

À la chasse de la **Matière Noire** au grand collisionneur du CERN

Anna Sfyrla



**UNIVERSITÉ
DE GENÈVE**

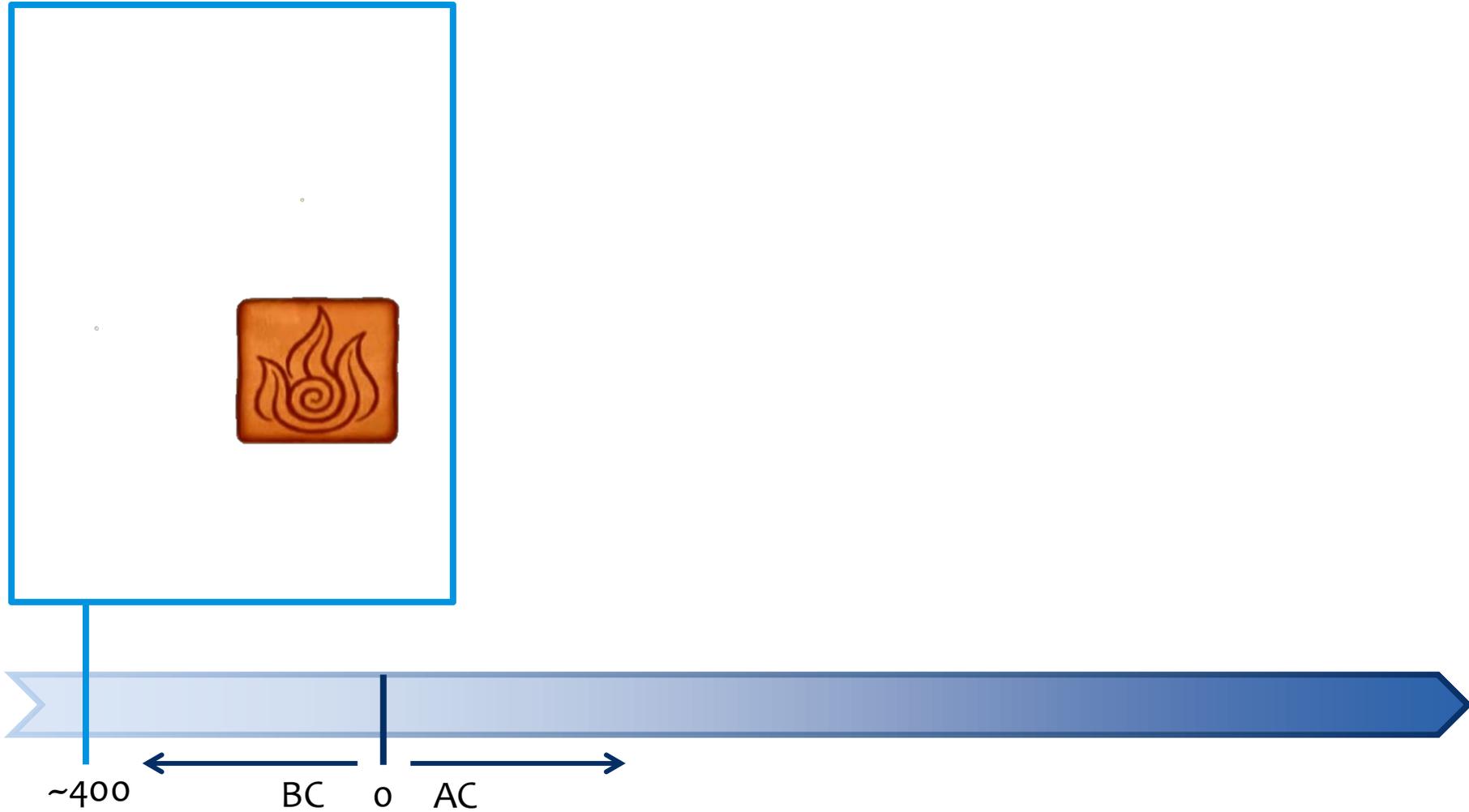
FACULTÉ DES SCIENCES
Section de physique



Matière



Matière



Matière

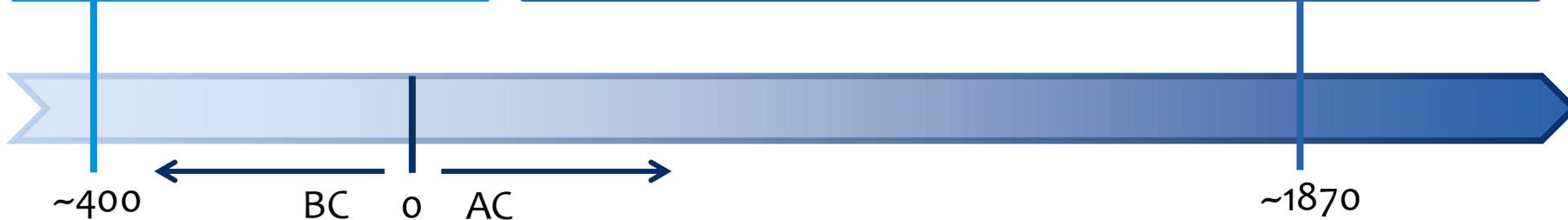


Periodic Table of the Elements

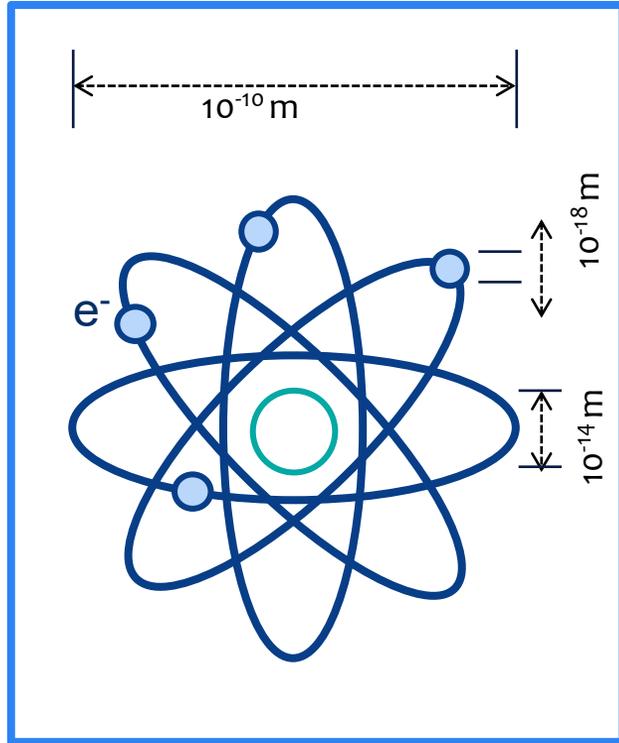
1 IA 11A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A	
1 H Hydrogen 1.008	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180	
3 Li Lithium 6.941	11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 9	10 VIII 10	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 84.96	
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29	
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon [222]	
87 Fr Francium [223]	88 Ra Radium [226]	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium [278]	114 Fl Flerovium [278]	115 Uup Ununpentium [278]	116 Lv Livermorium [276]	117 Uus Ununseptium [276]	118 Uuo Ununoctium [276]	
			57 La Lanthanum 138.905	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967	
			89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]	

Alkali Metal
Alkaline Earth
Transition Metal
Semimetal
Nonmetal
Basic Metal
Halogen
Noble Gas
Lanthanide
Actinide

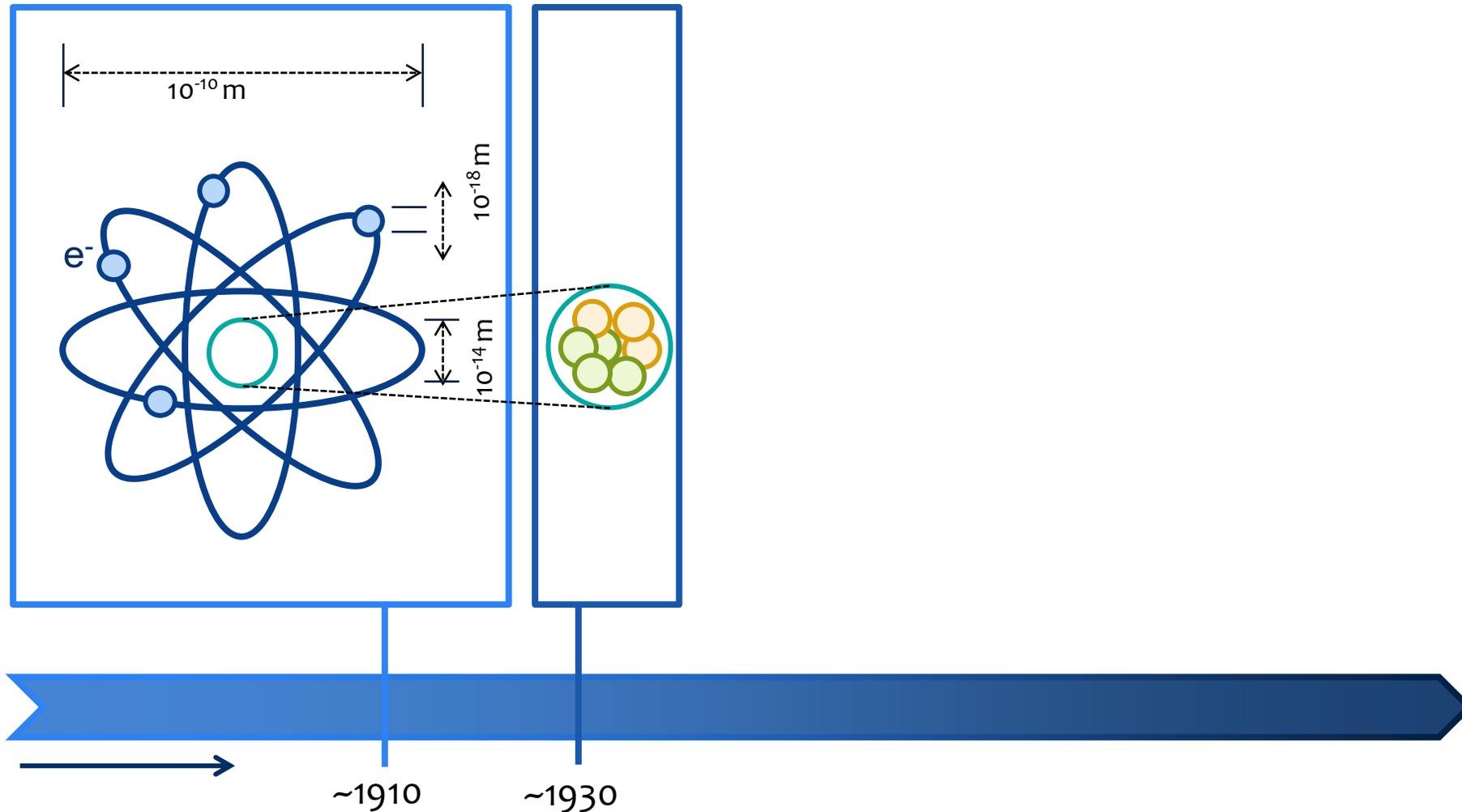
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chemistry.about.com
science-notes.org



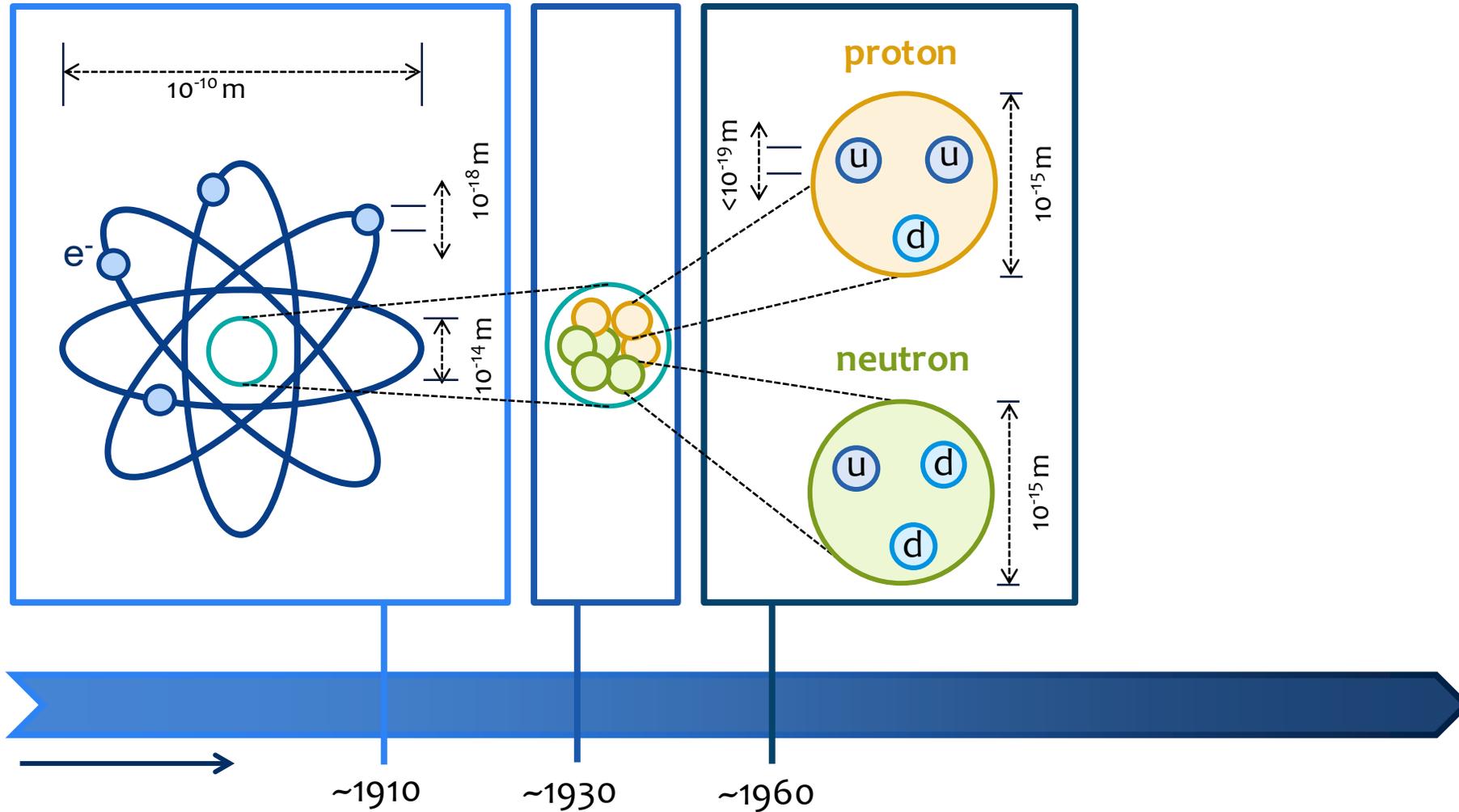
Matière



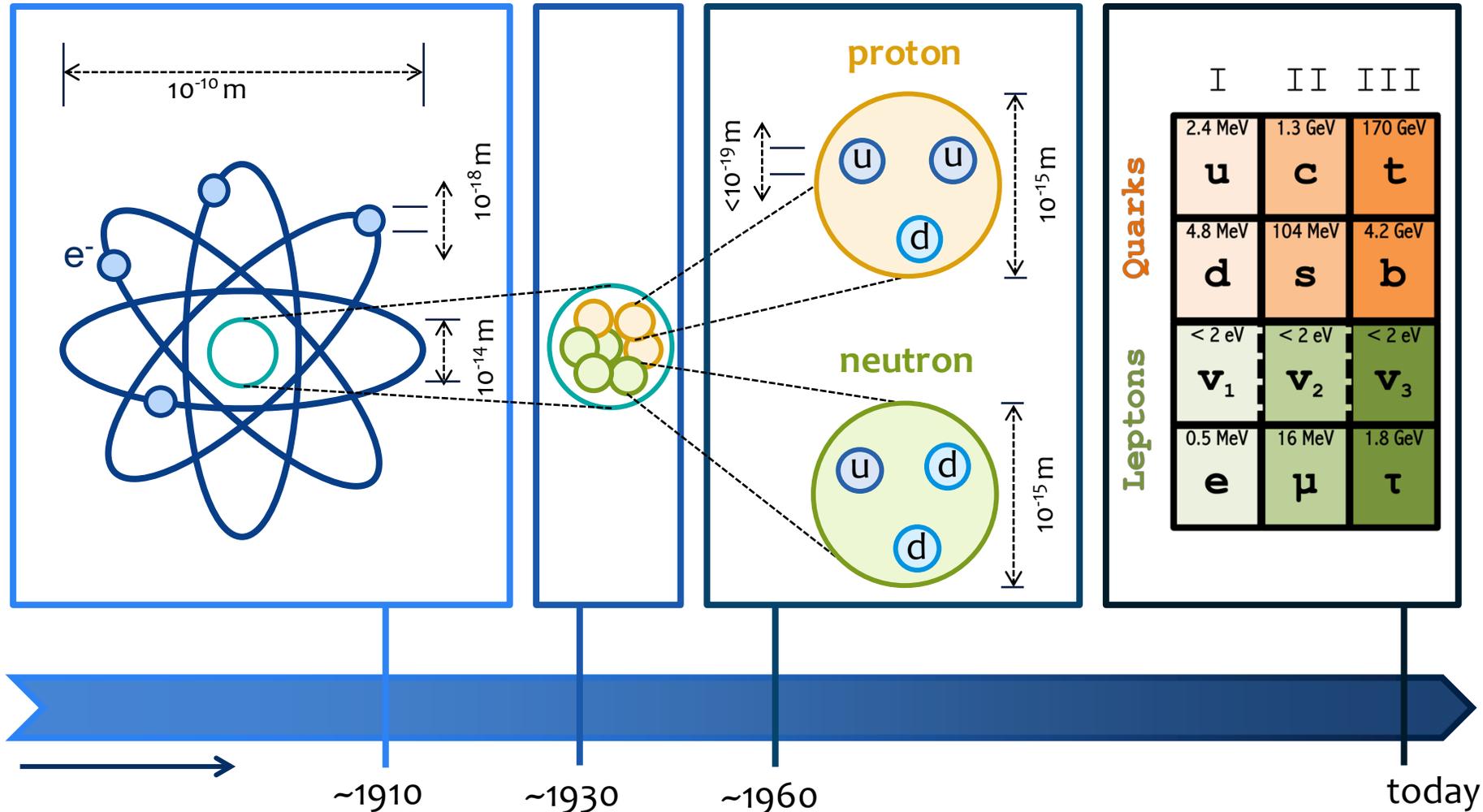
Matière



Matière



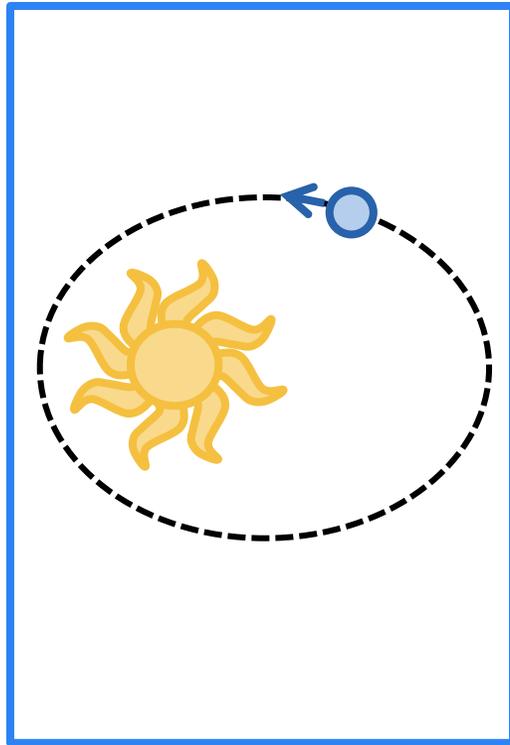
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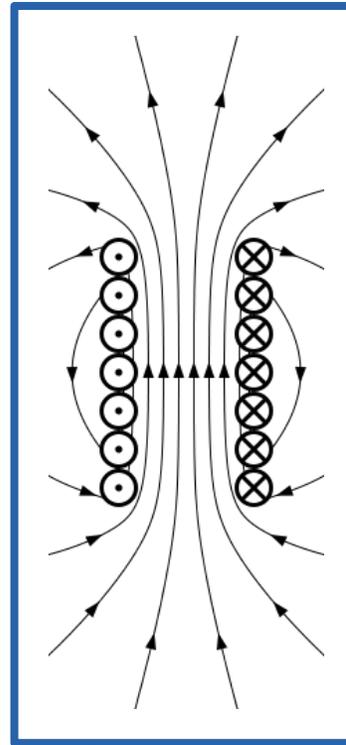
Forces



Forces



~1660

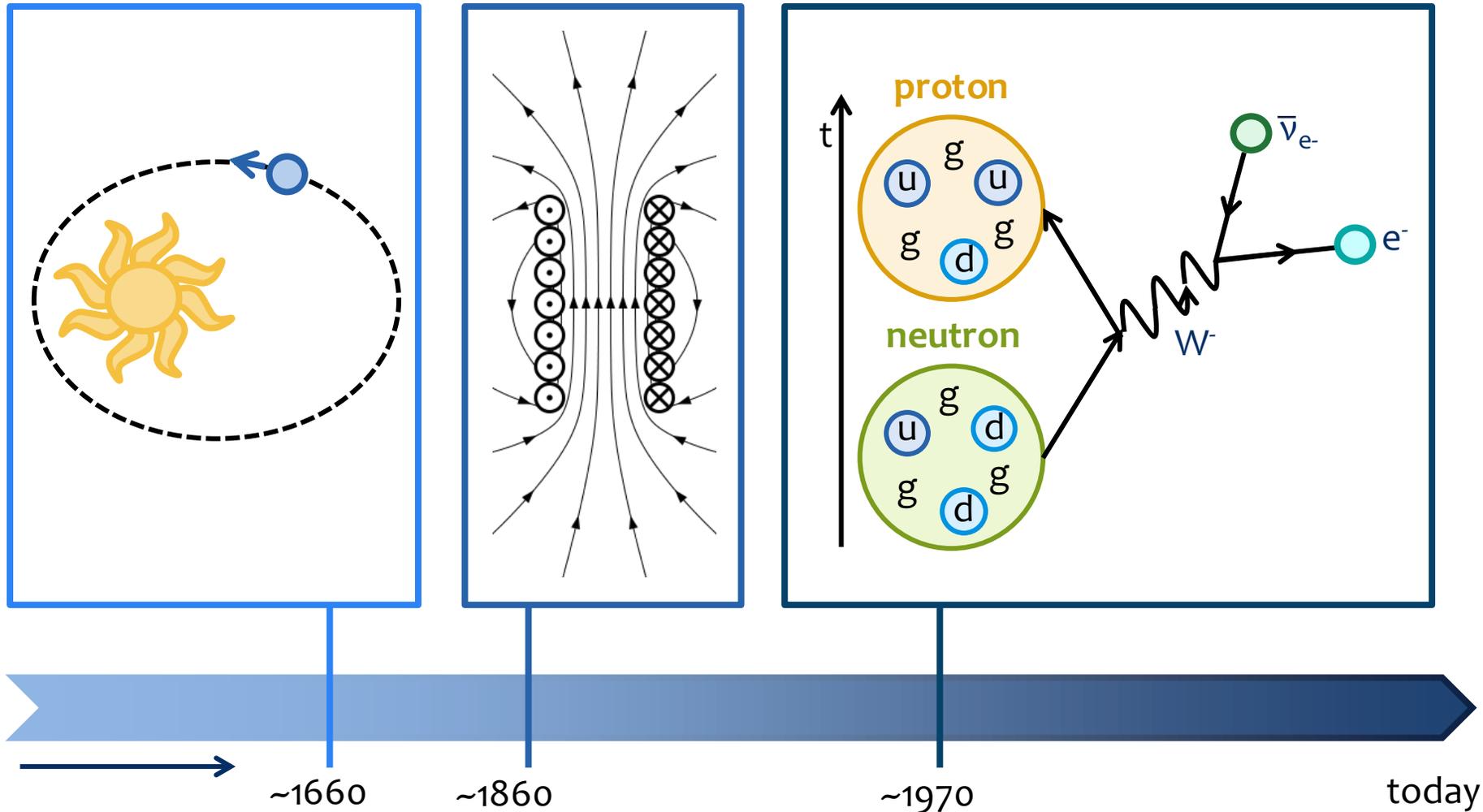


~1860



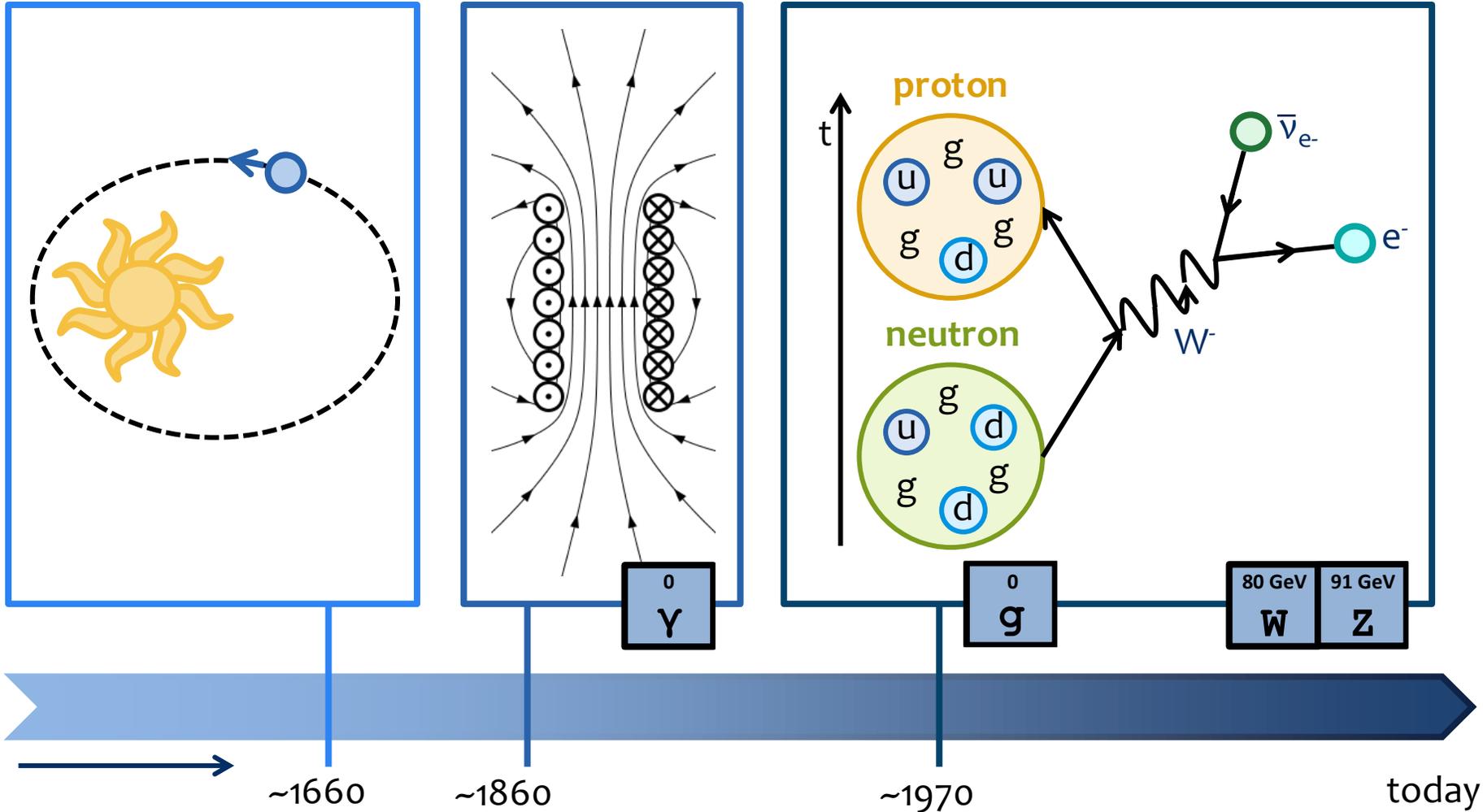
today

Forces

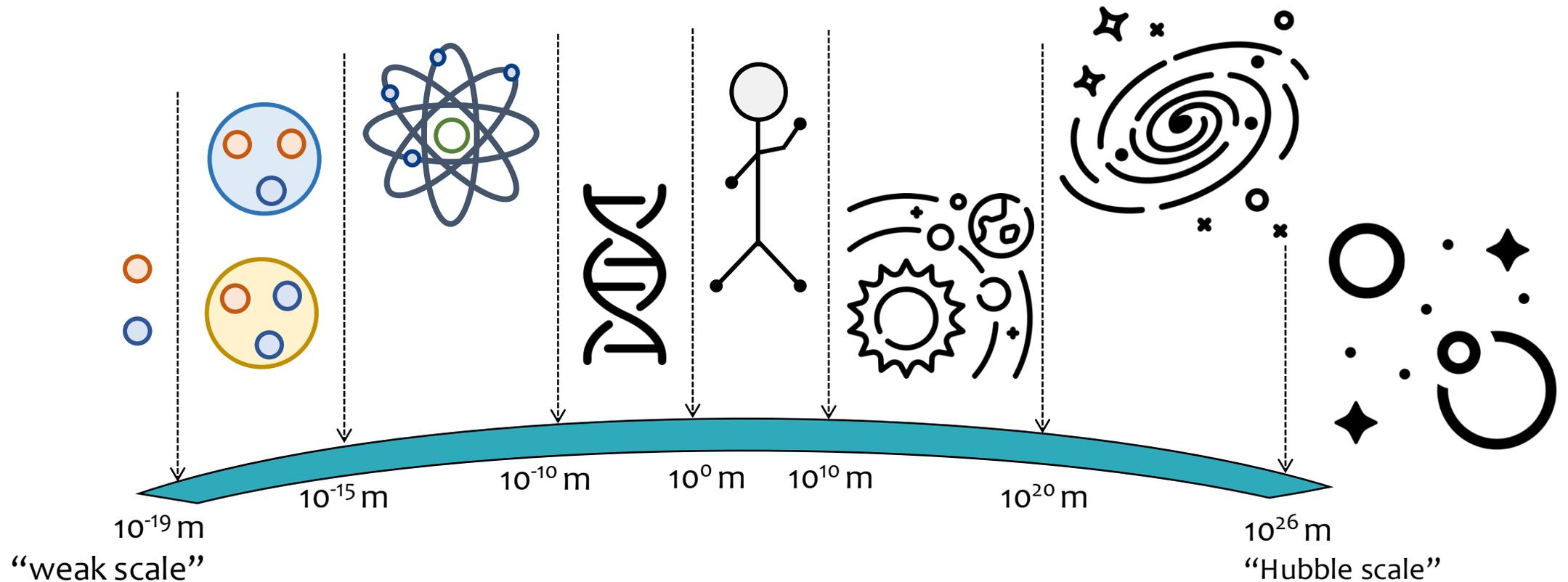


Forces

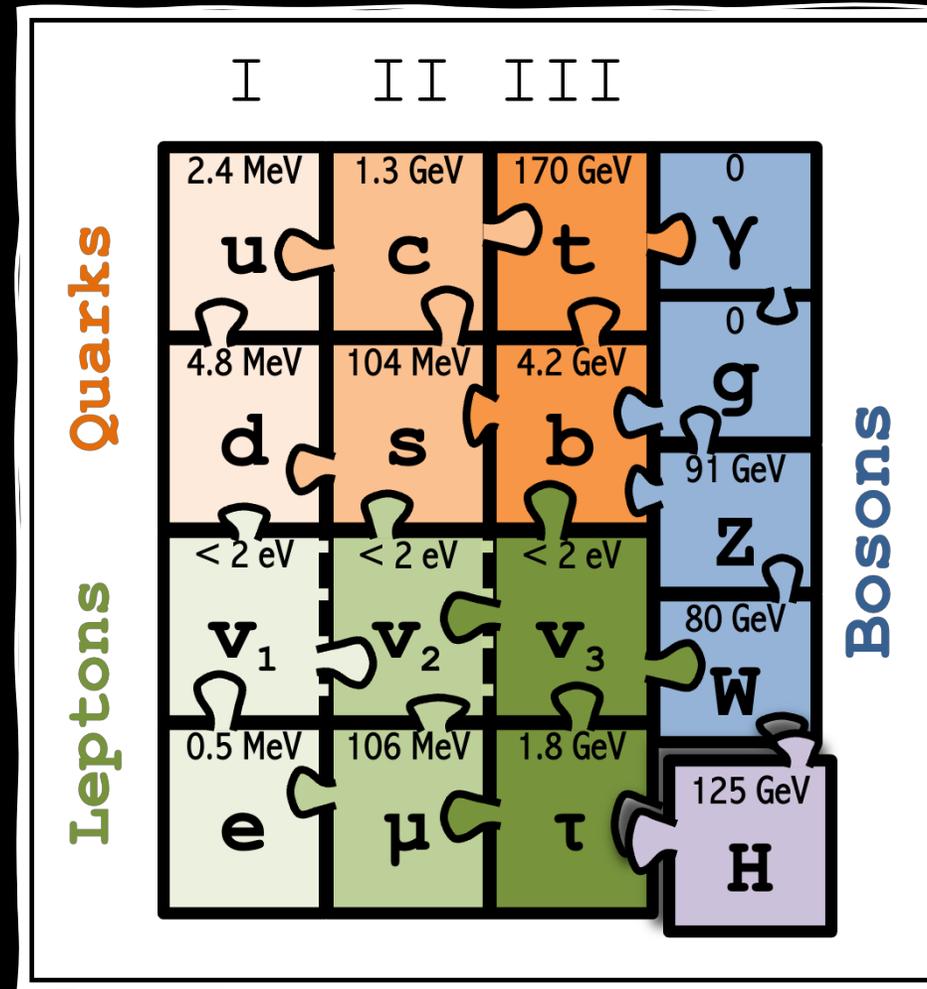
Force carriers: Bosons



Échelle des Forces



Le modèle standard



2013 NOBEL PRIZE IN PHYSICS

François Englert Peter W. Higgs



© The Nobel Foundation. Photo: Lovisa Engblom.

