

Particle Physics at Colliders : Experiment

Junghwan Goh
고정환
Kyung Hee University | 경희대학교

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2022 KIAS Particle Physics Summer Camp / 가속기 실험

KYUNG HEE UNIVERSITY

http://events.kias.re.kr/h/particle.physics2022/?pageNo=4641

	8/22(월)	8/23(화)	8/24(수)	8/25(목)
09:00 - 10:30	양평으로 이동	양자장론+표준모형4 (서민석)	암흑물질 이론 (신창섭)	우주론 (신창섭)
10:30 - 11:00		휴식		
11:00 - 12:30		BSM ideas (정성훈)	암흑물질 실험 (하창현)	콜로키움 (손민호)
12:30 - 14:30	점심식사			
14:30 - 16:00	양자장론+표준모형1 (서민석)	중성미자 이론 (송정현)	가속기 이론 (손민호)	귀가
16:00 - 16:30	휴식			
16:30 - 18:00	양자장론+표준모형2 (서민석)	중성미자 실험 (하창현)	가속기 실험 (고정환)	
18:00 - 20:00	저녁식사			
20:00 - 21:30	양자장론+표준모형3 (서민석)	실습(양자장론)	실습(가속기)	

Experimental Particle Physics: TL;DR



Create new particles



Take Pictures



Find something (un)expected

Experimental Particle Physics: TL;DR



Create new particles

Cosmic Ray
Radioactive materials
Particle accelerators



Take Pictures

Detectors
Data Analysis



Find something (un)expected

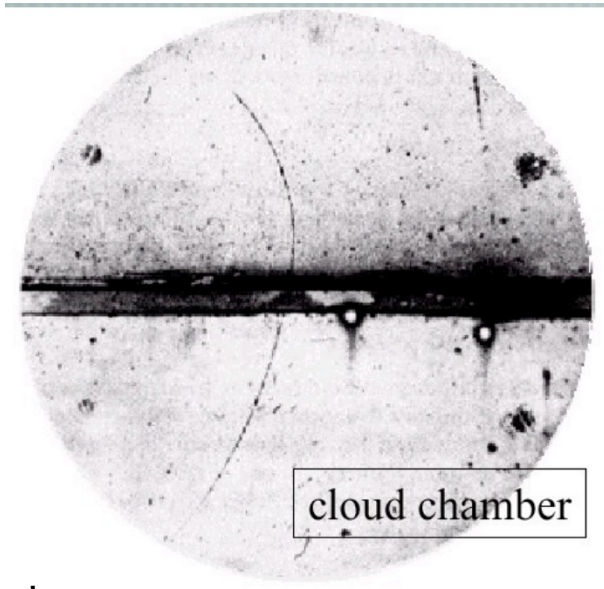
Theory
Interpretations
Statistics

Example: Positron



Theoretical prediction of
anti-particles – relativistic QM

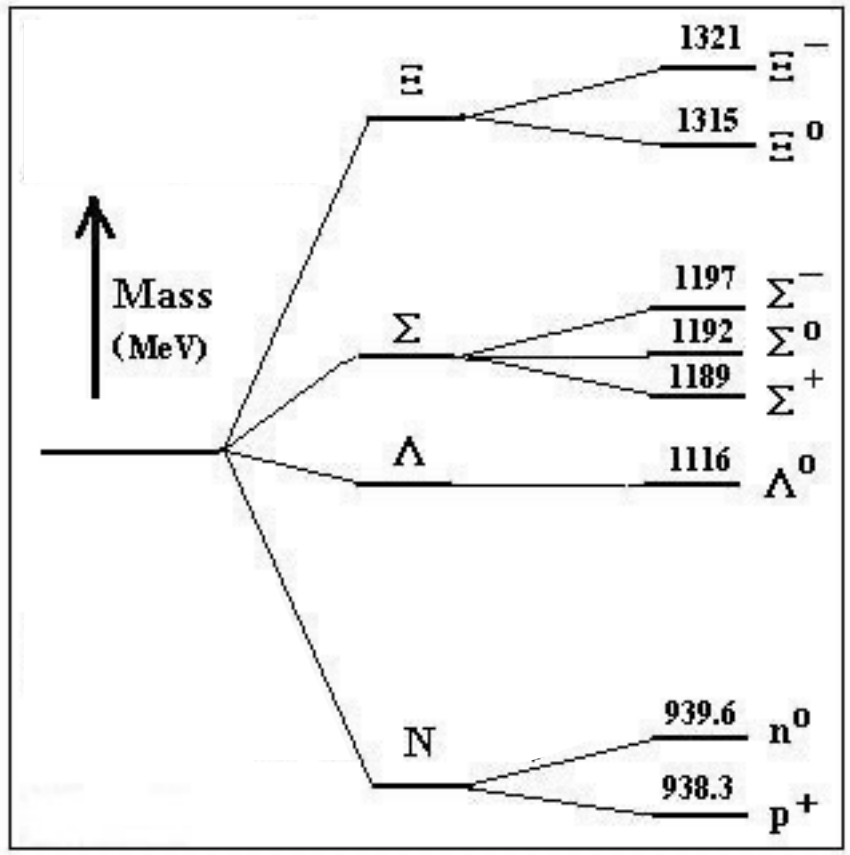
$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$





Experimental confirmation
a particle trajectory in the cloud chamber
with the same physical properties with opposite charge

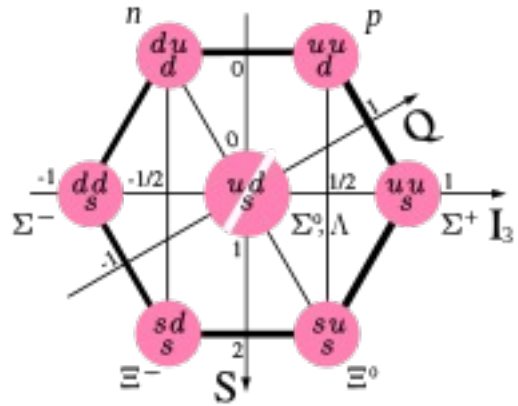
Another Example: Quark Model

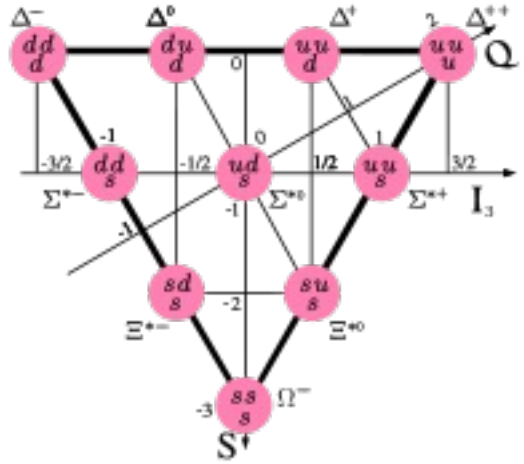


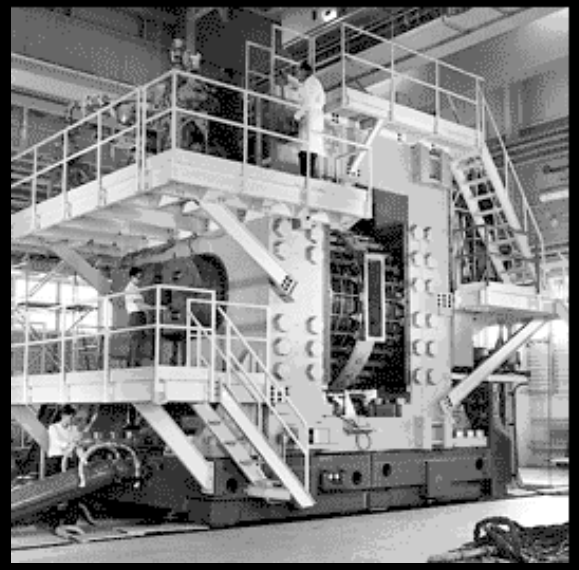
https://universe-review.ca/R15-10-groups05.htm

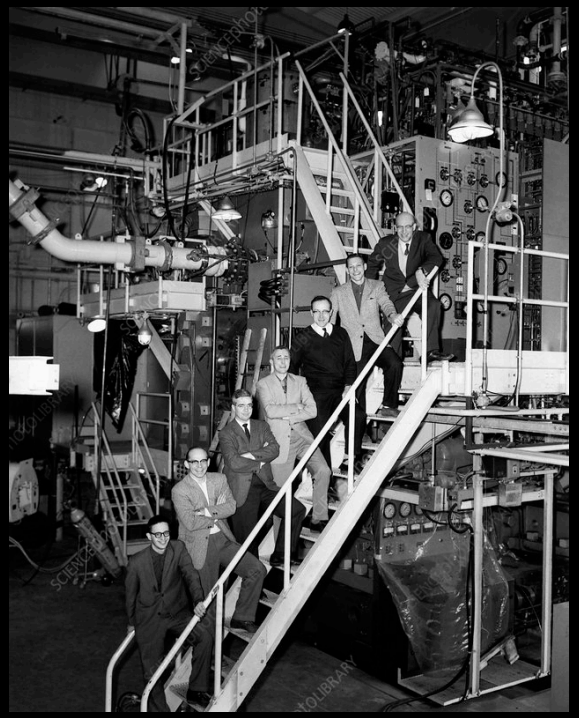
$q_i q_j q_k$	$J = 1/2$	$J = 3/2$
$\|uuu\rangle$		$\Delta^{++}(1230)$
$\|uud\rangle$	$p(938)$	$\Delta^{+}(1231)$
$\|udd\rangle$	$n(940)$	$\Delta^{0}(1232)$
$\|ddd\rangle$		$\Delta^{-}(1234)$
$\|uus\rangle$	$\Sigma^{+}(1189)$	$\Sigma^{+}(1383)$
$2^{-1/2}\|(ud+du)s\rangle$	$\Sigma^{0}(1192)$	$\Sigma^{0}(1384)$
$\|dds\rangle$	$\Sigma^{-}(1197)$	$\Sigma^{-}(1387)$
$2^{-1/2}\|(ud-du)s\rangle$	$\Lambda(1116)$	
$\|uss\rangle$	$\Xi^{0}(1315)$	$\Xi^{0}(1532)$
$\|dss\rangle$	$\Xi^{-}(1321)$	$\Xi^{-}(1535)$
$\|sss\rangle$		$\Omega^{-}(1672)$

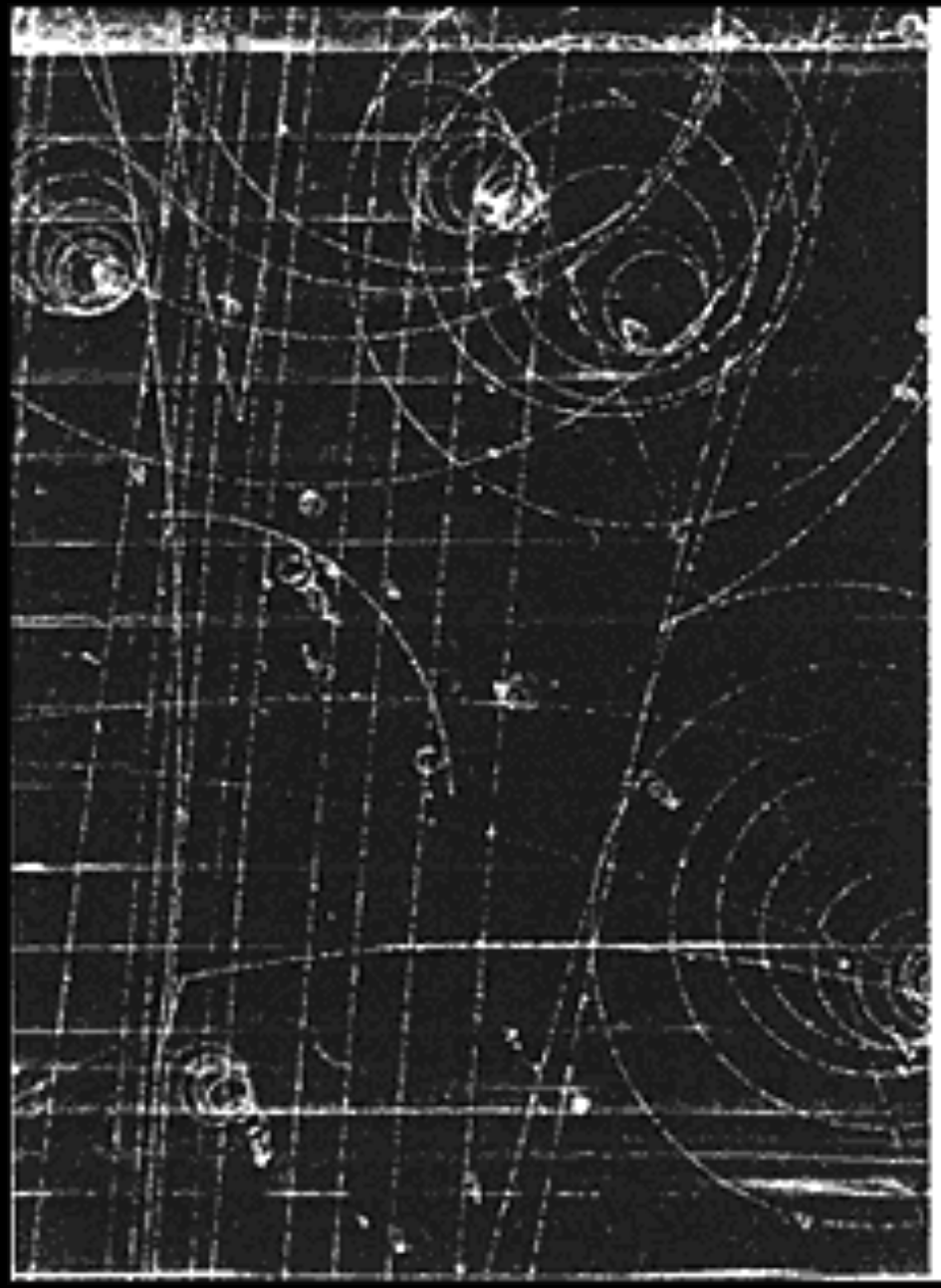
https://en.wikipedia.org/wiki/Baryon

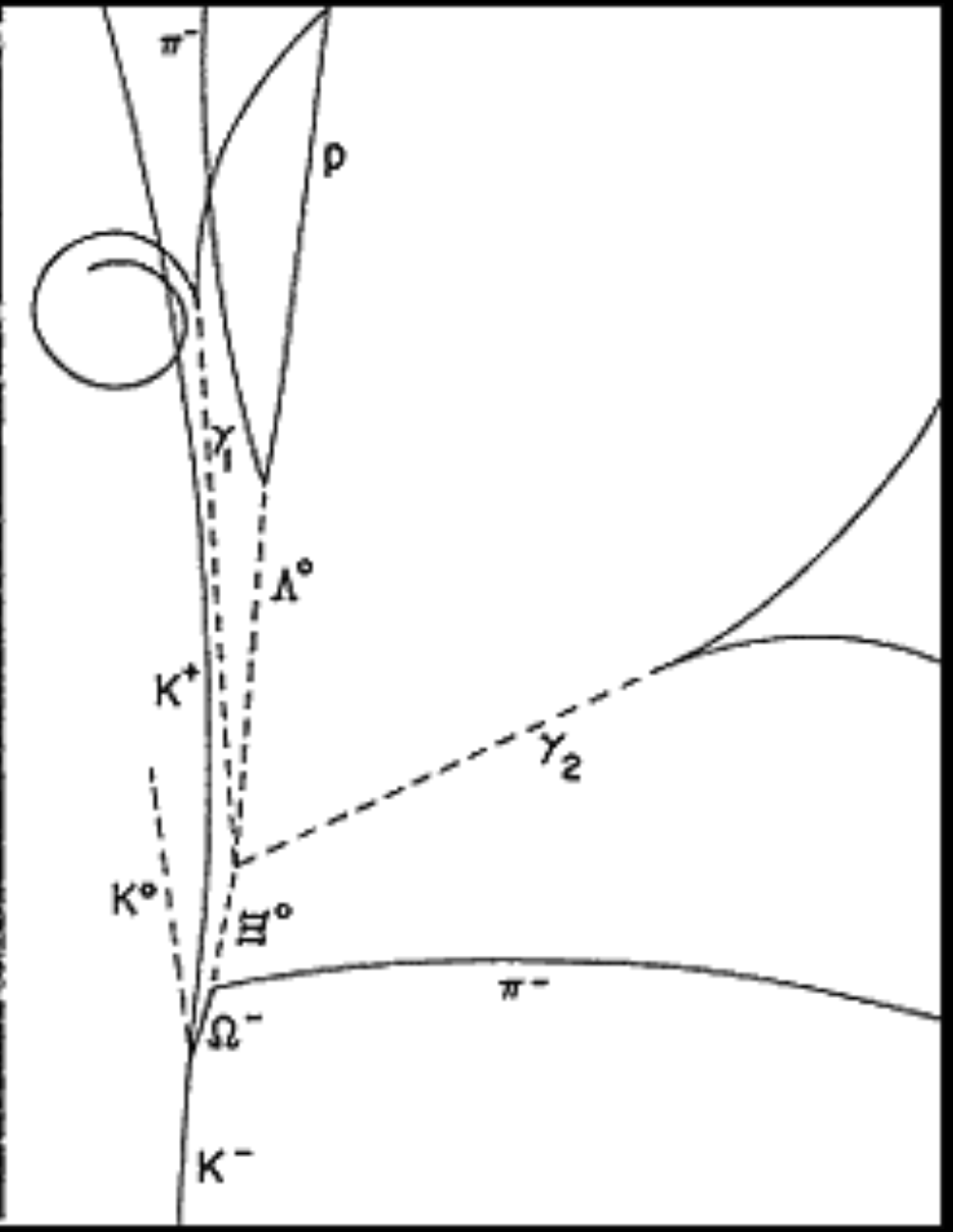


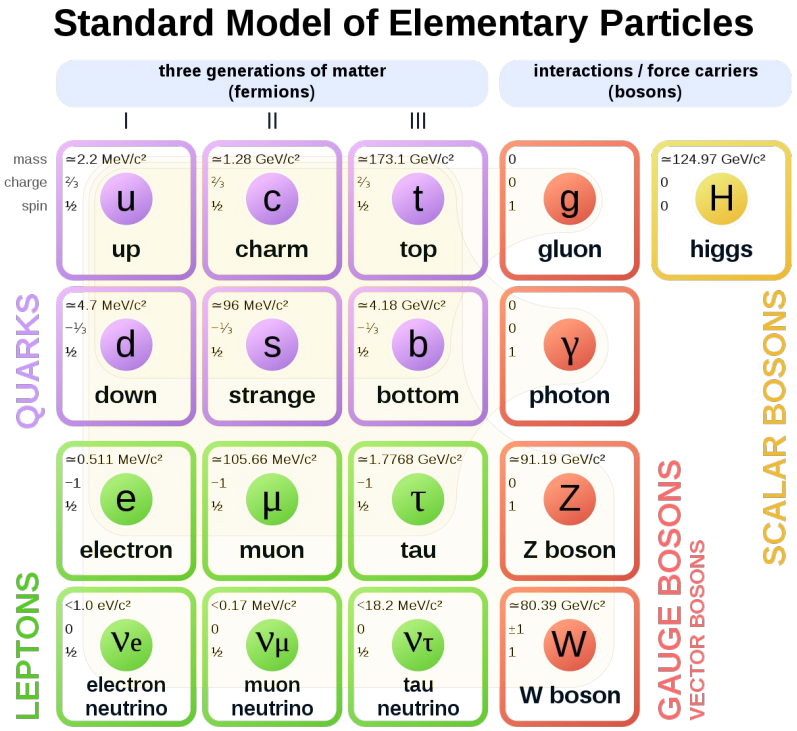


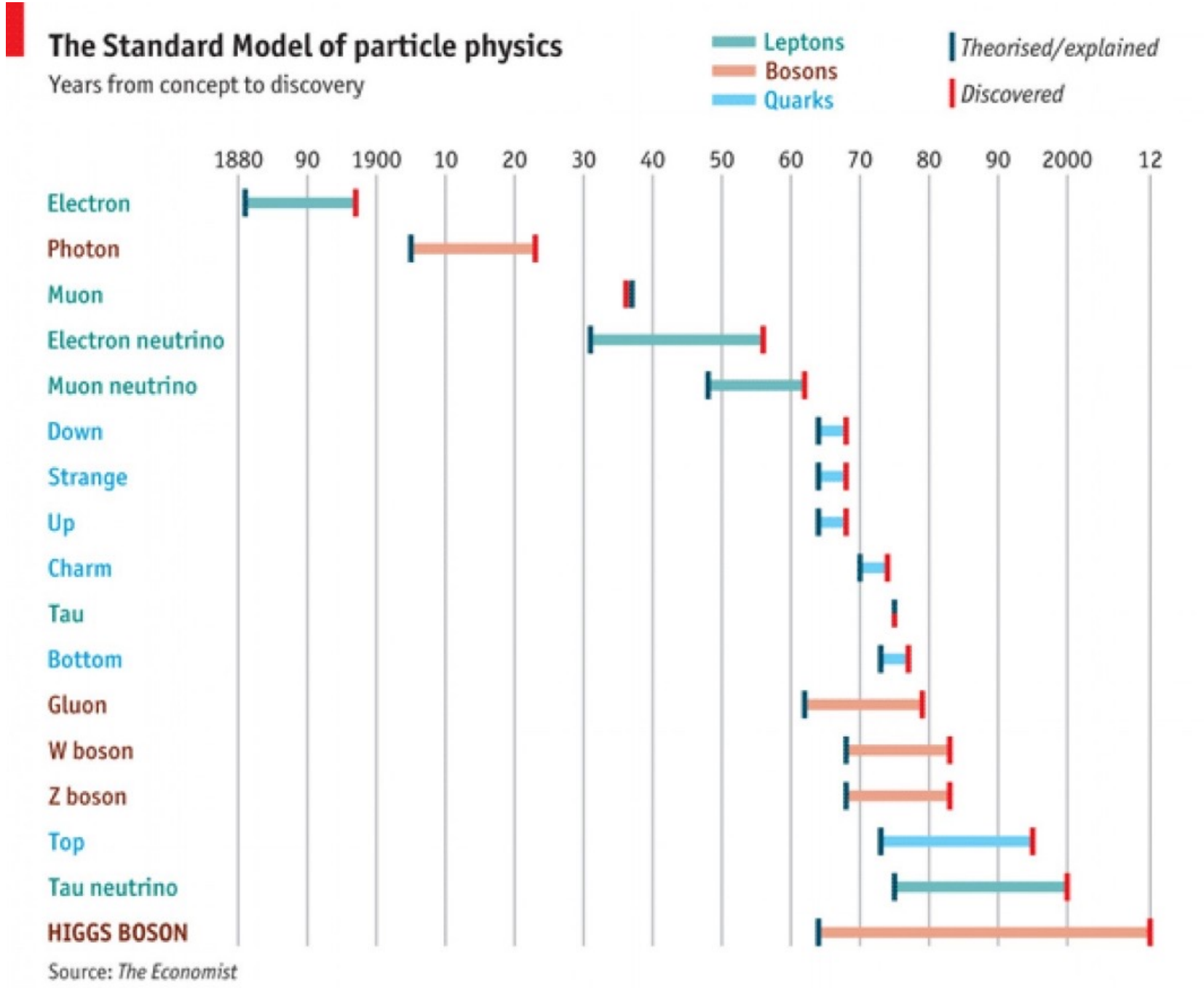







π⁻
ρ
γ₁
Λ°
K⁺
γ₂
K°
Ξ°
π⁻
Ω⁻
K⁻


Standard Model of Elementary Particles
three generations of matter (fermions)
interactions / force carriers (bosons)
I
II
III
mass
charge
spin
≃2.2 MeV/c²
⅔
½
u
up
≃1.28 GeV/c²
⅔
½
c
charm
≃173.1 GeV/c²
⅔
½
t
top
0
0
1
g
gluon
≃124.97 GeV/c²
0
0
H
higgs
QUARKS
≃4.7 MeV/c²
−⅓
½
d
down
≃96 MeV/c²
−⅓
½
s
strange
≃4.18 GeV/c²
−⅓
½
b
bottom
0
0
1
γ
photon
SCALAR BOSONS
≃0.511 MeV/c²
−1
½
e
electron
≃105.66 MeV/c²
−1
½
μ
muon
≃1.7768 GeV/c²
−1
½
τ
tau
≃91.19 GeV/c²
0
1
Z
Z boson
GAUGE BOSONS
VECTOR BOSONS
LEPTONS
<1.0 eV/c²
0
½
νe
electron neutrino
<0.17 MeV/c²
0
½
νμ
muon neutrino
<18.2 MeV/c²
0
½
ντ
tau neutrino
≃80.39 GeV/c²
±1
1
W
W boson


The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880
90
1900
10
20
30
40
50
60
70
80
90
2000
12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON
Source: The Economist

Experimental Particle Physics: TL;DR



Create new particles



Take Pictures

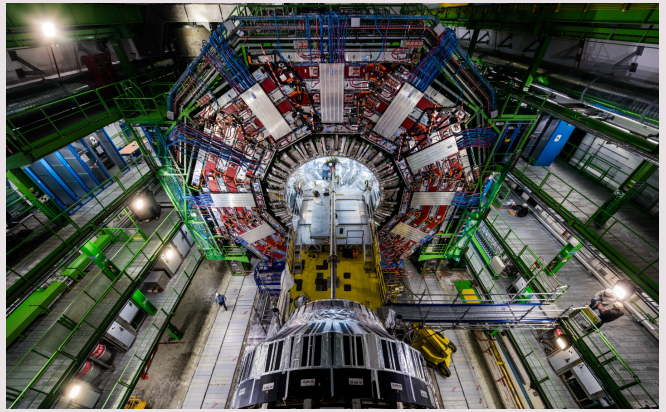


Find something (un)expected

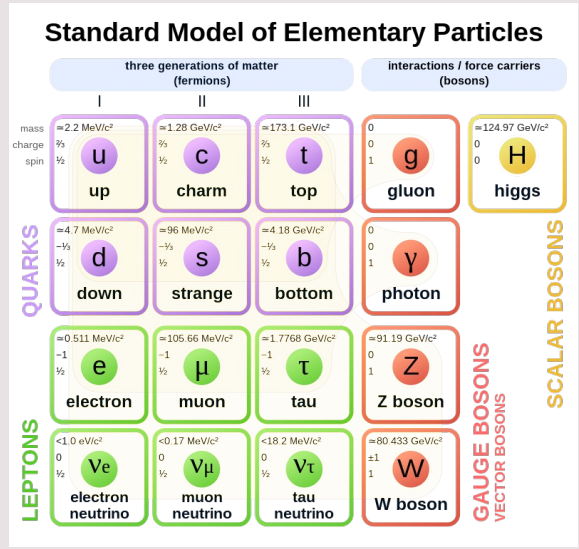
Experimental Particle Physics: TL;DR



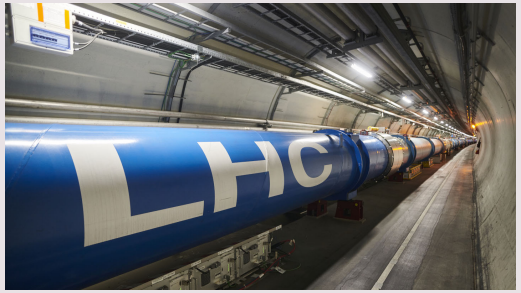
Create new particles

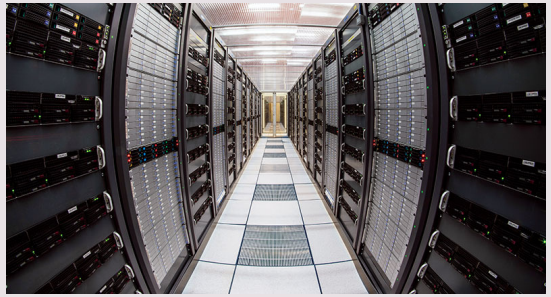


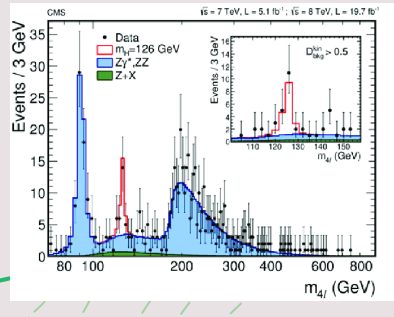
Take Pictures



Find something (un)expected







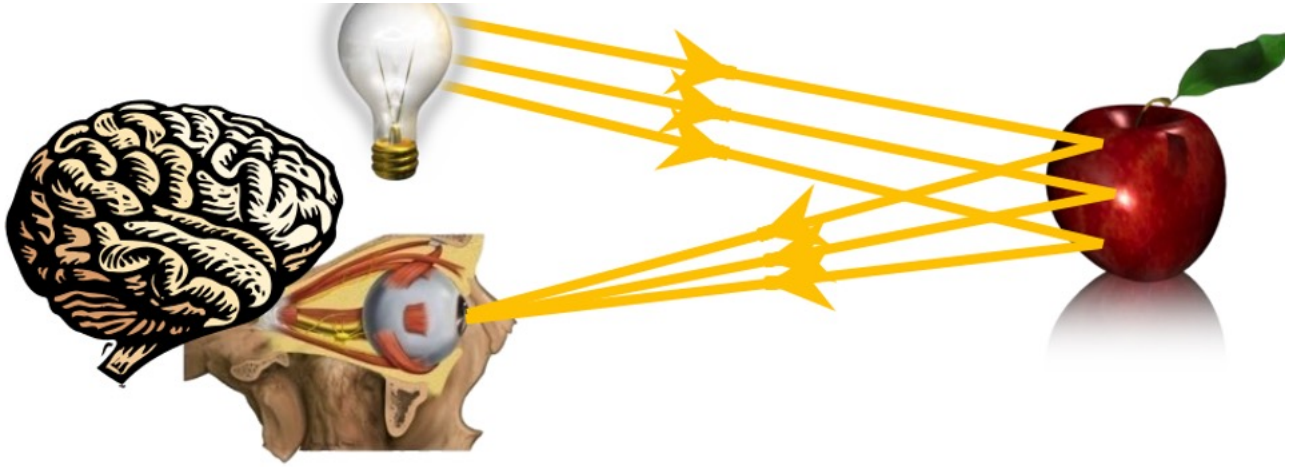
Goal of this afternoon-evening

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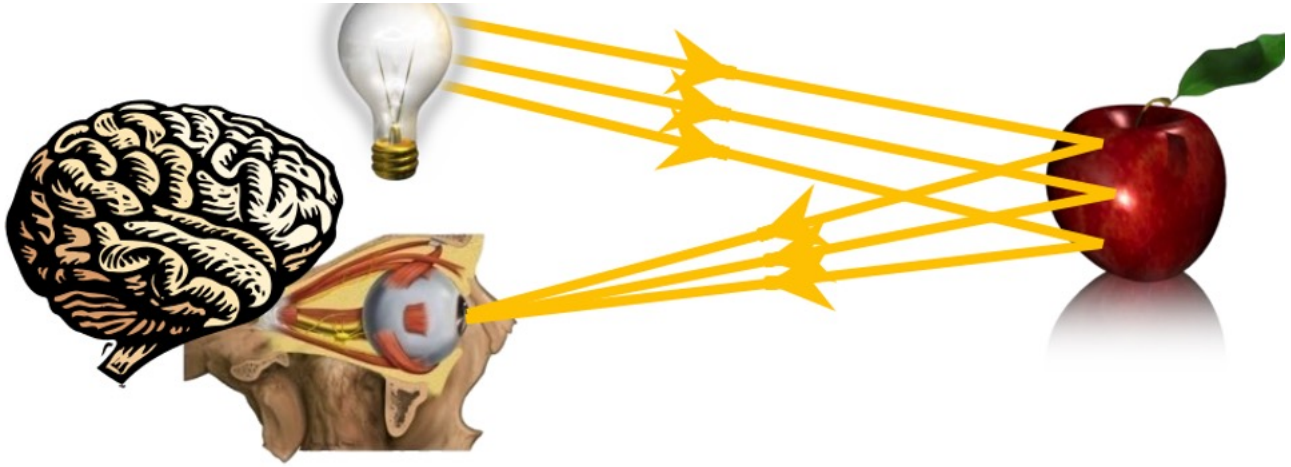
- Minimal introduction of Collider Physics
- *Brief idea* how to do a MC simulation
- Analyze *some* REAL DATA from LHC

