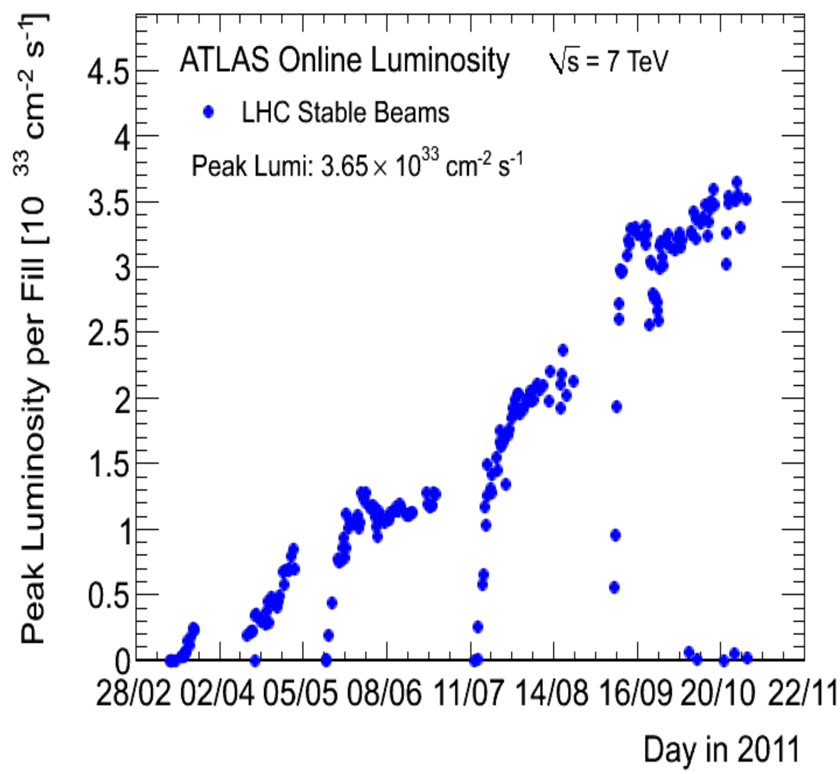
- 2010: L < 10^{32}cm^{-2}s^{-1}
- 2011: L ~ 4x10^{33}cm^{-2}s^{-1}
- 2012: L = 5x10^{33}cm^{-2}cm^{-1}
- > 2012: L = 10^{34}cm^{-2}s^{-1}, Upgrade: L = 5x10^{34}cm^{-2}s^{-1}

2011 LHC Performance

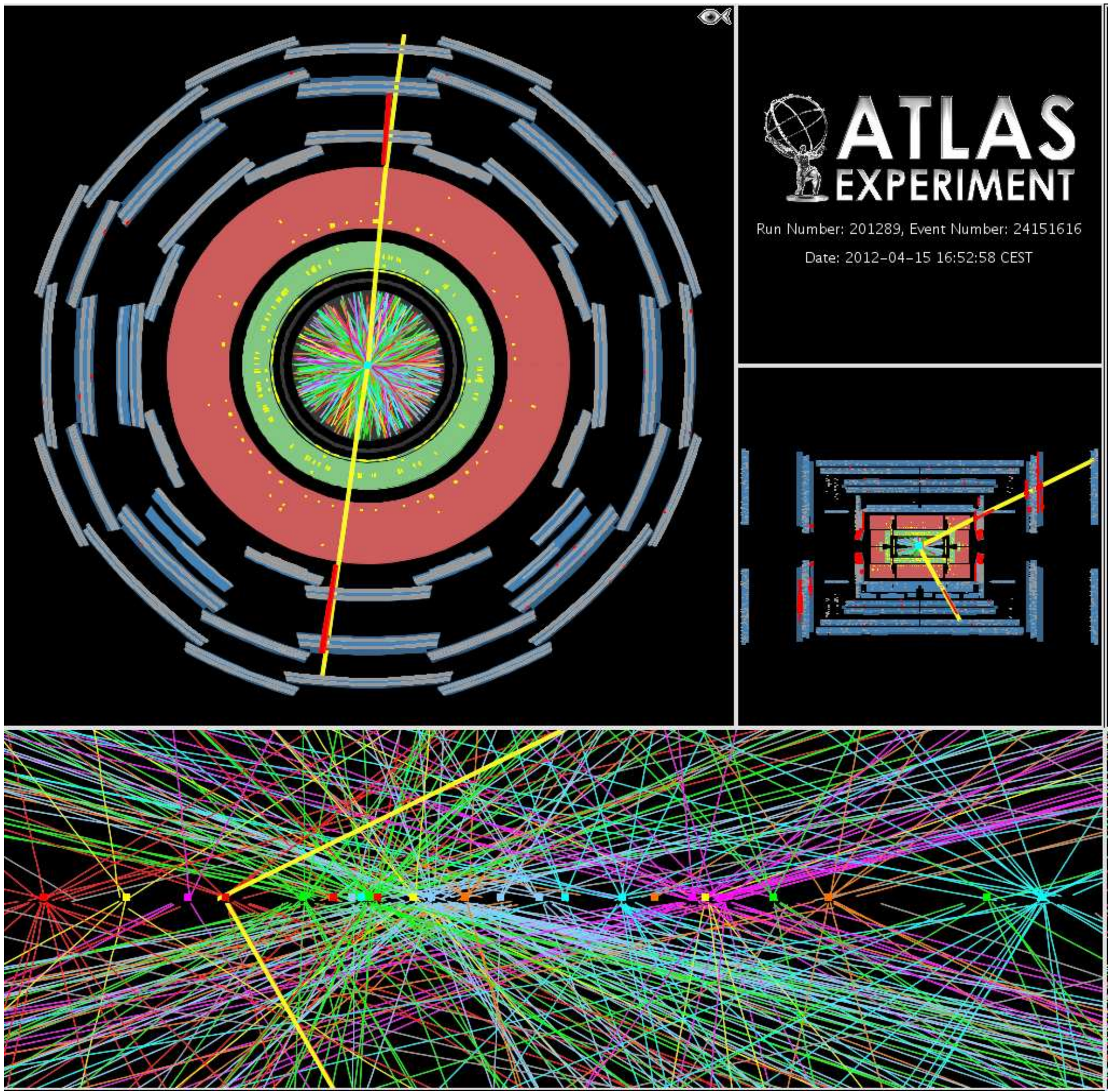


Integrated luminosity: excellent performance, better than expected!

specific luminosity: drastic increase over the year!



Pileup



- ~ 25 pileup events per bunch crossing at design luminosity
  - hundreds of tracks from different vertices per bunch crossing
  - sophisticated reconstruction (trackig) programs
  - Example: Z -> μμ

