



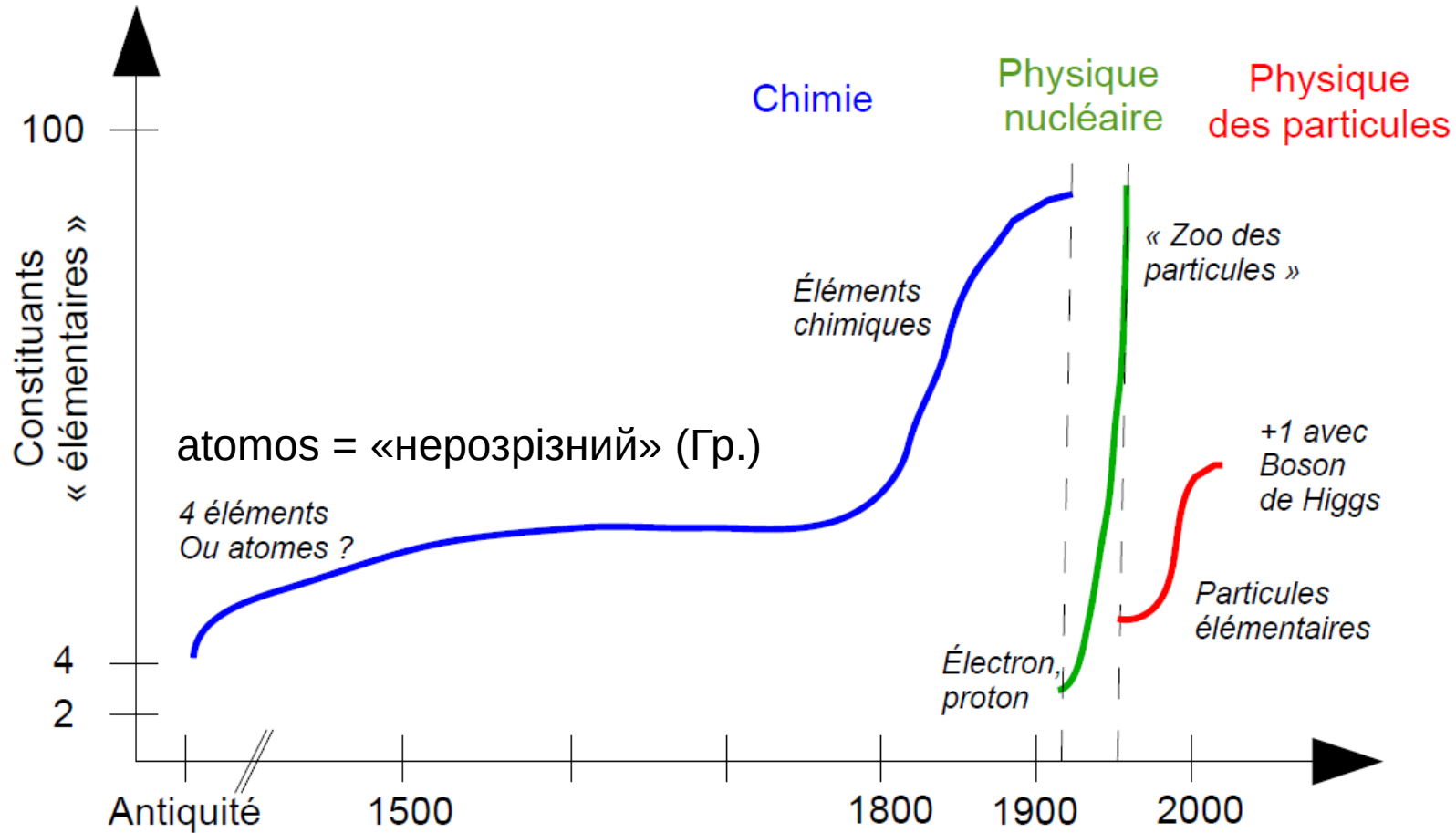
ATLAS EXPERIMENT

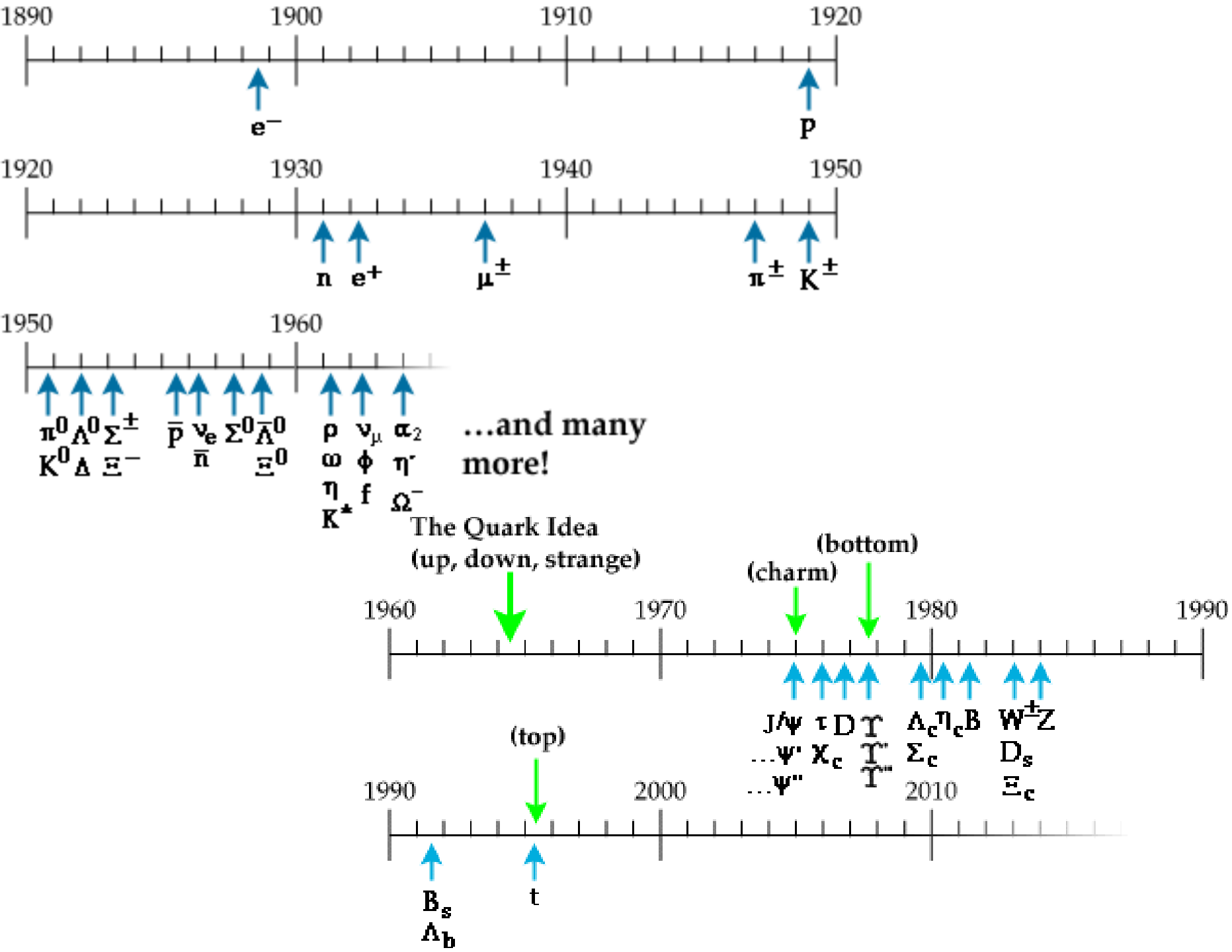
Run Number: 206962
Event Number: 38652990
Date: 2012-07-14, 08:31:06 CET
EtCut > 0.5 GeV
PtCut > 0.4 GeV
Electron: black
Cells: T1es, EMC

Фізика Великого Адронного Колайдера

Тетяна Берже-Гриньова
(LAPP Аннесу, Франція)

Мікросвіт - будівельні блоки

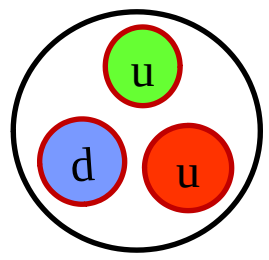




Кварковая модель

Gell-Mann (Nobel Prize in Physics 1969) & Zweig

Протон (p)



Нейтрон (n)

