Computing in Particle Physics

David Grellscheid
IPPP, Durham University
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What are the fundamental building blocks of Nature?

Quarks

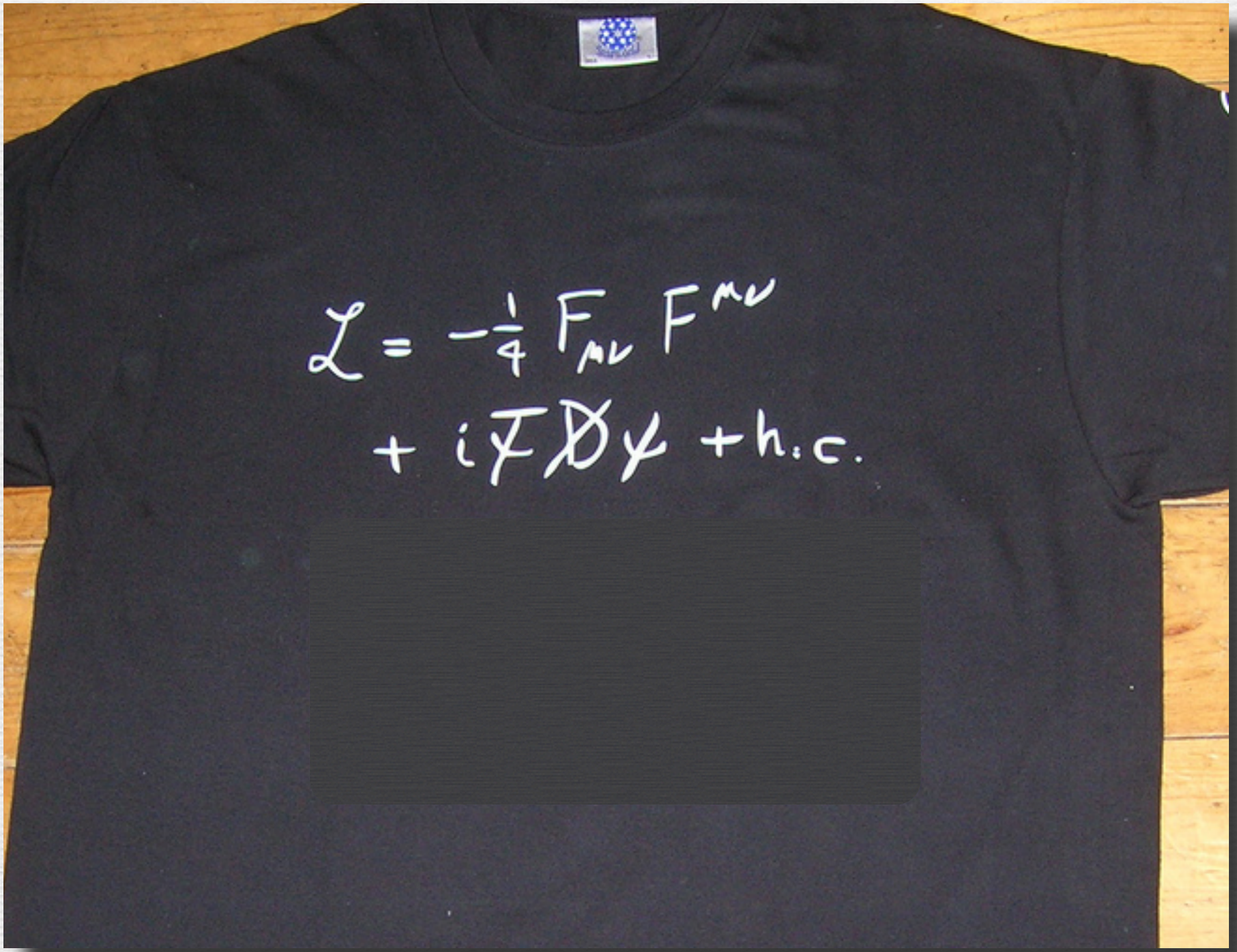
u up	***c*** charm	***t*** top
d down	***s*** strange	***b*** bottom

Leptons

ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
e electron	μ muon	τ tau

Force carriers

γ photon	
Z Z boson	
W W boson	
g gluon	


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \not{F} \not{D} \psi + h.c.$

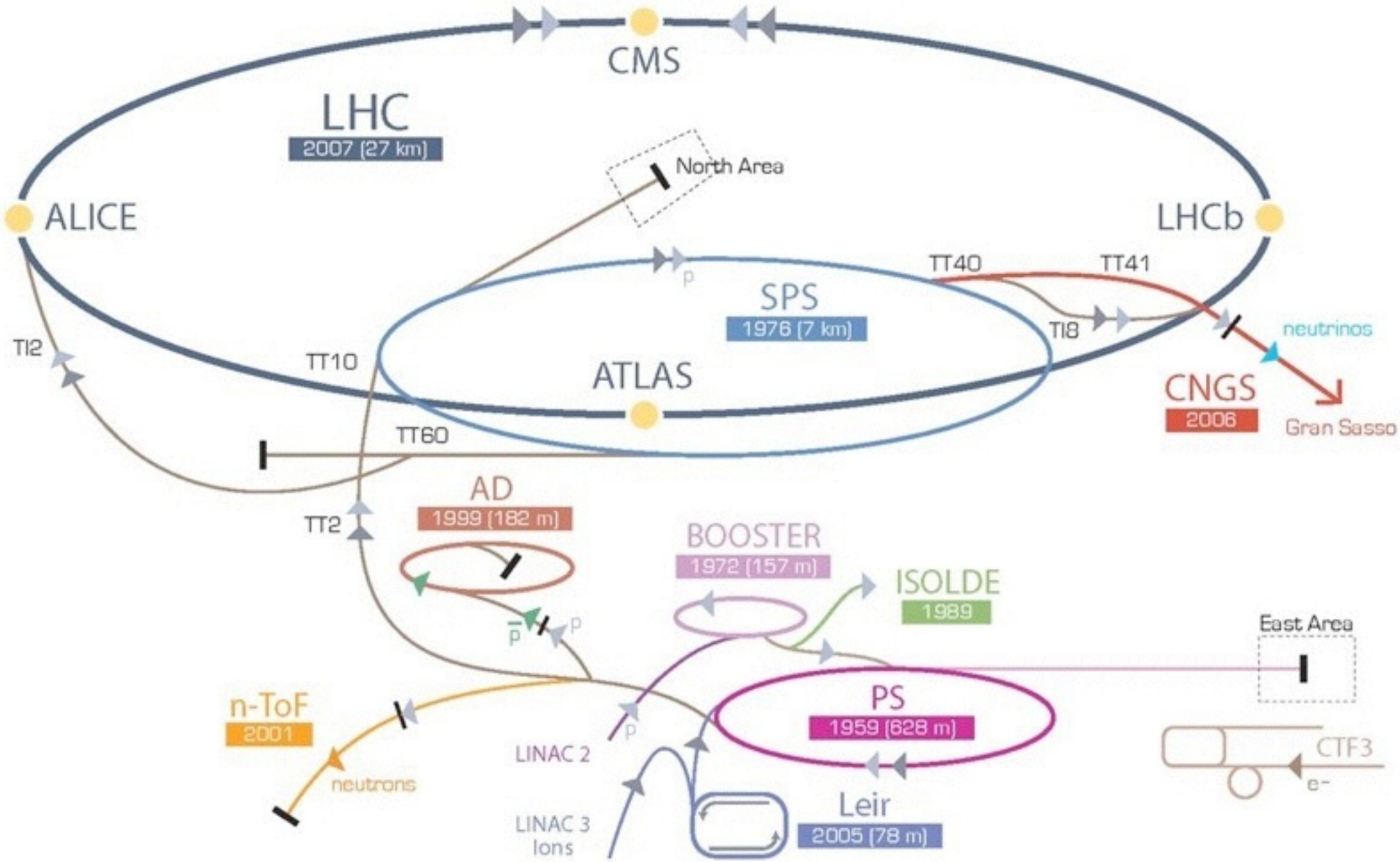
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i\bar{\psi} \not{D} \psi + \text{h.c.}$$

$$+ \psi_i y_{ij} \psi_j \phi + \text{h.c.}$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

CERN Accelerator Complex



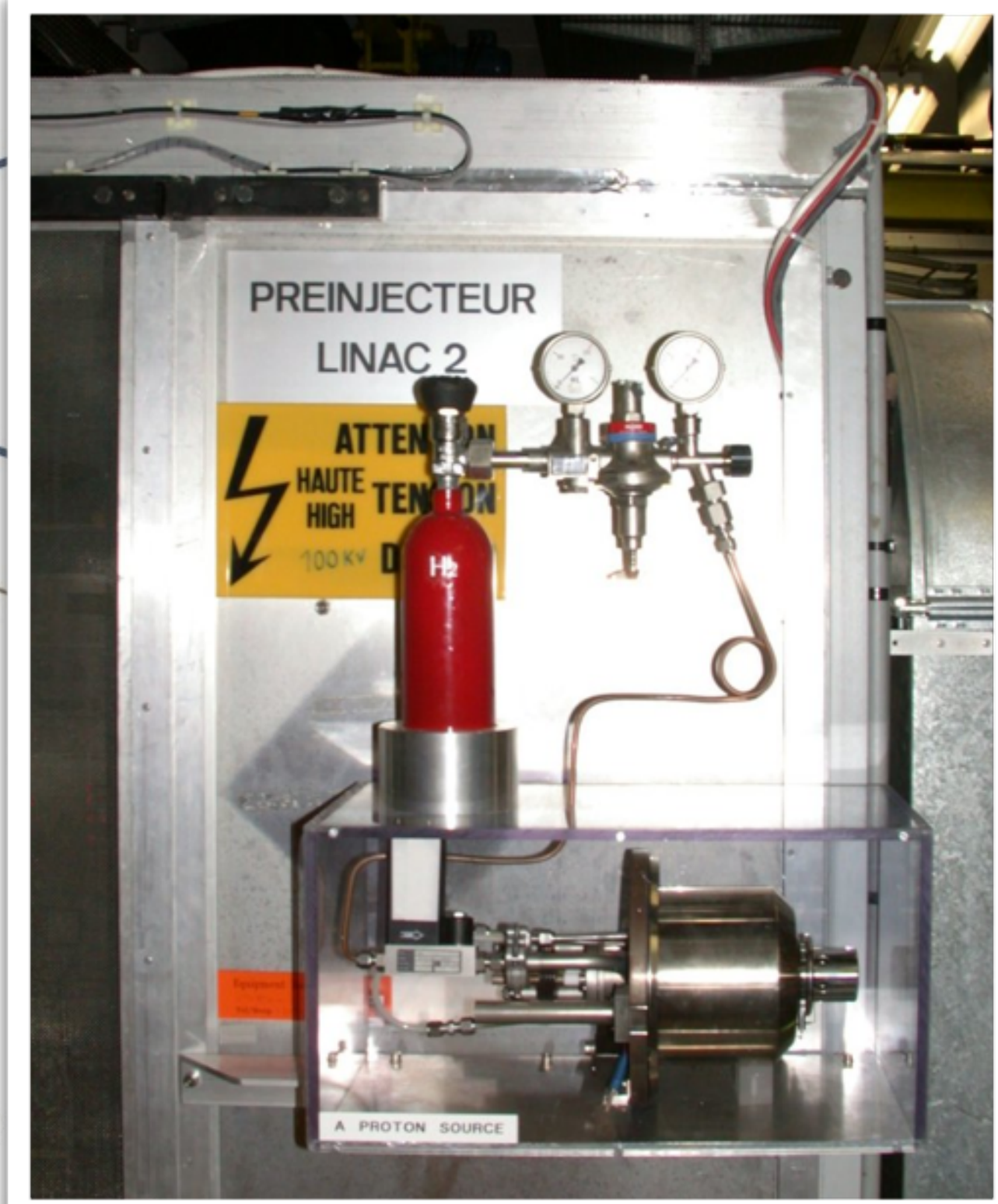
p (proton) ion neutrons p̄ (antiproton) proton/antiproton conversion neutrinos electron

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

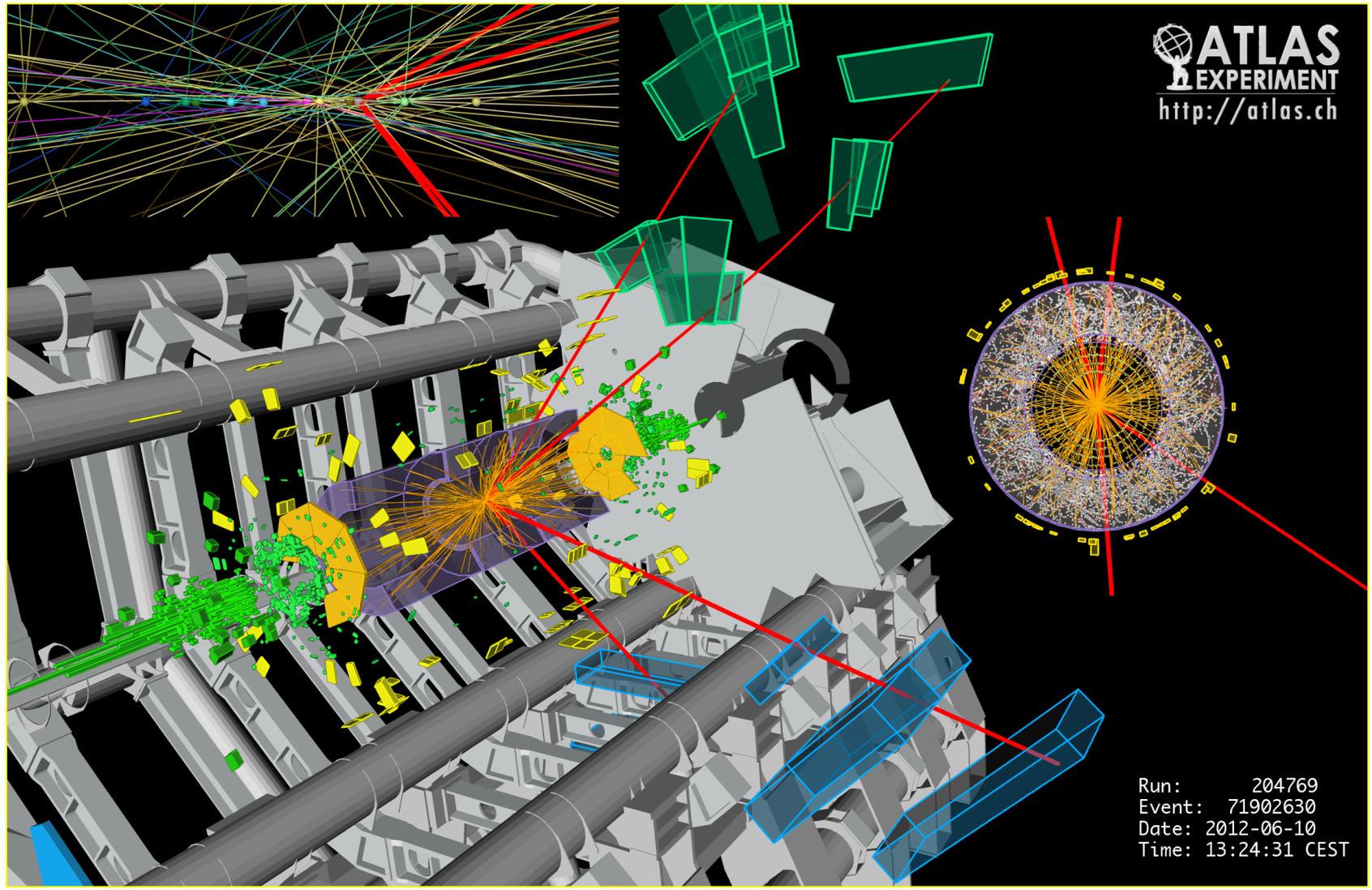
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

