Utilisation de l'image et de la vidéo en physique des particules

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cnrs dépasser les frontières IN2P3 Les deux infinis

Aix*Marseille université

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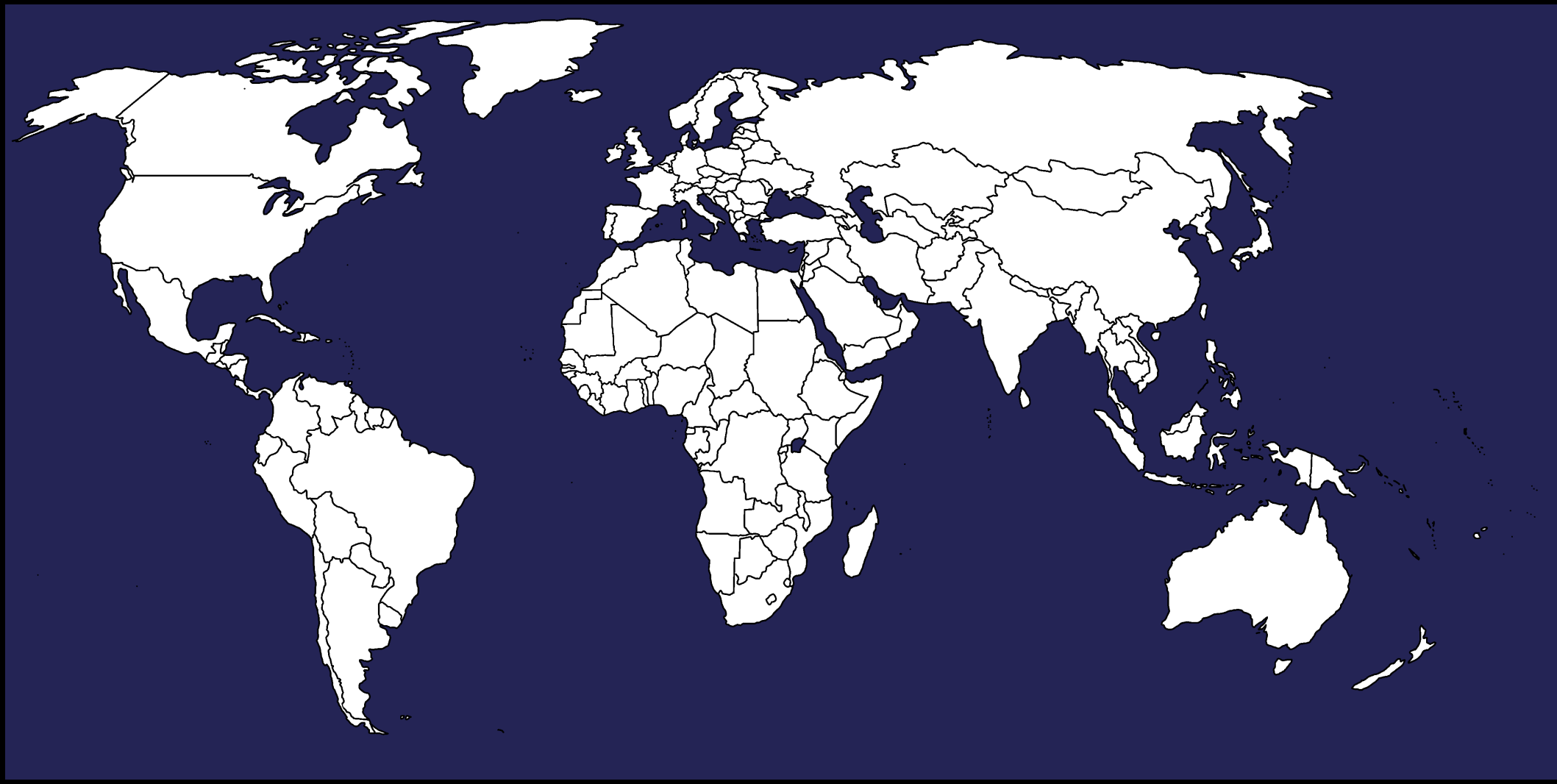
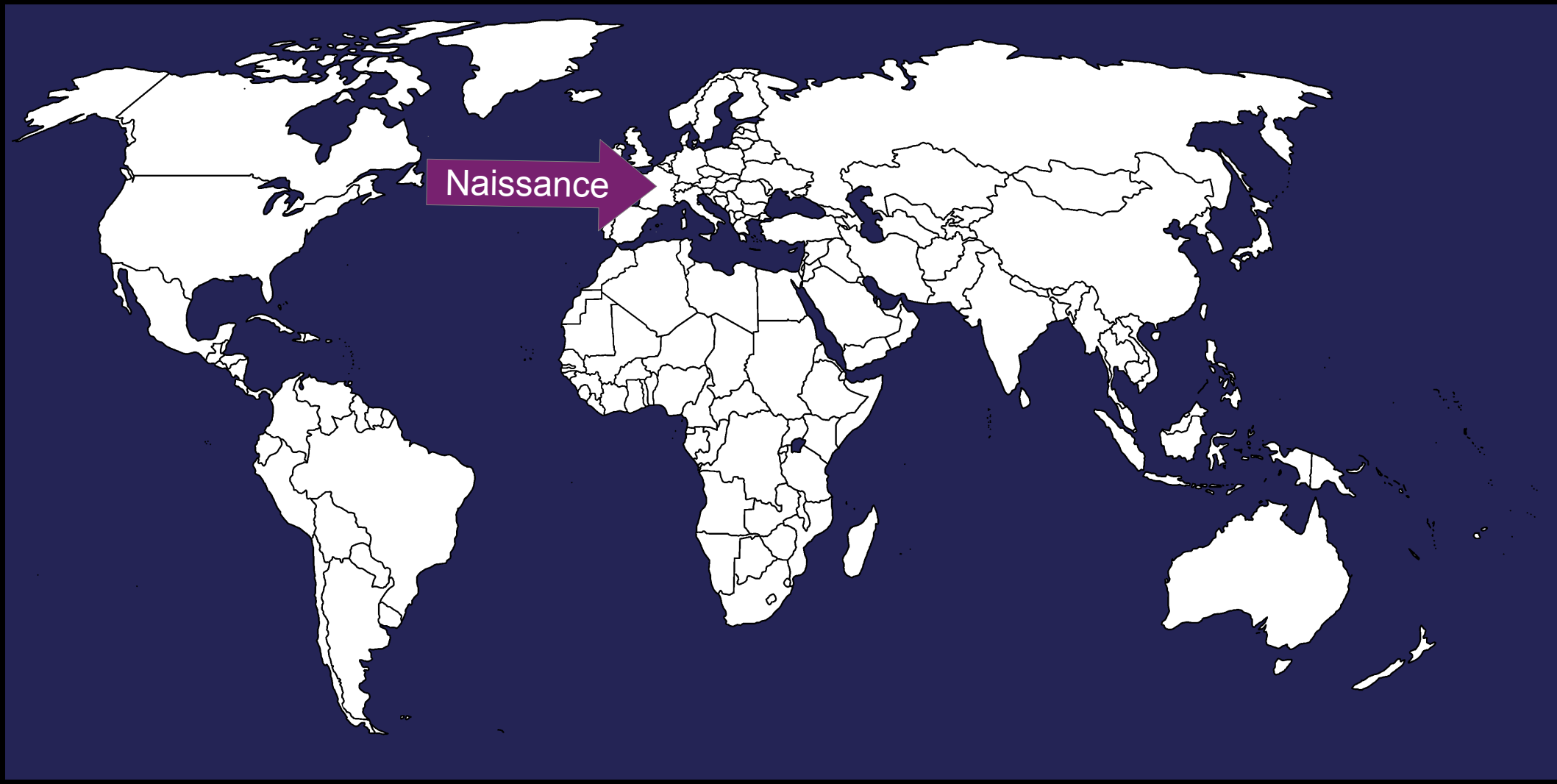
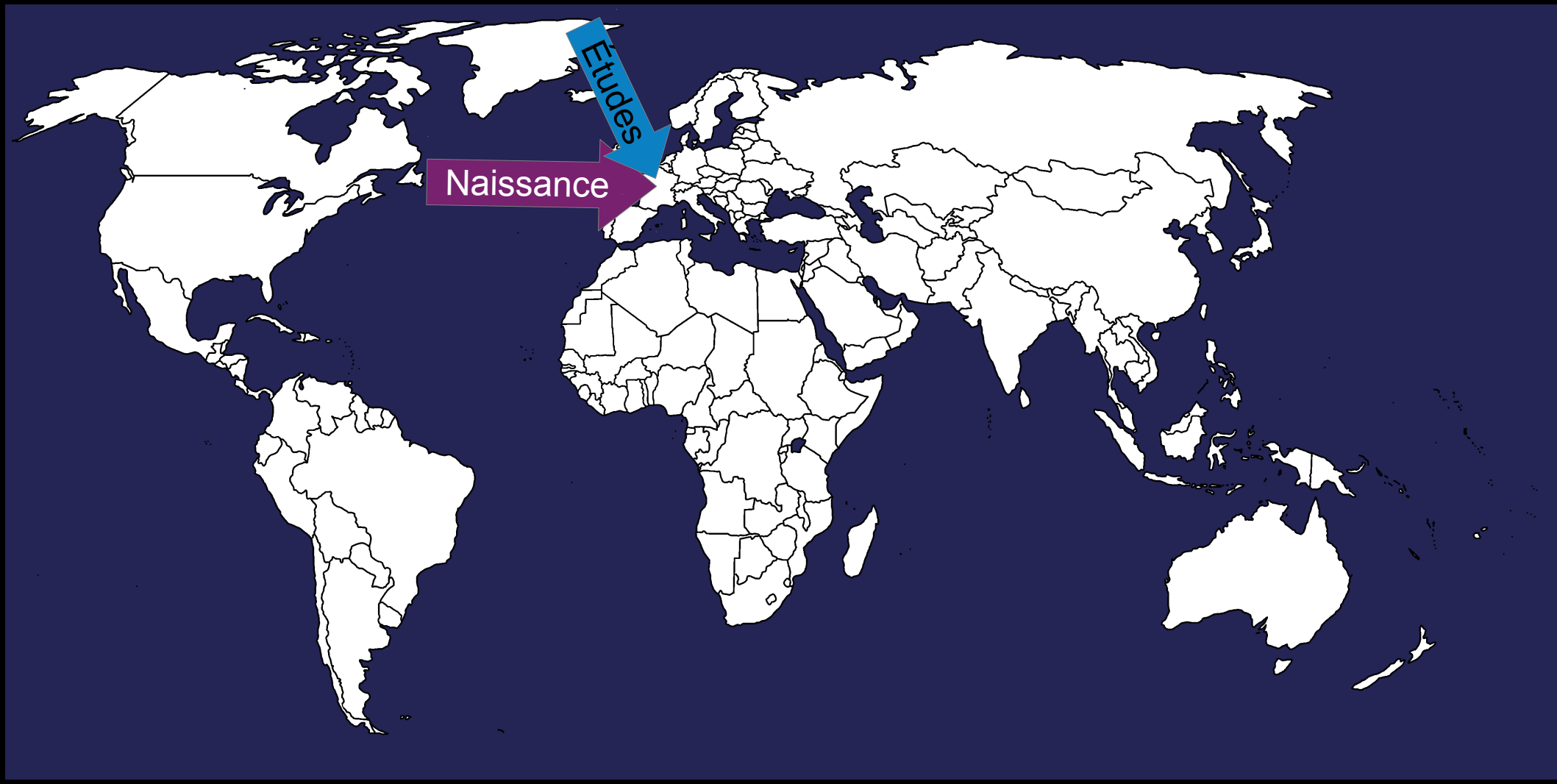
Mon parcours



