

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

Anna Sfyrla



**UNIVERSITÉ
DE GENÈVE**

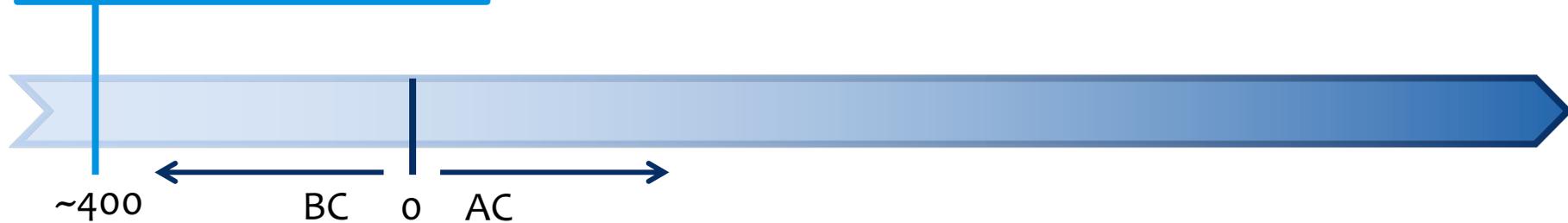
FACULTÉ DES SCIENCES
Section de physique



Matière



Matière



Matière



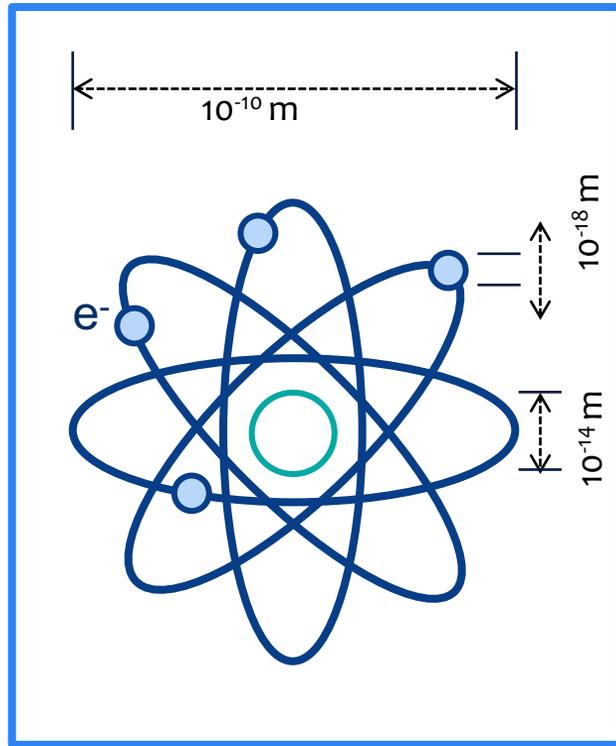
Periodic Table of the Elements

1 1A 11A																	18 VIIIA 8A																														
1 H Hydrogen 1.008	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	2 He Helium 4.003																														
3 Li Lithium 6.941	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																														
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 8	10 VIII 8	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 55.833	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 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80																														
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 222.015																														
87 Fr Francium 223.020	88 Ra Radium 226.025	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 [unknown]	114 Fl Flerovium [289]	115 Uup Ununpentium [unknown]	116 Lv Livermorium [293]	117 Uus Ununseptium [unknown]	118 Uuo Ununoctium [unknown]																														
<table border="1"> <tr> <td>57 La Lanthanum 138.906</td> <td>58 Ce Cerium 140.115</td> <td>59 Pr Praseodymium 140.908</td> <td>60 Nd Neodymium 144.24</td> <td>61 Pm Promethium 144.913</td> <td>62 Sm Samarium 150.36</td> <td>63 Eu Europium 151.966</td> <td>64 Gd Gadolinium 157.25</td> <td>65 Tb Terbium 158.925</td> <td>66 Dy Dysprosium 162.50</td> <td>67 Ho Holmium 164.930</td> <td>68 Er Erbium 167.25</td> <td>69 Tm Thulium 168.934</td> <td>70 Yb Ytterbium 173.04</td> <td>71 Lu Lutetium 174.967</td> </tr> <tr> <td>89 Ac Actinium 227.028</td> <td>90 Th Thorium 232.038</td> <td>91 Pa Protactinium 231.036</td> <td>92 U Uranium 238.029</td> <td>93 Np Neptunium 237.048</td> <td>94 Pu Plutonium 244.064</td> <td>95 Am Americium 243.061</td> <td>96 Cm Curium 247.070</td> <td>97 Bk Berkelium 247.070</td> <td>98 Cf Californium 251.080</td> <td>99 Es Einsteinium [254]</td> <td>100 Fm Fermium 257.095</td> <td>101 Md Mendelevium 258.1</td> <td>102 No Nobelium 259.101</td> <td>103 Lr Lawrencium [262]</td> </tr> </table>																		57 La Lanthanum 138.906	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 167.25	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]
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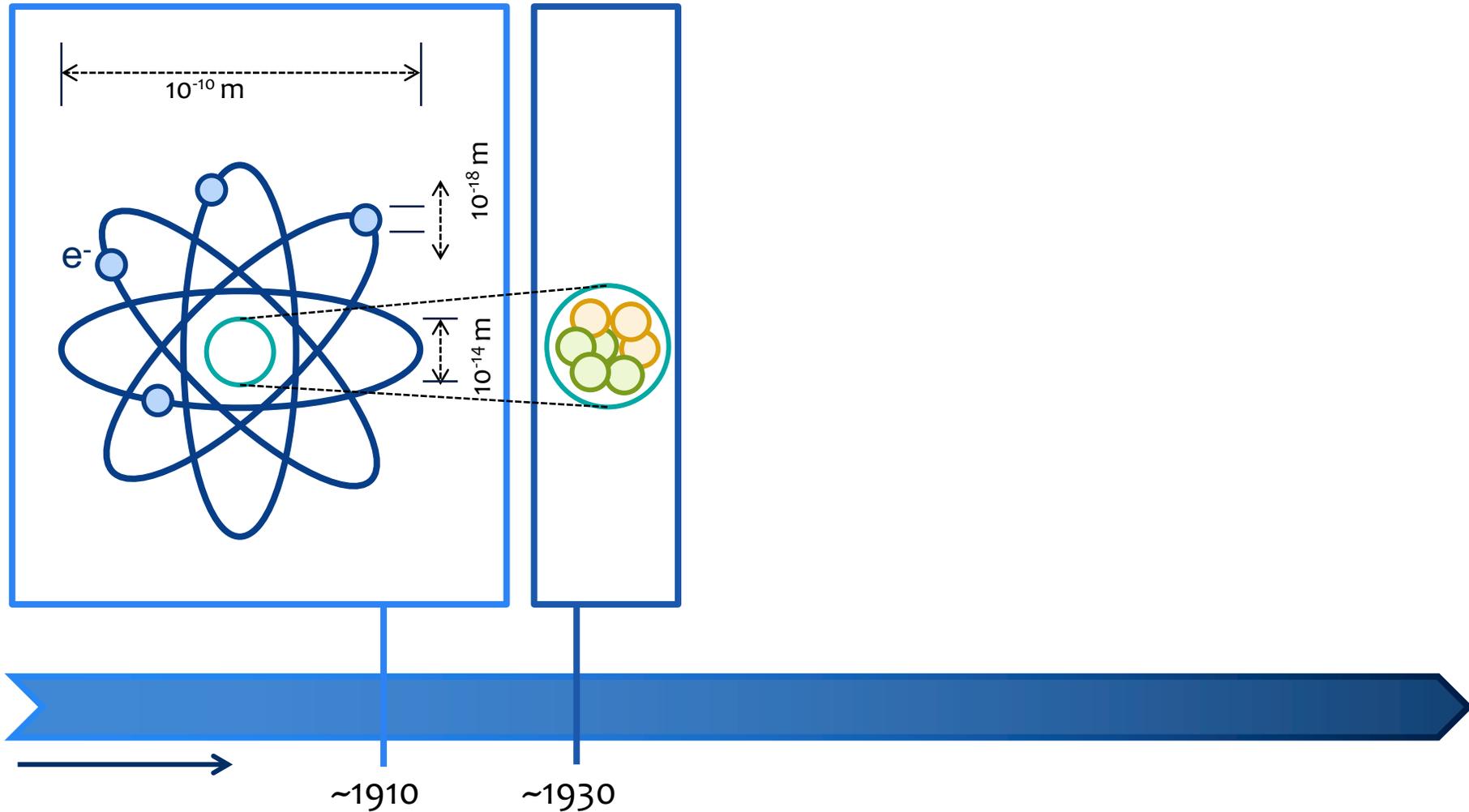
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sciencenotes.org



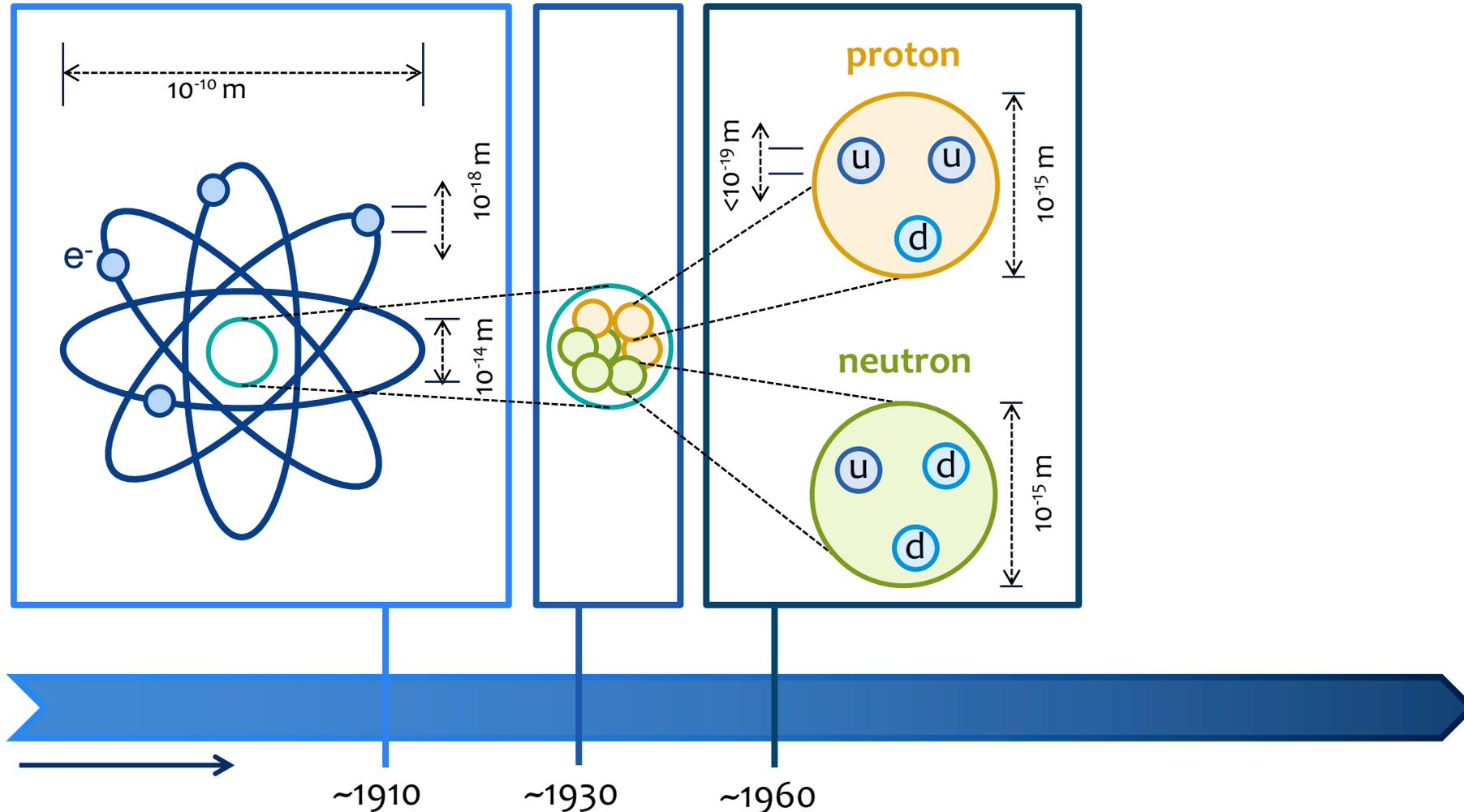
Matière



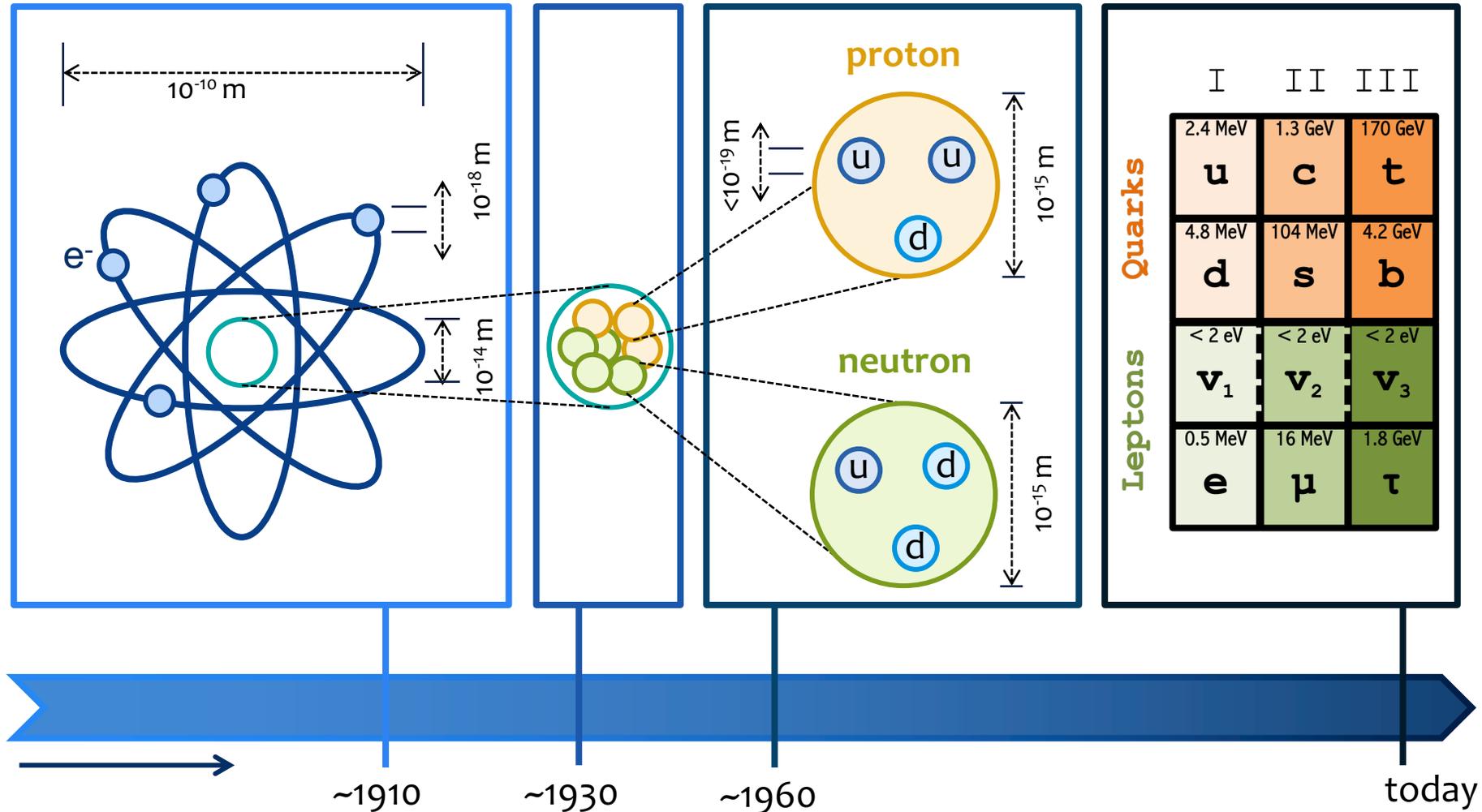
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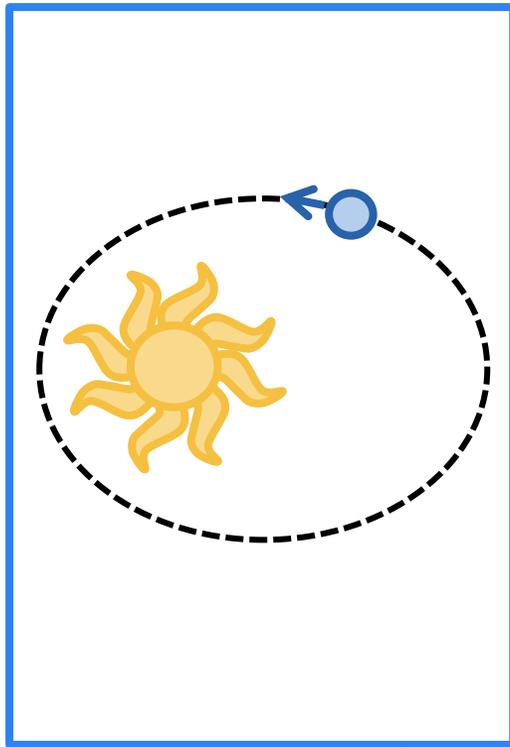
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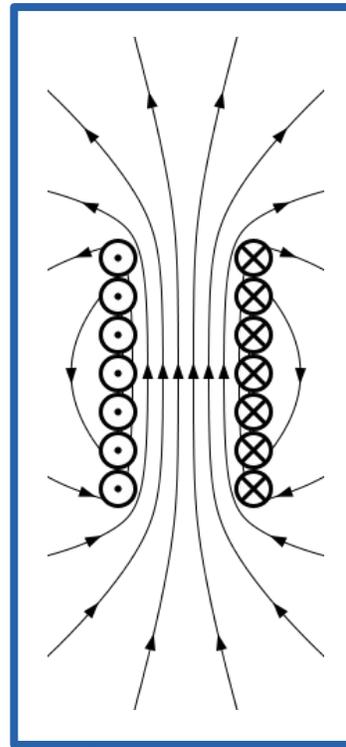
Forces



Forces



~1660

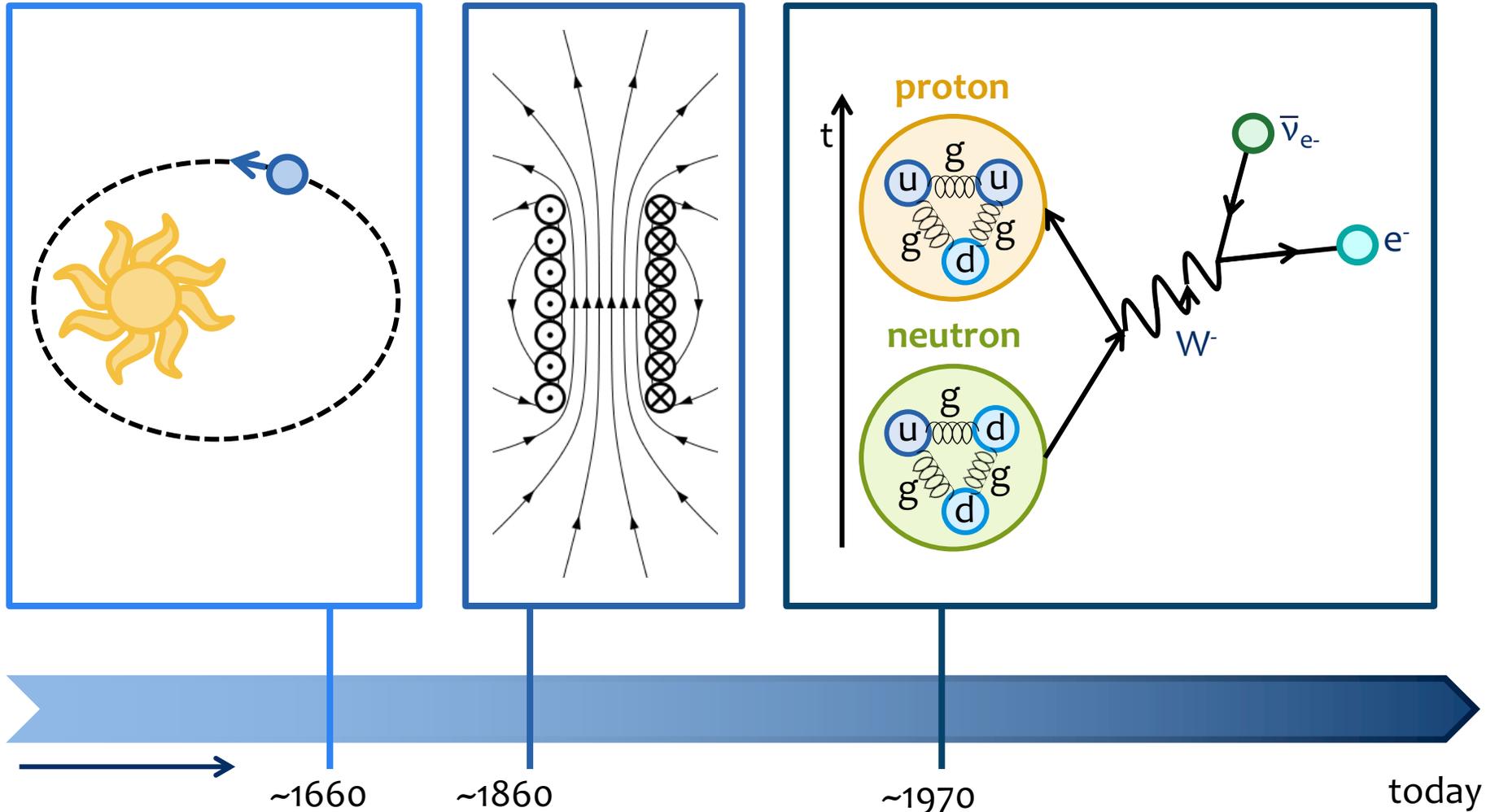


~1860



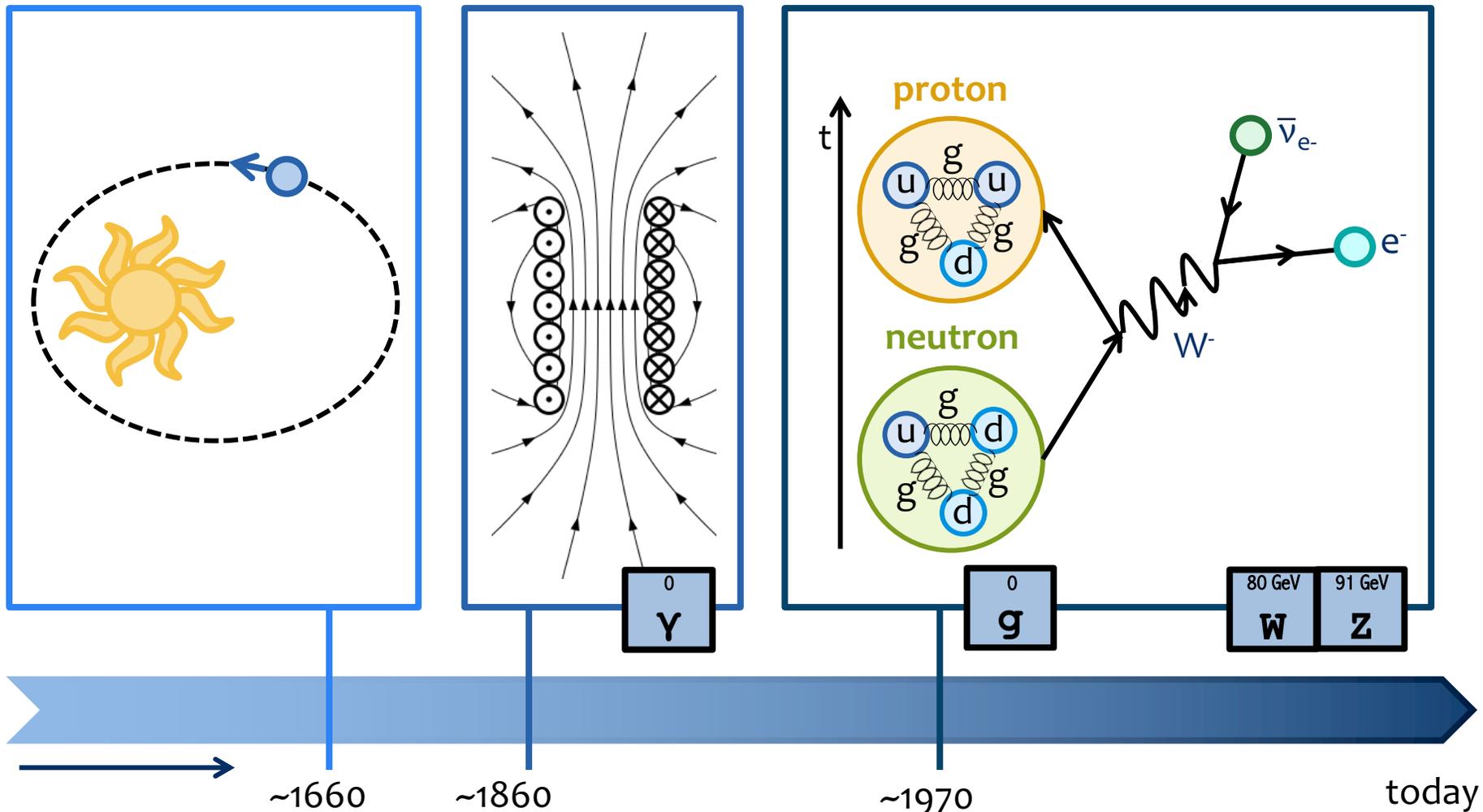
today

Forces

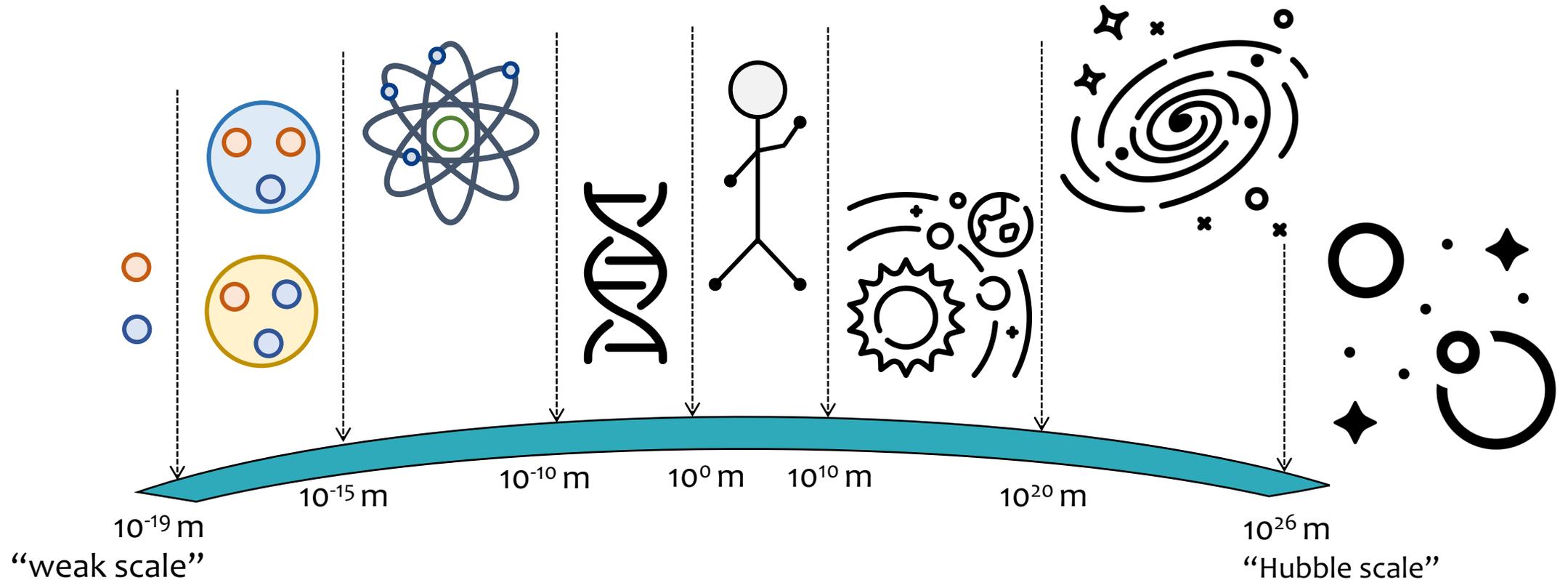


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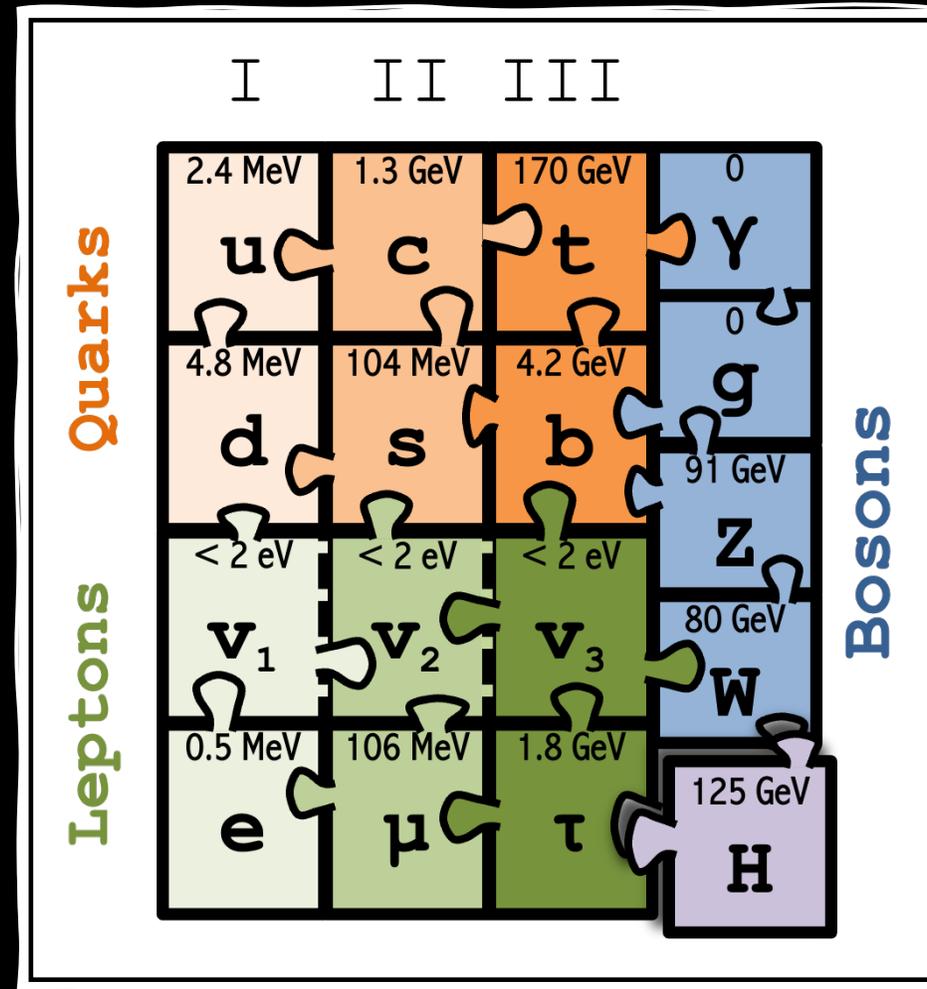
Force carriers: Bosons



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 ?

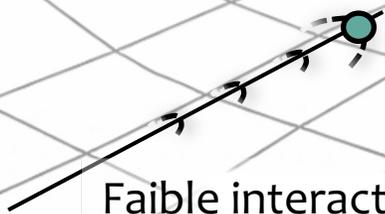
Le **boson de Higgs** = la signature observable du champ de Higgs

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 ?

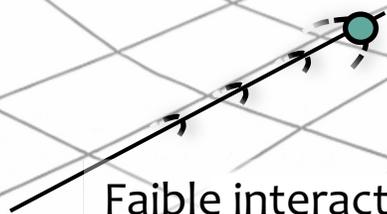
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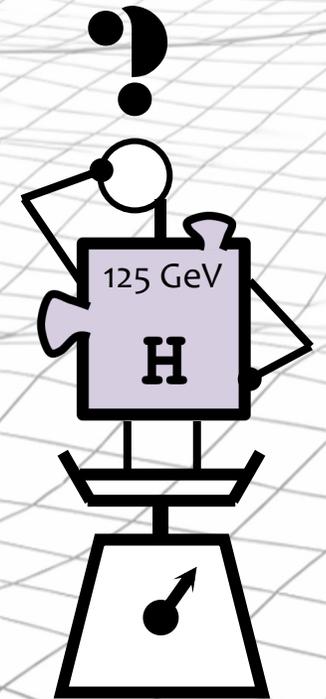
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Faible interaction: petite masse



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...juste une pièce du puzzle cosmique

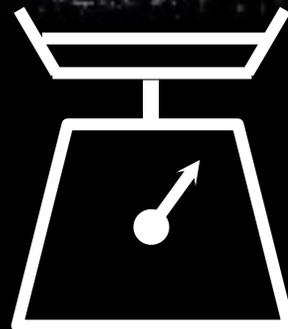
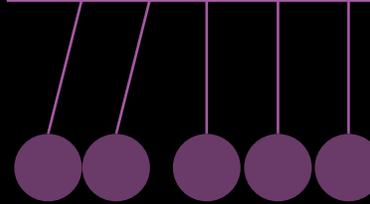
2.4 MeV u	1.3 GeV c	170 GeV t	0 γ
4.8 MeV d	104 MeV s	4.2 GeV b	0 g
<2 eV ν_L	<2 eV ν_M	<2 eV ν_H	91 GeV Z
0.5 MeV e	16 MeV μ	1.8 GeV τ	80 GeV W
			125 GeV H