CERN Accelerator Complex



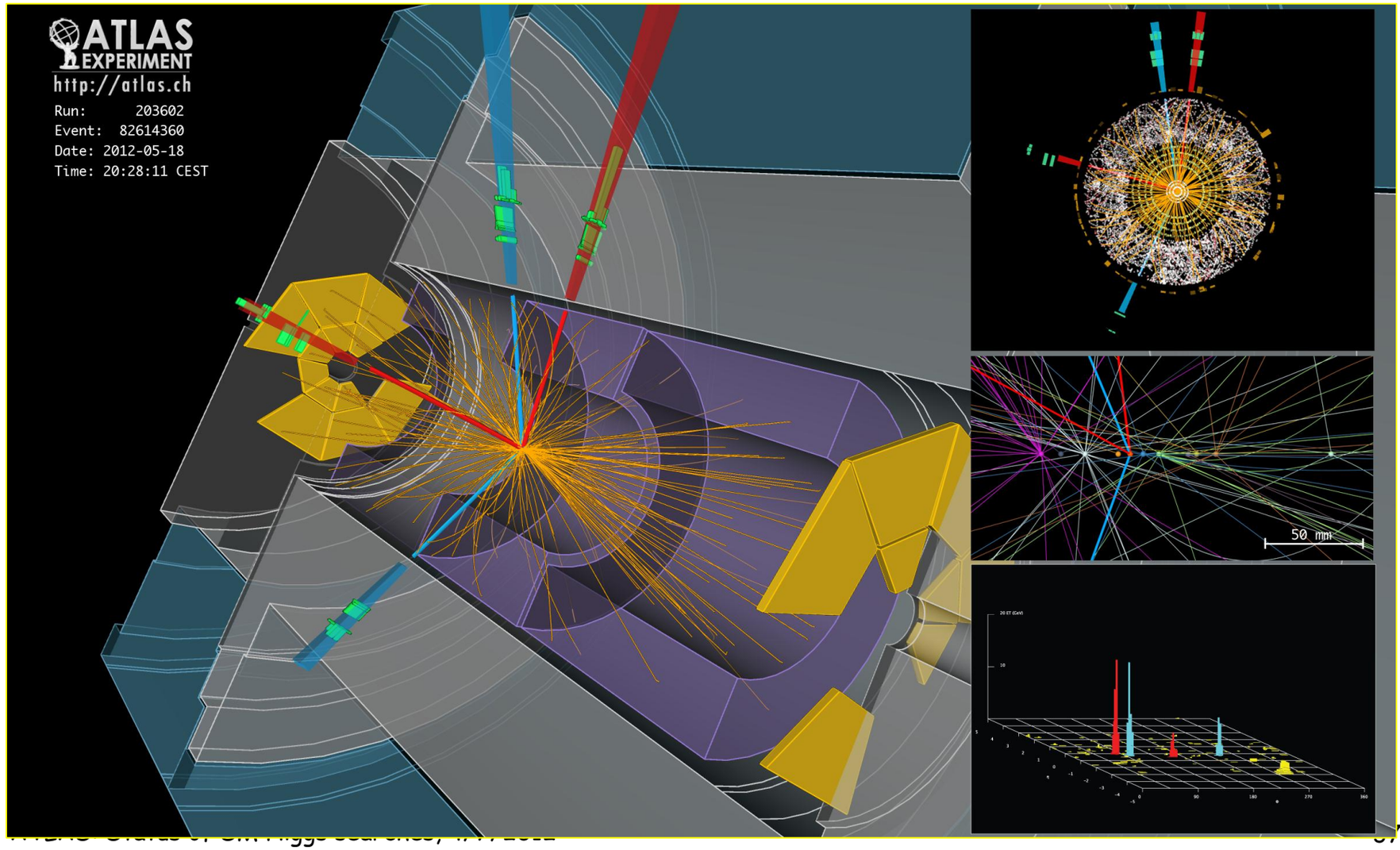
4μ candidate with $m_{4\mu}$= 125.1 GeV

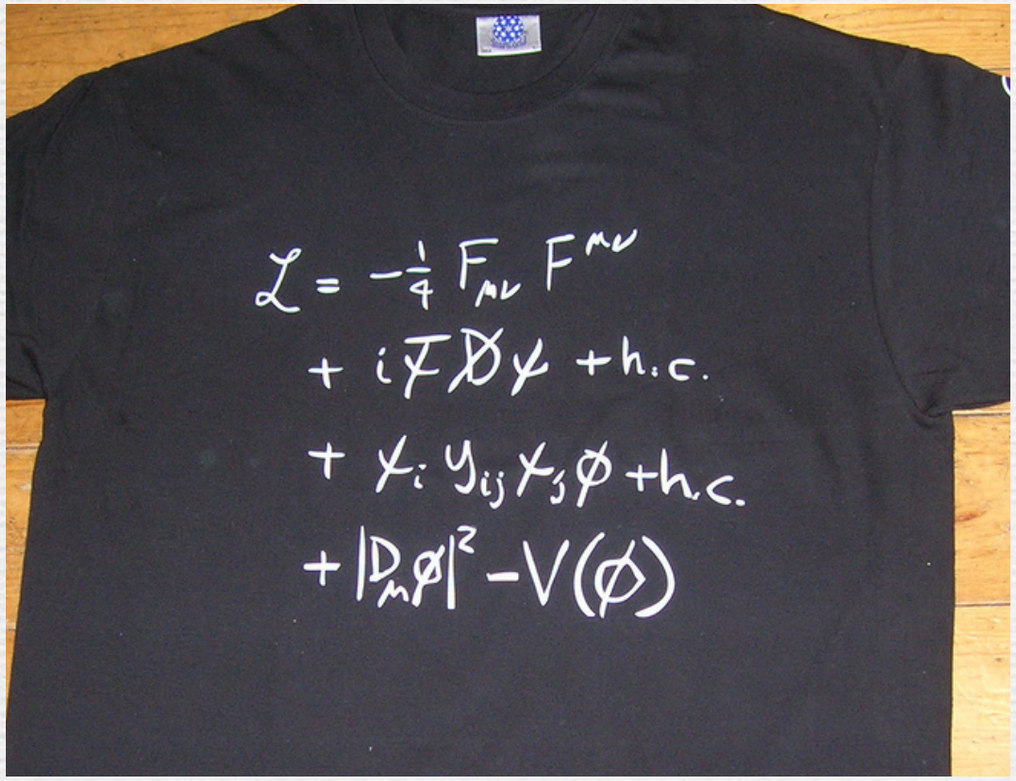
p_T (muons)= 36.1, 47.5, 26.4, 71 .7GeV m_{12}= 86.3 GeV, m_{34}= 31.6 GeV
15 reconstructed vertices

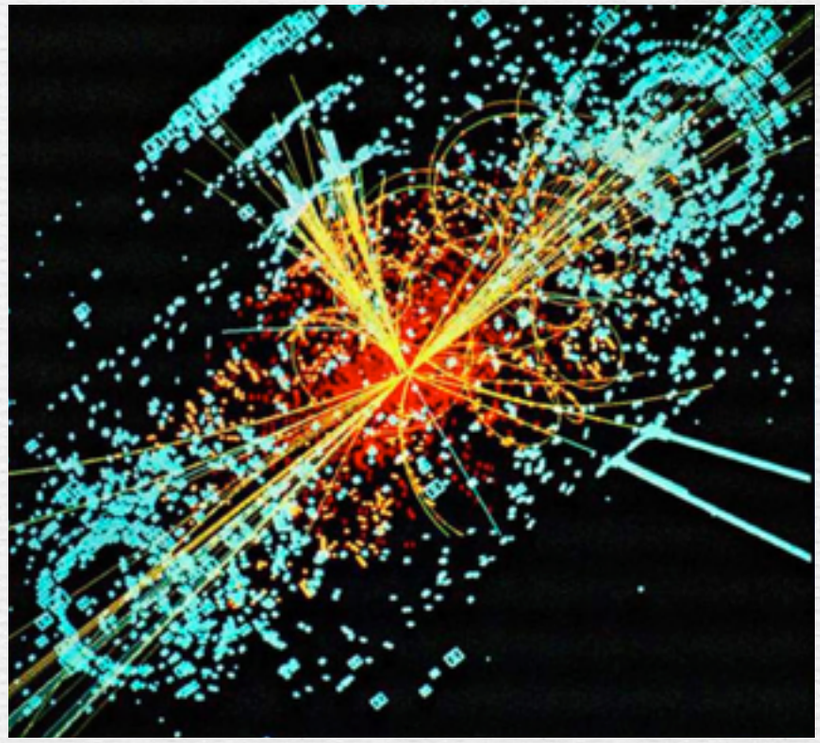


4e candidate with m_{4e}= 124.6 GeV

p_T (electrons)= 24.9, 53.9, 61.9, 17.8 GeV m_{12}= 70.6 GeV, m_{34}= 44.7 GeV
12 reconstructed vertices

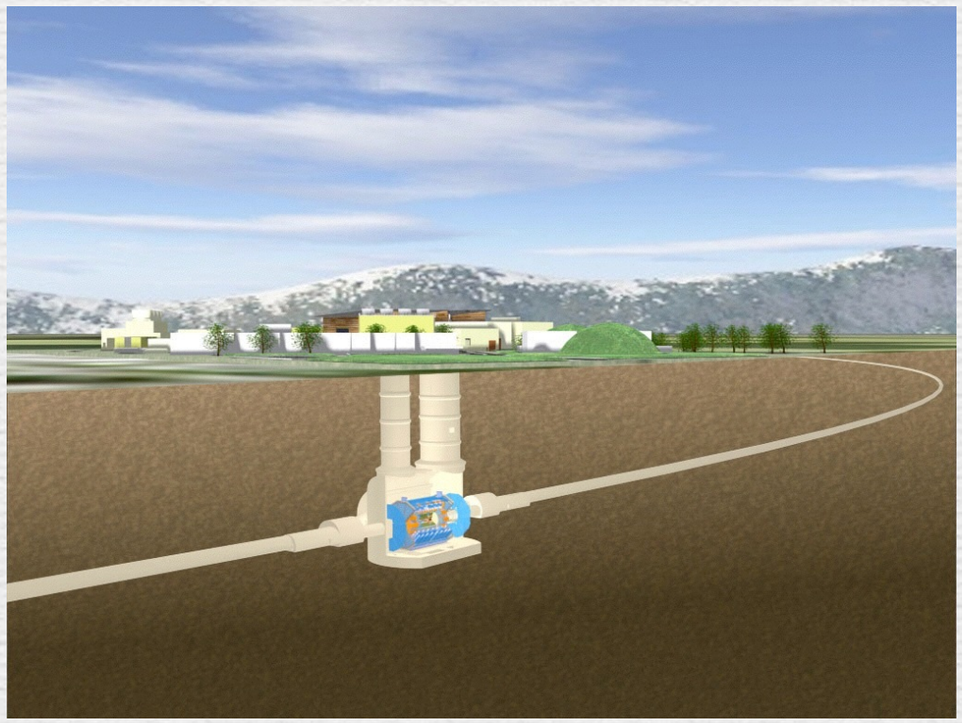


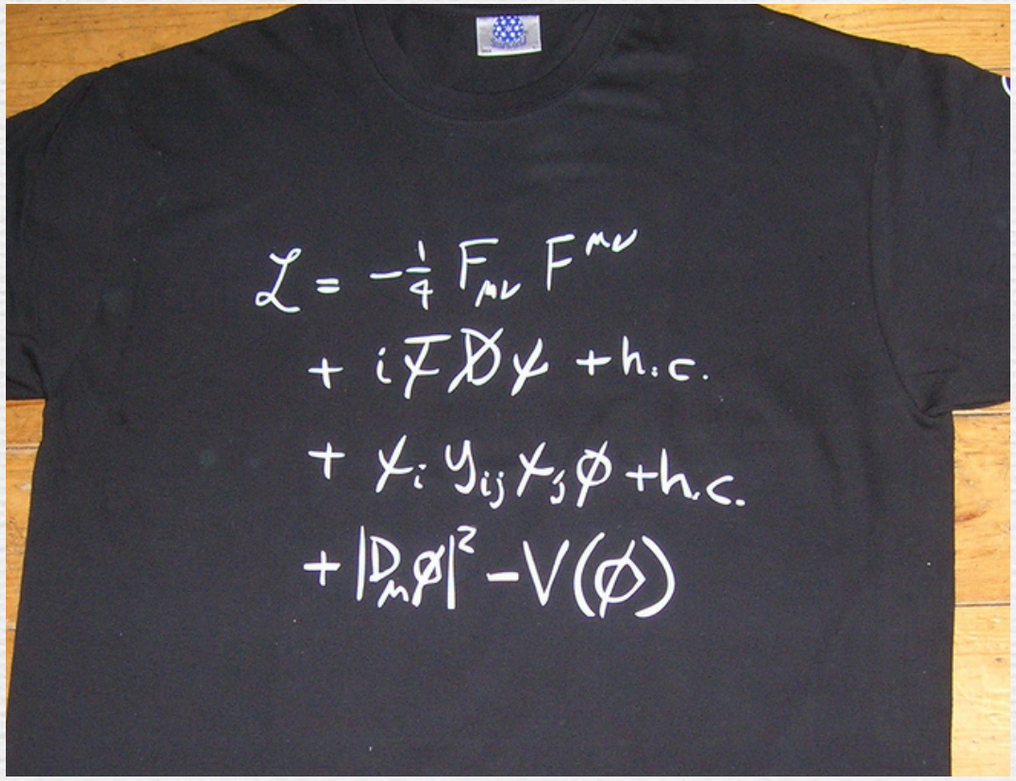


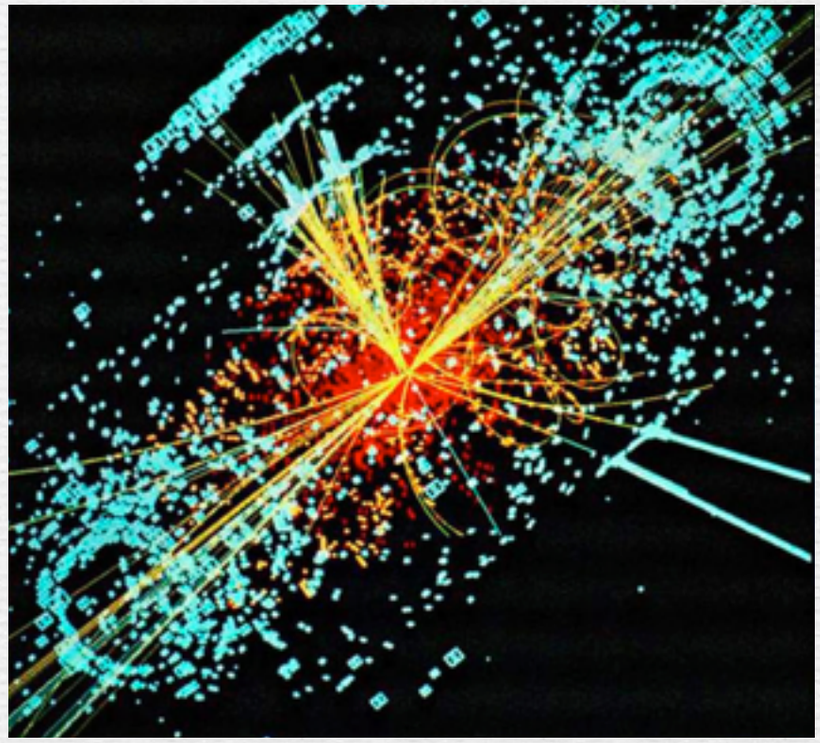


Theory

Experiment







?