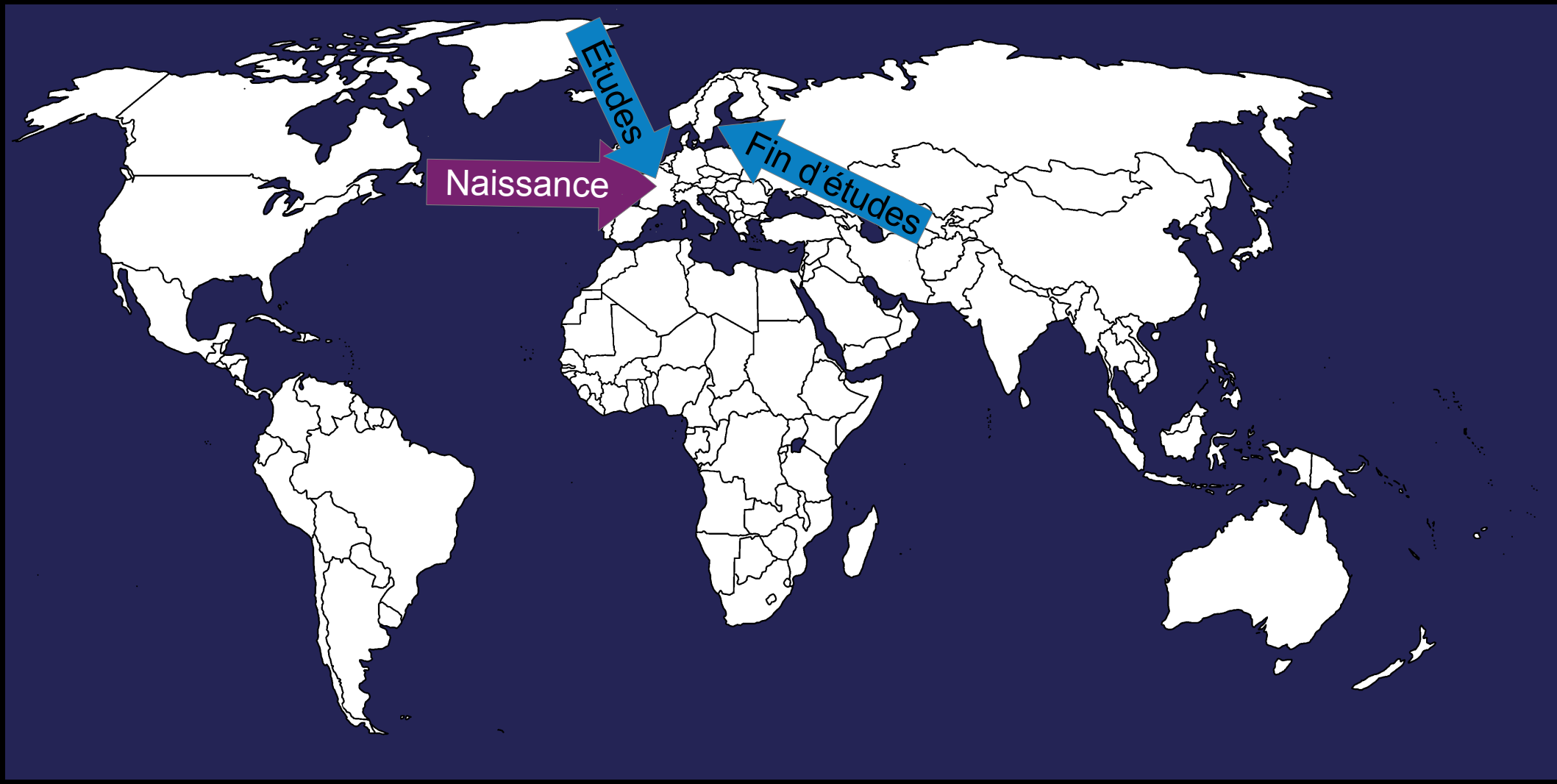
Mon parcours



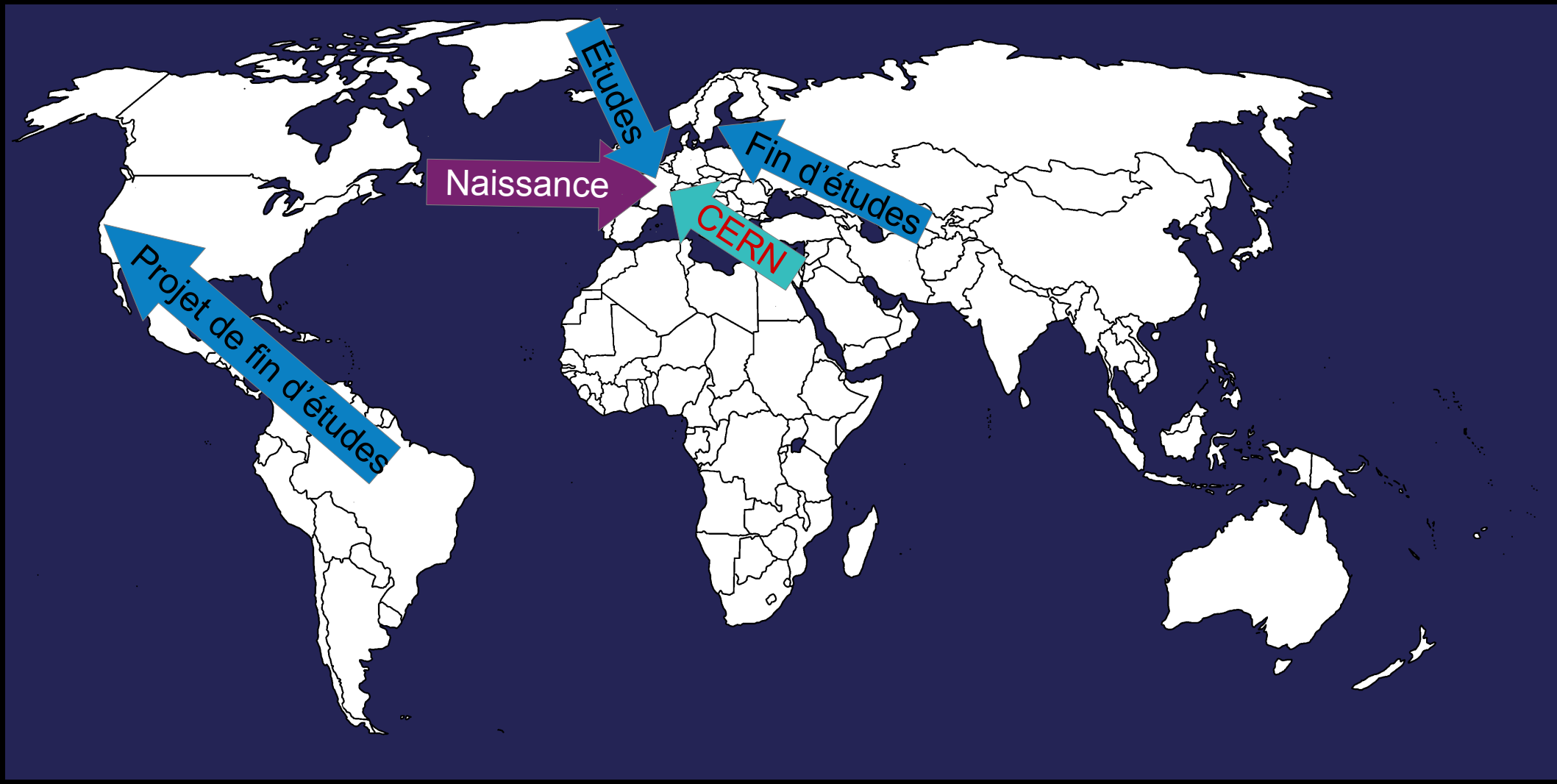
Mon parcours



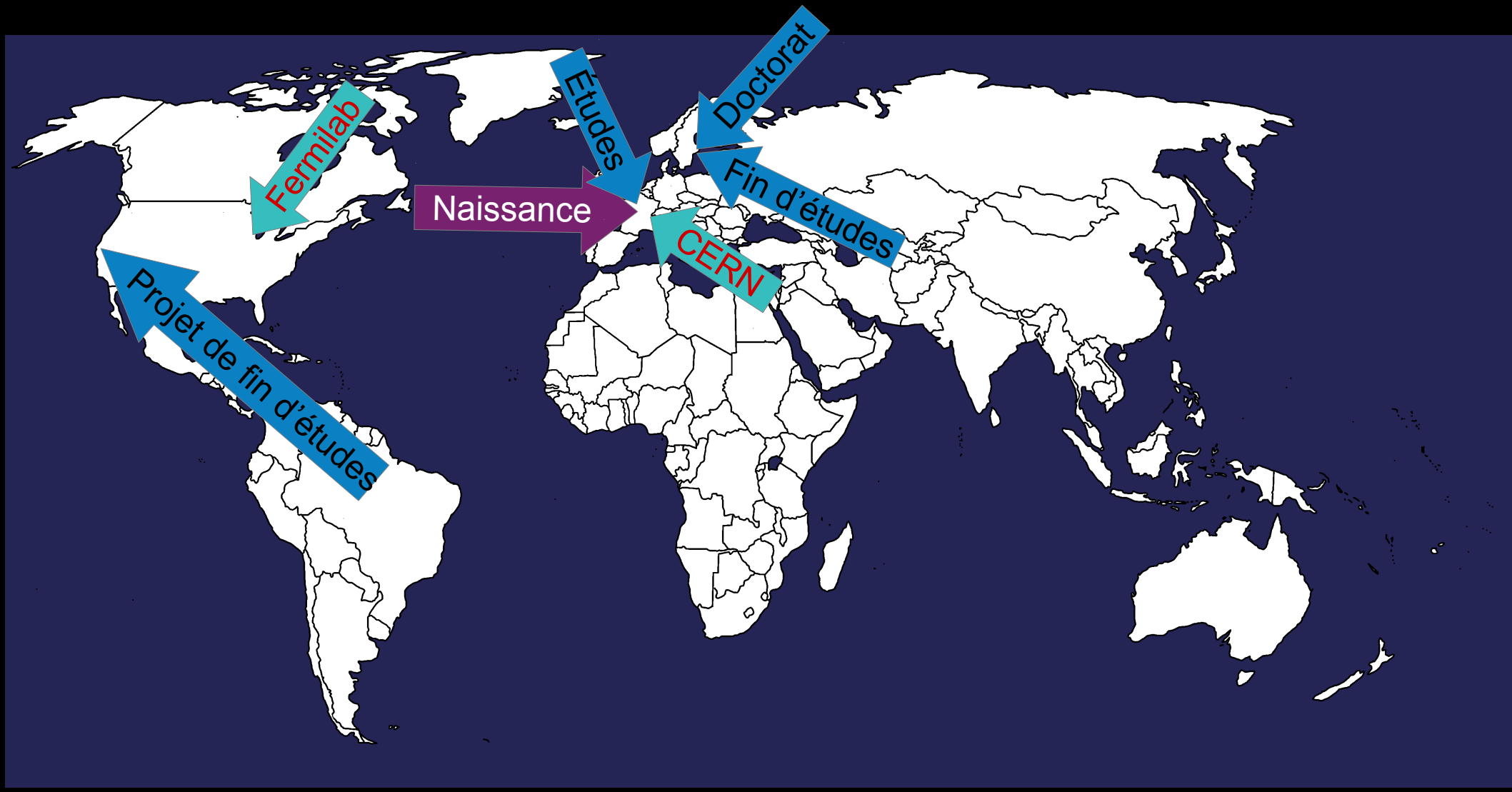
Mon parcours



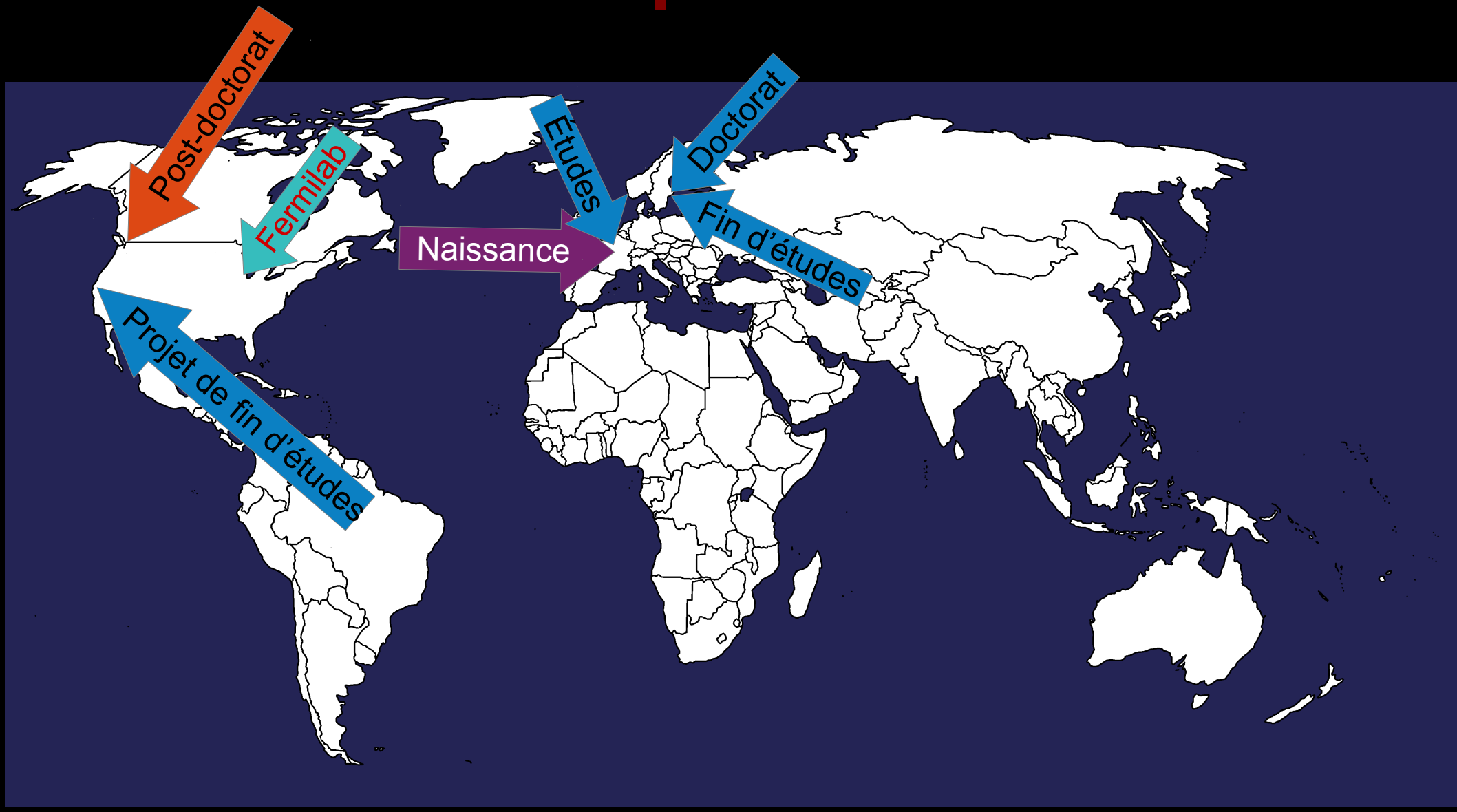
Mon parcours



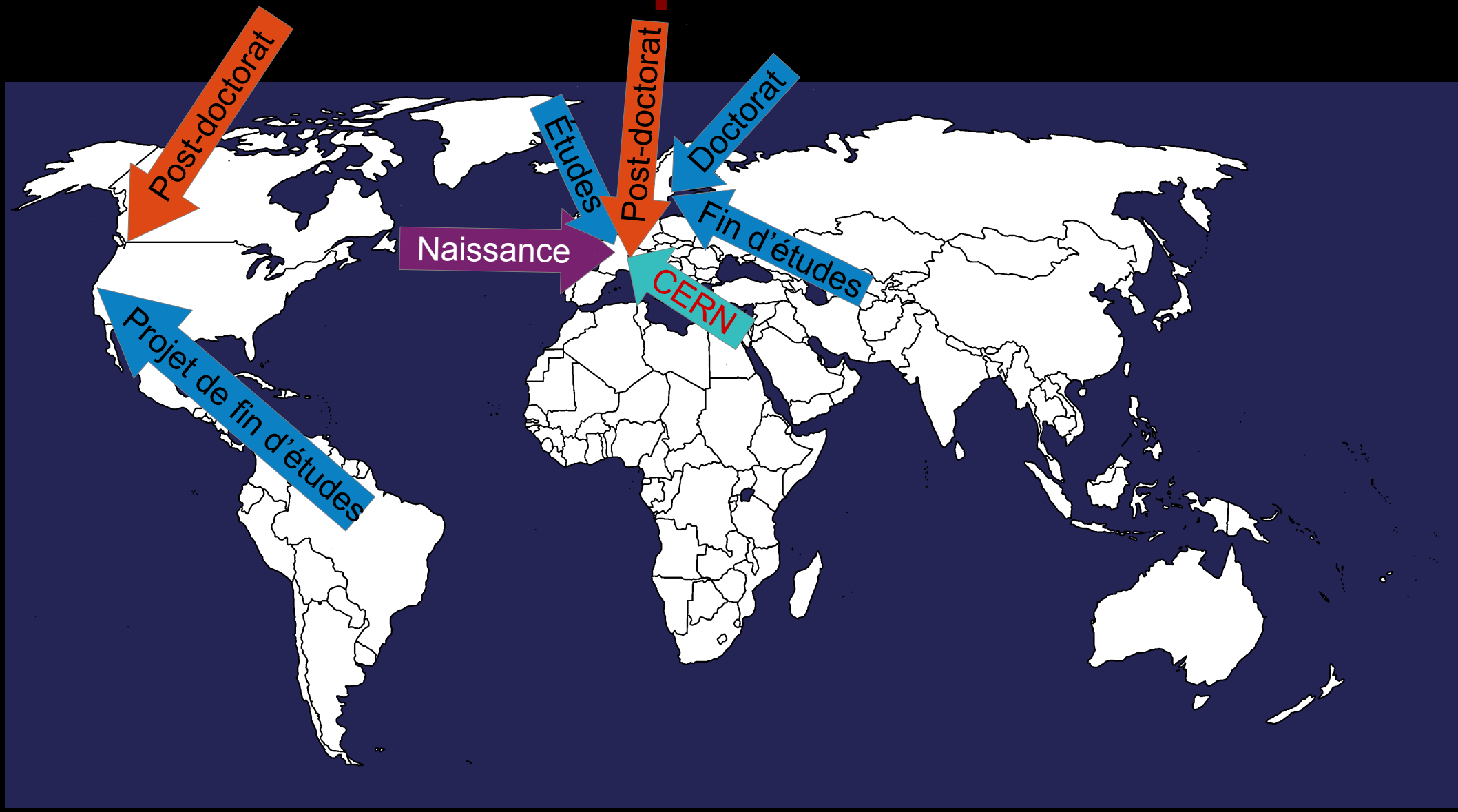
Mon parcours



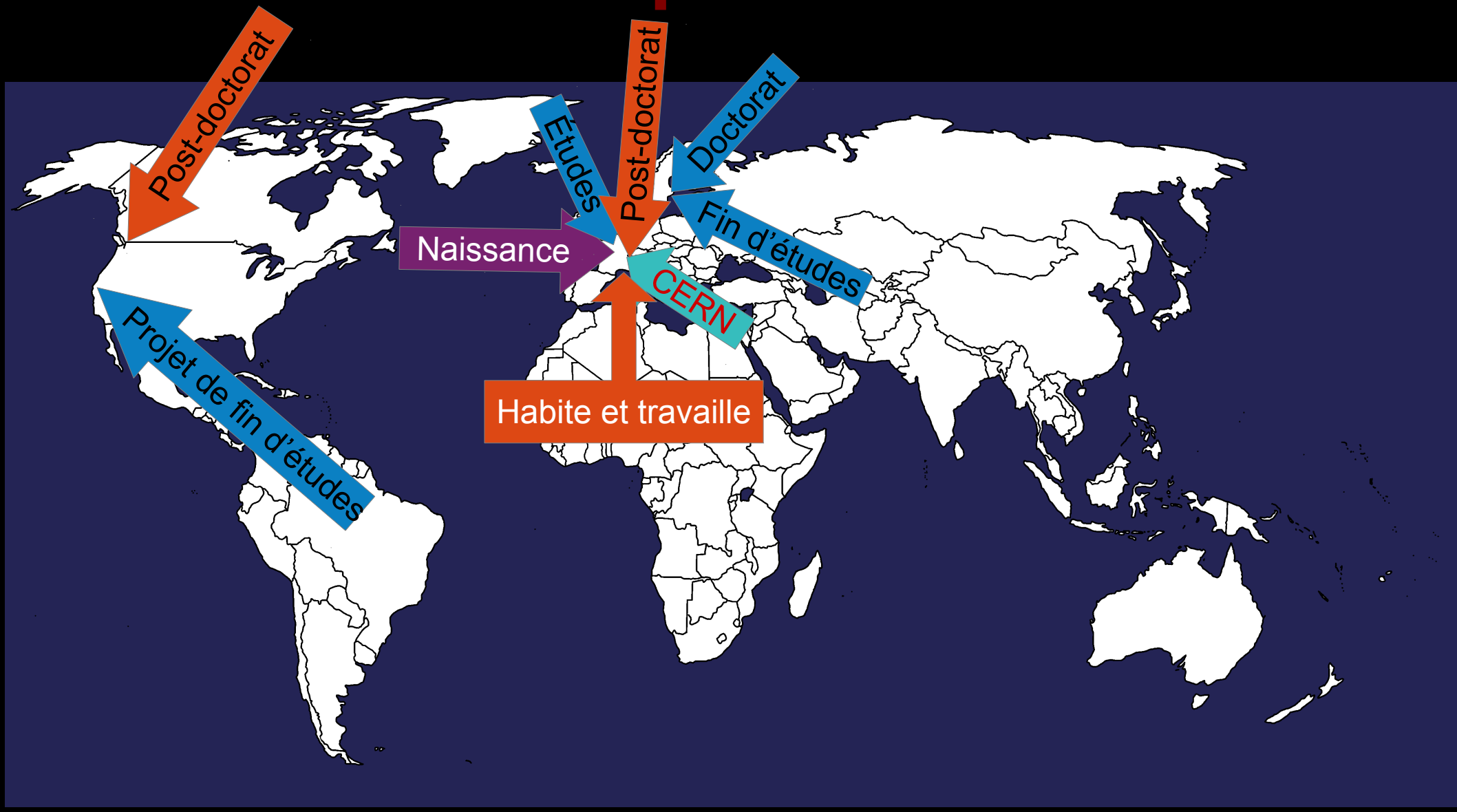
Mon parcours



Mon parcours



Mon parcours

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Le modèle standard

Quarks

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

Forces

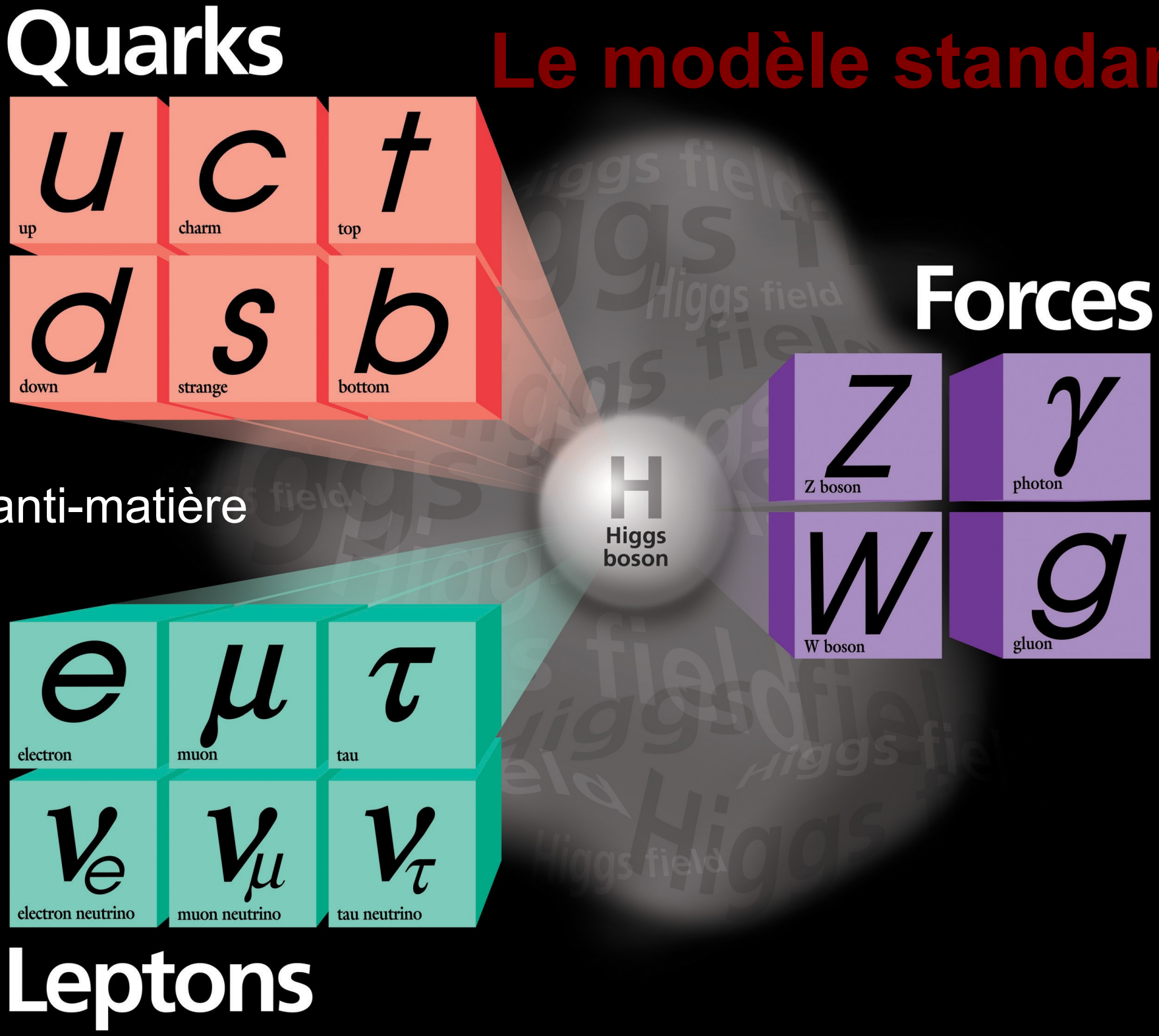
Z Z boson	γ photon
W W boson	g gluon

+ anti-matière

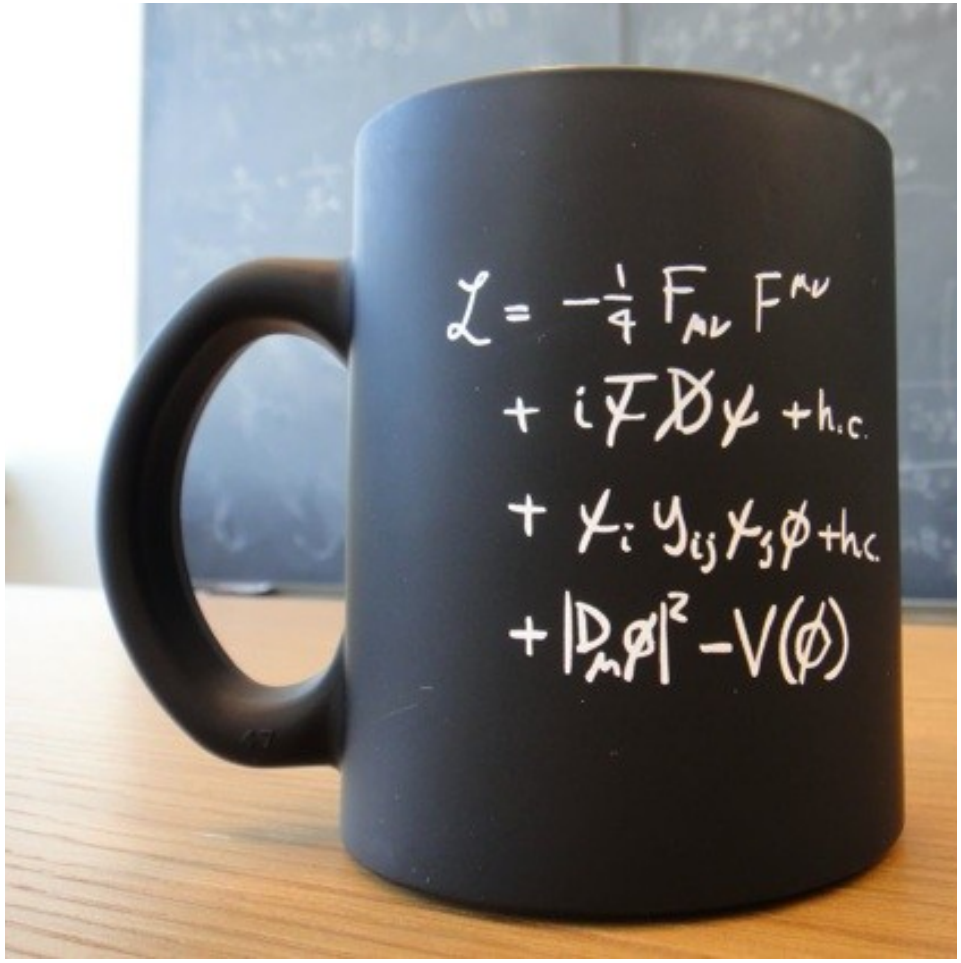
e electron	μ muon	τ tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

Leptons

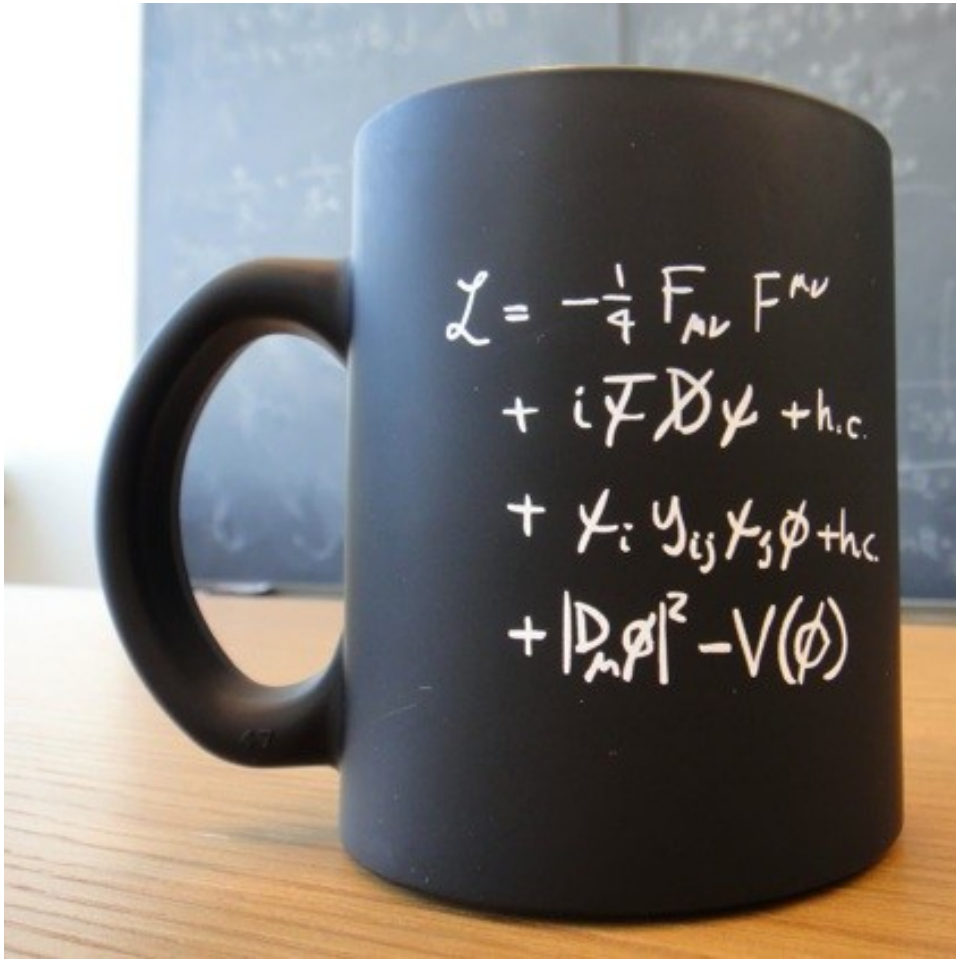
Le modèle standard



Le modèle standard

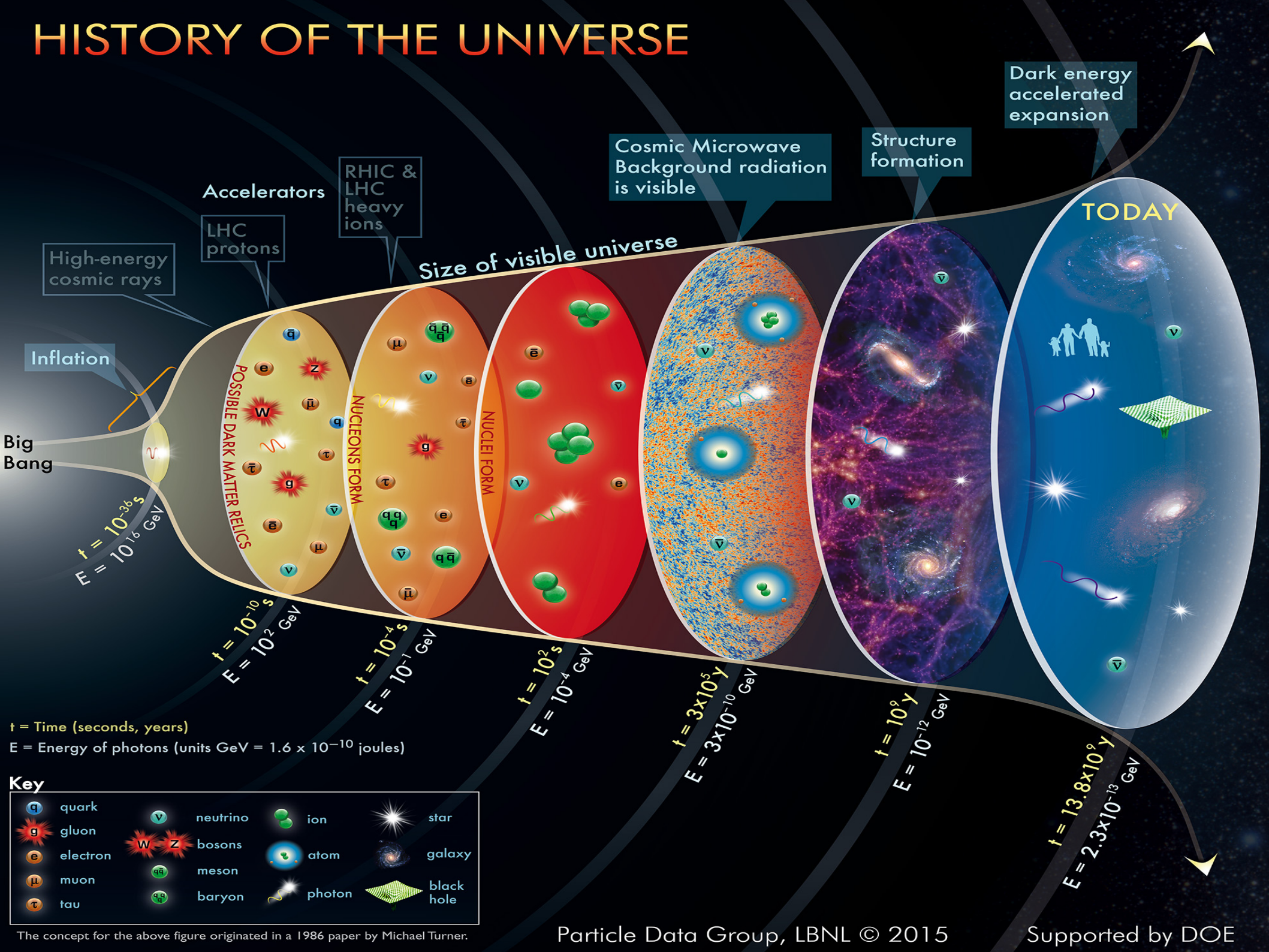


Le modèle standard



$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \\
&\tfrac{1}{2}\partial_\mu \boldsymbol{H} \partial_\mu \boldsymbol{H} - \tfrac{1}{2} m_h^2 \boldsymbol{H}^2 - \partial_\mu \boldsymbol{\phi}^+ \partial_\mu \boldsymbol{\phi}^- - M^2 \boldsymbol{\phi}^+ \boldsymbol{\phi}^- - \tfrac{1}{2}\partial_\mu \boldsymbol{\phi}^0 \partial_\mu \boldsymbol{\phi}^0 - \\
&\tfrac{1}{2c_w^2} M \boldsymbol{\phi}^0 \boldsymbol{\phi}^0 - \beta_h [\tfrac{2M^2}{g^2} + \tfrac{2M}{g}\boldsymbol{H} + \tfrac{1}{2}(\boldsymbol{H}^2 + \boldsymbol{\phi}^0\boldsymbol{\phi}^0 + 2\boldsymbol{\phi}^+\boldsymbol{\phi}^-)] + \tfrac{2M^4}{g^2}\alpha_h - \\
&igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + \\
&Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
&A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \\
&\tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
&Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[\boldsymbol{H}^3 + \\
&\boldsymbol{H}\boldsymbol{\phi}^0\boldsymbol{\phi}^0 + 2\boldsymbol{H}\boldsymbol{\phi}^+\boldsymbol{\phi}^-] - \tfrac{1}{8} g^2 \alpha_h [\boldsymbol{H}^4 + (\boldsymbol{\phi}^0)^4 + 4(\boldsymbol{\phi}^+\boldsymbol{\phi}^-)^2 + \\
&4(\boldsymbol{\phi}^0)^2 \boldsymbol{\phi}^+\boldsymbol{\phi}^- + 4\boldsymbol{H}^2\boldsymbol{\phi}^+\boldsymbol{\phi}^- + 2(\boldsymbol{\phi}^0)^2 \boldsymbol{H}^2] - gMW^+_\mu W^-_\mu \boldsymbol{H} - \\
&\tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu \boldsymbol{H} - \tfrac{1}{2} ig[W^+_\mu (\boldsymbol{\phi}^0 \partial_\mu \boldsymbol{\phi}^- - \boldsymbol{\phi}^- \partial_\mu \boldsymbol{\phi}^0) - W^-_\mu (\boldsymbol{\phi}^0 \partial_\mu \boldsymbol{\phi}^+ - \\
&\boldsymbol{\phi}^+ \partial_\mu \boldsymbol{\phi}^0)] + \tfrac{1}{2} g[W^+_\mu (\boldsymbol{H}\partial_\mu \boldsymbol{\phi}^- - \boldsymbol{\phi}^- \partial_\mu \boldsymbol{H}) - W^-_\mu (\boldsymbol{H}\partial_\mu \boldsymbol{\phi}^+ - \boldsymbol{\phi}^+ \partial_\mu \boldsymbol{H})] + \\
&\tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (\boldsymbol{H}\partial_\mu \boldsymbol{\phi}^0 - \boldsymbol{\phi}^0 \partial_\mu \boldsymbol{H}) - ig\tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \boldsymbol{\phi}^- - W^-_\mu \boldsymbol{\phi}^+) + \\
&igs_w M A_\mu (W^+_\mu \boldsymbol{\phi}^- - W^-_\mu \boldsymbol{\phi}^+) - ig\tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\boldsymbol{\phi}^+ \partial_\mu \boldsymbol{\phi}^- - \boldsymbol{\phi}^- \partial_\mu \boldsymbol{\phi}^+) + \\
&igs_w A_\mu (\boldsymbol{\phi}^+ \partial_\mu \boldsymbol{\phi}^- - \boldsymbol{\phi}^- \partial_\mu \boldsymbol{\phi}^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [\boldsymbol{H}^2 + (\boldsymbol{\phi}^0)^2 + 2\boldsymbol{\phi}^+\boldsymbol{\phi}^-] - \\
&\tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [\boldsymbol{H}^2 + (\boldsymbol{\phi}^0)^2 + 2(2s_w^2 - 1)^2 \boldsymbol{\phi}^+\boldsymbol{\phi}^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \boldsymbol{\phi}^0 (W^+_\mu \boldsymbol{\phi}^- + \\
&W^-_\mu \boldsymbol{\phi}^+) - \tfrac{1}{2} ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu \boldsymbol{H} (W^+_\mu \boldsymbol{\phi}^- - W^-_\mu \boldsymbol{\phi}^+) + \tfrac{1}{2} g^2 s_w A_\mu \boldsymbol{\phi}^0 (W^+_\mu \boldsymbol{\phi}^- + \\
&W^-_\mu \boldsymbol{\phi}^+) + \tfrac{1}{2} ig^2 s_w A_\mu \boldsymbol{H} (W^+_\mu \boldsymbol{\phi}^- - W^-_\mu \boldsymbol{\phi}^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \boldsymbol{\phi}^+\boldsymbol{\phi}^- - \\
&g^1 s_w^2 A_\mu A_\mu \boldsymbol{\phi}^+\boldsymbol{\phi}^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m_u^\lambda) u^\lambda_j - \\
&\bar{d}^\lambda_j (\gamma\partial + m_d^\lambda) d^\lambda_j + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)] + \\
&\tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3}s_w^2 - \\
&1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3}s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) e^\lambda) + \\
&(\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \\
&\gamma^5) u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m_e^\lambda}{M} [-\boldsymbol{\phi}^+ (\bar{\nu}^\lambda (1-\gamma^5) e^\lambda) + \boldsymbol{\phi}^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] - \\
&\tfrac{g}{2}\tfrac{m_e^\lambda}{M} [\boldsymbol{H}(\bar{e}^\lambda e^\lambda) + i\boldsymbol{\phi}^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \boldsymbol{\phi}^+ [-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + \\
&m_u^\lambda (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \boldsymbol{\phi}^- [m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \\
&\gamma^5) u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M} \boldsymbol{H} (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M} \boldsymbol{H} (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M} \boldsymbol{\phi}^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \\
&\tfrac{ig}{2}\tfrac{m_d^\lambda}{M} \boldsymbol{\phi}^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
&\tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
&\partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \\
&\partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
&\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} gM[\bar{X}^+ X^+ \boldsymbol{H} + \bar{X}^- X^- \boldsymbol{H} + \tfrac{1}{c_w^2} \bar{X}^0 X^0 \boldsymbol{H}] + \\
&\tfrac{1-2c_w^2}{2c_w} igM[\bar{X}^+ X^0 \boldsymbol{\phi}^+ - \bar{X}^- X^0 \boldsymbol{\phi}^-] + \tfrac{1}{2c_w} igM[\bar{X}^0 X^- \boldsymbol{\phi}^+ - \bar{X}^0 X^+ \boldsymbol{\phi}^-] + \\
&igMs_w [\bar{X}^0 X^- \boldsymbol{\phi}^+ - \bar{X}^0 X^+ \boldsymbol{\phi}^-] + \tfrac{1}{2} igM[\bar{X}^+ X^+ \boldsymbol{\phi}^0 - \bar{X}^- X^- \boldsymbol{\phi}^0]
\end{aligned}
$$