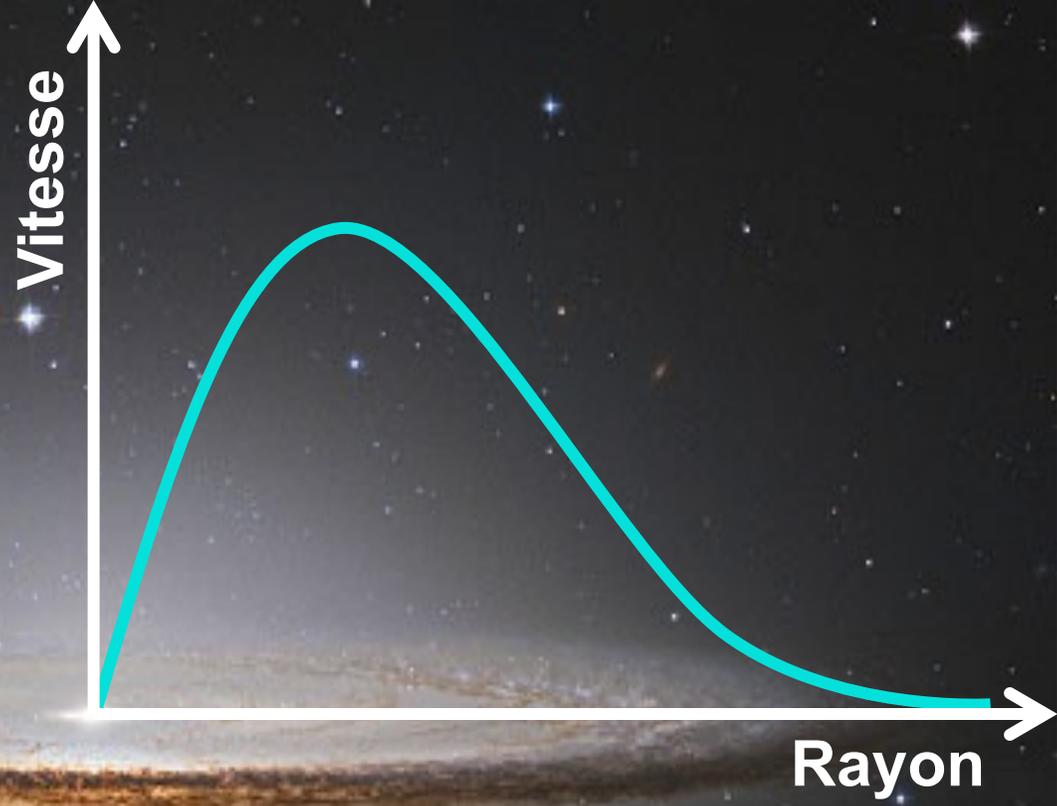
Théorie de la gravitation



Lois du mouvement

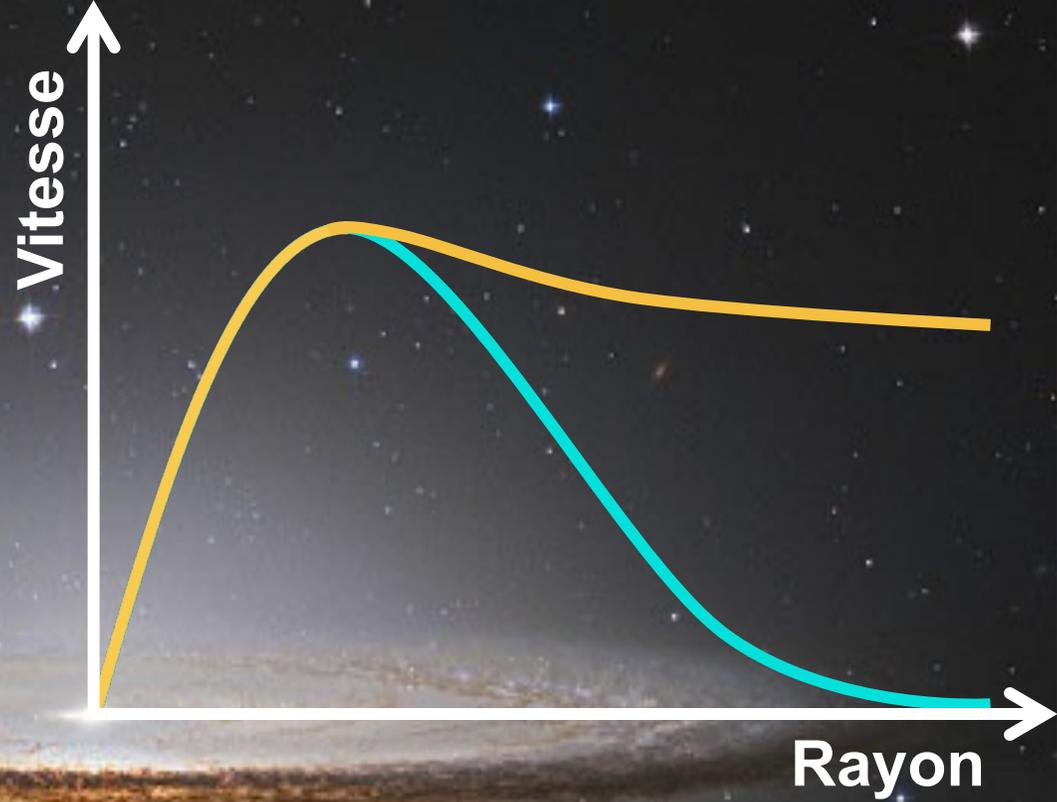


Prédit



Observé

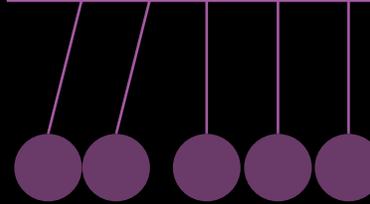
Prédit



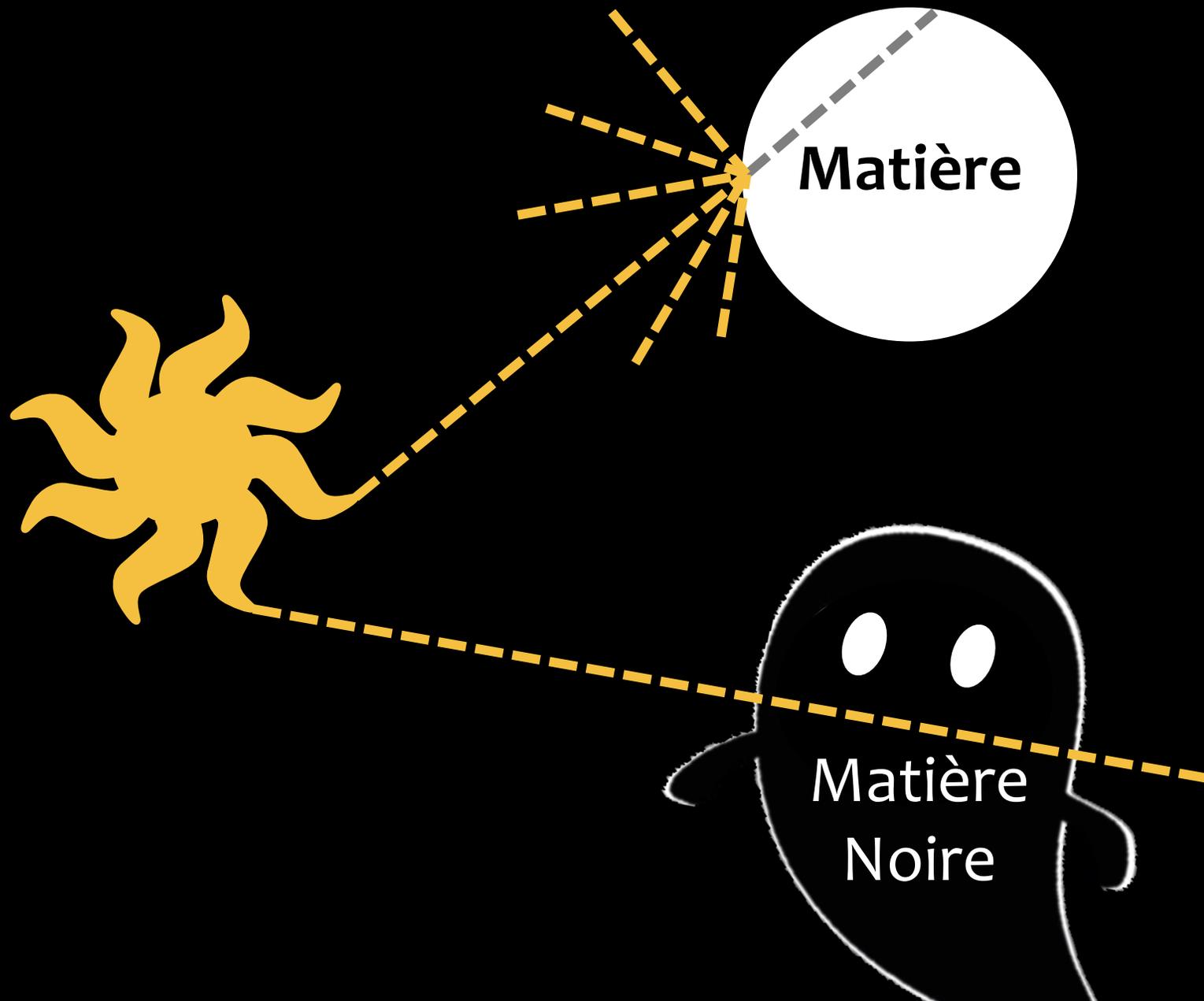
Théorie de la gravitation

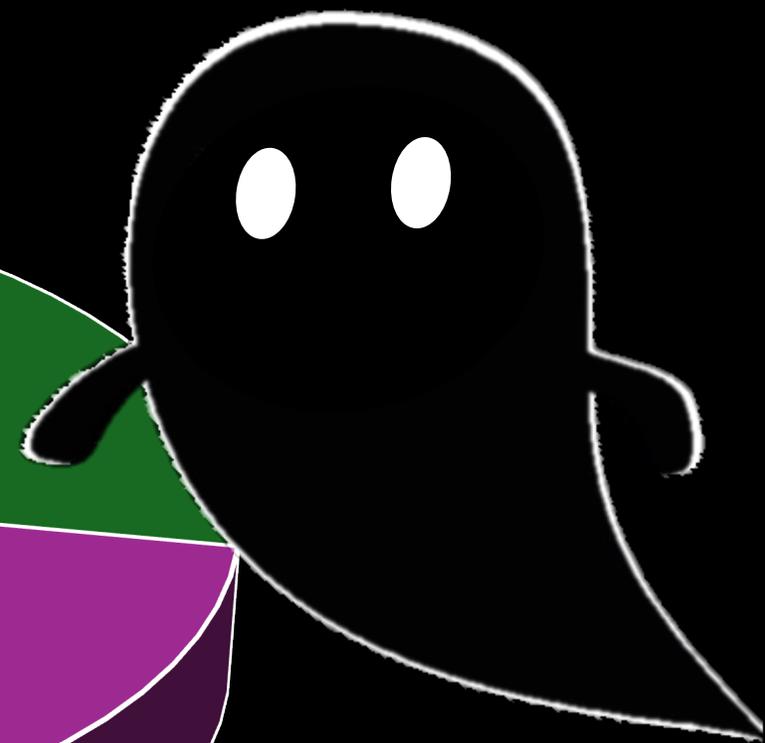
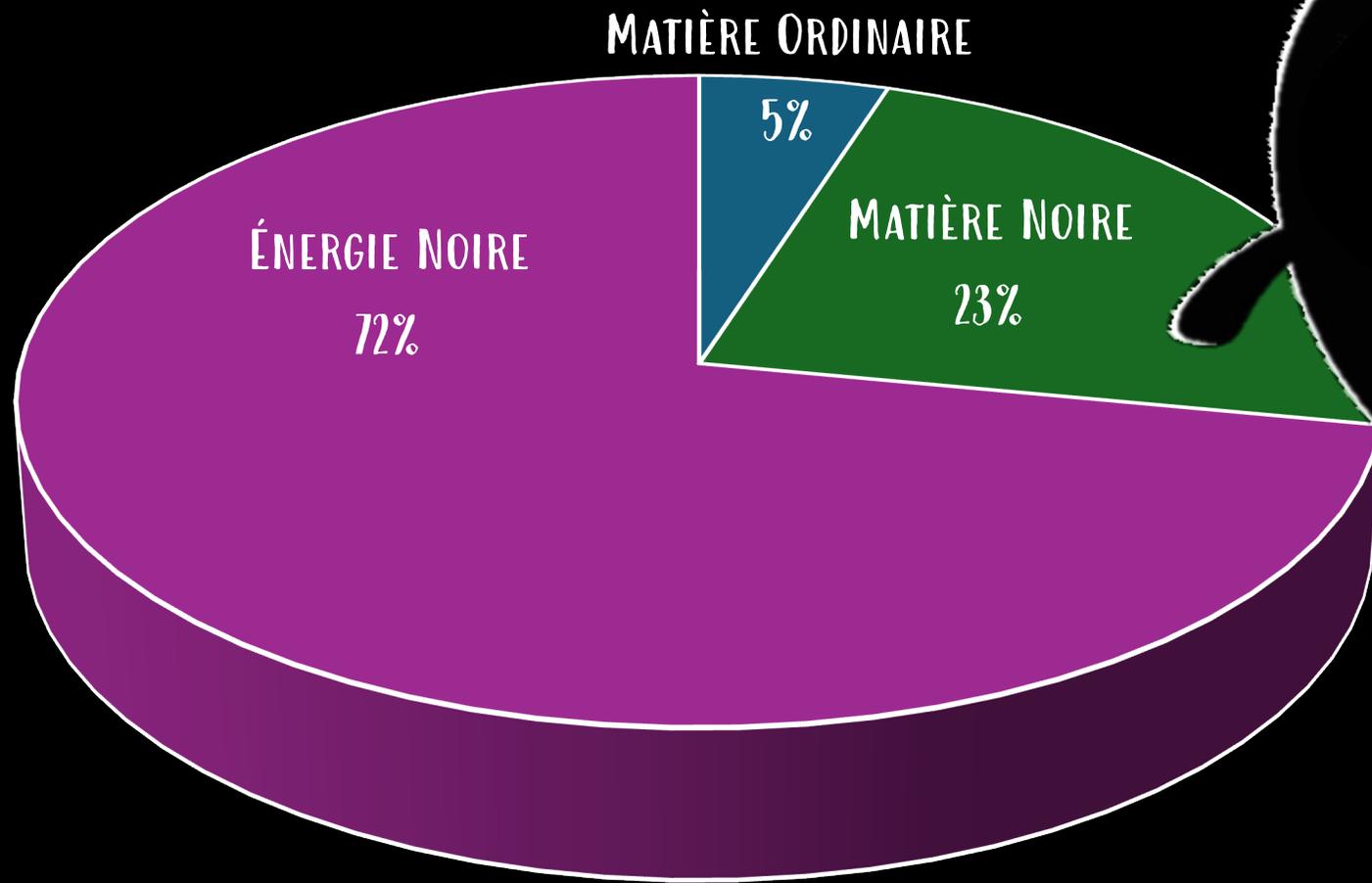


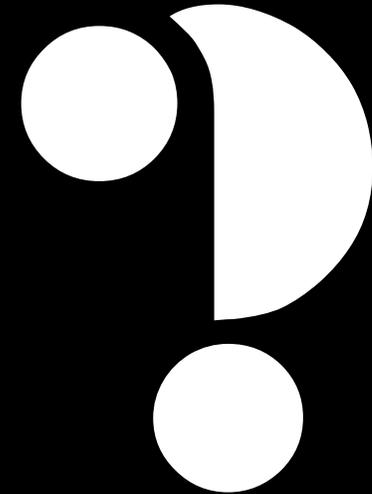
Lois du mouvement

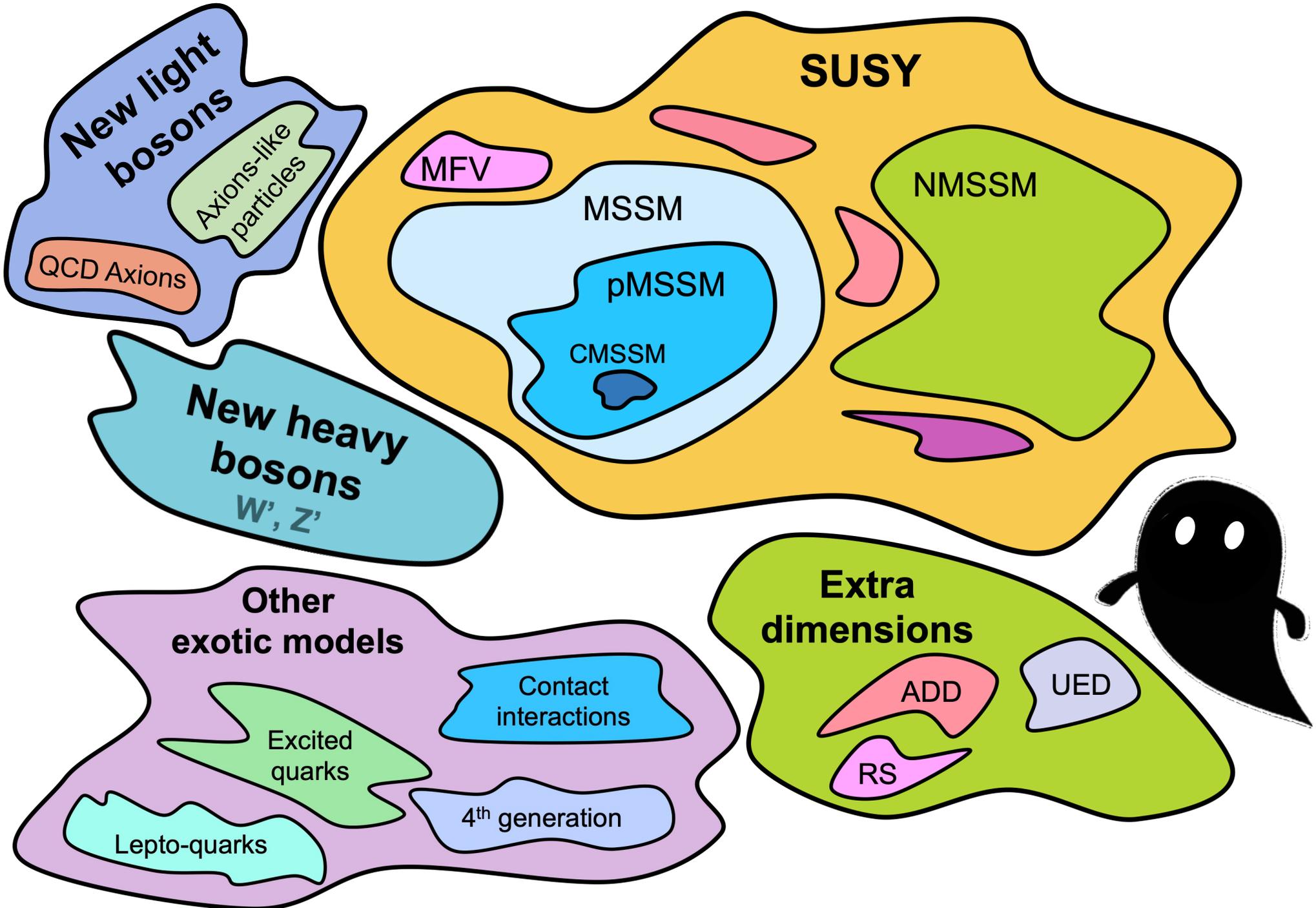


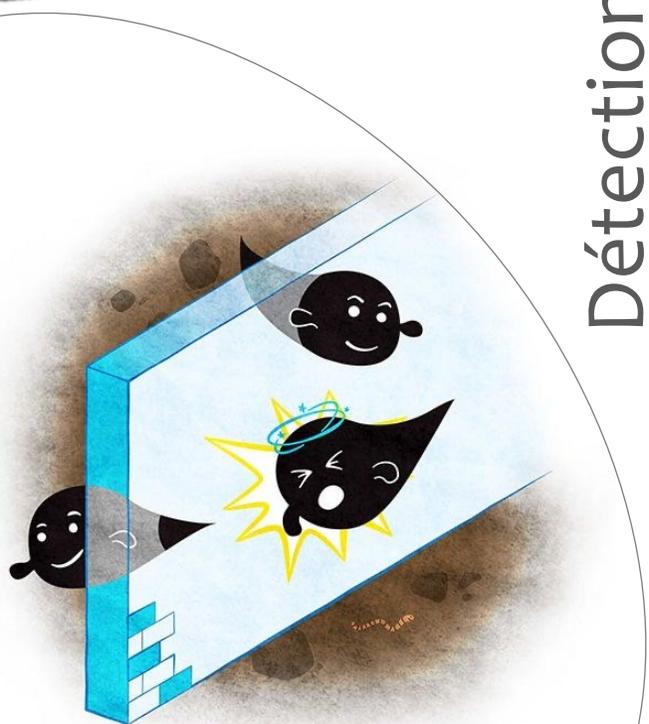










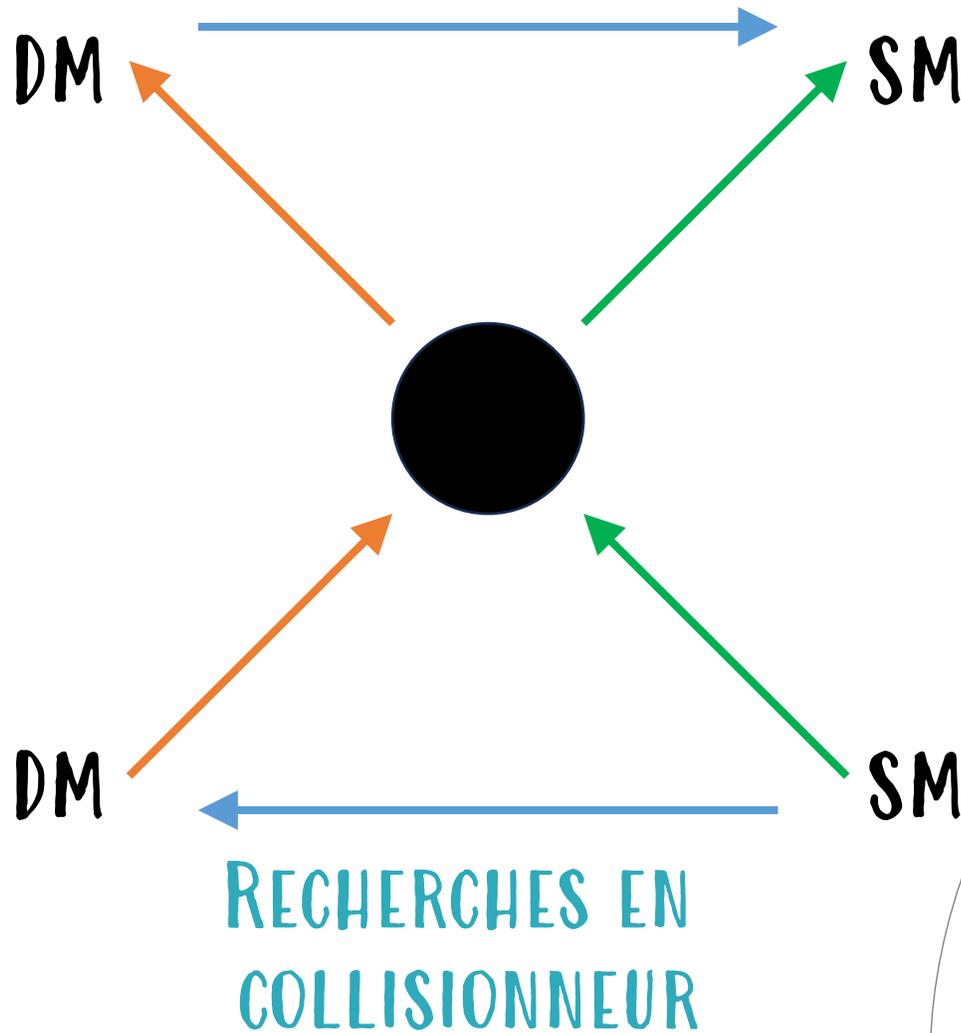


Direct detection

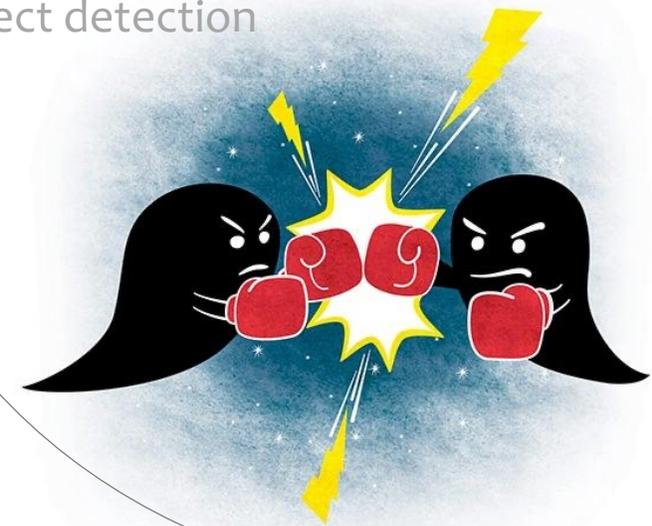
Détection directe

DIFFUSION DM-NOYAU

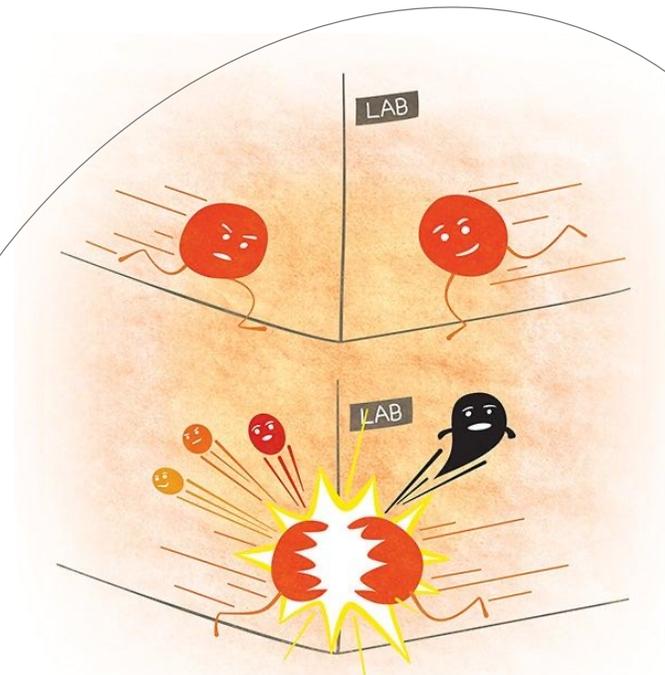
Détection indirecte
ANNIHILATION DE LA DM



Indirect detection

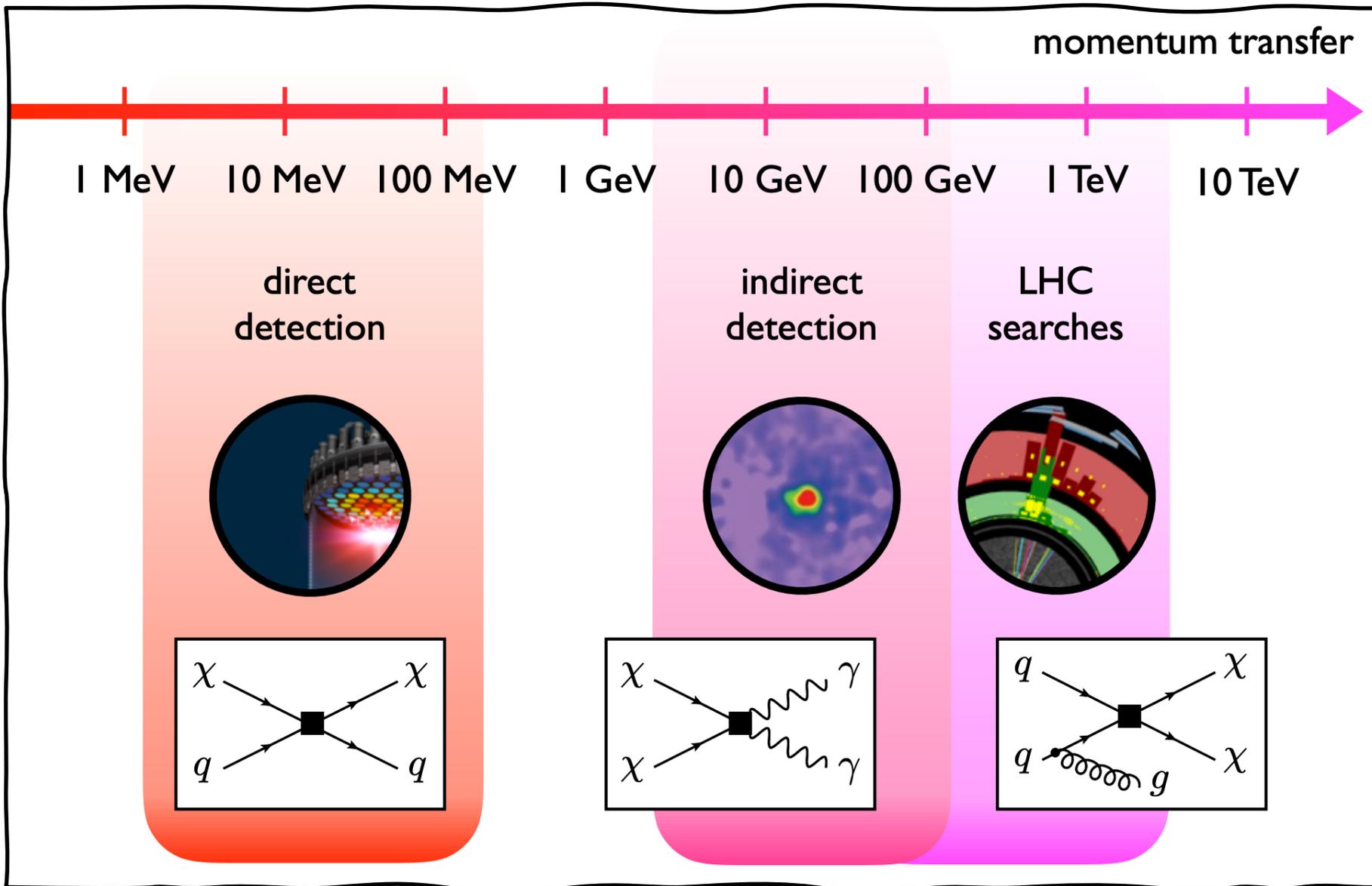


Collider searches



Drawings from

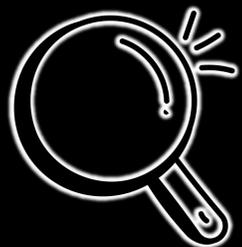
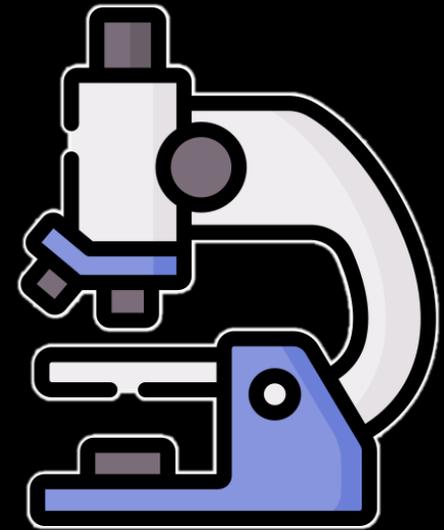
<https://www6.slac.stanford.edu/news/2016-02-08-three-ways-bust-ghostly-dark-matter>



Instruments

Comment “voit-on” les plus petites particules?

- Les **atomes** mesurent environ 10^{-10} mètres
- Les **protons** mesurent environ 10^{-15} mètres
- Les **particules élémentaires** (comme les quarks et les électrons) sont encore plus petites – possiblement ponctuelles, avec des tailles inférieures à 10^{-18} mètres.

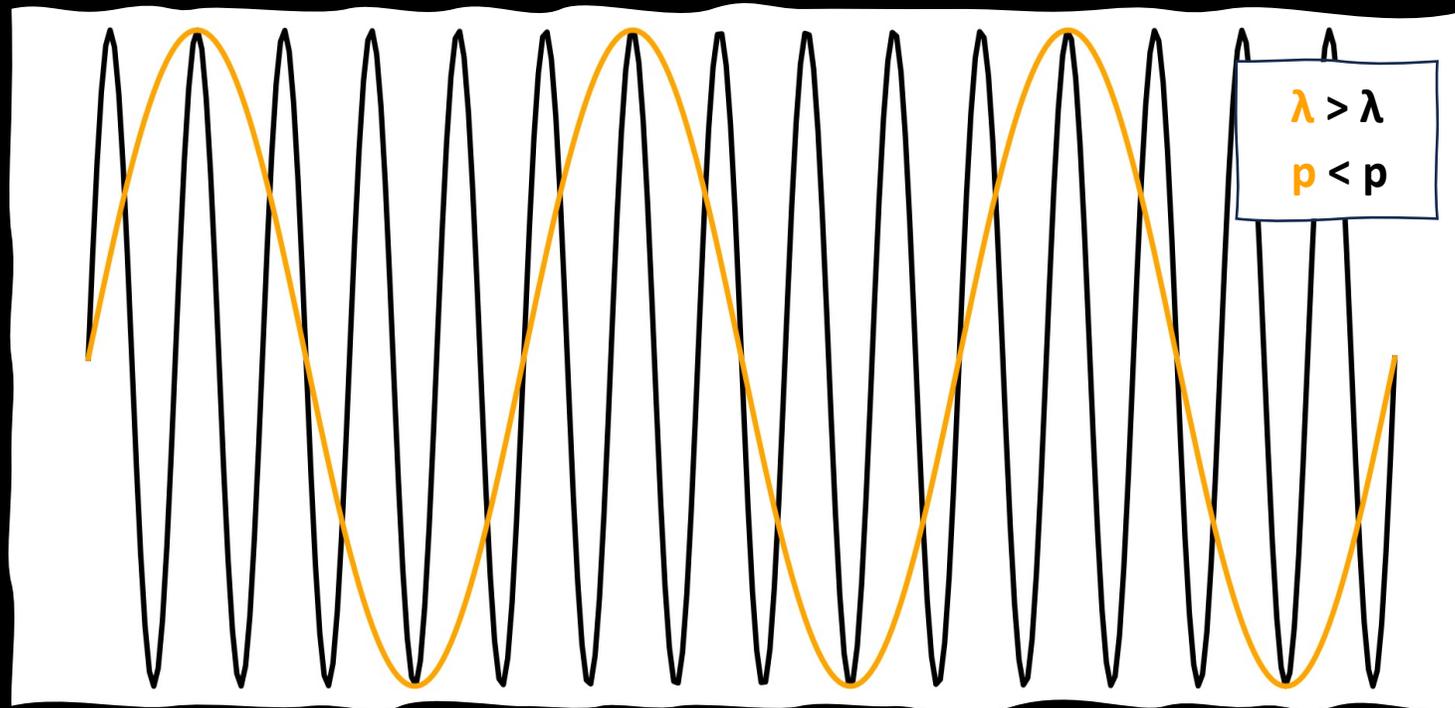


Nous ne les “voyons” pas directement — à la place, nous déduisons leur taille et leur structure grâce à des **collisions de particules à haute énergie** et des **expériences de diffusion**.

Petite distance \Leftrightarrow Haute énergie

Longueur d'onde λ associée à une
particule de quantité de mouvement p :

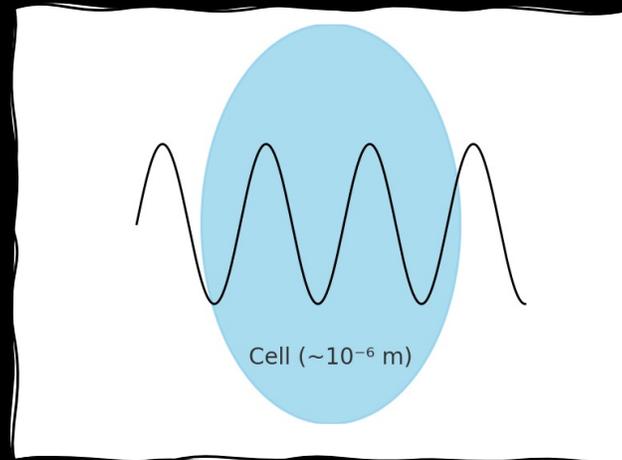
$$\lambda = \frac{\text{constant}}{p}$$



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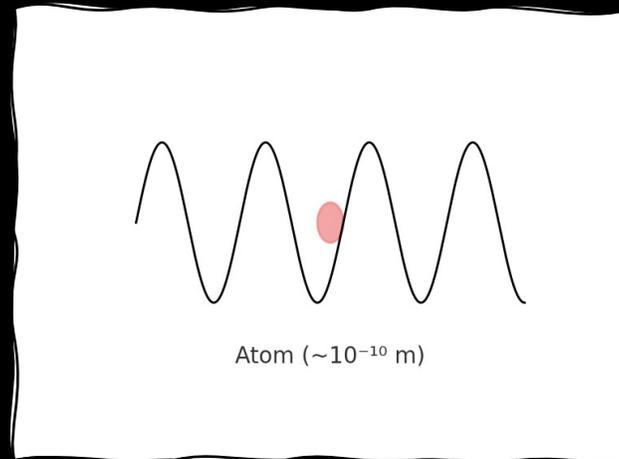
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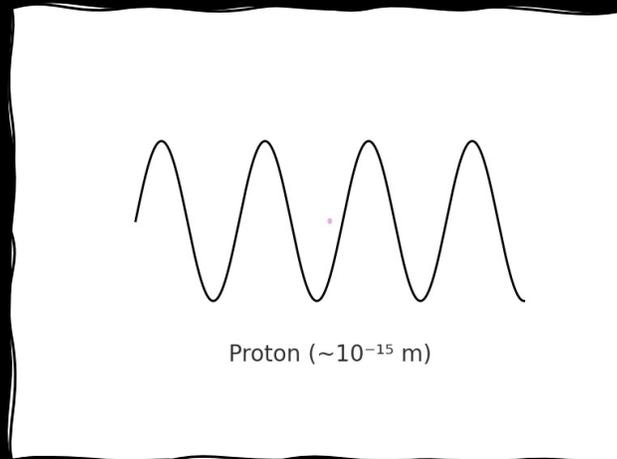
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Petite distance \Leftrightarrow Haute énergie

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Règle générale: On ne peut pas voir des objets plus petits que la longueur d'onde de la sonde que l'on utilise

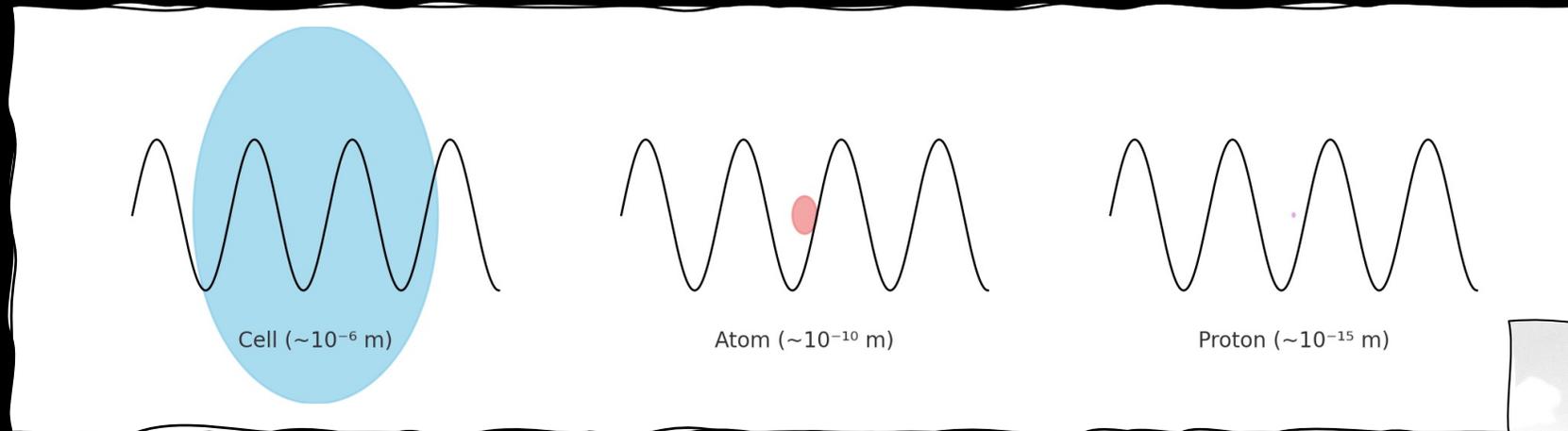
Pour détecter des objets plus petits, il faut des longueurs d'onde plus courtes, ce qui implique une quantité de mouvement et une énergie plus élevées.



Petite distance \Leftrightarrow Haute énergie

Longueur d'onde λ associée à une particule de quantité de mouvement p :

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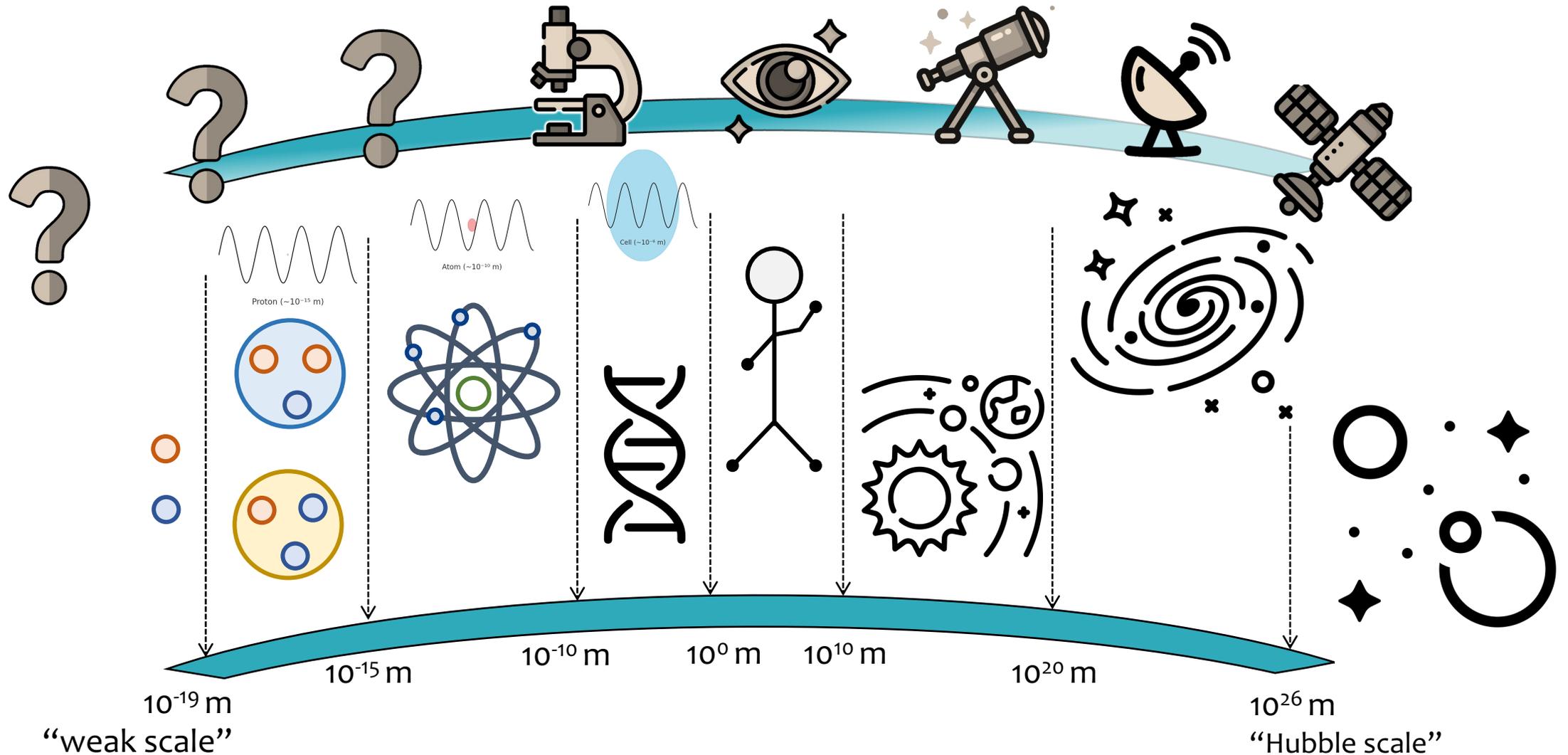


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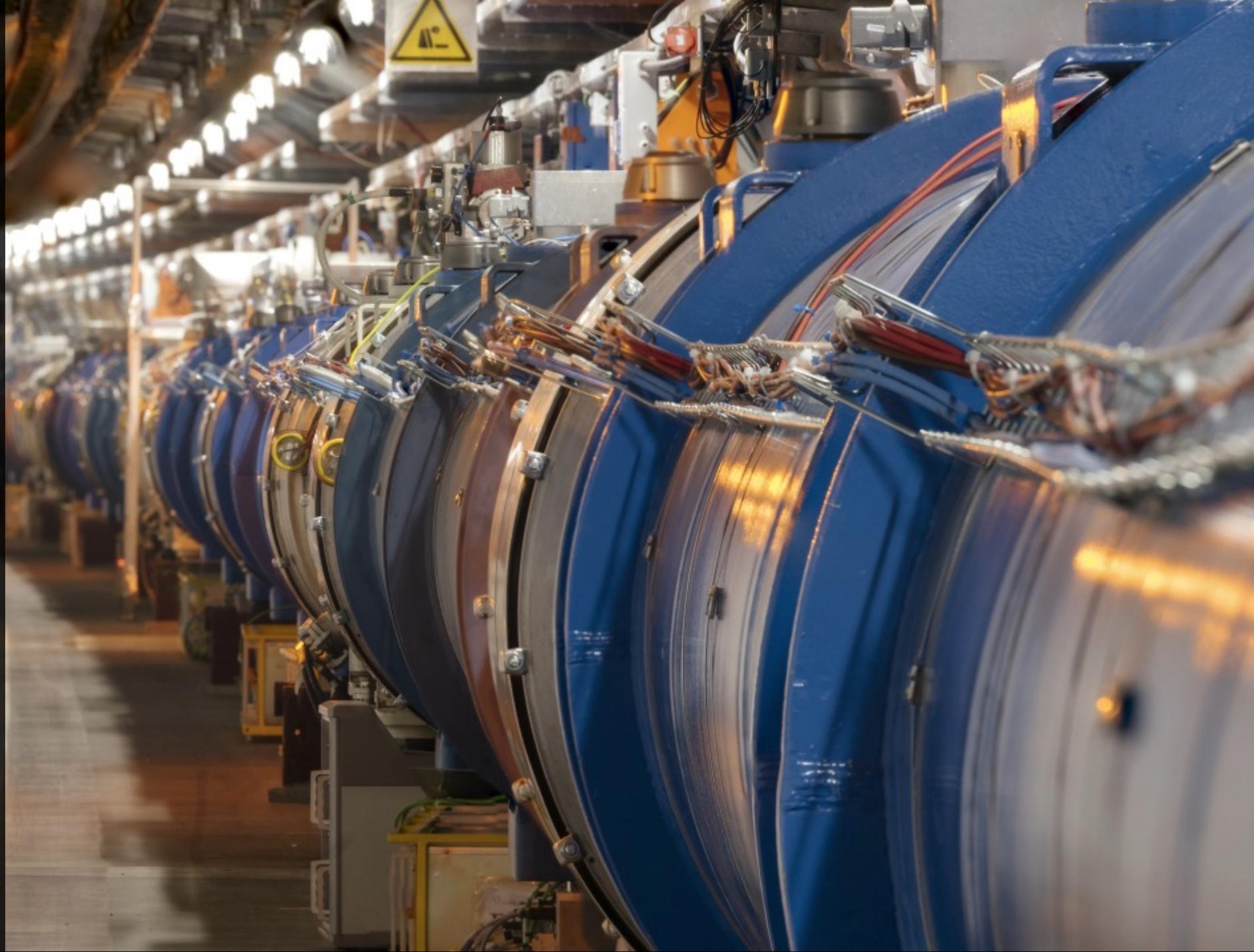


Échelle d'observations

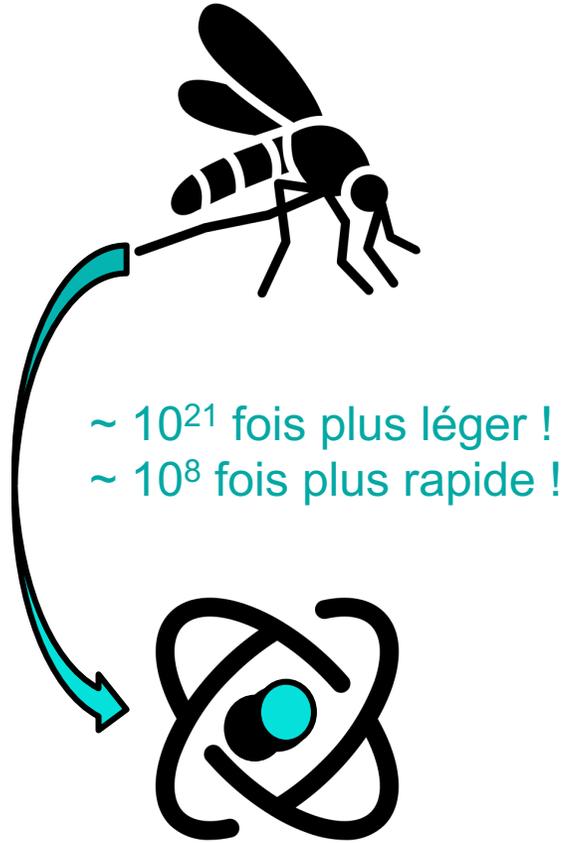


Large Hadron Collider (LHC)

- 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 ?



