DESY Summer Student Lectures 2009
Zeuthen, August 20-21, 2009

The LHC Experiments

Ulrich Husemann
Deutsches Elektronen-Synchrotron

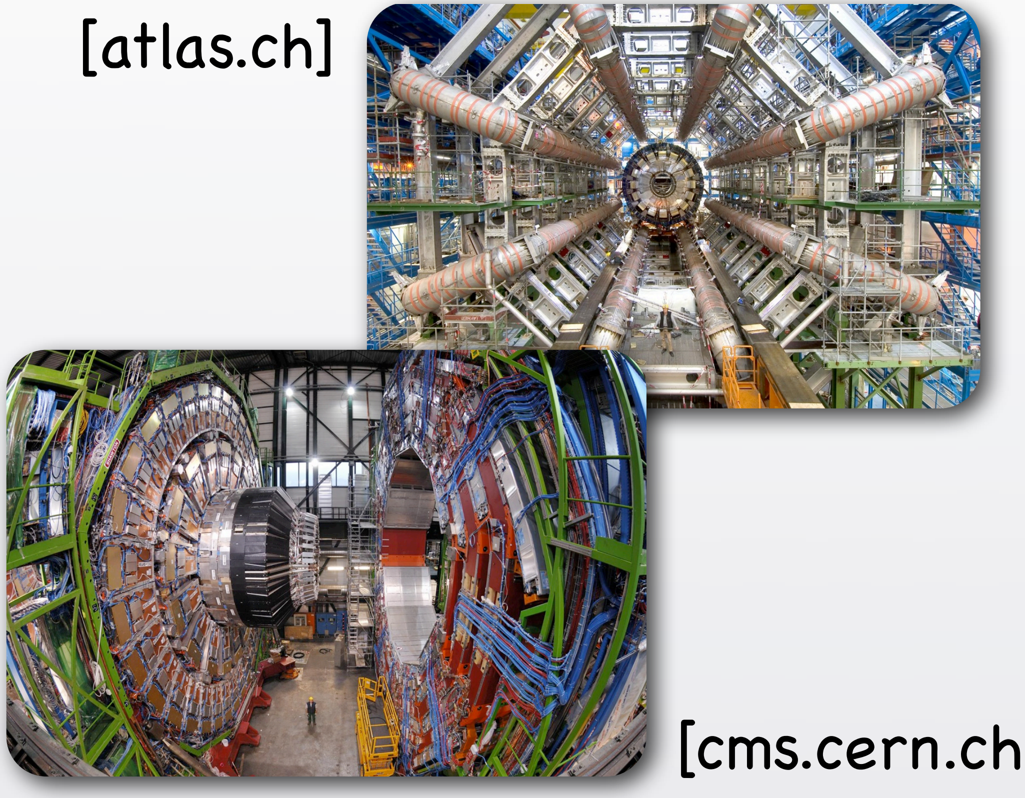
Opening Remarks

- Short biographical sketch: Ulrich Husemann
  - PhD: U Siegen (2005) → HERA-B experiment (DESY)
  - Postdoc (2005–2008): U Rochester, Yale U
    → CDF experiment (Tevatron p anti-p collider, Fermilab)
  - Since 2008: leader of a Young Investigator Group at DESY (Zeuthen site) → ATLAS experiment (LHC, CERN)

- Goals for the next two days:
  - These lectures should give you better understanding of experimental challenges at the Large Hadron Collider (LHC)
  - These are lectures, not a scientific seminar
    → you are encouraged to interrupt me and ask questions

Program

- Day 1: Machine and detectors
  - Open questions in particle physics
  - The LHC accelerator
  - How to build a LHC detector
  - Measuring momentum & energy
  - From raw data to physics results



[atlas.ch]

[cms.cern.ch]

Program

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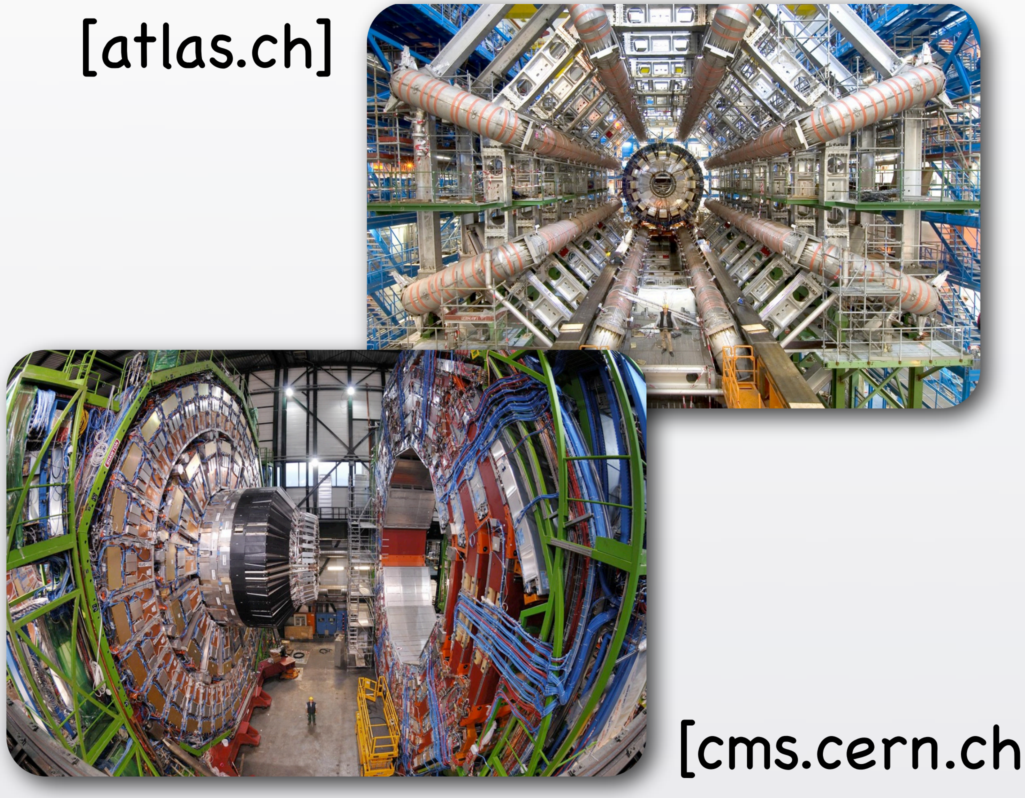
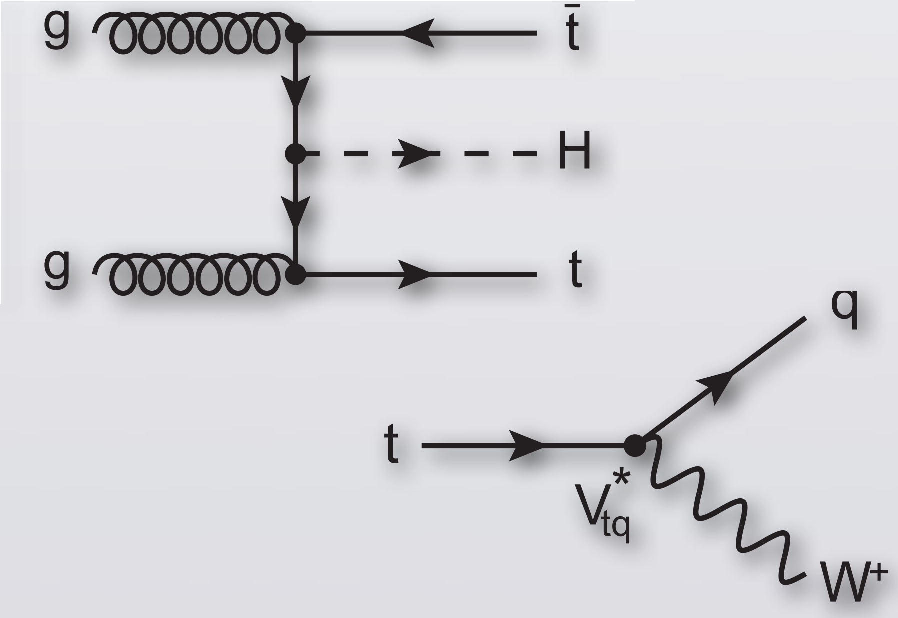
[atlas.ch]



[cms.cern.ch]

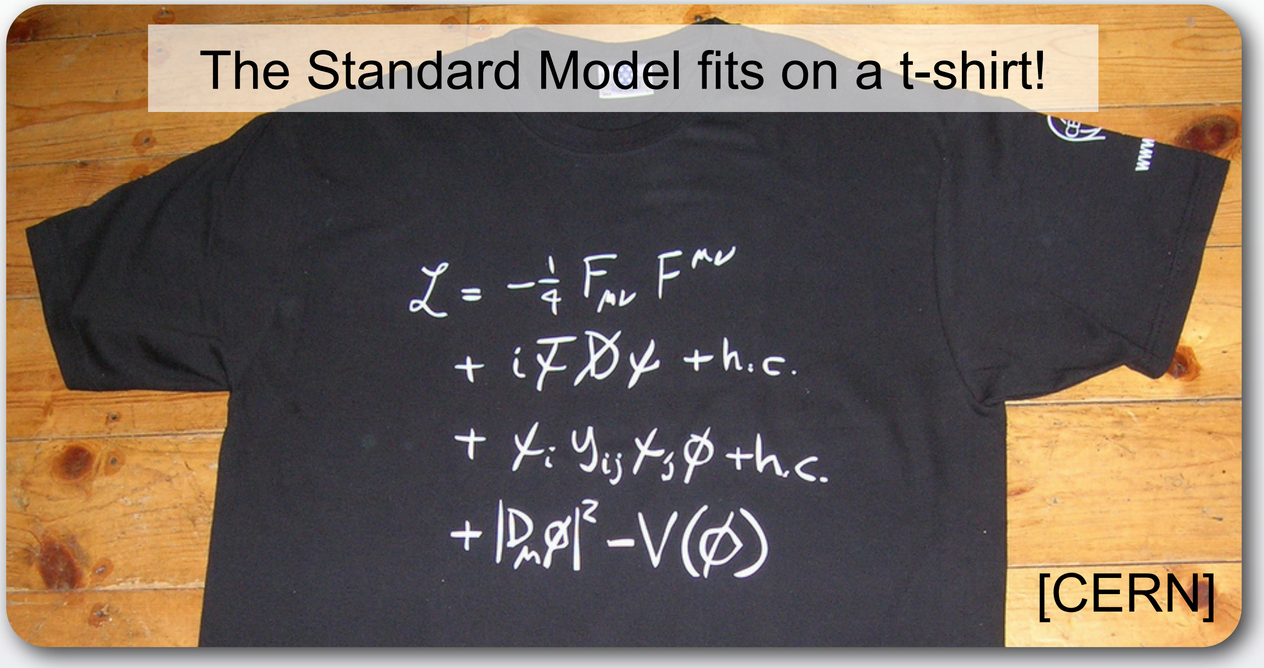


- Day 2: Towards LHC physics
  - Basics of hadron collider physics
  - First physics at the LHC
  - How to measure a cross section
  - Hunting for the Higgs

Chapter 1

Open Questions in Particle Physics

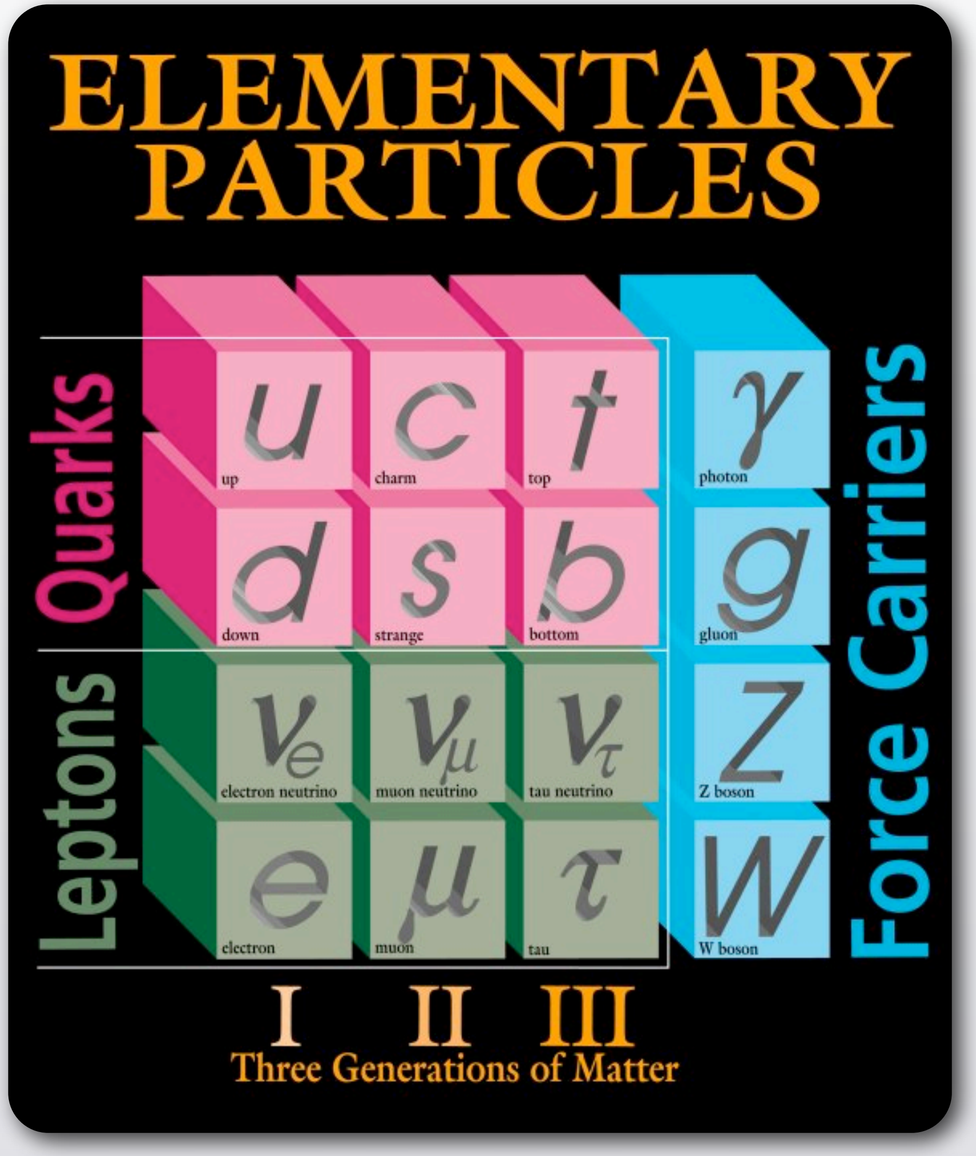
The Standard Model



The Standard Model fits on a t-shirt!

[CERN]

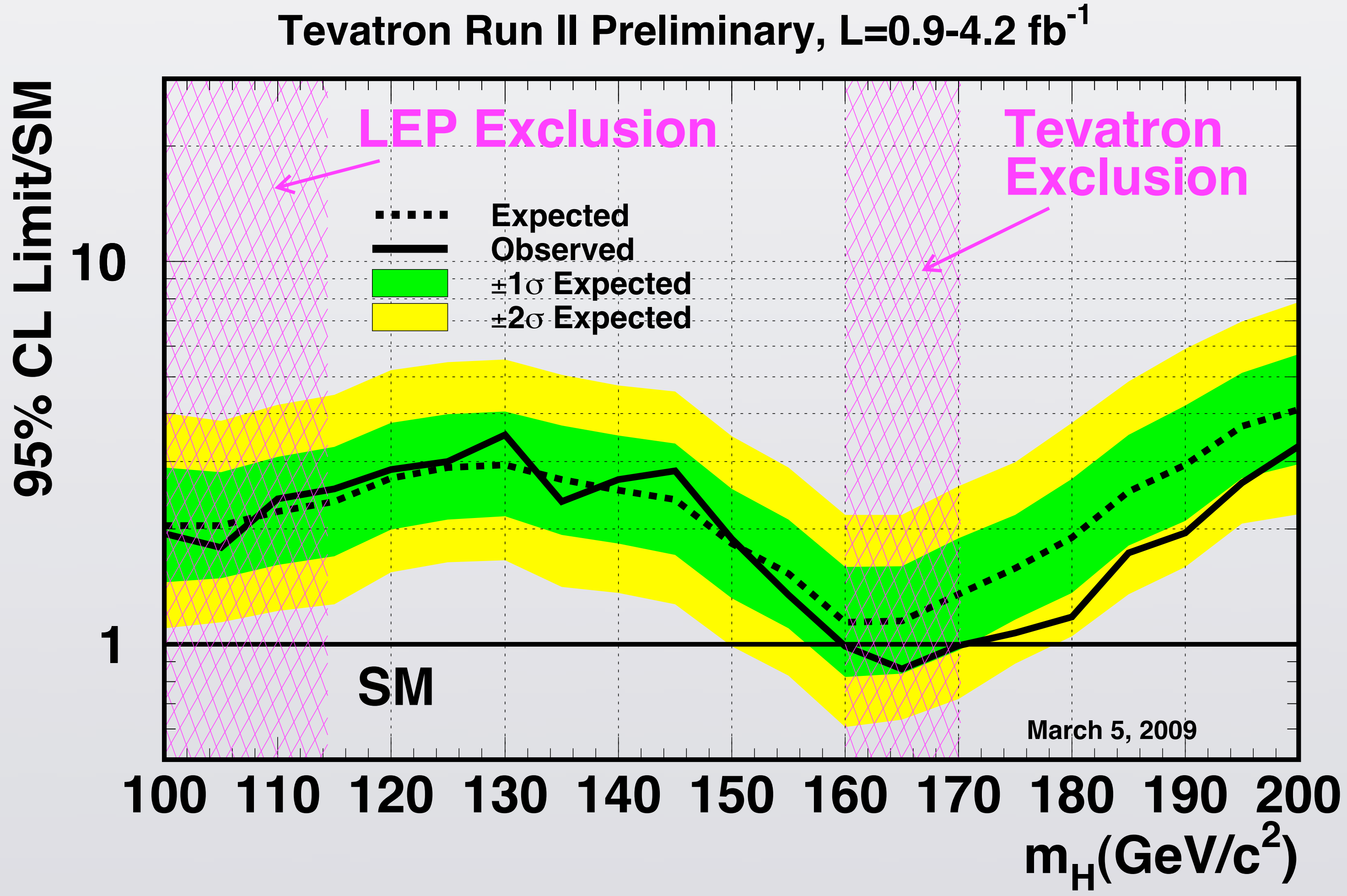
- Very economic model of nature at the fundamental level
  - 12 matter particles (fermions)
  - 3 forces (carriers: bosons)
- Experiments have confirmed this model to incredible precision, but…



[Fermilab Media Service]

…what about the Higgs?

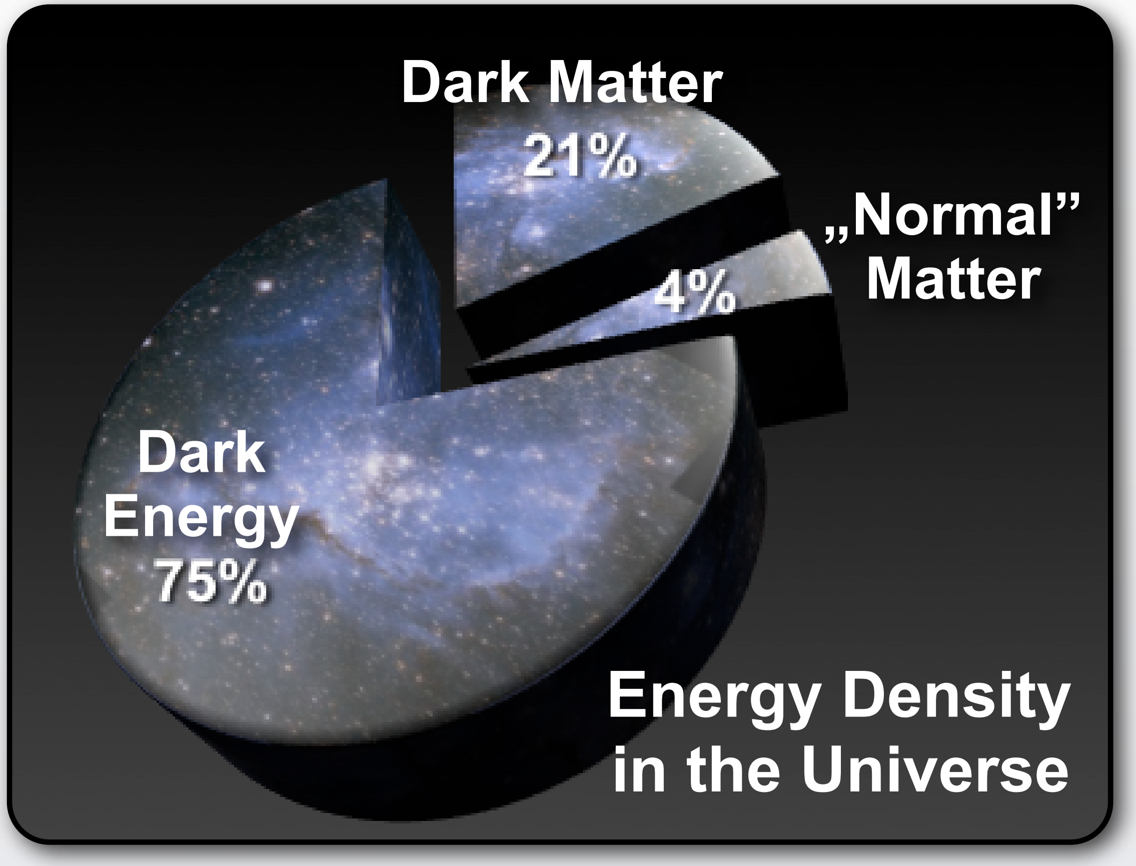
- Cornerstone of the SM: the Higgs boson
  - Responsible for electroweak symmetry breaking → masses for gauge bosons and fermions
  - Despite many efforts: not yet discovered…



March 5, 2009

[FERMILAB-PUB-09-060-E, arXiv:0903.4001 [hep-ex]]

Open Questions 2009



[http://www.research.vt.edu/resmag/sciencecol/2002asymmetry.html]

- But even with the Higgs: many open questions, e.g.
  - Unification of forces: why is gravity so much weaker than the other forces?
  - Energy density of the universe: only 4% baryonic matter
  - Matter/antimatter asymmetry: why is there almost no antimatter in the universe?

Answers?

- Many models of physics beyond the standard model (see lecture by S. Moch):
  - Supersymmetry (symmetry between bosons and fermions)
  - Extra space dimensions
  - New strong force
  - ...
- We need experiments to find out which path nature has chosen (maybe none of the above!)
- The Large Hadron Collider (LHC) at CERN will push the energy frontier: there is hope for a new era of discovery

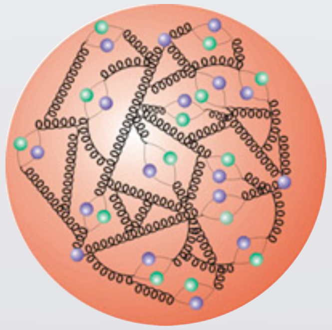
Chapter 2

The LHC Accelerator

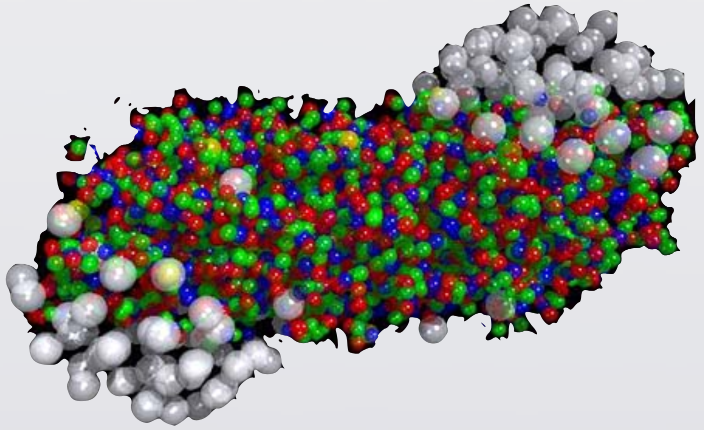
Particle Accelerators

- Particle accelerators: key technology for particle physics since the 1930ies (first cyclotron by E.O. Lawrence, UC Berkeley, 1929)
- Distinguish accelerator types by
  - Shape: linear accelerator (LINAC) vs. synchrotron
  - Particles accelerated: electrons, (anti-)protons, heavy ions

Electron
(Pointlike)



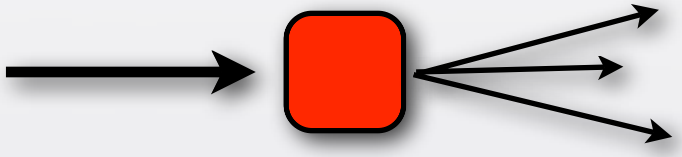
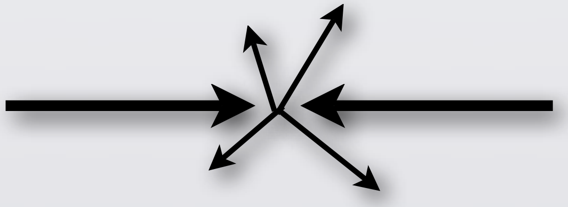
Proton
(Quarks & Gluons)



Collision of two Lead Nuclei

- More details: lecture by W. Decking

Types of Experiments

- Physics reach at accelerators driven by
  - Collision energy (in center of mass frame): $E = m$
  - Number of collisions ("luminosity" → later)
- Fixed target: 
  - Limited energy reach: $E_{\text{CMS}} = \sqrt{2E_{\text{beam}}\, m_{\text{target}}}$
  - Possibly very high beam intensities
- Colliding beams: 
  - Full energy of beams available for physics: $E_{\text{CMS}} = 2E_{\text{beam}}$
  - Need sophisticated steering of beams to reach large collision rate

LINAC vs. Synchrotron

LINAC	Synchrotron
Beams can be used only once: need high field gradient for acceleration, difficult to achieve high luminosities	Beams can be accelerated over many turns, stored for hours to days & re-used for collisions
Need excellent beam focusing at collision point (sub-micron beam spot)	Need strong magnets to keep beam on circular orbit
No synchrotron radiation	Energy loss through synchrotron radiation $\propto$ $(\text{mass})^{-4}$, per turn: $-\Delta E = \frac{4\pi e^2}{3R}\left(\frac{E}{m}\right)^4$

Lepton vs. Hadron Collider

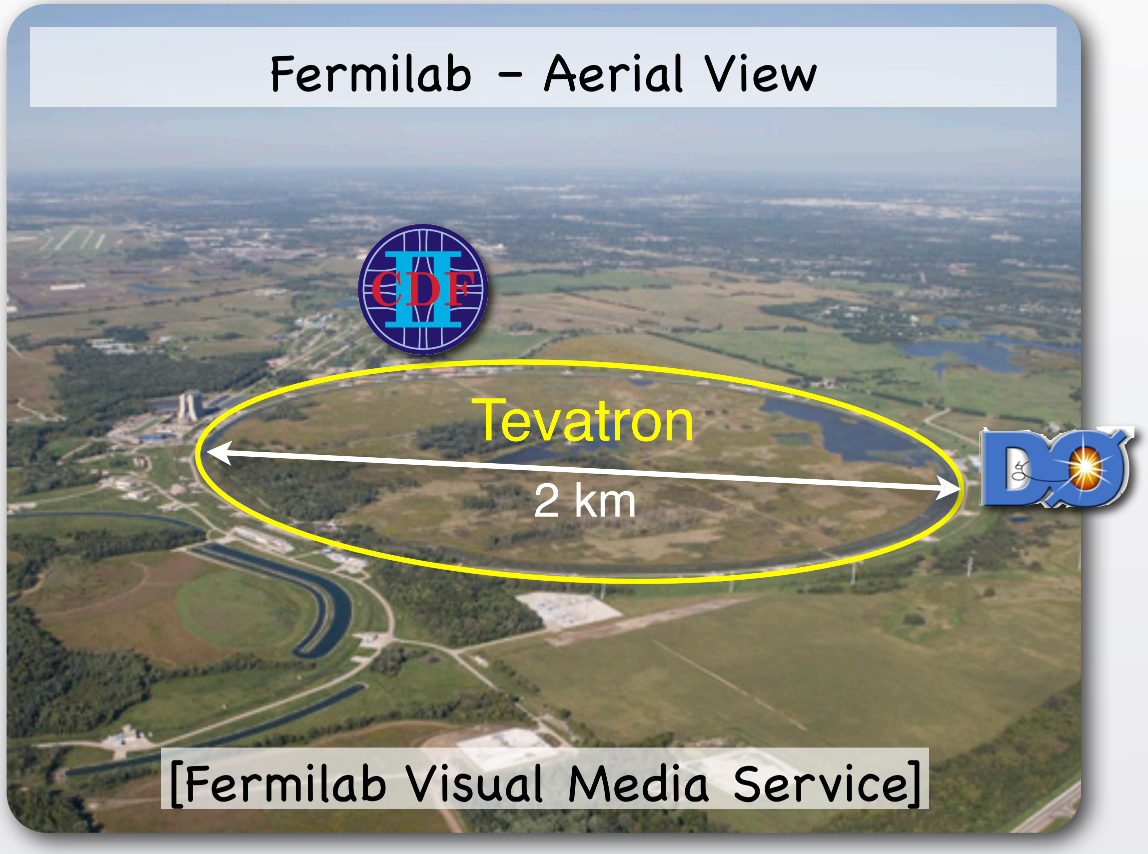
- Lepton = pointlike elementary particles
→ lepton colliders are "precision machines":
  - Well-defined initial state, E_{CMS} known → kinematics fixed
  - Synchrotron: maximum energy limited by synchrotron radiation (LEP II: about 100 MW at E_{CMS} = 209 GeV)
- Hadron = composite particle, complicated substructure
→ hadron colliders are "discovery machines":
  - Easier to store and accelerate → higher available energies
  - Hadron beam = "broadband" beam of partons
→ cover large energy range
- Approaches are complementary → use both

Accelerator Roadmap I

- Tevatron (Fermilab, 1987–2011?): proton-antiproton collider → discovery of the top quark, very broad physics program

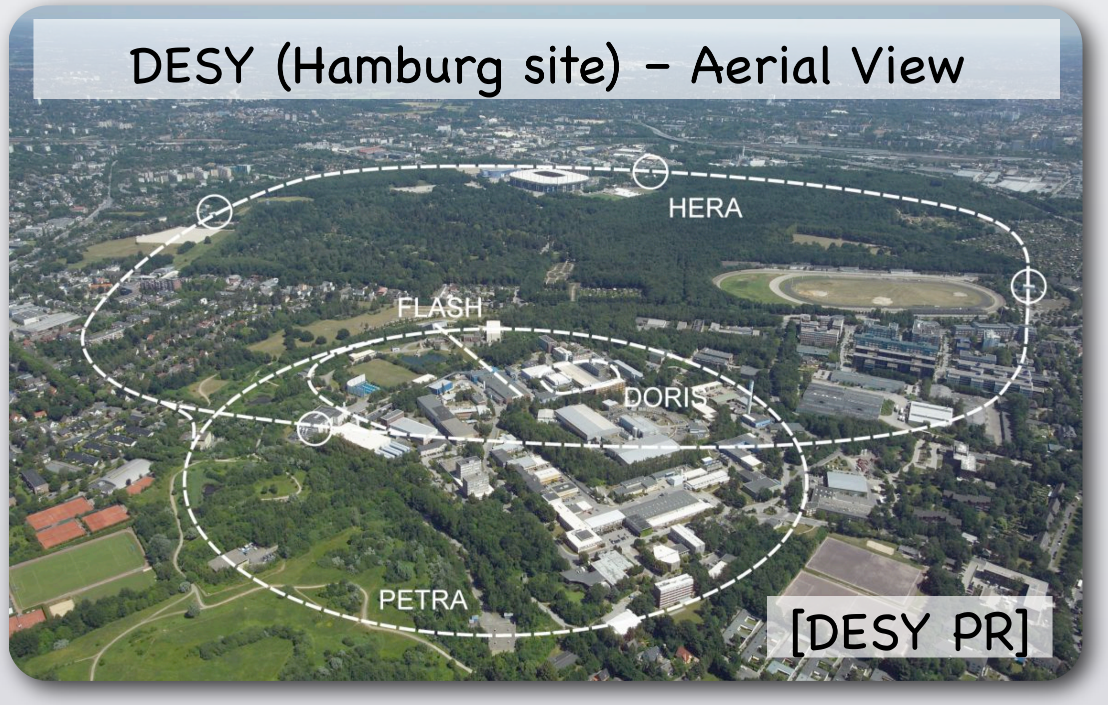
- LEP (CERN, 1989–2000): e^+e^- collider → precision electroweak physics, very broad physics program

- HERA (DESY, 1990–2007): $e^\pm p$ collider → proton structure, QCD, electroweak physics, …



Fermilab – Aerial View

[Fermilab Visual Media Service]



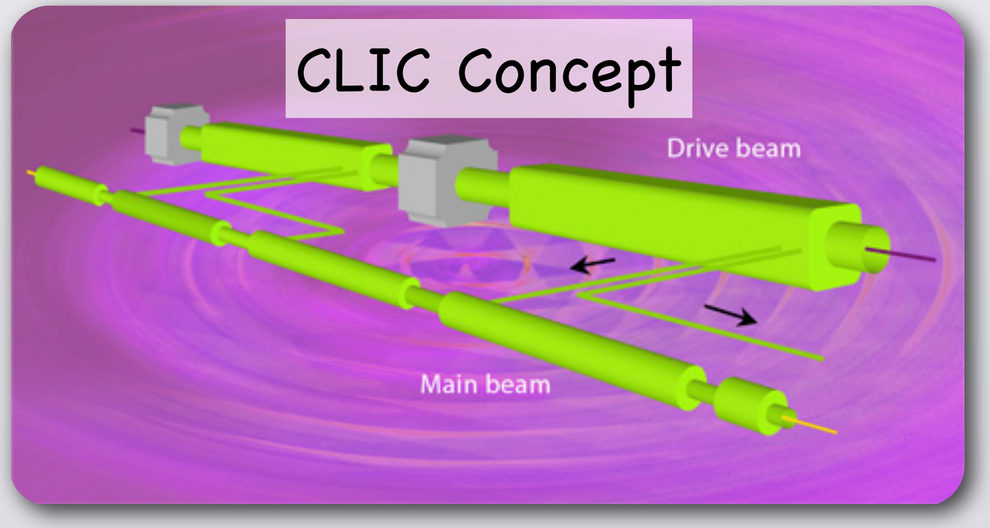
DESY (Hamburg site) – Aerial View

[DESY PR]

Accelerator Roadmap II

- Present & future accelerators:
  - Large Hadron Collider (CERN, from 2009): proton-proton collider → discoveries?
  - Linear e^+e^- collider (2020ies?): International Linear Collider (ILC) or Compact Linear Collider (CLIC) → precision measurements of new physics (see lecture by S. Riemann)
  - What's next? Muon collider? New $e^\pm p$ machine (e.g. LHeC)? → a lot depends on what LHC discovers


Artist's view of ILC Tunnel

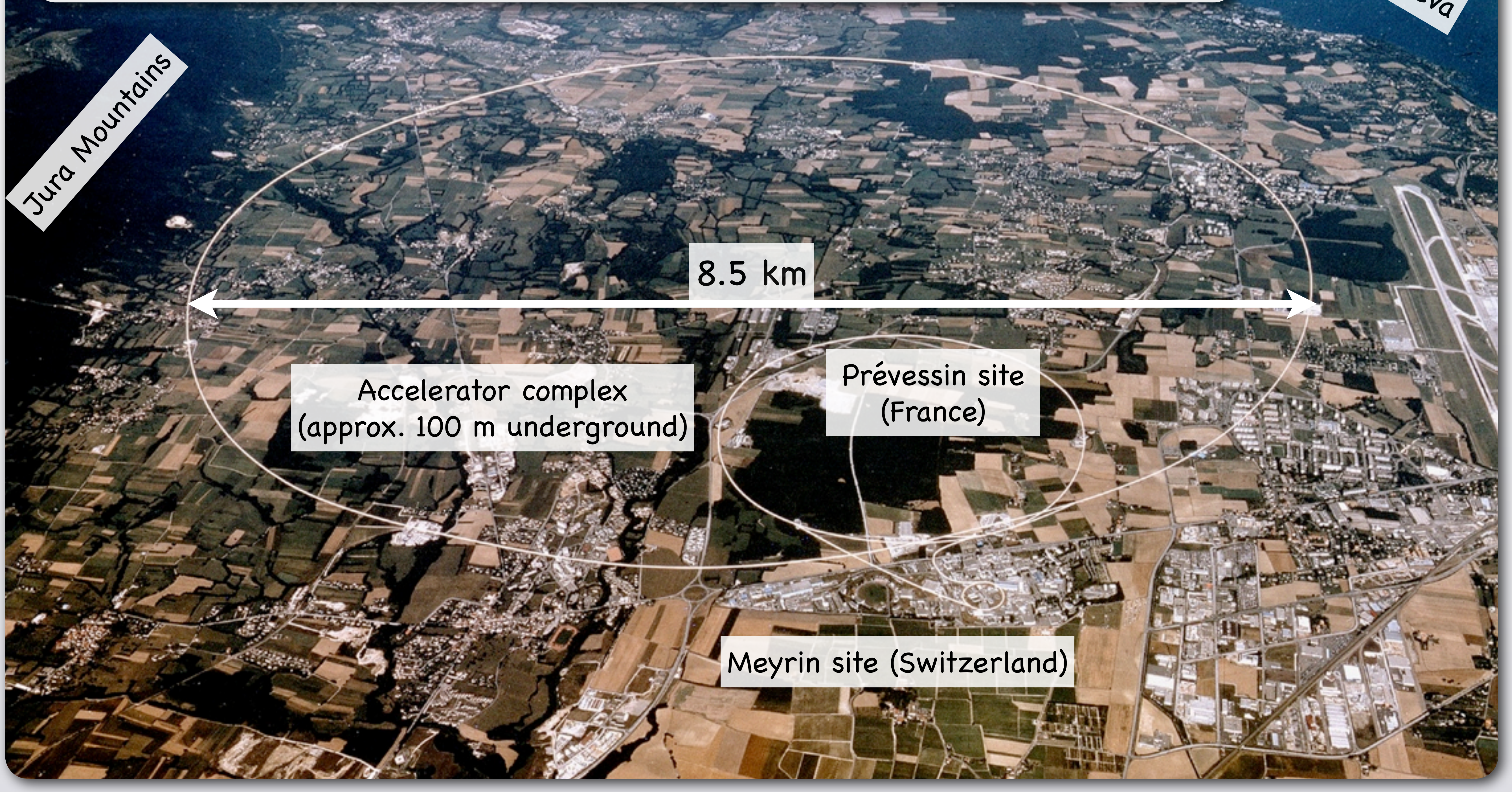

CLIC Concept

CERN = European Laboratory for Partice Physics

the world's largest particle physics laboratory, founded 1954

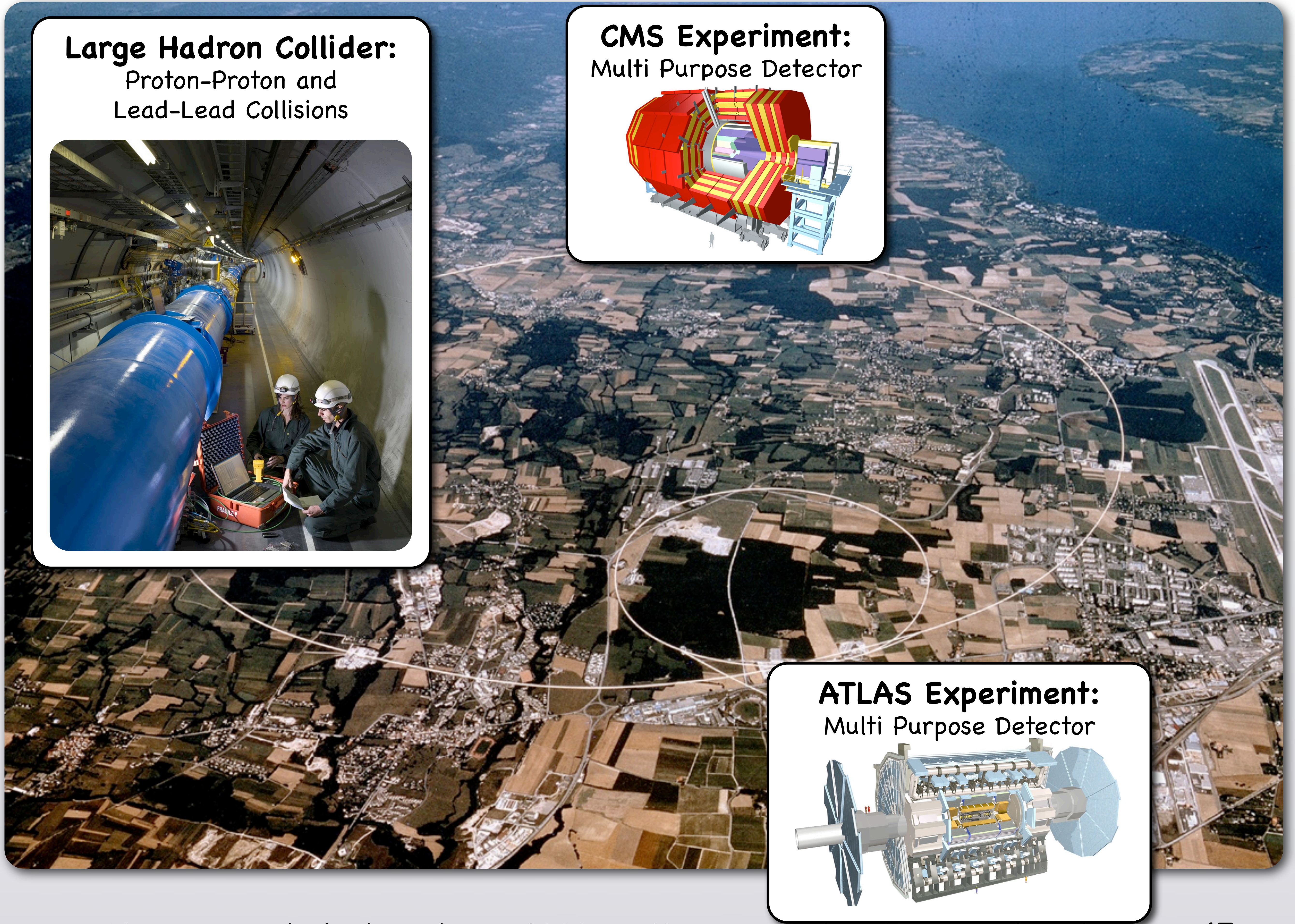
Historic name: "Conseil Européen pour la Recherche Nucléaire"

2500 employees, almost 10000 guest scientists from 85 nations



Large Hadron Collider:

Proton-Proton and
Lead-Lead Collisions



Large Hadron Collider:
Proton-Proton and
Lead-Lead Collisions

CMS Experiment:
Multi Purpose Detector

ATLAS Experiment:
Multi Purpose Detector

Large Hadron Collider:
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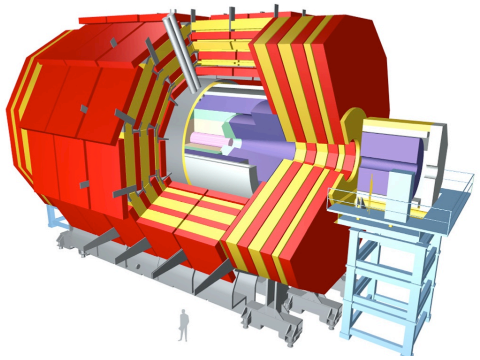
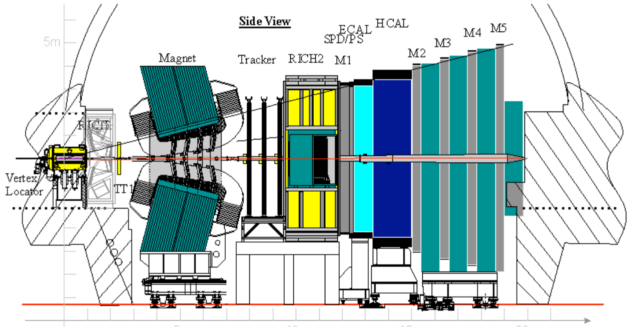
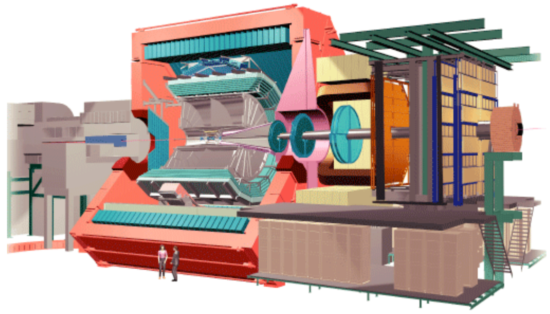


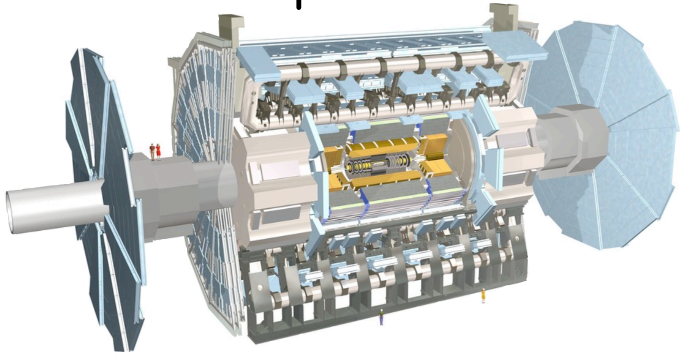
LHCb Experiment:
B Physics and CP Violation



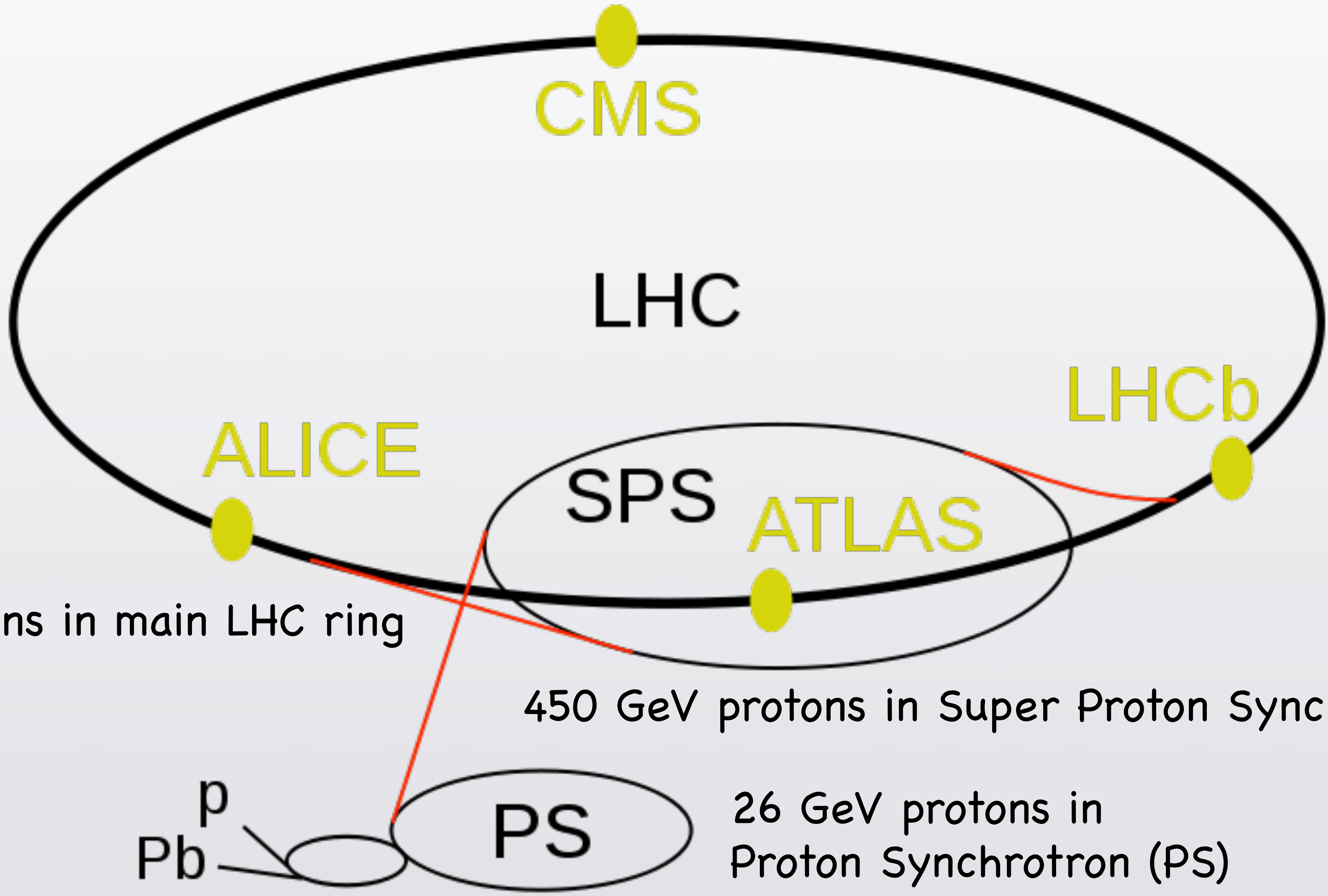
ALICE-Experiment:
Heavy Ion Physics



ATLAS Experiment:
Multi Purpose Detector



Pre-Accelerator Chain



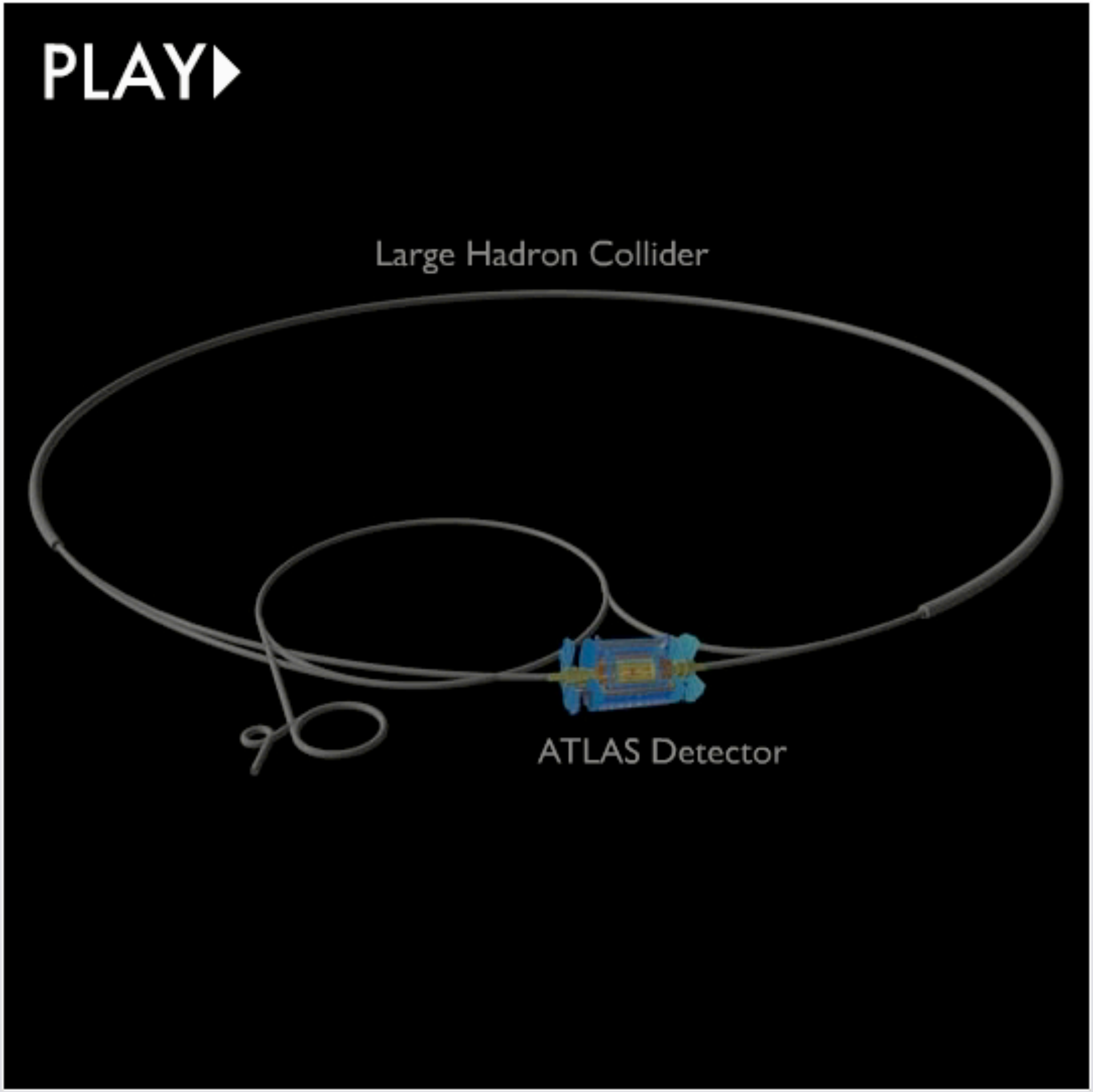
7 TeV protons in main LHC ring

450 GeV protons in Super Proton Synchrotron (SPS)

26 GeV protons in
Proton Synchrotron (PS)

50 MeV – 1.4 GeV protons
in LINAC/Booster

[atlas.ch]



[atlas.ch]

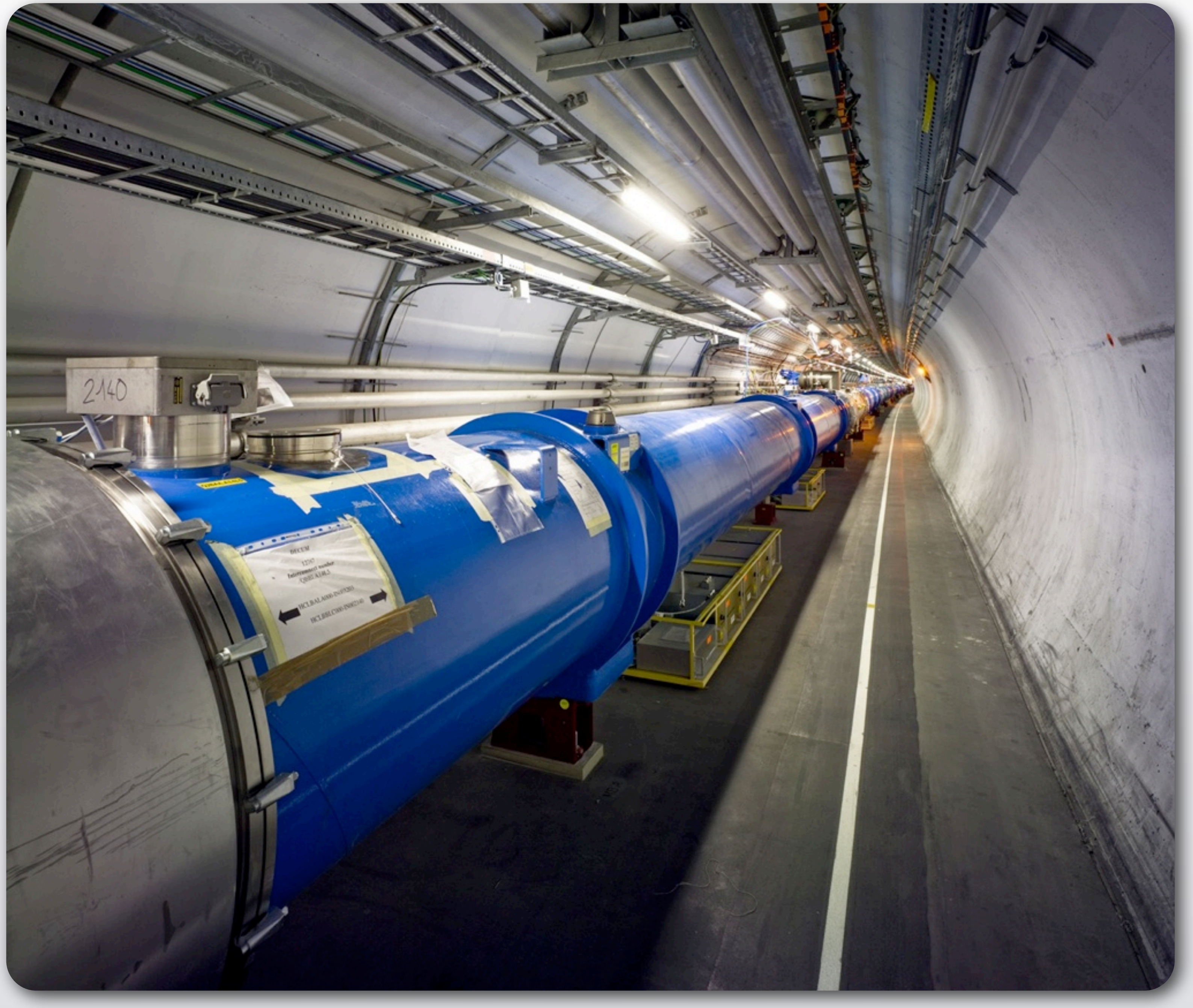
LHC: Facts & Figures

- Design considerations:
  - Has to fit into LEP tunnel → ring radius fixed
  - Highest possible dipole field: 8-9 Tesla → 7 TeV beam energy
- Magnet system:
  - 1232 dipole magnets, more than 7000 correction magnets
  - Superconducting magnets cooled with superfluid helium at 1.9 K → largest connected cryogenic system in the world
- Beams are stored in 2808 bunches (10^{11} protons each)
- Stored energy: 362 MJ (beam) + 600 MJ (magnets)