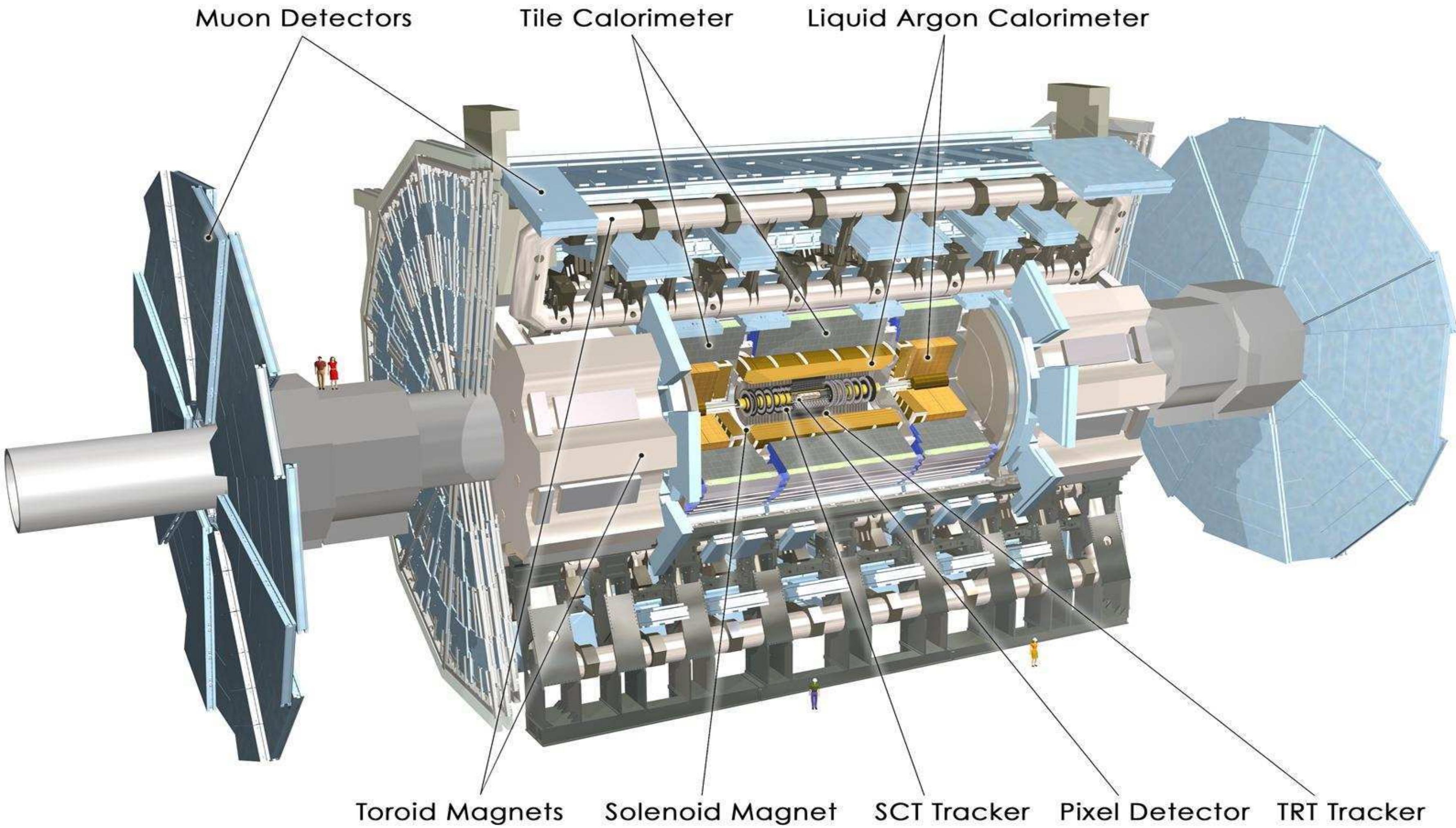
Signatures for new physics at LHC

- **High p_T objects (jets)**
  - Exclusions up to ~ 100 GeV by other experiments
- **High energetic leptons**
  - Leptons have no strong interaction: QCD suppression
  - Weak interaction: same strength for all lepton flavours
    - search for weakly decaying particles
- **Jets with b-quarks**
  - b-quarks suppressed in QCD jets (gluon jets)
  - Top quarks decays to b-quarks
  - Produced in weak decays at the Z-scale
- **Missing Energy**
  - QCD has only visible particles
  - Neutrions from weak decay only have moderate MET (~ 50 GeV)
  - New SUSY particles (DM) would cause a huge MET
  - Only transverse energy can be used (proton remnants in beam pipe)

Experiments at LHC

- **ATLAS**
  - Multi purpose experiment, all kind of searches at the energy frontier and standard model physics
  - Multipurpose trigger system
- **CMS**
  - Same purpose at ATALAS
- **LHCb**
  - Dedicated B-Physics spectrometers (CP violation), looking only at the forward part of the event
- **ALICE**
  - Specialized to heavy ion collisions, measure the quark gluon plasma
- **TOTEM**
  - Total cross section, elastic scattering and diffraction dissociation
- **LHCf**
  - Calorimetry in very forward region to test hadronic interaction modes for cosmic air showers

Experiment ATLAS



ATLAS Collaboration

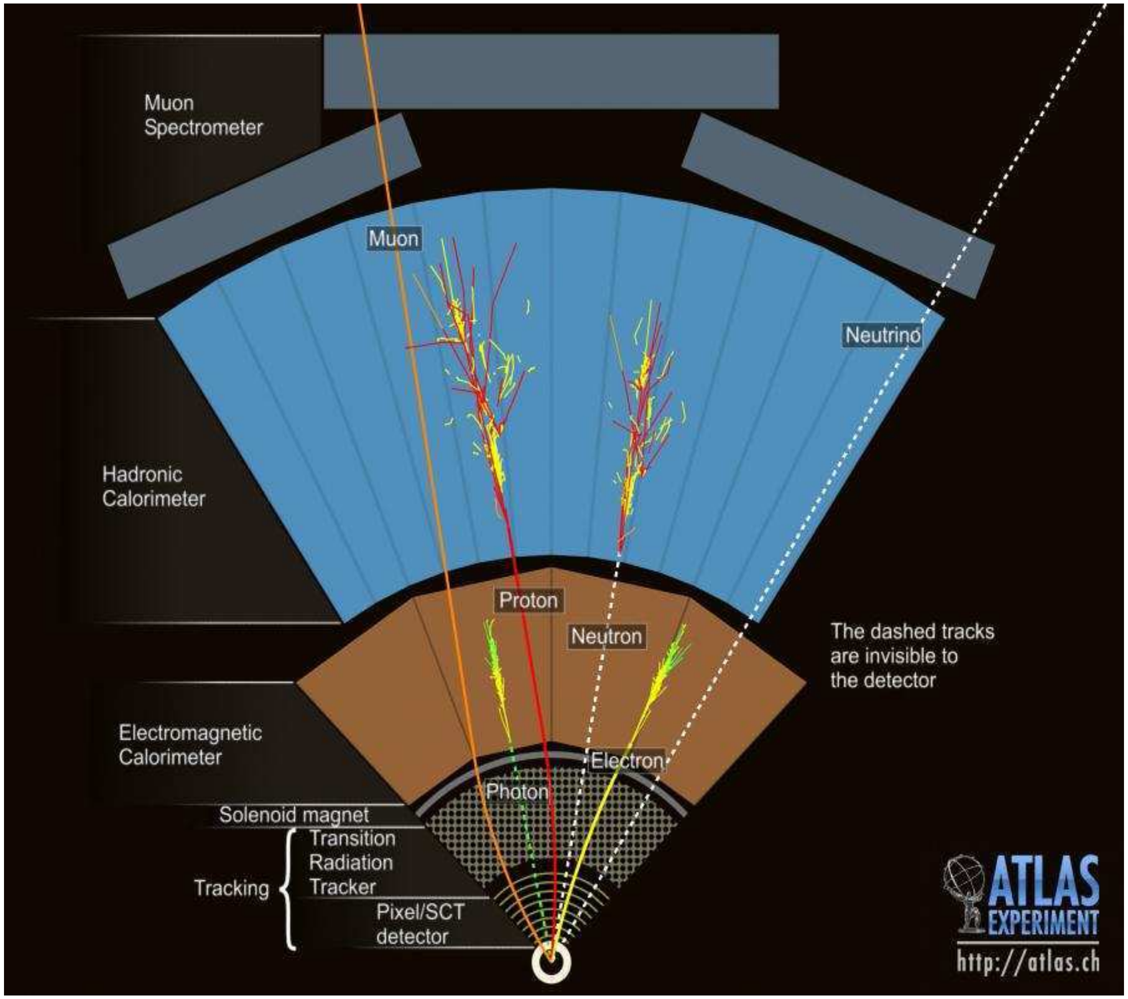
(Status 2010)

37 Länder
173 Institute
3000 Wissenschaftler

Albany, Alberta, NIKHE
Barcelona, Belgrade, Bergen, Berkeley LBL and UC, Bern, Birmingham, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Bucharest, Cambridge, Carleton, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, INP Cracow, FPNT Cracow, Dortmund, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Glasgow, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Naples, Naruto UE, New Mexico, Nijmegen, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Ritsumeikan, UFRJ Rio de Janeiro, Rochester, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, Southern Methodist Dallas, NPI Petersburg, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Toronto, TRIUMF, Tsukuba, Tufts, Udine, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, Wisconsin, Wuppertal, Yale, Yerevan

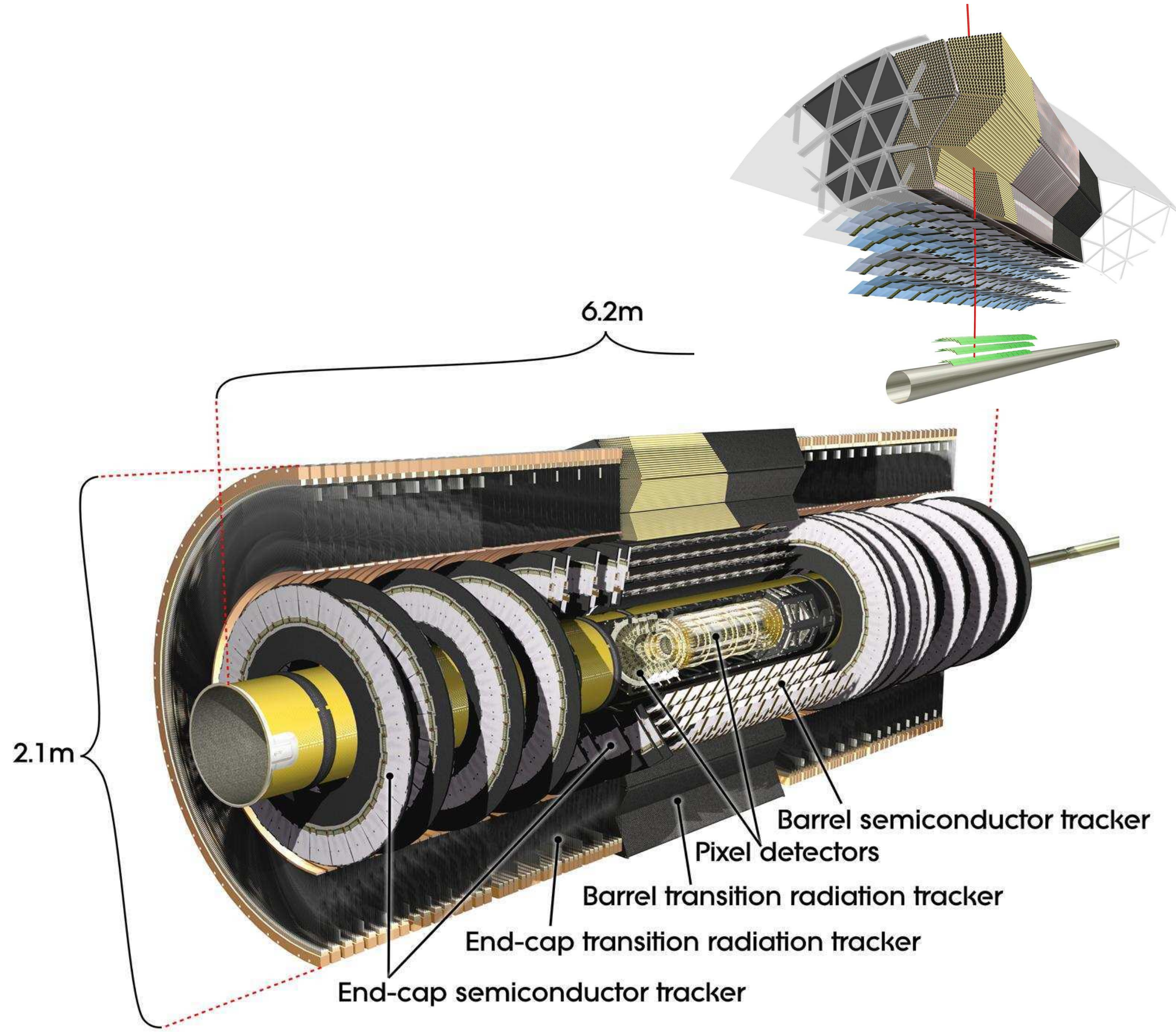
Schematic Overview of ATLAS

- Standard collider detector with barrel two and endcaps
- Inner tracker for charged particle momentum measurements
- Surrounded by superconducting coil (2T)
- Liquid argon EM calorimeter
- Scintillating tile HAD calorimeter
- Toroid system with precision chambers for muon momentum measurement