Disclaimer: I cannot cover everything …

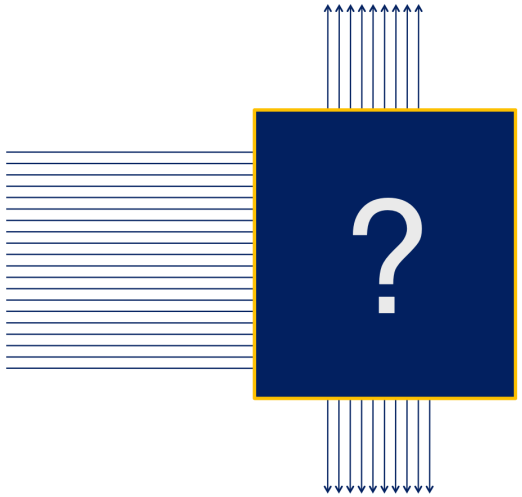
Probing objects

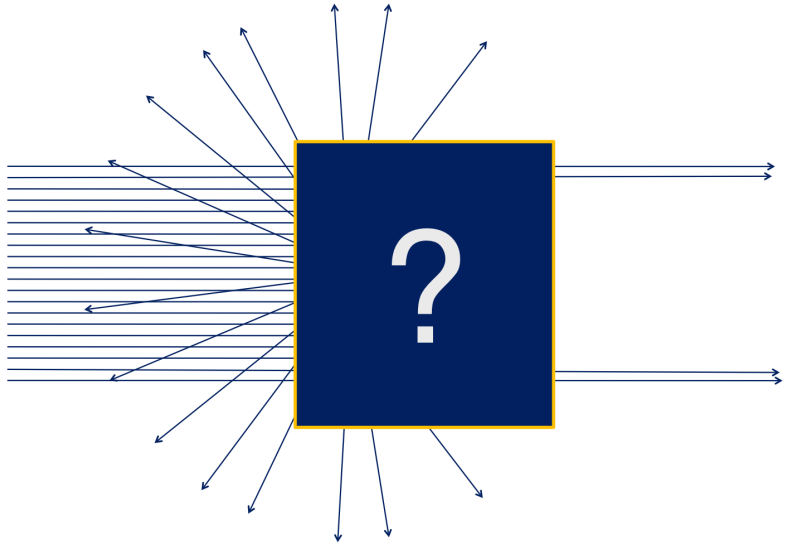


Probing objects

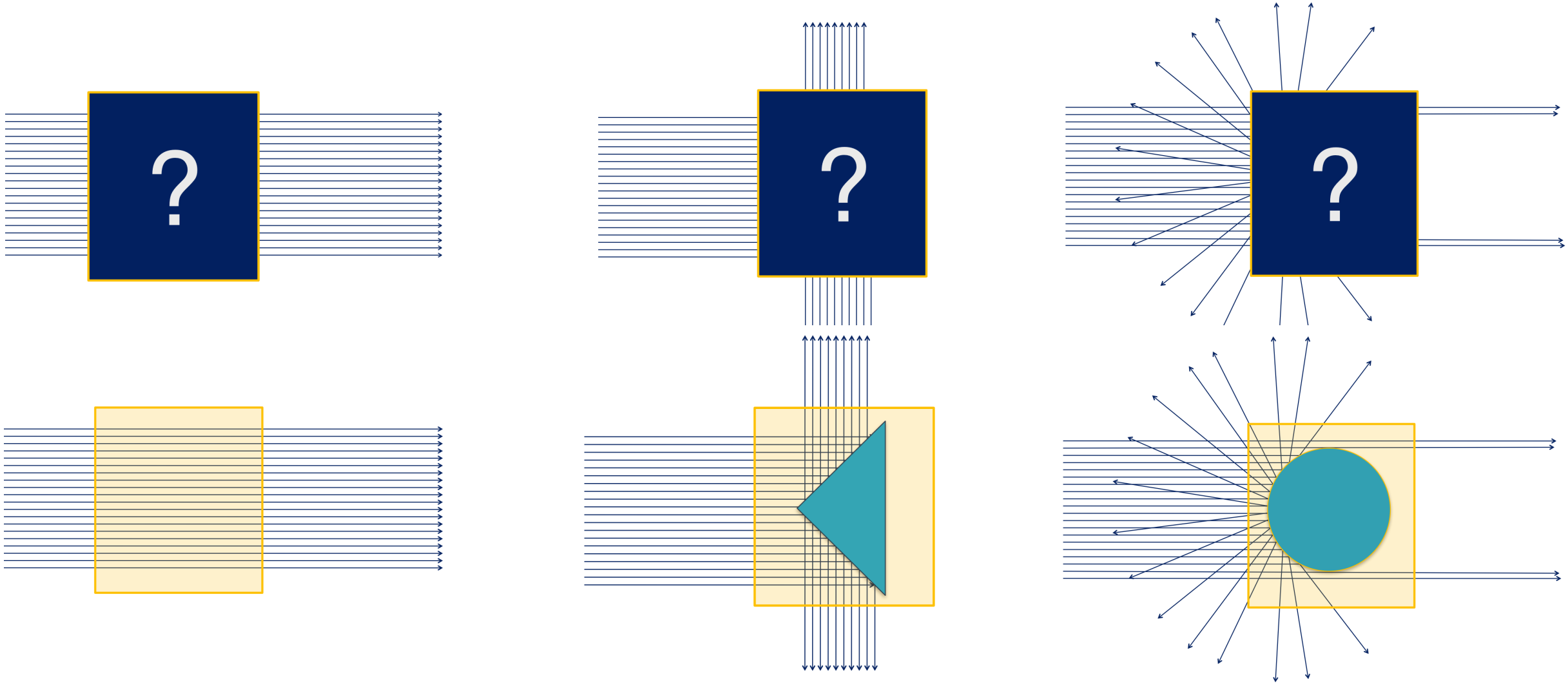




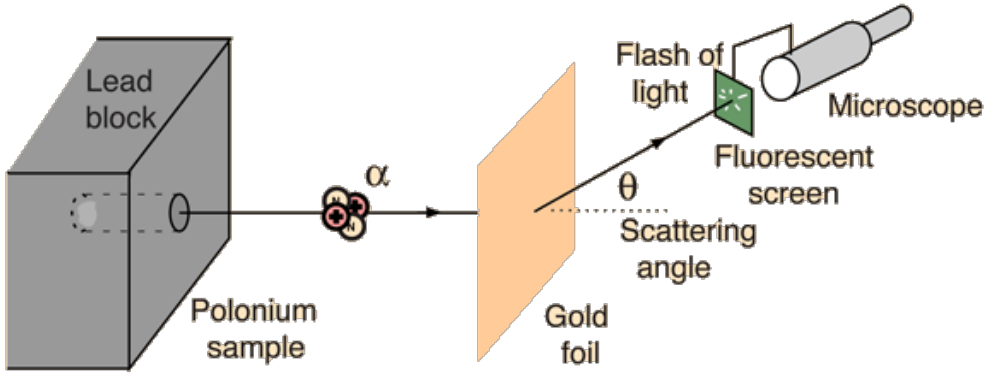


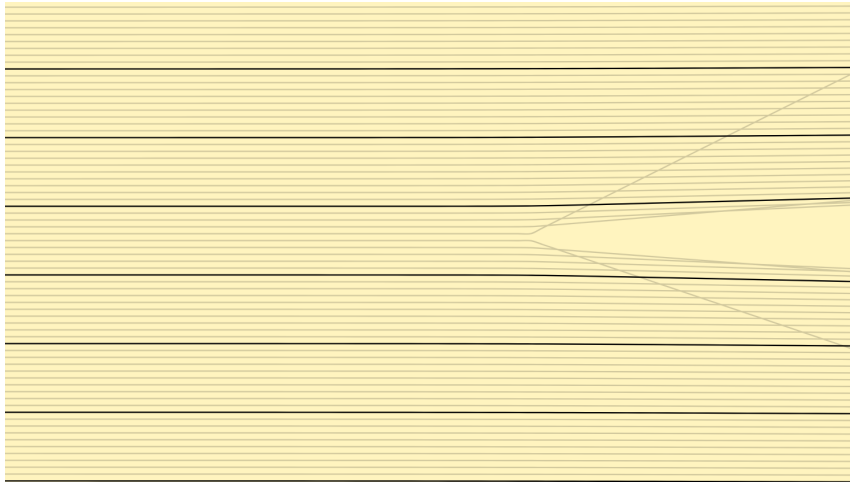


Probing objects



Probing objects smaller than atom…





$$N(\theta) = \frac{N_i n L Z^2 k^2 e^4}{4r^2 K E^2 \sin^4(\theta/2)}$$

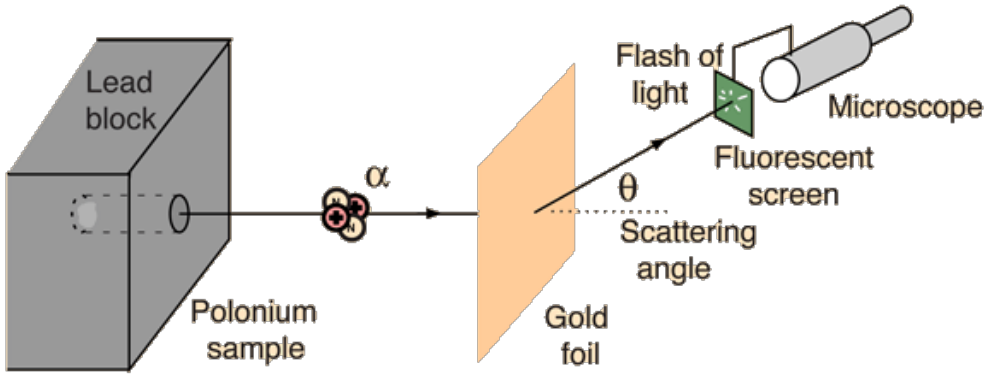
N_i = *number of incident alpha particles*
n = *atoms per unit volume in target*
L = *thickness of target*
Z = *atomic number of target*
e = *electron charge*
k = *Coulomb's constant*
r = *target-to-detector distance*
KE = *kinetic energy of alpha*
θ = *scattering angle*

Count number of flash of light on the screen

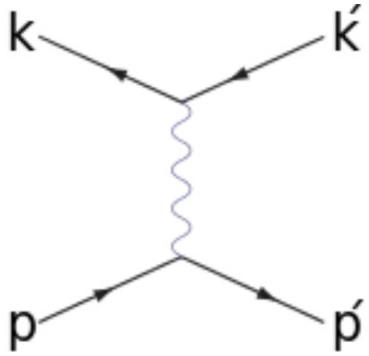
= Number of alpha particles as a function of …

= Differential cross sections

Probing objects smaller than atom…

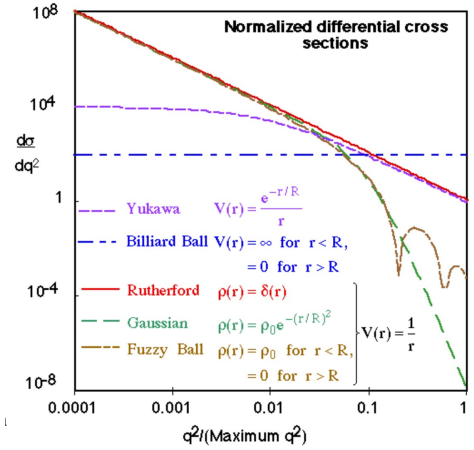


$$N(\theta) = \frac{N_i n L Z^2 k^2 e^4}{4r^2 K E^2 \sin^4(\theta/2)}$$

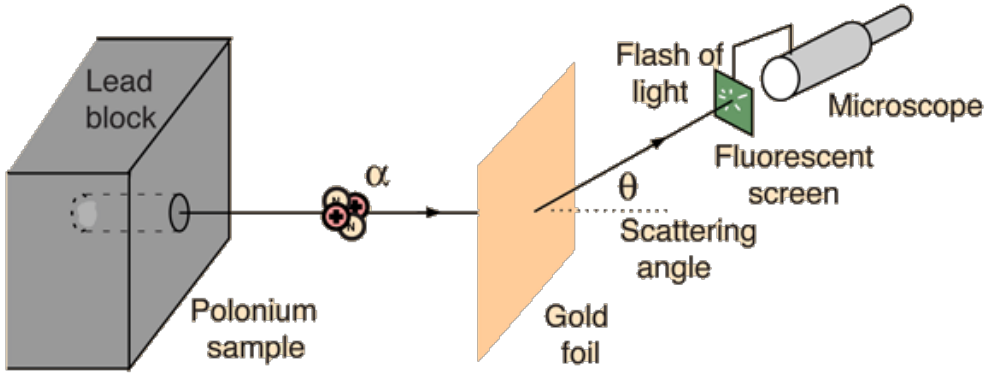


$$\sigma = \frac{S\hbar}{4\sqrt{(p_1 \cdot p_2)^2 - (m_1 m_2 c^2)^2}} \int |\mathcal{M}|^2 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - \ldots p_n) \times \prod_{j=3}^{n} \frac{1}{2\sqrt{\vec{p}_j^{\,2} + m^2 c^2}} \frac{d^3\vec{p}_j}{(2\pi)^3}$$

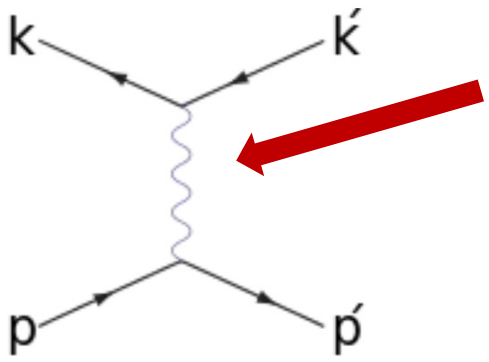
$$\mathcal{M}_1 = -\frac{g_e^2}{(p-p')^2} [\bar{u}(p')\gamma^\mu u(p)][\bar{v}(k')\gamma_\mu v(k)]$$



Probing objects smaller than atom…

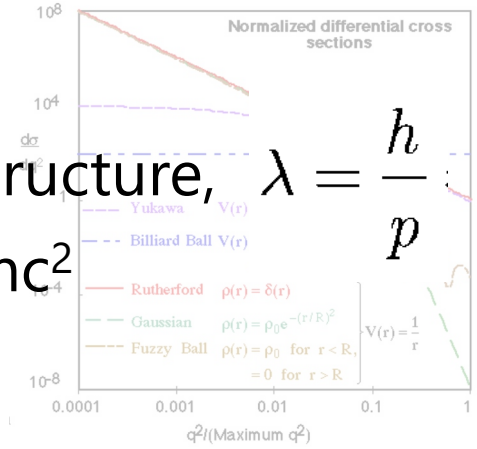


$$N(\theta) = \frac{N_i n L Z^2 k^2 e^4}{4r^2 K E^2 \sin^4(\theta/2)}$$

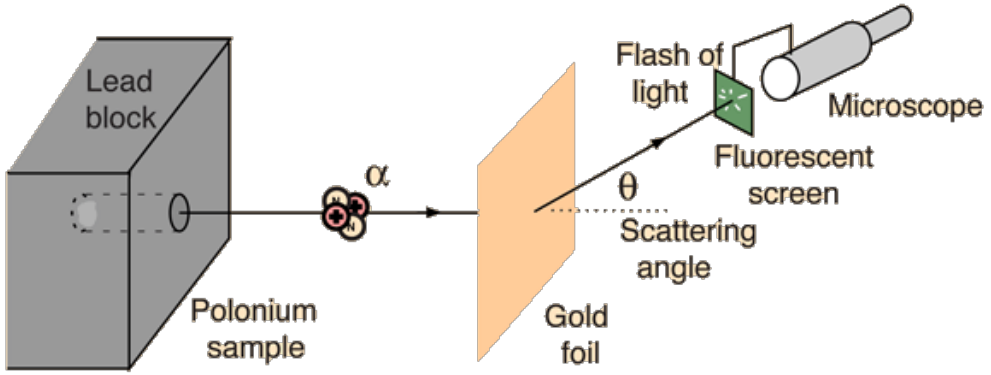


At Higher Energies:

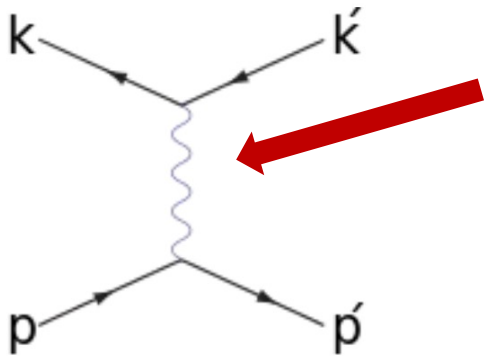
- Inelastic scattering, atomic / proton structure, $\lambda = \frac{h}{p}$
- Diagrams involving new particles, $E=mc^2$



Probing objects smaller than atom…



$$N(\theta) = \frac{N_i n L Z^2 k^2 e^4}{4r^2 K E^2 \sin^4(\theta/2)}$$



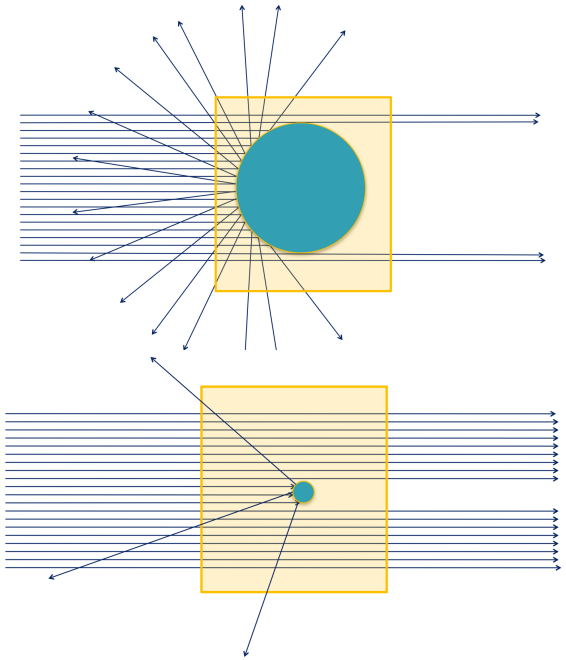
At Higher Energies:

- Inelastic scattering, atomic / proton structure, $\lambda = \frac{h}{p}$
- Diagrams involving new particles, $E=mc^2$

$$\mathcal{M}_1 = \ ? \quad \text{then} \quad \sigma = \ ?$$

Your theoretical model Phase space integration

Cross section & Luminosity



Recall Lessons from the Classical Mechanics textbook:

- Total cross section = πr^2, Area of the billiard ball
- Unit in Area, cm^2, At nucleus scale, ~100 fm^2 = 1 barn
- In Natural Unit system, $1GeV^{-2}$ = 0.3864 mb

In experiment:

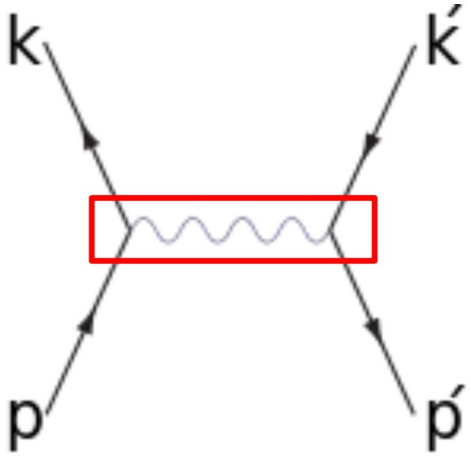
- Throw uniform particle beam along the z-axis,
  count number of particles with deflected path
- How many particles are thrown? = (integrated) Luminosity
  $N = \sigma \times \mathcal{L} \rightarrow \mathcal{L} = N/\sigma$ (inverse barn or fb^{-1}, pb^{-1}, etc)
- How many particles per unit time? = Instantaneous luminosity

In computer simulation:

-> Throw two uniform random numbers (x, y),
count number of entries with $x^2 + y^2 < r^2$

-> If the interaction has complicated dependency on KE…

Fixed target vs collider



$$m^2c^4 = q_\mu q^\mu = (E_k + E_p)^2 - (\vec{p}_k + \vec{p}_p)^2$$
$$= E_k^2 + E_p^2 + 2E_kE_p - k^2 - p^2 - 2\vec{k}\cdot\vec{p}$$
$$= m_k^2c^4 + m_p^2c^4 + 2(E_kE_p - p_kp_p\cos\theta)$$

Fixed target



$E_p = m_p$
$p_p = 0$

$$M^2 = m_k^2 + m_p^2 + 2m_pE_k \approx 2m_pE_k$$

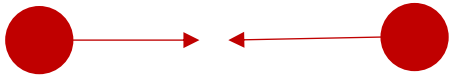
$$M \approx \sqrt{2mE}$$

Same physics, different observer



Different Beam Energy to produce same particle

Collider



$p_k = p_p$
$\cos\theta = -1$

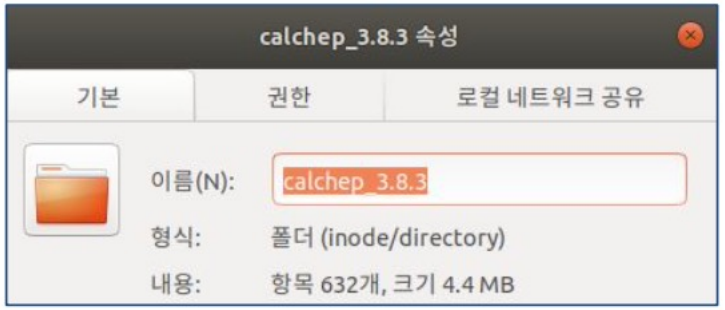
$$M^2 = m_k^2 + m_p^2 + 2(E_k\,E_p + p_k\,p_p) = (E_k + E_p)^2$$

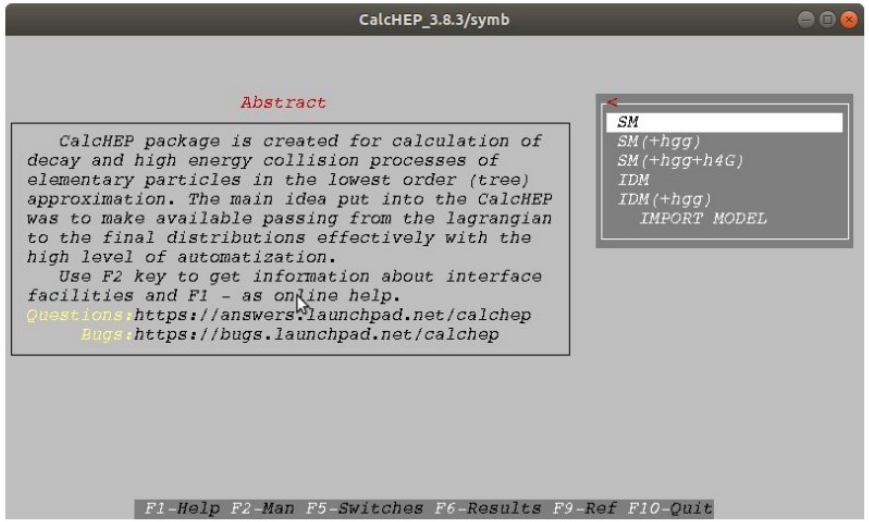
$$M = 2E$$

Exercise: Cross-section on your computer

CalcHEP (A. Pukhov et al):
http://theory.npi.msu.su/~pukhov/calchep.html

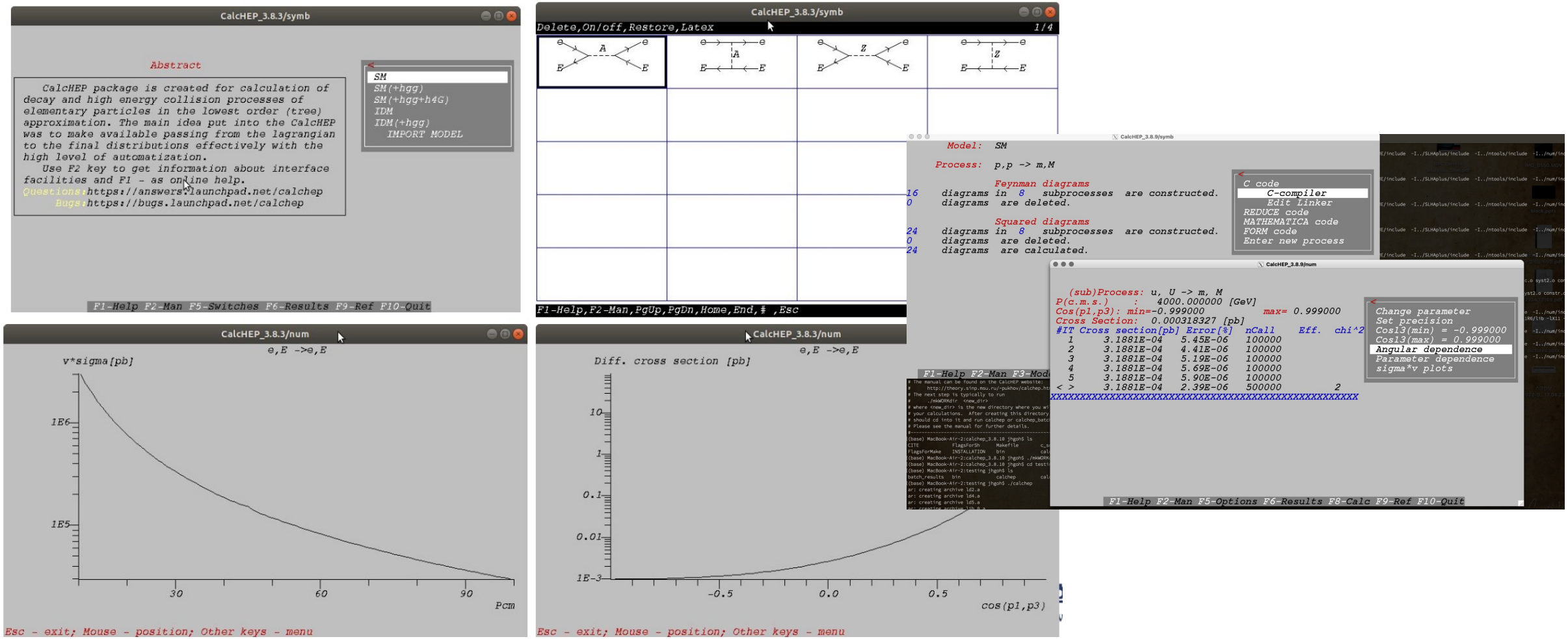






https://theory.sinp.msu.ru/~pukhov/CALCHEP/calchep_3.8.10.tgz

Demo: CalcHep



Producing particle beam

Recall the General Phys Electromagnetism:

☆ 전위차 (= 전압) :
전기장 안에서 두 지점의 전위의 차이

⇒ 균일한 전기장 안에서 전기력이 하는 일

$$W = Fd = qEd$$

⇒ 균일한 전기장 안에서 전위차와 전기장의 관계

$$V = V_A - V_B = \frac{W}{q} = Ed$$

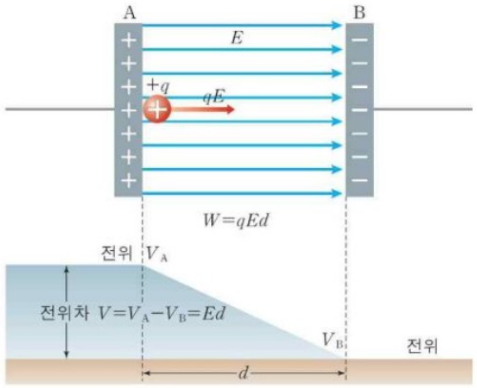


Image taken from highschool textbook

Producing particle beam

Recall the General Phys Electromagnetism:

☆ 전위차 (= 전압) :

