# Introduction to Standard Model

*seen by an LHC experimentalist…*


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* Many thanks to N. Morange for useful material



Journées de Rencontres Jeunes Chercheurs 2017, La Pommeraie, 28 Novembre 2017

# A wise man said..

During neutrinos introduction in JRJC2017, 26th November 2017

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You're certainly all familiar with the SM*

Beginning of the talk

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I'm sure you're all SM* experts

Towards the end of the talk

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Towards the end of the talk



***SM stands for Standard Model**

# Thank you for attention

**Let’s now pass to the students presentations!**

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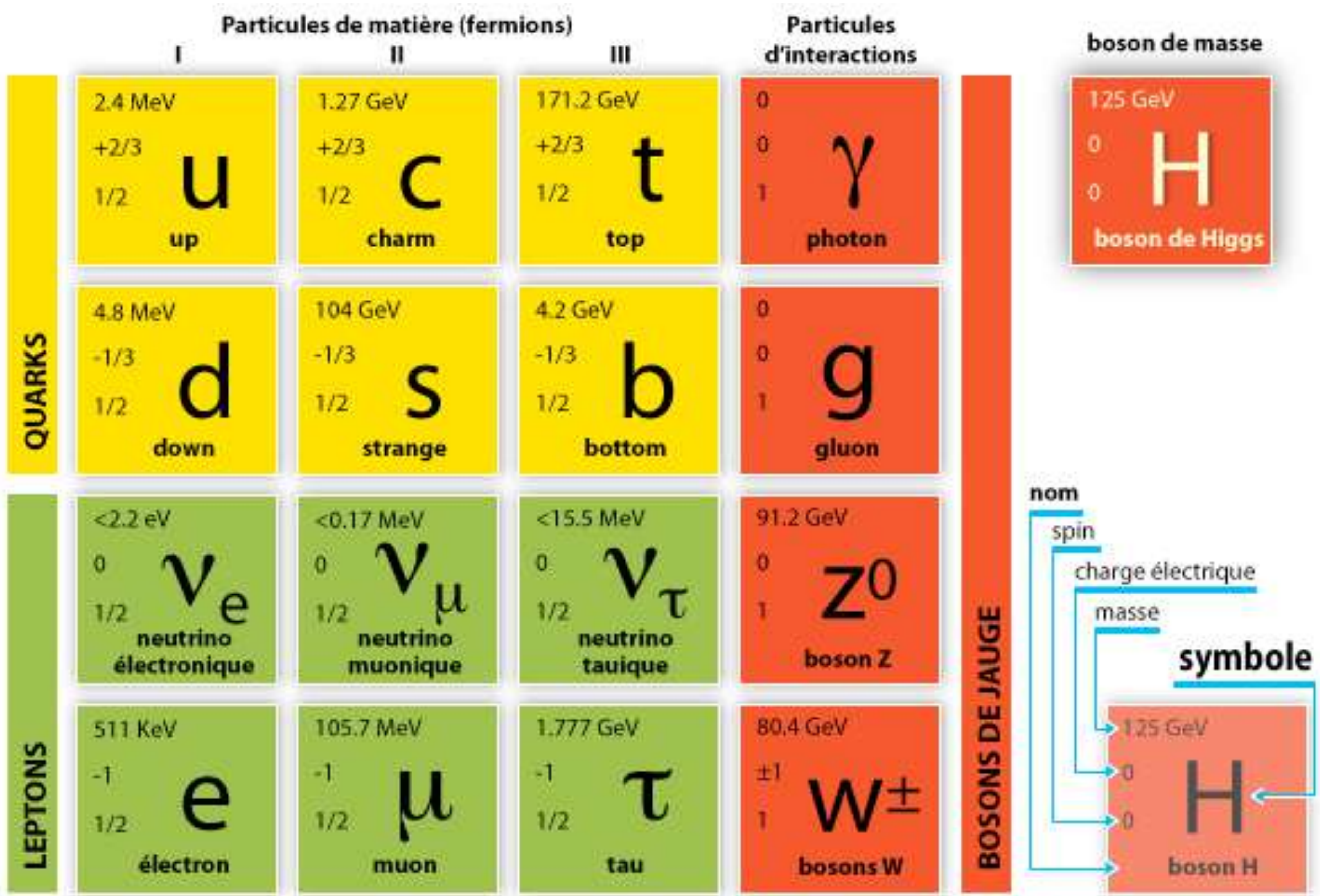
# The Standard Model

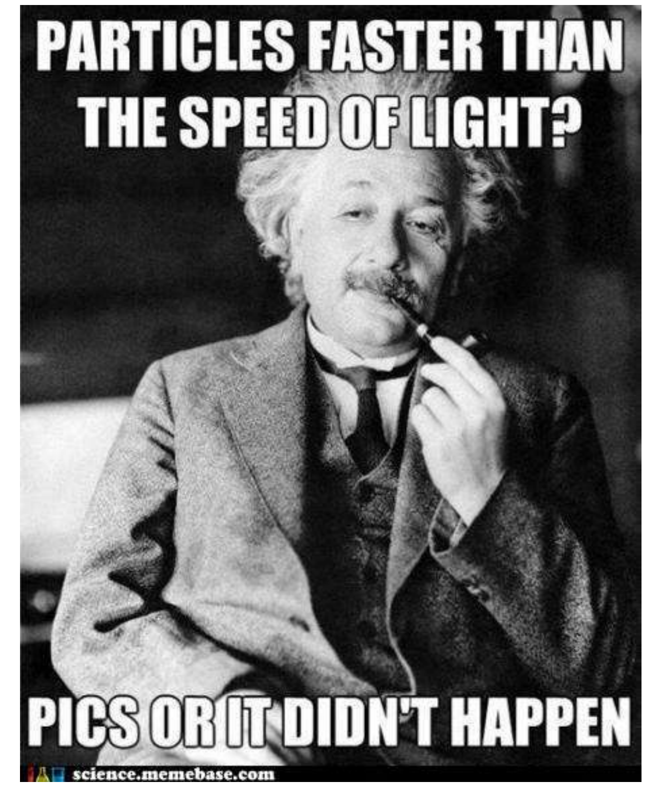
- **Matter** consists of elementary **particles**, which interact with each other via **forces**
- The **theory** describing **matter** and its **interactions** is the **Standard Model**



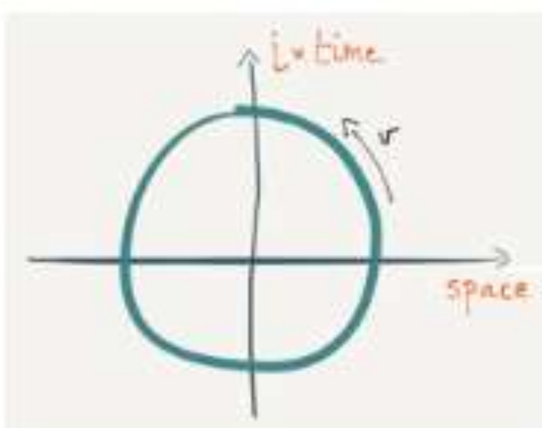
# The Standard Model

# The theoretical framework

## 1st element: special relativity

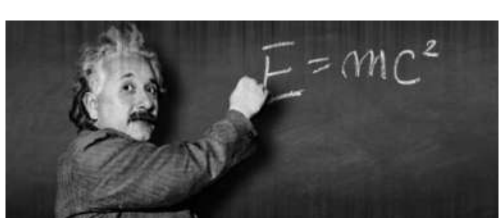



- All inertial observers see the same physics:
  - same light speed c
  - Lorentz symmetries = Space-time "rotations"




$$x^\mu = (t, \vec{x})$$
$$x^2 = \eta_{\mu\nu} x^\mu x^\nu = x^\mu x_\mu = \text{invariant}$$
$$\eta_{\mu\nu} = \text{diag}(1, -1, -1, -1)$$

- Energy-momentum relation: p = (E,**p**), $p^2 = m^2 = E^2 - \mathbf{p}^2$



# The theoretical framework

## 2nd element: quantum mechanics


- Determinism is not fundamental: $\Delta x^\mu \times \Delta p_\nu \geq (\hbar/2)\delta^\mu_\nu$
  - Nature is random → probability rules
  - The vacuum is not void, it fluctuates!

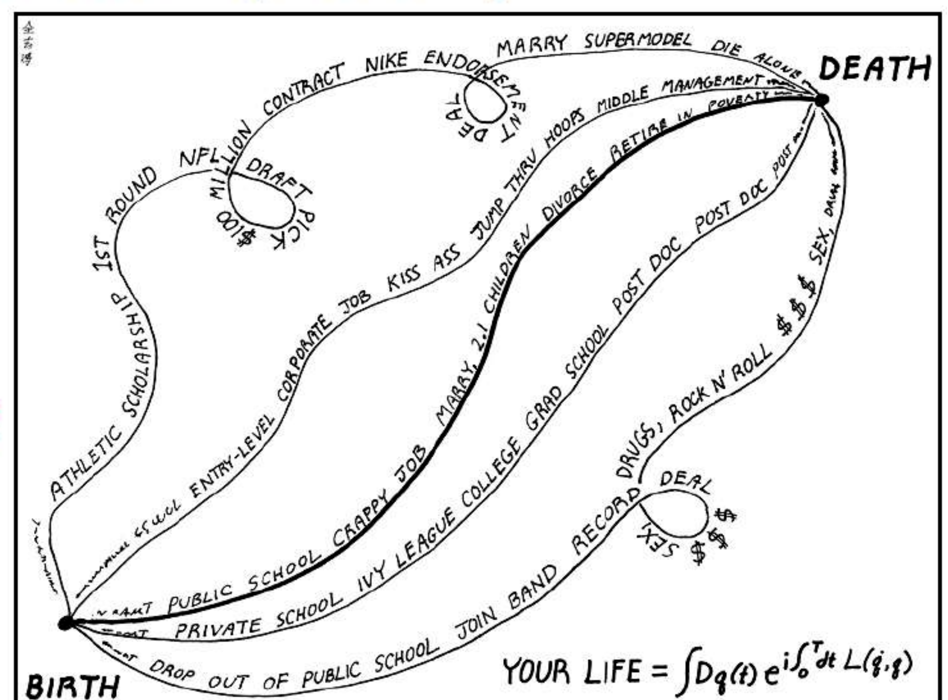
- Classical physics emerges from constructive interference of probability amplitudes:

**Feynman's path integral:**

$$A = \int [dq] \exp(iS[q(t), \dot{q}(t)])$$

**a rational for the least action principle**

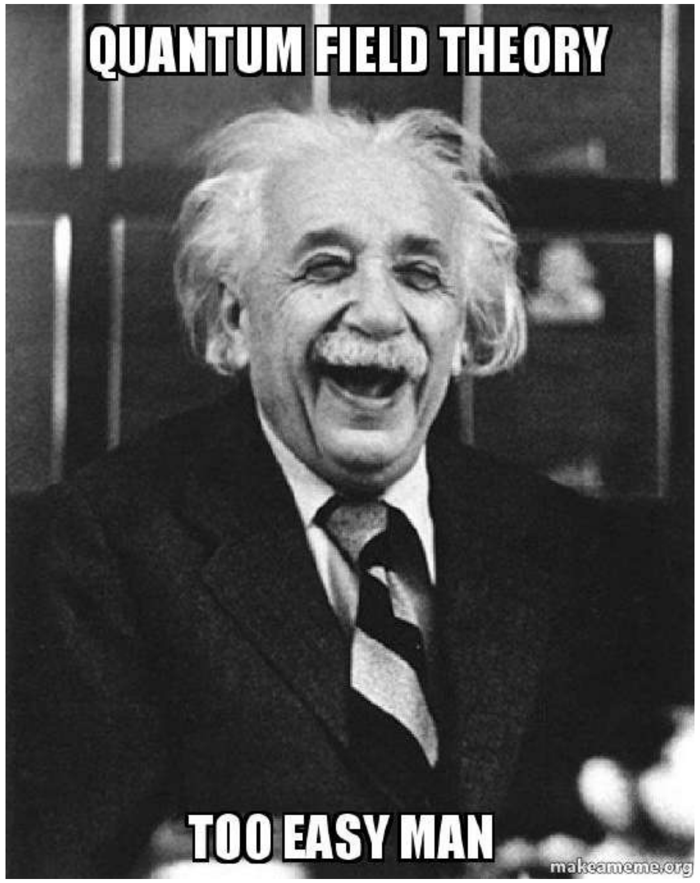
It replaces the classical notion of a single, unique classical trajectory, with a sum over an infinity of quantum-mechanically possible trajectories to compute a quantum amplitude.




The Path Integral Formulation of Your Life

# The theoretical framework

**Special Relativity + Quantum Mechanics** ⇒ **Quantum Field Theory**

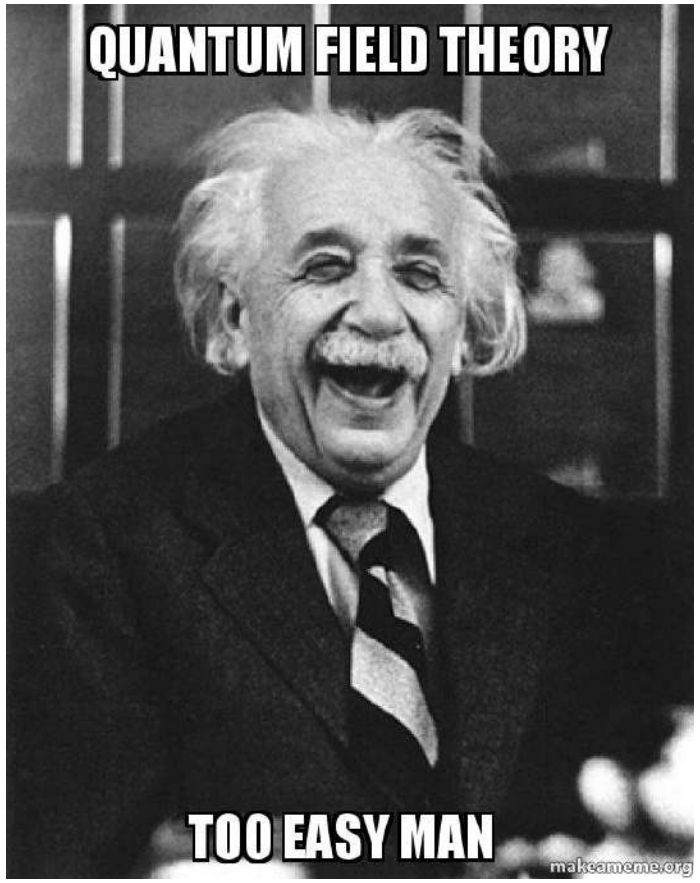



- ➡ **QFT** is the only known way to reconcile **QM** and **SR**
  - Relativistic wave equations are not sufficient
  - We need to change number and types of particles in particle interactions
  - Need for fields and quantise them "quantum fields"

- ➡ **Particles** = Excitations (quanta) of fields

# The theoretical framework

**Special Relativity + Quantum Mechanics** $\Rightarrow$ **Quantum Field Theory**

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- Relativistic wave equations are not sufficient
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➡ **Particles** = Excitations (quanta) of fields

A theory is born : **Standard Model**

The local **SU(3)×SU(2)×U(1)** gauge symmetry defines the SM

QCD

Electroweak

# The theoretical framework

- **Elegant theory**
  - Lagrangian formulation
  - A few free parameters
  - Contains both EW and QCD
  - Re-normalisable

1

$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\tfrac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} +$$
$$\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$

3

$$\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$
$$\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4

$$\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$
$$\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

5

$$\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] +$$
$$\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

# The mass problem

## ➡ Elegant theory

- Lagrangian formulation
- A few free parameters
- Contains both EW and QCD
- Re-normalisable
- Gauge bosons have to be of zero mass (the "mass problem")

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$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
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$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
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$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^-$$

3

$$- \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$
$$\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
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$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$
$$\gamma^5)u^\lambda_j)] +$$

4

$$\tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
$$\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
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5

$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$
$$\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] +$$
$$\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

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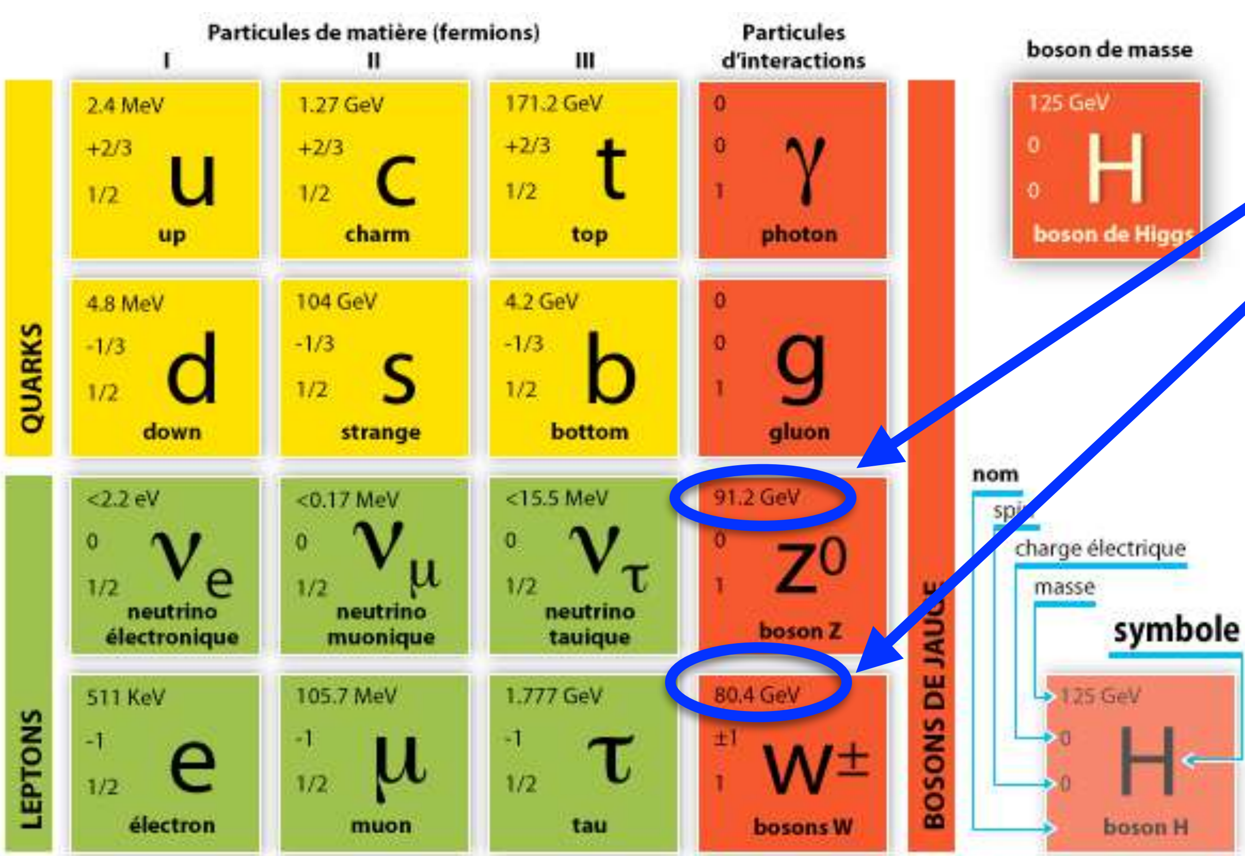
**W and Z bosons have a mass measured experimentally**

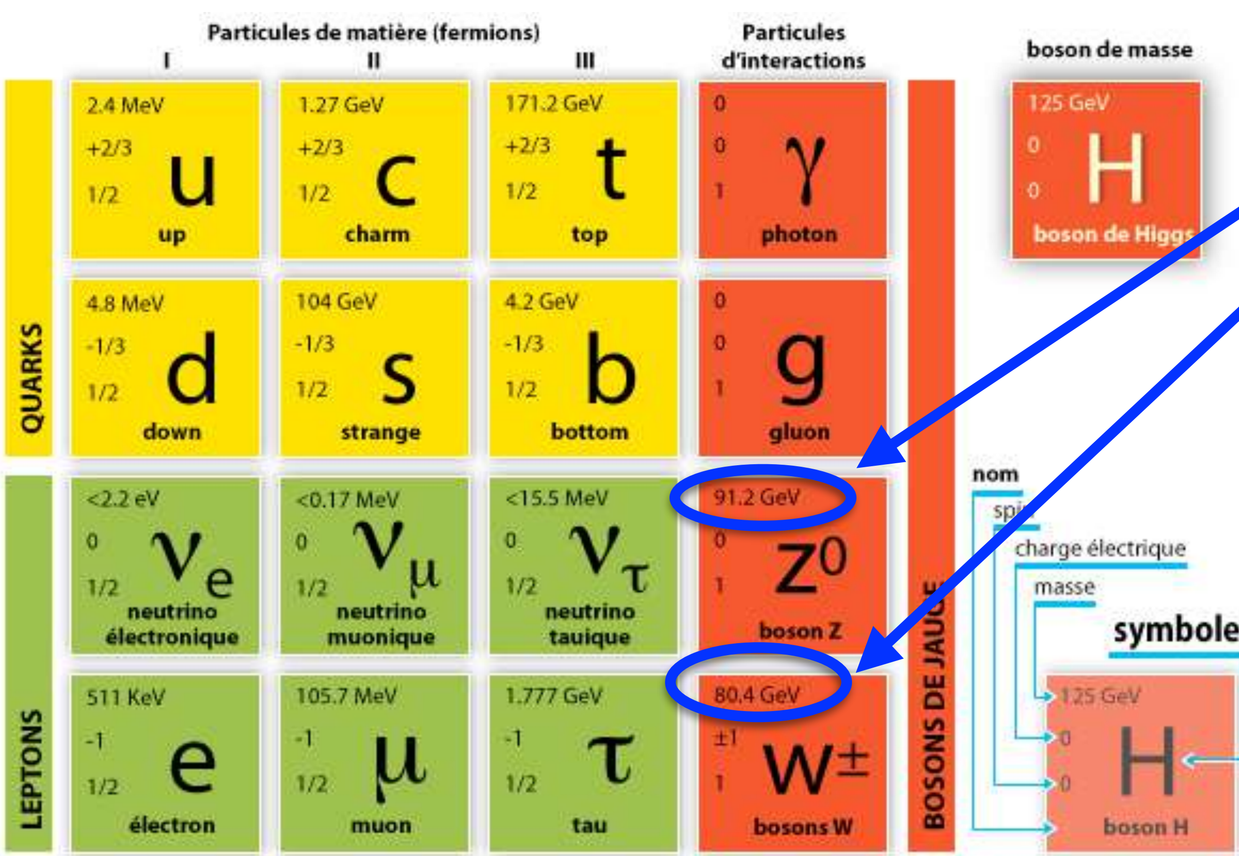


# The mass problem

## ➡ Elegant theory

- Lagrangian formulation
- A few free parameters
- Contains both EW and QCD
- Re-normalisable
- Gauge bosons have to be of zero mass (the "mass problem")

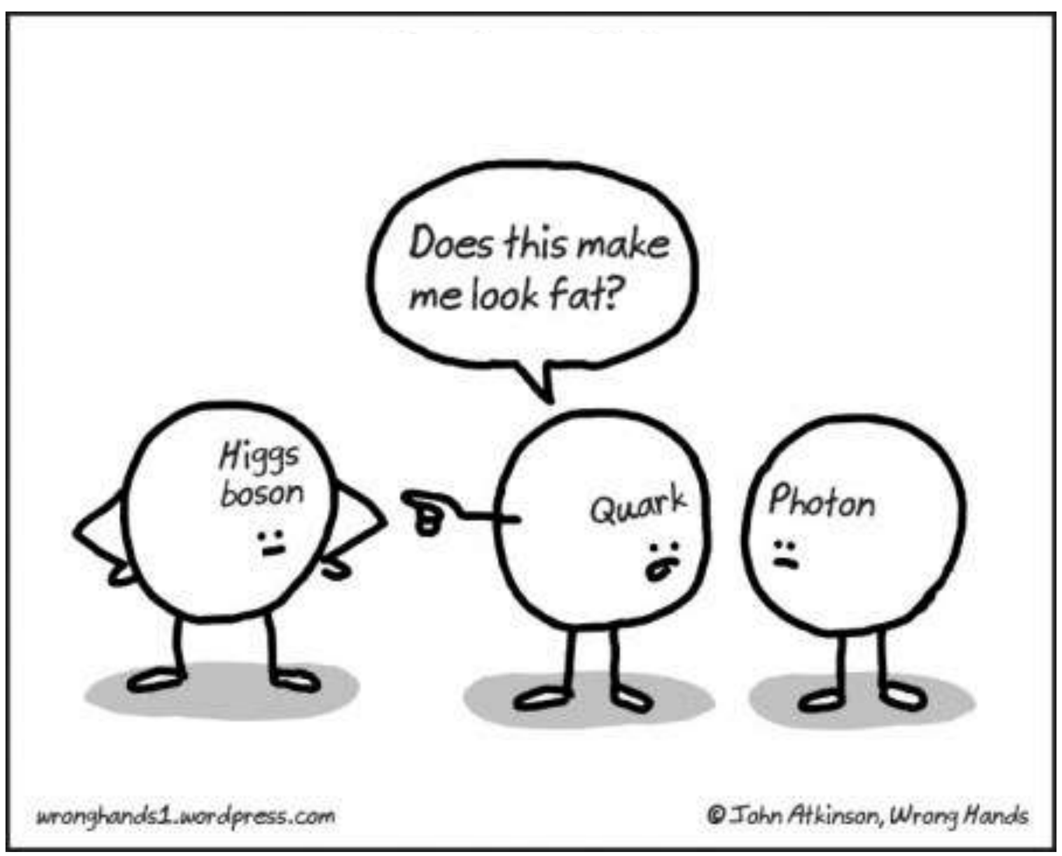
**W and Z bosons have a mass measured experimentally**




# The mass ~~problem~~

- **Elegant theory**
  - Lagrangian formulation
  - A few free parameters
  - Contains both EW and QCD
  - Re-normalisable
  - Gauge bosons have to be of zero mass (the "mass problem")

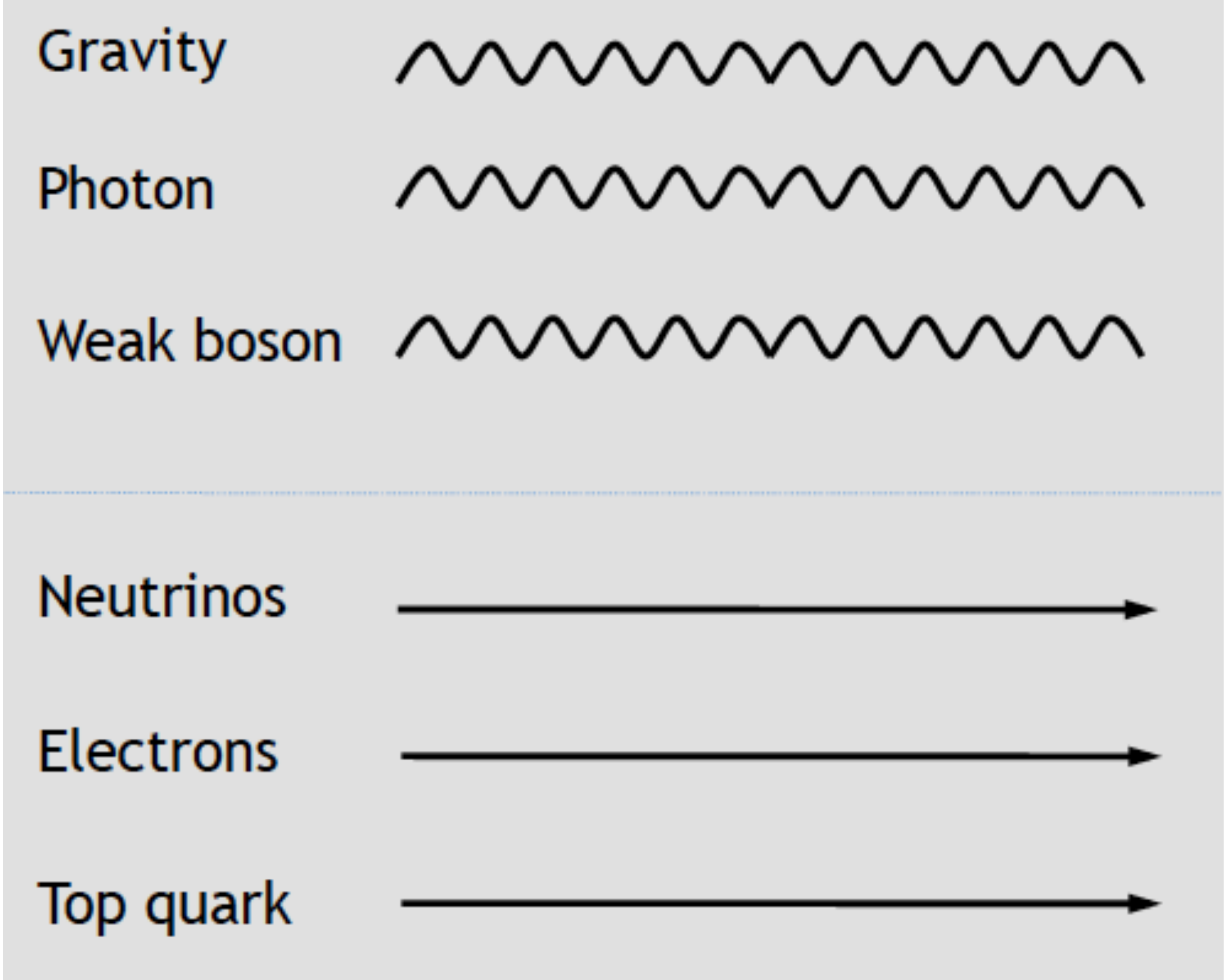
**Higgs mechanism to reconcile the theory with the observations**




