The Road to Discovery

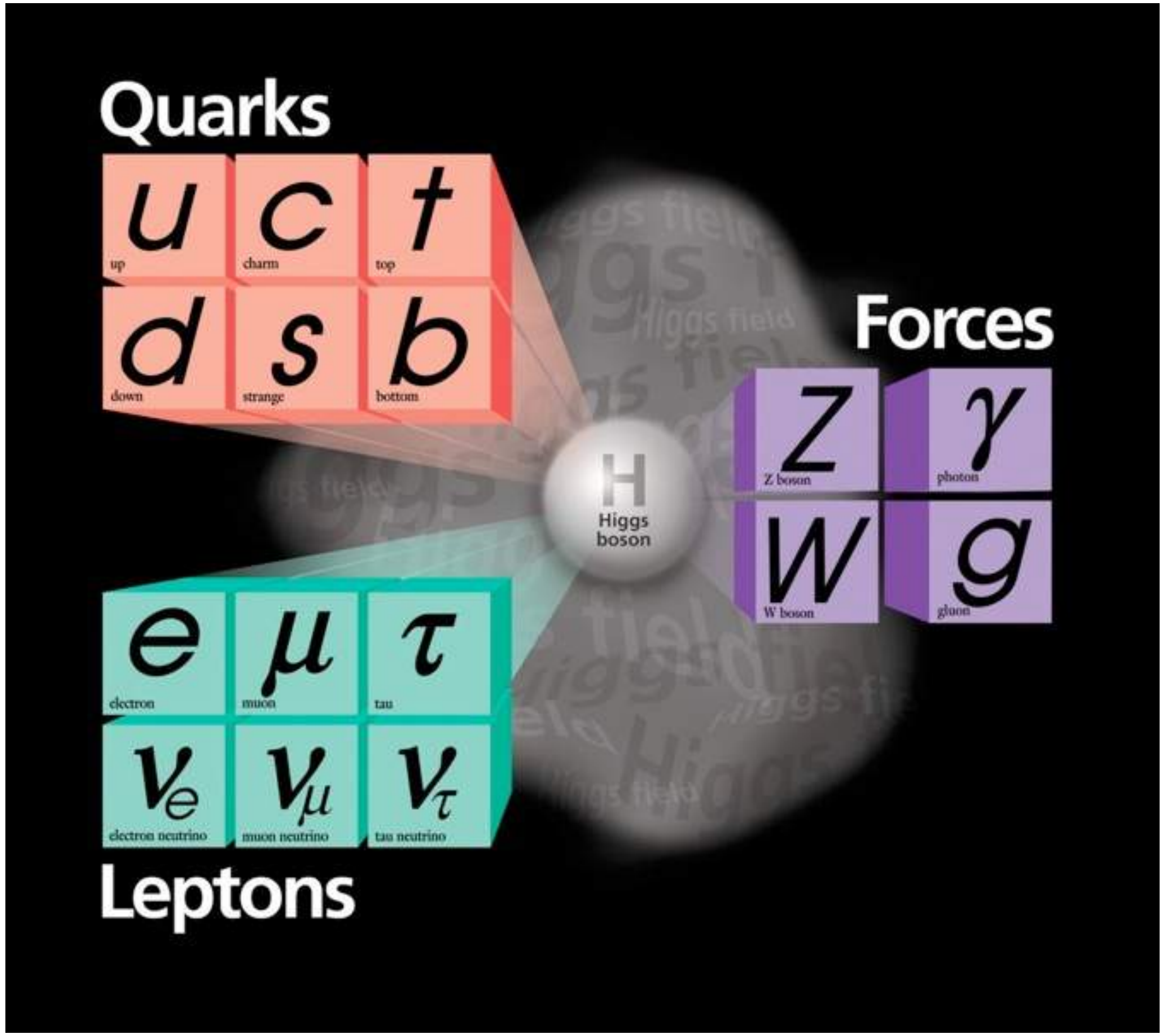
Gustaaf Brooijmans

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Overview

- Search for BSM physics primary focus
  - Direct searches and precision measurements
  - Use mainly direct searches at colliders, with focus on experimental aspects
    - Challenges posed at hadron colliders
    - Ease of generating false positives
    - Techniques to deal with limited knowledges
  - But far from exhaustive!
- Discussion of future projects

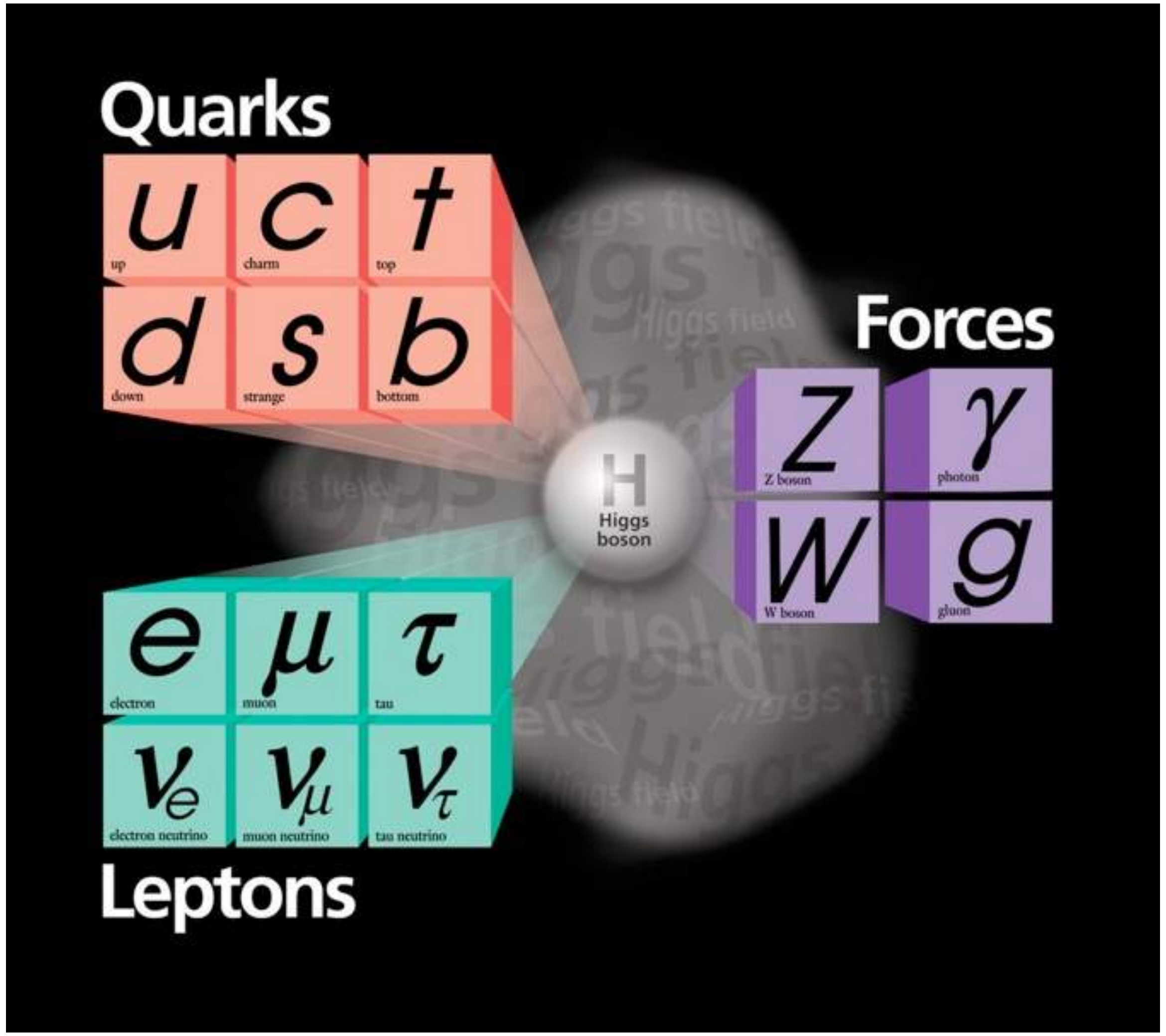
Standard Model Today



Triumph of Gauge Theories!

Standard Model Today

- Higgs discovery completes the Standard Model
  - Fully consistent, complete, precise description of strong, electromagnetic and weak interactions
- Even generate fermion masses
  - But that is the ***only*** property of fermions we "understand"



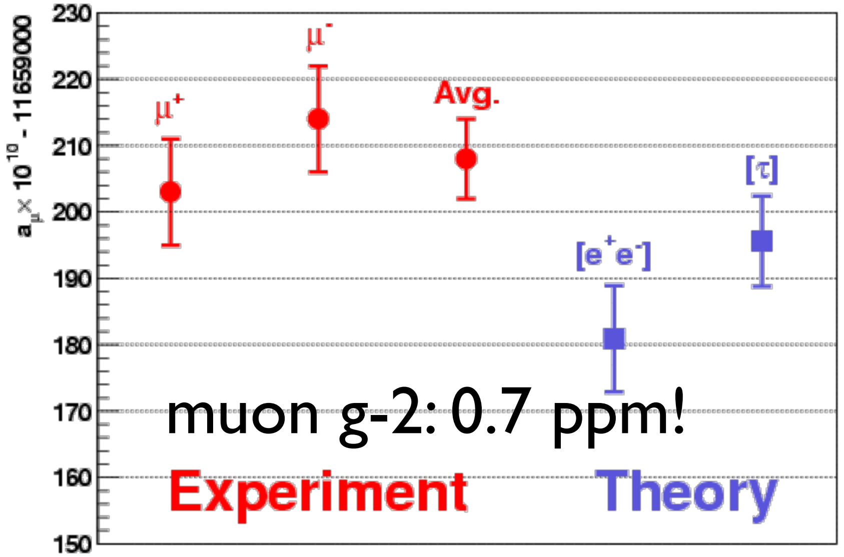
In Words

- Matter is built of spin 1/2 particles that interact by exchanging 3 different kinds of spin 1 particles corresponding to 3 different (gauge) interactions
- There appear to be 3 generations of matter particles
- The 4 different matter particles in each generation carry different combinations of quantized charges characterizing their couplings to the interaction bosons
- The matter fermions and the weak bosons have “mass” acquired by coupling to the Higgs boson
- Gravitation is presumably mediated by spin 2 gravitons
- Gravitation is extremely weak for typical particle masses
- There appear to be 3 macroscopic space dimensions

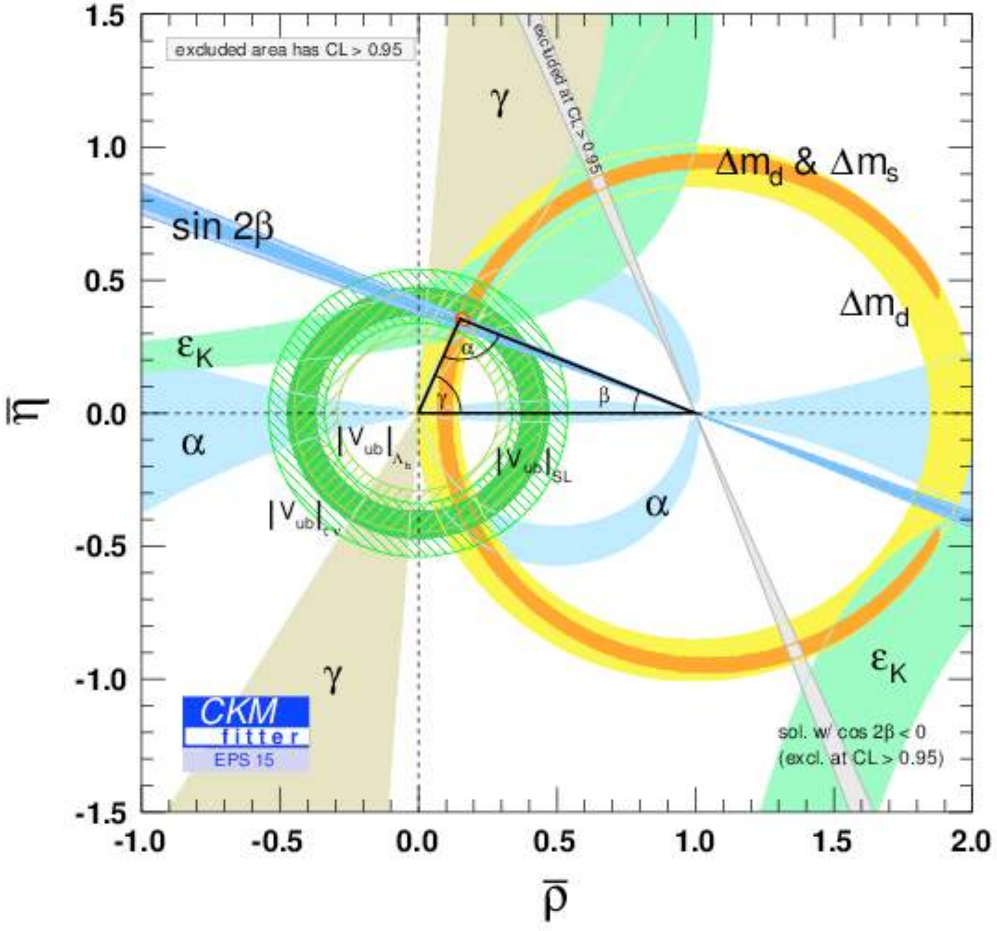
About the Standard Model

- It’s a theory of interactions:
  - Properties of fermions are inputs
    - In gauge paradigm, fermion properties “generate” interactions
  - Properties of interaction bosons in terms of couplings, propagations, masses are linked:
    - Measuring a few allows us to predict the rest, then measure and compare with expectation
- It’s remarkably successful:
  - Predictions verified to be correct at sometimes incredible levels of precision
  - After ~40 years, still no serious cracks

Precision Results



muon g-2: 0.7 ppm!



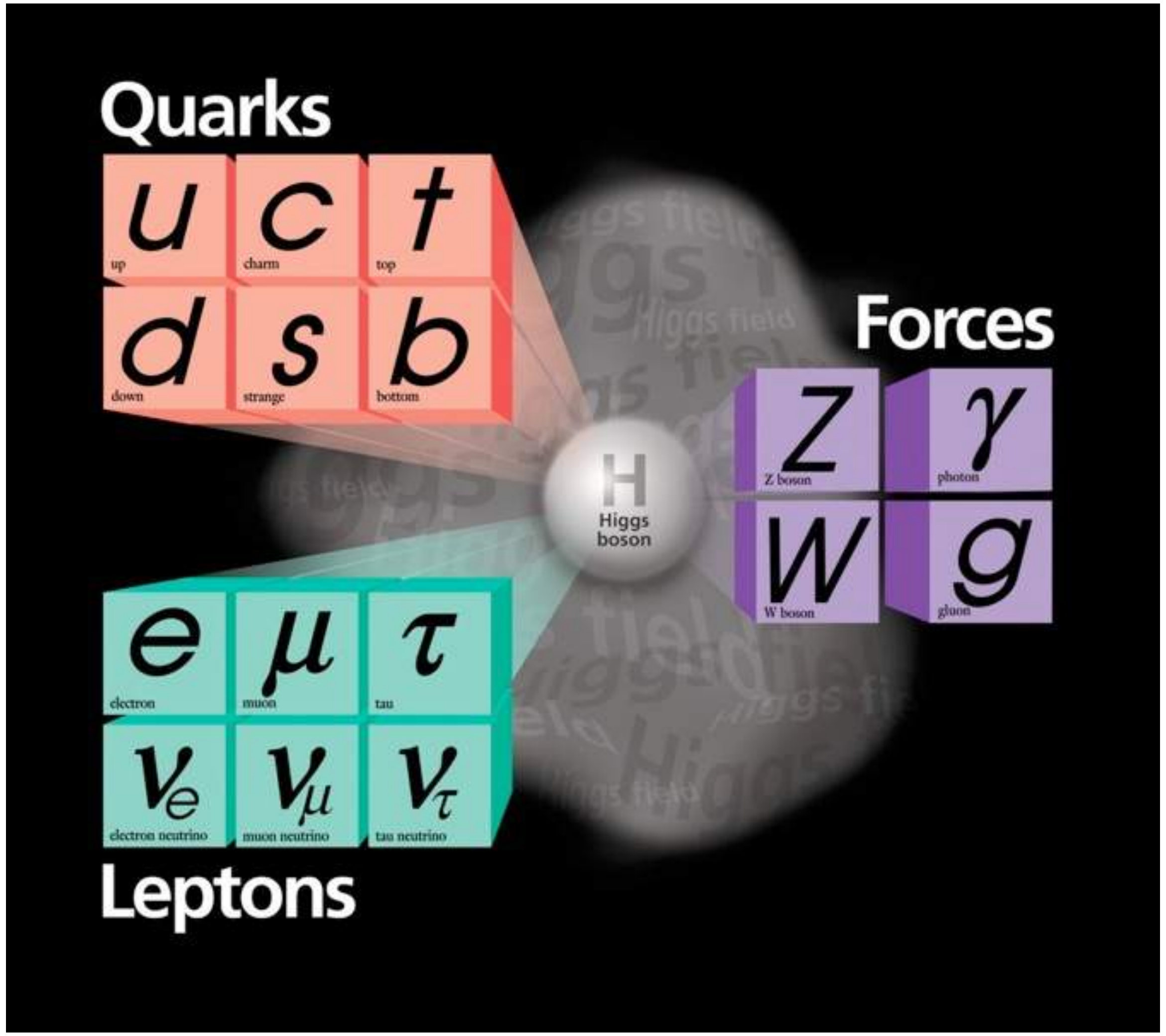
B, K physics

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

LEP, SLD & Tevatron

Lacking in the Standard Model

- Clear structure in fermionic sector unexplained
  - No understanding of the “charges”
  - Evidence of selective principle(s)
    - E.g. no neutral colored fermions
    - q(down) = q(e)/N_C
  - Interpreted as evidence for (grand) unification
    - Grand or less grand? (One or more scales?)



Lacking in the Standard Model

- Many cosmological issues
  - Dark matter and dark energy
  - Not enough CP violation in the quark sector for baryogenesis
  - Baryon number violation
    - Present in the SM through B-L (sphalerons)
    - Baryogenesis through leptogenesis and B-L?
      - Untestable?

Many Fundamental Questions

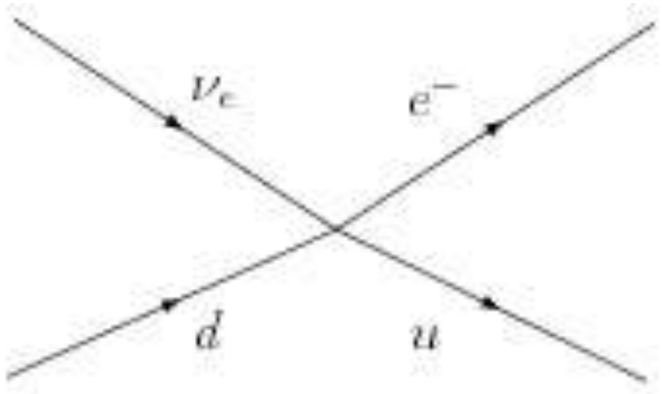
- What exactly *is* spin? Or color? Or electric charge? Why are they quantized?
- Are there only 3 generations? If so, why?
- Why are there e.g. no neutral, colored fermions?
- What is mass? Why are particles so light?
- Is there a link between particle and nucleon masses?
- How does all of this reconcile with gravitation? How many space-time dimensions are there really?
- …

Particles Solve Problems

(Problems Predict Particles)

Vector Boson Scattering

- There was in fact one known problem with the Standard Model (+ a second, related, lesser one):
  - If we collide W's or Z's (not so easy...), the scattering cross-section grows with the center of mass energy, and gets out of control (violates unitarity) at about 1.7 TeV: $\sigma(WW \rightarrow WW) \sim s$
- This is similar to "low" energy neutrino scattering:
  - If $q^2 << (M_W)^2$, looks like a "contact interaction", and cross-section grows with center of mass energy: $\sigma \sim s$



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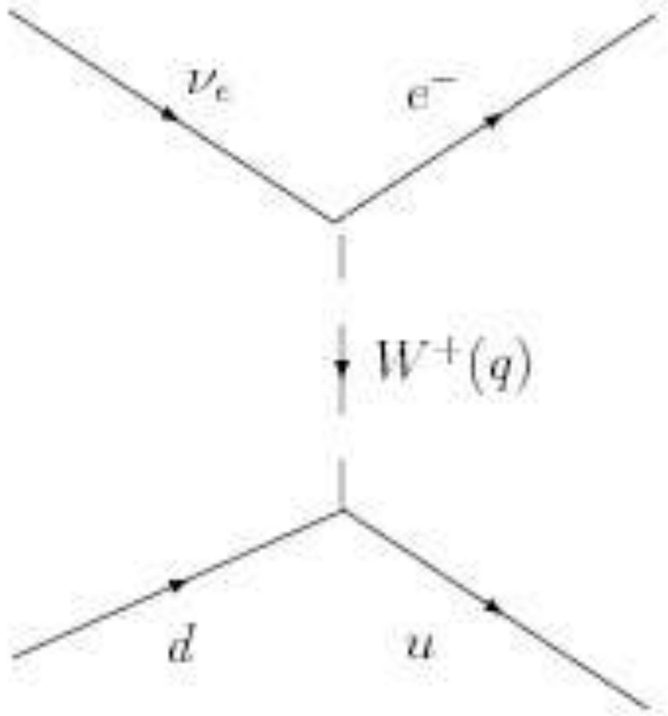
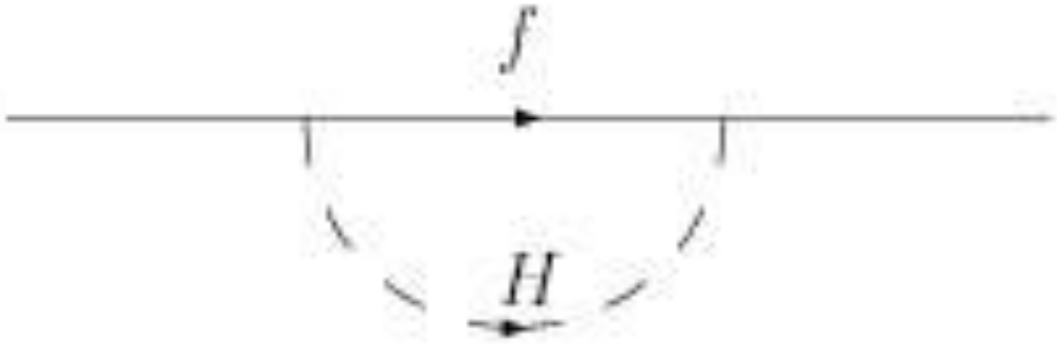