전기장 안에서 두 지점의 전위의 차이

⇒ 균일한 전기장 안에서 전기력이 하는 일

$$W = Fd = qEd$$

⇒ 균일한 전기장 안에서 전위차와 전기장의 관계

$$V = V_A - V_B = \frac{W}{q} = Ed$$

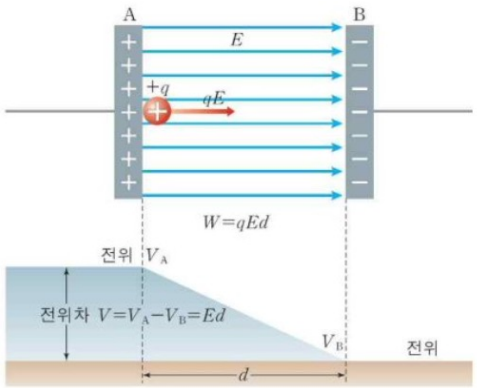
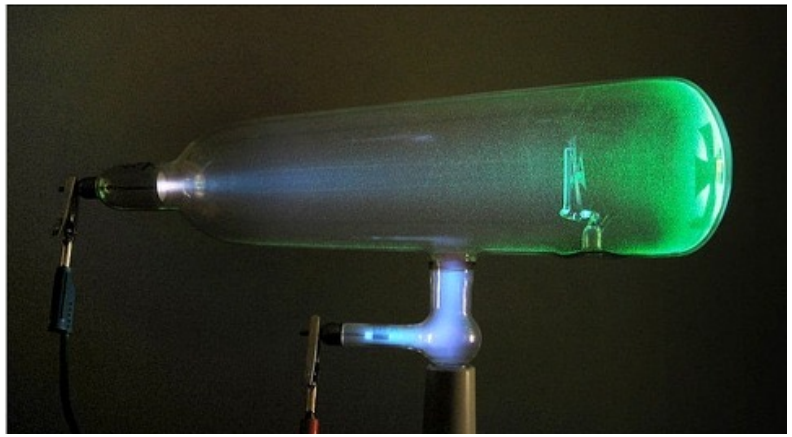


Image taken from highschool textbook





Producing particle beam

Recall the General Phys Electromagnetism:

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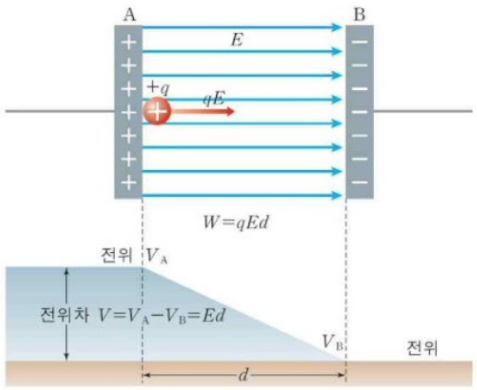
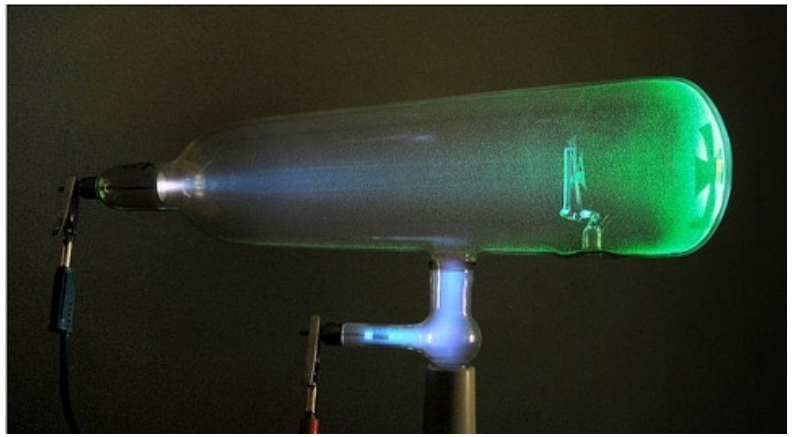
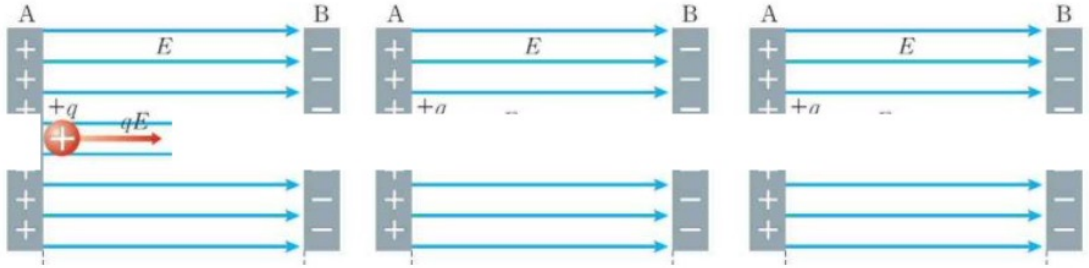


Image taken from highshoool textbook









Producing particle beam

Recall the General Phys Electromagnetism:

☆ 전위차 (= 전압) :
전기장 안에서 두 지점의 전위의 차이

⇒ 균일한 전기장 안에서 전기력이 하는 일

$$W = Fd = qEd$$

⇒ 균일한 전기장 안에서 전위차와 전기장의 관계

$$V = V_A - V_B = \frac{W}{q} = Ed$$

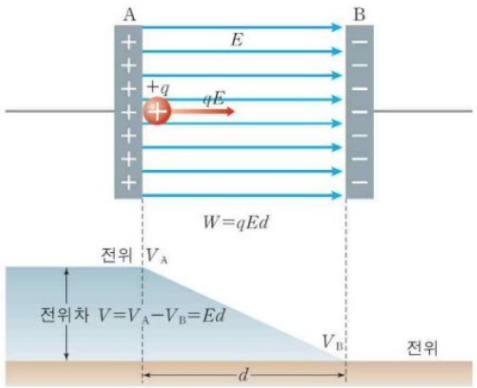
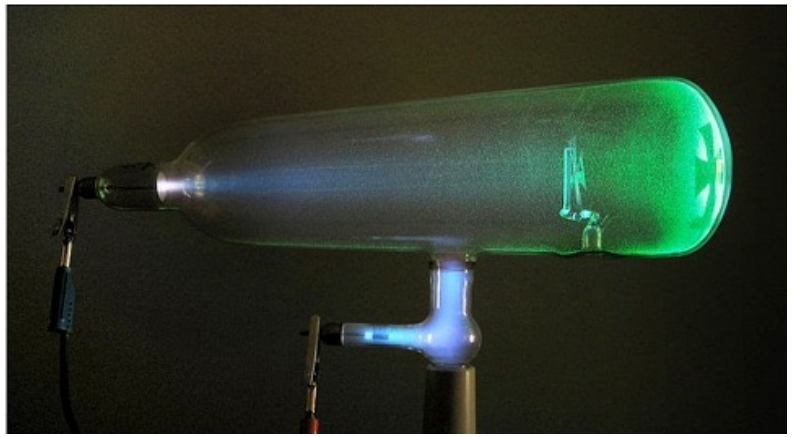
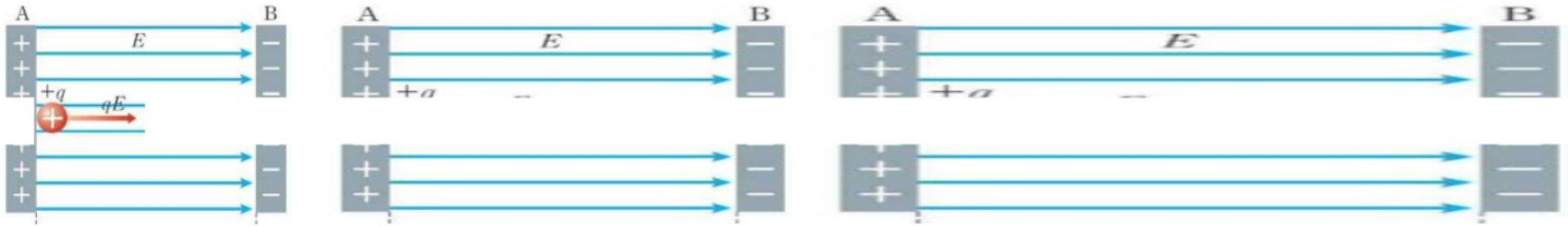


Image taken from highschool textbook

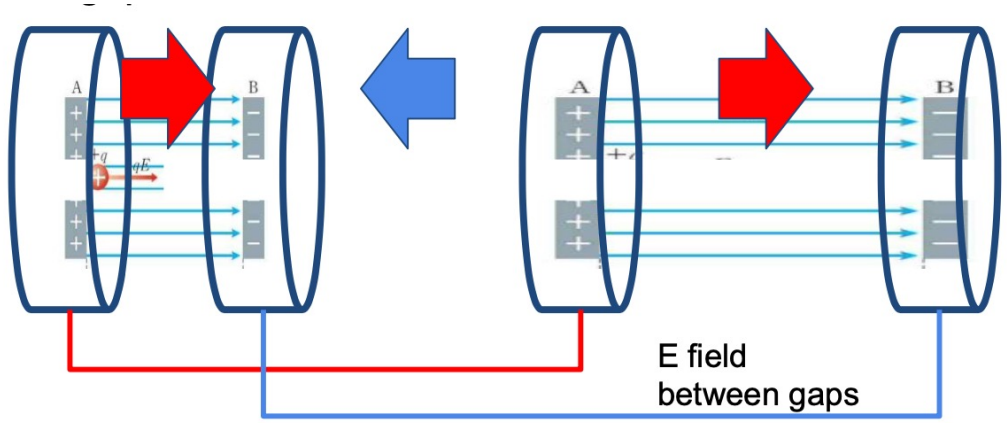


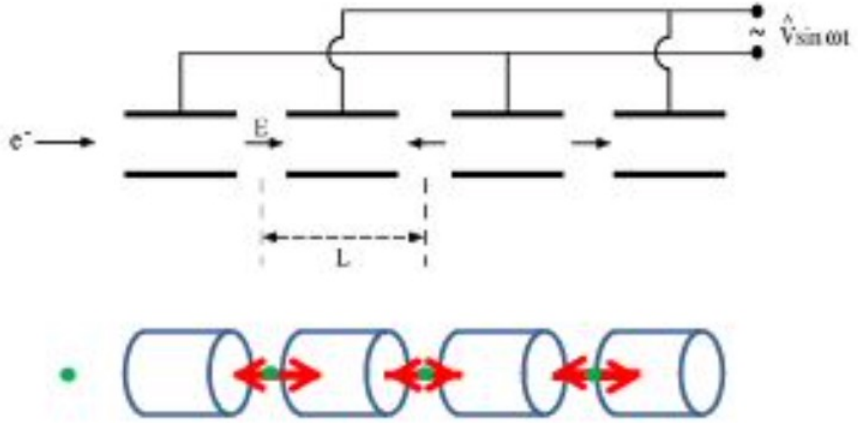




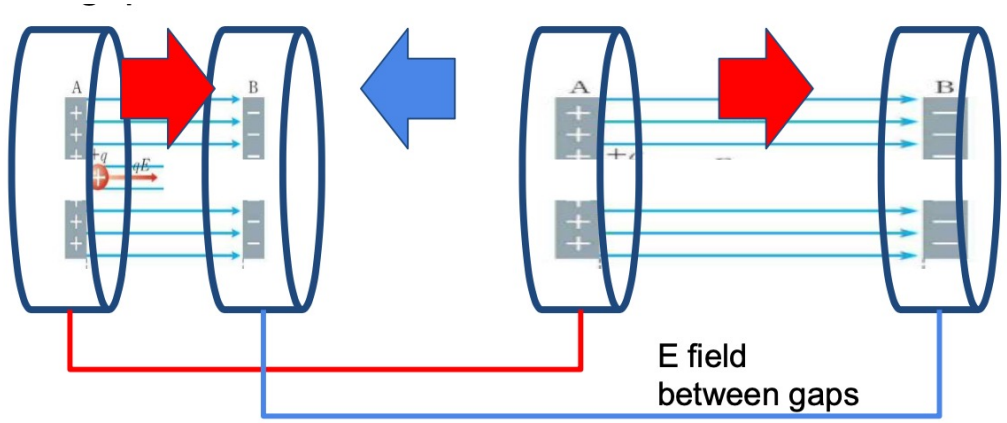


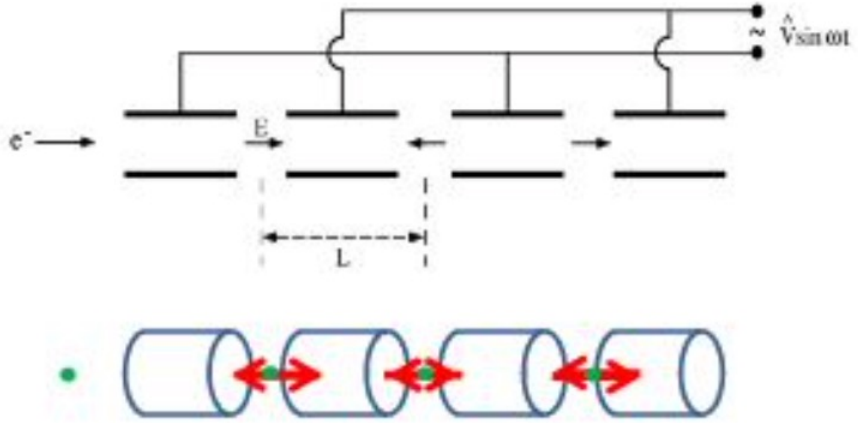
Producing particle beam

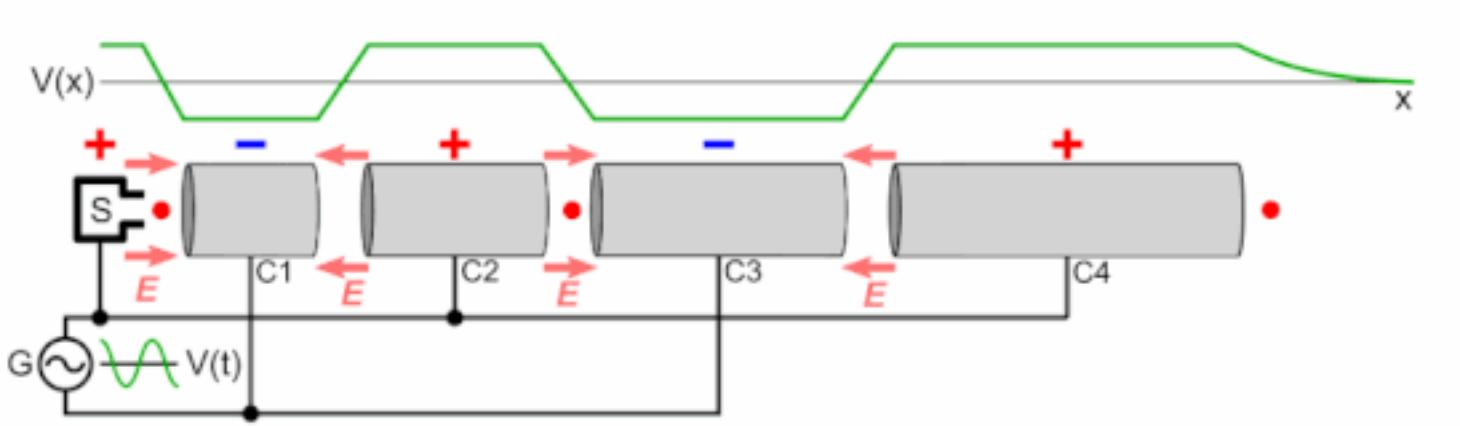




Producing particle beam



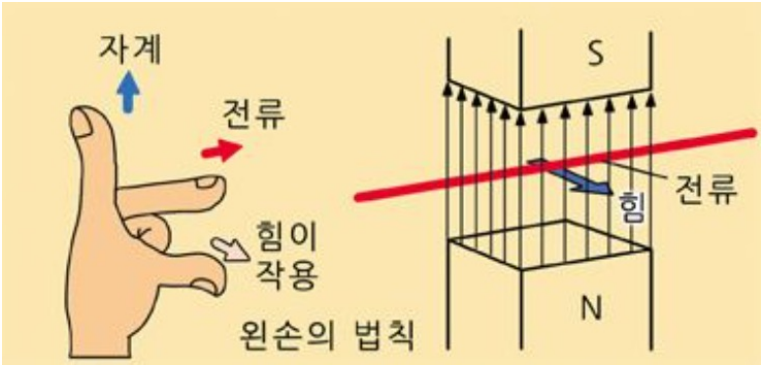




High E field & higher rate
-> Waveguide, RF cavity in EM

Beam Energy ~ Size

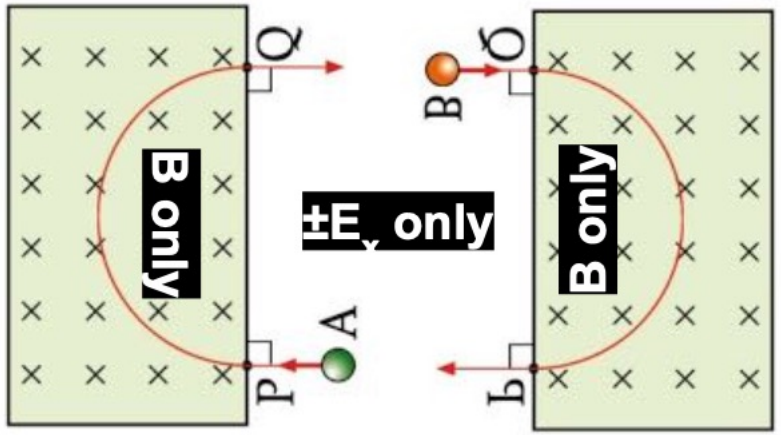
Circular Accelerator



Again, from Highschool textbooks & Gen. Phys textbooks:

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$$\rightarrow \frac{mv^2}{R} = qvB \rightarrow R = \frac{mv}{qB}$$





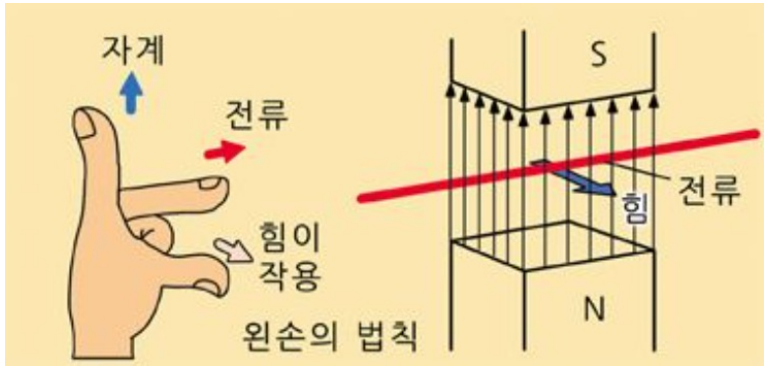
E. Lawrence, 27in Cyclotron

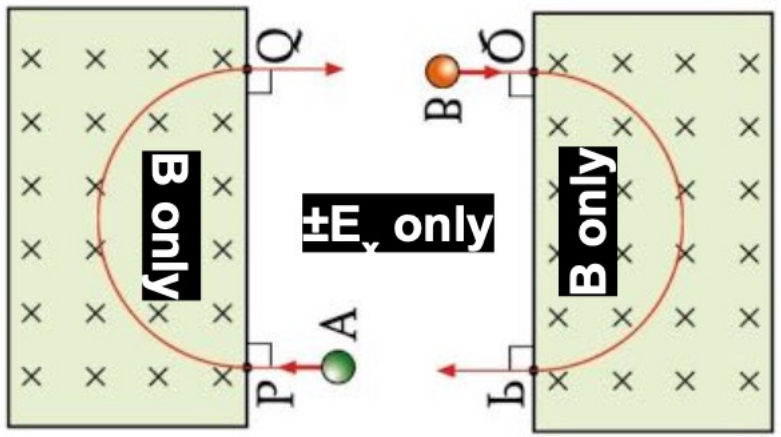
$$f = \frac{v}{2\pi R} = \frac{qB}{2\pi m}$$

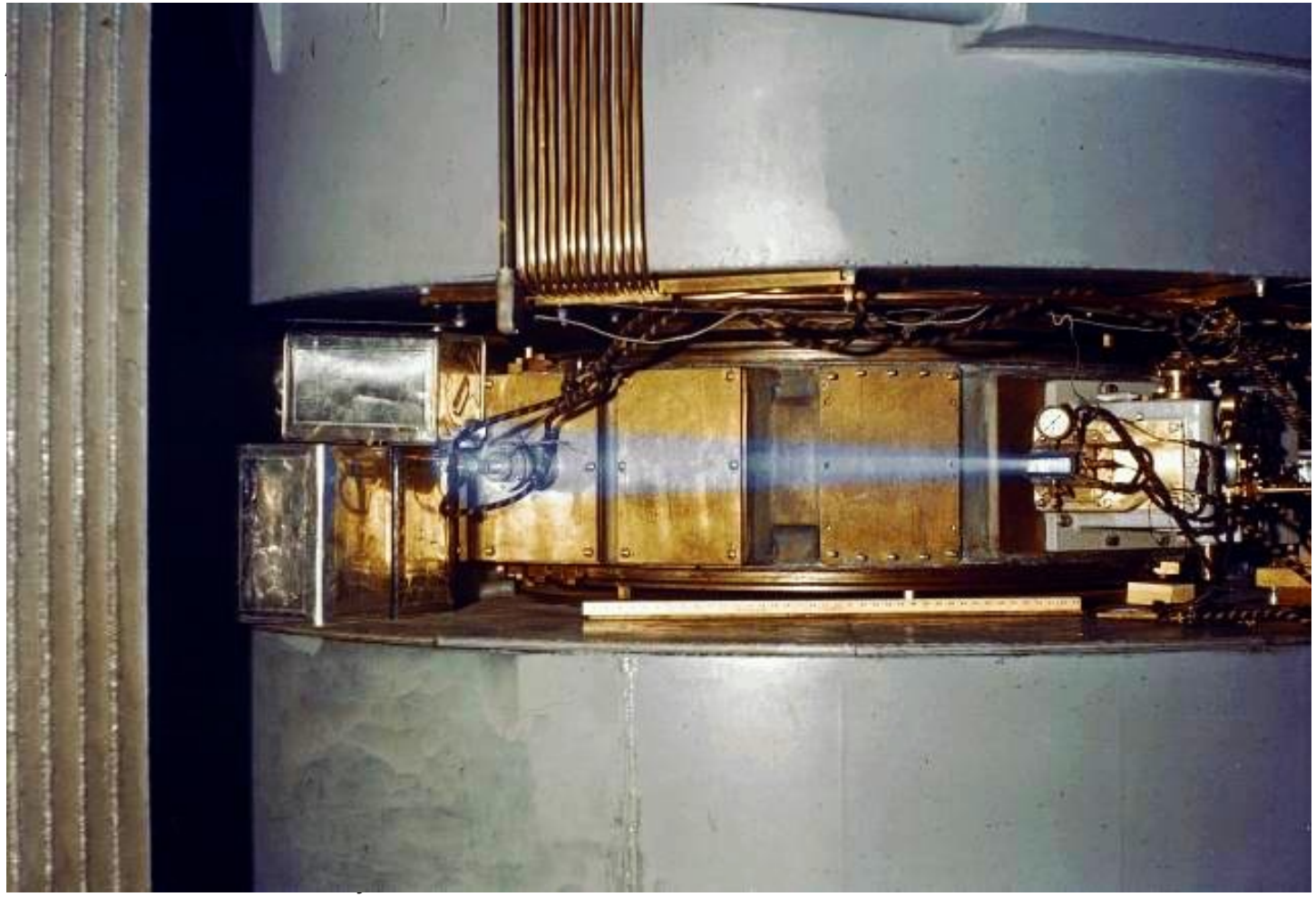
Limitation:

- Heavy!
- Breaks with relativistic effect

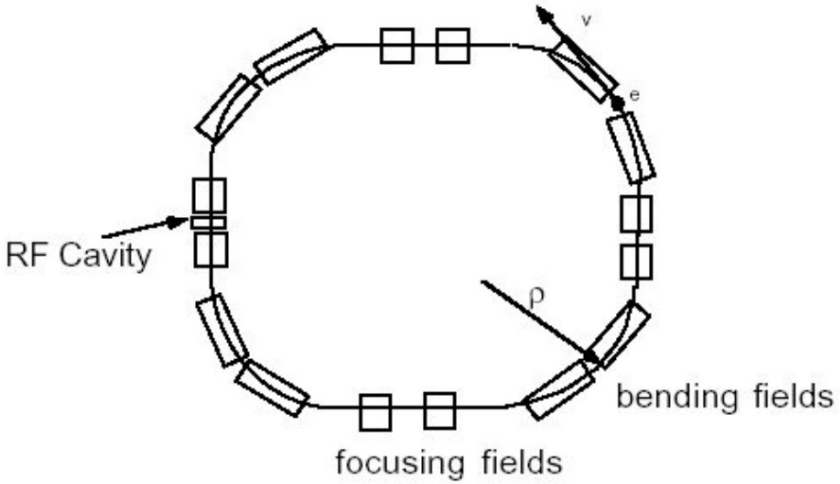
Circular Accelerator







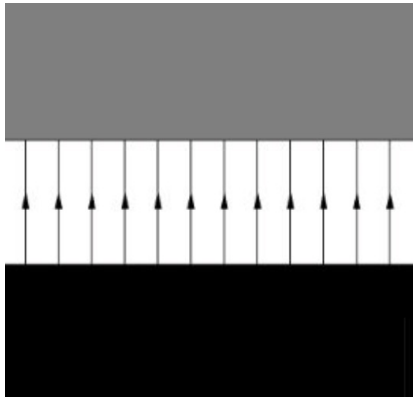
Synchrotron

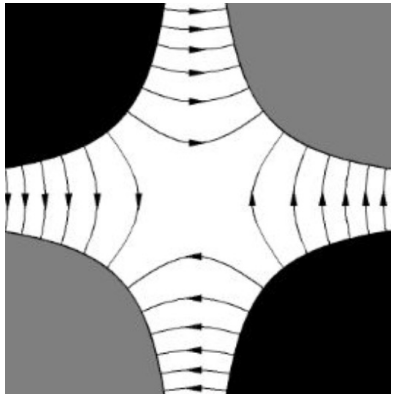


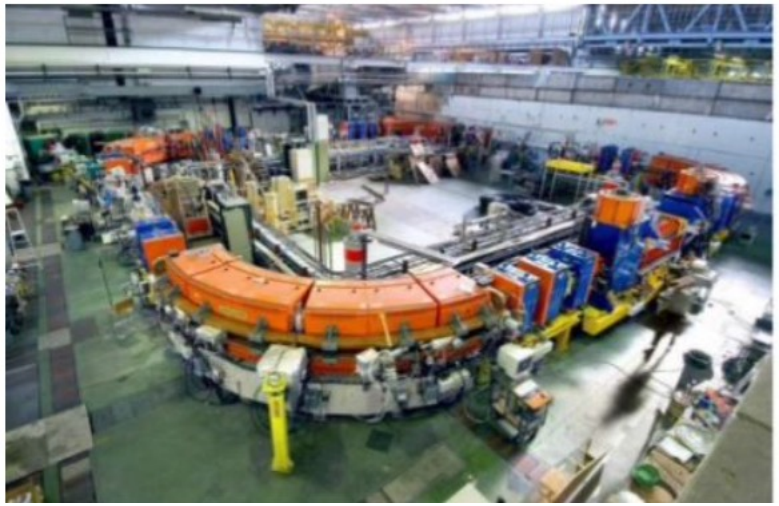
Accelerate with E field
Bending with B field

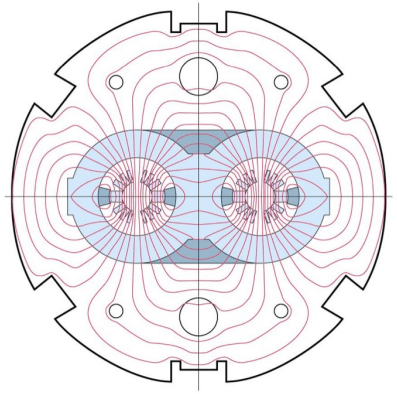
Technical challenges:

