Exploring the Frontier of Particle Physics: A Journey into the LHC and ATLAS Experiment

Miha Muškinja

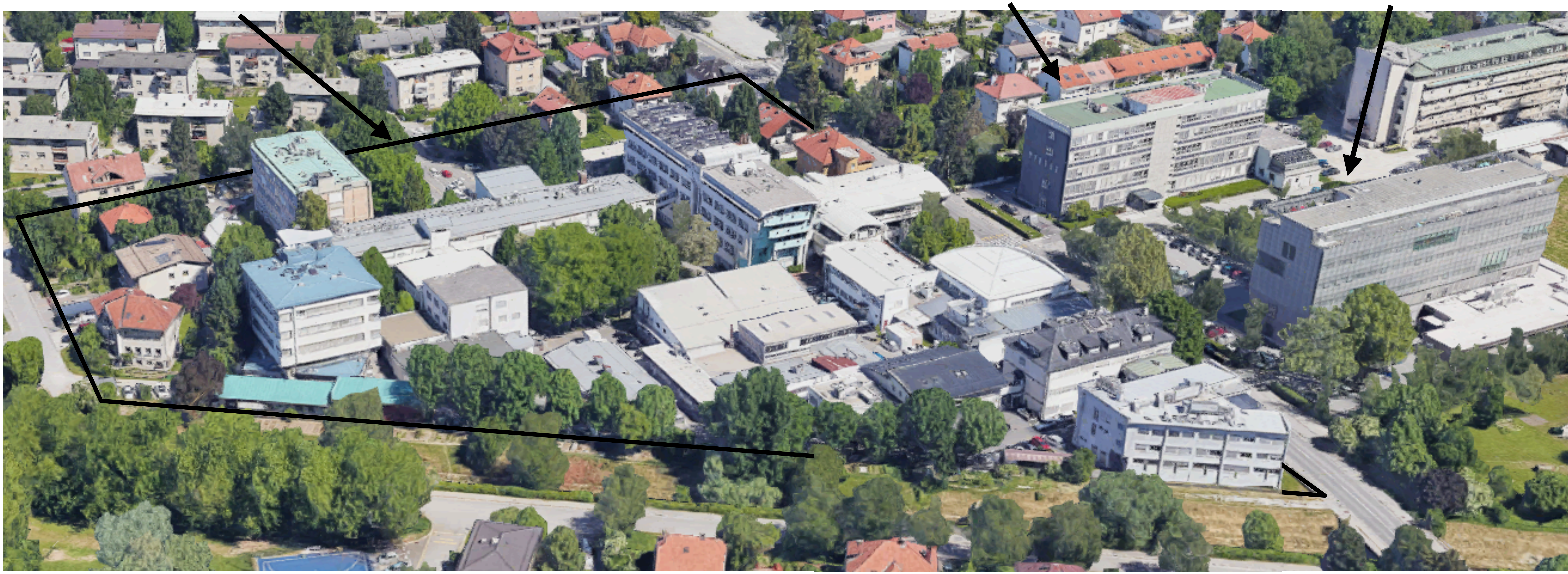
Physics in and Through Cosmology workshop
Friday, June 23, 2023

BERKELEY LAB

ATLAS EXPERIMENT

About me (studies)

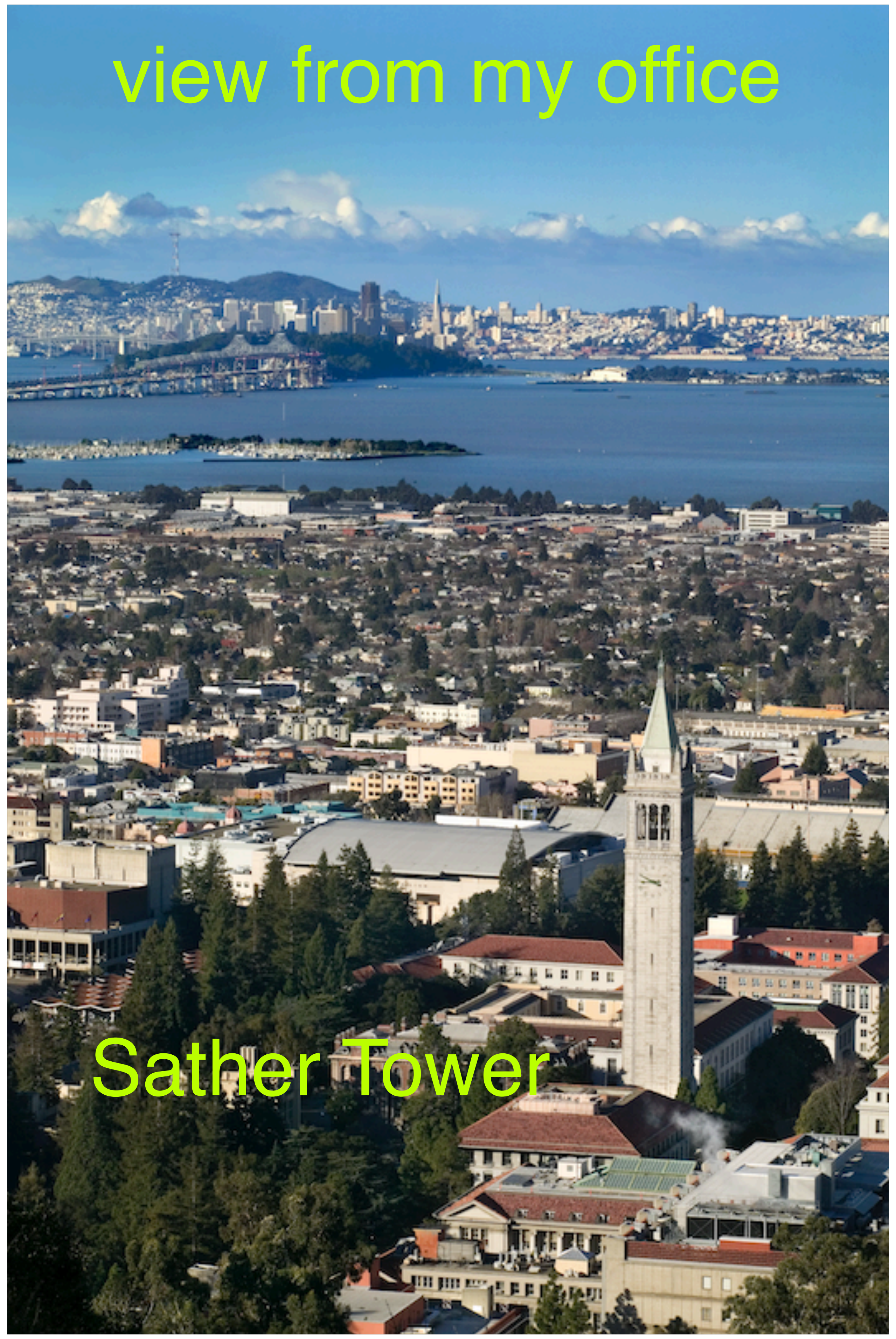
- Finished all my studies in University of Ljubljana in Slovenia (EU),
  - Bachelor, Masters, and PhD in physics from 2012 to 2018,
- For my PhD did research at the Jozef Stefan Institute on **particle physics**,
- The research was based on the data collected by the **ATLAS** experiment at **CERN**.



- One of the largest and most diverse scientific organizations in the world,
- About 16,000 scientists of more than 110 different nationalities work together,
- CERN's experimental program has consisted of hundreds of experiments spanning decades,
- **Common goal**: exploring the fundamental properties of nature (e.g. Higgs boson).

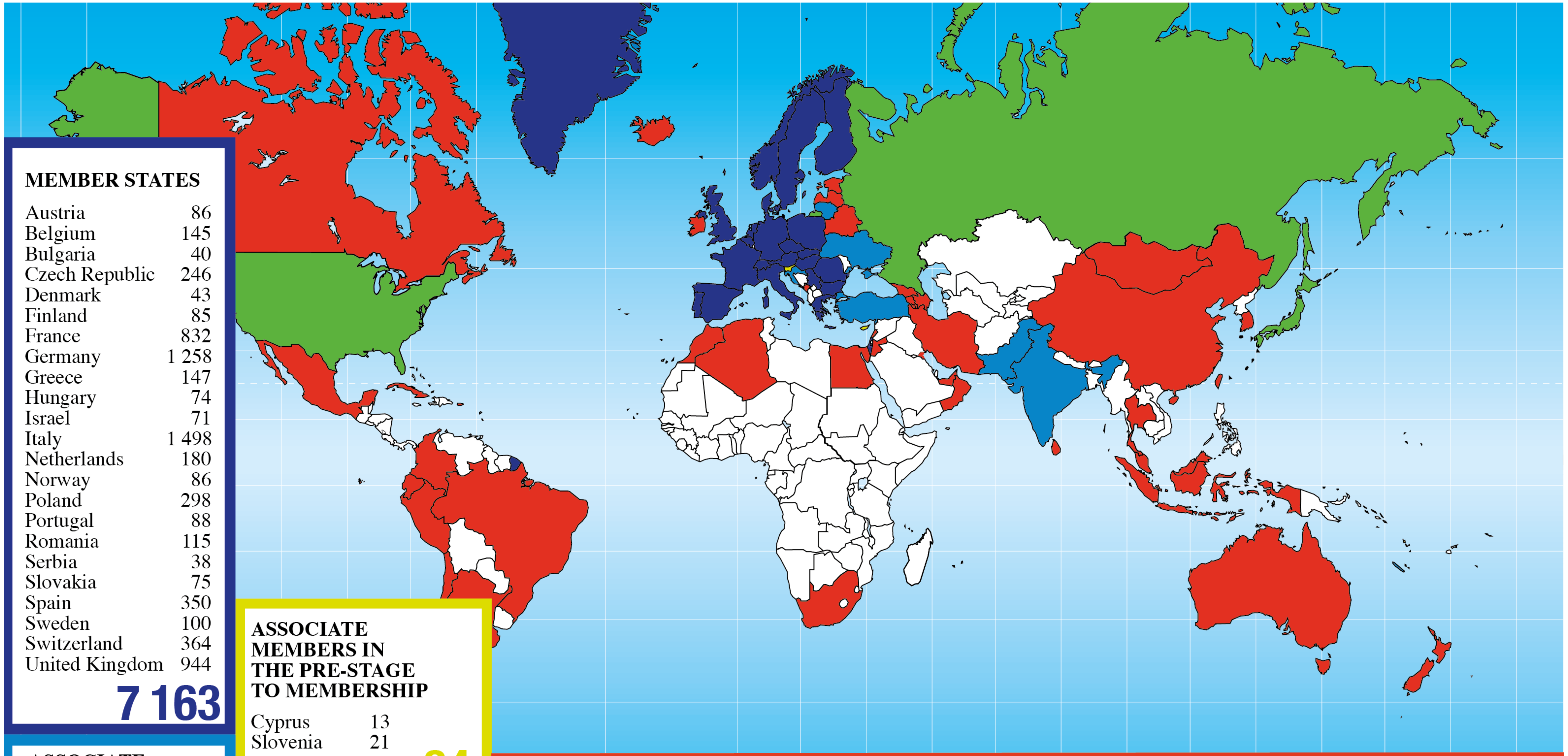
About me (now)

- Employed as a “Postdoctoral Research Fellow” at the Lawrence Berkeley National Laboratory,
- Arrived to Berkeley in 2018 and staying until October 2023,
- Lab conducts wide research in physics, computing, material science, quantum information, …
- I am part of the “ATLAS group” in the physics division. Our research based in CERN.



CERN participating countries

Distribution of All CERN Users by Location of Institute on 27 January 2020



MEMBER STATES

Austria	86
Belgium	145
Bulgaria	40
Czech Republic	246
Denmark	43
Finland	85
France	832
Germany	1 258
Greece	147
Hungary	74
Israel	71
Italy	1 498
Netherlands	180
Norway	86
Poland	298
Portugal	88
Romania	115
Serbia	38
Slovakia	75
Spain	350
Sweden	100
Switzerland	364
United Kingdom	944

7 163

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP

Cyprus	13
Slovenia	21

34

ASSOCIATE MEMBERS

Croatia	41
India	186
Lithuania	21
Pakistan	39
Turkey	128
Ukraine	35

450

OBSERVERS

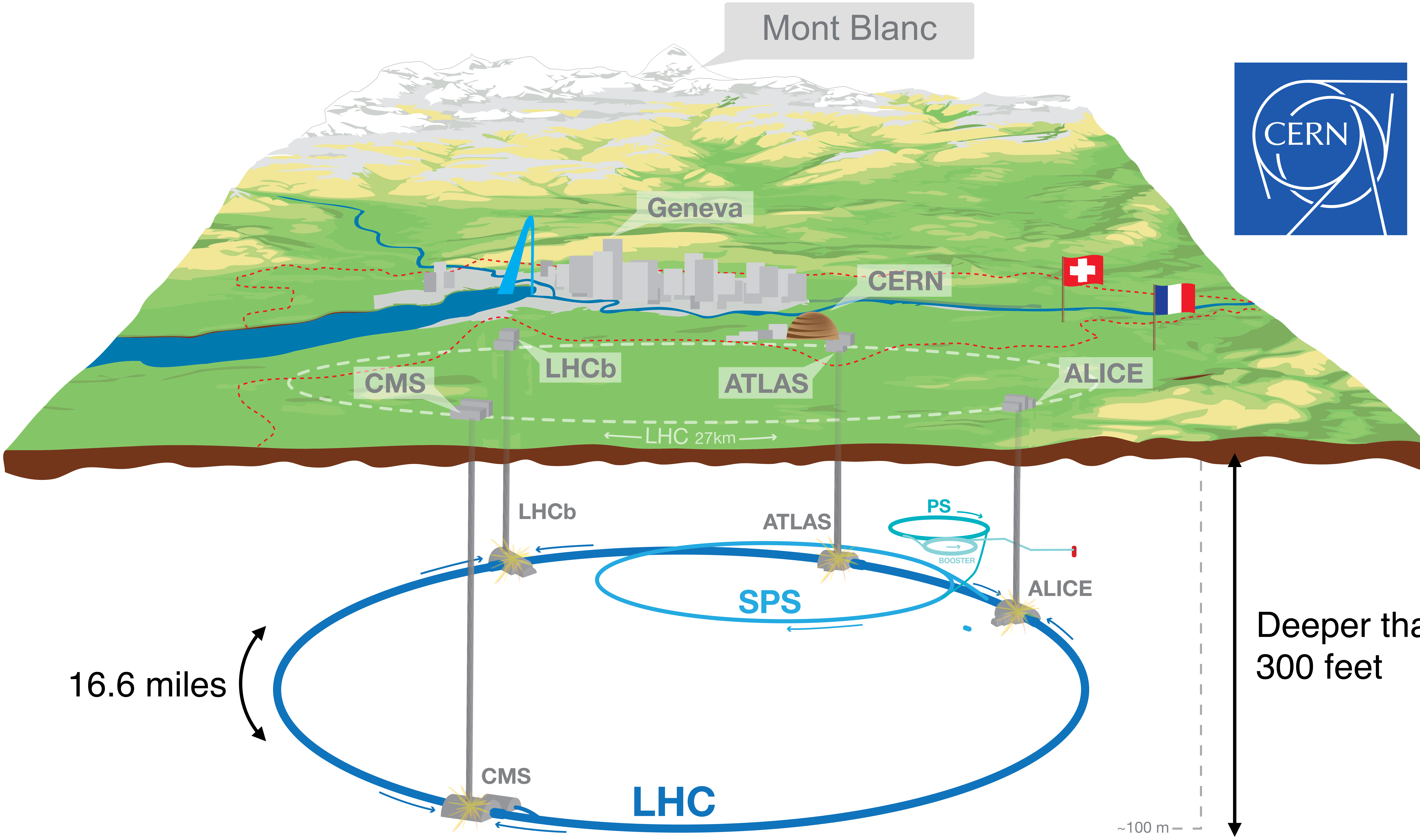
Japan	245
Russia	1 071
USA	1 960

3 276

OTHERS

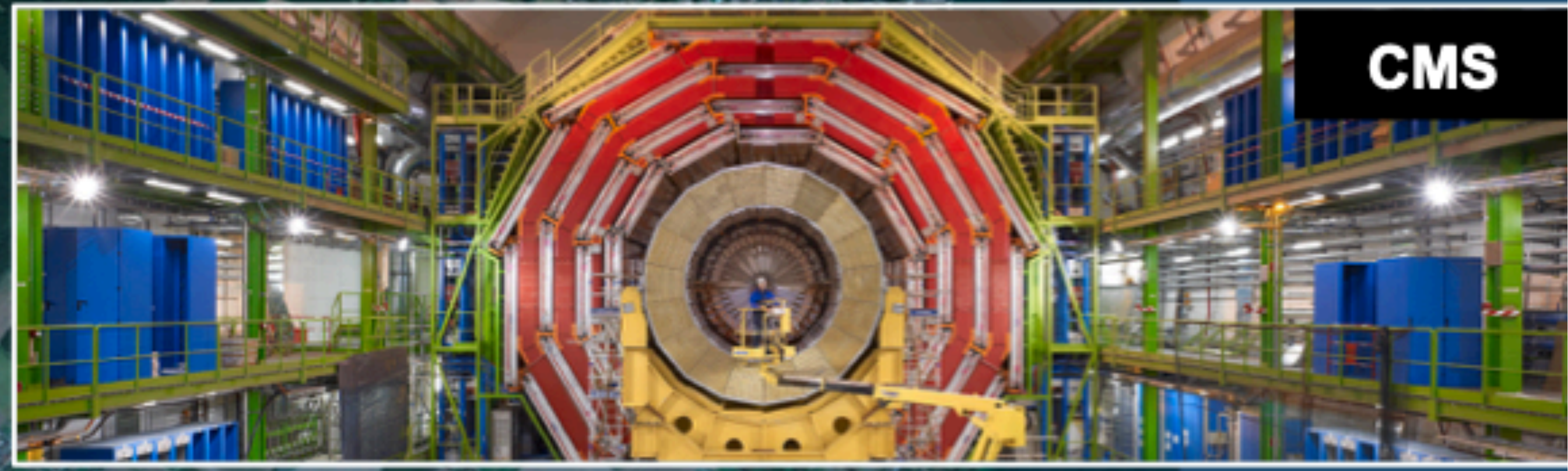
Algeria	3
Argentina	16
Armenia	13
Australia	23
Azerbaijan	2
Bahrain	3
Belarus	27
Brazil	114
Canada	206
Chile	22
China	362
Colombia	21
Cuba	3
Ecuador	4
Egypt	16
Estonia	24
Georgia	37
Hong Kong	21
Iceland	3
Indonesia	8
Iran	11
Ireland	7
Jordan	1
Korea	143
Kuwait	2
Latvia	2
Lebanon	15
Malaysia	9
Malta	4
Mexico	53
Mongolia	2
Montenegro	5
Morocco	16
New Zealand	11
Oman	1
Peru	3
Puerto Rico	1
Singapore	3
South Africa	80
Sri Lanka	8
Taiwan	55
Thailand	18
U.A.E.	2

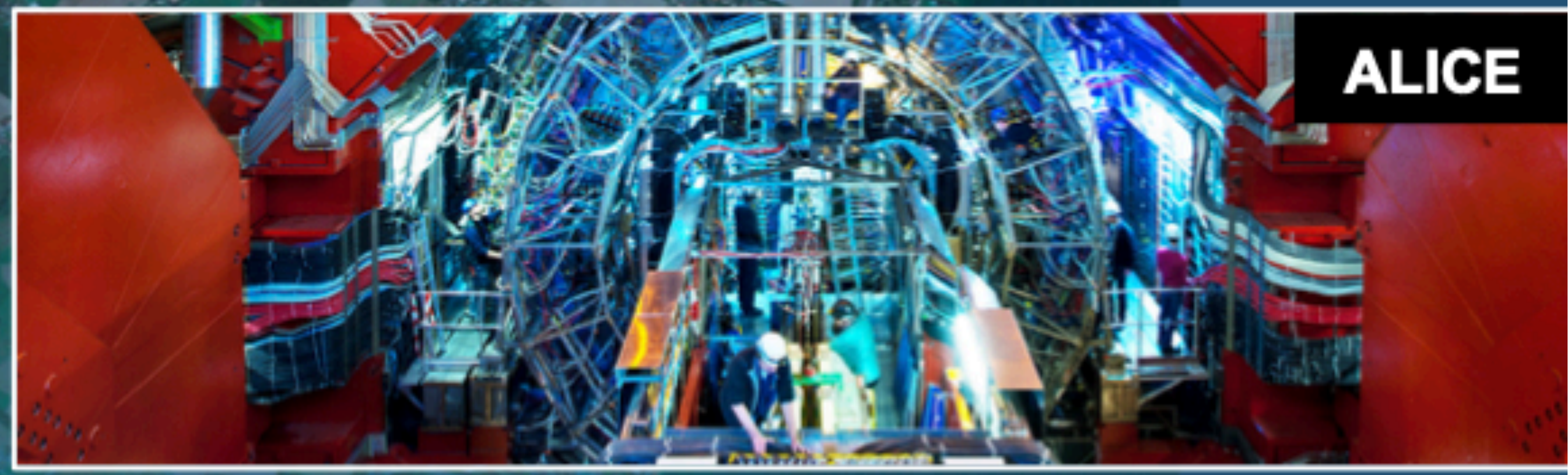
1 380



16.6 miles

Deeper than 300 feet

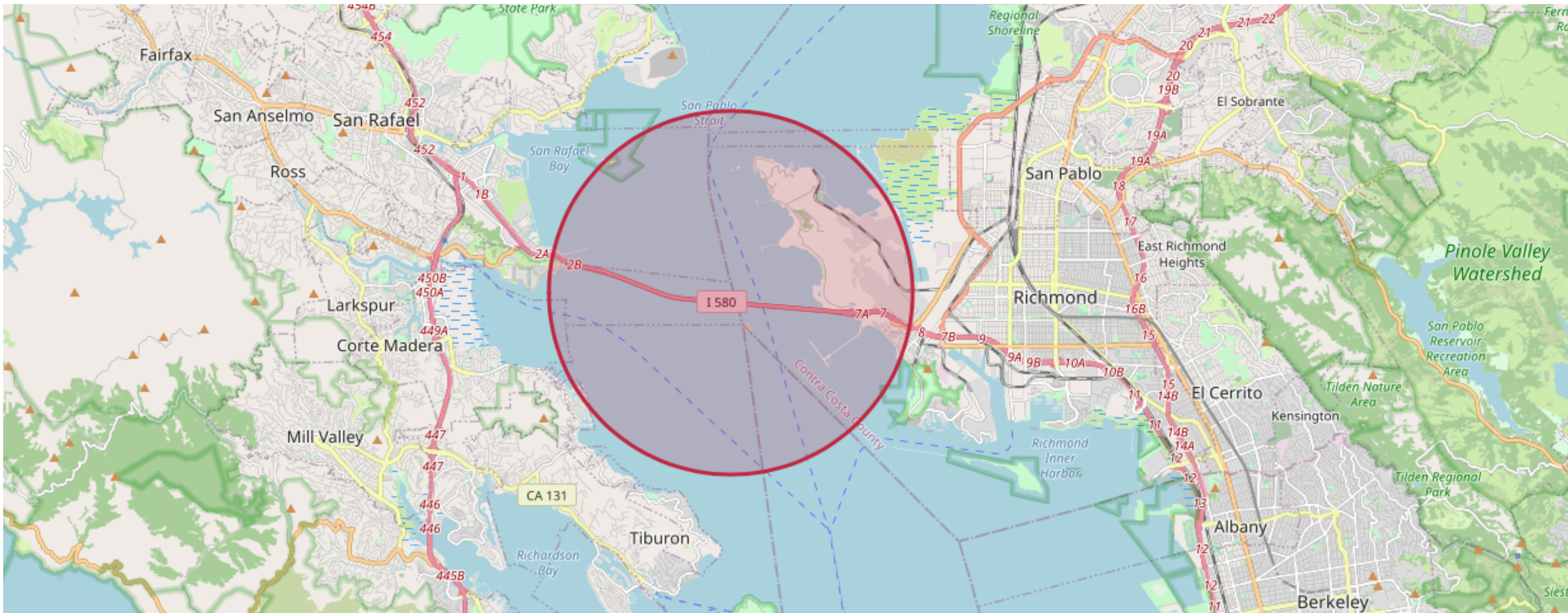




LHC — areal view

Size of the LHC in comparison

- Largest and most powerful “particle collider” in the world,
- Diameter of the Large Hadron Collider is about the same size as the Richmond bridge,
- Test it out: https://natronics.github.io/science-hack-day-2014/lhc-map/.



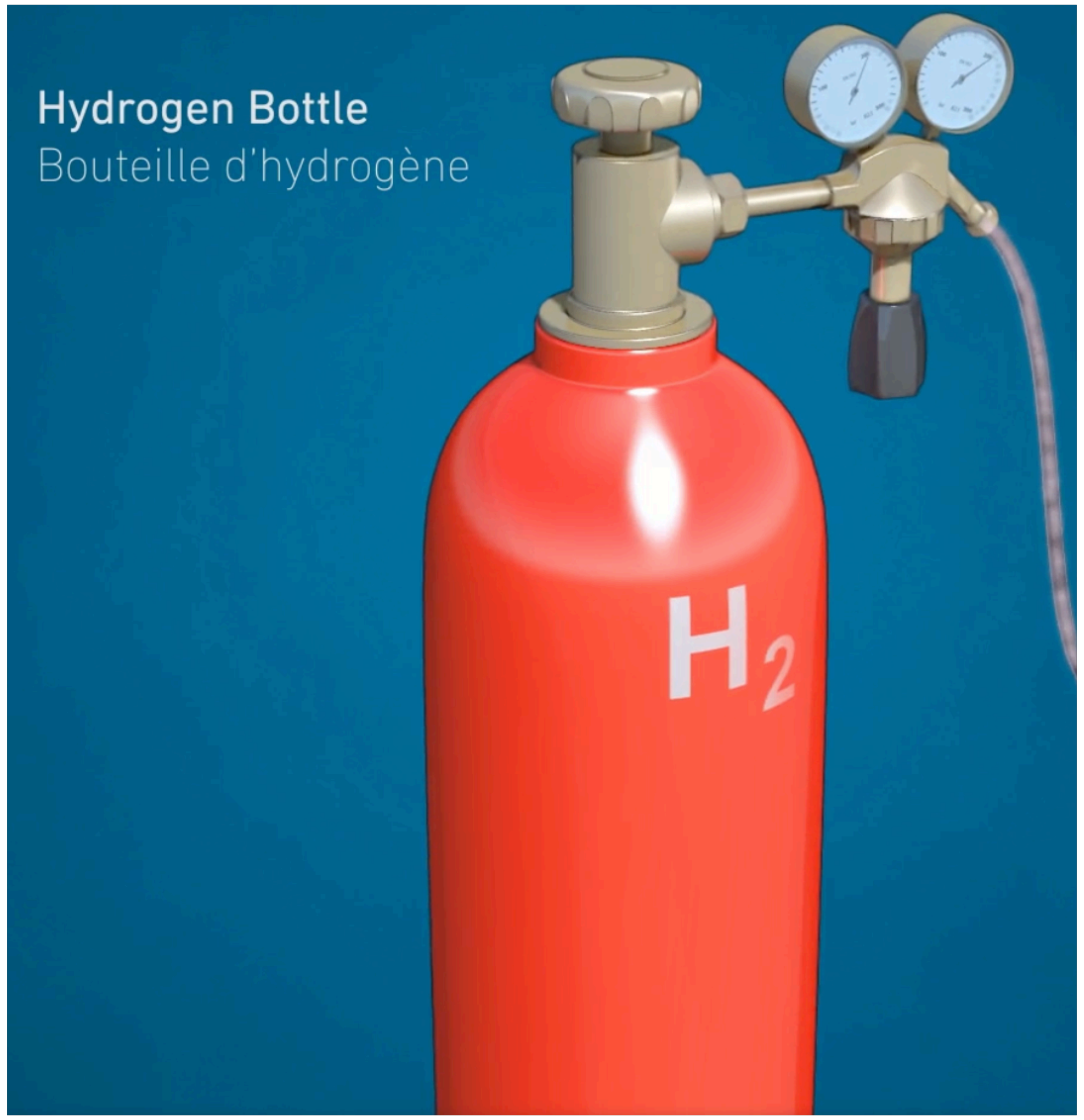
What is the purpose of the LHC?