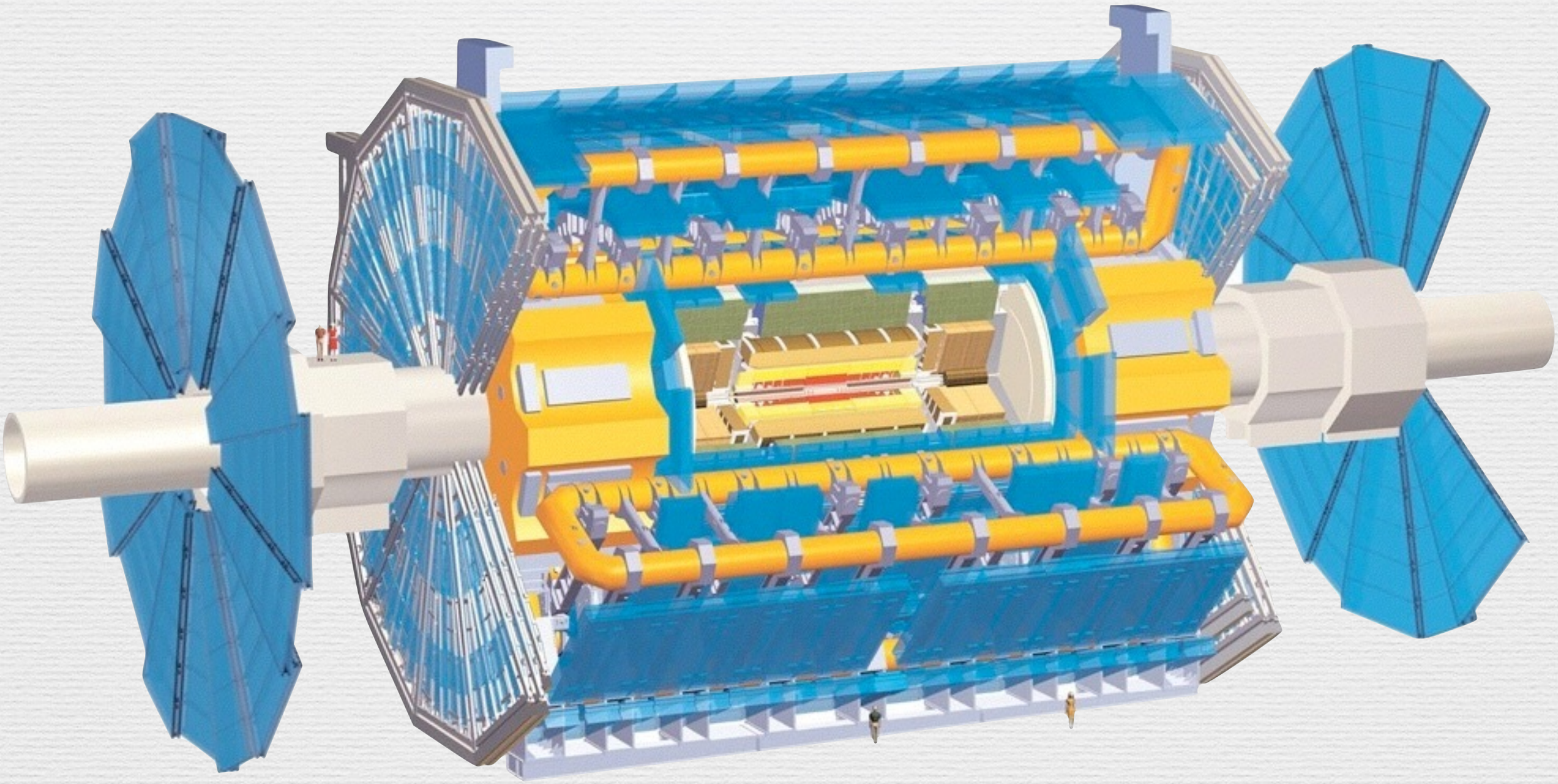
Theory ⟷ Experiment

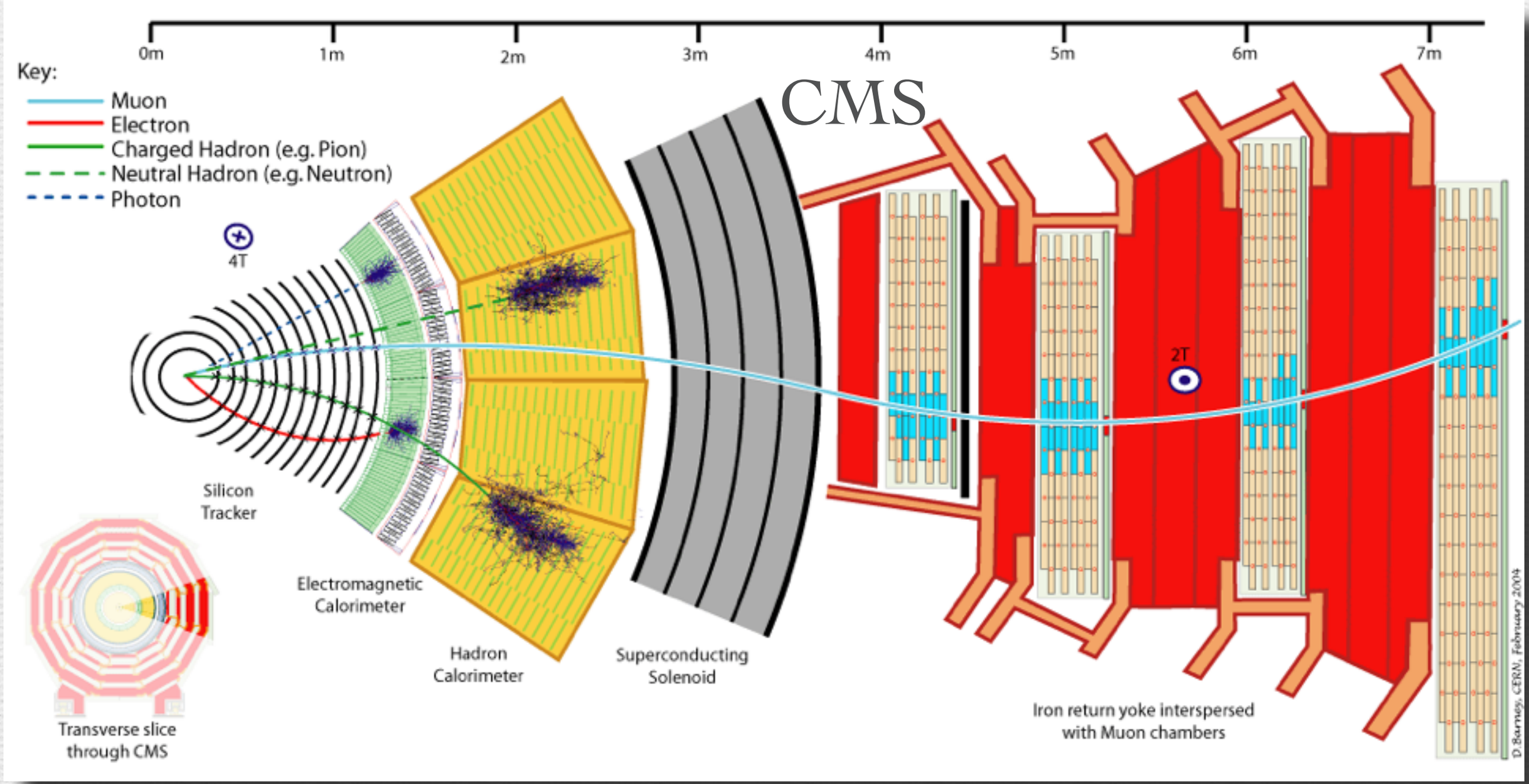
Proton bunches 25 ns apart

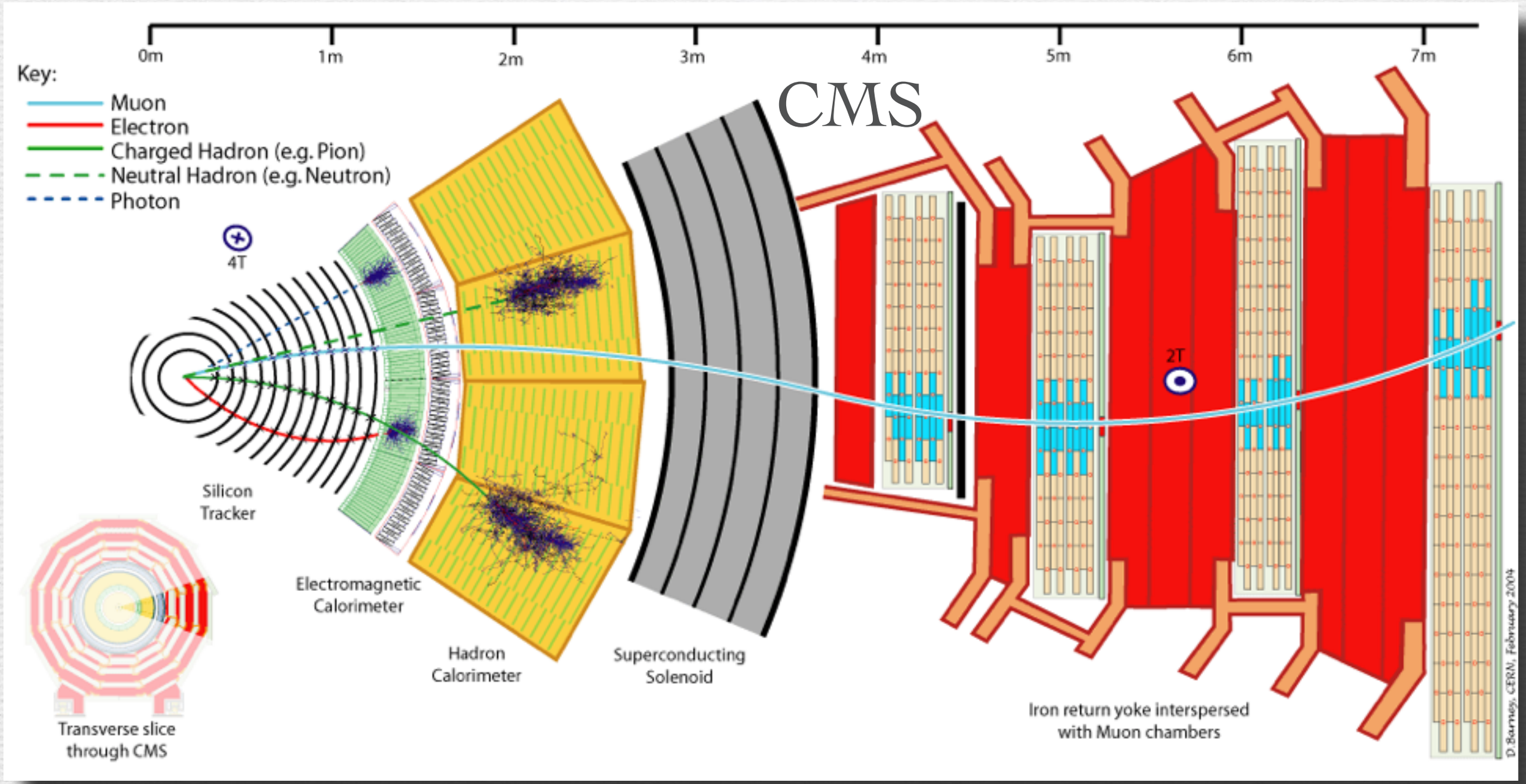
10^{11} protons per bunch

~25 collisions per crossing

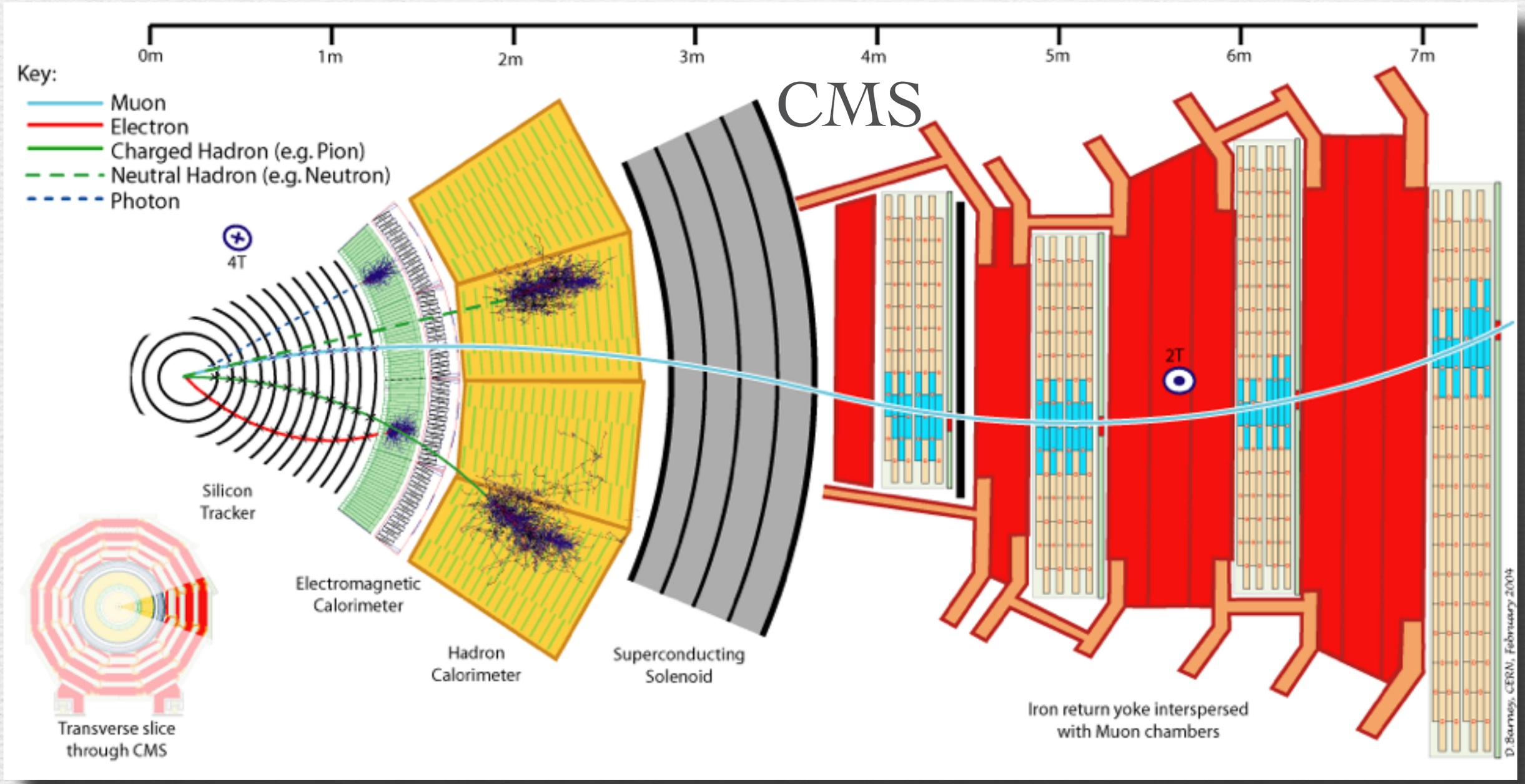
~100 million readout channels, every 25 ns




0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
CMS
4T
2T
Silicon
Tracker
Electromagnetic
Calorimeter
Hadron
Calorimeter
Superconducting
Solenoid
Iron return yoke interspersed
with Muon chambers
Transverse slice
through CMS
D.Barney, CERN, February 2004

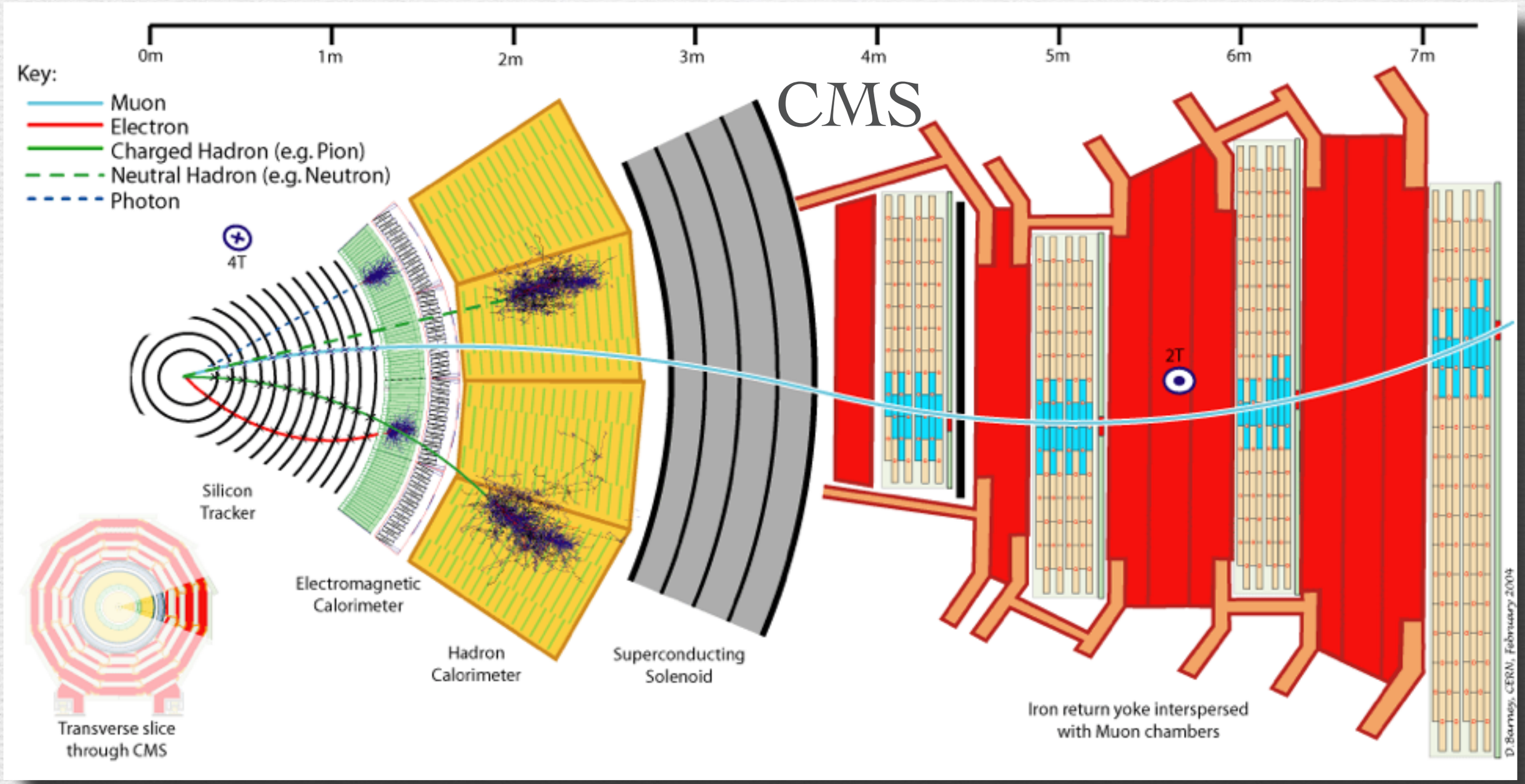


After zeroes removed, 1.6 MB / event



After zeroes removed, 1.6 MB / event

* 40 M events / s = 64 TB / s ?



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Can't save everything

Trigger system to keep only interesting events

	Incoming event rate per second	Outgoing event rate per second	Reduction factor
Level 1	40 000 000	100 000	400
Level 2	100 000	3 000	30
Level 3	3 000	200	15

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200 events / s * 1.6 MB / event = 320 MB / s