Le prix Nobel de physique 2013 a été décerné conjointement à François Englert et Peter W. Higgs

« pour la découverte théorique d'un mécanisme qui contribue à notre compréhension de l'origine de la masse des particules subatomiques, et qui a récemment été confirmé par la découverte de la particule fondamentale prédite, grâce aux expériences ATLAS et CMS menées au Grand collisionneur de hadrons du CERN ».

Le boson de Higgs, c'est quoi ?

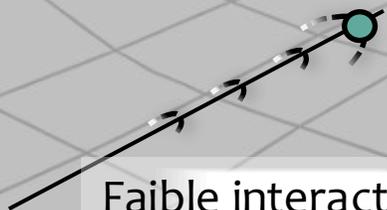
Le **boson de Higgs** = la signature observable du champ de Higgs

Le **champ de Higgs** = un champ invisible present partout dans l'espace

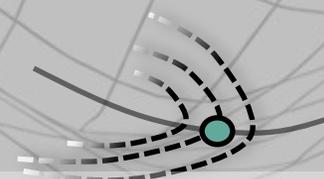
Les particules qui interagissent avec ce champ **acquièrent une masse**

Toutes les particules n'interagissent pas de la même façon

Plus l'interaction est forte, plus la masse est grande



Faible interaction: petite masse



Forte interaction: grande masse

Le boson de Higgs, c'est quoi ?

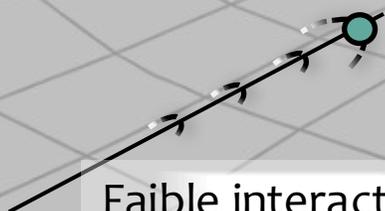
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Faible interaction: petite masse



Forte interaction: grande masse



...juste une pièce du puzzle cosmique

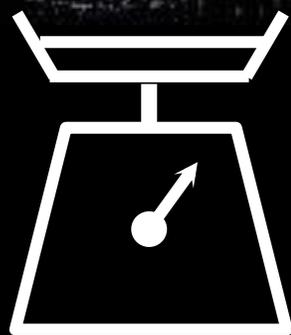
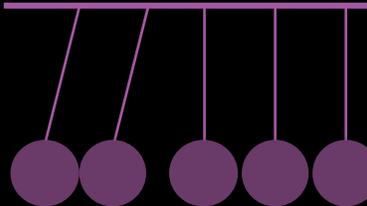
2.4 MeV u	1.3 GeV c	170 GeV t	0 γ
4.8 MeV d	104 MeV s	4.2 GeV b	0 g
<2 eV ν_L	<2 eV ν_M	<2 eV ν_H	91 GeV Z
0.5 MeV e	16 MeV μ	1.8 GeV τ	80 GeV W
			125 GeV H



Théorie de la gravitation



Lois du mouvement

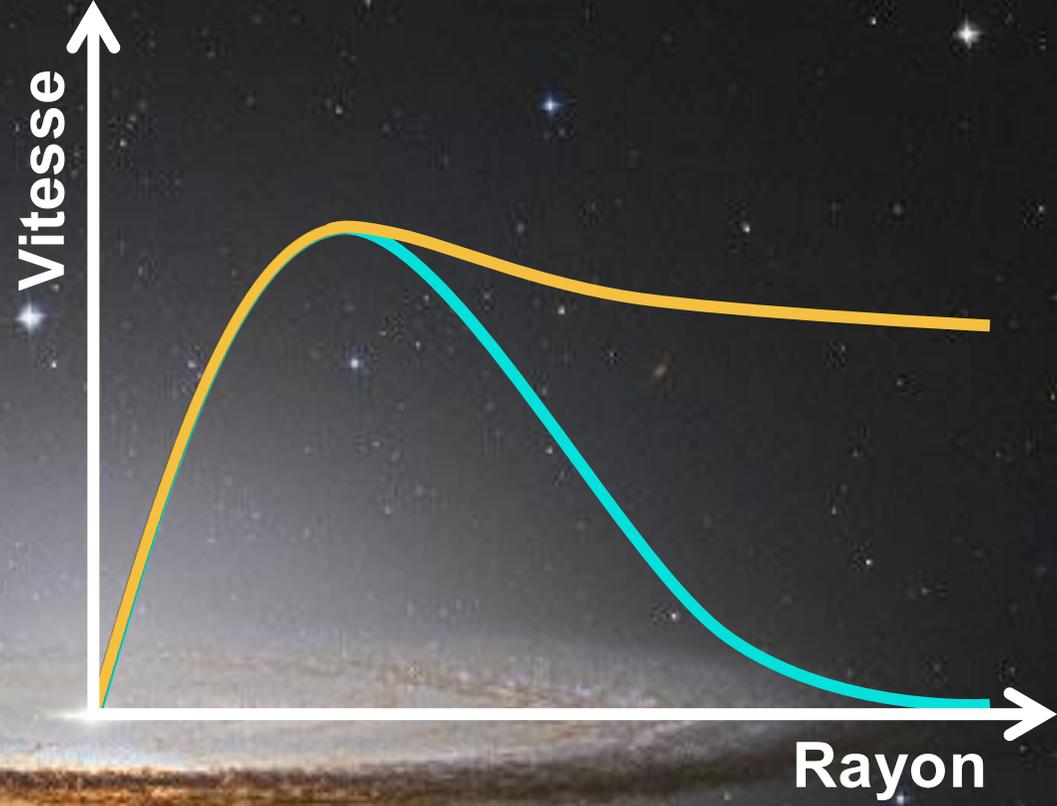


Prédit



Observé

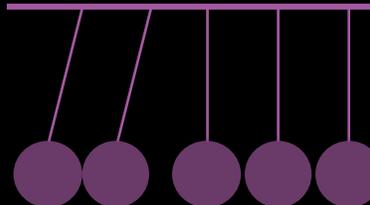
Prédit



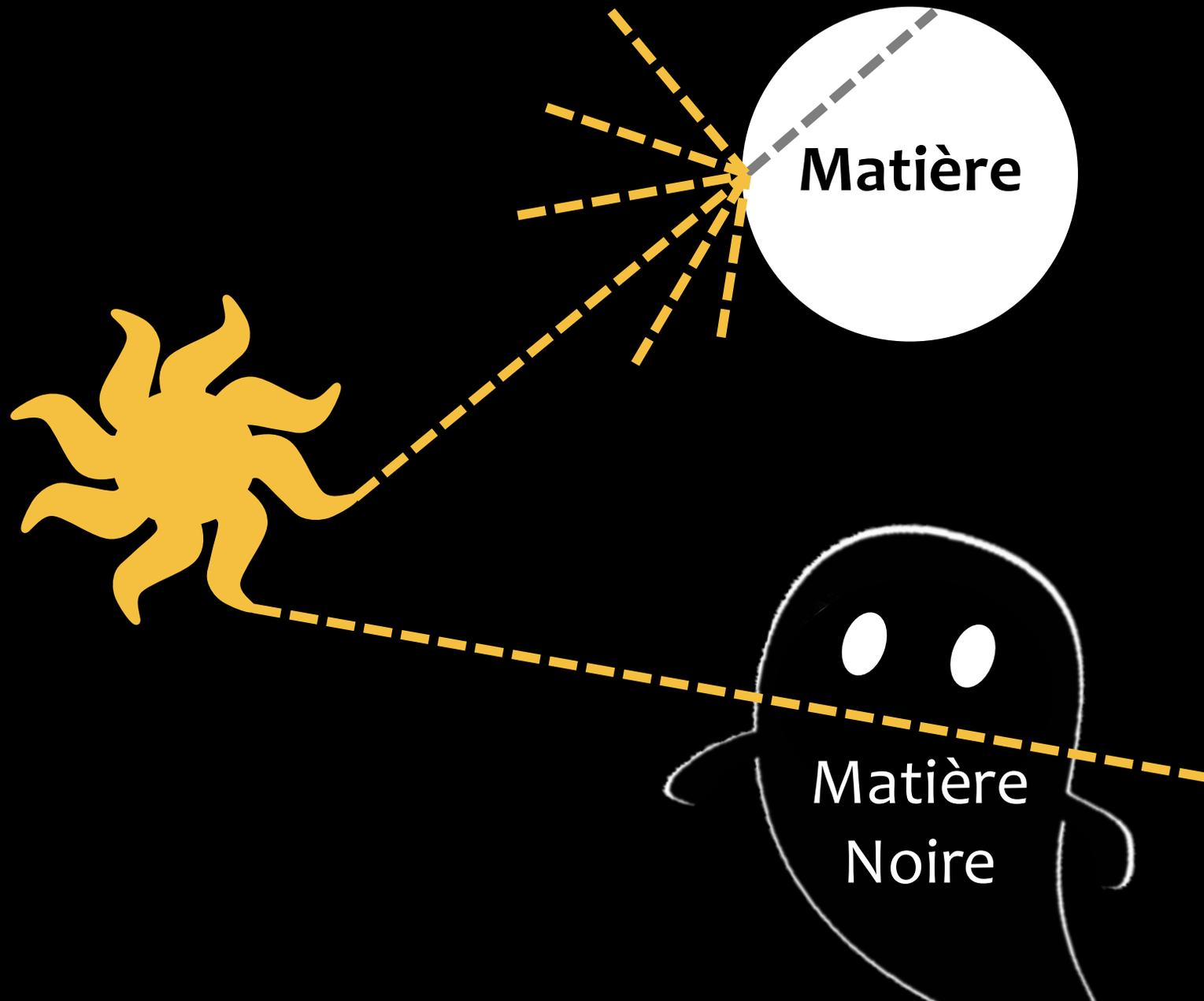
Théorie de la gravitation



Lois du mouvement

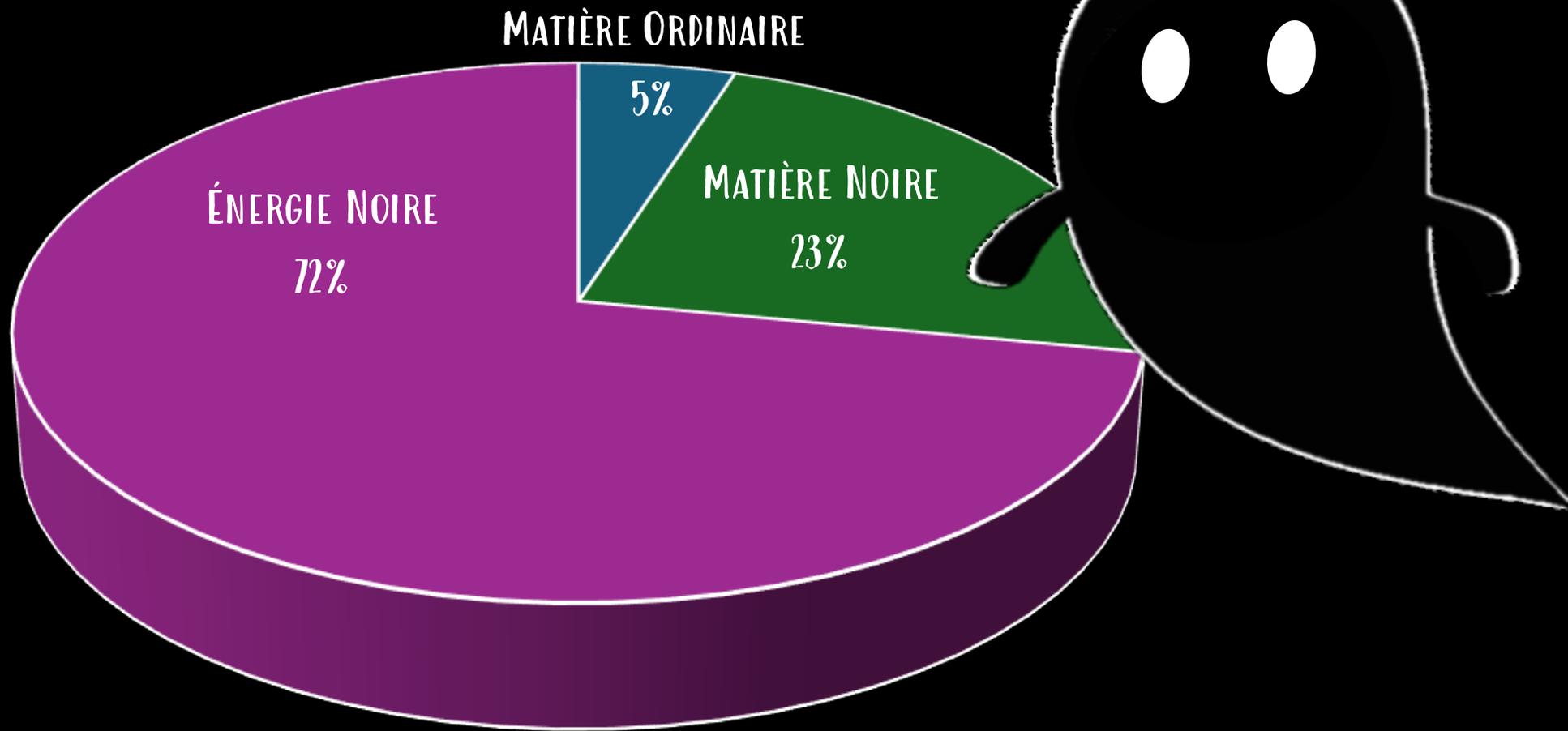


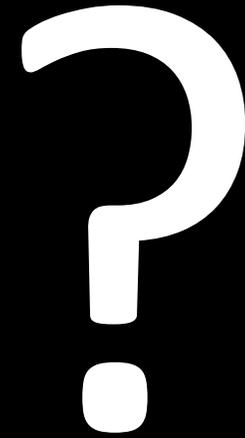


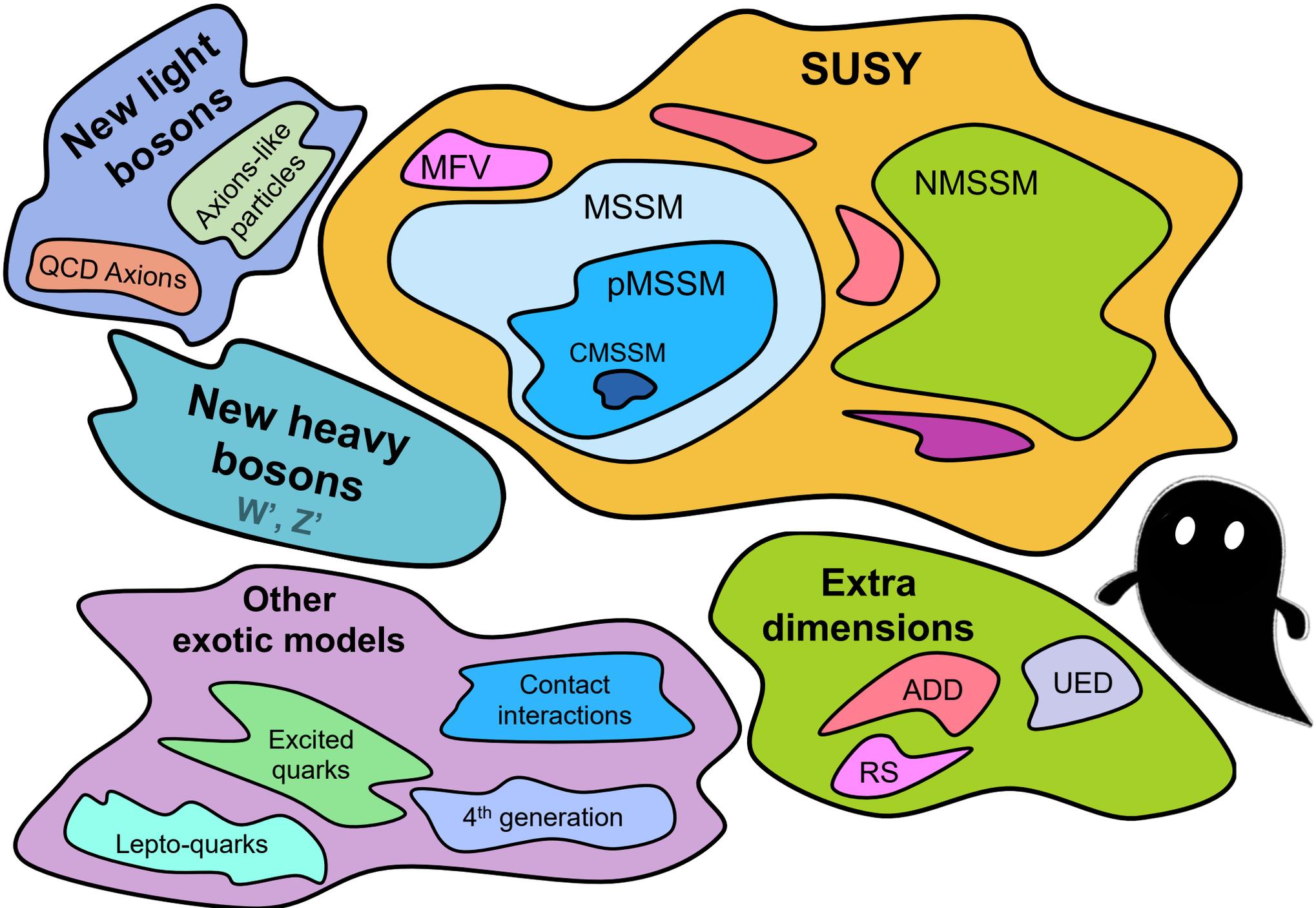


Matière

Matière
Noire

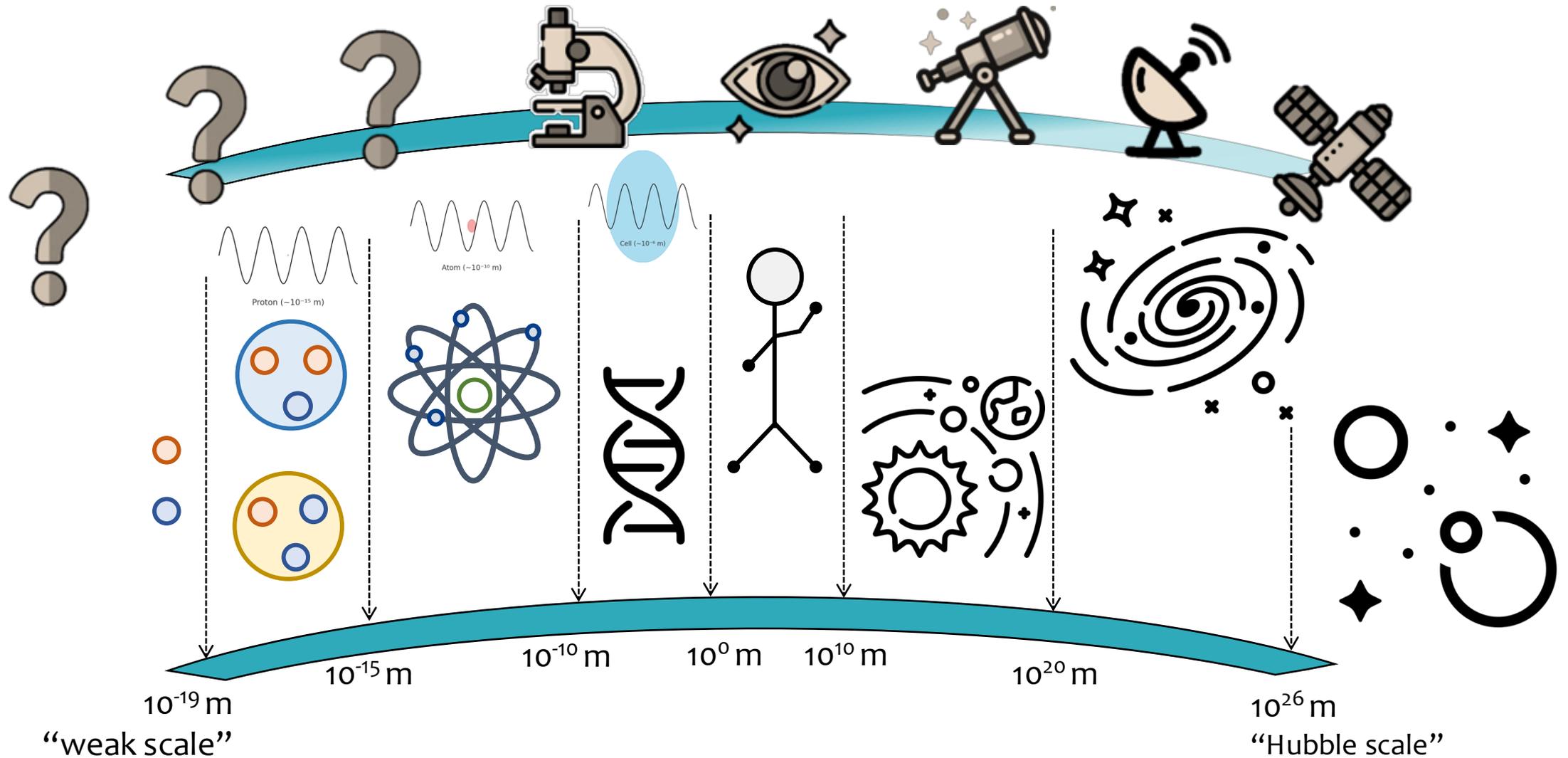






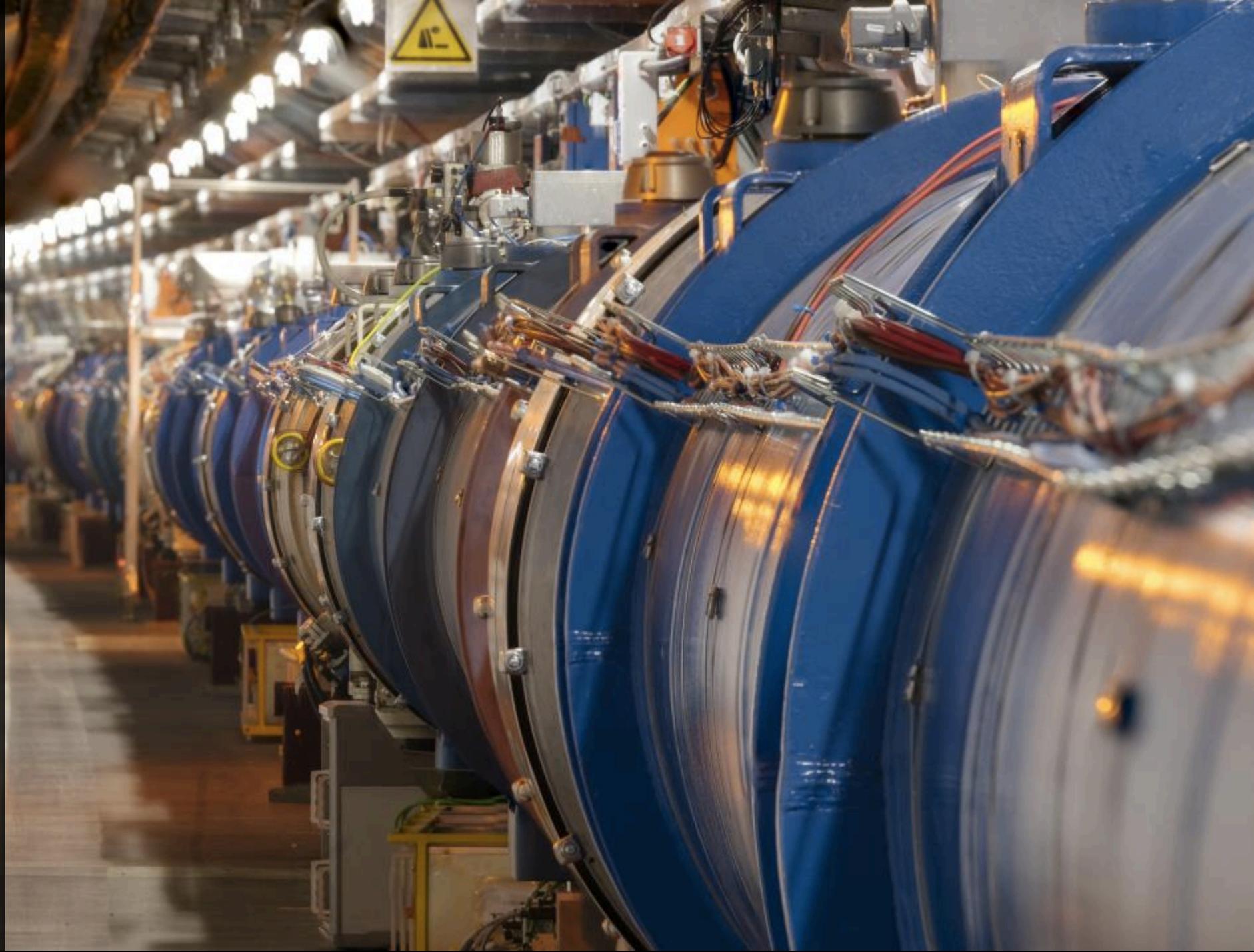
Instruments

Échelle d'observations

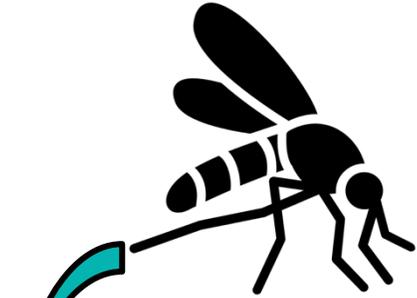


Large Hadron Collider (LHC)

- Anneau de 27 km de circonférence
- ~ 100 m sous terre
- ~ 9300 aimants supraconducteurs à 1,9 K ($-271\text{ }^{\circ}\text{C}$) pour guider et focaliser les faisceaux
- Protons et ions accélérés à plusieurs TeV puis mis en collision.



Quelle énergie d'un Proton dans le faisceau du LHC ?



~ 10^{21} fois plus léger !
~ 10^8 fois plus rapide !



Energie d'un **moustique** qui vole

masse = 2 mg = 2×10^{-6} kg

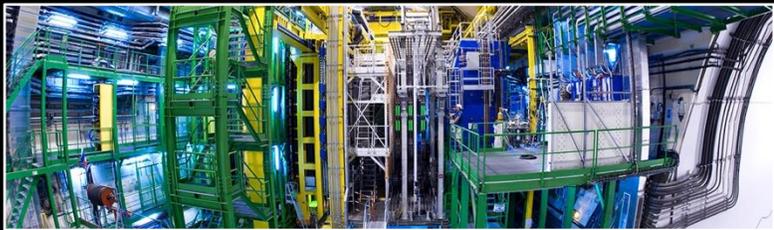
vitesse = 1 m/s

Energie cinétique du moustique = $\frac{1}{2} m v^2 = 10^{-6}$ J = **6.25 TeV**

Energie d'un **proton** au LHC: **6.8 TeV**

masse = $\sim 10^{-27}$ kg

vitesse = $\sim 300\,000\,000$ m/s = $\sim c$ (vitesse de la lumière)



