

# FUNDAMENTALS OF SCIENCE & FUNDAMENTAL SCIENCE



André David (CERN)



# Things you can't “unsee”

3

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





# Things you can't “unsee”

4

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





# Things you can't “unsee”

5

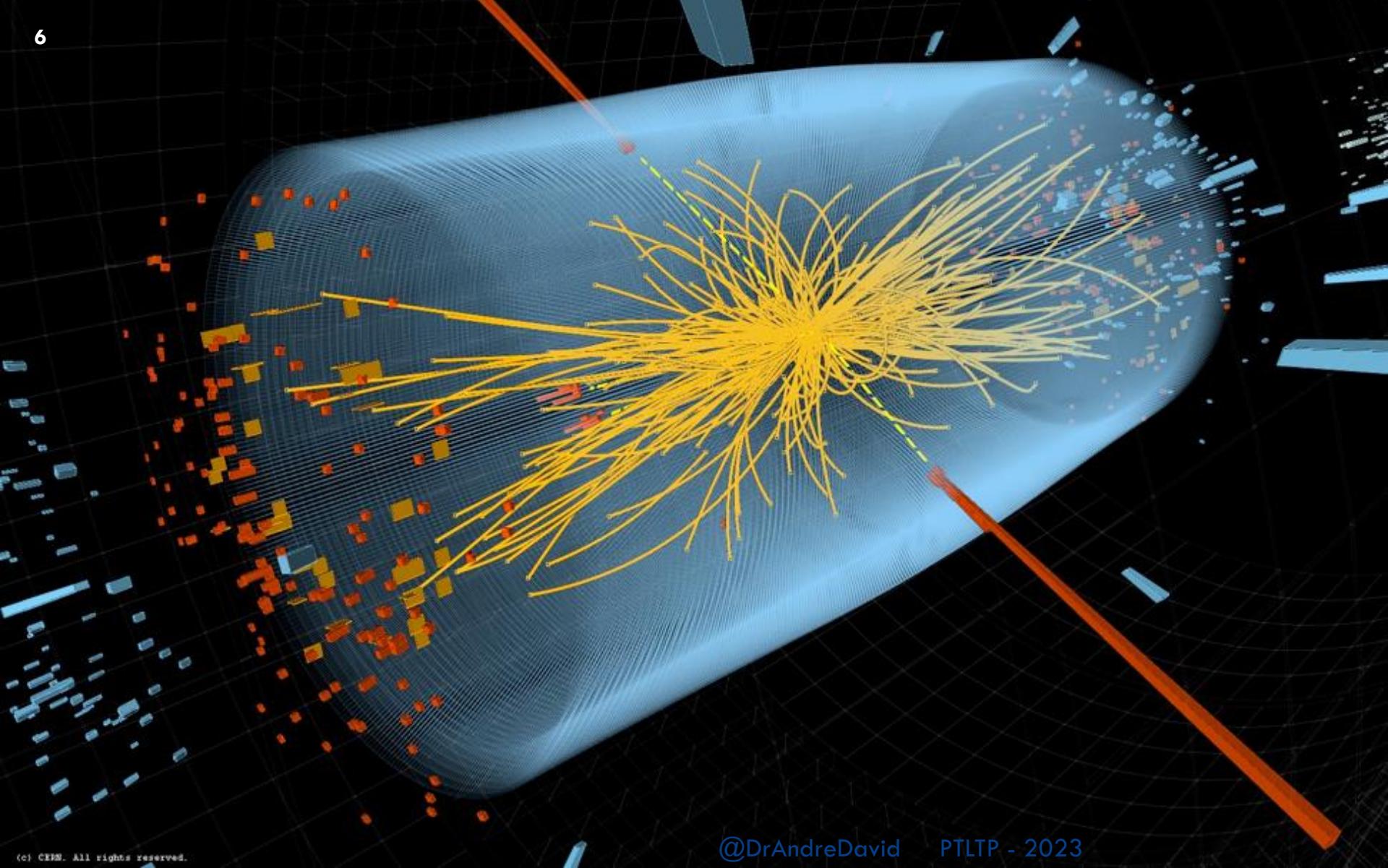
[ <http://cern.ch/go/Dxh7> ]





# 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 the shore. In the foreground, a small red lighthouse sits on a dark stone pier. Several people are standing on the pier, looking out at the powerful wave. A tall metal pole stands next to the lighthouse. The sky above the wave is bright and featureless.

**Nature**

A dramatic photograph of a massive, curling green wave crashing towards the shore. In the foreground, a red cylindrical lighthouse sits atop a dark stone pier. Several people are standing on the pier, looking out at the powerful wave. A tall metal pole stands next to the lighthouse. The sky above the wave is bright and featureless.

**Nature**

Theory

A dramatic photograph of a massive, curling green wave crashing towards the shore. In the foreground, a small red lighthouse stands on a dark stone pier. Several people are standing on the pier, looking out at the powerful wave. A tall metal pole stands next to the lighthouse. The sky above the wave is bright and overexposed.

**Nature**

Theory

Theorists  
(inside)

A photograph of a massive, emerald-green wave crashing over a small pier. A red lighthouse is situated on the pier, and several people are standing on the right side of the pier, watching the wave. The sky is clear and blue.

**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 foreground, a small white boat with two people is visible. The word "Nature" is printed in large, bold, black letters across the top center of the image.

# Nature

Experimentalists

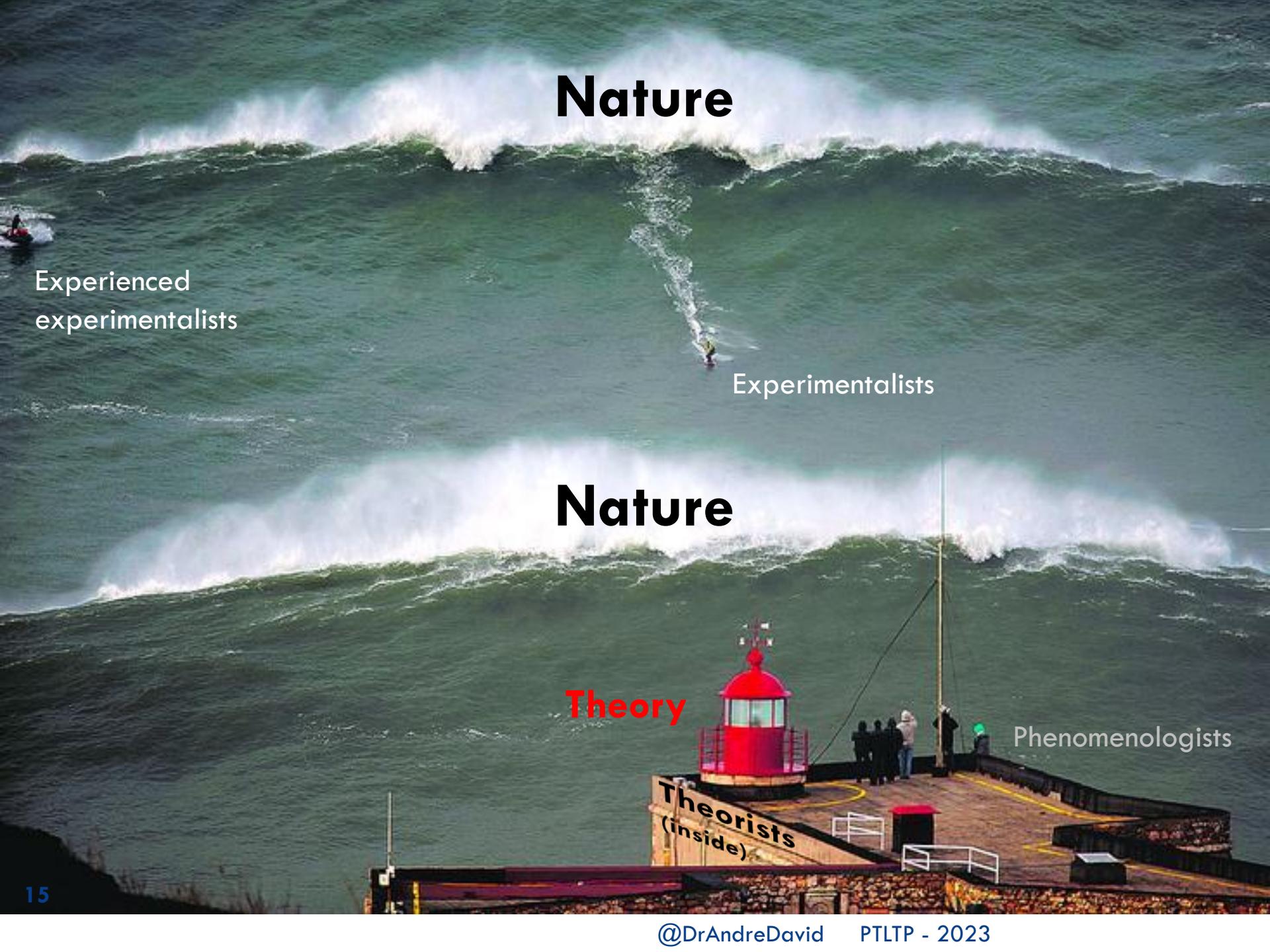
A photograph of a large, powerful green wave crashing on a beach. In the lower right foreground, a red lighthouse sits on a stone pier. Several people are standing on the pier, watching the wave. The word "Nature" is printed in large, bold, black letters across the middle left of the image.

# Nature

Theory

Theorists  
(inside)

Phenomenologists



# Nature

Experienced  
experimentalists

Experimentalists

# Nature

Theory

Theorists  
(inside)

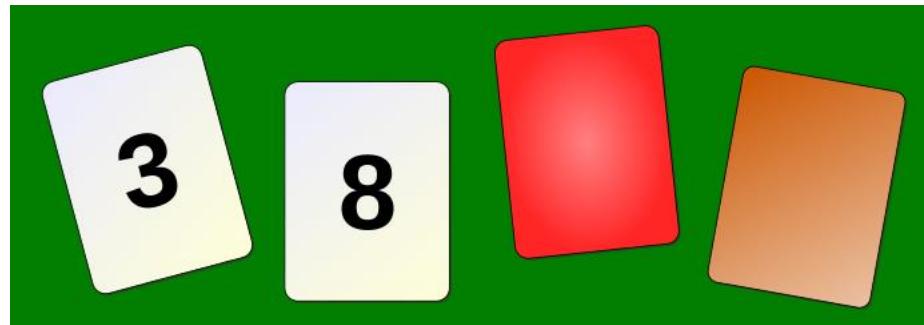
Phenomenologists

# Lógica (“formal” e “da batata”)

Ou como decidir que experiências fazer.

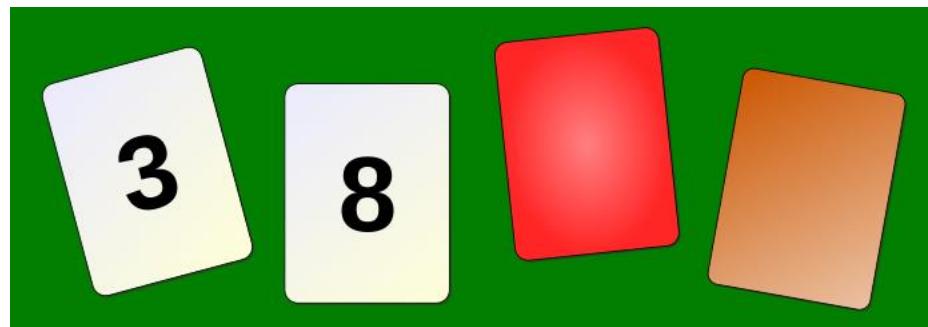
# Wason selection task

- “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?**”



# Wason selection task

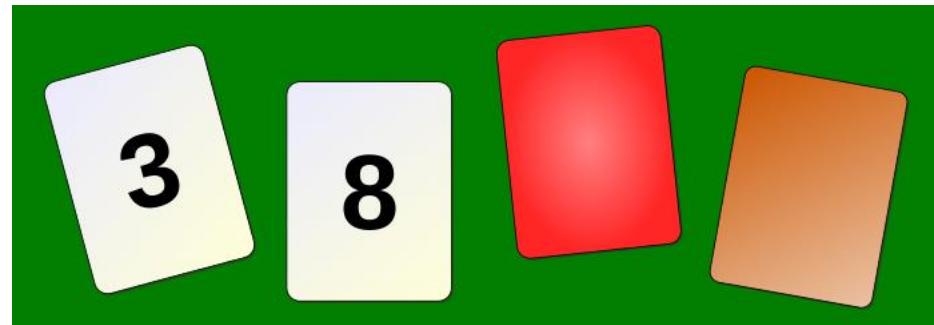
- “Há quatro cartas na mesa, cada uma com um número num lado e uma cor no outro. Podemos ver um 3, um 8, uma vermelha, e uma castanha. **Que carta(s) têm que ser viradas de forma a testar a veracidade da proposição que se uma carta tem um número par de um lado, então a cor do outro lado é vermelho?**”



# Trocado por miúdos

19

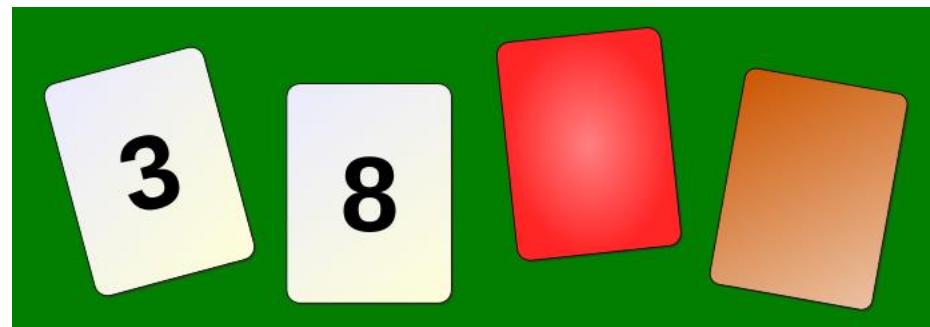
- Como testar a ideia que “**par  $\Rightarrow$  vermelho**”?



# Lógica (formal)

20

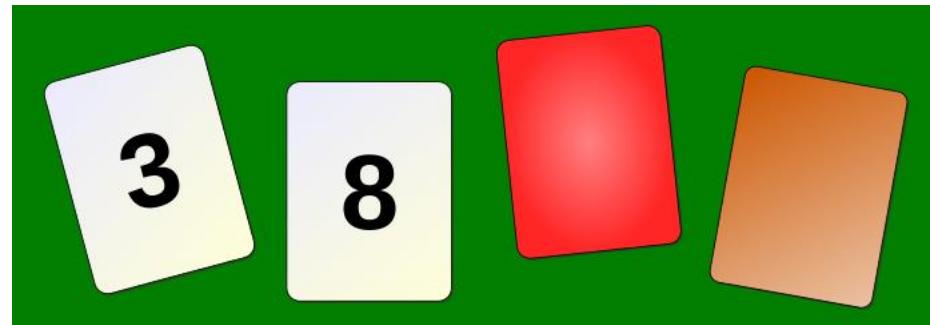
- $A \Rightarrow B$
- Ou seja:  
 $\text{par} \Rightarrow \text{vermelho}$



# Lógica (formal)

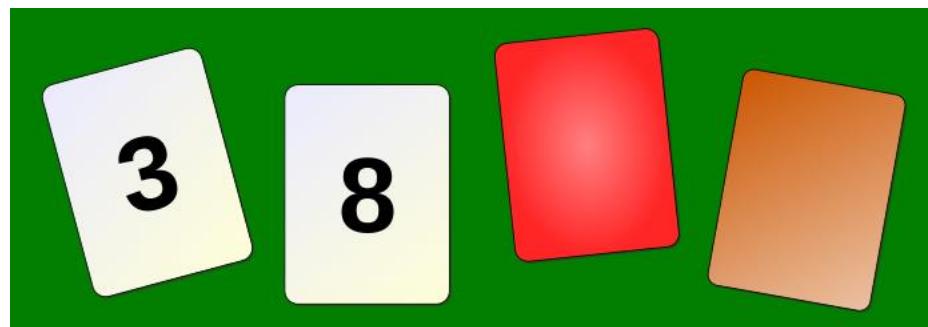
21

- $A \Rightarrow B \Leftrightarrow \neg B \Rightarrow \neg A.$
- Ou seja:  
 $\text{par} \Rightarrow \text{vermelho} \Leftrightarrow \neg \text{vermelho} \Rightarrow \neg \text{par}.$



# Lógica (da batata)

- $\text{par} \Rightarrow \text{vermelho}$   
 $\Leftrightarrow$   
 $\text{não-vermelho} \Rightarrow \text{não-par.}$
- O que é que a regra implica para cada uma das cartas?



# Respeitar a incerteza

# A importância da incerteza

24

[ <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



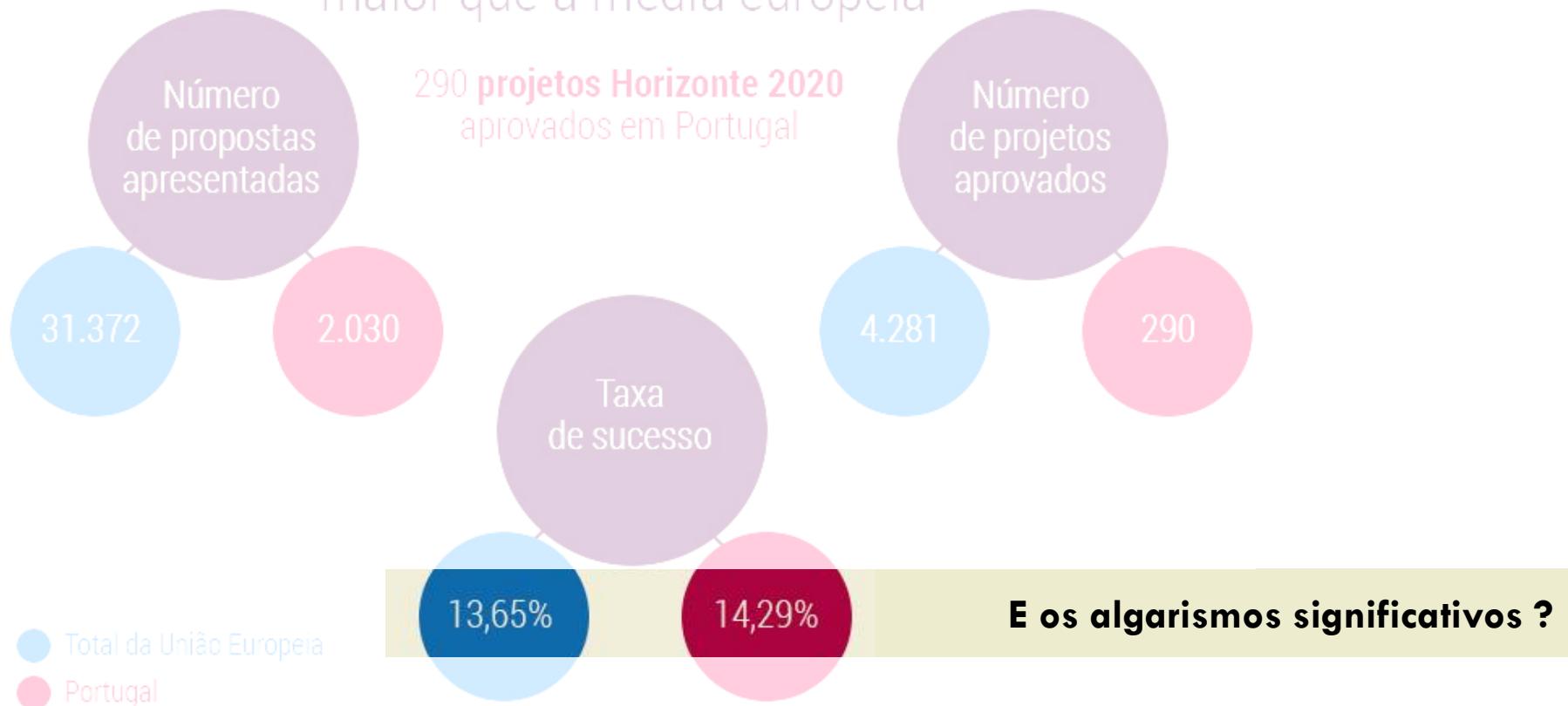
Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