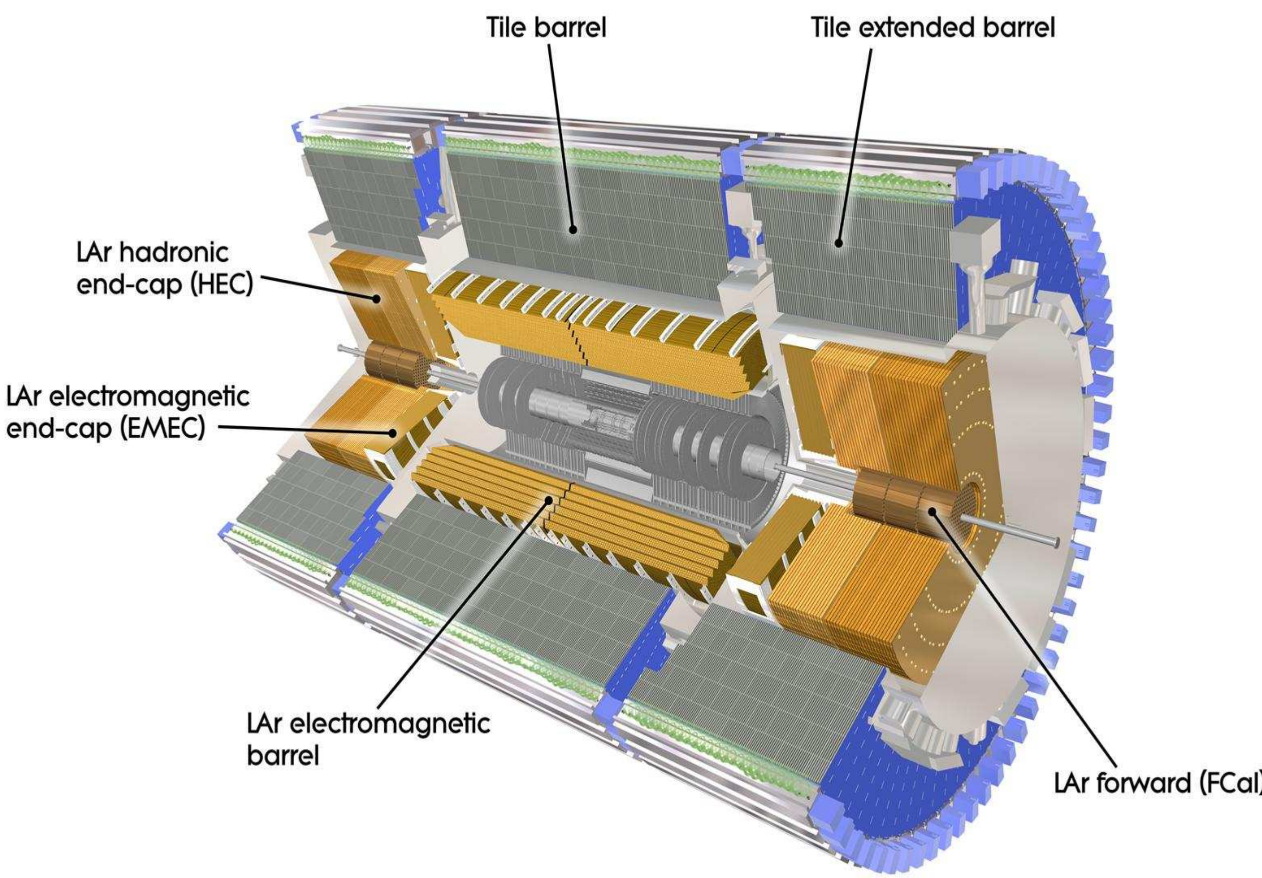
ATLAS Tracker

- **Pixel detectors** close to beam pipe for vertex precision measurement and b-tagging
- **Silicon strip** detectors for precision tracking
- **Transition radiation tracker** for particle ID (e,K,π) and to improve momentum resolution



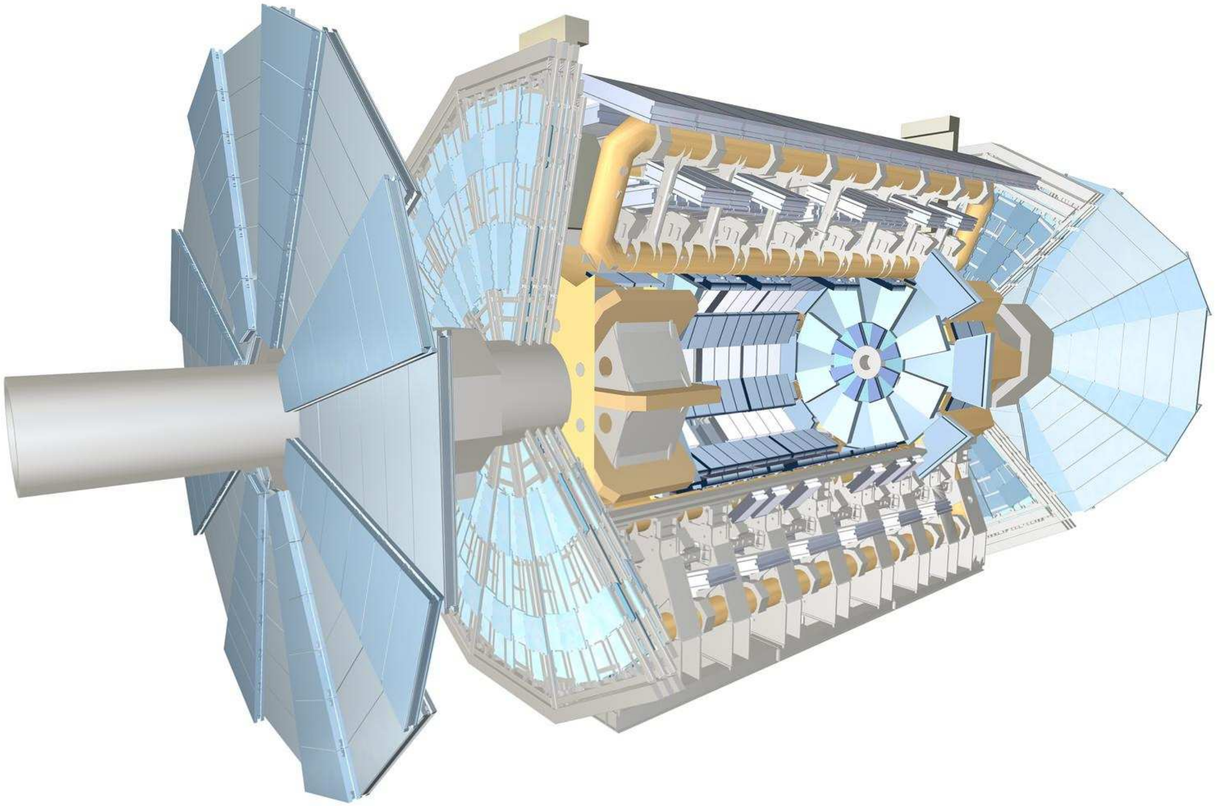
ATLAS Calorimeters

- Liquid Argon / Lead for EM
- Scintillating tiles / Fe for HAD
- Good spatial resolution allows reweighting procedures