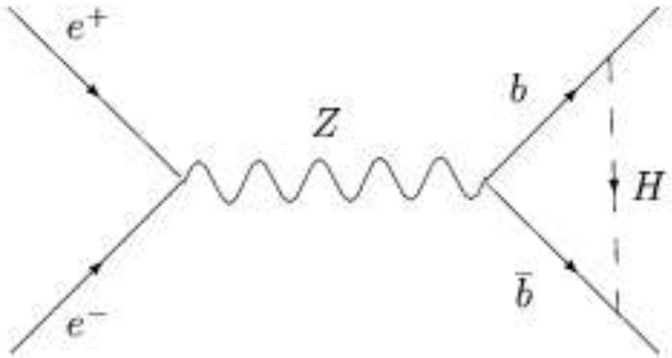
The Higgs Boson

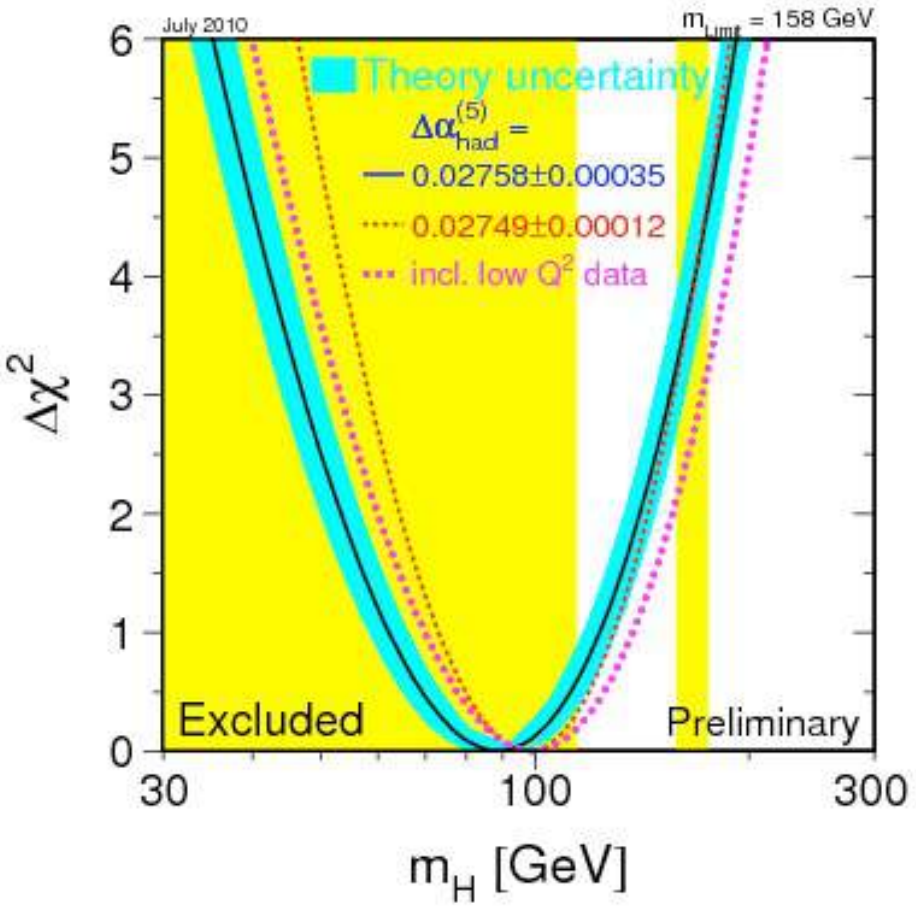
- One way to solve WW, is to introduce a massive, spinless particle (of mass < ~1 TeV)
  - Couplings to W and Z are fixed, quantum numbers are known...
  - .... to be those of the vacuum
  - Its mass is unknown, and its couplings to the fermions are unknown.... well, maybe
    - Fermions can acquire mass by coupling to this Higgs boson, so their couplings could be proportional to their masses. This is called the “Standard Model Higgs”



Precision Measurements

- In fact, we were able to say something about the standard model Higgs mass
  - If the fermions get their masses from the Higgs, we know all couplings and can infer the Higgs mass from precision measurements
  - Result is very sensitive to measured top quark, W boson masses
    - Really wants a “light” Higgs boson





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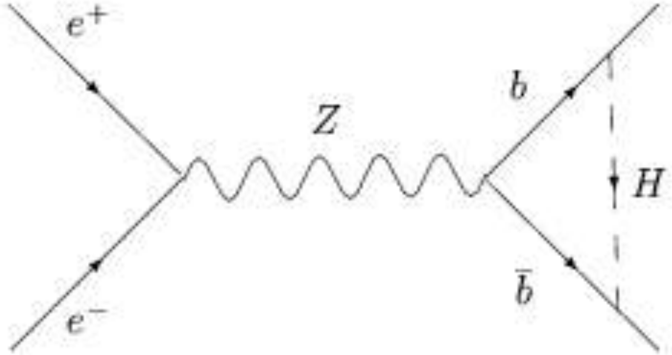
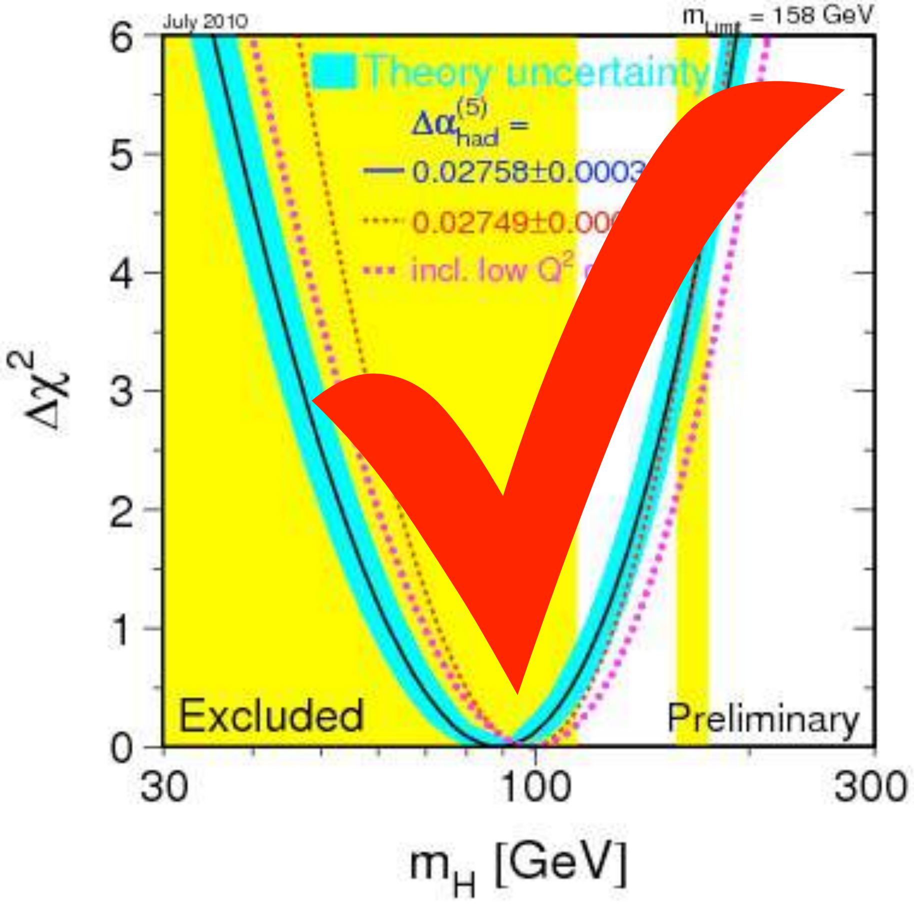
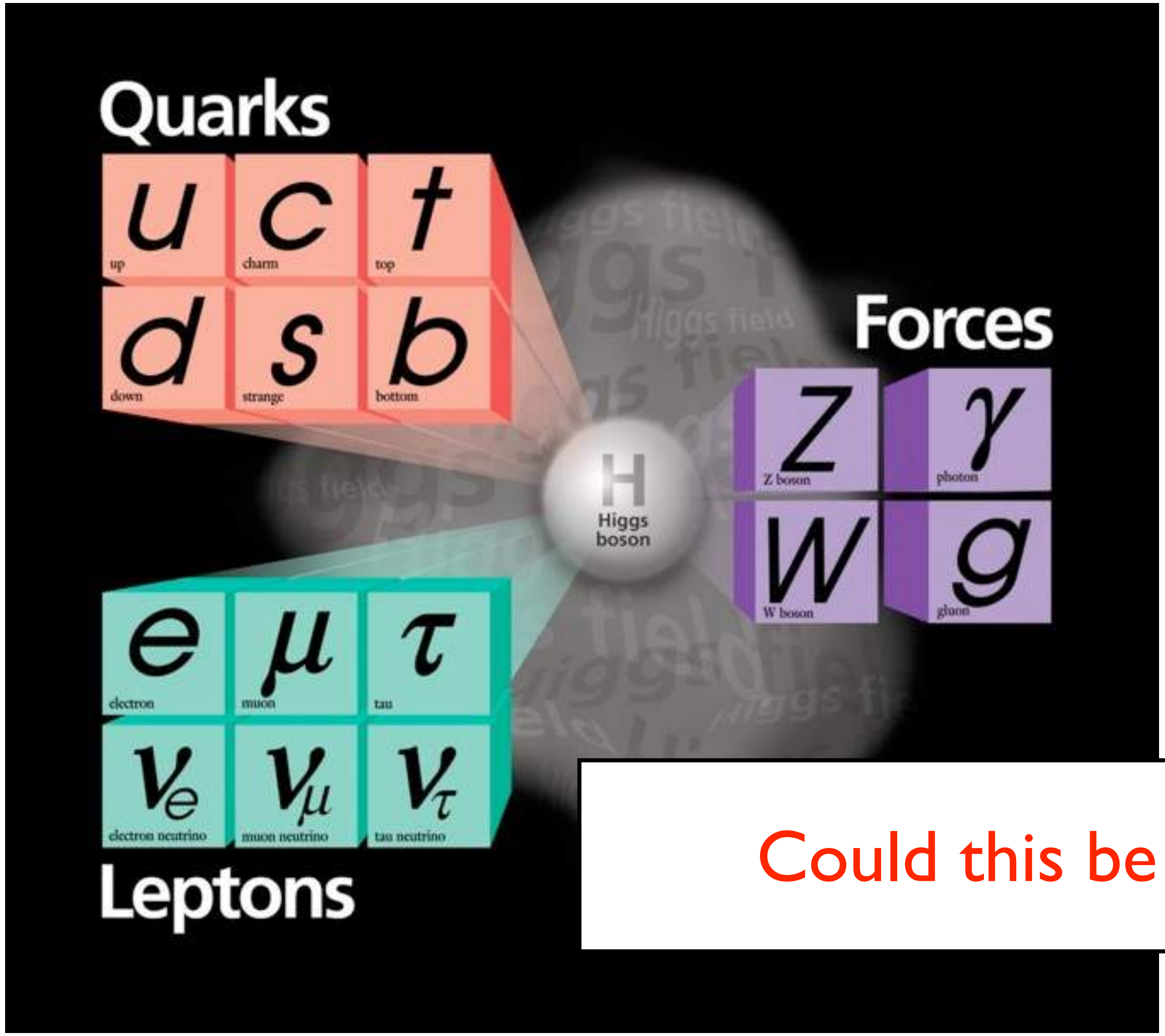




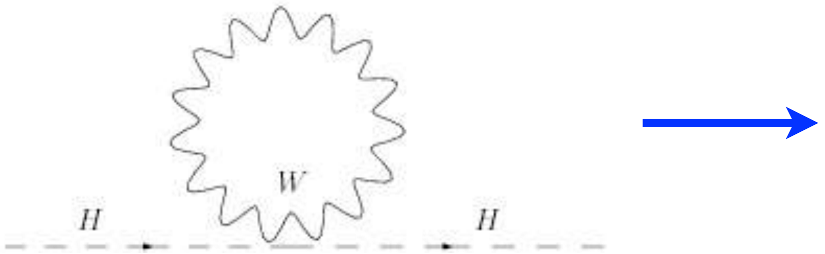
The Plot Thickens

New Physics?

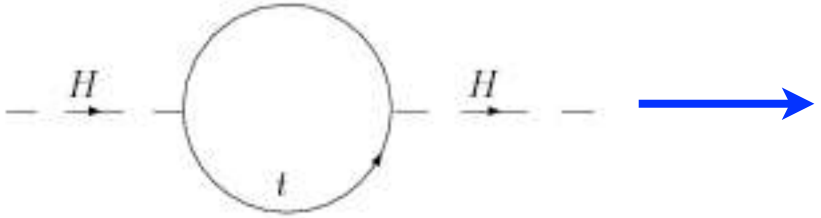


Could this be it?

Higgs Mass



$$\frac{1}{16\pi^2} g^2 E^2$$

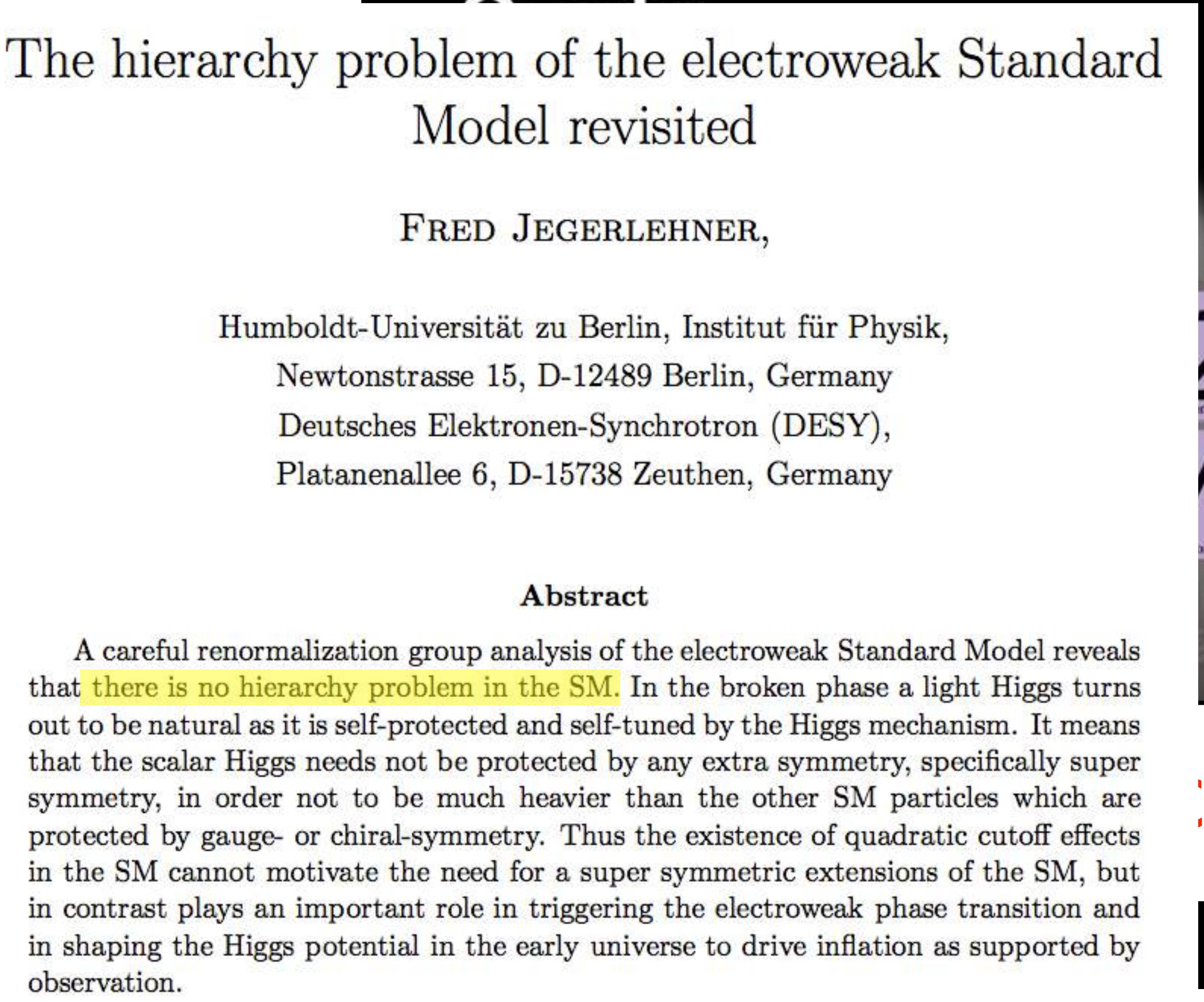


$$\frac{3}{16\pi^2} y_t^2 E^2$$

$$\frac{1}{16\pi^2} \lambda E^2$$

- Higgs, in fact, also acquires mass from coupling to W's, fermions, and itself!
  - These "mass terms" are quadratically divergent
  - Drive mass to limit of validity of the theory
- So we expect the Higgs mass to be close to the scale where new physics comes in....

New Physics?



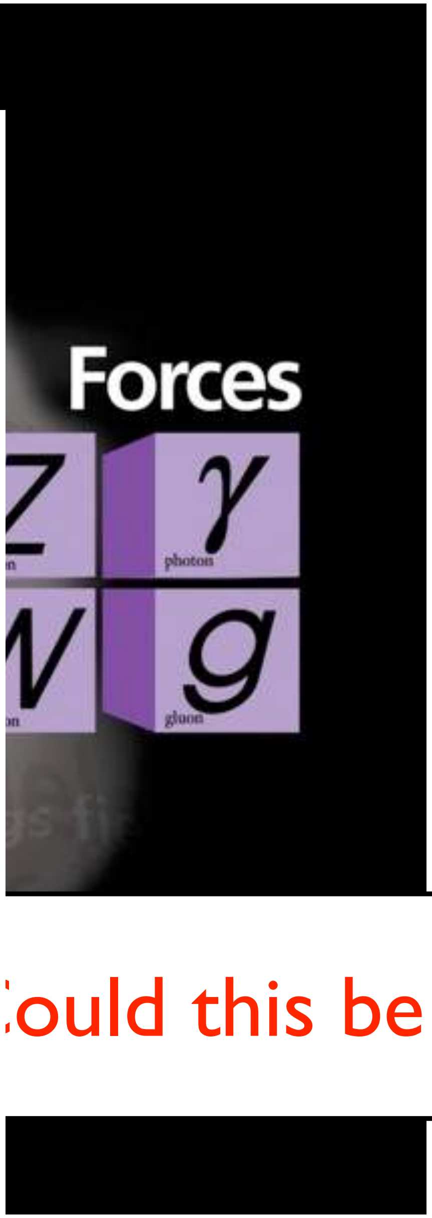
The hierarchy problem of the electroweak Standard Model revisited

FRED JEGERLEHNER,

Humboldt-Universität zu Berlin, Institut für Physik,
Newtonstrasse 15, D-12489 Berlin, Germany
Deutsches Elektronen-Synchrotron (DESY),
Platanenallee 6, D-15738 Zeuthen, Germany

Abstract

A careful renormalization group analysis of the electroweak Standard Model reveals that there is no hierarchy problem in the SM. In the broken phase a light Higgs turns out to be natural as it is self-protected and self-tuned by the Higgs mechanism. It means that the scalar Higgs needs not be protected by any extra symmetry, specifically super symmetry, in order not to be much heavier than the other SM particles which are protected by gauge- or chiral-symmetry. Thus the existence of quadratic cutoff effects in the SM cannot motivate the need for a super symmetric extensions of the SM, but in contrast plays an important role in triggering the electroweak phase transition and in shaping the Higgs potential in the early universe to drive inflation as supported by observation.



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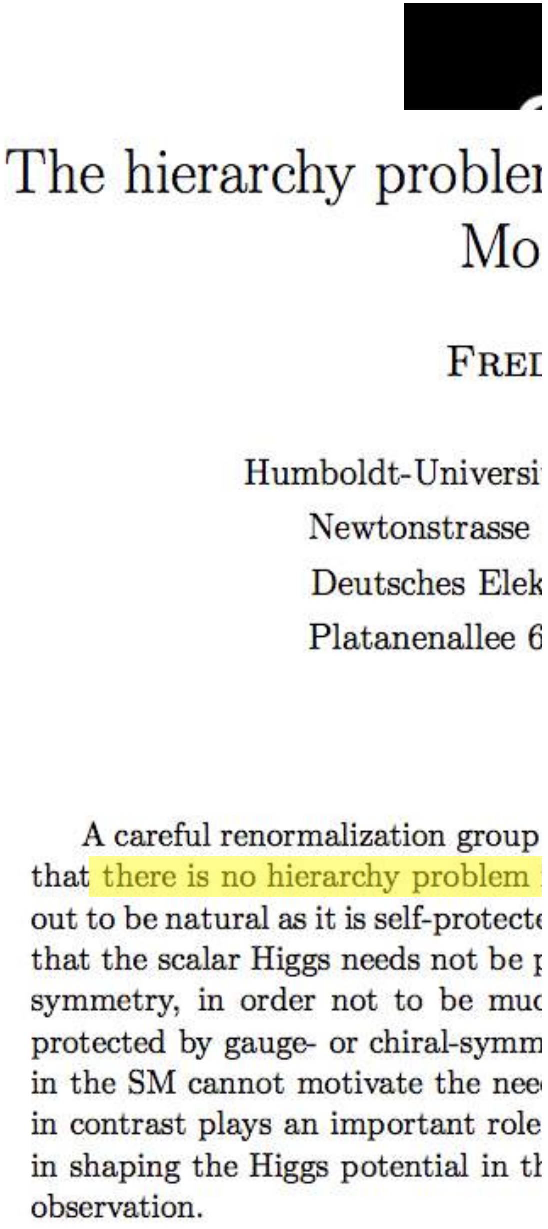
New Physics?



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The hierarchy probler
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A careful renormalization group
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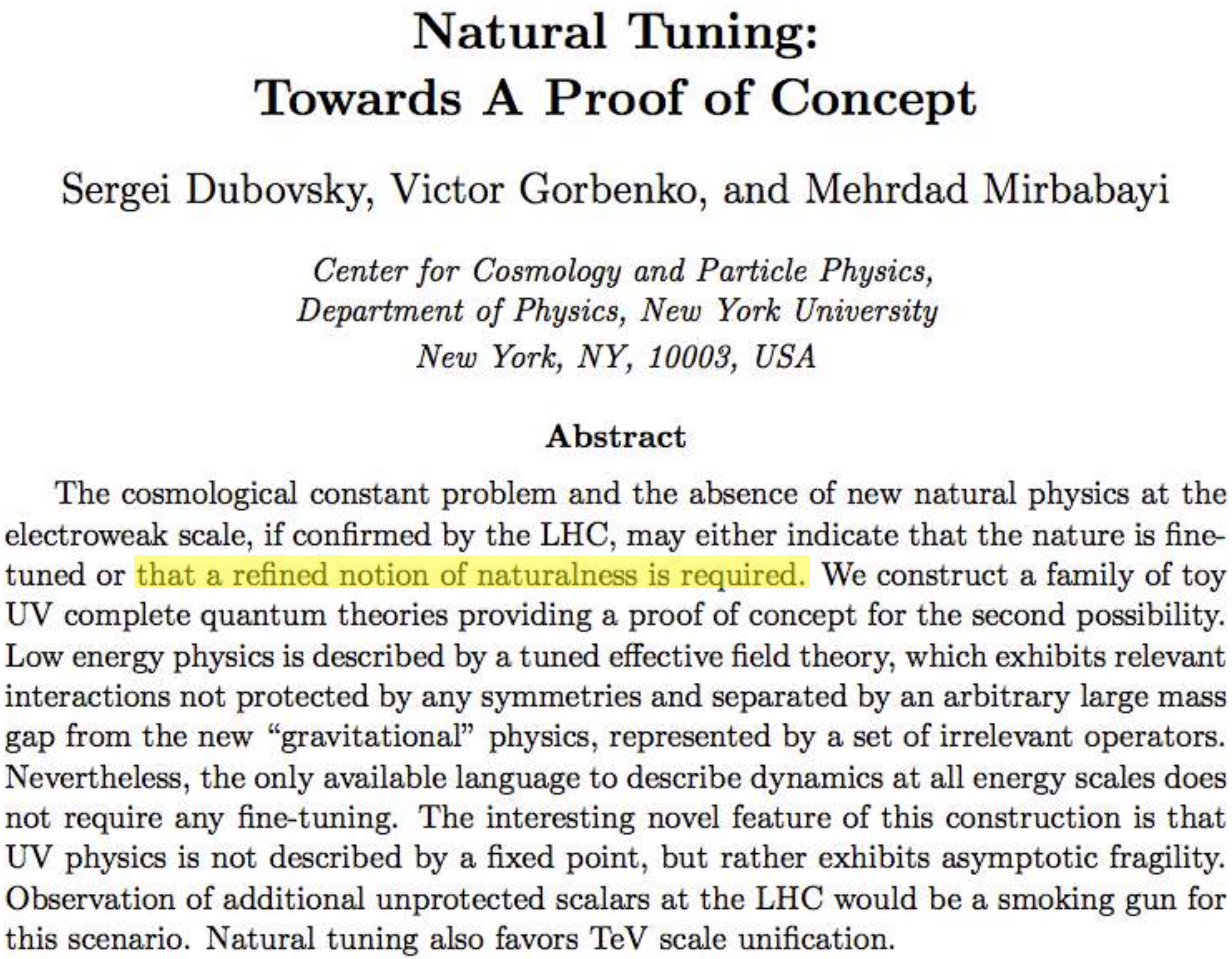