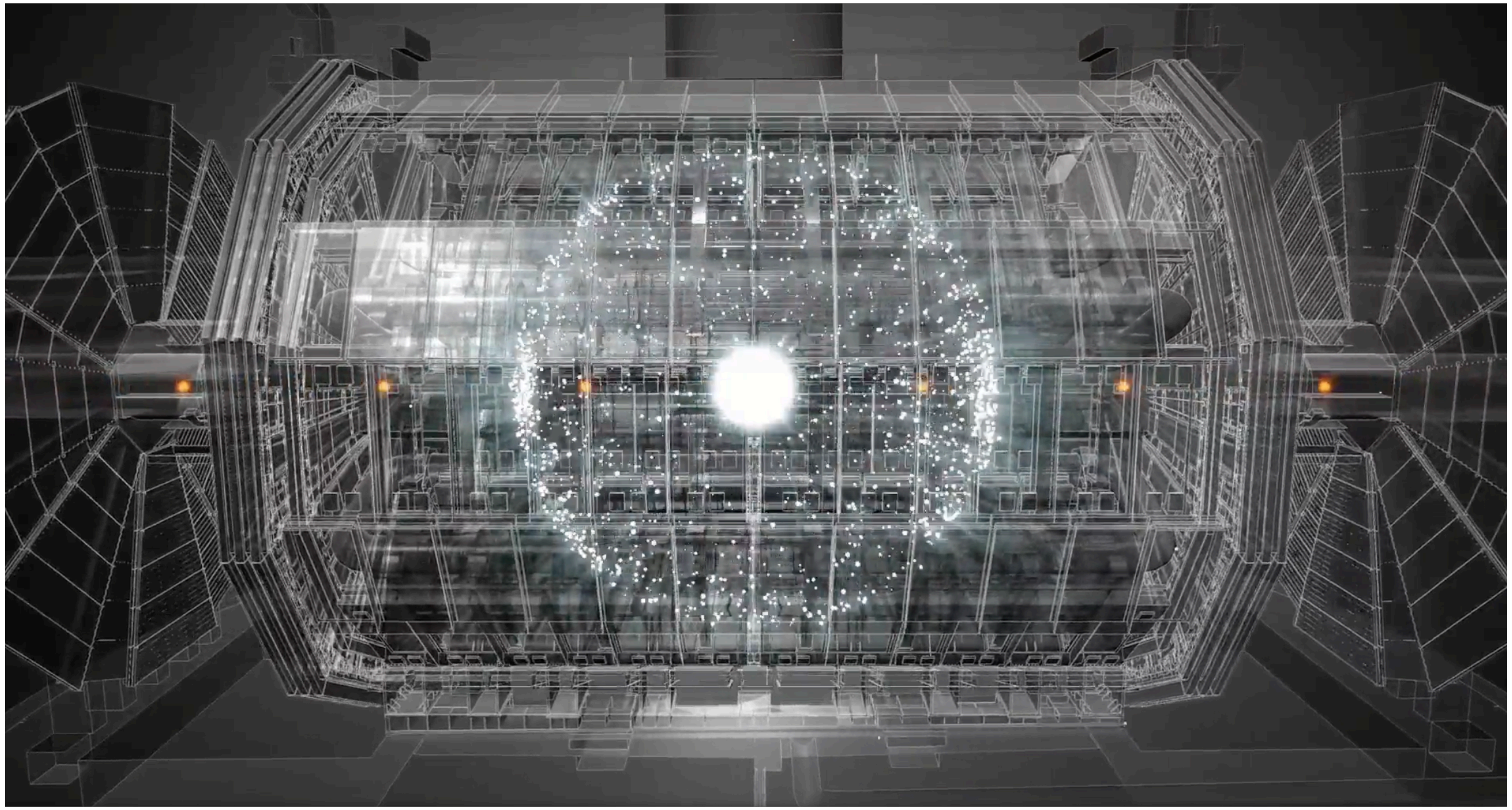
LHC: Path of protons

- The LHC accelerates protons almost to the speed of light (99.9999991% c),
- It facilitates proton-proton collisions at the center of **four experiments**:
  - ALICE, ATLAS, CMS, LHCb
- Hundreds of elementary particles are created in each collision (for example, a Higgs boson),
- Particle detectors collect the collision data,
- Physicists analyze the data to gain insights about the fundamental properties of nature.

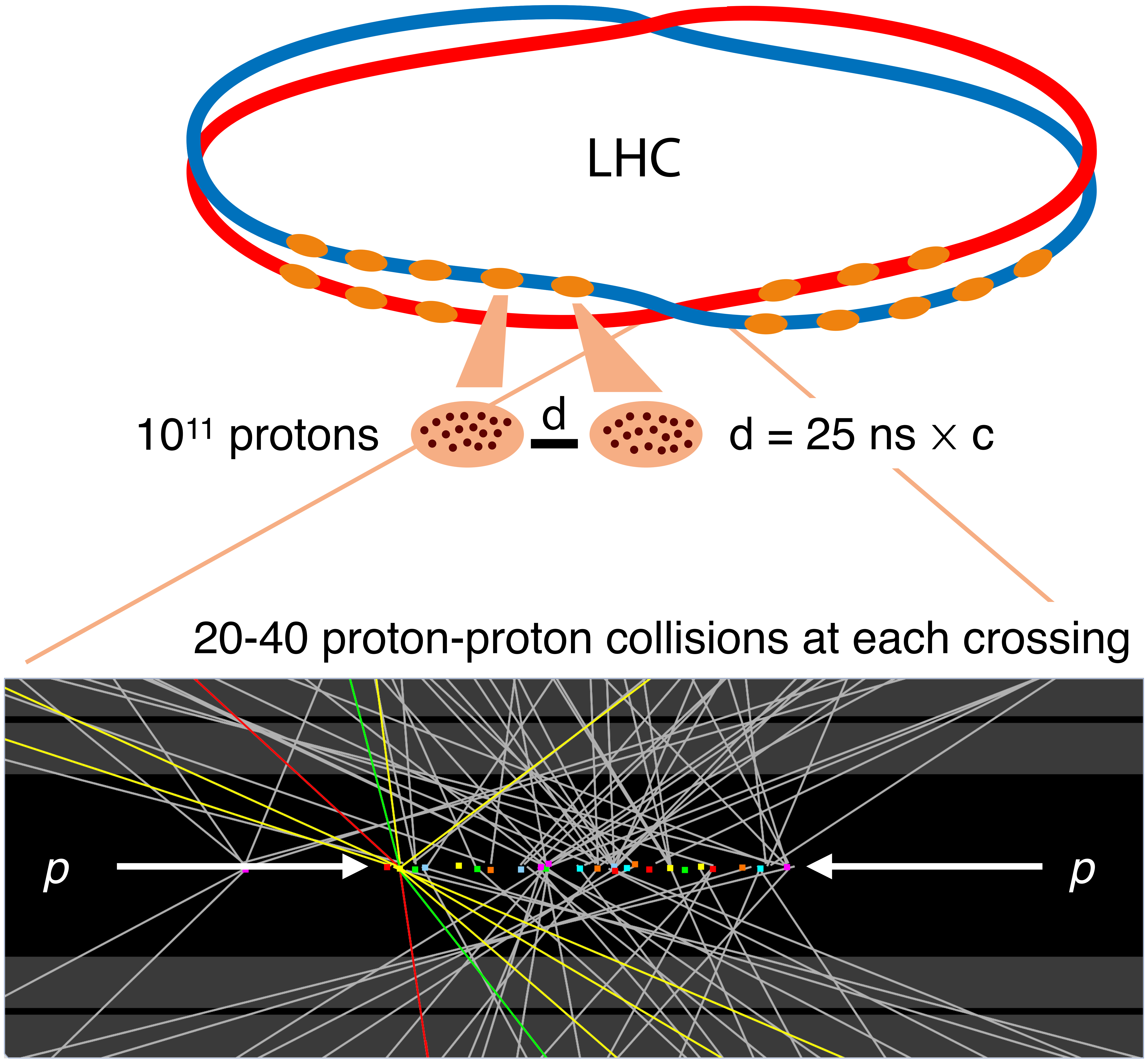
$\gamma > 7000$

Lorentz factor

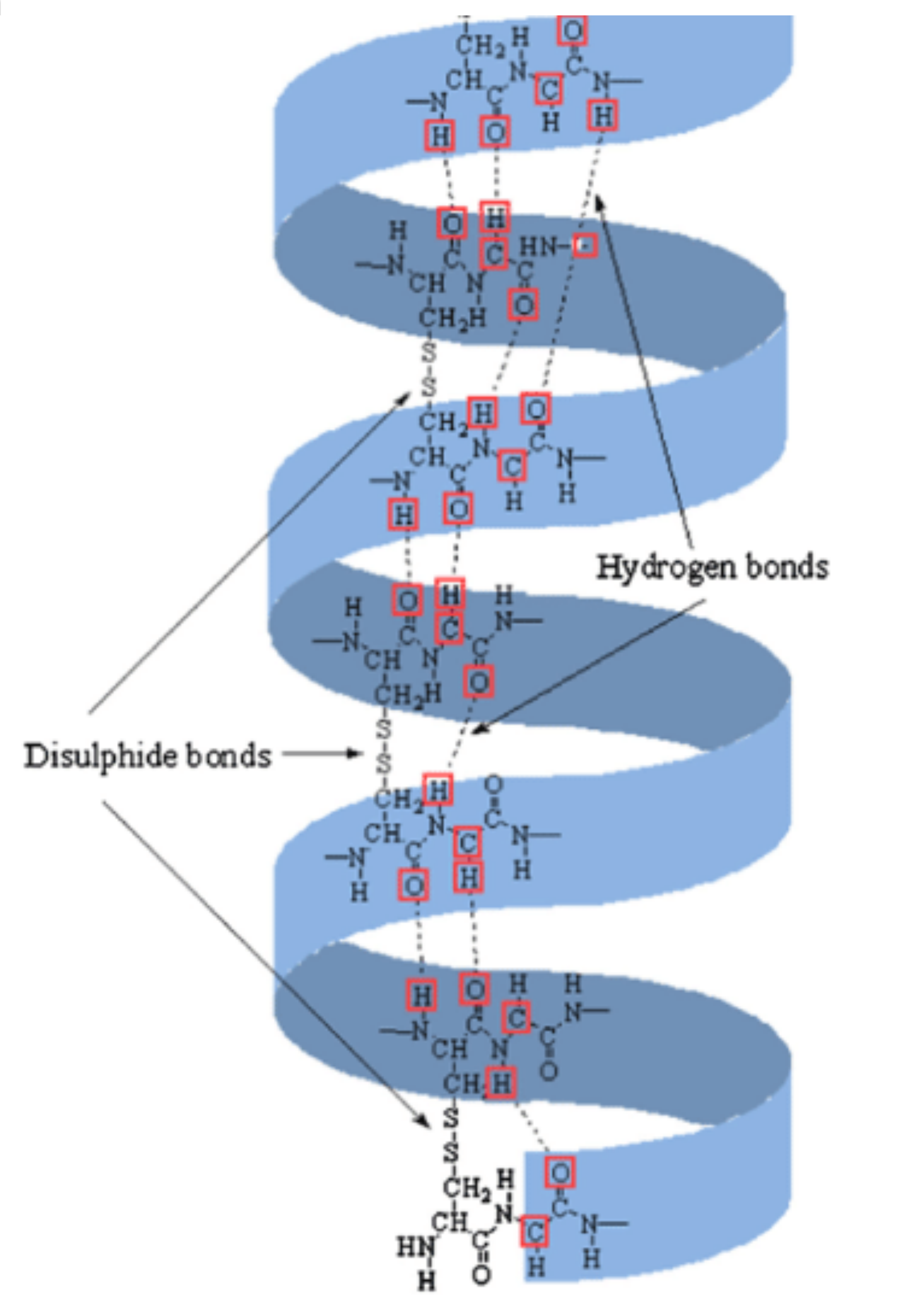




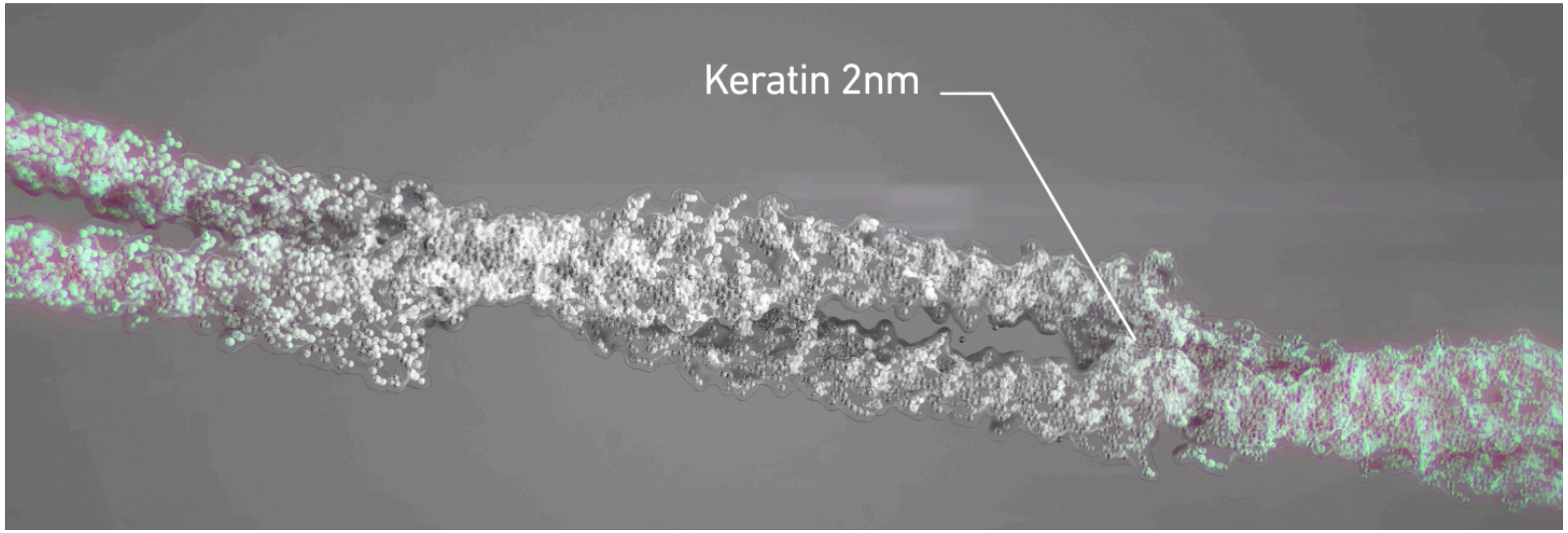
- Bunch structure of the proton beam:
  - Bunch crossing every 25 ns (40 MHz)
  - 10^{11} protons in each bunch
  - 20-40 *pp* collisions each crossing
- >1 billion *pp* collisions per second
- More than 25,000 collisions saved to disk per second
- Around **20 billion events** saved between 2015 and 2018
- Huge computing needs to analyze the recorded data!

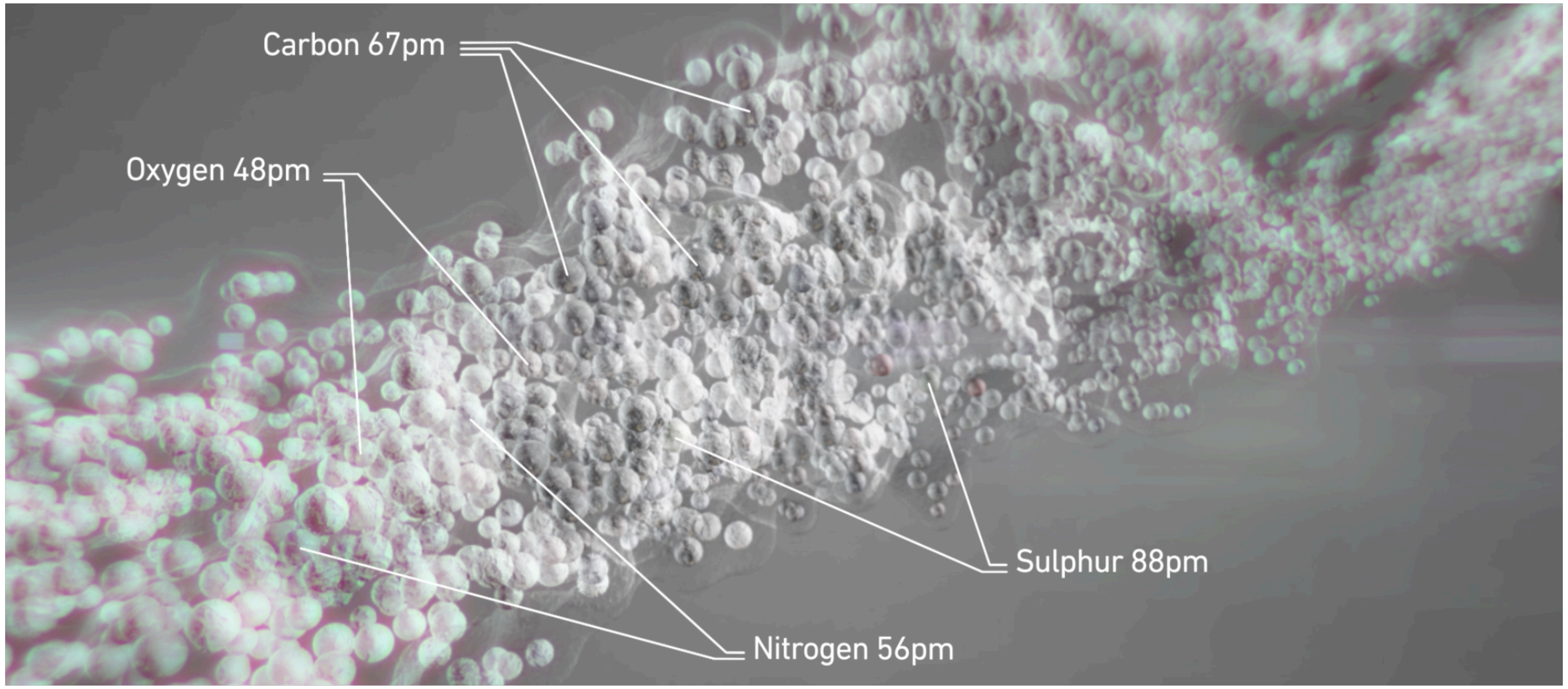


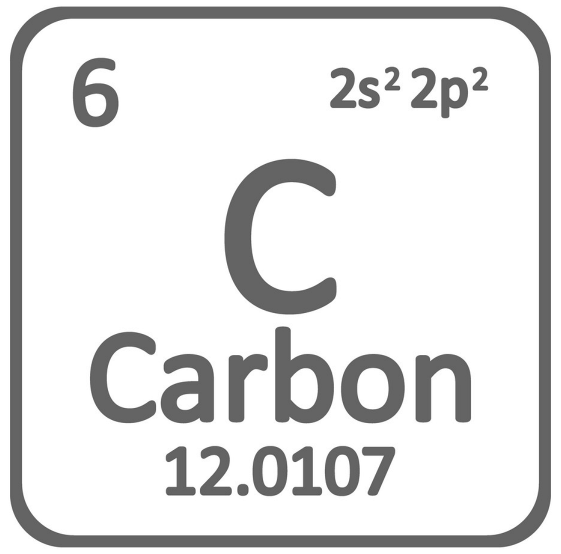
What is stuff made of?