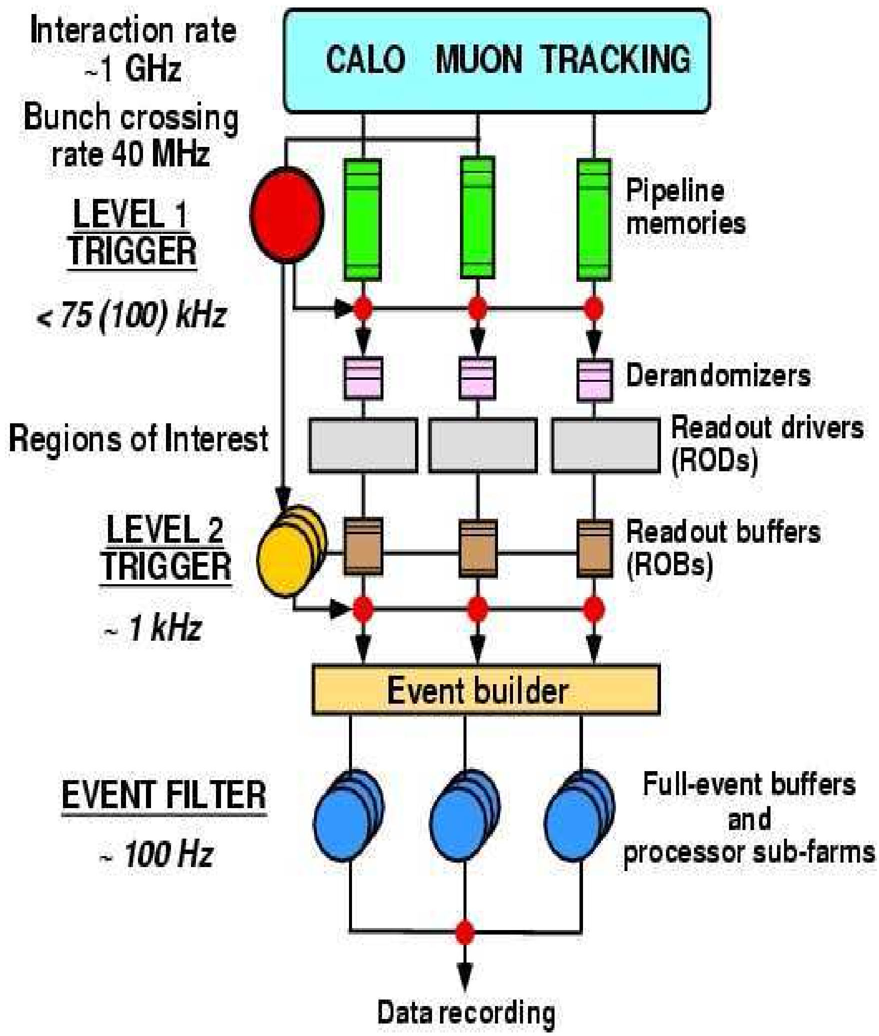
ATLAS Muon System

- Large Toroid magnet, air cooled
- High precision drift tubes
- Additional trigger specific chambers
- Large forward weels

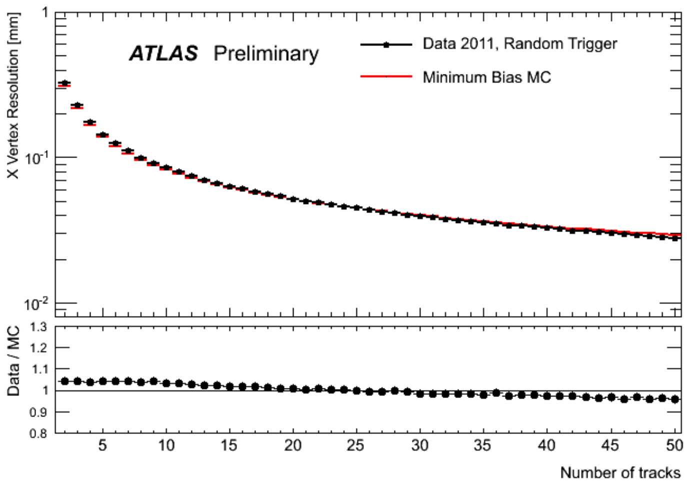


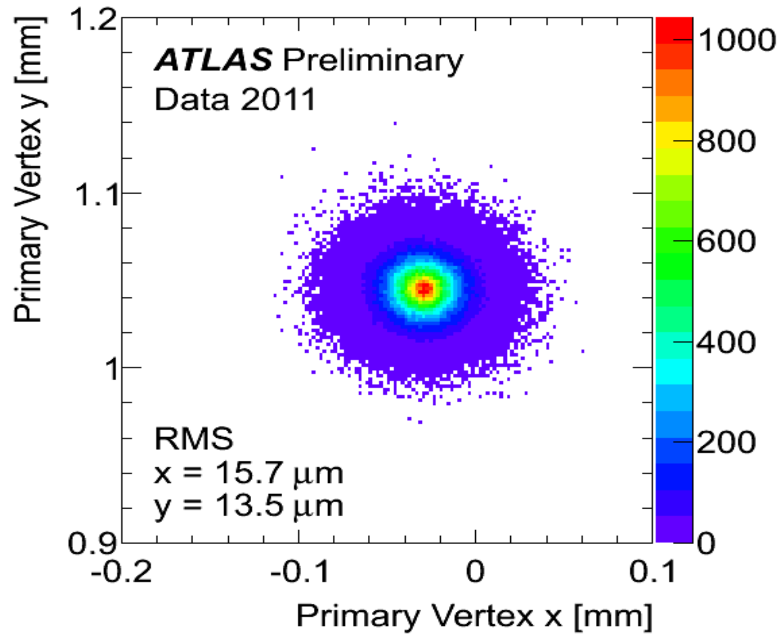
ATLAS Trigger System

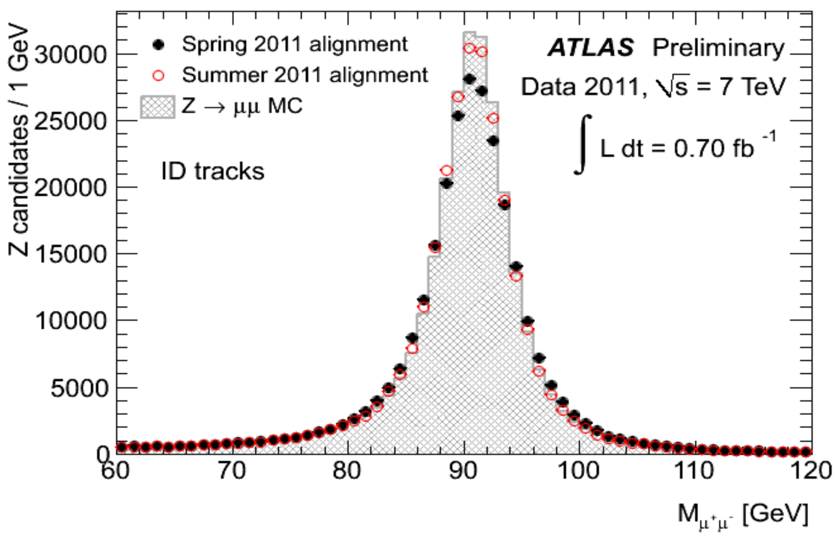
- 3 level system
- **LVL1: special hardware**
  - reduce rate to ~200 kHz
  - based on RoI from Mu and Calo
  - dead time free, pipelined
- **LVL2: standard PCs**
  - get full information inside RoI
  - processing time 10 ms
  - Reduce rate to ~ 1 kHz
  - Initiate event building and r/o
- **Event filter: standard PCs**
  - Full data access
  - Fast event reconstruction
  - Processing time 1 s
  - Reduced to 150 Hz logging rate



ATLAS Detector Performance: Tracking

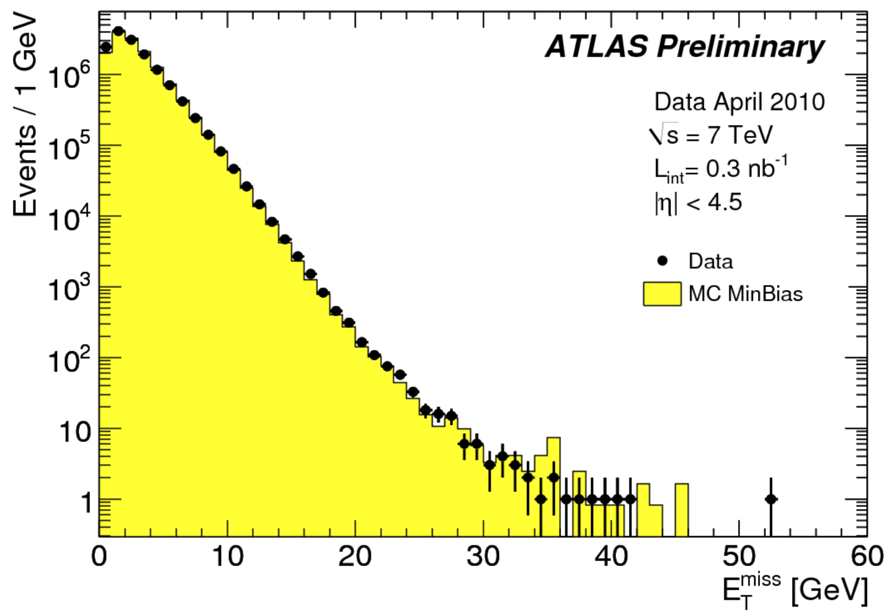




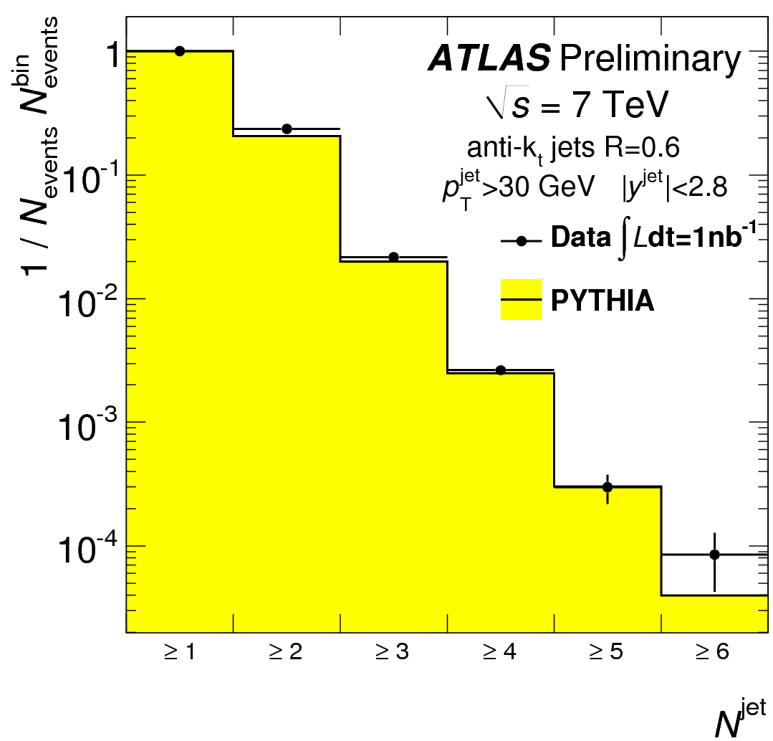


Vertex resolution vs. track multiplicity
Z-Boson mass resolution
Primary vertex measurement

