



FUNDAMENTALS OF SCIENCE & FUNDAMENTAL SCIENCE



André David (CERN)



Things you can't “unsee”

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[<http://cern.ch/go/Dxh7>]





Things you can't “unsee”

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[<http://cern.ch/go/Dxh7>]





Things you can't “unsee”

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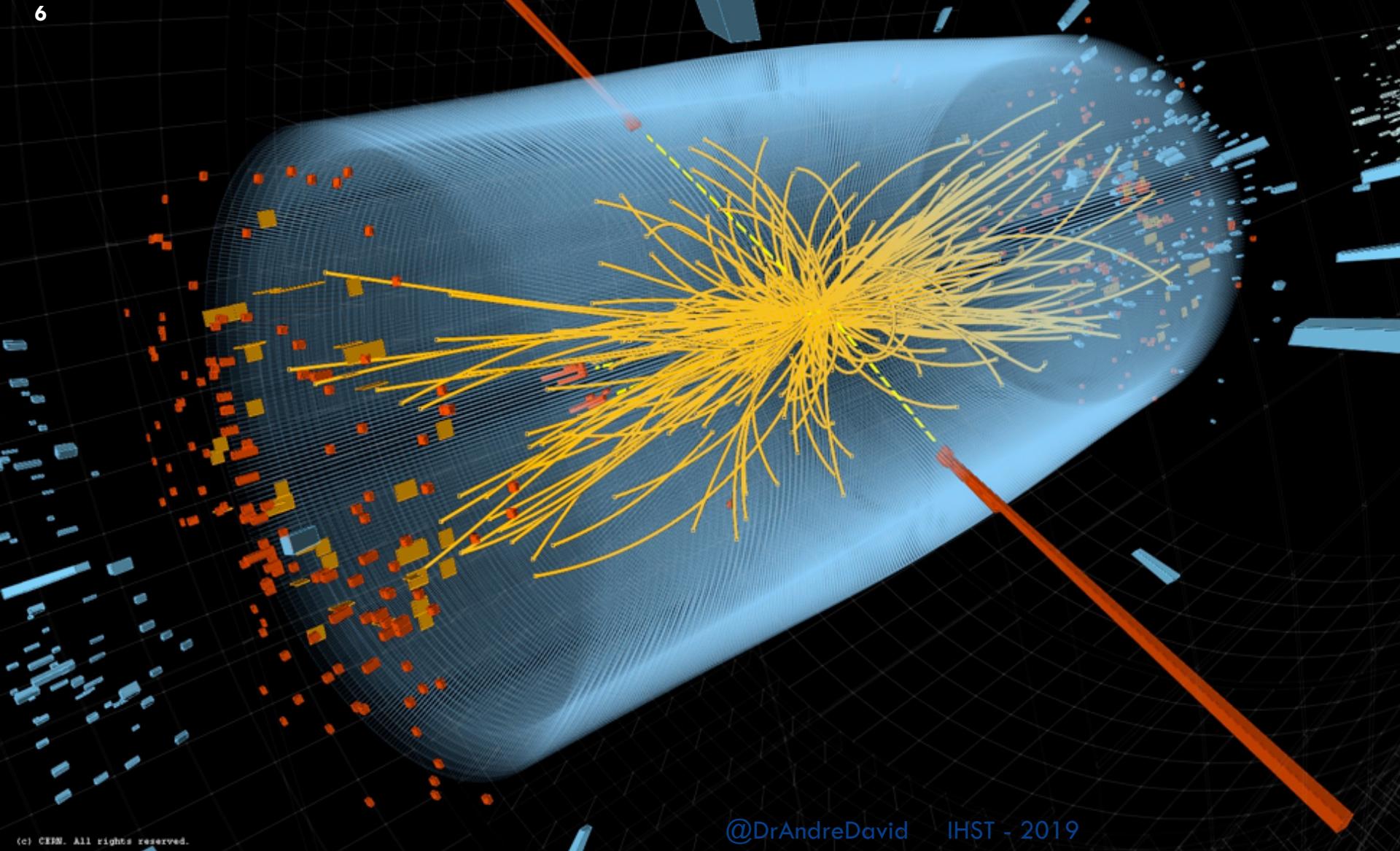
[<http://cern.ch/go/Dxh7>]





Final Run 1 $H \rightarrow \gamma\gamma$ analysis

6



About the role of experimentalists



A dramatic photograph of a massive, curling green wave crashing towards a red lighthouse on a pier. The wave is the central focus, its white spray contrasting with the dark green water. In the foreground, a red lighthouse stands on a concrete pier. Several people are standing on the pier, looking out at the massive wave. A tall metal pole with a cable is also visible on the pier.

Nature



Nature

Theory



Nature

Theory

Theorists
(inside)



Nature

Theory

Theorists
(inside)

Phenomenologists



Nature

Nature

Theory

Theorists
(inside)

Phenomenologists

A photograph of a massive, dark green ocean wave crashing onto a sandy beach. The wave's white foam is prominent at the top. In the upper left corner, a small white boat with a person is visible. The word "Nature" is printed in large, bold, black letters across the top center of the image.

Nature

Experimentalists

A photograph of a massive, dark green ocean wave crashing onto a beach. In the foreground, a red lighthouse sits on a stone pier. Several people are standing on the pier, watching the wave. The word "Nature" is printed in large, bold, black letters across the middle of the image.

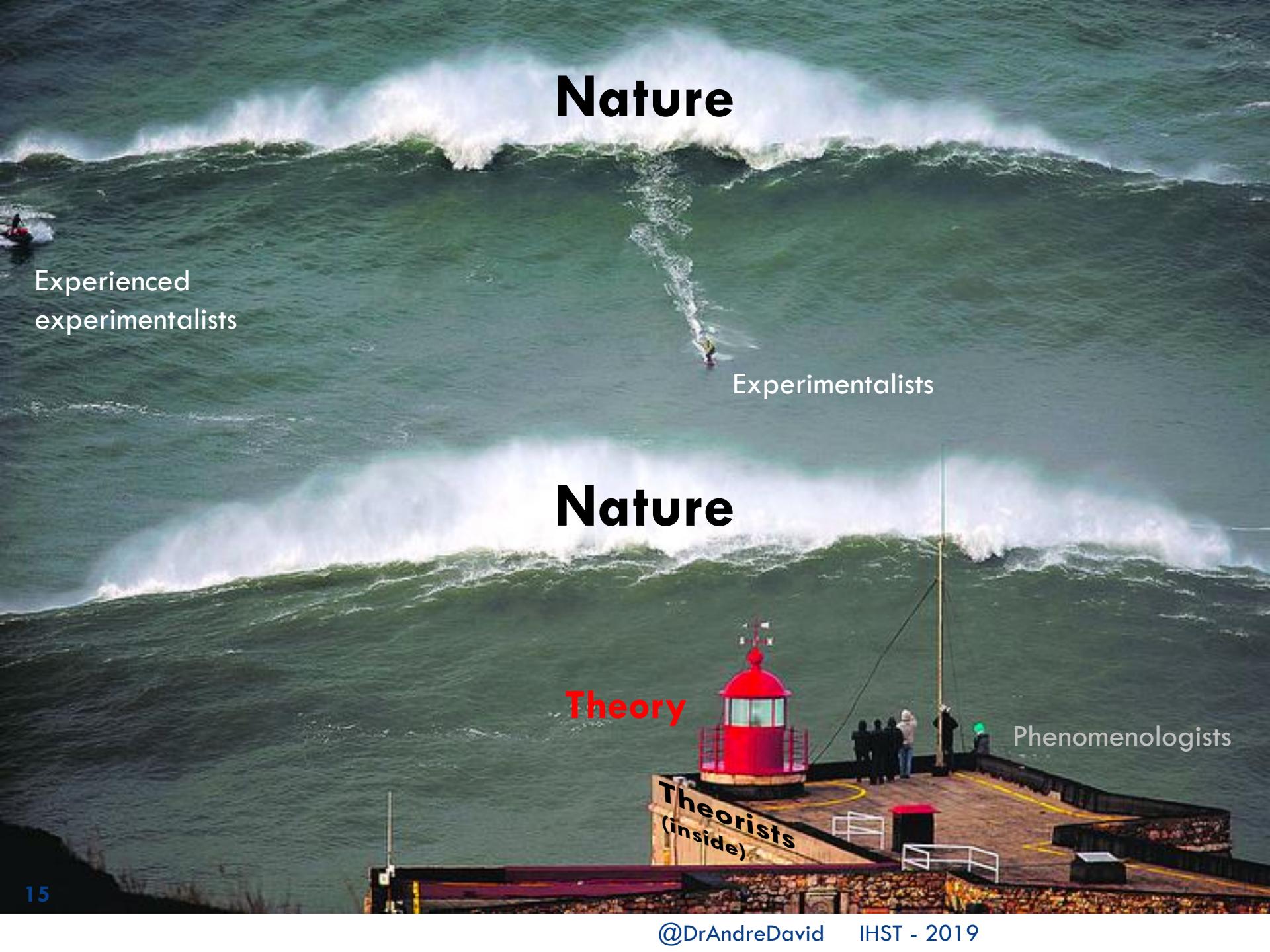
Nature

Theory

Theorists
(inside)

Phenomenologists

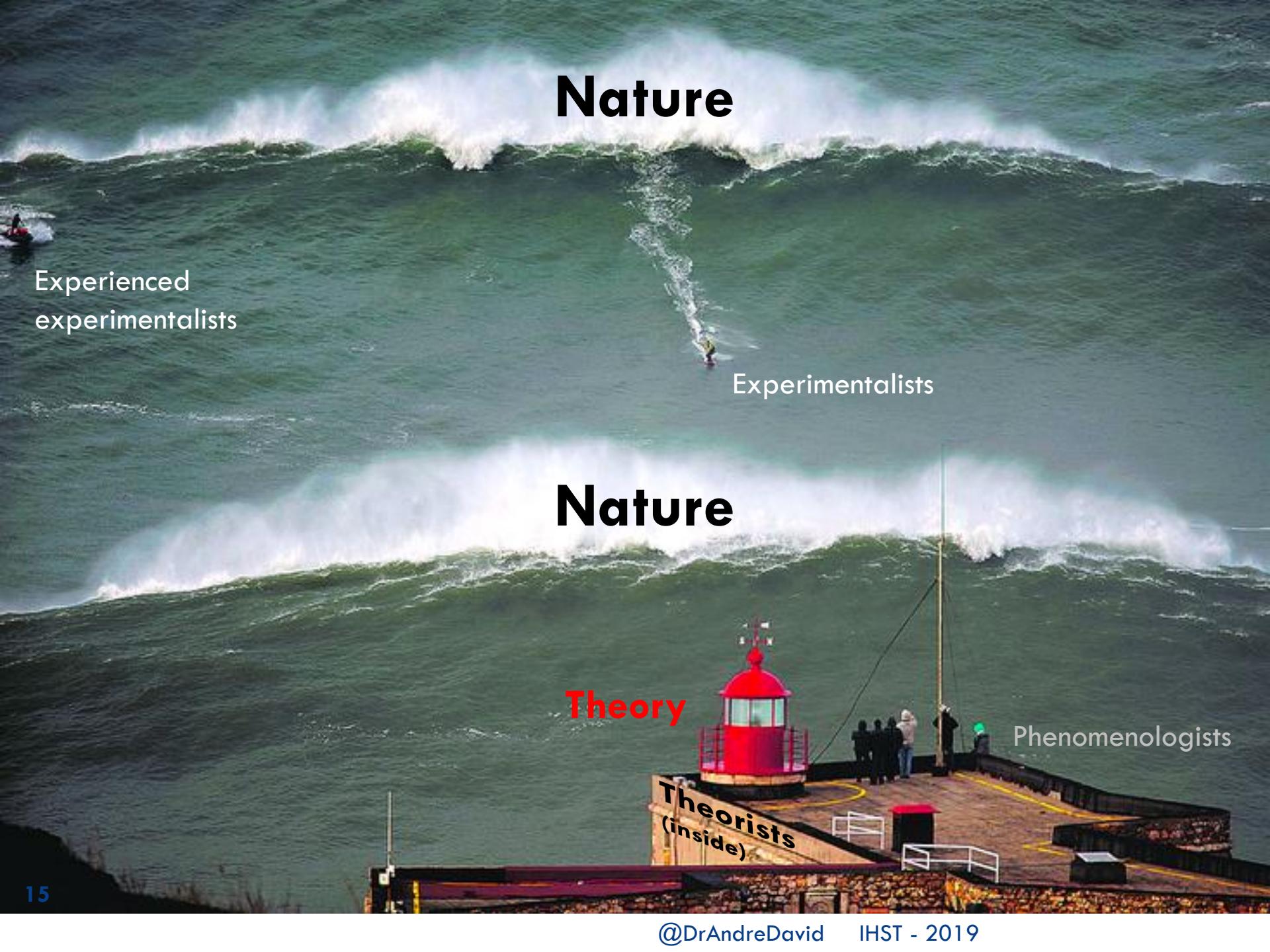
Nature



Experienced
experimentalists

Experimentalists

Nature



Theory

Theorists
(inside)

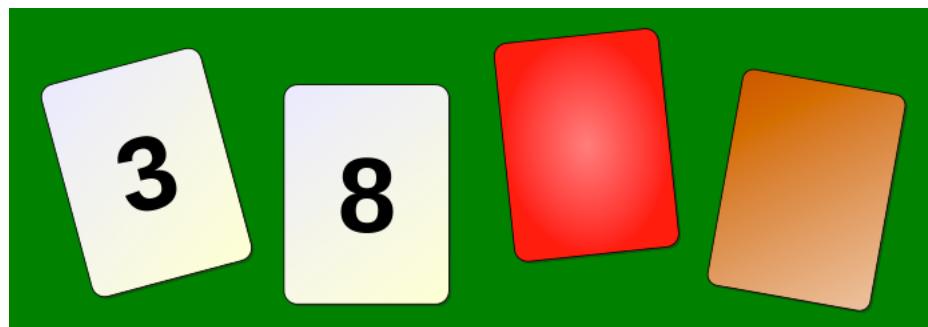
Phenomenologists

Formal logic vs. “Common sense”

Or, how to decide which experiments to perform.

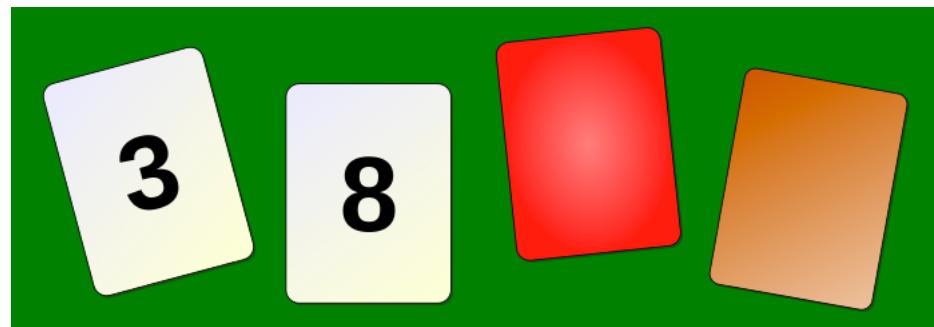
Wason selection task

- “You are shown a set of four cards placed on a table, each of which has a number on one side and a colored patch on the other side. The visible faces of the cards show 3, 8, red and brown. **Which card(s) must you turn over in order to test the truth of the proposition that if a card shows an even number on one face, then its opposite face is red?**”



In simple terms

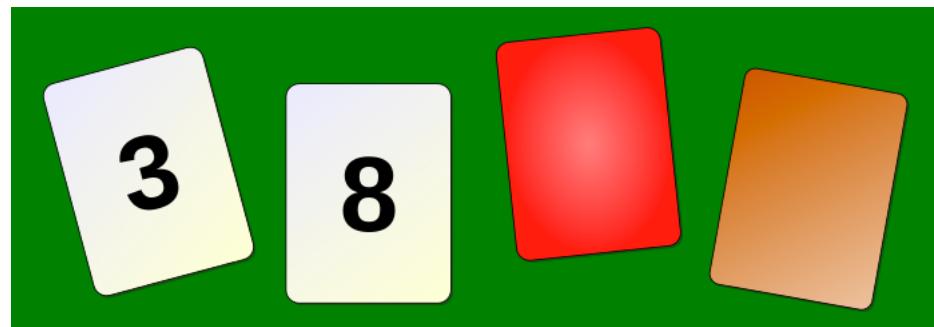
- How to test the idea that “**even implies red**”?



Formal logic

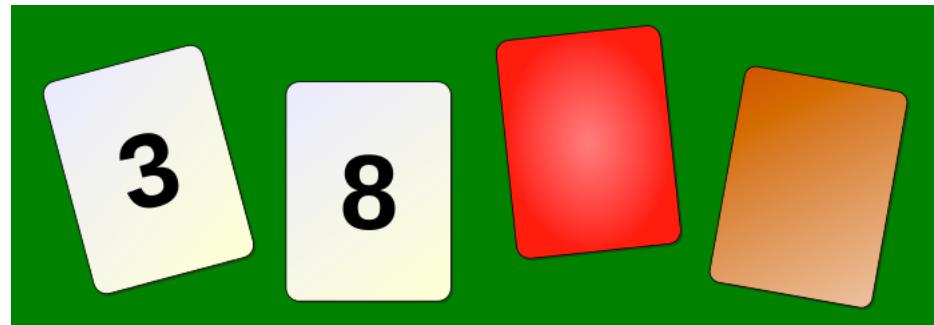
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- $A \Rightarrow B$
- That is:
 $\text{even} \Rightarrow \text{red}$



Formal logic

- $A \Rightarrow B \Leftrightarrow \neg B \Rightarrow \neg A.$
- That is:
 $\text{even} \Rightarrow \text{red} \Leftrightarrow \text{not-red} \Rightarrow \text{not-even}.$



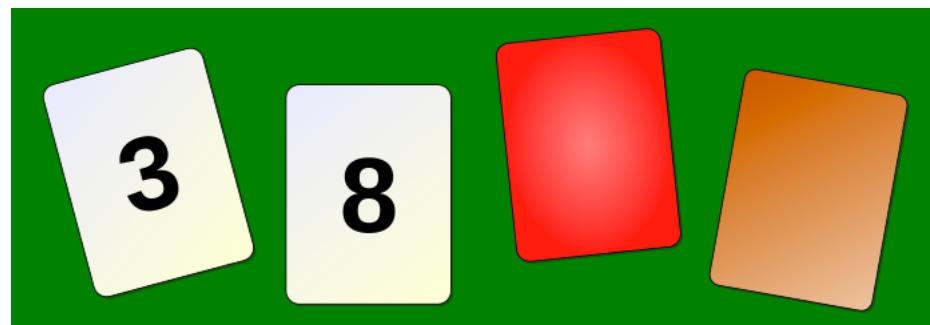
“Common sense”

- even \Rightarrow red

\Leftrightarrow

not-red \Rightarrow not-even.

- What does this imply for each of the cards?



Respect nature uncertainty

The importance of uncertainty

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[<http://observador.pt/especiais/transplante-de-medula-ossea-um-novo-e-grande-incentivo/>]

A taxa de sucesso em Portugal foi maior que a média europeia



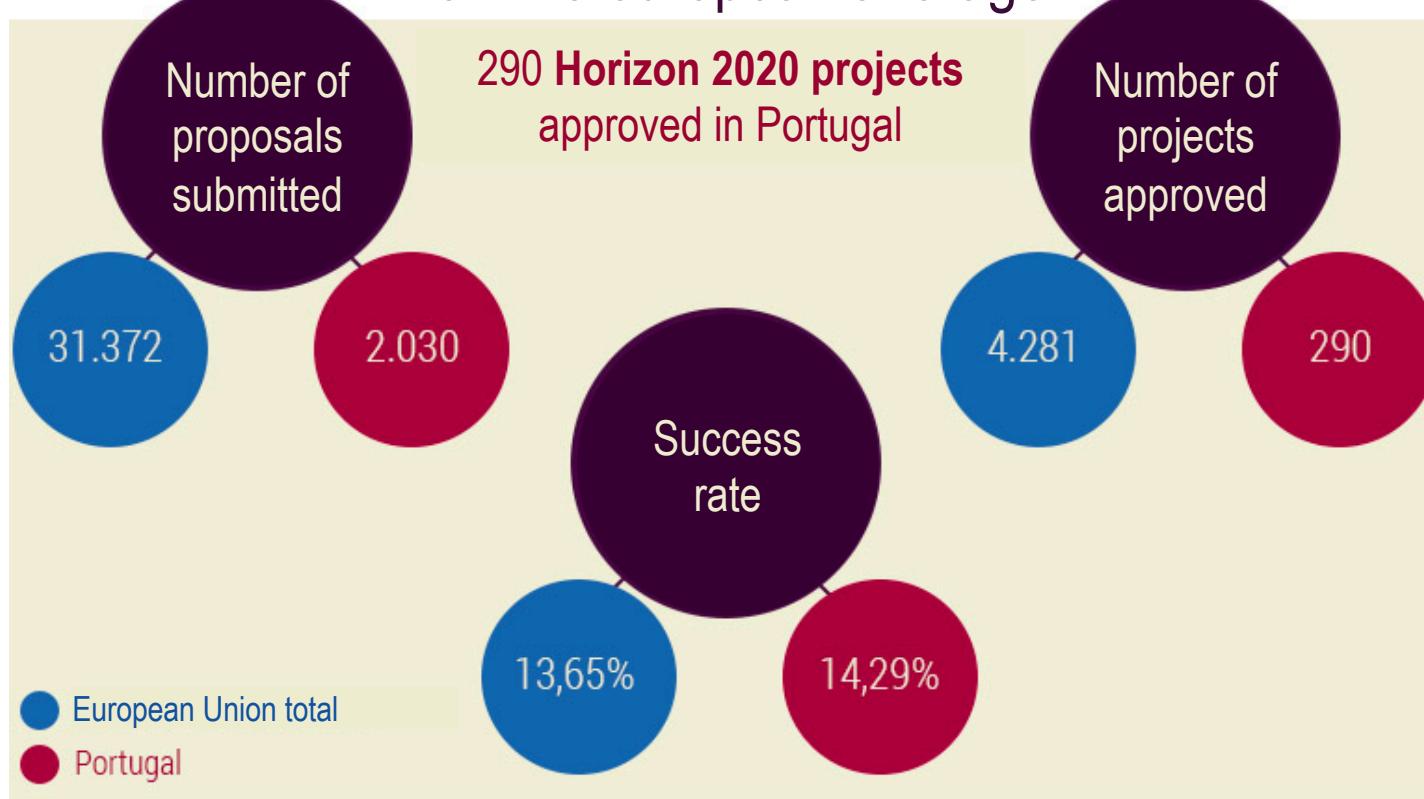
Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

The importance of uncertainty

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[<http://observador.pt/especiais/transplante-de-medula-ossea-um-novo-e-grande-incentivo/>]

The **success rate** in Portugal was higher than the european average



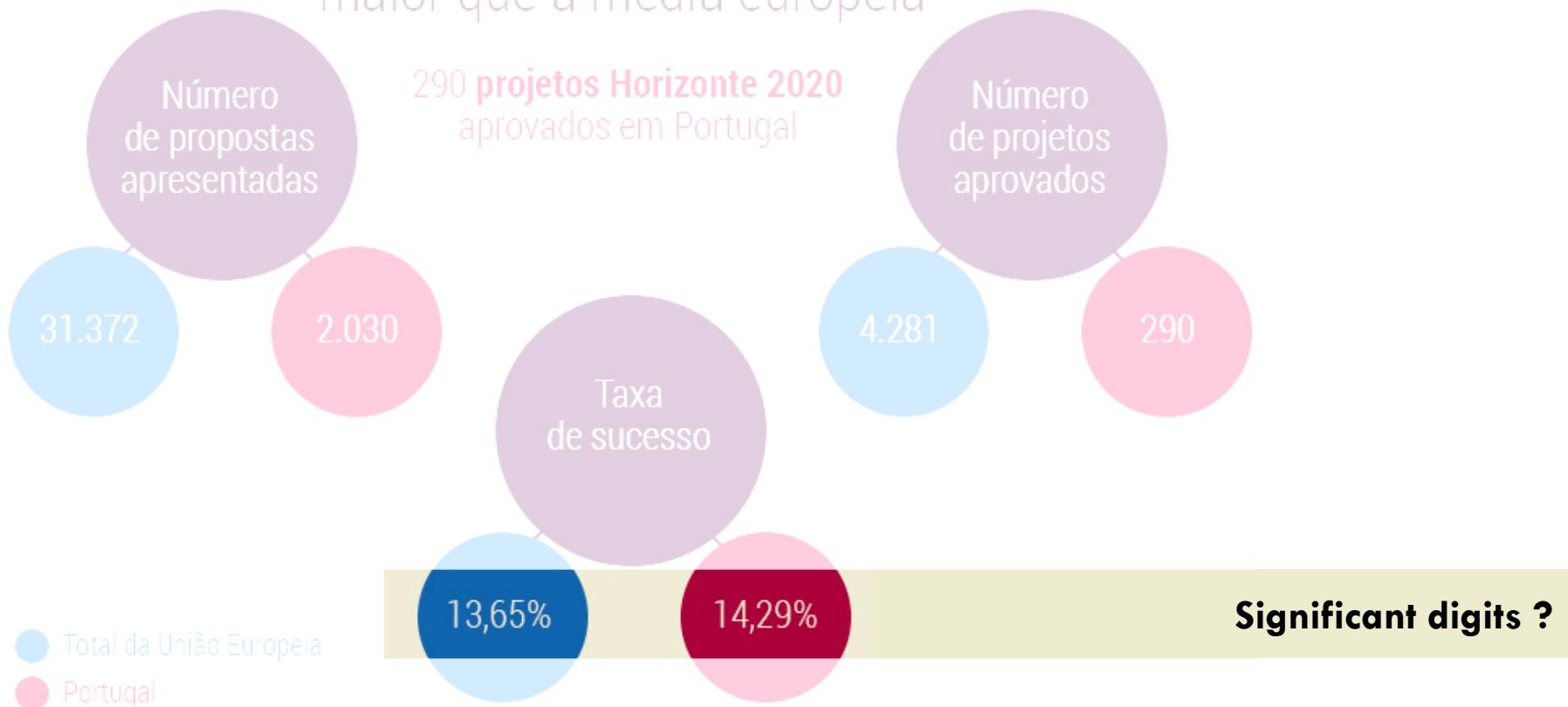
Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

The importance of uncertainty

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[<http://observador.pt/especiais/transplante-de-medula-ossea-um-novo-e-grande-incentivo/>]

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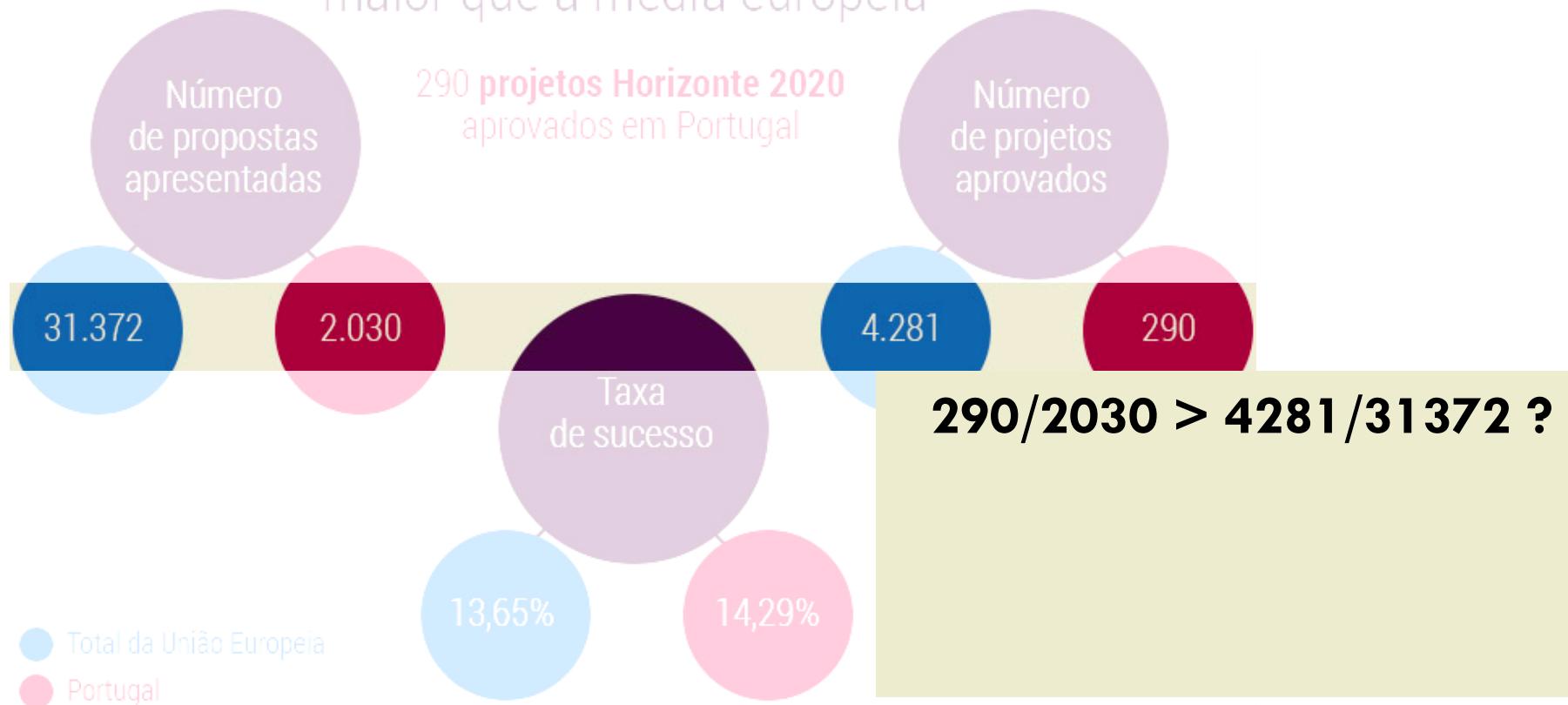
Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

The importance of uncertainty

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[<http://observador.pt/especiais/transplante-de-medula-ossea-um-novo-e-grande-incentivo/>]

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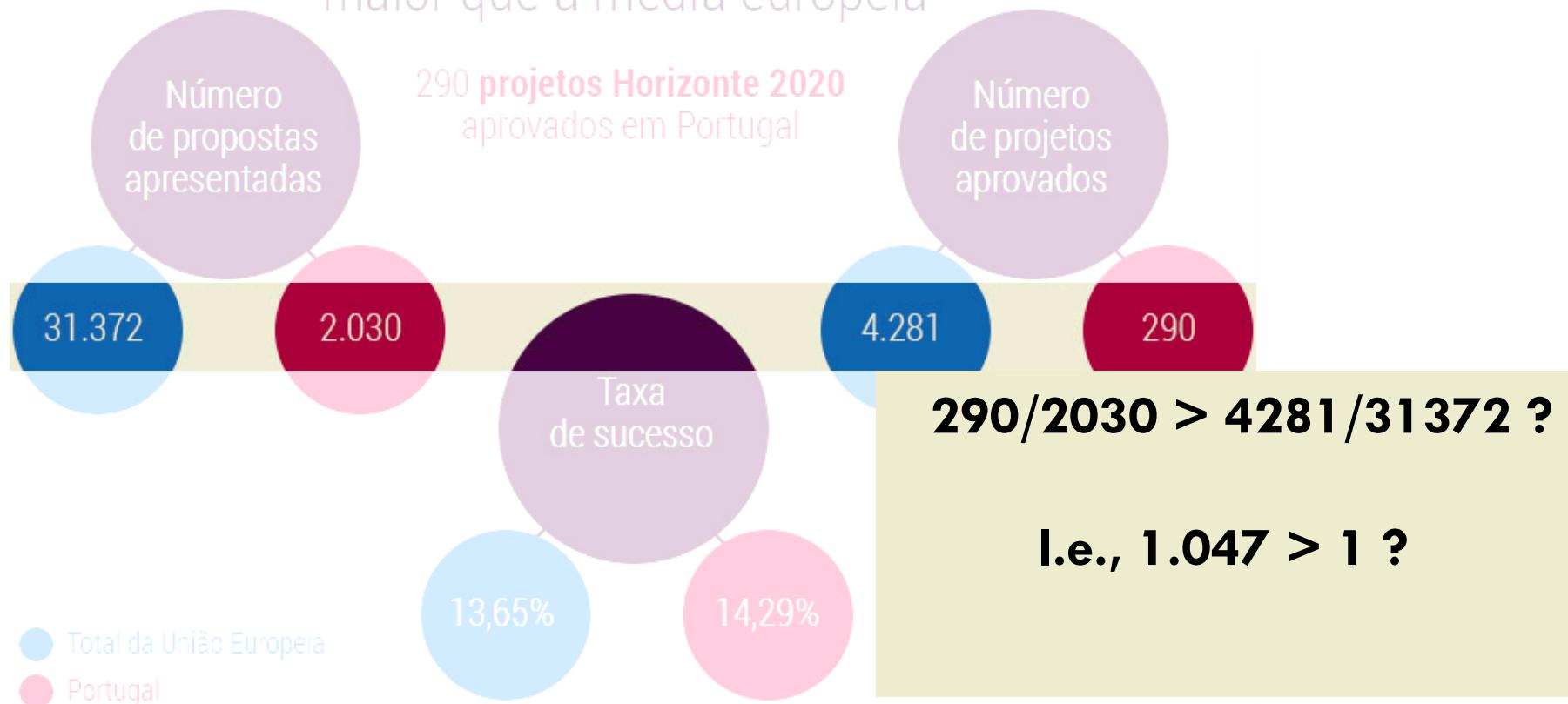
Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

The importance of uncertainty

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[<http://observador.pt/especiais/transplante-de-medula-ossea-um-novo-e-grande-incentivo/>]

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Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

The importance of uncertainty

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[<http://observador.pt/especiais/transplante-de-medula-ossea-um-novo-e-grande-incentivo/>]

\$ R

```
R version 3.2.2 (2015-08-14) -- "Fire Safety"
Copyright (C) 2015 The R Foundation for Statistical Computing
Platform: x86_64-apple-darwin14.5.0 (64-bit)

> library("rateratio.test")
> rateratio.test(c(290,4281),c(2030,31372),conf.level=0.90,alternative="greater")

      Exact Rate Ratio Test, assuming Poisson counts

data: c(290, 4281) with time of c(2030, 31372), null rate ratio 1
p-value = 0.2331
alternative hypothesis: true rate ratio is greater than 1
90 percent confidence interval:
 0.9664013      Inf
sample estimates:
Rate Ratio      Rate 1      Rate 2
1.0468849  0.1428571  0.1364593
```



Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

The importance of uncertainty

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[<http://observador.pt/especiais/transplante-de-medula-ossea-um-novo-e-grande-incentivo/>]

The **success rate** in Portugal was ~~higher~~ basically the same as than the european average



Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

Success: “rate is in line with”

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[<http://observador.pt/especiais/transplante-de-medula-ossea-um-novo-e-grande-incentivo/>]