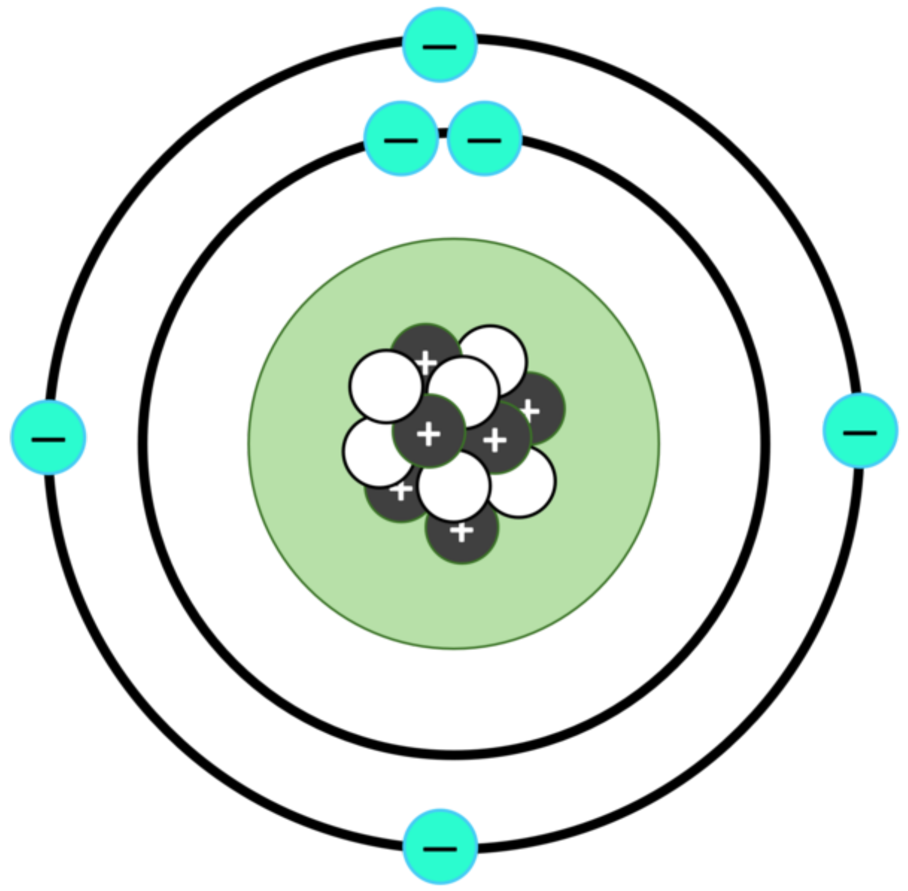


DOI:10.1016/j.jare.2019.01.014

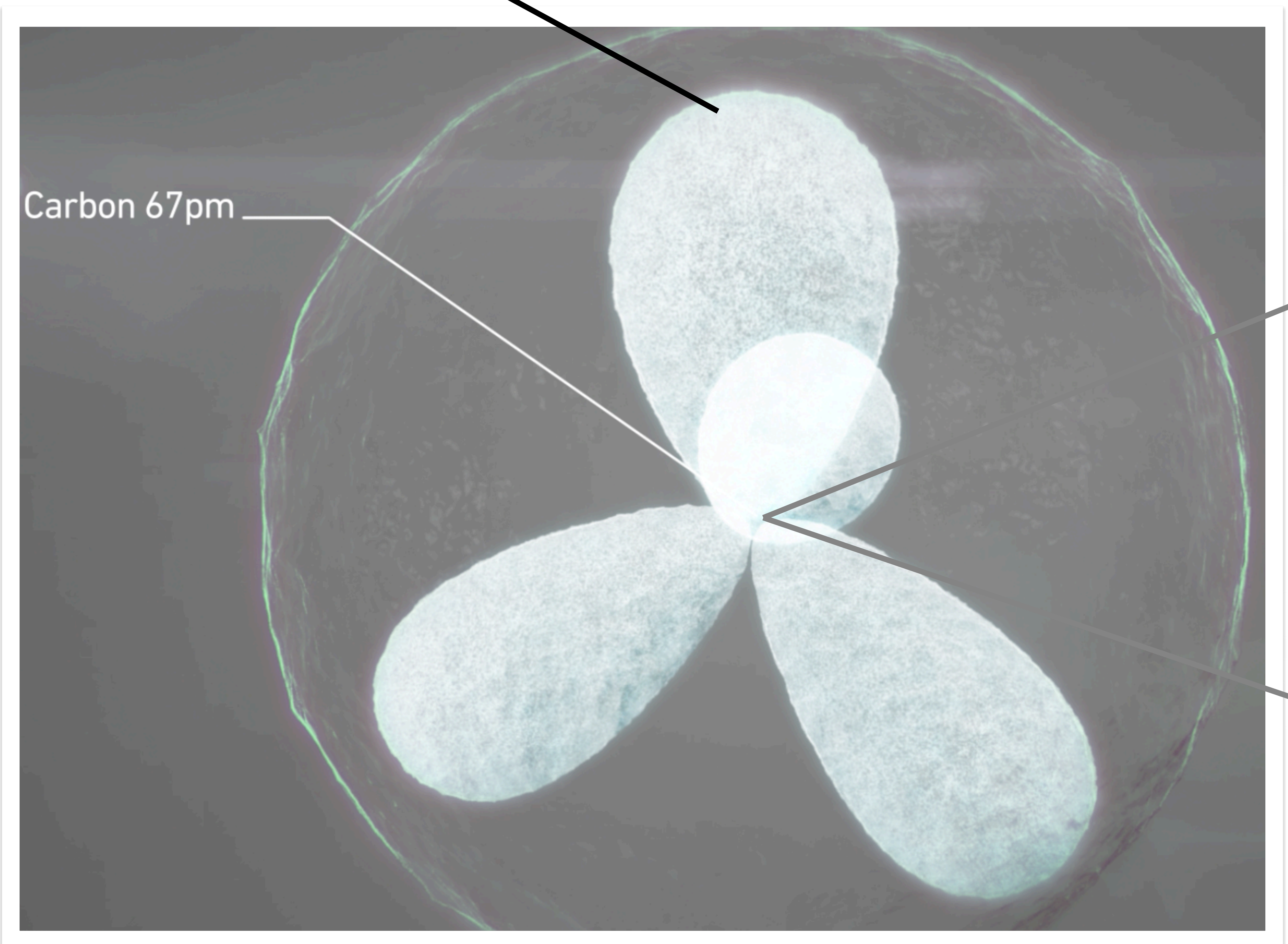




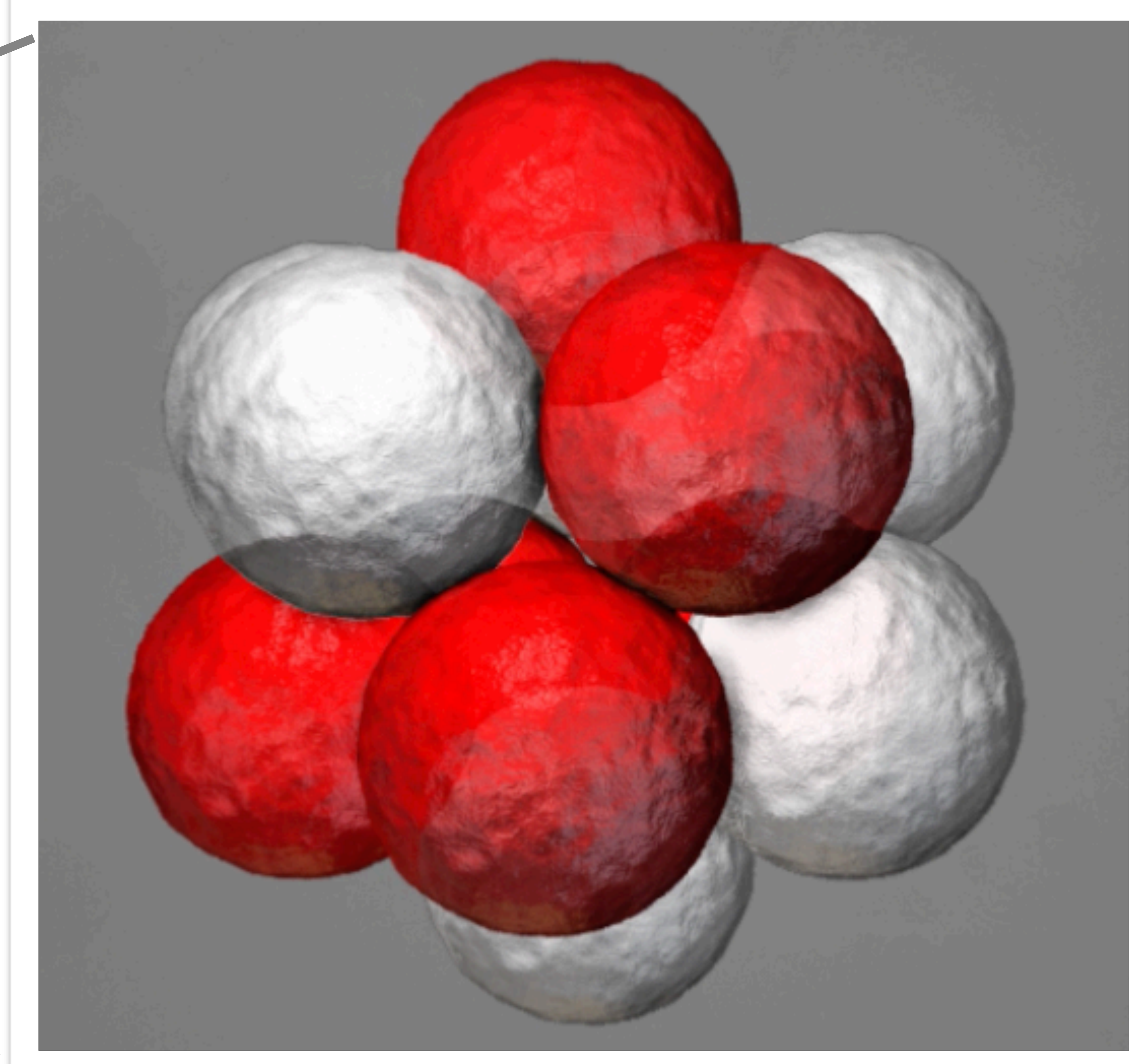




Electron orbitals



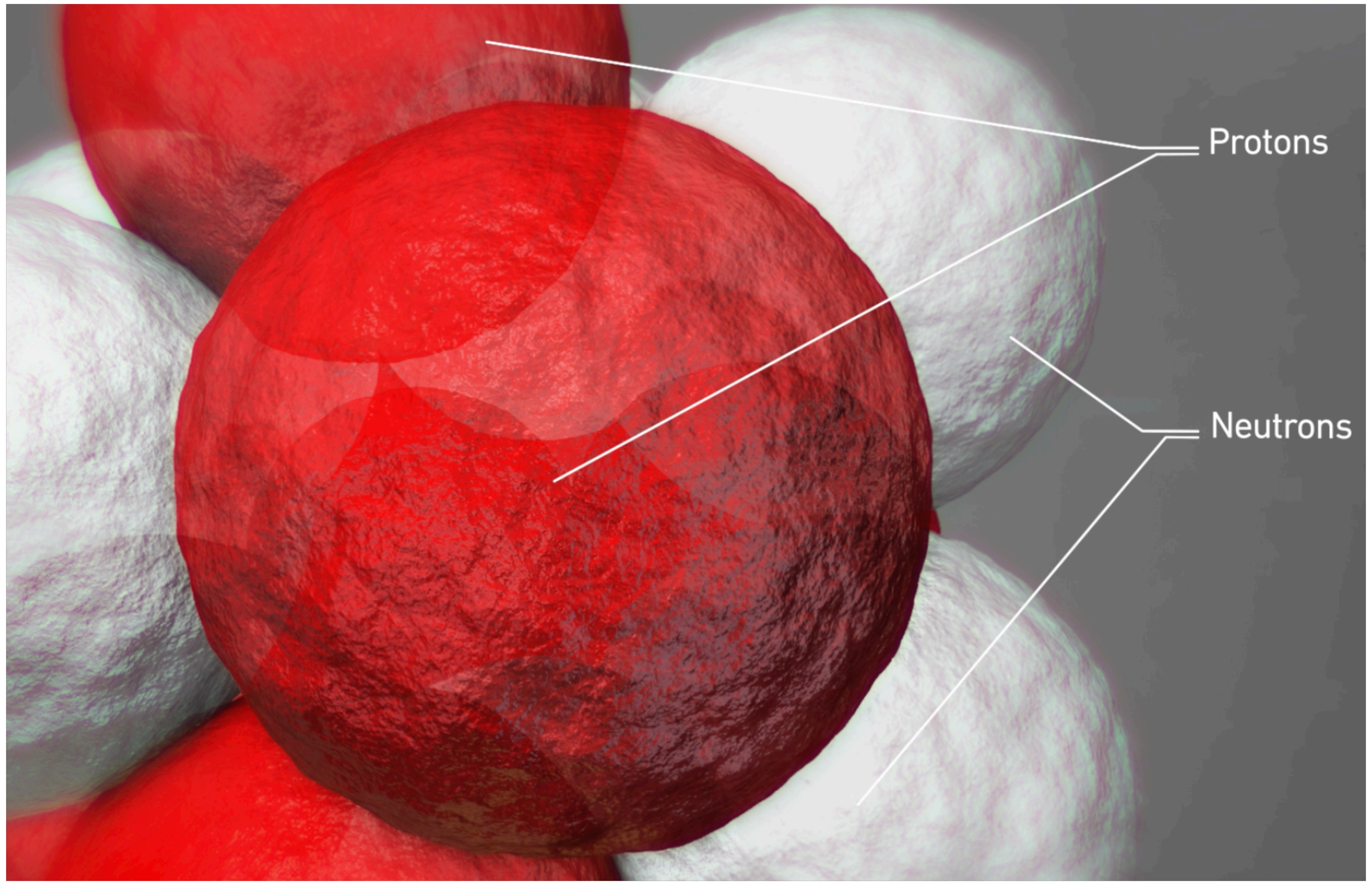
Carbon nucleus
- 6 protons
- 6 neutrons

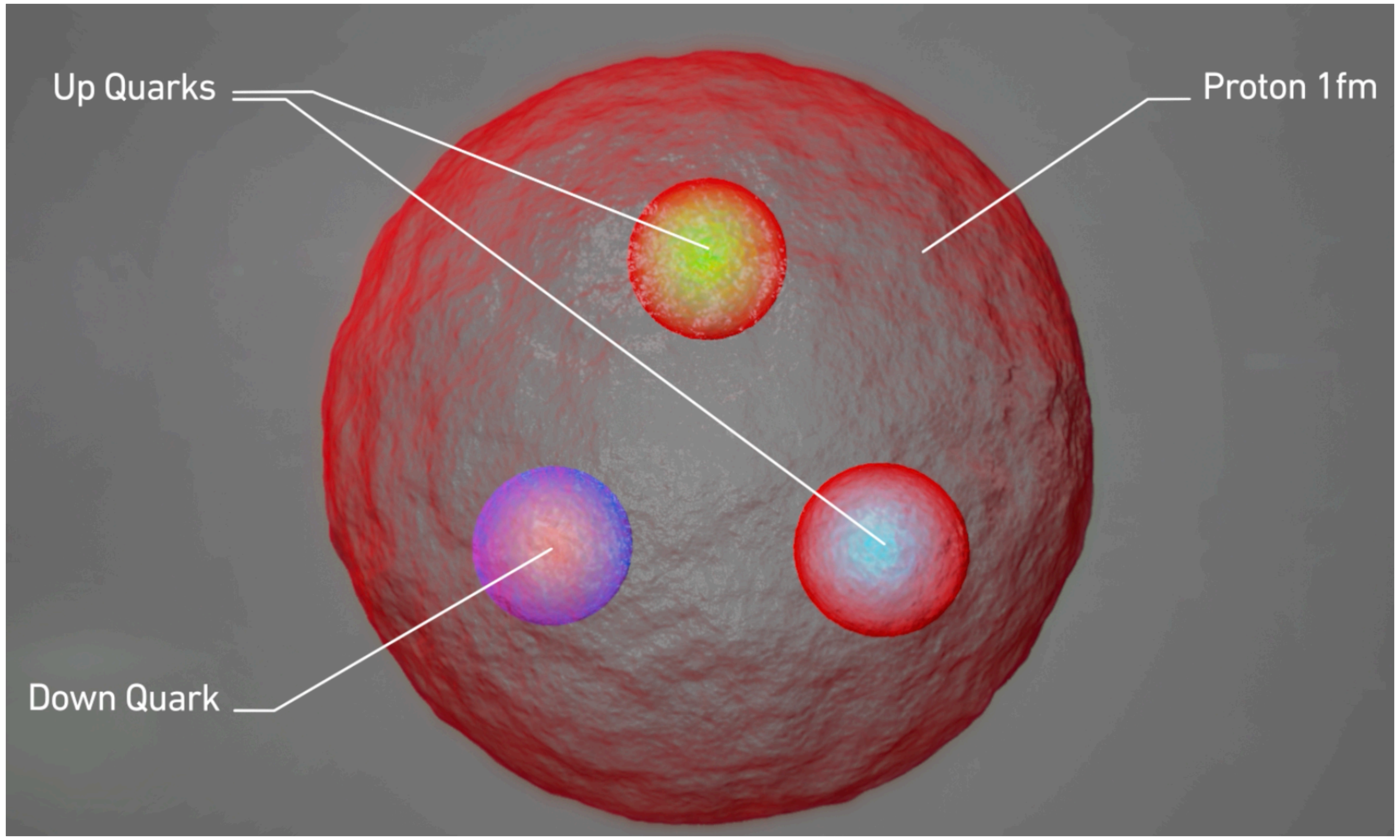


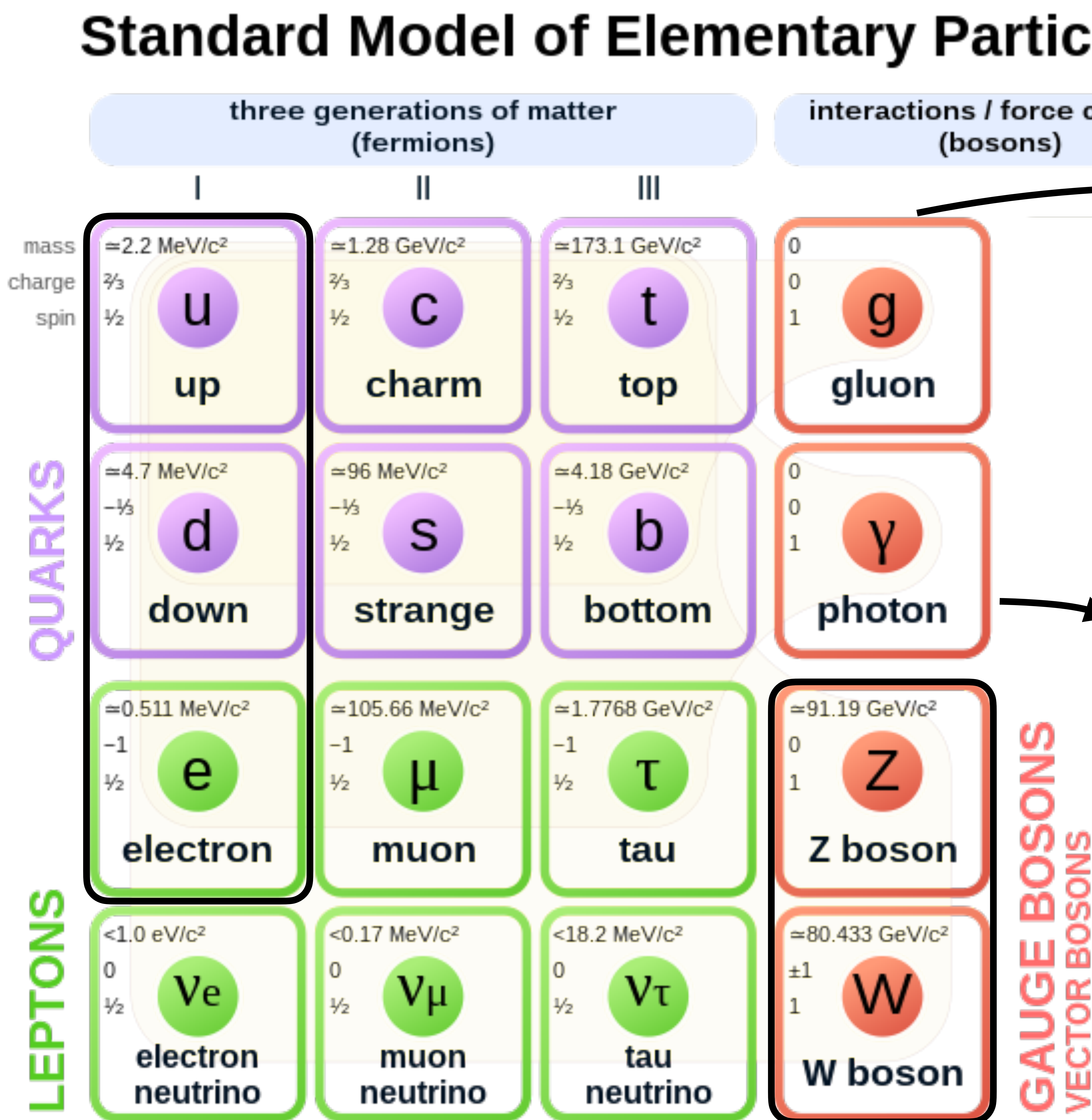
About 100,000 × smaller

The Proton

- Are protons and neutrons divisible?
- So far we think these are the elementary (non-divisible) particles that make up all matter:
  - Electrons
  - Up Quarks
  - Down Quarks






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
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top
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g
gluon
≃4.7 MeV/c²
−⅓
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d
down
≃96 MeV/c²
−⅓
½
s
strange
≃4.18 GeV/c²
−⅓
½
b
bottom
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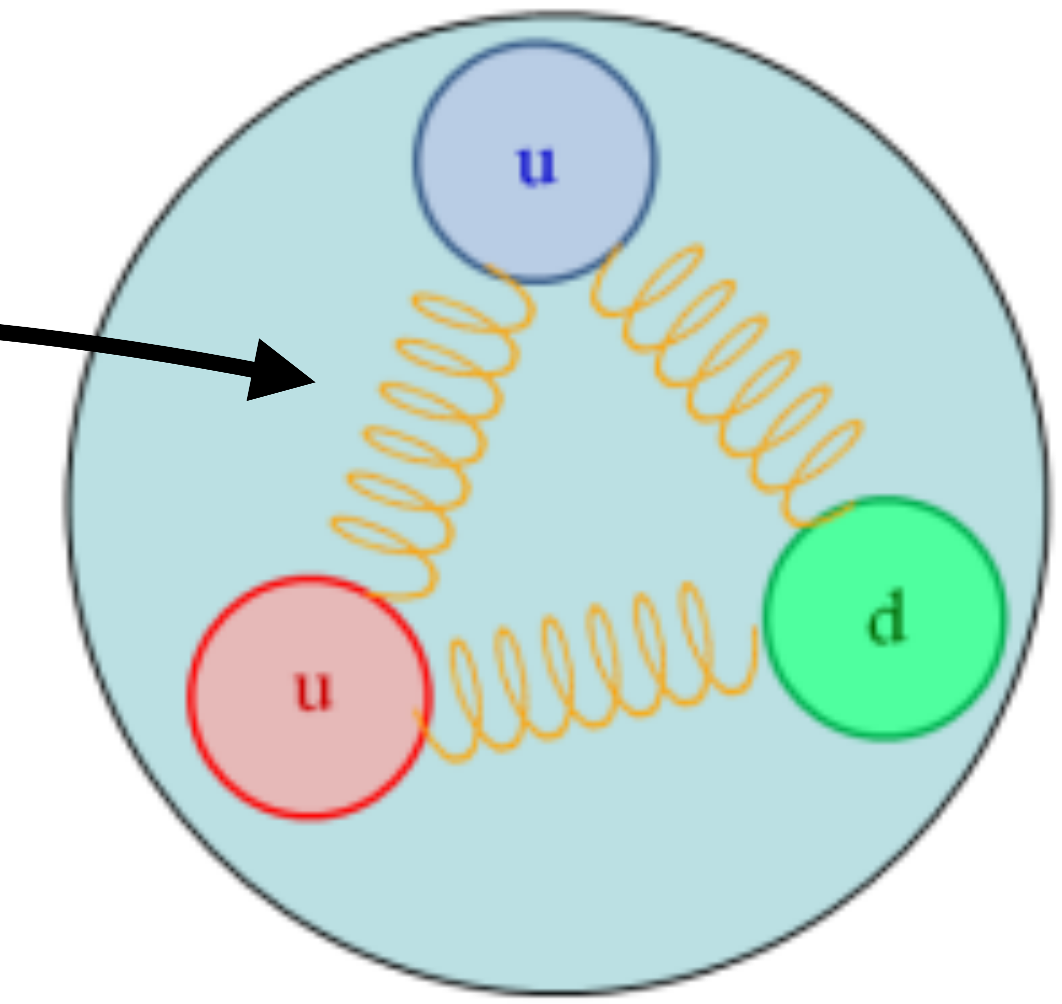
0
1
γ
photon
≃0.511 MeV/c²
−1
½
e
electron
≃105.66 MeV/c²
−1
½
μ
muon
≃1.7768 GeV/c²
−1
½
τ
tau
≃91.19 GeV/c²
0
1
Z
Z boson
<1.0 eV/c²
0
½
νe
electron neutrino
<0.17 MeV/c²
0
½
νμ
muon neutrino
<18.2 MeV/c²
0
½
ντ
tau neutrino
≃80.433 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS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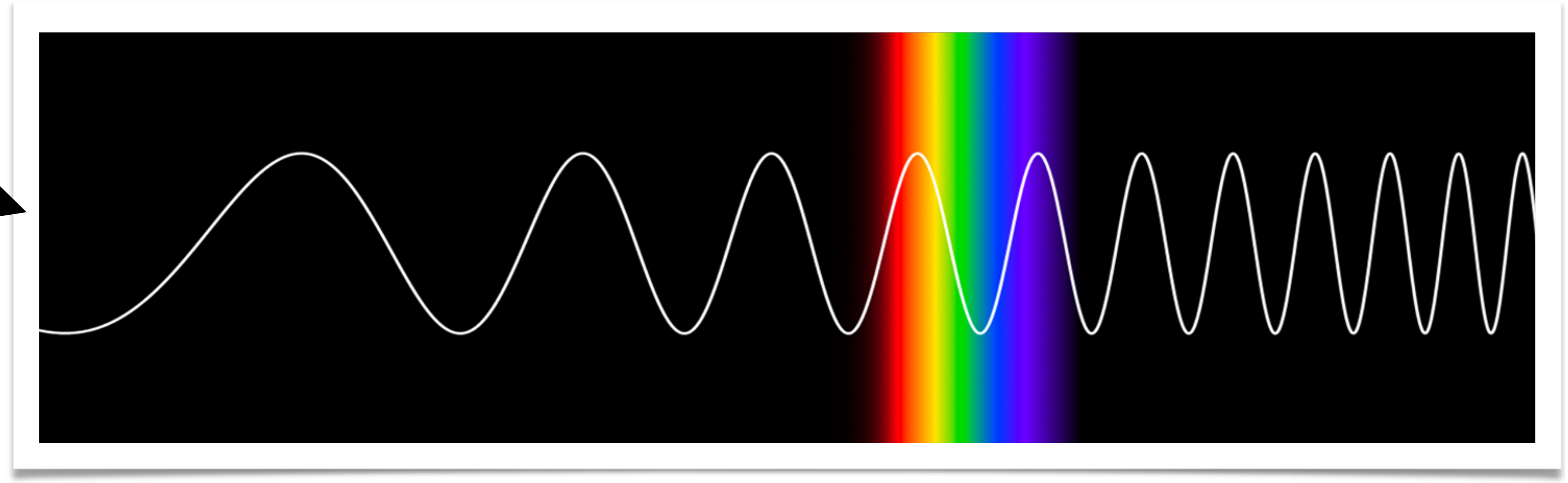
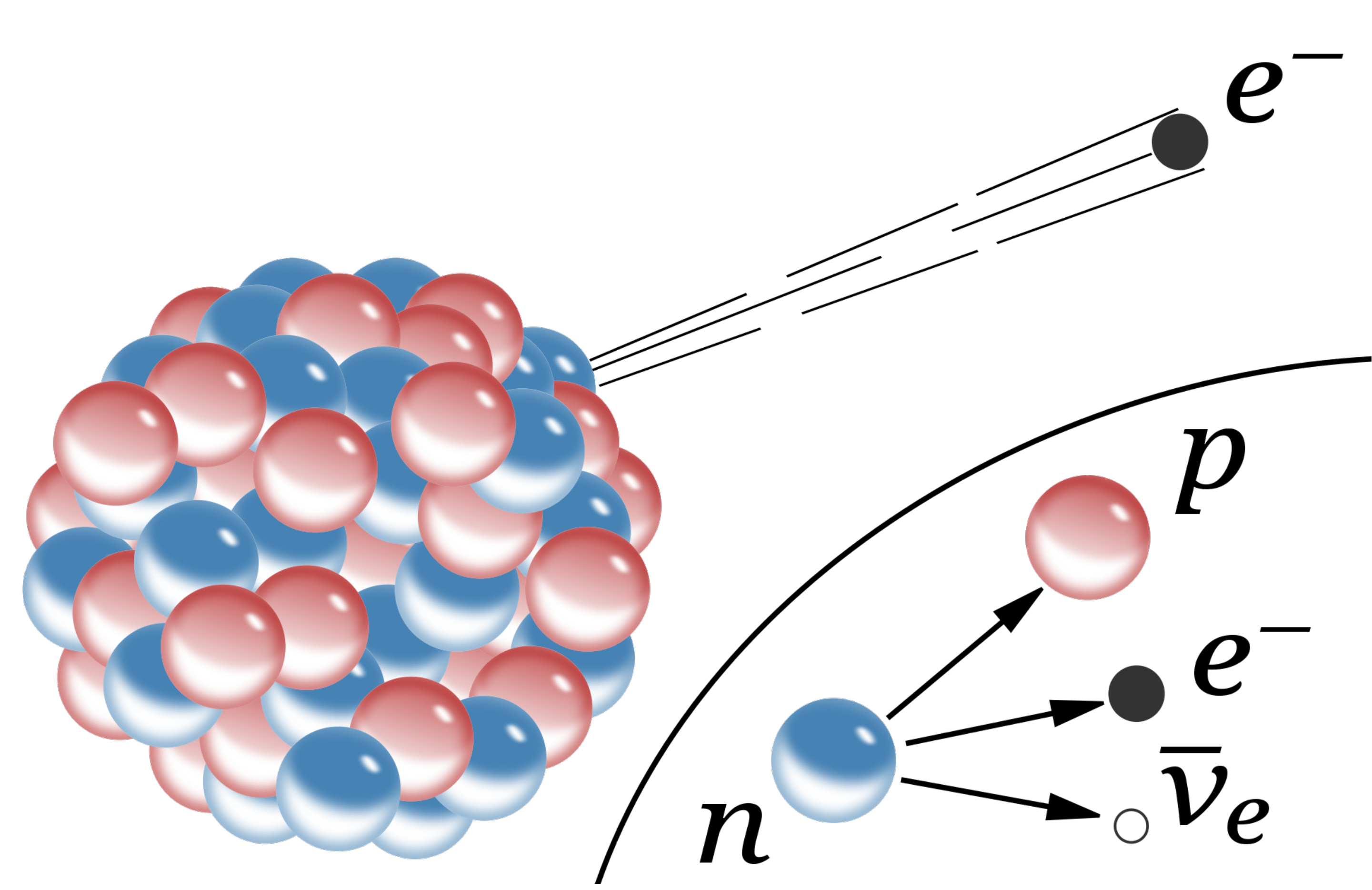
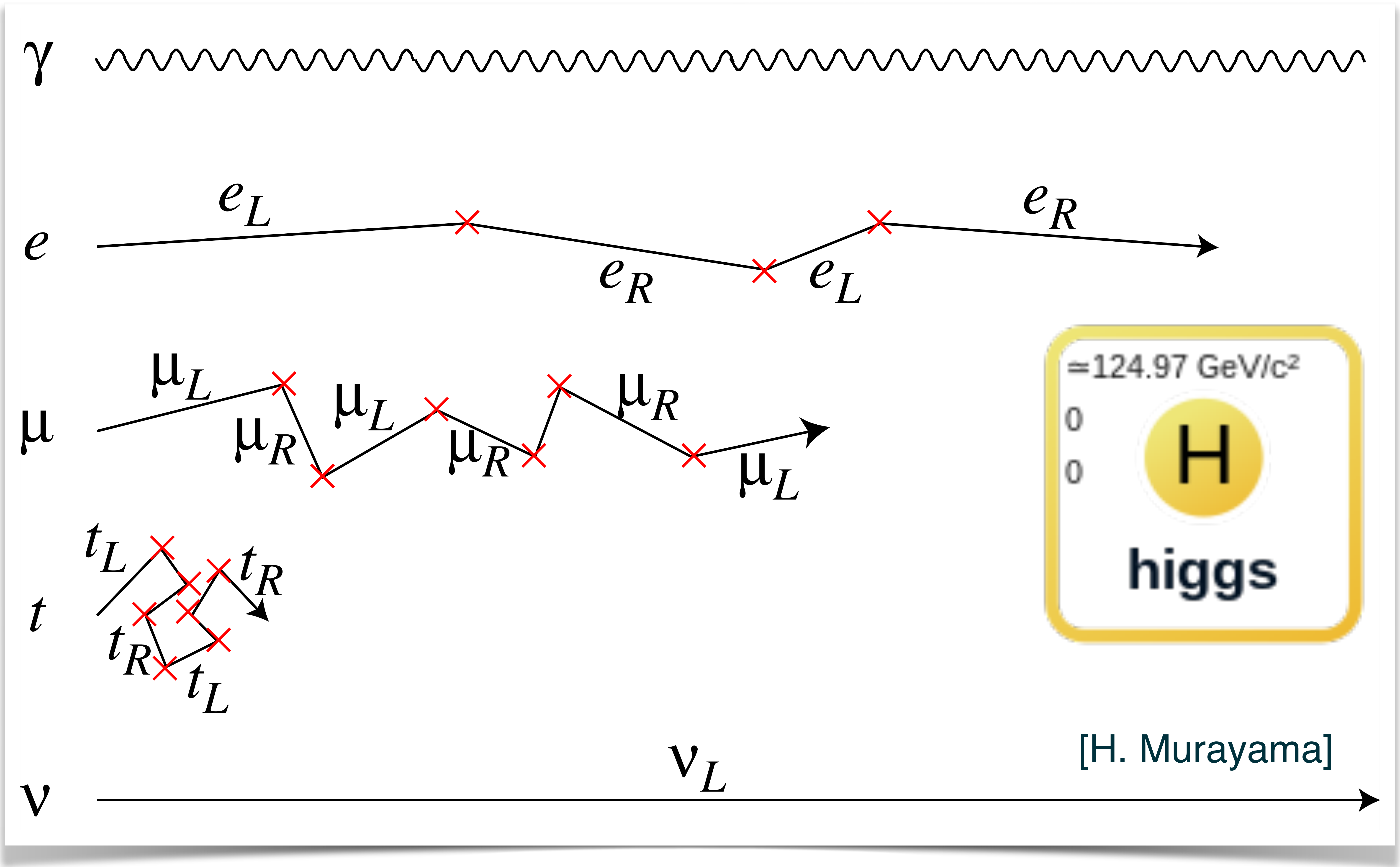



e⁻
p
e⁻
ν̄e
n

- Elementary particles get mass by interacting with the Higgs **field**,
  - The more often they interact with it, the heavier they are,
- Postulated in 1964,
- Discovered at the LHC on July 4th 2012.