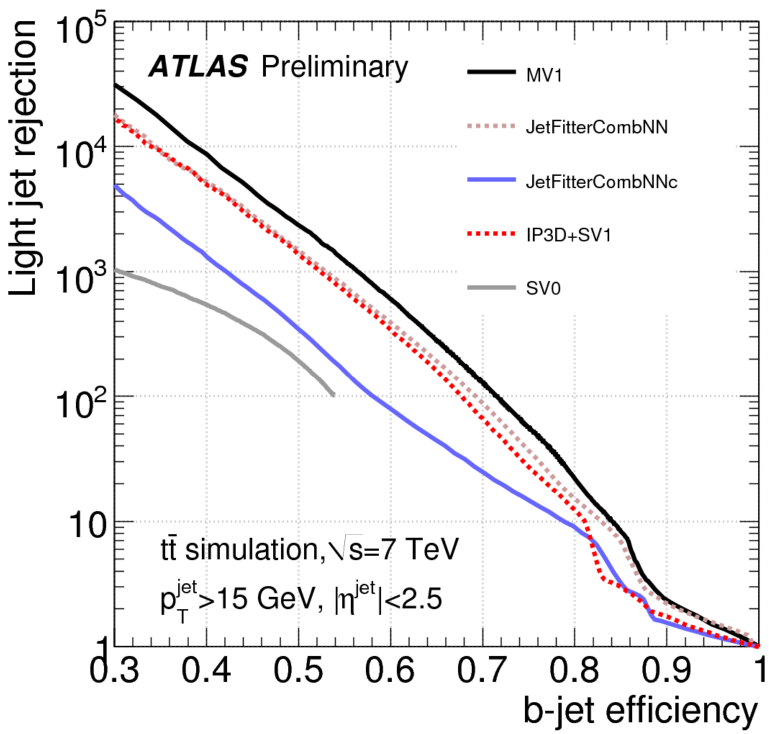
Detector Performance: Calorimeter

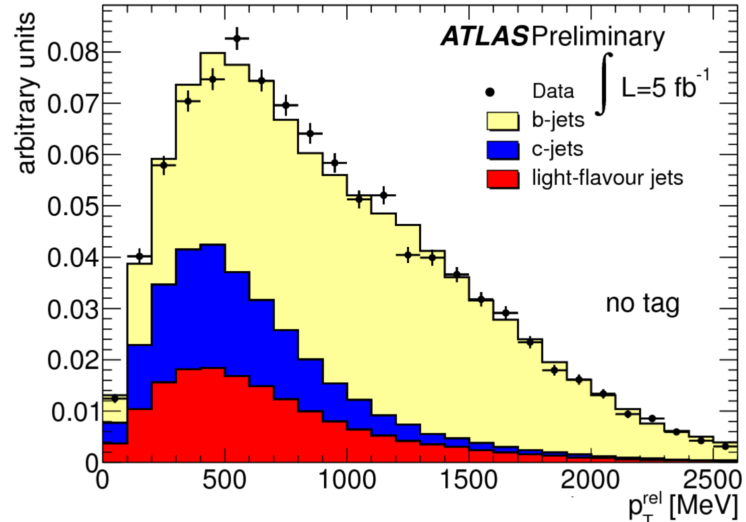


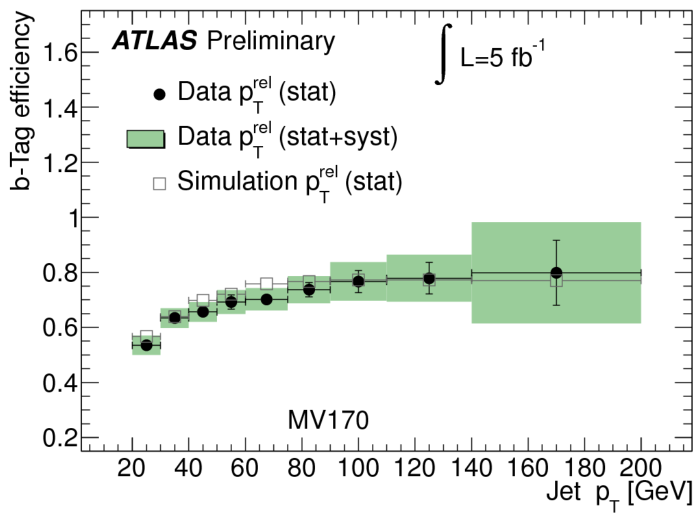
Data / MC comparison of missing Energy and jet multiplicity