Natural Tuning: Towards A Proof of Concept

Sergei Dubovsky, Victor Gorbenko, and Mehrdad Mirbabayi

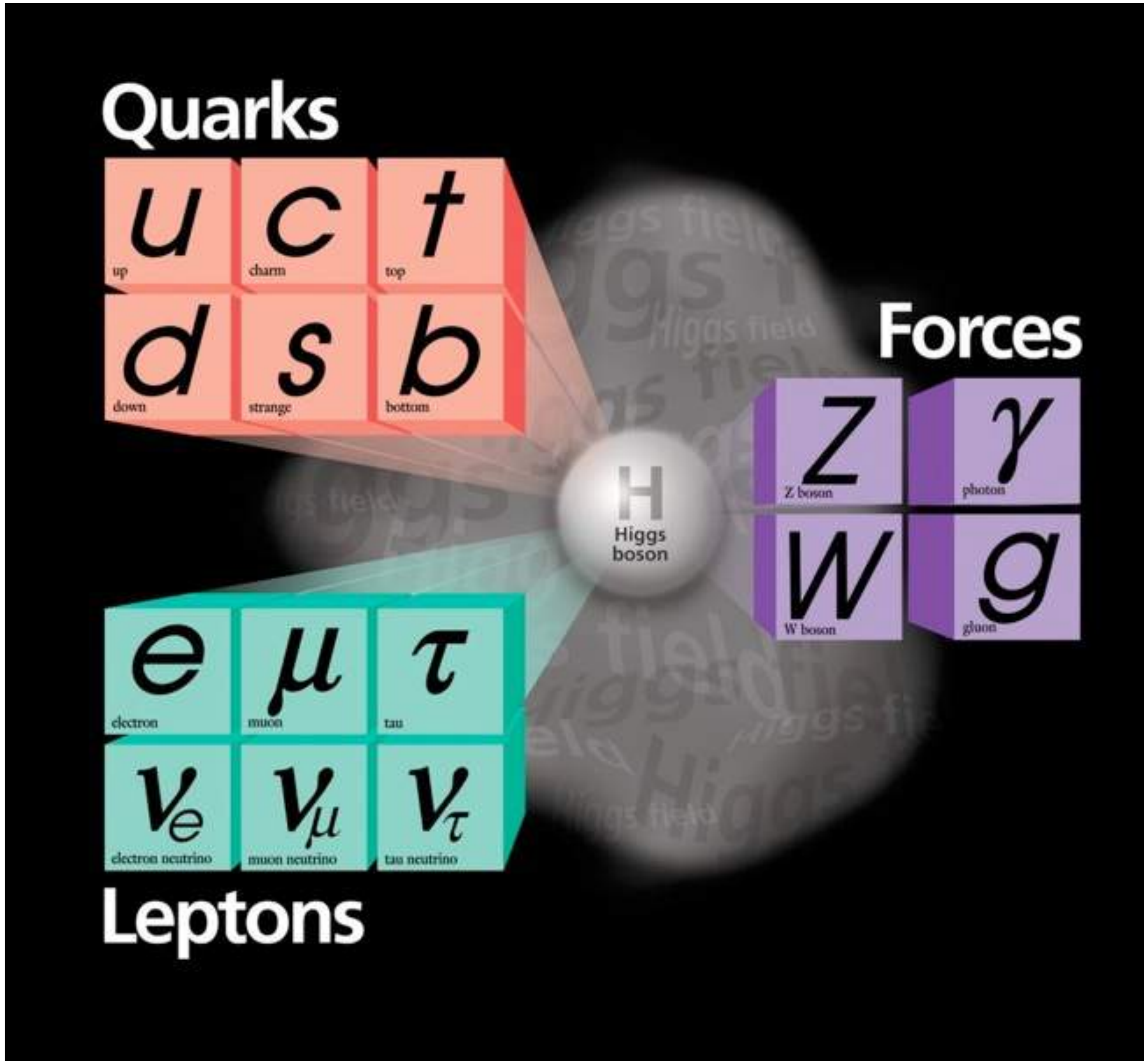
Center for Cosmology and Particle Physics,
Department of Physics, New York University
New York, NY, 10003, USA

Abstract

The cosmological constant problem and the absence of new natural physics at the electroweak scale, if confirmed by the LHC, may either indicate that the nature is fine-tuned or that a refined notion of naturalness is required. We construct a family of toy UV complete quantum theories providing a proof of concept for the second possibility. Low energy physics is described by a tuned effective field theory, which exhibits relevant interactions not protected by any symmetries and separated by an arbitrary large mass gap from the new "gravitational" physics, represented by a set of irrelevant operators. Nevertheless, the only available language to describe dynamics at all energy scales does not require any fine-tuning. The interesting novel feature of this construction is that UV physics is not described by a fixed point, but rather exhibits asymptotic fragility. Observation of additional unprotected scalars at the LHC would be a smoking gun for this scenario. Natural tuning also favors TeV scale unification.

Nevertheless

- Clear structure in fermionic sector unexplained
  - Evidence of some selective principle (why are there no neutral colored fermions? etc.)
  - Proton stability, running of couplings suggestive of at least one other scale **relevant to SM particles and interactions**, ~10^{15} GeV
    - Either fine-tuning, or a closer scale



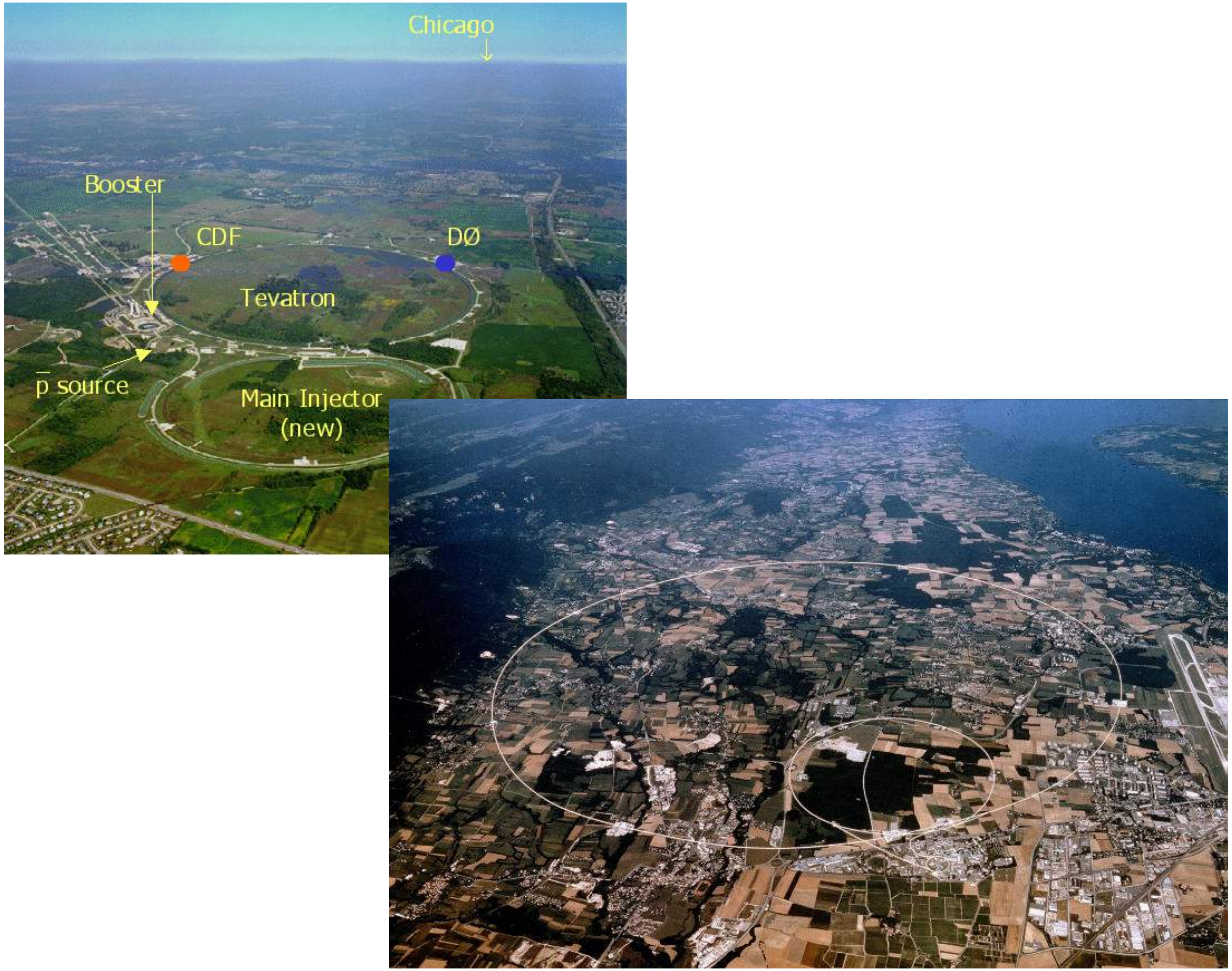
The Tools

Experimental Particle Physics

- Relies on beams of particles provided by
  - Nature: particle astrophysics
  - Accelerators and reactors
- Two types of experiments
  - Fixed target, where one beam is steered into a macroscopic target
  - Colliders, where two beams are collided head-on, leading to higher center-of-mass energy
    - Lorentz boost!

1990's

- Tevatron
  - proton-antiproton at ~2 TeV, collisions at 2.5 MHz
  - Top quark
- LEP
  - Z peak
  - Huge number of precision measurements
    - Strong indirect constraints



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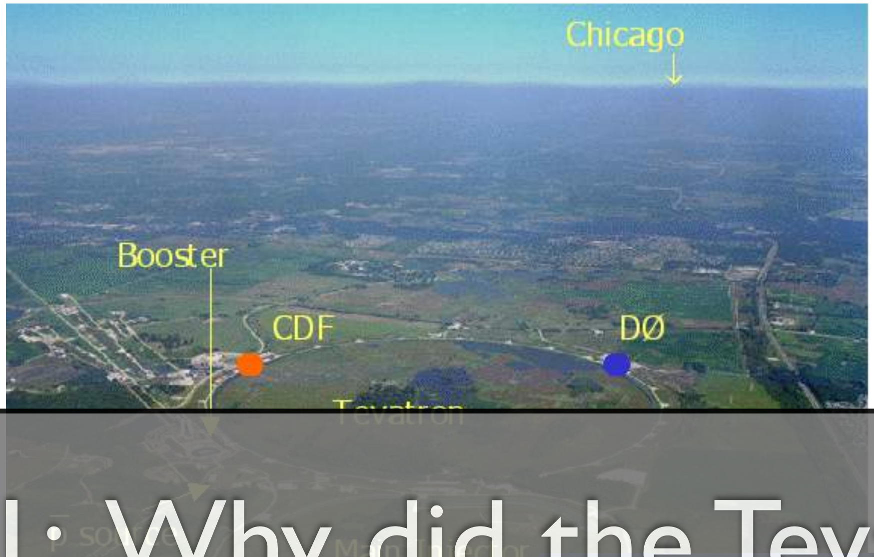
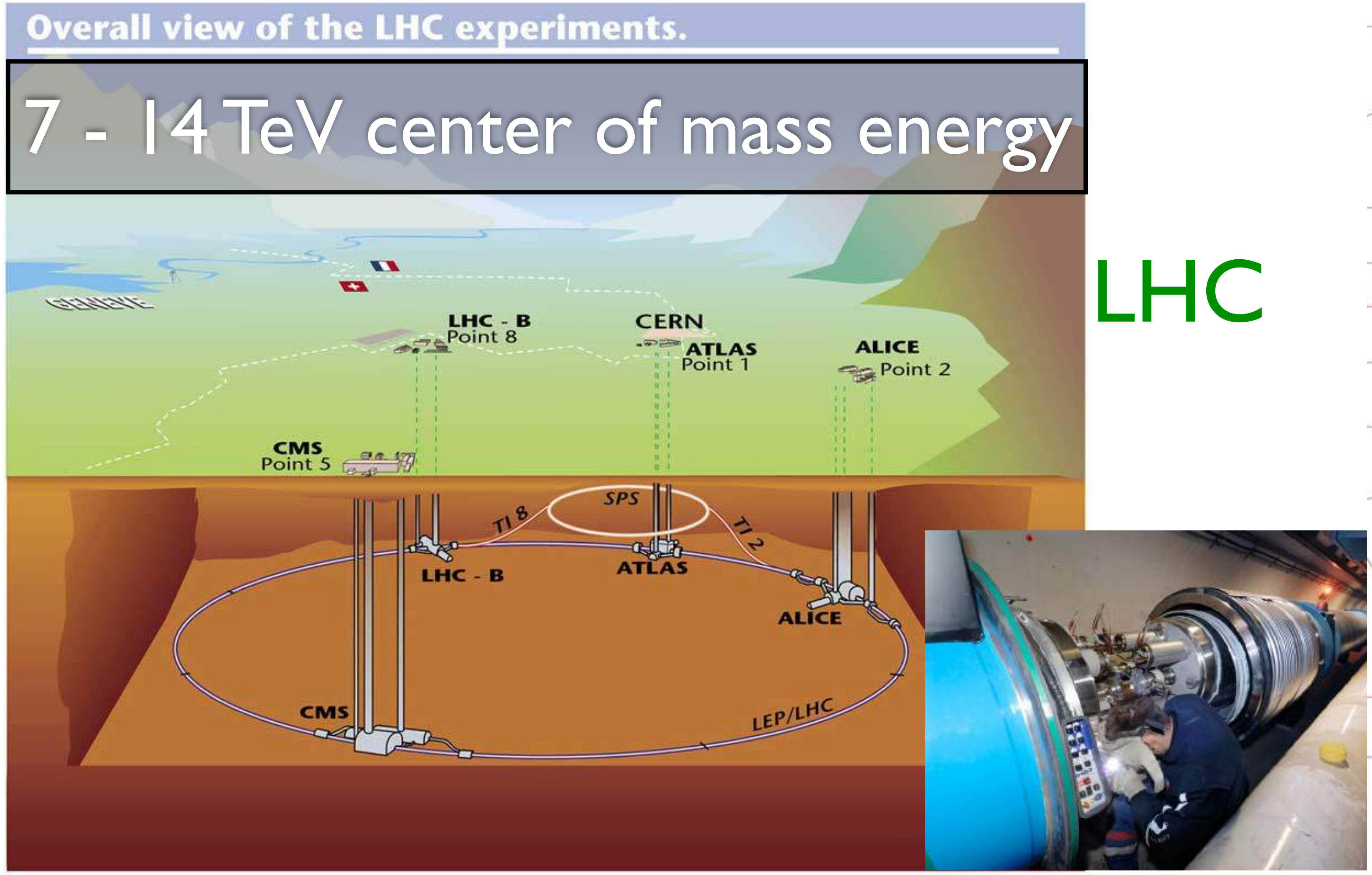


Question 1: Why did the Tevatron use antiprotons?

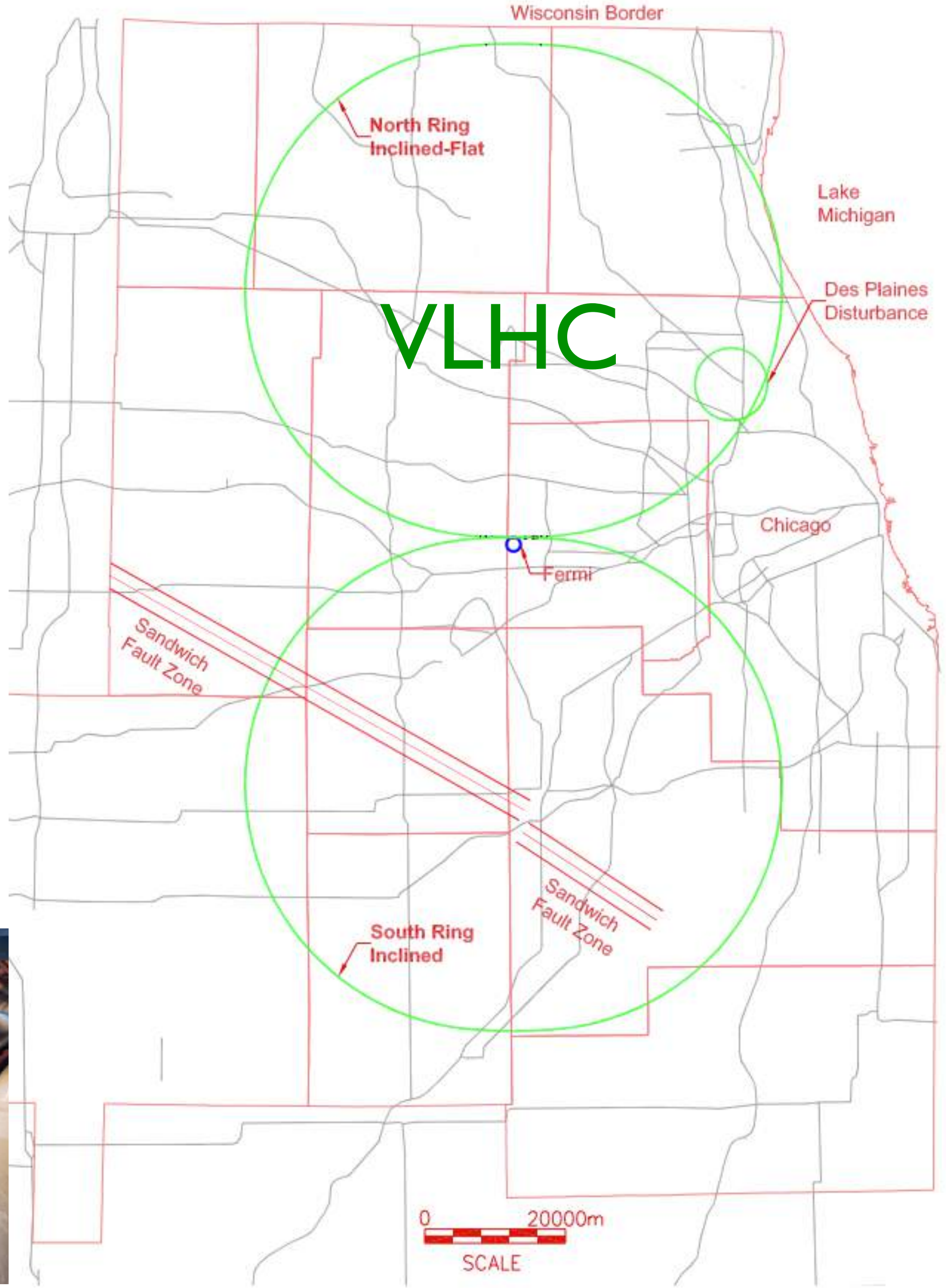
Energy Frontier

- Currently, hadron colliders:
  - High energy implies probing of short distances, and production of other, massive particles



7 - 14 TeV center of mass energy

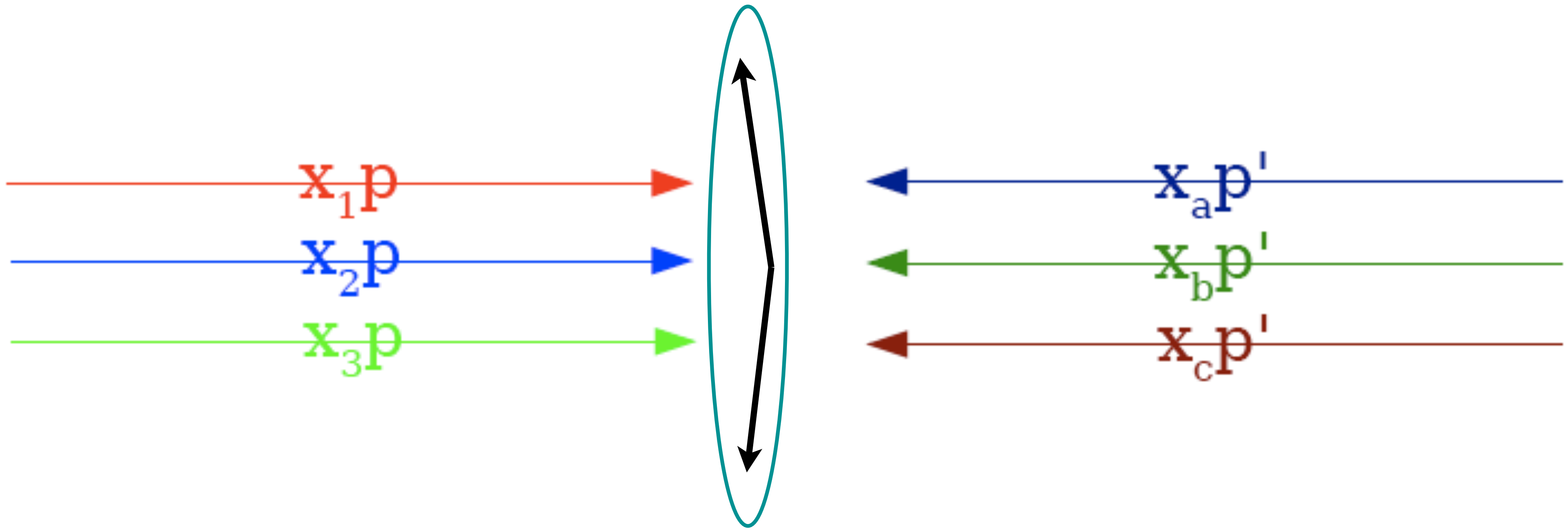
LHC



Hadron Colliders

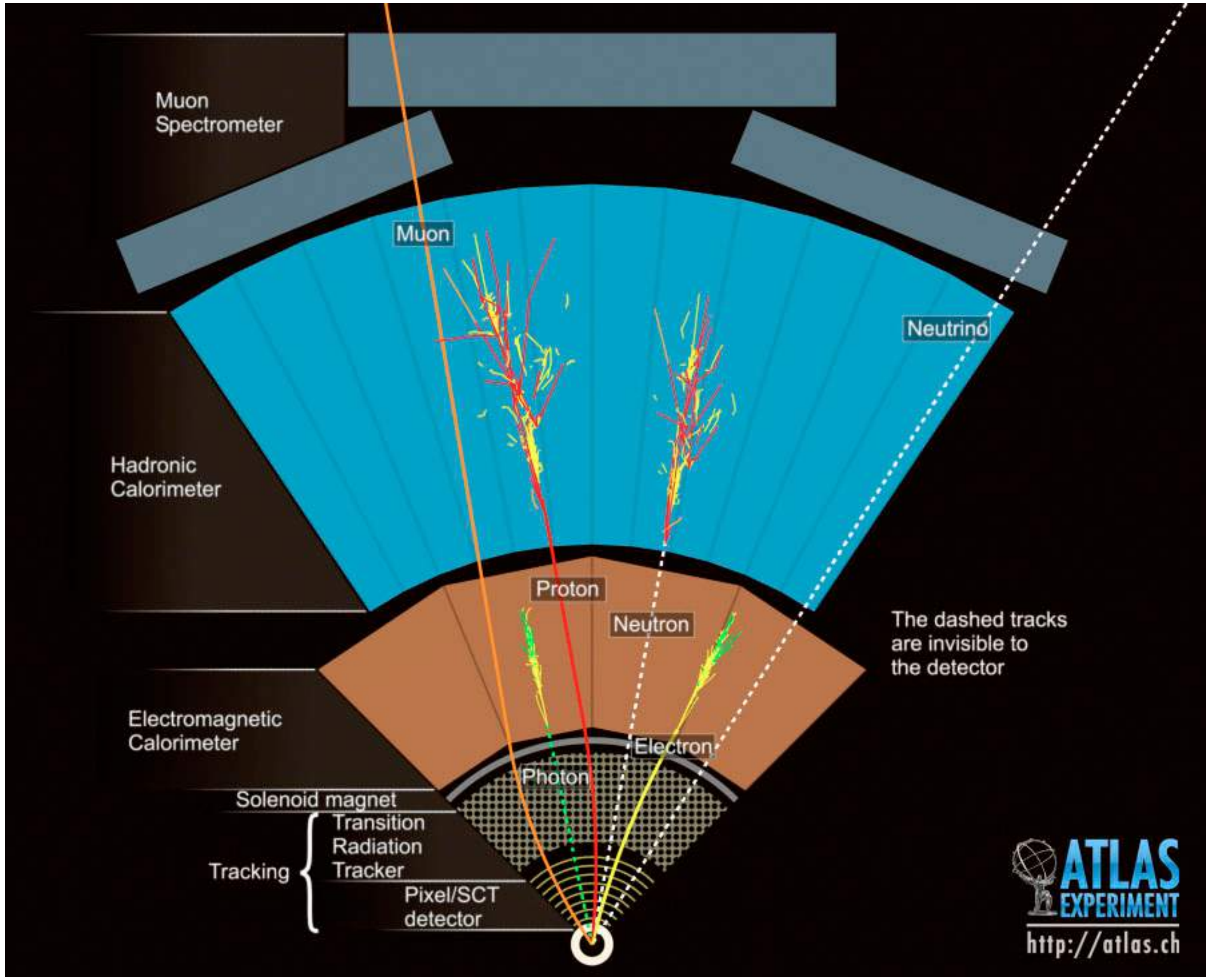
- ❖ Incoming longitudinal momentum not known:
  - "Hard interaction" is between one of the quarks and/or gluons from each proton, other quarks/gluons are "spectators"
- ❖ Longitudinal boost "flattens" event to a pancake