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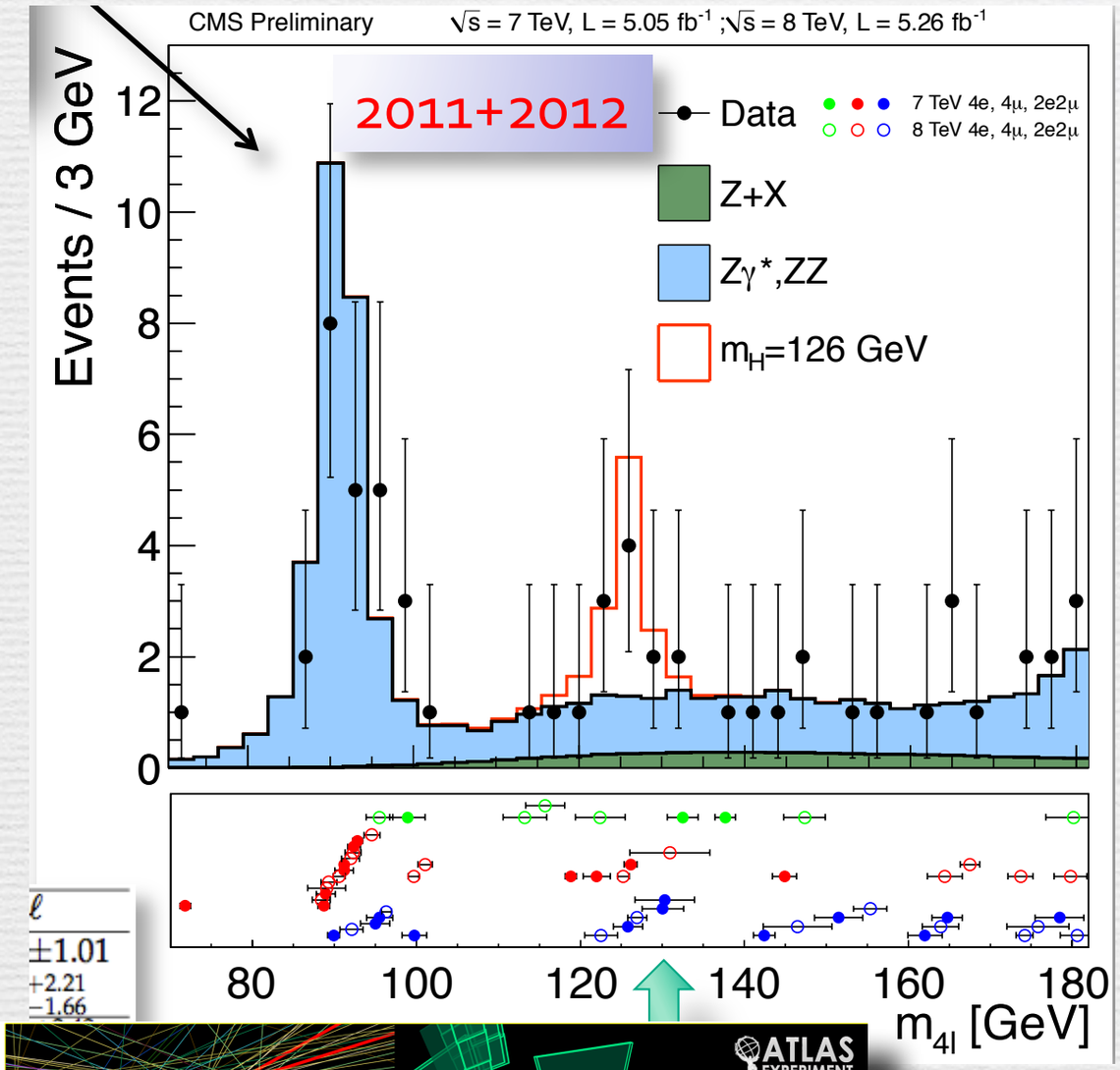
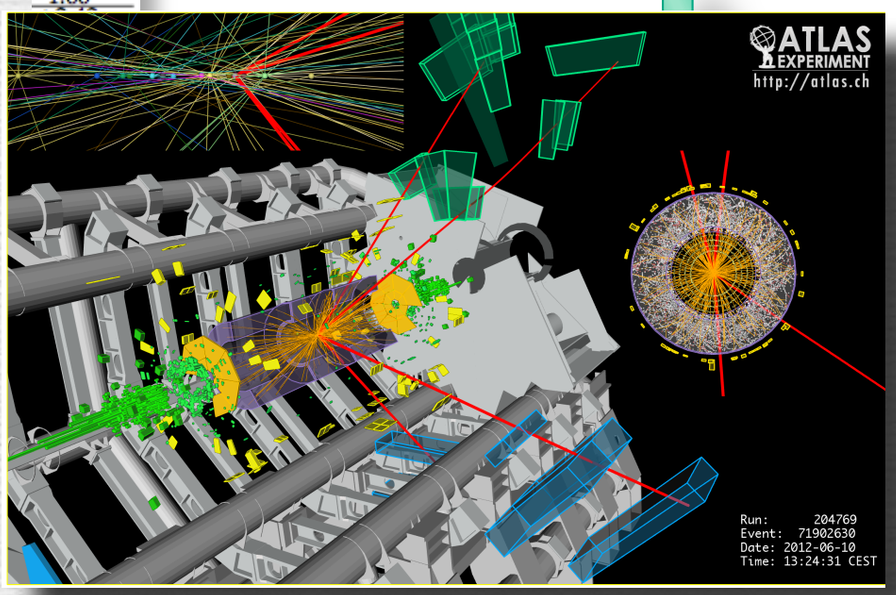
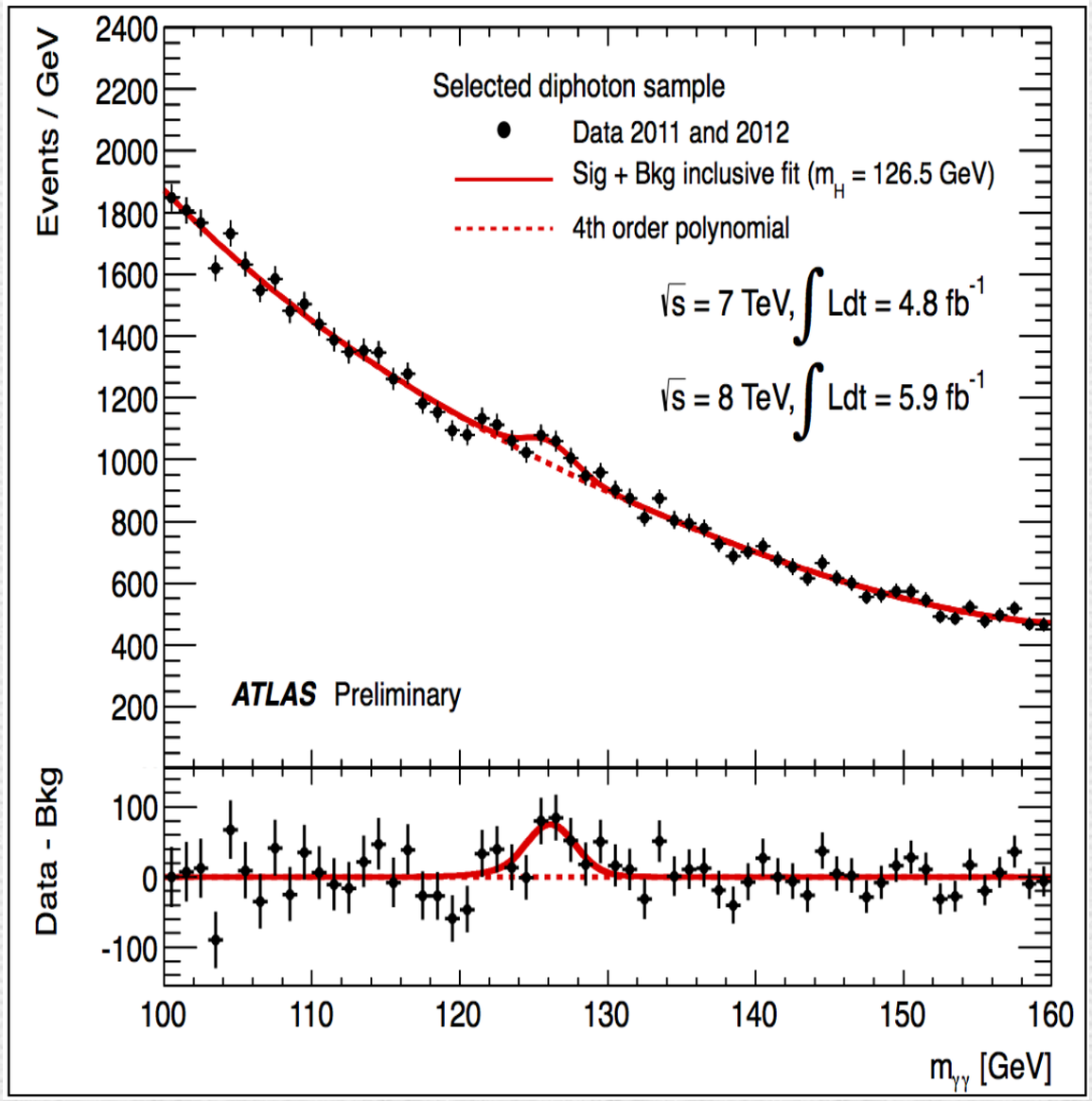
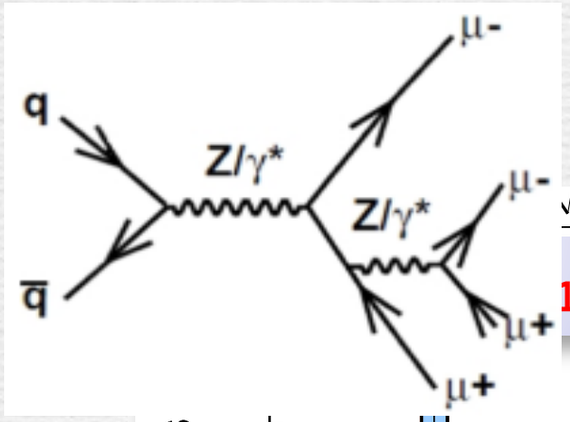
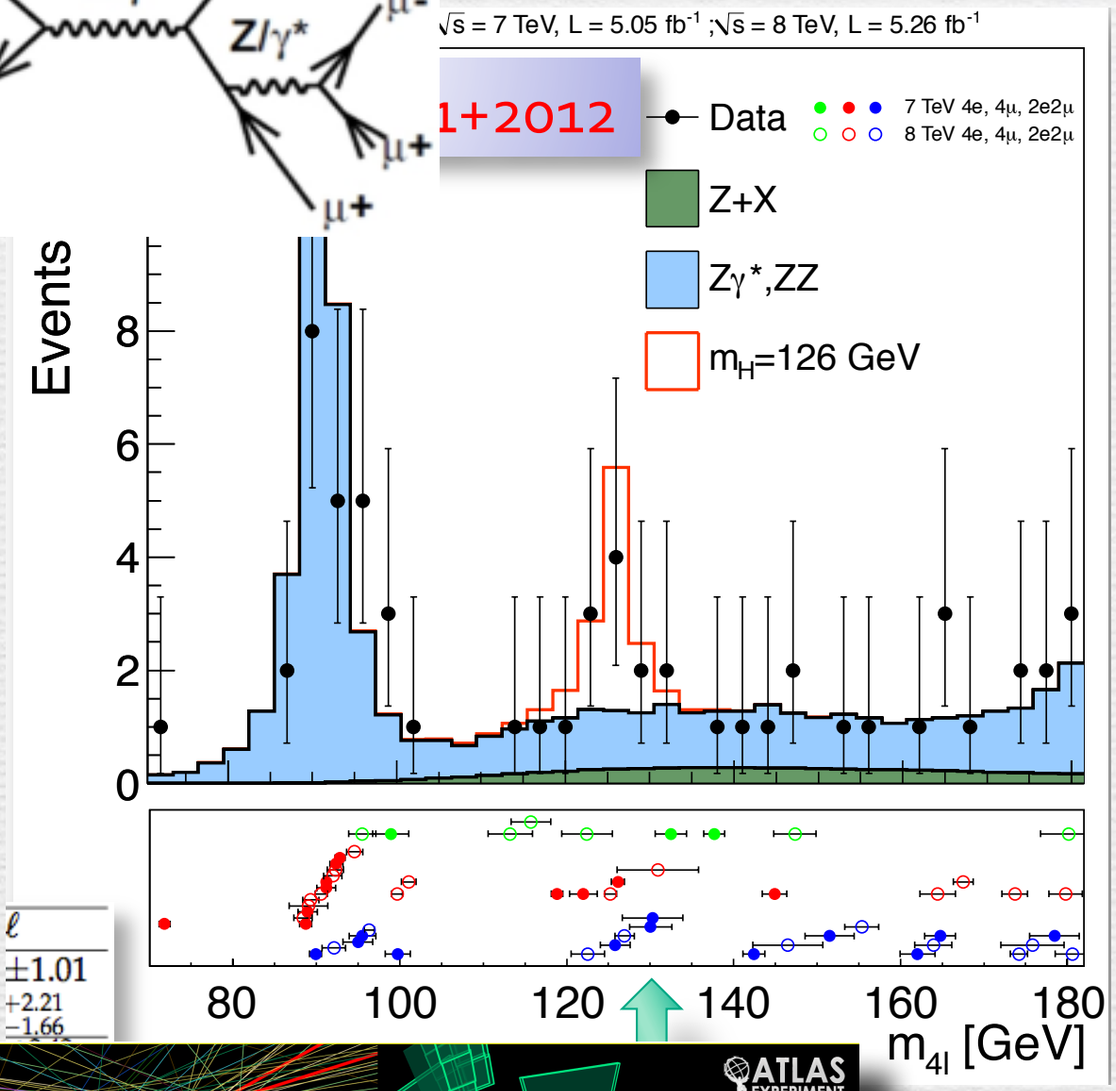
Analysis is done offline,
~3000 collaboration members should have
equal access to data worldwide


CMS Preliminary
√s = 7 TeV, L = 5.05 fb-1 ;√s = 8 TeV, L = 5.26 fb-1
2011+2012
Data
7 TeV 4e, 4μ, 2e2μ
8 TeV 4e, 4μ, 2e2μ
Z+X
Zγ*,ZZ
mH=126 GeV
Events / 3 GeV
m4l [GeV]


ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST


Selected diphoton sample
Data 2011 and 2012
Sig + Bkg inclusive fit (mH = 126.5 GeV)
4th order polynomial
√s = 7 TeV, ∫ Ldt = 4.8 fb-1
√s = 8 TeV, ∫ Ldt = 5.9 fb-1
ATLAS Preliminary
Events / GeV
Data - Bkg
mγγ [GeV]