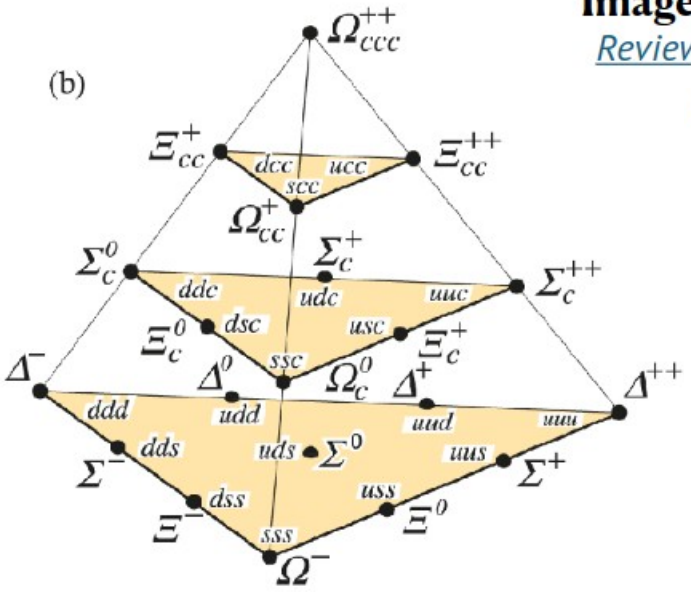
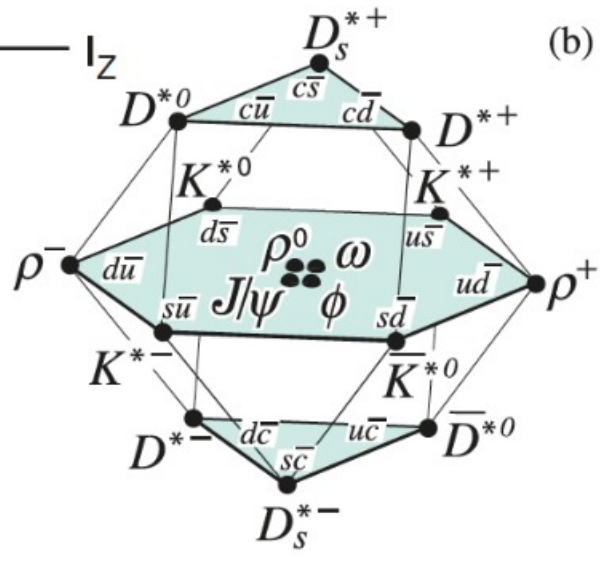
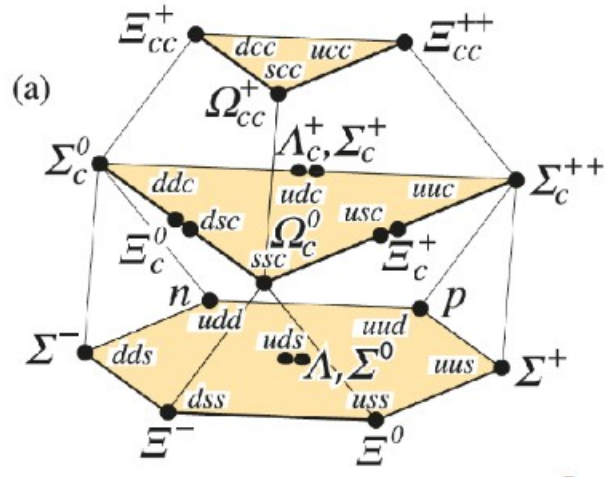
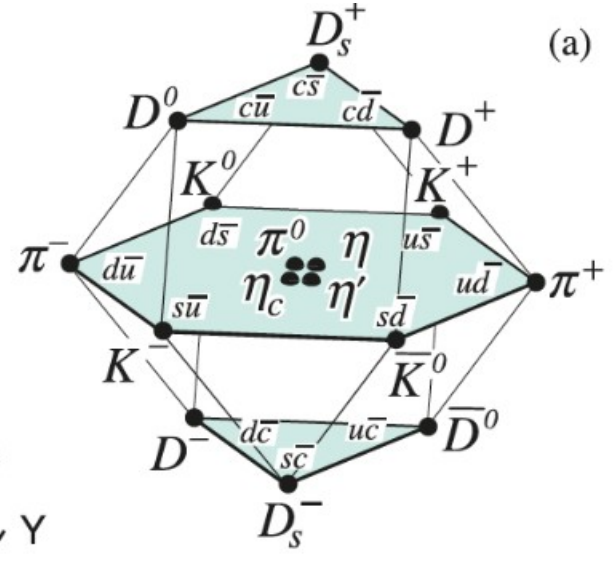
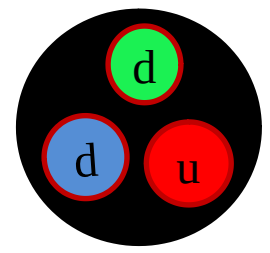
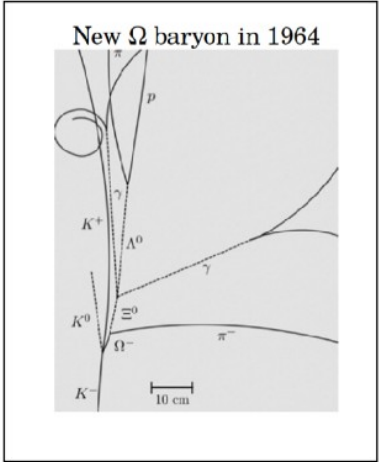


Image taken from PDG
Review of Particle Physics

First observation of sss state

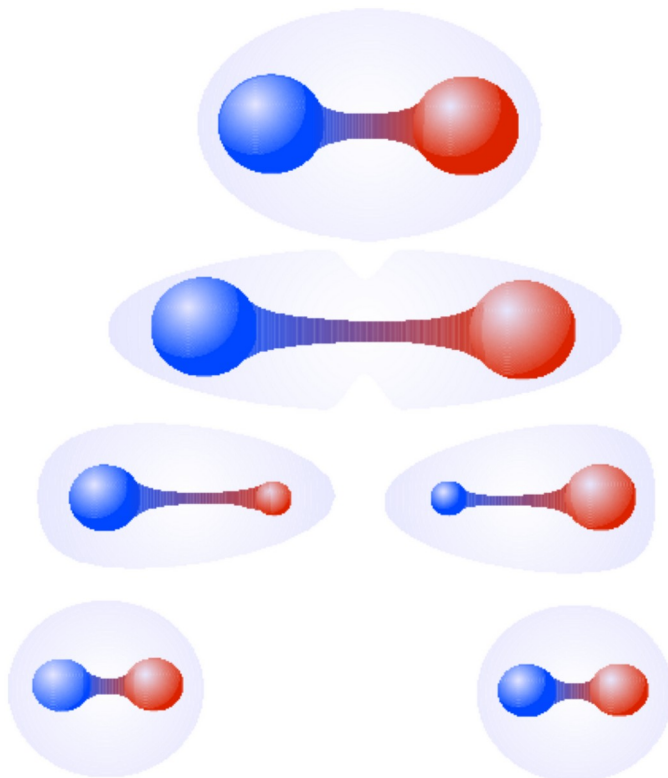


Квантова хромодинаміка

Описує сильну взаємодію; частка-носій - глюони

$$V_s = -\frac{4}{3} \frac{\alpha_s}{r} + kr$$

Кварки не існують у вільному стані вони формують «безбарвні» адрони:



Звичайні

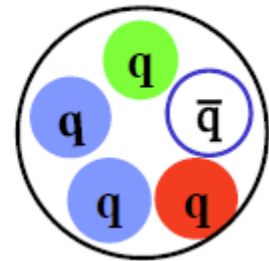
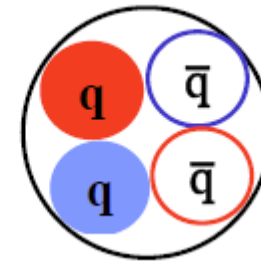
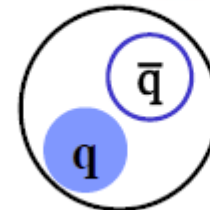
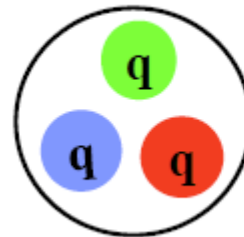
Екзотичні

Мезон

Баріон

Тетракварк

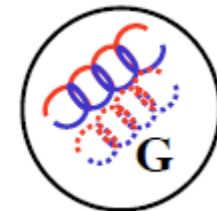
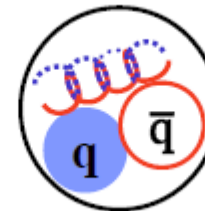
Пентакварк



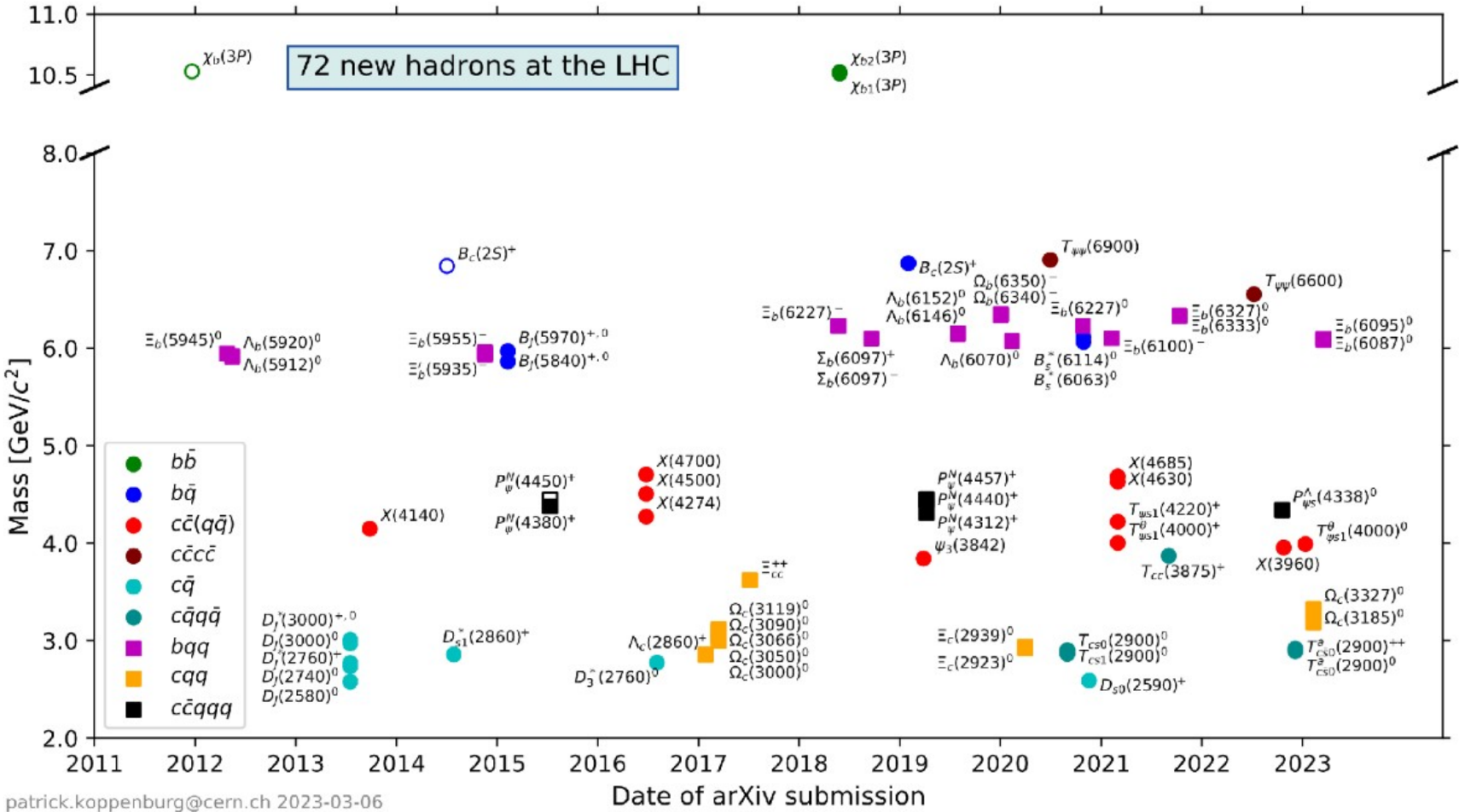
Баріоній

Гібрид

Глюбол



Нові відкриття на LHC



LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates.