LHC in Pictures

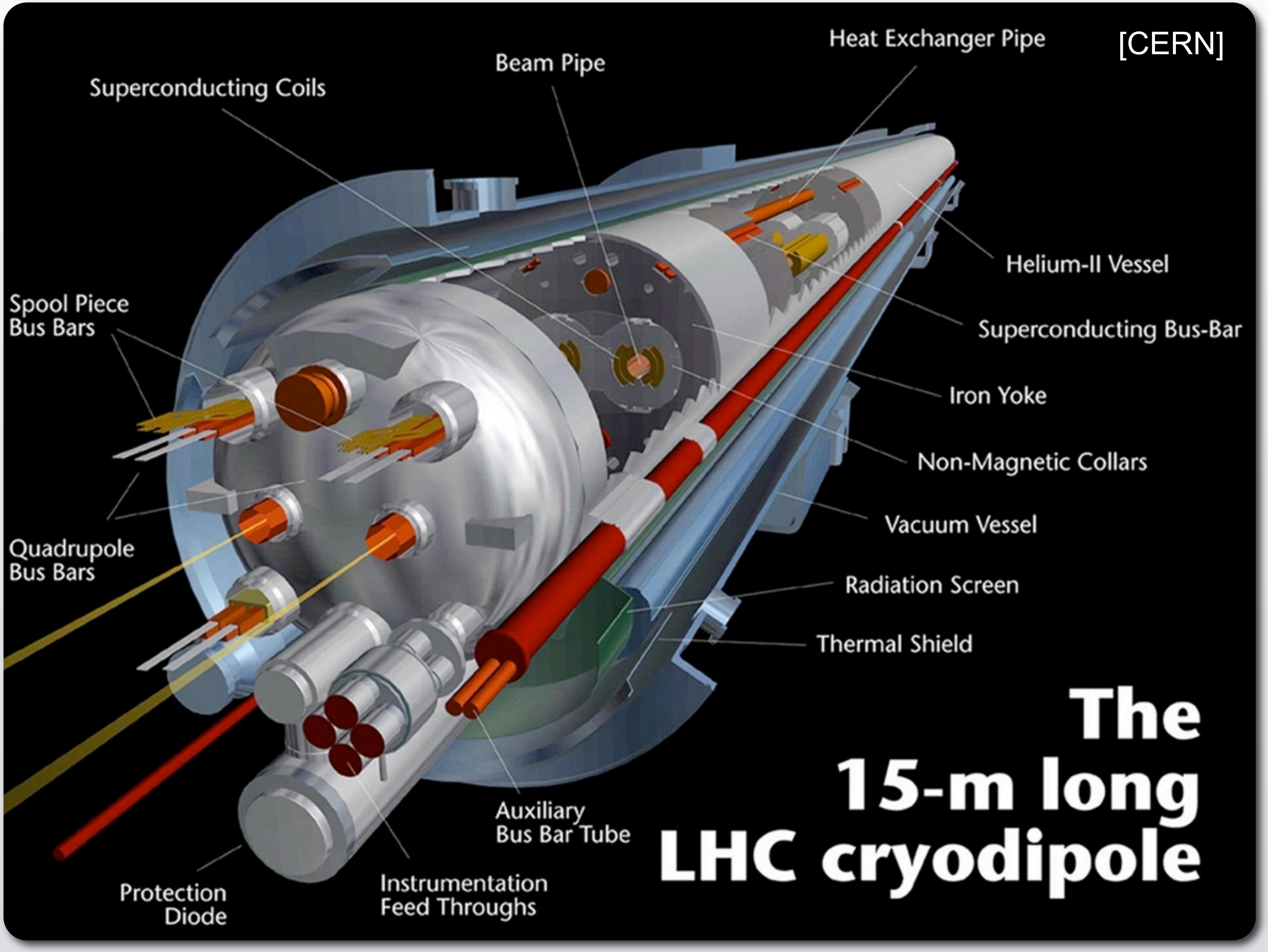
Last Dipole Lowered in Tunnel (2007)

LHC Tunnel View (July 2009)

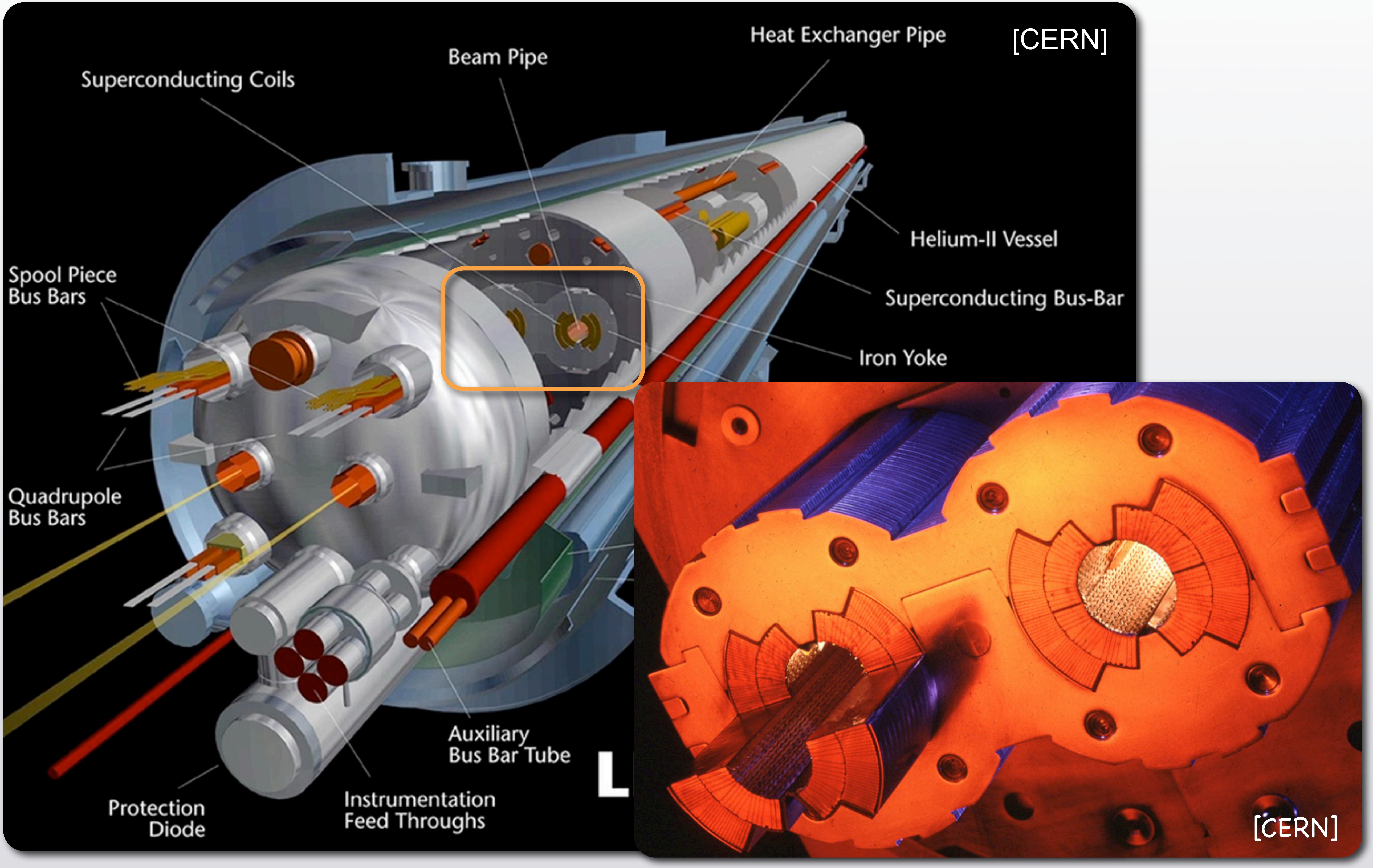


[atlas.ch]

LHC Dipole Magnets



LHC Dipole Magnets



[CERN]

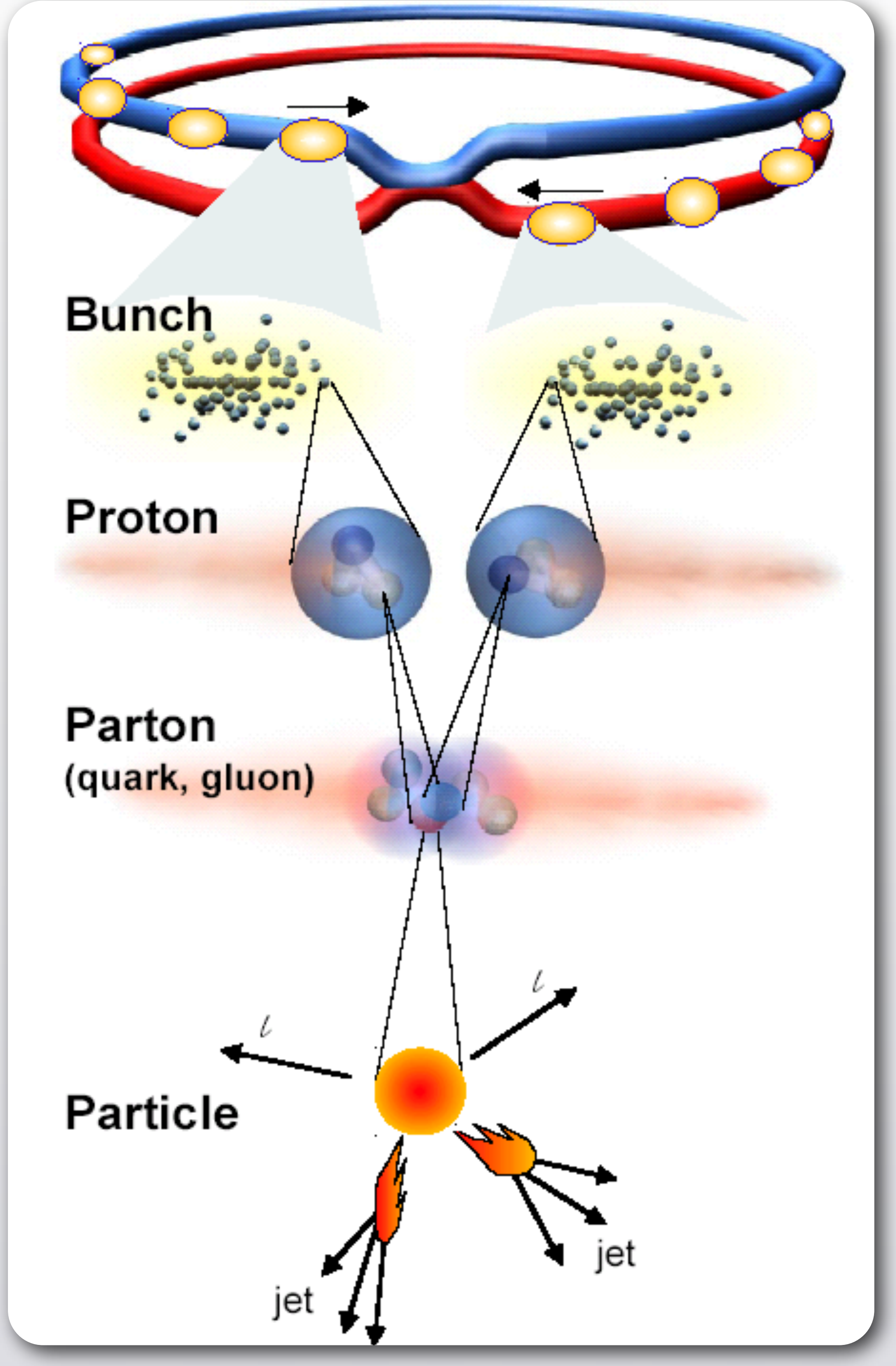
[CERN]

Luminosity & Cross Section

- Collision rate: $R \equiv \frac{\mathrm{d}N}{\mathrm{d}t} = \mathscr{L}\sigma$
  - Cross section σ: nature (theory)
  - Instantaneous luminosity defined by beam parameters:

    $$\mathscr{L} = f N \frac{n_1 n_2}{4\pi\varepsilon_x\varepsilon_y}$$

    f: revolution frequency
    N: number of bunches
    n_i: number of particles/bunch,
    $4\pi\varepsilon_x\varepsilon_y$: beam spot size
  - LHC design peak luminosity: 10^{34} cm^{-2} s^{-1} (cf. Tevatron today: 3.5×10^{32} cm^{-2} s^{-1})

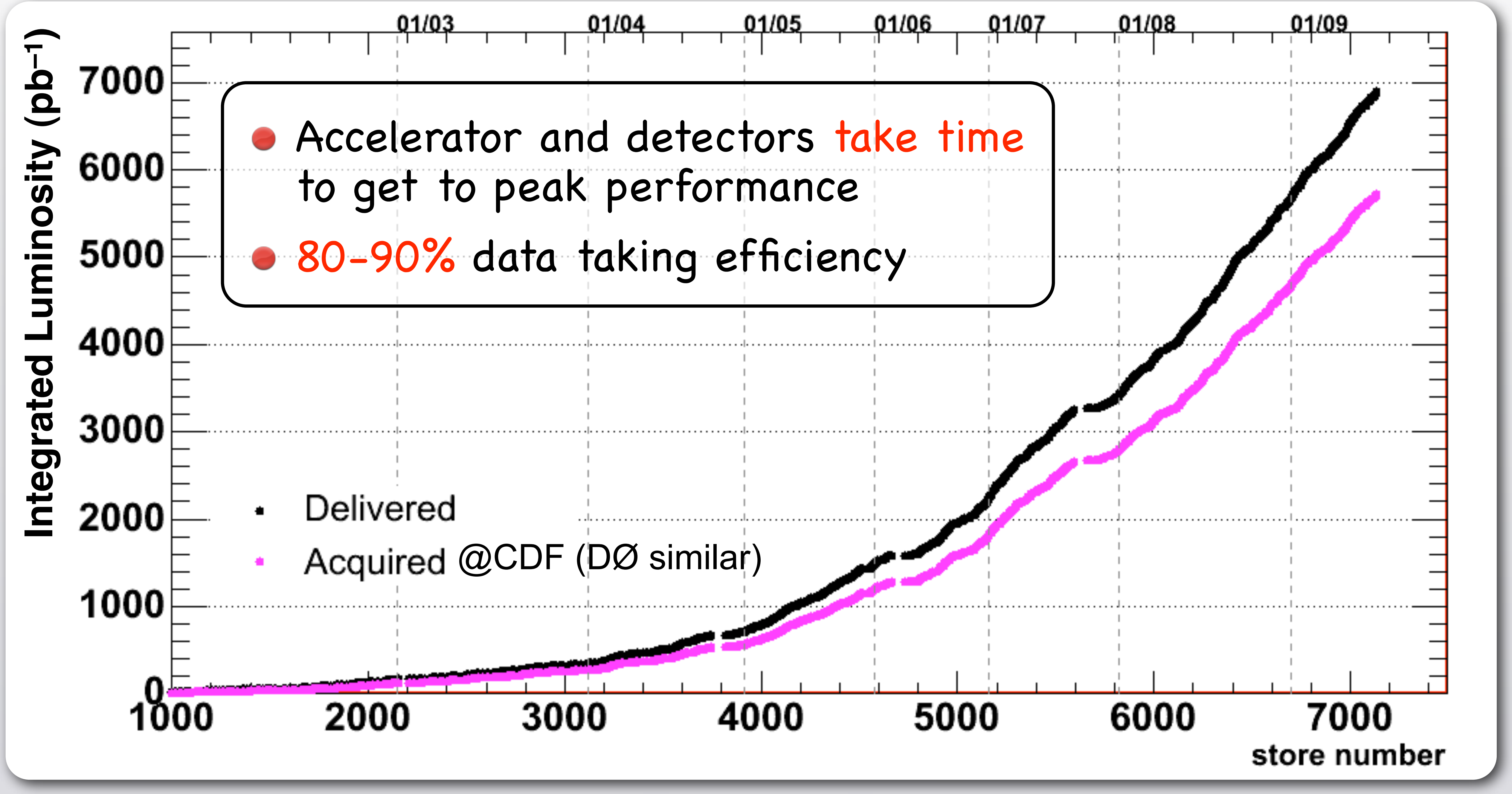


Luminosity & Cross Section

- Number of events produced: $N = \int \mathscr{L} \mathrm{d}t \, \sigma$
- Number of events observed: $N_{\mathrm{obs}} = \int \mathscr{L} \mathrm{d}t \, \sigma \, \varepsilon$
  - Depends on detection efficiency ε
  - Many factors: detector, trigger, data analysis, ... → tomorrow
- A word on units:
  - Cross section = area → HEP units: 1 cm^2 or 1 barn = 10^{-24} cm^2
  - Instantaneous luminosity = rate per cross section → $1 \text{ cm}^{-2} \text{ s}^{-1}$
  - Integrated luminosity = events per cross section → 1 inverse barn (e.g. Tevatron until now: 7 fb^{-1})
  - Example: top production cross section σ_{tt} @ Tevatron = 7 pb → $N_{tt} = 7 \text{ fb}^{-1} \times 7 \text{ pb}$ = 49,000 tops (per experiment)

A Lesson from the Past

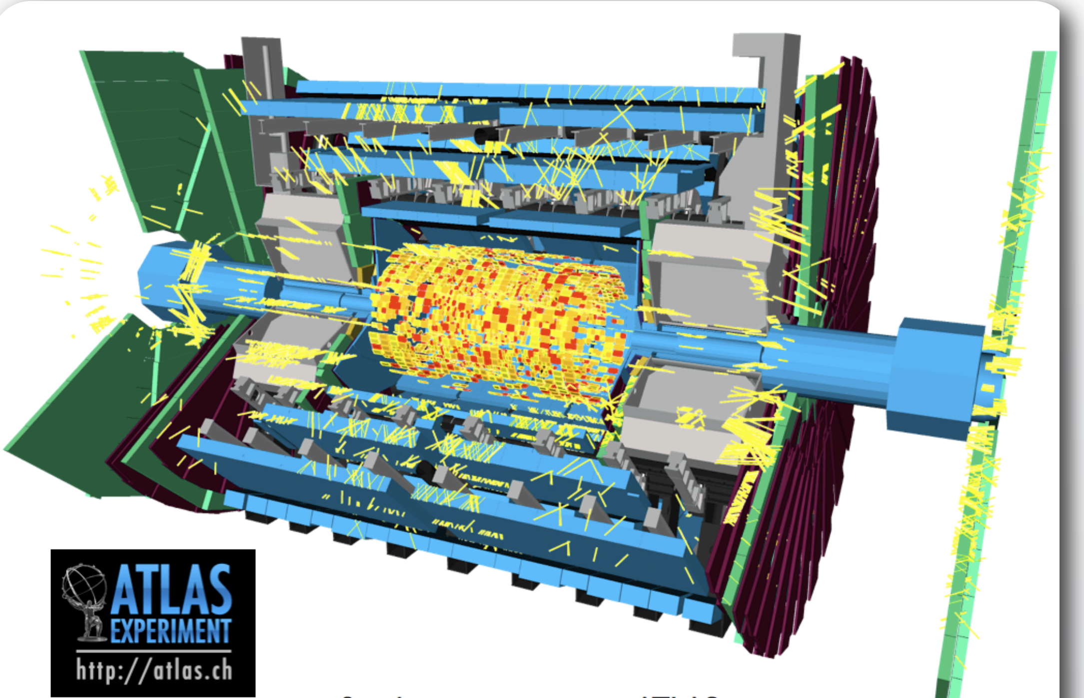
- How would the LHC startup look like?
  → Compare to Tevatron Run II integrated luminosity



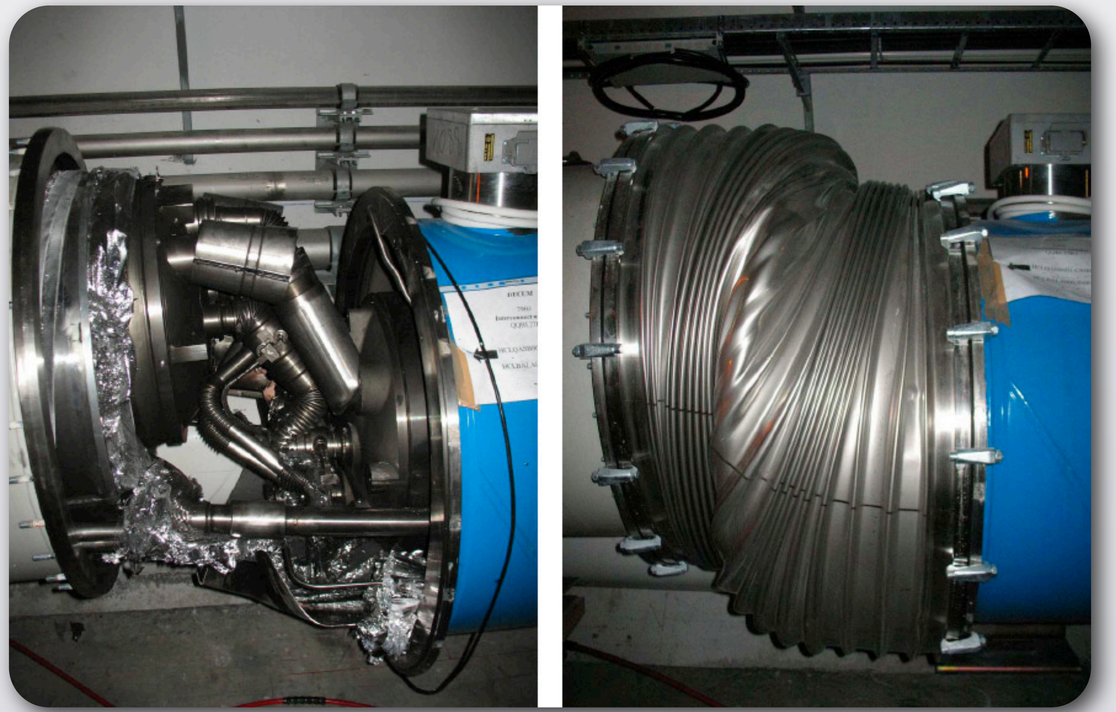
- Accelerator and detectors take time to get to peak performance
- 80-90% data taking efficiency

LHC Startup: Current Plan

- What happened in 2008:
  - September 10: first beam
    → very successful startup
  - September 19 incident
    → approx. 50 magnets damaged
- After 1 year of repairs, checks, and installation of better diagnostics
  - First beam expected middle of November
  - Beam energy limited to 3.5 TeV, increase to 5 TeV in 2010

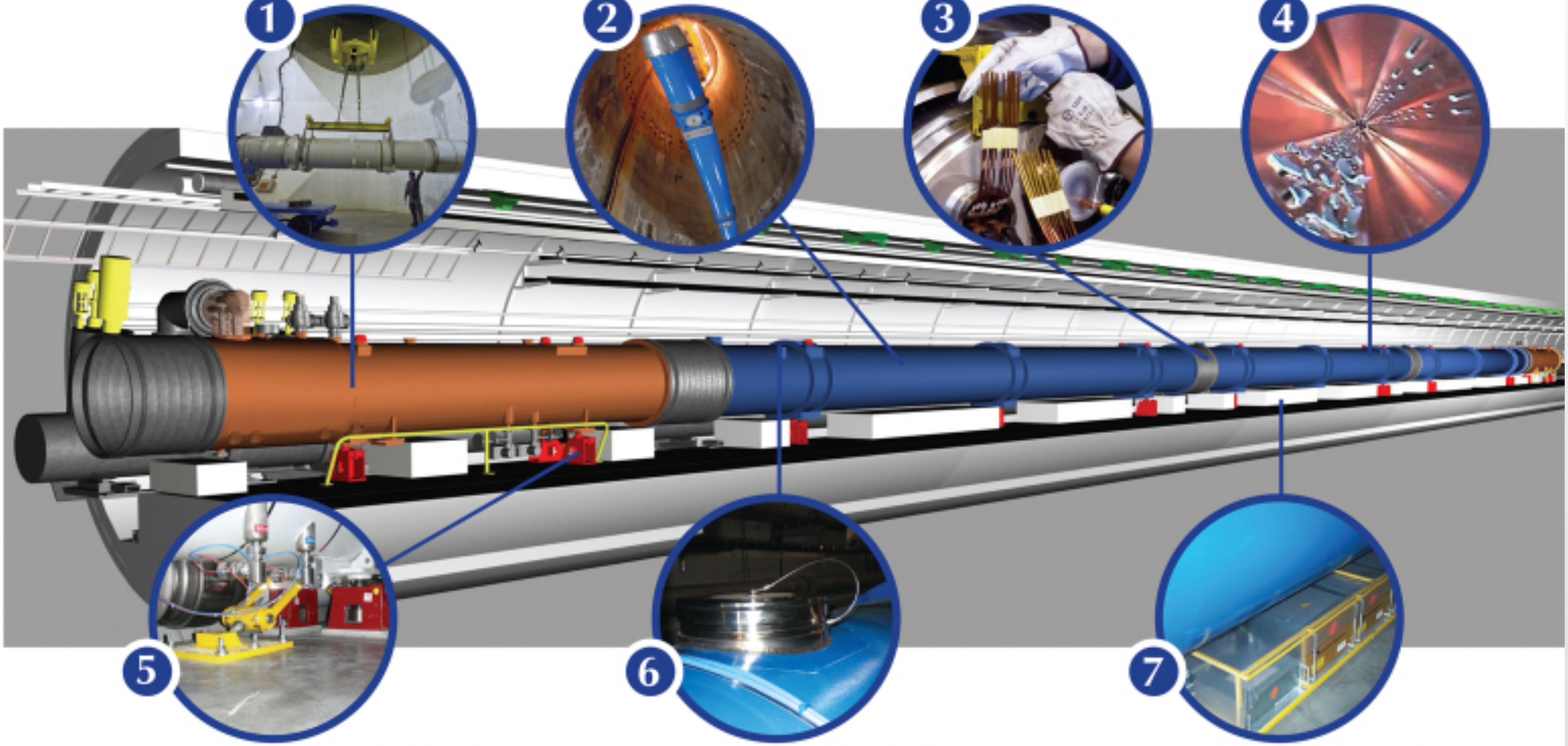


first beam event seen in ATLAS



[CERN]

The LHC repairs in detail



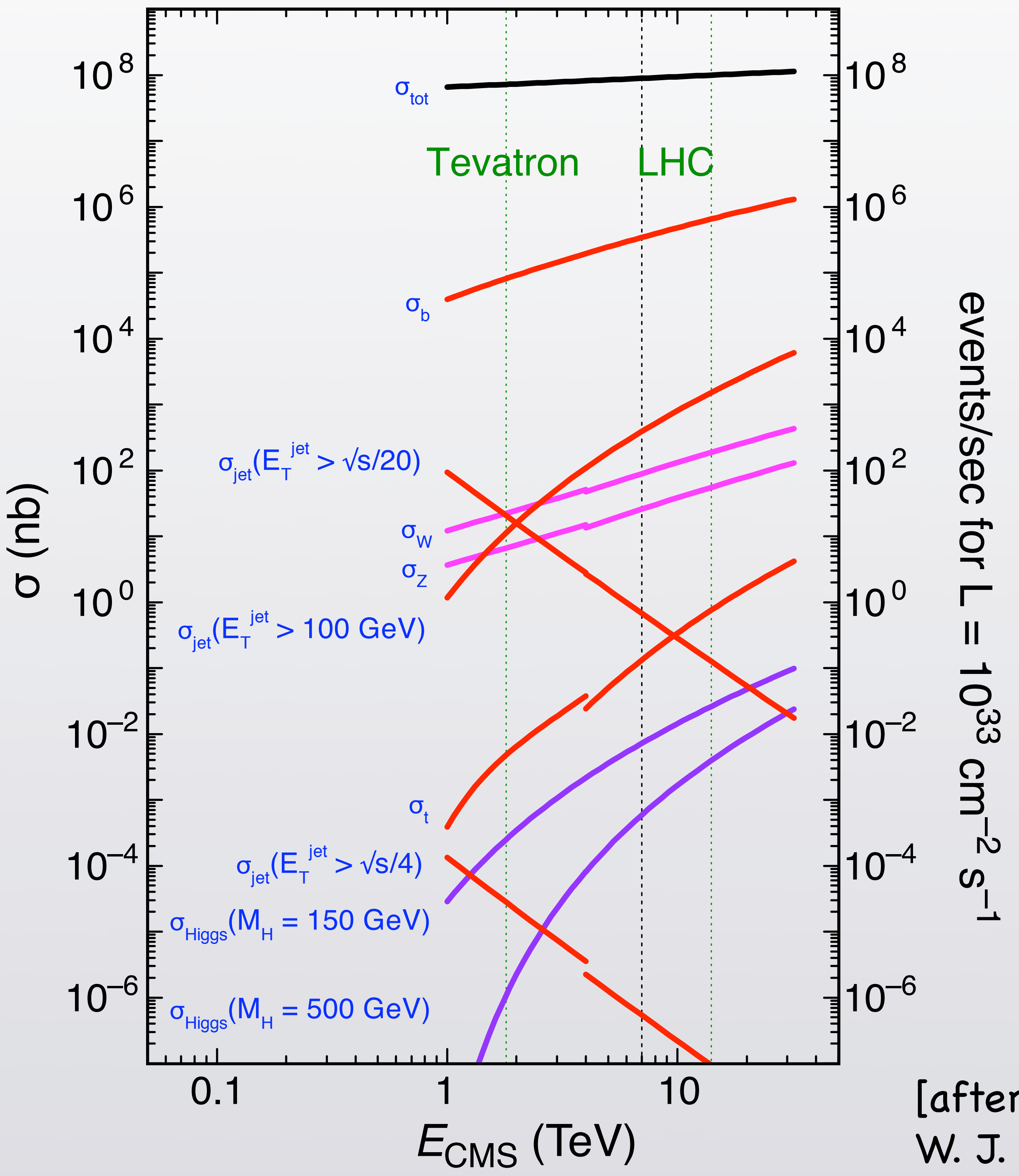
1. 14 quadrupole magnets replaced
2. 39 dipole magnets replaced
3. 54 electrical interconnections fully repaired. 150 more needing only partial repairs
4. Over 4 km of vacuum beam tube cleaned
5. A new longitudinal restraining system is being fitted to 50 quadrupole magnets
6. Nearly 900 new helium pressure release ports are being installed around the machine
7. 6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid

Chapter 3

How to Build a LHC Detector

Design Considerations I

proton–(anti)proton cross sections



- Search for physics beyond the standard model:
  - Short lifetimes: sensitivity to (all) decay products: charged leptons, neutrinos, photons, jets of hadrons, …
  - Small cross sections for production of new particles: very large (1 GHz) event rates → fast readout, massive data volume, online preselection necessary

[after: J. M. Campbell, J. W. Huston, W. J. Stirling, Rep. Prog. Phys. **70** (2007) 89]

Design Considerations II

- Key requirement for collider detectors: measure all possible properties of all collision products:
  - Combination of detector types for momentum, energy, origin, particle type, …
  - Hermetic "4π detector": cover most of solid angle
- Typical design: detector made out of several sub-detectors arranged like shells of an onion

[atlas.ch]

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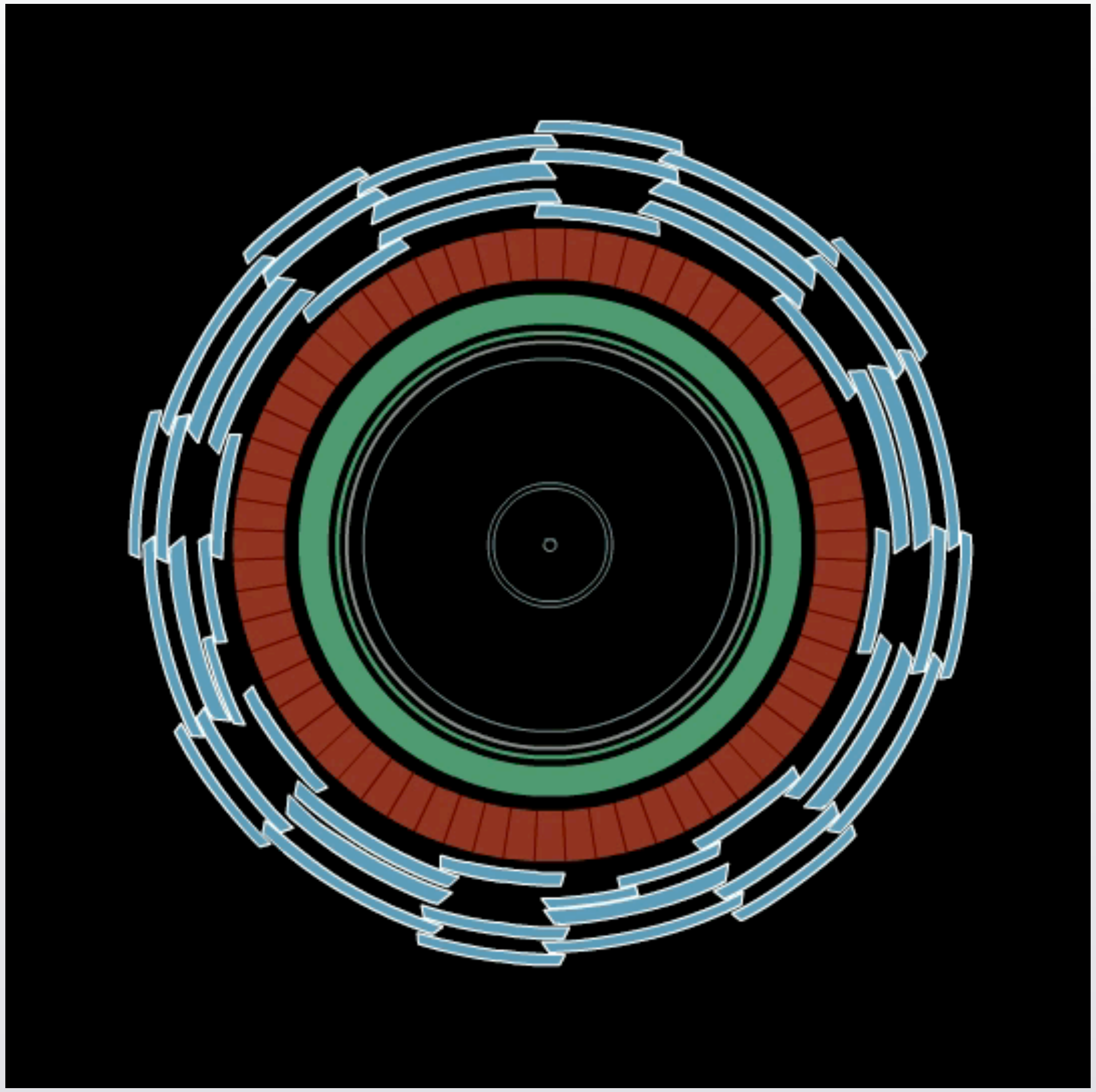

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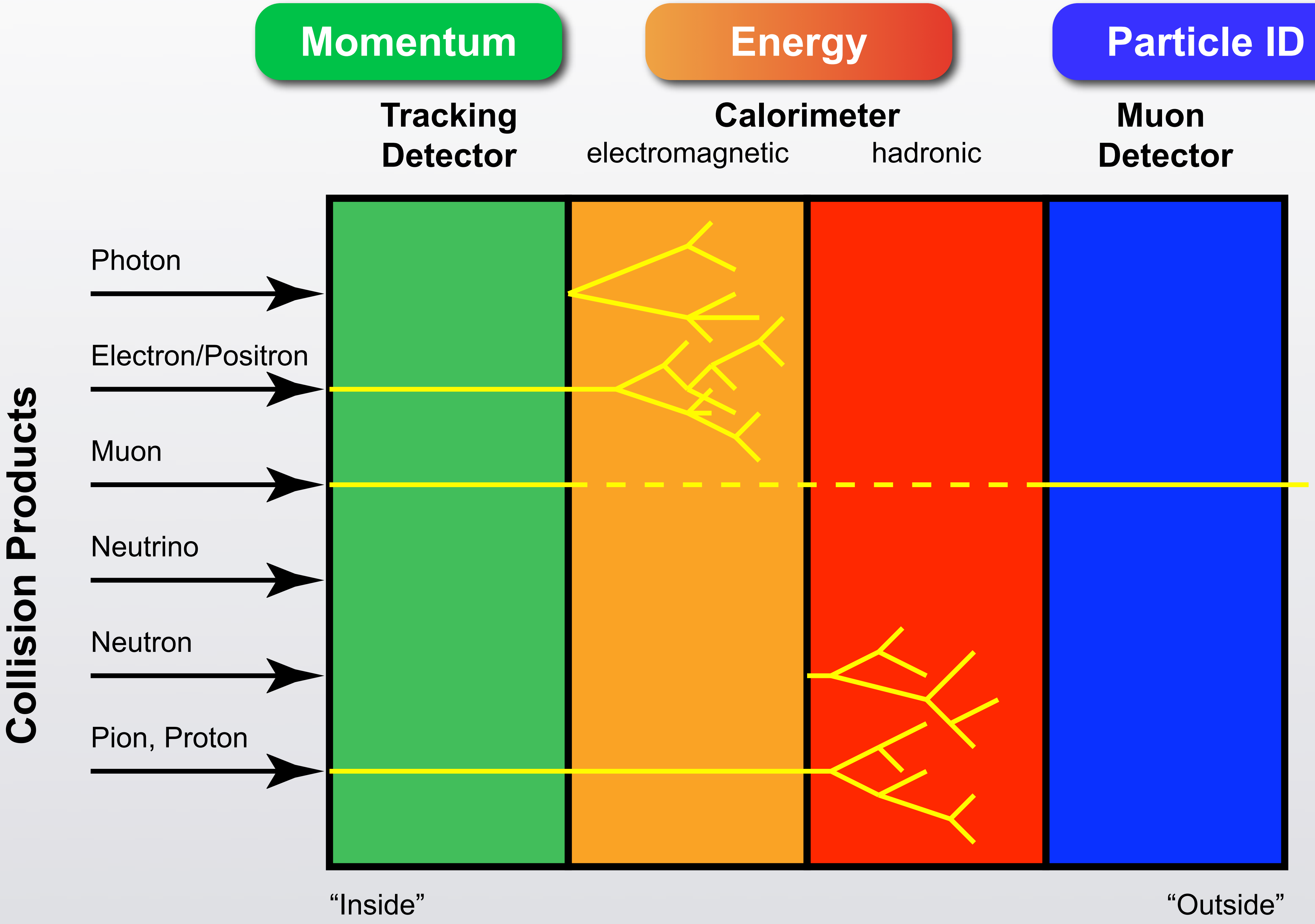
The “Onion Shell” Principle



Momentum

Energy

Particle ID

Tracking Detector

Calorimeter

electromagnetic

hadronic

Muon Detector

Collision Products

Photon

Electron/Positron

Muon

Neutrino

Neutron

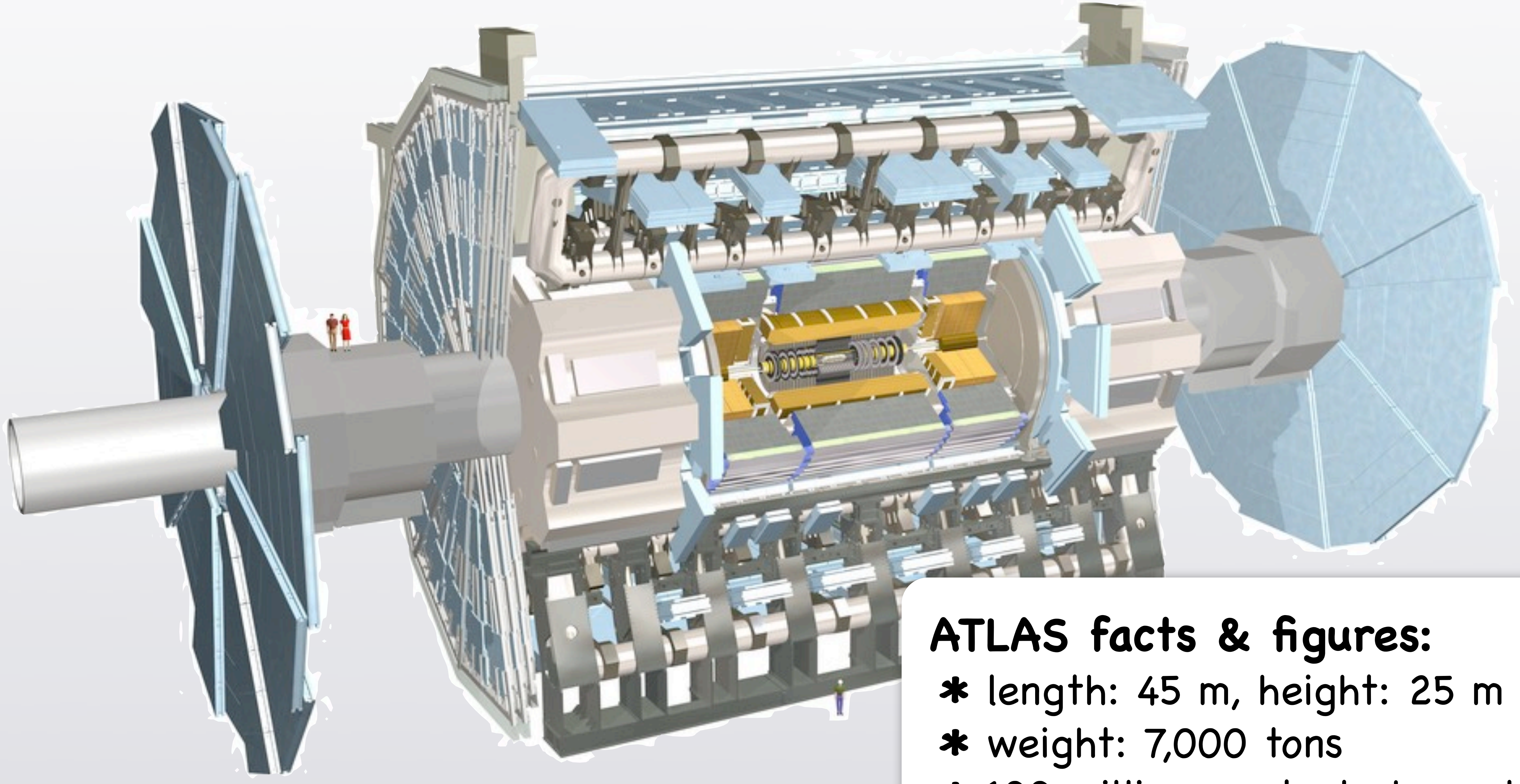
Pion, Proton

“Inside”

“Outside”

Flash Animation: Particles in CMS

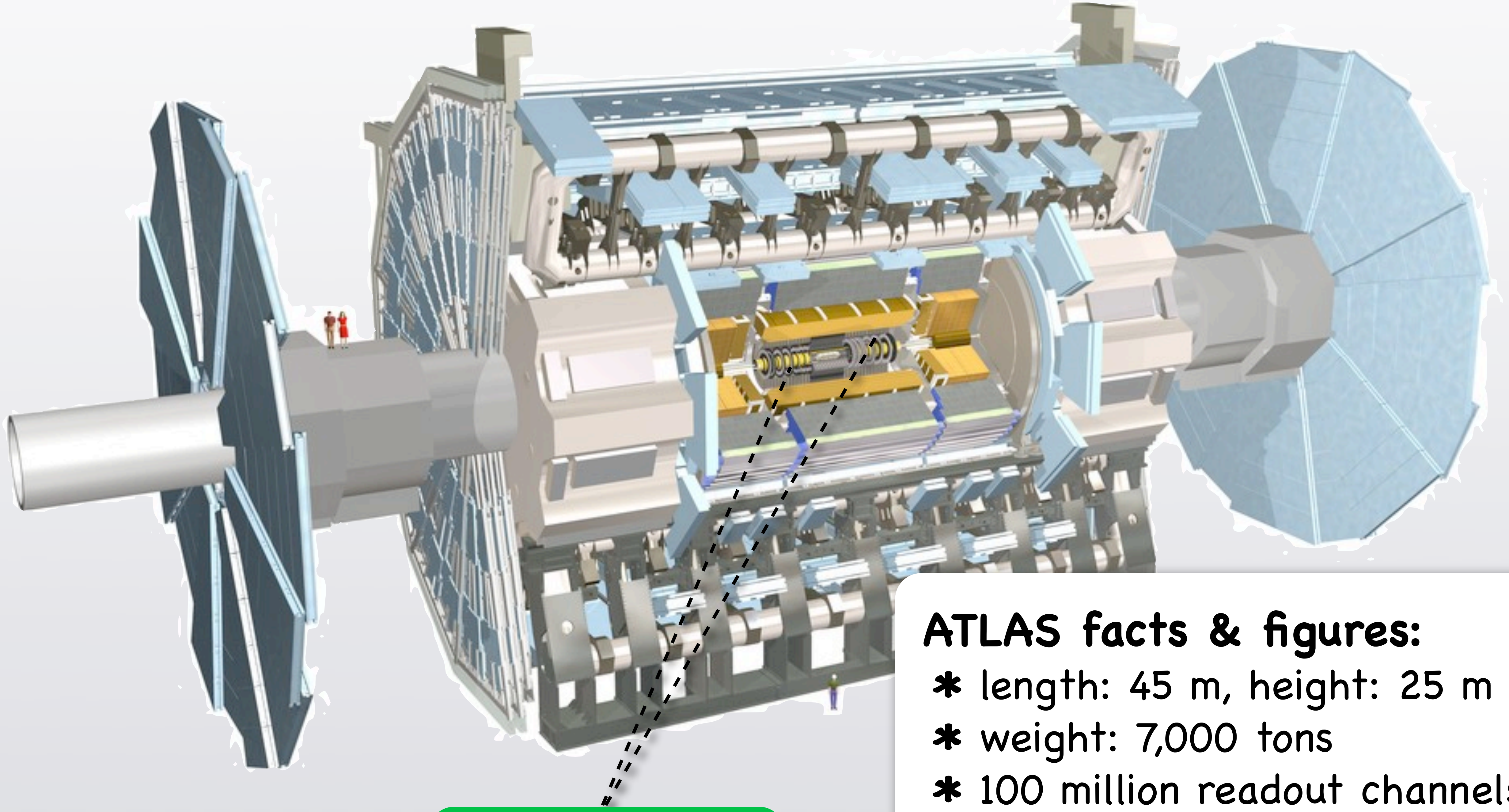
ATLAS



ATLAS facts & figures:

- length: 45 m, height: 25 m
- weight: 7,000 tons
- 100 million readout channels
- 2800 collaborators

ATLAS



Tracking Detectors

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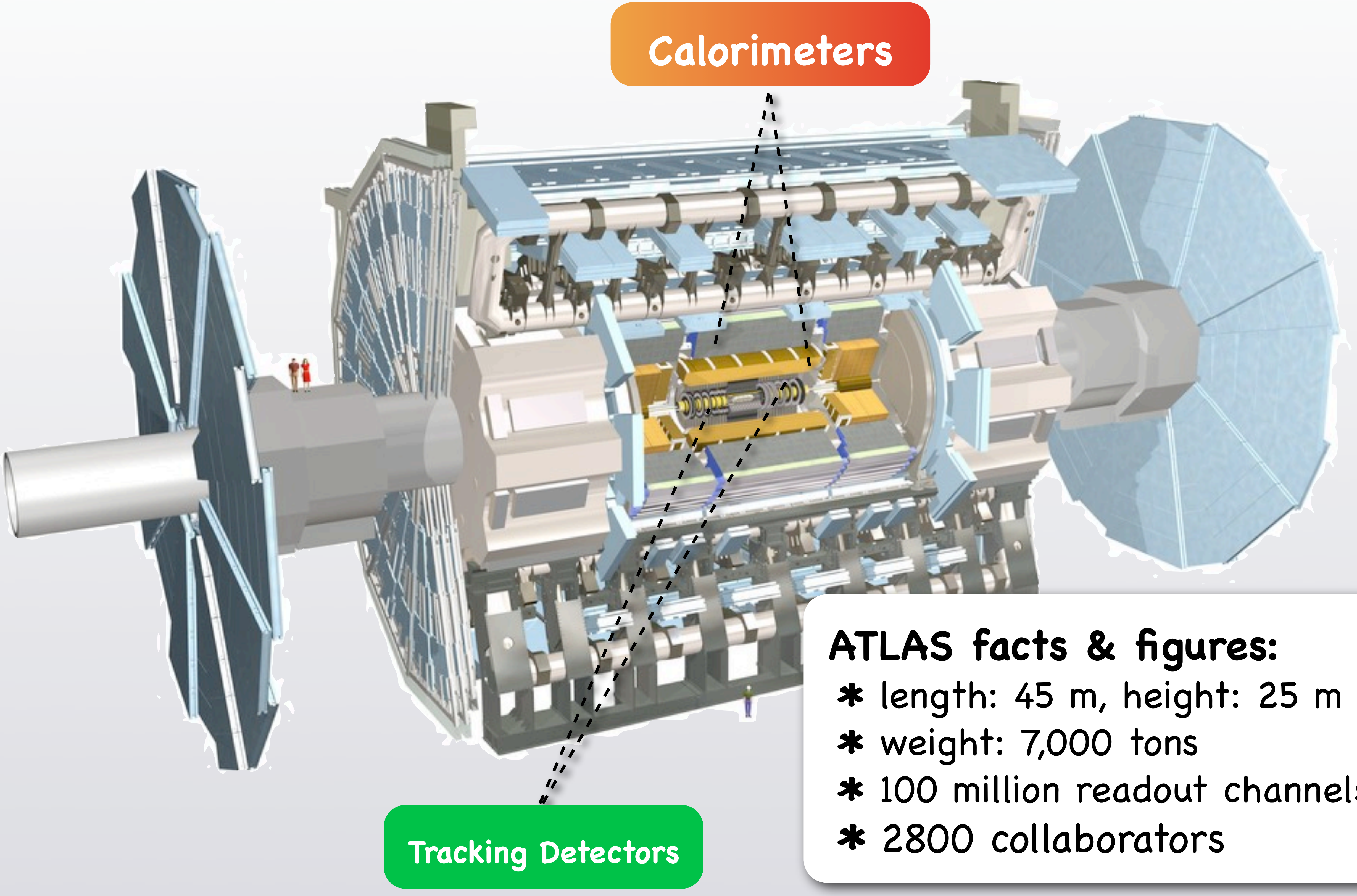

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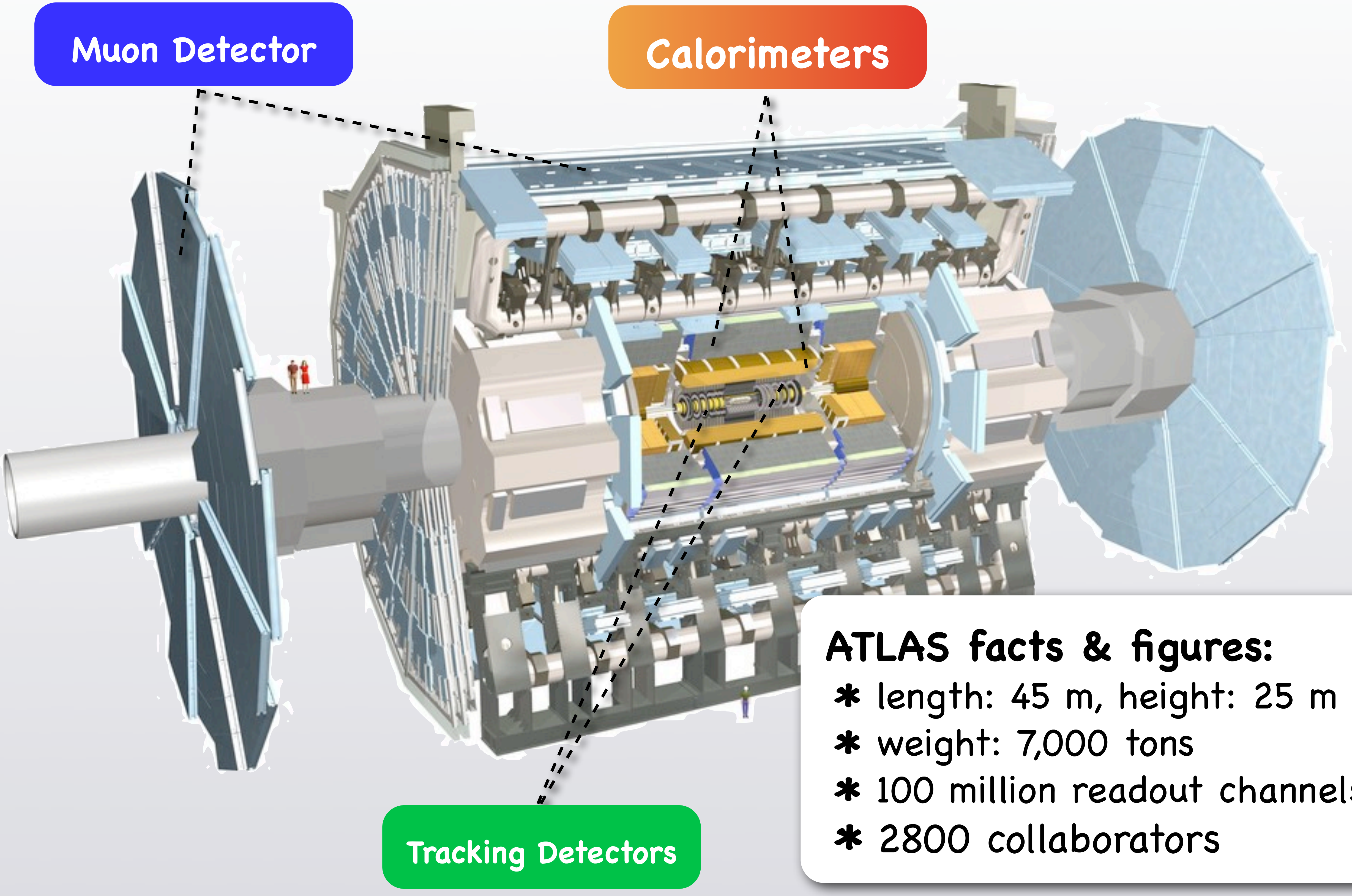

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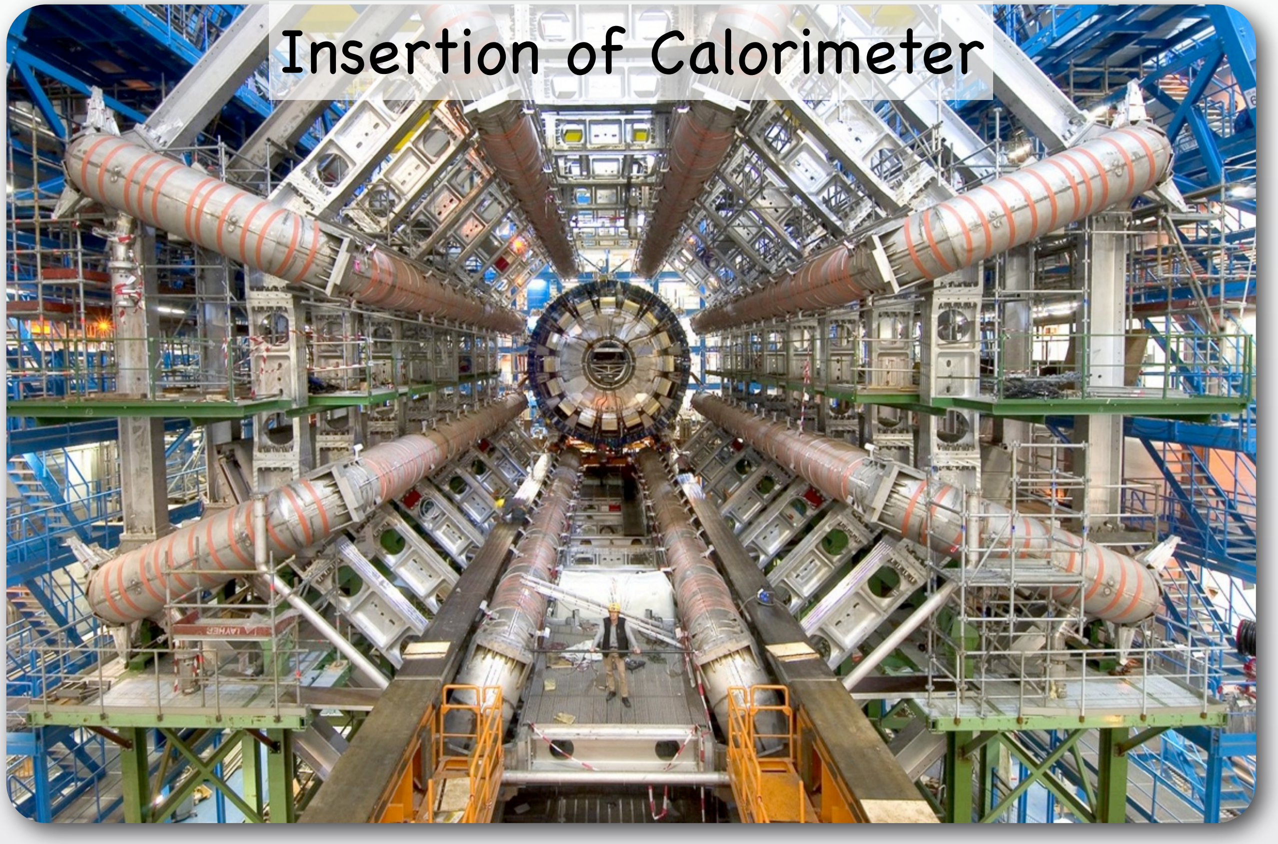
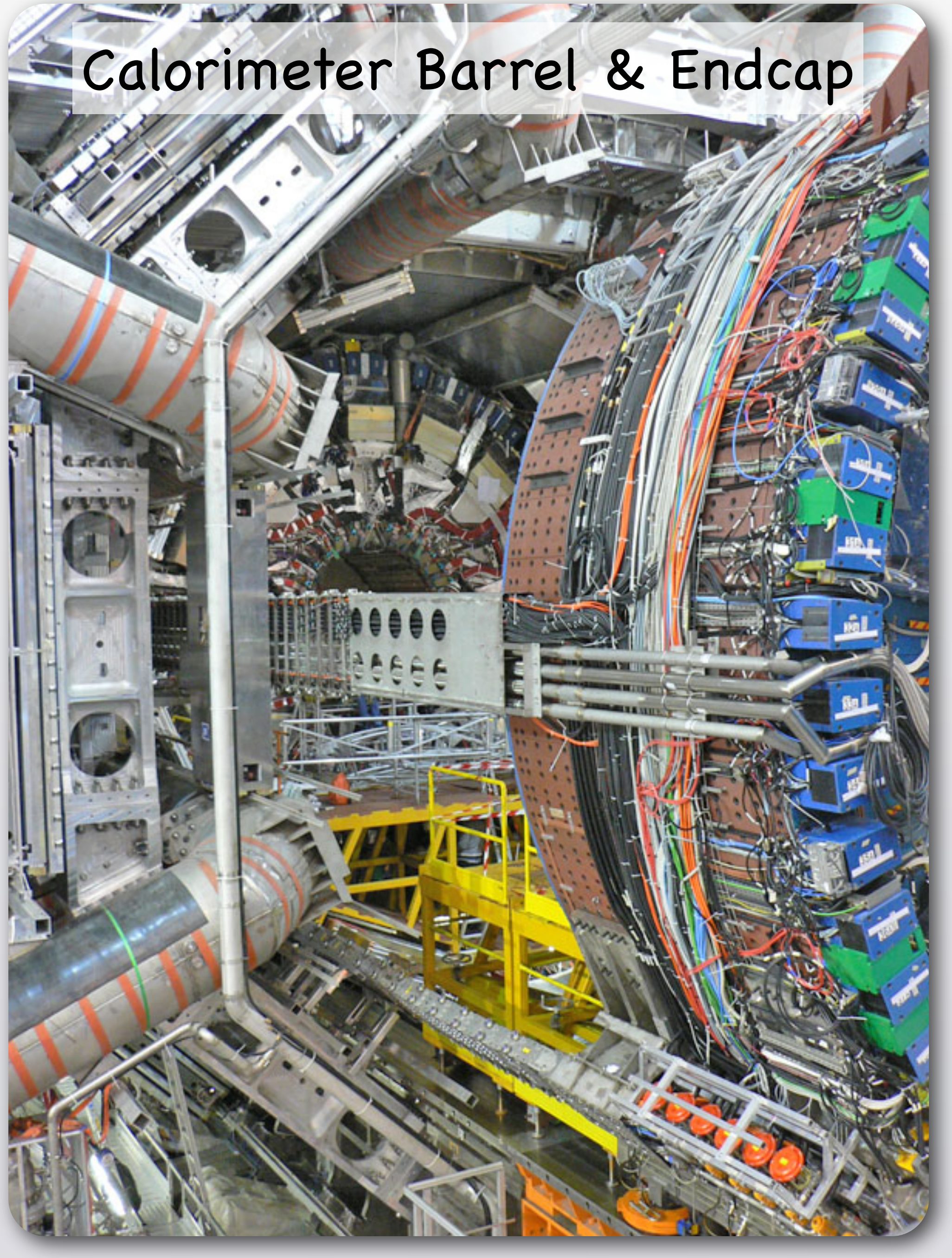
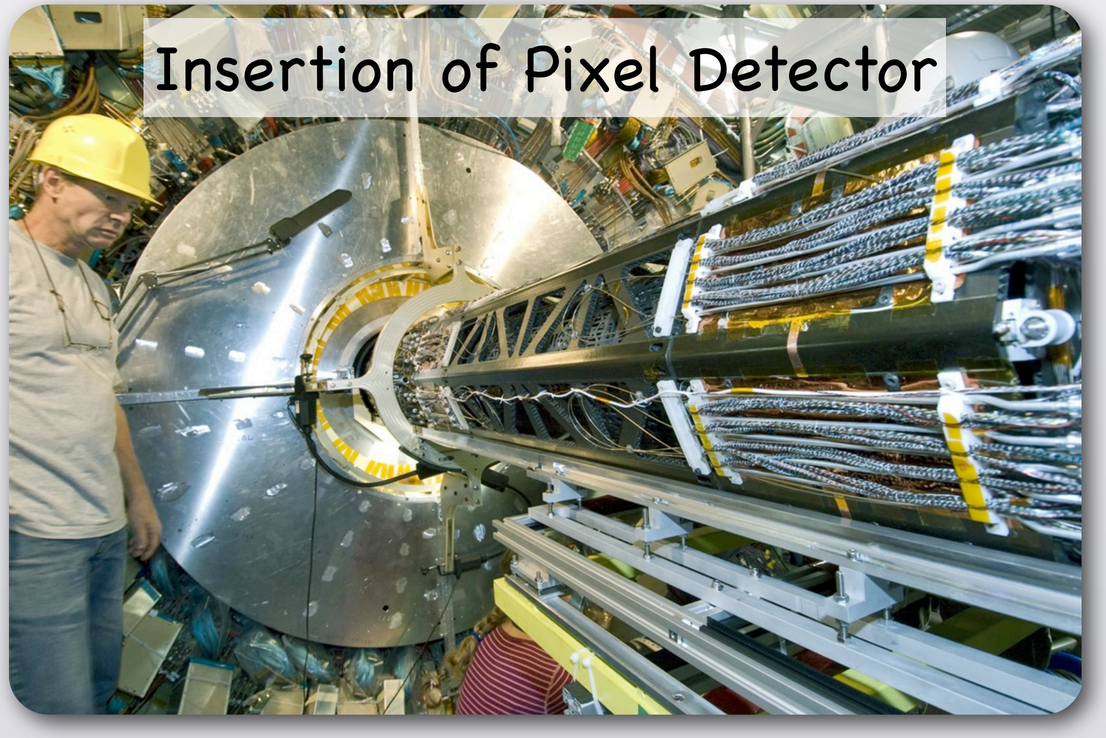
ATLAS Photo Gallery