A **taxa de sucesso** em Portugal está
em linha com a média europeia

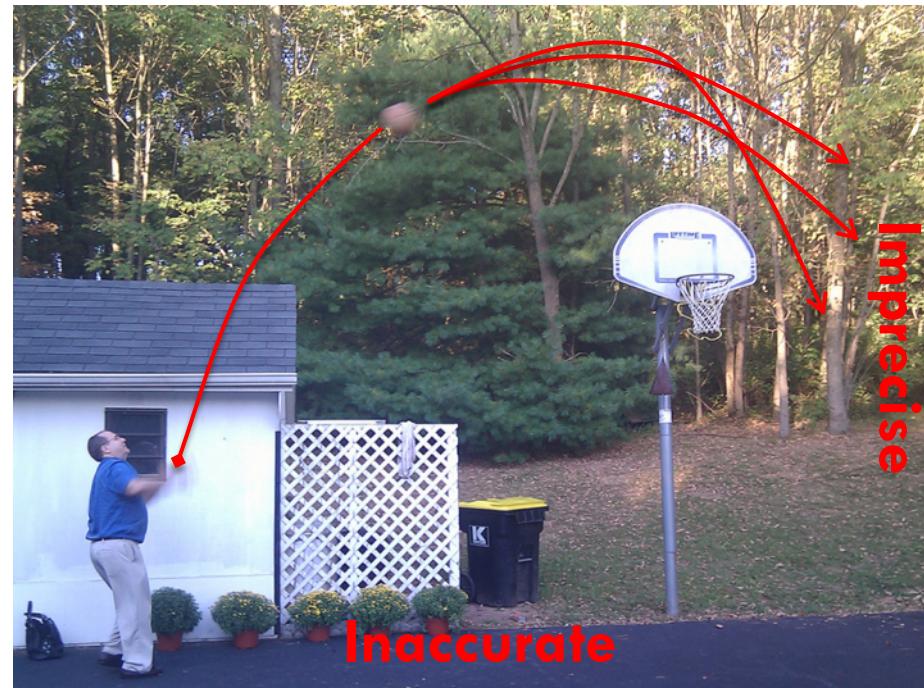


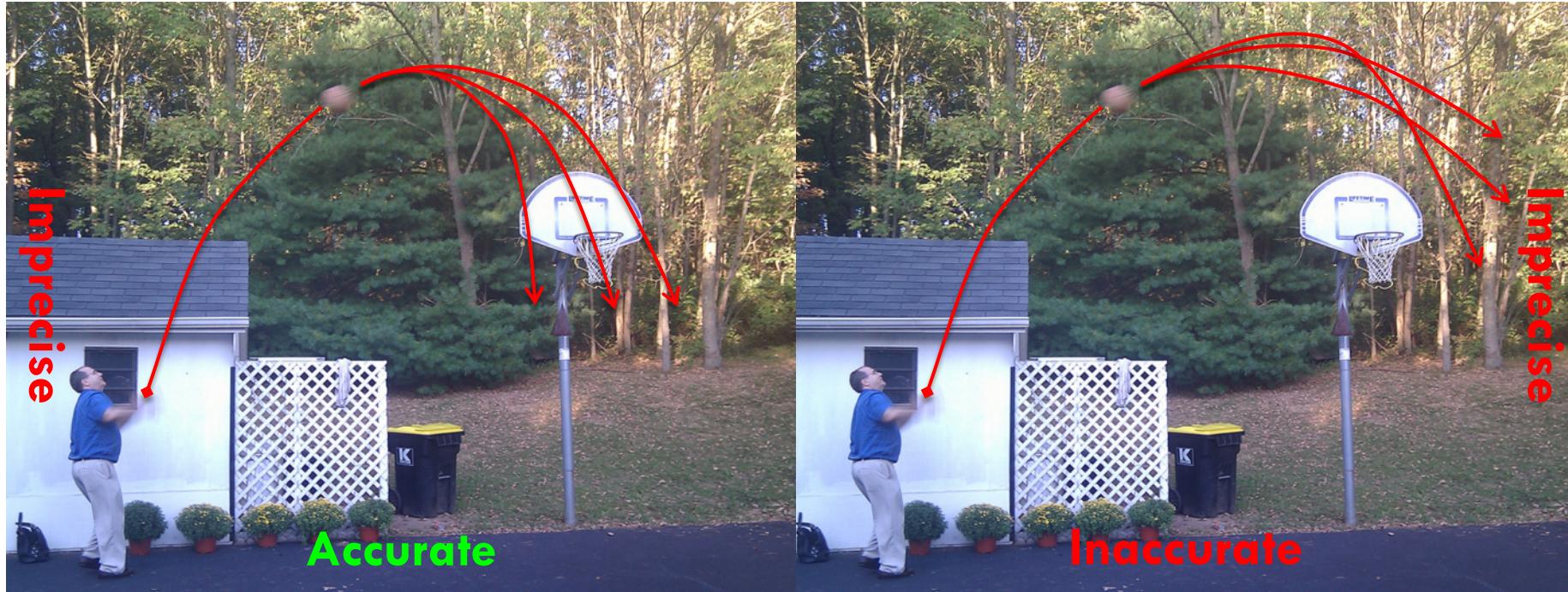
Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

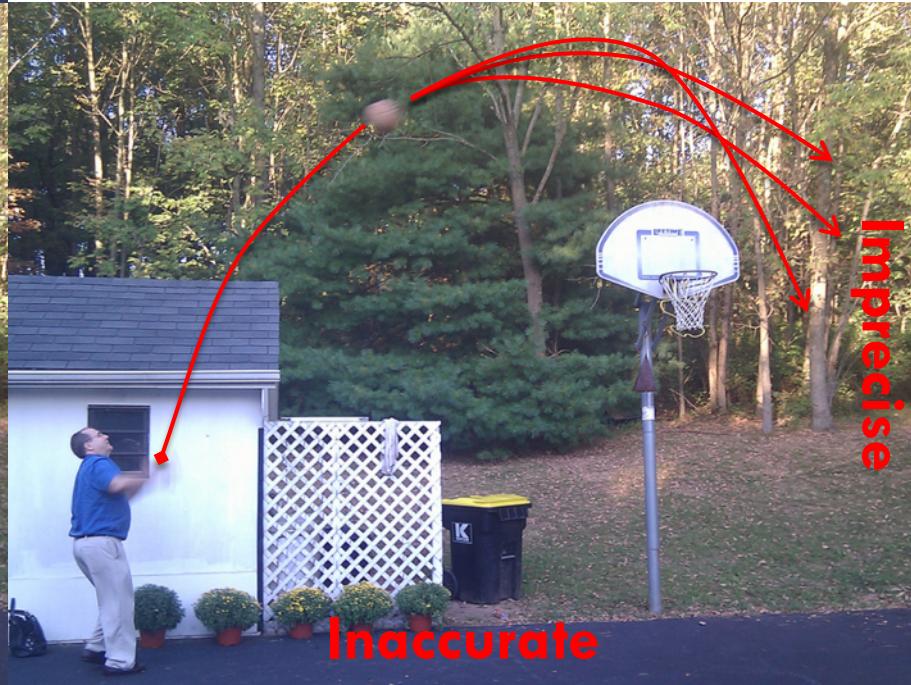
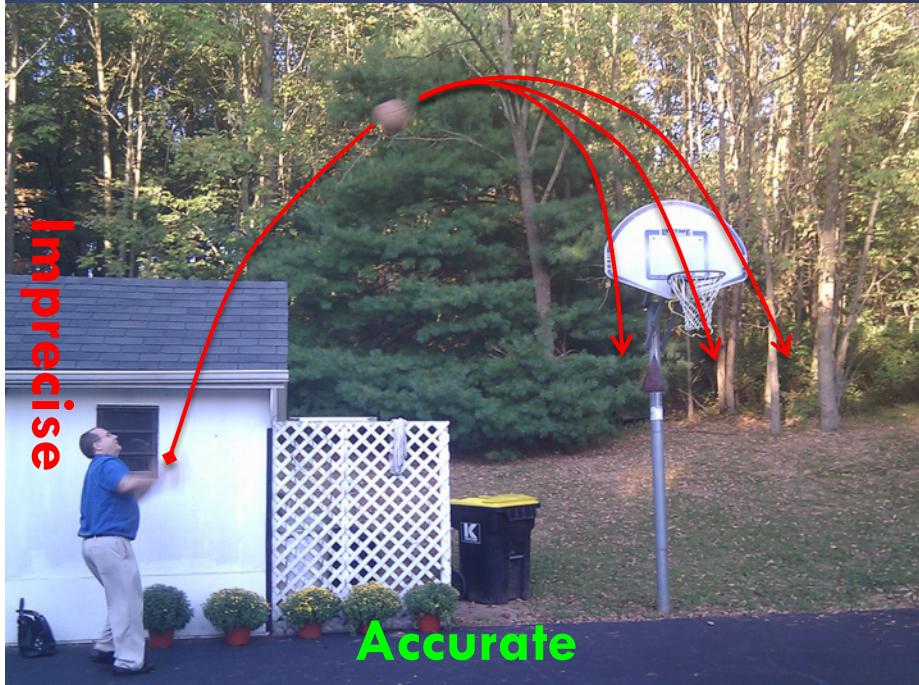
Accuracy and precision

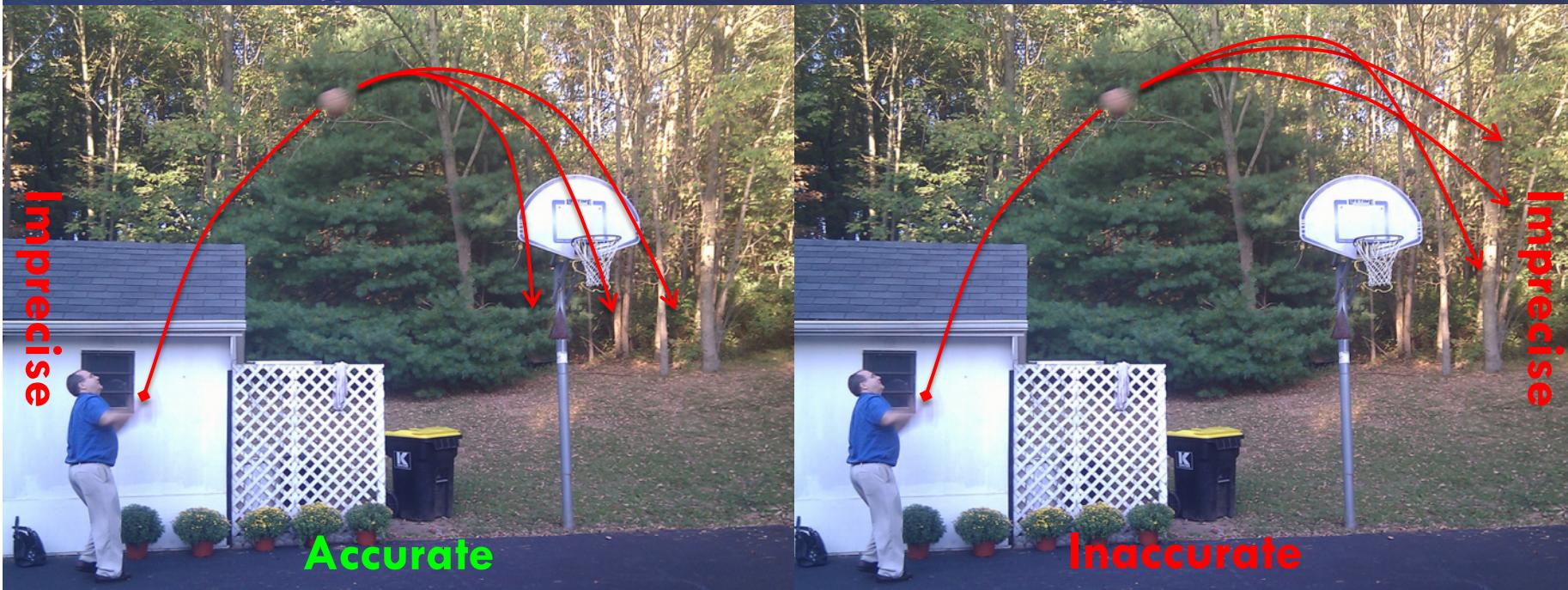
Error and uncertainty











Errors are not uncertainties

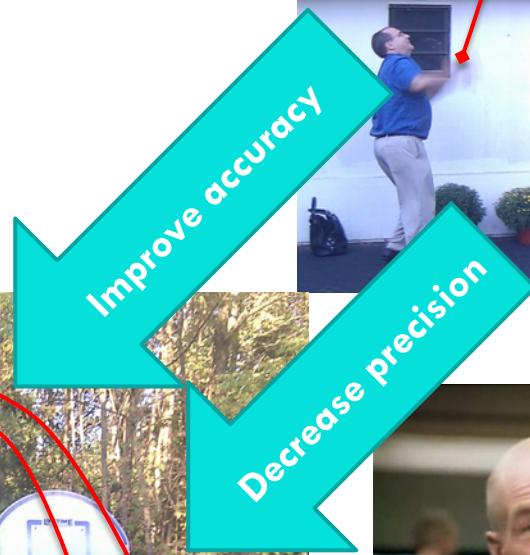
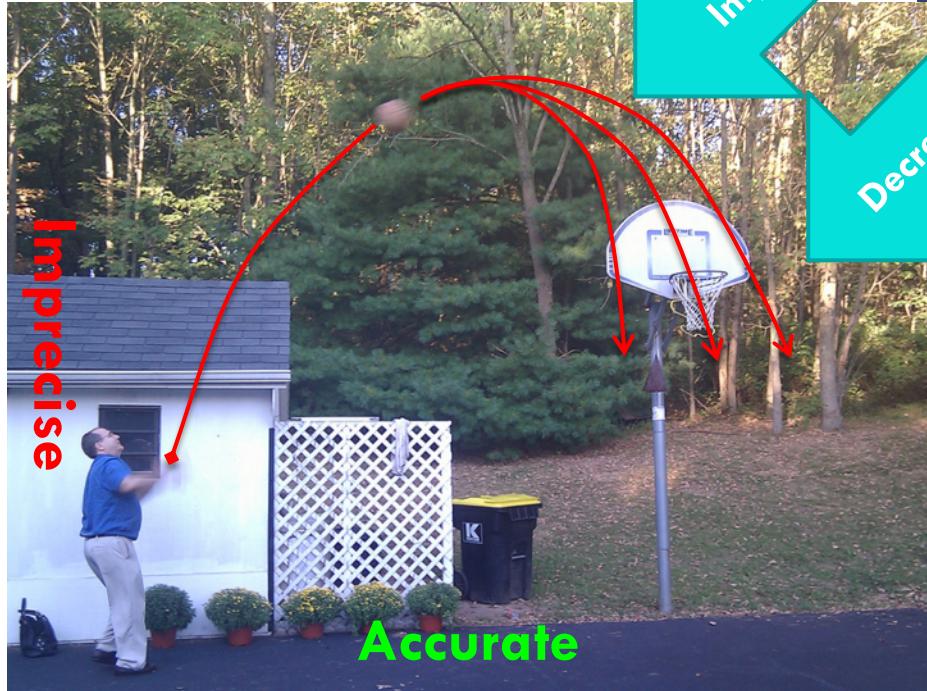
Let's not make *that* mistake.

Two words on error and uncertainty

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- **Error:** the result of a **bias** or **mistake**.
 - **Uncertainty:** the degree to which some thing is not known.
-
- ***It's a mistake to call errors uncertainties.***
 - E.g., experimentalists correct for systematic effects (biases).
 - Corrections come with added uncertainty.



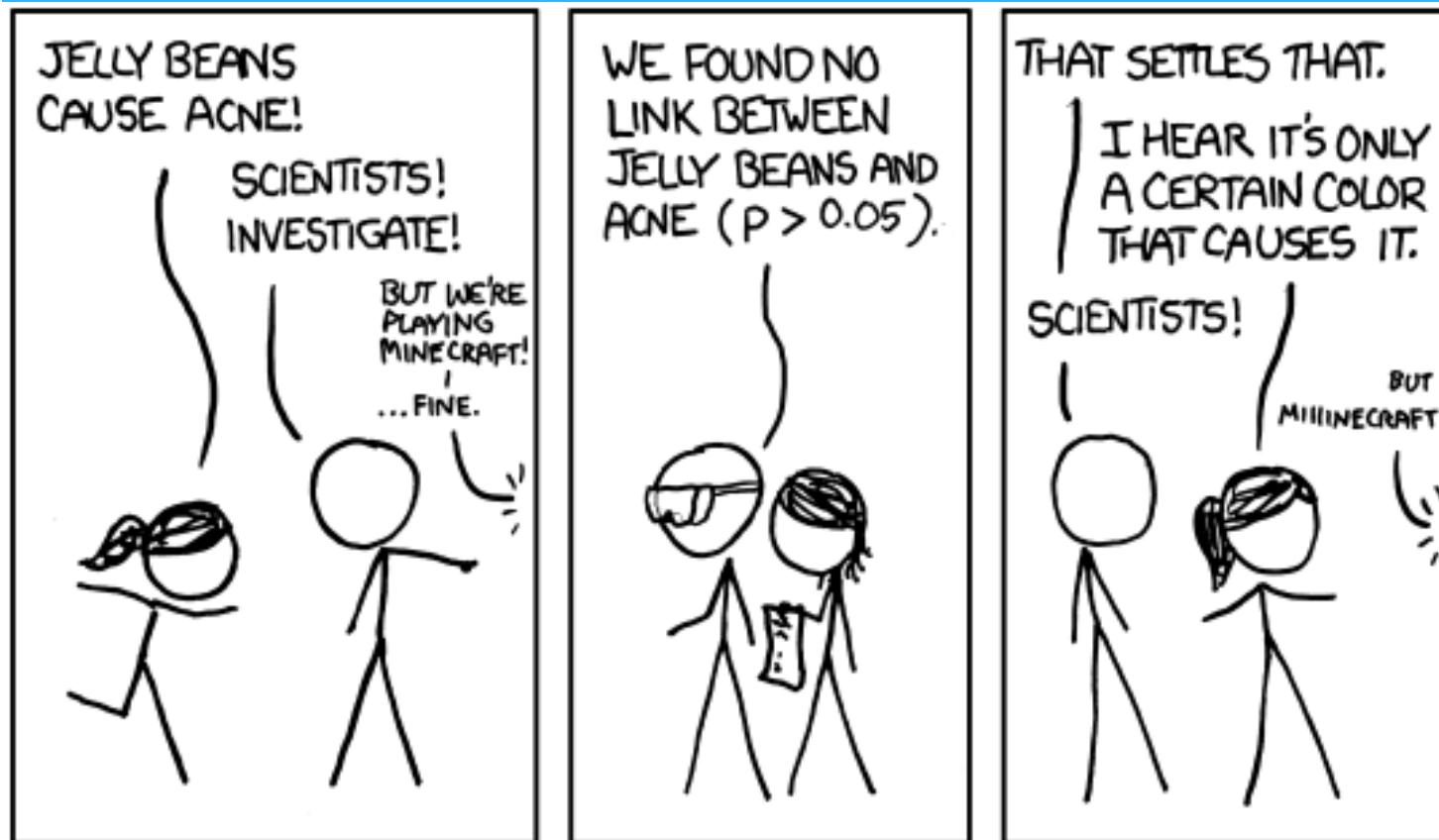


“If you try hard enough...”

Or the price of searching.

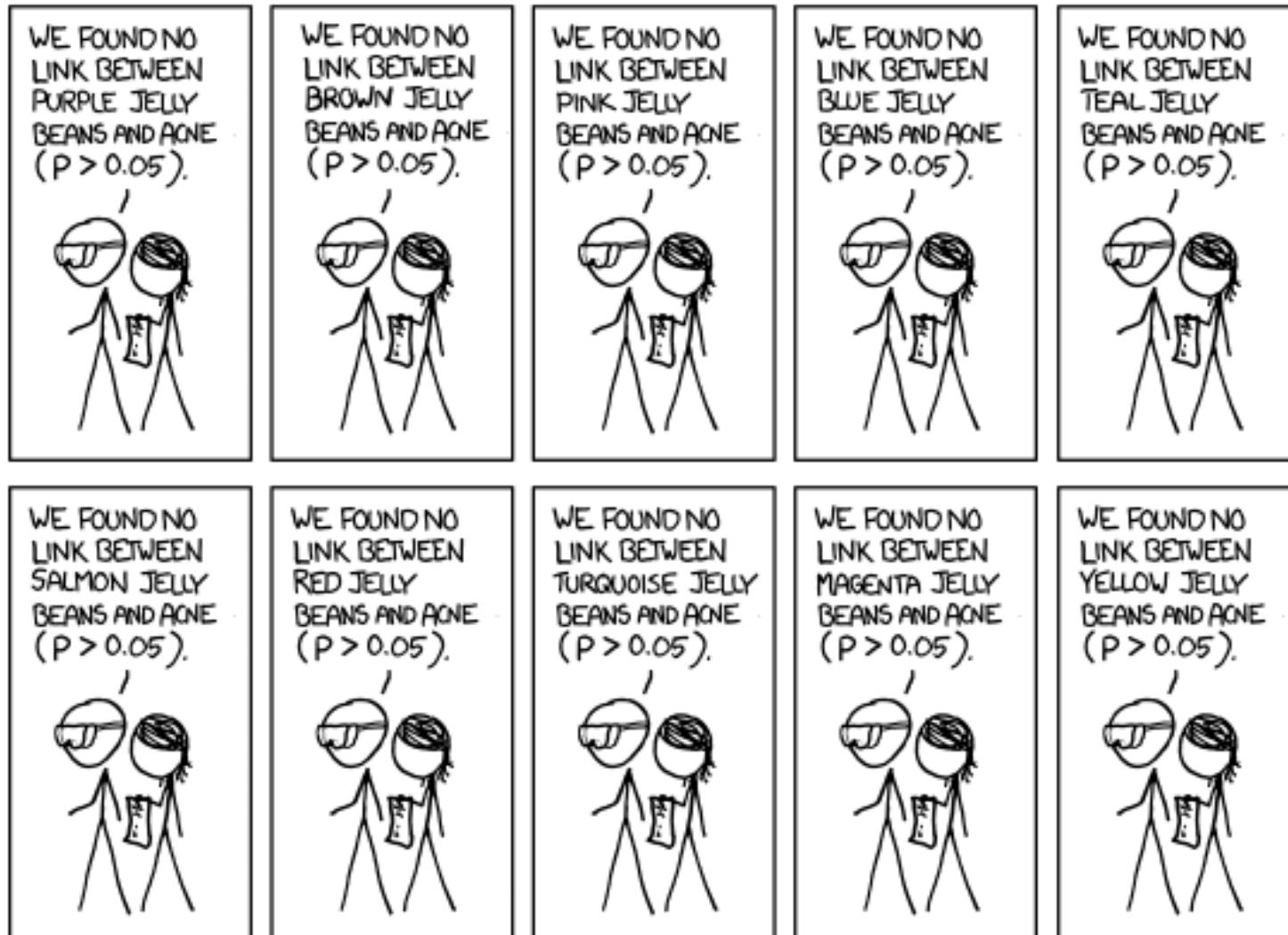
Significant – xkcd.com/882

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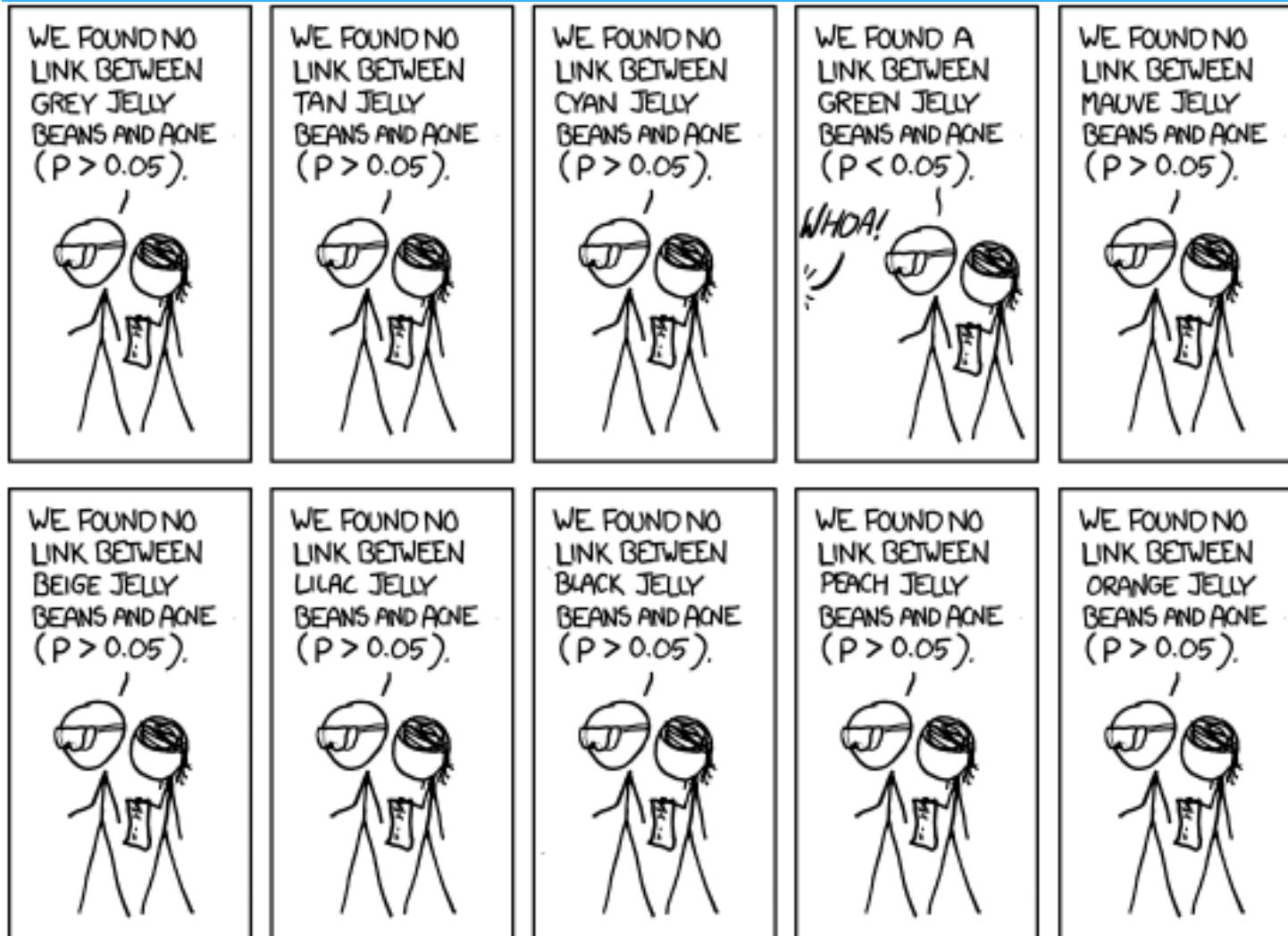
Significant – xkcd.com/882

42

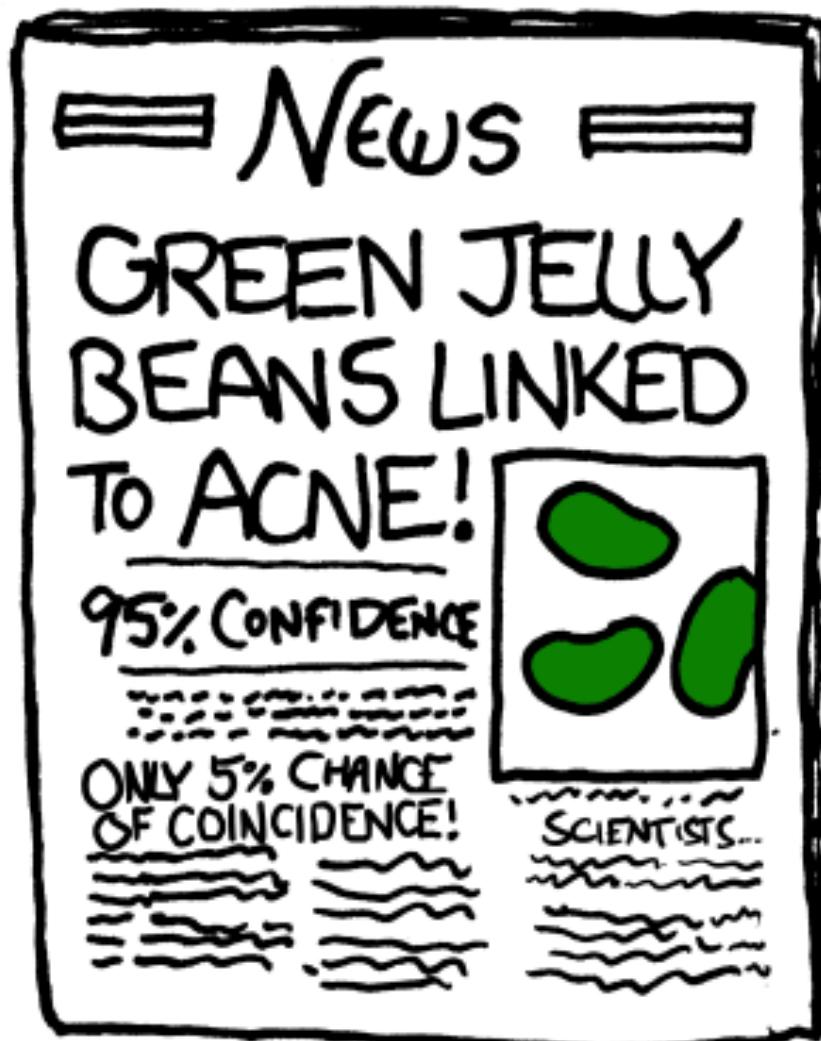


Significant – xkcd.com/882

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Significant – xkcd.com/882



Summary thus far

Theorists may see the next wave.

Experimentalists surf it.

Knowledge comes from disproving.

Respect uncertainty.

Don't mistake error for uncertainty.

The harder you look,
the more you'll find.

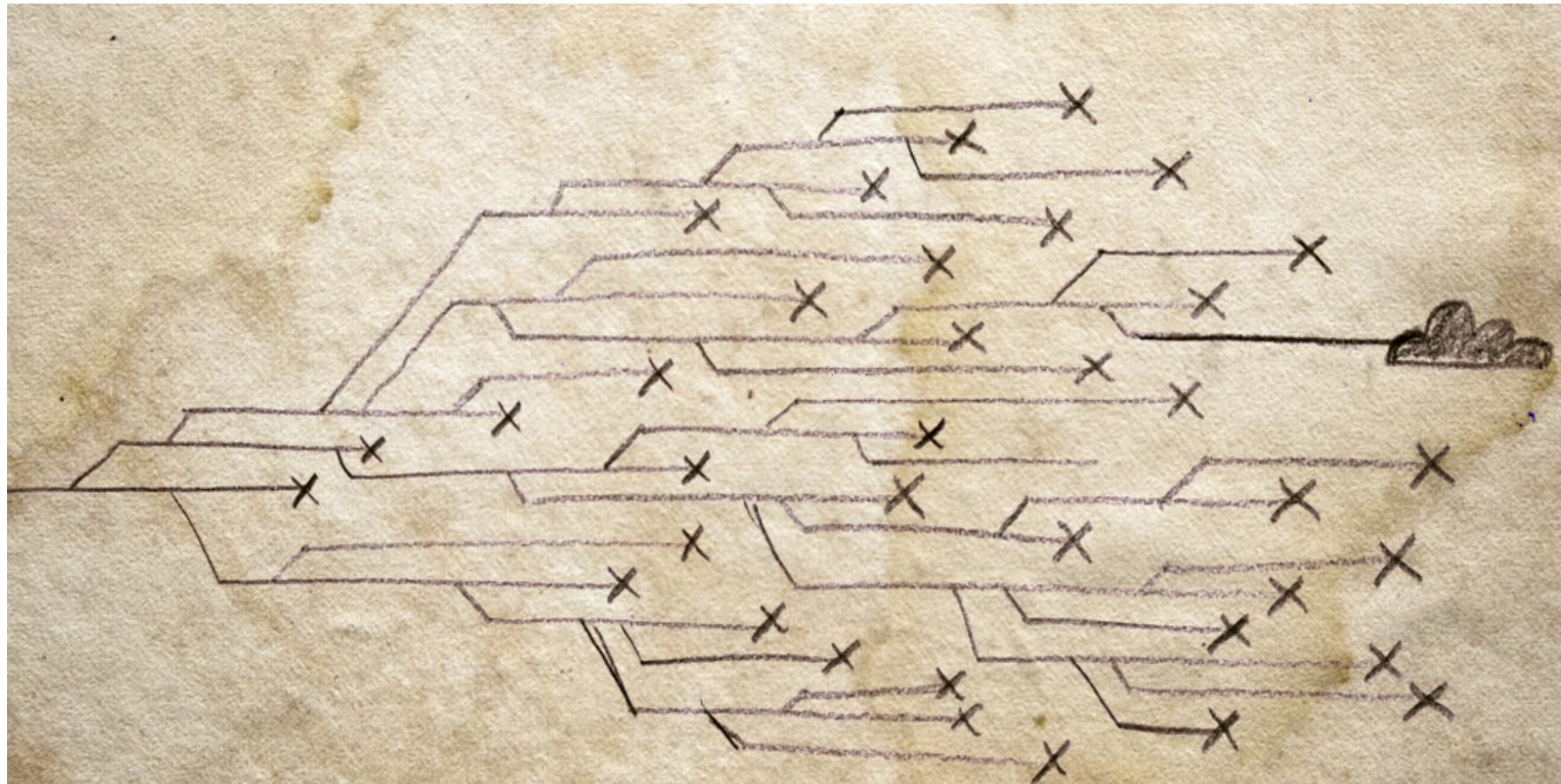
The experimental method

falsifying theories since the dawn of reason



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[opensource.com]



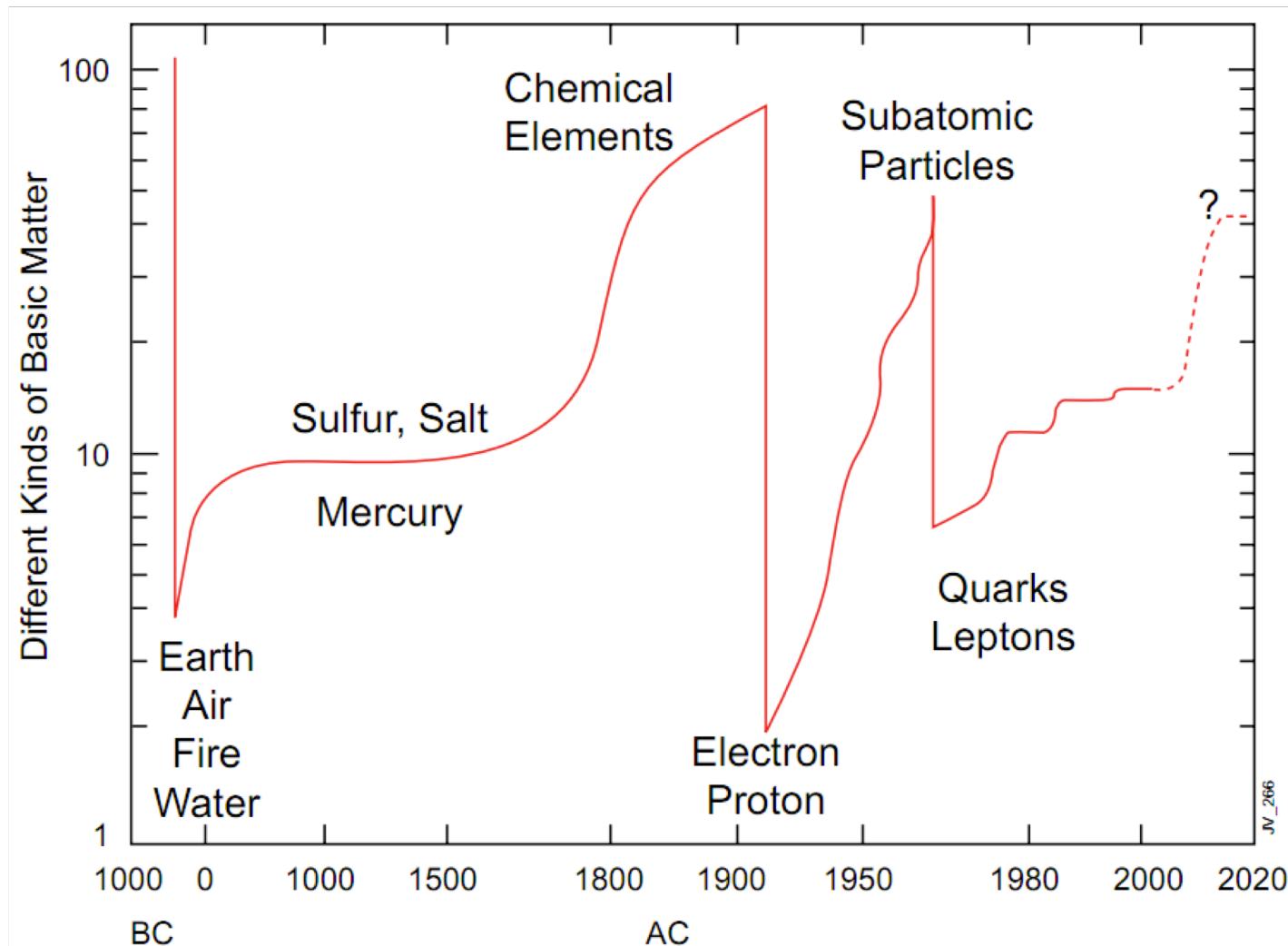
Crosses: experimental results pushing humans to track back and rethink their models.