q
q̄
Z/γ*
Z/γ*
μ-
μ-
μ+
μ+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1+2012
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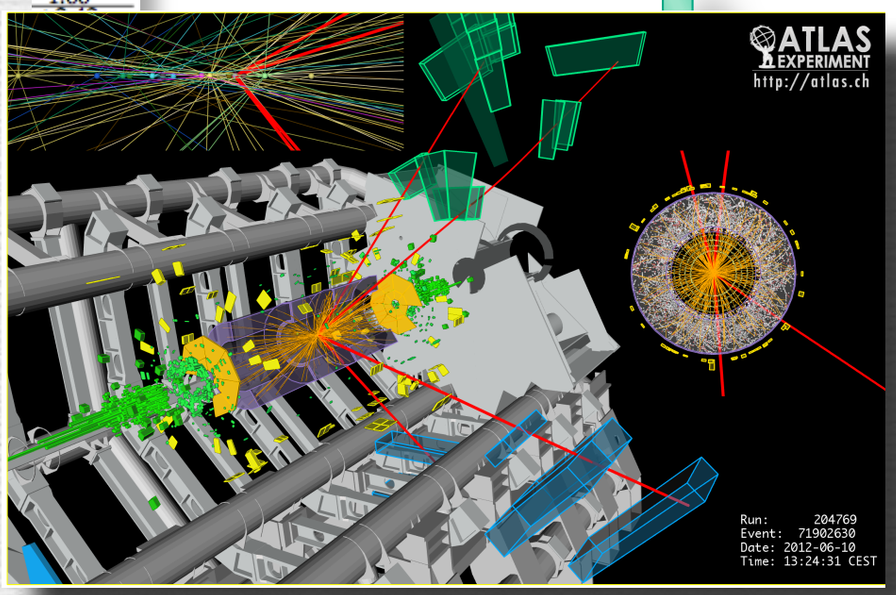
7 TeV 4e, 4μ, 2e2μ
8 TeV 4e, 4μ, 2e2μ
Z+X
Zγ*,ZZ
mH=126 GeV
Events
0
2
4
6
8
80
100
120
140
160
180
m4l [GeV]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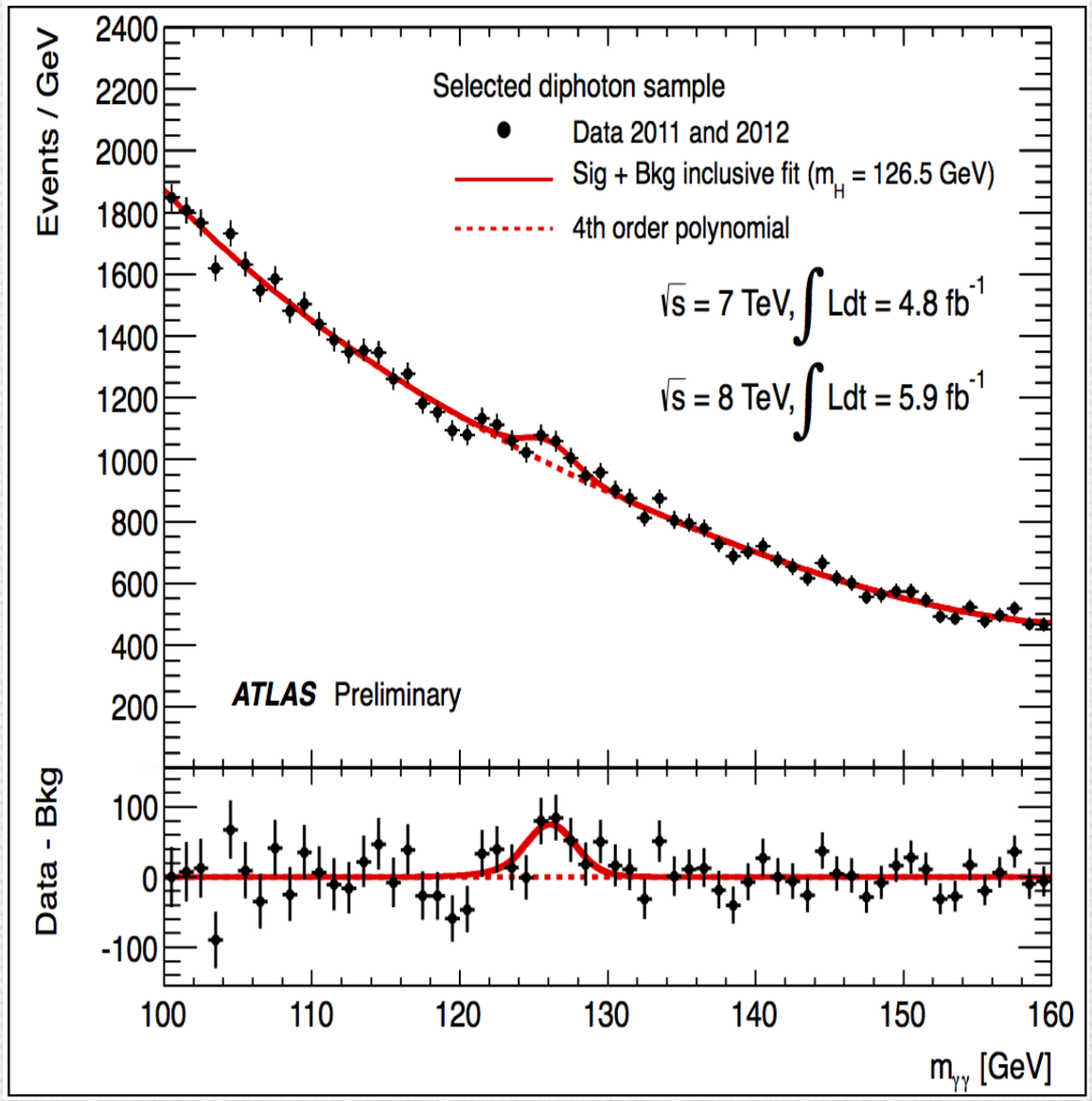
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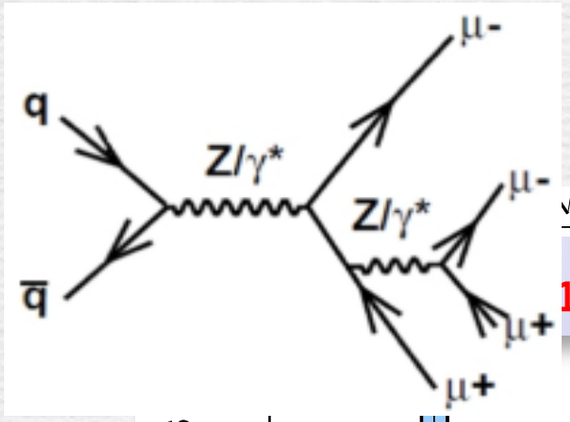
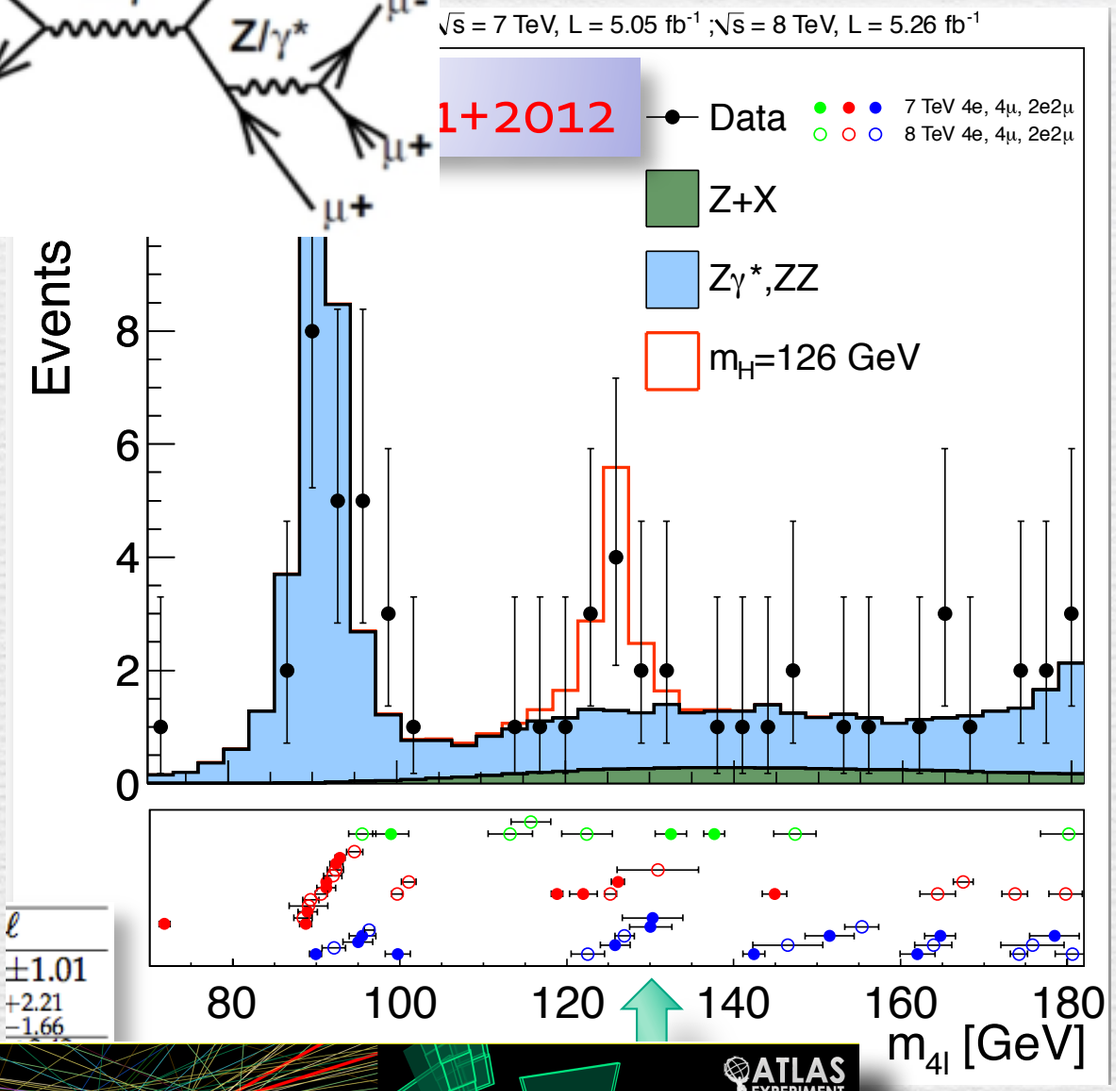
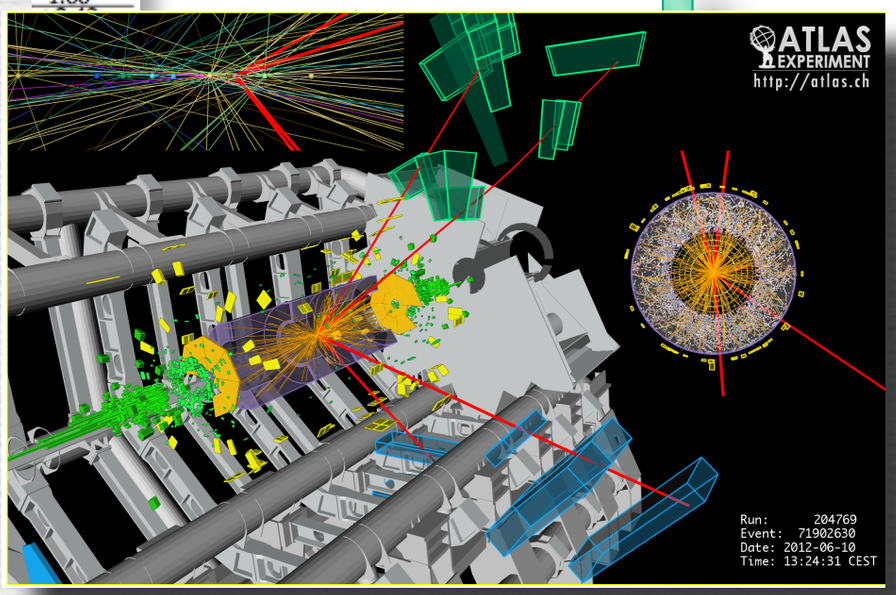
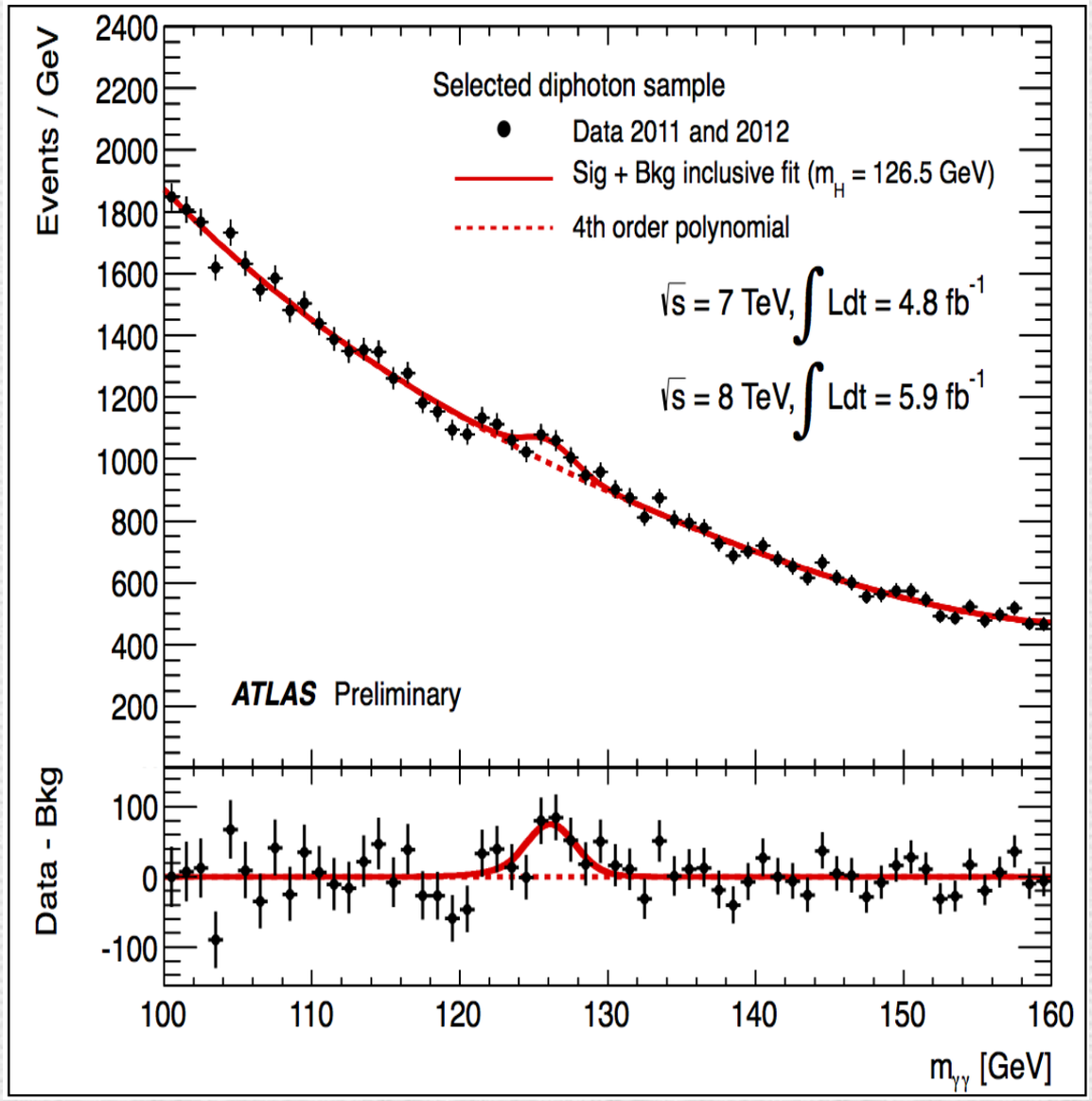
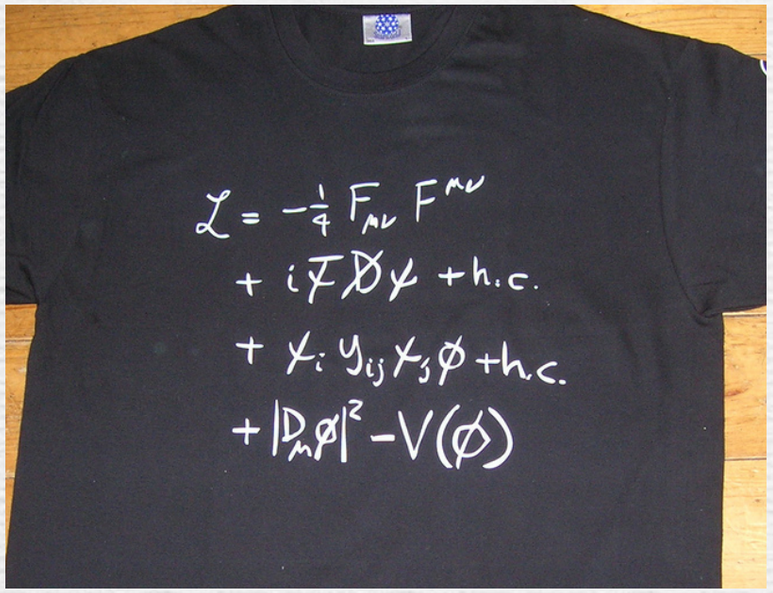






Need to get theory predictions.

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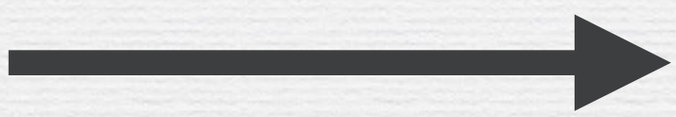

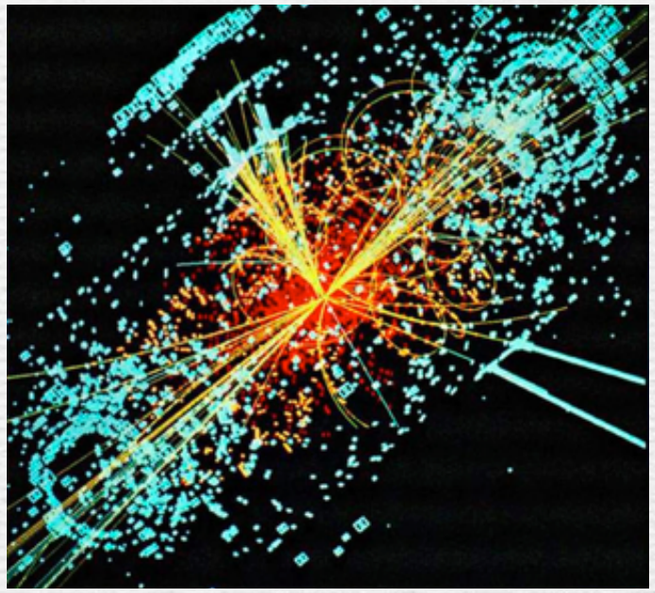

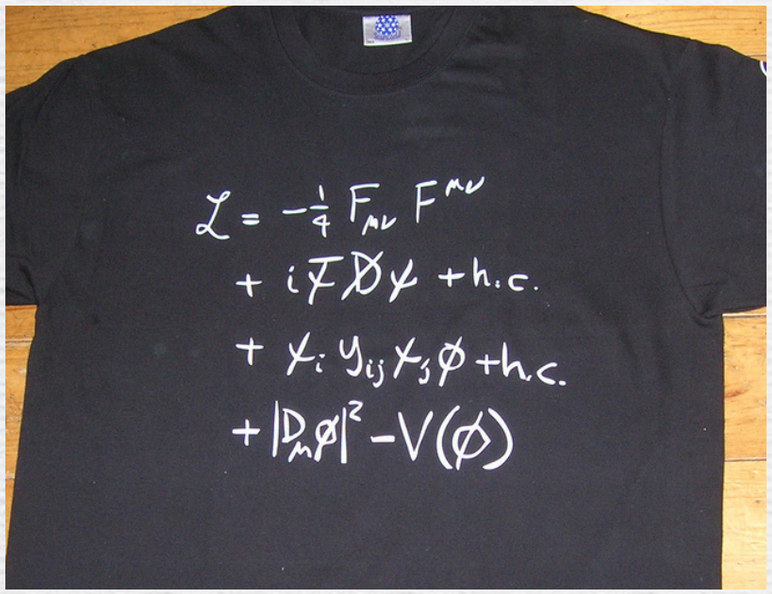
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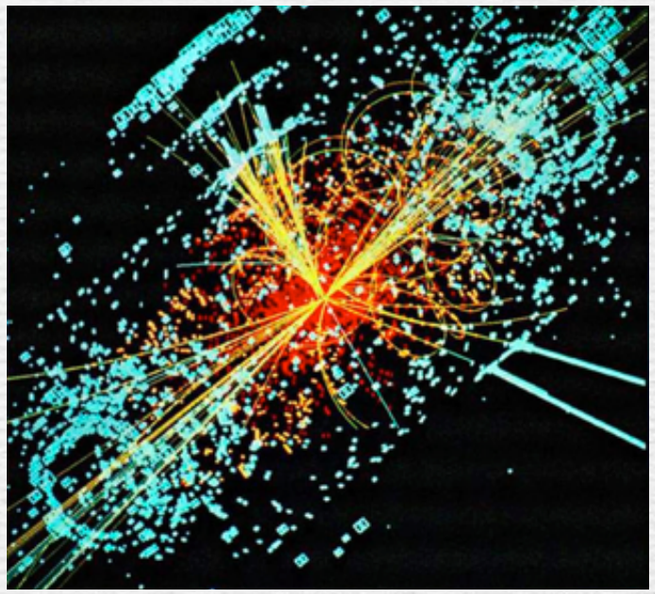
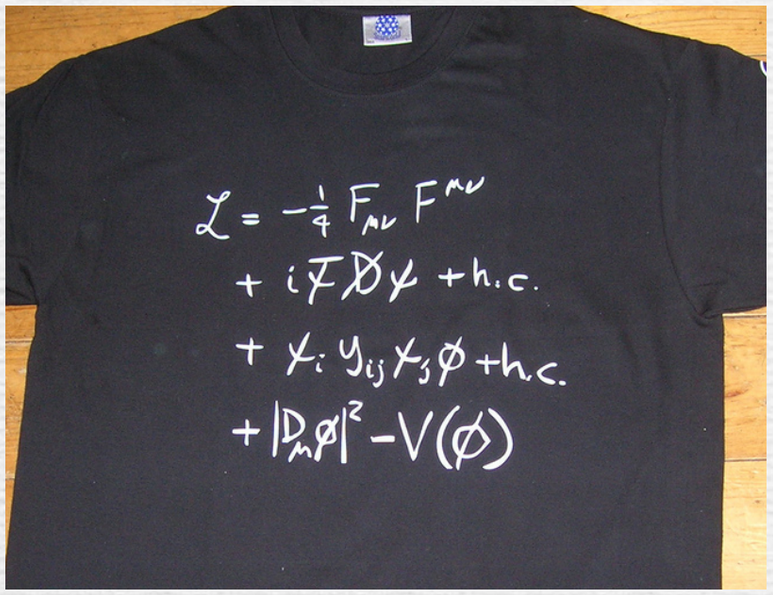
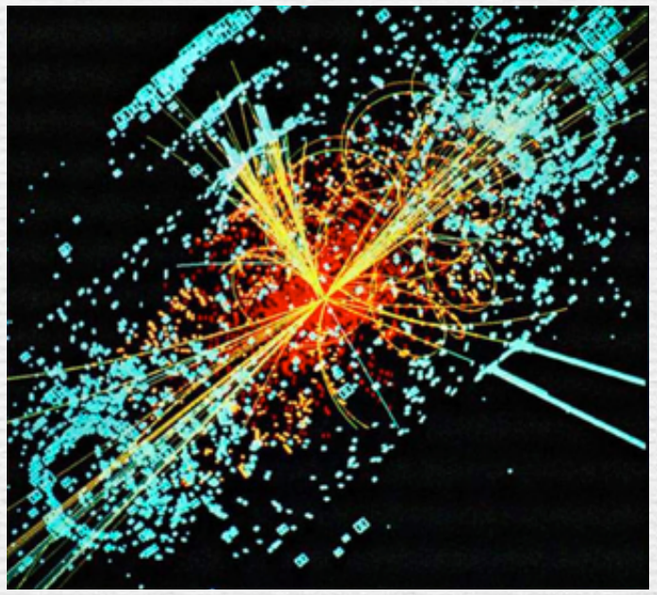
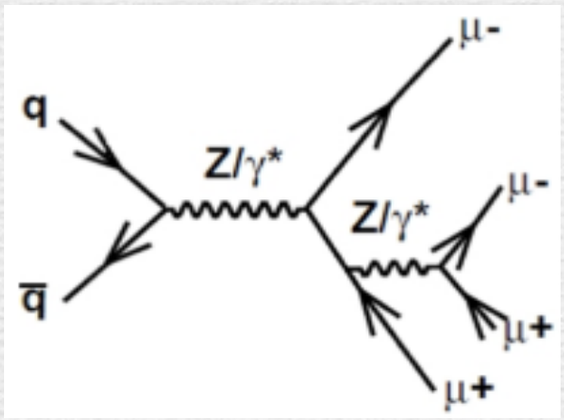