Insertion of Calorimeter



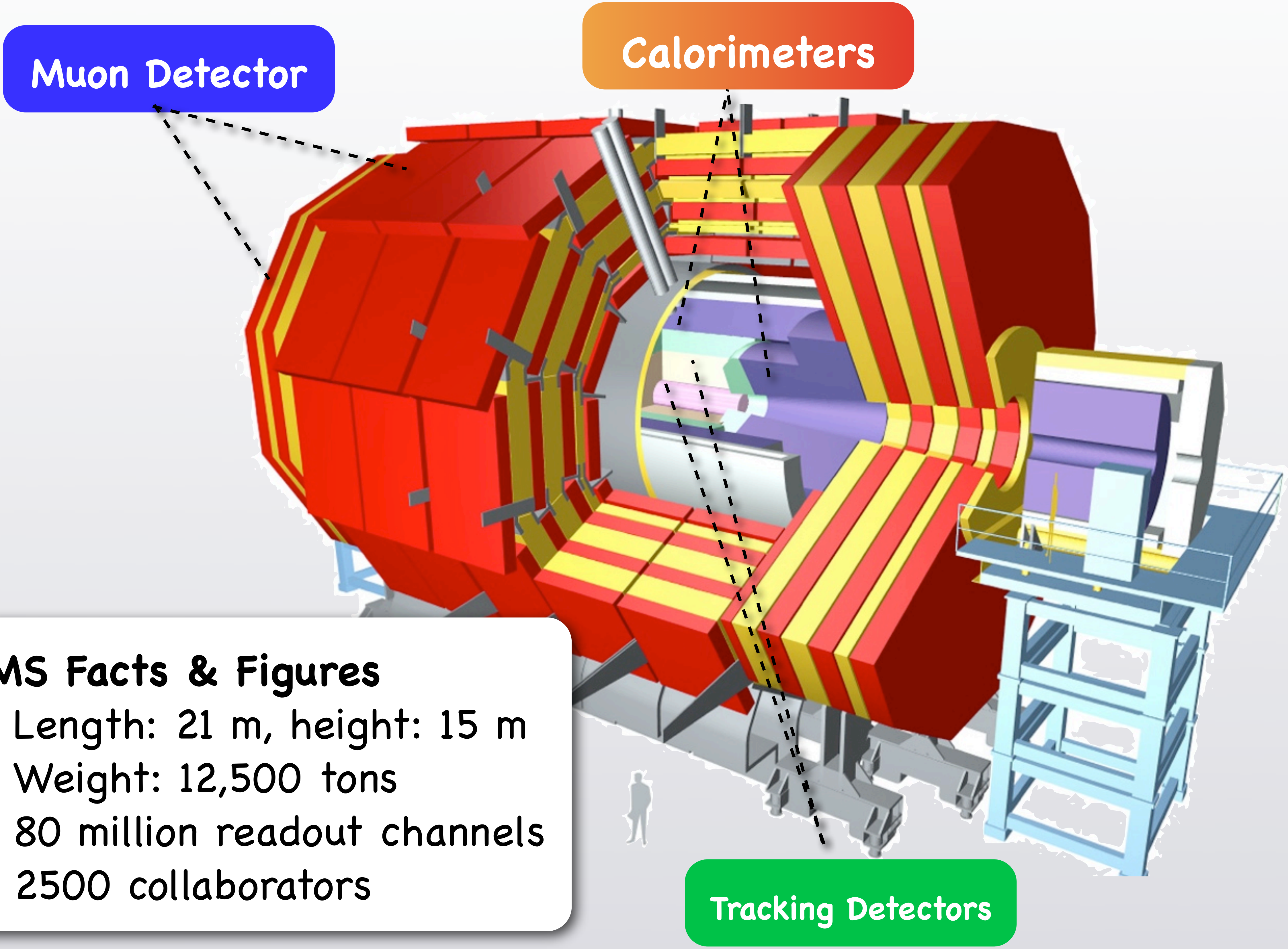
Calorimeter Barrel & Endcap



Insertion of Pixel Detector

[atlas.ch]

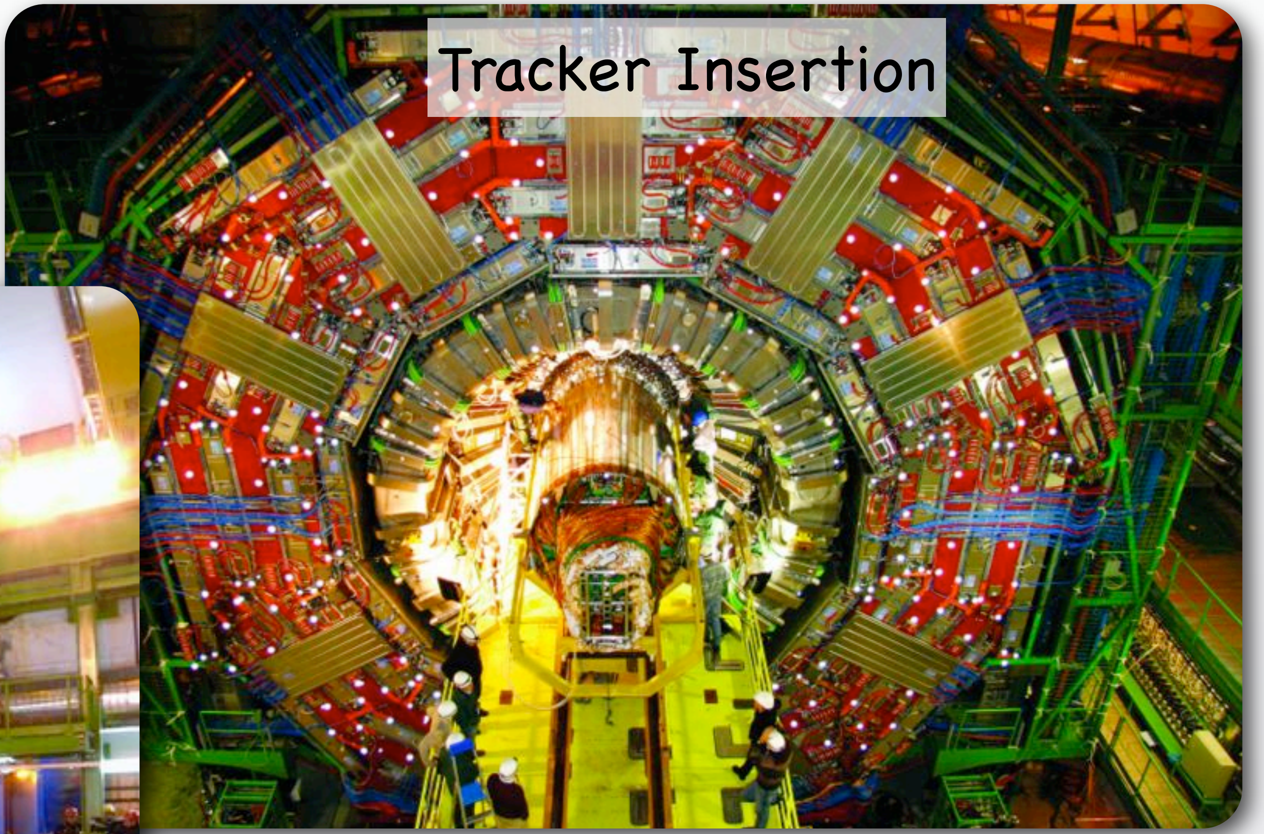
CMS

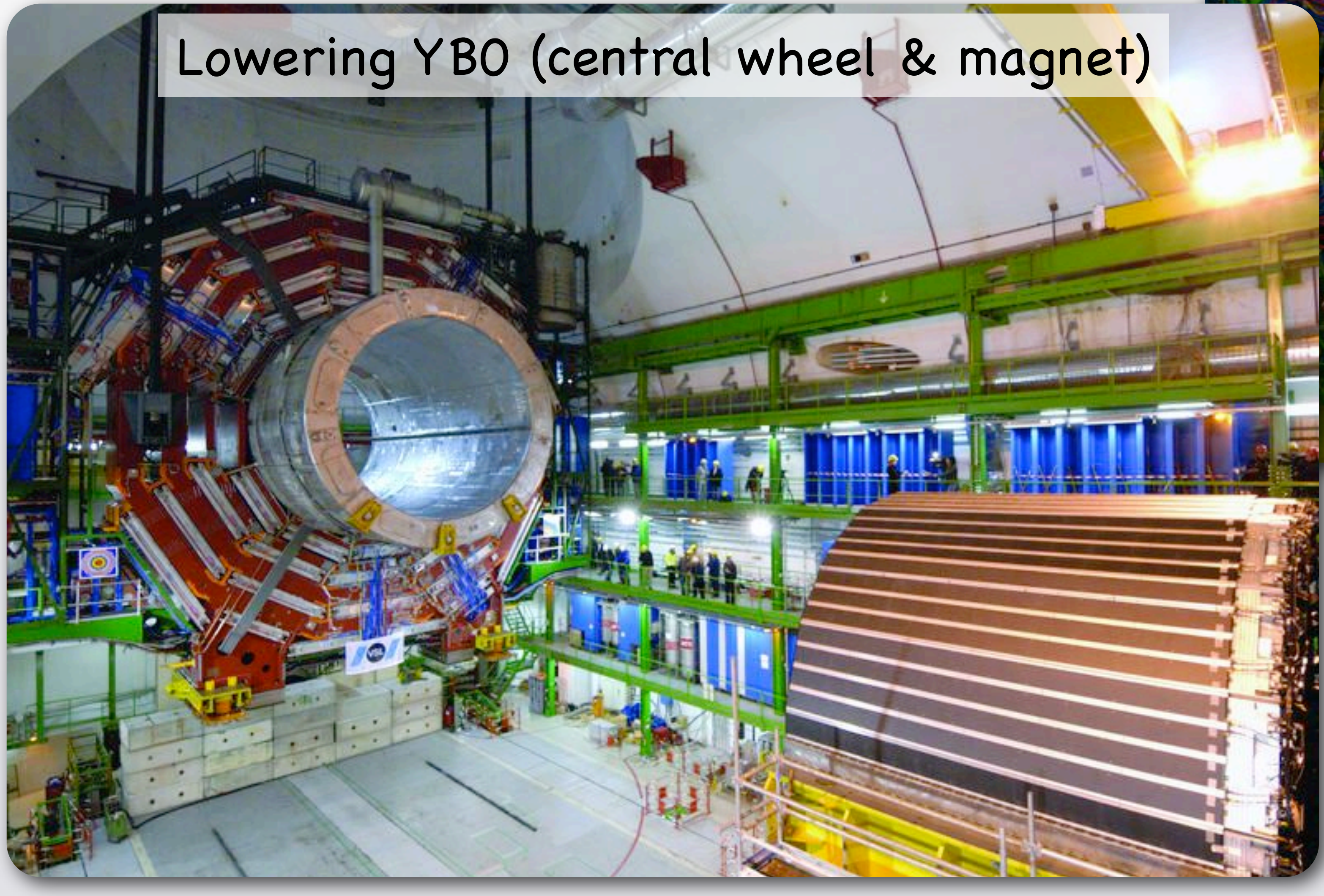


CMS Facts & Figures

- Length: 21 m, height: 15 m
- Weight: 12,500 tons
- 80 million readout channels
- 2500 collaborators

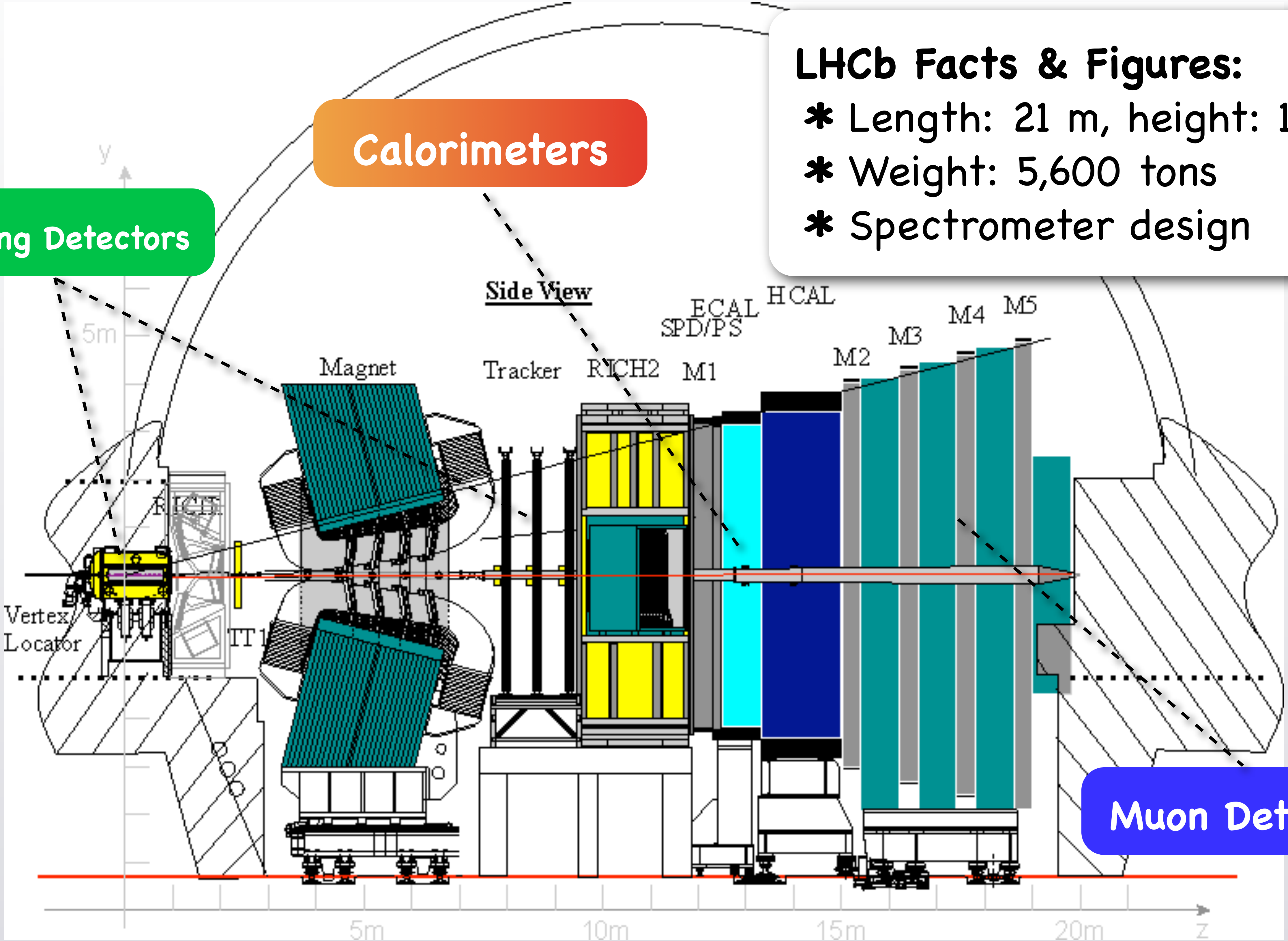
CMS Gallery


Tracker Insertion


Lowering YB0 (central wheel & magnet)


Off-detector Electronics

LHCb



Tracking Detectors

Calorimeters

Muon Detector

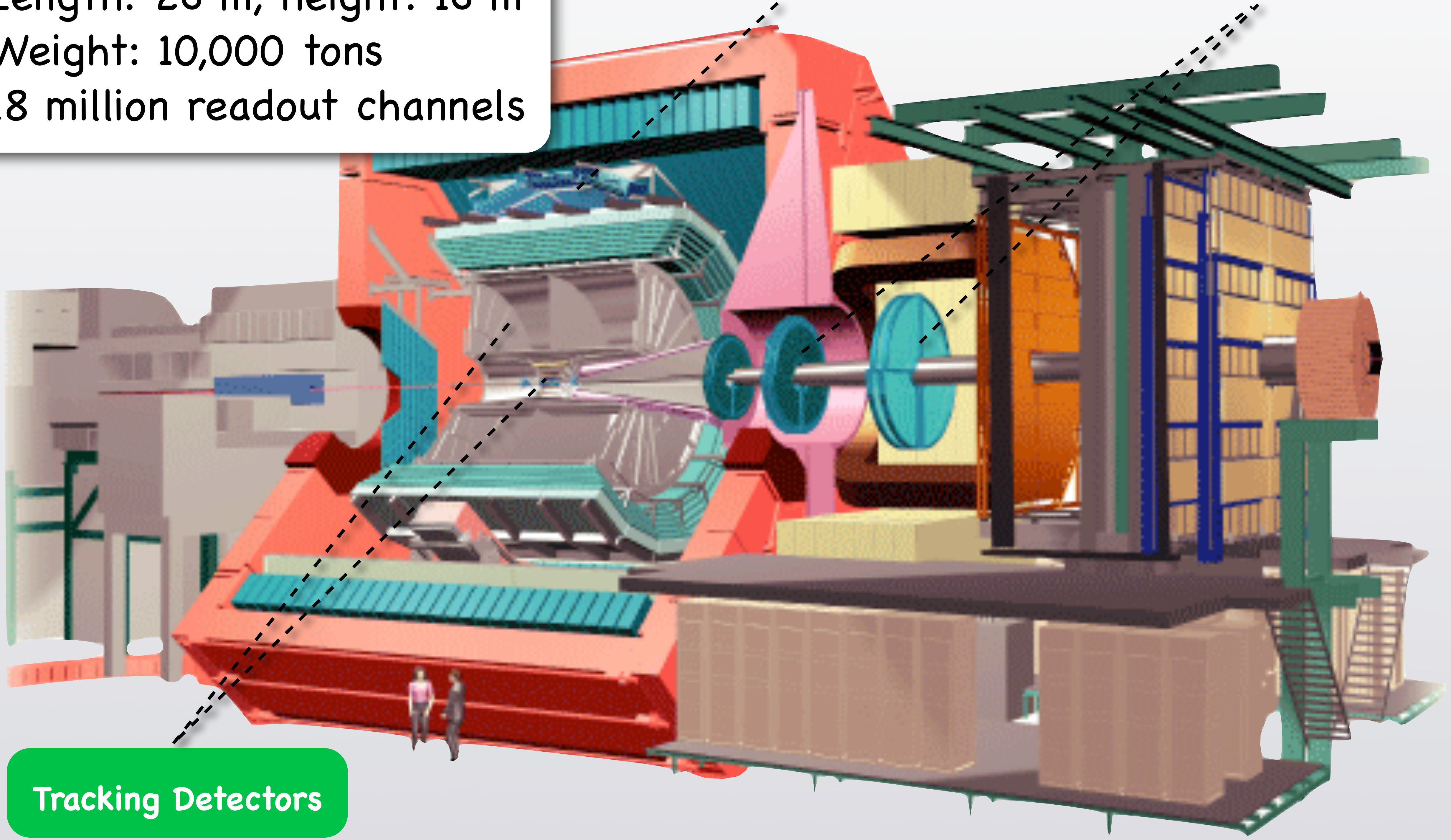
LHCb Facts & Figures:

- Length: 21 m, height: 10 m
- Weight: 5,600 tons
- Spectrometer design

ALICE

ALICE Facts & Figures

- Length: 26 m, height: 16 m
- Weight: 10,000 tons
- 18 million readout channels



Calorimeters

Muon Detector

Tracking Detectors

Chapter 4

Measuring Momentum & Energy

Photons

- **Photoelectric effect** (low energies): photon kicks electron out of atomic shell, photon gets absorbed
- **Compton effect** (medium energies): photon kicks electron out of atomic shell, changes wavelength
- **Electron-positron pair production** (high energies, > 10 MeV): photon converts into e^+e^- in Coulomb field of nucleus

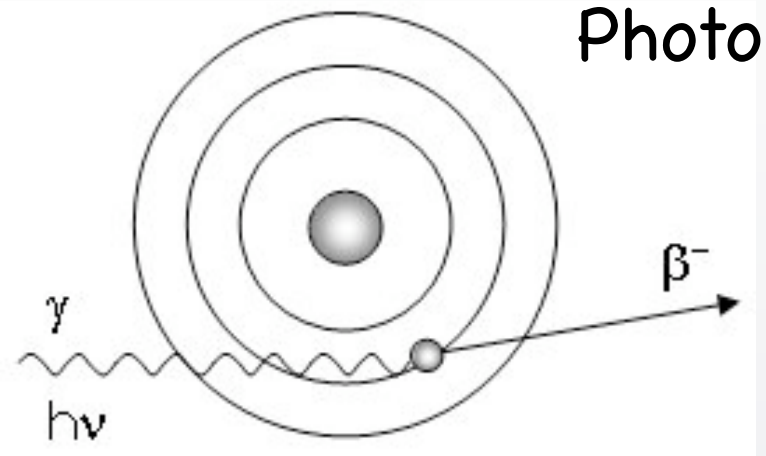
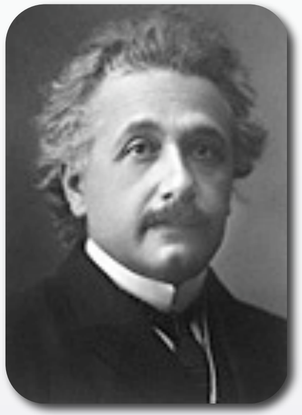
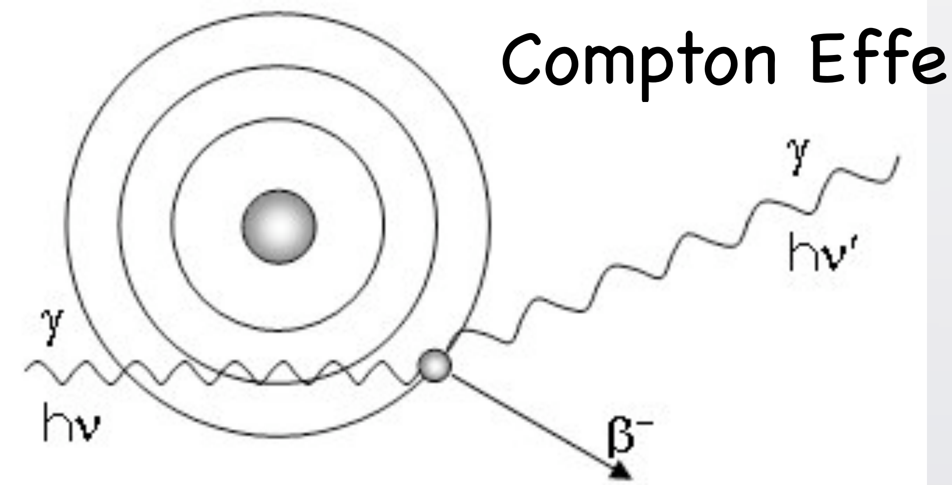


Photo Effect

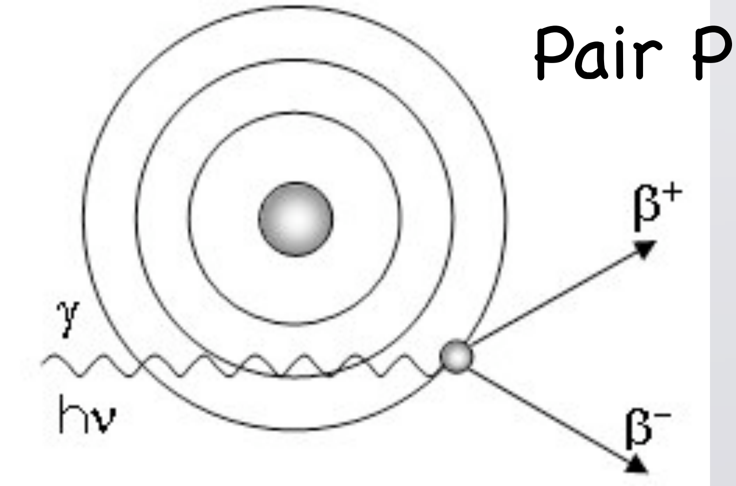


A. Einstein



Compton Effect

A.H. Compton



Pair Production

[www.sckcen.be]

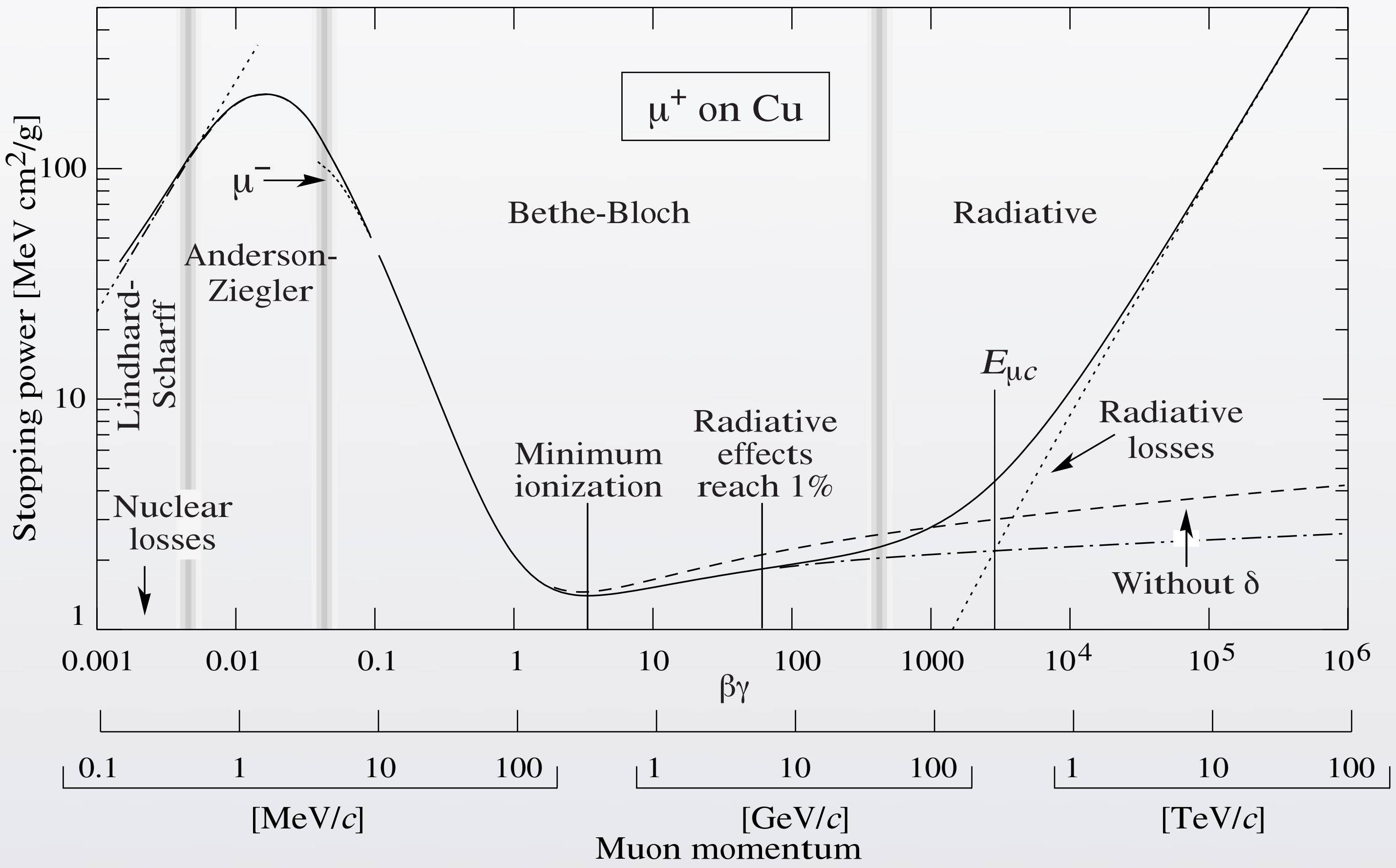
Charged Particles

- Semi-classical model ("Bethe-Bloch Formula")

H. Bethe

F. Bloch

- Charged particles lose energy via electromagnetic interactions with atoms: ionization
- Energy loss per unit length: -dE/dx
- dE/dx different for different particle types → particle ID

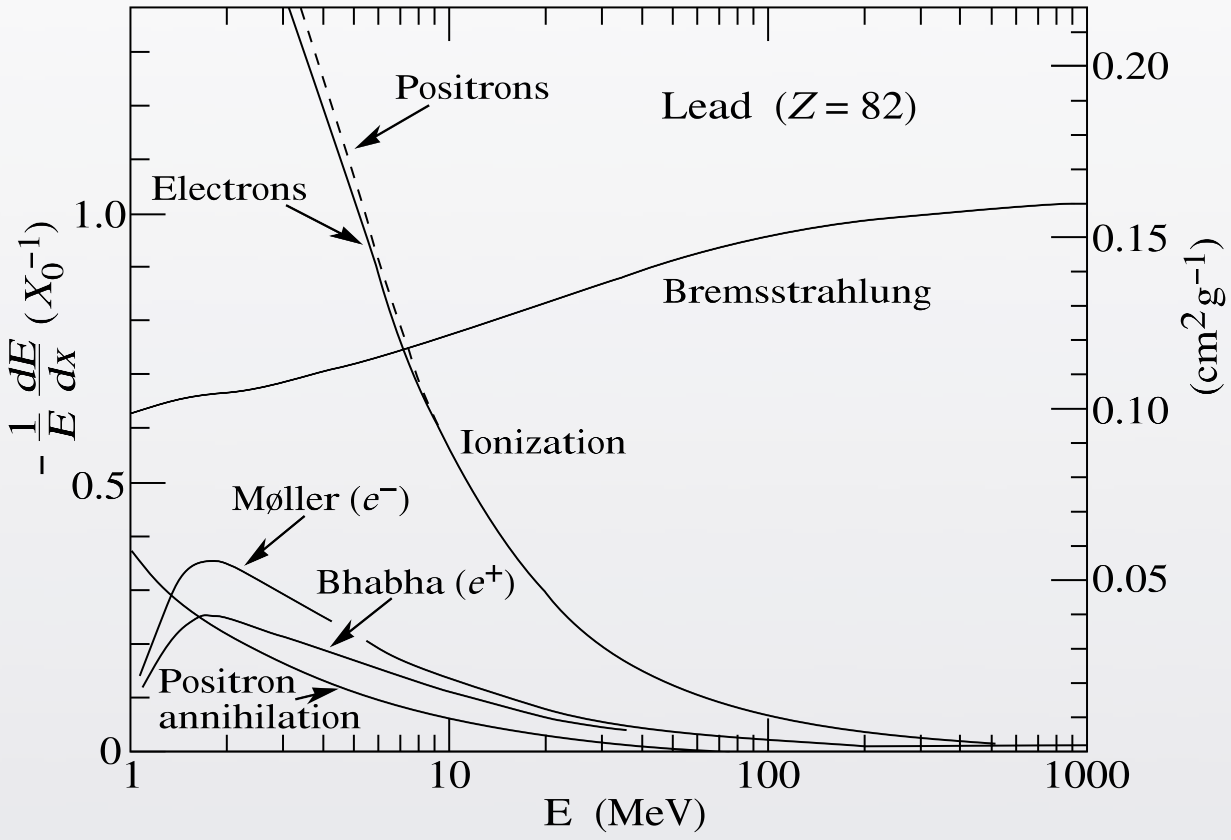


$$-\frac{\mathrm{d}E}{\mathrm{d}x} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

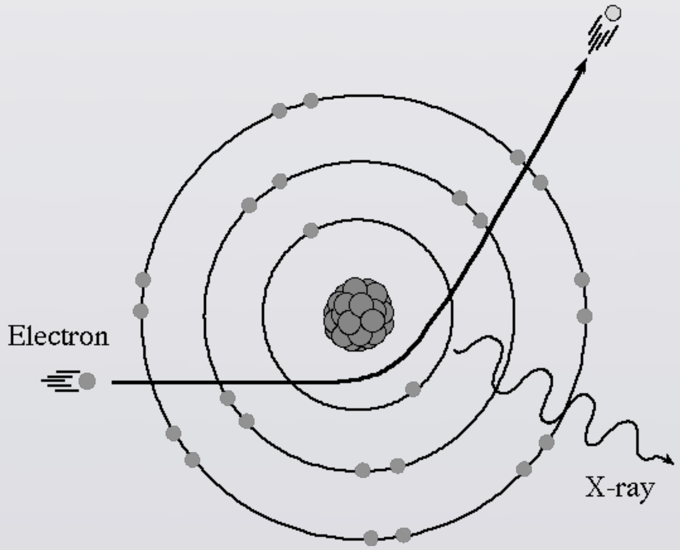
[Particle Data Group]

Electrons

- Electron energy loss: $-\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{E}{X_0}$
  - Small mass:
    m_e = (1/200) m_μ = (1/1800) m_p
  - Most important mechanism: Bremsstrahlung ($\propto 1/m^4$)
    → photon emission in Coulomb field of nucleus
  - Radiation length X_0 = characteristic scale (length × density) for electrons/photons:
    - Electron intensity down to 1/e
    - X_0 = 7/9 of mean free path for e^+e^- pair production from photons
    - X_0/ρ: water 36 cm, lead 0.56 cm

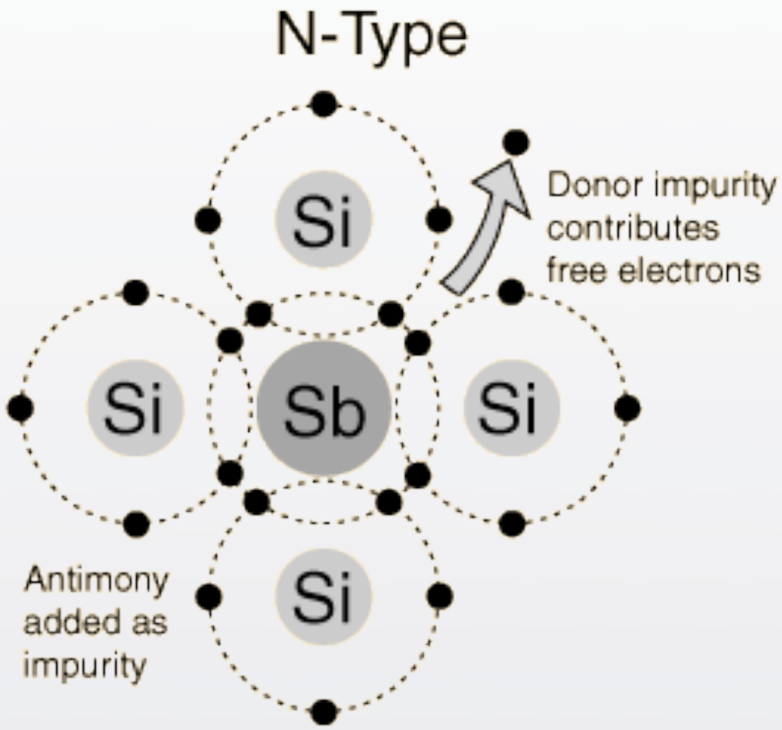


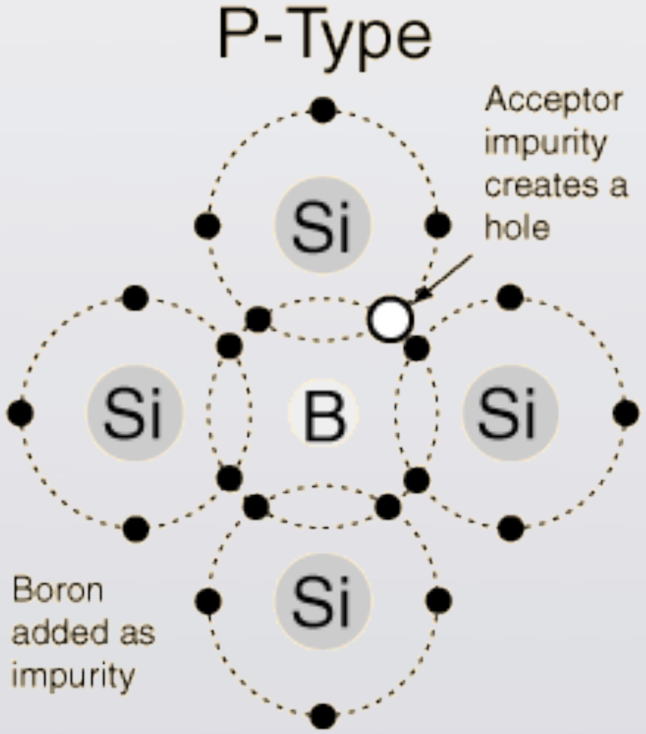
[Particle Data Group]



Doped Semiconductors

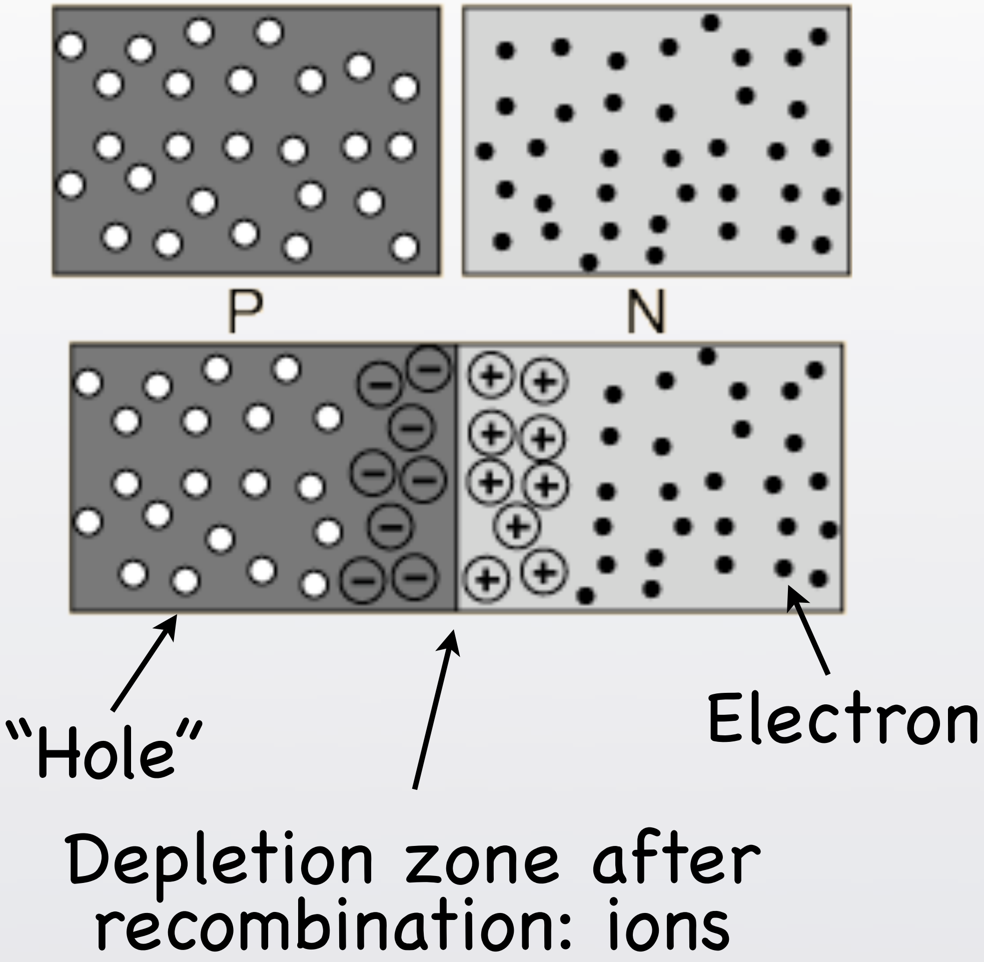
- Today's tracking detectors: based on semiconductors
- Typical semiconductors (e.g. silicon):
  - Crystal lattice with 4 valence electrons
  - Two kinds of charge carriers:
    - Negative – free electrons
    - Positive – electrons jump between free lattice positions ("holes")
- Modify properties by doping:
  - Add atoms with 5 valence electrons (P, As, Sb): "n-doped"
  - Add atoms with 3 valence electrons (B, Al, Ga, In): "p-doped"

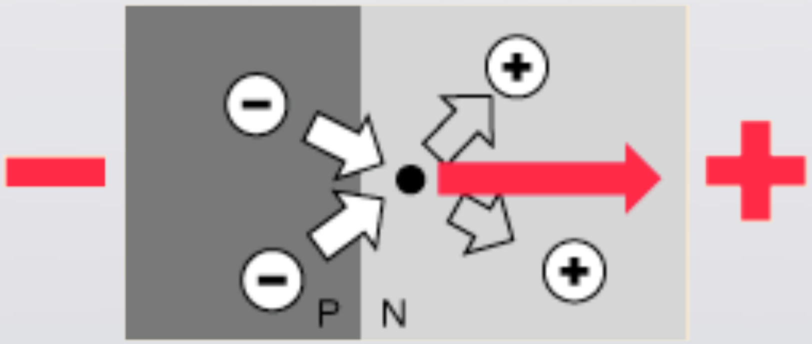




[hyperphysics.phy-astr.gsu.edu]

pn Junction & Depletion



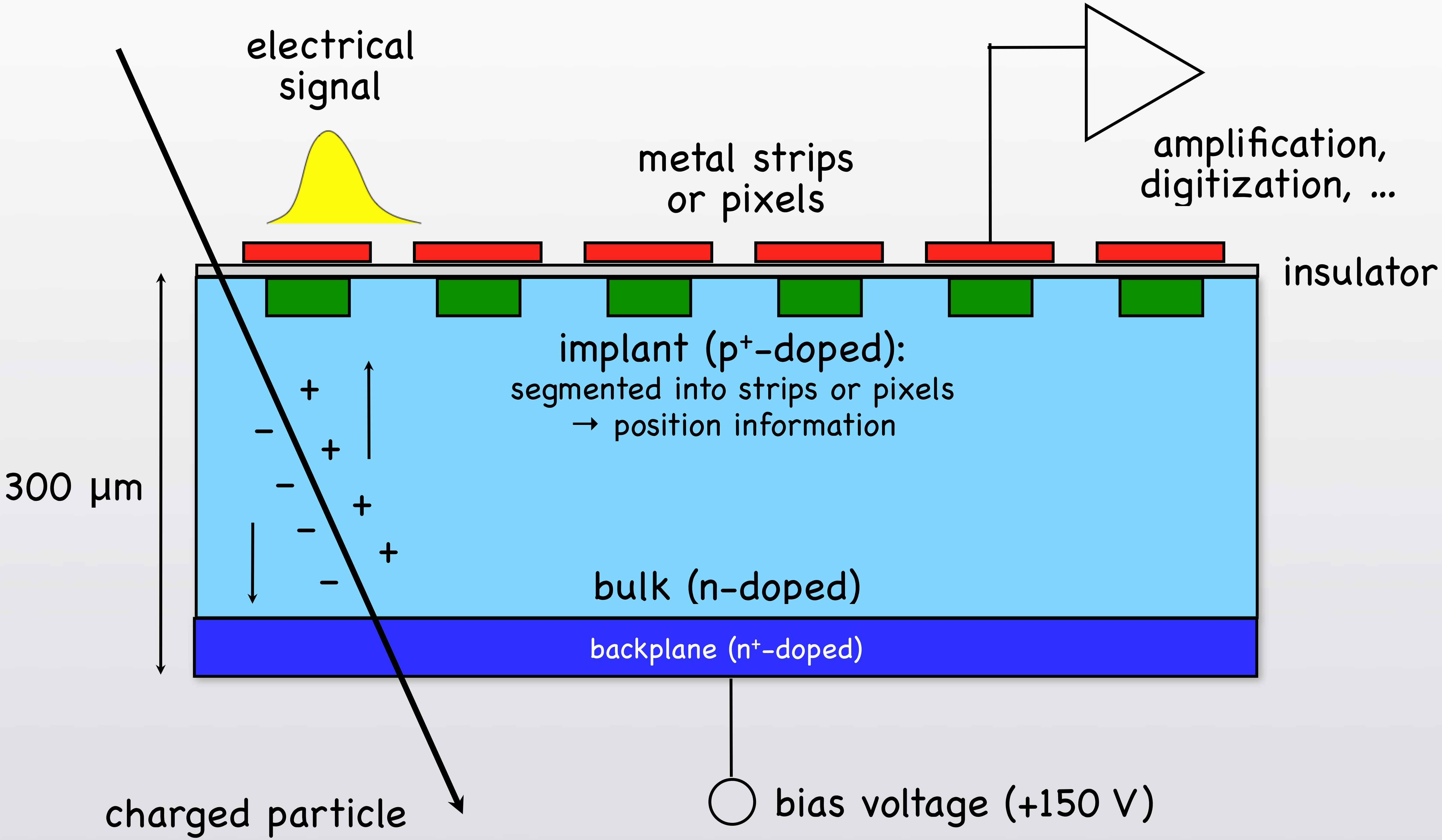


Bias Voltage

[hyperphysics.phy-astr.gsu.edu]

- Transition between p-doped and n-doped silicon
  - Charge carriers diffuse to other side and recombine
  - Formation of non-conducting zone ("depletion zone")
- Apply (reverse) bias voltage
  - Remove charge carriers → enlarge depletion zone
  - Charged particles ionize depletion zone → electrical signal

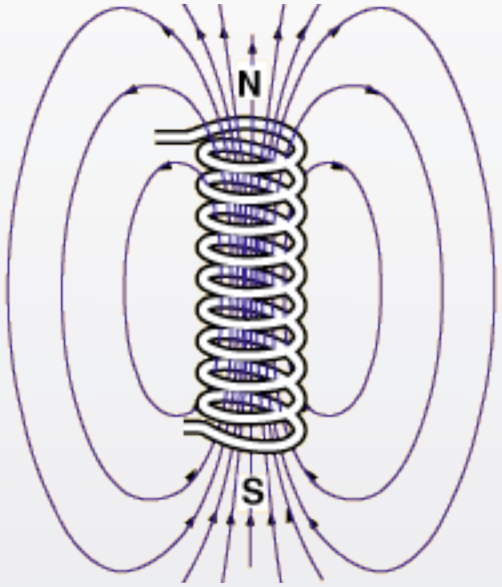
Silicon Detectors



Momentum Measurement

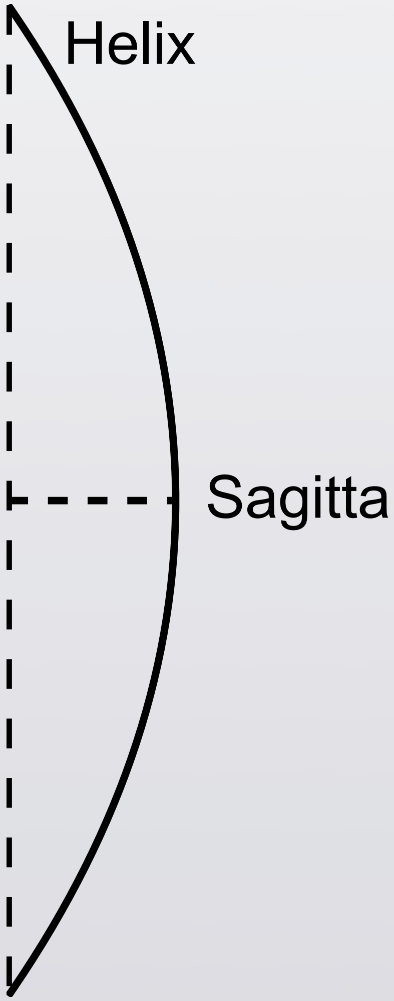
- Deflection of charged particles in magnetic field (Lorentz force)

$$e\vec{v} \times \vec{B} = \frac{mv^2}{r} \cdot \frac{\vec{r}}{r}$$



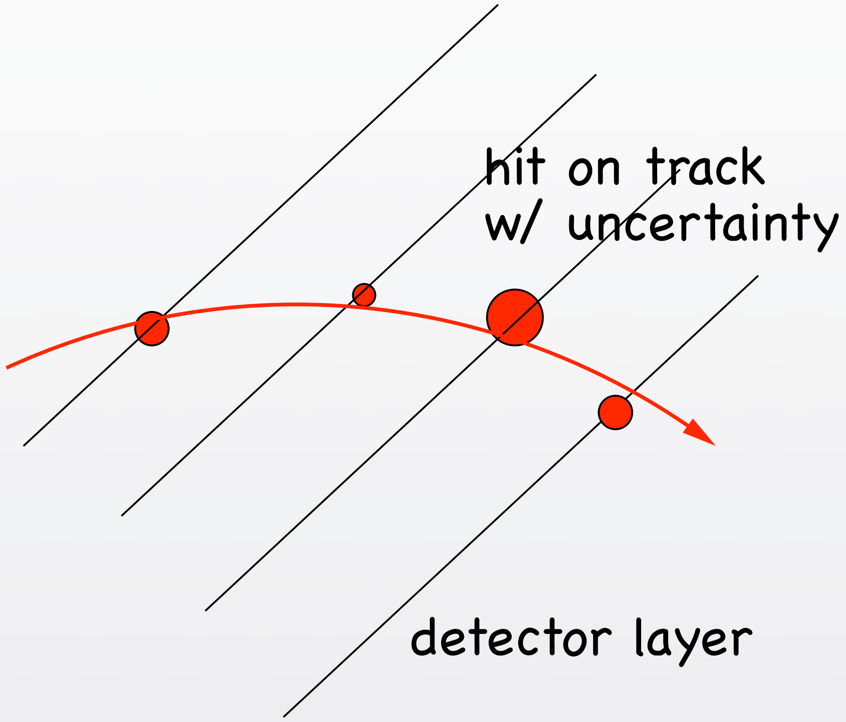
- Typical collider detector magnets
  - Solenoid magnet (superconducting)
  - ATLAS: toroid magnet in muon system
- Homogeneous magnetic field: particle trajectories are helices
- Momentum transverse to B field proportional to radius of curvature

$$p_{\mathrm{T}}[\mathrm{GeV}/c] = 0.3\,B[\mathrm{T}] \cdot r[\mathrm{m}]$$



Charged Particle Tracking

- Multi-layer detector
- Electrical signals in each layer → hits
- Track fit:
  - Pattern recognition: assign hits to track
  - Fit helix to hits
- Vertex fit: Do tracks come from common origin ("vertex")?