Evolutions & revolutions of the elements

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[Plot courtesy of Jim Virdee]

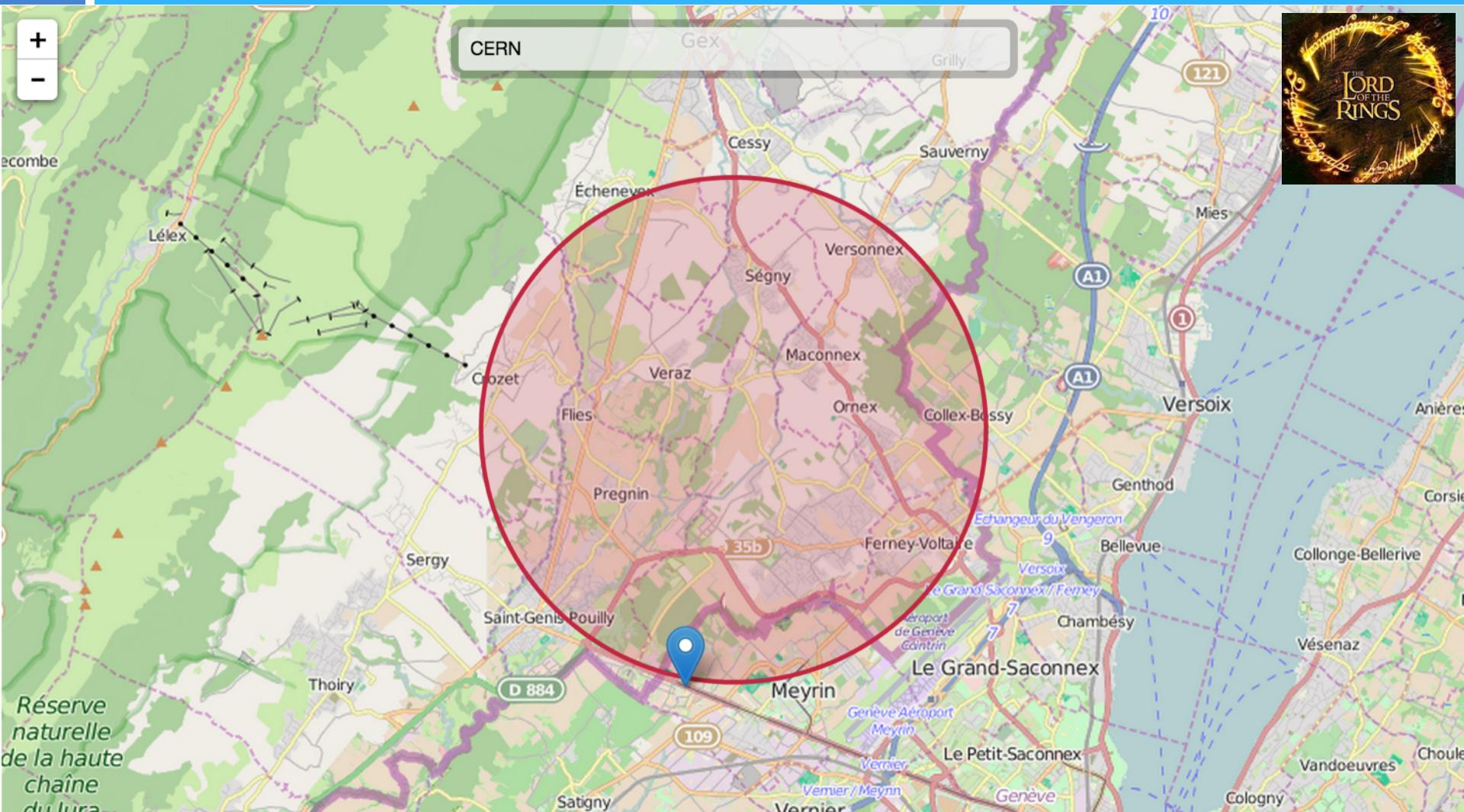




LHC – the lord of the rings

48

[<http://natronics.github.io/science-hack-day-2014/lhc-map/>]

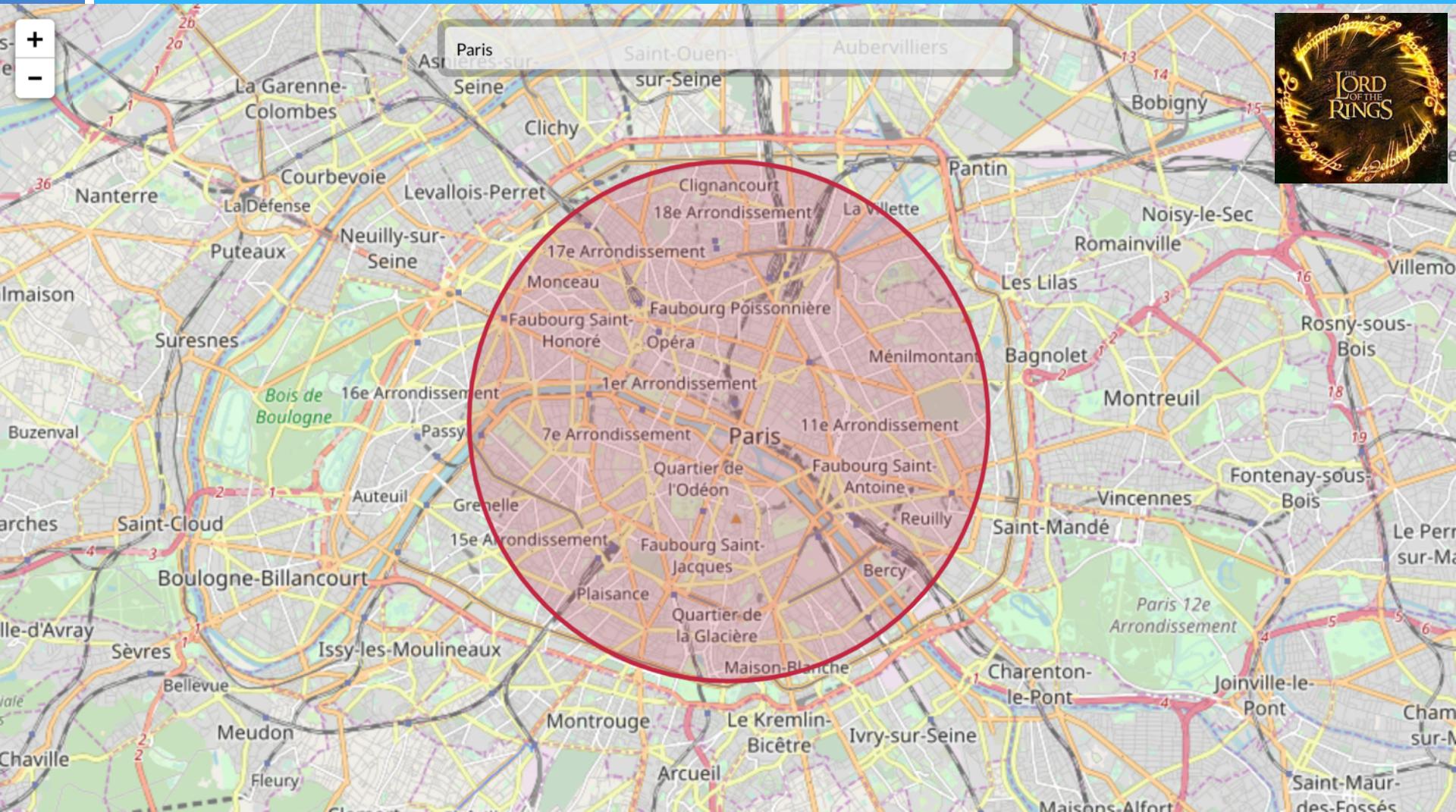




LHC – the lord of the rings

49

[<http://natronics.github.io/science-hack-day-2014/lhc-map/>]

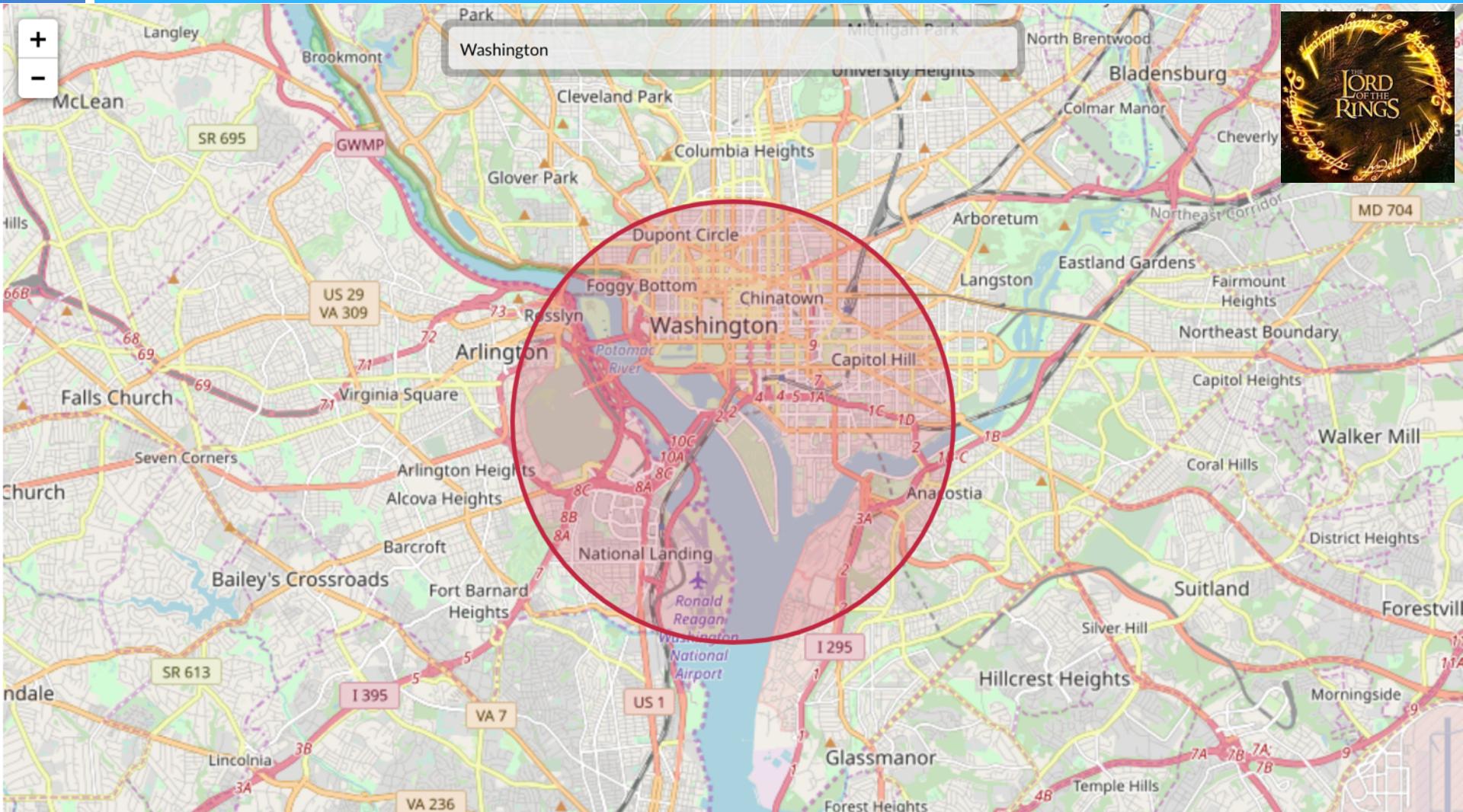




LHC – the lord of the rings

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[<http://natronics.github.io/science-hack-day-2014/lhc-map/>]

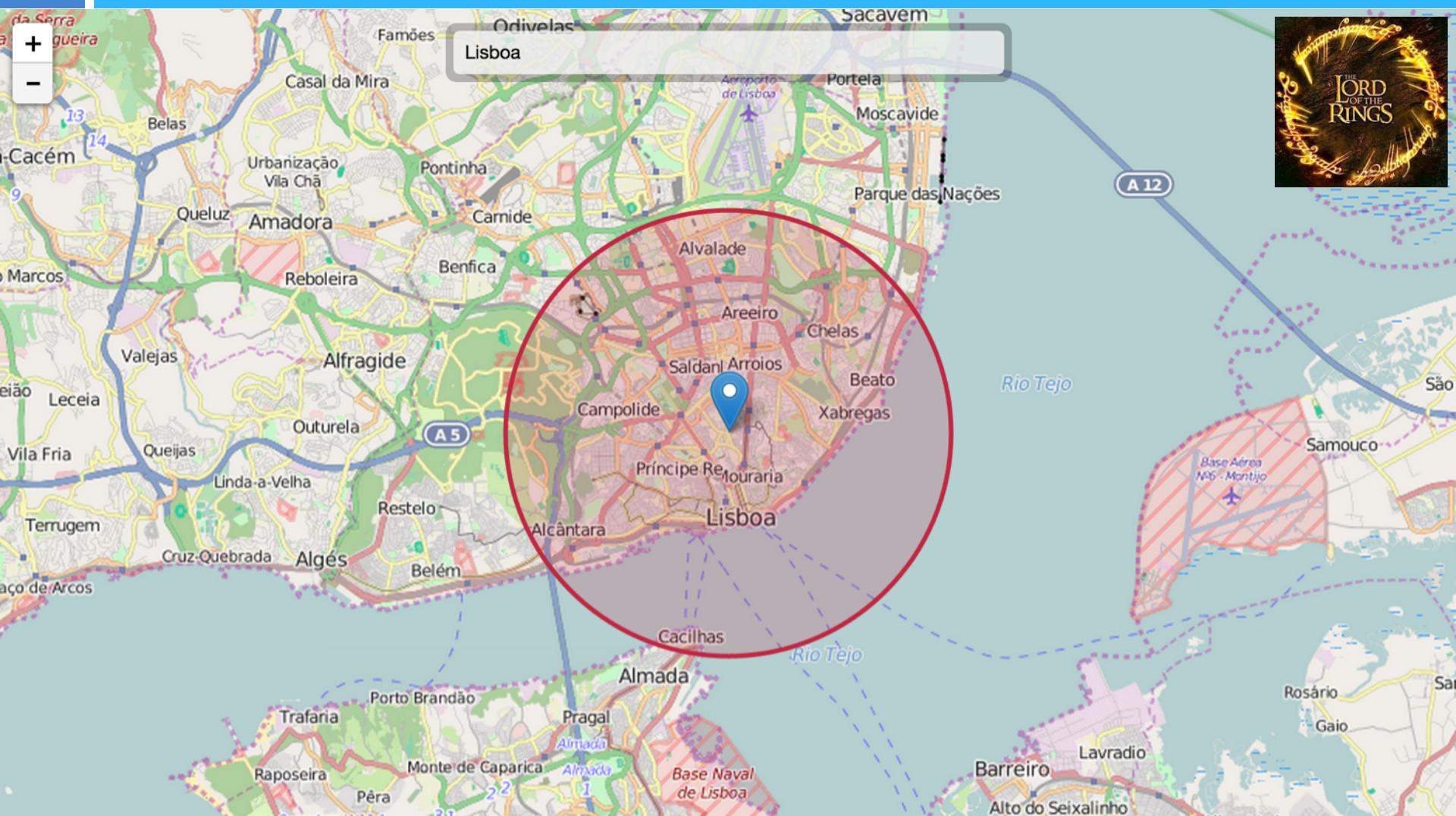




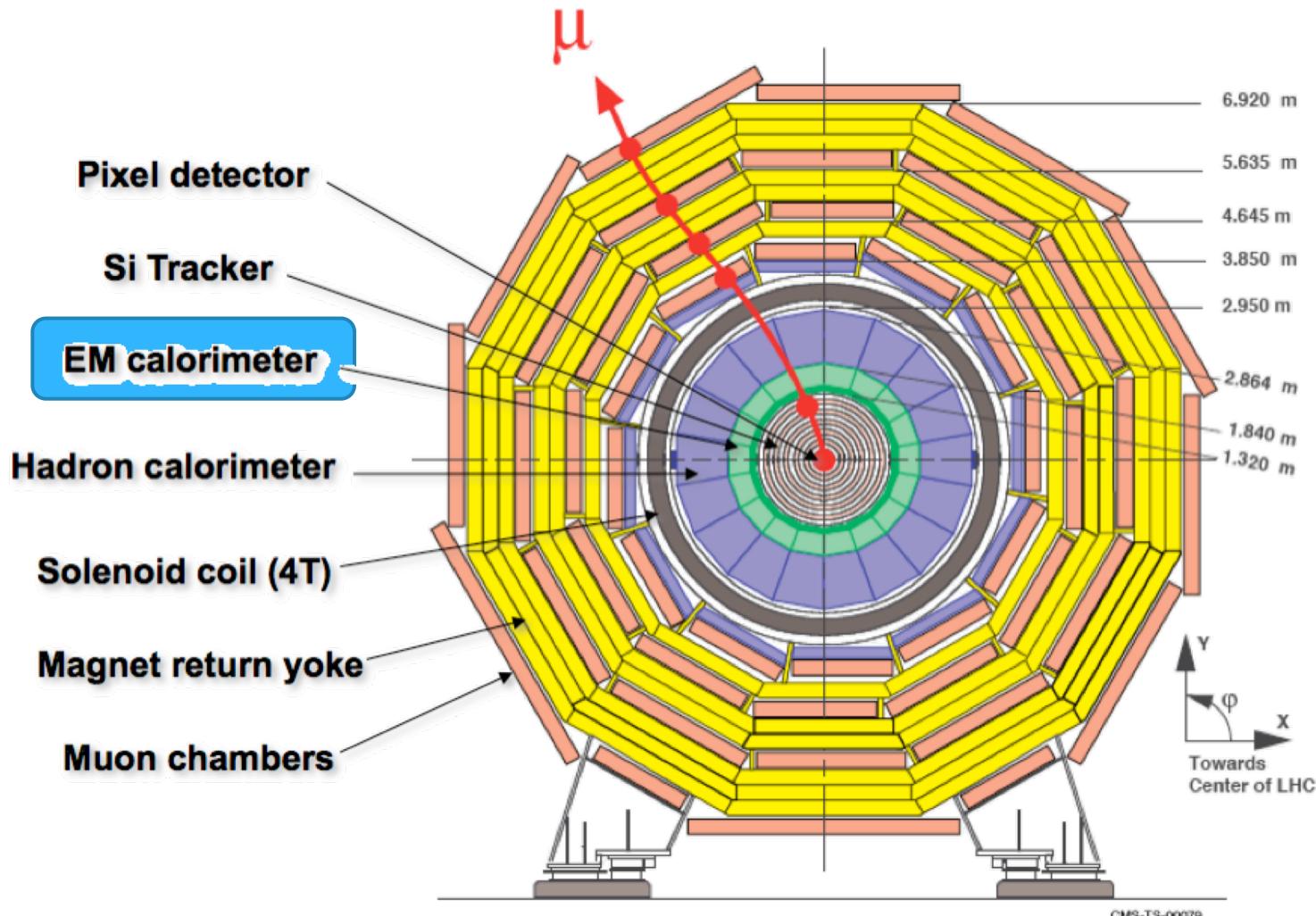
LHC – the lord of the rings

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[<http://natronics.github.io/science-hack-day-2014/lhc-map/>]

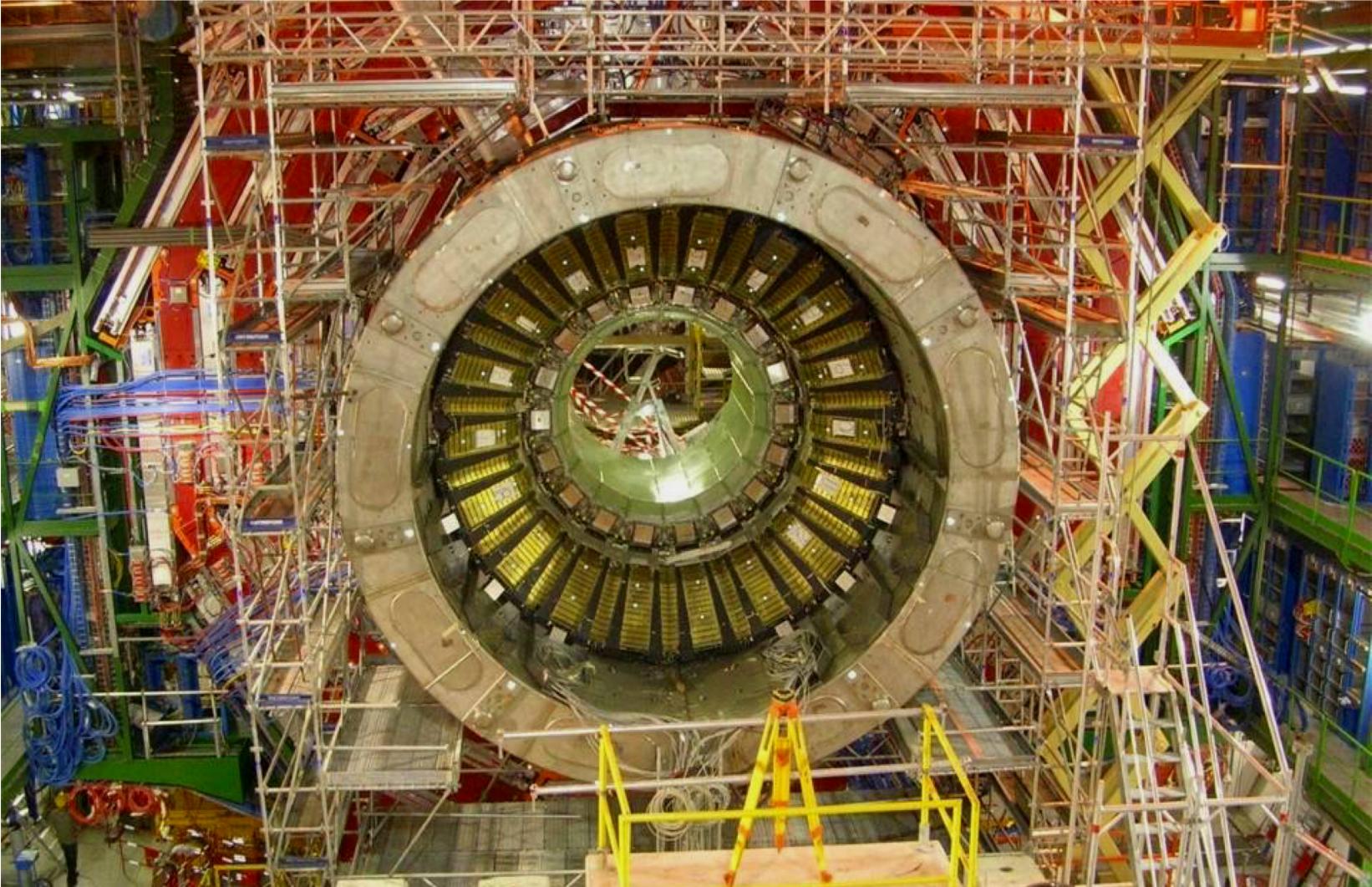


Particle detectors in CMS



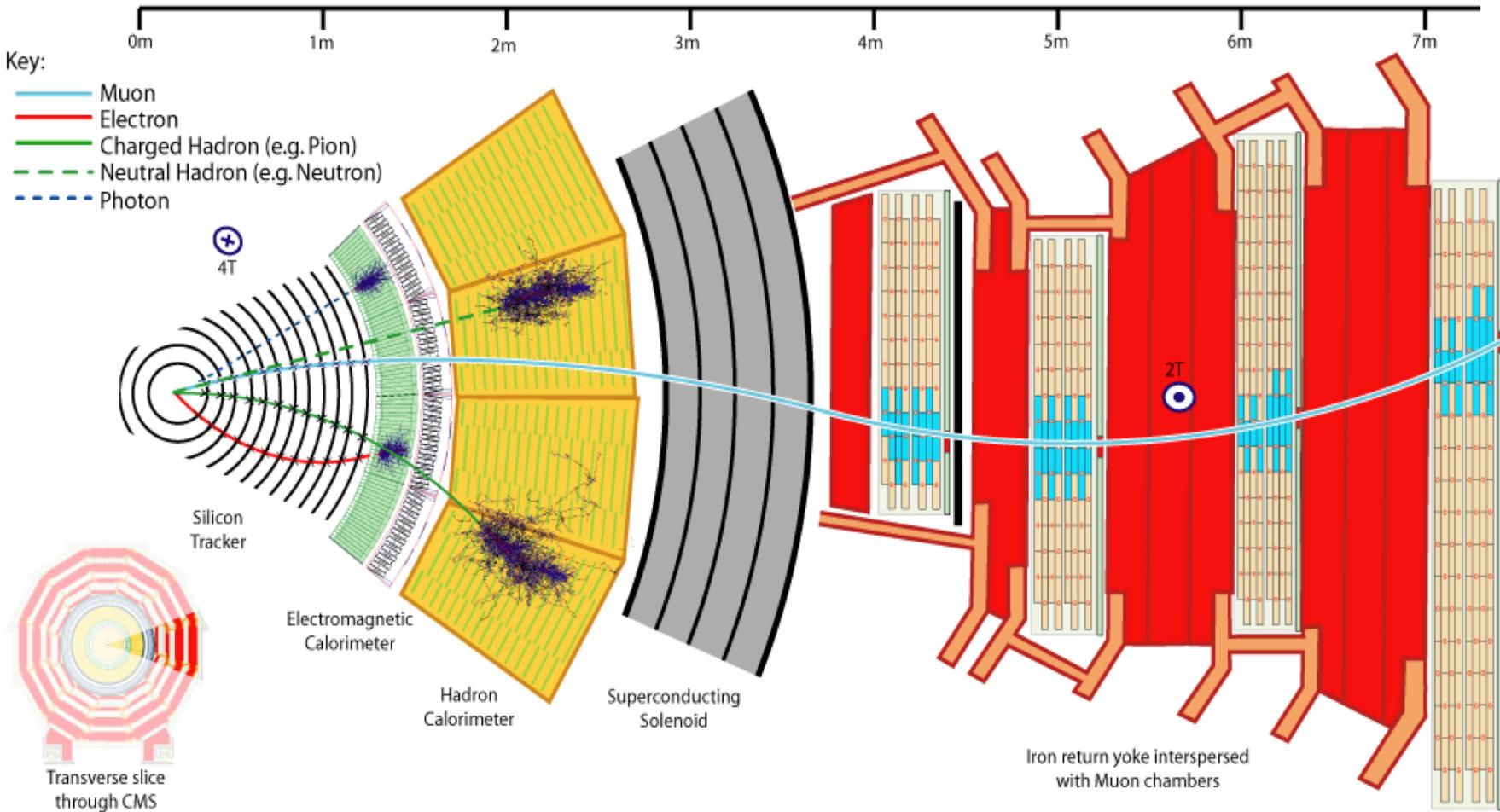
2007: ECAL barrel installed

53



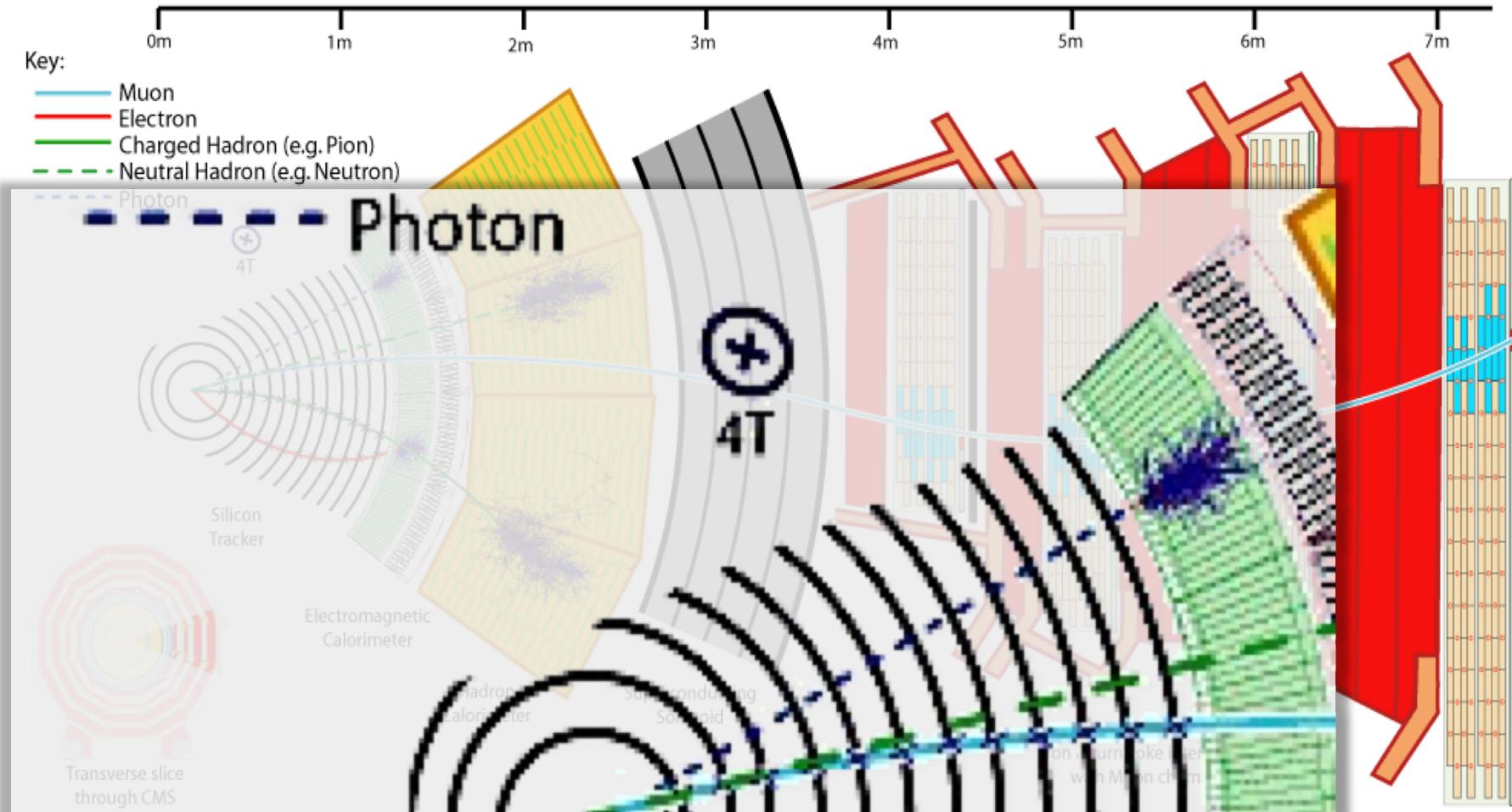
Detecting particles in CMS

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Detecting particles in CMS

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The Standard Model of Particle Physics

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[<http://cern.ch/go/dW6z>]

$$\begin{aligned} & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\ & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\ & M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (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^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \\ & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 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_\nu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \frac{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)^2 H^2] - gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{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)] + \\ & \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\ & W_\mu^- \phi^+) + igs_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\ & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 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}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\ & igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\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}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\ & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + \\ & (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\ & i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\ & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\ & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igs_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) + igs_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^+) + igs_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\ & igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \\ & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igM s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0] \end{aligned}$$



The Standard Model of Particle Physics

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[<http://cern.ch/go/dW6z>]

$$\begin{aligned} & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\ & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\ & M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - ig s_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^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \\ & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 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_\nu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \frac{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)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{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)] + \\ & \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\ & W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\ & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 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}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\ & ig s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\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}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\ & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + \\ & (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_d^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\ & i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\ & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\ & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\ & \partial_\mu \bar{X}^+ Y) + ig c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\ & ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \\ & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0] \end{aligned}$$

The Standard Model of Particle Physics

[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 \\
 & M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu \\
 & A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\nu^+ \\
 & W_\nu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H \\
 & \frac{1}{2}g[W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H) \\
 & W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 \\
 & \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial \\
 & ig s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu \\
 & \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu} \\
 & i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\kappa \\
 & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_e^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + ig c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

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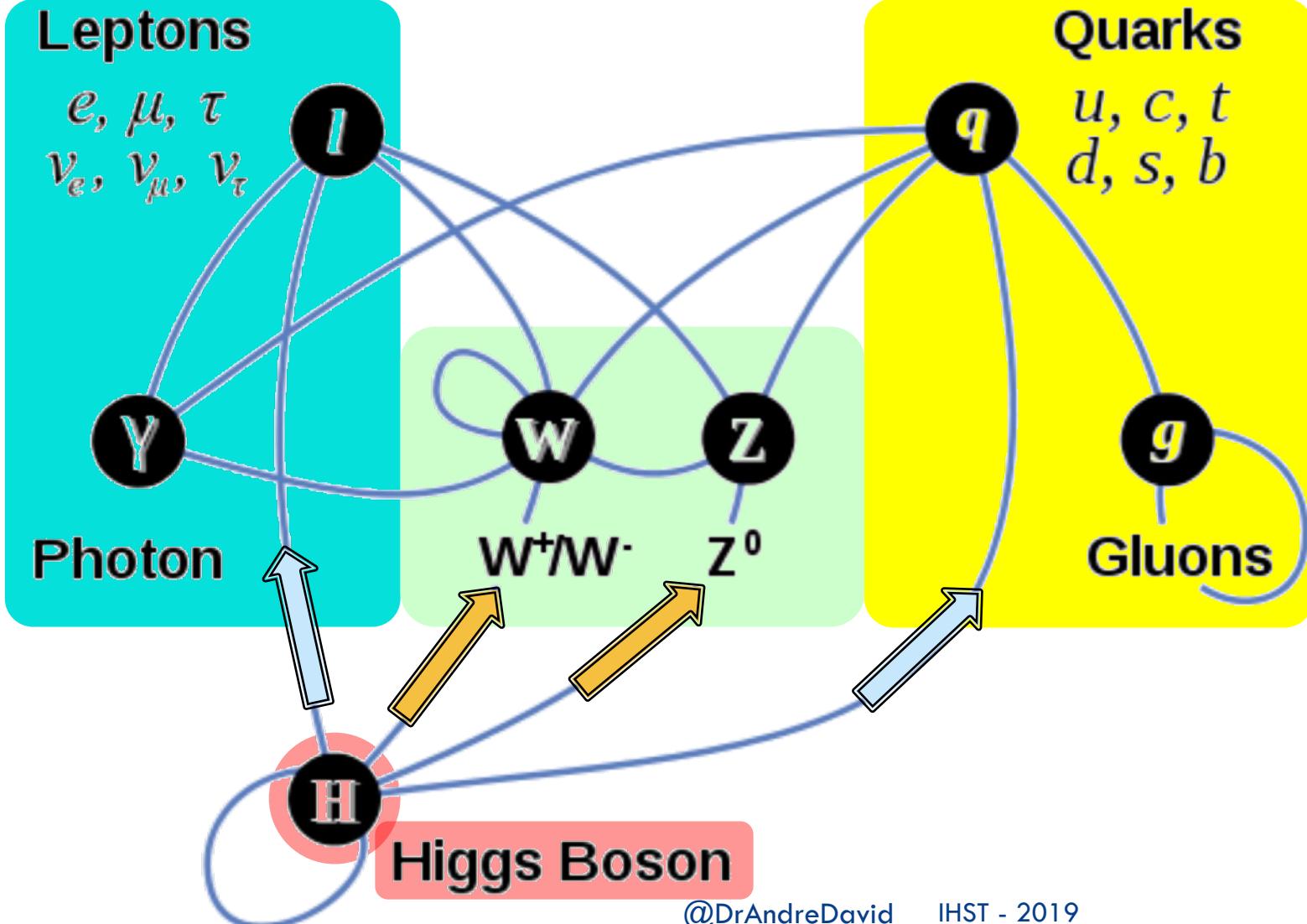
The Standard Model of Particle Physics

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Electromagnetic force – light

Weak force – star combustion

Strong force – protons and neutrons



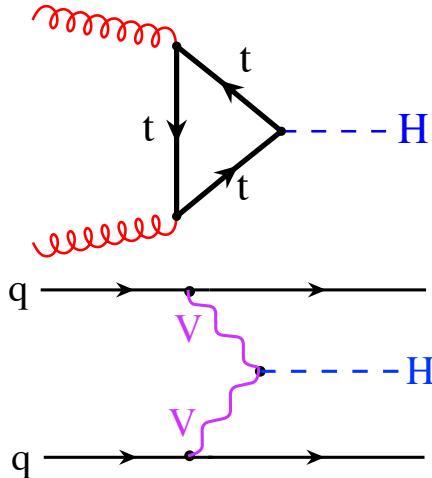
How SM Higgses are born



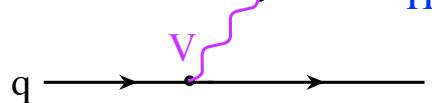
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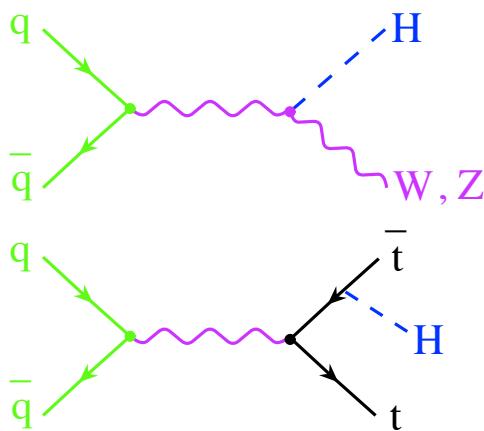
- Gluon fusion**