➡ We usually work in the plane transverse to the beam



Detecting Particles

- Detection strategy is driven by energy loss:
  - All charged particles ionize gases, semiconductors ⟹ track detectors
    - (Usually embedded in magnetic field to measure momenta)
  - e, γ, μ: electromagnetic interactions
    - Specific shower shapes
  - π, K, p, n, …: electromagnetic + strong interactions
  - Many (most) particles decay before reaching track detectors



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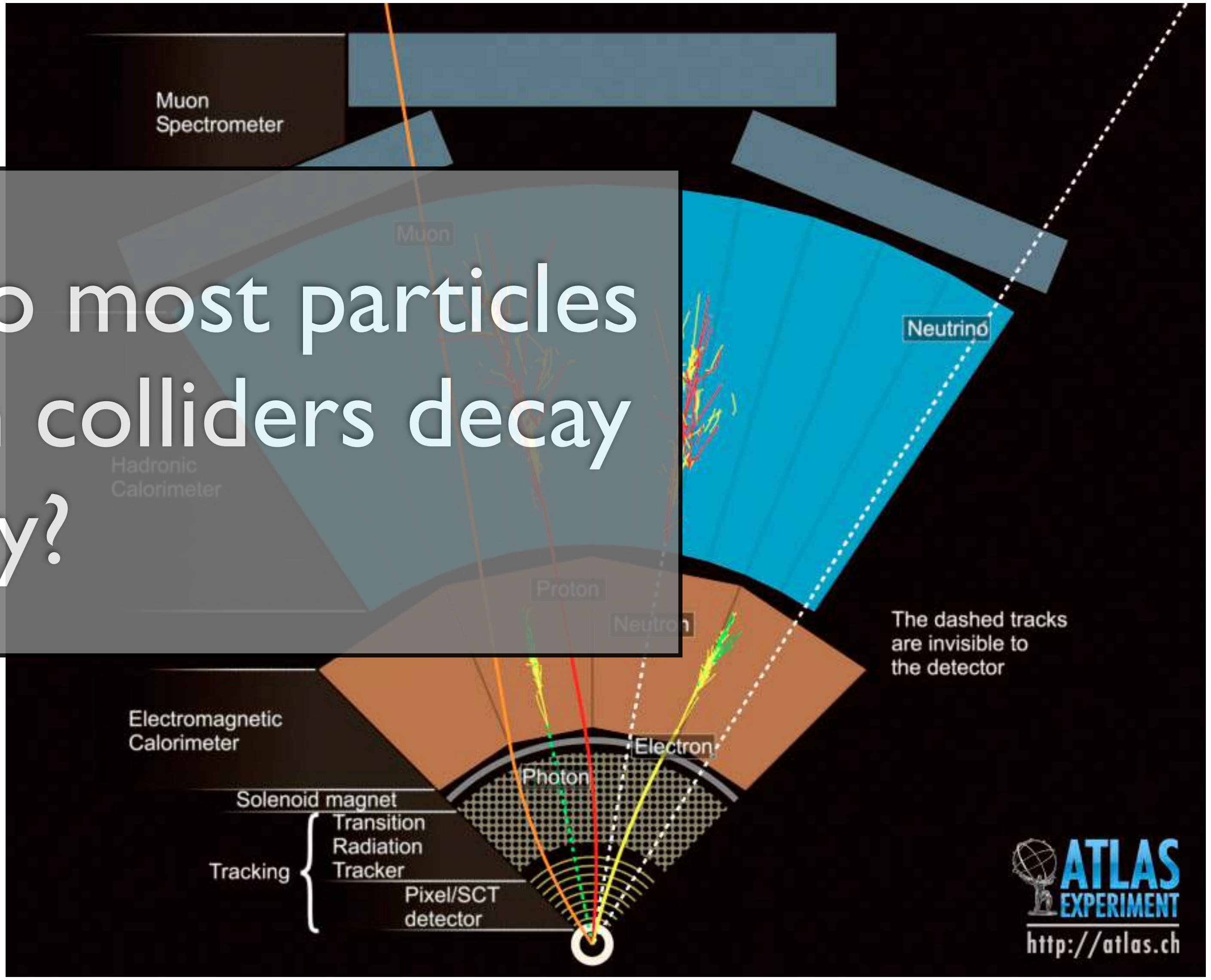
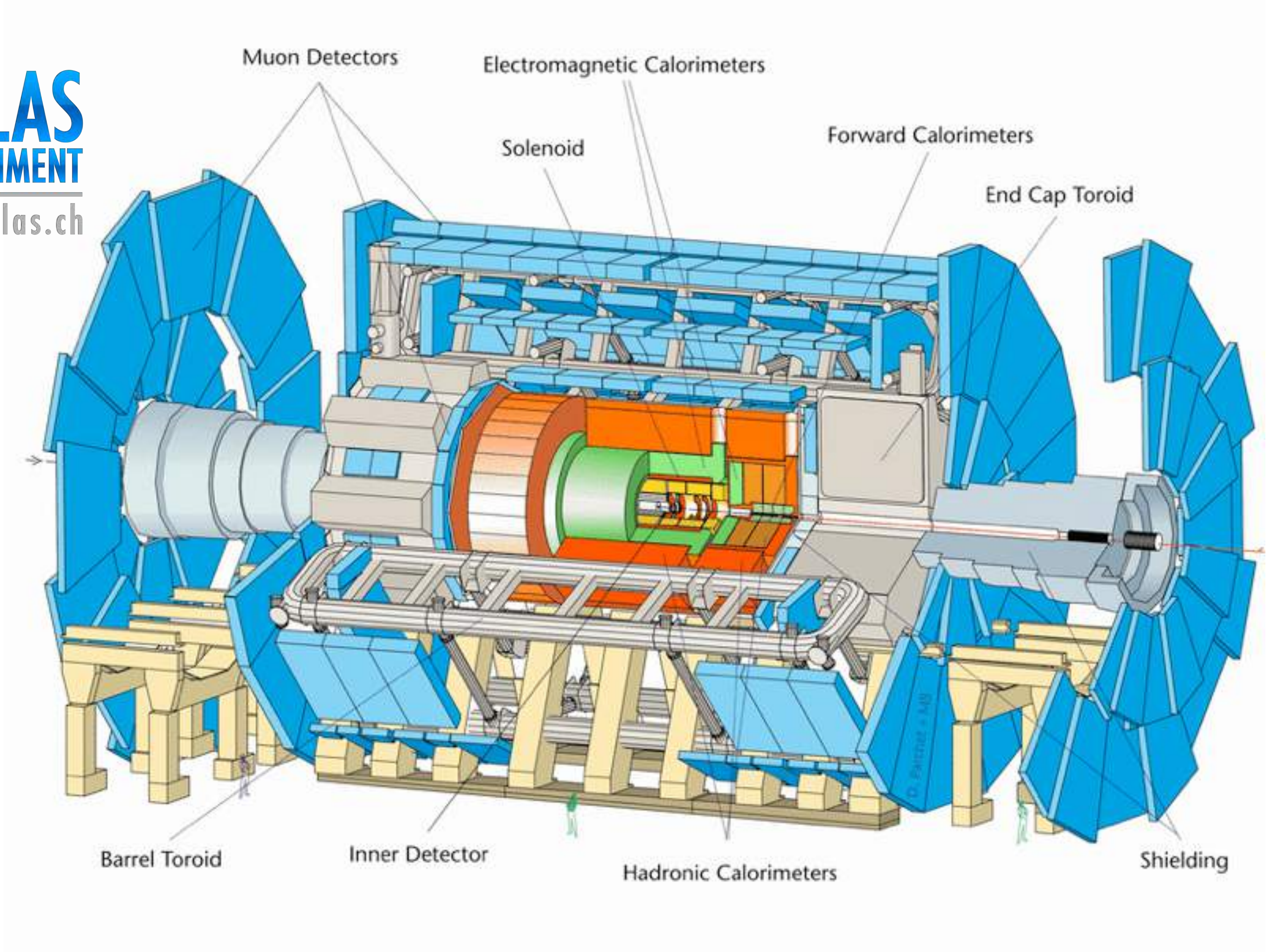
Question 2: Why do most particles produced at hadron colliders decay quickly?



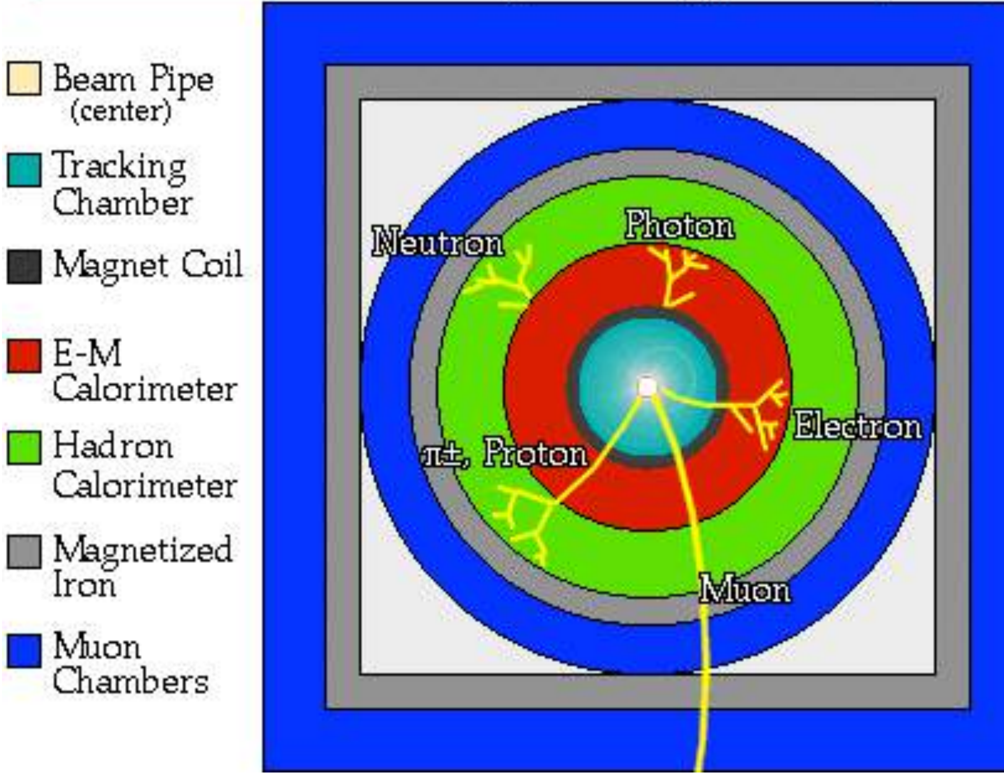
Detectors

- Make best possible measurement of all particles coming out of collisions

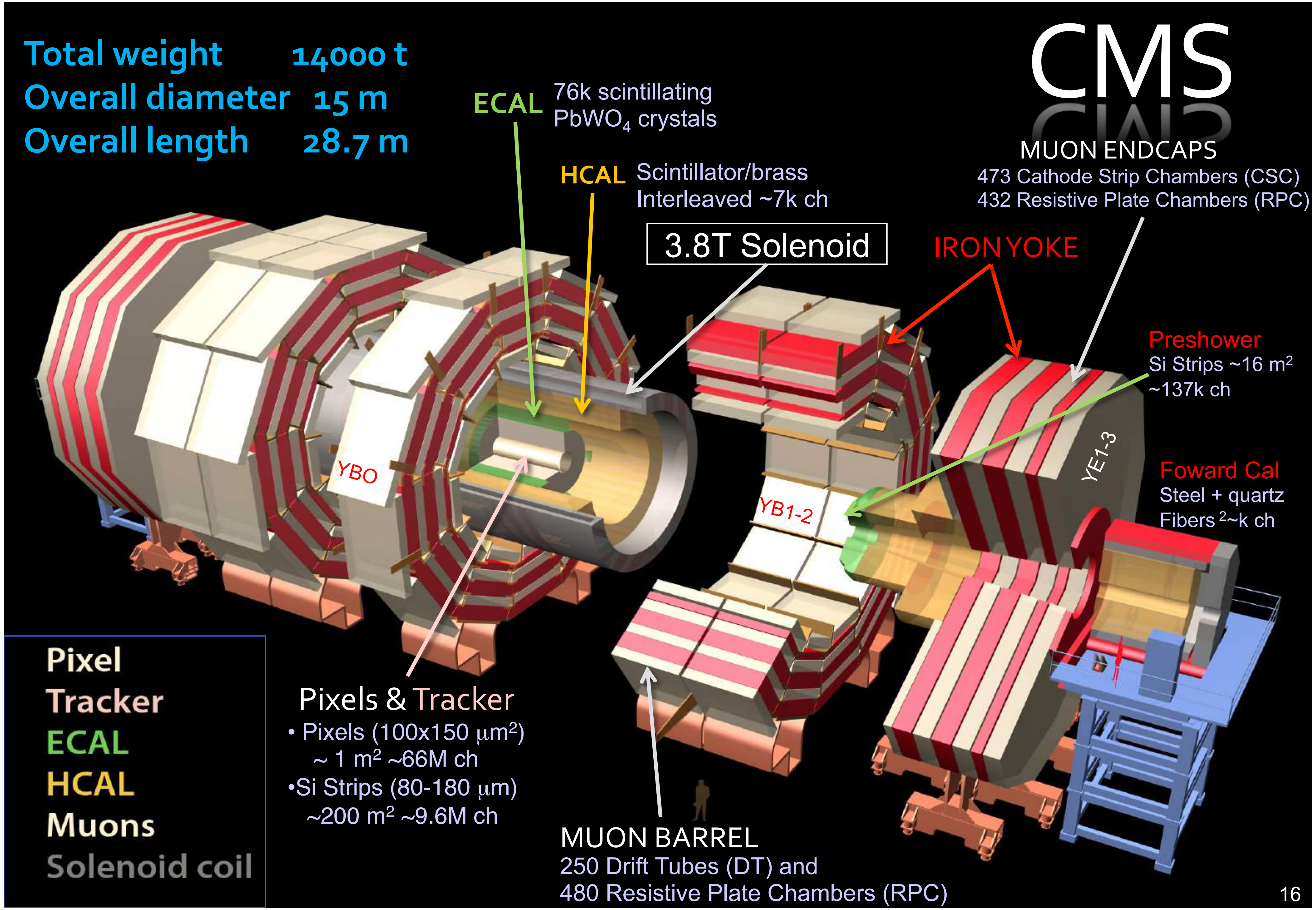
ATLAS EXPERIMENT
http://atlas.ch



A detector cross-section, showing particle paths



CMS



Total weight	14000 t
Overall diameter	15 m
Overall length	28.7 m

CMS

ECAL 76k scintillating $PbWO_4$ crystals

HCAL Scintillator/brass Interleaved ~7k ch

3.8T Solenoid

MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)

IRON YOKE

Preshower
Si Strips ~16 m^2
~137k ch

Foward Cal
Steel + quartz
Fibers ^{2}~k ch

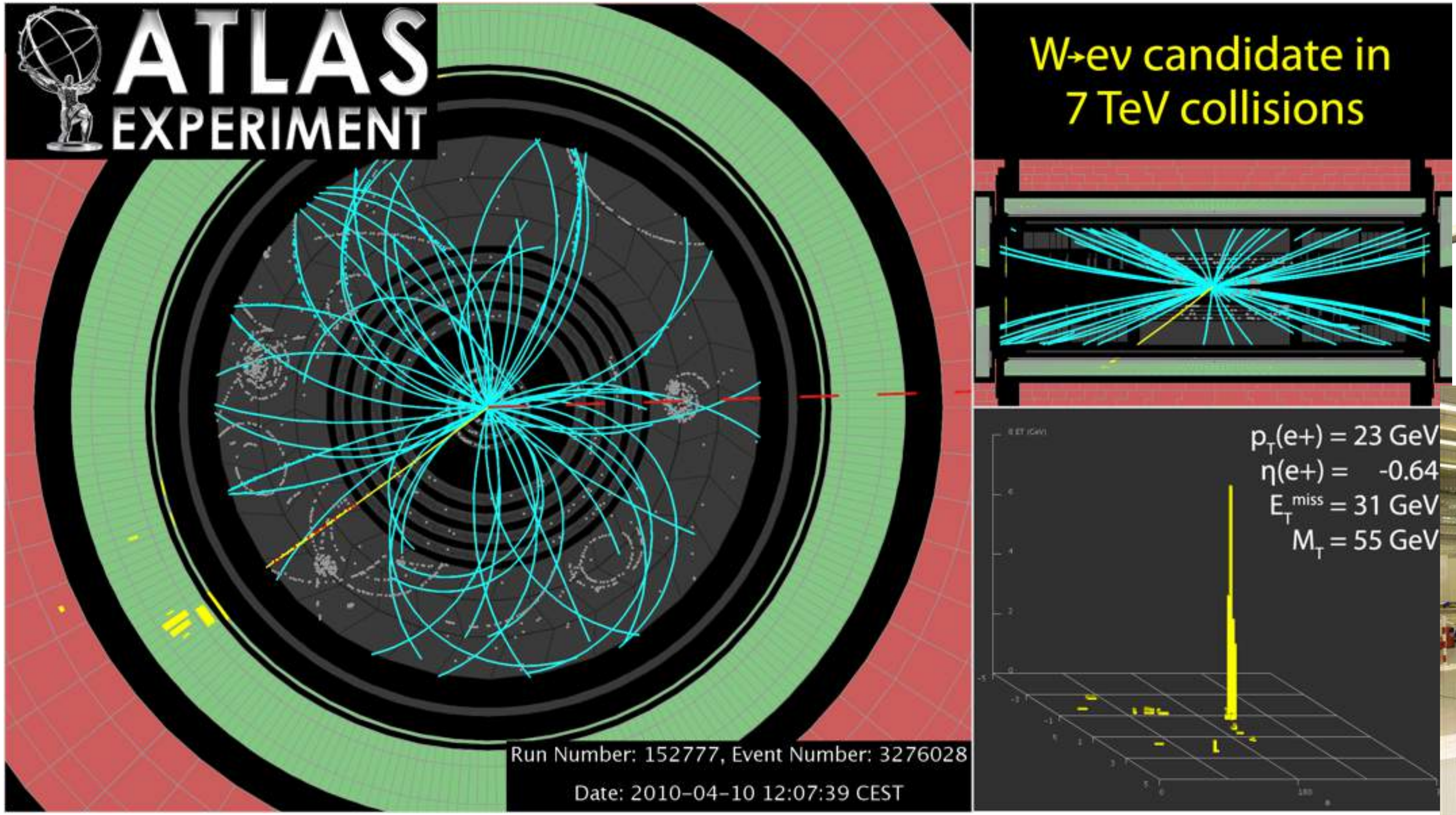
- Pixel
- Tracker
- ECAL
- HCAL
- Muons
- Solenoid coil

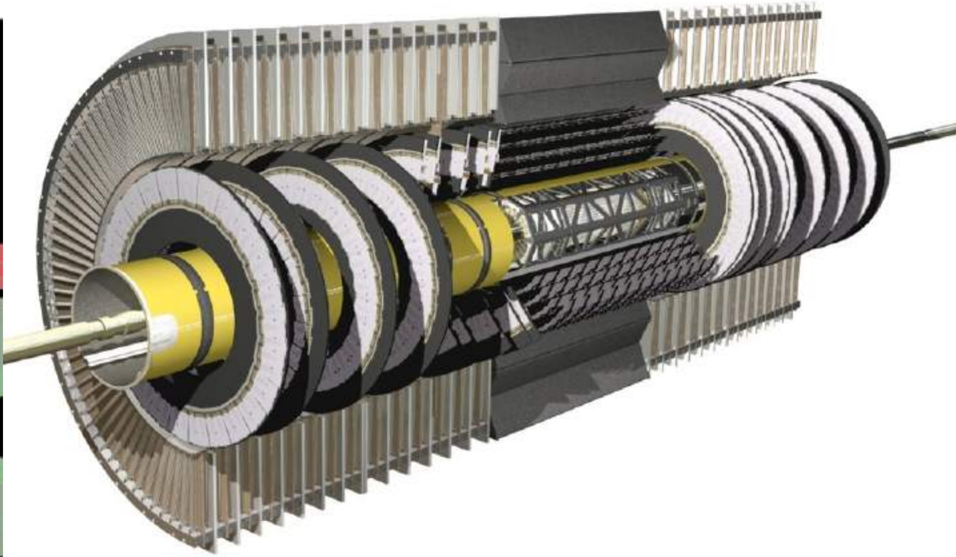
Pixels & Tracker
- Pixels (100x150 μm^2)
  ~ 1 m^2 ~66M ch
- Si Strips (80-180 μm)
  ~200 m^2 ~9.6M ch

MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

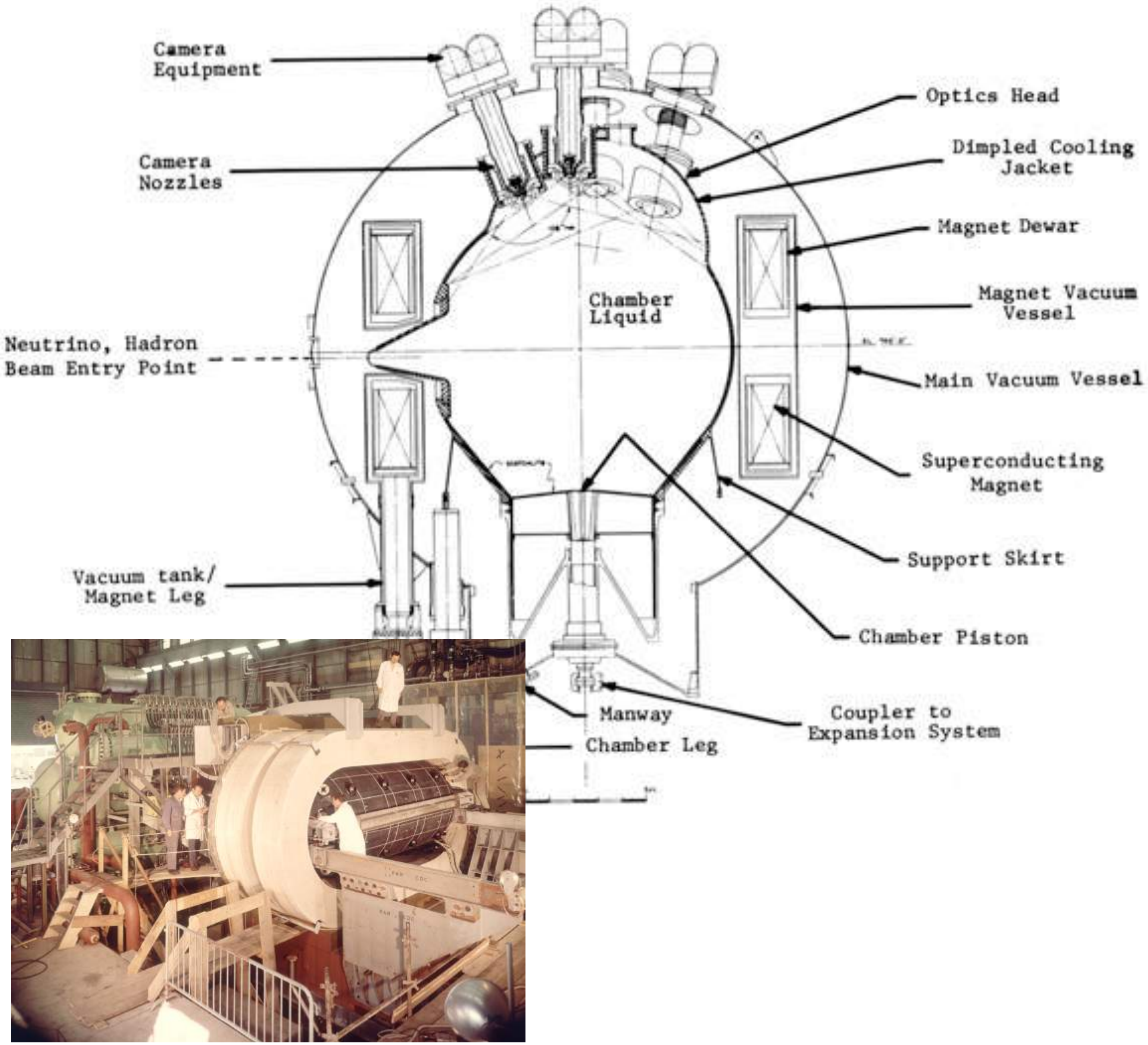
Charged Particles

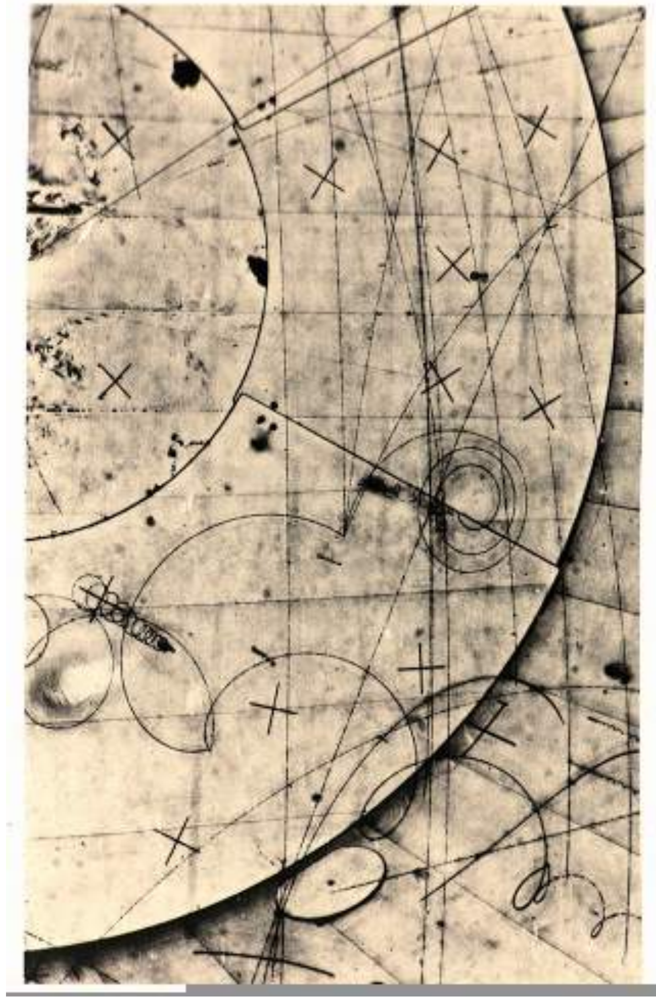
- Combination of pixels, silicon strips ("SCT") and straw tube transition radiation tracker (TRT)
  - High precision needed for secondary vertexing, precise momentum measurement

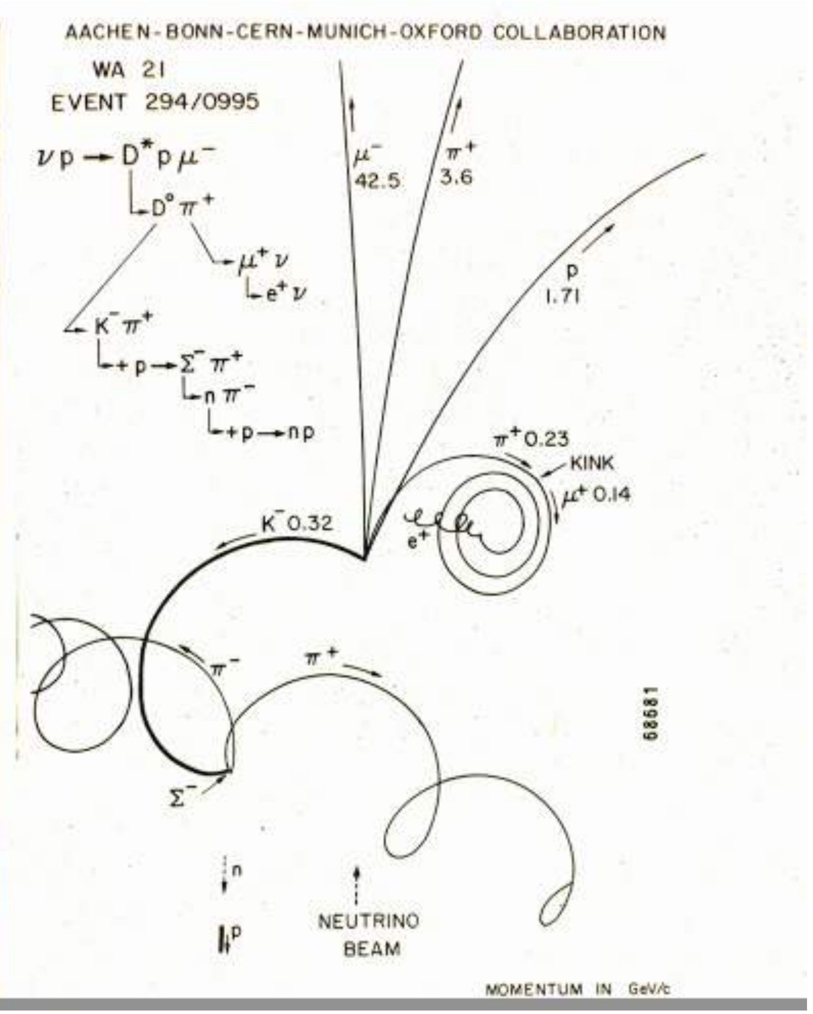




Bubble Chambers







Silicon Detectors

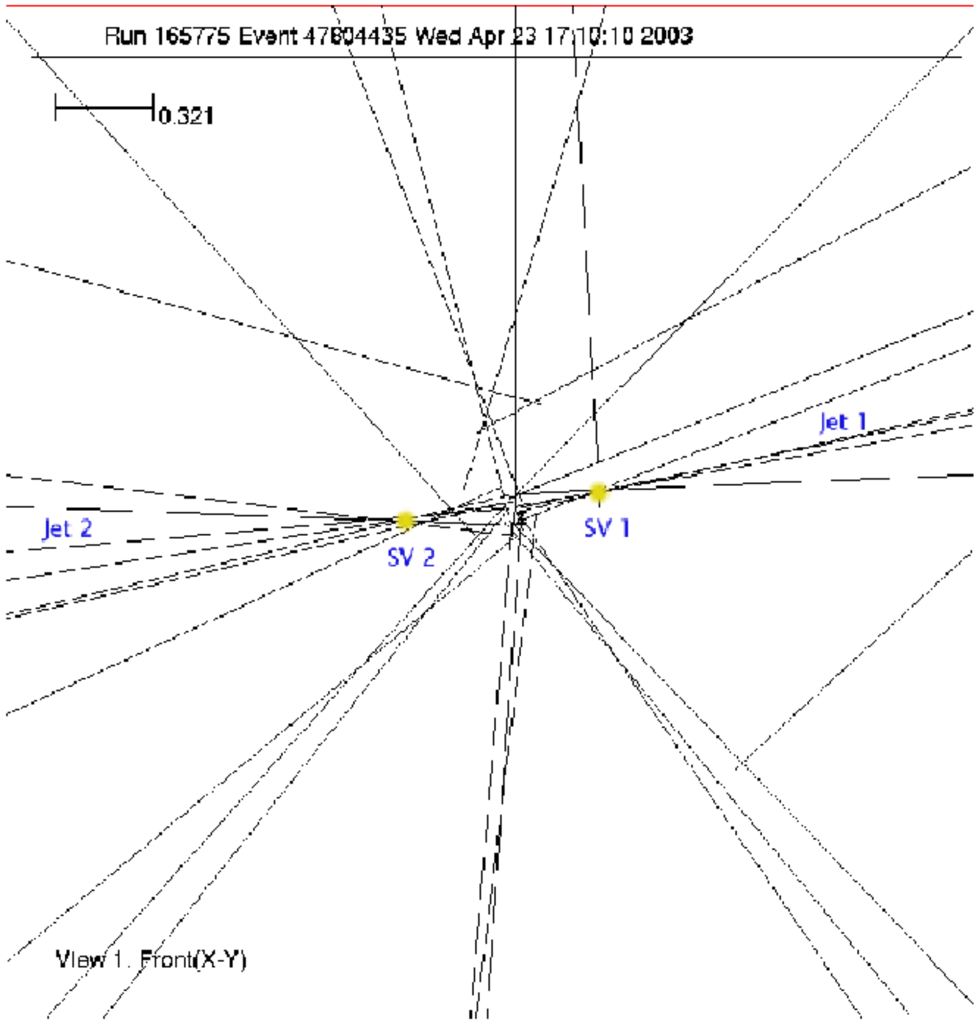
❖ Principle of operation:

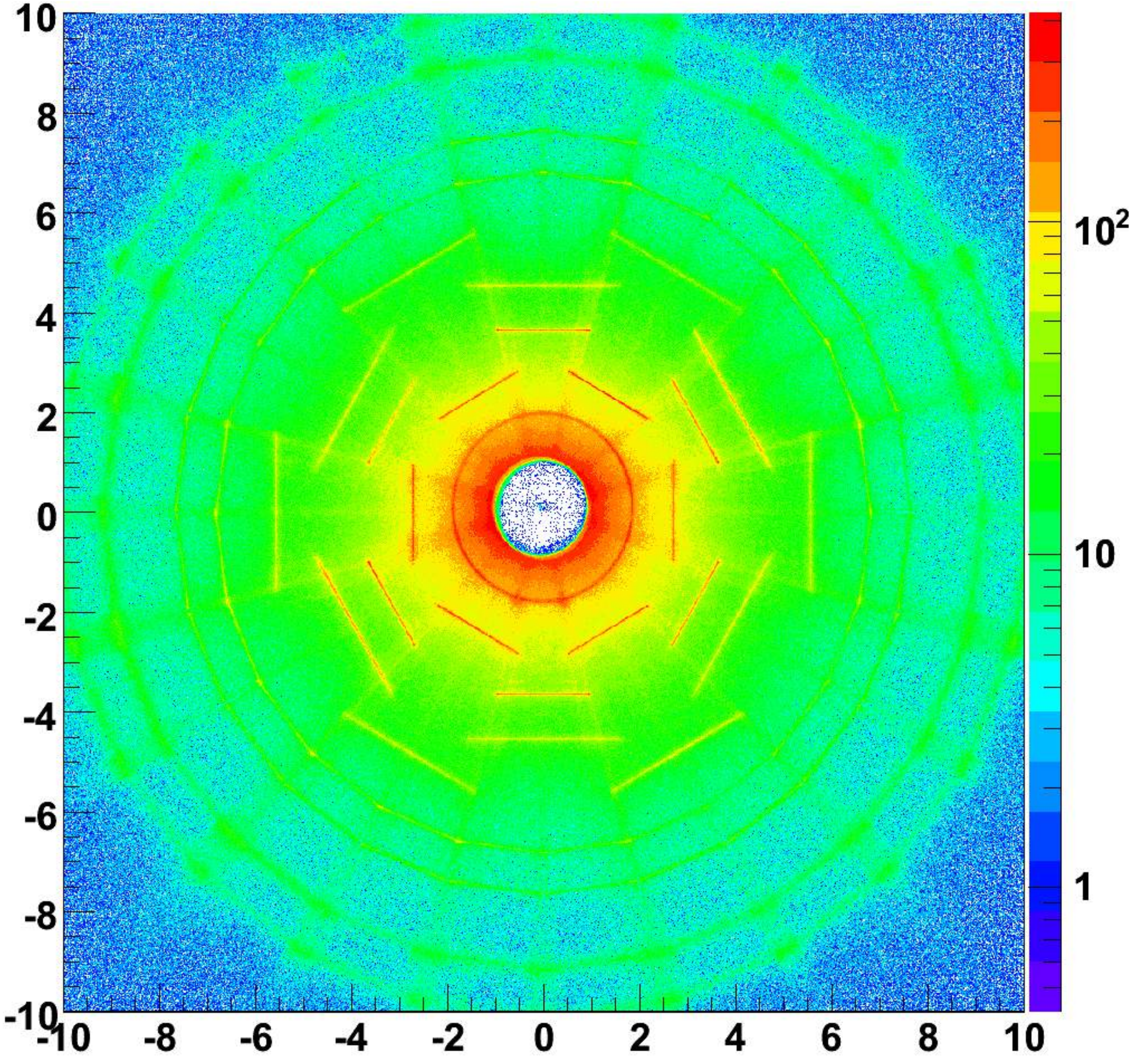
- Ionizing particle (charged) produces electron-hole pairs along its track (with number ~energy loss)
- External electric field (generated by metal layer on detector) forces electrons to migrate to anode, holes to cathode
- Charge is collected on thin conducting strips, $\mathcal{O}$(50 μm) apart, and measured
- Pro: excellent position resolution (5-10 μm)
- Con: very expensive (fabrication, number of channels), dense: silicon+on-board readout electronics (small signals) + cooling & support infrastructure

➡ Photon conversions, multiple scattering degrade resolution

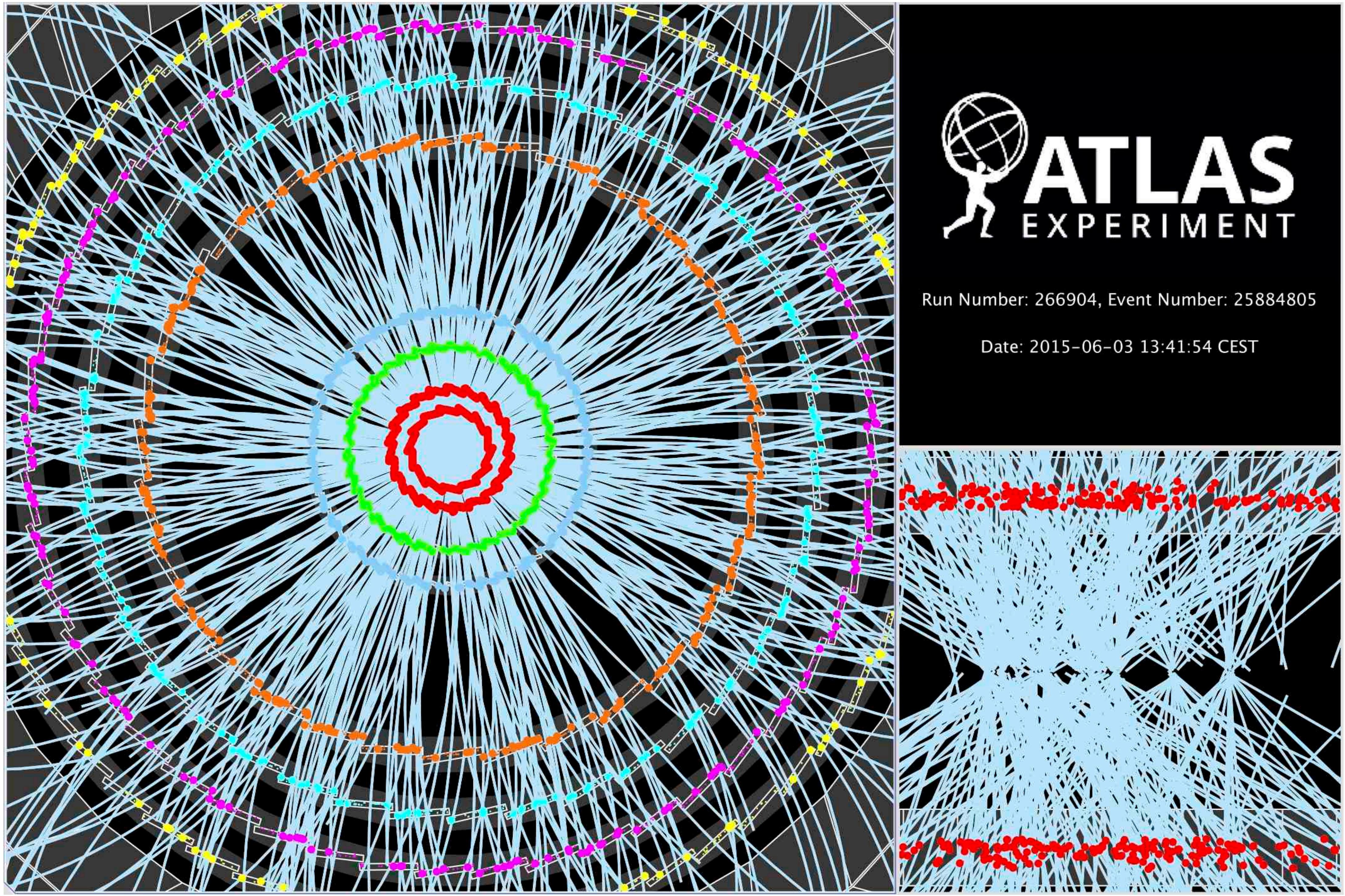
Useful Conversions?

- Photon conversions aren't completely useless…





“Pile-Up”


ATLAS EXPERIMENT
Run Number: 266904, Event Number: 25884805
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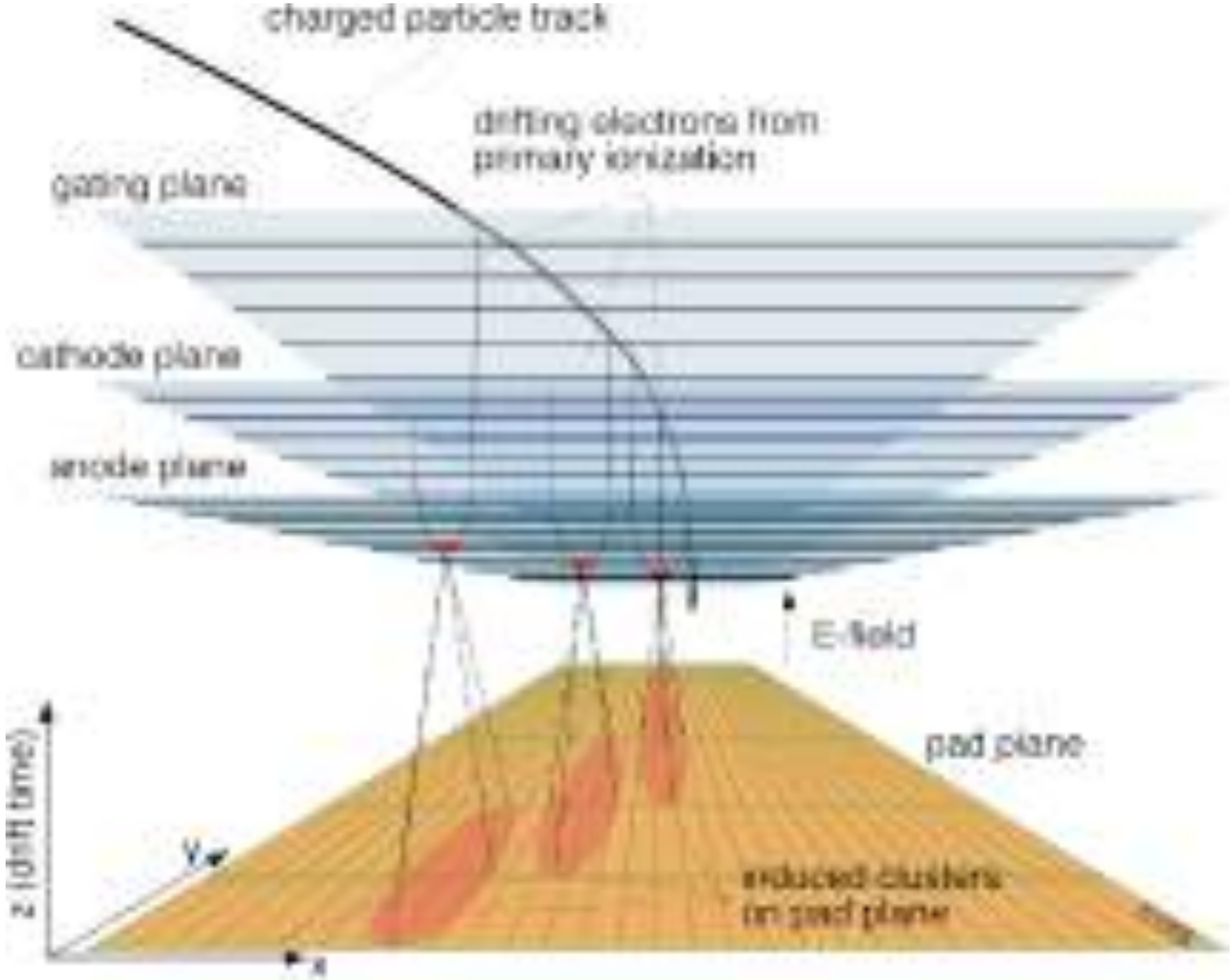
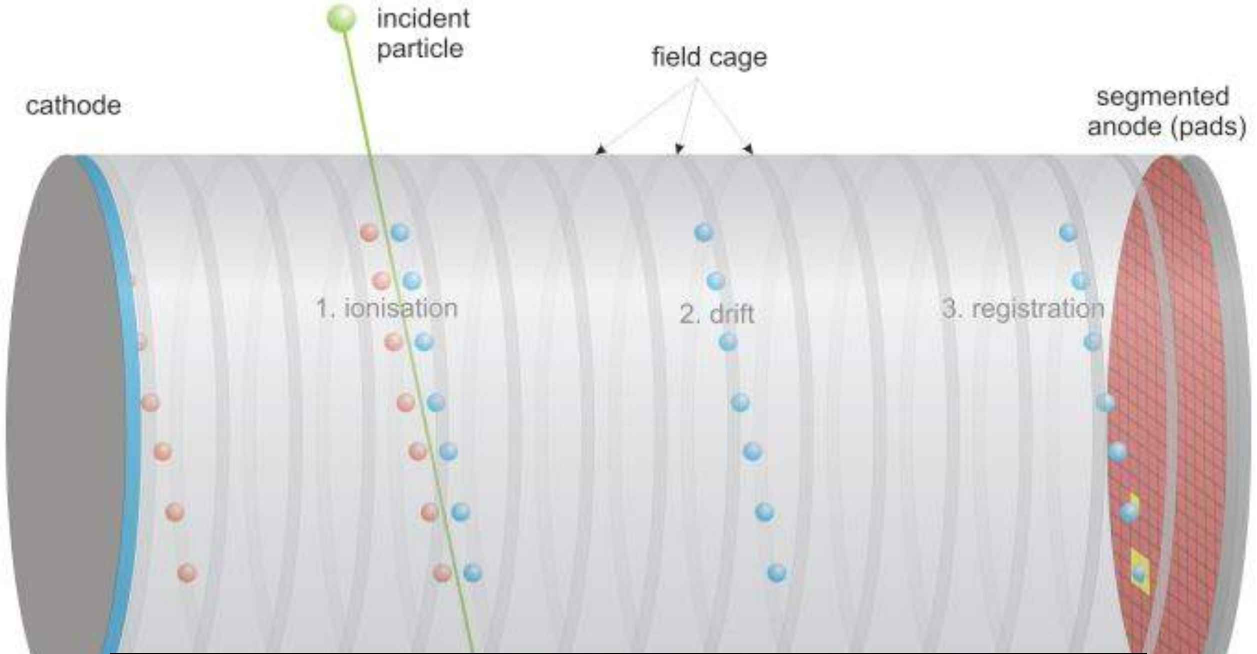
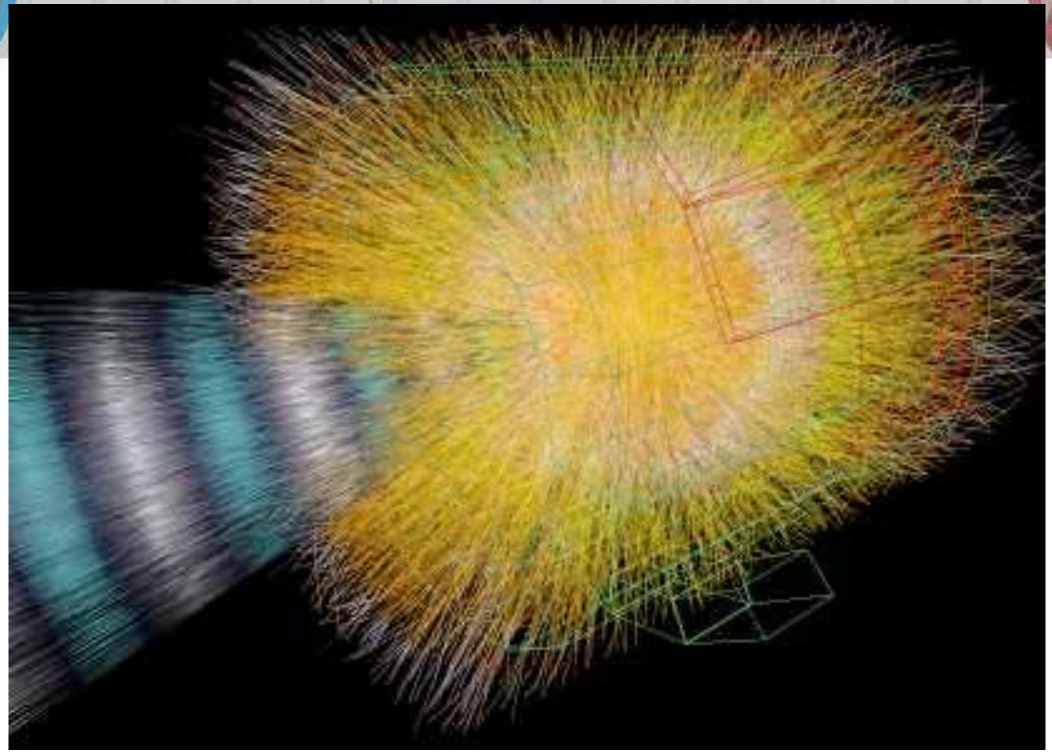
Wire Chambers