- No more single frequency, synchronise each elements
- Beam stability, focusing



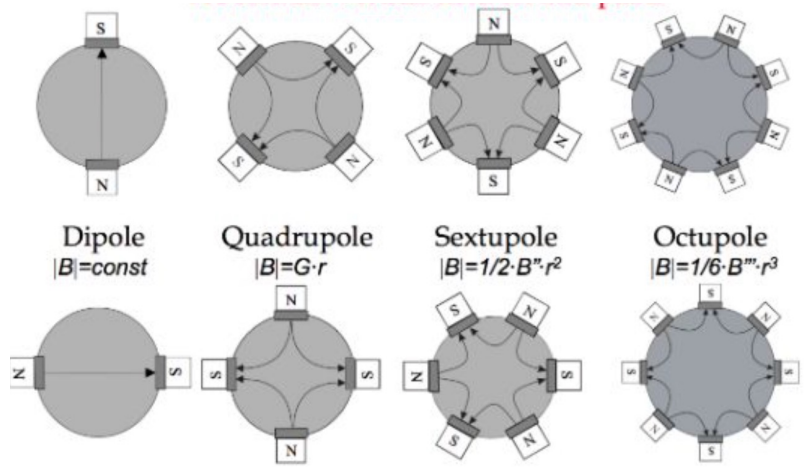




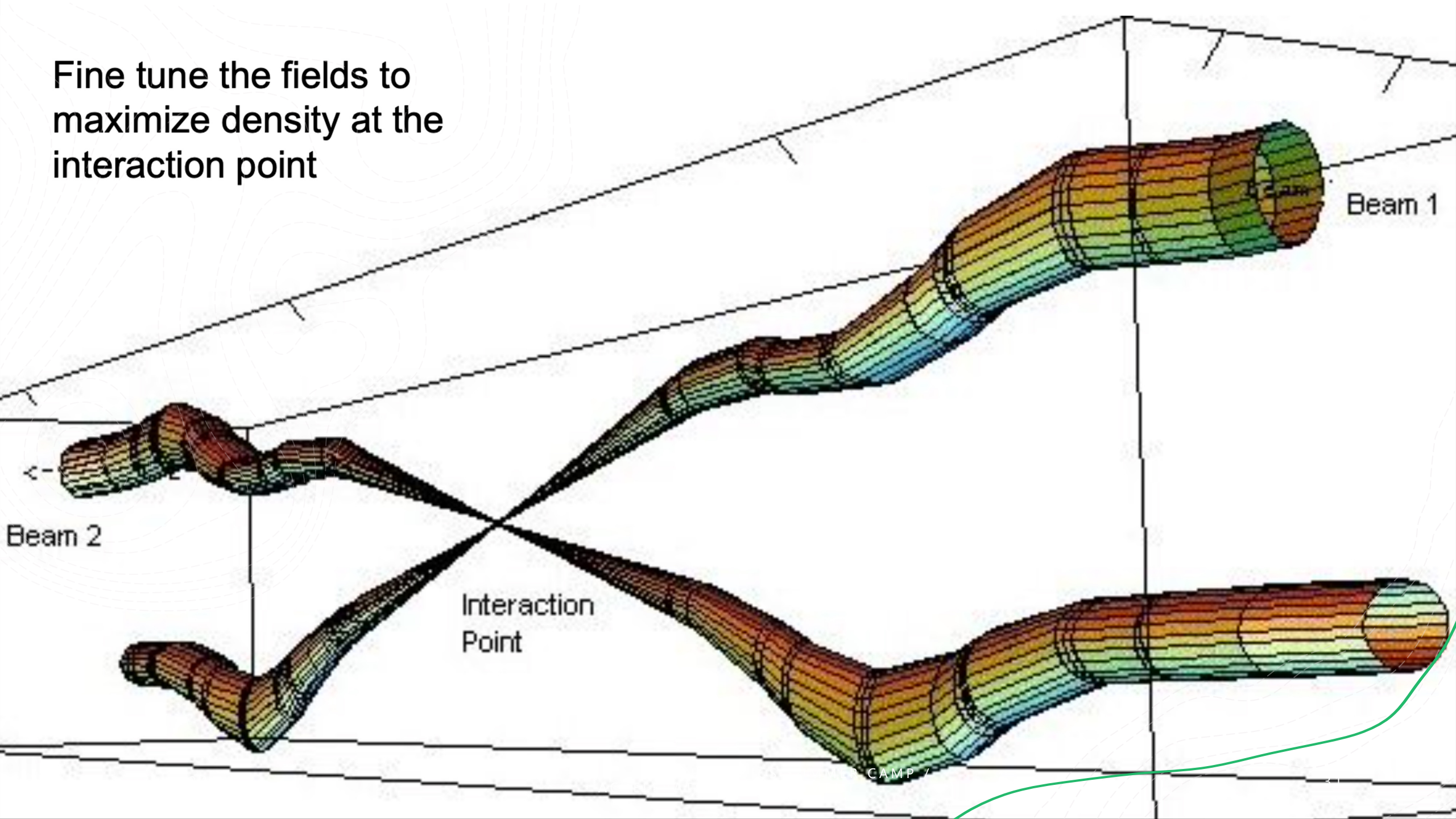


Computed magnetic flux map at B_0=10 Tesla

CERN LEIR accelerator
(Low Energy Ion Ring)

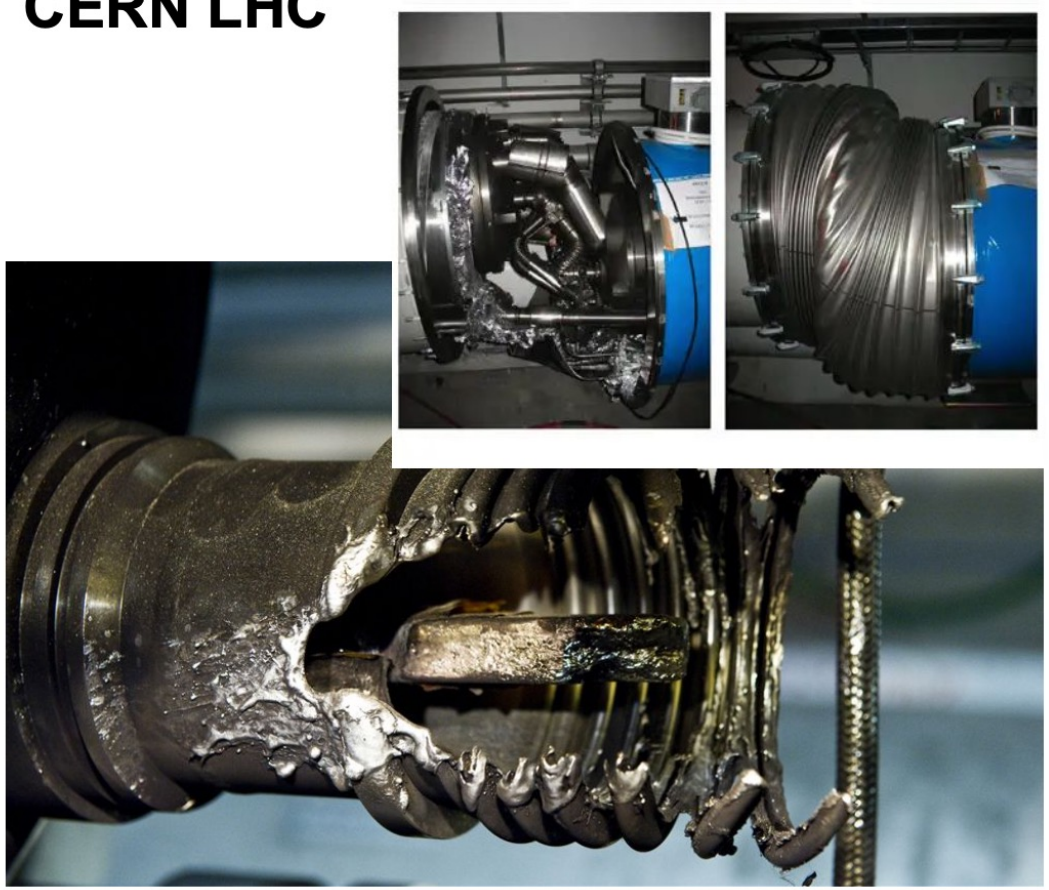


Fine tune the fields to maximize density at the interaction point

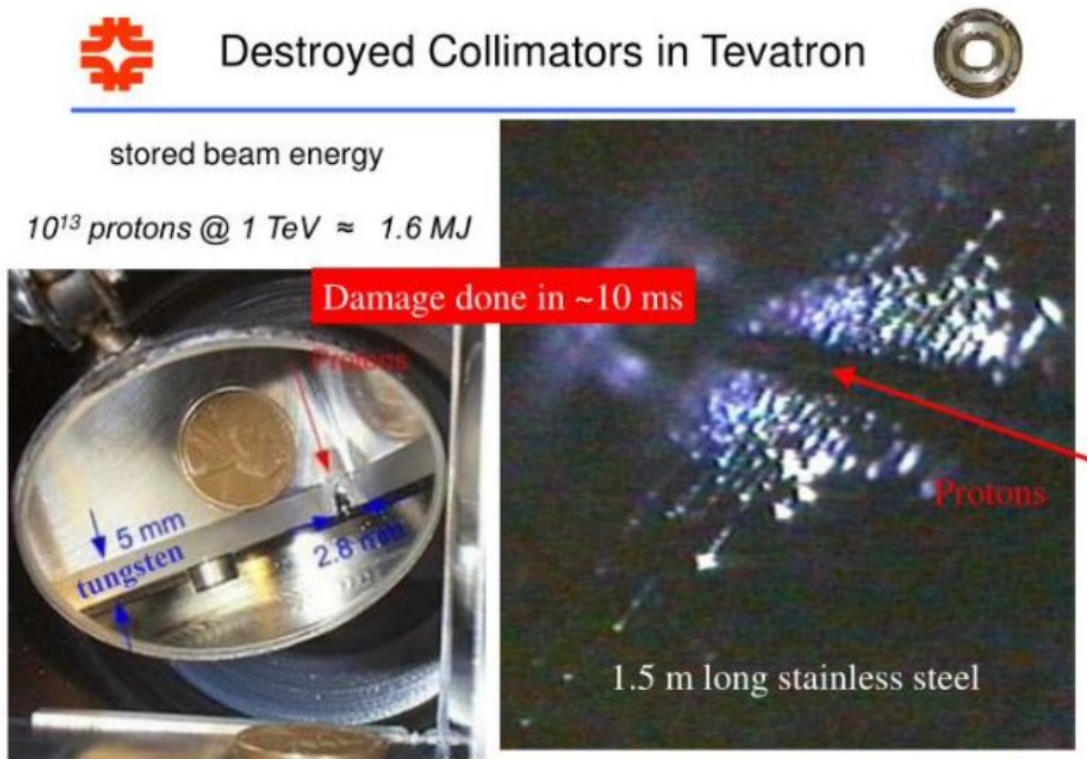


In practice,,,

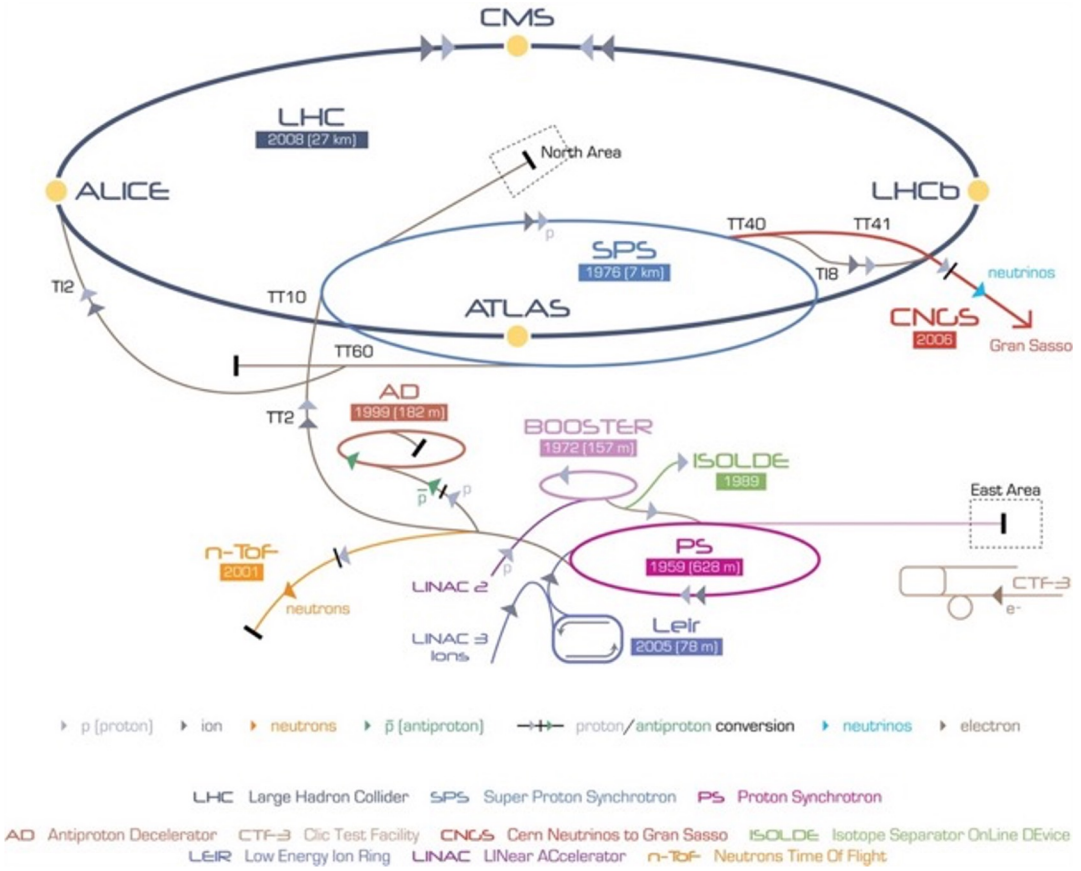
2008 indent at CERN LHC



Beam quench at FNAL

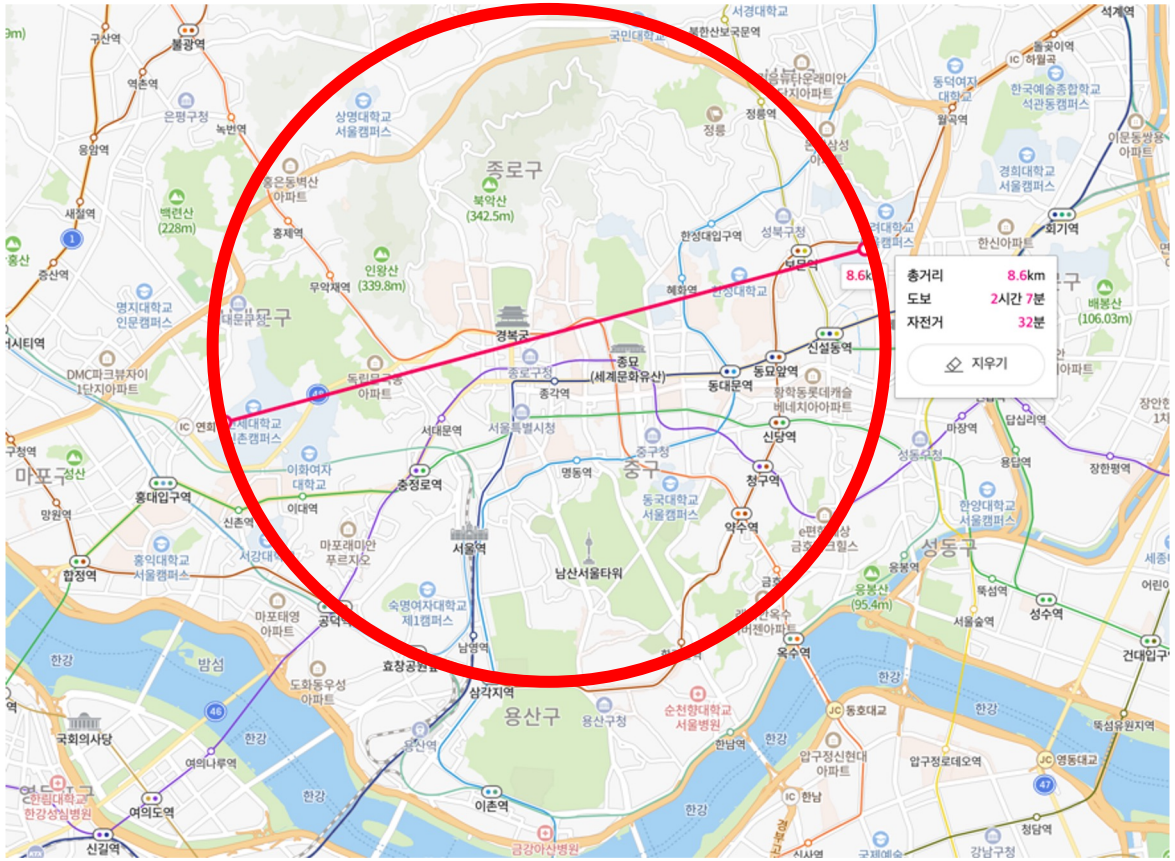


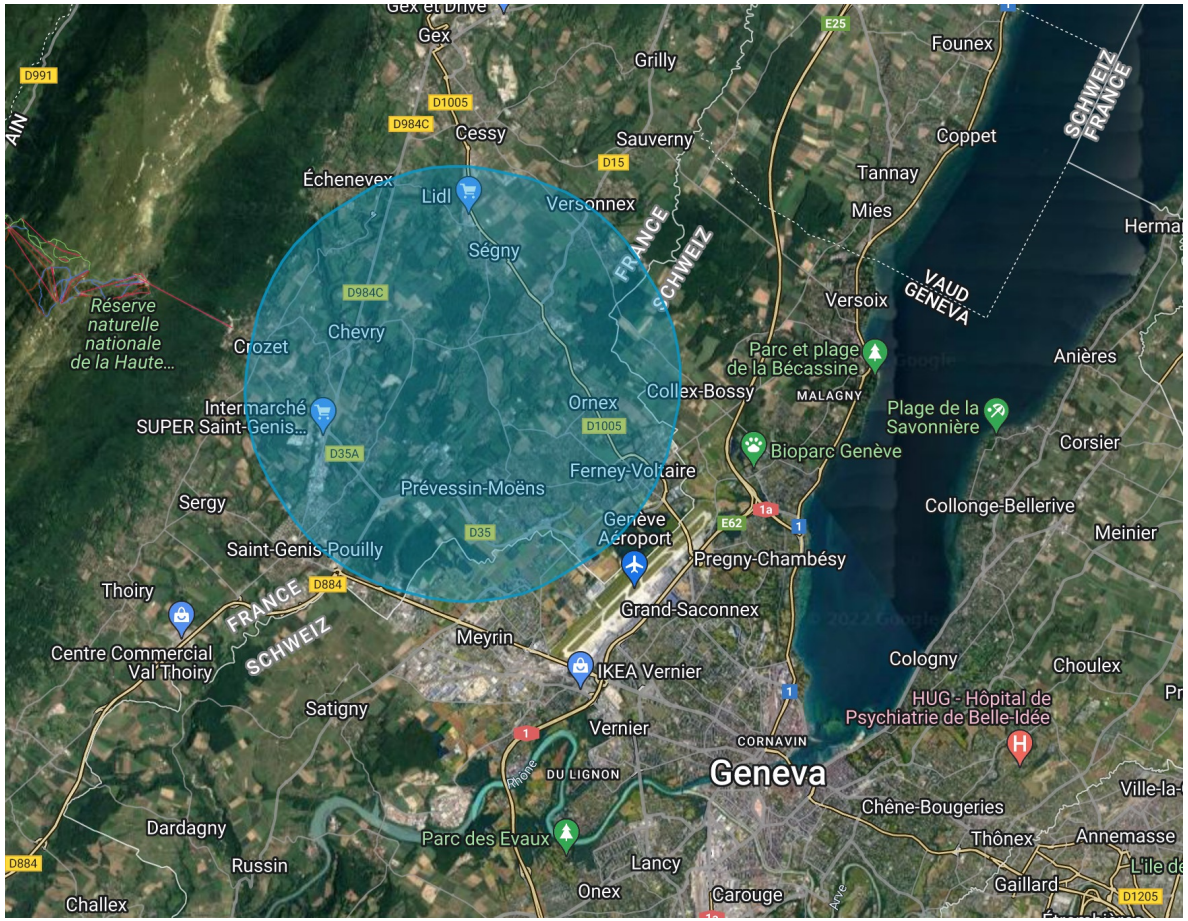
LHC complex


CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
CTF-3
LINAC 2
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)
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
CTF-3 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