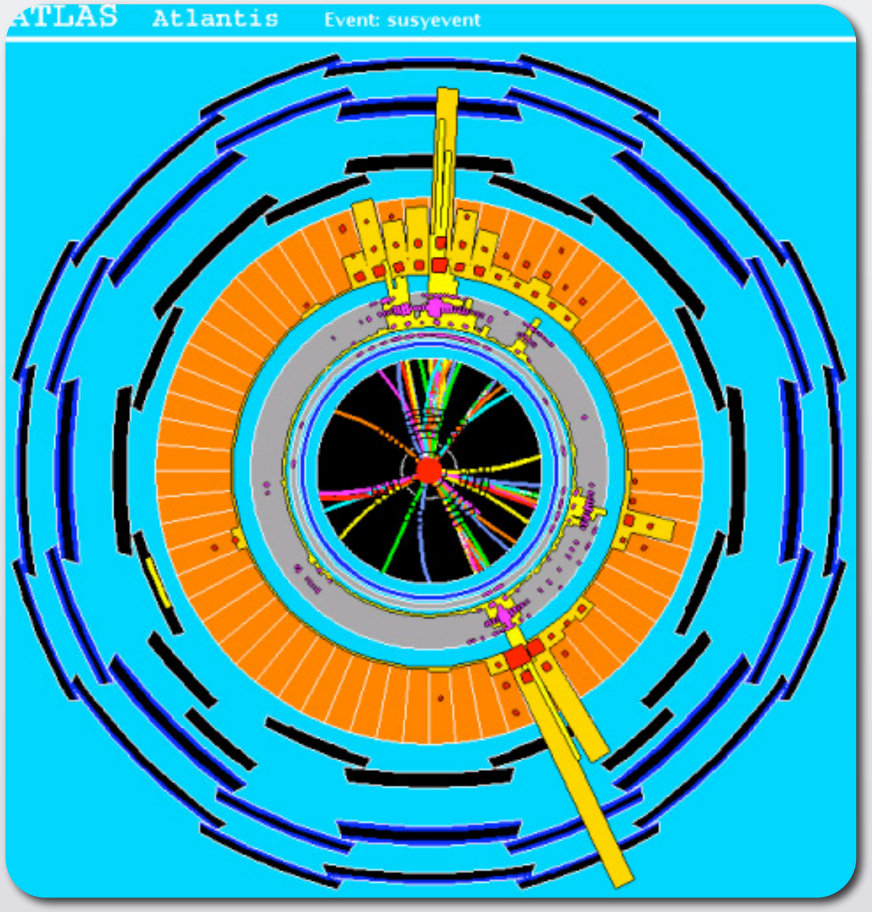


Track fit: minimize

$$\chi^2 = \sum_i \frac{(x_i - \overline{x})^2}{\sigma_i^2}$$

x_i measurement

σ_i uncertainty



Simulated decay of a supersymmetric particle (side view)

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    assign l
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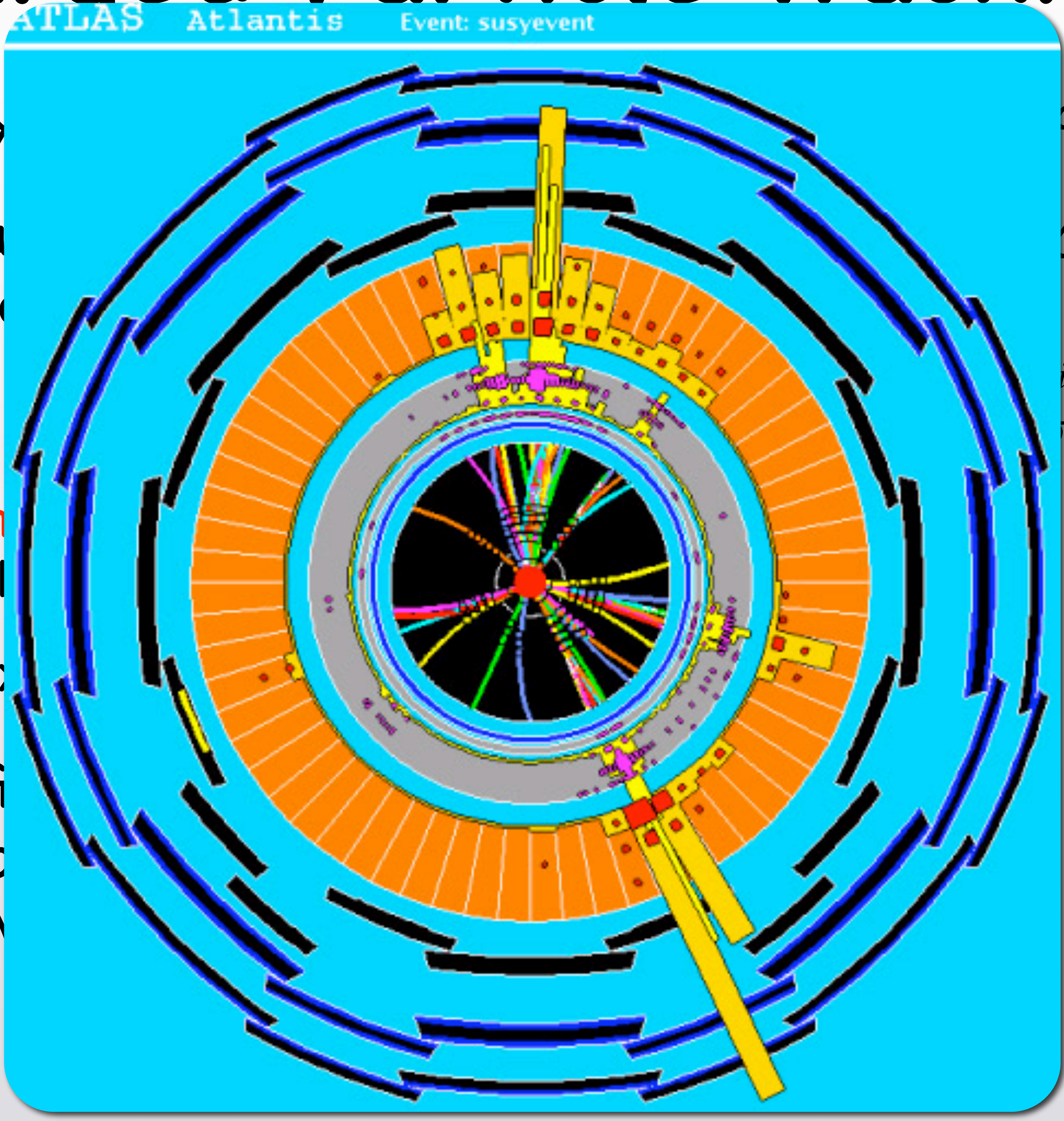

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Simulated decay of
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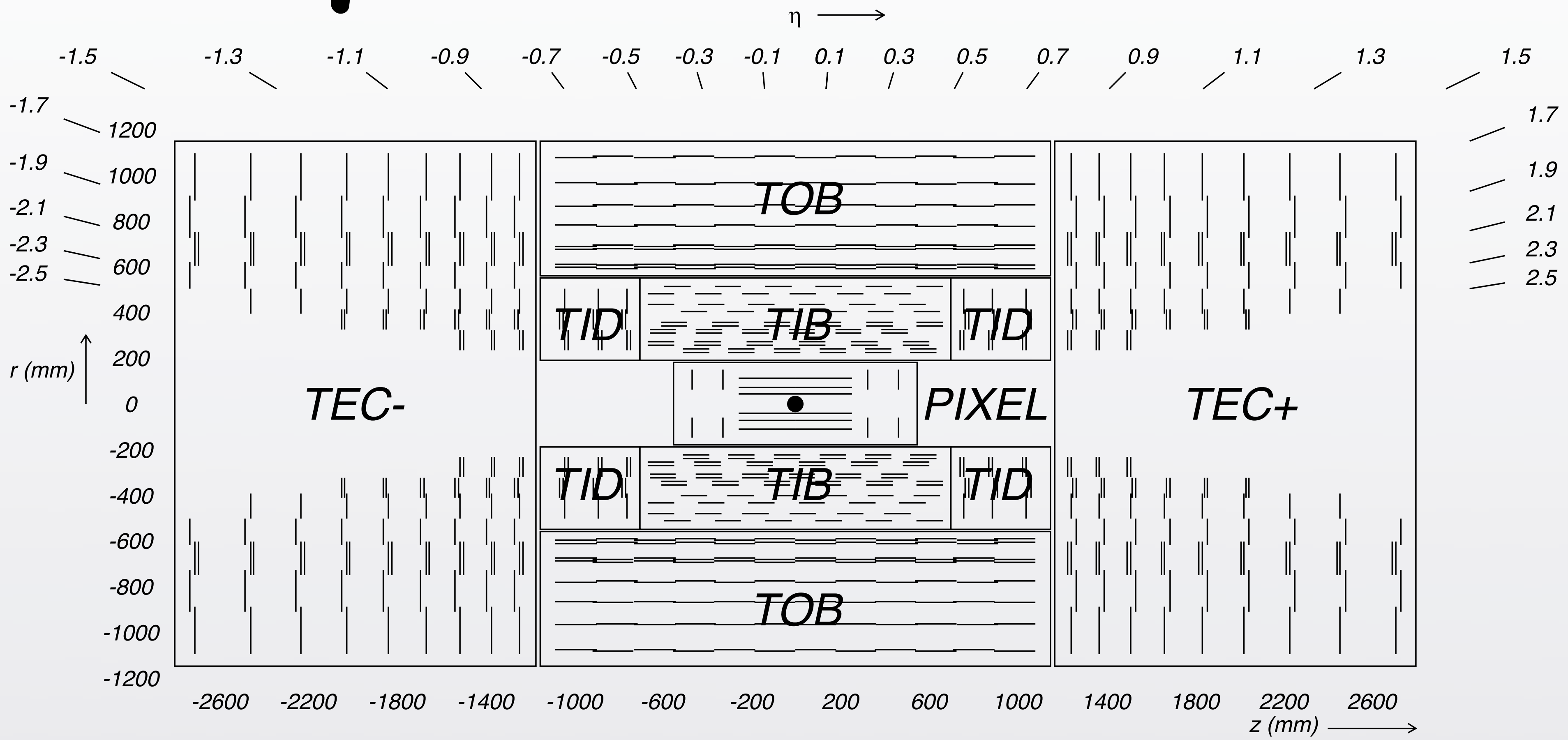
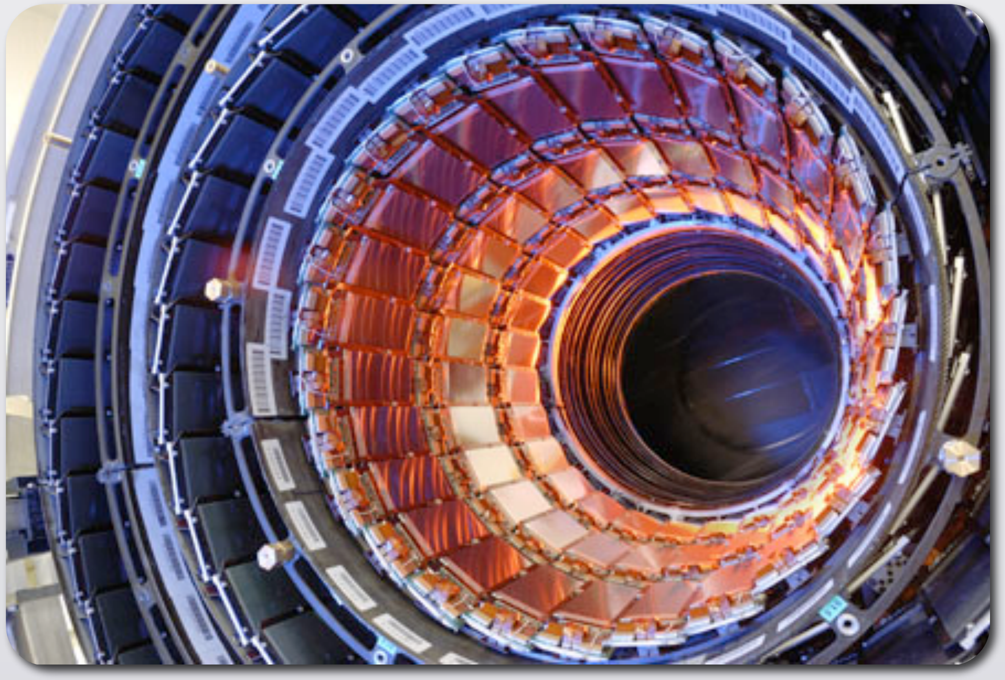
Example: CMS Tracker



- All-silicon tracker: more than 200 m^2 sensitive area, more than 60 million channels
- Inner layers: pixel detectors
  → 15–30 μm (3D) hit resolution
- Outer layers: strip detectors
  → 8–64 μm (2D) hit resolution



CMS Tracker Inner Barrel

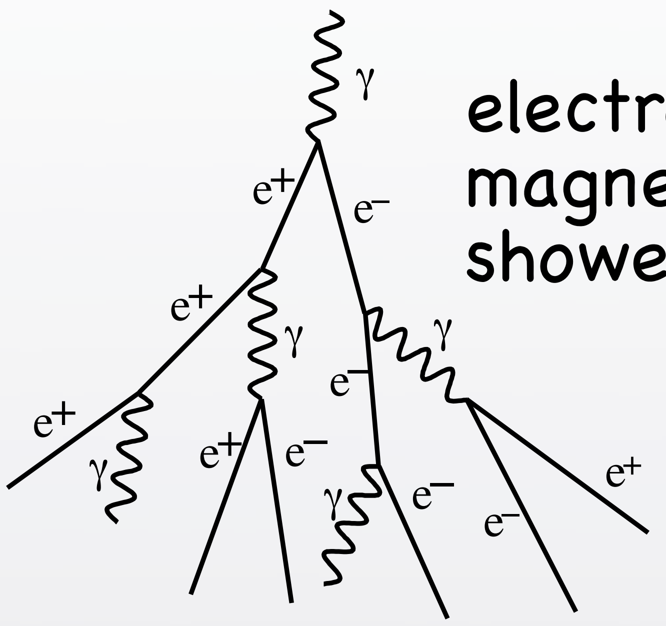
Calorimeters

- Historical name: calorimeter = "heat-meter"
- Particle physics: calorimeter = "energy-meter"
- Basic idea: measure energy of a particle via its absorption in heavy material

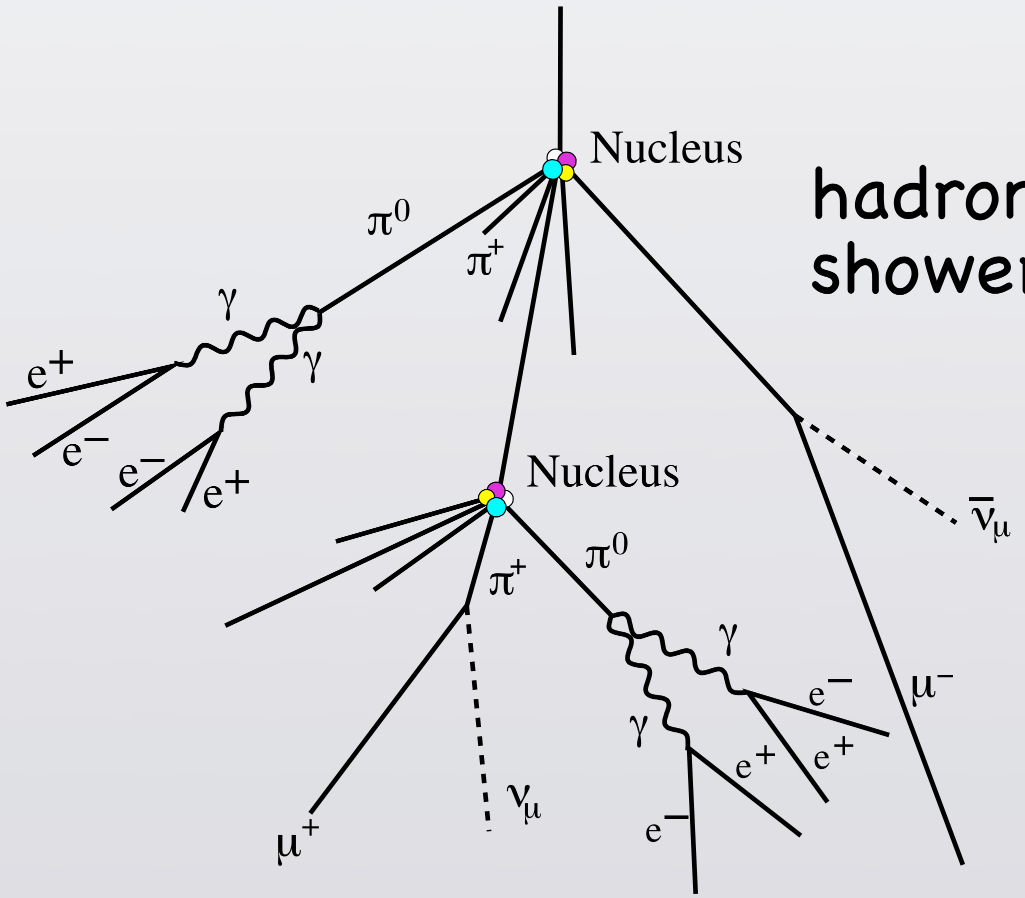
"Look, our new total absorption calorimeter!"

Particle Showers

- Interaction with matter in calorimeter: shower of new particles
- Distinguish different interactions
  - Electromagnetic calorimeter
  - hadronic calorimeter
- Total length of all tracks in the shower proportional to energy of primary particle
- Particle ID via shower shape



electro-magnetic shower



hadronic shower

Calorimeter Types

- Homogeneous calorimeters:
  - Crystals, e.g. CsI(Tl), $PbWO_4$
  - Liquid noble gases, e.g. argon
- Sampling calorimeters:
  - Metal–scintillator: lead, iron, uranium + plastic scintillator
  - Metall–liquid noble gases: lead, copper, brass + LAr
- Calorimeter resolution:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} + b + \frac{c}{E}$$

$PbWO_4$: used for electro-magnetic calorimeter in CMS

Segment of liquid argon calorimeter (ATLAS)

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Fluctuations

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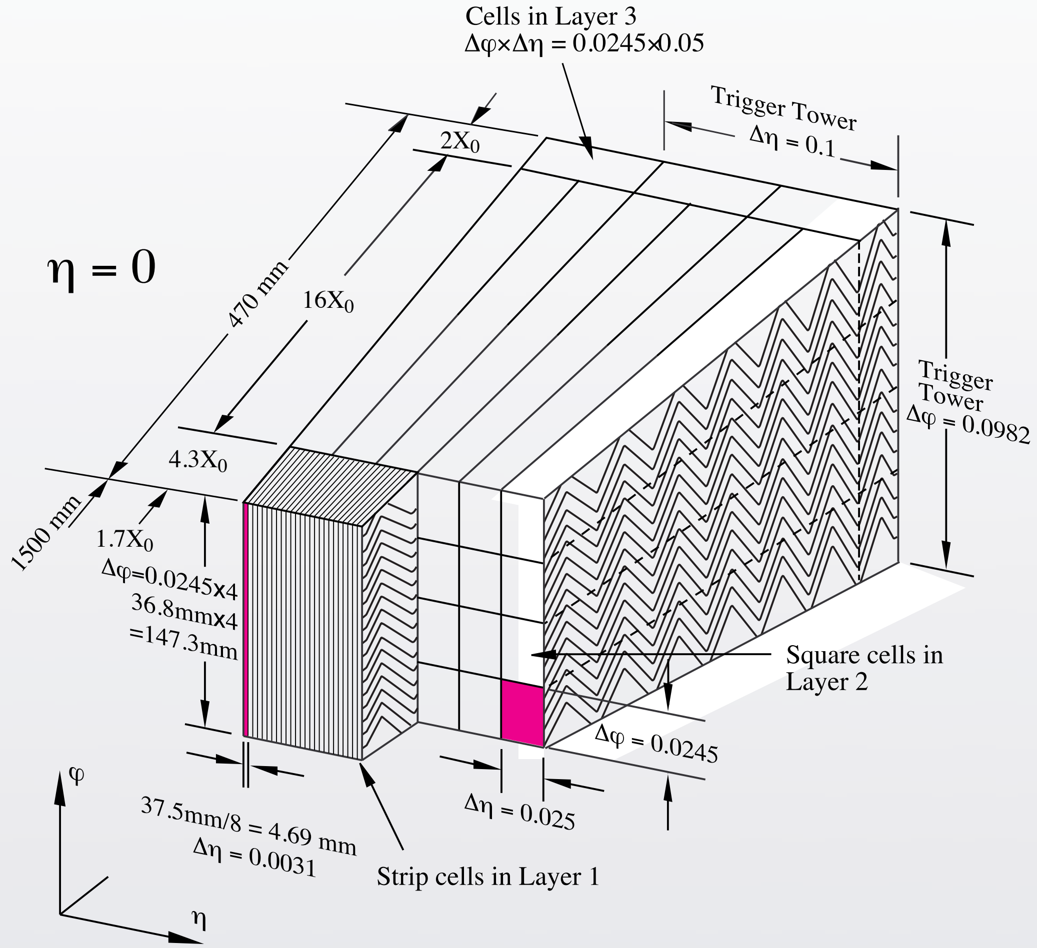
Fluctuations Calibration Noise

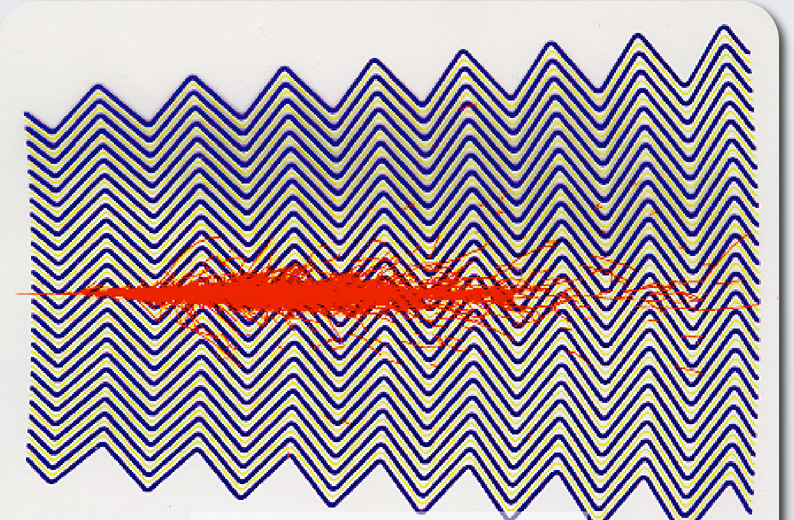
$PbWO_4$: used for electromagnetic calorimeter in CMS

Segment of liquid argon calorimeter (ATLAS)

ATLAS LAr Calorimeter

- Liquid argon (LAr) calorimeter
  - Particle ionizes ultra-pure LAr (operating at 80 K, liquid N_2)
  - Ions drift to electrodes (voltage: 2000 V) → electrical signal
- ATLAS electromagnetic calorimeter
  - Absorber material: lead plates
  - "Accordion" structure: fast readout, no gaps in coverage





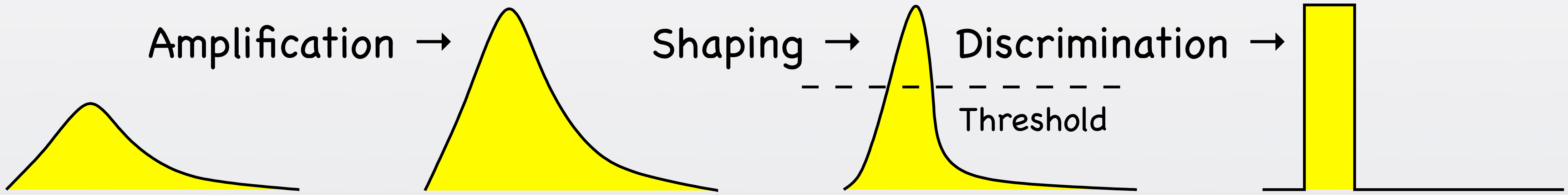
Simulated shower

Chapter 5

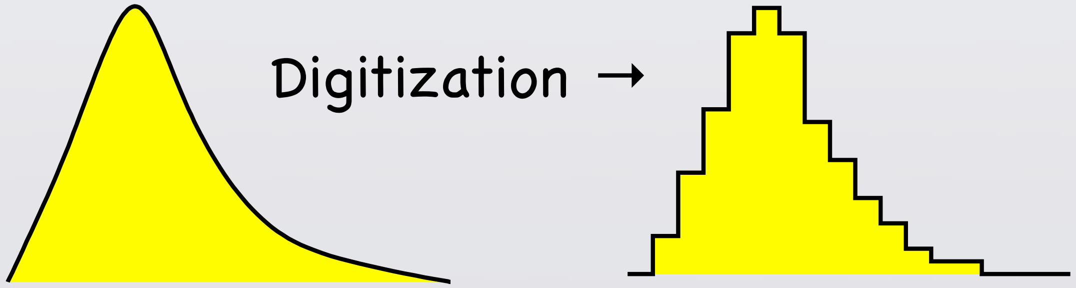
From Raw Data to Physics Results

Frontend Electronics

- Detector output = small analog signals
  → first processing close to detector (at "frontend")
- Example 1: ASD = amplifier-shaper-discriminator



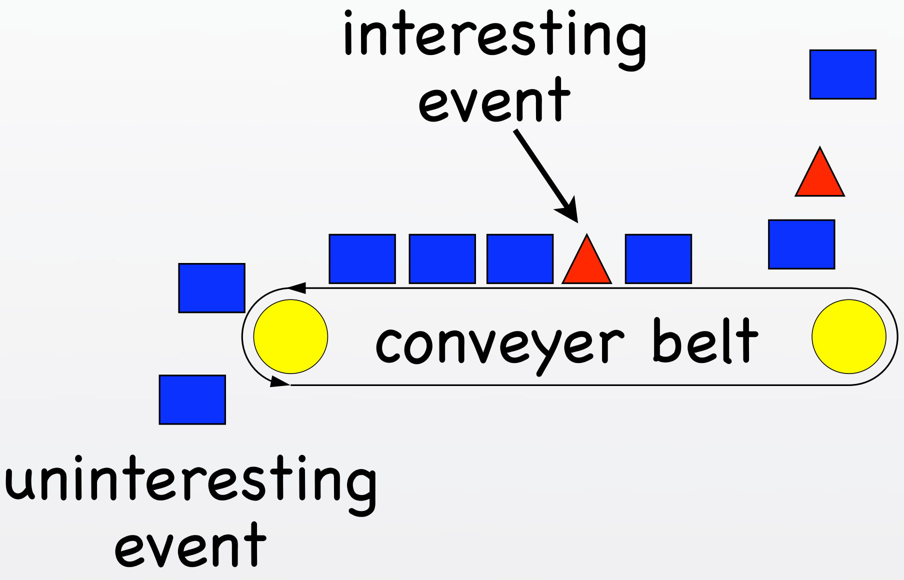
- Example 2: ADC = analog-to-digital converter



- Data transmission: optical fibers (very little attenuation, not influenced by electromagnetic interference)

Online Data Processing

- Challenge: data rate of
  1 billion collisions/second
  - Impossible to store/process with current technology
  - Luckily: > 99.999999% of all collisions "uninteresting"
    → fast selection of interesting collisions



Online Data Processing

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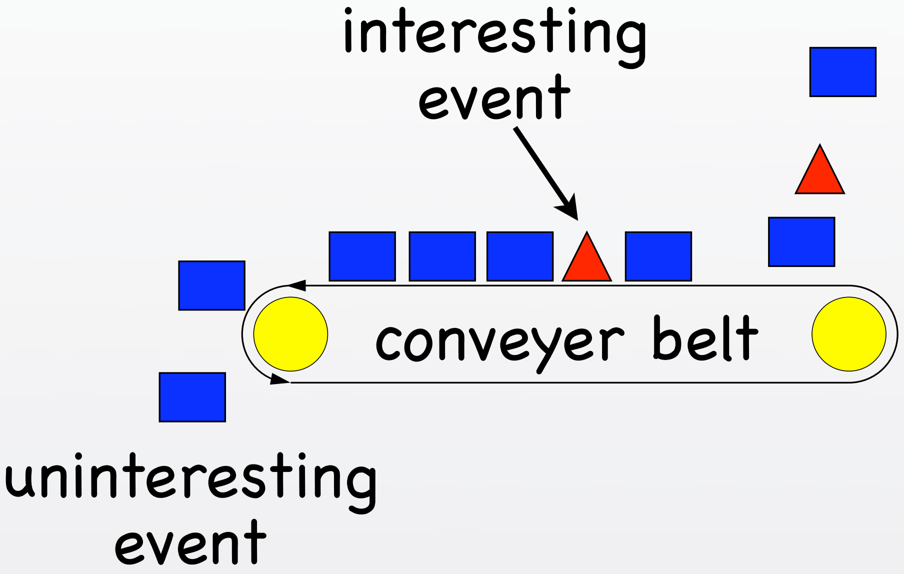
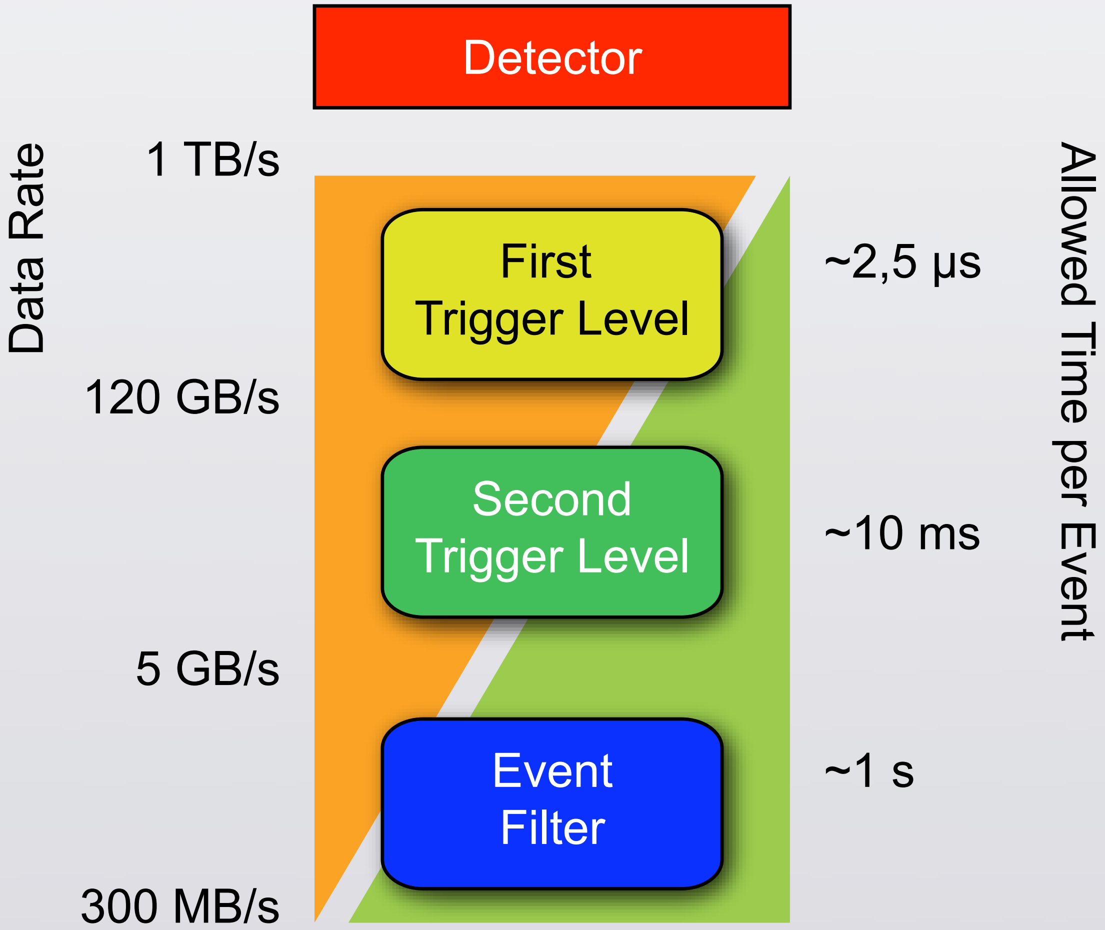
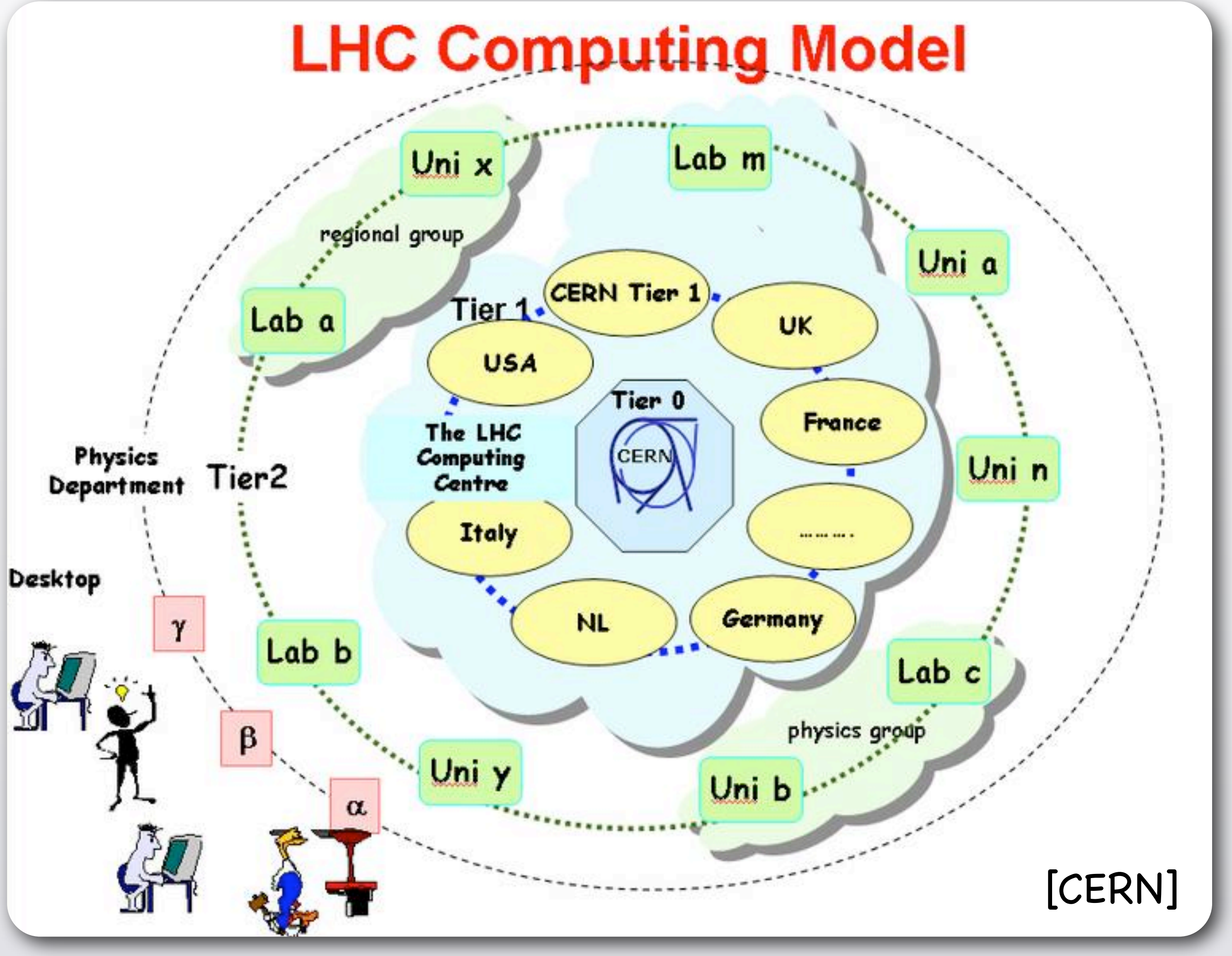
  - Impossible to store/process with current technology
  - Luckily: > 99.999999% of all collisions "uninteresting" → fast selection of interesting collisions
- Solution: trigger = multi-level online data filter
  - Fast pre-selection of simple signals (custom electronics)
  - Process pre-selected events on computer farm (more information)





Grid Computing

- Challenge:
  - Data rate: 15 PBytes/year from all LHC experiments
  - Processing power: about 100,000 computers
- Solution: grid computing
  - Distribute computing power and storage worldwide
  - Get the application to the data
  - LHC: "multi-tier" approach



[CERN]

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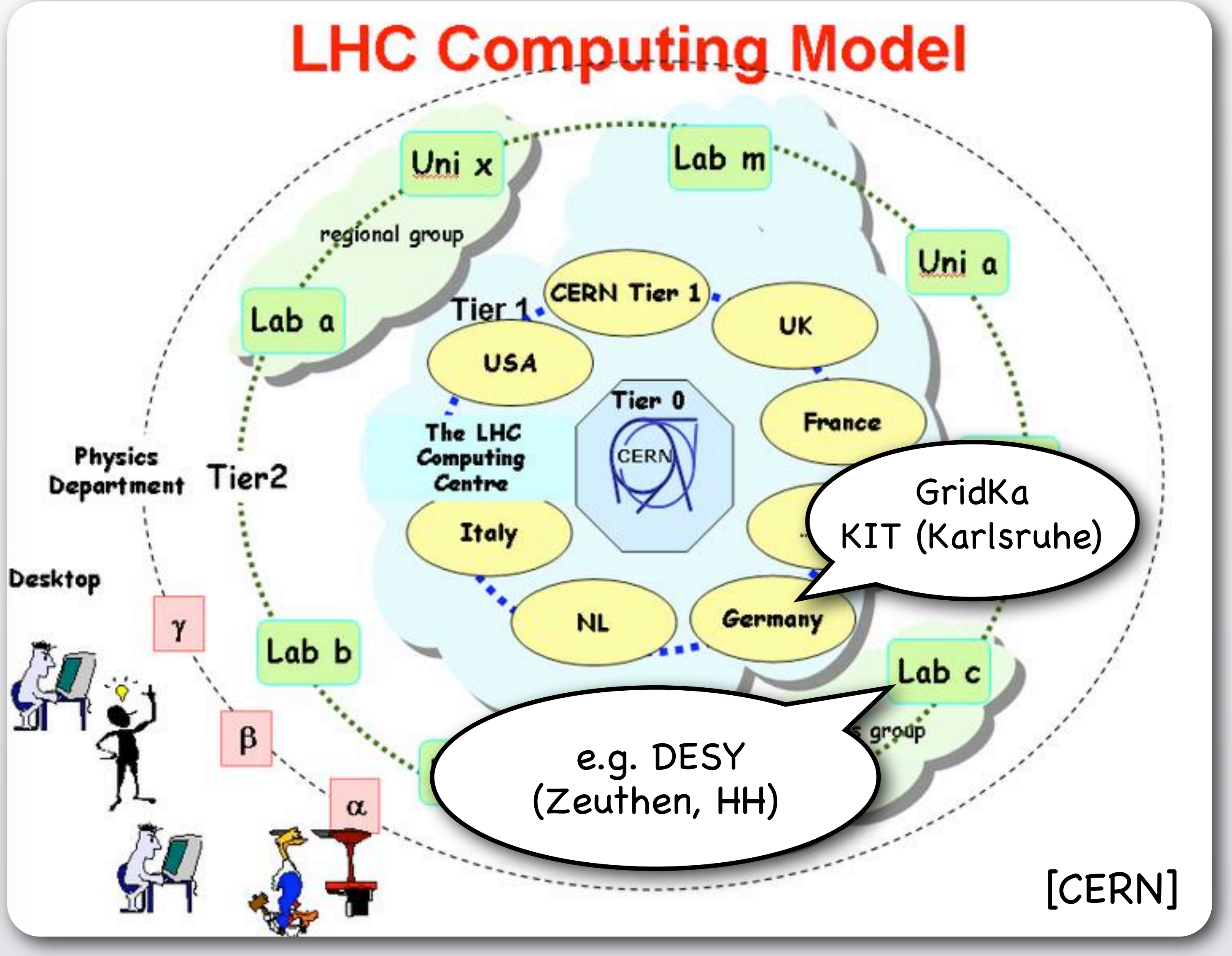


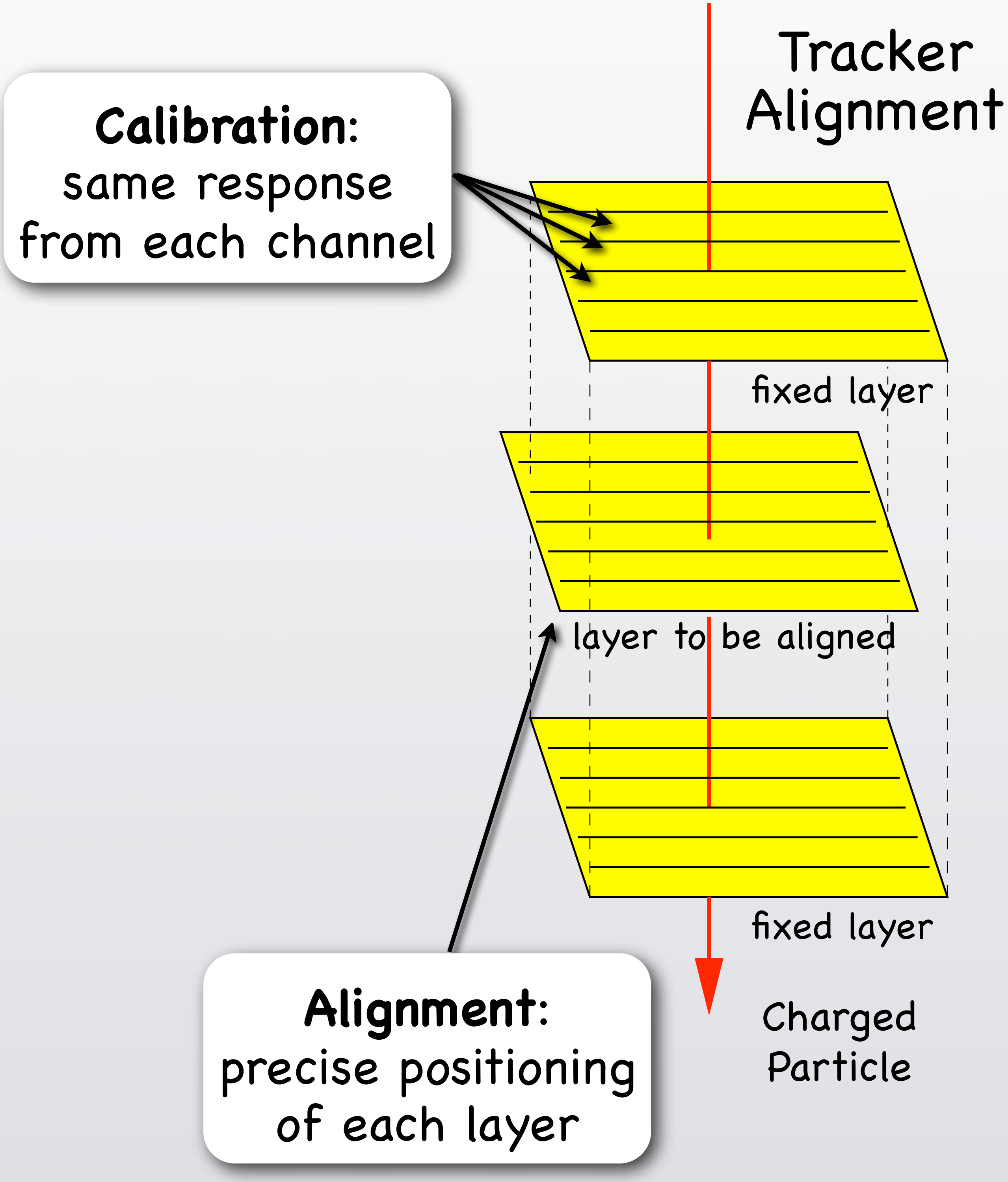
GridKa KIT (Karlsruhe)

e.g. DESY (Zeuthen, HH)

[CERN]

Calibration & Alignment

- Calibration:
  - Detector response may very from channel to channel and in time
  - Goal: uniform response
- Alignment:
  - Physics requires resolutions of 10–50 µm → precise knowledge of detector position
  - Coarse alignment: survey
  - Fine alignment: data – charged particle tracks

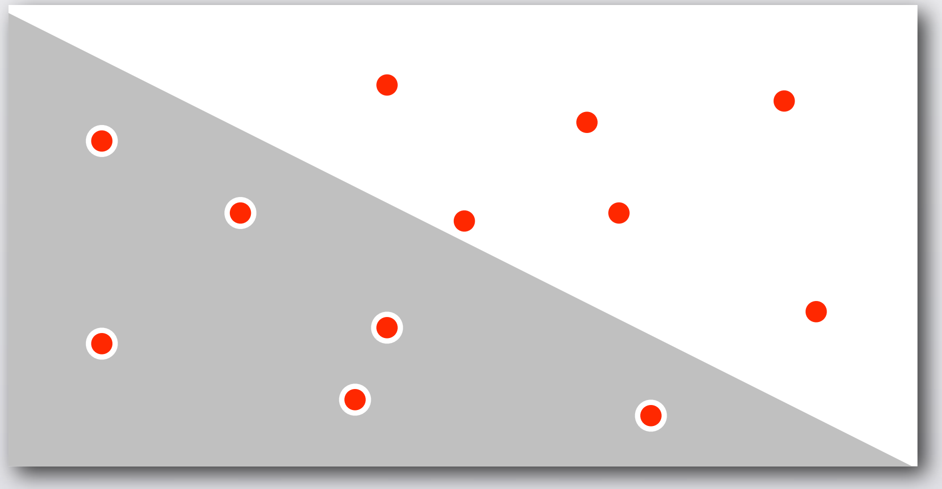


Monte Carlo Simulations

- Monte Carlo (MC) simulations: numerical methods based on random numbers

> "It's called 'Monte Carlo' because you're playing on someone else's money." [B. Jacobsen, Berkeley]

- Example: MC integration



Integral proportional to #random points under the curve

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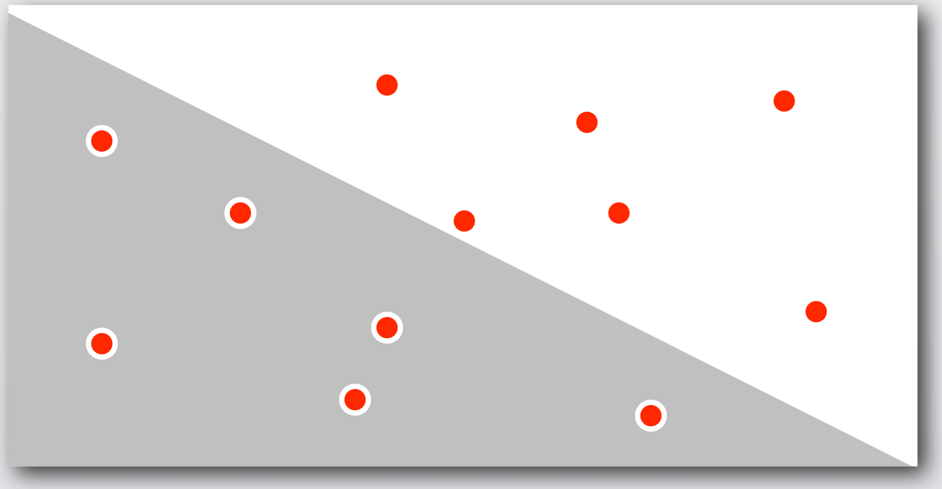

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MC simulations in particle physics

Event Generator:
simulate physics process
(quantum mechanics: probabilities!)

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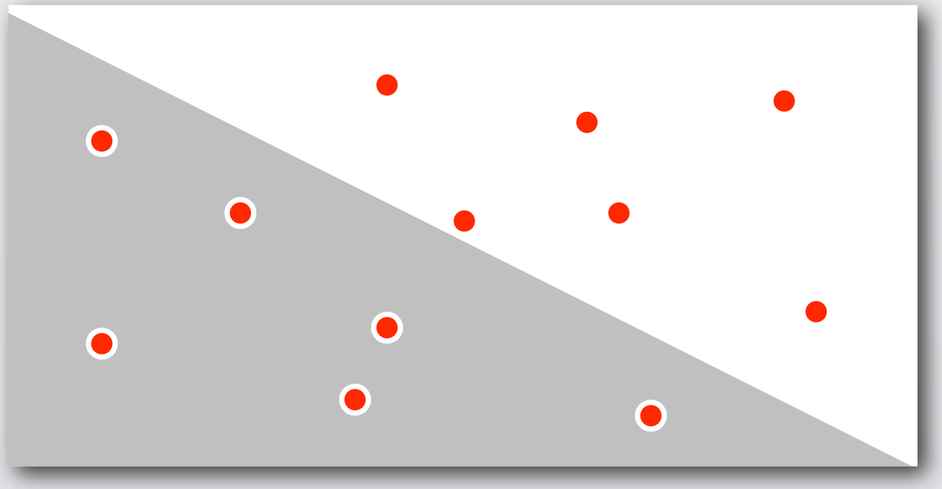

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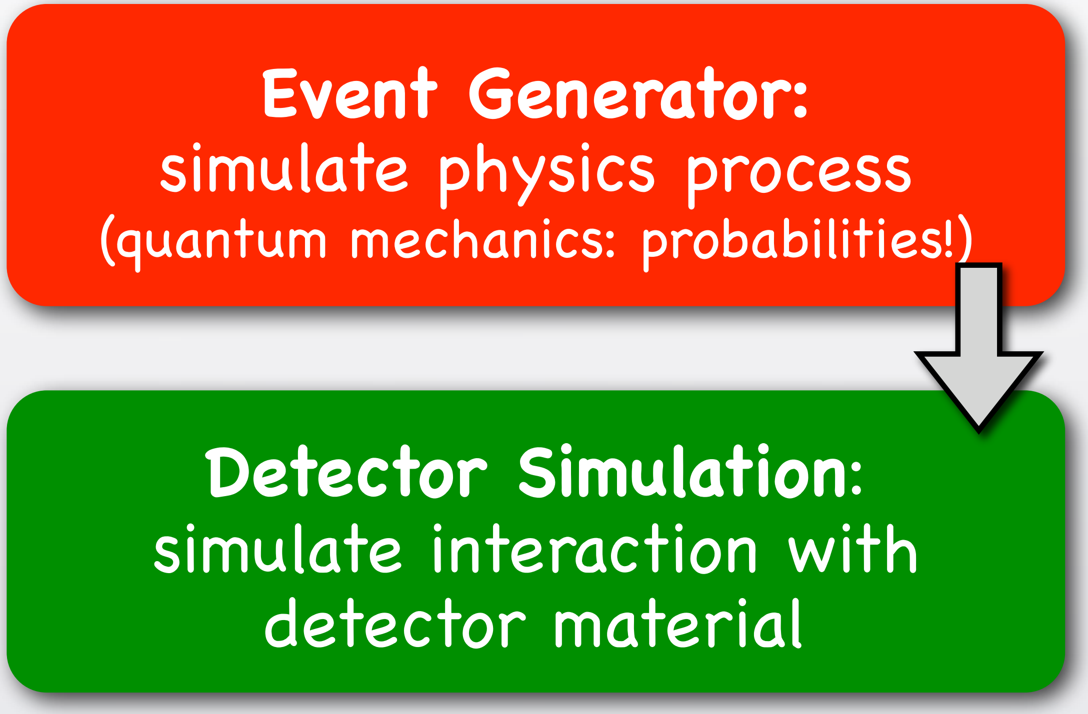

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simulate interaction with detector material

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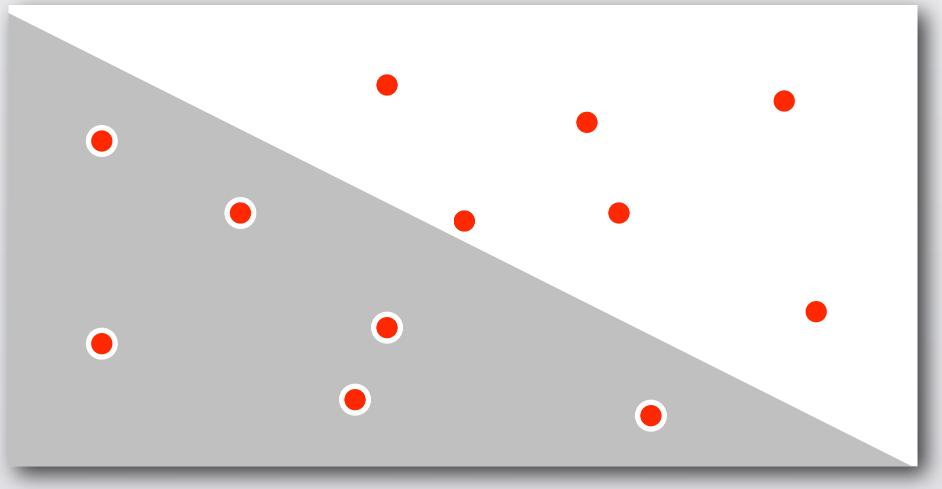

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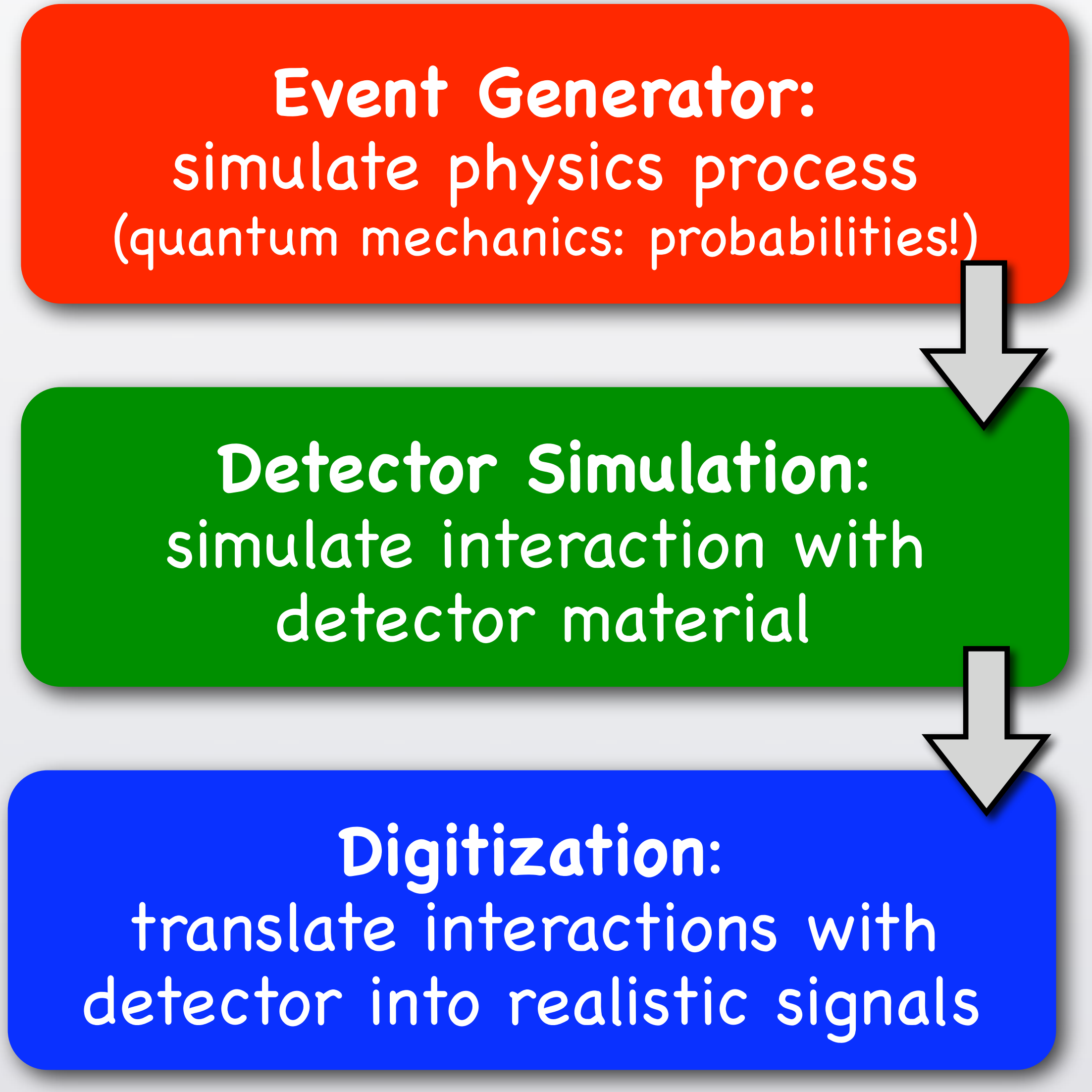

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Detector Simulation: simulate interaction with detector material

Digitization: translate interactions with detector into realistic signals

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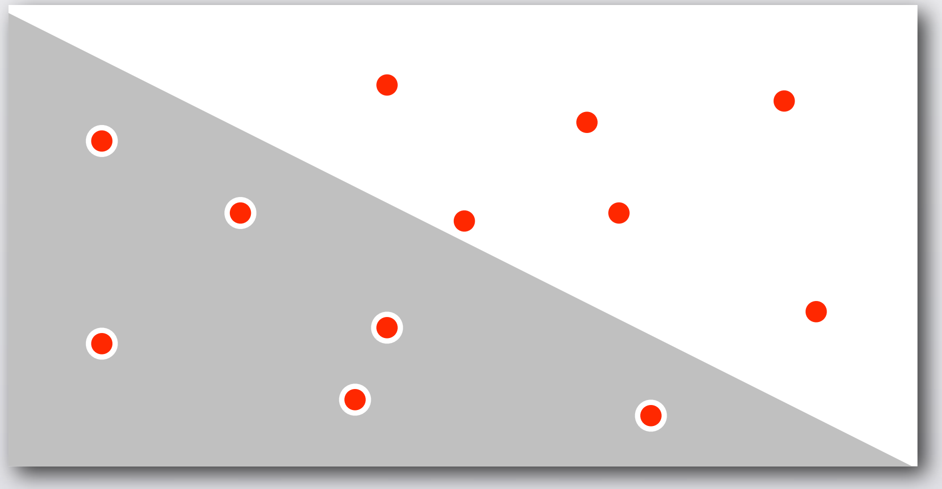

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MC simulations in particle physics

Event Generator: simulate physics process (quantum mechanics: probabilities!)