Monte Carlo event generators

Nature

Theory model

Event generator

Detector

Trigger

Simulated events

Reconstructed events

Analysis

Event generator

Matrix element

Parton shower

Hadronization

Decays

Event generator

Matrix element

Monte-Carlo integration

Parton shower

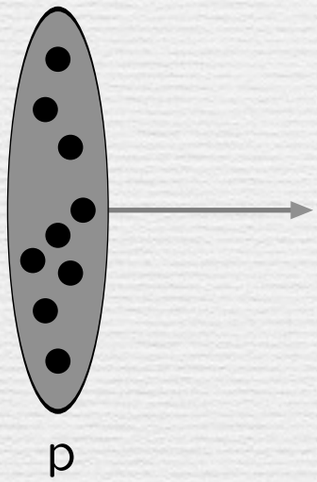
Markov chain

Hadronization

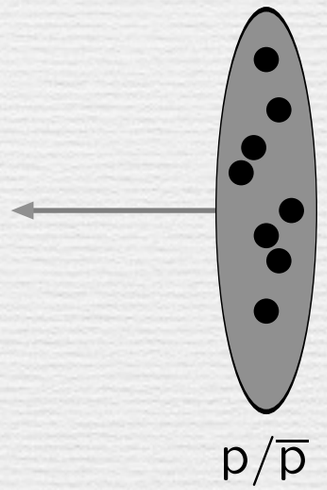
book-keeping

Decays

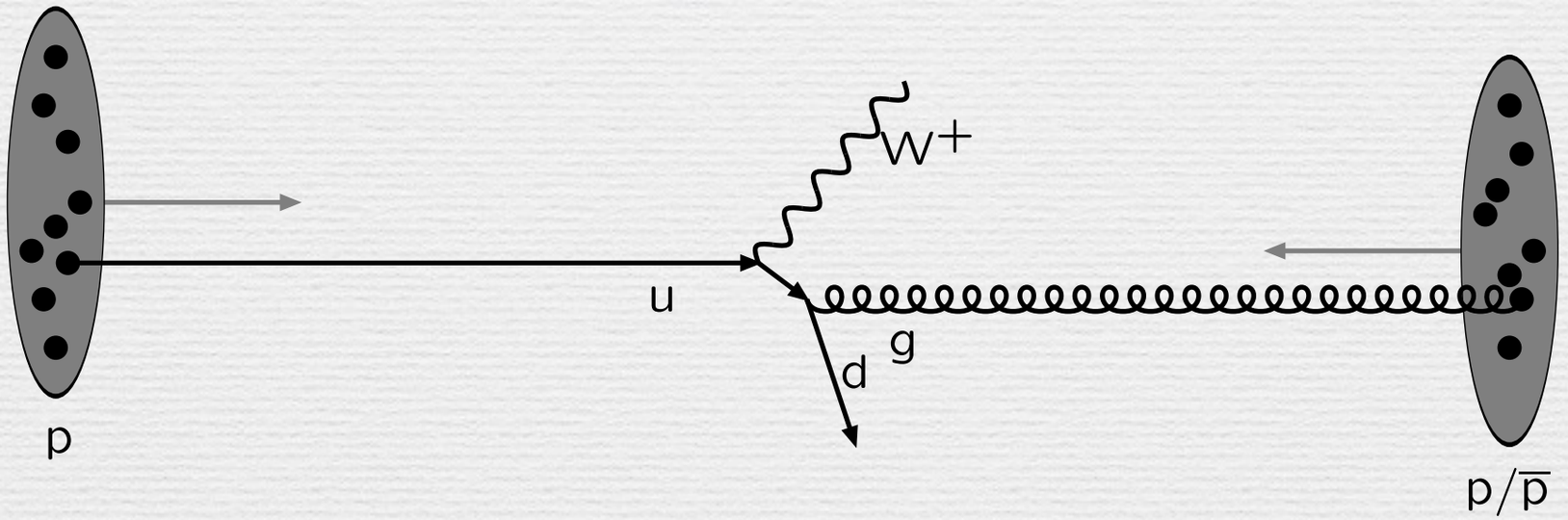
Monte-Carlo integration

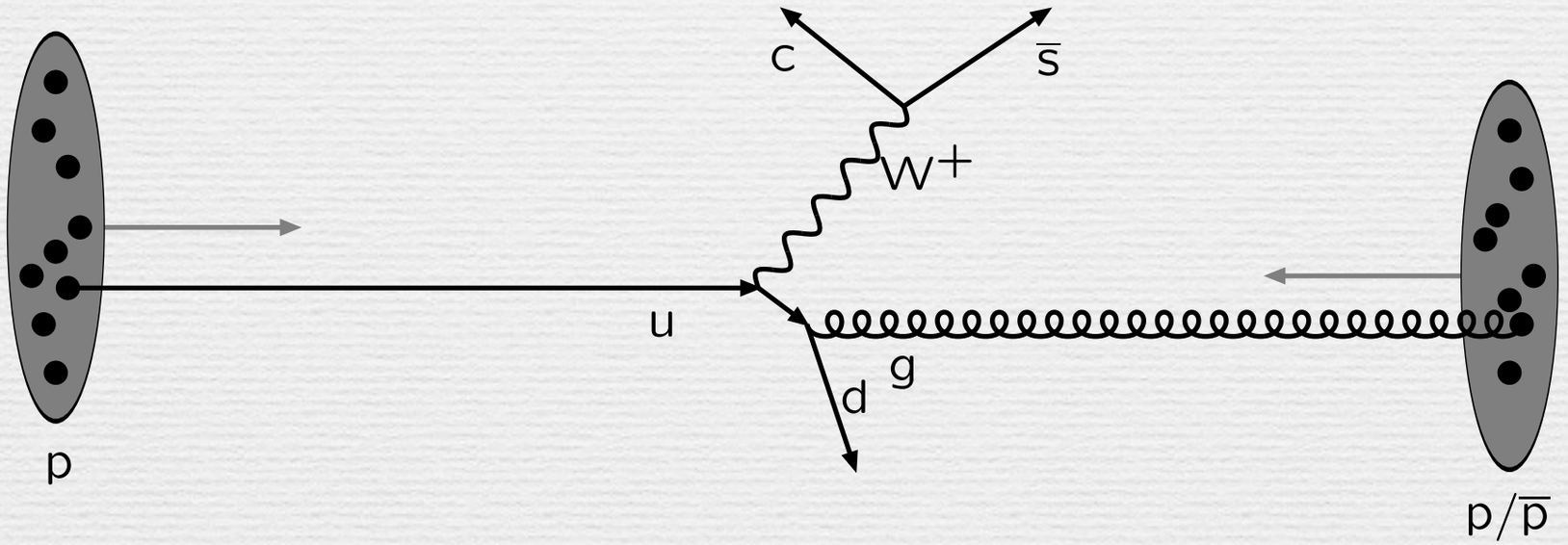


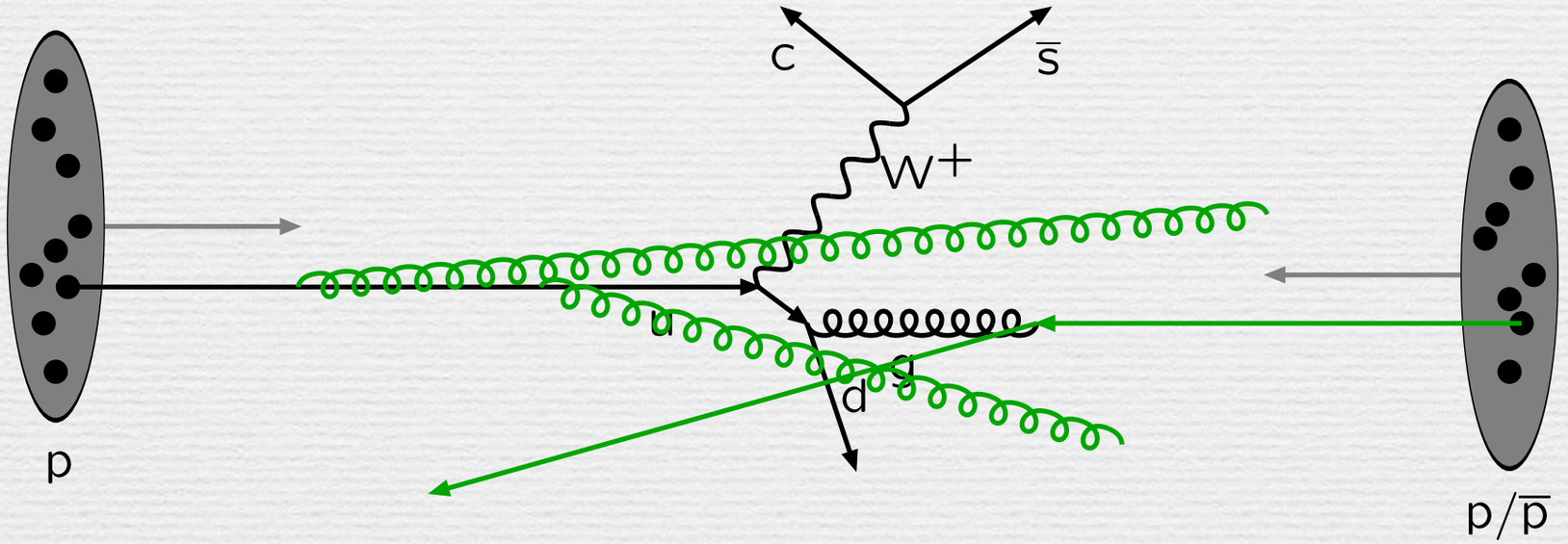
p