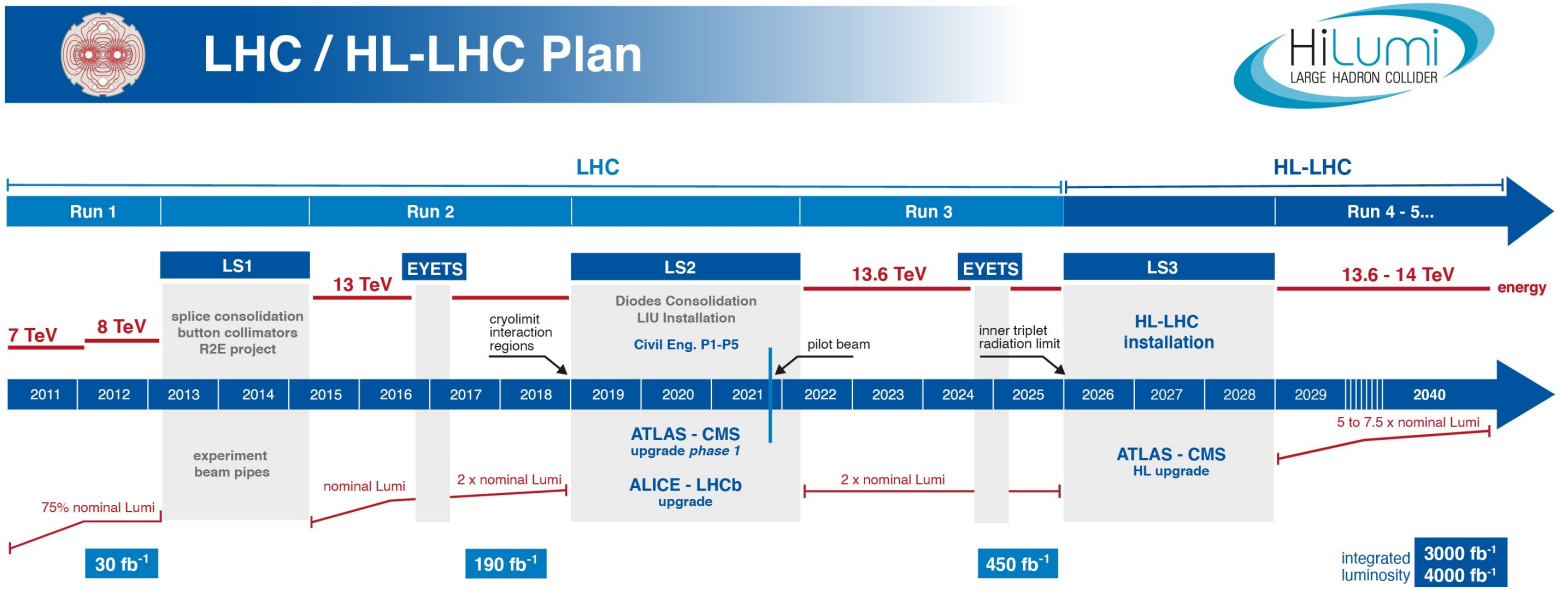
LHC complex - size

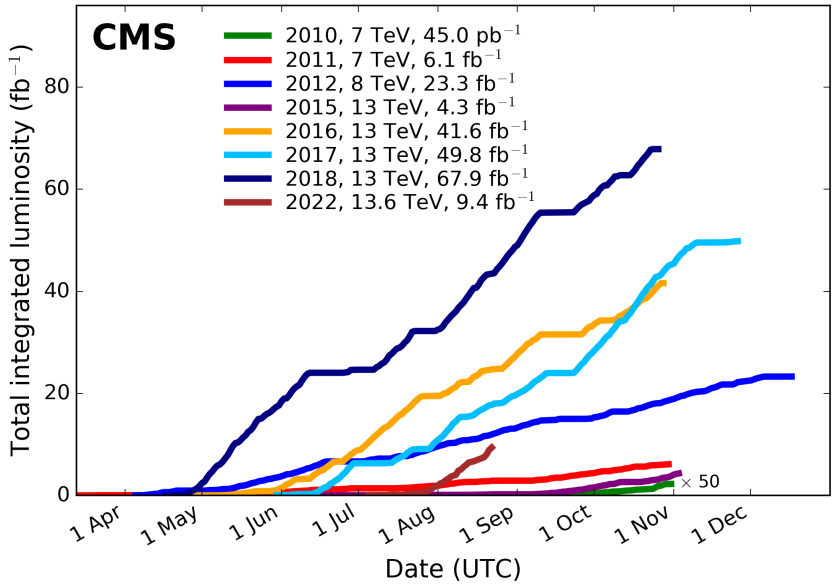


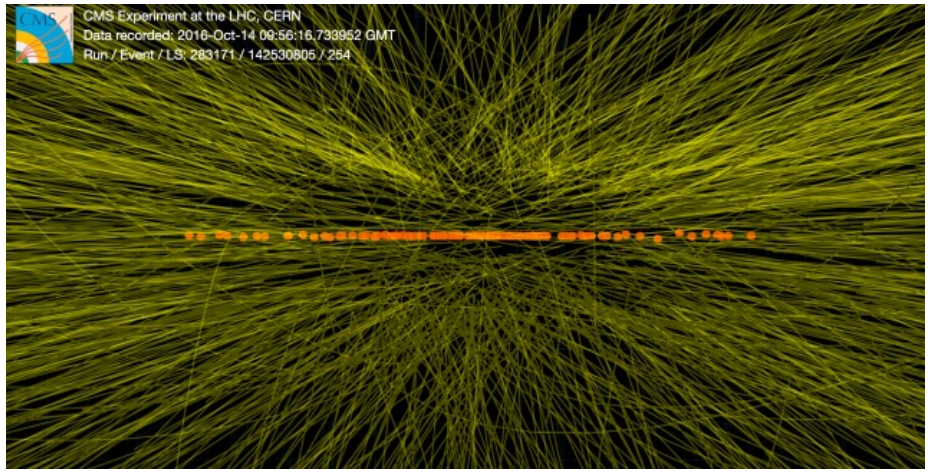


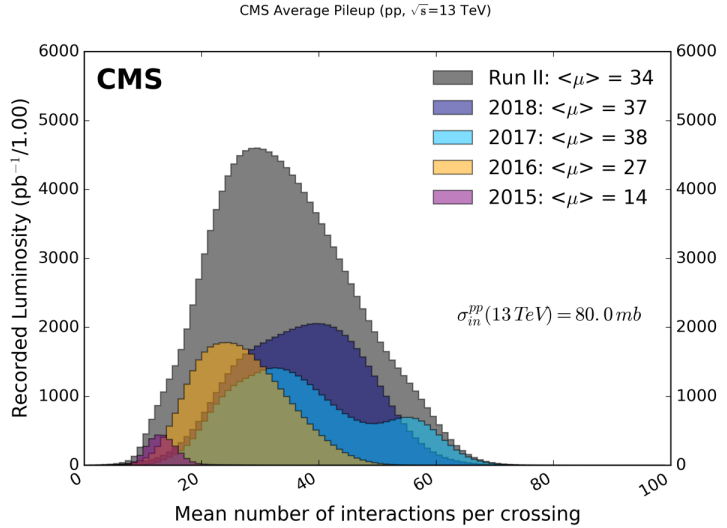
https://howlargeisthelhc.com/#/

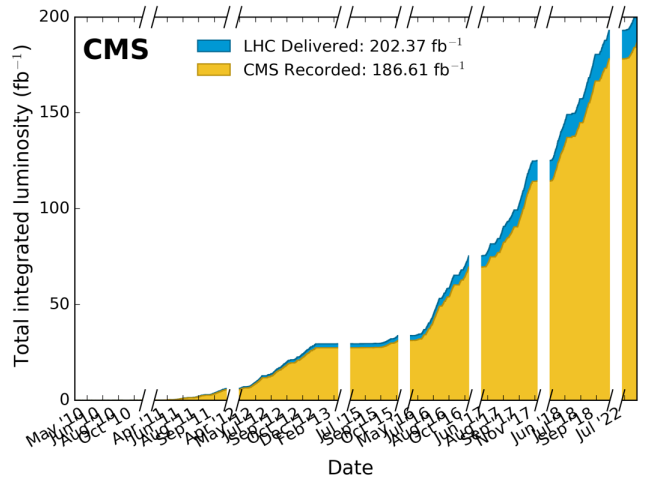
Just little bit more on LHC









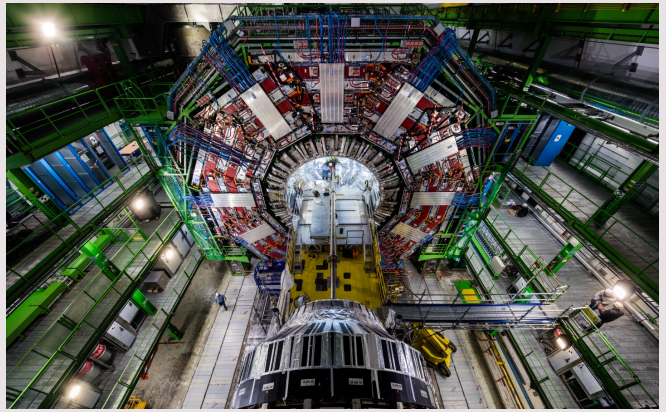


https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

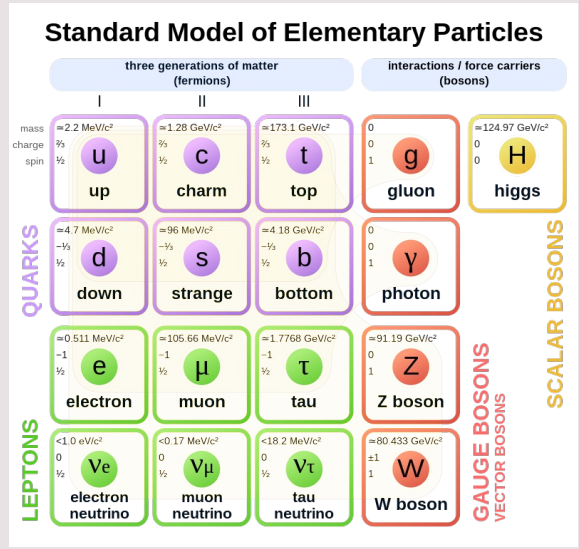
Experimental Particle Physics: TL;DR



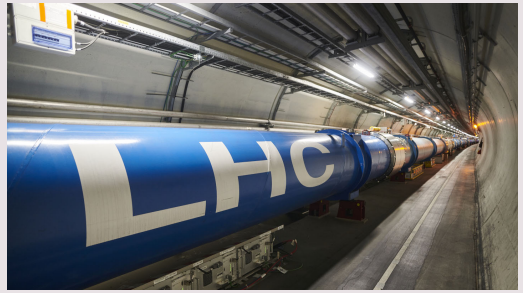
Create new particles

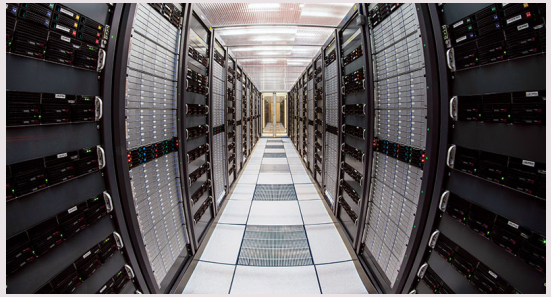


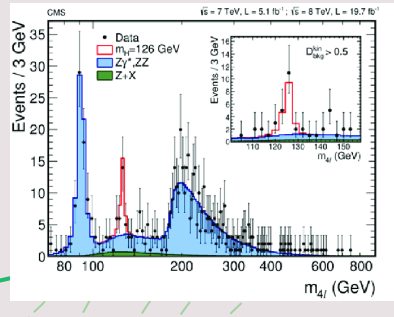
Take Pictures



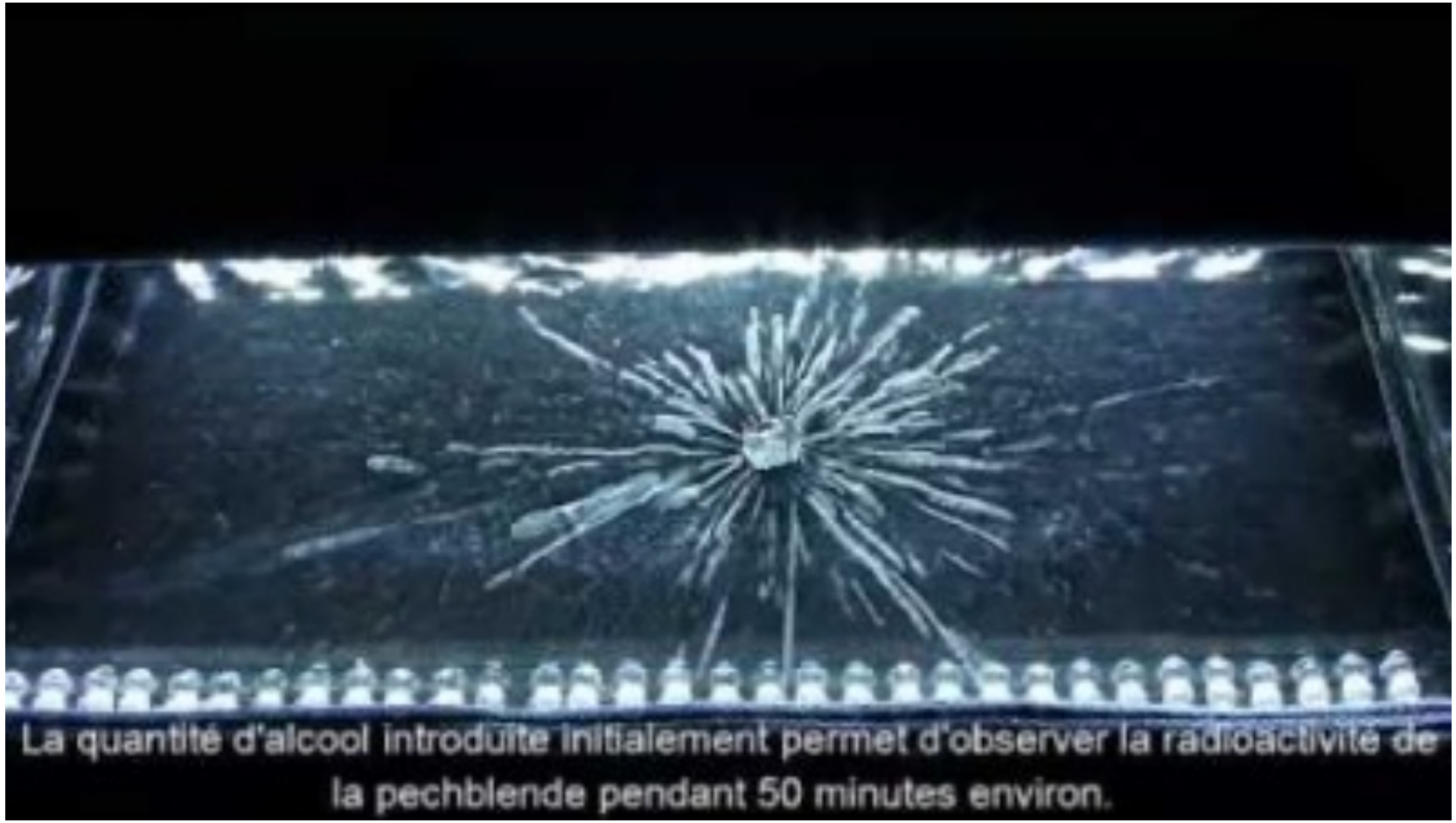
Find something (un)expected







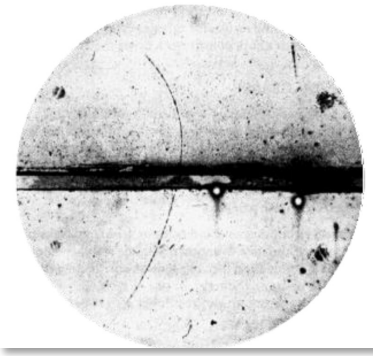
Particle Detection: Cloud chamber



Cloud chamber at Home



Particle trajectory

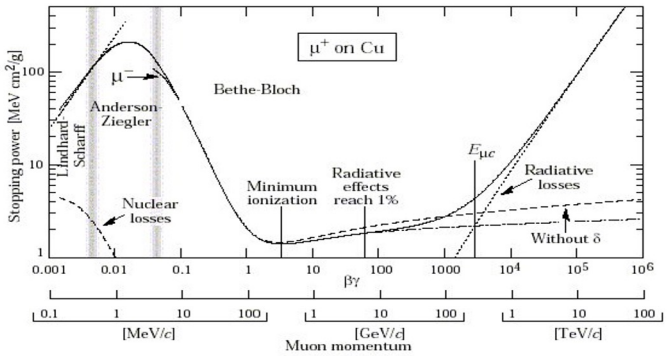


Magnetic field 15000 Gauss, chamber diameter 15cm. A 63 MeV positron passes through a 6mm lead plate, leaving the plate with energy 23MeV.

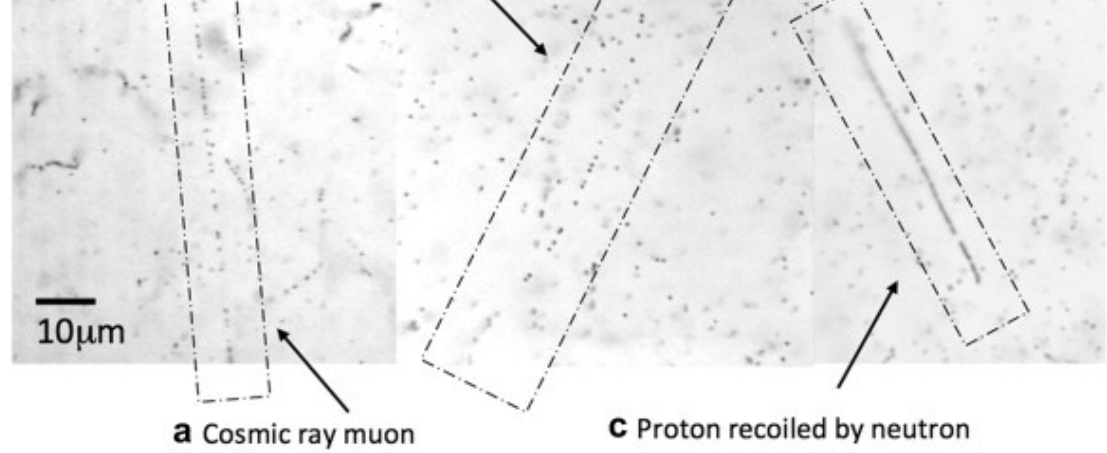
The ionization of the particle, and its behaviour in passing through the foil are the same as those of an electron.

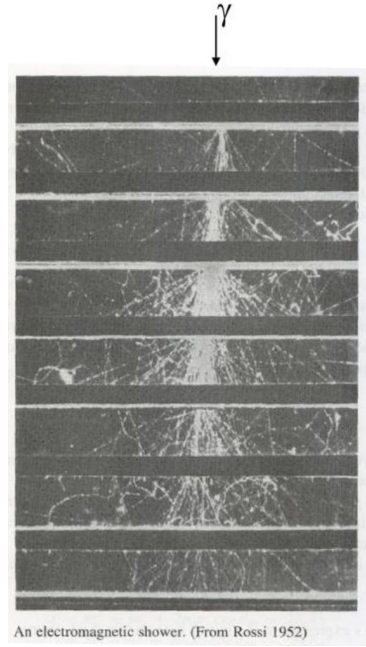
$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$$R = \frac{p}{0.3B}$$ Curvature -> Momentum

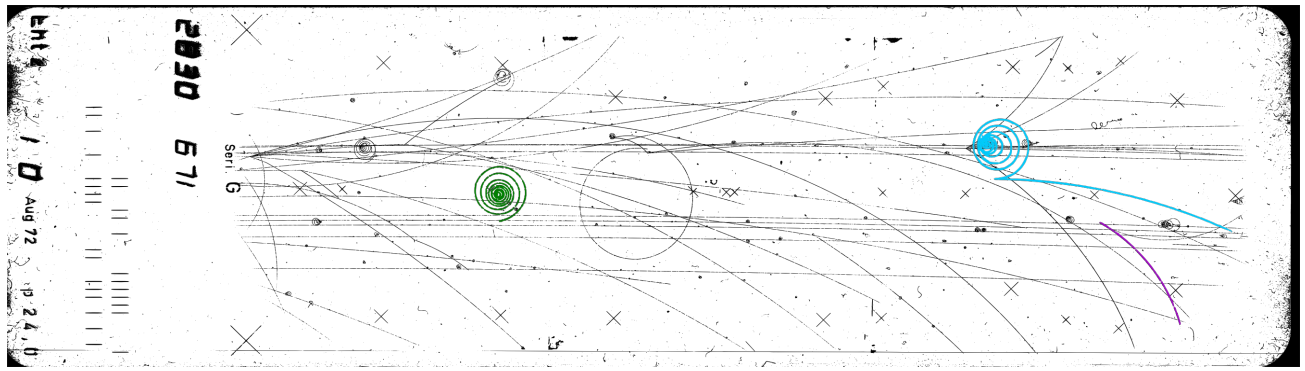


Energy Loss in media





An electromagnetic shower. (From Rossi 1952)



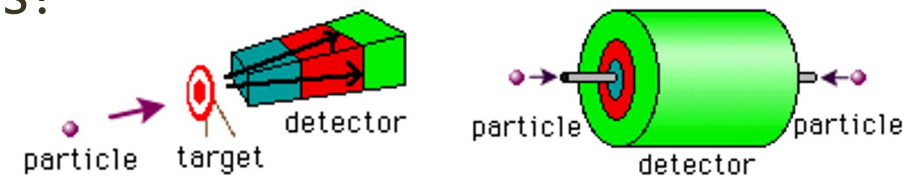
”Stable” particles

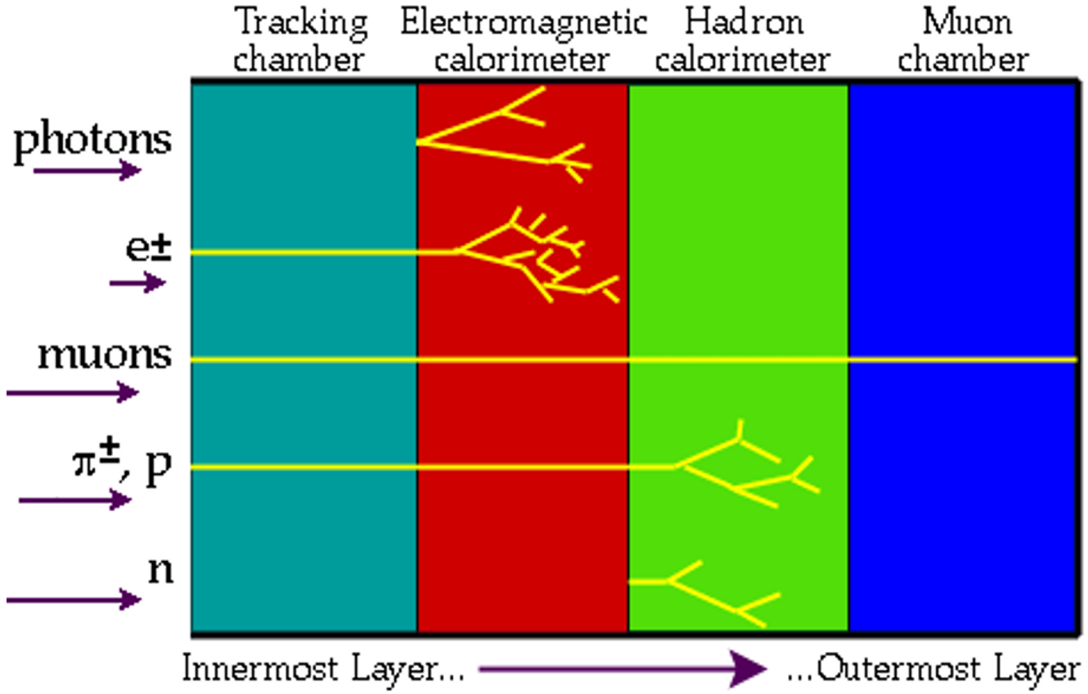
- Only 7+ particles:
  - p, n, $e^{\pm}$, $\mu^{\pm}$, γ, $\pi^{\pm}$, $K^{\pm}$, (K^0, ν)
- (Somehow) Distinguishable by their charge, interaction, energy loss
  - EM interaction?
    - Bends under B fields?
  - Nuclear interaction?
  - Minimum (but nonzero) interaction?
  - Or invisible?
  - Decays?

	Charge	EM	Nucl.	Decays
p	O	O	O	X
n	X	X	O	X
$e^{\pm}$	O	O	X	X
$\mu^{\pm}$	O	X	X	X
γ	X	O	X	X
$\pi^{\pm}$, $K^{\pm}$	O	O	O	
K^0	X	X		O
ν	X	X	X	X

”Stable” particles

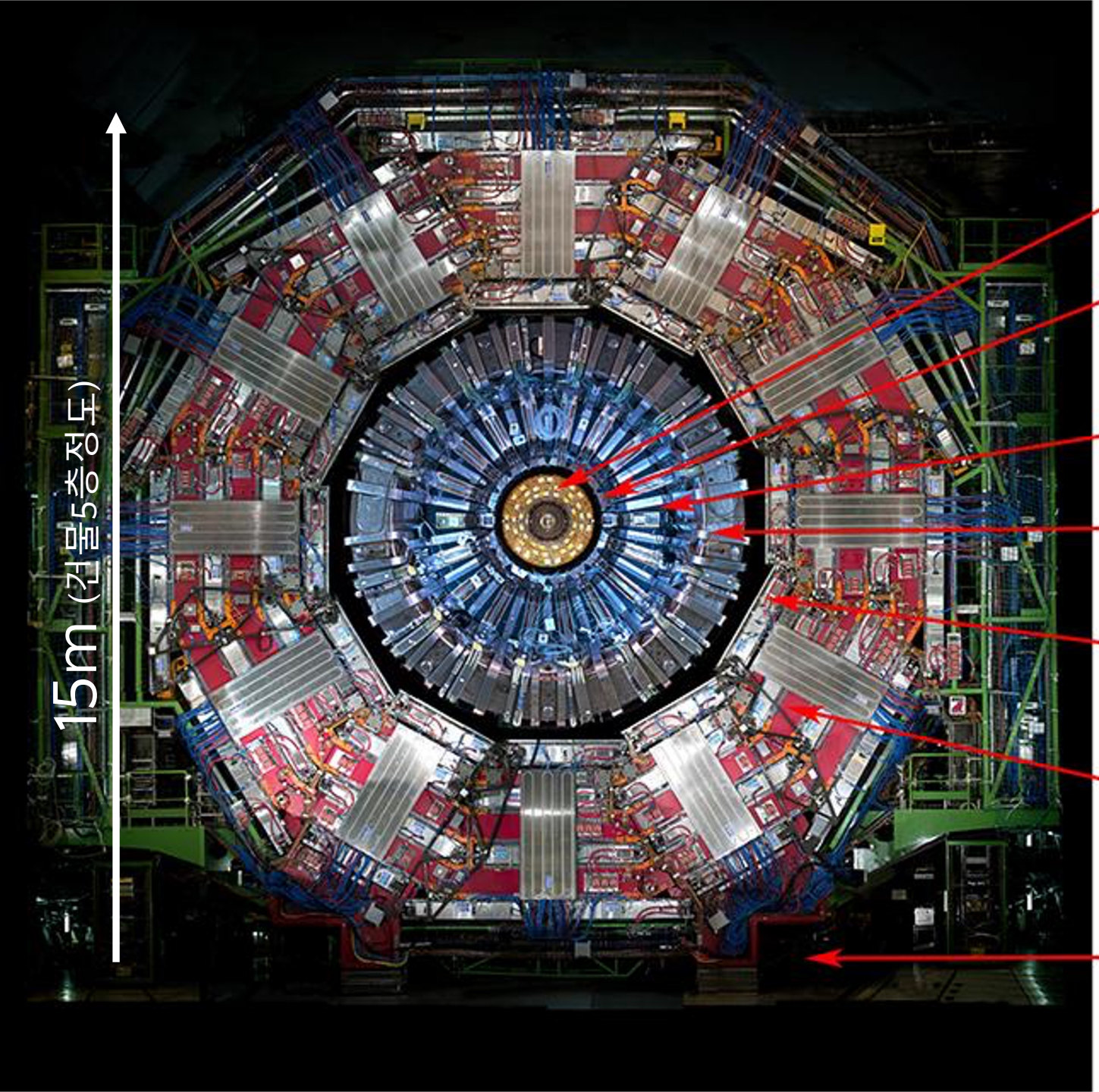
- Only 7+ particles:
  - p, n, $e^{\pm}$, $\mu^{\pm}$, γ, $\pi^{\pm}$, $K^{\pm}$, (K^0, ν)
- (Somehow) Distinguishable by their charge, interaction, energy loss
  - EM interaction?
    - Bends under B fields?
  - Nuclear interaction?
  - Minimum (but nonzero) interaction?
  - Or invisible?
  - Decays?





CMS Experiment





Tracking system
Germany, Italy, France, Belgium, USA, Austria, Finland, Switzerland, CERN...

Electromagnetic Calorimeter
Russia, China, France, Italy, Japan, UK, Switzerland, Greece, Taiwan

Hadron Calorimeter
USA, Russia, Ukraine, Turkey, Iran, India, Hungary...

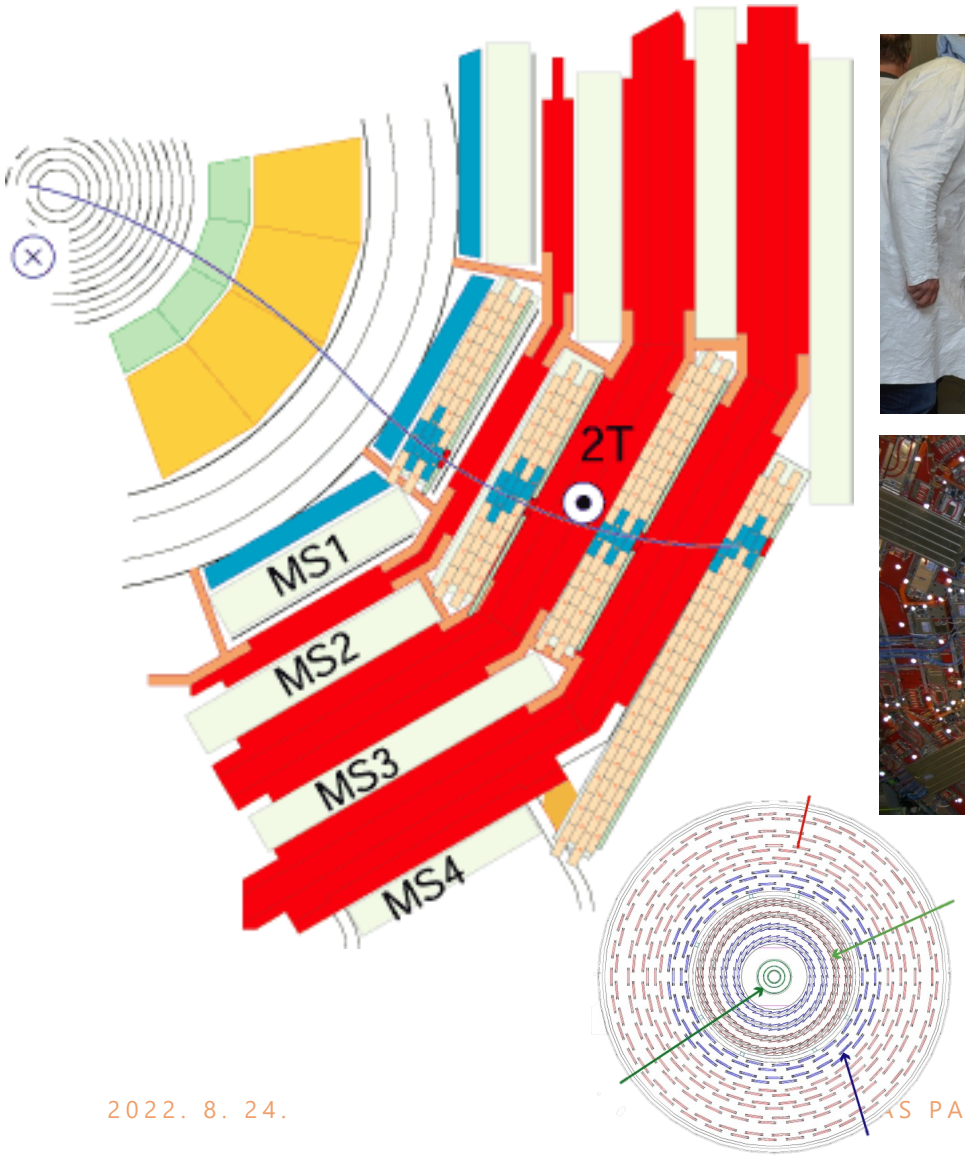
Solenoid
France, Italy, Switzerland, Finland, CERN, UK, Japan, Croatia

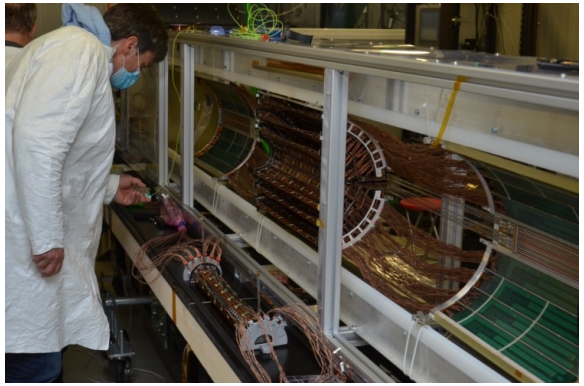
Muon system
Italy, Germany, Spain, USA, Russia, Belgium, Bulgaria, South Korea, Pakistan, CERN

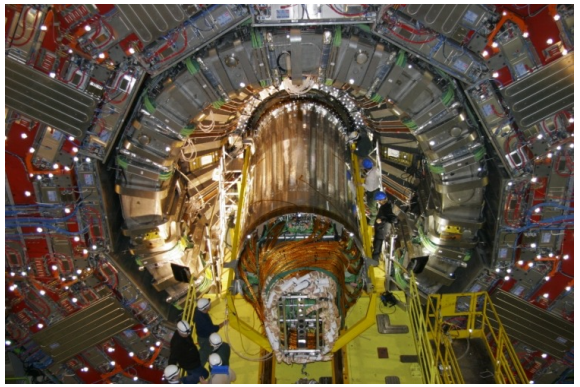
Flux-return yoke
Germany, Russia, Czechia, Japan, CERN

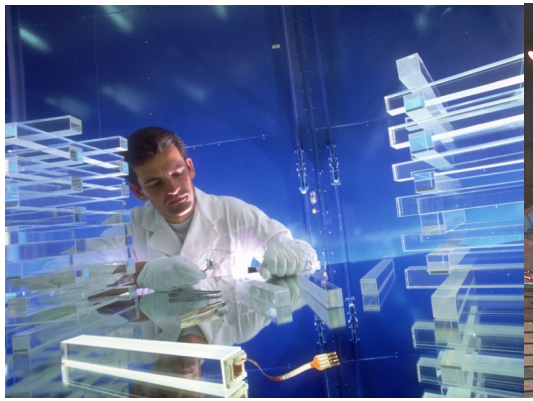
Support system
China, Pakistan, USA

Particle Detection at CMS

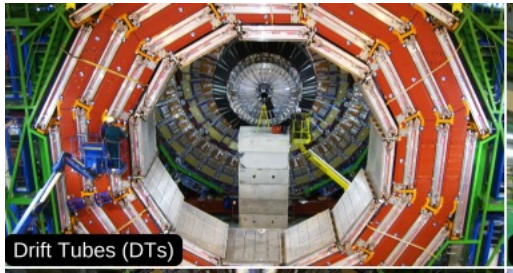


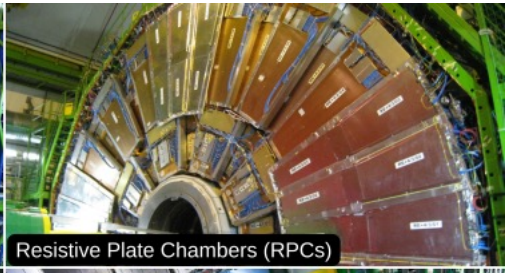








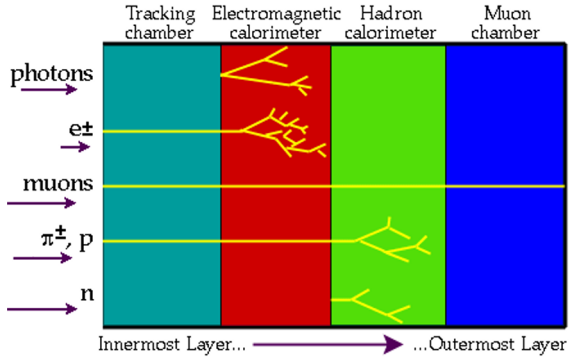


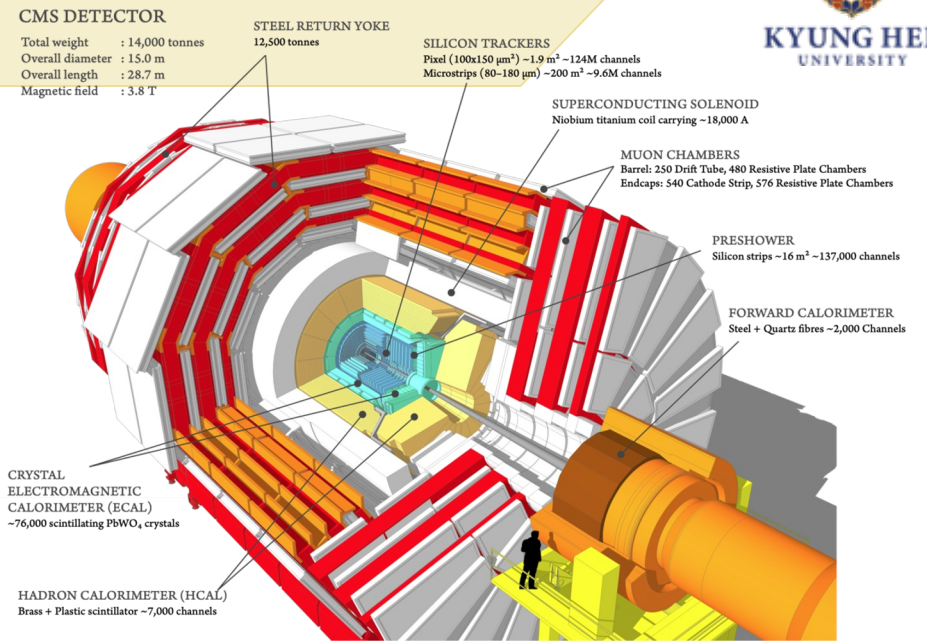


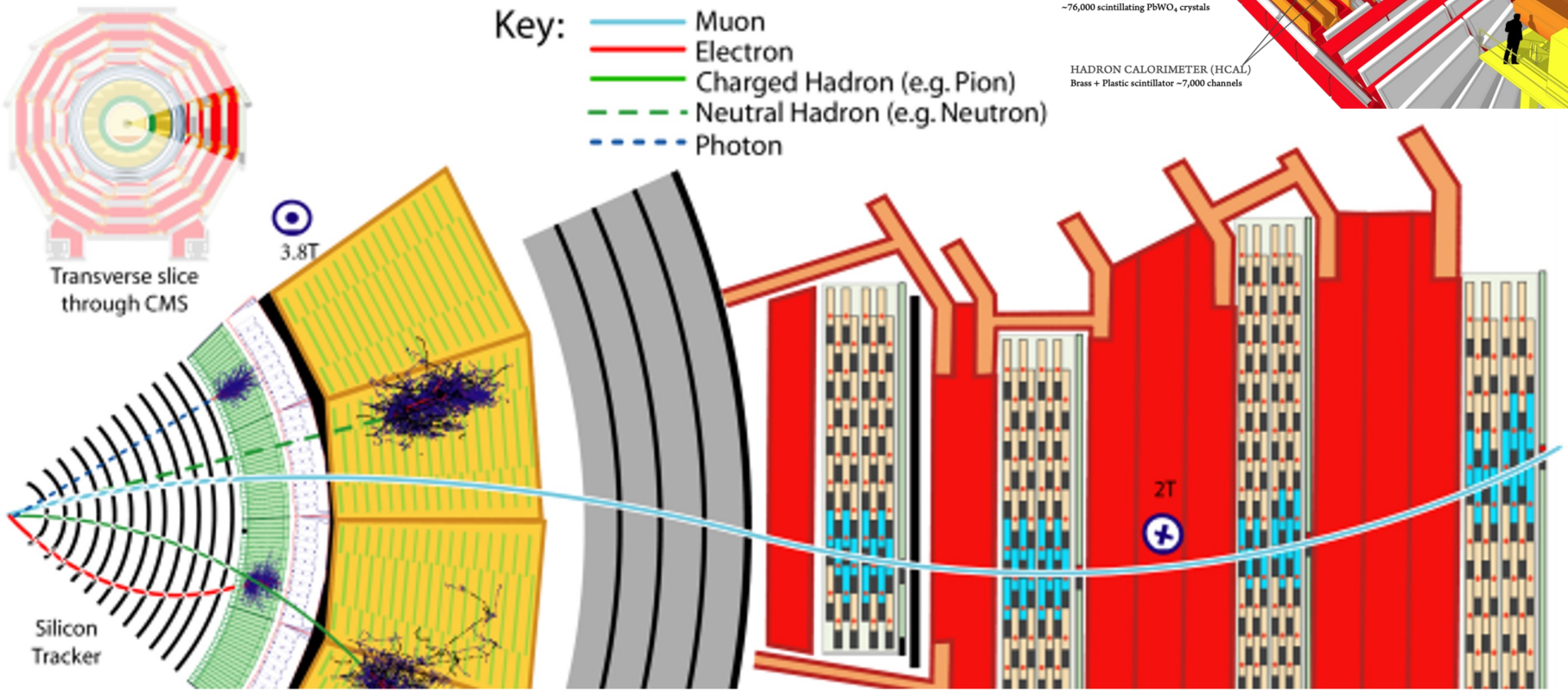




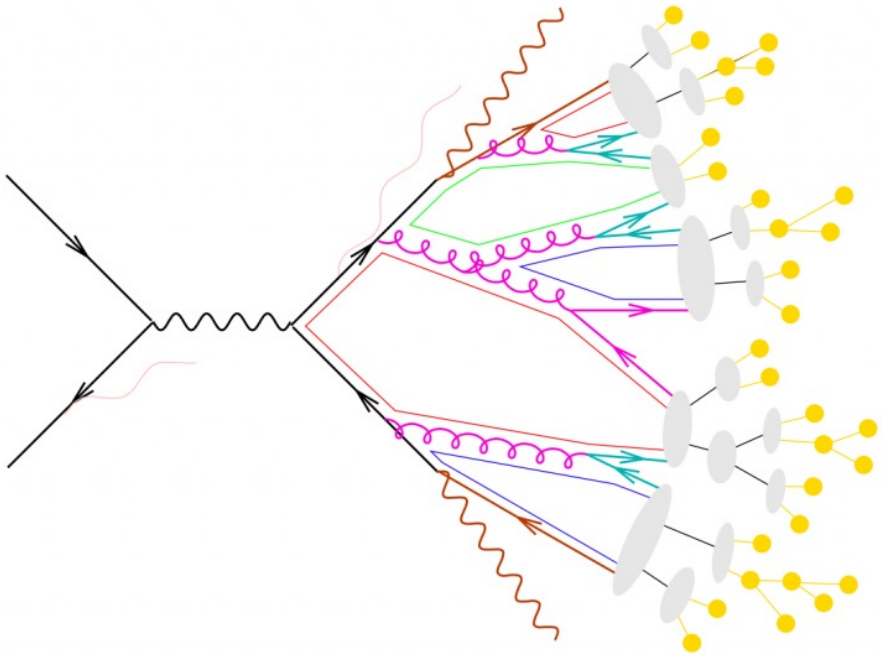
Particle Identification in CMS



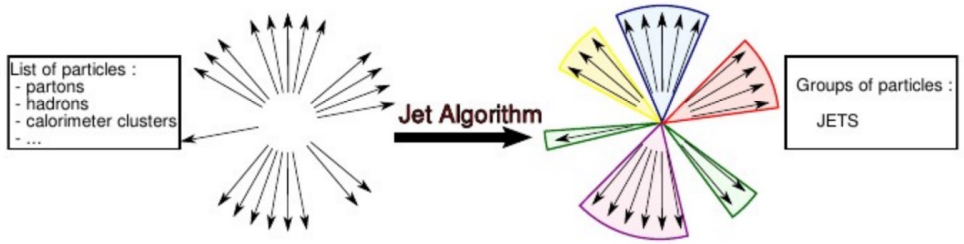


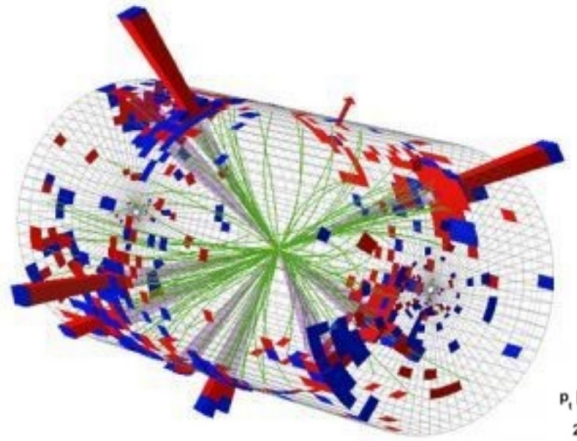


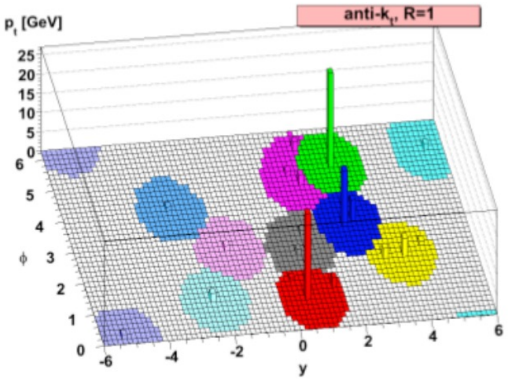
Quarks, Gluons = “Jet”