# Higgs mechanism

At the very early age of the universe

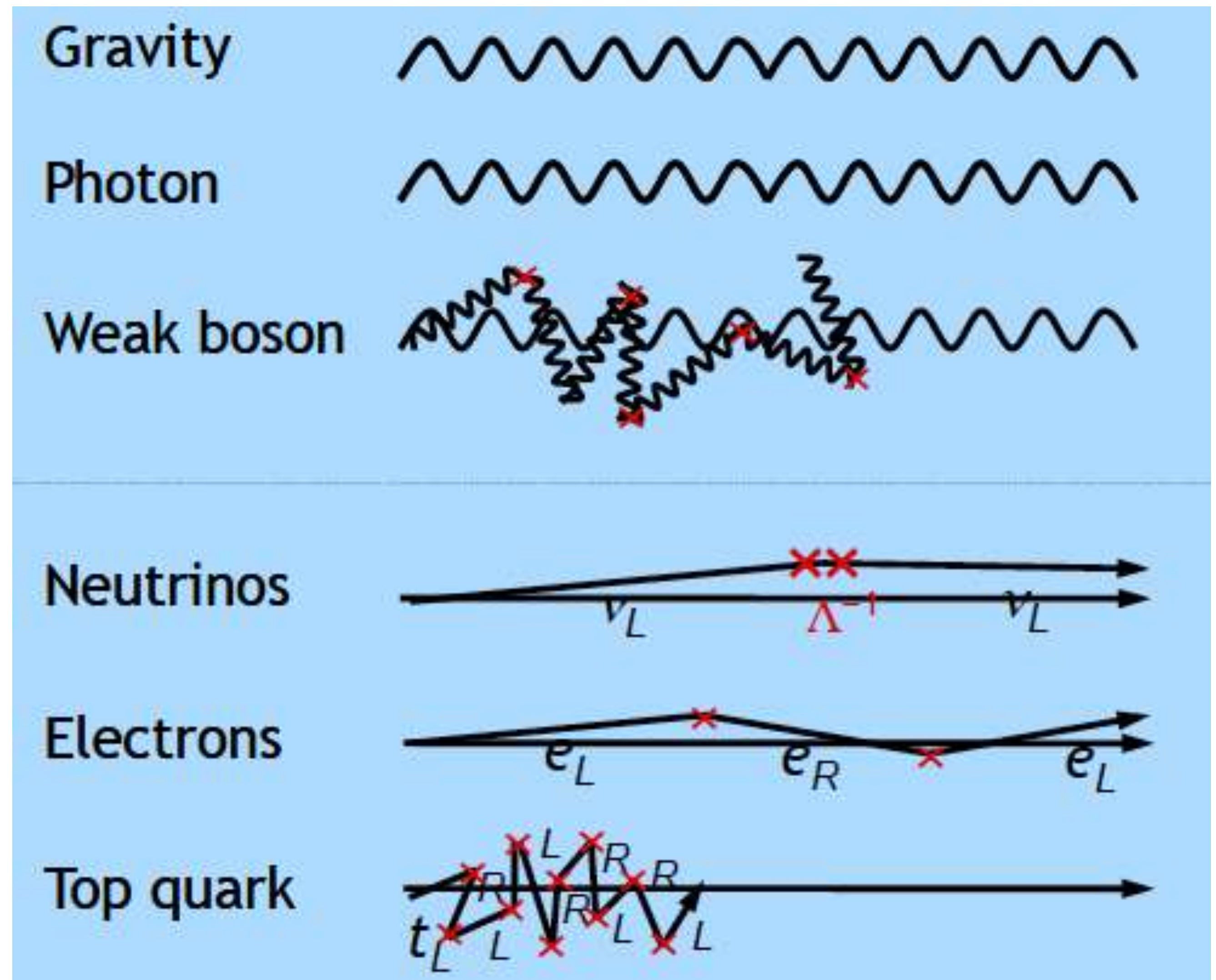
- The **Higgs field** fills all space without **any effect** on the **particles**
- Particles are moving at the speed of light, being **mass-less**



# Higgs mechanism

At the universe age of **~$10^{-10}$ s** :

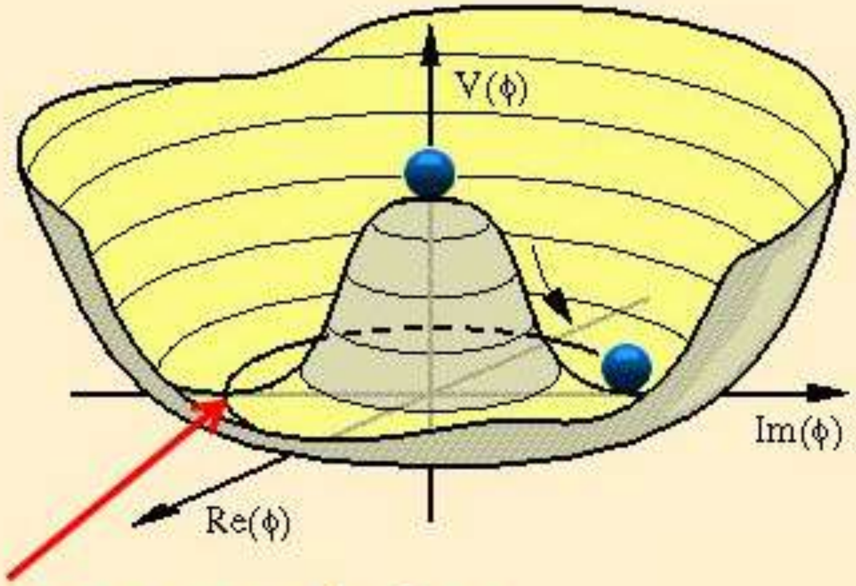
- The Higgs field that fills all the space, acquires a **vacuum expectation value** (VEV) that is **non zero**
- Some particles interact with the Higgs field and as a result they're slowed down ( = acquiring mass)




**- Mass is not an intrinsic property of particles,** but results from an **interaction** with the Higgs field that fills the space!!

**- The Higgs boson is the particle corresponding to the Higgs field**

# Higgs mechanism




- Lagrangian additional term:

$$L_{Higgs} = (D^{\mu}\Phi)^{+}(D_{\mu}\Phi) - V(\Phi^{+}\Phi)$$

$$V(\Phi^{+}\Phi) = -\mu^{2}\Phi^{+}\Phi + \lambda(\Phi^{+}\Phi)^{2}$$

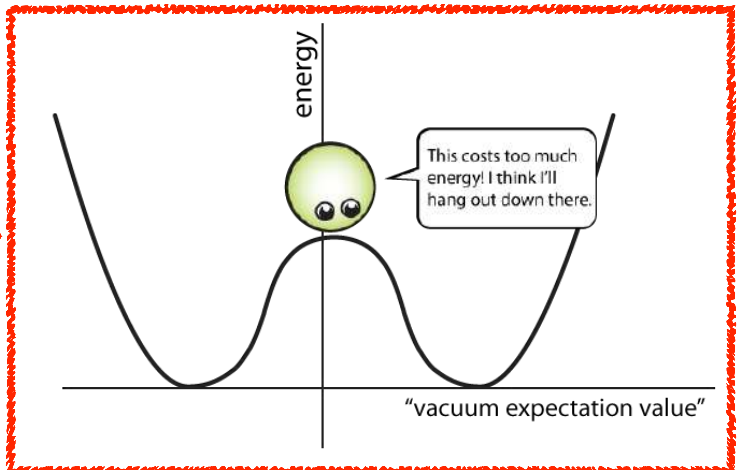
- $\mu^2, \lambda > 0$: infinite number of degenerate vacuum states

$$\frac{\partial V}{\partial \Phi^{+}\Phi} = 0 \Rightarrow \Phi^{+}\Phi\Big|_{vacuum} = \frac{\mu^{2}}{2\lambda} \qquad v^{2} \equiv \frac{\mu^{2}}{\lambda}$$

"Higgs field vacuum expectation value"

Choose one vacuum state ⇔ spontaneous symmetry breaking

**Higgs VEV of 246 GeV**



# QCD and jets

- LHC primarily a **pp** collider: **QCD** theory plays a critical role
  - SU(3) gauge group, describes the **strong interaction**
  - 8 gluons, 6 known quarks
  - **Asymptotic freedom** between quarks and gluons
    - At **high energy** q/g interact **weakly** allowing **perturbative calculations**
    - At **low energy** interaction becomes **strong** resulting into the **confinement** of quarks and gluons to **composite hadrons**

- In the experiments we are measuring **jets**
  - A proxy to the initial quark or gluon

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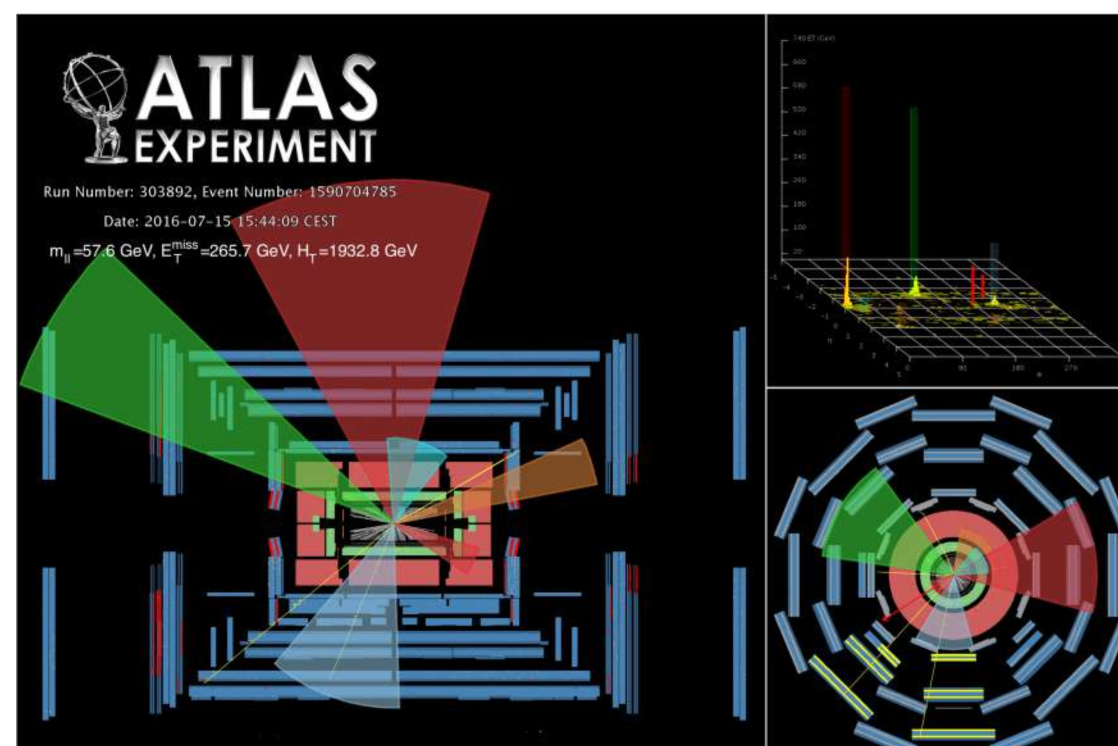
- In the experiments we are measuring **jets**
  - A proxy to the initial quark or gluon
  - **Jets** are produced **abundantly** in **LHC**

# What are jets?

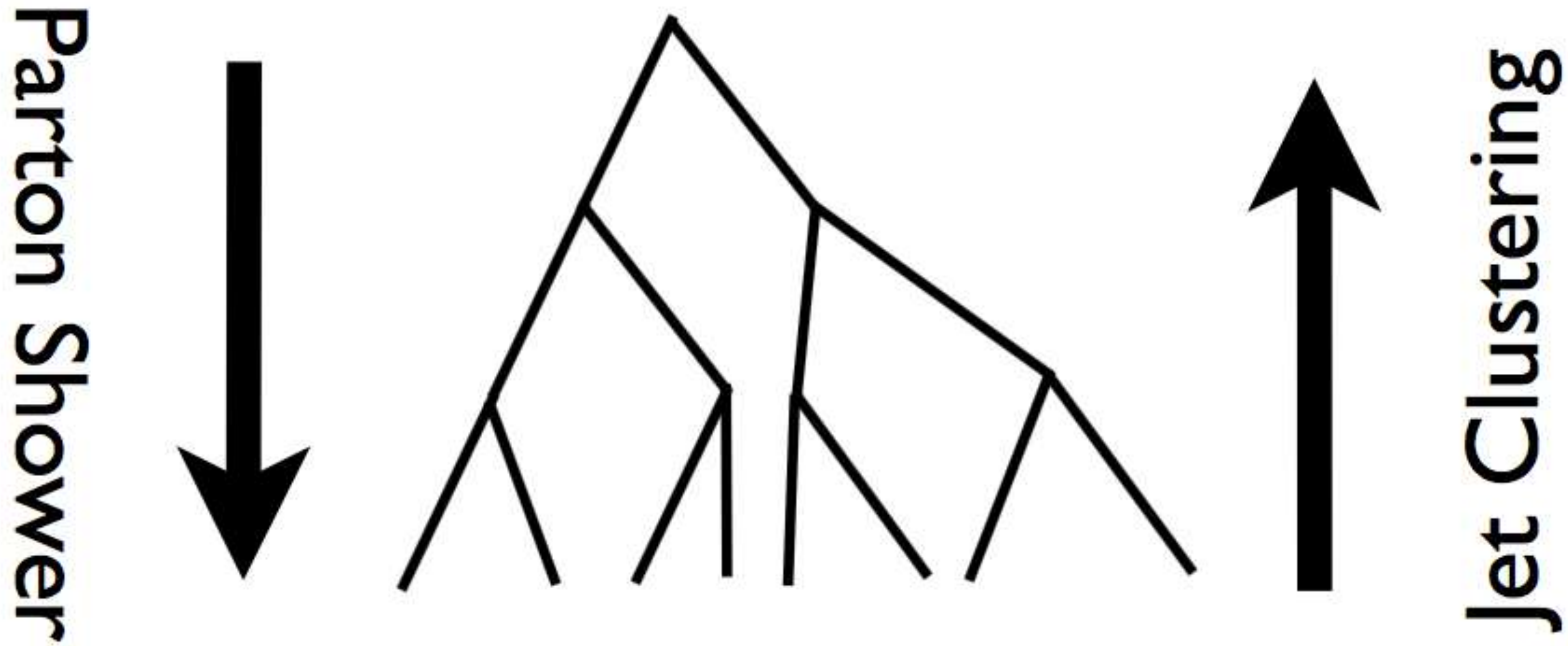
- Jets are the outputs of **clustering algorithms** that group **inputs,** typically **calorimeter energy clusters**
  - A proxy to the hard scattered parton (quark or gluon)

# What are jets?


- Jets are the outputs of **clustering algorithms** that group **inputs,** typically **calorimeter energy clusters**
  - ✦ A proxy to the hard scattered parton (quark or gluon)
- The challenge of jets comes from **QCD physics**: **parton shower** and **hadronization**
  - ✦ The particles we measure -π, K, *p*, *n*, etc- are **not** the particles from the hard scattering

# Jet algorithms

- Naively, jet algorithms are the inverse of the parton shower



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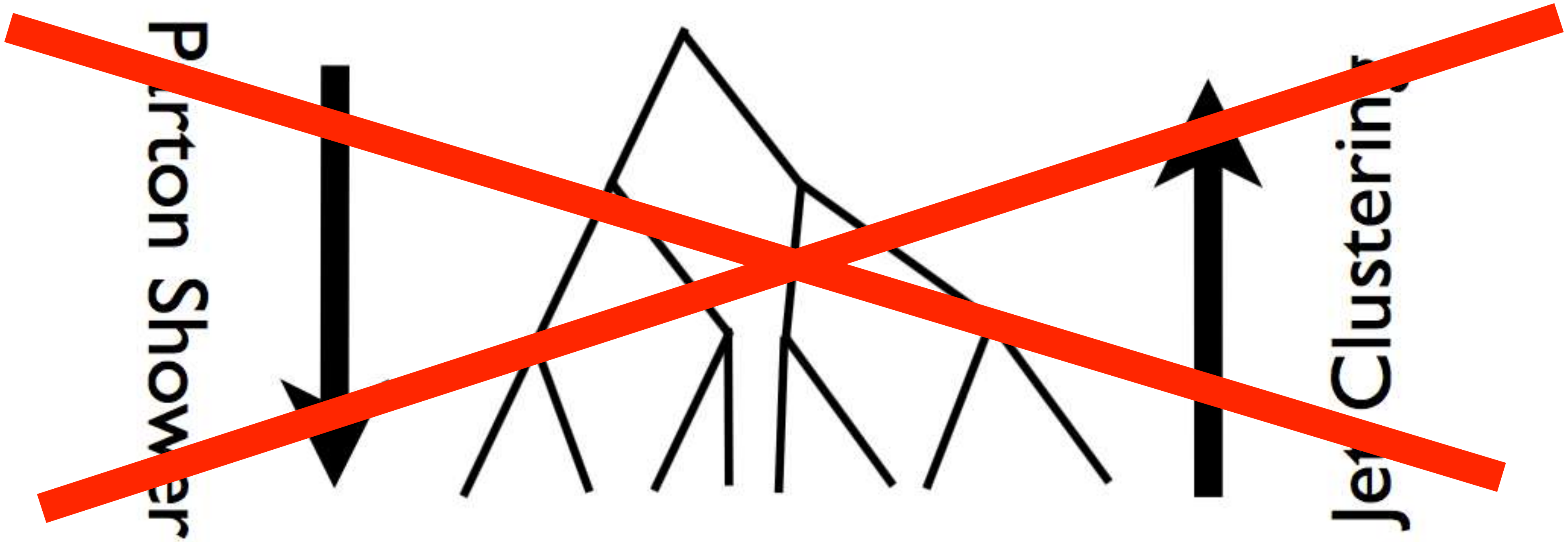
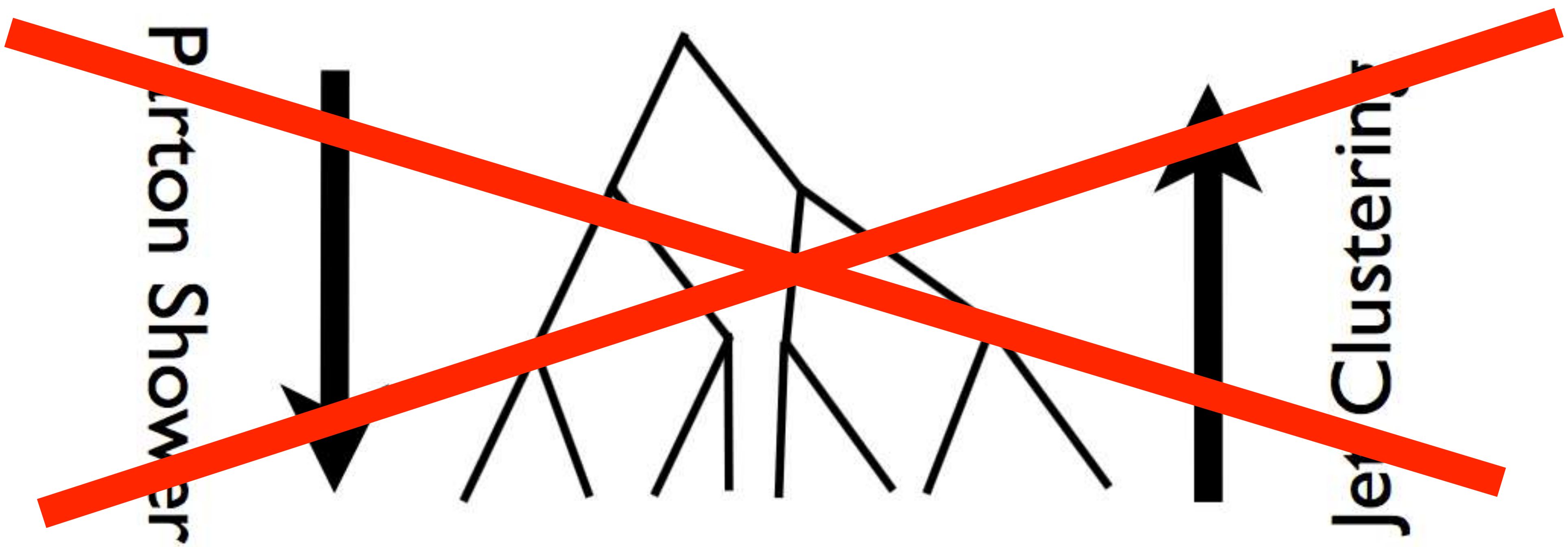


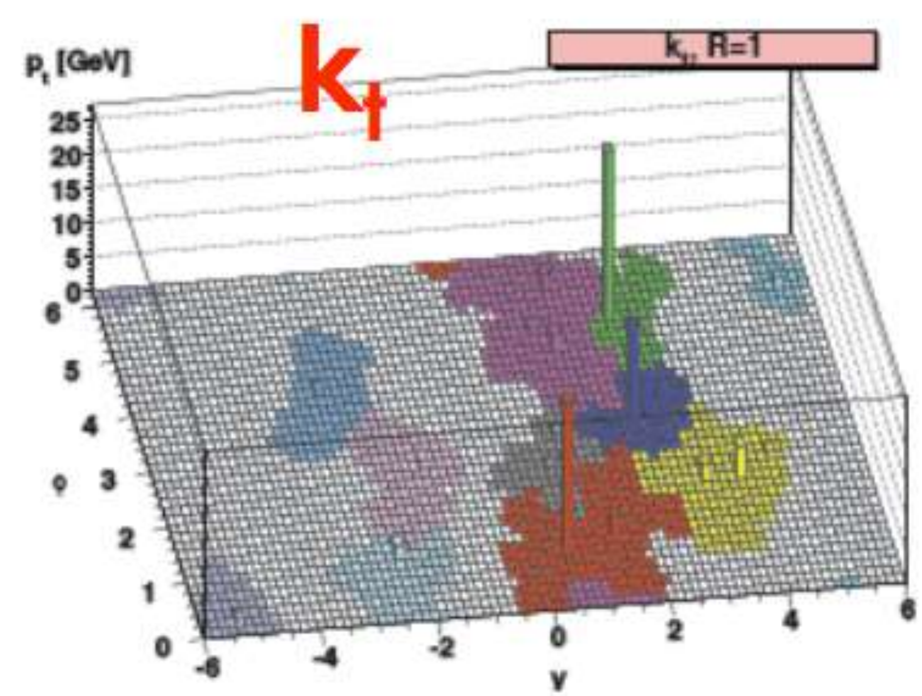

- <u>But the parton shower is actually not invertible!</u>
- There is no correct jet algorithm. Choice depends on the physics case

# Jet algorithms

- Naively, jet algorithms are the inverse of the parton shower



- <u>But the parton shower is actually not invertible!</u>
- There is no correct jet algorithm. Choice depends on the physics case
- **Anti-$k_T$** family of jet algorithms: the **standard** at **LHC** experiments
  - ✦ Regular shape objects (**easy to calibrate**, **more resilient to pile-up**)
  - ✦ Jet size based on the event kinematics