Energie d'un **moustique** qui vole

masse = 2 mg = 2×10^{-6} kg

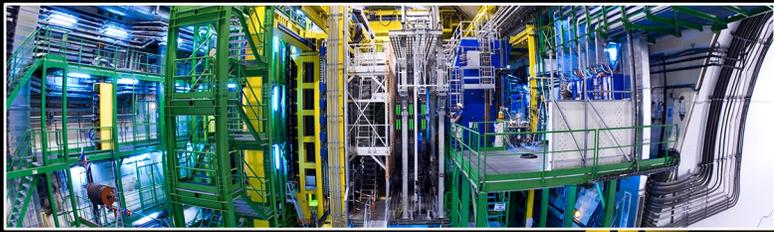
vitesse = 1 m/s

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)



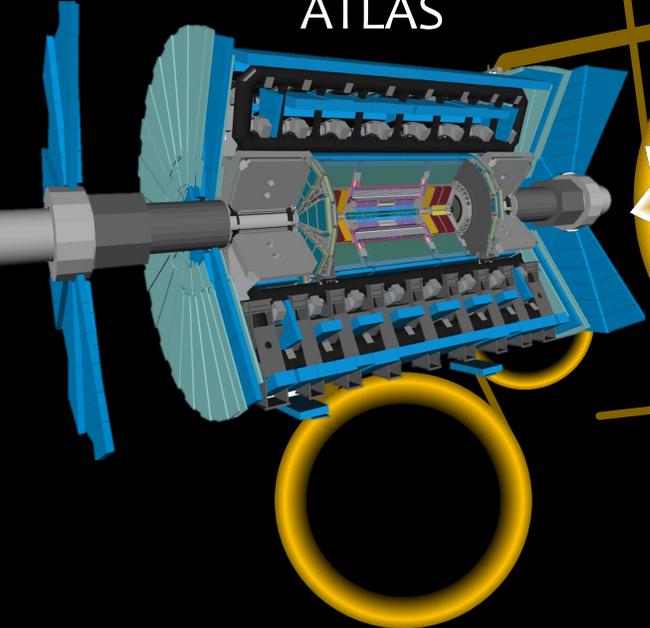
ALICE

PARTICLE BEAMS

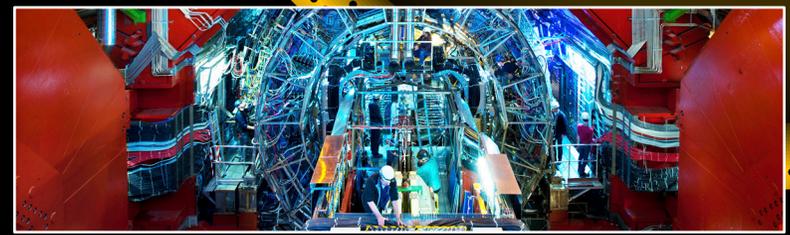
CMS



ATLAS



LHCb



LARGE HADRON COLLIDER

BEAM INJECTION CHAIN



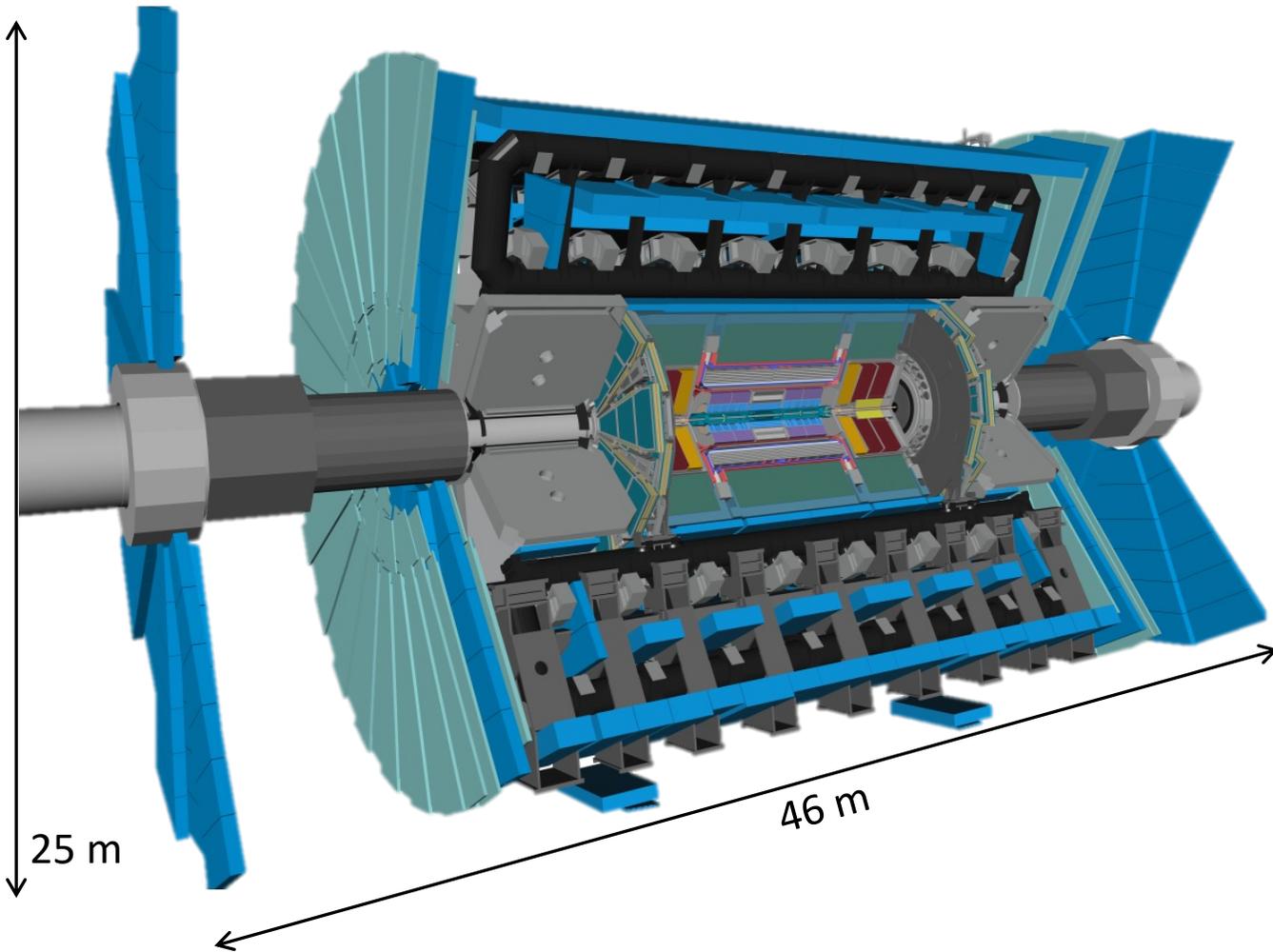


L'expérience ATLAS au LHC



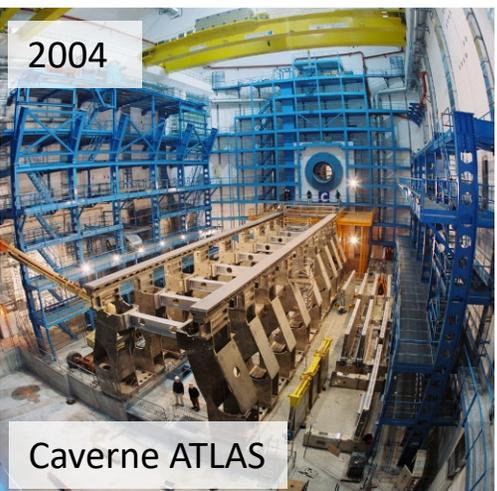


Le détecteur ATLAS en chiffres



- ✓ 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



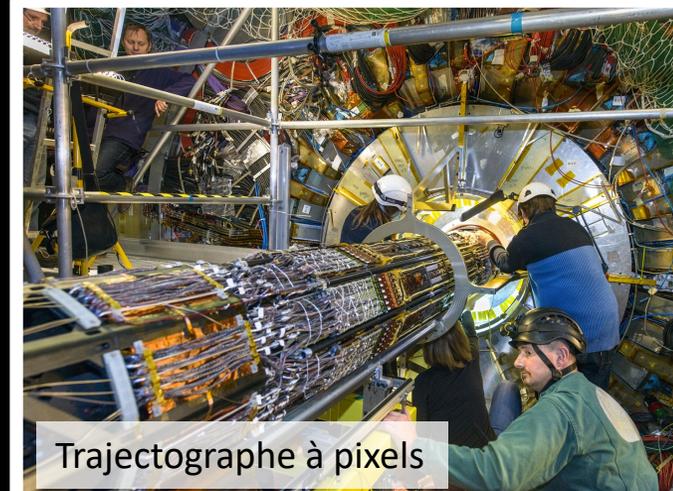
Caverne ATLAS



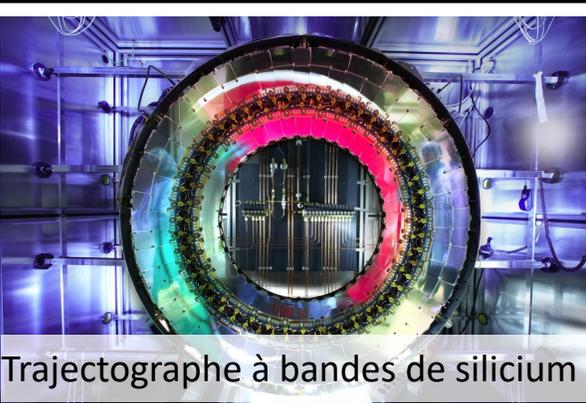
Aimant toroidaux



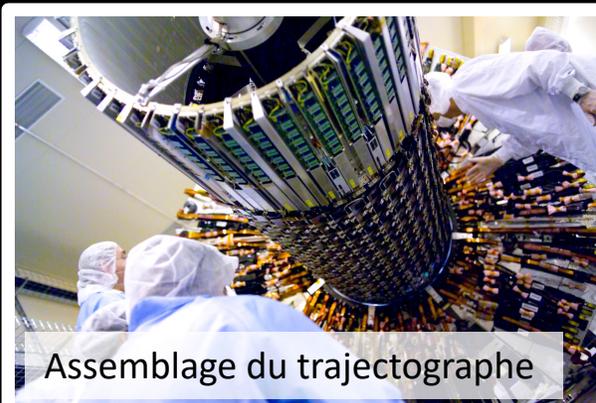
Calorimètre



Trajectographe à pixels

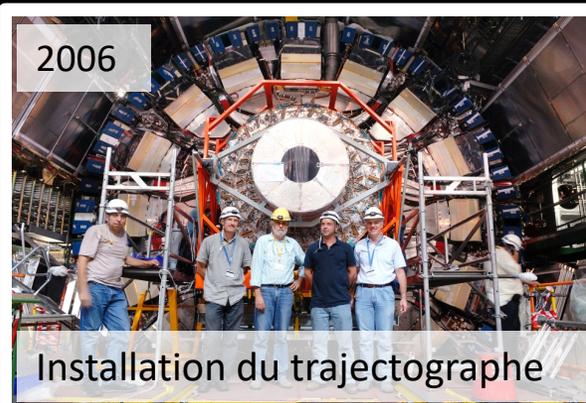


Trajectographe à bandes de silicium



Assemblage du trajectographe

2006



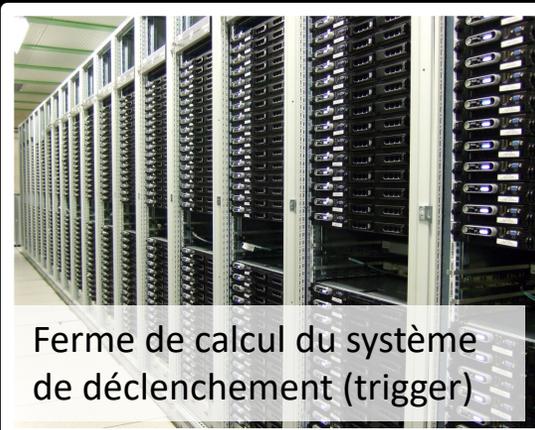
Installation du trajectographe



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



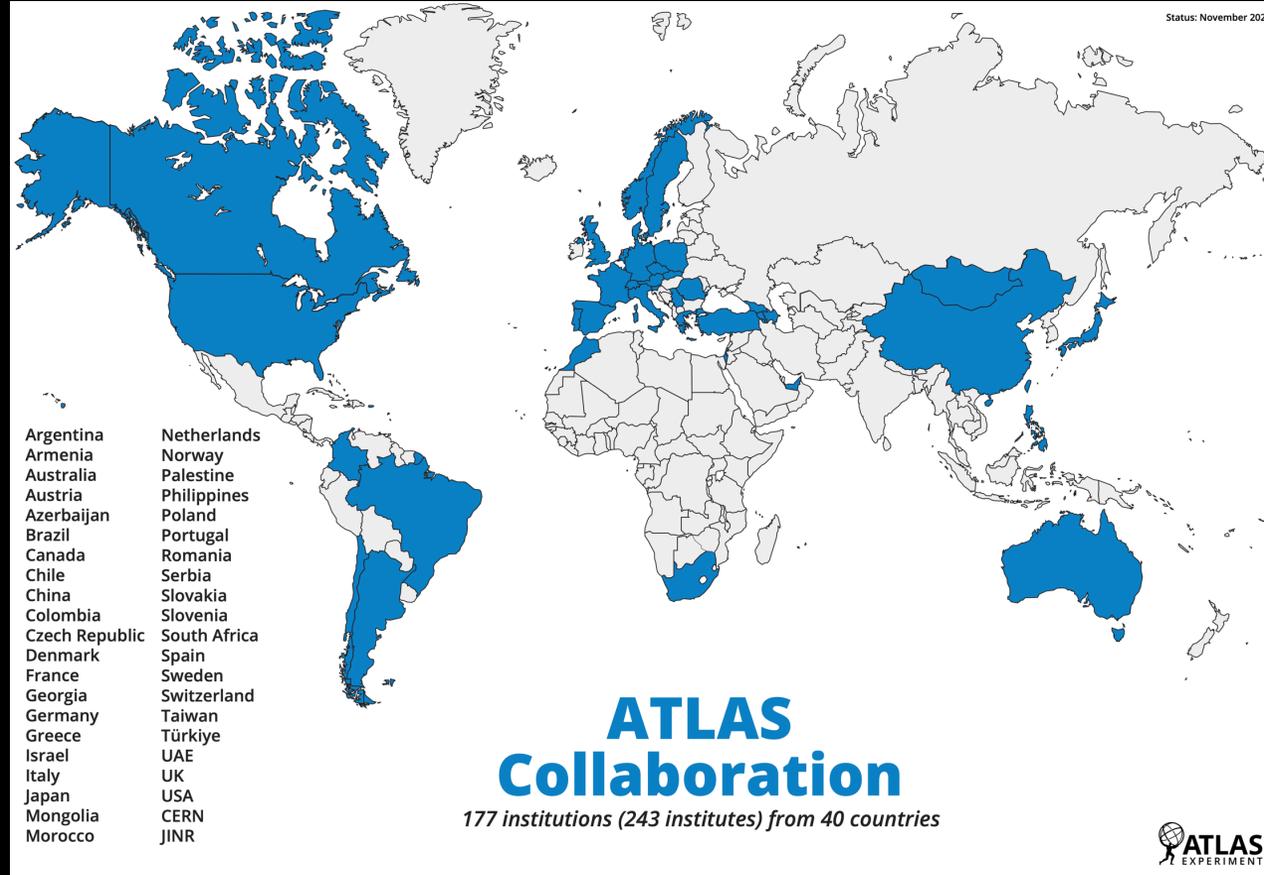
177

Institutions



1200

Doctoral students



La collaboration ATLAS



3000

Scientific authors



40

Countries



177

Institutions

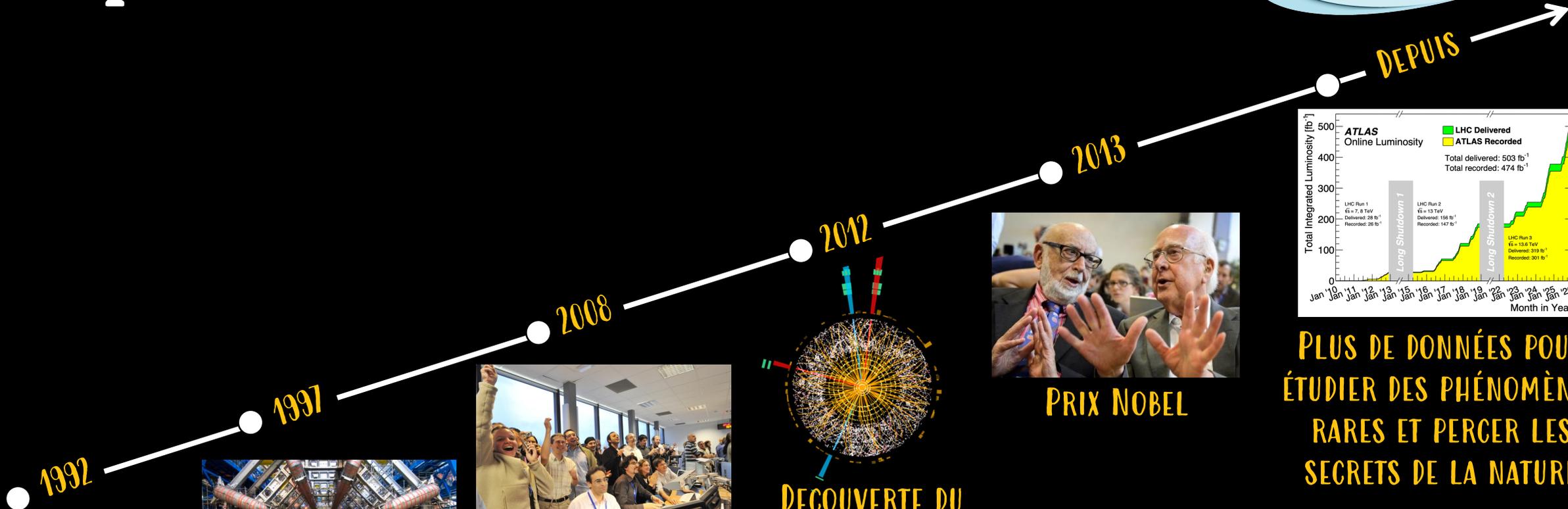


1200

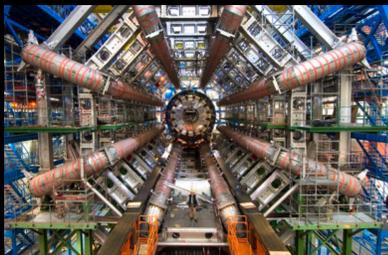
Doctoral students



Un peu d'histoire ...



**SOUSSION DE
LETTRE D'INTERÊT**



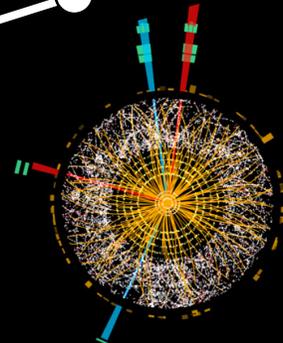
**APPROBATION DE
L' EXPERIENCE**

1997



**PREMIÈRES DONNÉES
DU LHC À ATLAS**

2008



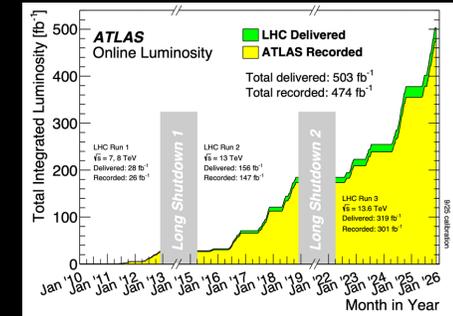
**DECOUVERTE DU
BOSON DE HIGGS**

2012



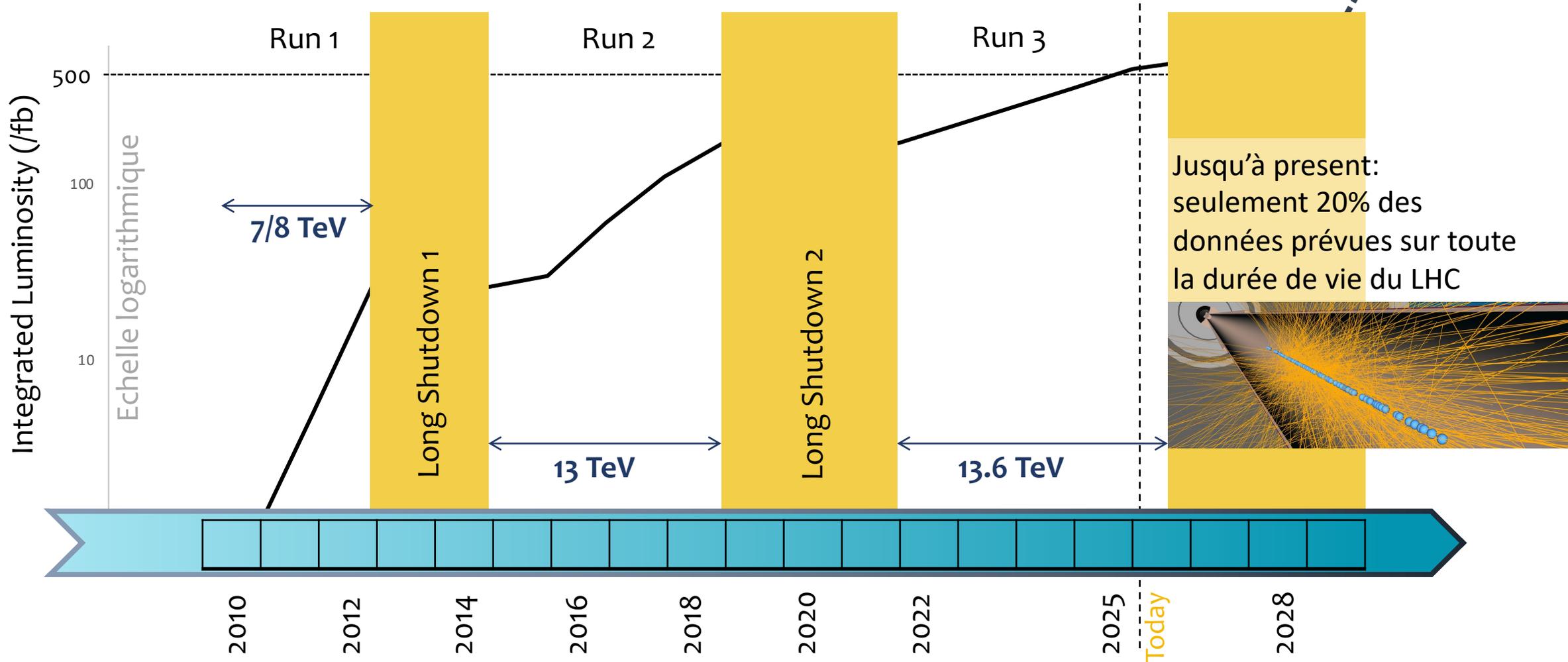
PRIX NOBEL

2013

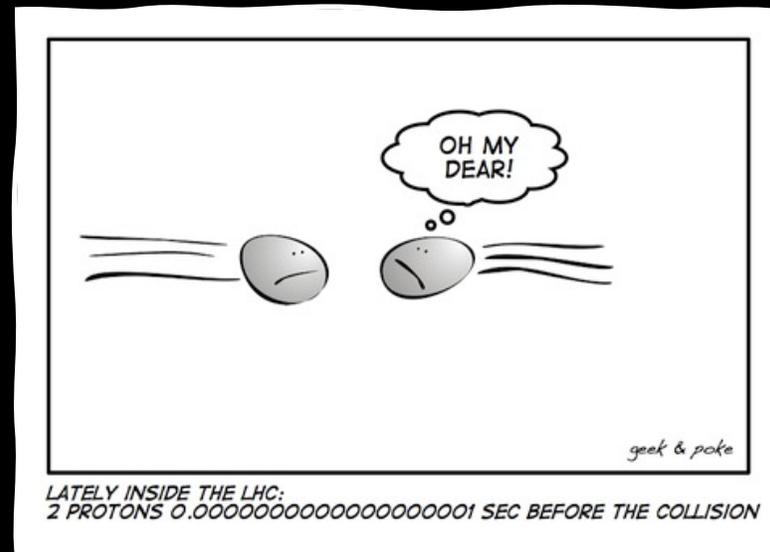


**PLUS DE DONNÉES POUR
ÉTUDIER DES PHÉNOMÈNES
RARES ET PERCER LES
SECRETS DE LA NATURE**

Run 1, Run 2, Run 3 et au-delà

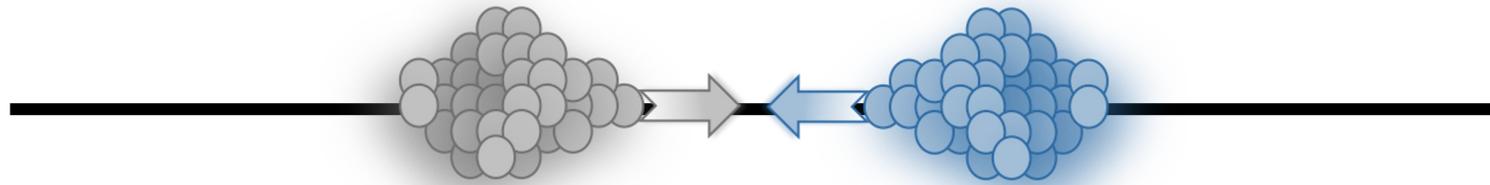


Dans une collision proton-proton



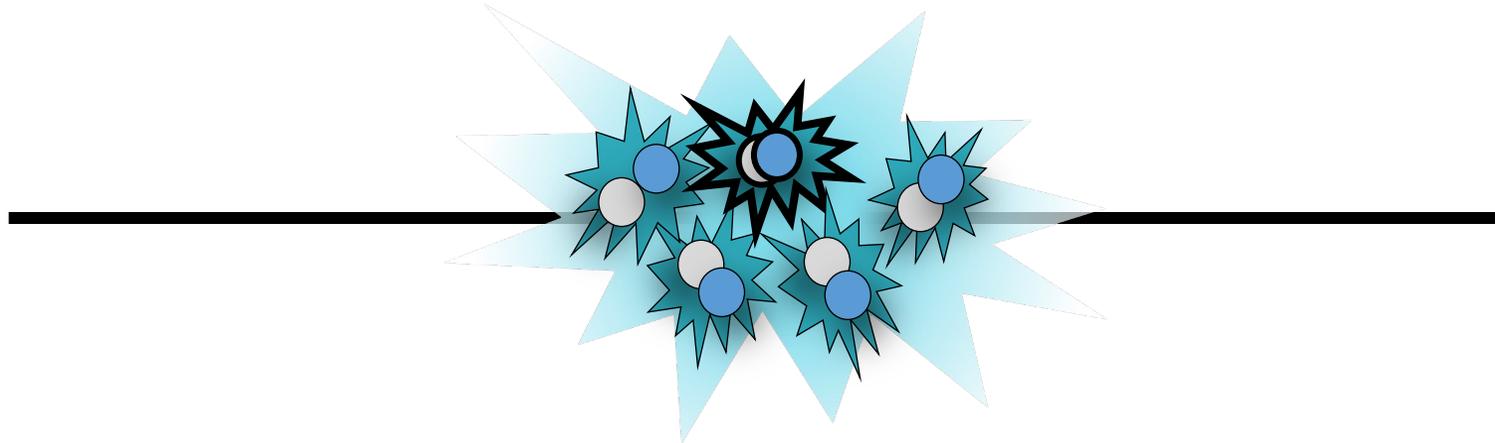


La collision proton-proton



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

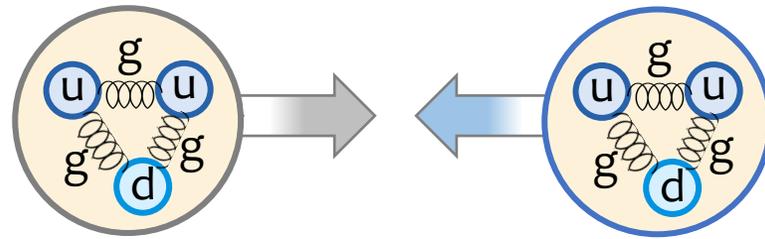
La collision proton-proton



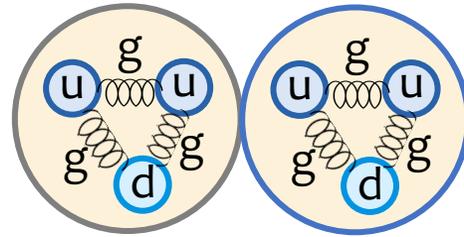
$\sim 1.8 \times 10^{11}$ protons par paquet
Espacement entre paquets: 25 ns

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

La collision proton-proton

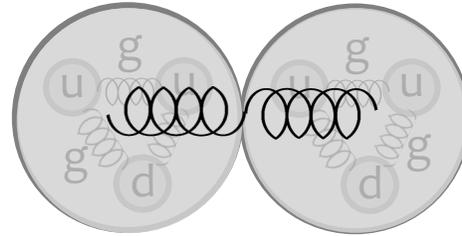


La collision proton-proton

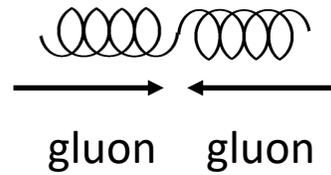


La collision proton-proton

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

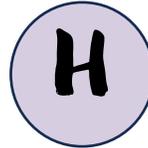


La collision proton-proton



La collision proton-proton

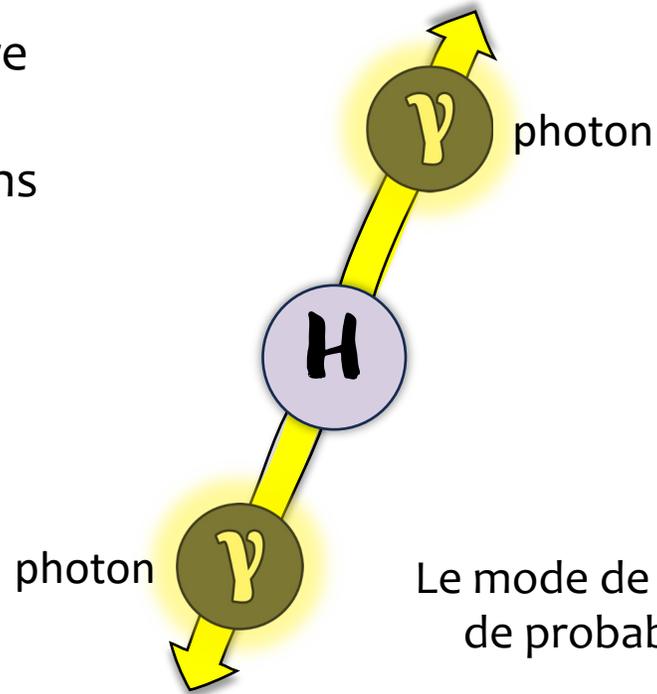
L'interaction parton-parton conduit à la production de particules
Par exemple ici: le boson de Higgs



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

La collision proton-proton

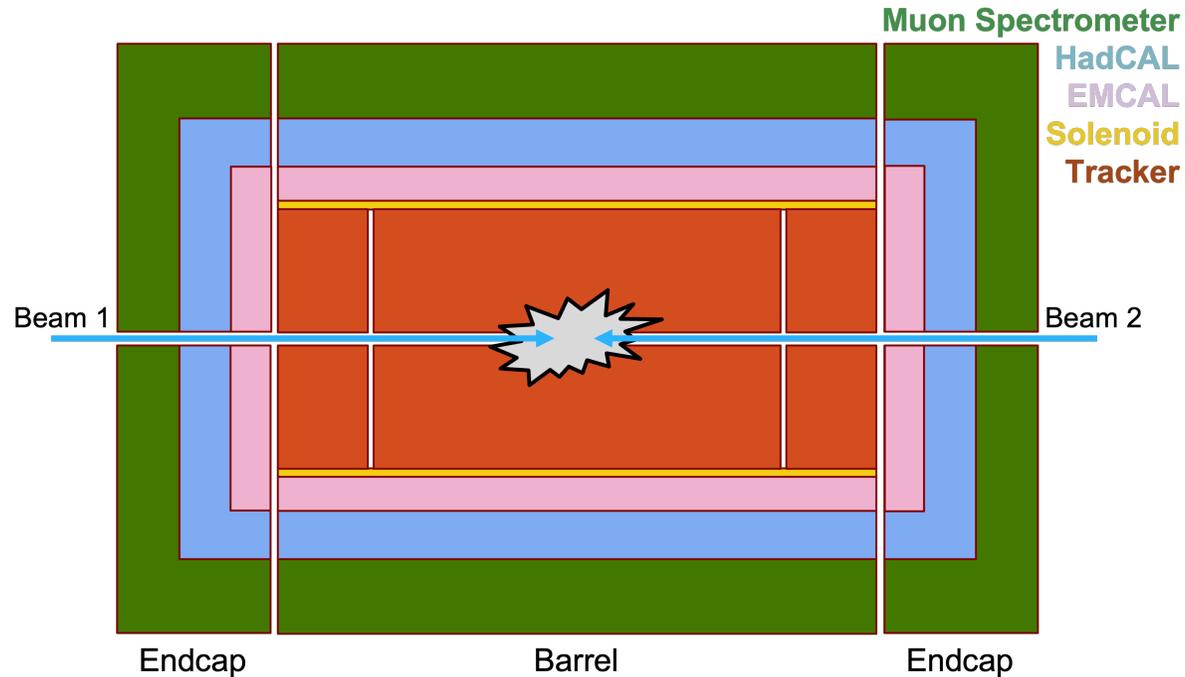
Le boson de Higgs se désintègre
presque instantanément
Par exemple ici: en deux photons



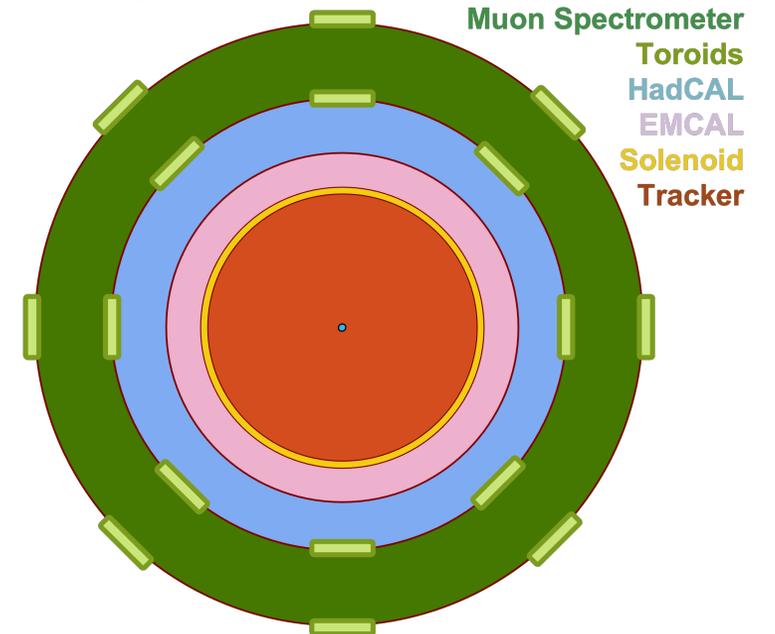
Le mode de désintégration de chaque particule dépend
de probabilités calculables dans le cadre théorique

Détecteurs à usage général au LHC

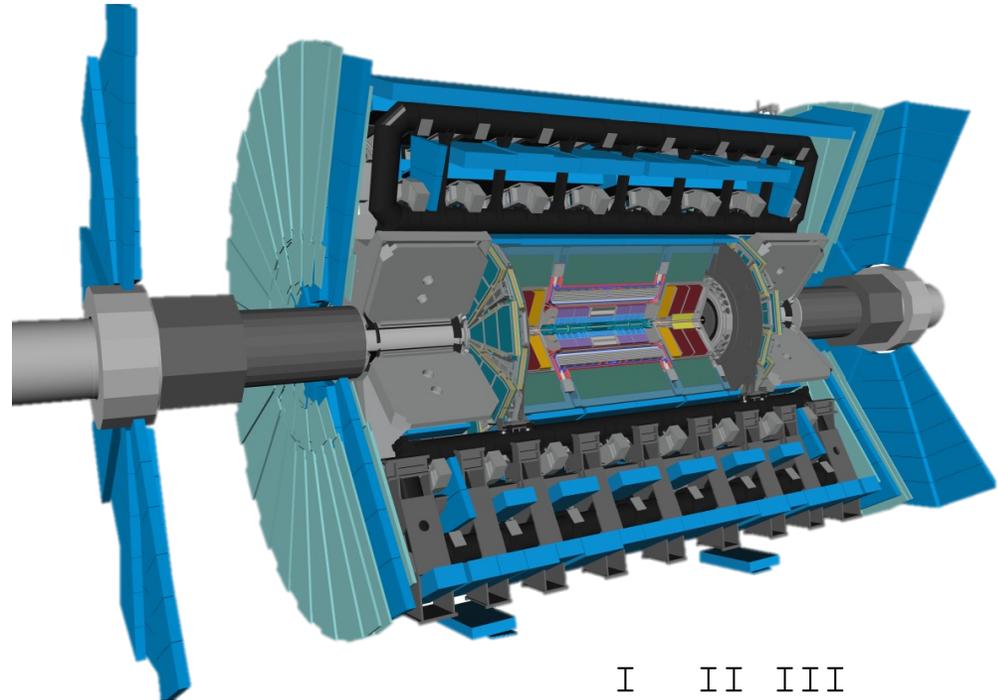
Simplified Detector Longitudinal View



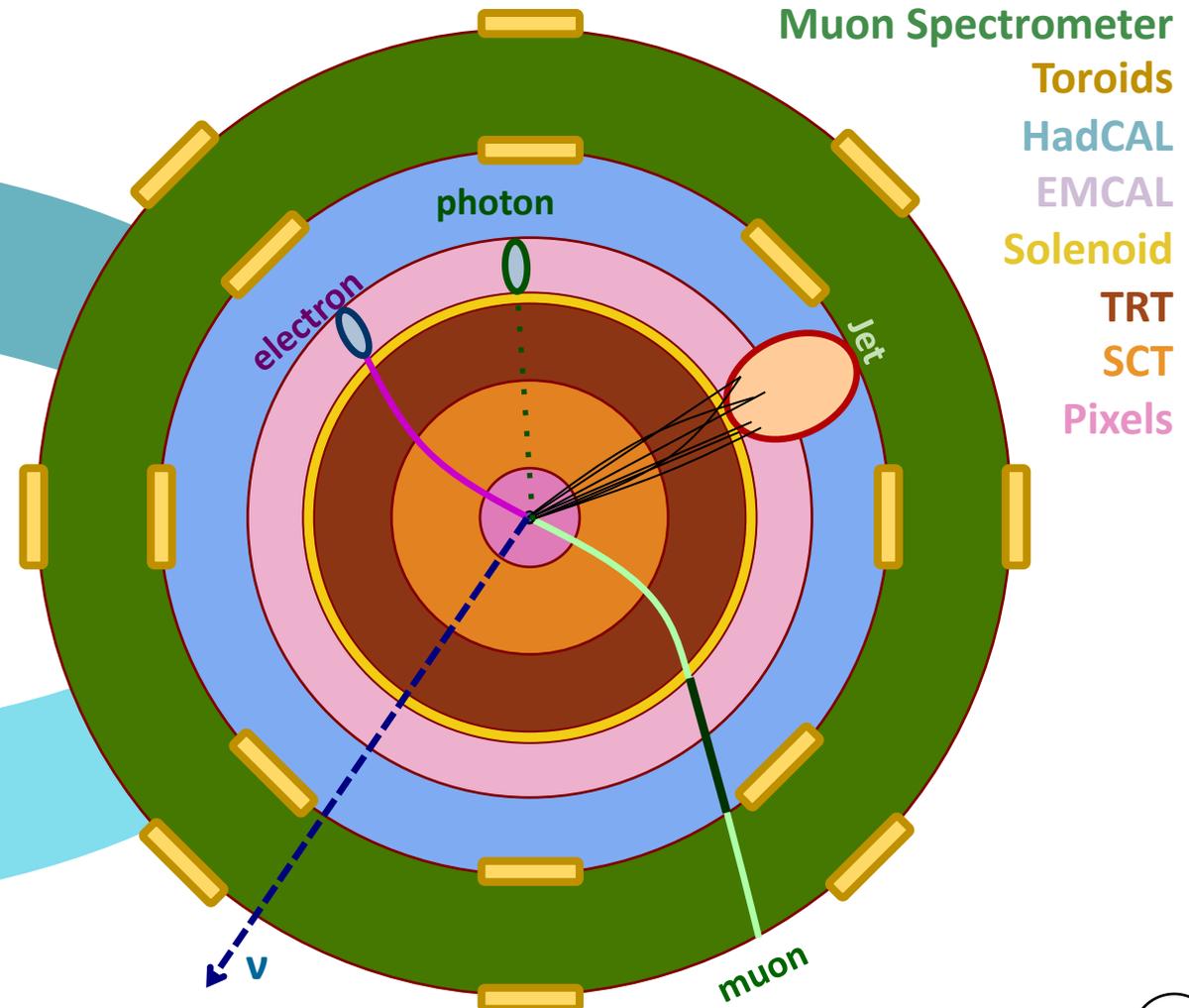
Simplified Detector Transverse View



Comment observer les particules dans le détecteur?