Paolo Gandini

CERN Seminar - 25th April 2023

10

Pentaquarks and Tetraquarks

- Several results drew attention in press
- Some results were actually unforeseen from the initial LHCb roadmap → LHCb is truly a GPD
- Here is just a small recap: milestones

2015

[Phys. Rev. Lett. 115, 072001](#)



Featured in Physics

Editors' Suggestion

Open Access

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \rightarrow J/\psi K^- p$ Decays

R. Aaij *et al.* (LHCb Collaboration)

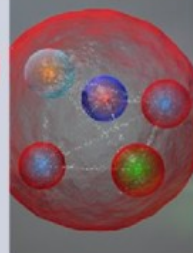
Phys. Rev. Lett. **115**, 072001 – Published 12 August 2015

PhysiCS See Viewpoint: [Elusive Pentaquark Comes into View](#)

Was $P_c(4450)^+$.
Later resolved into $P_\psi^N(4440)^+$ and $P_\psi^N(4457)^+$.

LHCb claims discovery of two pentaquarks
LHCb collaboration at CERN

physics world
**TOP 10
BREAKTHROUGH
2015**



2016

[Phys. Rev. Lett. 118, 022003](#)



Editors' Suggestion

Open Access

Observation of $J/\psi \phi$ Structures Consistent with Exotic States from Amplitude Analysis of $B^+ \rightarrow J/\psi \phi K^+$ Decays

R. Aaij *et al.* (LHCb Collaboration)

Phys. Rev. Lett. **118**, 022003 – Published 11 January 2017

+ **many other more recent observations**

Really difficult to make justice to so many nice results

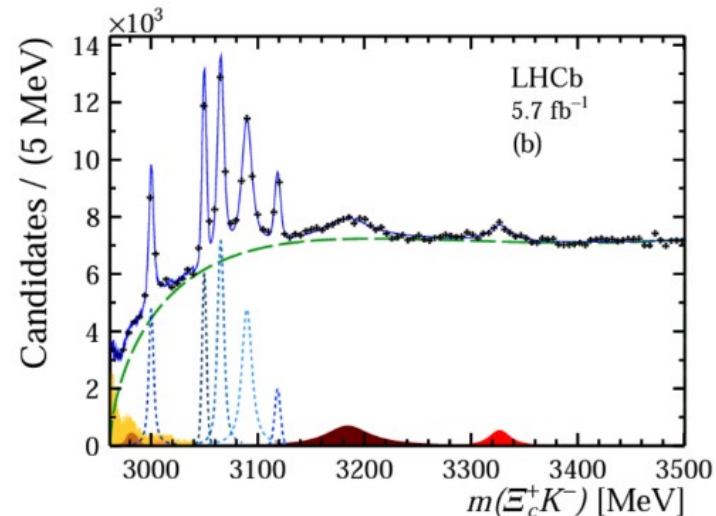
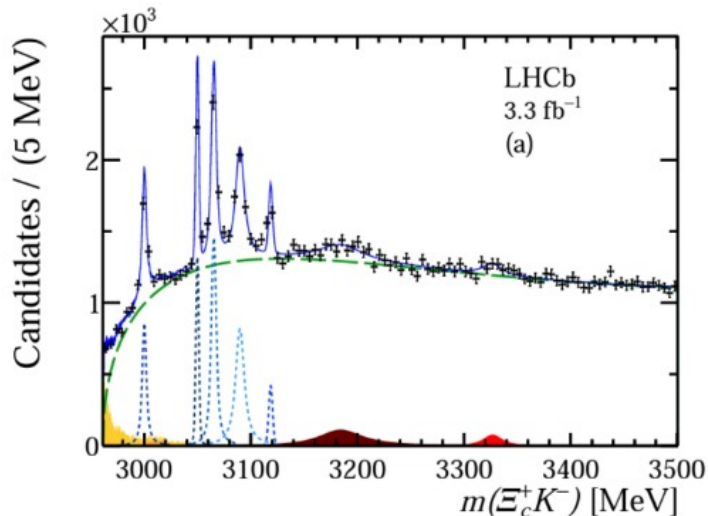
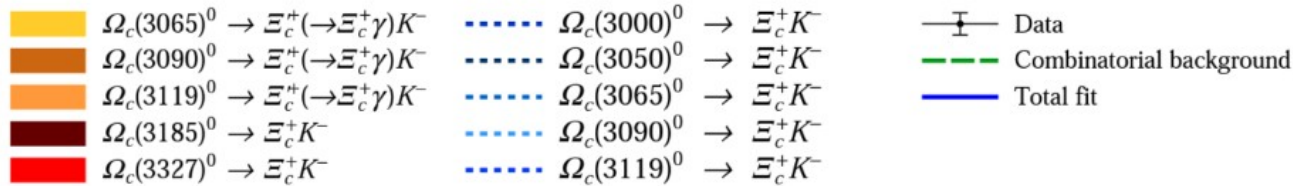
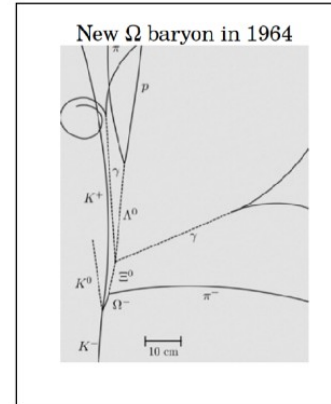
Observation of five new narrow Ω_c^0 states $\rightarrow \Xi_c^+ K^-$

2023

arXiv:2302.04733

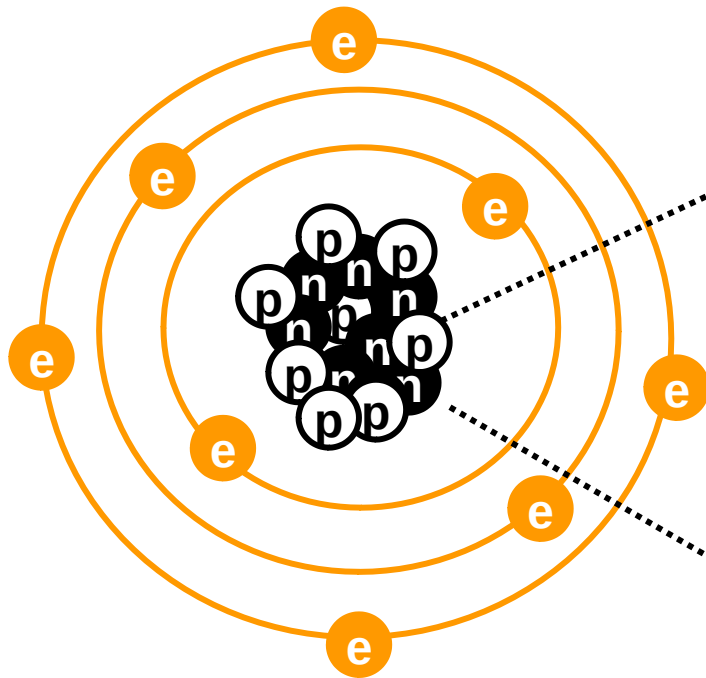
- Very recent paper with the observation of two new broad states
- Two new excited states, $\Omega_c^0(3185)0$ and $\Omega_c^0(3327)$, are observed
- Still debate on the spin-state assignment
- Several studies of possible feed-downs from higher mass resonances are considered

First observation of sss state

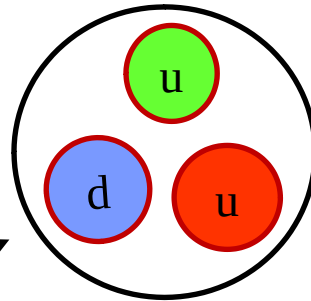


Світ навколо нас

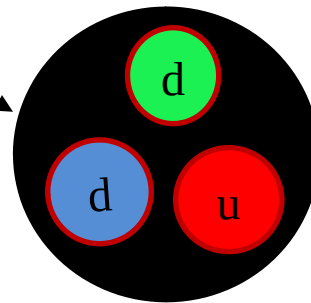
Атом Кисню



протон



нейтрон



1968: SLAC

u

up quark

1968: SLAC

d

down quark

1956: Savannah River Plant

ν_e

electron neutrino

1897: Cavendish Laboratory

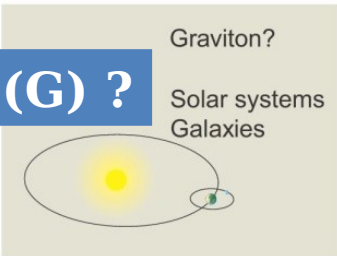
e

electron

Взаємодії у природі

Гравітаційне

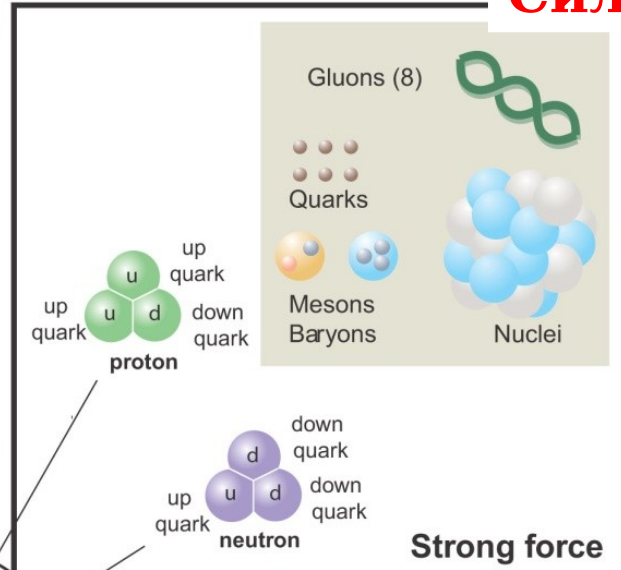
Гравитон (G) ?