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \to bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster → hadrons
- hadronic decays

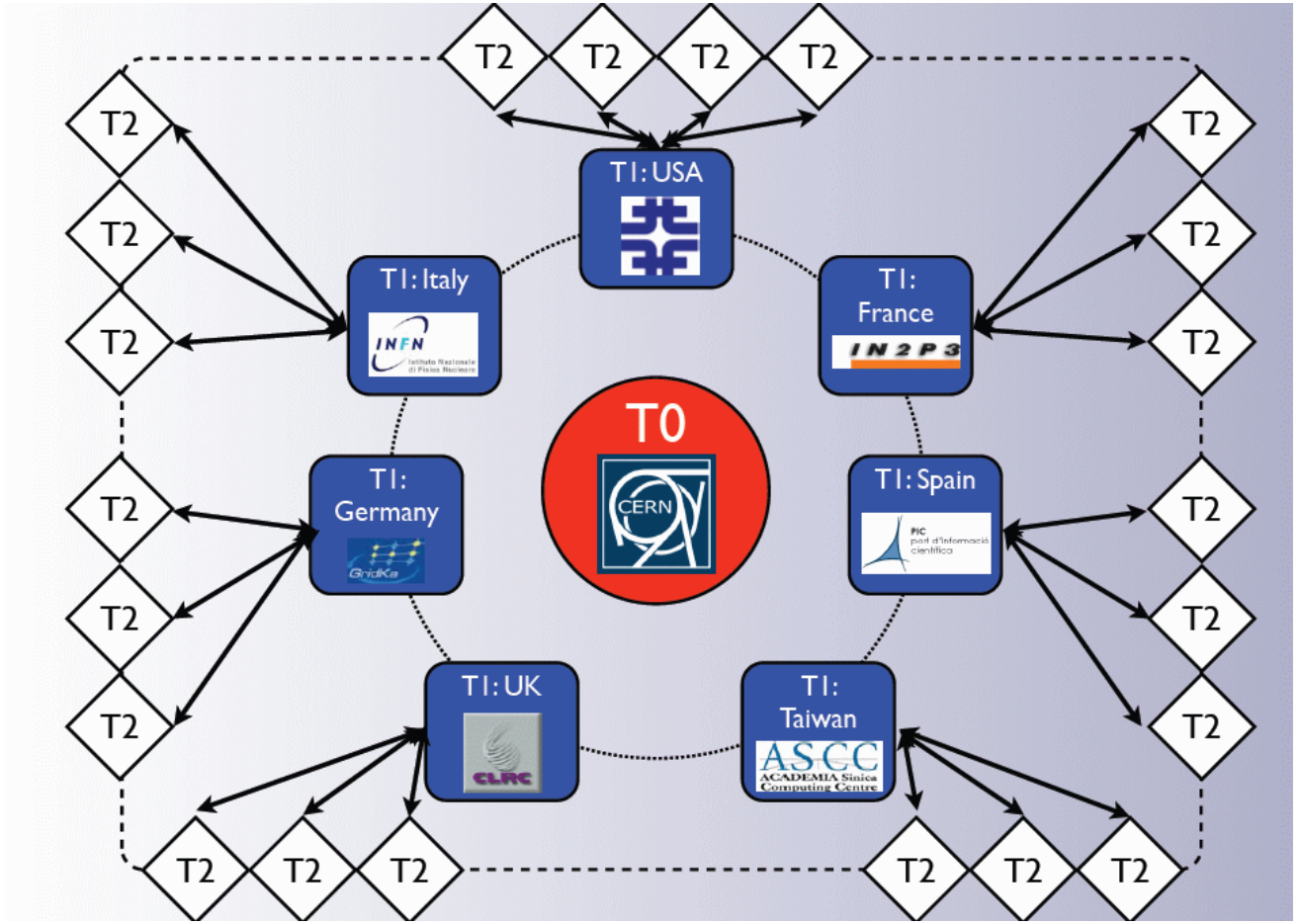






Jets from c,b quarks:
- Displaced vertices from long-lived particles
- Deep Learning algorithms to identify flavor
“b-Taggging” or “Flavor Tagging”

Data processing

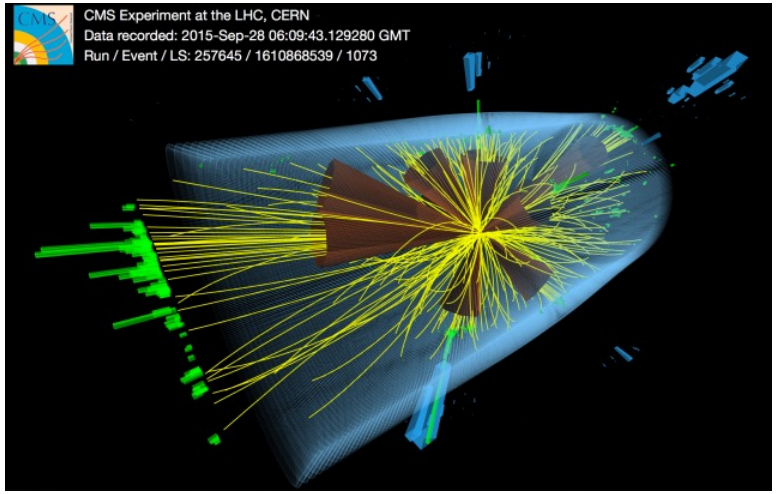


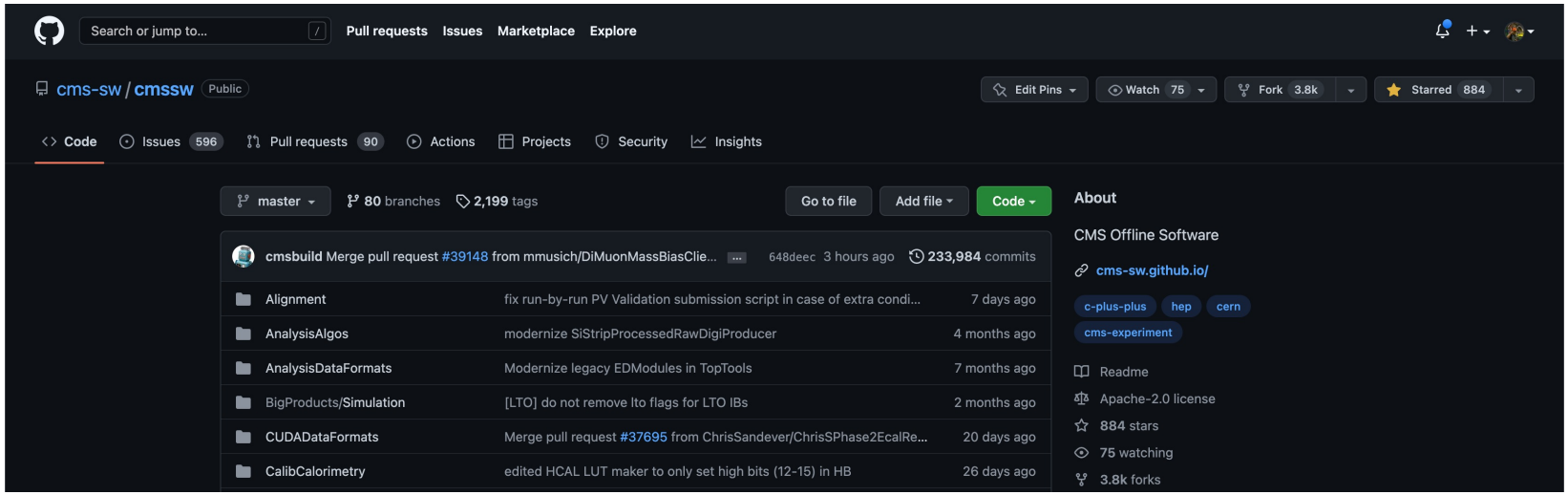




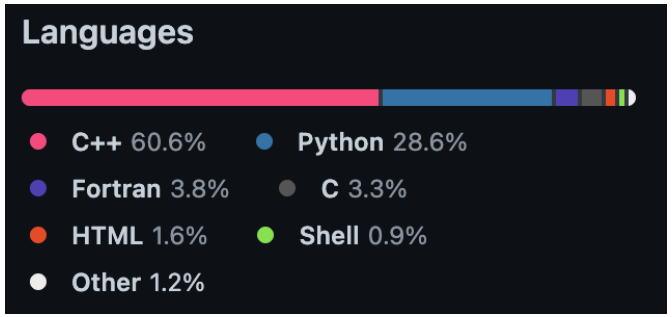
Software

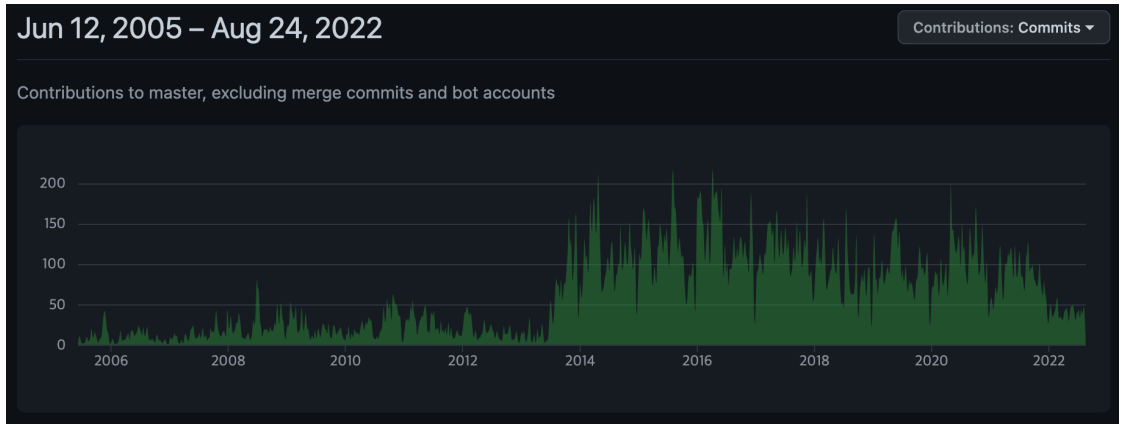
https://github.com/cms-sw/cmssw



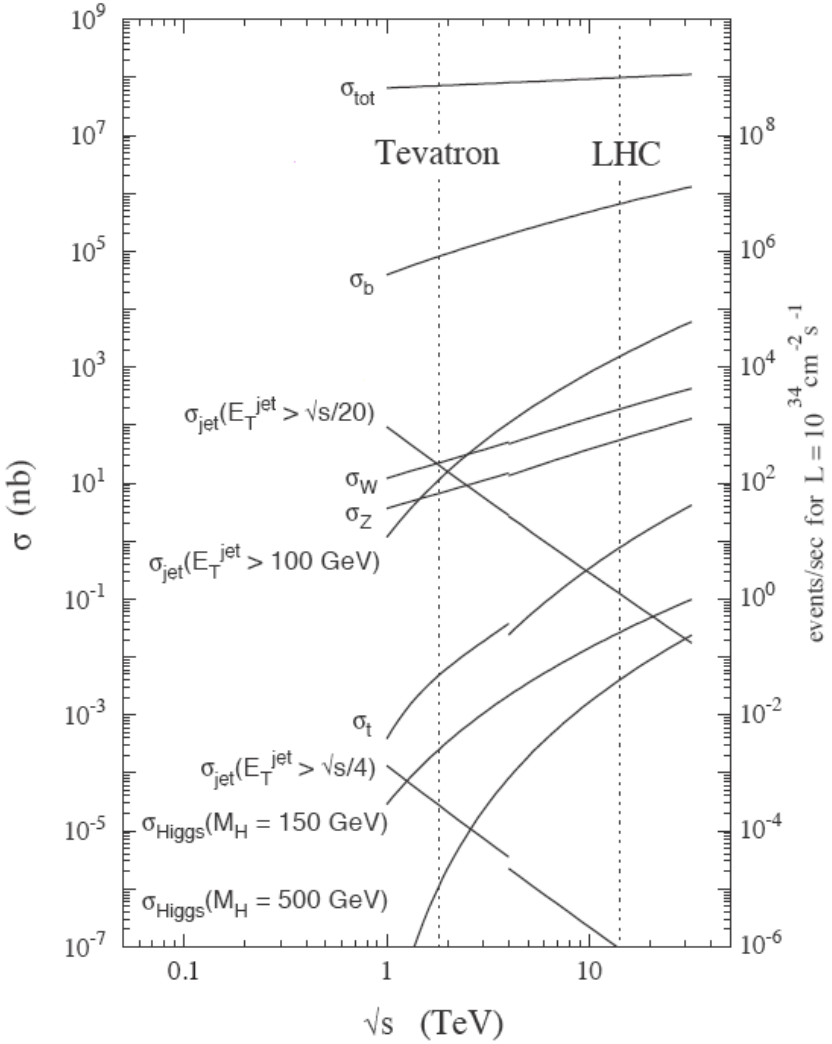


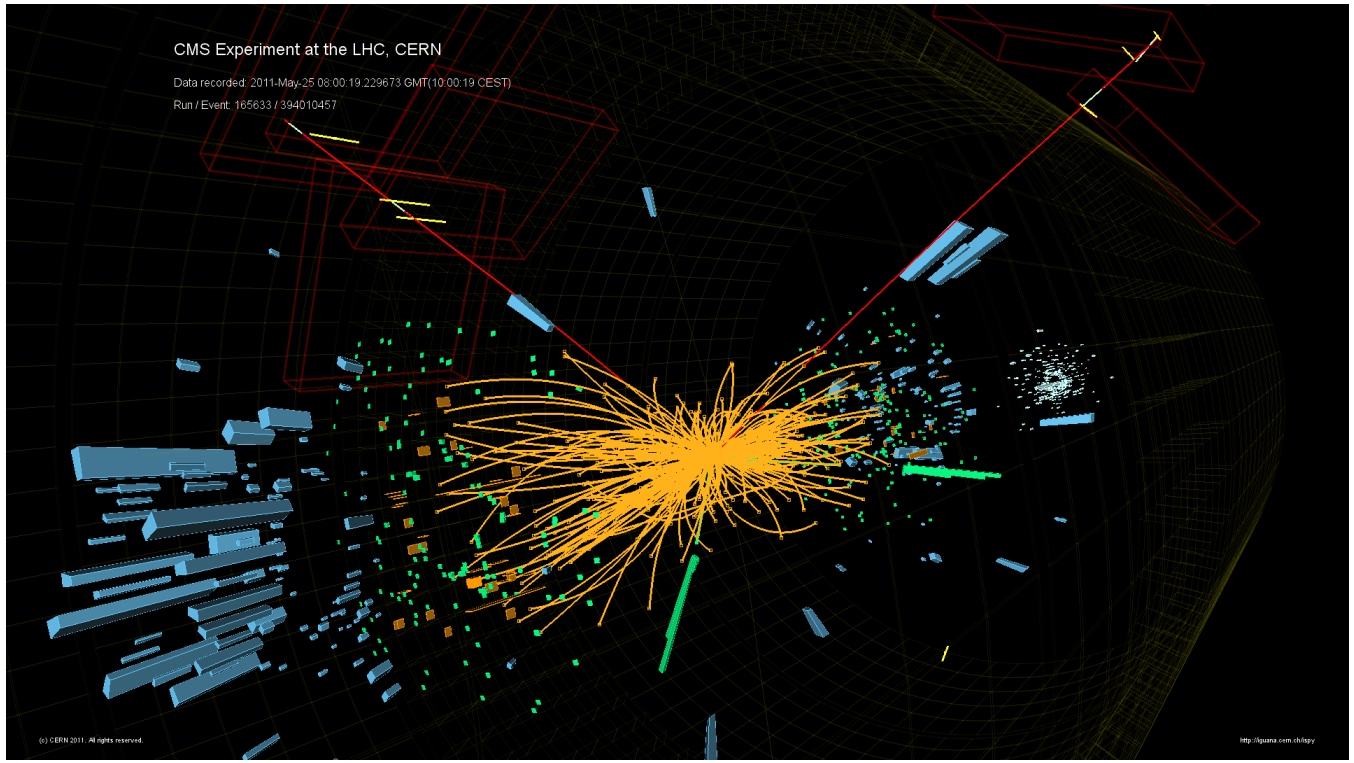


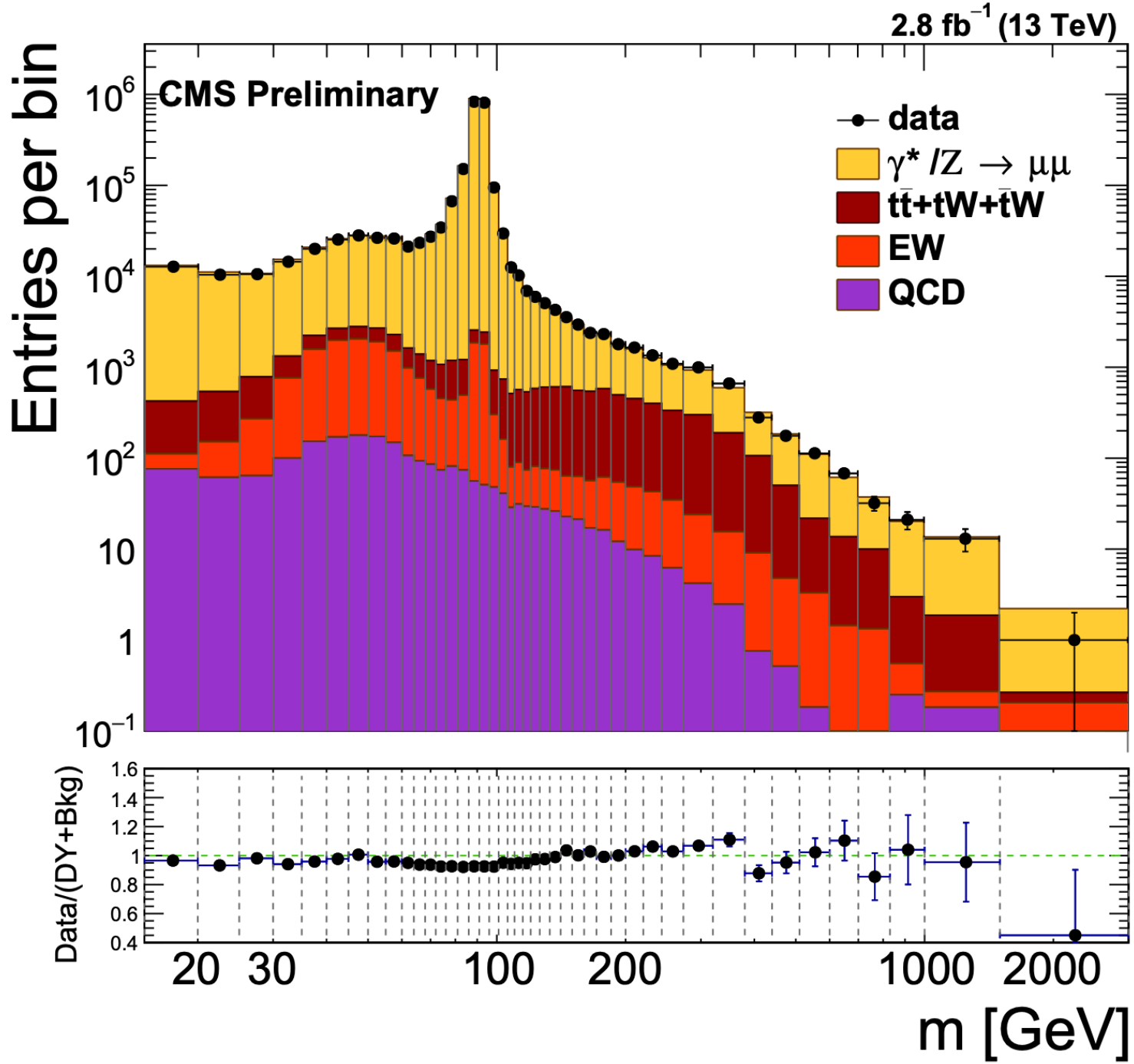




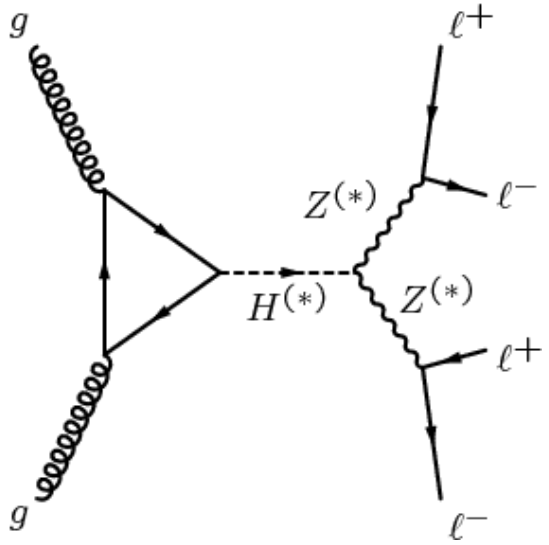
Done? NO.

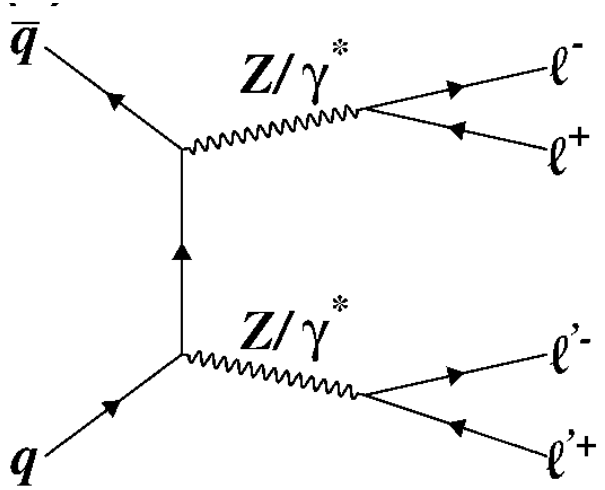

Tevatron
LHC
σ_{tot}
σ_b
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100\ GeV)$
σ_t
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/4)$
$\sigma_{Higgs}(M_H = 150\ GeV)$
$\sigma_{Higgs}(M_H = 500\ GeV)$
σ (nb)
events/sec for $L = 10^{34}\ cm^{-2}\ s^{-1}$
$\sqrt{s}$ (TeV)
10^9
10^7
10^5
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^8
10^6
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
0.1
1
10


CMS Experiment at the LHC, CERN
Data recorded: 2011-May-25 08:00:19.229673 GMT(10:00:19 CEST)
Run / Event: 165633 / 394010457

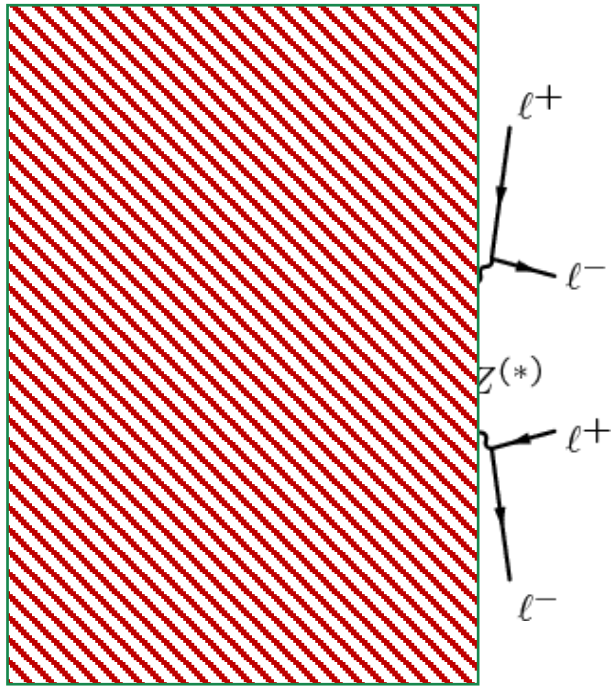

2.8 fb^{-1} (13 TeV)
CMS Preliminary
data
γ* /Z → μμ
tt̄+tW+t̄W
EW
QCD
Entries per bin
Data/(DY+Bkg)
m [GeV]