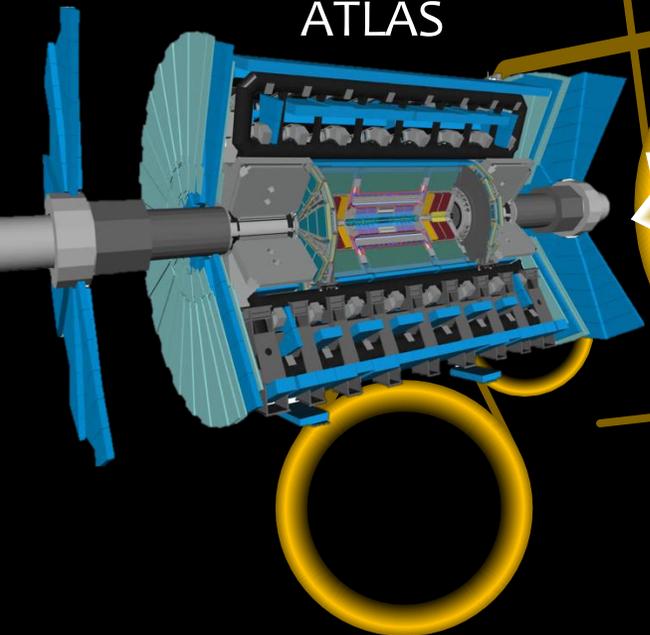
ALICE

PARTICLE BEAMS

CMS



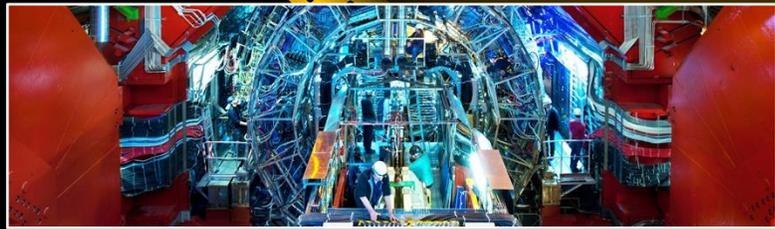
ATLAS



LHCb

LARGE HADRON COLLIDER

BEAM INJECTION CHAIN

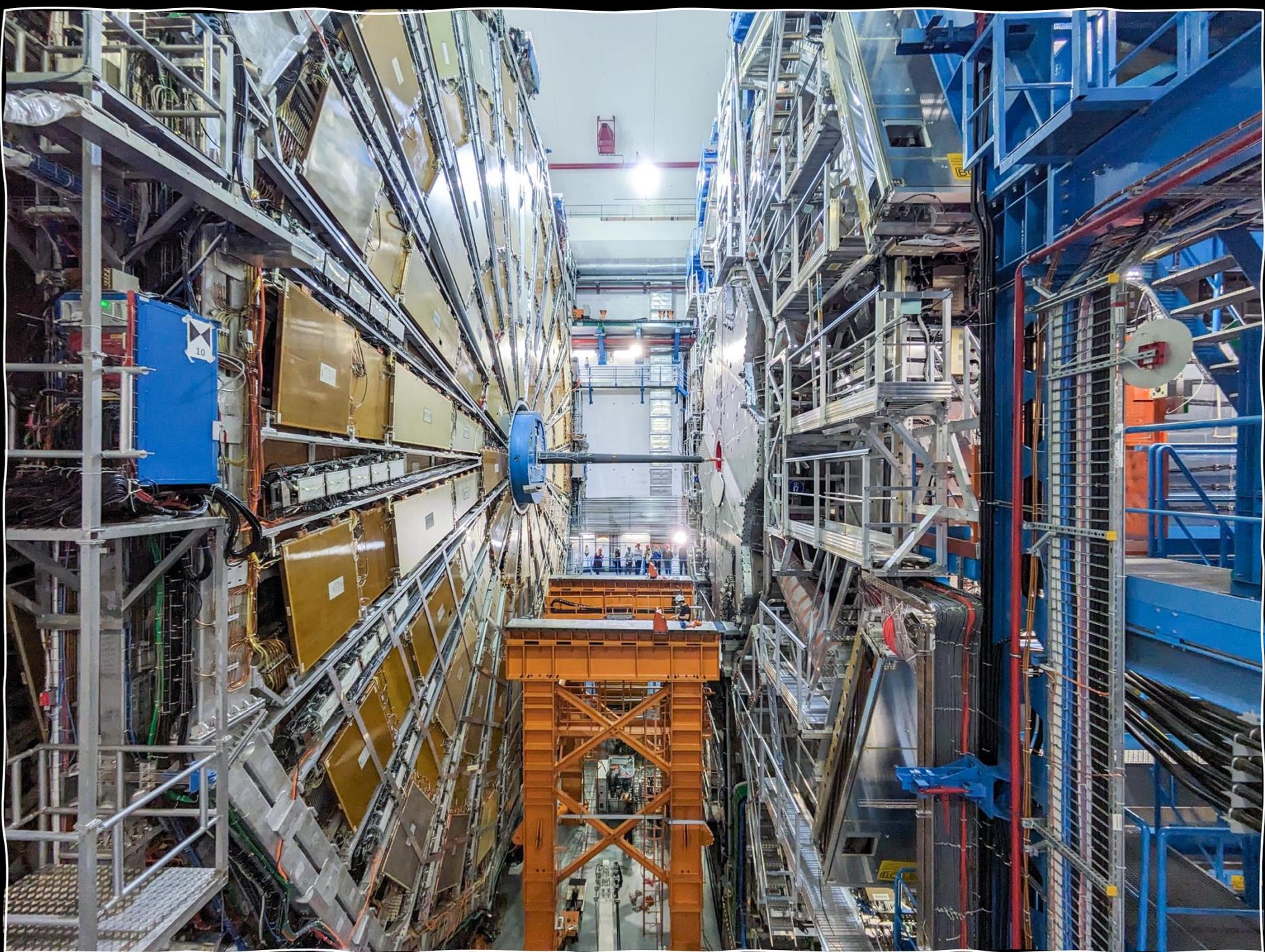




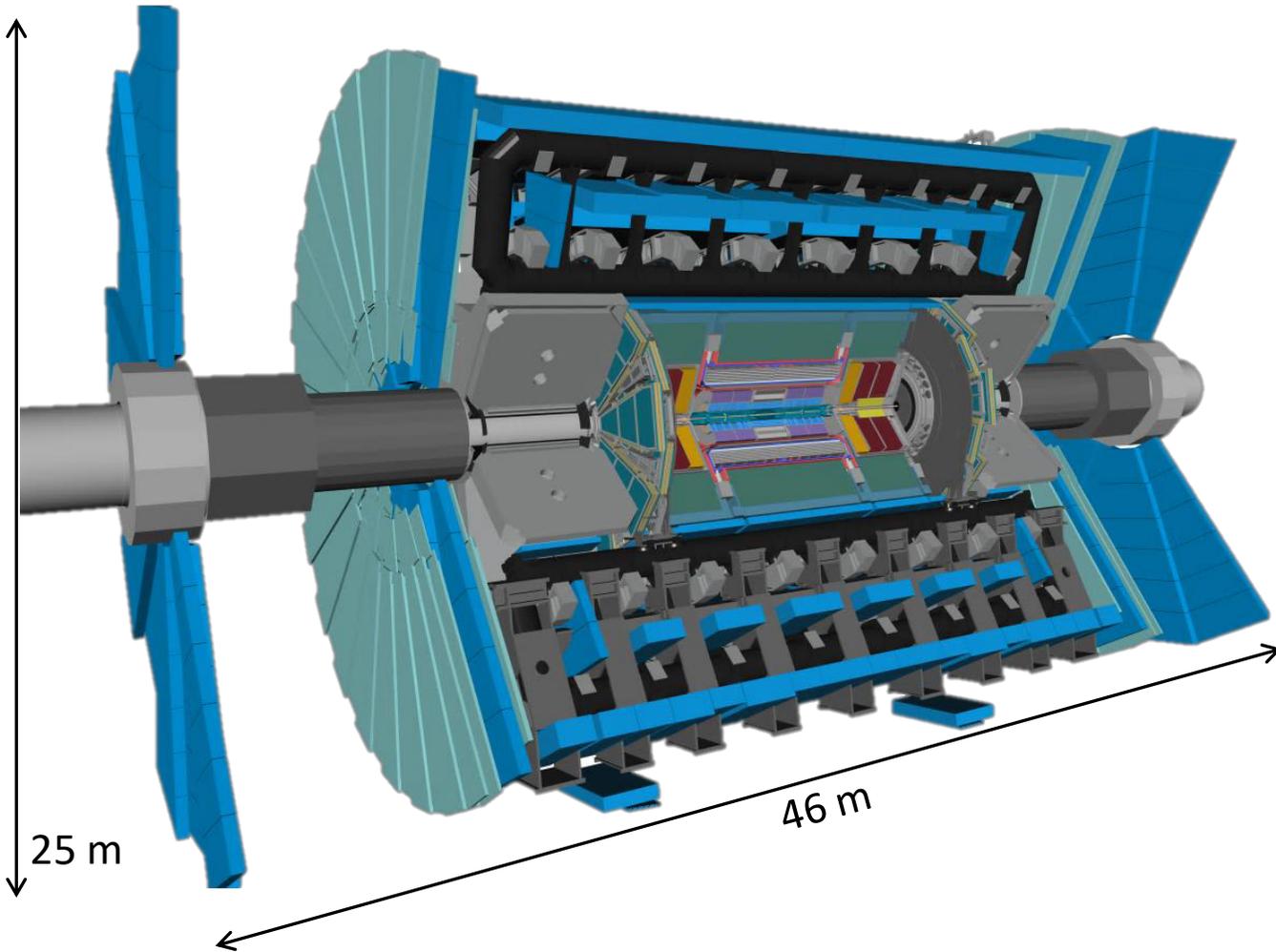


L'expérience ATLAS au LHC

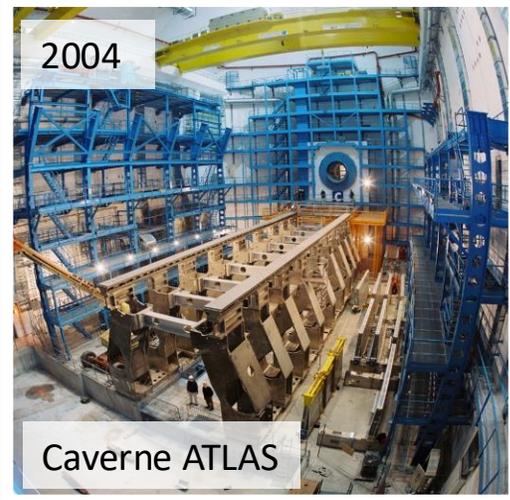




Le détecteur ATLAS en chiffres

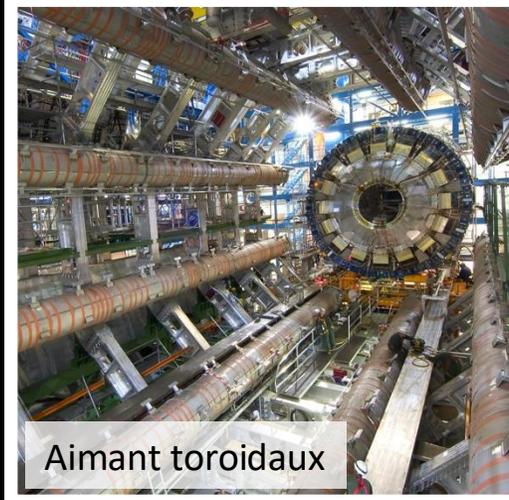


- ✓ Poids: 7 kilotonnes 
- ✓ Aimants supraconducteurs de 2 à 4 T
- ✓ Position des particules enregistrée avec une précision de l'ordre de 10 μm
- ✓ 100 millions de canaux
- ✓ 1 milliard de collisions par seconde
- ✓ 1 000 événements par seconde enregistrés
- ✓ 1.2 EB de données sur disque et sur bande
1 EB = 10^{12} MB \approx 250 000 000 films HD \approx 1.7 milliards de CD-ROM
- ✓ 0.5 millions de coeurs CPU utilisées 7/24
- ✓ 100 milliards d'événements collectés



2004

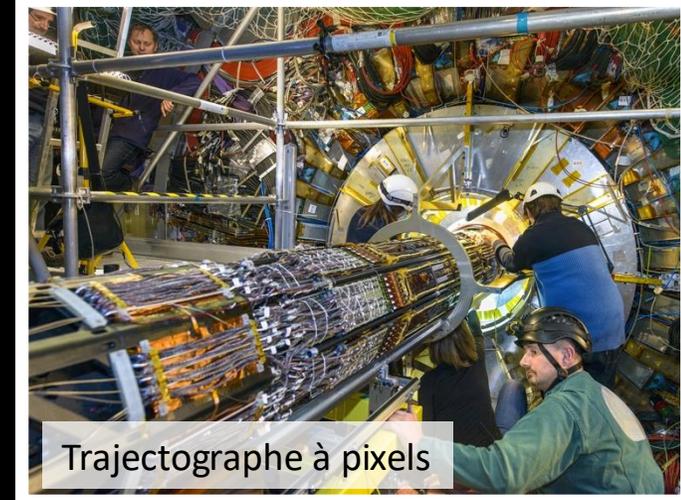
Caverne ATLAS



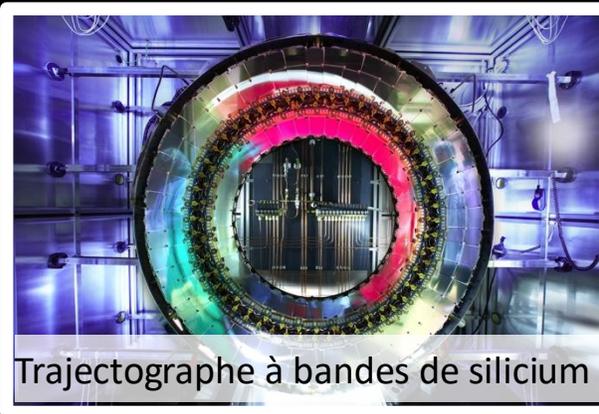
Aimant toroidaux



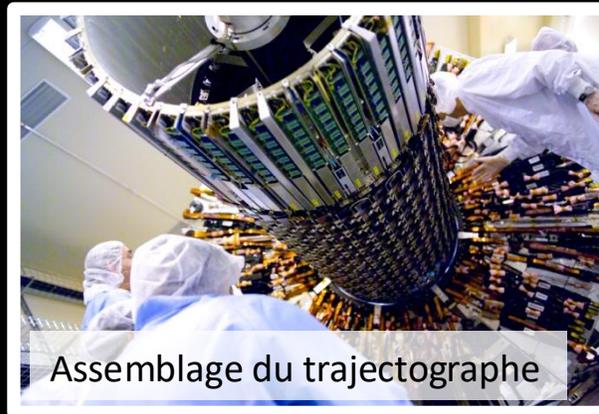
Calorimètre



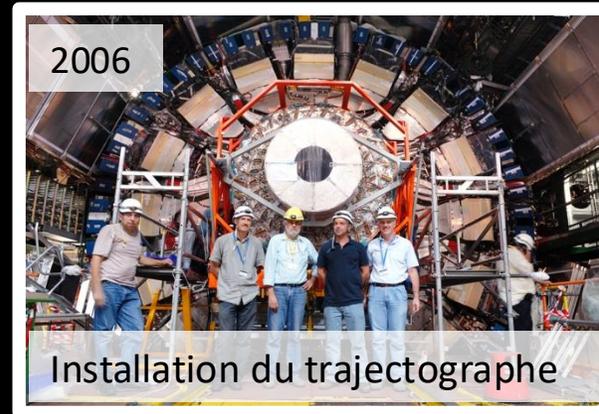
Trajectographe à pixels



Trajectographe à bandes de silicium



Assemblage du trajectographe



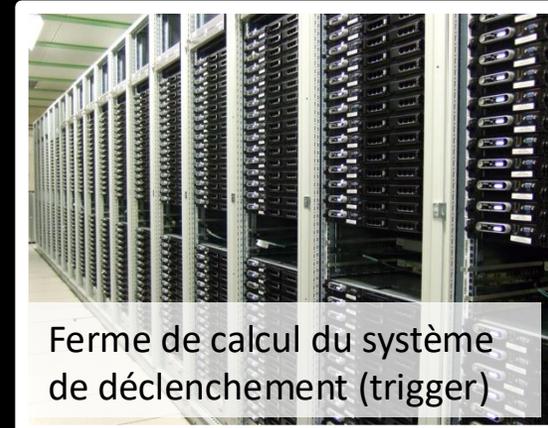
2006

Installation du trajectographe



2014

Installation du trajectographe à pixels le plus interne



Ferme de calcul du système de déclenchement (trigger)

- Capteurs rapides et résistants aux radiations
- Stabilité et précision des structures
- Systèmes de lecture extrêmement rapides
- Infrastructure informatique capable de traiter des volumes de données gigantesques

La collaboration ATLAS



3000

Scientific authors



40

Countries



177

Institutions



1200

Doctoral students



La collaboration ATLAS



3000

Scientific authors



40

Countries



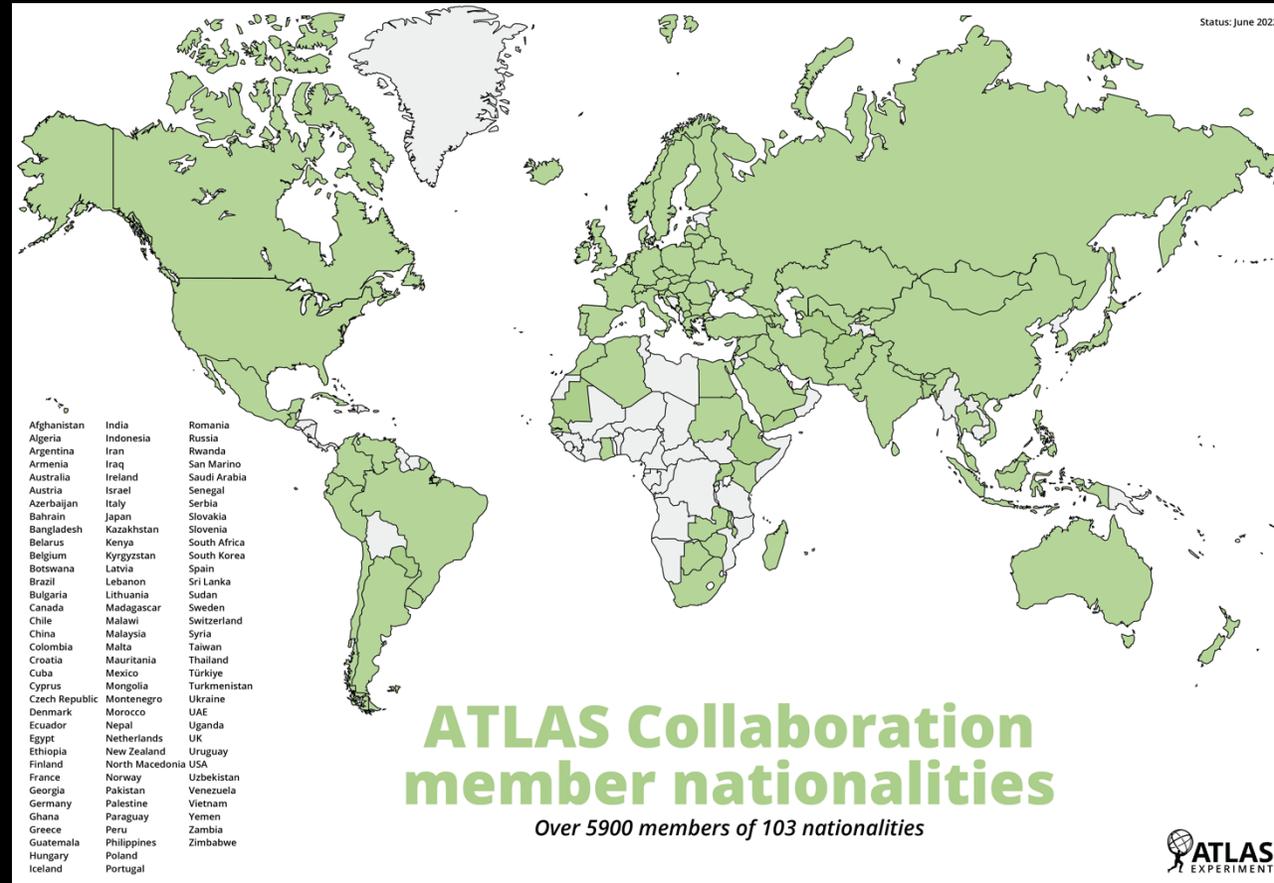
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Institutions

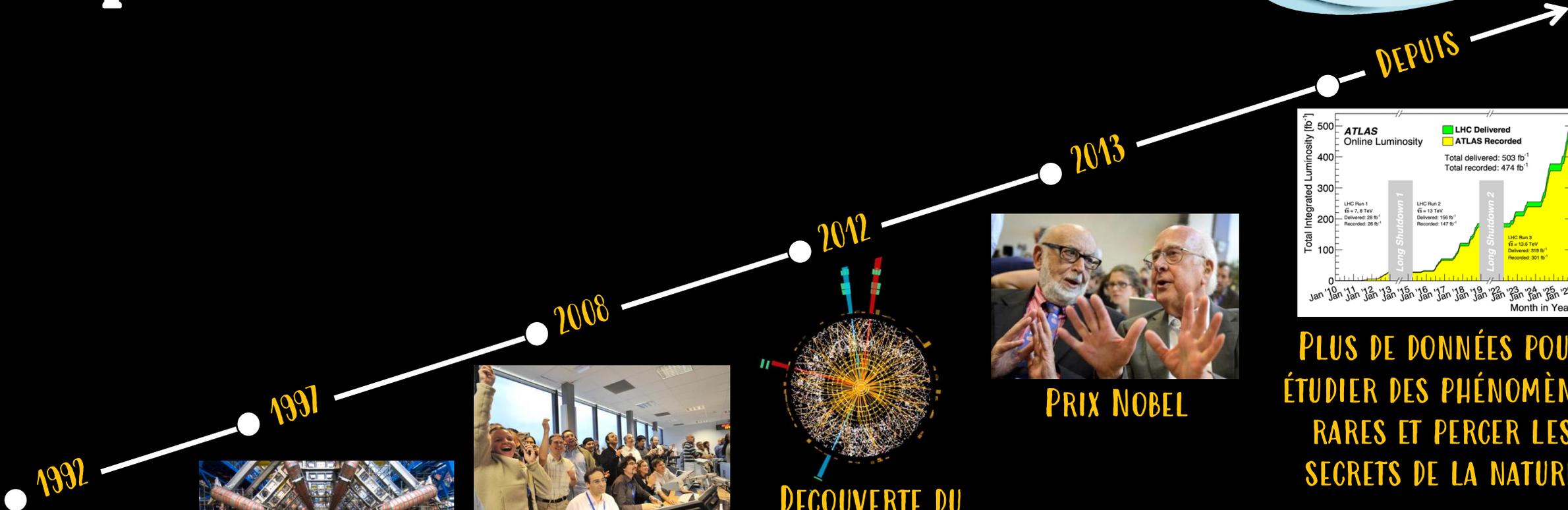


1200

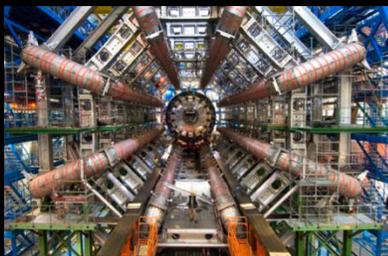
Doctoral students



Un peu d'histoire ...



SOUSSION DE LETTRE D'INTERÊT



APPROBATION DE L' EXPERIENCE

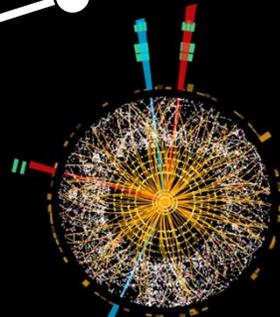
1997

1992



PREMIÈRES DONNÉES DU LHC À ATLAS

2008



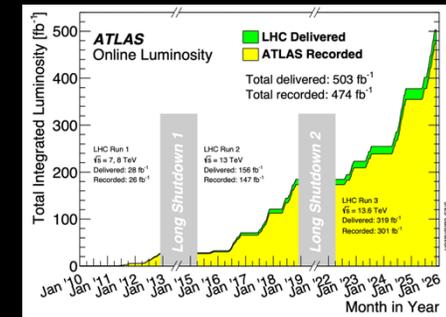
DECOUVERTE DU BOSON DE HIGGS

2012



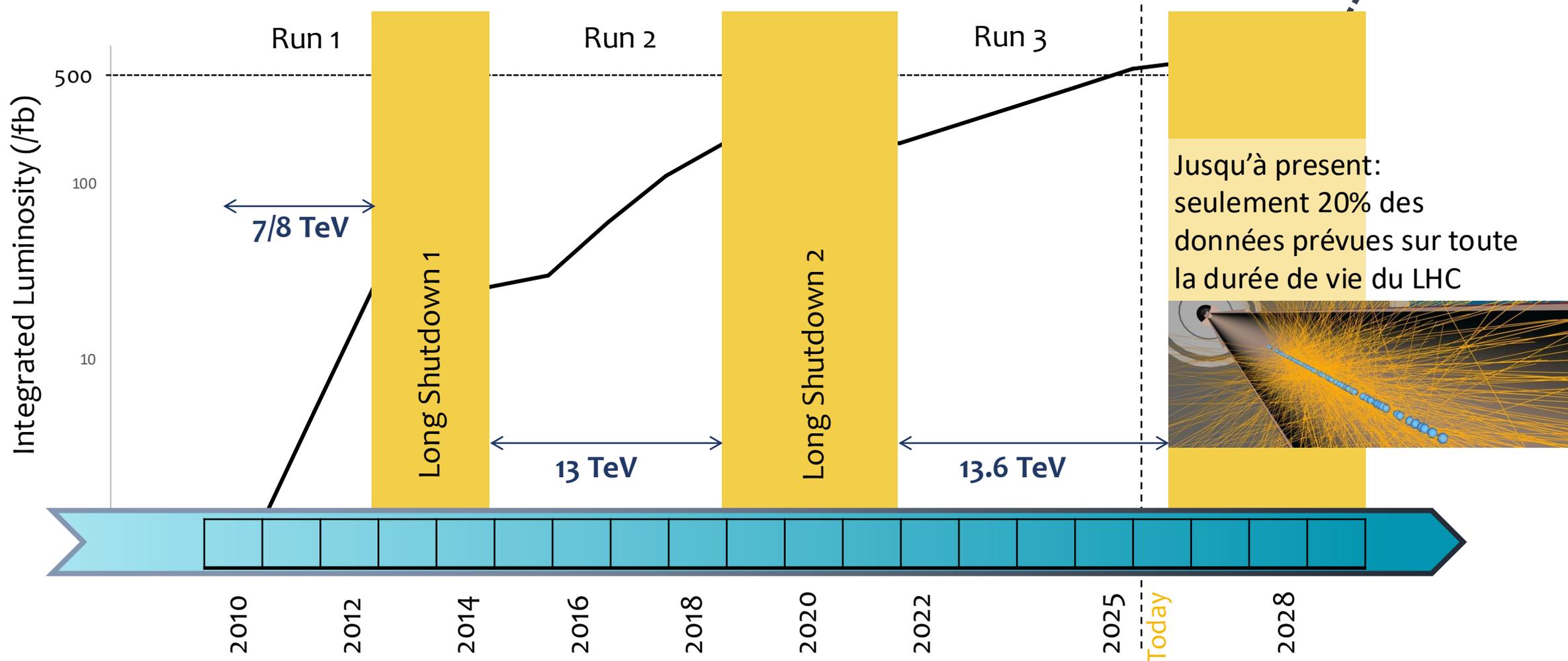
PRIX NOBEL

2013

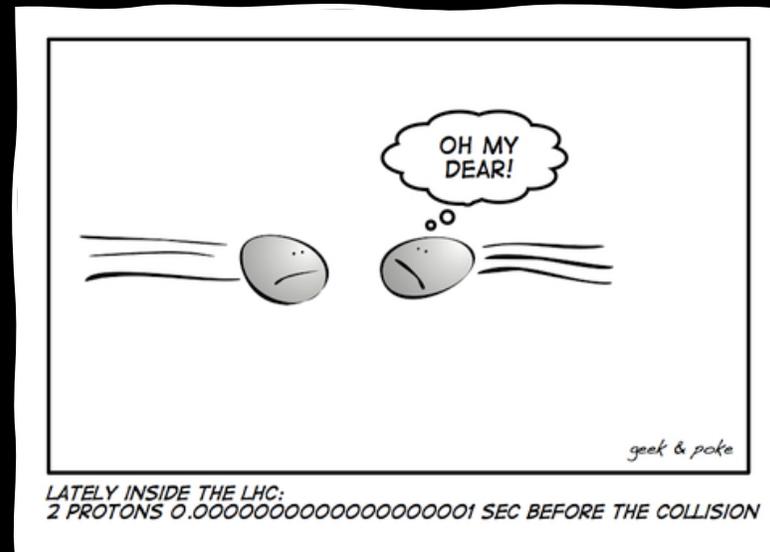


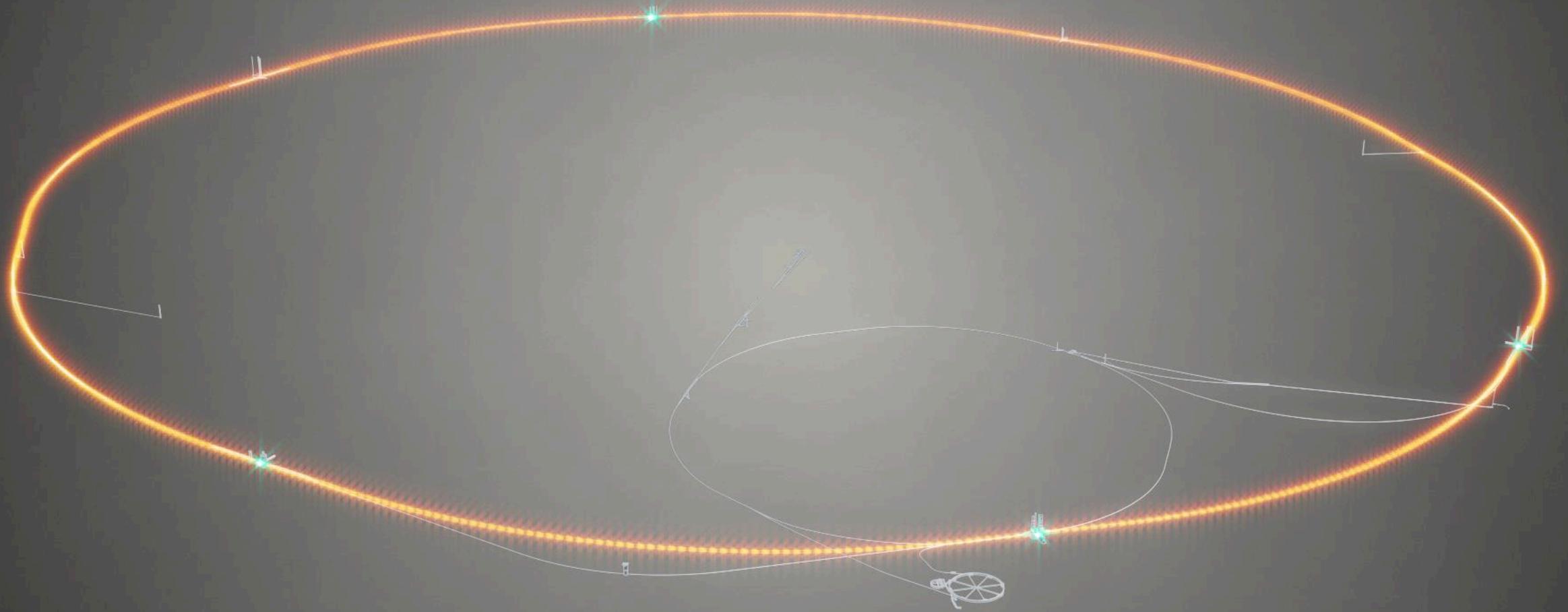
PLUS DE DONNÉES POUR ÉTUDIER DES PHÉNOMÈNES RARES ET PERCER LES SECRETS DE LA NATURE

Run 1, Run 2, Run 3 et au-delà

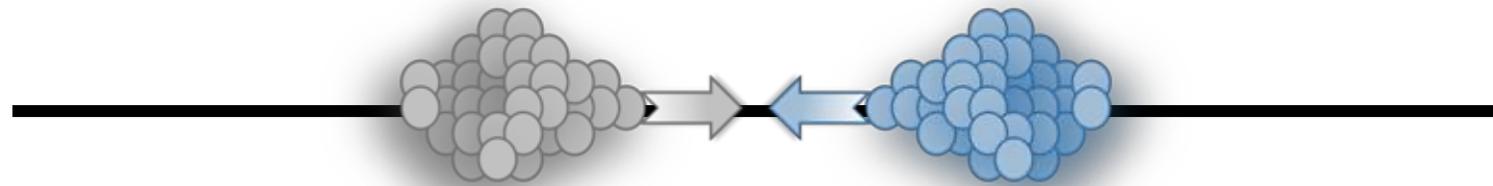


Dans une collision proton-proton



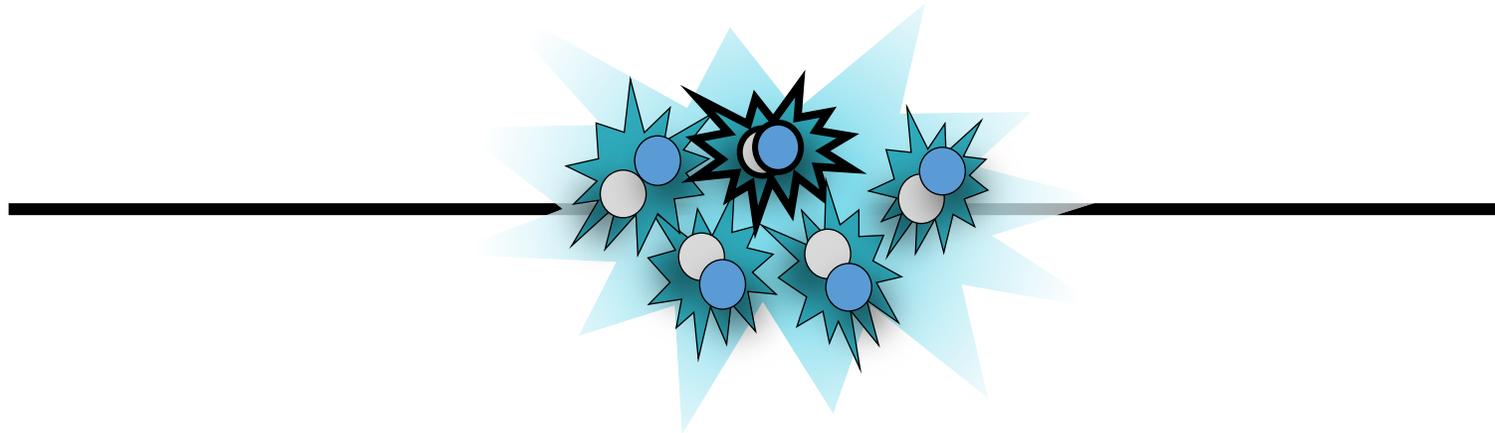


La collision proton-proton



Paquets de protons
 $\sim 1.8 \times 10^{11}$ protons par paquet
Espacement entre paquets: 25 ns

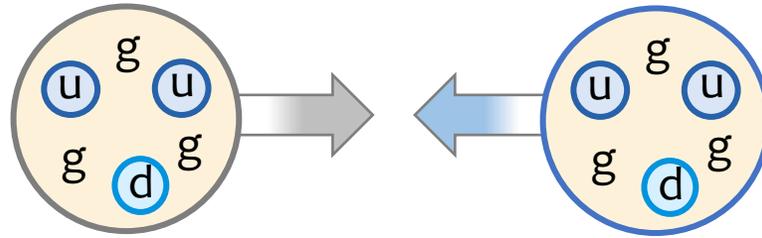
La collision proton-proton



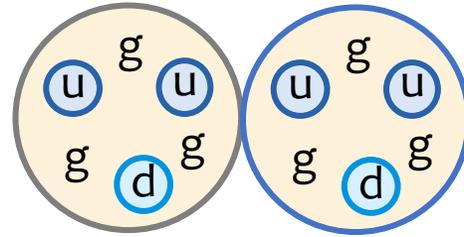
$\sim 1.8 \times 10^{11}$ protons par paquet
Espacement entre paquets: 25 ns

Jusqu'à 60–70 collisions proton-proton par croisement de paquets

La collision proton-proton

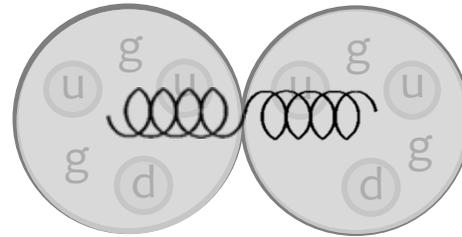


La collision proton-proton

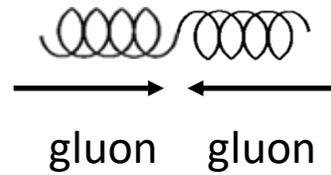


La collision proton-proton

Les “partons” (constituants of the protons) de chaque proton peuvent interagir
Par exemple ici: deux gluons