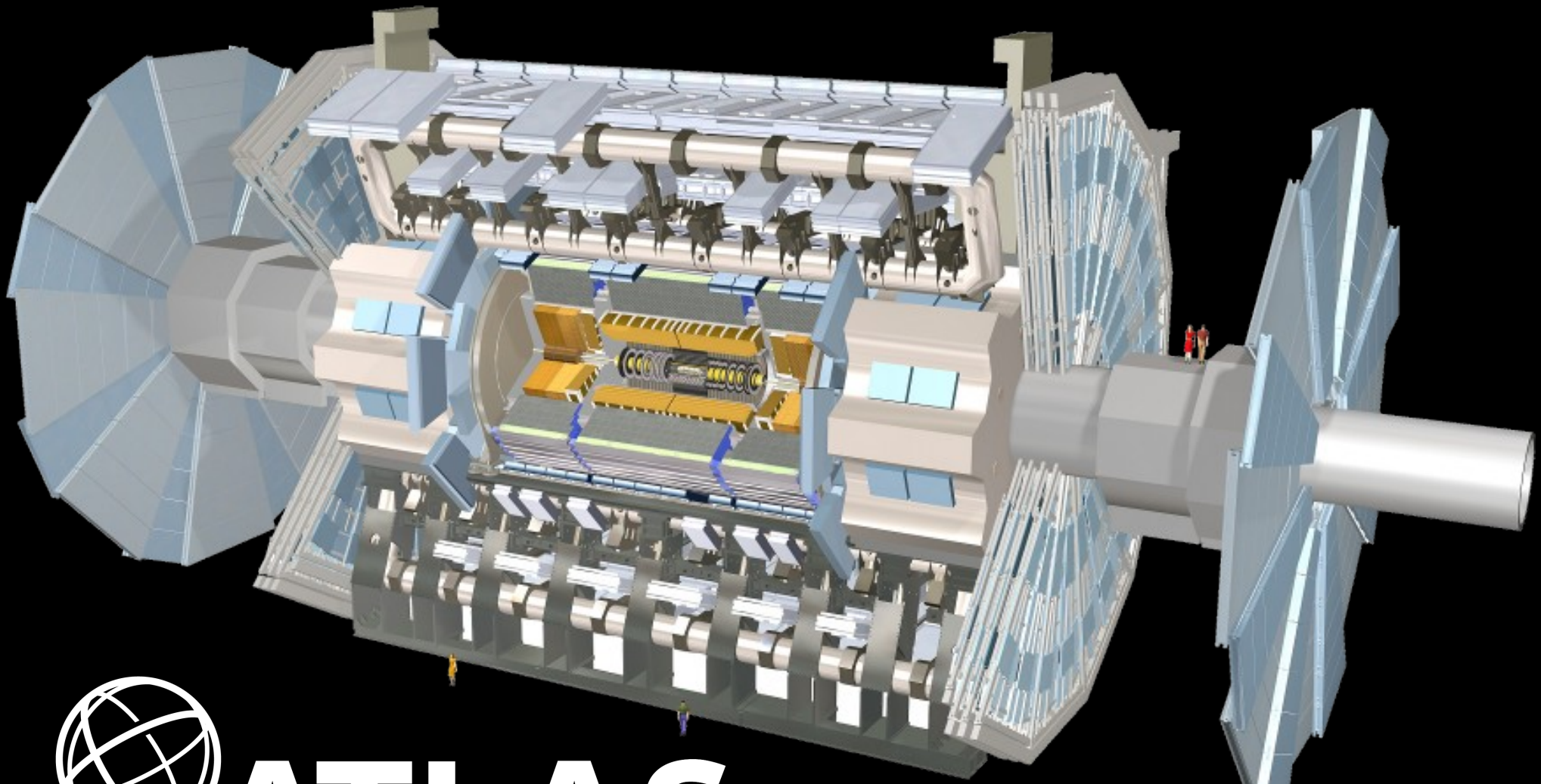
HISTORY OF THE UNIVERSE



The concept for the above figure originated in a 1986 paper by Michael Turner.

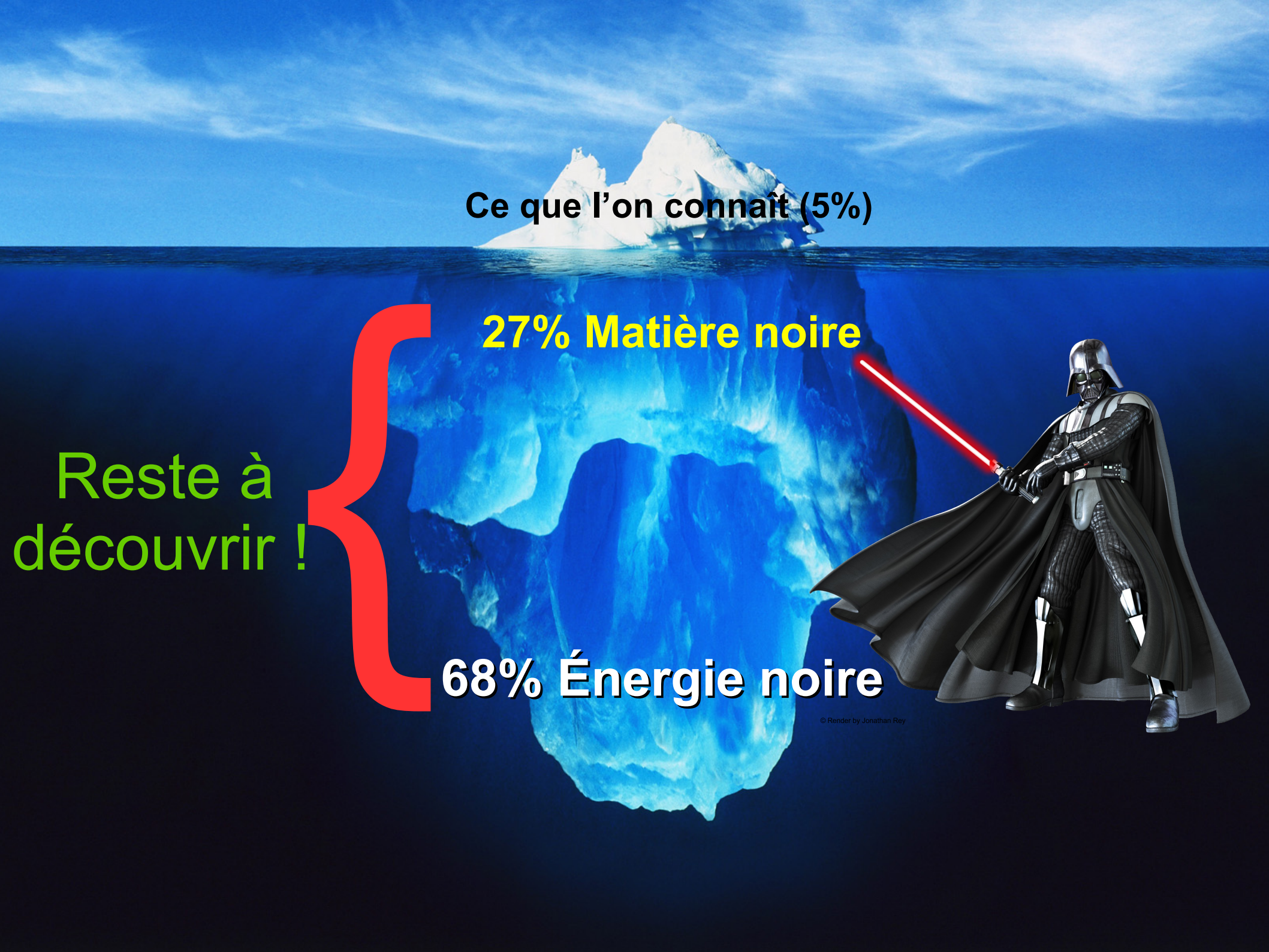
Supported by DOE

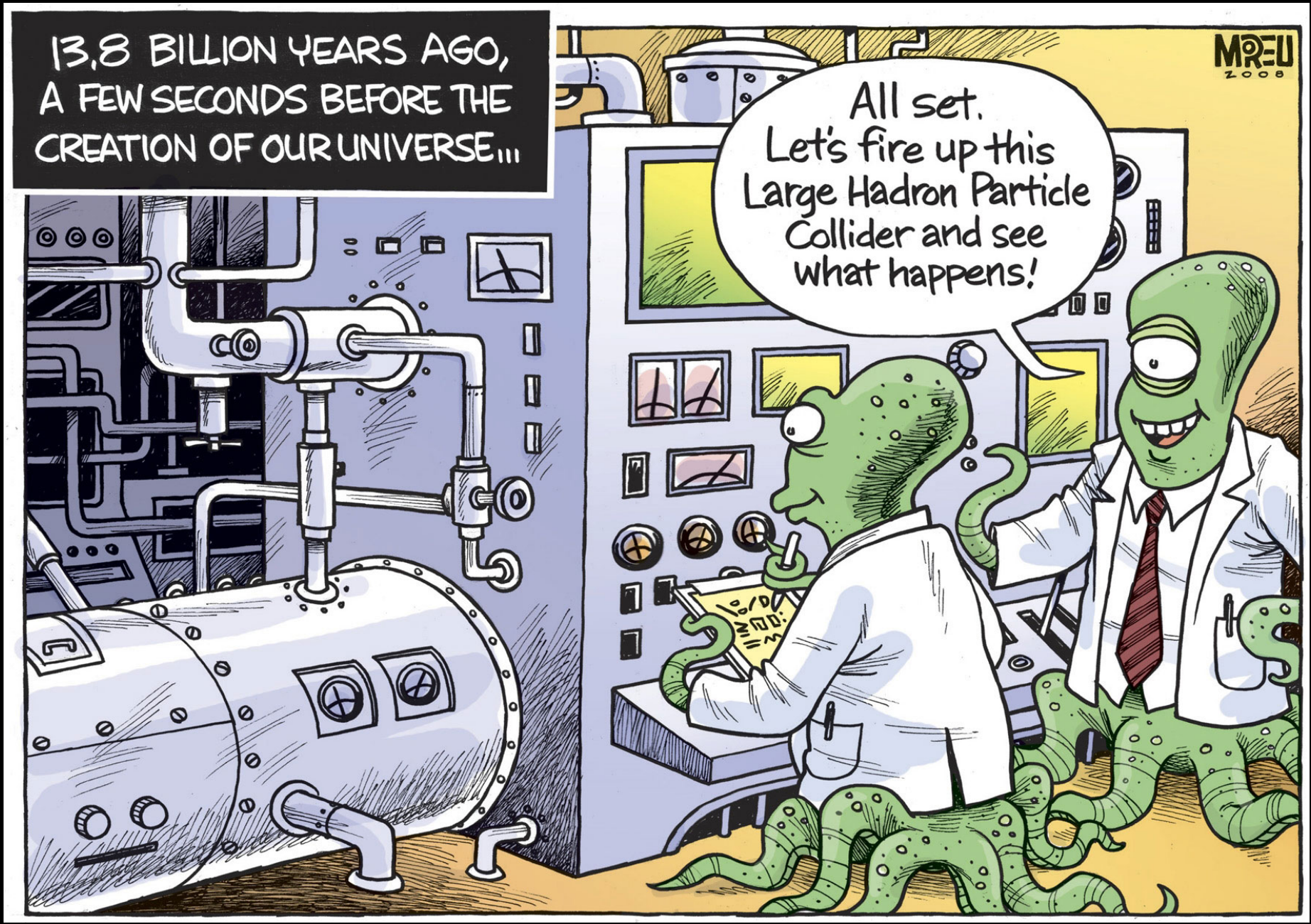
Le LHC
(grand collisionneur de hadrons)



ATLAS
EXPERIMENT


Ce que l’on connaît (5%)


Ce que l'on connaît (5%)
27% Matière noire
Reste à découvrir !
68% Énergie noire
© Render by Jonathan Rey


13,8 BILLION YEARS AGO, A FEW SECONDS BEFORE THE CREATION OF OUR UNIVERSE...
All set. Let's fire up this Large Hadron Particle Collider and see what happens!
MOREU 2008

Salle de contrôle

LHC Page1	Fill: 7495	E: 0 Z GeV	18-03-19 21:30:01

SHUTDOWN: NO BEAM

Comments (21-Feb-2019 12:08:02)

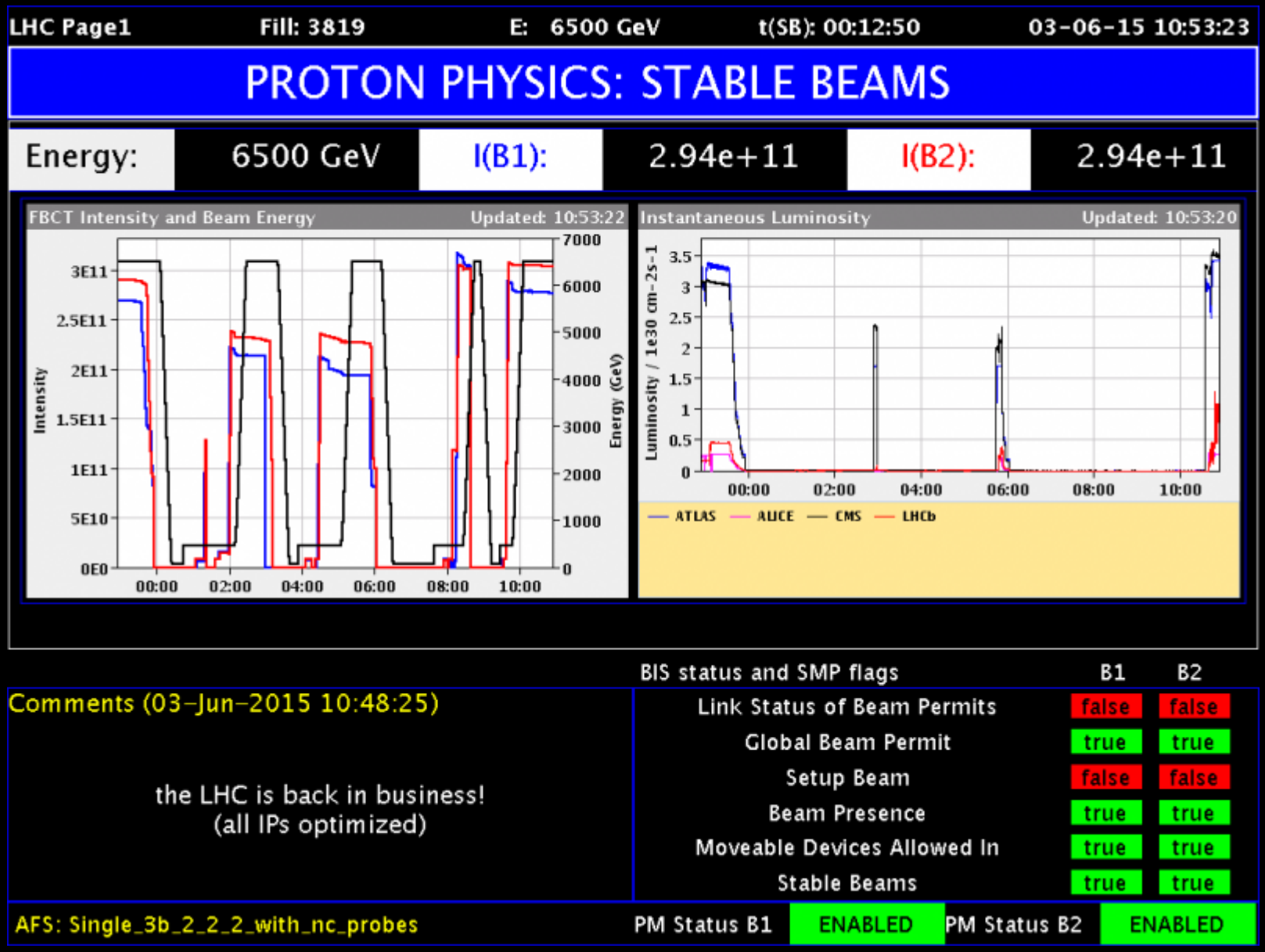
LS2

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	false	false
Setup Beam	false	false
Beam Presence	false	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

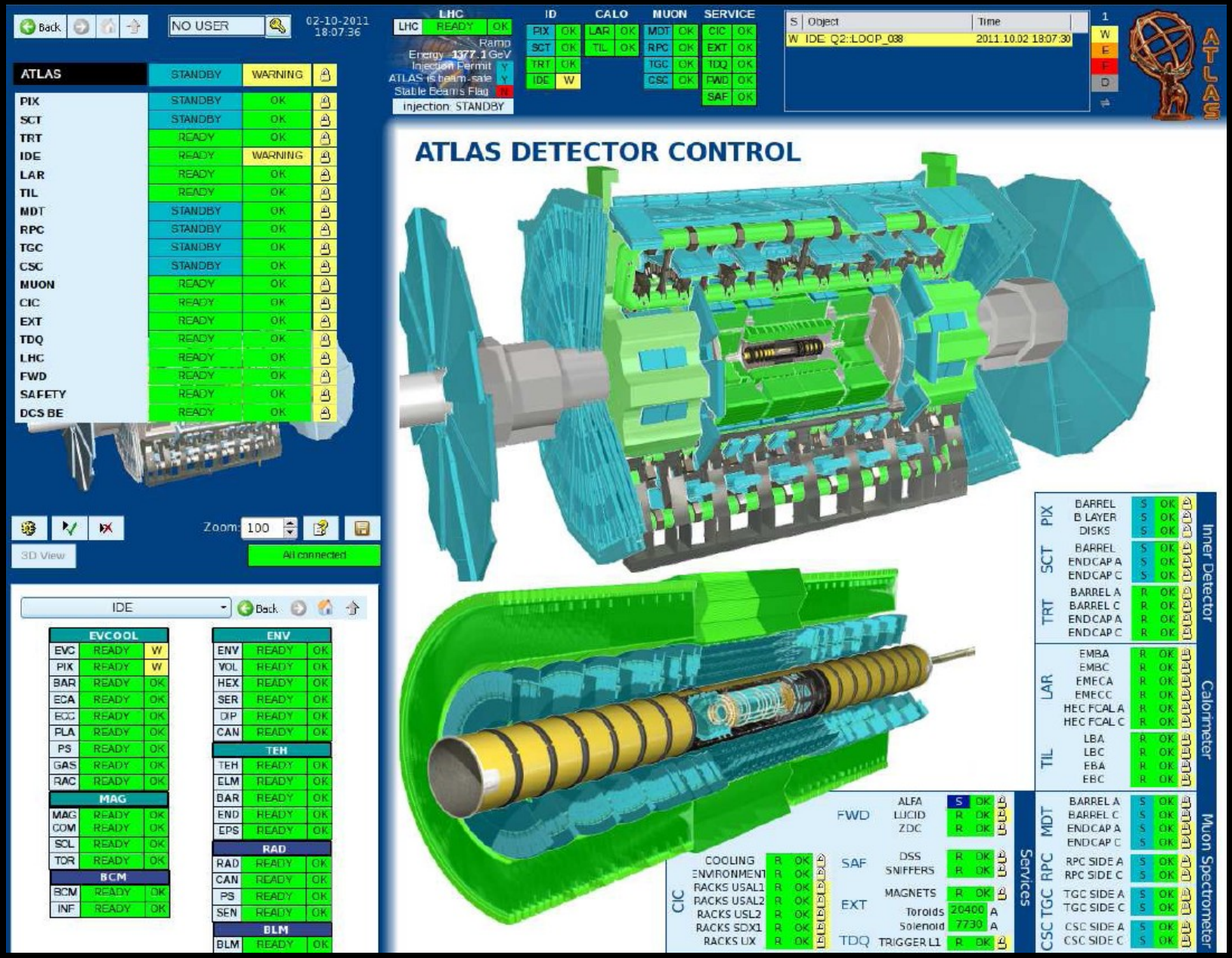
AFS: 75_150ns_733Pb_733_702_468_42bpi_20inj