Gravity Force



Сильне

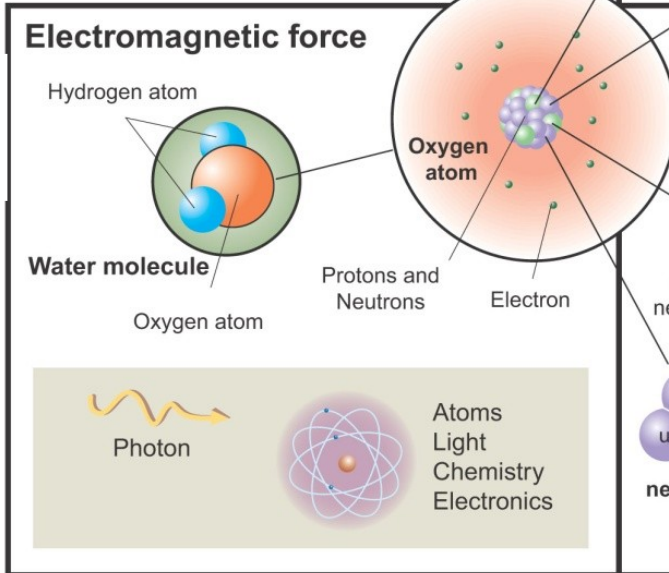


Strong force

**8
Глюон (g)**

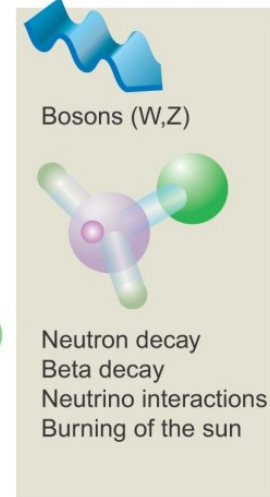
**Електро-
магнітне**

**ФОТОН
γ**



Electromagnetic force

Weak force



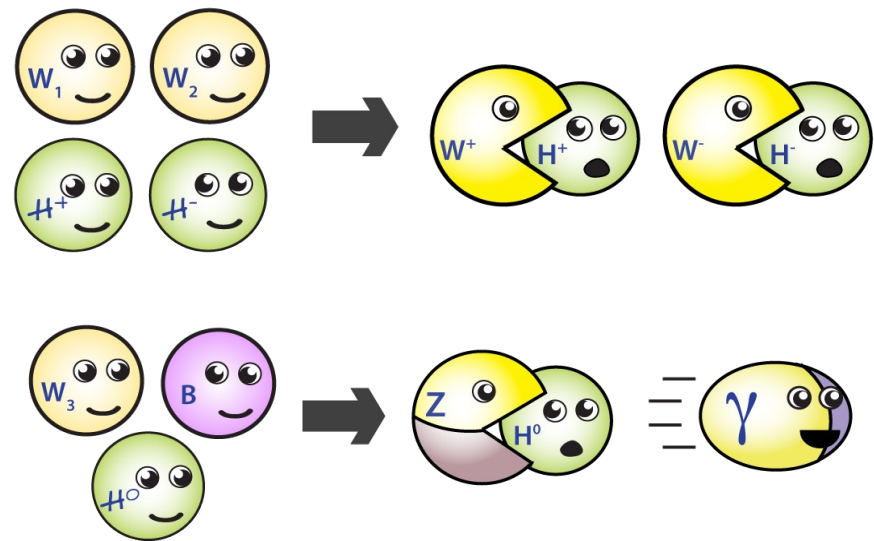
Слабке

**Бозони
W[±], Z**

Порушення електрослабкої симетрії



Чому бозони W і Z мають масу, а фотон безмасовий?



<https://www.quantumdiaries.org/2011/11/21/why-do-we-expect-a-higgs-boson-part-i-electroweak-symmetry-breaking/>

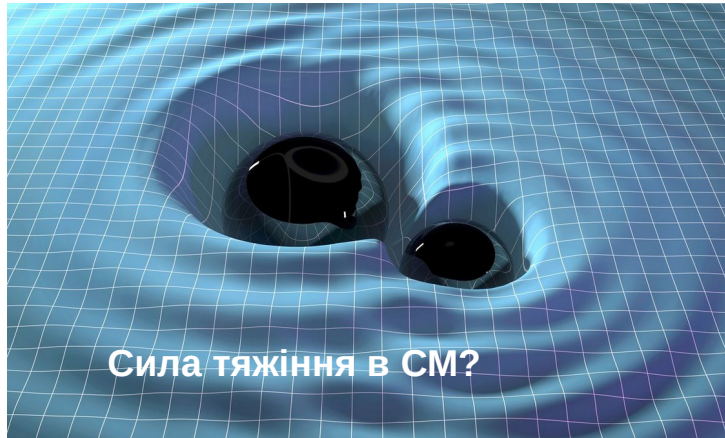
Механізм Хіггса підтверджено відкриттям бозона Хіггса в 2012 році.

Стандартна Модель (СМ)

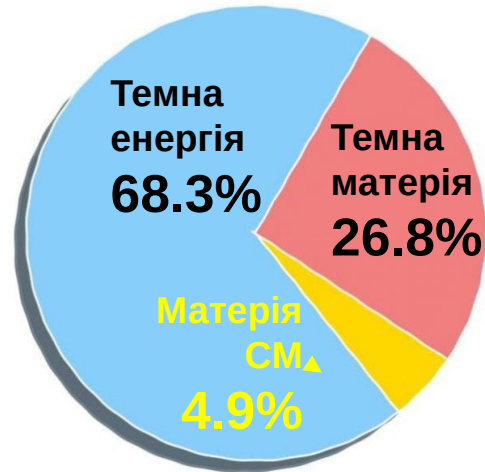
**Стандартна модель
описує сильні,
слабкі та
електромагнітні
взаємодії**

1968: SLAC u up quark	1974: Brookhaven & SLAC c charm quark	1995: Fermilab t top quark	1979: DESY g gluon
1968: SLAC d down quark	1947: Manchester Univ.. s strange quark	1977: Fermilab b bottom quark	1923: Washington Univ. γ photon
1956: Savannah River Plant ν_e electron neutrino	1982: Brookhaven ν_μ muon neutrino	2000: Fermilab ν_τ tau neutrino	1983: CERN W W boson
1897: Cavendish Laboratory e electron	1937: Caltech & Harvard μ muon	1976: SLAC τ tau	1983: CERN Z Z boson
			2012: CERN H Higgs boson

Відкриті питання СМ



MARK GARLICK/SCIENCE PHOTO LIBRARY/Getty Images



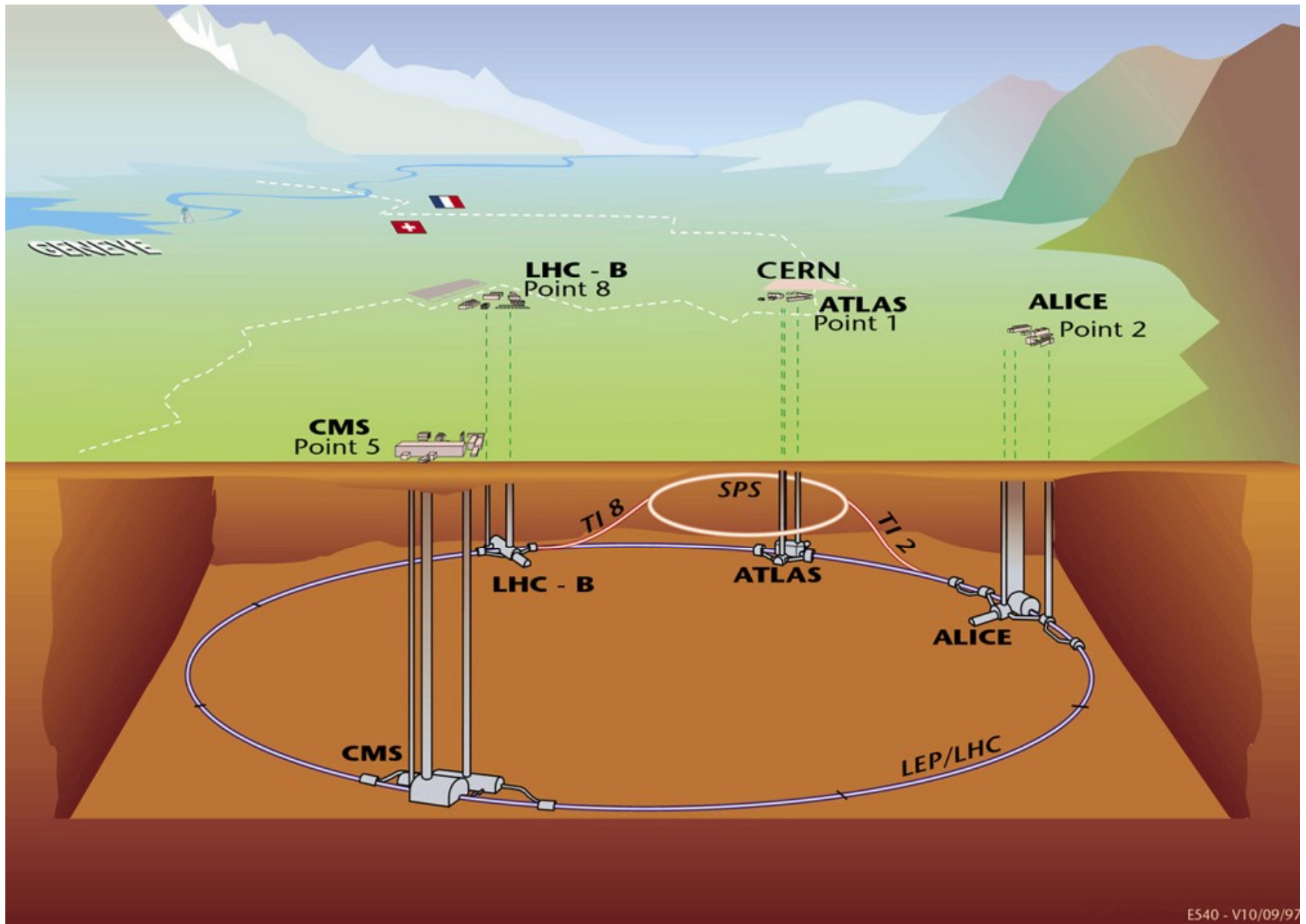
	I	II	III	
Quarks	u 2.4 MeV	c 1.3 GeV	t 170 GeV	γ 0
	d 4.8 MeV	s 104 MeV	b 4.2 GeV	g 0
Leptons	ν_1 < 2 eV	ν_2 < 2 eV	ν_3 < 2 eV	Z 91 GeV
	e 0.5 MeV	μ 106 MeV	τ 1.8 GeV	W 80 GeV
				H 125 GeV

Чому 3 покоління лептонів у СМ?