# A importância da incerteza

25

[ <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

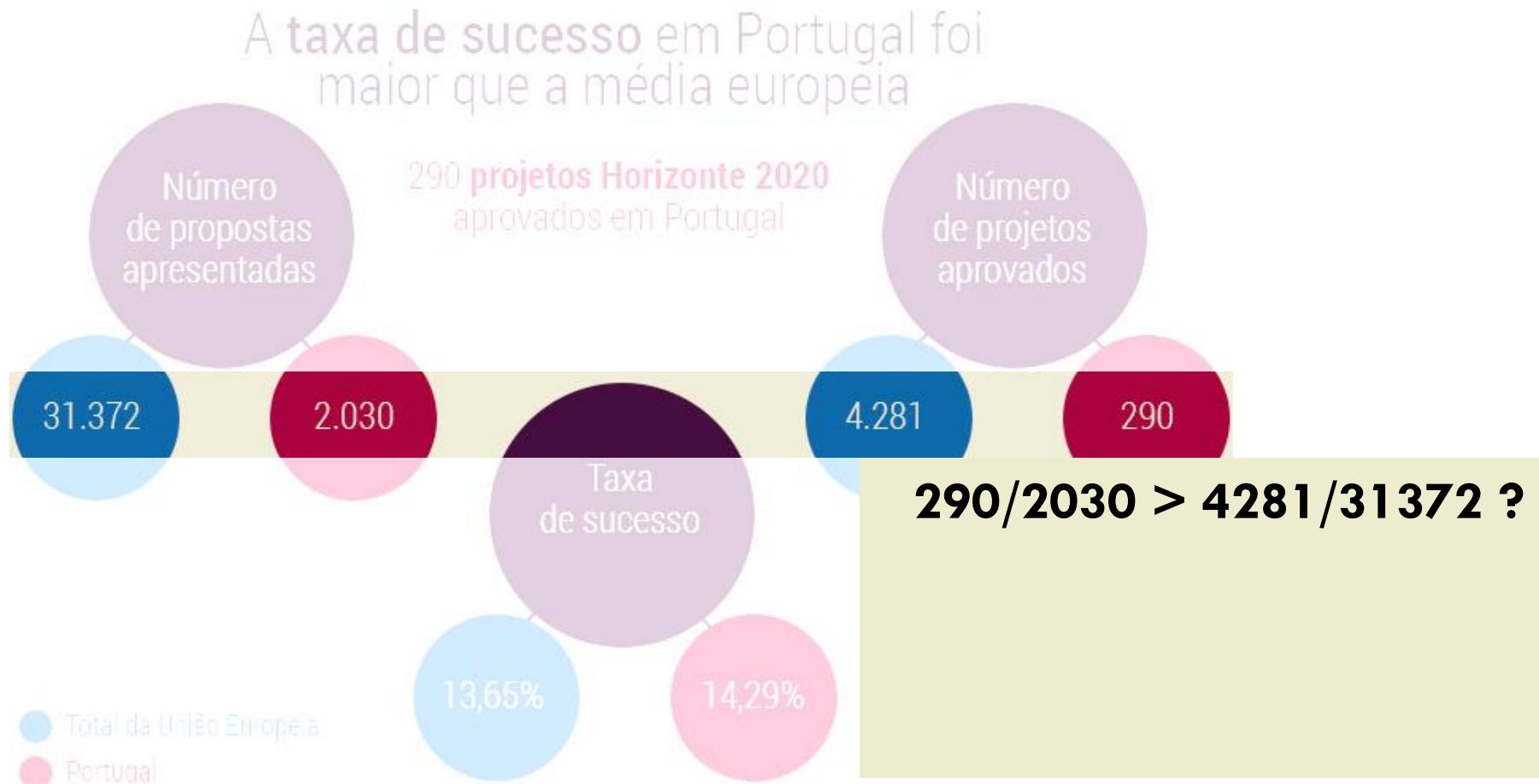


Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

# A importância da incerteza

26

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

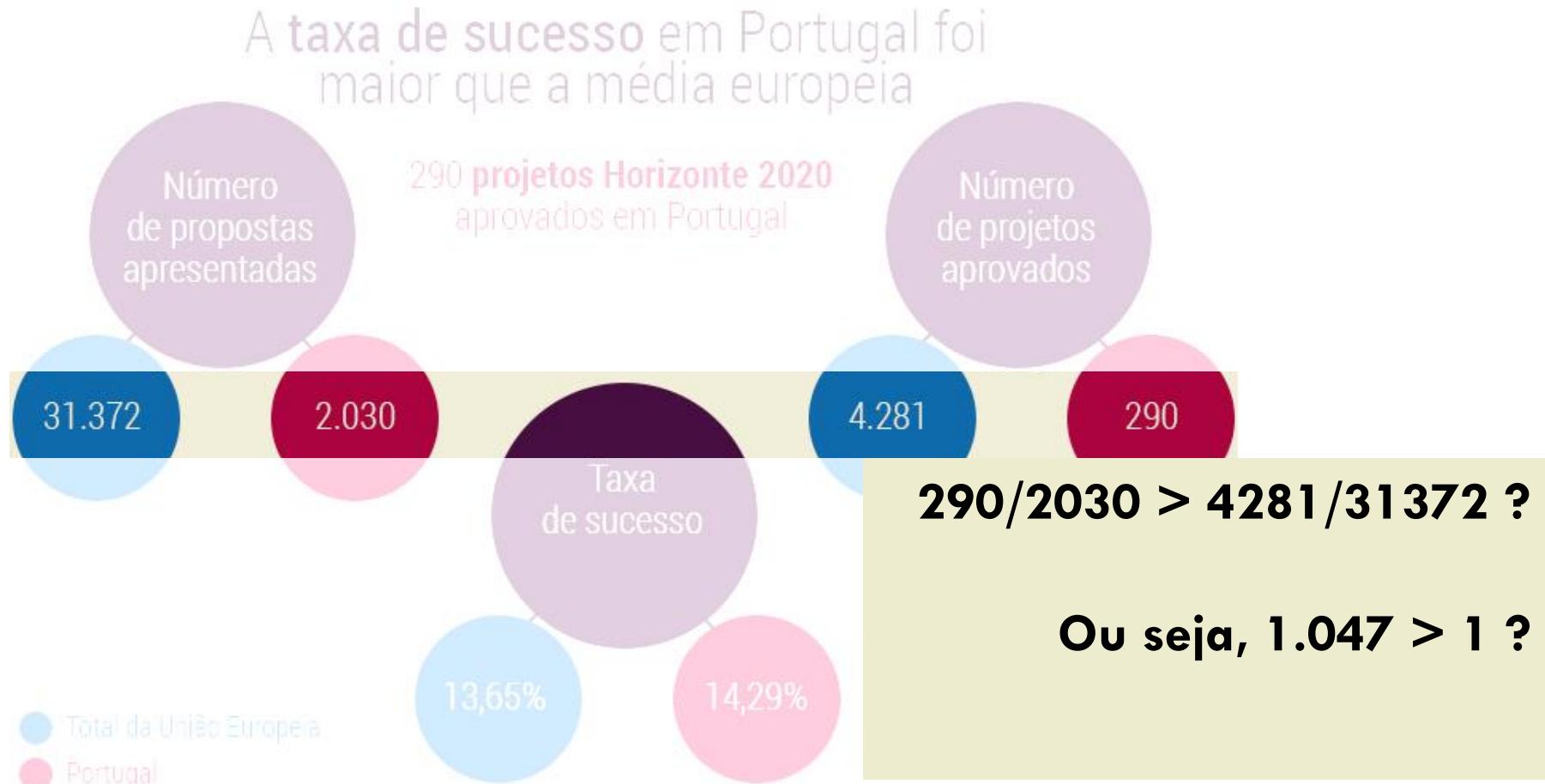


Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

# A importância da incerteza

27

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



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

# A importância da incerteza

28

[ <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
```

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

# A importância da incerteza

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

A taxa de sucesso em Portugal foi **basicamente a mesma**  
~~maior~~ que a média europeia



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

# Um final feliz: artigo actualizado

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

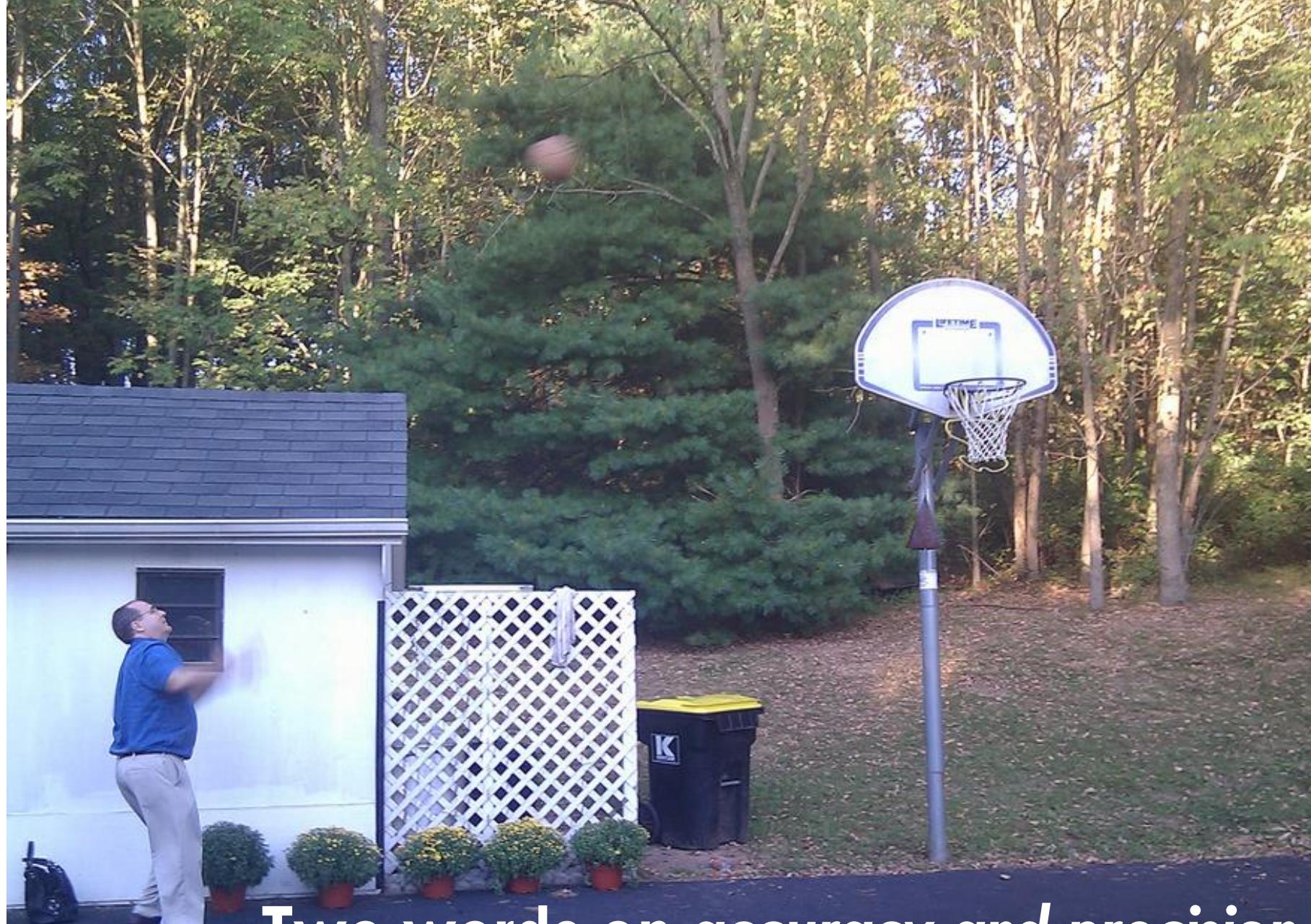
A **taxa de sucesso** em Portugal está  
em linha com a média europeia



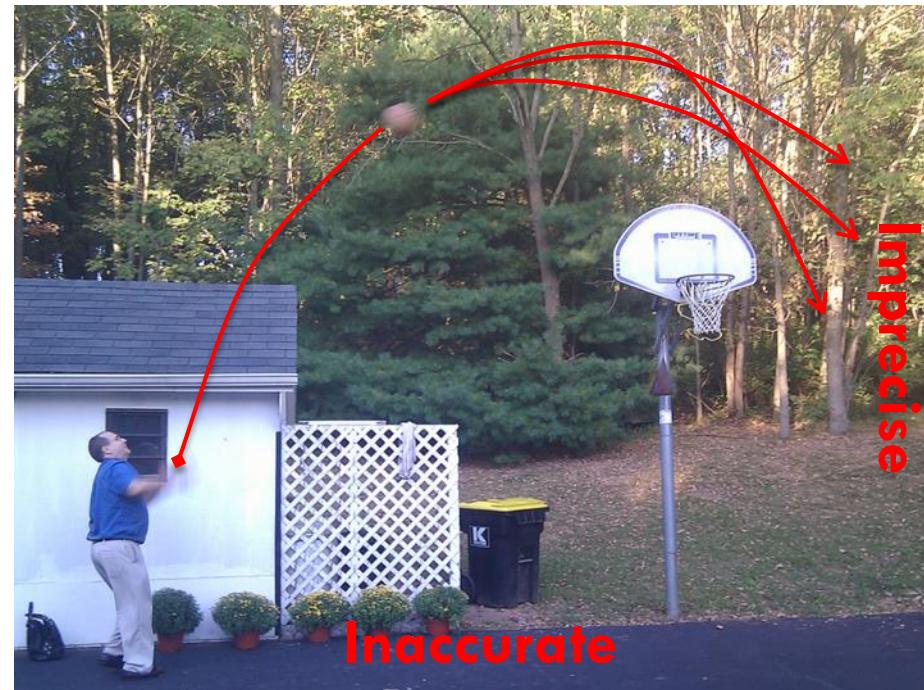
Fonte: Gabinete de Promoção do Programa Quadro de I&DT/Ministério da Educação e Ciência

# Exactidão e precisão

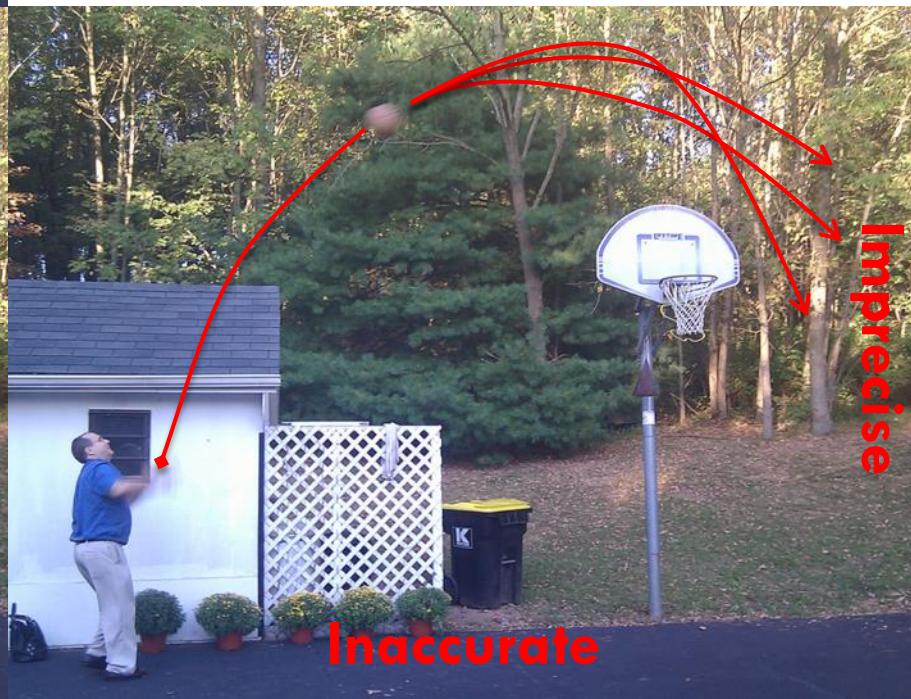
Erro e incerteza

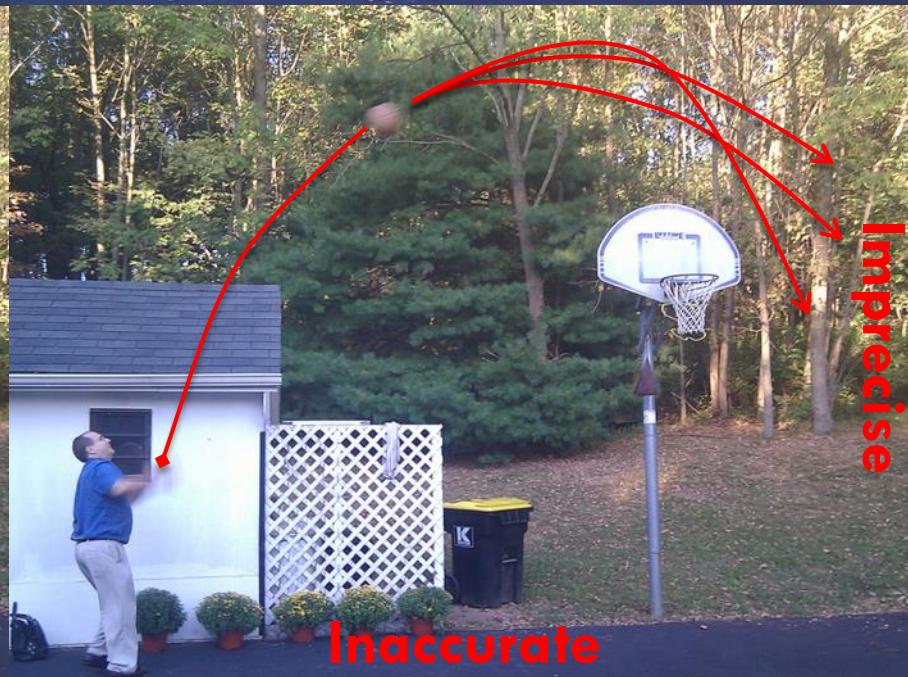
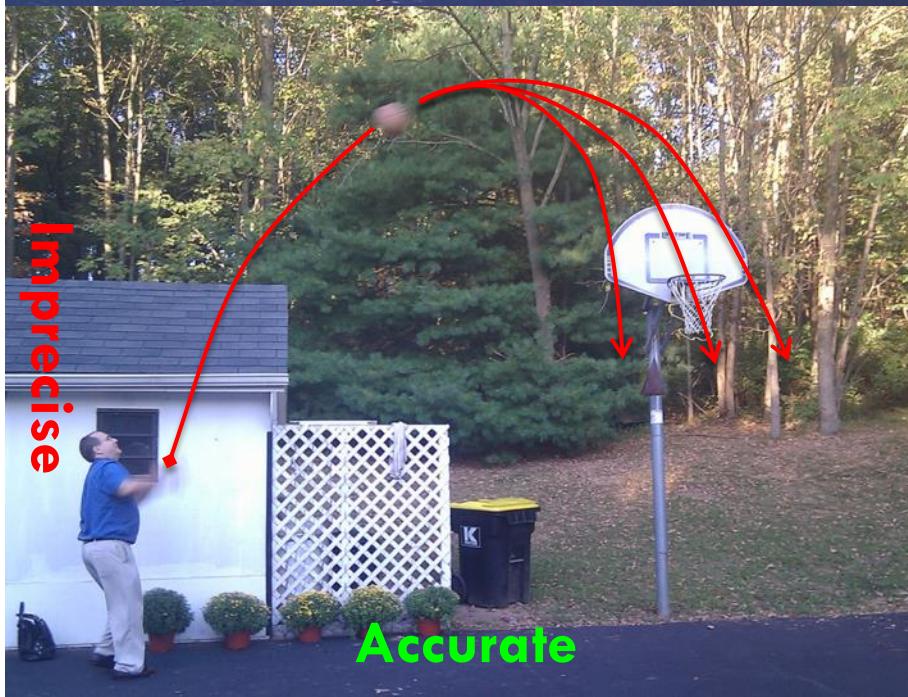


**Two words on accuracy and precision**







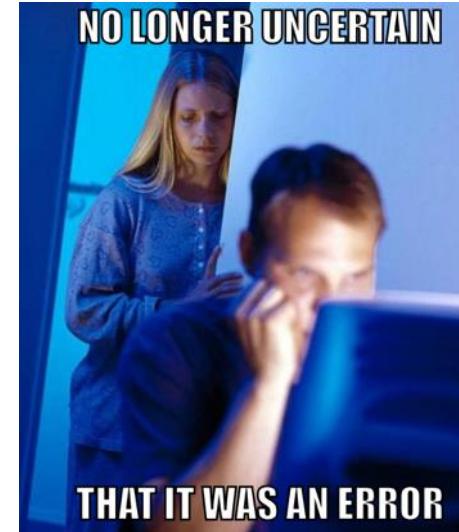


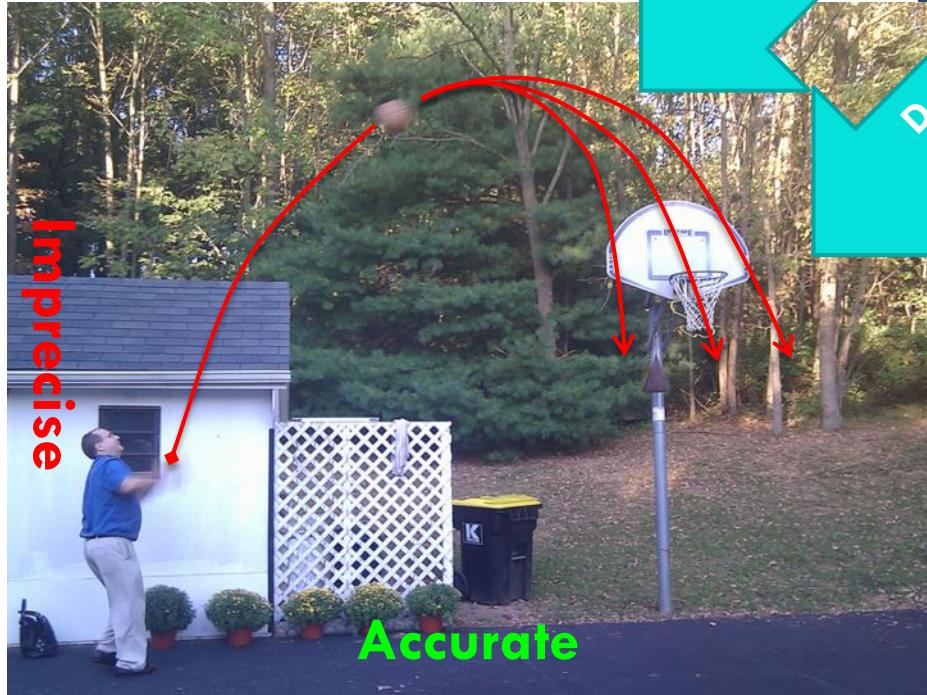
# Erros não são incertezas

# 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.



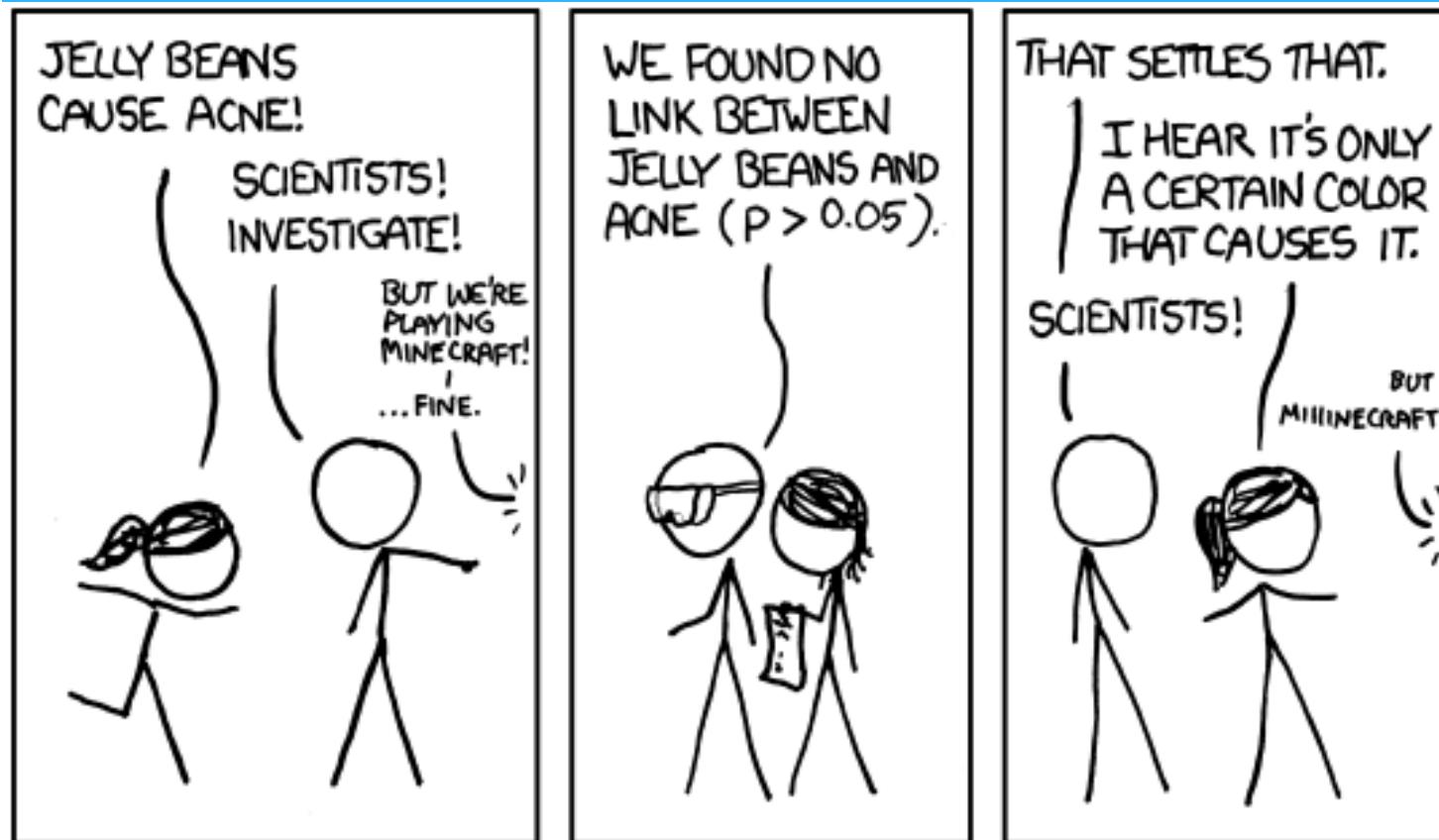


“Água mole em pedra dura...”

Ou o preço de pesquisar coisas novas.

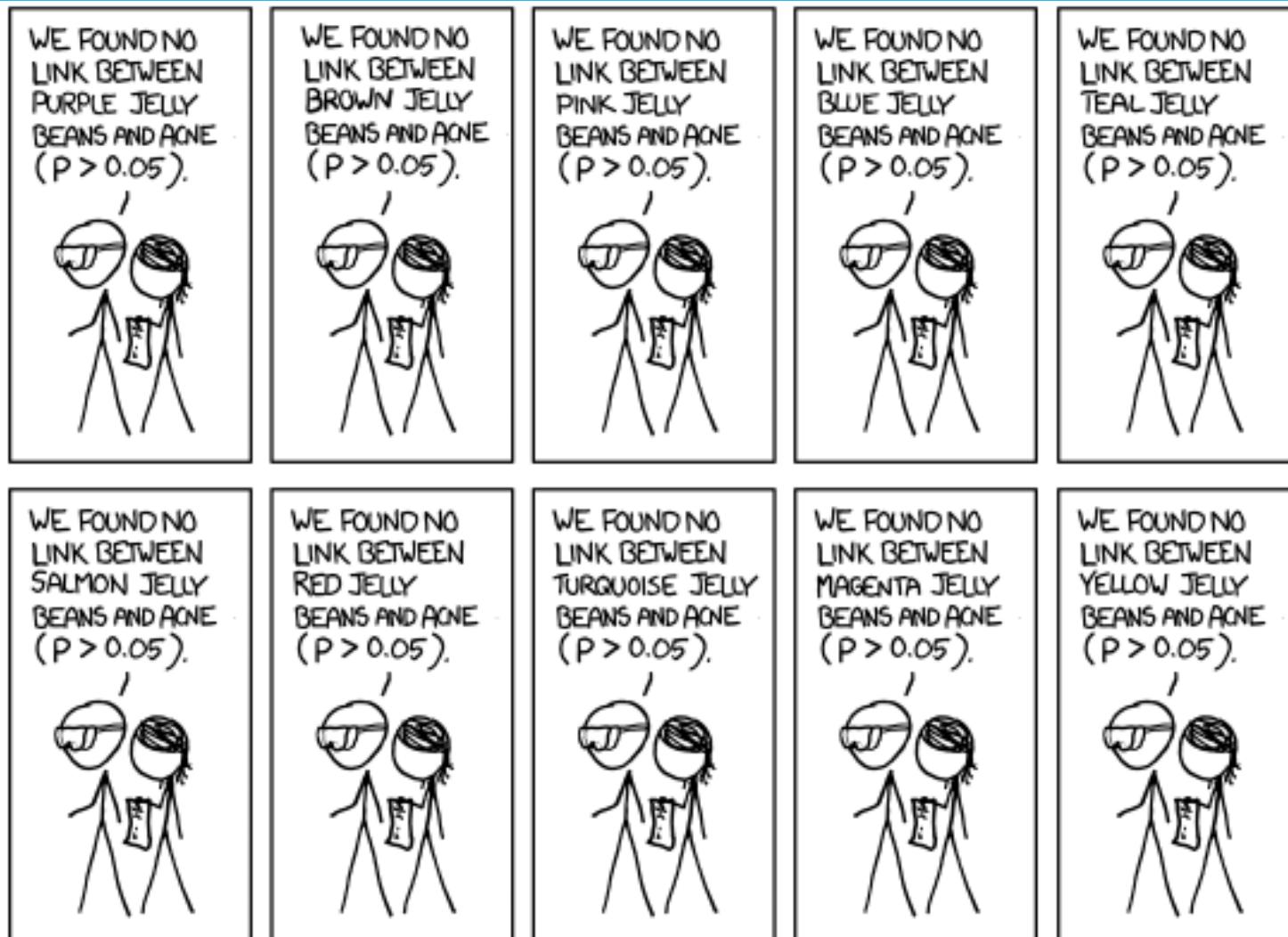
# Significant – [xkcd.com/882](https://xkcd.com/882)

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# Significant – [xkcd.com/882](https://xkcd.com/882)

42



# Significant – [xkcd.com/882](https://xkcd.com/882)

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WE FOUND NO  
LINK BETWEEN  
GREY JELLY  
BEANS AND ACNE  
( $P > 0.05$ ).



WE FOUND NO  
LINK BETWEEN  
TAN JELLY  
BEANS AND ACNE  
( $P > 0.05$ ).



WE FOUND NO  
LINK BETWEEN  
CYAN JELLY  
BEANS AND ACNE  
( $P > 0.05$ ).



WE FOUND A  
LINK BETWEEN  
GREEN JELLY  
BEANS AND ACNE  
( $P < 0.05$ ).



WE FOUND NO  
LINK BETWEEN  
MAUVE JELLY  
BEANS AND ACNE  
( $P > 0.05$ ).



WE FOUND NO  
LINK BETWEEN  
BEIGE JELLY  
BEANS AND ACNE  
( $P > 0.05$ ).



WE FOUND NO  
LINK BETWEEN  
LILAC JELLY  
BEANS AND ACNE  
( $P > 0.05$ ).



WE FOUND NO  
LINK BETWEEN  
BLACK JELLY  
BEANS AND ACNE  
( $P > 0.05$ ).



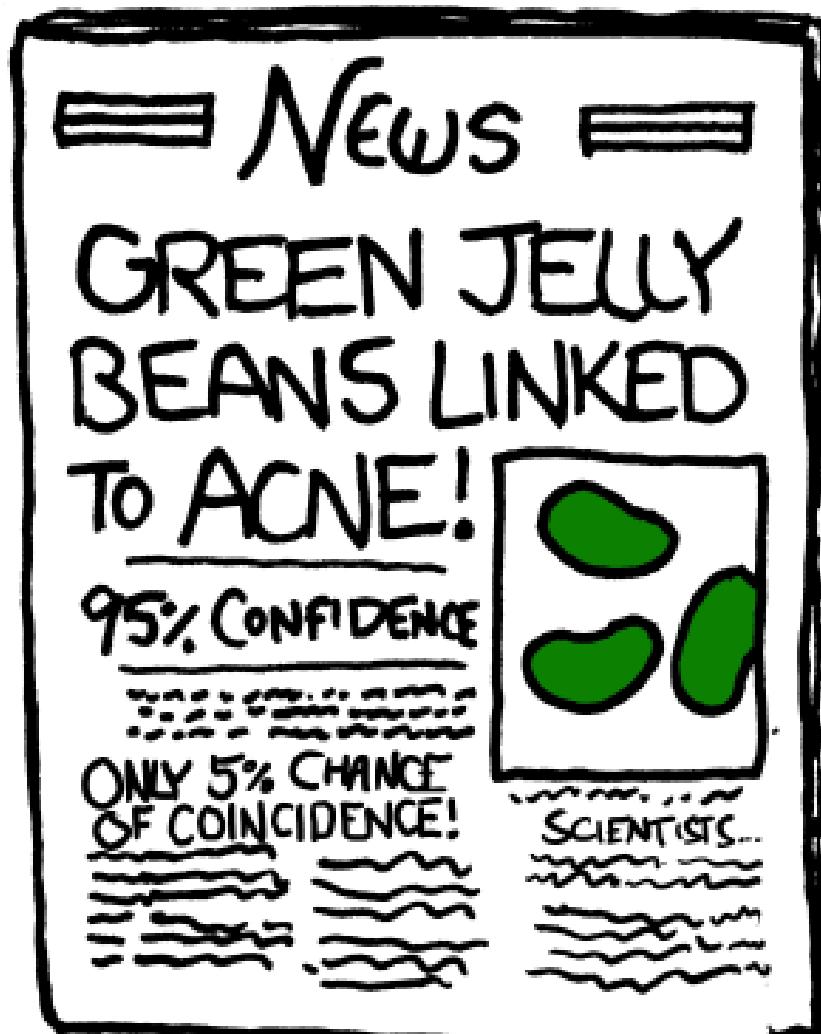
WE FOUND NO  
LINK BETWEEN  
PEACH JELLY  
BEANS AND ACNE  
( $P > 0.05$ ).



WE FOUND NO  
LINK BETWEEN  
ORANGE JELLY  
BEANS AND ACNE  
( $P > 0.05$ ).



# Significant – xkcd.com/882





# An offer you can't refuse

45

- I sent you correct buy/sell stock predictions every week for the last 10 weeks.



# An offer you can't refuse

46

- I sent you correct buy/sell stock predictions every week for the last 10 weeks.
- What's the probability of that happening by chance?

# An offer you can't refuse

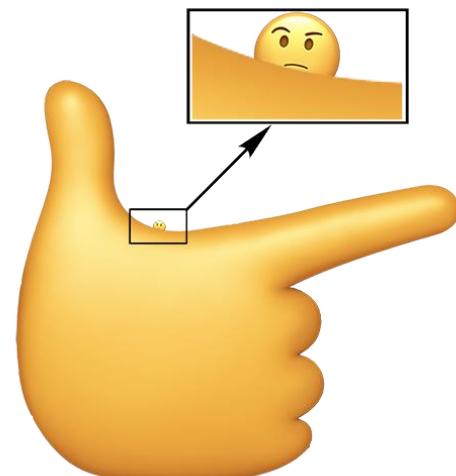
47

- I sent you correct buy/sell stock predictions every week for the last 10 weeks.
  - What's the probability of that happening at random?
- Surely you should send me \$1000 to invest for you.
  - Right?



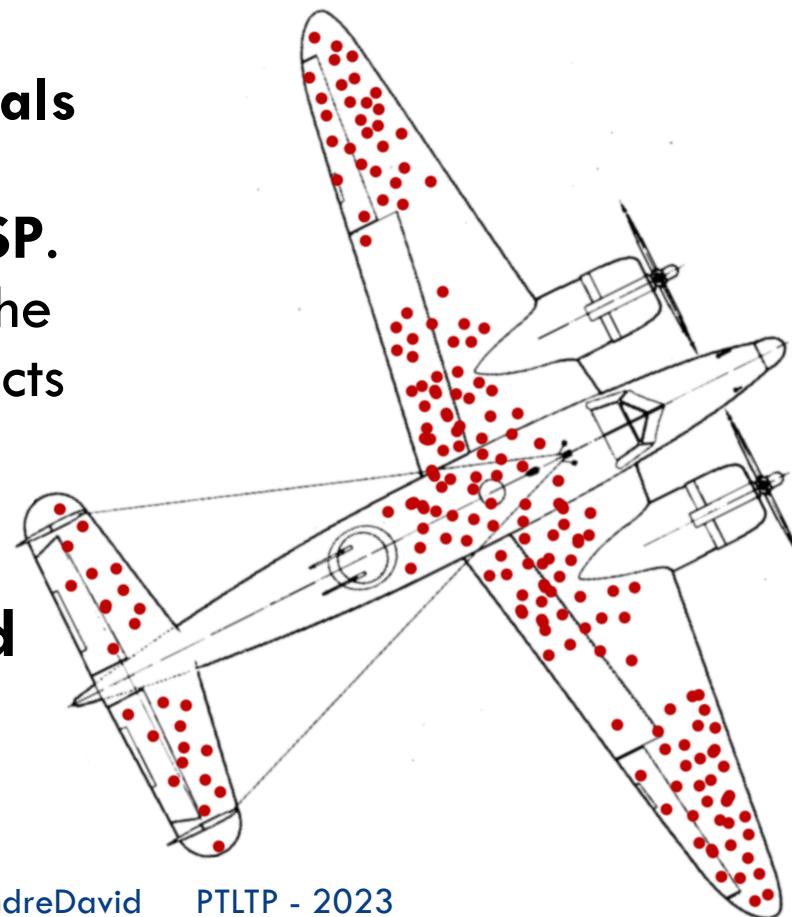
# An offer you can't refuse

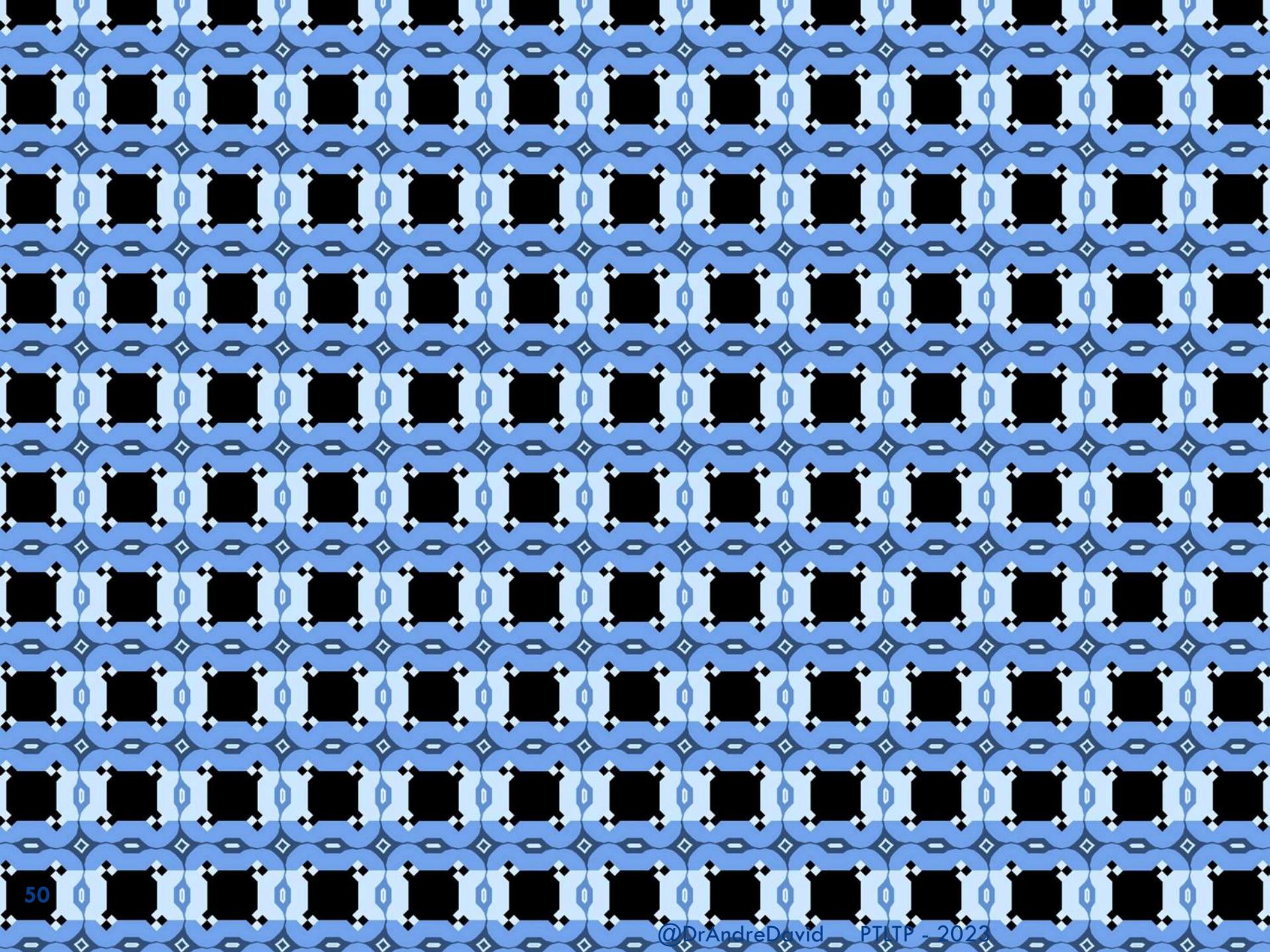
- I sent you correct buy/sell stock predictions every week for the last 10 weeks.
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  - Right?

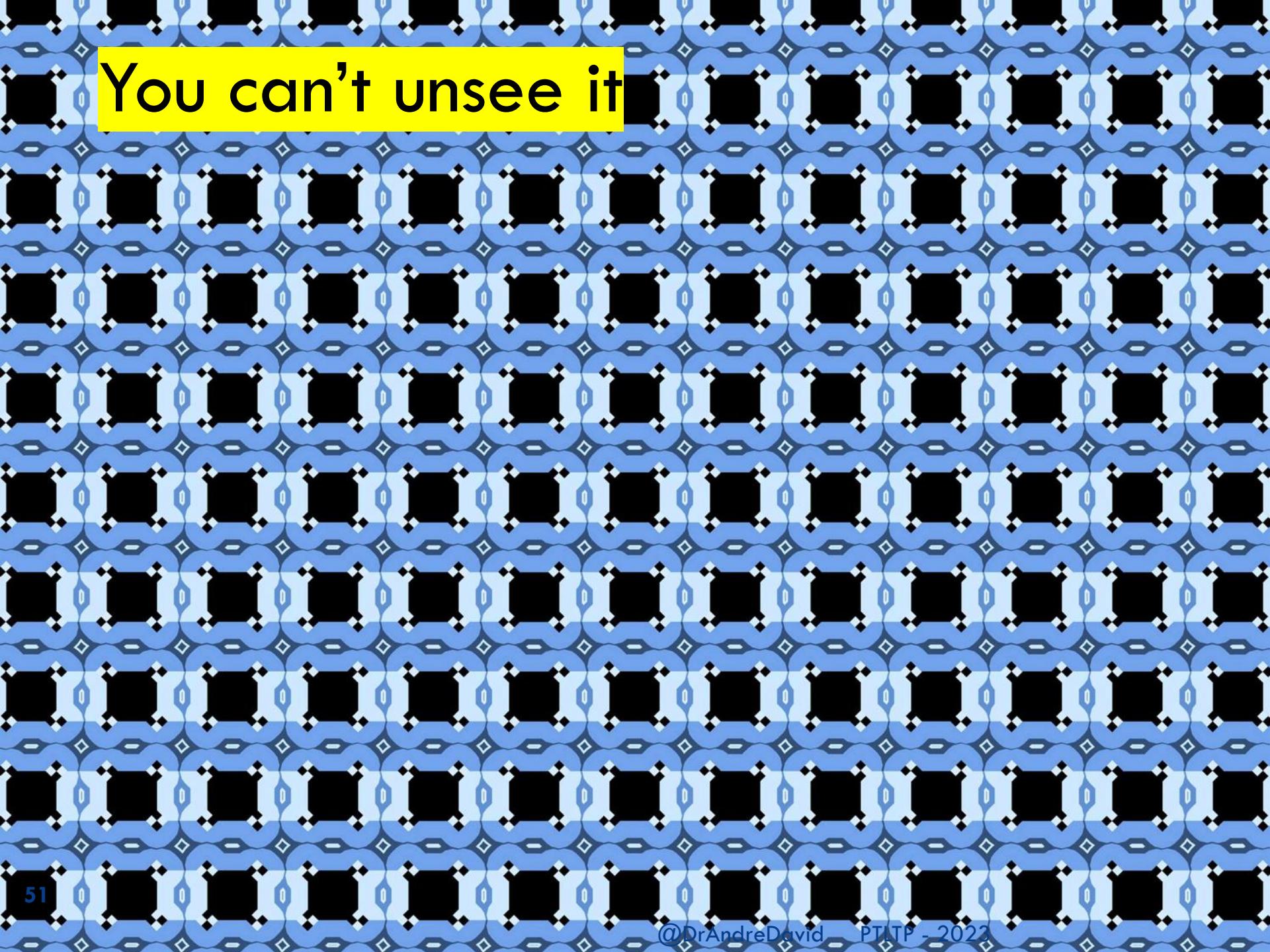


# What is the denominator/context?

- Survivorship bias.
  - “the parapsychology researcher Joseph Banks Rhine **believed he had identified the few individuals from hundreds of potential subjects who had powers of ESP.** His calculations were based on the improbability of these few subjects guessing”
- **Important when reporting and story-telling.**







You can't unsee it

You can't unsee it

Theorists may see the next wave.

Experimentalists surf it.

You can't unsee it

Theorists may see the next wave.

Experimentalists surf it.

Knowledge comes from disproving.

You can't unsee it

Theorists may see the next wave.

Experimentalists surf it.

Knowledge comes from disproving.

Respect uncertainty

You can't unsee it

Theorists may see the next wave.

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Knowledge comes from disproving.

Respect uncertainty.

Don't mistake error for uncertainty.

You can't unsee it

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 find.

What is the denominator?

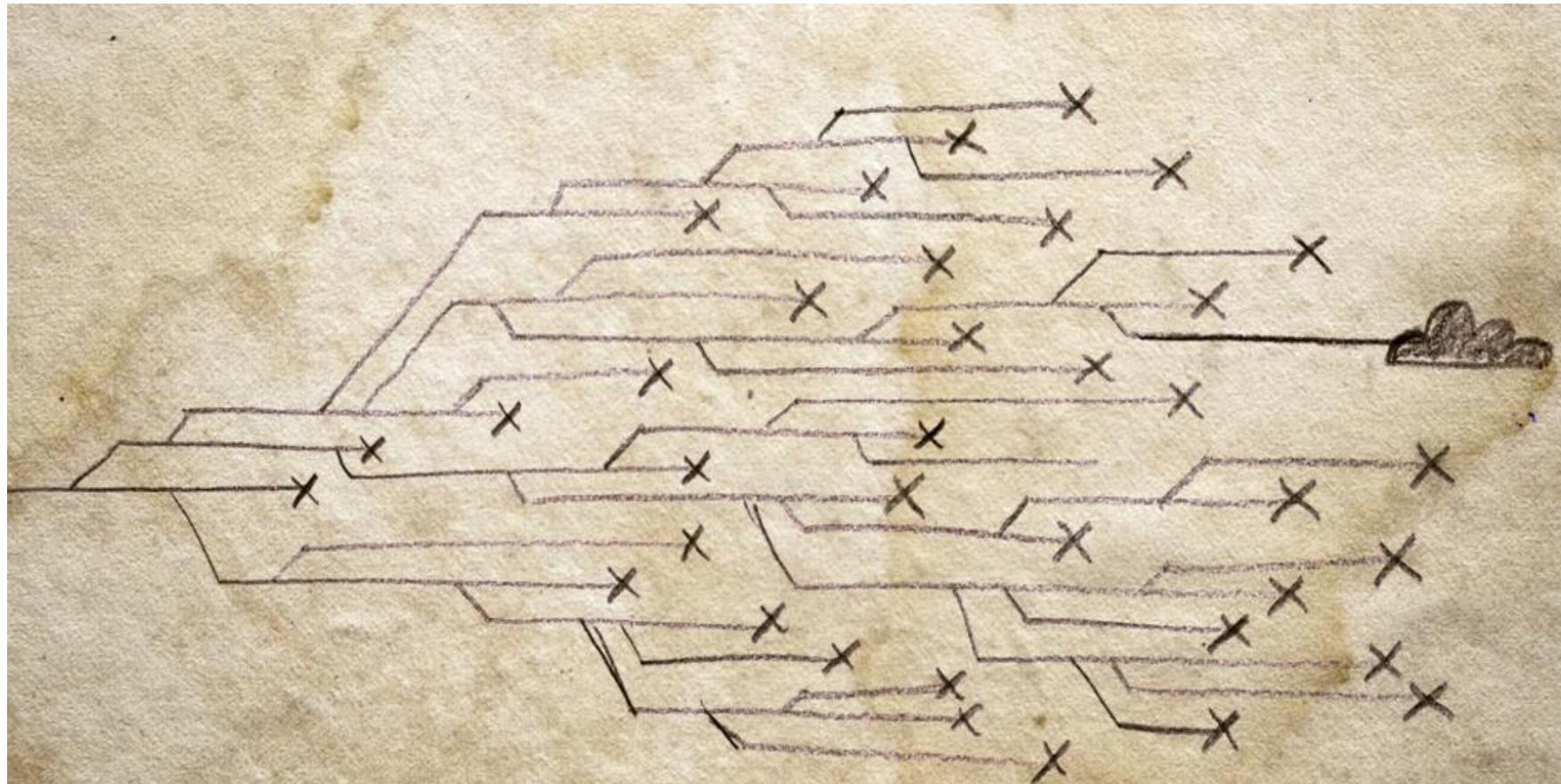