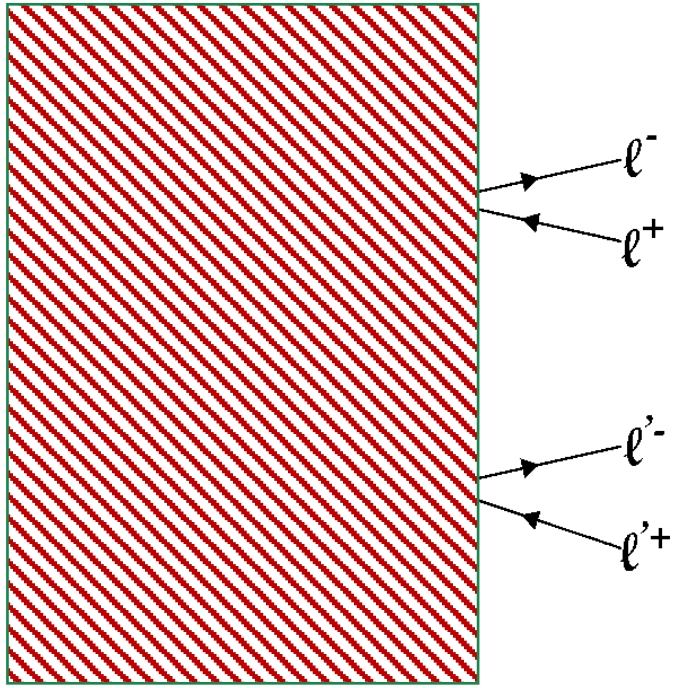
What we see is…



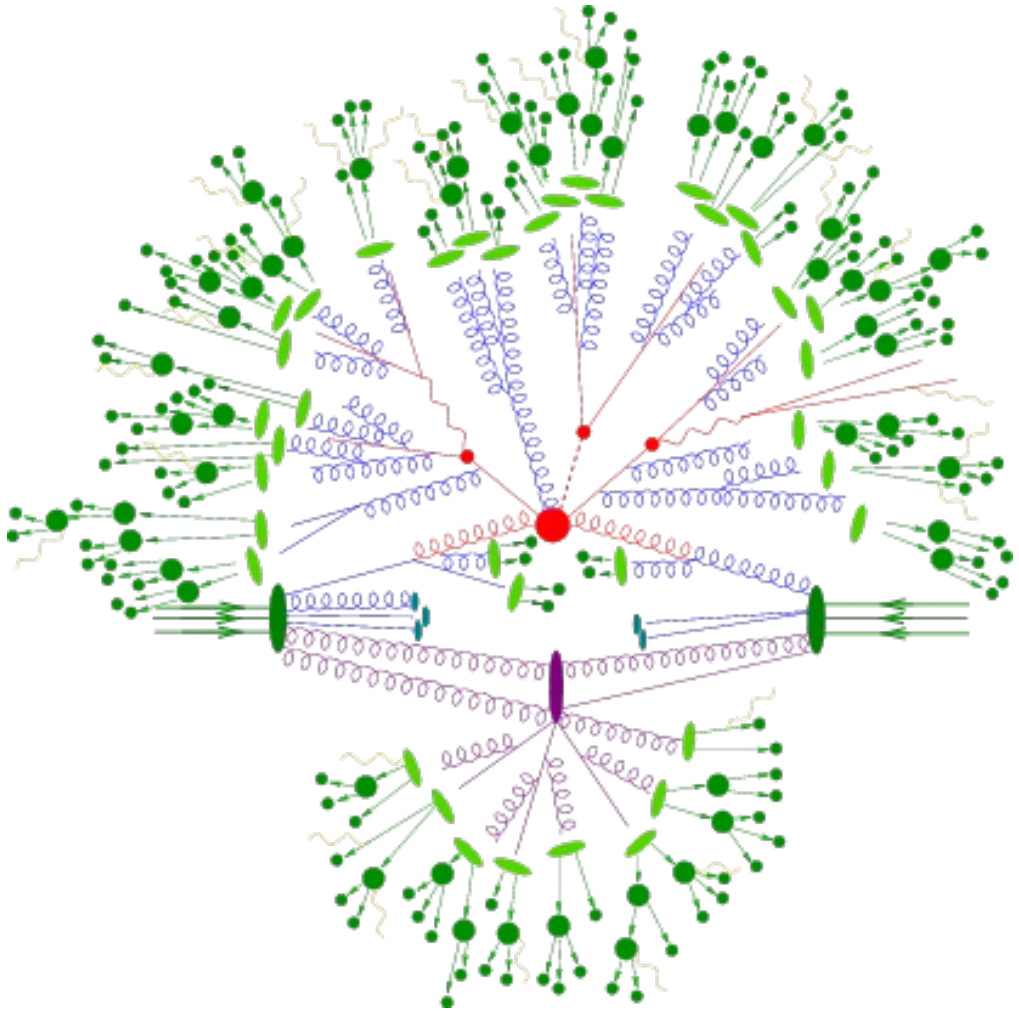


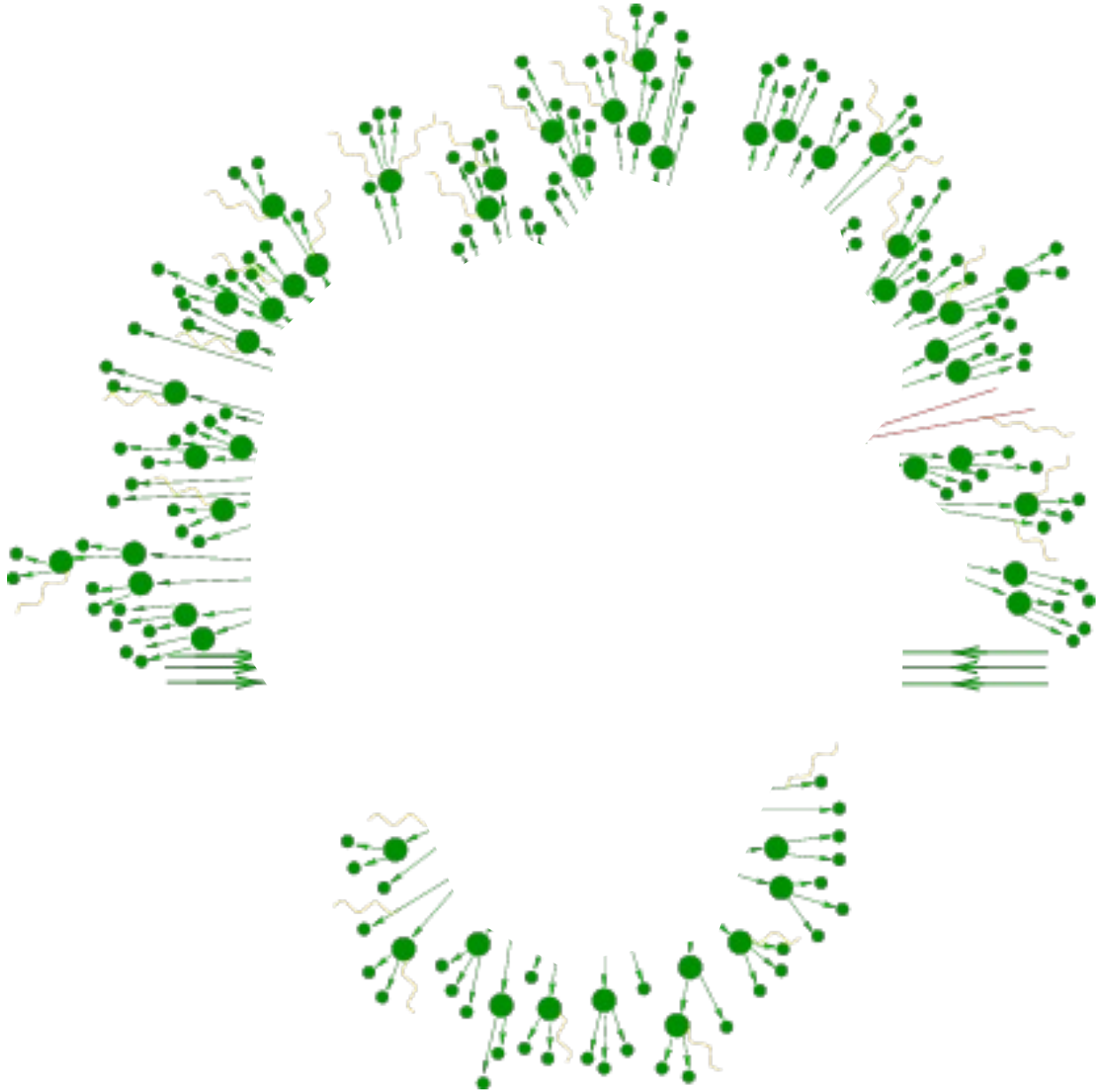
What we see is…

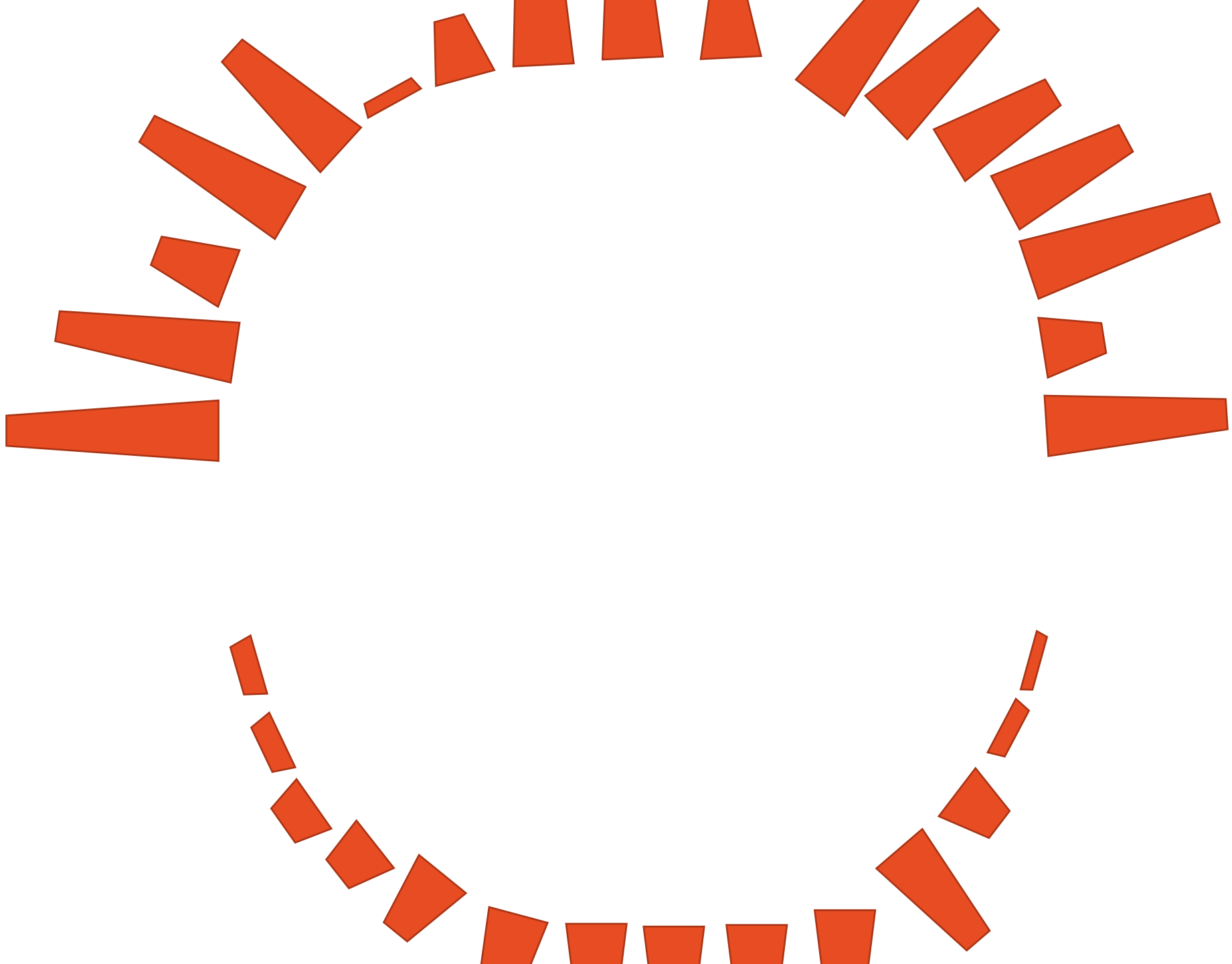


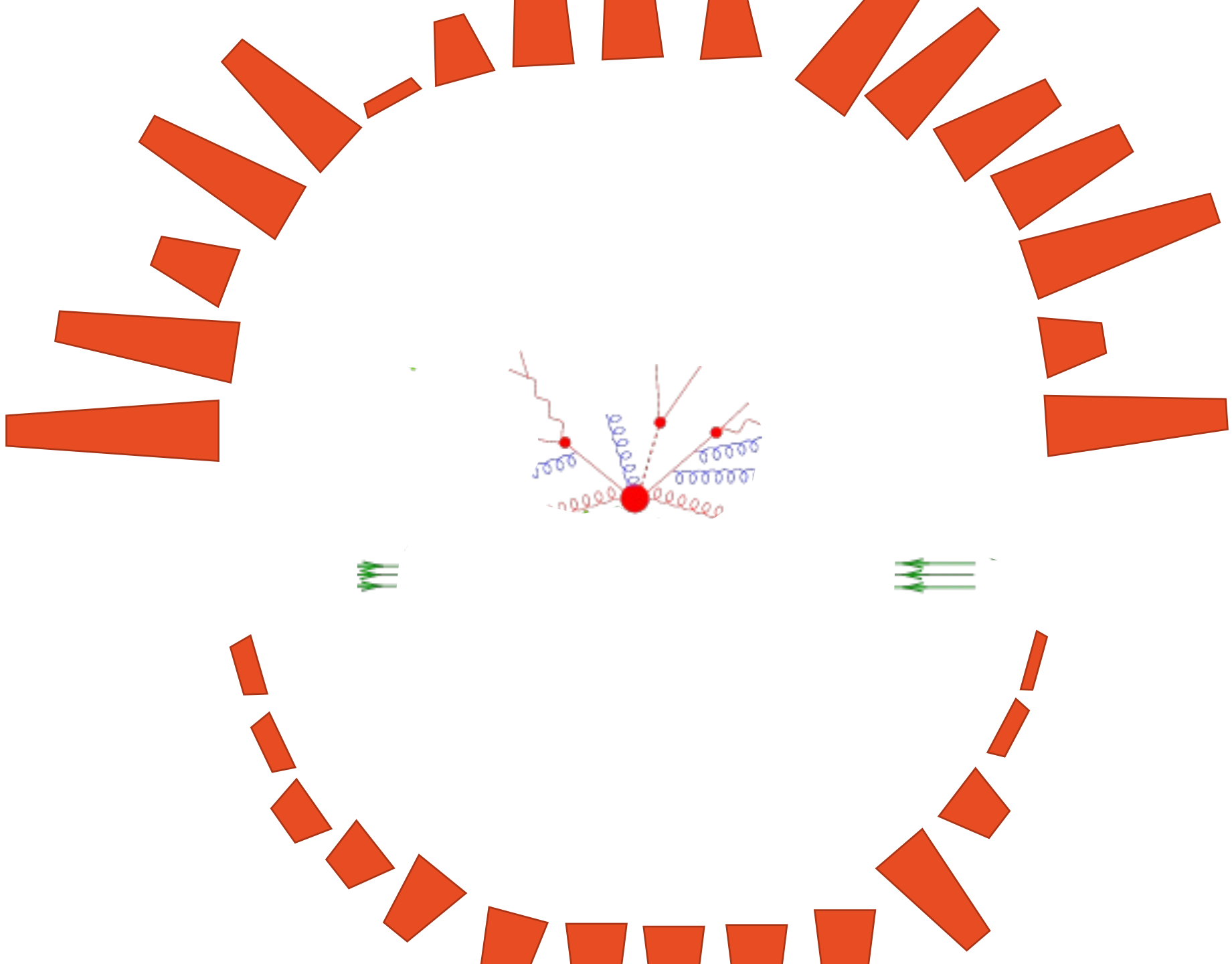


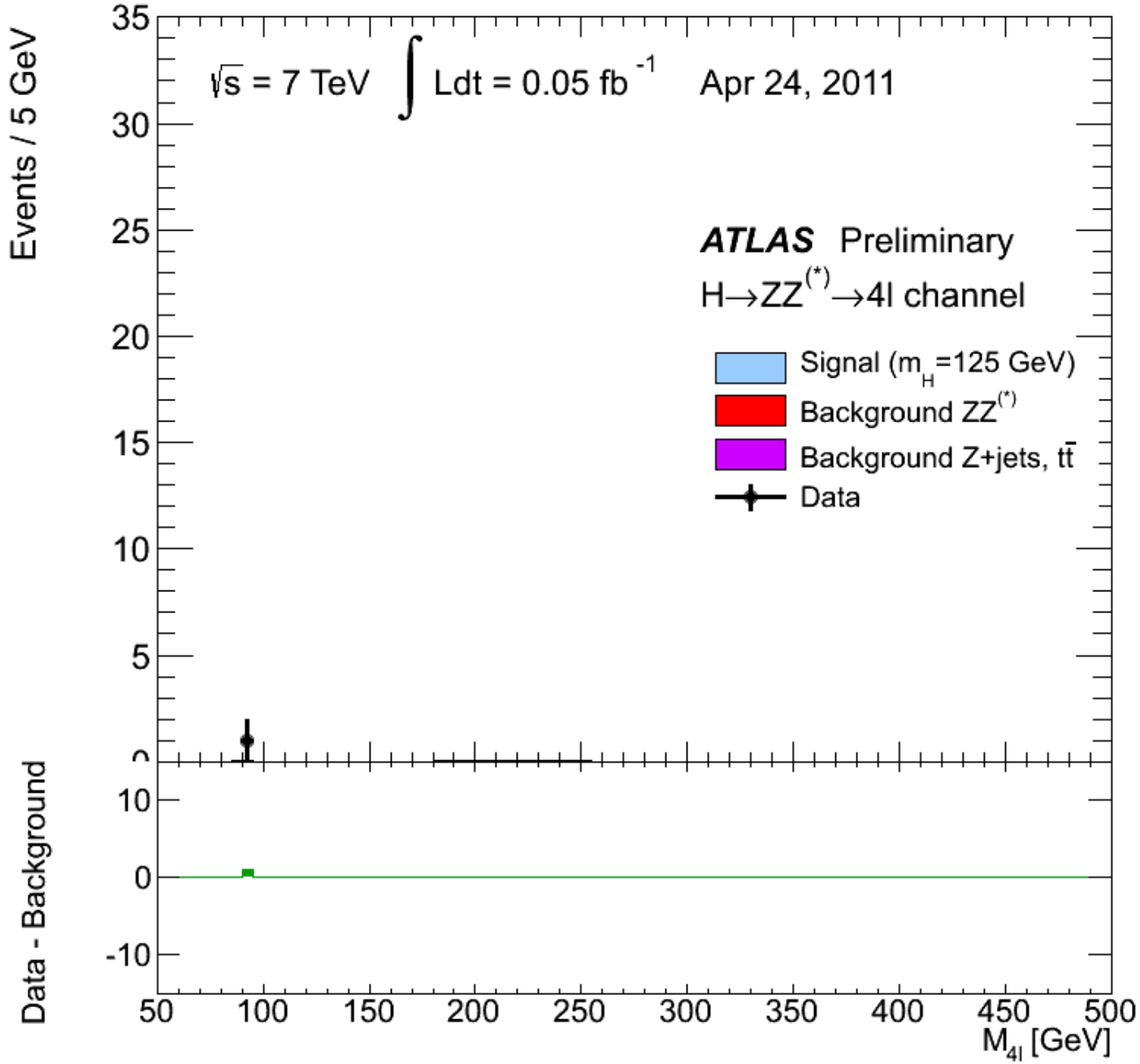
What we see is…

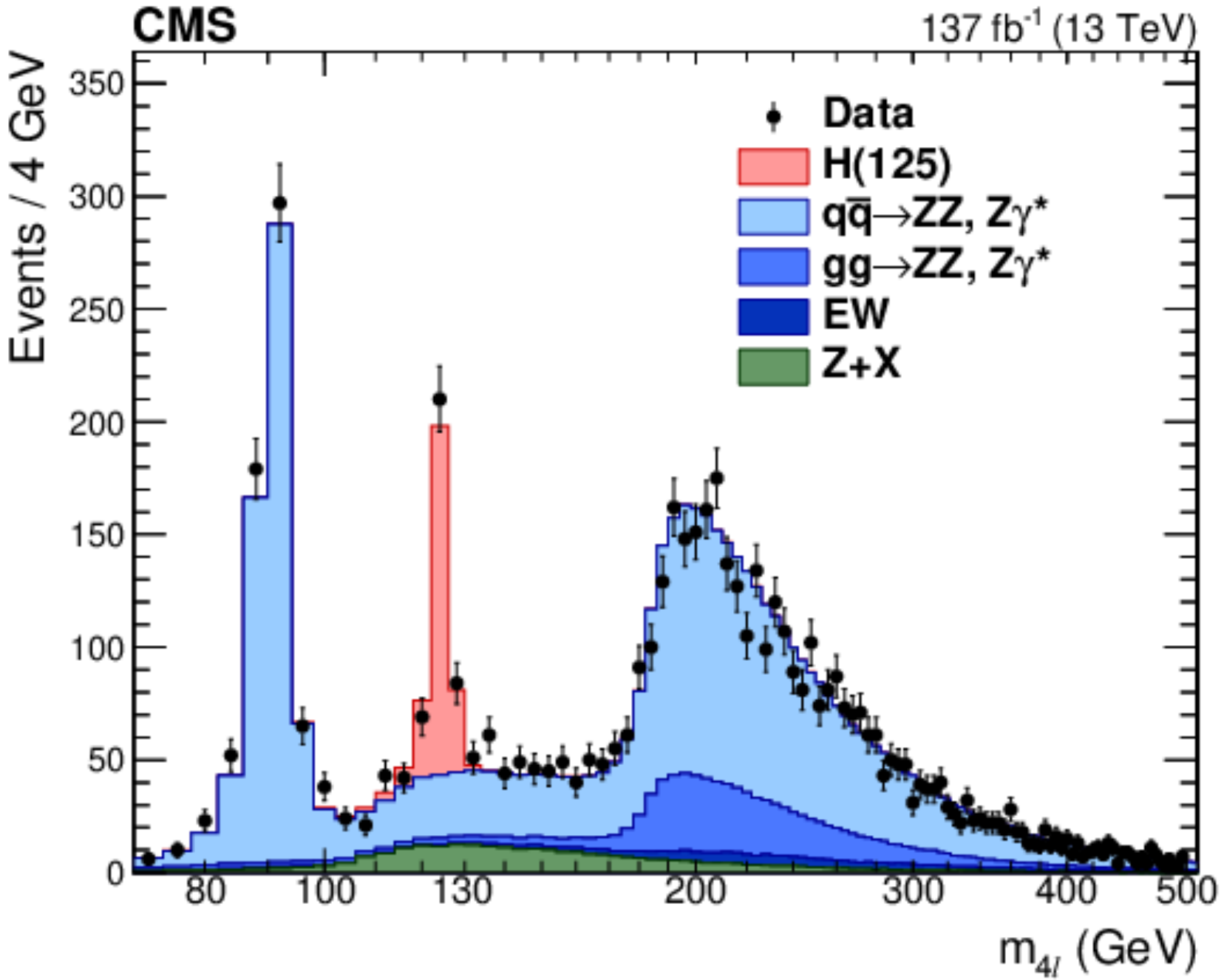




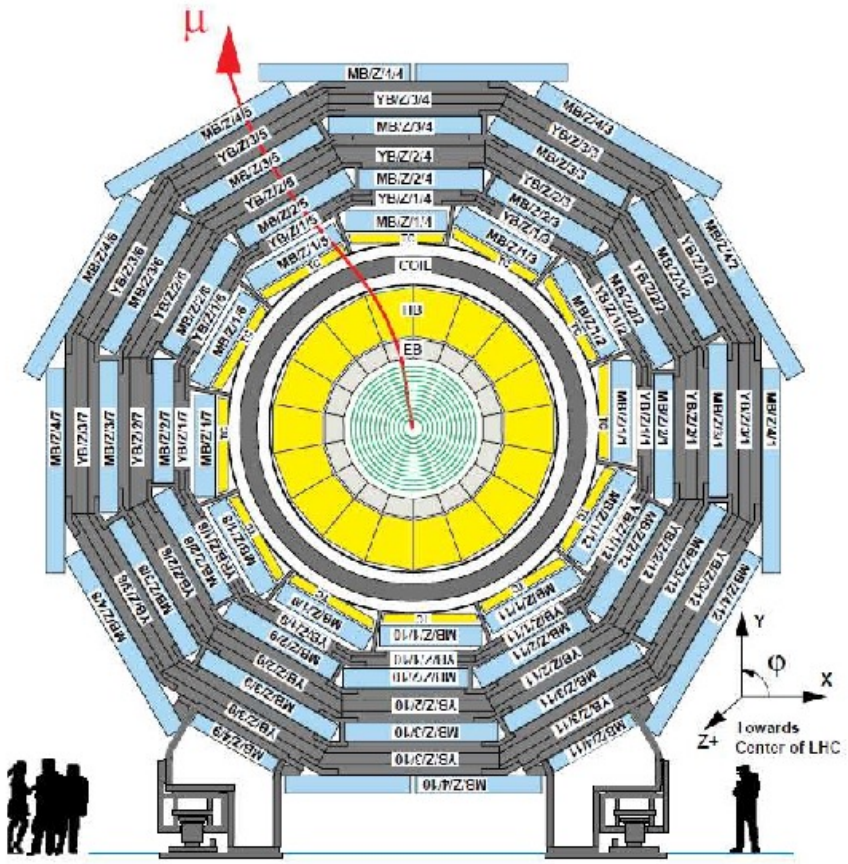


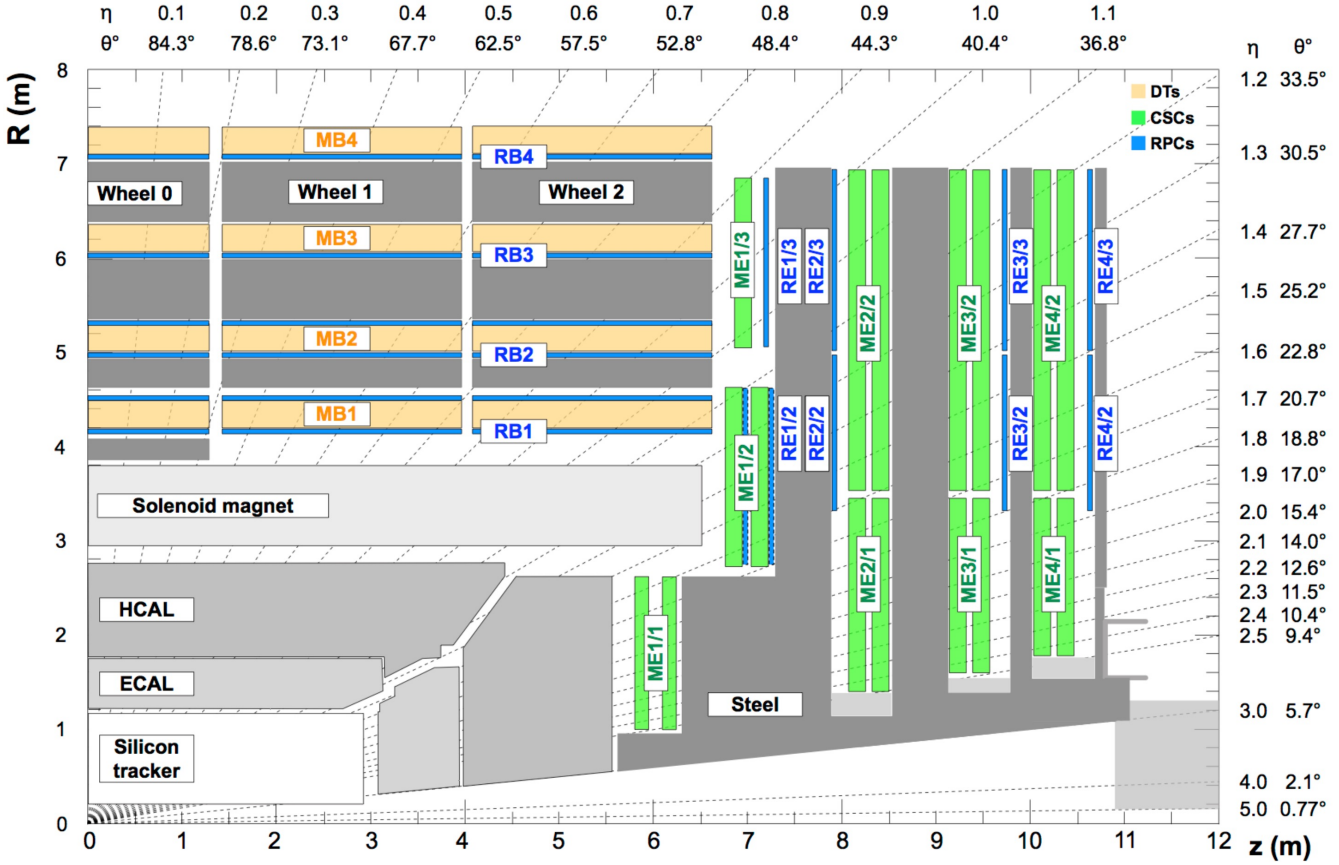



√s = 7 TeV ∫ Ldt = 0.05 fb -1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]

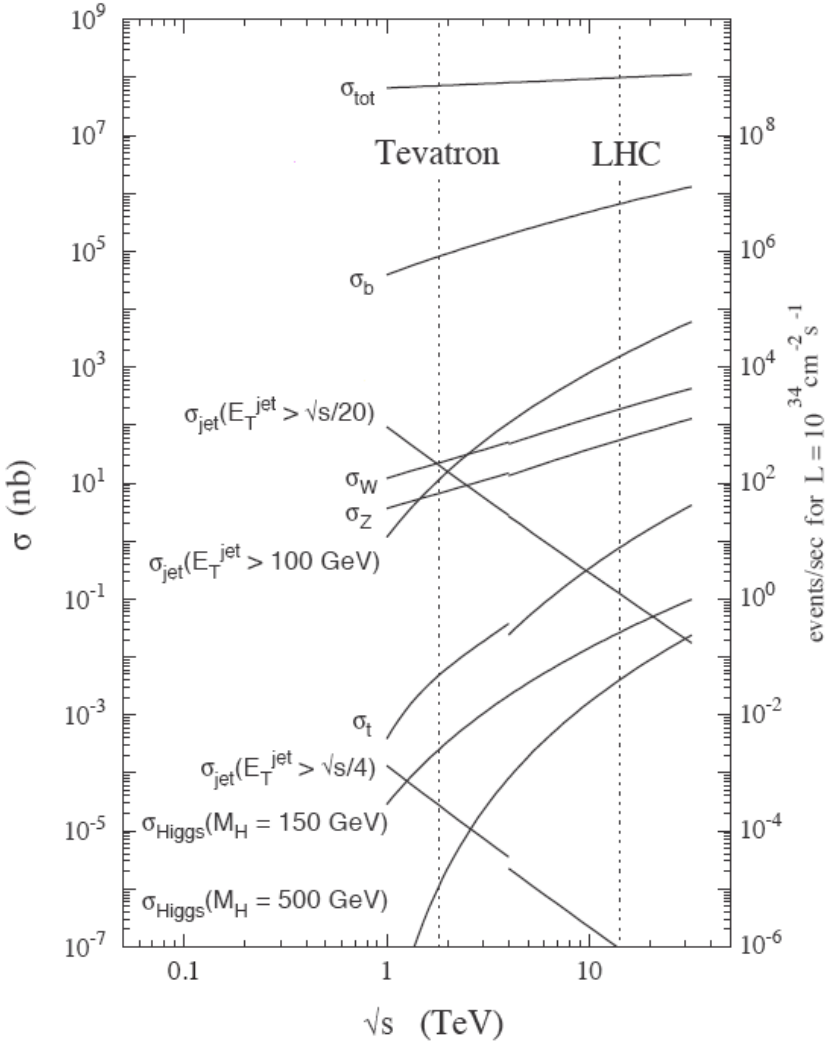

CMS
137 fb-1 (13 TeV)
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
EW
Z+X
Events / 4 GeV
0
50
100
150
200
250
300
350
80
100
130
200
300
400
500
m4l (GeV)