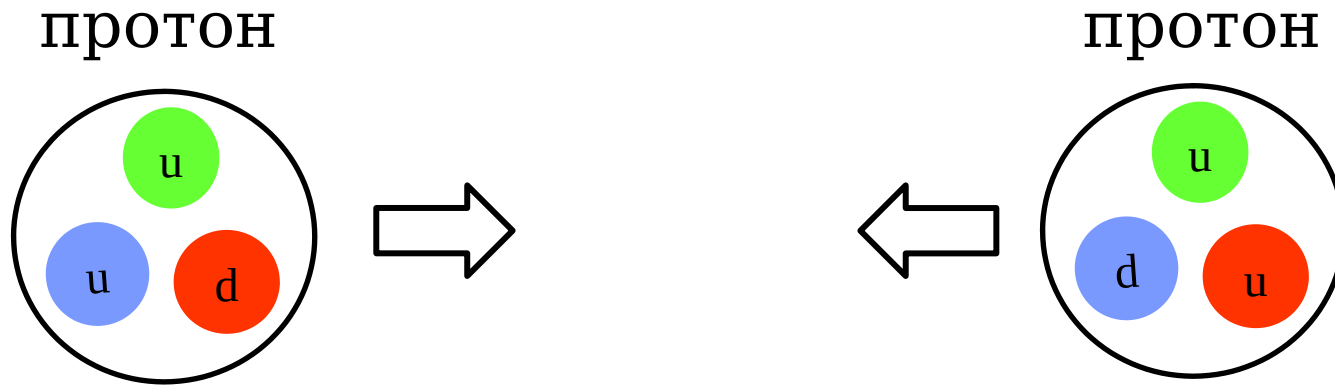
Стандартна модель — це не повна теорія, а низькоенергетичне наближення більш глобальної теорії.

Як знайти цю глобальну теорію? Шляхом пошуку нових частинок, передбачених цією теорією або характеризуючи відхилення від прогнозів СМ.

Великий адронный колайдер



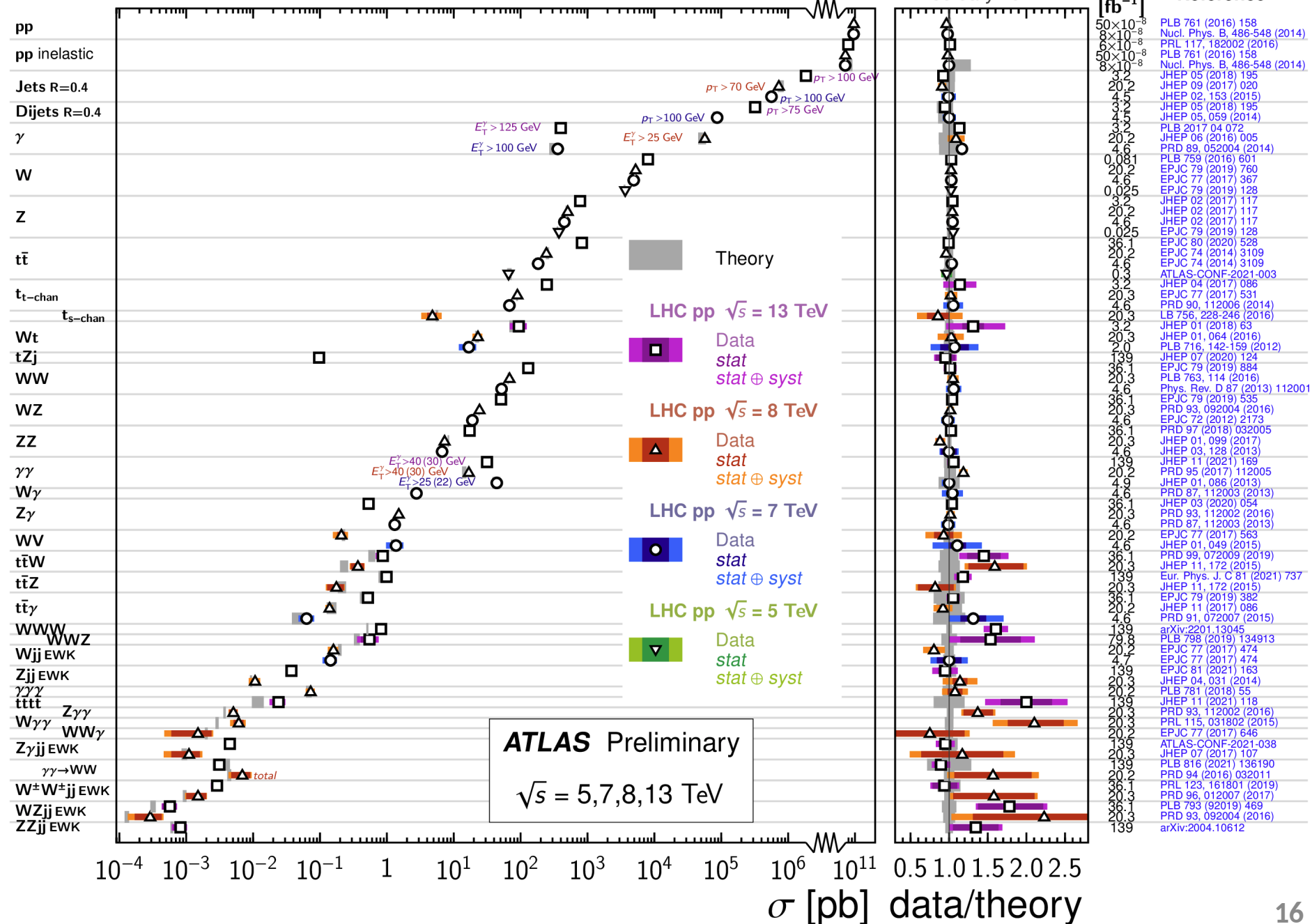
Великий адронный колайдер



$$E = mc^2$$

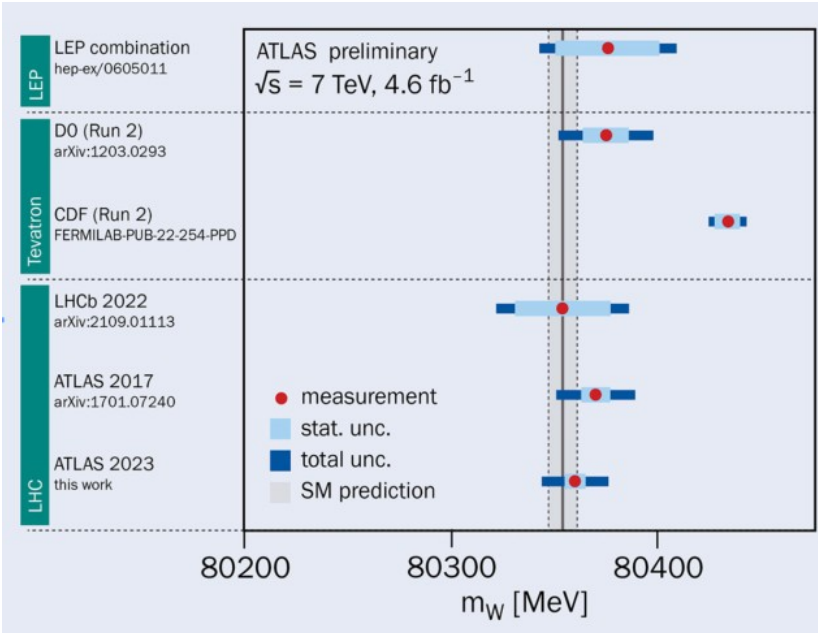
Standard Model Production Cross Section Measurements

Status:
February 2022



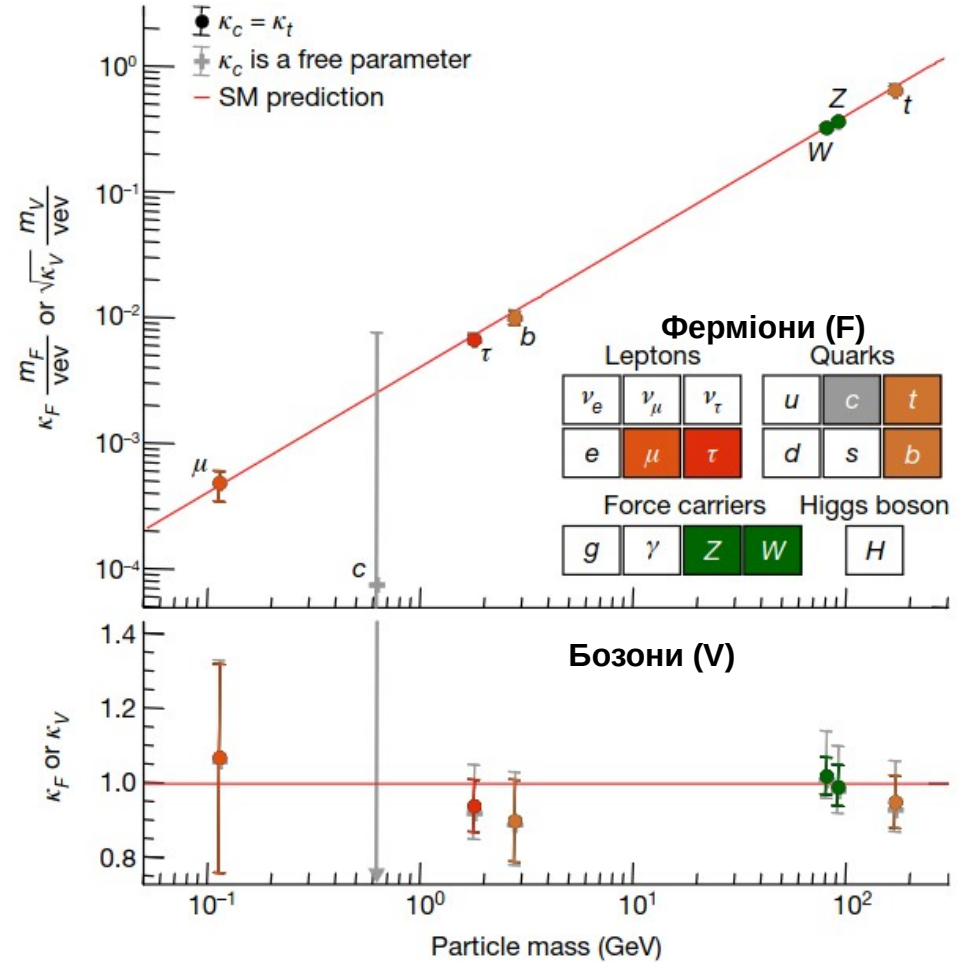
Властивості частинок СМ

Маса W-бозона



40 років з відкриття W в 1983 році!