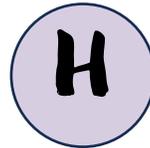


La collision proton-proton



La collision proton-proton

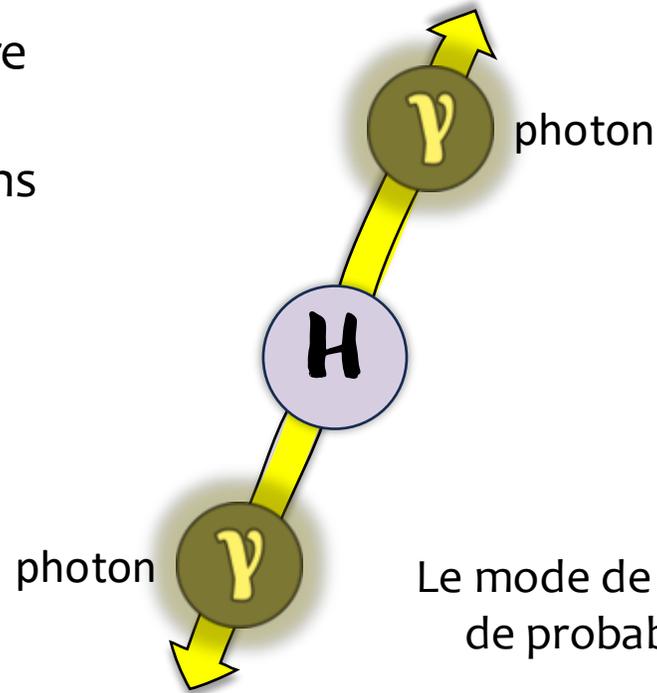
L'interaction parton-parton conduit à la production de particules
Par exemple ici: le boson de Higgs



La fréquence à laquelle certaines particules sont produites
dépend de probabilités calculables dans le cadre théorique

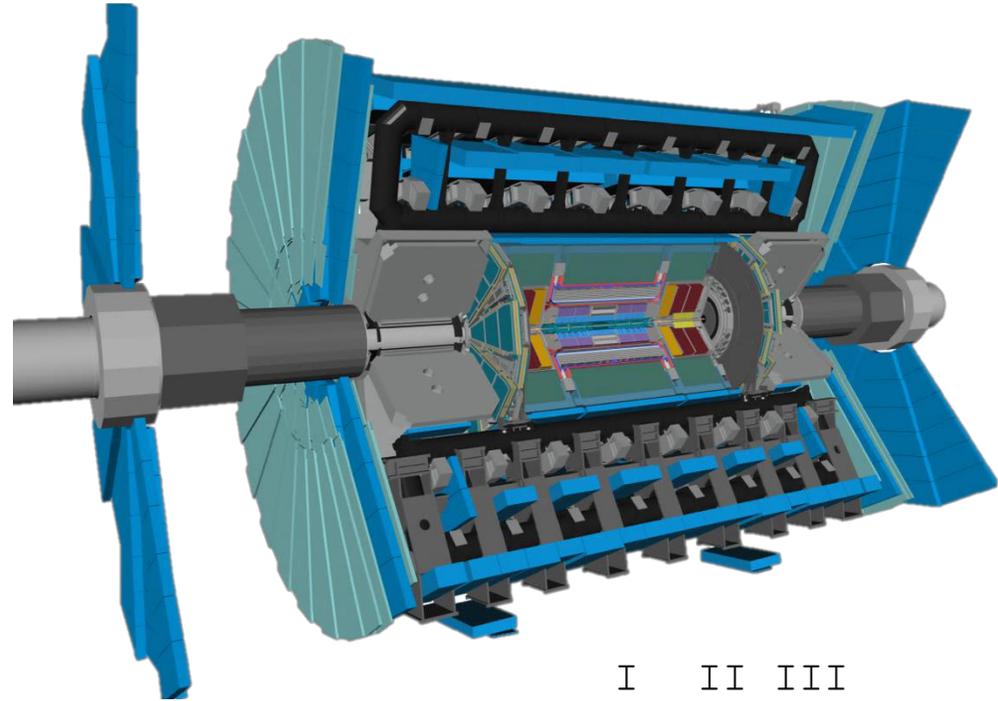
La collision proton-proton

Le boson de Higgs se désintègre
presque instantanément
Par exemple ici: en deux photons

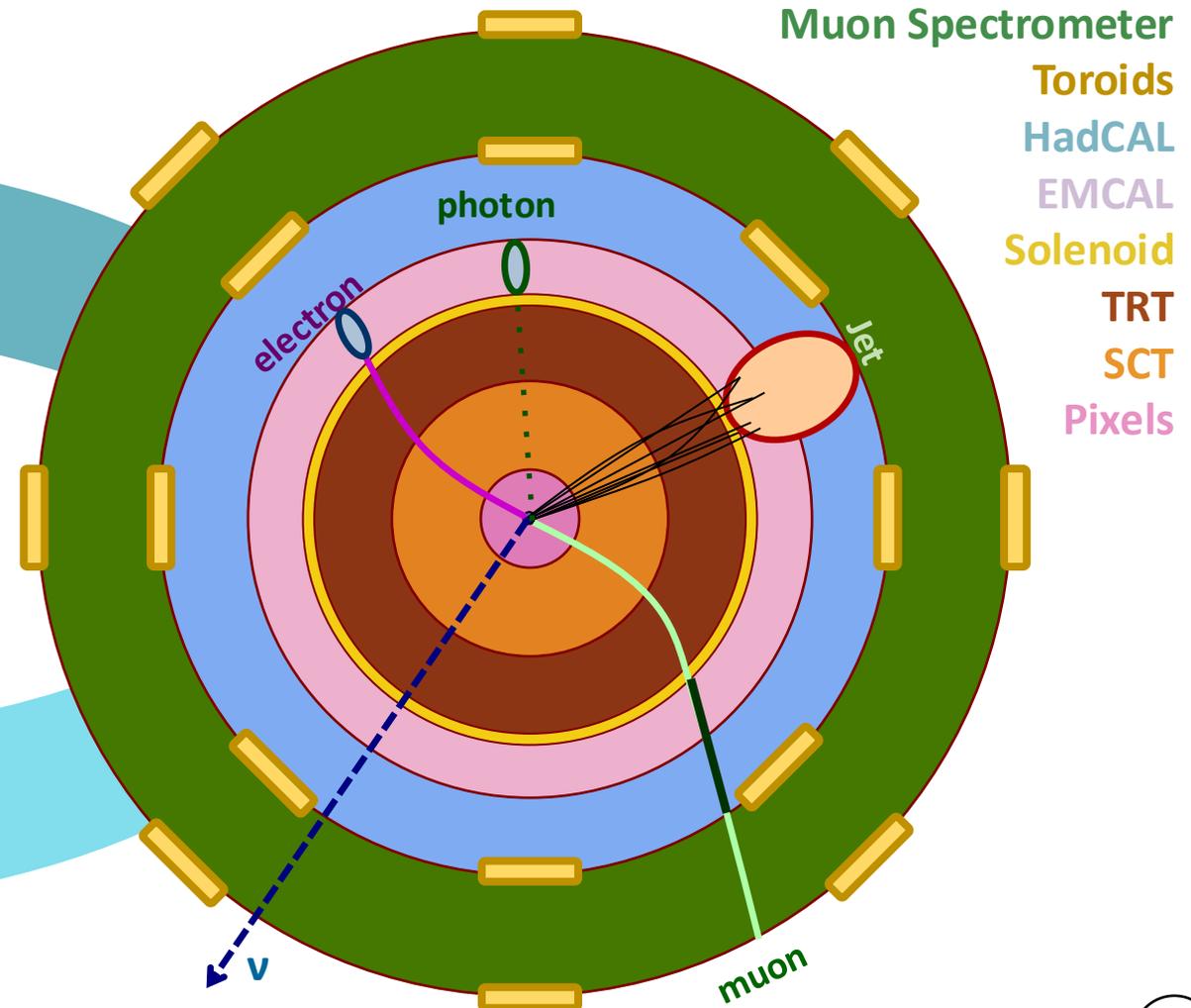


Le mode de désintégration de chaque particule dépend
de probabilités calculables dans le cadre théorique

Comment observer les particules dans le détecteur?



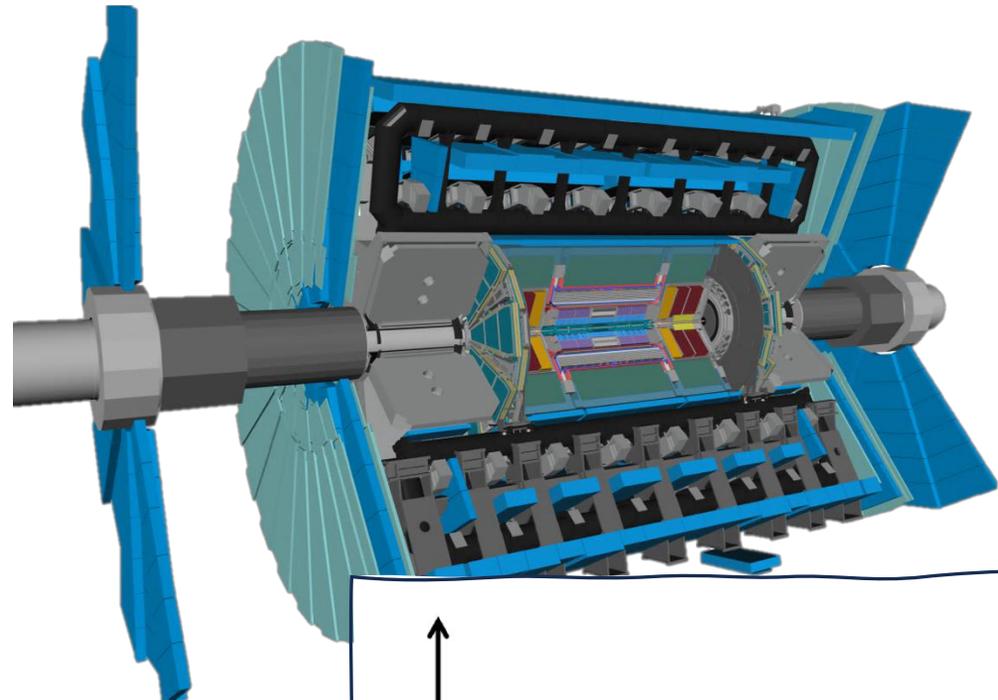
Vue transverse simplifiée du détecteur



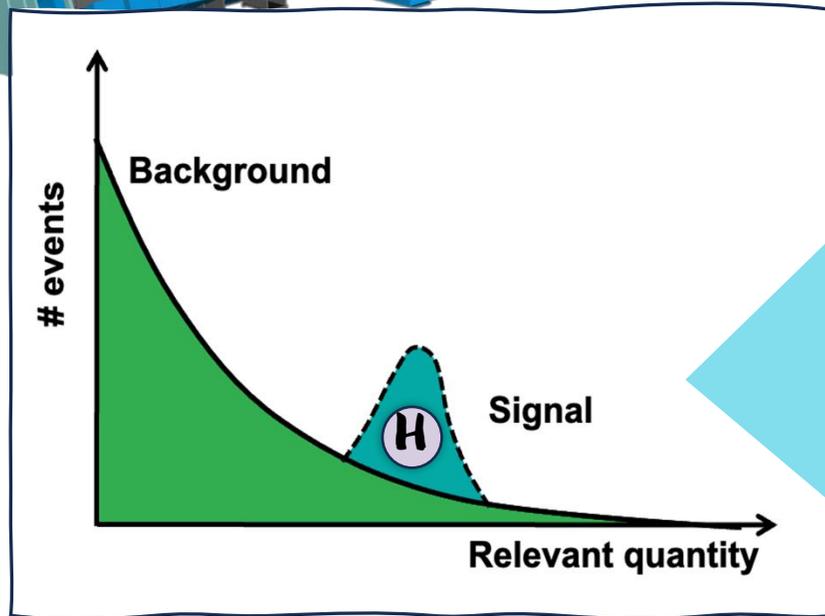
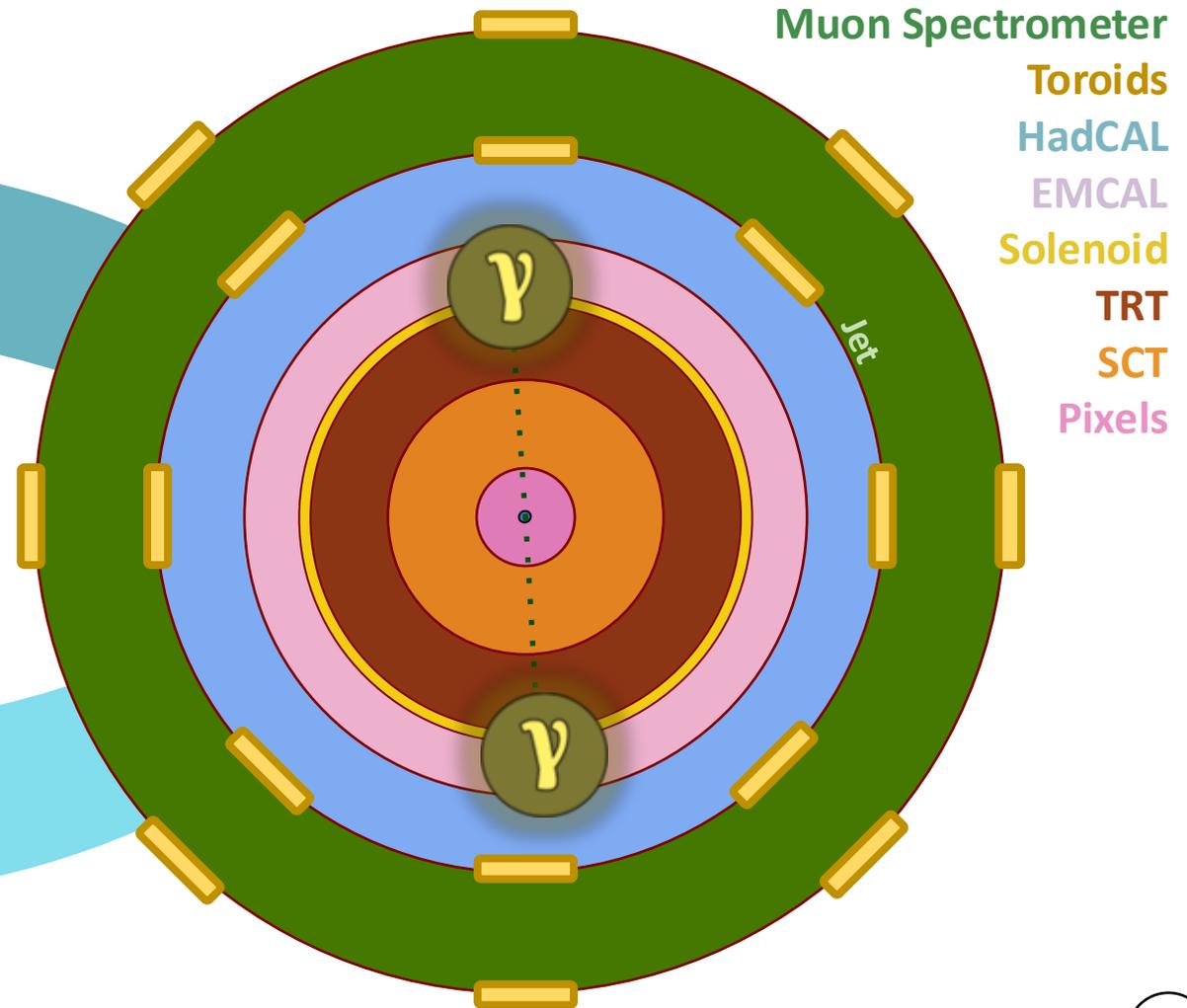
	I	II	III	
Quarks	2.4 MeV u	1.3 GeV c	170 GeV t	0 γ
	4.8 MeV d	104 MeV s	4.2 GeV b	0 g
	< 2 eV ν_1	< 2 eV ν_2	< 2 eV ν_3	91 GeV Z
Leptons	0.5 MeV e	106 MeV μ	1.8 GeV τ	80 GeV W
				125 GeV H

Bosons

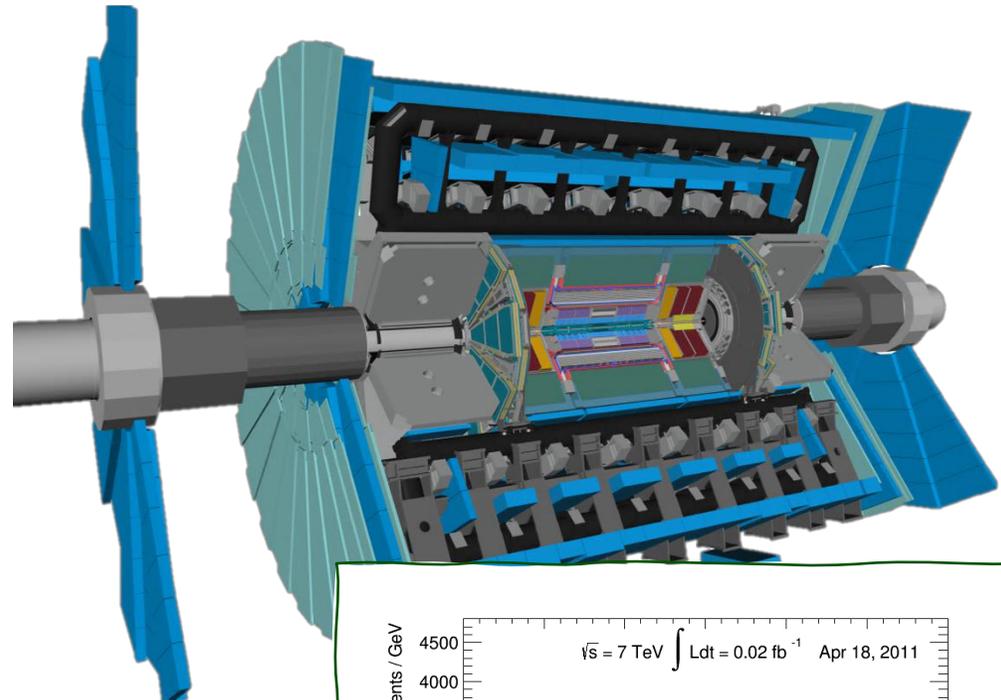
...et le boson de Higgs (e.g. en photons) ?



Vue transverse simplifiée du détecteur



...et le boson de Higgs?



Vue transverse simplifiée du détecteur

Muon Spectrometer

Toroids

HadCAL

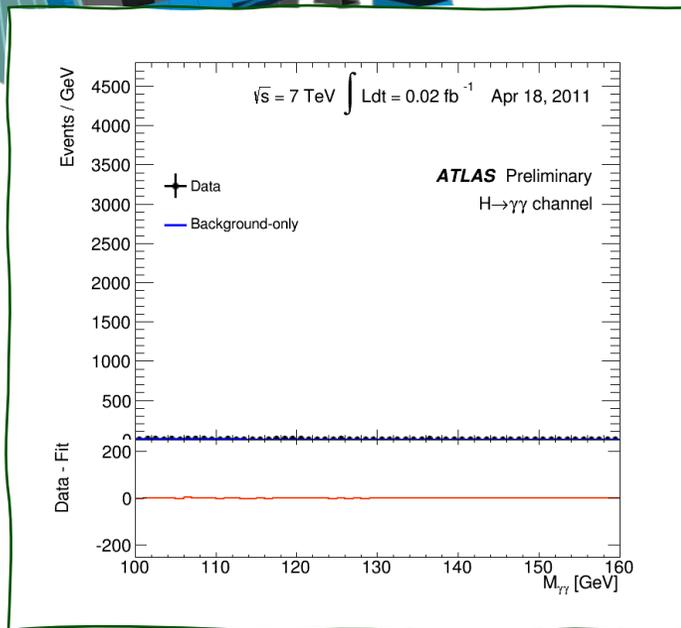
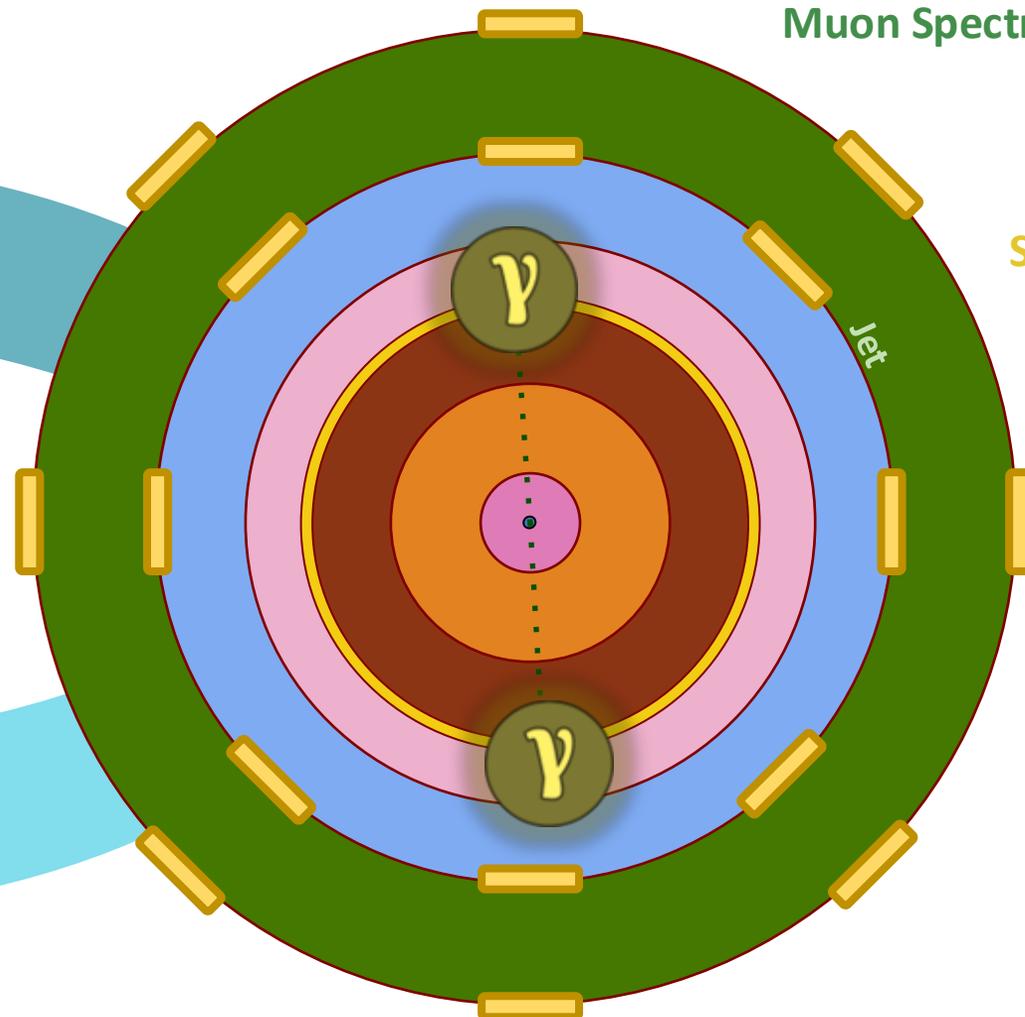
EMCAL

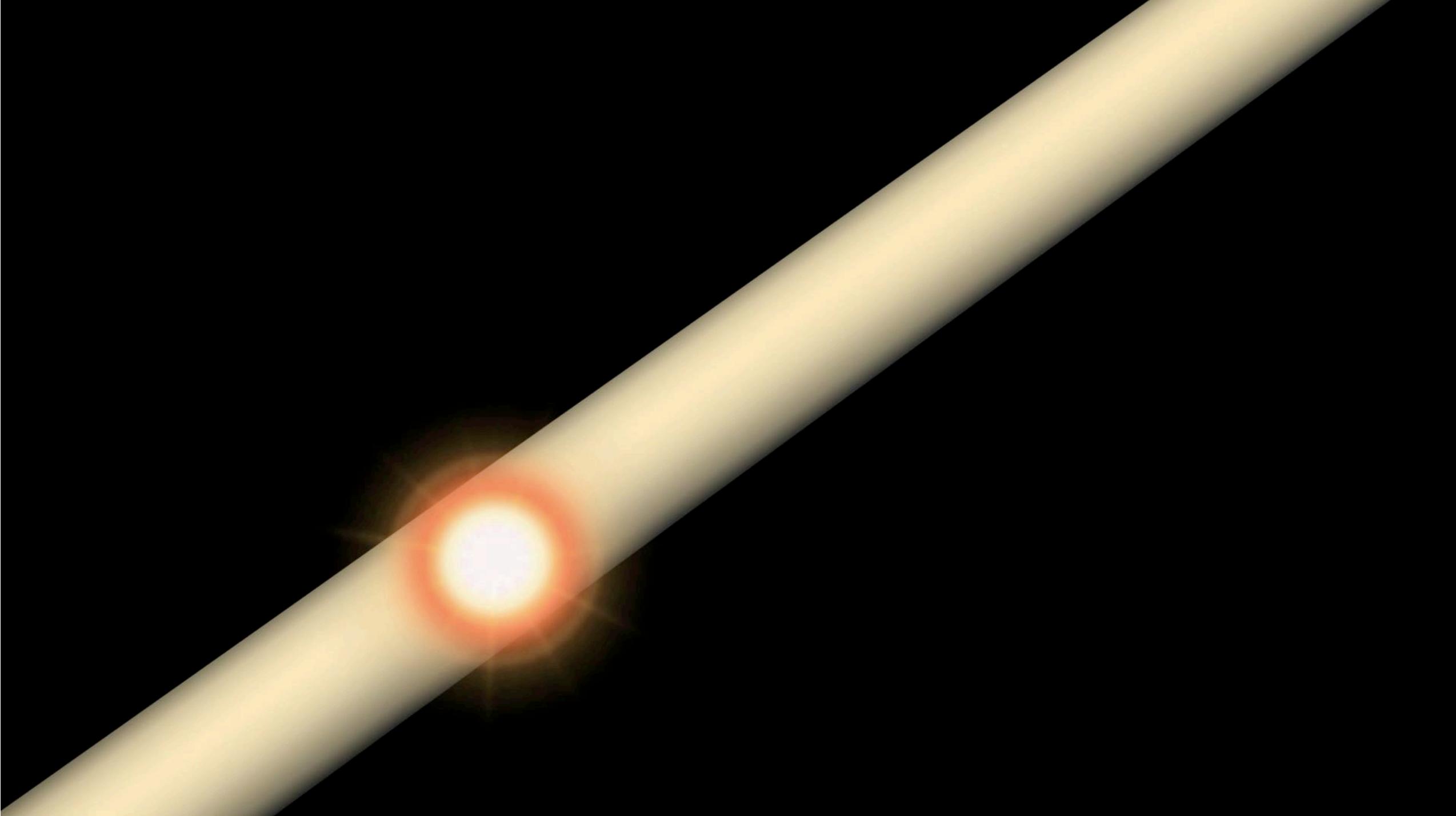
Solenoid

TRT

SCT

Pixels



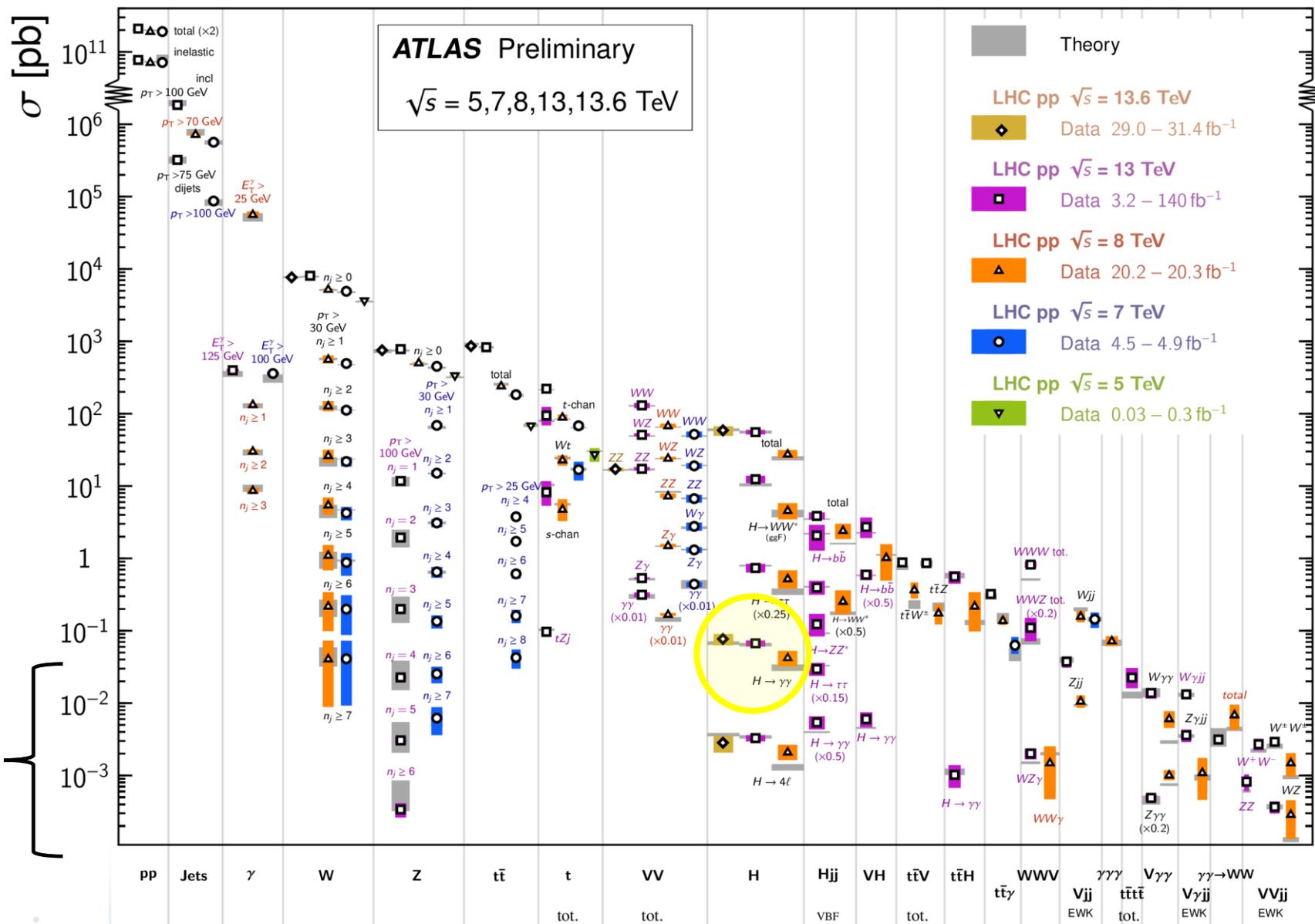


État du Modèle Standard

État du Modèle Standard

Standard Model Production Cross Section Measurements

Status: June 2024



Certains aspects fondamentaux restent à explorer

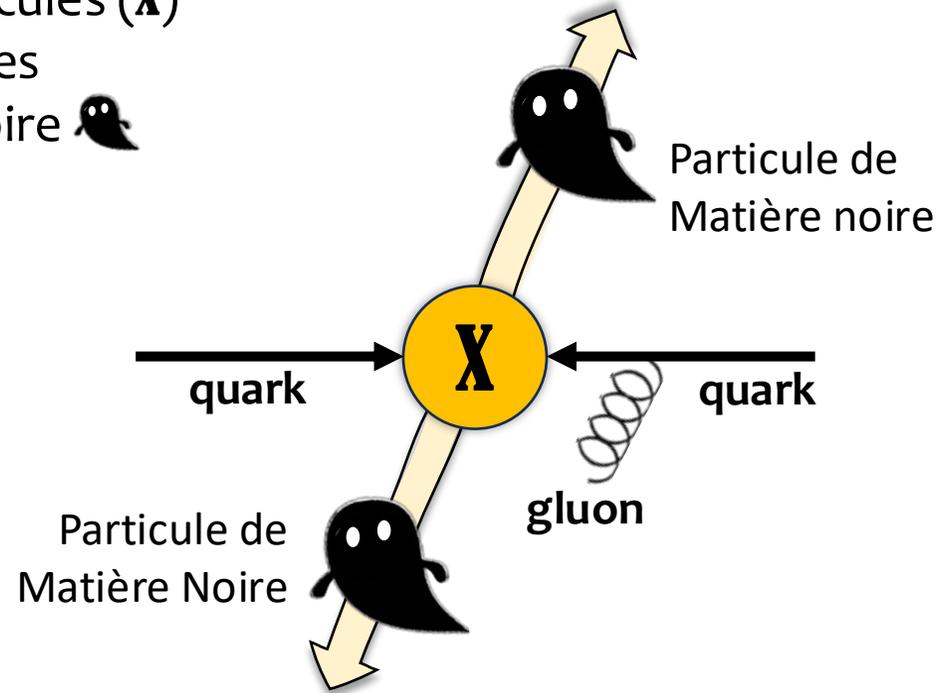


Et la Matière Noire?



La collision proton-proton

D'une manière similaire on peut avoir la création de nouvelles particules (X) qui se désintègrent à des particules de matière noire 



Plusieurs théories proposent ces phénomènes!

Comment “voir” la Matière Noire à ATLAS?