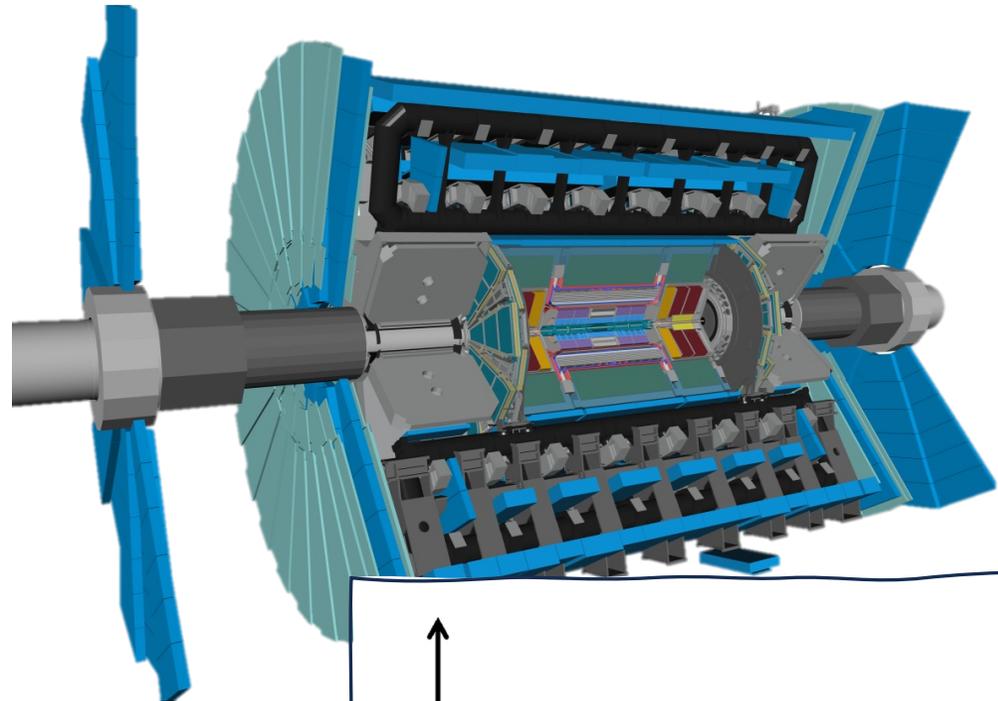


Vue transverse simplifiée du détecteur

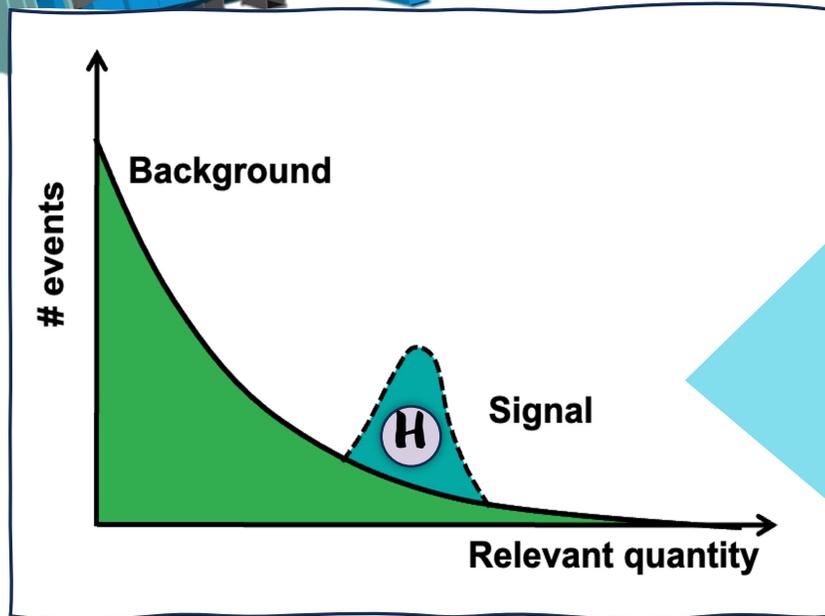
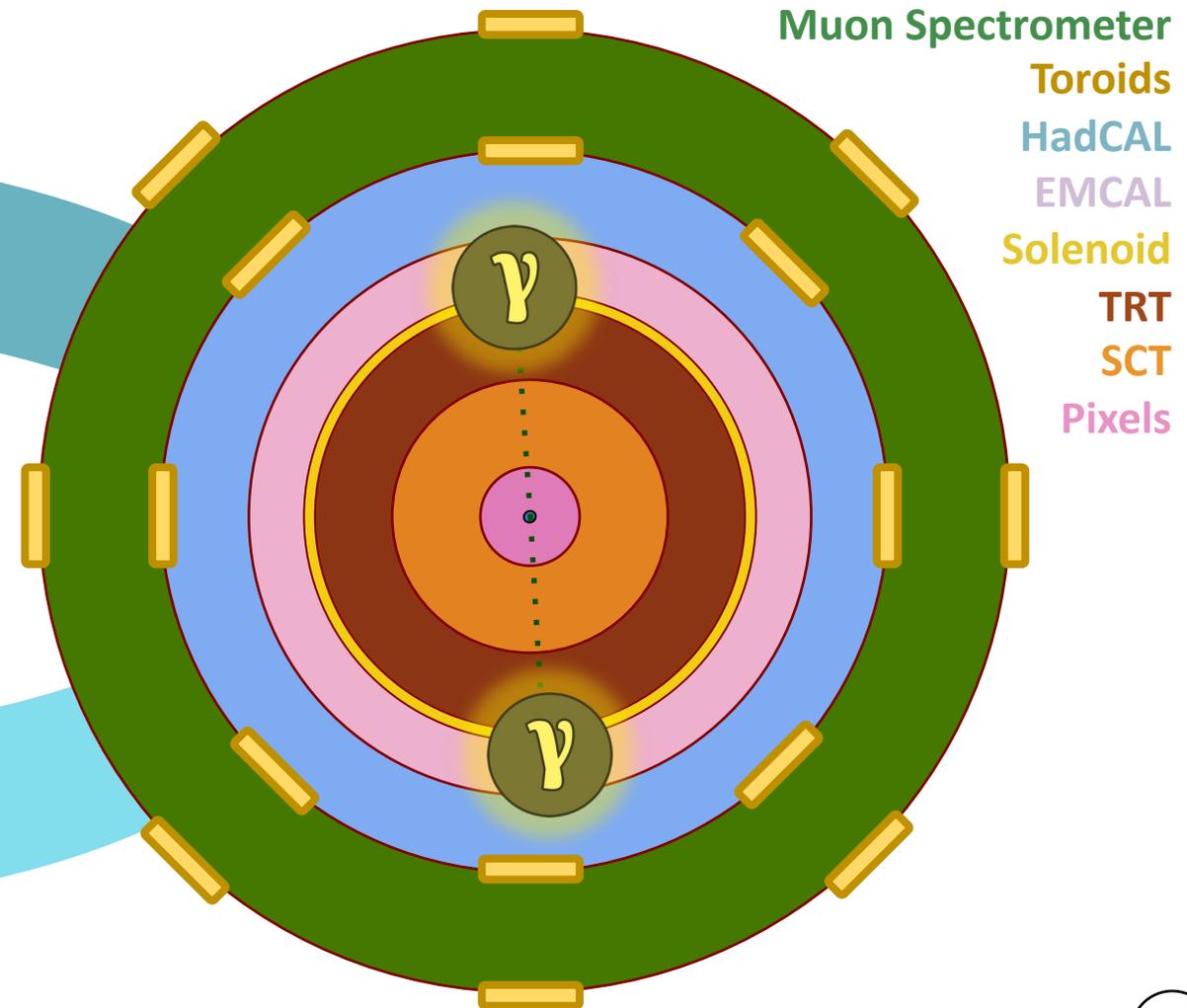


	I	II	III	
Quarks	2.4 MeV u	1.3 GeV c	170 GeV t	0 γ
	4.8 MeV d	104 MeV s	4.2 GeV b	0 g
	< 2 eV ν_1	< 2 eV ν_2	< 2 eV ν_3	91 GeV Z
Leptons	0.5 MeV e	106 MeV μ	1.8 GeV τ	80 GeV W
				125 GeV H
				Bosons

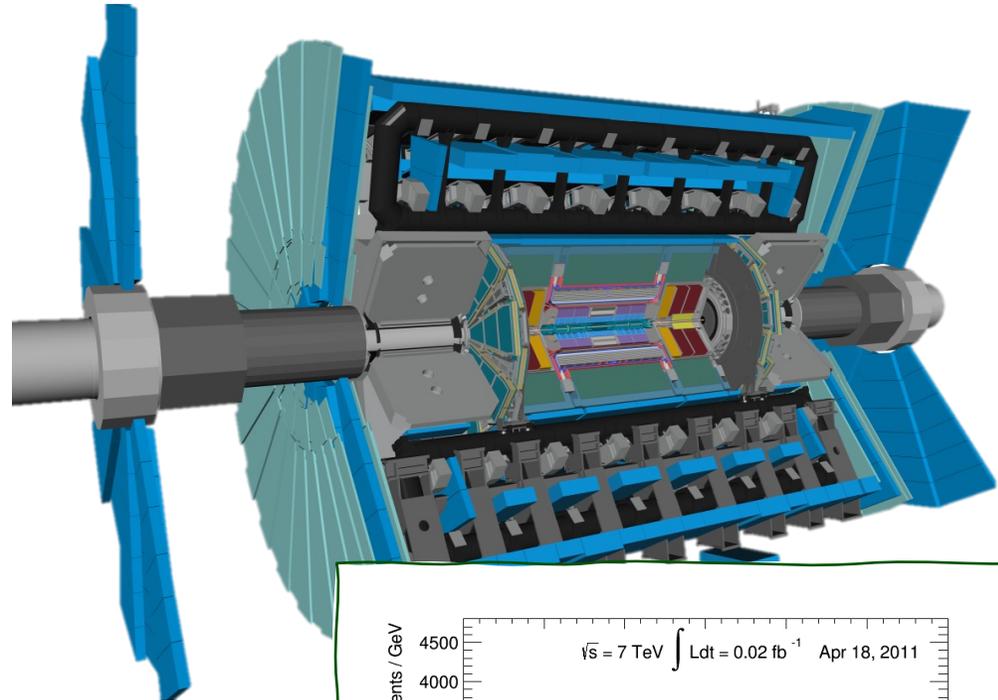
...et le boson de Higgs (e.g. en photons) ?



Vue transverse simplifiée du détecteur



...et le boson de Higgs?



Vue transverse simplifiée du détecteur

Muon Spectrometer

Toroids

HadCAL

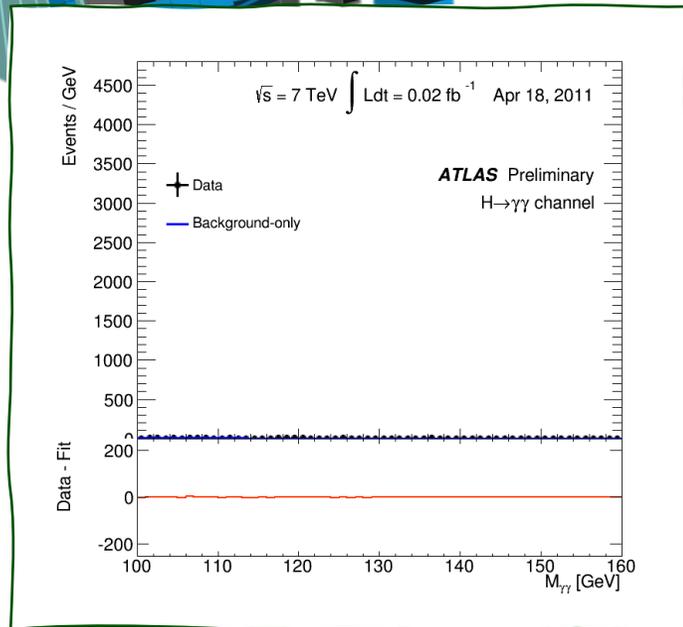
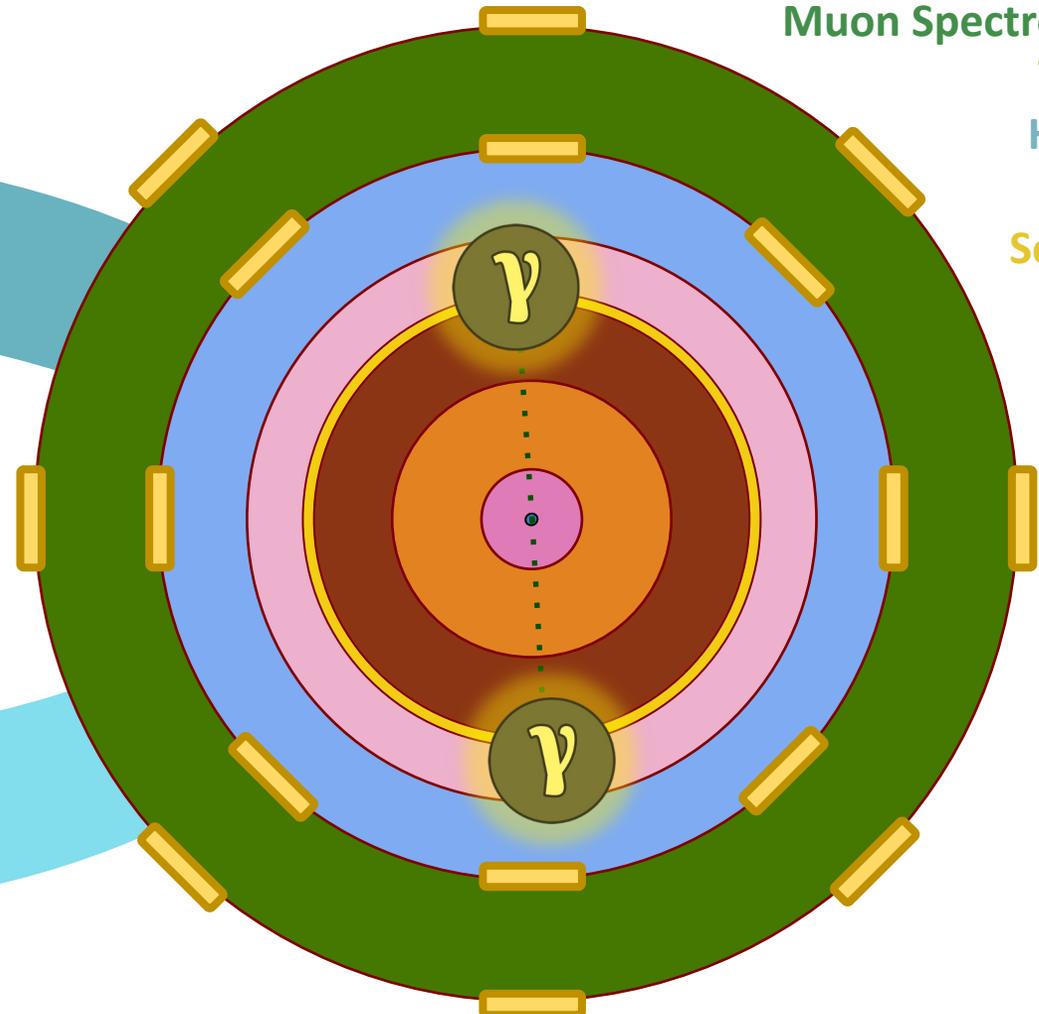
EMCAL

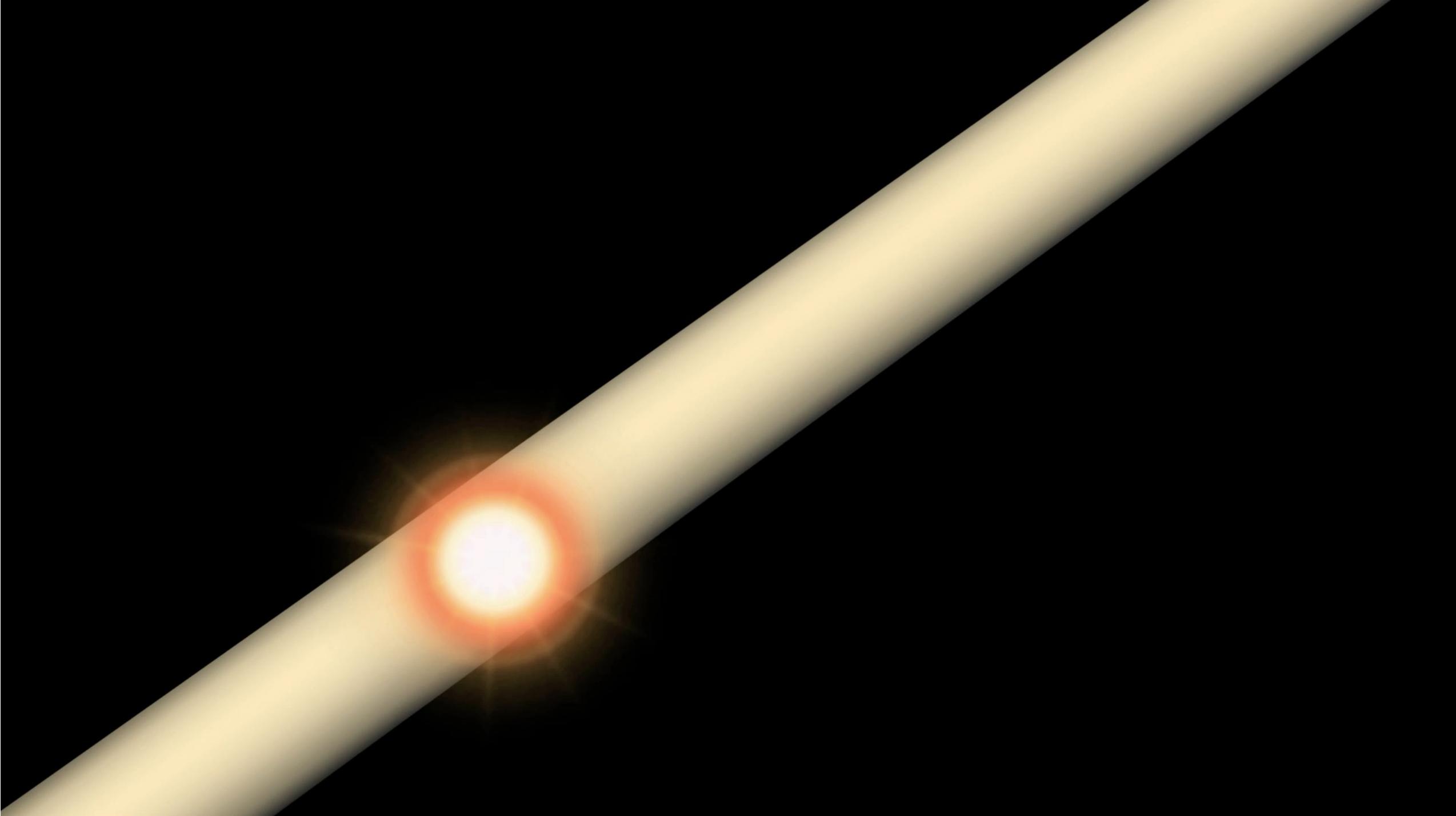
Solenoid

TRT

SCT

Pixels

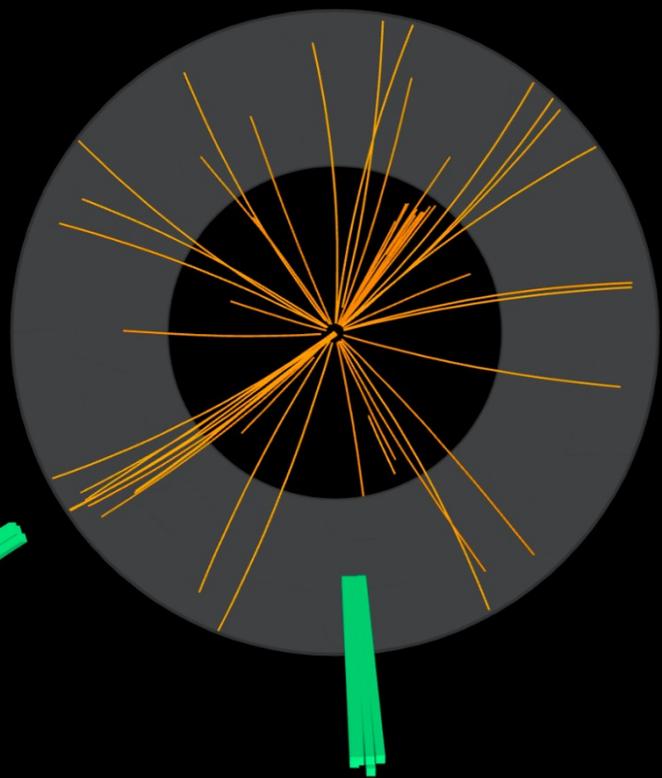
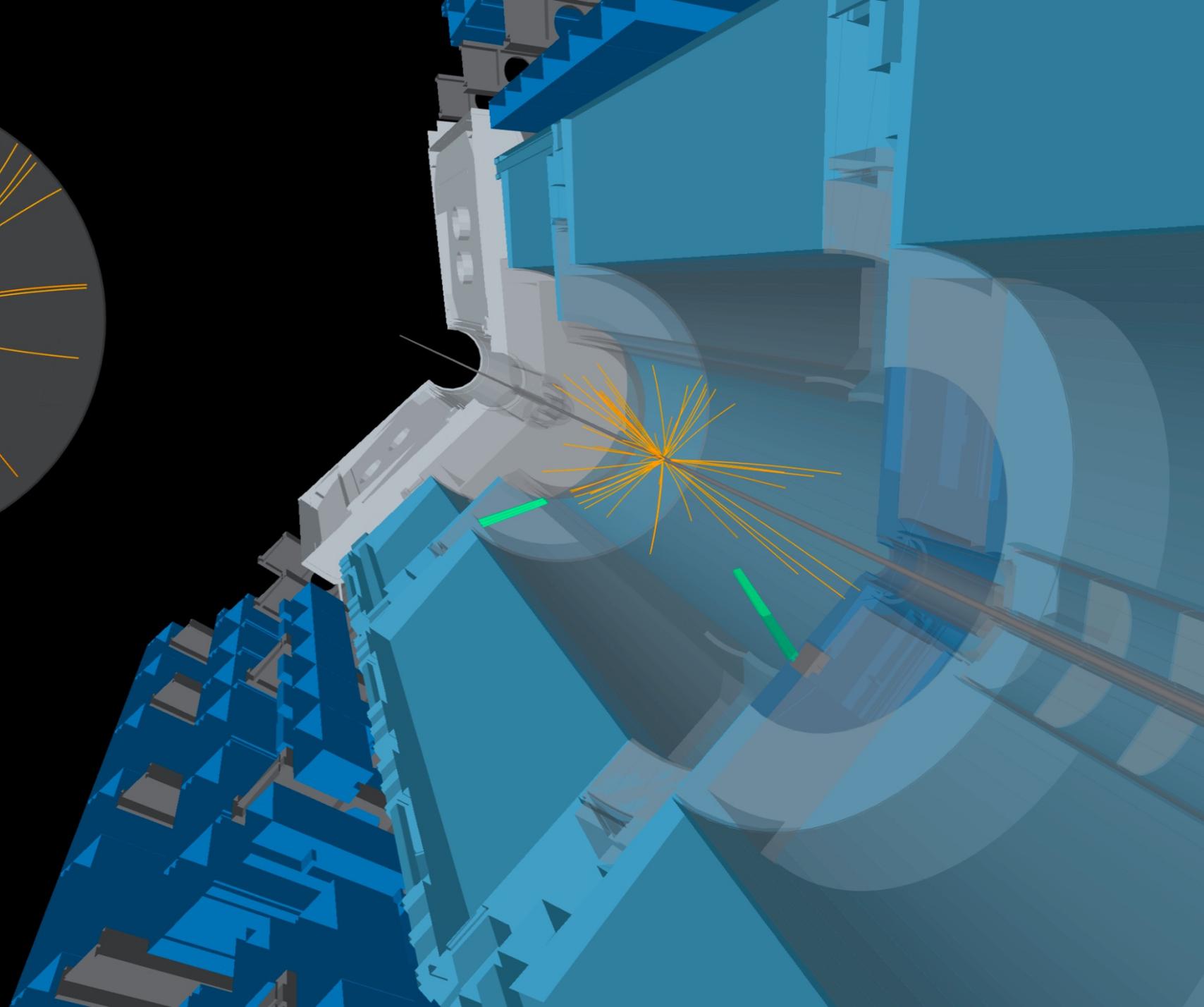


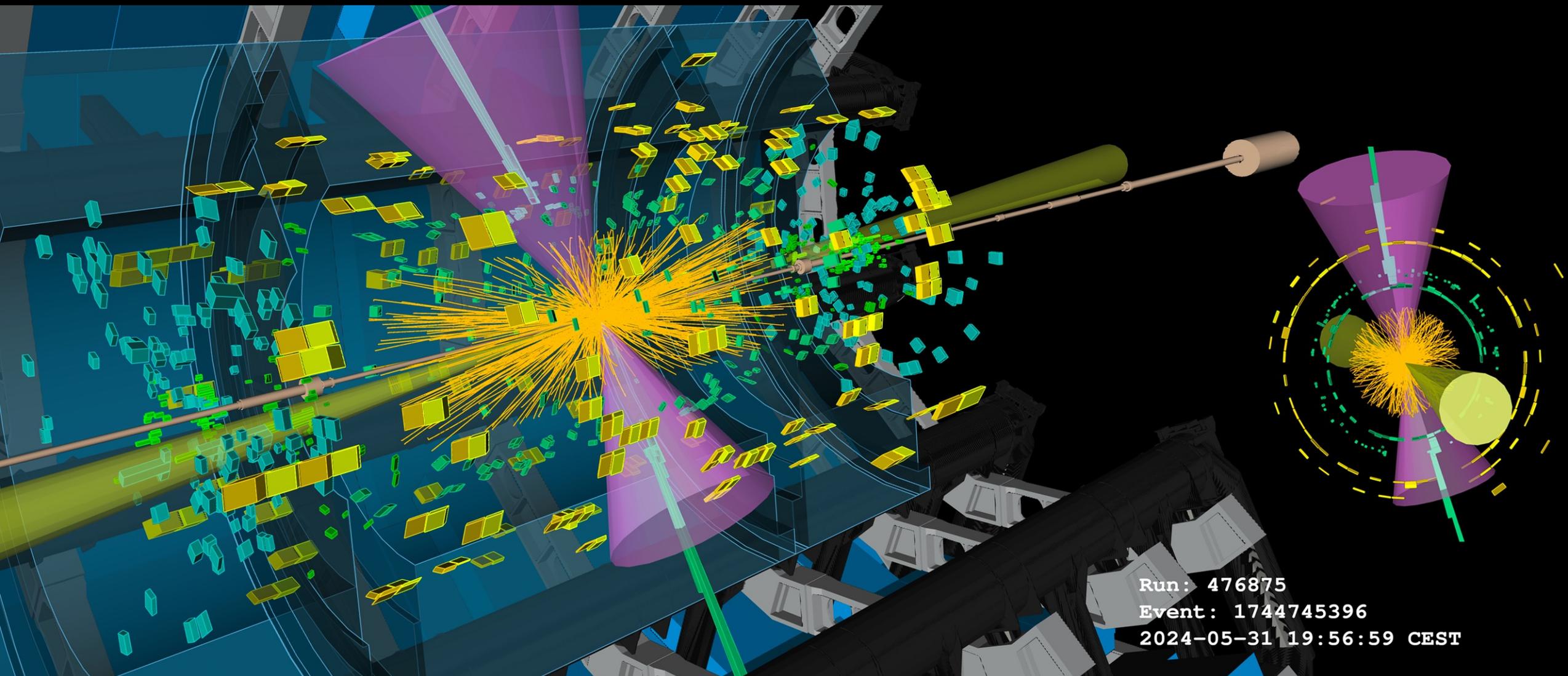


Run: 438298

Event: 1246008193

2022-10-30 04:04:50 CET





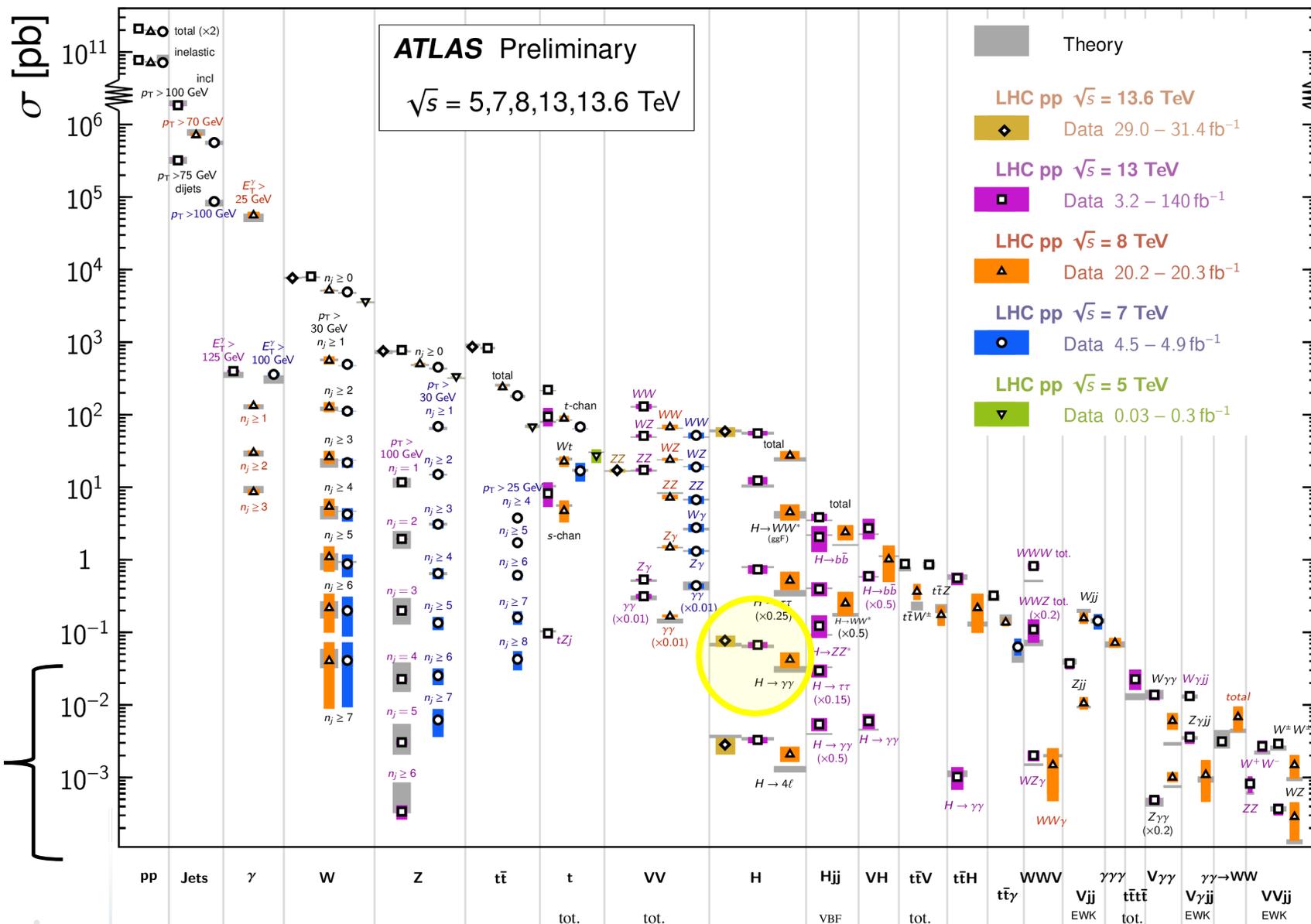
Run: 476875
Event: 1744745396
2024-05-31 19:56:59 CEST

État du Modèle Standard

État du Modèle Standard

Standard Model Production Cross Section Measurements

Status: June 2024



Certains aspects fondamentaux restent à explorer

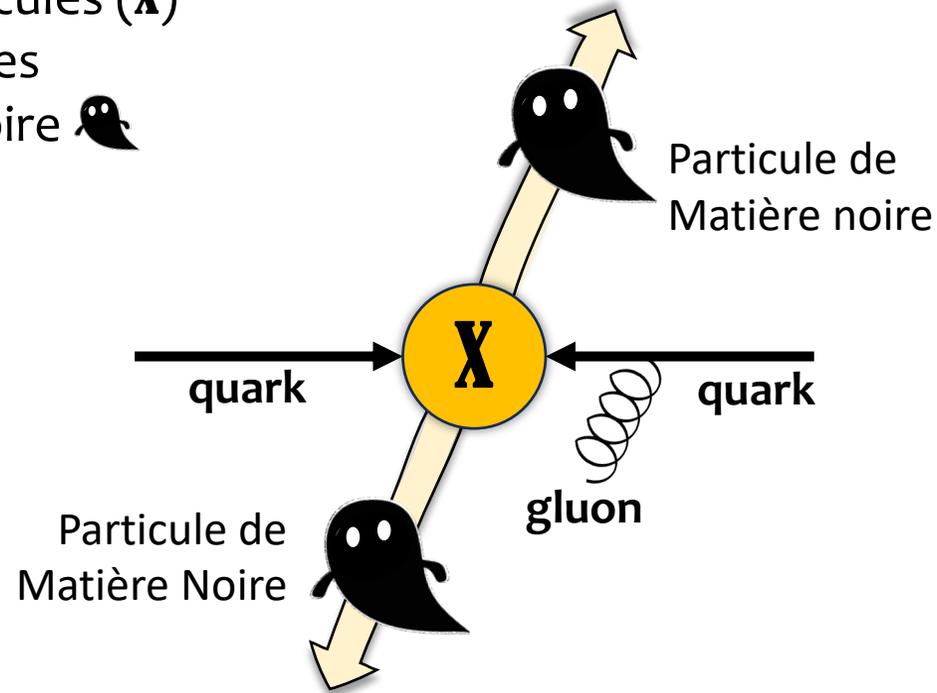


Et la Matière Noire?



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!

Missing Transverse Momentum – ME_T



In the transverse plane:

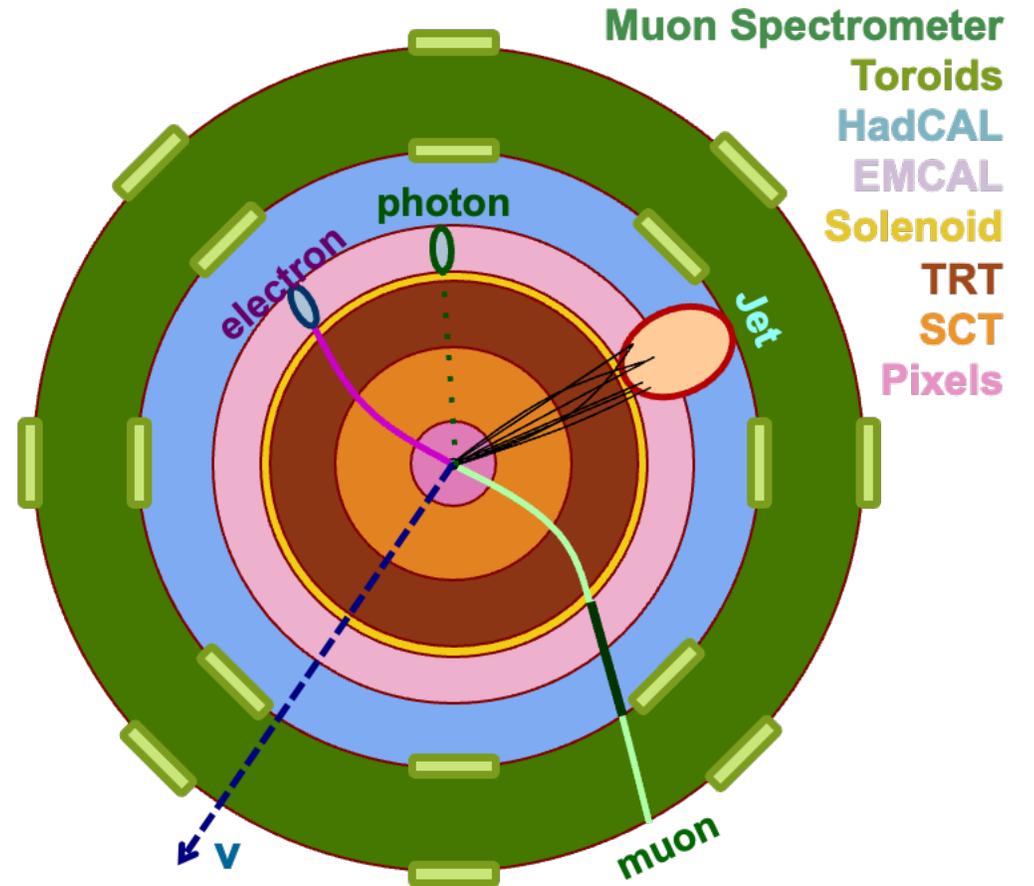
$$\sum_i \vec{p}_{T,i} = 0$$

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



Comment “voir” la Matière Noire à ATLAS?