b-Jet Tagging

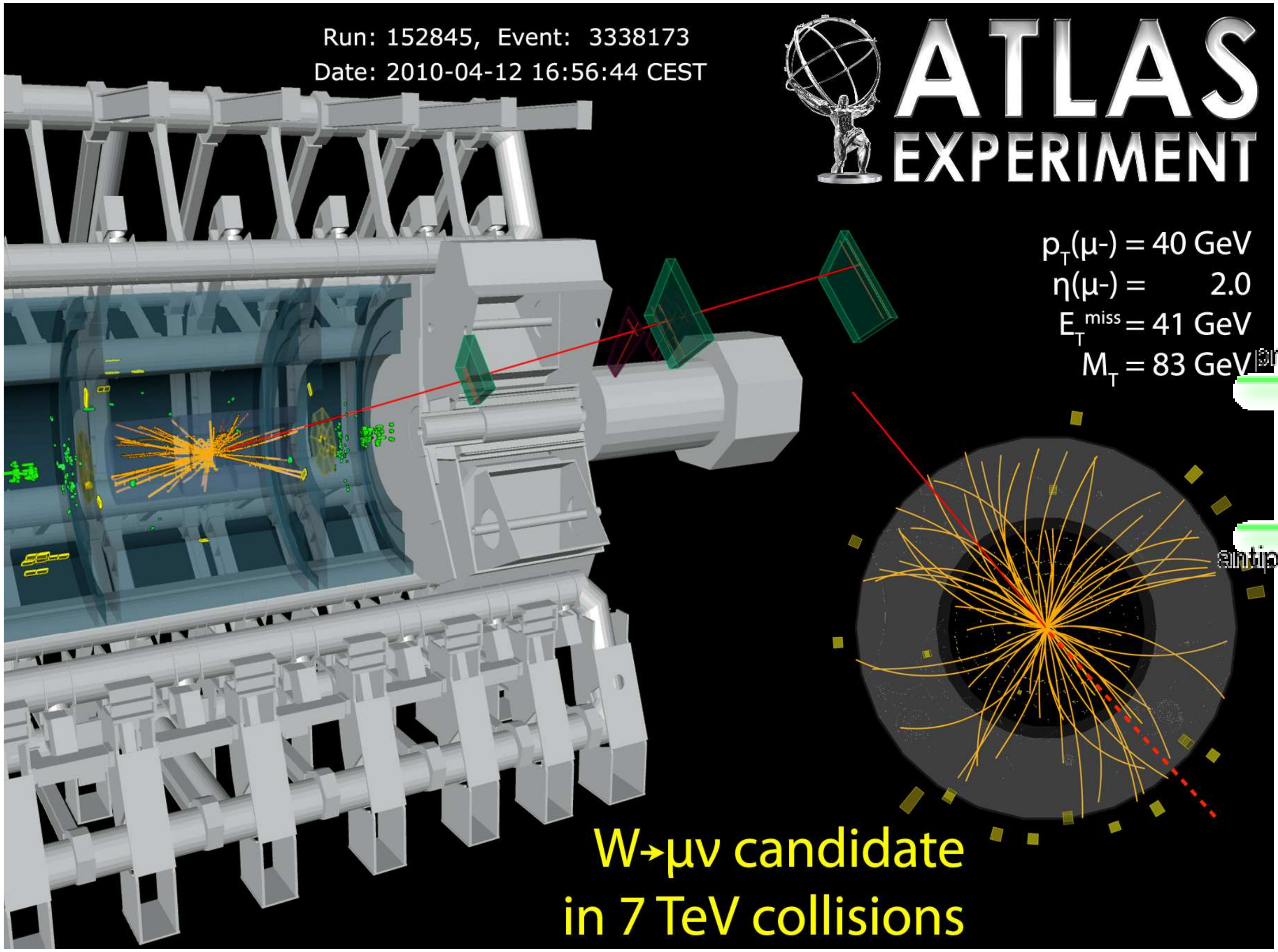


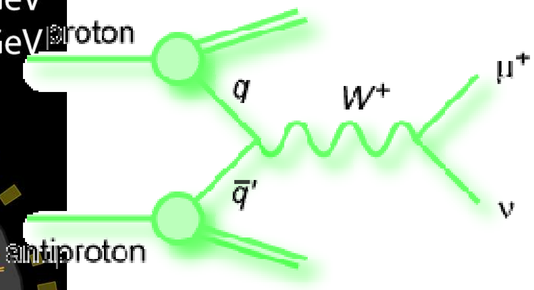




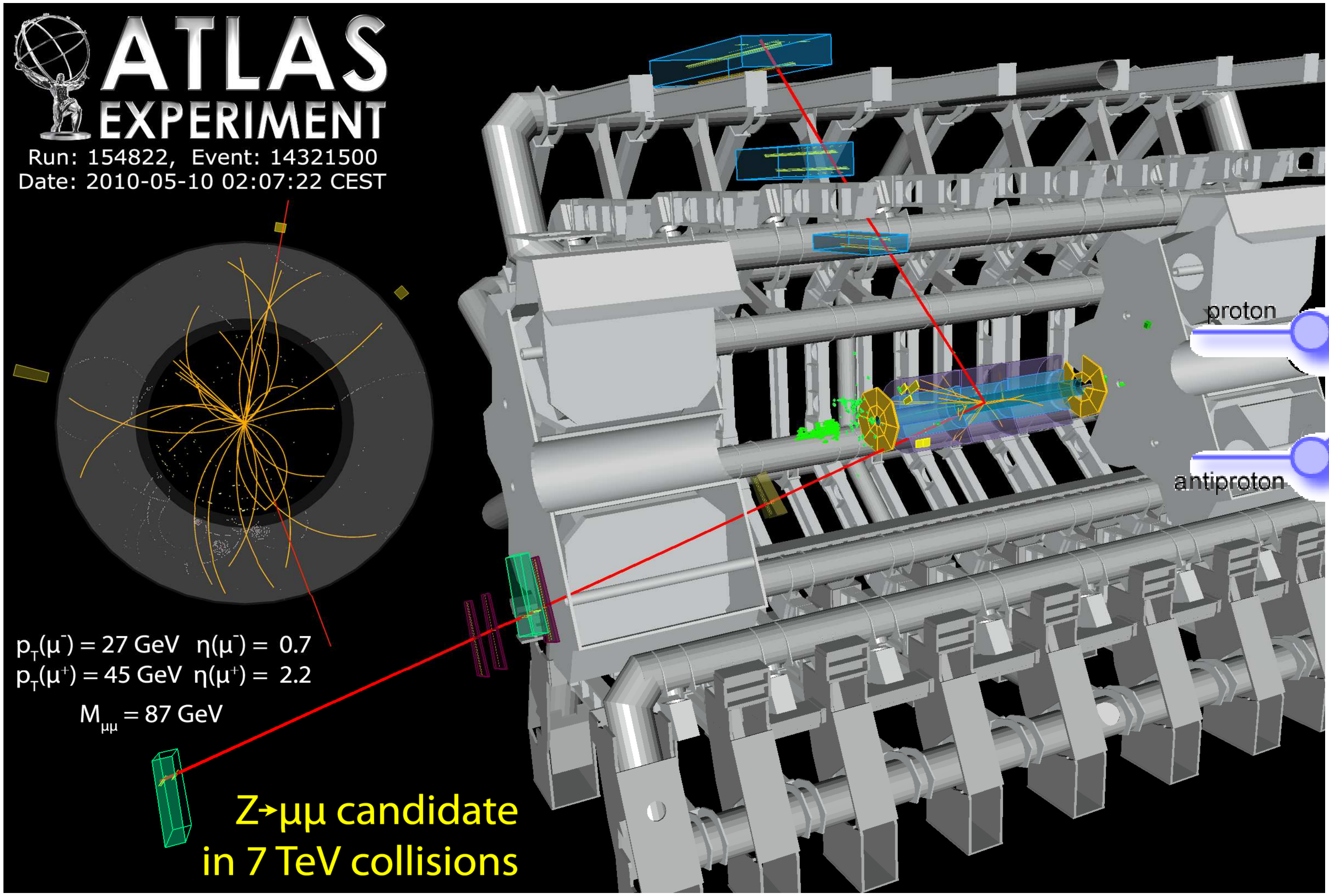
Light jet rejection power
b-jet enrichment with pTrel
Measurement of b-jet efficiency