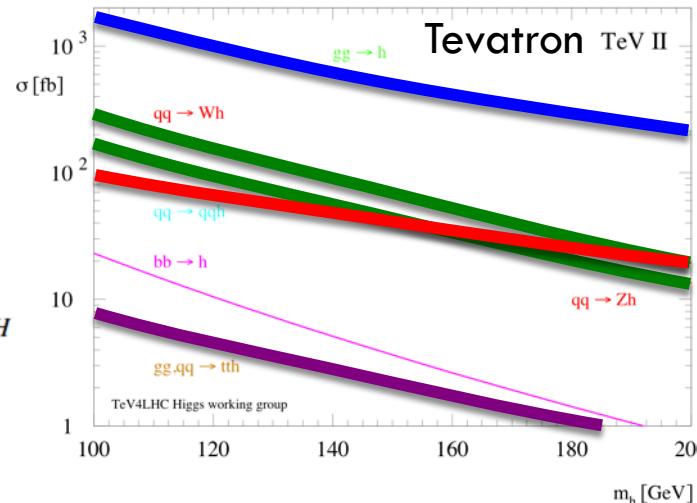
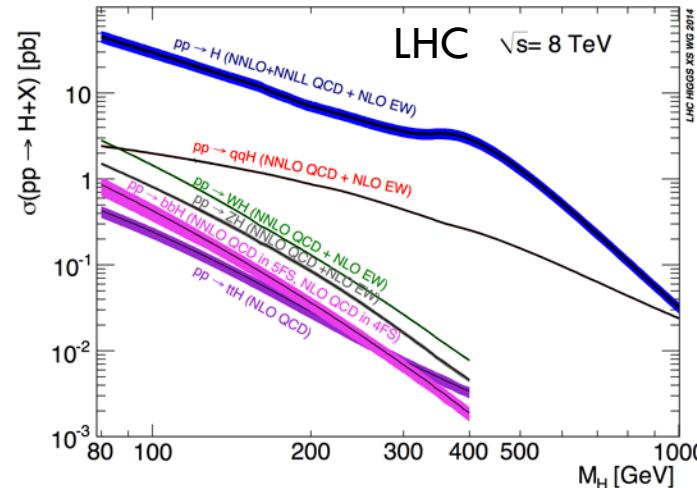
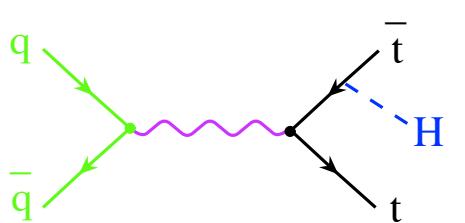
- VBF**



- WH, ZH**



- bbH, ttH**



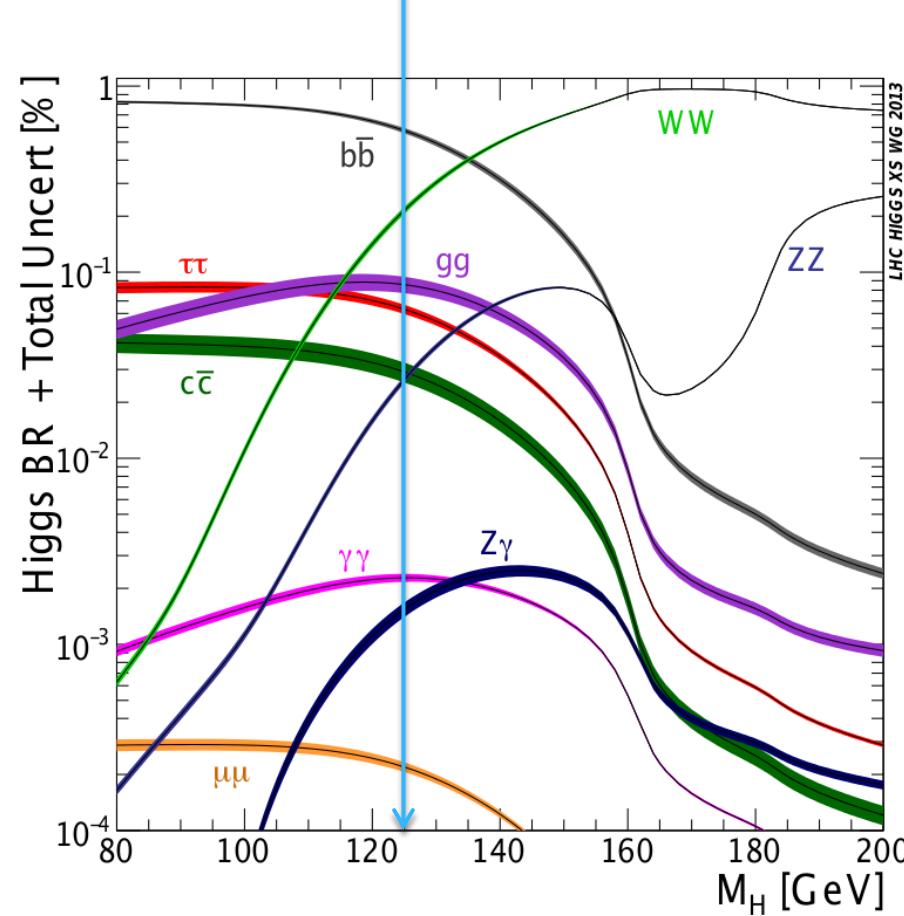
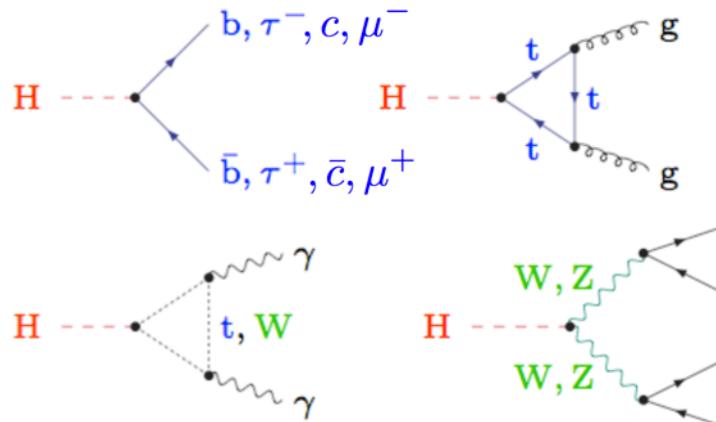
How SM Higgses die



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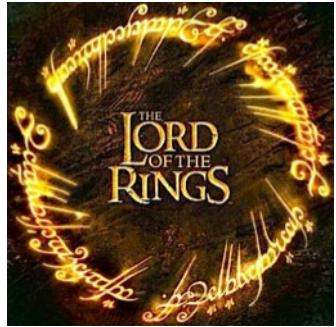
[<http://cern.ch/go/qkh6>][arXiv:1208.1993][arXiv:1408.0827]

- Couplings and kinematics drive BR ($b\bar{b}$, WW , $\tau\tau$, ZZ).
- Decays with photons ($\gamma\gamma$, $Z\gamma$) through loops.





Putting it all together



$$\begin{aligned}
 & -[\partial_x g_{\mu}^{\alpha} \partial_x g_{\nu}^{\beta} - g_x \delta^{\mu \alpha} \partial_x g_{\nu}^{\beta} g_{\rho}^{\sigma} - \frac{1}{2} g_x^2 f^{abc} \delta^{\mu \alpha} \partial_x g_{\nu}^{\beta} g_{\rho}^{\sigma} + \frac{1}{2} g_x^2 (g_{\mu}^{\alpha} \delta^{\nu \beta} g_{\rho}^{\sigma}) g_{\rho}^{\sigma} + \tilde{G}^{\rho} \delta^{\mu \alpha} \partial_x G^{\nu} g_{\rho}^{\sigma} - \\
 & M^2 \phi^2 \phi^2 - [\partial_x \phi^2 \partial_x \phi^2 - \frac{1}{2} M^2 M^2 \phi^2] - \partial_x [\frac{M^2}{2} + M^2 H + \frac{1}{2} (H^2 + \phi^2 \phi^2 + 2 \phi^2 \phi)] + \frac{M^2}{2} \alpha_2 - i g s_w [\partial_x \partial_x W^3 W^3 - \\
 & W^3_W^3 W^3] - Z^0_W (W^3_W \partial_x W^3 - W^3_W \partial_x W^3) + Z^0_W (W^3_W \partial_x W^3 - W^3_W \partial_x W^3)] - i g s_w A_y (W^3_W W^3 - W^3_W W^3) - \\
 & A_y (W^3_W \partial_x W^3 - W^3_W \partial_x W^3) - A_y (W^3_W \partial_x W^3 - W^3_W \partial_x W^3) - i g s_w [W^3_W W^3_W W^3_W + g^2 T^3_W W^3_W W^3_W + \\
 & g^2 c^2_Z Z^0_W Z^0_W W^3_W + Z^0_W Z^0_W W^3_W] - g^2 s_w A_y W^3_W W^3_W + g^2 T^3_W W^3_W W^3_W + \\
 & W^3_W W^3] - 2 A_y Z^0_W W^3_W - s g^2 H^2 + H^2 \phi^2 + 2 H^2 \phi^2 + 1 g^2 \alpha_s [H + (\phi^2)^2 + 4 (\phi^2 \phi^2)^2 + 2 H^2 \phi^2 + 2 H^2 \phi^2 + \\
 & 4 H^2 \phi^2 + 2 (2 \phi^2)^2 H^2] - g s_w W^3_W W^3_H - \frac{1}{2} g^2 Z^0_W Z^0_W H - \frac{1}{2} g [W^3_W (\phi^2 \partial_x \phi^2 - \phi^2 \partial_x \phi^2) - W^3_W (\phi^2 \partial_x \phi^2 - \phi^2 \partial_x \phi^2) + \\
 & g [W^3_W (\partial_x \phi^2 - \phi^2 \partial_x H) - W^3_H (\partial_x \phi^2 - \phi^2 \partial_x H)] + g s_w (Z^0_W H \phi^2 \phi^2 - \phi^2 \partial_x H) - i g^2 M^2 Z^0_W (W^3_W \phi^2 - \\
 & W^3_W \phi^2) + i g s_w M A_y (W^3_W \phi^2 - W^3_W \phi^2) - i g^2 \frac{c^2_Z}{2} Z^0_W (\phi^2 \partial_x \phi^2 - \phi^2 \partial_x \phi^2) + i g s_w A_y (\phi^2 \partial_x \phi^2 - \phi^2 \partial_x \phi^2) - \\
 & \frac{1}{2} g^2 W^3_W W^3_H [H^2 + (\phi^2)^2 + 2 \phi^2 \phi^2] - \frac{1}{2} g^2 \frac{c^2_Z}{2} Z^0_W Z^0_W [H^2 + (\phi^2)^2 + 2 (2 \phi^2 - 1)^2 \phi^2 \phi^2] - \frac{1}{2} g^2 \frac{c^2_Z}{2} Z^0_W \delta^0 (W^3_W \phi^2 + \\
 & W^3_W \phi^2) - \frac{1}{2} g^2 \frac{c^2_Z}{2} Z^0_W H (W^3_W \phi^2 - W^3_W \phi^2) + \frac{1}{2} g^2 s_w A_y J_\mu (W^3_W \phi^2 - W^3_W \phi^2) - \\
 & g^2 \frac{c^2_Z}{2} (2 \phi^2 - 1) Z^0_W A_y \phi^2 - g^2 s_w A_y A_y \phi^2 \phi^2 - \bar{e}^2 (\phi^2 + m^2) e^2 - \bar{e}^2 (\phi^2 + m^2) e^2 - \bar{e}^2 (\phi^2 + m^2) e^2 - d^2 (\gamma + m^2) d^2 + \\
 & i g s_w A_y - (d^2 \gamma^2 e^2)^2 + \{(\bar{e}^2 \gamma^2 e^2) - \{(\bar{d}^2 \gamma^2 d^2)\}\} + \frac{d^2}{2} Z^0_W (\bar{e}^2 \gamma^2 (1 + \gamma^2) e^2) + \{(\bar{e}^2 \gamma^2 (1 + \gamma^2) e^2) + (\bar{e}^2 \gamma^2 (1 + \gamma^2) e^2)\} + (\bar{d}^2 \gamma^2 (1 + \gamma^2) d^2) + \\
 & (d^2 \gamma^2 (1 + \gamma^2) d^2)\} + \frac{d^2}{2} Z^0_W [(\bar{e}^2 \gamma^2 (1 + \gamma^2) e^2) + (\bar{e}^2 \gamma^2 (1 + \gamma^2) e^2)] + \frac{d^2}{2} Z^0_W [(\bar{d}^2 \gamma^2 (1 + \gamma^2) d^2) + \\
 & (\bar{d}^2 \gamma^2 (1 + \gamma^2) d^2)] + \frac{d^2}{2} Z^0_W [-\phi^2 (\bar{e}^2 (1 + \gamma^2) e^2) + \phi^2 (\bar{e}^2 (1 + \gamma^2) e^2)] - \frac{d^2}{2} Z^0_W [H (e^2 e^2) + \\
 & i g^2 (\bar{e}^2 \gamma^2 e^2)] + \frac{i g^2}{2} Z^0_W \phi^2 [-m g^2 (\bar{e}^2 C_{\mu \nu} (1 - \gamma^2) e^2)] + m^2 (\bar{e}^2 C_{\mu \nu} (1 + \gamma^2) e^2)] - \frac{i g^2}{2} Z^0_W \phi^2 [m g^2 (\bar{d}^2) \bar{d}^2 C_{\mu \nu} (1 + \gamma^2) d^2] - \\
 & m g^2 (\bar{d}^2 C_{\mu \nu} (1 - \gamma^2) d^2) - \frac{i g^2}{2} H (\bar{e}^2 e^2) - \frac{i g^2}{2} H (\bar{d}^2 d^2) + \frac{1}{2} \frac{g^2}{2} \delta^0 (\bar{e}^2 \gamma^2 e^2) + \frac{1}{2} \frac{g^2}{2} \delta^0 (\bar{d}^2 \gamma^2 d^2) + \bar{X}^+ (\bar{P} - \\
 & M^2) X^+ + \bar{X}^- (\bar{P} - M^2) X^- + X^0 (\bar{P}^2 - \frac{M^2}{2}) X^0 + \bar{Y} (\bar{P}^2) + i g s_w W^3_\mu (\partial_x \bar{X}^+ X^- - \partial_x \bar{X}^- X^+) + i g s_w W^3_\mu (\partial_x \bar{Y} X^- - \\
 & \partial_x \bar{X}^+ Y) + i g s_w W^3_\mu (\partial_x \bar{X}^- X^0 - \partial_x \bar{X}^0 X^-) + i g M [X^+ X^- H + \bar{X}^- X^0 H + \frac{1}{2} X^0 X^0 H] + \frac{1}{2} \frac{g^2}{2} (i g M) [\bar{X}^+ X^0 \phi^2 - \\
 & X^- X^0 \phi^2] + \frac{1}{2} \frac{g^2}{2} (i g M) [X^0 X^- \phi^2 - X^0 X^0 \phi^2] + i g M s_w [X^0 X^- \phi^2 - X^0 X^0 \phi^2] + \frac{1}{2} [g M] [X^+ X^- \phi^2 - \bar{X}^- X^0 \phi^2]
 \end{aligned}$$

?

2011: nothing else in the horizon

63

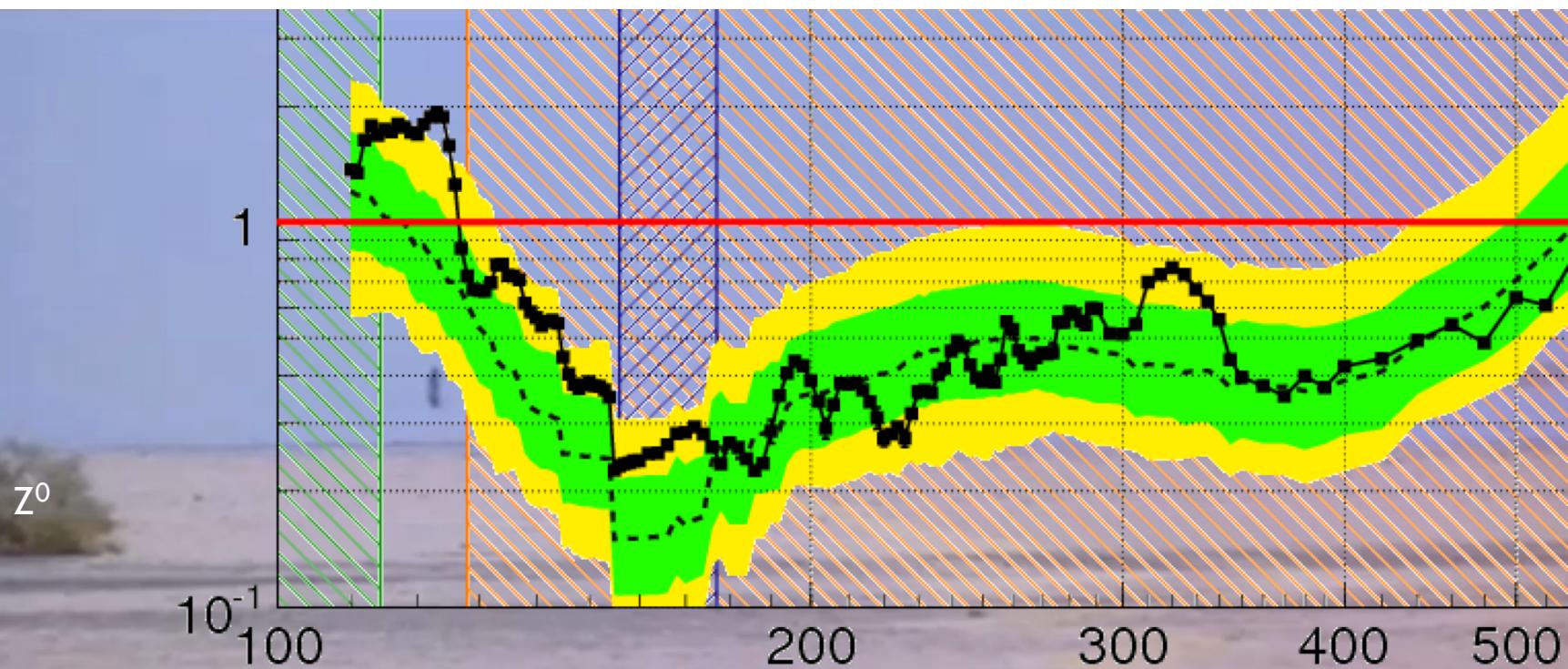
["Lawrence of Arabia" idea from C. Grojean]

- We first saw that we could not exclude a narrow range.



2011: nothing else in the horizon

- We first saw that we could not exclude a narrow range.



Some theorists...

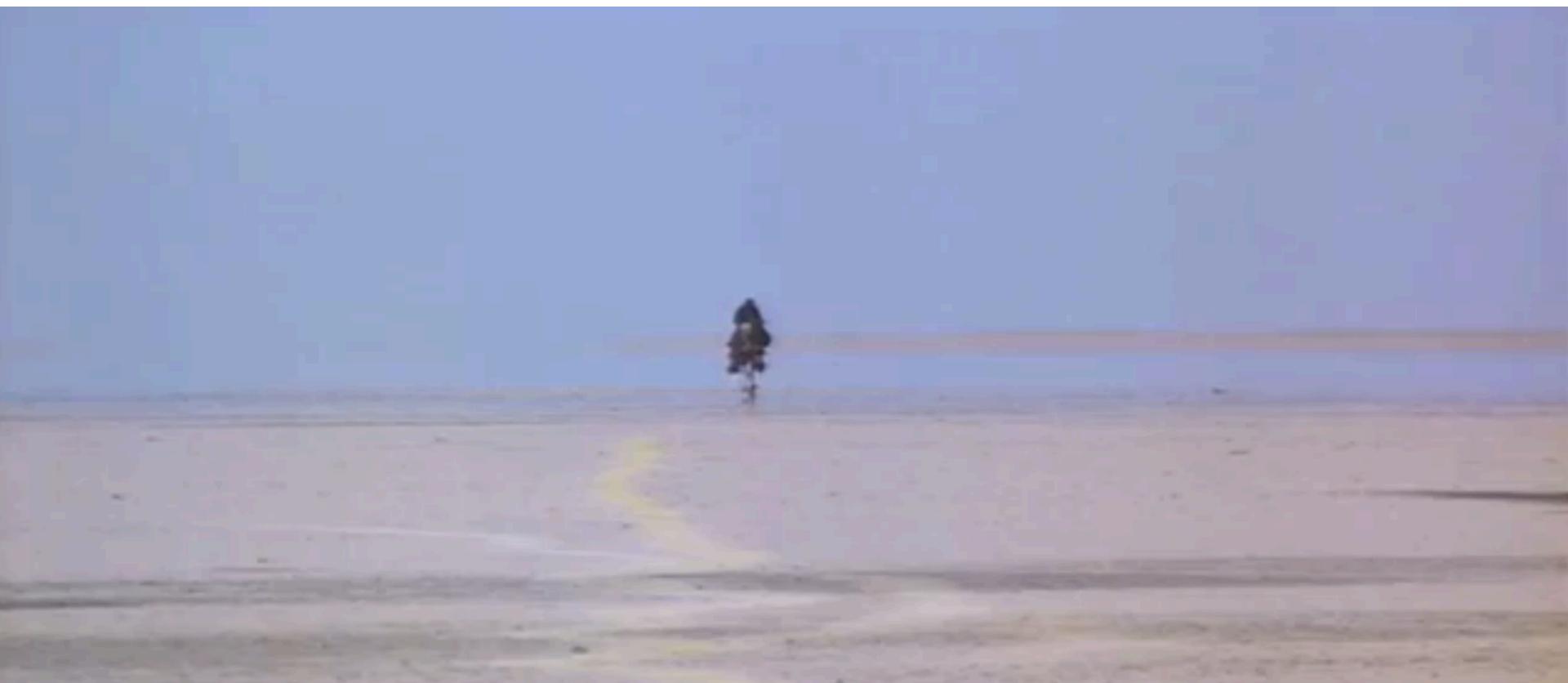


65



2012: a rider!

- We discovered a peak rising from the background.

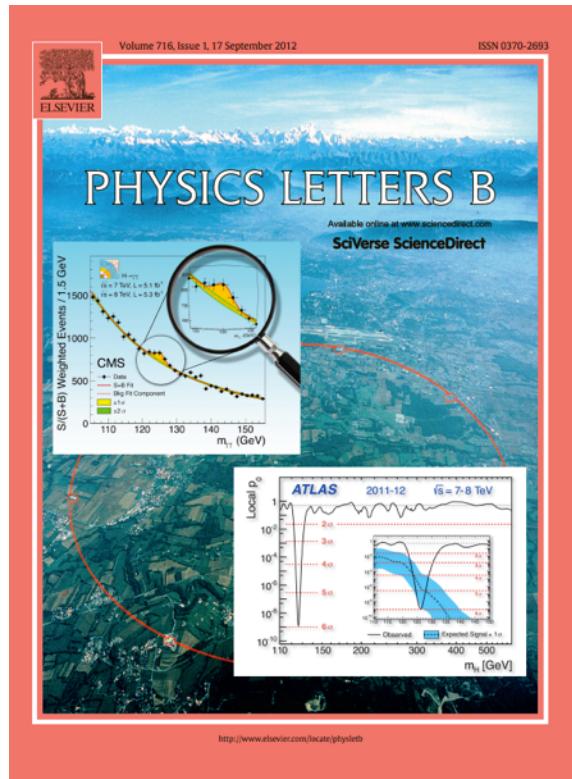


July 4, 2012

Looking up to a new boson

67

[<http://cern.ch/go/q8jx>]

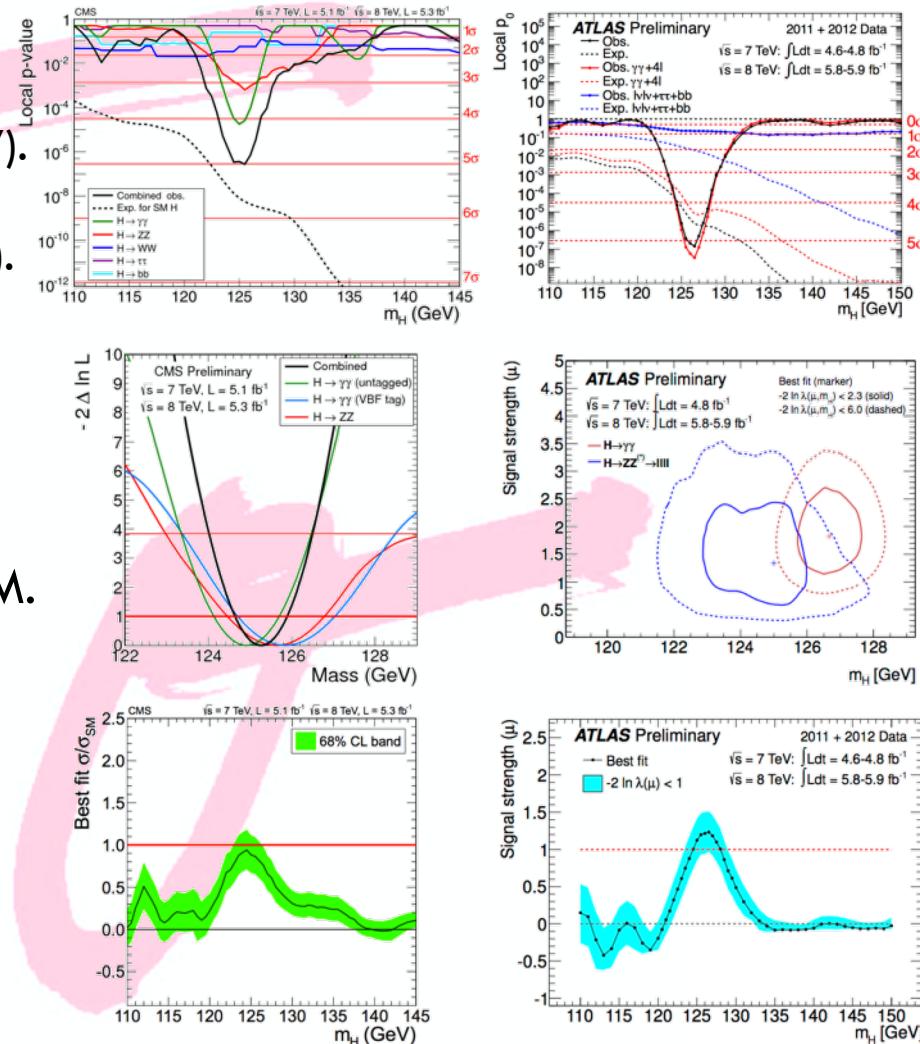
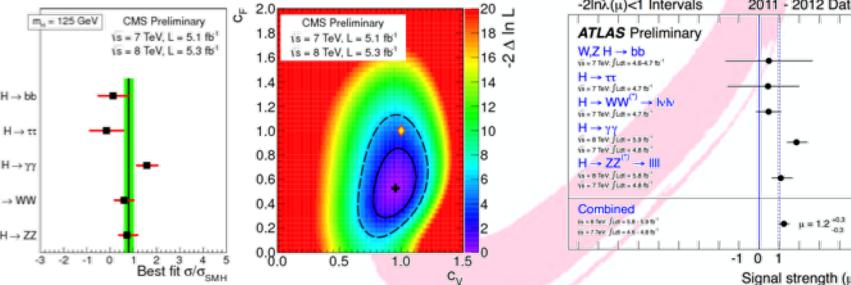


Higgsdependence day recap

68

[<http://cern.ch/go/q8jx>]

- Both experiments at 5.0σ .
 - One above SM expectations...
 $\sigma_{\text{ATLAS}}/\sigma_{\text{SM}} = 1.2 \pm 0.3$ (at 126.5 GeV).
 - ...the other one below.
 $\sigma_{\text{CMS}}/\sigma_{\text{SM}} = 0.80 \pm 0.20$ (at 125 GeV).
- Mass
 - ATLAS: min. p-value at 126.5 GeV.
 - CMS: $m_x = 125.3 \pm 0.6$ GeV.
- “Proto-couplings” compatible with SM.
- **“More data needed...”**



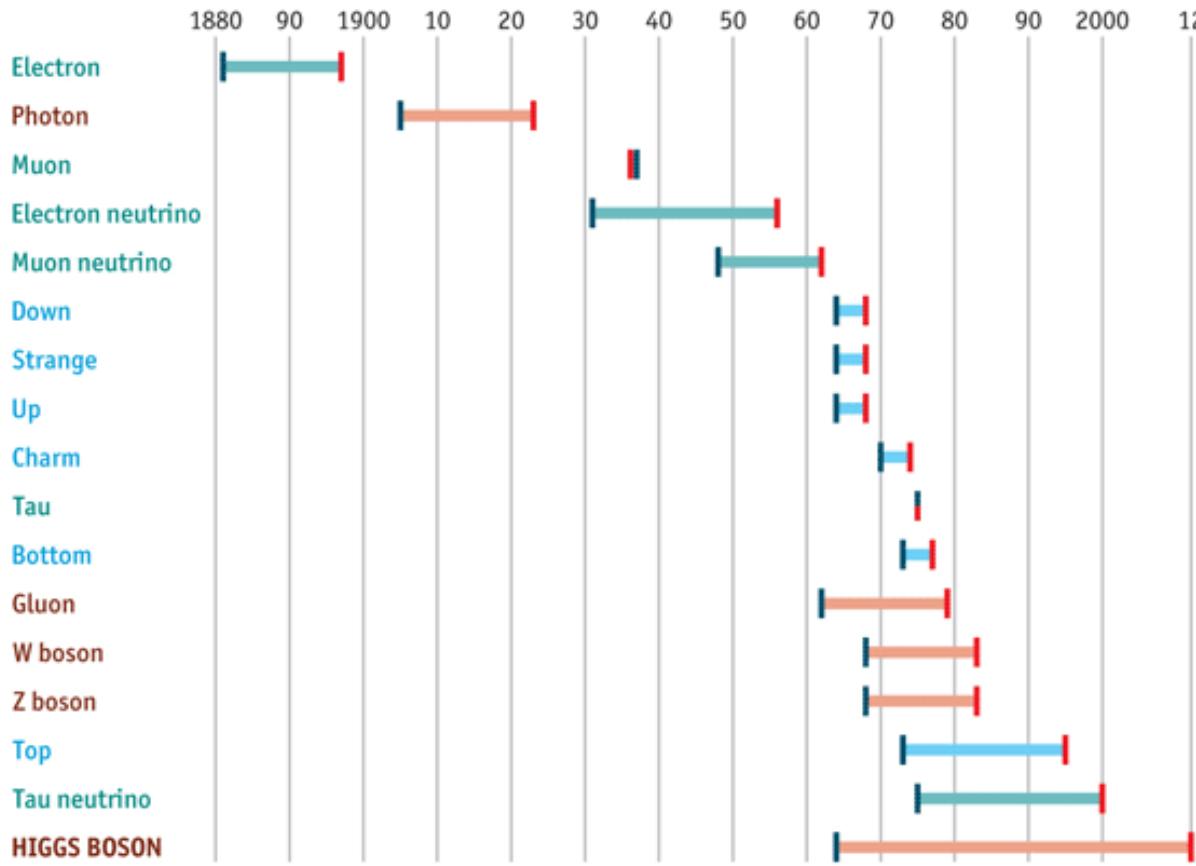
Evolutions & revolutions of the elements

69

The Standard Model of particle physics

Years from concept to discovery

— Leptons
— Bosons
— Quarks
| Theorised/explained
| Discovered



Source: *The Economist*

Evolutions & revolutions of the elements

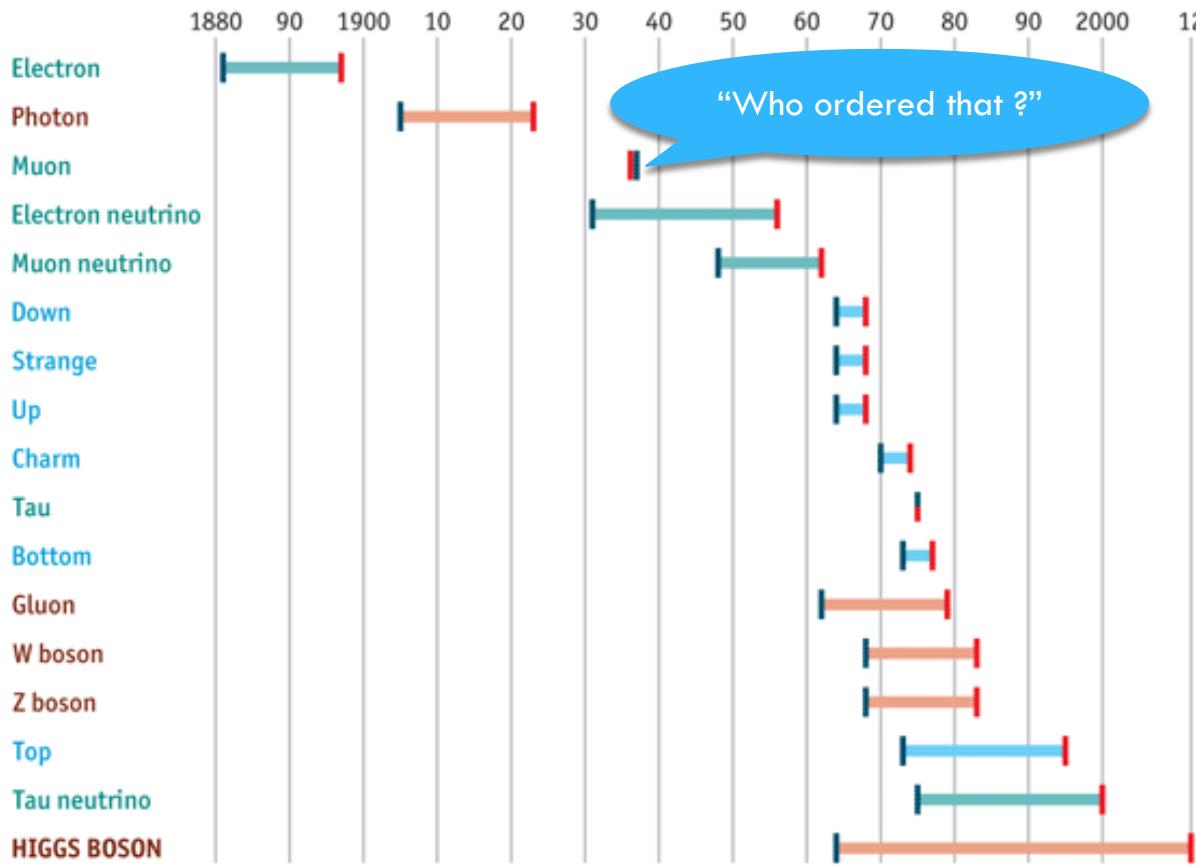
70

The Standard Model of particle physics

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Leptons
Bosons
Quarks

Theorised/explained
Discovered



Source: *The Economist*

Evolutions & revolutions of the elements

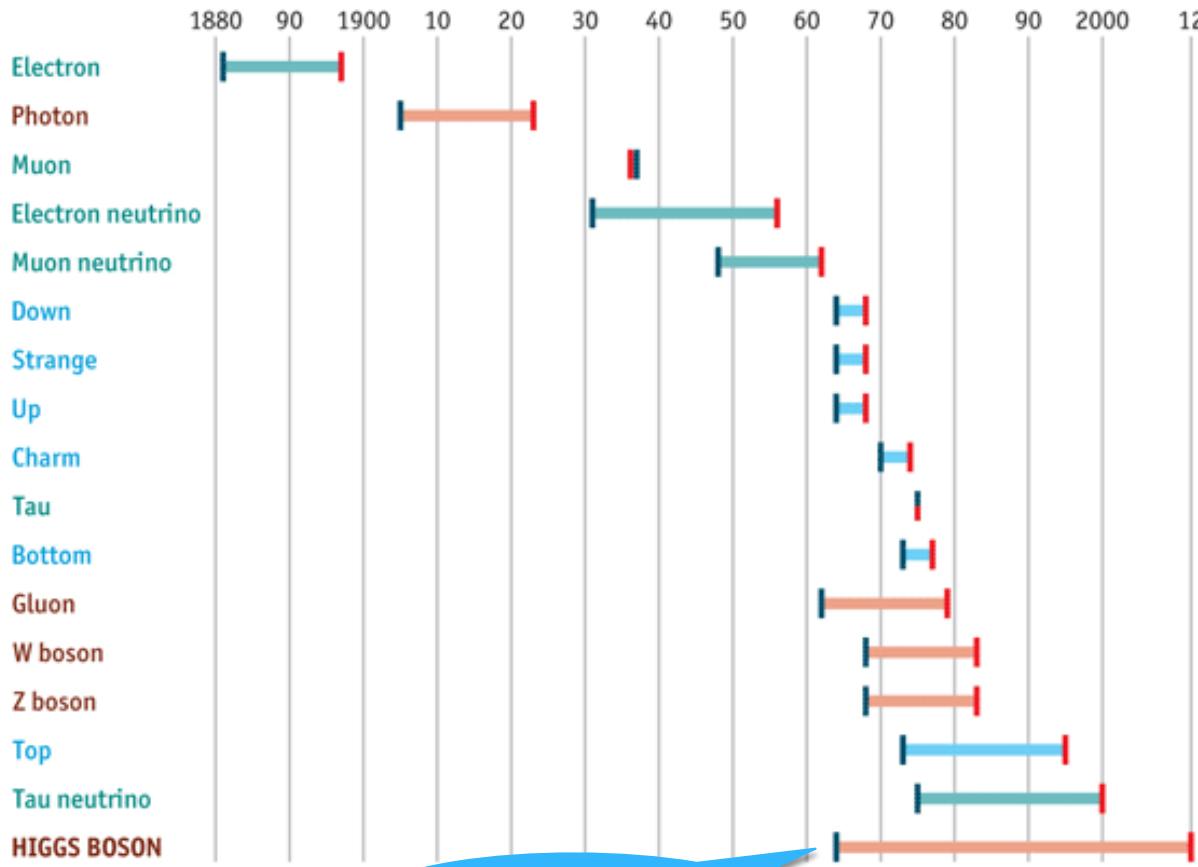
71

The Standard Model of particle physics

Years from concept to discovery

Leptons
Bosons
Quarks

Theorised/explained
Discovered



Source: *The Economist*

Almost 50 years !