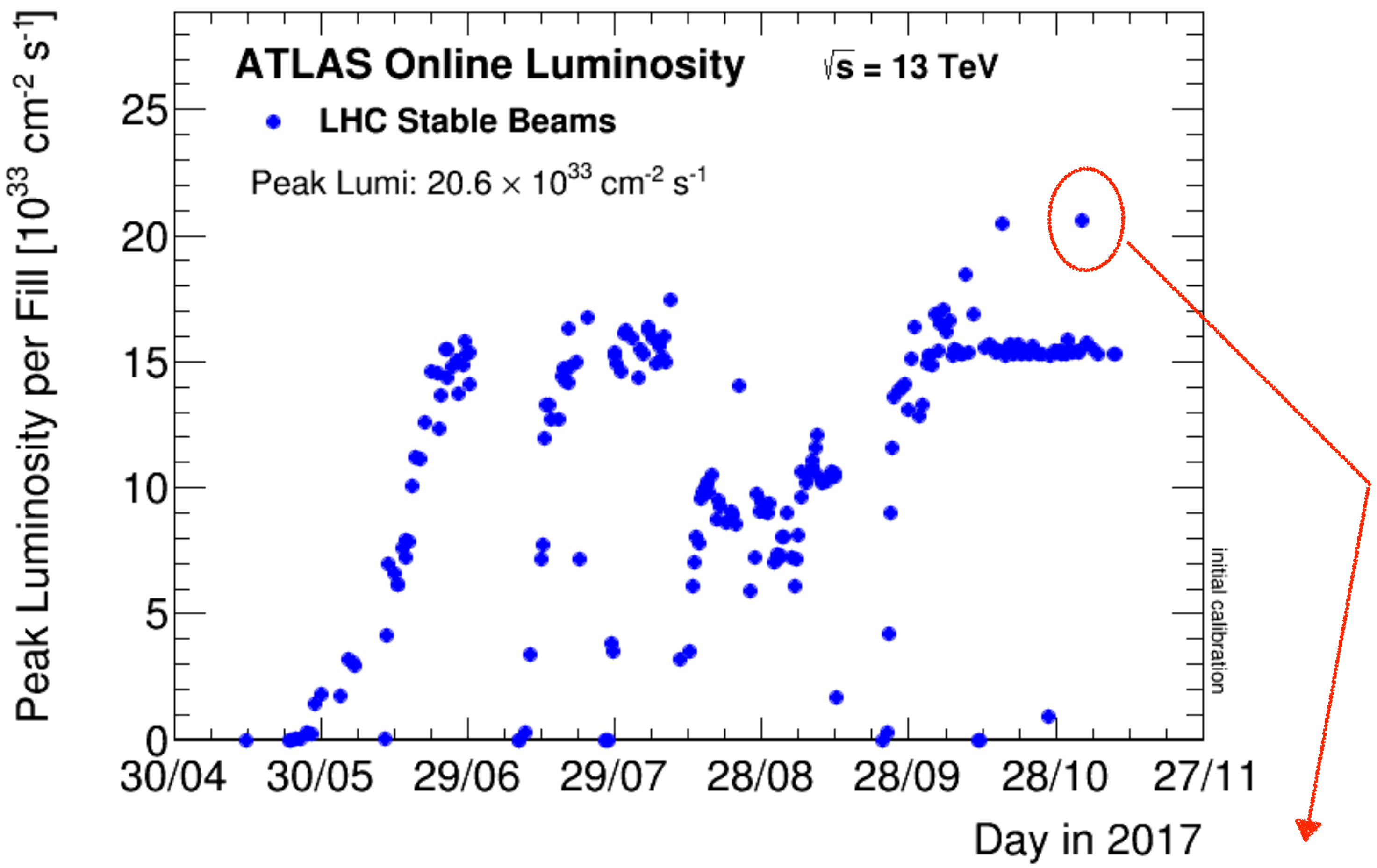


# The Large Hadron Collider


- **Primarily a p-p collider of 27km circumference situated at CERN**

# The Large Hadron Collider

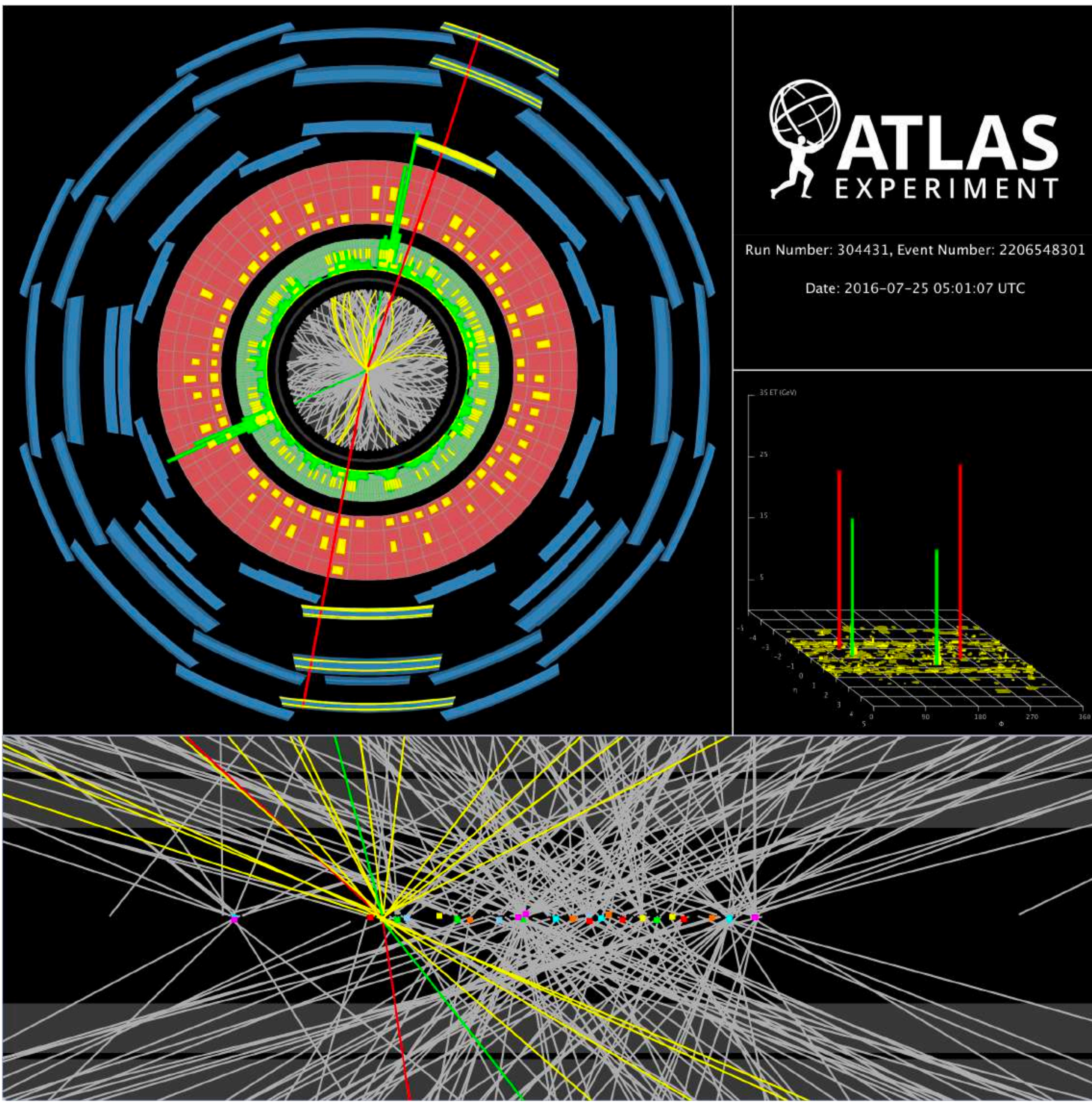
$$N_{events} = \sigma \times L$$

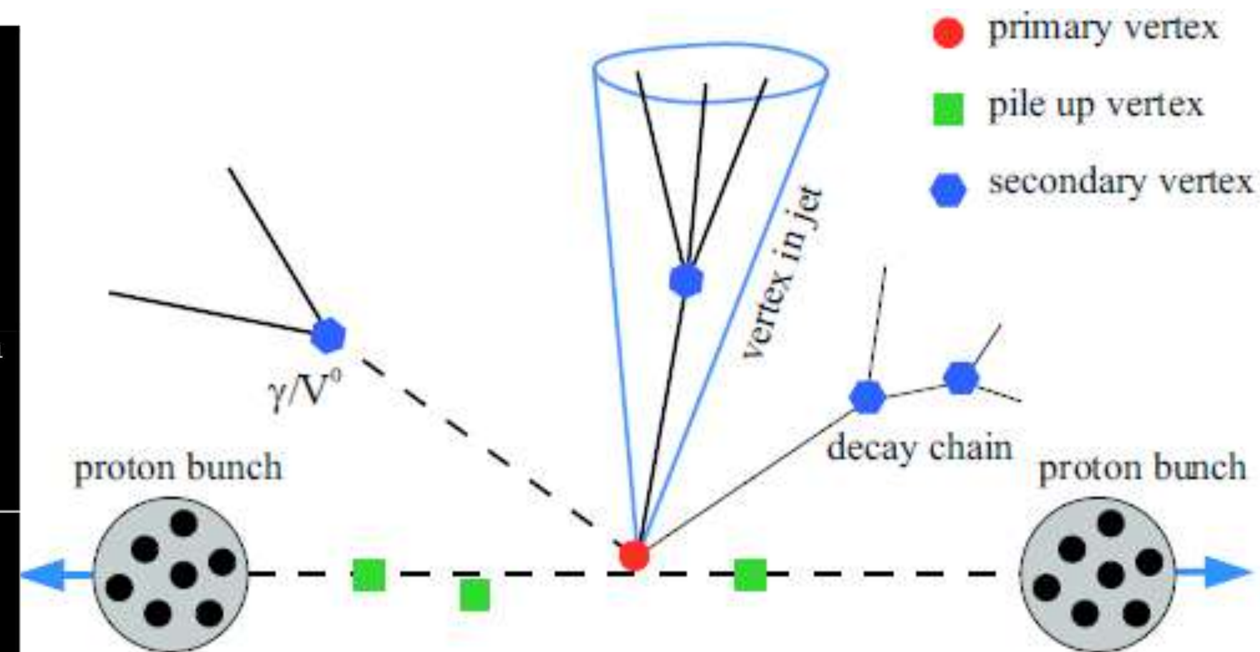


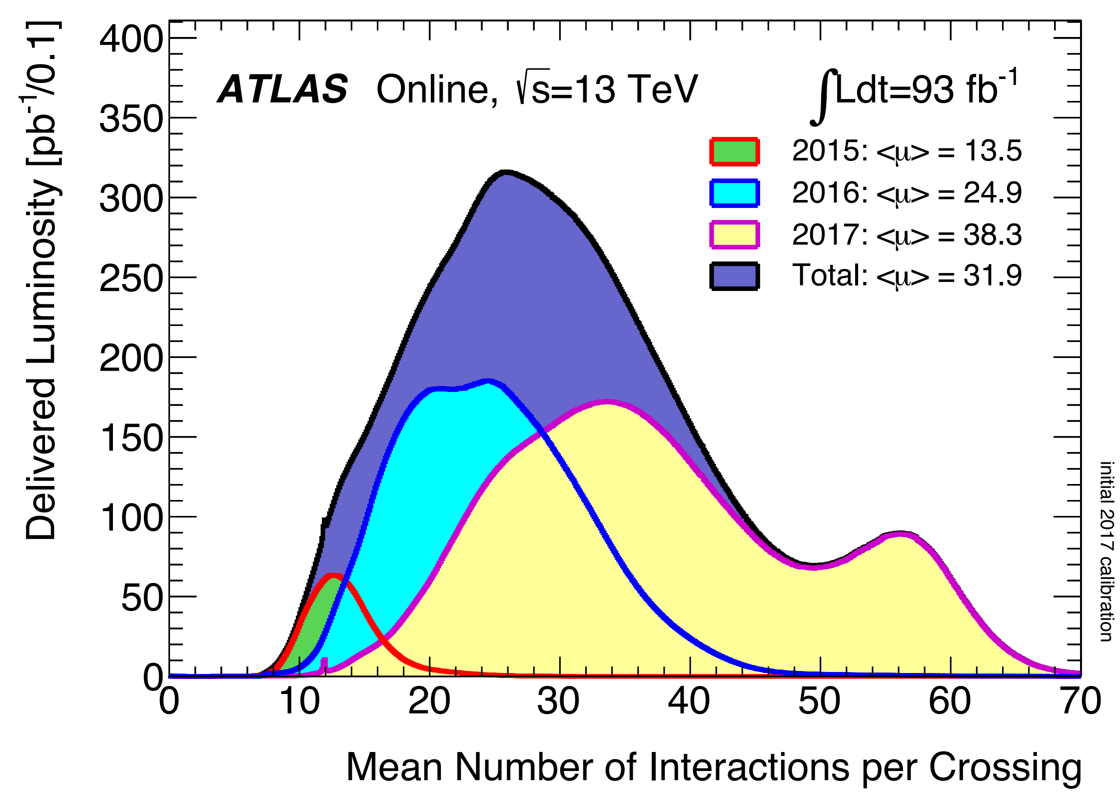

- This year peak lum. 20.6 $nb^{-1}$ : ~250 $W \to l\nu$ events/s
- 2 times larger than LHC design luminosity!!!

**Outstanding LHC performance!!!**

# The price of high lumi: pile-up

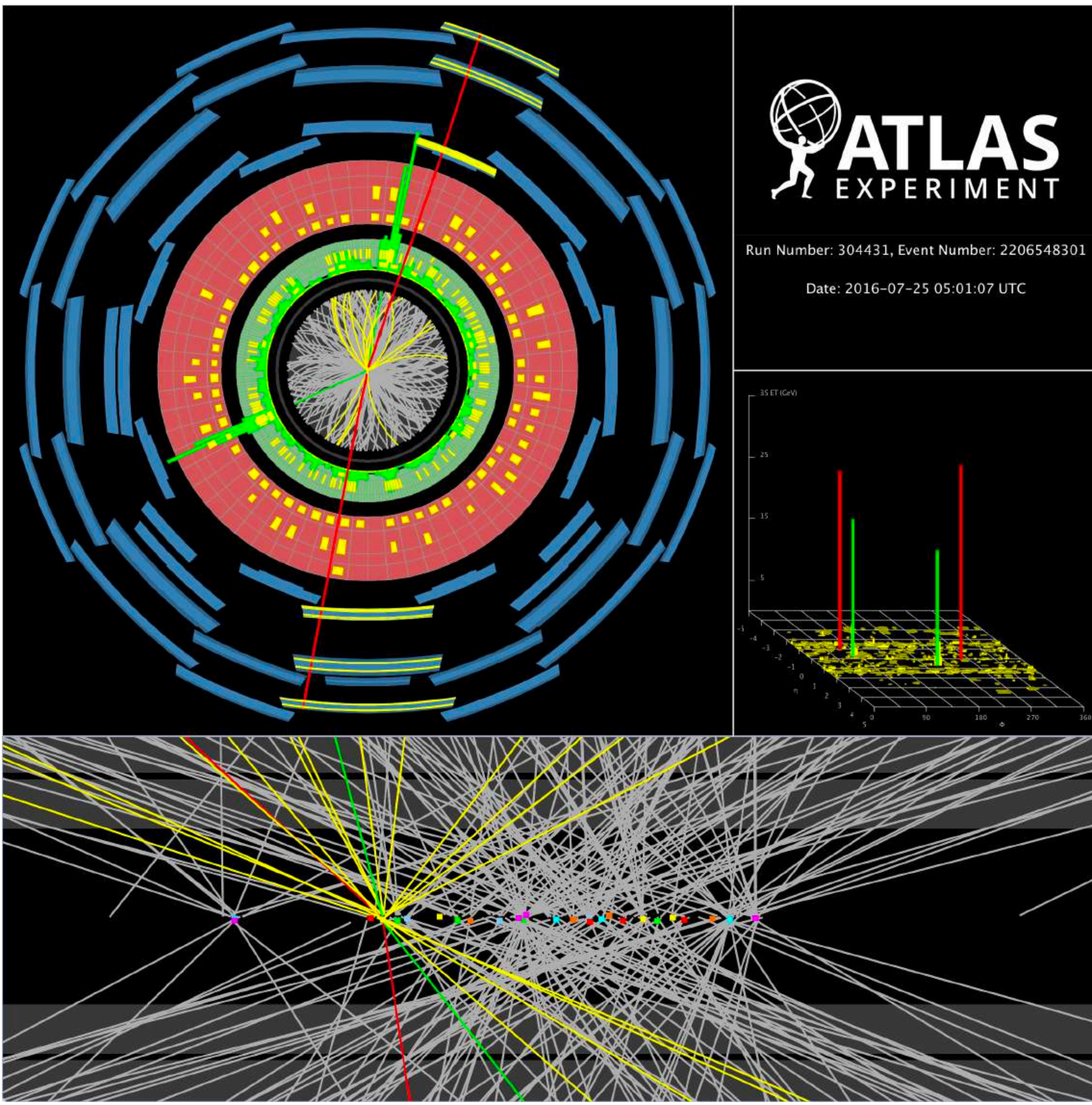


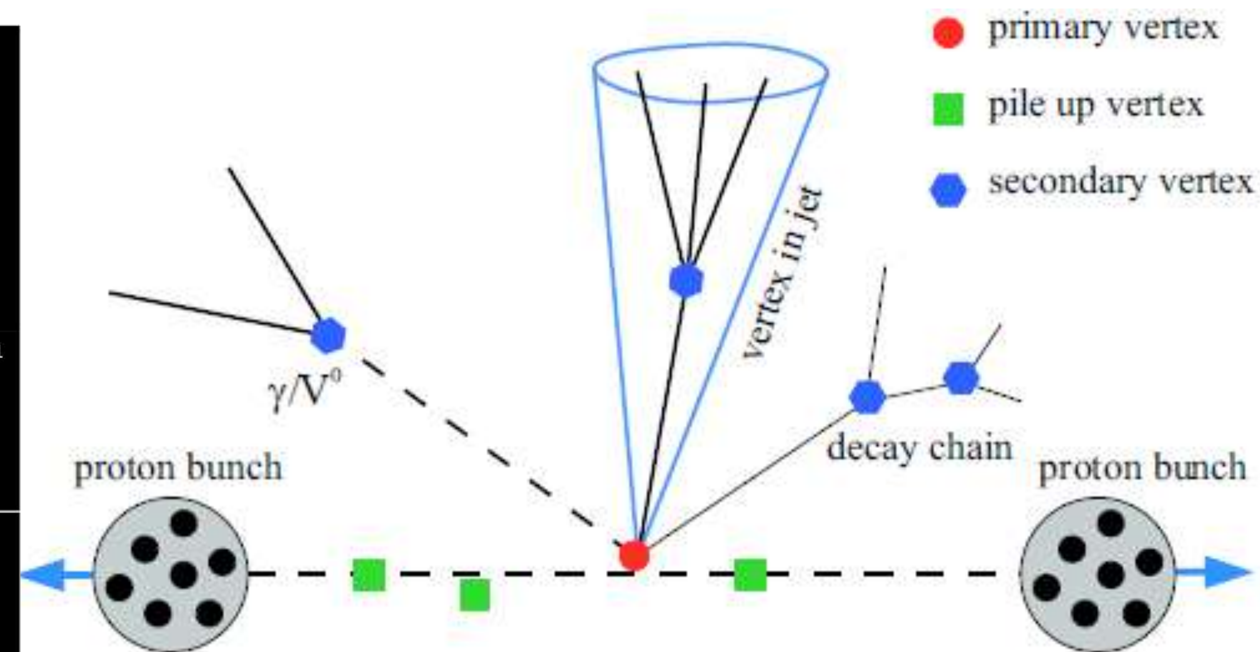



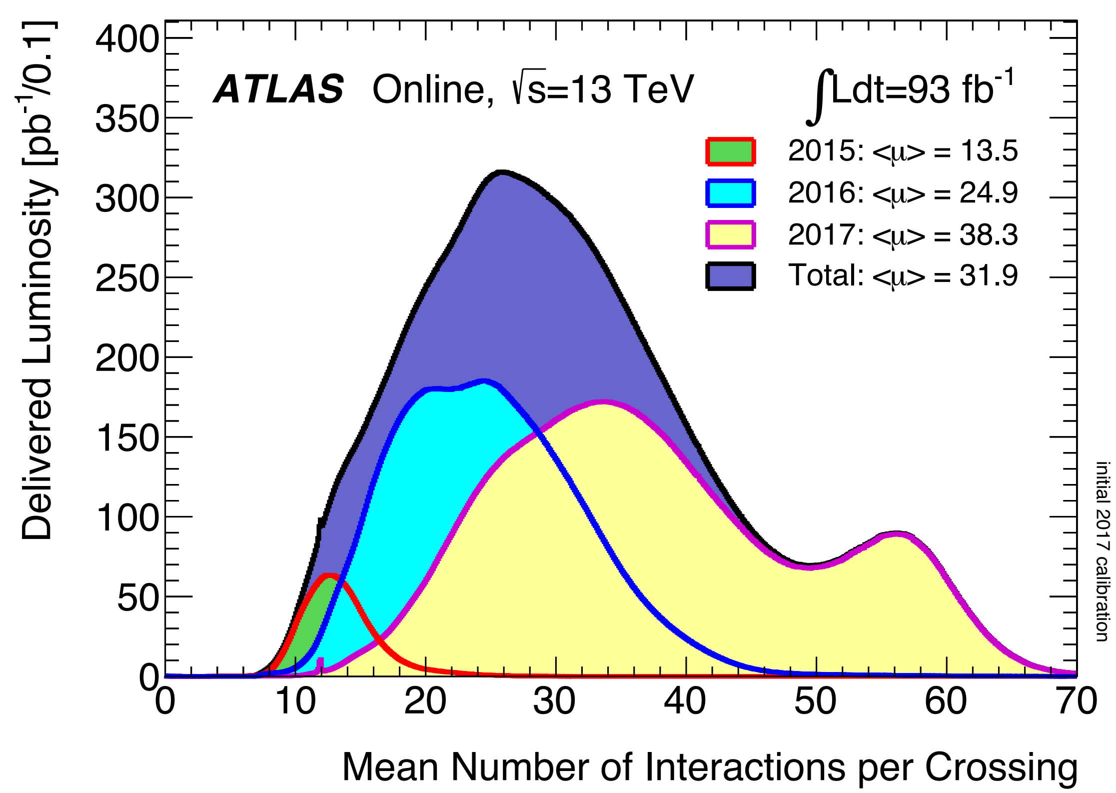




- 25 pile-up vertices

# The price of high lumi: pile-up



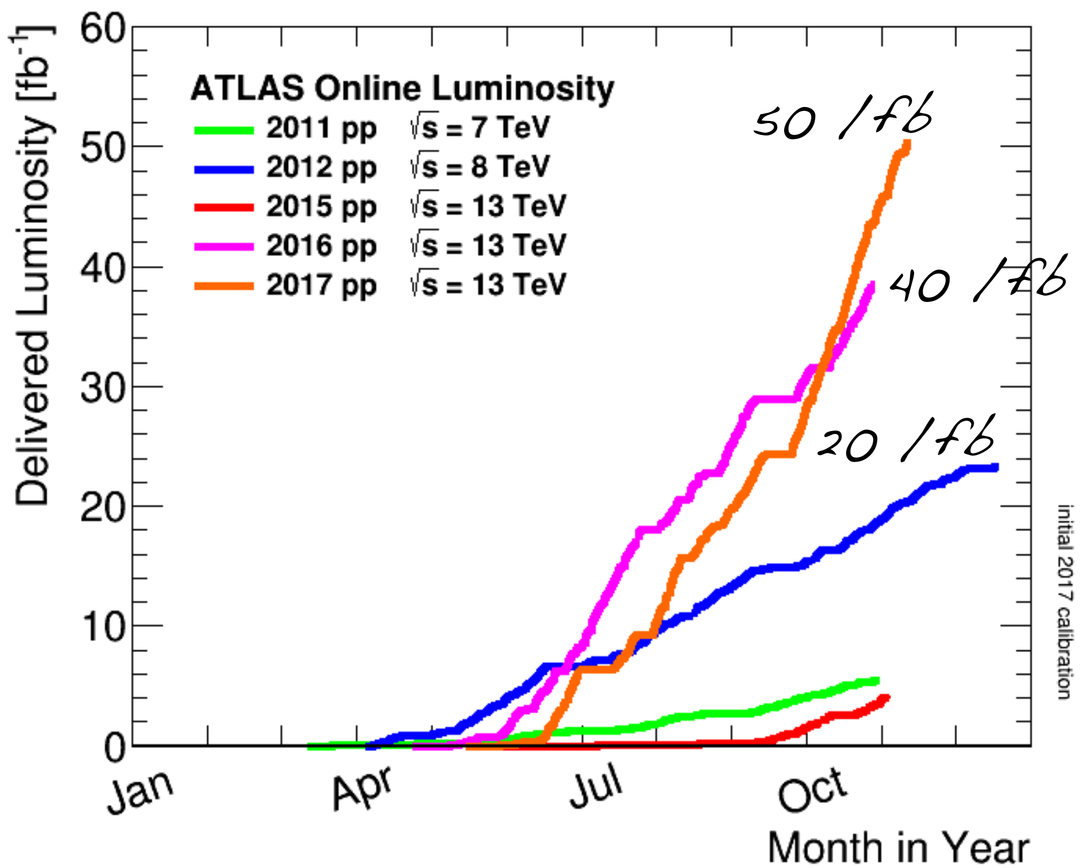




- 25 pile-up vertices, **can you tell which candidate event is it??**

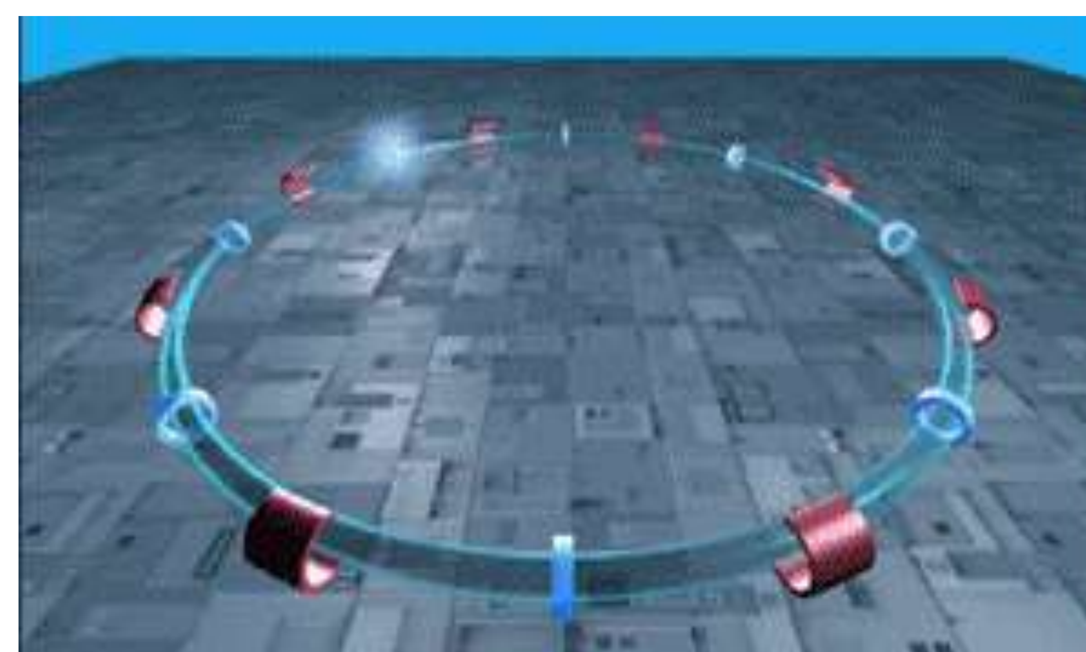
# The Large Hadron Collider

- Collisions:

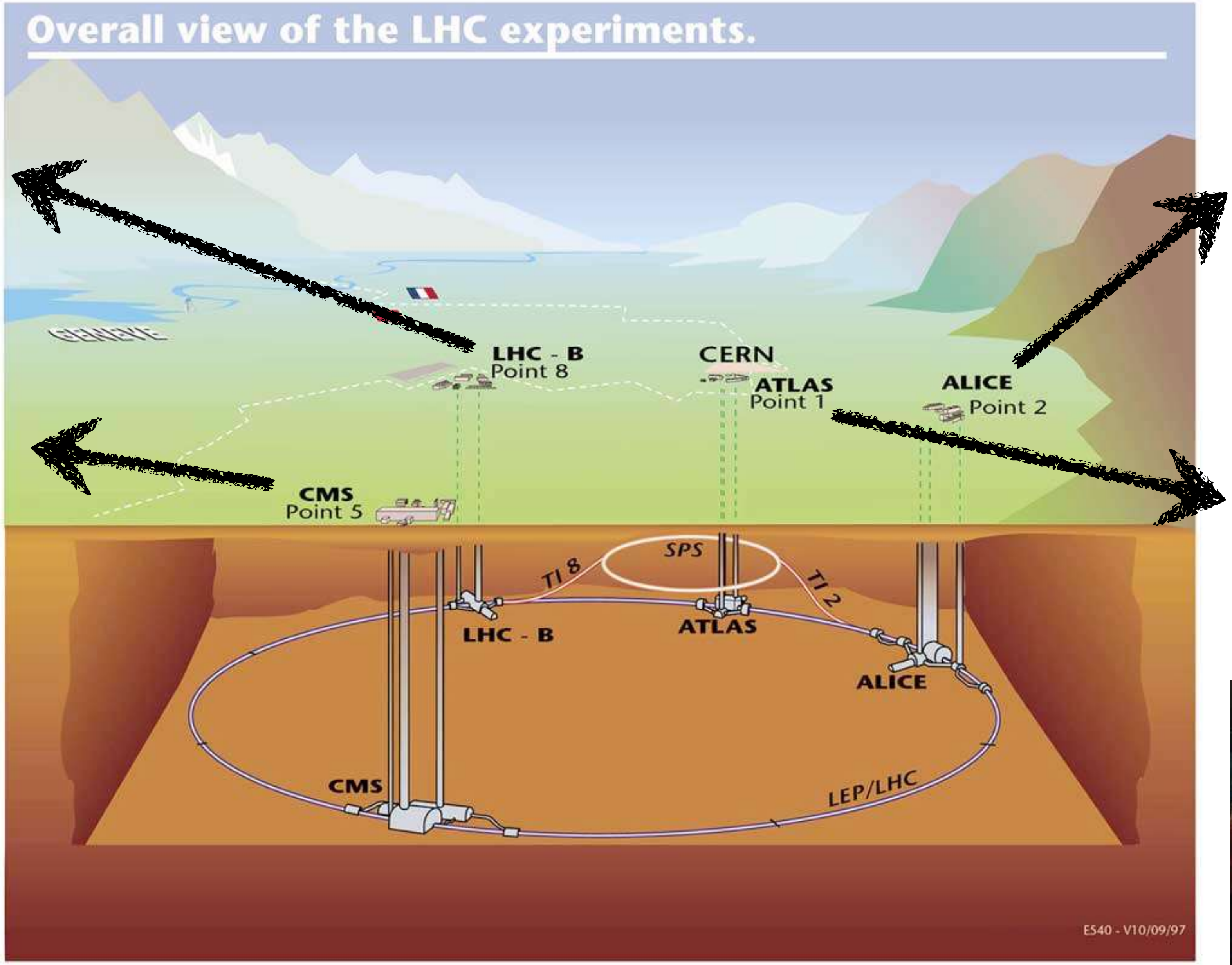


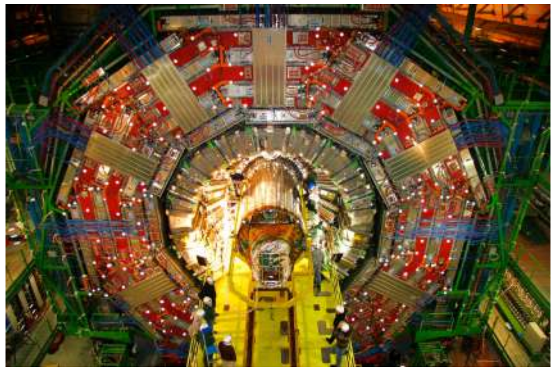

- Tevatron had collected 10 /fb in 10 years
- We expect another ~50 /fb next year, for a total of ~150 /fb at the end of Run-2 (2015-2018)
- Future goals
  - 300 /fb until 2023
  - >3000 /fb at the end or the HL-LHC to start in 2026