Vue transverse simplifiée du détecteur

Muon Spectrometer

Toroids

HadCAL

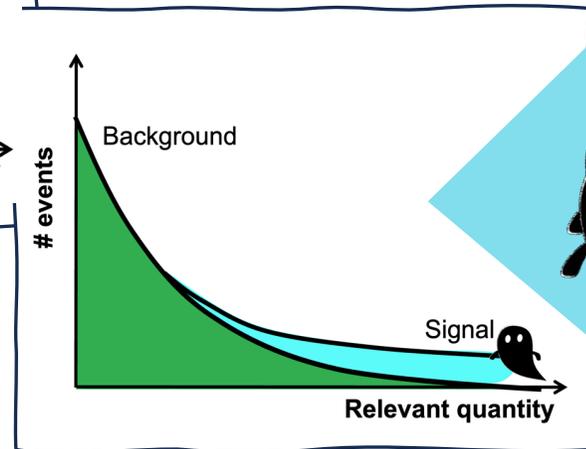
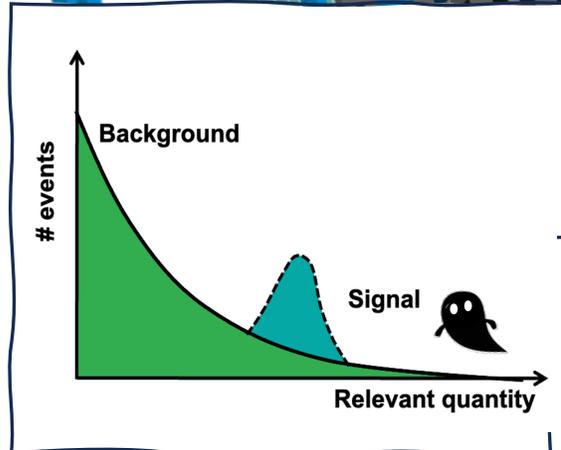
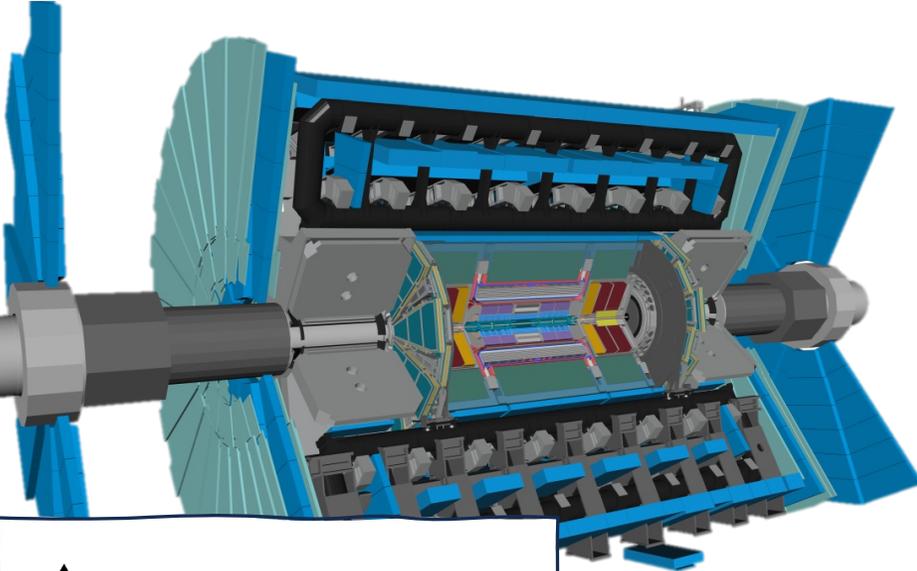
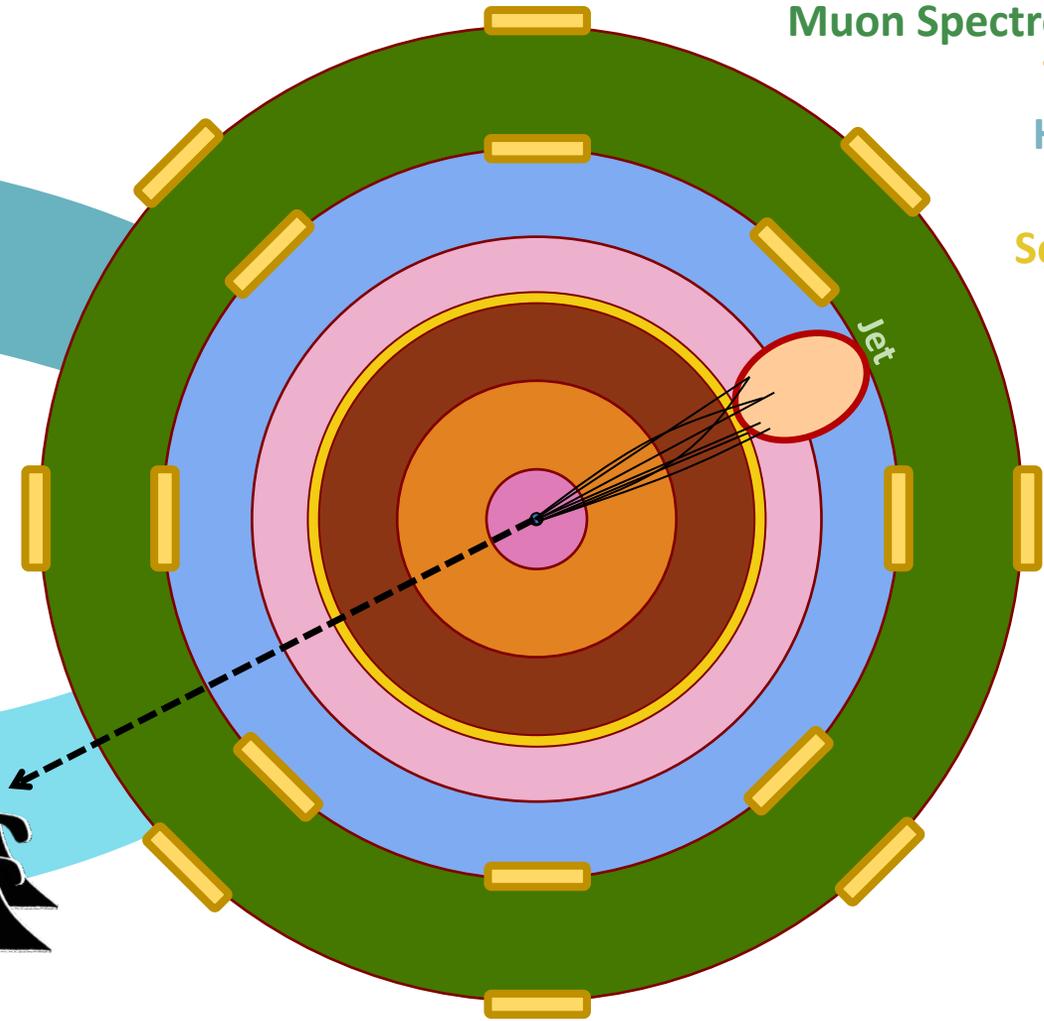
EMCAL

Solenoid

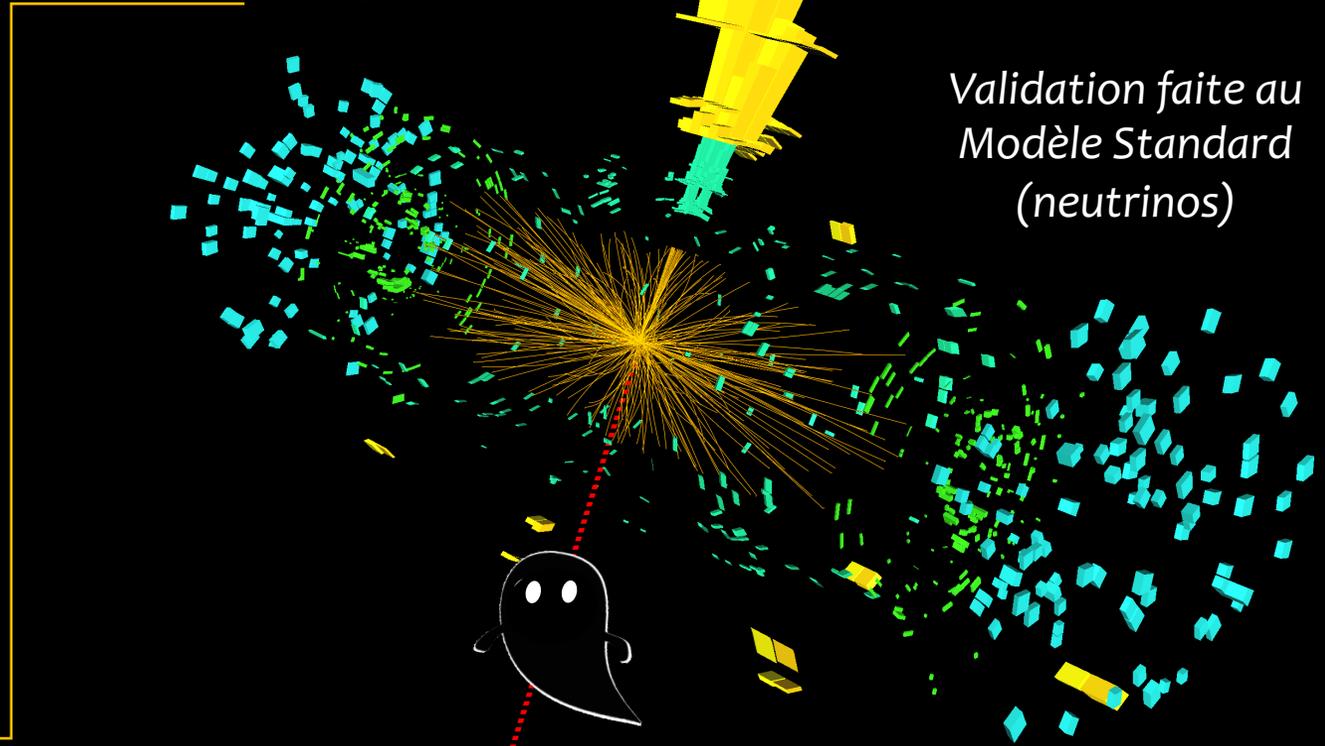
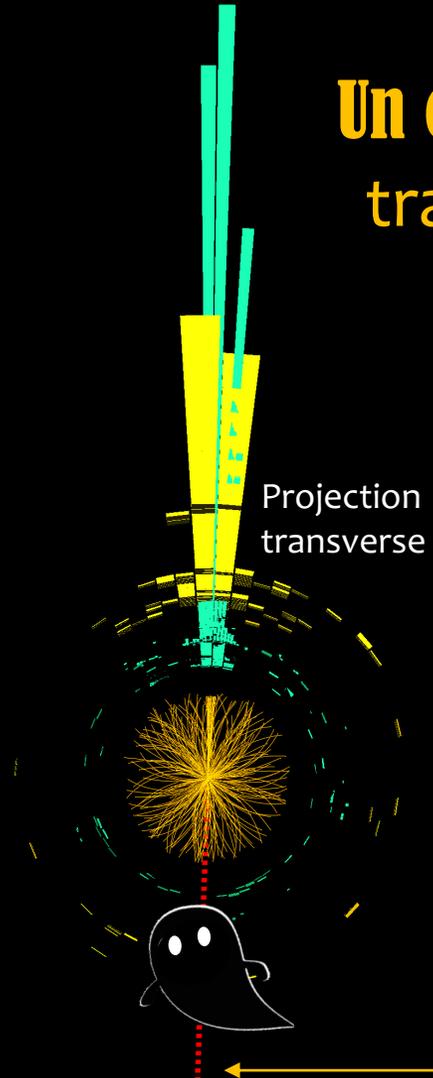
TRT

SCT

Pixels



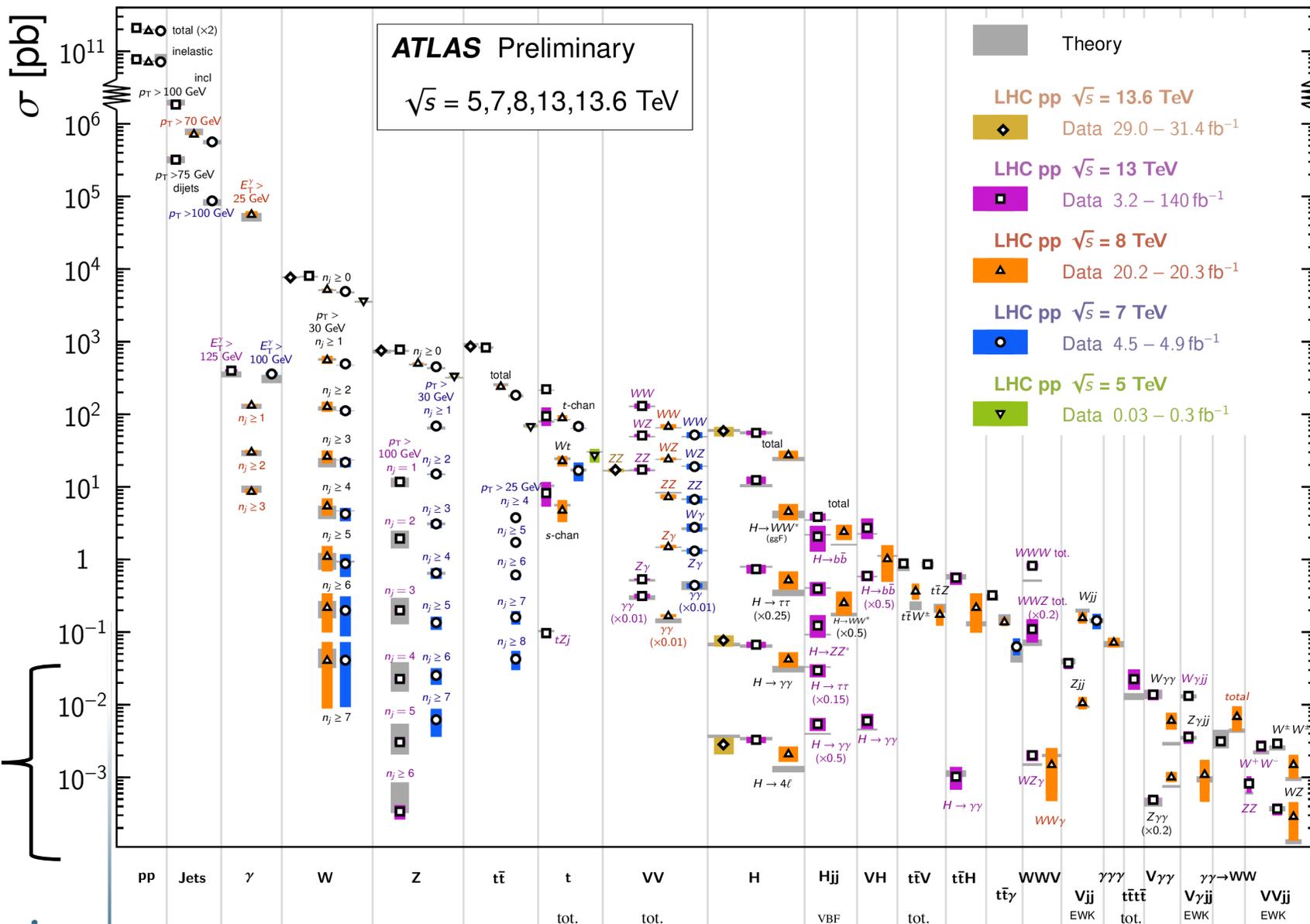
Un candidat de Matière Noire traverserait le détecteur sans interagir avec



État du Modèle Standard

Standard Model Production Cross Section Measurements

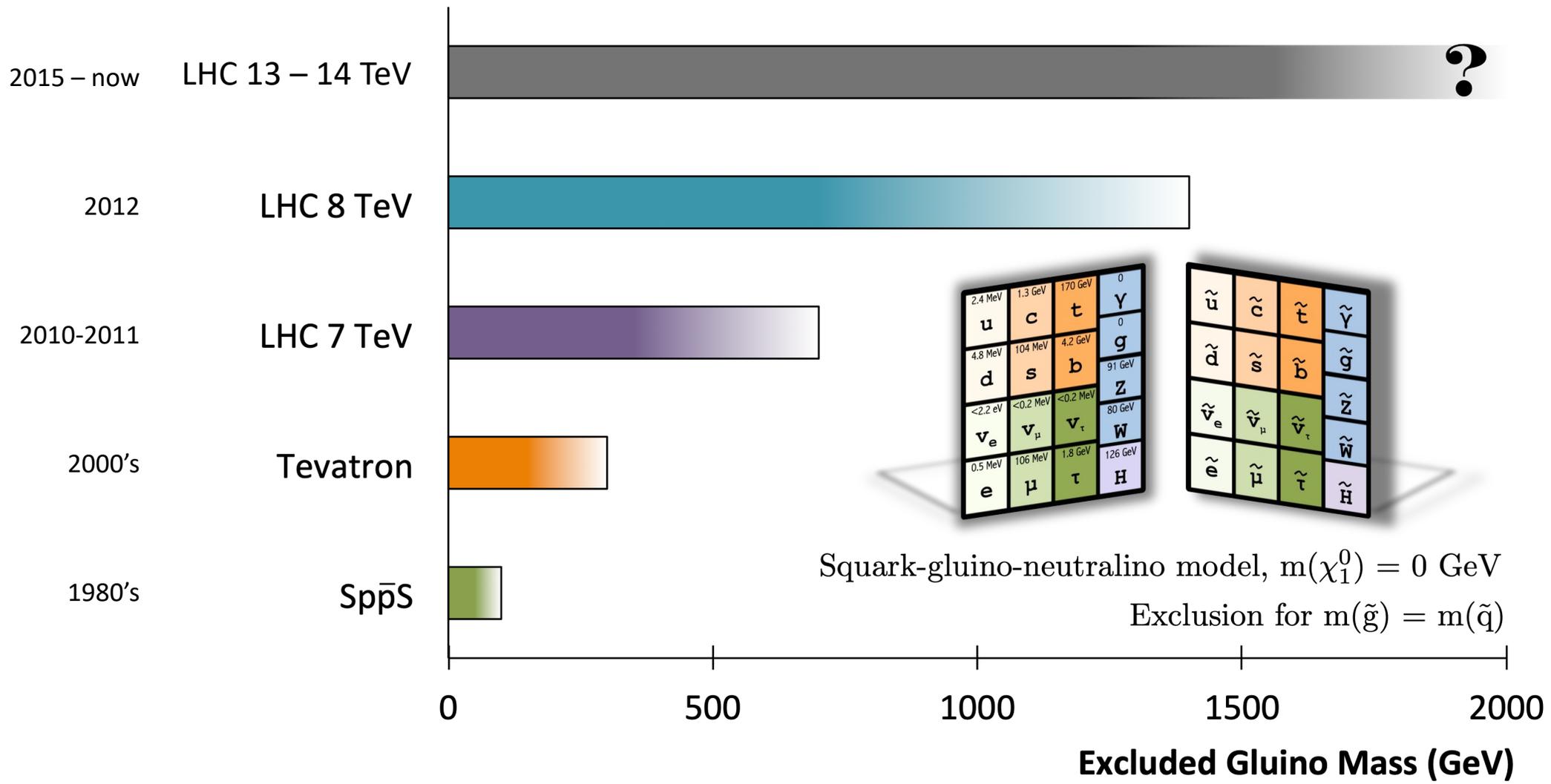
Status: June 2024



Certains aspects fondamentaux restent à explorer

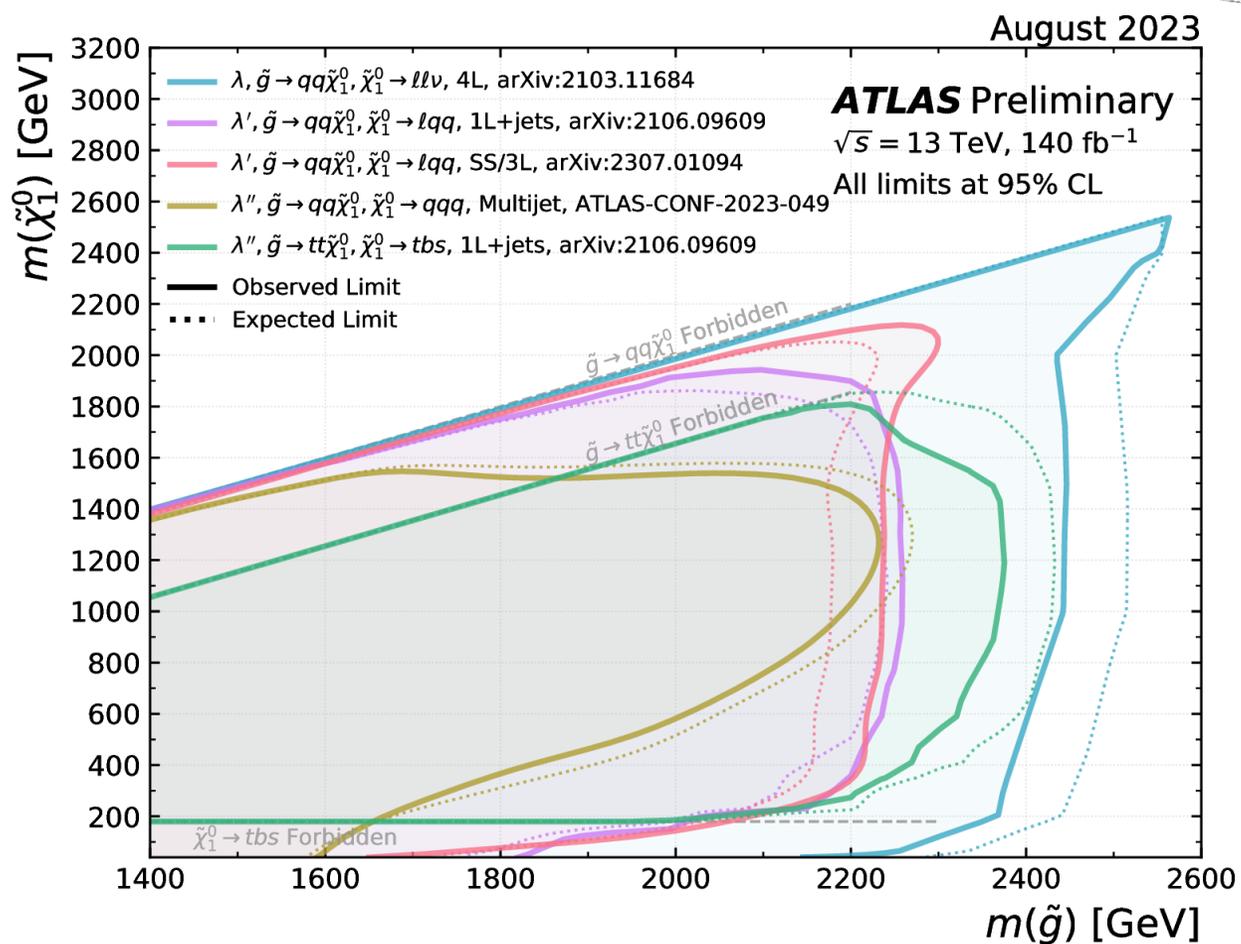
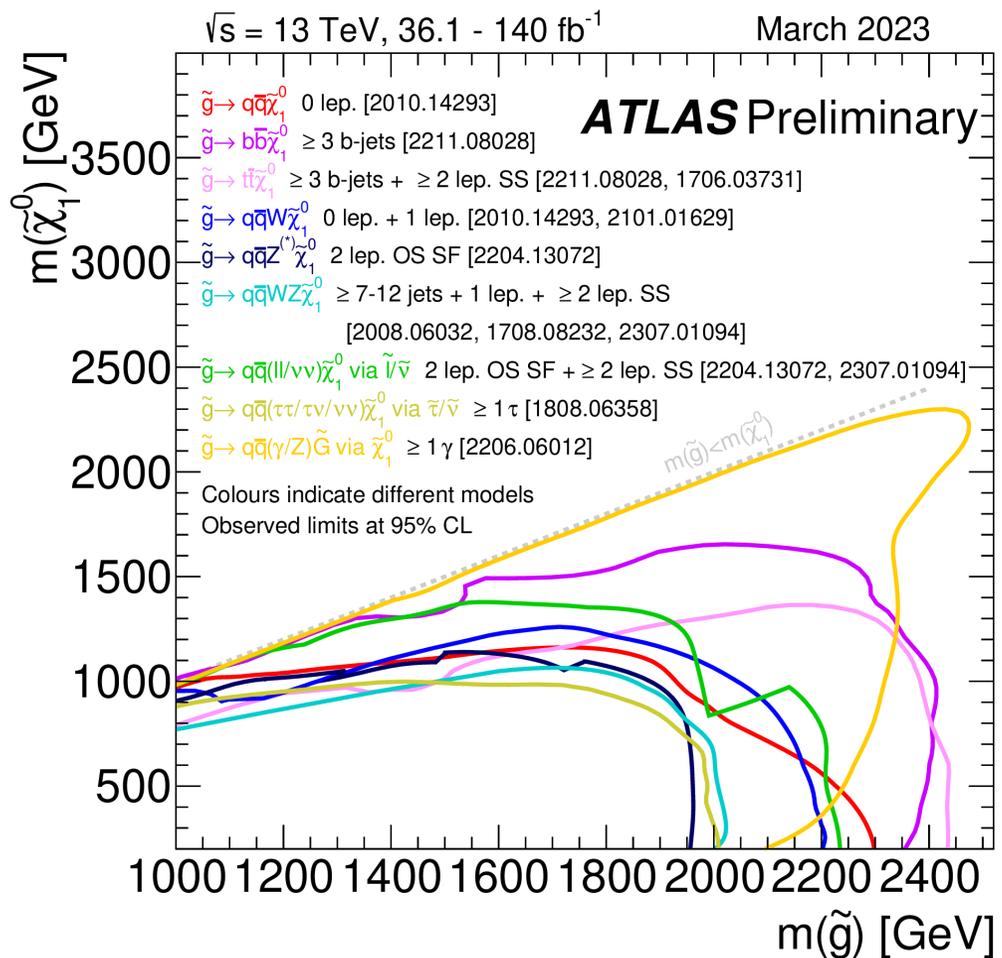


Nouvelle physique



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.

SUSY searches: A plethora of results



Many other searches...



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2022

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference		
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1-4 j	Yes	139	M_D 11.2 TeV $n=2$	2102.10874	
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	M_S 8.6 TeV $n=3$ HLZ NLO	1707.04147	
	ADD QBH	-	2 j	-	37.0	M_{th} 8.9 TeV $n=6$	1703.09127	
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{th} 9.55 TeV $n=6, M_D=3$ TeV, rot BH	1512.02586	
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	139	G_{KK} mass 4.5 TeV $k/\overline{M}_{Pl} = 0.1$	2102.13405	
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV $k/\overline{M}_{Pl} = 1.0$	1808.02380	
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu q\bar{q}$	1 e, μ	2j / 1J	Yes	139	G_{KK} mass 2.0 TeV $k/\overline{M}_{Pl} = 1.0$	2004.14636	
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	1 e, μ	$\geq 1b, \geq 1J/2j$	Yes	36.1	g_{KK} mass 3.8 TeV $\Gamma/m = 15\%$	1804.10823	
	2UED / RPP	1 e, μ	$\geq 2b, \geq 3j$	Yes	36.1	KK mass 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow t\bar{t}) = 1$	1803.09678	
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	139	Z' mass 5.1 TeV	1903.06248
SSM $Z' \rightarrow \tau\tau$		2 τ	-	-	36.1	Z' mass 2.42 TeV	1709.07242	
Leptophobic $Z' \rightarrow b\bar{b}$		-	2 b	-	36.1	Z' mass 2.1 TeV	1805.09299	
Leptophobic $Z' \rightarrow t\bar{t}$		0 e, μ	$\geq 1b, \geq 2J$	Yes	139	Z' mass 4.1 TeV $\Gamma/m = 1.2\%$	2005.05138	
SSM $W' \rightarrow \ell\nu$		1 e, μ	-	Yes	139	W' mass 6.0 TeV	1906.05609	
SSM $W' \rightarrow \tau\nu$		1 τ	-	Yes	139	W' mass 5.0 TeV	ATLAS-CONF-2021-025	
SSM $W' \rightarrow t\bar{t}$		-	$\geq 1b, \geq 1J$	-	139	W' mass 4.4 TeV	ATLAS-CONF-2021-043	
HVT $W' \rightarrow WZ \rightarrow \ell\nu q\bar{q}$ model B		1 e, μ	2j / 1J	Yes	139	W' mass 4.3 TeV	2004.14636	
HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell'$ model C		3 e, μ	2j (VBF)	Yes	139	W' mass 340 GeV	ATLAS-CONF-2022-005	
HVT $W' \rightarrow WH$ model B		0 e, μ	$\geq 1b, \geq 2J$	Yes	139	W' mass 3.2 TeV	2007.05293	
LRSM $W_R \rightarrow \mu N_R$	2 μ	1 J	-	80	W_R mass 5.0 TeV $m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679		
CI	CI $qqqq$	-	2 j	-	37.0	Λ 21.8 TeV η_{LL}	1703.09127	
	CI $\ell\ell qq$	2 e, μ	-	-	139	Λ 35.8 TeV η_{LL}	2006.12946	
	CI $e\bar{e} b\bar{b}$	2 e	1 b	-	139	Λ 1.8 TeV $g_s = 1$	2105.13847	
	CI $\mu\bar{\mu} b\bar{b}$	2 μ	1 b	-	139	Λ 2.0 TeV $g_s = 1$	2105.13847	
	CI $t\bar{t} t\bar{t}$	$\geq 1e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	Λ 2.57 TeV $ C_{4t} = 4\pi$	1811.02305	
	DM	Axial-vector med. (Dirac DM)	0 e, μ, τ, γ	1-4 j	Yes	139	m_{med} 2.1 TeV $g_a=0.25, g_s=1, m(\chi)=1$ GeV	2102.10874
Pseudo-scalar med. (Dirac DM)		0 e, μ, τ, γ	1-4 j	Yes	139	m_{med} 376 GeV $g_a=1, g_s=1, m(\chi)=1$ GeV	2102.10874	
Vector med. Z' -2HDM (Dirac DM)		0 e, μ	2 b	Yes	139	m_{med} 3.1 TeV $\tan\beta=1, g_Z=0.8, m(\chi)=100$ GeV	2108.13391	
Pseudo-scalar med. 2HDM+a		multi-channel	-	-	139	m_{med} 560 GeV $\tan\beta=1, g_s=1, m(\chi)=10$ GeV	ATLAS-CONF-2021-036	
LQ	Scalar LQ 1 st gen	2 e	$\geq 2j$	Yes	139	LQ mass 1.8 TeV $\beta = 1$	2006.05872	
	Scalar LQ 2 nd gen	2 μ	$\geq 2j$	Yes	139	LQ mass 1.7 TeV $\beta = 1$	2006.05872	
	Scalar LQ 3 rd gen	1 τ	2 b	Yes	139	LQ_3^+ mass 1.2 TeV $\mathcal{B}(LQ_3^+ \rightarrow b\tau) = 1$	2108.07665	
	Scalar LQ 3 rd gen	0 e, μ	$\geq 2j, \geq 2b$	Yes	139	LQ_3^+ mass 1.24 TeV $\mathcal{B}(LQ_3^+ \rightarrow t\nu) = 1$	2004.14060	
	Scalar LQ 3 rd gen	$\geq 2e, \mu, \geq 1\tau$	$\geq 1j, \geq 1b$	-	139	LQ_3^+ mass 1.43 TeV $\mathcal{B}(LQ_3^+ \rightarrow t\tau) = 1$	2101.11582	
	Scalar LQ 3 rd gen	0 e, $\mu, \geq 1\tau$	0-2j, 2b	Yes	139	LQ_3^+ mass 1.26 TeV $\mathcal{B}(LQ_3^+ \rightarrow b\nu) = 1$	2101.12527	
	Vector LQ 3 rd gen	1 τ	2 b	Yes	139	LQ_3^+ mass 1.77 TeV $\mathcal{B}(LQ_3^+ \rightarrow b\tau) = 0.5, Y\text{-M coupl.}$	2108.07665	
Heavy quarks	VLQ $TT \rightarrow Zt + X$	2e/2 μ $\geq 3e, \mu$	$\geq 1b, \geq 1j$	-	139	T mass 1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3} T_{5/3} / T_{5/3} \rightarrow Wt + X$	2(SS) $\geq 3e, \mu$	$\geq 1b, \geq 1j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	1807.11883	
	VLQ $T \rightarrow Ht/Zt$	1 e, μ	$\geq 1b, \geq 3j$	Yes	139	T mass 1.8 TeV	SU(2) singlet, $\kappa_T = 0.5$	ATLAS-CONF-2021-040
	VLQ $Y \rightarrow Wb$	1 e, μ	$\geq 1b, \geq 1j$	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$	1812.07343
	VLQ $B \rightarrow Hb$	0 e, μ	$\geq 2b, \geq 1j, \geq 1J$	-	139	B mass 2.0 TeV	SU(2) doublet, $\kappa_B = 0.3$	ATLAS-CONF-2021-018
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	q^* mass 6.7 TeV	only u^* and d^* , $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	-	36.7	q^* mass 5.3 TeV	only u^* and d^* , $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \rightarrow b\bar{g}$	-	1 b, 1 j	-	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	-	-	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	-	-	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
	Other	Type III Seesaw	2,3,4 e, μ	$\geq 2j$	Yes	139	N^0 mass 910 GeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$
LRSM Majorana ν		2 μ	2 j	-	36.1	N_R mass 3.2 TeV	DY production	1809.11105
Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$		2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$		2,3,4 e, μ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	ATLAS-CONF-2022-010
Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$		3 e, μ, τ	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
Multi-charged particles		-	-	-	36.1	multi-charged particle mass 1.22 TeV	DY production, $ q = 5e$	1812.03673
Magnetic monopoles		-	-	-	34.4	monopole mass 2.37 TeV	DY production, $ g = 1g_D, \text{spin } 1/2$	1905.10130

$\sqrt{s} = 8$ TeV $\sqrt{s} = 13$ TeV partial data $\sqrt{s} = 13$ TeV full data

10⁻¹ 1 10 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown.

[†]Small-radius (large-radius) jets are denoted by the letter j (J).

Many other searches...



Model	Signature	$\int \mathcal{L} dt$ [fb ⁻¹]	Mass limit	Reference						
Inclusive Searches	$q\bar{q}, \bar{q} \rightarrow q\tilde{\chi}_1^0$	0 e, μ mono-jet	2-6 jets 1-3 jets	E_T^{miss} E_T^{miss}	139 139	\tilde{q} [1x, 8x Degen.] \tilde{q} [8x Degen.]	1.0 0.9	1.85	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 5$ GeV	2010.14293 2102.10874
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 e, μ	2-6 jets	E_T^{miss}	139	\tilde{g} \tilde{g}	2.3 Forbidden	1.15-1.95	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{\chi}_1^0) = 1000$ GeV	2010.14293 2010.14293
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$	1 e, μ	2-6 jets			139	\tilde{g}		$m(\tilde{\chi}_1^0) < 600$ GeV	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets		E_T^{miss}	139	\tilde{g}		$m(\tilde{\chi}_1^0) < 700$ GeV	CERN-EP-2022-014
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 e, μ SS e, μ	7-11 jets 6 jets		E_T^{miss} E_T^{miss}	139 139	\tilde{g} \tilde{g}	1.15 1.97	$m(\tilde{\chi}_1^0) < 600$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	2008.06032 1909.08457
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ	3 b 6 jets		E_T^{miss} E_T^{miss}	79.8 139	\tilde{g} \tilde{g}	2.25 1.25	$m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	ATLAS-CONF-2018-041 1909.08457
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e, μ	2 b	E_T^{miss}	139	\tilde{b}_1 \tilde{b}_1	1.255 0.68		$m(\tilde{\chi}_1^0) < 400$ GeV 10 GeV $< \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527 2101.12527
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$	0 e, μ 2 τ	6 b 2 b	E_T^{miss} E_T^{miss}	139 139	\tilde{b}_1 \tilde{b}_1	Forbidden 0.13-0.85	0.23-1.35	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	1908.03122 2103.08189
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, μ	≥ 1 jet		E_T^{miss}	139	\tilde{t}_1	1.25	$m(\tilde{\chi}_1^0) = 1$ GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, μ	3 jets/1 b		E_T^{miss}	139	\tilde{t}_1	Forbidden	$m(\tilde{\chi}_1^0) = 500$ GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	1-2 τ	2 jets/1 b		E_T^{miss}	139	\tilde{t}_1	Forbidden	$m(\tilde{\tau}_1) = 800$ GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ 0 e, μ	2 c mono-jet		E_T^{miss} E_T^{miss}	36.1 139	\tilde{c} \tilde{t}_1	0.85 0.55	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	1805.01649 2102.10874
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	1-2 e, μ	1-4 b		E_T^{miss}	139	\tilde{t}_1	0.067-1.18	$m(\tilde{\chi}_2^0) = 500$ GeV	2006.05880	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ	1 b		E_T^{miss}	139	\tilde{t}_2	Forbidden	$m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV	2006.05880	
EW direct	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ	Multiple ℓ /jets $ee, \mu\mu$	≥ 1 jet	E_T^{miss} E_T^{miss}	139 139	$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$	0.96 0.205		$m(\tilde{\chi}_1^0) = 0$, wino-bino $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ via WW	2 e, μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	0.42		$m(\tilde{\chi}_1^0) = 0$, wino-bino	1908.08215
	$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via Wh	Multiple ℓ /jets		E_T^{miss}	139	$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$	Forbidden	1.06	$m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	1.0		$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$	[$\tilde{\tau}_L, \tilde{\tau}_{R,L}$]	0.16-0.3 0.12-0.39	$m(\tilde{\chi}_1^0) = 0$	1911.06660
	$\tilde{\ell}_{L,R}, \tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ $ee, \mu\mu$	0 jets ≥ 1 jet		E_T^{miss} E_T^{miss}	139 139	$\tilde{\ell}$ $\tilde{\ell}$	0.7 0.256	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10$ GeV	1908.08215 1911.12606
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ 0 e, μ	≥ 3 b 0 jets ≥ 2 large jets		E_T^{miss} E_T^{miss} E_T^{miss}	36.1 139 139	\tilde{H} \tilde{H} \tilde{H}	0.13-0.23 0.55 0.45-0.93	$\text{BR}(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$ $\text{BR}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	1806.04030 2103.11684 2108.07586	
Long-lived particles	Direct $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	139	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm$	0.66 0.21		Pure Wino Pure higgsino	2201.02472 2201.02472
	Stable \tilde{g} R-hadron	pixel dE/dx		E_T^{miss}	139	\tilde{g}	2.05			CERN-EP-2022-029
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	pixel dE/dx		E_T^{miss}	139	\tilde{g}	[$\tau(\tilde{g}) = 10$ ns]	2.2	$m(\tilde{\chi}_1^0) = 100$ GeV	CERN-EP-2022-029
	$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$	Displ. lep		E_T^{miss}	139	$\tilde{\ell}, \tilde{\mu}$ $\tilde{\tau}$ $\tilde{\tau}$	0.7 0.34 0.36		$\tau(\tilde{\ell}) = 0.1$ ns $\tau(\tilde{\ell}) = 0.1$ ns $\tau(\tilde{\ell}) = 10$ ns	2011.07812 2011.07812 CERN-EP-2022-029
RPV	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp / \tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 e, μ			139	$\tilde{\chi}_1^\pm / \tilde{\chi}_1^0$	[BR(Z τ)=1, BR(Z e)=1]	0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 e, μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$	[$\lambda_{333} \neq 0, \lambda_{12k} \neq 0$]	0.95 1.55	$m(\tilde{\chi}_1^0) = 200$ GeV	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\bar{q}$	4-5 large jets			36.1	\tilde{g}	[$m(\tilde{\chi}_1^0) = 200$ GeV, 1100 GeV]	1.3 1.9	Large λ'_{12}	1804.03568
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple			36.1	\tilde{t}_1	[$\lambda'_{323} = 2e-4, 1e-2$]	0.55 1.05	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like $m(\tilde{\chi}_1^\pm) = 500$ GeV	ATLAS-CONF-2018-003
	$\tilde{t}_1, \tilde{t}_1 \rightarrow bbs$	$\geq 4b$			139	\tilde{t}_1	Forbidden	0.95		2010.01015
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b			36.7	\tilde{t}_1	[qq, bs]	0.42 0.61		1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, μ 1 μ	2 b DV		E_T^{miss} E_T^{miss}	36.1 136	\tilde{t}_1 \tilde{t}_1	1.0 1.0	$\text{BR}(\tilde{t}_1 \rightarrow be/\bar{b}\mu) > 20\%$ $\text{BR}(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta = 1$	1710.05544 2003.11956	
$\tilde{\chi}_1^\pm / \tilde{\chi}_2^0 / \tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^\pm \rightarrow bbs$	1-2 e, μ	≥ 6 jets			139	$\tilde{\chi}_1^0$	0.2-0.32	Pure higgsino	2106.09609	