# The experimental method

## falsifying theories since the dawn of reason

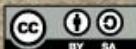


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[ opensource.com ]



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

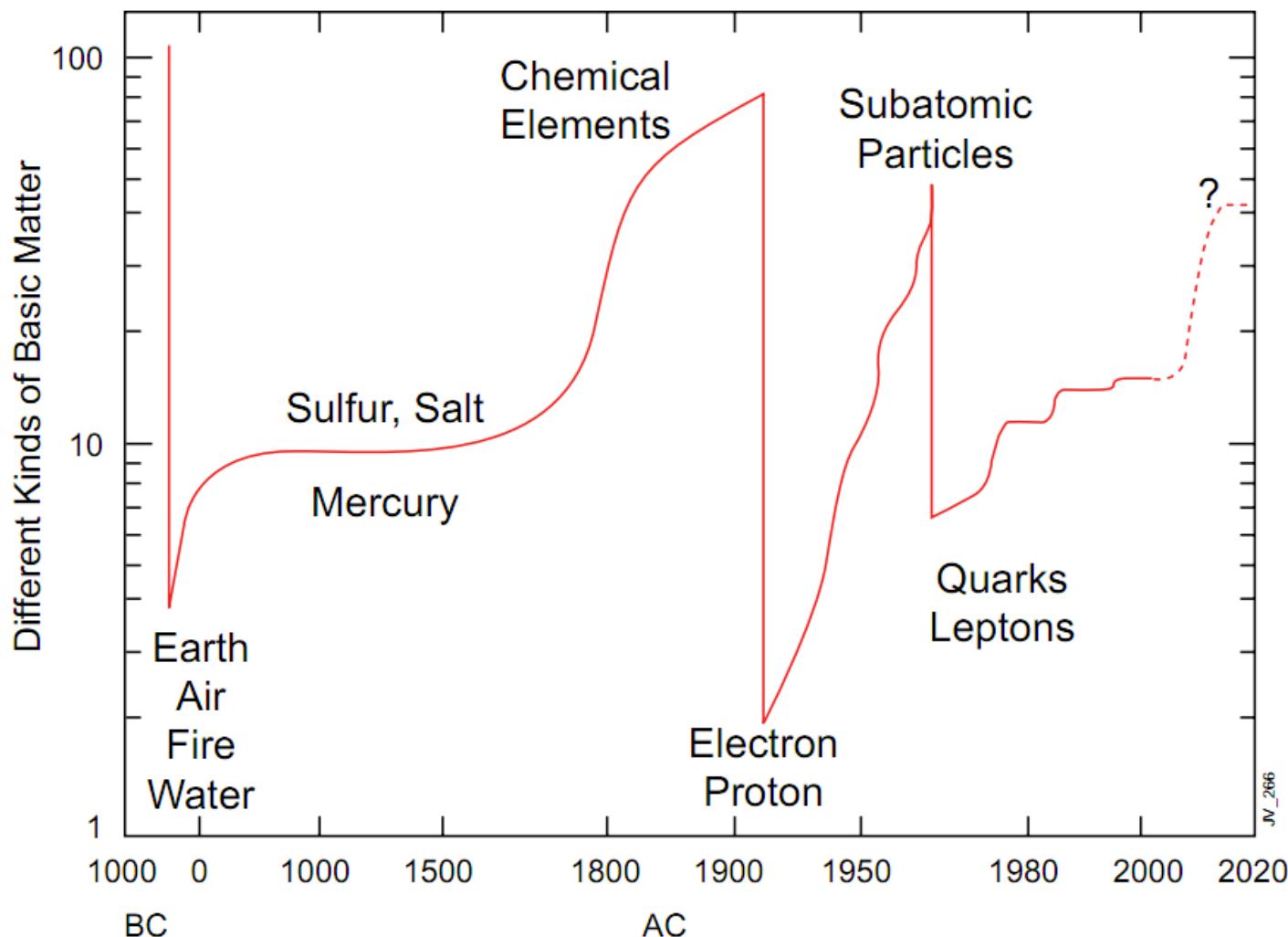


# Evolutions & revolutions of the elements



58

[ Plot courtesy of Jim Virdee ]

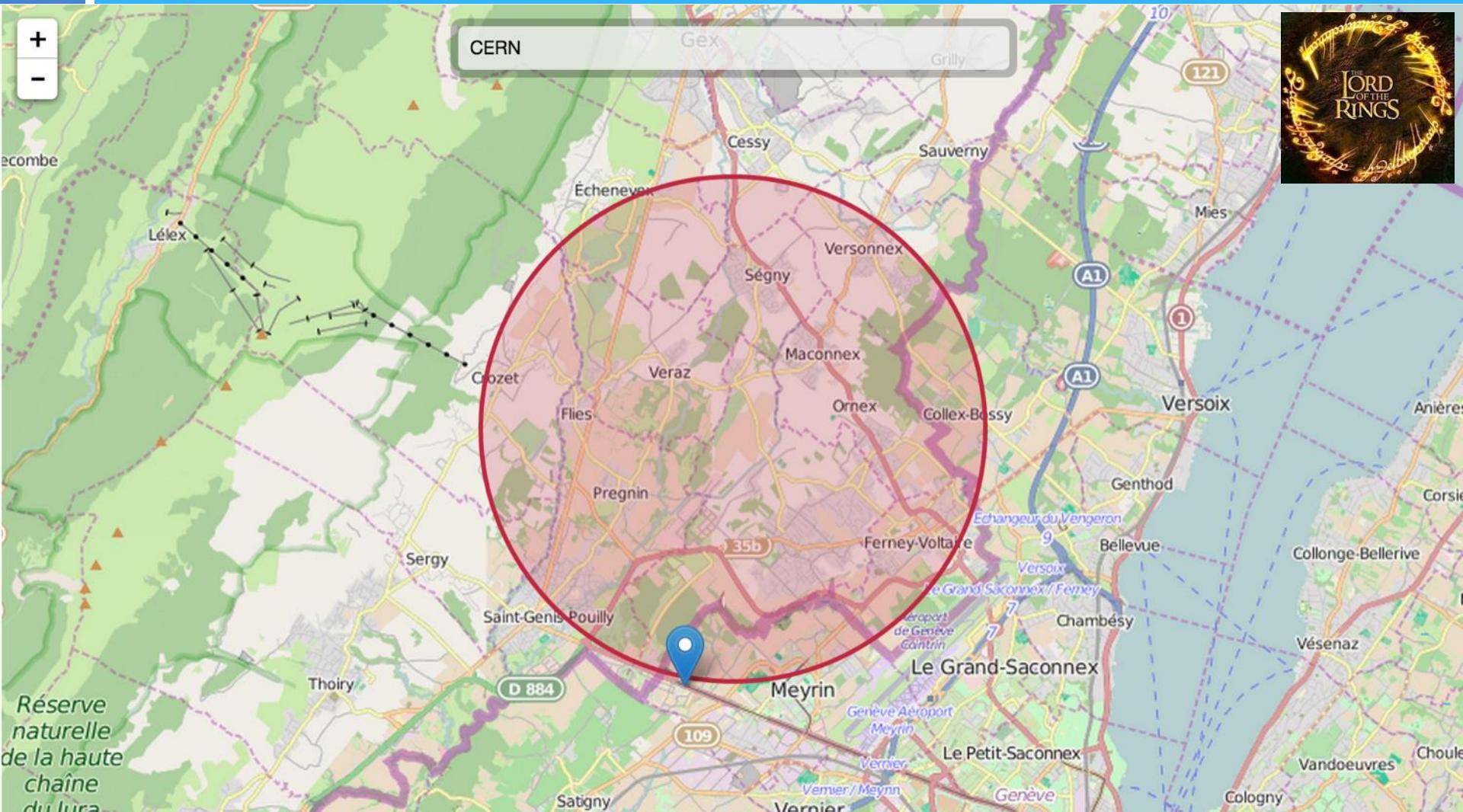




# LHC – the lord of the rings

59

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

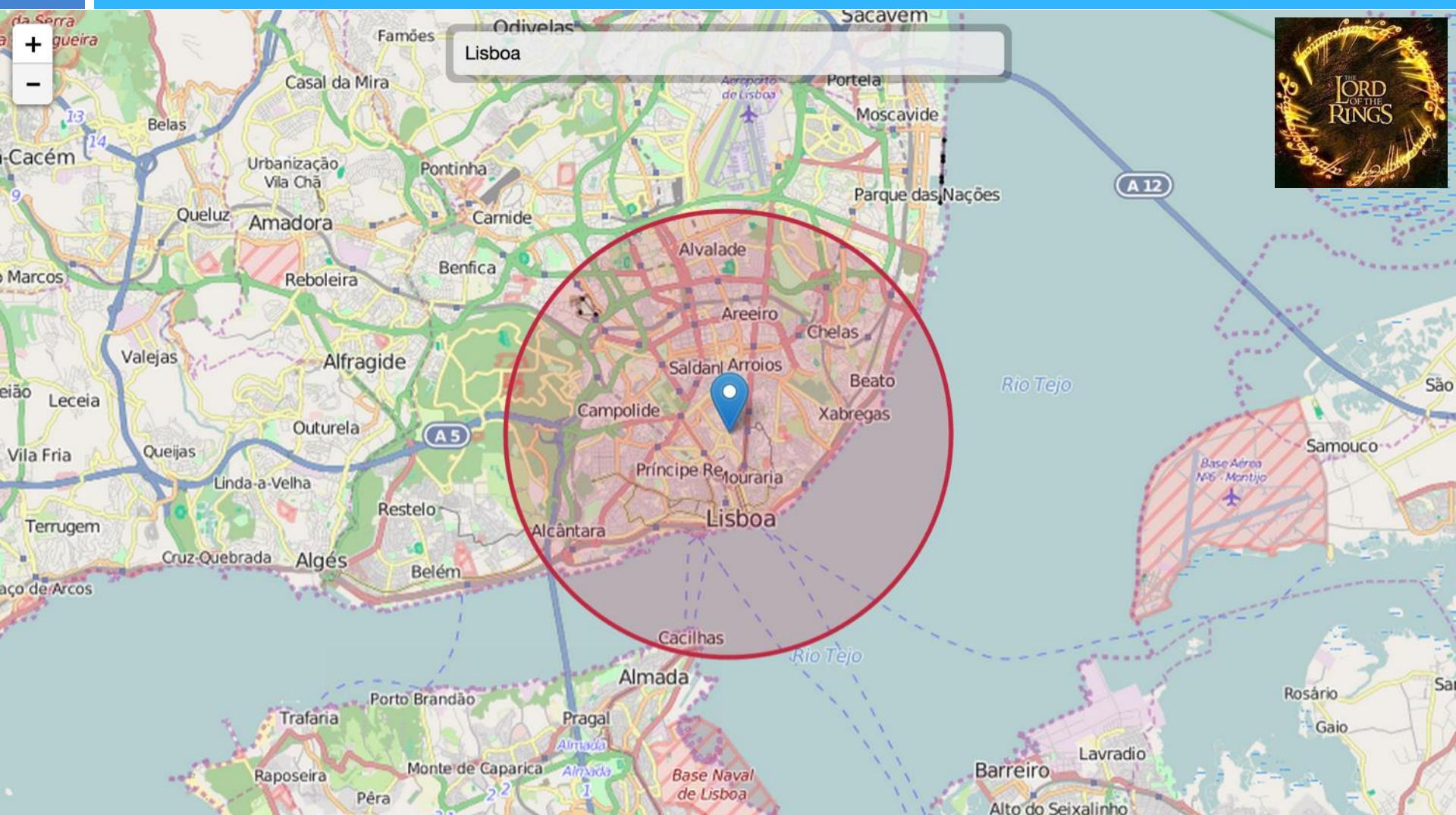




# LHC – the lord of the rings

60

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

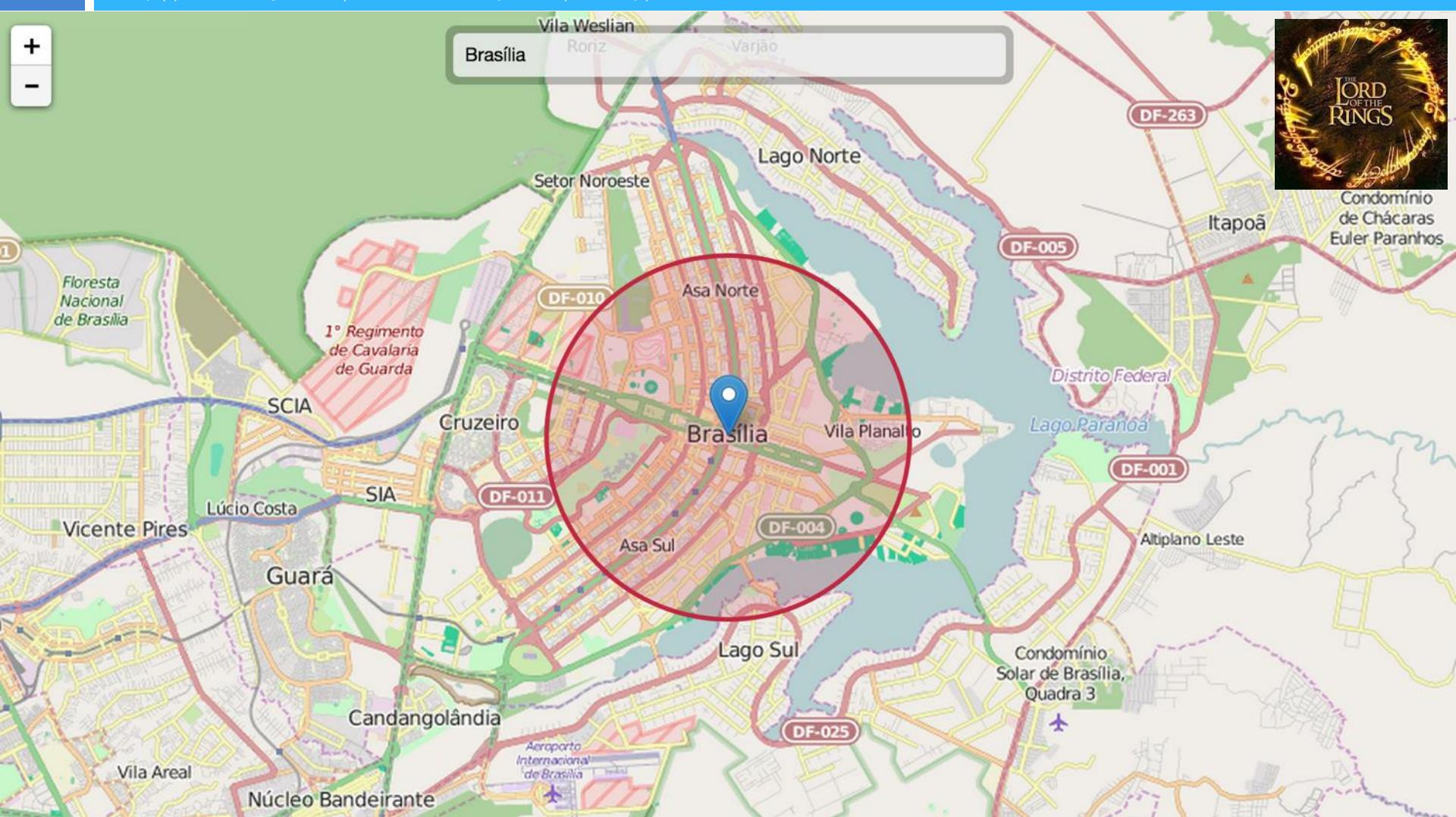




# LHC – the lord of the rings

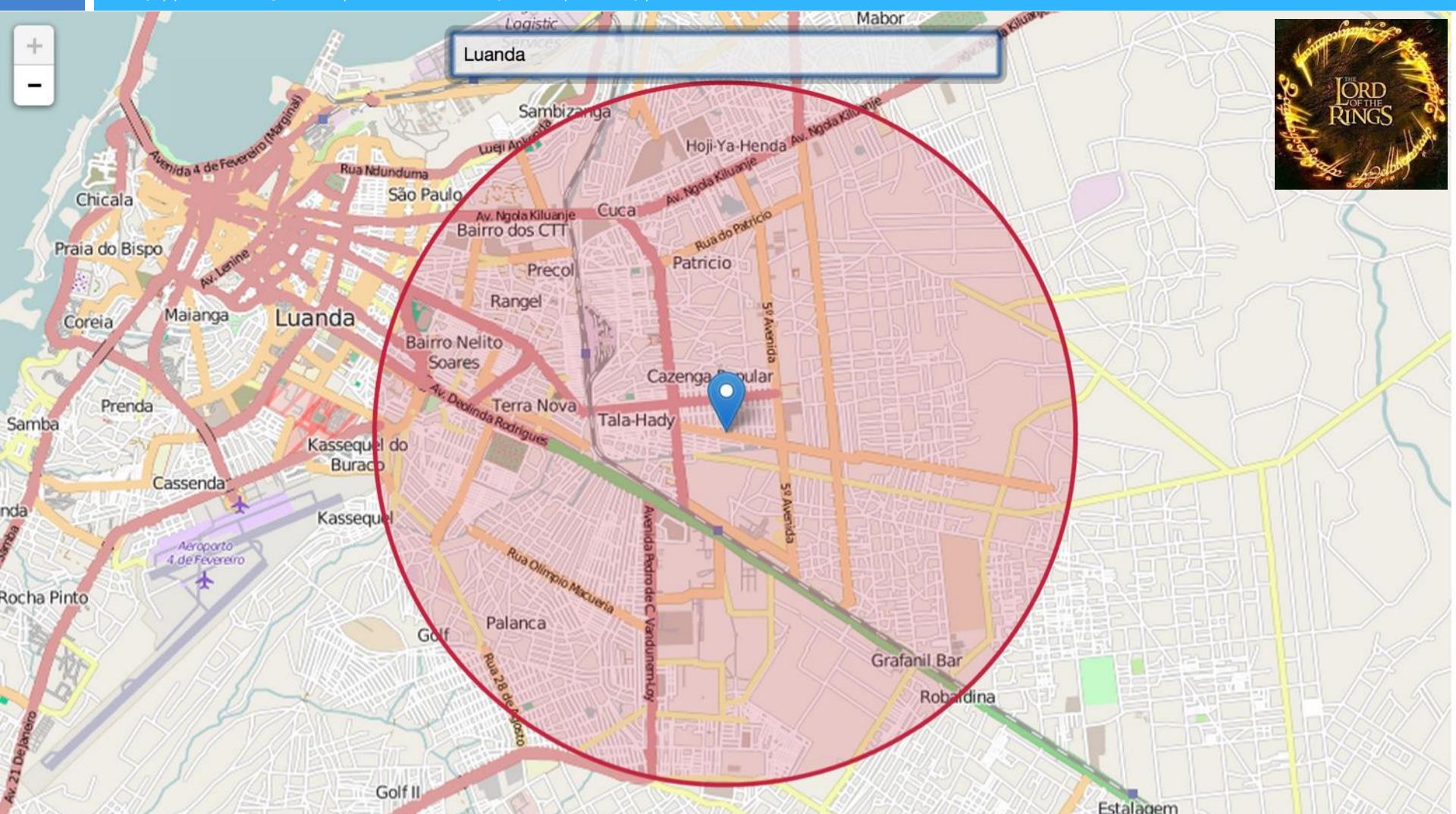
61

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



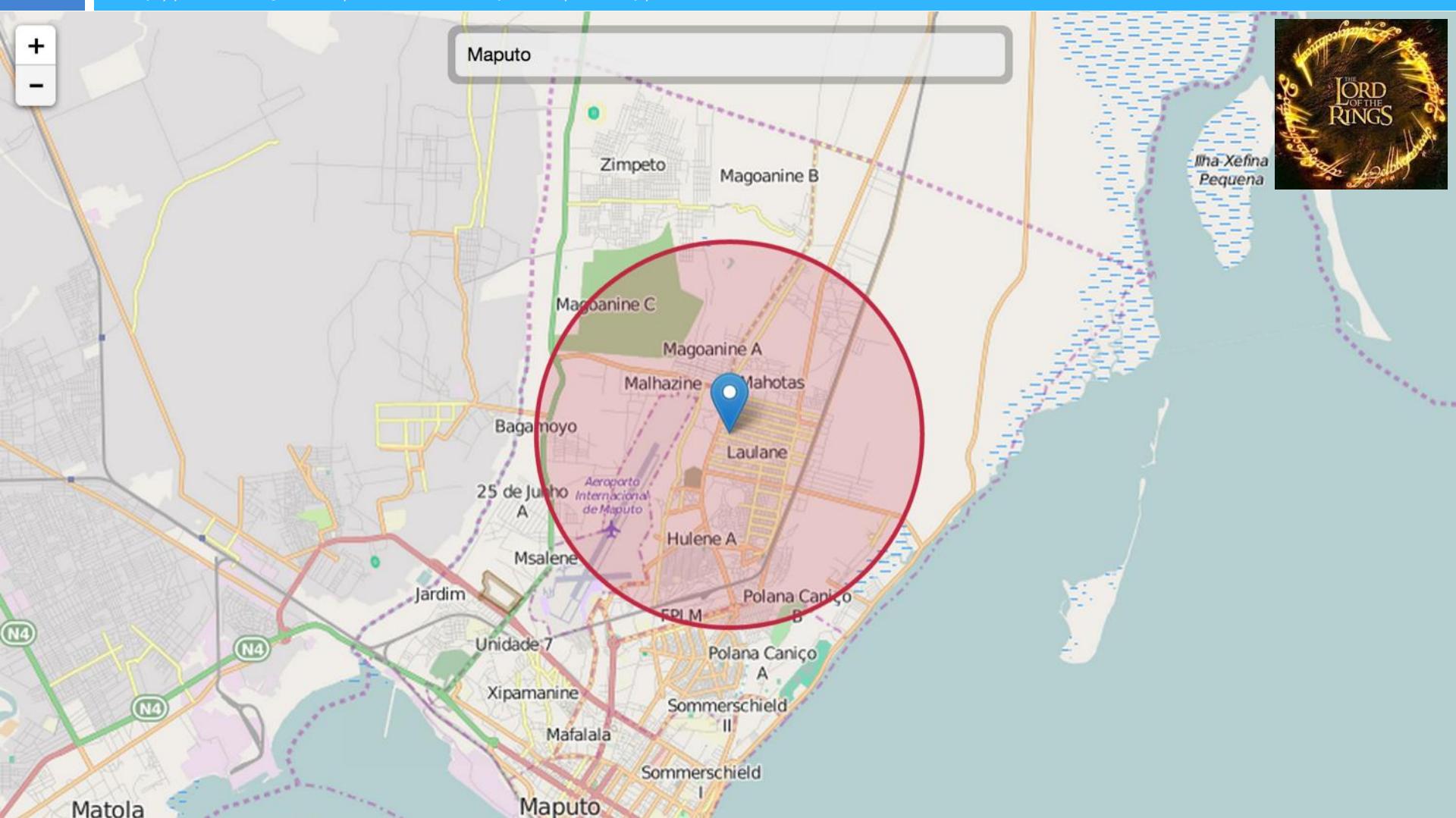
# LHC – the lord of the rings

62

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

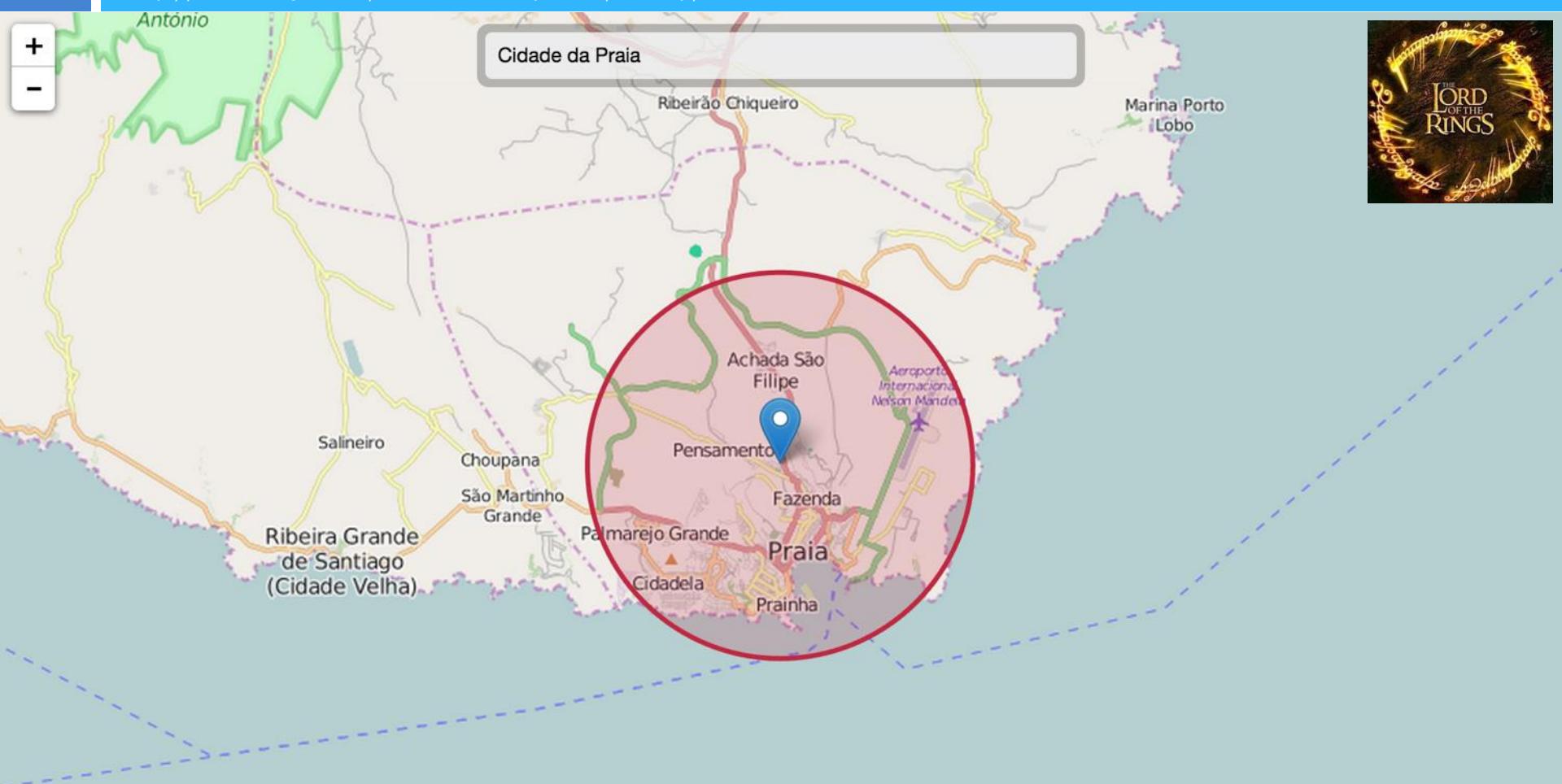
# LHC – the lord of the rings

63

[\[ http://natronics.github.io/science-hack-day-2014/lhc-map/ \]](http://natronics.github.io/science-hack-day-2014/lhc-map/)

# LHC – the lord of the rings

64

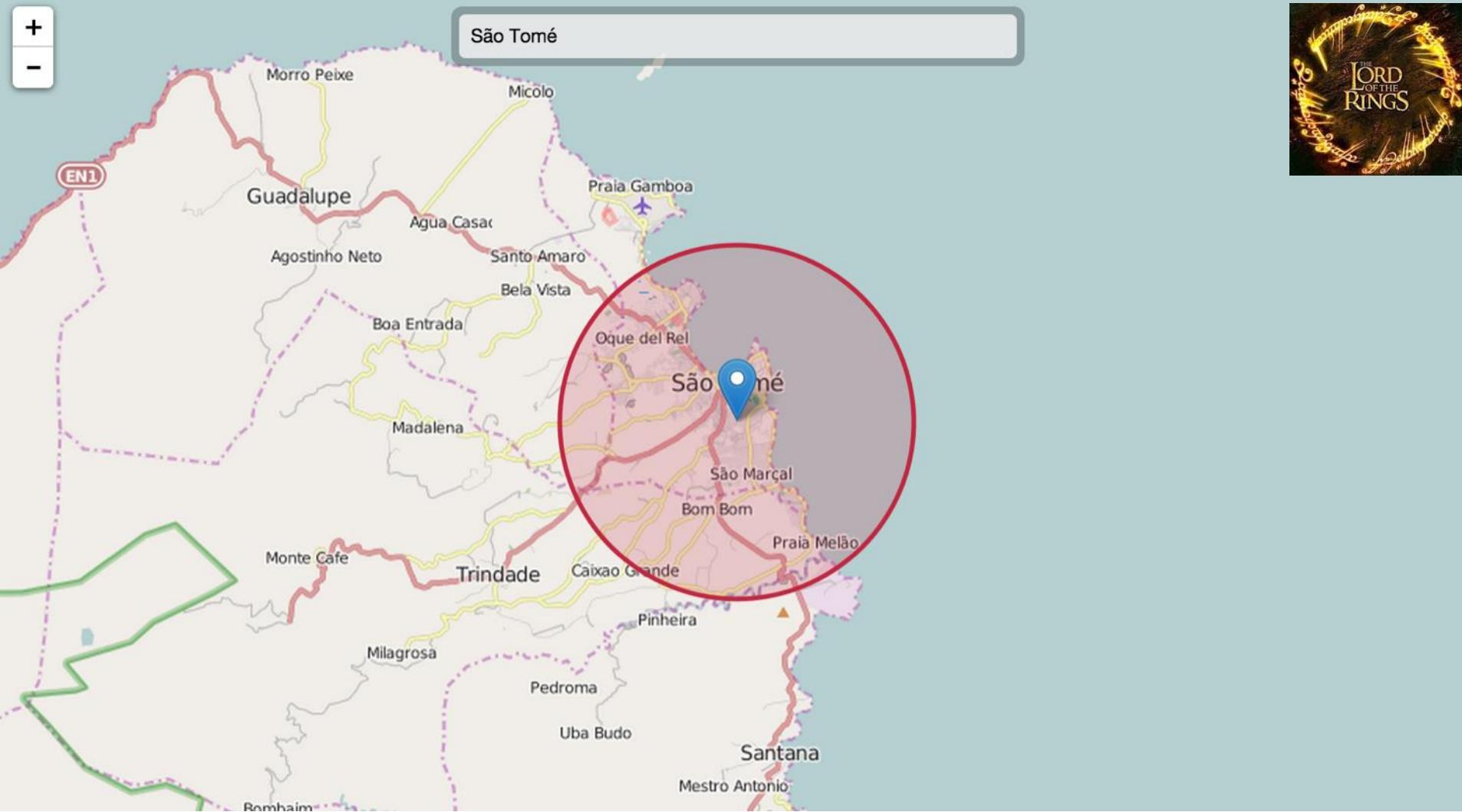
[ <http://natronics.github.io/science-hack-day-2014/lhc-map/> ]



# LHC – the lord of the rings

65

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

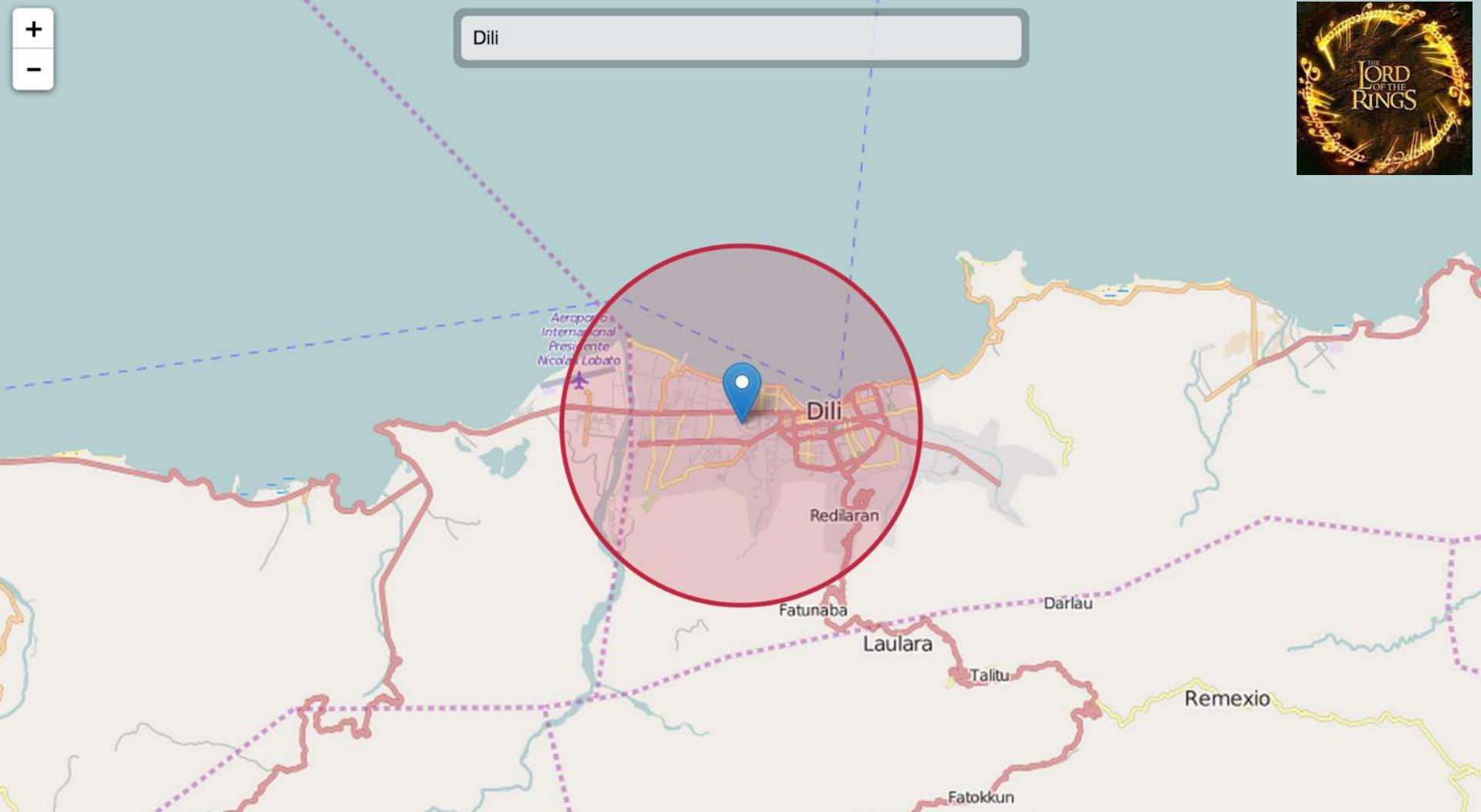




# LHC – the lord of the rings

66

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

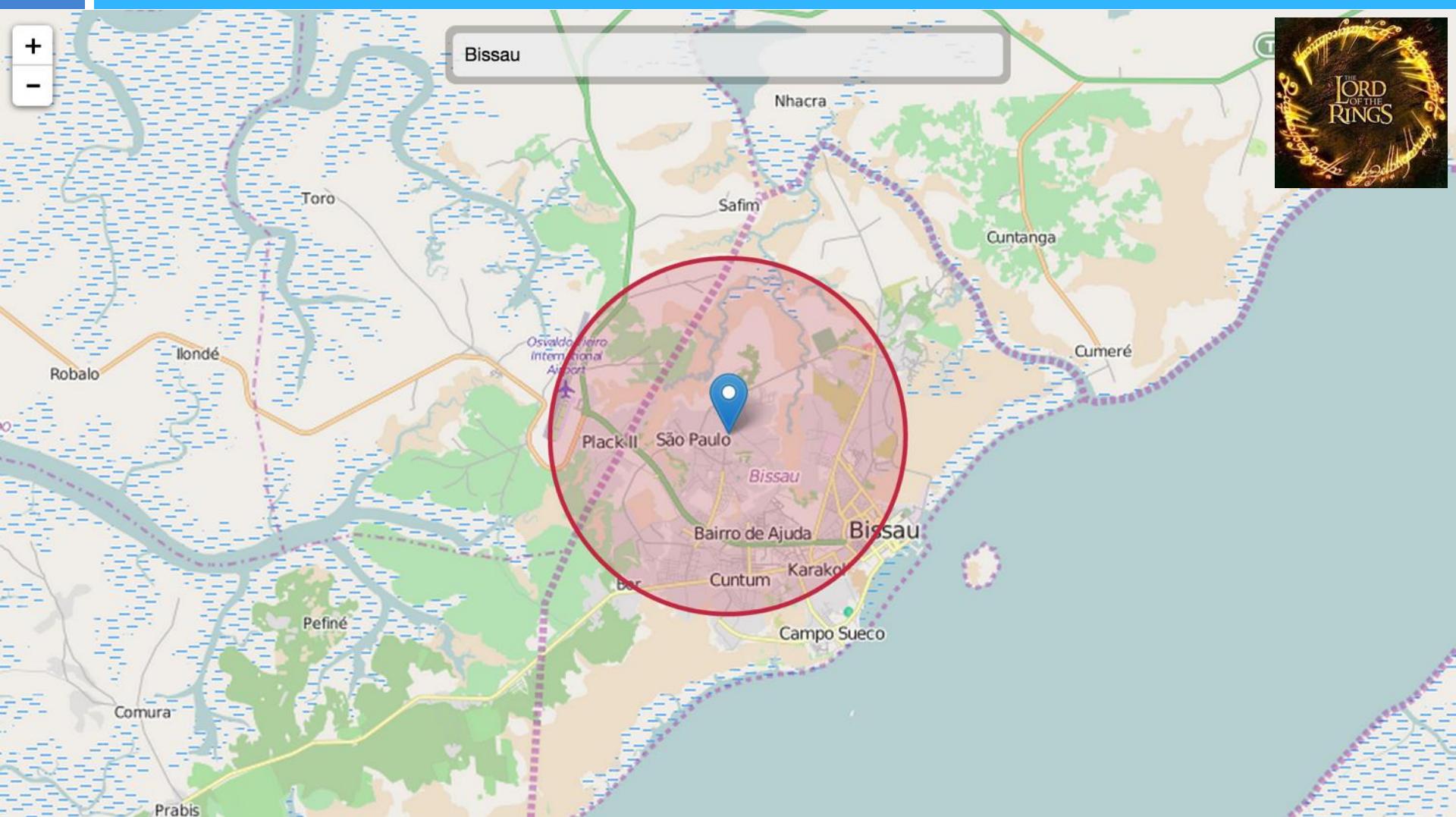




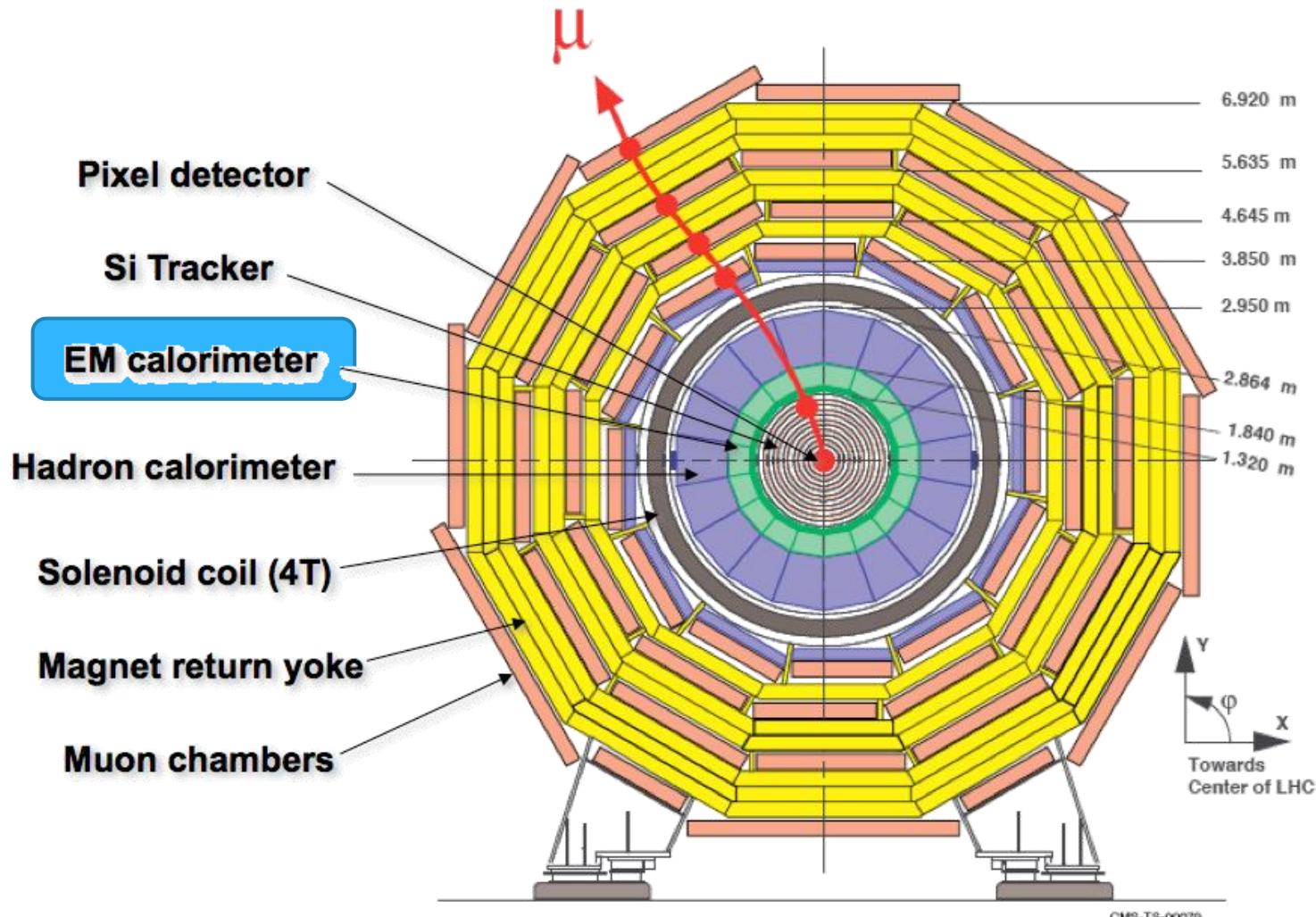
# LHC – the lord of the rings

67

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



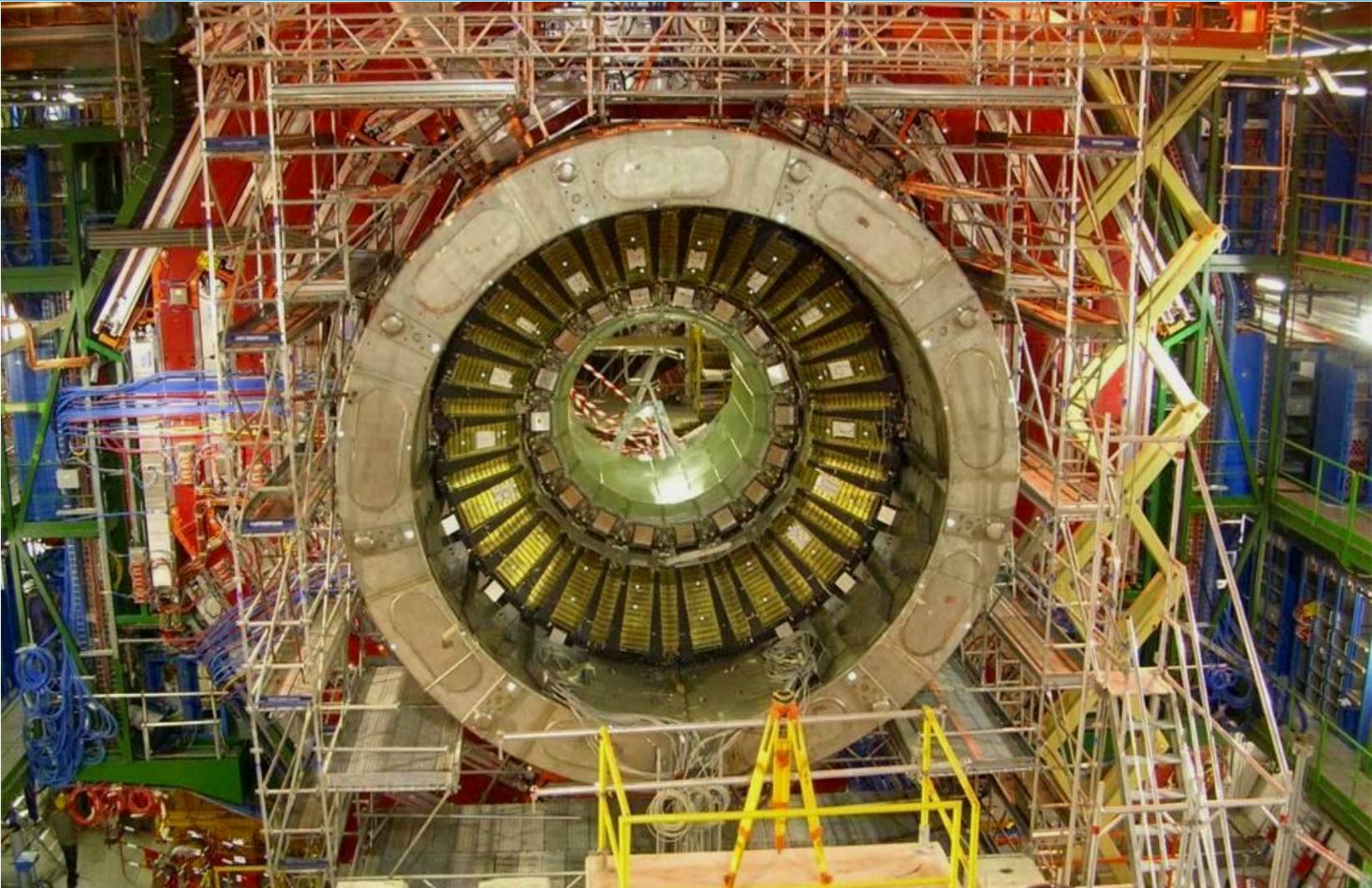
# Particle detectors in CMS



CMS-TS-00079

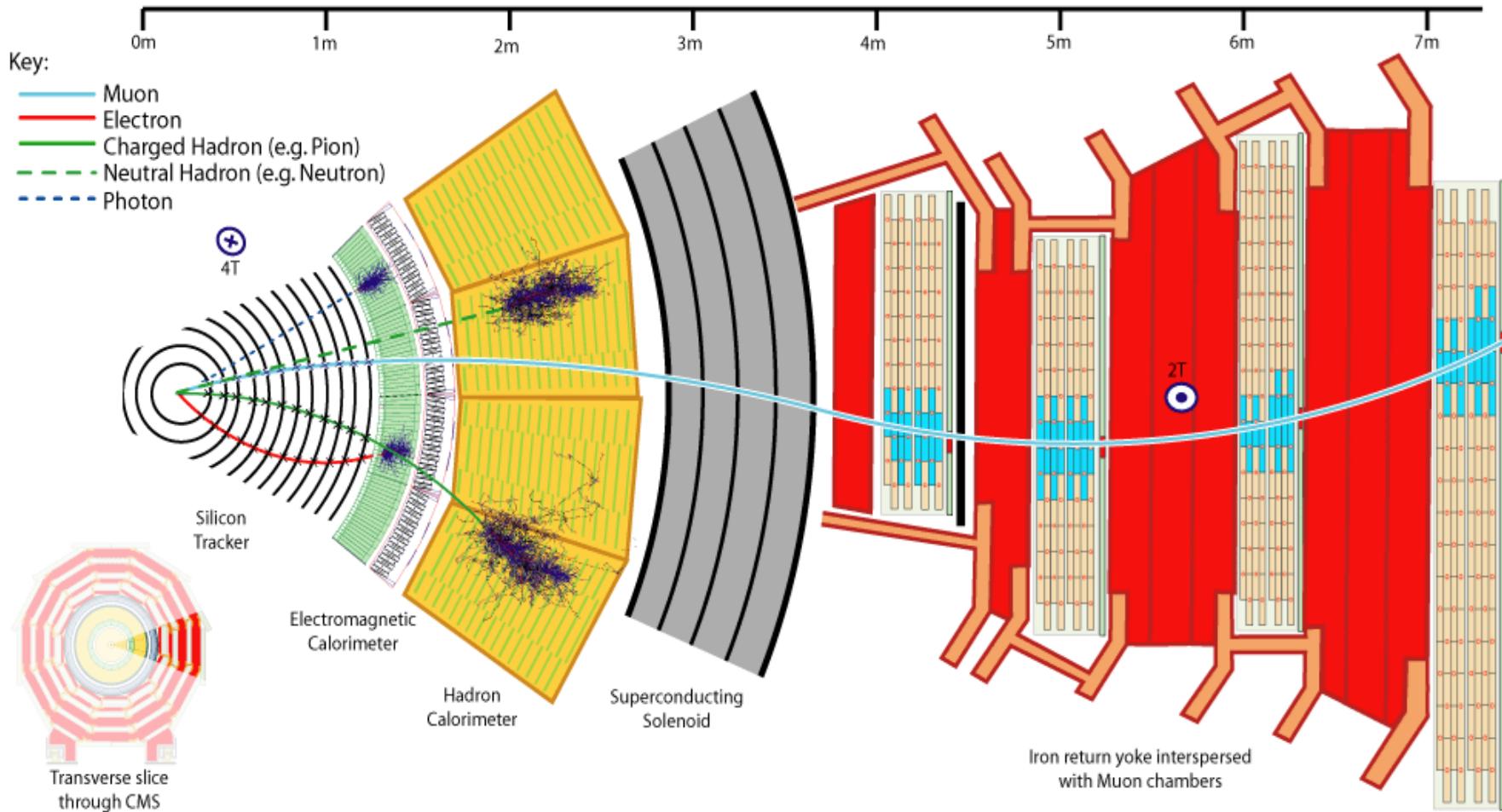
# 2007: ECAL barrel installed

69



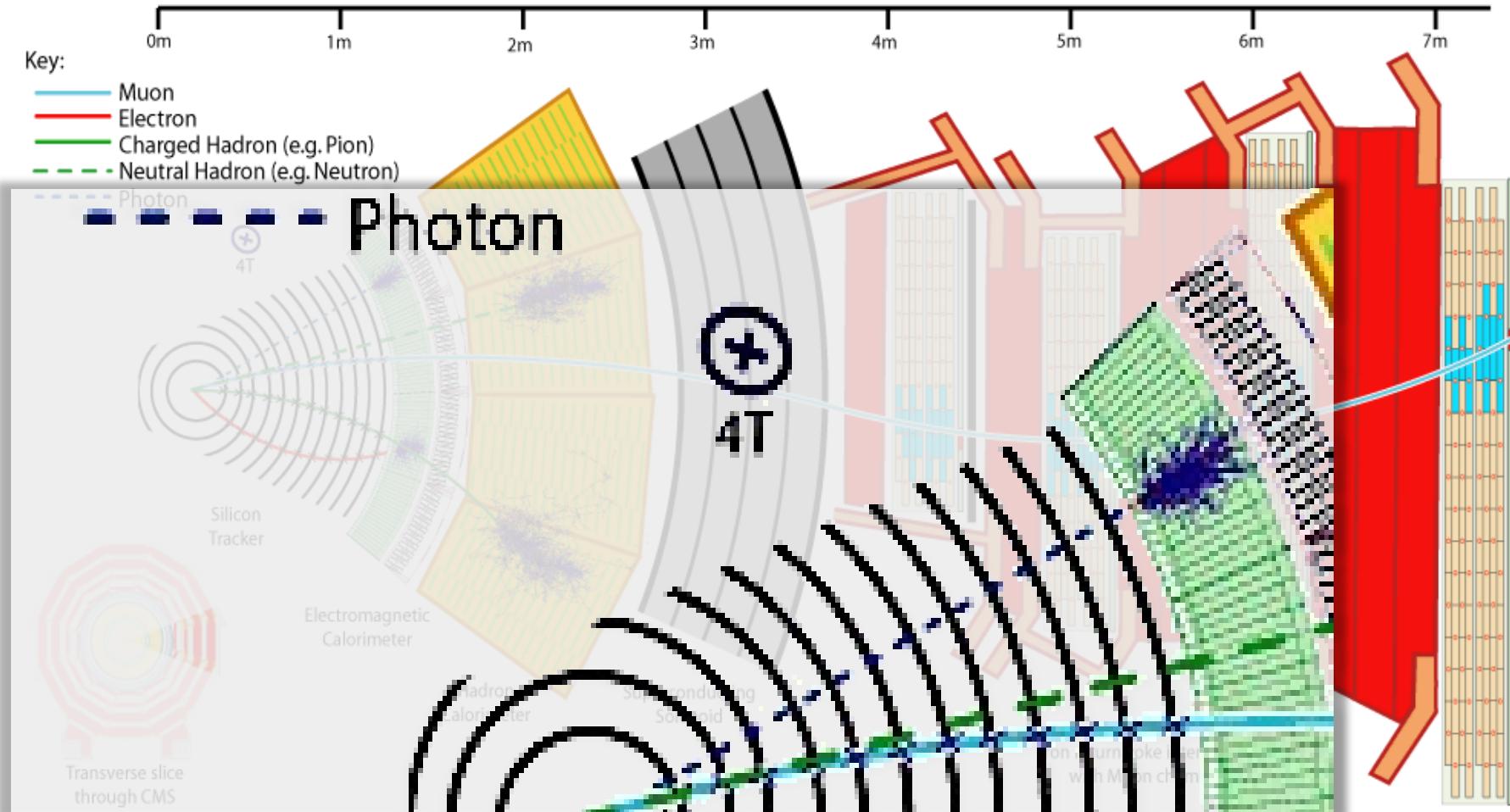
# Detecting particles in CMS

70



# Detecting particles in CMS

71





# 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 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^+)] - 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}$$



# 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 - \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_\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}$$

# The Standard Model of Particle Physics

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[\[ http://cern.ch/go/dW6z \]](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^2} 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

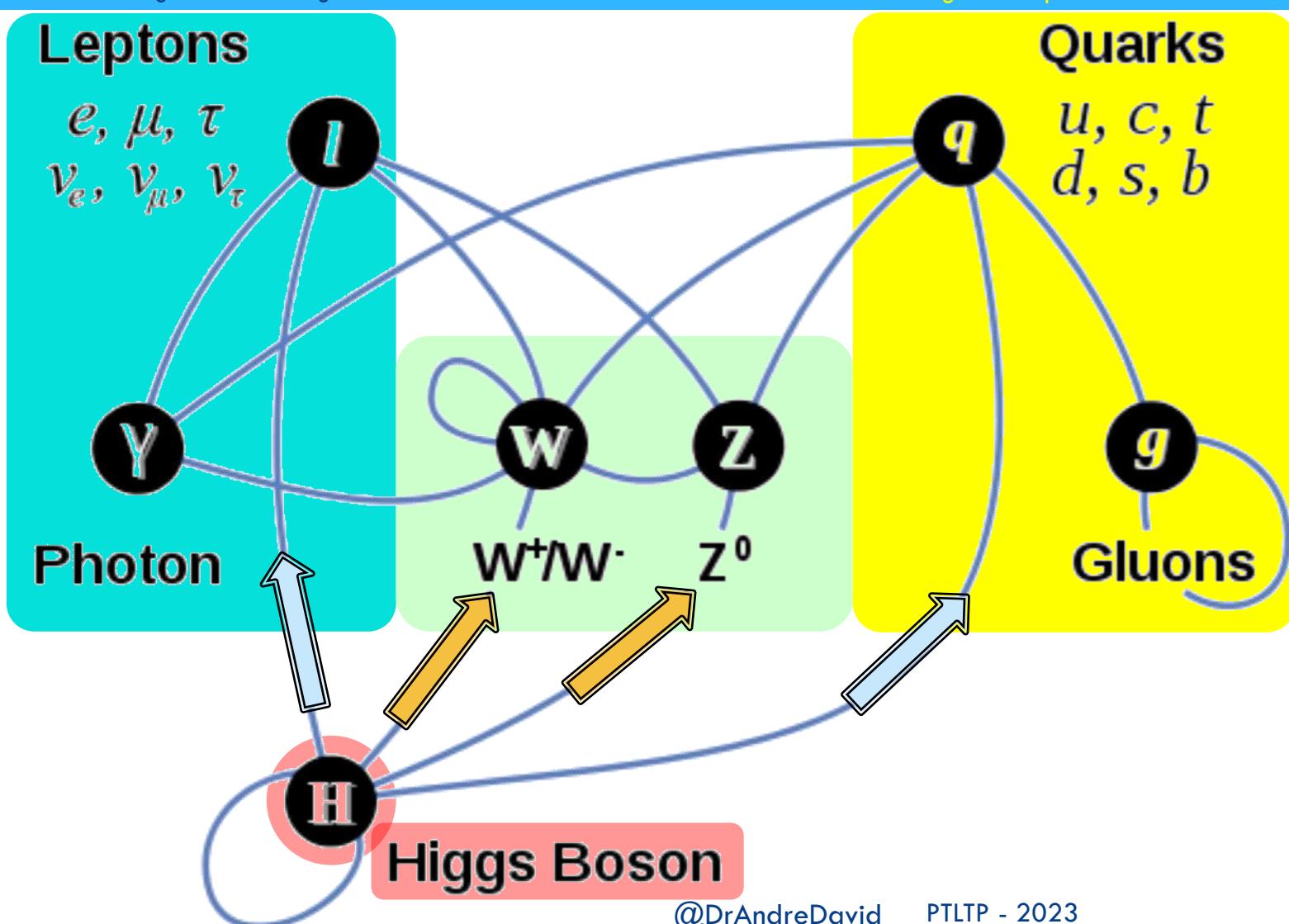


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Electromagnetic force – light

Weak force – star combustion

Strong force – protons and neutrons

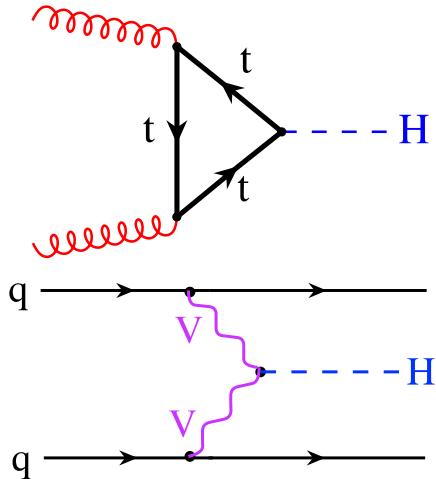


# How SM Higgses are born

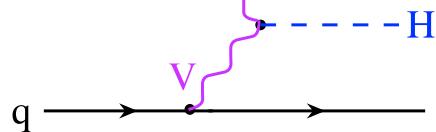
76

[ <http://cern.ch/go/cWH8> ] [ <http://cern.ch/go/SnJ8> ]

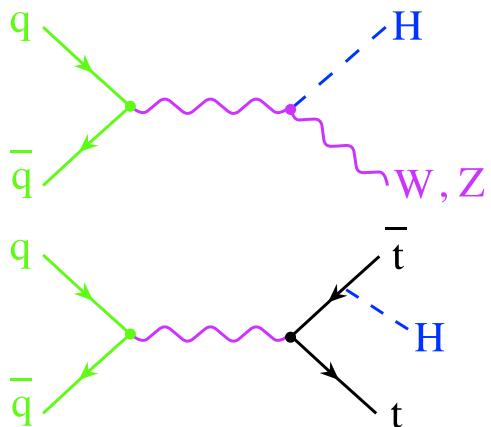
- Gluon fusion**



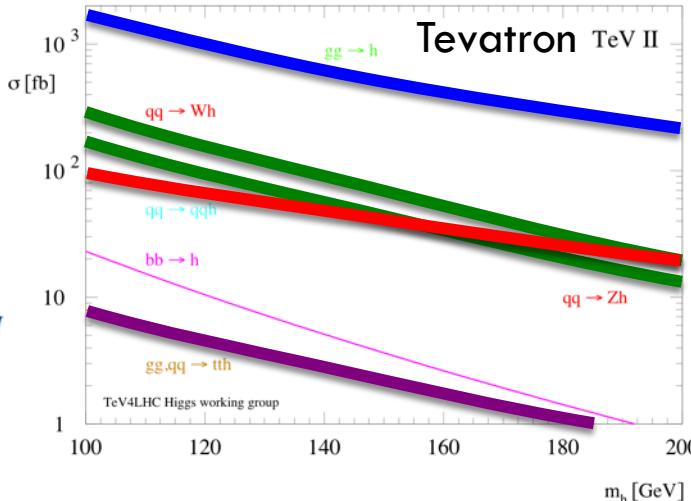
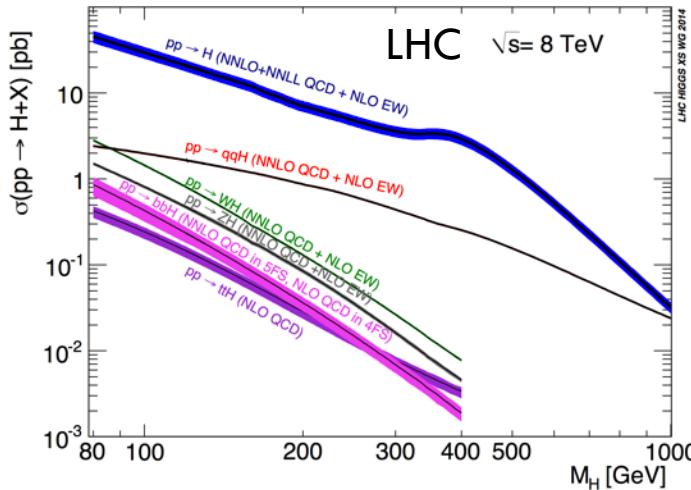
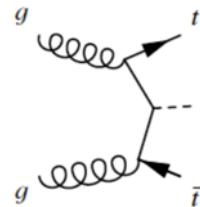
- VBF**



- WH, ZH**



- bbH, ttH**

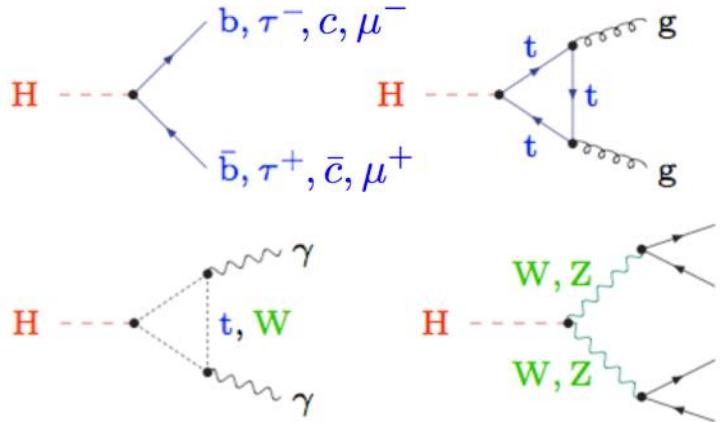


# How SM Higgses die

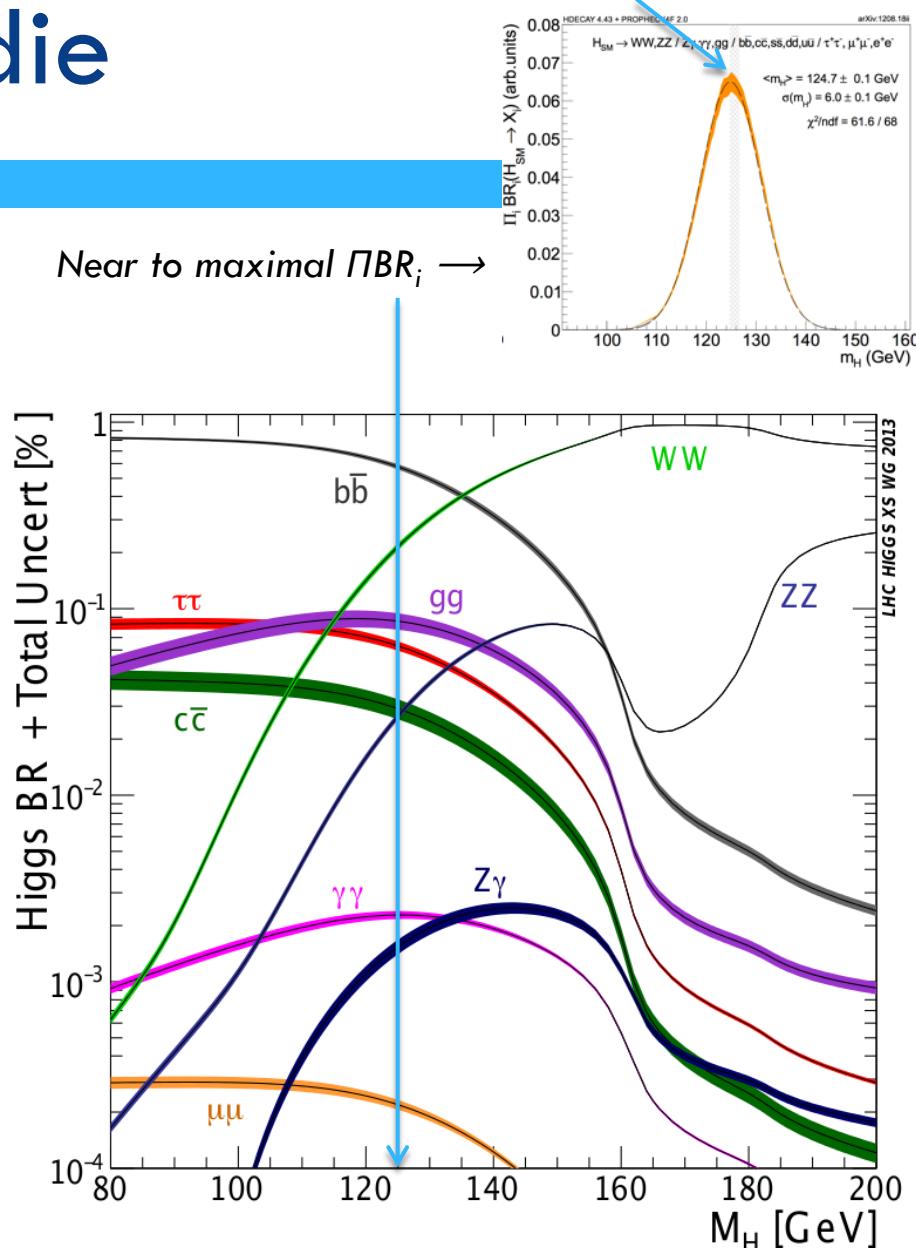
77

[ <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.

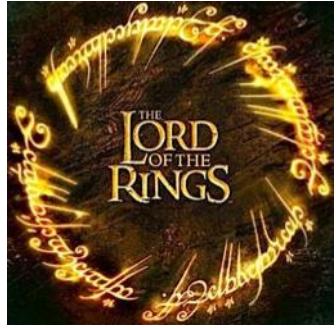


Near to maximal  $\Pi BR_i \rightarrow$





# Putting it all together



$$\begin{aligned}
 & -[\partial_x g_1^{\mu\nu}\partial_x g_{\nu}^{\rho} - g_1^{\mu\rho}\partial_x g_{\nu}^{\rho}\partial_x g_{\nu}^{\mu} - \frac{1}{2}g_1^{\mu\rho}\partial_x^{\mu}\partial_x^{\rho}g_{\nu}^{\sigma}g_{\sigma}^{\tau}g_{\tau}^{\nu}]g_{\rho}^{\sigma} + \frac{1}{2}g_1^{\mu}(\eta^{\sigma\tau}\eta^{\rho\nu})g_{\rho}^{\sigma} + \tilde{G}^{\rho}\partial^{\sigma}G + g_2^{\mu\rho}\partial_x\tilde{G}^{\sigma}g_{\sigma}^{\nu} - \\
 & M^2\phi^2\phi^2 - [\partial_x\phi^2\partial_x\phi^2 - \frac{1}{2}M^2\phi^2\phi^2 - \partial_x(\frac{M^2}{2} + M^2H + \frac{1}{2}(H^2 + \phi^2\phi^2 + 2\phi^2\phi^2)) + \frac{M^2}{2}\alpha_{\phi} - ig\partial_x[\partial_x\phi]^2W_{\mu}^{\nu}W_{\nu}^{\mu} - \\
 & W_{\mu}^{\nu}W_{\nu}^{\mu}) - Z^{\mu}(\partial_x^{\mu}W_{\nu}^{\mu} - W_{\mu}^{\nu}\partial_x^{\mu}) + Z^{\mu}_*(\partial_x^{\mu}W_{\nu}^{\mu} - W_{\mu}^{\nu}\partial_x^{\mu})] - ig\partial_xA_{\mu}(\partial_x^{\mu}W_{\nu}^{\mu} - W_{\mu}^{\nu}\partial_x^{\mu}) - \\
 & A_{\mu}(\partial_x^{\mu}W_{\nu}^{\mu} - W_{\mu}^{\nu}\partial_x^{\mu}) - A_{\mu}(\partial_x^{\mu}W_{\nu}^{\mu} - W_{\mu}^{\nu}\partial_x^{\mu}) - ig\partial_xW_{\mu}^{\nu}W_{\nu}^{\mu} + ig\partial_xW_{\mu}^{\nu}W_{\nu}^{\mu} + g^2c_1^2(Z^{\mu}W_{\nu}^{\mu}Z^{\nu}W_{\mu}^{\mu}) - g^2s_w^2s_{w_*}c_w(A_{\mu}W_{\nu}^{\mu} - A_{\mu}W_{\nu}^{\mu}) + g^2s_w^2s_{w_*}c_w(A_{\mu}W_{\nu}^{\mu} - \\