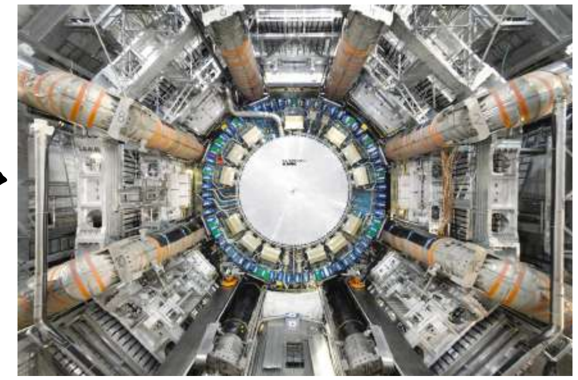
- Collisions happening every 25 ns (40 MHz)



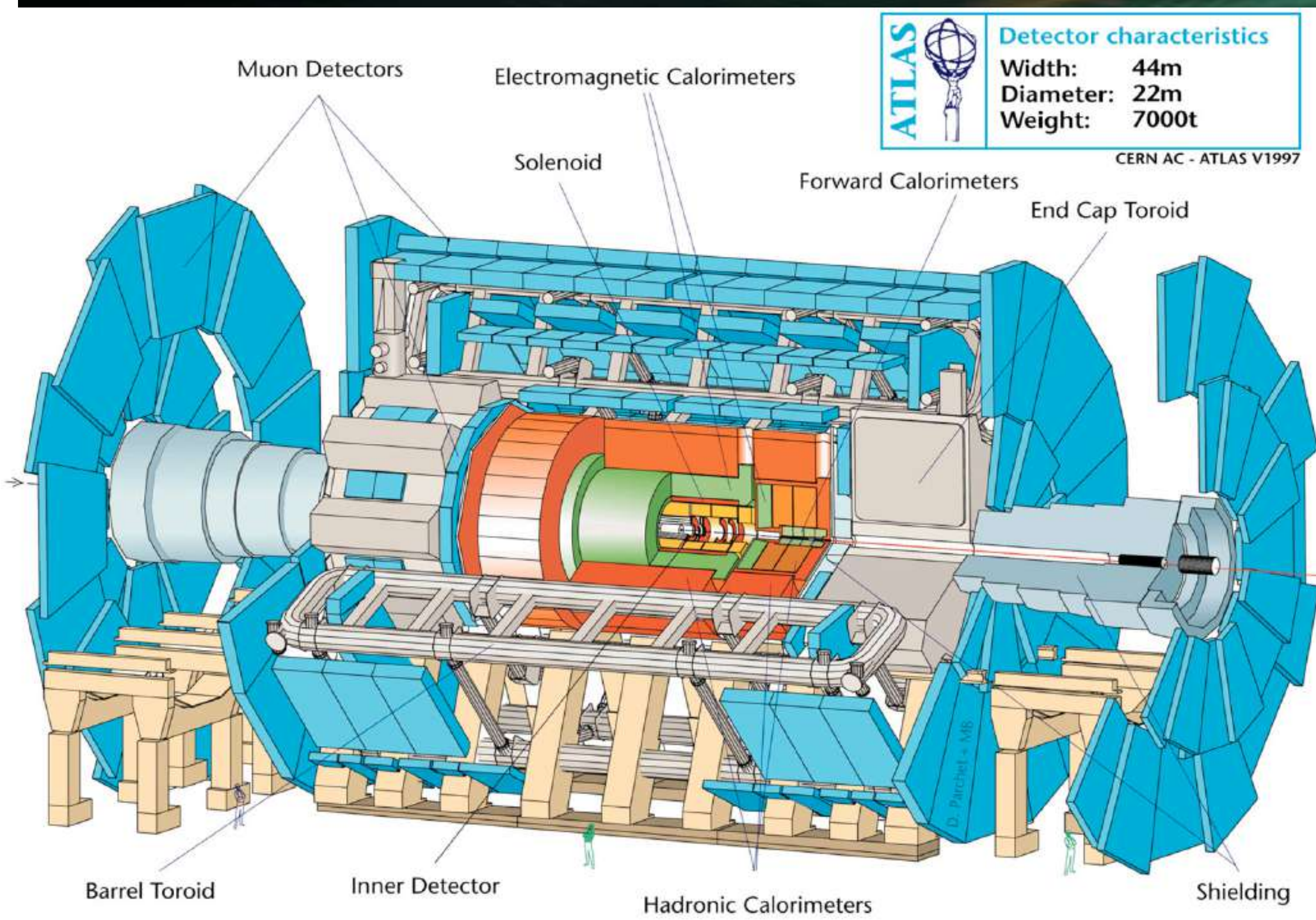
# Main LHC experiments

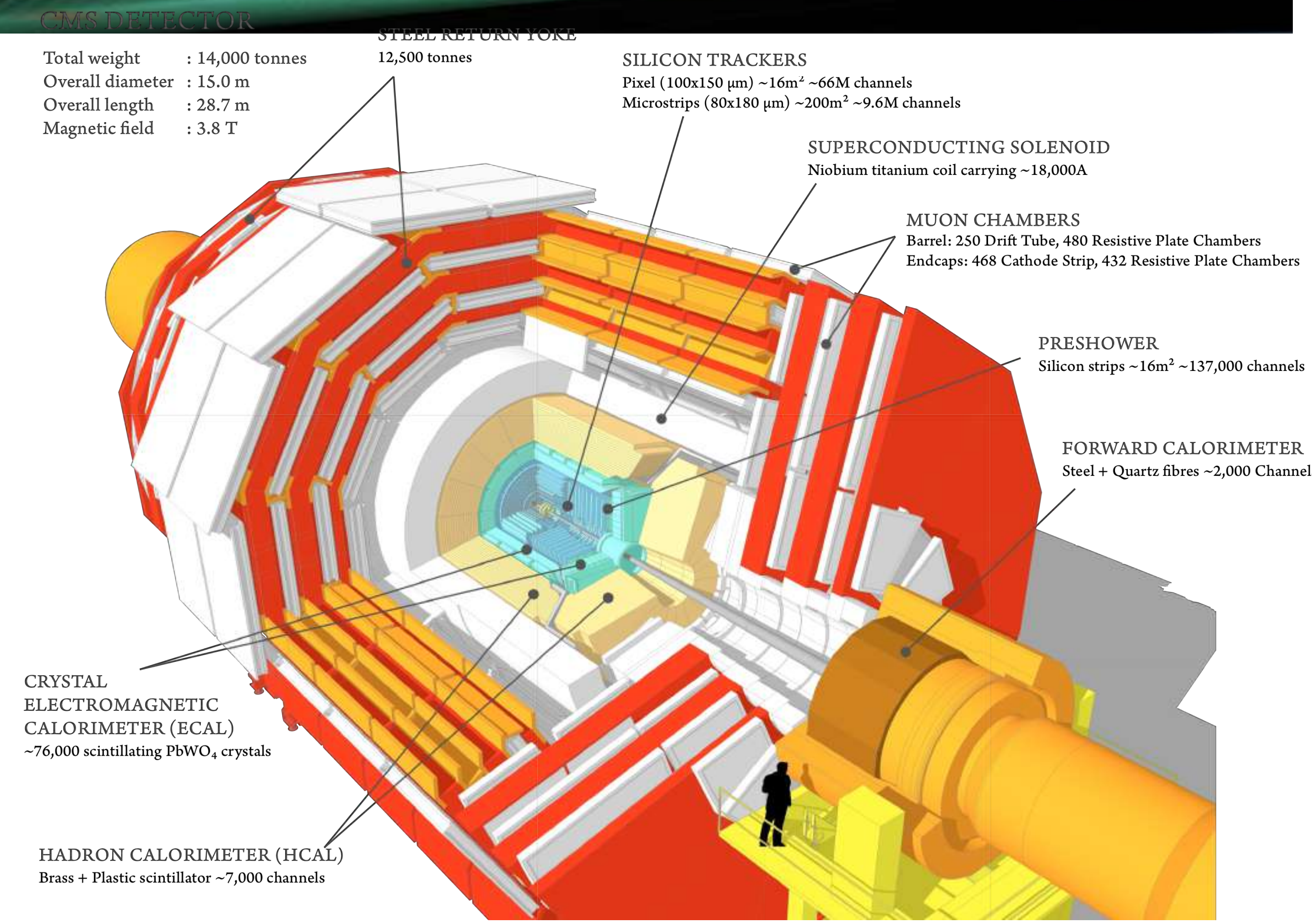




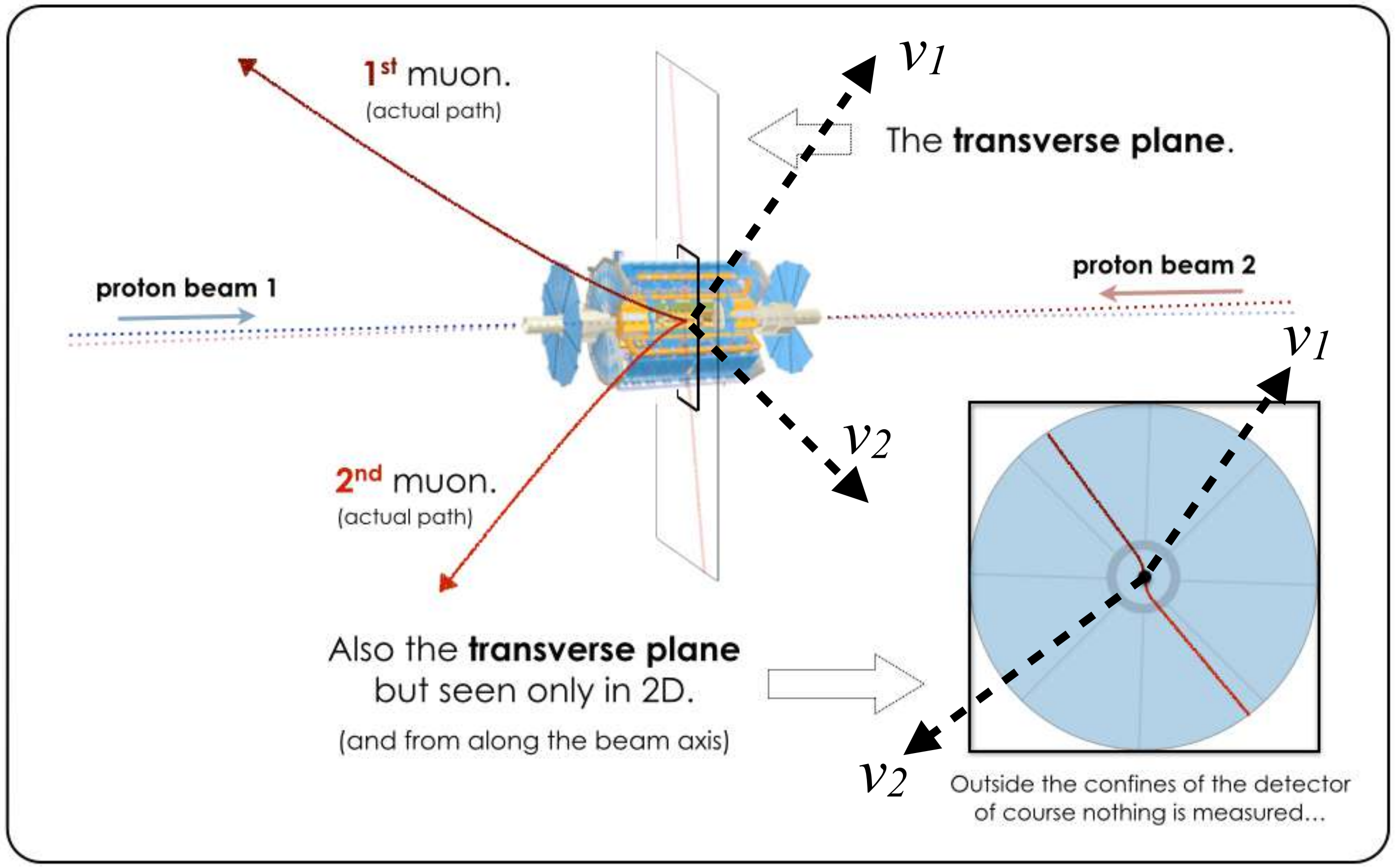

# ATLAS - CMS




- Excellent vertex and tracking system
  - ✦ **Our best handle against pileup**
- Large coverage of muon detection
- Excellent calorimetry with extended coverage to enable accurate jet and **transverse missing energy** measurements

# (Transverse) missing energy

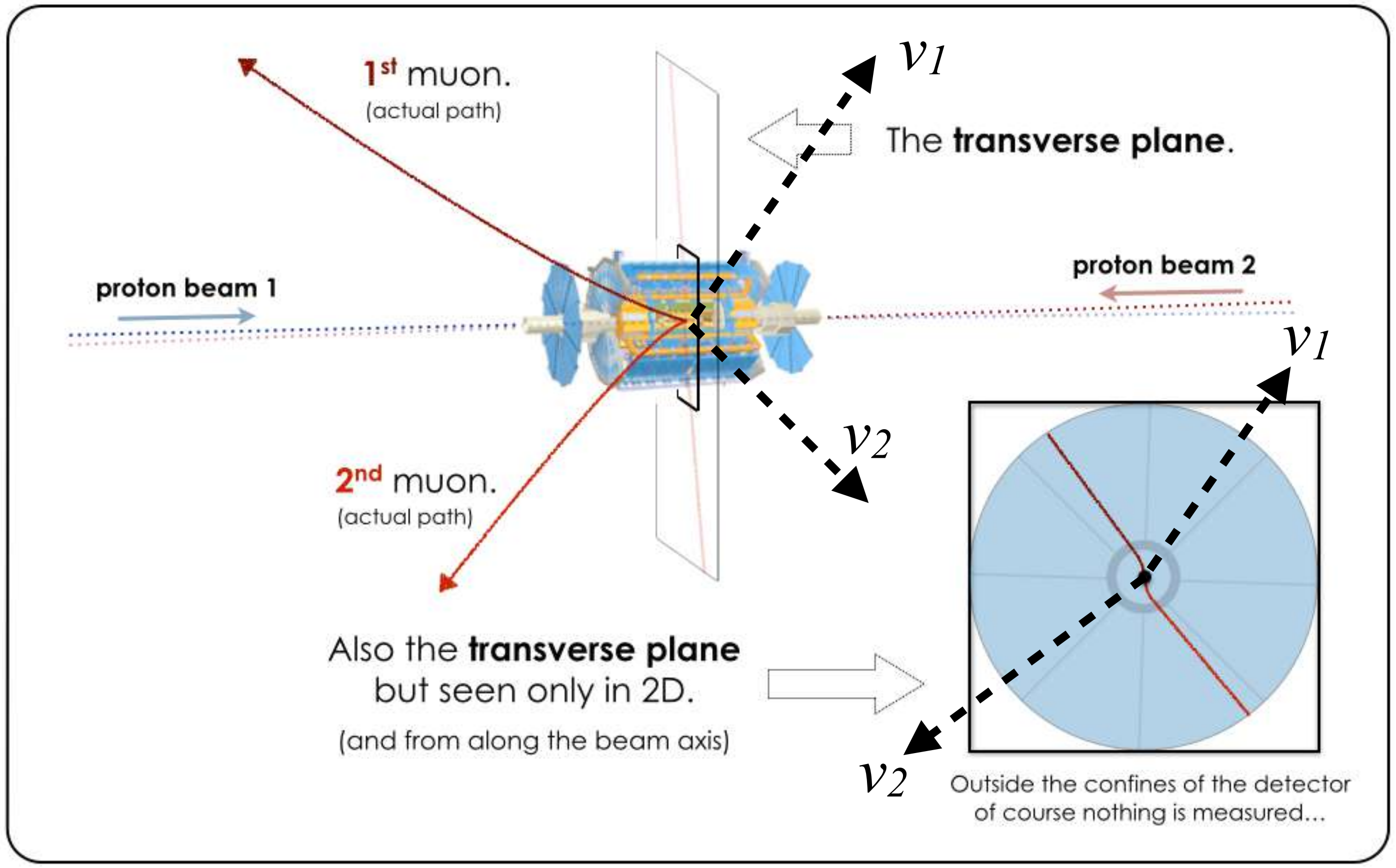



- $E_T^{initial} = E_T^{final}$ ⇔
- $0 = E_T^{final}$ ⇔
- $0 = E_T^{detectable} + E_T^{undetectable}$ ⇔
- $E_T^{undetectable} = - E_T^{detectable}$ ⇔
- $E_T^{miss} = - E_T^{detectable}$ ⇔

← *for this simplified example*

- $E_T^{miss} = - (E_T^{muon1} + E_T^{muon2})$

# (Transverse) missing energy

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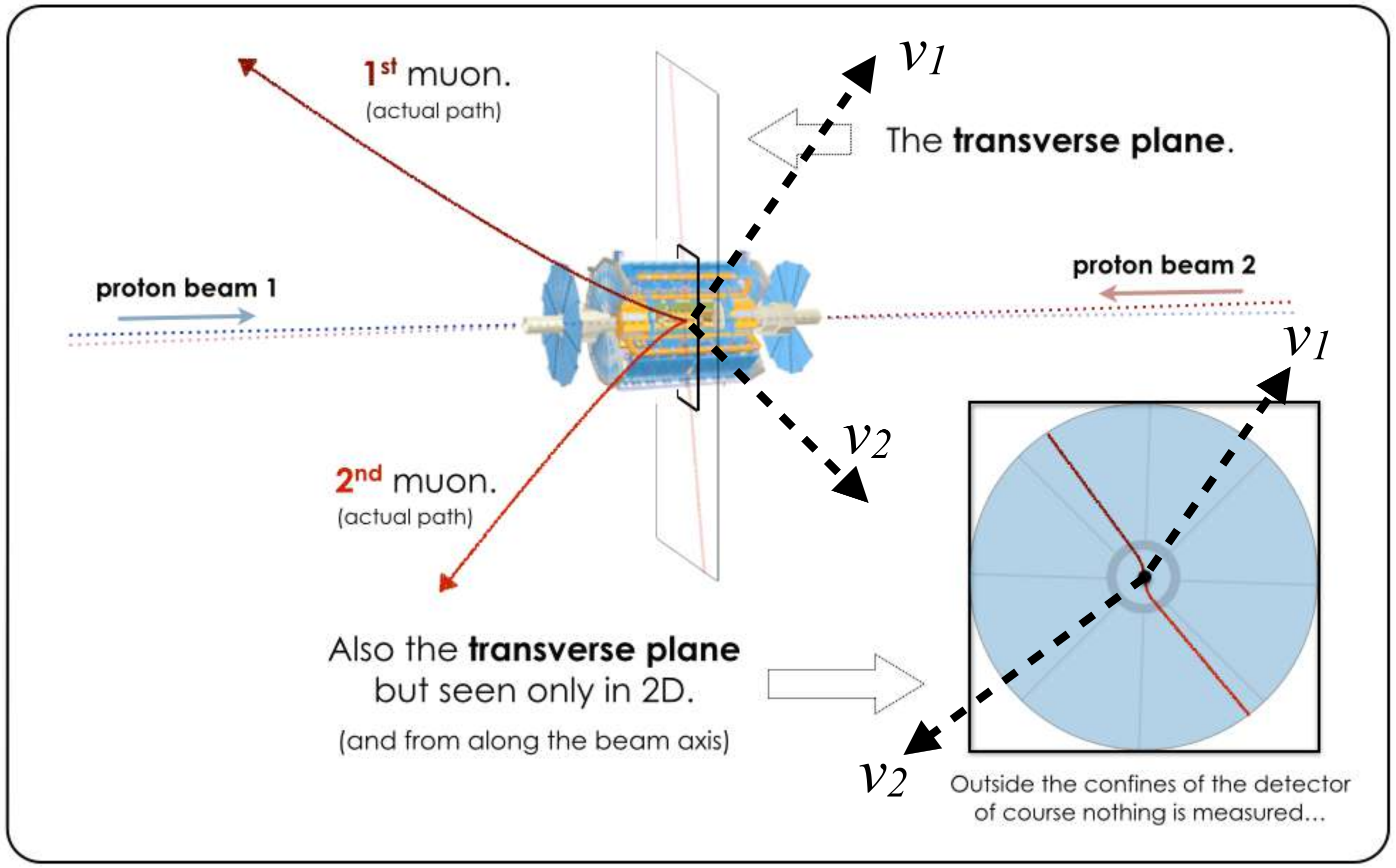
- $E_T^{miss} = - (E_T^{muon1} + E_T^{muon2})$

*In reality things are much more complicated, but in a simple manner, and for each event*

- $E_T^{miss} = - (E_T^{electrons} + E_T^{photons} + E_T^{muons} + E_T^{jets} + E_T^{soft\ energy\ not\ related\ to\ an\ object})$

# (Transverse) missing energy

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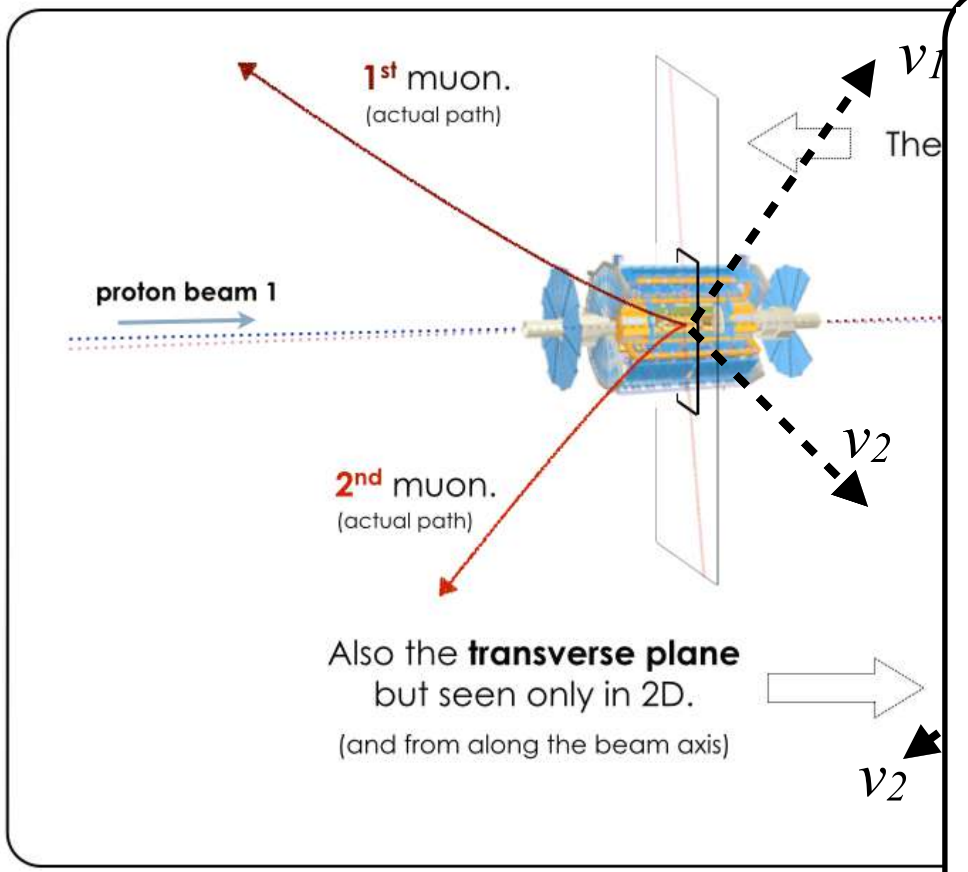
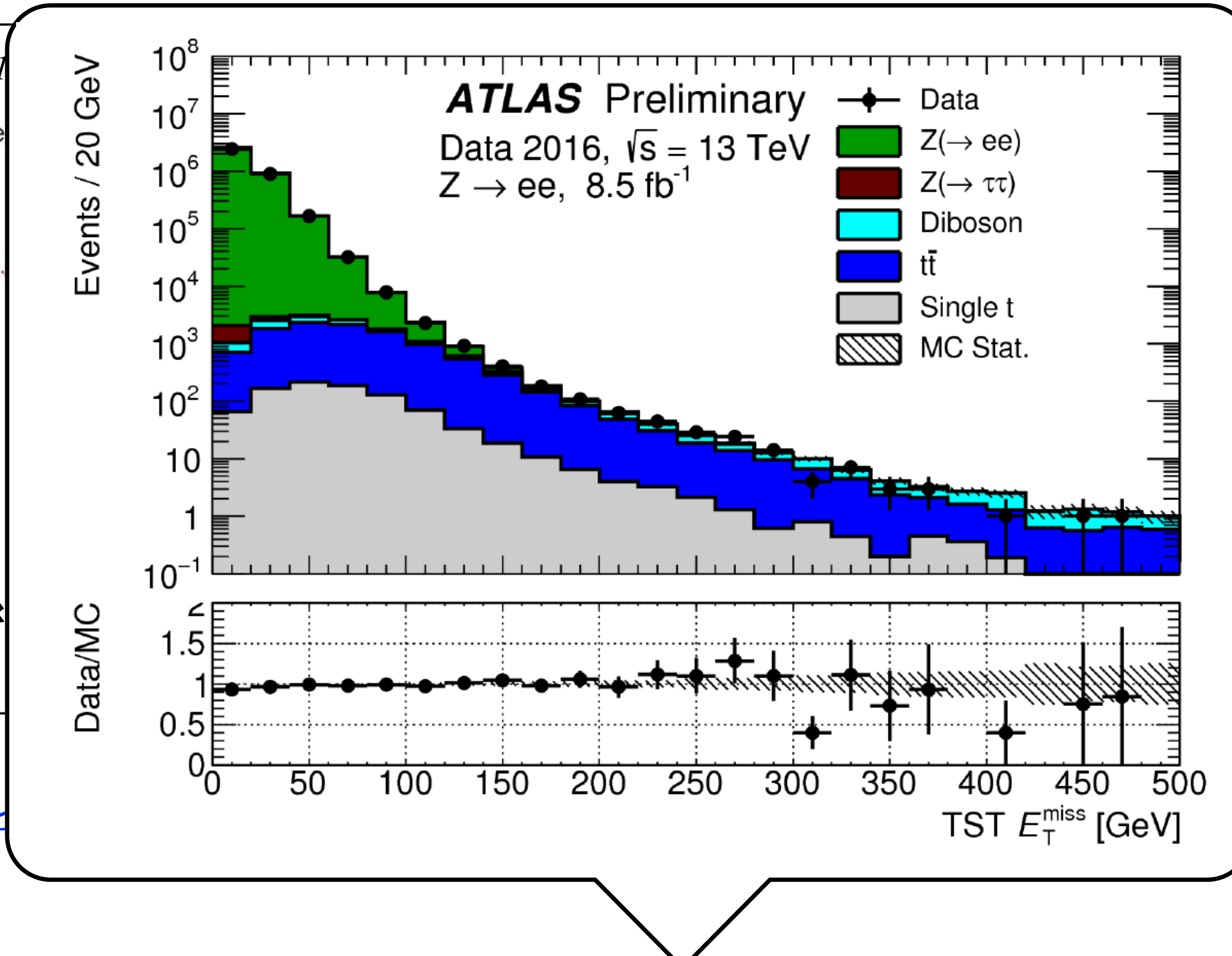
- *Don't get fooled next time you hear "missing energy". It is actually all the visible (non-missed) energy with a "-" sign in front..* 😀

# (Transverse) missing energy




ple

uon2)

*In reality things are much mo*

*and for each event*

- $E_T^{miss}$ = - ($E_T^{electrons}$ + $E_T^{photons}$ + $E_T^{muons}$ + $E_T^{jets}$ + $E_T^{\text{soft energy not related to an object}}$)