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

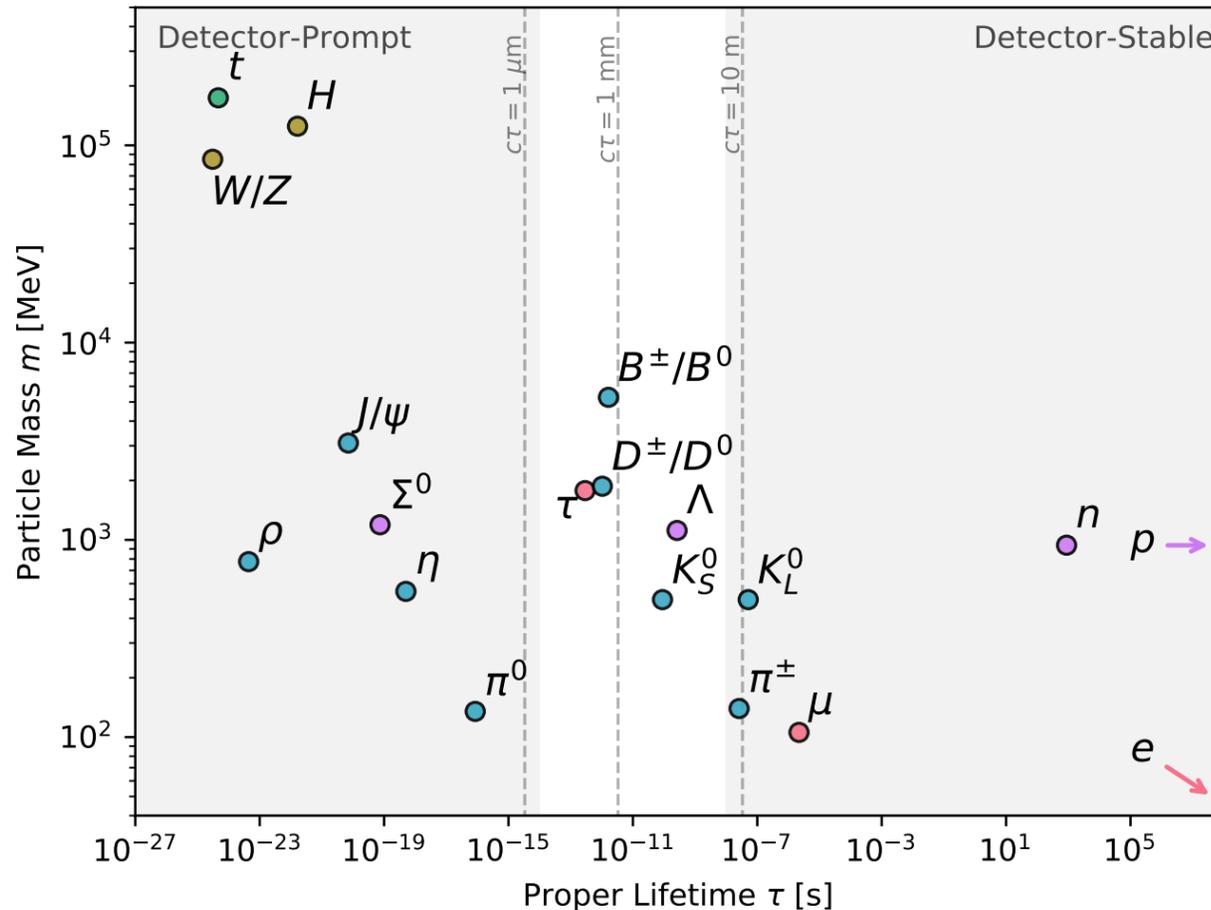
Searches for exotic signatures



Non-conventional Signatures

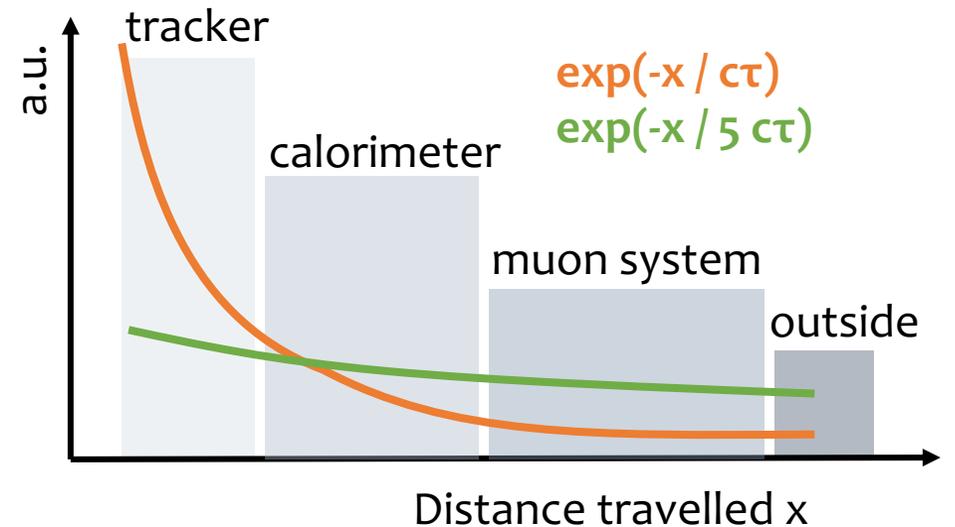
e.g. Signatures of long-lived particles

The SM contains a large number of metastable particles

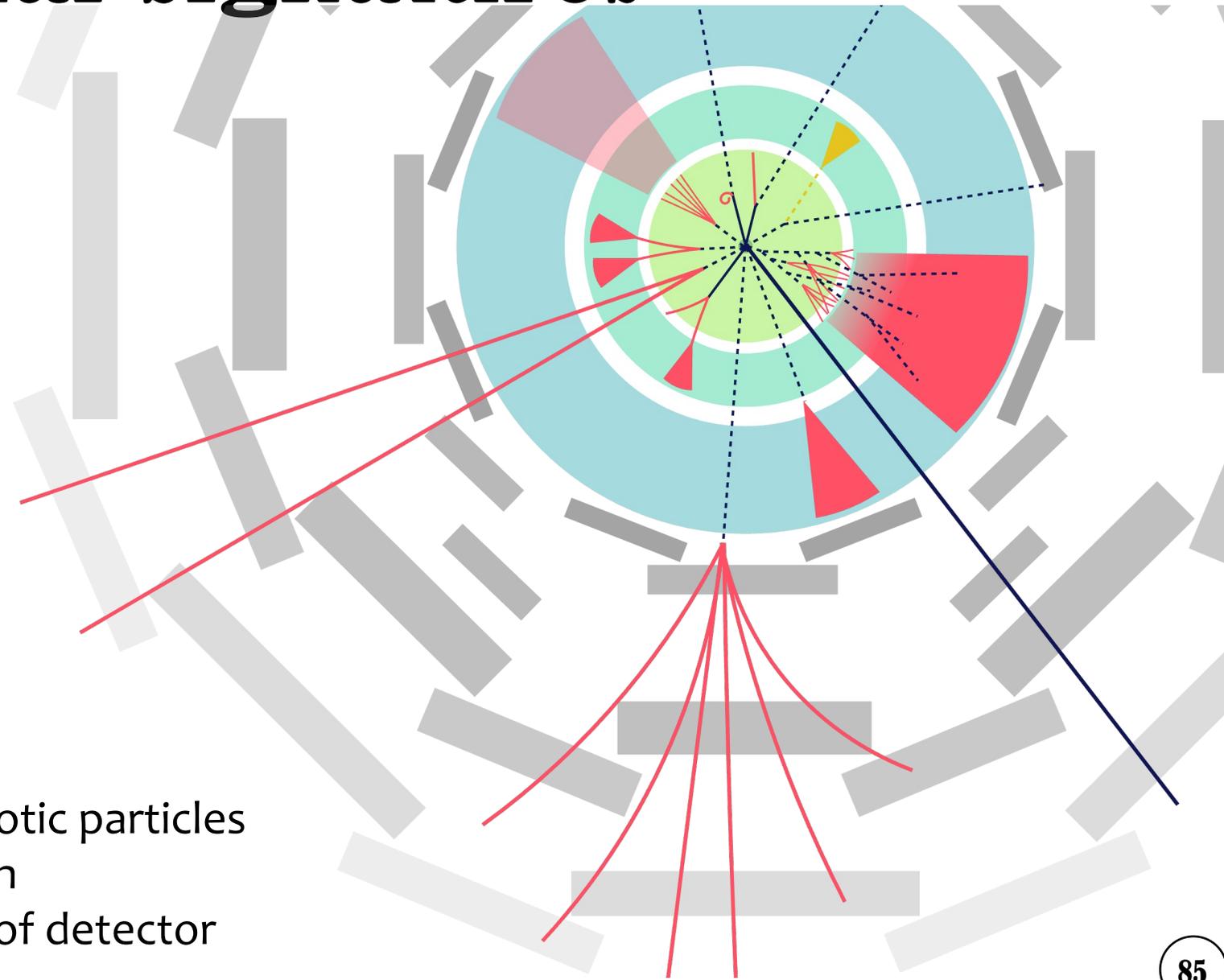


$$\frac{dN}{dt} = -\frac{N}{\tau}$$

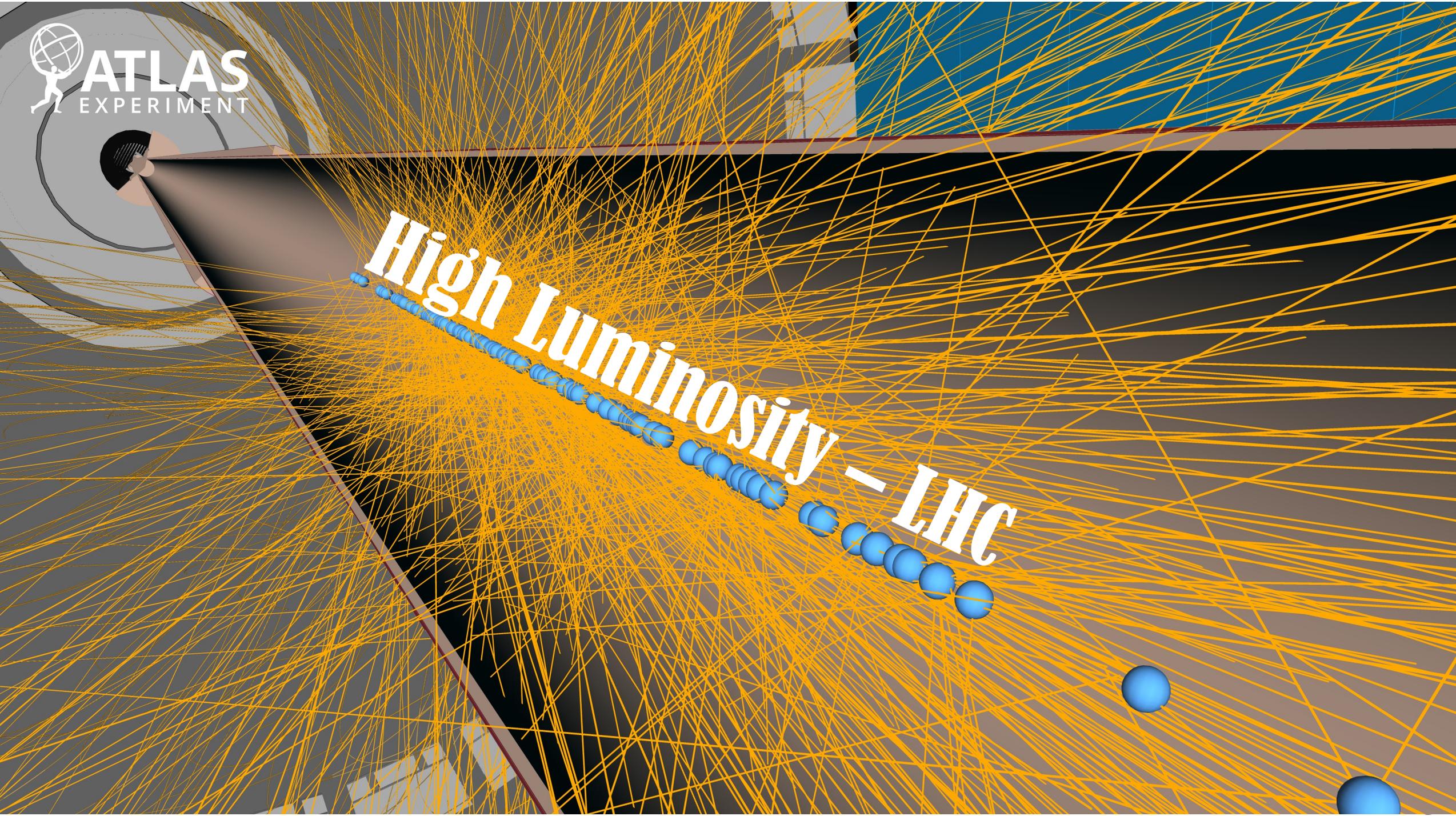
$$\Rightarrow N(t) = N_0 e^{-t/\tau}$$



Non-conventional Signatures



- Many interesting possibilities of exotic particles
- Unique challenges in reconstruction
- Possible with good understanding of detector



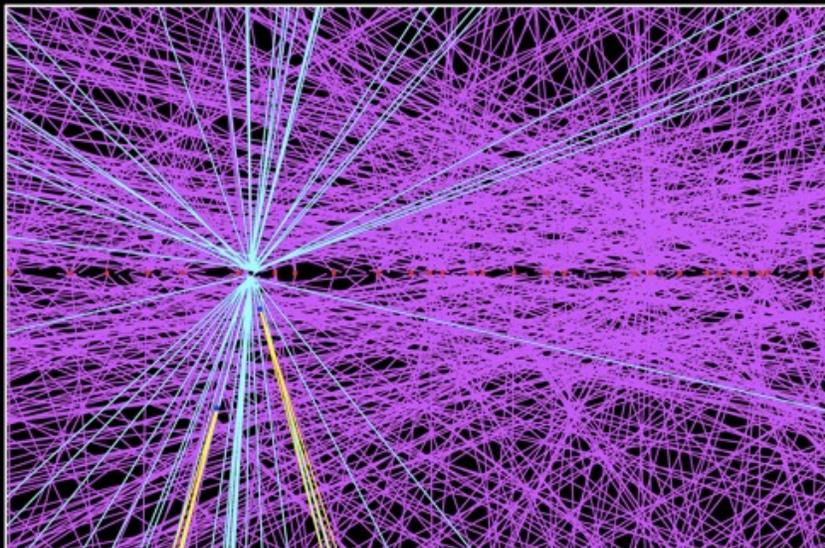
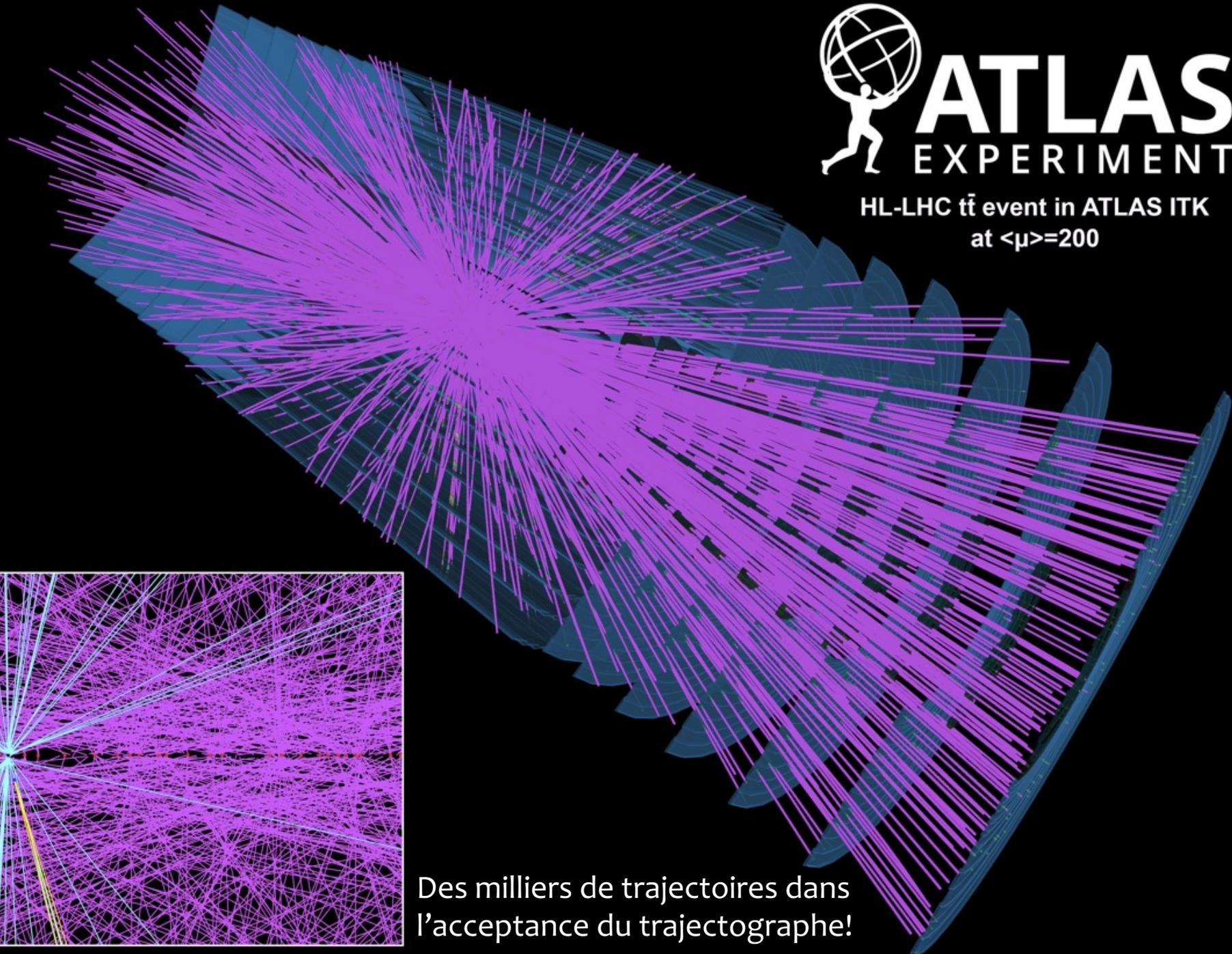
High Luminosity — LHC

The diagram illustrates the High Luminosity LHC (HL-LHC) project. It shows a cross-section of the LHC tunnel with a beam pipe. A dense stream of blue particles is shown entering from the left, and a dense stream of yellow particles is shown exiting to the right. The text 'High Luminosity — LHC' is written in a stylized font across the beam pipe. The background is a dark blue and black gradient with a grid pattern.



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!

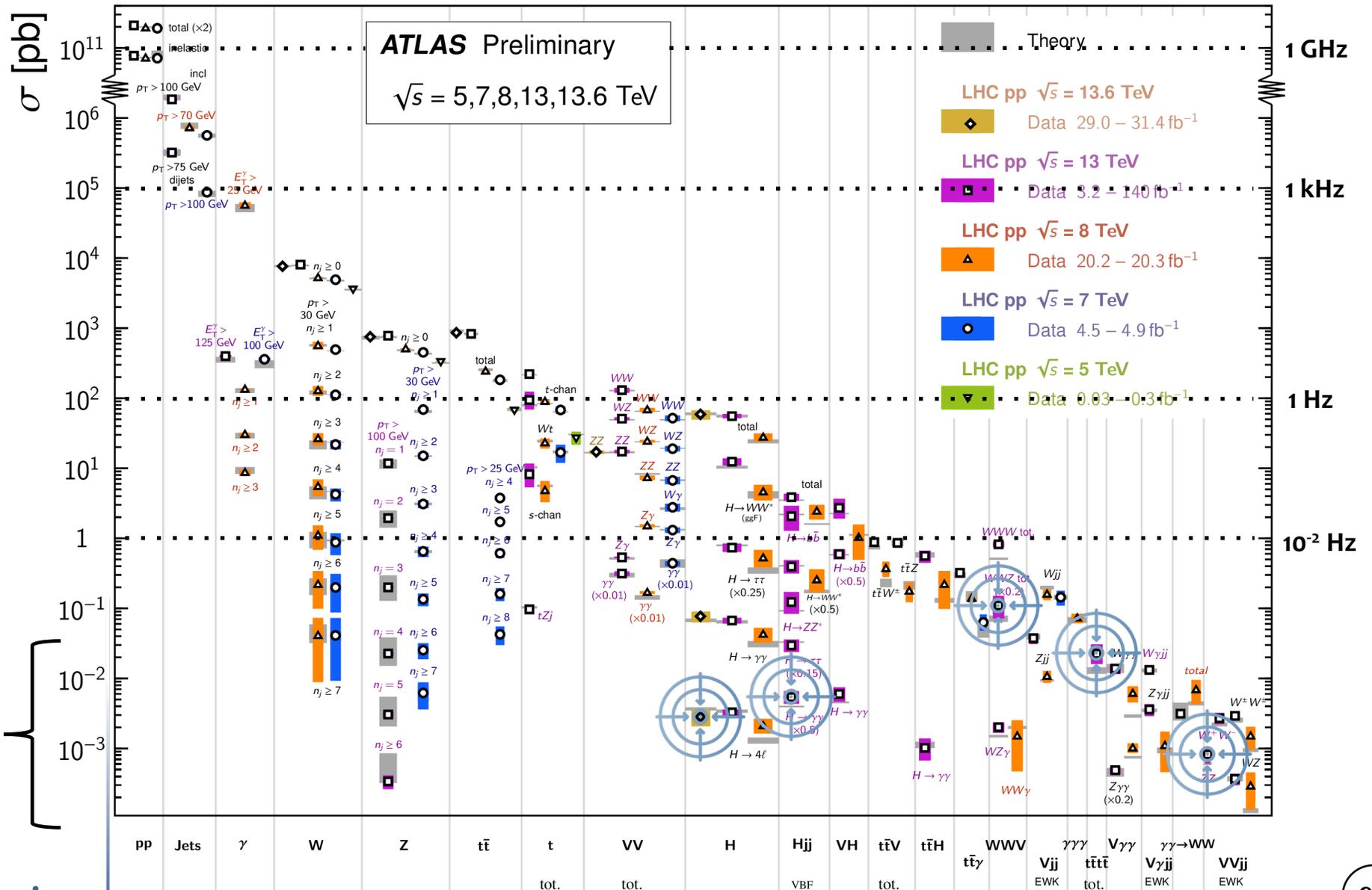
Objectifs physiques du HL-LHC: Précision & Exploration

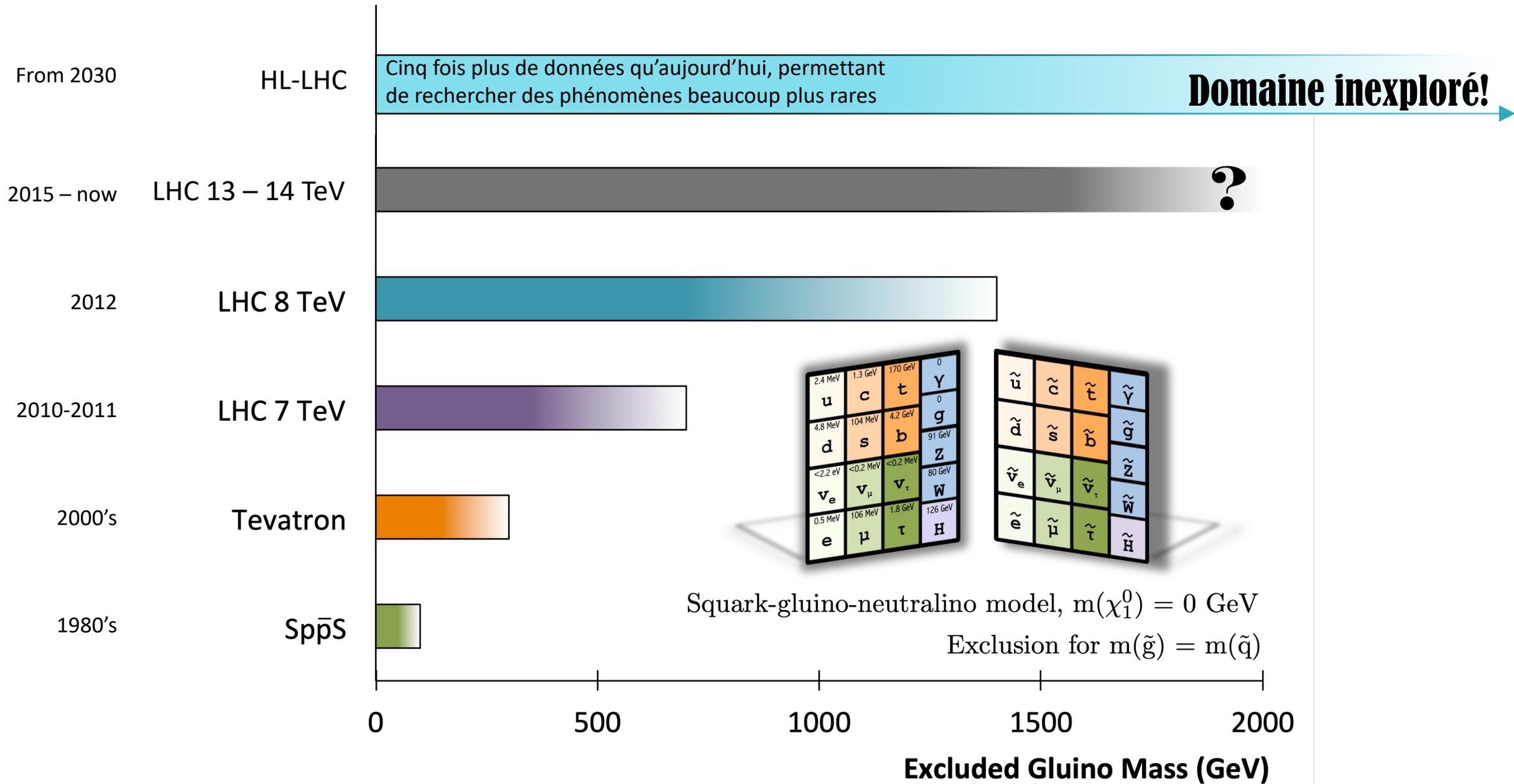
Certains aspects fondamentaux restent à explorer

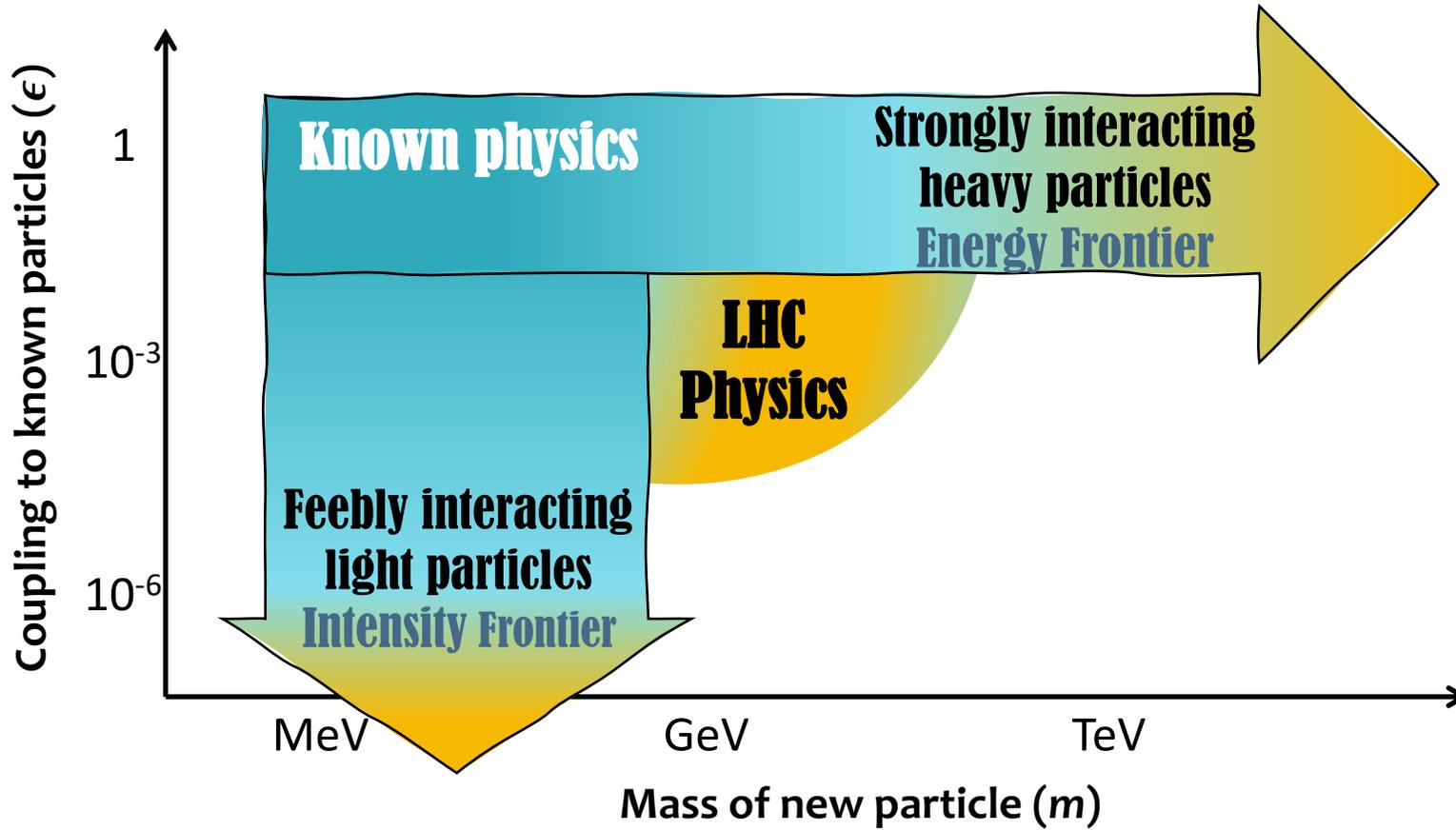
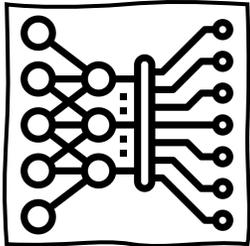
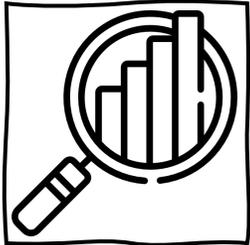
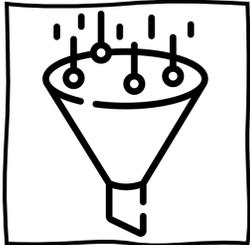
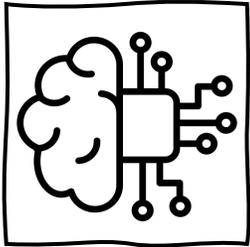


Nouvelle physique

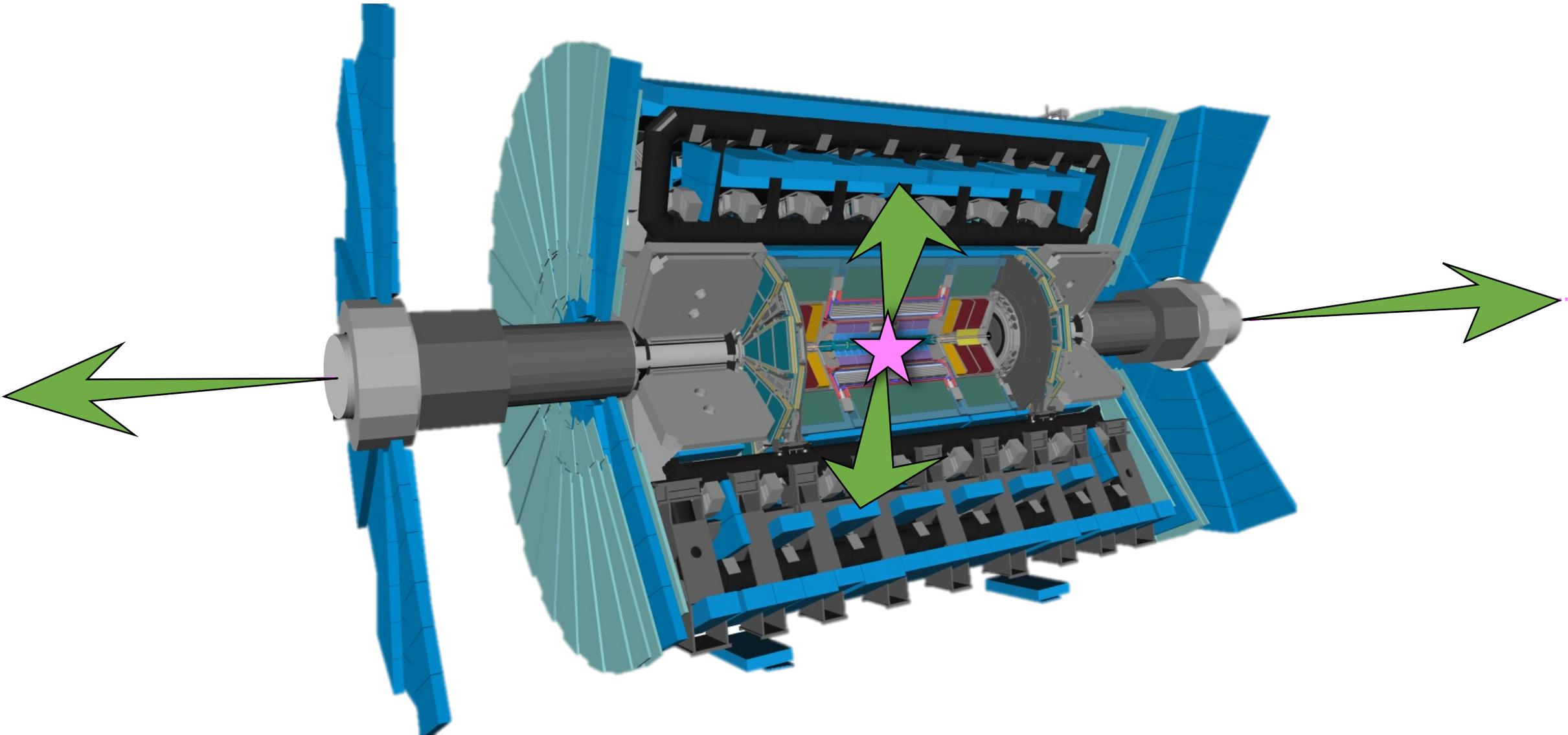
Standard Model Production Cross Section Measurements



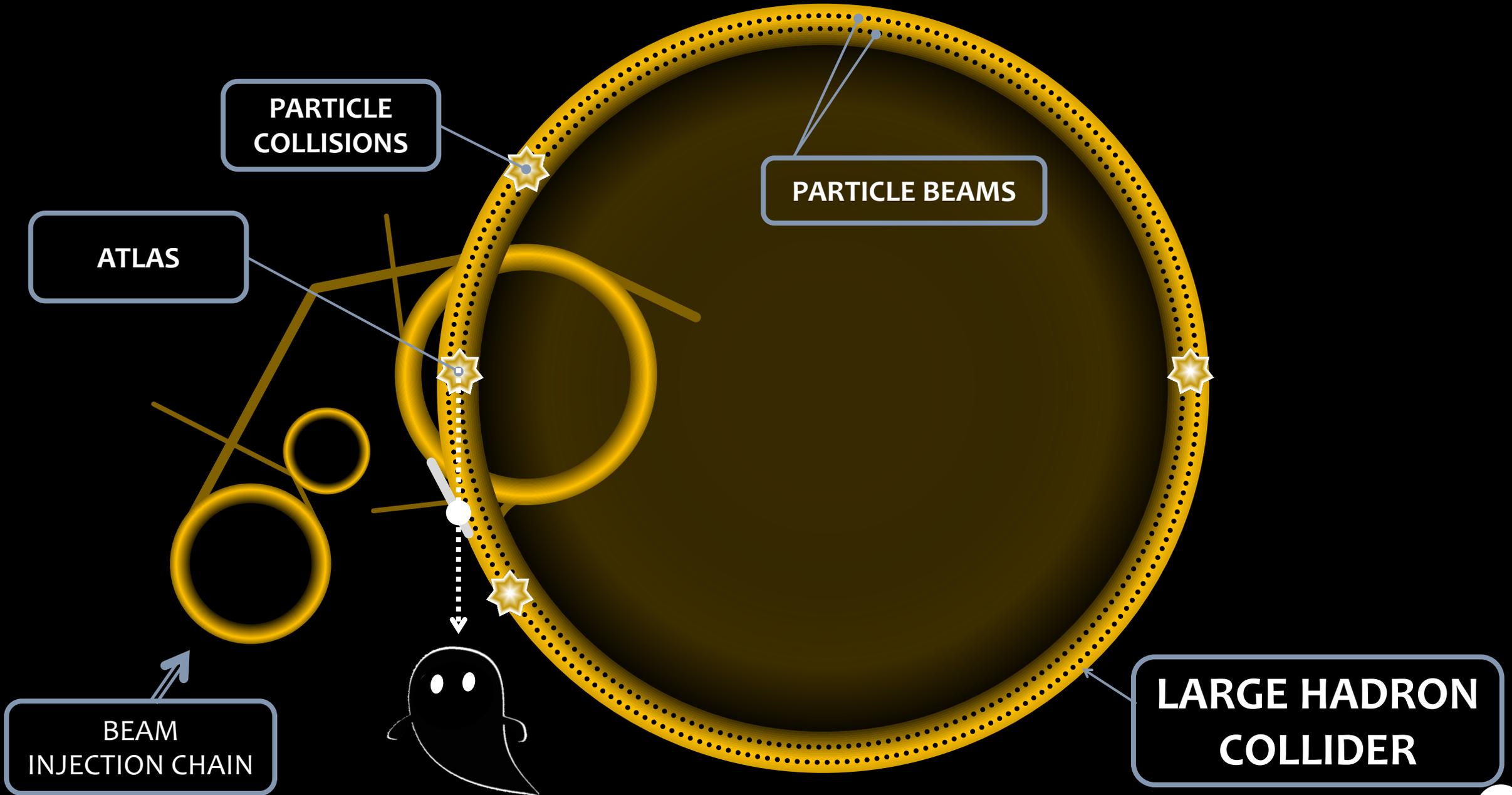


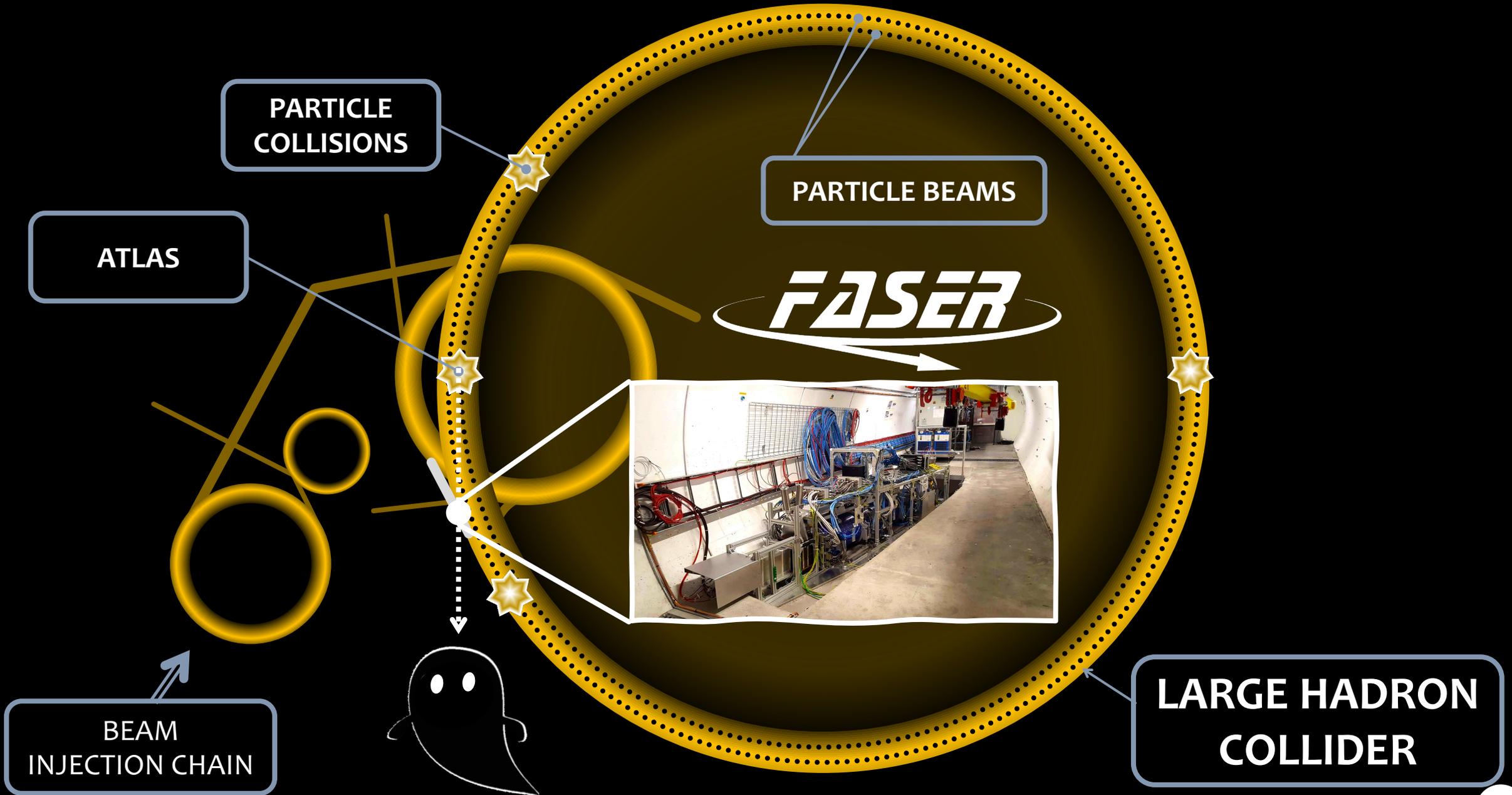


- 🎯 Améliorer l'instrumentation / diversifier les méthodes expérimentales
- 🎯 Collecter davantage de données
- 🎯 Explorer des énergies plus élevées



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







CMU 2t

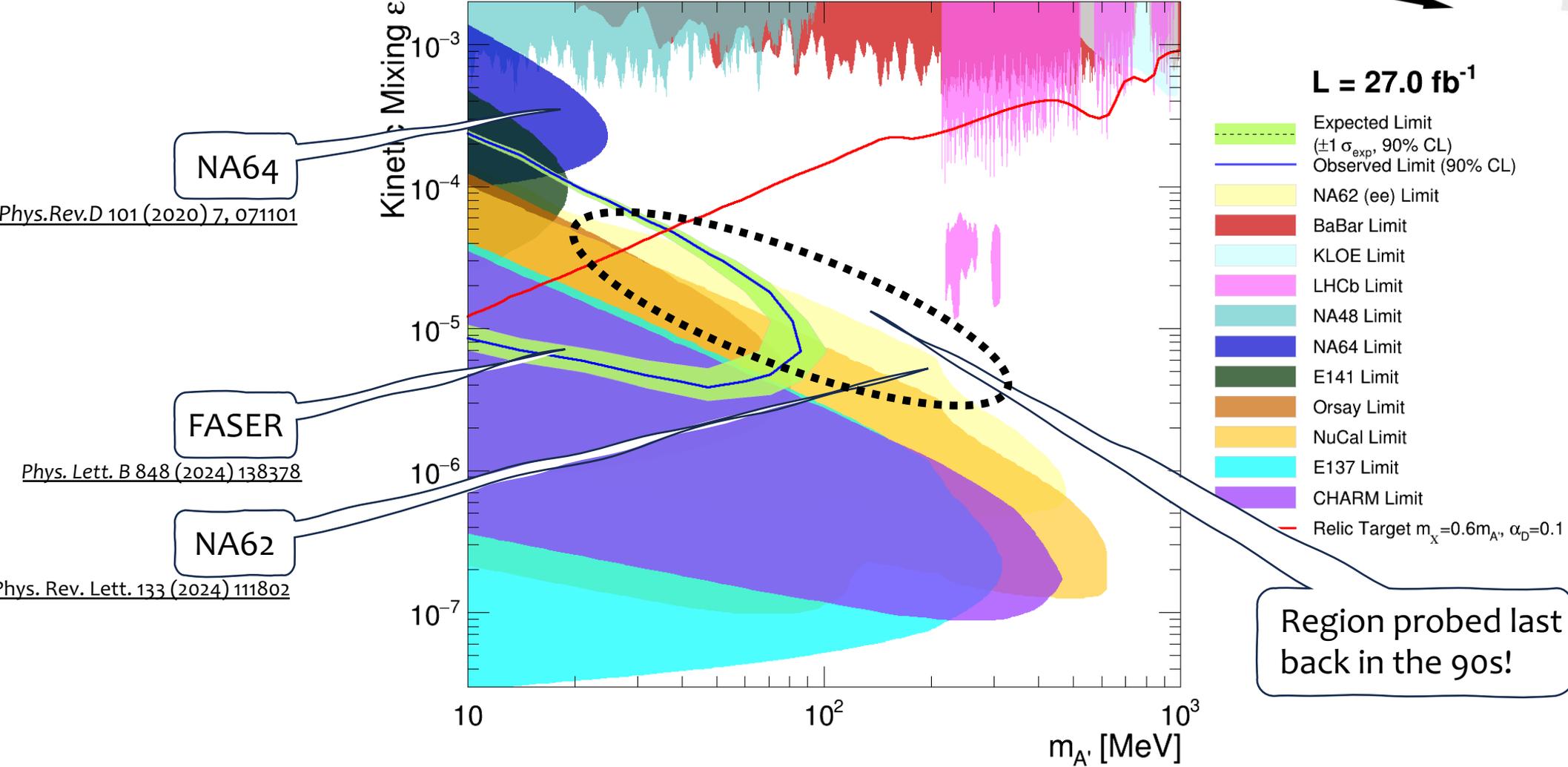
ATTENTION
TENSION
DANGER



FASER

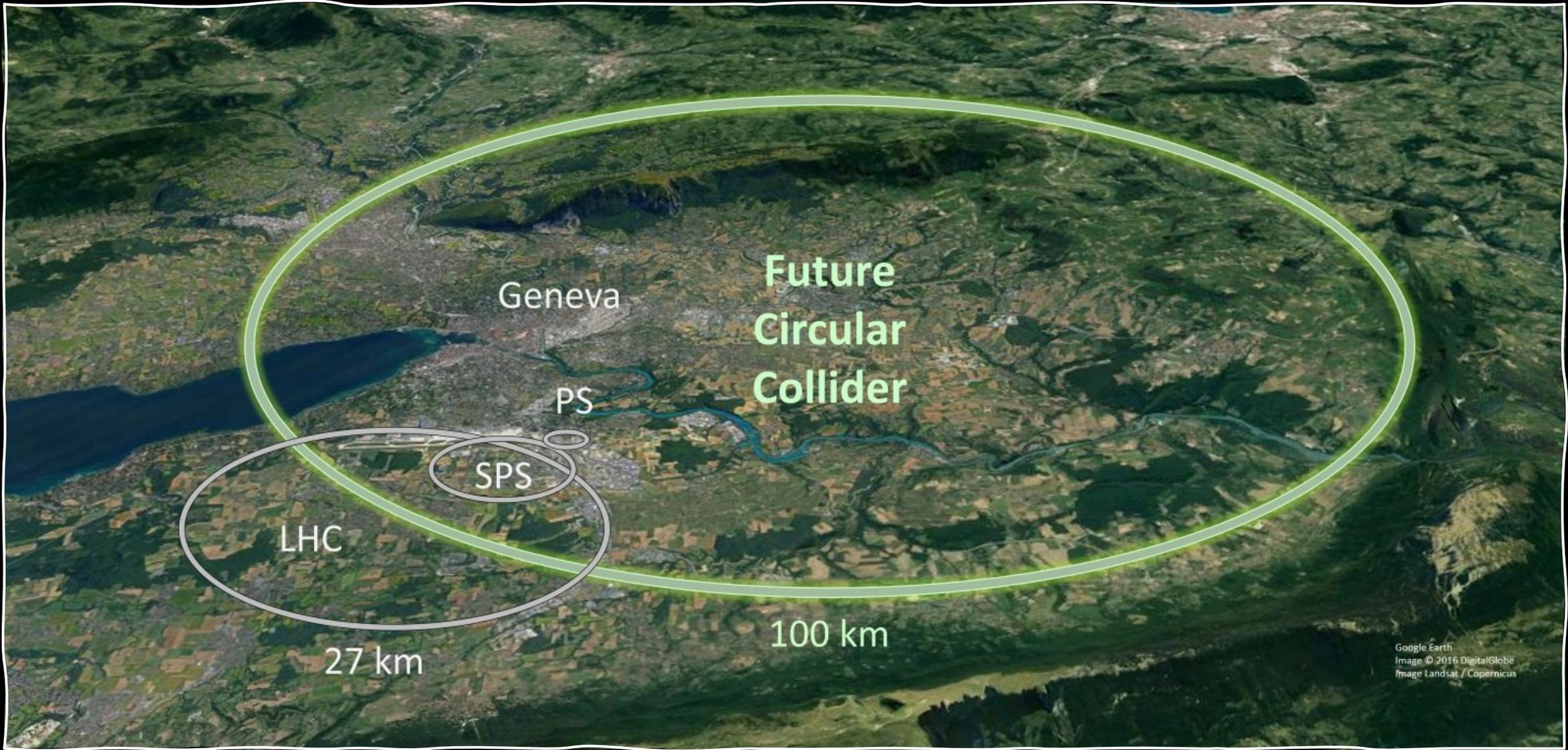
FASER

Searches for DARK Photons



Qu'y a-t-il au-delà du LHC ?