 & W_{\mu}^{\nu}) - 2A_{\mu}Z^{\mu}W_{\nu}^{\mu} - ig\partial_x^2H^2 + 2H\phi^2\phi^2 - ig\partial_x^2H + (\phi^2)^2 + 4(\phi^2\phi^2)\phi^2\phi^2 + \\
 & 4H\phi^2\phi^2 + 2(\phi^2)^2H^2] - g\eta W_{\mu}^{\nu}W_{\nu}^{\mu}H - \frac{1}{2}g^2Z^{\mu}Z^{\nu}H - ig(W_{\mu}^{\nu}(\partial_x^{\mu}\phi^2 - \phi^2\partial_x^{\mu}) - W_{\mu}^{\nu}(\partial_x^{\mu}\phi^2 - \phi^2\partial_x^{\mu}) + \\
 & igW_{\mu}^{\nu}(\partial_x^{\mu}\phi^2 - \phi^2\partial_x^{\mu}) - W_{\mu}^{\nu}(\partial_x^{\mu}\phi^2 - \phi^2\partial_x^{\mu}) + ig(\partial_x^{\mu}H\partial_x^{\nu}\phi^2 - \phi^2\partial_x^{\mu}H) - ig^2M^2Z^{\mu}(\partial_x^{\mu}\phi^2 - \\
 & W_{\mu}^{\nu}\phi^2) + igs_wMA_{\mu}(\partial_x^{\mu}W_{\nu}^{\mu} - W_{\mu}^{\nu}\partial_x^{\mu}) - ig^2\frac{c_w}{2}s_wZ^{\mu}(\partial_x^{\mu}\phi^2 - \phi^2\partial_x^{\mu}) + igs_wA_{\mu}(\partial_x^{\mu}\phi^2 - \phi^2\partial_x^{\mu}) - \\
 & \frac{1}{2}g^2W_{\mu}^{\nu}W_{\nu}^{\mu}[H^2 + (\phi^2)^2 + 2\phi^2\phi^2] - \frac{1}{2}g^2Z^{\mu}Z^{\nu}H^2 + (\phi^2)^2 + 2(2\phi^2_2 - 1)^2\phi^2\phi^2] - \frac{1}{2}g^2Z^{\mu}Z^{\nu}\partial^{\mu}(W_{\mu}^{\nu}\phi^2 + \\
 & W_{\mu}^{\nu}\phi^2) - ig\frac{c_w}{2}s_wZ^{\mu}H(\partial_x^{\mu}W_{\nu}^{\mu} - W_{\mu}^{\nu}\partial_x^{\mu}) + ig^2s_wA_{\mu}H(\partial_x^{\mu}W_{\nu}^{\mu} - W_{\mu}^{\nu}\partial_x^{\mu}) - \\
 & g^2\frac{c_w}{2}(2\phi^2_2 - 1)Z^{\mu}A_{\mu}\phi^2 - g^2s_w^2A_{\mu}A_{\mu}\phi^2 - \epsilon^2(\phi^2 + m^2)c^2 - \rho^2\partial_x^2\phi^2 - \eta^2_1(\eta^2 + m^2_1)d^2 - d_1(\gamma^2 + m^2_2)d^2 + \\
 & igs_wA_{\mu}[(\phi^2\gamma^2\epsilon^2) - \{(\phi^2\gamma^2\eta^2_1) - \{d_1^2(\eta^2\epsilon^2)\}\} + \frac{d_2^2}{2}(\rho^2\gamma^2(1 + \gamma^2)c^2) + (\eta^2\gamma^2(4\phi^2_2 - 1 - \gamma^2)c^2) + (\phi^2\gamma^2(1 + \gamma^2)C_wd^2)] + \frac{s_w}{2}W_{\mu}^{\nu}[(\partial_x^{\mu}\phi^2 + \\
 & \gamma^2\eta^2\epsilon^2) + (\partial_x^{\mu}\gamma^2(1 - \eta^2)c^2)] + \frac{d_2^2}{2}W_{\mu}^{\nu}[(\phi^2\gamma^2(1 + \gamma^2)c^2) + \phi^2(\epsilon^2(1 - \gamma^2)\eta^2\epsilon^2) - \frac{1}{2}\frac{c_w}{2}H(c^2\epsilon^2) + \\
 & i\phi^2(\epsilon^2\lambda^2\eta^2\epsilon^2)] + \frac{1}{2}\frac{c_w}{2}\phi^2[-m_1^2(\partial_x^{\mu}C_w(1 - \gamma^2)\eta^2\epsilon^2) + m_1^2(\partial_x^{\mu}C_w(1 + \gamma^2)\eta^2\epsilon^2)] + \\
 & m_2^2(\partial_x^{\mu}C_w(-\gamma^2\eta^2\epsilon^2) - \frac{1}{2}\frac{c_w}{2}H(\partial_x^{\mu}\eta^2\epsilon^2) - \frac{1}{2}\frac{c_w}{2}H(\partial_x^{\mu}\eta^2\epsilon^2) + \frac{1}{2}\frac{c_w}{2}\phi^2(\eta^2\gamma^2\epsilon^2d^2) + X^*(\partial_x^{\mu} - \\
 & M^2)X^* + X^*(\partial_x^{\mu} - M^2)X^* + X^*(\partial_x^{\mu} - M^2)X^* + \tilde{Y}(\partial_x^{\mu})^2 + ig_sW_{\mu}^{\nu}(\partial_x^{\mu}X^*X^* - \partial_x^{\mu}\tilde{X}^*\tilde{X}^*) + ig_sW_{\mu}^{\nu}(\partial_x^{\mu}\tilde{Y}^*\tilde{X}^* - \\
 & \partial_x^{\mu}\tilde{X}^*Y^*) + ig_sW_{\mu}^{\nu}(\partial_x^{\mu}X^*X^* - \partial_x^{\mu}\tilde{X}^*\tilde{X}^*) + ig_sW_{\mu}^{\nu}(\partial_x^{\mu}\tilde{X}^*Y^*) + ig_sW_{\mu}^{\nu}(\partial_x^{\mu}\tilde{X}^*\tilde{X}^* - \partial_x^{\mu}\tilde{X}^*X^*) + \\
 & ig_sA_{\mu}(\partial_x^{\mu}X^*X^* - \partial_x^{\mu}\tilde{X}^*\tilde{X}^*) + g[M(X^*X^*H + \tilde{X}^*\tilde{X}^*H + \frac{1}{2}\tilde{X}^*X^*H) + \frac{1}{2}\tilde{X}^*X^*H] + ig[M(\tilde{X}^*\tilde{X}^*H - \\
 & X^*X^*H)] + \frac{1}{2}g[M(X^*X^* - X^*X^*) + igMs_w(X^*X^* - X^*X^*) + \frac{1}{2}g[M(X^*X^*\phi^2 - \tilde{X}^*\tilde{X}^*\phi^2)]
 \end{aligned}$$


# 2011: nothing else in the horizon

79

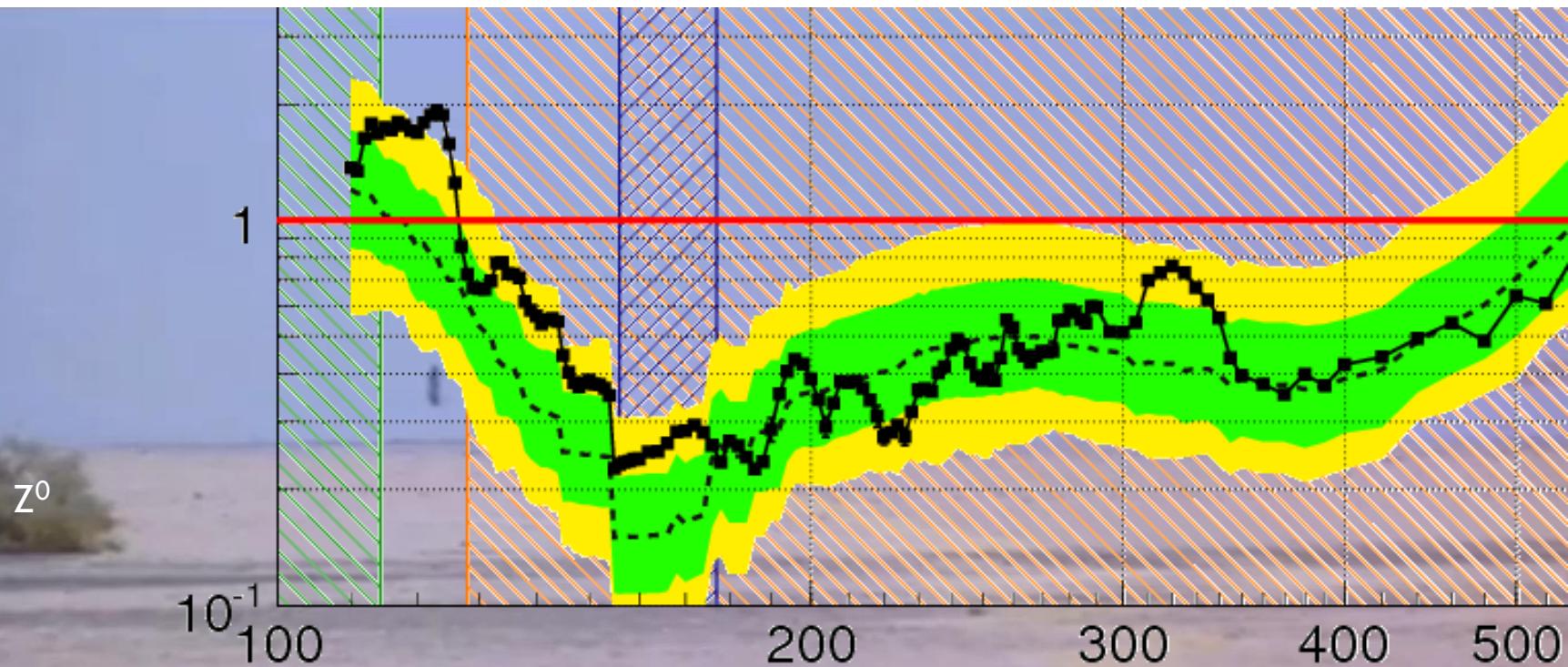
[“Lawrence of Arabia” idea from C. Grojean]

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



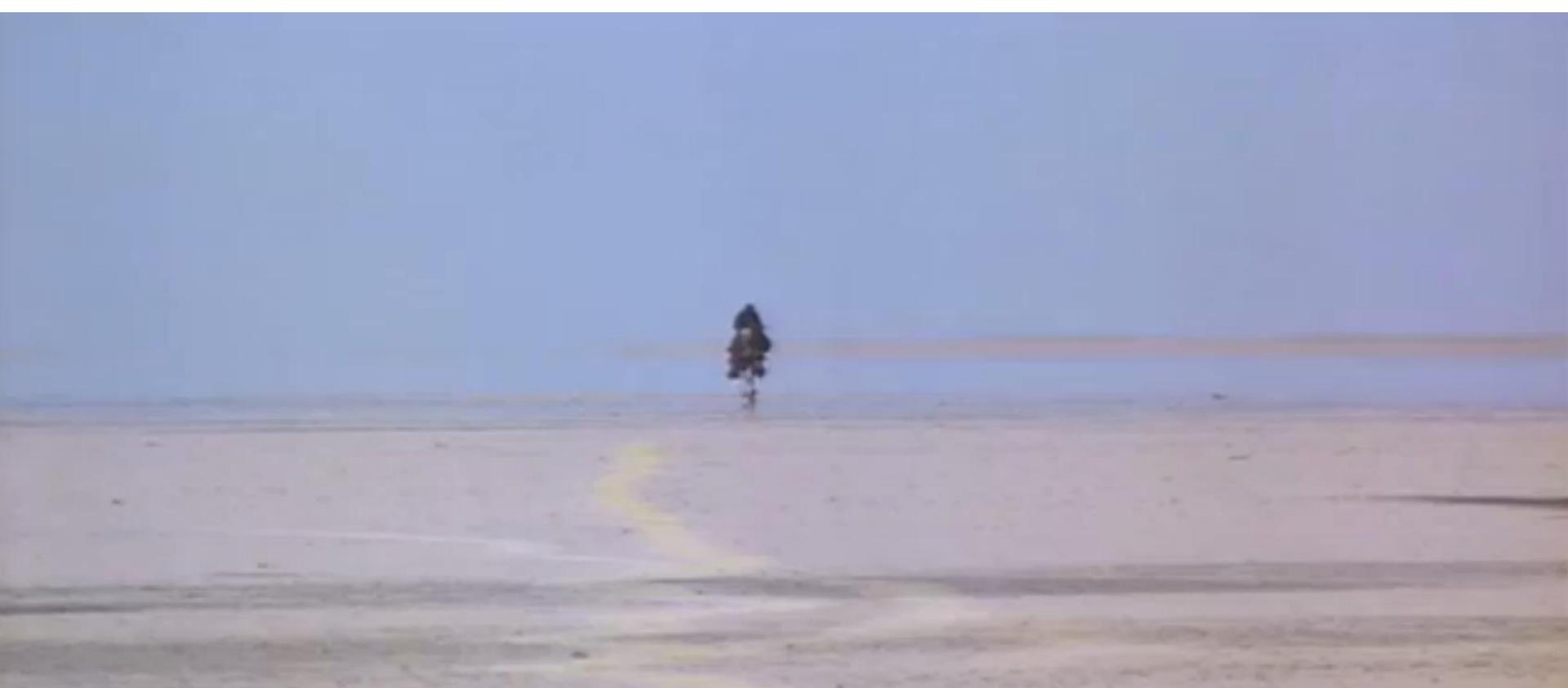
# 2011: nothing else in the horizon

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



# 2012: a rider!

- We discovered a peak rising from the background.



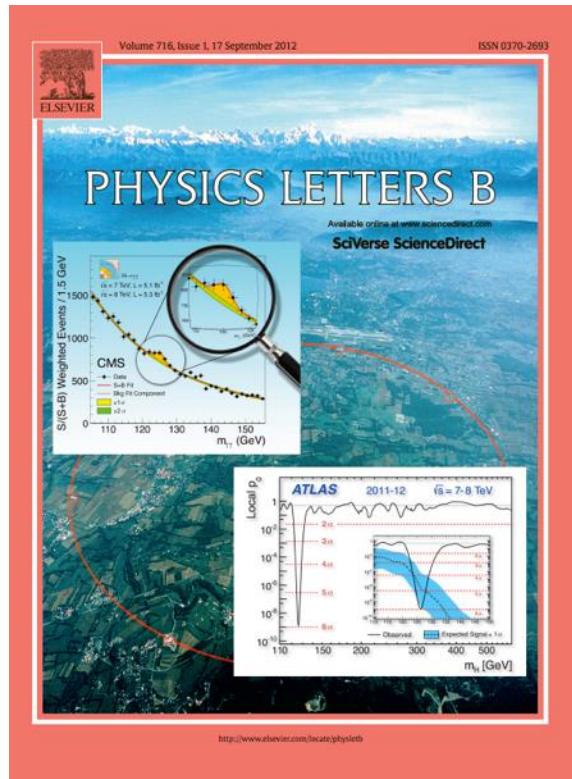
# July 4, 2012

## Looking up to a new boson



82

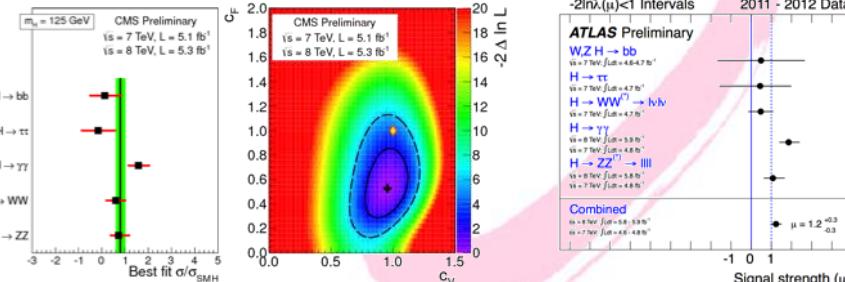
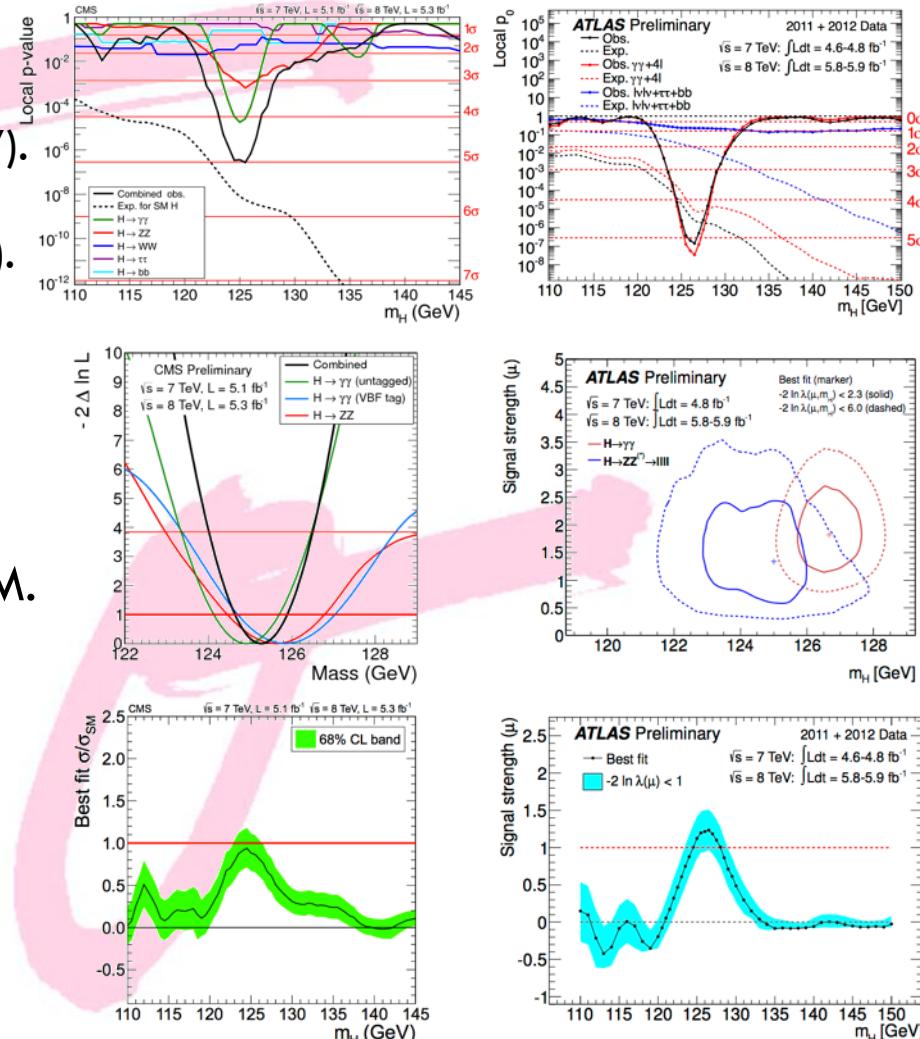
[ <http://cern.ch/go/q8jx> ]



# Higgsdependence day recap

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

- Both experiments at  $5.0\sigma$ .
  - 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...”**



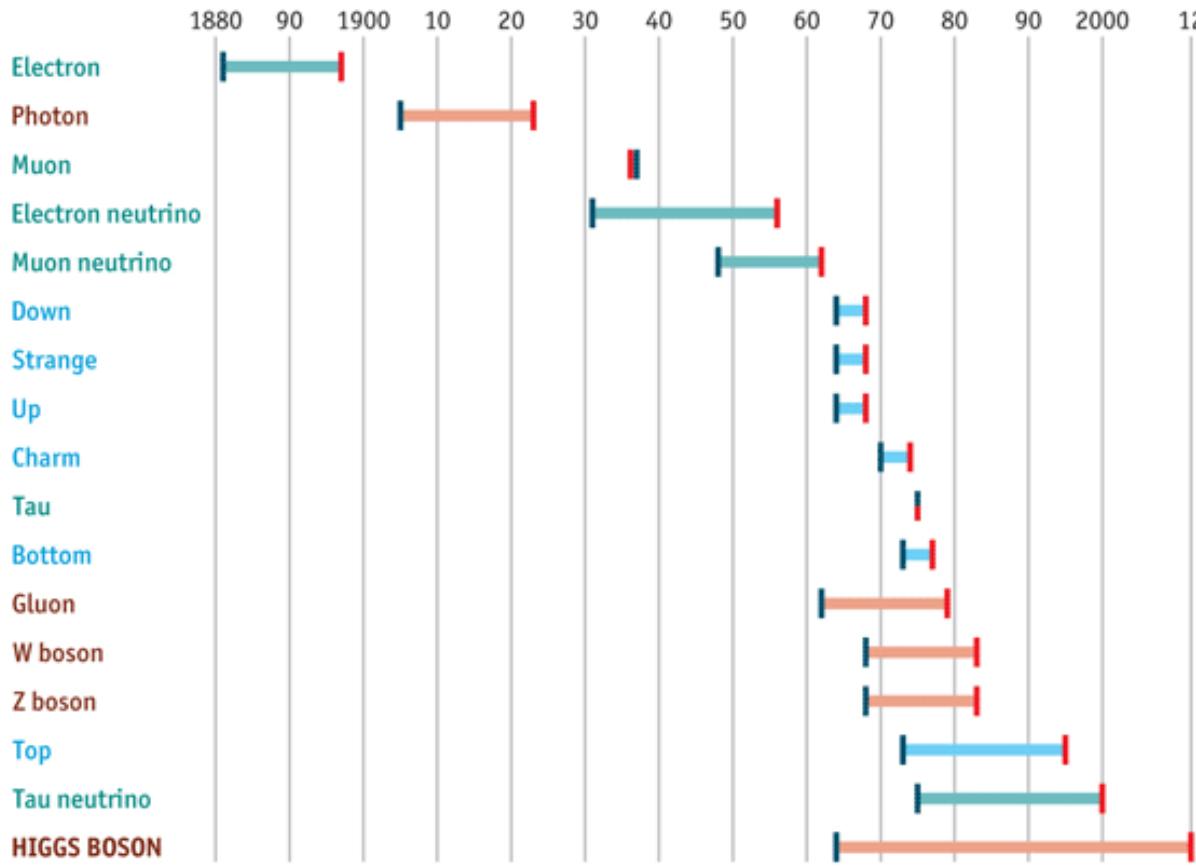
# Evolutions & revolutions of the elements

## 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

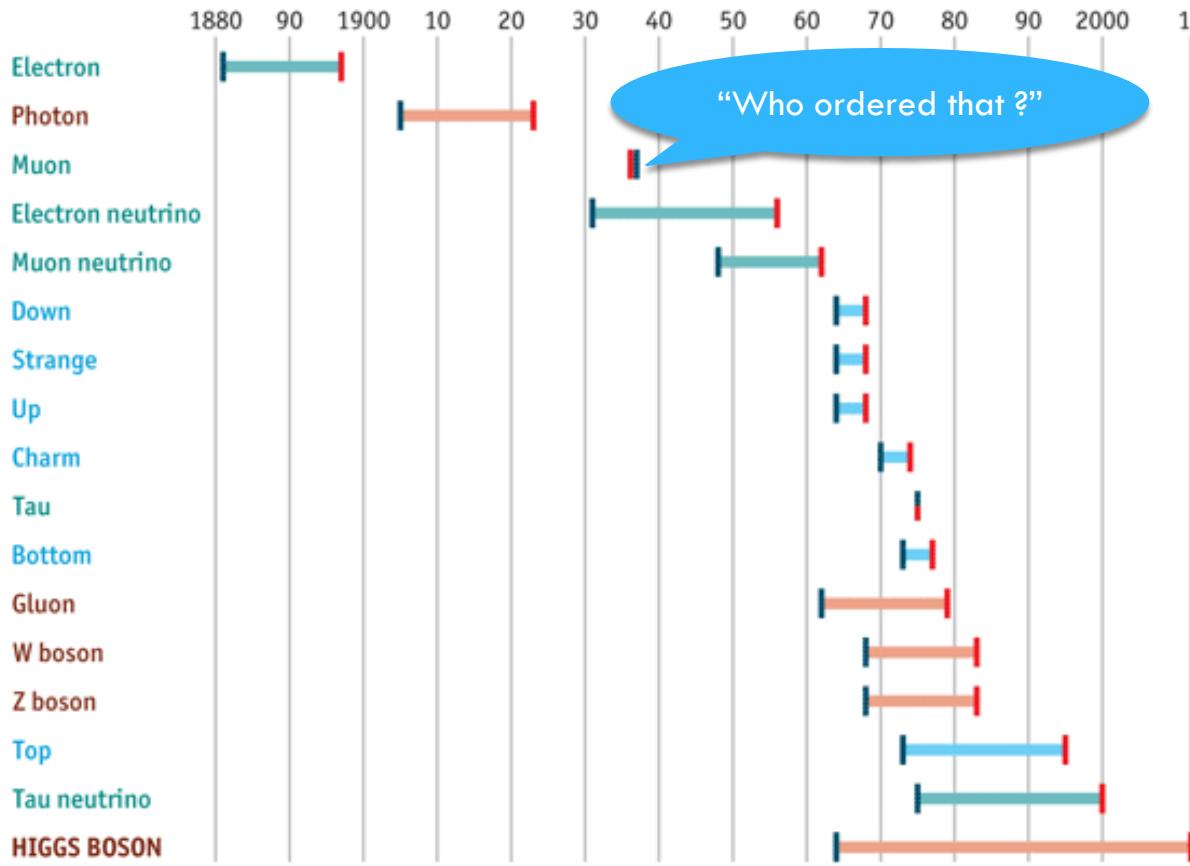
85

## The Standard Model of particle physics

Years from concept to discovery

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Discovered



Source: *The Economist*

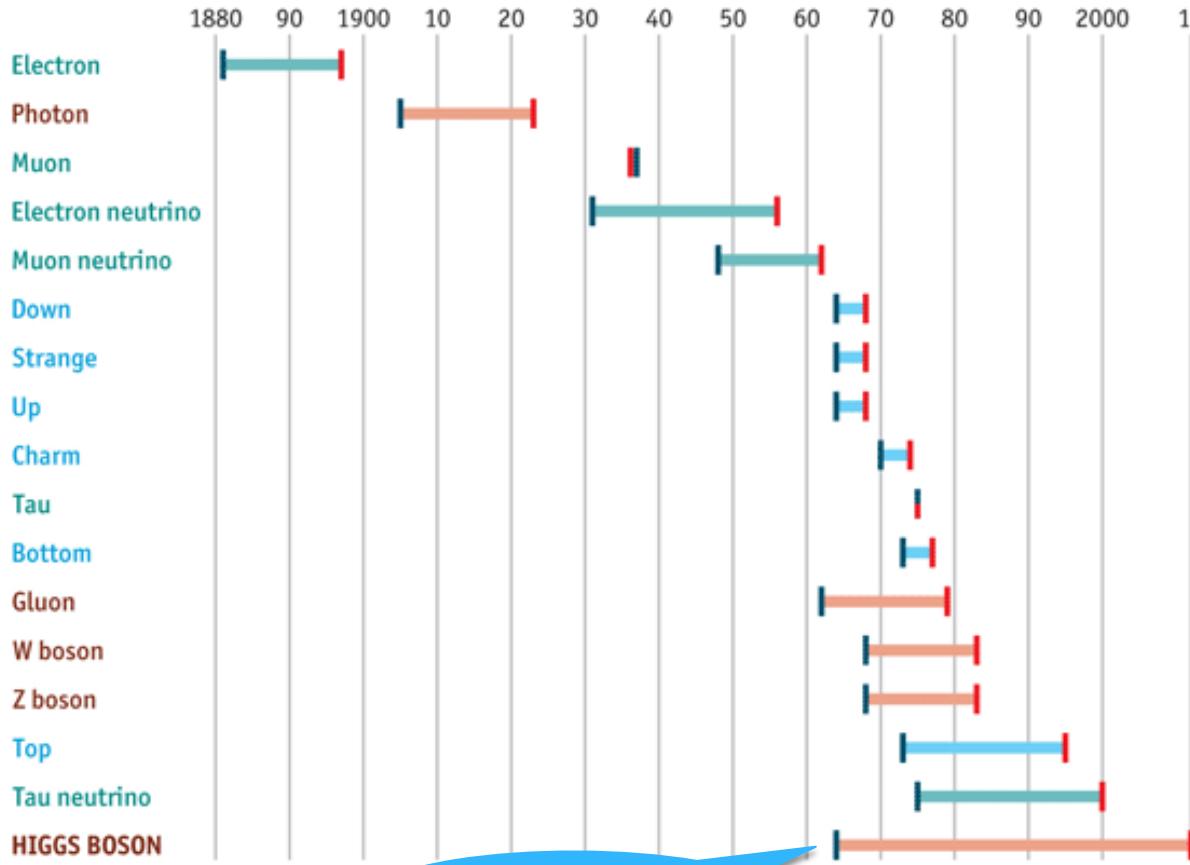
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Discovered



Source: *The Economist*

Almost 50 years !

2012 2011 2010 2009 2008

## 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

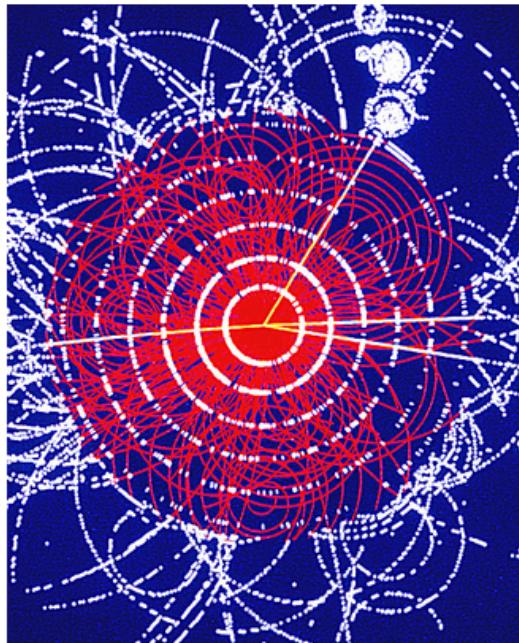
 20

 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