- Costs limit the area/volume for silicon detectors
- For the (very large) muon systems, use wire chambers
  - Anode wires and cathode planes or wires in a gaseous environment
    - Ionizing particles ionize gas, electrons and ions drift, measure collected charge
  - Pro: much cheaper, still good position resolution (~100 μm) if measure drift time (hence the name “drift chamber”)
    - Best performance for slow drift and low gain
  - Con: surprisingly difficult to build, as signals small but area large - effectively big antennas; drift chambers are slow

Extreme Case: TPC

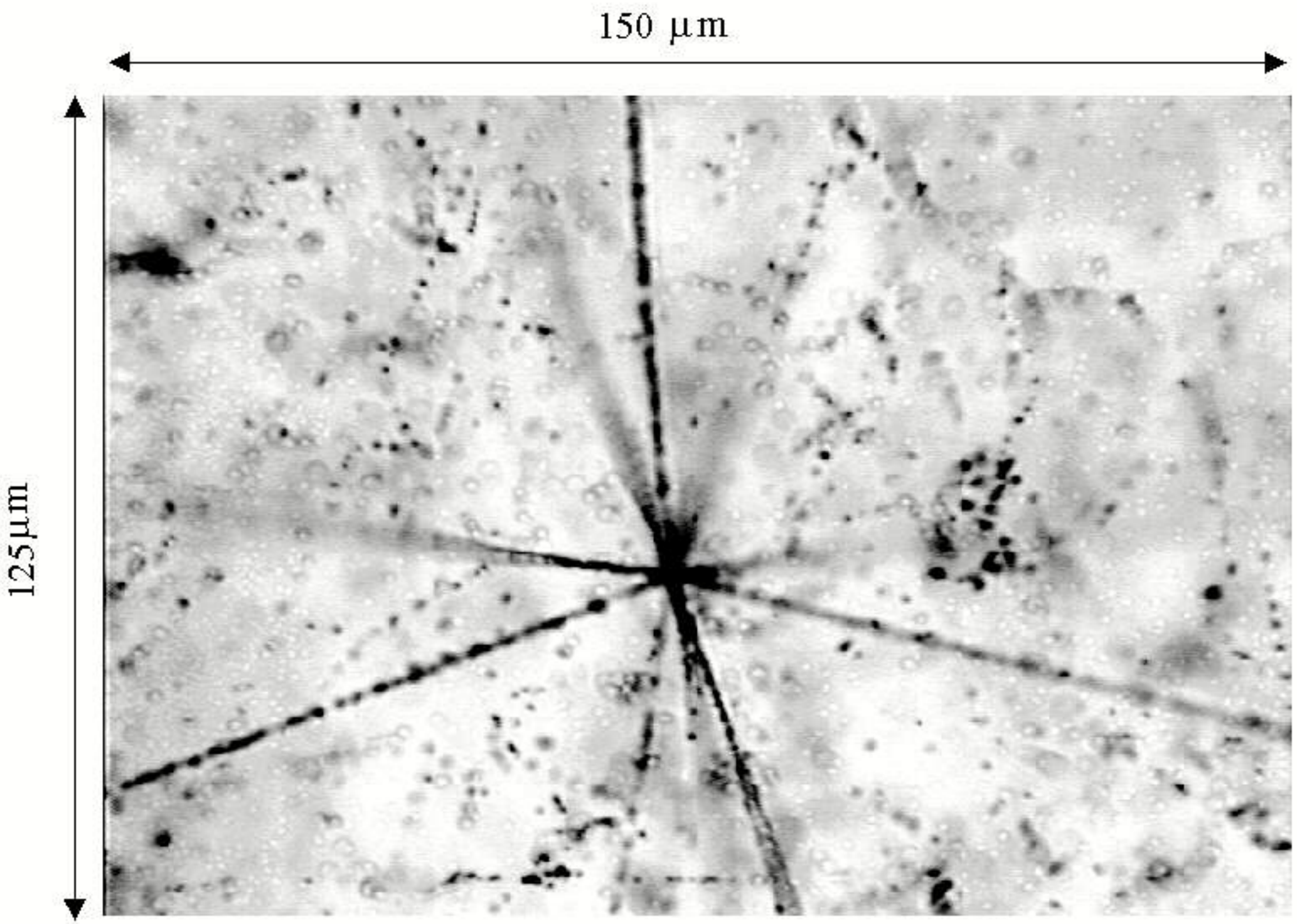






Nuclear Emulsions

- The original particle detector
  - Full 3D, ~3 μm hit resolution, but horrendously slow
- Used most recently in neutrino experiments



(about 10^{13} fields like this one!)

Scintillator

- Ionizing particles excites molecules/atoms, which emit photons at specific wavelengths
  - Scintillating substance(s) used to dope transparent medium, often plastic, sometimes liquid
  - Can be used in calorimetry, or for tracking (by doping optical fibers)
- Pro: relatively easy to build and operate (no gas, high voltage only in read-out), very fast
- Con: typically not very radiation-tolerant

Scintillator Readout

- For calorimeters: photomultipliers or “avalanche photodiodes”
  - PMTs exploit photoelectric effect to convert photons to electrons, then multiply using successive “dynodes”
  - “Quantum efficiency” is the fraction of photons that lead to an observable signal
  - Now also SiPMs, becoming mature
- For tracking devices
  - Image intensifiers with CCDs (slow, expensive)
  - Visible Light Photon Counters, operated at cryogenic temperatures: high QE, fast, expensive, very complex to operate

Calorimetry

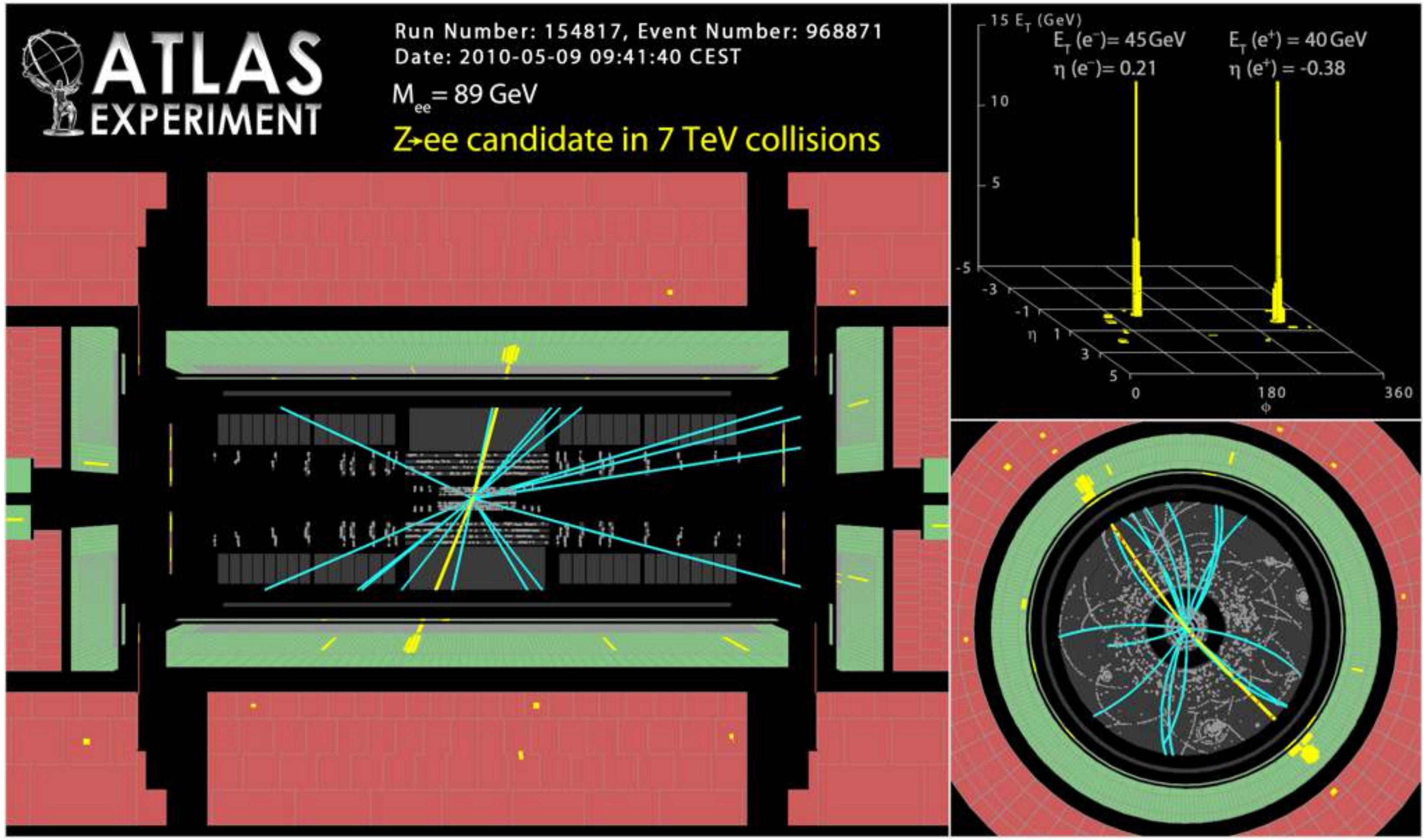
- Track reconstruction only allows measurement of charged particles and their momenta
- Calorimetry:
  - Measure energies of all particles; distinguish electrons and photons from hadrons
  - General strategy: absorb particles, measure deposited energy
    - Absorption by forcing cascades of interactions (strong or electromagnetic) in dense material, i.e. “showers”
    - Fine calorimeter granularity allows reconstruction of shower shape, structure, direction, …

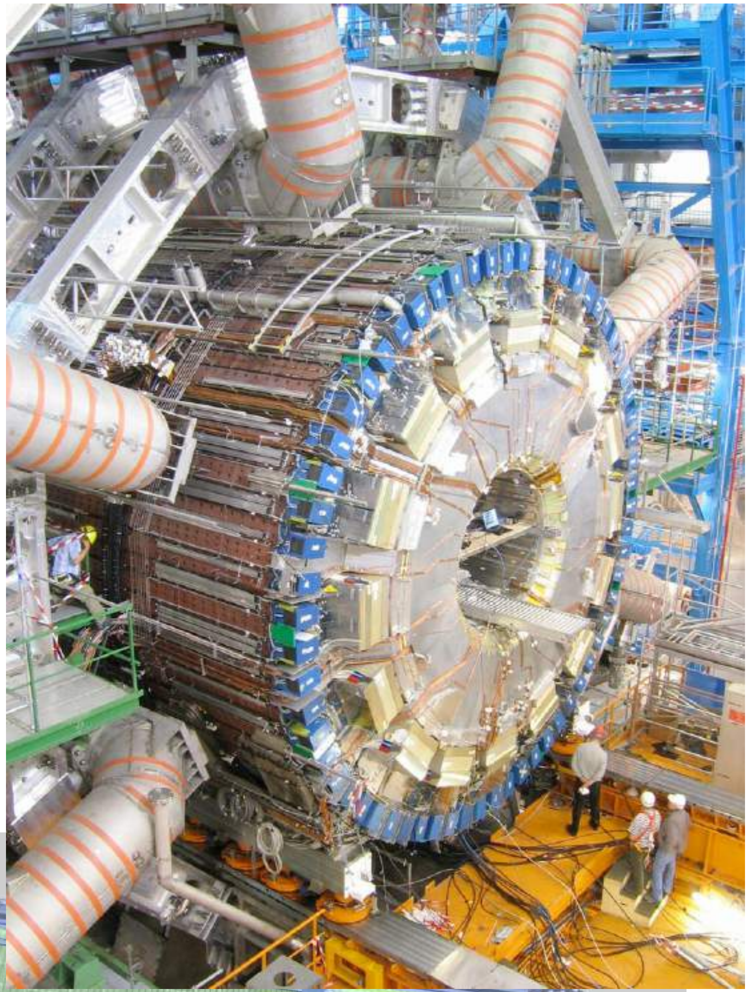
Calorimetry

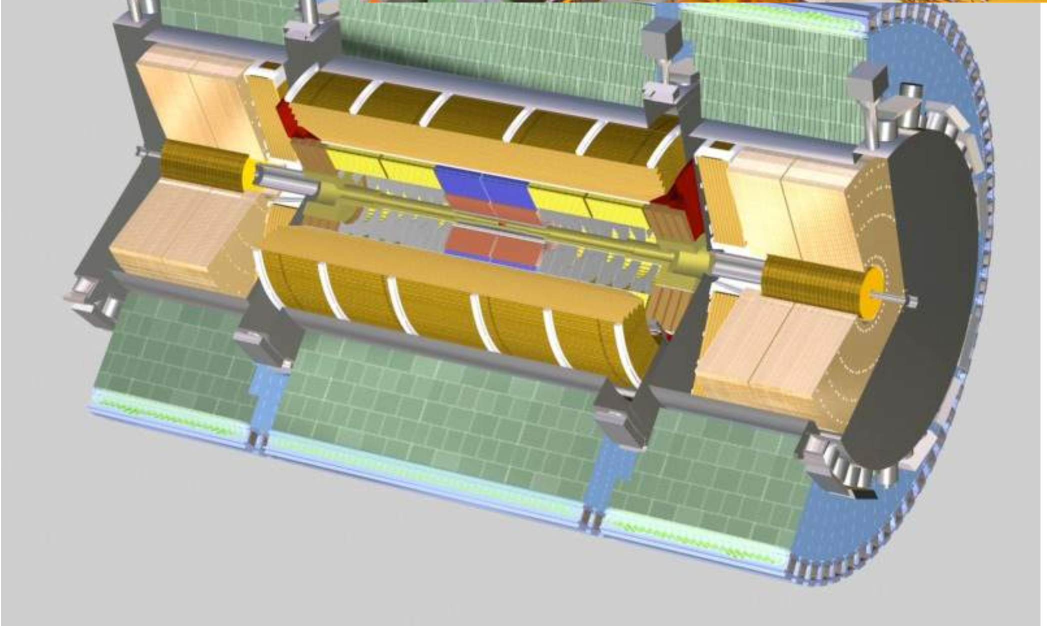
- Key issue is fraction of deposited energy that's visible
  - Basic calorimeter = interleaved plates of lead and scintillator
    - But energy deposited in the lead is invisible
      - Increasingly sophisticated geometries or materials:
        - "Spaghetti calorimeters" have scintillating fibers embedded in the lead
        - Crystals with much higher density but transparency comparable to glass, eg. NaI or $PbWO_4$
      - Scintillators and crystals not very radiation tolerant
        - Noble liquid calorimeters: collect ionization charge instead of light
    - In addition, a lot of the energy deposited in nuclei is invisible!
      - "Hadronic" energy resolution intrinsically worse then "electromagnetic"

Calorimetry

- ❖ Liquid Argon & Pb accordion (EM & forward), crystals
- ❖ Scintillator & steel/copper/tungsten (hadronic)