[H. Murayama]

The Nobel Prize in Physics 2013


© Nobel Media AB. Photo: A. Mahmoud
François Englert
Prize share: 1/2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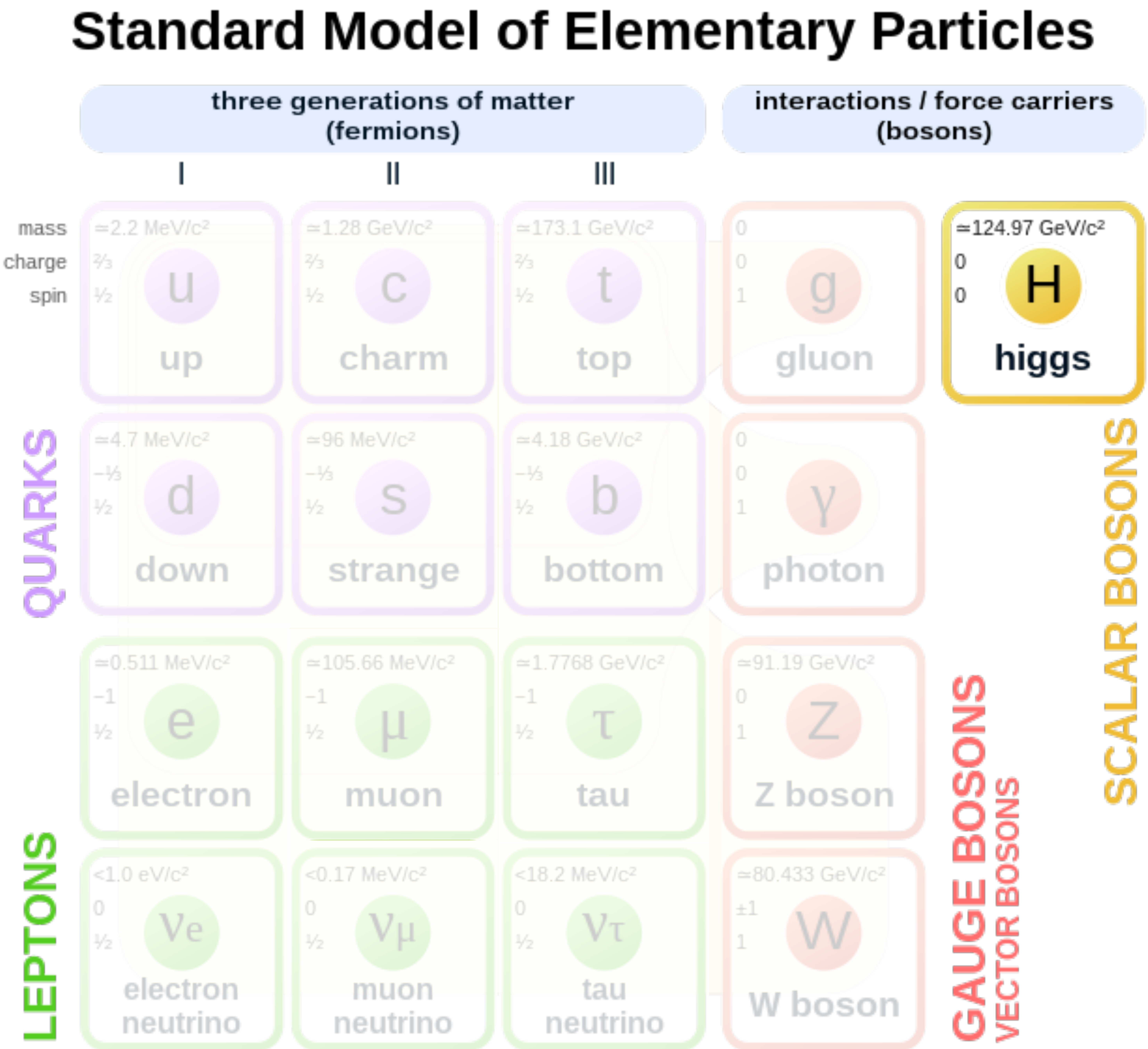
Peter W. Higgs
Prize share: 1/2


Fabiola Gianotti
Rolf-Dieter Heuer
Joseph Incandela
UC Santa Barbara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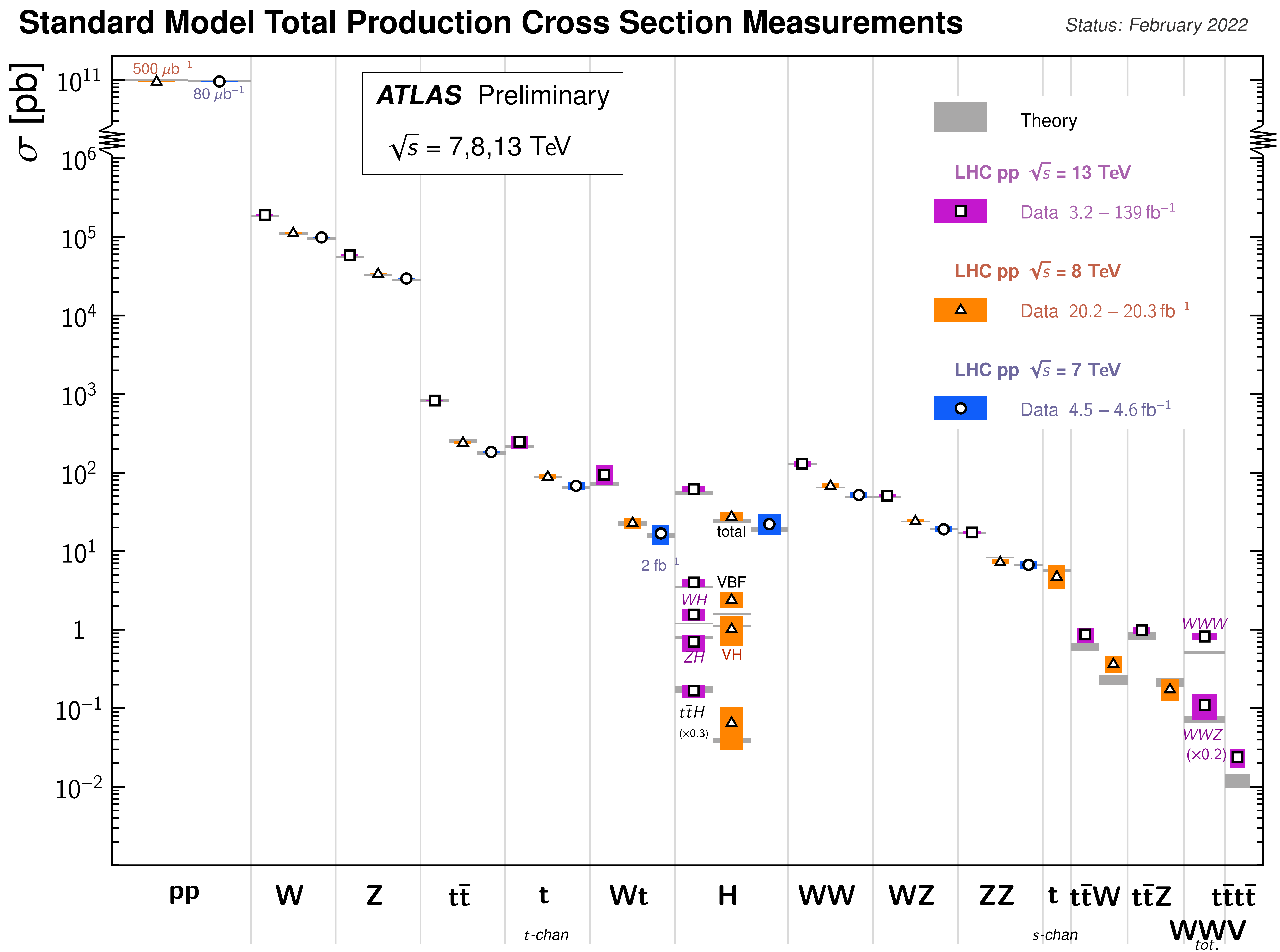
≈80.433 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS

- Successfully explains almost all experimental results from many different experiments,
- At the LHC, it correctly predicts the probabilities of many “interactions” across more than 10 orders of magnitudes.



Free parameters in the Standard Model

Parameters of the Standard Model [hide]

#	Symbol	Description	Renormalization scheme (point)	Value
1	m_e	Electron mass		0.511 MeV
2	m_μ	Muon mass		105.7 MeV
3	m_τ	Tau mass		1.78 GeV
4	m_u	Up quark mass	$\mu_{\overline{MS}} = 2$ GeV	1.9 MeV
5	m_d	Down quark mass	$\mu_{\overline{MS}} = 2$ GeV	4.4 MeV
6	m_s	Strange quark mass	$\mu_{\overline{MS}} = 2$ GeV	87 MeV
7	m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
8	m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
9	m_t	Top quark mass	On shell scheme	173.5 GeV
10	θ_{12}	CKM 12-mixing angle		13.1°
11	θ_{23}	CKM 23-mixing angle		2.4°
12	θ_{13}	CKM 13-mixing angle		0.2°
13	δ	CKM CP violation Phase		0.995
14	g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
15	g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
16	g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
17	θ_{QCD}	QCD vacuum angle		~0
18	v	Higgs vacuum expectation value		246 GeV
19	m_H	Higgs mass		125.09 ±0.24 GeV

- The Standard Model has 19 free parameters that need to be experimentally determined,
  - Once they are known, we can make predictions,
- Many physicists think that 19 is too much and that there must be a more fundamental theory with fewer arbitrary parameters.

Charged lepton and quark masses

CKM matrix / CP violation

Gauge couplings (three fundamental forces)

CP violation in QCD (non-existent)

Higgs vev, related to Z, W, and H masses

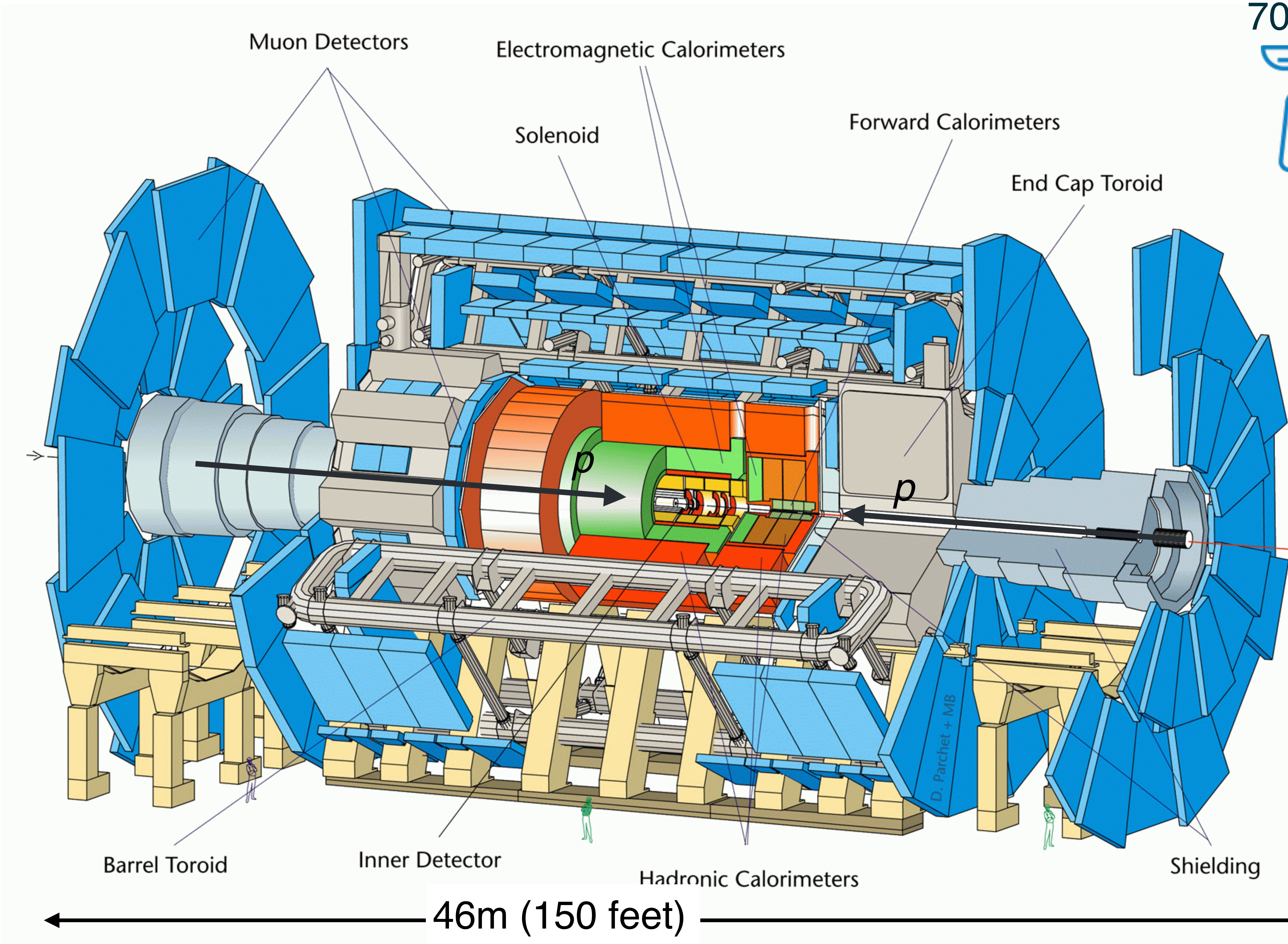
Higgs mass measured by ATLAS and CMS at LHC

- **Quantum Gravity**— the SM breaks down at short distance when gravity becomes important. Generally inconsistent with General Relativity,
- **Dark Matter**— we know it exists from cosmological observations, but we don't know how (if) it interacts with the Standard Model,
- **Neutrino masses**— the origin of neutrino masses is unknown,
- **Matter-antimatter asymmetry**— something in the early Universe caused matter to dominate.

- The SM also has several fine-tuning and "aesthetic" issues:
  - **The Hierarchy Problem** (or the Higgs mass fine-tuning problem),
  - **Grand Unification**— do the electromagnet, weak, and strong forces unite?
  - **Particle Masses**— why do fermion masses span orders of magnitudes; what is the related symmetry?
  - **The Strong CP Problem**— why $\theta_{\text{QCD}} \sim 0$ (e.g. neutron has no Electric Dipole Moment).

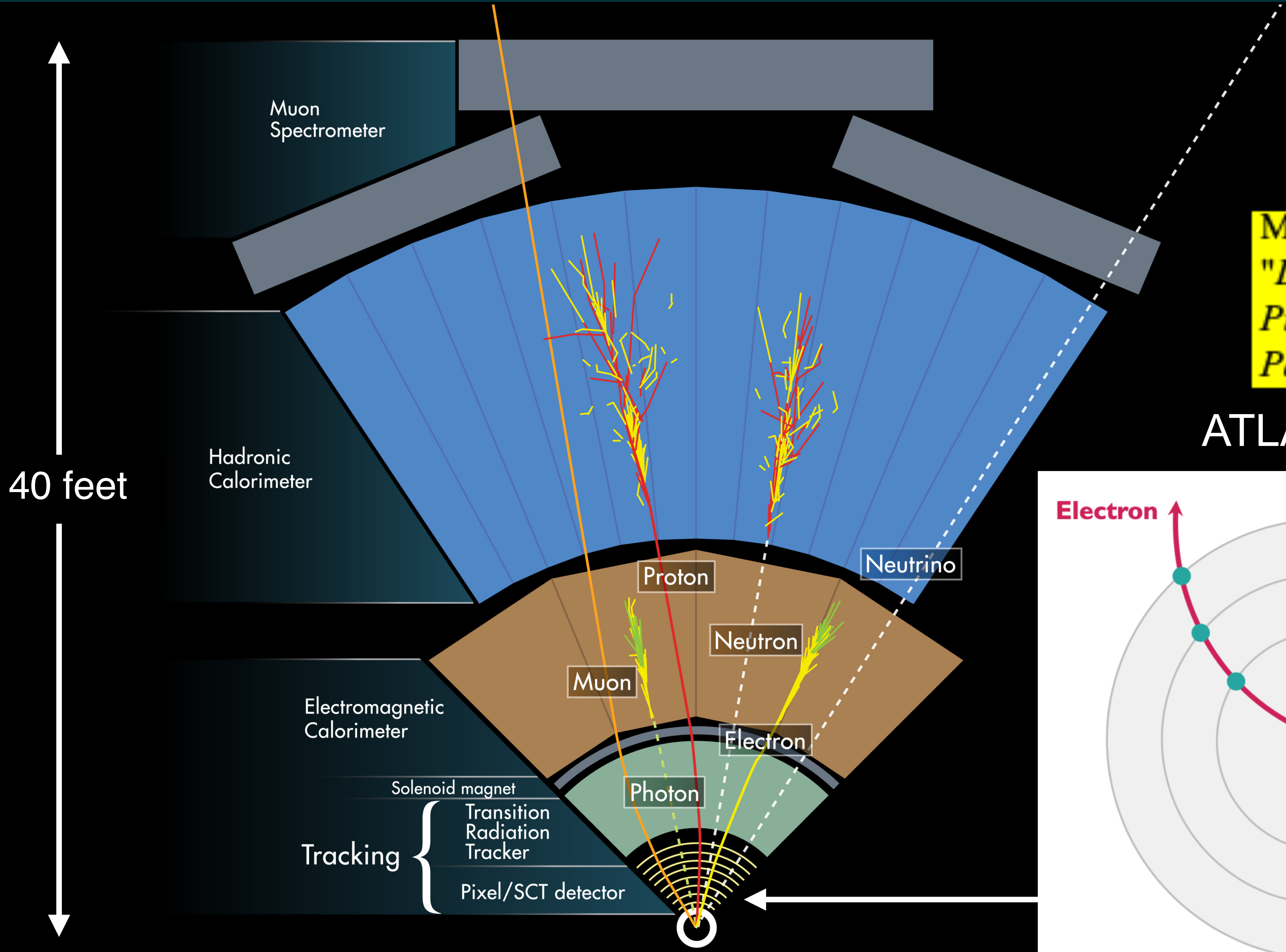
- The goal of our experiments is addressing these problems and finding physics Beyond the SM (BSM).

How do we detect these particles?



25m (82 feet)

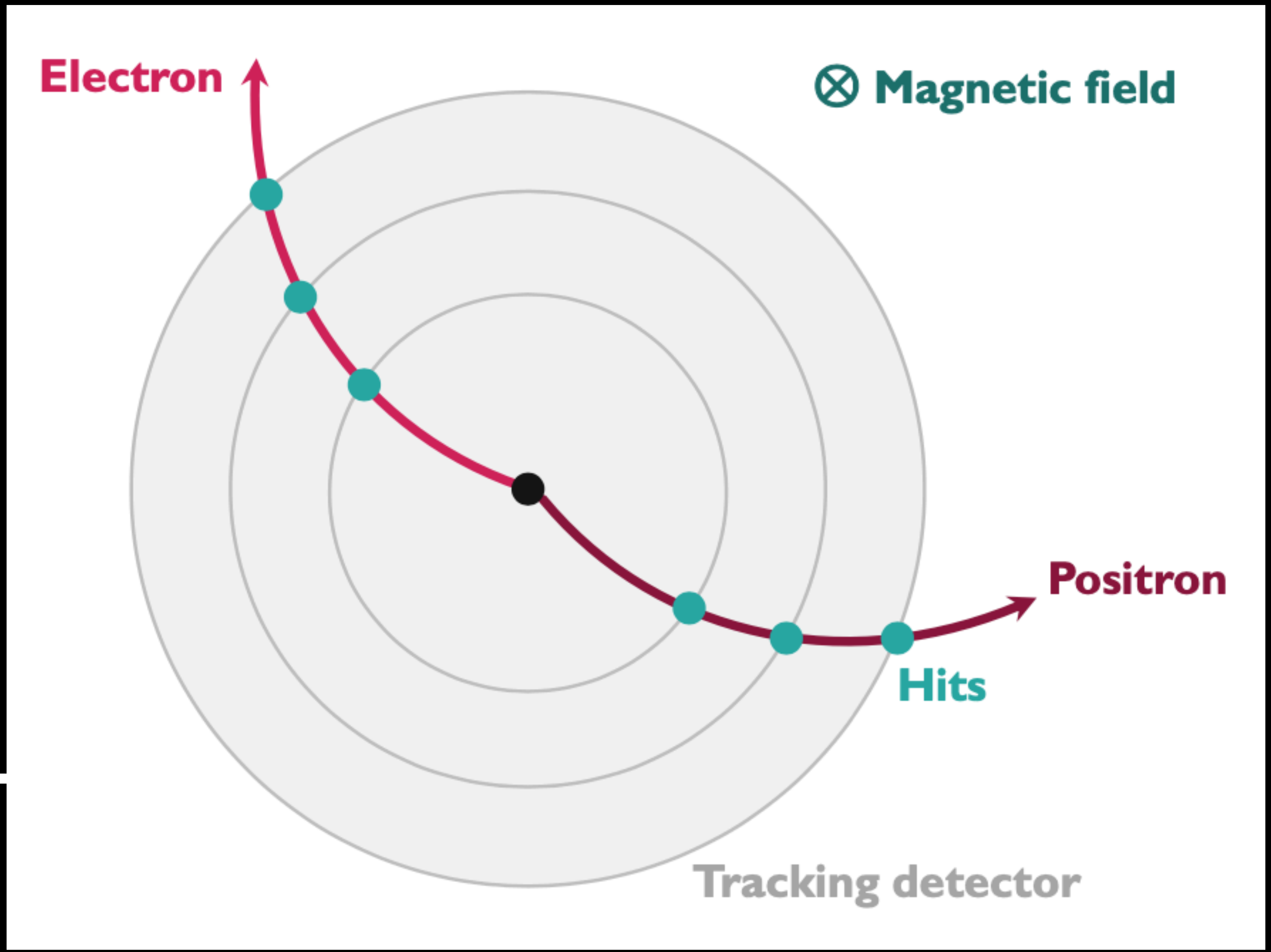
46m (150 feet)



Tuesday June 27

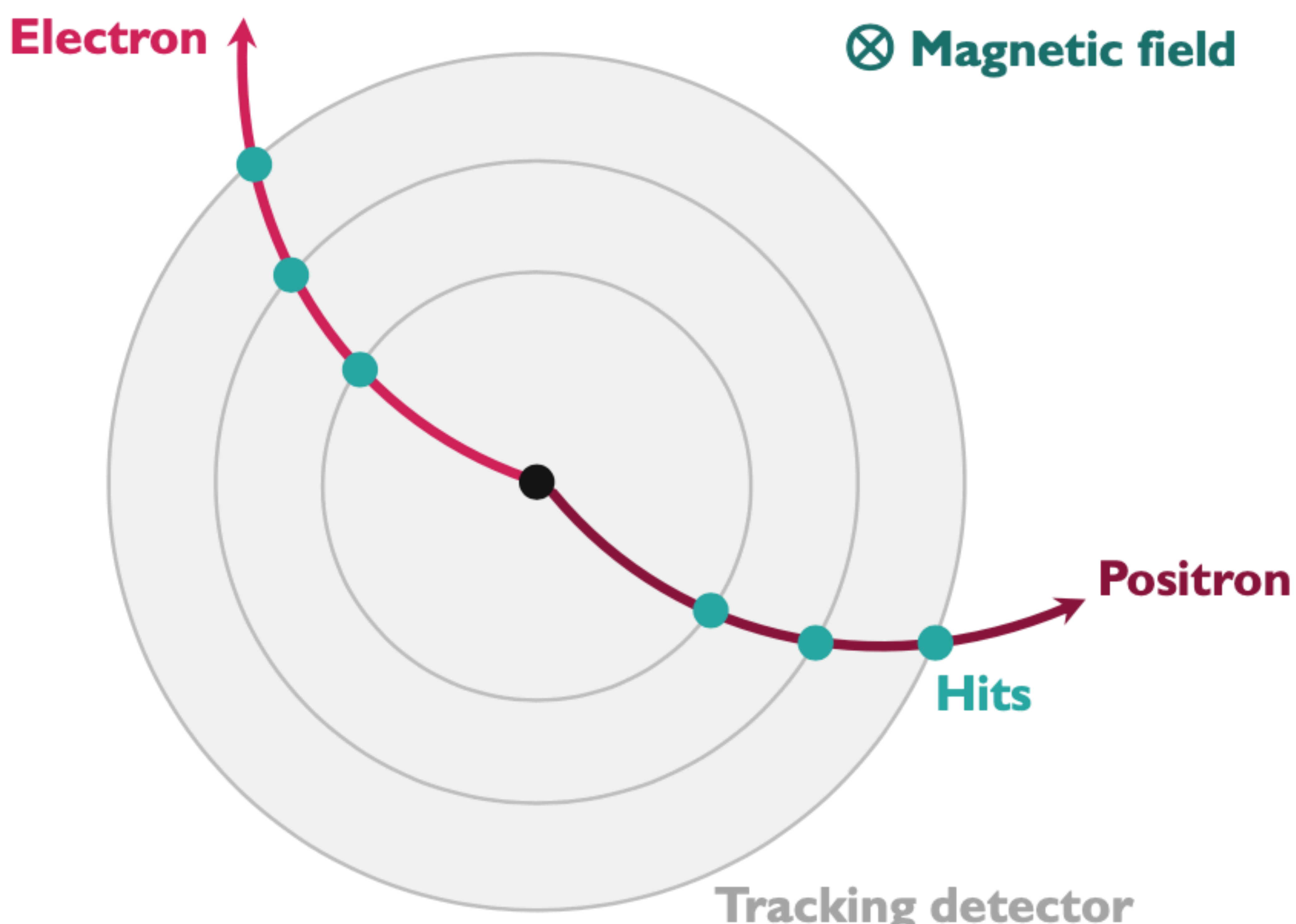
Maria Mironova
"Discovering Invisible: Pixel Detectors in Particle Physics"

ATLAS Pixel Detector

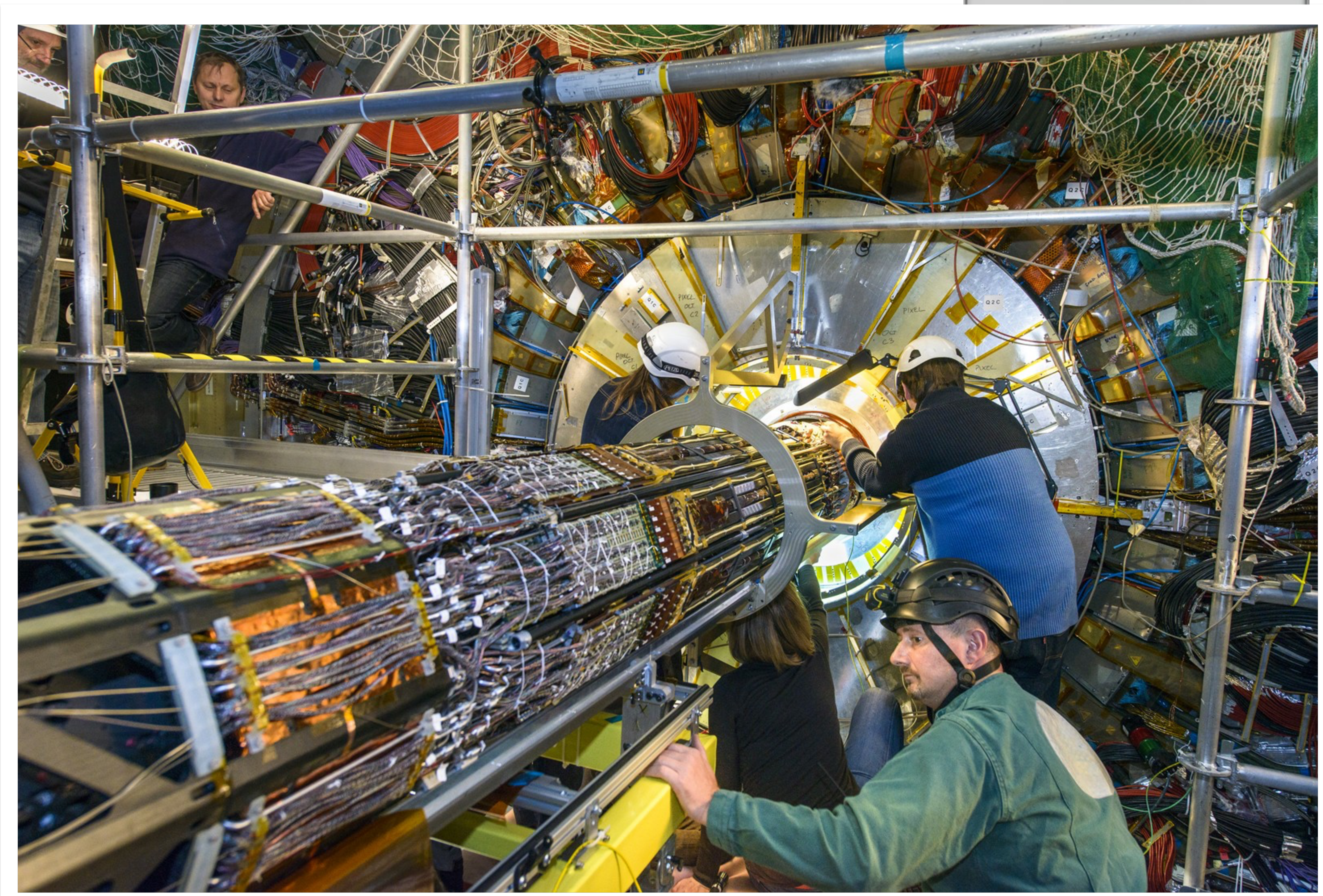


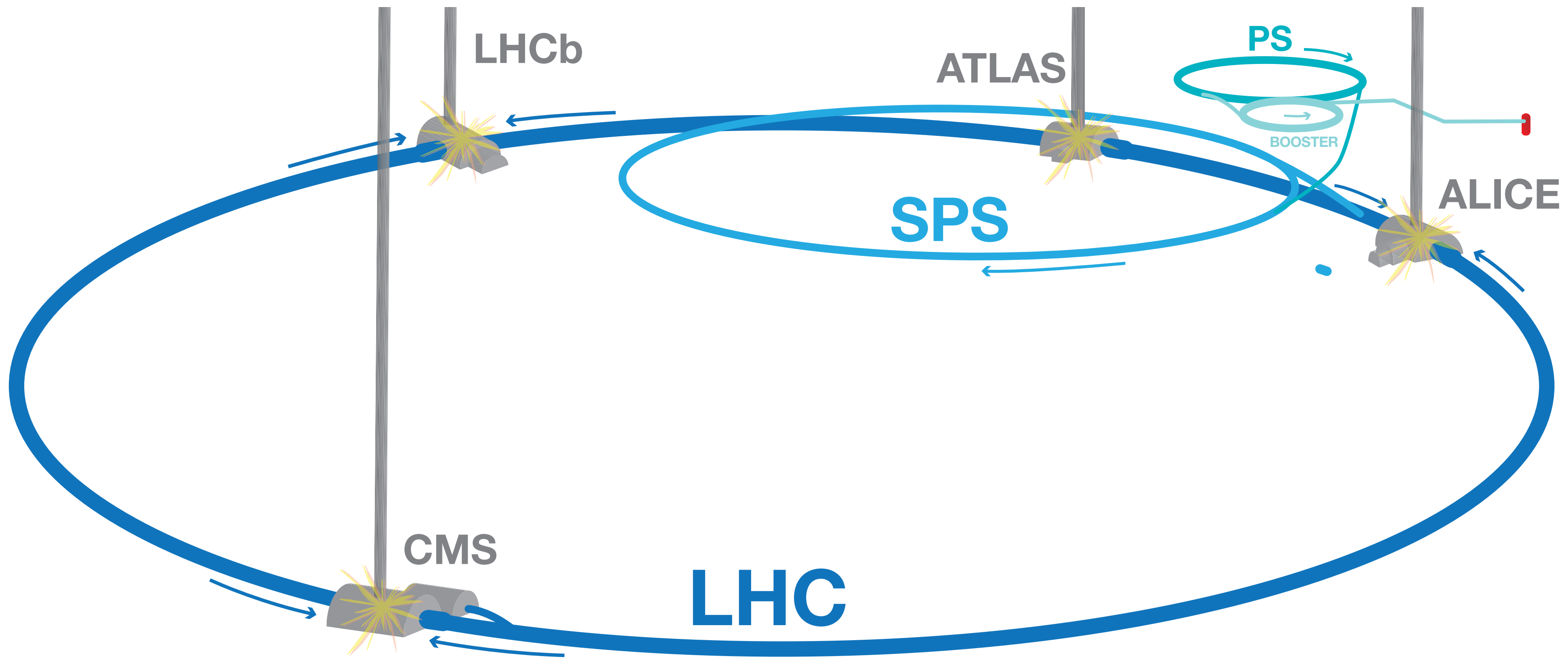
How much data we collect?