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Most Emailed

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?

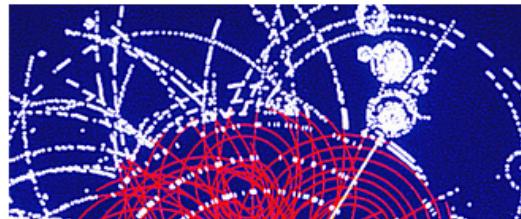
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### THE CANDIDATES

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[VOTE](#) 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**

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



89

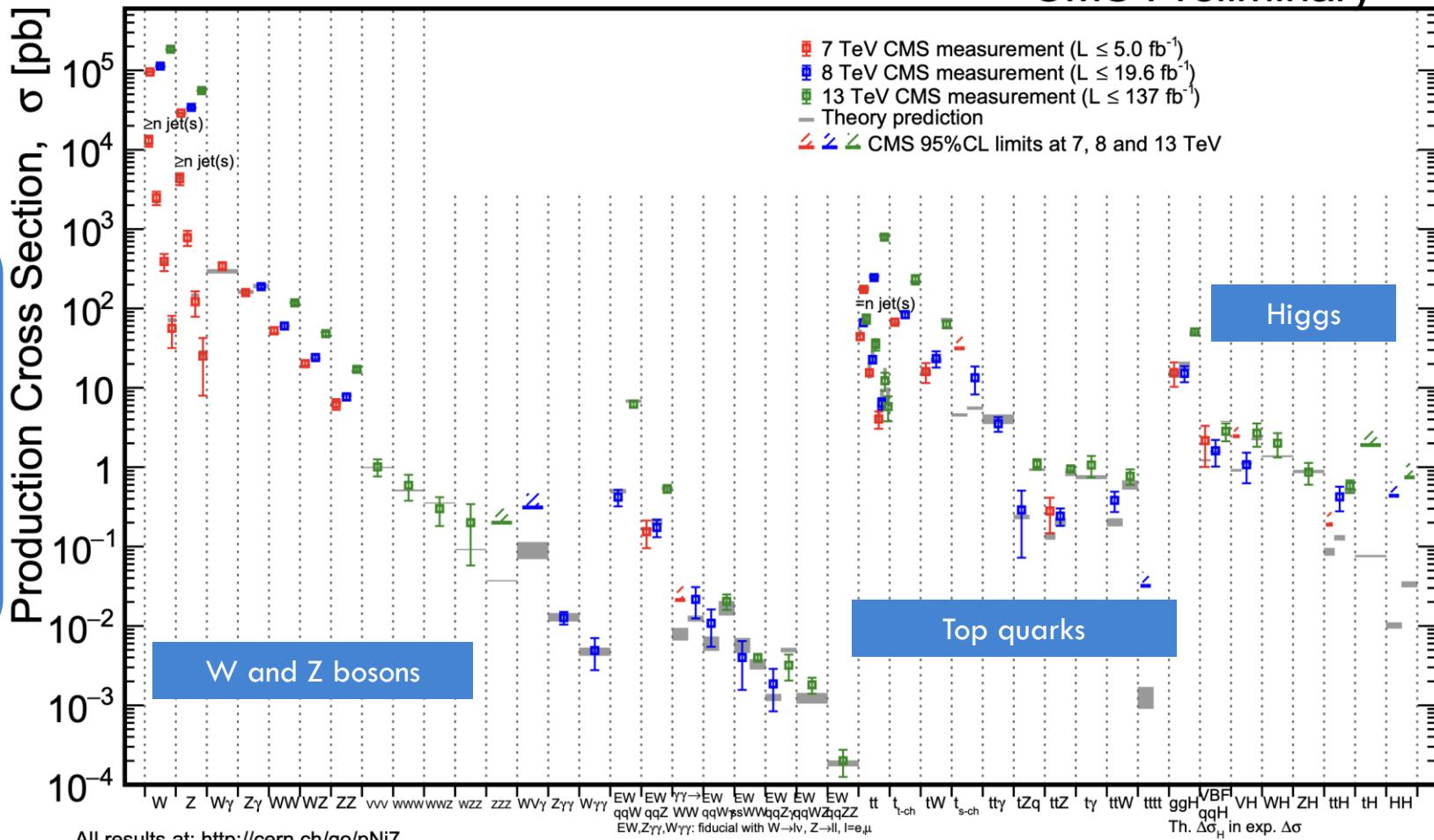
"Yesterday's discovery is today's calibration, and tomorrow's background." – V. L. Telegdi [ <http://cern.ch/go/lf9C> ] [ <http://cern.ch/go/KD8D> ]

Inelastic collisions:  $\sim 7 \times 10^{10}$   
May 2020

CMS Preliminary



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



# 2013: a rider with a gun

90

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

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





91

# Nobel prizes...



The Nobel Prize in Physics 2013  
François Englert, Peter Higgs

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## 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...

92



The Nobel Prize in Physics 2013  
François Englert, Peter Higgs

Share this:      1.8K

## The Nobel Prize 2013



Photo: A. Mahmoud

François Englert

Prize share: 1/2

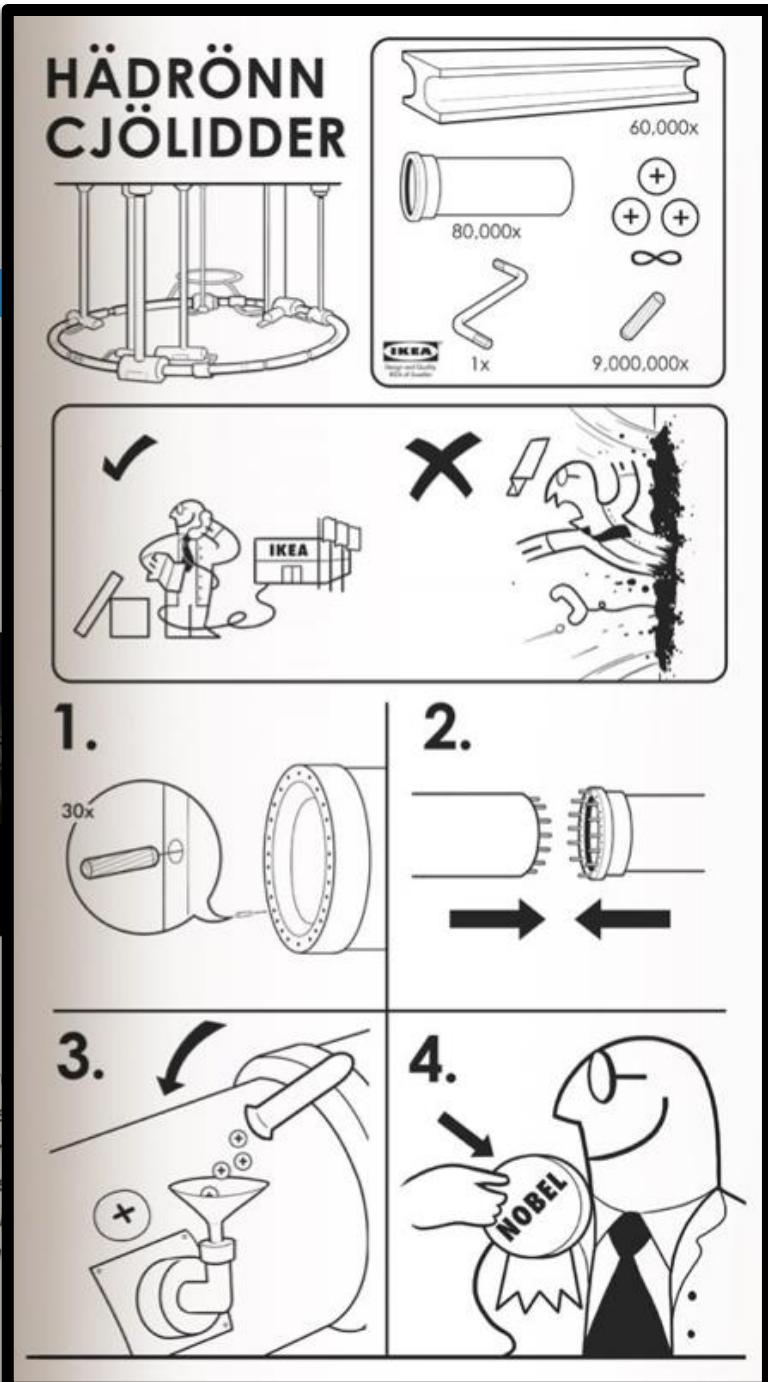


Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

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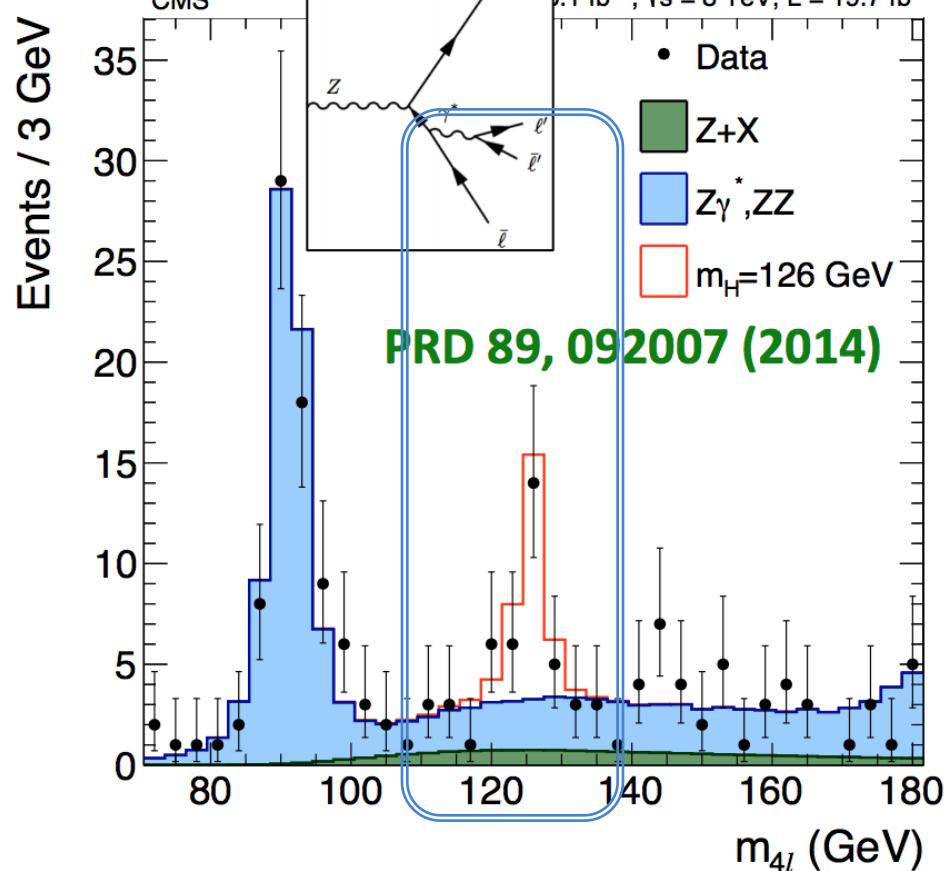
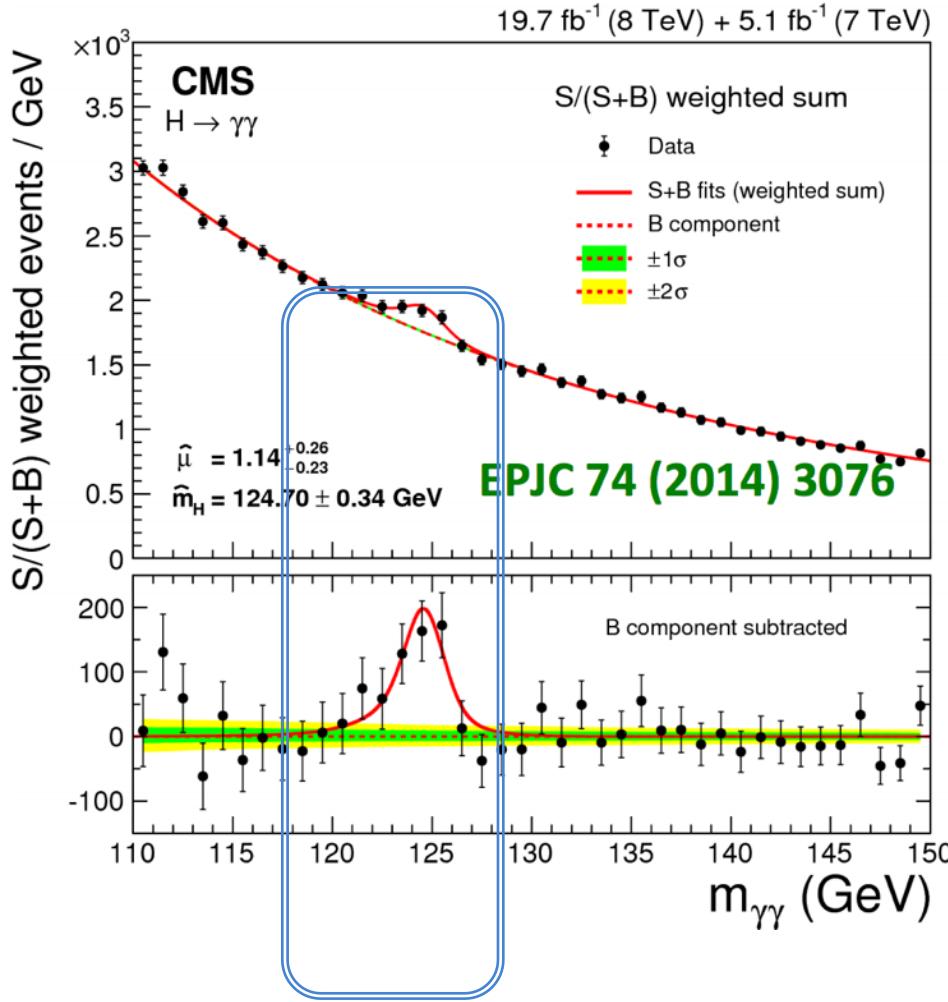
# What is the Higgs boson mass?

Something that the SM does not predict.

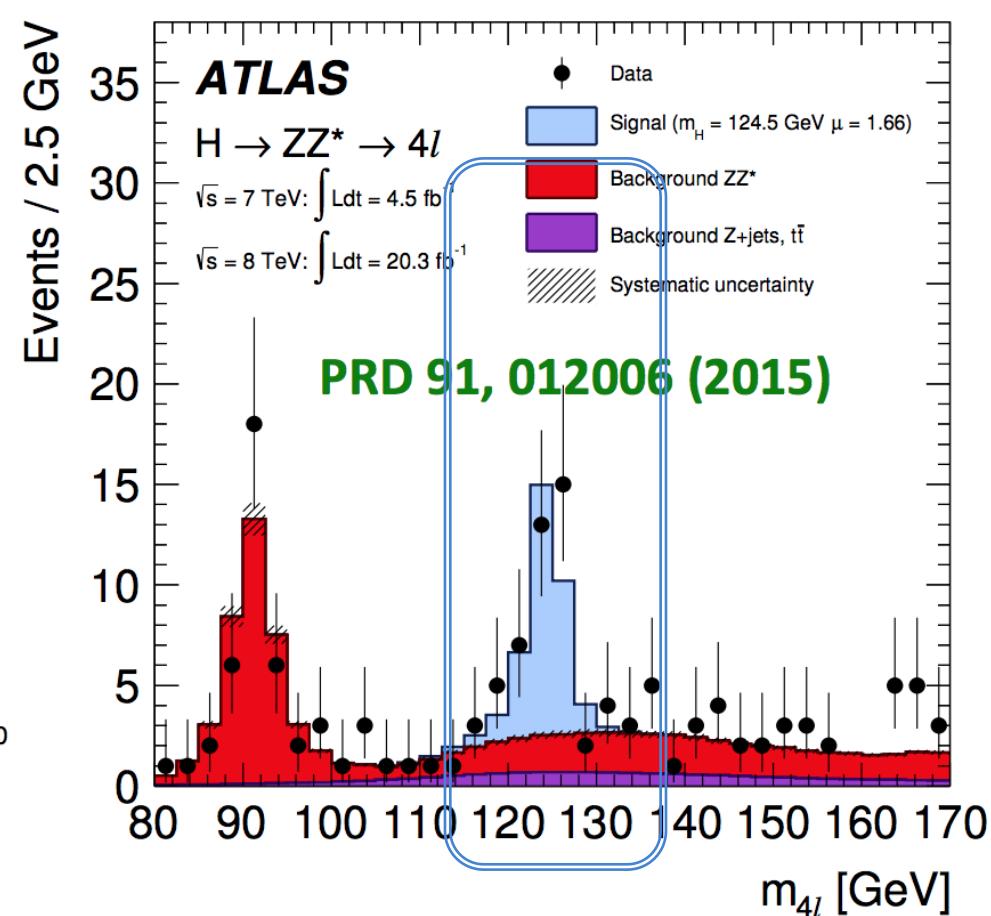
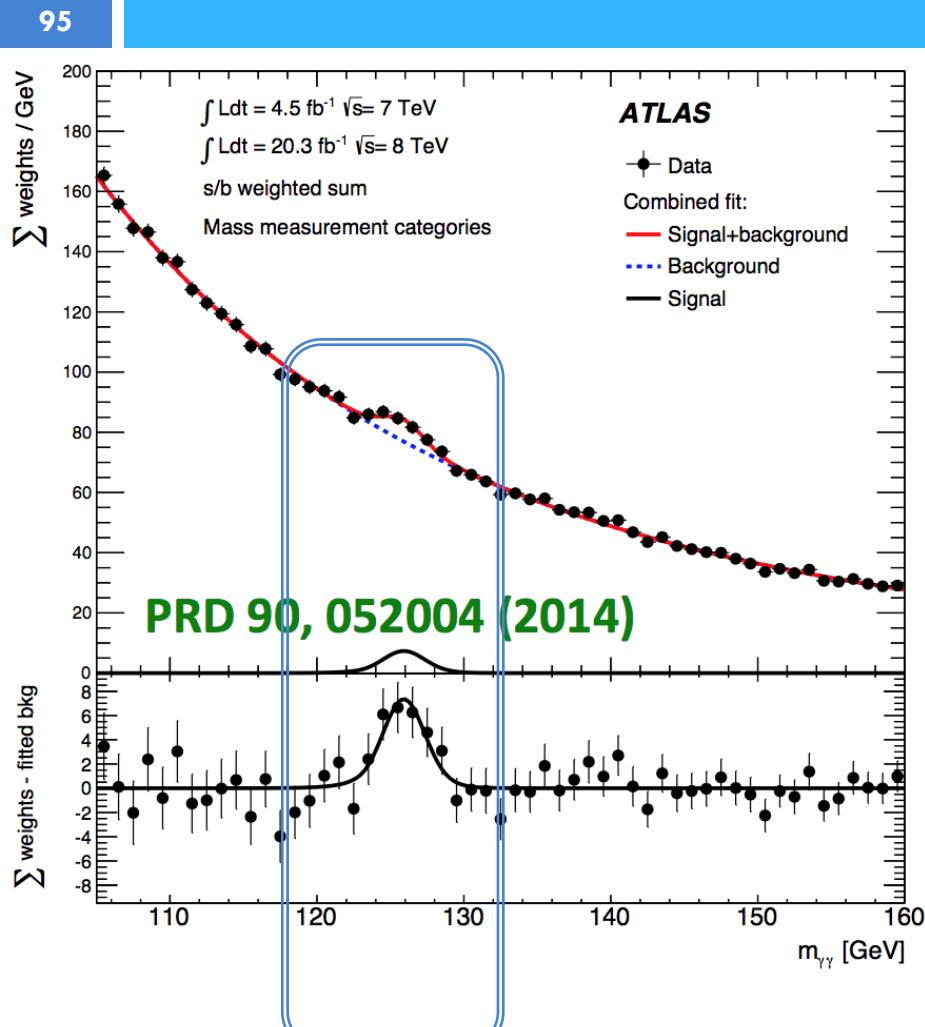
Something we can measure!

# Mass peaks: mass measurements

94



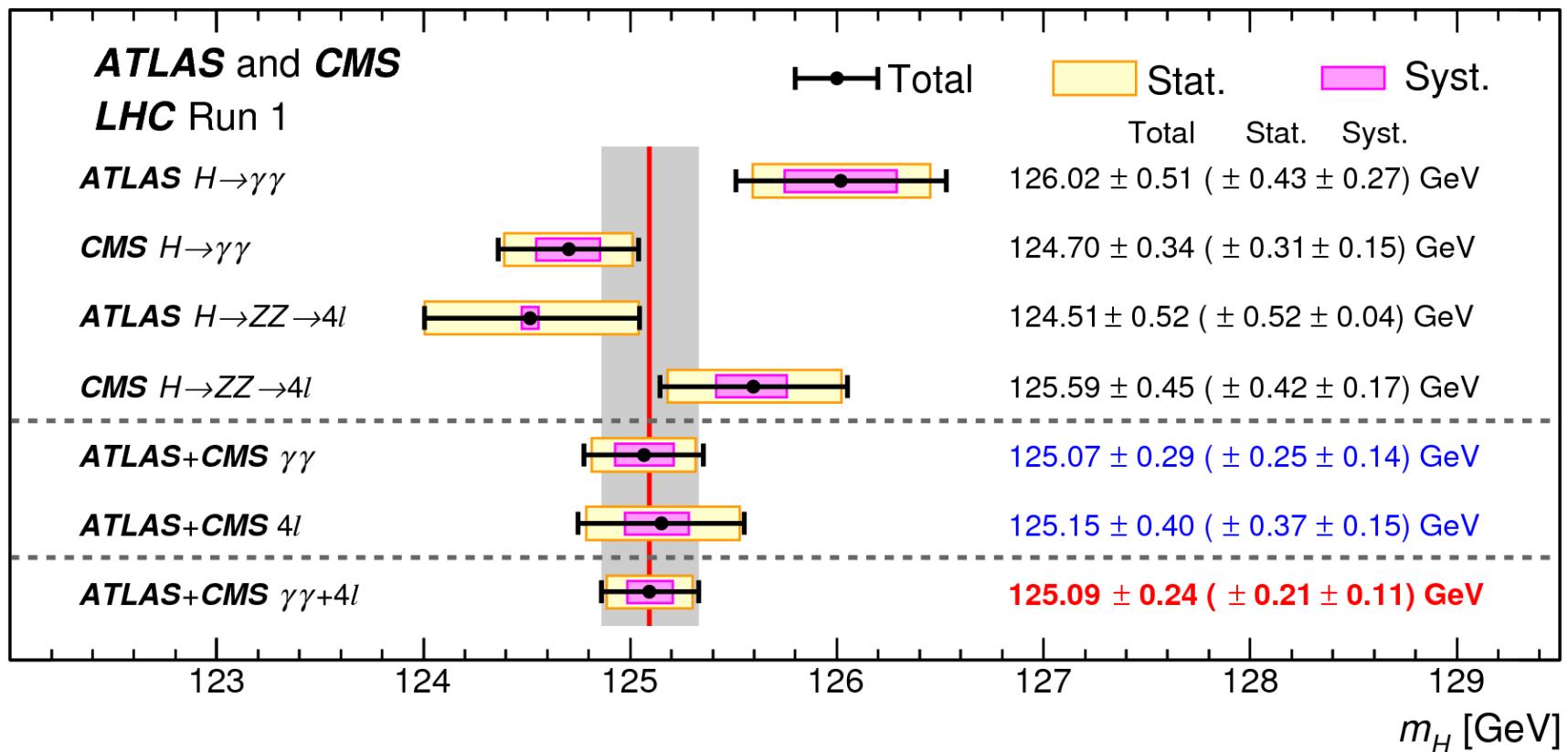
# Mass peaks: mass measurements



# Combined LHC mass measurement

96

[ arXiv:1503.07589 ]





# Combined LHC mass measurement

97

[ 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



98

# 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)

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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

99

[ <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 - \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_\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_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^+) + 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_\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_\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+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] - gMW_\mu^+ W_\mu^- I - \frac{1}{2}\frac{M^2}{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}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 [A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \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^- (\phi^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^+ \partial_\mu \phi^- + \phi^- \partial_\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}(\gamma \partial + m_e^\lambda) u_j^\lambda - d_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - 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) + \frac{1}{3}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 + \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) 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 (1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda (1 + \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda (1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda (1 + \gamma^5) u_j^\lambda)] - \frac{g 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 m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\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

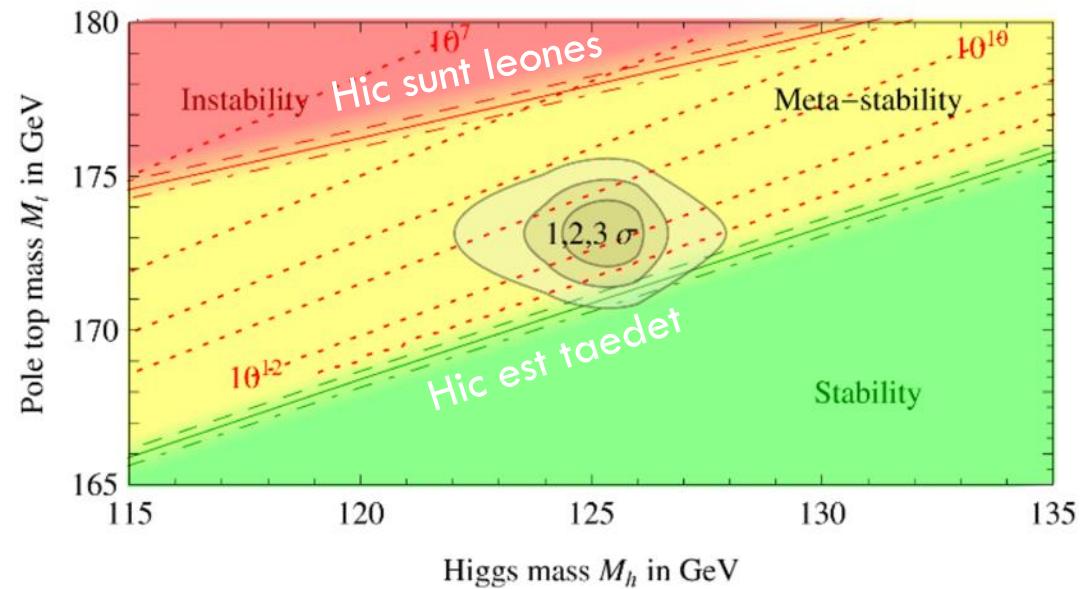
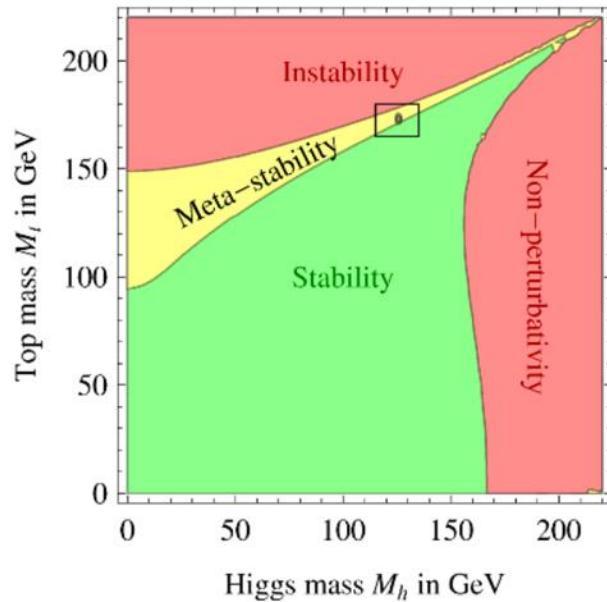
[ <http://cern.ch/go/dW6z> ]

$$\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 - \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_\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} (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 \partial_\mu \phi^0 - \phi^0 \partial_\mu H]) + \\
& \text{Valid up to } \sim \text{Planck scale ?}
\end{aligned}$$

$$\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_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^\lambda) + 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}$$

# 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 - \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_\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} (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 \partial_\mu \phi^0 - \phi^0 \partial_\mu H]) + \\
& \text{Valid up to } \sim \text{Planck scale ?}
\end{aligned}$$

$$\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_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^\lambda) + 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