PM Status B1 ENABLED PM Status B2 ENABLED

Salle de contrôle

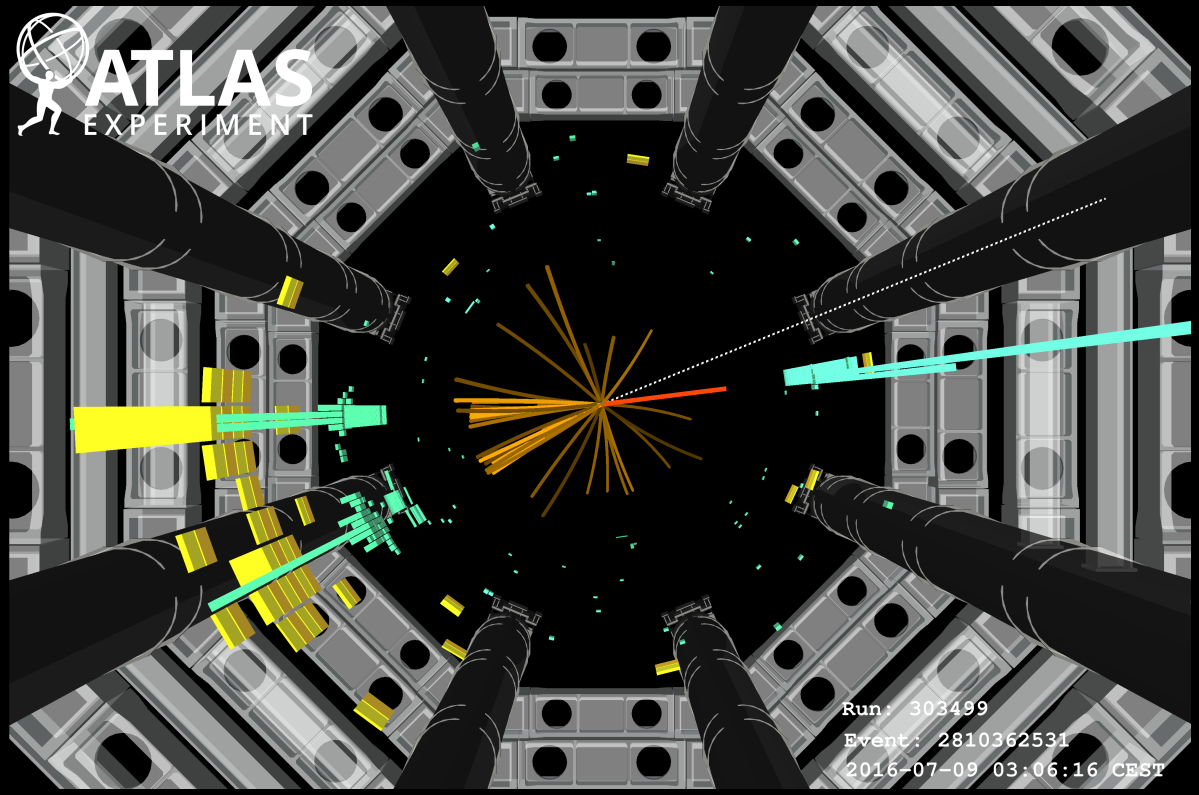


Salle de contrôle



Event displays

Event displays



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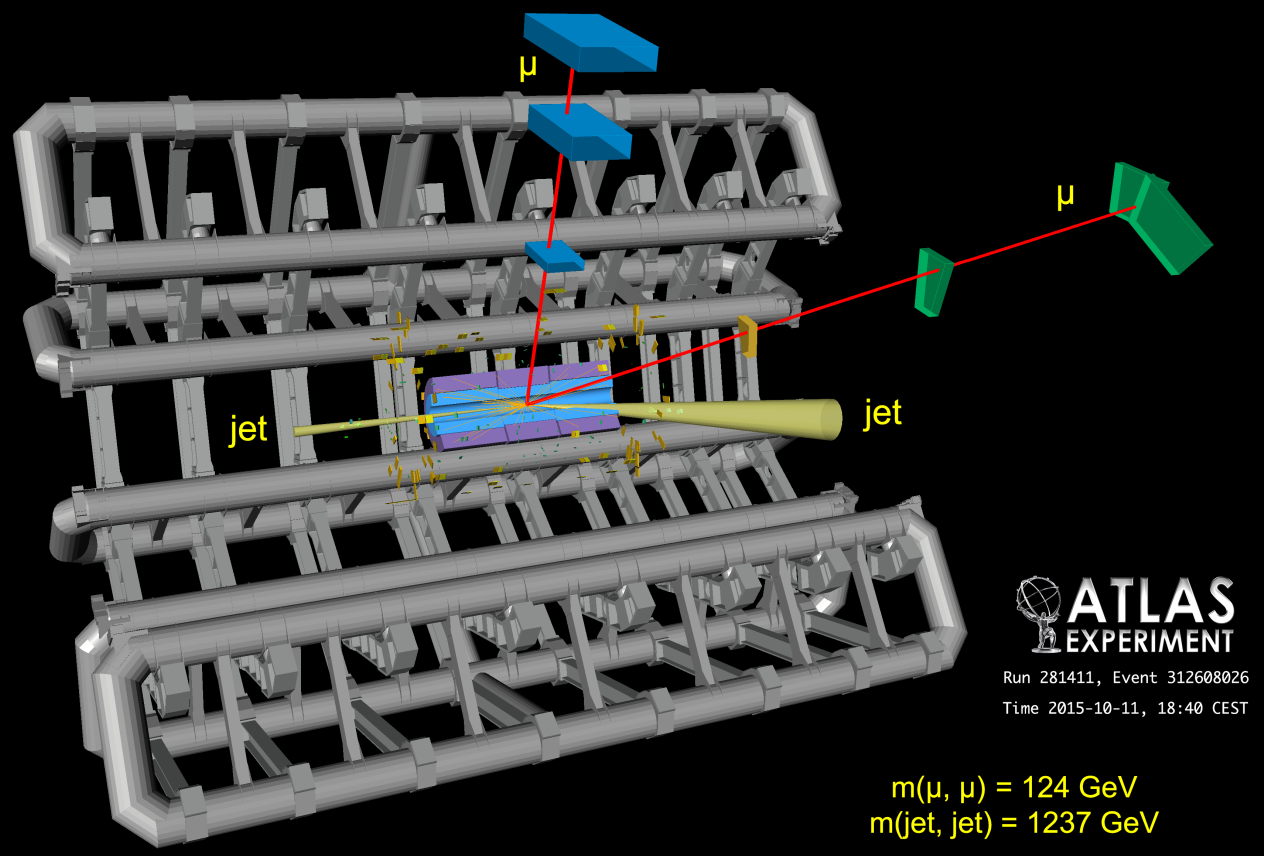
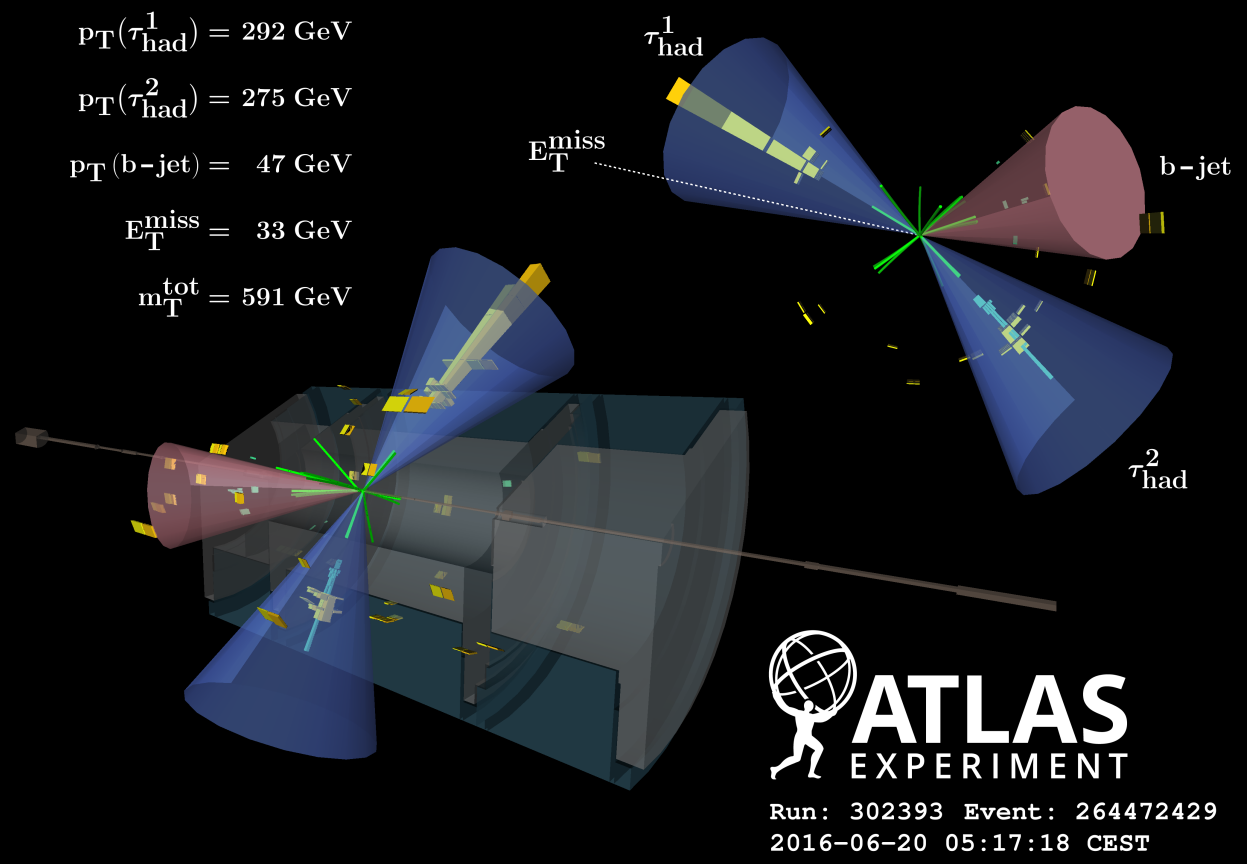
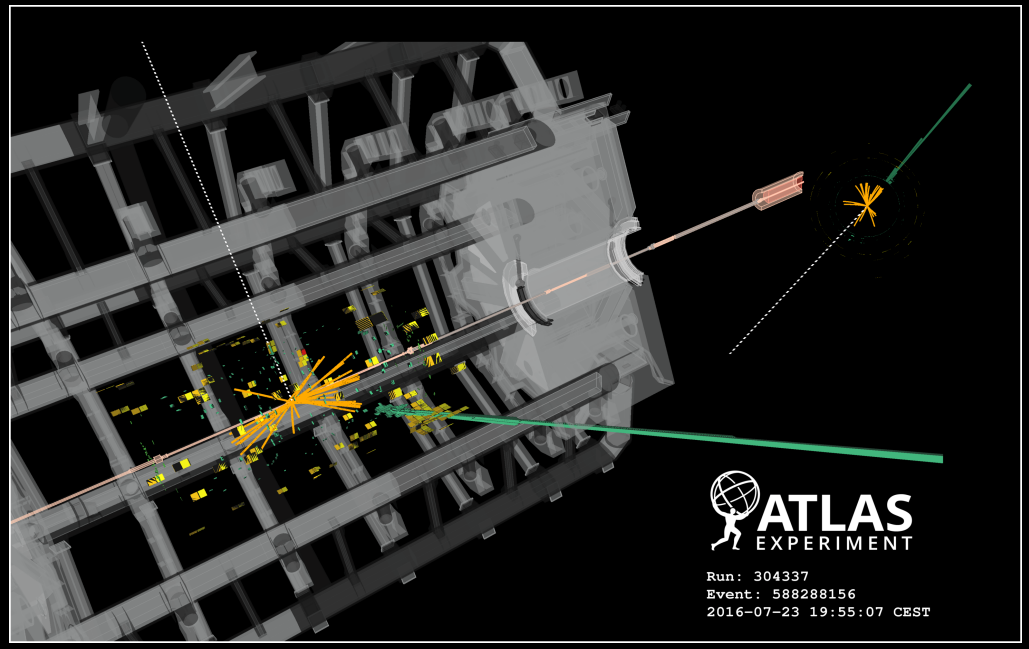