- ATLAS Pixel detector:
  - 92 million pixels (50×400 or 50×250 μm² size)
- iPhone 14 Pro camera:
  - 48 million pixels (1-2 μm size)
- ATLAS Pixel equivalent to ~1000 iPhone photos per second!



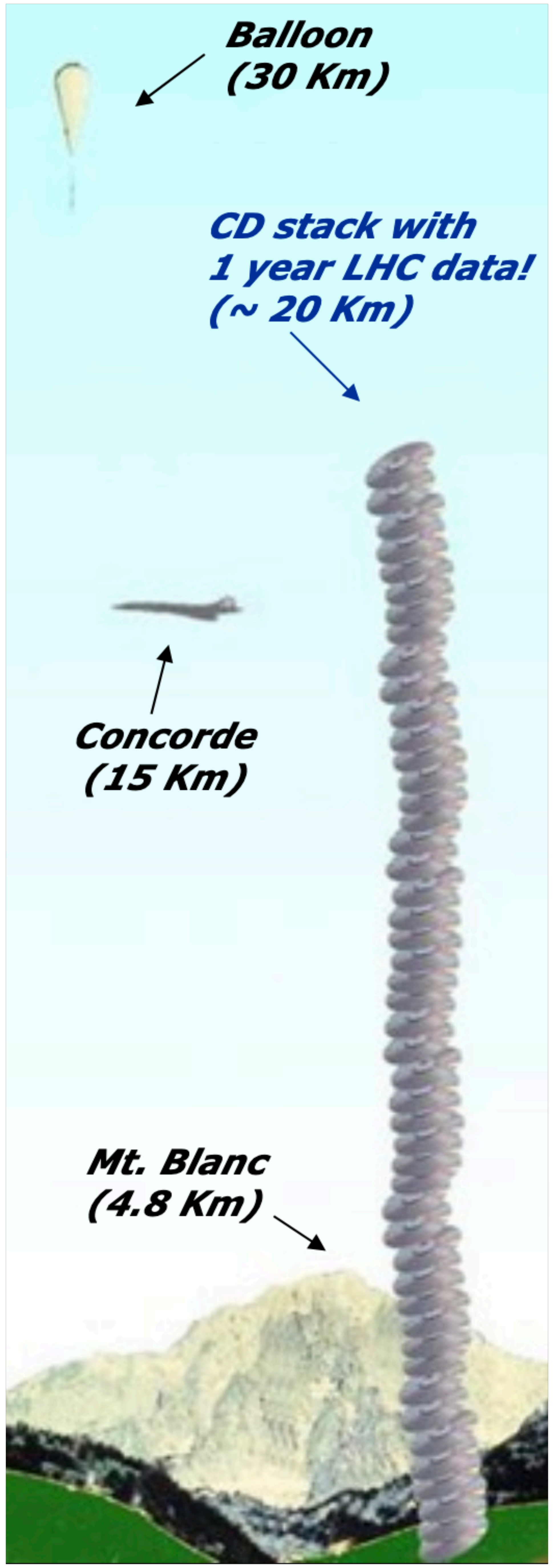
From: Maria Mironova





About 160 PB of data per year
160 PB
160,000 TB
160,000,000 GB

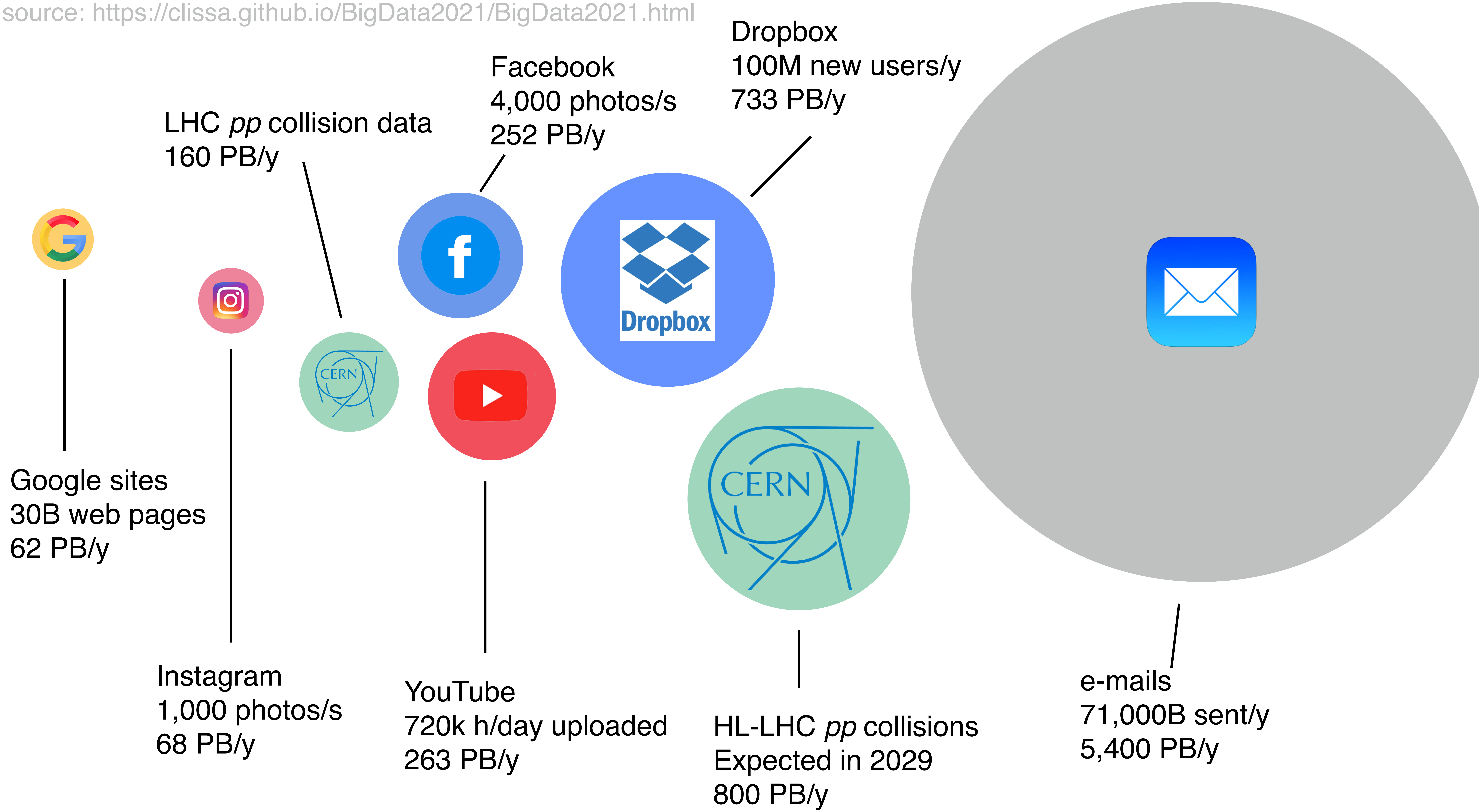
Typical hard-drive
~1 TB



- Historically, people used to compare the amount of LHC data to the number of CD-ROMs required to store it…
- Not very intuitive nowadays 😅

How much data does the LHC generate?

source: https://clissa.github.io/BigData2021/BigData2021.html



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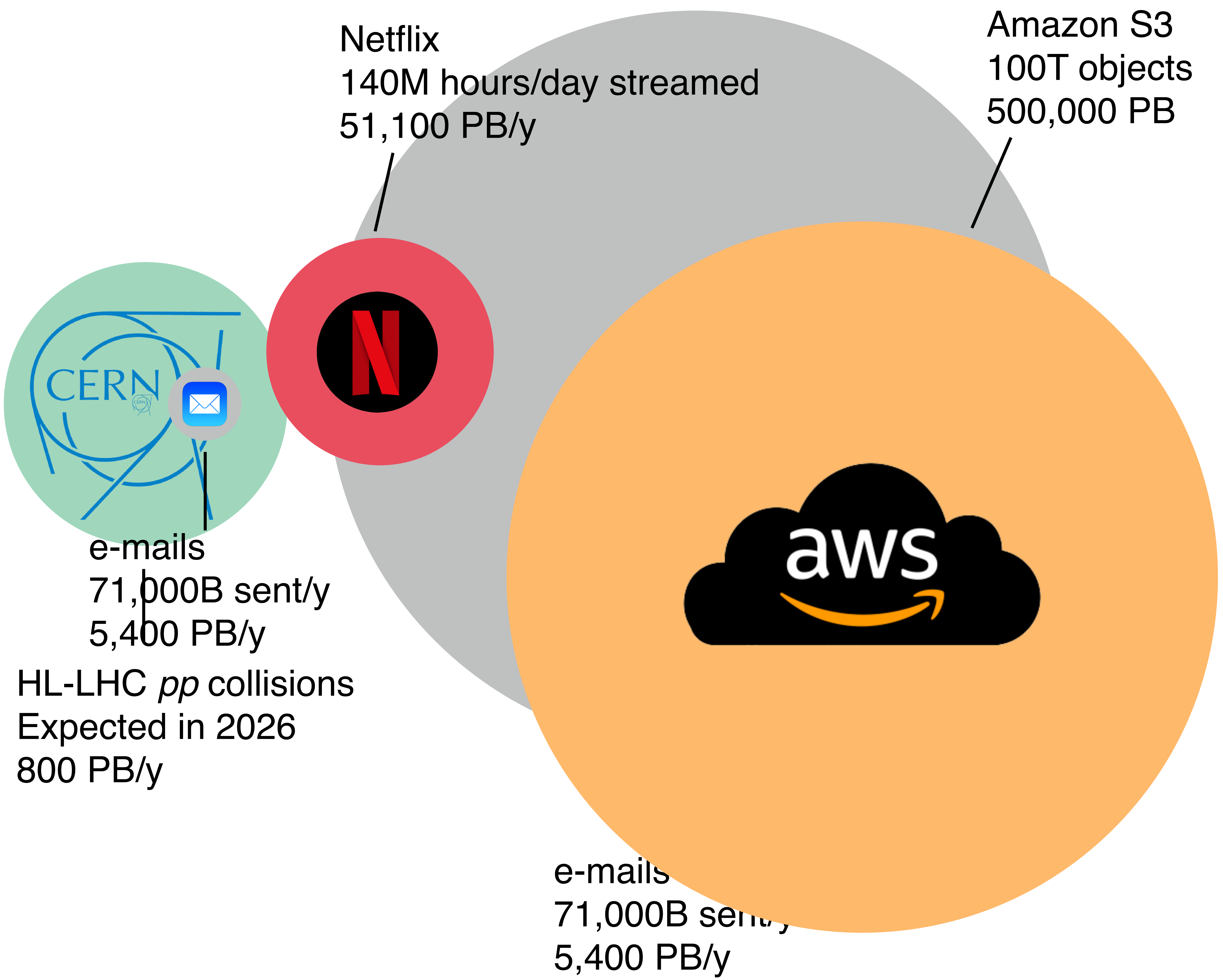
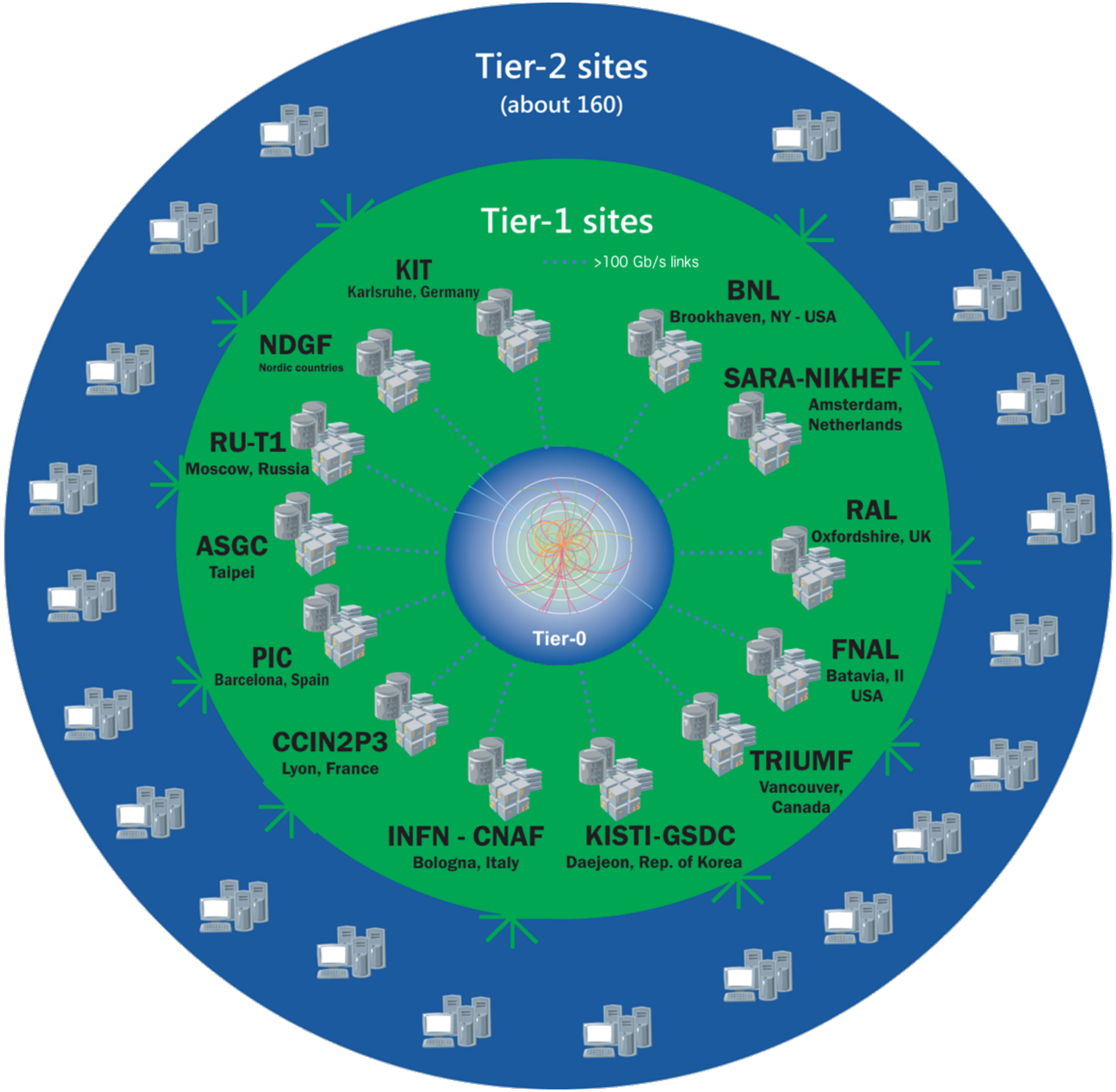


Data processing

The Worldwide LHC Computing Grid (GRID)

- Largest scientific computing system:
  - 42 countries
  - 170 computing centers
  - Over 1,000,000 computing cores
  - 2,000 PB of storage

- **Tier 0**: is at the CERN Data Center
- **Tier 1**: 13 large computing centers around the world
- **Tier 2**: 160 universities and institutes with sufficient computing power
- **Tier 3**: Local sites providing computing support for their researchers



The GRID network

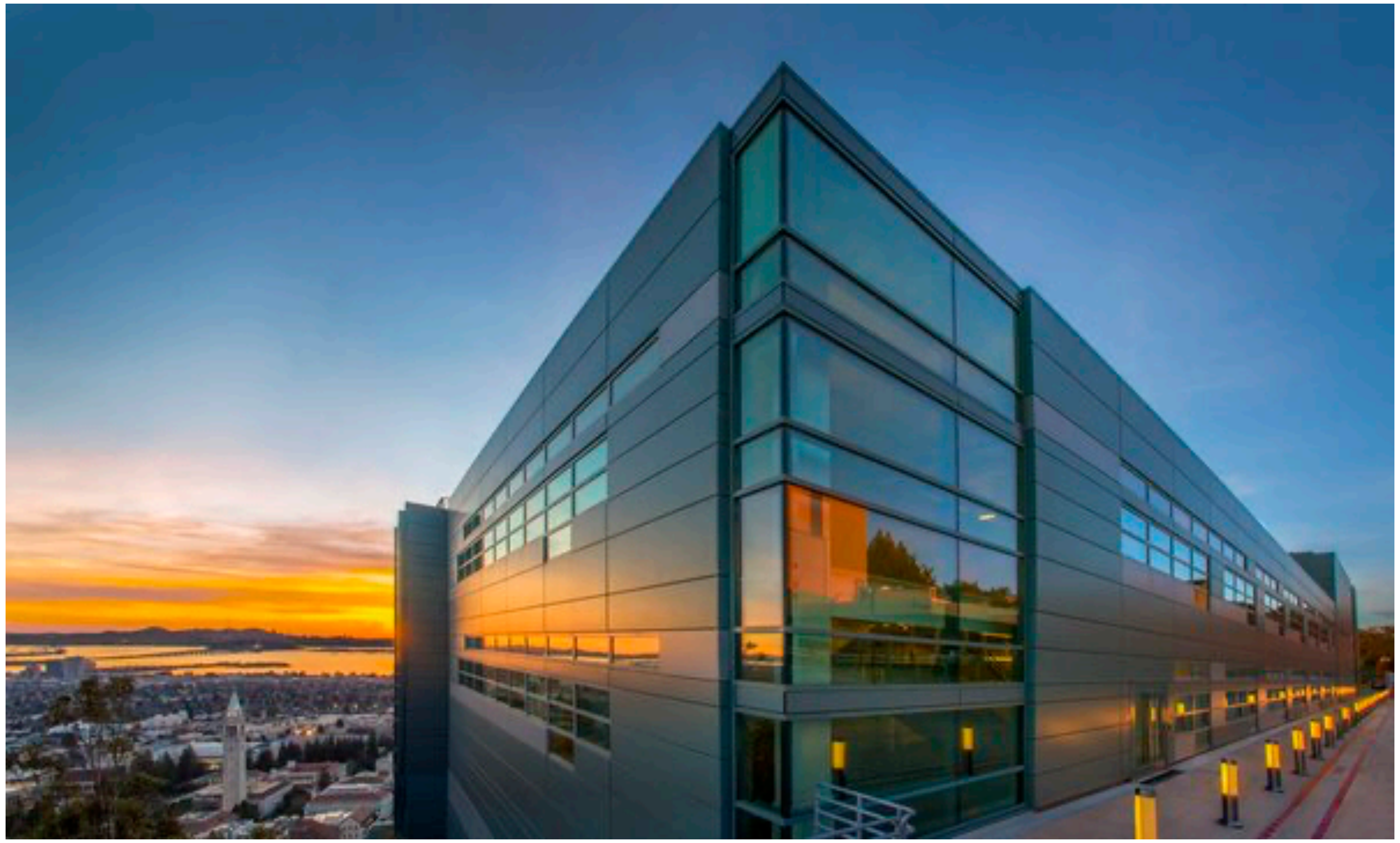
https://home.cern/science/computing/grid

National Energy Research Scientific Computing Center (NERSC)

- NERSC provides computing resources for US researchers
- In the ATLAS group at LBL we are using it both as a ‘Tier 2’ and ‘Tier 3’ GRID site
- It hosts supercomputers, a.k.a. High Performance Computers (HPC)

www.top500.org

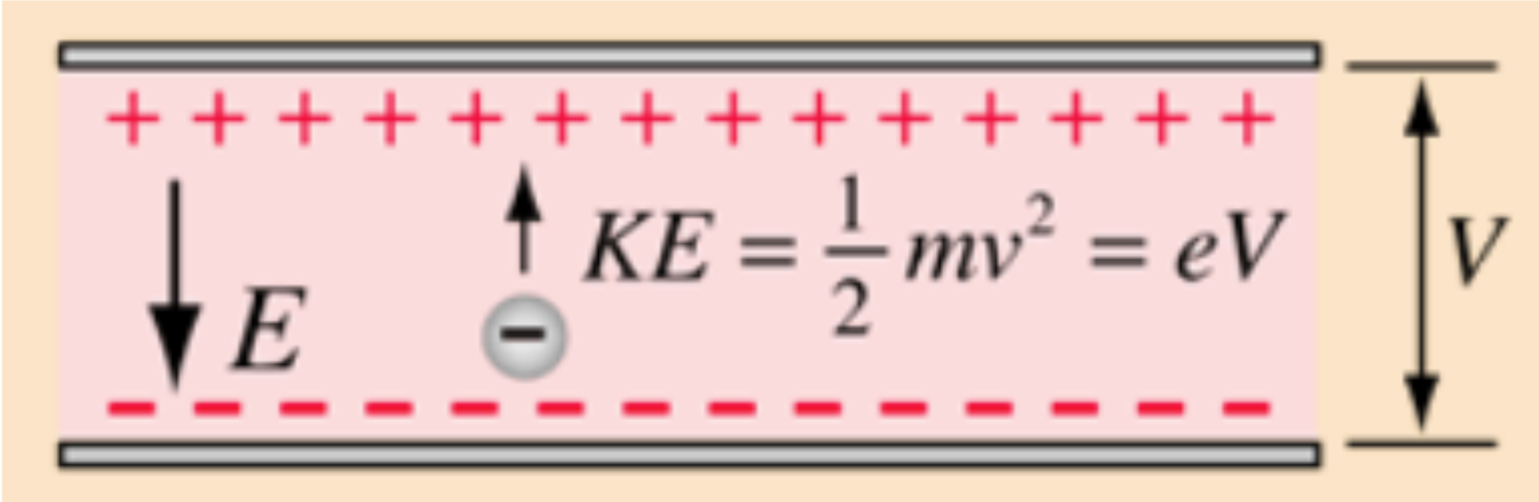
Rank	System	Cores	Rmax (PFlop/s)	Rpeak (PFlop/s)	Power (kW)
1	**Frontier** - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE DOE/SC/Oak Ridge National Laboratory United States	8,730,112	1,102.00	1,685.65	21,100
2	**Supercomputer Fugaku** - Supercomputer Fugaku, A64FX 48C 2.2GHz, Tofu interconnect D, Fujitsu RIKEN Center for Computational Science Japan	7,630,848	442.01	537.21	29,899
	…				
8	**Perlmutter** - HPE Cray EX235n, AMD EPYC 7763 64C 2.45GHz, NVIDIA A100 SXM4 40 GB, Slingshot-10, HPE DOE/SC/LBNL/NERSC United States	761,856	70.87	93.75	2,589



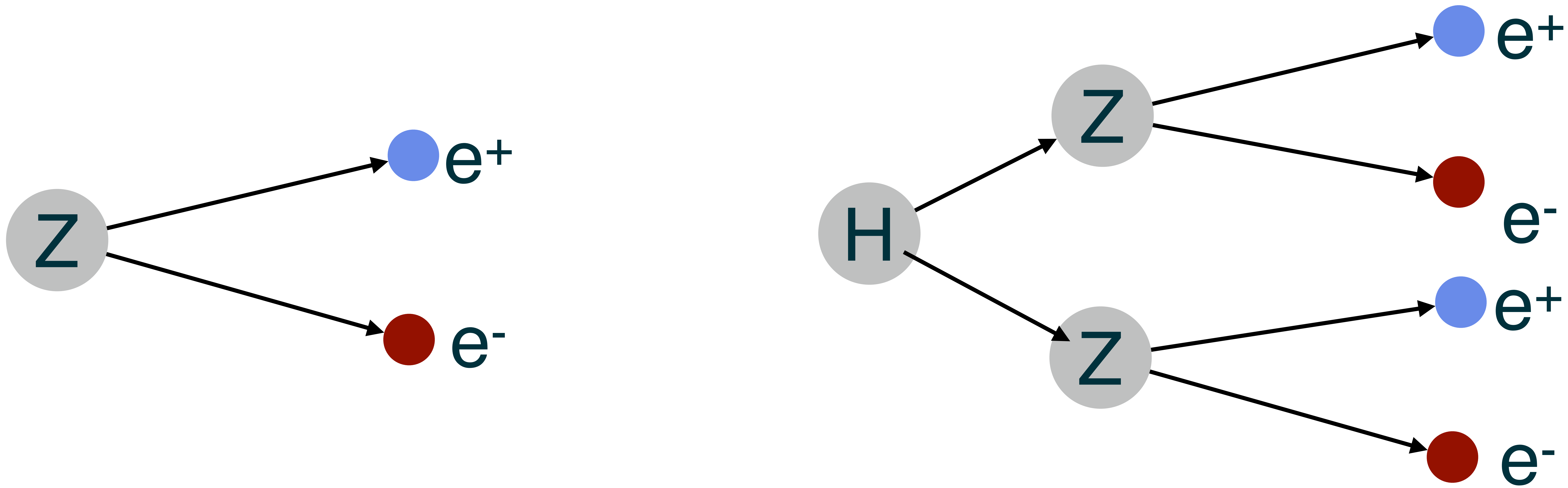
Example analysis

Natural units

- We are using the 'natural units' convention:
  - $\hbar = c = 1$
- Energy, mass, and momentum same units:
  - $E^2 = m^2c^4 + p^2c^2 \rightarrow E^2 = m^2 + p^2$
- Energy expressed in "electron Volts",
- Defined as kinetic energy of an electron accelerated in a 1 V potential,
- 1 eV = 1.6×10^{-19} J