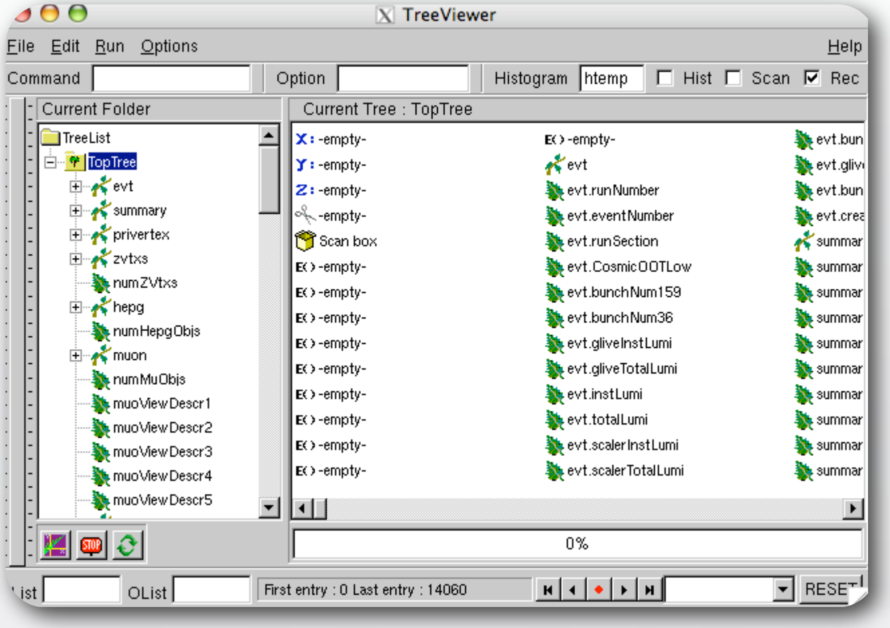
Detector Simulation: simulate interaction with detector material

Digitization: translate interactions with detector into realistic signals

Reconstruction/Analysis: as for real data

Data Analysis

- Object-oriented data analysis framework ROOT (http://root.cern.ch)
- Sketch of analysis steps:
    - Separate "interesting" (say, Higgs) from "uninteresting" events: cuts, fits, neural networks, ...
    - Compare with MC simulations
- Collaboration checks & approves results
  → show at conferences
- Publish in international physics journal



Histogram htemp ☐ Hist ☐ Scan ☑ Rec

First entry : 0 Last entry : 14060

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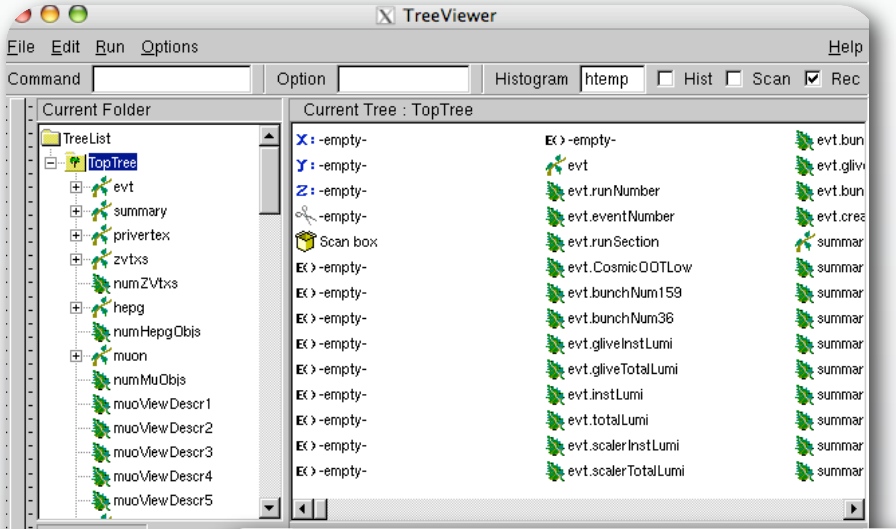

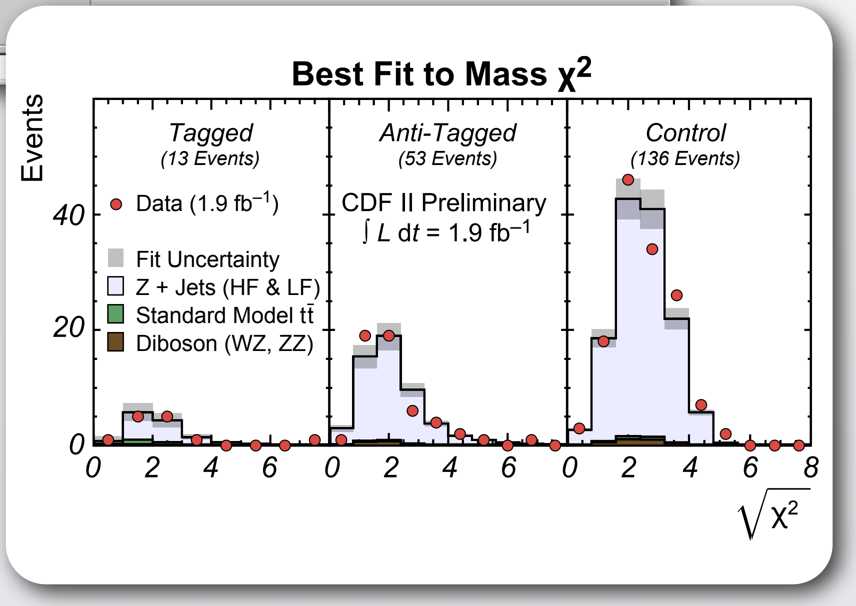

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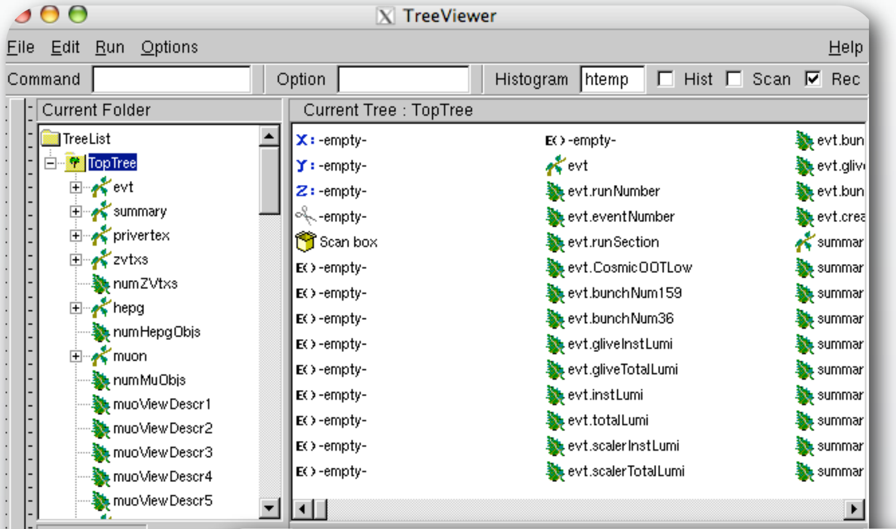
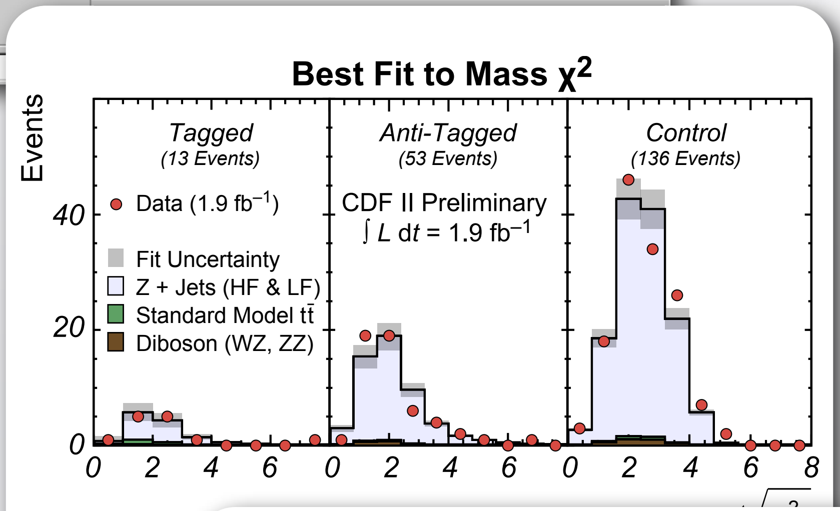
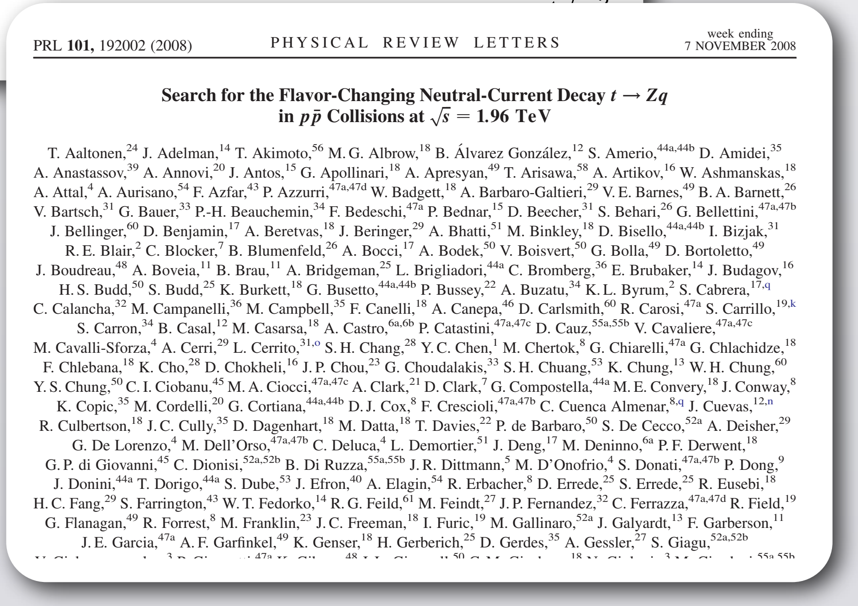
- Object-oriented data analysis framework ROOT (http://root.cern.ch)
- Sketch of analysis steps:
  - Separate "interesting" (say, Higgs) from "uninteresting" events: cuts, fits, neural networks, ...
  - Compare with MC simulations
- Collaboration checks & approves results → show at conferences
- Publish in international physics journal







PRL **101,** 192002 (2008) PHYSICAL REVIEW LETTERS week ending 7 NOVEMBER 2008

Search for the Flavor-Changing Neutral-Current Decay $t \to Zq$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,[24] J. Adelman,[14] T. Akimoto,[56] M. G. Albrow,[18] B. Álvarez González,[12] S. Amerio,[44a,44b] D. Amidei,[35] A. Anastassov,[39] A. Annovi,[20] J. Antos,[15] G. Apollinari,[18] A. Apresyan,[49] T. Arisawa,[58] A. Artikov,[16] W. Ashmanskas,[18] A. Attal,[4] A. Aurisano,[54] F. Azfar,[43] P. Azzurri,[47a,47d] W. Badgett,[18] A. Barbaro-Galtieri,[29] V. E. Barnes,[49] B. A. Barnett,[26] V. Bartsch,[31] G. Bauer,[33] P.-H. Beauchemin,[34] F. Bedeschi,[47a] P. Bednar,[15] D. Beecher,[31] S. Behari,[26] G. Bellettini,[47a,47b] J. Bellinger,[60] D. Benjamin,[17] A. Beretvas,[18] J. Beringer,[29] A. Bhatti,[51] M. Binkley,[18] D. Bisello,[44a,44b] I. Bizjak,[31] R. E. Blair,[2] C. Blocker,[7] B. Blumenfeld,[26] A. Bocci,[17] A. Bodek,[50] V. Boisvert,[50] G. Bolla,[49] D. Bortoletto,[49] J. Boudreau,[48] A. Boveia,[11] B. Brau,[11] A. Bridgeman,[25] L. Brigliadori,[44a] C. Bromberg,[36] E. Brubaker,[14] J. Budagov,[16] H. S. Budd,[50] S. Budd,[25] K. Burkett,[18] G. Busetto,[44a,44b] P. Bussey,[22] A. Buzatu,[34] K. L. Byrum,[2] S. Cabrera,[17,q] C. Calancha,[32] M. Campanelli,[36] M. Campbell,[35] F. Canelli,[18] A. Canepa,[46] D. Carlsmith,[60] R. Carosi,[47a] S. Carrillo,[19,k] S. Carron,[34] B. Casal,[12] M. Casarsa,[18] A. Castro,[6a,6b] P. Catastini,[47a,47c] D. Cauz,[55a,55b] V. Cavaliere,[47a,47c] M. Cavalli-Sforza,[4] A. Cerri,[29] L. Cerrito,[31,o] S. H. Chang,[28] Y. C. Chen,[1] M. Chertok,[8] G. Chiarelli,[47a] G. Chlachidze,[18] F. Chlebana,[18] K. Cho,[28] D. Chokheli,[16] J. P. Chou,[23] G. Choudalakis,[33] S. H. Chuang,[53] K. Chung,[13] W. H. Chung,[60] Y. S. Chung,[50] C. I. Ciobanu,[45] M. A. Ciocci,[47a,47c] A. Clark,[21] D. Clark,[7] G. Compostella,[44a] M. E. Convery,[18] J. Conway,[8] K. Copic,[35] M. Cordelli,[20] G. Cortiana,[44a,44b] D. J. Cox,[8] F. Crescioli,[47a,47b] C. Cuenca Almenar,[8,q] J. Cuevas,[12,n] R. Culbertson,[18] J. C. Cully,[35] D. Dagenhart,[18] M. Datta,[18] T. Davies,[22] P. de Barbaro,[50] S. De Cecco,[52a] A. Deisher,[29] G. De Lorenzo,[4] M. Dell'Orso,[47a,47b] C. Deluca,[4] L. Demortier,[51] J. Deng,[17] M. Deninno,[6a] P. F. Derwent,[18] G. P. di Giovanni,[45] C. Dionisi,[52a,52b] B. Di Ruzza,[55a,55b] J. R. Dittmann,[5] M. D'Onofrio,[4] S. Donati,[47a,47b] P. Dong,[9] J. Donini,[44a] T. Dorigo,[44a] S. Dube,[53] J. Efron,[40] A. Elagin,[54] R. Erbacher,[8] D. Errede,[25] S. Errede,[25] R. Eusebi,[18] H. C. Fang,[29] S. Farrington,[43] W. T. Fedorko,[14] R. G. Feild,[61] M. Feindt,[27] J. P. Fernandez,[32] C. Ferrazza,[47a,47d] R. Field,[19] G. Flanagan,[49] R. Forrest,[8] M. Franklin,[23] J. C. Freeman,[18] I. Furic,[19] M. Gallinaro,[52a] J. Galyardt,[13] F. Garberson,[11] J. E. Garcia,[47a] A. F. Garfinkel,[49] K. Genser,[18] H. Gerberich,[25] D. Gerdes,[35] A. Gessler,[27] S. Giagu,[52a,52b]

Summary of Day 1

- LHC accelerator
  - Proton-proton collider at CERN starting in 2009
  - Design center of mass energy: 14 TeV
  - Search for: Higgs boson, physics beyond standard model, ...
- Detectors at the LHC
  - Two multi-purpose detectors: ATLAS, CMS
  - Multi-purpose detectors: measure momentum, energy, ID, etc. of as many particles as possible → onion shell
  - Two smaller more specialized detectors: LHCb, ALICE
  - Long way from raw data to physics results

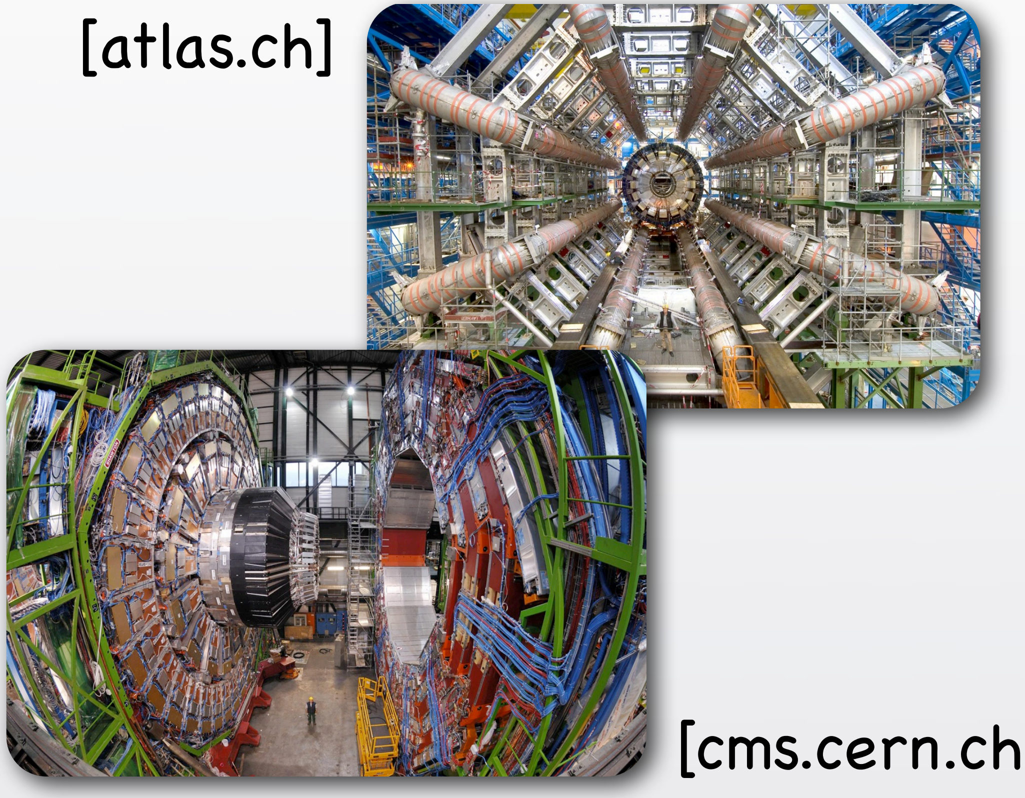
DESY Summer Student Lectures 2009
Zeuthen, August 20-21, 2009

The LHC Experiments

Ulrich Husemann
Deutsches Elektronen-Synchrotron

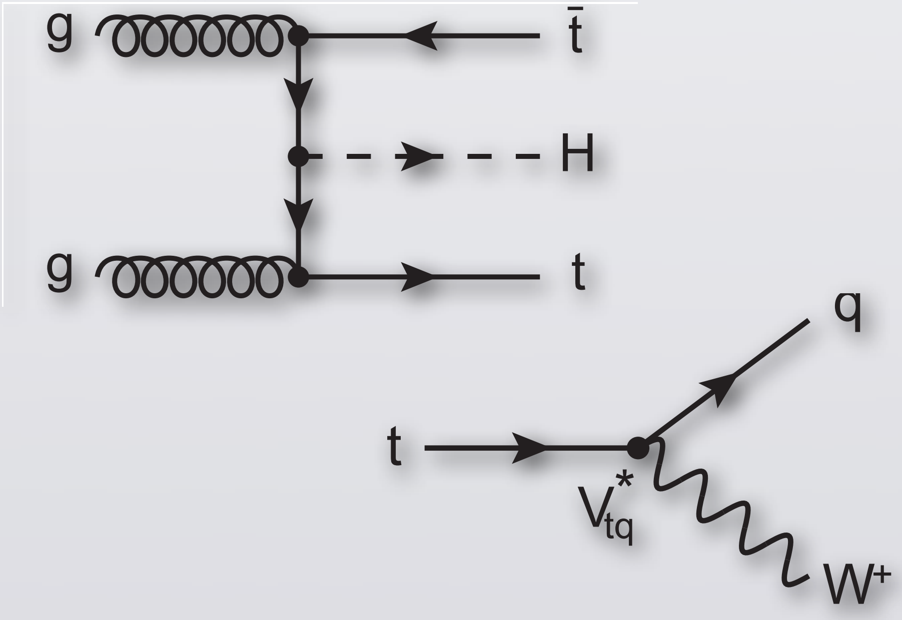
Program

- Day 1: Machine and detectors
  - Open questions in particle physics
  - The LHC accelerator (follow-up)
  - How to build a LHC detector
  - Measuring momentum & energy
  - From raw data to physics results



[atlas.ch]

[cms.cern.ch]



- Day 2: Towards LHC physics
  - Basics of hadron collider physics
  - First physics at the LHC
  - How to measure a cross section
  - Hunting for the Higgs

Program

- Day 1: Machine and detectors
  - Open questions in particle physics
  - The LHC accelerator (follow-up)
  - How to build a LHC detector
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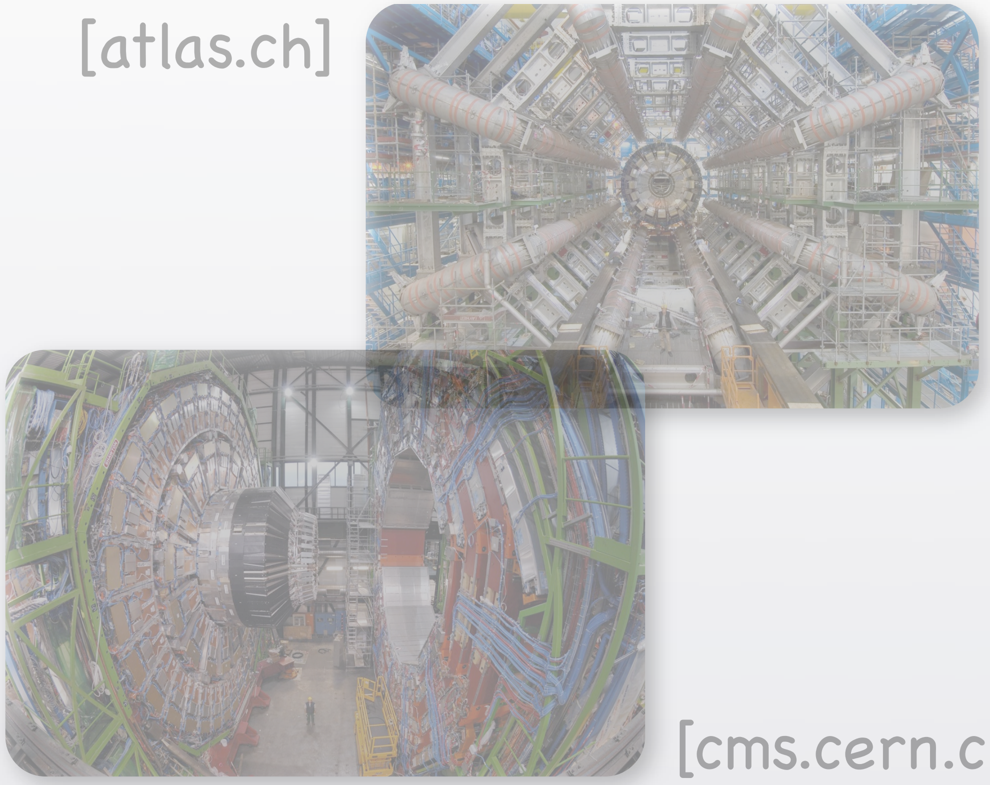
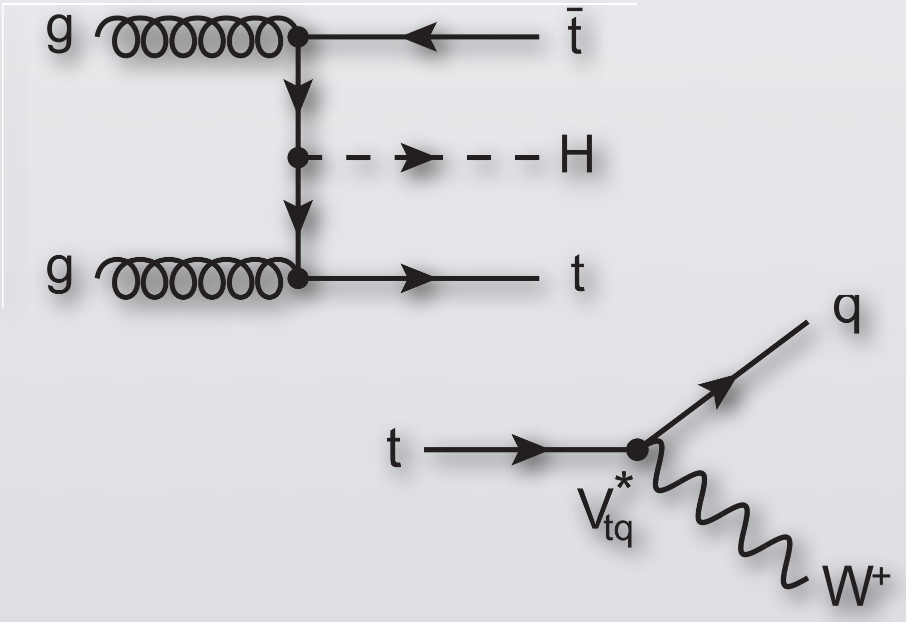


[atlas.ch]

[cms.cern.ch]



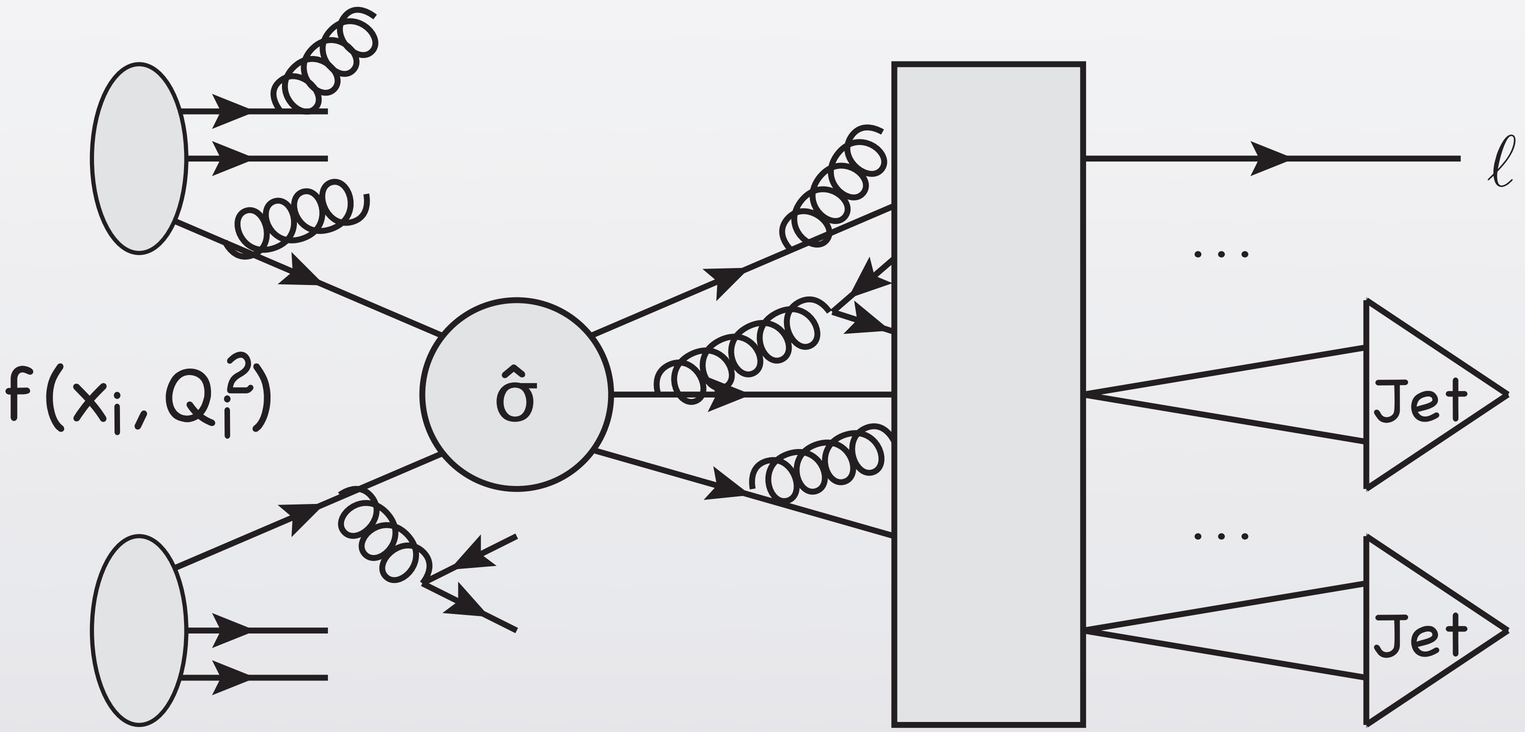
- Day 2: Towards LHC physics
  - Basics of hadron collider physics
  - First physics at the LHC
  - How to measure a cross section
  - Hunting for the Higgs

Chapter 6

Basics of Hadron Collider Physics

Theorists' View

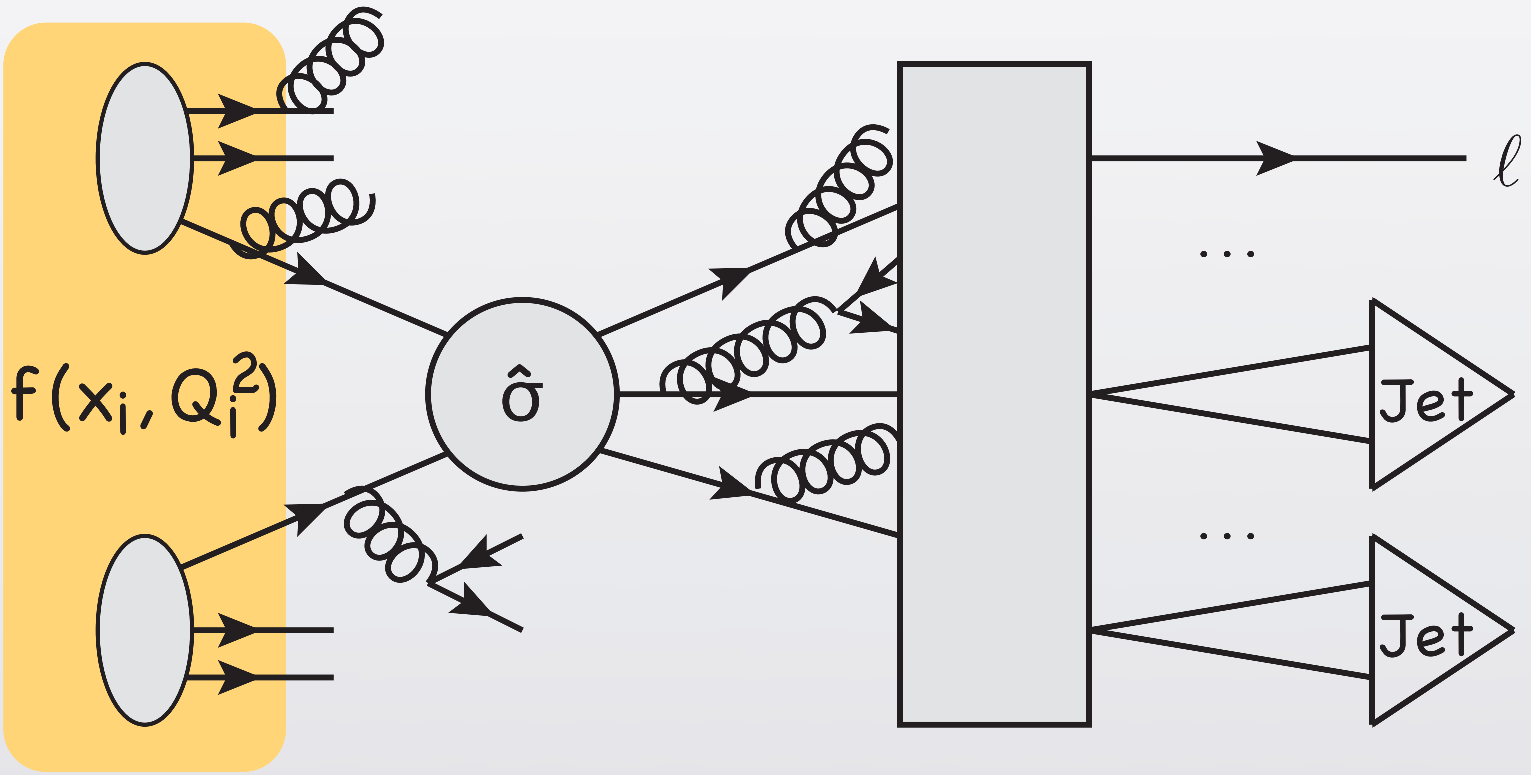
- Theoretical picture of hadron-hadron collisions (see lecture by S. Moch):



$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = \sum_{j,k} \int \mathrm{d}\hat{X}\, f_j(x_1, Q_i^2)\, f_k(x_2, Q_i^2)\, \frac{\mathrm{d}\hat{\sigma}_{fi}(Q_i^2, Q_f^2)}{\mathrm{d}\hat{X}}\, F(\hat{X} \to X; Q_i^2, Q_f^2)$$

Theorists' View

- Theoretical picture of hadron-hadron collisions (see lecture by S. Moch):

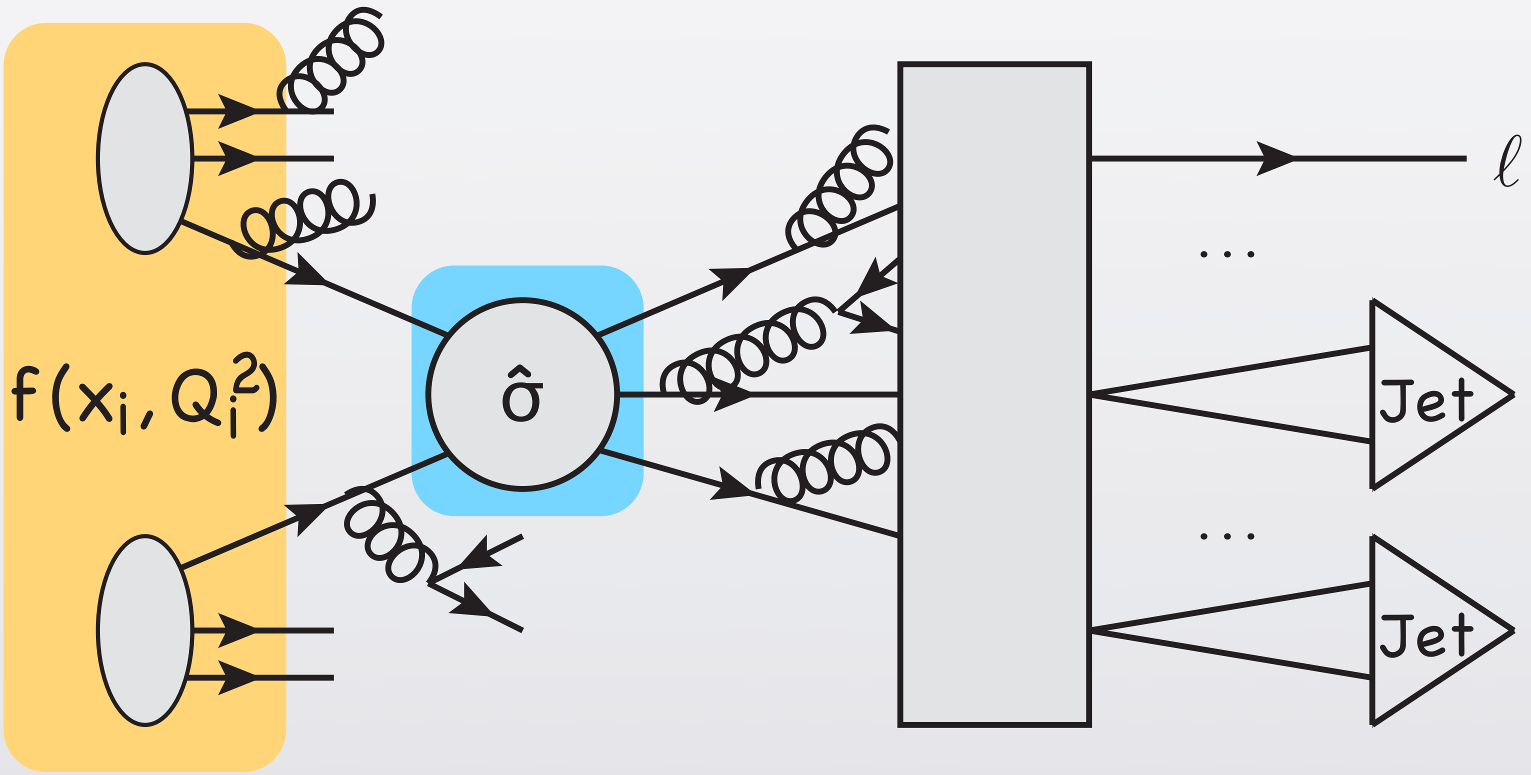


$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = \sum_{j,k} \int \mathrm{d}\hat{X}\, f_j(x_1, Q_i^2)\, f_k(x_2, Q_i^2)\, \frac{\mathrm{d}\hat{\sigma}_{fi}(Q_i^2, Q_f^2)}{\mathrm{d}\hat{X}}\, F(\hat{X} \to X; Q_i^2, Q_f^2)$$

Parton Distribution Functions (PDF)

Theorists' View

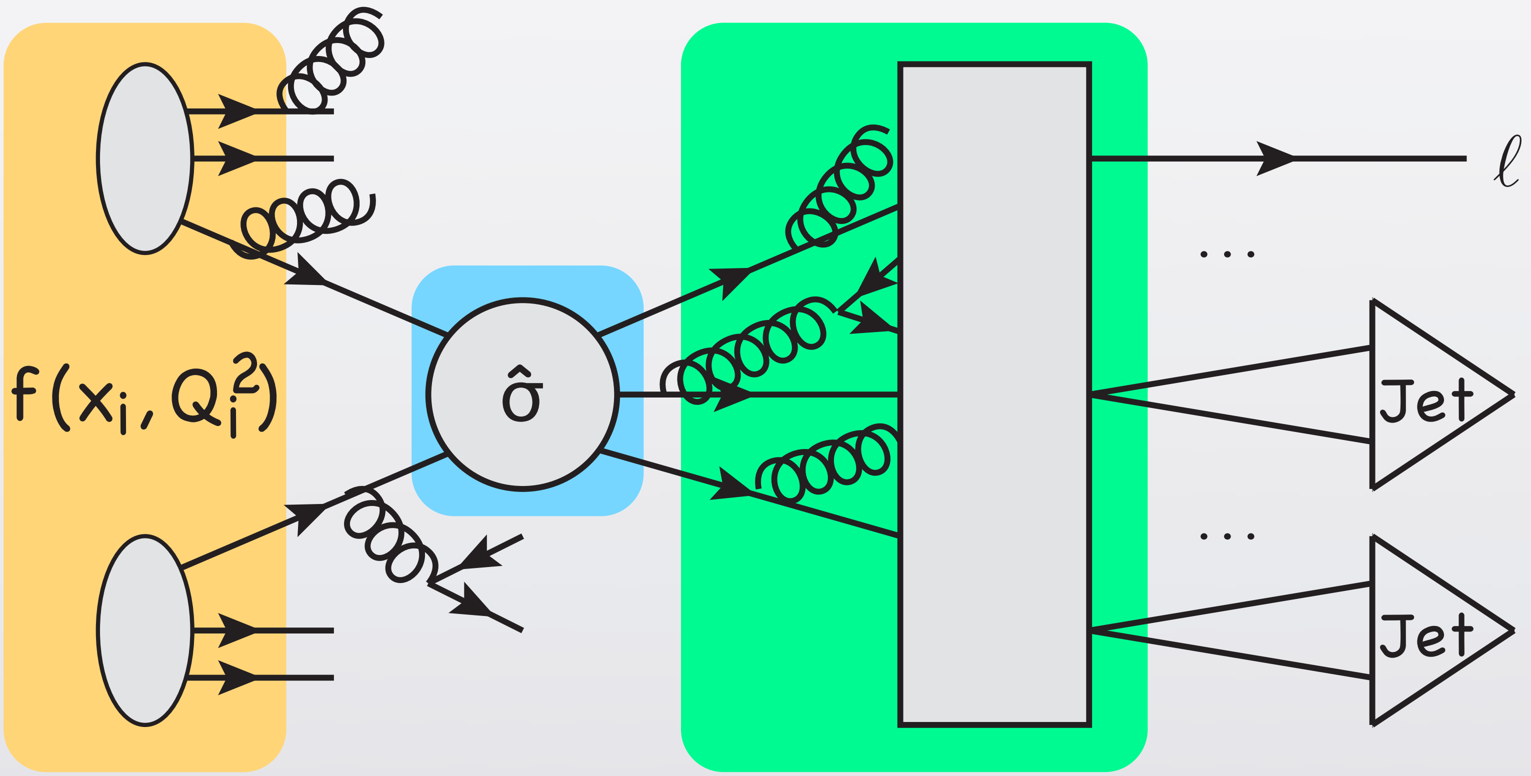
- Theoretical picture of hadron-hadron collisions (see lecture by S. Moch):



$$\frac{d\sigma}{dX} = \sum_{j,k} \int d\hat{X} \underbrace{f_j(x_1, Q_i^2)\, f_k(x_2, Q_i^2)}_{\text{Parton Distribution Functions (PDF)}} \underbrace{\frac{d\hat{\sigma}_{fi}(Q_i^2, Q_f^2)}{d\hat{X}}}_{\text{"Hard" Cross Section}} F(\hat{X} \to X; Q_i^2, Q_f^2)$$

Theorists' View

- Theoretical picture of hadron-hadron collisions (see lecture by S. Moch):



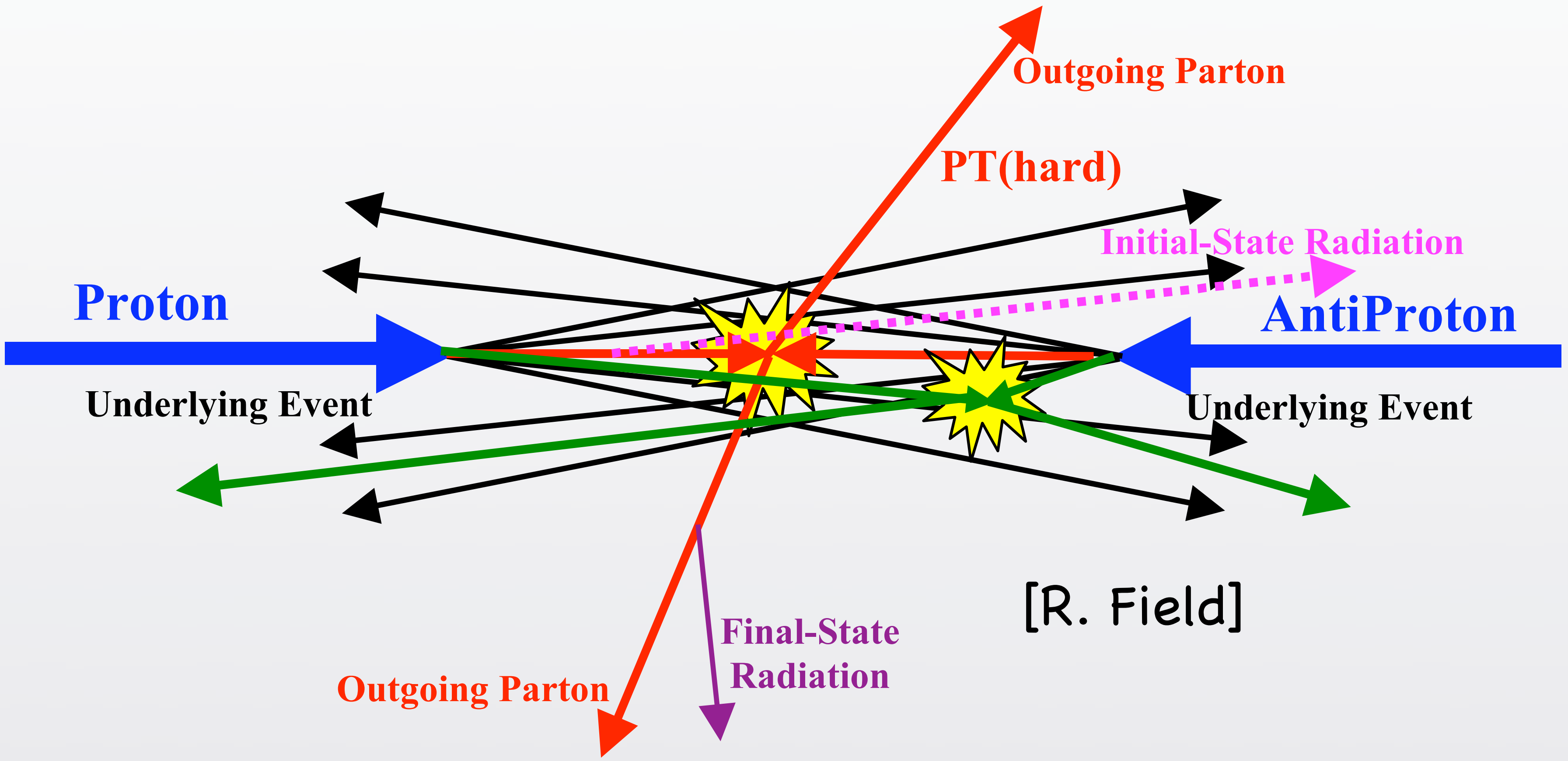
$$\frac{d\sigma}{dX} = \sum_{j,k} \int d\hat{X}\, f_j(x_1, Q_i^2)\, f_k(x_2, Q_i^2)\, \frac{d\hat{\sigma}_{fi}(Q_i^2, Q_f^2)}{d\hat{X}}\, F(\hat{X} \to X; Q_i^2, Q_f^2)$$

Parton Distribution Functions (PDF)

"Hard" Cross Section

Hadronization

Experimentalists' View

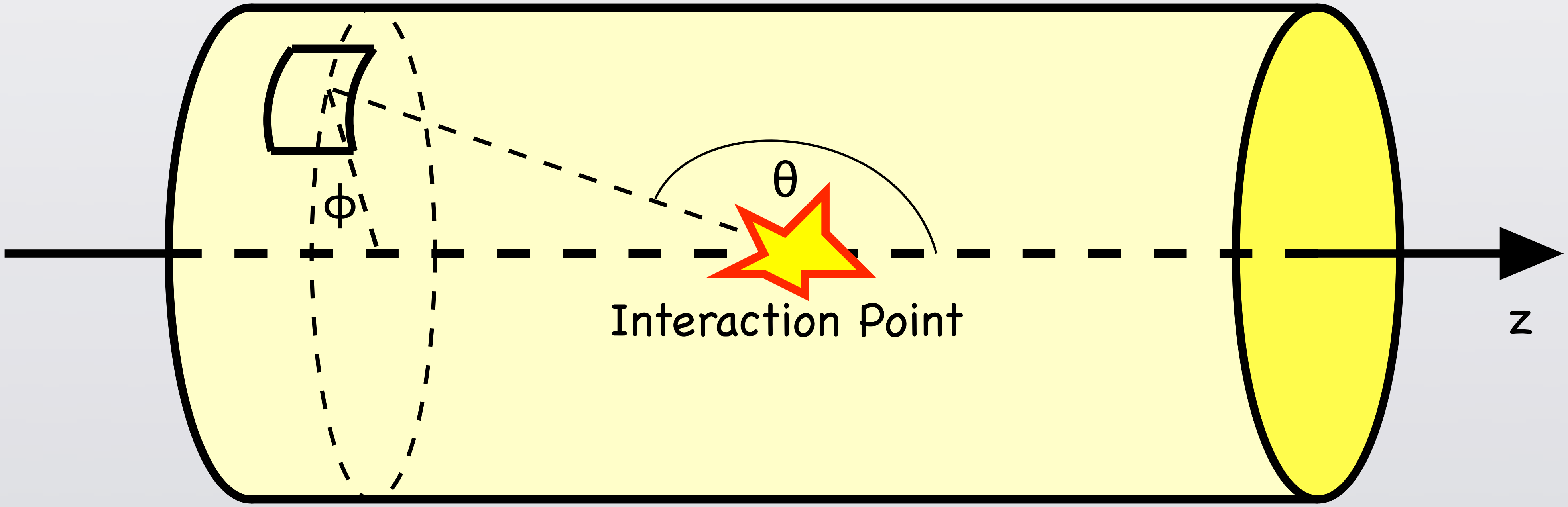


[R. Field]

- Hadronic collisions are messy:
  - Hard scattering of partons
  - Initial and final state radiation
  - Underlying event
  - Pileup of simultaneous collisions
- Known unknowns:
  - Which partons made hard scattering, what are their momenta?
  - What about the other partons?
  - Which jet ↔ which parton?

Hadron Collider Kinematics

- Some basic definitions for typical kinematic quantities at hadron colliders
- Onion shell structure → cylindrical coordinate system
  - Polar angle θ: angle with z axis (beam axis)
  - Azimuthal angle ϕ: angle with x axis (towards ring center)



Pseudorapidity η

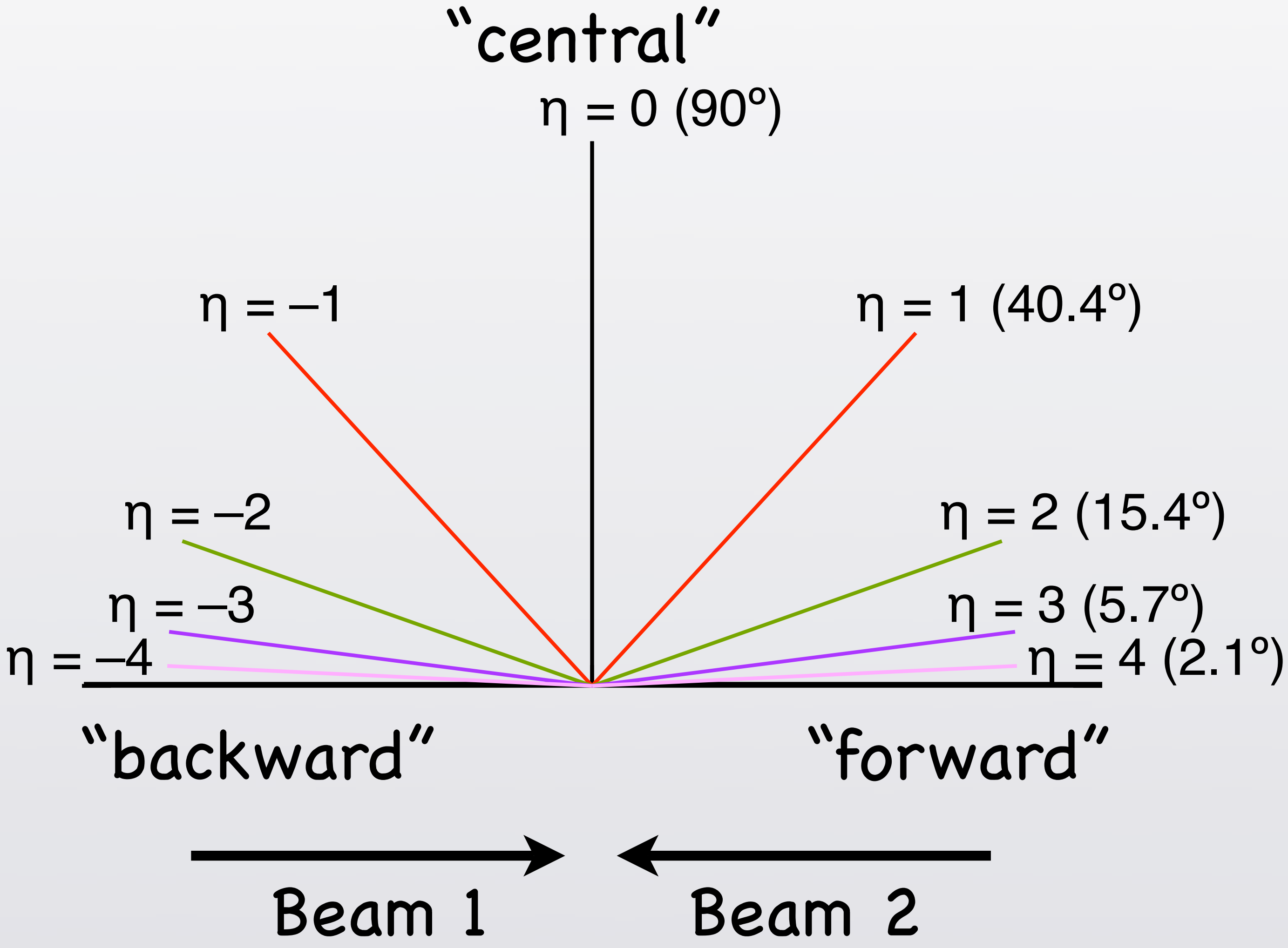
- Use pseudorapidity instead of polar angle θ

  $$\eta = -\ln\tan(\theta/2)$$

- Why pseudorapidity?
  - Good approximation of rapidity y (used in theoretical calculations)

    $$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

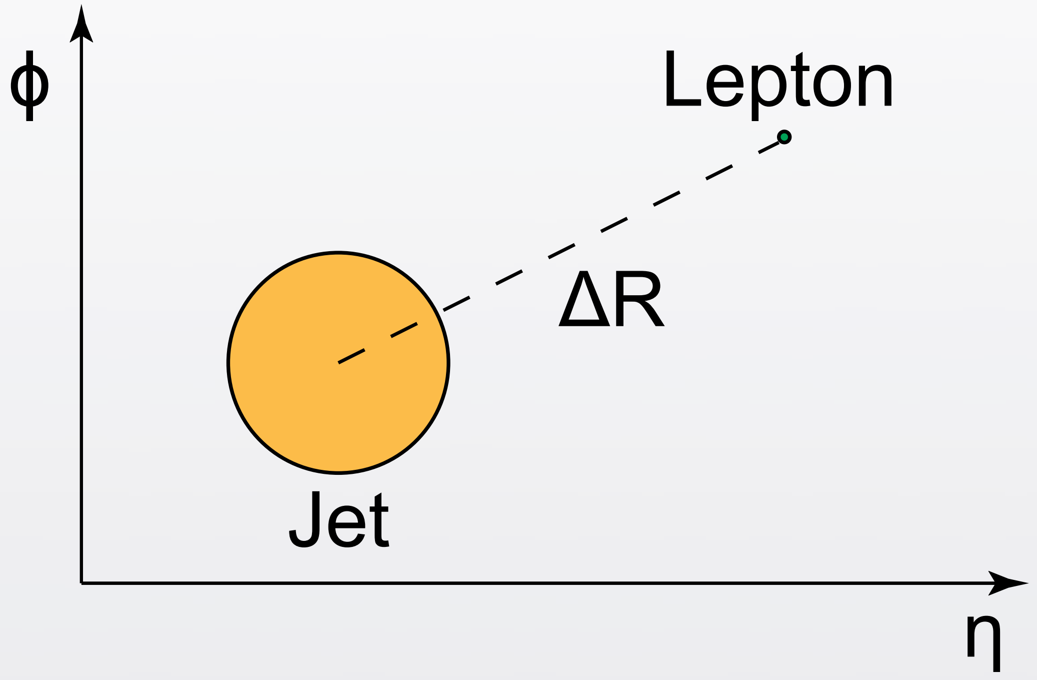
    for momentum >> mass
  - Depends only on θ, not on mass of particle



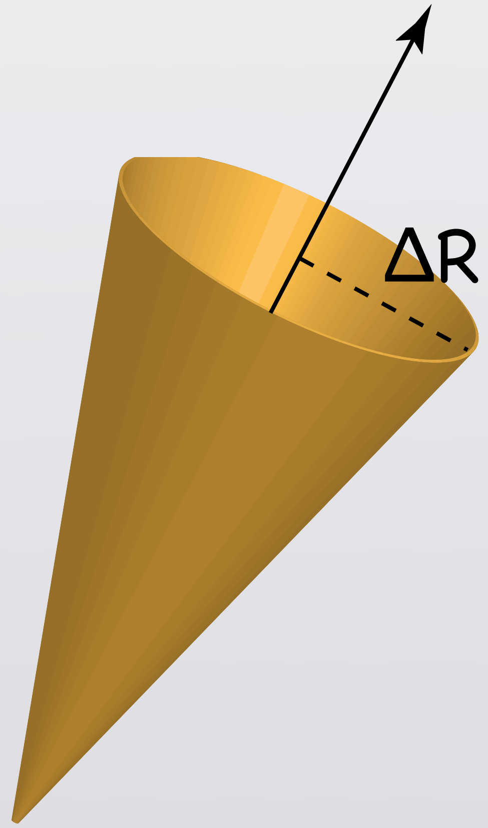
Distance ΔR

- Separation of two objects in the detector
  → distance in η-ϕ space

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$



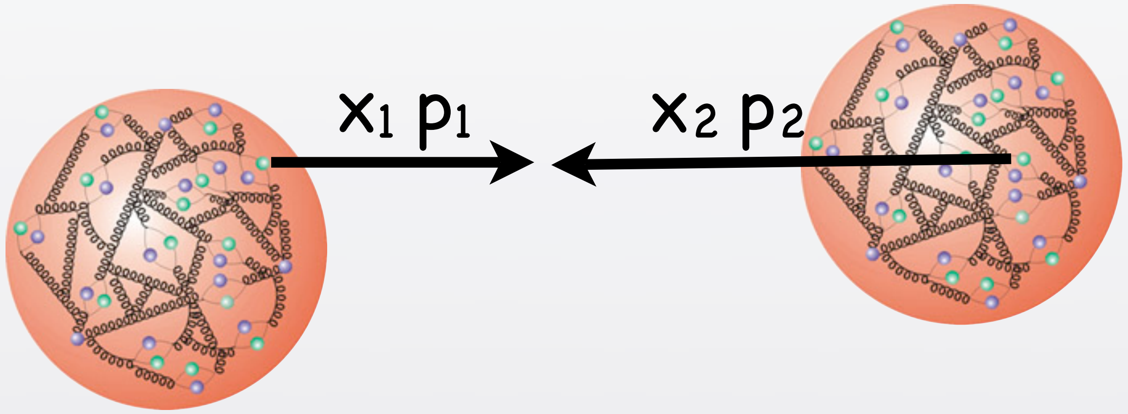
- Typical application: "cone algorithms" for jet reconstruction
  - Jet = all particles in a "cone" with radius ΔR
  - Radii: ΔR = 0.4, 0.7, 1.0



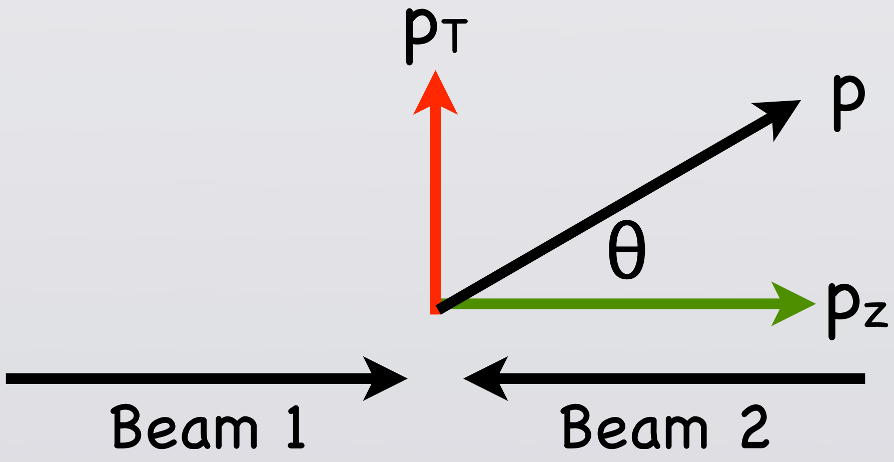
Transverse Quantities

- Hadron collider kinematics:
  - Collisions of partons carrying unknown fractions x_i of hadron momentum (to good approximation: all partons collinear with beam)
  - Rest frame of parton-parton collision unknown → center of mass energy unknown
- Any quantity transverse to beam is Lorentz-invariant, e.g. transverse momentum

$$p_T = \sqrt{p_x^2 + p_y^2} = p \sin\theta$$

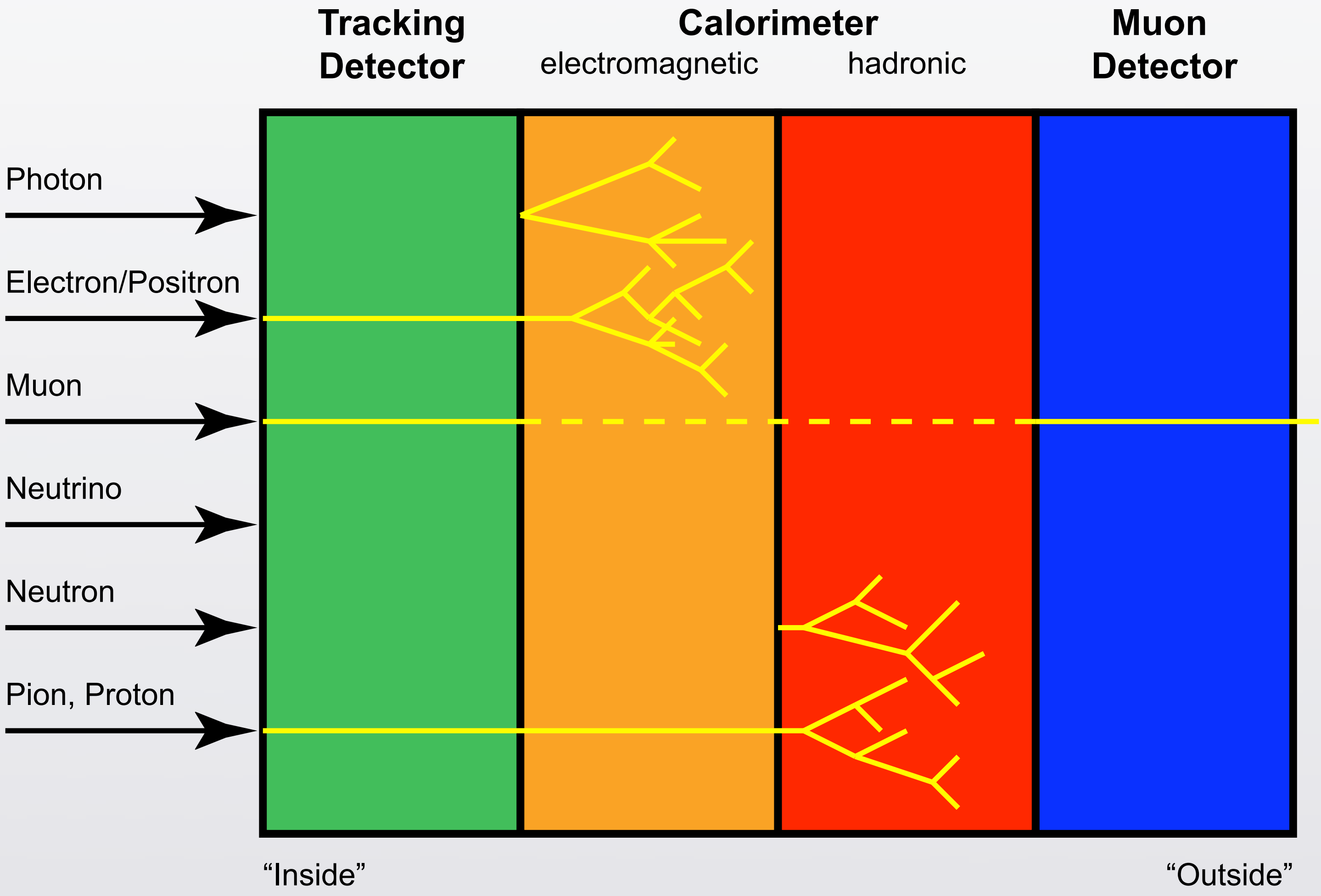


$$\hat{E}^2_{\mathrm{CMS}} = x_1 x_2 E^2_{\mathrm{CMS}}$$



Particle Reconstruction

- Onion shell revisited:
  - Photons: cluster in electromagnetic calorimeter, no track
  - Electrons: track matched to cluster in electromagnetic calorimeter
  - Muons: track matched to signal in muon detector



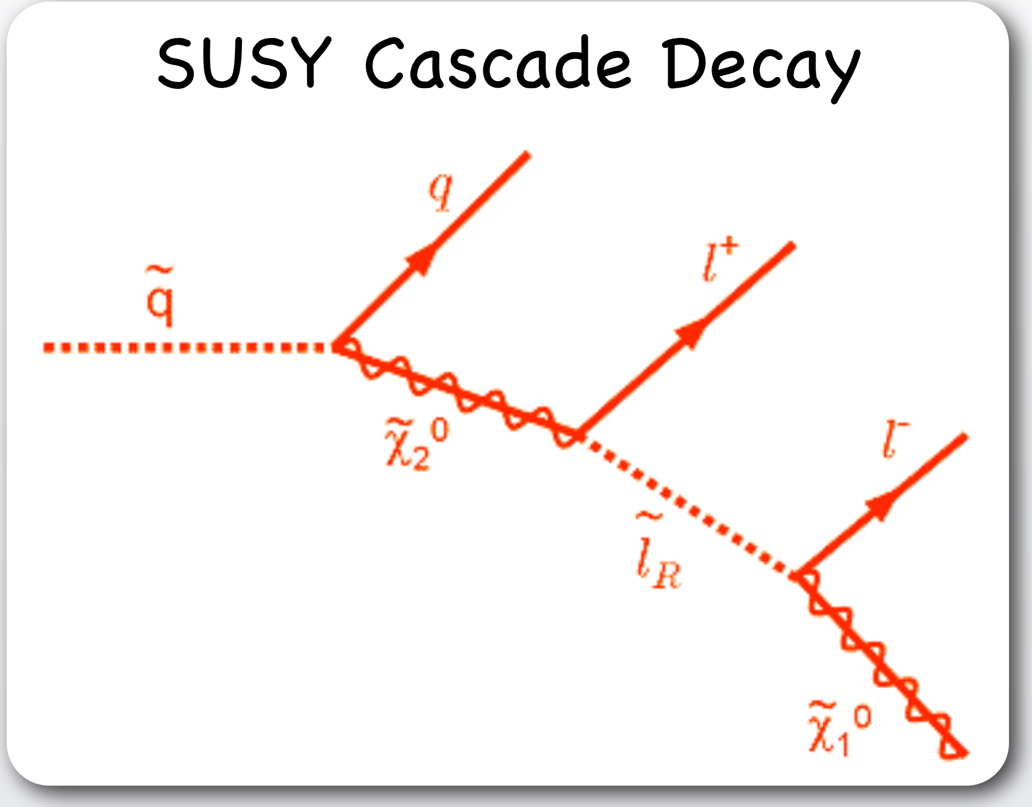
  - Neutrinos: detected indirectly via "missing transverse energy"
  - Jets of hadrons: tracks matched to clusters in electromagnetic and hadronic calorimeter

Neutrinos et al.