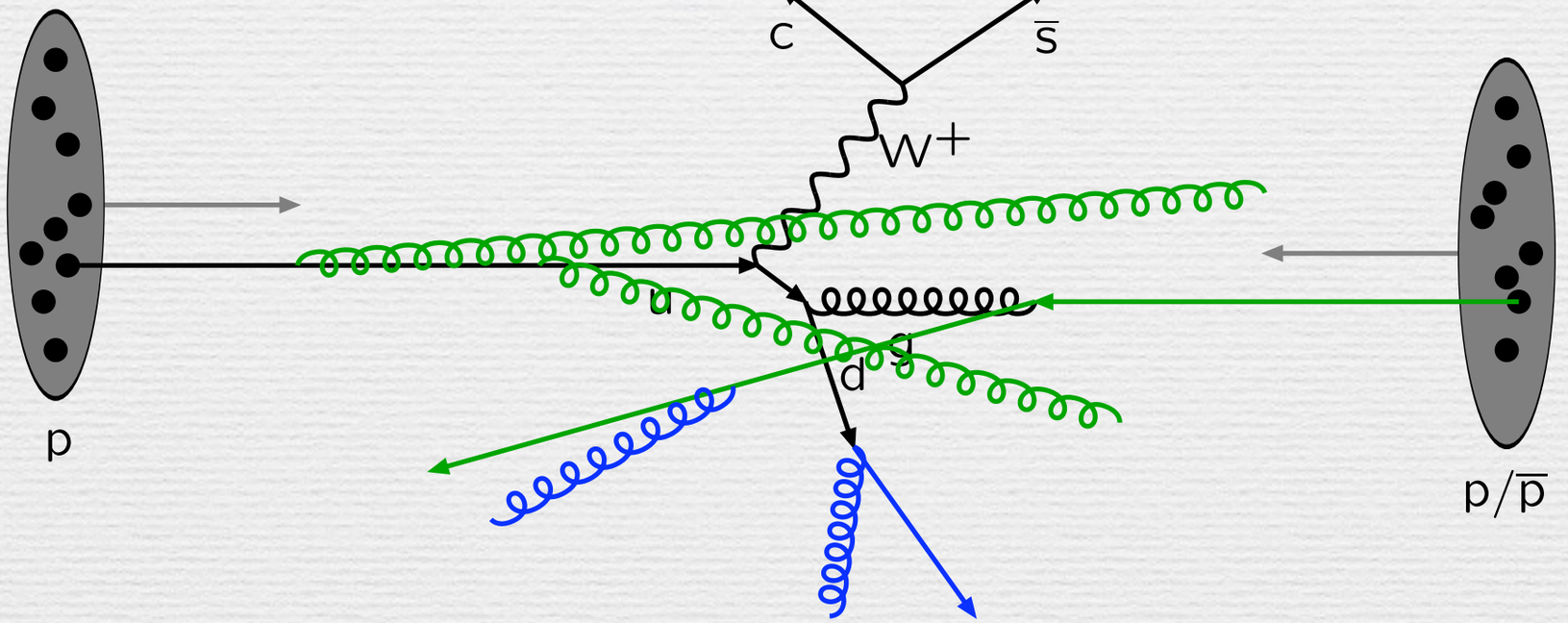


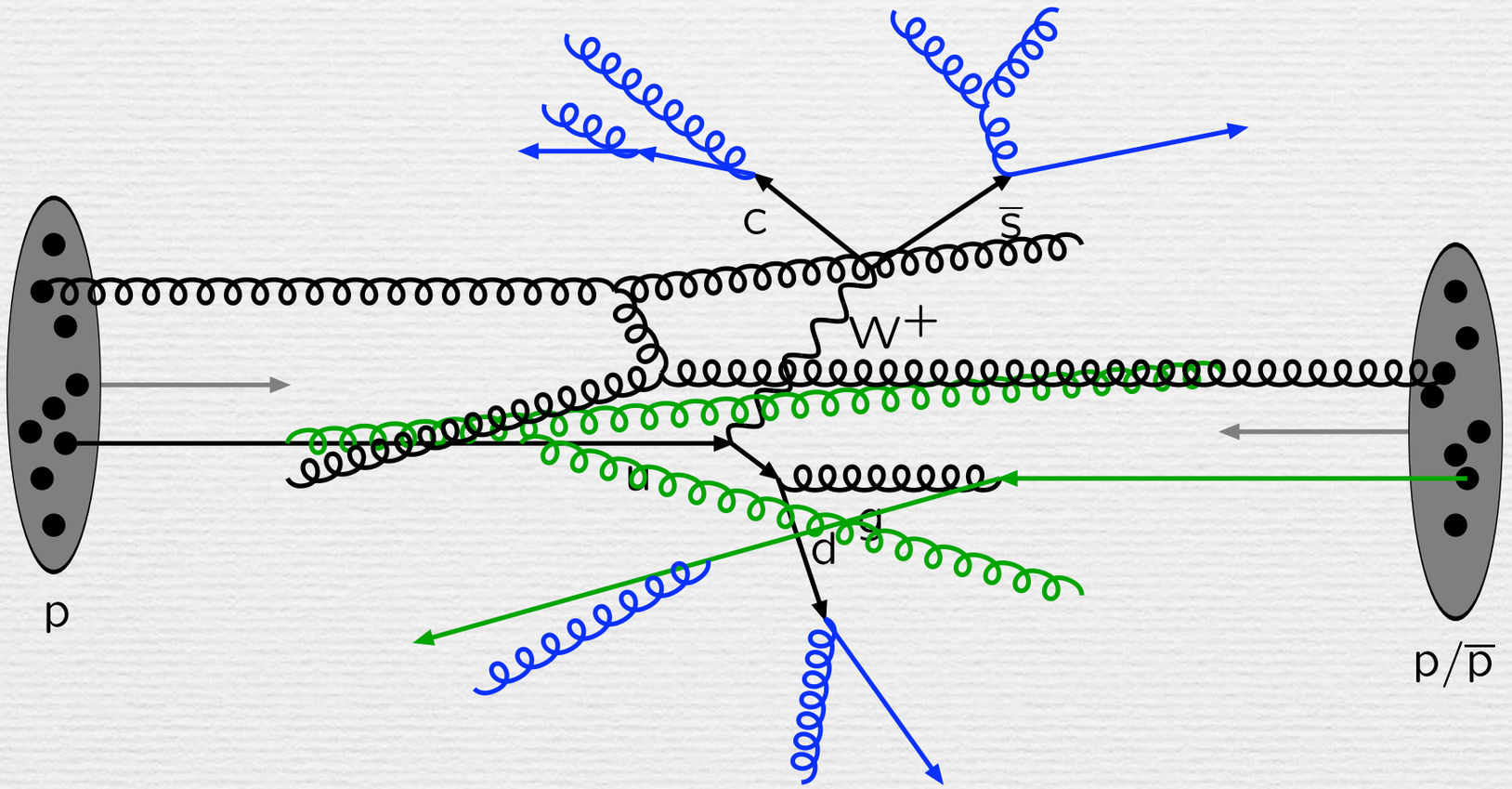
$p/\bar{p}$


W+
u
g
d
p
p/p̄


c
$\bar{s}$
W+
u
g
d
p
p/$\bar{p}$


c
s̄
W+
u
d̄
d
p
p/p̄


c
s̄
W+
u
d̄
d
p
p/p̄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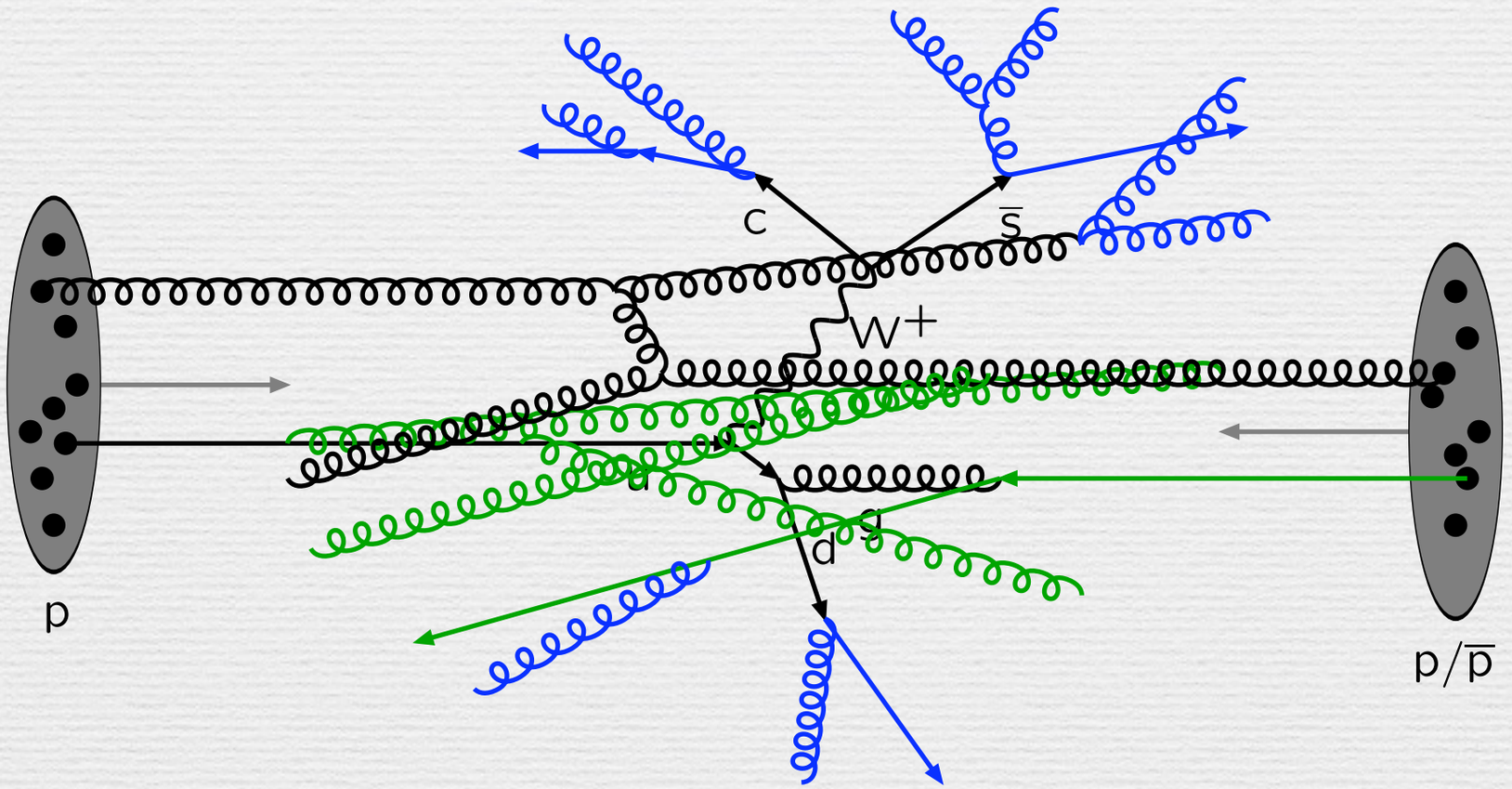
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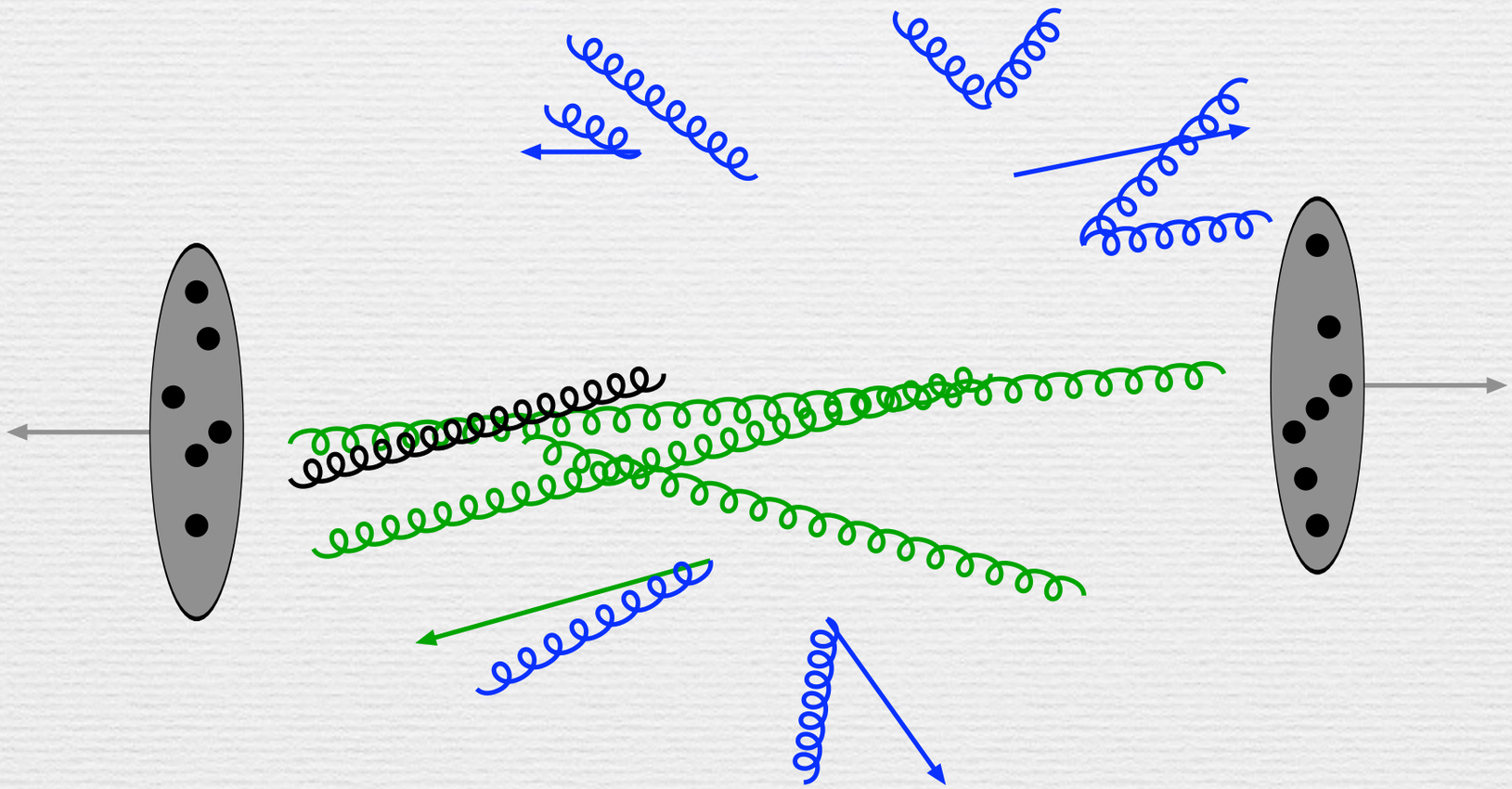
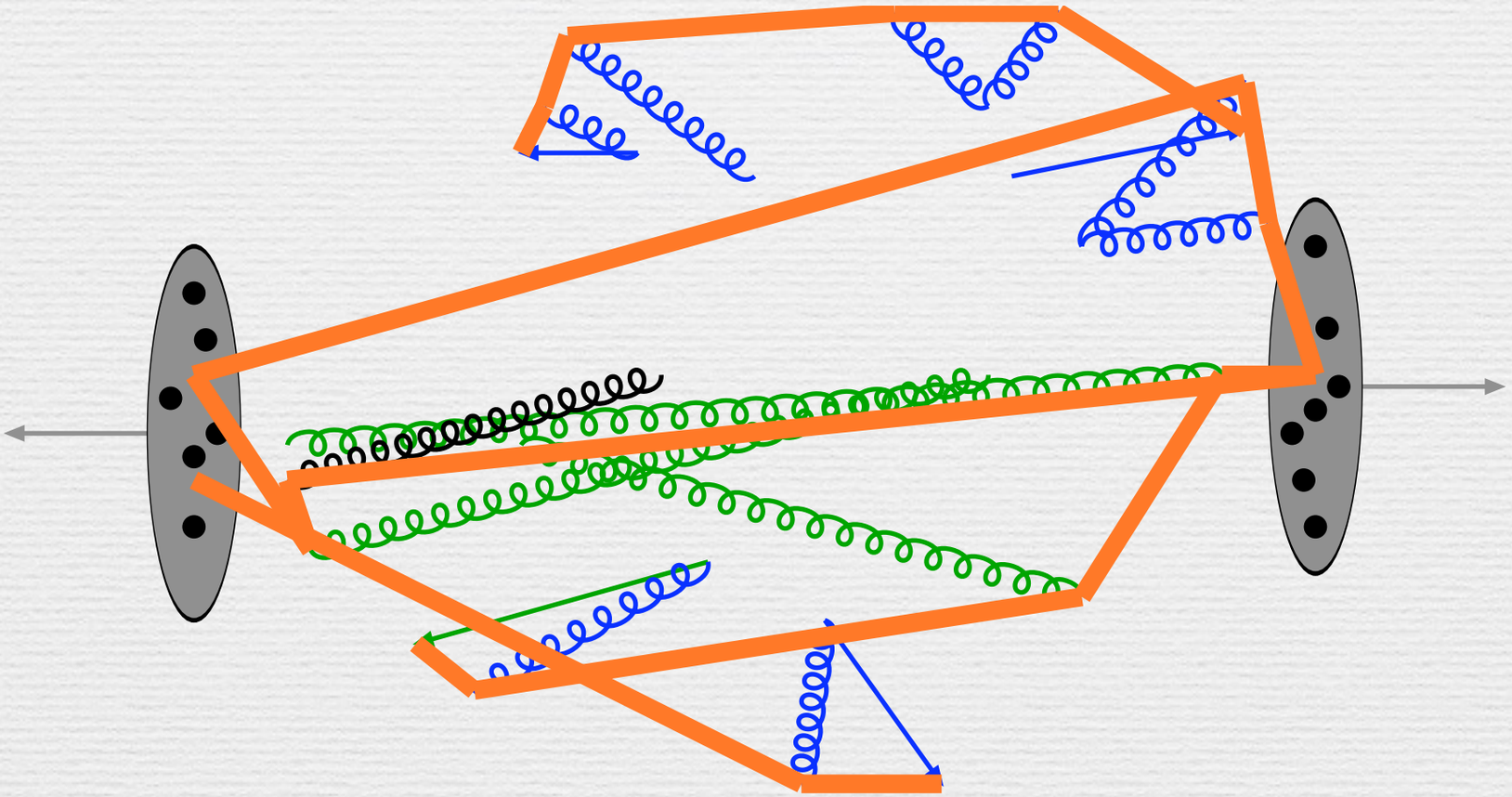
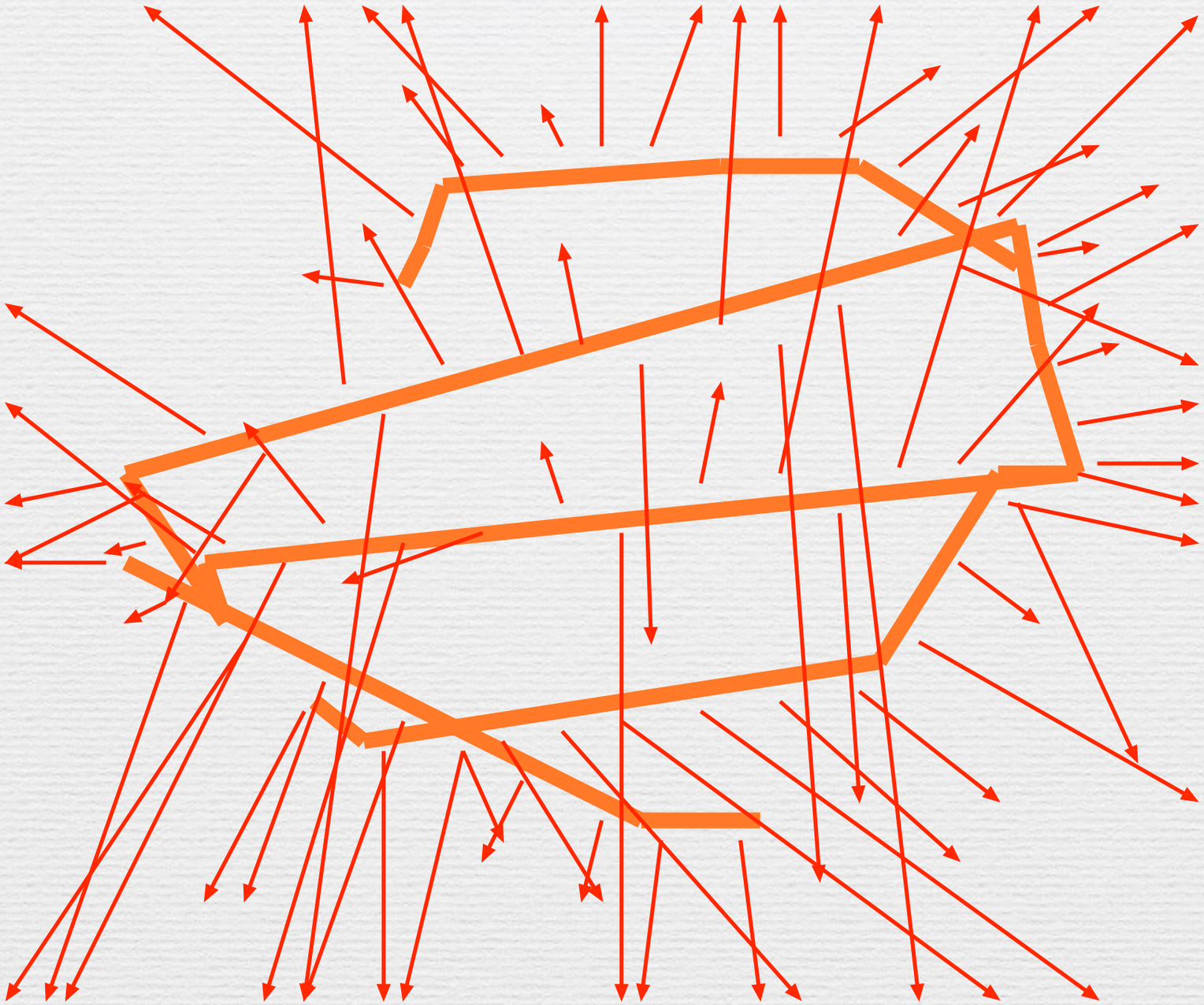
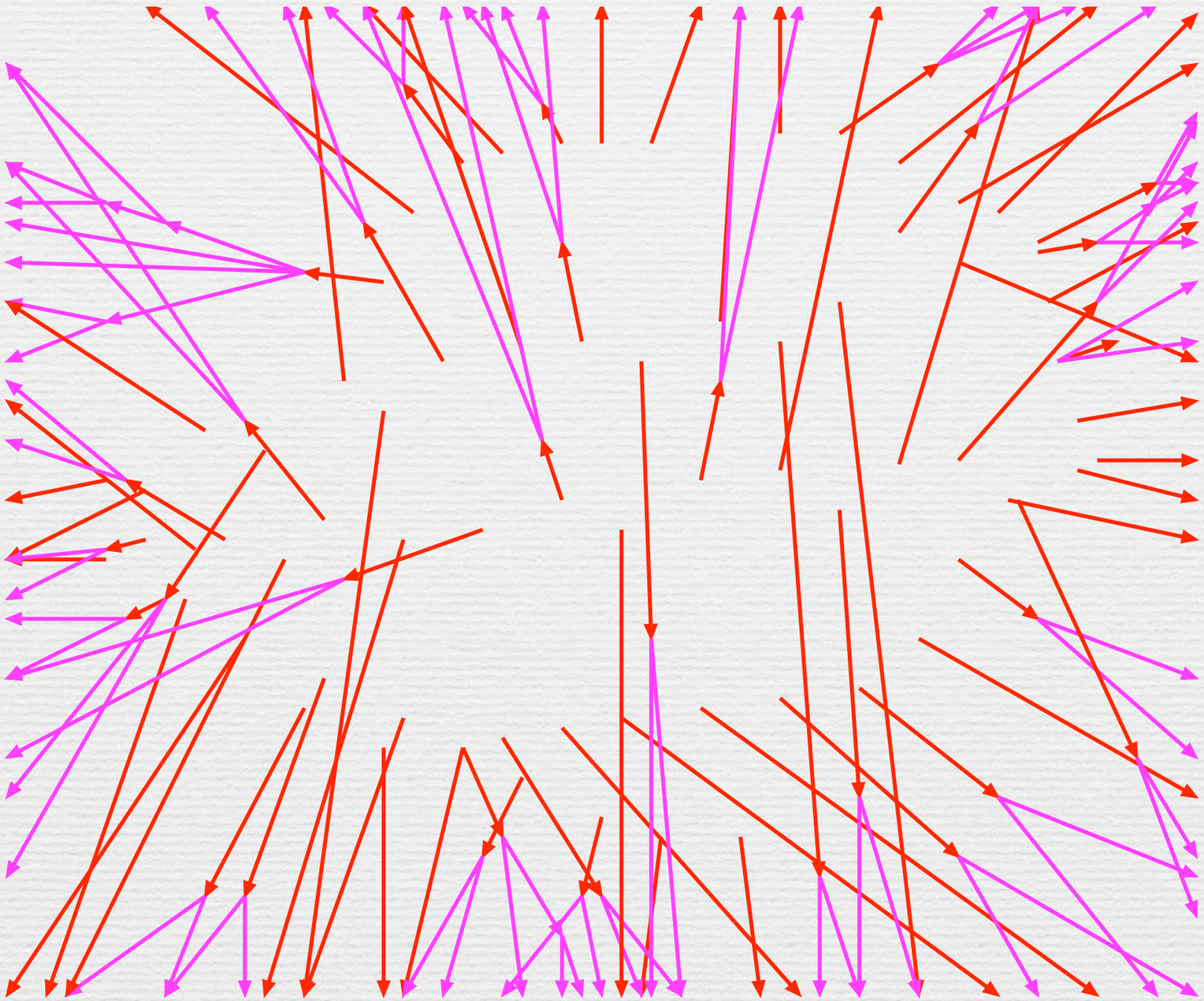
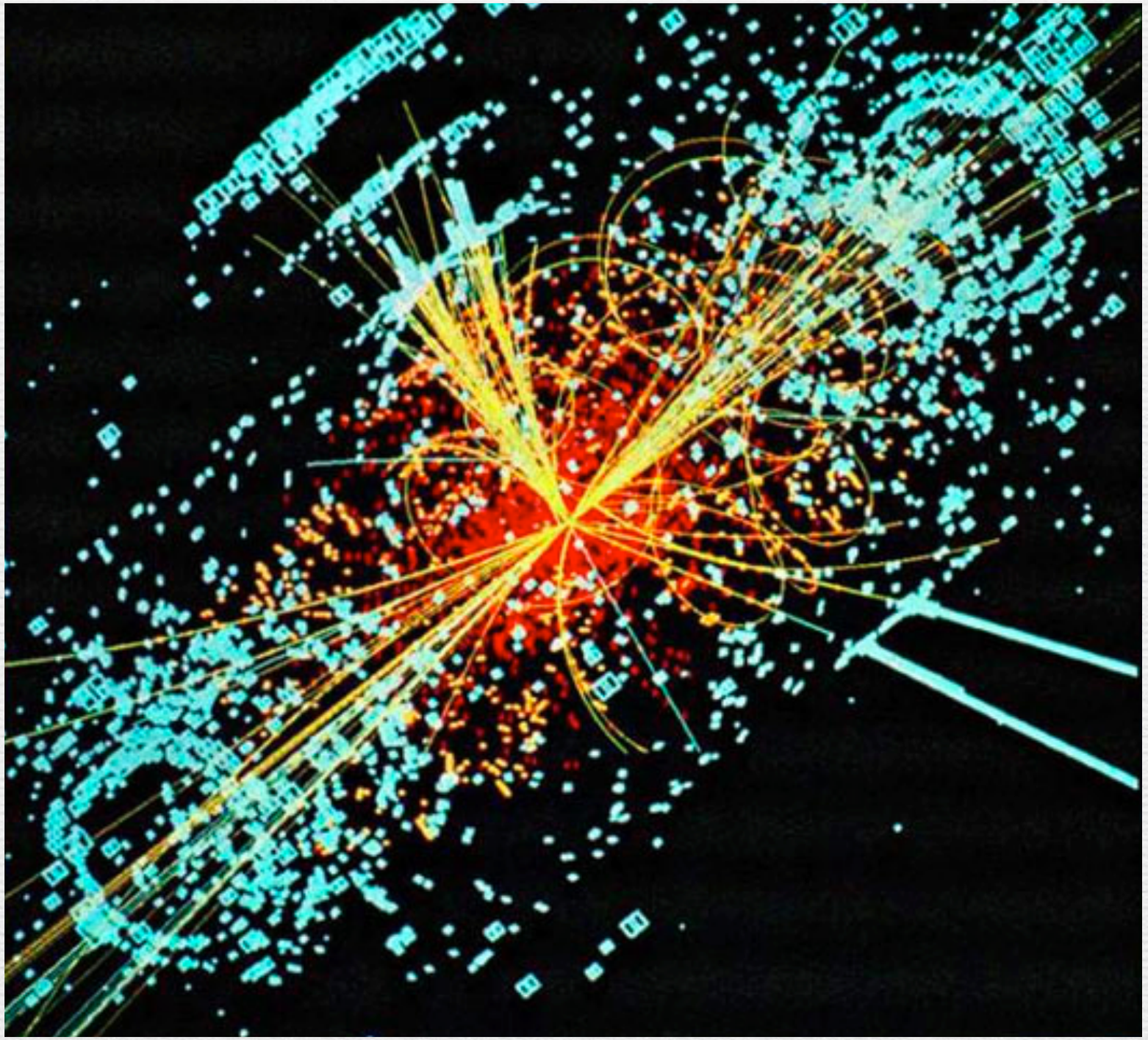
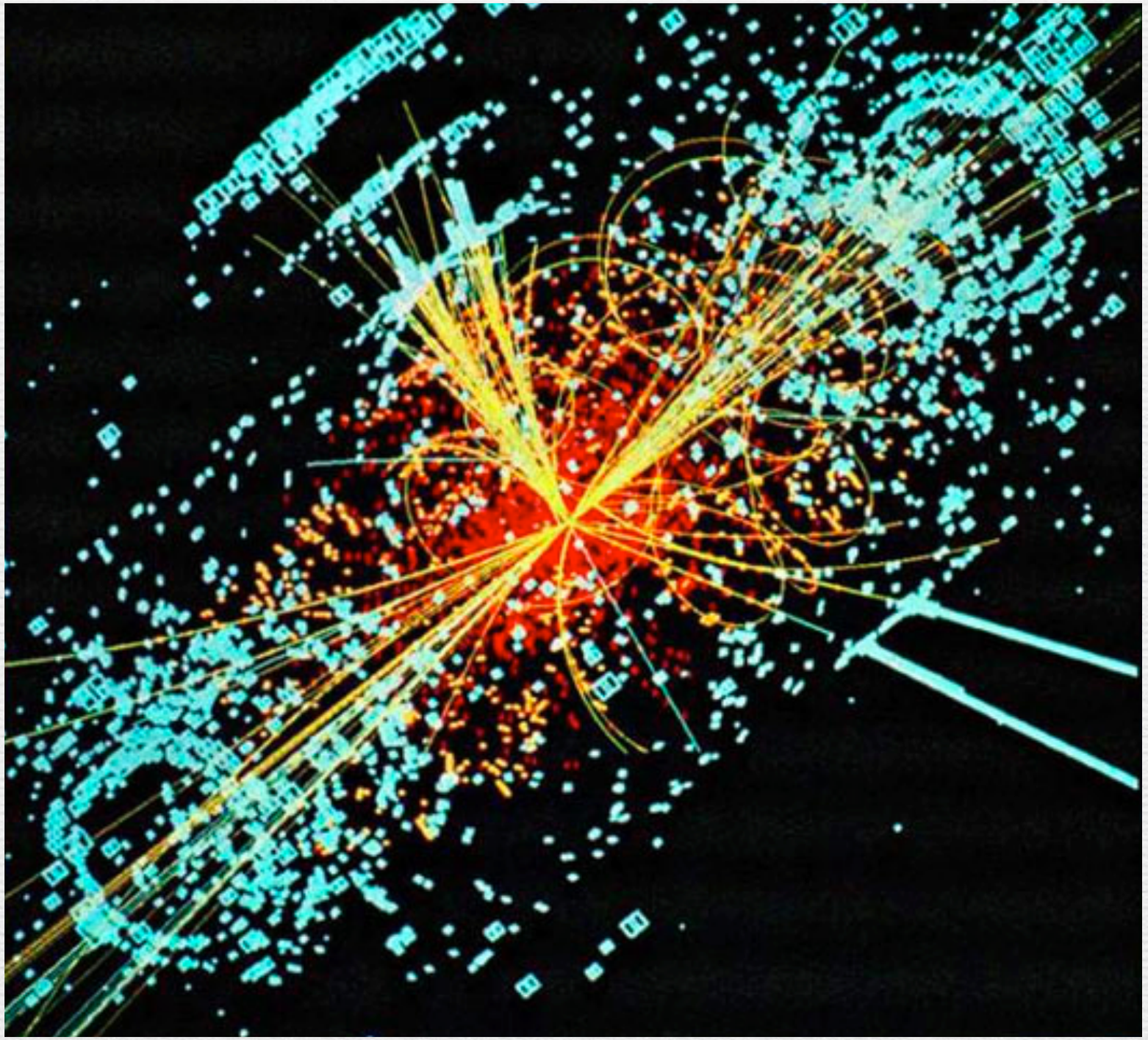