Взаємодія частинок з полем бозона Хіггса лінійно залежить від їх маси



Nature volume 607, pages 52–59 (2022)

«Як частки отримують масу»

Поле бозона Хіггса



Надточні вимірювання

Потенціал поля Хіггса

Вакуумне очікуване значення (vev): $\nu = \left(\frac{-\mu^2}{\lambda} \right)^{\frac{1}{2}}$

$$M_W = g\nu/2$$

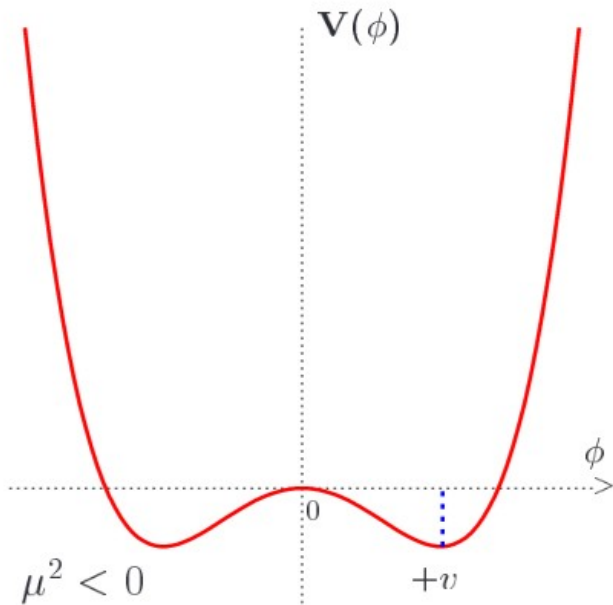
$$M_Z = g\nu/2\cos\theta_W$$

$$\nu = (\sqrt{2}G_F)^{-1/2} \sim 246 \text{ GeV}$$

Маса бозона Хіггса

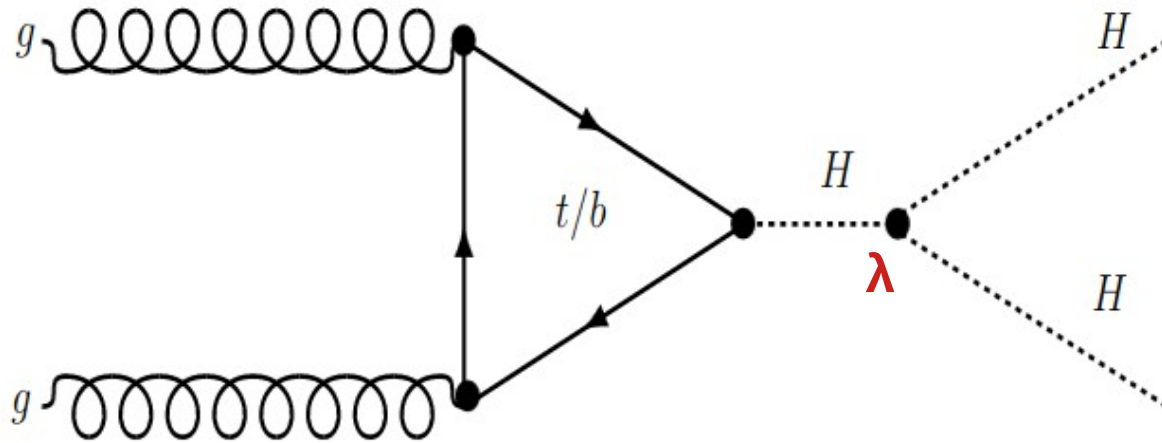
$$M_H = \sqrt{-2\mu^2} = \sqrt{2\lambda}\nu$$

λ = константа самозв'язку бозона Хіггса

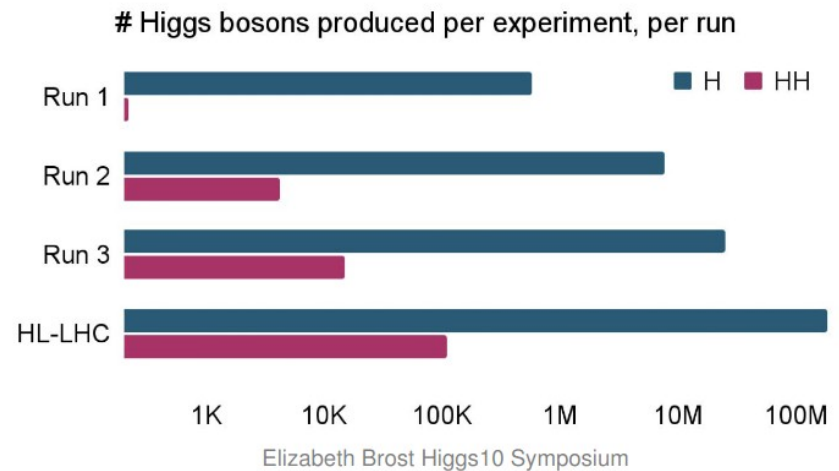
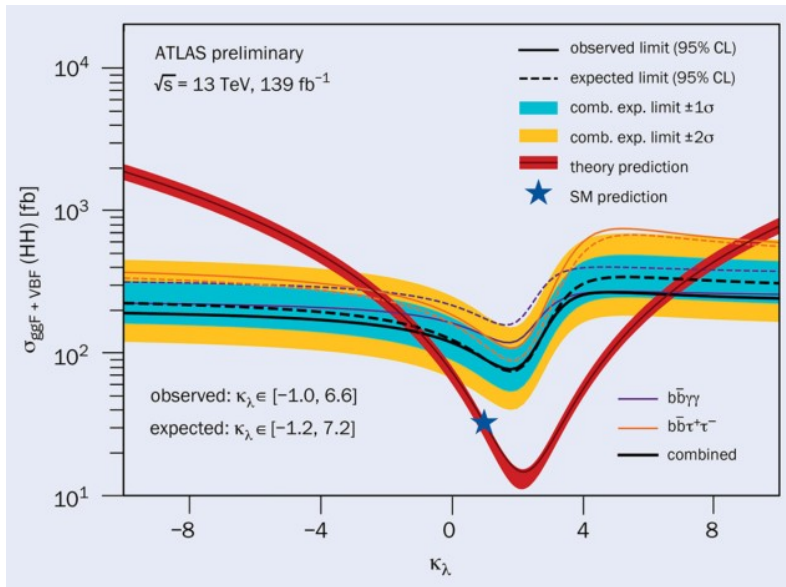


$$V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$

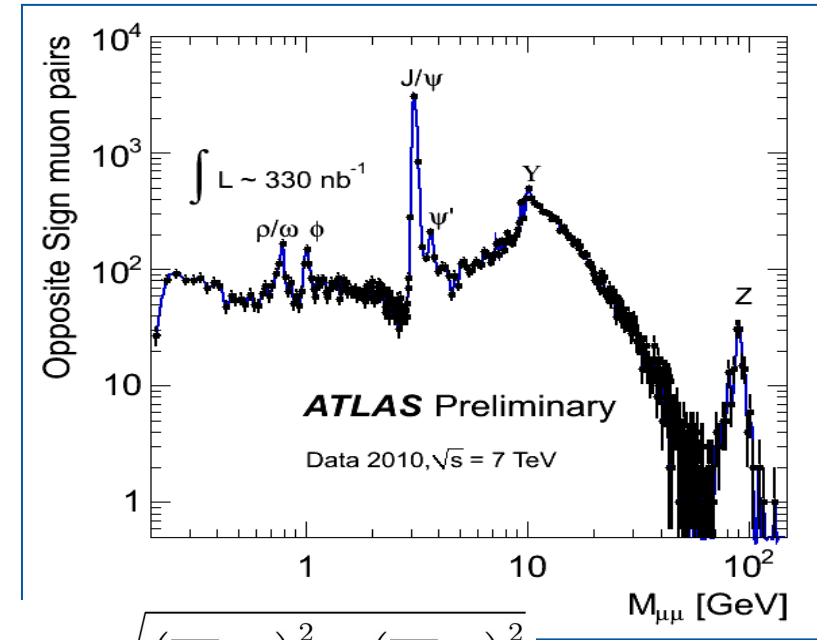
Константа самозв'язку бозона Хіггса



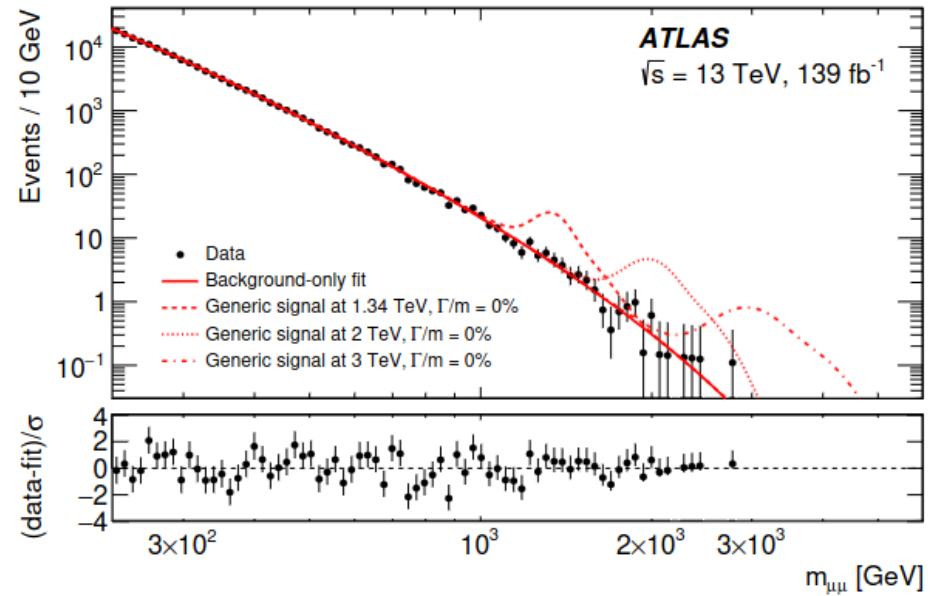
Цю константу також можна виміряти незалежно, використовуючи події з двома бозонами Хіггса. => Перехресна перевірка прогнозів СМ @ HL-LHC.