Vue transverse simplifiée du détecteur

Muon Spectrometer

Toroids

HadCAL

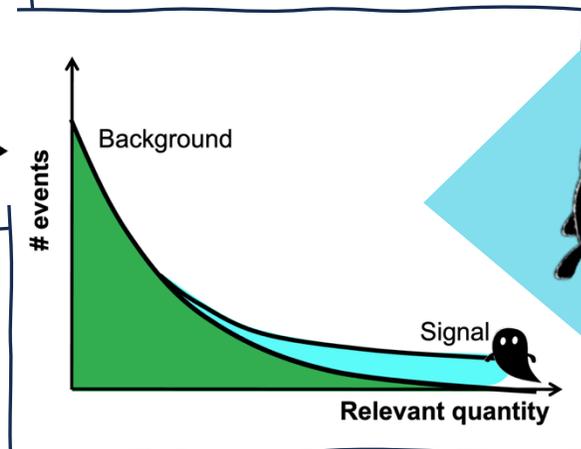
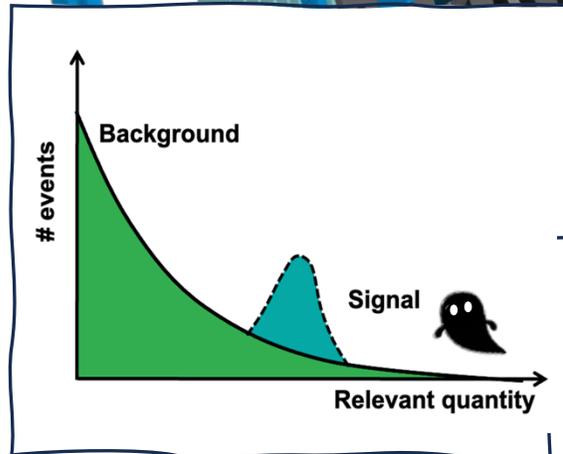
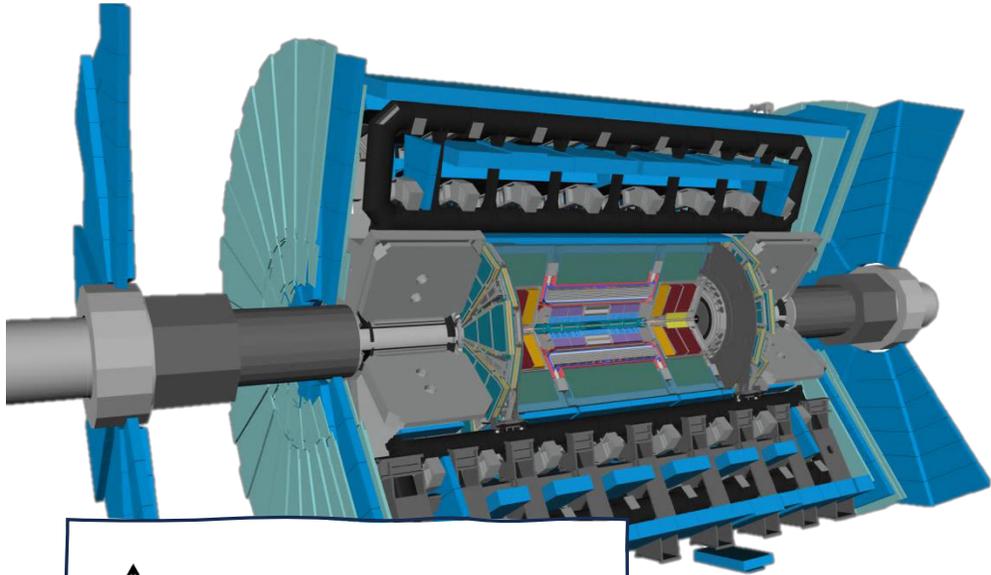
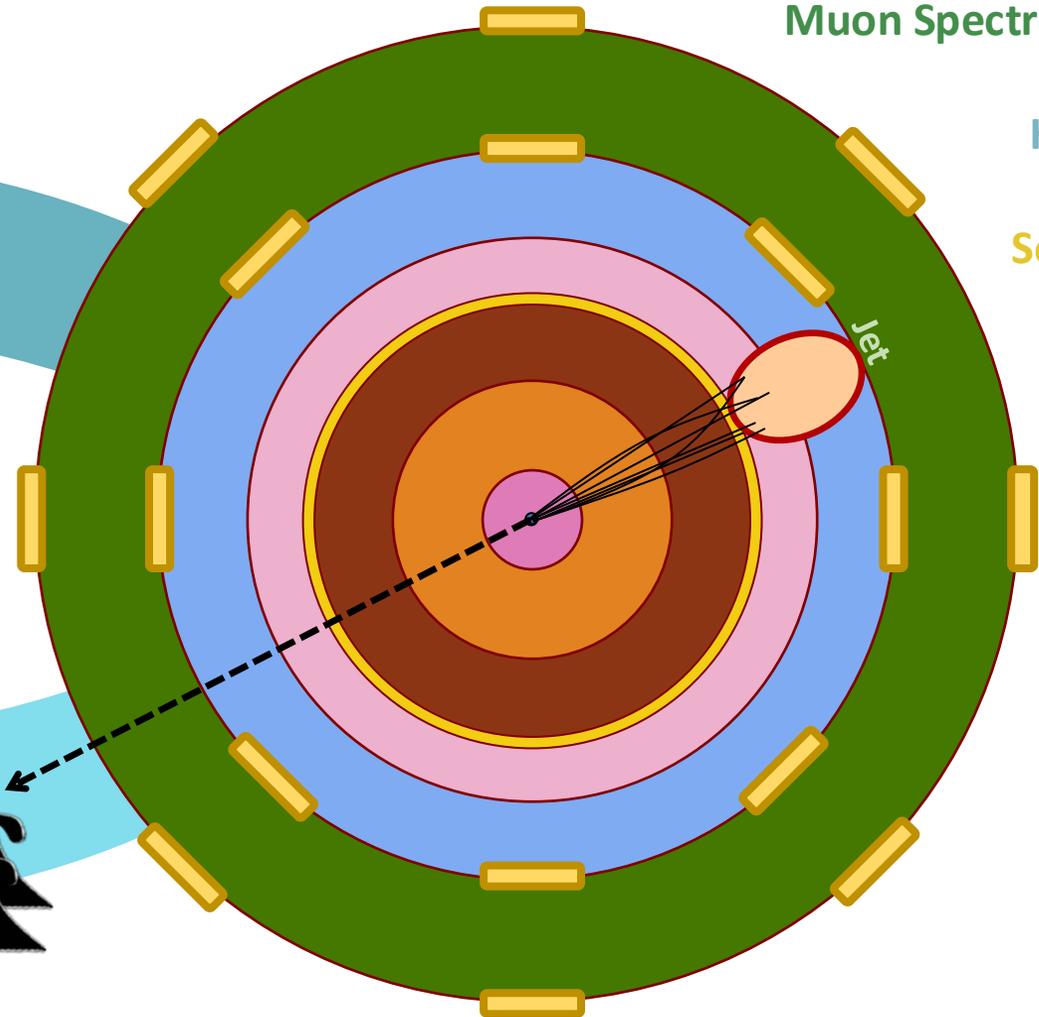
EMCAL

Solenoid

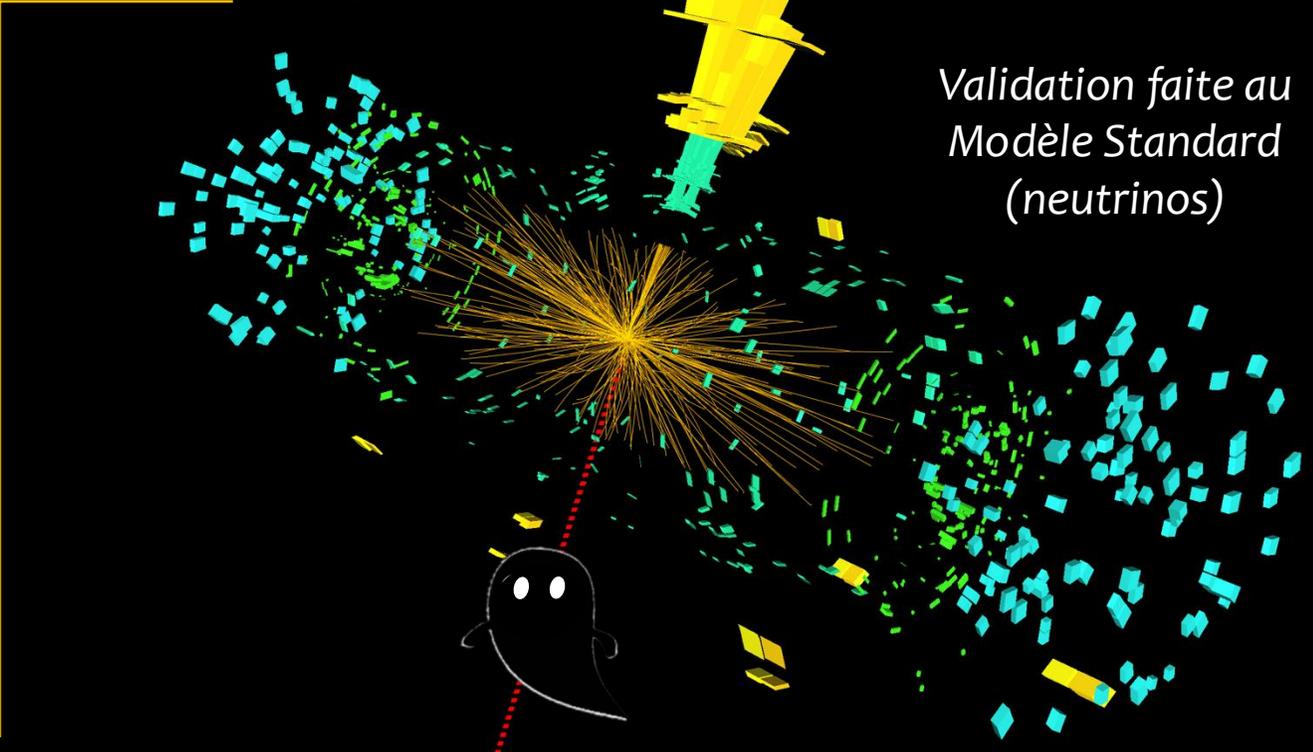
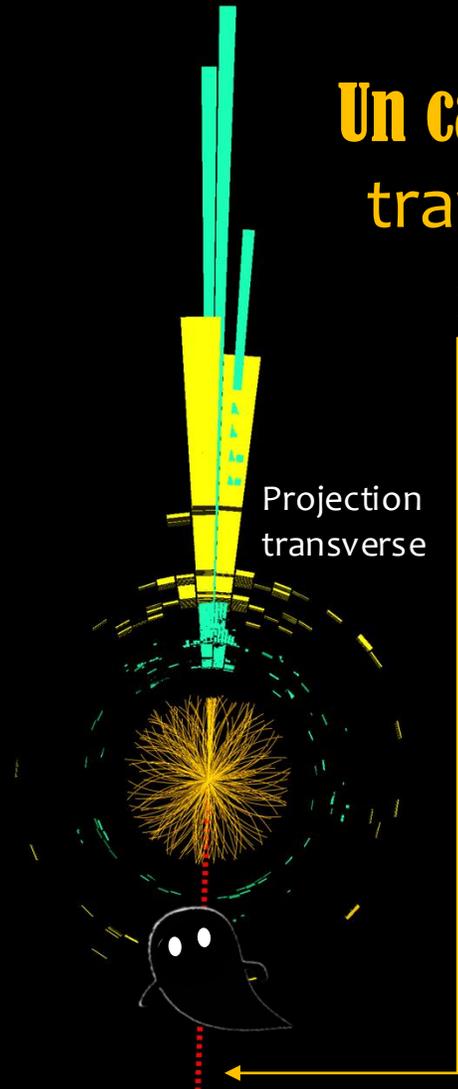
TRT

SCT

Pixels



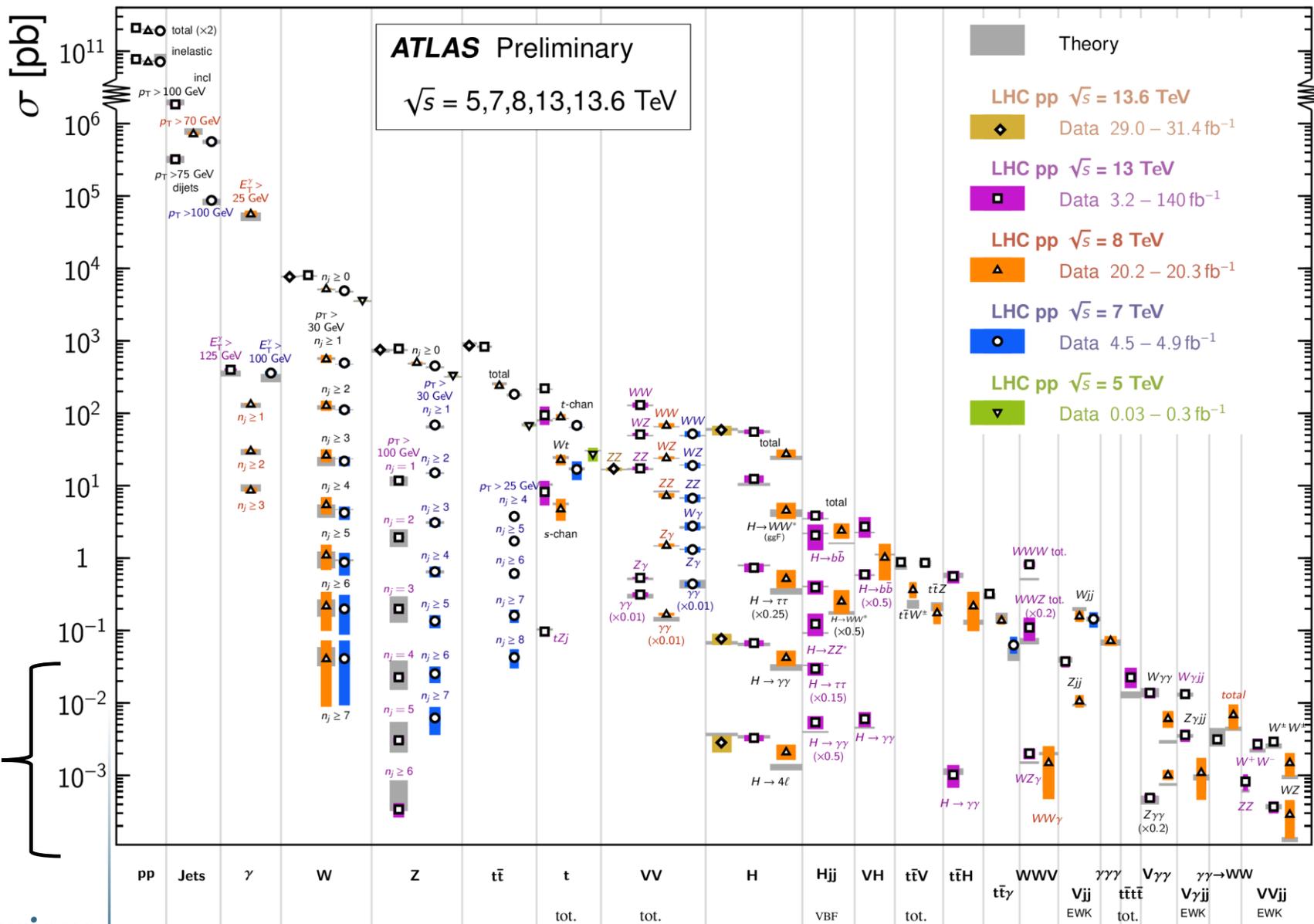
Un candidat de Matière Noire traverserait le détecteur sans interagir avec



État du Modèle Standard

Standard Model Production Cross Section Measurements

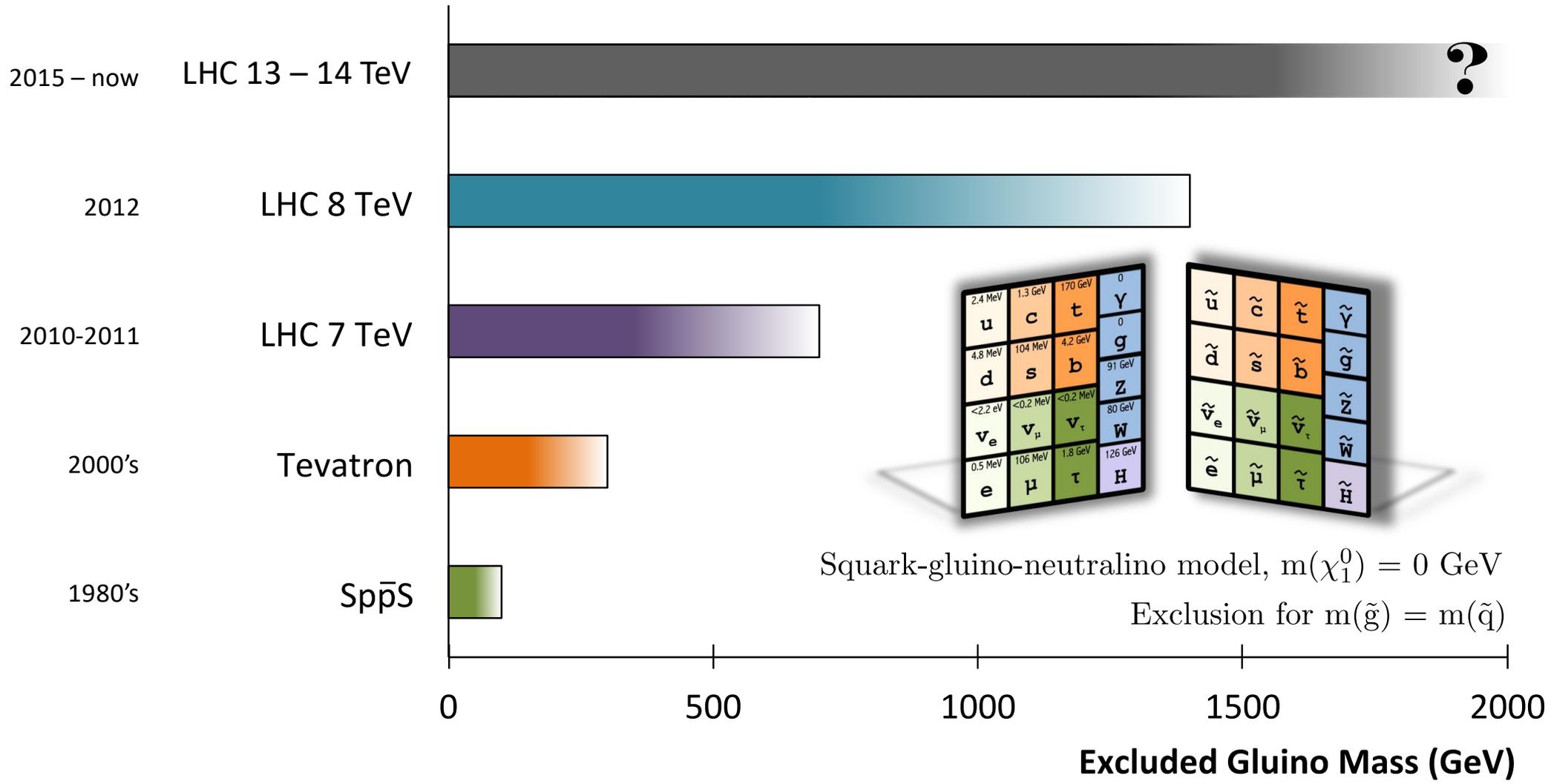
Status: June 2024



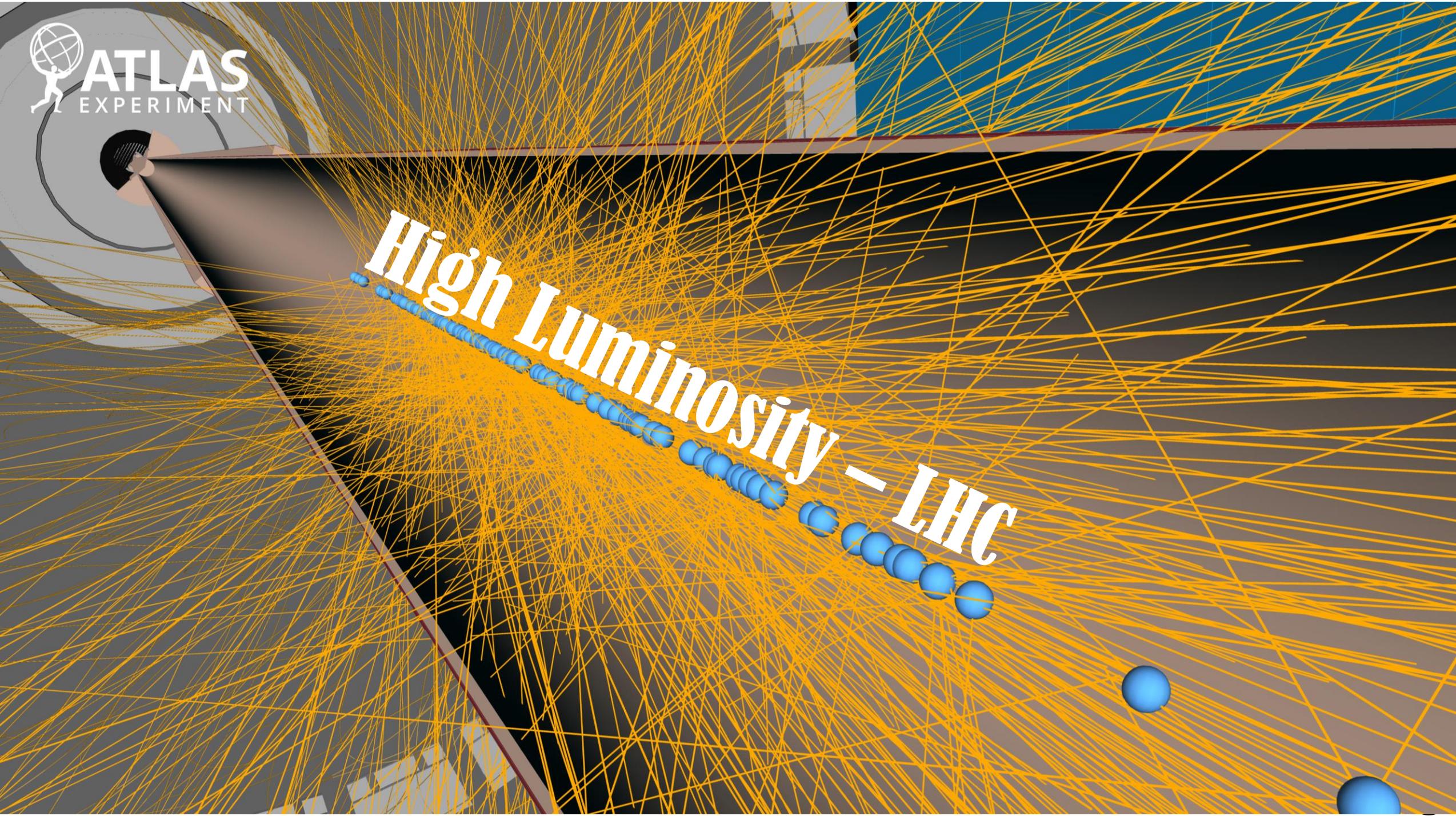
Certains aspects fondamentaux restent à explorer



Nouvelle physique



La matière noire reste l'une des plus grandes questions ouvertes de la science.
 Des résultats comme ceux-ci nous rapprochent de la véritable réponse.



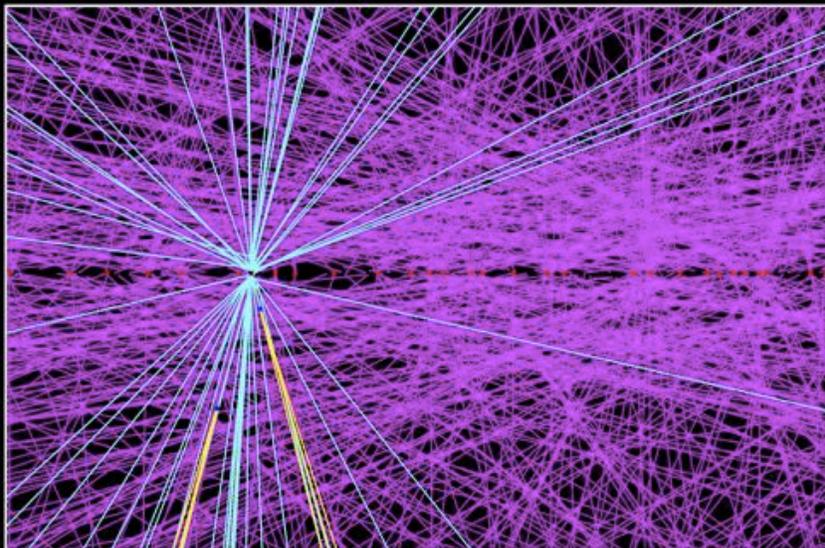
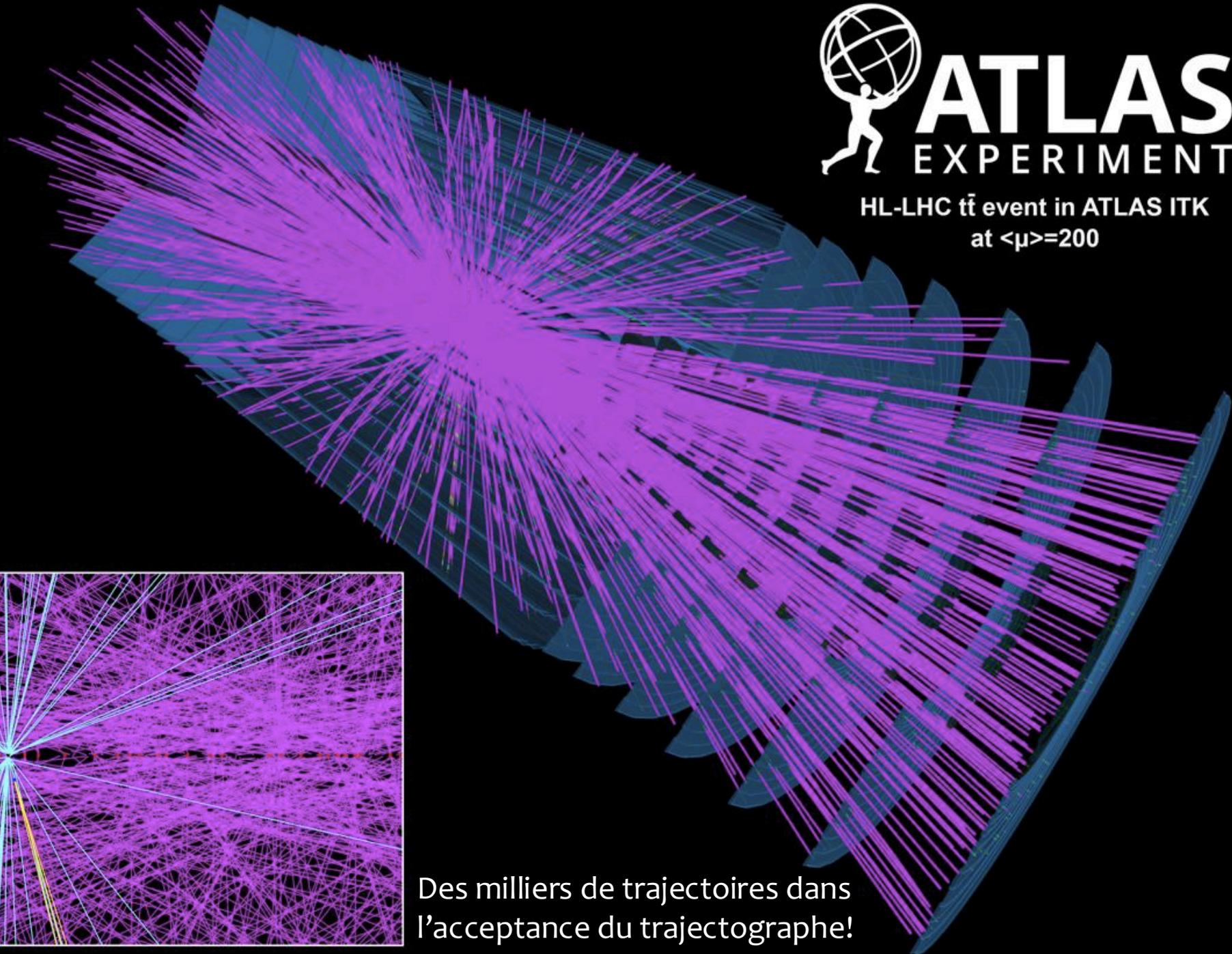
High Luminosity — LHC

The image shows a perspective view of a particle accelerator beam pipe. The pipe is a dark, tapered cylinder extending from the top left towards the bottom right. Inside the pipe, a dense stream of blue spheres represents the particle bunches. A massive, chaotic web of thin yellow lines radiates from the pipe, filling the background and representing the high particle density and interactions at high luminosity. The background is a dark grey with some blue and white architectural elements visible at the top.



ATLAS EXPERIMENT

HL-LHC $t\bar{t}$ event in ATLAS ITK
at $\langle\mu\rangle=200$



Des milliers de trajectoires dans
l'acceptance du trajectographe!