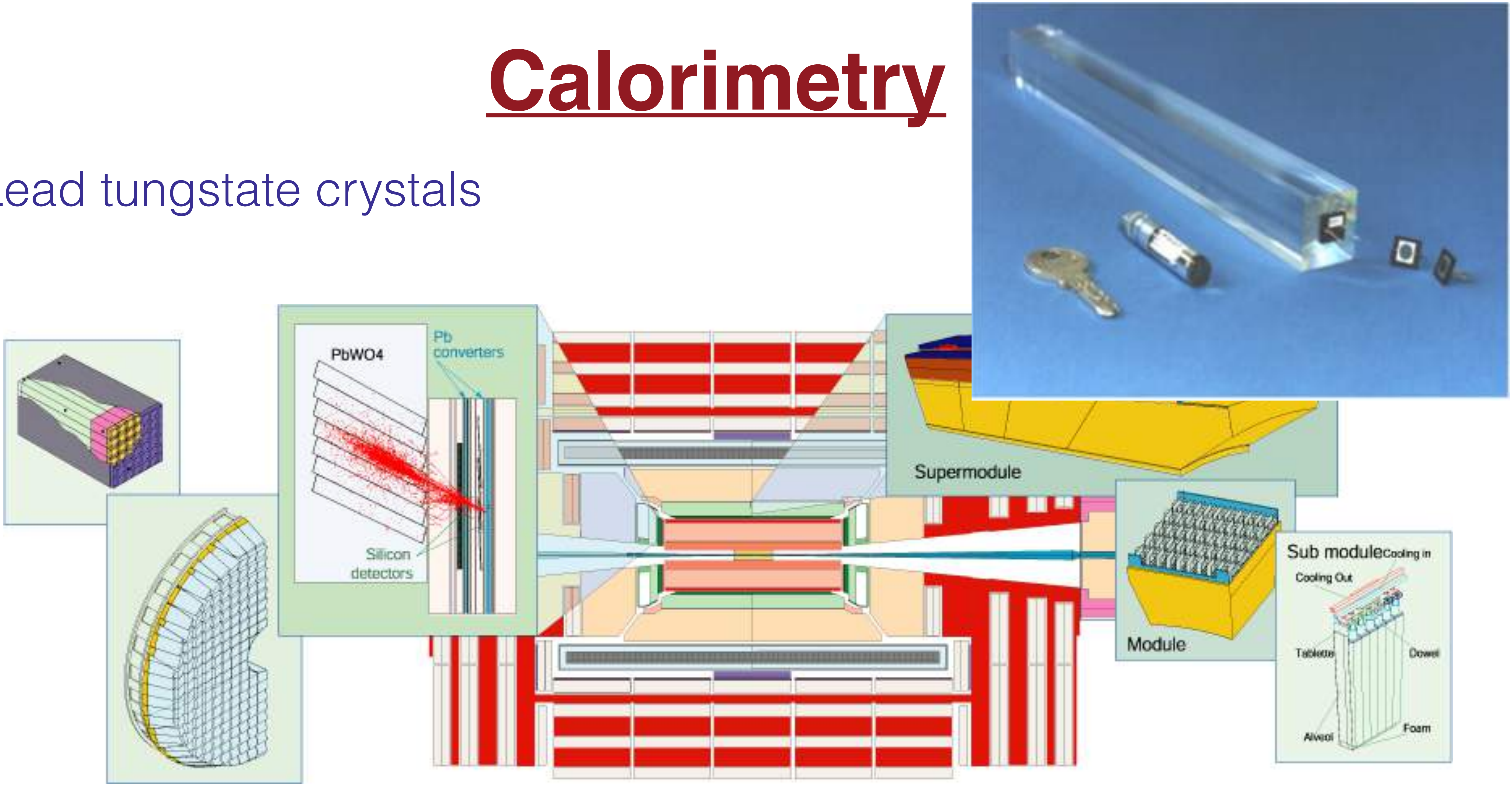






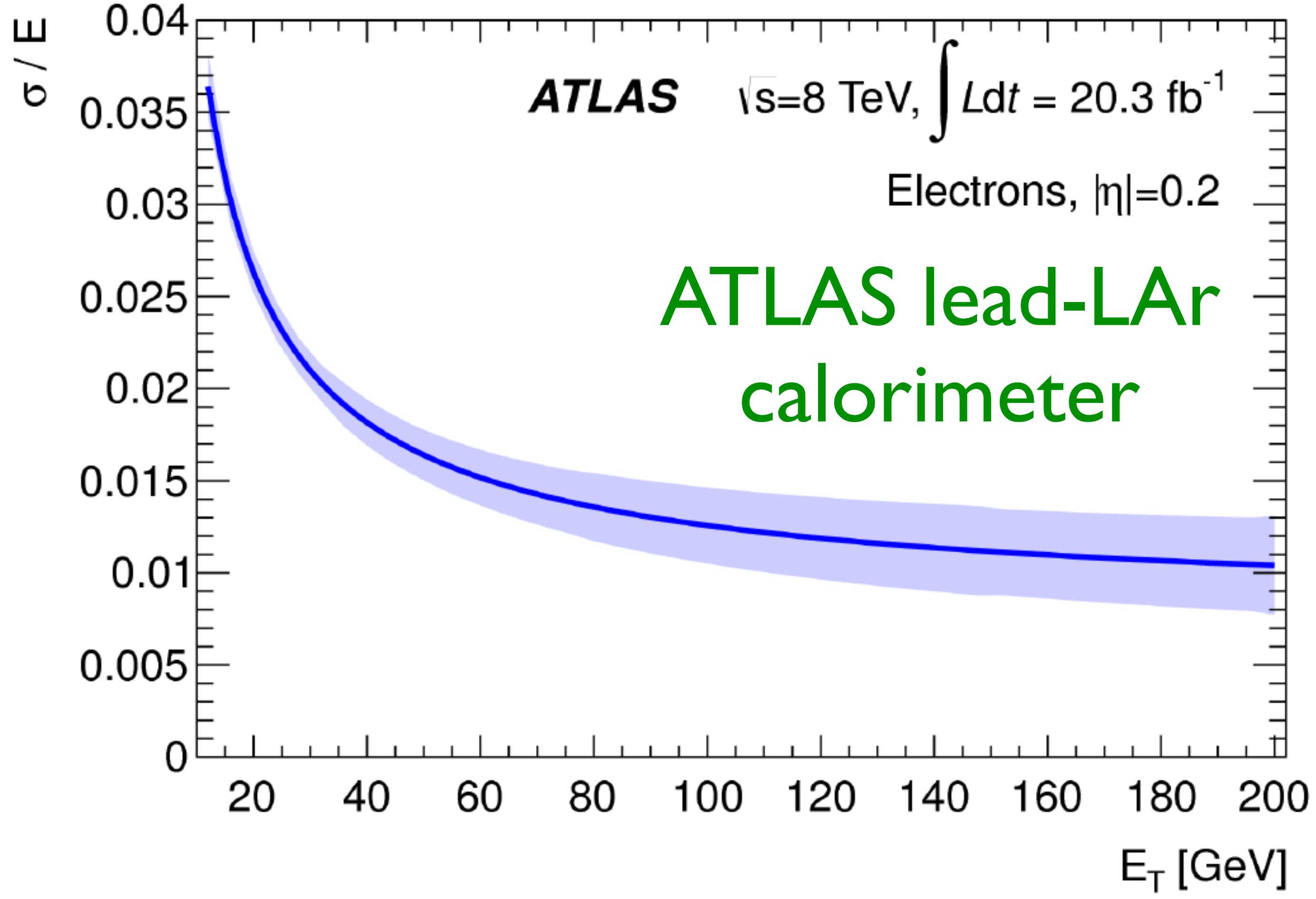
Calorimetry

- Lead tungstate crystals

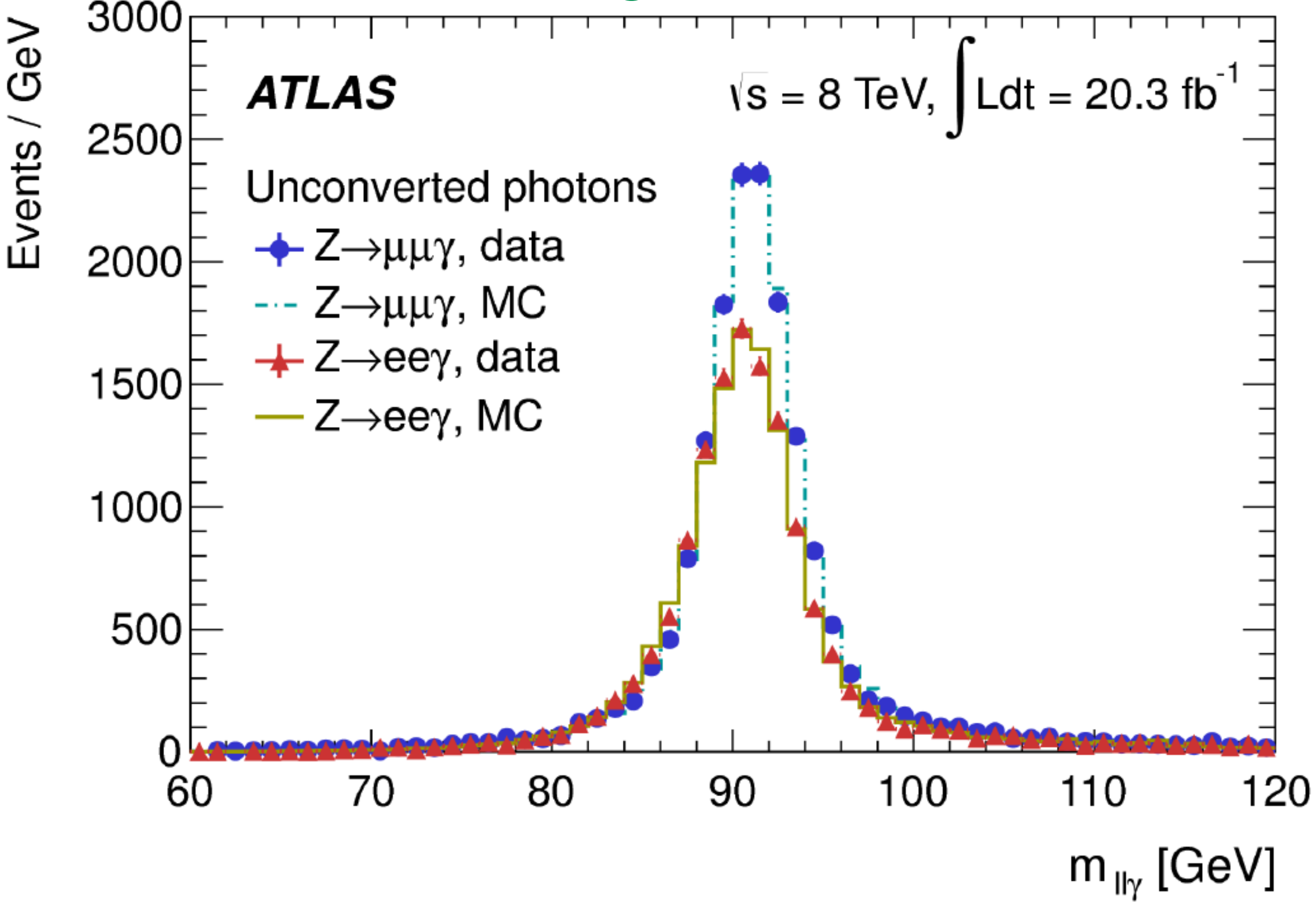


Electromagnetic

- Since sample statistically, resolution ~ 1/√E
  - For electromagnetic, 10%/√E typical

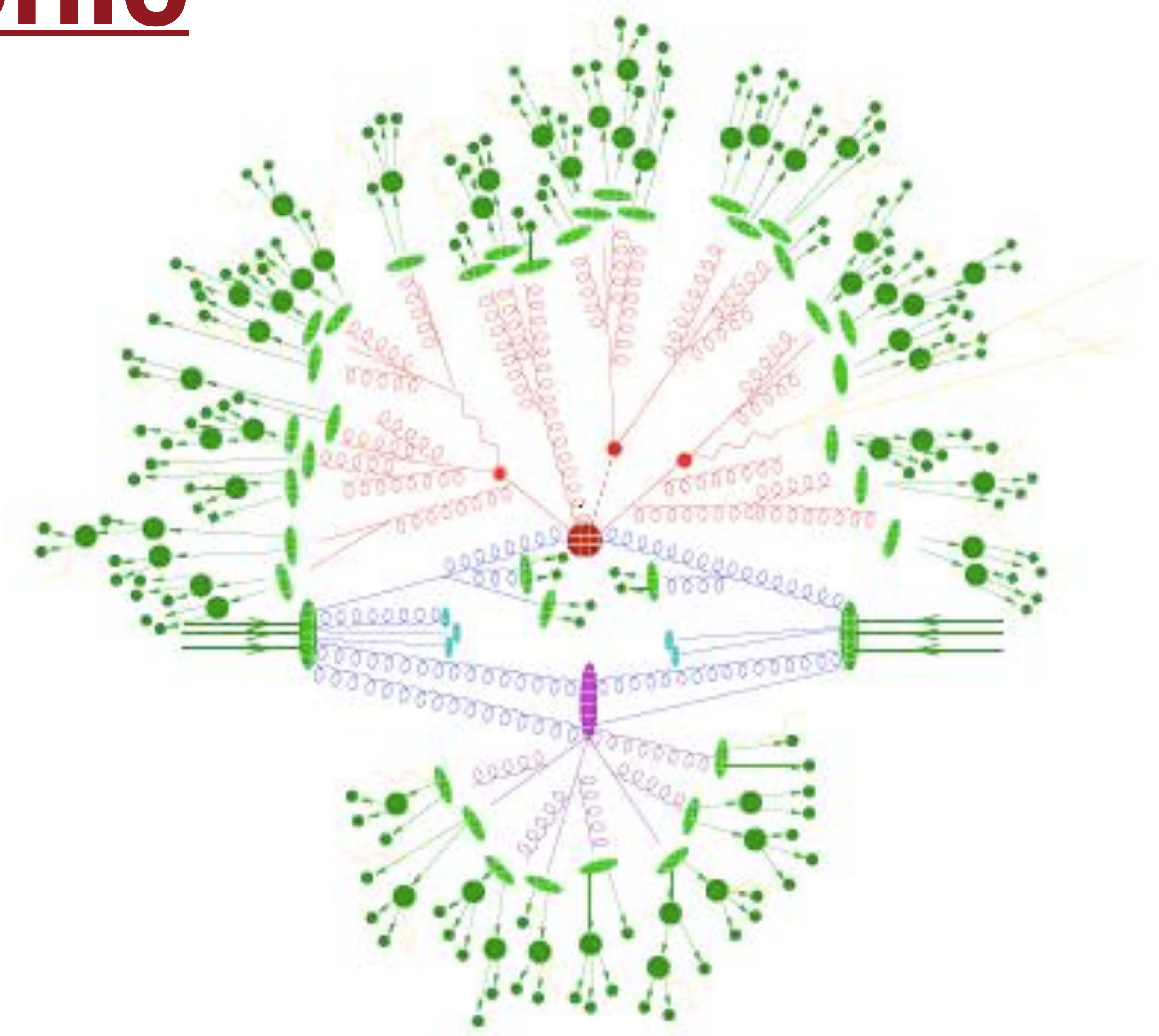


Calibrate photon energy response using Z → ℓℓ γ



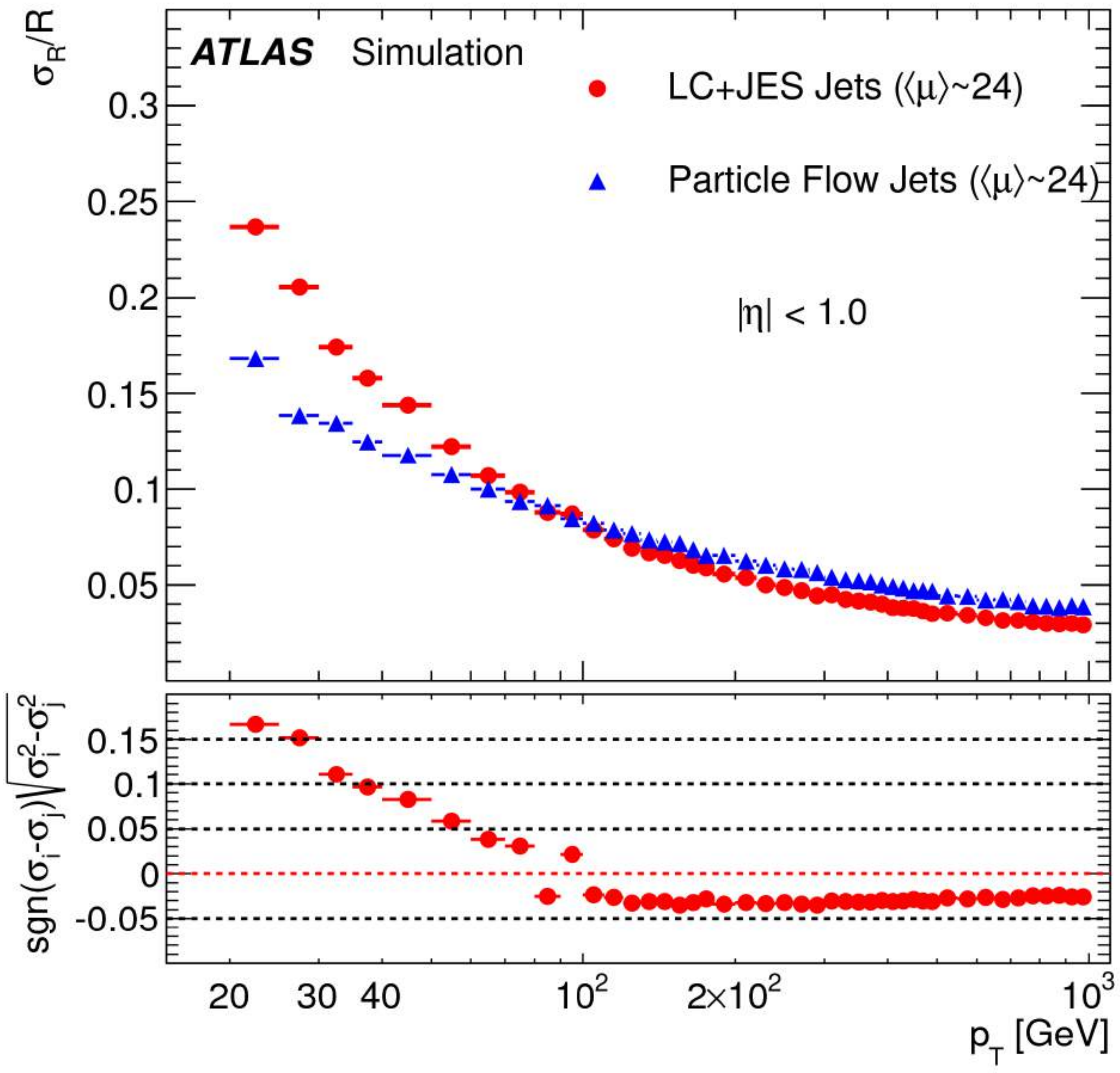
Hadronic

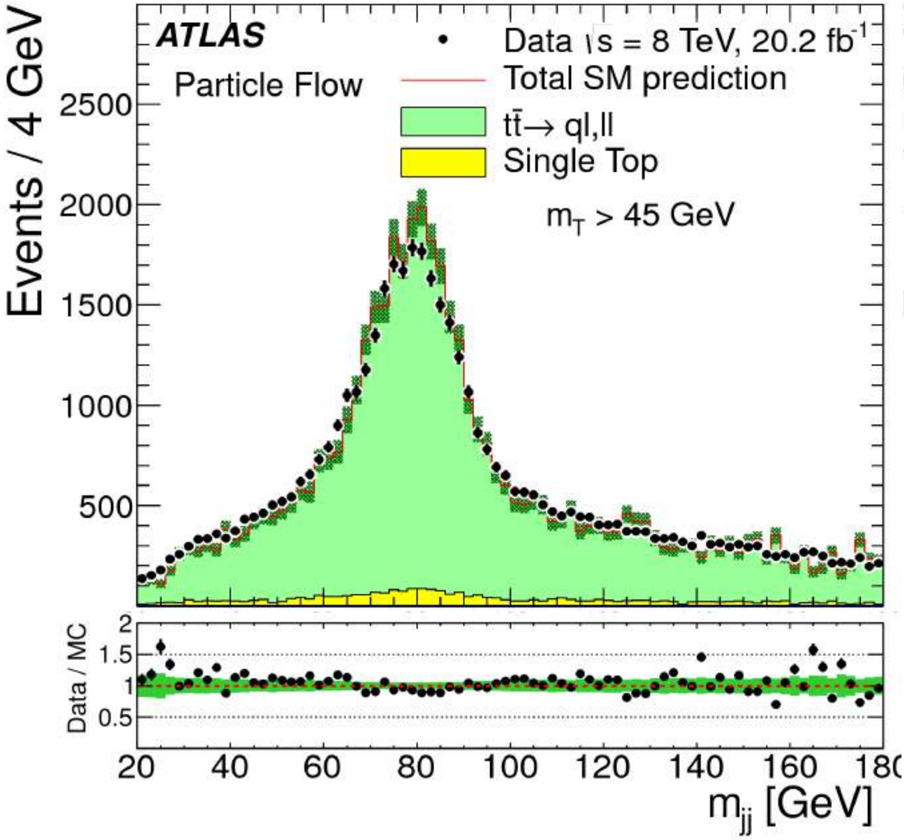
- Calorimeter energy resolution intrinsically quite limited
  - Use “particle flow”: measure charged hadron momenta from tracks, leaving only neutral to calorimeter
    - To be effective, minimize overlap in calorimeter → finely segmented calorimeter, strong magnetic field
      - Still, a single pion shower has radius ~0.1-0.2

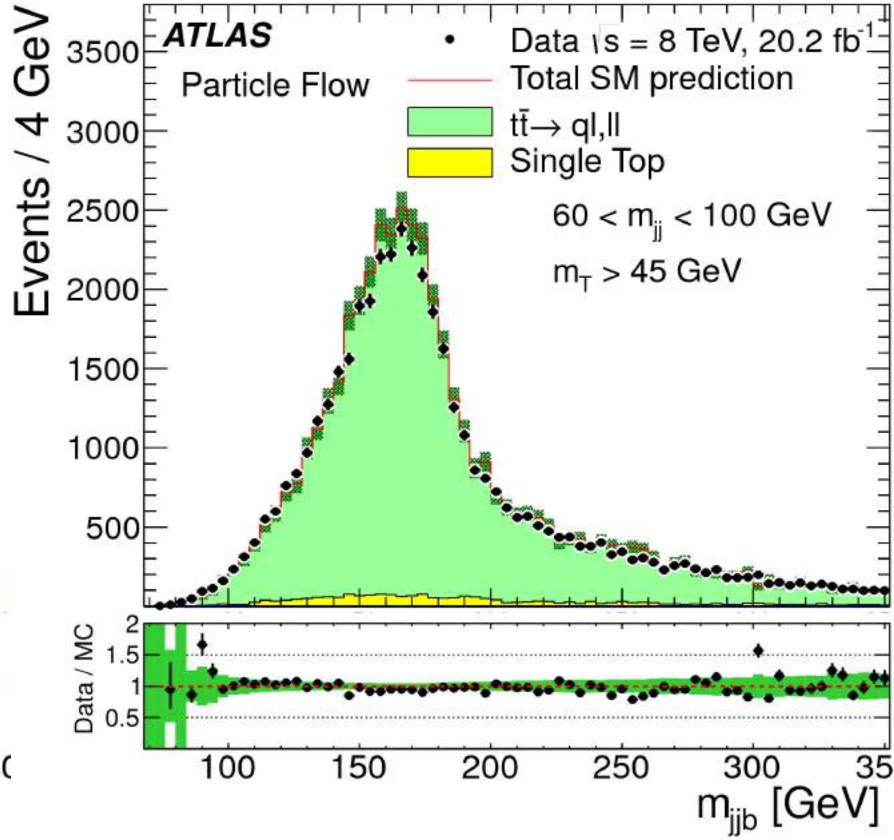


Drawing by F. Krauss

Hadronic

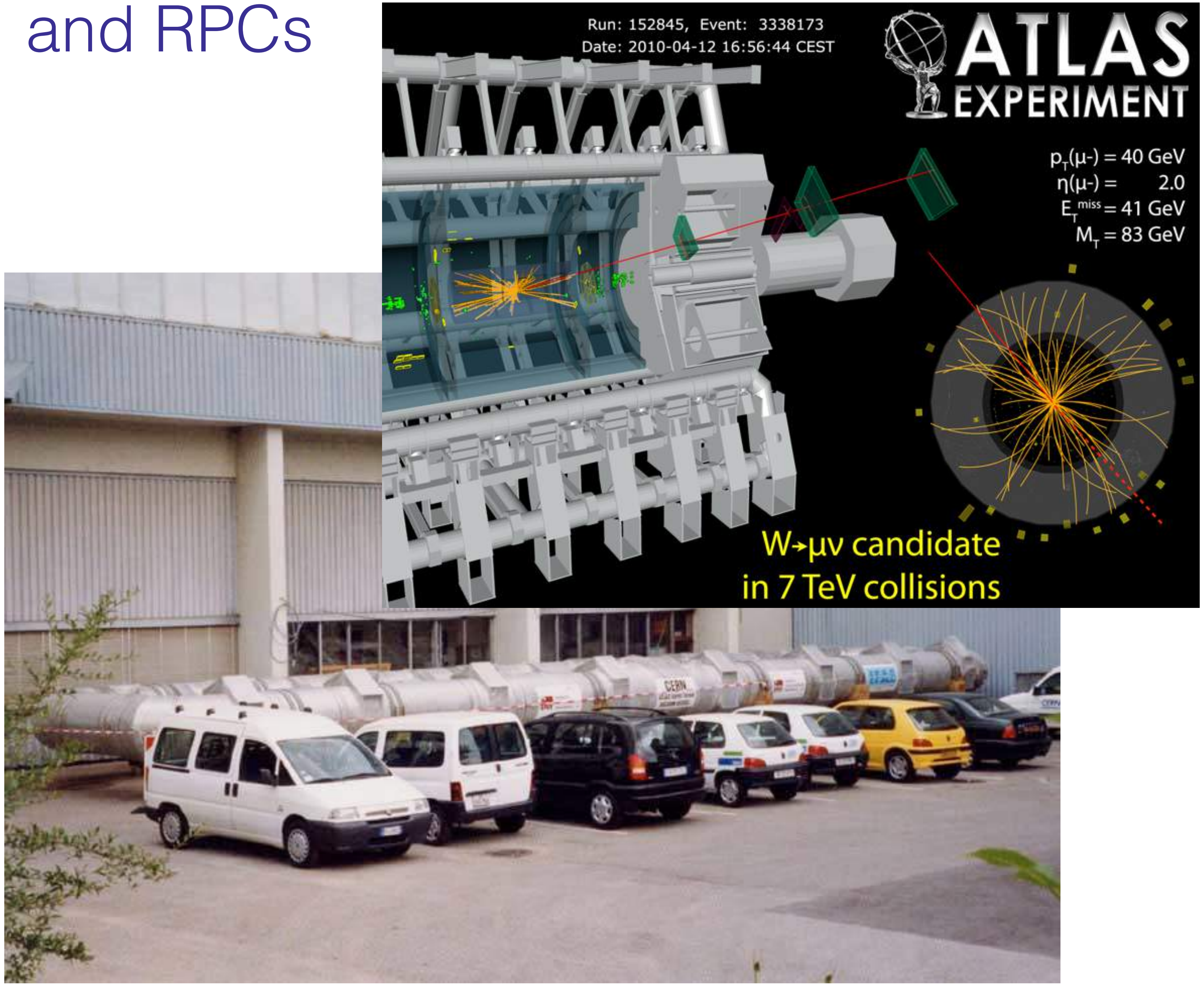

ATLAS Simulation
LC+JES Jets (⟨μ⟩~24)
Particle Flow Jets (⟨μ⟩~24)
|η| < 1.0
σ_R/R
0.3
0.25
0.2
0.15
0.1
0.05
sgn(σ_i-σ_j)√(σ_i²-σ_j²)
0.15
0.1
0.05
0
-0.05
20
30
40
10²
2×10²
10³
p_T [GeV]

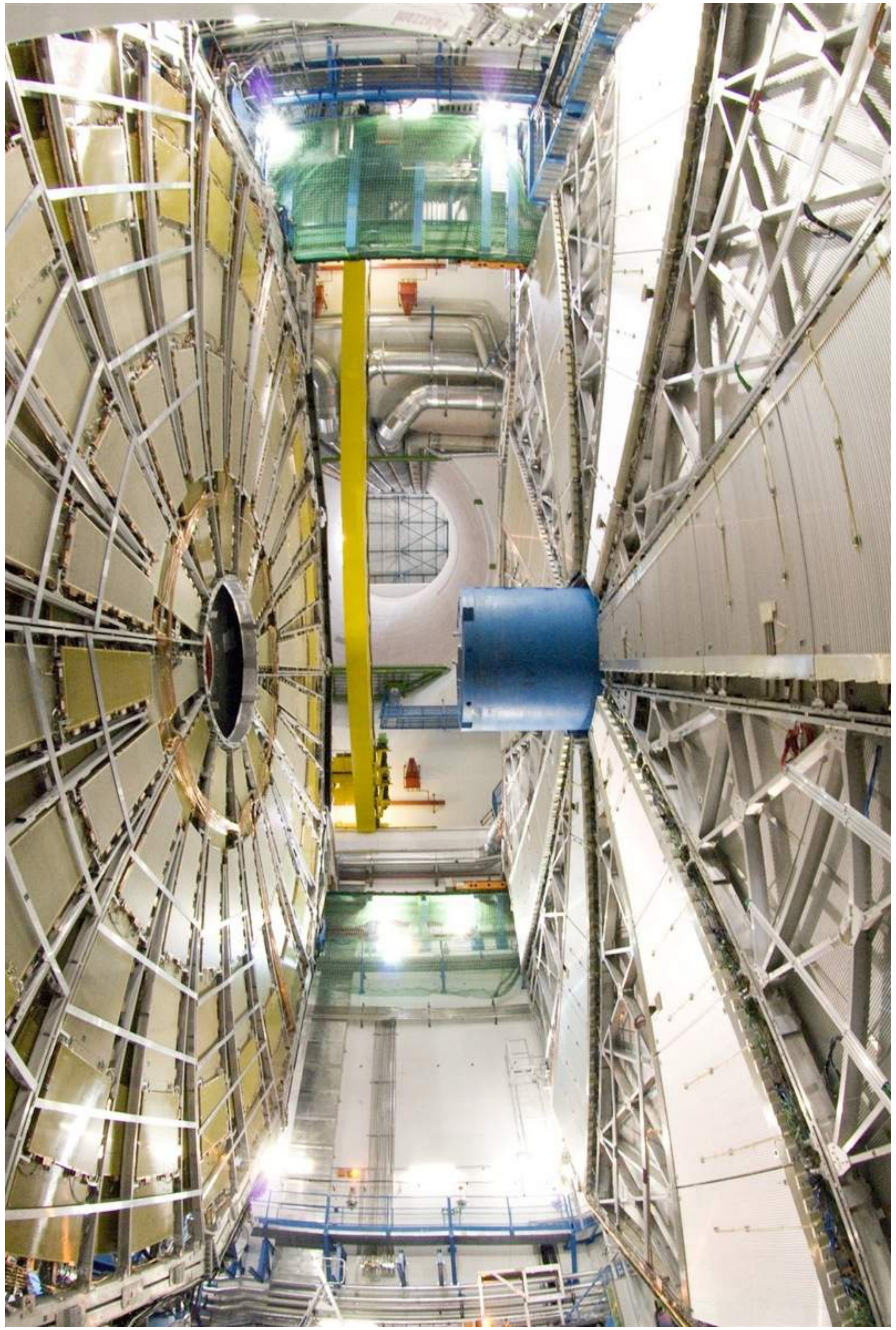

ATLAS
Particle Flow
Data √s = 8 TeV, 20.2 fb⁻¹
Total SM prediction
tt̄→ ql,ll
Single Top
m_T > 45 GeV
Events / 4 GeV
2500
2000
1500
1000
500
Data / MC
2
1.5
1
0.5
20
40
60
80
100
120
140
160
180
m_jj [GeV]