Пошук нових частинок



$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$



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

Status: July 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 $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	M_D 11.2 TeV $n=2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_S 8.6 TeV $n=3$ HLZ NLO	1707.04147
	ADD QBH	-	$2 j$	-	139	M_{th} 9.4 TeV $n=6$	1910.08447
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{th} 9.55 TeV $n=6, M_D=3 \text{ TeV, rot BH}$	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	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 $G_{KK} \rightarrow WV \rightarrow \ell\nu qq$	$1 e, \mu$	$2 j / 1 J$	Yes	139	G_{KK} mass 2.0 TeV $k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	G_{KK} mass 3.8 TeV $\Gamma/m = 15\%$	1804.10823
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	1803.09678
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 5.1 TeV
SSM $Z' \rightarrow \tau\tau$		2τ	-	-	36.1	Z' mass 2.42 TeV	1709.07242
Leptophobic $Z' \rightarrow bb$		-	$2 b$	-	36.1	Z' mass 2.1 TeV	1805.09299
Leptophobic $Z' \rightarrow tt$		$0 e, \mu, \tau$	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass 4.1 TeV $\Gamma/m = 1.2\%$	2005.05138
SSM $W' \rightarrow \ell\nu$		$1 e, \mu$	-	Yes	139	W' mass 6.0 TeV	1906.05609
SSM $W' \rightarrow \tau\nu$		1τ	-	Yes	139	W' mass 5.0 TeV	ATLAS-CONF-2021-025
SSM $W' \rightarrow tb$		-	$\geq 1 b, \geq 1 J$	-	139	W' mass 4.4 TeV	ATLAS-CONF-2021-043
HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B		$1 e, \mu$	$2 j / 1 J$	Yes	139	W' mass 4.3 TeV $g_V = 3$	2004.14636
HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell' \ell'$ model C		$3 e, \mu$	$2 j$ (VBF)	Yes	139	W' mass 340 GeV $g_V = 3, g_V^{CH} = 1, g_R = 0$	ATLAS-CONF-2022-005
HVT $W' \rightarrow WH \rightarrow \ell\nu bb$ model B		$1 e, \mu$	$1-2 b, 1-0 j$	Yes	139	W' mass 3.3 TeV $g_V = 3$	2207.00230
HVT $Z' \rightarrow ZH \rightarrow \ell\nu\nu bb$ model B	$0, 2 e, \mu$	$1-2 b, 1-0 j$	Yes	139	Z' mass 3.2 TeV $g_V = 3$	2207.00230	
LRSM $W_R \rightarrow \mu N_R$	2μ	$1 J$	-	80	W_R mass 5.0 TeV $m(N_R) = 0.5 \text{ TeV, } g_L = g_R$	1904.12679	
CI	CI $qqqq$	-	$2 j$	-	37.0	Λ 21.8 TeV η_{LL}	1703.09127
	CI $\ell\ell qq$	$2 e, \mu$	-	-	139	Λ 35.8 TeV η_{LL}	2006.12946
	CI $e e b s$	$2 e$	$1 b$	-	139	Λ 1.8 TeV $g_* = 1$	2105.13847
	CI $\mu\mu b s$	2μ	$1 b$	-	139	Λ 2.0 TeV $g_* = 1$	2105.13847
	CI $t t t t$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Λ 2.57 TeV $ C_{4t} = 4\pi$	1811.02305
	DM	Axial-vector med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	m_{med} 2.1 TeV $g_q=0.25, g_\tau=1, m(\chi)=1 \text{ GeV}$
Pseudo-scalar med. (Dirac DM)		$0 e, \mu, \tau, \gamma$	$1-4 j$	Yes	139	m_{med} 376 GeV $g_q=1, g_\tau=1, m(\chi)=1 \text{ GeV}$	2102.10874
Vector med. Z' -2HDM (Dirac DM)		$0 e, \mu, \tau$	$2 b$	Yes	139	m_{med} 3.1 TeV $\tan\beta=1, g_Z=0.8, m(\chi)=100 \text{ GeV}$	2108.13391
Pseudo-scalar med. 2HDM+a		multi-channel	-	-	139	m_{med} 560 GeV $\tan\beta=1, g_\tau=1, m(\chi)=10 \text{ GeV}$	ATLAS-CONF-2021-036
LQ	Scalar LQ 1 st gen	$2 e$	$\geq 2 j$	Yes	139	LQ mass 1.8 TeV $\beta = 1$	2006.05872
	Scalar LQ 2 nd gen	2μ	$\geq 2 j$	Yes	139	LQ mass 1.7 TeV $\beta = 1$	2006.05872
	Scalar LQ 3 rd gen	1τ	$2 b$	Yes	139	LQ ₃ mass 1.2 TeV $\mathcal{B}(LQ_3^+ \rightarrow b\tau) = 1$	2108.07665
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	LQ ₃ mass 1.24 TeV $\mathcal{B}(LQ_3^0 \rightarrow t\nu) = 1$	2004.14060
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau$	$\geq 1 j, \geq 1 b$	-	139	LQ ₃ mass 1.43 TeV $\mathcal{B}(LQ_3^0 \rightarrow t\tau) = 1$	2101.11582
	Scalar LQ 3 rd gen	$0 e, \mu, \geq 1 \tau$	$0-2 j, 2 b$	Yes	139	LQ ₃ mass 1.26 TeV $\mathcal{B}(LQ_3^0 \rightarrow b\nu) = 1$	2101.12527
	Vector LQ 3 rd gen	1τ	$2 b$	Yes	139	LQ ₃ mass 1.77 TeV $\mathcal{B}(LQ_3^0 \rightarrow b\tau) = 0.5, \text{Y-M coupl.}$	2108.07665
	Vector-like fermions	VLQ $TT \rightarrow Zt + X$	$2e/2\mu \geq 3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	T mass 1.4 TeV SU(2) doublet
VLQ $BB \rightarrow Wt/Zb + X$		multi-channel	-	-	36.1	B mass 1.34 TeV SU(2) doublet	1808.02343
VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$		$2(SS) \geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	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 $T \rightarrow Ht/Zt$		$1 e, \mu, \tau$	$\geq 1 b, \geq 3 j$	Yes	139	T mass 1.8 TeV SU(2) singlet, $\kappa_T = 0.5$	ATLAS-CONF-2021-040
VLQ $Y \rightarrow Wb$		$1 e, \mu, \tau$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$	1812.07343
VLQ $B \rightarrow Hb$		$0 e, \mu, \tau$	$\geq 2 b, \geq 1 j, \geq 1 J$	-	139	B mass 2.0 TeV SU(2) doublet, $\kappa_B = 0.3$	ATLAS-CONF-2021-018
VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	τ' mass 898 GeV SU(2) doublet	ATLAS-CONF-2022-044	
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 $q^* \rightarrow q\gamma$	1γ	$1 j$	-	36.7	q^* mass 5.3 TeV only u^* and $d^*, \Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	139	b^* mass 3.2 TeV	1910.0447
	Excited lepton ℓ^*	$3 e, \mu$	-	-	20.3	ℓ^* mass 3.0 TeV	1411.2921
	Excited lepton ν^*	$3 e, \mu, \tau$	-	-	20.3	ν^* mass 1.6 TeV $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1411.2921
Other	Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2 j$	Yes	139	N^0 mass 910 GeV	2202.02039
	LRSM Majorana ν	2μ	$2 j$	-	36.1	N_R mass 3.2 TeV $m(W_R) = 4.1 \text{ TeV, } g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$	$2, 3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV DY production	ATLAS-CONF-2022-010
	Higgs triplet $H^{\pm\pm} \rightarrow \tau\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
	Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV DY production, $ q = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV DY production, $ g = 1g_D, \text{spin } 1/2$	1905.10130

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

10⁻¹ 1 10 Mass scale [TeV]

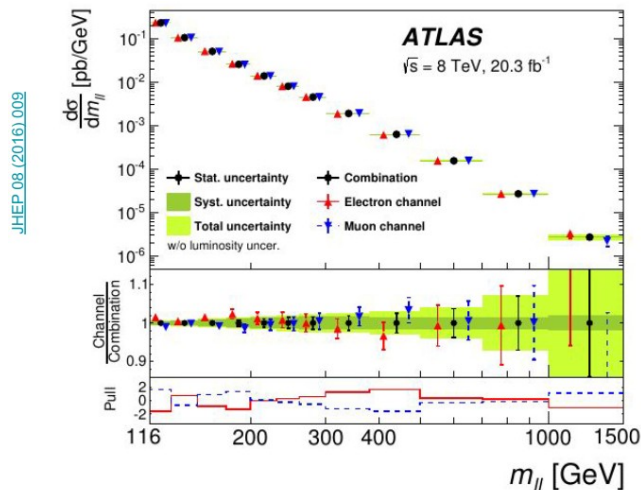
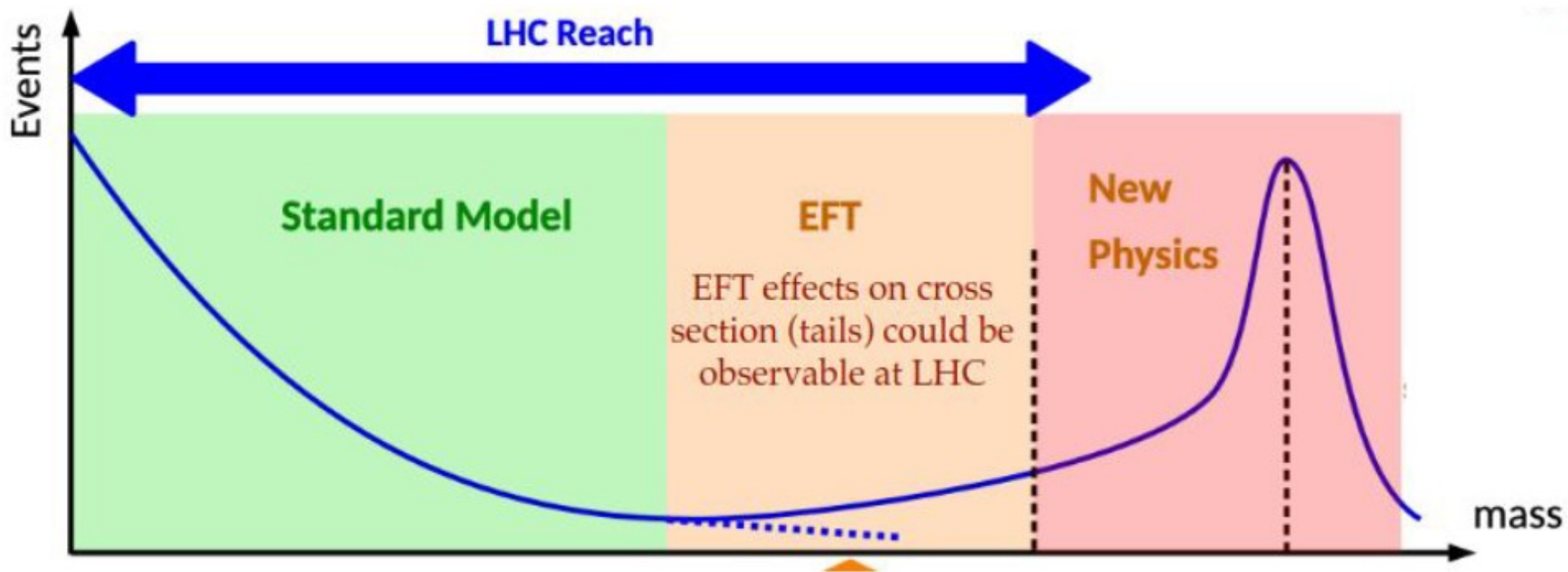
*Only a selection of the available mass limits on new states or phenomena is shown.