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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 - \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_\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 \partial_\mu \phi^0 - \phi^0 \partial_\mu H]) + \\
& W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}a^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) + \frac{1}{2}ia^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 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + (\bar{u}_j^\kappa \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa) + (\bar{d}_j^\lambda \gamma^\mu (1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \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_d^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_u^\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}$$

Valid up to ~Planck scale ?

But: dark matter, matter-antimatter, etc.

$$\begin{aligned}
& 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{2}{3}s_w^2 - \gamma^5) d_j^\gamma)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\nu^\gamma \gamma^\mu (1 + \gamma^5) e^\gamma) + (u_j^\gamma \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(e^\gamma \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_d^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_u^\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}$$



# The Next Standard Model

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

$$\begin{aligned}
 & -\frac{1}{2}g_{\mu\nu}^{ab}\partial_\nu g_\mu^a - g_a f^{abc}\partial_\mu Z_\nu^a \partial_\nu^b g_\mu^c - \frac{1}{4}g_\mu^{ab}f^{abc}\partial_\mu^b g_\mu^c + \frac{1}{2}ig_1^2(\bar{\psi}_1^\mu \gamma^\alpha \psi_1^\mu)g_\mu^a + \bar{G}^\mu \partial^\nu G^\mu + g_a f^{abc}\partial_\mu \bar{G}^\mu G^\mu \psi_\mu^a - \\
 & \partial_\mu^a W_\mu^b \partial_\nu W_\nu^a - M^2 W_\mu^a W_\nu^a - \frac{1}{2}\partial_\mu Z_\mu^0 Z_\mu^0 - \frac{1}{2g_2^2}M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\mu \partial_\nu A_\nu - \frac{1}{2}\partial_\mu H \partial_\nu 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^+ \partial_\mu \phi^0 - \frac{1}{2g_1^2}M \phi^0 \phi^0 - \partial_\mu [\frac{2M^2}{g_1^2}H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g_1^2}a_{bb} - ig s_w[\partial_\mu Z_m^0(W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\mu^0(W_\mu^+ \partial_\nu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+)] - ig s_w[\partial_\mu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
 & A_\mu (W_\mu^+ \partial_\nu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+) + A_\mu (W_\mu^+ \partial_\nu W_\nu^- - W_\nu^- \partial_\mu 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_\mu^0 W_\mu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 c_w(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 + \frac{1}{2}g \frac{M}{g_2^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig W_\mu^+(g^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^-(g^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{M}{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-\sqrt{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}{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 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^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}g^2 \frac{c_w}{s_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}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 e^A - u_j^A (\gamma \partial + m_u^A) u_j^A - \bar{d}_j^A (\gamma \partial + m_d^A) d_j^A + \\
 & ig s_w A_\mu [-(\bar{e}^A \gamma^\mu e^A) + \frac{2}{3}(\bar{u}_j^A \gamma^\mu u_j^A) - \frac{1}{3}(\bar{d}_j^A \gamma^\mu d_j^A)] + \frac{ig}{4c_w} Z_\mu^0 (\bar{e}^A \gamma^\mu (1 + \gamma^5) e^A) + (\bar{e}^A \gamma^\mu (1 S_\mu^0 - 1 - \gamma^5) e^A) + (u_j^A \gamma^\mu (\frac{1}{3} S_\mu^0 - \\
 & 1 - \gamma^5) u_j^A) + (\bar{d}_j^A \gamma^\mu (1 - \frac{2}{3} S_\mu^0 - \gamma^5) d_j^A)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{e}^A \gamma^\mu (1 + \gamma^5) e^A) + (\bar{d}_j^A \gamma^\mu (1 + \gamma^5) d_j^A)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^A \gamma^\mu (1 + \\
 & \gamma^5) e^A) + (\bar{d}_j^A C_{\alpha\beta}^A \gamma^\mu (1 + \gamma^5) d_j^A)] + \frac{ig}{2\sqrt{2}} W_\mu^0 [-\bar{e}^A (\bar{e}^A \gamma^\mu (1 - \gamma^5) e^A) + \phi^- (\bar{e}^A (1 + \gamma^5) e^A)] - \frac{g \frac{m_e}{M}}{2} [H (\bar{e}^A e^A) + \\
 & i \phi^0 (\bar{e}^A \gamma^\mu e^A)] + \frac{ig}{2M^2} \phi^{0*} [-m_u^A (\bar{u}_j^A C_{\lambda\alpha} (1 - \gamma^5) d_j^A) + m_d^A (\bar{d}_j^A C_{\lambda\alpha} (1 + \gamma^5) d_j^A) + \frac{ig}{2M\sqrt{2}} \delta^A [m_d^A (\bar{d}_j^A C_{\lambda\alpha}^T (1 + \gamma^5) d_j^A) - \\
 & m_u^A (\bar{u}_j^A C_{\lambda\alpha}^T (1 - \gamma^5) d_j^A) - \frac{g \frac{m_u}{M}}{2} H (\bar{u}_j^A u_j^A) - \frac{g \frac{m_d}{M}}{2} H (\bar{d}_j^A d_j^A) + \frac{ig \frac{m_u}{M}}{2} \phi^0 (\bar{u}_j^A \gamma^5 u_j^A) - \frac{ig \frac{m_d}{M}}{2} \phi^0 (\bar{d}_j^A \gamma^5 d_j^A)] + X^+ (\bar{d}^{0*} - \\