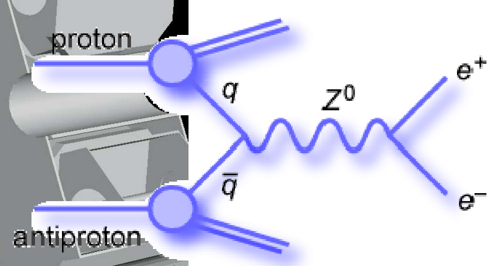
Eventdisplay: W-Boson



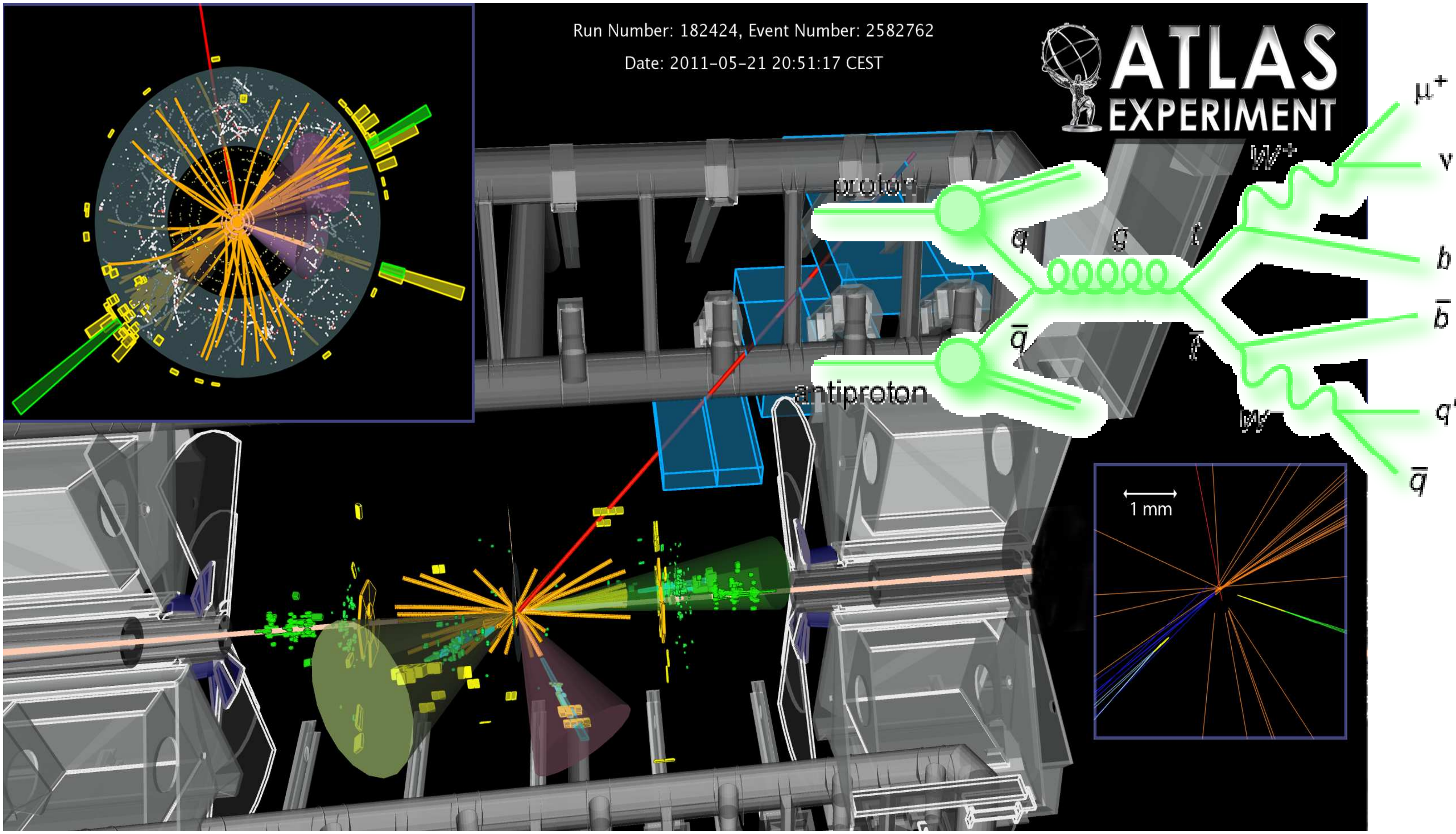


Eventdisplay: Z-Boson

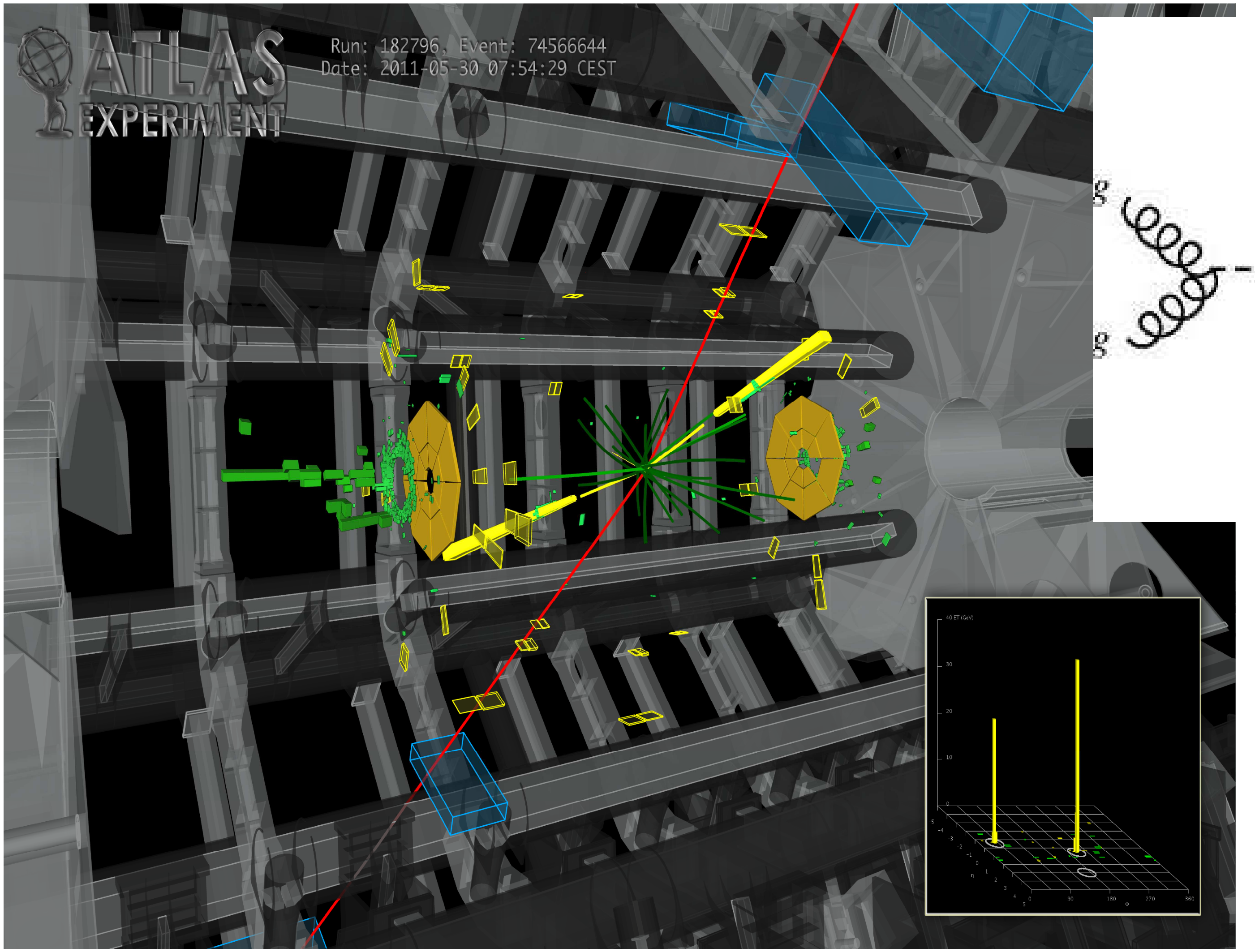


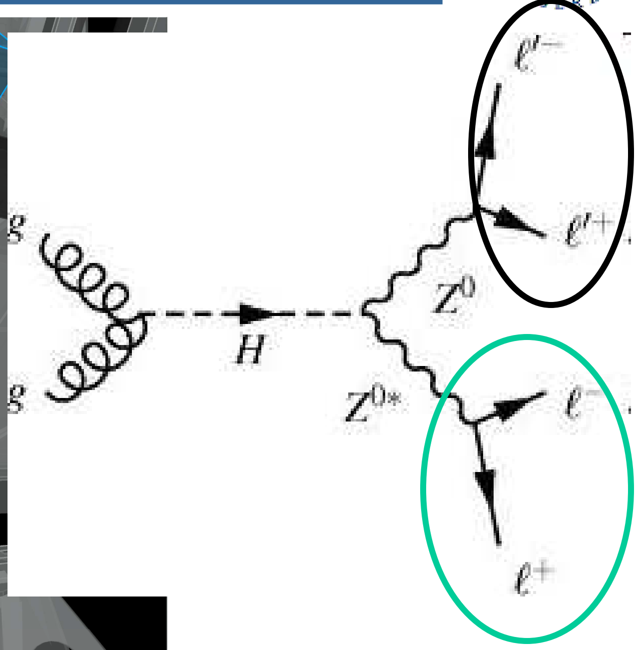


Eventdisplay: Top event

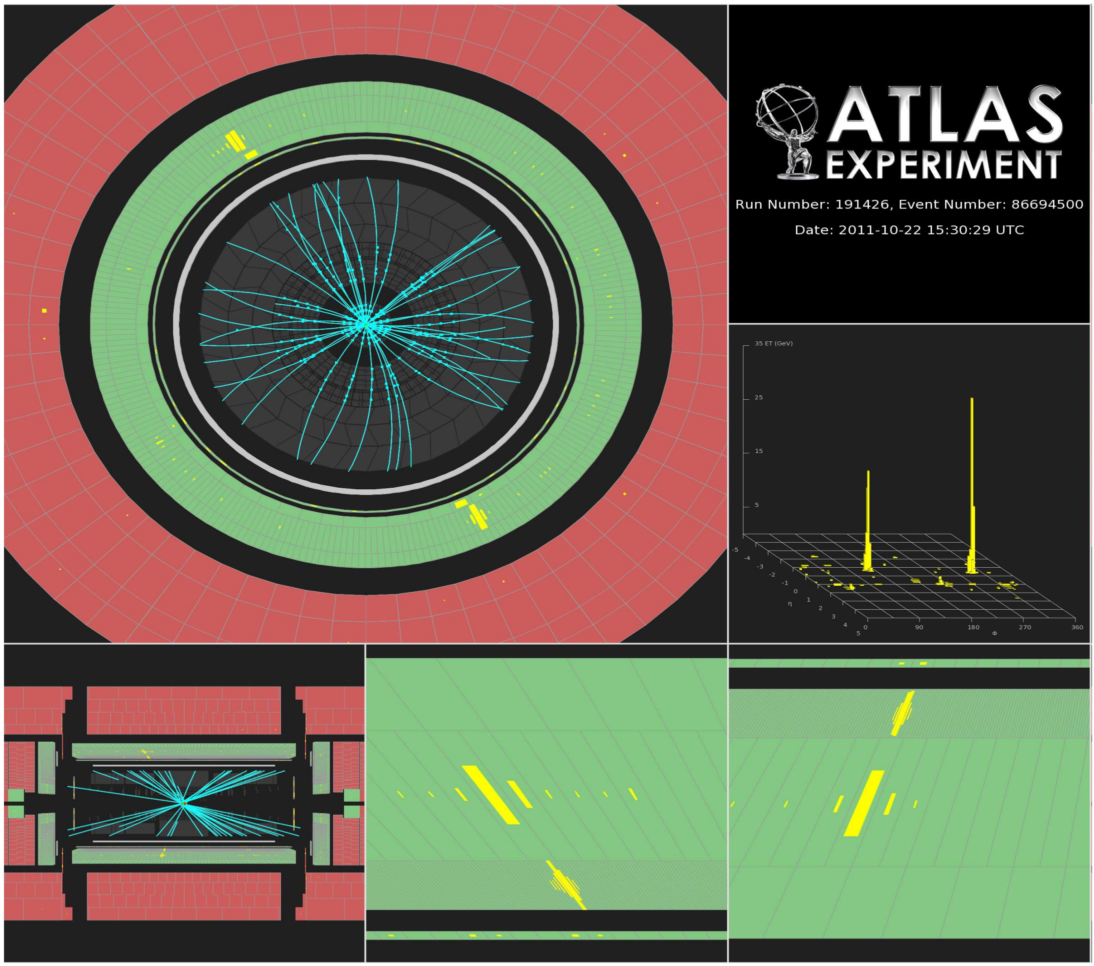


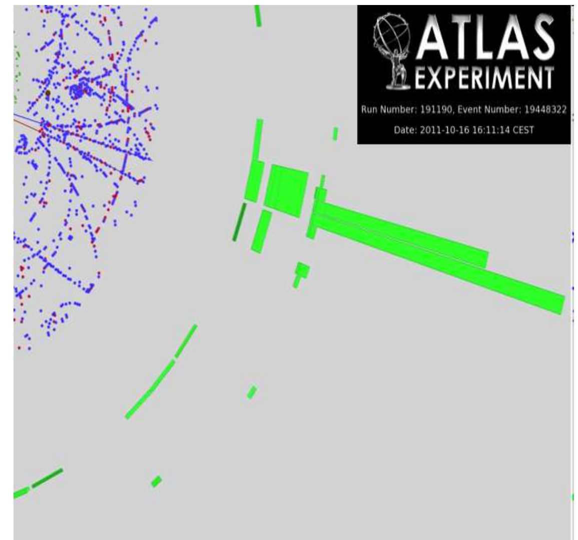
Higgs-Decay candidate in 2 Z (4 leptons)