Who Should Be TIME's Person of the Year 2012?

As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

1.5k

536

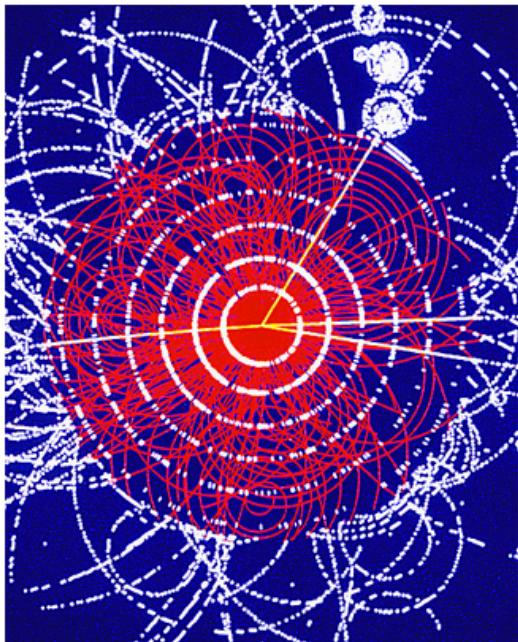
20

7

THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012



SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

What do you think?

Should The Higgs Boson be TIME's Person of the Year 2012?

Definitely No Way

VOTE

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

18 of 40

WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?

[The Candidates](#)

[Video](#)

[Poll Results](#)

PAST PERSONS OF THE YEAR



2011: The Protester

2010: Facebook's Mark Zuckerberg



2009: Ben Bernanke

2008: Barack Obama

[Most Read](#)

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1 Who Should Be TIME's Person of the Year 2012?

2 LIFE Behind the Picture: The Photo That Changed the Face of AIDS

3 Nativity-Scene Battles: Score One for the Atheists

4 The \$7 Cup of Starbucks: A Logical Extension of the Coffee Chain's Long-Term Strategy

[2012](#) [2011](#) [2010](#) [2009](#) [2008](#)

Who Should Be TIME's Person of the Year 2012?

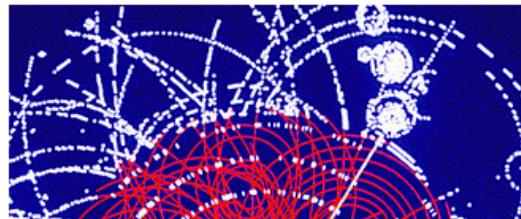
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THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012



What do you think?

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Definitely No Way

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 18 of 40 

WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?

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[Video](#)

[Poll Results](#)

PAST PERSONS OF THE YEAR



2011: The Protester

2010: Facebook's Mark Zuckerberg



last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The

On the shoulders of giants

detector makers & theory calculators



74

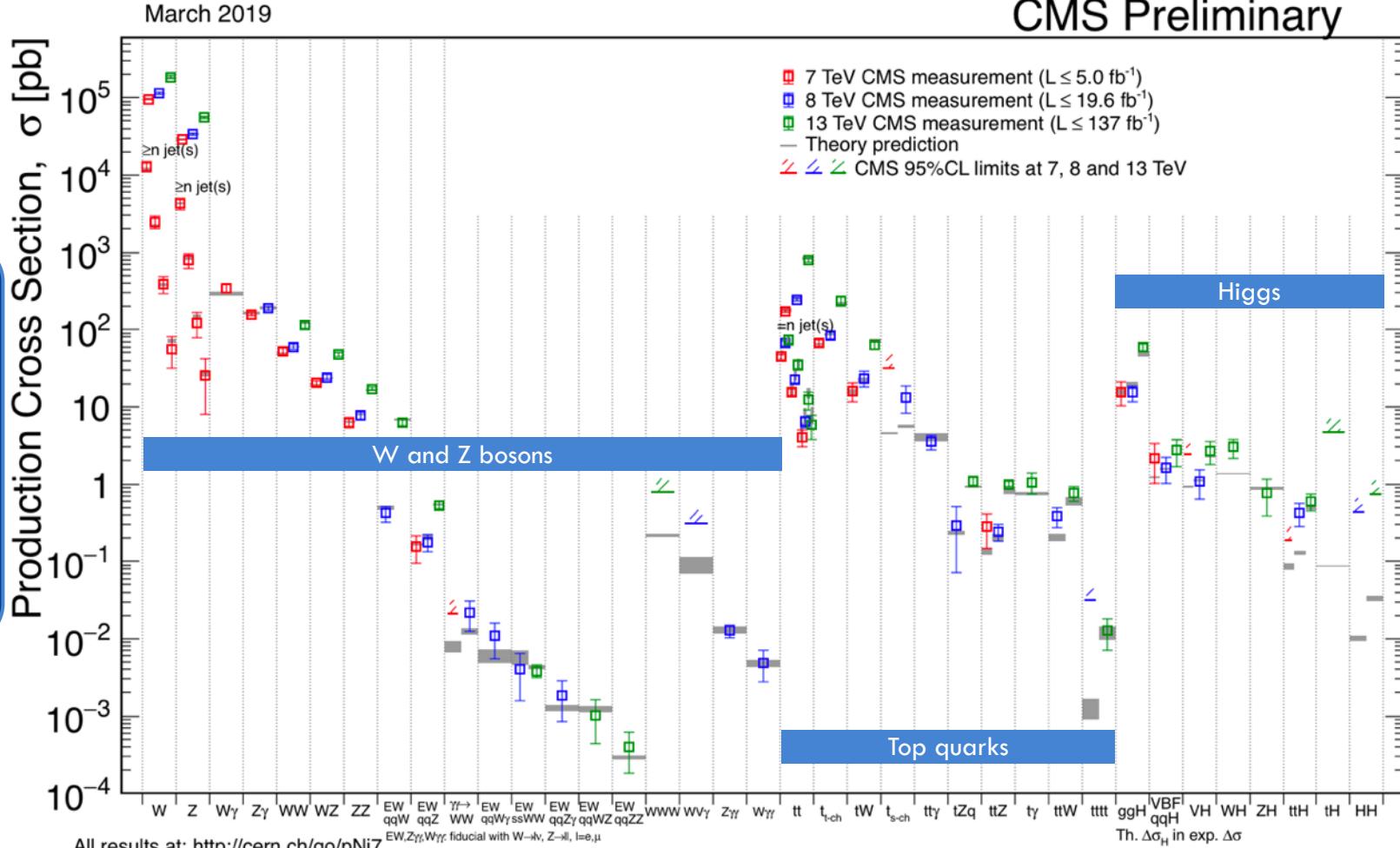
"Yesterday's discovery is today's calibration, and tomorrow's background." – V. L. Telegdi [<http://cern.ch/go/lf9C>] [<http://cern.ch/go/W6KQ>]

Inelastic collisions: $\sim 7 \times 10^{10}$ pb

March 2019

CMS Preliminary

Nine
orders of
magnitude
of EWK,
top, and
Higgs
Physics



2013: a rider with a gun

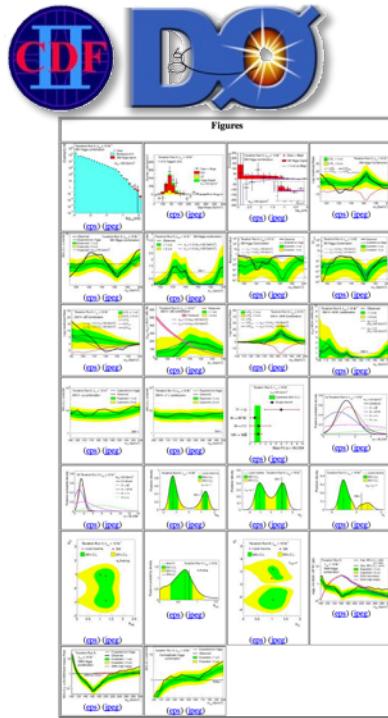
75

[“Lawrence of Arabia” idea from C. Grojean]

- By early 2013 a clear Higgs-like picture emerged.



(self-inflicted) Mission: impossible



- Present a coherent view of (some) Higgs coupling results from LHC (and Tevatron) experiments.
- Any mistake is the speaker's fault (send email).

Oversimplified big picture

T – Tevatron; A – ATLAS; C – CMS; combination drivers in red.

	$H \rightarrow bb^-$			$H \rightarrow \tau\tau$			$H \rightarrow WW$			$H \rightarrow ZZ$			$H \rightarrow \gamma\gamma$			$H \rightarrow Z\gamma$			$H \rightarrow \text{inv.}$			$H \rightarrow \mu\mu$			$H \rightarrow cc^-$ $H \rightarrow HH$		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	★	★	★	★	★	★	★	★	★	★	★	-	★	★				-	★	★	-			
VBF			★	★	★			★	★		★	★		★	★	-		★		★		★	-	★	-		
VH	★	★	★	★		★	★	★	★	★	★	★		★	★	-			★	★	-			-			
$t\bar{t}H$		★	★	★		★	★							★	★	-					-			-			

- Still much to explore on the rarer ends.
(to the right and to the bottom) (and outside this picture □)

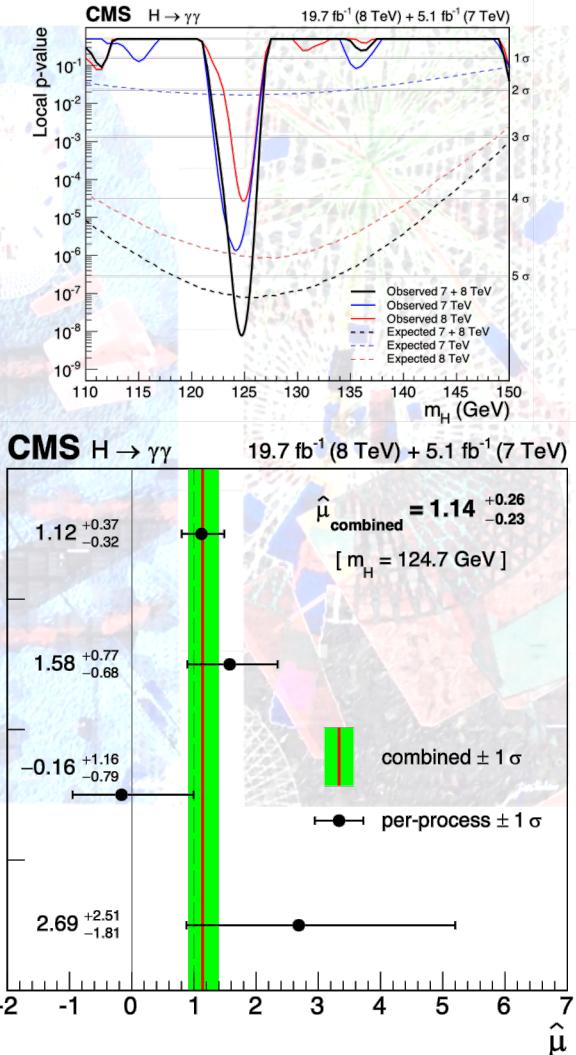
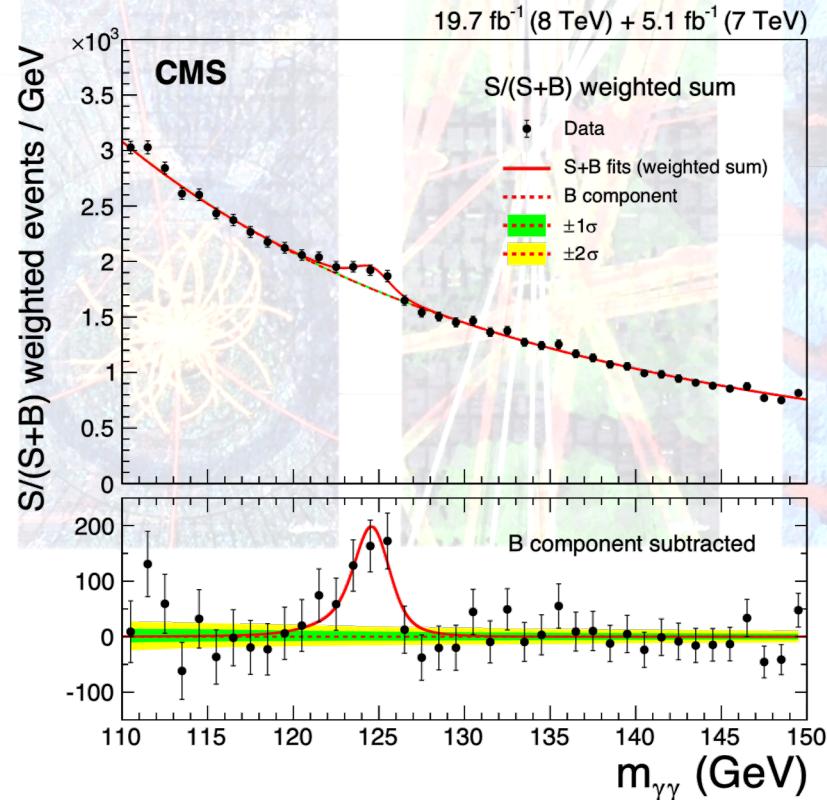
H \rightarrow $\gamma\gamma$ vignettes

78

[EPJC 74 (2014) 3076]



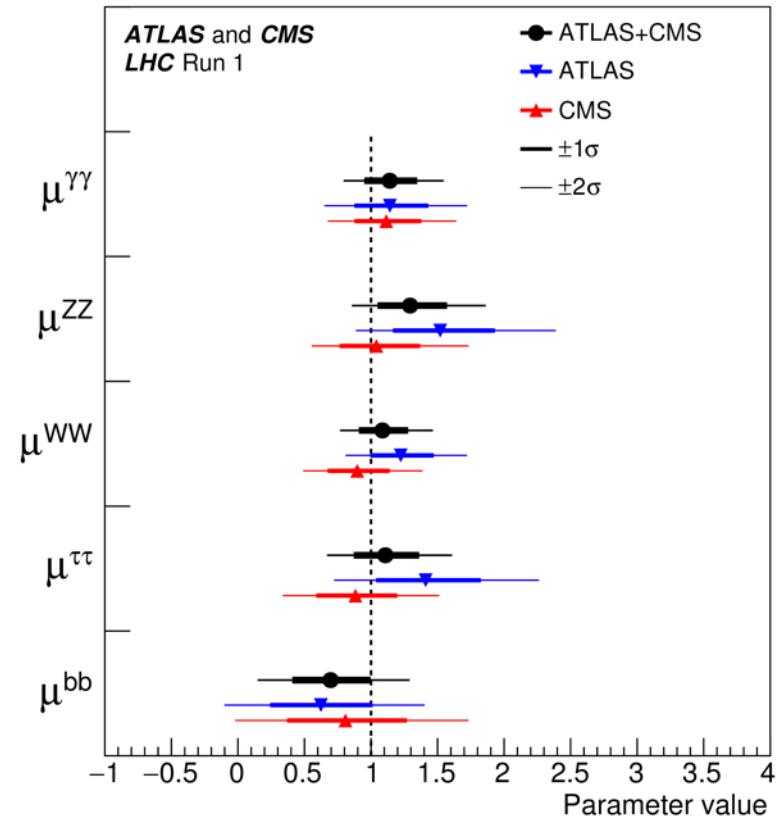
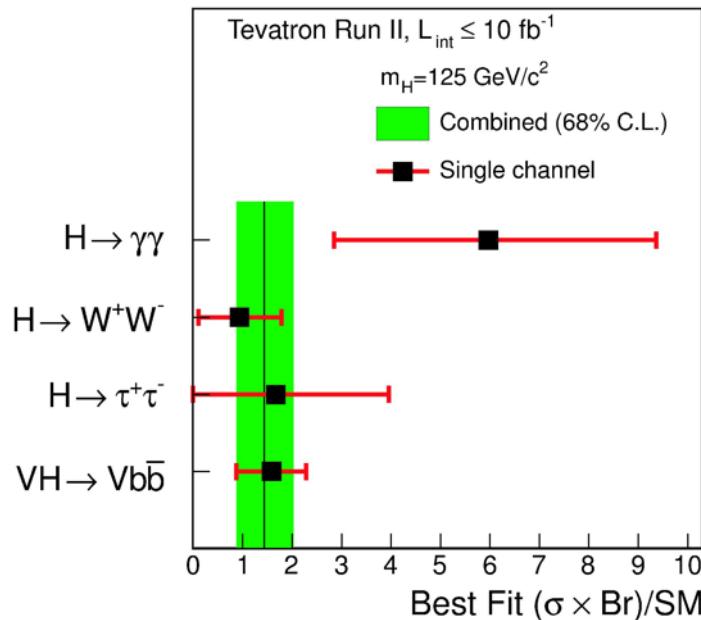
- 5.7σ (5.2σ exp.)
- $m_H = 124.70 \pm 0.31$ (stat.) ± 0.15 (syst.) GeV
- $\sigma/\sigma_{SM} = 1.14 \pm 0.21$ (stat.) ± 0.11 (theo.) ± 0.07 (syst.)



Relative signal strengths

79

[arXiv:1303.6346] [JHEP 08 (2016) 045]

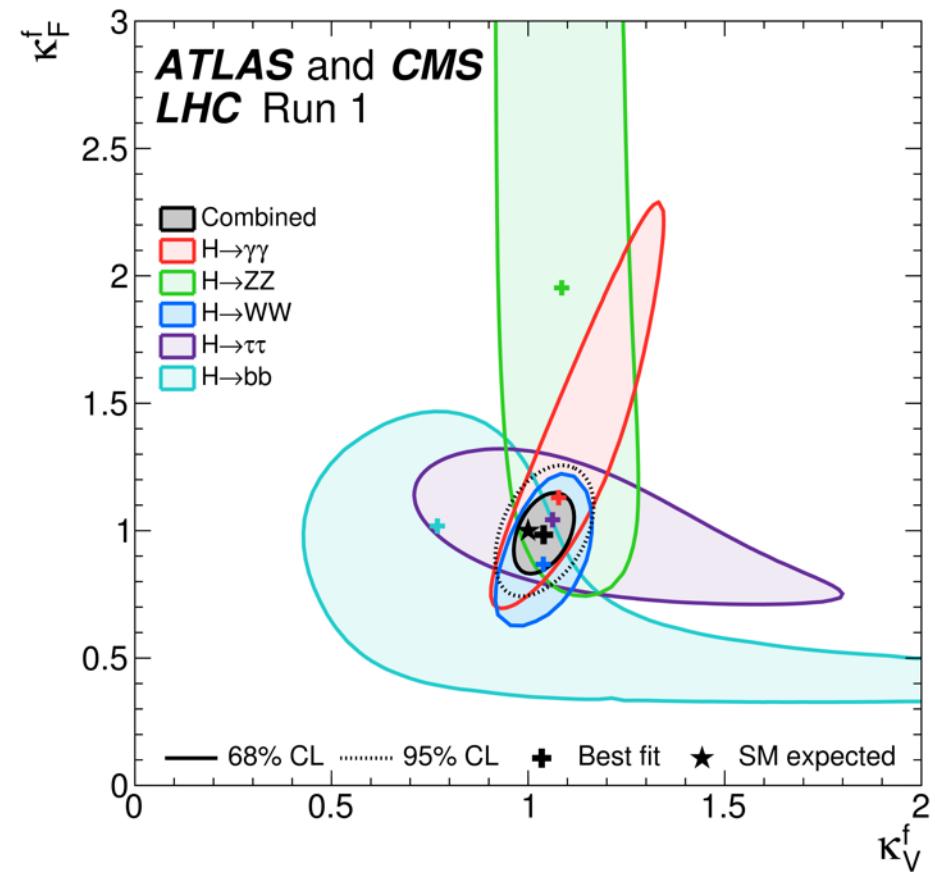
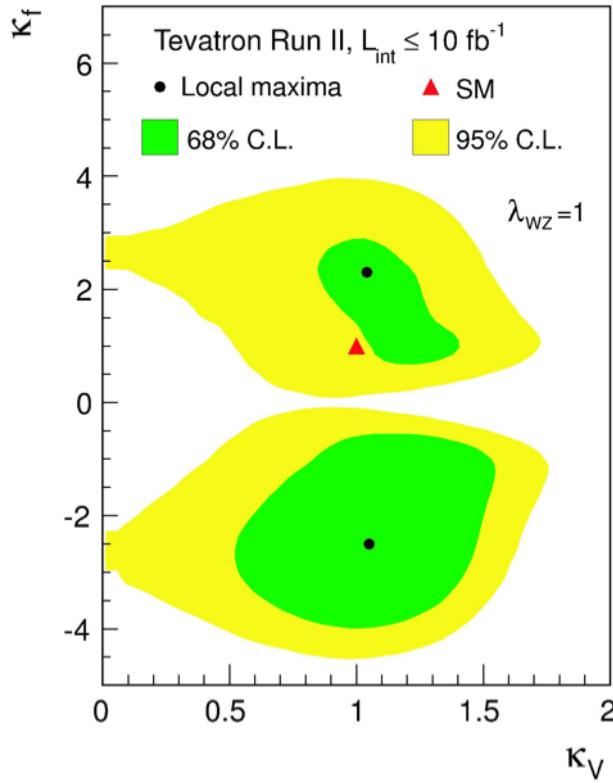


	Tevatron	ATLAS+CMS
m_H	125 GeV	125.09 GeV
$\mu = \sigma/\sigma_{\text{SM}}$	$1.44^{+0.59}_{-0.56}$	1.09 ± 0.11

Weak bosons and fermions

80

[arXiv:1303.6346] [JHEP 08 (2016) 045]



Tevatron

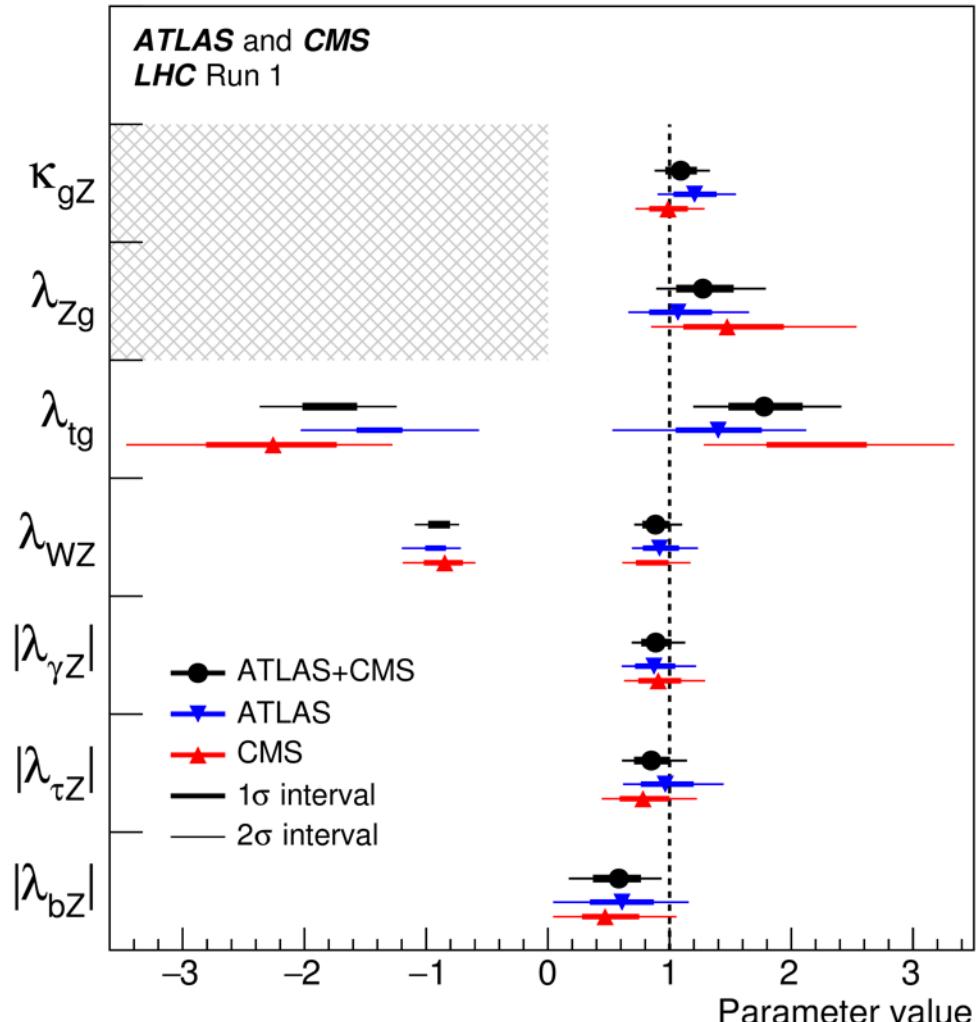
$p(\text{SM})$

-

ATLAS+CMS

$< 1\sigma$

The deviations that we do not (yet) see



Nobel prizes...



The Nobel Prize in Physics 2013
François Englert, Peter Higgs

Share this: [f](#) [g+](#) [t](#) [+](#) [1.8K](#) [e-mail](#)

The Nobel Prize in Physics 2013



Photo: A. Mahmoud

François Englert

Prize share: 1/2



Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Nobel prizes...

83



The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize 2013



Photo: A. Mahmoud

François Englert

Prize share: 1/2

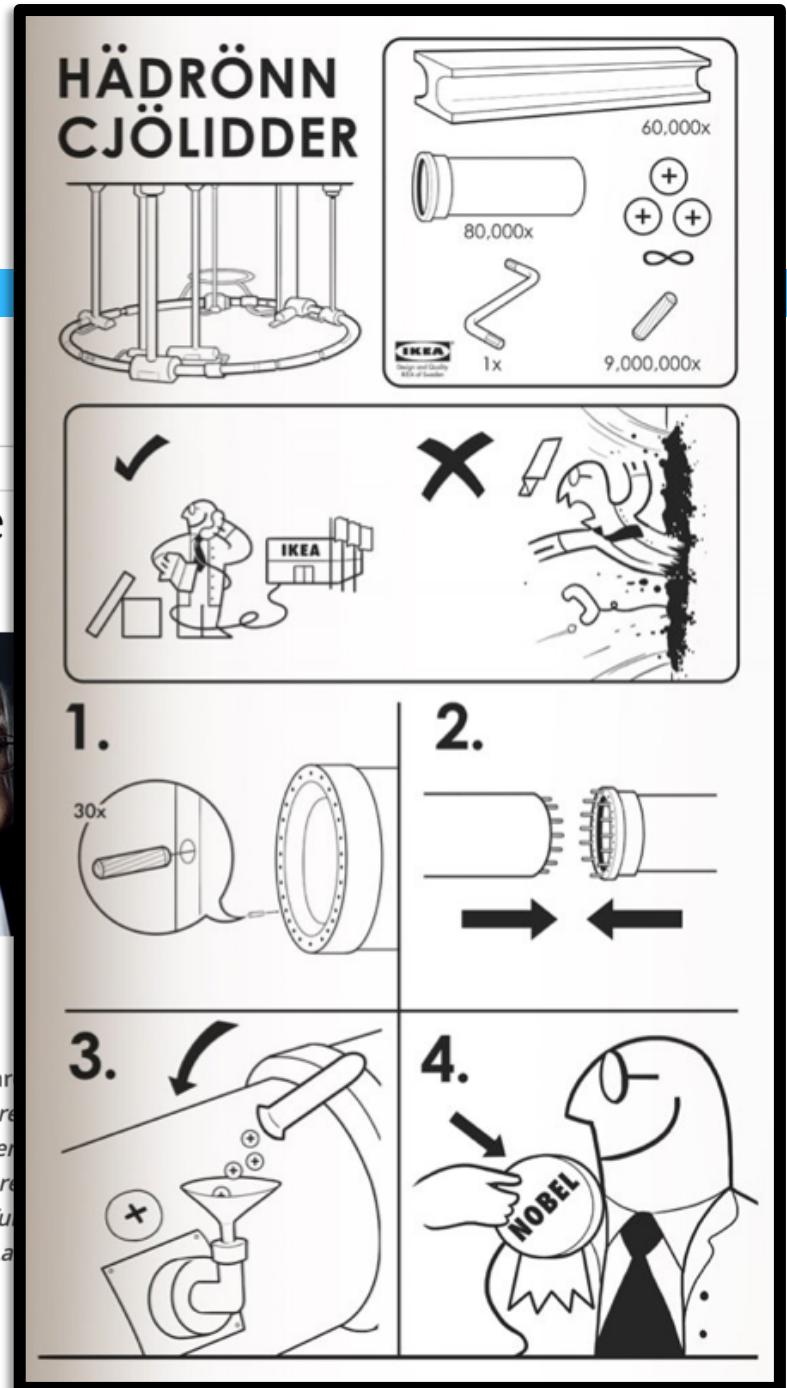


Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded to François Englert and Peter W. Higgs "for the theoretical prediction of the mechanism that contributes to our understanding of the mass of subatomic particles, and which was confirmed through the discovery of the predicted fundamental particle, the Higgs boson, in 2012 at CERN's Large Hadron Collider".



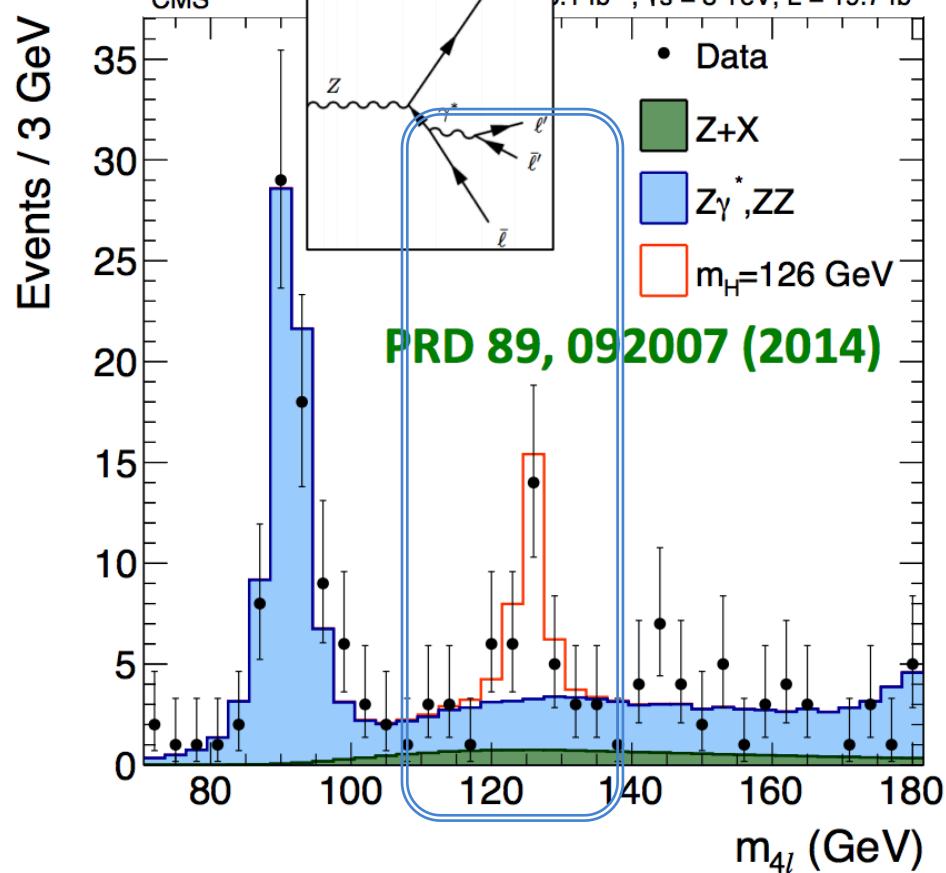
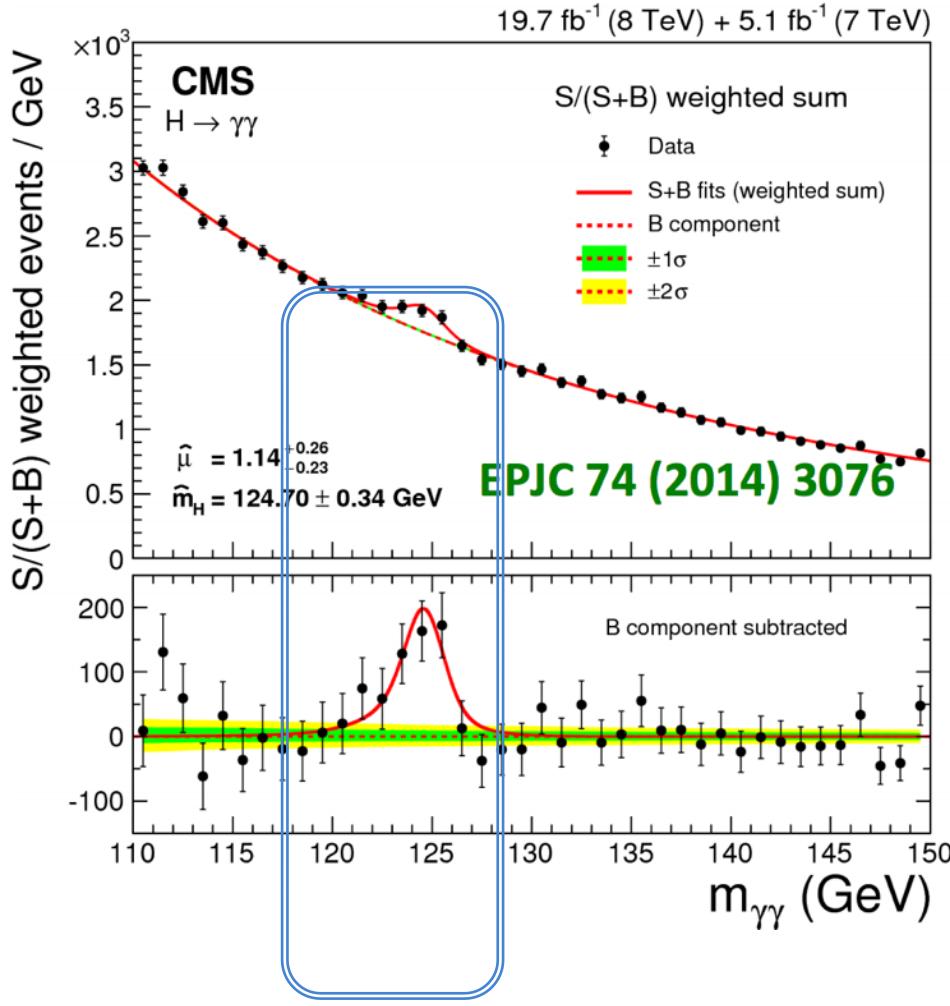
What is the Higgs boson mass?

Something that the SM does not predict.

Something we can measure!