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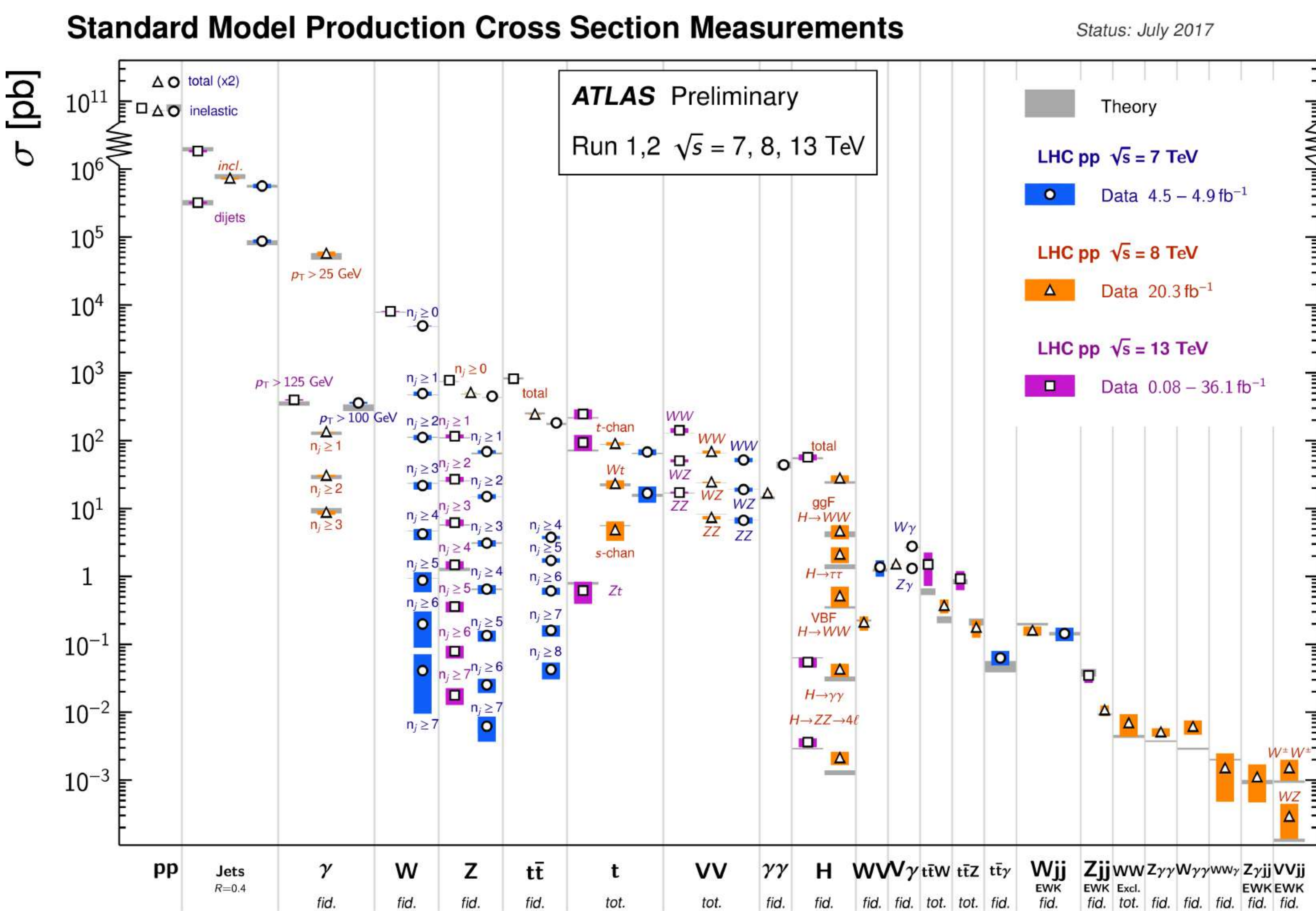
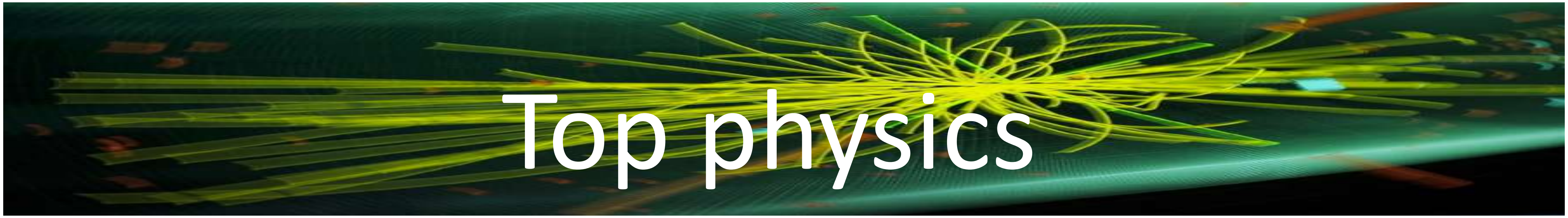
# SM, “jusqu’ici tout va bien”

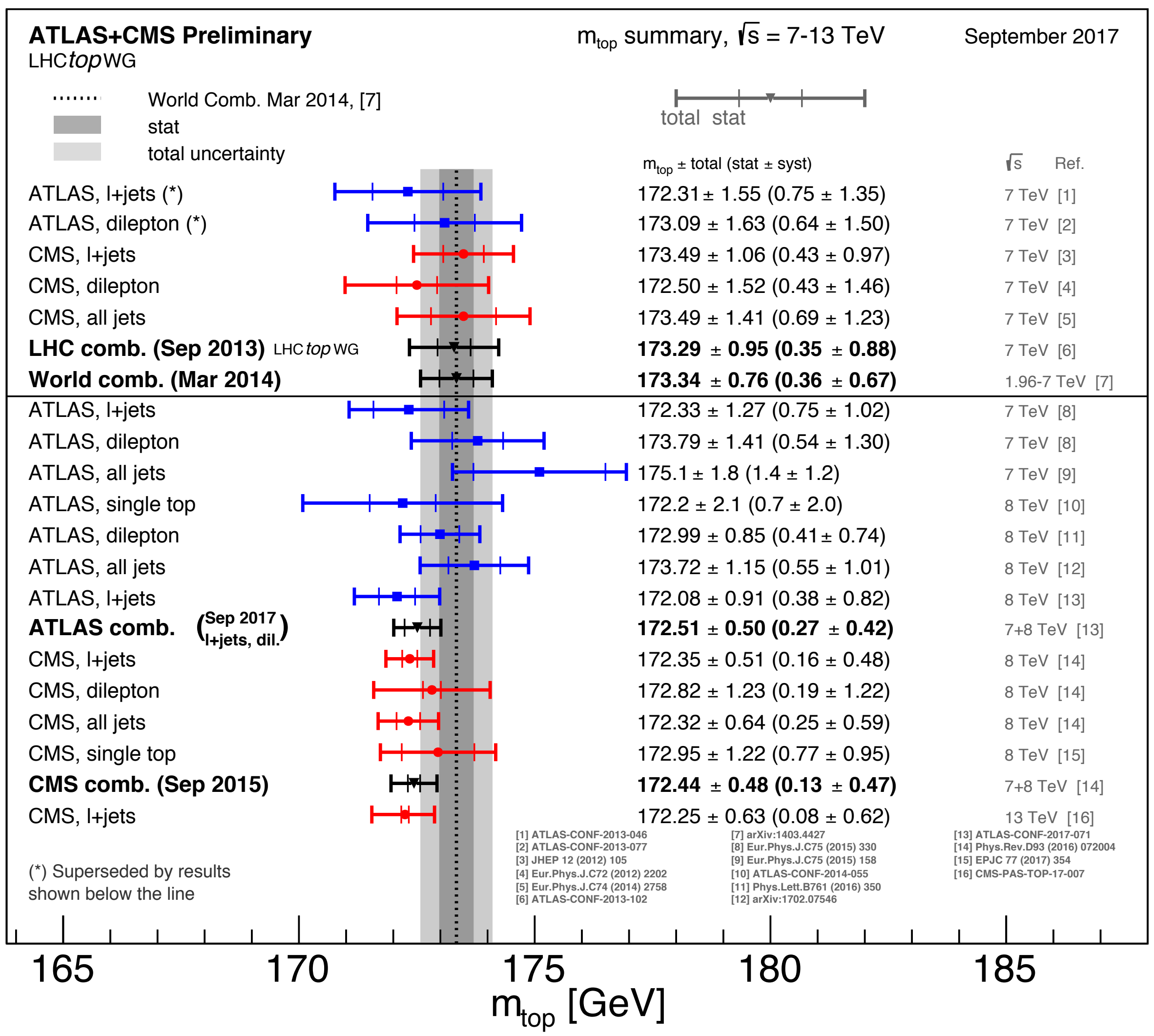


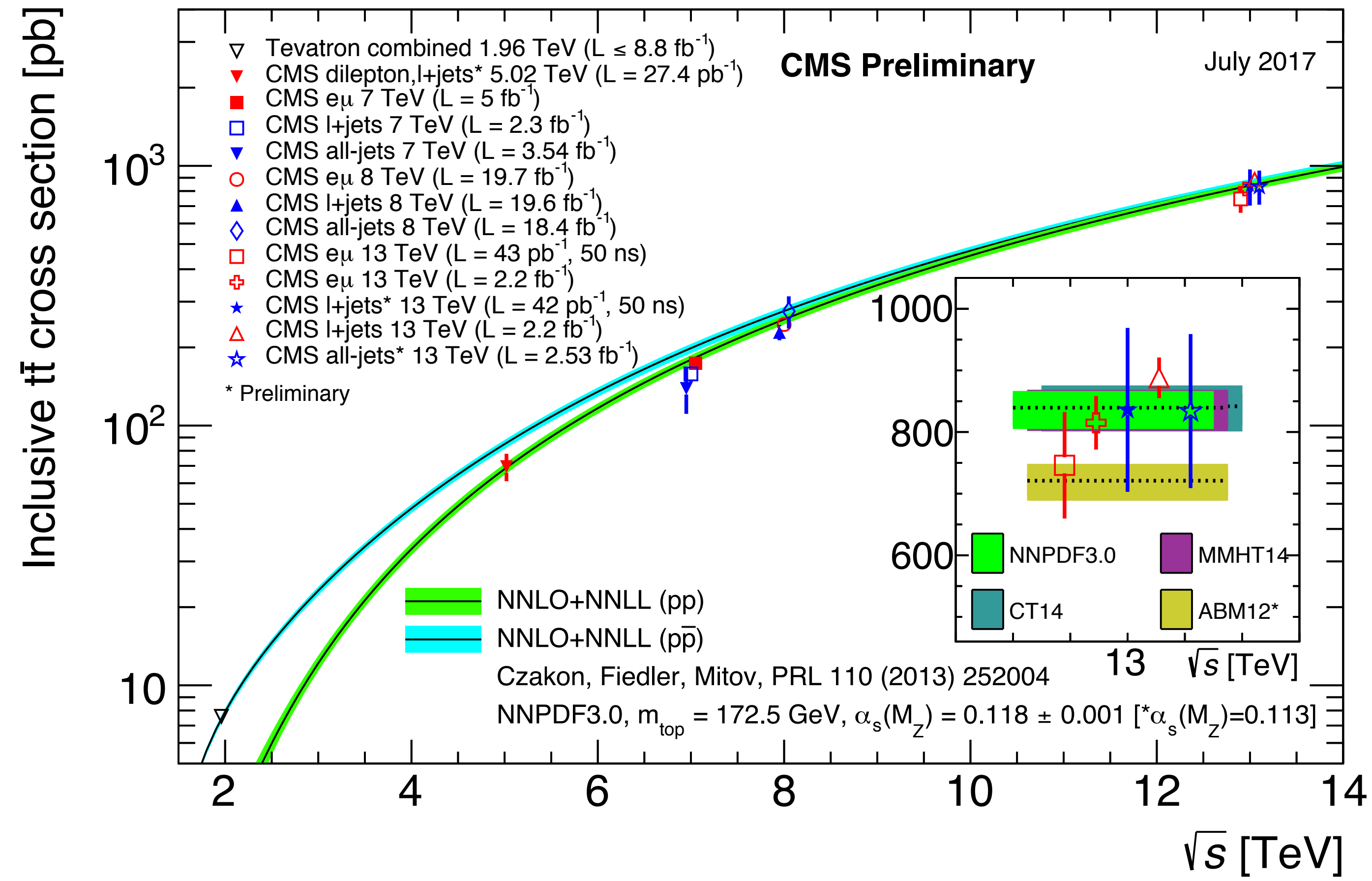

A plethora of SM measurements in ATLAS & CMS reveal a very good agreement with the SM predictions to our current knowledge



# Top physics

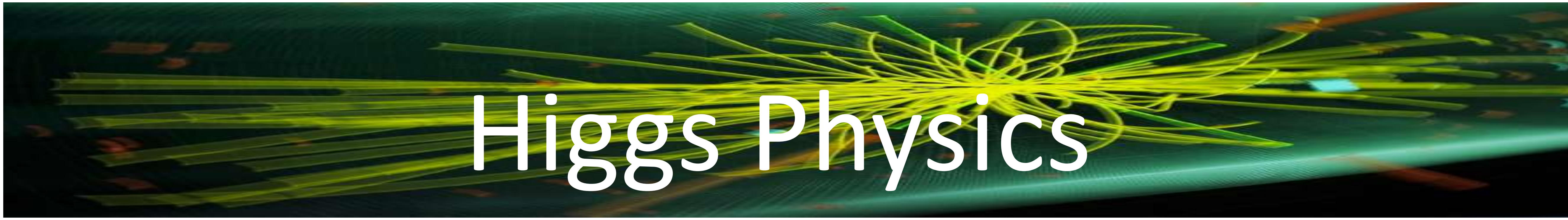
- LHC is a top factory, a lot of measurements of cross section and mass




- Top is the heaviest known particle. If new physics exists, it's expected to couple with the mass
- **Top sensitive to new physics**
- Top rare processes ttZ, ttbb, … are important background for various analyses (ttH)

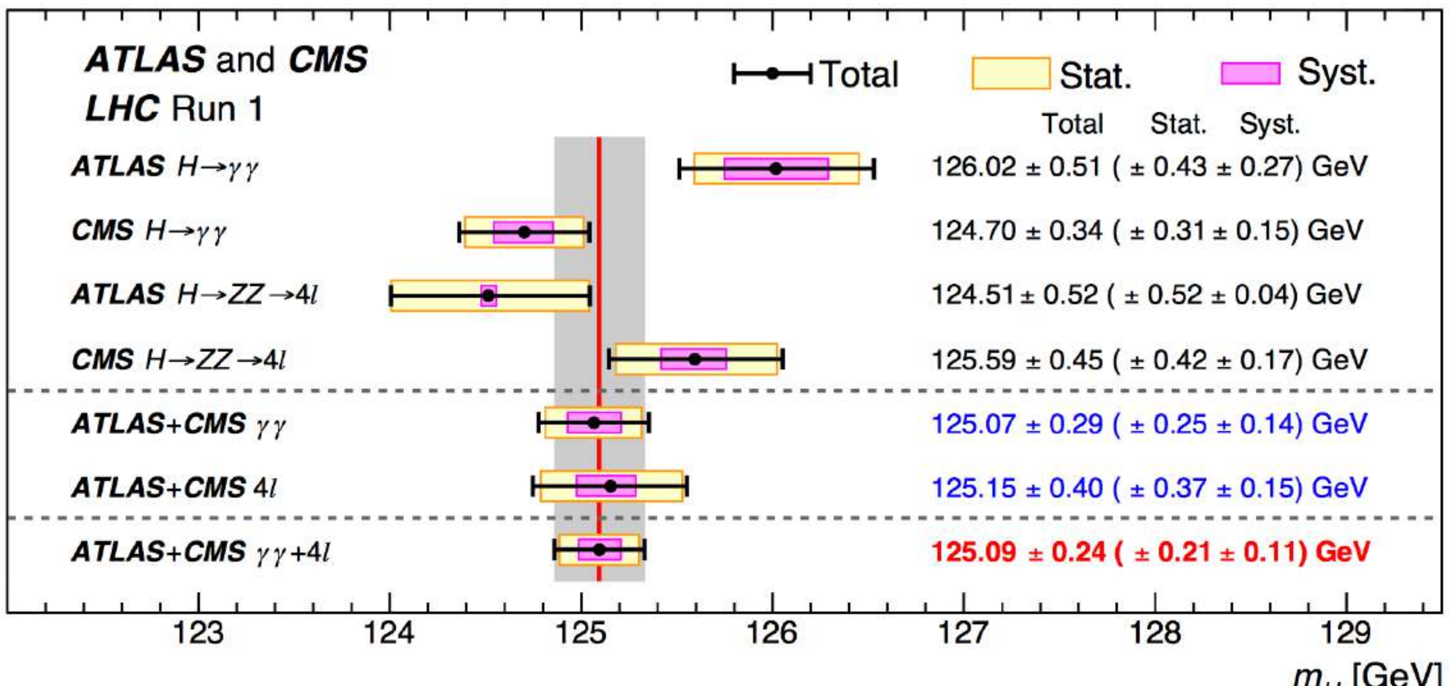
Nicolas Tonon



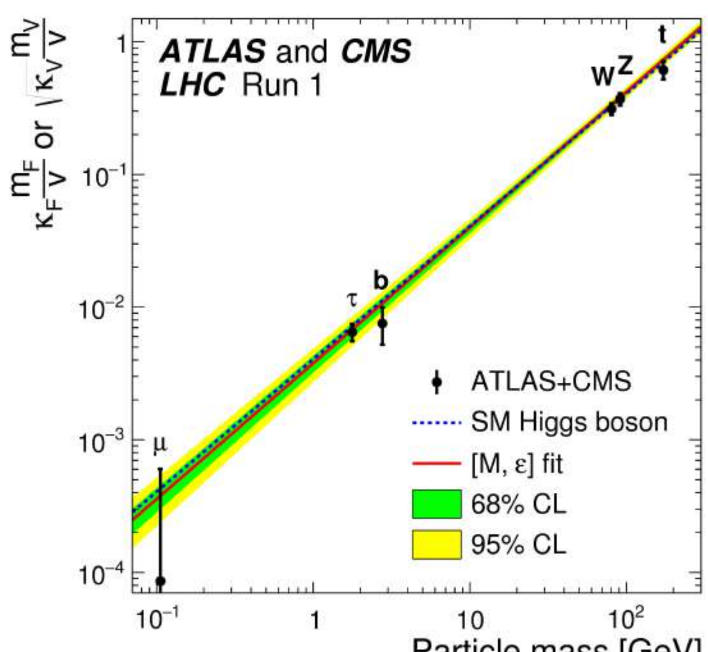
# Higgs Physics

- Higgs boson discovery announced in July 2012 by both ATLAS and CMS
- Most sensitive channels: H→γγ and H→ZZ*→4l

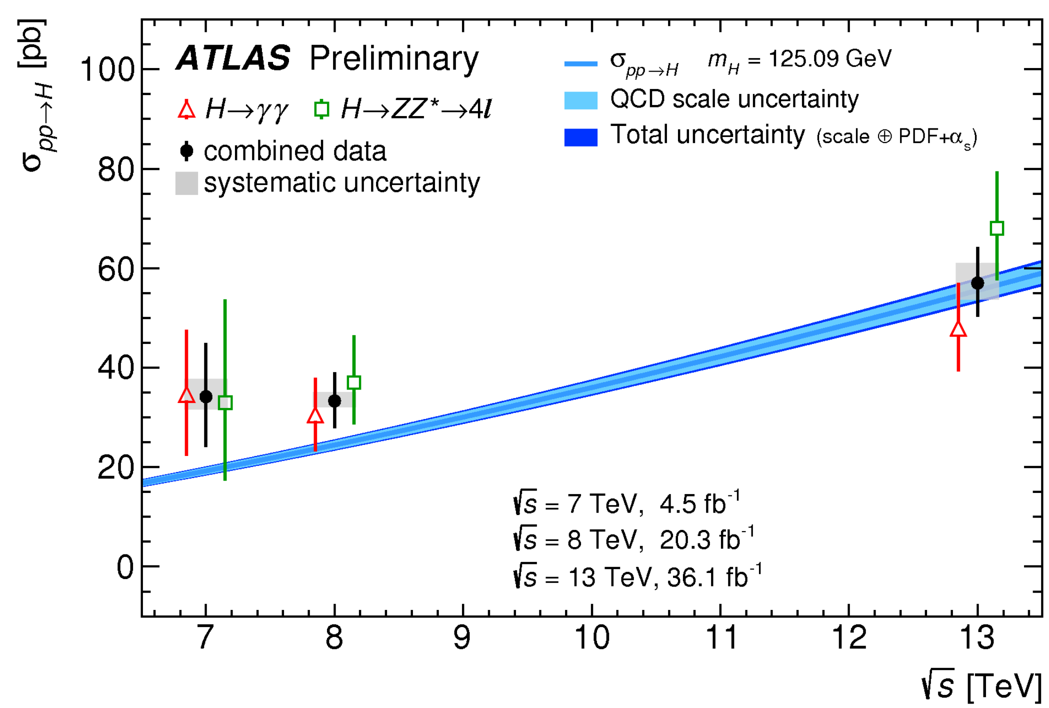
Saskia Falke



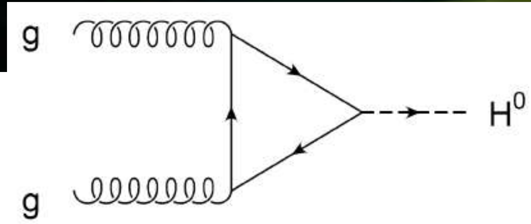

- ATLAS and CMS combined measurement of its mass gives a precessions of 2 per mile!
- Precision will be improved in Run 2



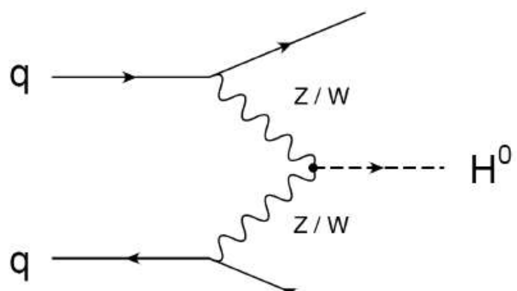

- Results consistent to SM predictions within uncertainties



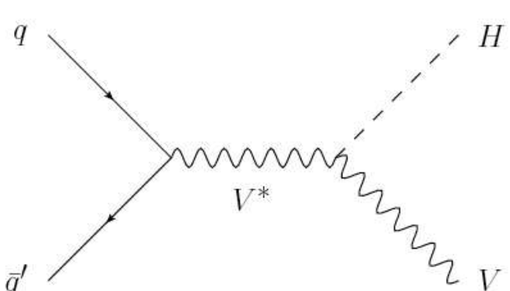
# Higgs Physics



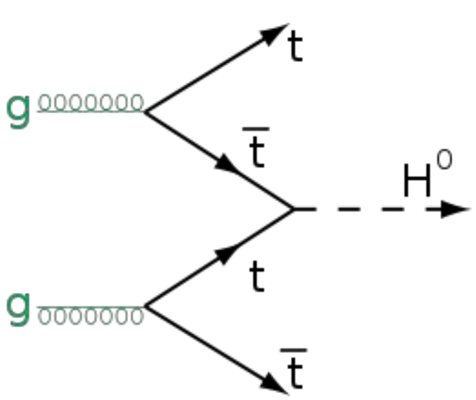

ggF: σ=19.2 pb



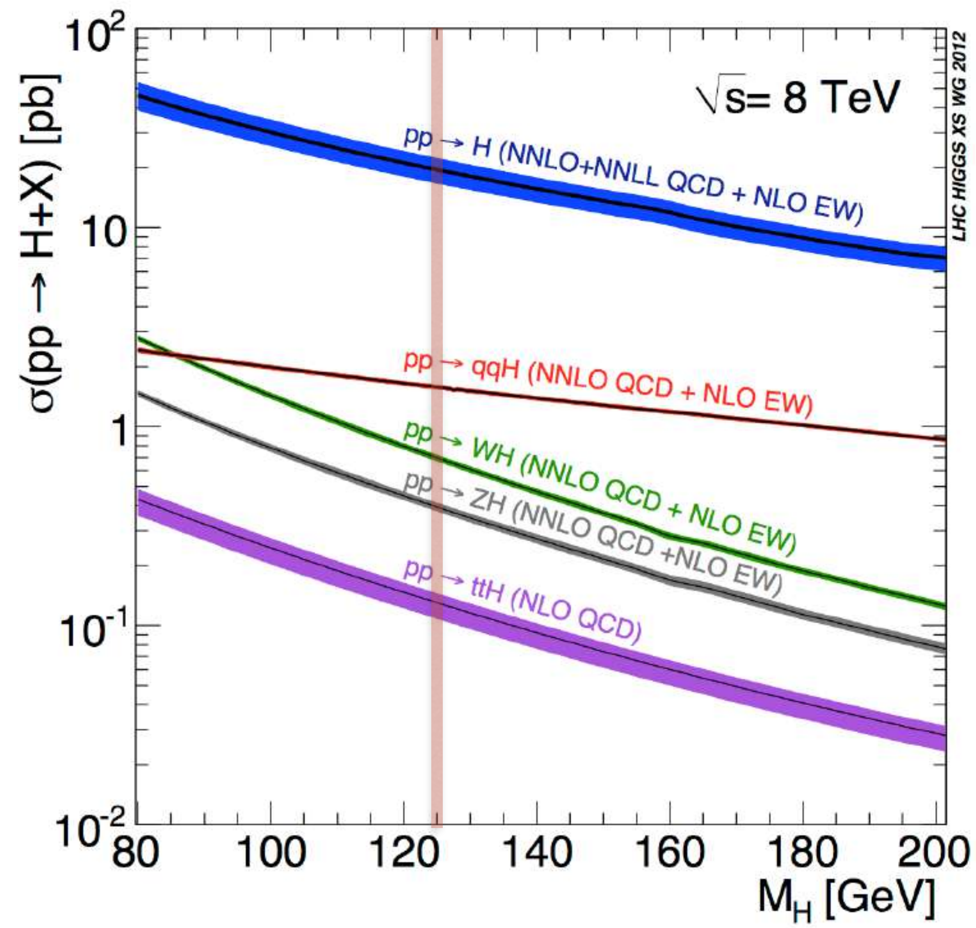

VBF: σ=1.6 pb

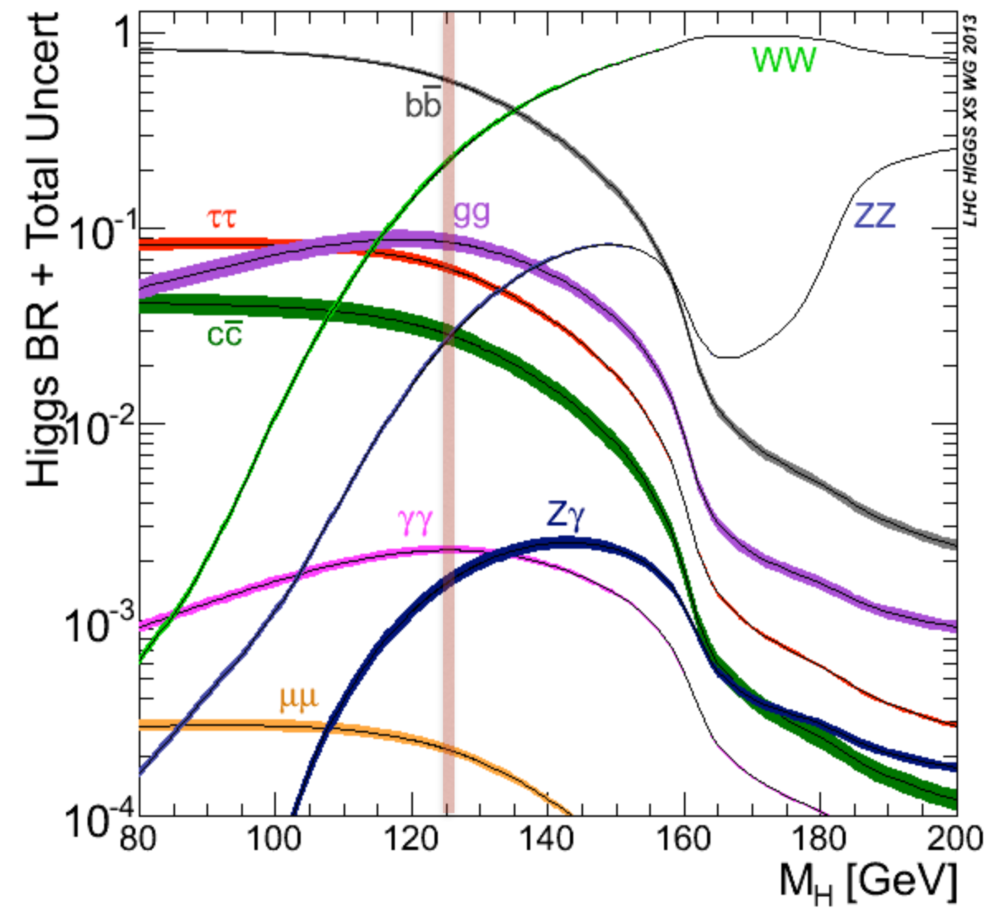



WH: σ=0.7 pb
ZH: σ=0.4 pb

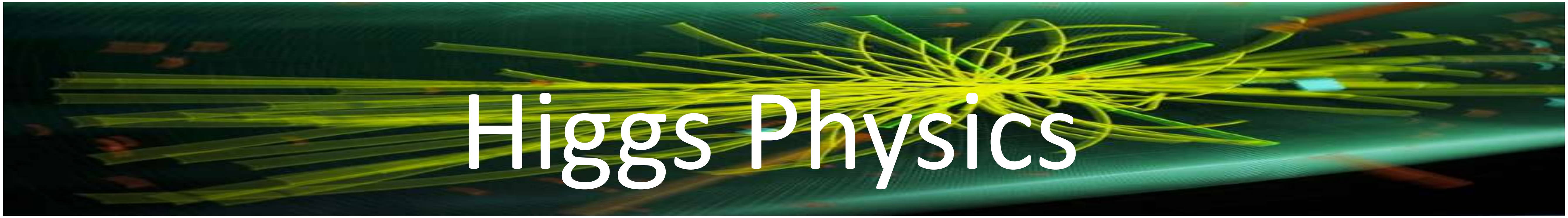



ttH: σ=0.13 pb




- Given a fixed $m_H$, all the couplings, production mode and decay rates can be calculated
- Gluon fusion being the main decay mode in LHC
- **H→bb** the highest branching ratio, accessible via VH production mode
- **ttH** the only way to mesure directly the Higgs boson coupling to the heaviest known elementary particle (top quark)




JRJC 2016... (pardon my french :) )

## 125 GeV: une masse "magique"

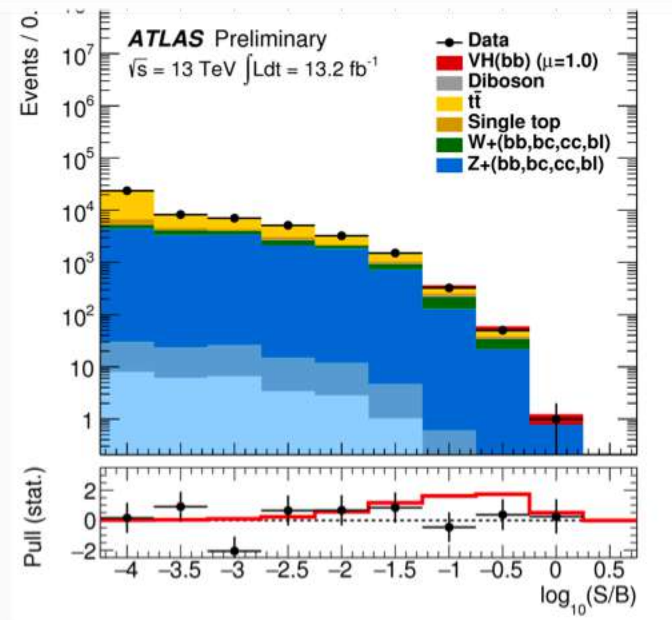
- Beaucoup de canaux ouverts !
- Mais certains plus durs que d'autres...