m(μ, μ) = 124 GeV
m(jet, jet) = 1237 GeV

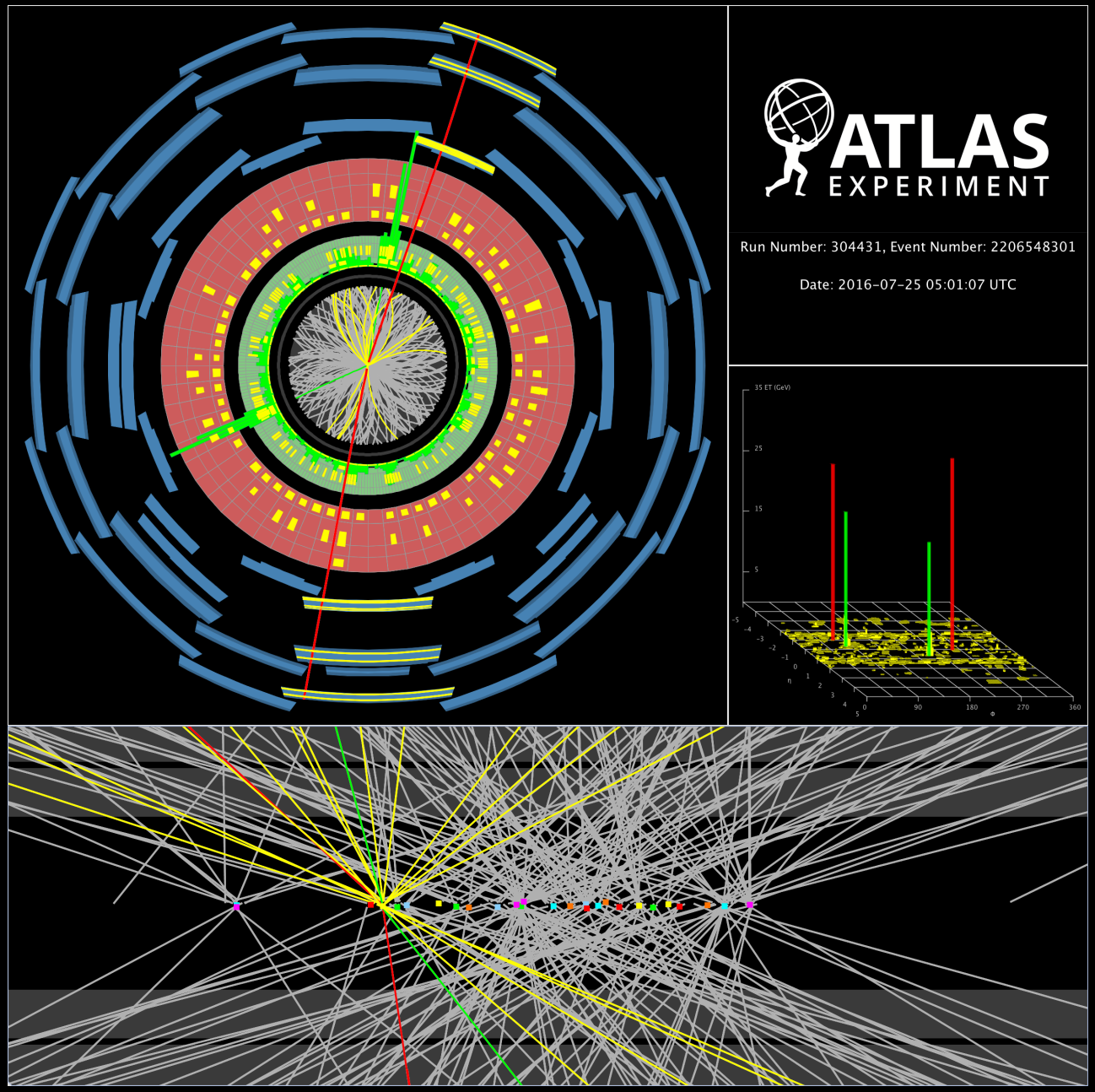
Event displays



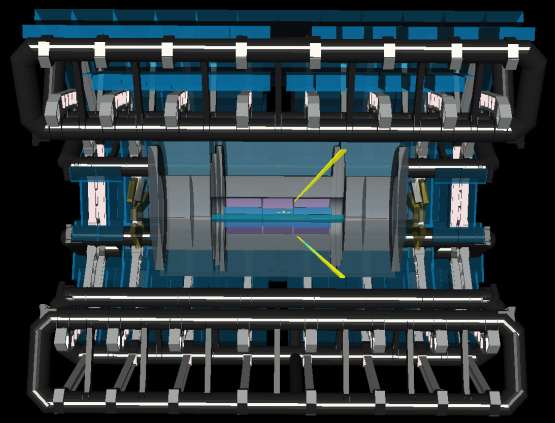
Event displays



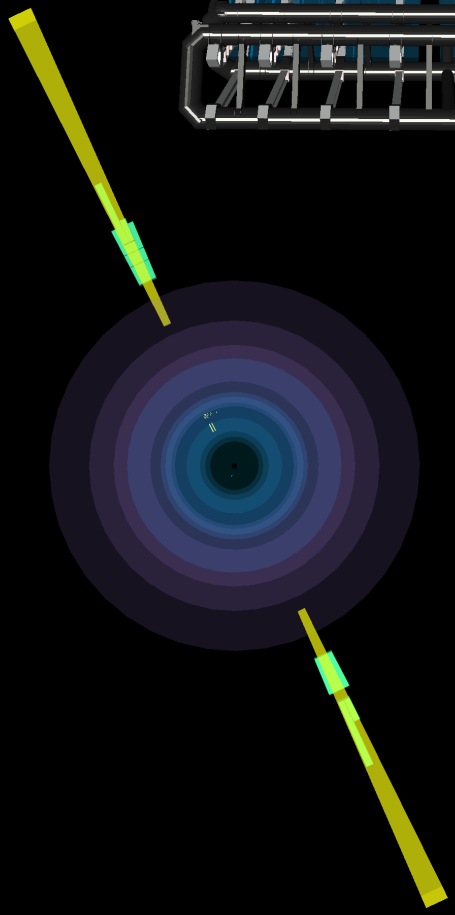
Event displays

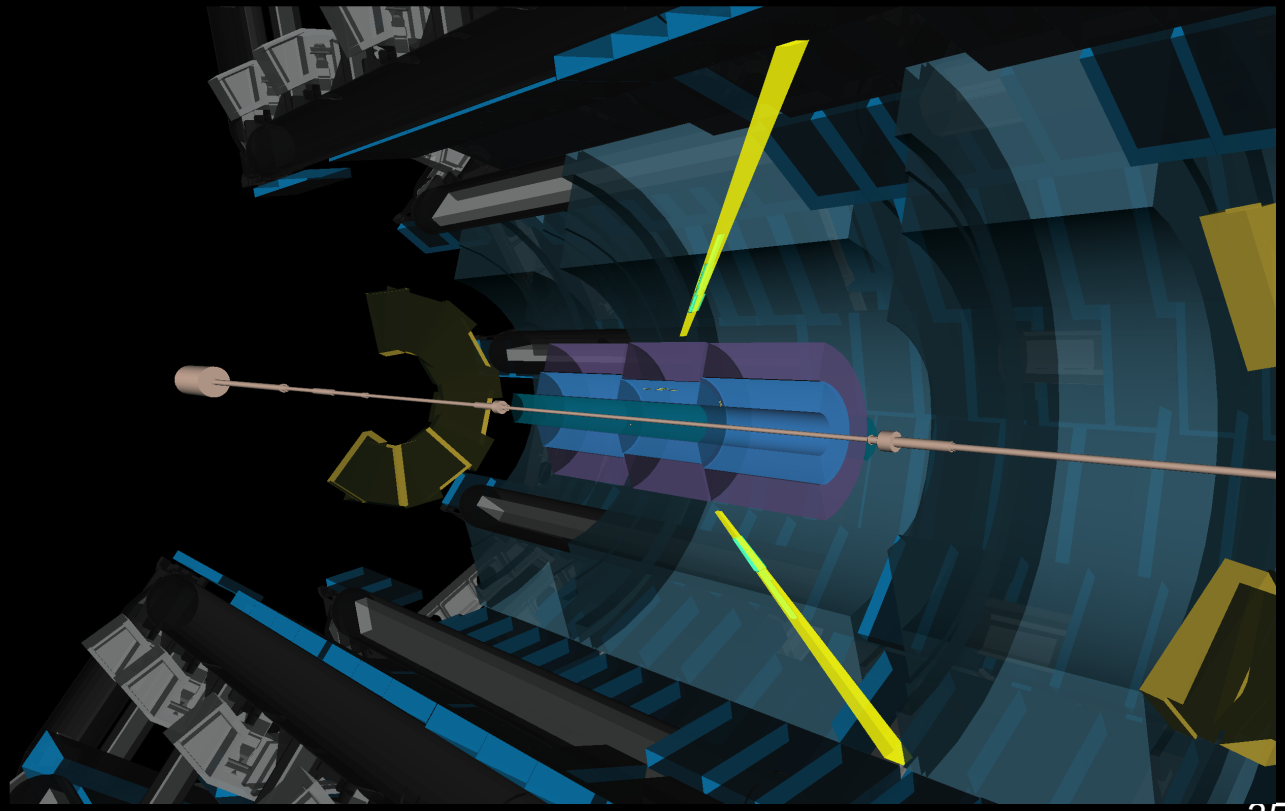


Event displays

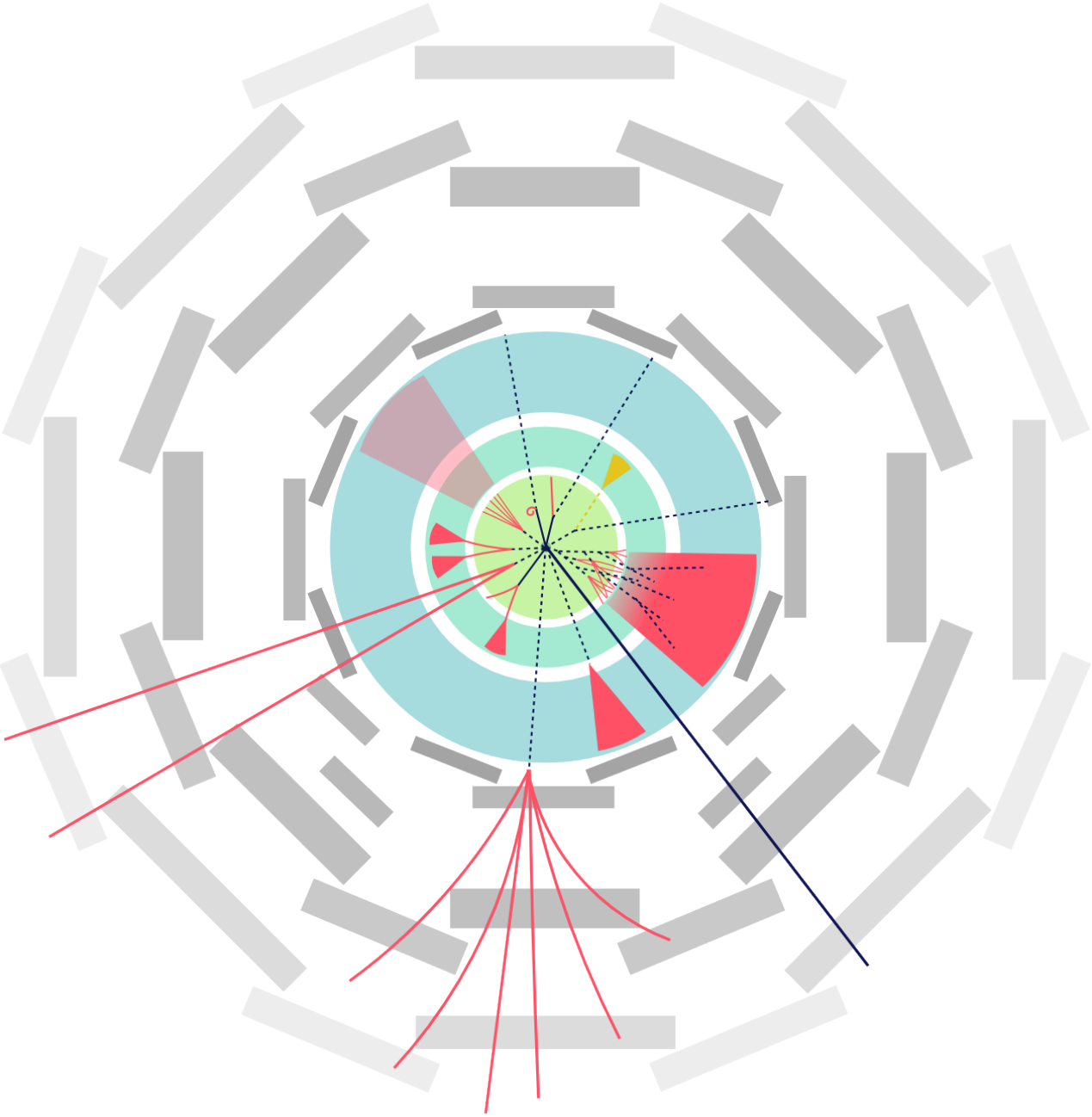


Run: 287931
Event: 461251458
2015-12-13 09:51:07 CEST

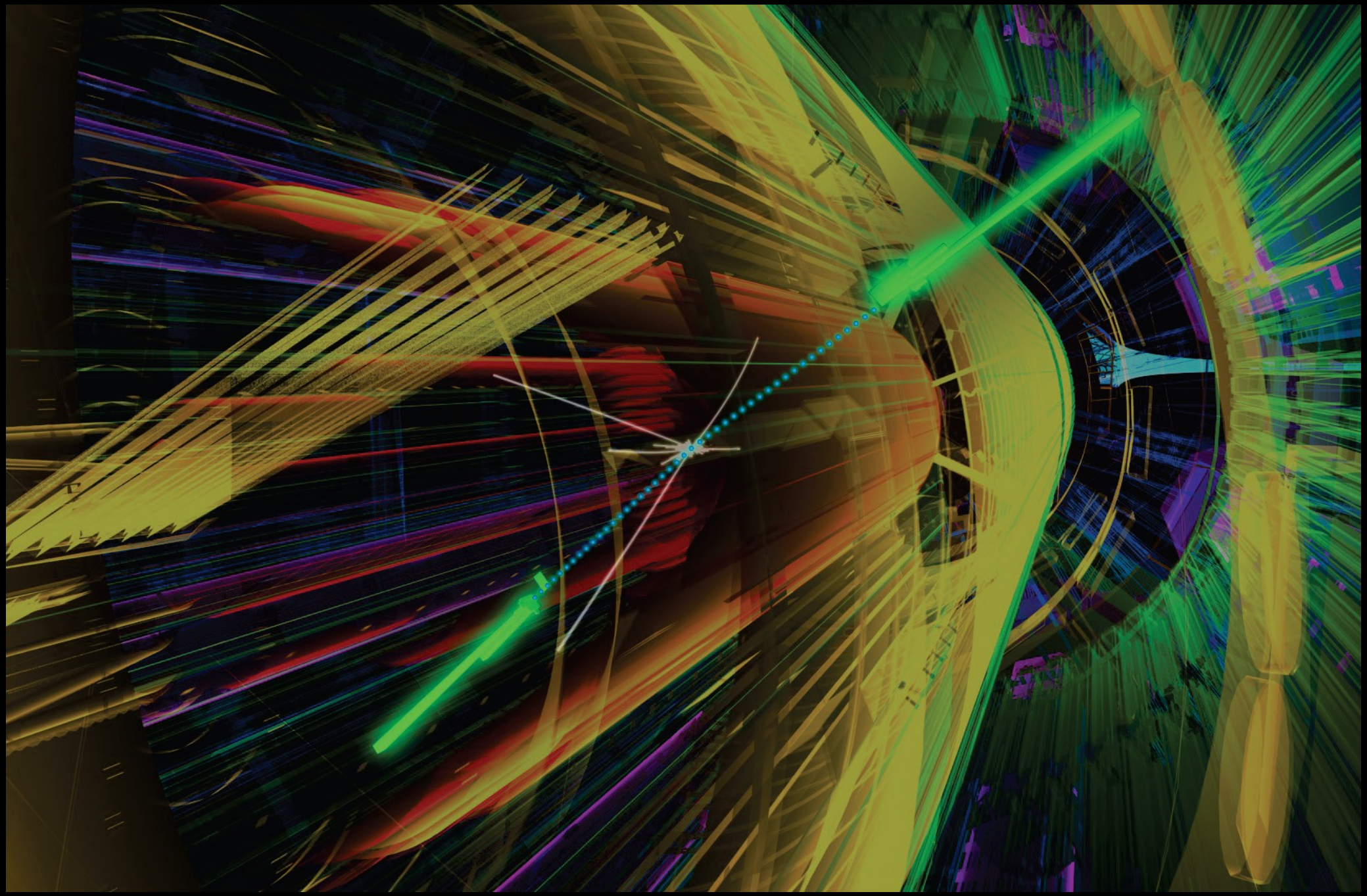




Event displays

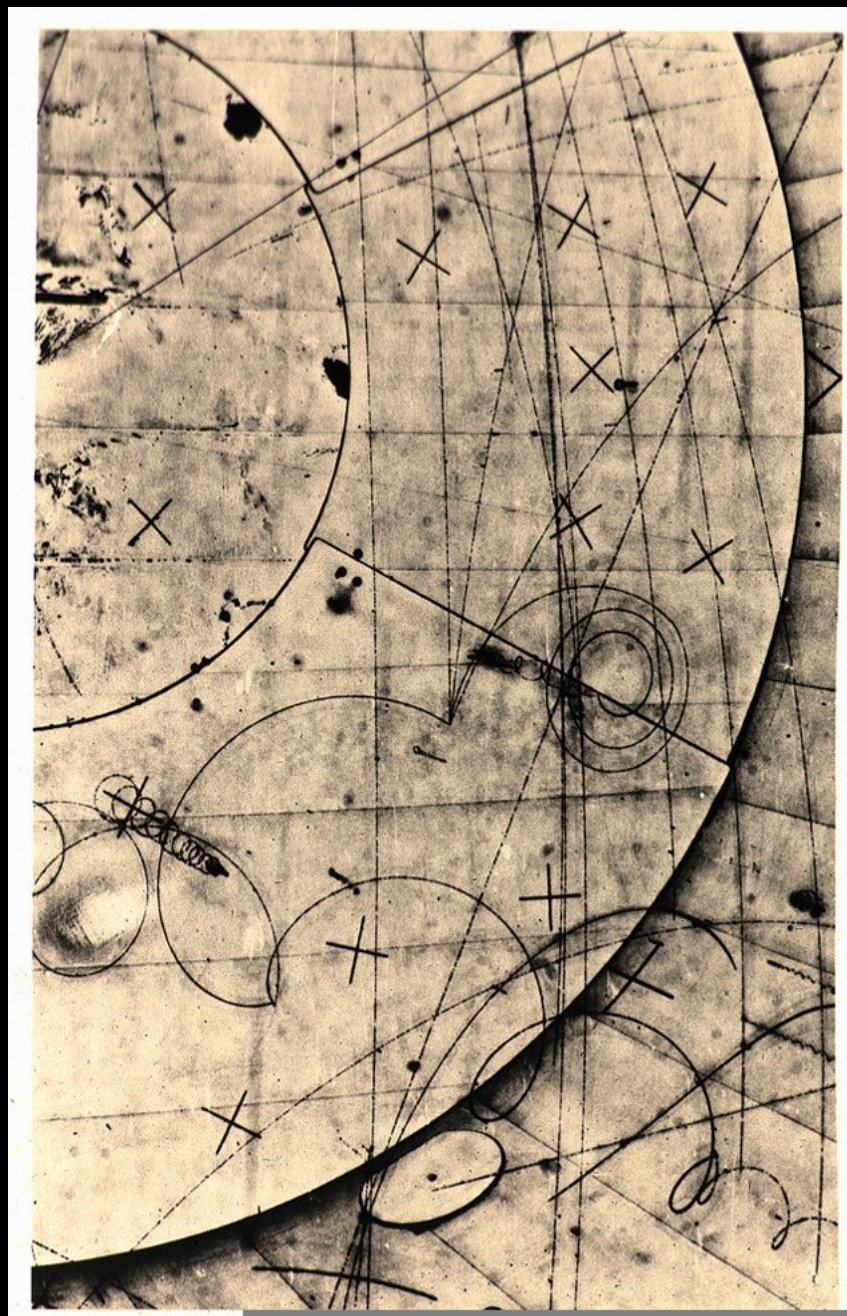


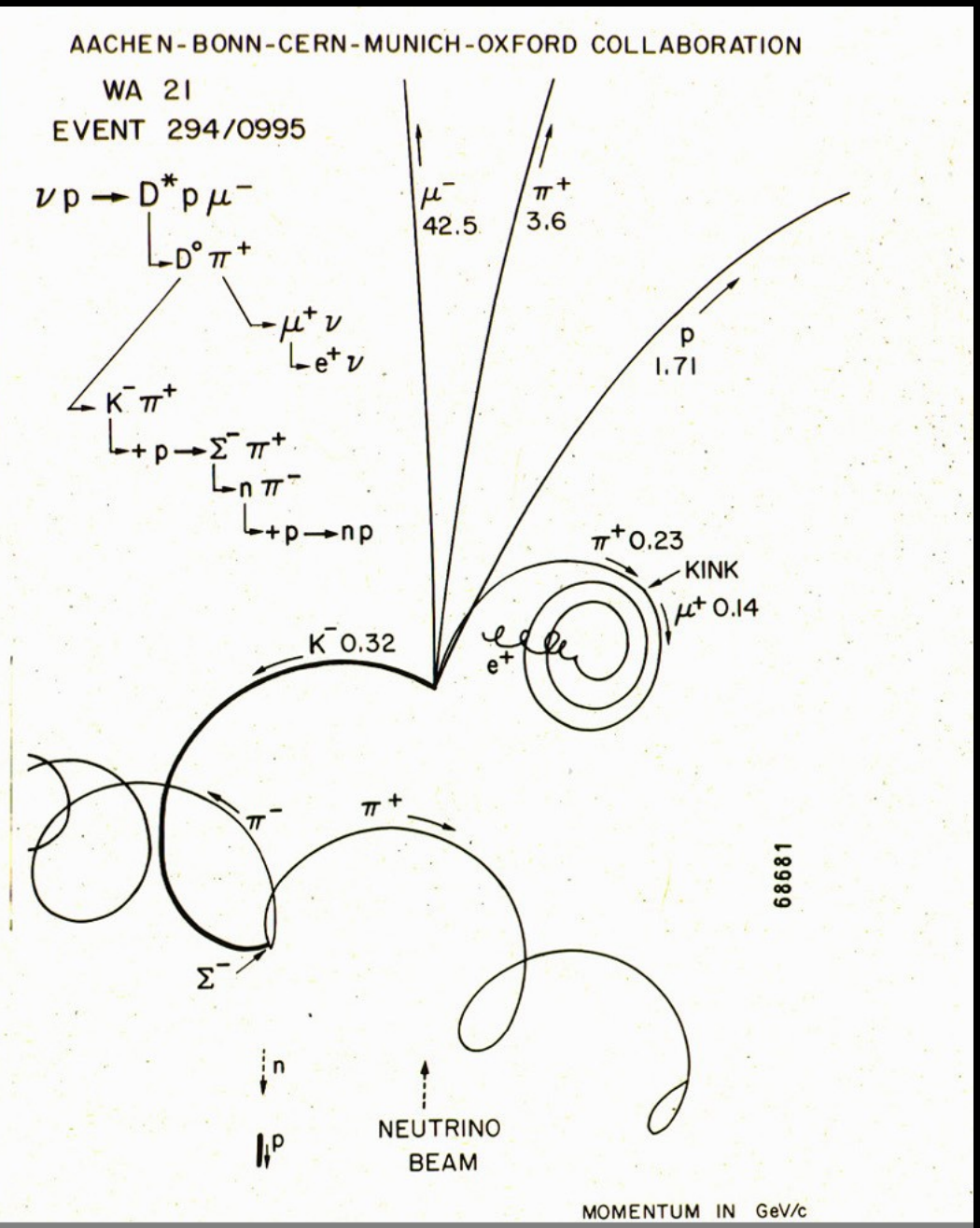
Visualisation



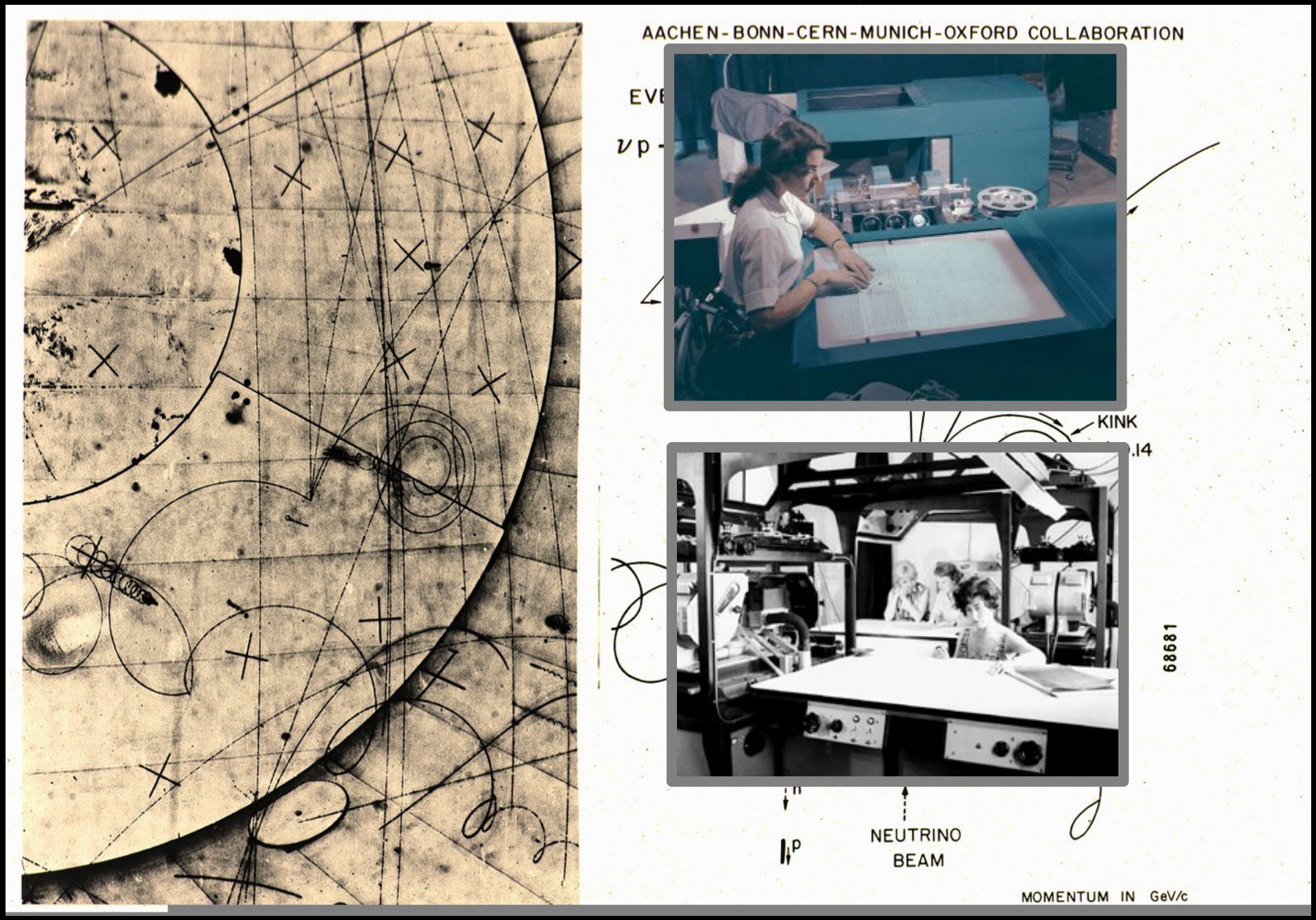
« Vraies » photographies

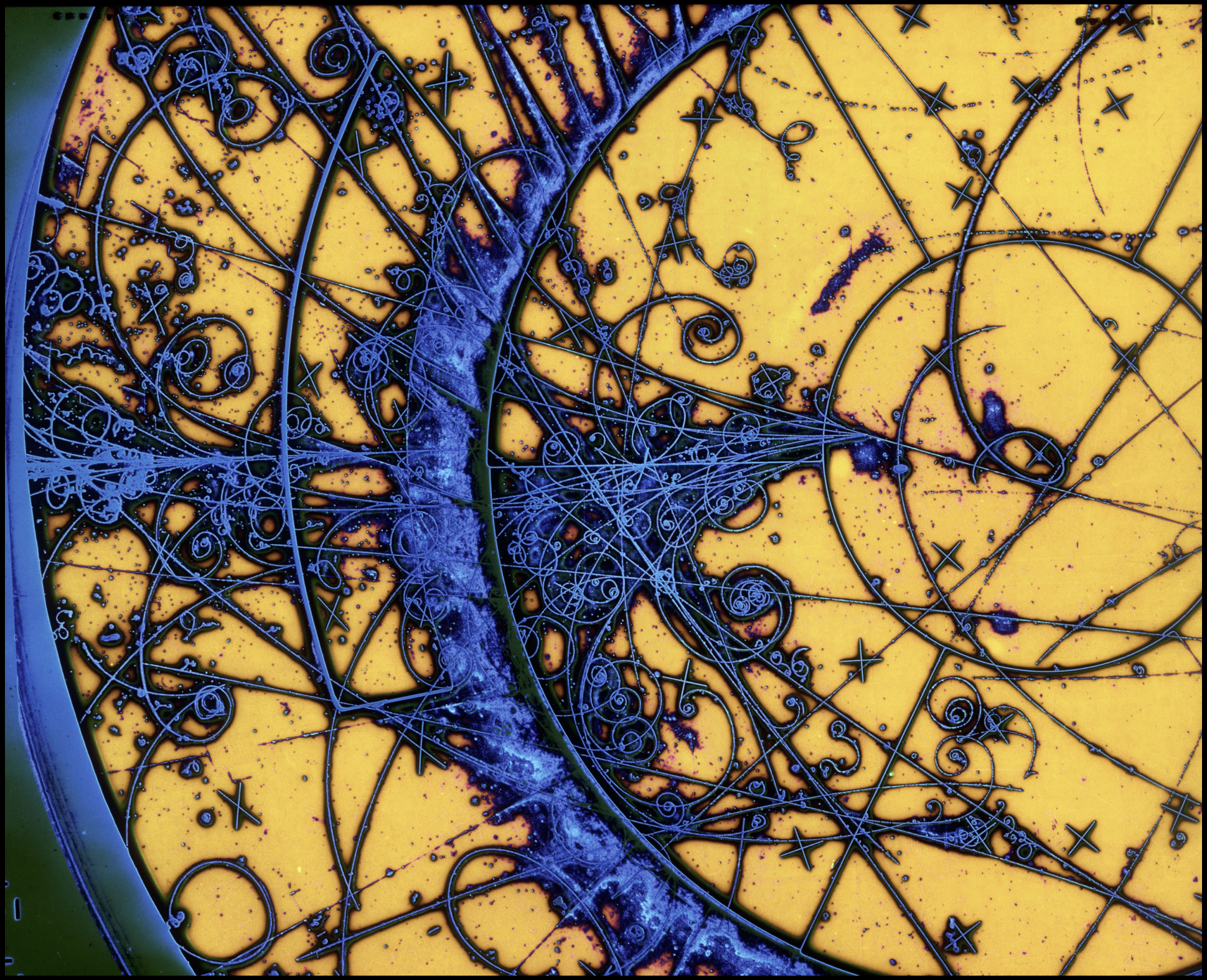
« Vraies » photographies





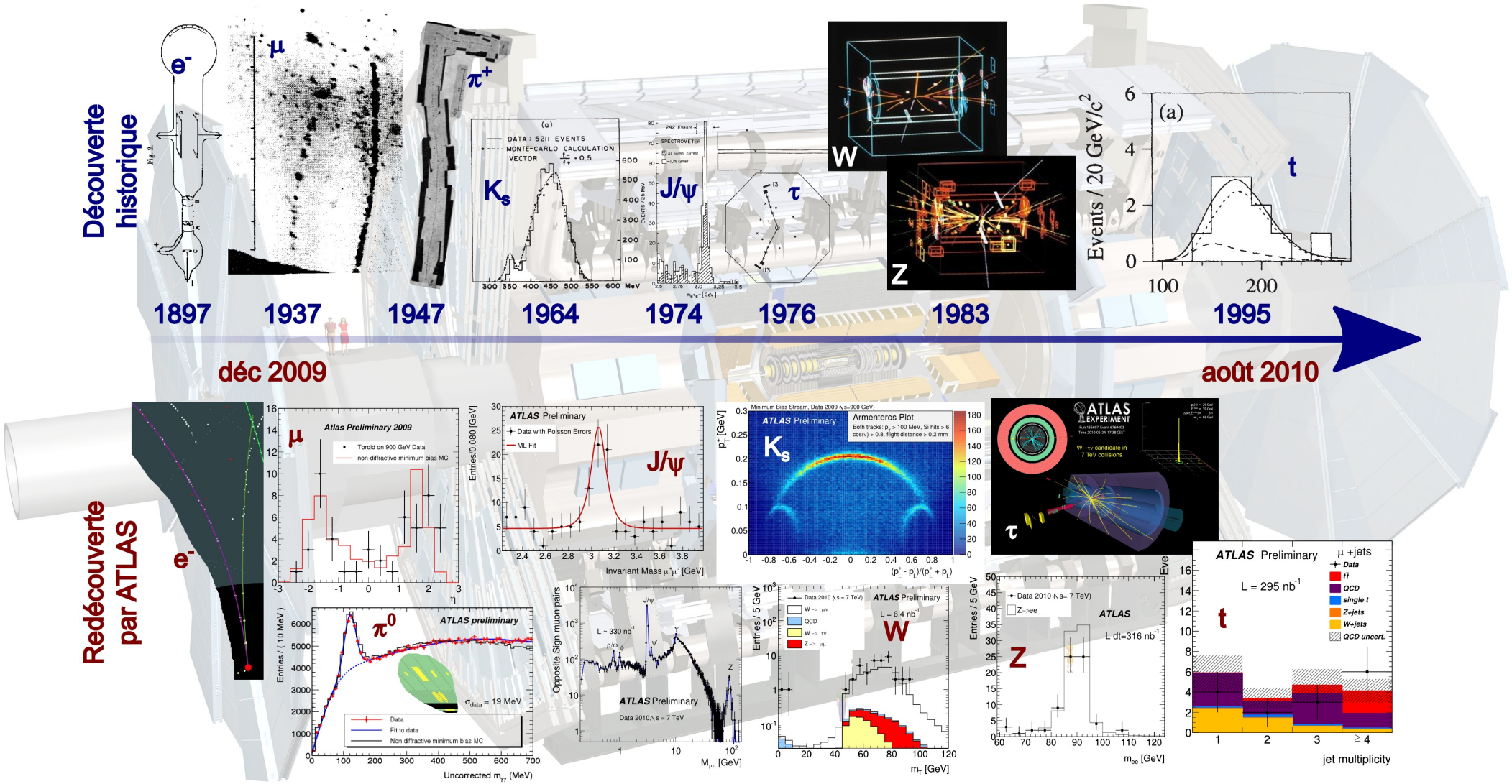
« Vraies » photographies



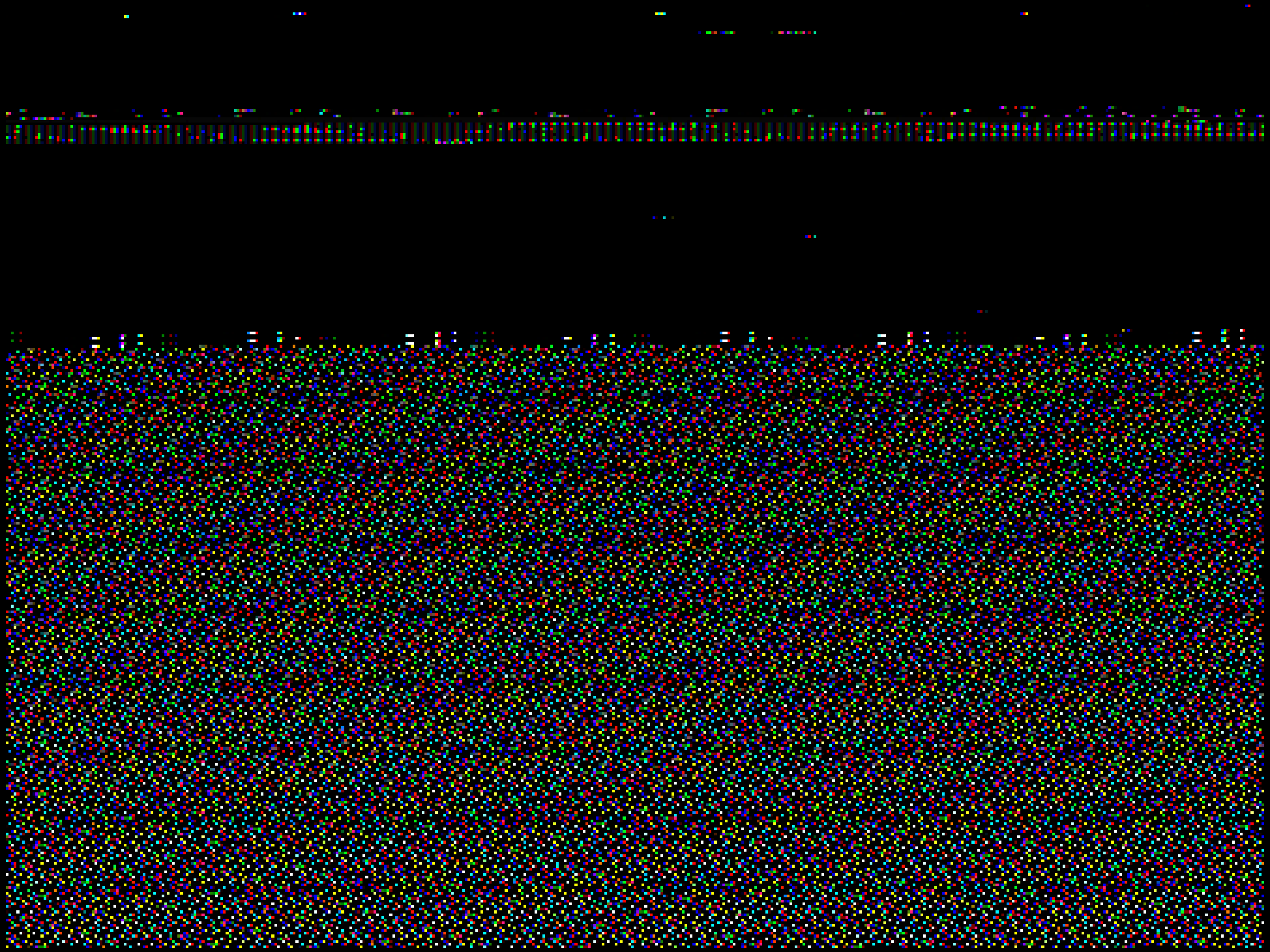


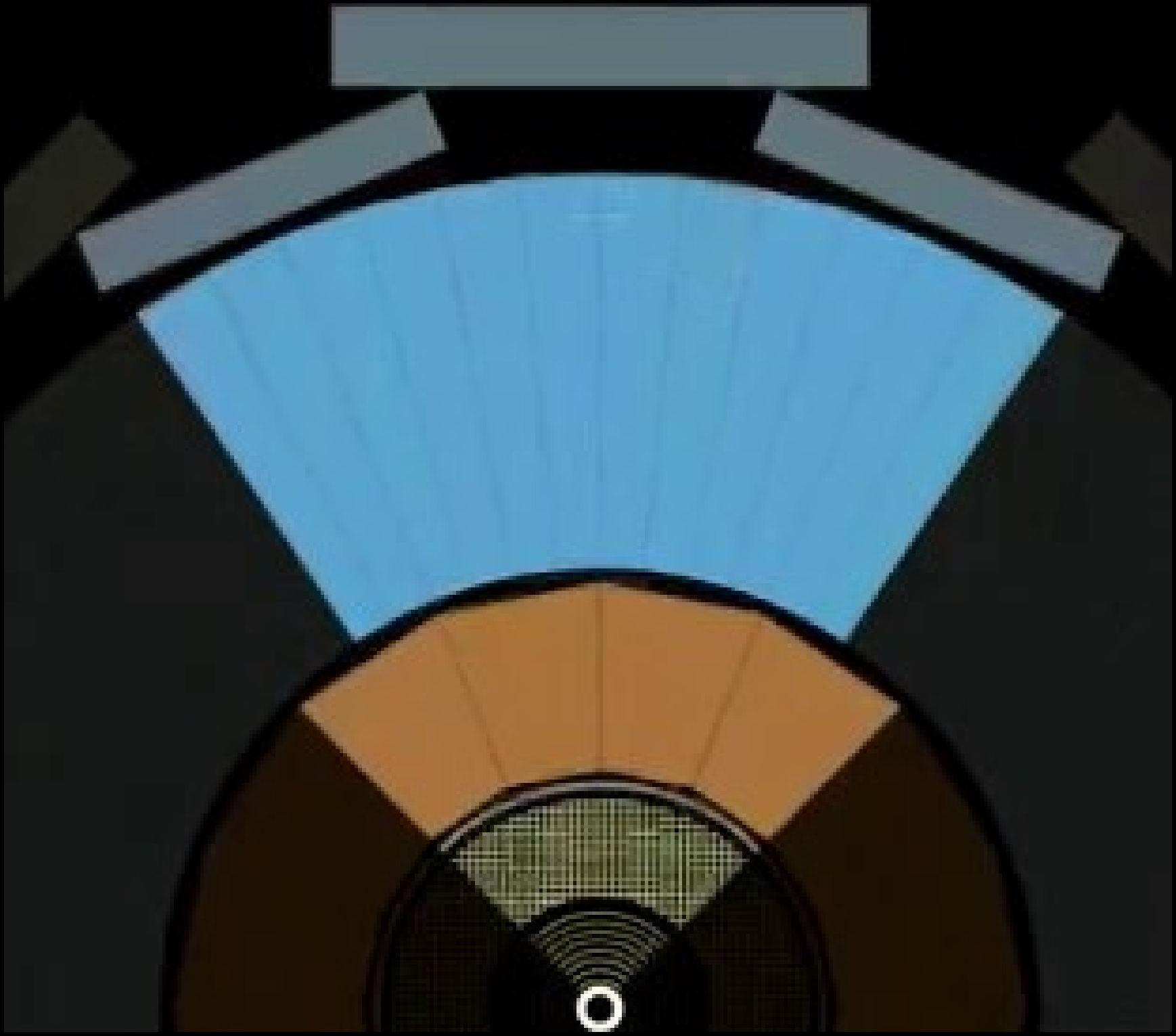
Le modèle standard redécouvert

LHC 2010 : un siècle en un an



3D

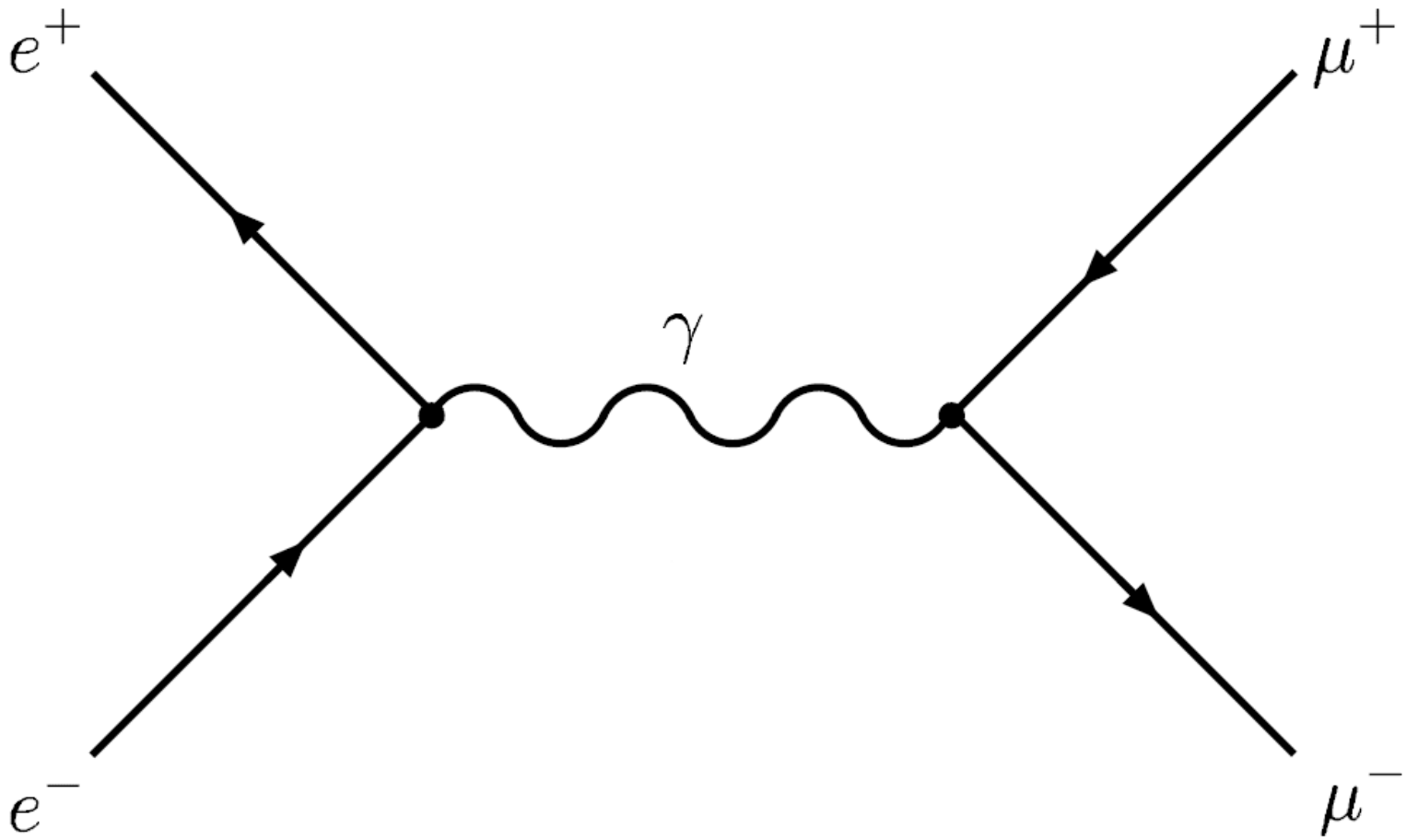




Diagrammes de Feynman