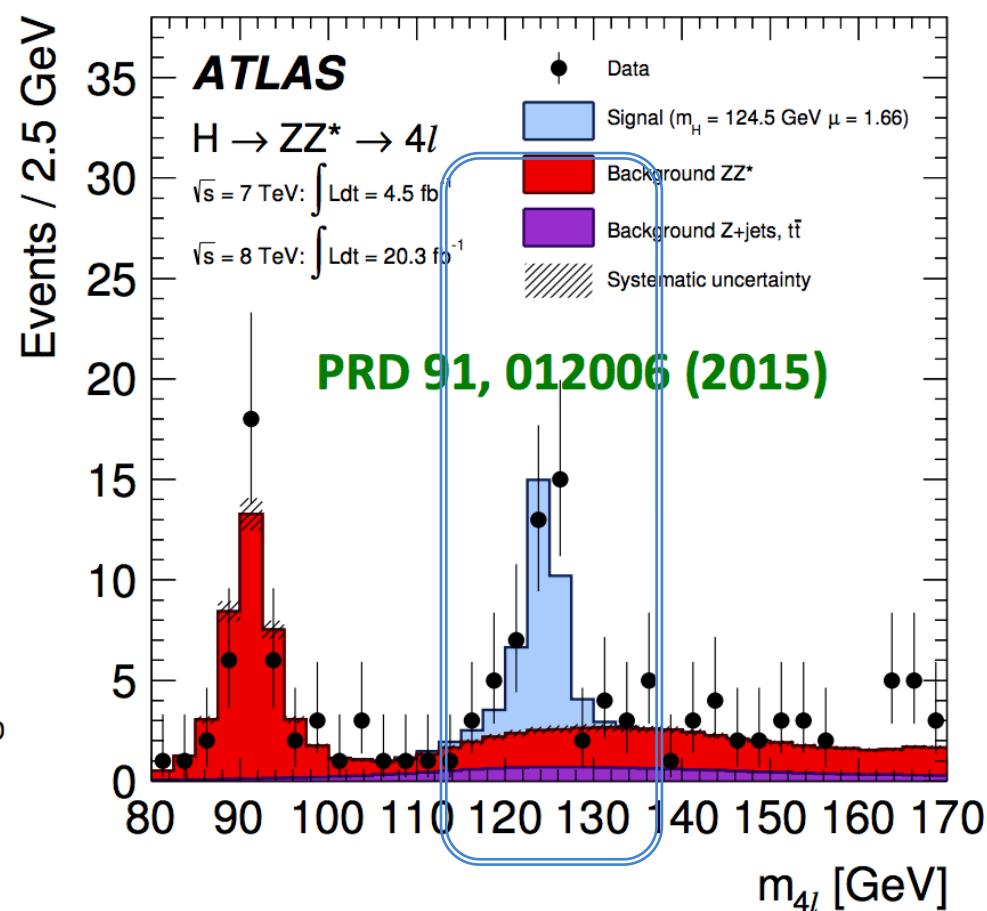
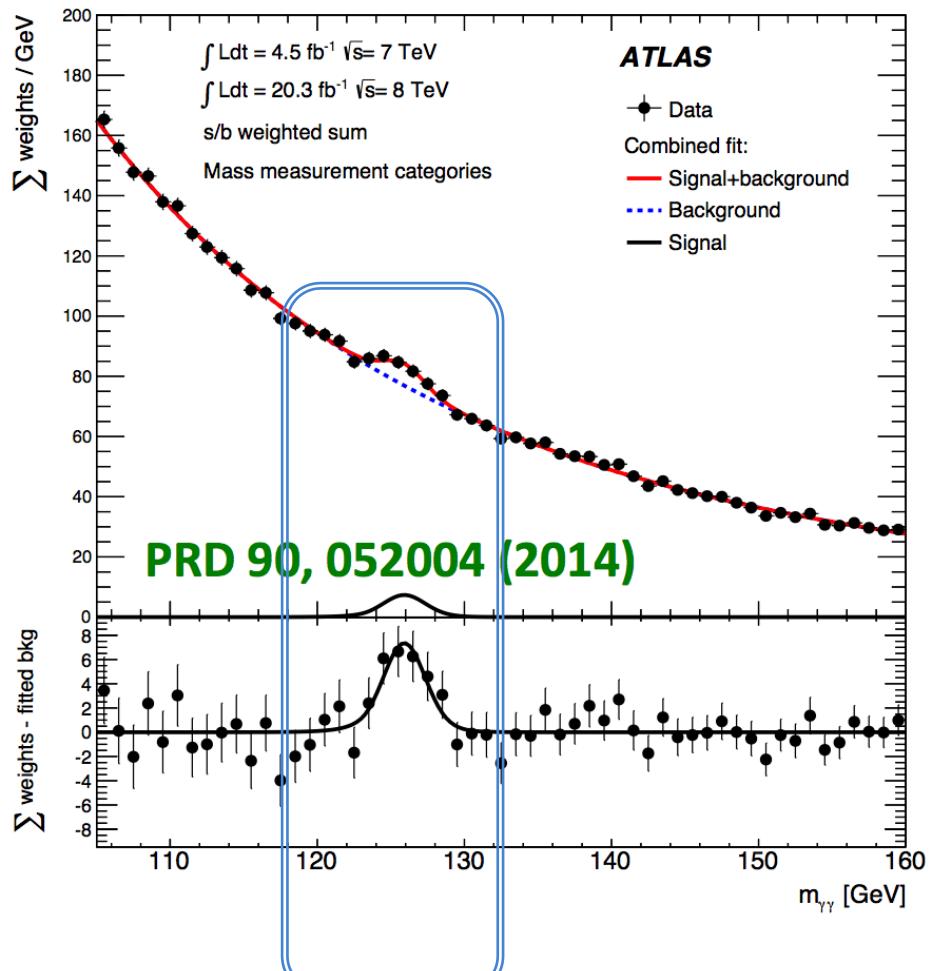
Mass peaks: mass measurements

85

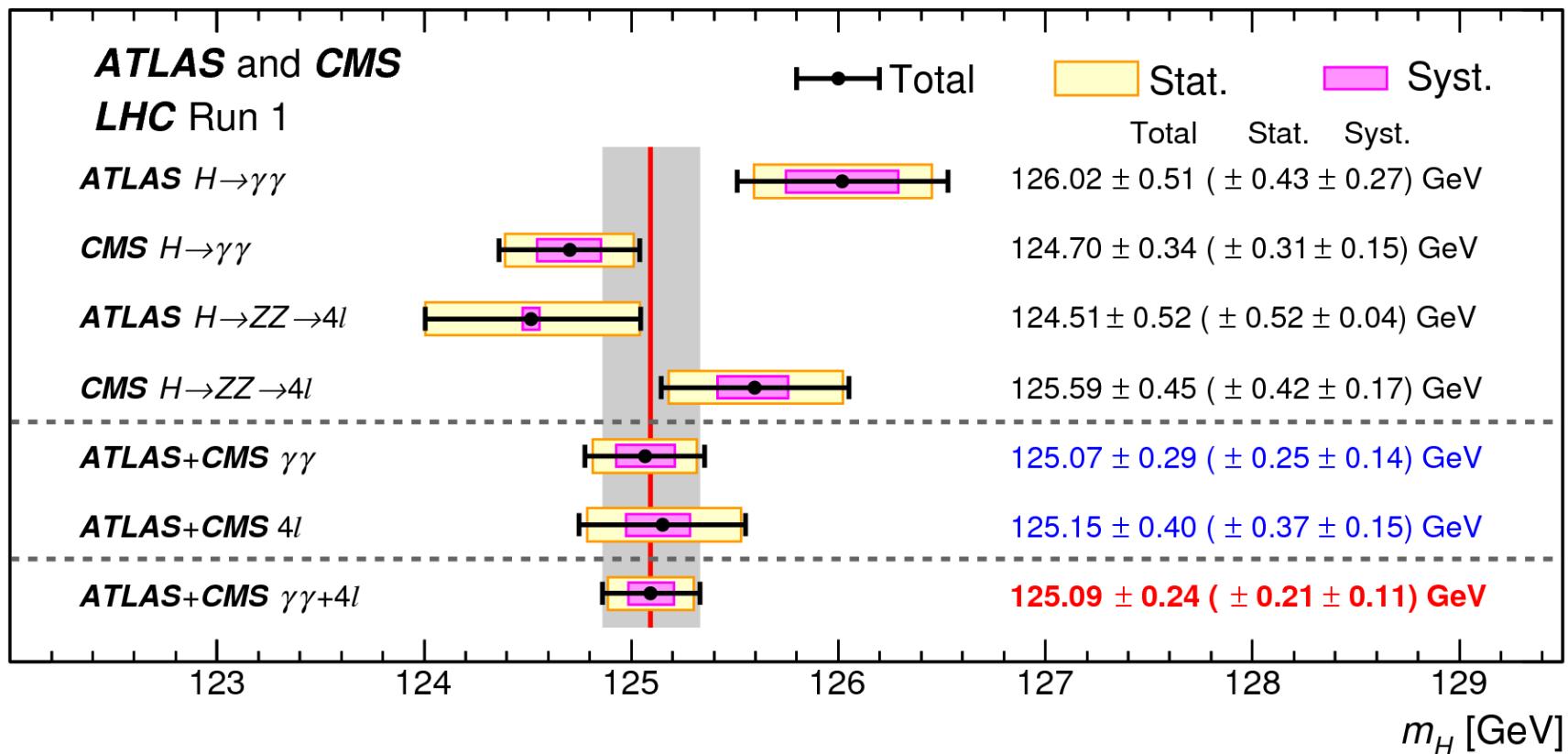


Mass peaks: mass measurements

86



Combined LHC mass measurement





Combined LHC mass measurement

[arXiv:1503.07589]

$$m_H = 125.09 \pm 0.21 \text{ (stat)}$$

$\pm 0.11 \text{ (scale)}$

$\pm 0.02 \text{ (other)}$

$\pm 0.01 \text{ (theory*)}$

**Stat. uncertainty
dominates overall.**
**Energy scale syst. can
be improved.**

Run 2 will reduce
uncertainty !

GeV

For the record

- ~5150 authors.
- Found that there are two:
 - Archana Sharma
(both CMS)
 - Andrea Bocci
 - Muhammad Ahmad
 - F. M. Giorgi
(one CMS, one ATLAS)



Physics paper sets record with more than 5,000 authors

Detector teams at the Large Hadron Collider collaborated for a more precise estimate of the size of the Higgs boson.

Davide Castelvecchi

15 May 2015



CERN

Thousands of scientists and engineers have worked on the Large Hadron Collider at CERN.

A physics paper with 5,154 authors has — as far as anyone knows — broken the record for the largest number of contributors to a single research article.



Standard Model of Particle Physics

90

[<http://cern.ch/go/dW6z>]

$$\begin{aligned} & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\ & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\ & M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (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^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \\ & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 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_\nu^0 (W_\mu^+ W_\nu^- - \\ & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \frac{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)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{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)] + \\ & \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\ & W_\mu^- \phi^+) + igs_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\ & \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\ & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\ & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 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}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\ & igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\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}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\ & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\ & i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\ & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\ & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igs_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) + igs_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^+) + igs_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\ & igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \\ & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0] \end{aligned}$$



Standard Theory of Particle Physics

[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
 & \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_b^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (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^+)] - \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + \\
 & g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - ga[H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^- - \frac{1}{2}g\alpha_h [H^4 + (\phi^0)^4] - 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- I - \frac{1}{2} \frac{M}{c_w^2} Z_\mu^0 H - \frac{1}{2}ig V_\mu^+ (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
 & \frac{1}{2}g[W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+)] - igs_w [A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g \frac{2c_w^2}{c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+)] - \\
 & \frac{1}{4}g^2 V_\mu^+ V_\mu^- [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu [W_\mu^+ \phi^- + W_\mu^- \phi^+] - \frac{1}{2}g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \delta^{\lambda\kappa} (\gamma \partial + m_e^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\
 & igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{u}_j^\lambda \gamma^\mu d_j^\lambda) + \bar{Z}_\mu^0 [(\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}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \bar{d}_j^\lambda \gamma^\mu) + (\bar{d}_j^\lambda \gamma^\mu (1 + \gamma^5) u_j^\lambda) + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \\
 & i\phi^0 (\bar{e}^\lambda \gamma^\mu e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
 & m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig c_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) + ig c_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^+) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$



Standard Theory of Particle Physics

[<http://cern.ch/go/dW6z>]

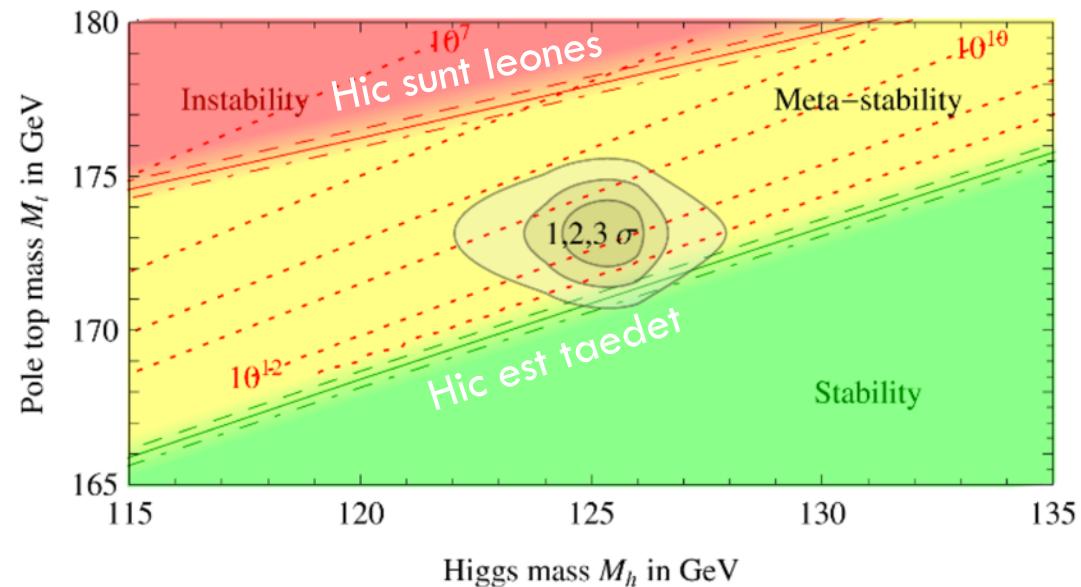
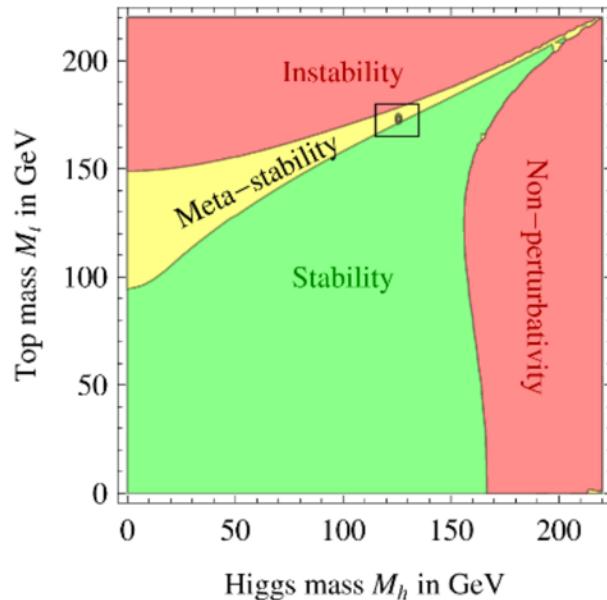
$$\begin{aligned}
& -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
& \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
& M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (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^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \\
& g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 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_\nu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \frac{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)^2 H^2] - gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{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)] + \\
& \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w}{c} M Z_\mu^0 (W_\mu^+ \phi^- - \\
& W_\mu^- \phi^+) + igs_w \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H \dots]) +
\end{aligned}$$

Valid up to ~Planck scale ?

$$\begin{aligned}
& W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
& g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 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}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\
& igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\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}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
& 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + \\
& (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_d^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
& i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
& m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
& M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igs_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) + igs_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^+) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
& ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \\
& \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}$$

The fate/character of the Universe

[JHEP 08 (2012) 098]



- The SM vacuum stability depends crucially on the masses of the top quark and Higgs boson.



Standard Theory of Particle Physics

[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
& -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
& \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
& M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (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^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \\
& g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 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_\nu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \frac{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)^2 H^2] - gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{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)] + \\
& \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w}{c} M Z_\mu^0 (W_\mu^+ \phi^- - \\
& W_\mu^- \phi^+) + igs_w \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H \dots]) +
\end{aligned}$$

Valid up to ~Planck scale ?

$$\begin{aligned}
& W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
& g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 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}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + \\
& igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z_\mu^0 [(\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}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
& 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + \\
& (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_d^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
& i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - \\
& m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - \\
& M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + ig c_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) + ig c_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^+) + ig c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
& igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \\
& \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}$$



Standard Theory of Particle Physics

$$\begin{aligned}
& -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \\
& \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
& M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - ig c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - ig s_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^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \\
& g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 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_\nu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - 2 A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] - \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
& 4 H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{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)] + \\
& \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w^2} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w^2} M Z_\mu^0 (W_\mu^+ \phi^- - \\
& W_\mu^- \phi^+) + ig s_w \\
& \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H
\end{aligned}$$

Valid up to \sim Planck scale ?

But: dark matter, matter-antimatter, etc.

But: dark matter, matter-antimatter, etc.



The Next Standard Model

[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{2}g_{\mu\nu}^{\alpha\beta}\partial_\mu q_\nu^\alpha - g_\mu f^{abc}\partial_\mu Z_a^b q_\nu^c - \frac{1}{4}q_\mu^a f^{abc}q_\nu^b q_\rho^c + \frac{1}{4}ig_c^2(\bar{q}_\mu^a \gamma^\mu q_\nu^a)q_\rho^c + \tilde{G}^a \partial^\mu G^a + g_a f^{abc}\partial_\mu \tilde{G}^a G^b q_\nu^c - \\
 & \partial_\mu W_p^+ \partial_\nu W_n^- - M^2 W_p^+ W_n^- - \frac{1}{2}\partial_\mu Z_p^0 \partial_\nu Z_p^0 - \frac{1}{2g_s^2}M^2 Z_p^0 Z_p^0 - \frac{1}{4}\partial_\mu A_\mu \partial_\nu A_\nu - \frac{1}{8}\partial_\mu H \partial_\nu H - \frac{1}{8}m_b^2 H^2 - \partial_\mu \phi^+ \partial_\nu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^+ \partial_\nu \phi^0 - \frac{1}{2g_s^2}M \phi^0 \phi^0 - \partial_\mu [\frac{2M^2}{g_s^2} + \frac{2M}{g_s^2}H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g_s^2}a_b - ig s_w[\partial_\mu Z_p^0 W_p^+ W_n^- \\
 & - W_p^+ W_n^-] - Z_p^0(W_p^+ \partial_\mu W_n^- - W_n^- \partial_\mu W_p^+) - ig s_w[\partial_\mu A_\mu (W_p^+ W_n^- - W_p^+ W_n^-) - \\
 & A_\mu (W_p^+ \partial_\mu W_n^- - W_n^- \partial_\mu W_p^+) + A_\mu (W_p^+ \partial_\mu W_n^- - W_n^- \partial_\mu W_p^+)] - \frac{1}{2}g^2 W_p^+ W_n^- W_p^+ W_n^- + \frac{1}{2}g^2 W_p^+ W_n^- W_p^+ W_n^- + \\
 & g^2 c_w^2(Z_p^0 W_p^+ Z_p^0 W_n^- - Z_p^0 Z_p^0 W_p^+ W_n^-) + g^2 s_w^2(A_\mu W_p^+ A_\mu W_n^- - A_\mu A_\mu W_p^+ W_n^-) + g^2 s_w c_w[A_\mu Z_p^0 (W_p^+ W_n^- - \\
 & W_p^+ W_n^-) - 2A_\mu Z_p^0 W_p^+ W_n^-] = ga[H^2 + H\phi^2 \phi^0 + 2H\phi^+ \phi^-] - \frac{1}{2}g^2 a_b[H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2 - g W_p^+ W_n^- H - \frac{1}{2}g \frac{M}{g_s^2} Z_p^0 Z_p^0 H - \frac{1}{2}ig W_p^+ (g^0 \partial_\mu \phi^- - \phi^- \partial_\mu g^0) - W_\mu^-(g^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu g^0)] + \\
 & \frac{1}{2}g[W_p^+(H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_n^-(H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w}(Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H)) - ig \frac{1}{c_w} M Z_\mu^0 (W_p^+ \phi^- - \\
 & W_n^- \phi^+) + ig s_w M A_\mu (W_p^+ \phi^- - W_n^- \phi^+) - ig \frac{1-\gamma^5}{2g_s^2} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{2}g^2 W_p^+ W_n^- [H^2 + (\phi^0)^2 + 2(\phi^+ \phi^-)] - \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 [H^4 + (\phi^0)^4 + 2(2S_\mu^0 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 \phi^0 (W_p^+ \phi^- + \\
 & W_n^- \phi^+) - \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 H (W_p^+ \phi^- - W_n^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_p^+ \phi^- + W_n^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu H (W_p^+ \phi^- - W_n^- \phi^+) - \\
 & g^2 \frac{1}{c_w}(2S_\mu^0 - 1) Z_\mu^0 A_\mu \phi^0 \phi^- - g^1 c_w^2 A_\mu A_\mu \phi^0 \phi^- - \bar{e}^A (\gamma \partial + m_e^A) e^A - \bar{e}^A (\gamma \partial + m_e^A) e^A - \bar{e}_j^A (\gamma \partial + m_e^A) e_j^A - \bar{e}_j^A (\gamma \partial + m_e^A) e_j^A + \\
 & (g s_w A_\mu [-(\bar{e}^A \gamma^\mu e^A) + \frac{1}{2}(\bar{e}_j^A \gamma^\mu e_j^A) - \frac{1}{2}(\bar{d}_j^A \gamma^\mu d_j^A)]) + \frac{ig}{4m_e^2} Z_\mu^0 [(\bar{e}^A \gamma^\mu (1 + \gamma^5) e^A) + (\bar{e}_j^A \gamma^\mu (1 + \gamma^5) e_j^A) + (\bar{d}_j^A \gamma^\mu (1 + \gamma^5) d_j^A)] + \frac{ig}{2m_e^2} W_p^+ [(\bar{e}^A \gamma^\mu (1 + \gamma^5) e^A) + \\
 & (\bar{d}_j^A \gamma^\mu (1 + \gamma^5) d_j^A)] + \frac{ig}{2m_e^2} W_n^- [(\bar{e}^A \gamma^\mu (1 + \gamma^5) e^A) + (\bar{d}_j^A \gamma^\mu (1 + \gamma^5) d_j^A)] + \frac{ig}{2m_e^2} W_p^- [(\bar{e}^A \gamma^\mu (1 + \gamma^5) e^A) + \\
 & (\bar{d}_j^A \gamma^\mu (1 + \gamma^5) d_j^A)] + \frac{ig}{2M^2} \phi^0 [-(m_e^A \bar{e}_j^A (1 + \gamma^5) e^A) + \phi^+ (\bar{e}^A (1 + \gamma^5) e^A)] - \frac{ig}{2M^2} [H (\bar{e}^A e^A + \\
 & i \phi^0 (\bar{e}^A \gamma^\mu e^A)] + \frac{ig}{2M^2} \phi^0 [-(m_e^A \bar{e}_j^A C_{\lambda\mu} (1 - \gamma^5) d_j^A) + m_e^A \bar{e}_j^A C_{\lambda\mu} (1 + \gamma^5) d_j^A] + \frac{ig}{2M^2} \phi^0 [m_e^A (\bar{d}_j^A C_{\lambda\mu}^T (1 + \gamma^5) e_j^A) - \\
 & m_e^A \bar{d}_j^A C_{\lambda\mu}^T (1 - \gamma^5) e_j^A] - \frac{g^2 m_b^2}{2M^2} H (\bar{u}_j^A u_j^A) - \frac{g^2 m_b^2}{2M^2} H (\bar{d}_j^A d_j^A) + \frac{g^2 m_b^2}{2M^2} \phi^0 (\bar{u}_j^A \gamma^5 u_j^A) - \frac{ig m_b^2}{2M^2} \phi^0 (\bar{d}_j^A \gamma^5 d_j^A) + X^+ (\partial^2 - \\
 & M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{2}) X^0 + \bar{Y} \partial^2 Y + ig s_w W_p^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_p^+ (\partial_\mu \bar{X}^- X^- - \partial_\mu \bar{X}^+ X^+) + \\
 & ig s_w A_\mu (\partial_\mu \bar{X}^0 X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M [\bar{X}^+ X^0 H + \bar{X}^- X^- H + \frac{1}{2} \bar{X}^0 X^0 H] + \frac{1-2\gamma^5}{2g_s^2} ig M [X^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2g_s^2} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$



The Next Standard Model

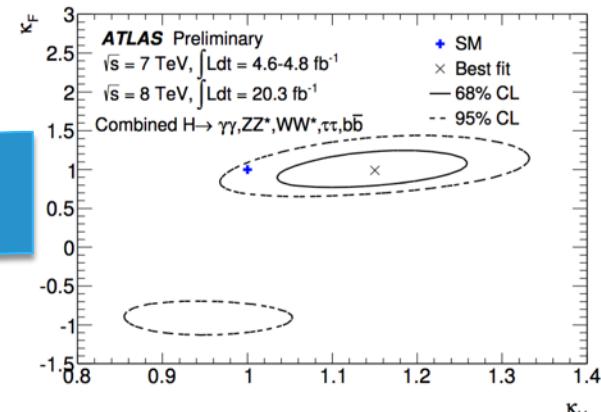
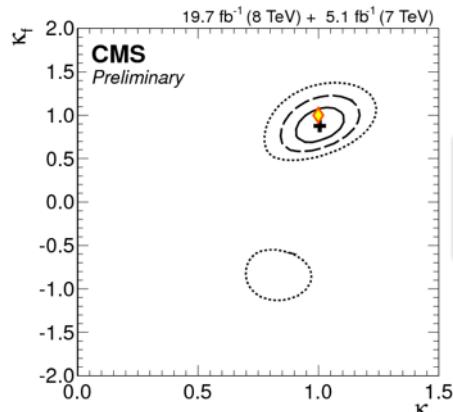
[<http://cern.ch/go/dW6z>]

$$\begin{aligned}
 & -\frac{1}{4}g_{\nu\mu}^{ab}\partial_\nu g_\mu^a - g_\nu f^{abc}\partial_\mu Z_\nu^a\partial_\mu^b g_\nu^c - \frac{1}{4}g_\nu^{ab}f^{abc}\partial_\mu Z_\nu^a\partial_\mu^b(g_\nu^c + \frac{1}{2}ig_\nu^2(\bar{\psi}_\nu^\alpha\gamma^\mu\psi_\nu^\alpha))g_\mu^a + \bar{G}^a\partial^b G^b + g_\nu f^{abc}\partial_\mu \bar{G}^a G^b g_\mu^c - \\
 & \partial_\mu W_\mu^+\partial_\nu W_\nu^- - M^2 W_\mu^+ W_\nu^- - \frac{1}{2}\partial_\nu Z_\mu^0\partial_\mu Z_\nu^0 - \frac{1}{2}g_\mu^2 M^2 Z_\mu^0 Z_\nu^0 - \frac{1}{4}\partial_\mu A_\mu \partial_\nu A_\nu - \frac{1}{8}\partial_\mu H \partial_\nu H - \frac{1}{8}m_\mu^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^+ \partial_\mu \phi^0 - \frac{1}{2}g_\mu^2 M \phi^0 \phi^0 - \partial_\mu [\frac{2M^2}{g_\mu^2} + \frac{2M}{g_\mu^2}H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g_\mu^2}a_{bb} - ig s_w[\partial_\mu Z_\mu^0 W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-] - Z_\mu^0(W_\mu^+ \partial_\nu W_\nu^- - W_\mu^- \partial_\nu W_\mu^+) - ig s_w[\partial_\mu A_\mu (W_\mu^+ W_\mu^- - W_\nu^+ W_\nu^-) - \\
 & A_\nu (W_\mu^+ \partial_\nu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\nu^- - W_\mu^- \partial_\mu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\nu^+ W_\nu^- W_\mu^+ W_\mu^- + \\
 & g^2 c_w^2(Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2(A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w(A_\mu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\mu^+ W_\nu^-) - ga[H^2 + H\phi^2 \phi^0 + 2H\phi^+ \phi^-] - \frac{1}{2}g^2 a_{bb}[H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + \\
 & 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - g W_\mu^+ W_\mu^- H - 2g \frac{M}{g_\mu^2} Z_\mu^0 Z_\nu^0 H - \frac{1}{2}ig W_\mu^+ (g^0 \partial_\mu \phi^- - \phi^- \partial_\mu g^0) - W_\mu^-(g^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu g^0)] + \\
 & \frac{1}{2}g[W_\mu^+(H\partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^-(H\partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w}(Z_\mu^0(H\partial_\mu \phi^0 - \phi^0 \partial_\mu H)) - ig \frac{2c_w}{g_\mu^2} M Z_\mu^0 (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) + (gs_w M A_\mu)(W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-\gamma^5}{2c_w} Z_\mu^0(\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^+ - \phi^- \partial_\mu \phi^-) - \\
 & \frac{1}{2}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2(\phi^+ \phi^-)] - \frac{1}{2}g^2 \frac{1}{c_w} Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2S_\mu^0 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{c_w}{s_w} Z_\mu^0 \phi^2 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}g^2 \frac{c_w^2}{s_w^2} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 \delta^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{c_w}{s_w}(2S_\mu^0 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - g^1 s_w^2 A_\mu A_\nu \phi^+ \phi^- - \bar{e}^A(\gamma \partial + m_e^A) e^A - \bar{e}^A \gamma \partial \nu^A - \bar{e}_j^A(\gamma \partial + m_e^A) u_j^A - \bar{e}_j^A(\gamma \partial + m_e^A) d_j^A + \\
 & (gs_w A_\mu[-(\bar{e}^A \gamma^\mu e^A) + \frac{1}{2}(\bar{e}_j^A \gamma^\mu u_j^A) - \frac{1}{2}(\bar{d}_j^A \gamma^\mu d_j^A)] + \frac{ig}{4c_w} Z_\mu^0 (\bar{e}^A \gamma^\mu (1 + \gamma^5) \nu^A) + (\bar{e}^A \gamma^\mu (1 + \gamma^5) u^A) + (\bar{d}_j^A \gamma^\mu (1 + \gamma^5) e^A) + (\bar{d}_j^A \gamma^\mu (1 + \gamma^5) d^A) - \\
 & (D_j^A \gamma^\mu (1 - \frac{1}{2}S_\mu^0 - \gamma^5) d^A)] + \frac{ig}{2c_w} W_\mu^+[(\bar{e}^A \gamma^\mu (1 + \gamma^5) \bar{e}^A) + (\bar{d}_j^A \gamma^\mu (1 + \gamma^5) \bar{D}_j^A)] + \frac{ig}{2c_w} W_\mu^-[(\bar{e}^A \gamma^\mu (1 + \\
 & \gamma^5) \nu^A) + (\bar{d}_j^A \gamma^\mu (1 + \gamma^5) u_j^A)] + \frac{ig}{2c_w} m_e^A[-(\bar{e}^A \gamma^\mu (1 - \gamma^5) \nu^A) + (\bar{e}^A \gamma^\mu (1 + \gamma^5) e^A)] - \frac{ig}{2c_w} [H(\bar{e}^A \nu^A + \\
 & i\phi^0(\bar{e}^A \gamma^\mu e^A)] + \frac{ig}{2M\sqrt{2}} \phi^{bt}[-m_e^A(\bar{e}_j^A C_{\lambda\alpha}(1 - \gamma^5) d_j^A) + m_e^A(\bar{e}_j^A C_{\alpha\lambda}(1 + \gamma^5) d_j^A) + \frac{ig}{2M\sqrt{2}} \phi^{bt} [m_e^A(\bar{D}_j^A C_{\lambda\alpha}^T(1 + \gamma^5) u_j^A) - \\
 & m_e^A(\bar{D}_j^A C_{\alpha\lambda}^T(1 - \gamma^5) u_j^A) - \frac{g^2 m_e^2}{2} H(\bar{u}_j^A u_j^A) - \frac{g^2 m_e^2}{2} H(\bar{d}_j^A d_j^A) + \frac{g^2 m_e^2}{2} \phi^{bt}(\bar{D}_j^A \gamma^5 u_j^A) - \frac{ig m_e^2}{2} \phi^{bt}(\bar{D}_j^A \gamma^5 d_j^A)] + X^{+b}(\partial^2 - \\
 & M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{2})X^0 + \bar{Y}\partial^2 Y + ig s_w W_\mu^+(\partial_\mu \bar{X}^+ X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^-(\partial_\mu \bar{X}^- X^+ - \partial_\mu \bar{X}^- X^-) + \\
 & ig s_w A_\mu(\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{2}\bar{X}^0 X^0 H] + \frac{1-2\gamma_5}{2c_w} ig M[X^+ X^0 \phi^+ - \\
 & \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M[\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + ig M s_w[\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}g M[\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$



Something
else

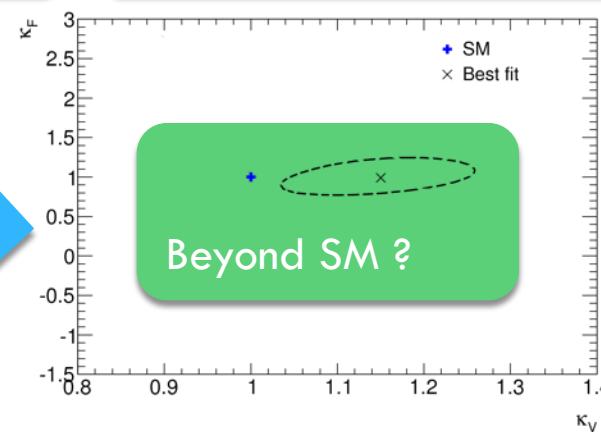
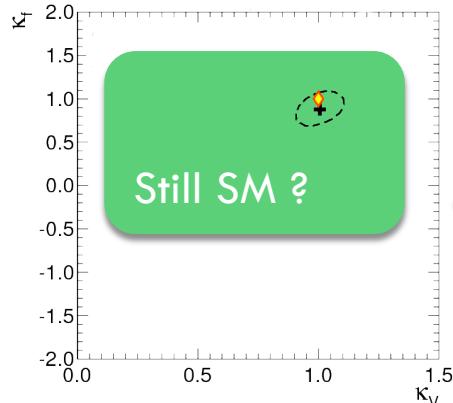
The future is in precision and accuracy



Accelerator physicists
More collisions

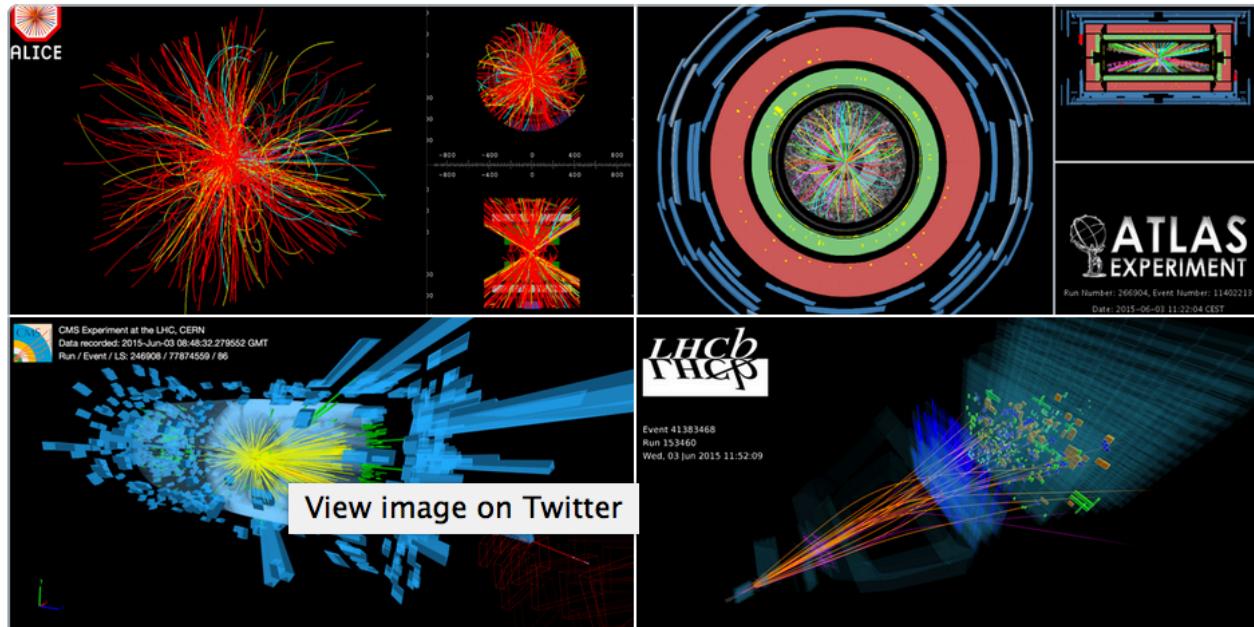
Experimentalists
Better detectors & analyses

Theorists
Better predictions



Back to the #13TeV future

99



CERN 
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 Follow

The LHC experiments are back in business with record energy collisions of **#13TeV**: cern.ch/go/D7z6

12:41 PM - 3 Jun 2015



853

558

Back to the #13TeV future



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Science & Environment

Large Hadron Collider turns on 'data tap'

By Paul Rincon
Science editor, BBC News website

3 June 2015 | [Science & Environment](#)



The CMS experiment team celebrated when the first collisions occurred



750 GeV diphoton excess

From Wikipedia, the free encyclopedia

The **750 GeV diphoton excess** in particle physics was an anomaly in data collected at the **Large Hadron Collider** (LHC) in 2015, which could have been an indication of a new particle or **resonance**.^{[8][9]} The anomaly was absent in data collected in 2016, suggesting that the diphoton excess was a statistical fluctuation.^{[1][2]} In the interval between the December 2015 and August 2016 results, the anomaly generated considerable interest in the scientific community, including about 500 theoretical studies.^[10] The hypothetical particle was denoted by the **Greek letter F** (pronounced digamma) in the scientific literature, owing to the decay channel in which the anomaly occurred.^[3] The data, however, were always less than five **standard deviations** (sigma) different from that expected if there was no new particle, and, as such, the anomaly never reached the accepted level of **statistical significance** required to announce a discovery in particle physics.^[11] The digamma was refuted in August 2016 publications.