 & M^2) X^+ + \bar{X}^- (\bar{d}^2 - M^2) X^- + \bar{X}^0 (\bar{d}^2 - \frac{M^2}{g_1^2}) X^0 + \bar{Y} \partial^2 Y + ig s_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 s_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^-) + ig s_w W_\mu^0 (\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}{2} \bar{X}^0 X^0 H] + \frac{1-2g}{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}g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$



# The Next Standard Model

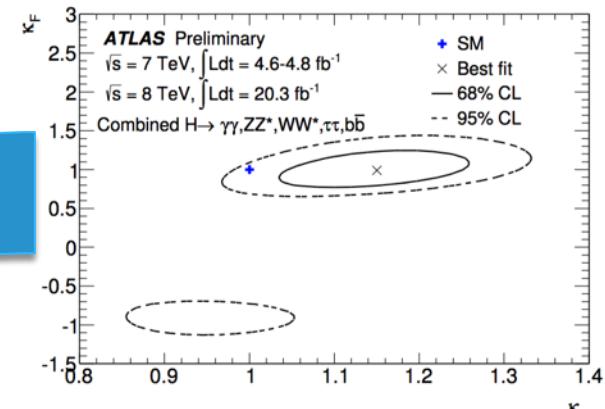
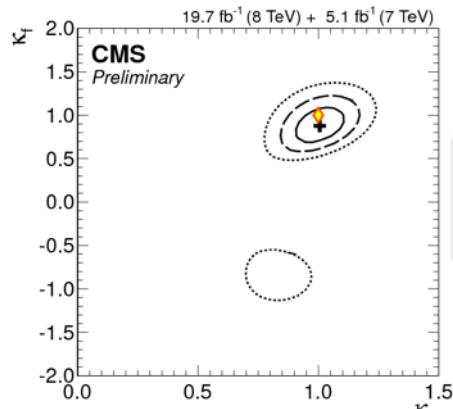
[ <http://cern.ch/go/dW6z> ]

$$\begin{aligned}
 & -\frac{1}{2}g_{\mu\nu}^{ab}\partial_\nu g_\mu^a - g_{\mu\nu}f^{abc}\partial_\mu Z_\nu^a\partial_\mu^b g_\nu^c - \frac{1}{4}g_\mu^{ab}f^{abc}\partial_\mu^b g_\nu^c + \frac{1}{2}ig_c^2(\bar{\psi}_l^\mu \gamma^\alpha \psi_l^\mu)g_\mu^a + \bar{G}^\mu \partial^\nu G^\mu + g_{\mu\nu}f^{abc}\partial_\mu \bar{G}^\mu G^\nu g_\mu^a - \\
 & \partial_\mu W_\mu^a\partial_\nu W_\nu^a - M^2 W_\mu^a W_\nu^a - \frac{1}{2}\partial_\mu Z_\mu^a\partial_\nu Z_\nu^a - \frac{1}{2g_s^2}M^2 Z_\mu^a Z_\nu^a - \frac{1}{2}\partial_\mu A_\mu \partial_\nu A_\nu - \frac{1}{4}\partial_\mu H \partial_\nu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\nu \phi^- - \\
 & M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^+ \partial_\mu \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_{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_\nu^- \partial_\mu W_\mu^+)] - ig s_w[\partial_\mu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \\
 & A_\mu (W_\mu^+ \partial_\nu W_\nu^- - W_\nu^- \partial_\mu W_\mu^+) + A_\mu (W_\mu^+ \partial_\nu W_\nu^- - W_\nu^- \partial_\mu 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_\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 + \frac{1}{2}g \frac{M}{g_s^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) - i g \frac{s_w}{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-s_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}{2}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2(\phi^+ \phi^-)] - \frac{1}{4}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2S_\mu^0 - 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}g^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}g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - \\
 & g^2 \frac{s_w^2}{c_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}^5(\gamma \partial + m_e^5)e^5 - \bar{e}^5 \gamma \partial e^5 - u_j^5(\gamma \partial + m_u^5)u_j^5 - \bar{d}_j^5(\gamma \partial + m_d^5)d_j^5 + \\
 & ig s_w A_\mu [-(\bar{e}^5 \gamma^\mu e^5) + \frac{2}{3}(\bar{u}_j^5 \gamma^\mu u_j^5) - \frac{1}{3}(\bar{d}_j^5 \gamma^\mu d_j^5)] + \frac{ig}{4c_w} Z_\mu^0 (\bar{e}^5 \gamma^\mu (1 + \gamma^5) e^5) + (\bar{e}^5 \gamma^\mu (4S_\mu^0 - 1 - \gamma^5) e^5) + (\bar{u}_j^5 \gamma^\mu (1 + \gamma^5) u_j^5) + (\bar{d}_j^5 \gamma^\mu (1 + \gamma^5) d_j^5) + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{e}^5 \gamma^\mu (1 + \gamma^5) e^5) + (\bar{u}_j^5 \gamma^\mu (1 + \gamma^5) u_j^5)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^5 \gamma^\mu (1 + \gamma^5) e^5) + (\bar{d}_j^5 \gamma^\mu (1 + \gamma^5) d_j^5)] + \frac{ig}{2M} [H(\bar{e}^5 e^5) + \\
 & i\phi^5(\bar{e}^5 \gamma^\mu e^5)] + \frac{ig}{2M\sqrt{2}} \phi^{5t} [-m_u^5(\bar{u}_j^5 C_{\lambda\alpha}(1 - \gamma^5) u_j^5) + m_d^5(\bar{d}_j^5 C_{\lambda\alpha}(1 + \gamma^5) d_j^5) + \frac{ig}{2M\sqrt{2}} \phi^{5t} [m_u^5(\bar{u}_j^5 C_{\lambda\alpha}^T(1 + \gamma^5) u_j^5) - \\
 & m_d^5(\bar{d}_j^5 C_{\lambda\alpha}^T(1 - \gamma^5) d_j^5) - \frac{g^2 m_u^2}{2} H(\bar{u}_j^5 u_j^5) - \frac{g^2 m_d^2}{2} H(\bar{d}_j^5 d_j^5) + \frac{2g^2 m_u^2}{2} \phi^{5t}(\bar{u}_j^5 \gamma^5 u_j^5) - \frac{2g^2 m_d^2}{2} \phi^{5t}(\bar{d}_j^5 \gamma^5 d_j^5)] + X^{+}(\bar{d}^{2t} - \\
 & M^2)X^{+} + \bar{X}^{-}(\bar{d}^{2t} - M^2)X^{-} + \bar{X}^0(\bar{d}^{2t} - \frac{M^2}{2})X^0 + \bar{Y} \partial^2 Y + ig s_w W_\mu^+(\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^-(\partial_\mu \bar{X}^- X^- + \\
 & \partial_\mu \bar{X}^+ X^+) + 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}{2}X^0 X^0 H] + \frac{1-2g}{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

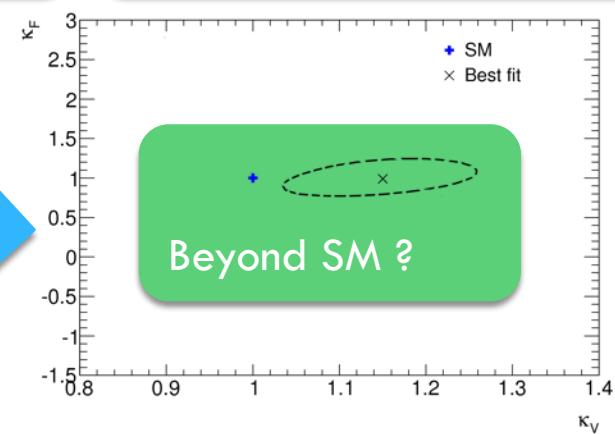
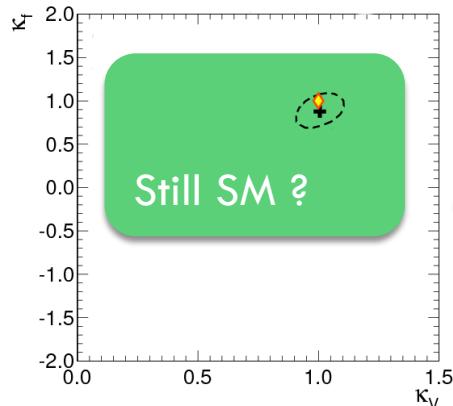
# The future is in precision and accuracy



Accelerator physicists  
**More collisions**

Experimentalists  
**Better detectors & analyses**

Theorists  
**Better predictions**



# Moving forward

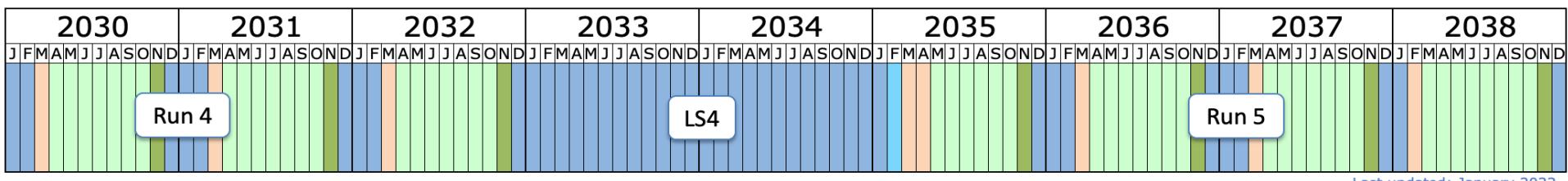
- We must examine this Higgs to the fullest extent !
  - It may be the only clue to leave the SM oasis and cross the desert.





# Deeper into the rabbit hole

109



Last updated: January 2022