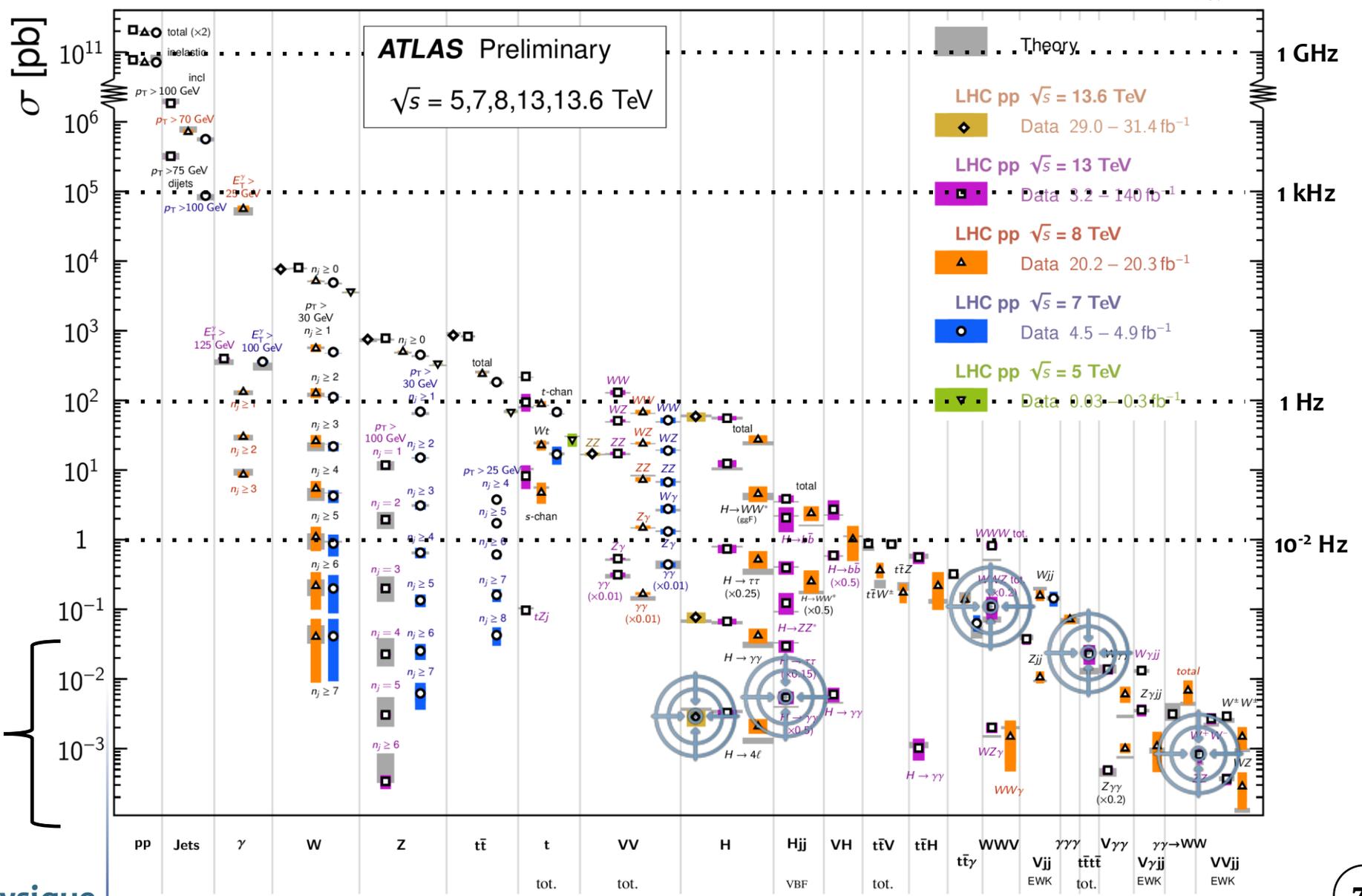
Objectifs physiques du HL-LHC: Précision & Exploration

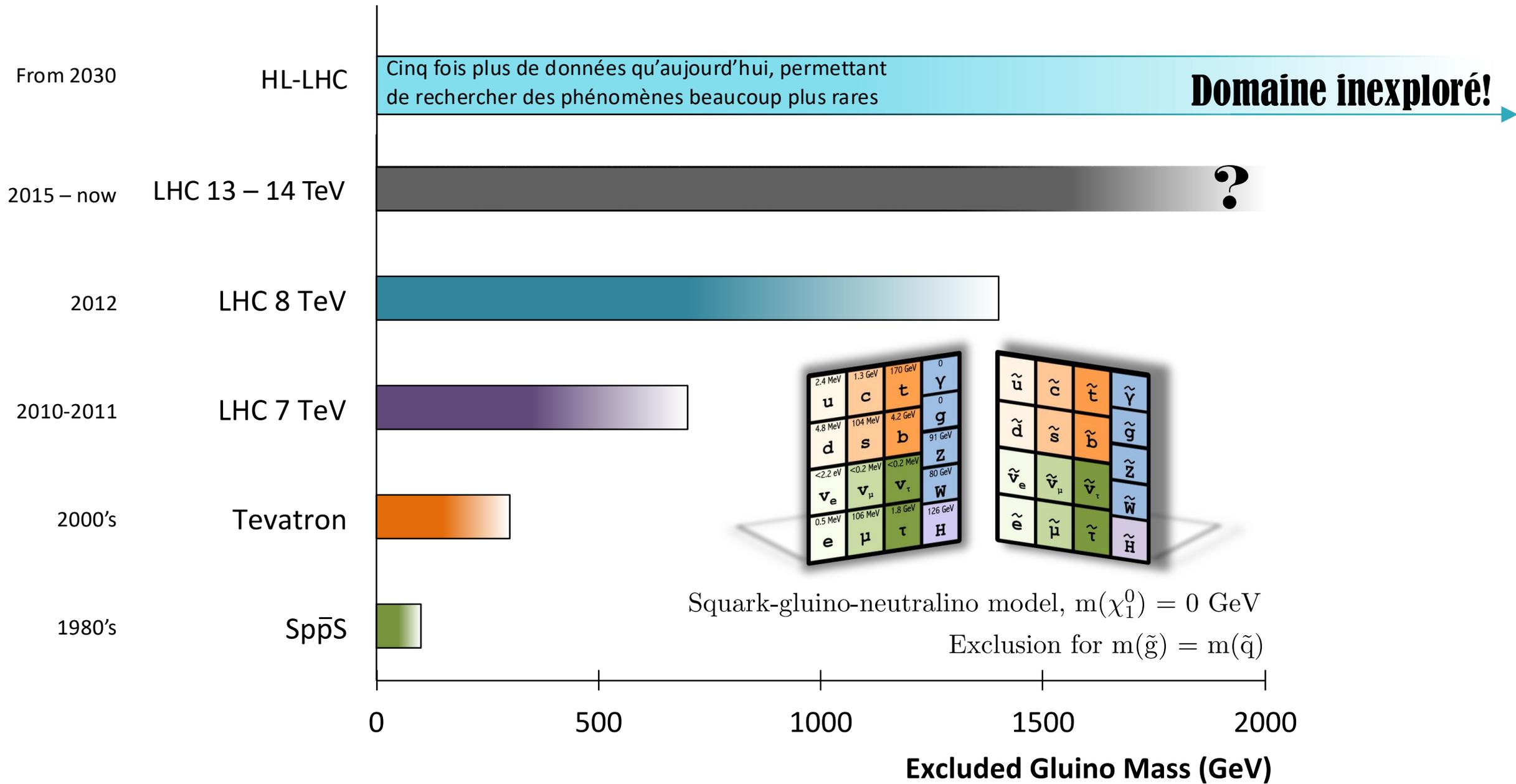
Certains aspects fondamentaux restent à explorer

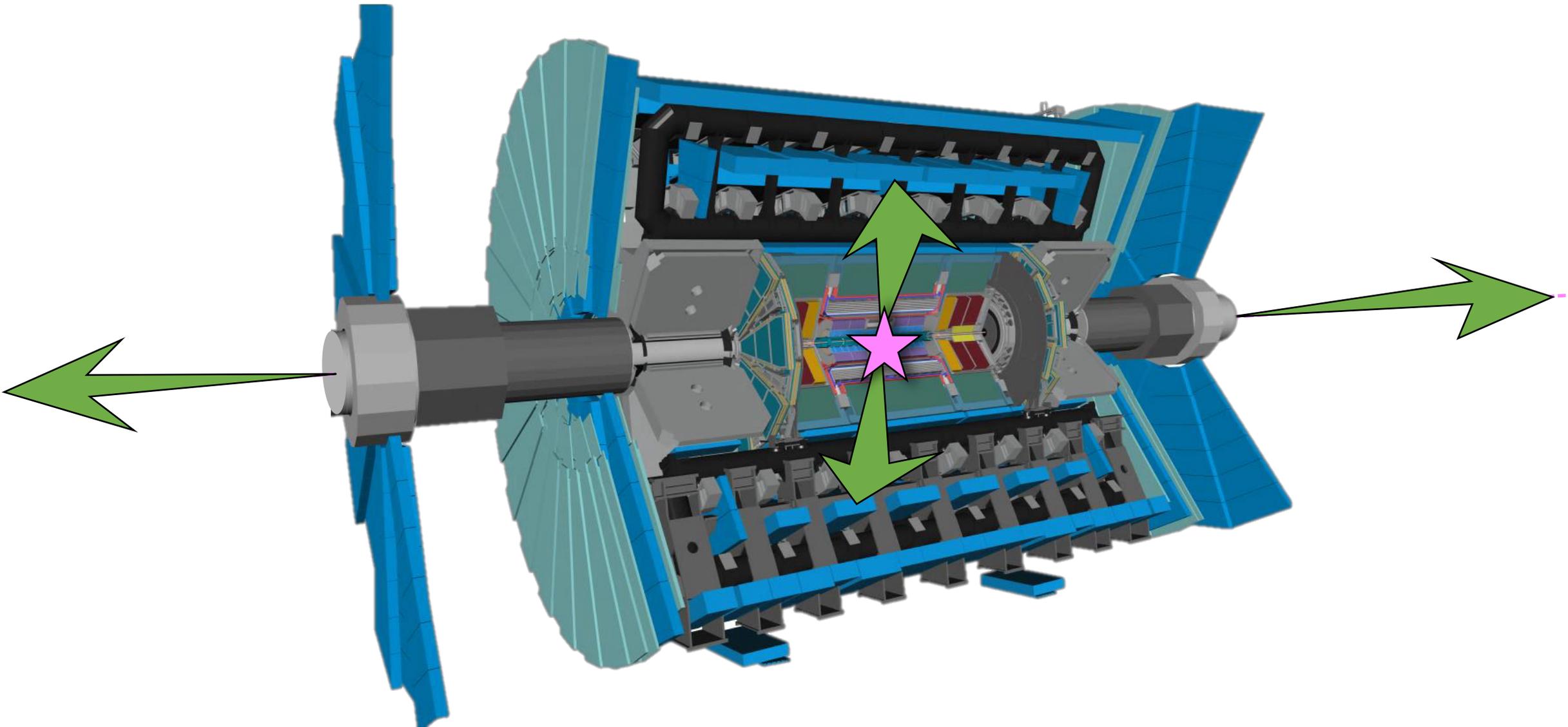


Nouvelle physique

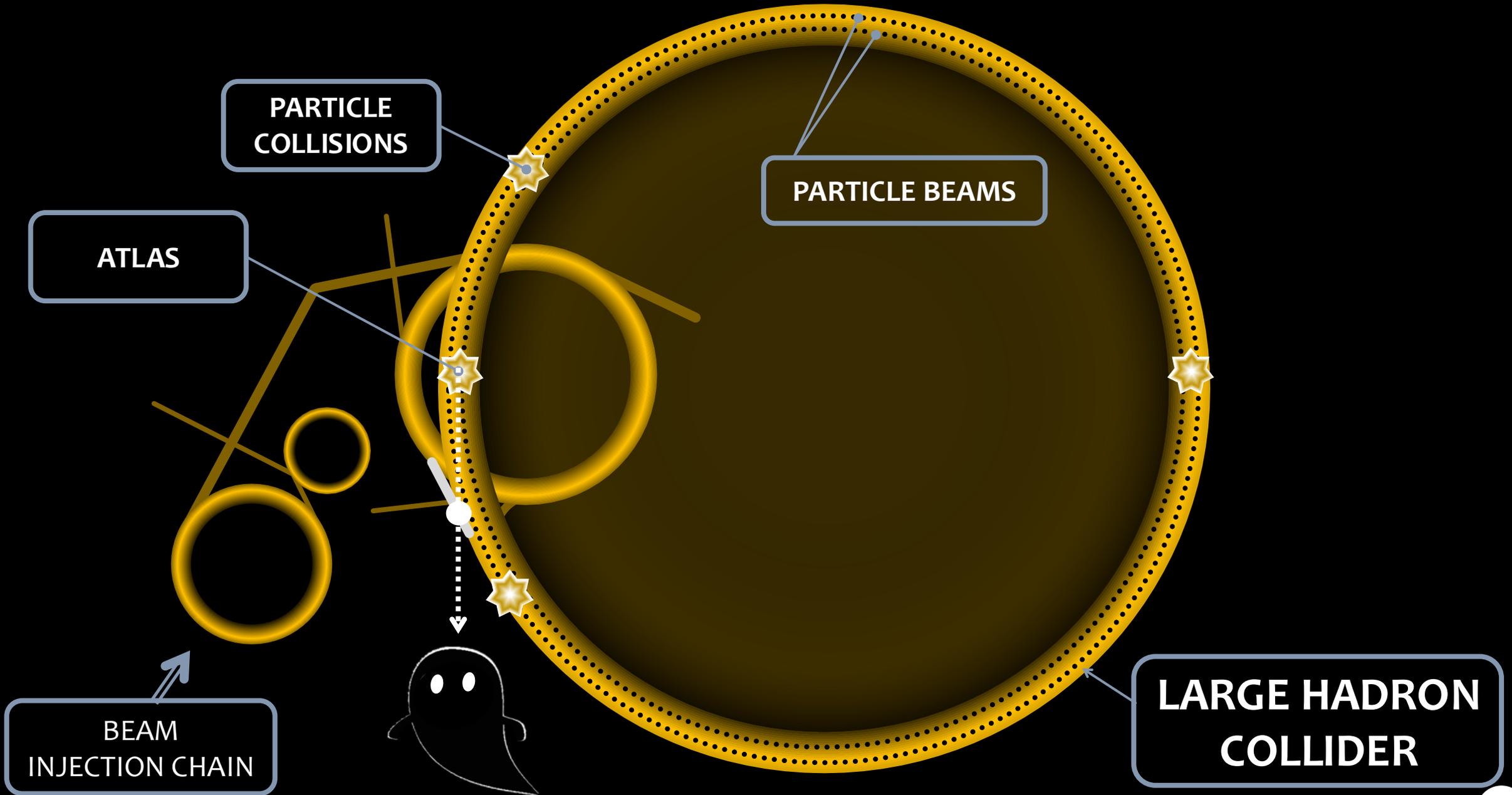
Standard Model Production Cross Section Measurements

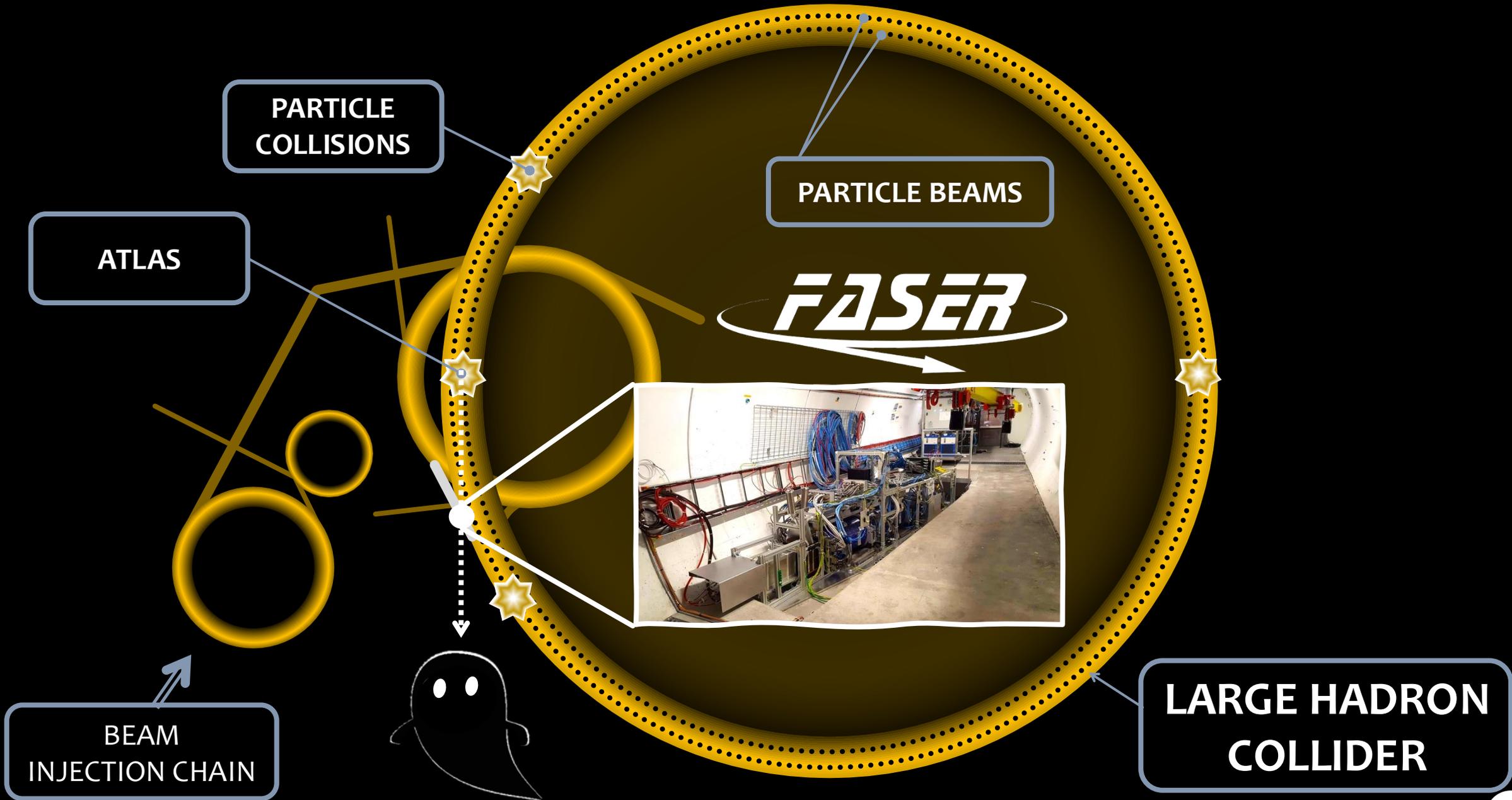






**Les expériences
très avant
("very forward")
du LHC**







CMU 2t

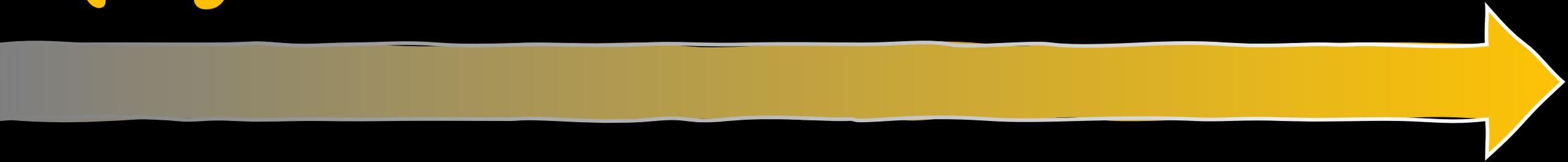
ATTENTION
TENSION
DANGER

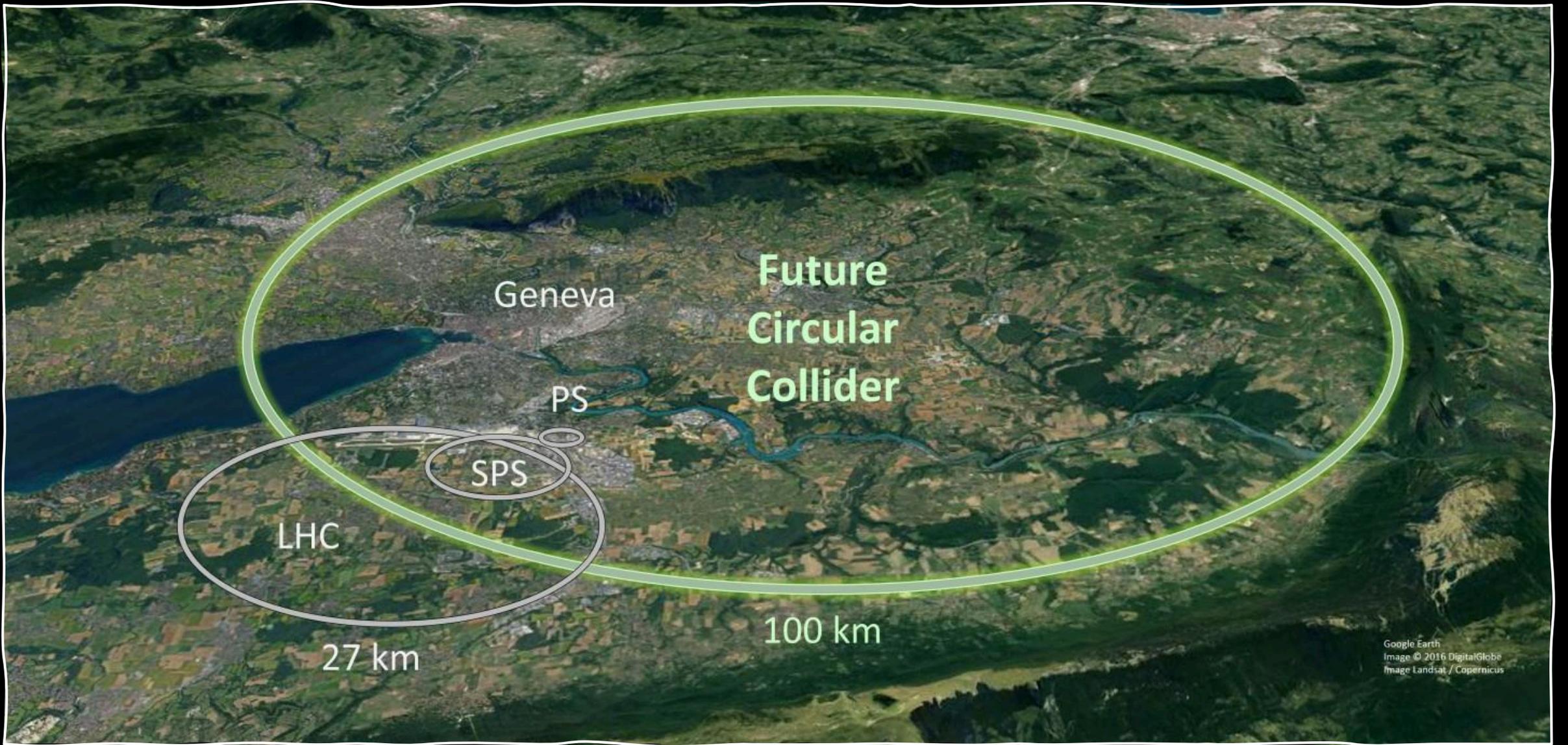


FASER

FASER

Qu'y a-t-il au-delà du LHC ?





Google Earth
Image © 2016 DigitalGlobe
Image Landsat / Copernicus

En bref:

La recherche de la Matière Noire au CERN



- Le **Modèle Standard** est un cadre remarquable qui explique une grande partie de l'Univers connu – mais il est **incomplet**.
- L'un des plus grands mystères: **qu'est-ce que la Matière Noire?**
- Pour explorer les **constituants les plus fondamentaux** de la nature, nous devons atteindre des **énergies toujours plus élevées**, grâce à des collisions de particules **extrêmement énergétiques**.
- Ces collisions peuvent produire des candidats de matière noire, que les **expériences du CERN** recherchent activement.
- La prochaine grande découverte en physique est peut-être toute proche – et il faut être prêt à la reconnaître.
- En chemin, nous stimulons **des innovations technologiques** de pointe dont l'impact dépasse le domaine de la physique des particules.

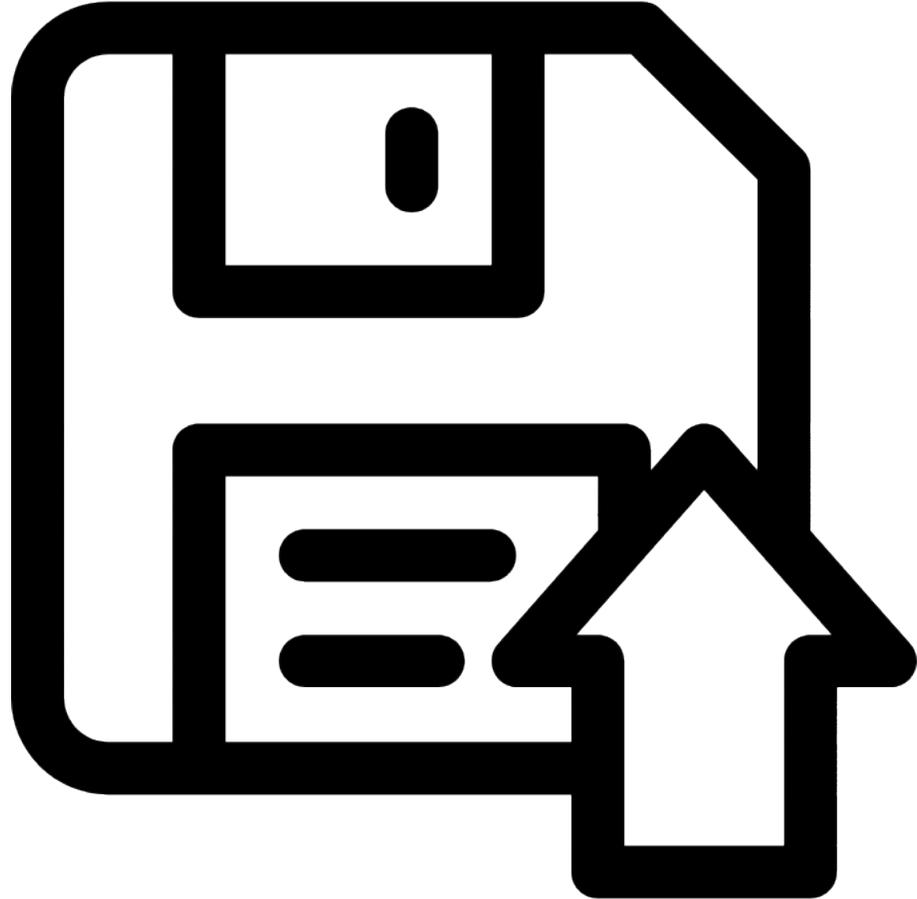
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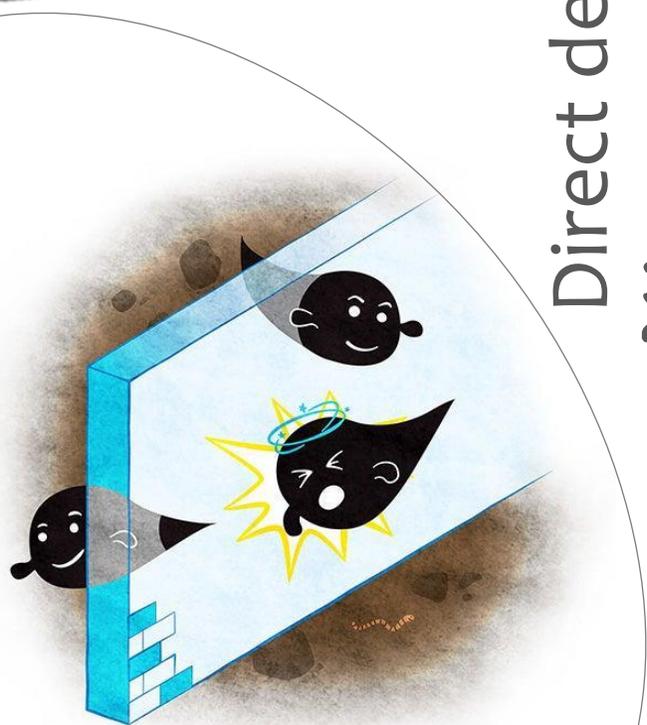






Direct detection

DM - NUCLEON SCATTERING



Direct detection

Indirect detection
DM ANNIHILATION

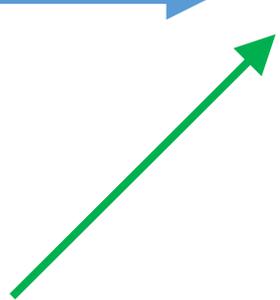
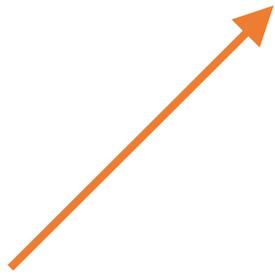
DM



SM



DM

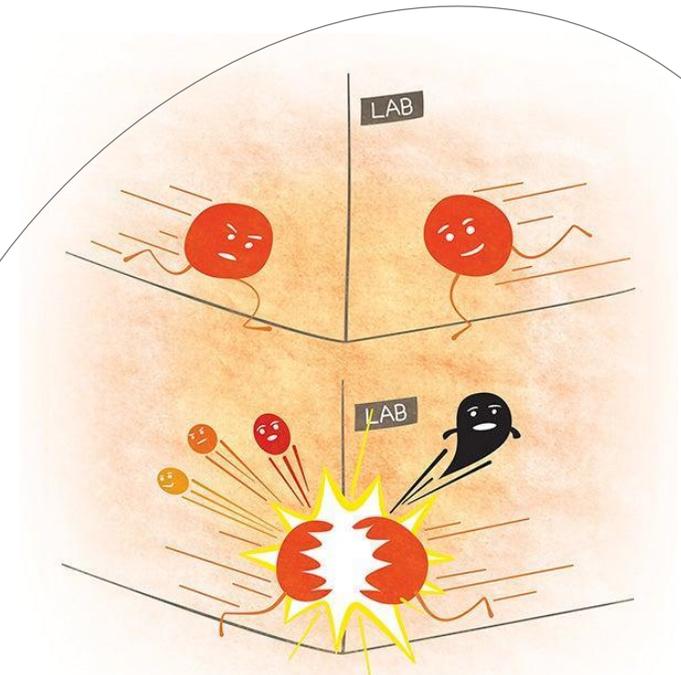
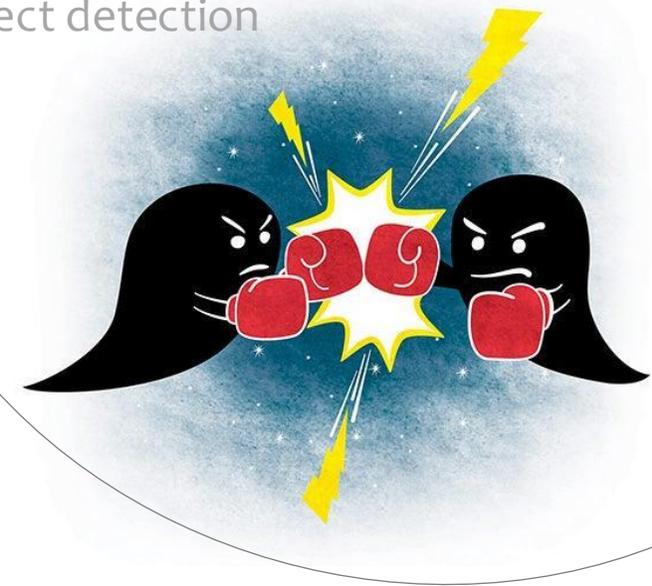


SM

COLLIDER SEARCHES



Indirect detection

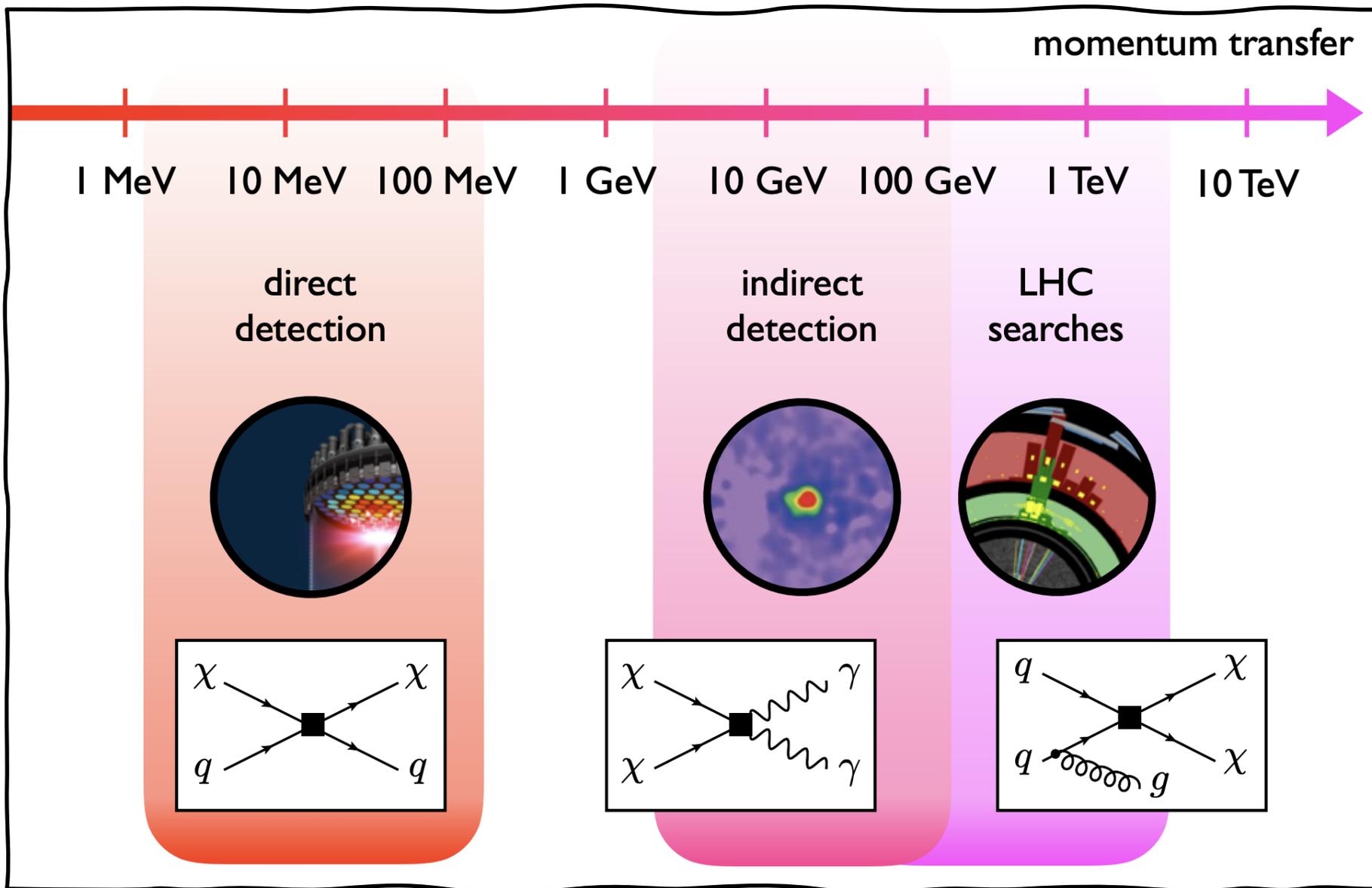


Collider searches

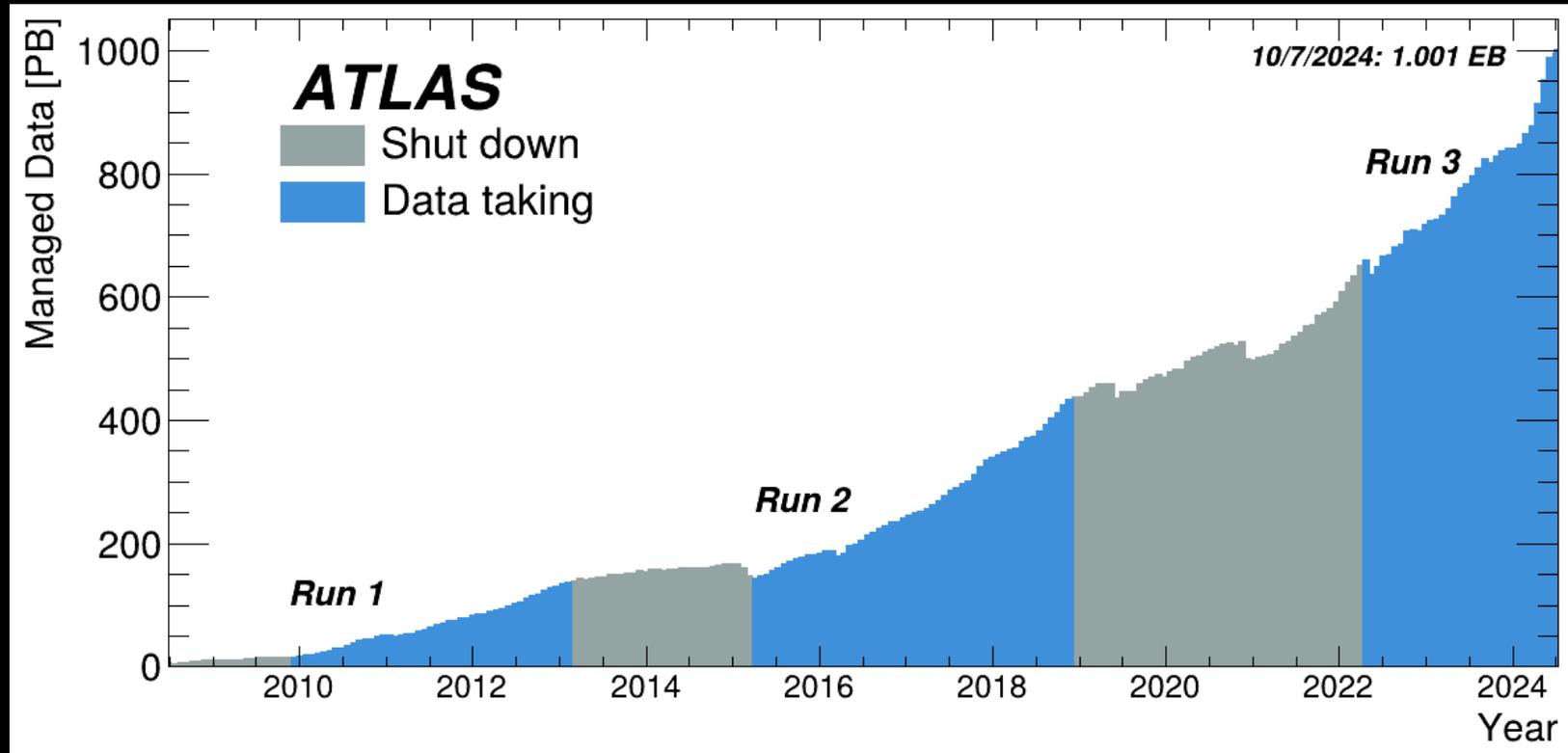
Drawings from

<https://www6.slac.stanford.edu/news/2016-02-08-three-ways-bust-ghostly-dark-matter>