Simulated data sets of millions of events

Nature

Detector

Trigger

Reconstructed events

Theory model

Event generator

Simulated events

Analysis

Nature

Detector

Trigger

Reconstructed events

Theory model

Event generator

Simulated events

need millions!

~15 s per event

Analysis

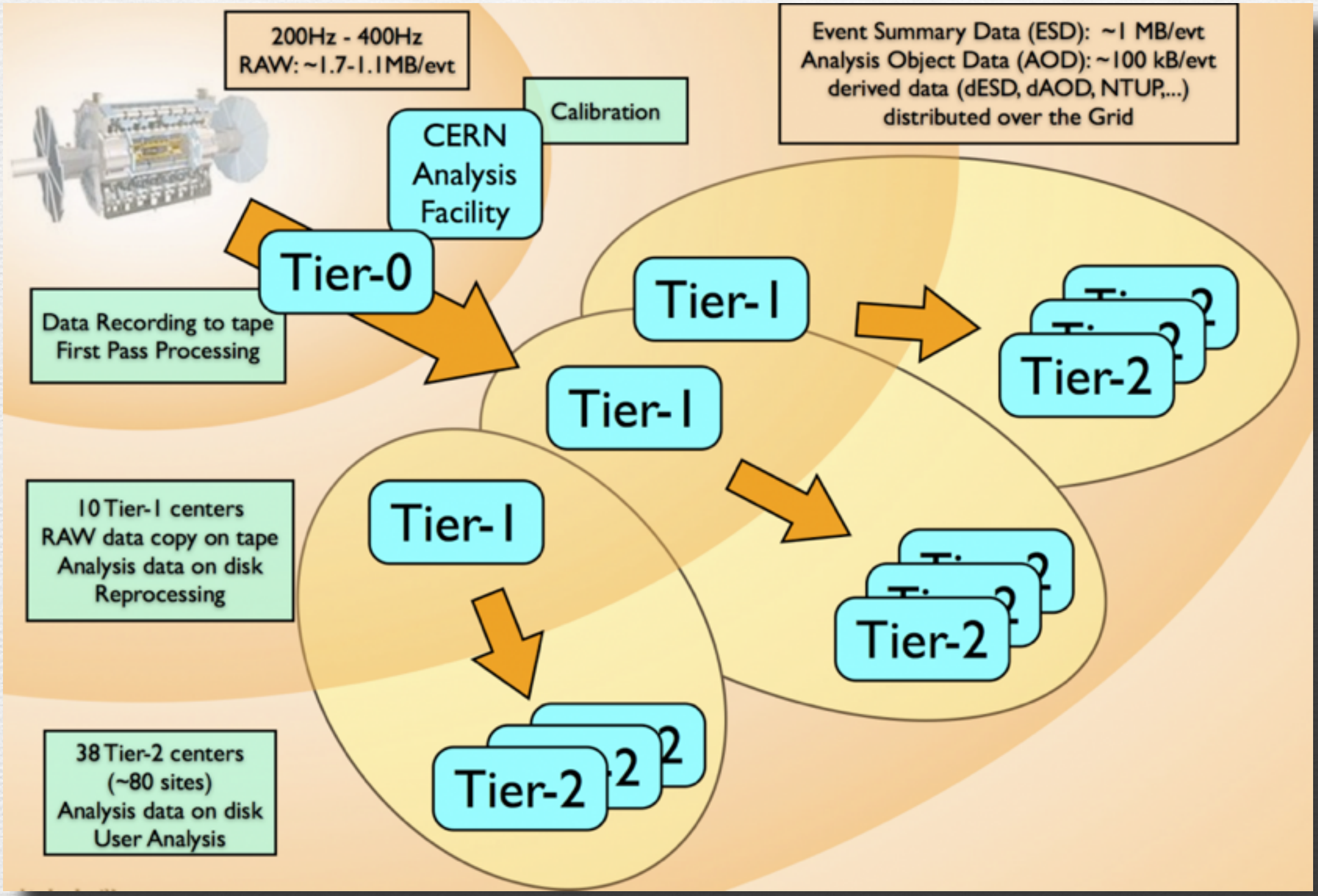
Each event independent

Batch farms are OK, but typical university clusters not large enough

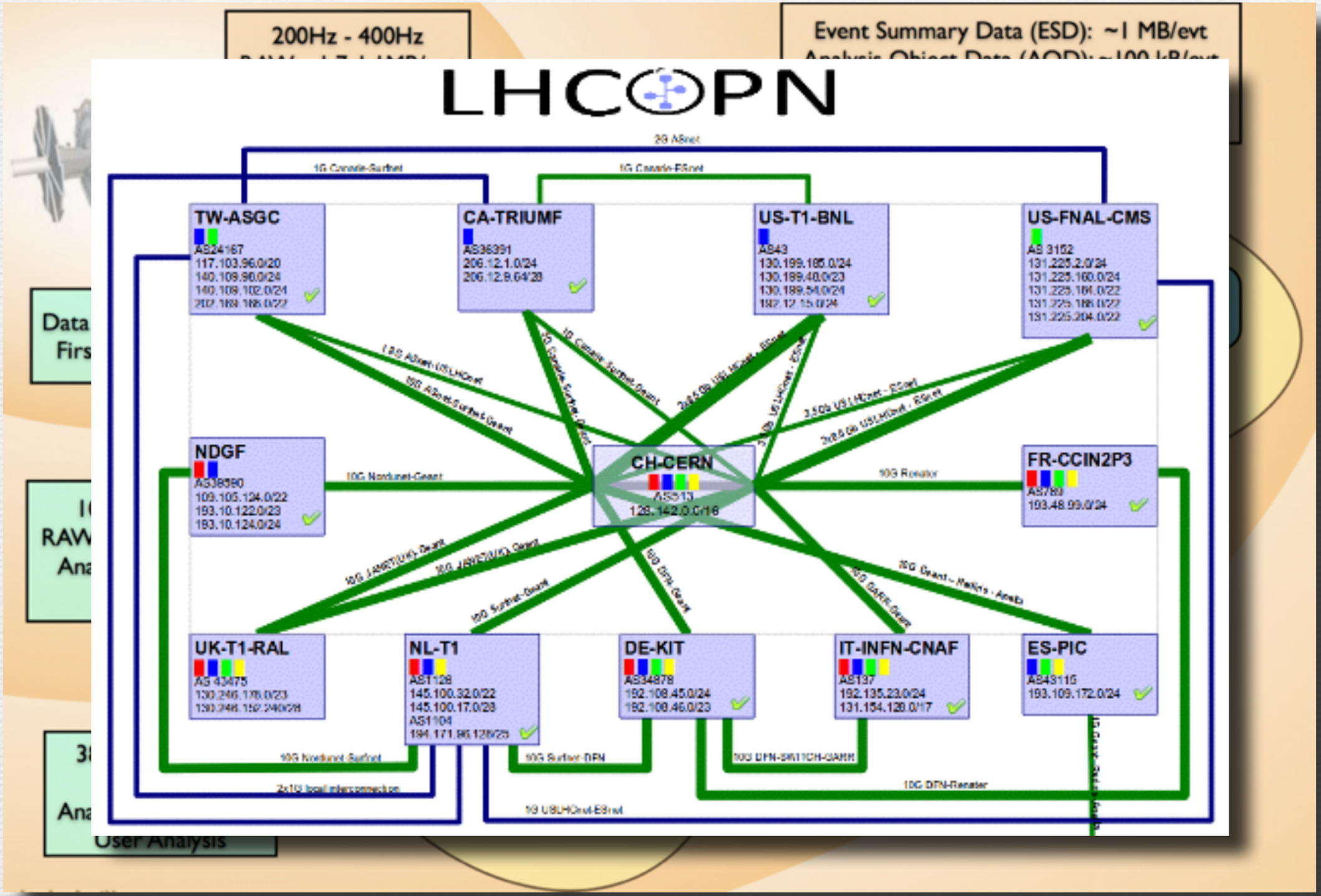
Connect all participants transparently:

Worldwide LHC Computing Grid

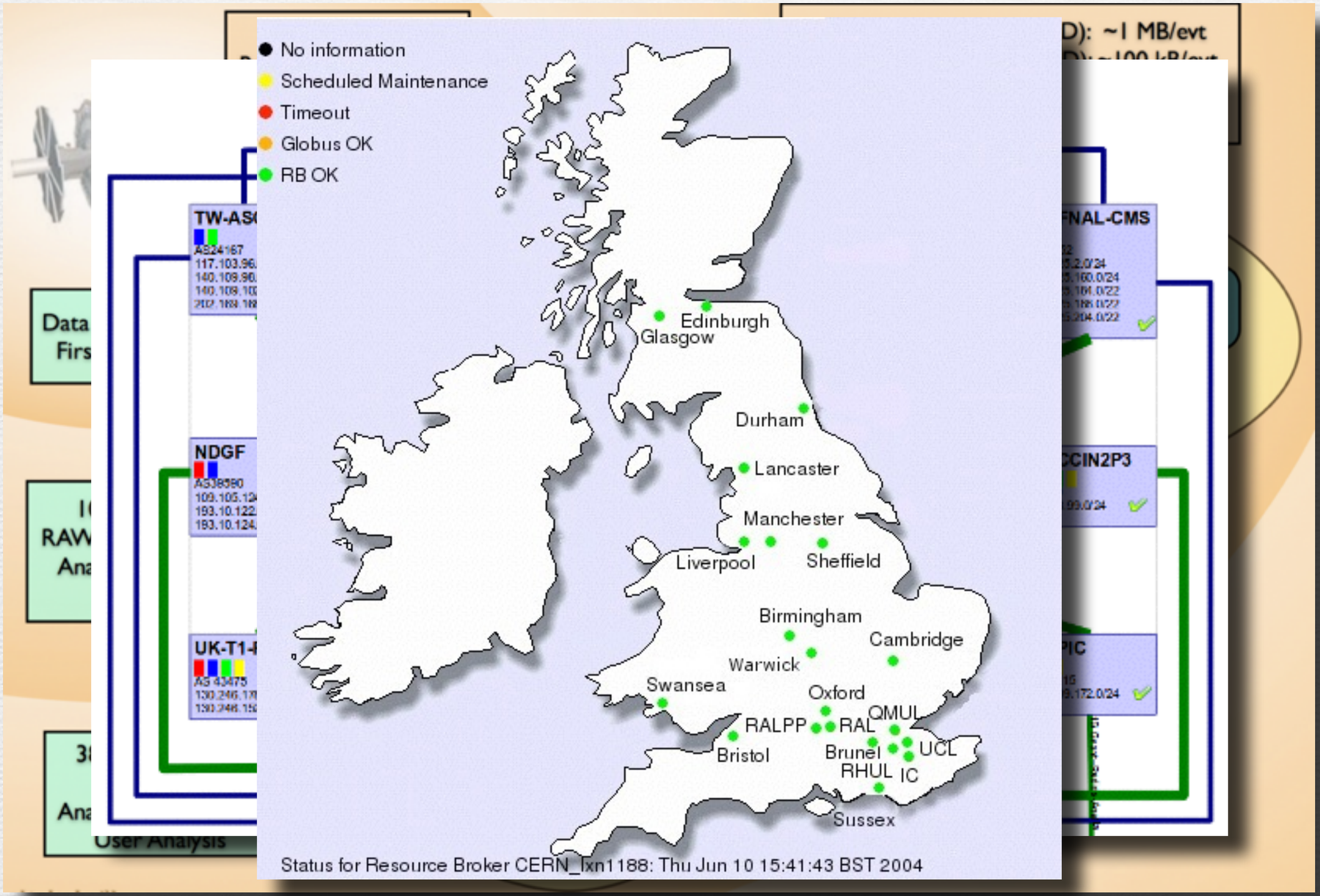
WLCG tiered structure



WLCG tiered structure



WLCG tiered structure



WLCG tiered structure

World Wide Web

The WorldWideWeb (W3) is a wide-area hypermedia information retrieval initiative aiming to give universal access to a large universe of documents.

Everything there is online about W3 is linked directly or indirectly to this document, including an executive summary of the project, Mailing lists , Policy , November's W3 news , Frequently Asked Questions .

What's out there?
: Pointers to the world's online information, subjects , W3 servers, etc.

Help
: on the browser you are using

Software Products
: A list of W3 project components and their current state. (e.g. Line Mode ,X11 Viola , NeXTStep , Servers , Tools , Mail robot , Library)

Technical
: Details of protocols, formats, program internals etc

Bibliography
: Paper documentation on W3 and references.

People
: A list of some people involved in the project.

History
: A summary of the history of the project.

How can I help ?
: If you would like to support the web..

Getting code
: Getting the code by anonymous FTP , etc.