Geneva

Future
Circular
Collider

PS

SPS

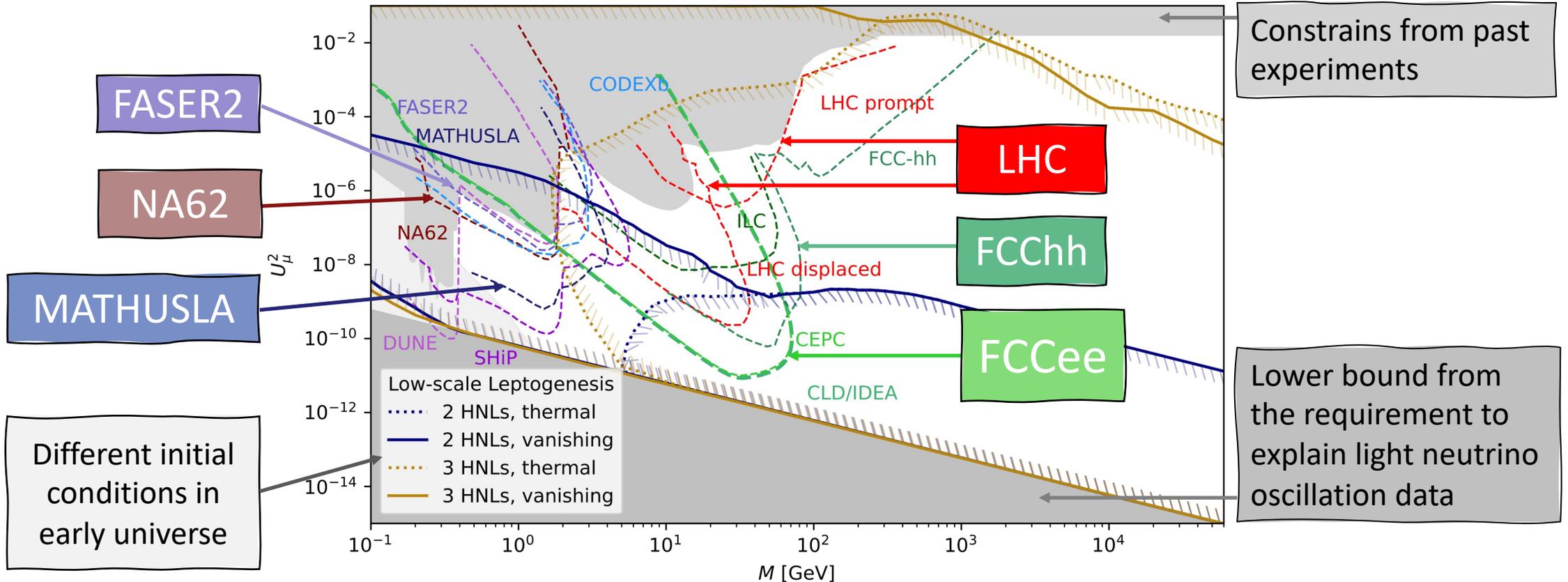
LHC

27 km

100 km

Google Earth
Image © 2016 DigitalGlobe
Image Landsat / Copernicus

Reach for heavy Neutral Leptons in future experiments



FCC-ee running at the Z-pole has the potential to exclude the region of masses and couplings down to the see-saw limit

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**.

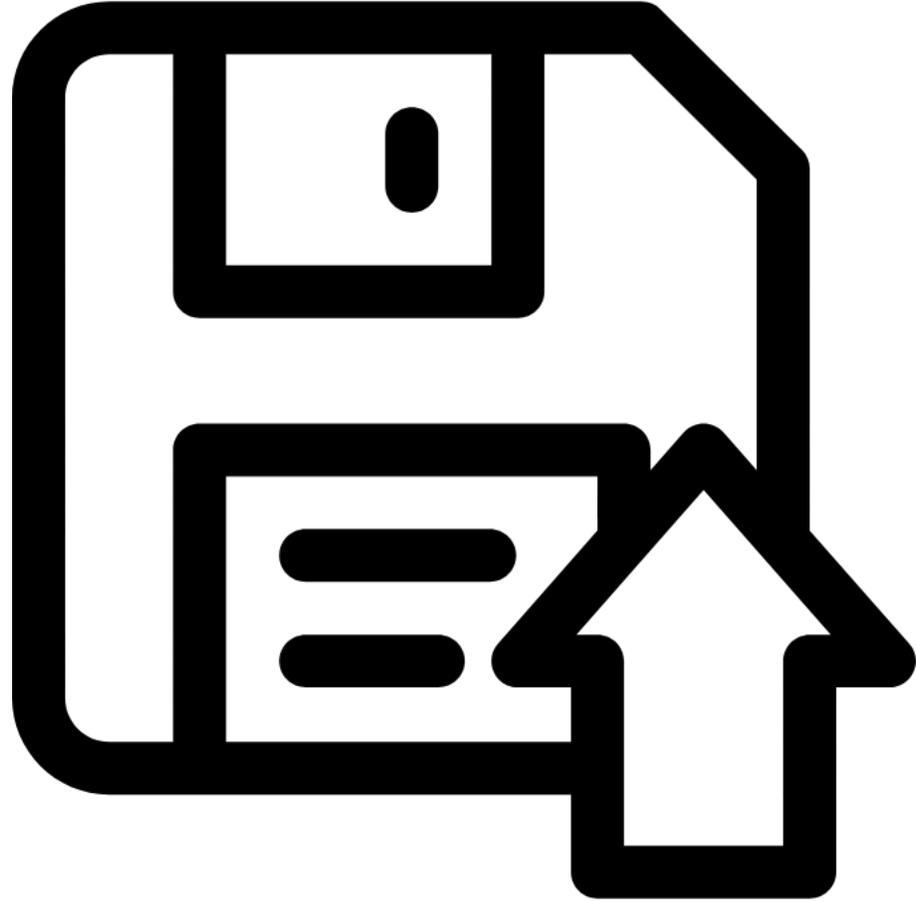
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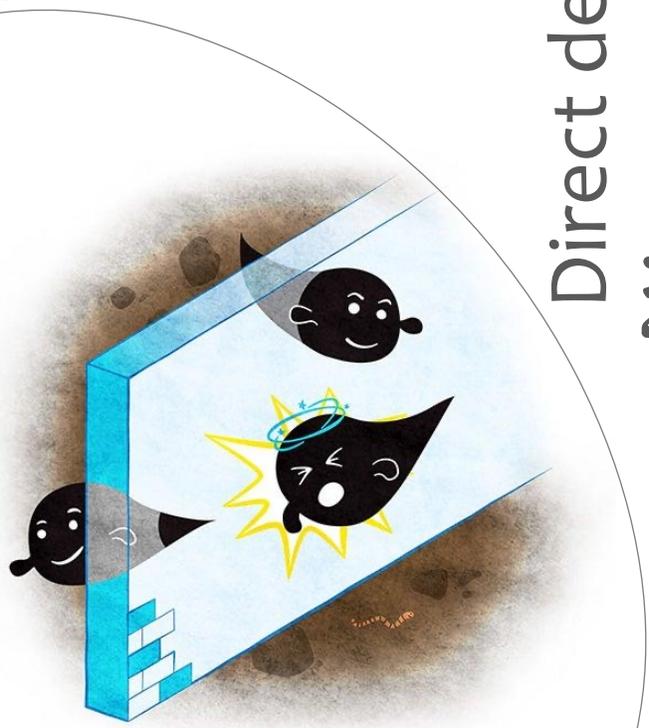






Direct detection

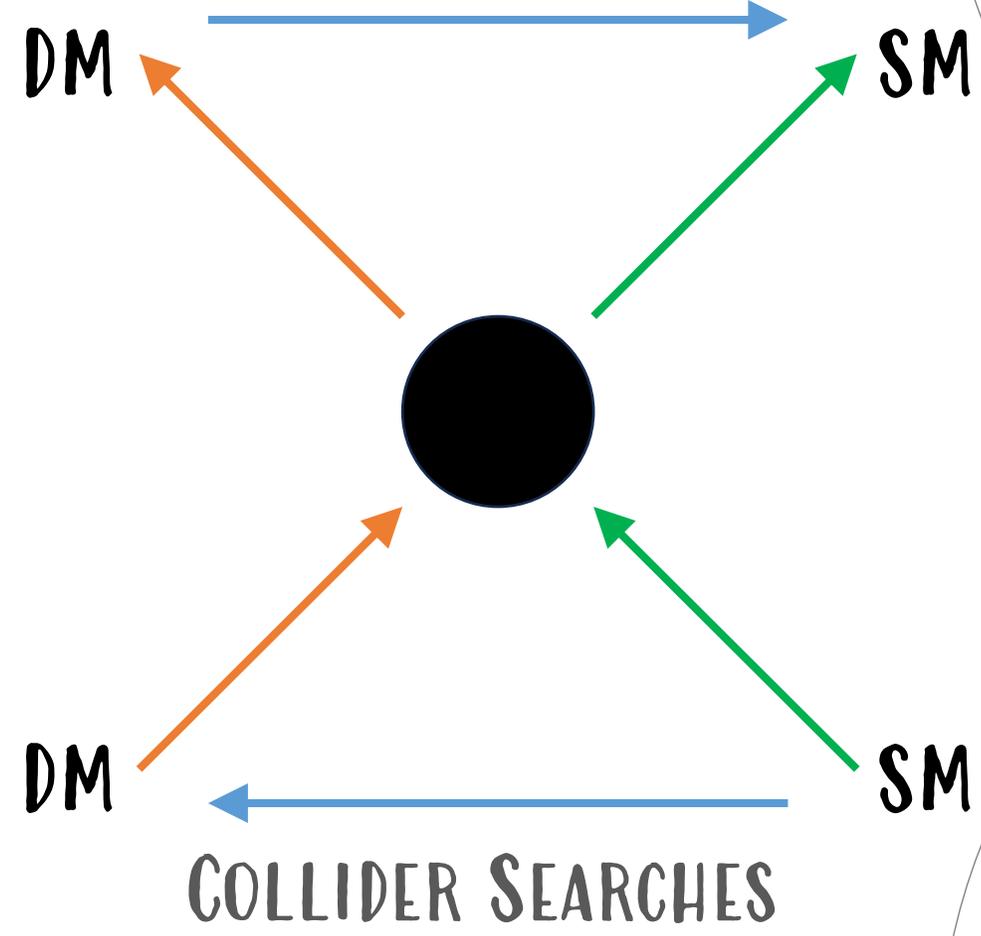
DM - NUCLEON SCATTERING



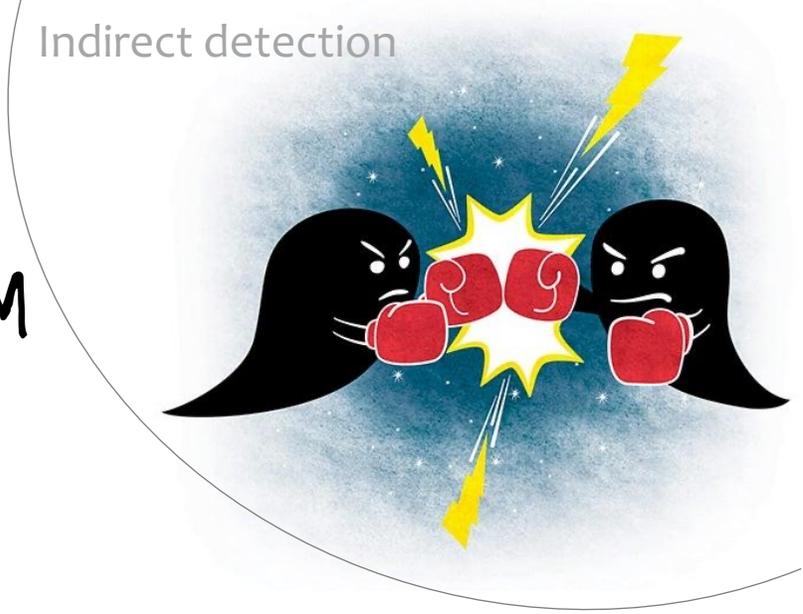
Direct detection

Indirect detection

DM ANNIHILATION



Indirect detection

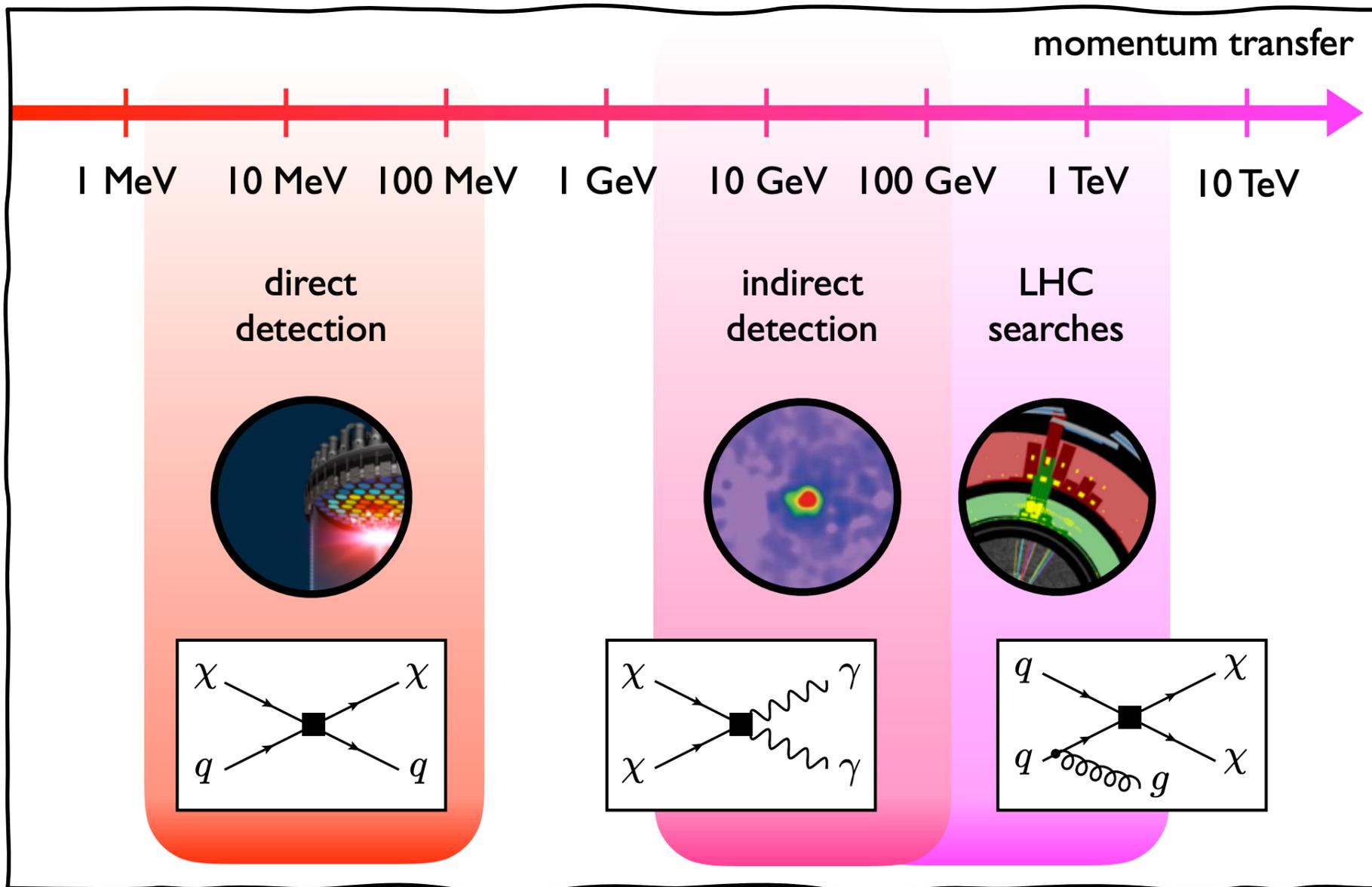


Collider searches

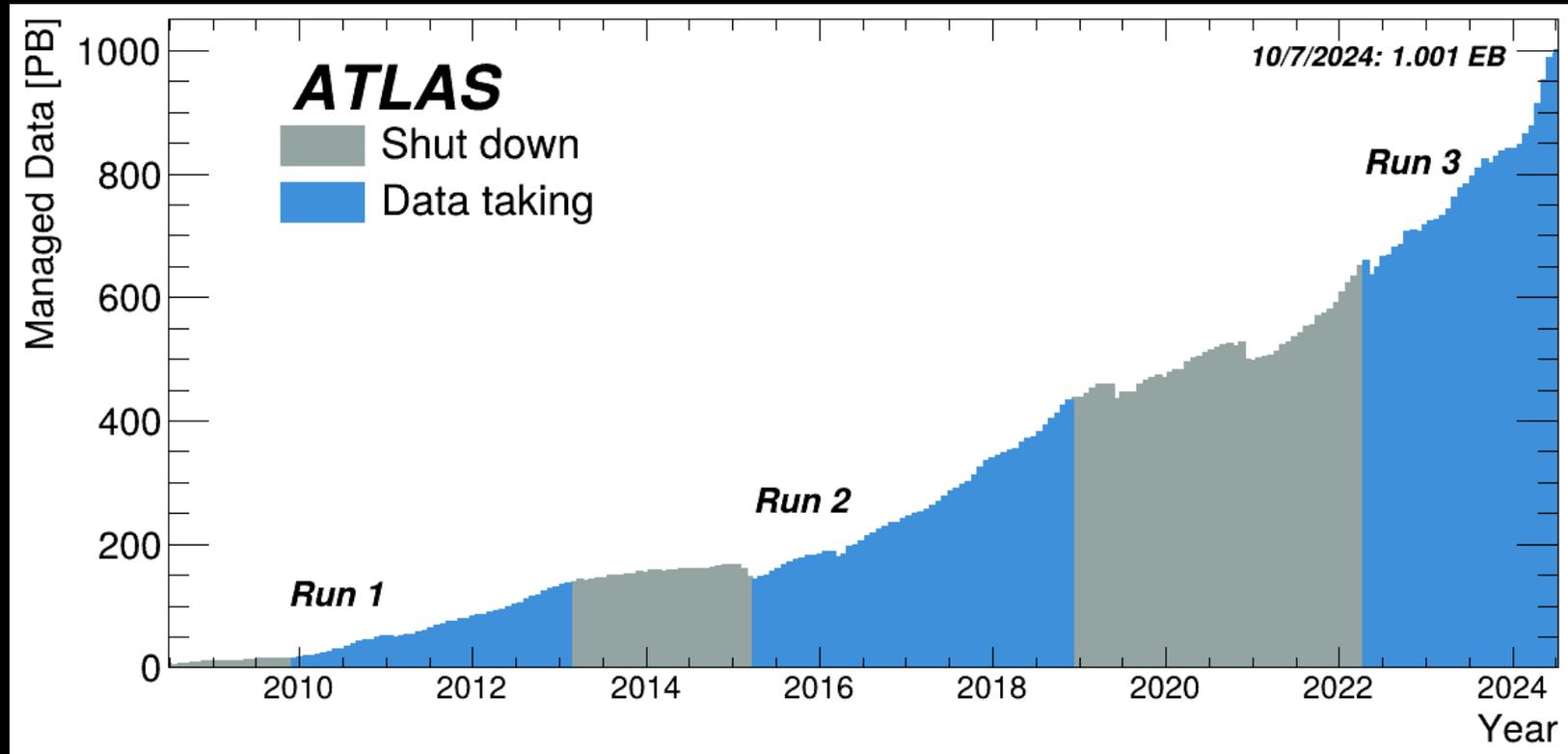
Drawings from

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

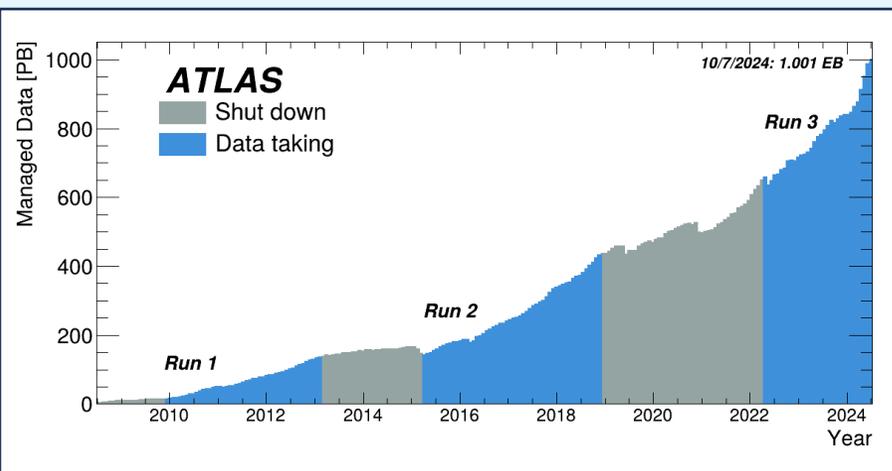
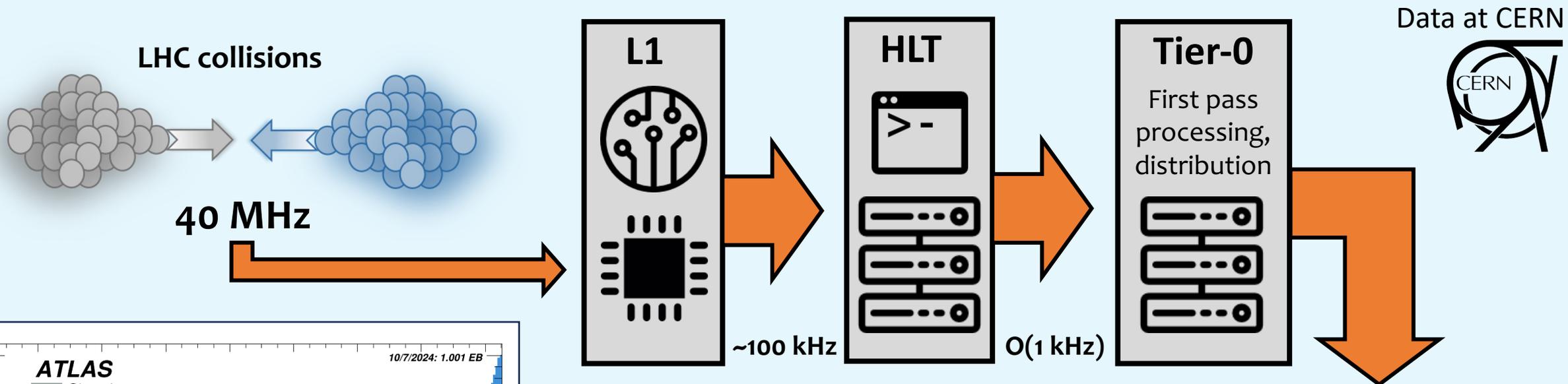




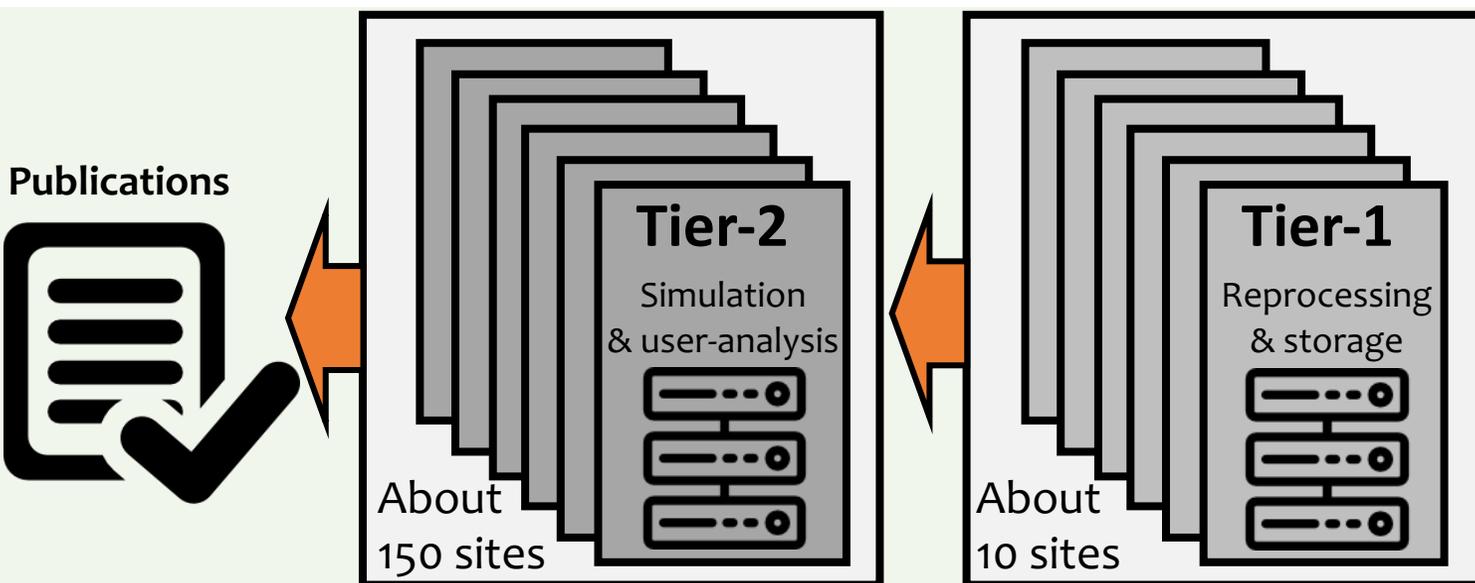
ATLAS Computing – data size



ATLAS Computing Path



Data in the world



Missing Transverse Momentum – ME_T



In the transverse plane:

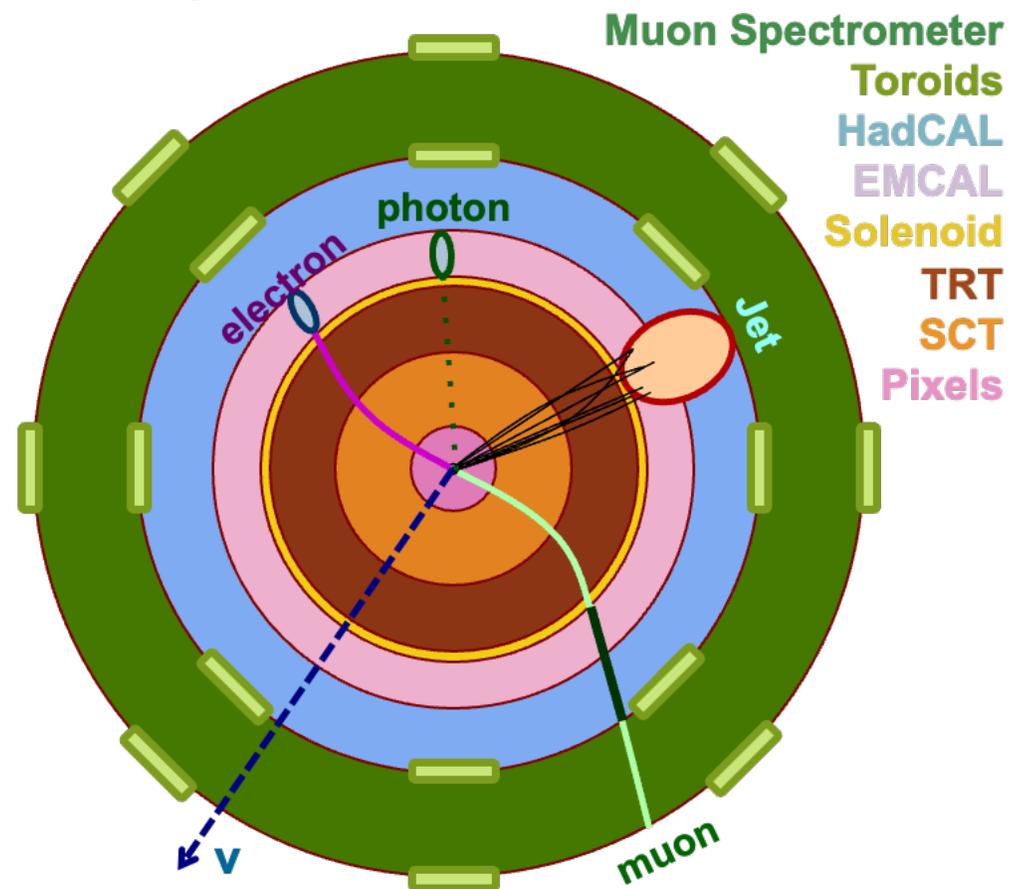
$$\sum_i \vec{p}_{T,i} = 0$$

OR DARK MATTER
CANDIDATES!

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

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

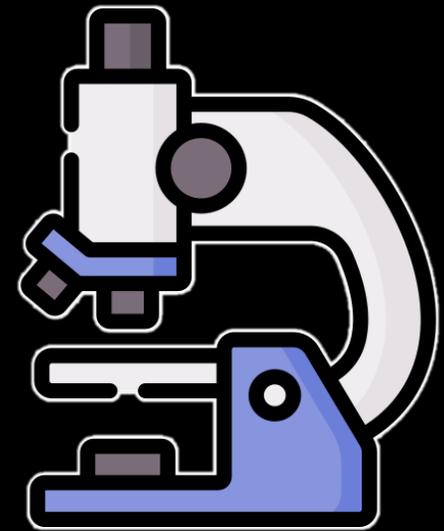
Simplified Detector Transverse View



INSTRUMENTS!

HOW DO WE “SEE” THE SMALLEST PARTICLES?

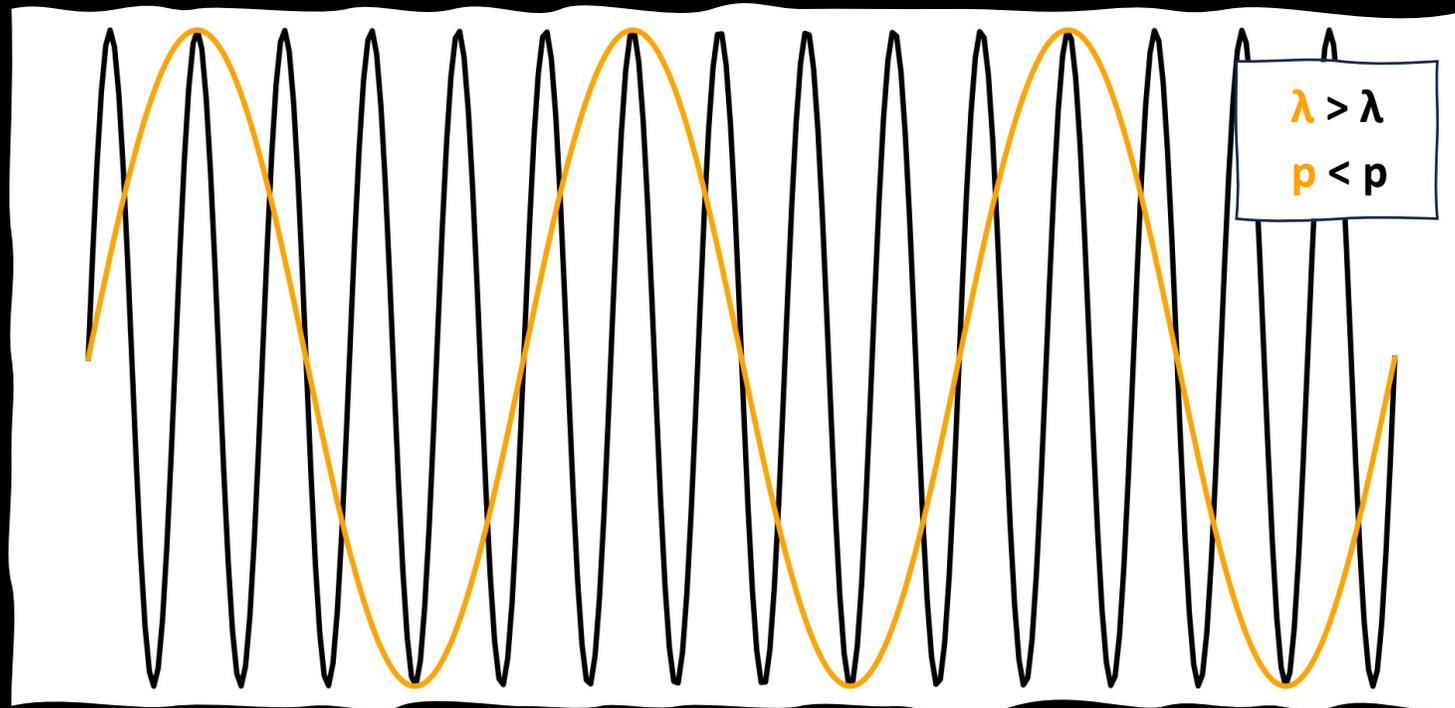
- Atoms are about 10^{-10} meters in size
- Protons are around 10^{-15} meters
- Elementary particles (like quarks and electrons) are even smaller — possibly point-like, with sizes below 10^{-18} meters.



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

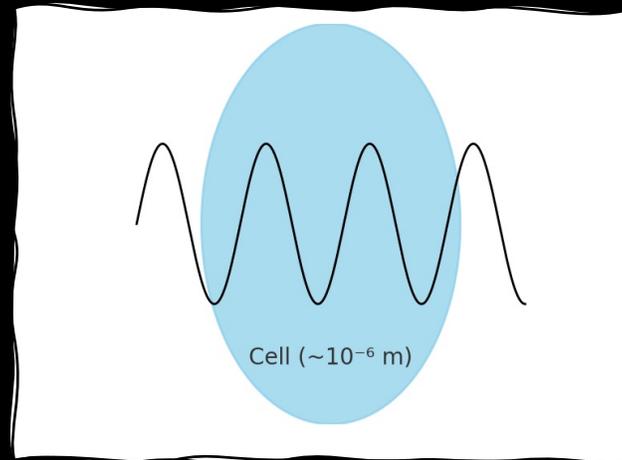
SMALL DISTANCE \Leftrightarrow HIGH ENERGY

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



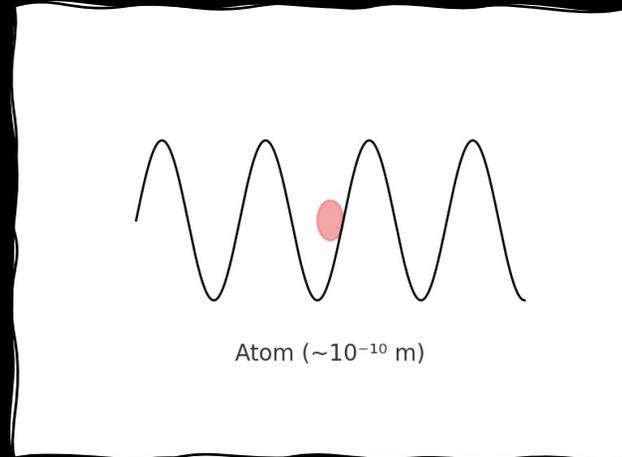
SMALL DISTANCE \Leftrightarrow HIGH ENERGY

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



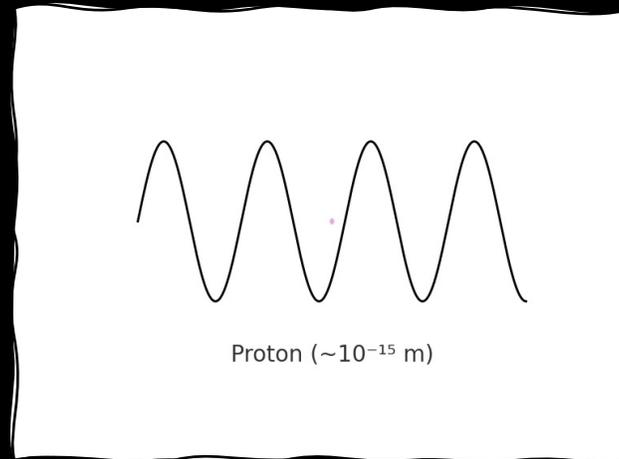
SMALL DISTANCE \Leftrightarrow HIGH ENERGY

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



SMALL DISTANCE \Leftrightarrow HIGH ENERGY

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



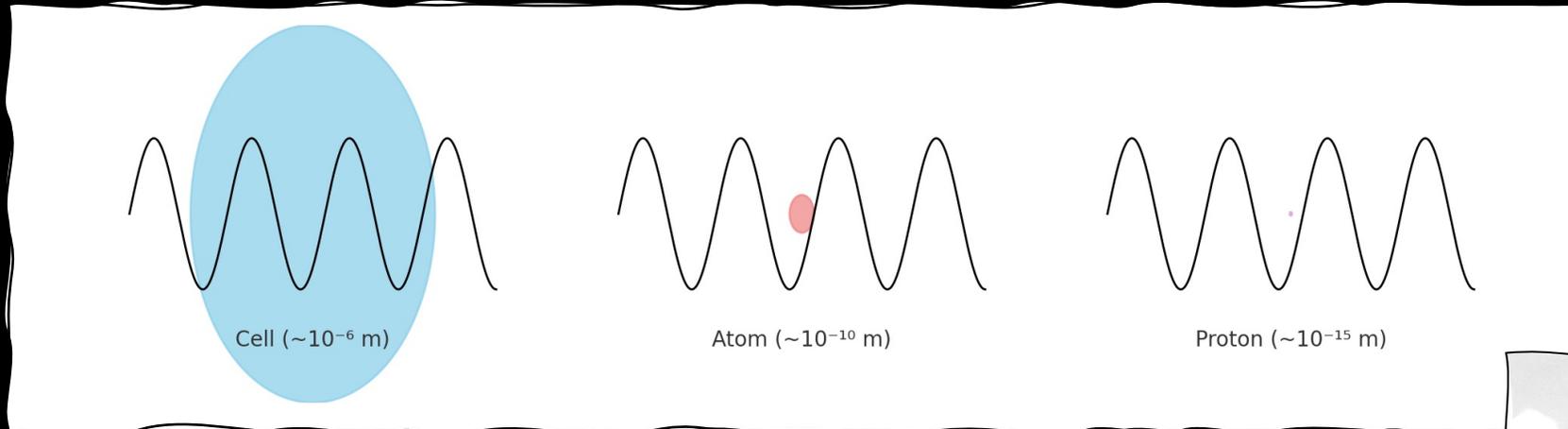
Rule of thumb: You can't see things smaller than the wavelength of the probe you're using.

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:

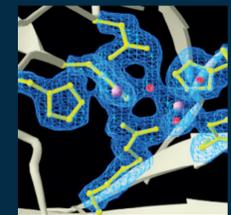


Superconducting magnetic energy storage

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

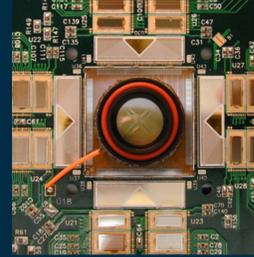
Hadron therapy

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.