- Weakly interacting neutral particles (neutrinos, neutralinos, ...)
  - Very important part of many decays (top, SUSY, ...)
  - Escape detector undetected
- Indirect detection using conservation of transverse momentum:
  - Assuming that all parton momenta are parallel to the beam:

$$\sum \vec{p}_T = 0$$

  - Large imbalance if high-energy neutral particle carries away p_T



SUSY Cascade Decay

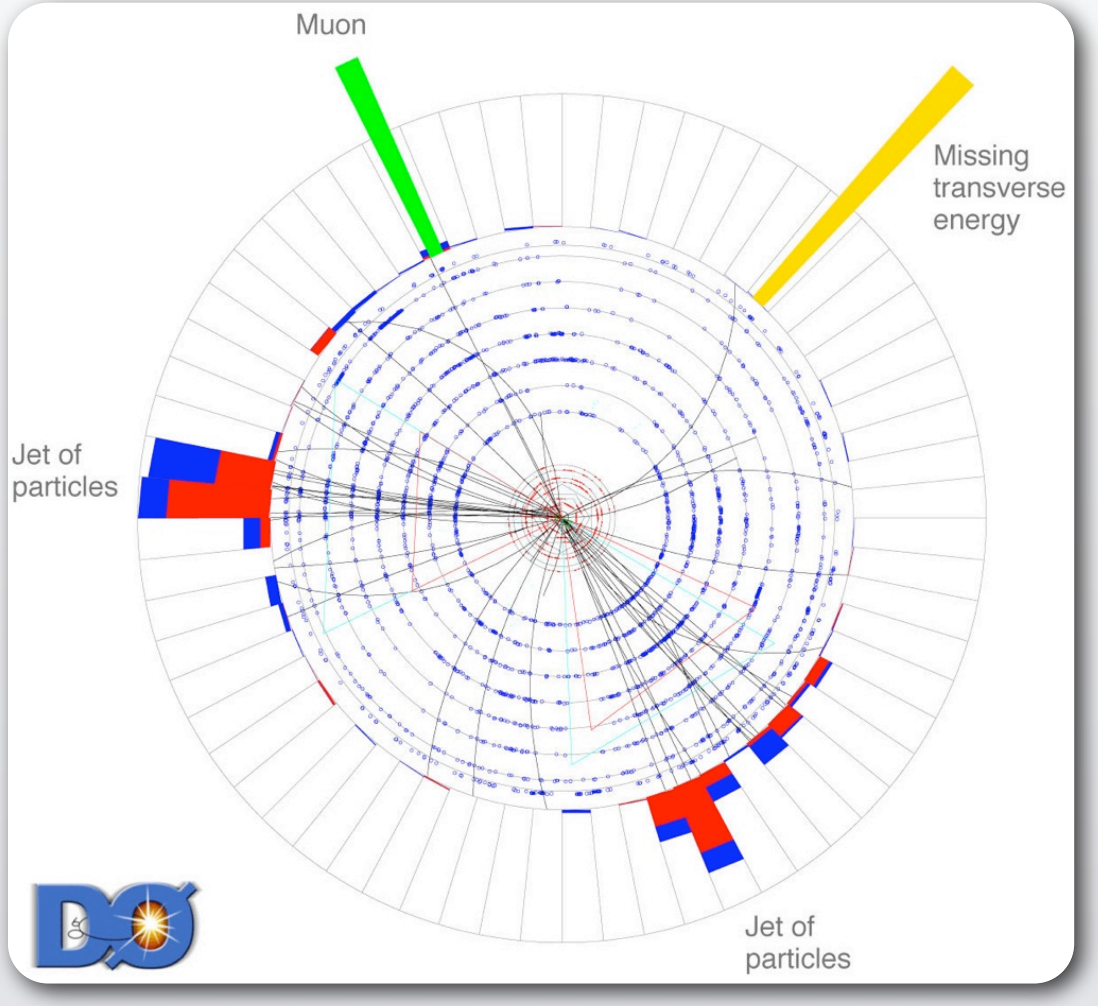
Missing Transverse Energy

- Missing transverse energy ("missing E$_T$", "MET"): imbalance in sum of all calorimeter energy, weighted with polar angle

$$\vec{\not{E}}_T = - \sum_{\text{calo cells}} E_i \sin\theta_i \begin{pmatrix} \cos\phi_i \\ \sin\phi_i \\ 0 \end{pmatrix}$$

- Experimentally difficult: many sources of "fake" MET
  - Muons only deposit little energy in calorimeter
  - Other particles may escape through cracks, dead modules, …

DØ Single Top Candidate



Jet Reconstruction

- No free quarks/gluons: partons hadronize to a (more or less collimated) spray of particles → “jet”
- A jet is not a uniquely defined concept, depends on jet reconstruction algorithm, two classes:
  - “Cone” algorithms: group all particles in a cone:

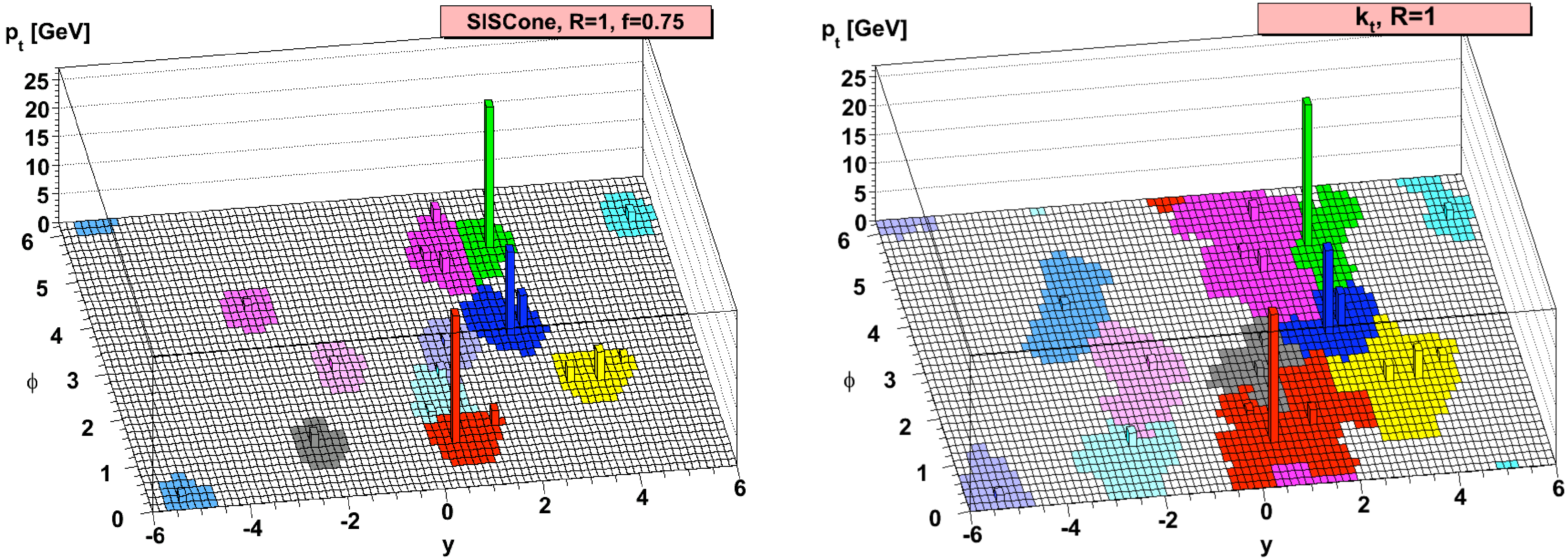
$$\Delta_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2} < R$$

  - “Sequential recombination” algorithms: group particles according to distance times some power 2p of their transverse momentum k_T, stop if d_{iB} is the shortest distance

$$d_{ij} = \min(k_{T,i}^{2p}, k_{T,j}^{2p}) \frac{\Delta_{ij}^2}{R^2}, \quad d_{iB} = k_{T,i}^{2p}$$

Jet Reconstruction

- Two algorithms on the same (simulated) event:

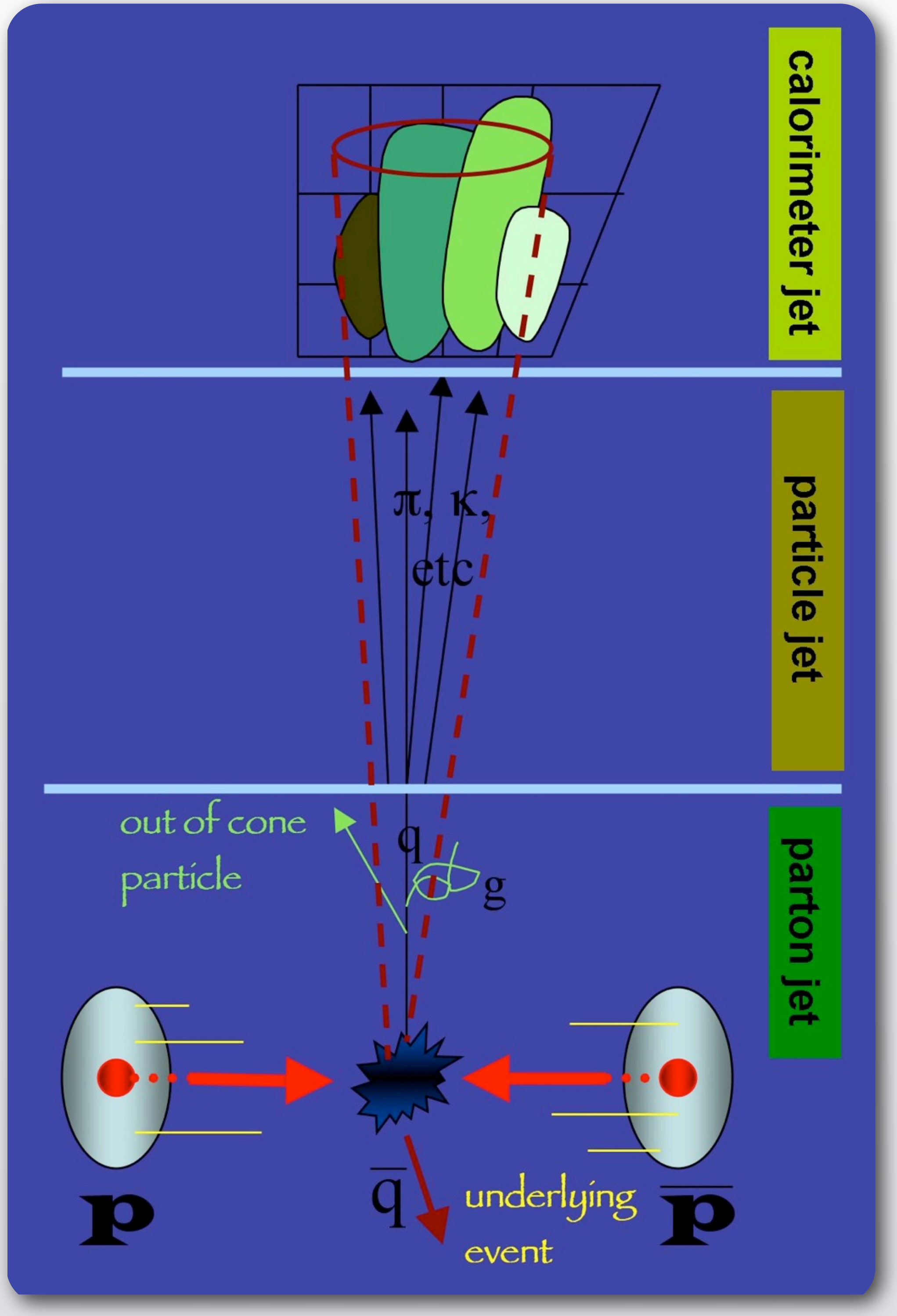


cone algorithm (R=1)

recombination algorithm (R=1)

[M. Cacciari, G. P. Salam, G. Soyez, JHEP **04** (2008) 063]

Jet Energy Scale

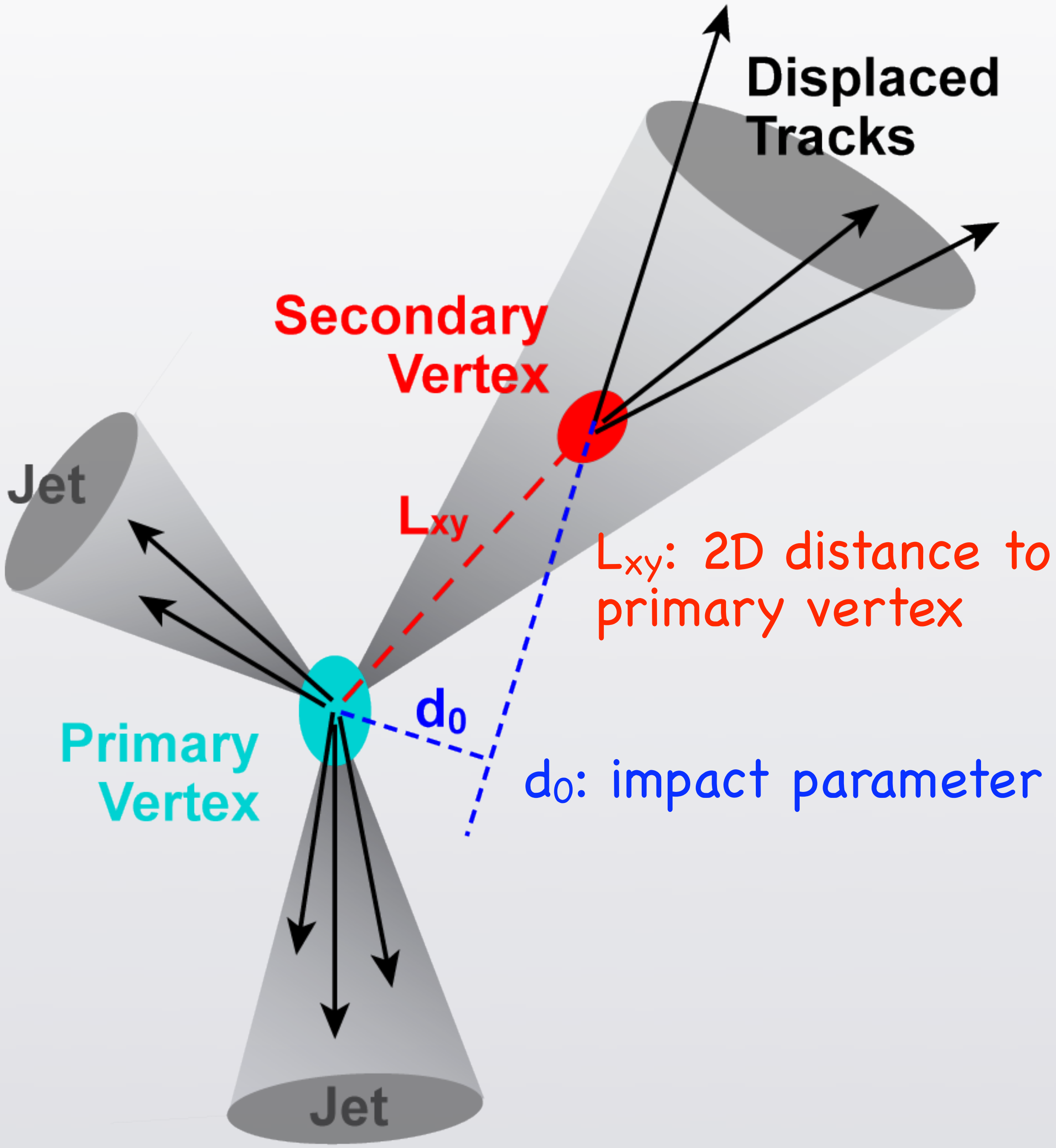


[CDF]

- Measure jet energy, but want parton energy (before hadronization)
- Complicated correction procedure: calibration of jet energy scale ("JES")
  - Different calorimeter response to: different particle types, different energies, noise, ...
  - Additional energy: underlying event, simultaneous interactions
  - Particles not grouped into jet ("out of cone")

B-Tagging

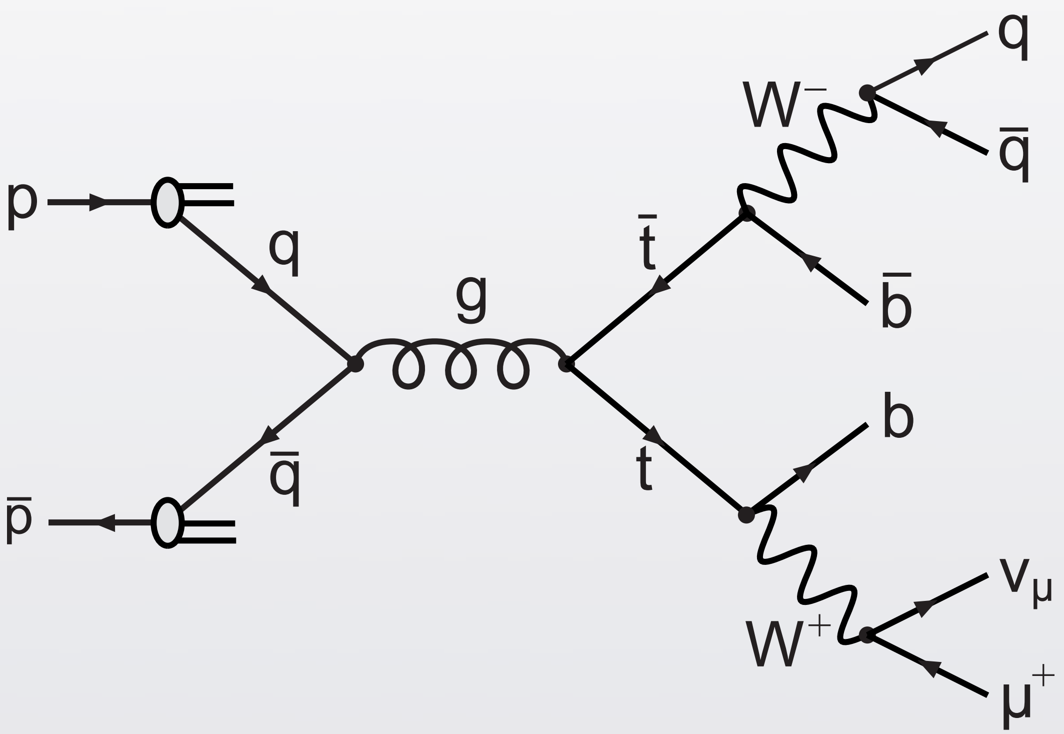
- Interesting particles decay into final states w/ b quarks
  - E.g. H → bb, t → Wb
  - Need powerful tools for "b-tagging"
- B-tagging approaches:
  - B hadrons are massive and "long-lived" (cτ of $B^{\pm}$: 491 μm) → displaced secondary vertex
  - Semileptonic decays $B \to l\nu X$ → jets with soft leptons
- Key: silicon vertex detectors



[DØ]

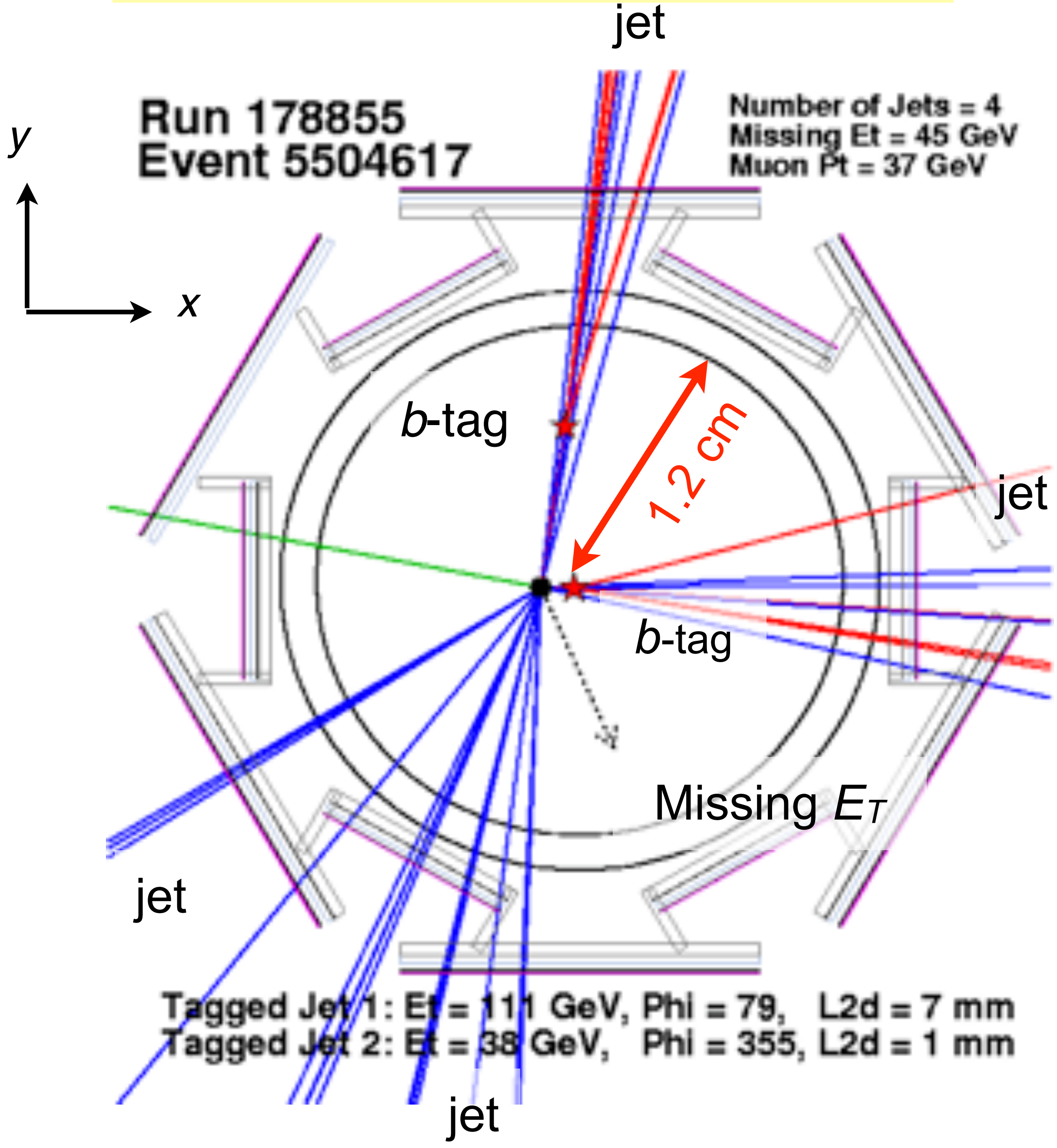
Putting it all together

- Example: top pair decay ("lepton + jets") at CDF



- Lepton (here: μ)
- Neutrino (MET)
- Quarks (4 jets, 2 b-tagged)

Double-Tag Event in Layer 00 of the CDF Silicon Detector

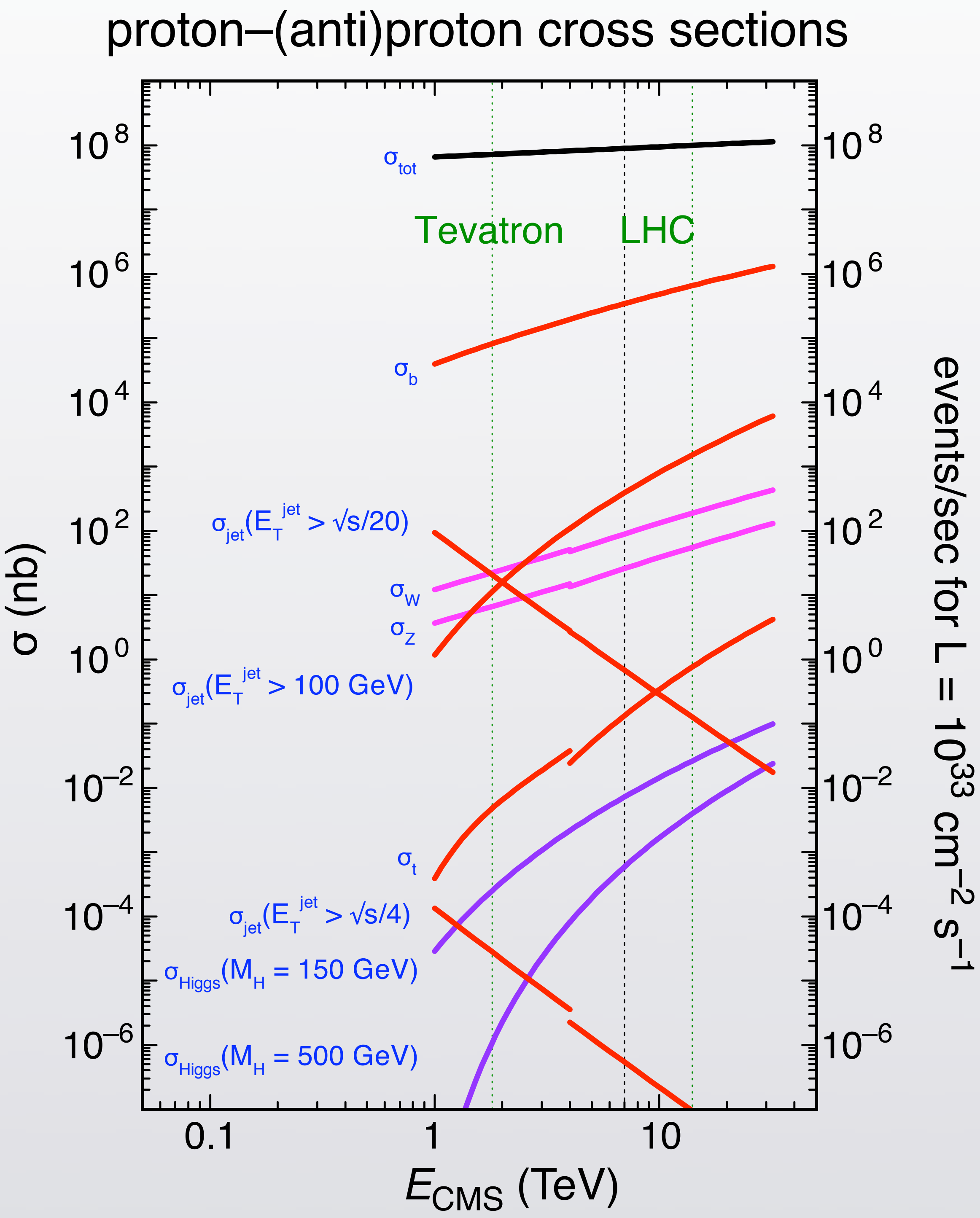


Chapter 7

First Physics at the LHC

First LHC Data

- Reminder: production cross sections at E_{CMS} = 7–14 TeV
  - Total inelastic: $\sigma_{tot} \approx$ 100 mb → drives total event rate
  - W bosons: σ_W = 100–150 nb
  - Z bosons: σ_Z = 30–60 nb
  - Top: σ_t = 150–900 pb
- Assuming 100 pb^{-1} in the first year → rediscover the SM!
  - Lots of QCD
  - 10^7 W – 3×10^6 Z – 15,000 top (produced, not reconstructed!)

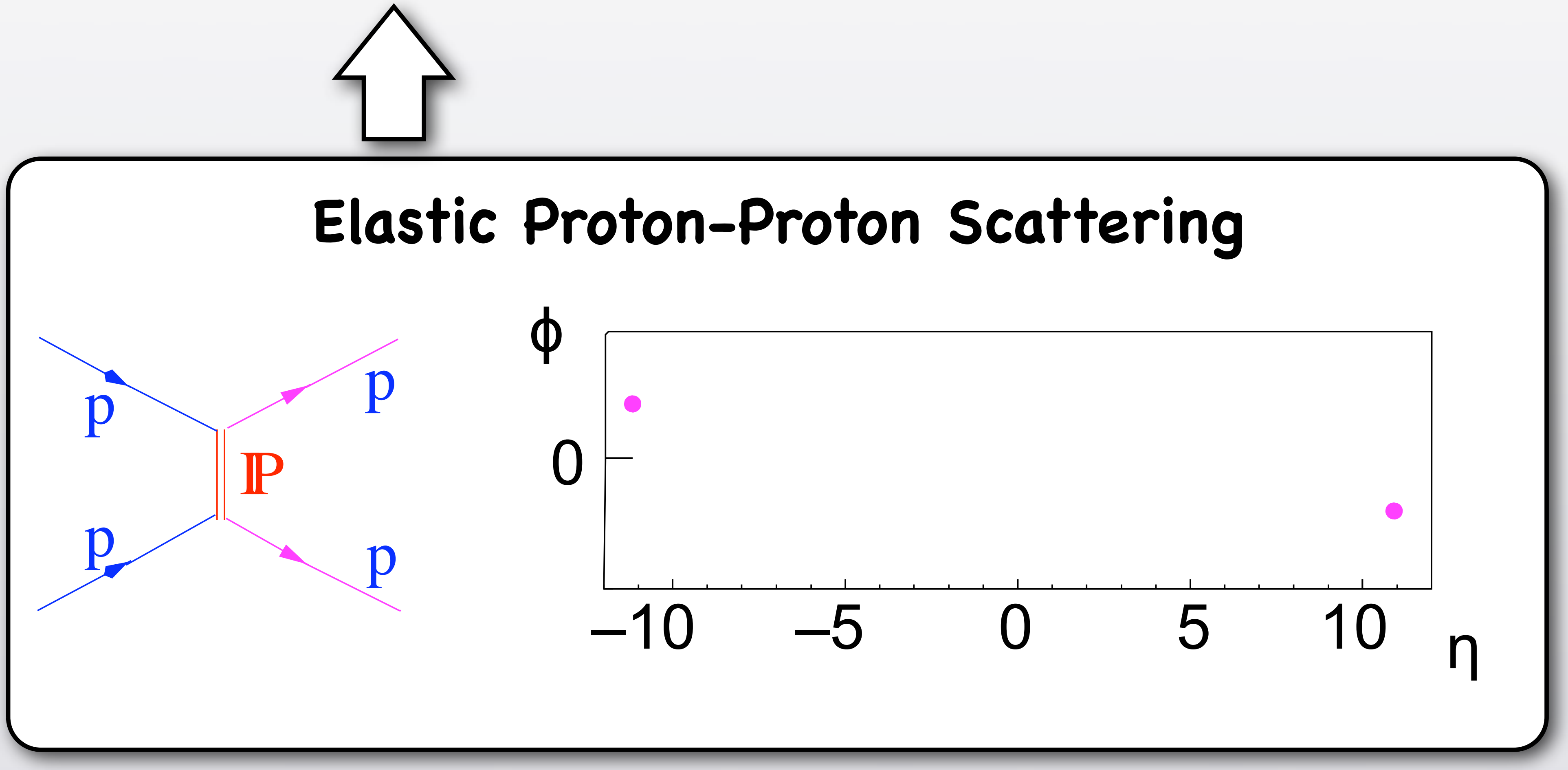


[after: J. M. Campbell, J. W. Huston, W. J. Stirling, Rep. Prog. Phys. **70** (2007) 89]

Total Cross Section

- Total proton-proton cross section:

$$\sigma_{\rm tot} = \sigma_{\rm elas} + \sigma_{\rm SD} + \sigma_{\rm DD} + \sigma_{\rm ND} + \sigma_{\rm CD}$$



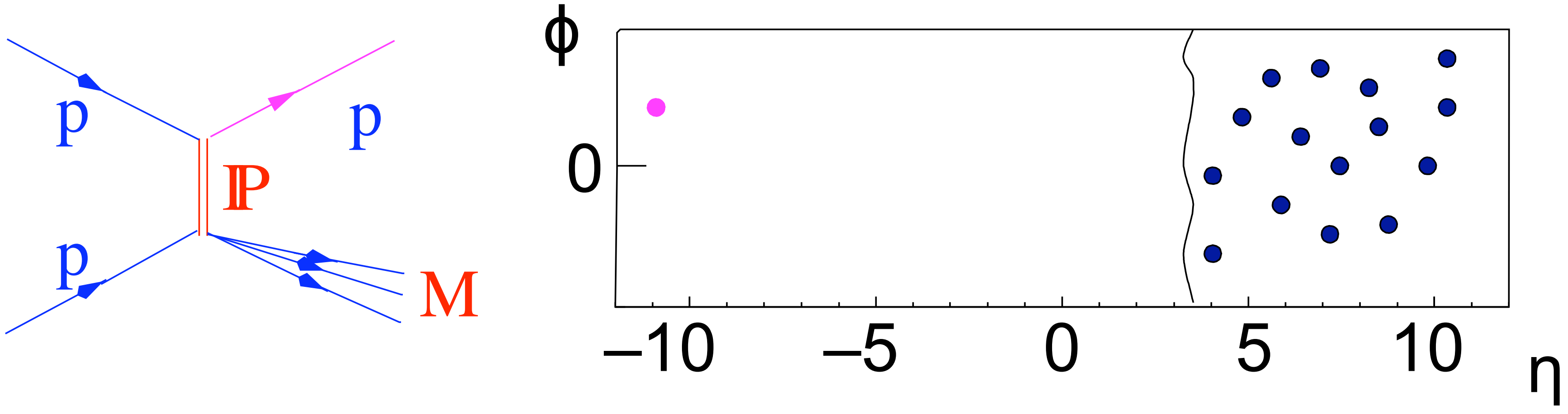
[after M. Leyton, Rencontres de Moriond QCD 2009]

Total Cross Section

- Total proton-proton cross section:

$$\sigma_{\text{tot}} = \sigma_{\text{elas}} + \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{ND}} + \sigma_{\text{CD}}$$

Single Diffractive Dissociation



[after M. Leyton, Rencontres de Moriond QCD 2009]

Total Cross Section

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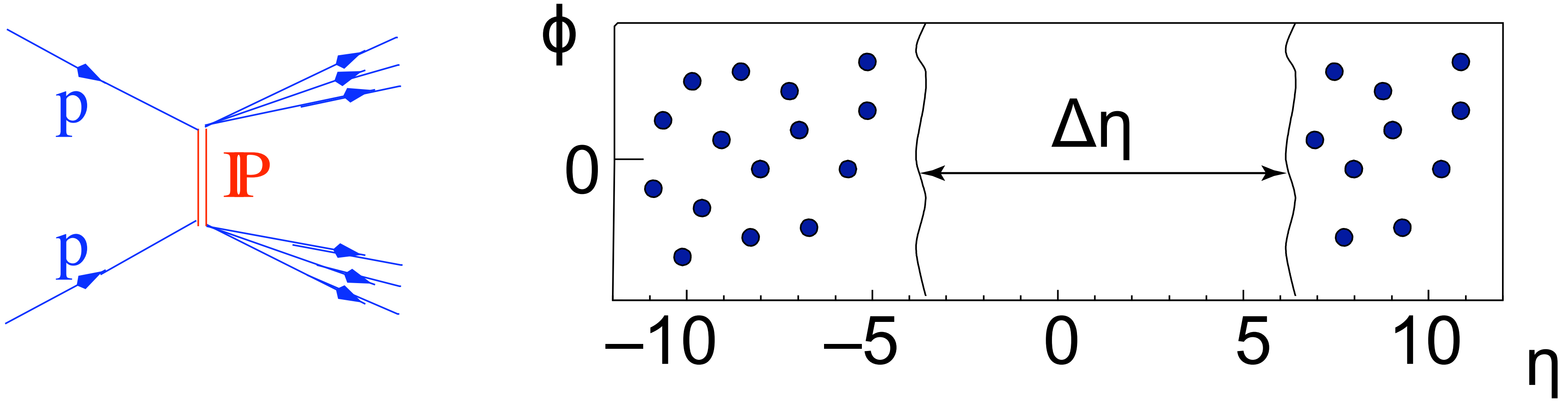
$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{elas}} + \sigma_{\mathrm{SD}} + \sigma_{\mathrm{DD}} + \sigma_{\mathrm{ND}} + \sigma_{\mathrm{CD}}$$

Double Diffractive Dissociation



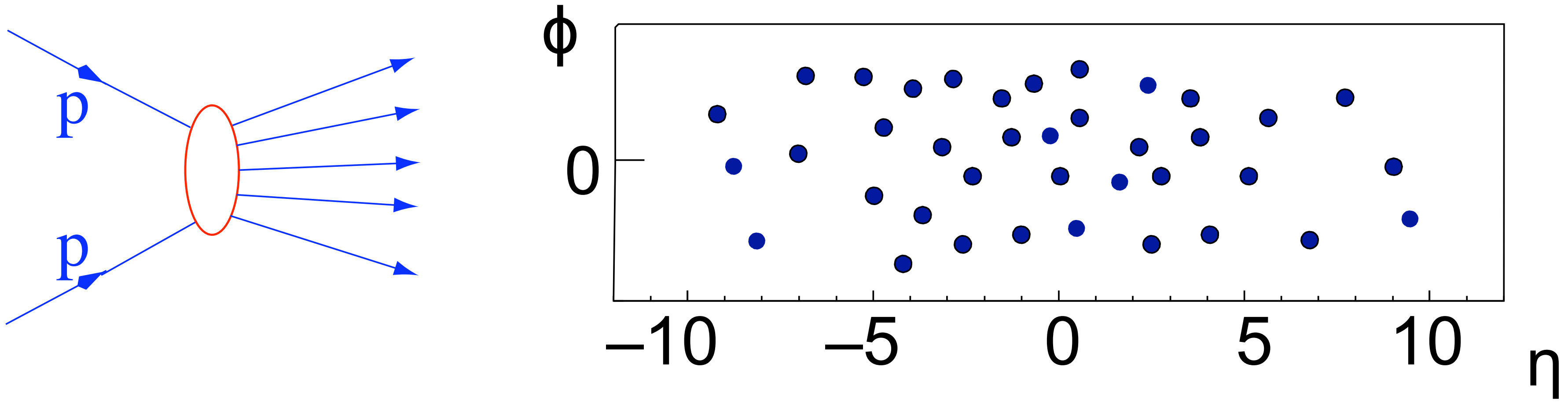
[after M. Leyton, Rencontres de Moriond QCD 2009]

Total Cross Section

- Total proton-proton cross section:

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{elas}} + \sigma_{\mathrm{SD}} + \sigma_{\mathrm{DD}} + \sigma_{\mathrm{ND}} + \sigma_{\mathrm{CD}}$$

Non-Diffractive Inelastic Scattering



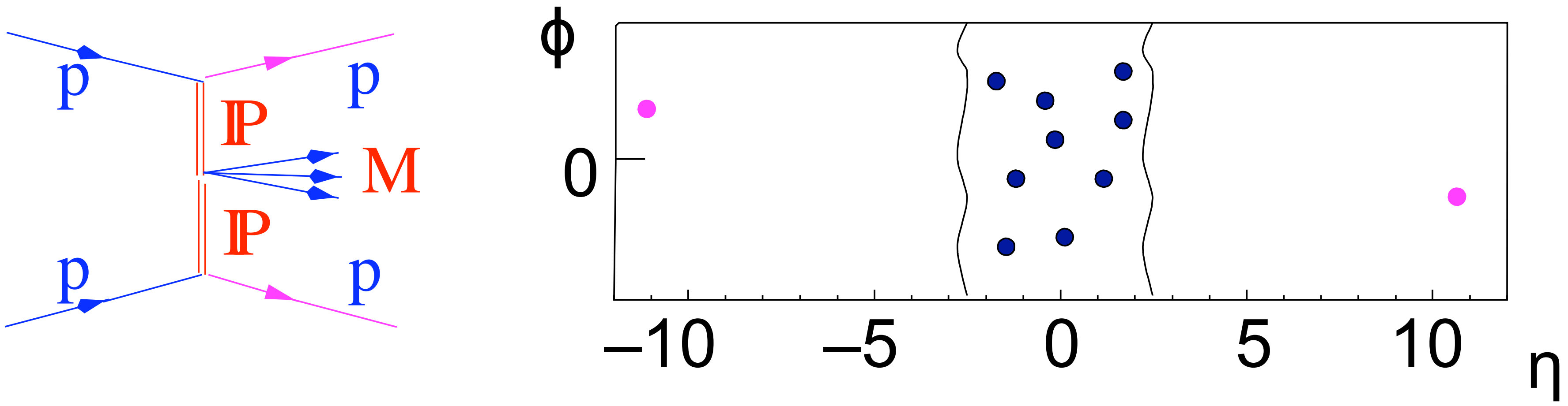
[after M. Leyton, Rencontres de Moriond QCD 2009]

Total Cross Section

- Total proton-proton cross section:

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{elas}} + \sigma_{\mathrm{SD}} + \sigma_{\mathrm{DD}} + \sigma_{\mathrm{ND}} + \sigma_{\mathrm{CD}}$$

Central Diffractive Dissociation



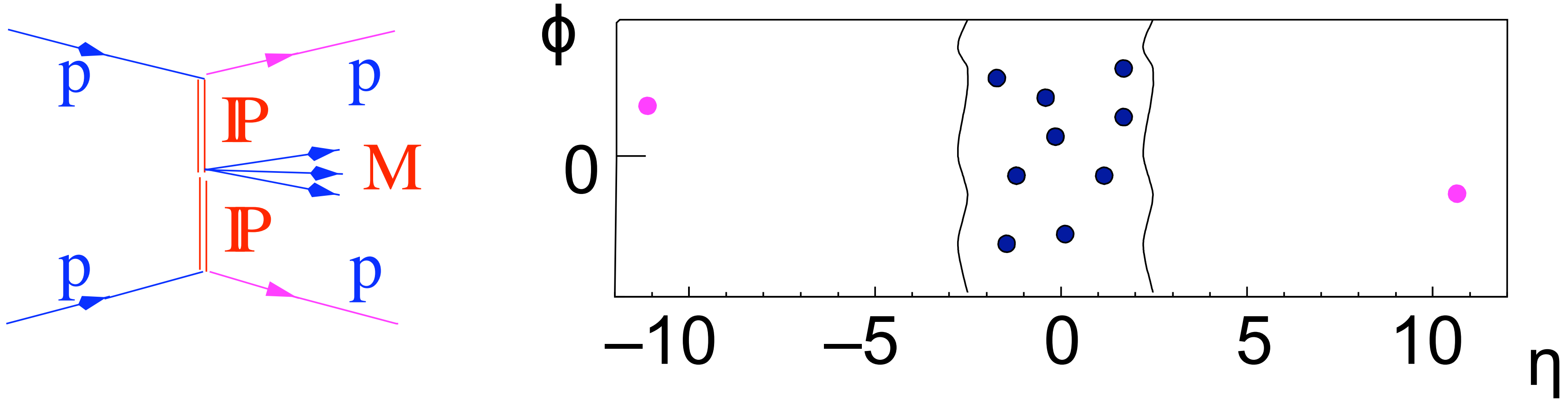
[after M. Leyton, Rencontres de Moriond QCD 2009]

Total Cross Section

- Total proton-proton cross section:

$$\sigma_{\text{tot}} = \sigma_{\text{elas}} + \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{ND}} + \sigma_{\text{CD}}$$

Central Diffractive Dissociation



[after M. Leyton, Rencontres de Moriond QCD 2009]

“Minimum bias” = non-single diffractive: $\sigma_{\text{MB}} = \sigma_{\text{DD}} + \sigma_{\text{ND}}$

Minimum Bias Physics

- Physics with sample recorded with trigger on minimum detector activity (with minimum influence on selection)
- Interesting in itself: proton-proton scattering in a new energy regime
- Can be done with the first few 100,000 triggers ("day 1")
- Important for higher luminosities: at 10^{34} cm^{-2} s^{-1}, each event accompanied by 25 minimum bias events ("pileup")

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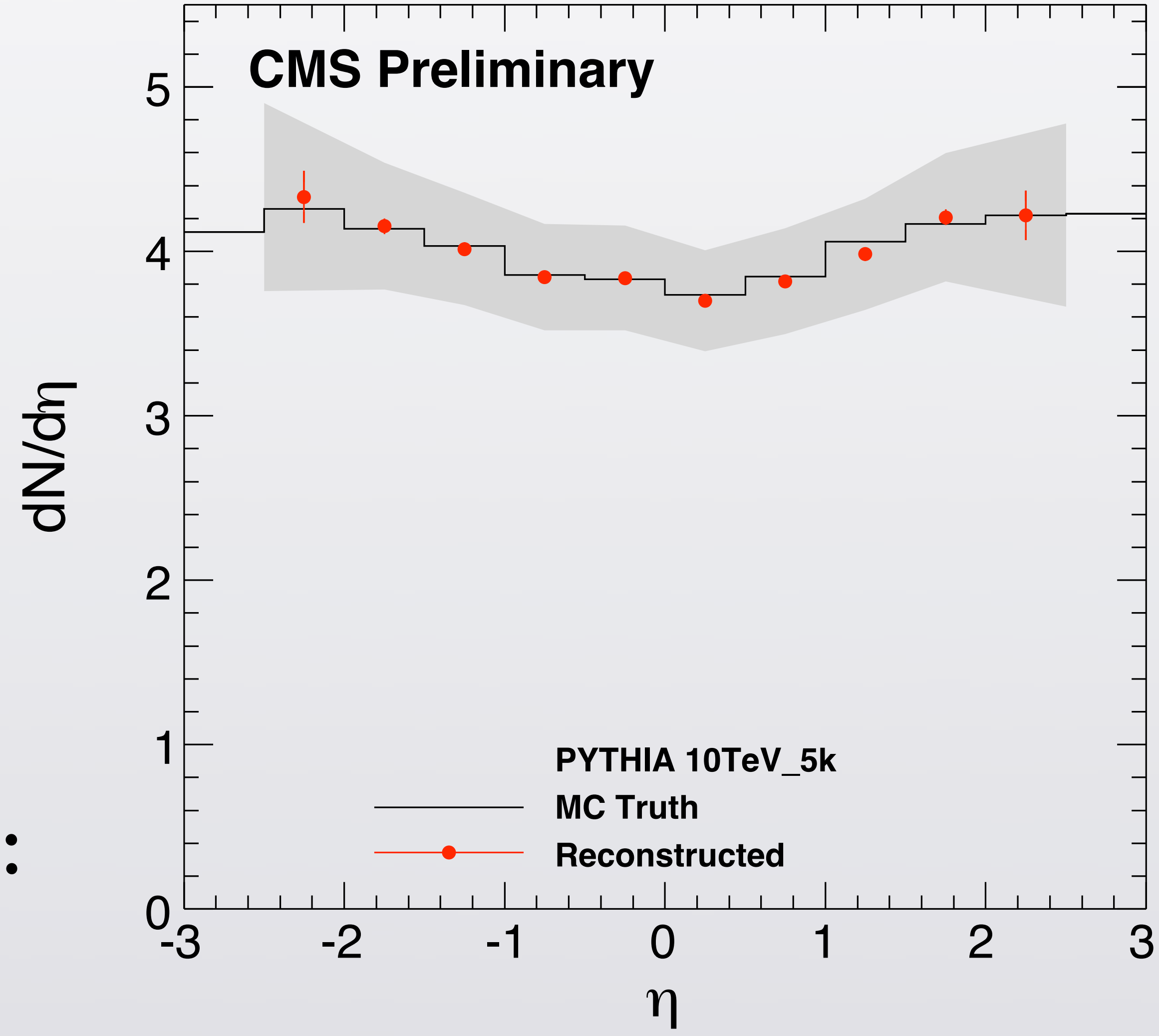
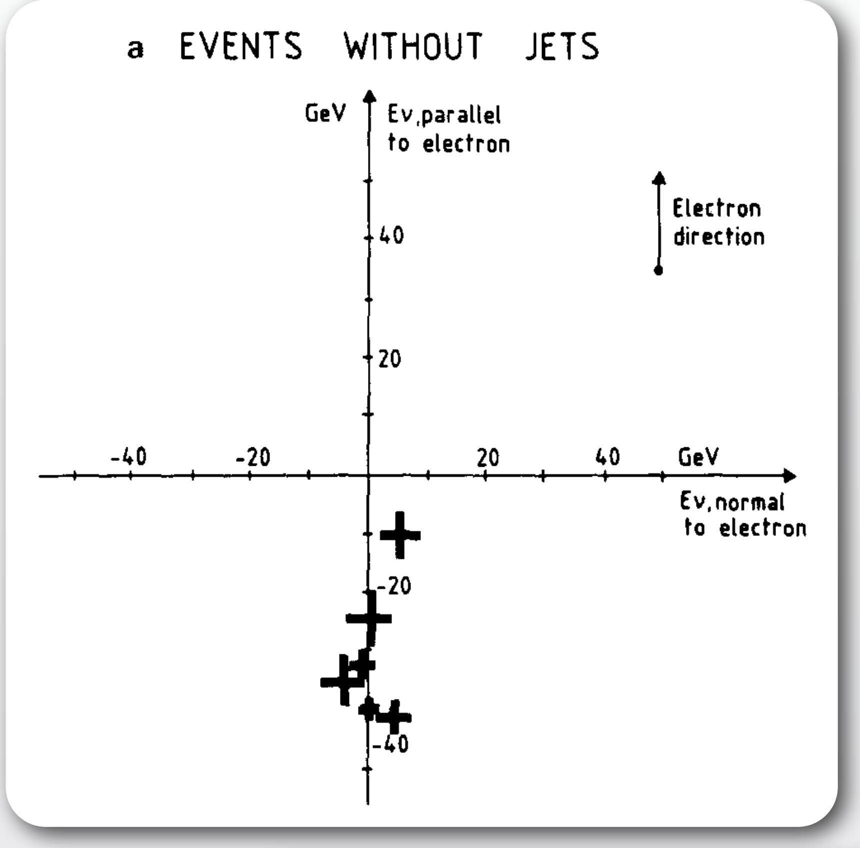
Example: Pseudorapidity Density of Charged Particles



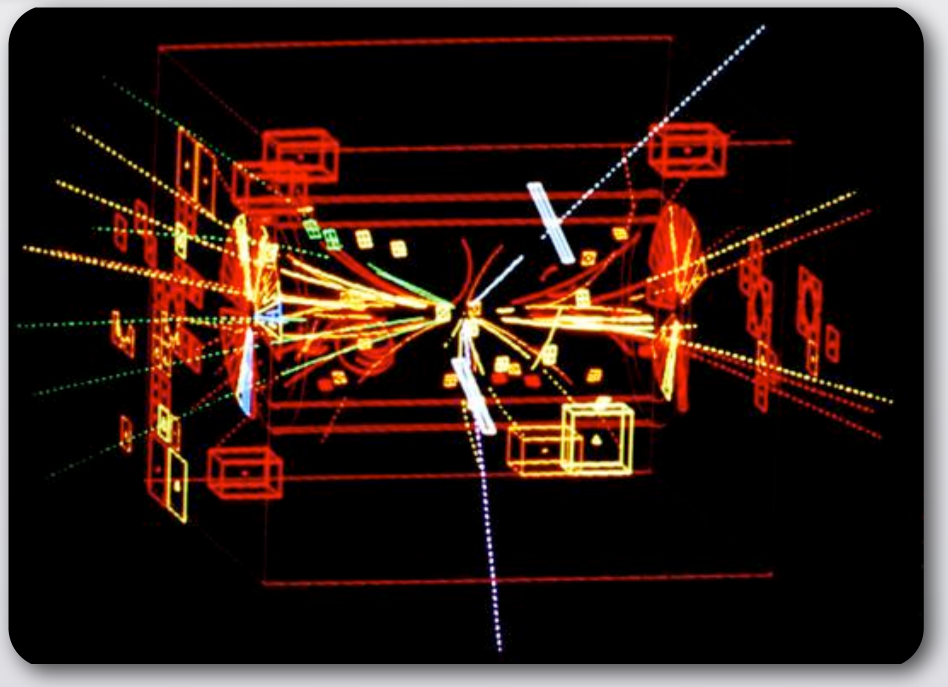
[CMS PAS QCD-09-002]

“Standard Candles”: W, Z

- The old motto in physics: “Yesterday’s signal is today’s background is tomorrow’s calibration source”
- Prime calibration source at the LHC: W and Z bosons
  - Discovered at Sp$\bar{p}$S (CERN) in 1982/1983
  - Properties (mass, cross section, etc.) known very precisely from LEP, SLC, Tevatron
  - Easy to select & trigger on



[G. Arnison et al., Phys. Lett. 122B (1983) 103]



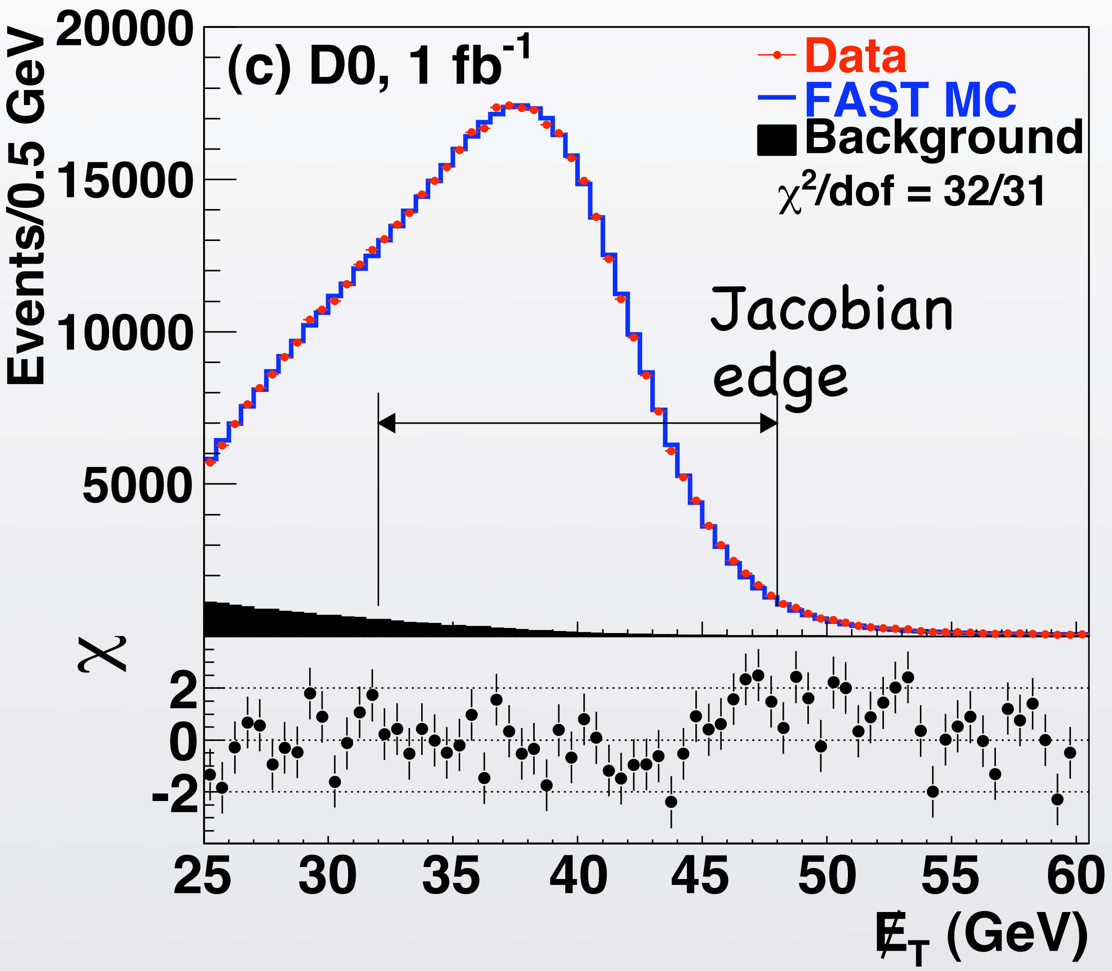
Z Event at UA1 [CERN]

W Selection

- Reconstruction of W → lν:
  - Trigger & selection: single isolated high-p_T lepton (e.g. $p_T > 20$ GeV)
  - Typical observables: p_T of lepton, MET, "transverse mass"

$$m_T^2 = 2p_T^\ell \cdot p_T^\nu \left(1 - \cos(\Delta\phi^{\ell\nu})\right)$$

  - "Jacobian edge" e.g. in MET: sharp edge at 1/2× W mass
- W → eν used e.g. for
  - Cross section → luminosity
  - Missing transverse energy



[DØ, arXiv:0908.0766]

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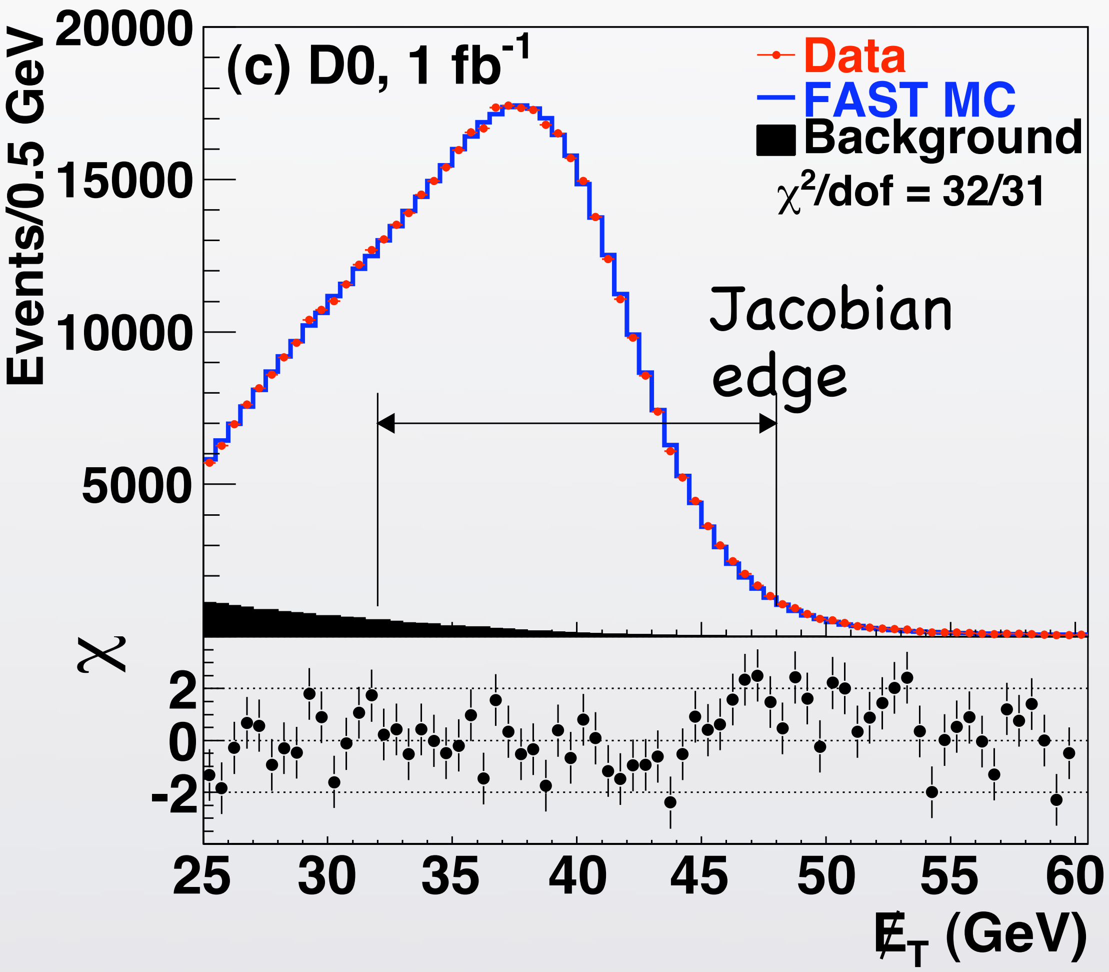