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

Ми не здаємося



Погляд за межі енергії LHC

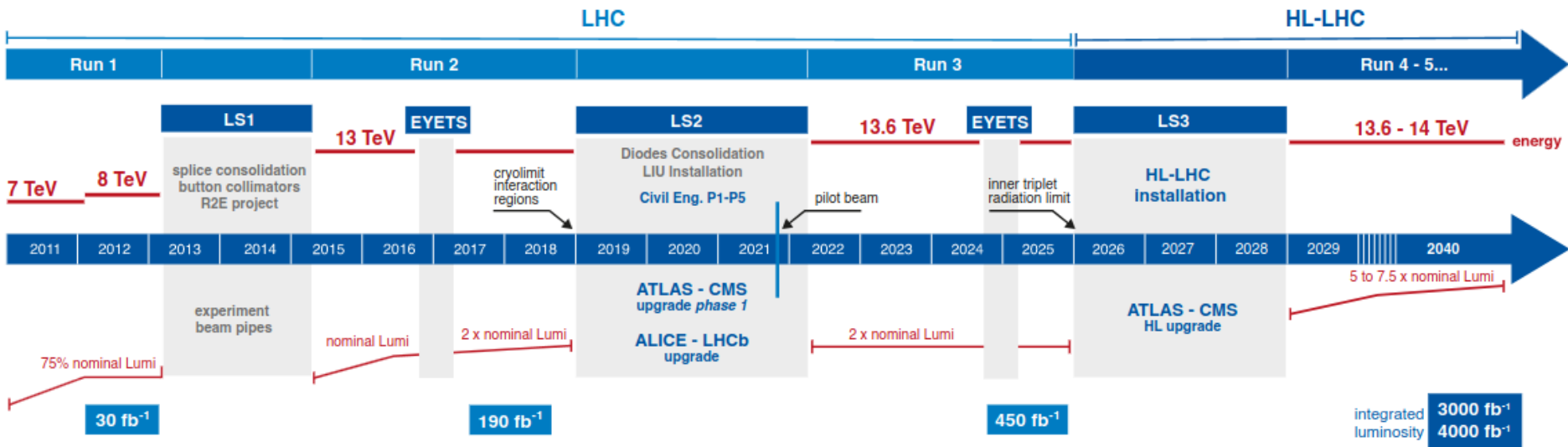


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Програма LHC



LHC / HL-LHC Plan



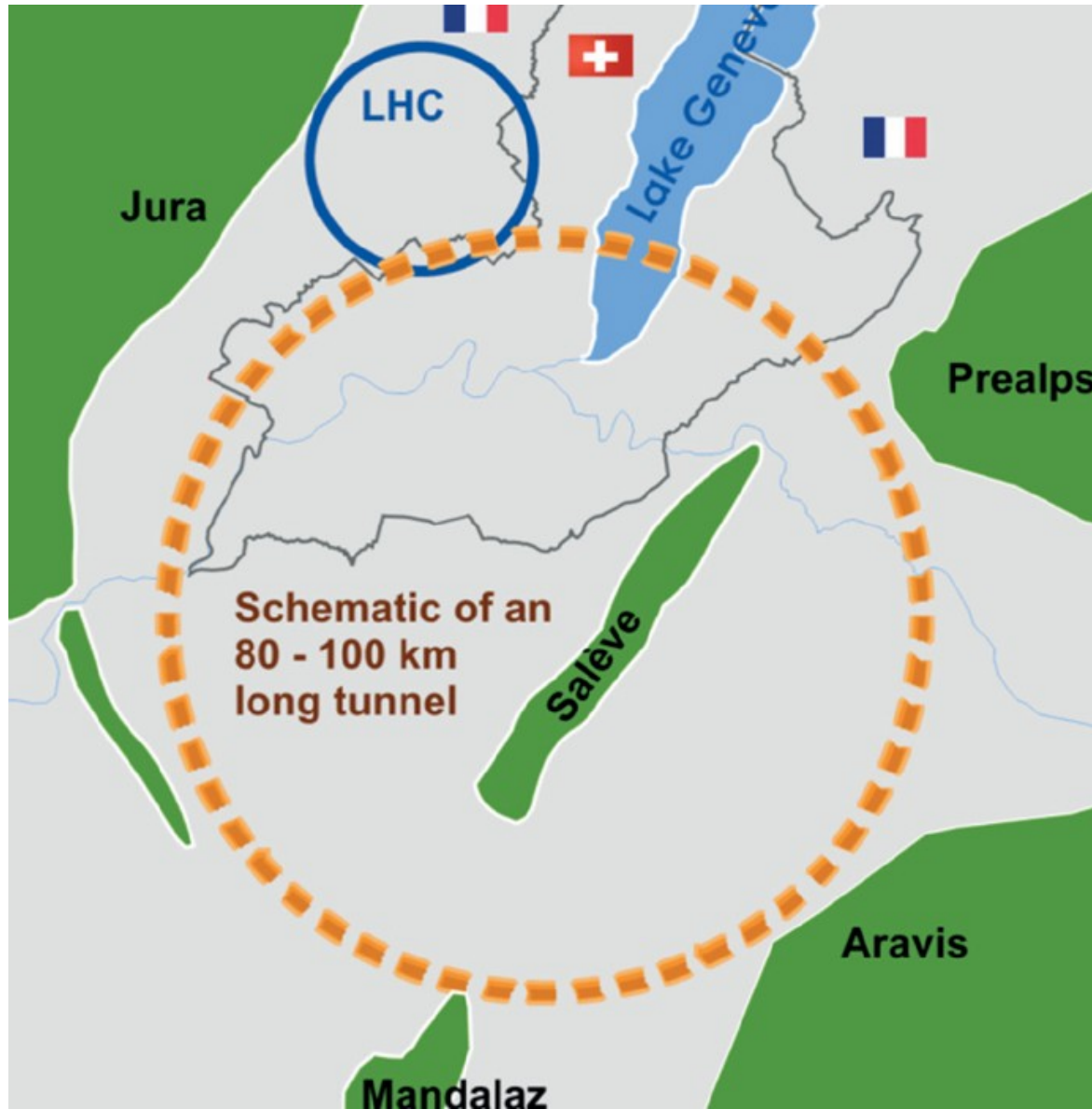
HL-LHC TECHNICAL EQUIPMENT:



HL-LHC CIVIL ENGINEERING:



Прискорювачі майбутнього



Дякую за увагу !

Backups

- neutral particle
- ▶ jet
- charged particle
- ⚡ highly ionizing particle
- electron
- muon
- photon

Displaced leptonic vertices
 ee, mumu channels:
 ATLAS, 8 TeV, 20.3fb⁻¹: [Phys. Rev. D 92, 072004](#)
 CMS, 8 TeV, 20fb⁻¹: [Phys. Rev. D 91 \(2015\) 052012](#)
 emu channel:
 CMS, 13 TeV, 2.6fb⁻¹: [CMS-PAS-EXO-16-022](#)

Displaced vertices + MET
 ATLAS, 13 TeV, 32.8fb⁻¹:
[CERN-EP-2017-202](#)

Displaced jets in the ID
 8TeV result: [PRD 92, 012010 \(2015\)](#)

Disappearing tracks
 ATLAS, 13 TeV, 36.1fb⁻¹: [SUSY-2016-06](#)
 CMS, 13 TeV, 38.4fb⁻¹: [CMS-PAS-EXO-16-044](#)

Displaced jets in the Calorimeter
 ATLAS, 13 TeV, 3.2fb⁻¹:
[ATLAS-CONF-2016-103](#)
 CMS, 13 TeV,
 2.6fb⁻¹: [EXO-16-003](#)

Stopped LLPs NOT IN FILLED BUNCH CROSSING
 CMS, 13 TeV, 36.1fb⁻¹:
[CMS-EXO-16-004](#)

Displaced jets in the MS
 8TeV result:
[PRD 92, 012010 \(2015\)](#)

Late photons
 ATLAS, 8TeV, 20.3fb⁻¹: [Phys. Rev. D. 90, 112005 \(2014\)](#)
 CMS, 8 TeV, 19.1fb⁻¹: [CMS-PAS-EXO-12-035](#)

Highly ionising particles
 8TeV result: [PRD 93, 052009 \(2016\)](#)

(Meta-) Stable Charged LLPs
 ATLAS, 13 TeV, 3.2fb⁻¹:
[Phys. Rev. D 93, 112015 \(2016\)](#)
[Physics Letters B \(2016\), pp. 647-665](#)
 CMS, 13 TeV, 2.5fb⁻¹:
[Phys. Rev. D 94 \(2016\) 112004](#)

Displaced Lepton-jets
 13 TeV result, 3.2fb⁻¹:
[ATLAS-CONF-2016-042](#)