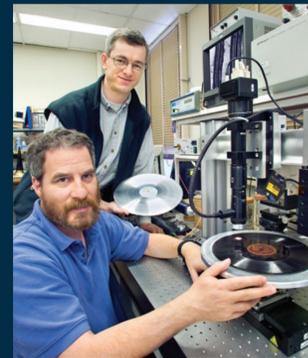
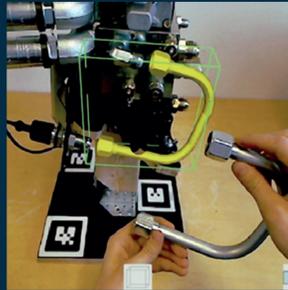


Retina project

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.

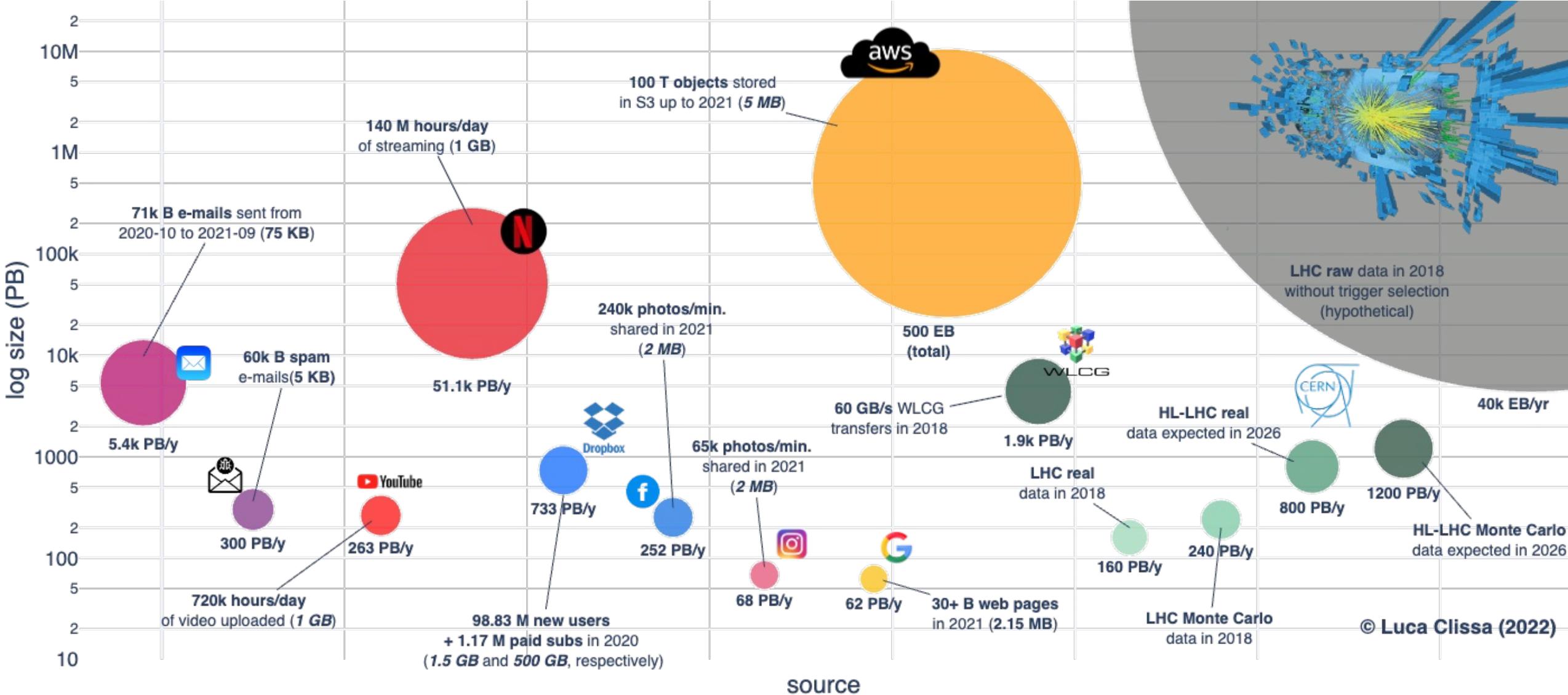
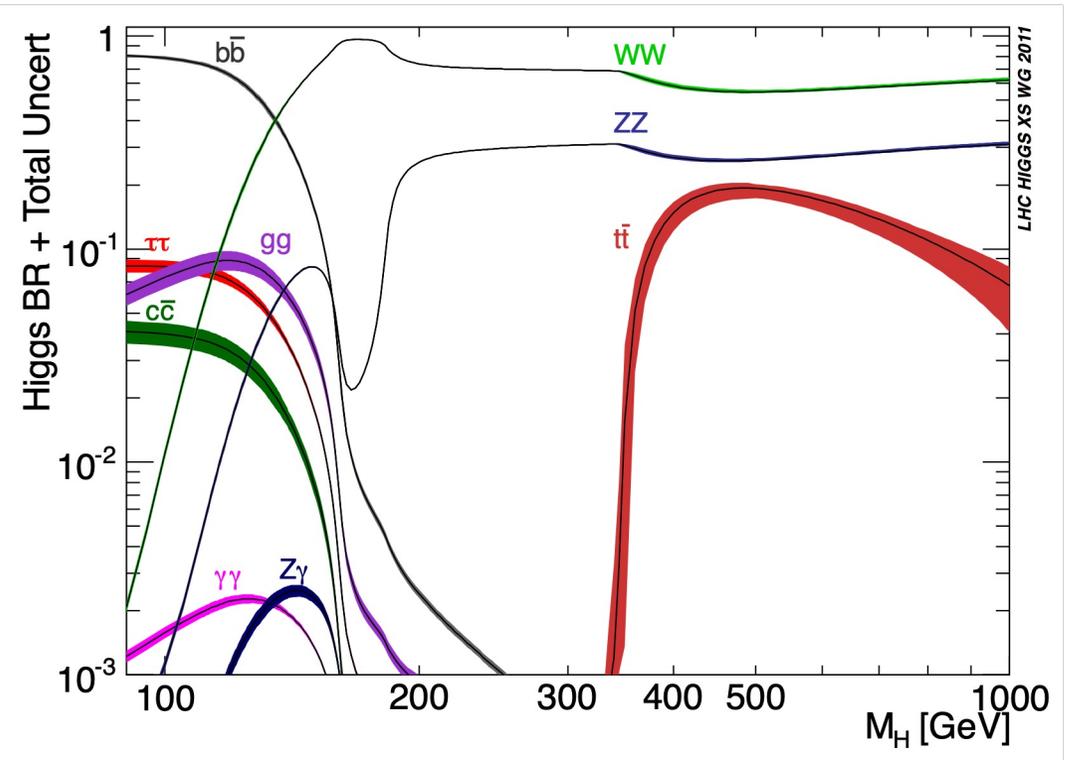
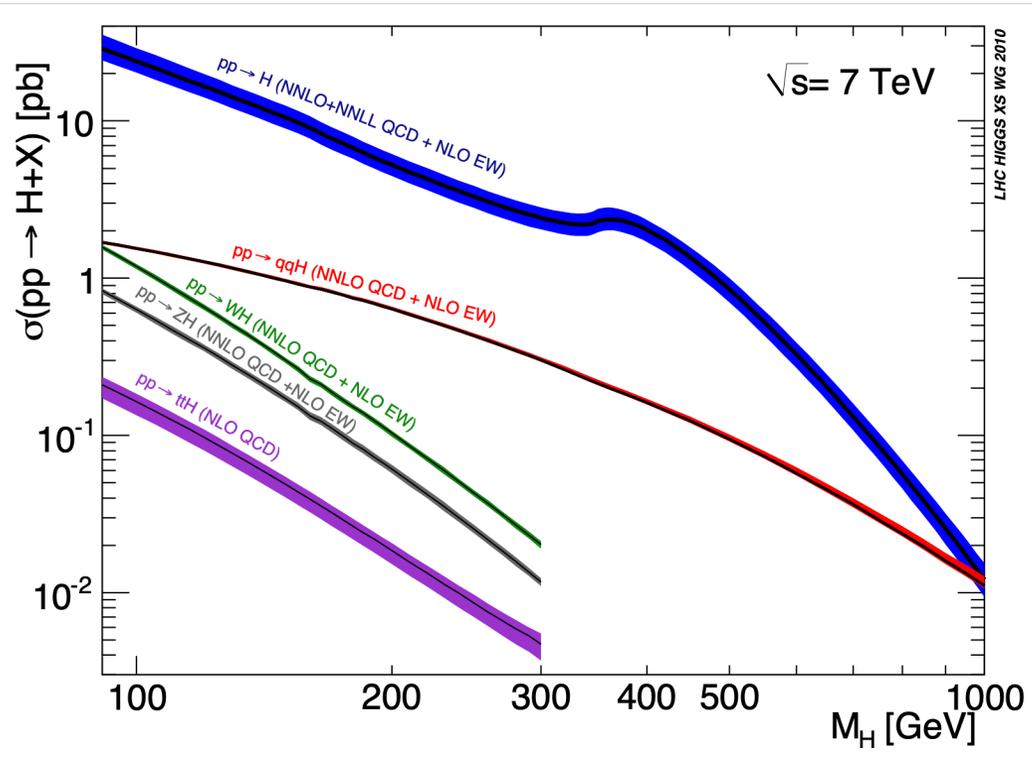


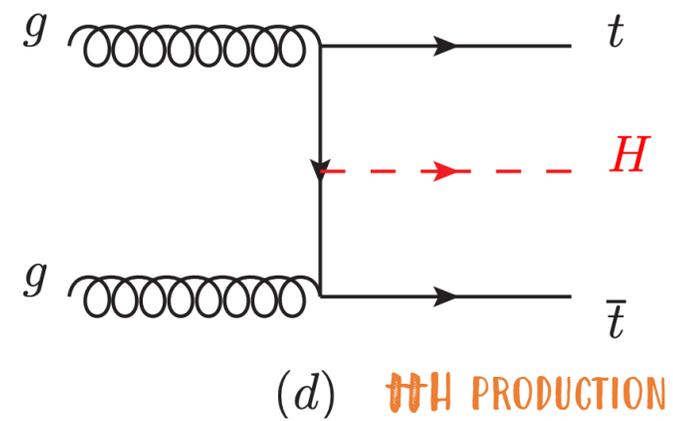
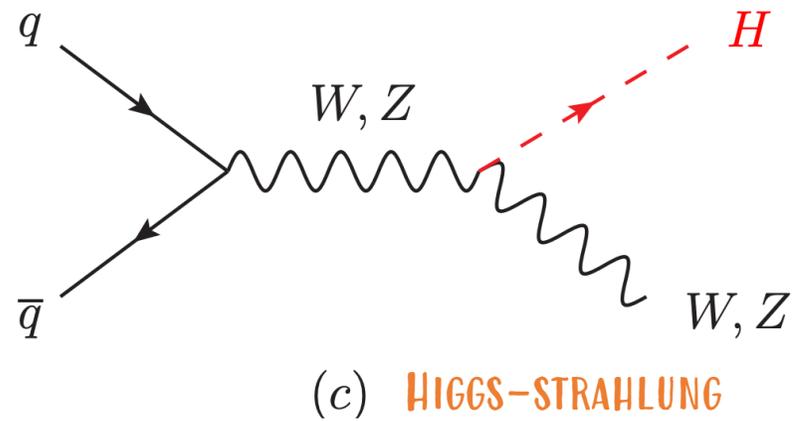
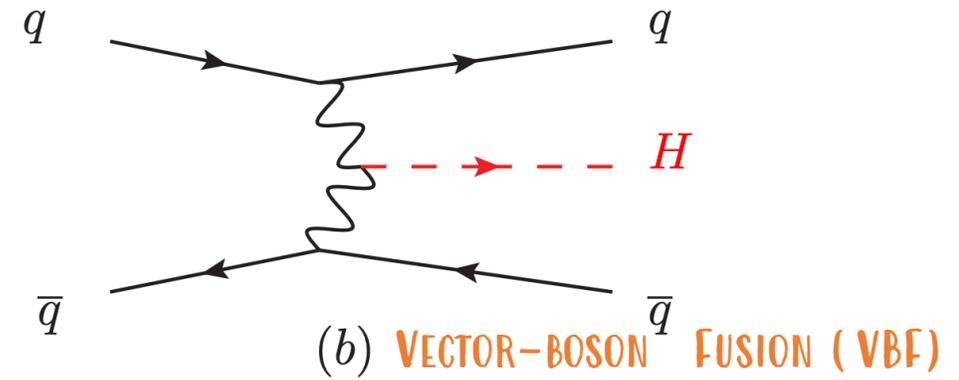
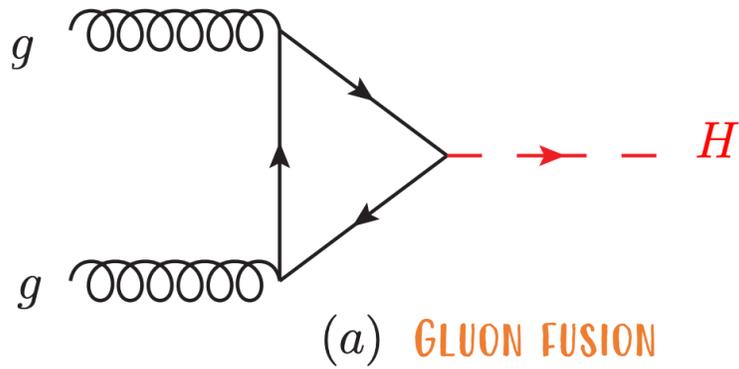
Figure 2.3: **Big Data sizes.** Bubble plot of the orders of magnitude of data produced by important big data players. The balloon areas illustrate the amount of data and the text annotations highlight the key factors considered in the estimates. Average per-unit sizes are reported in parentheses, where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

Theory – before the discovery



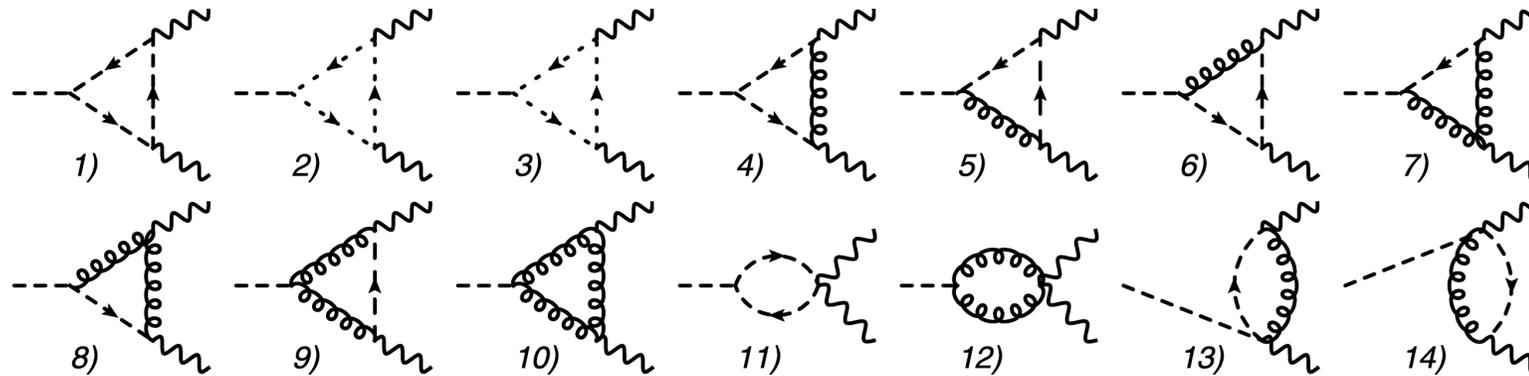
WHERE IS THE HIGGS??

Production mechanisms



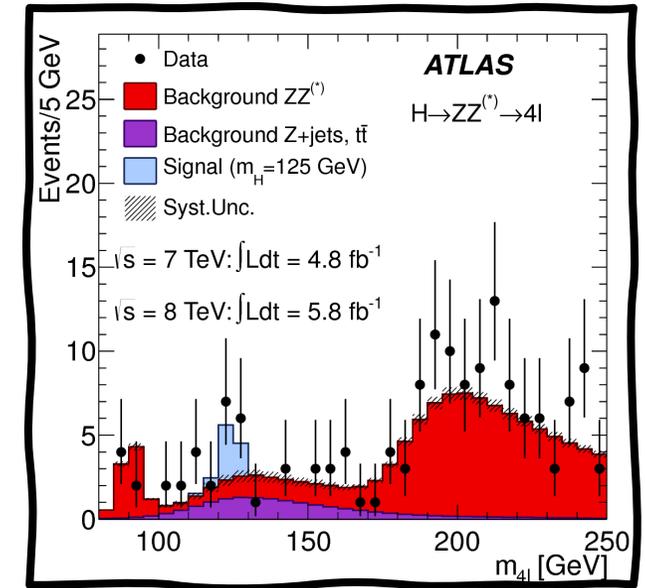
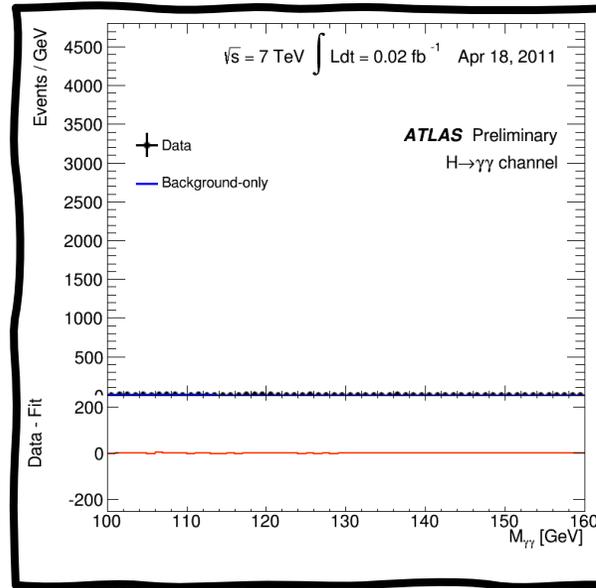
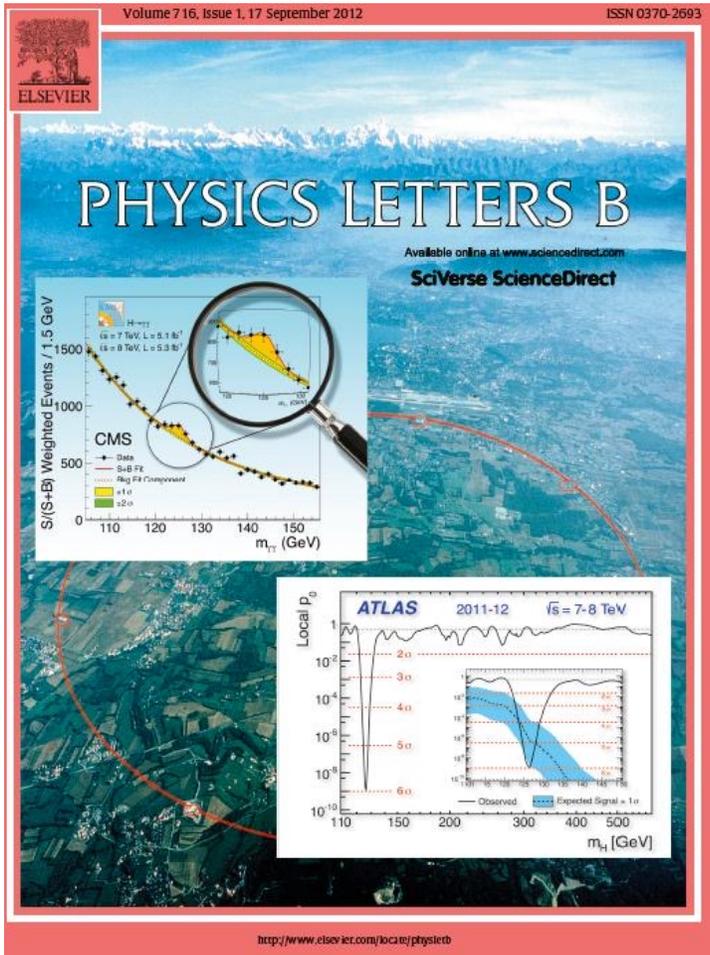
Higgs Decays

$H \rightarrow \gamma\gamma$

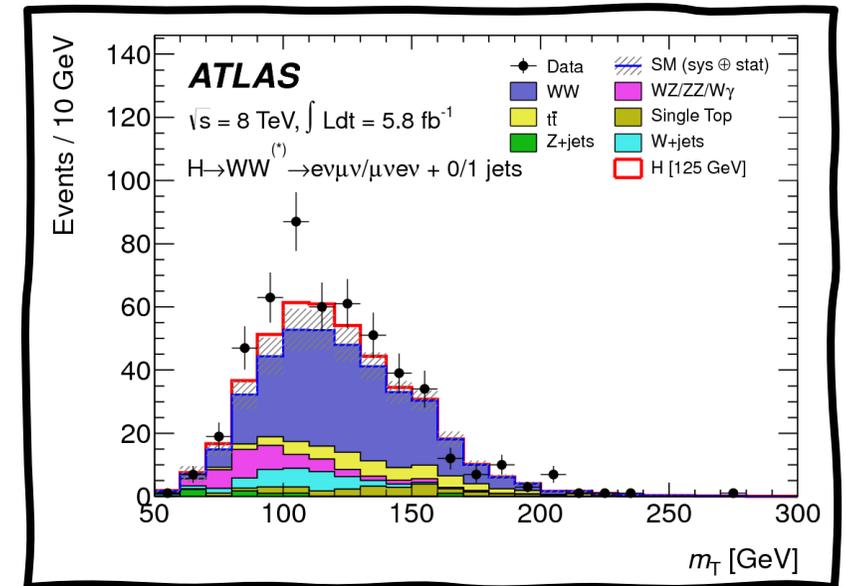


One-loop diagrams of the W-boson loop contribution in the Higgs [boson](#) decay into two photons. Crossed diagrams are not shown. Curved, wiggled, dashed, dashed with arrows and dotted lines correspond to the photon, W-boson, Higgs scalar, [Goldstone bosons](#) and the Faddeev–Popov ghosts, respectively.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

The Higgs Discovery

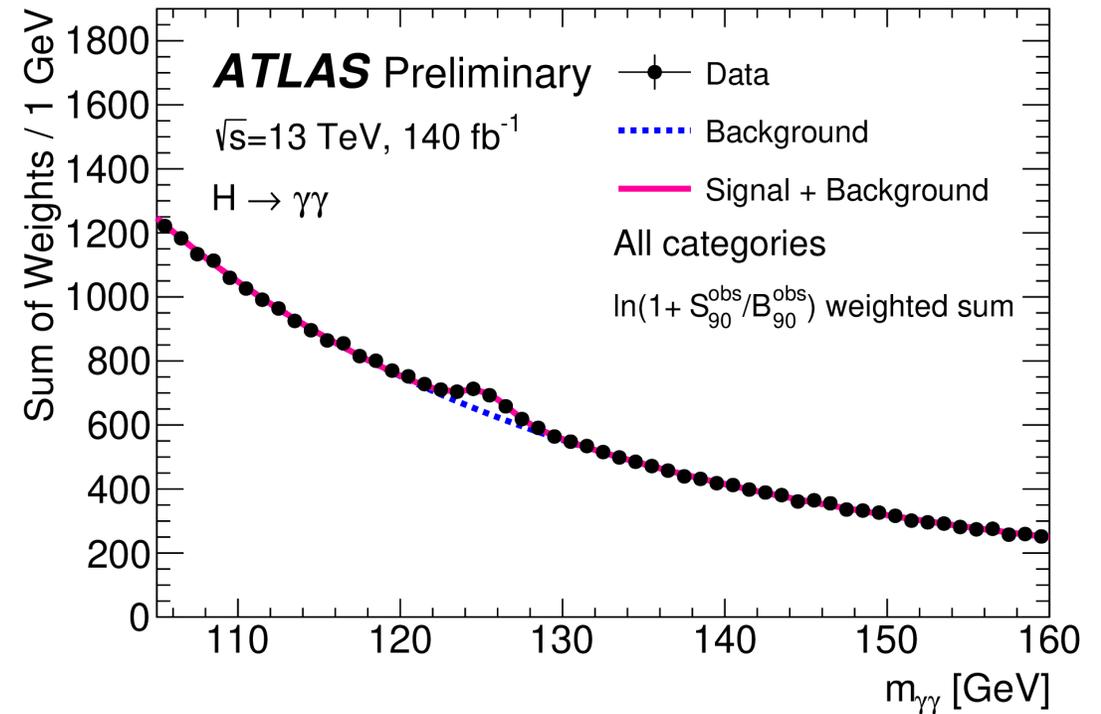
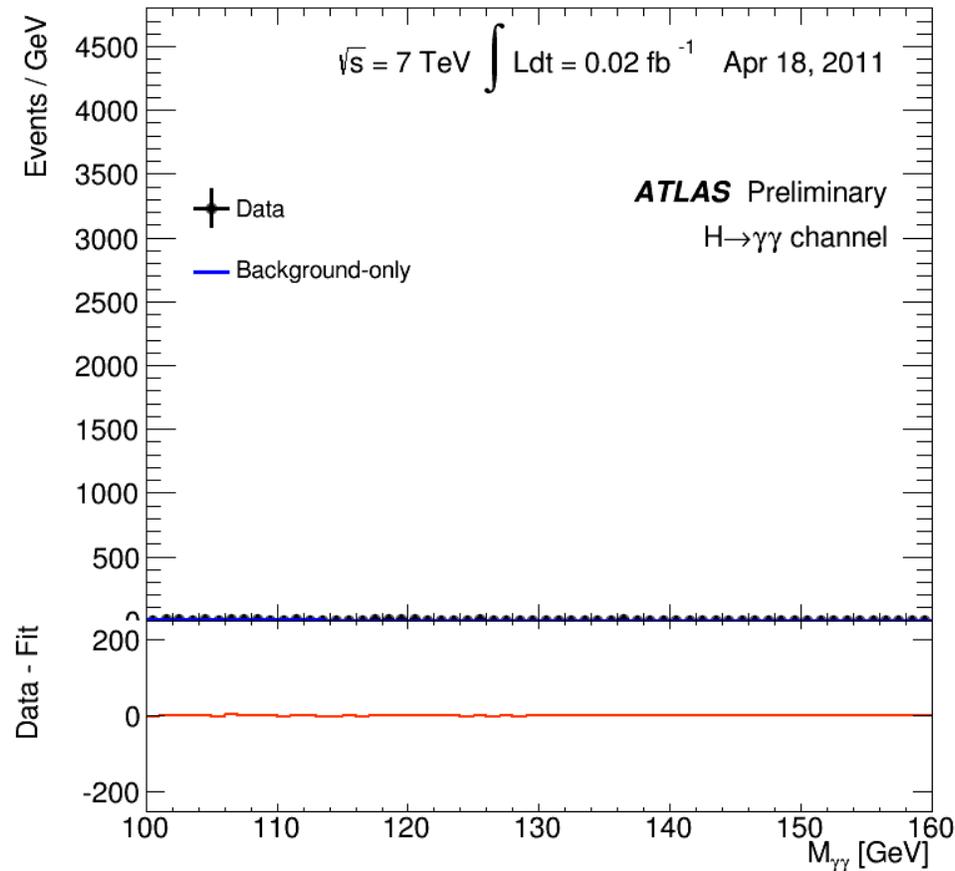


The three channels that contributed to the discovery



Higgs discovery (in photon final states)

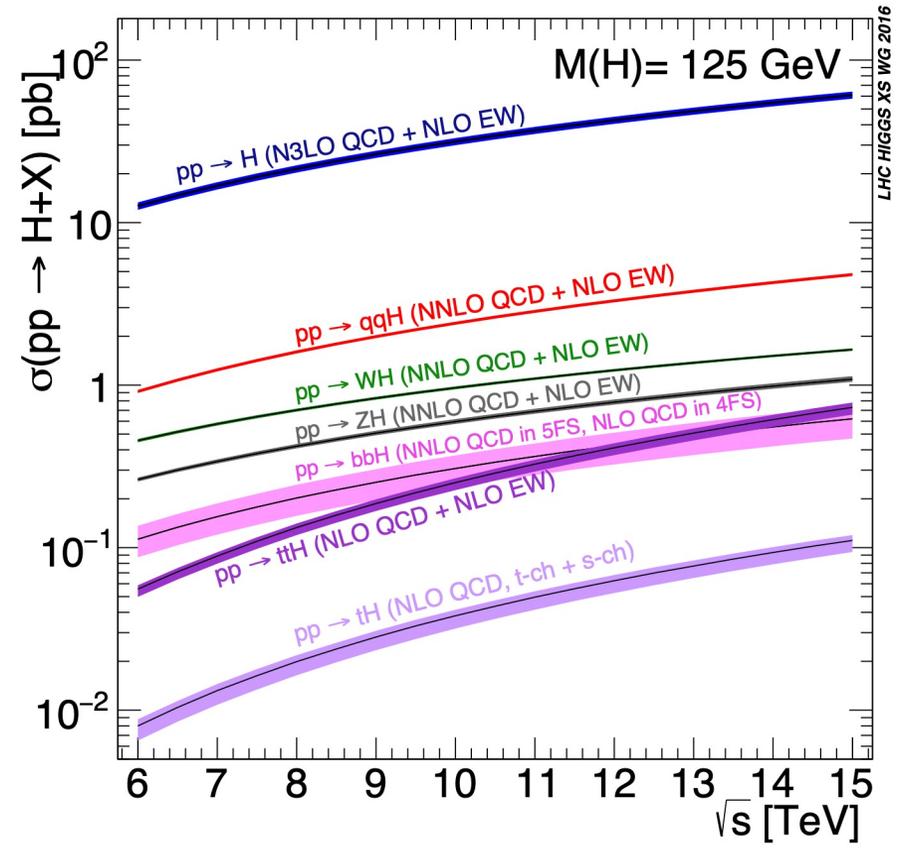
among those used to discover the Higgs boson...



...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

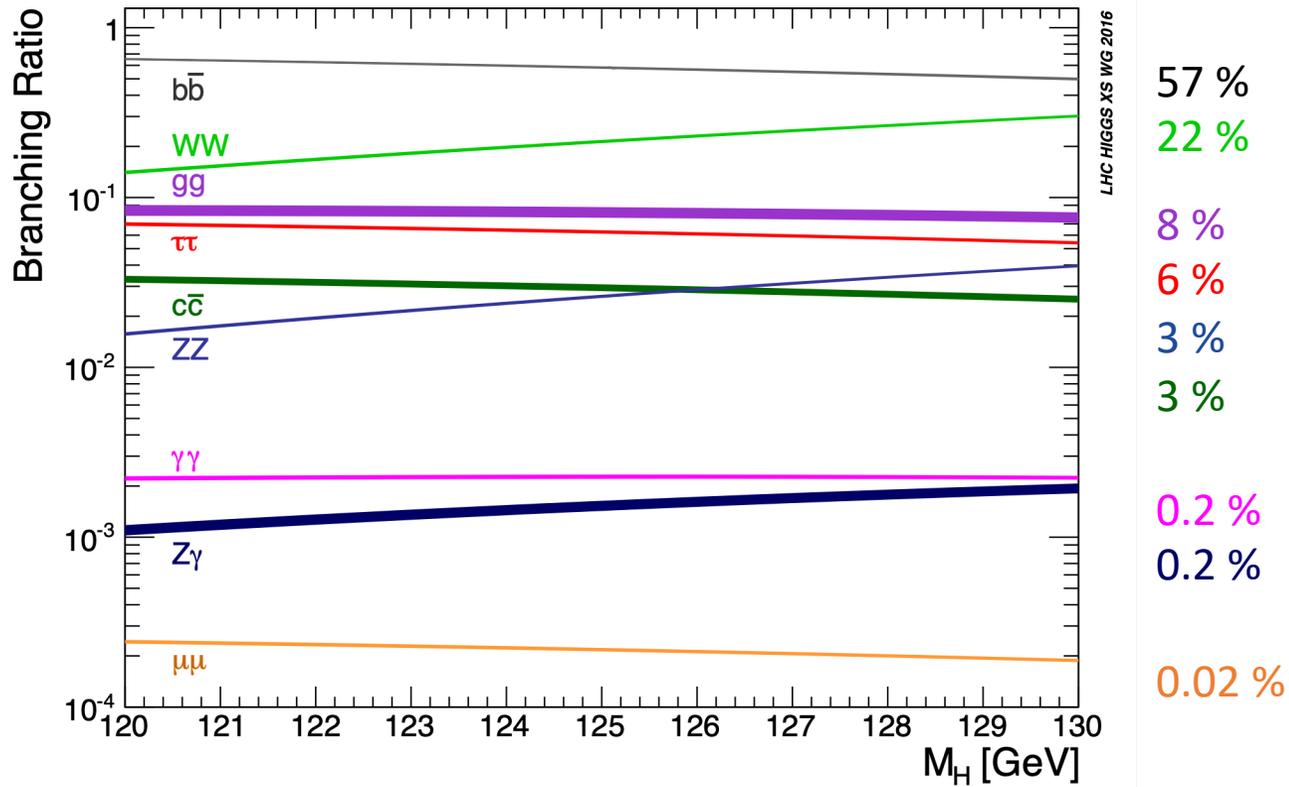
WH

ABOUT 400 K EVENTS

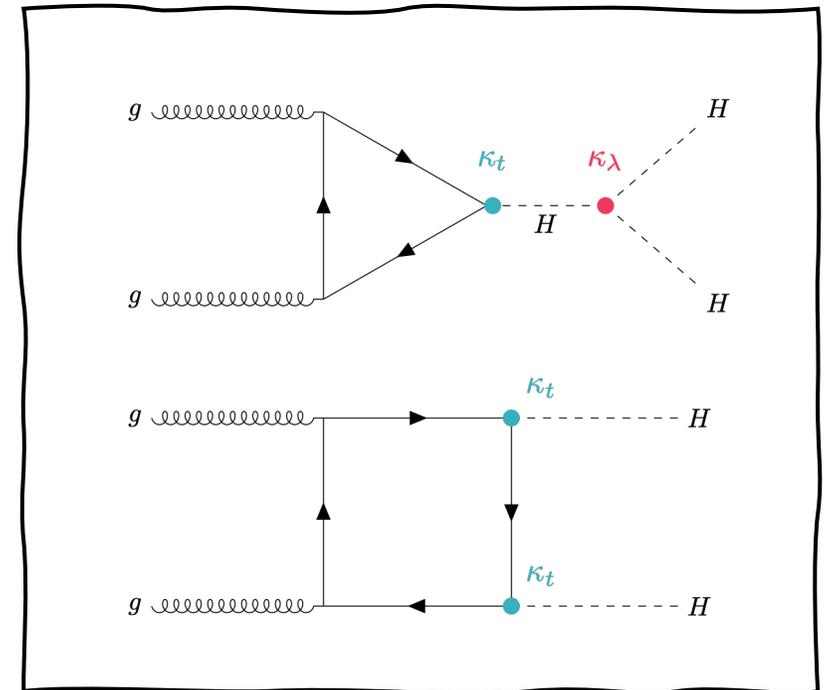
ttH

ABOUT 100 K EVENTS

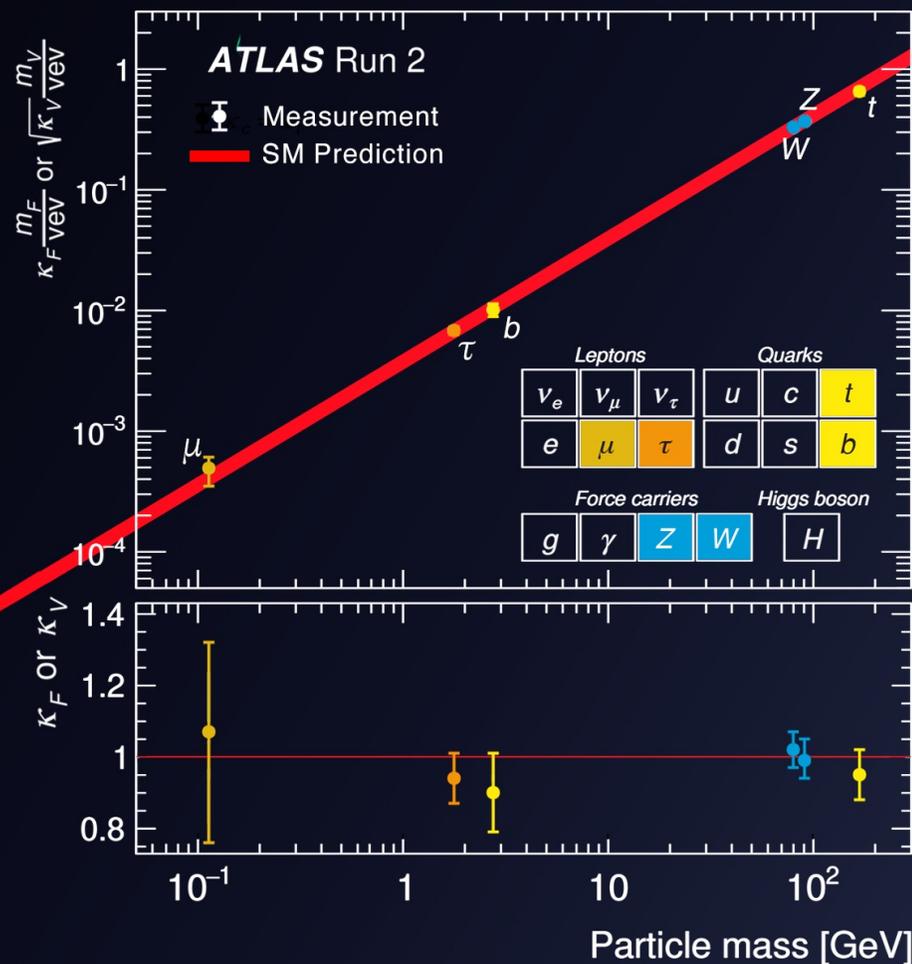
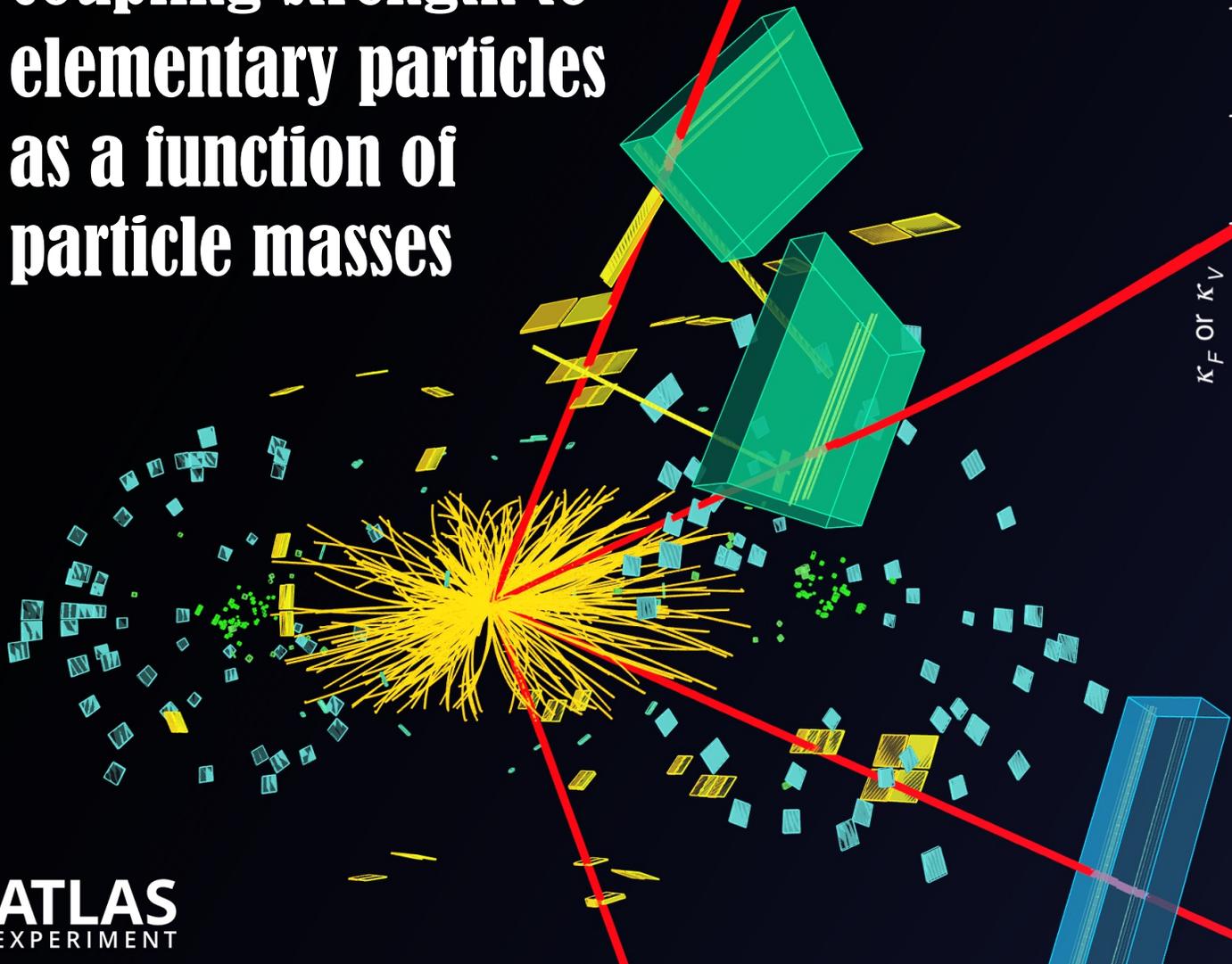
How can the Higgs be further studied?



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.