December 2015 data [\[edit\]](#)

On December 15, 2015, the **ATLAS** and **CMS** collaborations at **CERN** presented results from the second operational run of the **Large Hadron Collider** (LHC) at the **center of mass** energy of 13 TeV, the highest ever achieved in proton-proton collisions. Among the results, the **invariant mass** distribution of pairs of high-energy photons produced in the collisions showed an excess of events compared to the **Standard Model** prediction at around 750 GeV/c^2 . The **statistical significance** of the deviation was reported to be 3.9 and 3.4 **standard deviations** (locally) respectively for each experiment.

The excess could have been explained by the production of a new particle (the digamma) with a mass of about 750 GeV/c^2 that decayed into two photons. The **cross-section** at 13 TeV centre of mass energy required to explain the excess, multiplied by the **branching fraction** into two photons, was estimated to be

$$\sigma(pp \rightarrow F) \times \text{Br}(F \rightarrow \gamma\gamma) \approx 5 \text{ fb}$$

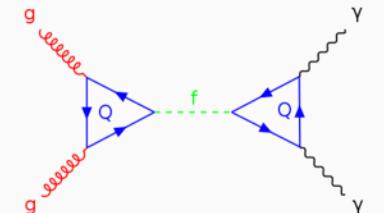
(fb=femtobarns)

This result, while unexpected, was compatible with previous experiments, and in particular with the LHC measurements at a lower centre of mass energy of 8 TeV.

August 2016 data [\[edit\]](#)

Analysis of a larger sample of data, collected by ATLAS and CMS in the first half 2016, did not confirm the existence of the **F** particle, which indicates that the excess seen in 2015 was a statistical fluctuation.^{[1][2]}

Digamma

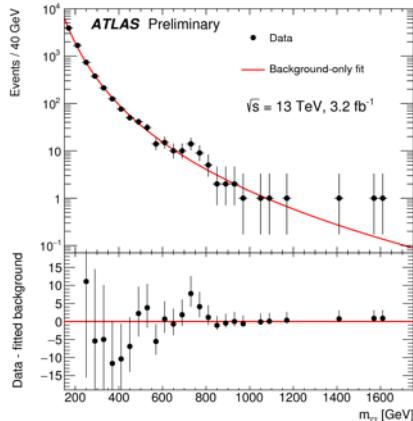


Possible production and decay mechanism of the digamma resonance at LHC.

Composition Elementary particle

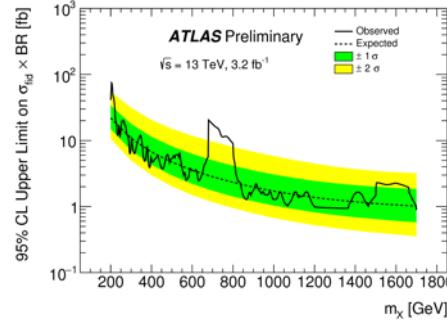
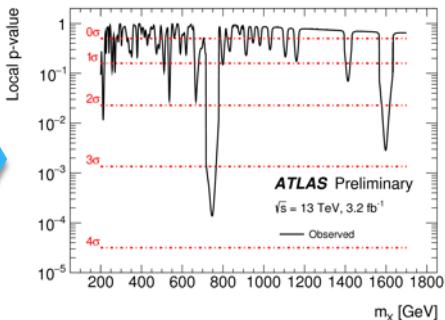
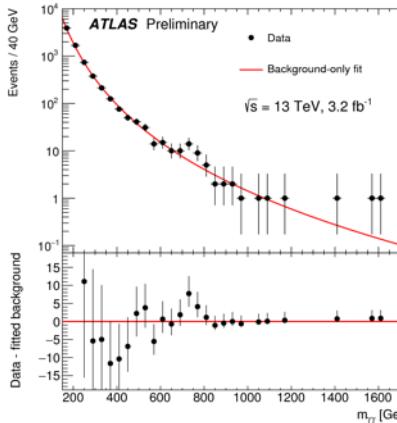
Statistics	suspected bosonic
Status	Refuted; absent in August 2016 data ^{[1][2]}
Symbol	F , ^[3] $F(750)$, ^[4] ϕ , ^[5] X , ^[6] η_{zy} ^[7]
Discovered	Resonance of mass ≈ 750 GeV decaying into two photons could have been seen by CERN in 2015 ^{[8][9]} (though sufficient statistical significance never reached)
Mass	$\approx 750 \text{ GeV}/c^2$ (CMS + ATLAS) ^{[8][9]}
Decay width	$< 50 \text{ GeV}/c^2$ ^{[8][9]}
Decays into	two photons (hinted in 2015 data; ^{[8][9]} absent in 2016 data ^{[1][2]}) two Z-bosons (predicted) one photon + one Z-boson (predicted) two W bosons (predicted) two gluons (predicted)

Diphoton resonances



>90% prompt-prompt, $\sigma_m/m \sim 1\%$

Diphoton resonances



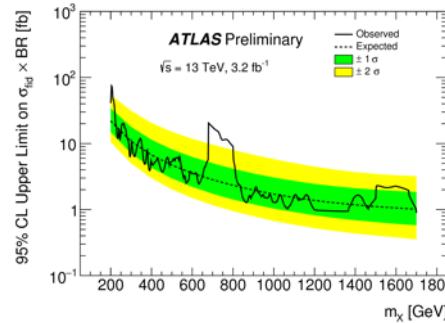
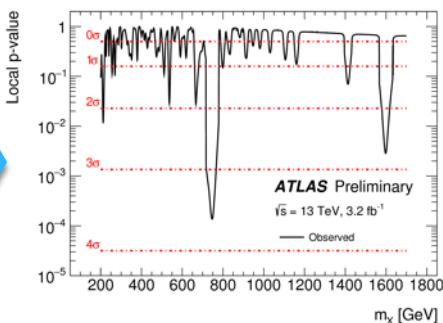
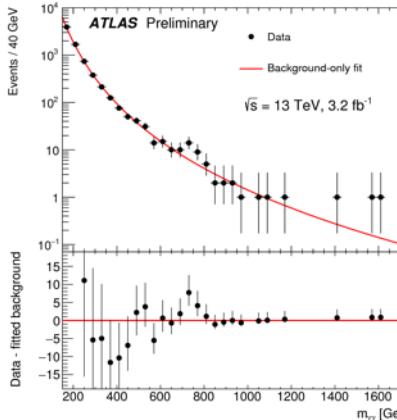
For $m_\chi = 750 \text{ GeV}$

$3.6\sigma \rightarrow 2.0\sigma \text{ after LEE}$

($3.9\sigma \rightarrow 2.3\sigma$ for $\Gamma = 6\%$)

>90% prompt-prompt, $\sigma_m/m \sim 1\%$

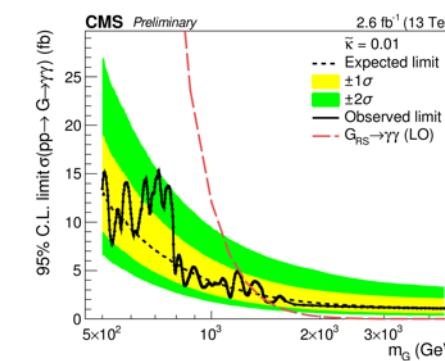
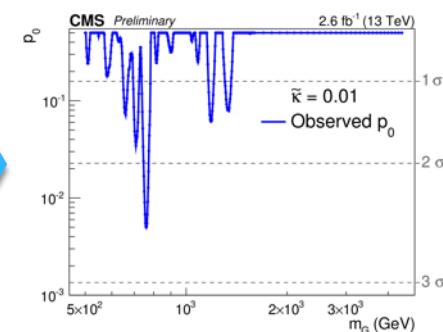
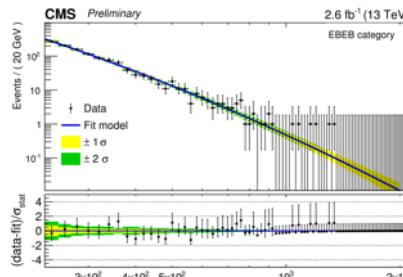
Diphoton resonances



For $m_\chi = 750$ GeV

$3.6\sigma \rightarrow 2.0\sigma$ after LEE
 $(3.9\sigma \rightarrow 2.3\sigma \text{ for } \Gamma = 6\%)$

>90% prompt-prompt, $\sigma_m/m \sim 1\%$



For $m_G = 760$ GeV

$2.6\sigma \rightarrow 1.2\sigma$ after LEE

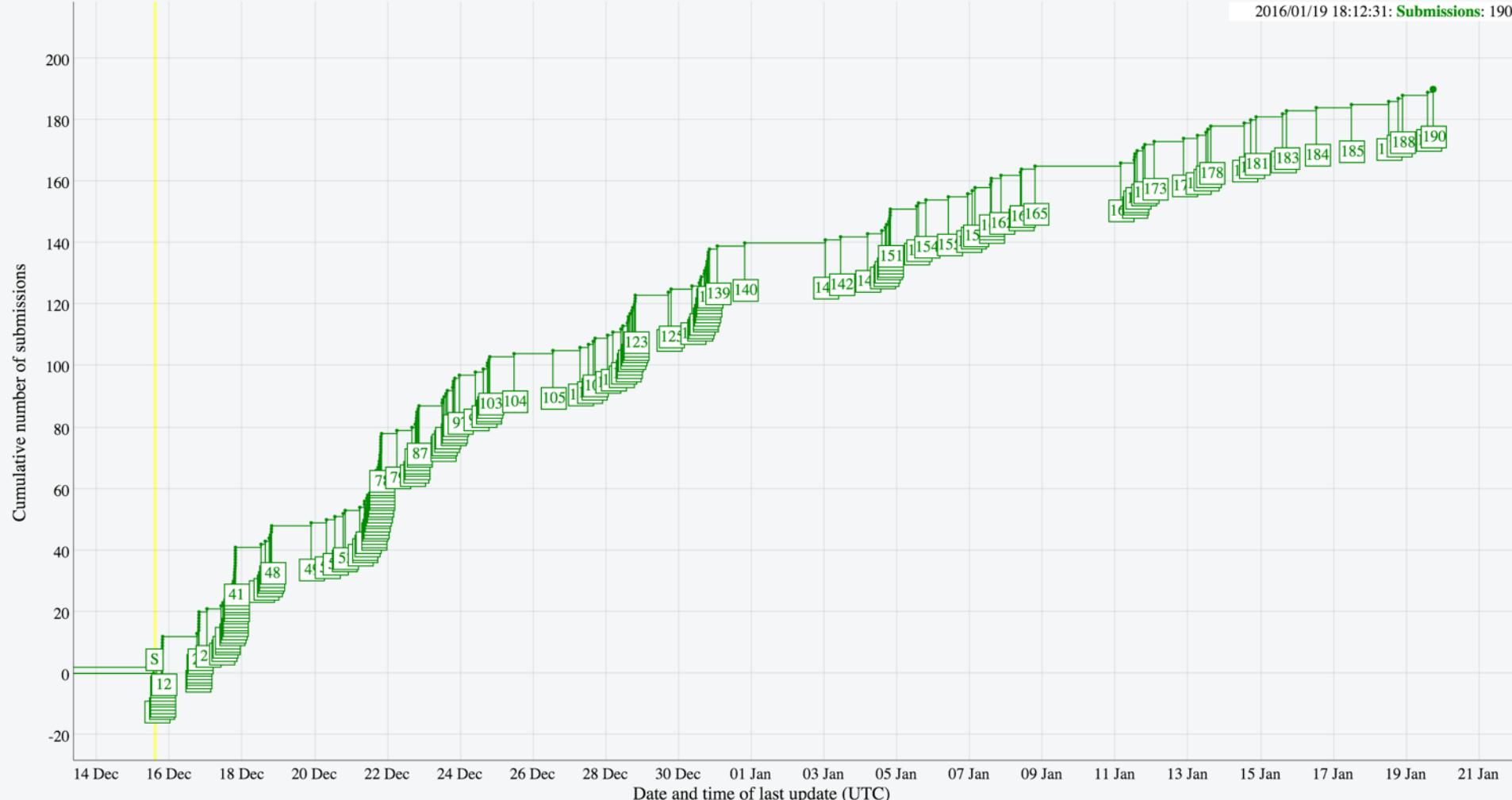


Post-seminar stampede

105

[<http://cern.ch/go/DZt8>]#Run2Seminar and subsequent $\gamma\gamma$ -related arXiv submissions

2016/01/19 18:12:31: Submissions: 190





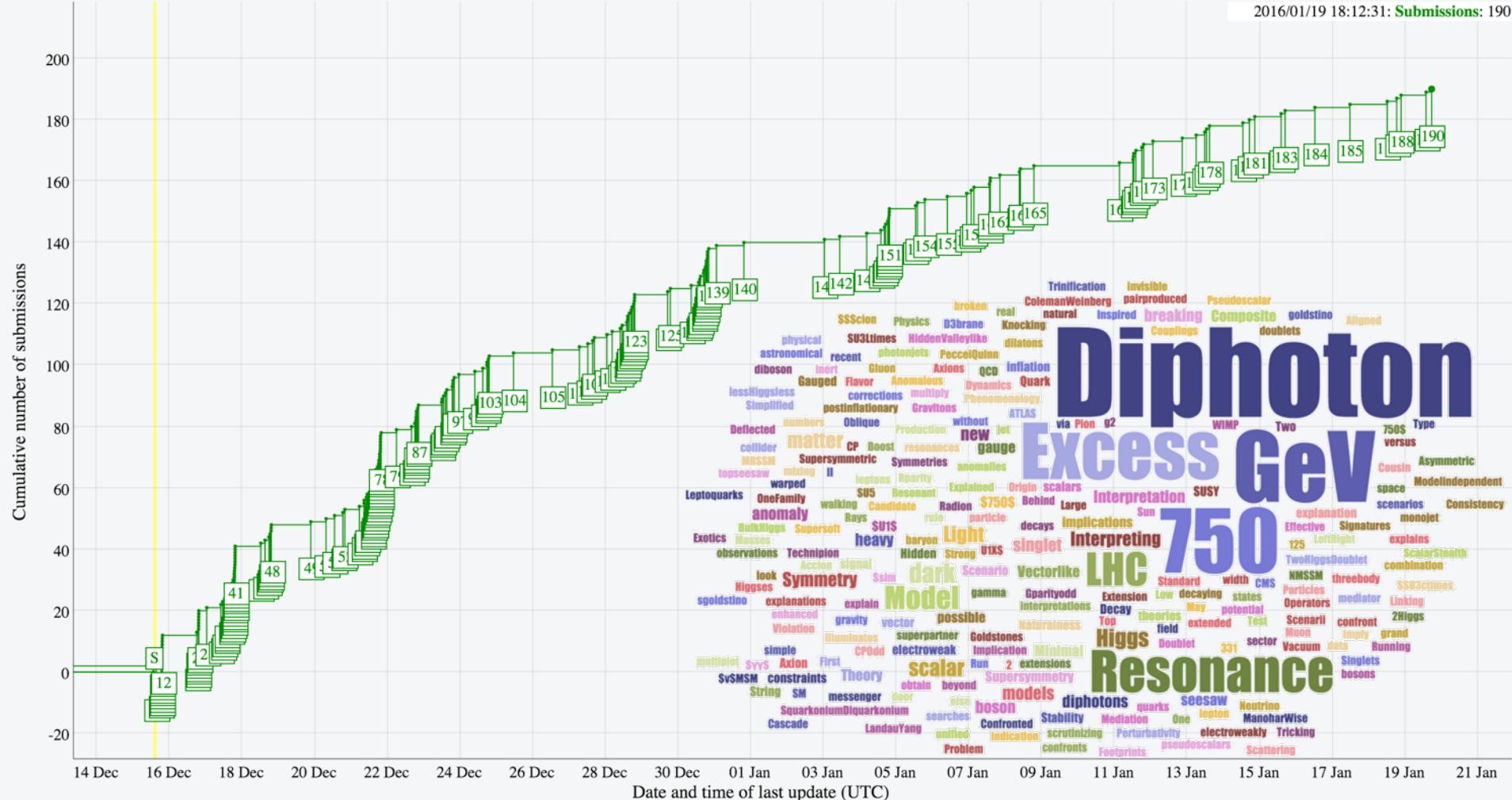
Post-seminar stampede

106

[<http://cern.ch/go/DZt8>]

#Run2Seminar and subsequent $\gamma\gamma$ -related arXiv submissions

2016/01/19 18:12:31: **Submissions:** 190



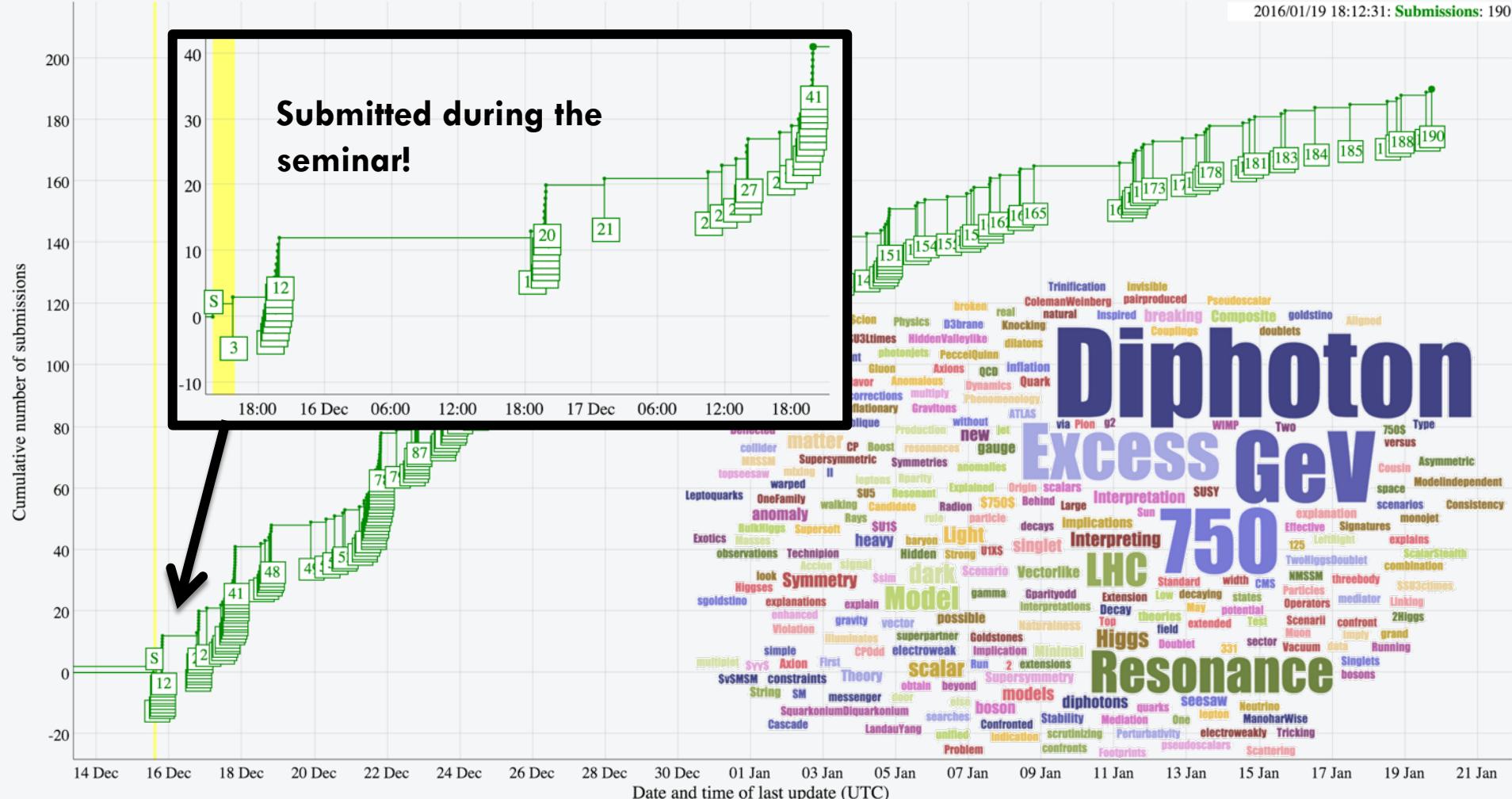


Post-seminar stampede

107

[\[http://cern.ch/go/DZt8 \]](http://cern.ch/go/DZt8)#Run2Seminar and subsequent $\gamma\gamma$ -related arXiv submissions

2016/01/19 18:12:31: Submissions: 190



Perhaps a whole fixion sector?



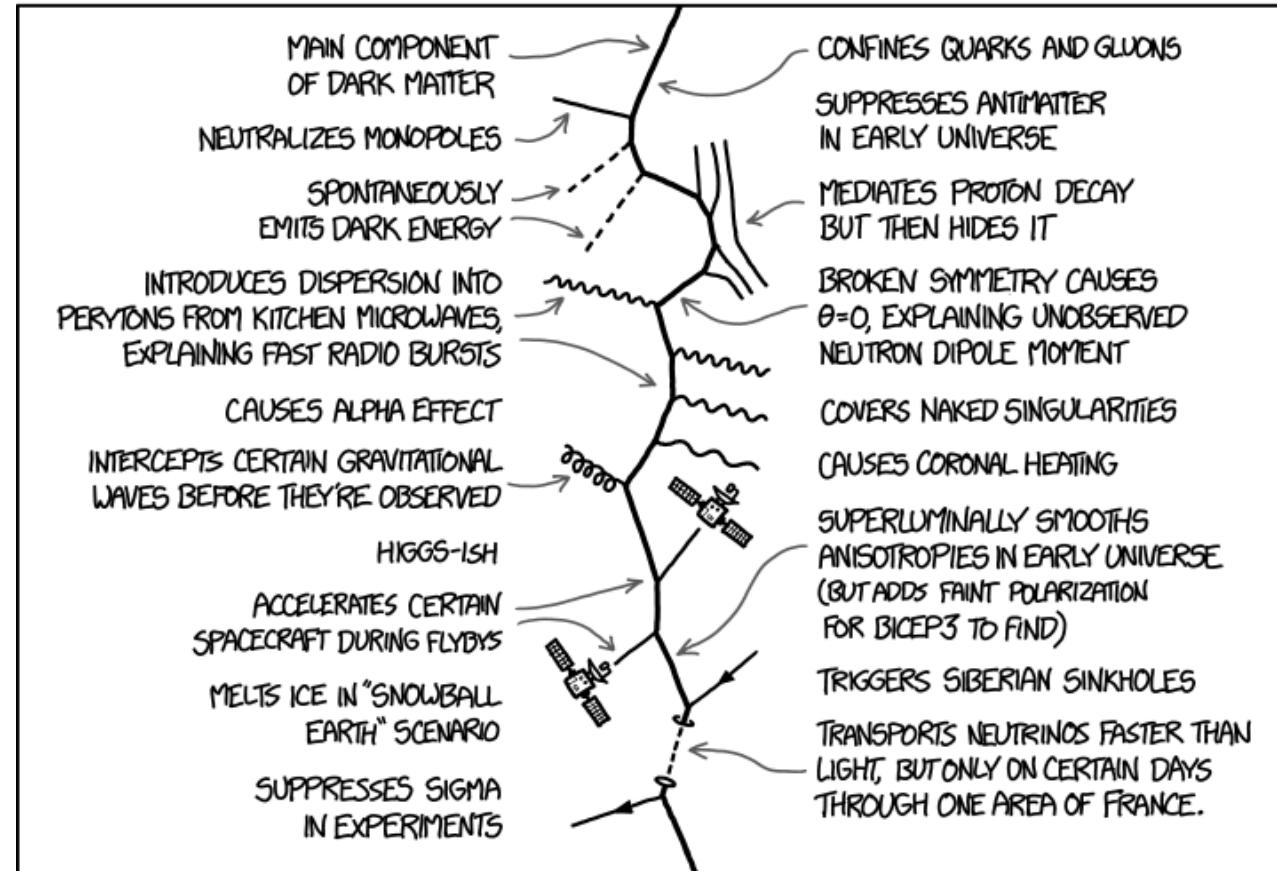
108

[<http://xkcd.com/1621>]

A CHRISTMAS GIFT FOR PHYSICISTS:

THE FIXION

A NEW PARTICLE THAT EXPLAINS EVERYTHING

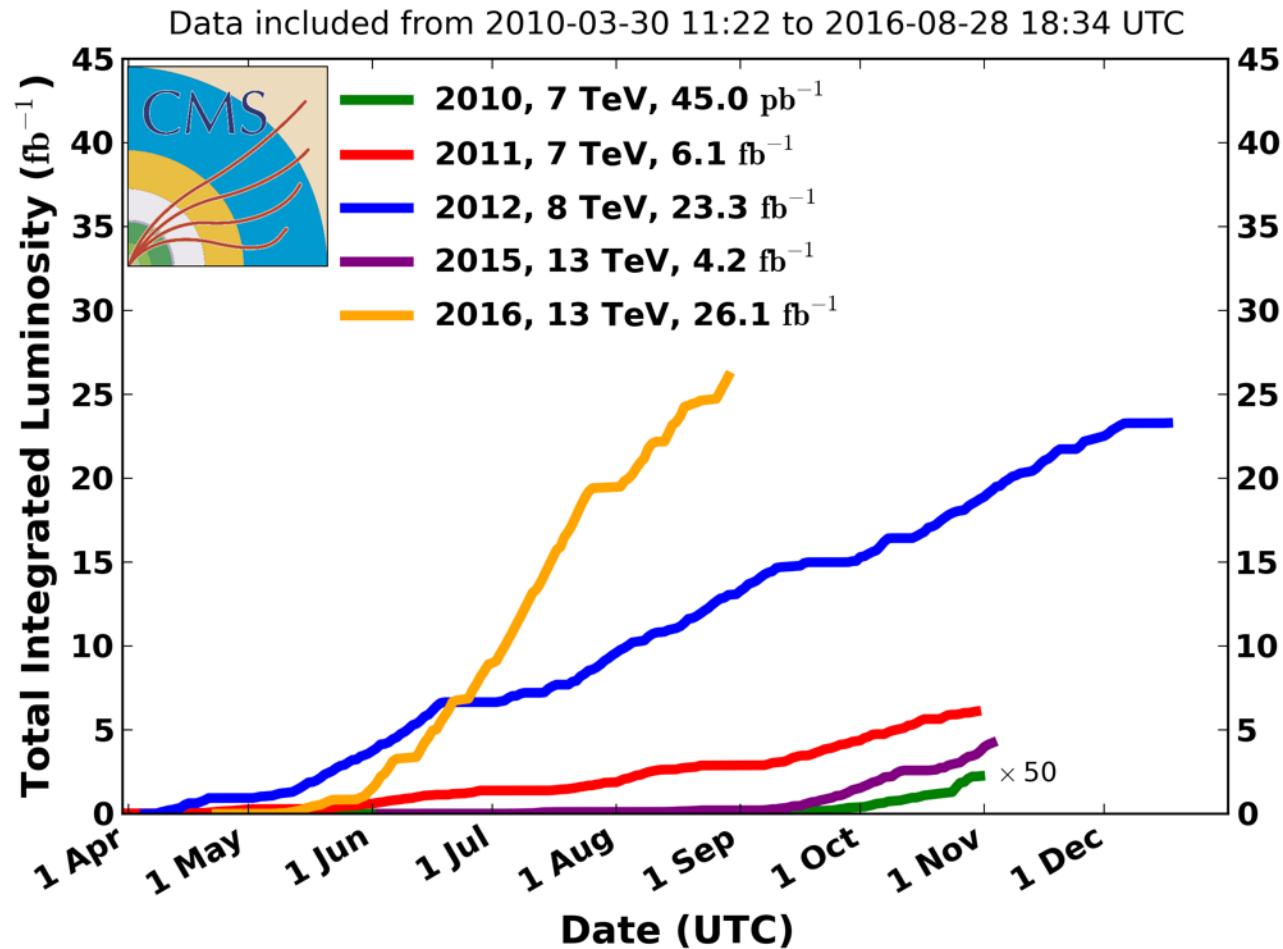


#MoarData



109

CMS Integrated Luminosity, pp

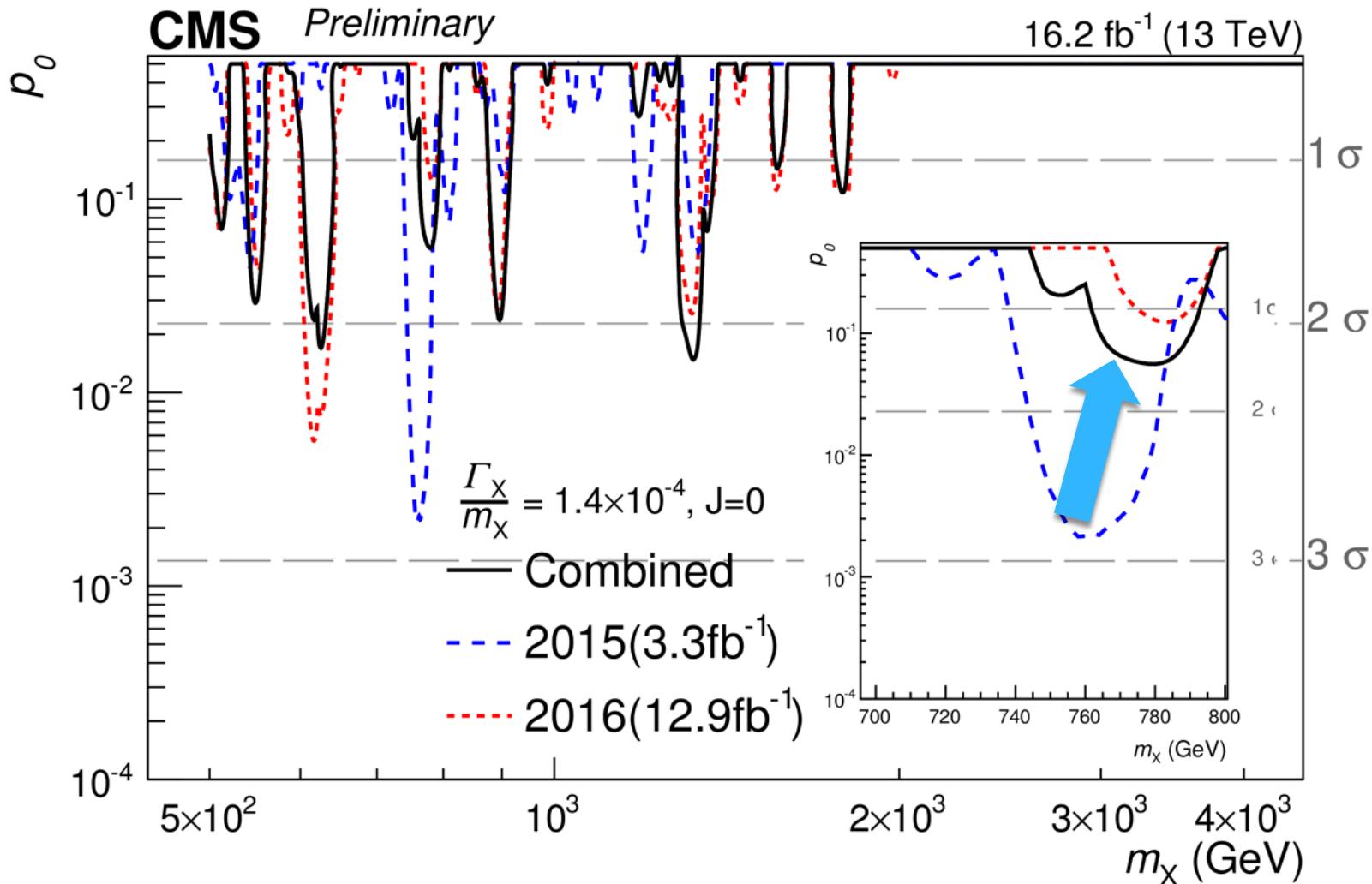


The effect of #MoarData



110

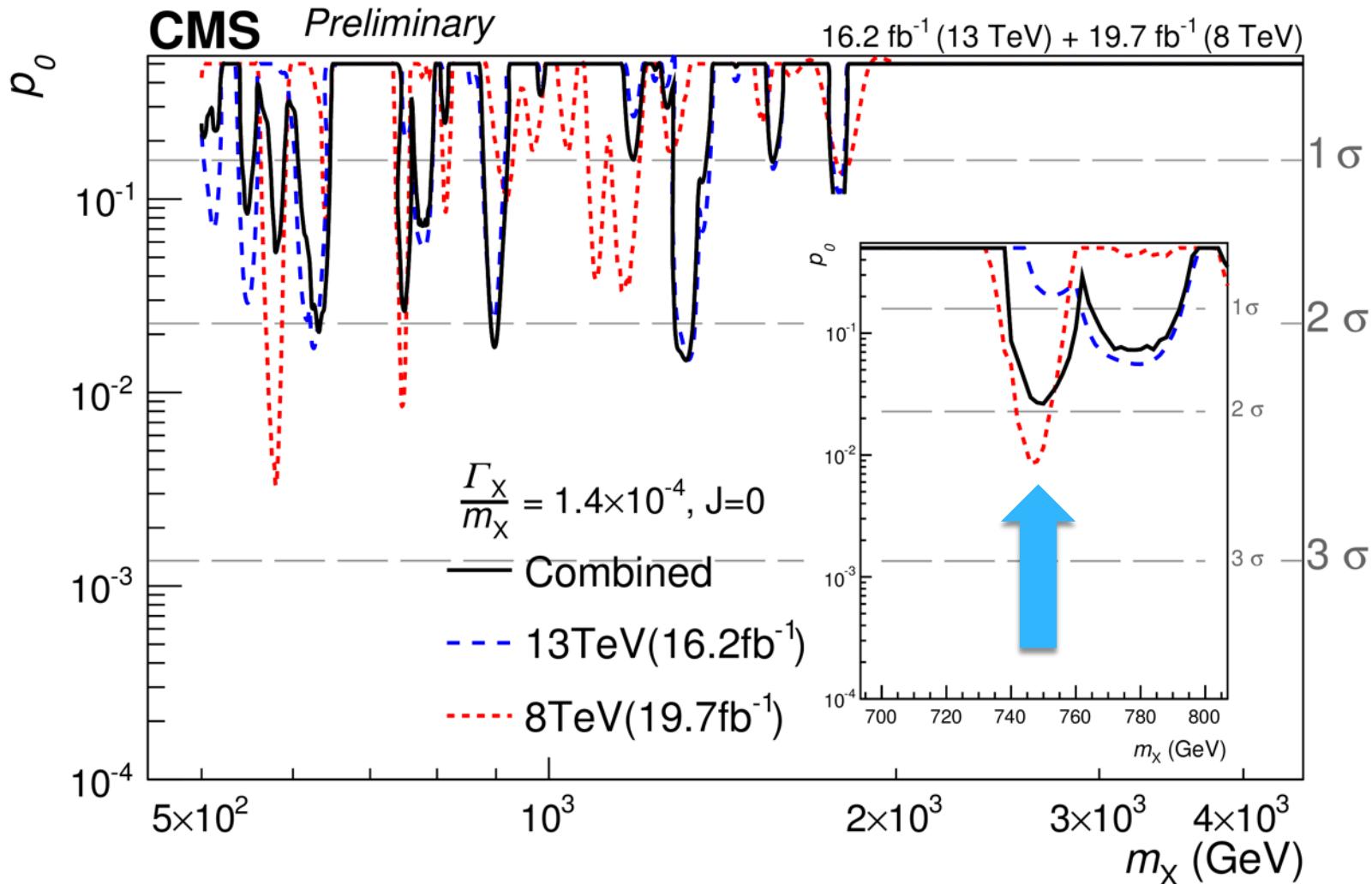
[CMS-PAS-EXO-16-027]