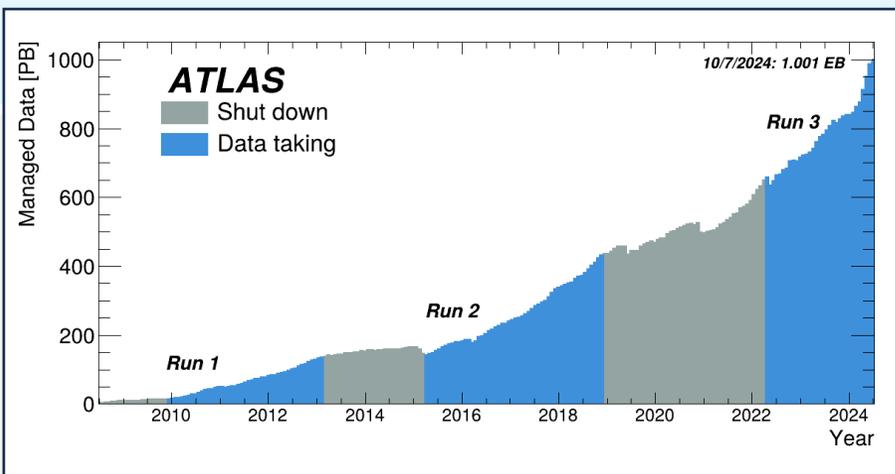
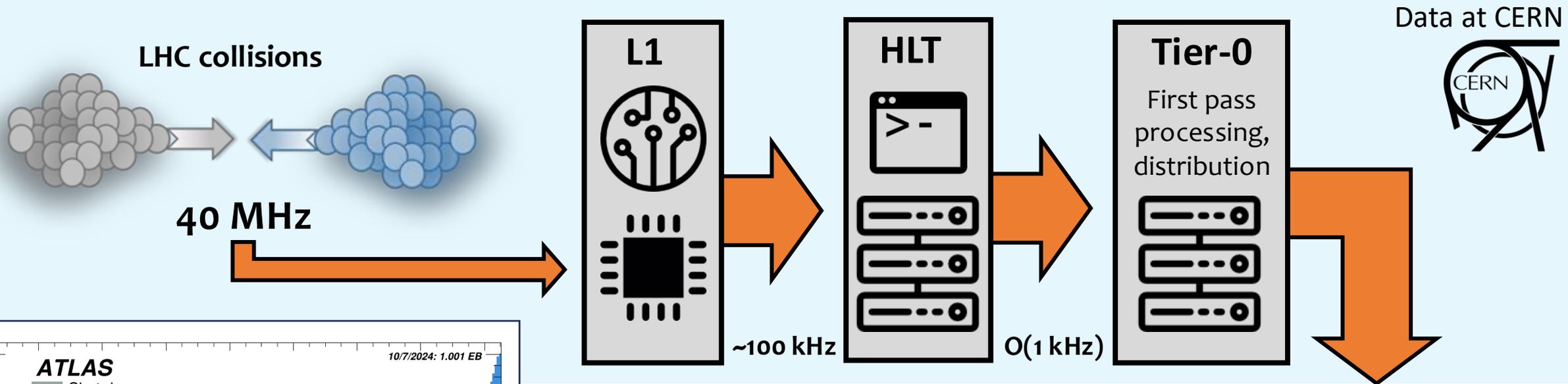




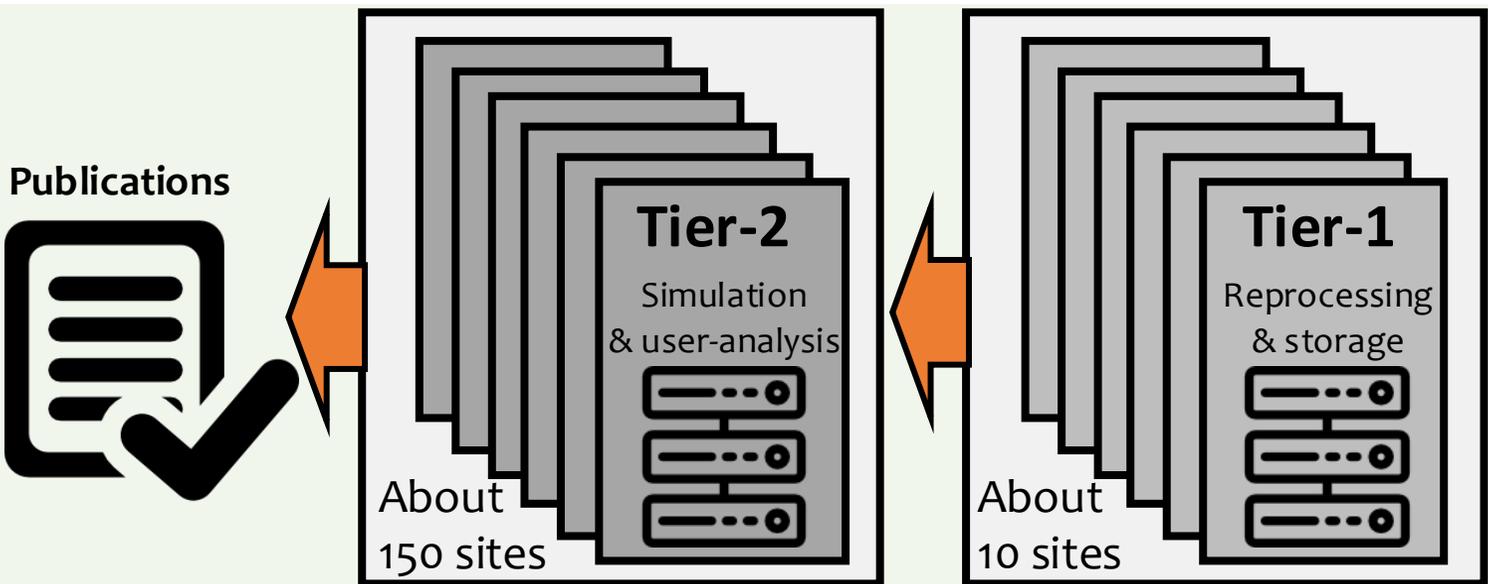
ATLAS Computing – data size



ATLAS Computing Path



Data in the world



Missing Transverse Momentum – \cancel{E}_T



In the transverse plane:

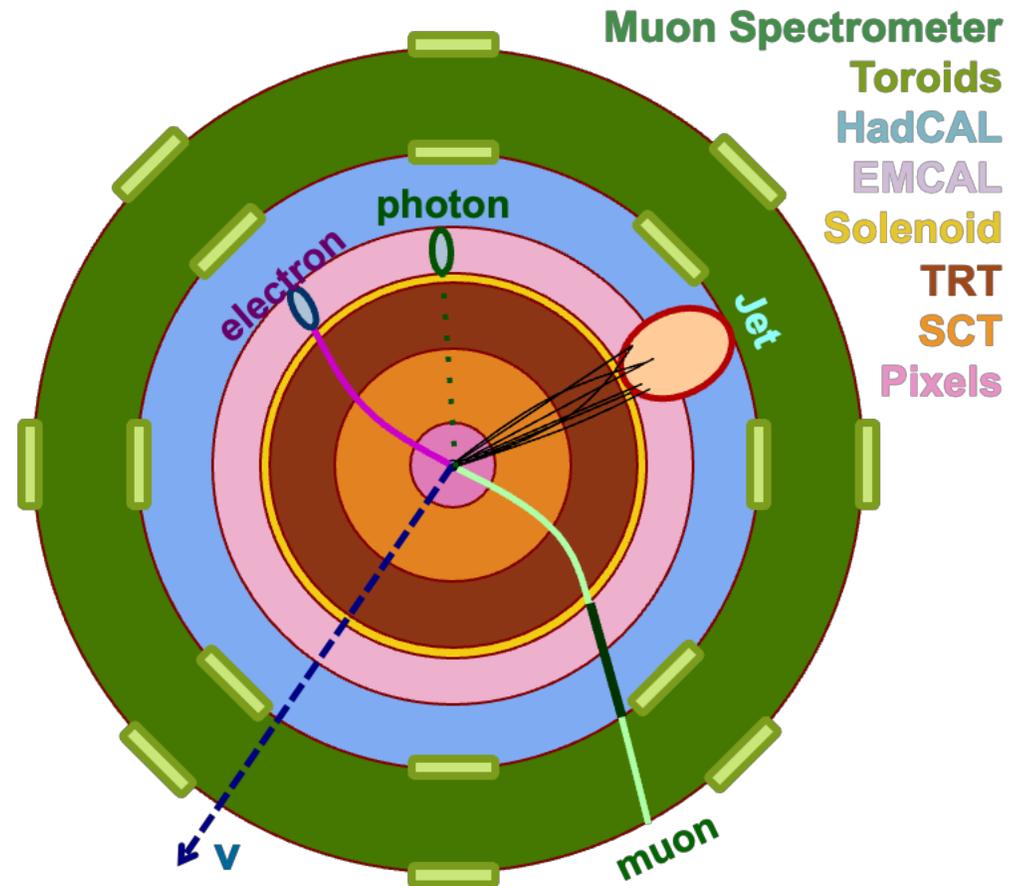
$$\sum_i \vec{p}_{T,i} = 0$$

OR DARK MATTER
CANDIDATES!

So for what we can't directly measure (e.g. neutrinos)

$$E_T^{\text{miss}} = -\sum_i \vec{p}_{T,i}$$

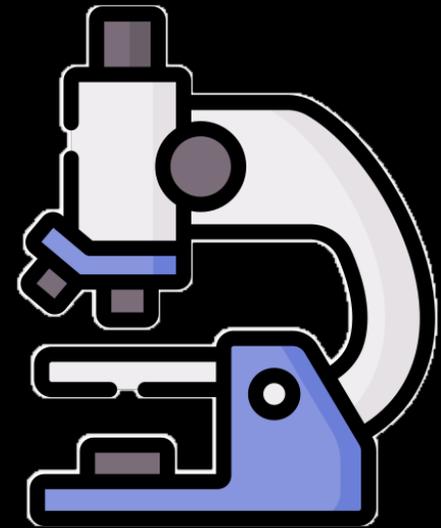
Simplified Detector Transverse View



INSTRUMENTS!

HOW DO WE “SEE” THE SMALLEST PARTICLES?

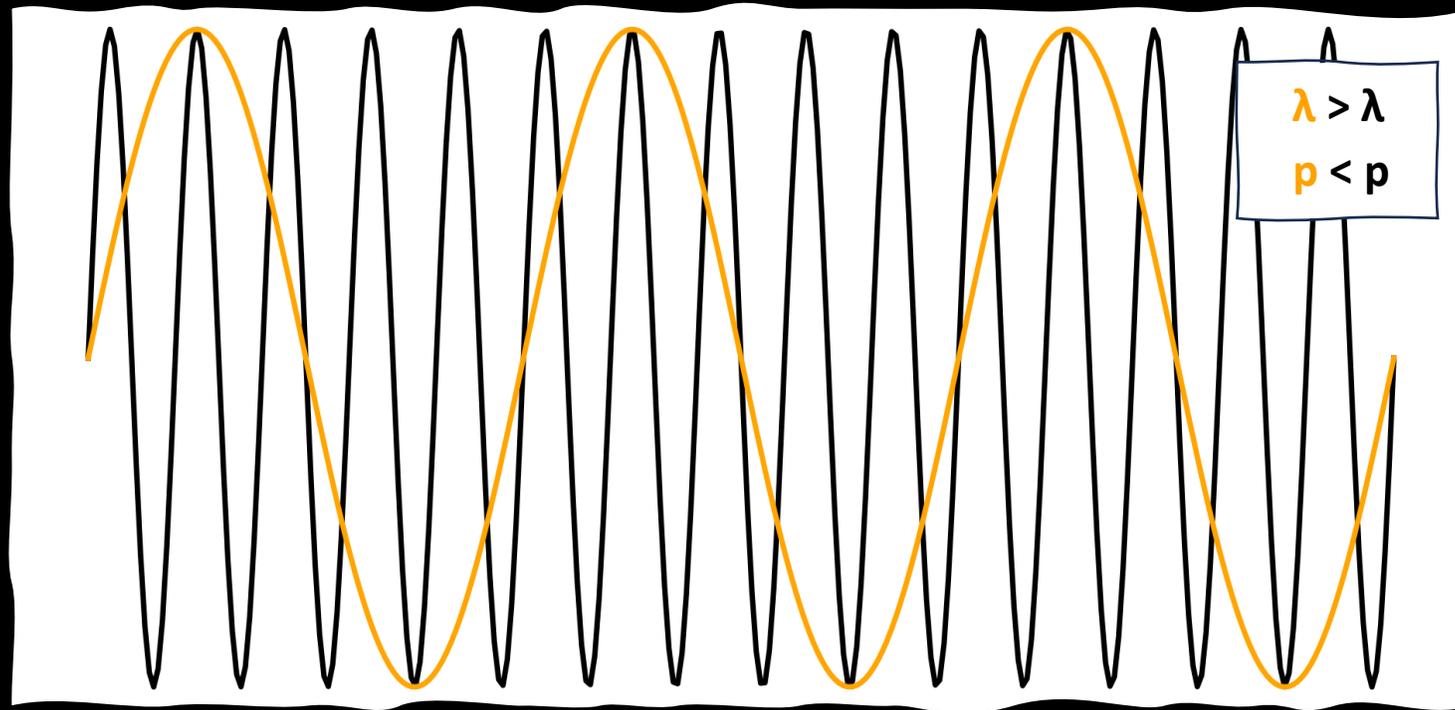
- Atoms are about 10^{-10} meters in size
- Protons are around 10^{-15} meters
- Elementary particles (like quarks and electrons) are even smaller — possibly point-like, with sizes below 10^{-18} meters.



We don't “see” them directly — instead, we infer their size and structure through high-energy particle collisions and scattering experiments.

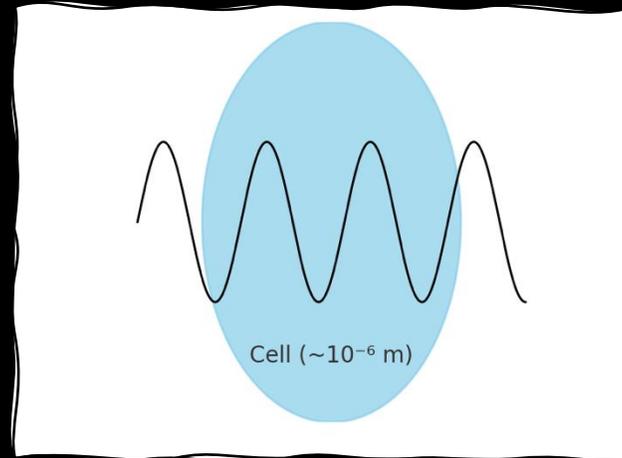
SMALL DISTANCE \Leftrightarrow HIGH ENERGY

Wavelength λ associated with a particle of momentum p : $\lambda = \frac{\text{constant}}{p}$



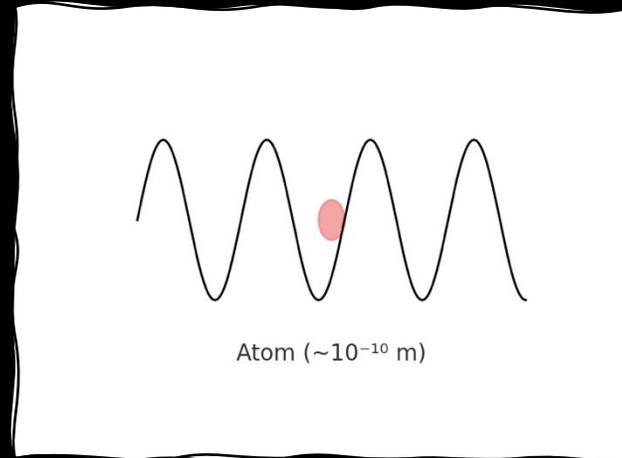
SMALL DISTANCE \Leftrightarrow HIGH ENERGY

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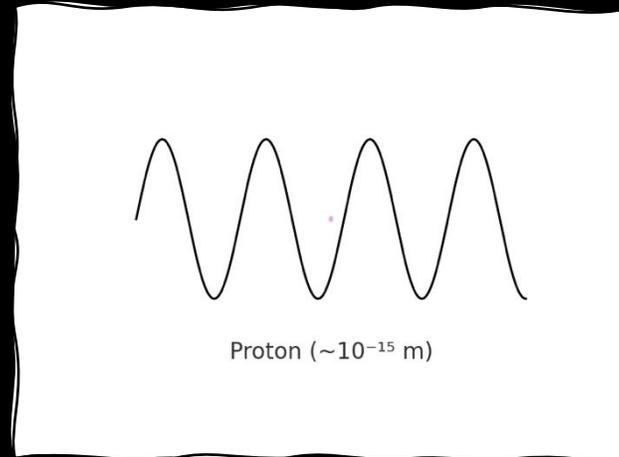
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SMALL DISTANCE \Leftrightarrow HIGH ENERGY

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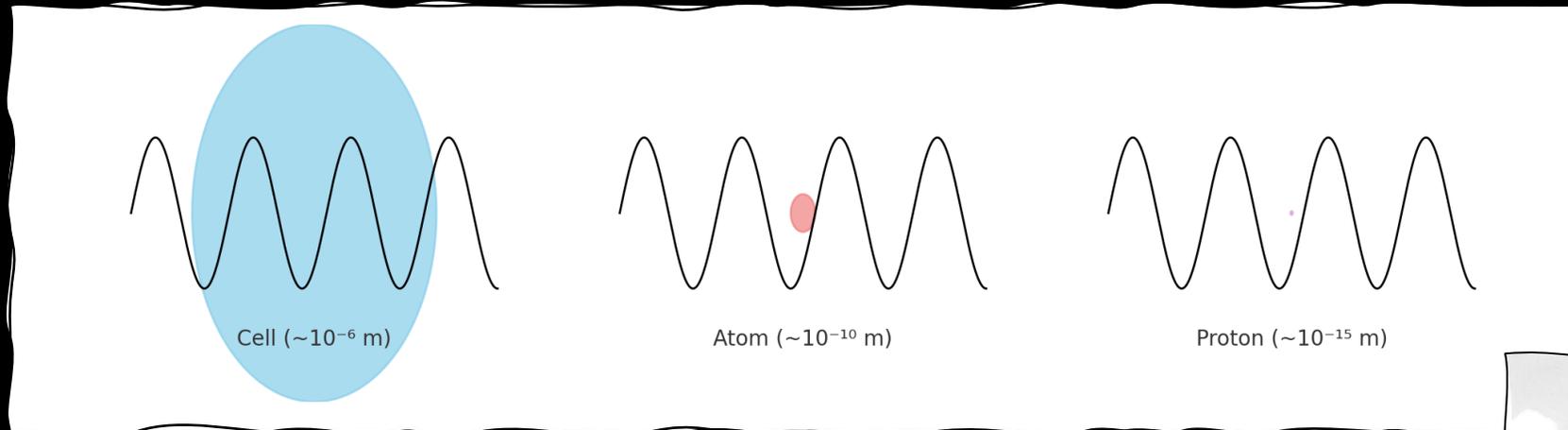
Rule of thumb: You can't see things smaller than the wavelength of the probe you're using.

To detect **smaller things**, you need **shorter wavelengths**, which means **higher momentum and energy!**



SMALL DISTANCE \Leftrightarrow HIGH ENERGY

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Everyday Applications

The search for answers to fundamental questions about the properties of matter and the forces of nature requires state-of-the-art research and development, which often leads to innovation. Here are a few examples of how ATLAS' knowledge and technological innovation have been applied to everyday life:

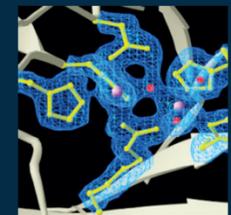


Superconducting magnetic energy storage

ATLAS' knowledge of the fabrication of super-conducting coils may enable the manufacture of high-performance energy storage systems.

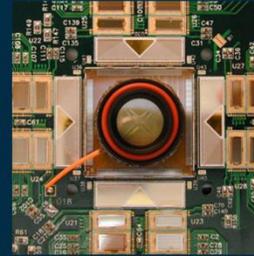
Hadron therapy

Diamond sensors developed for the ATLAS detector's upgrade are used to monitor hadron therapy beams, which are more effective than x-rays or electron beams in destroying tumours while sparing healthy surrounding tissues.



Medical imaging

3D silicon sensors developed for the ATLAS detector's upgrade make visualisation of x-rays possible with enhanced resolution. Most medical imaging techniques require detection of photons in different energy ranges.

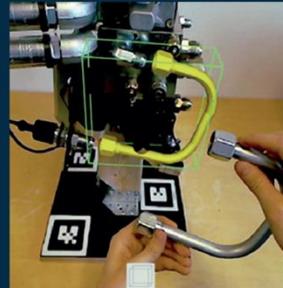


Retina project

Based on the silicon microstrip detector technology used in ATLAS, a recording system for large-scale neural activity has been developed. Experiments are able to understand how living neural systems process and encode information. This could one day give artificial sight for the blind.

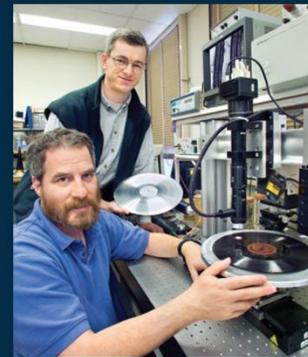
Augmented reality

ATLAS is investigating innovative pattern recognition technologies, a key building block for augmented reality applications, which enables personnel involved in delicate maintenance operations to virtually visualize working procedures, minimizing the time of intervention and risk of errors. This technology has several industrial applications.



Sound reproduction

Precision optical image processing methods used to measure and align each of 16000 silicon detectors of the ATLAS SemiConductor Tracker can be applied to measuring precisely the shape of the grooves on mechanical sound carriers such as phonograph discs and cylinder records. This technology is being developed for use in recorded sound archives and collections to restore and preserve delicate or damaged samples and historical sound recordings.



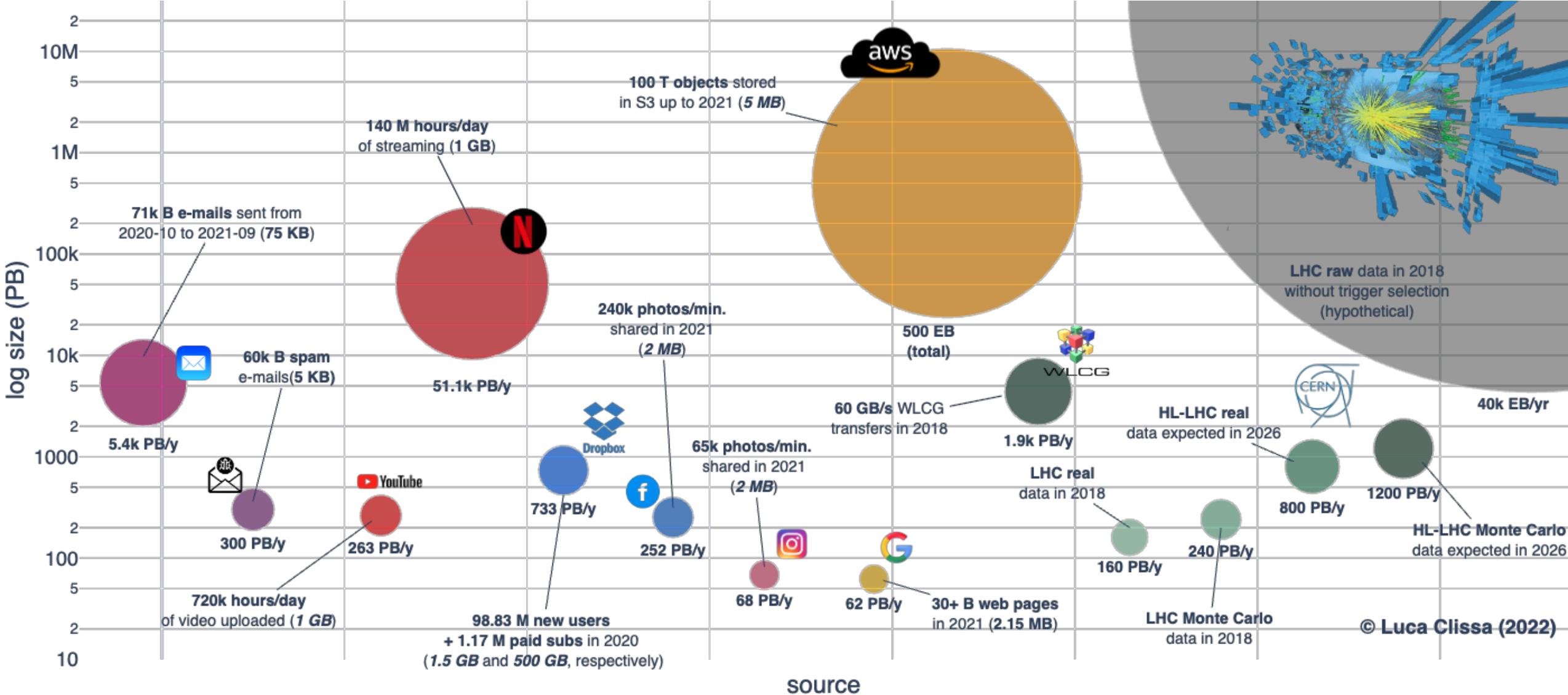
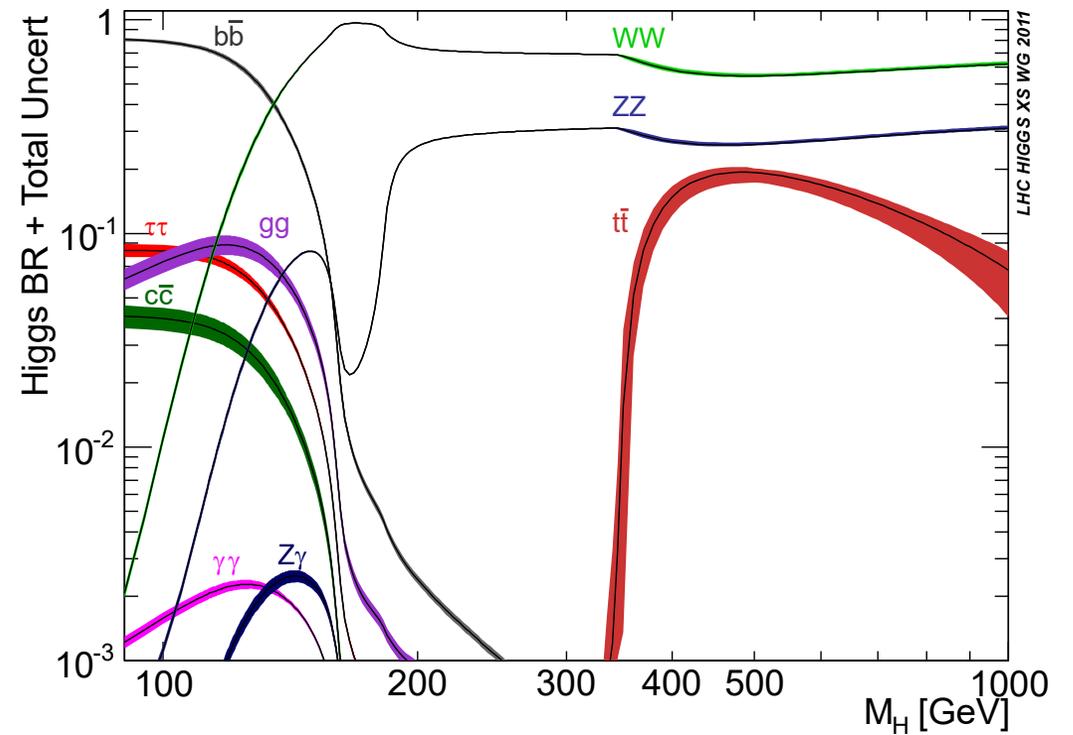
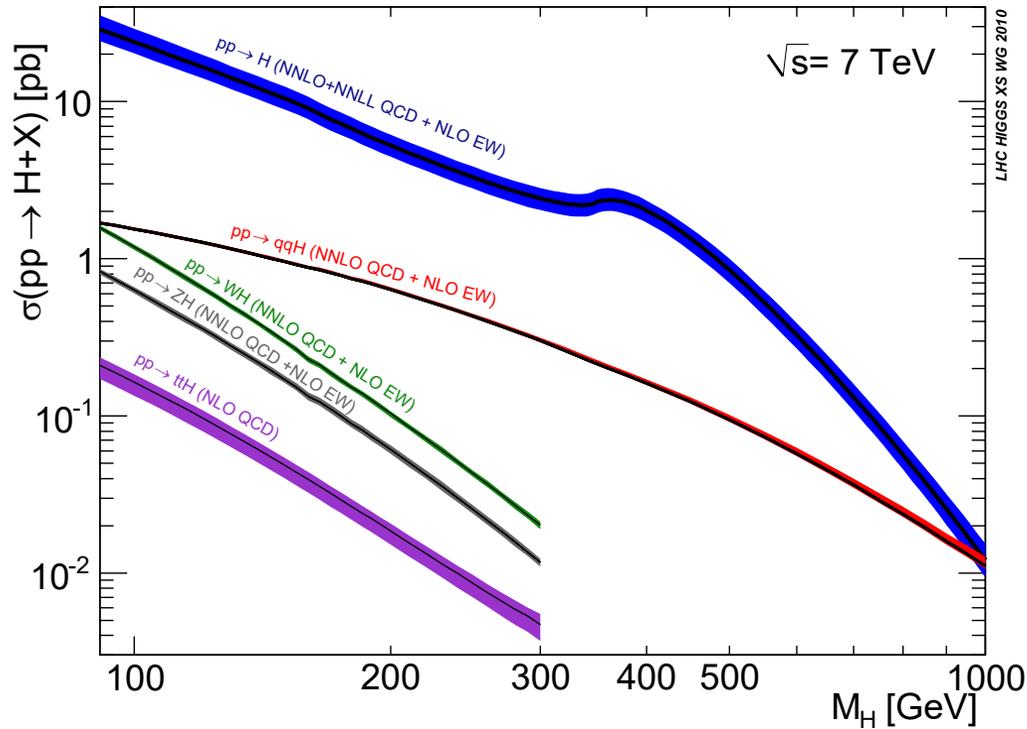


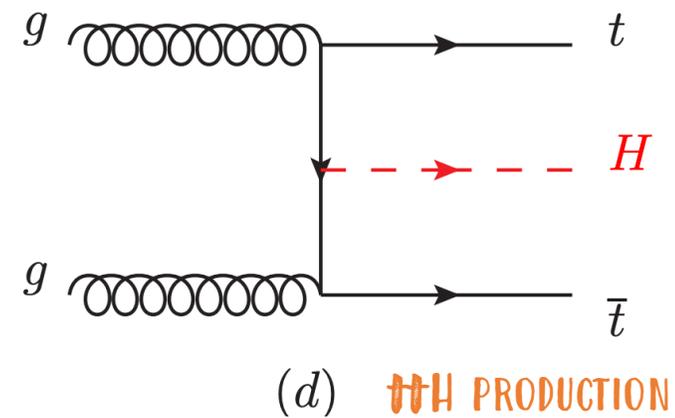
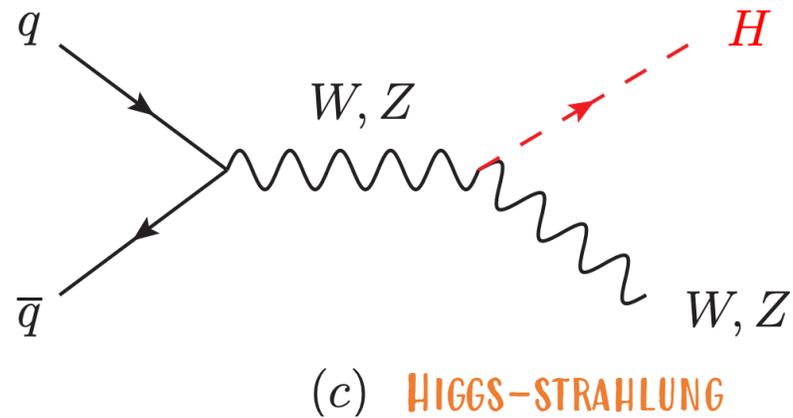
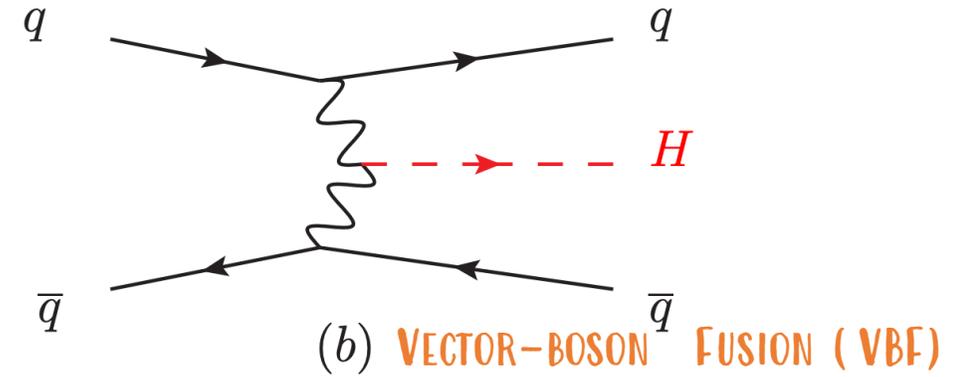
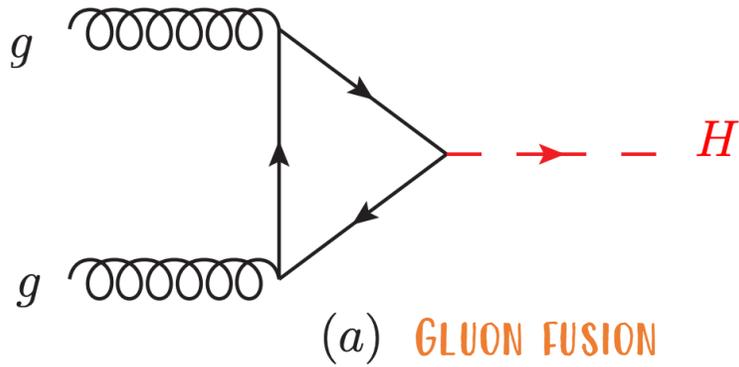
Figure 2.3: **Big Data sizes.** Bubble plot of the orders of magnitude of data produced by important big data players. The balloon areas illustrate the amount of data and the text annotations highlight the key factors considered in the estimates. Average per-unit sizes are reported in parentheses, where italic indicates measures reconstructed based on likely assumptions because no references were found.