## Défis pour surpasser le Run 1

- $\tau\tau$, $WW$ étaient limités par les systématiques au Run 1
- Beaucoup de travail pour améliorer la précision
- Pas encore d'analyse 13 TeV publiques !

## La hype du Run II

- Mises en évidence attendues dans l'année (?)
- Couplage au $b$: $VH(bb)$, $ttH(bb)$
- Présentation de Charles
- Couplage au top (mesure directe): $ttH$, avec $H \to bb$, $H \to$multi-leptons, $H \to \gamma\gamma$
- Présentations de Kevin, Ana Elena, Robert
- Tous des canaux très difficiles ! Estimation des fonds et contrôle des systématiques cruciaux !




| Uncertainty Source | $\Delta\mu$ | |
|---|---|---|
| $t\bar{t}+\geq 1b$ modelling | +0.34 | −0.33 |
| Jet flavour tagging | +0.19 | −0.19 |
| Background model statistics | +0.18 | −0.18 |
| $t\bar{t}+\geq 1c$ modelling | +0.17 | −0.17 |
| Jet energy scale and resolution | +0.18 | −0.18 |
| $t\bar{t}H$ modelling | +0.20 | −0.13 |
| $t\bar{t}$+light modelling | +0.14 | −0.14 |
| Other background modelling | +0.16 | −0.15 |
| Fake lepton uncertainties | +0.11 | −0.12 |
| Jet-vertex association, pileup modelling | +0.09 | −0.09 |
| Luminosity | +0.09 | −0.09 |
| $t\bar{t}Z$ modelling | +0.08 | −0.07 |
| Light lepton $(e,\mu)$, photon, and $\tau$ ID, isolation, trigger | +0.04 | −0.04 |
| Total systematic uncertainty | +0.57 | −0.54 |
| $t\bar{t}+\geq 1b$ normalisation | +0.24 | −0.24 |
| $t\bar{t}+\geq 1c$ normalisation | +0.11 | −0.11 |
| Statistical uncertainty | +0.38 | −0.38 |
| Total uncertainty | +0.69 | −0.66 |

N. Morange (LAL Orsay) 2

# Higgs Physics

JRJC 2016... (pardon my french :) )

### 125 GeV: une masse "magique"

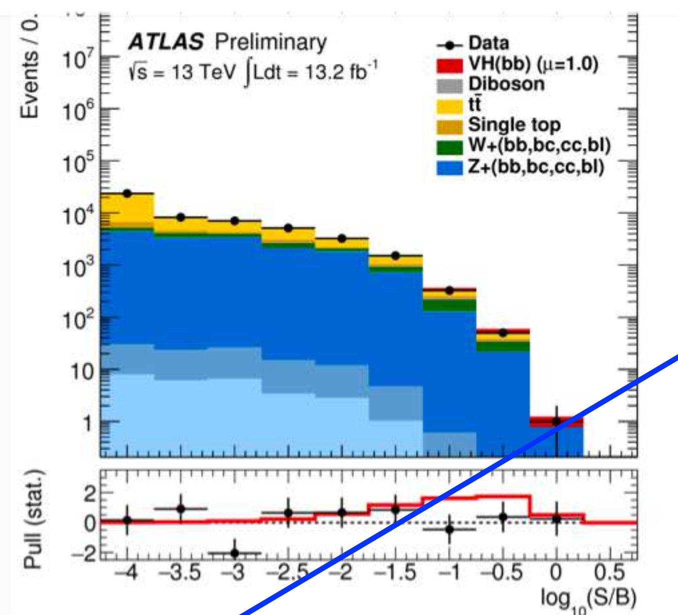
- Beaucoup de canaux ouverts !
- Mais certains plus durs que d'autres...

### Défis pour surpasser le Run 1

- $\tau\tau$, *WW* étaient limités par les systématiques au Run 1
- Beaucoup de travail pour améliorer la précision
- Pas encore d'analyse 13 TeV publiques !

### La hype du Run II

- Mises en évidence attendues dans l'année (?)
- Couplage au *b*: *VH*(*bb*), *ttH*(*bb*)
- Présentation de Charles
- Couplage au top (mesure directe): *ttH*, avec $H \rightarrow bb$, $H \rightarrow$ multi-leptons, $H \rightarrow \gamma\gamma$
- Présentations de Kevin, Ana Elena, Robert
- Tous des canaux très difficiles ! Estimation des fonds et contrôle des systématiques cruciaux !




| Uncertainty Source | $\Delta\mu$ | |
|---|---|---|
| $t\bar{t}+\geq 1b$ modelling | +0.34 | −0.33 |
| Jet flavour tagging | +0.19 | −0.19 |
| Background-model statistics | +0.18 | −0.18 |
| $t\bar{t}+\geq 1c$ modelling | +0.17 | −0.17 |
| Jet energy scale and resolution | +0.18 | −0.18 |
| $t\bar{t}H$ modelling | +0.20 | −0.13 |
| $t\bar{t}$+light modelling | +0.14 | −0.14 |
| Other background modelling | +0.16 | −0.15 |
| Fake lepton uncertainties | +0.11 | −0.12 |
| Jet-vertex association, pileup modelling | +0.09 | −0.09 |
| Luminosity | +0.09 | −0.09 |
| $t\bar{t}Z$ modelling | +0.08 | −0.07 |
| Light lepton $(e,\mu)$, photon, and $\tau$ ID, isolation, trigger | +0.04 | −0.04 |
| Total systematic uncertainty | +0.57 | −0.54 |
| $t\bar{t}+\geq 1b$ normalisation | +0.24 | −0.24 |
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| Statistical uncertainty | +0.38 | −0.38 |
| Total uncertainty | +0.69 | −0.66 |

N. Morange (LAL Orsay) 2

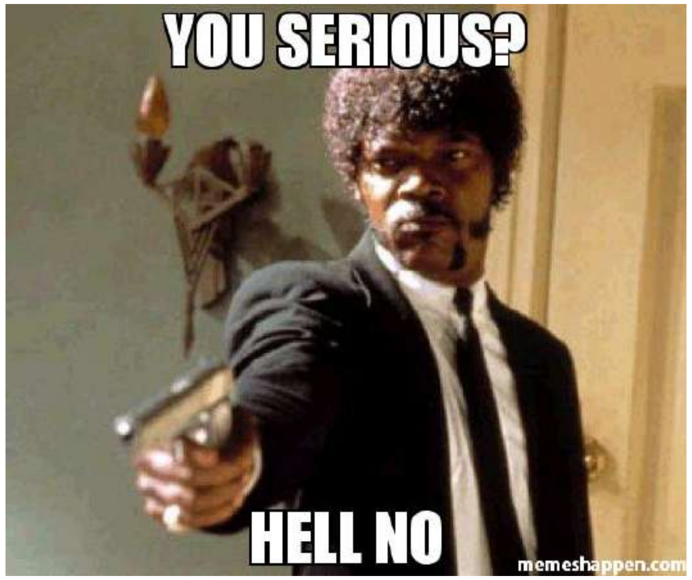
JRJC 2017

VH(bb)
I. Luise

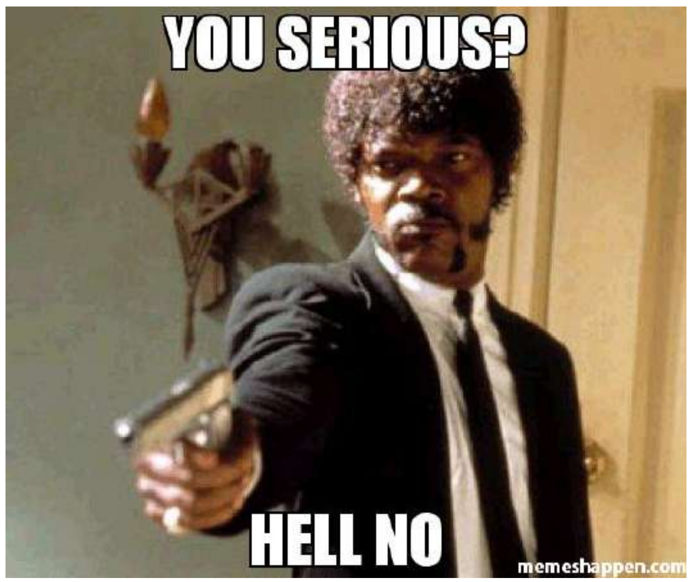
ttH saga
- N. Brahimi
- H. Nguyen
- Z. Guo

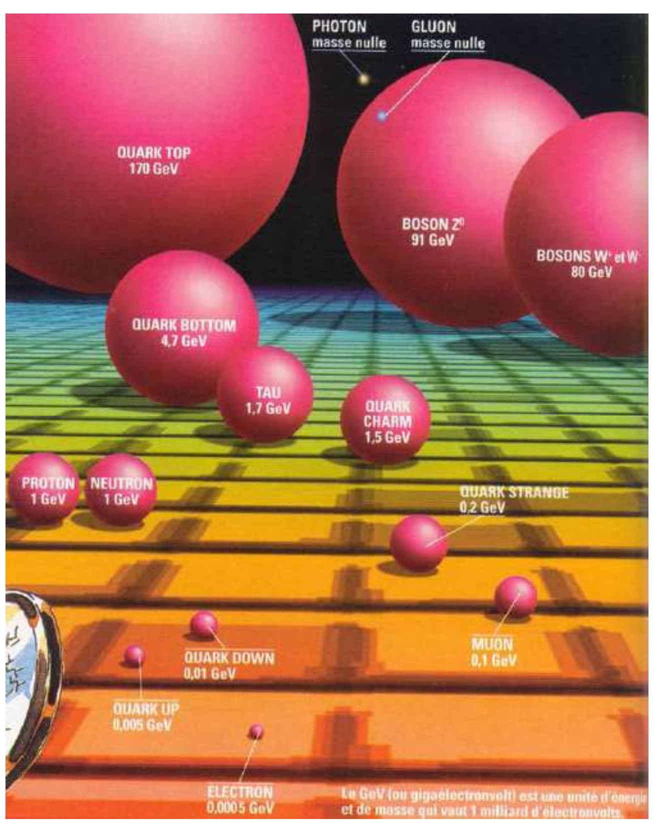
# Is SM enough?

# Is SM enough?



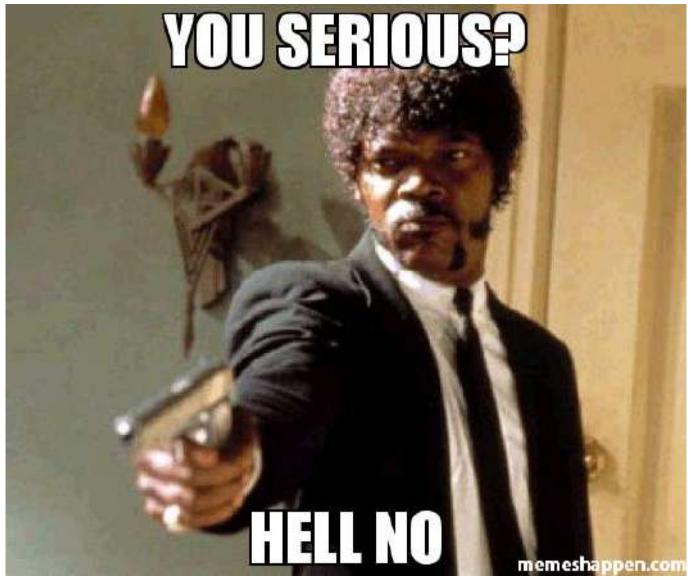
# Is SM enough?

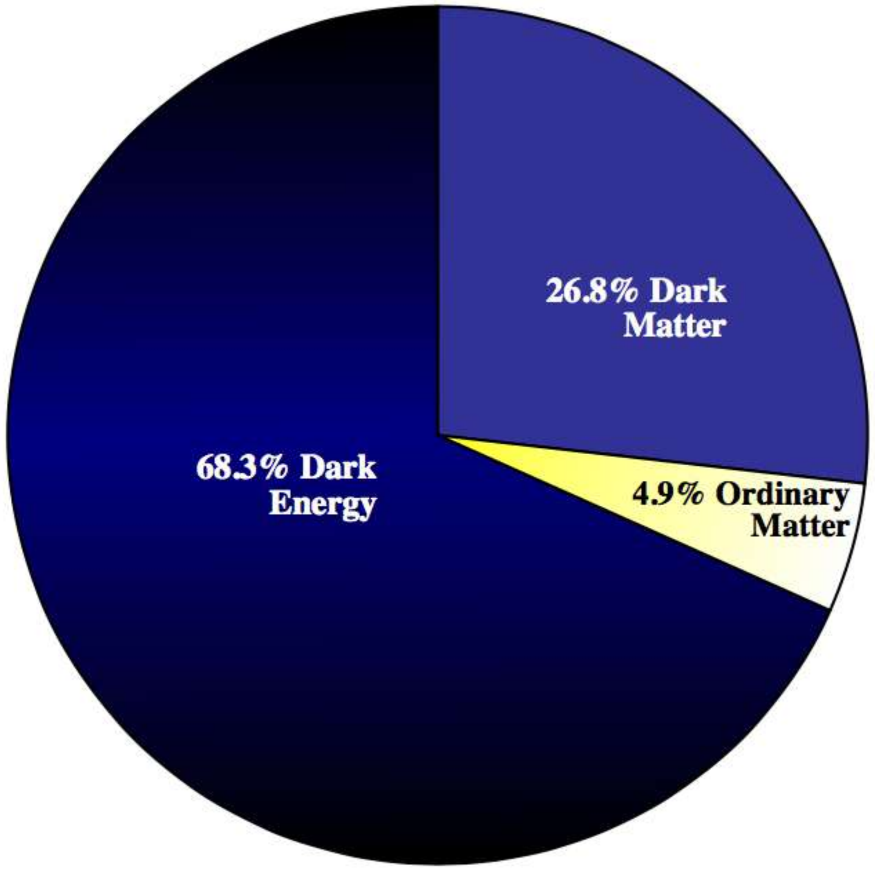


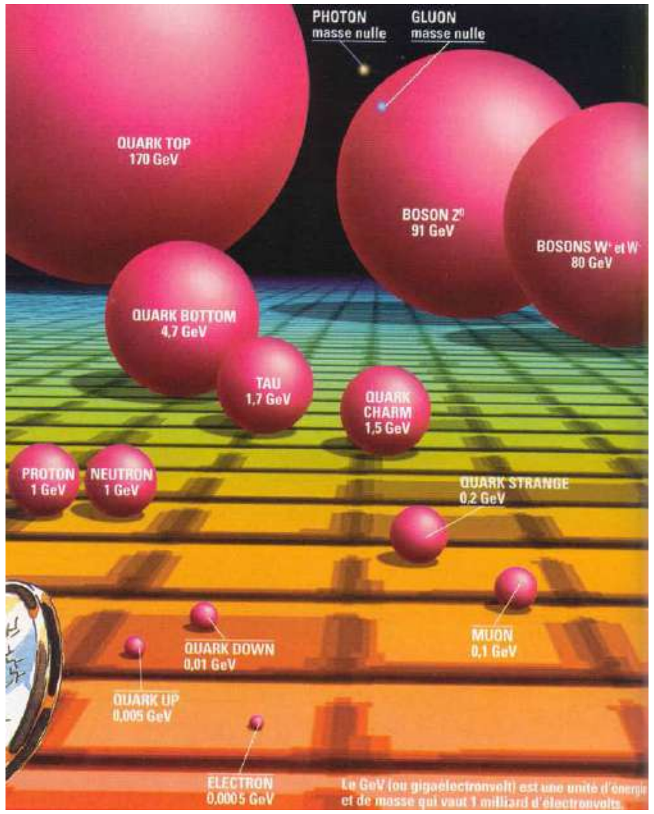




Why particle masses are so different?

# Is SM enough?




Why particle masses are so different?

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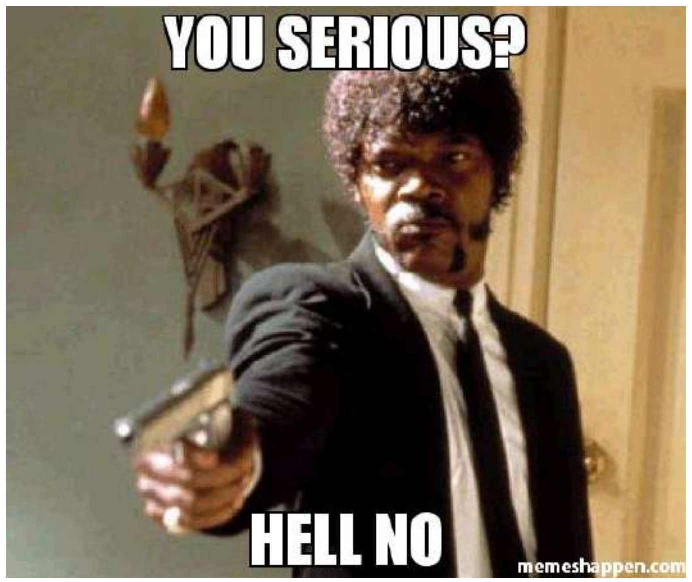
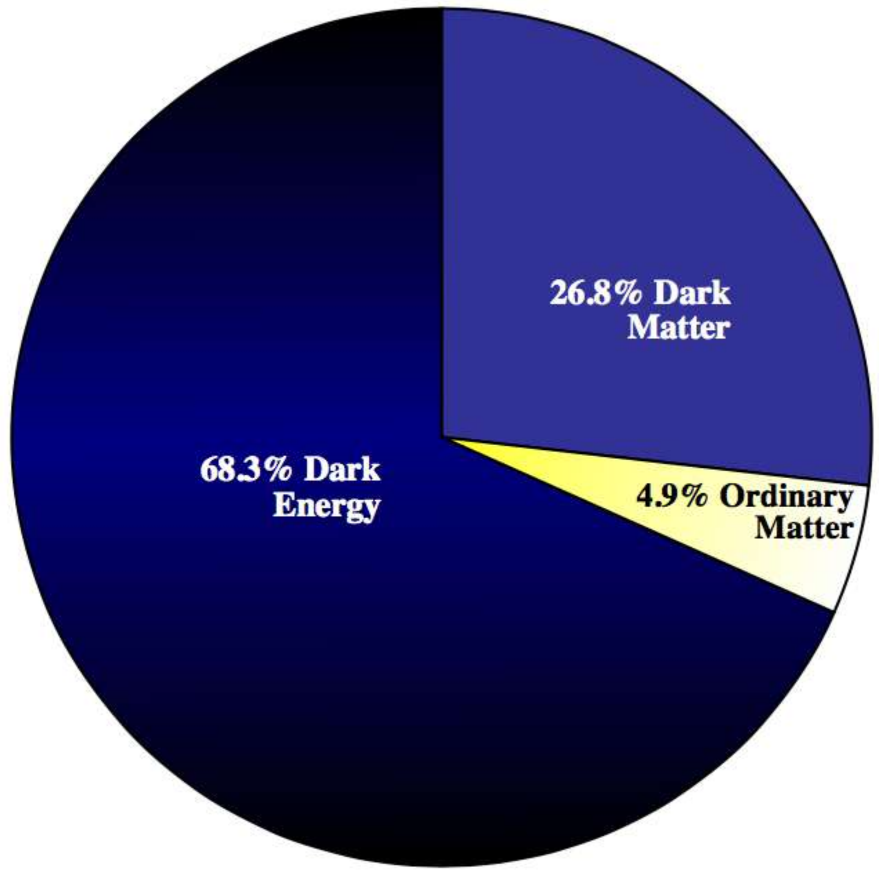
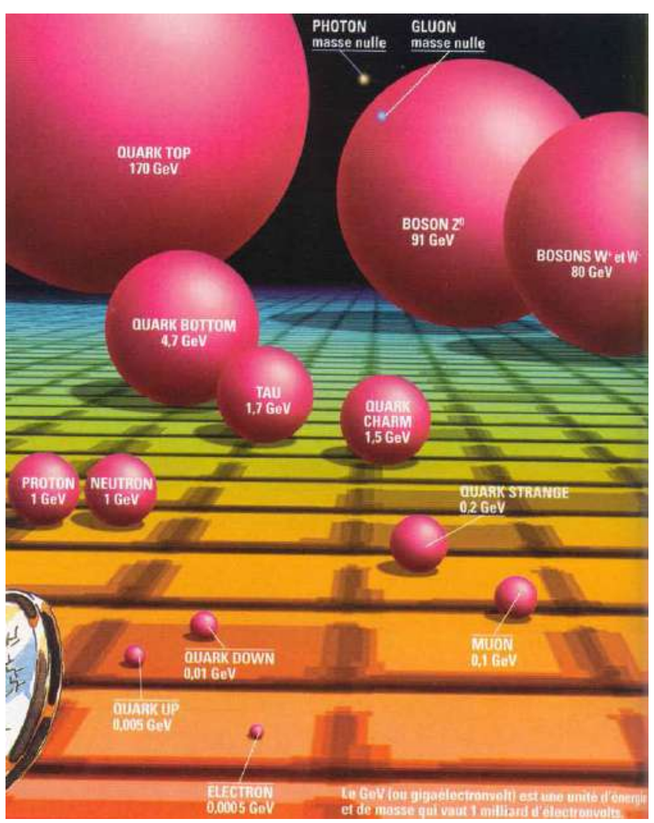



neutrinos have mass, yo dumb SM!




Why particle masses are so different?