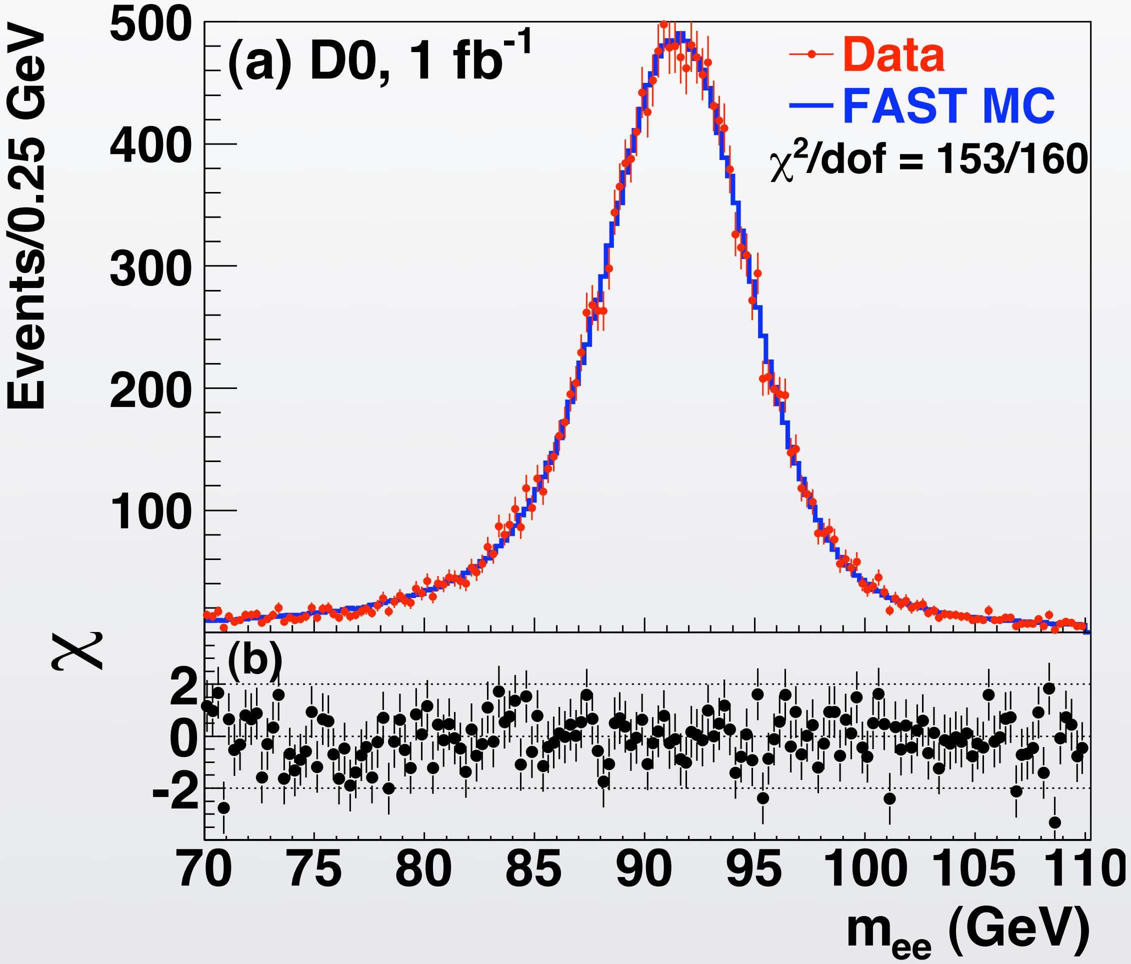
[DØ, arXiv:0908.0766]

Tevatron Run II: excellent understanding of W and Z (after 8 years of data taking…)

Z Selection

- Reconstruction of Z → l^+l^-:
  - Trigger: 1–2 isolated high-p_T leptons (e.g. p_T > 20 GeV)
  - Selection: lepton pair with opposite charge sign, invariant mass in window around $m_Z \approx 91$ GeV

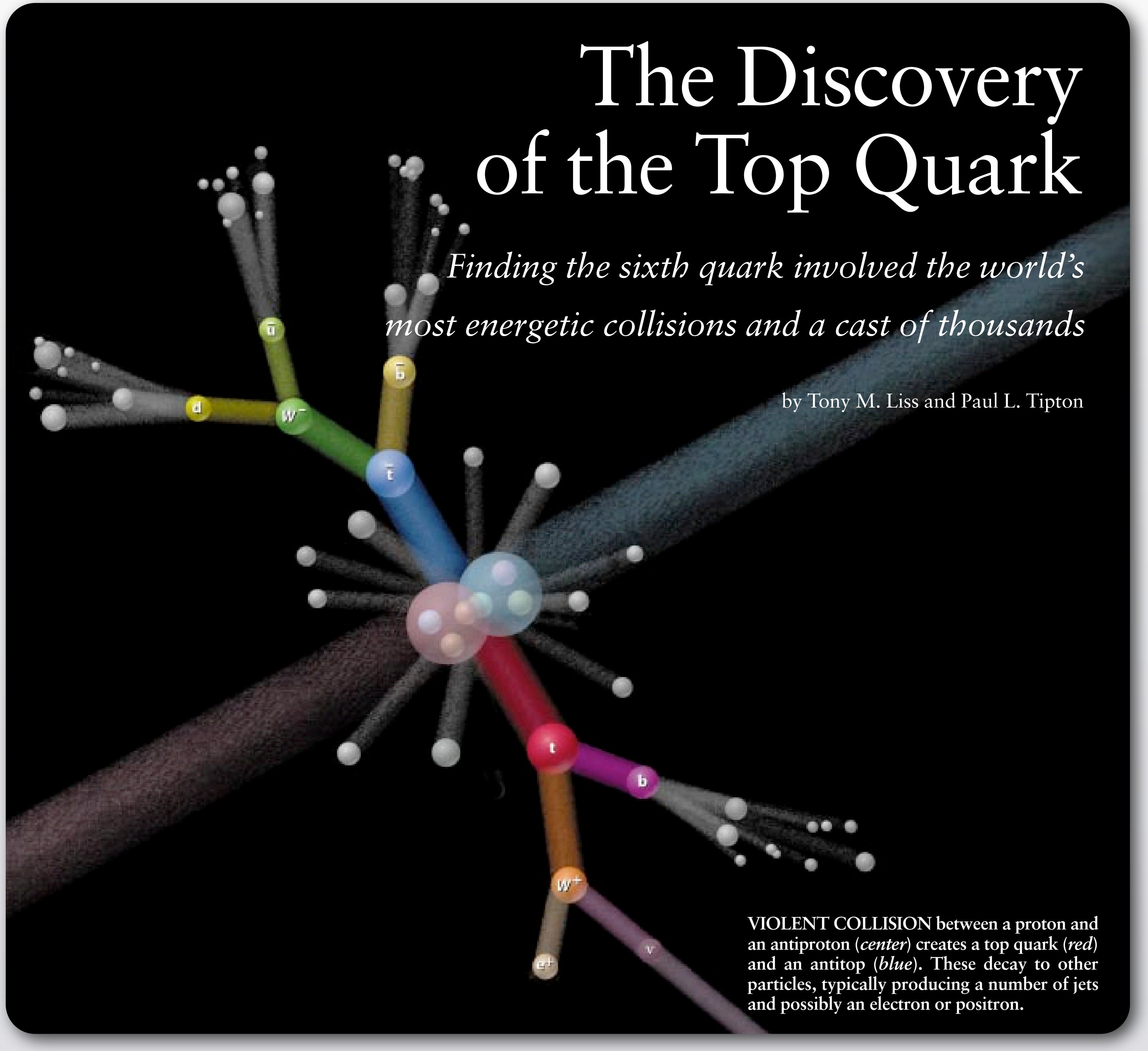
$$m^2_{\ell^+\ell^-} = (E^{\ell^+} + E^{\ell^-})^2 - (\vec{p}^{\,\ell^+} + \vec{p}^{\,\ell^-})^2$$



[DØ, arXiv:0908.0766]

- Z → e^+e^- used e.g. for
  - Electron energy scale
  - Trigger efficiency
  - Cross section → luminosity

The Top Quark



The Discovery of the Top Quark

Finding the sixth quark involved the world's most energetic collisions and a cast of thousands

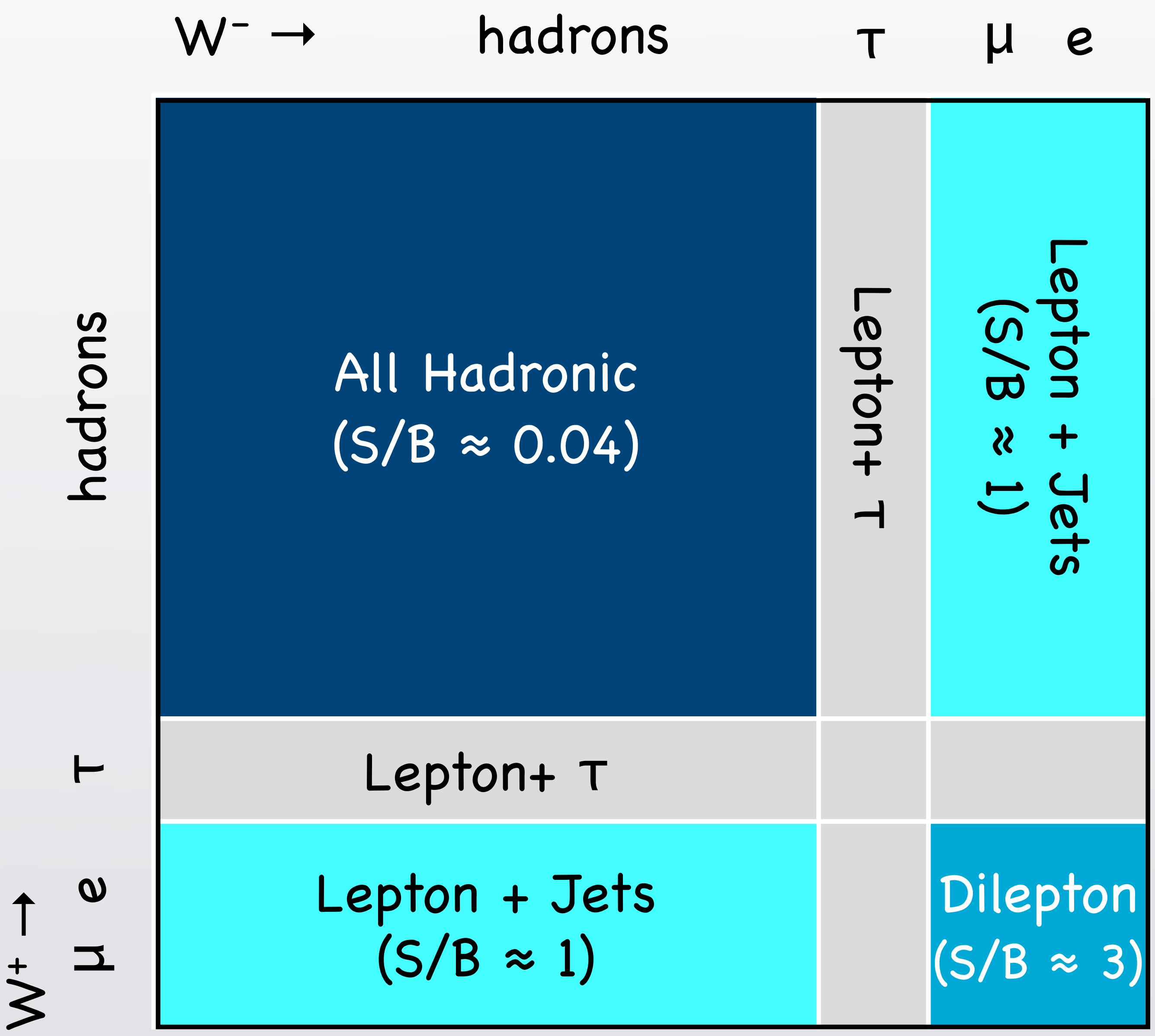
by Tony M. Liss and Paul L. Tipton

VIOLENT COLLISION between a proton and an antiproton (*center*) creates a top quark (*red*) and an antitop (*blue*). These decay to other particles, typically producing a number of jets and possibly an electron or positron.

[Scientific American, September 1997]

- Top quark discovery 1995 at the Tevatron
- The top is special:
  - Heavy: m_t = 173 GeV (cf. gold atom)
  - The only "free quark": decays before hadronization
- Tevatron: about 100k tops produced to date
- LHC = "top quark factory" → millions!

Top Decays

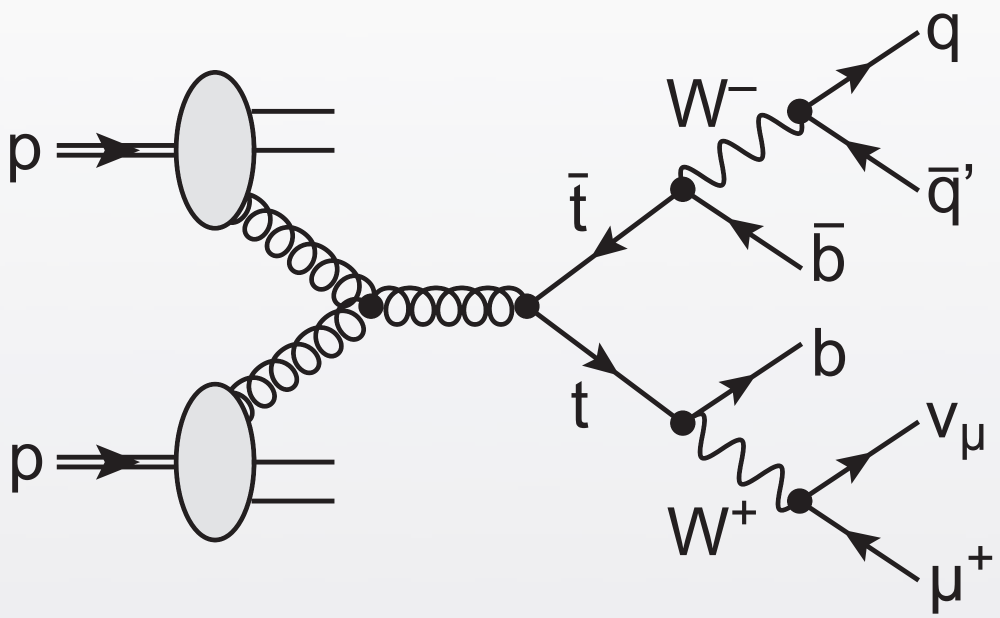


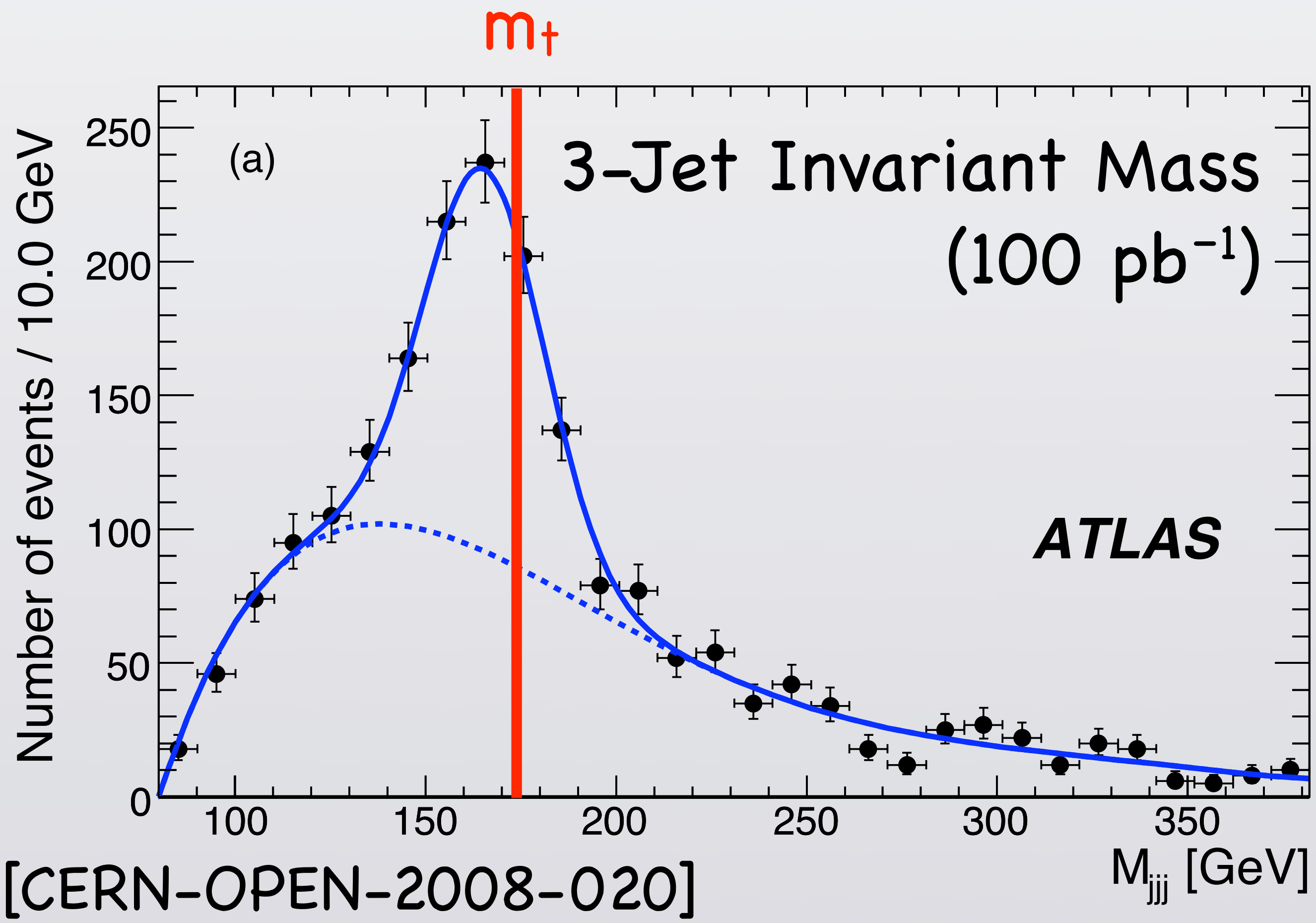
W⁺ → \ W⁻ →	hadrons	τ	μ e
hadrons	All Hadronic (S/B ≈ 0.04)	Lepton+ τ	Lepton + Jets (S/B ≈ 1)
τ	Lepton+ τ		
μ e	Lepton + Jets (S/B ≈ 1)		Dilepton (S/B ≈ 3)

- SM top decay:
  t → Wb (BR ≈ 100%)
- tt decay characterized by W decays:
  - All-Hadronic: large QCD background
  - Lepton+Jets: "gold-plated" channel
  - Dilepton: very clean, but small branching fraction
- Main background process: "W+jets"

Top as a “Standard Candle”

- Top moves from signal to calibration source, too!
  - Produced copiously @ LHC
  - Key background for new physics
  - Final states contain “everything”: leptons, MET, many jets (always two from b quarks)
- Use top to calibrate e.g.
  - (B-)jet energy scale
  - B-tagging algorithms





[CERN-OPEN-2008-020]

Chapter 8

How to Measure a Cross Section

Counting Experiment

- Simplest approach to measuring cross sections: "counting experiment" (also: "cut & count method")
- Master formula:

$$\sigma = \frac{N^{\mathrm{obs}} - N^{\mathrm{bkg}}}{\int \mathscr{L}\,\mathrm{d}t \cdot \varepsilon}$$

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Number of observed events

just count…

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Luminosity

determined by accelerator, triggers, ...

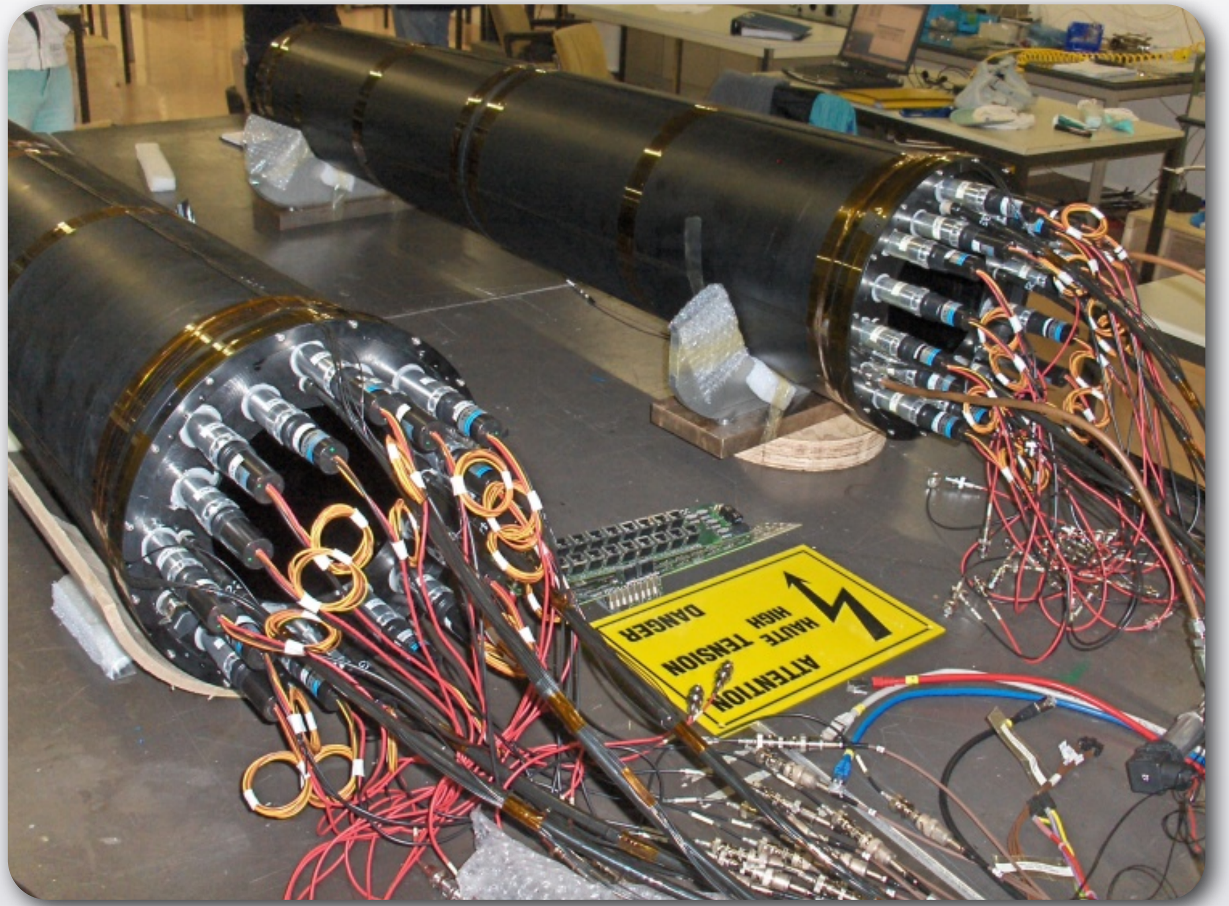
Efficiency

many factors, optimized by experimentalist

Luminosity

- Accelerator "generates" luminosity (cf. yesterday's lecture)
- Experiments: measure luminosity with specialized detectors
  - Principle: measure rate of well-known process
  - Example ATLAS: LUCID = Cherenkov counters to measure rate of inelastic pp scattering at $|\eta| \approx 5.8$ (accuracy: approx. 5%)

ATLAS LUCID Detectors



[atlas.ch]

- Trigger "prescale": take only every n-th triggered event → effective luminosity reduced by factor of n

Signal Selection

- Design selection criteria ("cuts") to isolate signal from background
- Optimize e.g. on:
  - Signal-to-background ratio: $N^{\text{sig}}/N^{\text{bkg}}$
  - Signal significance: $N^{\text{sig}}/\sqrt{N^{\text{sig}}+N^{\text{bkg}}}$
  - Optimization uses simulated data (MC) or control samples
  - Don't optimize by looking at the signal in data!

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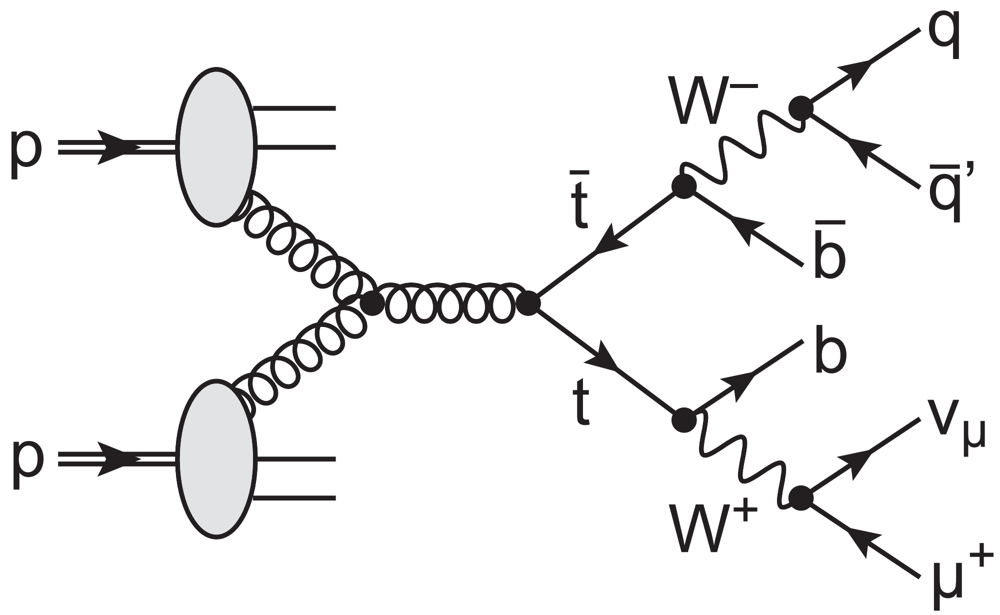
Example: Top (Lepton+Jets)



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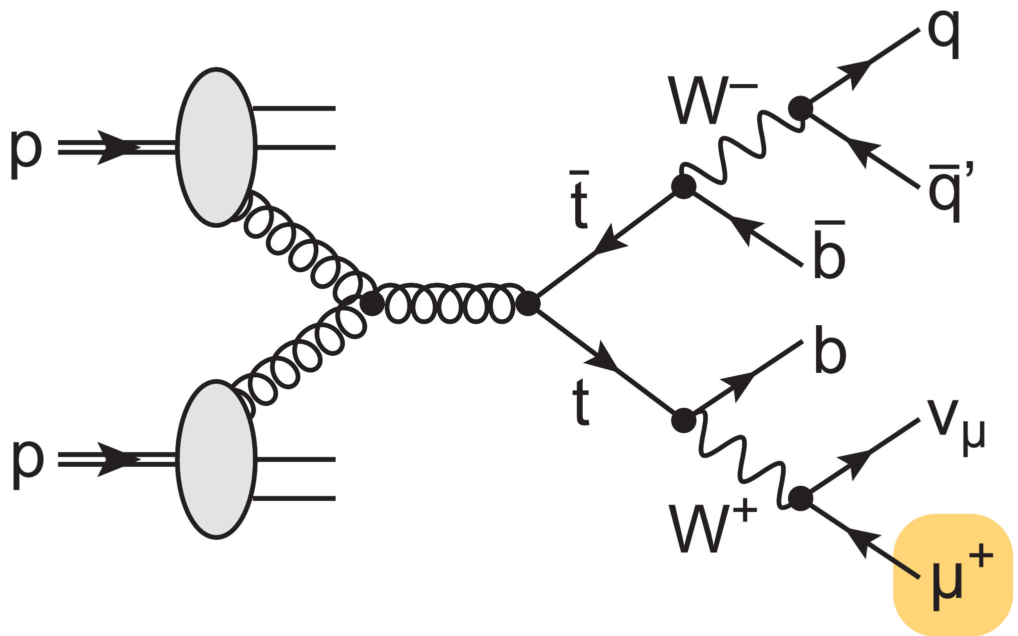

high-p_T lepton: $p_T > 20$ GeV

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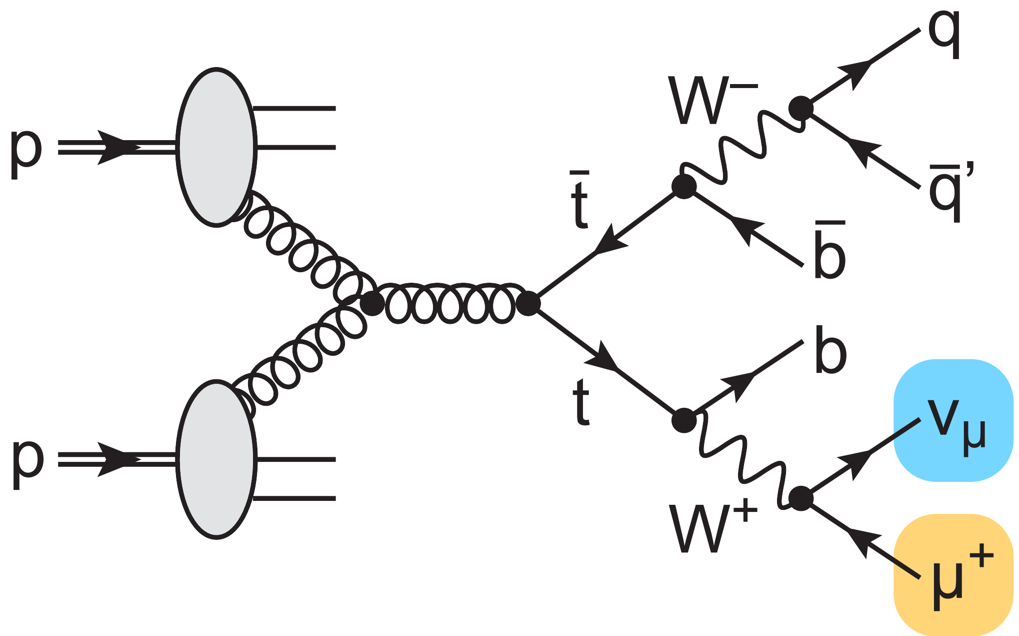

high-p_T lepton: $p_T > 20$ GeV

neutrino: MET > 30 GeV

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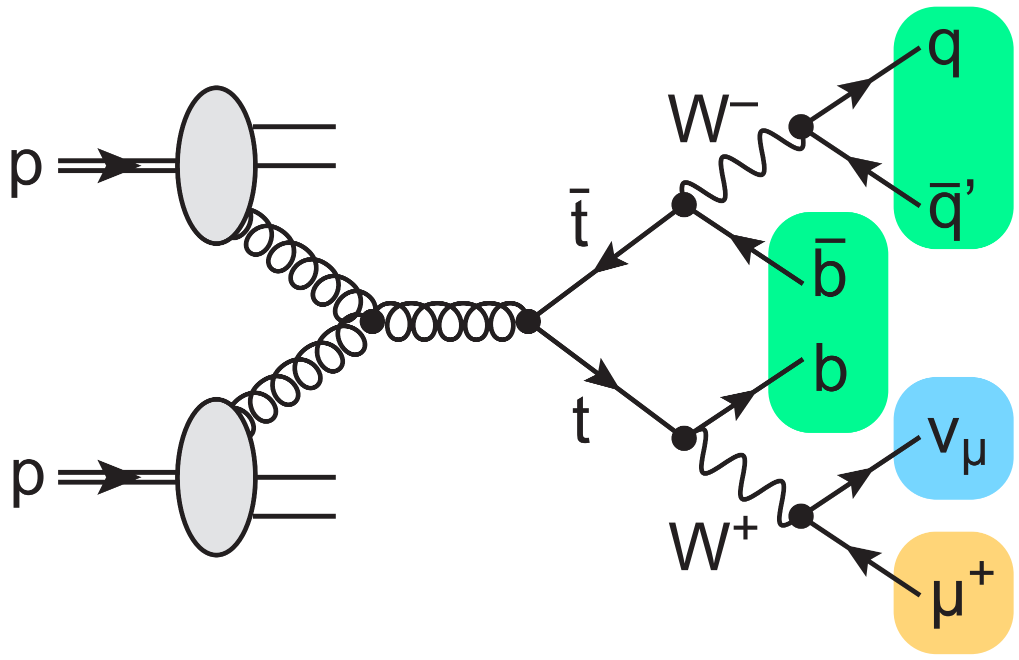

high-p_T lepton: p_T > 20 GeV

neutrino: MET > 30 GeV

4 high-p_T jets: p_T > 40 GeV

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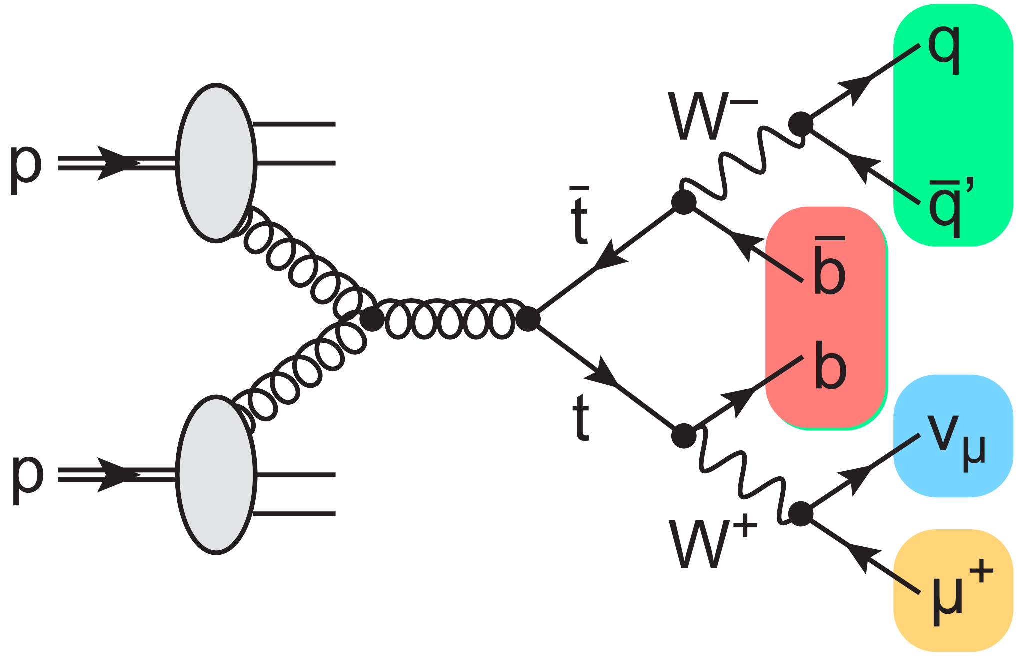


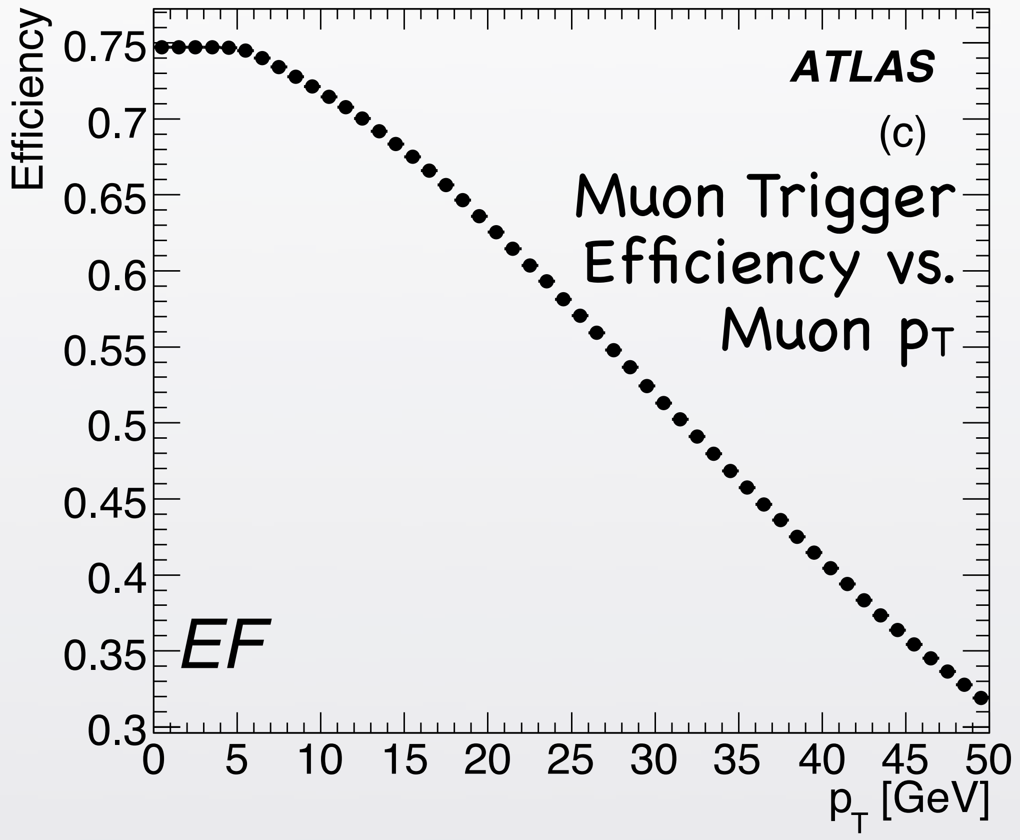
high-p_T lepton: p_T > 20 GeV

neutrino: MET > 30 GeV

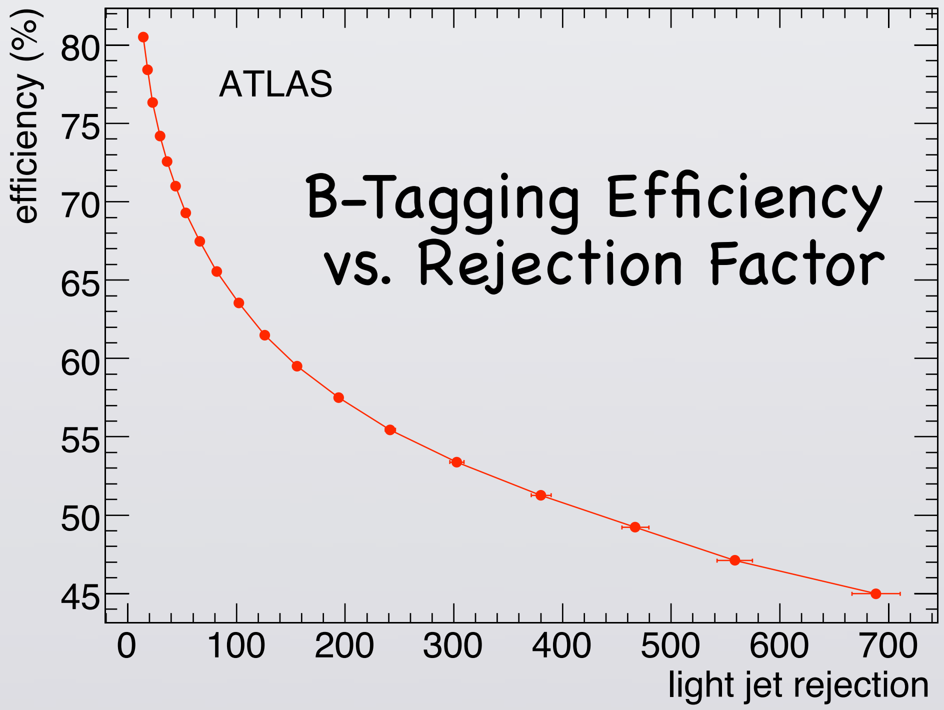
4 high-p_T jets: p_T > 40 GeV

2 b-jets: 1 or 2 b-tags

Efficiency



Muon Trigger Efficiency vs. Muon p_T



B-Tagging Efficiency vs. Rejection Factor

[CERN-OPEN-2008-020]

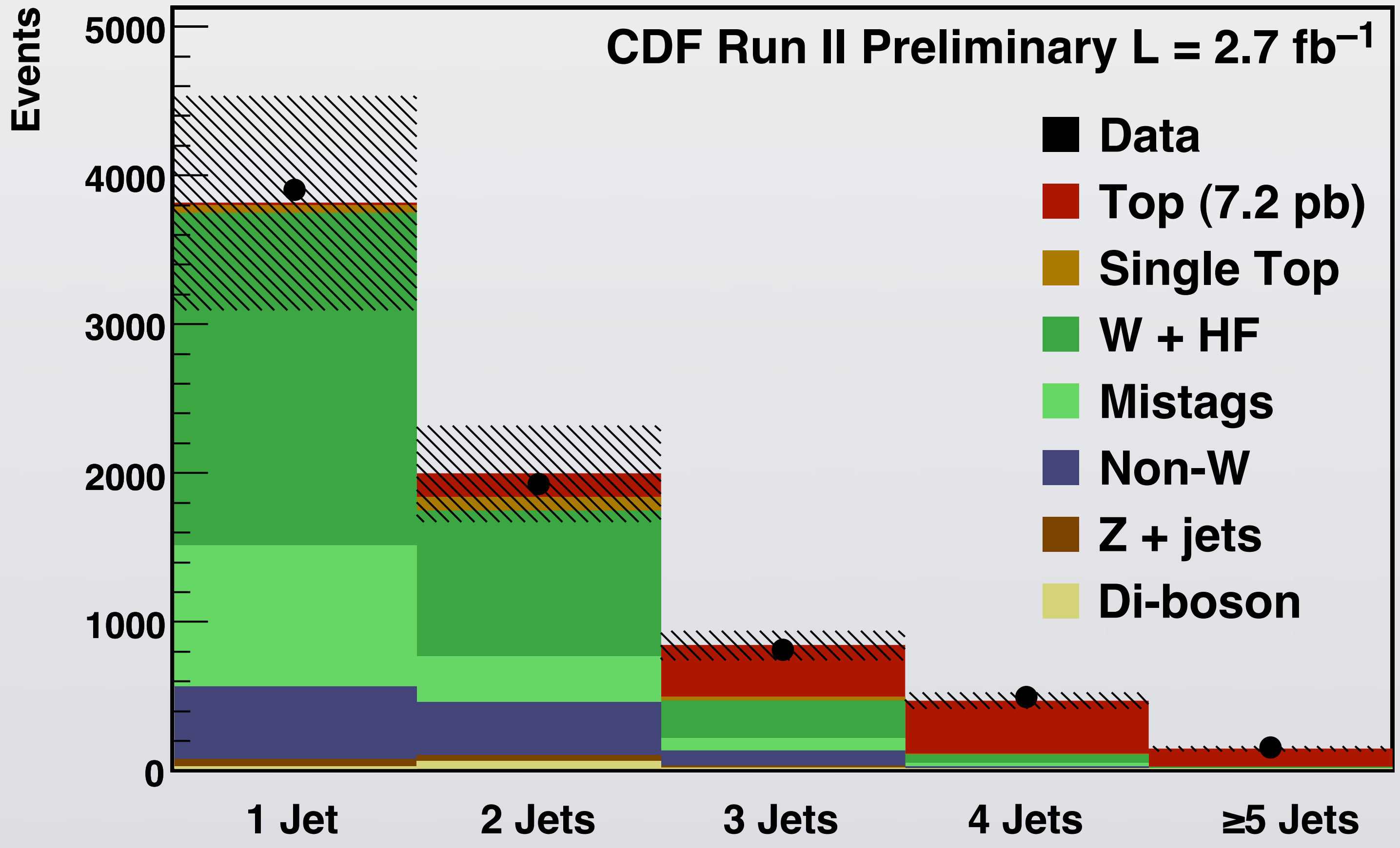
- Efficiency measured in MC or control samples:

$$\varepsilon = \frac{\text{Number of events used in analysis}}{\text{Number of events produced}}$$

- Composed of many factors:
  - Cut efficiency (data/MC)
  - Geometric acceptance (MC)
  - Trigger efficiency (from data)
  - Particle ID efficiency (data)
- Each factor could depend on event properties (η, ϕ, p_T, …)

Background

- Physics background:
  - From data (control samples) & MC simulation
  - Which processes are indistinguishable from signal and pass signal selection?



- "Instrumental" background: from data
  - Misidentification, e.g. jet looks like ("fakes") electron
  - Noise in detectors, beam backgrounds, ...

[http://www-cdf.fnal.gov/physics/new/top/2008/xsection/ttbar_secvtx_3invfb/]

Cross Section Summary

Number of observed events
just count...

Background
measured from data/ calculated from theory

$$\sigma = \frac{N^{\mathrm{obs}} - N^{\mathrm{bkg}}}{\int \mathscr{L}\,\mathrm{d}t \cdot \varepsilon}$$

Luminosity
determined by accelerator, triggers, ...

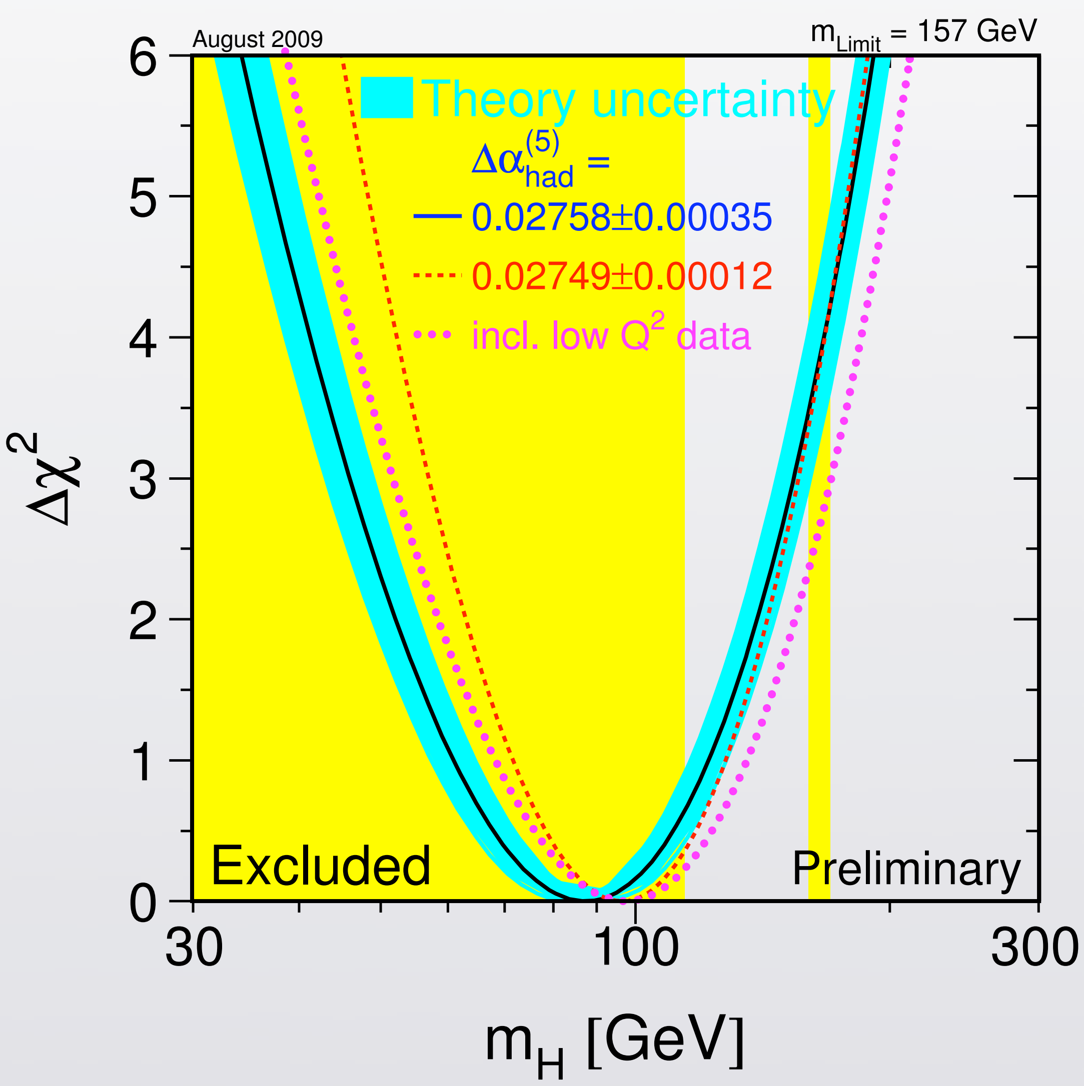
Efficiency
many factors, optimized by experimentalist

Chapter 9

Hunting for the Higgs

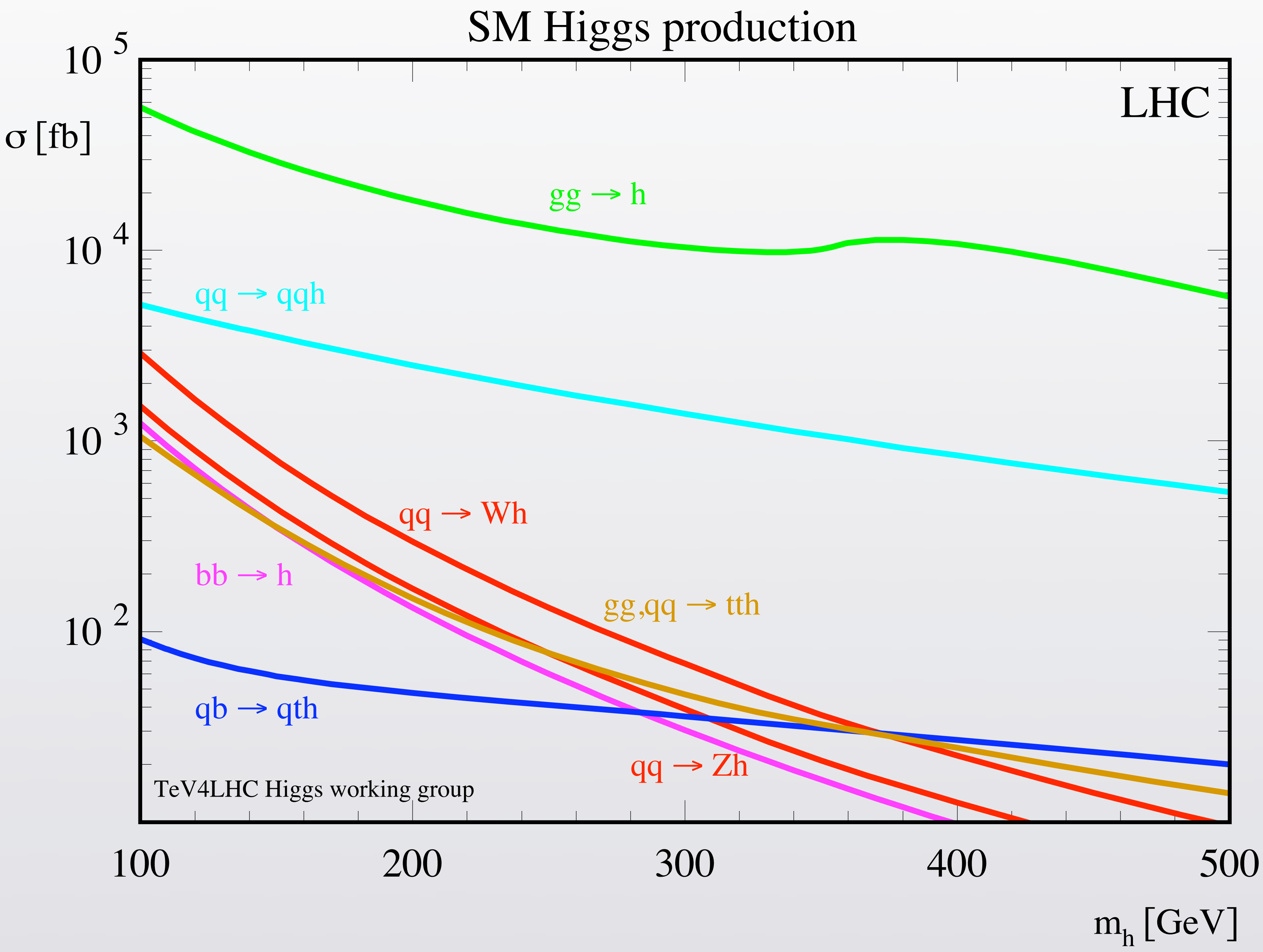
Motivation

- Higgs boson: cornerstone of SM
  - Electroweak symmetry breaking, masses of particles
  - Common lore: "If there's a Higgs, the LHC will find it!"
  - Higgs search is still hard work and will likely take many years
- What we know about the Higgs:
  - Everything (production channels, decay rates) … but the mass
  - Indirect (weak) mass constraints from electroweak precision measurements: $m_H < 157$ GeV


"Blue Band Plot" 2009

[http://lepewwg.web.cern.ch/LEPEWWG/]

LHC Higgs Production



[http://maltoni.home.cern.ch/maltoni/TeV4LHC/index.html]

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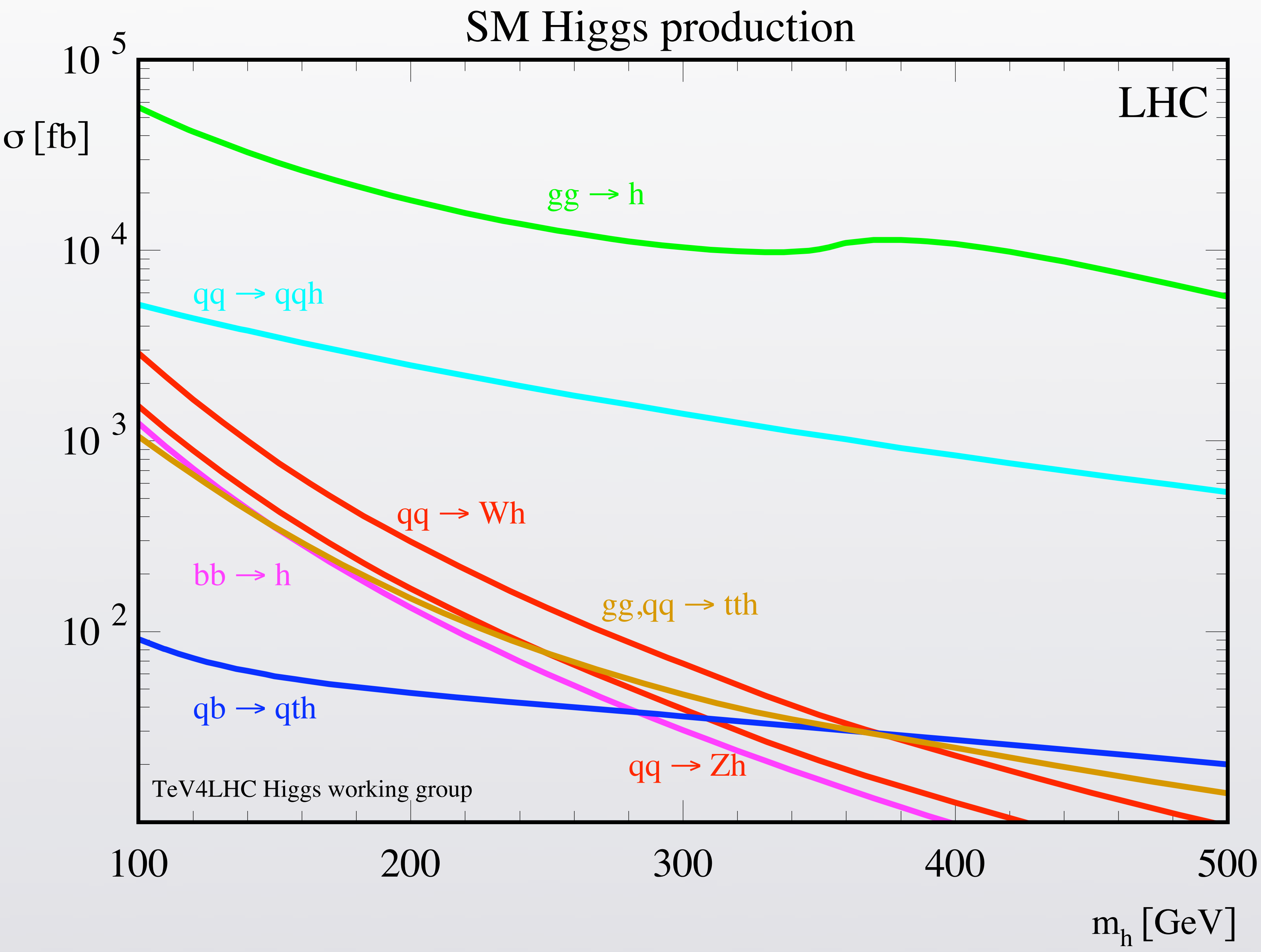

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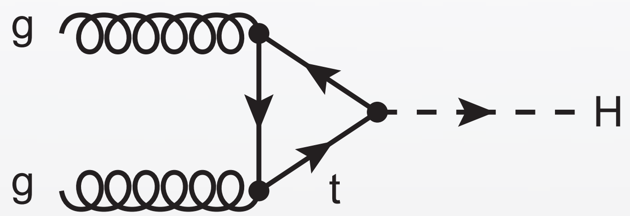
Gluon Gluon Fusion