$$\mathcal{M} = \frac{e^2}{(p_1 + p_2)^2}[\bar{u}_3 \gamma_\mu v_4][\bar{v}_2 \gamma^\mu u_1]$$

Diagrammes de Feynman



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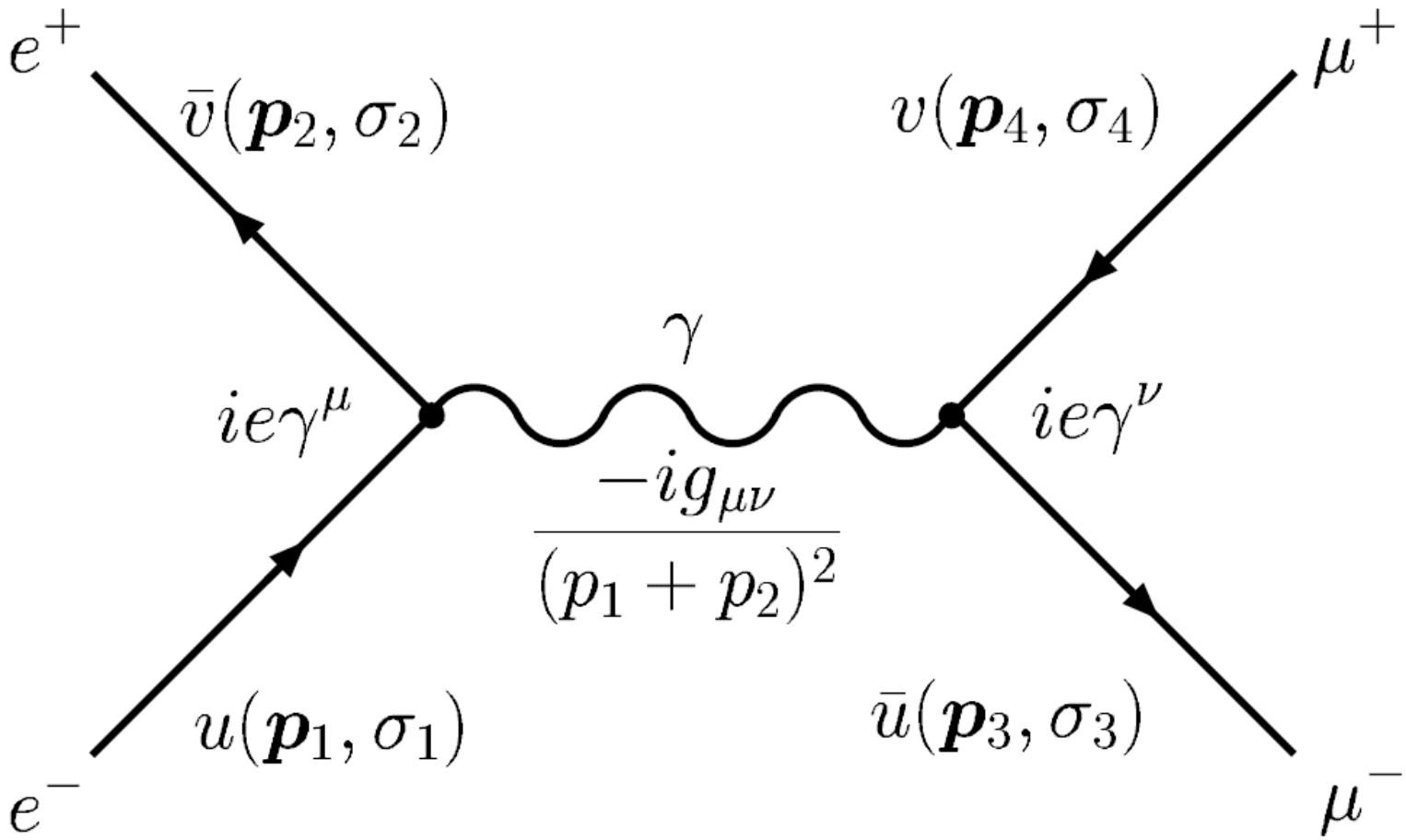
Diagrammes de Feynman



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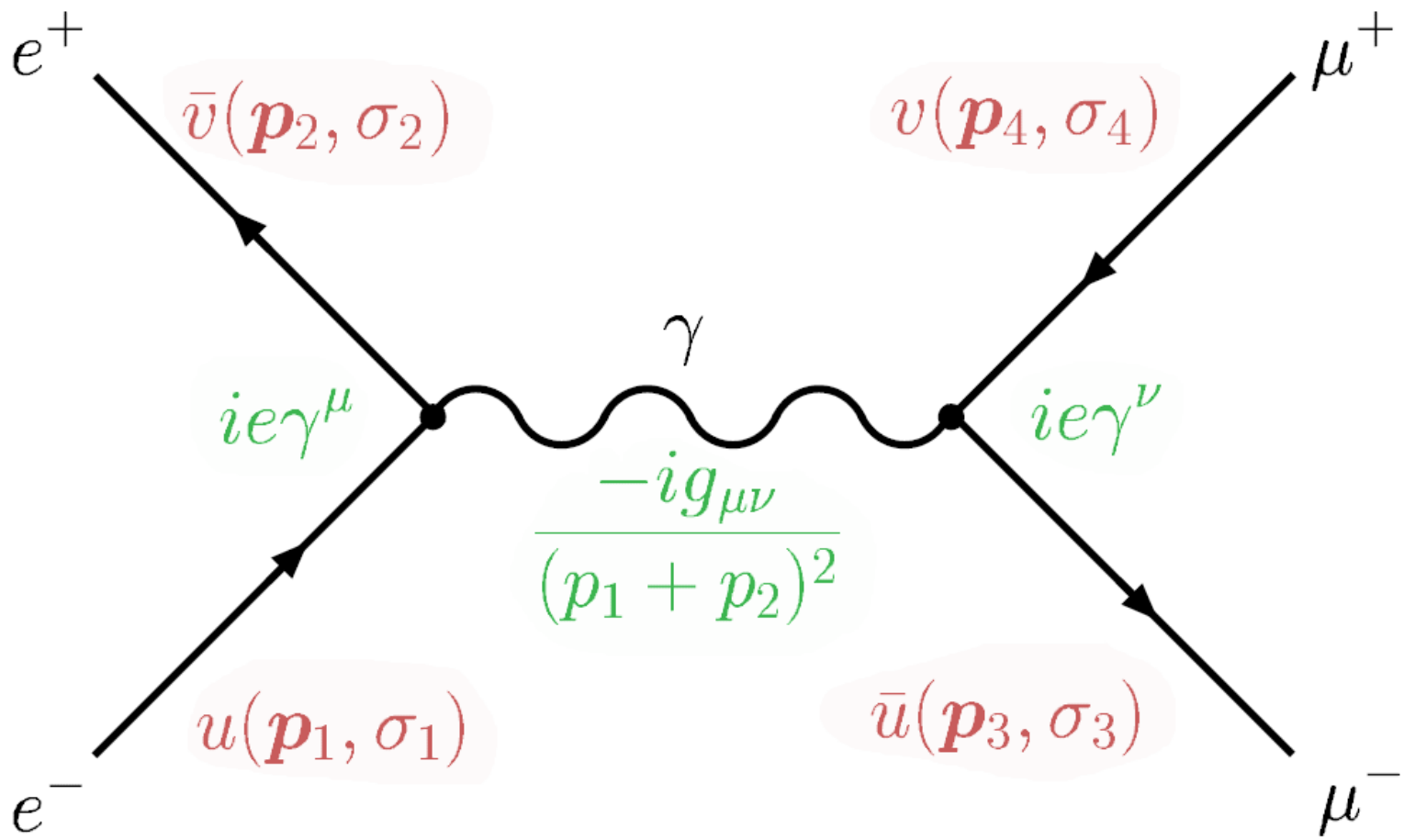
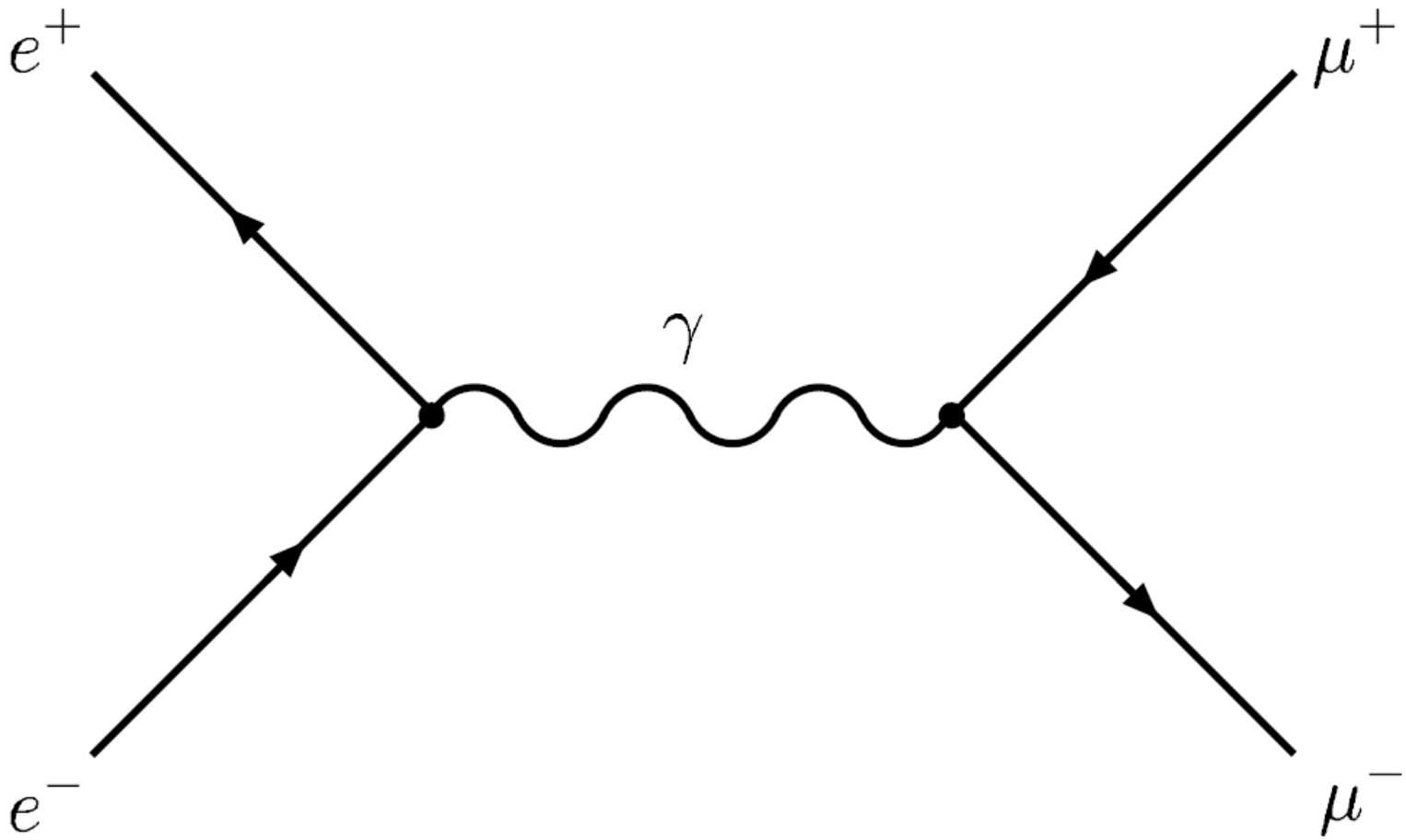
Diagrammes de Feynman



$$-i\mathcal{M} = [\bar{u}(\boldsymbol{p}_3, \sigma_3)(ie\gamma^\nu)v(\boldsymbol{p}_4, \sigma_4)] \frac{-ig_{\mu\nu}}{(p_1+p_2)^2} [\bar{v}(\boldsymbol{p}_2, \sigma_2)(ie\gamma^\mu)u(\boldsymbol{p}_1, \sigma_1)]$$

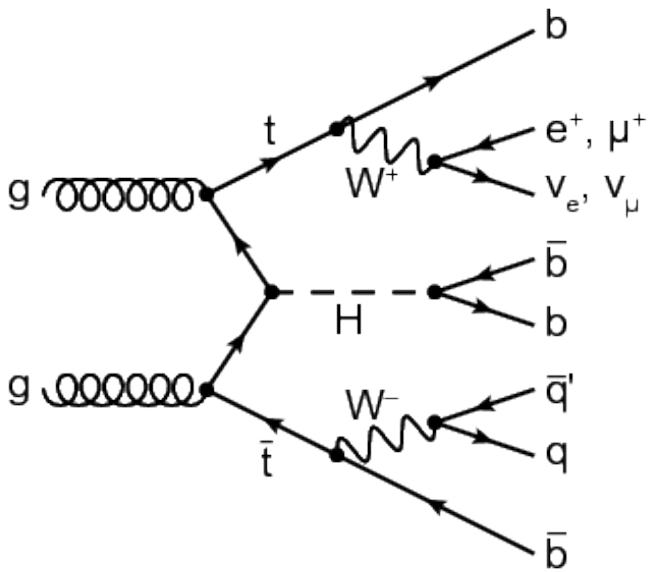
$$\mathcal{M} = \frac{e^2}{(p_1+p_2)^2}[\bar{u}_3\gamma_\mu v_4][\bar{v}_2\gamma^\mu u_1]$$

Diagrammes de Feynman

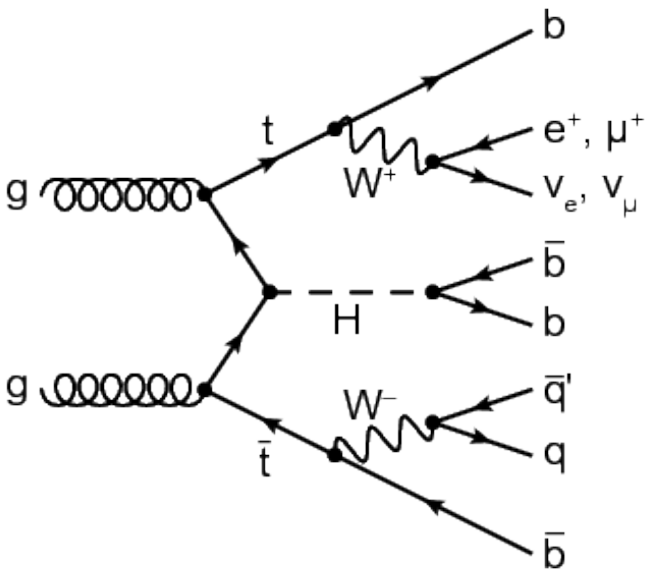


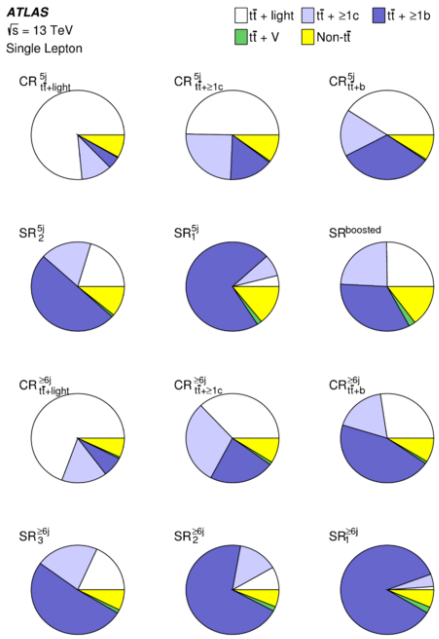
$$\mathcal{M} = \frac{e^2}{(p_1 + p_2)^2}[\bar{u}_3 \gamma_\mu v_4][\bar{v}_2 \gamma^\mu u_1]$$