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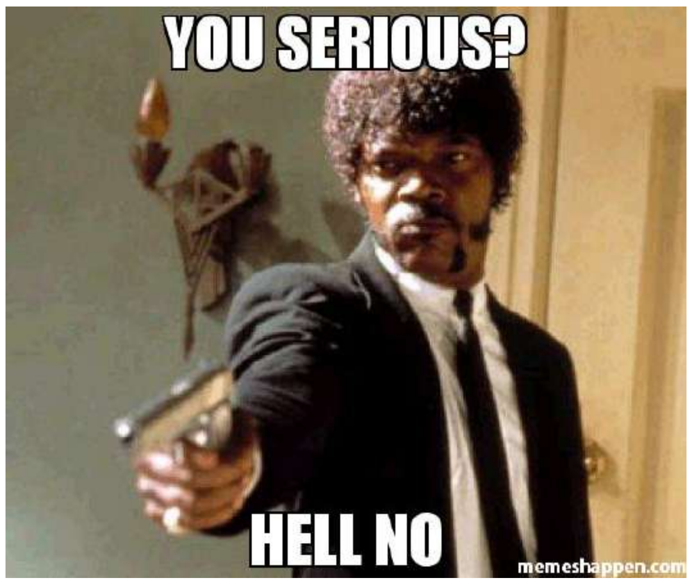


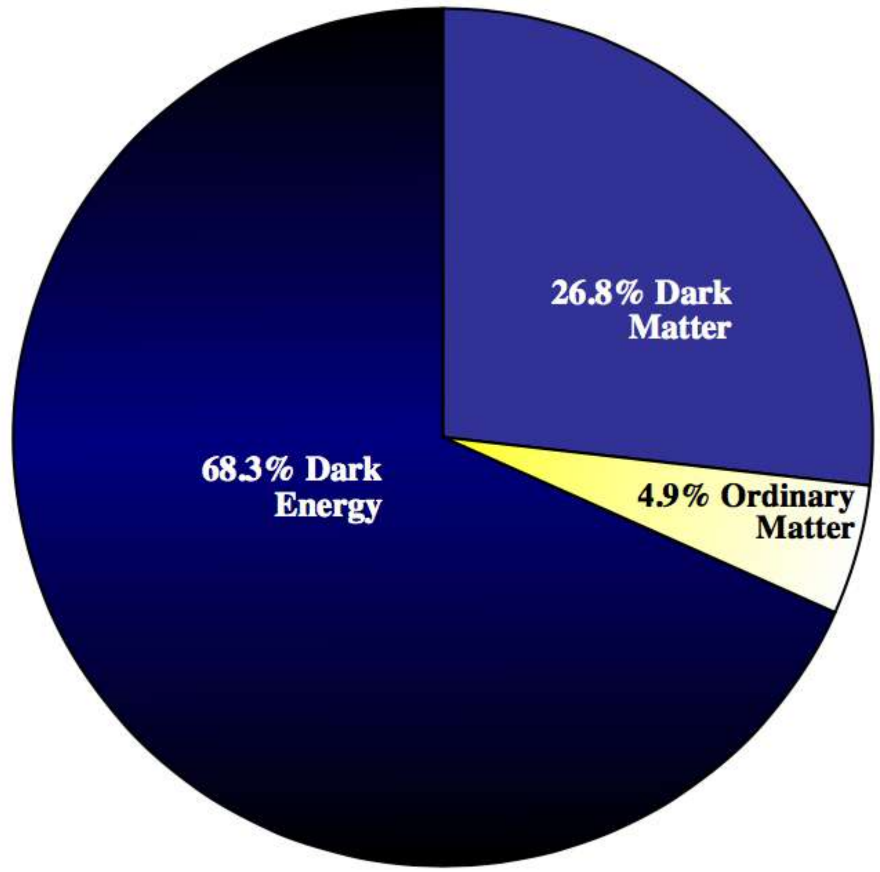


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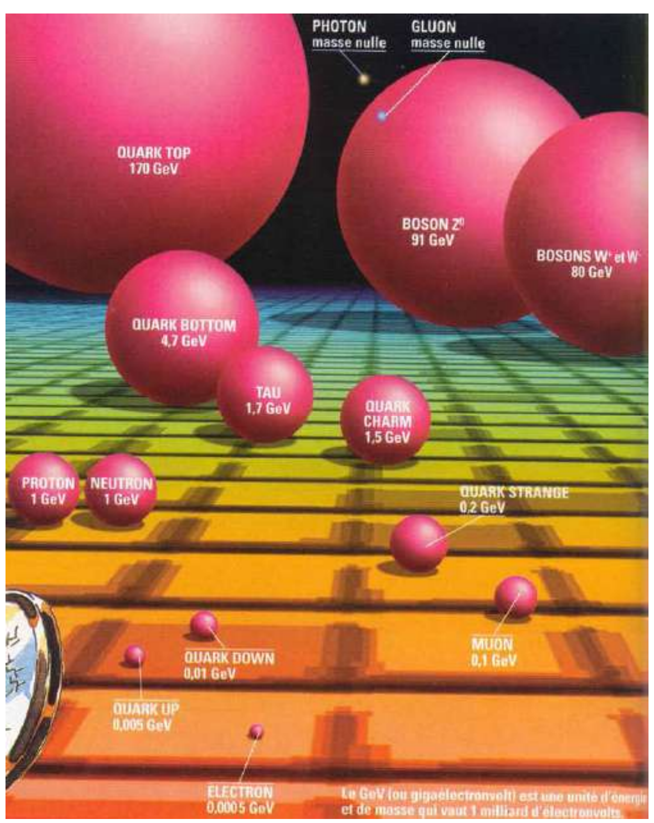
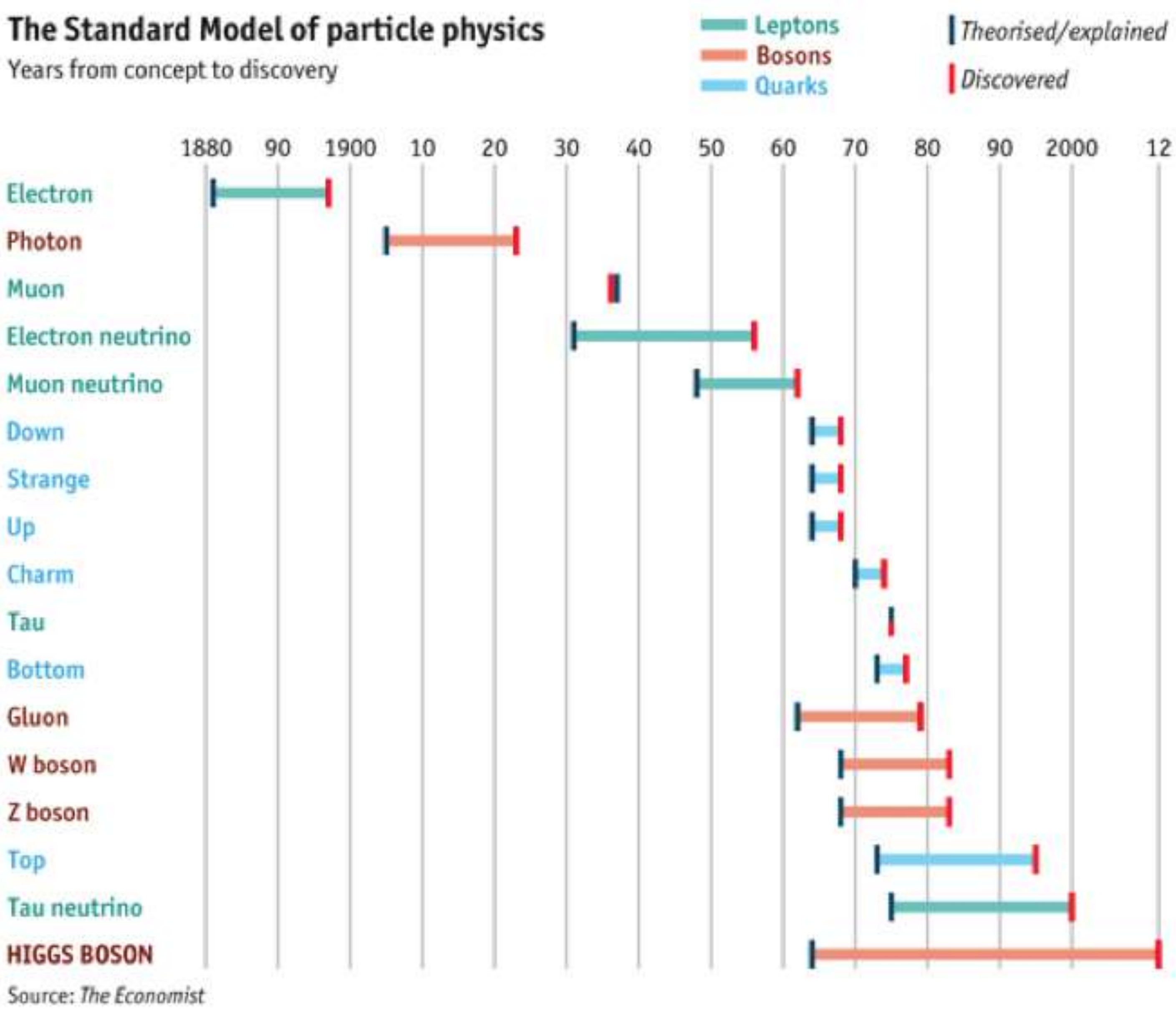


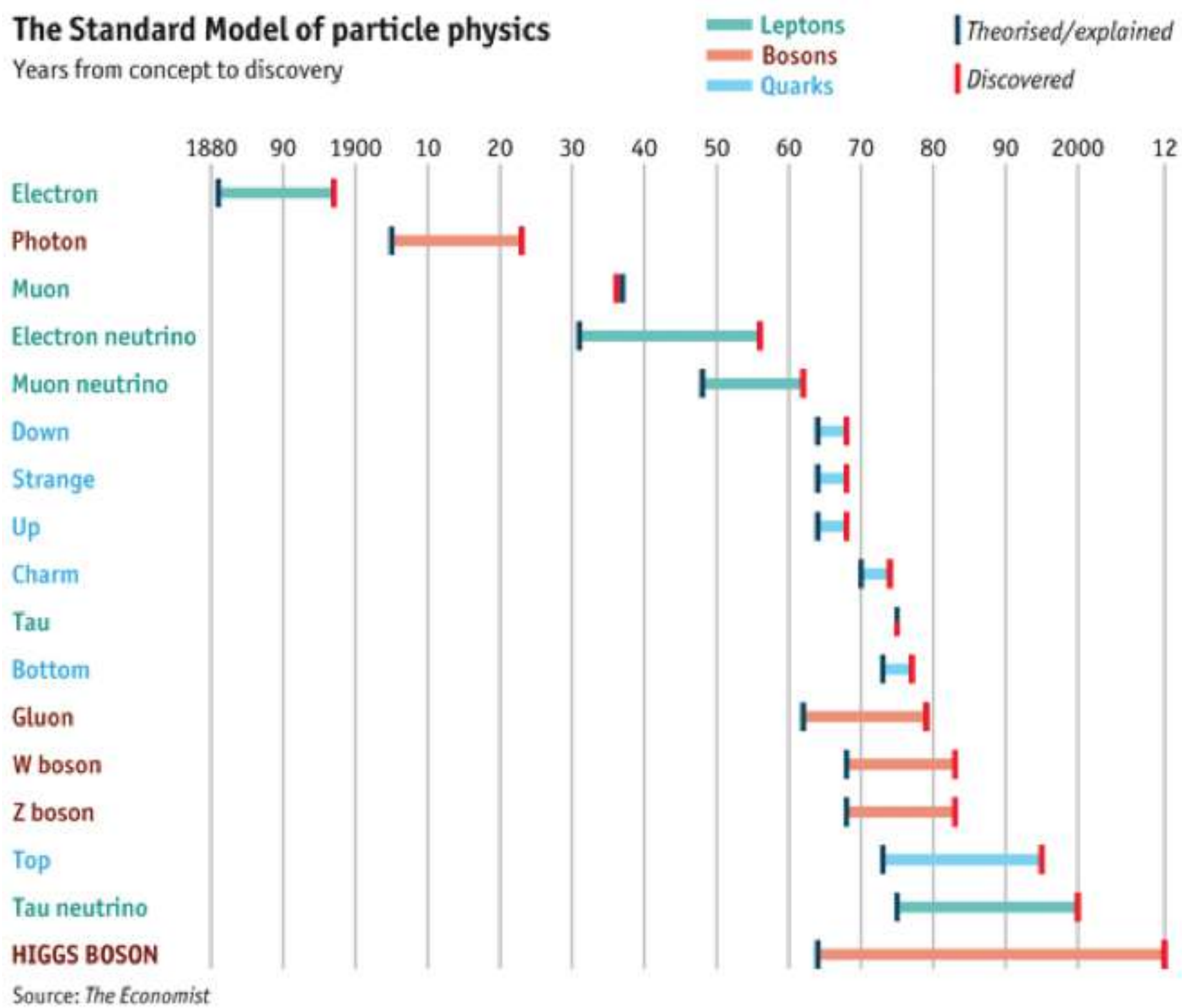

Why particle masses are so different?

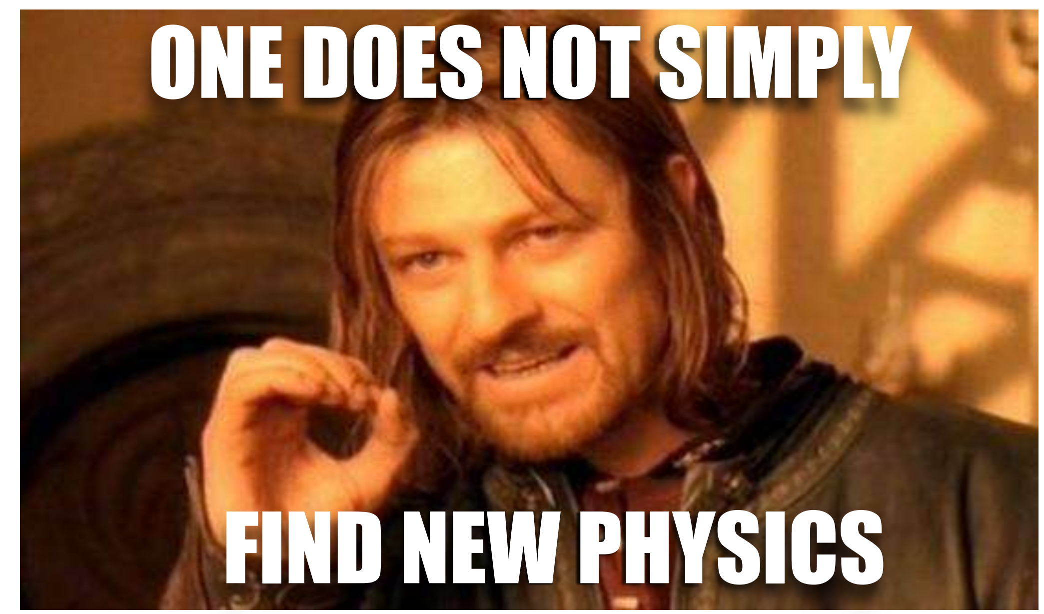
Find New Physics particles!!!

# OK, let's find some new particles…



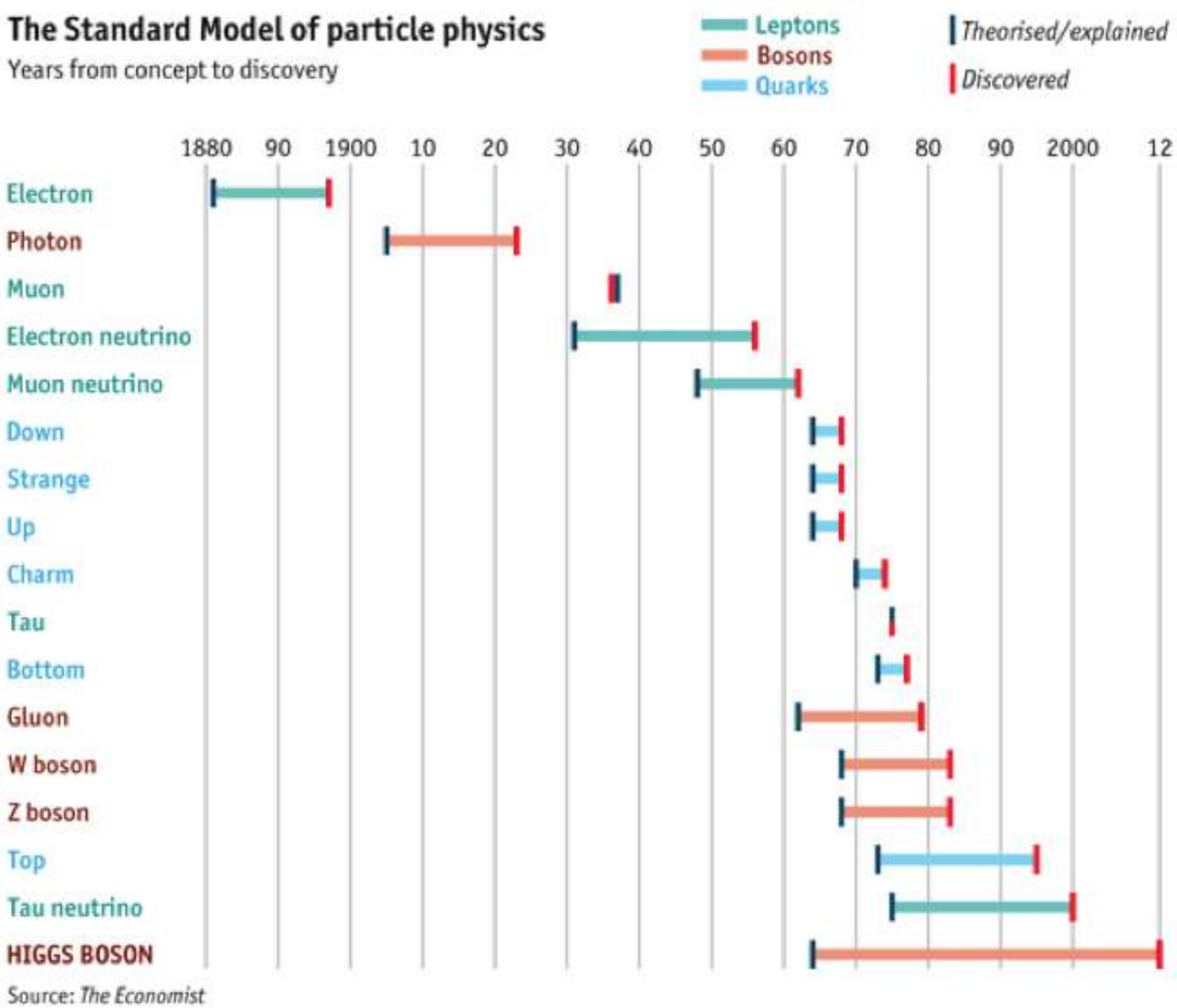
# OK, let's find some new particles…

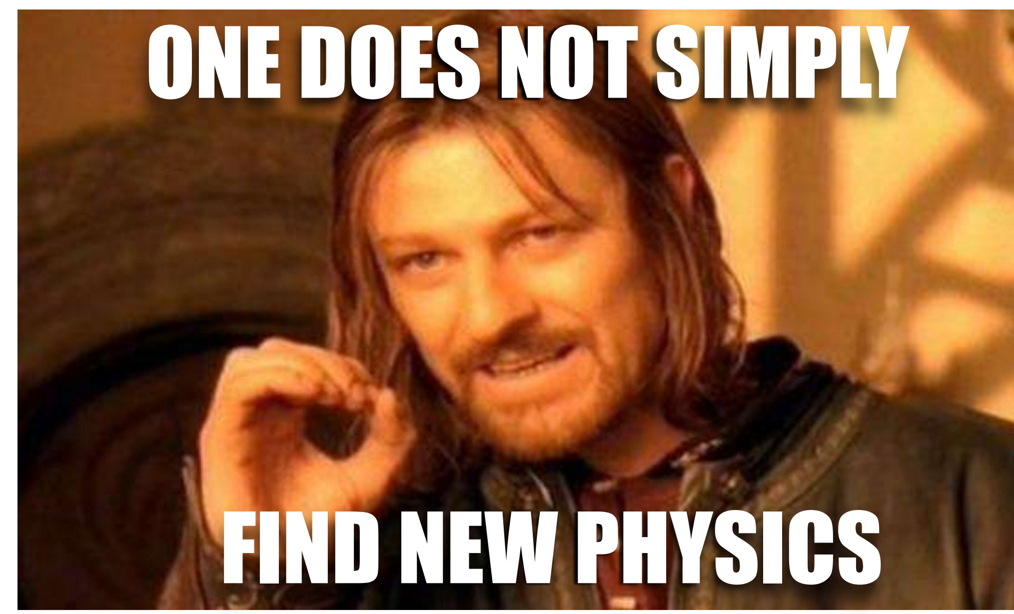



Particle x ?

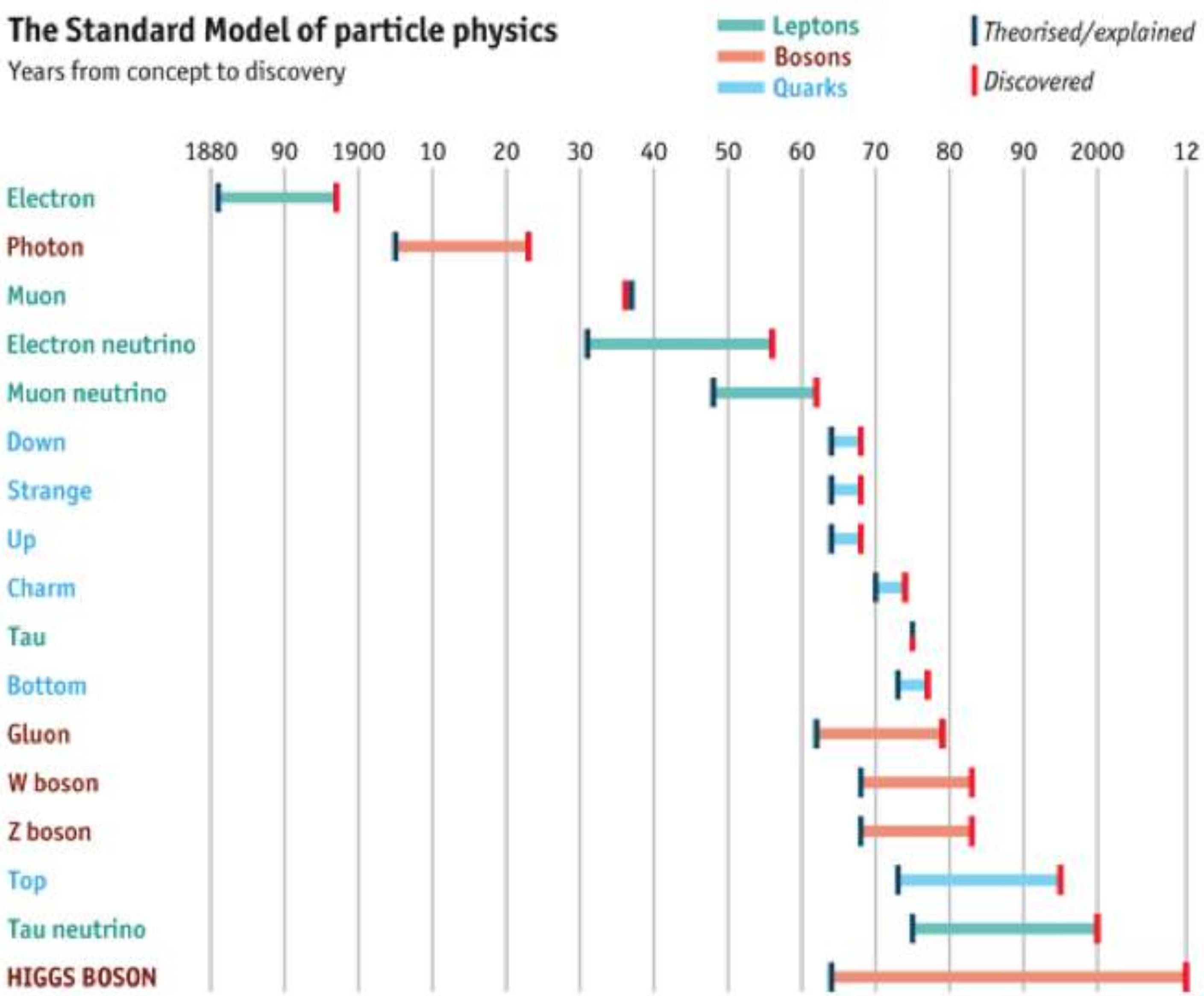
# OK, let's find some new particles…



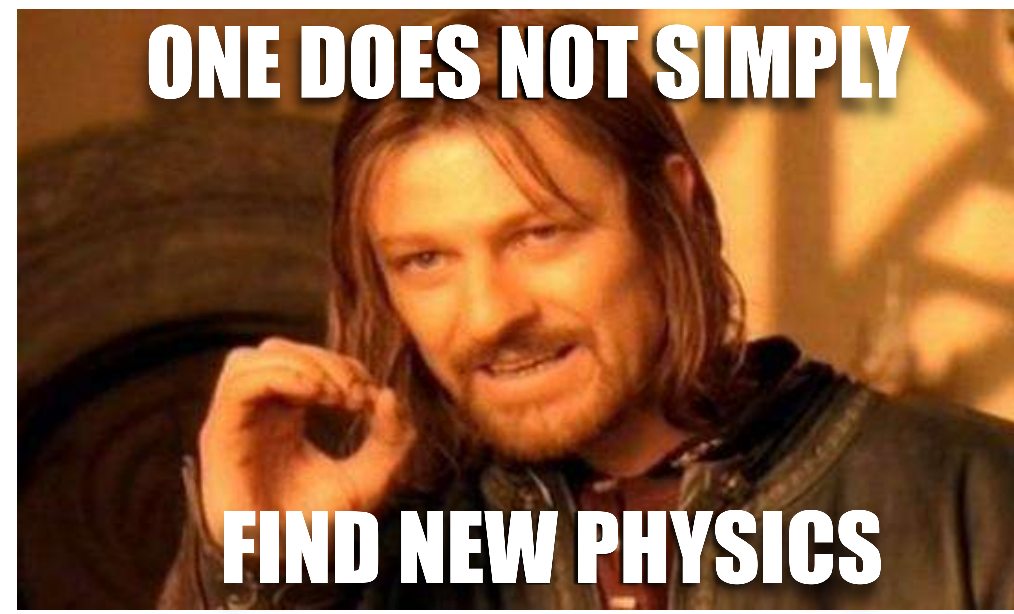

Particle x ?

# OK, let's find some new particles…



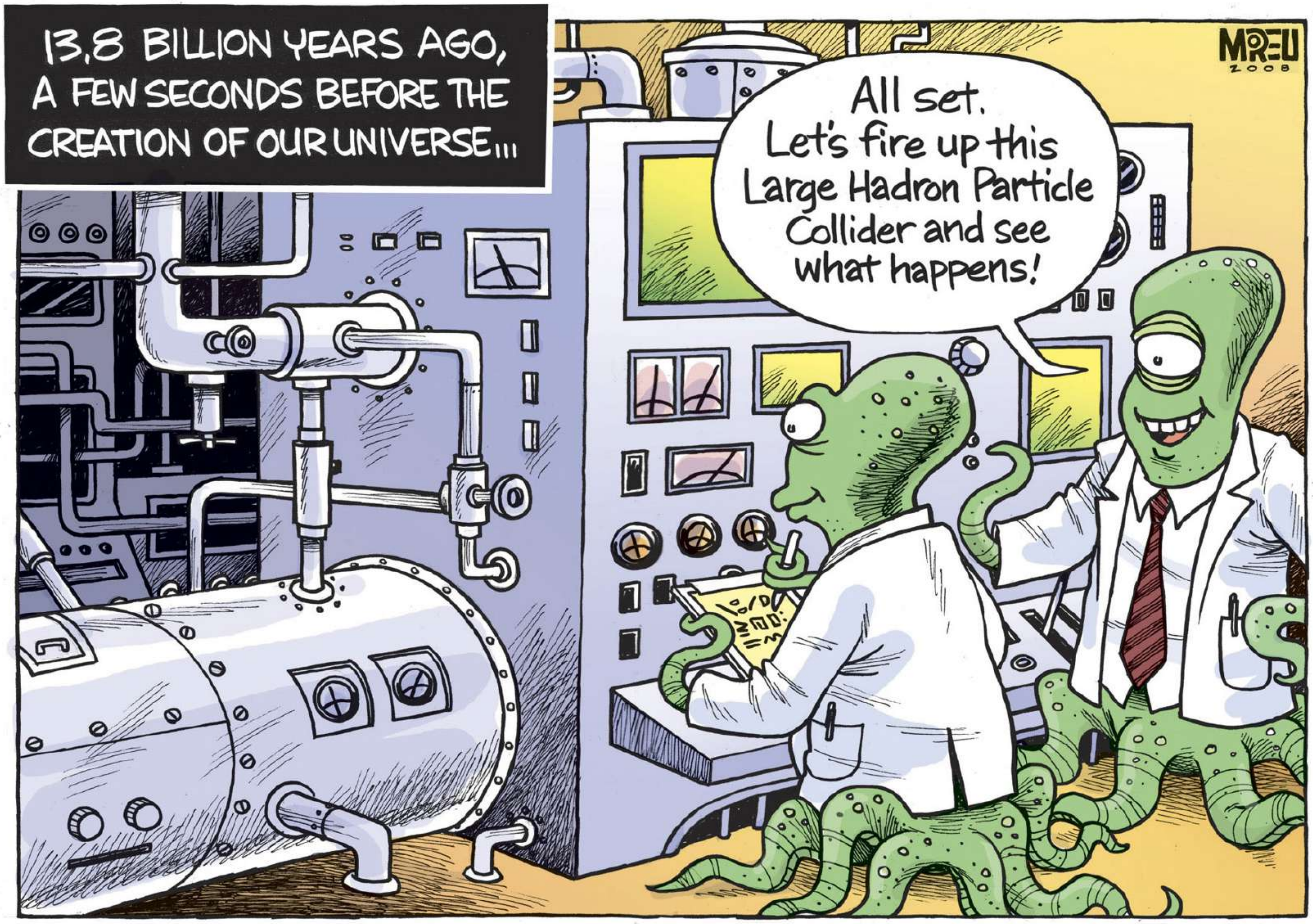

Source: *The Economist*

Particle x ?