ATLAS
Particle Flow
Data √s = 8 TeV, 20.2 fb⁻¹
Total SM prediction
tt̄→ ql,ll
Single Top
60 < m_jj < 100 GeV
m_T > 45 GeV
Events / 4 GeV
3500
3000
2500
2000
1500
1000
500
Data / MC
2
1.5
1
0.5
100
150
200
250
300
35
m_jjb [GeV]

Muons

- Air-core toroids/flux return; wire chambers and RPCs

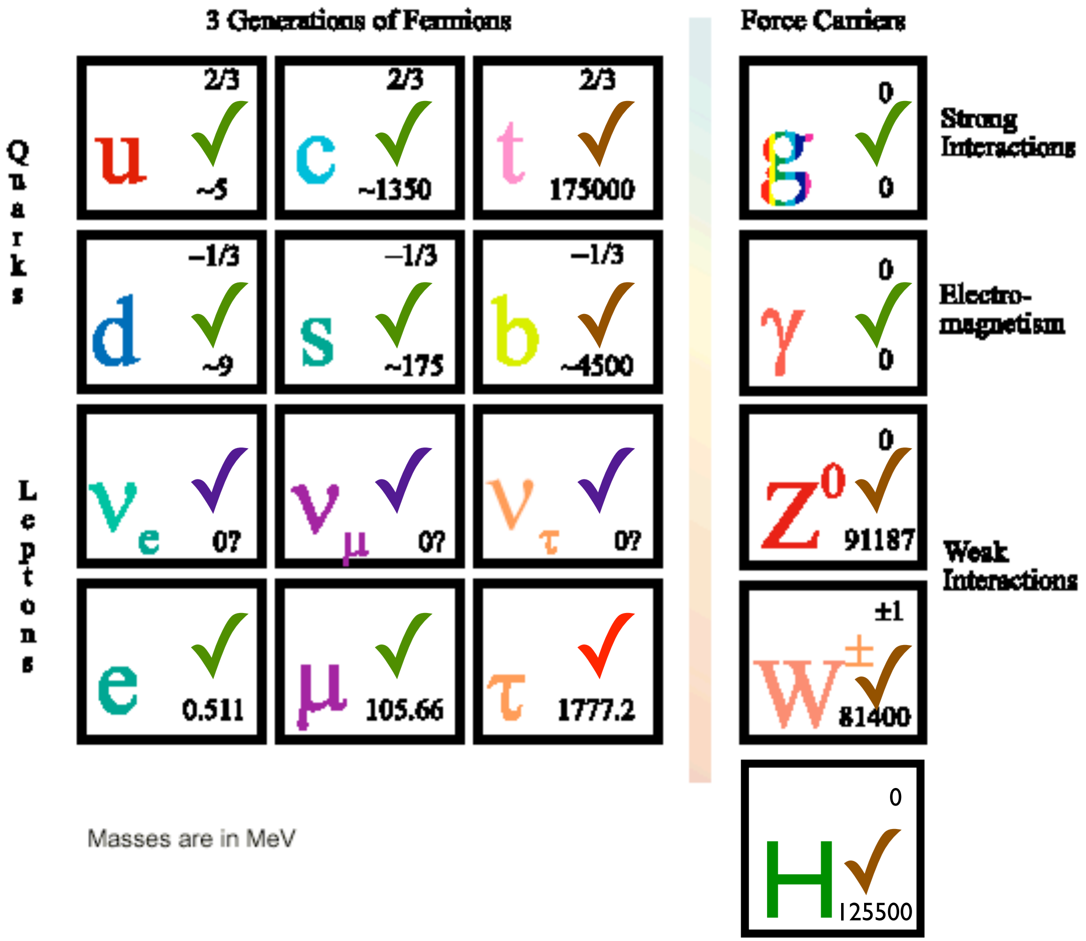




Neutrinos*

*(100% acceptance)

Detecting Particles



Masses are in MeV

✓: Detect with high efficiency

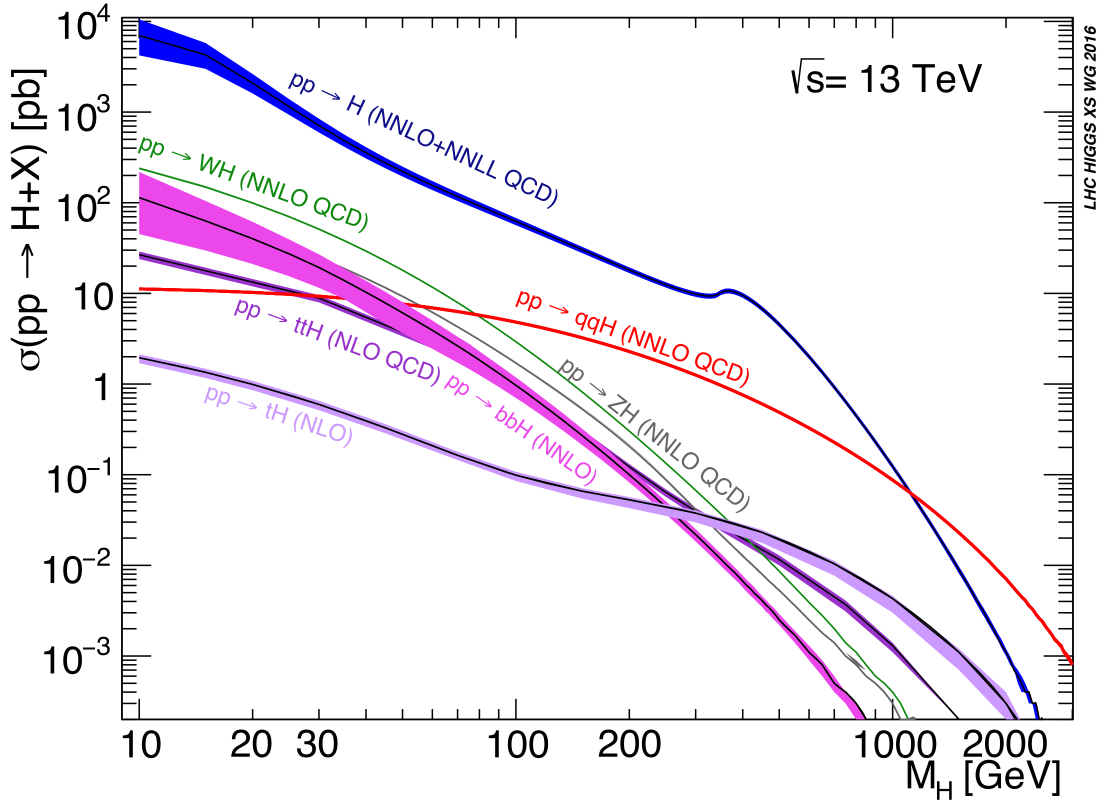
✓: Detect by missing transverse energy

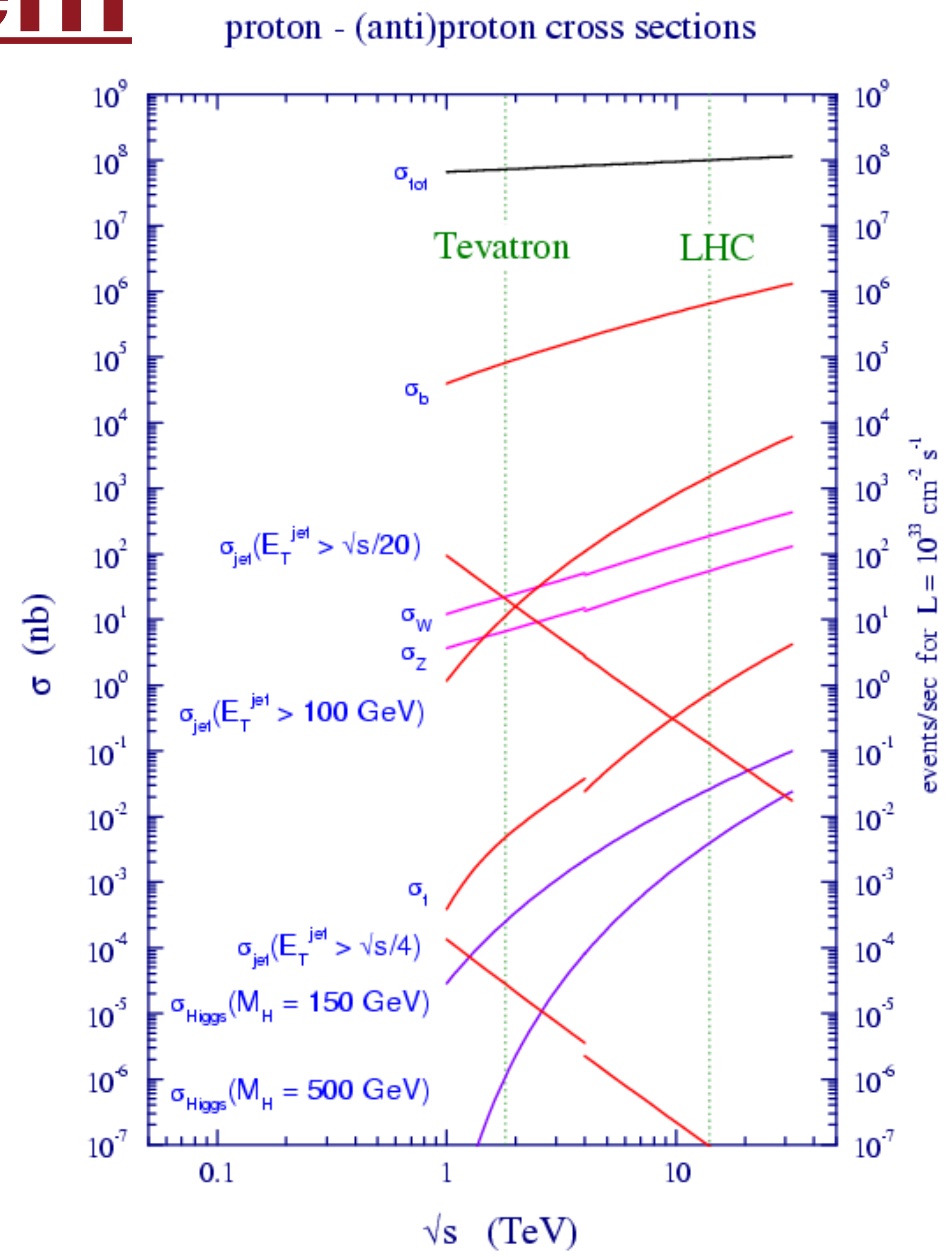
✓: Detect through decays: t→Wb, W/Z → leptons, ...

Hadron Colliders: Triggering

The Problem

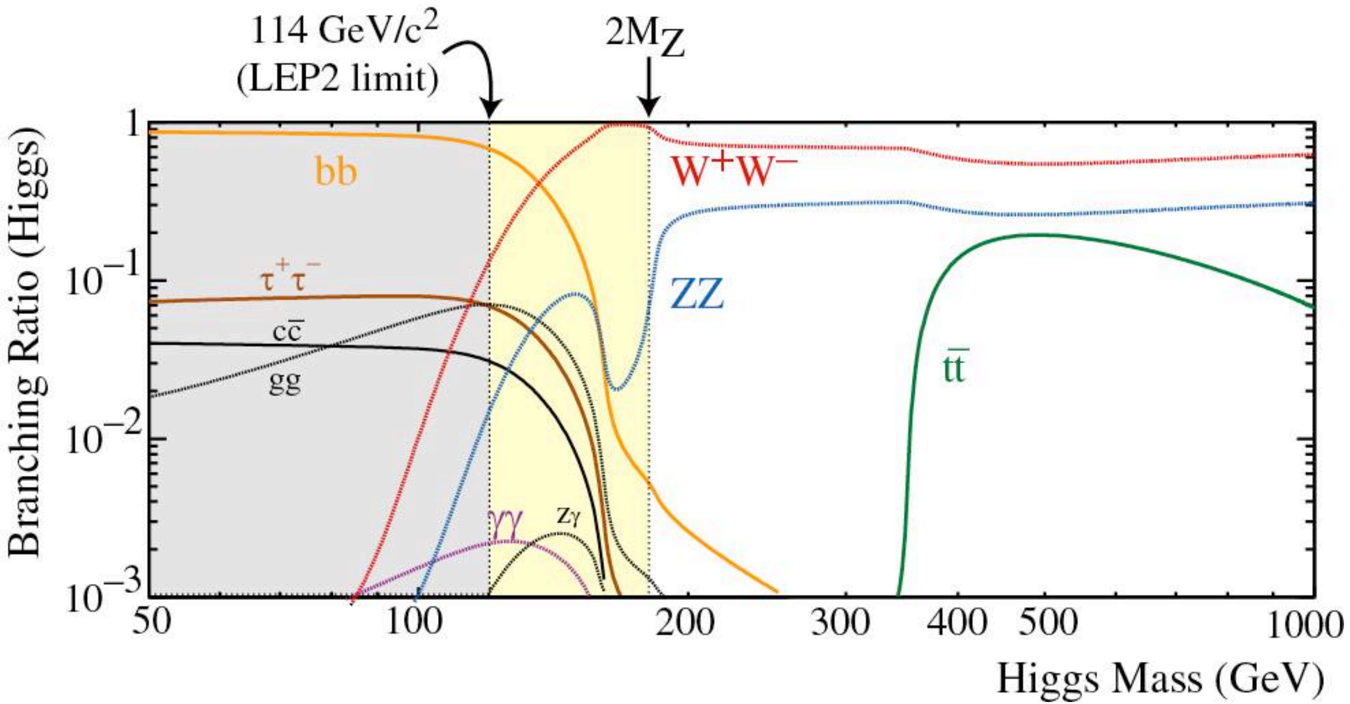
- ❖ Total cross-section is large
  - 80 mb at 10^{32} is 8 MHz!
  - H production, ~50 pb at 10^{32} is 5 Hz
    - But most of those are not detectable!

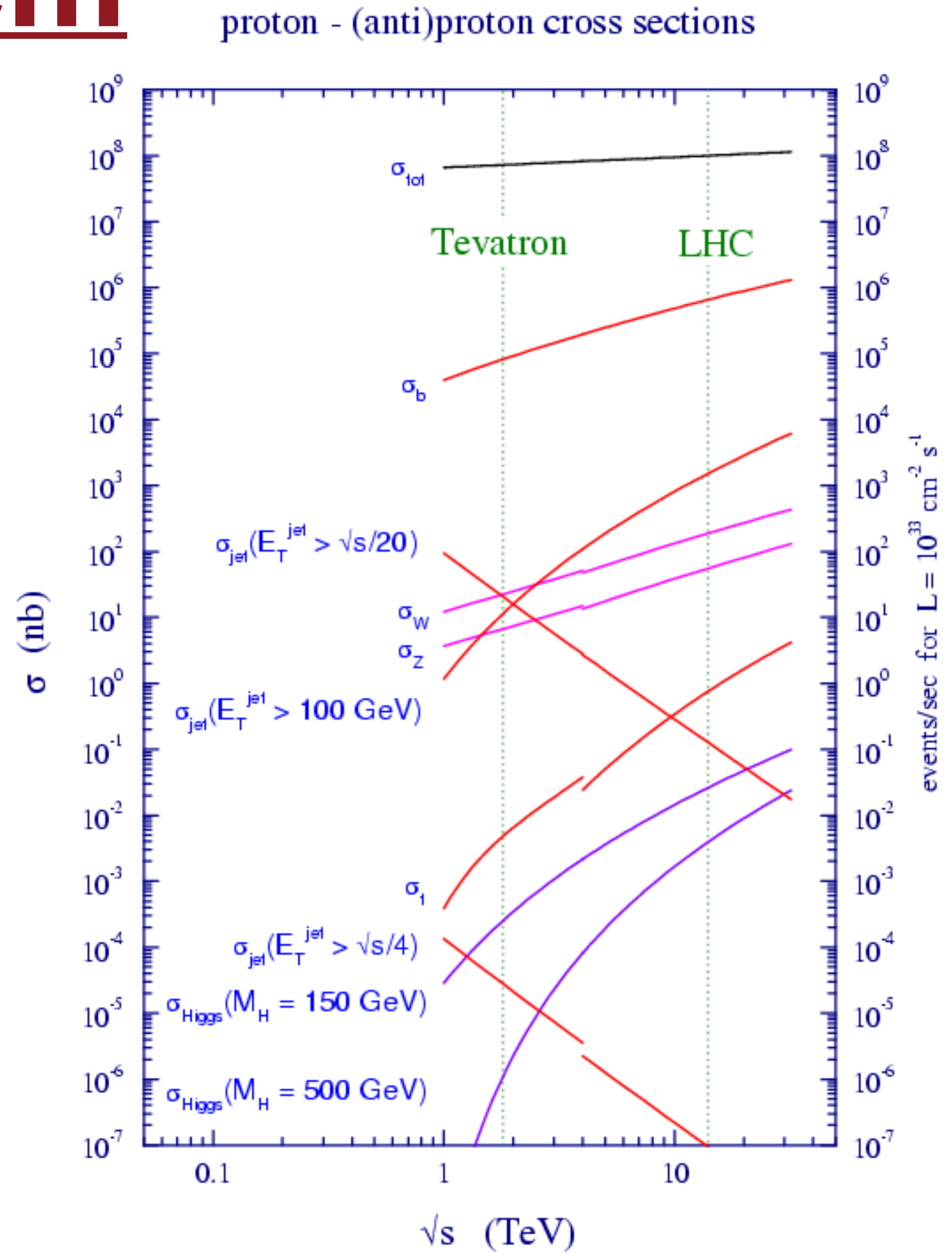




The Problem

- ❖ Total cross-section is large
  - 80 mb at 10^{32} is 8 MHz!
  - H production, ~50 pb at 10^{32} is 5 Hz
    - But most of those are not detectable!
    - LHC runs at ~2×10^{34}, ~0.5 fb^{-1} or 25k H bosons per day





Triggering

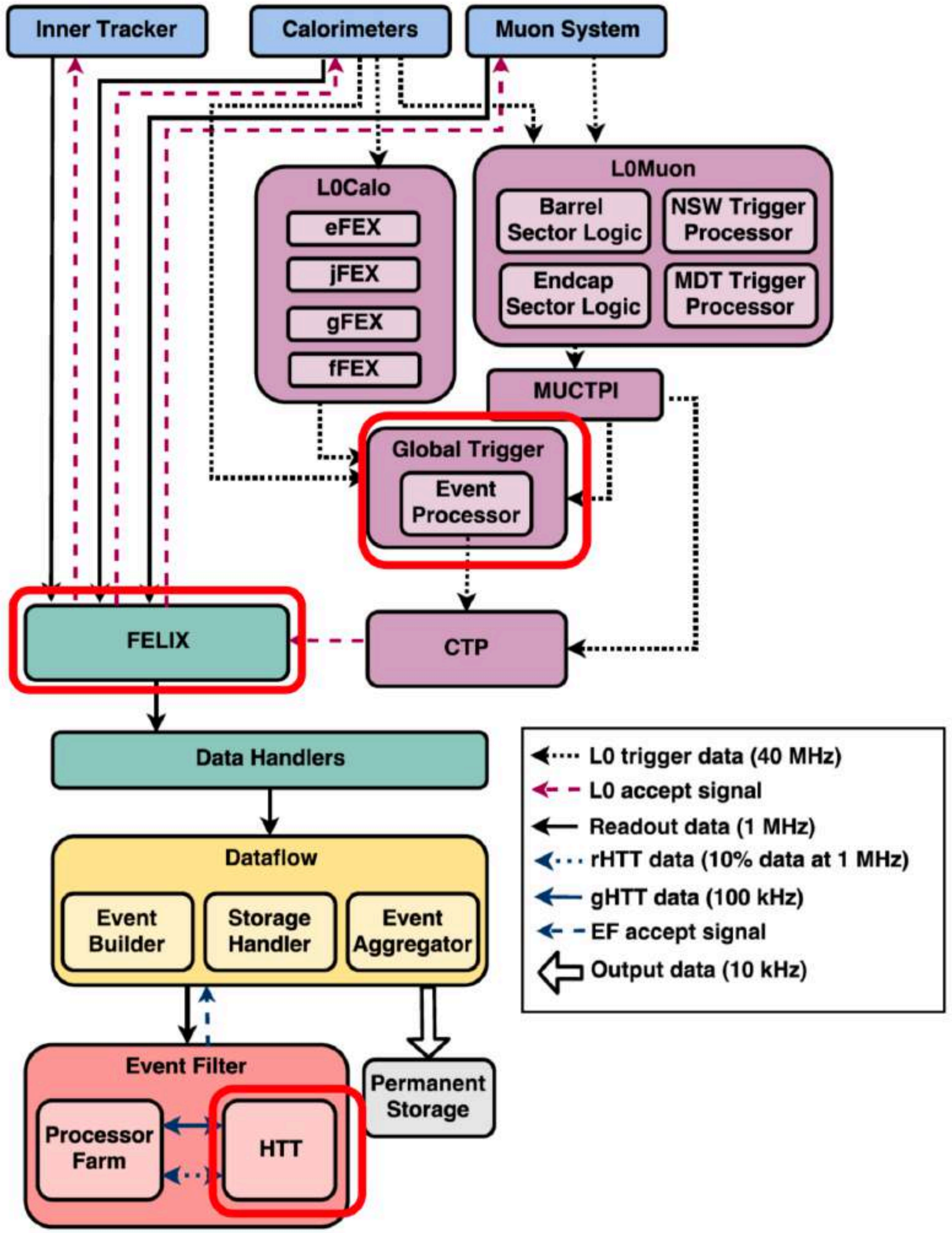
- Goal: select interesting events for offline analysis, while minimizing dead time
- “Interesting” is subjective
  - Depends on physics priorities (need for compromise in multi-purpose experiments)
  - Only interesting if event passes offline cuts
  - Includes events needed to validate analysis
    - Determination of efficiencies
    - Control samples
    - …

Constraints

- During decision-making process, data need to be “stored”
  - ATLAS produces 100s of Tbps
- Architectures are evolving
  - Closing in on shipping all data off-detector, where pipelines can be implemented in cheap RAM, not exposed to particle-induced upsets
    - For hermetic experiments, only inner tracker data still on-detector
  - Always at the forefront during design, antiquated during construction
    - E.g. HL-LHC, installation ~2025, will use mainly 10 Gbps links

Looking Forward

- ❖ Typical HL-LHC parameters:
  - Level-1 hardware trigger, ~10 μs latency
    - Access to fine-grained calorimeter and muon system data
  - High-level trigger (asynchronous)
    - Software with access to full detector data, run fast versions of offline algorithms
    - Track reconstruction may run on custom hardware, not clear if can be done in software…



Inner Tracker
Calorimeters
Muon System
L0Calo
eFEX
jFEX
gFEX
fFEX
L0Muon
Barrel Sector Logic
NSW Trigger Processor
Endcap Sector Logic
MDT Trigger Processor
MUCTPI
Global Trigger
Event Processor
FELIX
CTP
Data Handlers
Dataflow
Event Builder
Storage Handler
Event Aggregator
Event Filter
Processor Farm
HTT
Permanent Storage

L0 trigger data (40 MHz)
L0 accept signal
Readout data (1 MHz)
rHTT data (10% data at 1 MHz)
gHTT data (100 kHz)
EF accept signal
Output data (10 kHz)