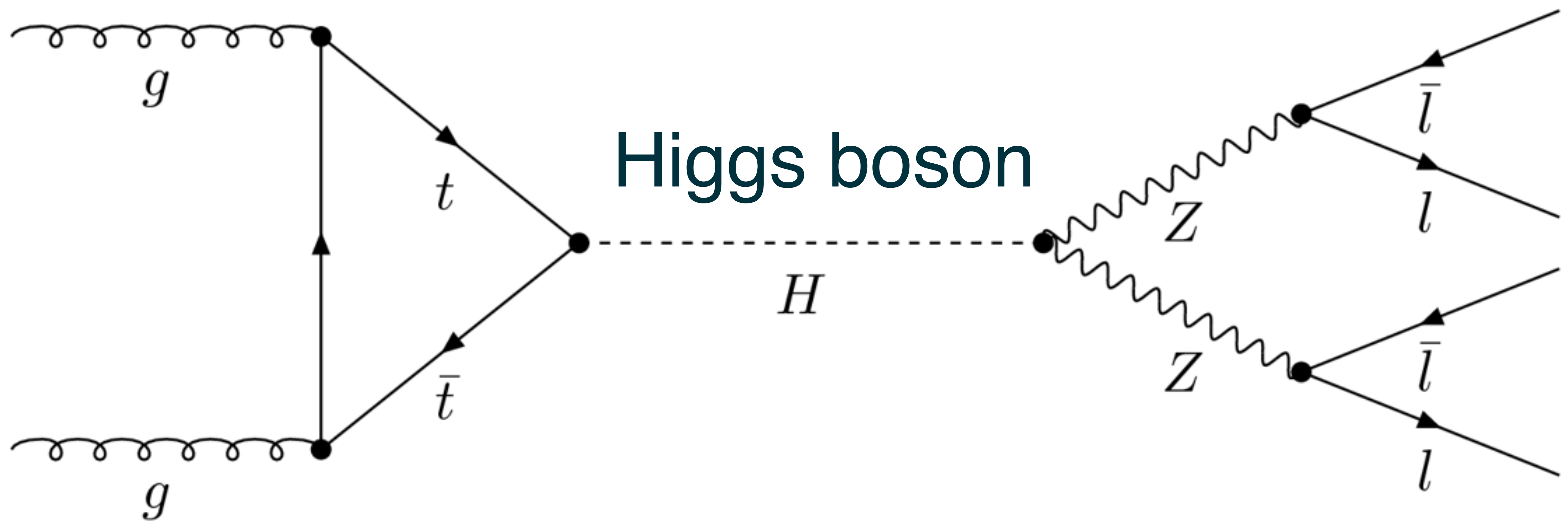


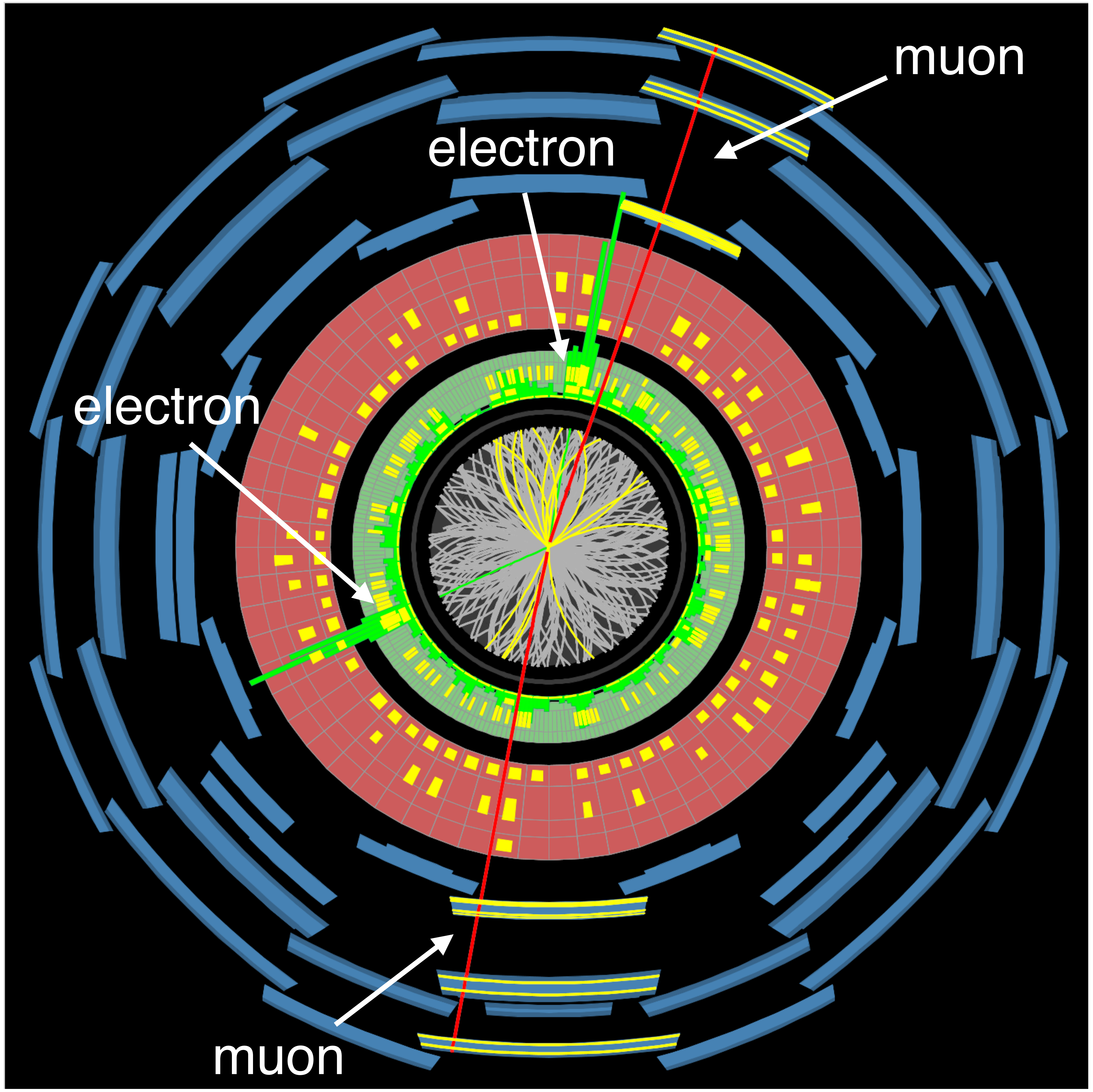
	Units	
Quantity	$\hbar = c = 1$	Conventional
Energy	GeV	GeV
Velocity	1	c
Angular Momentum	1	hbar
Mass	GeV	GeV / c^2
Length	1 / GeV	(c $\times$ hbar) / GeV
Time	1 / GeV	hbar / GeV



- The ATLAS detector measures the momentum of final particles only (e, μ, ɣ, …),
- With these we can reconstruct the **mass** of the initial particle (Z boson or H boson),
  - Z boson: 90 GeV,
  - H boson: 125 GeV,
- However, because the detector has some measurement error, the reconstructed mass will be scattered around the true mass.

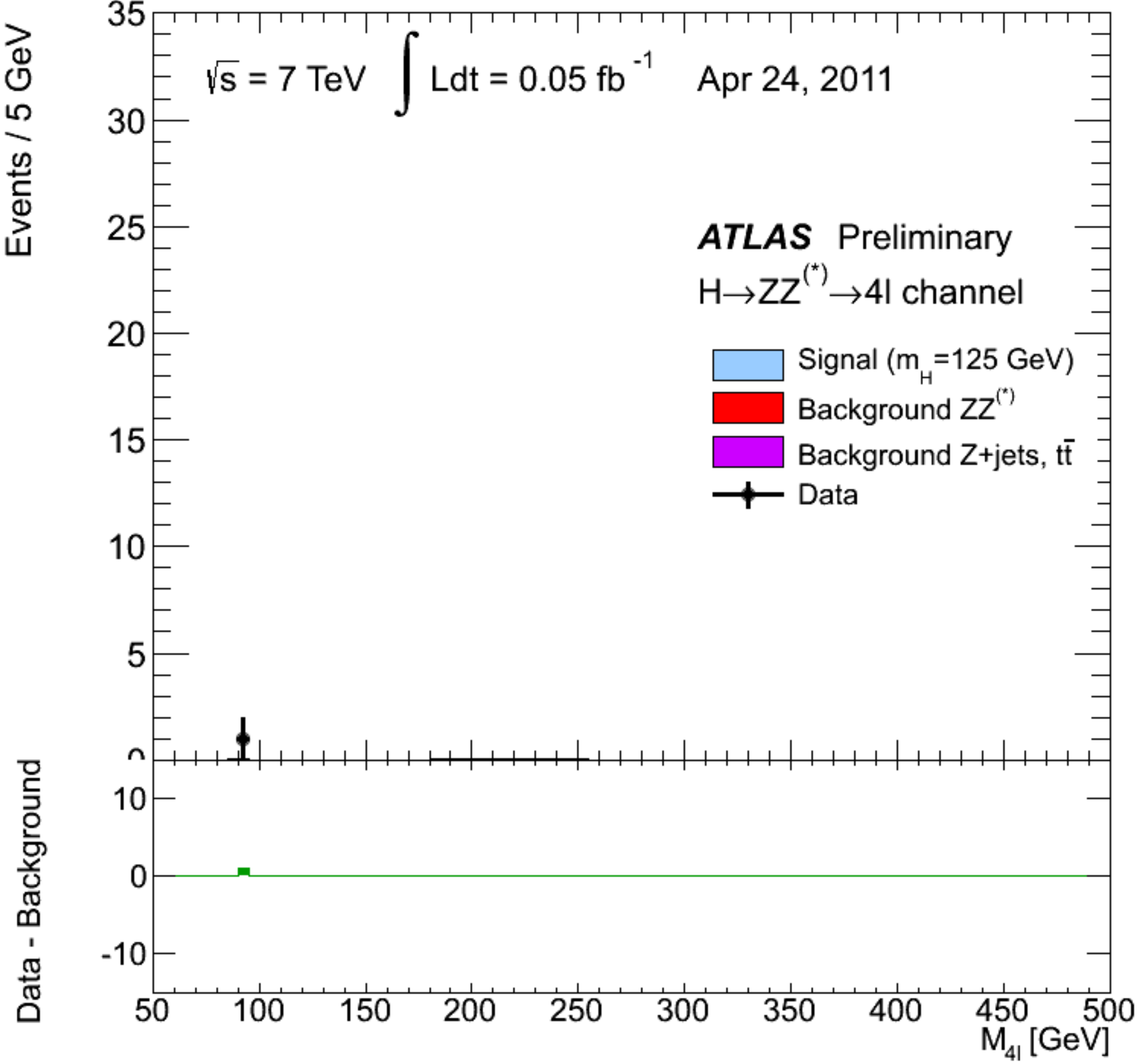
pp collision   4 leptons (electrons or muons)





- **Analysis steps**:
  - Determine the number of *pp* collisions which resulted in a creation of a Higgs boson decaying into four leptons
  - Determine the number of **expected** such events given the theoretical predictions (Standard Model)
  - Compare measurement to prediction— eventually confirms the existence of a Higgs boson

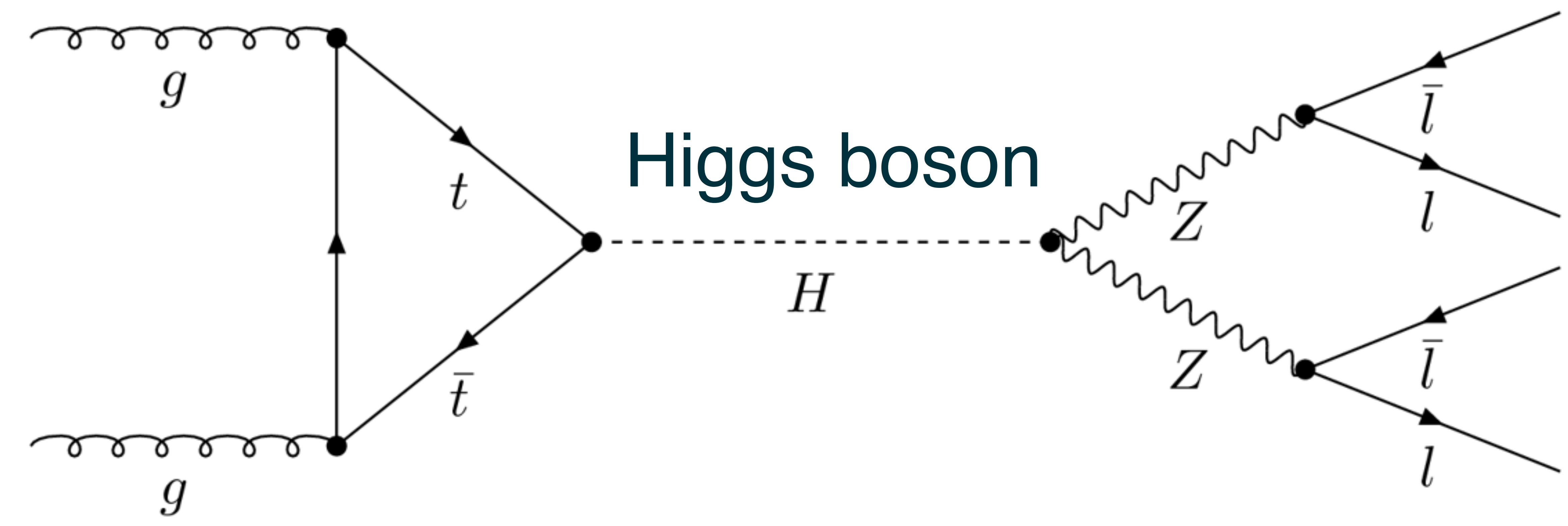
https://cds.cern.ch/record/2230893/



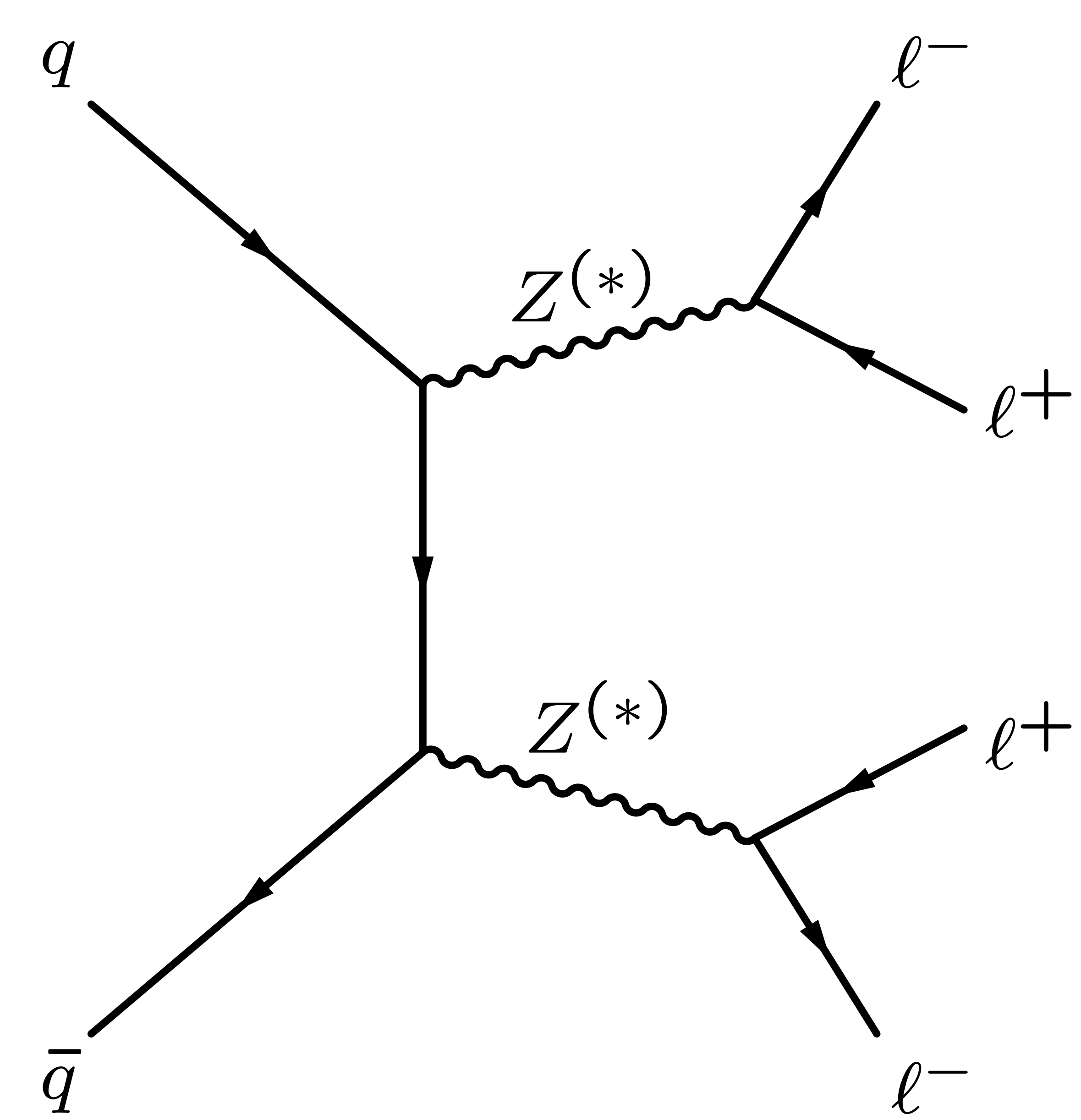
"Invariant mass" of the 4 leptons

Signal

pp collision 4 leptons (electrons or muons)



Background

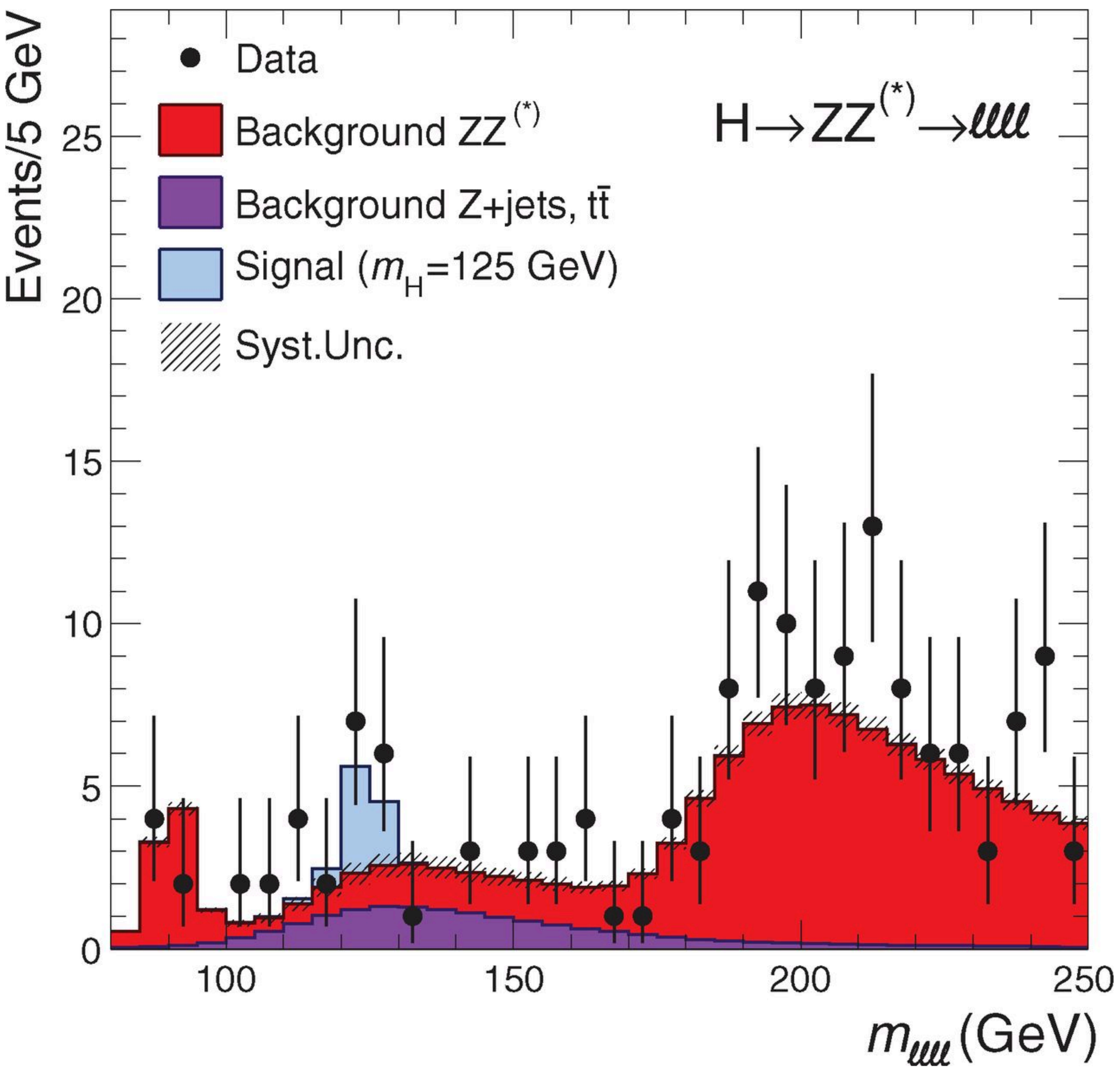


Indistinguishable from the signal

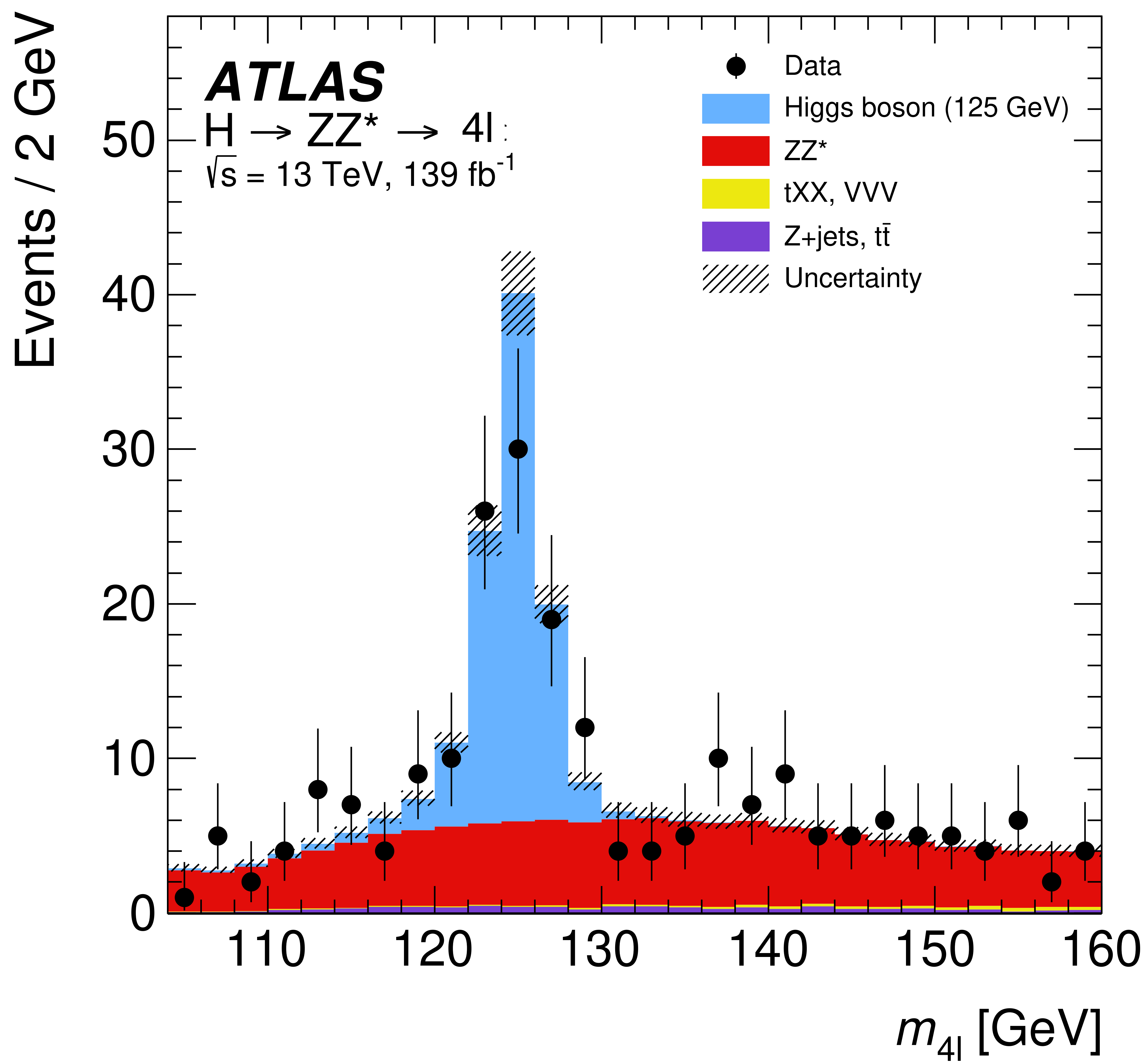
The amount of background typically estimated by simulating *pp* collisions.

Analysis workflow example: Higgs decay to 4 leptons

Higgs discovery time (**2012**)

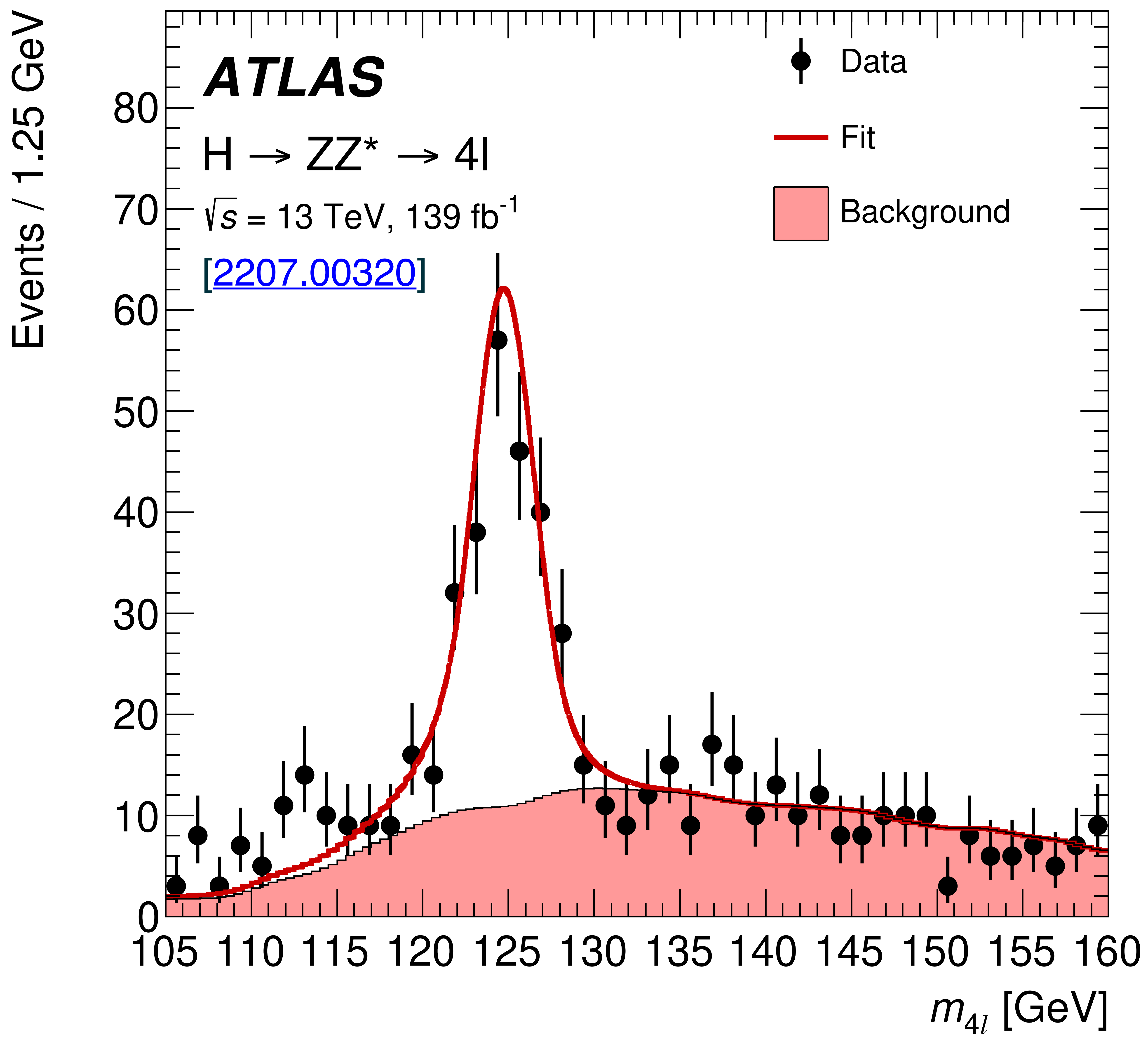


Now (**2022**)
About ~20 times more data
The Higgs peak is much more visible!