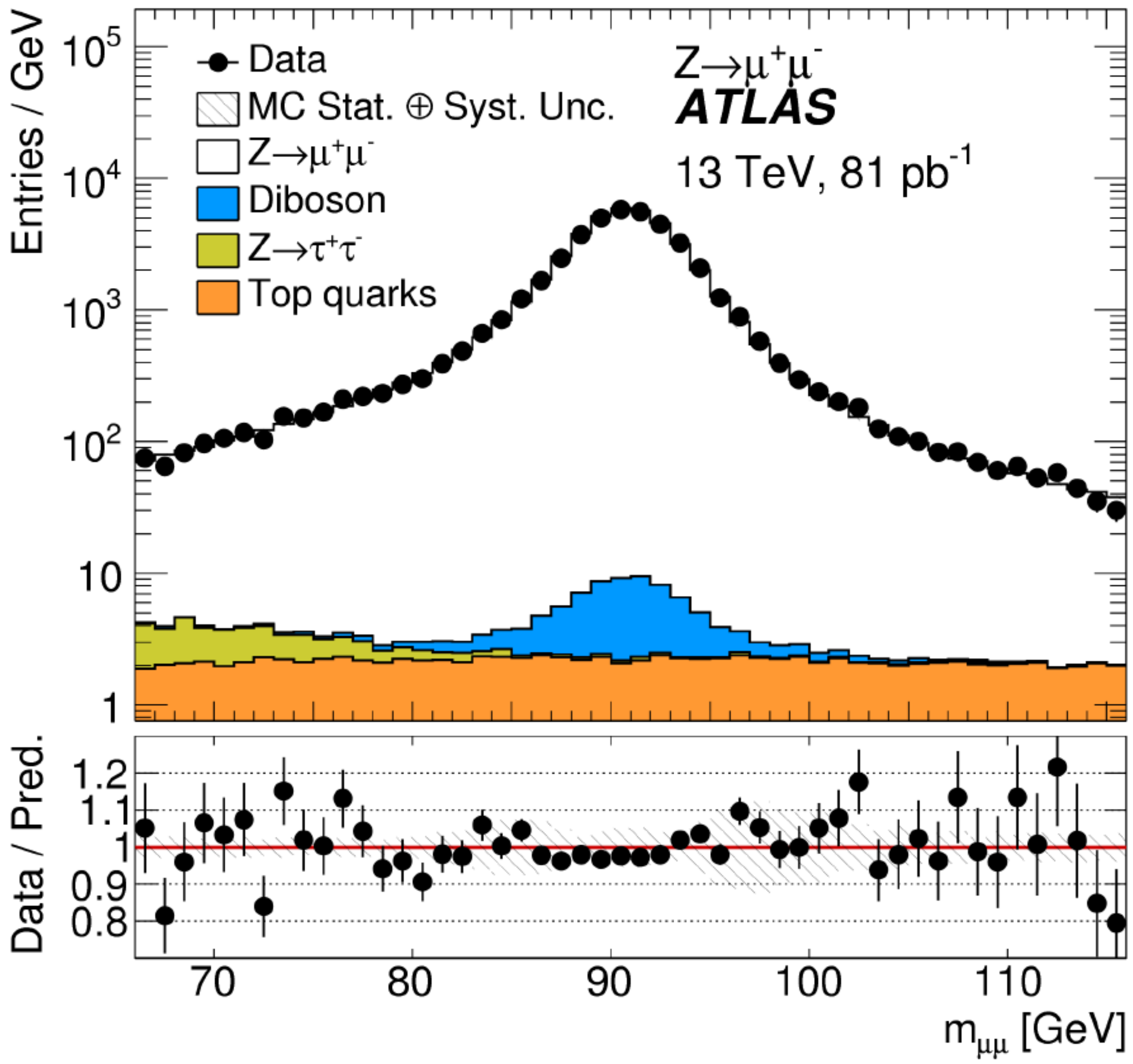


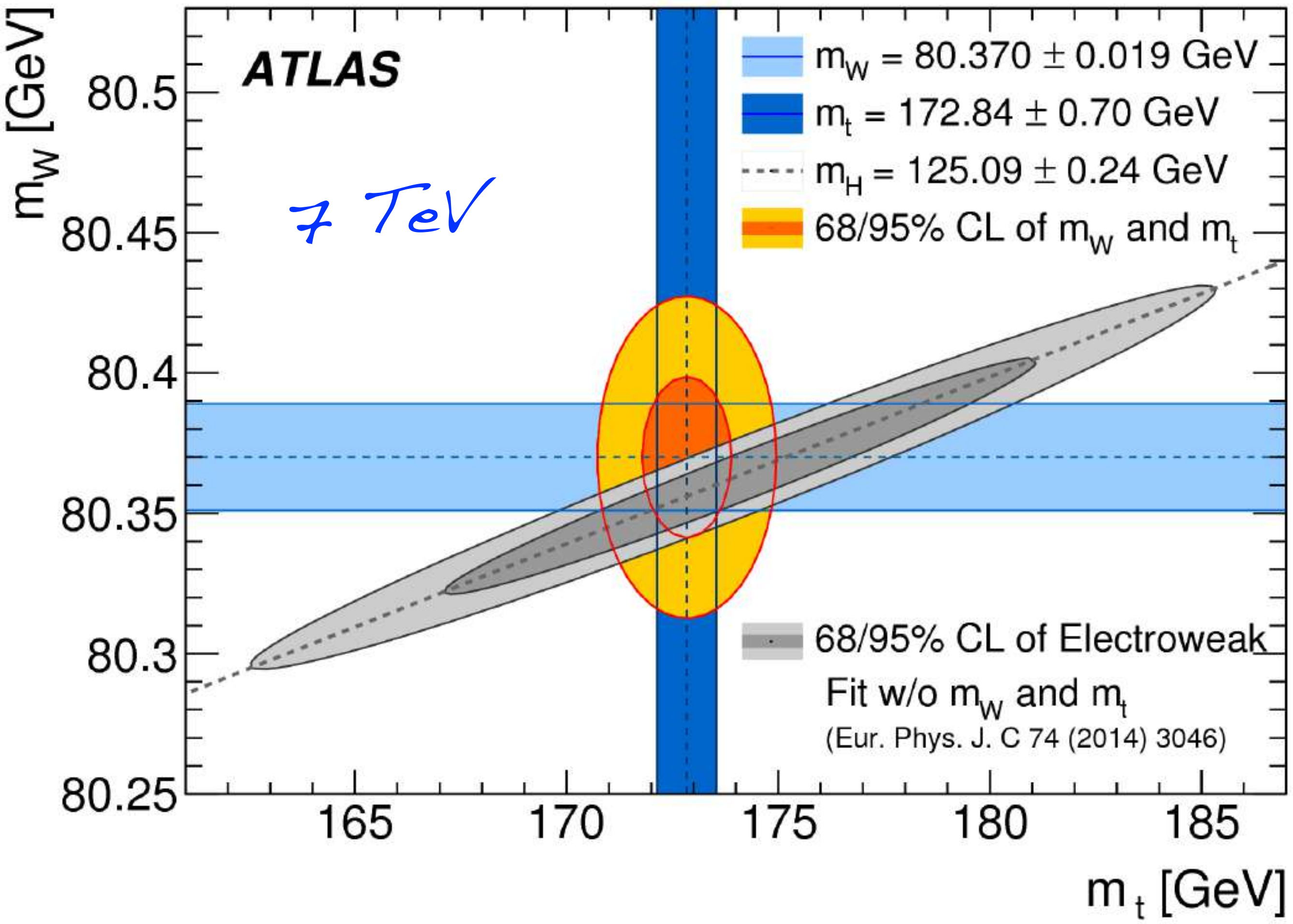
# Conclusions



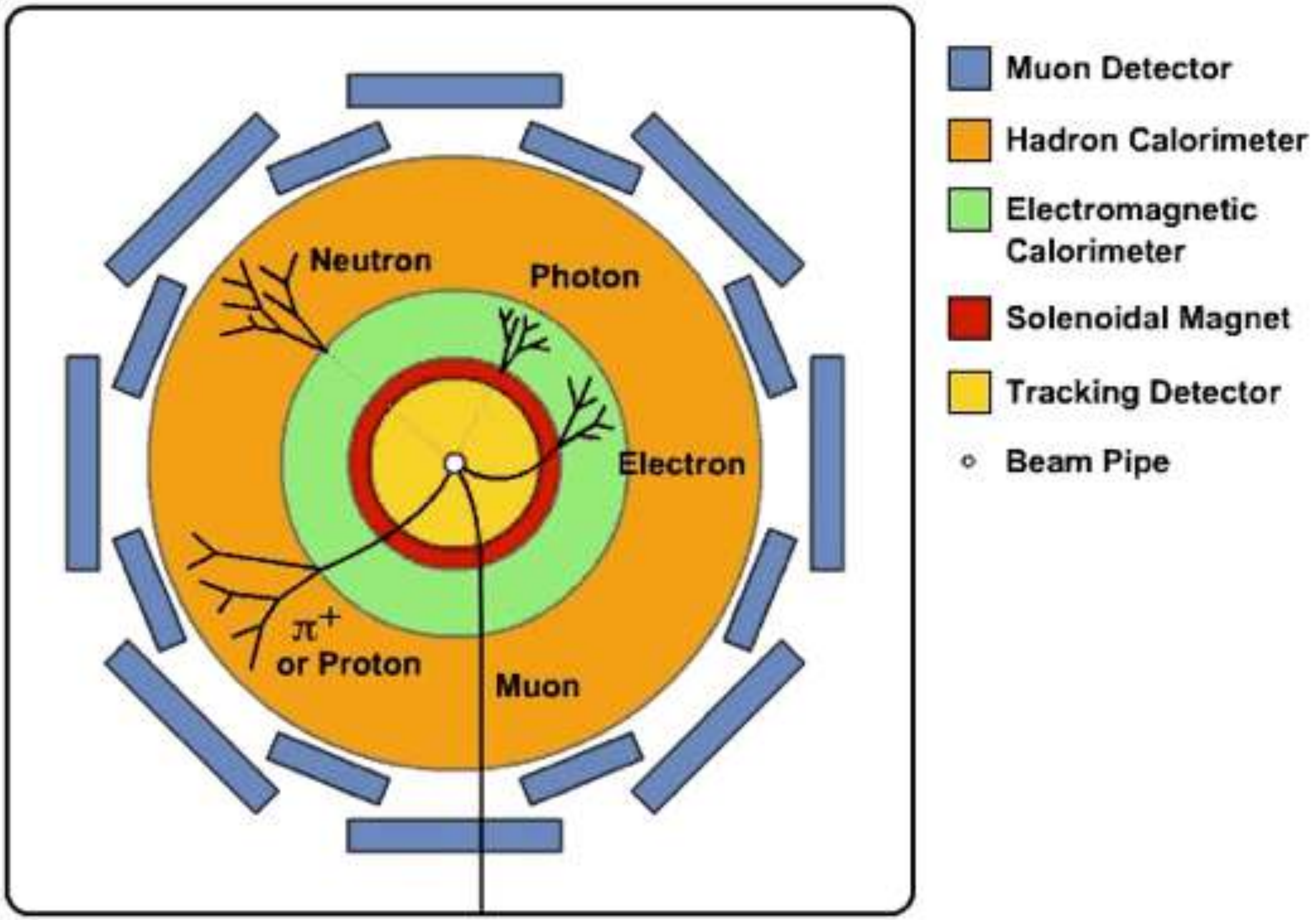
# back-up

# Eletroweak


Entries / GeV
Data
MC Stat. ⊕ Syst. Unc.
Z→μ⁺μ⁻
Diboson
Z→τ⁺τ⁻
Top quarks
Z→μ⁺μ⁻
ATLAS
13 TeV, 81 pb⁻¹
Data / Pred.
m_μμ [GeV]


ATLAS
7 TeV
m_W = 80.370 ± 0.019 GeV
m_t = 172.84 ± 0.70 GeV
m_H = 125.09 ± 0.24 GeV
68/95% CL of m_W and m_t
68/95% CL of Electroweak
Fit w/o m_W and m_t
(Eur. Phys. J. C 74 (2014) 3046)
m_W [GeV]
m_t [GeV]

# Comment détecter les particules produites ?

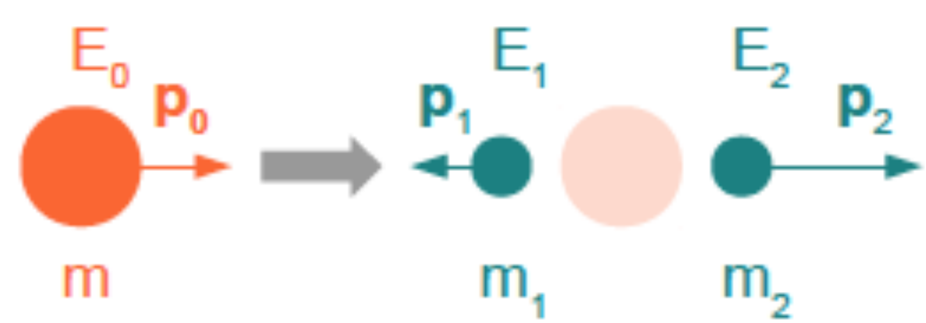



## Relativité restreinte

$E^2 = m^2c^4 + p^2c^2$ (p: quantité de mouvement)
→ transformation énergie cinétique - masse

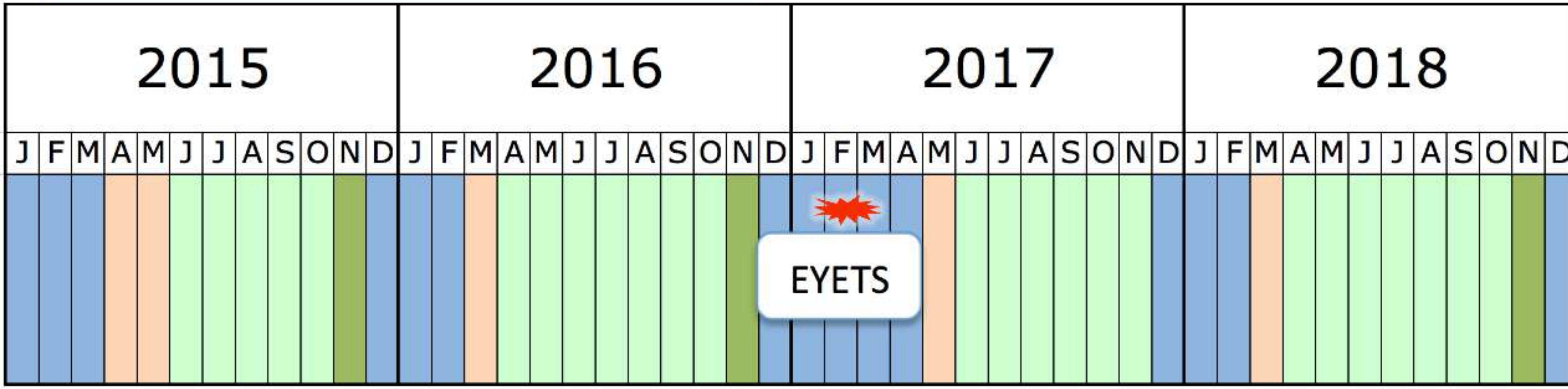
Création de particules «lourdes» lors de collisions de particules plus légères:

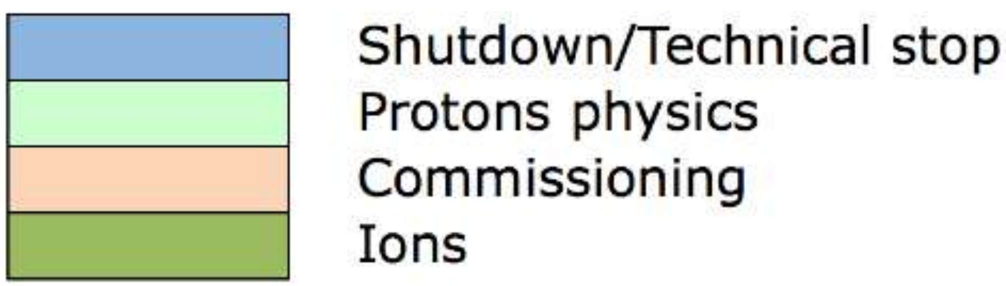

Désintégration de particules lourdes instables en particules plus légères:



# Run 2 and Run 3

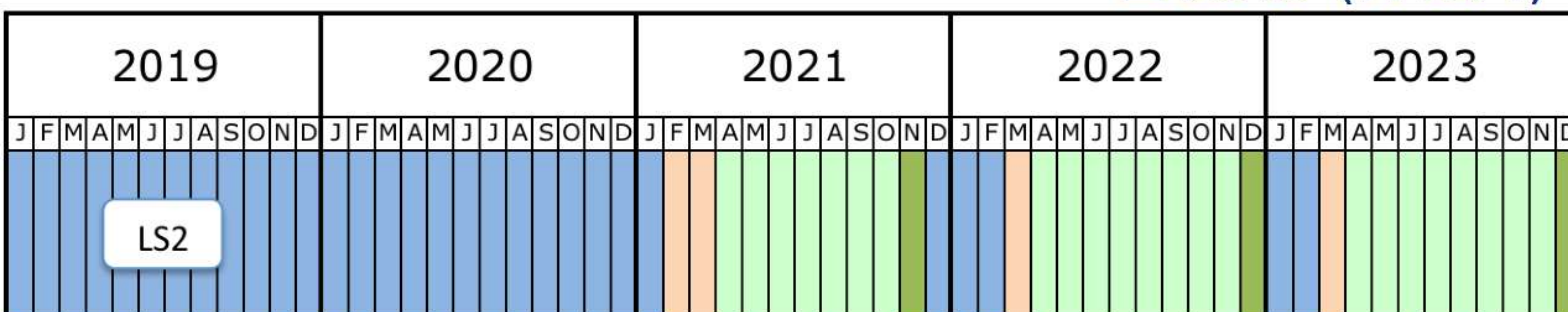
Ion runs end of 2018 (Pb-Pb)



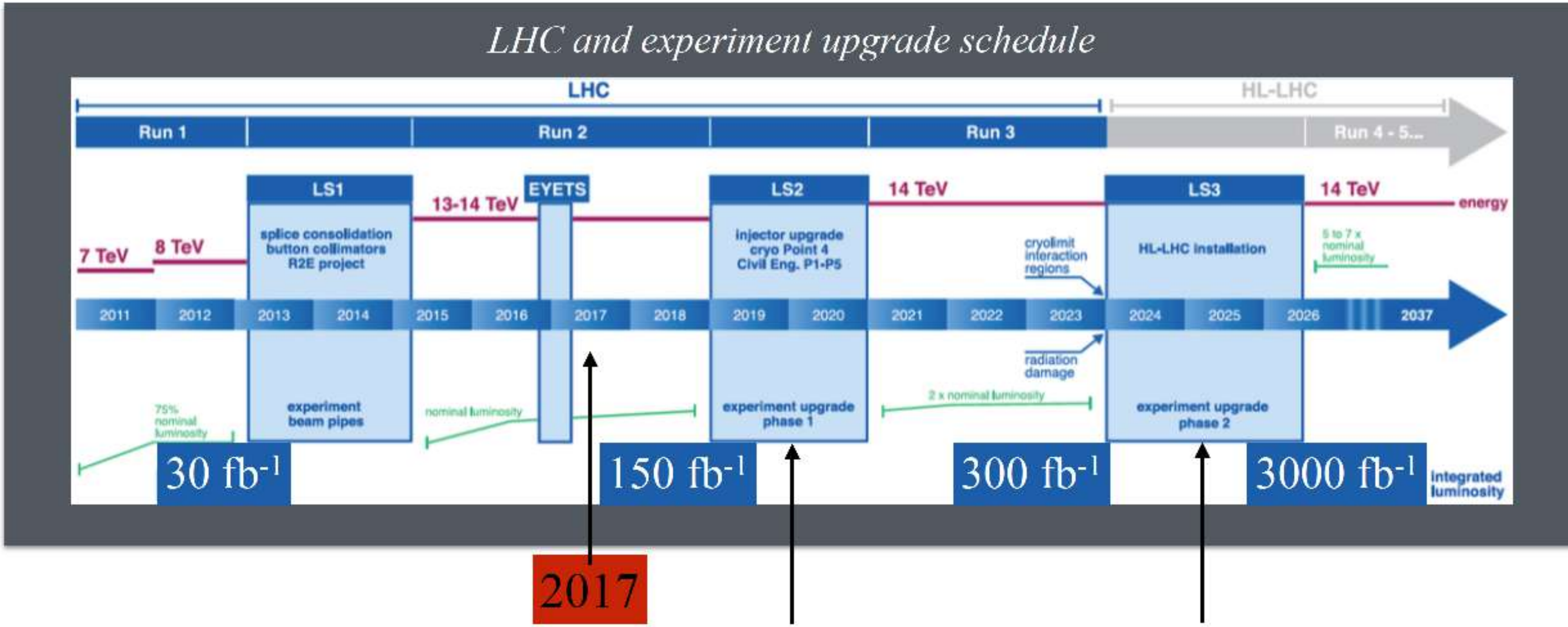

**>120 $fb^{-1}$ (13 TeV)**

**$\Sigma$ 300 $fb^{-1}$ (14 TeV ?)**



# Timeline for upgrades






Upgrade 2019

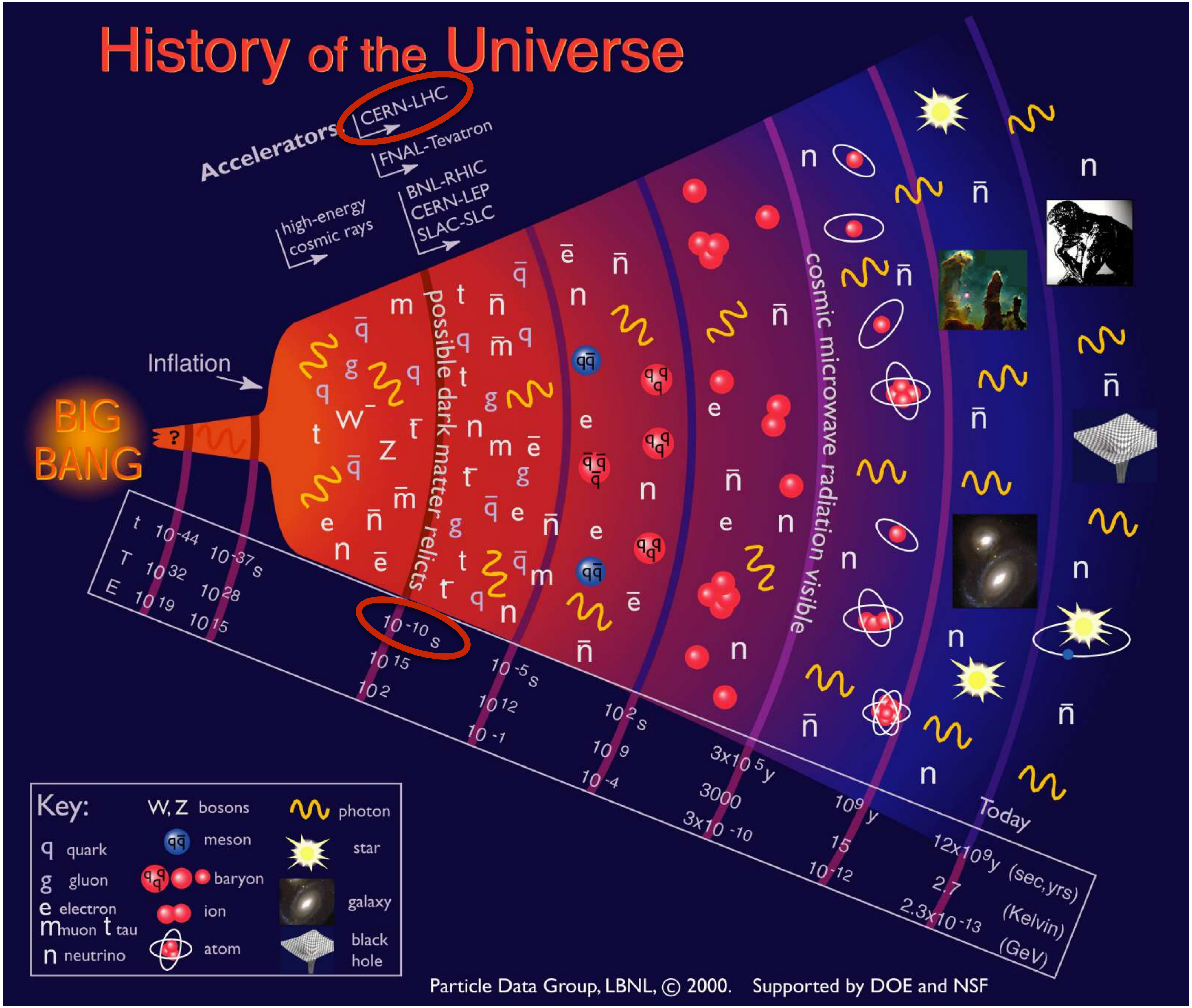
Upgrade 2024

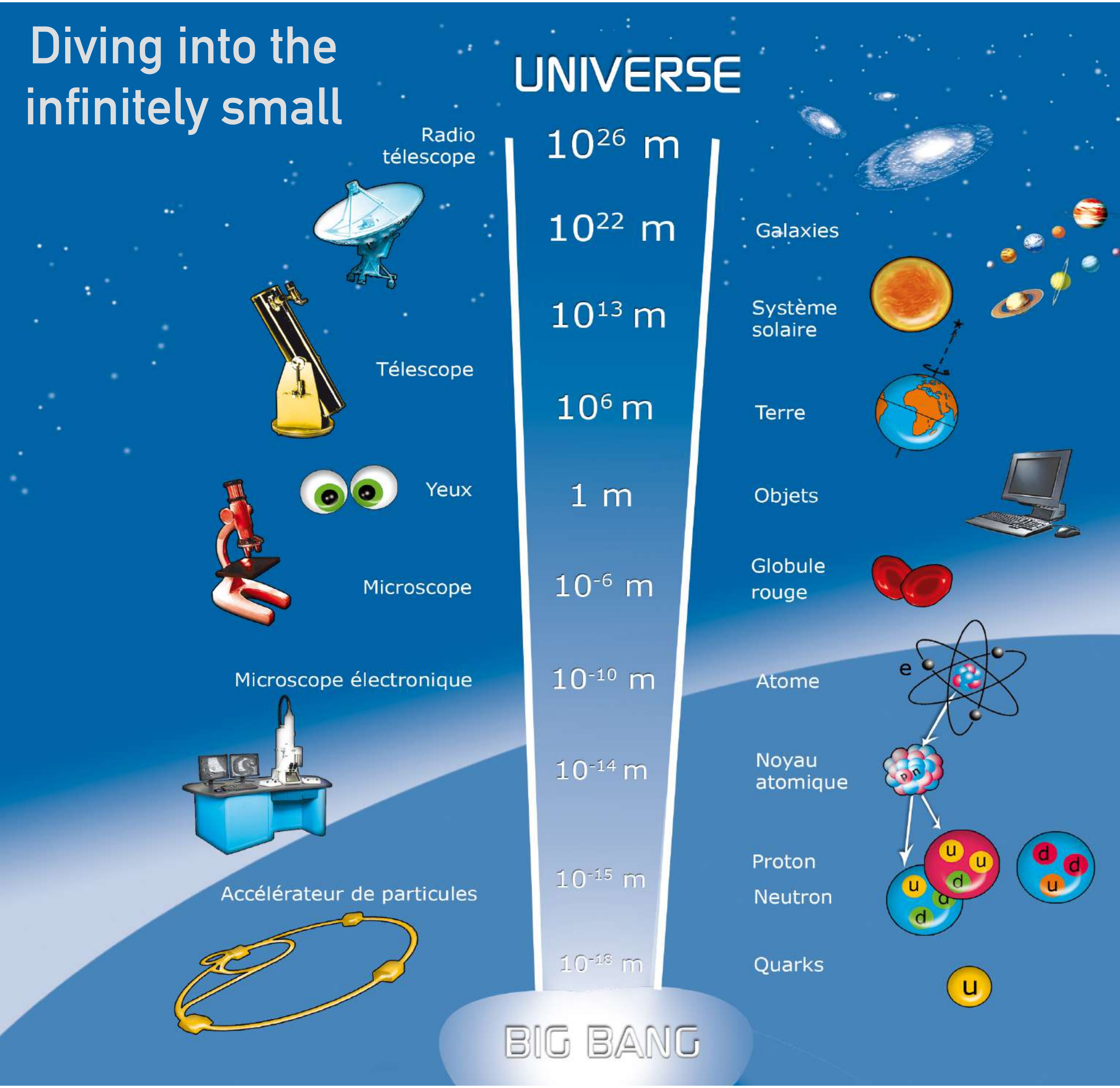
## ATLAS upgrade

- *2019: significant upgrades in trigger readout electronics and L1 trigger electronics*
- *2024: upgrades to tracker, calorimeters, muon system and trigger*

**Needed to cope with increasing pileup & add new features**

# Faire des expériences dans les mêmes conditions que $10^{-10}$ s après le Big Bang !






## Difference in dimensions