Theory – before the discovery



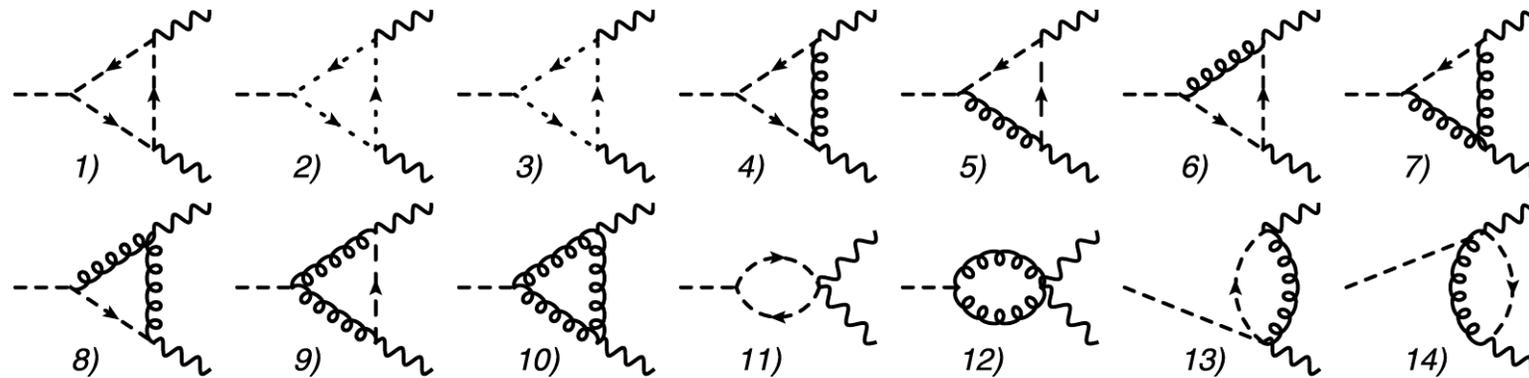
WHERE IS THE HIGGS??

Production mechanisms



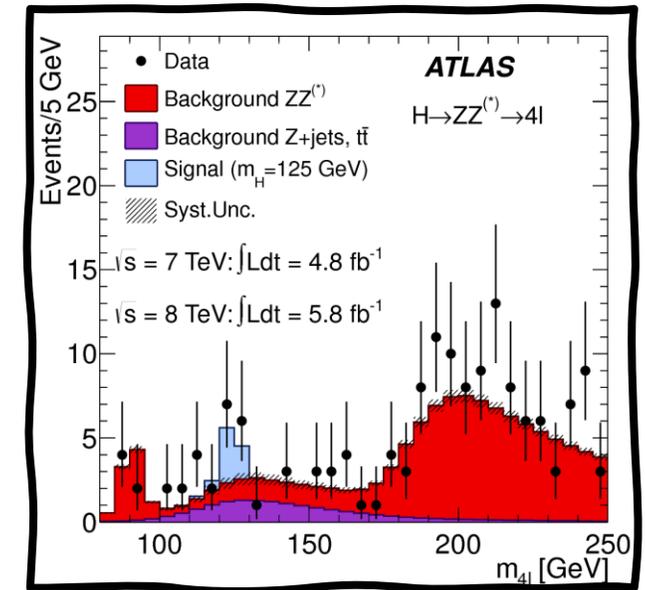
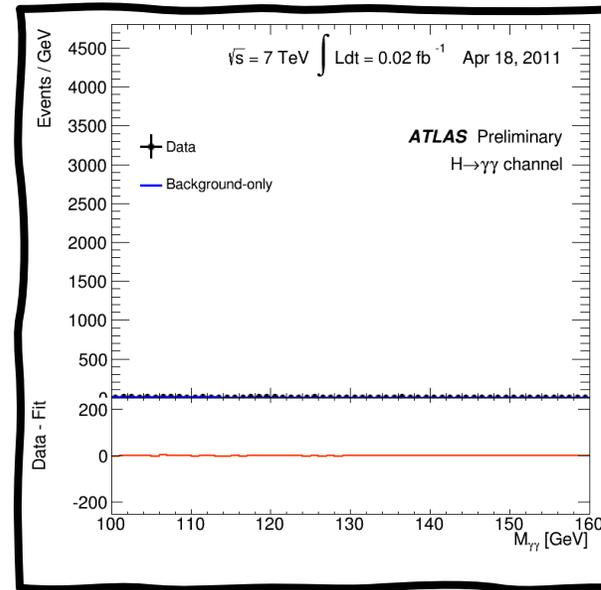
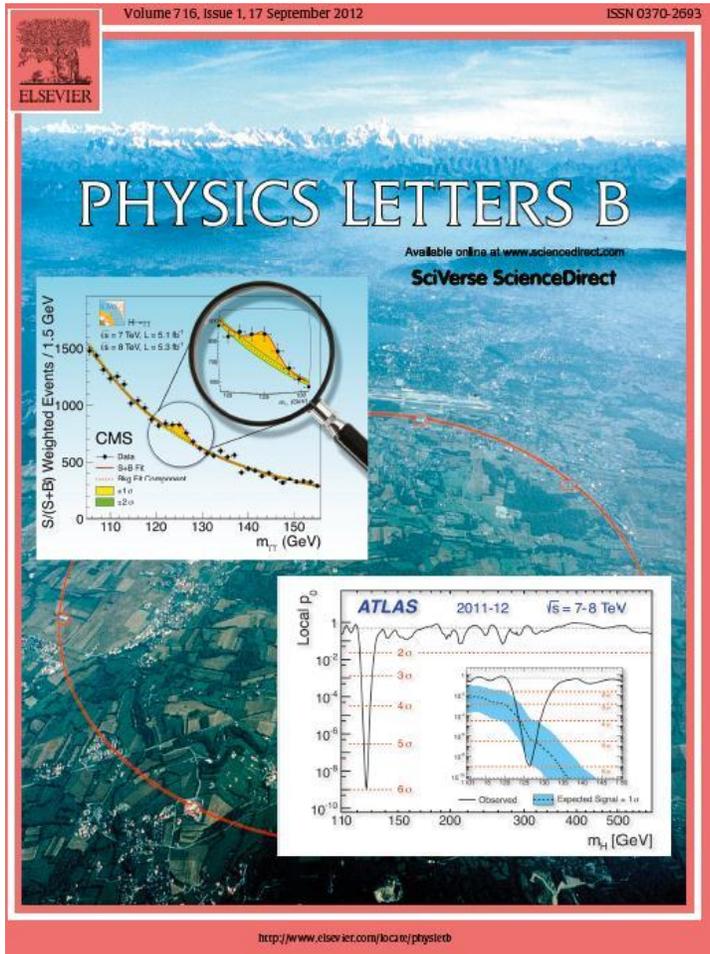
Higgs Decays

$H \rightarrow \gamma\gamma$

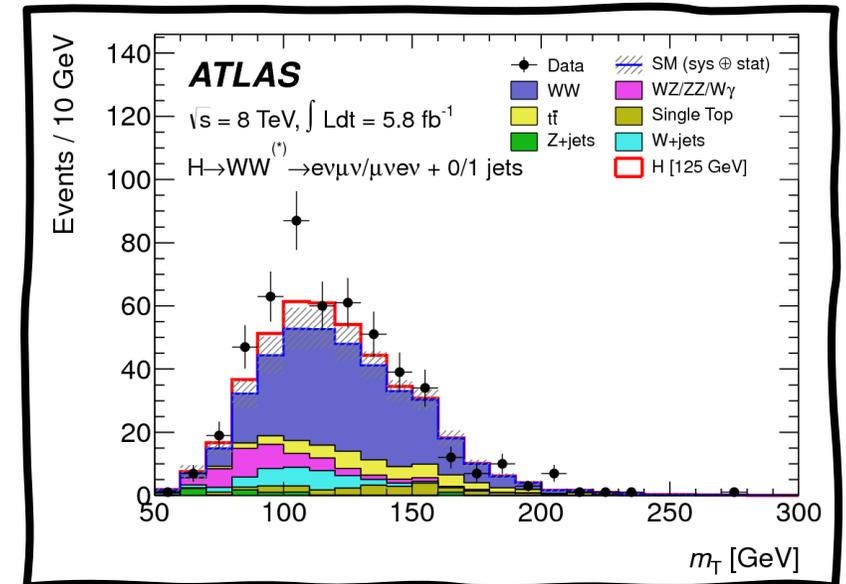


One-loop diagrams of the W-boson loop contribution in the Higgs [boson](#) decay into two photons. Crossed diagrams are not shown. Curved, wiggled, dashed, dashed with arrows and dotted lines correspond to the photon, W-boson, Higgs scalar, [Goldstone bosons](#) and the Faddeev–Popov ghosts, respectively. [arXiv:1804.04852](#)

The Higgs Discovery

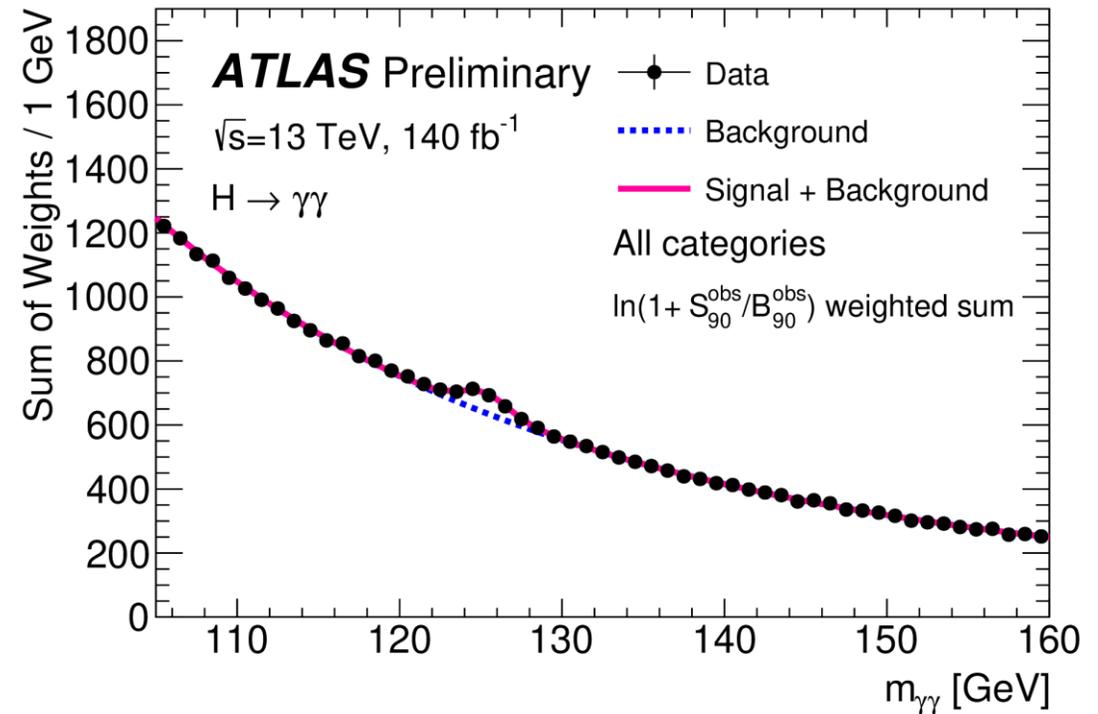
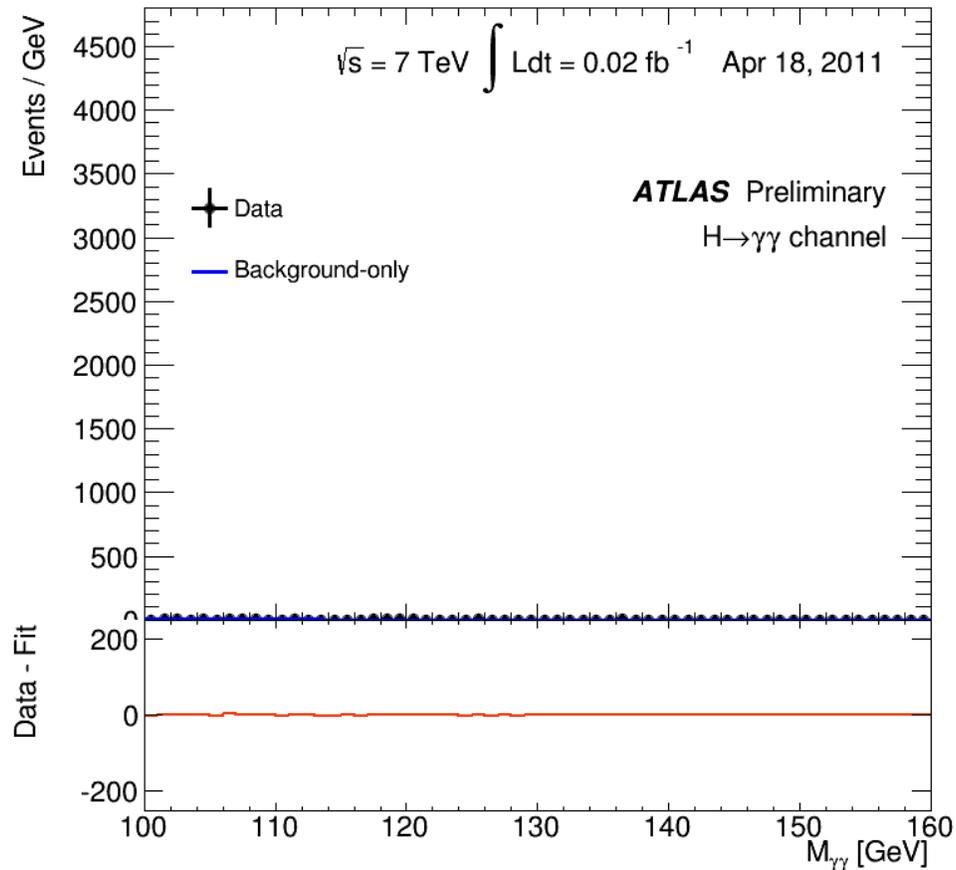


The three channels that contributed to the discovery



Higgs discovery (in photon final states)

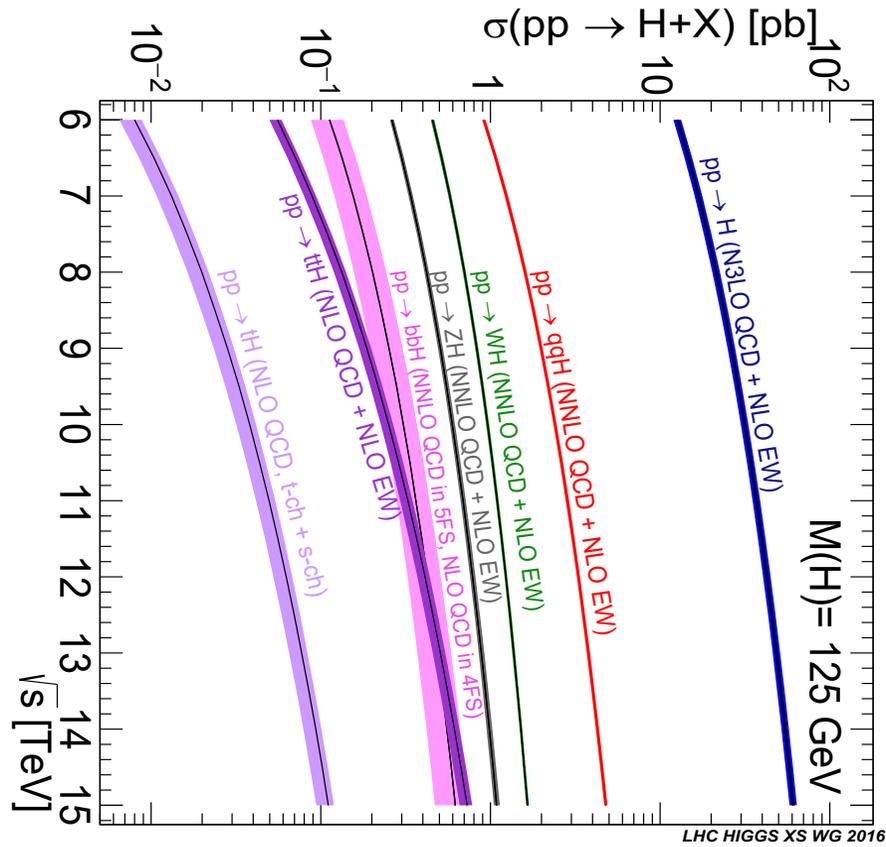
among those used to discover the Higgs boson...



...and still used to keep on studying its properties, e.g. its mass

What stats of Higgs available?

Assume Run2 : 150/fb



ggF

ABOUT 8 M EVENTS

VBF

ABOUT 600 K EVENTS

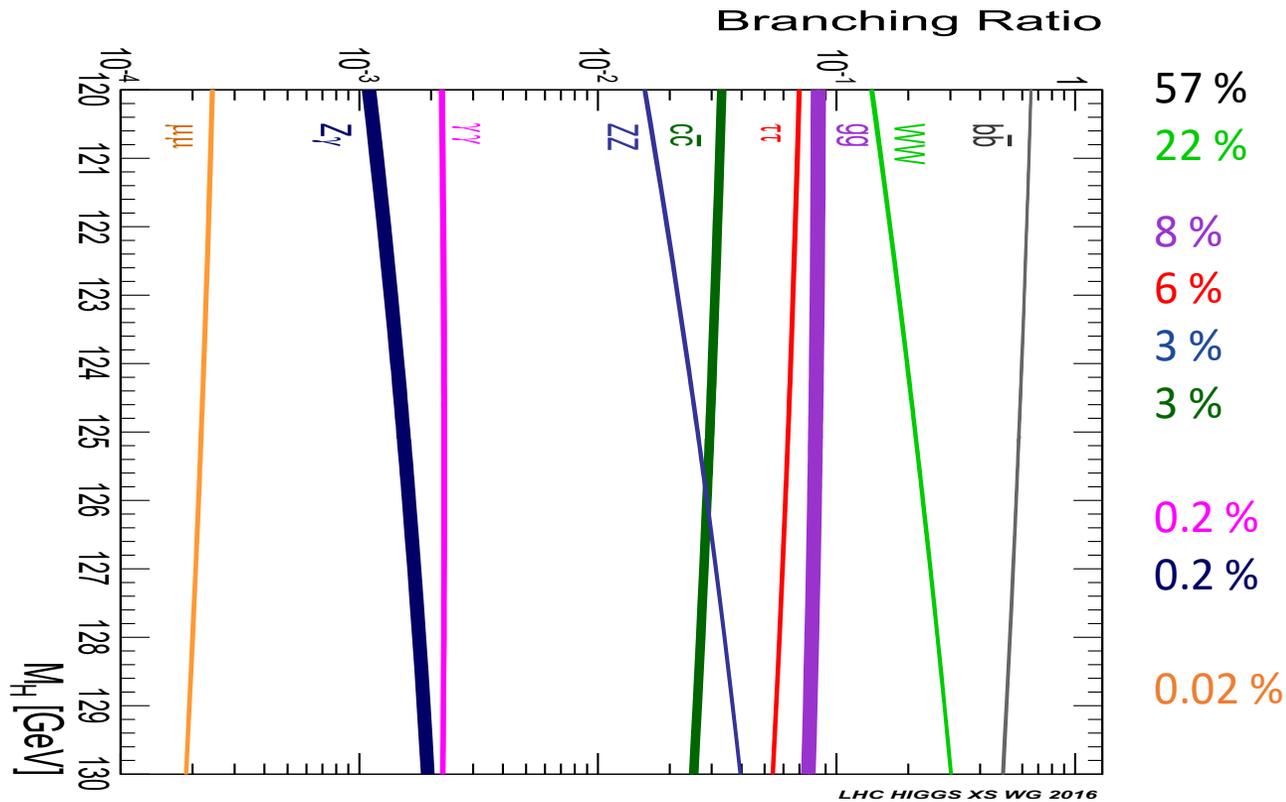
VH

ABOUT 400 K EVENTS

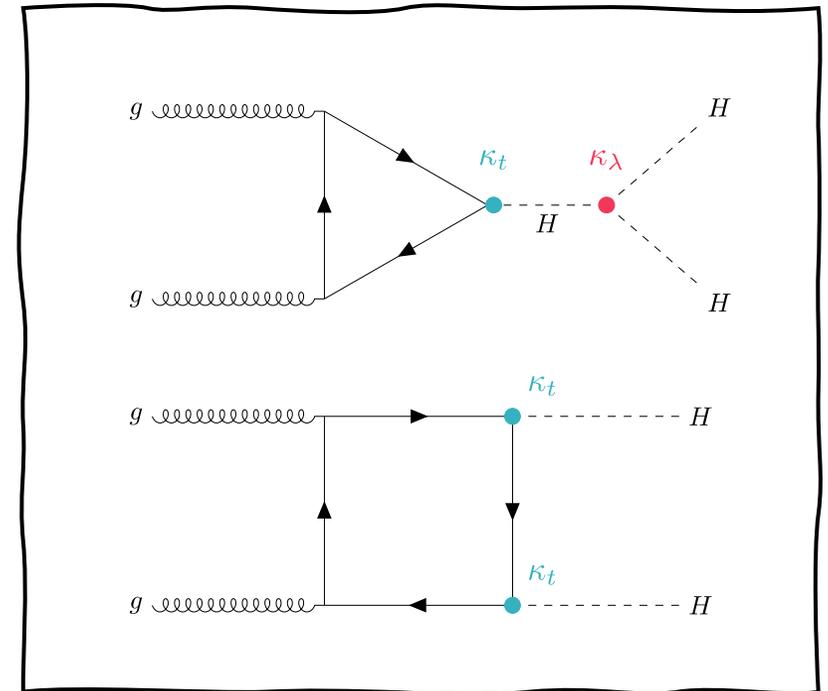
ttH

ABOUT 100 K EVENTS

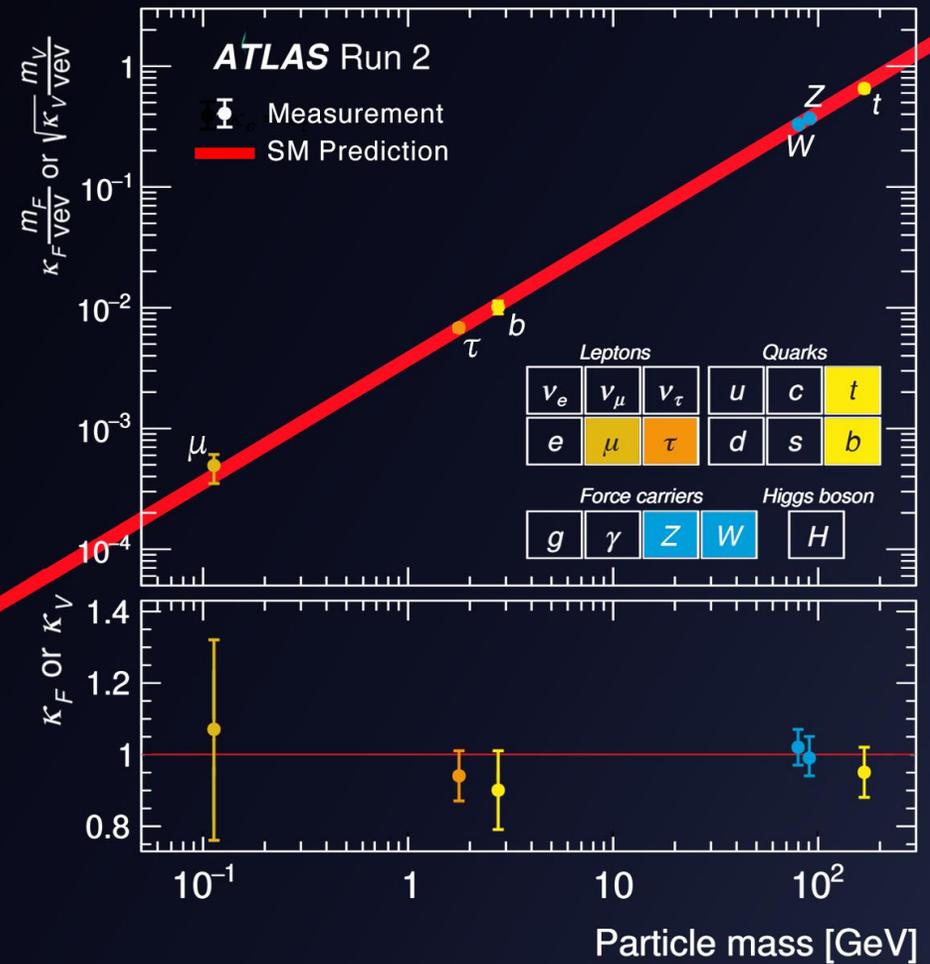
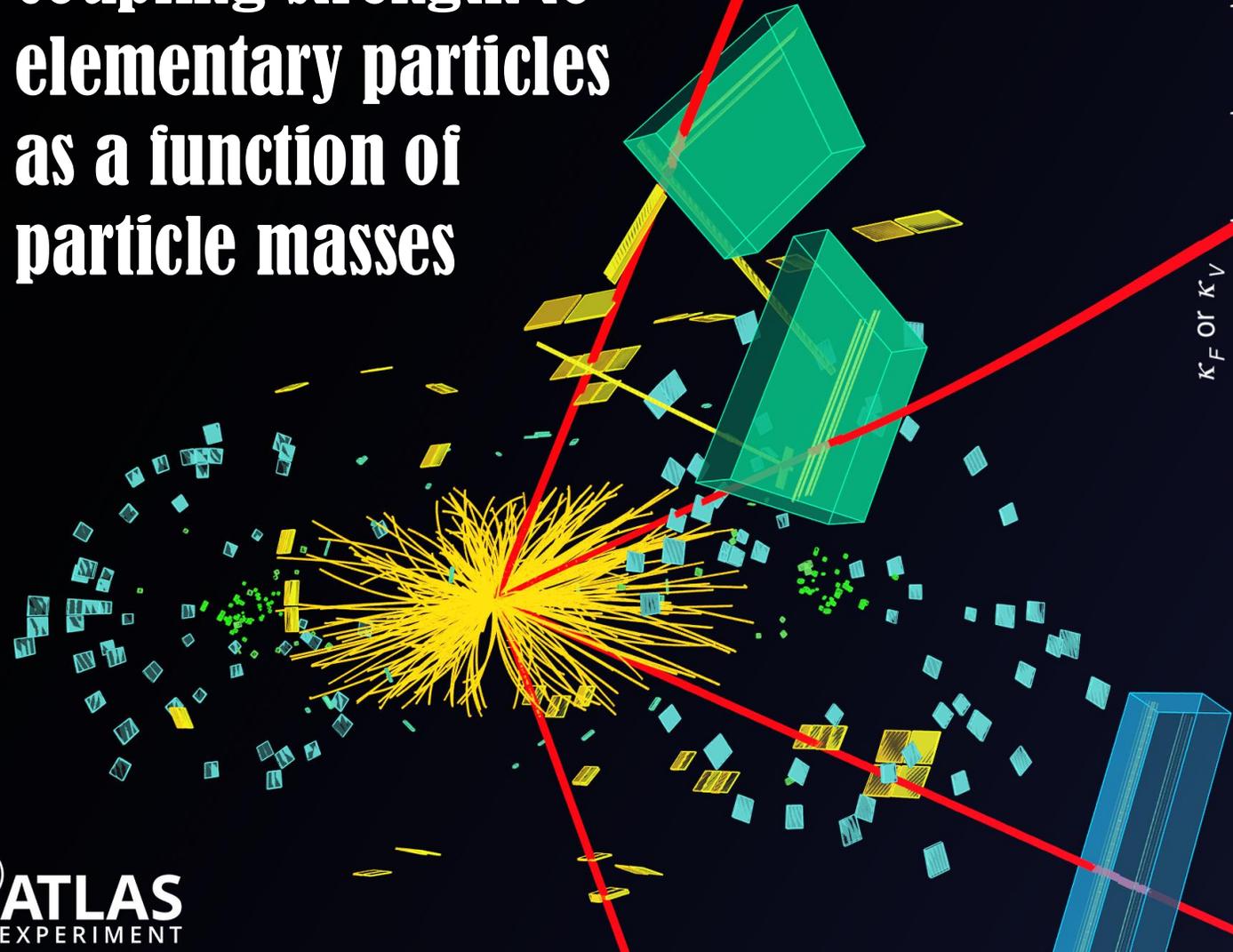
How can the Higgs be further studied?



Not yet observed!
Sensitive to new physics



Measured modifiers of the Higgs boson coupling strength to elementary particles as a function of particle masses



Linear dependence for fermions and square-root for weak bosons. The diagonal red line represents the BEH mechanism's prediction of non-universal, mass-dependent interactions.