Analyse de données

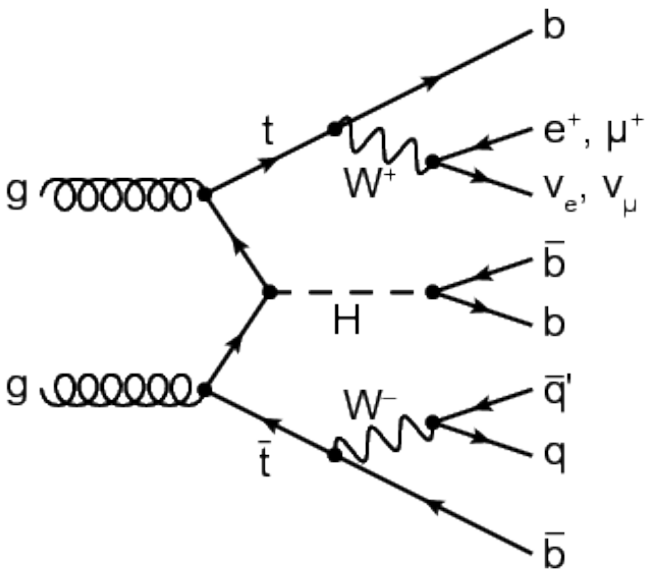


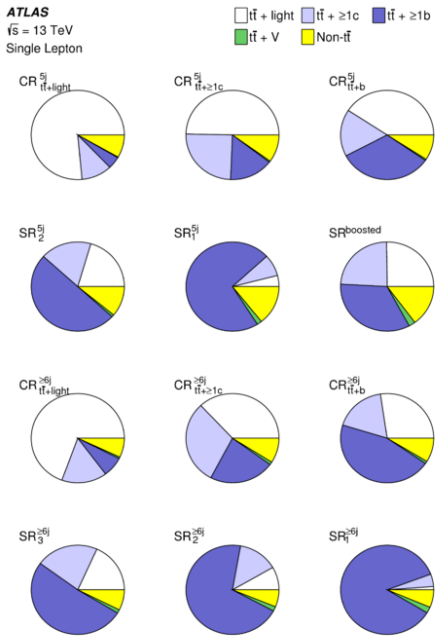
Analyse de données

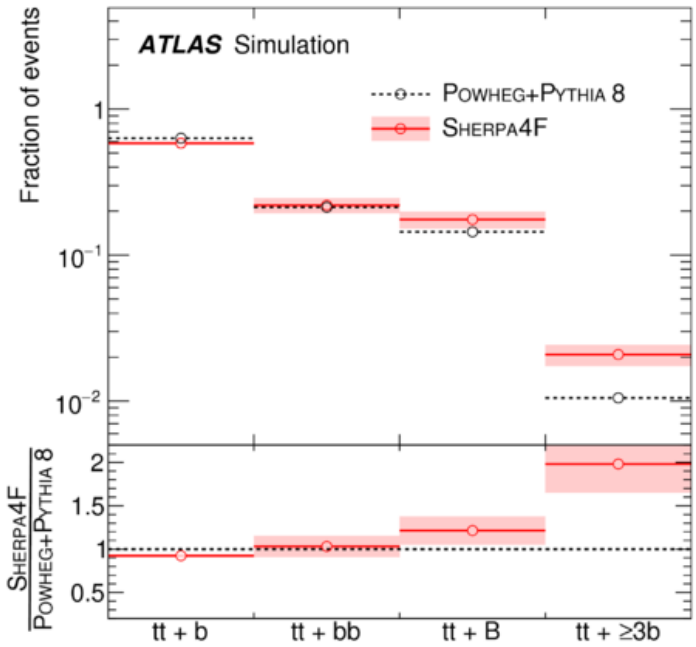




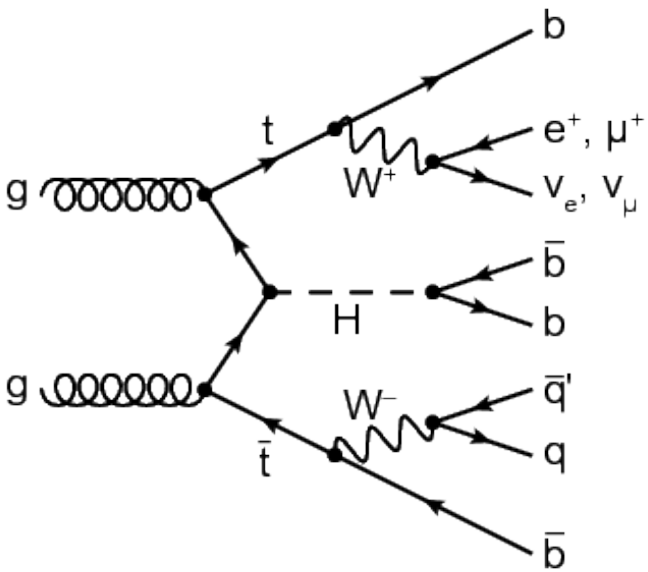
Analyse de données

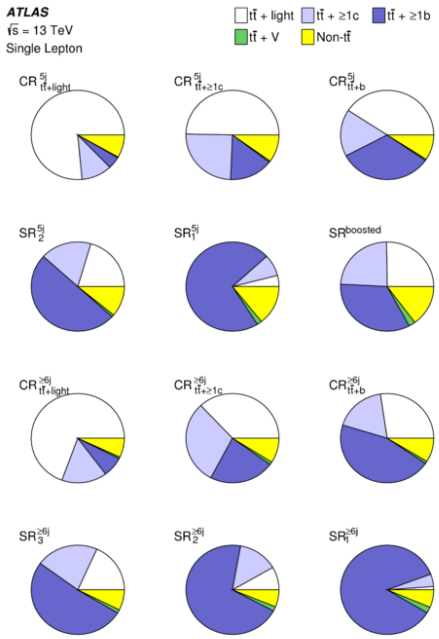


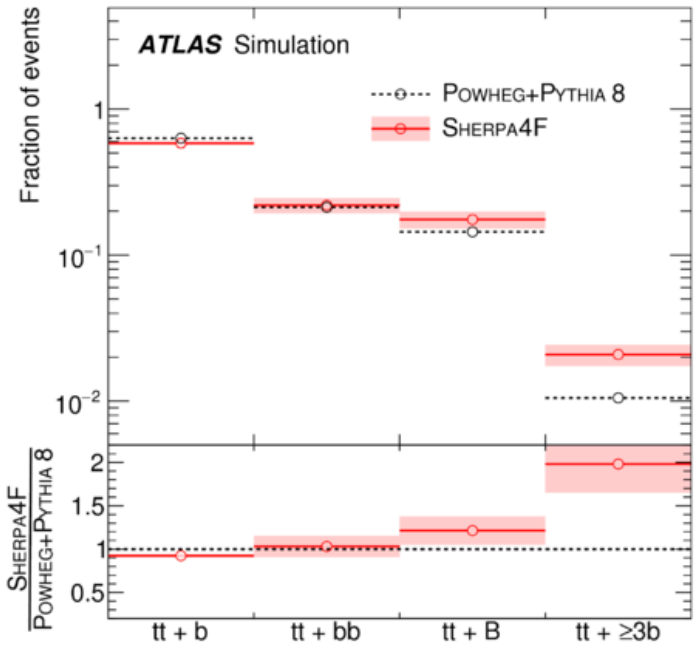


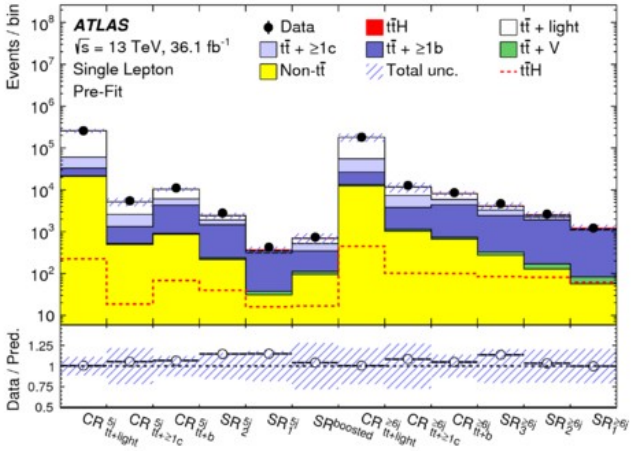


Analyse de données

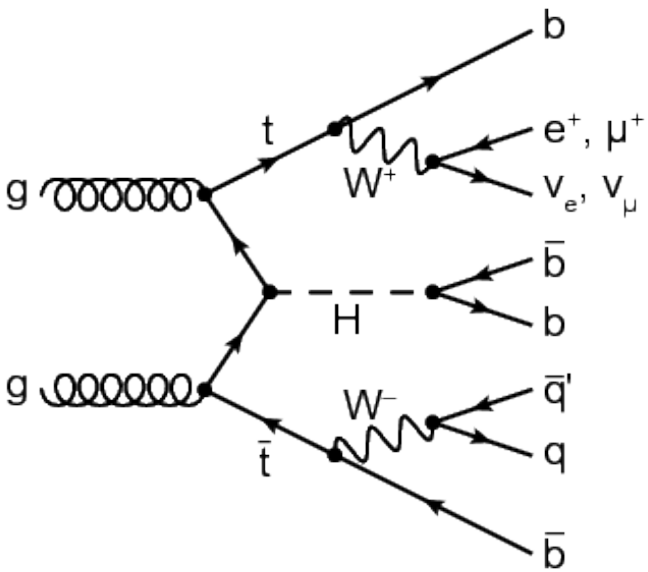


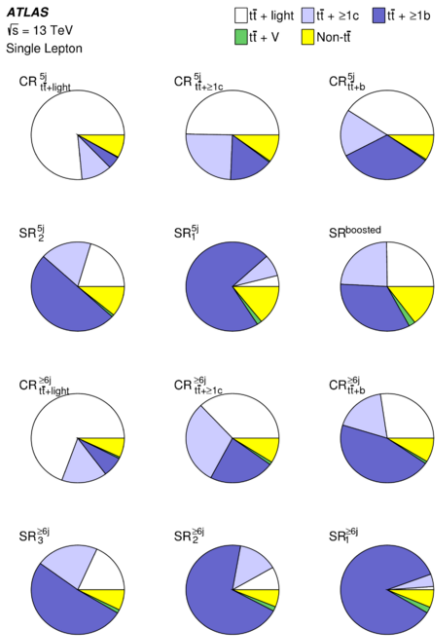


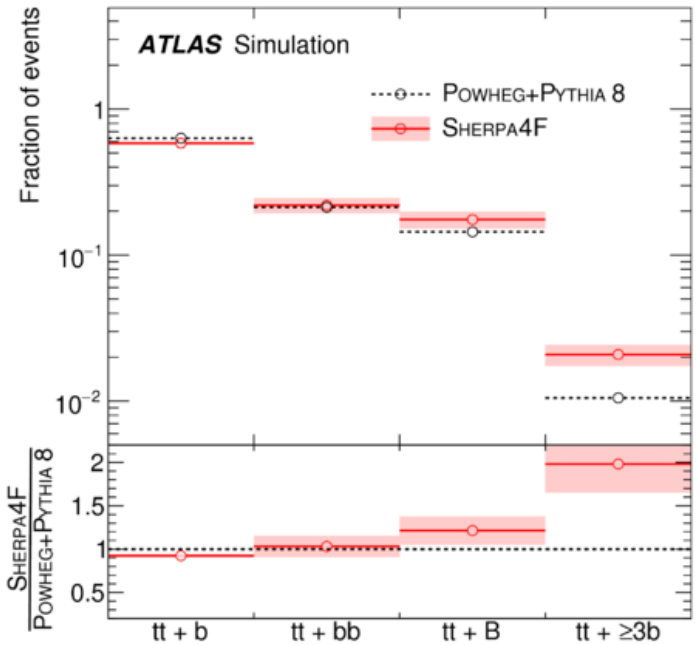


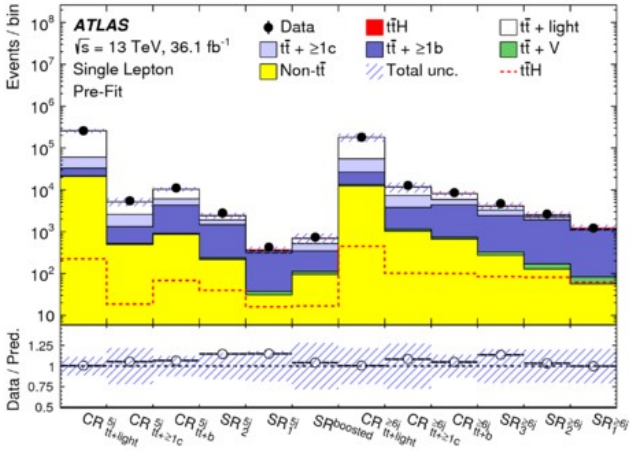


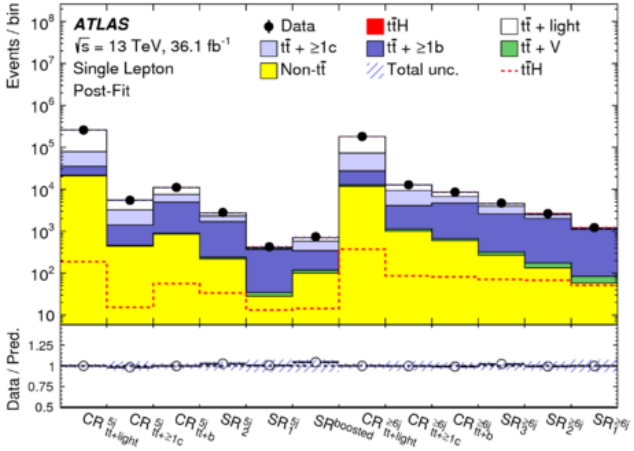
Analyse de données



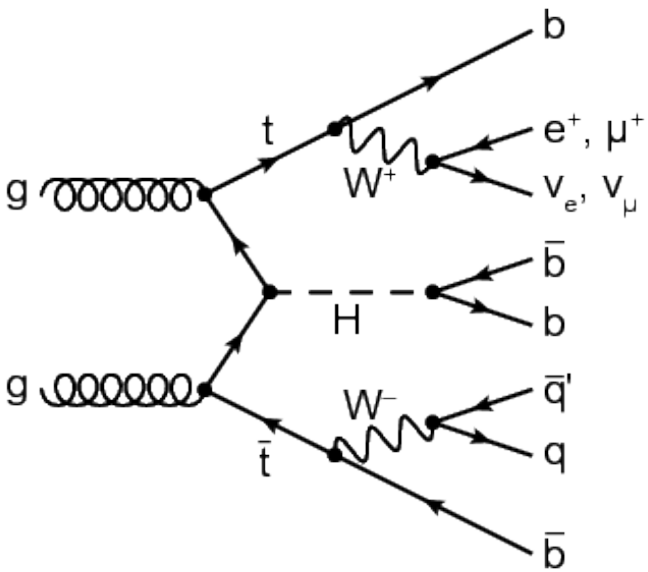


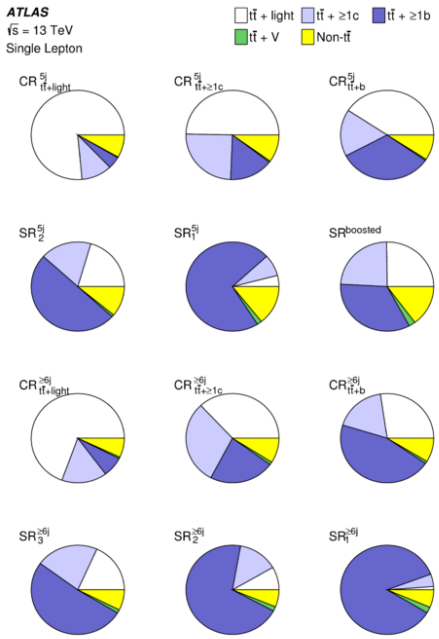


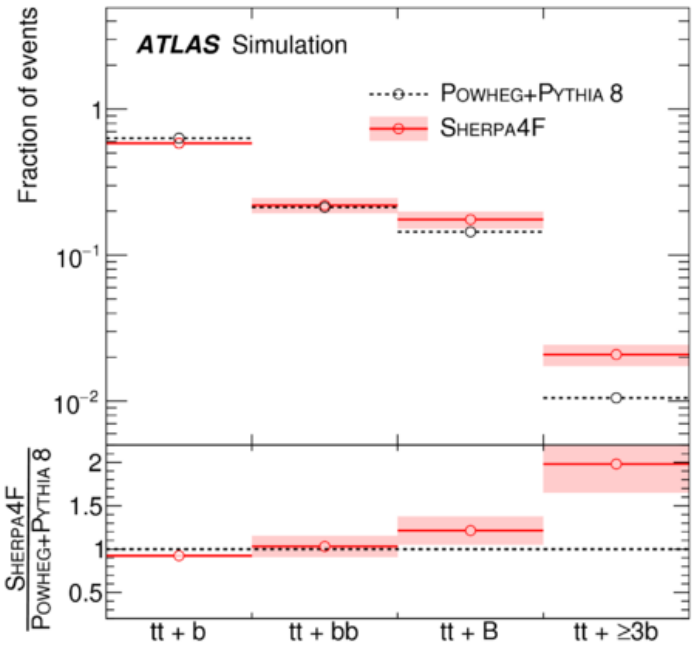


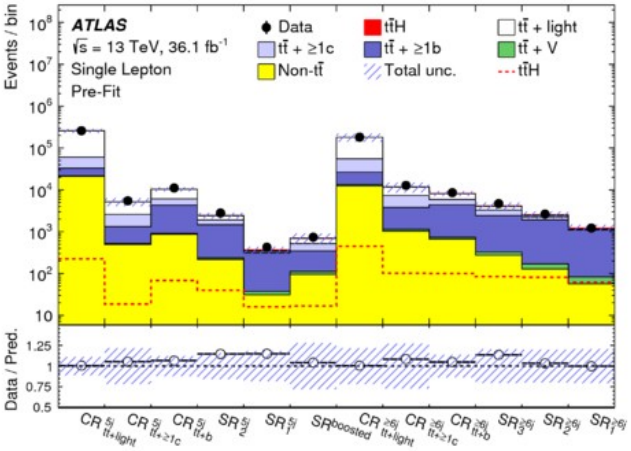


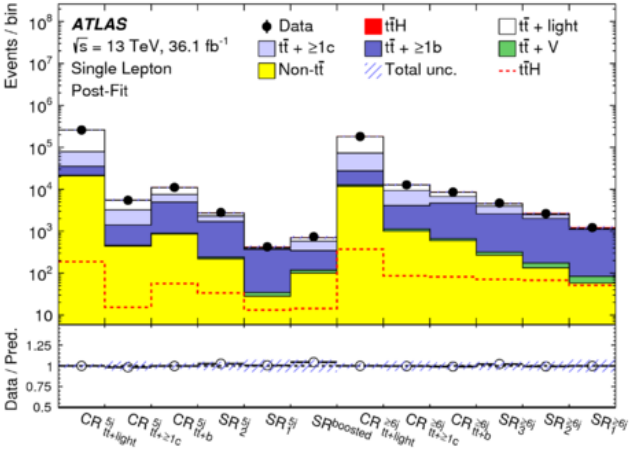
Analyse de données







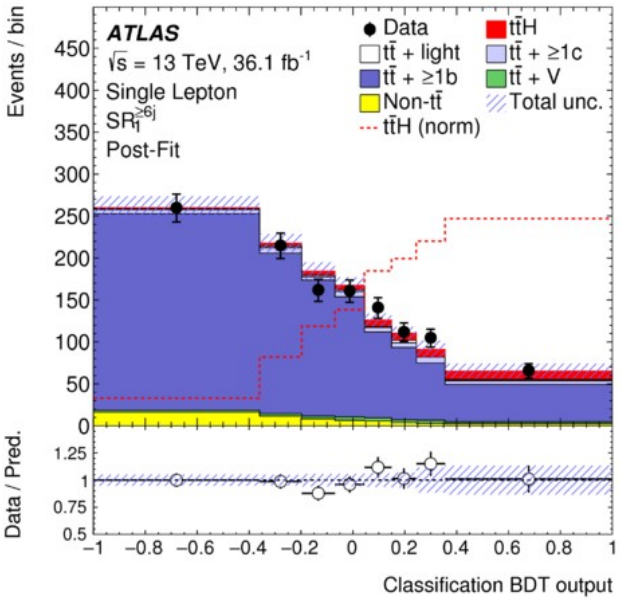




Sample	$CR^{5j}_{t\bar{t}+light}$ Pre-fit	$CR^{5j}_{t\bar{t}+light}$ Post-fit	$CR^{5j}_{t\bar{t}+\geq 1c}$ Pre-fit	$CR^{5j}_{t\bar{t}+\geq 1c}$ Post-fit	$CR^{5j}_{t\bar{t}+b}$ Pre-fit	$CR^{5j}_{t\bar{t}+b}$ Post-fit
$t\bar{t}H$	224 ± 22	190 ± 140	18.7 ± 2.5	15 ± 12	68.0 ± 7.6	57 ± 42
$t\bar{t}$ + light	197 000 ± 26 000	179 900 ± 4900	2580 ± 720	2300 ± 210	4250 ± 920	3560 ± 240
$t\bar{t} + \geq 1c$	27 500 ± 4300	44 100 ± 5500	1280 ± 500	1840 ± 250	1770 ± 270	2590 ± 390
$t\bar{t} + \geq 1b$	11 300 ± 1100	13 500 ± 1300	790 ± 130	944 ± 94	3400 ± 440	4030 ± 320
$t\bar{t} + V$	589 ± 55	584 ± 54	23.2 ± 4.1	21.3 ± 2.9	48.1 ± 5.9	46.6 ± 5.4
Non-$t\bar{t}$	21 300 ± 4100	20 900 ± 3200	520 ± 180	440 ± 100	960 ± 190	860 ± 160
Total	258 000 ± 29 000	259 320 ± 910	5200 ± 1100	5560 ± 160	10 400 ± 1300	11 140 ± 290
Data	259 320		5465		11 095	

Sample	SR^{5j}_{2} Pre-fit	SR^{5j}_{2} Post-fit	SR^{5j}_{1} Pre-fit	SR^{5j}_{1} Post-fit	$SR^{boosted}$ Pre-fit	$SR^{boosted}$ Post-fit
$t\bar{t}H$	40.1 ± 5.1	34 ± 25	15.9 ± 2.1	13.3 ± 9.8	16.9 ± 1.9	14 ± 10
$t\bar{t}$ + light	500 ± 210	393 ± 67	15 ± 33	12.5 ± 9.3	180 ± 120	112 ± 32
$t\bar{t} + \geq 1c$	436 ± 92	610 ± 100	30 ± 17	28 ± 14	168 ± 70	235 ± 39
$t\bar{t} + \geq 1b$	1230 ± 200	1450 ± 110	273 ± 53	335 ± 25	236 ± 89	229 ± 33
$t\bar{t} + V$	19.9 ± 2.9	19.7 ± 2.4	6.4 ± 1.3	6.4 ± 1.2	16.1 ± 2.9	16.6 ± 2.4
Non-$t\bar{t}$	269 ± 64	220 ± 52	54 ± 11	28.1 ± 8.4	104 ± 30	101 ± 26
Total	2440 ± 390	2724 ± 70	371 ± 68	423 ± 23	710 ± 200	708 ± 40
Data	2798		426		740	

Analyse de données



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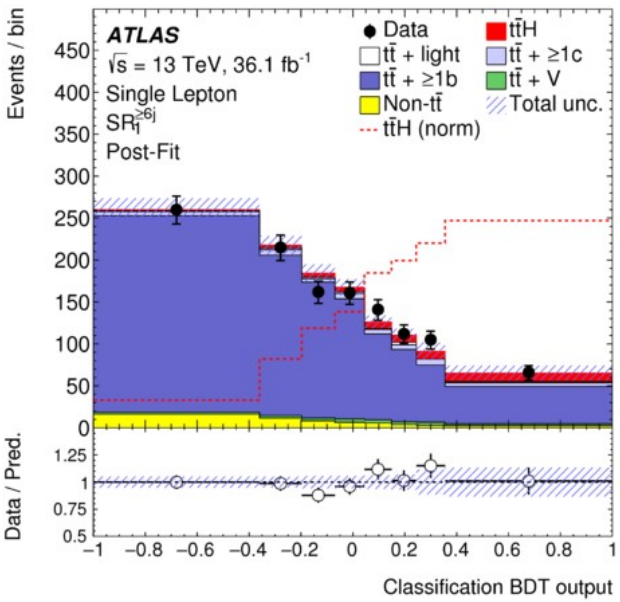

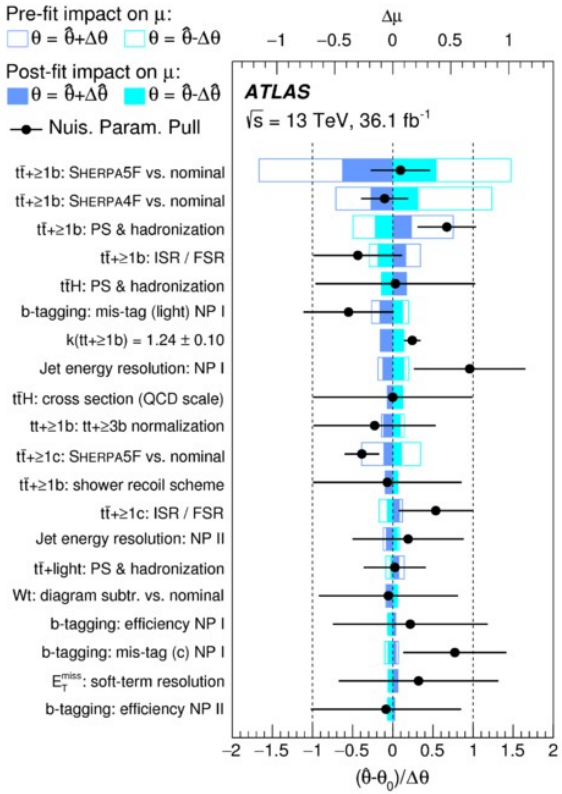

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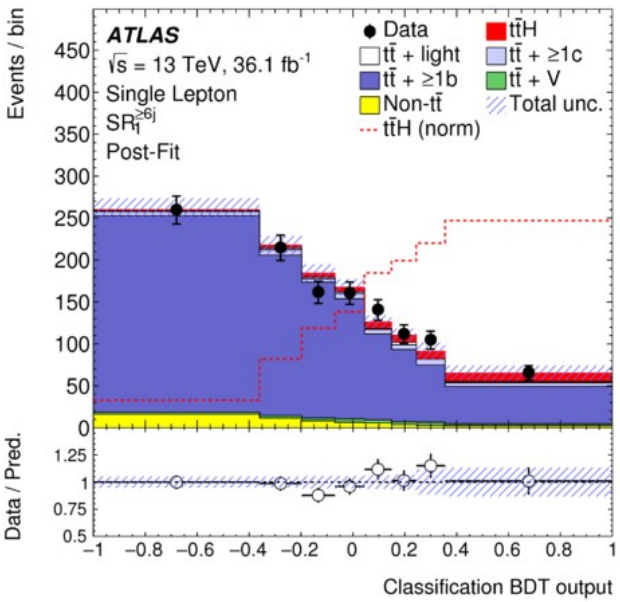
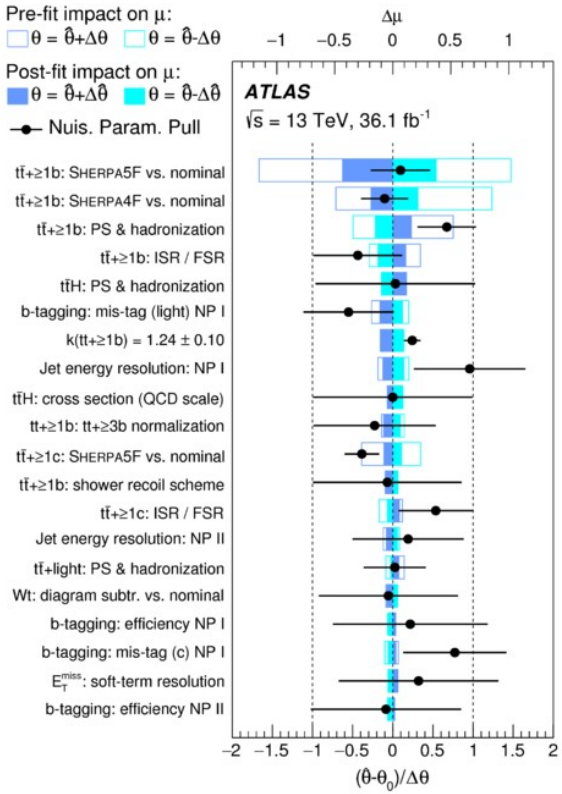
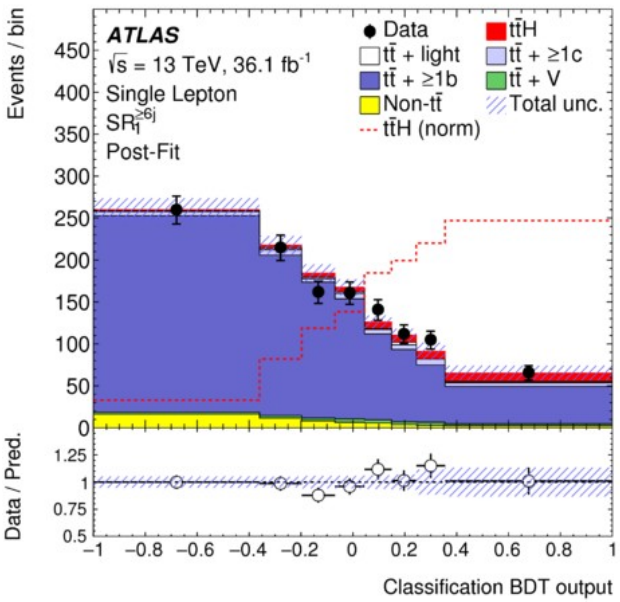
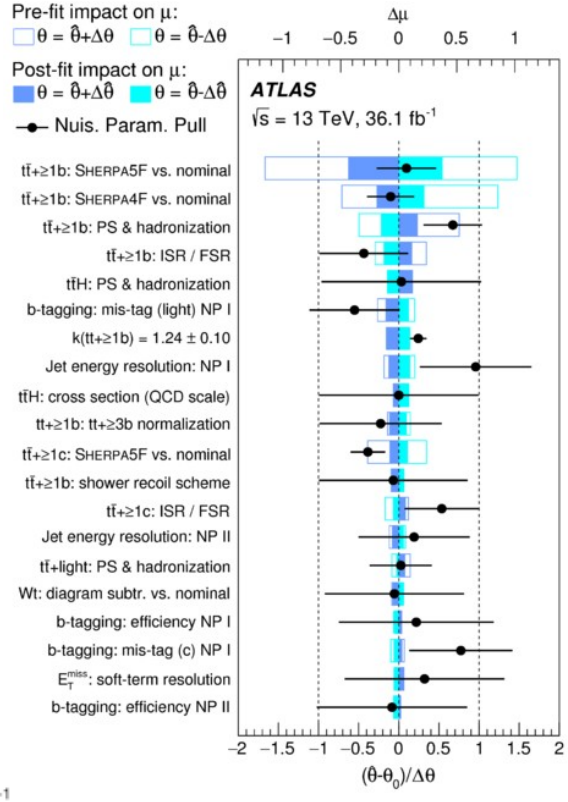




Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t}+\geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+0.03	−0.05
Other background modeling	+0.08	−0.08
$t\bar{t}+$light modeling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e,μ) id., isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t}+\geq 1b$ normalization	+0.09	−0.10
$t\bar{t}+\geq 1c$ normalization	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

Analyse de données





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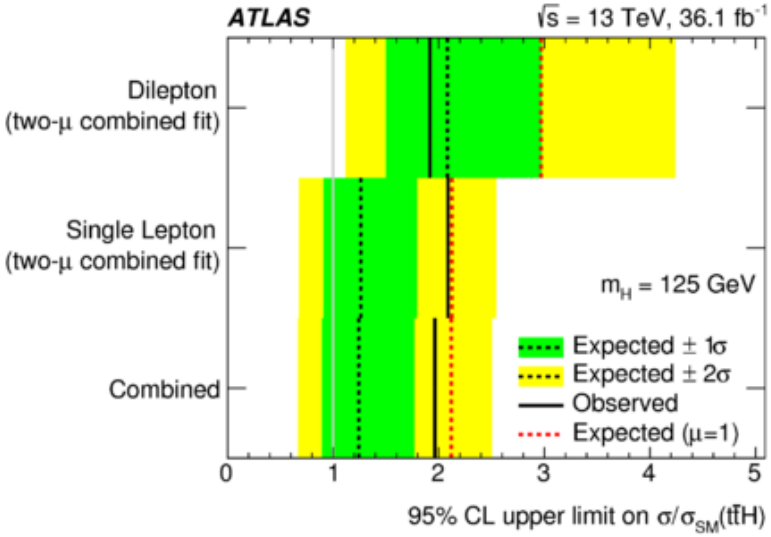
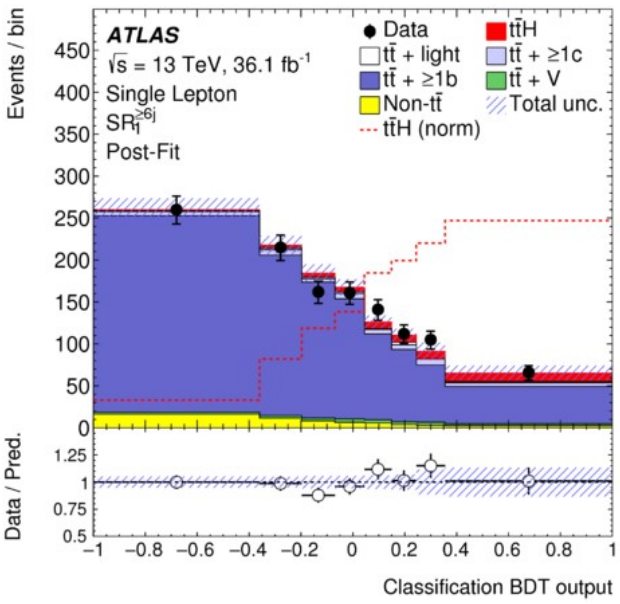
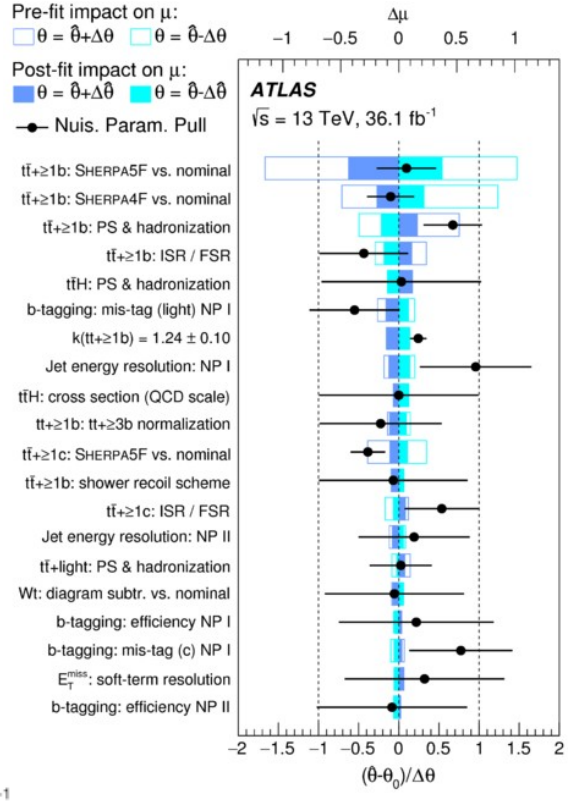


Analyse de données





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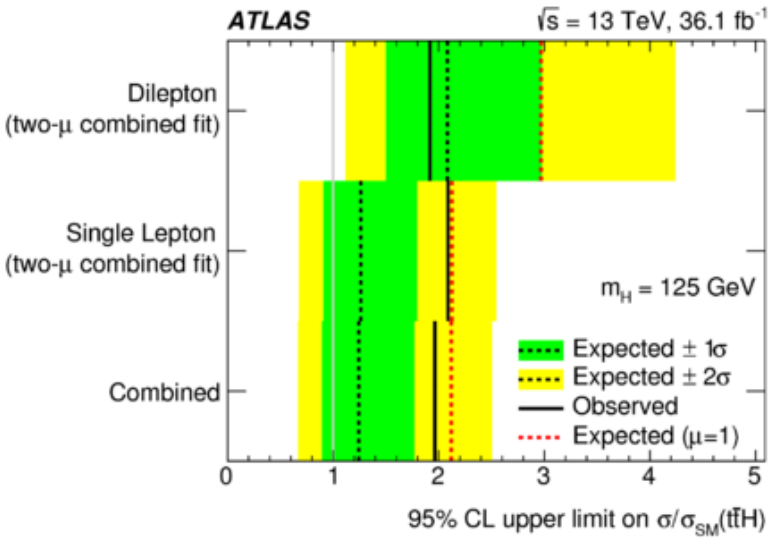
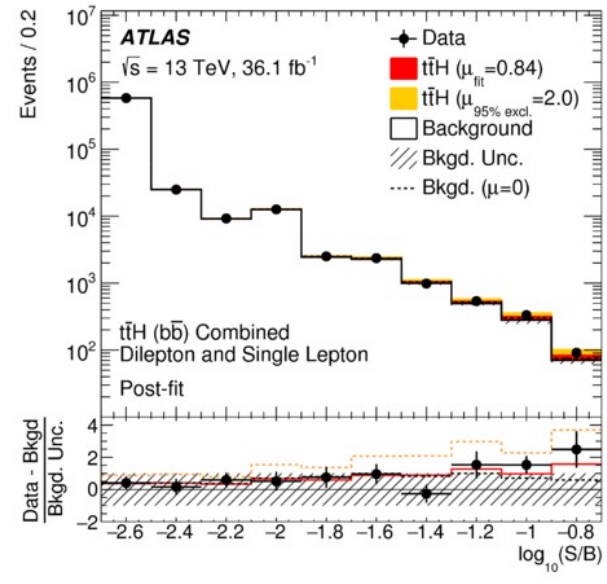
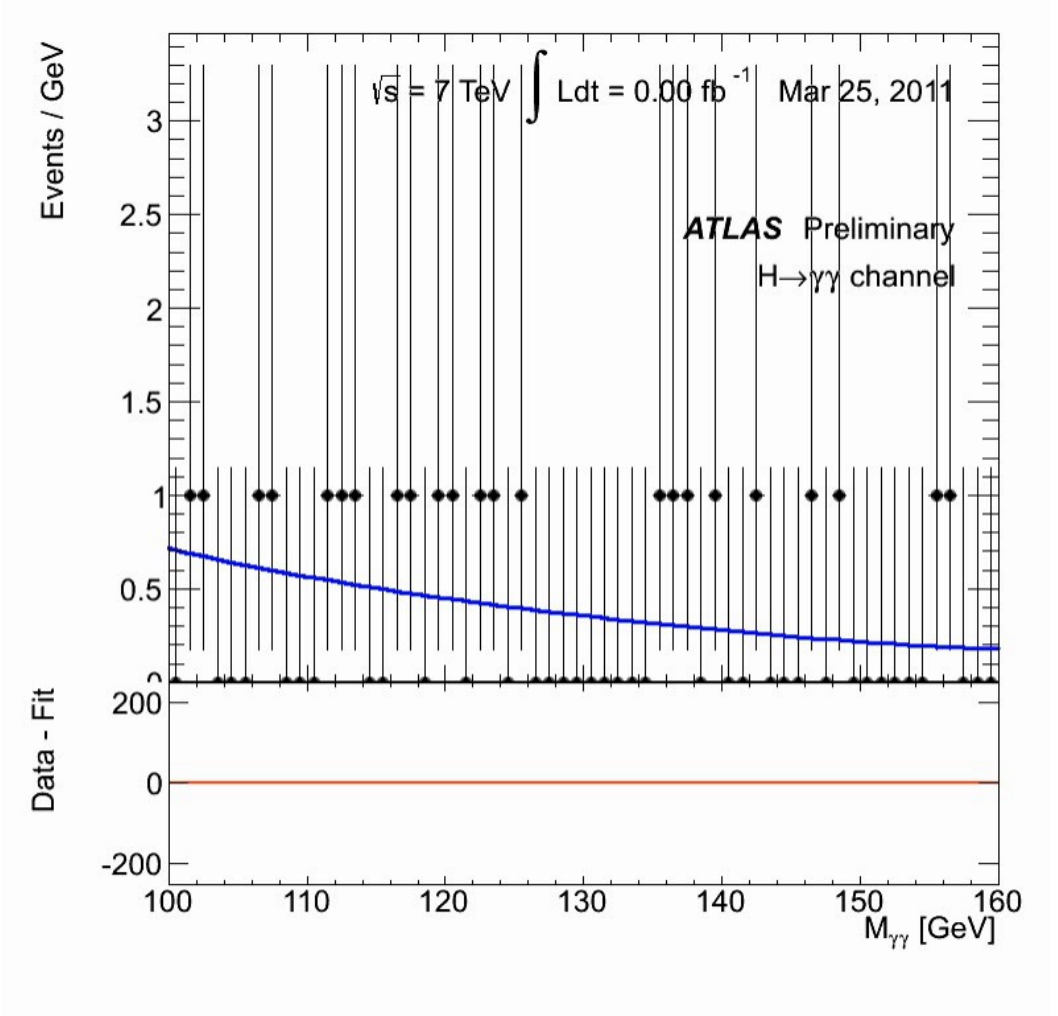
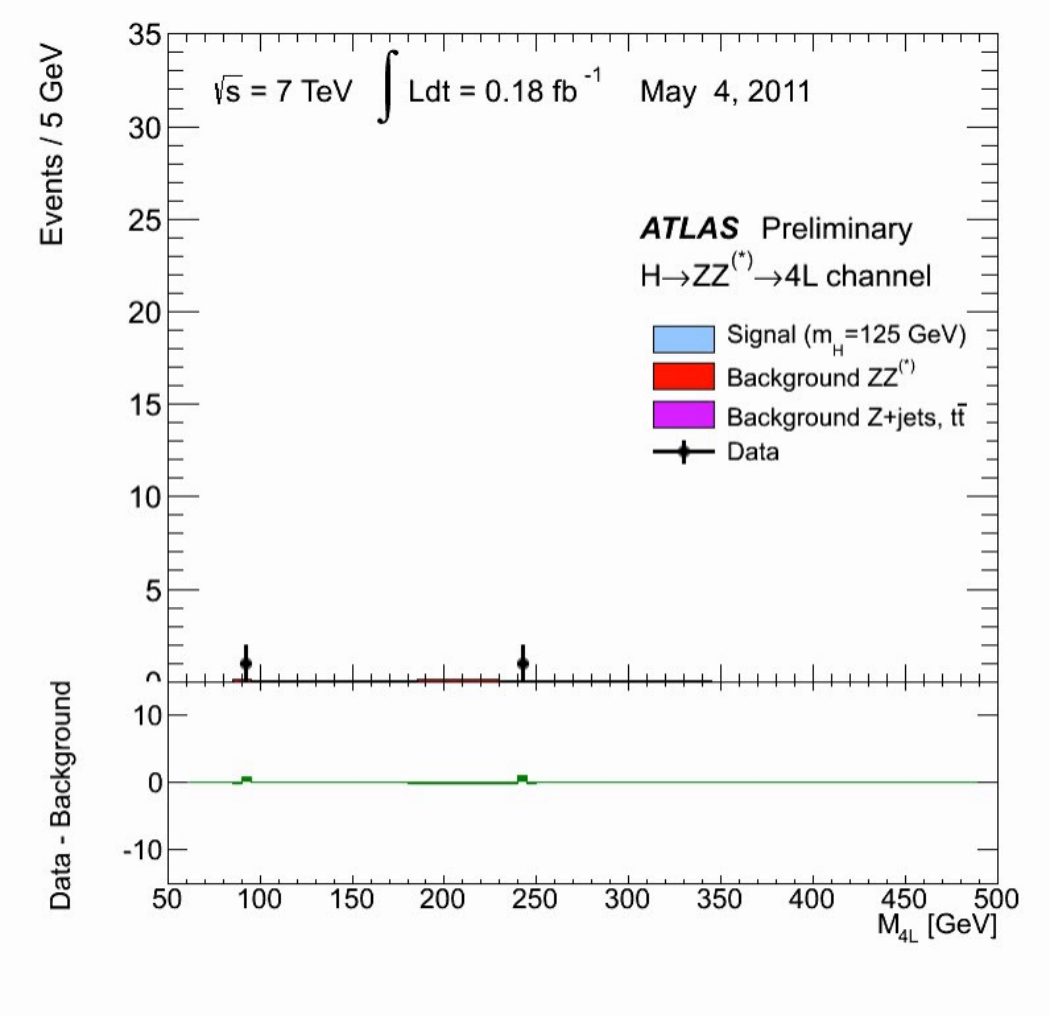




Analyse de données

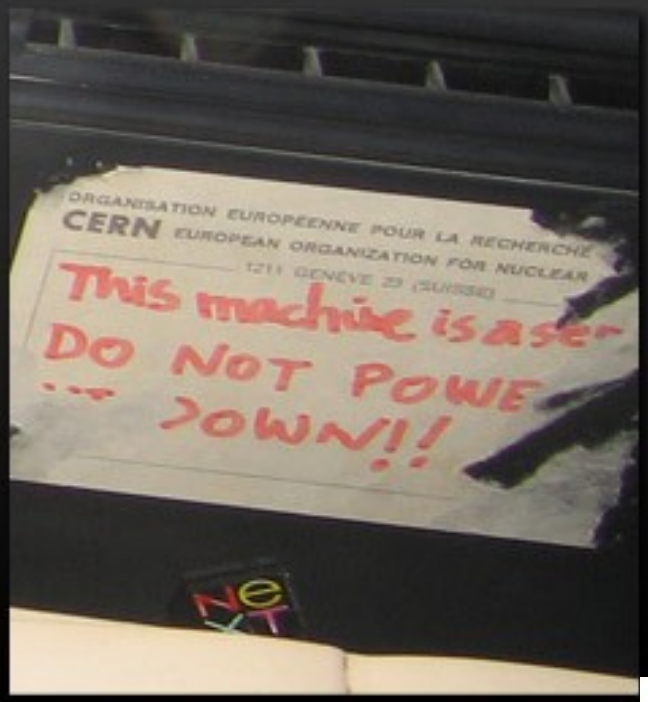




$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ^* \rightarrow 4l$

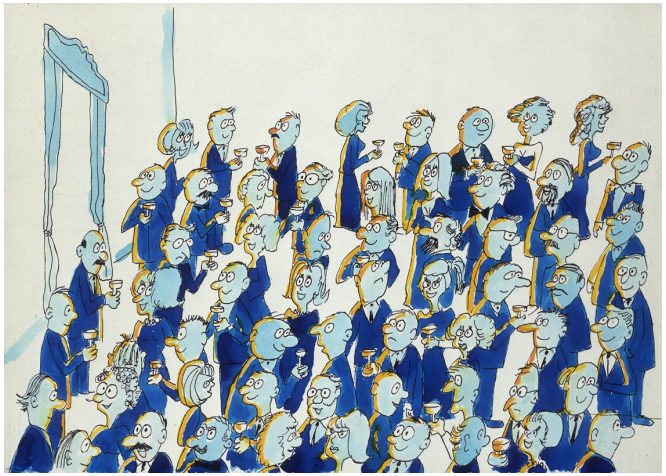
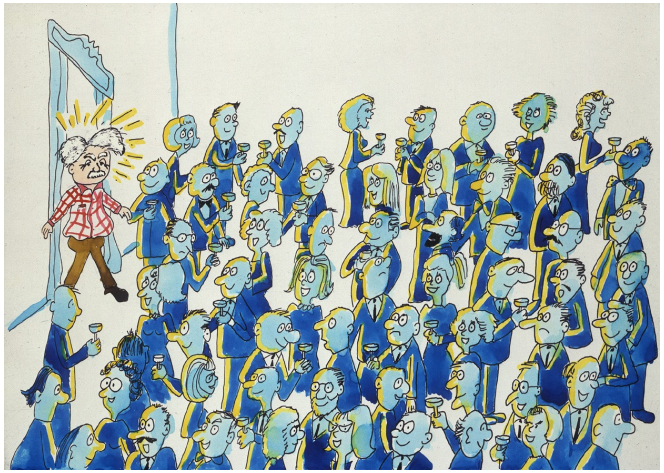
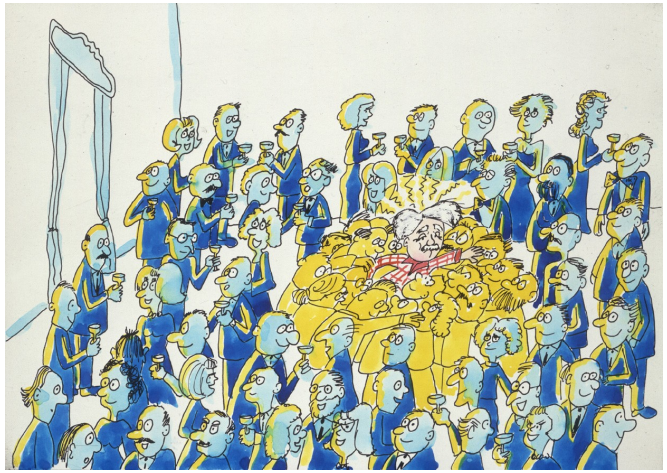
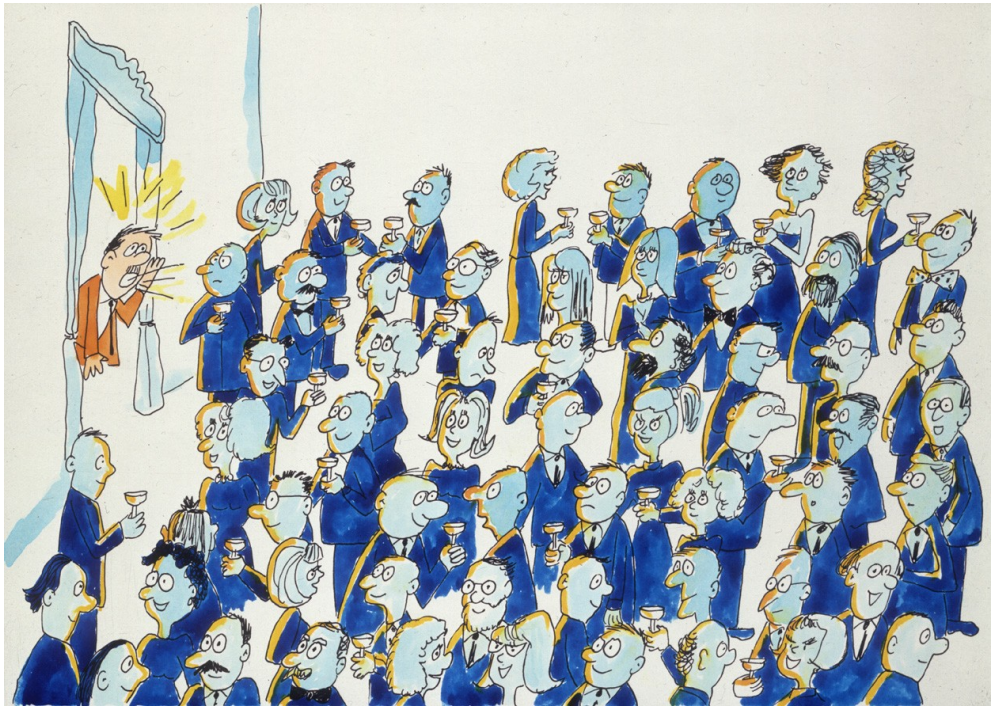
CERN, where the Web was born!

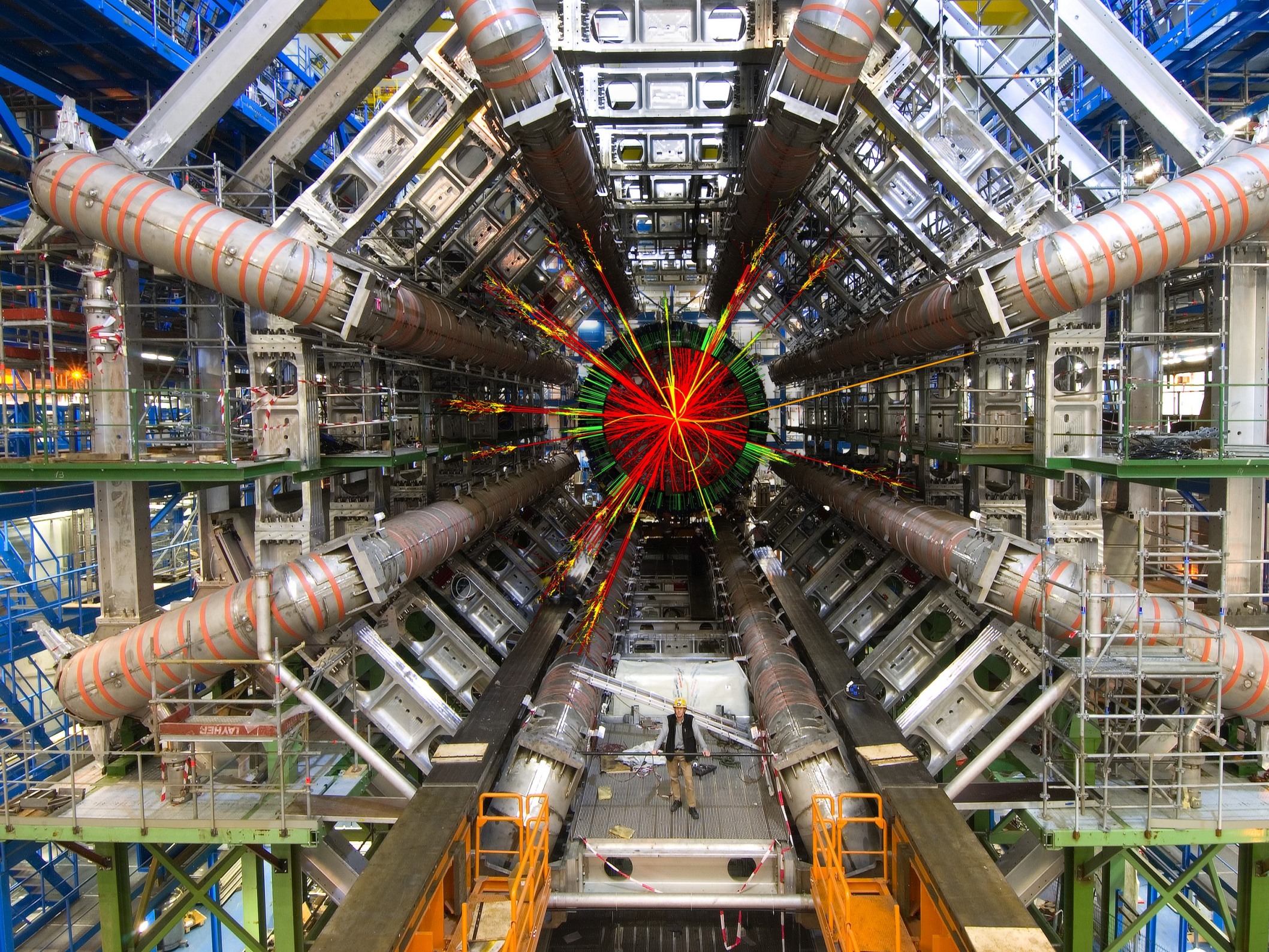


« vague, but exciting »

Recette de l'Univers

Mécanisme de Higgs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