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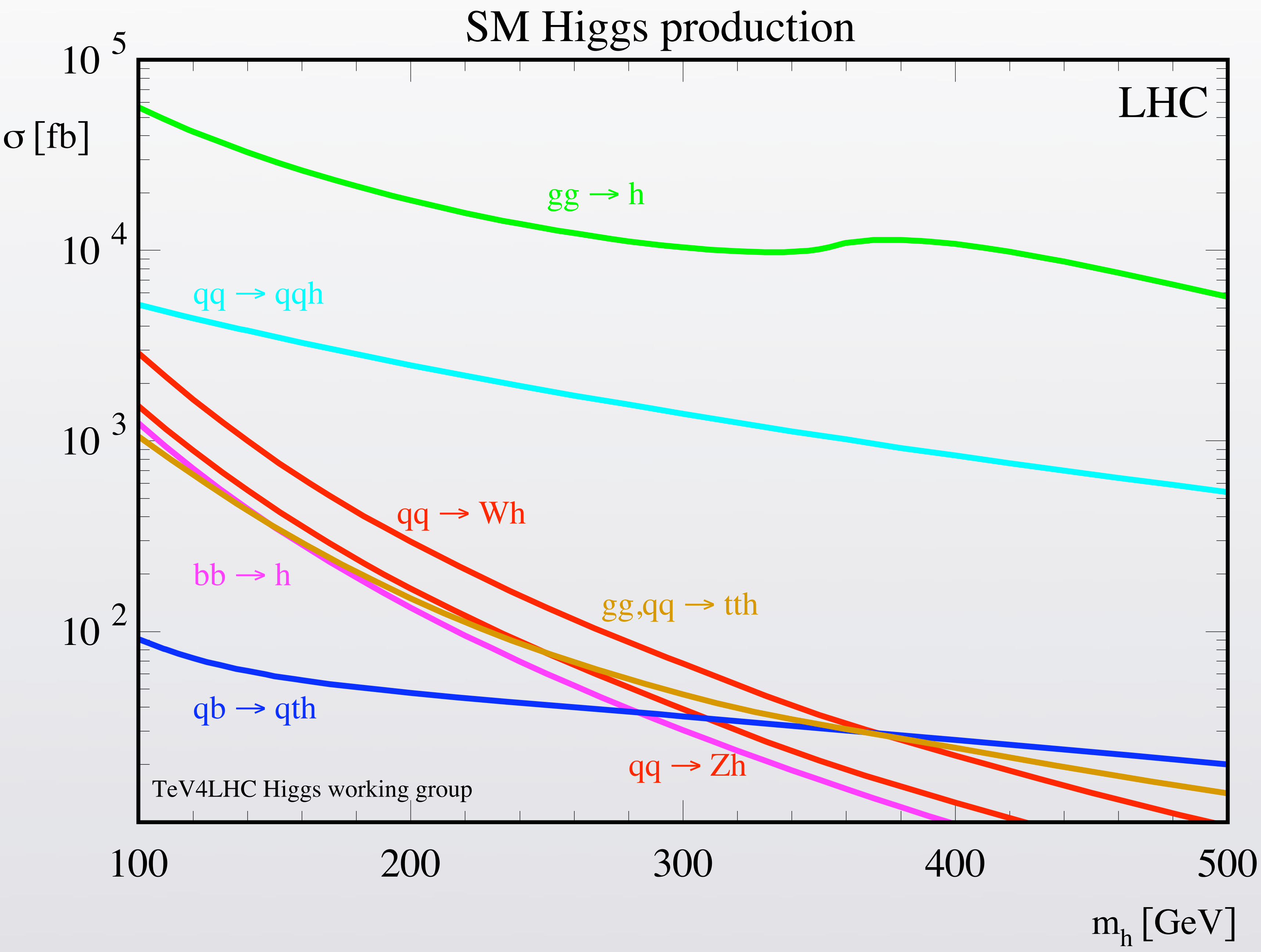

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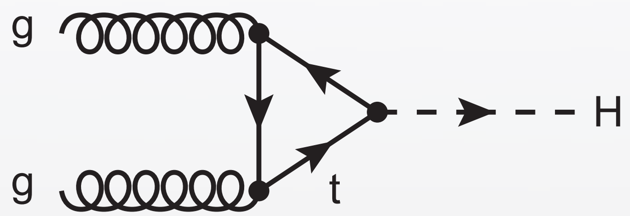
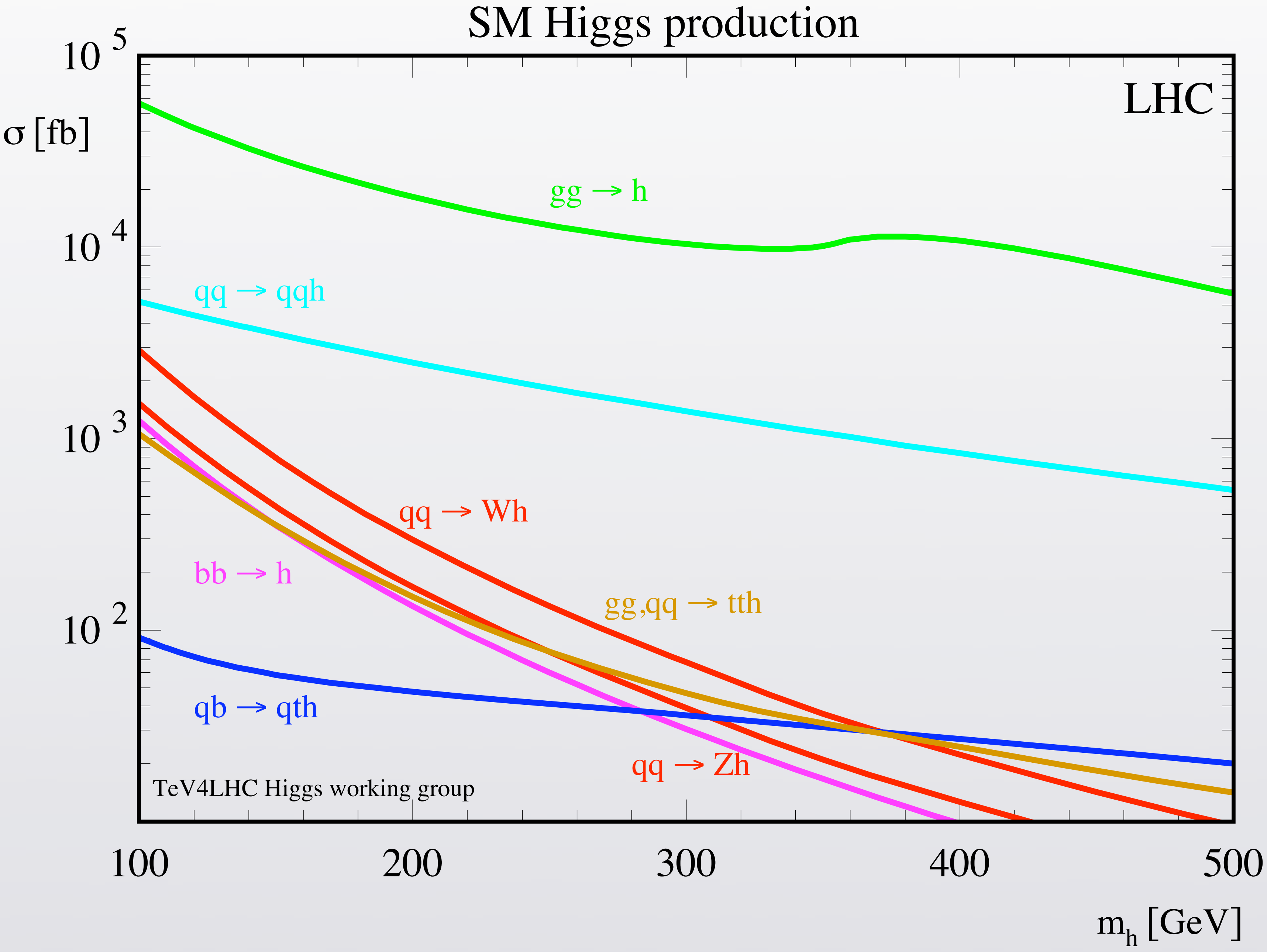


Associated Production I

LHC Higgs Production



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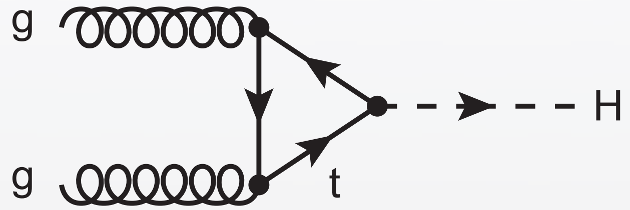
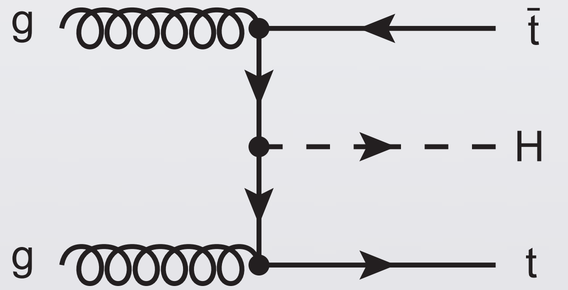


Associated Production I

Associated Production II



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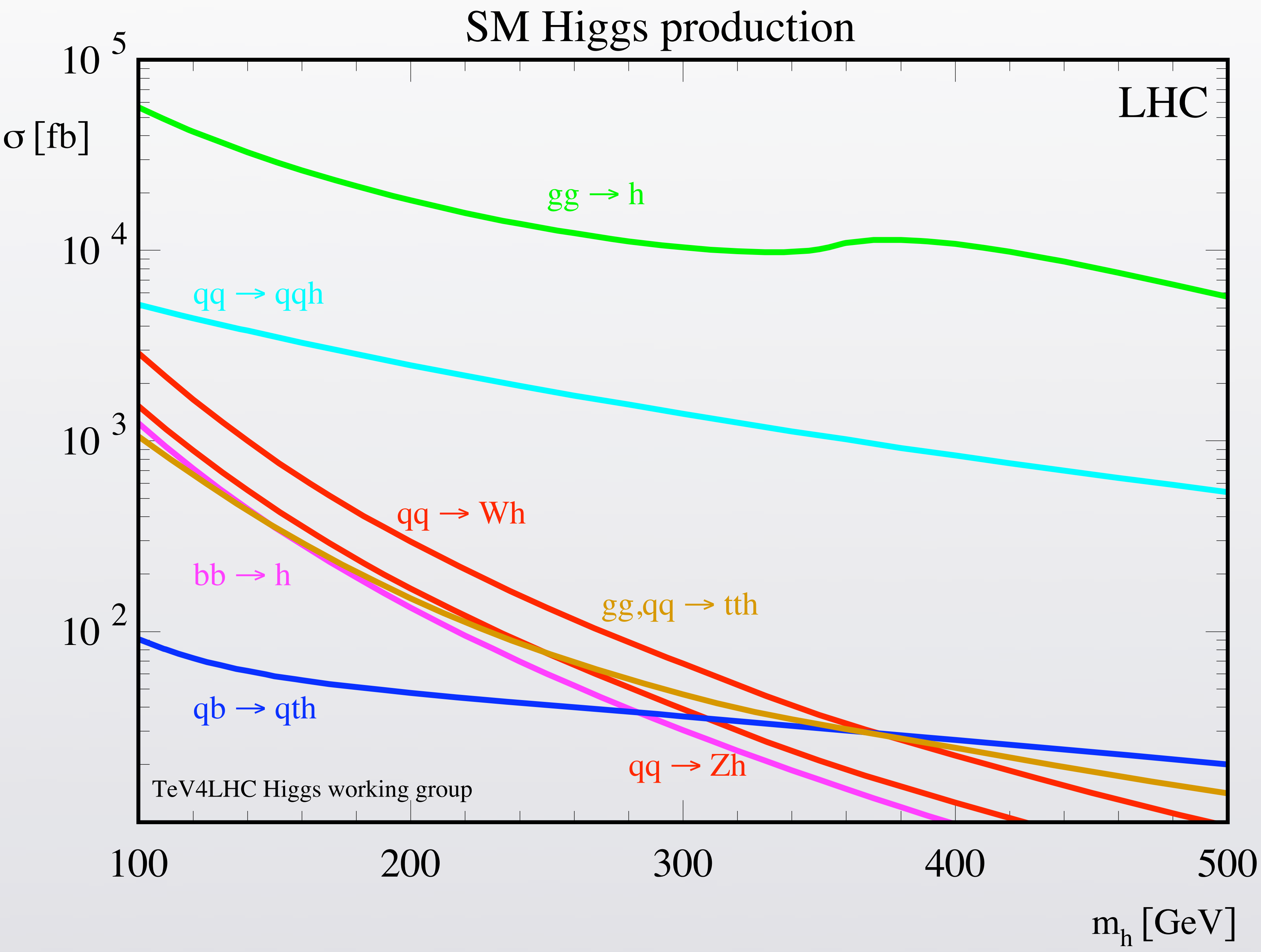

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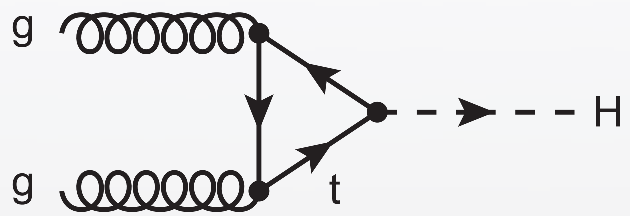

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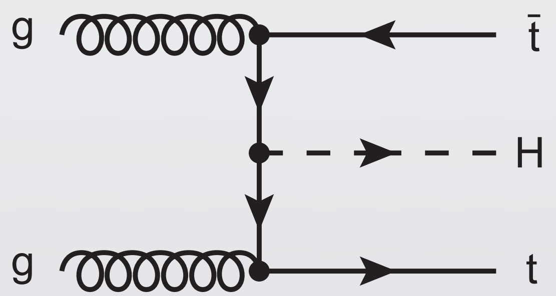
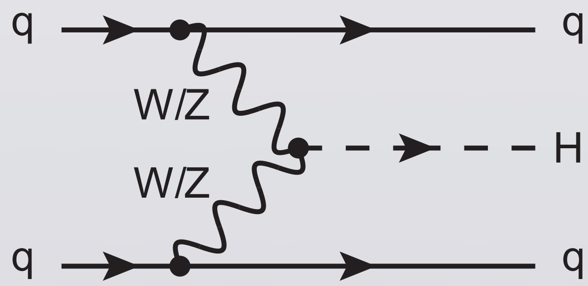
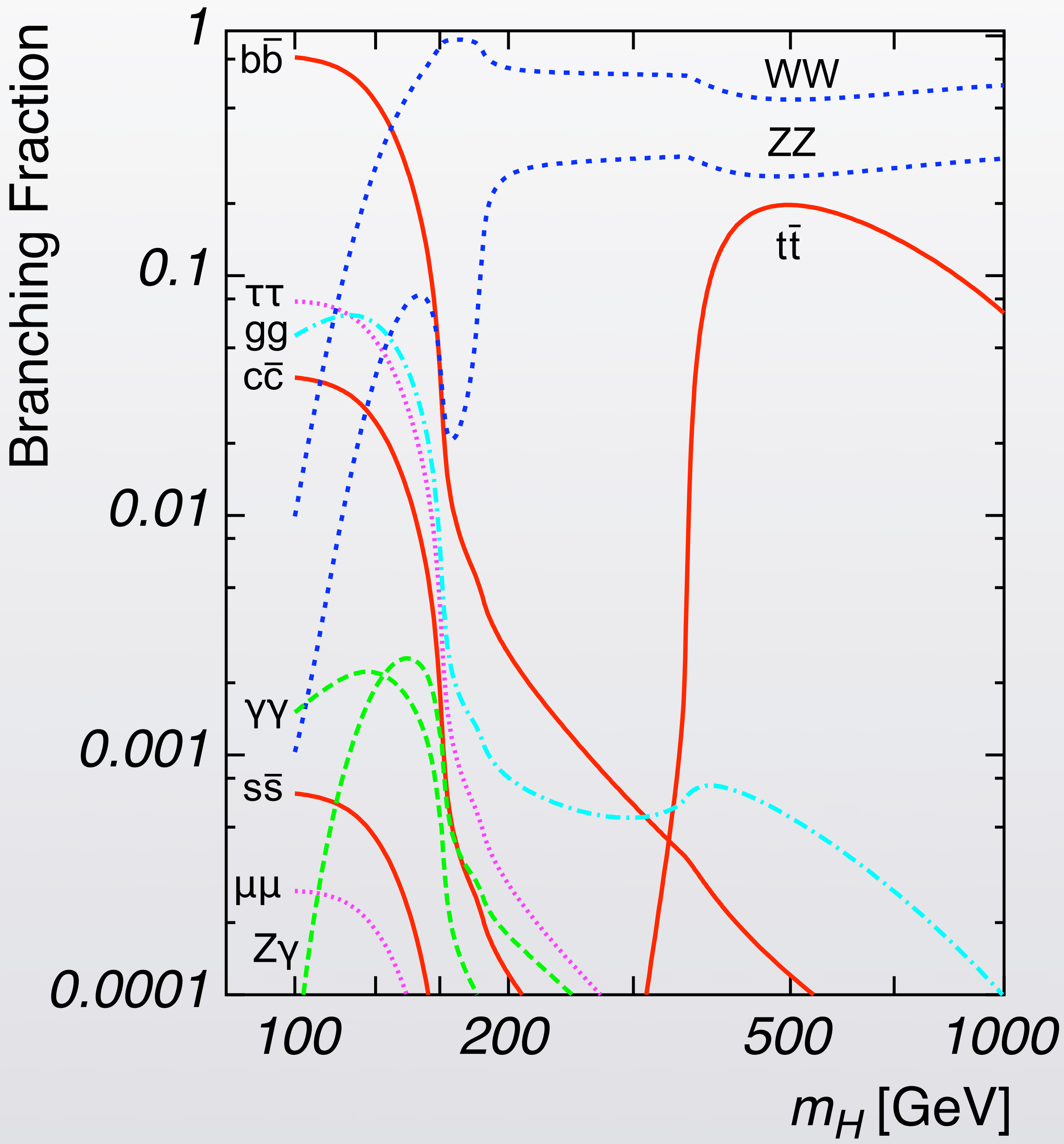


Vector Boson Fusion



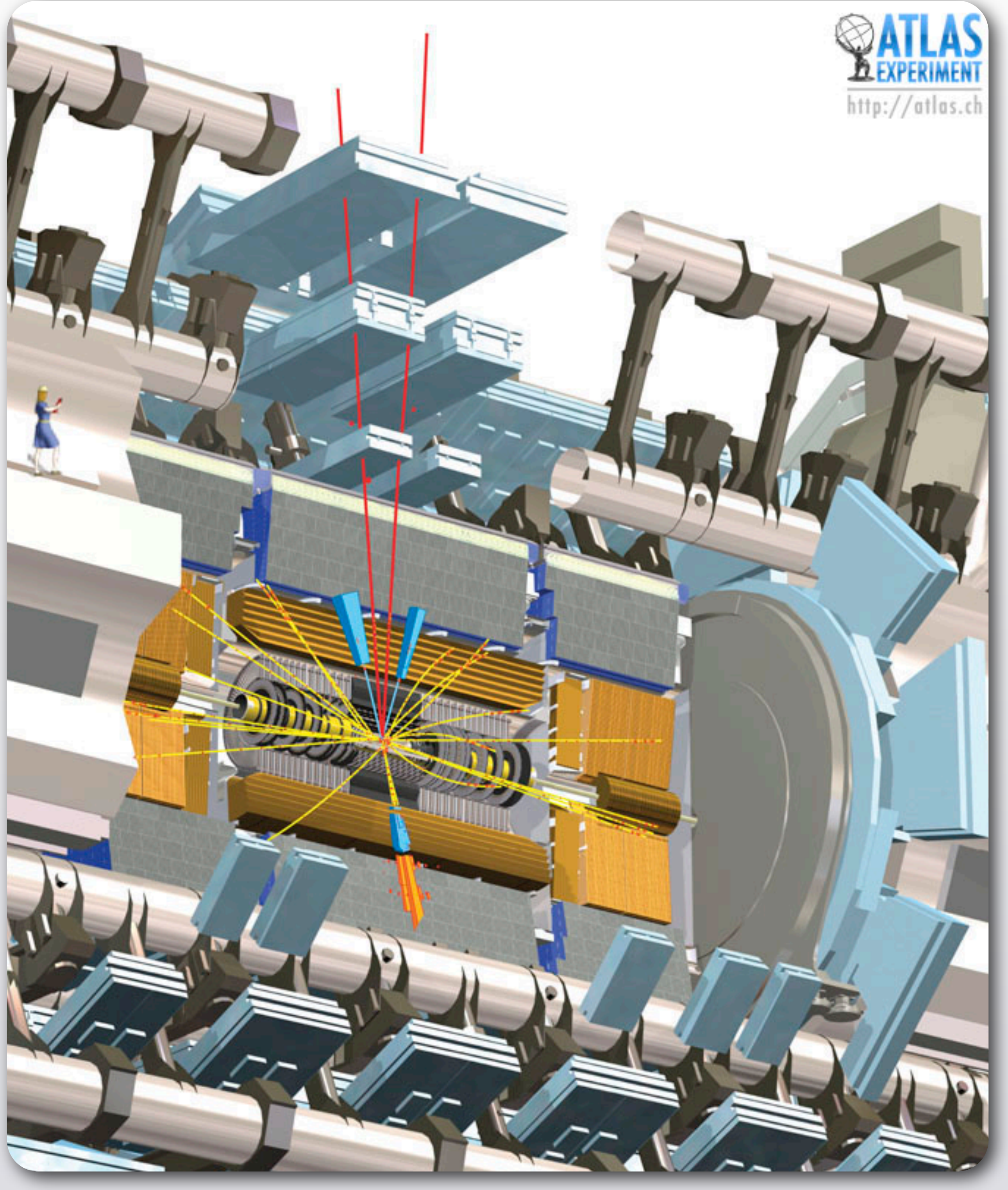
Higgs Decays

- Higgs coupling proportional to mass of particle
- Preferred decay: heaviest particle kinematically allowed
  - m_H < 150 GeV: H → bb, ττ
  - m_H > 150 GeV: H → WW, ZZ
- But there is background…
  - QCD overwhelms H → bb: only in associated production, e.g. HZ → bbqq
  - Very clean: H → $ZZ^{(*)}$ → 4 l



[after: A. Djouadi, Phys. Rept. **457** (2008) 1]

$H \rightarrow ZZ^{(*)} \rightarrow 4l$



- m_H = 150 GeV:
  $\sigma \times BR$ = 10.6 fb
- Very clean signature:
  - Four isolated leptons
  - At least one lepton pair with Z invariant mass
- Main backgrounds:
  - ZZ diboson production
  - Z + bb with semileptonic b decays
  - tt w/ semileptonic b

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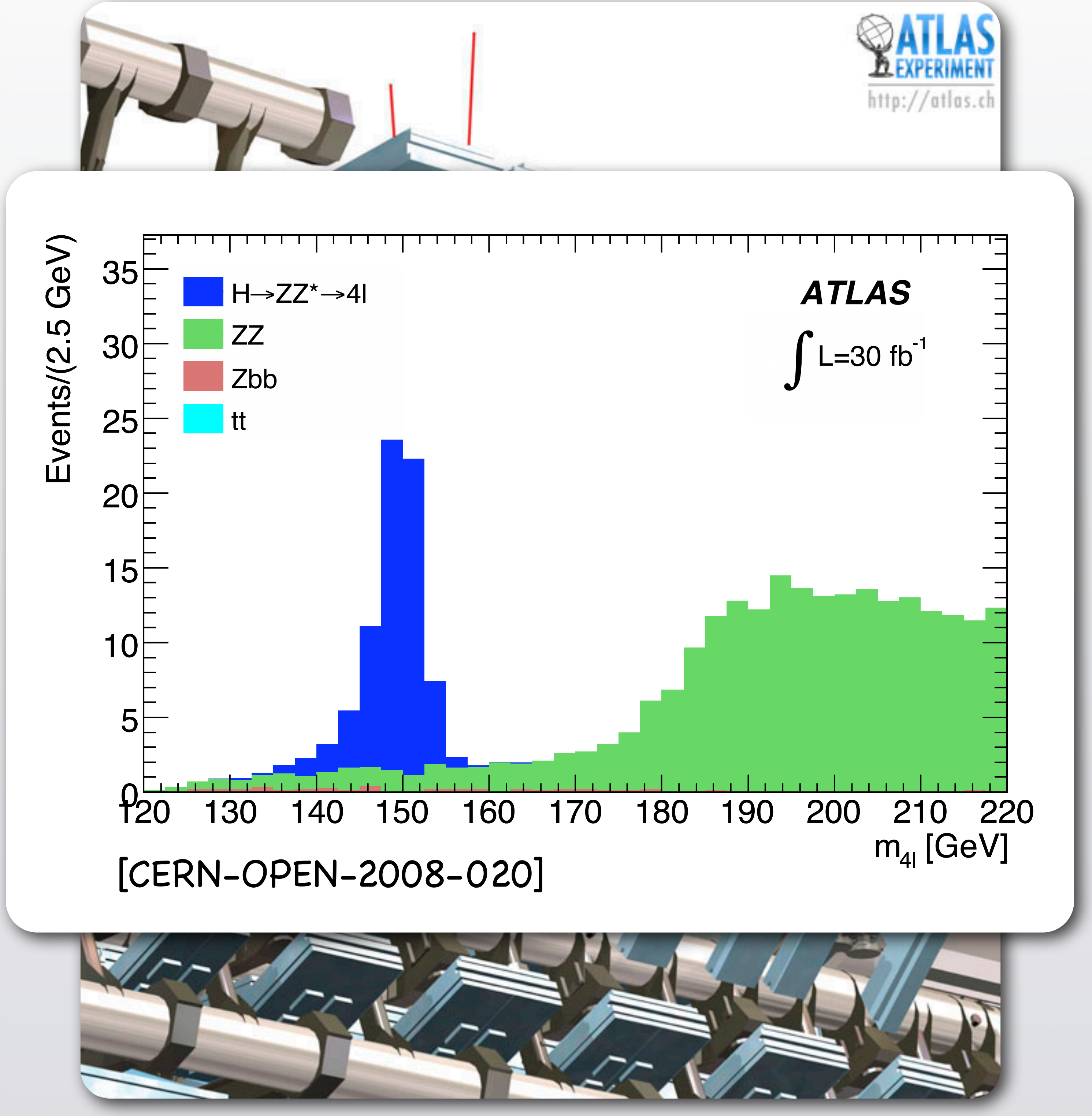

[CERN-OPEN-2008-020]

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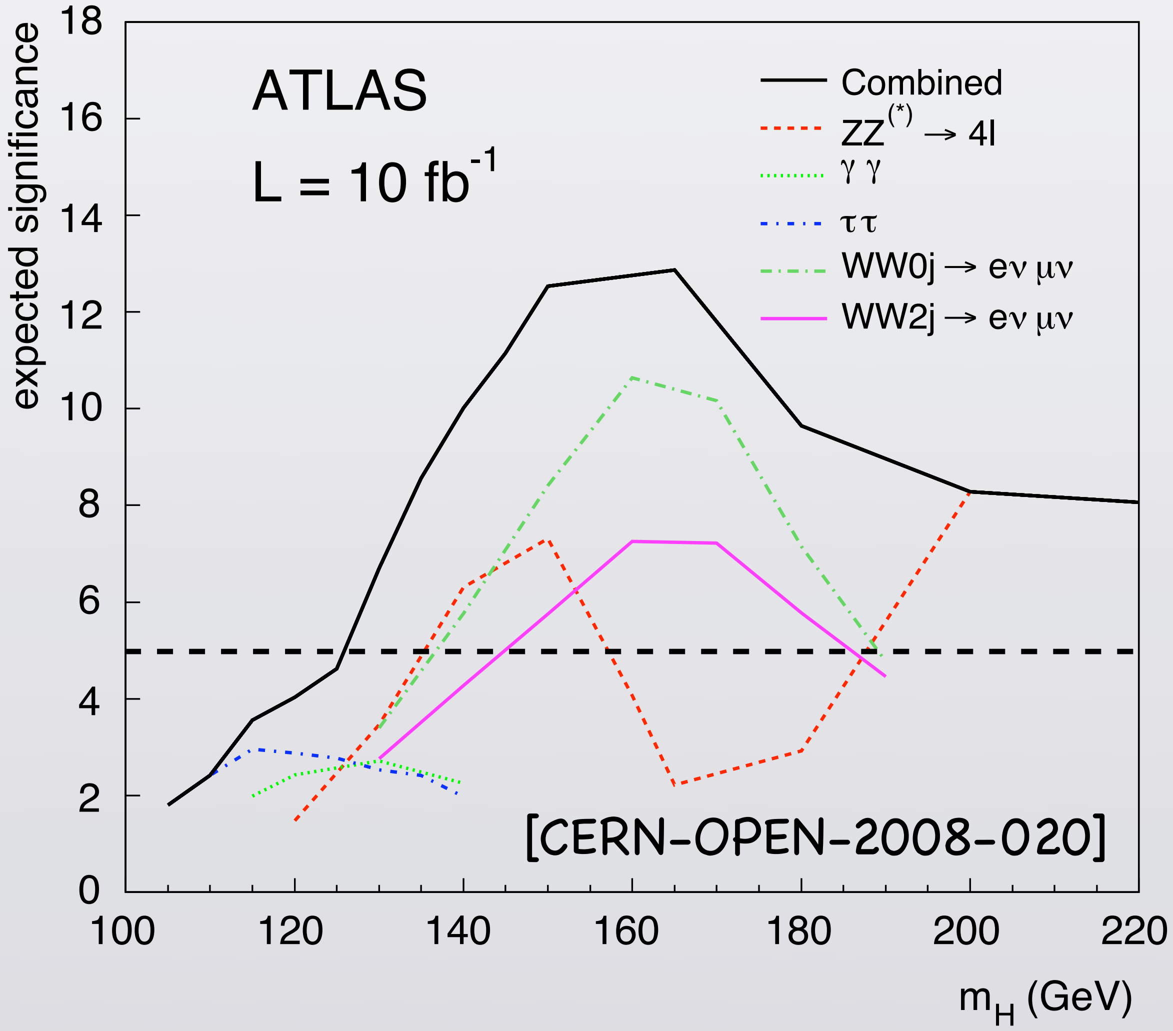
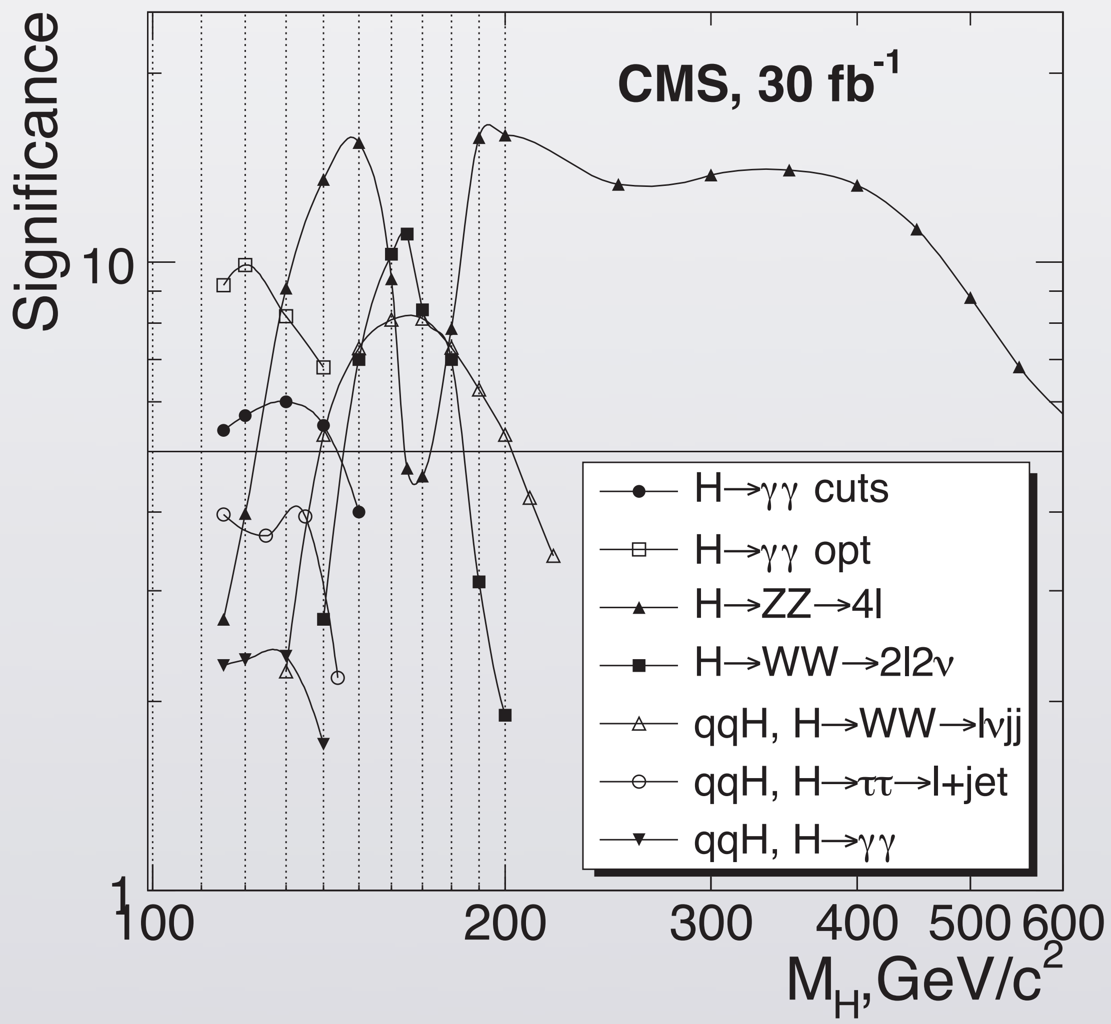
Higgs Discovery Potential

- Combine many channels to cover full Higgs mass range
- Convention: claim "discovery" if Gaussian probability for mistaking background for signal < 5.7×10^{-7} ("5σ")



[CERN-OPEN-2008-020]



[J. Phys. G: Nucl. Part. Phys. 34 (2007) 995]

Summary of Day 2

- Hadron collider physics: discovery physics in a messy environment
  - Observables: transverse quantities (p_T, MET, ...)
  - Need good understanding of leptons & jets (esp. from b quarks)
- LHC startup: first beam in November 2009
  - First physics at the LHC: minimum bias, W/Z, top
  - Go for discovery (Higgs, supersymmetry, extra dimesions)...
  - ... but be patient...

Thank you for your attention!

References

- Eva Halkiadakis, Introduction to the LHC Experiments, TASI Summer School 2009
  http://www.physics.rutgers.edu/~evahal/talks.html
- Karl Jakobs, Physics at Hadron Colliders, CERN Summer Student Lectures 2004-2006
  http://james.physik.uni-freiburg.de/~jakobs/Physik-Schulen/summer-school/
- Sven Moch, Theory at LHC, this lecture series
  http://www-zeuthen.desy.de/~moch/seminars/seminars.html

Follow-up

- Equation of motion: $\vec{F} = \dot{\vec{p}} = e\vec{v} \times \vec{B}$
- Solution: characteristic "synchrotron frequency" $\omega = \dfrac{eB}{m}$
- Lorentz force = centripetal force: $evB = mR\omega^2 = m\left(\dfrac{eB}{m}\right)^2$
- For highly relativistic particles:

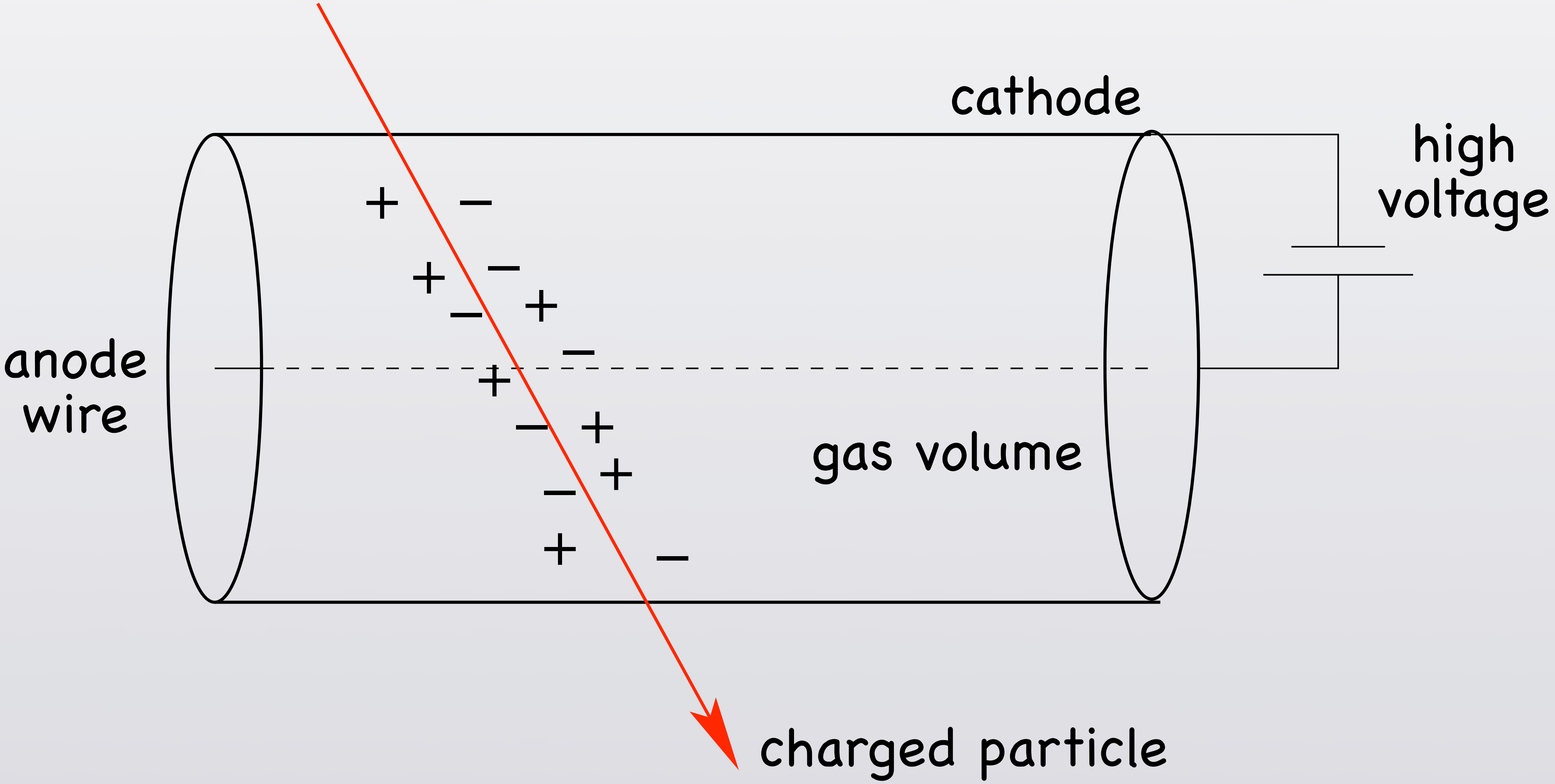
$$\beta \equiv \frac{v}{c}, \quad \gamma \equiv \frac{1}{\sqrt{1-\beta^2}}, \quad mc^2 \rightarrow \gamma mc^2 = E$$

- Solve for energy: $E = \dfrac{ecBR}{\beta}$
- LHC numbers: $B = 8\,\mathrm{T}, R = 4250\,\mathrm{m} \rightarrow E = 10\,\mathrm{TeV}$
- Note: only about 2/3 of the ring equipped with dipoles

Back

Gaseous Detectors

- Charged particles cross detector with “counting gas”: ionisation (requires 5× more energy than silicon)
- High voltage between anode and cathode: gas amplification (“Townsend avalanche”)



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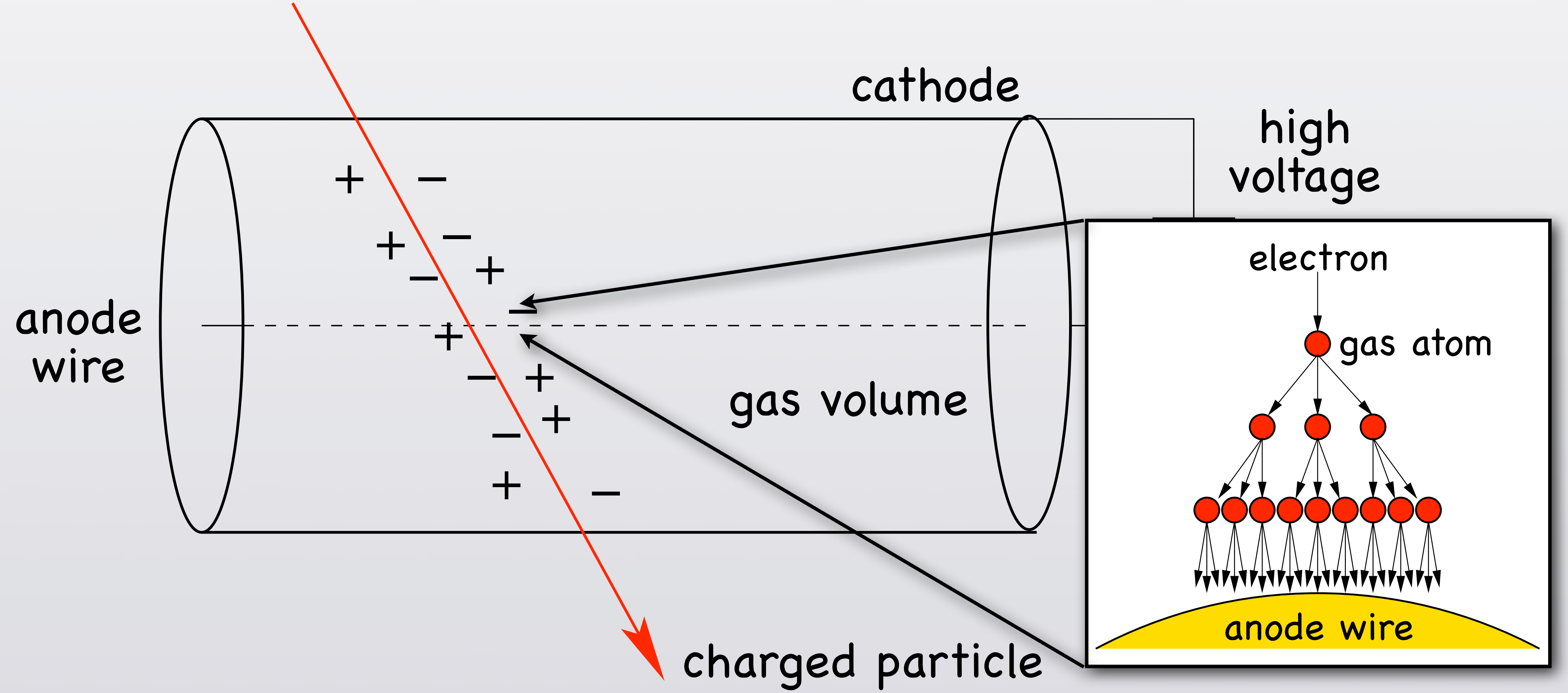
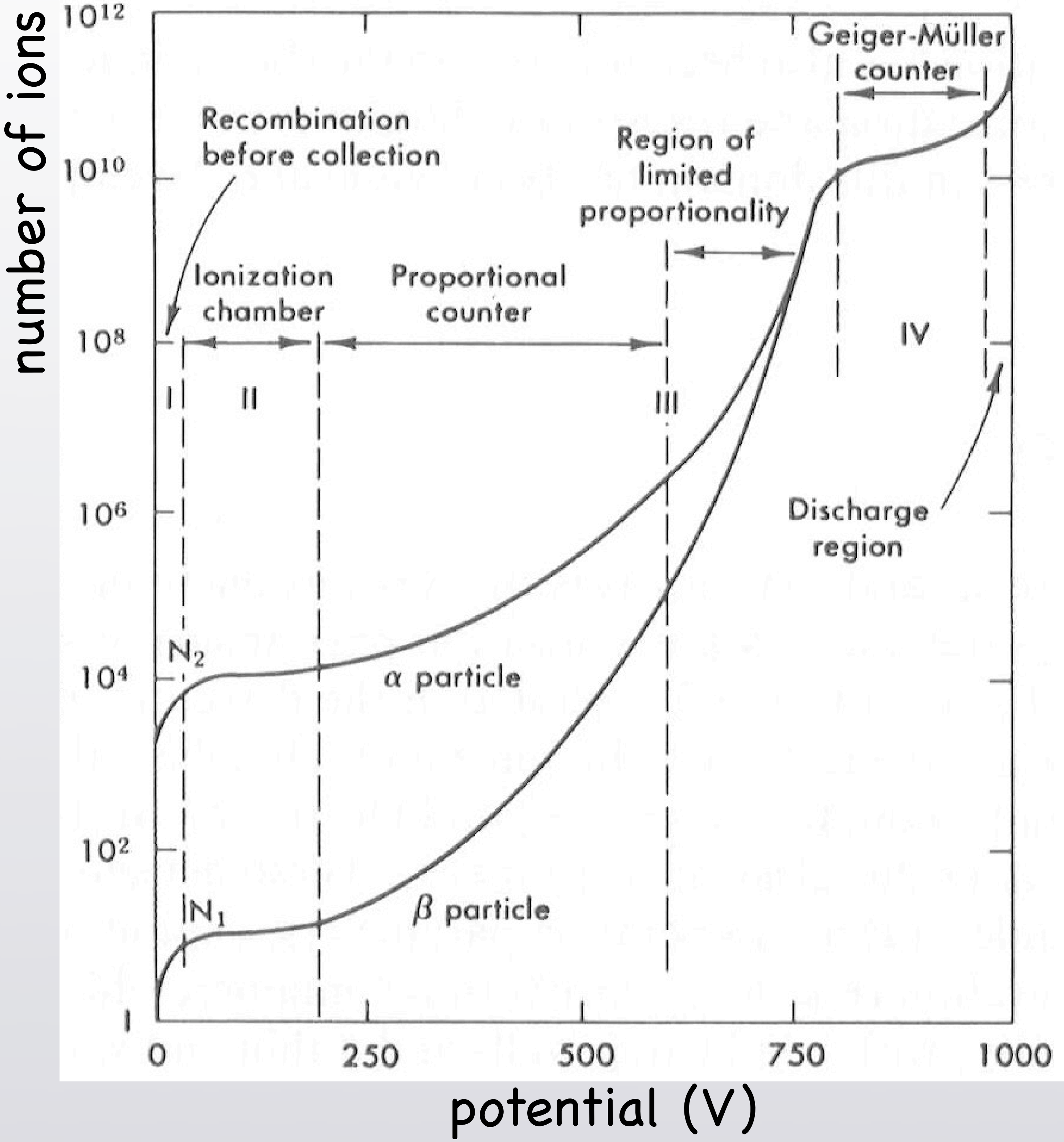


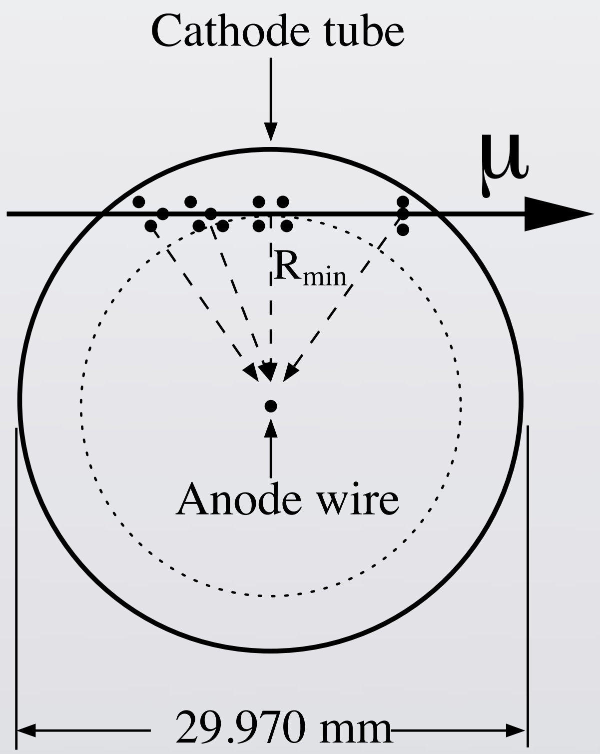
Counter Modes



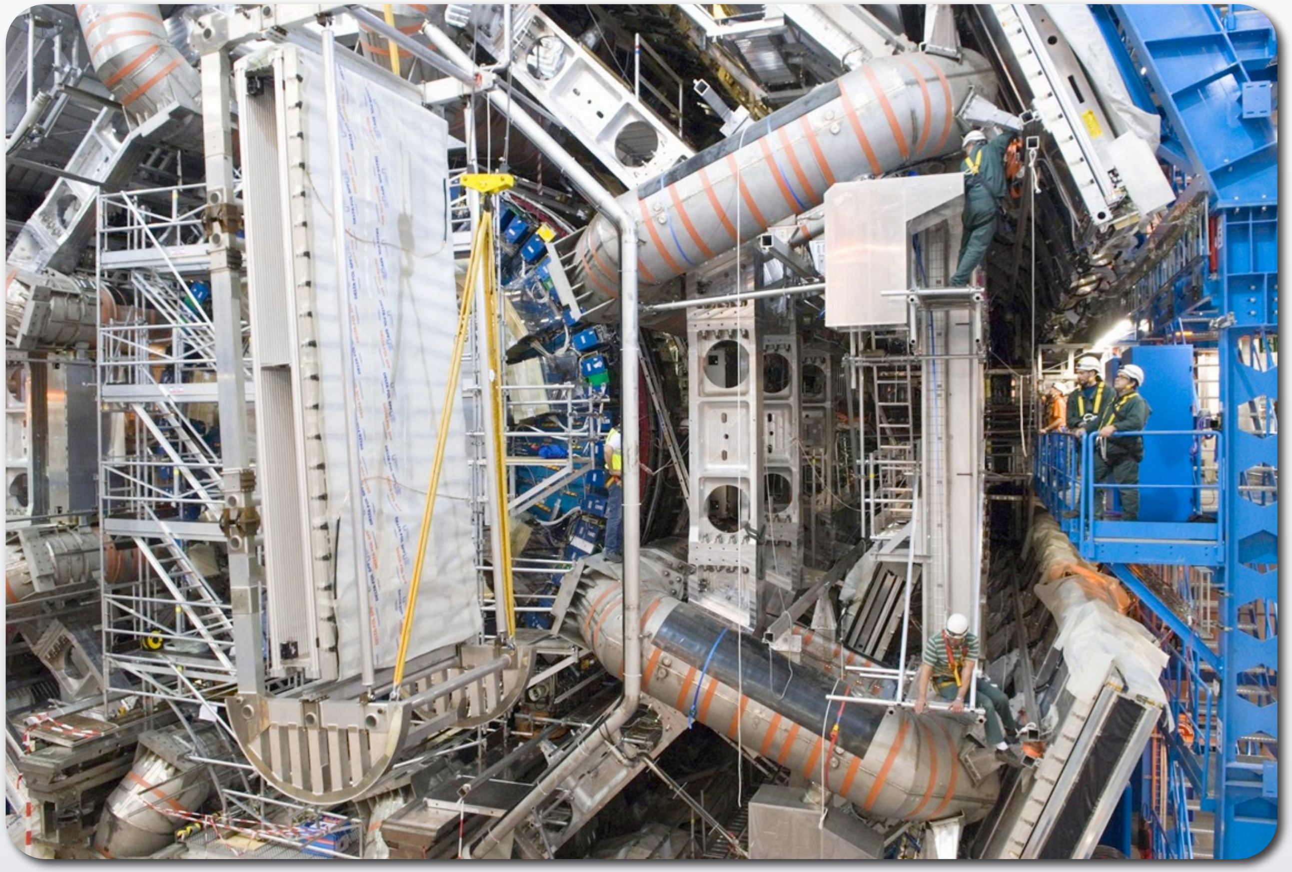
- **Ionization chamber**: no gas amplification
- **Proportional counter**: signal proportional to primary ionization
- **Geiger-Müller** mode: count number of particles crossing
- Typical counting gas mixture:
  - **Counting**: argon
  - **Quenching** of avalanche: CO_2

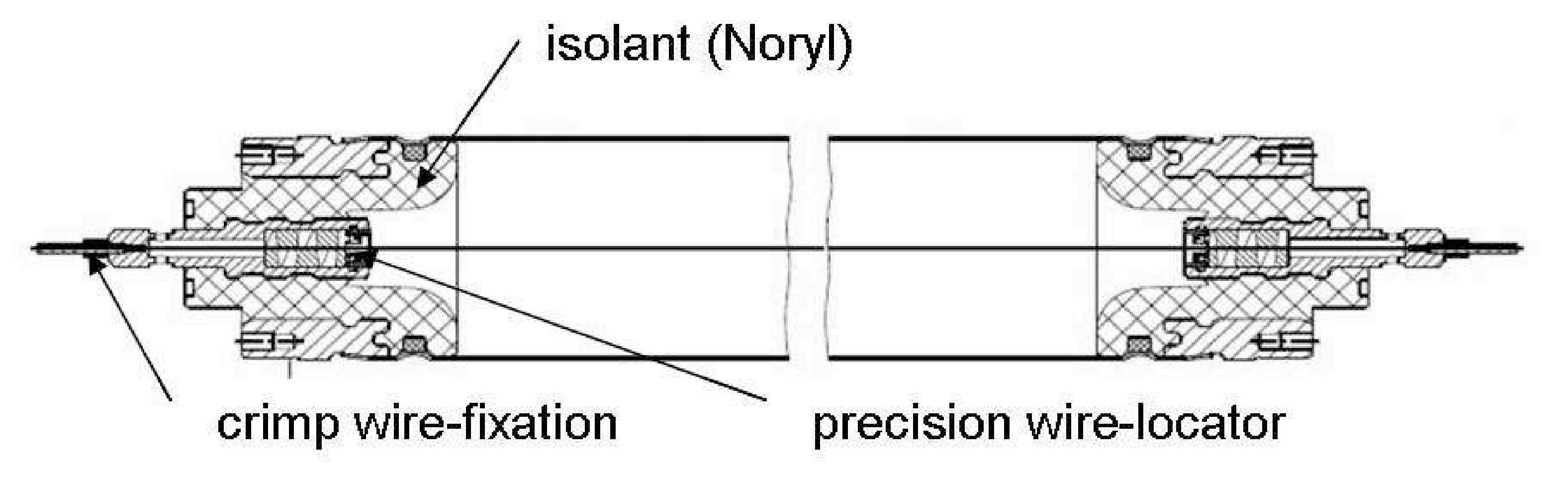
ATLAS MDT Detector

- Muon momentum ATLAS:
  - 5500 m² of "monitored drift tubes" (MDT)
  - Strong toroidal magnetic field



counting gas: argon/CO_2 (93%,7%)
operating voltage: 3000 V





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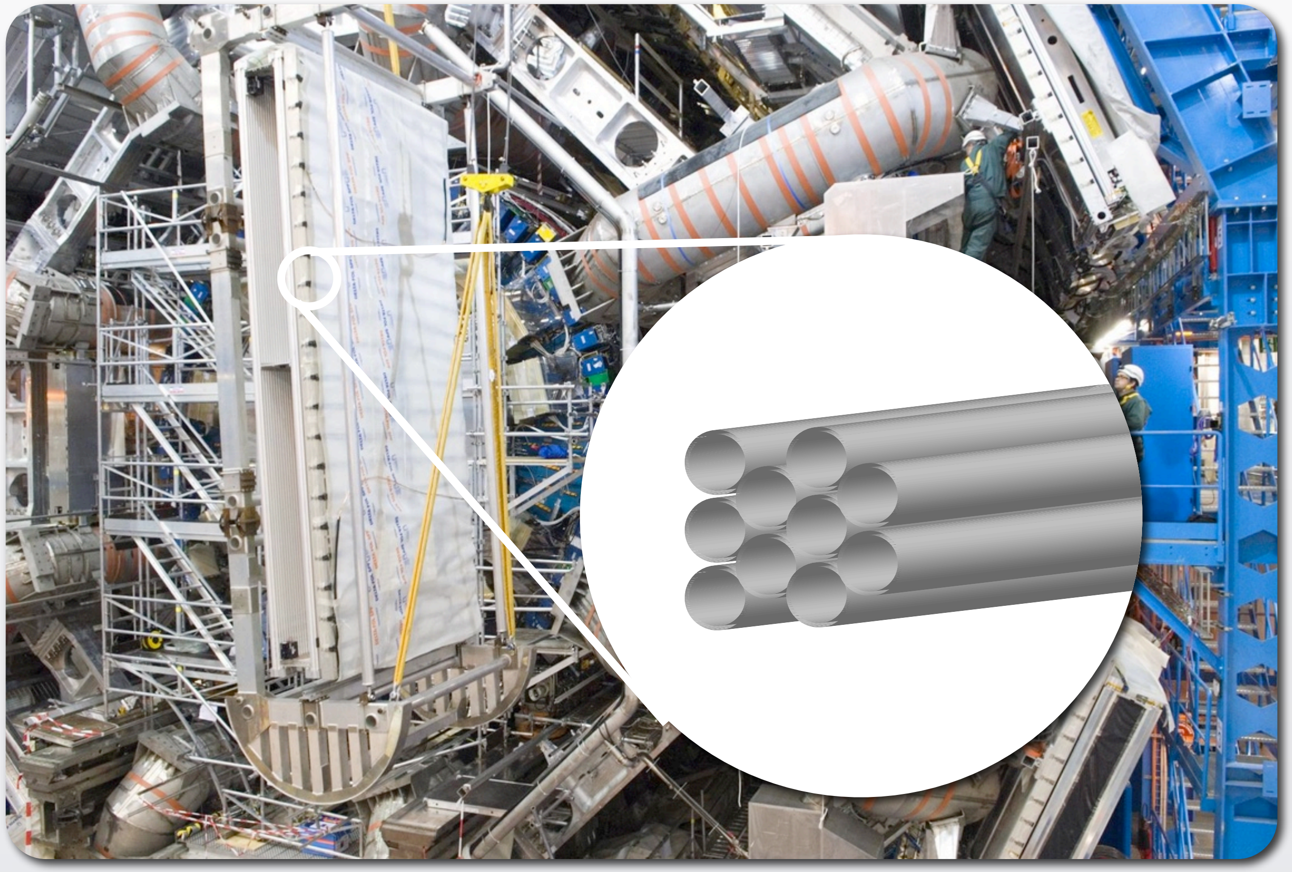

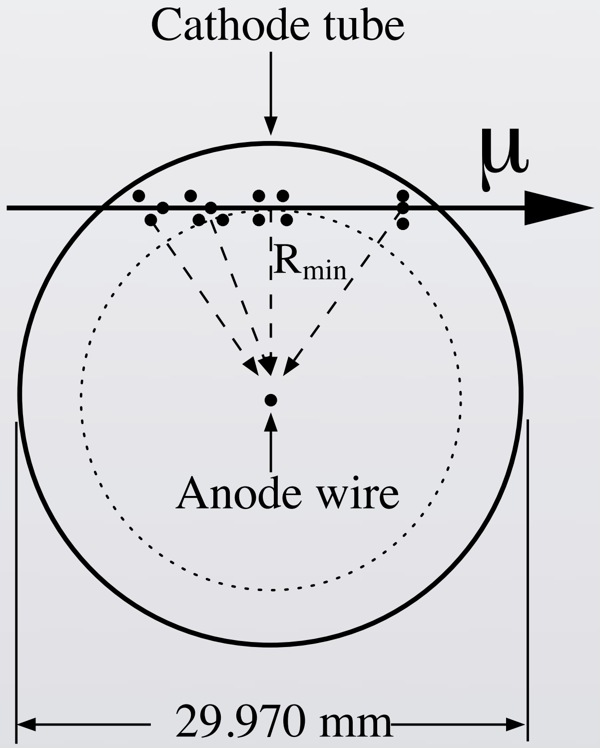

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