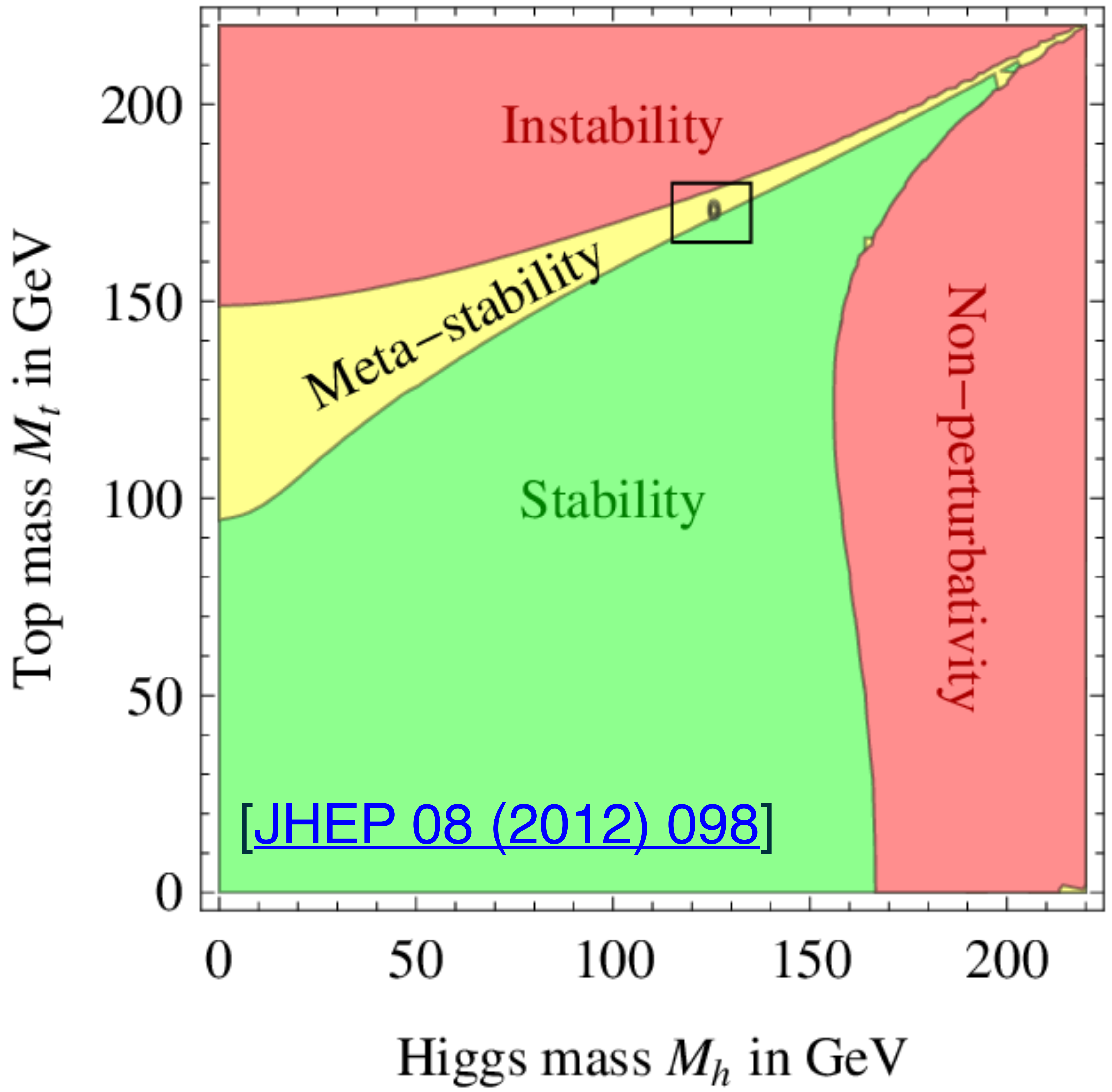


The Higgs boson mass measurement

- Measured from H→ZZ*→4ℓ and H→γγ due to best measurement resolution,



- Run 2 H→ZZ*→4ℓ ATLAS measurement:
  - 124.99 ± 0.18 (stat.) ± 0.04 (syst.) GeV
- Run 1 ATLAS + CMS combination:
  - 125.09 ± 0.24 (stat.) ± 0.11 (syst.) GeV

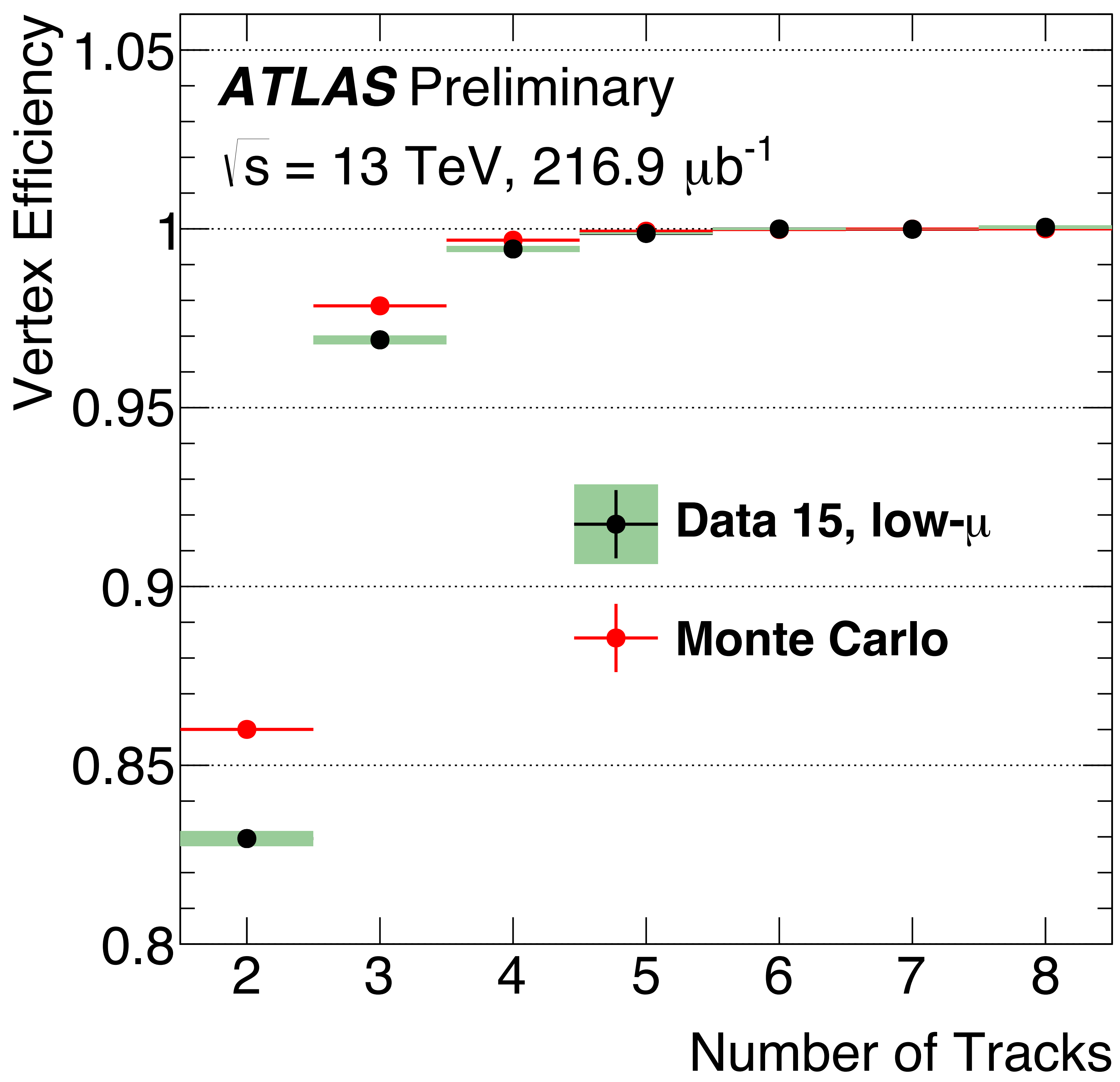


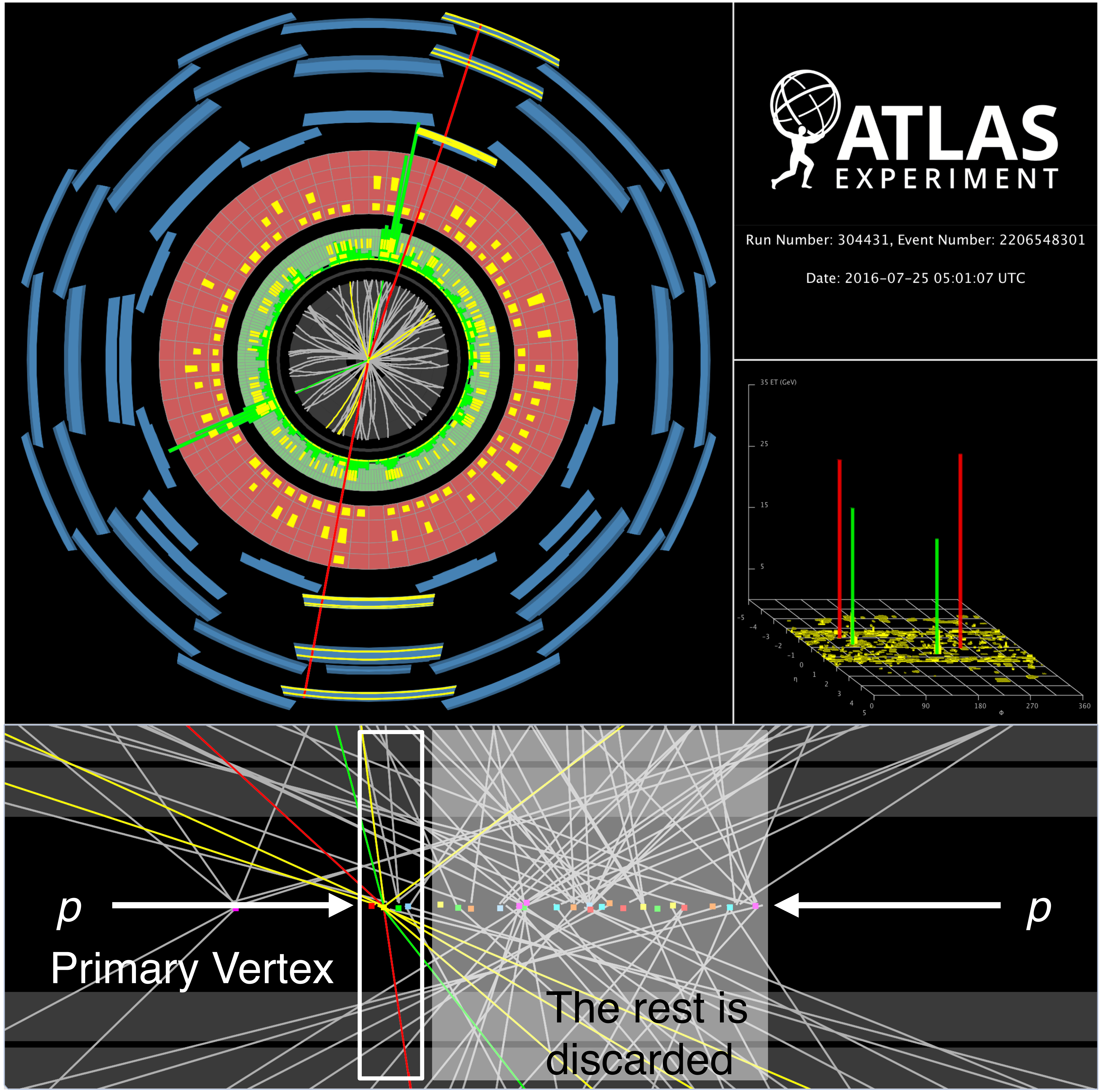
Questions?

Object reconstruction in ATLAS

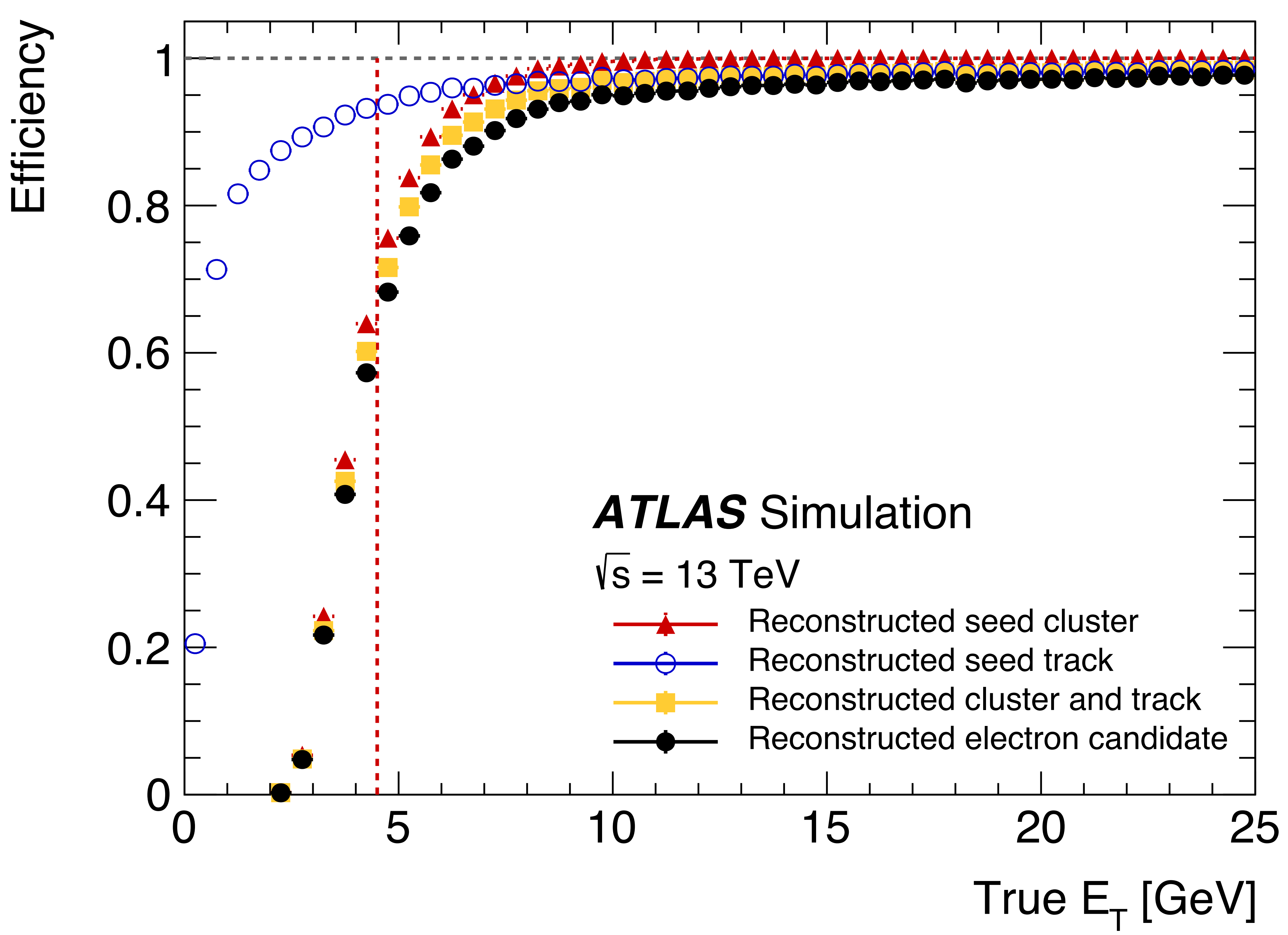
The Primary Vertex

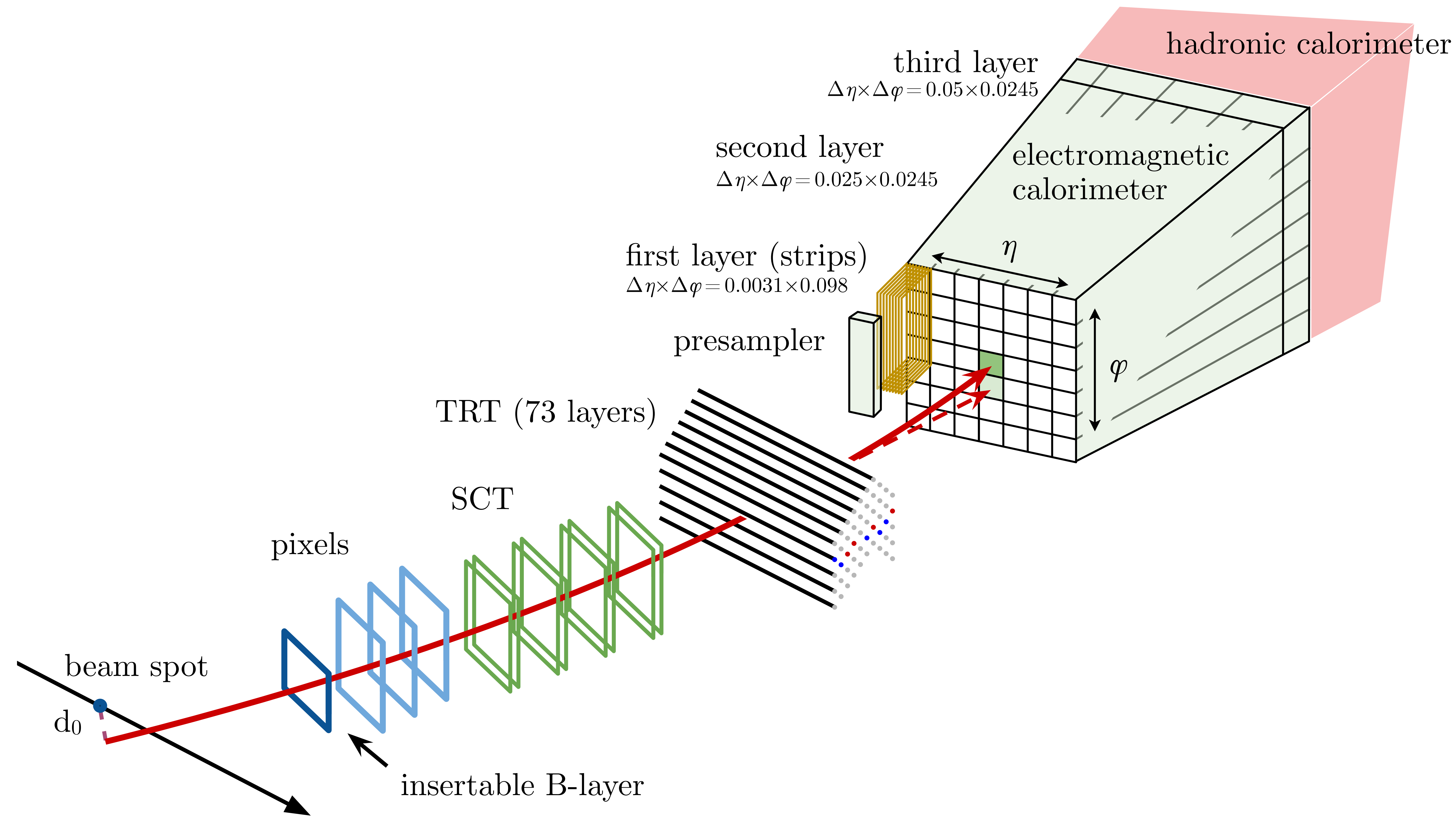
- Requiring that the reconstructed objects are all associated with the same vertex is key in reducing the pileup,
- Unlikely to have two “interesting” proton-proton collisions in a single bunch crossing,
- Typically during data analysis we select the vertex with the highest energy (scalar sum of track momenta) as the “**Primary Vertex**”.



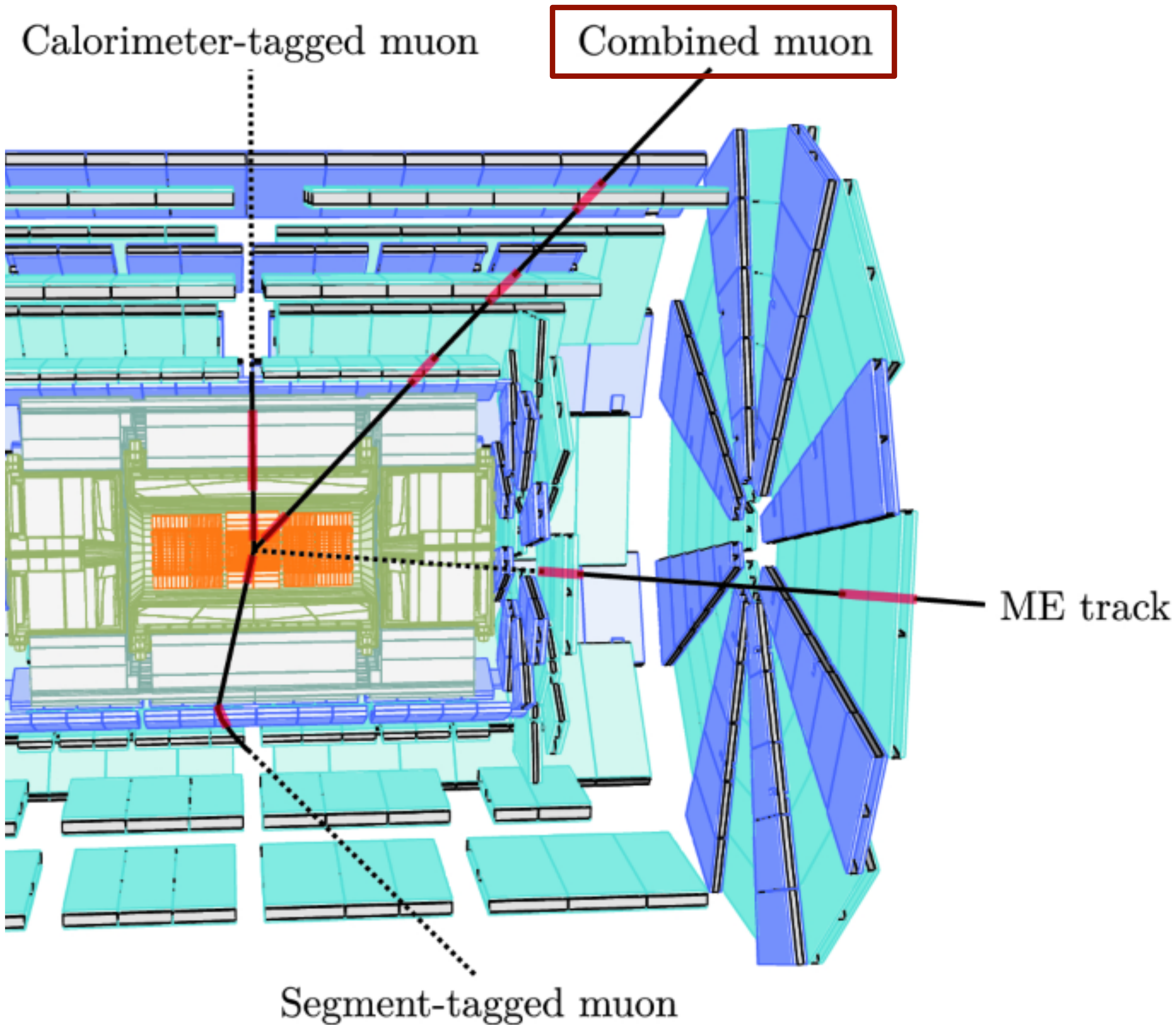


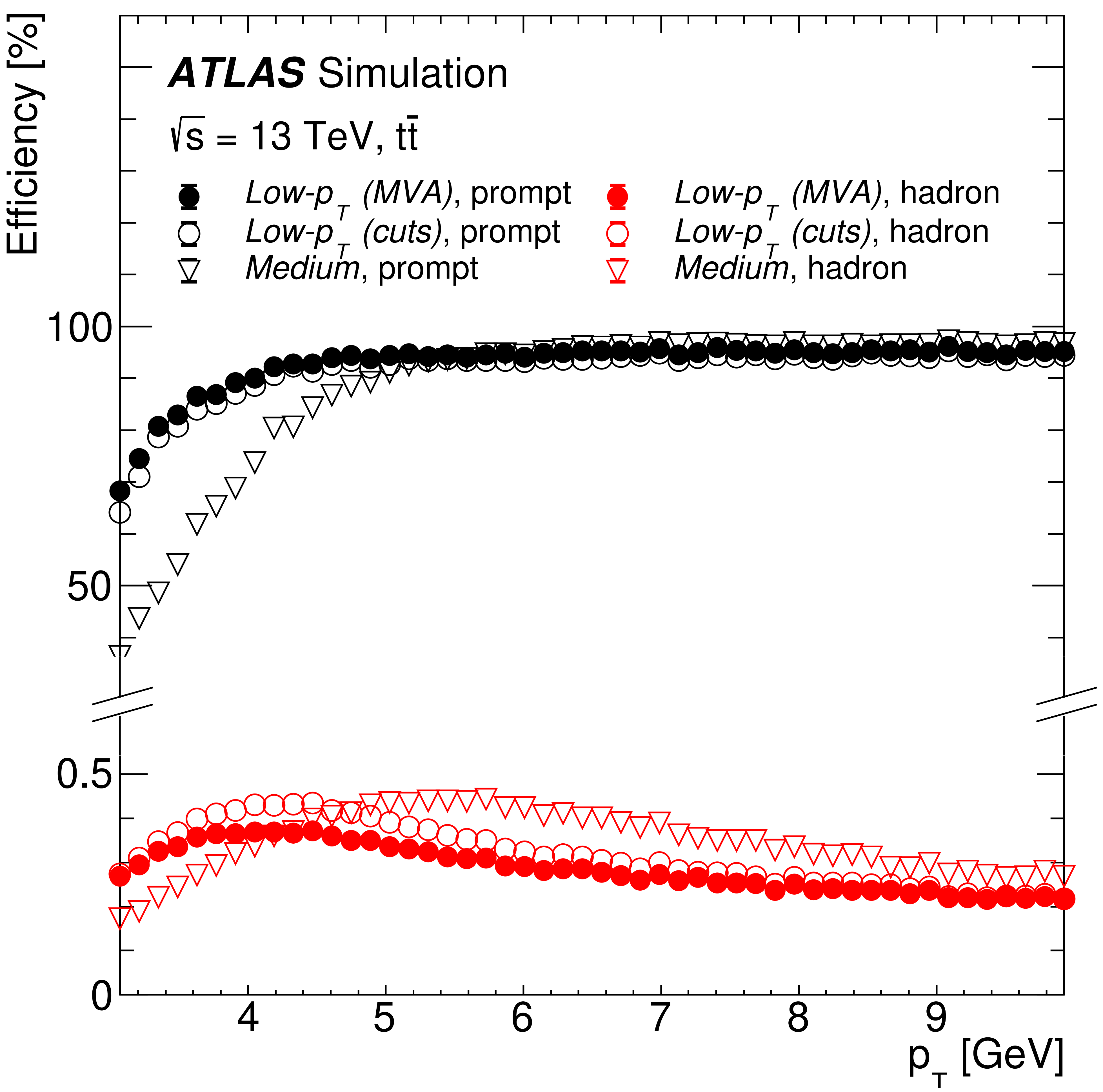
- Electrons identifies as Inner Detector tracks matched to a EM calorimeter cluster,
- Reconstruction efficiency above 95% for electron energies above ~10 GeV,
- Additional selection criteria to separate electrons from hadrons objects with similar signatures,
  - Detailed information about hits in the Inner Detector,
  - Shower shape in EM calorimeters.