Detector cannot be perfect

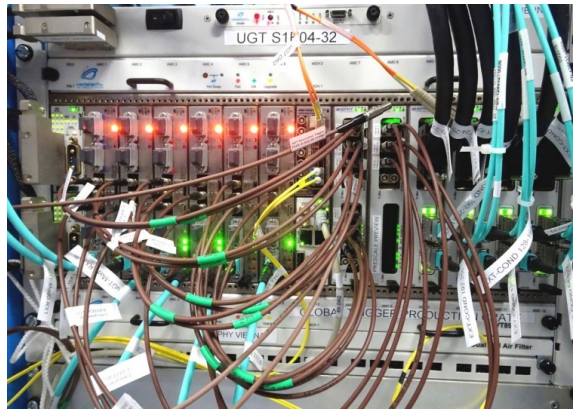


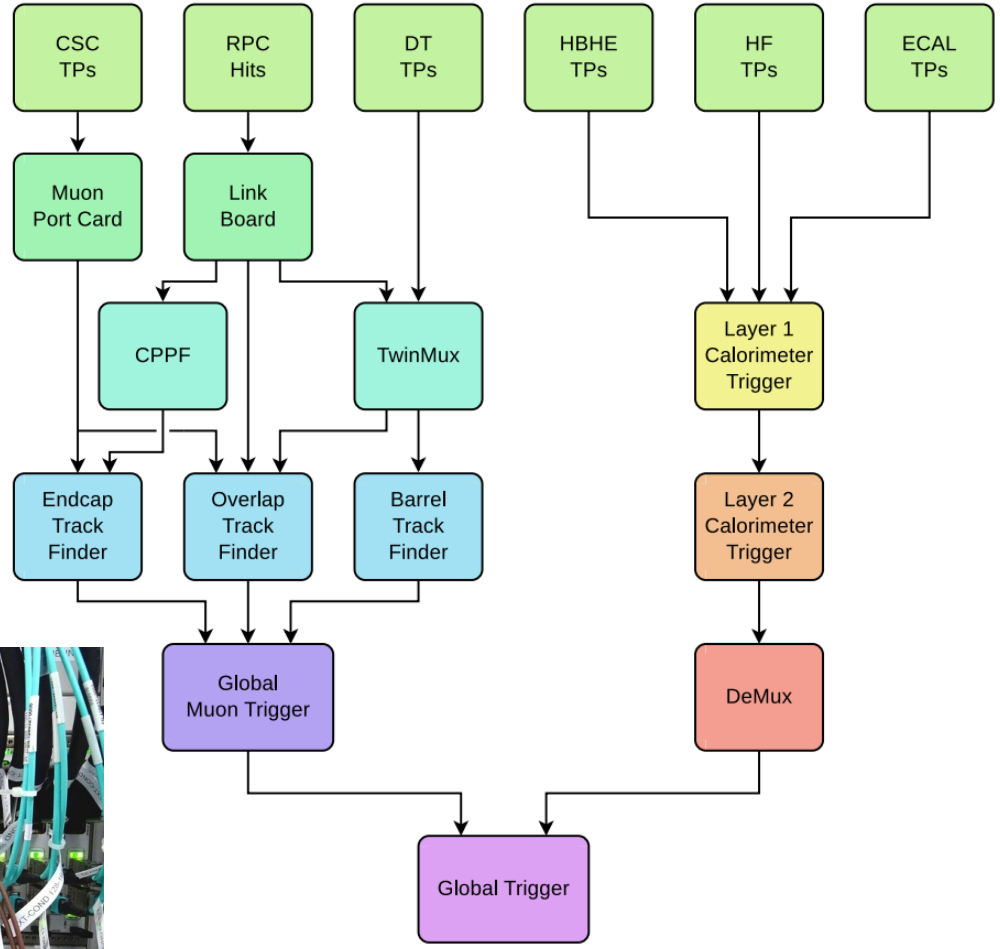


Most of events are not in our interest…

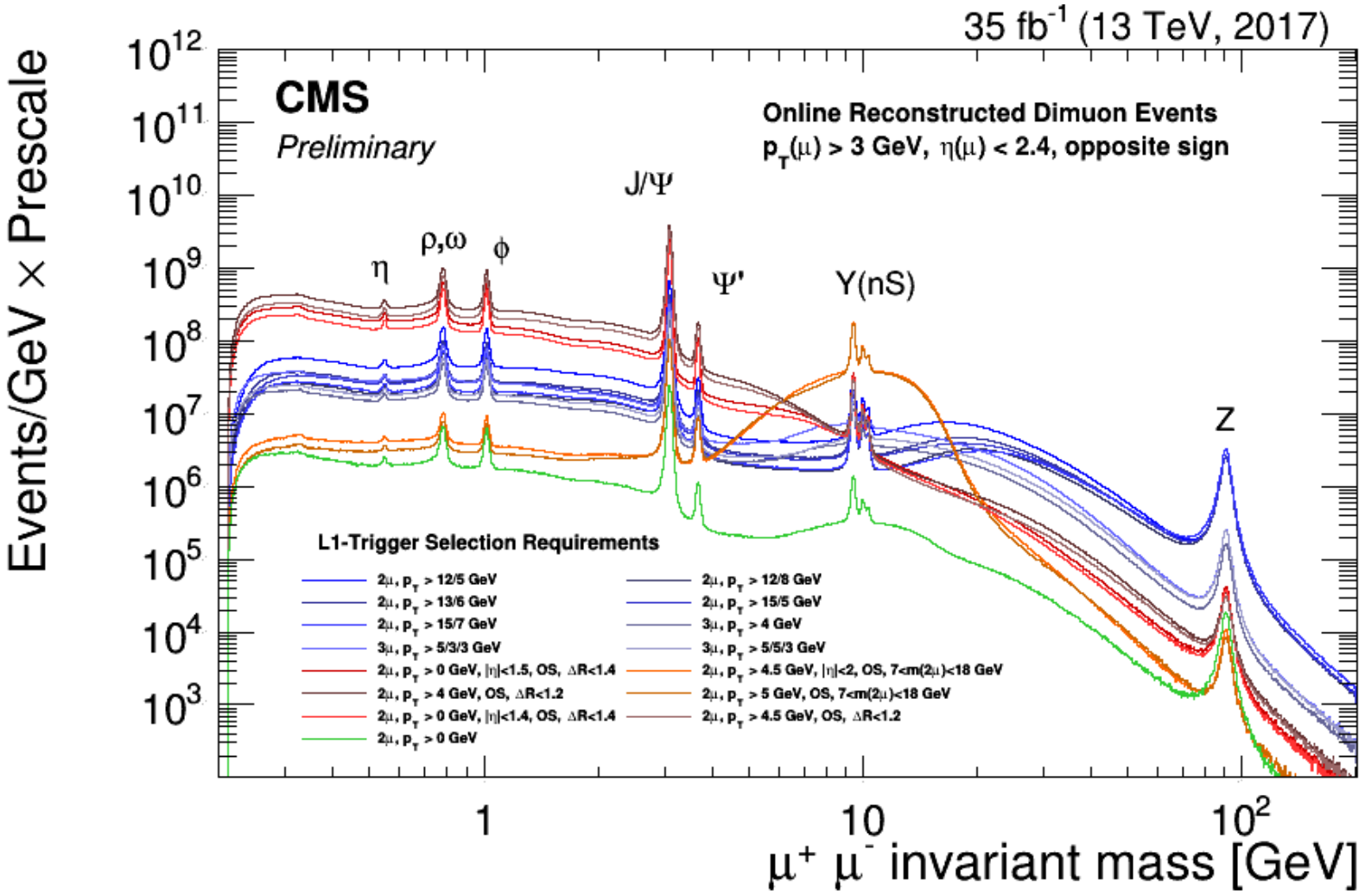


Decision has to be done <25ns

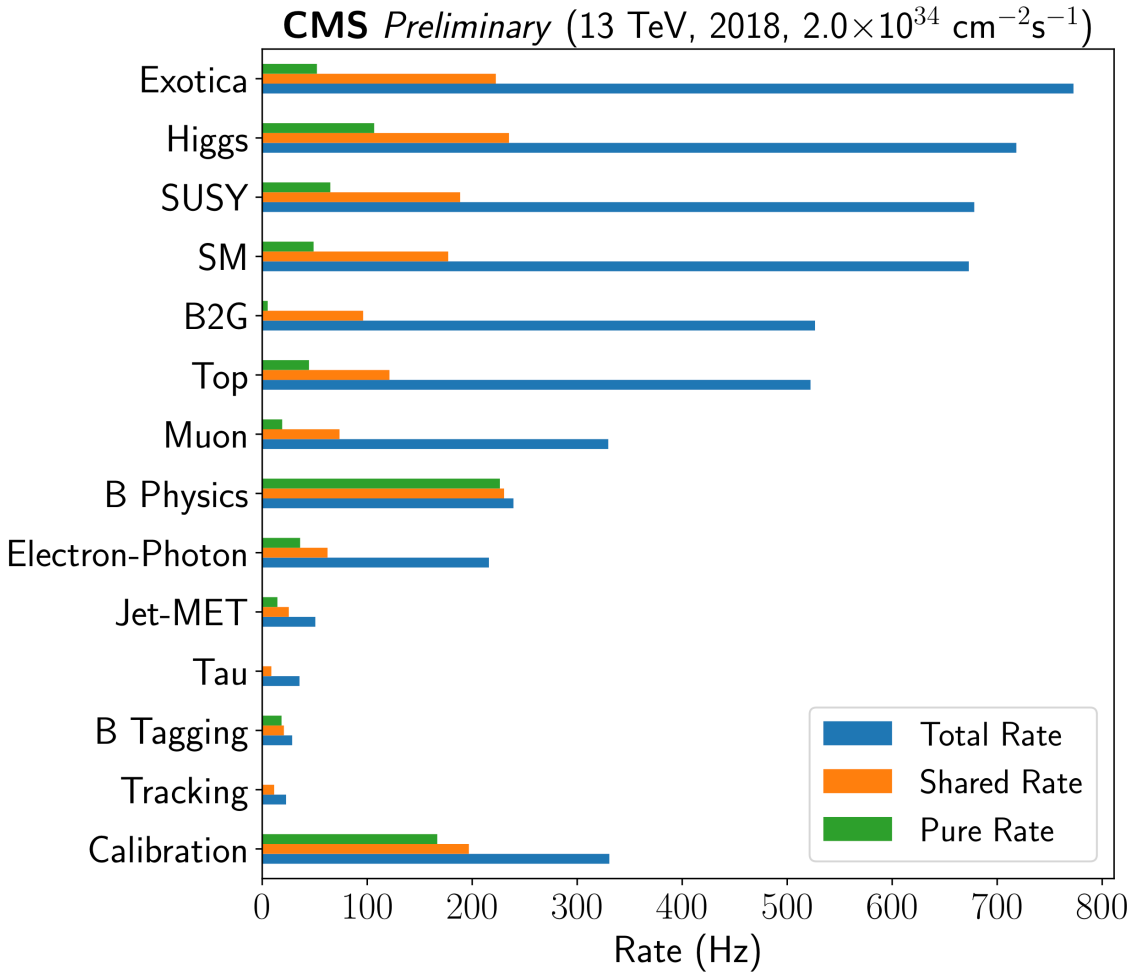


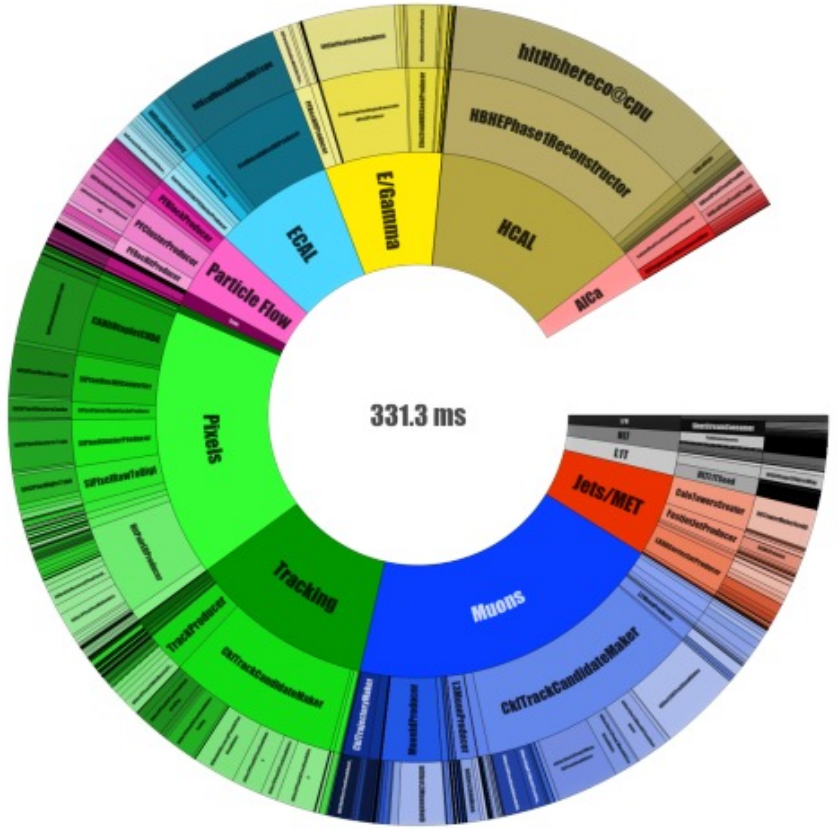


If we are interested in events with two muons



High Level Trigger





Exercise2: MC generation with Madgraph

KYUNG HEE UNIVERSITY

Experimentalist view:

we usually don't do the computation "by hand"

but is it advised to do it for the intuition

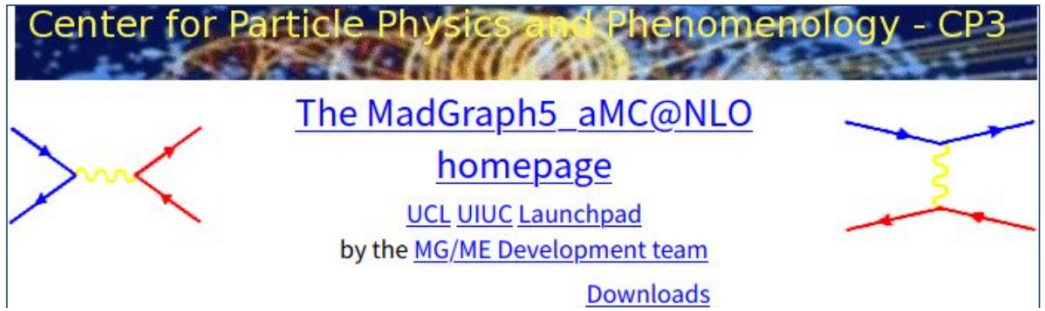
not to be fooled by the SW

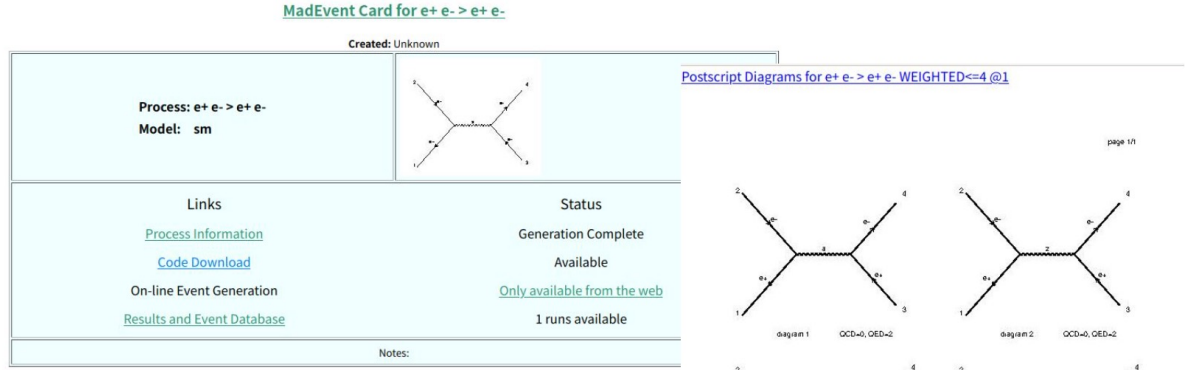
https://launchpad.net/mg5amcnlo

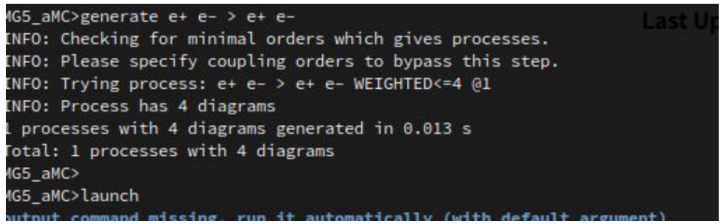
+Add Delphes Detector simulation

MadGraph/aMC@NLO does the job https://launchpad.net/mg5amcnlo

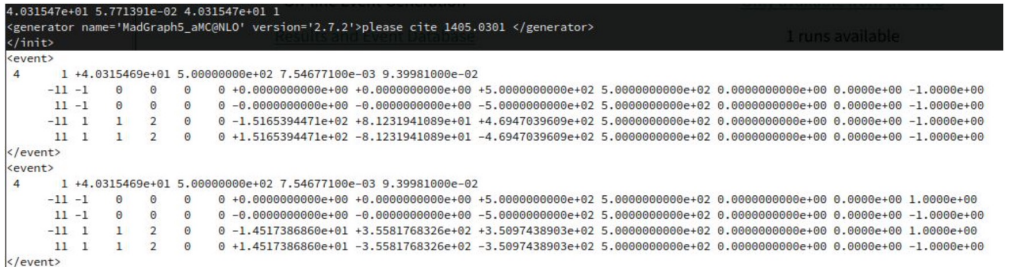
http://madgraph.phys.ucl



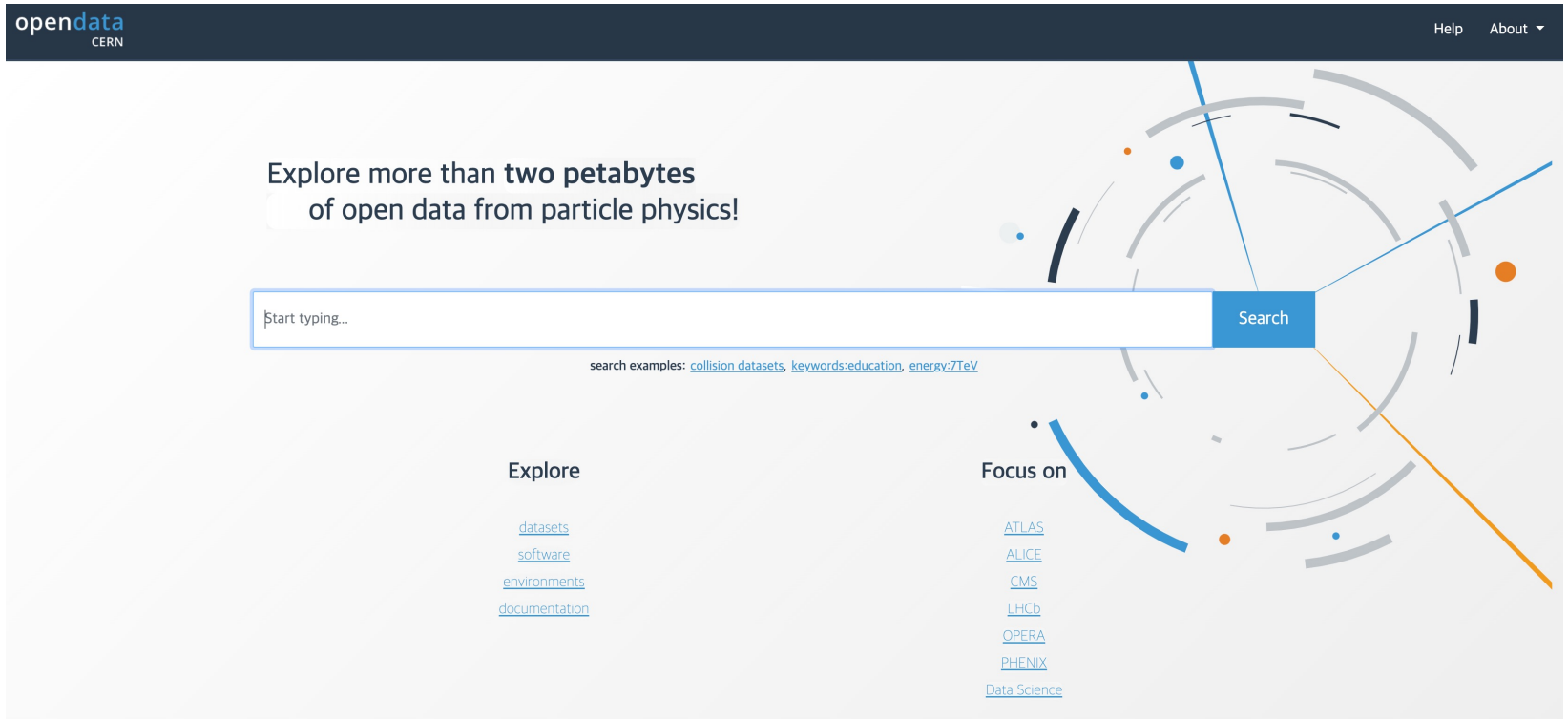




First output in "LHE" format



Want to be more realistic?

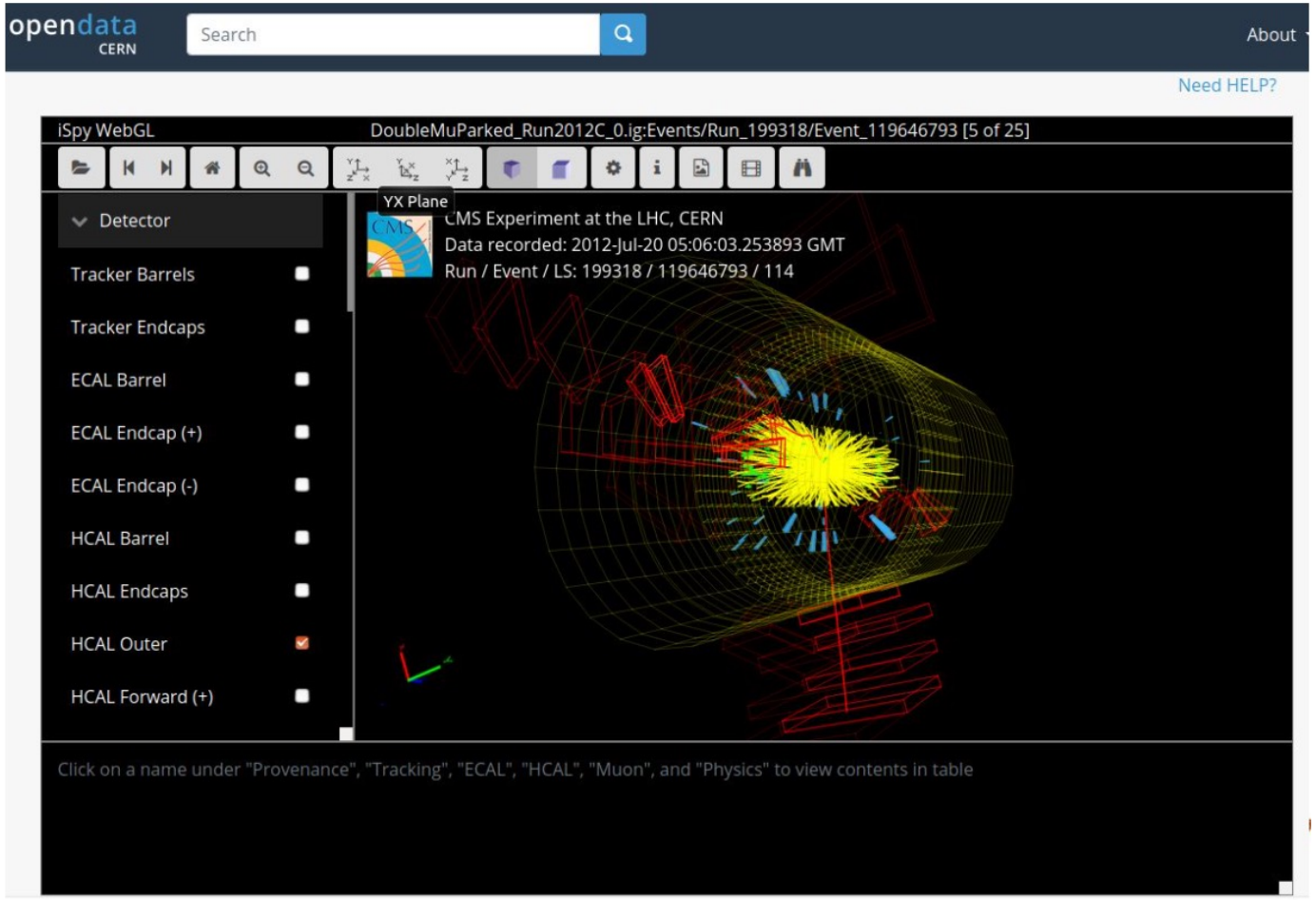


https://opendata.cern.ch/

Let's try!

Exercise 3: CMS Event Display

http://opendata.cern.ch/visualise/events/CMS



Exercise 4: Zee mass distribution

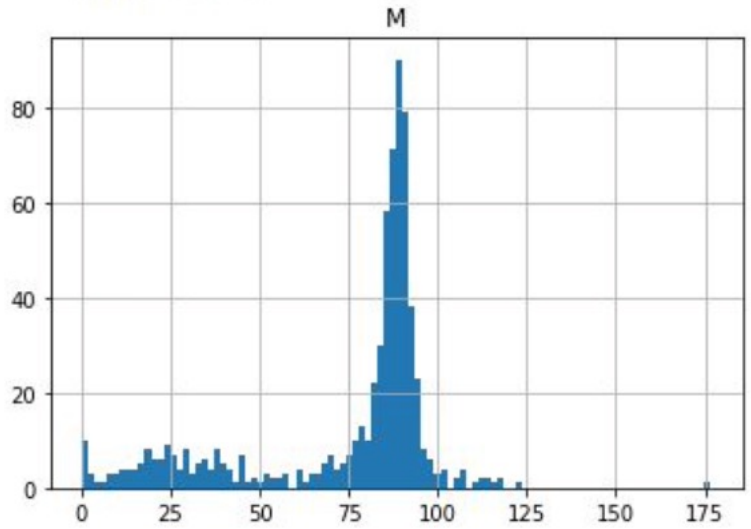
http://opendata.cern.ch/record/306/files/Zee.csv

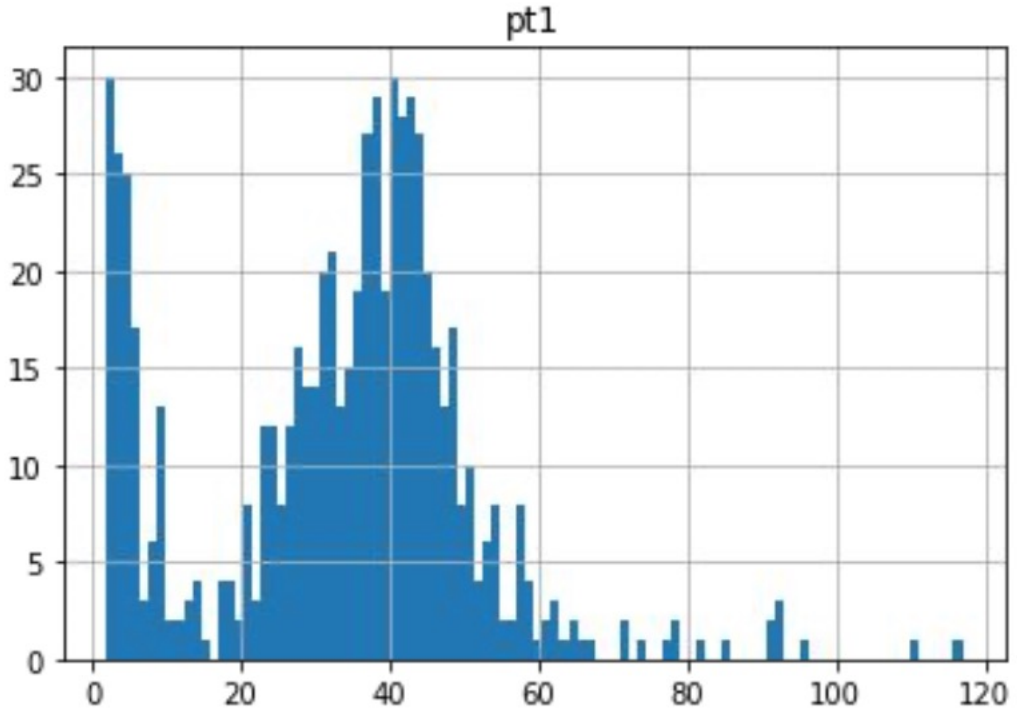
```
import pandas as pd
```

```
[23] df = pd.read_csv("Zee.csv")
```

```
[25] df.hist("M", bins=100)
```

```
array([[<matplotlib.axes._subplots.AxesSubplot object a
        dtype=object)
```





Not satisfied? Exercise 5: NanoAOD

https://opendata.cern.ch/record/12365
Run2012B_DoubleMuParked dataset in reduced NanoAOD format for education and outreach

https://hep.khu.ac.kr/download/2022/KIAS_Summer_Camp

Still Not satisfied?

Producing NanoAOD from the CMS AOD dataset
(warning: needs huge storage ~TB,
computing resources – we will show a demo only)

https://hep.khu.ac.kr/download/2022/KIAS_Summer_Camp/