The effect of even #MoarData

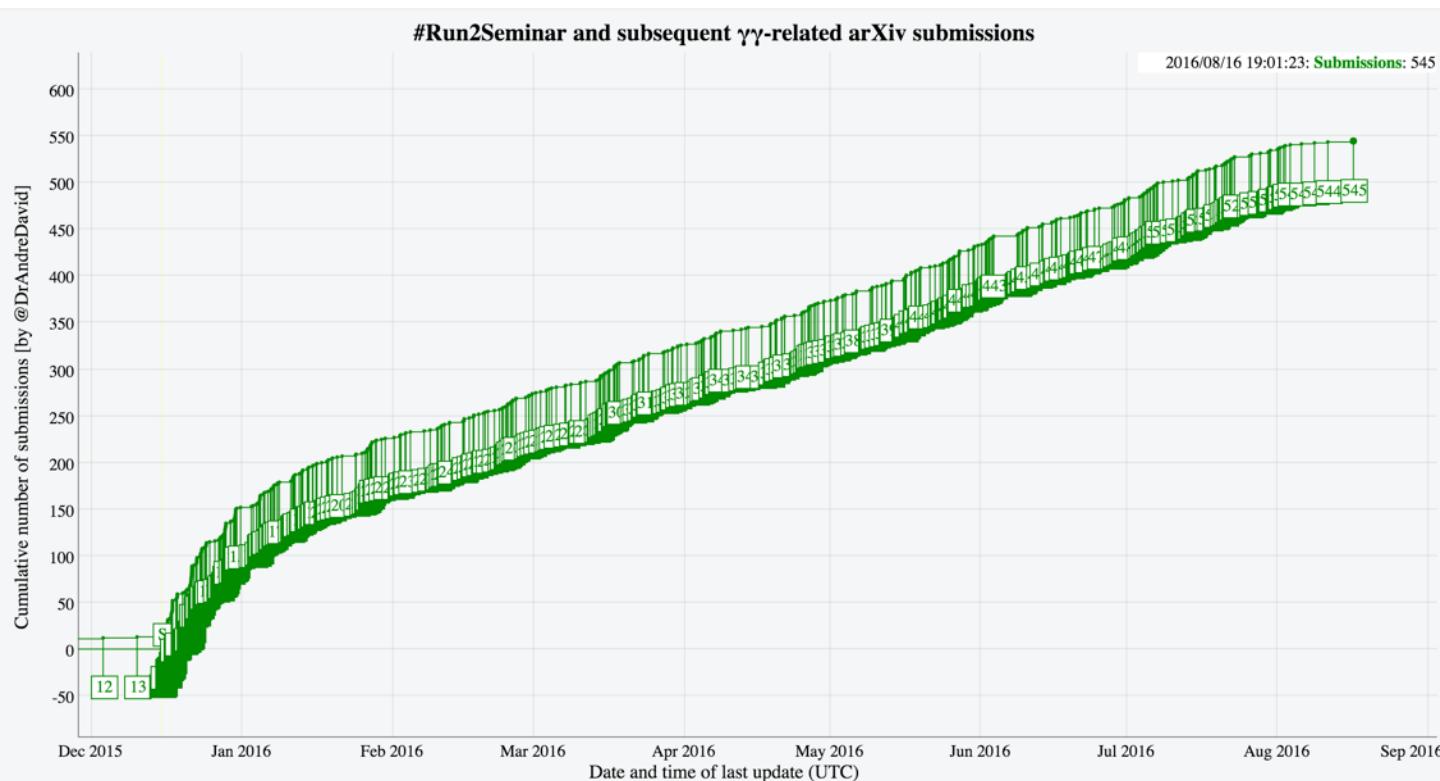
111

[CMS-PAS-EXO-16-027]



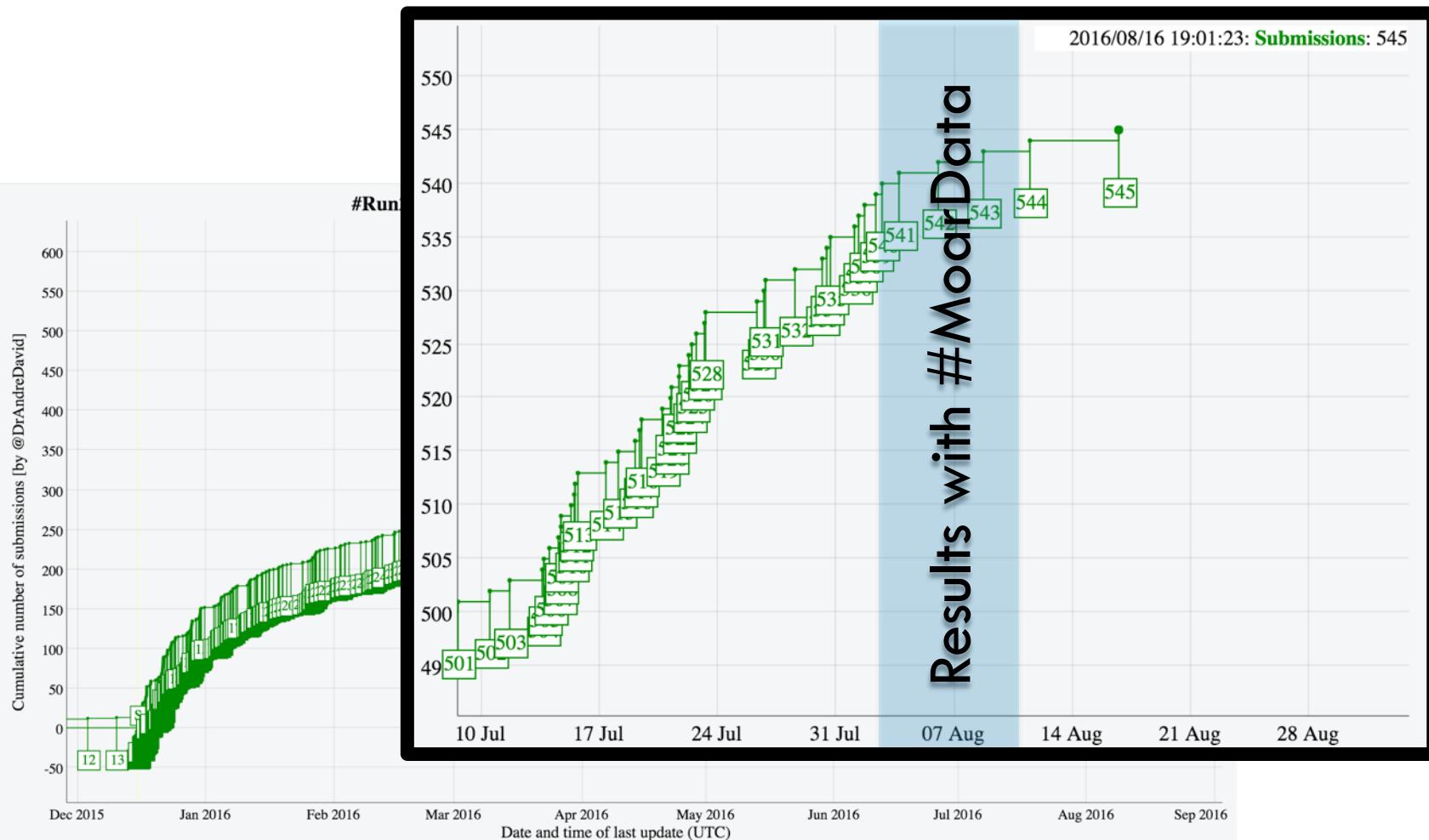
Stampede no “moar”

112

[<http://cern.ch/go/DZt8>]

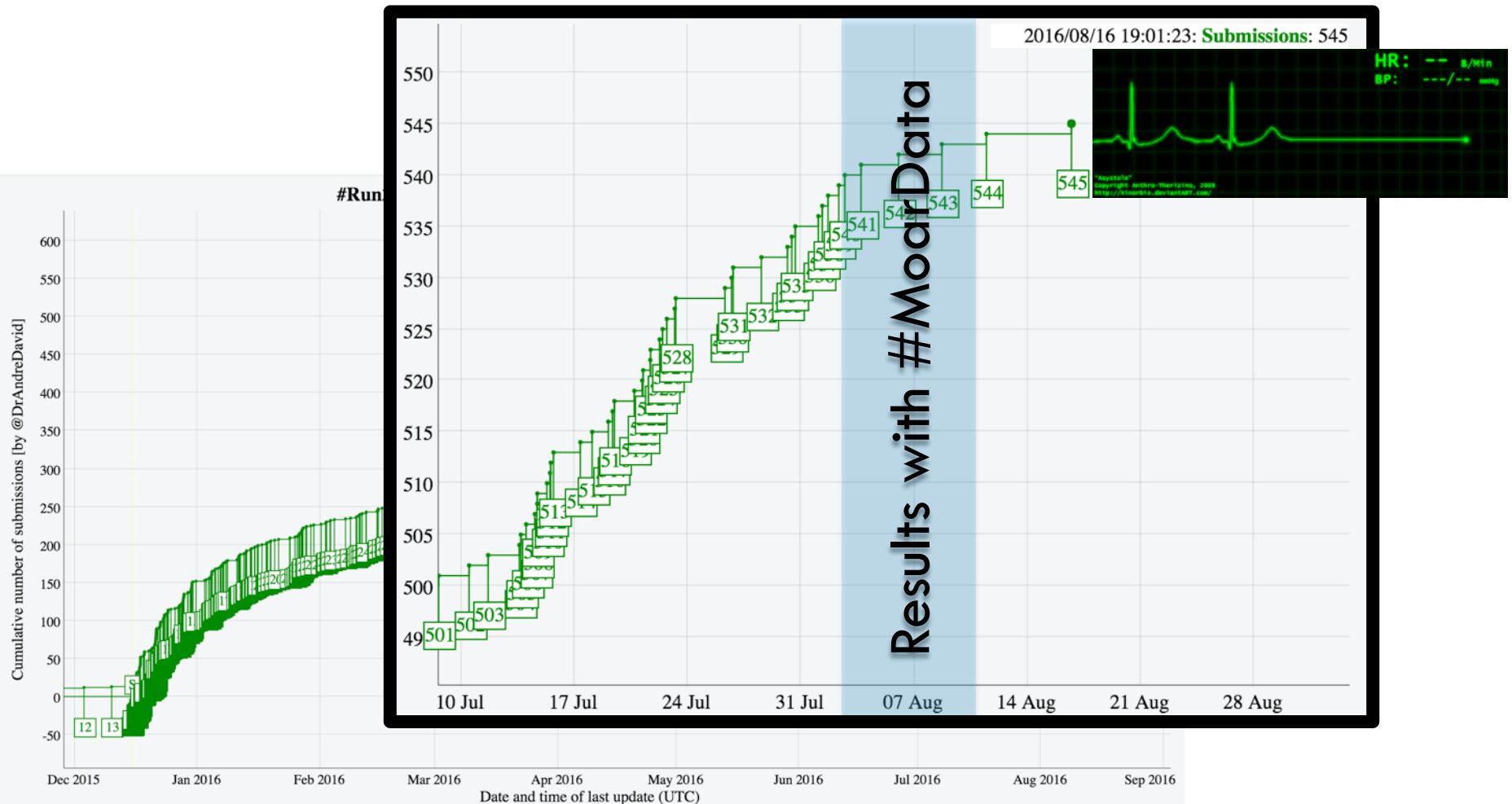
Stampede no “moar”

113

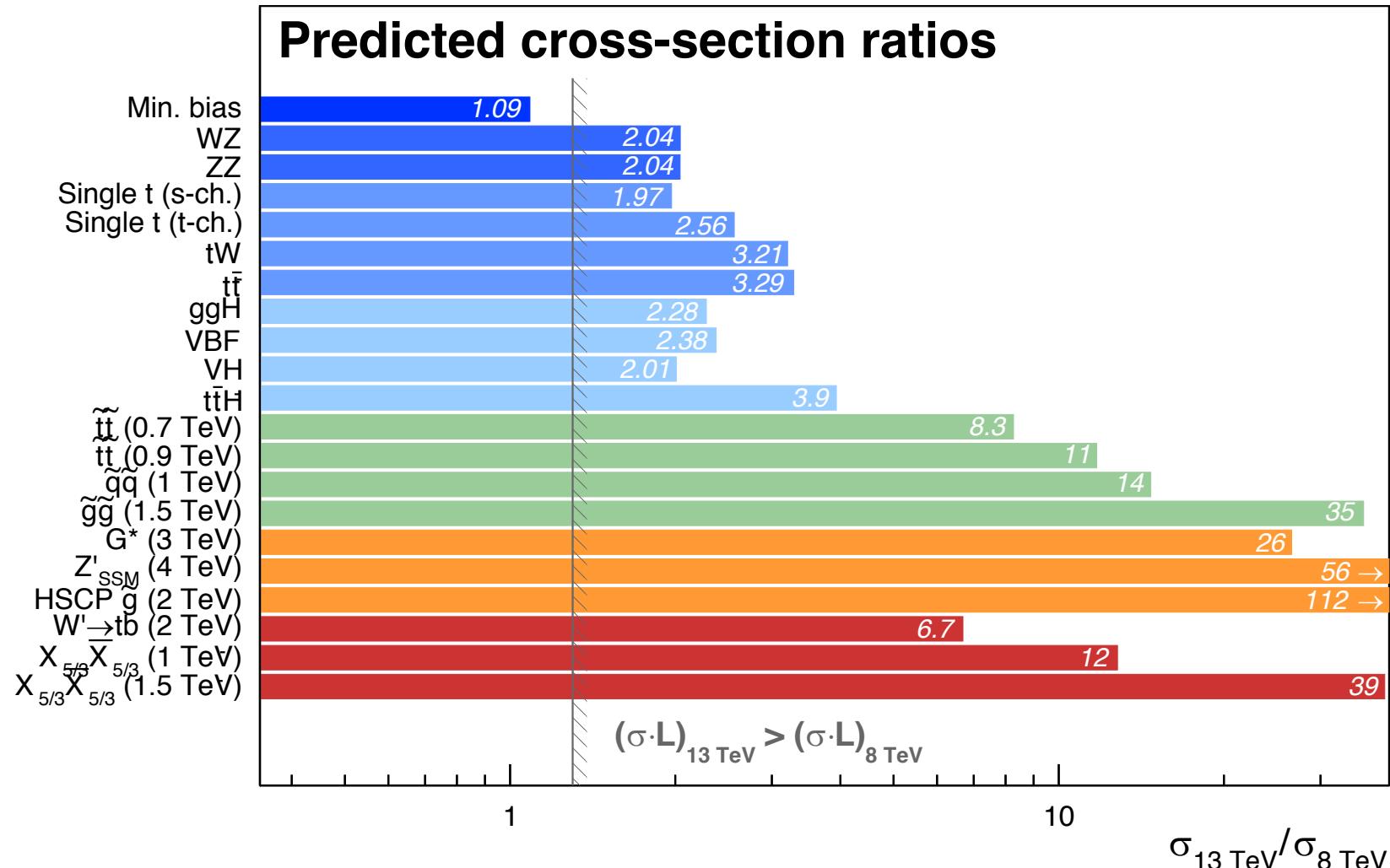
[<http://cern.ch/go/DZt8>]

Stampede no “moar”

114

[<http://cern.ch/go/DZt8>]

The future is bright

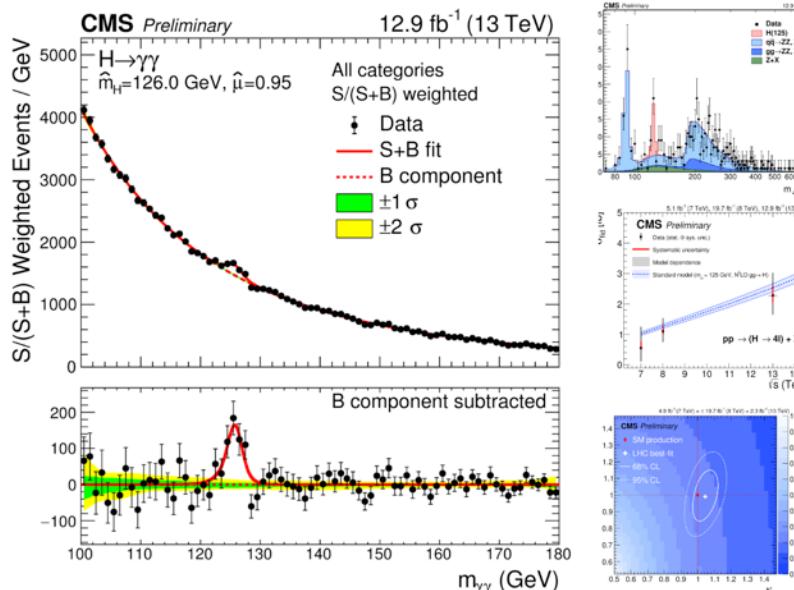


Unlike mirages the Higgs is still with us



André David
@DrAndreDavid

Very proud of the #Higgs #physics results from @CMSExperiment presented at #ICHEP2016!



RETWEETS
8 LIKES
19

12:43 AM - 6 Aug 2016

Lisbon, Portugal

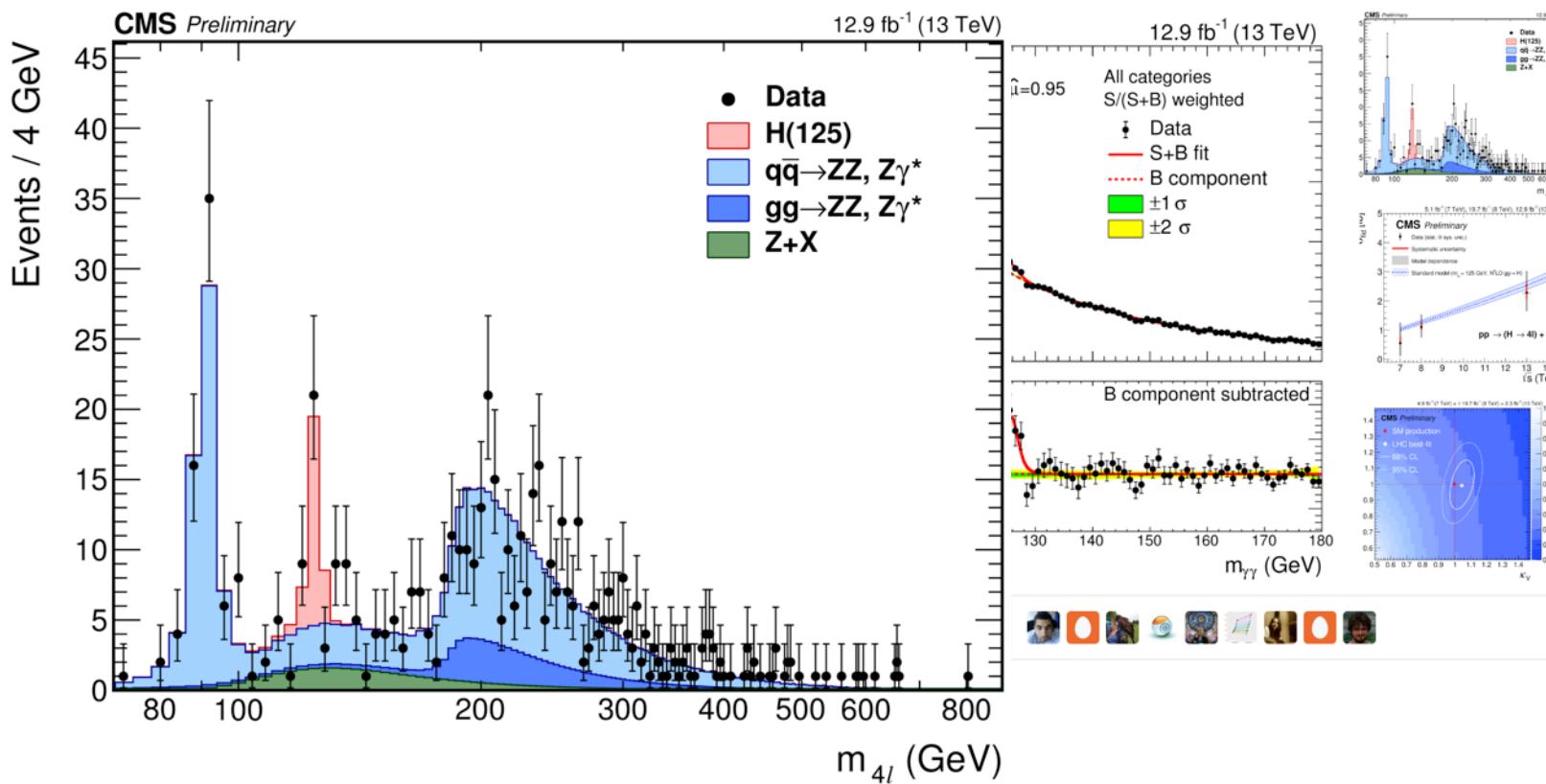
CMS Experiment CERN

Unlike mirages the Higgs is still with us



André David
@DrAndreDavid

Very proud of the #Higgs #physics results from
@CMSExperiment presented at #ICHEP2016!

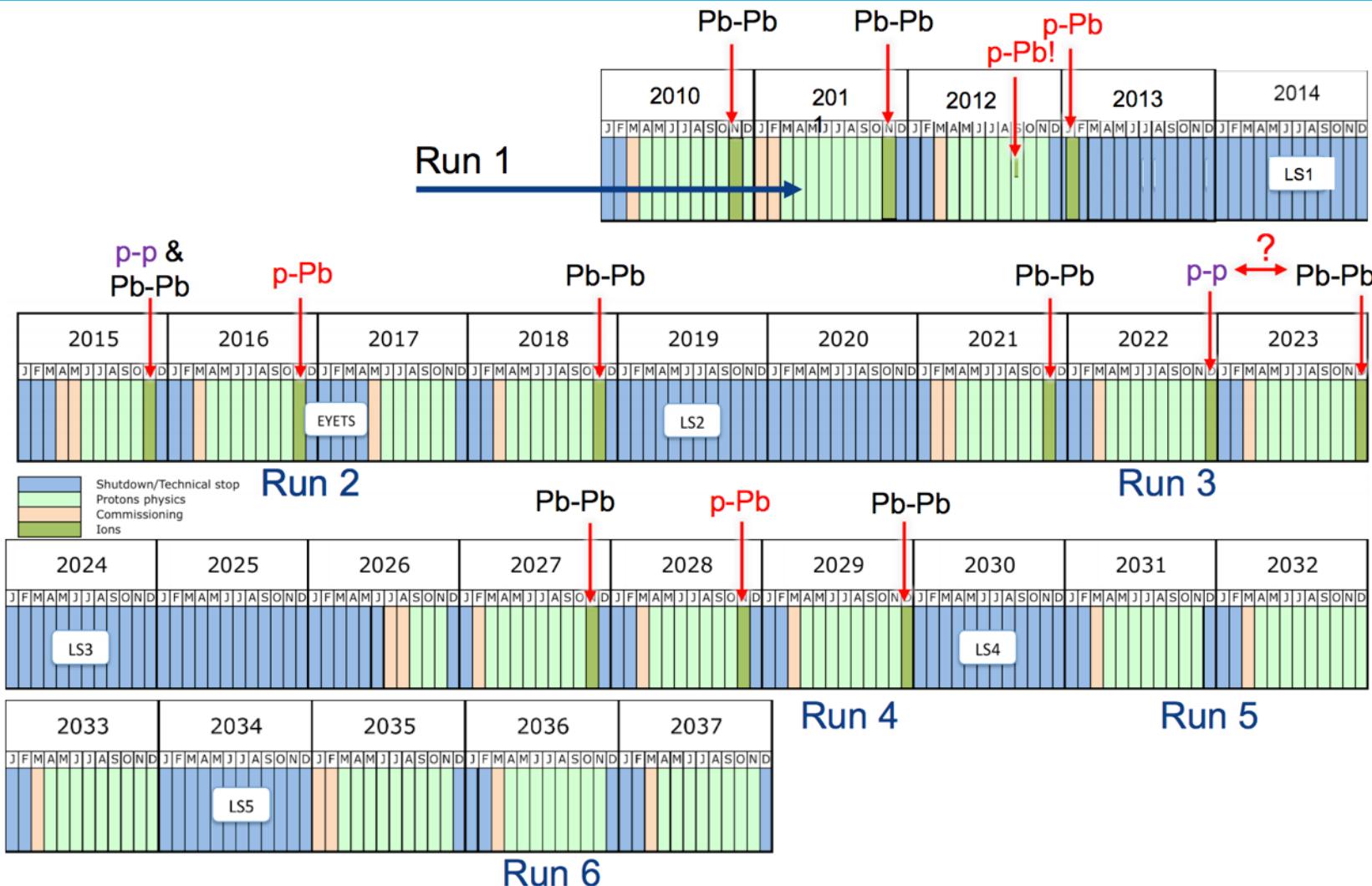


Moving forward

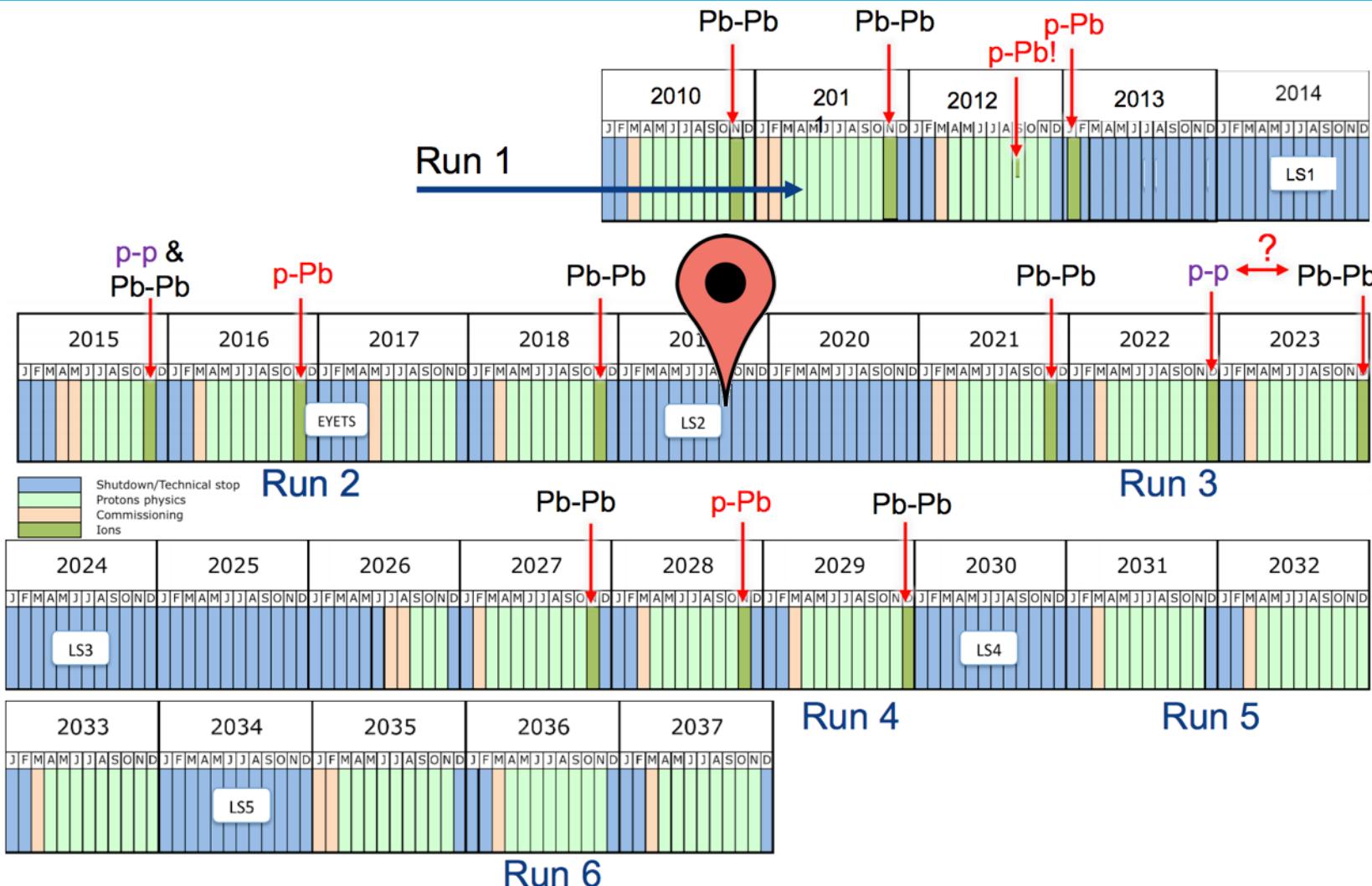
- We must examine this Higgs to the fullest extent !
 - It may be the only clue to leave the SM oasis and cross the desert.



Deeper into the rabbit hole



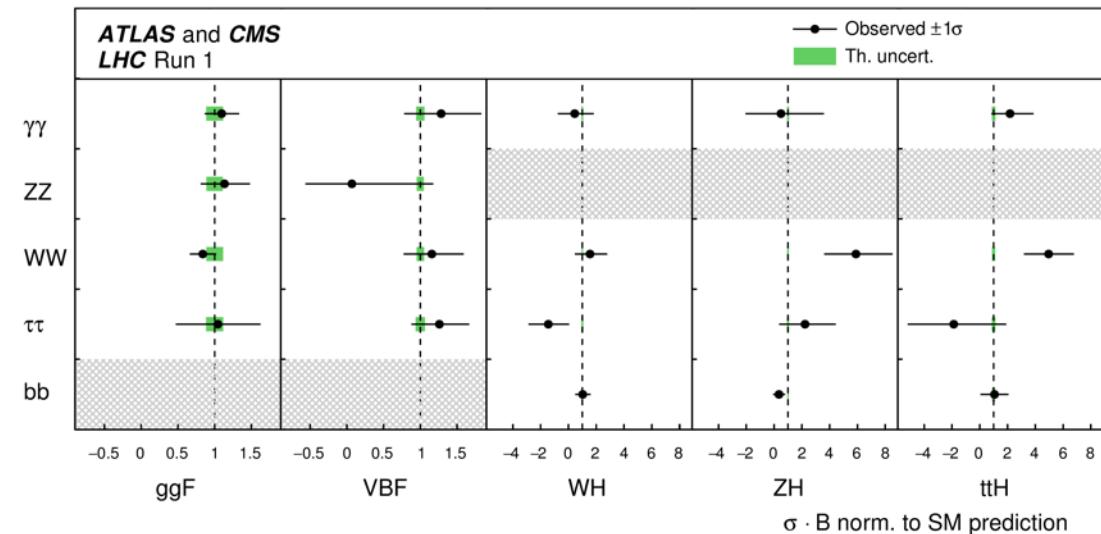
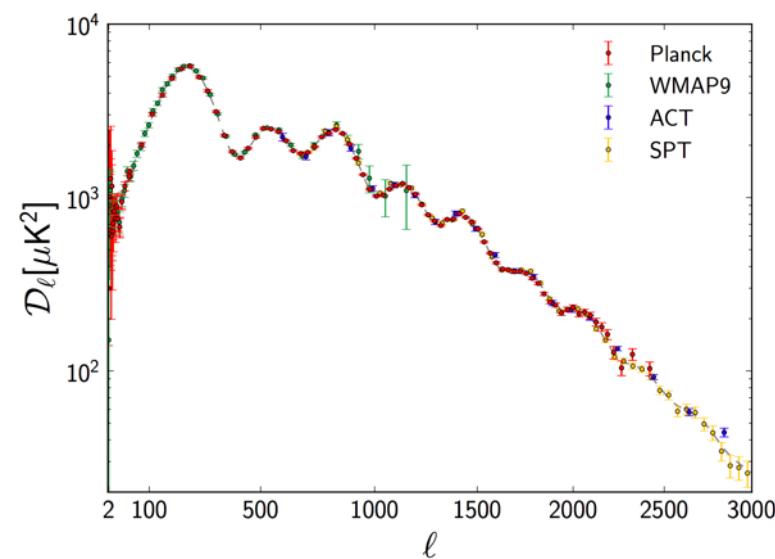
Deeper into the rabbit hole



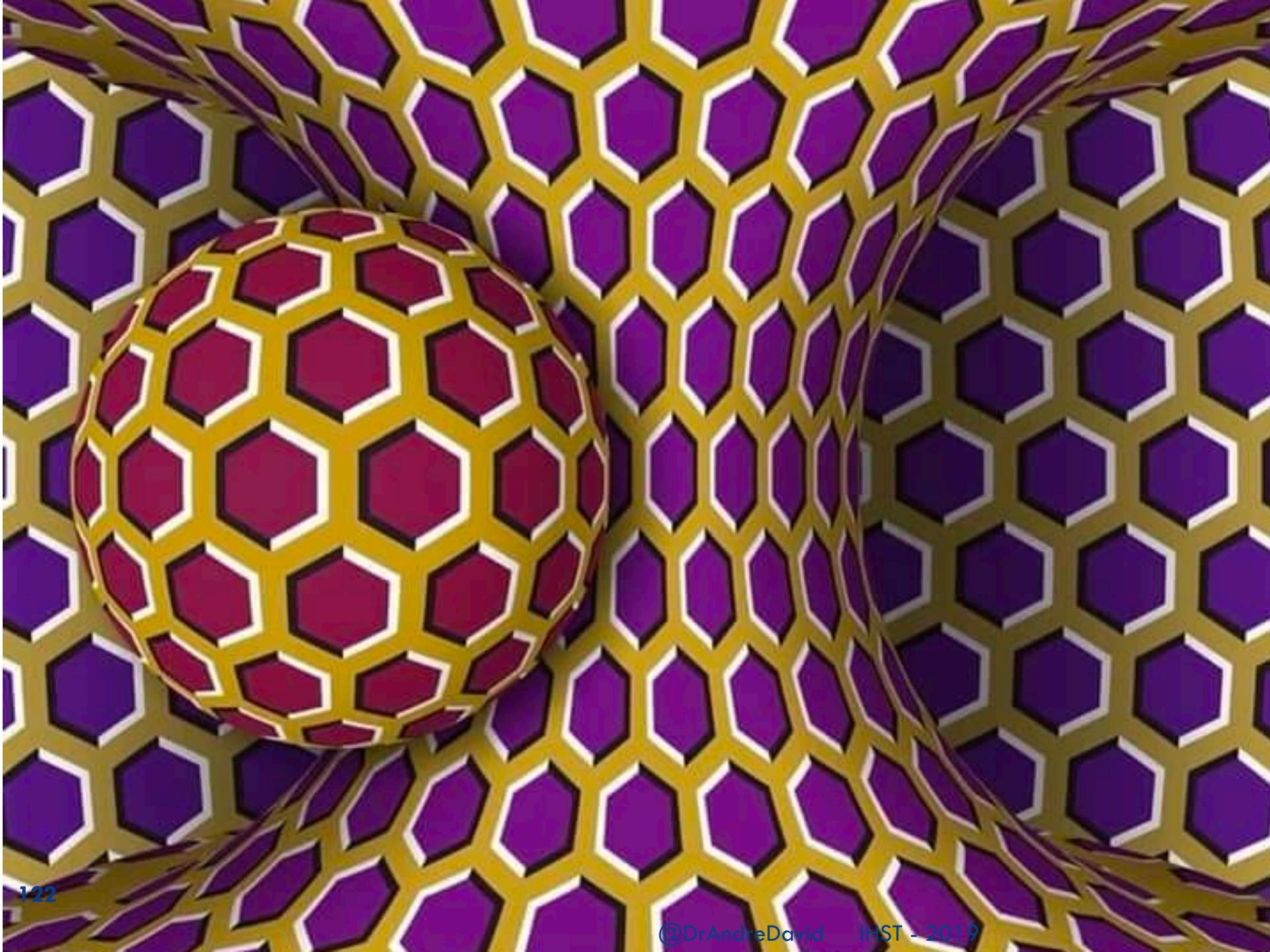
The ~~beautiful~~ ~~boring~~ Universe today

[arXiv:1303.5062] [JHEP 08 (2016) 045]

- Up above:
“Simple six-parameter Λ CDM”.
- Down below:
(Not-as-simple) ~ 20 -parameter Standard Model of Particle Physics.



Looking forward to surprises at higher energy: PeV neutrinos, #MoarData at LHC 13 TeV, ...





“...and references therein.”

- Experiments' pages on Higgs results:
 - ATLAS: <http://cern.ch/go/7IDT>
 - CMS: <http://cern.ch/go/6qmZ>
 - Tevatron: <http://cern.ch/go/h9jX>
 - CDF: <http://cern.ch/go/q8NV>
 - D0: <http://cern.ch/go/9Djq>
- Partial list of conferences and workshops:
 - Higgs Days 2013: <http://cern.ch/go/6zBp>
 - ECFA HL-LHC workshop: <http://cern.ch/go/SFW6>
 - Higgs EFT 2013: <http://cern.ch/go/bR7w>
 - Higgs Couplings 2013: <http://cern.ch/go/THp9>
 - Moriond 2014: <http://cern.ch/go/k8FP>
 - Bernasque 2014: <http://cern.ch/go/Pz7I>
 - ICHEP 2014: <http://cern.ch/go/8Btf>
 - Rencontres du Vietnam 2014: <http://cern.ch/go/9ZJJ>
 - Zuoz Summer School 2014: <http://cern.ch/go/9SHw>
 - Higgs Days 2014: <http://cern.ch/go/lfP6>
 - Higgs Couplings 2014: <http://cern.ch/go/HMm6>