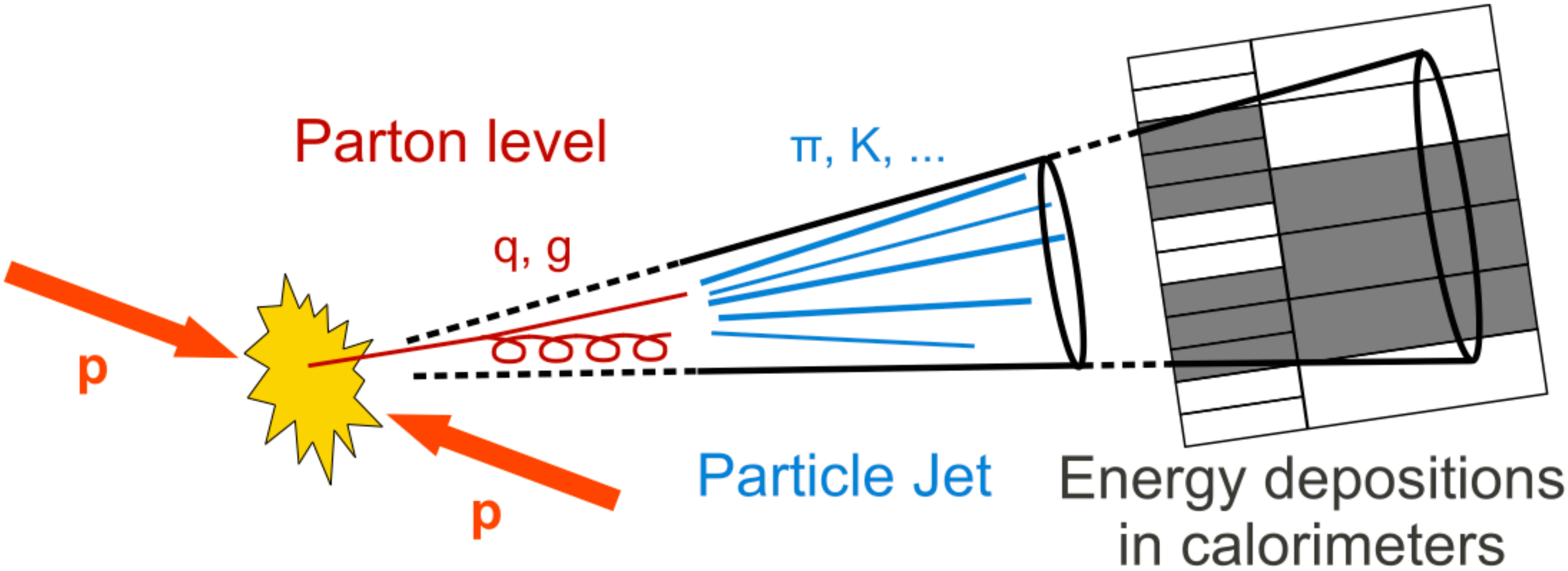
- Best momentum resolution comes from a combined measurement with ID and MS information,
- Reconstruction / identification efficiency above 95% for muon energies above ~5 GeV,
- Additional track-based and calorimeter-based requirements to reduce contamination from “fake” muons,
  - Generally, much fewer fake muons than fake electrons.





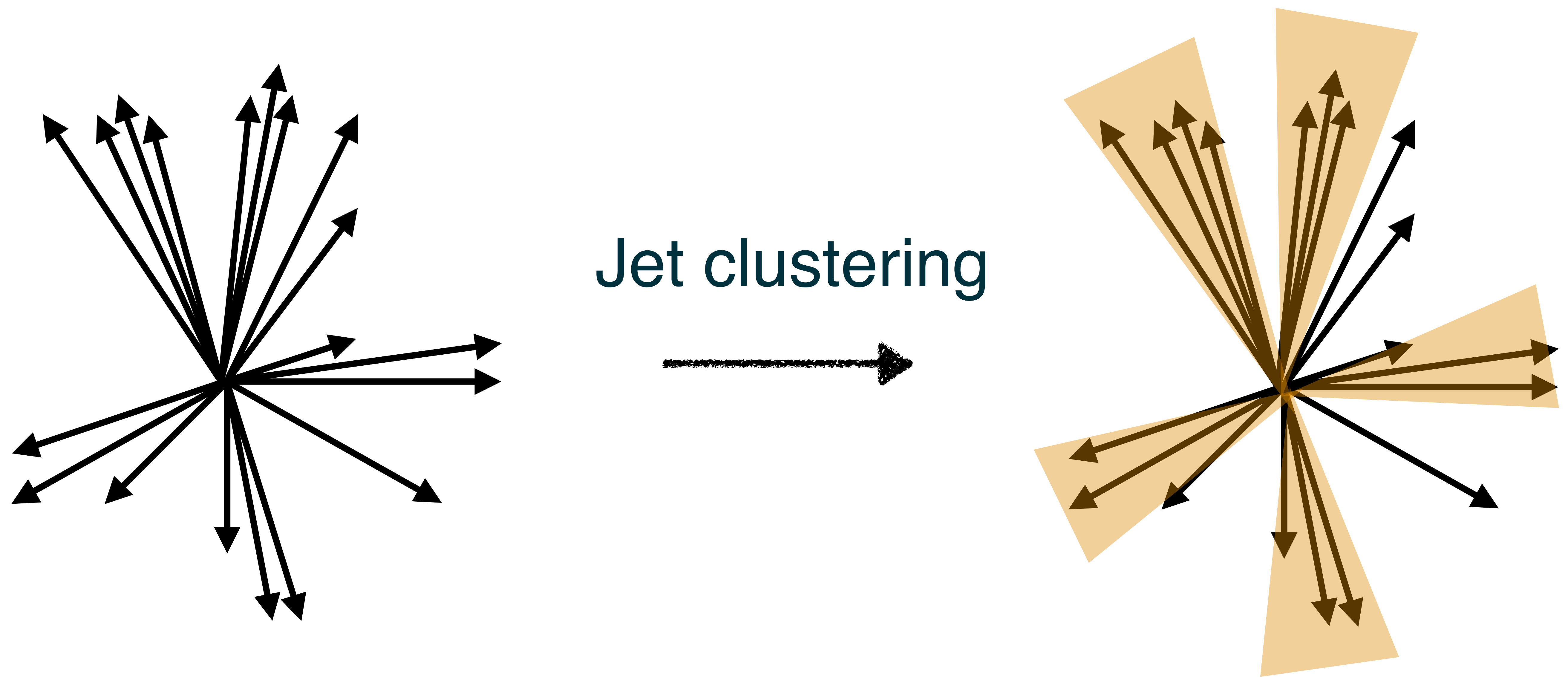
Jet reconstruction (what are jets?)

- Quarks and gluons produced in proton-proton collisions materialize as “jets” in the detector,
- Jet formation governed by Quantum Chromodynamics (QCD):
  - **Fragmentation**: high energy quarks and gluons radiate more gluons and produce a shower,
  - **Hadronization**: when quarks and gluons “slow down” they form bound states (hadrons),
- Hadrons are absorbed in the hadronic calorimeter; charged hadrons also leave tracks in the ID.



- Jet reconstruction generally performed in two steps:
  - Find jet constituents,
  - Use a “jet clustering” algorithm to determine which constituents belong in which jet.

Jet constituents:
- calo clusters,
- ID tracks,
- Hadrons,
- Electrons / muons,
- …



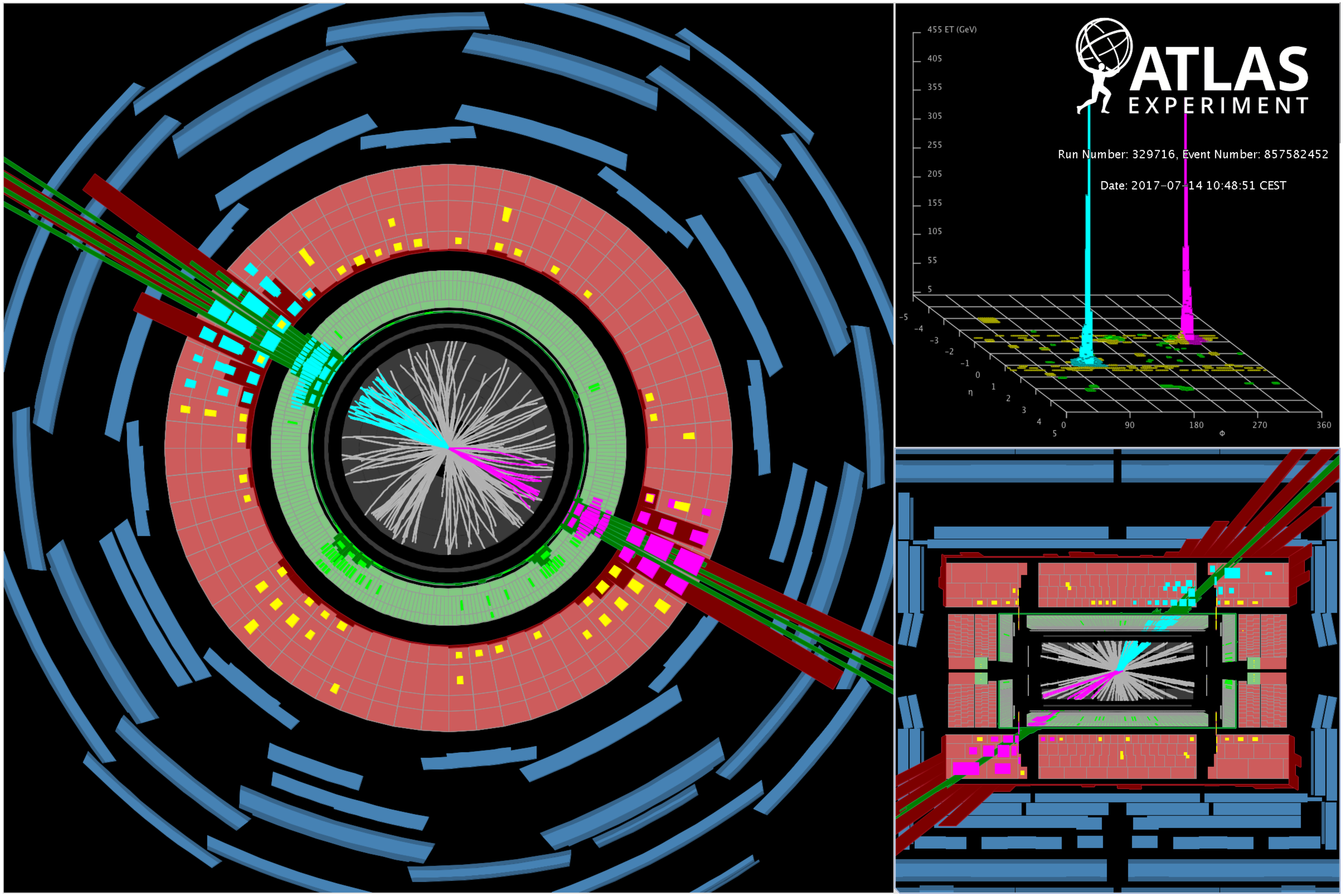
Most commonly the “**anti-kT**” clustering algorithm used [0802.1189].

Radius size parameter of $\Delta R = 0.4$ typically used.

- Historically ATLAS used the “EMTopo” reconstruction algorithm:
  - Only calorimeter clusters used as jet constituents,
- Recently ATLAS started using the “particle flow” algorithm:
  - Calorimeter information is combined with the ID tracking information to reconstruct individual particles before they are subject to the clustering algorithm— better pileup resilience.

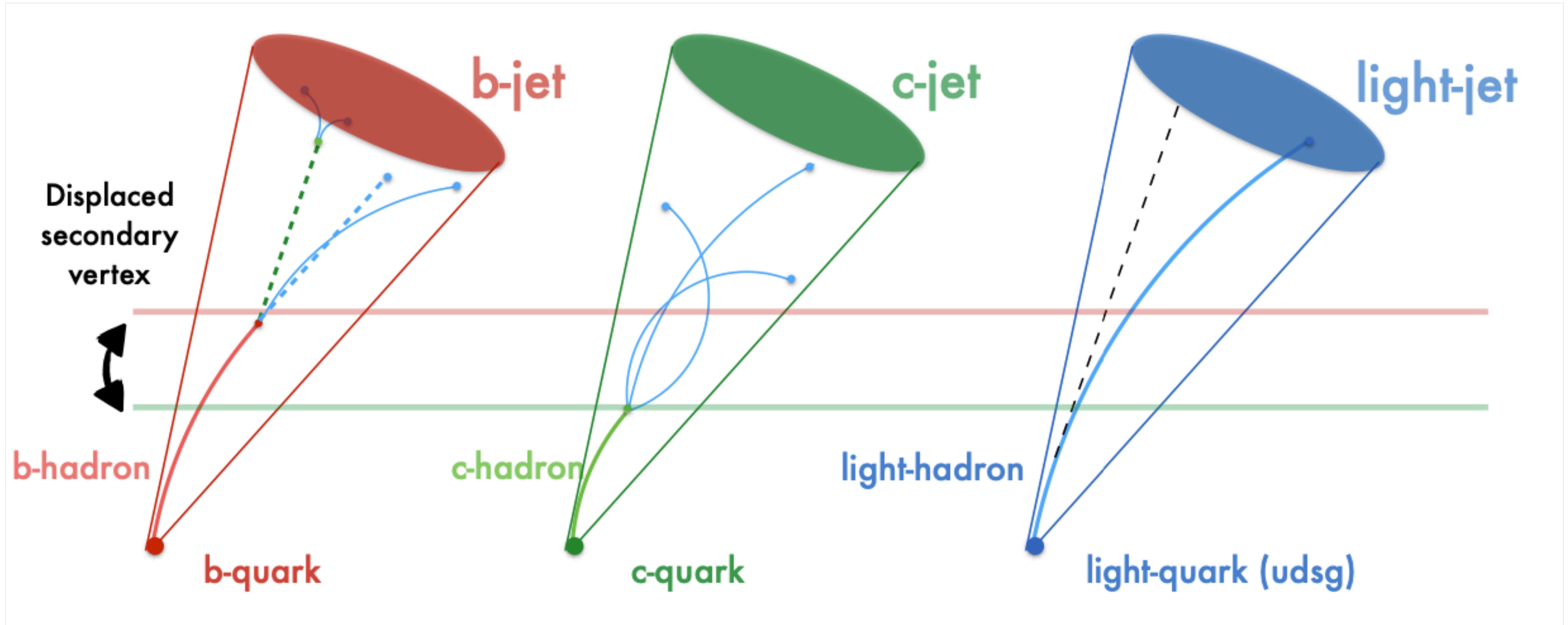
Example di-jet event

- Example event with two high momentum jets with an invariant mass of 9.3 TeV.



Jet “Flavor Tagging”

- Jets arising from “heavy flavor” quarks (c- and b-quarks) have distinct properties and can be partially separated from “light-jets”— the process is called jet Flavor Tagging,
- b-jets and c-jets typically contain a displaced hadron (e.g. B+, D+, …) which forms a secondary vertex,
  - c-hadron lifetime: **100-300 μm/c**
  - b-hadron lifetime: **400-500 μm/c**
- **Machine Learning** algorithms are trained to distinguish between b-jets, c-jets, and light-jets based on the small differences in ID tracking and calorimeter signatures between these jets.

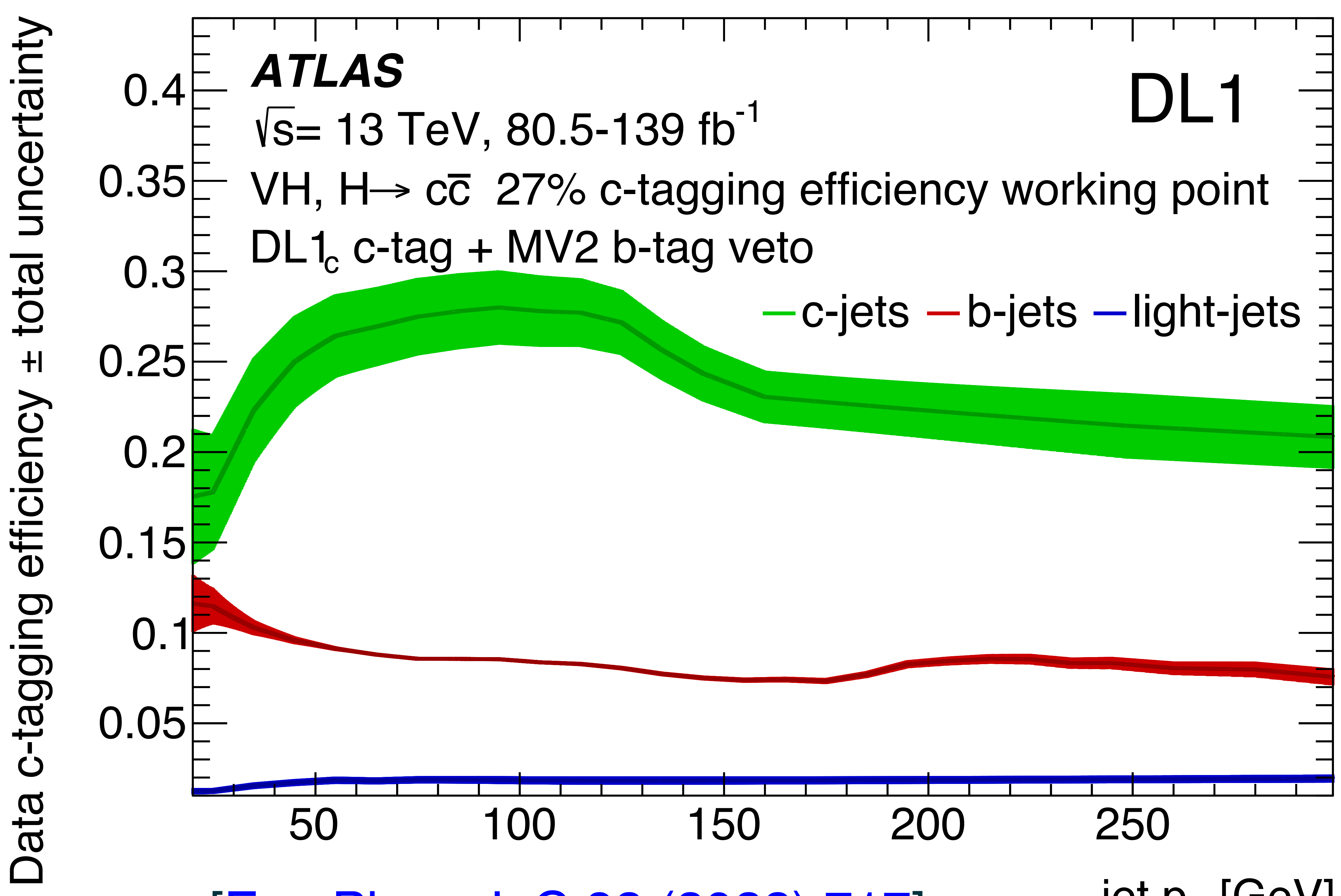


Credits: Marko Stamenkovic

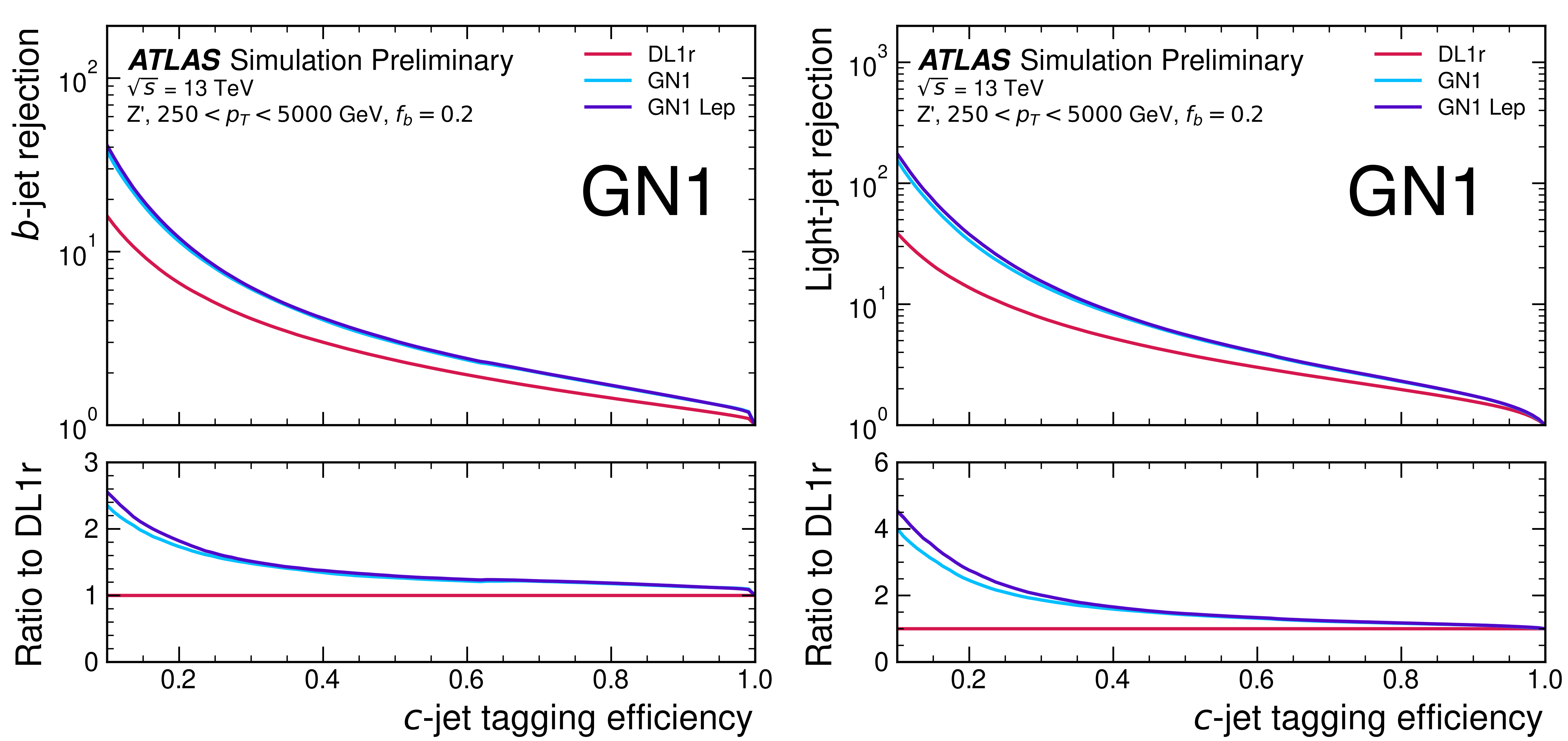
- Performance of flavor tagging efficiencies has been drastically improving in the past years,
  - More complex ML architecture (BDT → DNN → GNN) and more low-level information included,
- In ATLAS typically have Neural Networks with three output nodes (c-jet, b-jet, light-jet "probability").

- "DL1" DNN used so far:
  - About 27% efficiency to tag c-jets
  - Rejection factor of 12.5 (63) for b-jets (light-jet)

- "GN1" tagger based on a Graph Neural Network:
  - Up to 2× better expected rejection power at the same c-jet tagging efficiency.



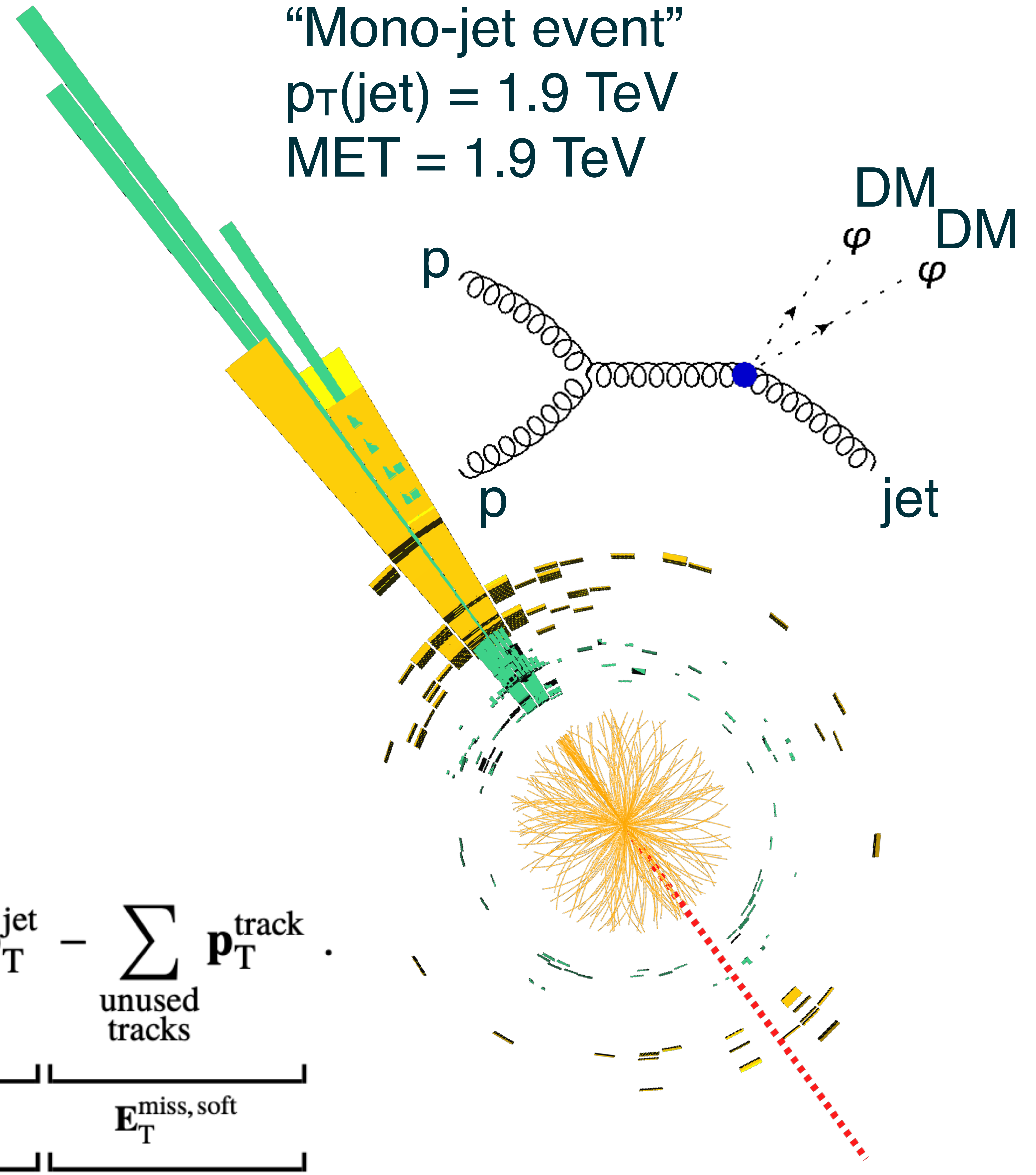
[Eur. Phys. J. C 82 (2022) 717]



[ATL-PHYS-PUB-2022-027]

- Neutrinos leave no trace in the detector because they only interact with the weak force,
- However, many SM particles decay into neutrinos, e.g. $W^- \rightarrow \ell^- \bar{\nu}$,
- As a proxy for the neutrino energy we define the "Missing Transverse Momentum (MET)":
  - Vectorial sum of all particle momenta in the transverse plane should be zero,
  - Non-zero only due to the undetected neutrinos and the finite detector resolution,
- BSM particles (e.g. Dark Matter) would also leave a similar signature in the detector.

"Mono-jet event"
p_T(jet) = 1.9 TeV
MET = 1.9 TeV



$$\mathbf{E}_T^{\text{miss}} = \underbrace{\underbrace{-\sum_{\substack{\text{selected}\\\text{electrons}}} \mathbf{p}_T^{e}}_{\mathbf{E}_T^{\text{miss},e}} \underbrace{-\sum_{\substack{\text{accepted}\\\text{photons}}} \mathbf{p}_T^{\gamma}}_{\mathbf{E}_T^{\text{miss},\gamma}} \underbrace{-\sum_{\substack{\text{accepted}\\\tau\text{-leptons}}} \mathbf{p}_T^{\tau_{\text{had}}}}_{\mathbf{E}_T^{\text{miss},\tau_{\text{had}}}} \underbrace{-\sum_{\substack{\text{selected}\\\text{muons}}} \mathbf{p}_T^{\mu}}_{\mathbf{E}_T^{\text{miss},\mu}} \underbrace{-\sum_{\substack{\text{accepted}\\\text{jets}}} \mathbf{p}_T^{\text{jet}}}_{\mathbf{E}_T^{\text{miss,jet}}}}_{\text{hard term}} \underbrace{\underbrace{-\sum_{\substack{\text{unused}\\\text{tracks}}} \mathbf{p}_T^{\text{track}}}_{\mathbf{E}_T^{\text{miss,soft}}}}_{\text{soft term}} .$$

- Dedicated object reconstruction algorithms covered:
  - **Electrons**: combined tracking and EM calorimeter information,
  - **Muons**: combined tracking information from ID and MS,
  - **Jets**: collimated ID tracks and calorimeter clusters (EM and HAD),
    - **Jet Flavor Tagging** (c-jets, b-jets, light-jets),
  - **Missing Energy**: proxy for neutrinos or non-interacting BSM particles (Dark Matter).

- Also commonly reconstruct:
  - **Photons**: similar as electrons but without ID tracks,
  - **Taus**: decay almost instantly via weak force:
    - Pair of electron / muon plus neutrino,
    - Hadrons (similar as jets).