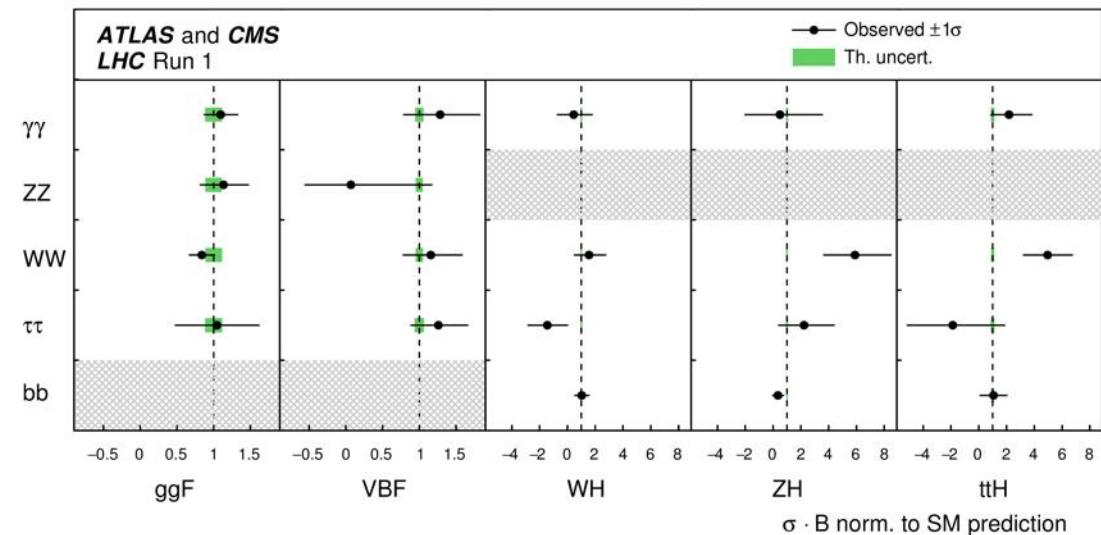
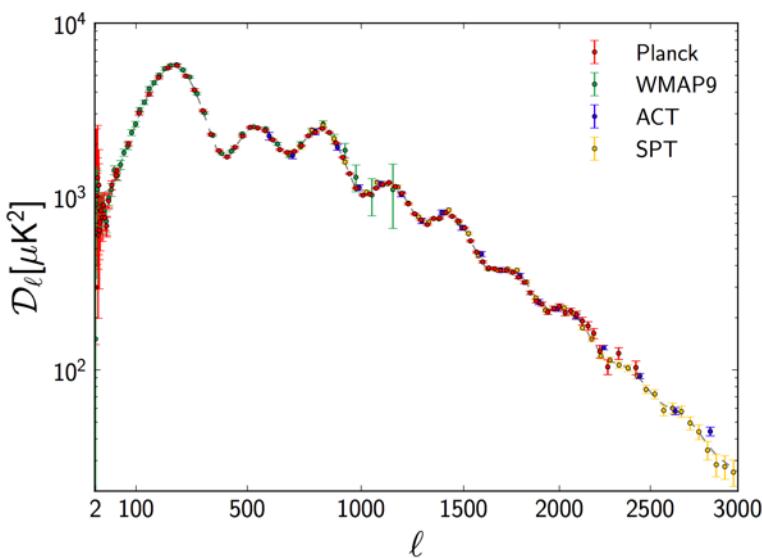
- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning/magnet training

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

110

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

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

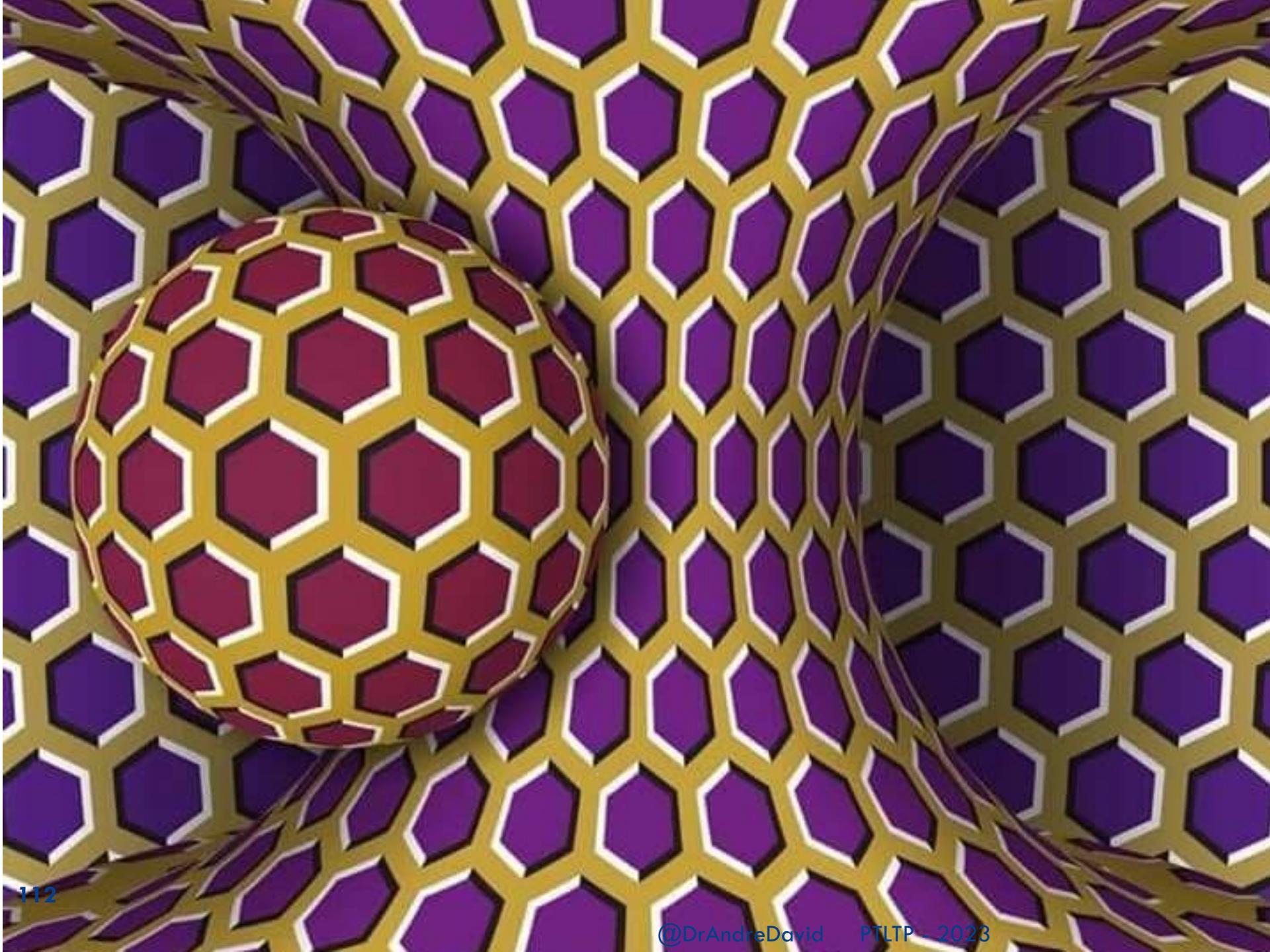


Looking forward to surprises at higher energy: PeV neutrinos, #MoarData at LHC 13 TeV, ...

# TERMOS E CONDIÇÕES GERAIS DE UTILIZAÇÃO

111

- Não deixe perguntas por fazer. Seja crítico.
- Pensar mais pode fazer-lhe bem.
- Os resultados dependem de convicções e crenças pré-existentes. Agite-as antes de tirar conclusões.
- Mantenha-se aberto a outros pontos de vista.
- O conhecimento não gera infelicidade e pode ajudar a combatê-la.
- A ciência desilude quem não está alinhado com a realidade.
- Os presentes Termos e Condições são regidos e interpretados de acordo com o método científico.
- É competente o método experimental com exclusão de qualquer outro para dirimir quaisquer conflitos que resultem da interpretação e aplicação dos presentes Termos e Condições.





# “...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>

# 750 reasons not to



# 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**.<sup>[8][9]</sup> The anomaly was absent in data collected in 2016, suggesting that the diphoton excess was a statistical fluctuation.<sup>[1][2]</sup> 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.<sup>[10]</sup> 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.<sup>[3]</sup> 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.<sup>[11]</sup> 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  $\text{GeV}/c^2$ . 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  $\text{GeV}/c^2$  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

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

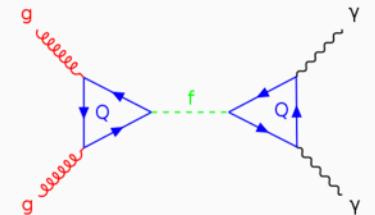
(fb=femtobarns)

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.<sup>[1][2]</sup>

### Digamma

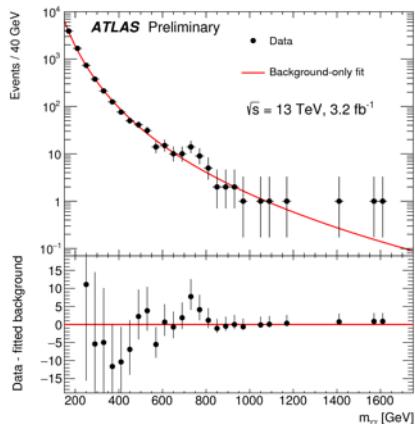


Possible production and decay mechanism of the digamma resonance at LHC.

### Composition Elementary particle

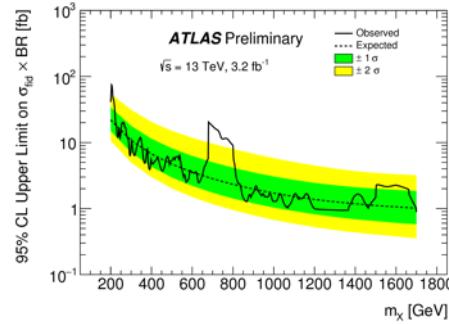
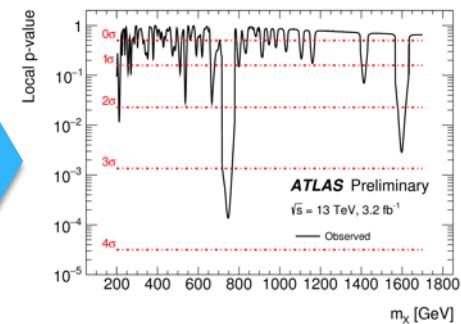
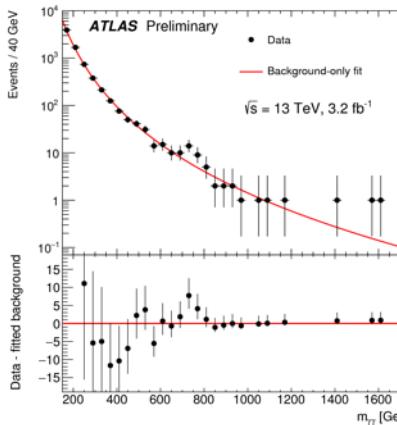
<b>Statistics</b>	suspected bosonic
<b>Status</b>	Refuted; absent in August 2016 data <sup>[1][2]</sup>
<b>Symbol</b>	$F$ , <sup>[3]</sup> $F(750)$ , <sup>[4]</sup> $\phi$ , <sup>[5]</sup> $X$ , <sup>[6]</sup> $\eta_{zy}$ <sup>[7]</sup>
<b>Discovered</b>	Resonance of mass $\approx 750$ GeV decaying into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

# Diphoton resonances



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

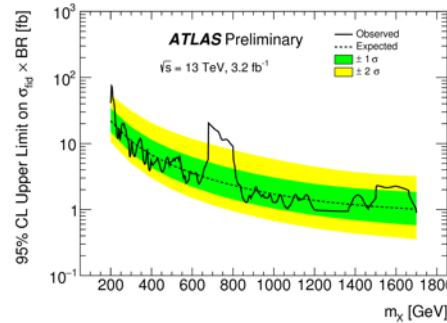
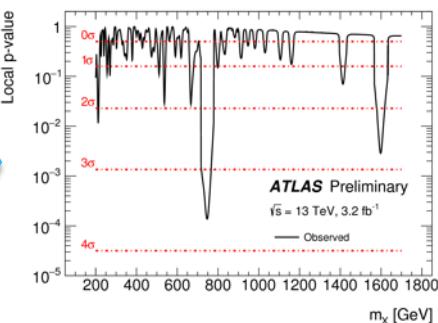
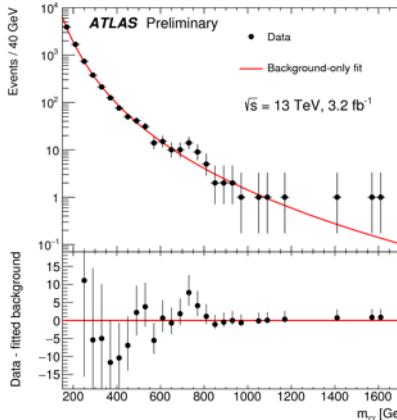
# Diphoton resonances



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

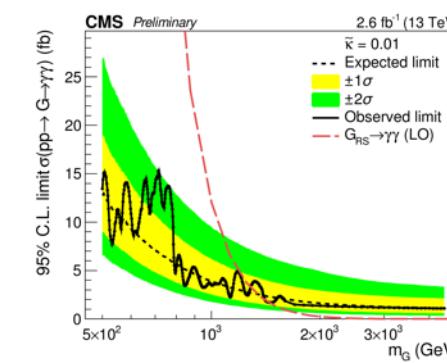
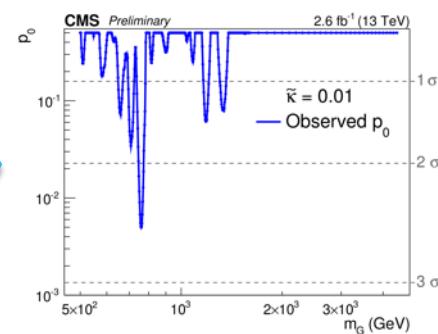
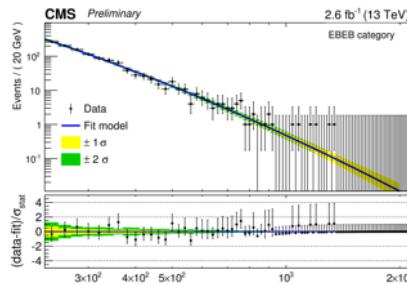
For  $m_X = 750 \text{ GeV}$   
 $3.6\sigma \rightarrow 2.0\sigma \text{ after LEE}$   
 $(3.9\sigma \rightarrow 2.3\sigma \text{ for } \Gamma = 6\%)$

# Diphoton resonances



For  $m_X = 750 \text{ GeV}$   
 $3.6\sigma \rightarrow 2.0\sigma$  after LEE  
 $(3.9\sigma \rightarrow 2.3\sigma \text{ for } \Gamma = 6\%)$

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



For  $m_G = 760 \text{ GeV}$   
 $2.6\sigma \rightarrow 1.2\sigma$  after LEE

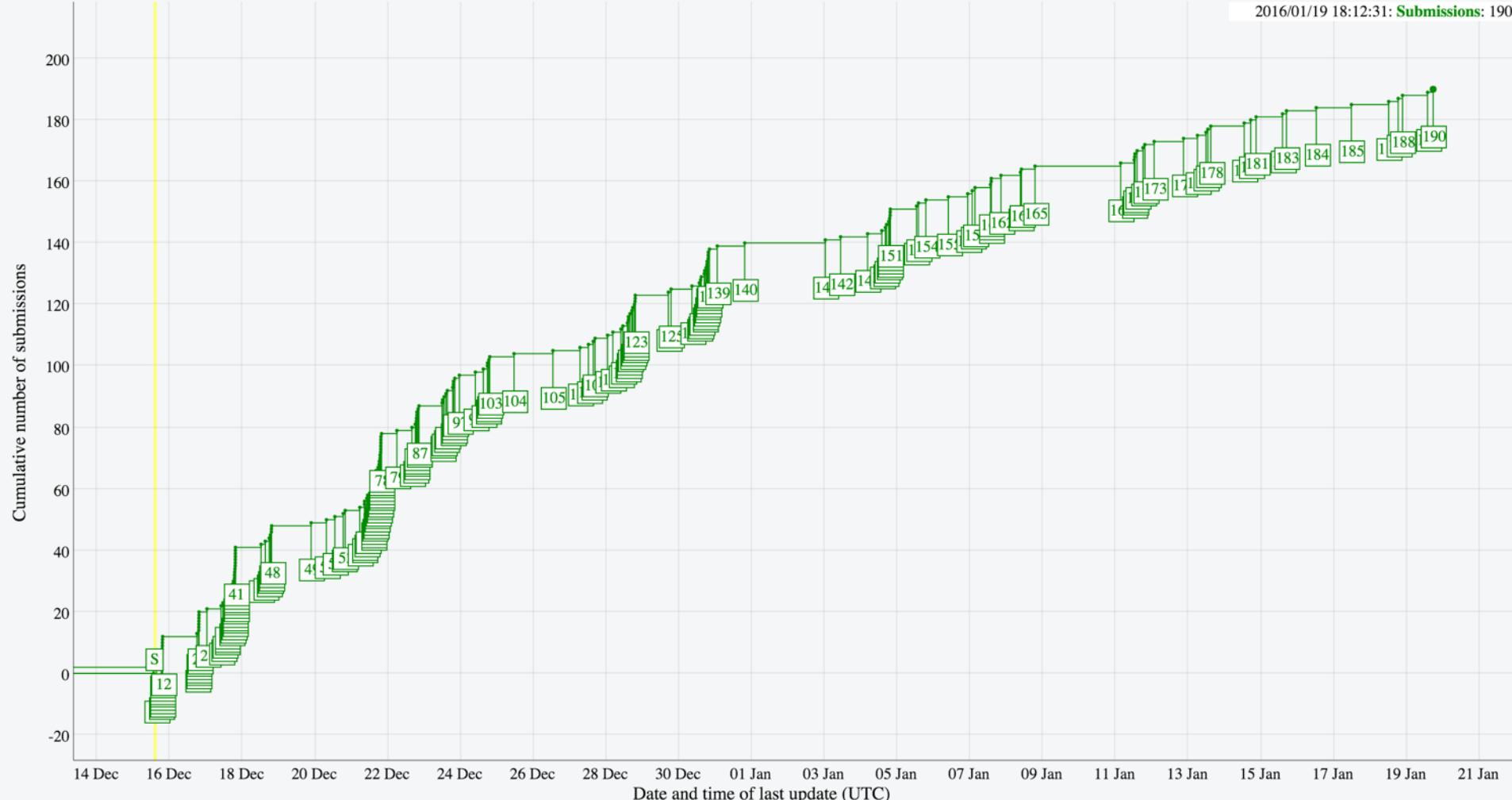


# Post-seminar stampede

119

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

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



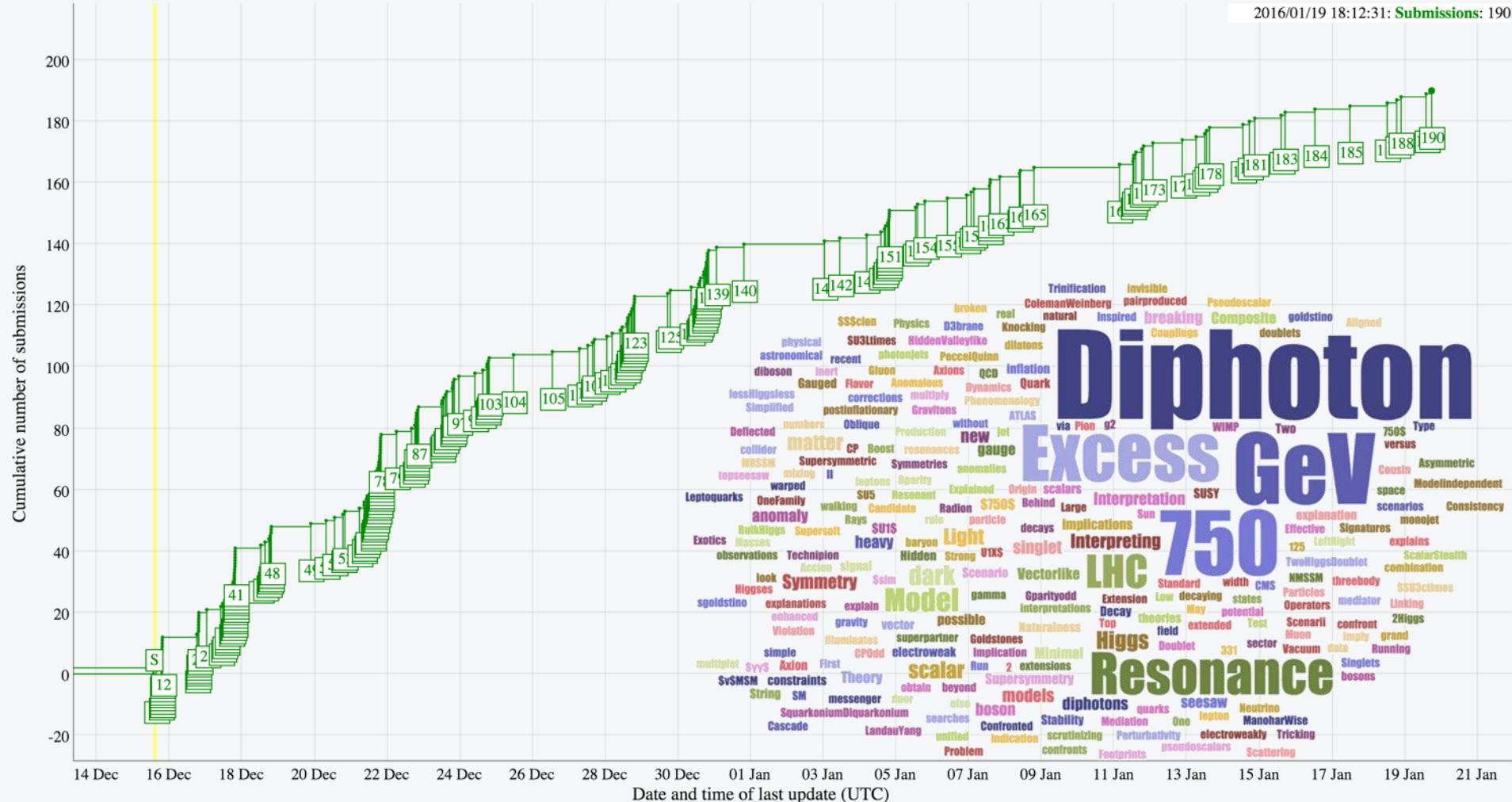


# Post-seminar stampede

120

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

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





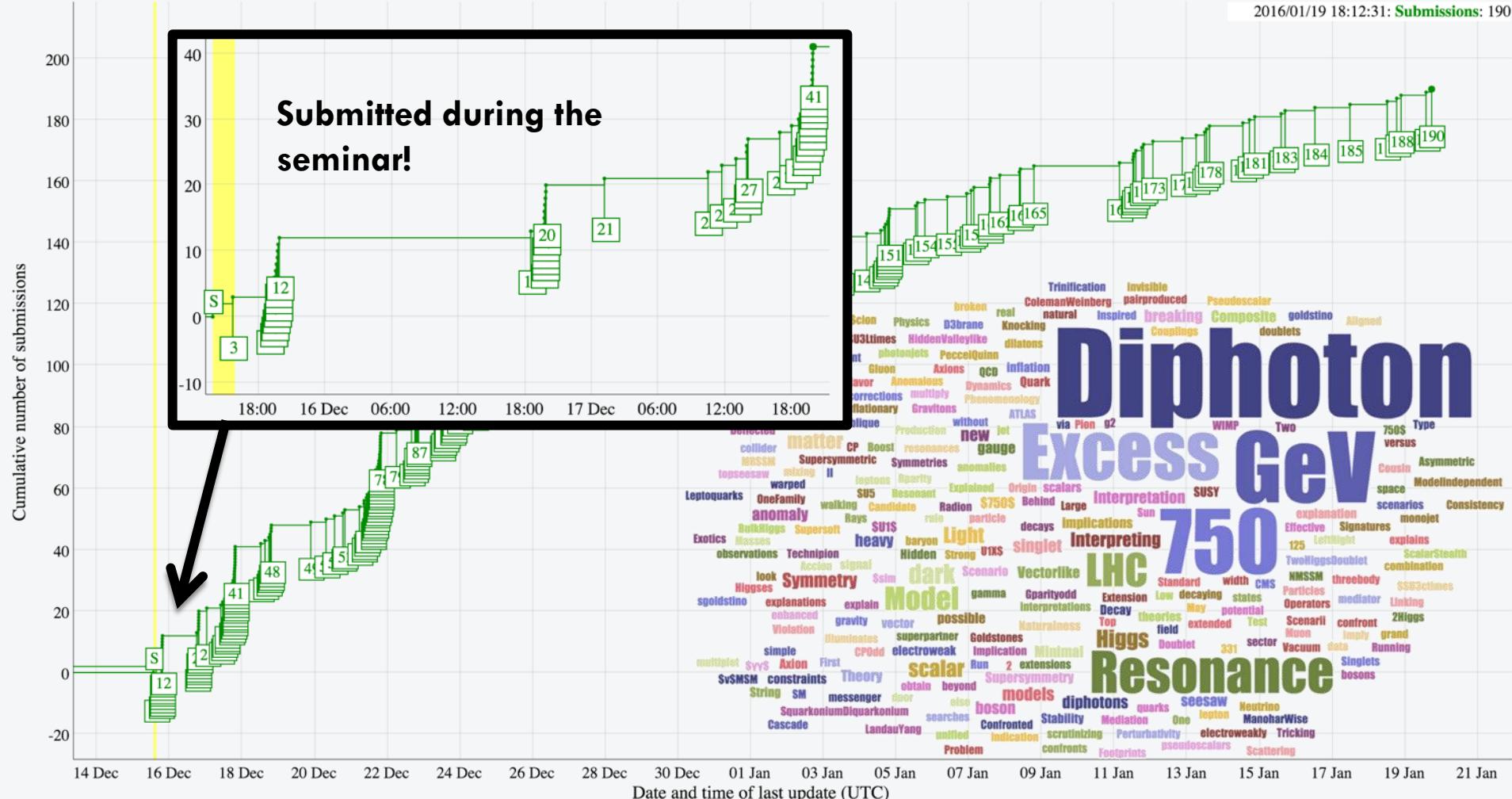
# Post-seminar stampede

121

[ <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?



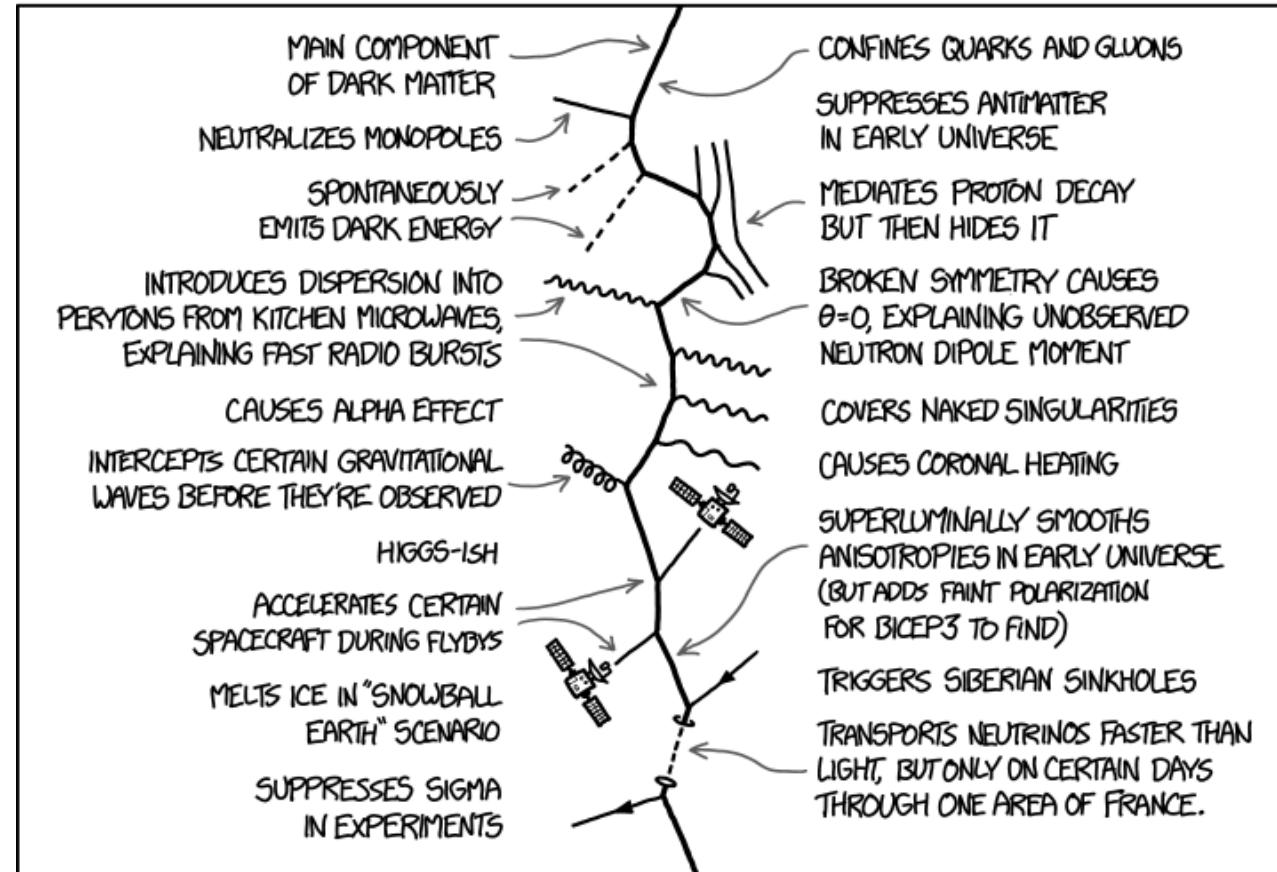
122

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

A CHRISTMAS GIFT FOR PHYSICISTS:

## THE FIXION

A NEW PARTICLE THAT EXPLAINS EVERYTHING

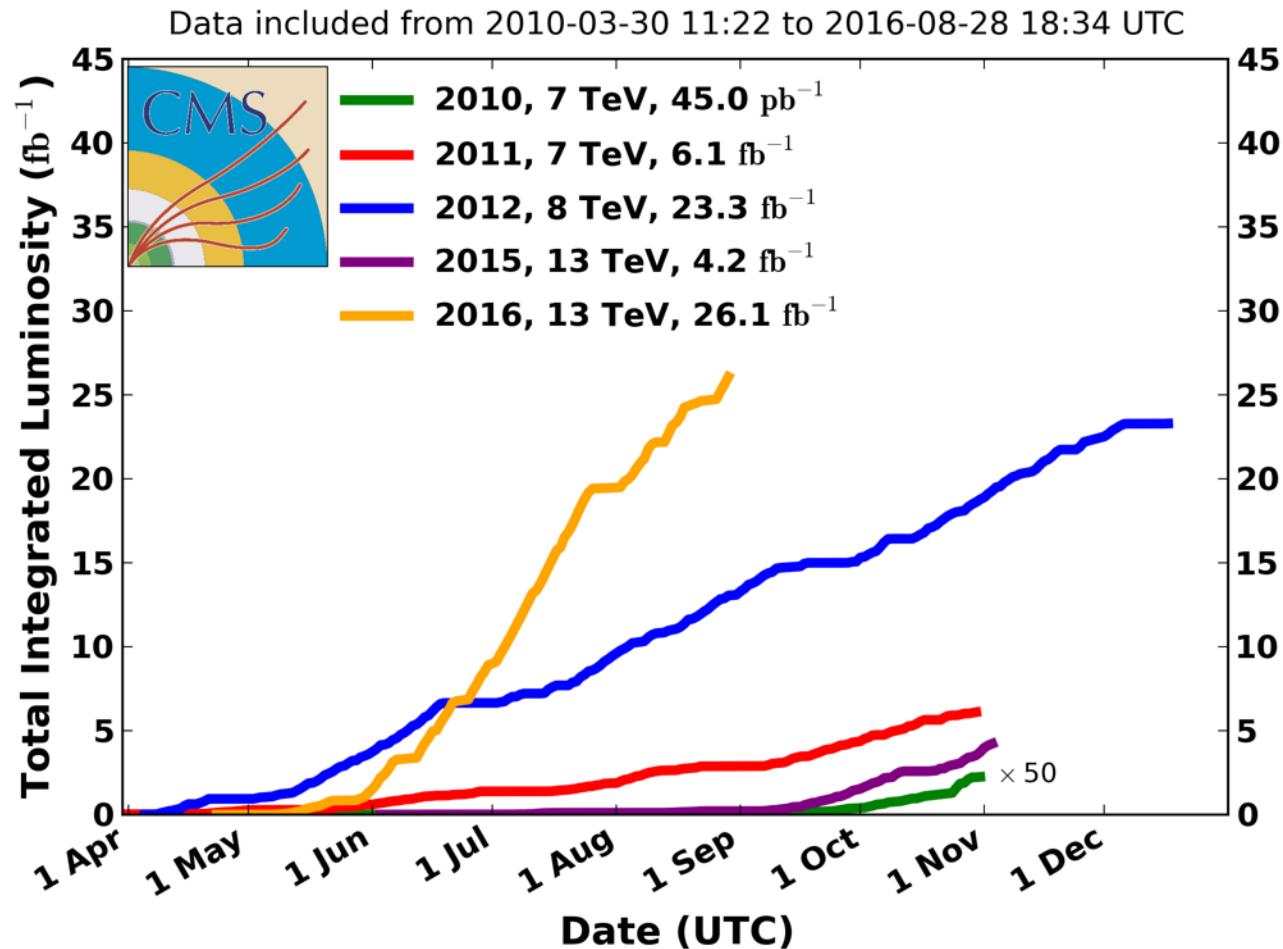


# #MoarData



123

## CMS Integrated Luminosity, pp

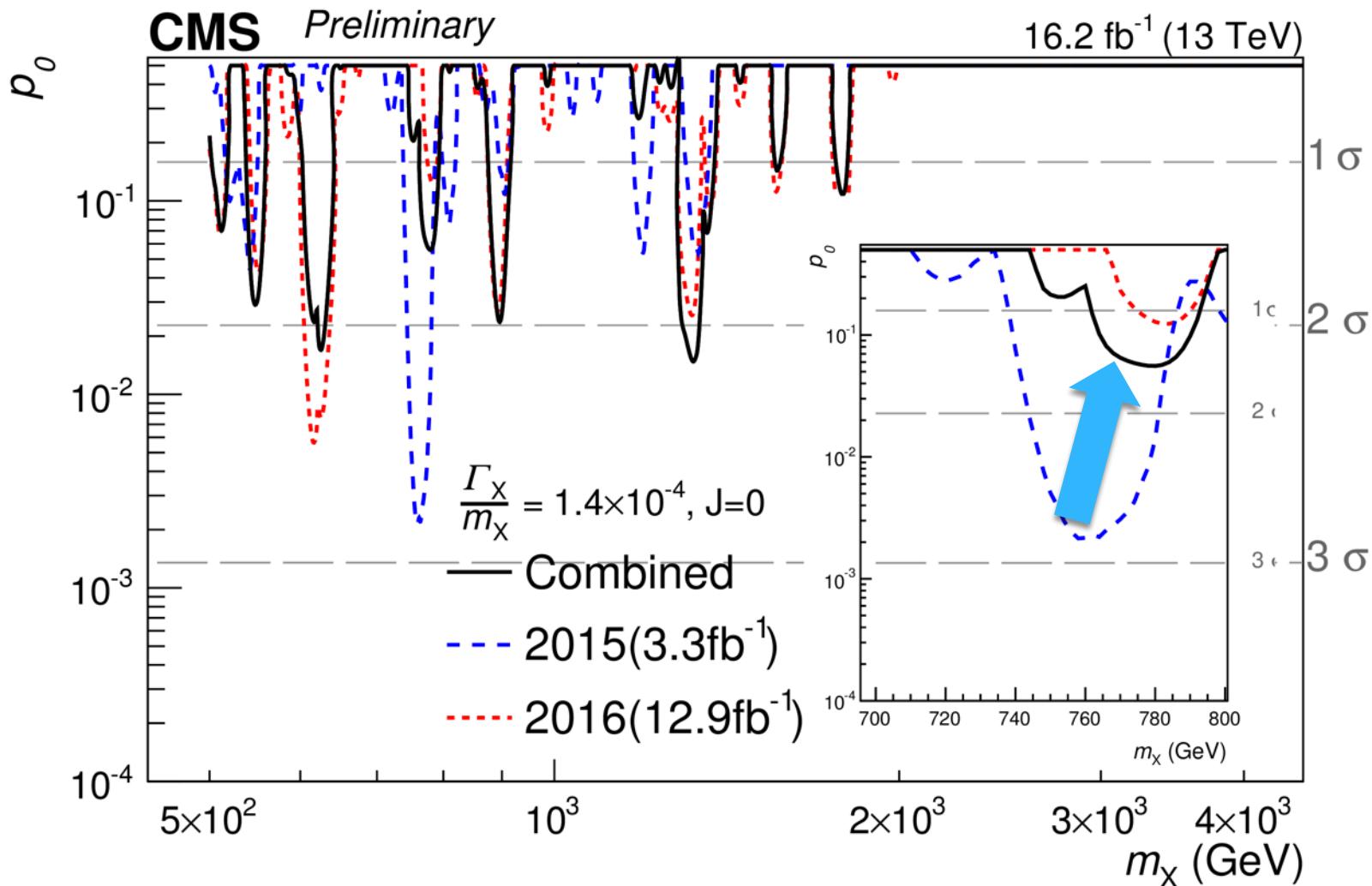




# The effect of #MoarData

124

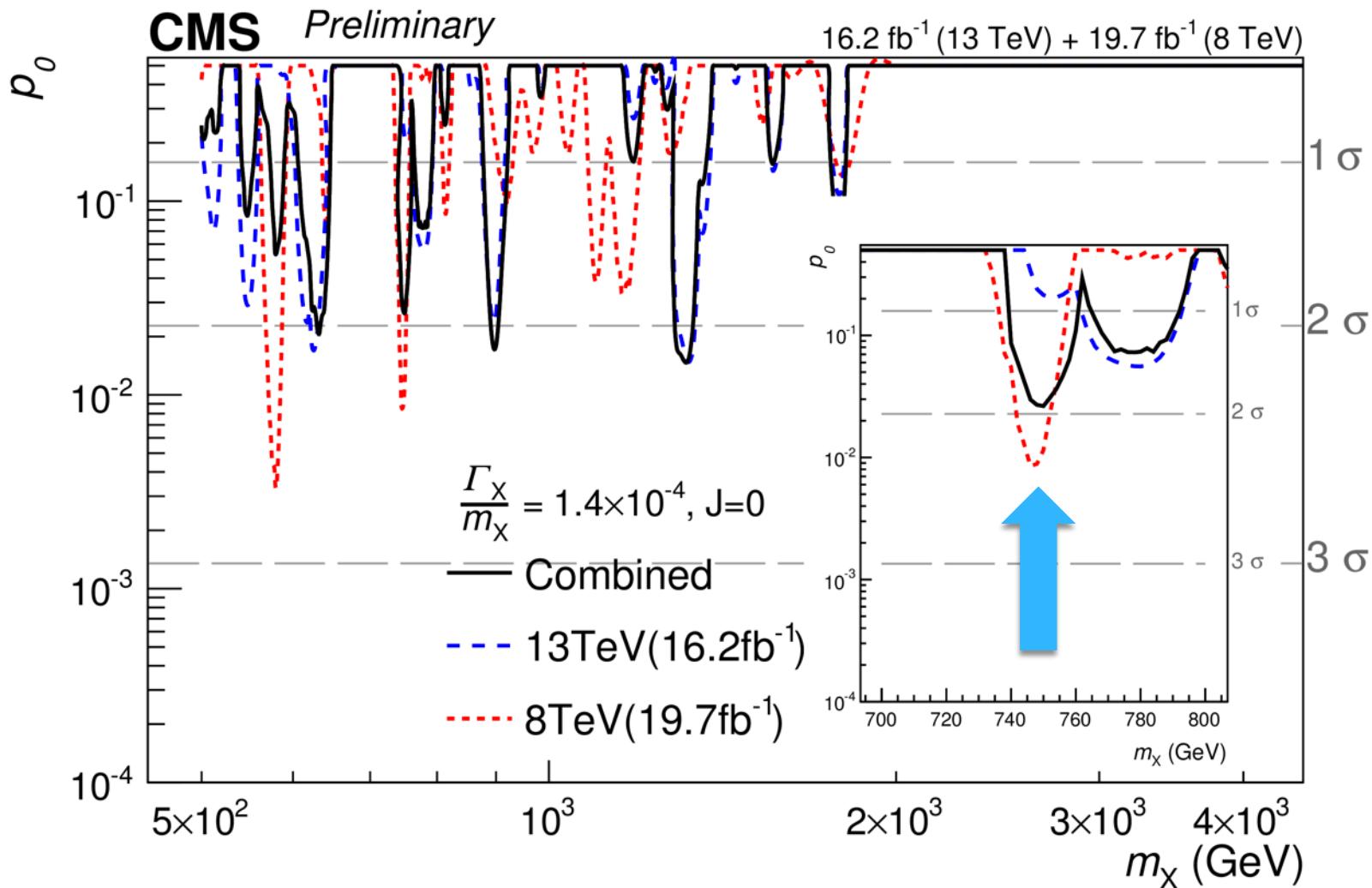
[ CMS-PAS-EXO-16-027 ]



# The effect of even #MoarData

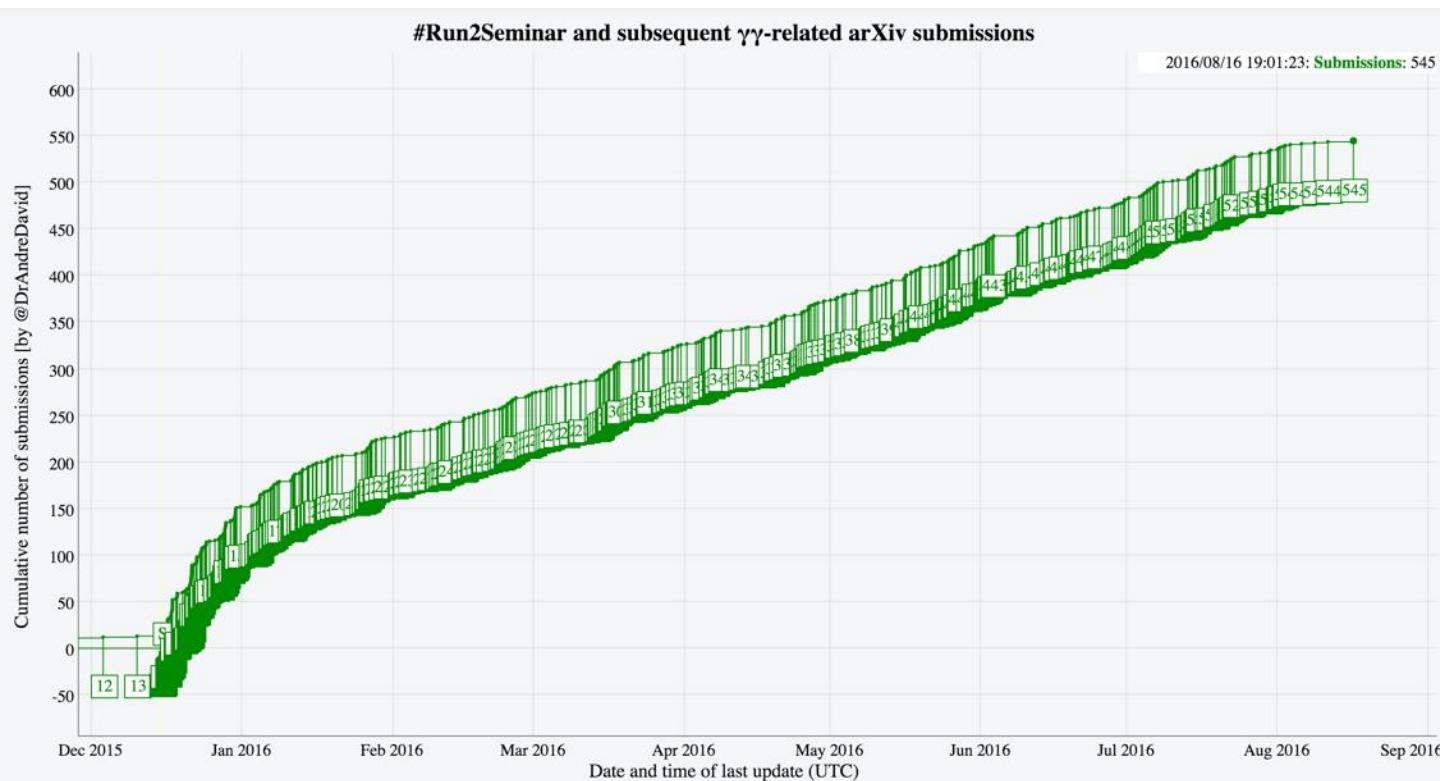
125

[ CMS-PAS-EXO-16-027 ]



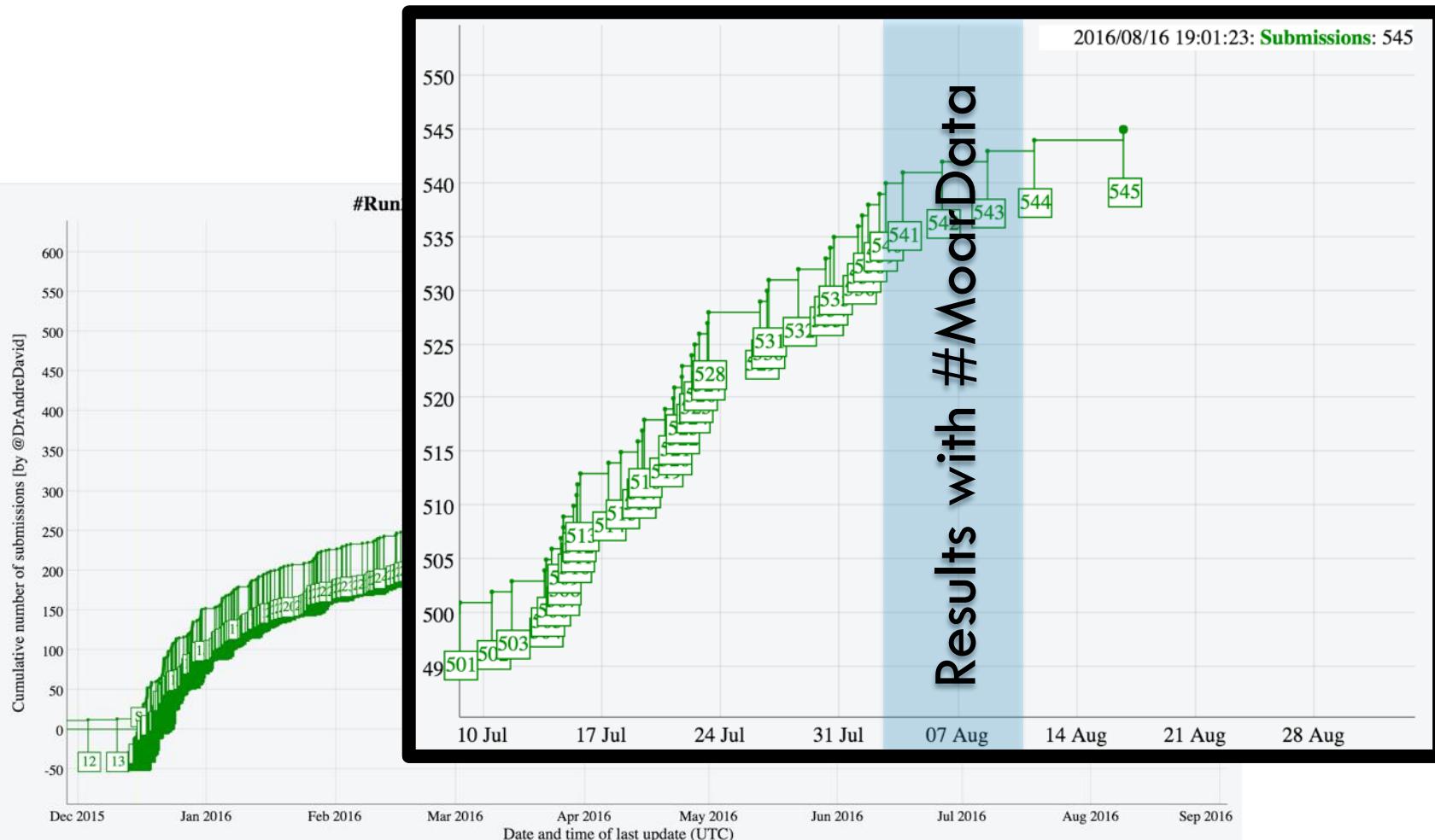
# Stampede no “moar”

126

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

# Stampede no “moar”

127

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

# Stampede no “moar”

128

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