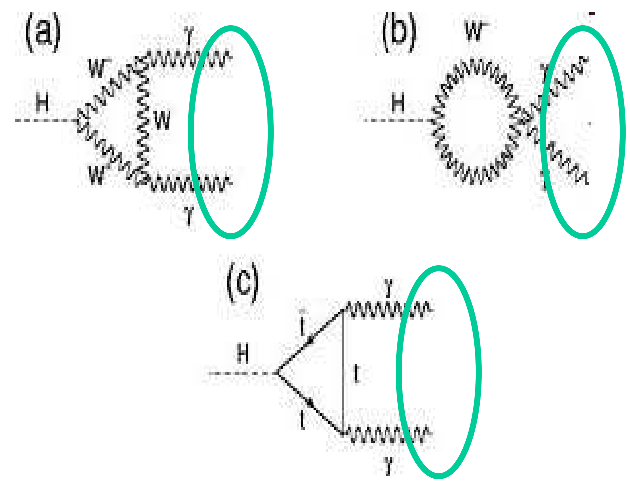




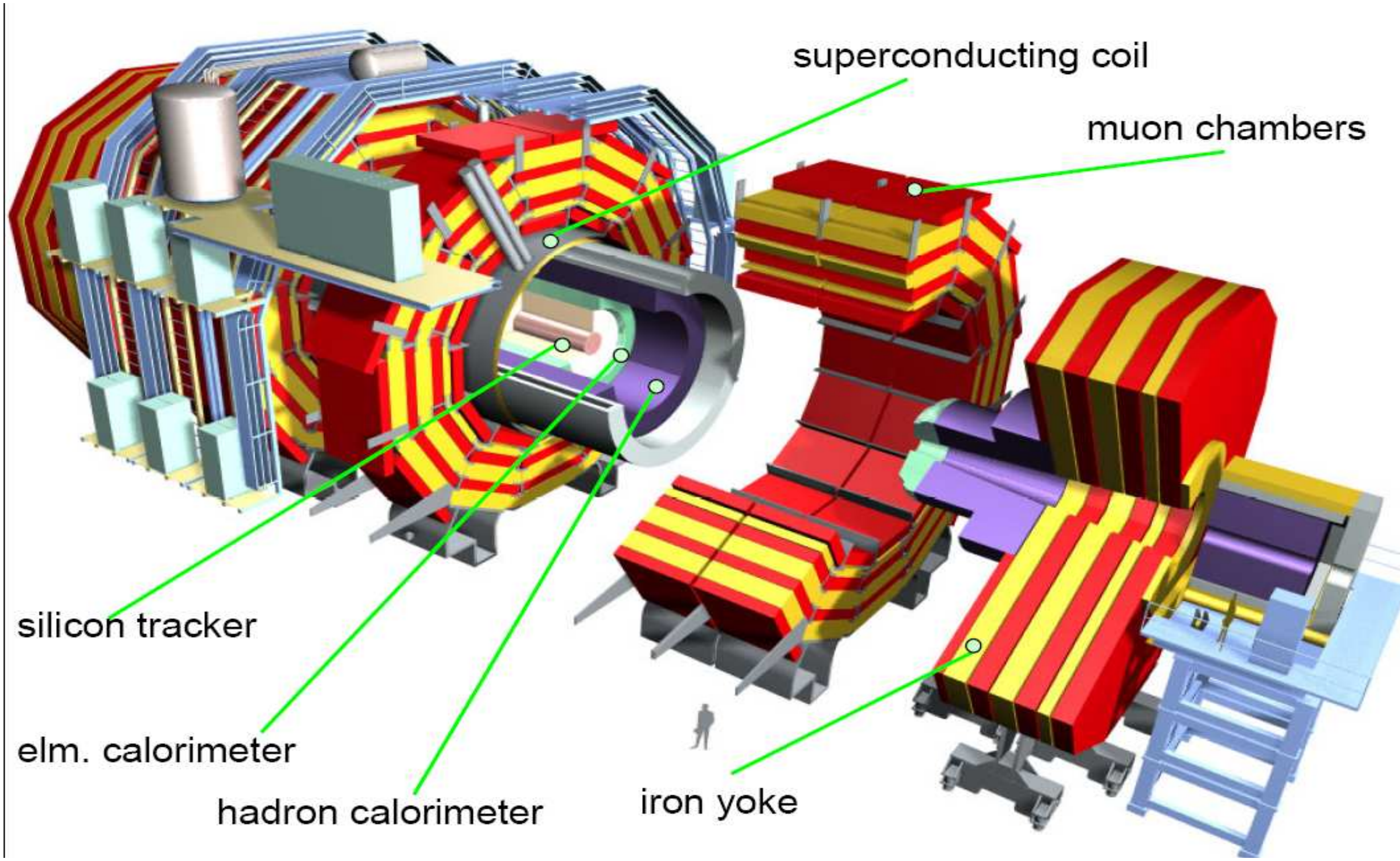
Higgs Decay candidate in 2 gamma







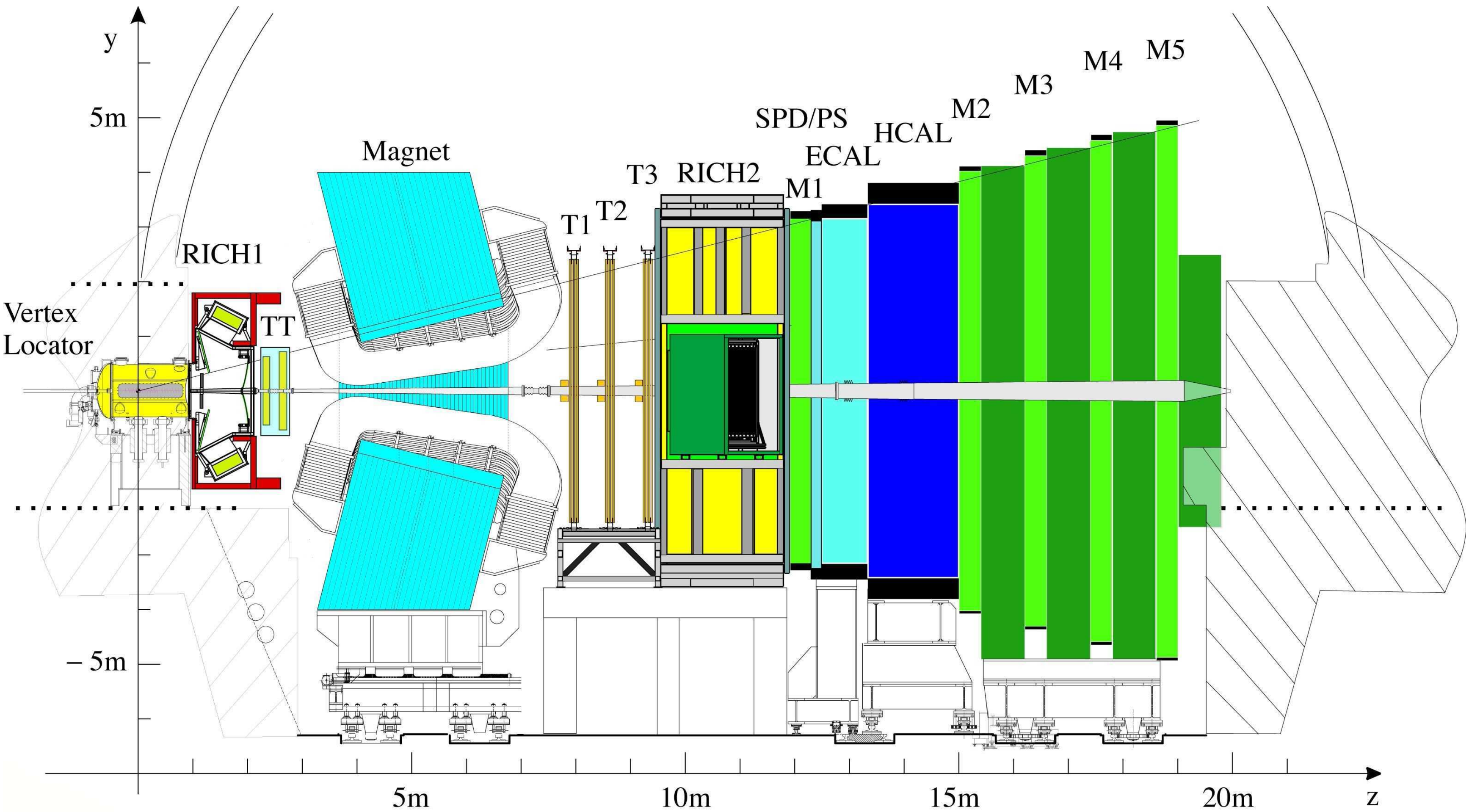
The CMS experiment



CMS

- Similar concept to ATLAS, but some differences in details
  - Full silicon tracker
  - Larger coil with larger B-field (4 T)
    - Better momentum resolution
  - No extra magnetic field for muons
  - Crystal calorimeter with better energy and worse spatial resolution
  - Hardon calorimeter with worse granularity do not allow reweighting
  - Event building after L1 trigger, only one higher level trigger
- Cross check with different multipurpose experiments essential for discoveries

LHCb Experiment (Spectrometer)



LHCb Experiment

- Huge B-cross section, looking only in (one) forward direction
  - Optimized for forward region coverage, particle ID and lepton trigger
- Dedicated spectrometer with specialized physics program and trigger
  - CKM Matrix and CP violations
- Advantages compared to e+e- B-factories
  - Access to heavier B-states as Bs
  - Large statistics gives access to rare decays as Bs -> μμ
- Disadvantages
  - Large backgrounds from non B-events (QCD)
  - No trigger for hadronic B-decays